



Particle Physics

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The Plan

Part 1: Standard Model & experimental techniques

Part 2: Theory basics and precision tests

Part 3: Physics at the LHC

Part I

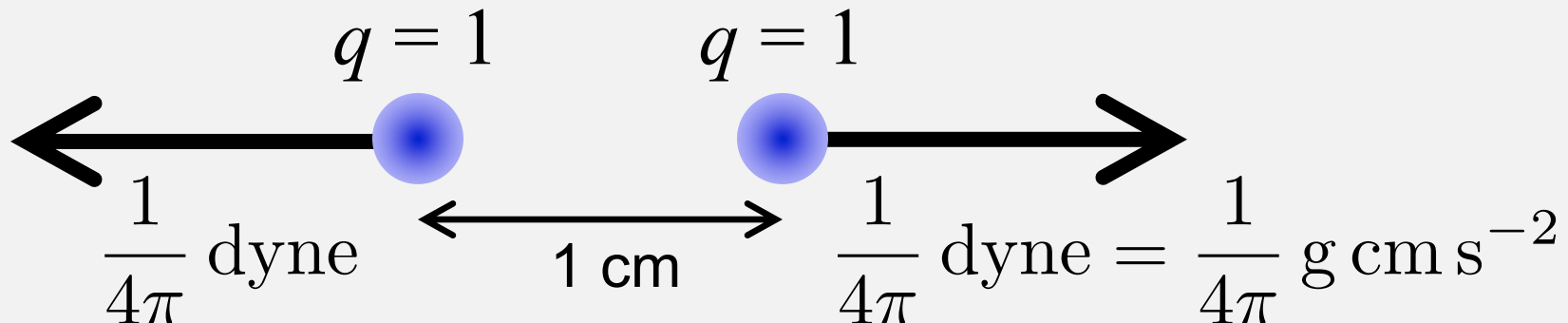
- Elements of the Standard Model: Matter & Forces
- Accelerators
- Detectors

Preliminary remarks: units

$$\hbar = c = 1$$

Heaviside-Lorentz units $\epsilon_0 = 1$

$$e = \sqrt{4\pi\alpha} = \sqrt{\frac{4\pi}{137.03\dots}} > 0$$



Four-vectors in special relativity

covariant: $(a^\mu) \equiv (a^0, a^1, a^2, a^3) \equiv (a^0, \vec{a})$

Lorentz-transforms like $(t, x, y, z) \equiv (t, \vec{x})$

contravariant:

$$\begin{aligned}(a_\mu) &\equiv (a_0, a_1, a_2, a_3) \\ &\equiv (a^0, -a^1, -a^2, -a^3) = (a^0, -\vec{a})\end{aligned}$$

products: $ab \equiv a_\mu b^\mu = a^\mu b_\mu = a^0 b^0 - \vec{a} \cdot \vec{b}$
are invariant under Lorentz transformations

Examples:

$$(x^\mu) = (t, \vec{x}) \quad \text{space-time}$$

$$(\partial_\mu) = \left(\frac{\partial}{\partial x^\mu} \right) = \left(\frac{\partial}{\partial t}, \vec{\nabla} \right) \quad \text{4-derivative}$$

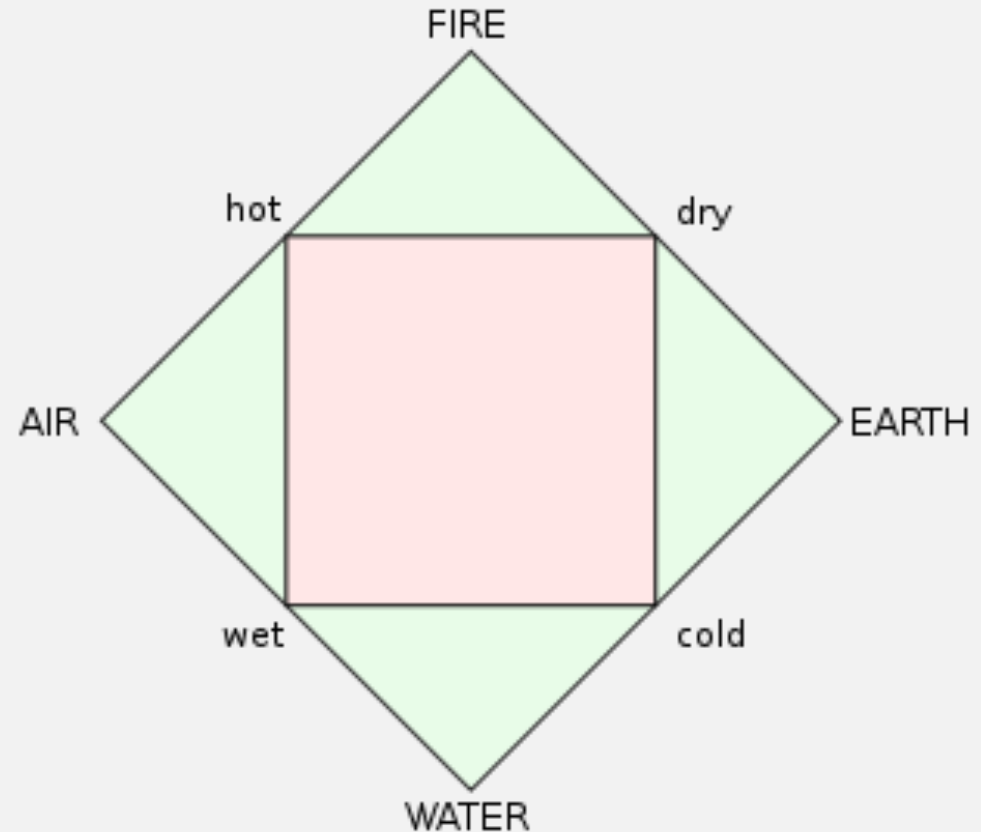
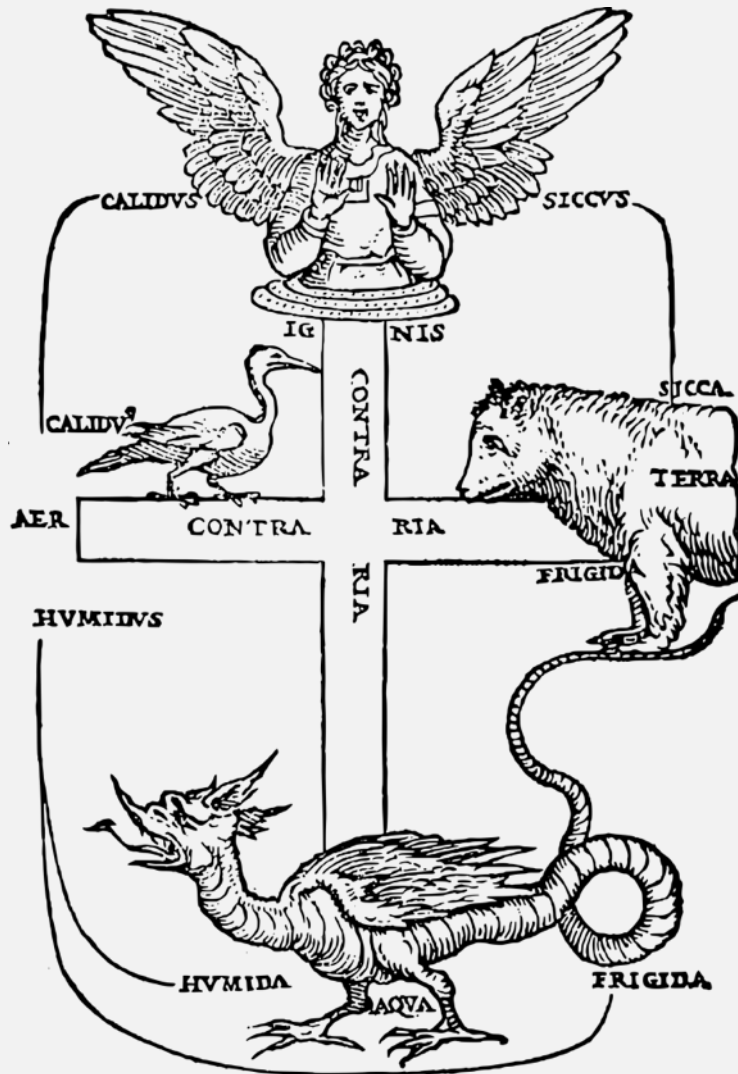
$$(A^\mu) = (\phi, \vec{A}) \quad \text{electromagnetic 4-potential}$$

$$(j^\mu) = (\rho, \vec{j}) \quad \text{electromagnetic 4-current}$$

$$(p^\mu) = (E, \vec{p}) \quad \text{4-momentum} \quad \boxed{p^2 = p_\mu p^\mu = m^2}$$

$$(i\partial^\mu) = \left(i\frac{\partial}{\partial t}, -i\vec{\nabla} \right) \quad \text{4-momentum operator}$$

Structure of Matter (Empedokles et al., ≈ 500 b.C.)



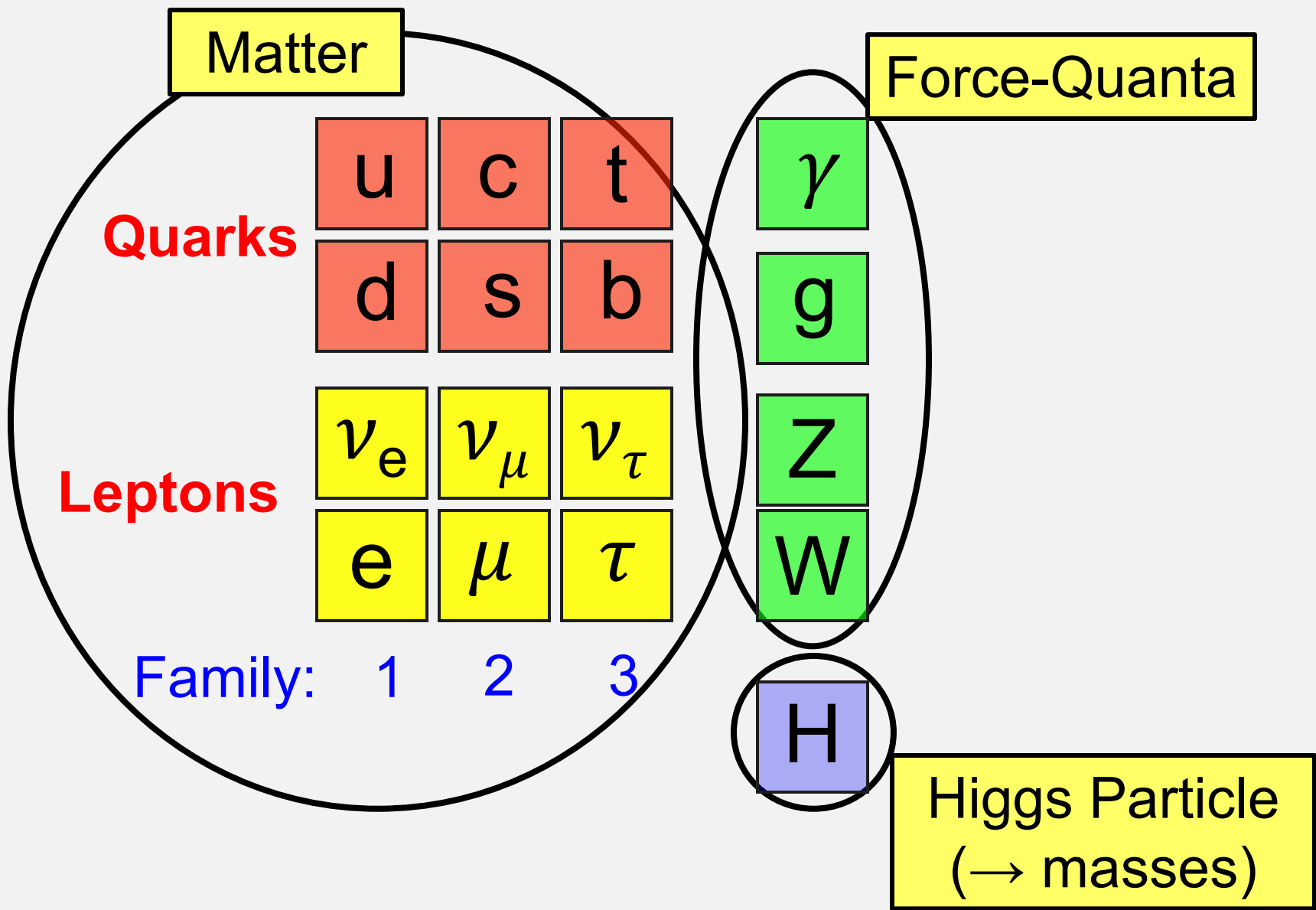
- quite successful
- lots of applications
- ... somewhat coarse

Structure of Matter (Mendelejev, Meyer, 1869)

Periodensystem der Elemente																	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Wasserstoff 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Bor 10.81	6 C Kohlenstoff 12.01	7 N Stickstoff 14.01	8 O Sauerstoff 15.999	9 F Fluor 18.998	10 Ne Neon 20.18
11 Na Natrium 22.99	12 Mg Magnesium 24.31											13 Al Aluminium 26.98	14 Si Silicium 28.09	15 P Phosphor 30.97	16 S Schwefel 32.07	17 Cl Chlor 35.45	18 Ar Argon 39.95
19 K Kalium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titan 47.88	23 V Vanadium 50.94	24 Cr Chrom 52.00	25 Mn Mangan 54.94	26 Fe Eisen 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.70	29 Cu Kupfer 63.55	30 Zn Zink 65.41	31 Ga Gallium 69.72	32 Ge Germanium 72.64	33 As Arsen 74.92	34 Se Selen 78.96	35 Br Brom 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirkon 91.22	41 Nb Niobium 92.91	42 Mo Molybdän 95.94	43 Tc Technetium [98]	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silber 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Zinn 118.71	51 Sb Antimon 121.76	52 Te Tellur 127.60	53 I Iod 126.90	54 Xe Xenon 131.29
55 Cs Cäsium 132.91	56 Ba Barium 137.33	La-Lu	72 Hf Hafnium 178.49	73 Ta Tantal 180.95	74 W Wolfram 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platin 195.08	79 Au Gold 196.97	80 Hg Quecksilber 200.59	81 Tl Thallium 204.38	82 Pb Blei 207.2	83 Bi Bismut 208.98	84 Po Polonium [209]	85 At Astat [210]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium [226]	Ac-Lr	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [263]	107 Bh Bohrium [262]	108 Hs Hassium [265]	109 Mt Meitnerium [266]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [272]							

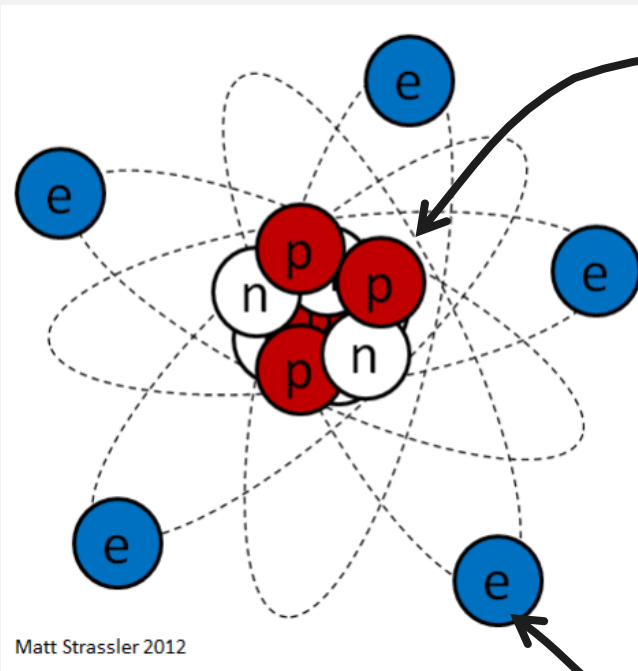
- basis of modern Chemistry
- ... sub-atomic/sub-nucleonic phenomena not covered

Structure of Matter (CERN et al., 2012)



Matter Particles

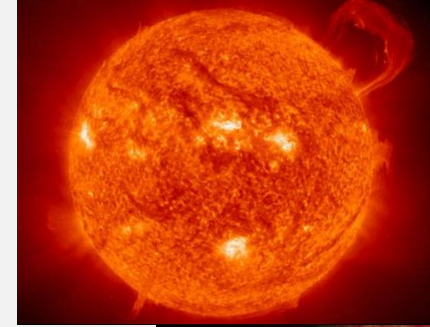
Atom



Nucleus

u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e	μ	τ

Sun

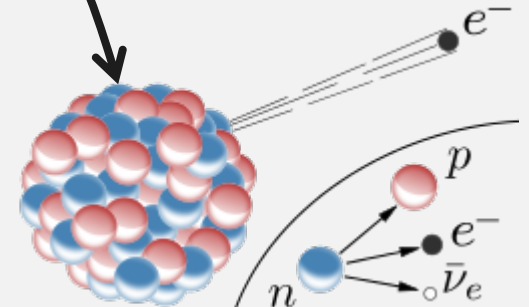


Supernova



Shell

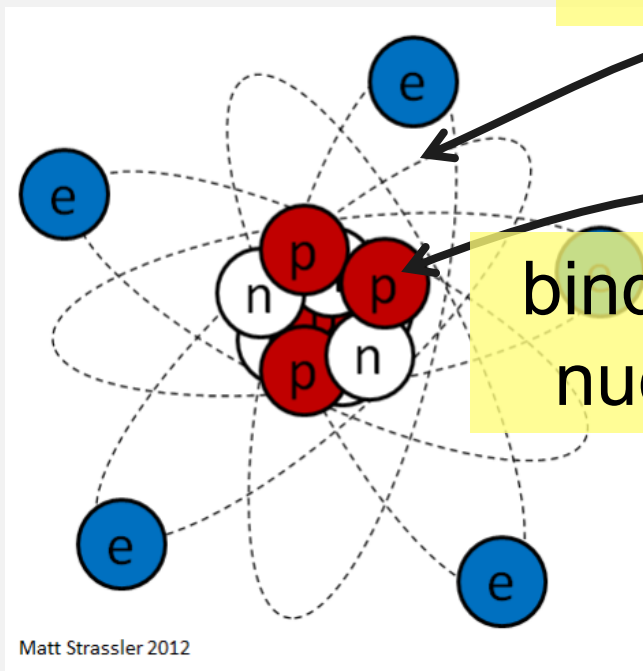
Radioactivity



Force Particles

Atom

binding
of shell



binding of
nucleus

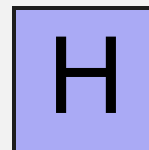


Photon (light)

Gluon

Field quanta of
weak force
(radioactivity)

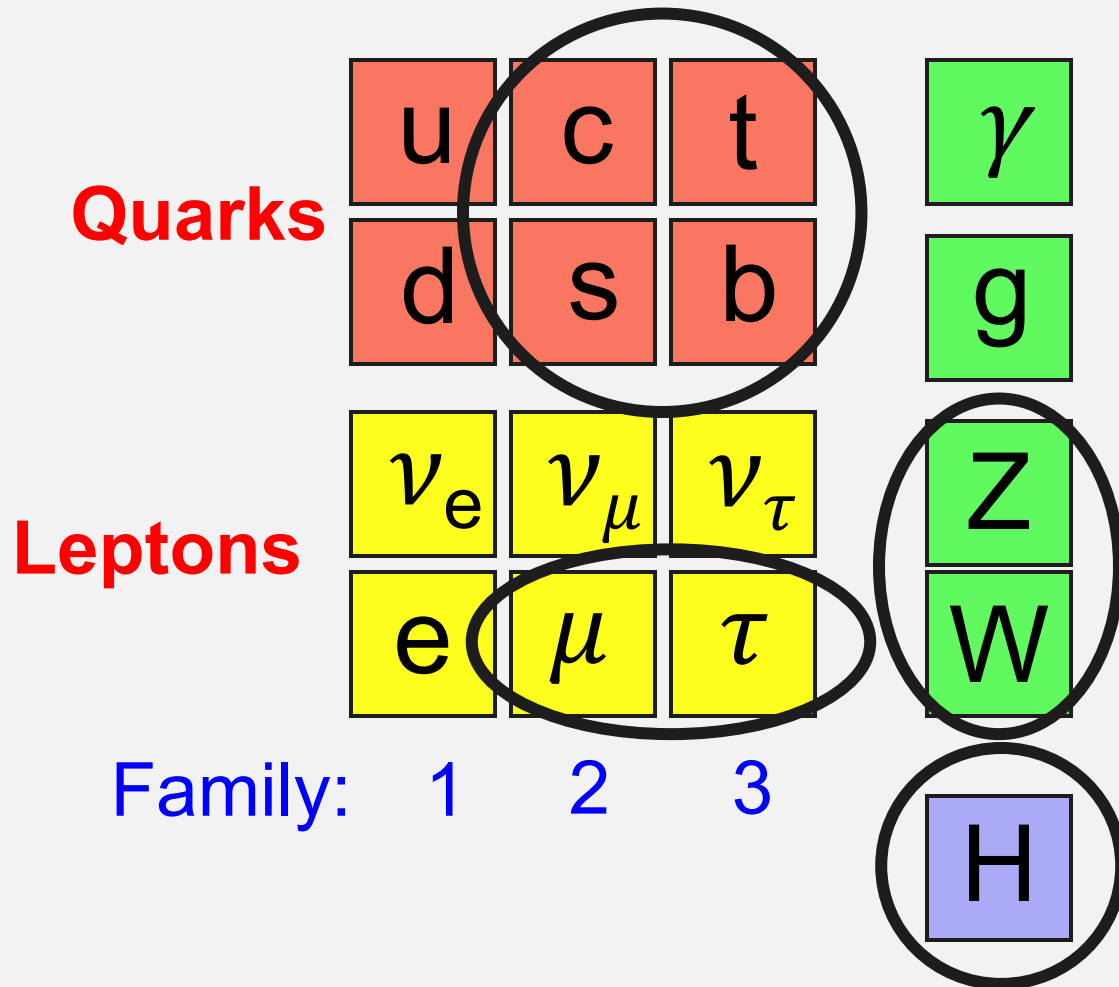
Mass Creation Particles



Higgs Boson

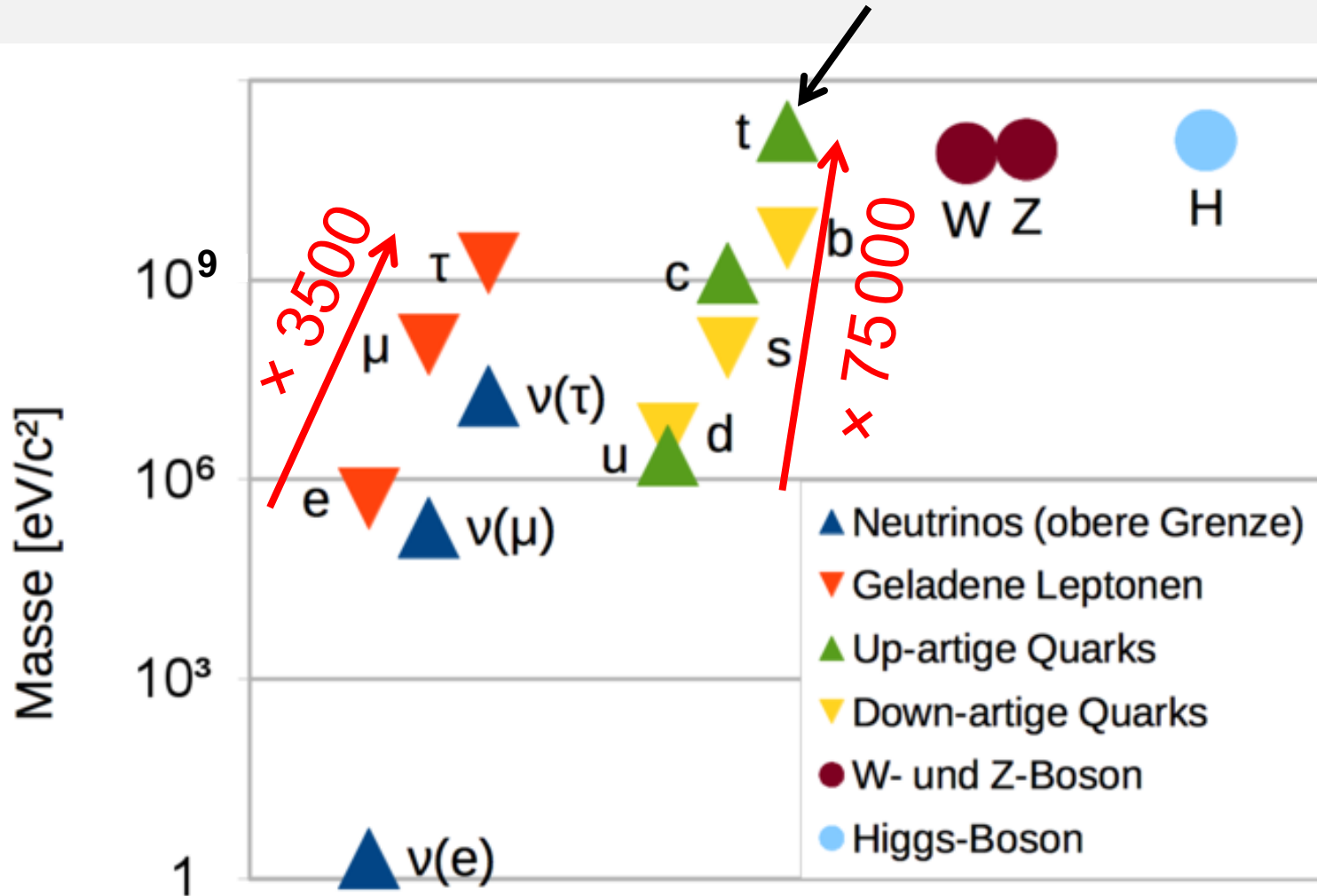
Heavy particles are very unstable ...

but can be made at accelerators for short times



Mass spectrum extremely weird ... and unexplained!!!

$$m(\text{t-Quark}) \approx 180 \cdot m(\text{Proton})$$



Quarks / Gluons (**partons**): **confined** in **hadrons** **you'll never walk alone**

Quarks

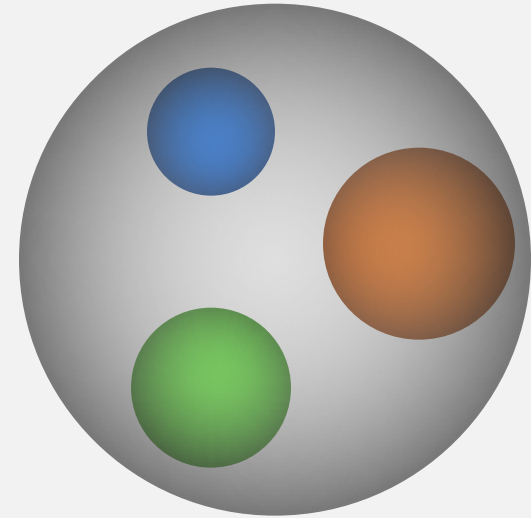
u	c	t
d	s	b

Gluons

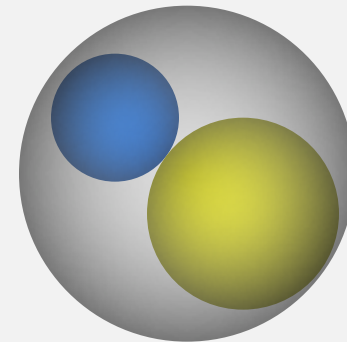


**Anti-
quarks**

$\bar{u}$	$\bar{c}$	$\bar{t}$
$\bar{d}$	$\bar{s}$	$\bar{b}$



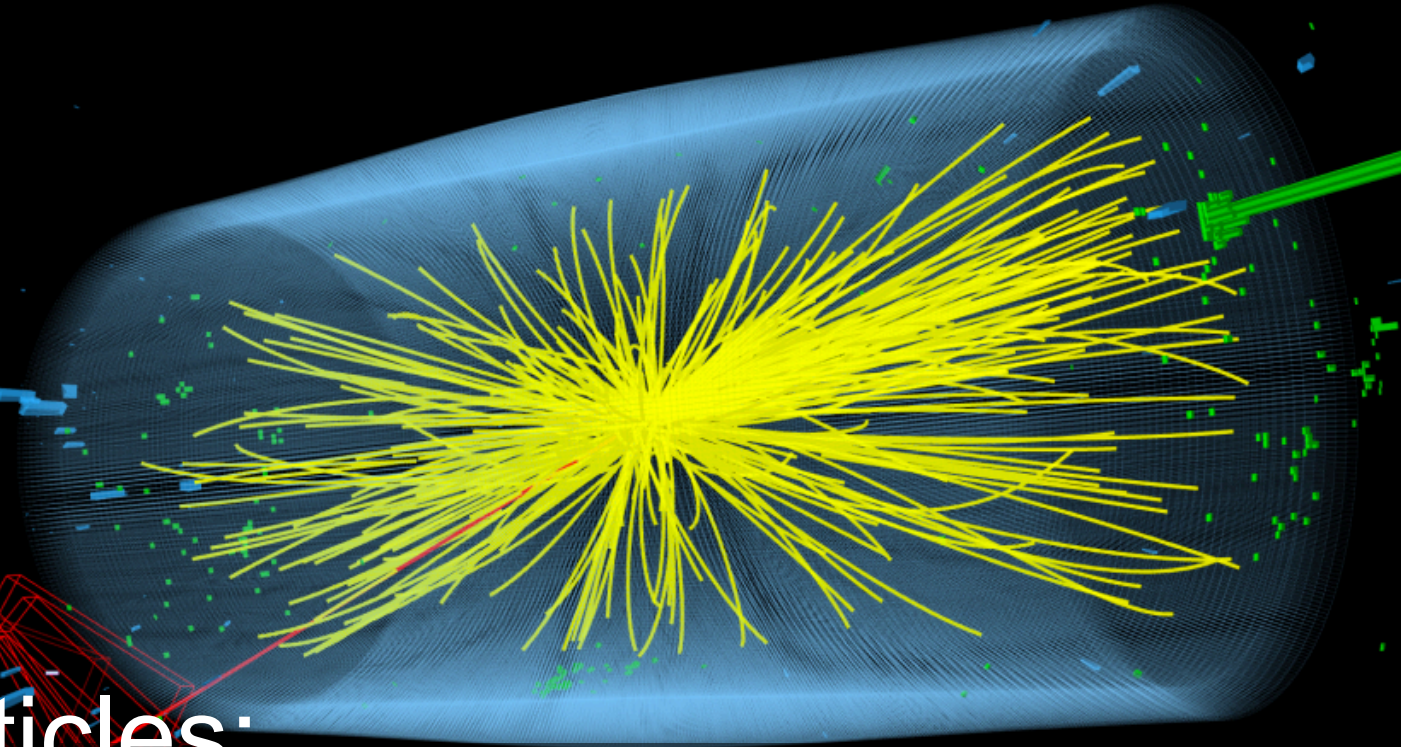
Baryon: 3 (valence) quarks



Meson: 1 (valence) quark
1 (valence) antiquark



What is the stuff going through the detector?



Stable particles:

e^-

e^+

ν

$\bar{\nu}$

γ

p $\bar{p}$ (+ some nuclei)

Mean flight distance of unstable particles

weak decays

$$p = 10 \text{ GeV}$$

$$p = 10^{19} \text{ eV}$$

$n, \bar{n}$

19 au

91 kpc

$\pi^\pm$

560 m

3.8 au

strange

$\lesssim 300 \text{ m}$

$\lesssim 0.5 \text{ au}$

charm

$\mathcal{O}(2 \text{ mm})$

$\mathcal{O}(2000 \text{ km})$

bottom

$\mathcal{O}(1 \text{ mm})$

$\mathcal{O}(1000 \text{ km})$

$\mu^\pm$

58 km

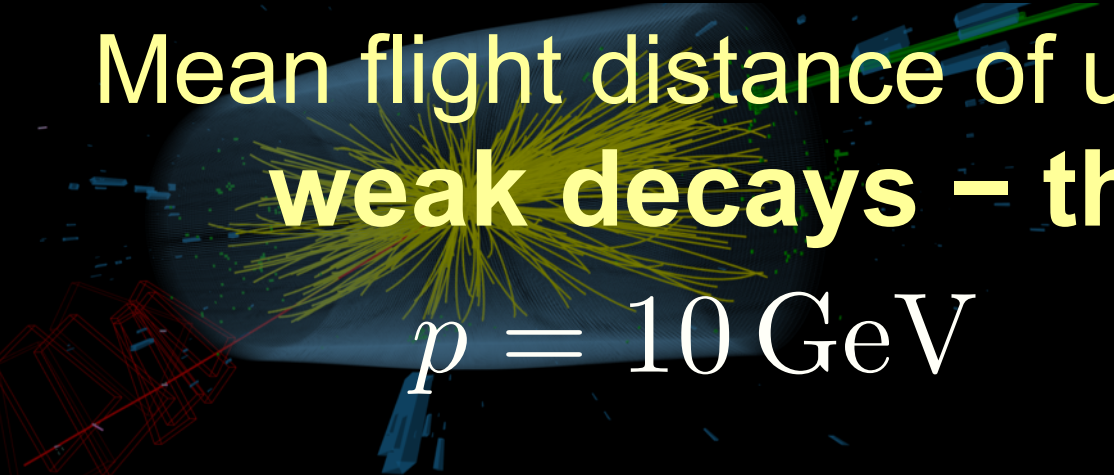
390 au

$\tau^\pm$

0.5 mm

500 km

Mean flight distance of unstable particles **weak decays – the heavies**

A visualization of a particle detector, likely a bubble chamber or cloud chamber, showing a central point of origin with many thin, radiating lines representing the tracks of particles produced in a decay. The tracks are more dense and numerous in the upper left portion of the image.
$$p = 10 \text{ GeV}$$

$$p = 10^{19} \text{ eV}$$

t – quark	0.006 fm
Z	0.009 fm
$W^{\pm}$	12 fm
H	3.9 fm

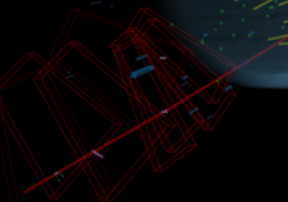
6 nm

9 nm

12 nm

3.9 μm

Mean flight distance of unstable particles **electromagnetic decays**



$p = 10 \text{ GeV}$

$p = 10^{19} \text{ eV}$

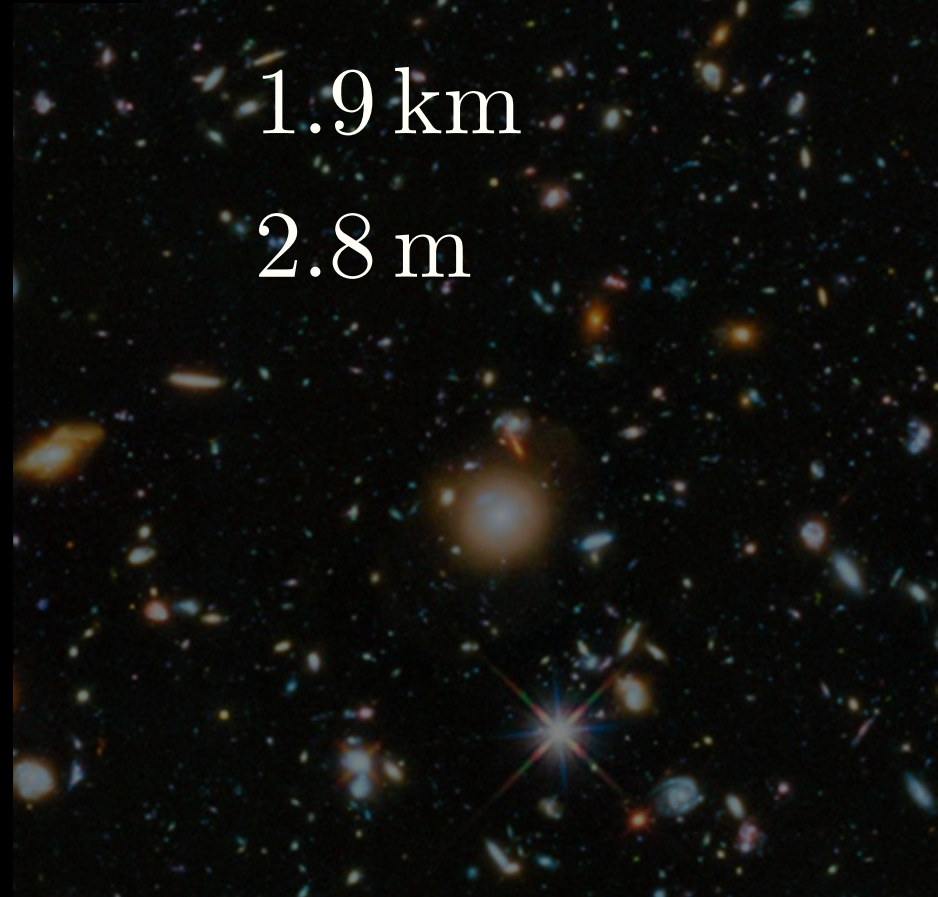
π^0 $1.9 \mu\text{m}$

η 2.8 nm

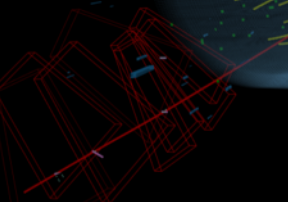
$\vdots$

1.9 km

2.8 m



Mean flight distance of unstable particles **strong decays**



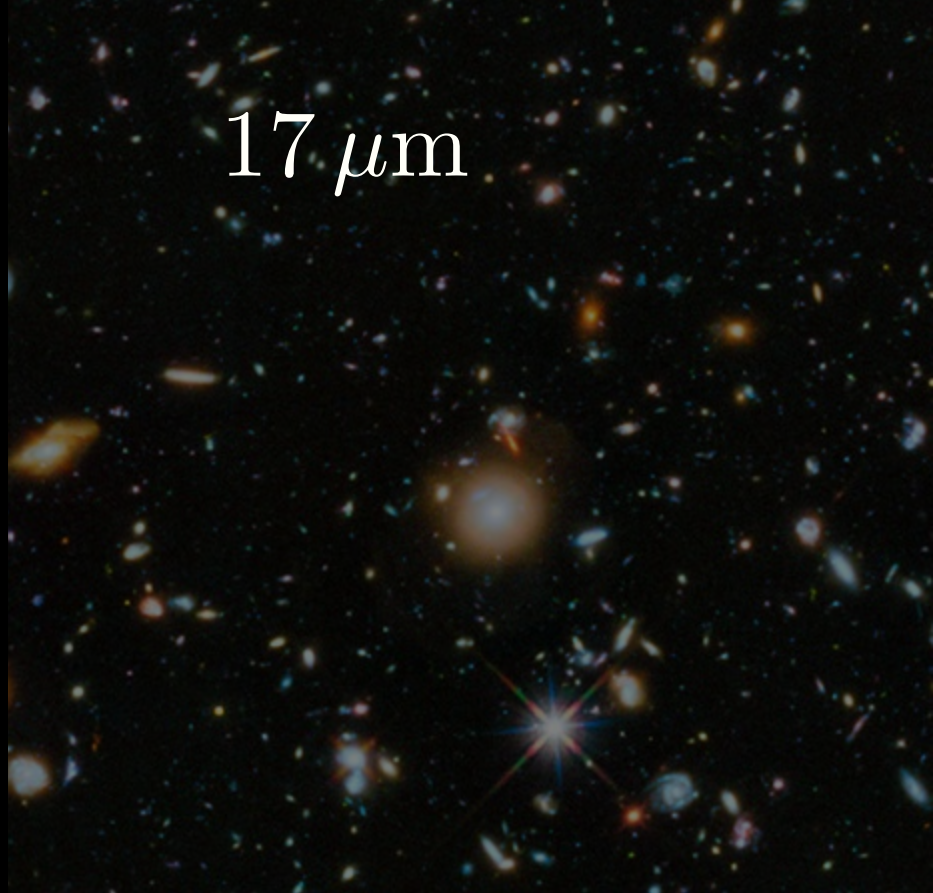
A schematic diagram of a particle detector, showing a central interaction region with a red line indicating a particle's path and various detector components represented by blue and red outlines.

$$p = 10 \text{ GeV}$$

$$p = 10^{19} \text{ eV}$$

$$\rho^0 \quad 17 \text{ fm}$$

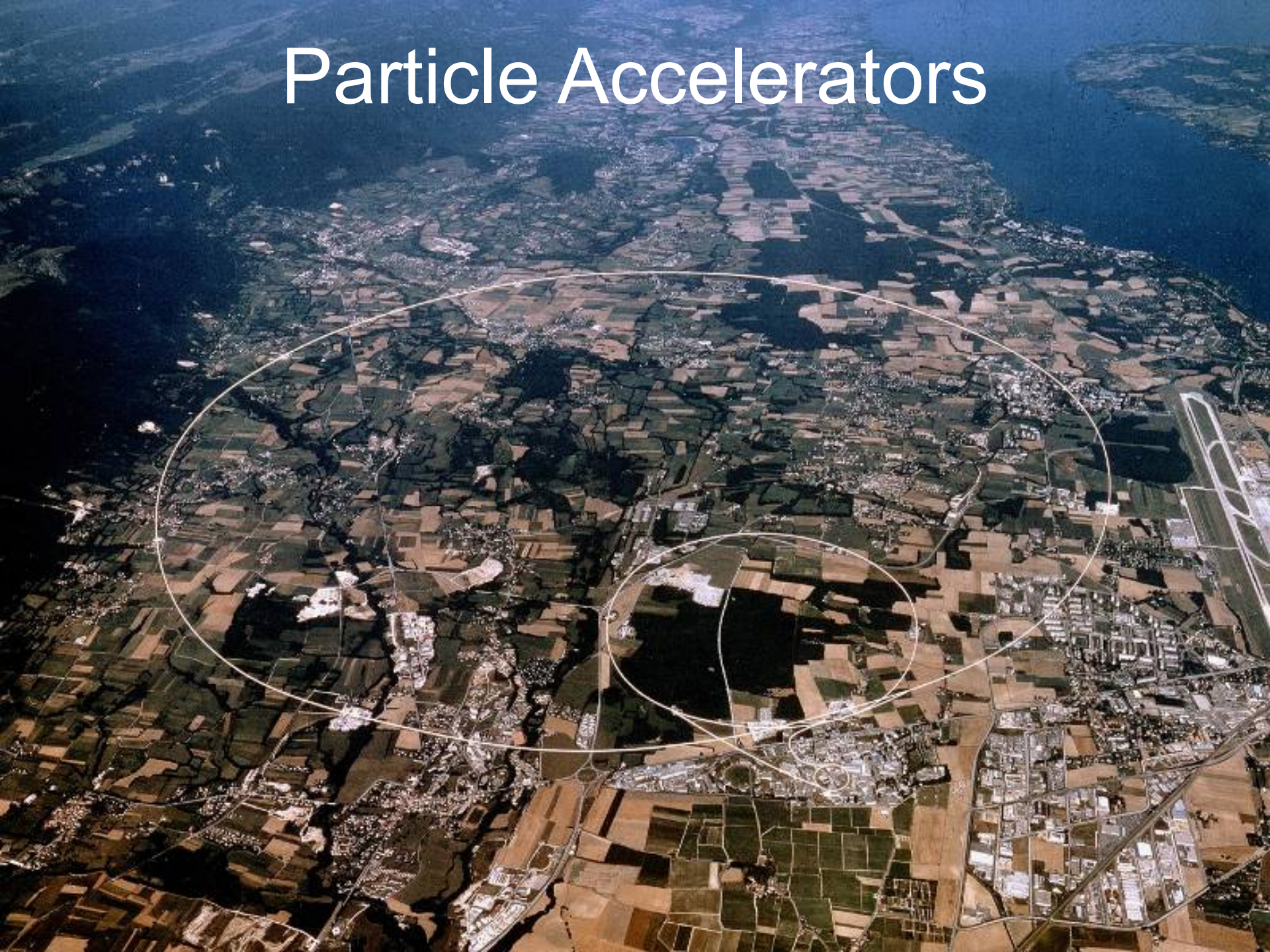
⋮



A deep-field astronomical image showing a vast field of galaxies and distant star clusters against a black background. A bright star with a prominent four-pointed diffraction pattern is visible in the lower right corner.

$$17 \mu\text{m}$$

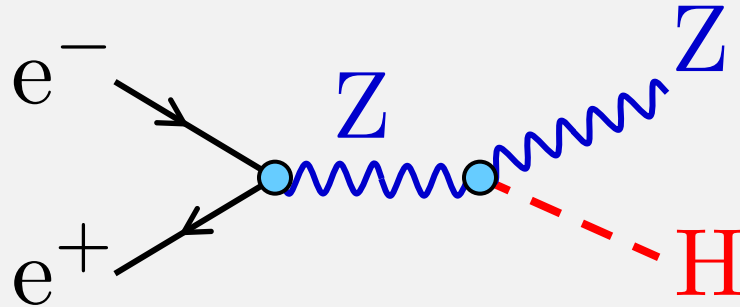
Particle Accelerators



Why do we need them?

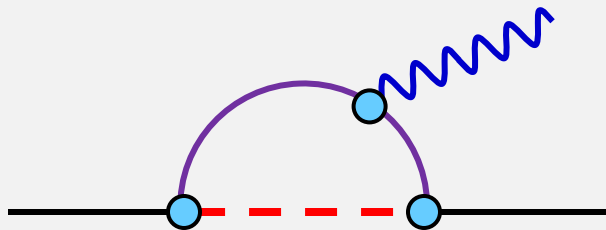
➤ Discover new heavy particles / field quanta

1. Create them



⇒ needs **high cm energy**

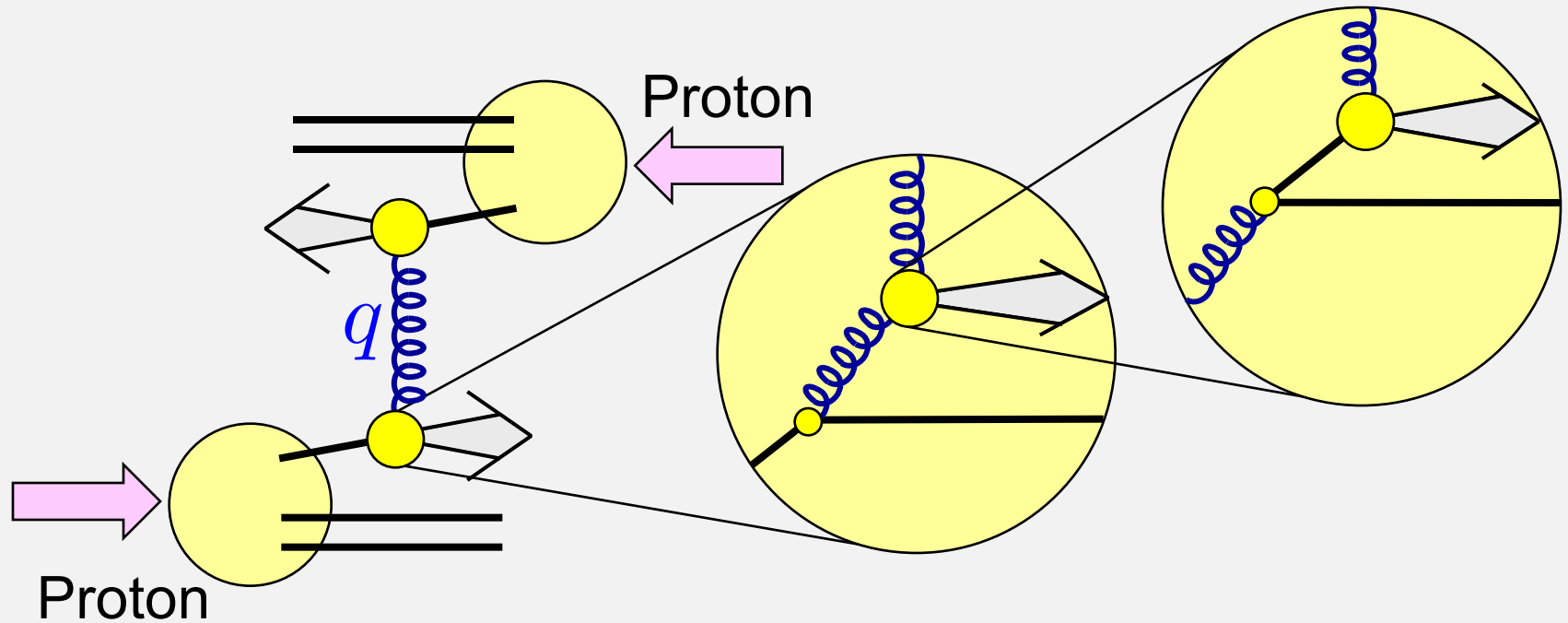
2. Measure their contributions in quantum fluctuations



virtual particles
(off-mass-shell)
in quantum loops

⇒ needs high precision ⇒ **high luminosity**

➤ Resolve structure / test small distances



resolved distances (proton rest frame): $\lambda = \hbar/|\vec{q}|$

$$\lambda \ll 1 \text{ fm} \Rightarrow |q^2| \gg m_p^2$$

$\Rightarrow$ needs **high momentum transfer**

$\Rightarrow$ needs **high cm energy**

How do we design them?

beam particle
e.g. proton



$$p_1 = (E_1, \vec{p}_1)$$

beam/target
particle e.g. proton



$$p_2 = (E_2, \vec{p}_2)$$

Centre of mass energy:

$$E_{\text{CM}} = \sqrt{s} \equiv \sqrt{(p_1 + p_2)^2}$$

Case 1: Fixed target configuration

beam particle
e.g. proton



$$p_1 = (E_1, \vec{p}_1)$$

target at rest



$$p_2 = (m_2, \vec{0})$$

Centre of mass energy:

$$\begin{aligned}\sqrt{s} &= \sqrt{(p_1 + p_2)^2} = \sqrt{m_1^2 + m_2^2 + 2p_1 p_2} \\ &= \sqrt{m_1^2 + m_2^2 + 2m_2 E_1} \approx \sqrt{2m_2 E_1}\end{aligned}$$

Case 2: Colliding beams

example: symmetric collider: e^+e^- , $p\bar{p}$, pp



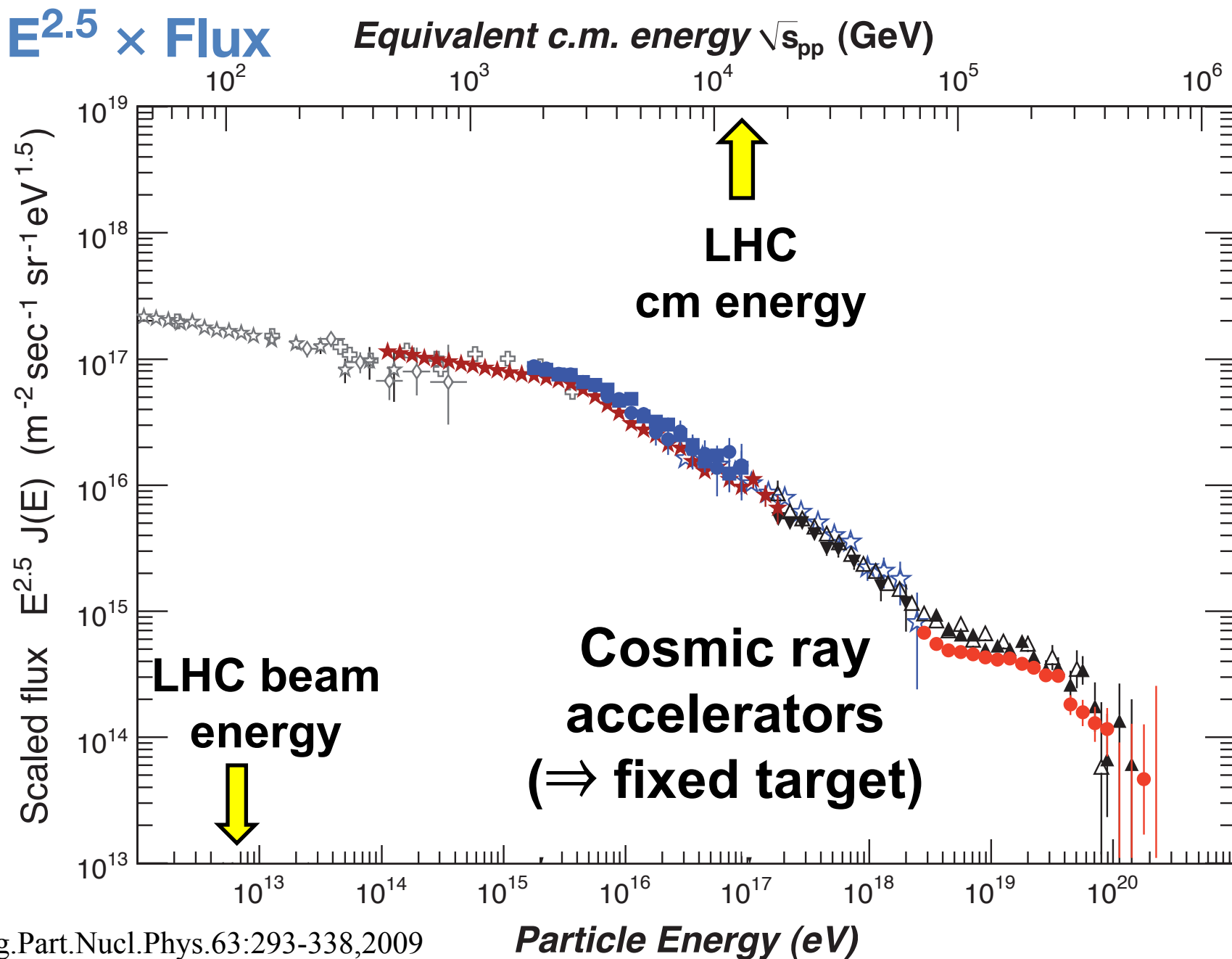
$$p_1 = (E, \vec{p})$$



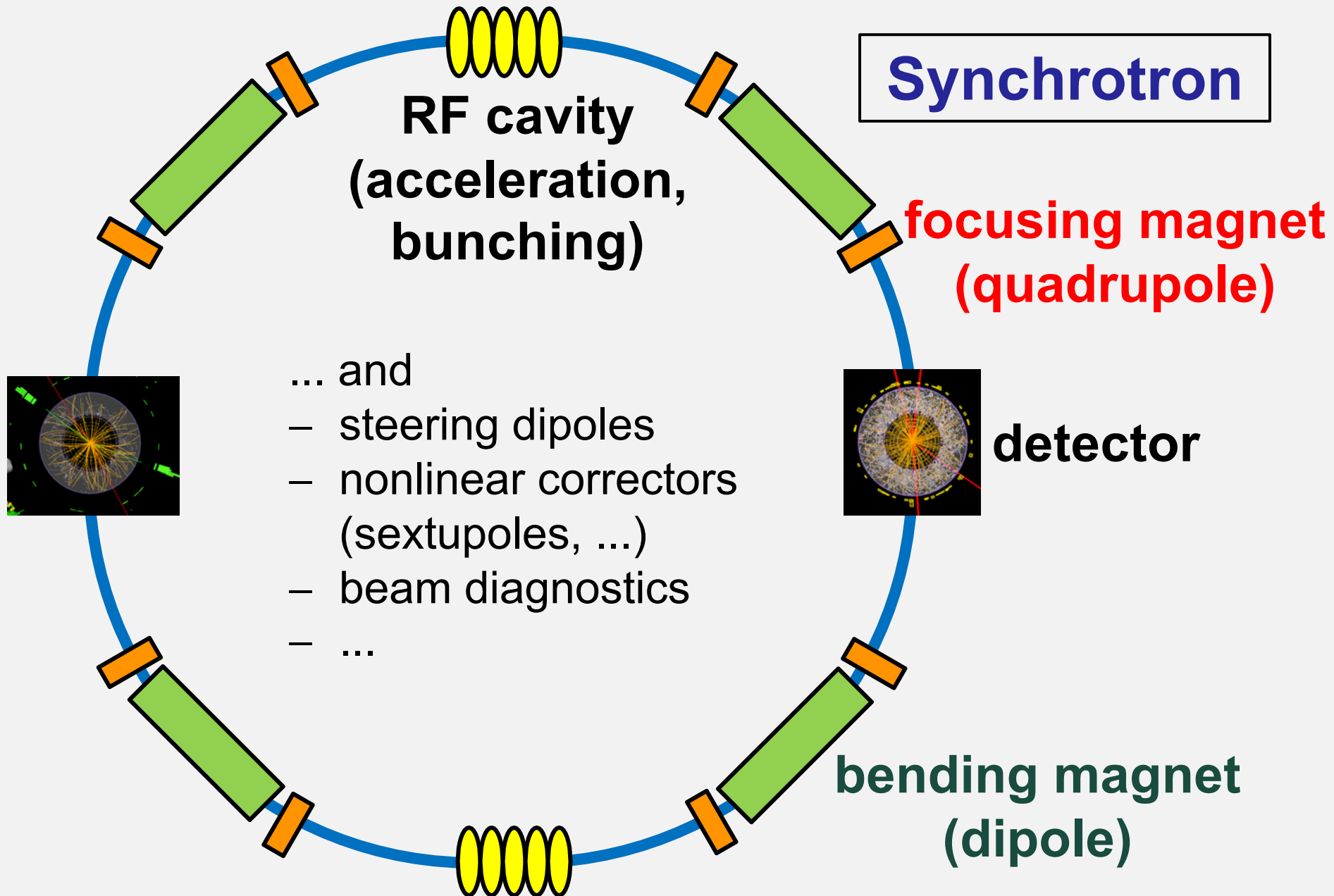
$$p_2 = (E, -\vec{p})$$

Centre of mass energy:

$$\sqrt{s} = \sqrt{(p_1 + p_2)^2} = \sqrt{(2E)^2} = 2E$$



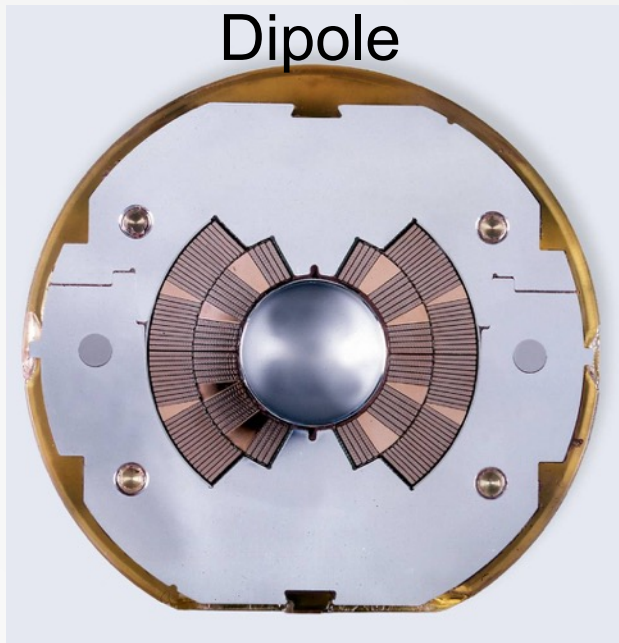
Storage Ring(s): **fixed target** or **collider**



Example: LHC

all super-conducting

Dipoles	1232
Quadrupoles	400
Sextupoles	2464
Octupoles/decapoles	1568
Orbit correctors	642
Others	376
Total	~ 6700



bending beams
around the arcs

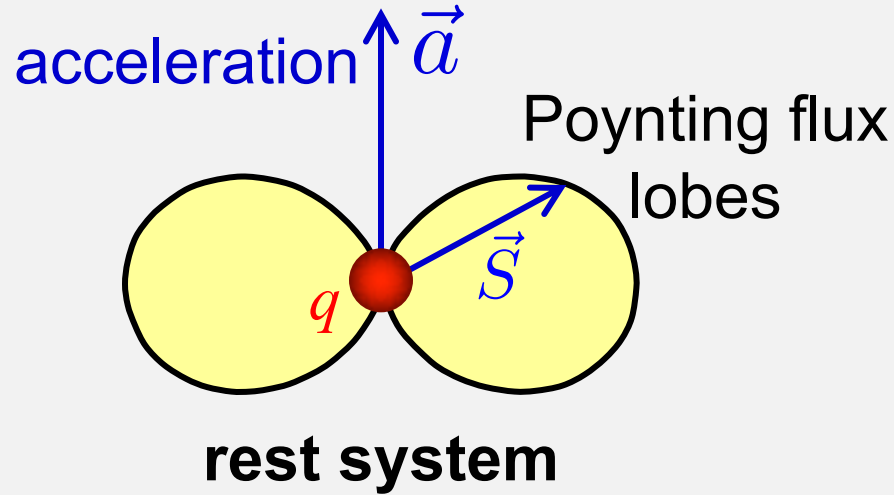


beam focusing



correct **nonlinear**
aberrations

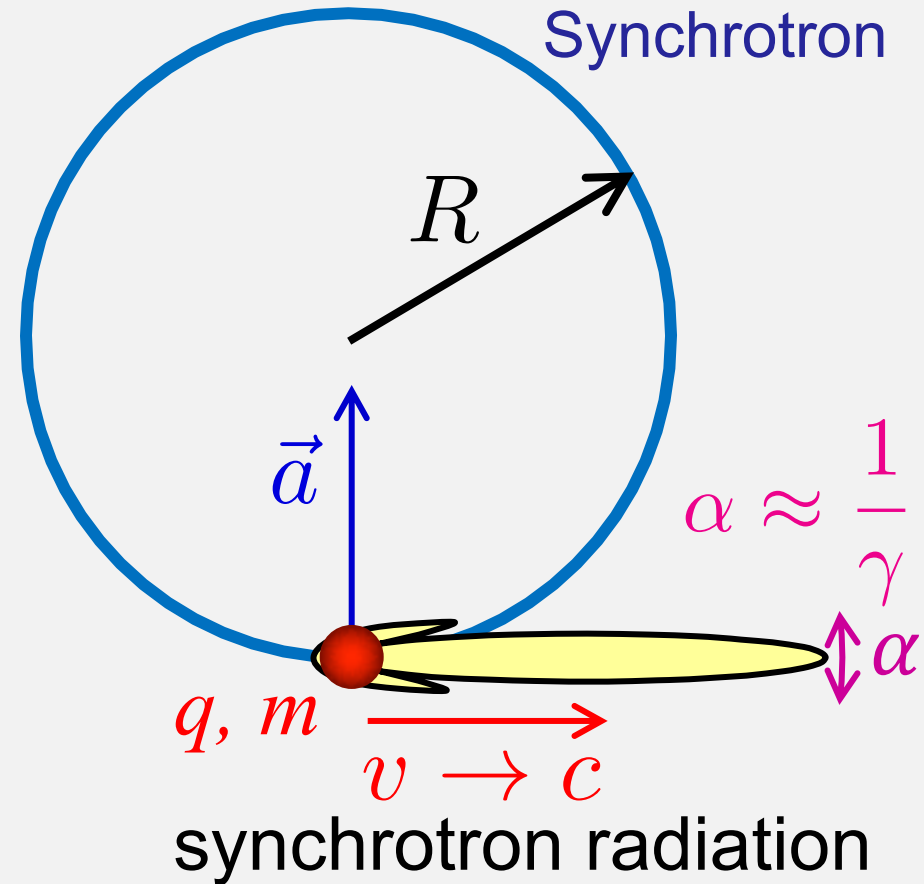
Radiation: accelerate electrons or protons?



radiation loss (1 particle)

$$P = \frac{q^2}{6\pi} \gamma^4 R^{-2}$$

$$\Delta E_{1 \text{ turn}} = \frac{q^2}{3} \gamma^4 R^{-1}$$



$$\gamma = \frac{E}{m}$$

Example: LHC (pp)

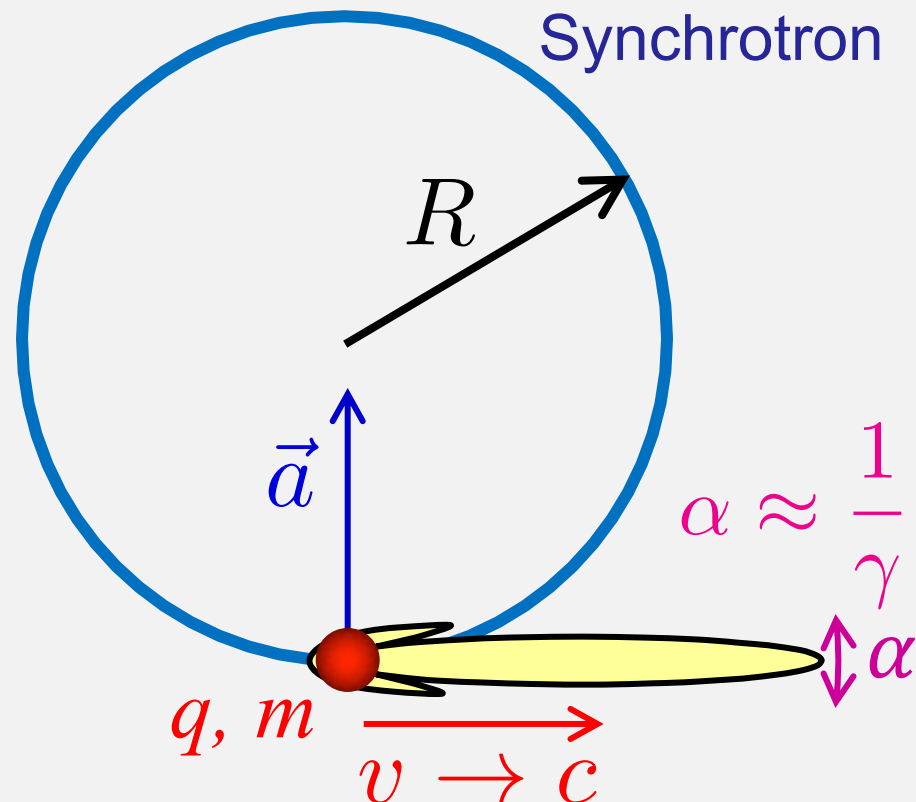
bunches: 2808 (per beam)

particles: 1.15×10^{11}

bending field: 8.33 T = 83.3 kG

beam energy: 7 TeV

$$R = \frac{\gamma m v}{e B} \quad v \approx c = 1 \quad \frac{\gamma m}{e B}$$



radiation power per proton beam:

$$P = \frac{e^2}{6\pi} \gamma^4 R^{-2} = \frac{e^4}{6\pi} \left(\frac{\gamma}{m} \right)^2 B^2$$

$$P_{\text{beam}} = 2808 \times 1.15 \times 10^{11} \times P \approx 6 \text{ kW}$$

LHC with $e^\pm$?

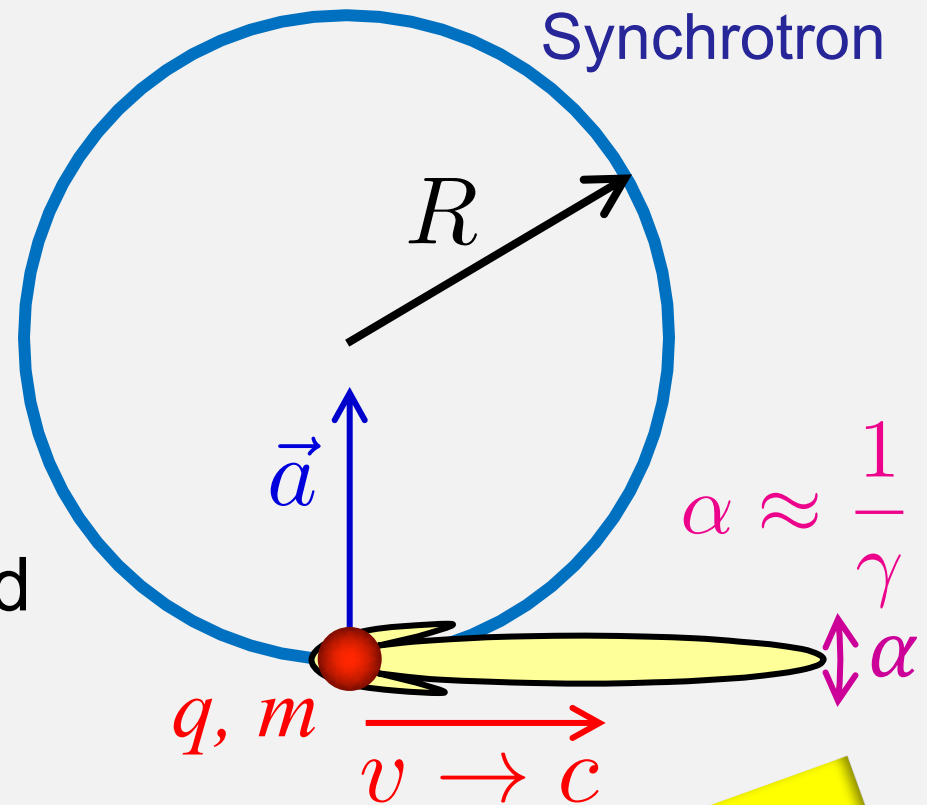
$$R = \frac{\gamma m v}{e B} \quad v \approx c = 1 \quad \frac{\gamma m}{e B}$$

tunnel (R), magnets (B) fixed

$$\Rightarrow \gamma_e m_e = \gamma_p m_p$$

$$\Rightarrow \frac{\gamma_e}{m_e} = \frac{\gamma_p}{m_p} \left(\frac{m_p}{m_e} \right)^2$$

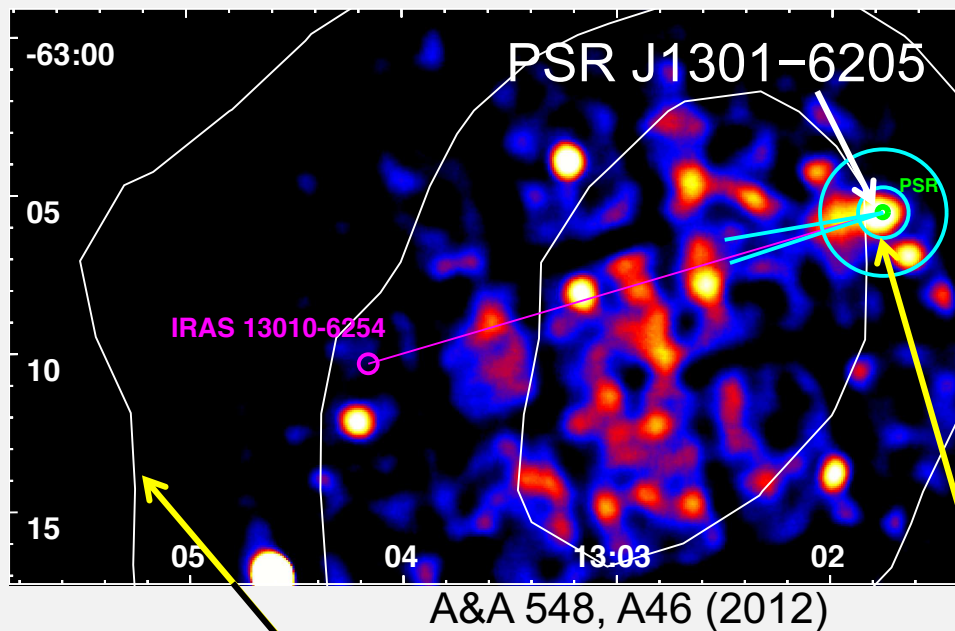
$$\Rightarrow P_e = \left(\frac{m_p}{m_e} \right)^4 P_p \approx 1.14 \times 10^{13} P_p$$



hopeless

Conclusion: electron/positron beams radiate strongly ... also in astrophysical accelerators

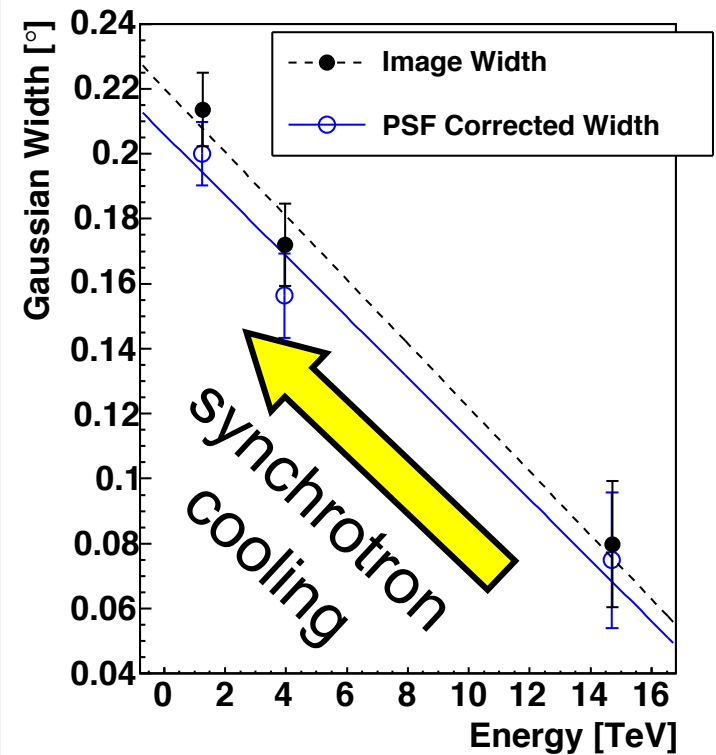
H.E.S.S. J1303-631
(pulsar wind nebula)



$$E_\gamma > 700 \text{ GeV}$$

Inverse Compton scattering of
synchrotron cooled electrons

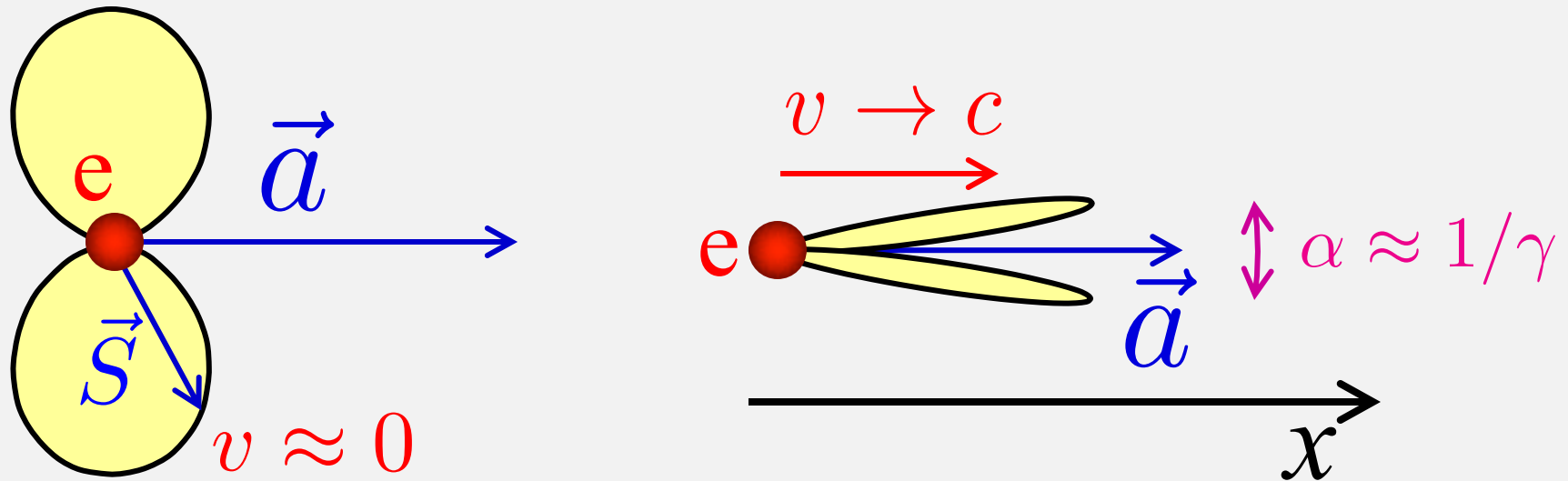
H.E.S.S. J1303-631 size



$$2 \text{ keV} < E_\gamma < 8 \text{ keV}$$

X-ray synchrotron nebula
(XMM Newton)

Go linear! Towards TeV electron beams



International Linear Collider (design layout)

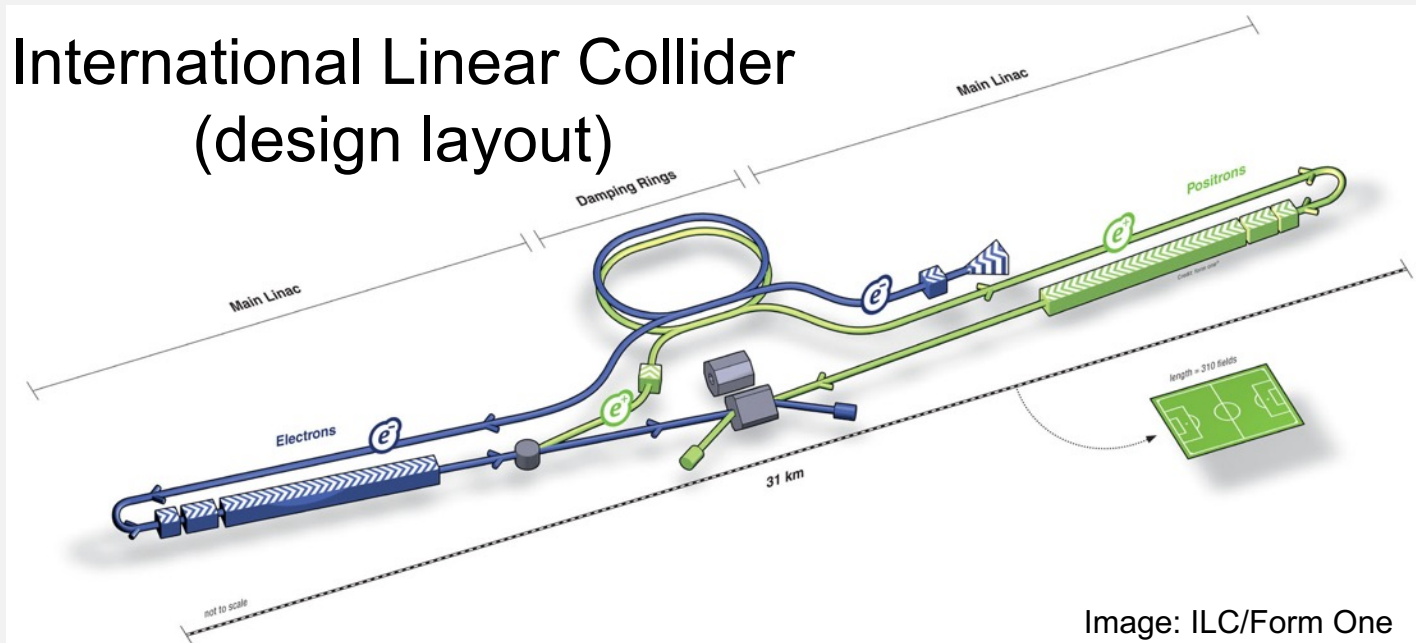
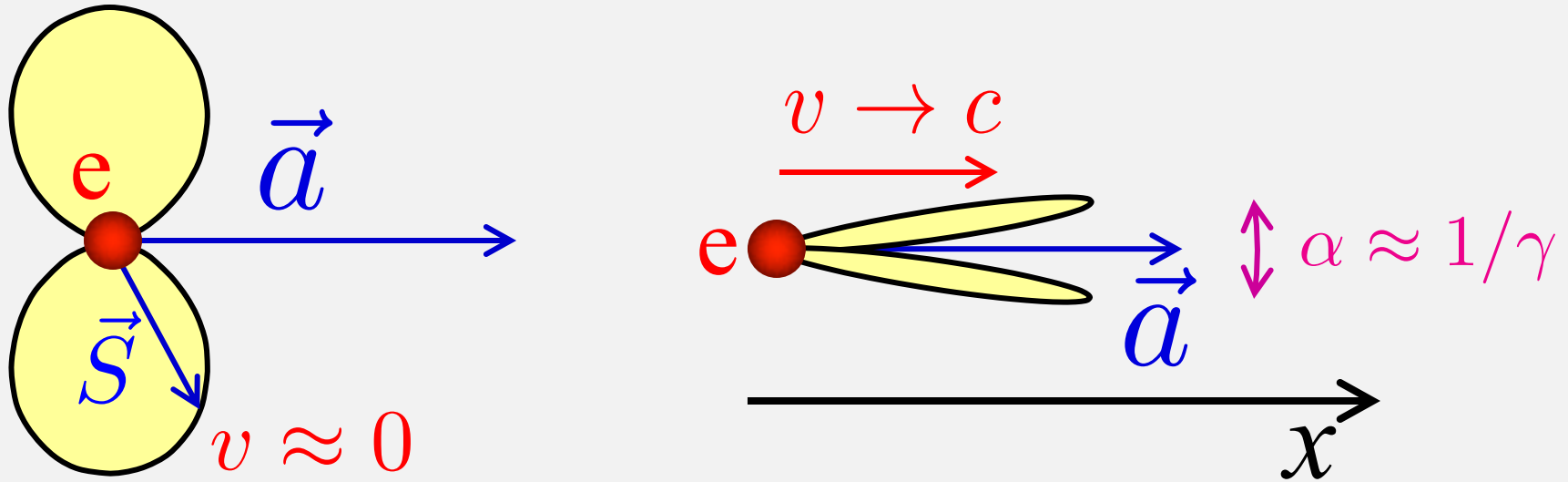


Image: ILC/Form One

Go linear! Towards TeV electron beams



$$\frac{P_{\text{rad}}}{P_{\text{acc}}} = \frac{e^2}{6\pi m_e^2} \frac{dE}{dx}$$

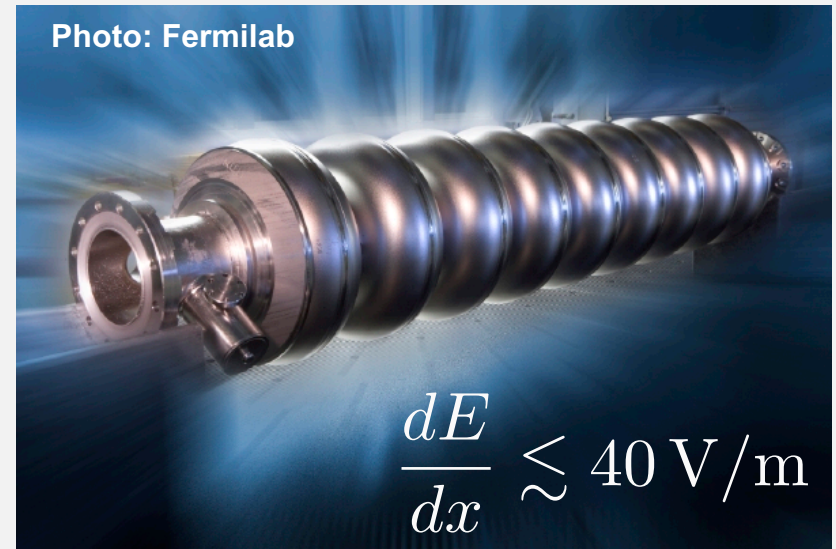
$$= 3.7 \times 10^{-15} \left. \frac{dE}{dx} \right|_{\frac{\text{MeV}}{\text{m}}}$$

$$\frac{P_{\text{rad}}}{P_{\text{acc}}} = 3.7 \times 10^{-15} \left. \frac{dE}{dx} \right|_{\frac{\text{MeV}}{\text{m}}}$$

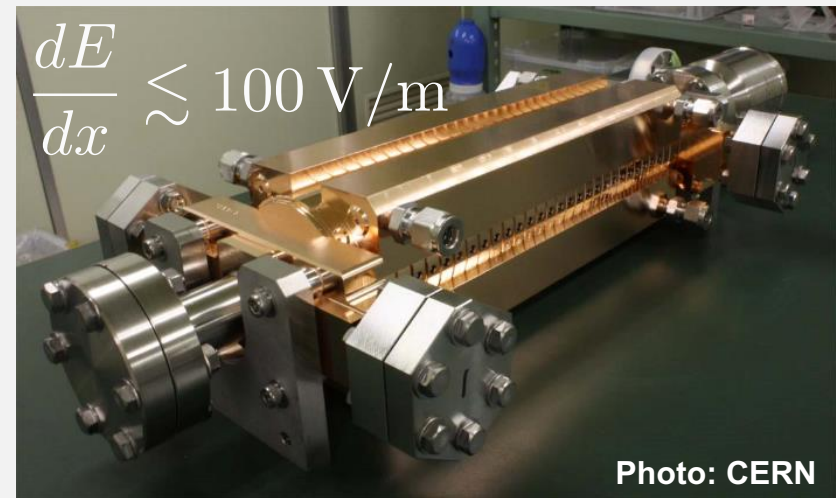
$$\left. \frac{P_{\text{rad}}}{P_{\text{acc}}} \right|_{\text{ILC}} \lesssim 1,5 \times 10^{-13}$$

$$\left. \frac{P_{\text{rad}}}{P_{\text{acc}}} \right|_{\text{CLIC}} \lesssim 3.7 \times 10^{-13}$$

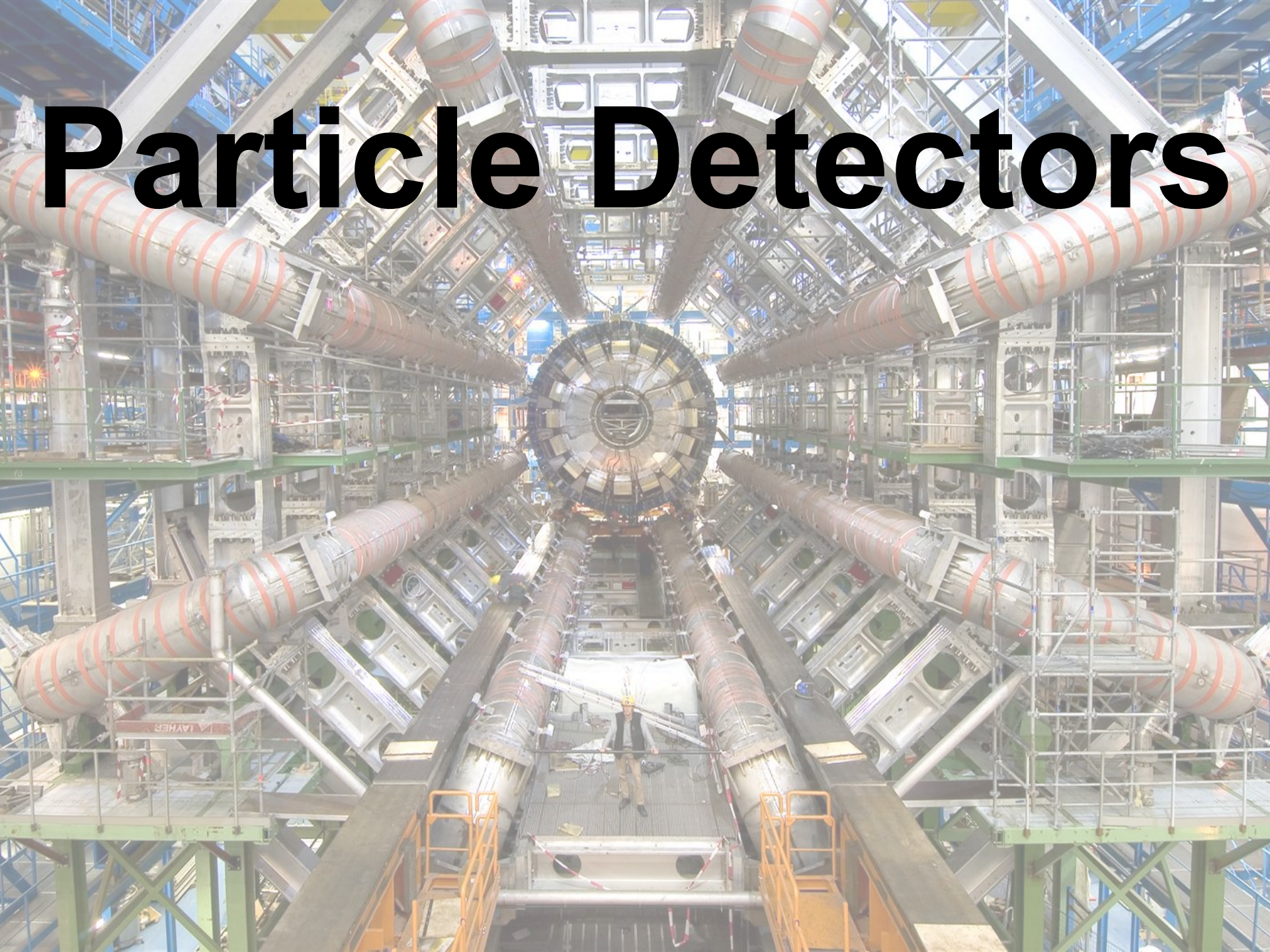
Radiation losses are
totally negligible!



ILC: 9 cell Niobium cavity
(superconducting)



CLIC: copper accelerating
structure (beam driven)



Particle Detectors

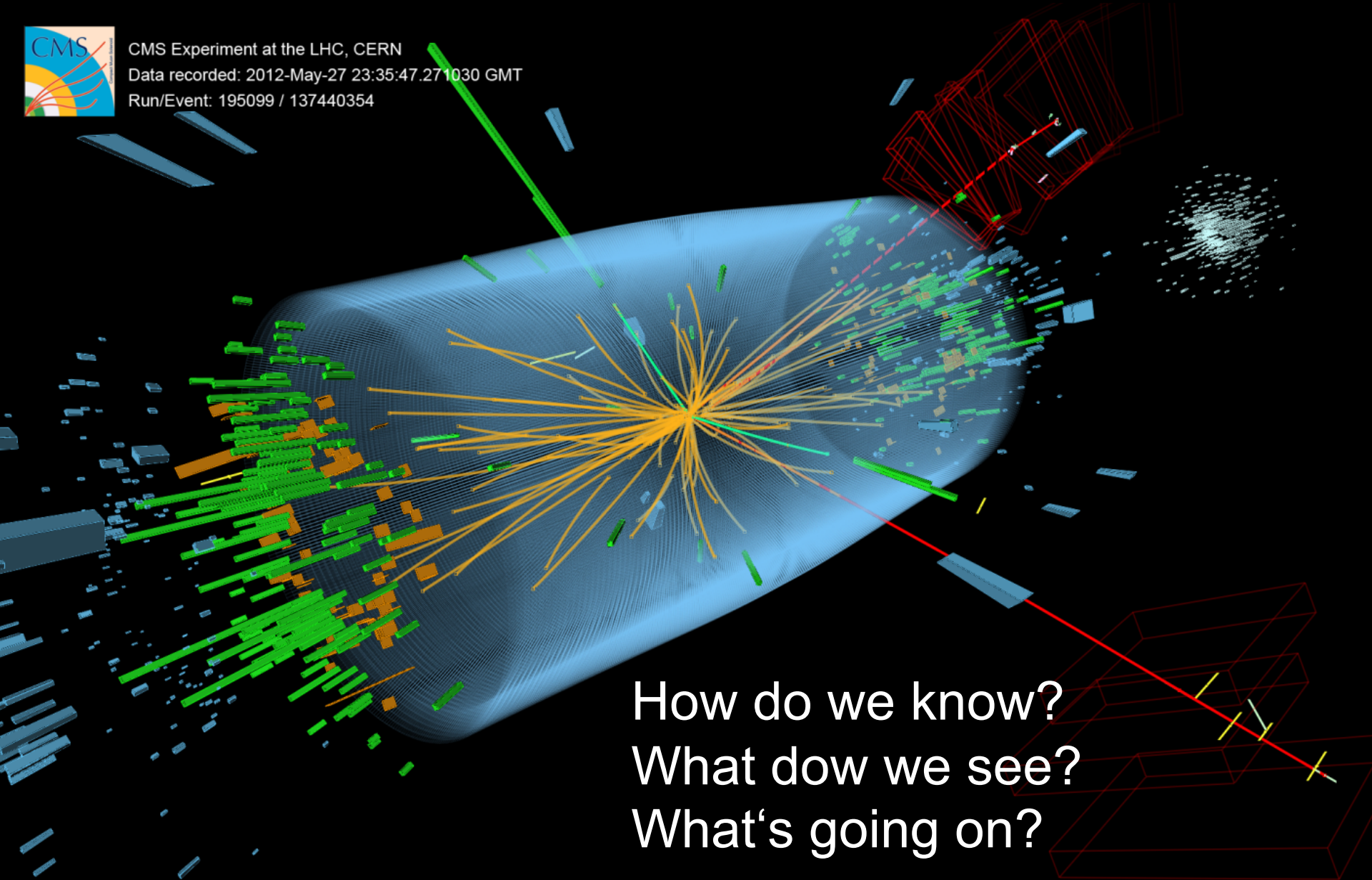
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



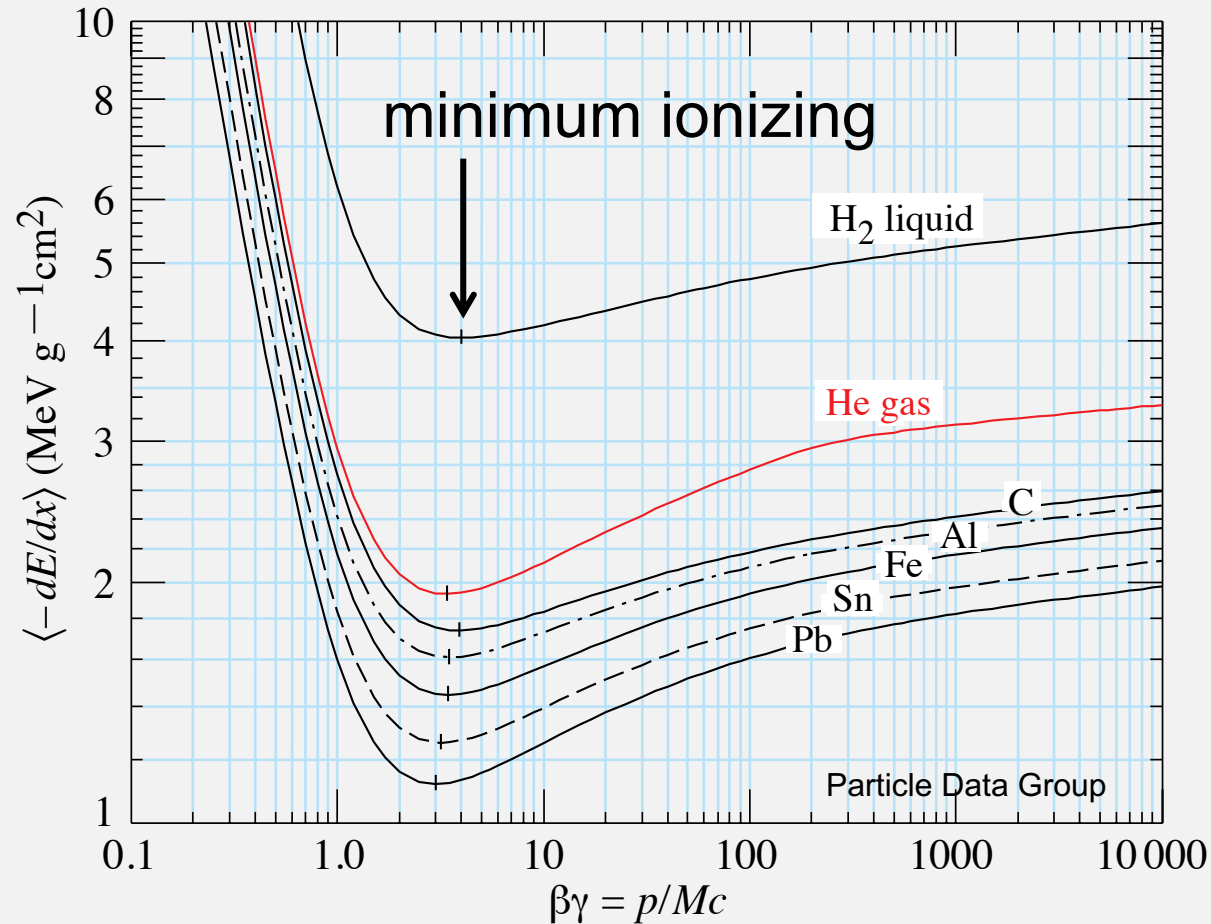
How do we know?
What do we see?
What's going on?

1) Ionisation: $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, p , $\bar{p}$

$$\rho_{\text{air}} \approx 1.2 \text{ mg/cm}^3$$

$$\rho_{\text{Ar}} \approx 1.7 \text{ mg/cm}^3$$

$$\rho_{\text{Fe}} = 7.9 \text{ g/cm}^3$$



- particles are relativistic $\Rightarrow$ ionization close to minimum
- energy loss due to ionization is insignificant

Example: Argon gas

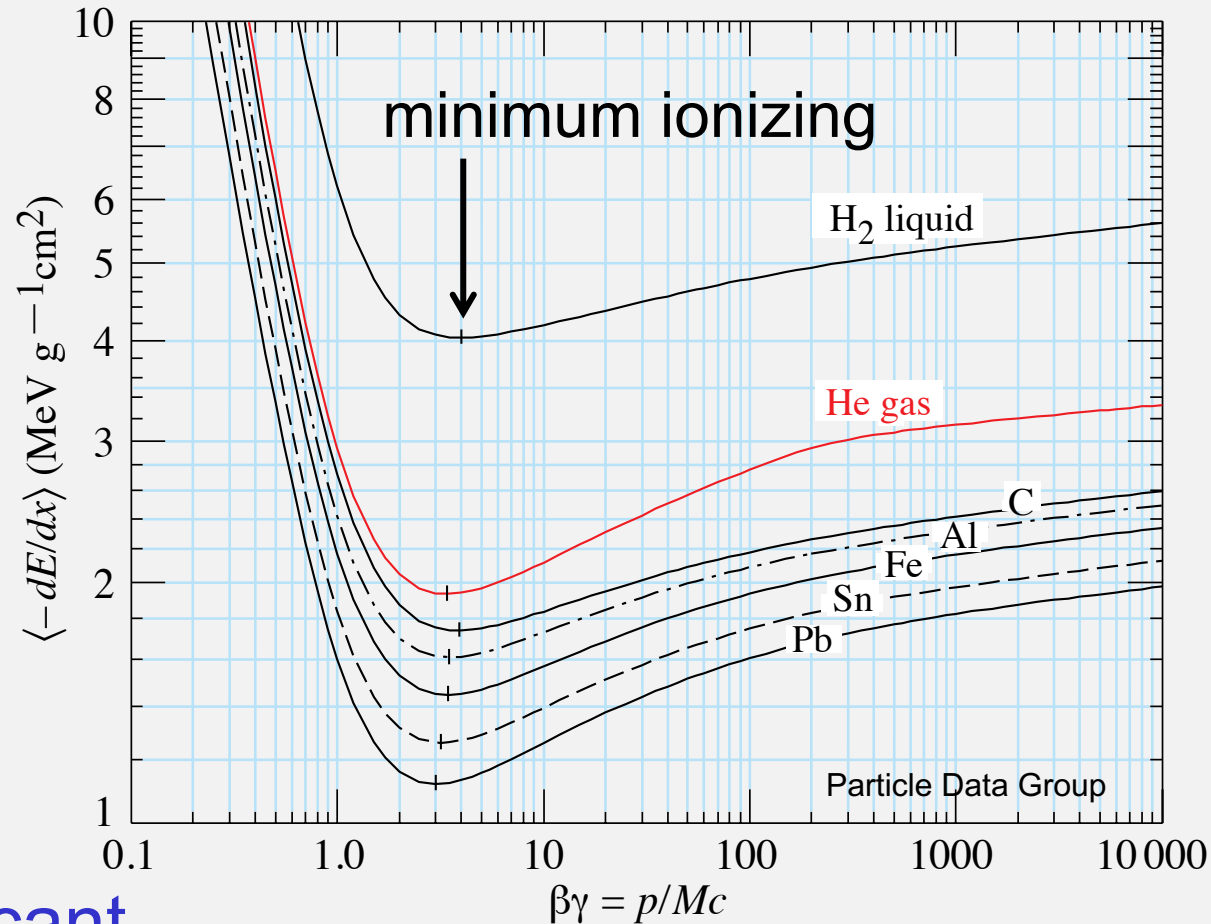
$$\frac{dE}{dx} \approx 2.5 \text{ keV/cm}$$

ionisation energy:

$$E_I = 15.7 \text{ eV}$$

e⁻-ion-pairs:

$$N \approx 100/\text{cm}$$



- ionization is significant
- cm-length scales needed
- (gas-)amplification of primary ionization needed

Example: Silicon wafers (thickness $300\text{ }\mu\text{m}$)

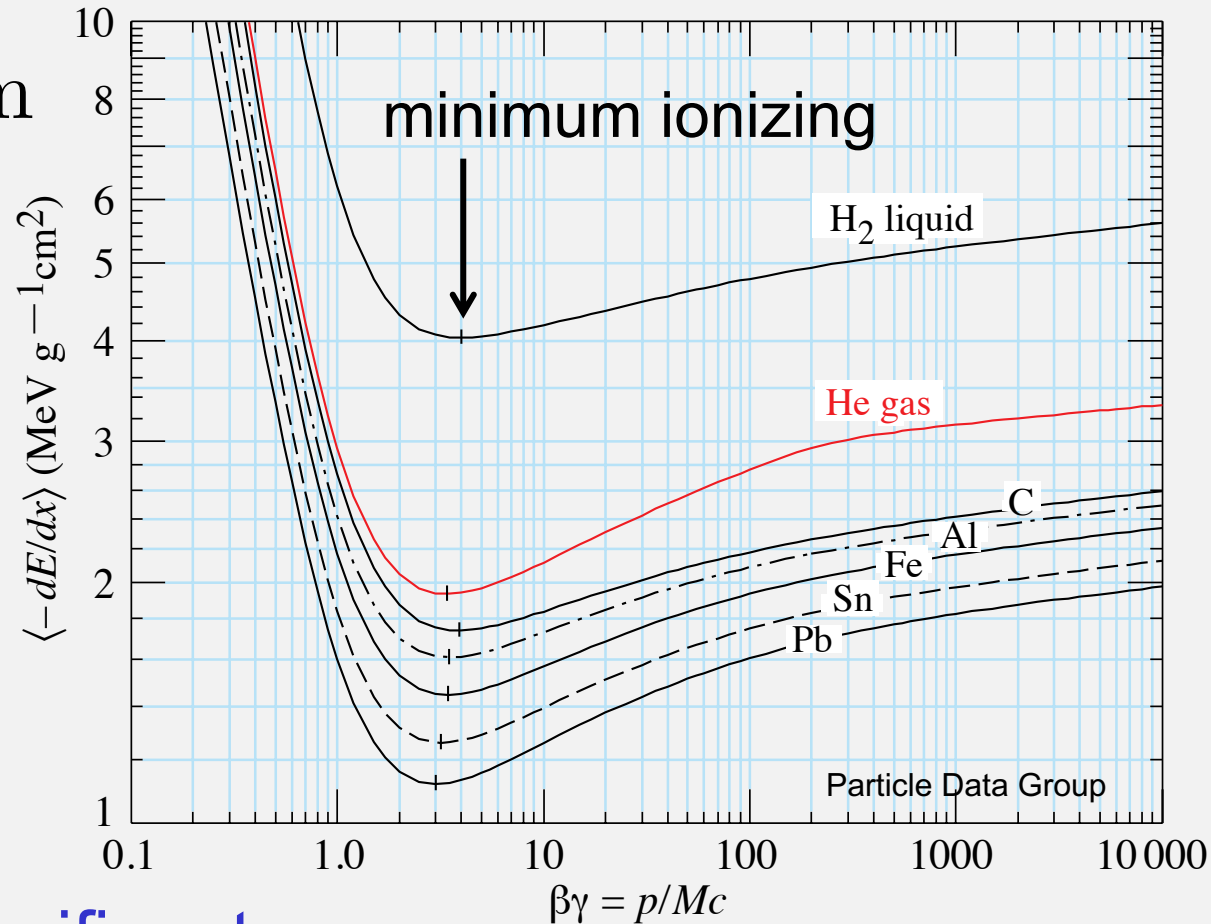
$$\frac{dE}{dx} \approx 1.7\text{ MeV/cm}$$

band gap:

$$E_{\text{gap}} = 1.1\text{ eV}$$

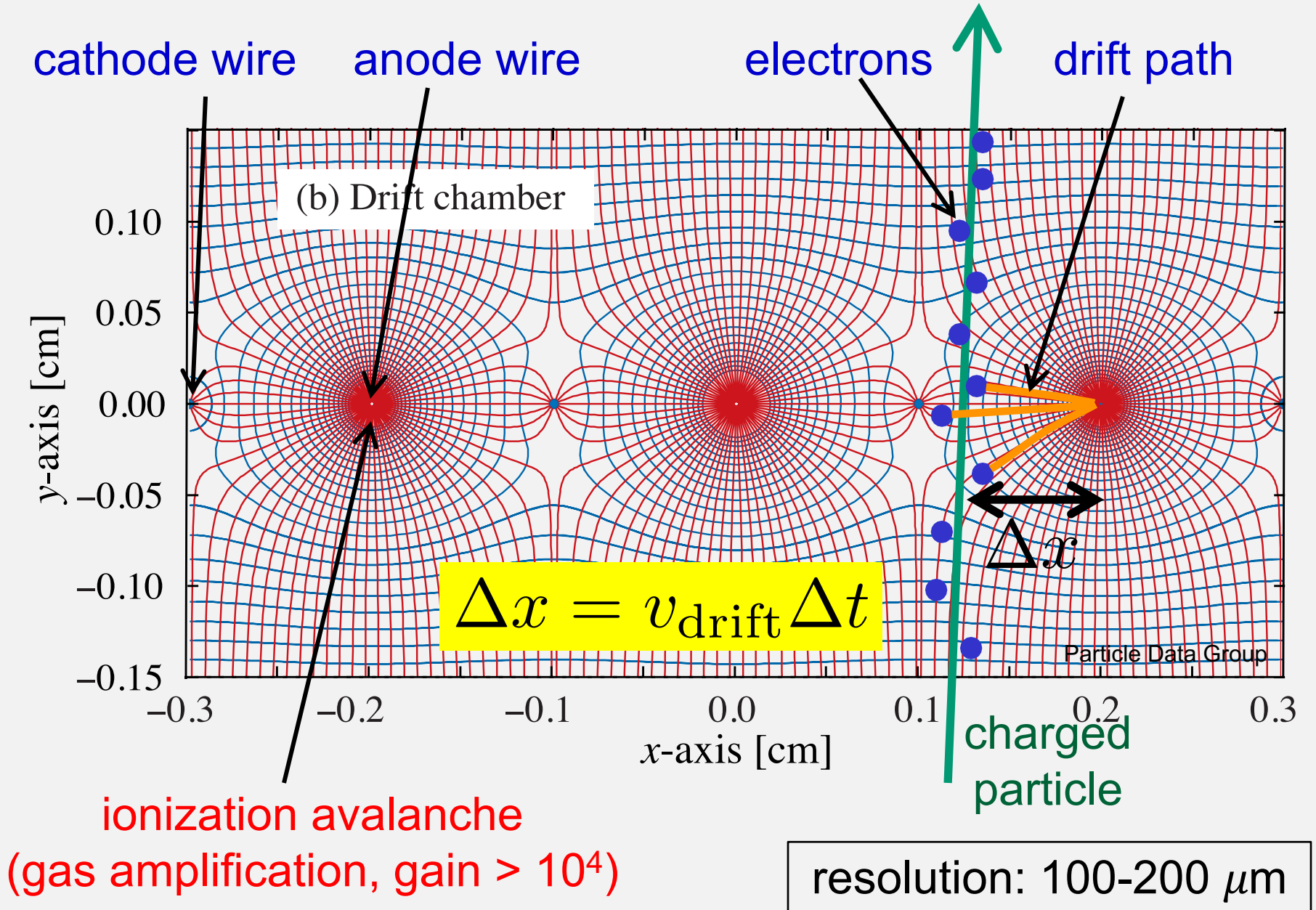
e^- -hole-pairs:

$$N \approx 73/\mu\text{m}$$



- charge creation significant
- $100\text{ }\mu\text{m}$ -length scales needed
- sufficient charge for pre-amplification ($S/N > 10$)

Example: drift chamber (gaseous detector)



Installing the CDF drift chamber

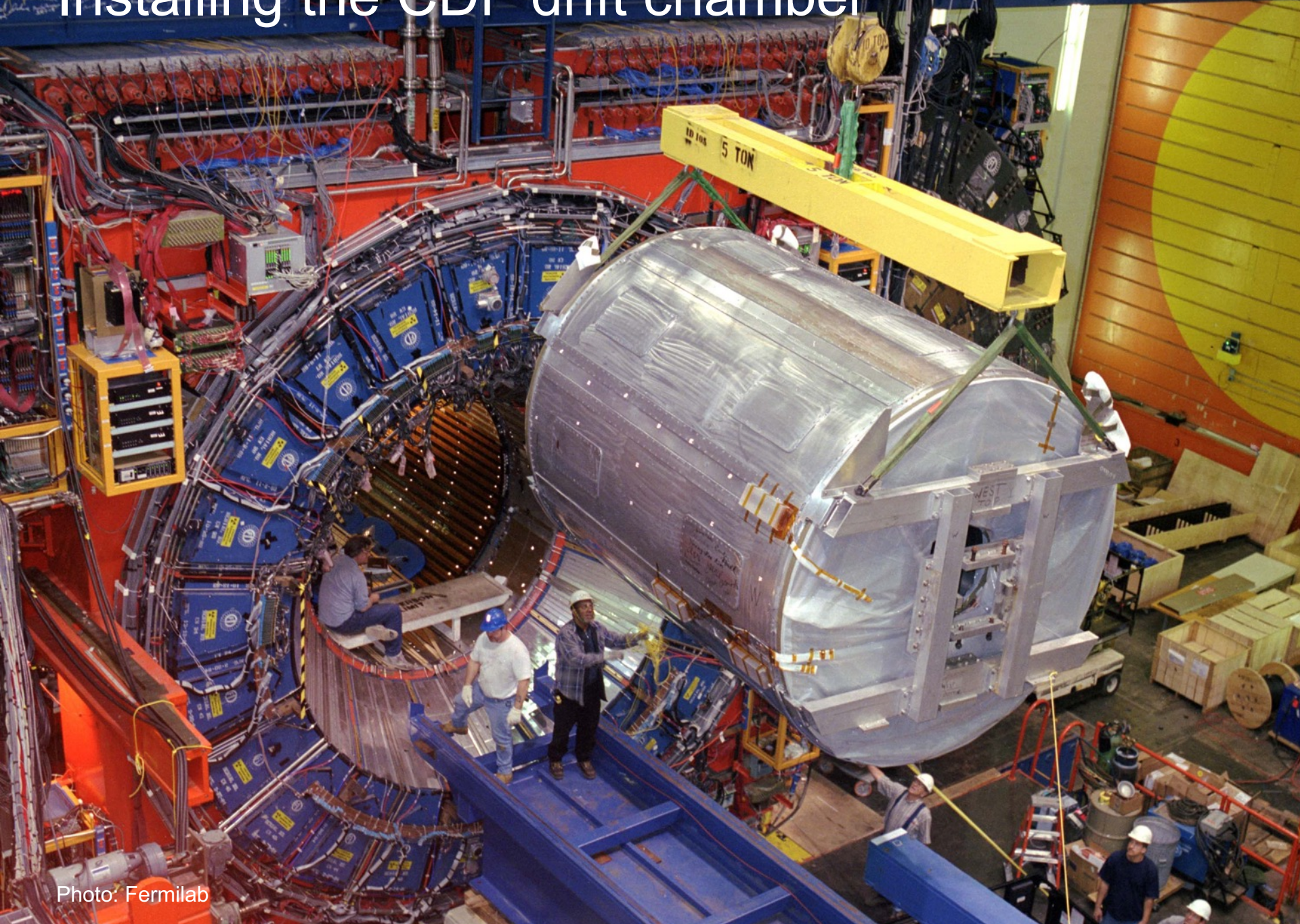


Photo: Fermilab

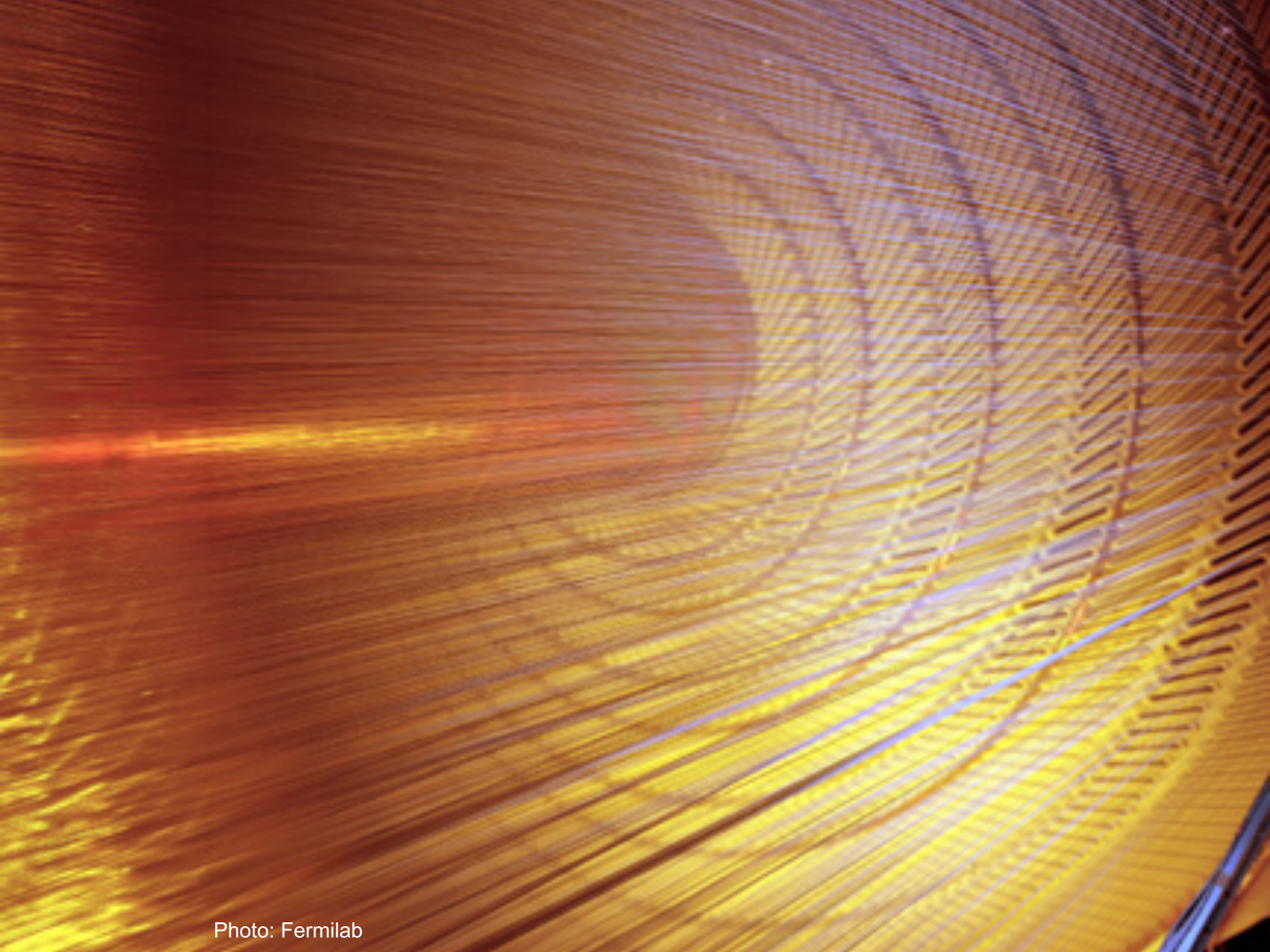
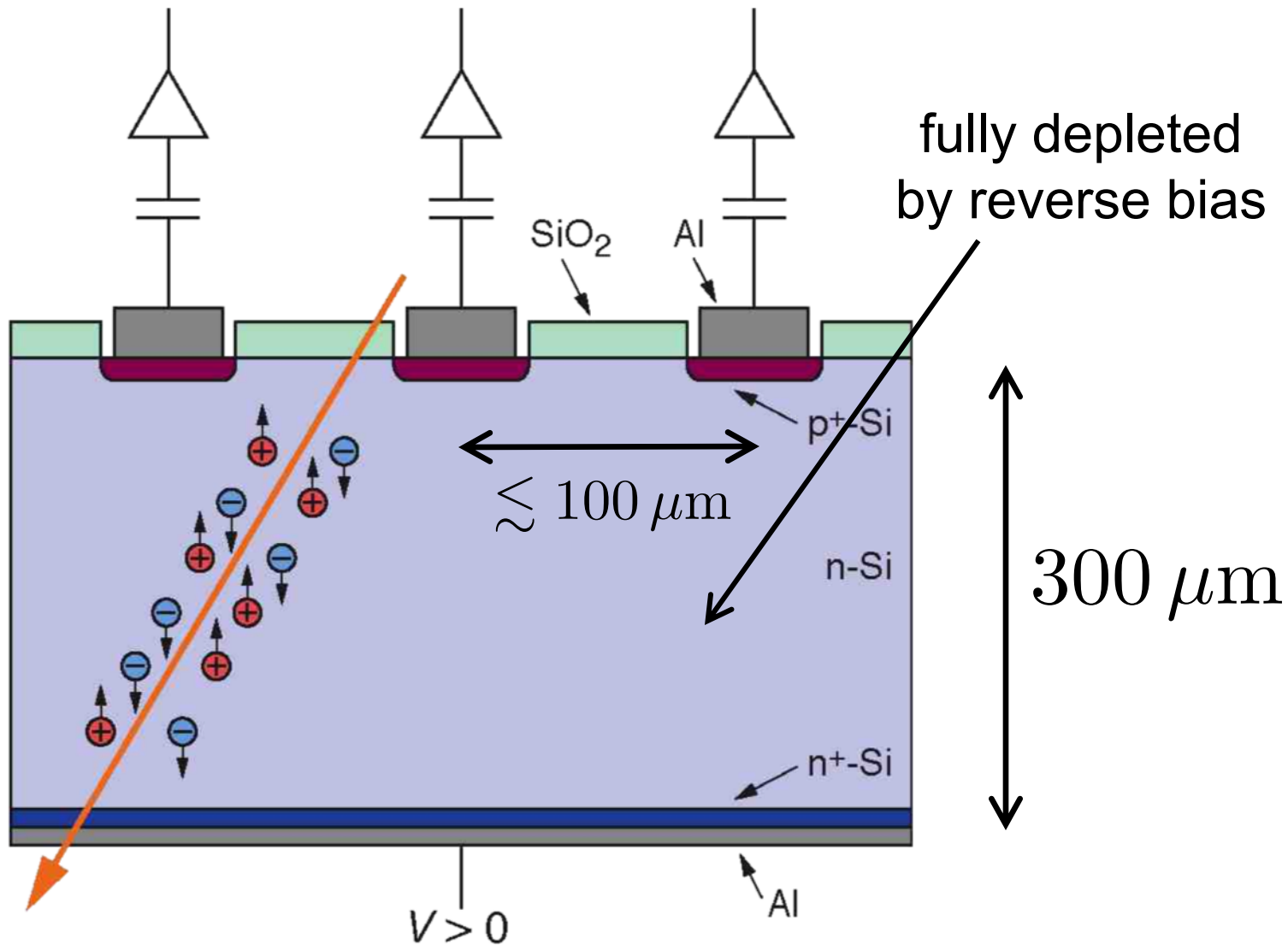


Photo: Fermilab

Example: silicon strip/pixel detector



typical resolution: $10\ \mu\text{m}$

Inside the CMS silicon tracker

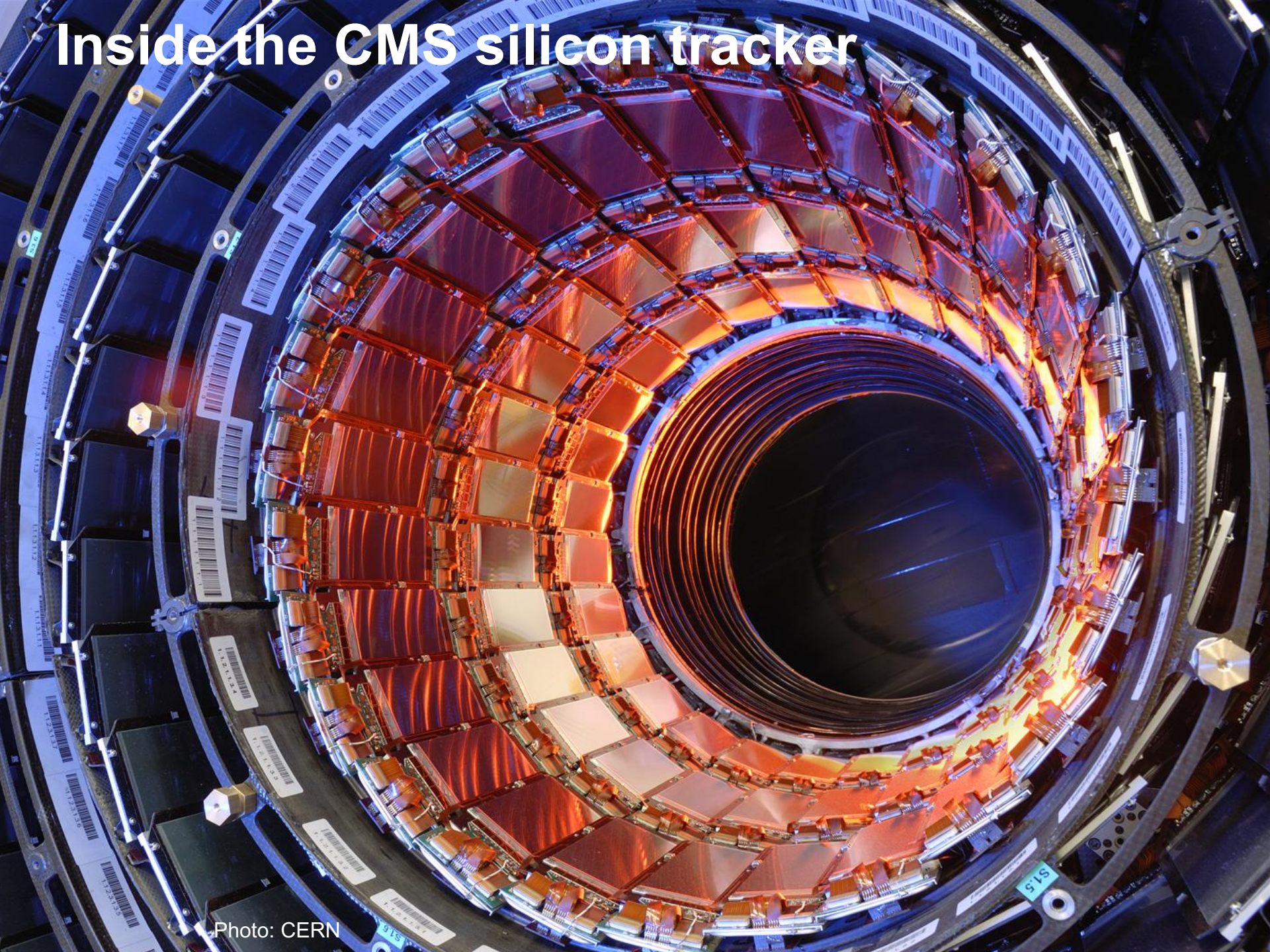
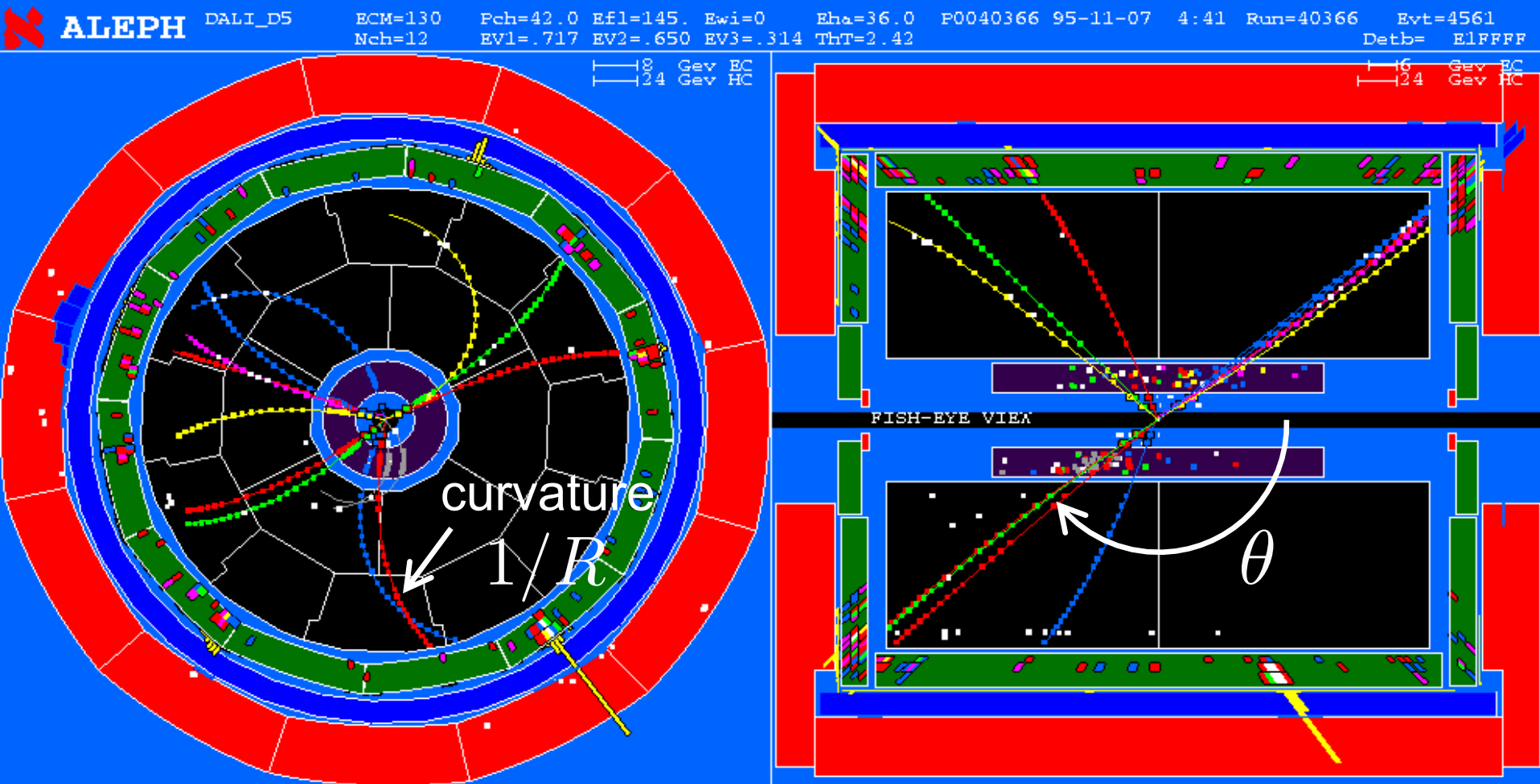


Photo: CERN

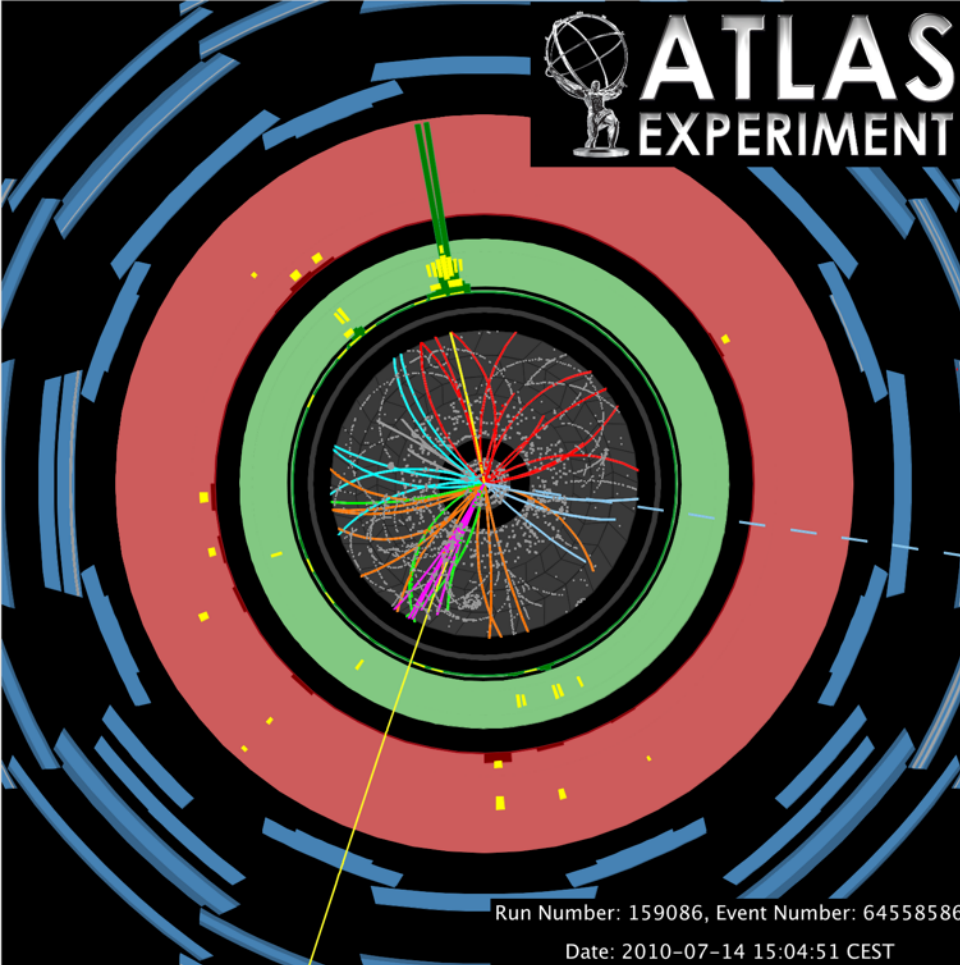


Curvature of ionization tracks in solenoidal magnetic field:

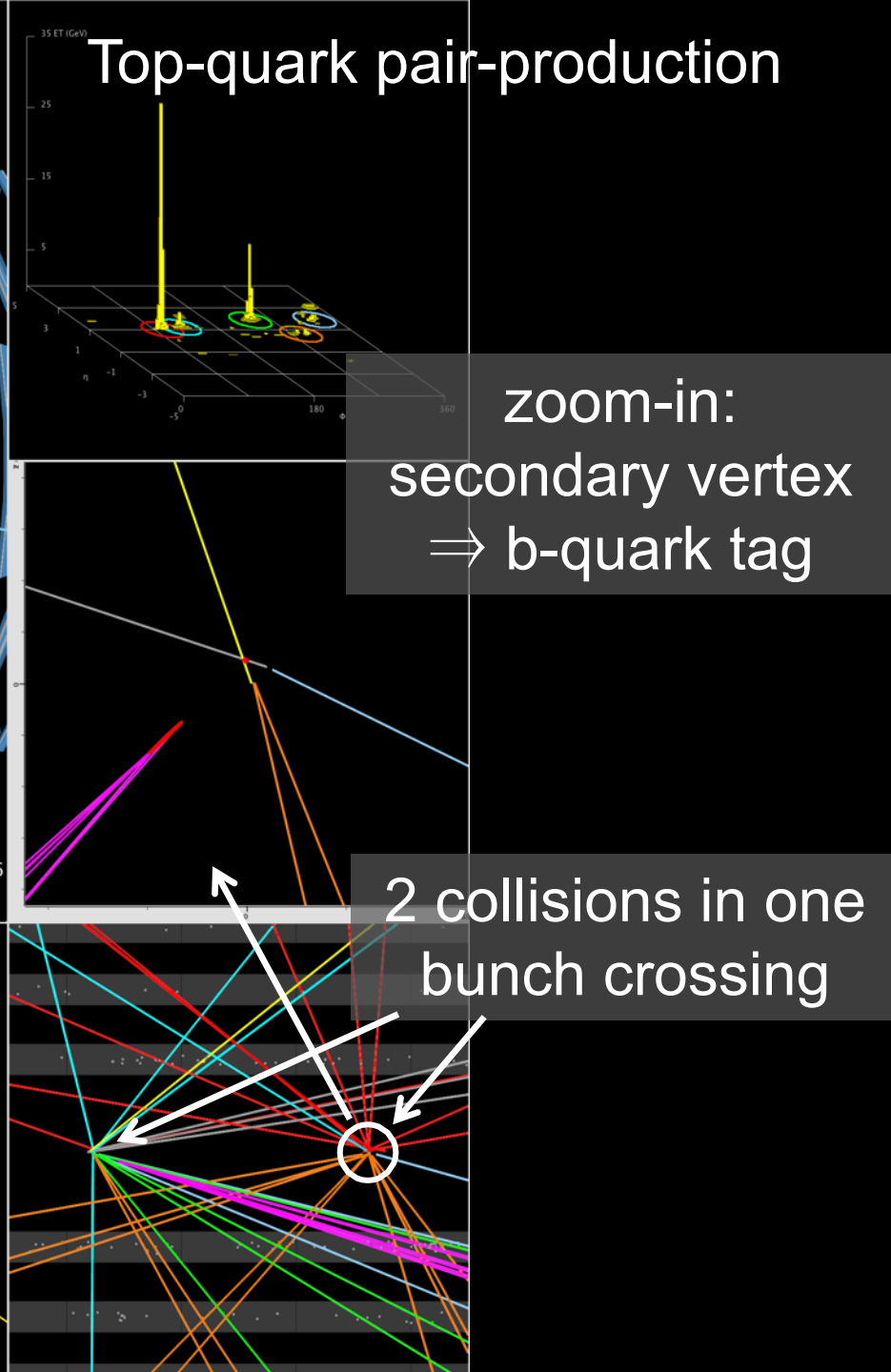
$$p_T = \pm eRB \quad \text{sign of charged measured}$$

$$p_L = p_T \cot \theta$$

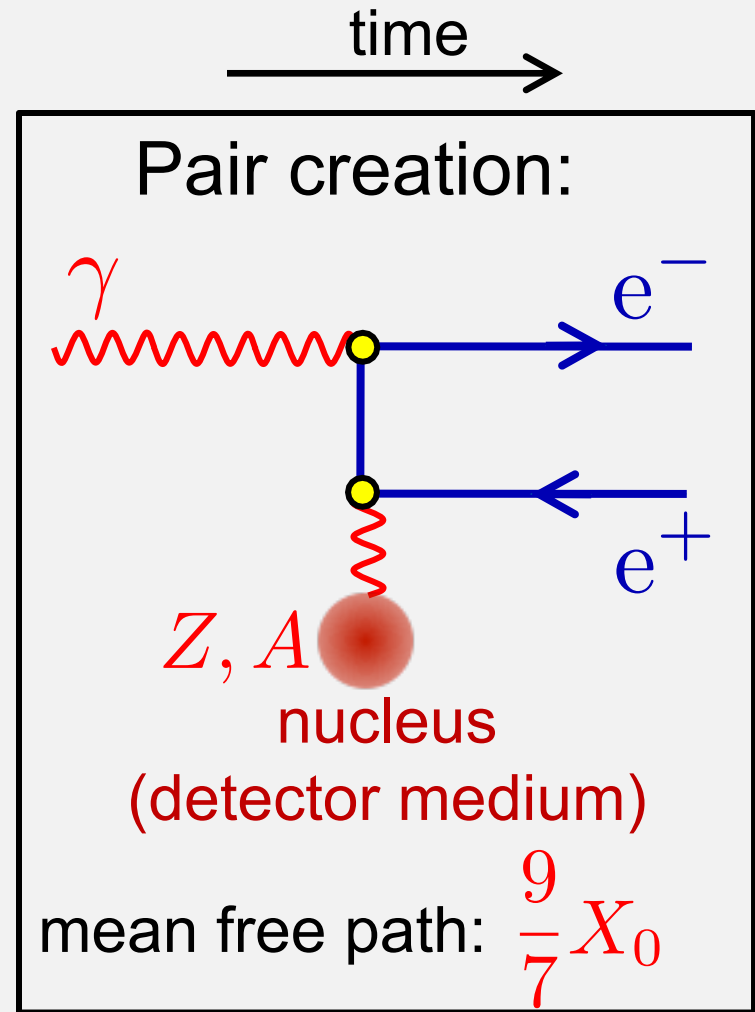
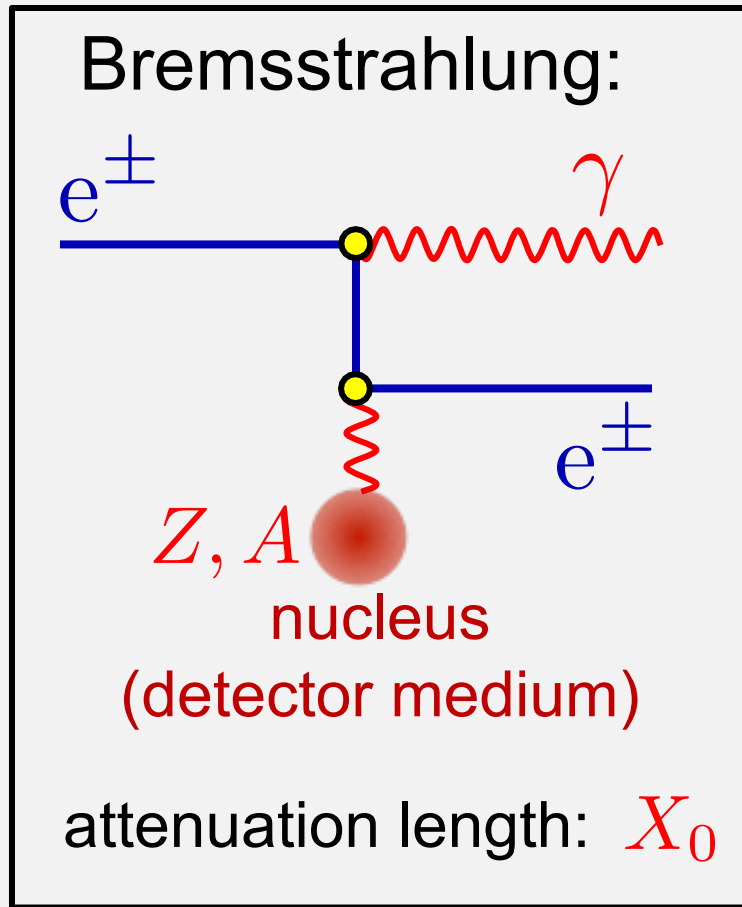
$$E = \sqrt{\vec{p}^2 + m^2} \quad m \text{ assumed or from particle id.}$$



Top-quark pair-production



2) Radiation: $e^\pm$, γ



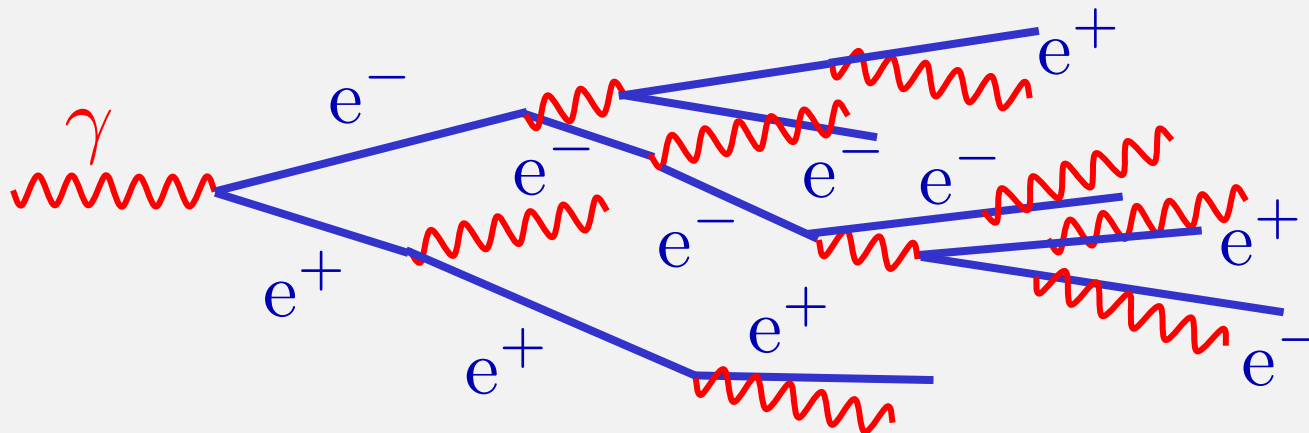
Radiation length:
$$X_0 = \frac{1}{4\alpha^3} \frac{A}{N_A \rho} \frac{m^2}{Z^2 \ln \frac{183}{Z^{\frac{1}{3}}}}$$

Application: electromagnetic calorimeters

only dominant for
electrons/positrons

Radiation length:
$$X_0 = \frac{1}{4\alpha^3} \frac{A}{N_A \rho} \frac{m^2}{Z^2} \ln \frac{183}{Z^{\frac{1}{3}}}$$

high Z materials (e.g. Pb)
are good absorbers



electromagnetic shower



Photo: CERN

scintillating lead-tungstate (PbWO_4) crystals for ECAL of CMS



$$\frac{\sigma_E}{E} \approx \frac{3\%}{\sqrt{E/\text{GeV}}} \quad (\text{at high energies})$$

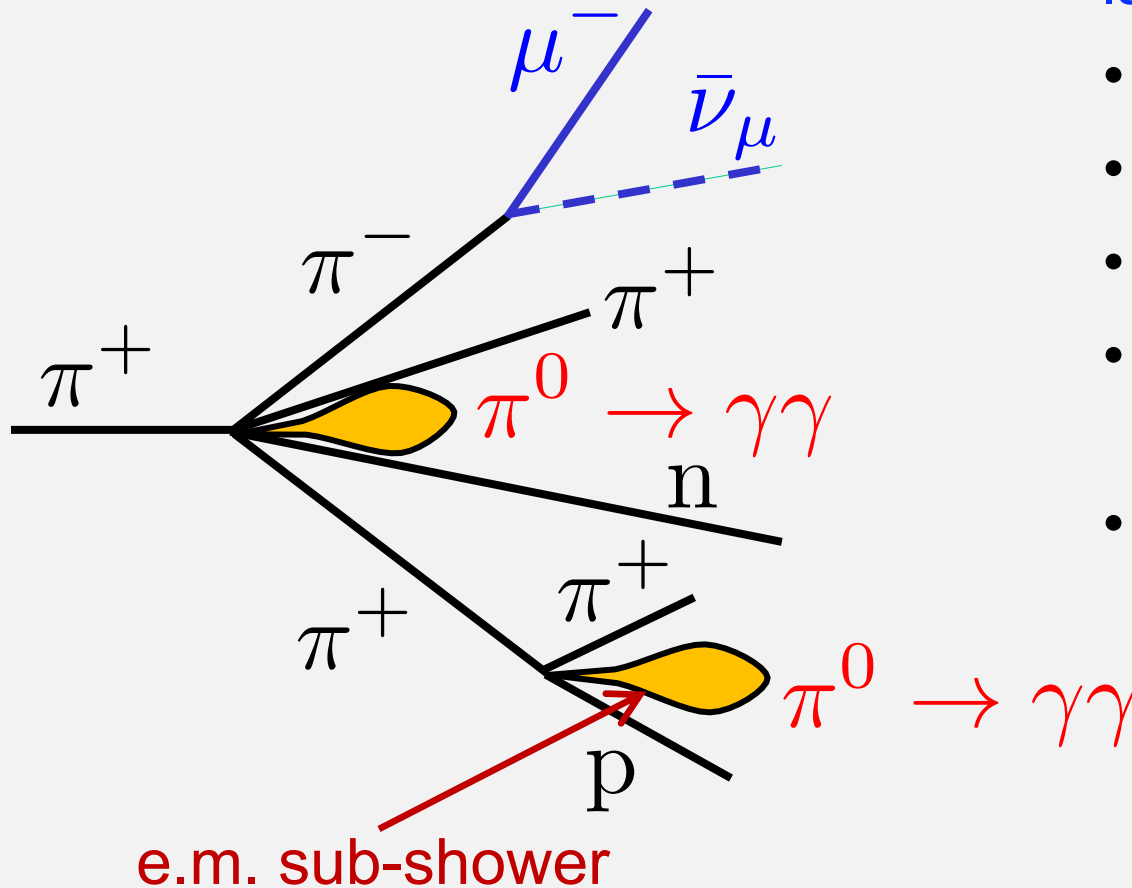
Photo: CERN

2) Absorbing hadrons (charged and neutral):

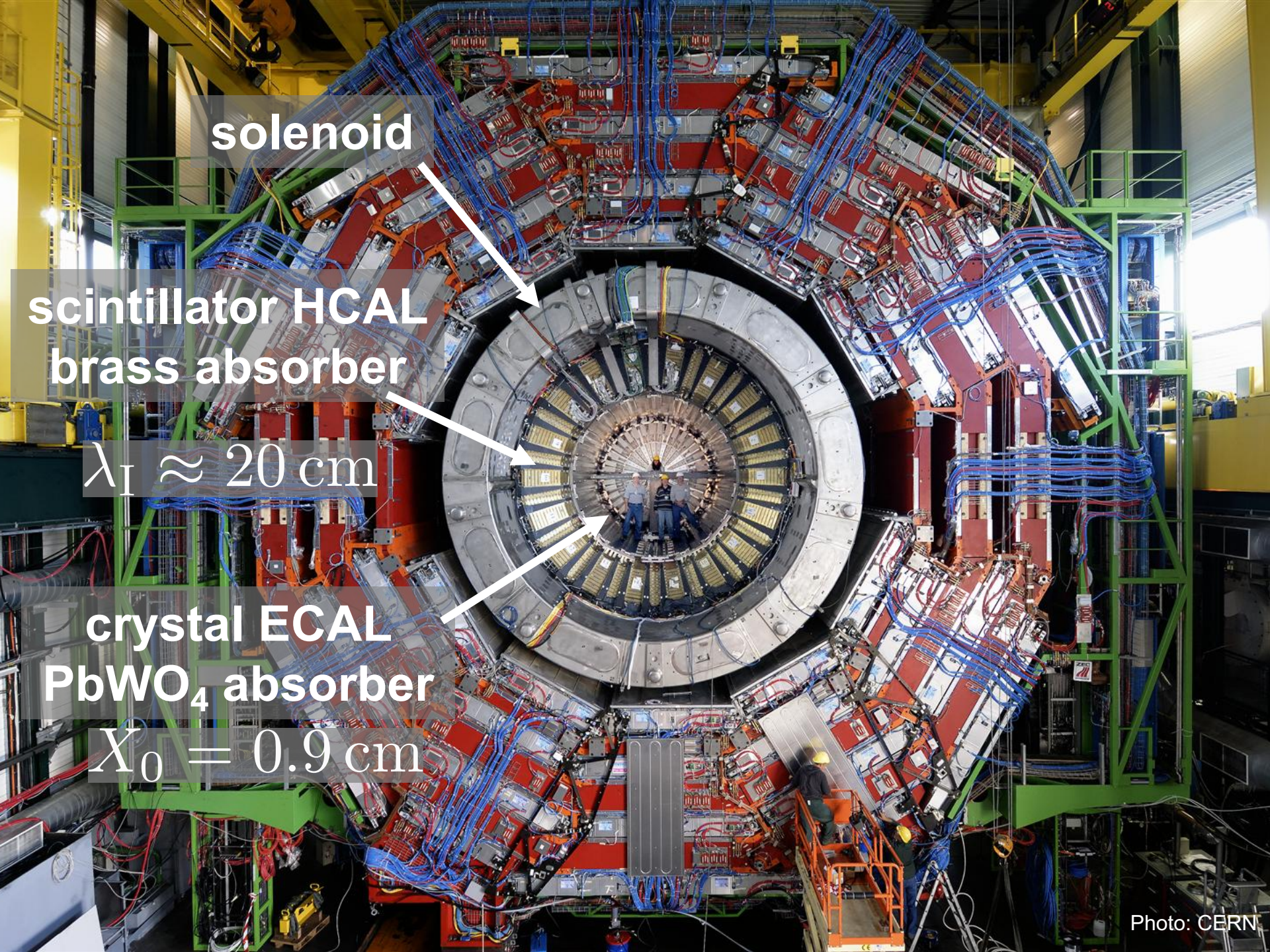
strong interaction $\Rightarrow$ attenuation length scale $\lambda_I \propto A^{-1}$
 $\Rightarrow$ use material of large mass density (e.g. iron yoke of magnet)

large fluctuations

- escaping neutrinos
- escaping muons
- escaping neutrons
- energy loss by nuclear fission
- electromagnetic sub-showers



$$\frac{\sigma_E}{E} \approx \frac{100\%}{\sqrt{E/\text{GeV}}}$$



The image shows the ATLAS detector, a large cylindrical structure composed of several concentric layers. The outermost layer is the solenoid, which is a large cylindrical magnet. Inside the solenoid is the scintillator HCal (Hadronic Calorimeter), followed by a brass absorber. The innermost layer is the crystal ECAL (Electromagnetic Calorimeter), which contains PbWO₄ absorbers. The detector is surrounded by a complex network of cables and support structures. The central part of the detector is a large circular structure with a central core. The overall structure is supported by a green metal framework. The image is taken from a high angle, looking down into the detector.

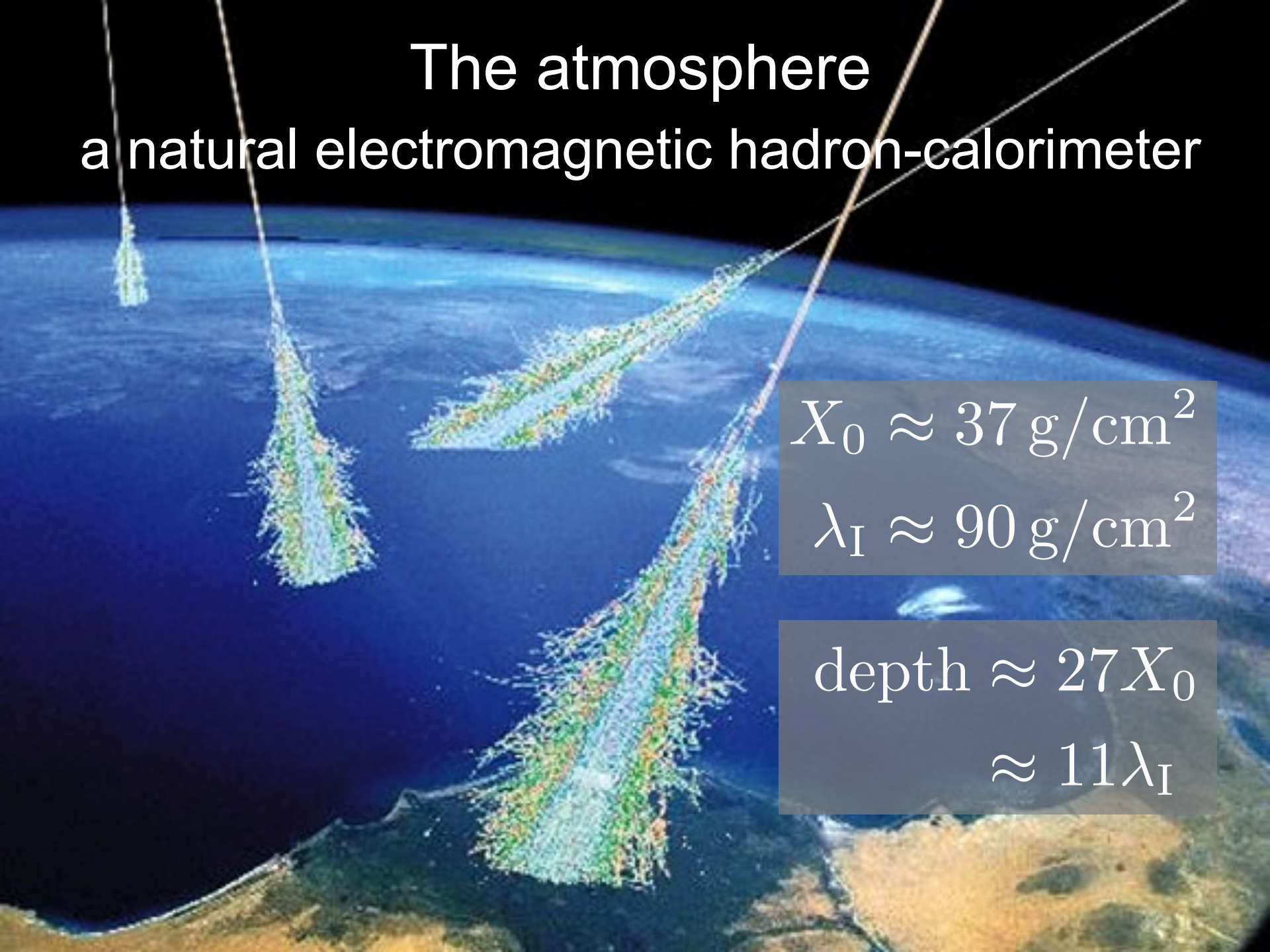
solenoid

scintillator HCal
brass absorber

$\lambda_I \approx 20 \text{ cm}$

crystal ECAL
PbWO₄ absorber
 $X_0 = 0.9 \text{ cm}$

The atmosphere a natural electromagnetic hadron-calorimeter

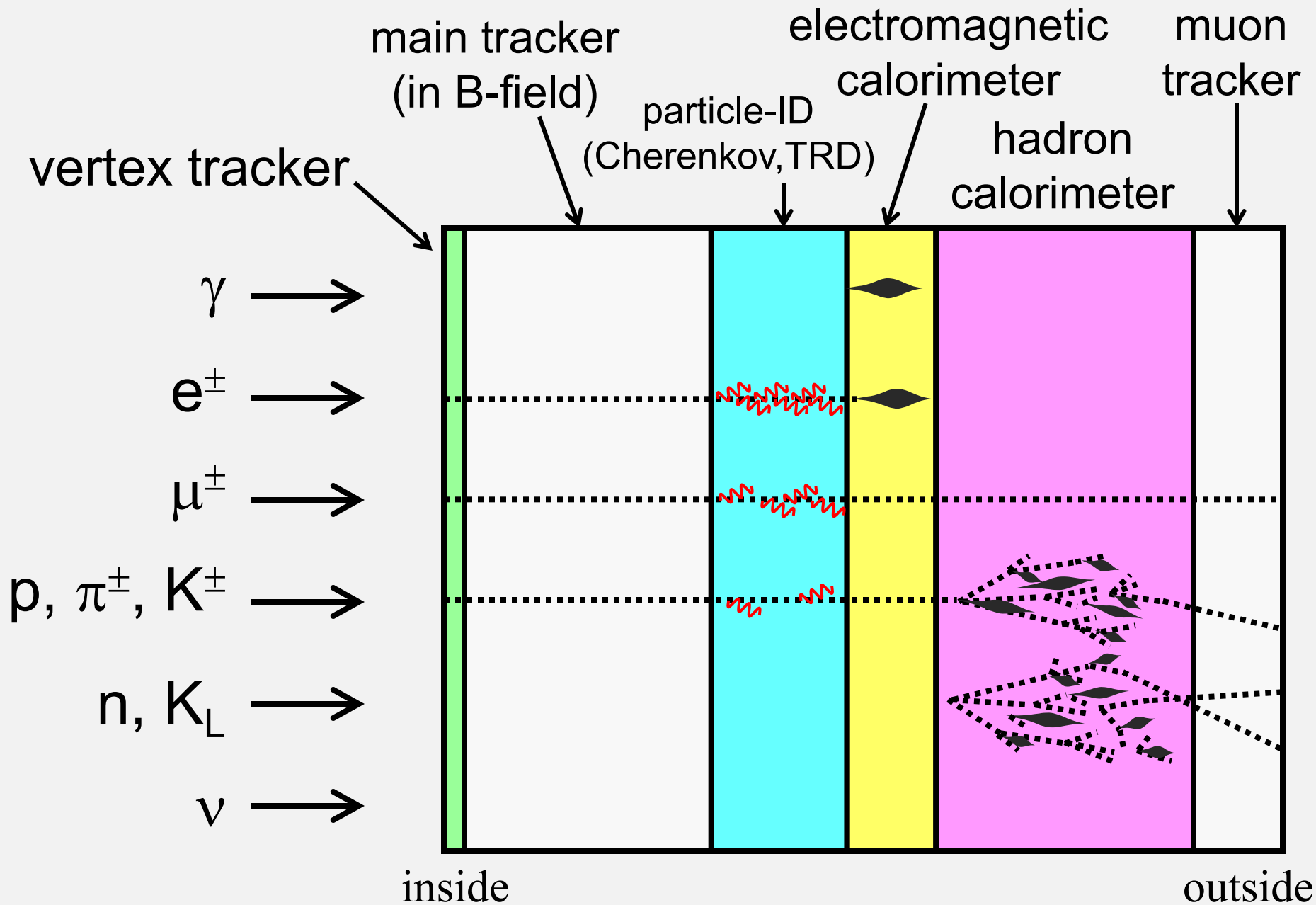
An aerial photograph of the Earth's surface, showing a coastline and some land. Overlaid on the image are several particle showers, which are depicted as branching, tree-like structures of colored lines (green, blue, and orange) representing the paths of particles as they travel through the atmosphere. These showers originate from the top of the frame and spread out as they descend towards the ground. The background is a clear blue sky, and the Earth's surface is visible at the bottom of the frame.
$$X_0 \approx 37 \text{ g/cm}^2$$

$$\lambda_I \approx 90 \text{ g/cm}^2$$

$$\text{depth} \approx 27 X_0$$

$$\approx 11 \lambda_I$$

The fingerprints of "stable" particles



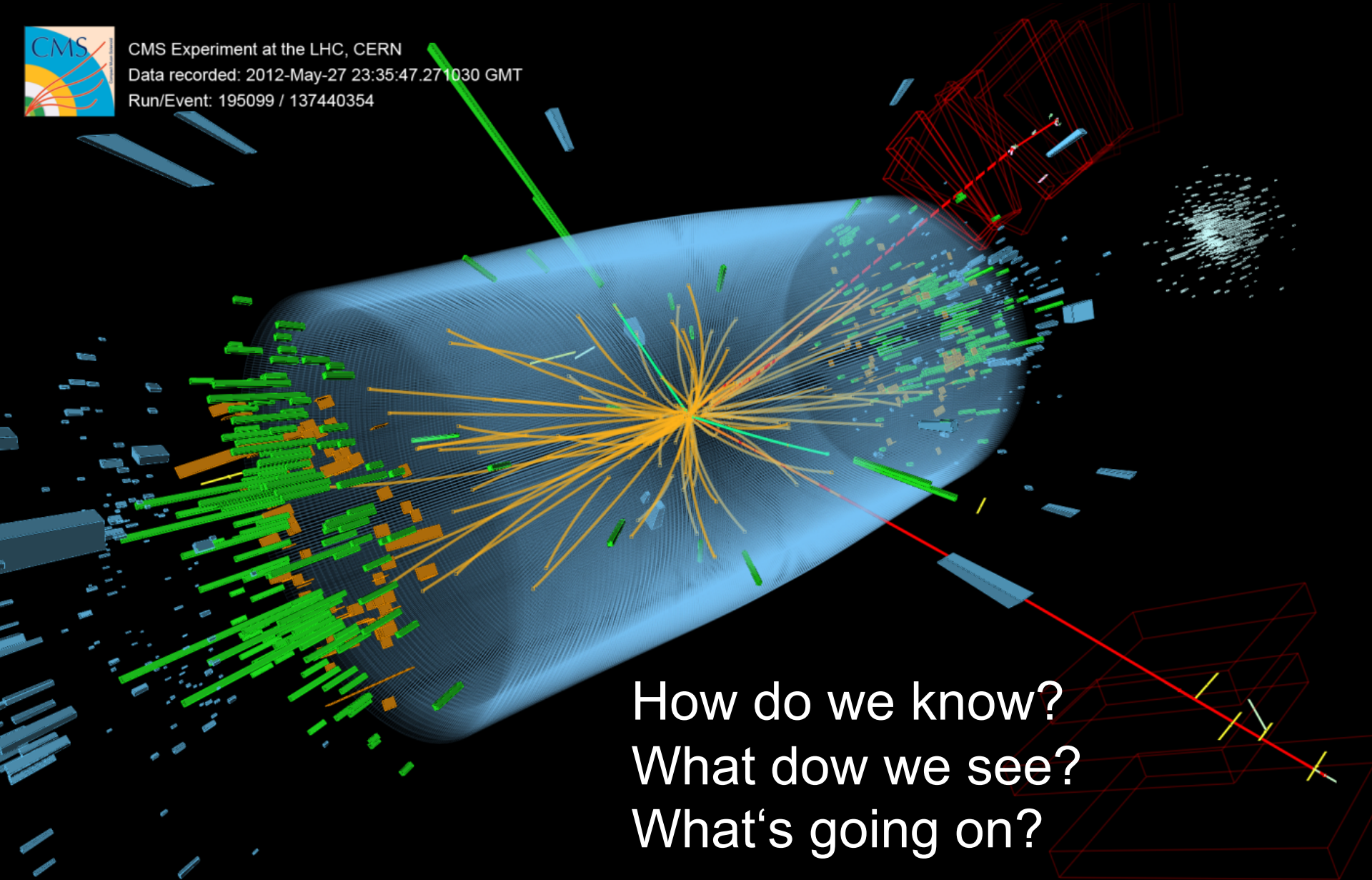
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



How do we know?
What do we see?
What's going on?

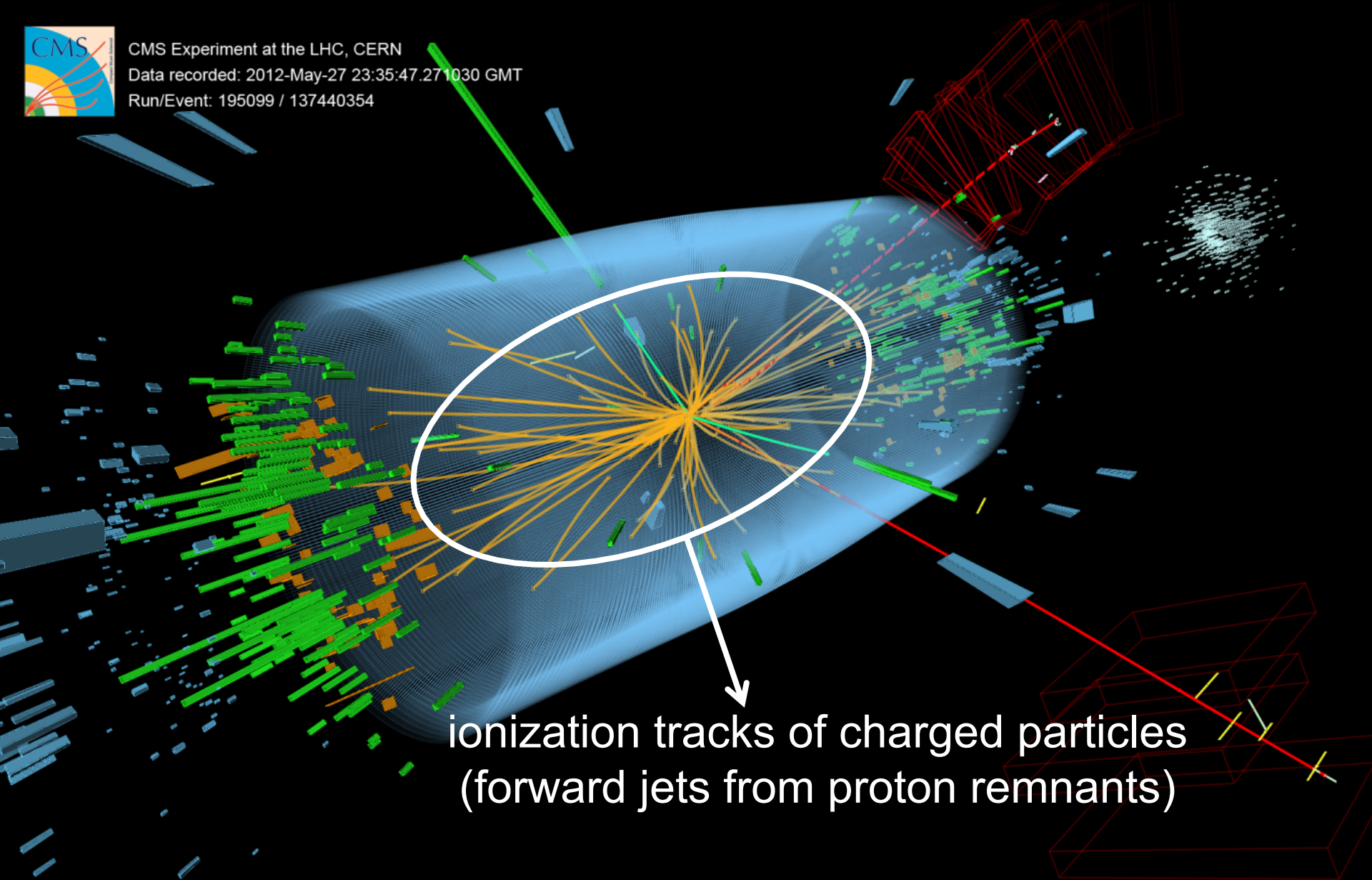
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



ionization tracks of charged particles
(forward jets from proton remnants)

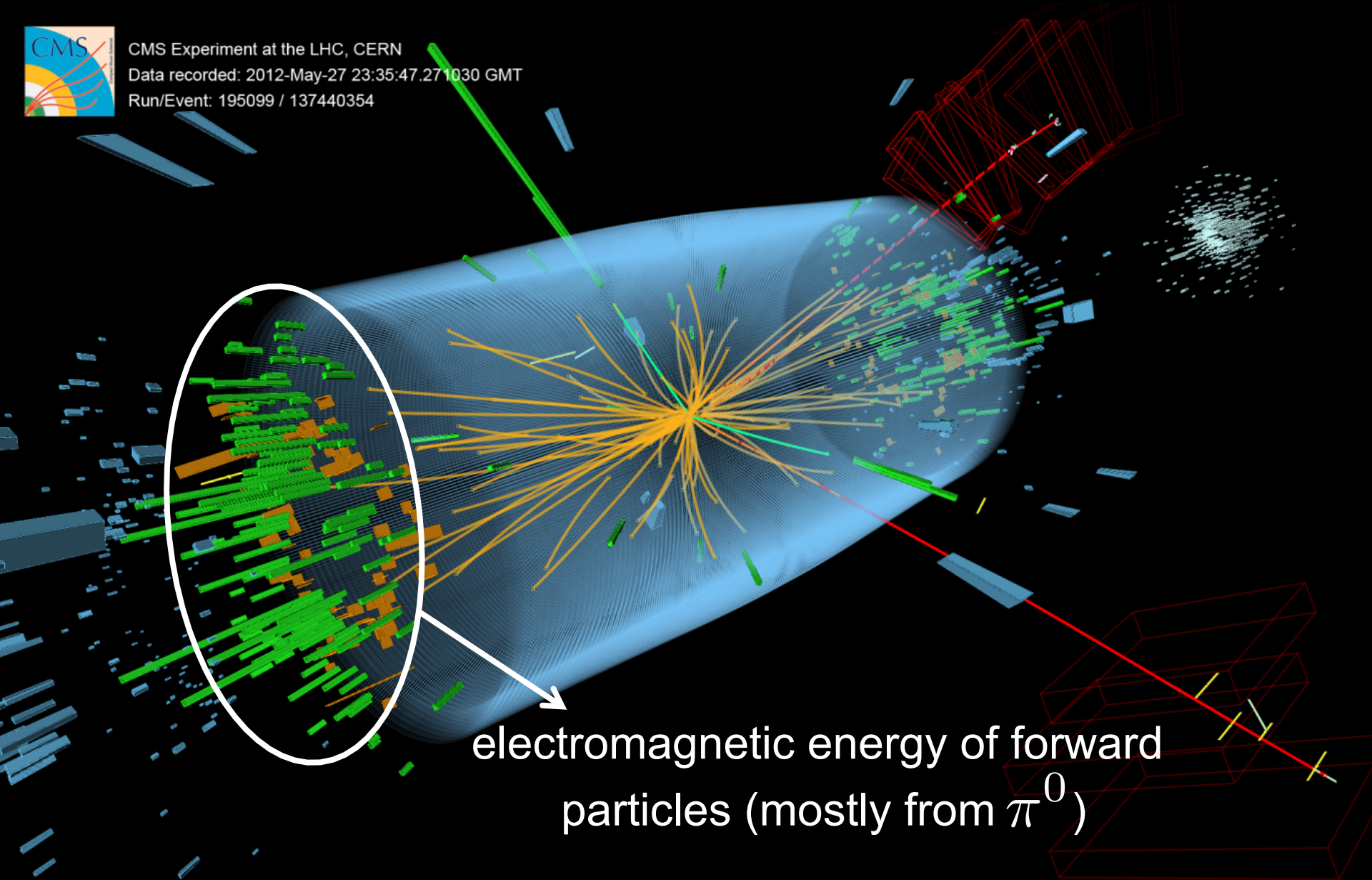
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



electromagnetic energy of forward
particles (mostly from π^0)

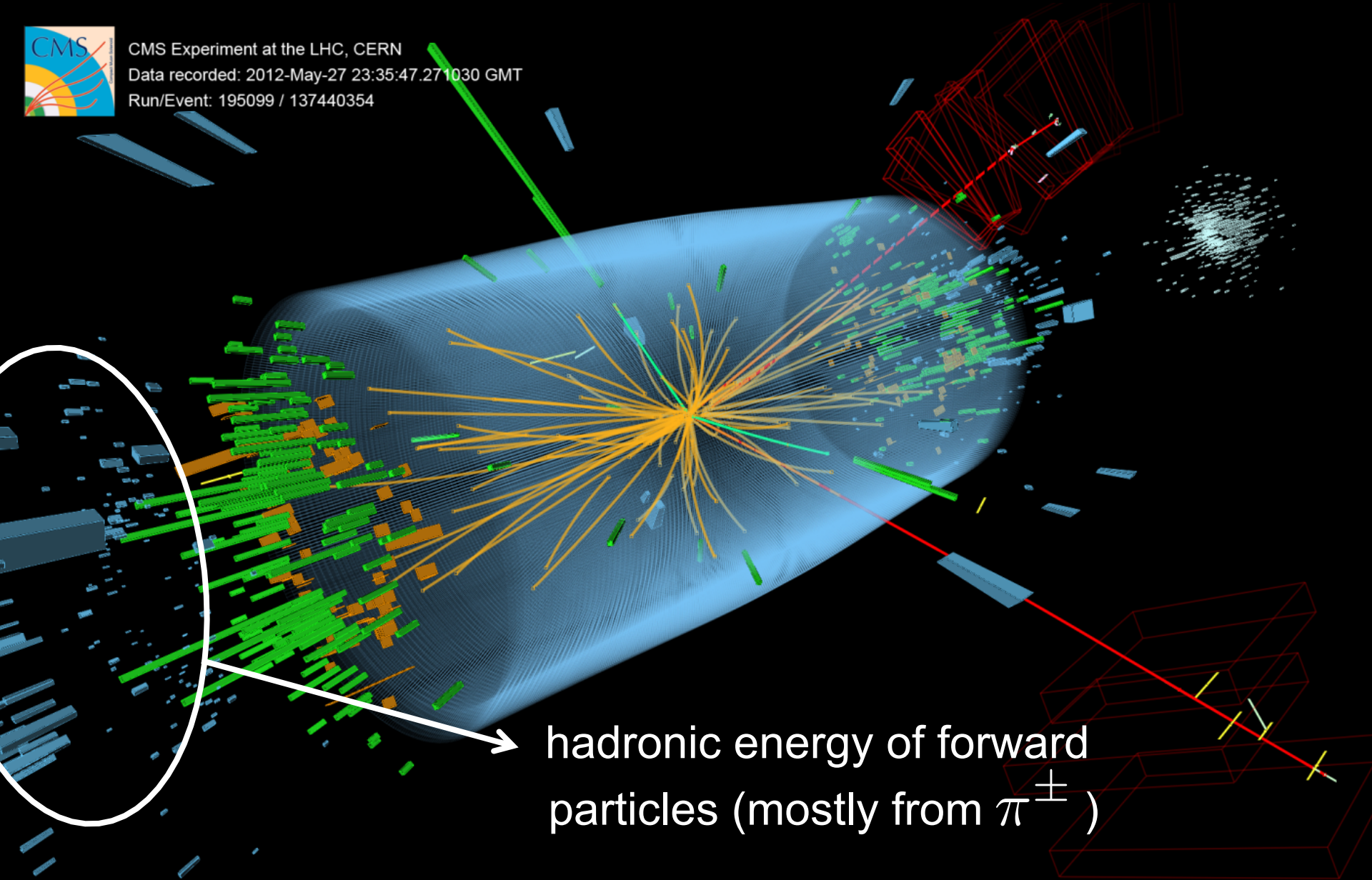
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



hadronic energy of forward particles (mostly from $\pi^\pm$)

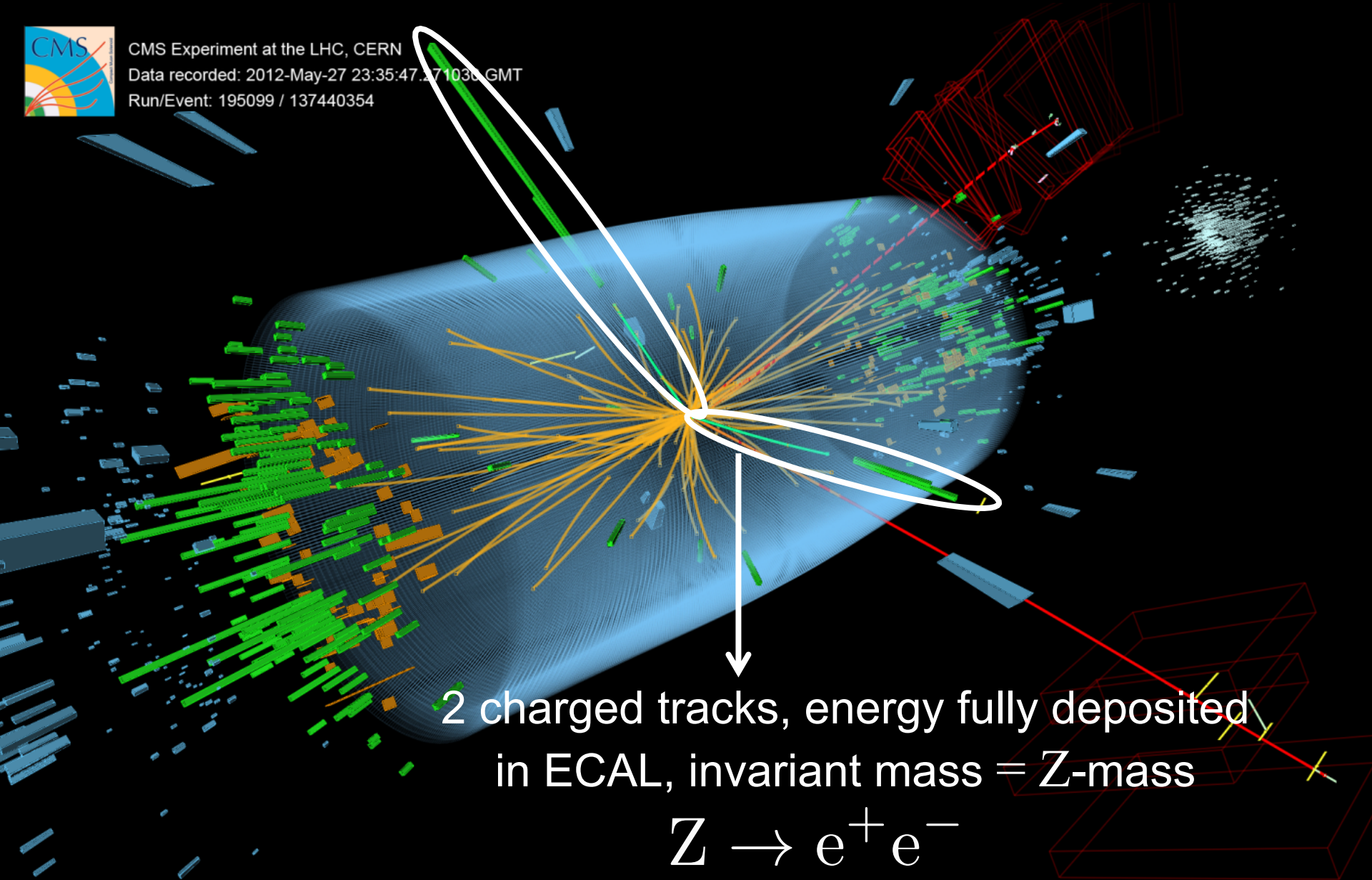
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.171036 GMT

Run/Event: 195099 / 137440354



2 charged tracks, energy fully deposited
in ECAL, invariant mass = Z-mass

$$Z \rightarrow e^+ e^-$$

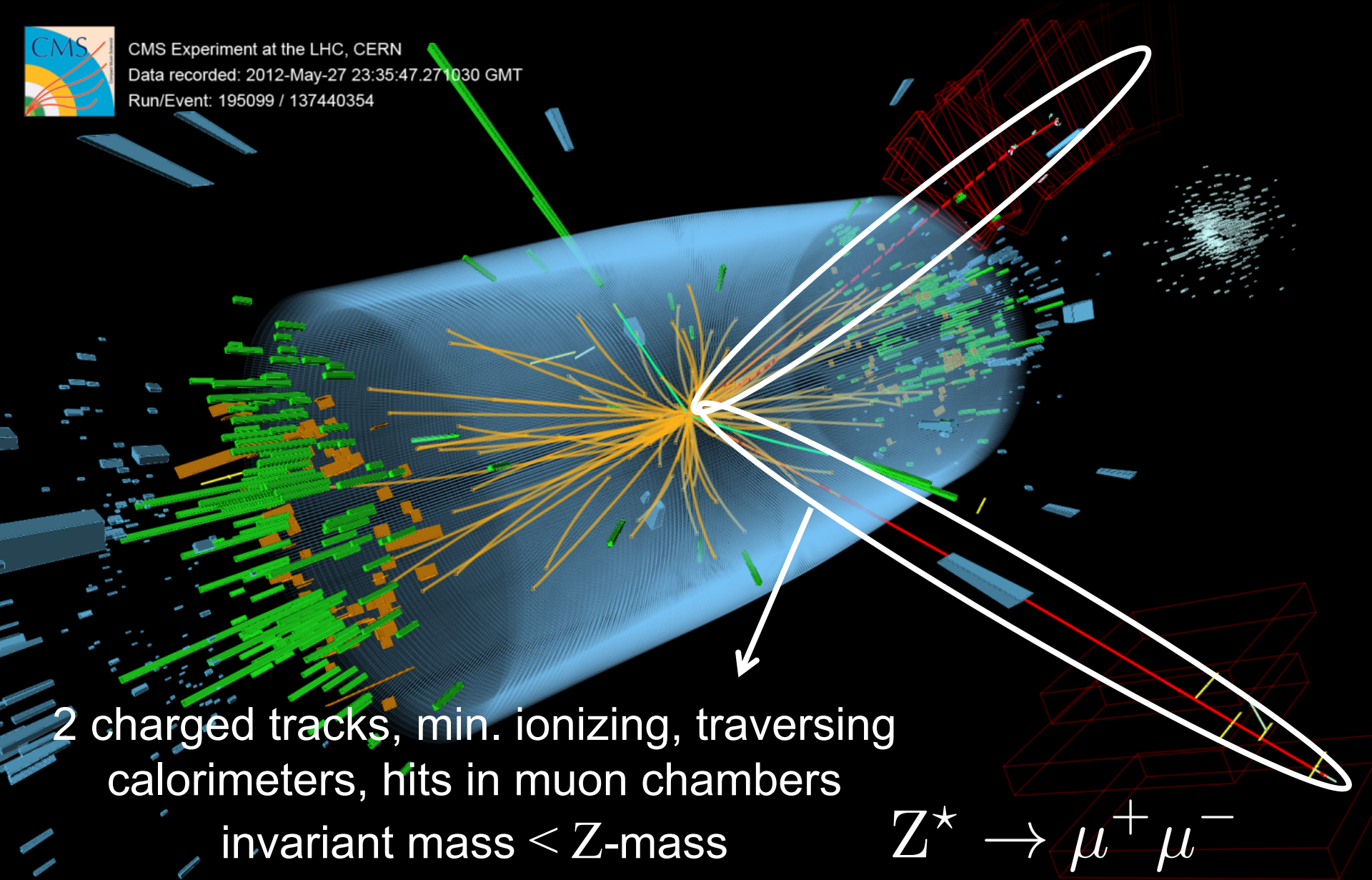
$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



2 charged tracks, min. ionizing, traversing
calorimeters, hits in muon chambers

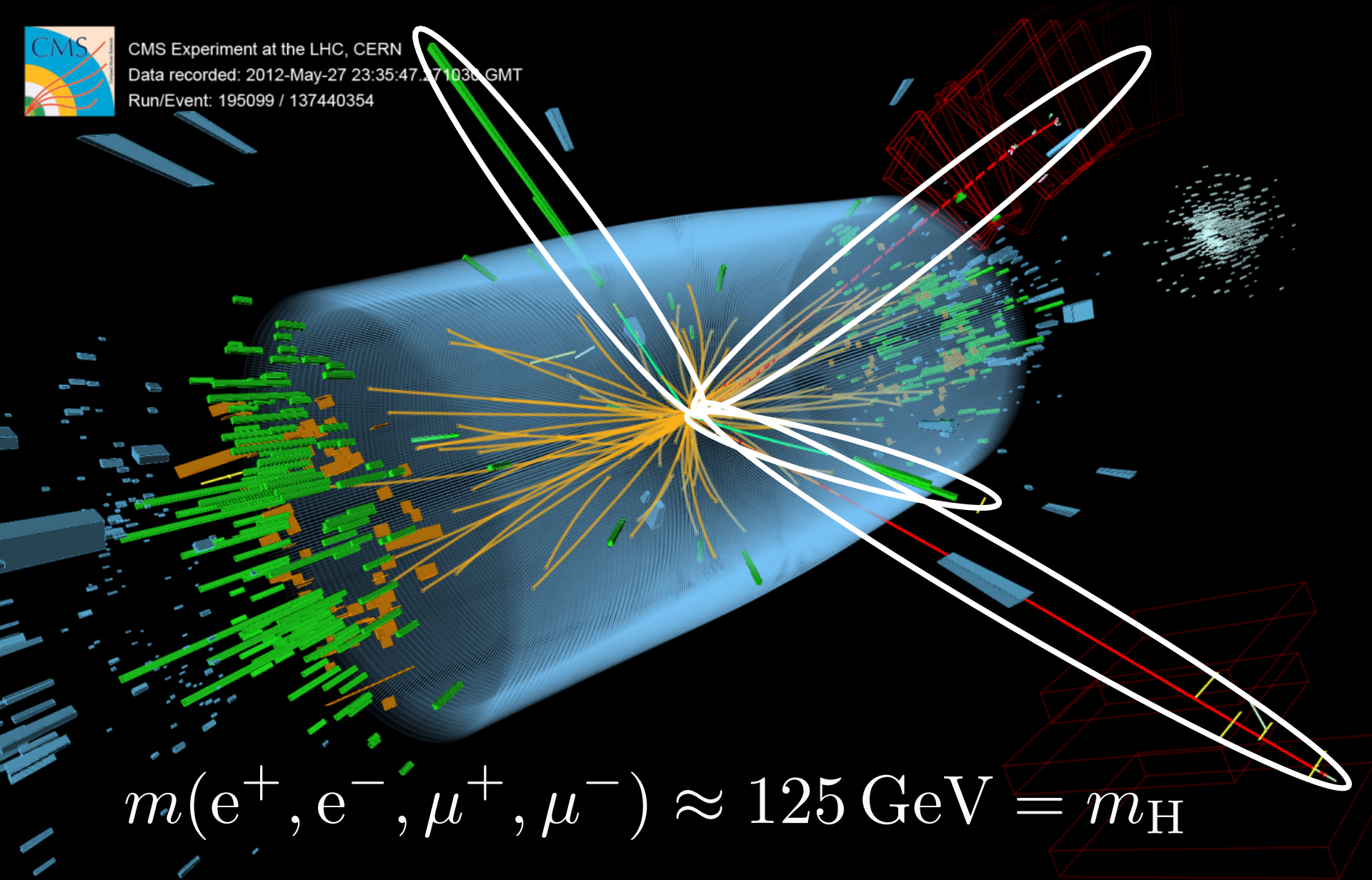
invariant mass $< Z$ -mass

$$Z^* \rightarrow \mu^+ \mu^-$$

$$H \rightarrow ZZ \rightarrow \mu^+ \mu^- e^+ e^-$$

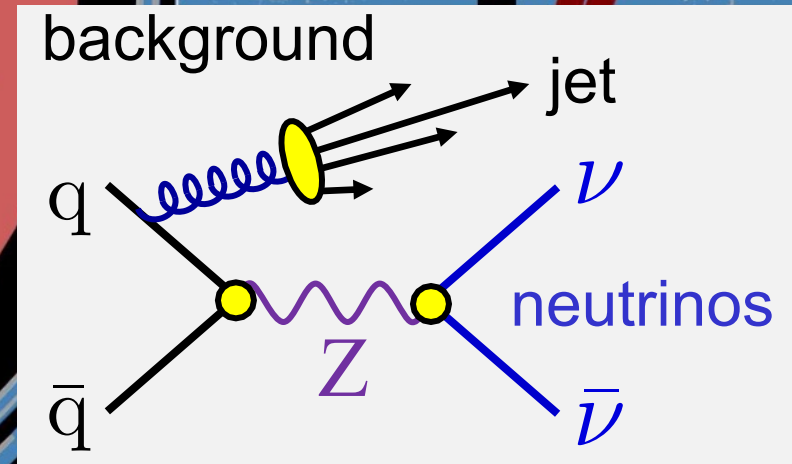
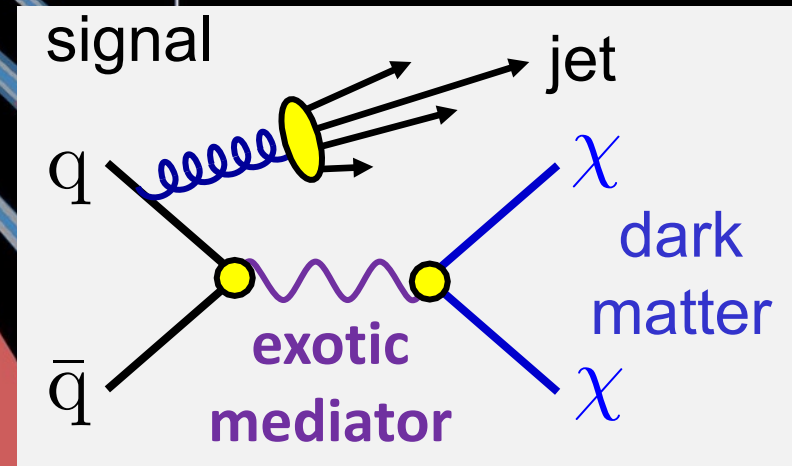
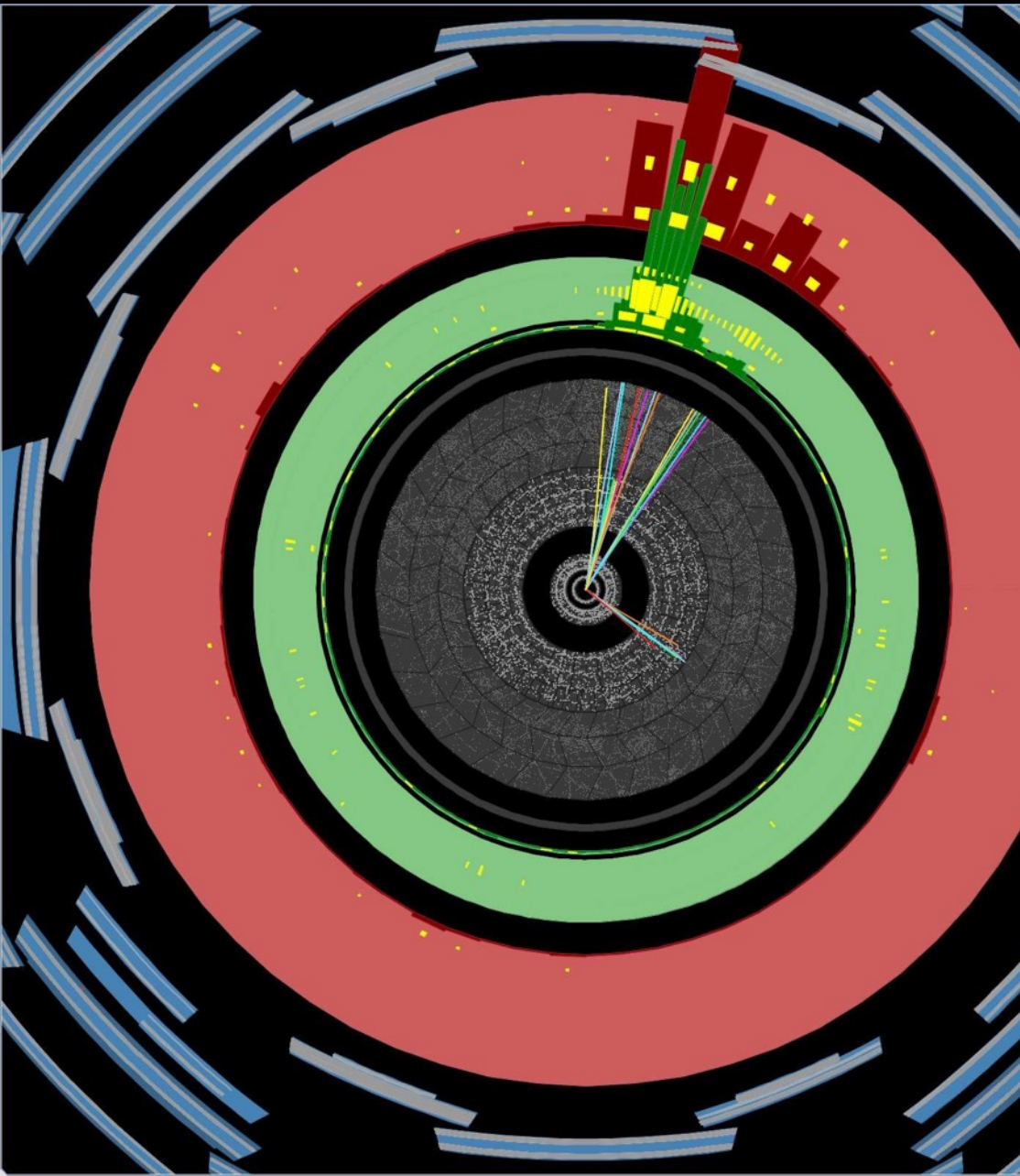


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271036 GMT
Run/Event: 195099 / 137440354



$$m(e^+, e^-, \mu^+, \mu^-) \approx 125 \text{ GeV} = m_H$$

The relevance of missing (transverse) energy



Part II

- Theory: (somewhat rough) basics
- Precision tests at e^+e^- -colliders

Reminder: examples of 4-vectors

$$(x^\mu) = (t, \vec{x}) \quad \text{space-time}$$

$$(\partial_\mu) = \left(\frac{\partial}{\partial x^\mu} \right) = \left(\frac{\partial}{\partial t}, \vec{\nabla} \right) \quad \text{4-derivative}$$

$$(A^\mu) = (\phi, \vec{A}) \quad \text{electromagnetic 4-potential}$$

$$(j^\mu) = (\rho, \vec{j}) \quad \text{electromagnetic 4-current}$$

$$(p^\mu) = (E, \vec{p}) \quad \text{4-momentum}$$

$$p^2 = p_\mu p^\mu = m^2$$

$$(i\partial^\mu) = \left(i\frac{\partial}{\partial t}, -i\vec{\nabla} \right) \quad \text{4-momentum operator}$$

$$\text{hence: } (i\partial_\mu)(i\partial^\mu) = -\partial_\mu \partial^\mu \quad m^2\text{-operator}$$

Relativistic quantum mechanics of a (free) spin-0 particle

particle mass: m

m^2 -operator: $-\partial_\mu \partial^\mu$

wave function ϕ

$$\left. \begin{array}{l} \text{particle mass: } m \\ m^2\text{-operator: } -\partial_\mu \partial^\mu \end{array} \right\} -\partial_\mu \partial^\mu \phi = m^2 \phi$$

Klein-Gordon equation: $(\partial_\mu \partial^\mu + m^2)\phi = 0$

Formulation via Lagrange density:

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi)}_{\text{kinetic energy}} - \underbrace{\frac{1}{2}m^2 \phi^2}_{\text{mass term} \quad (\leftrightarrow \text{potential energy})}$$

$\partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} - \frac{\partial \mathcal{L}}{\partial \phi} = 0$

Relativistic quantum mechanics of a (free) spin- $\frac{1}{2}$ particle

$$\text{Dirac equation: } (i\gamma^\mu \partial_\mu - m)\psi = 0$$

ψ : 4 component (spinor) wave function (complex)
describes particle and antiparticle, each spin up or down

γ^μ : 4×4 Dirac matrices

Formulation via Lagrange density:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

ψ has 4 complex components $\Rightarrow$ 8 degrees of freedom

ψ 4 independent degrees of freedom

$\bar{\psi} \equiv \psi^\dagger \gamma^0$ 4 independent degrees of freedom

Classical electromagnetism – massless spin-1 particles

Free photon (Maxwell eq. without sources):

$$\partial_\mu F^{\mu\nu} = 0$$

... with e.m. field strength tensor $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

Lorentz gauge:

$$\partial_\mu A^\mu = 0 \quad \Rightarrow$$

$$\partial_\mu \partial^\mu A^\nu = 0$$

Klein-Gordon equation for
massless spin-1 particle

Formulation via Lagrange density:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

Charged spin-1/2 particle in electromagnetic field

Dirac equation: $(i\gamma^\mu D_\mu - m)\psi = 0$

Covariant derivative: $D_\mu = \partial_\mu + ieQA_\mu$

Charge operator eQ acts on ψ : $eQ\psi = q_\psi\psi$

Formulation via Lagrange density:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}}$$

$$\mathcal{L}_{\text{int}} = -\underbrace{q_\psi(\bar{\psi}\gamma^\mu\psi)}_{\text{e.m. 4-current}}A_\mu = -j^\mu A_\mu$$

Towards Quantum Field Theorie

classical wave functions $\rightarrow$ operators (in Fock space)

$\Rightarrow$ #particles/quanta can change in interactions

Examples:

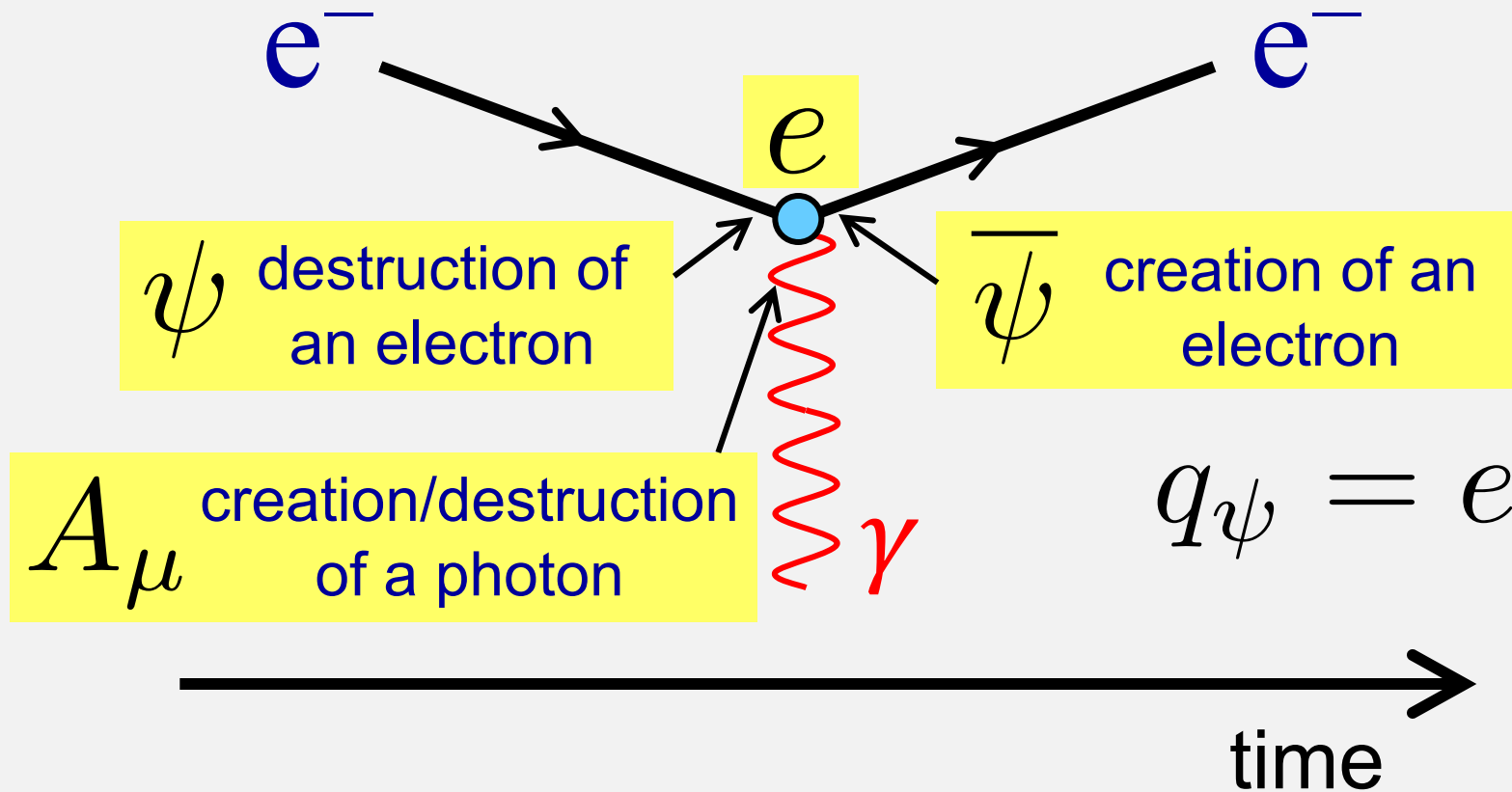
ψ_e destruction of an electron
 creation of a positron

$\overline{\psi}_e$ creation of an electron
 destruction of a positron

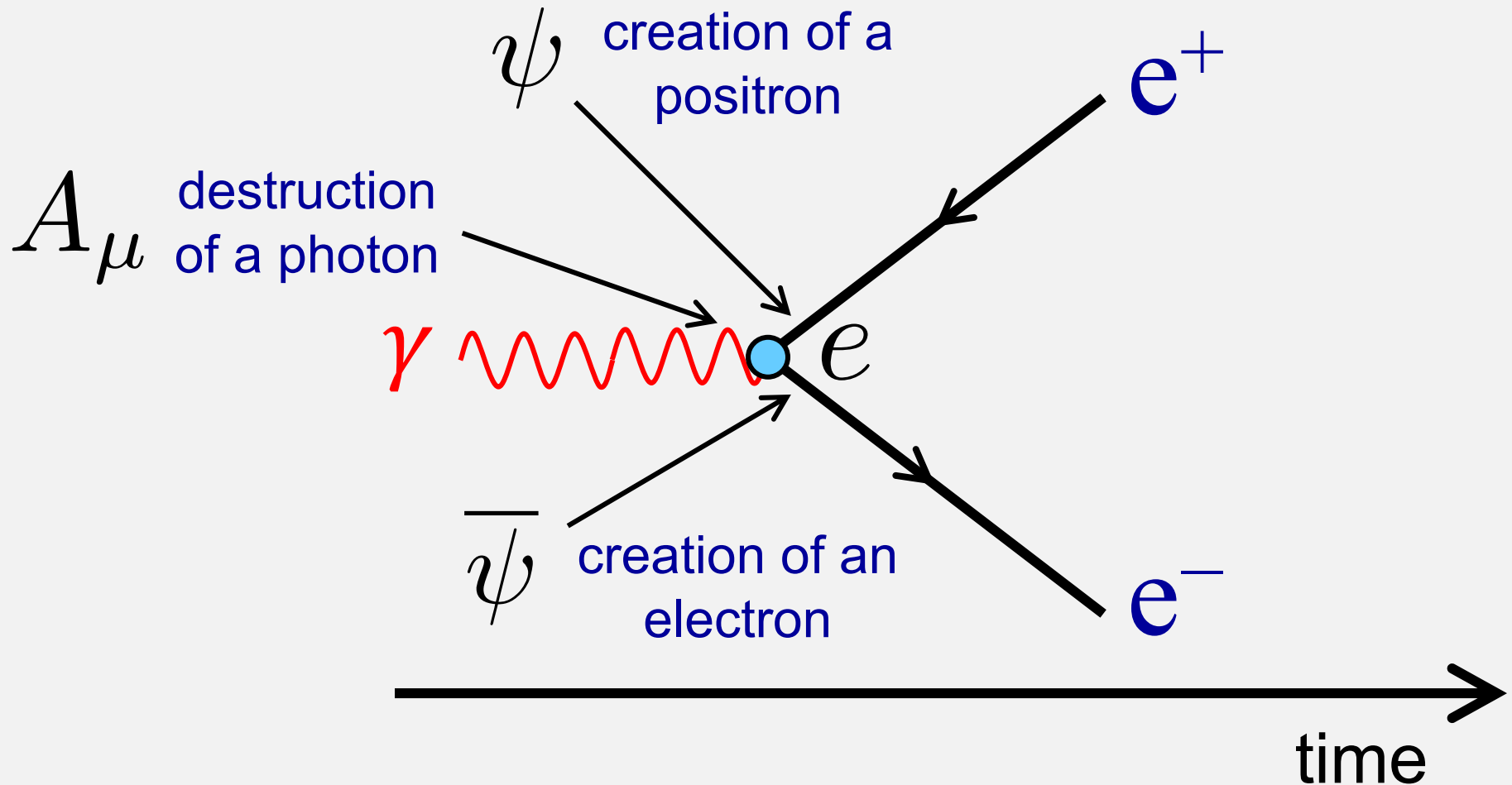
A_μ creation / destruction of a photon

$\mathcal{L}_{\text{int}}$ and fundamental couplings (**vertices**)

$$\mathcal{L}_{\text{int}} = -q_\psi (\bar{\psi} \gamma^\mu \psi) A_\mu = -j^\mu A_\mu$$

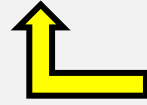


... turn it any way you like ...



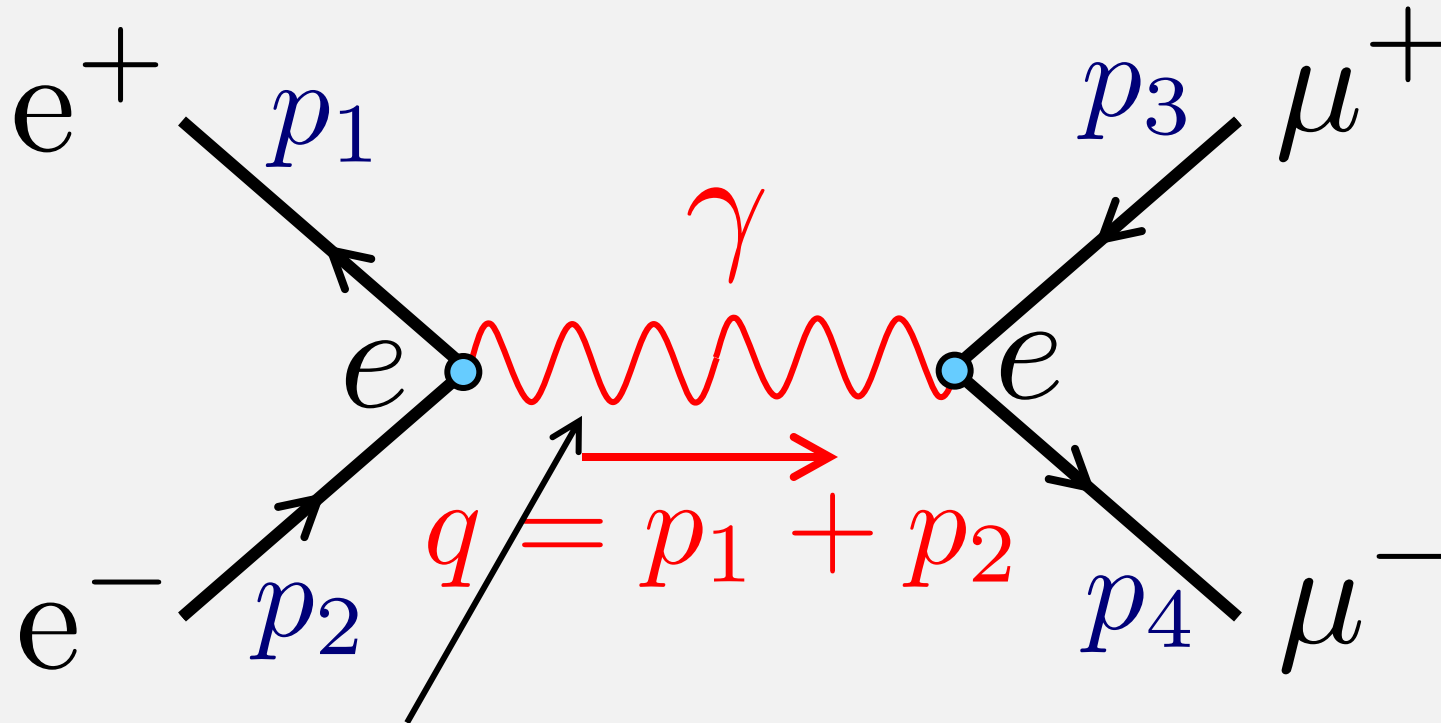
- anti-fermion $\triangleq$ fermion moving backwards in time
- fermion lines never end (e.m. current)

building Feynman diagrams



pronounced like “fine man”

→ scattering amplitudes in perturbative expansion in powers of e



virtual photon ($\hat{=}$ potential in momentum space)

real (free) photon: $p_\gamma^2 = m_\gamma^2 = 0$

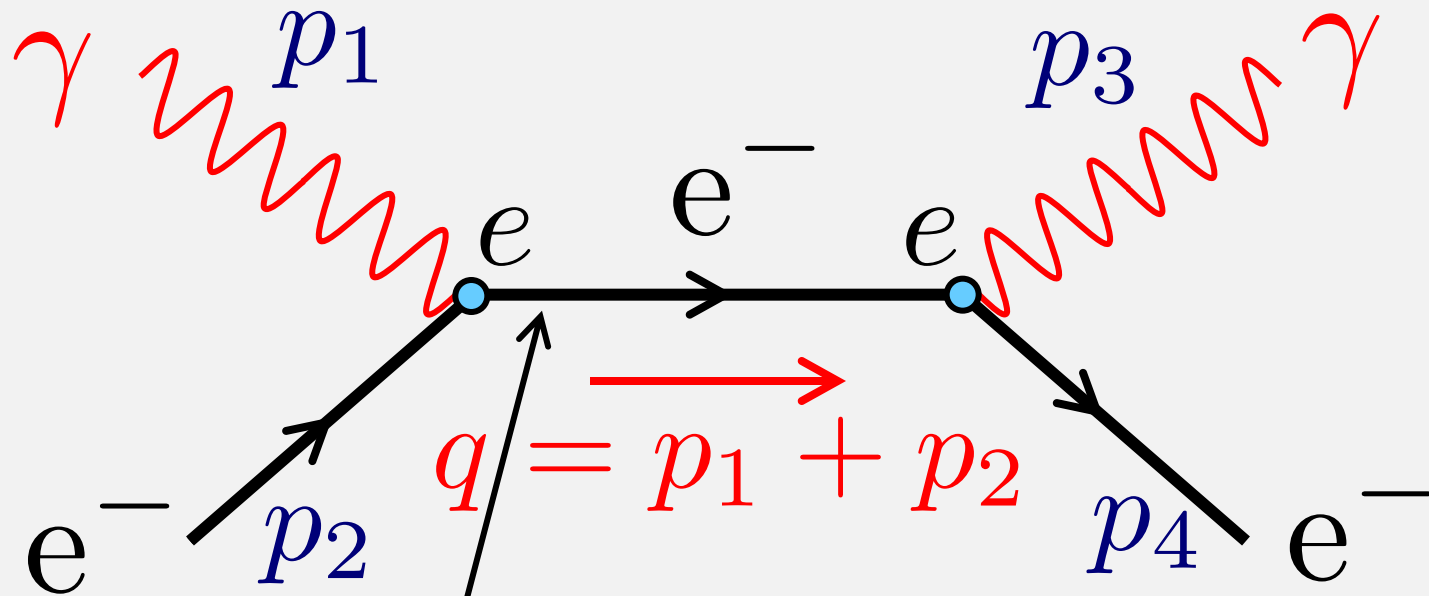
virtual photon: $p_\gamma^2 = q^2 \neq 0$

... anybody can go virtual ...

e.g. (inverse) Compton scattering

real photon

real photon



real electron

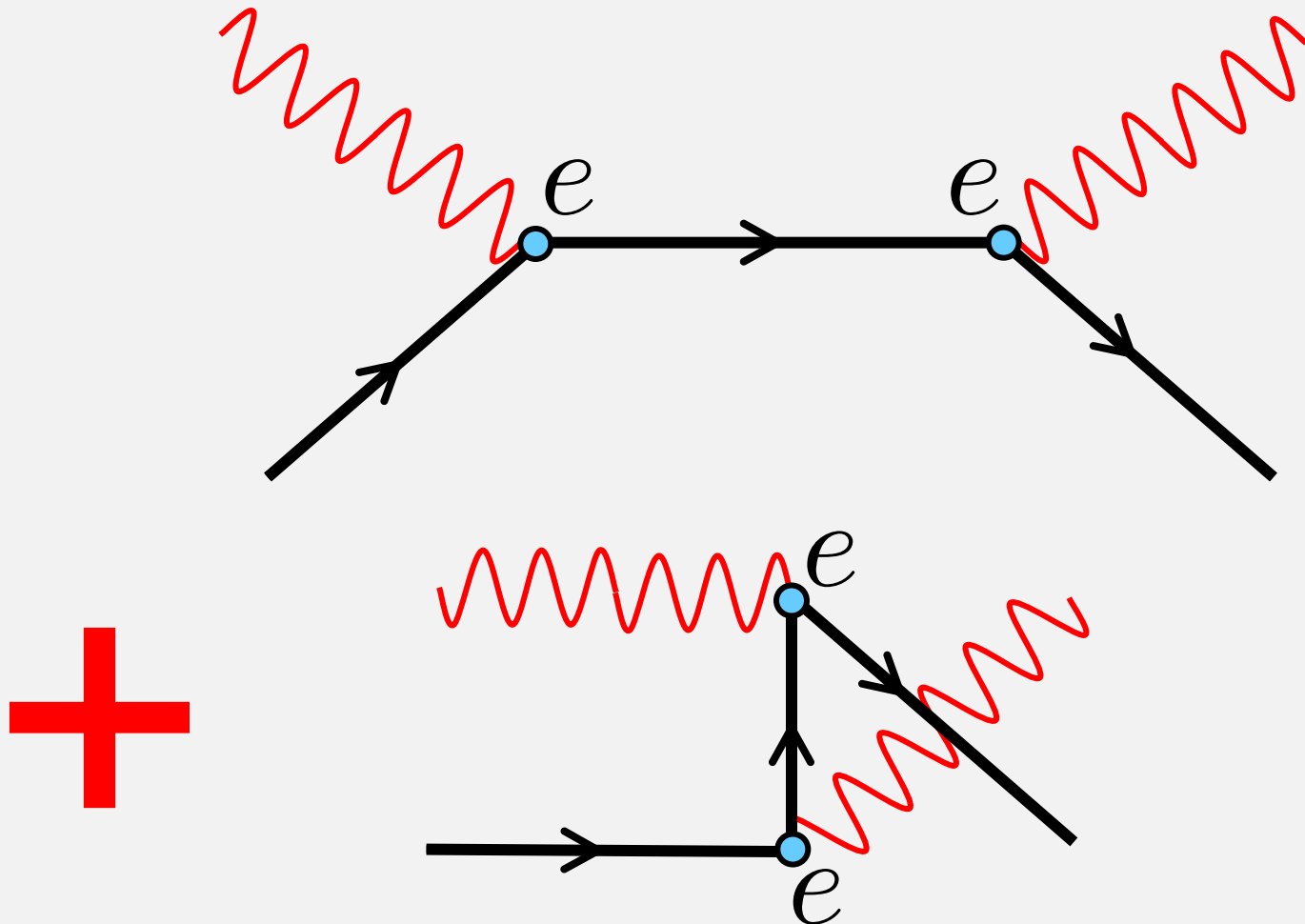
real electron

virtual electron: $p_e^2 = q^2 \neq m_e^2$

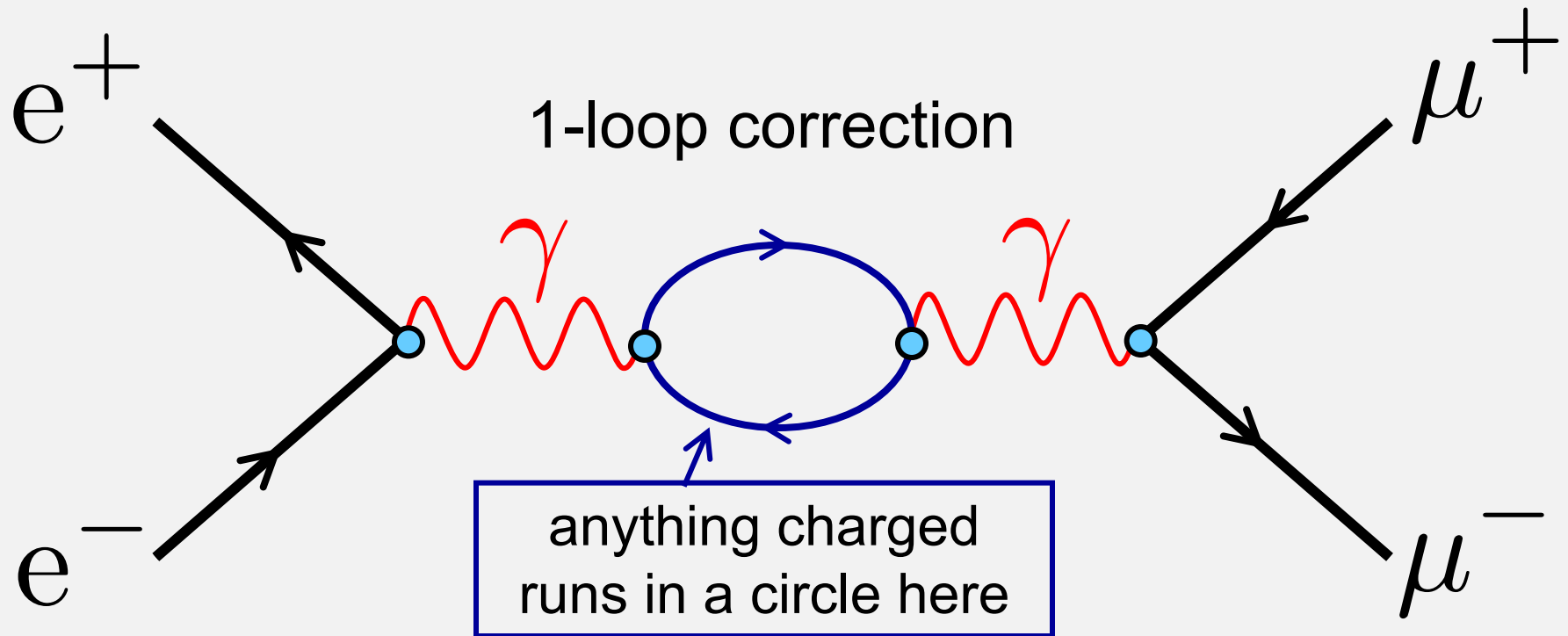
QFT: anything possible happens (all at once)

always add **all** amplitudes for a given order

e.g. (inverse) Compton scattering



Quantum fluctuations: small but important



- sensitive to new (heavy) particles: they are virtual in the loop
- most exciting: rare processes which can only occur via loops

The heart of the theory: gauge invariance

Two unrelated(?) **symmetries**:

1) Electrodynamics:

arbitrary



gauge transformation $A_\mu \rightarrow A_\mu - \partial_\mu \Lambda(x)$

leaves Maxwell equations unchanged

form a $U(1)$ group

2) Quantum mechanics:

global phase transformation $\psi \rightarrow e^{i\alpha} \psi$

leaves equations for **free** particles unchanged,

e.g. $\mathcal{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi$

$$\rightarrow \bar{\psi} e^{-i\alpha} (i\gamma_\mu \partial^\mu - m) e^{i\alpha} \psi = \mathcal{L}$$

But this only works for global phase ($\alpha = \text{const.}$)

3) Quantum electrodynamics:

local phase transformation $\psi \rightarrow e^{i\alpha(x)}\psi$
changes free particle Lagrangian, e.g.

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\gamma_{\mu}\partial^{\mu} - m)\psi \\ &\rightarrow \mathcal{L} - (\bar{\psi}\gamma_{\mu}\psi)\partial^{\mu}\alpha(x)\end{aligned}$$

but this can be compensated for an **interacting**
particle by a properly chosen **gauge** transformation

$$A_{\mu} \rightarrow A_{\mu} - \partial_{\mu}\Lambda(x)$$

**Local phase invariance implies a force field with
gauge invariance!**

Putting it all together:

Covariant derivative $D_\mu = \partial_\mu + ieQ A_\mu$

Local gauge transformation

$$\psi \rightarrow e^{iQ\alpha(x)} \psi = e^{i(q_\psi/e)\alpha(x)} \psi$$

$$A_\mu \rightarrow A_\mu - \frac{1}{e} \partial_\mu \alpha(x)$$

$$\Rightarrow D_\mu \psi \rightarrow e^{iQ\alpha(x)} D_\mu \psi$$

Quantum electrodynamics (gauge invariant)

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Generalized phase transformation for strong force?

charge number operator

particle with electric charge

$$\psi \rightarrow e^{iQ\alpha(x)}\psi$$

Note: Each quarks comes in 3 distinct variants (“**colors**”)

Interpretation: The strong force has 3 different charges

$$\psi = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} \rightarrow e^{i(T^1\alpha^1(x) + T^2\alpha^2(x) + \dots + T^8\alpha^8(x))} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix}$$

amplitudes of
color-components

Why 8 phases?

$$\psi' = \underbrace{e^{iT^a \alpha^a}}_{\downarrow} \psi, \quad T^a \alpha^a = T^1 \alpha^1 + \dots + T^8 \alpha^8$$

complex 3×3 matrix

18 real parameters

unitary
(normalization fixed)

9 real parameters less

special (det = 1)
(no overall phase factor)

1 real parameter less

8 degrees of freedom

Special Unitary Group
(degree 3)

$SU(3)$

Building a gauge theory for $SU(3)$:

$U(1)$ symmetry

1 photon $A_\mu(x)$

gauge transformation:

$$\psi \rightarrow e^{iQ\alpha(x)} \psi$$

$$D_\mu \psi \rightarrow e^{iQ\alpha(x)} D_\mu \psi$$

covariant derivative:

$$D_\mu = \partial_\mu + ieQ A_\mu$$

electric unit charge
(coupling strength)

$SU(3)$ symmetry

8 gluons $A_\mu^a(x)$

gauge transformation:

$$\psi \rightarrow e^{iT^a \alpha^a(x)} \psi$$

$$D_\mu \psi \rightarrow e^{iT^a \alpha^a(x)} D_\mu \psi$$

covariant derivative:

$$D_\mu = \partial_\mu + ig_s T^a A_\mu^a$$

unit color charge
(coupling strength of strong force)

Dynamics of the $SU(3)$ gluons:

$U(1)$ symmetry

1 photon $A_\mu(x)$

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$[Q, Q] = 0$$

$U(1)$ is **abelian**

$SU(3)$ symmetry

8 gluons $A_\mu^a(x)$

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a$$

$$\Rightarrow -g_s f^{abc} A_\mu^b A_\nu^c$$

gauge invariance

$$[T^a, T^b] = i f^{abc} T^c$$

real numbers

$SU(3)$ is **non-abelian**

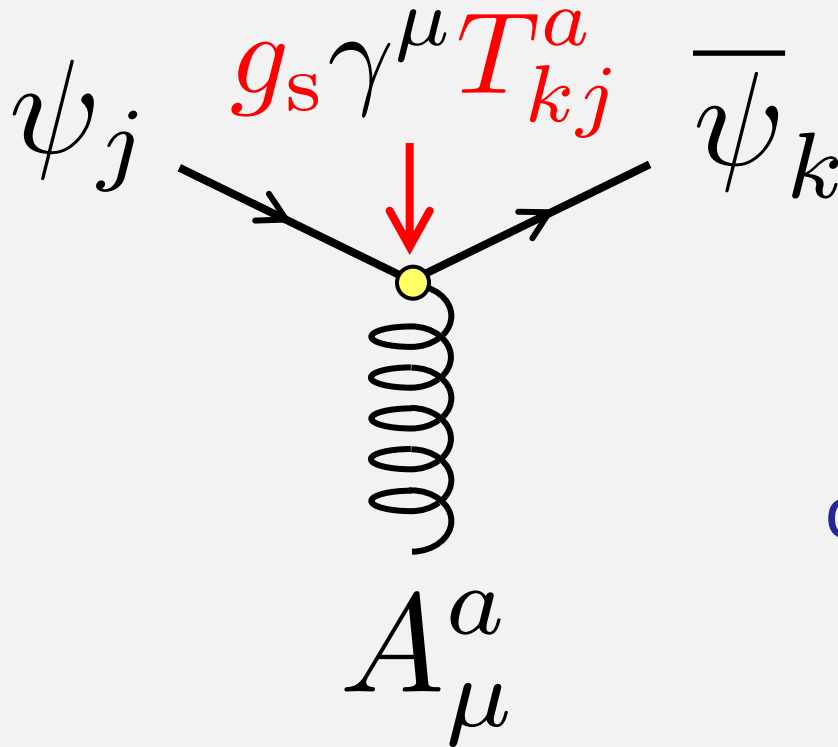
Quantum Chromodynamics

$$\begin{aligned}
 \mathcal{L} &= \overset{\text{quark}}{\downarrow} \bar{\psi} \left(\overset{\text{gluons in here}}{\downarrow} i\gamma^\mu D_\mu - m \right) \psi - \overset{\text{gluon dynamics}}{\downarrow} \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} \\
 &= \mathcal{L}_{g_s=0} \quad \text{free propagation of quarks/gluons} \\
 &\quad - g_s \left(\bar{\psi} \gamma^\mu T^a \psi \right) A_\mu^a \quad \text{qg-interaction} \\
 &\quad + \mathcal{L}_{\text{ggg}} \quad \sim g_s f^{abc} A^a A^b A^c \\
 &\quad + \mathcal{L}_{\text{gggg}} \quad \sim g_s^2 f^{abc} f^{ade} A^b A^c A^d A^e
 \end{aligned}$$

$SU(3)$ non-abelian $\Leftrightarrow$ gluons self-interact
 $\Leftrightarrow$ gluons are colored $\Leftrightarrow$ gluons modify quark color

quark-gluon interaction

$$g_s (\bar{\psi} \gamma^\mu T^a \psi) A_\mu^a = g_s (\bar{\psi}_k \gamma^\mu T_{kj}^a \psi_j) A_\mu^a$$

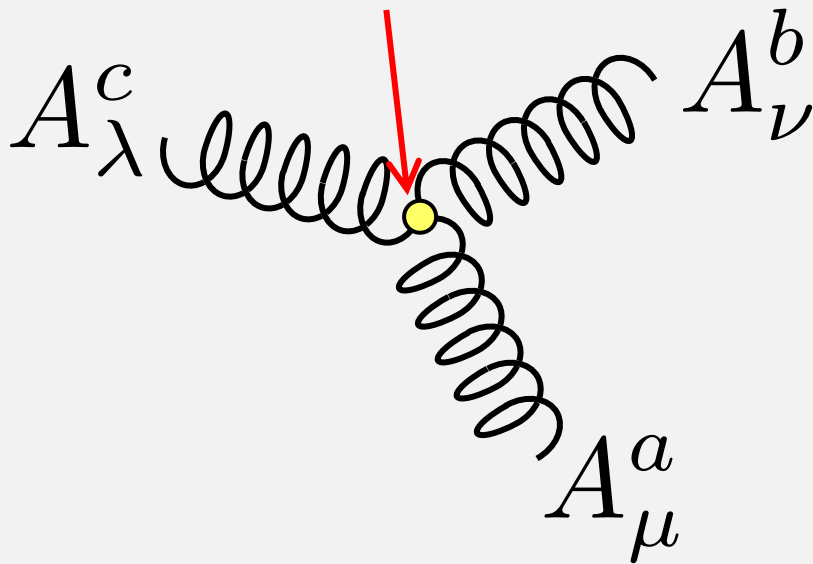


quark color
changes from j to k

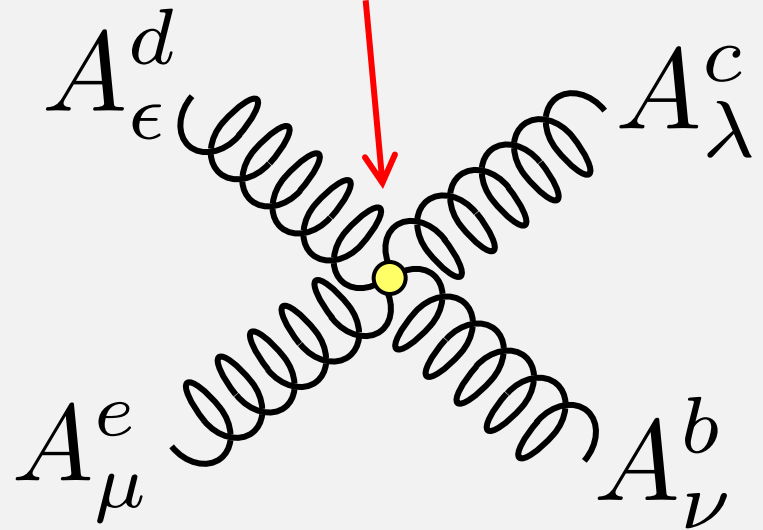
gluon-gluon interactions

$$\sim g_s f^{abc} A^a A^b A^c \quad \sim g_s^2 f^{abc} f^{ade} A^b A^c A^d A^e$$

$$\sim g_s f^{abc}$$



$$\sim g_s^2 f \cdots f \cdots$$



$\Rightarrow$ much more (highly non-trivial) dynamics to be verified experimentally

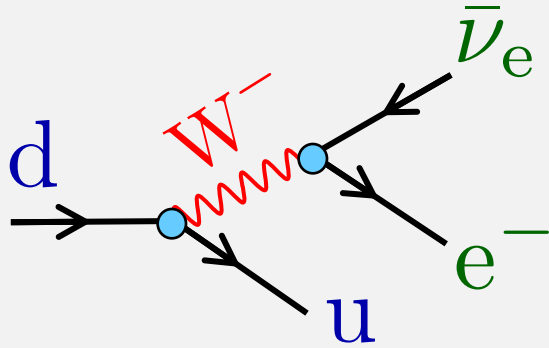
The same
procedure for the
weak force?

Guess a phase-symmetry!

Observation 1: radioactive β -decay

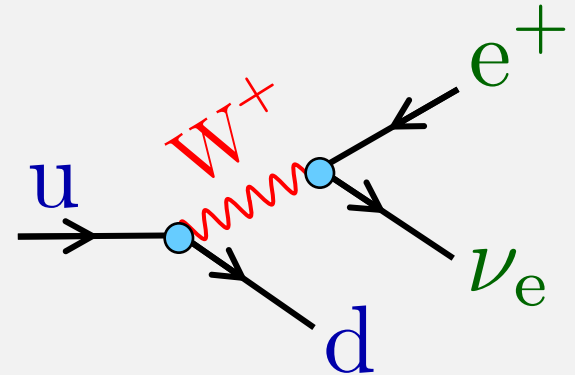
β^- -decay

$$n \rightarrow p e^- \bar{\nu}_e$$

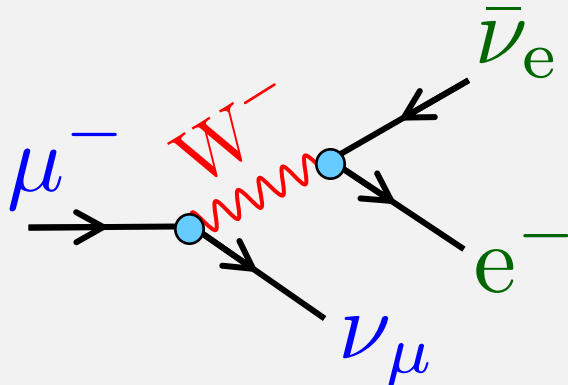


β^+ -decay

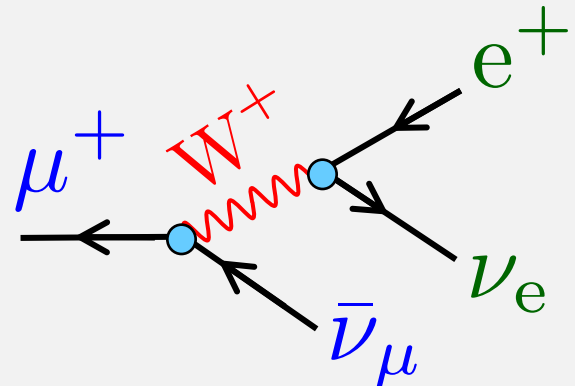
$$p \rightarrow n e^+ \nu_e$$



$$\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$$

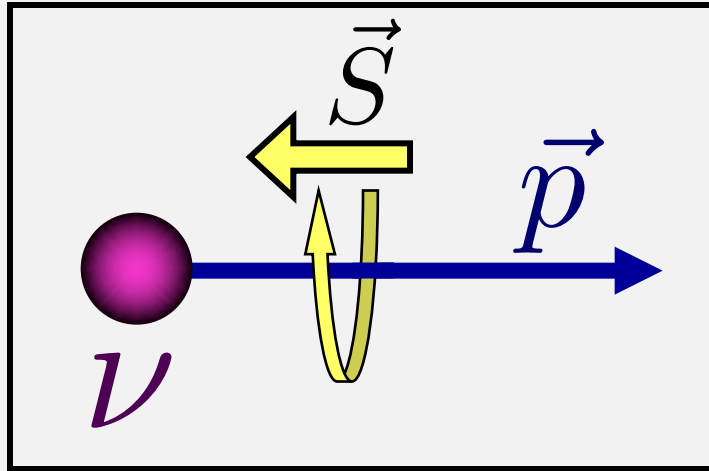


$$\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$$

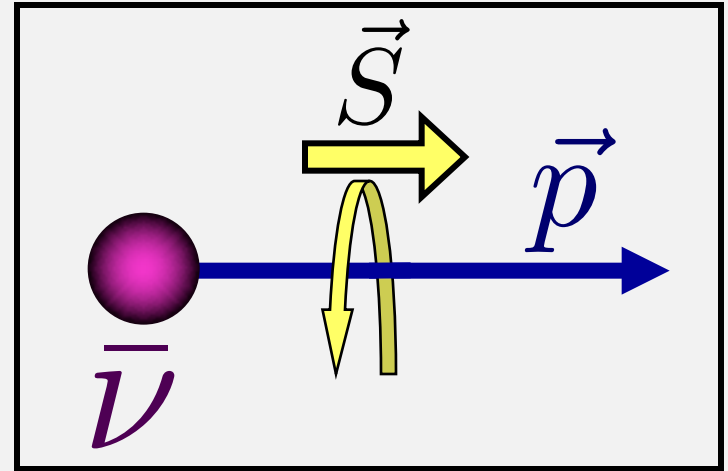


Surprise: β -decay fermions have handedness

Visualization of handedness for massless particles:



left-handed fermion



right-handed antifermion

Dirac fermion:

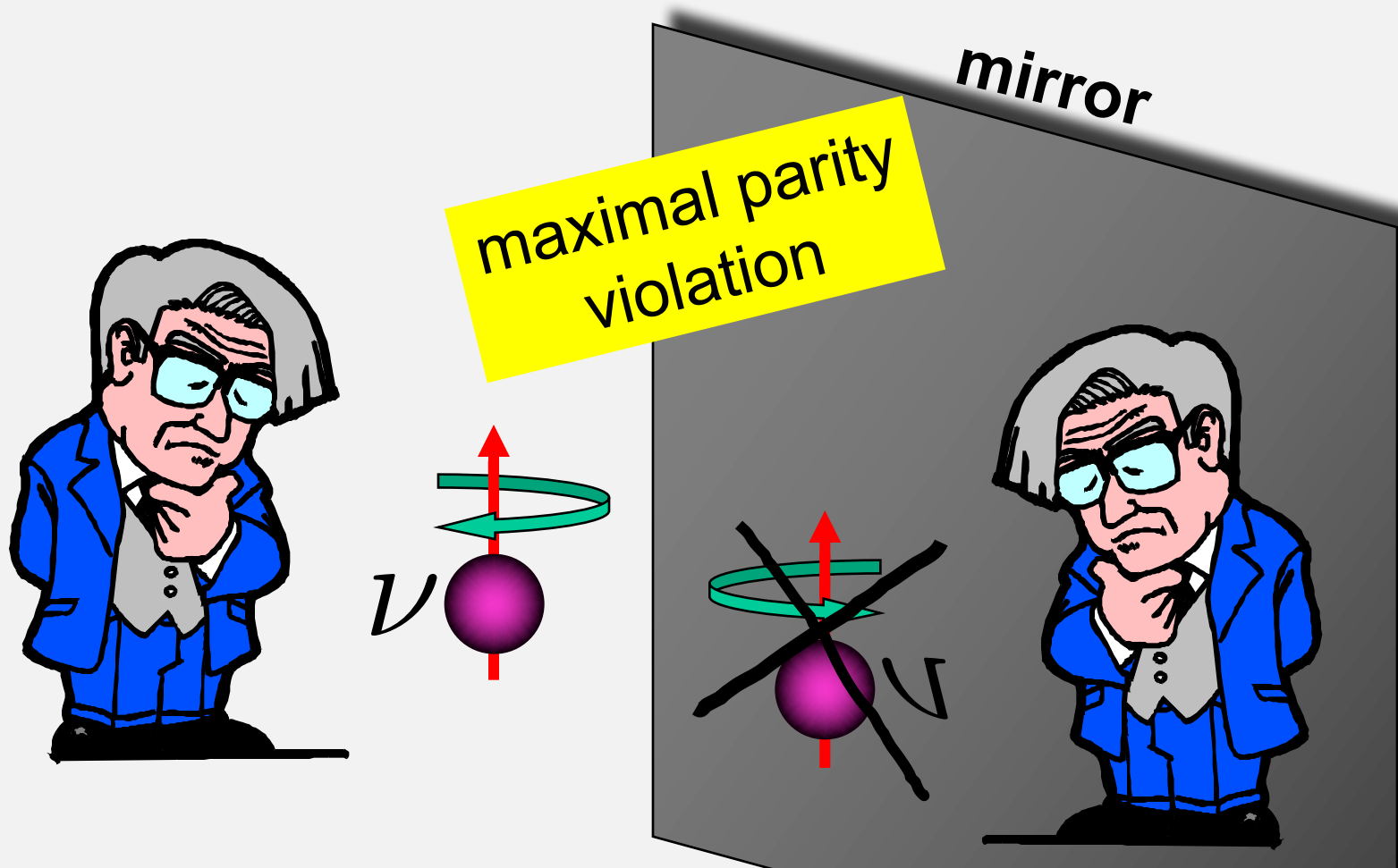
$$\psi = \psi_L + \psi_R$$

photons
gluons

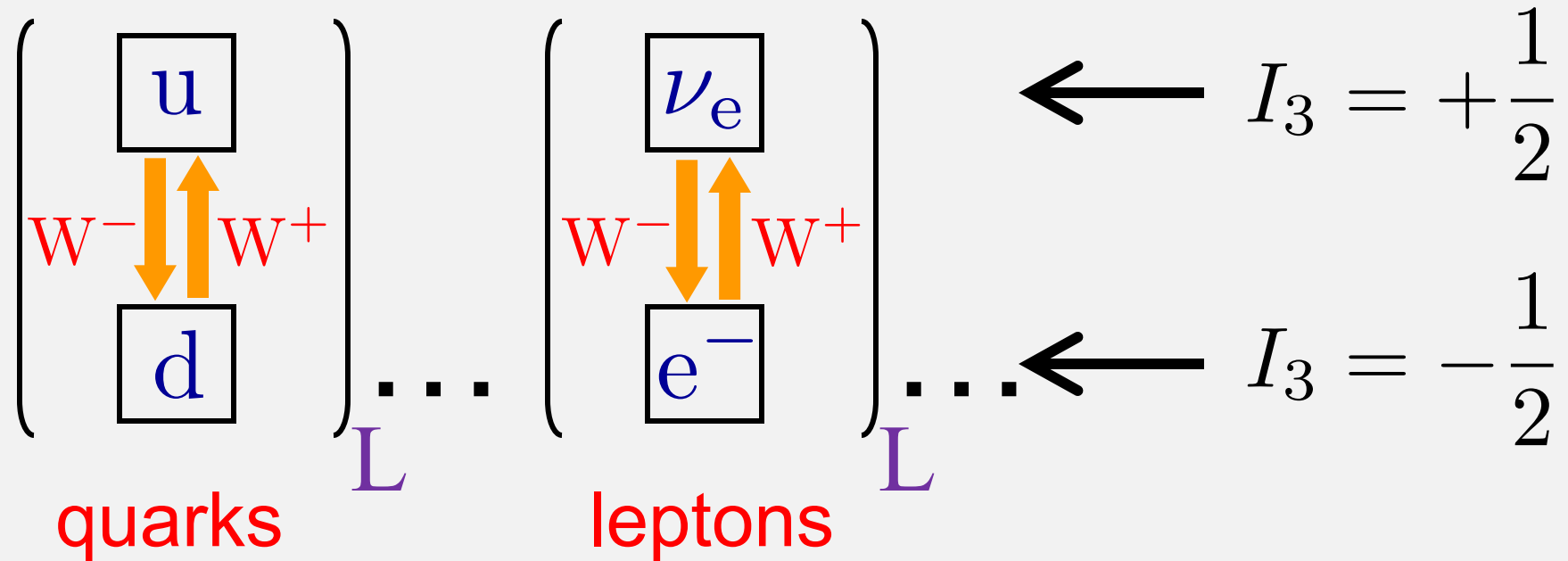
$W^\pm$ bosons

Conclusion: Weak force is different $\rightarrow W^\pm$ bosons
are only coupling to **left-handed fermions**
and **right-handed anti-fermions**

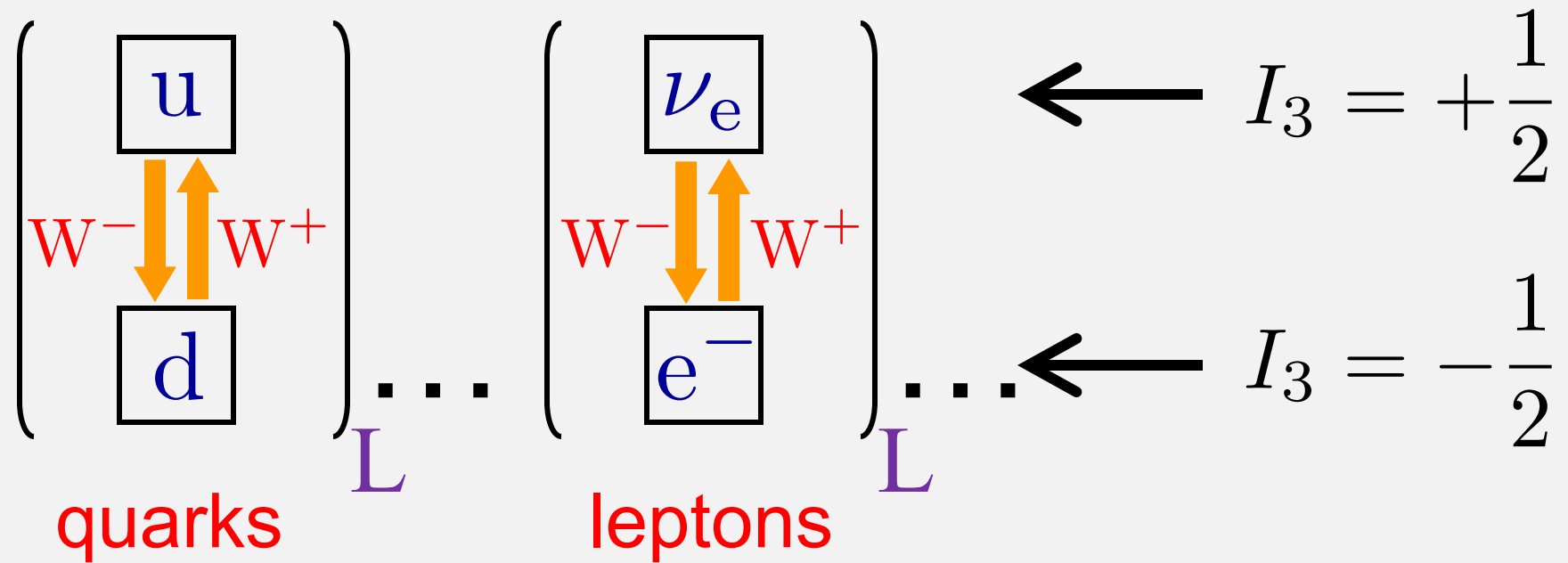
Consequence:



- left-handed fermions carry **weak charge I_3**
- left-handed fermions live in **weak doublets**



- W -bosons carry **weak charge** $I_3(W^\pm) = \pm 1$
- ... and **electric charge** $Q(W^\pm) = \pm 1$
- right-handed fermions are I_3 -neutral
 $e_R^-, u_R, d_R, \dots : I_3 = 0$



- looks like spin rotations
- left-handed fermions in doublets: $I = \frac{1}{2}$, $I_3 = \pm \frac{1}{2}$

Naming convention:

- the **weak charge** I_3 is called **weak isospin**
- this is the eigen-value of the 3rd component of the **weak isospin vector** $\vec{I}$

Try gauge group

$SU(2)_L$ ← left-handed

$$\psi_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \rightarrow e^{i(T^1 \alpha^1(x) + T^2 \alpha^2(x) + T^3 \alpha^3(x))} \begin{pmatrix} u \\ d \end{pmatrix}_L$$

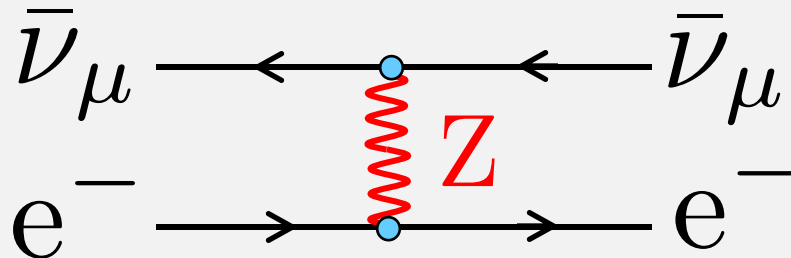
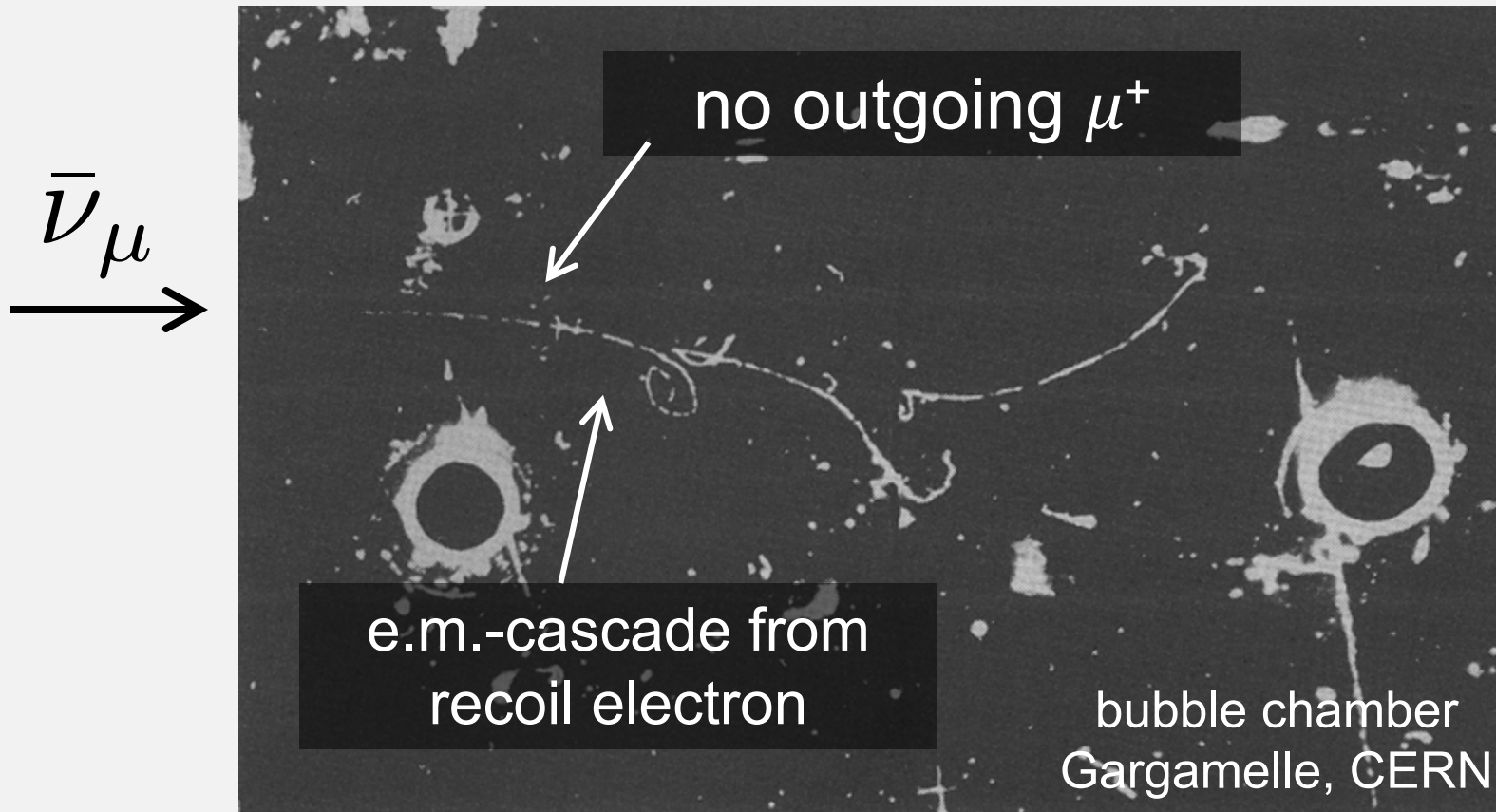
Charge number operators: $T^j = \frac{1}{2} \tau^j$ ← Pauli matrices

Gauge bosons:

	I_3	Q	
$I = 1$	$+1$	$+1$	← there must be a neutral boson
	0	0	
	-1	-1	

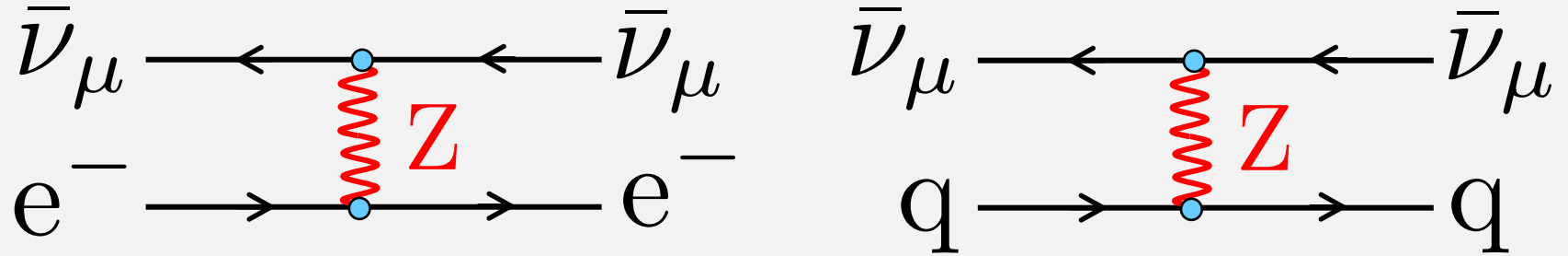
$\left(\begin{array}{c} \boxed{W^+} \\ \boxed{W^0} \\ \boxed{W^-} \end{array} \right)$

Discovery of neutral weak gauge bosons



there is a neutral boson which couples to weak charge (neutrinos)

Observation (from neutrino scattering)



Z-bosons couple to a **mixture** of right- and left-handed particles ... somewhere between an **$SU(2)$** -boson and a **$U(1)$** -photon!

Try more complicated gauge symmetry

$$SU(2)_L \times U(1)_Y$$

$U(1)$ -charge, called **weak hypercharge**

members of $SU(2)_L$ -multiplets must have identical Y

$I = 1/2$	I_3	Q
$\begin{pmatrix} \boxed{u} \\ \boxed{d} \end{pmatrix}_L$	$+1/2$	$+2/3$
	$-1/2$	$-1/3$

$I = 1/2$	I_3	Q
$\begin{pmatrix} \boxed{\nu_e} \\ \boxed{e^-} \end{pmatrix}_L$	$+1/2$	0
	$-1/2$	-1

$I = 1$	I_3	Q
$\begin{pmatrix} \boxed{W^+} \\ \boxed{W^0} \\ \boxed{W^-} \end{pmatrix}$	$+1$	$+1$
	0	0
	-1	-1

$$Y(W) = 0$$

$$\Rightarrow Y \propto Q - I_3$$

Convention:

$$Y = 2(Q - I_3)$$

weak and e.m. charges
are mixed in $U(1)_Y$

Standard Model of electro-weak interactions

$$SU(2)_L$$

$$U(1)_Y$$

charge number operator

$$I_3$$

$$Y$$

unit charge (convention)

$$g$$

$$g'/2$$

gauge bosons

	W^+	W^0	W^-	B
I_3	+1	0	-1	0
Y	0	0	0	0

quantum-mixing
possible

$SU(2)_L$ $U(1)_Y$

unit charge (convention)

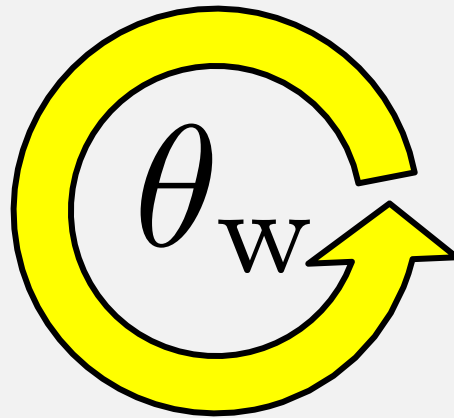
 g $g'/2$

gauge bosons

	W^+	W^0	W^-	B
I_3	+1	0	-1	0
Y	0	0	0	0

physical force particles

$$\begin{pmatrix} W^0 \\ B \end{pmatrix}$$



$$\begin{pmatrix} Z \\ A \end{pmatrix}$$

identify this
as photon

 $\Rightarrow$ electro-weak unification

$$g \sin \theta_w = g' \cos \theta_w = e$$

Electro-weak unification

$$g \sin \theta_w = g' \cos \theta_w = e$$

So why is the weak force weaker than the e.m. force?

gauge boson, mass m

Klein-Gordon equation: $(\partial_\mu \partial^\mu + m^2) A^\nu = 0$

static solution for potential ϕ with $(A^\nu) = (\phi, \vec{A})$

Yukawa
potential

$$\phi \propto \frac{e^{-mr}}{r}$$

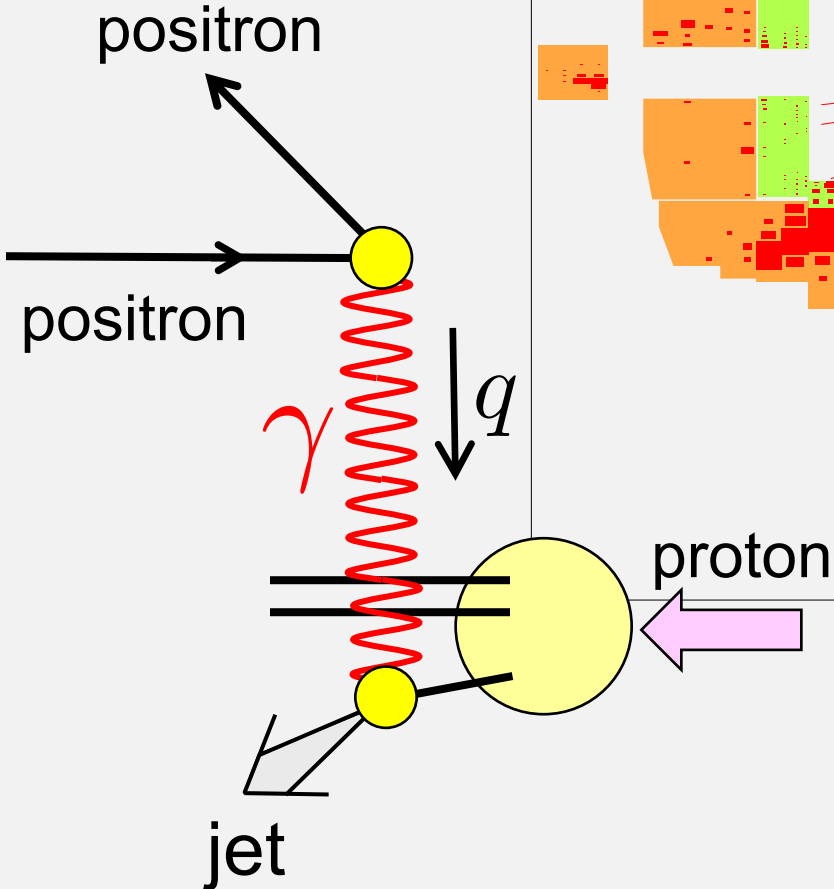
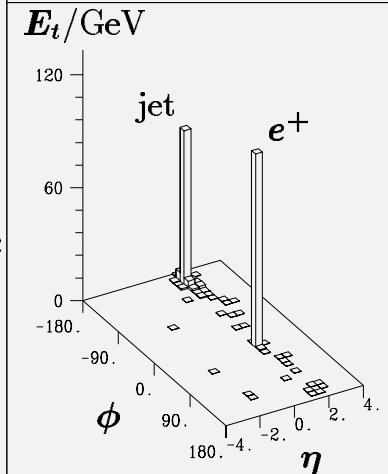
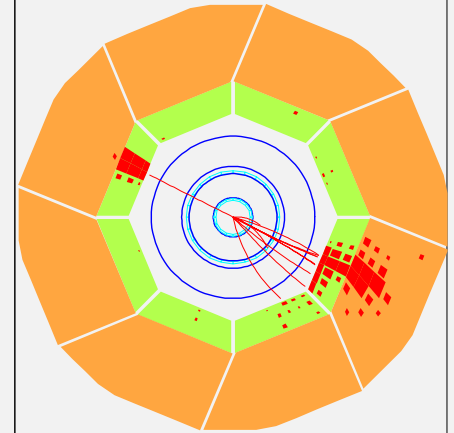
$$\text{range } \bar{r} = \frac{1}{m}$$

	mass	range
γ	0	∞
Z	91 GeV	0.0022 fm
$W^\pm$	80 GeV	0.0025 fm

it is a simple
mass-effect

Photon in action at ep-collider HERA (DESY)

$$Q^2 = 25030 \text{ GeV}^2, \quad y = 0.56, \quad M = 211 \text{ GeV}$$

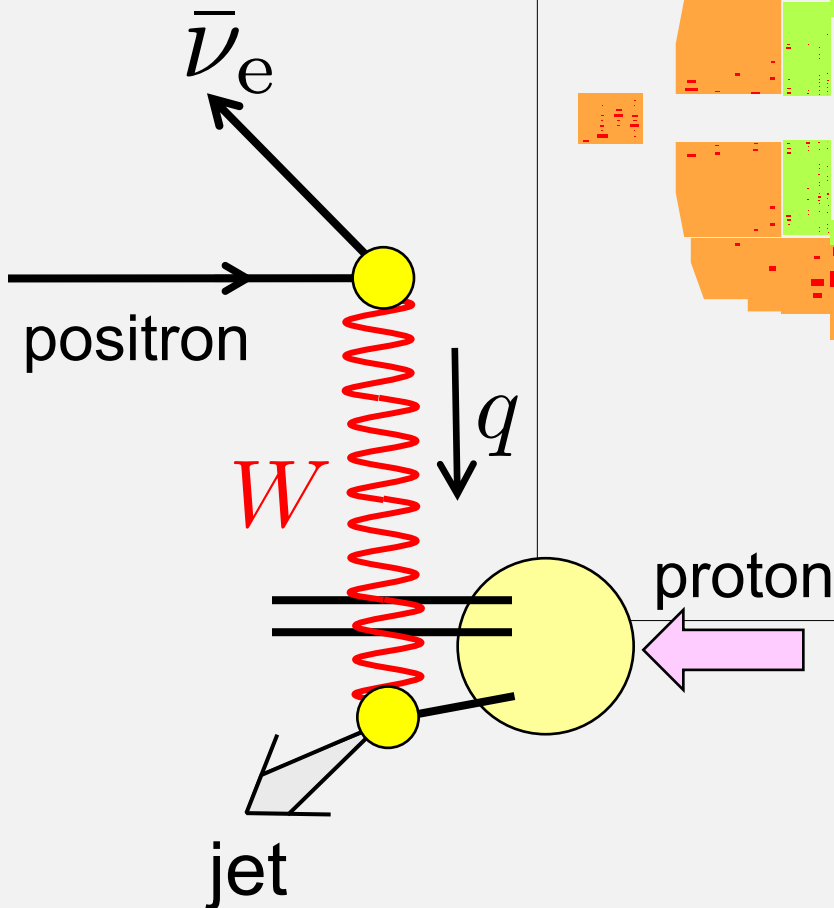
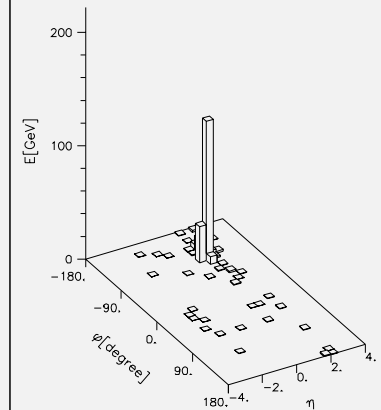
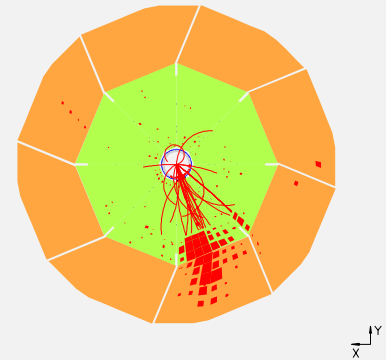
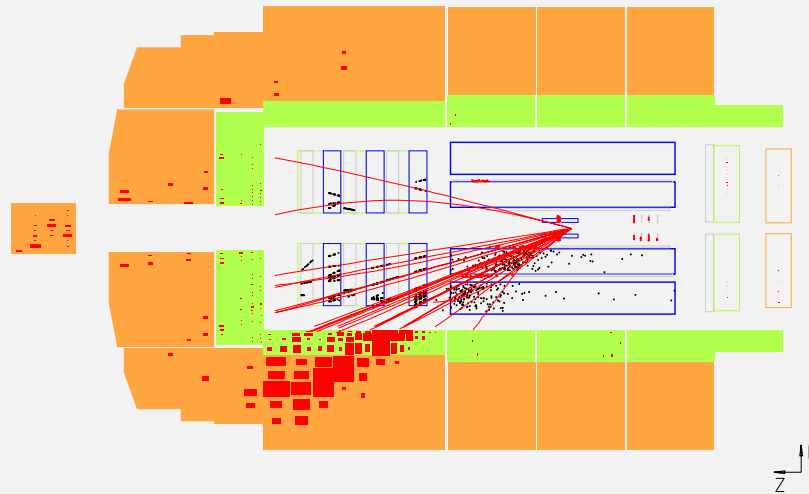


$$q^2 \equiv -Q^2$$

Weak interaction at ep-collider HERA (DESY)

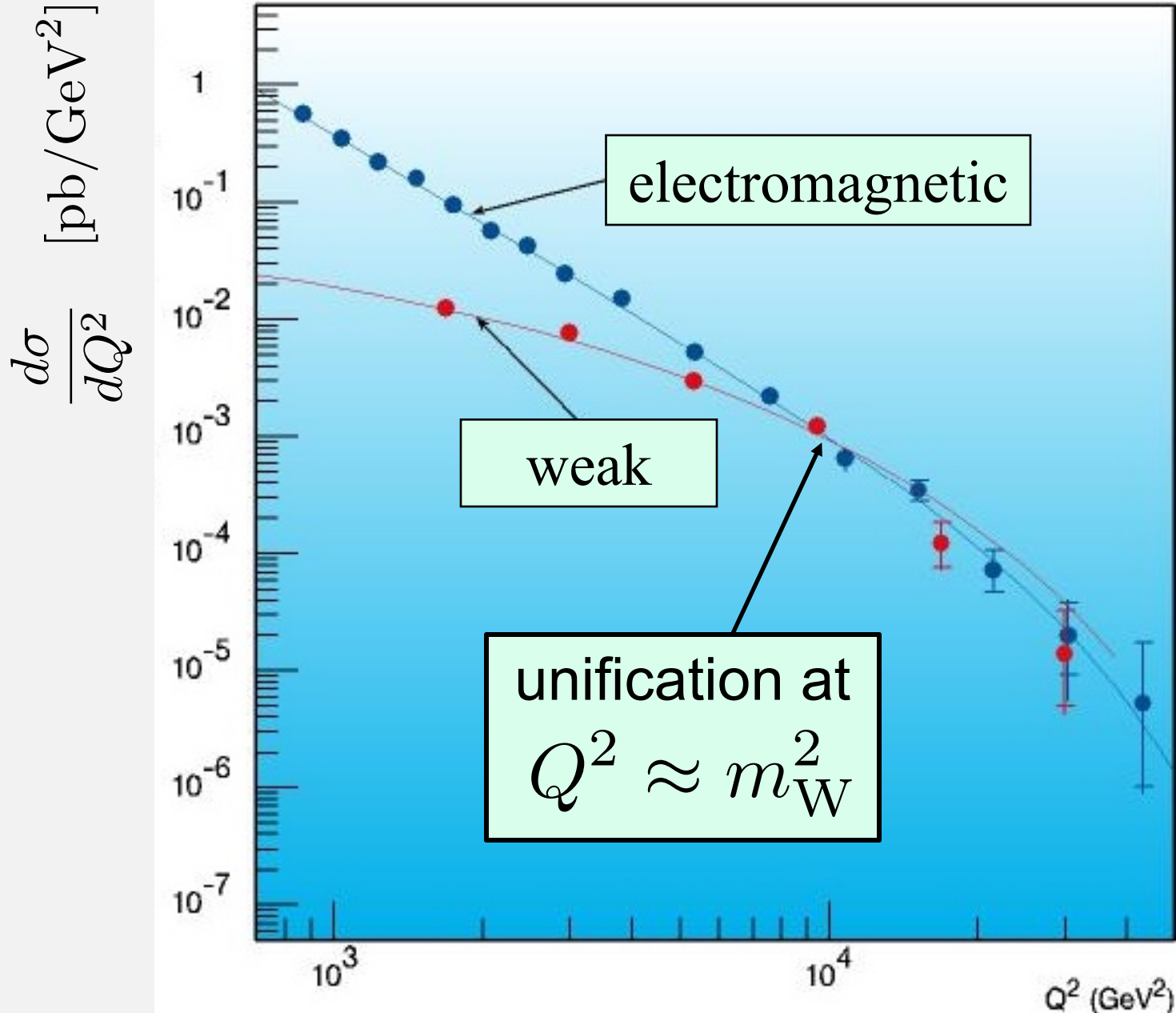
...just from the HOTLINE

$$Q^{*2} = 21475 \quad y = 0.55 \quad M = 198$$

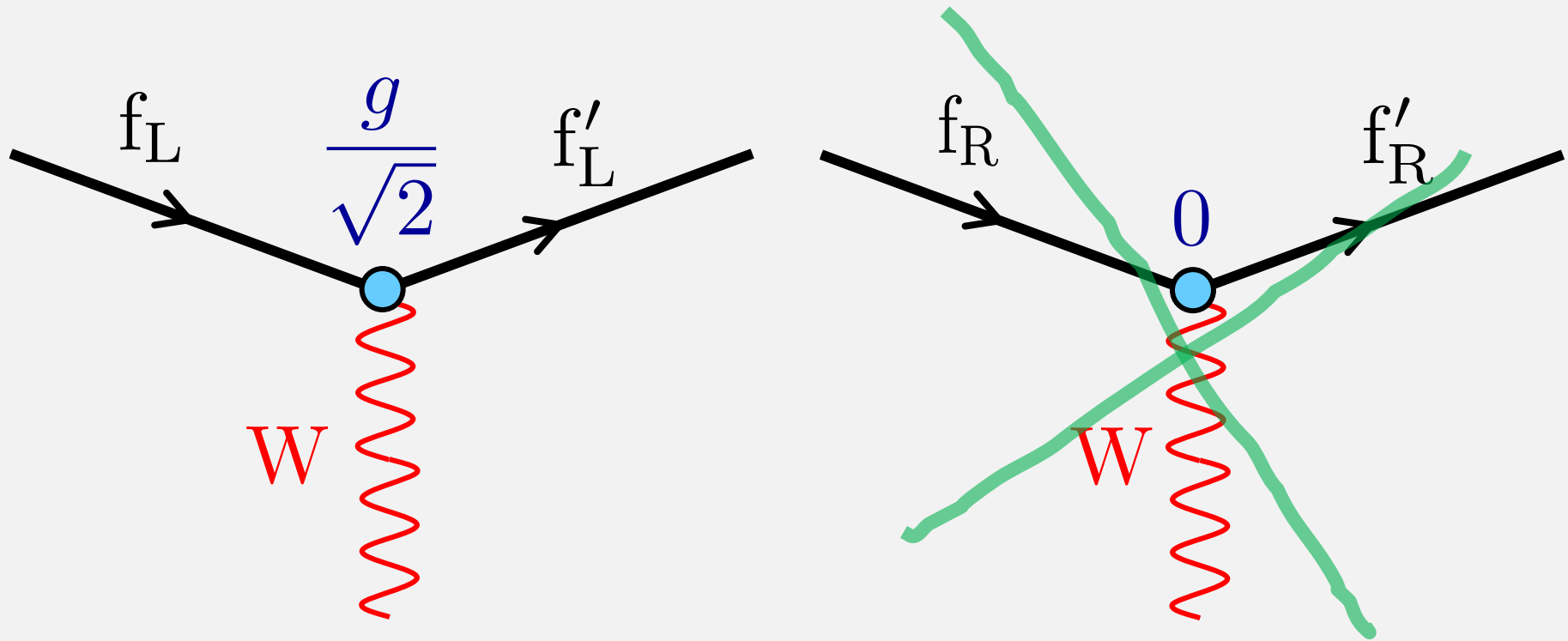


$$q^2 \equiv -Q^2$$

Compare forces at ep-collider HERA (DESY)



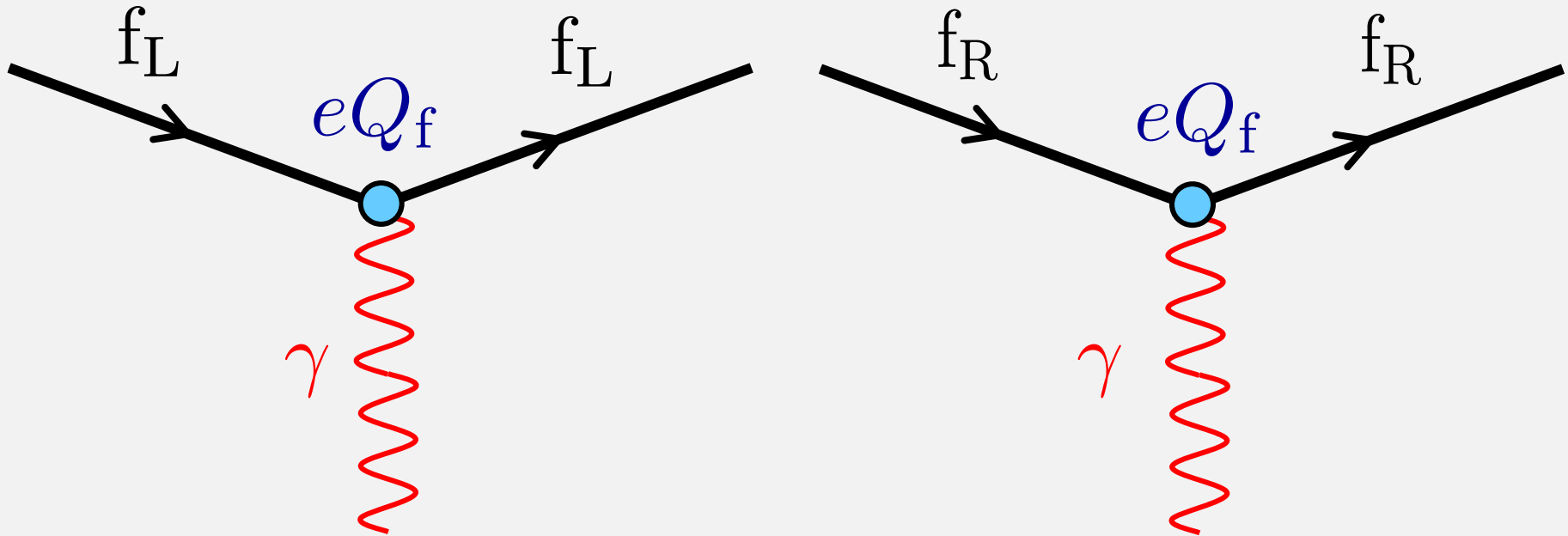
Electroweak couplings to fermions: $W^\pm$



purely left-handed

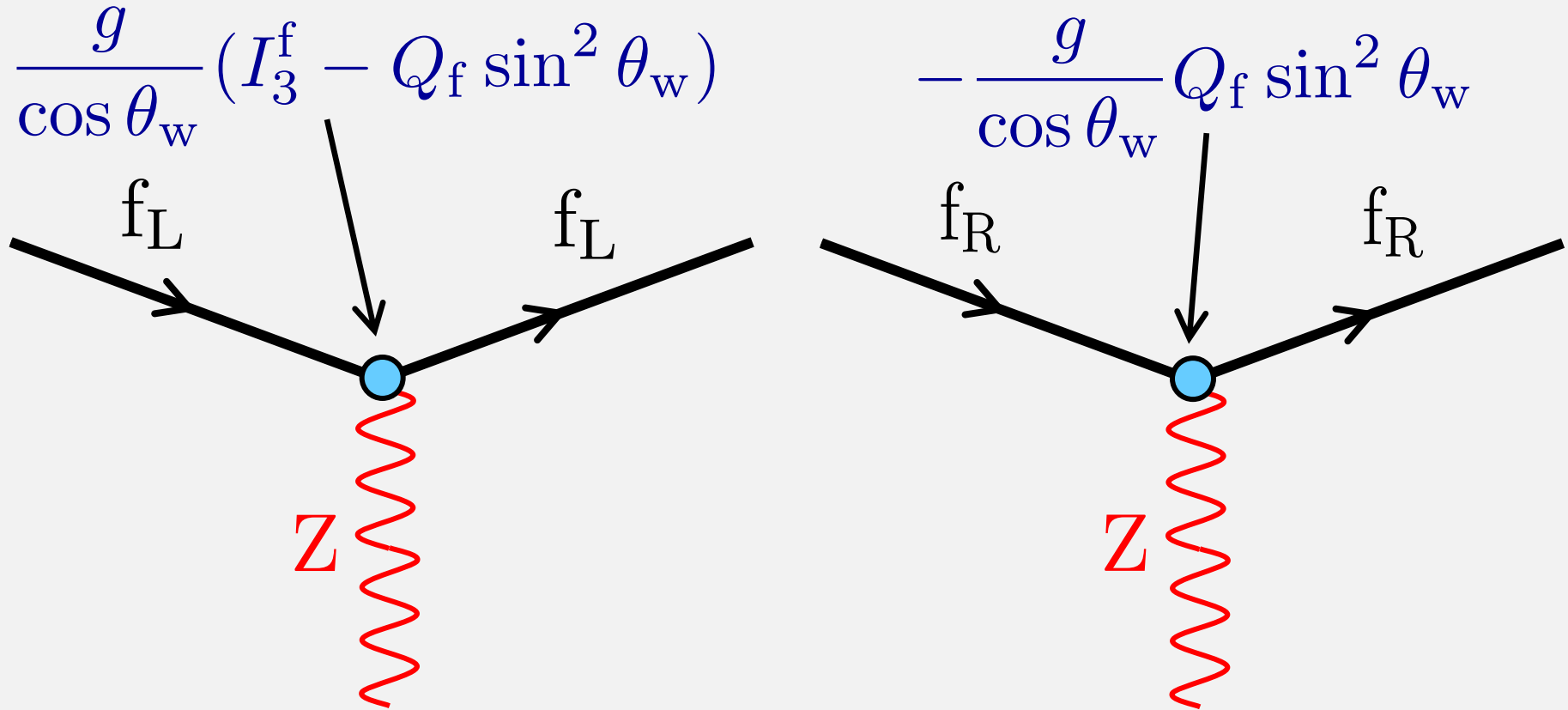
Electroweak couplings to fermions:

γ



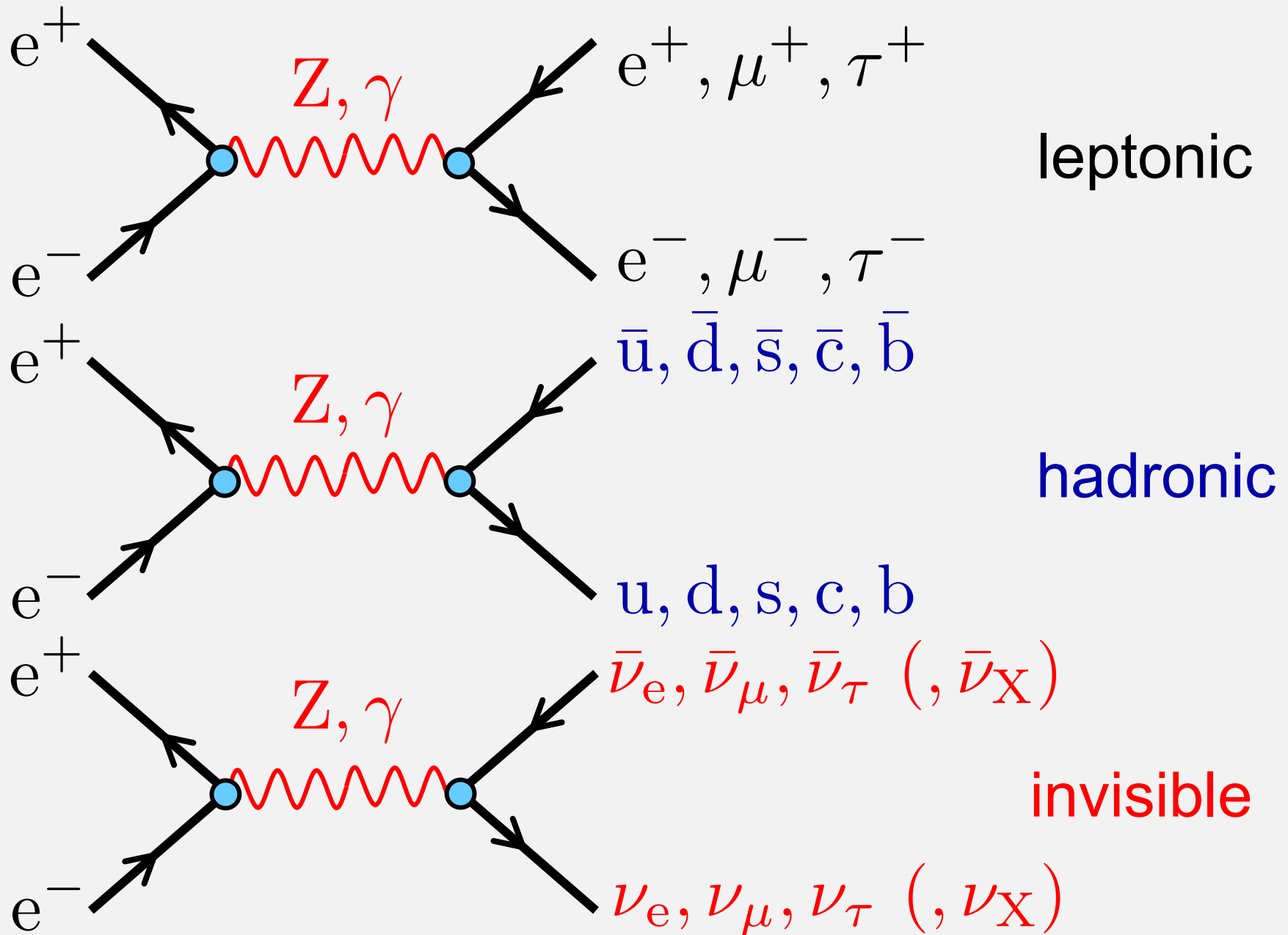
left-right symmetric

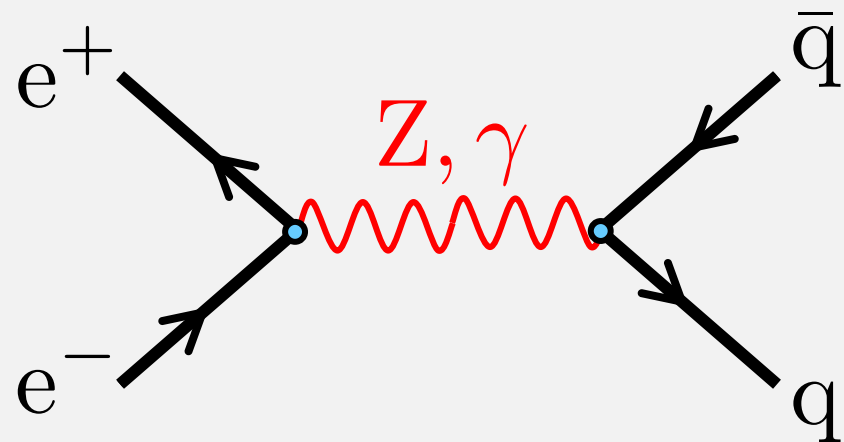
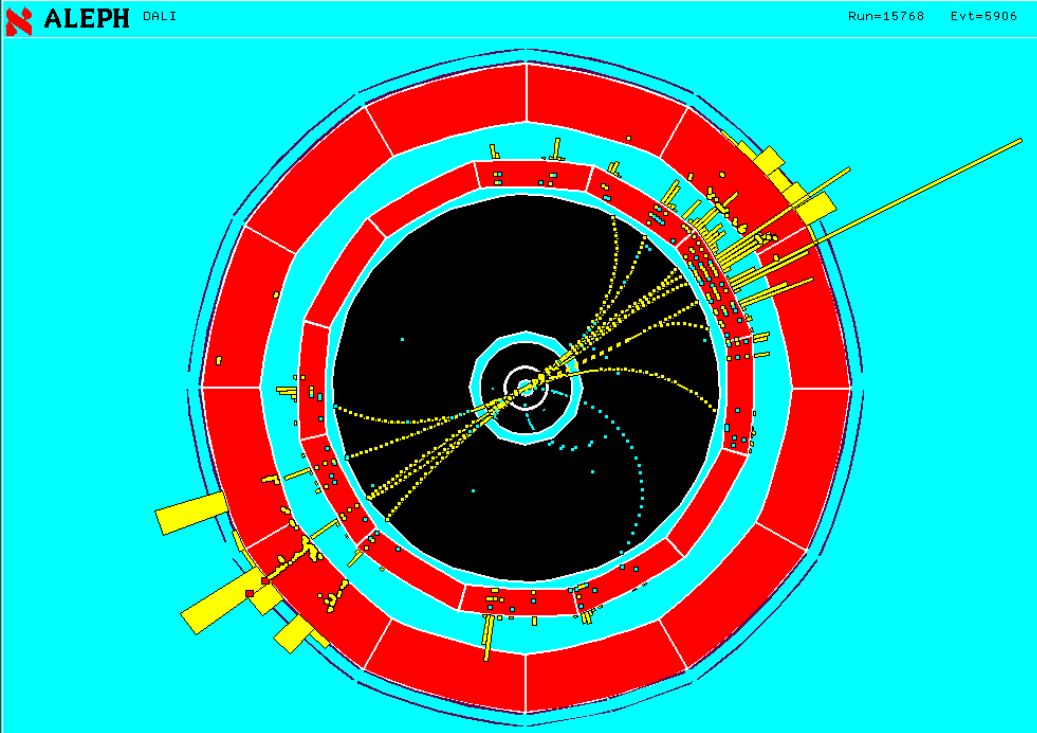
Electroweak couplings to fermions: Z



left and right, but not symmetric

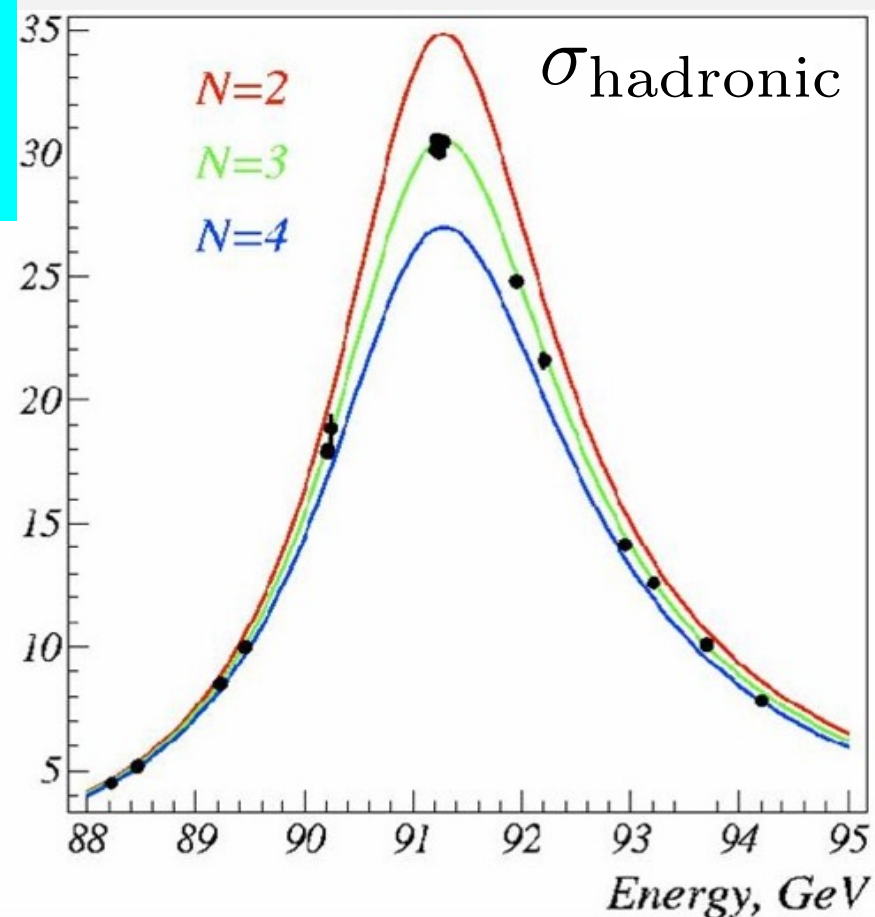
Precision measurements at e^+e^- -colliders:



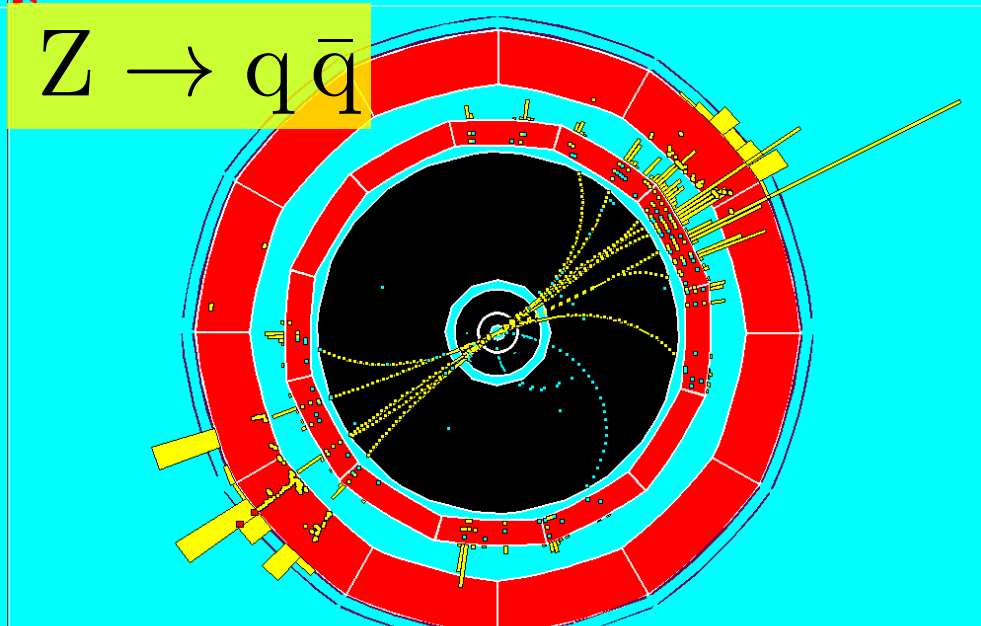
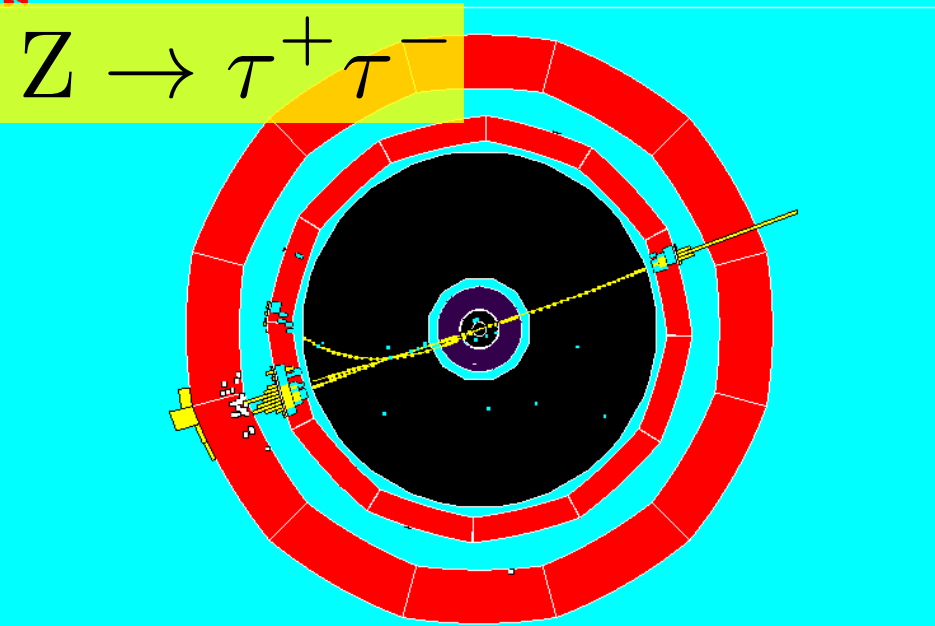
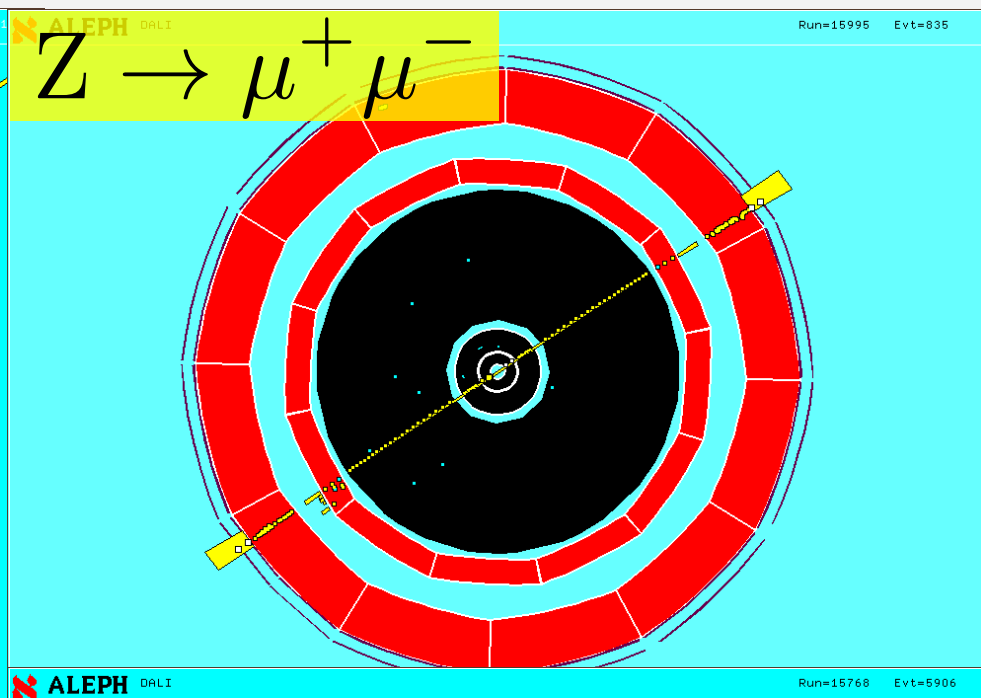
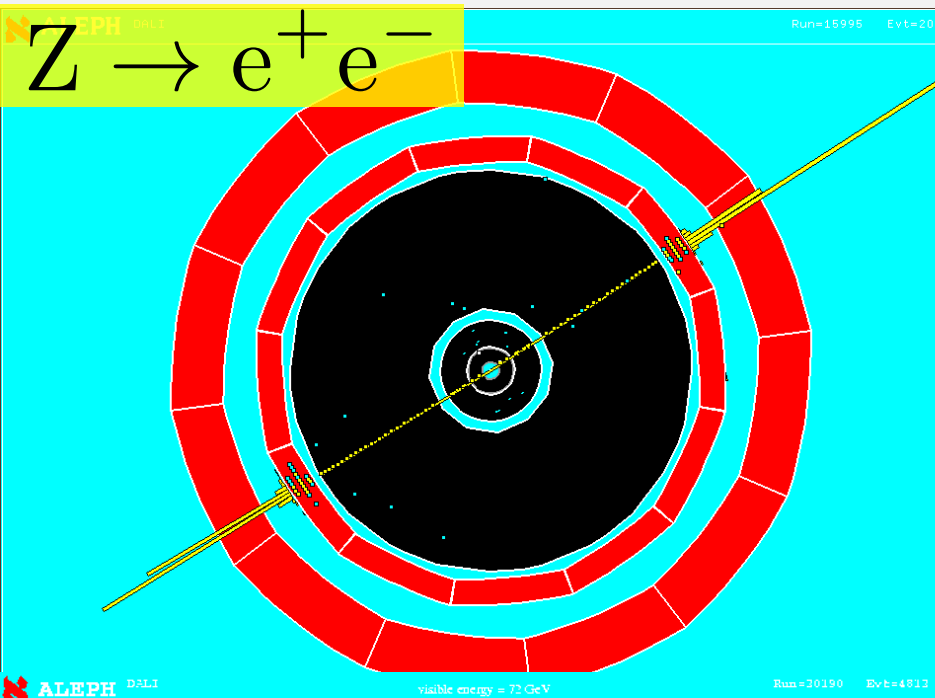


Z-resonance curve $\Rightarrow$

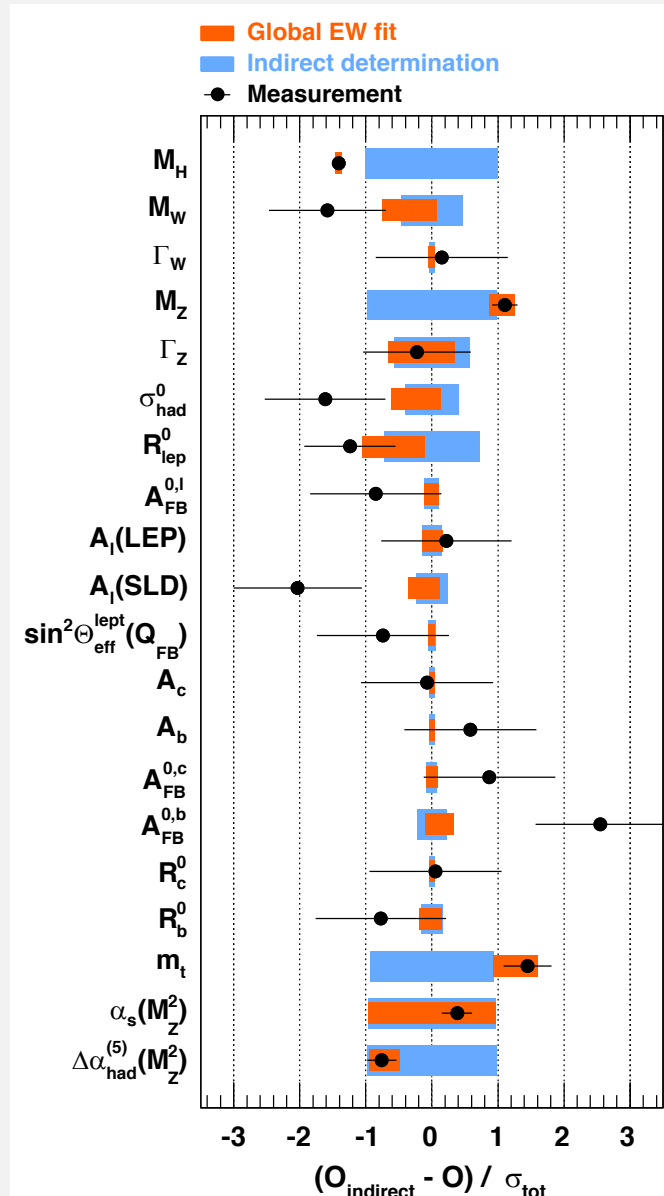
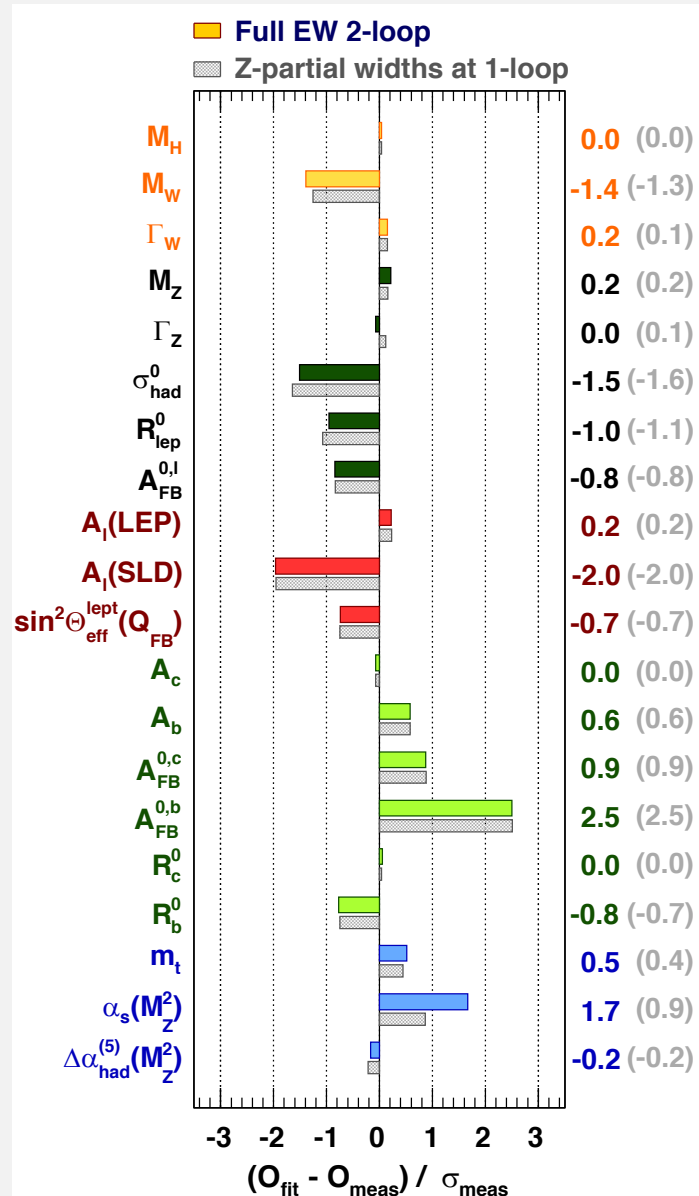
- mass
- width
- exactly three families
- overall coupling strengths



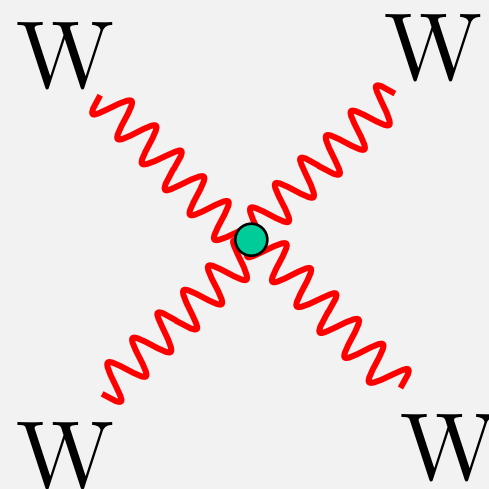
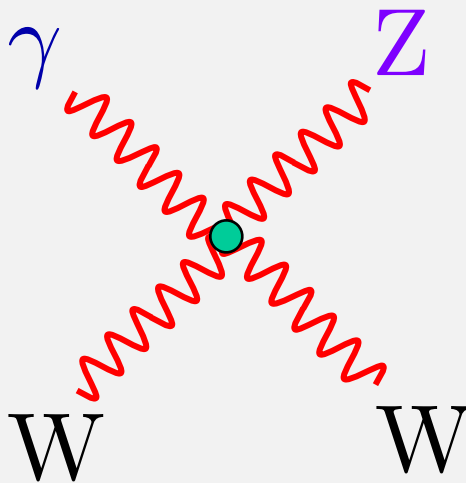
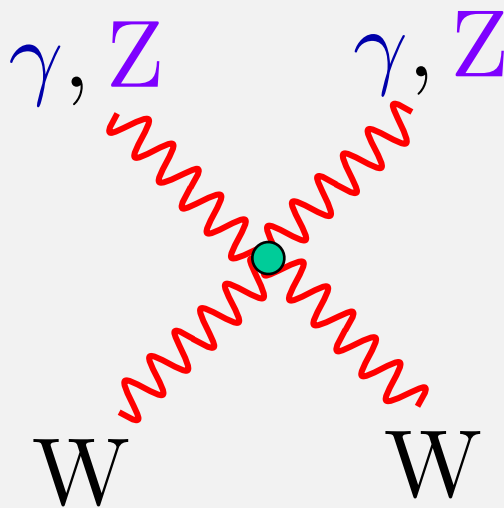
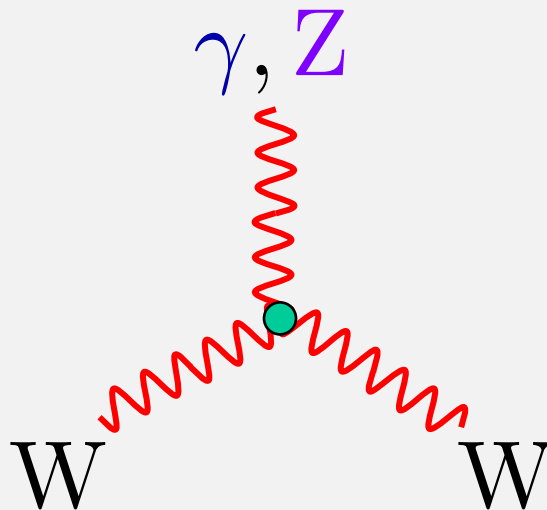
Couplings: branching fractions / angular distributions of...



Electroweak fits prove highest level of internal consistency at quantum loop level



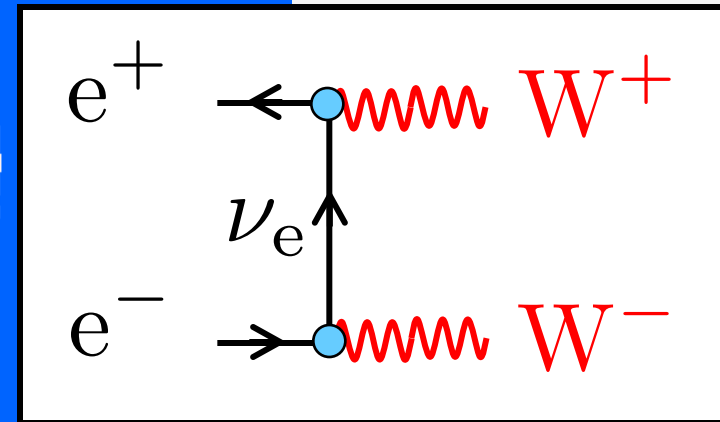
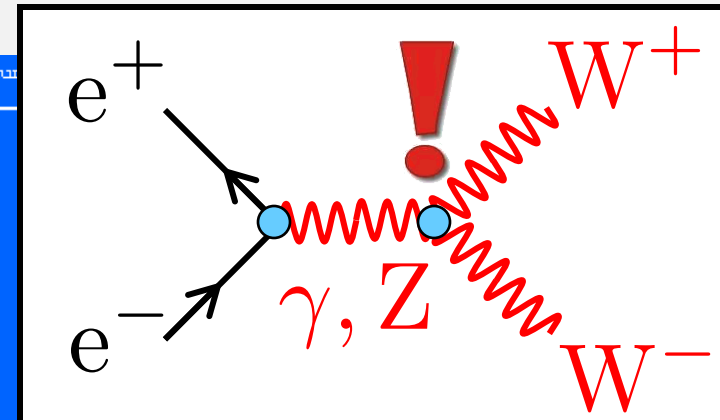
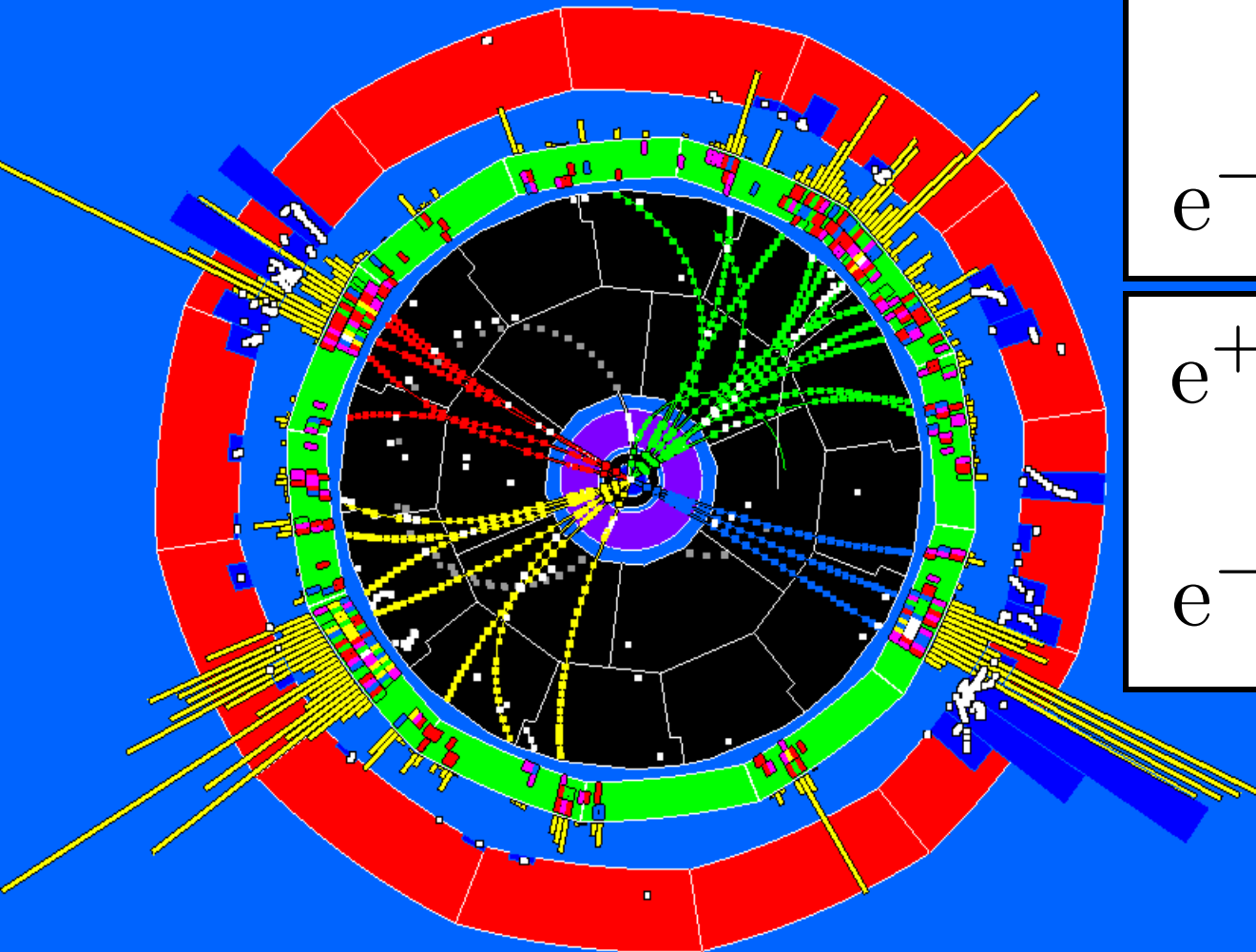
$SU(2)_L$ is non-abelian $\Rightarrow$ self-couplings



Example:

$$e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2 q_3\bar{q}_4 \rightarrow 4\text{jets}$$

EPH DALI_F1 BCM=189.0 Pch=99.7 Bfl=190. Bwi=117. Bha=37.0 GOOD_SAM
Nch=28 EV1=0 EV2=0 EV3=0 ThT=0 98-06-24 9:02



Part III

- Testing the Standard Model at the LHC
- Computing cross sections for pp-collisions
- The Higgs boson
- A glimpse beyond the Standard Model

Large Hadron Collider (LHC)

period	$\sqrt{s}$ [TeV]	integrated luminosity [events per fb]
2011	7	5.6
2012	8	23
2015-18	13	100
2020-22	14	300
2025-?	14	3000

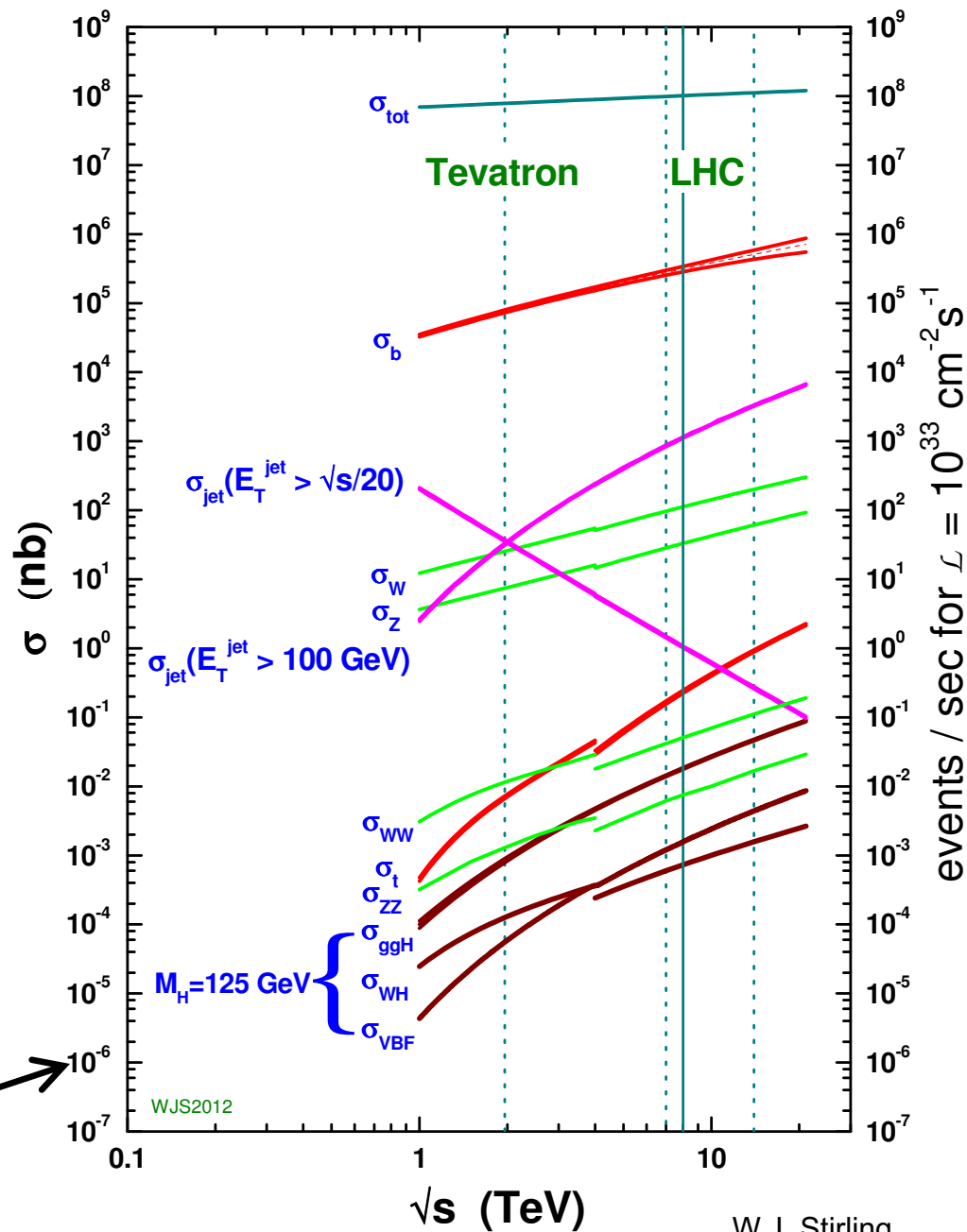
$$1 \text{ fb} = 1 \times 10^{-39} \text{ cm}^2$$

Cross sections

type	#events/fb
all	10^{14}
$b\bar{b}$	7×10^{11}
$W^\pm$	2×10^8
Z	6×10^7
$t\bar{t}$	10^6
WW	10^5
ZZ	2×10^4
H	6×10^4

1 fb

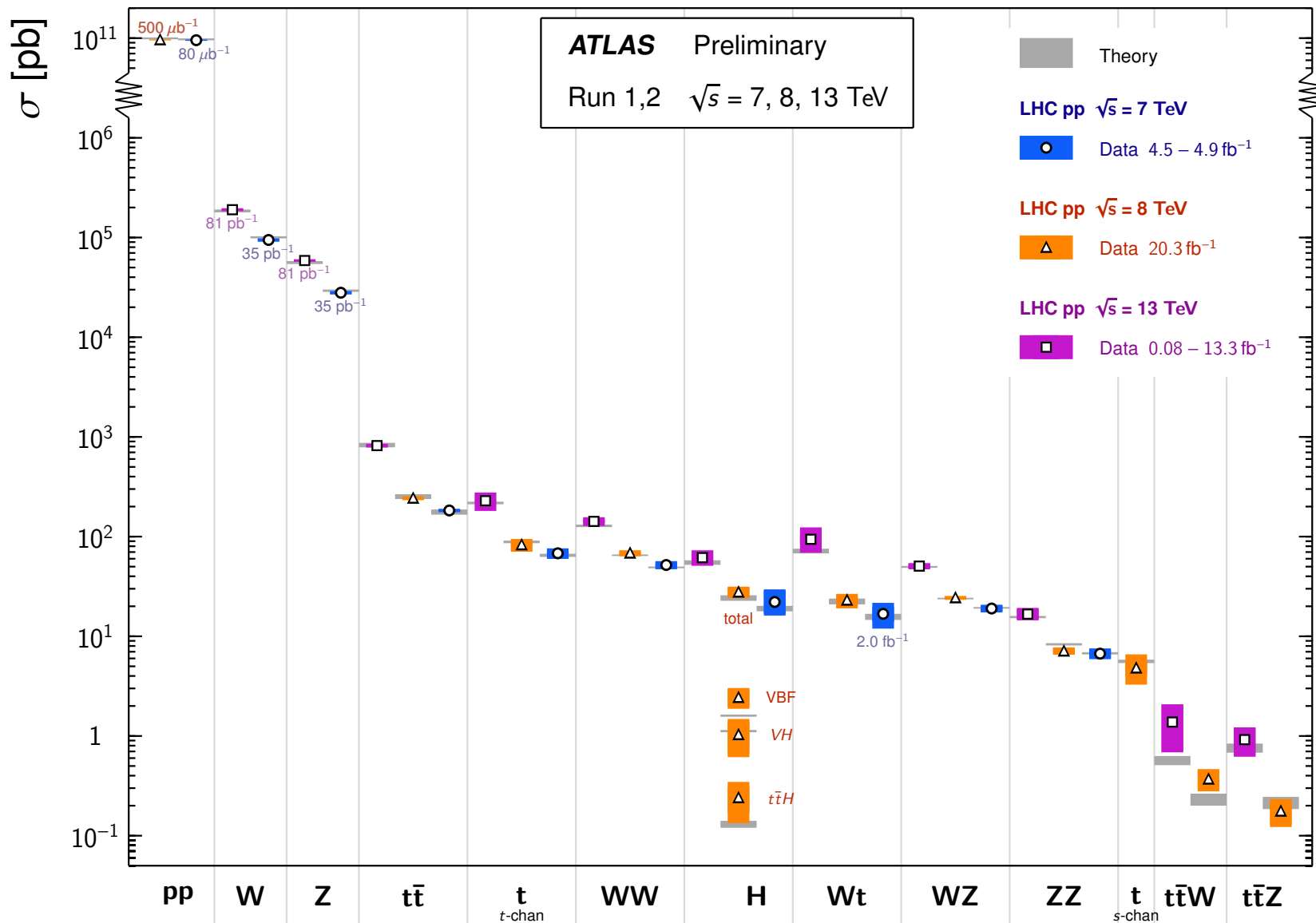
proton - (anti)proton cross sections



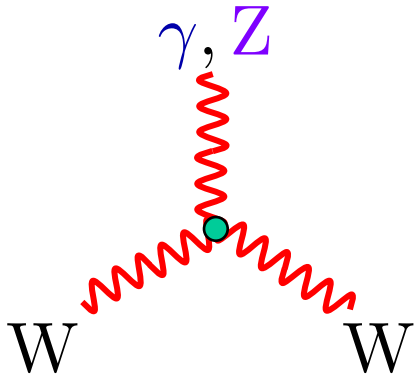
Wonderful agreement with measurements!

Standard Model Total Production Cross Section Measurements

Status: August 2016

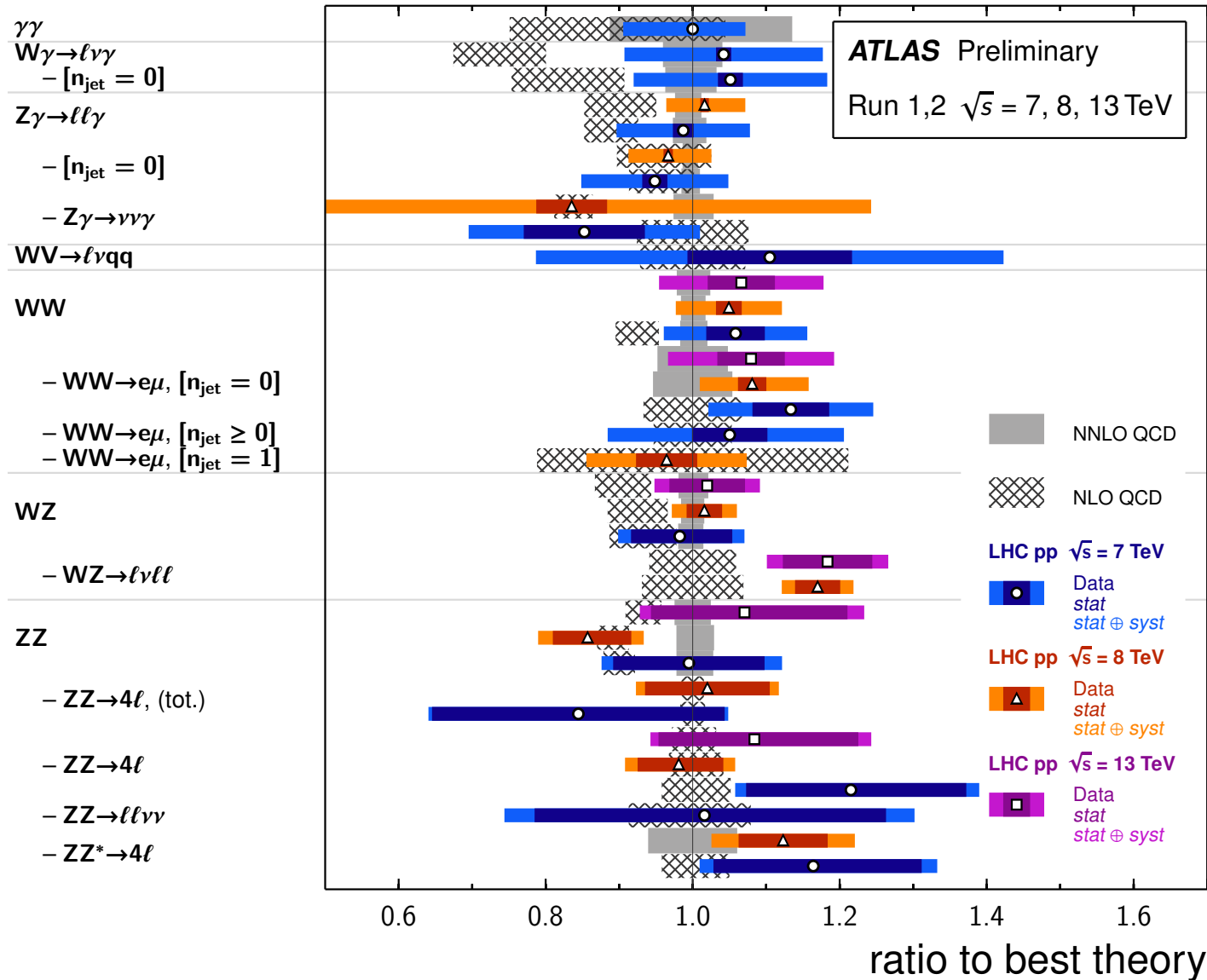


A closer look at Diboson production:

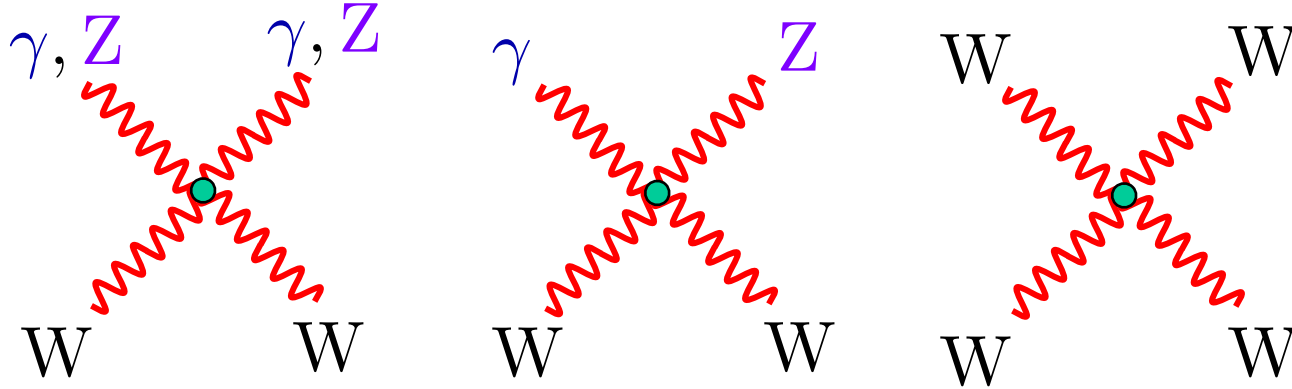


Diboson Cross Section Measurements

Status: August 2016



First look at processes sensitive to quartic couplings

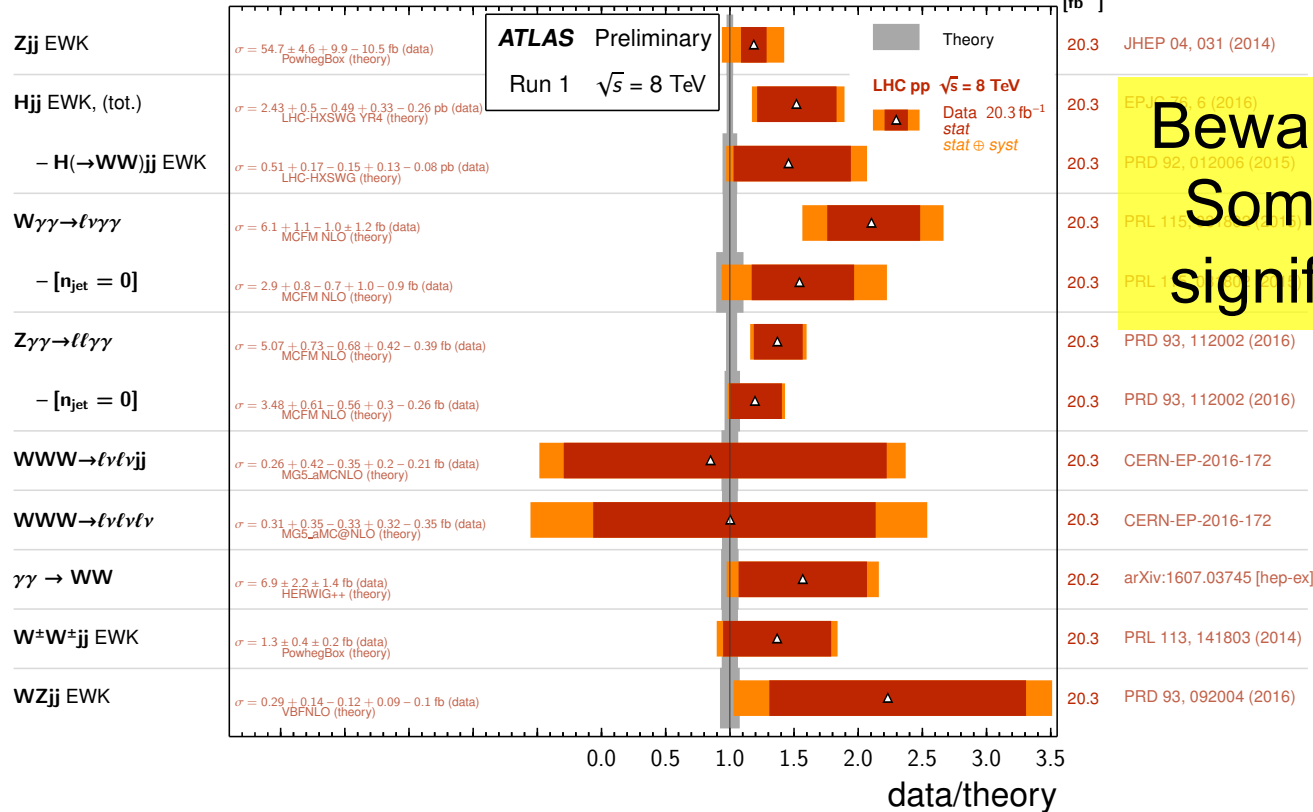


VBF, VBS, and Triboson Cross Section Measurements

Status: August 2016

$\int \mathcal{L} dt$
[fb⁻¹]

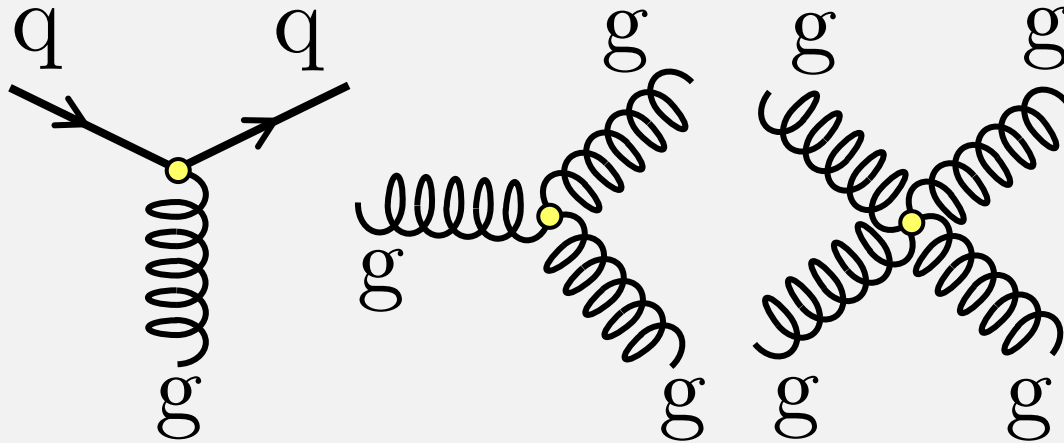
Reference



Beware! Low statistics!
Some processes not significantly detected!

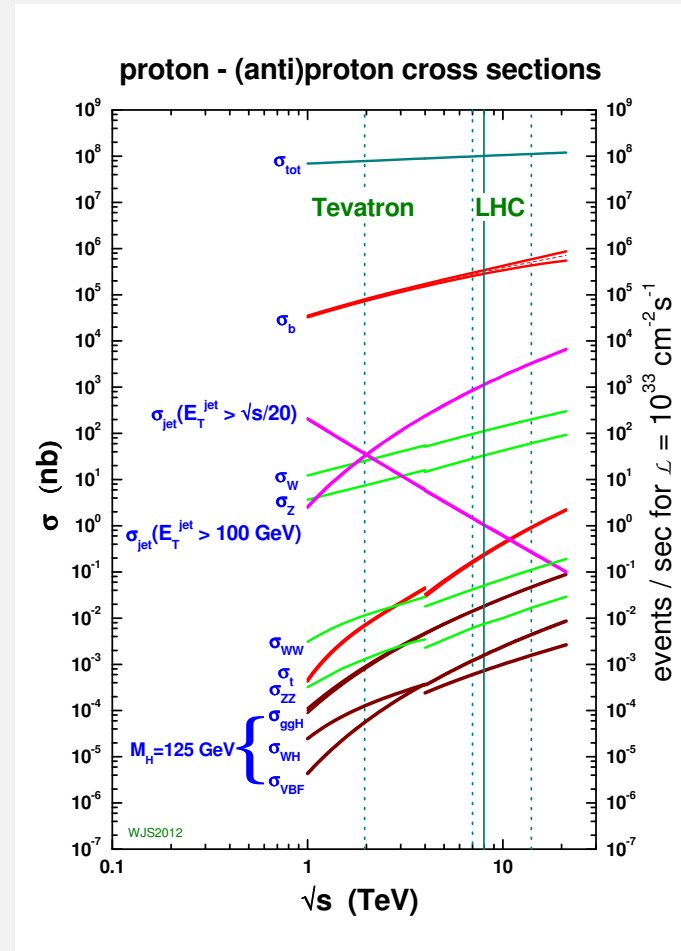
How to compute these cross-sections?

Quantum Chromodynamics $\Rightarrow$



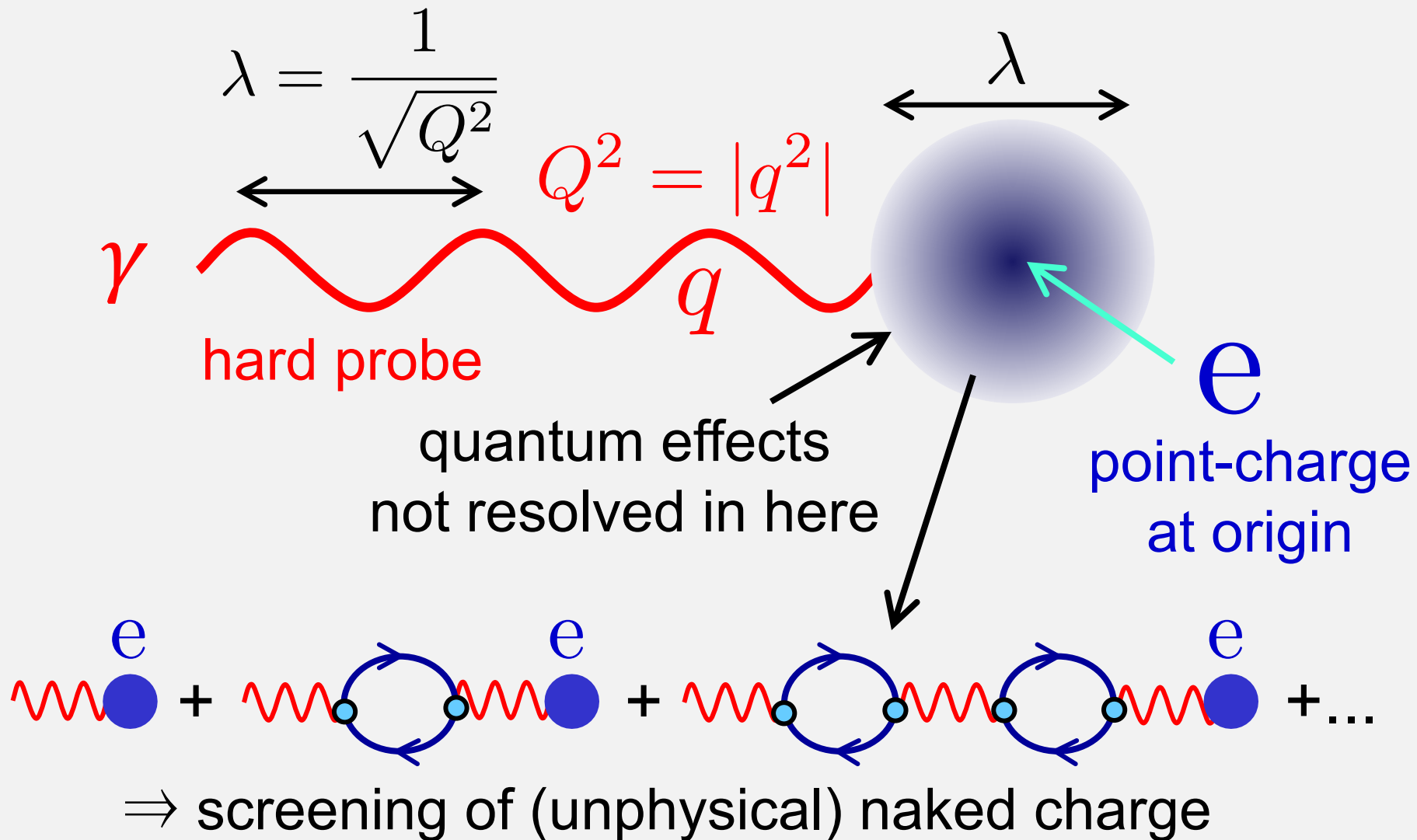
but free quarks and gluons are not observed; they show up as jets!

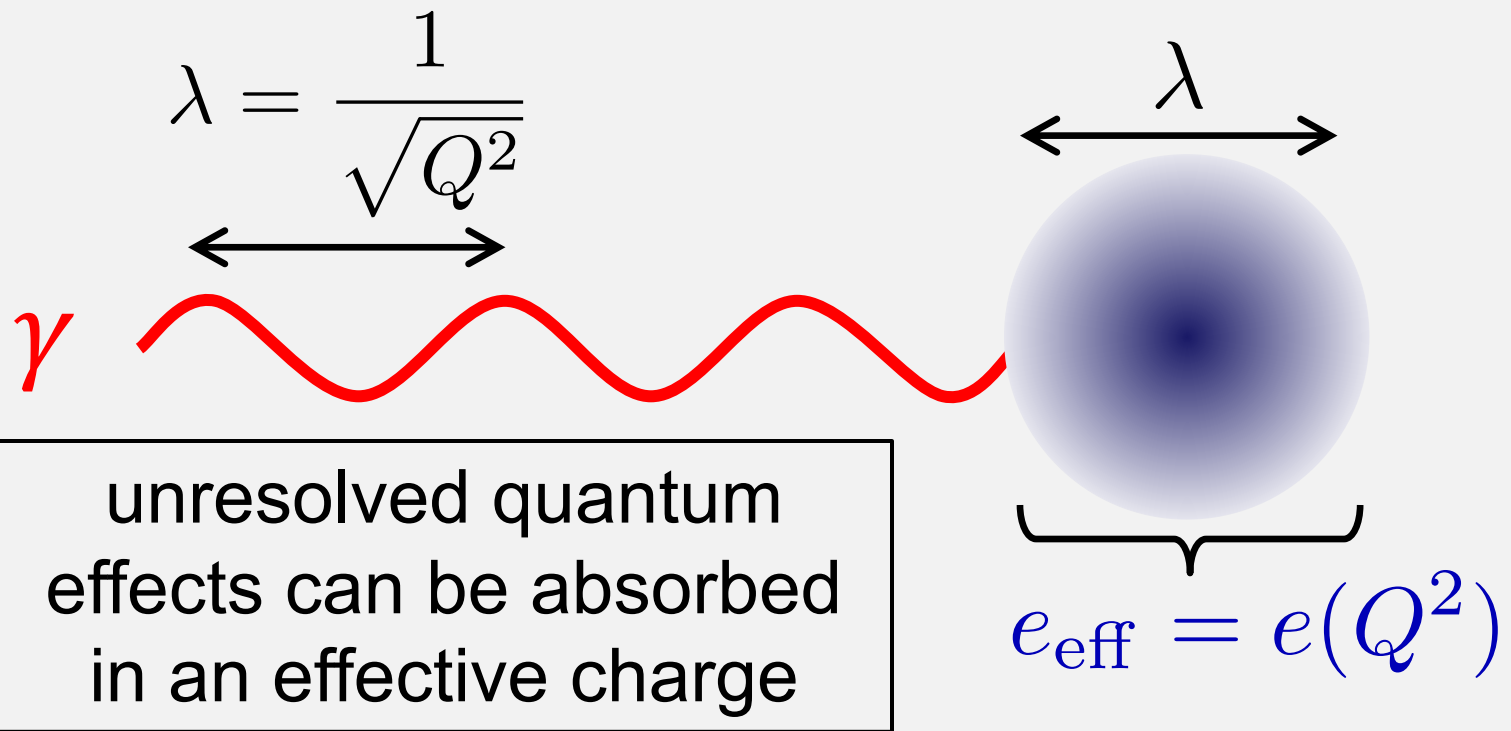
We need:



(1) Why are quarks and gluons never free?

First look at a positron – this can be free





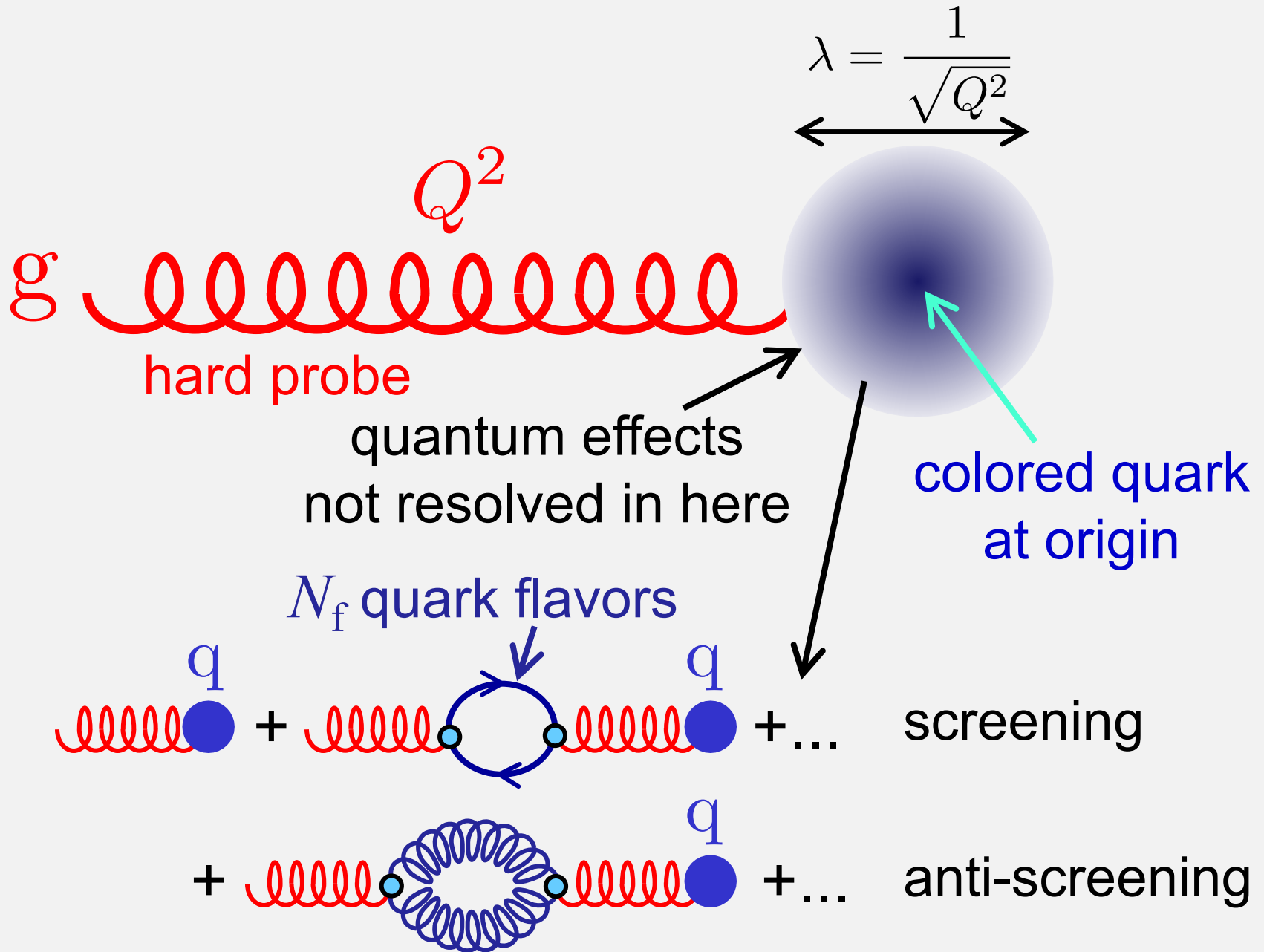
summing up the leading loops $\Rightarrow$

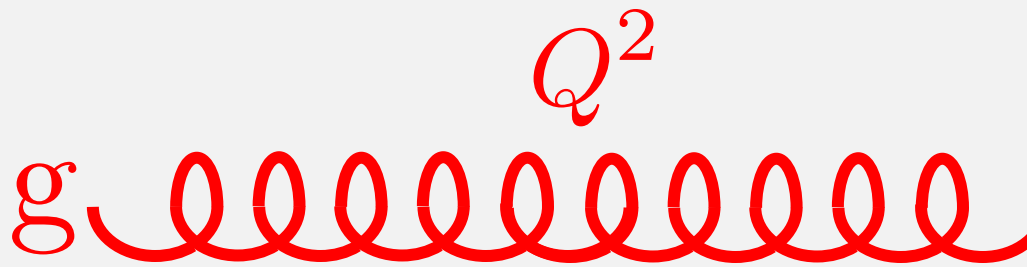
$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log\left(\frac{Q^2}{\mu^2}\right)}$$

reference scale

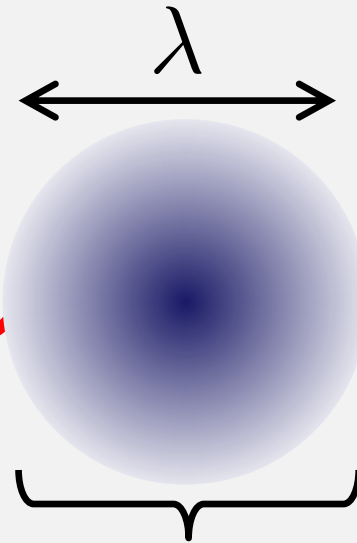
$$\frac{\partial \alpha}{\partial Q^2} > 0$$

Now look at a quark with a unit color charge





unresolved quantum effects
can be absorbed in an
effective color charge



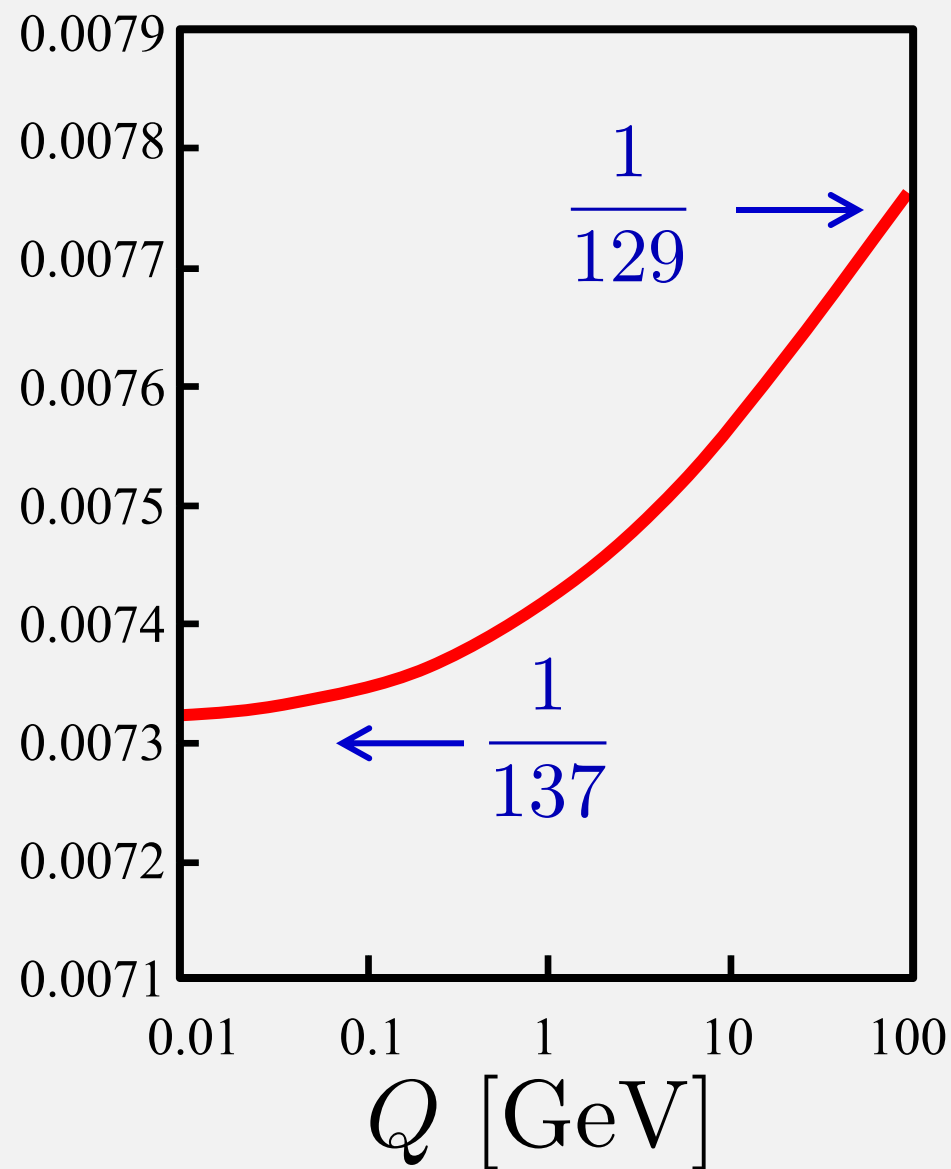
$$\alpha_s = \frac{g_s^2}{4\pi}$$

$$g_{\text{seff}} = g_s(Q^2)$$

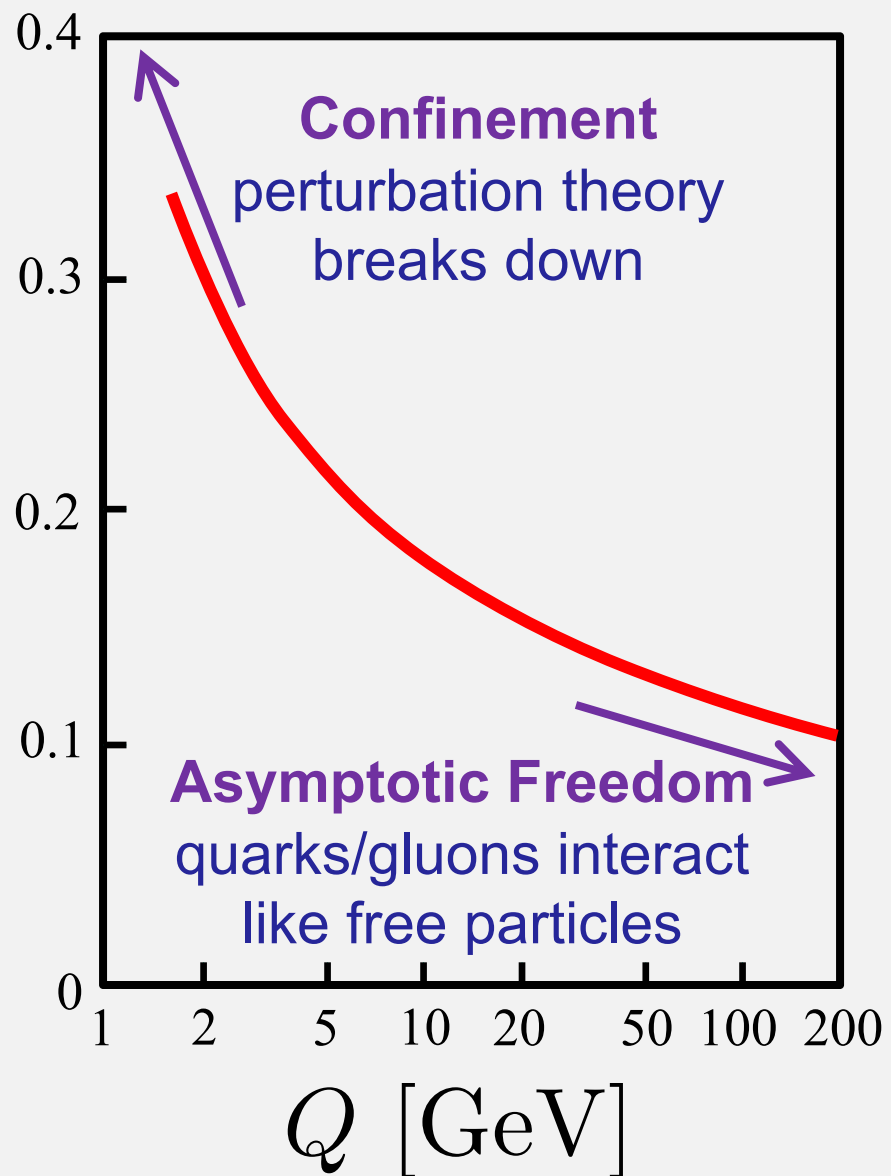
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{(33 - 2N_f)\alpha_s(\mu^2)}{12\pi} \log\left(\frac{Q^2}{\mu^2}\right)}$$

$33 - 2N_f > 0 \Rightarrow$ anti-screening of gluons wins

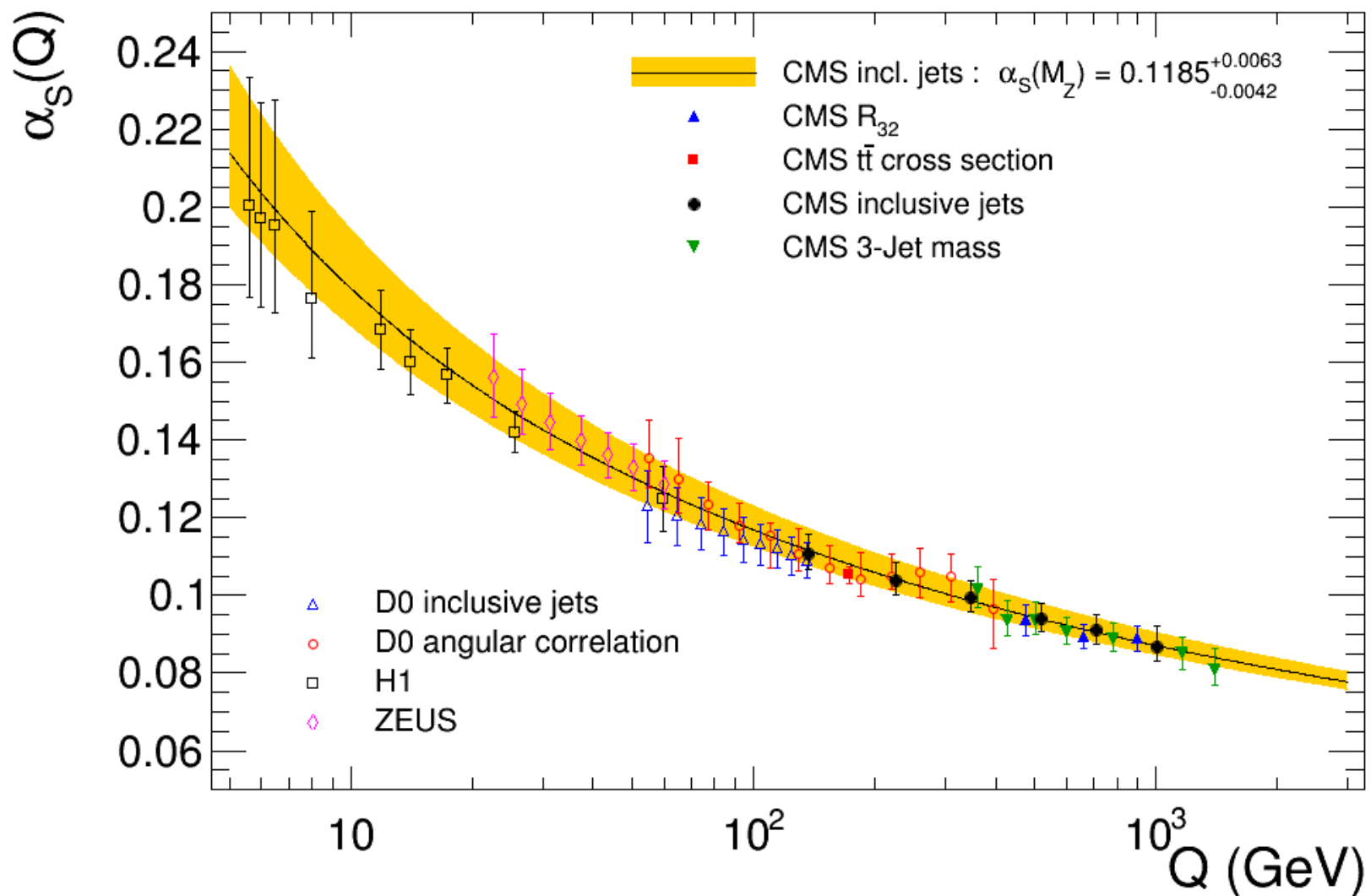
$$\alpha(Q^2)$$



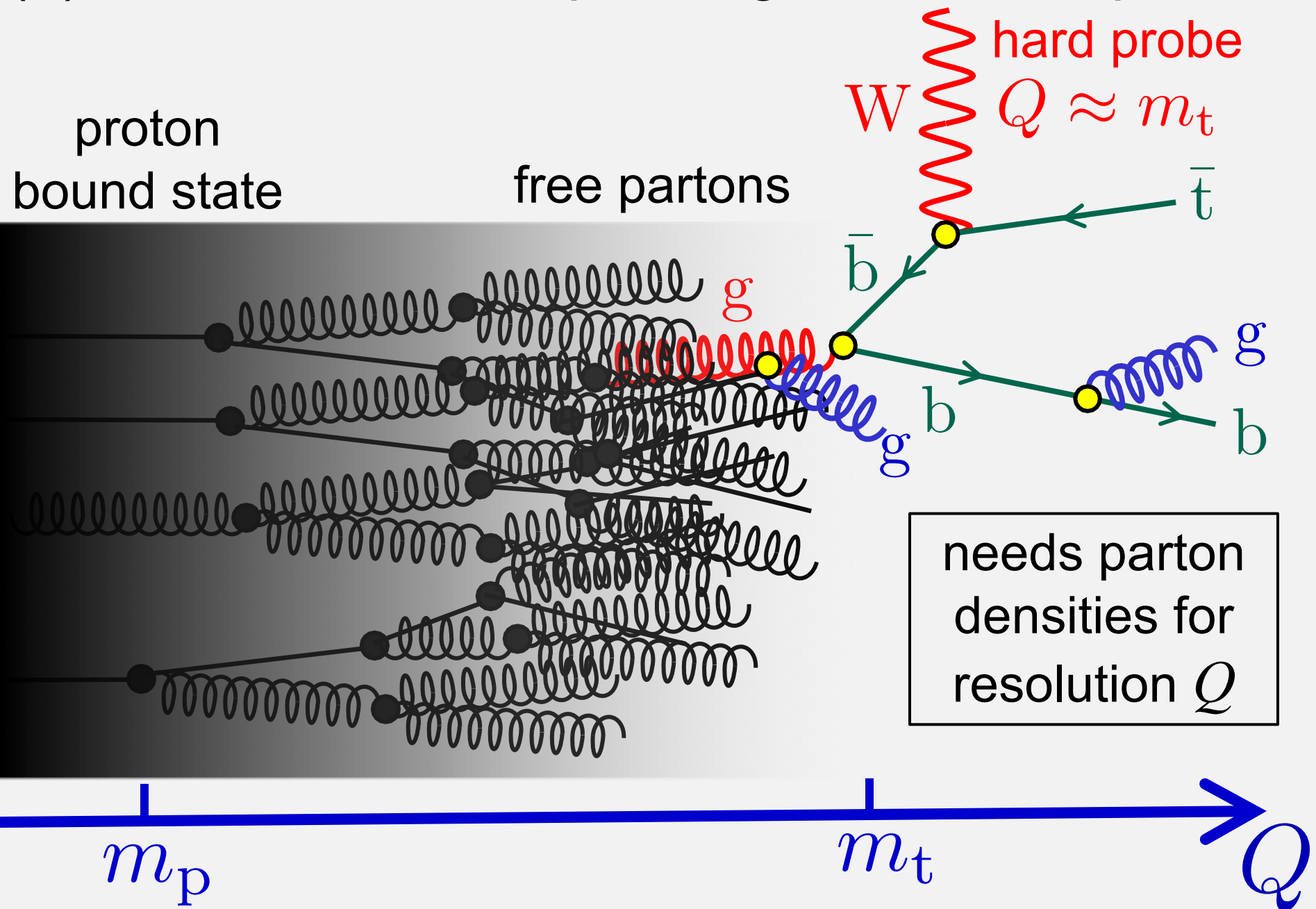
$$\alpha_s(Q^2)$$



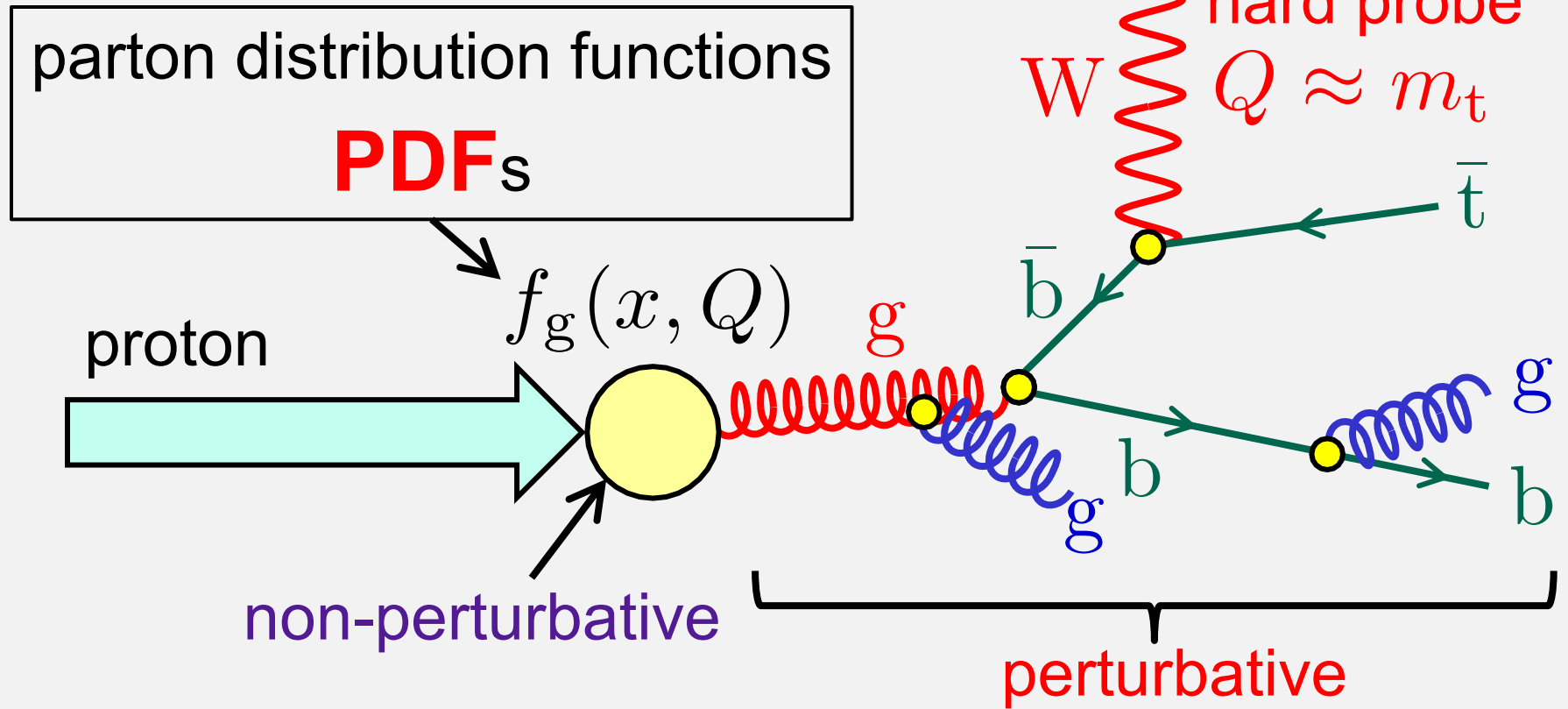
Experimentally accessible, e.g. $\alpha_s \sim \frac{\sigma(X+1 \text{ jet})}{\sigma(X)}$



(2) How to treat the quarks/gluons in the protons



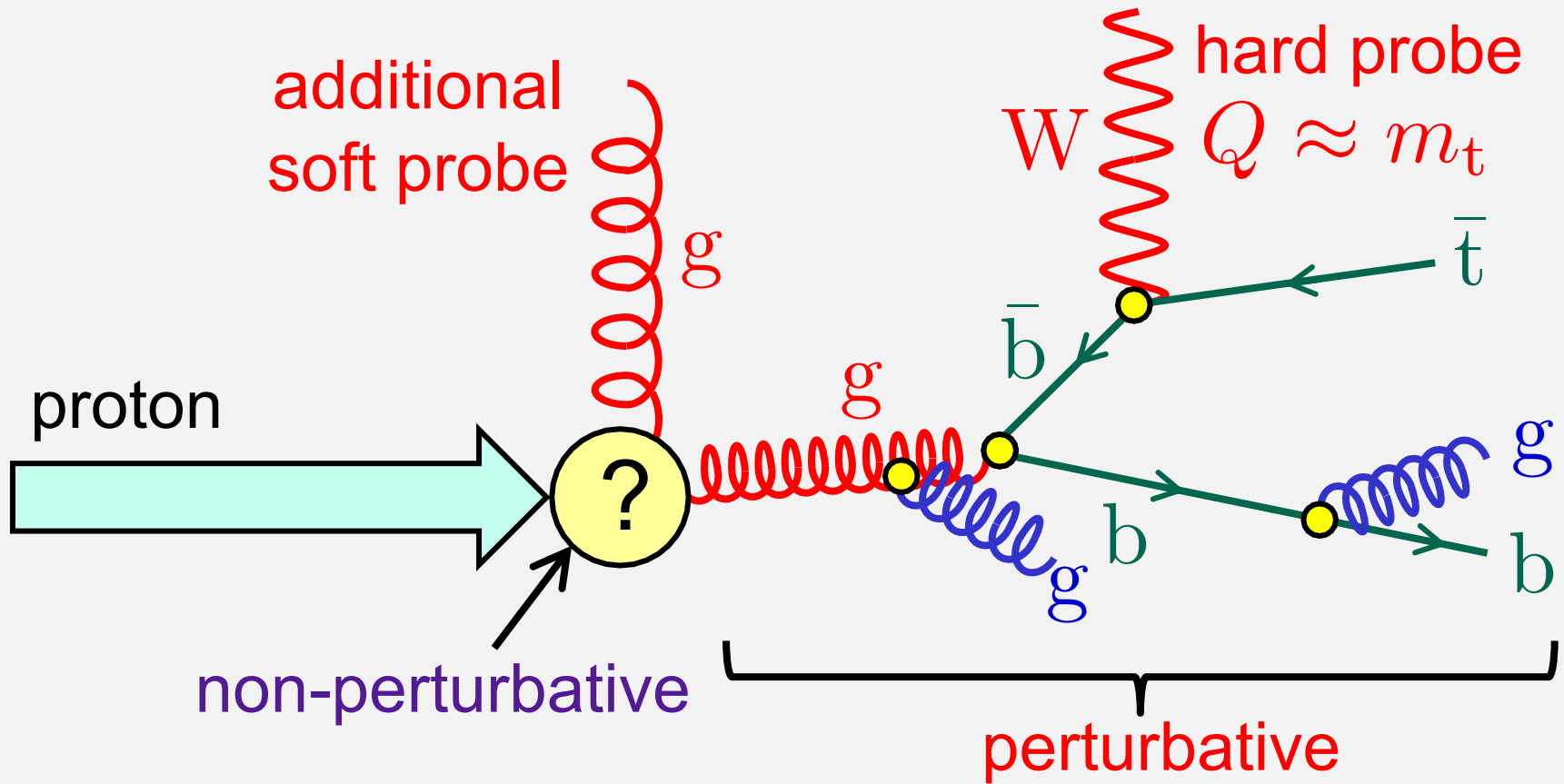
(2) How to treat the quarks/gluons in the protons



x = fraction of $(E \rightarrow \infty)$ proton momentum carried by parton

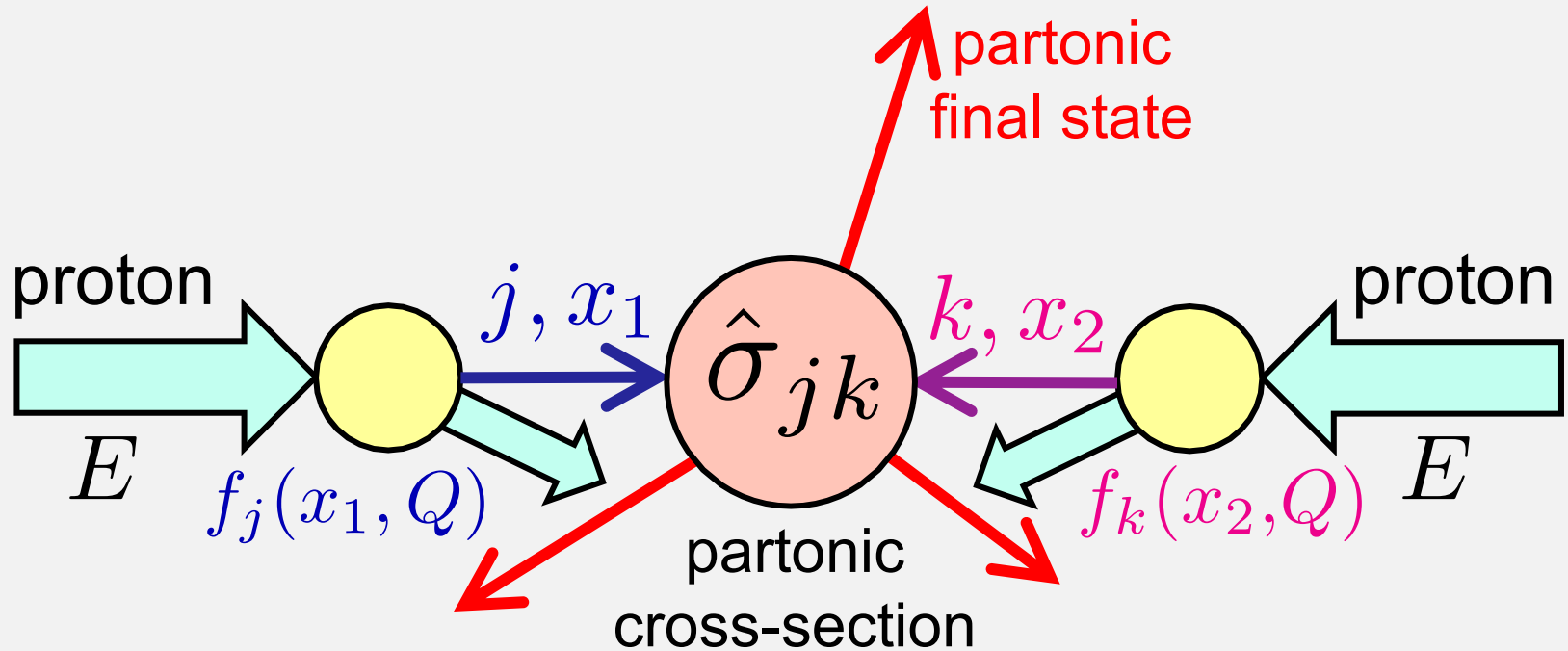
$f_j(x, Q) dx$ = number of partons of type j (probed with resolution Q) with momentum fraction in $[x, x + dx]$

Can this be spoiled by soft gluon-exchange?



Factorization theorem: cross-sections can **always** be factorized into a partonic cross section and the parton distribution functions. The answer is independent of the resolution (**factorization scale**), at which the two parts are split apart.

The master formula



$$\sigma = \sum_{j,k} \int dx_1 f_j(x_1, Q) \int dx_2 f_k(x_2, Q) \times \hat{\sigma}_{jk}(\hat{s}, Q)$$

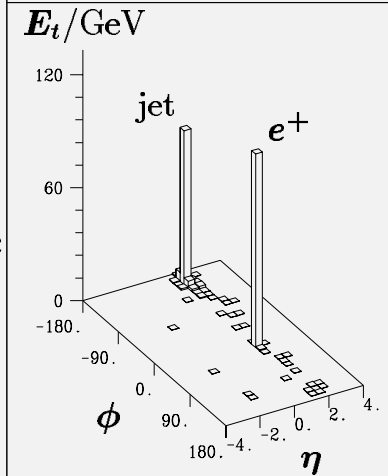
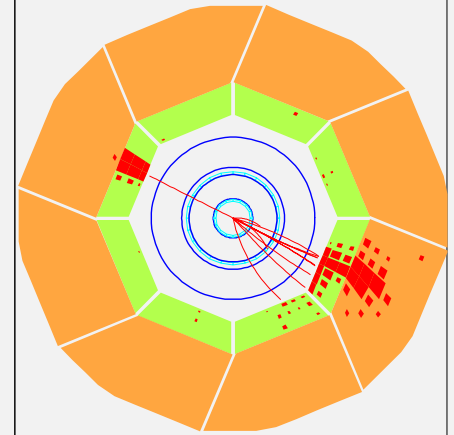
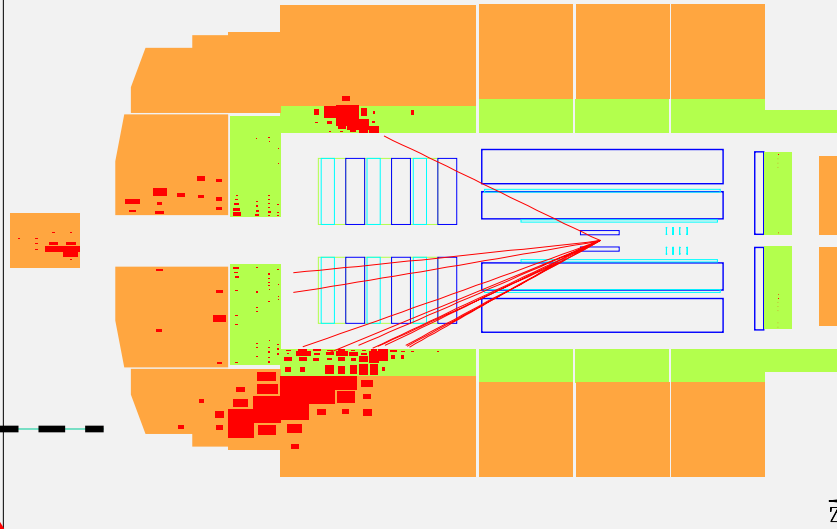
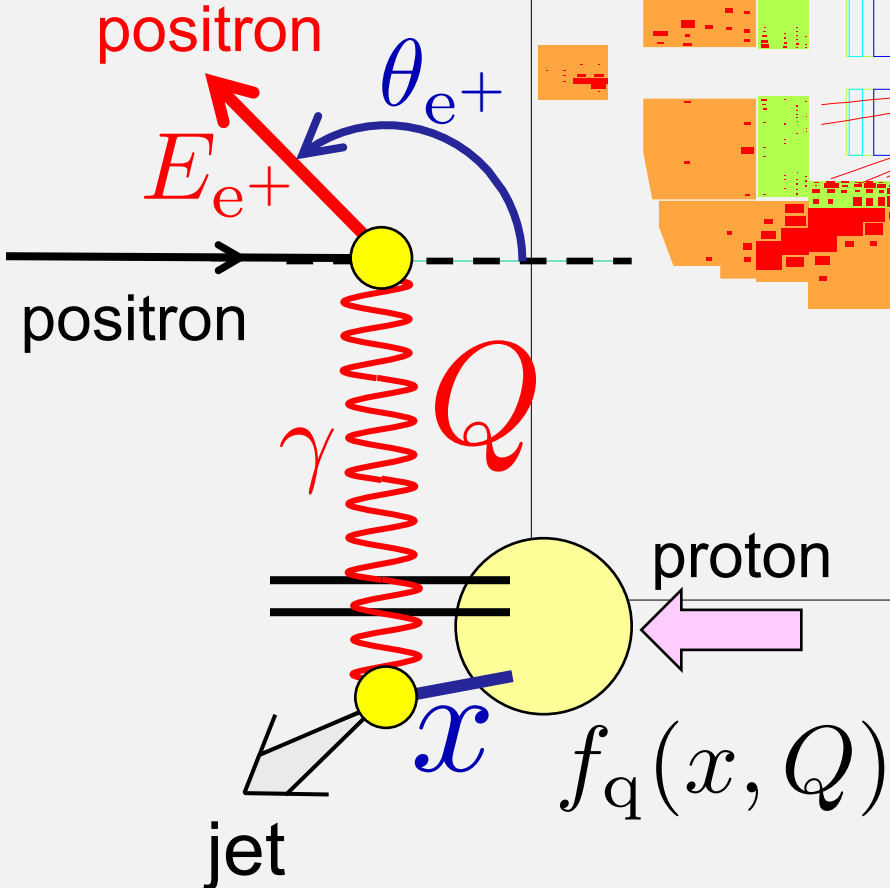
partonic center of mass energy

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2} \times \sqrt{s} \ll \sqrt{s}$$

coupling strengths
depend on Q

Measurement of PDFs at ep -collider HERA (DESY)

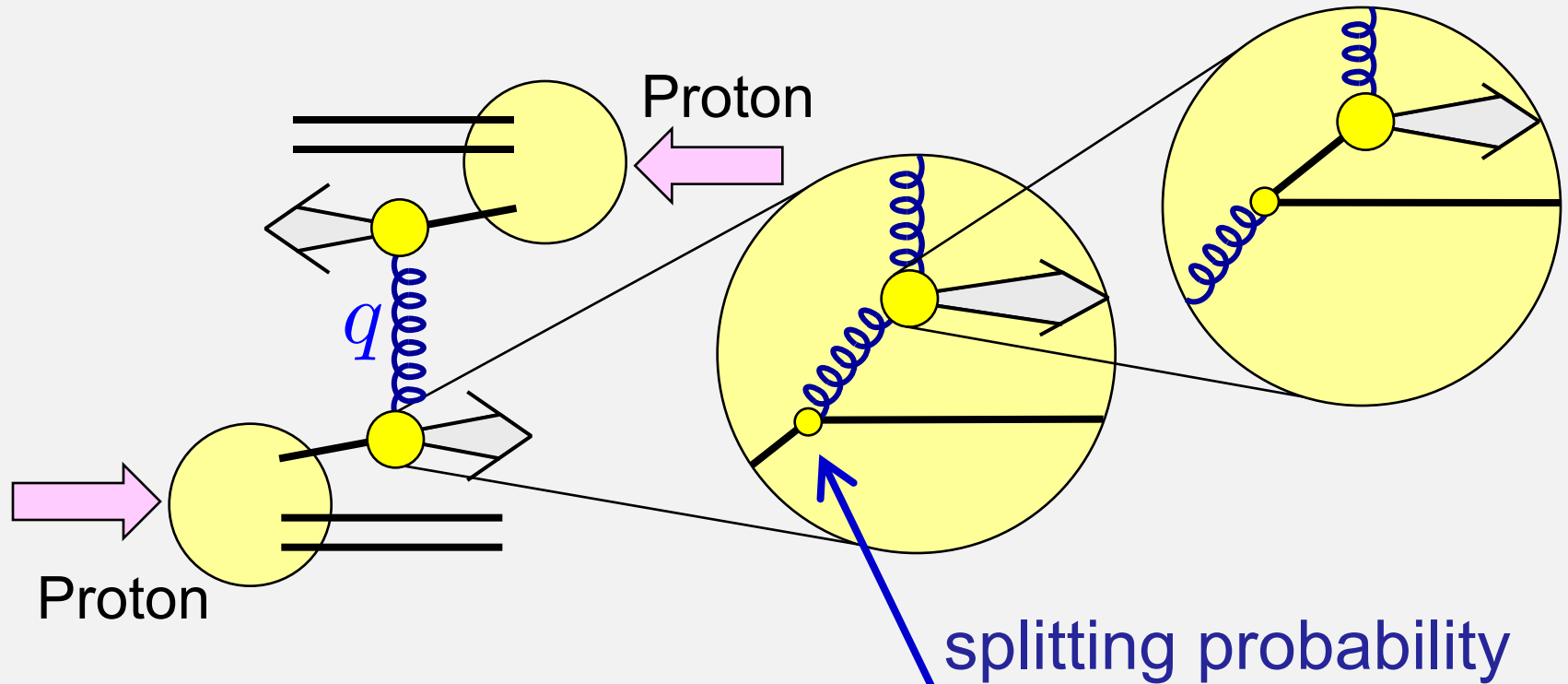
$$Q^2 = 25030 \text{ GeV}^2, \quad y = 0.56, \quad M = 211 \text{ GeV}$$



$$E_{e+}, \theta_{e+} \Rightarrow x, Q$$

measured

How to extrapolate from Q_{HERA} to Q_{LHC} ?

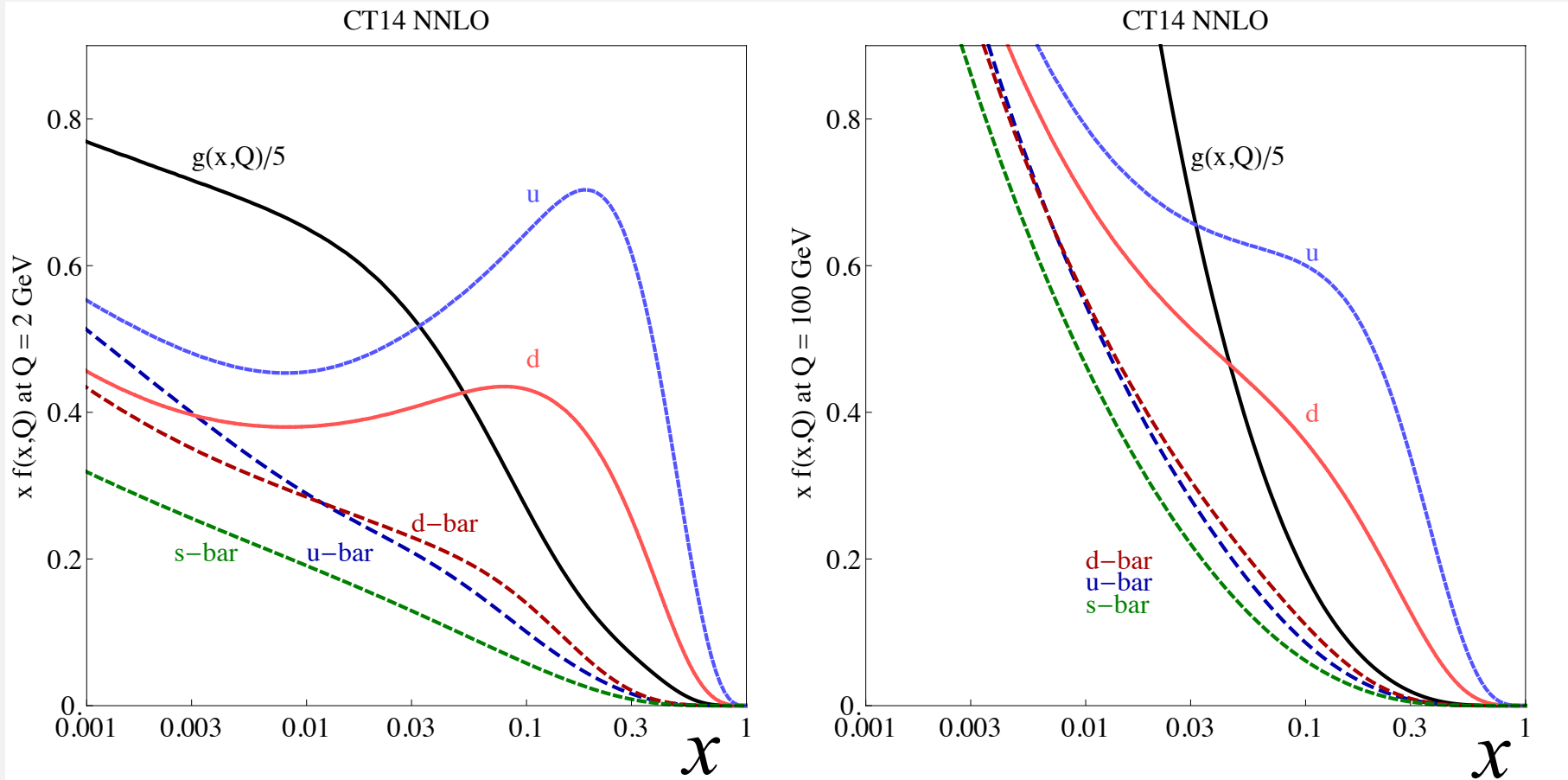


Self-similarity of the quark/gluon structure of the proton:

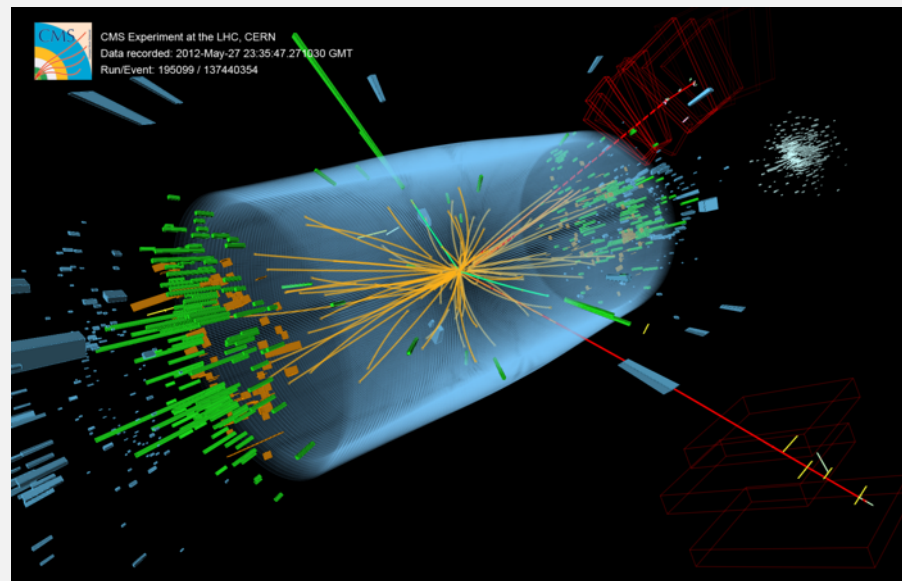
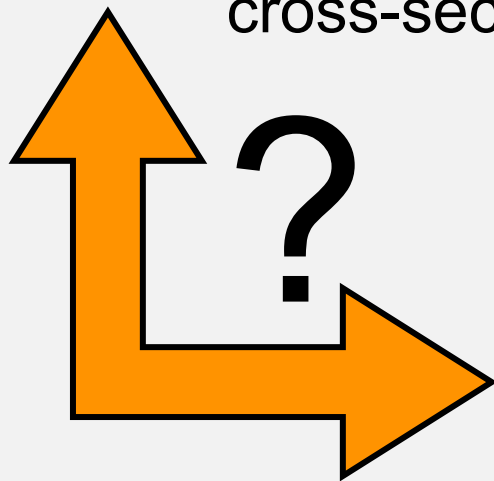
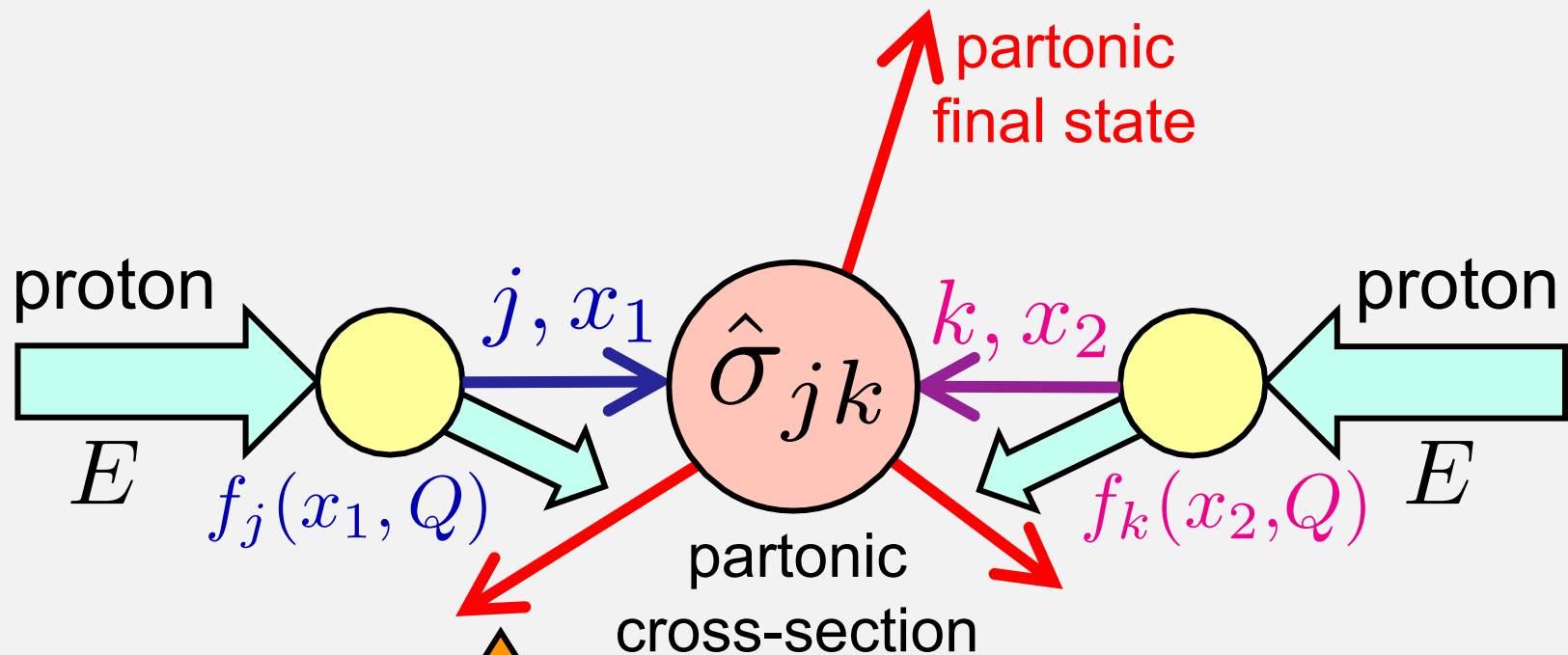
$$Q^2 \frac{df(x, Q)}{dQ^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}\right) f(y, Q)$$

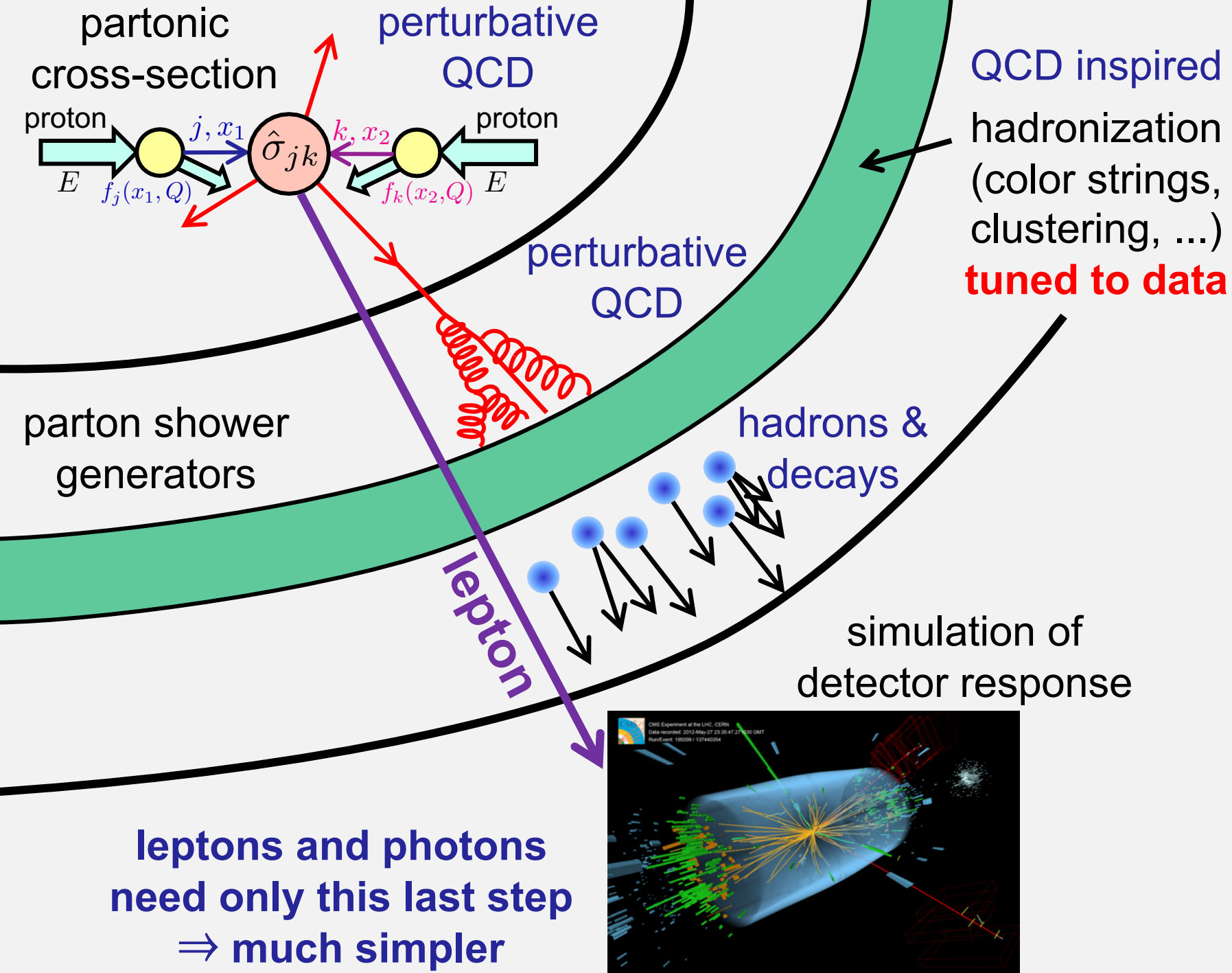
Analytical fits of parton distribution functions

$$Q = 2 \text{ GeV} \quad x f(x, Q) \quad Q = 100 \text{ GeV}$$

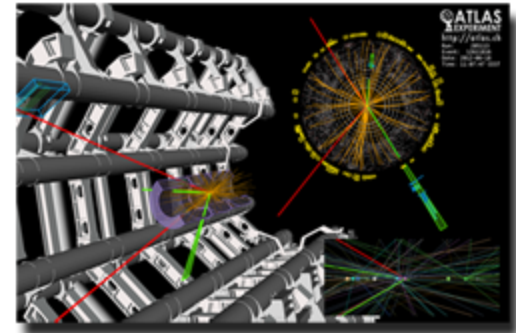
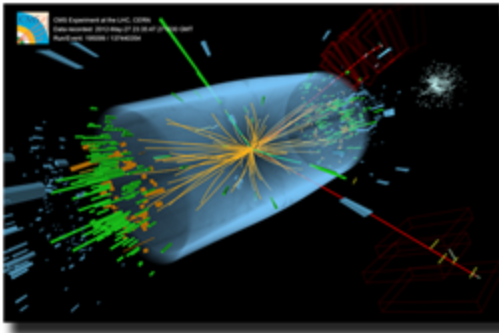


(3) How to connect to final states on hadron level?





The problem of masses



Fundamental problem 1

Gauge theory construction $\Rightarrow$ massless particles

Examples:

a) Massive vector boson:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{gauge invariant}} + \underbrace{\frac{1}{2}m^2 A_\mu A^\mu}_{\text{not gauge invariant}}$$

gauge invariant **not** gauge invariant

with gauge transformation: $A_\mu \rightarrow A_\mu - \partial_\mu f(x)$

$$M_Z \approx 91 \text{ GeV}$$
$$M_W \approx 80 \text{ GeV}$$

?

b) Massive fermion:

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\gamma^\mu \partial_\mu - \textcolor{red}{m})\psi + \mathcal{L}_{\text{int}} \\ &= \underbrace{i\bar{\psi}\gamma^\mu \partial_\mu \psi + \mathcal{L}_{\text{int}}}_{\text{gauge invariant}} - \underbrace{\textcolor{red}{m}(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)}_{\text{not gauge invariant}}\end{aligned}$$

with gauge transformation:

$$\psi_L \rightarrow e^{iT^j \alpha^j(x) + iY \beta(x)} \psi_L$$

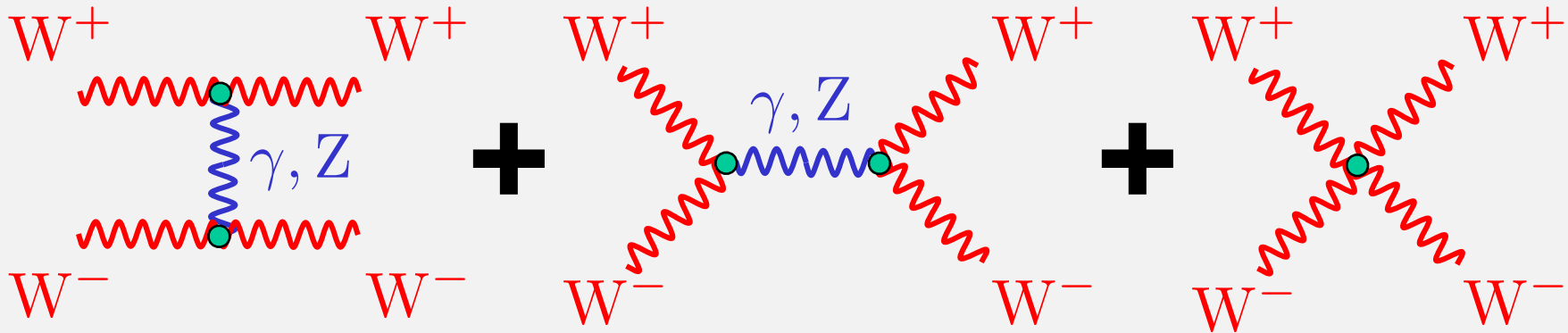
$$\psi_R \rightarrow e^{iY \beta(x)} \psi_R$$

$$\begin{aligned}m_\tau &\approx \textcolor{red}{1.8 \text{ GeV}} \\ m_t &\approx \textcolor{red}{173 \text{ GeV}}\end{aligned} \quad \textcolor{purple}{?}$$

Fundamental problem 2 (ignoring problem 1)

Theory is misbehaved at (very) large energies!

Scattering of two W-bosons:



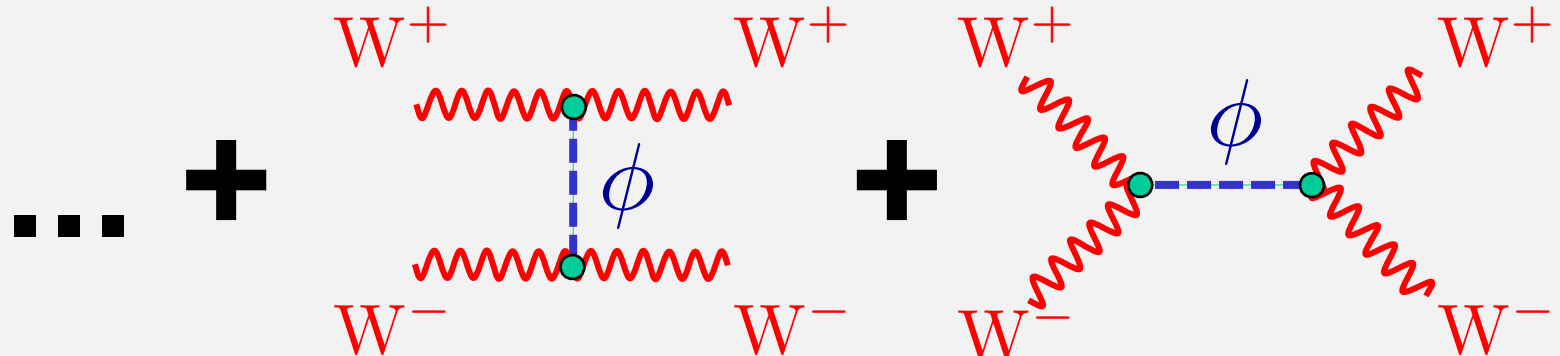
$$\propto \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

⇒ scattering probability > 1 at high enough energies

⇒ violation of **unitarity** bound

... this can be fixed by additional amplitudes

... if these involve a neutral **scalar** (spin 0) particle ϕ



The diagram shows two Feynman diagrams representing scalar exchange between W bosons. The first diagram shows a vertical exchange of a scalar particle ϕ between two pairs of W bosons (W⁺ and W⁻). The second diagram shows a horizontal exchange of a scalar particle ϕ between two pairs of W bosons (W⁺ and W⁻). Both diagrams are preceded by an ellipsis and a plus sign, indicating they are part of a larger sum of amplitudes.

$$\propto m_{\phi}^2 \quad \text{for } s \rightarrow \infty$$

$\Rightarrow$ theory becomes **ultra-violet complete**

Note:

Such cancellations work because of gauge **symmetry**

Solution:

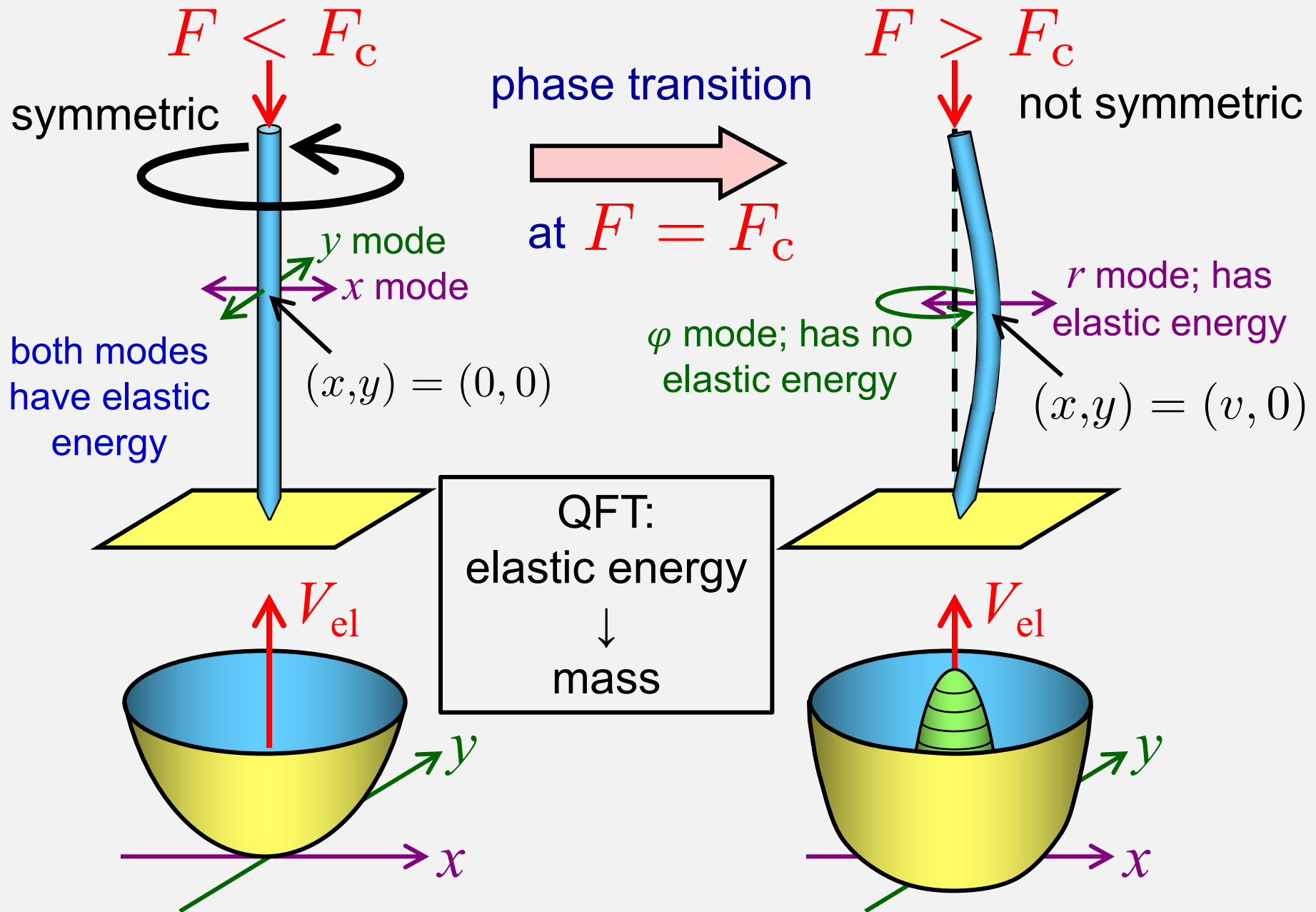
Spontaneous breaking of the

$$SU(2)_L \times U(1)_Y$$

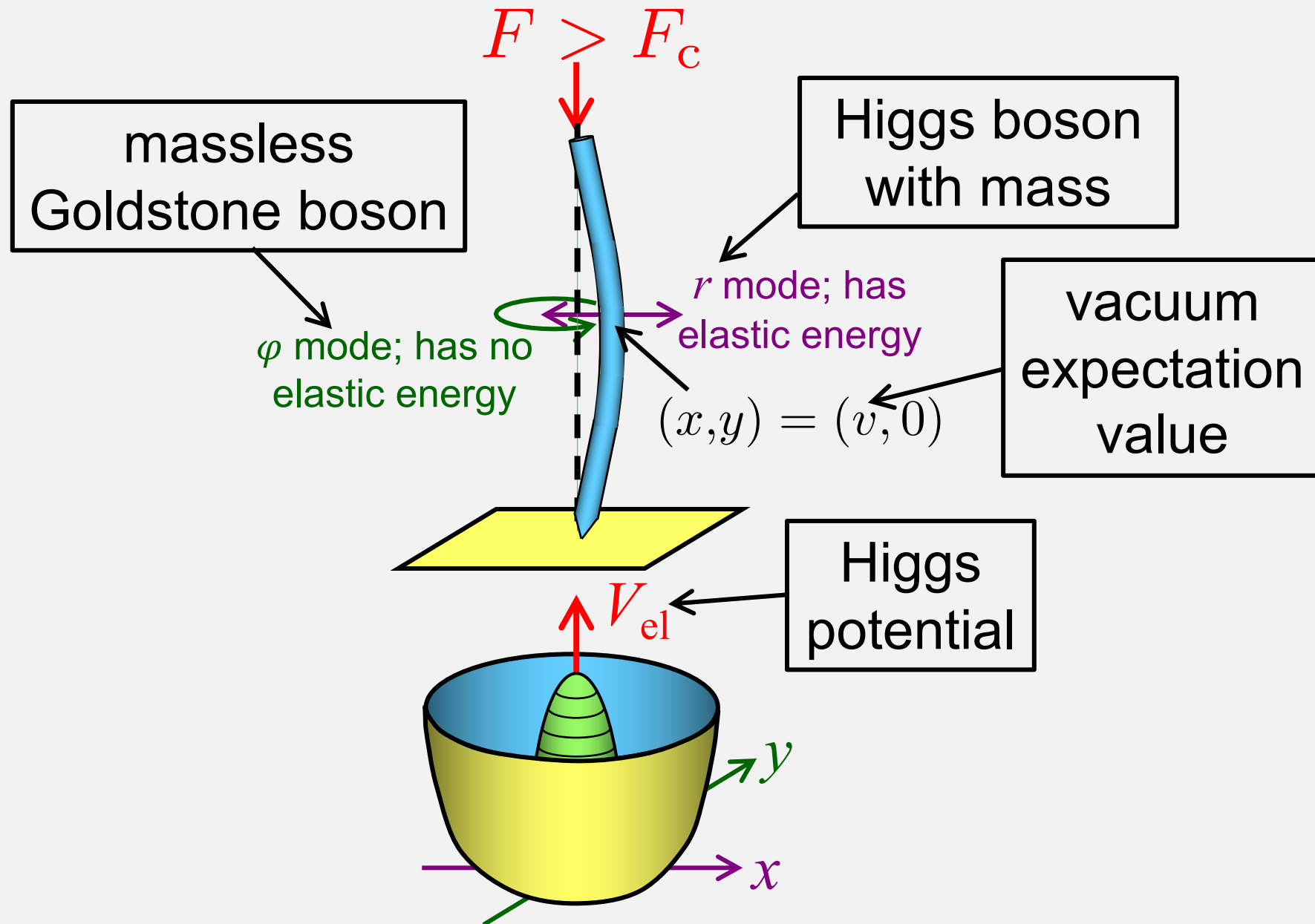
gauge symmetry

involving an additional scalar field

Classical example: buckling of an elastic rod



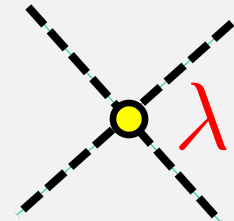
Correspondence with QFT (somewhat rough):



example:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

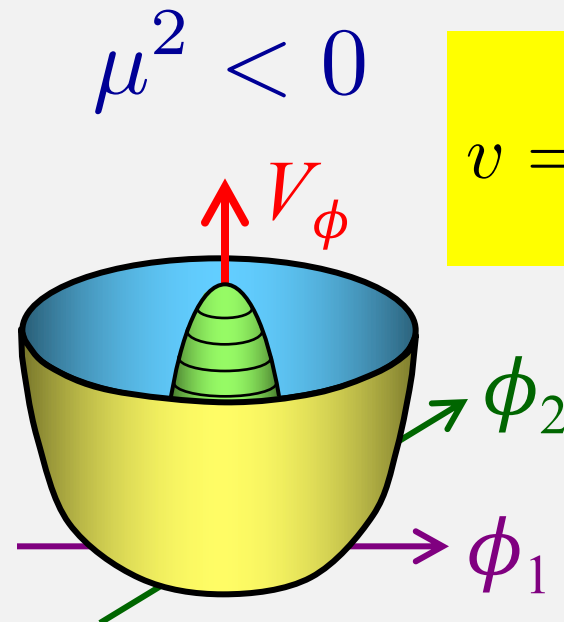
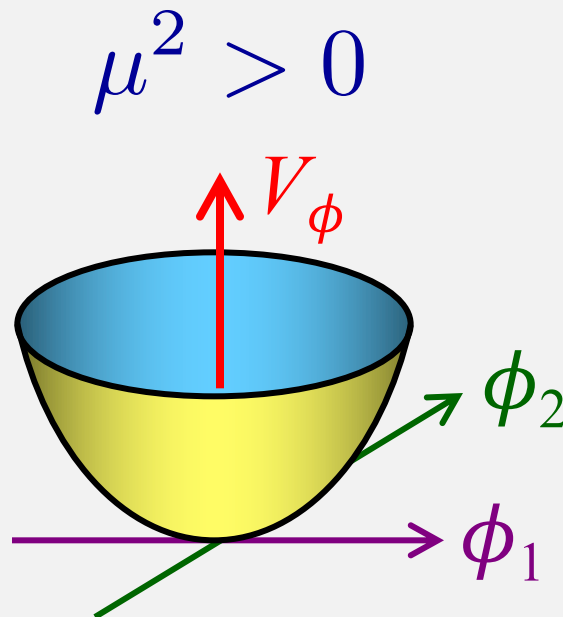
mass term



$$\mathcal{L}_\phi = (D^\mu \phi)^\star (D_\mu \phi) - \left(\mu^2 \phi^\star \phi + \lambda (\phi^\star \phi)^2 \right)$$

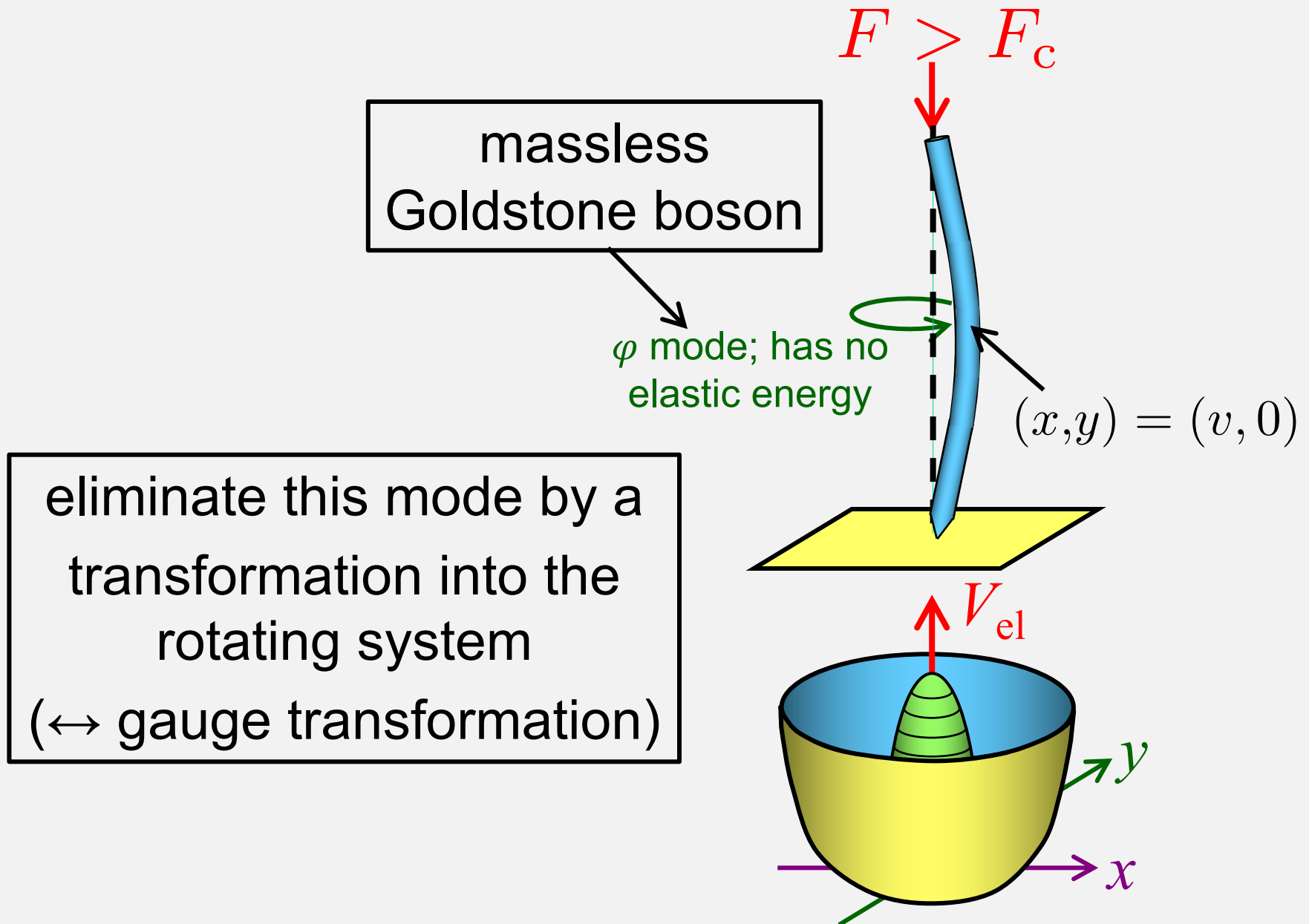
kinetic energy & interaction
with a $U(1)$ gauge field

Higgs potential V_ϕ

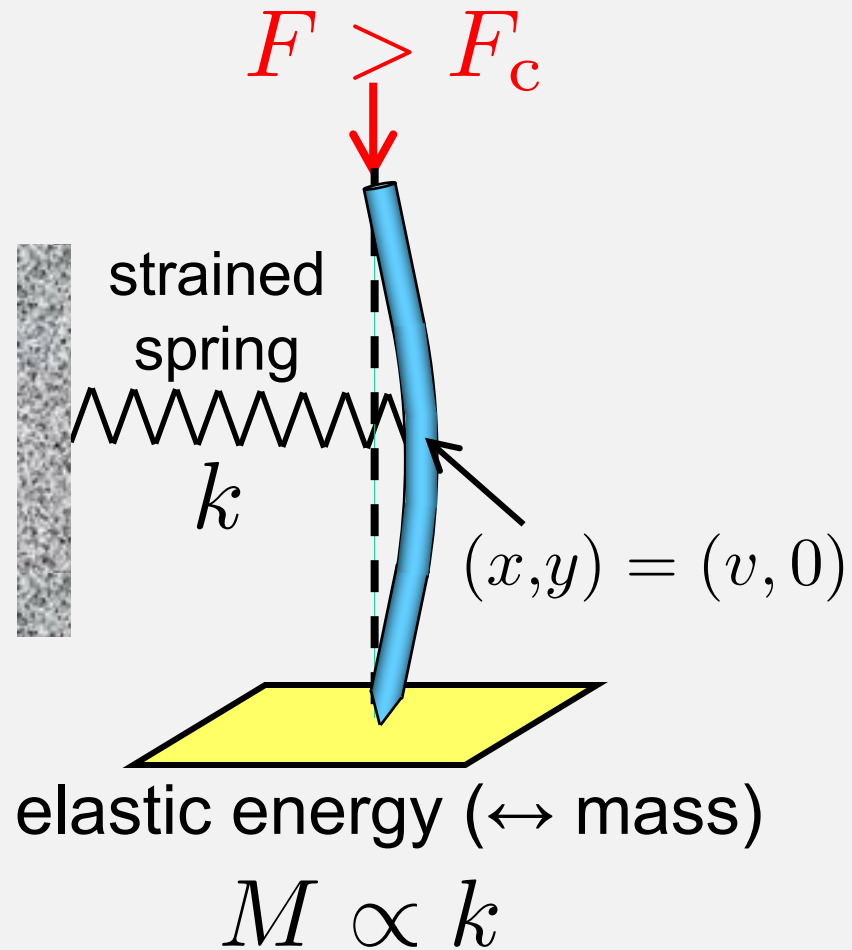
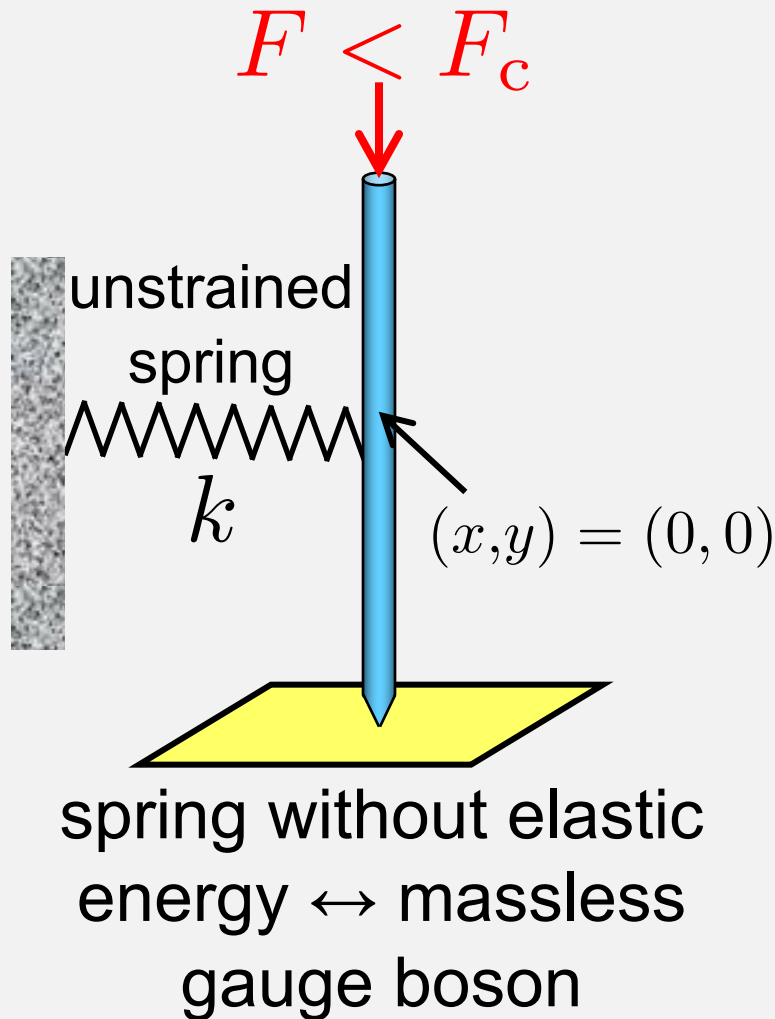


$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

But: there are no (known) massless scalars in nature



ϕ -interactions with the gauge boson



The coupling k of the Higgs mode is
proportional to the mass M of the gauge boson

Minimal Higgs sector in the Standard Model

$SU(2)_L$ doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

Y	I_3	Q
1	$+\frac{1}{2}$	$+1$
	$-\frac{1}{2}$	0

$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger (D_\mu \phi) - (\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2)$$

$\mu^2 < 0 \Rightarrow$ degenerated ground states:

$$\langle \phi^\dagger \phi \rangle_0 = \frac{v^2}{2} \quad \text{with} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

Spontaneous symmetry breaking:

$$\langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Which symmetries break?

$$\langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\tau^1 \langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix} \neq 0$$

$$T^1 \downarrow$$

$$\tau^2 \langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} = \frac{-i}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix} \neq 0$$

$$T^2 \downarrow$$

$$\tau^3 \langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} = \frac{-1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$$

$$T^3 \downarrow$$

$$Y \langle \phi \rangle_0 = 1 \times \langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$$

$$Y \downarrow$$

$$Q \langle \phi \rangle_0 = \frac{1}{2} (Y + \tau_3) \langle \phi \rangle_0 = 0$$

$$Q \checkmark$$

$$M_W > 0, M_Z > 0, M_\gamma = 0$$



1 Higgs **H**

Numbers

$$M_W = \frac{1}{2} v g = 80.4 \text{ GeV}$$

$$M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2} = 91.2 \text{ GeV}$$

$$v = 246 \text{ GeV}$$

Predicted: $M_\gamma = 0$, $M_Z = \frac{M_W}{\cos \theta_w}$

Not predicted: M_W

$$M_H = \sqrt{2\lambda} v$$

Implementation of fermion masses

Example: electron

$$\mathcal{L}_{eH} = -\frac{m_e}{v} \left[\overbrace{(\bar{\nu}_e, \bar{e})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R}^{\text{invariant under } SU(2)_L} + \text{h.c.} \right]$$

$$Y = \underbrace{1 + 1 - 2}_{\text{invariant under } U(1)_Y} = 0$$

Expanded around vacuum:

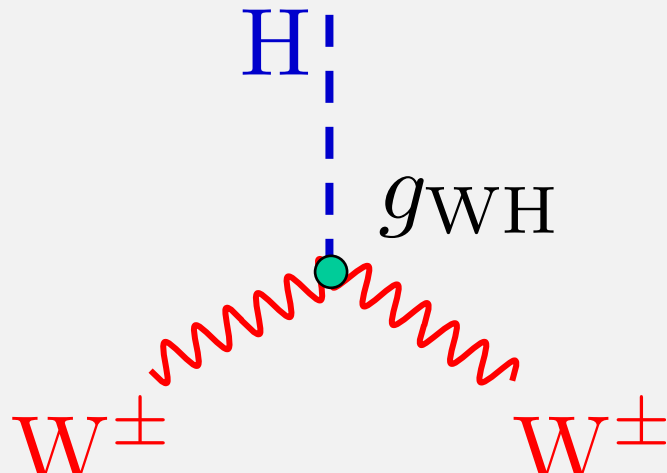
$$\mathcal{L}_{eH} = -m_e \bar{e}e - \frac{m_e}{v} \bar{e}e H$$

mass term

(mass value not predicted)

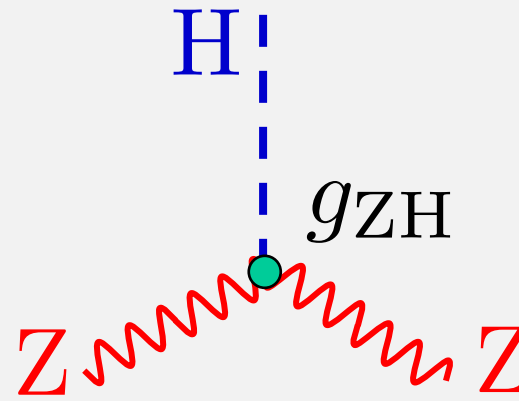
Yukawa coupling

Higgs coupling strength is proportional to mass
examples:



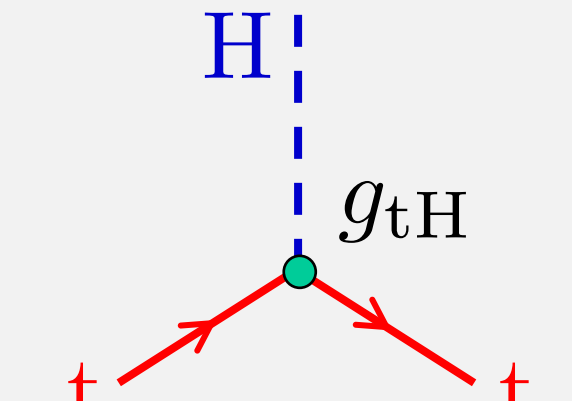
A Feynman diagram showing a Higgs boson (H) as a vertical dashed blue line at the top. It connects to a green circular vertex. From this vertex, two red wavy lines representing $W^\pm$ bosons extend downwards and outwards. The coupling is labeled g_{WH} .

$$\propto g M_W = \frac{2M_W^2}{v}$$



A Feynman diagram showing a Higgs boson (H) as a vertical dashed blue line at the top. It connects to a green circular vertex. From this vertex, two red wavy lines representing Z bosons extend downwards and outwards. The coupling is labeled g_{ZH} .

$$\propto \frac{g}{\cos \theta_w} M_Z = \frac{2M_Z^2}{v}$$



A Feynman diagram showing a Higgs boson (H) as a vertical dashed blue line at the top. It connects to a green circular vertex. From this vertex, two red straight lines with arrows representing top quarks (t) extend downwards and outwards. The coupling is labeled g_{tH} .

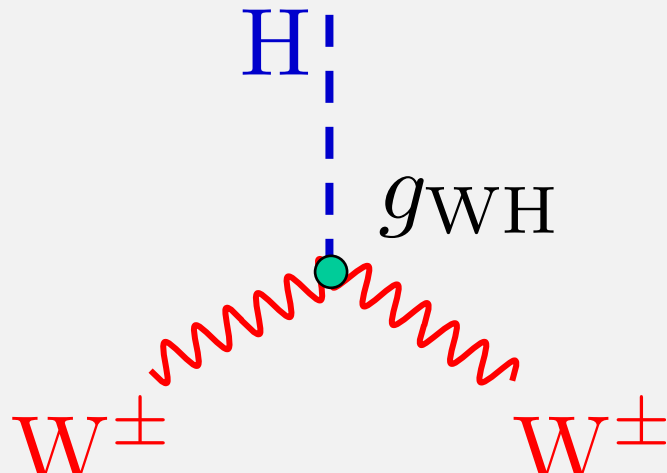
$$\propto g \frac{m_t}{2M_W} = \frac{m_t}{v}$$

note: $\frac{m_t}{v} = \frac{173 \text{ GeV}}{246 \text{ GeV}} = 0.70 = \mathcal{O}(1)$

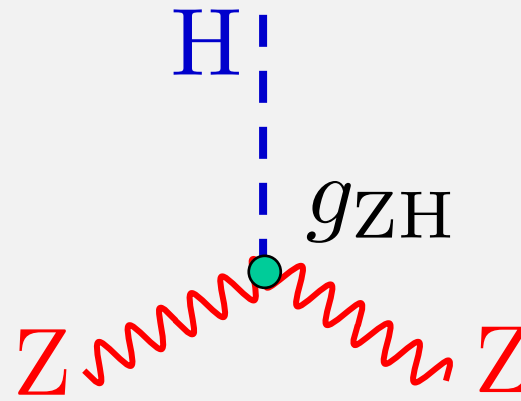
The top-quark is a golden key for testing the Higgs sector

Higgs coupling strength is proportional to mass

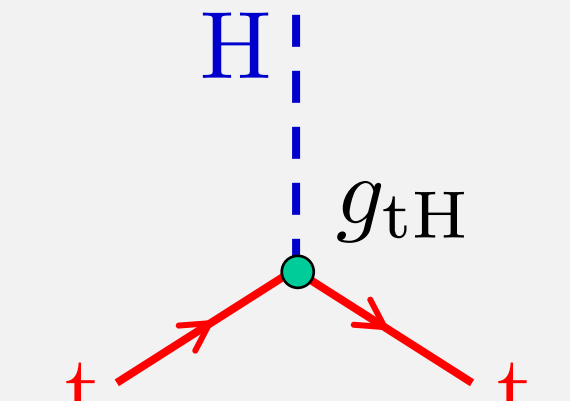
examples:



$$\propto g M_W = \frac{2M_W^2}{v}$$



$$\propto \frac{g}{\cos \theta_w} M_Z = \frac{2M_Z^2}{v}$$



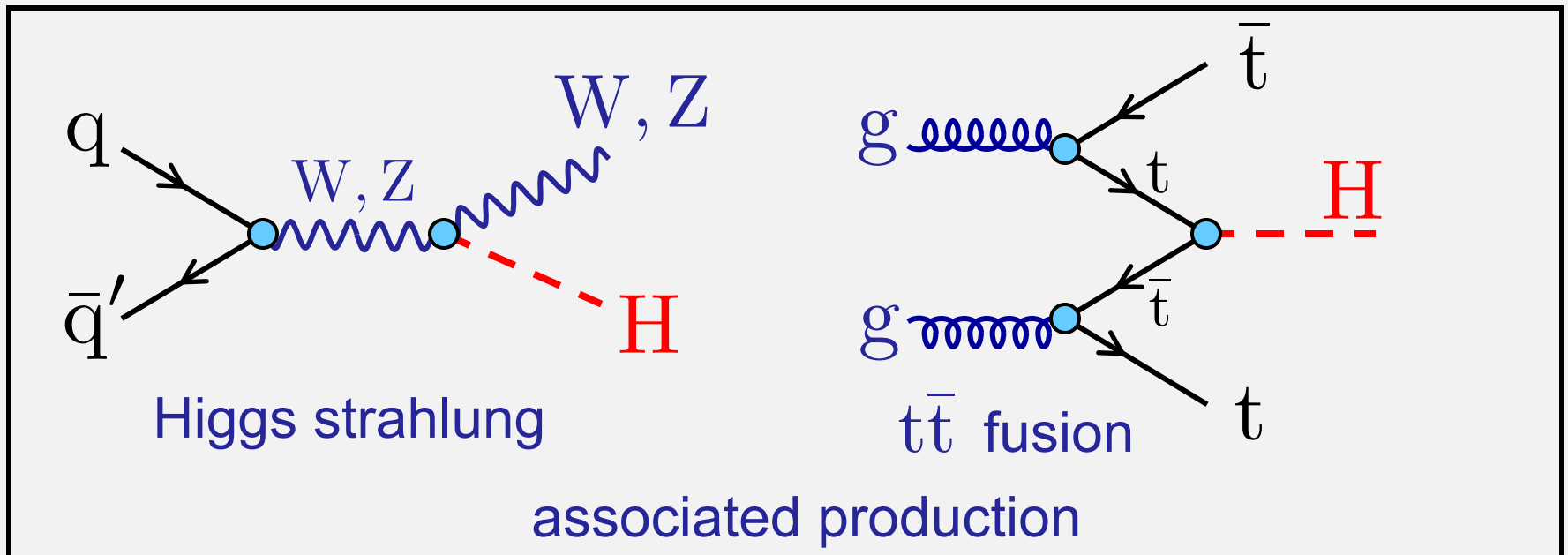
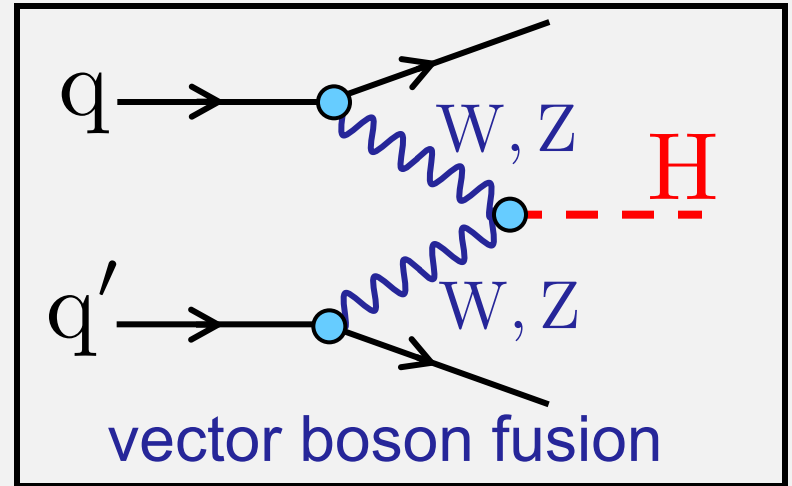
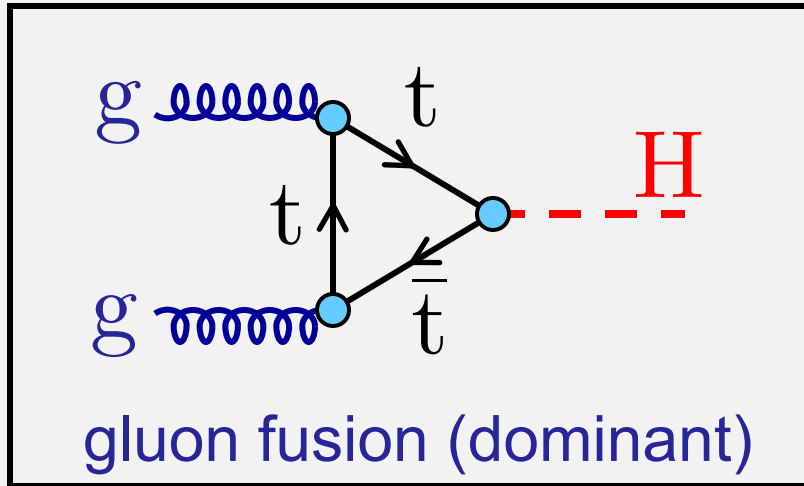
$$\propto g \frac{m_t}{2M_W} = \frac{m_t}{v}$$

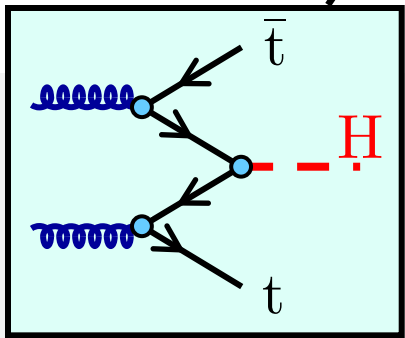
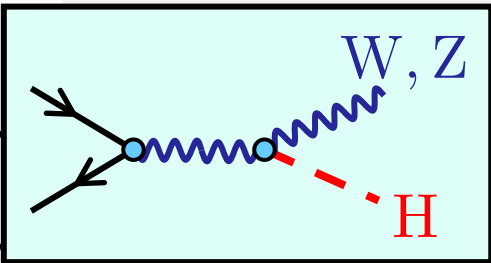
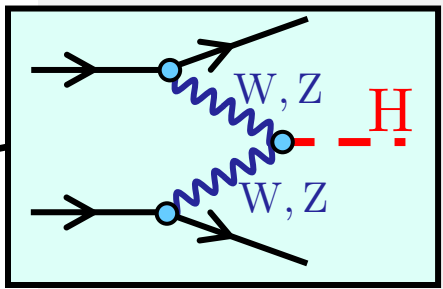
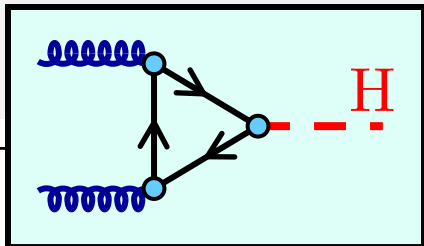
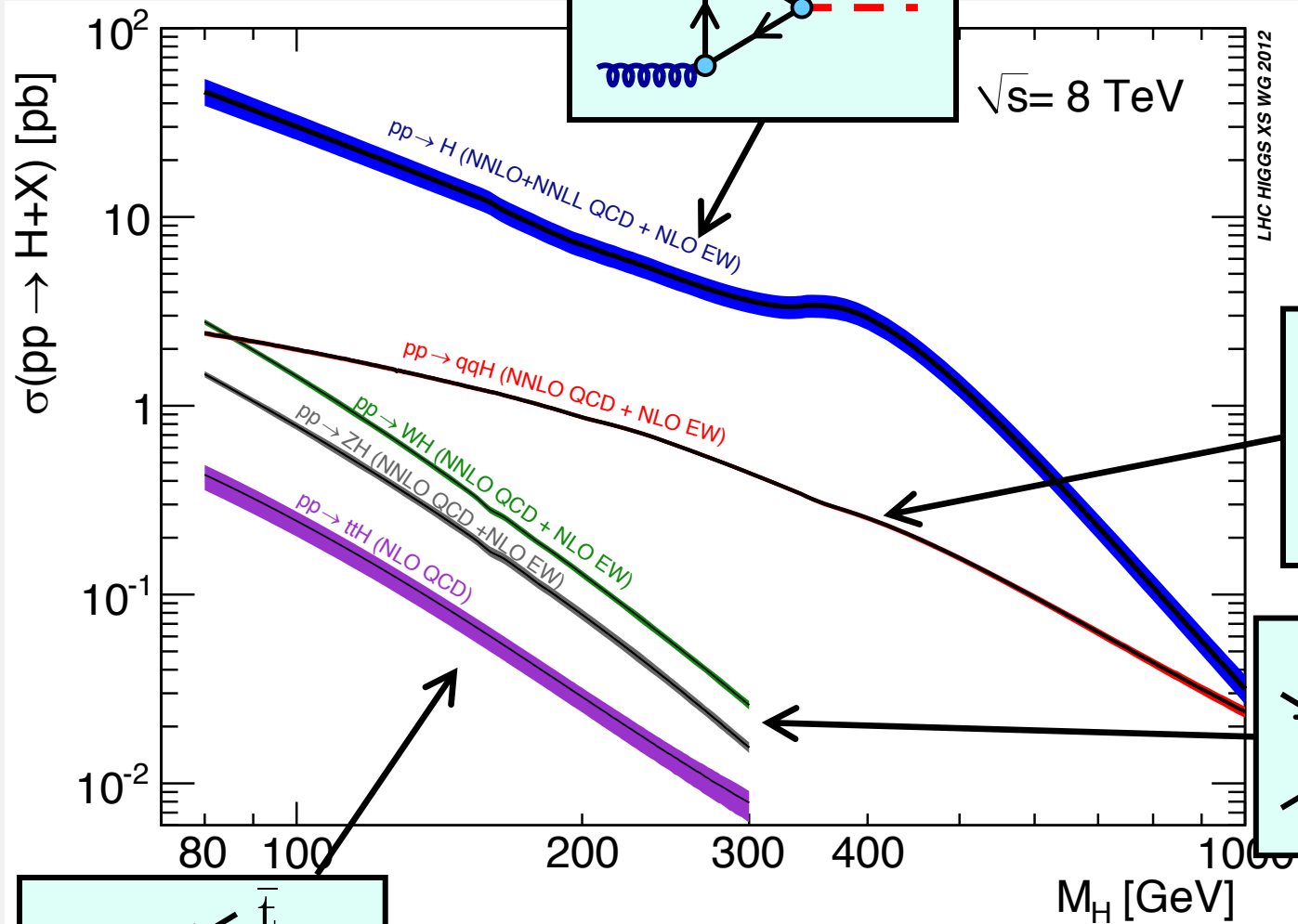
note:

$$\frac{M_V}{v} = \sqrt{\frac{|g_{VH}|}{2v}}, \quad \frac{m_F}{v} = |g_{FH}|$$

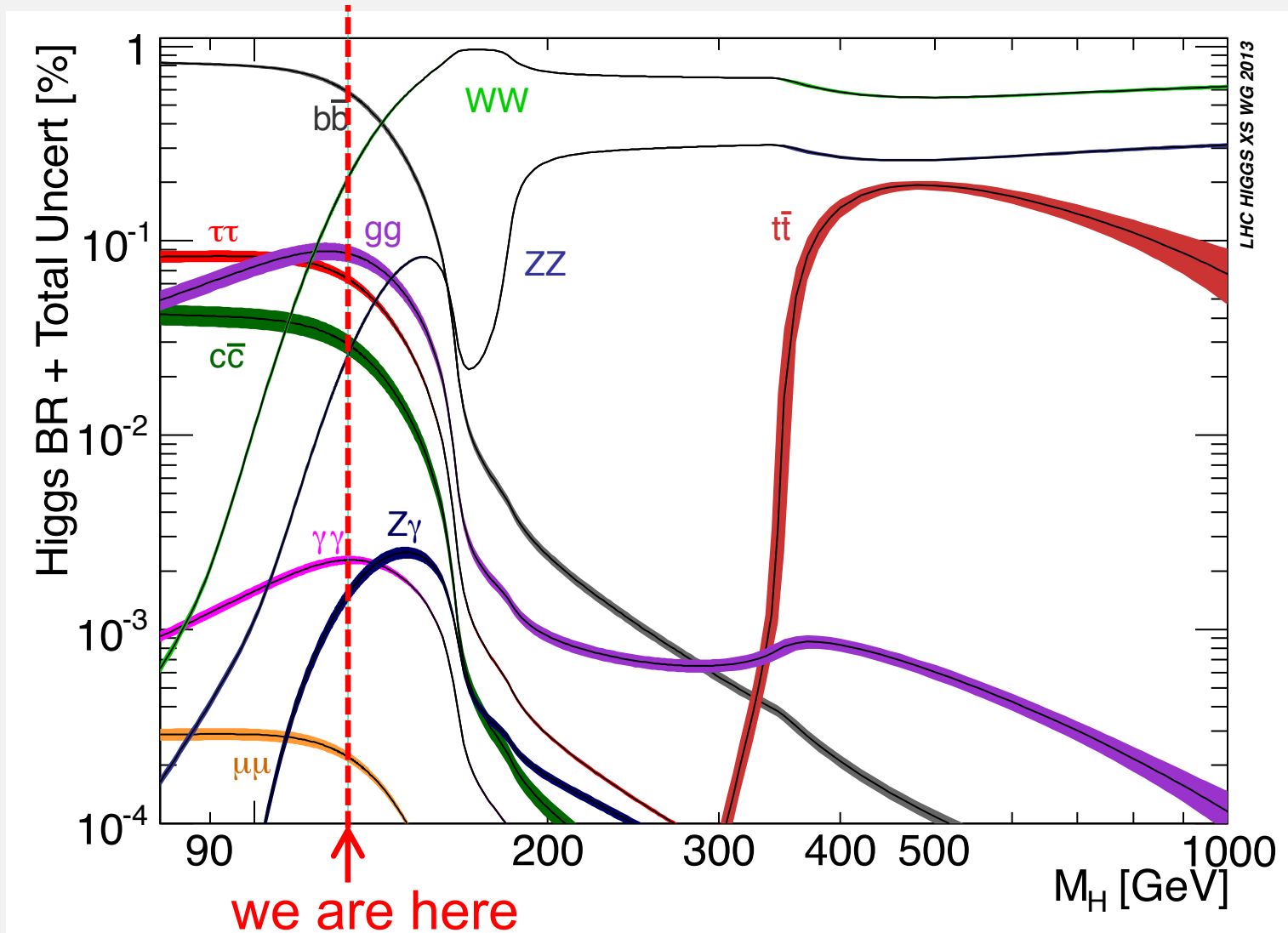
$V = W, Z$ $F = \text{fermion}$

Higgs production at the LHC



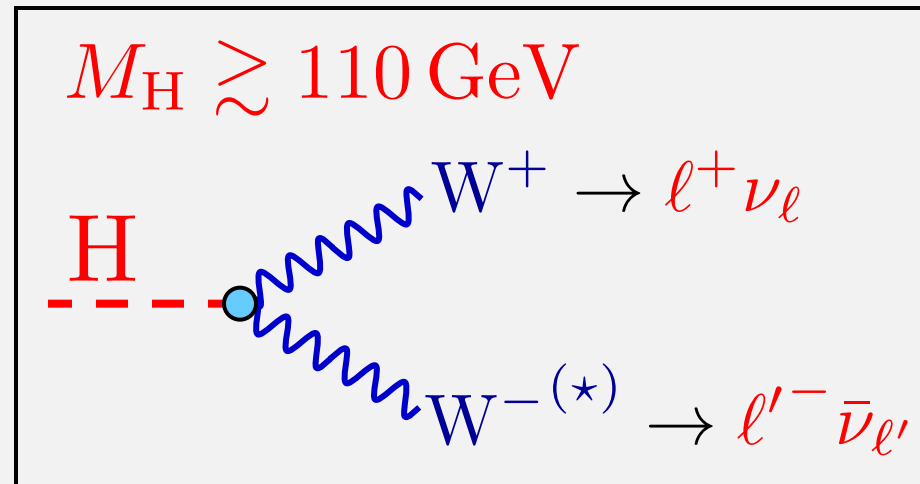
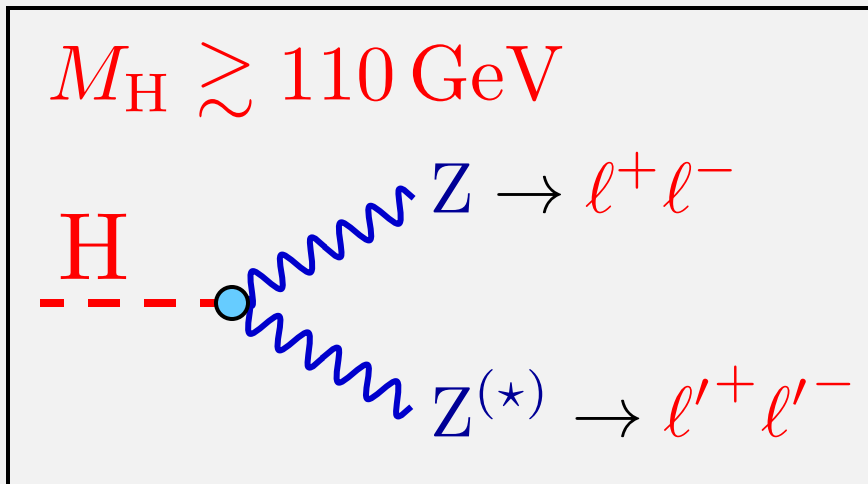
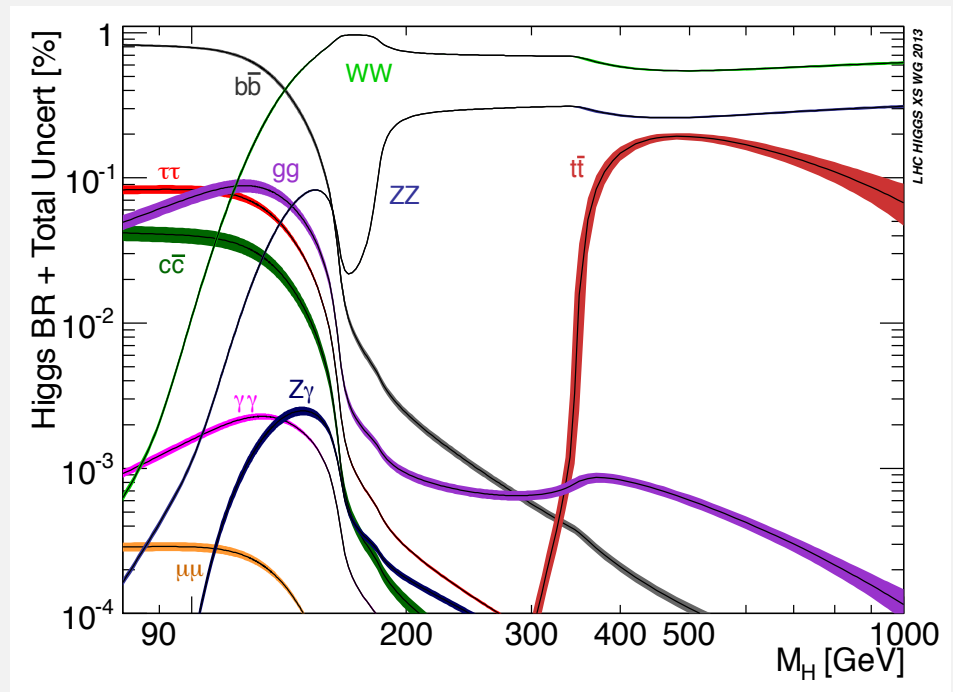
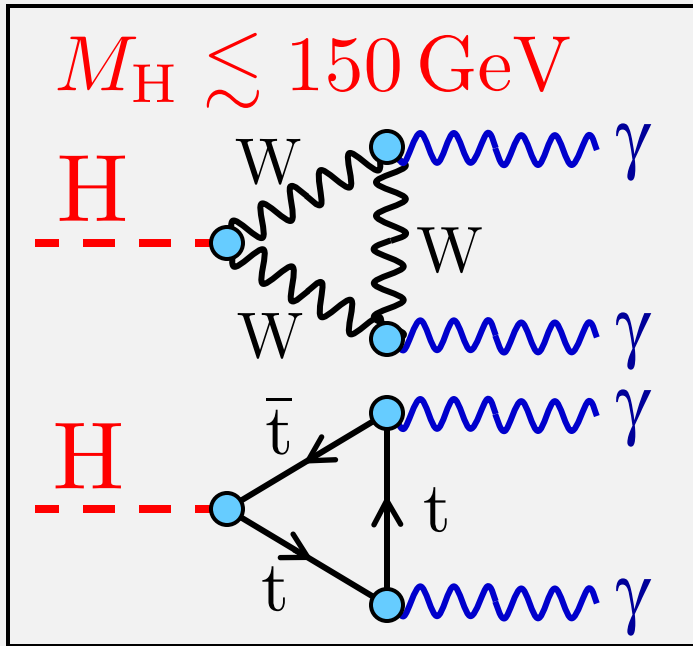


Higgs decay fractions vs. mass

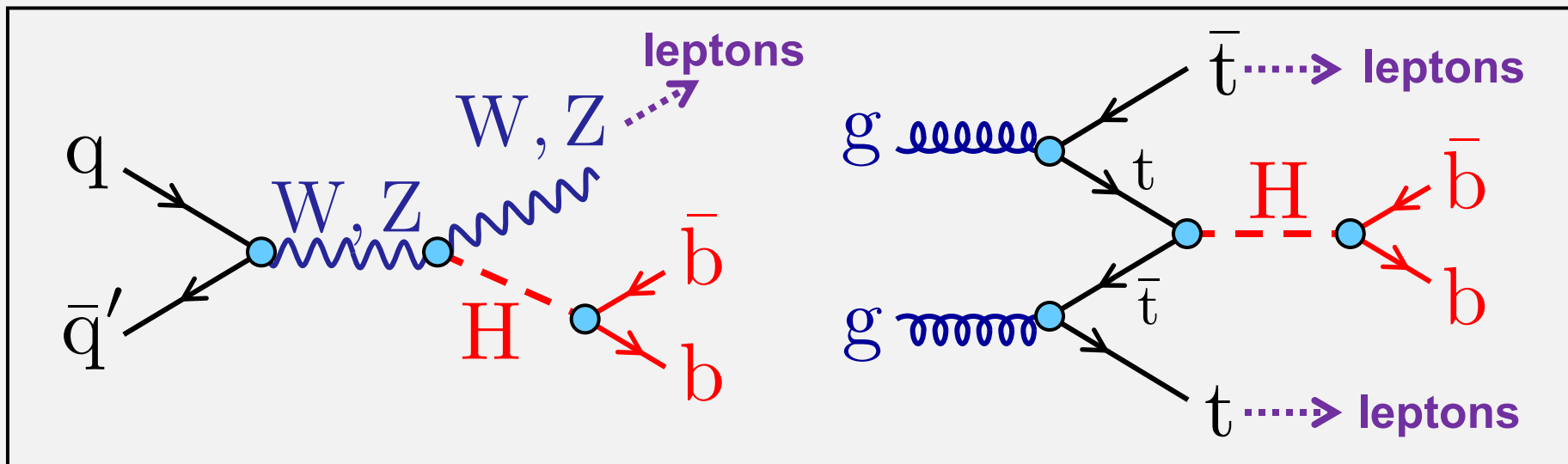
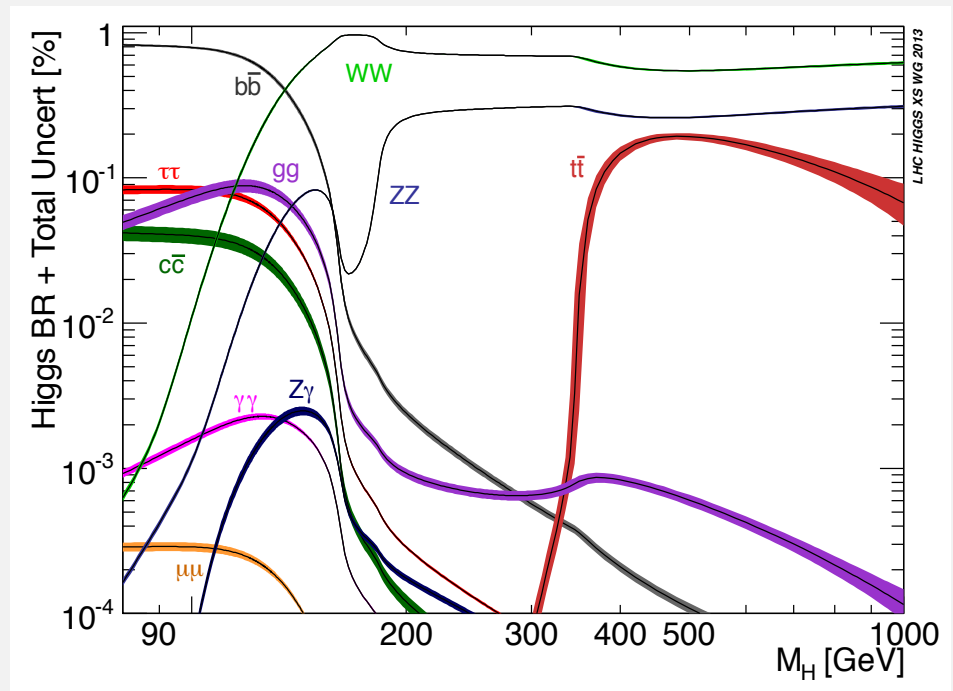
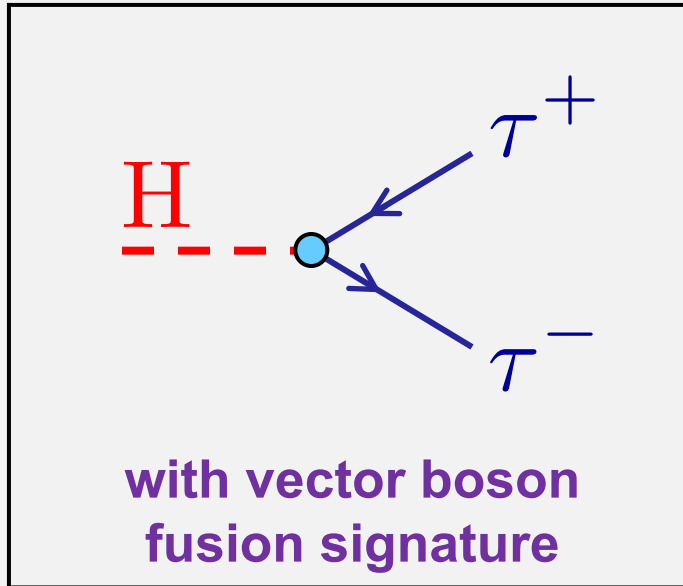


125 GeV Higgs sits in **sweet-spot**: all but $\sim 11\%$ (gg , $c\bar{c}$) of decays observable at LHC

Prime decay channels for detection:

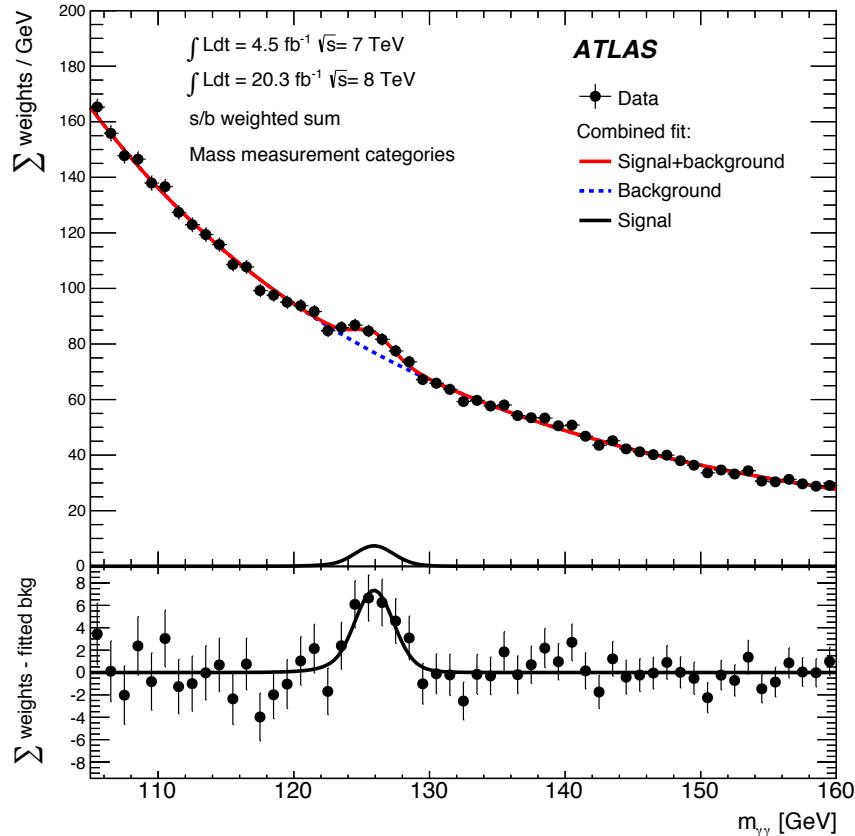


Decays to fermions (important but more difficult)



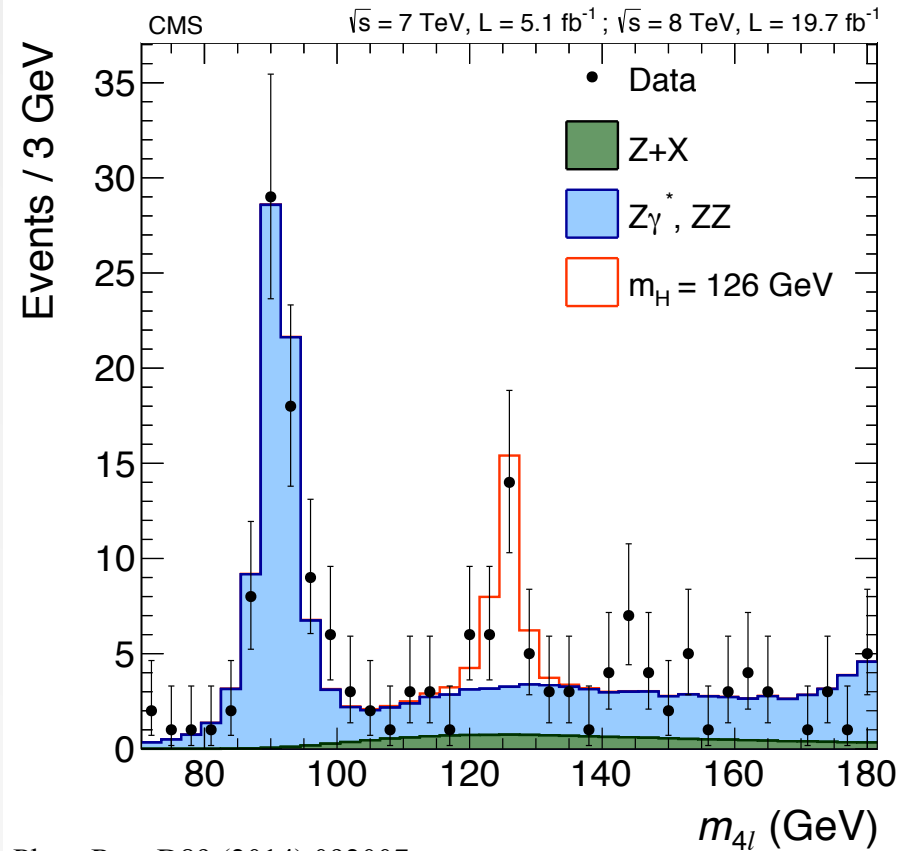
Discovery

$$H \rightarrow \gamma\gamma$$



Phys. Rev. D90 (2014) 112015

$$H \rightarrow ZZ^* \rightarrow 4\ell$$



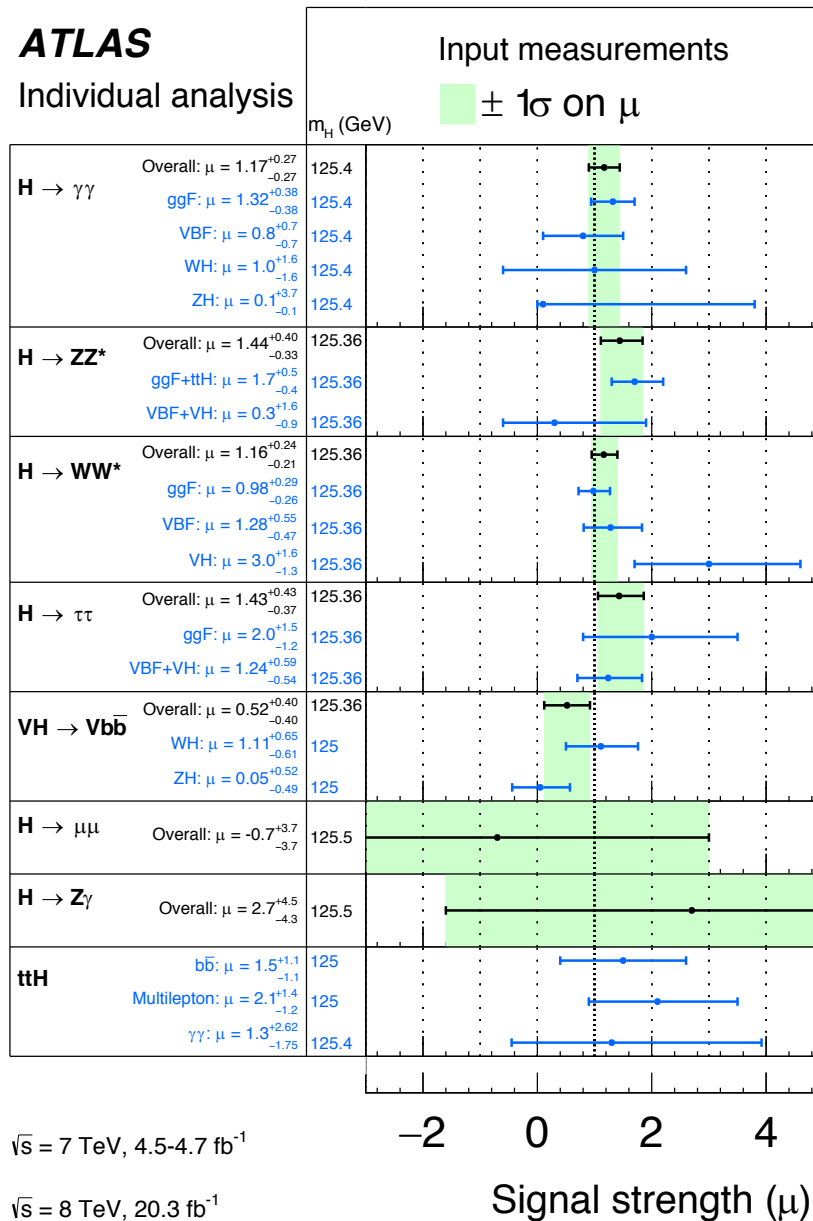
Phys. Rev. D89 (2014) 092007

$M_H \approx 125 \text{ GeV}$; angular distributions confirm: $J^P = 0^+$

Measurement of production and decay rates

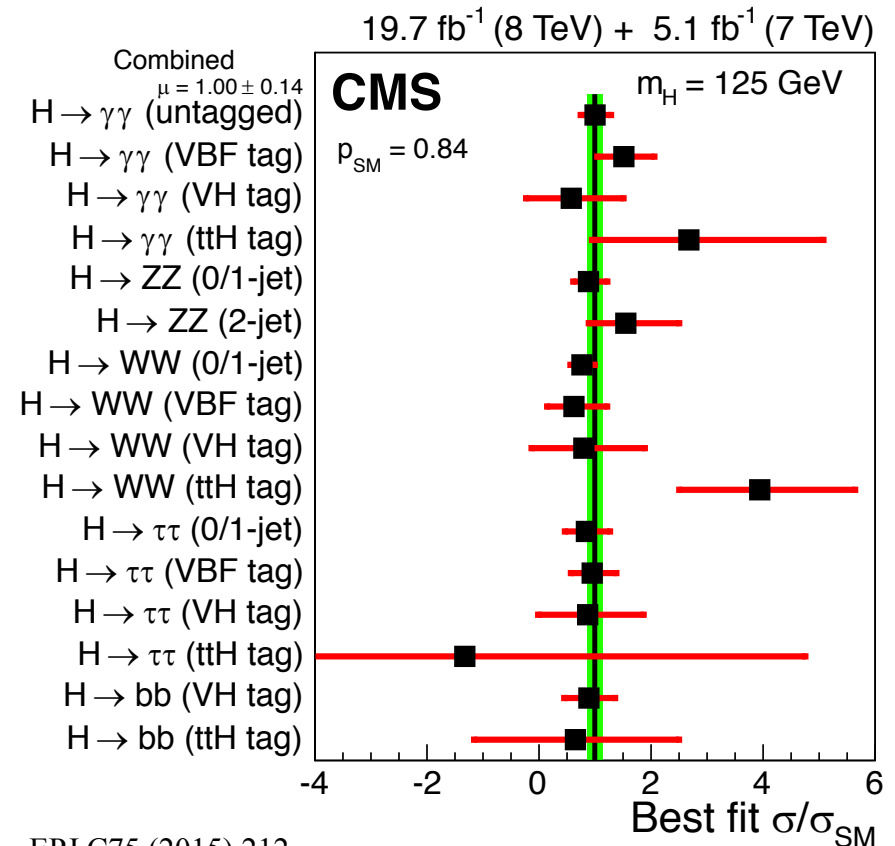
ATLAS

Individual analysis



EPJ C76 (2016) 6

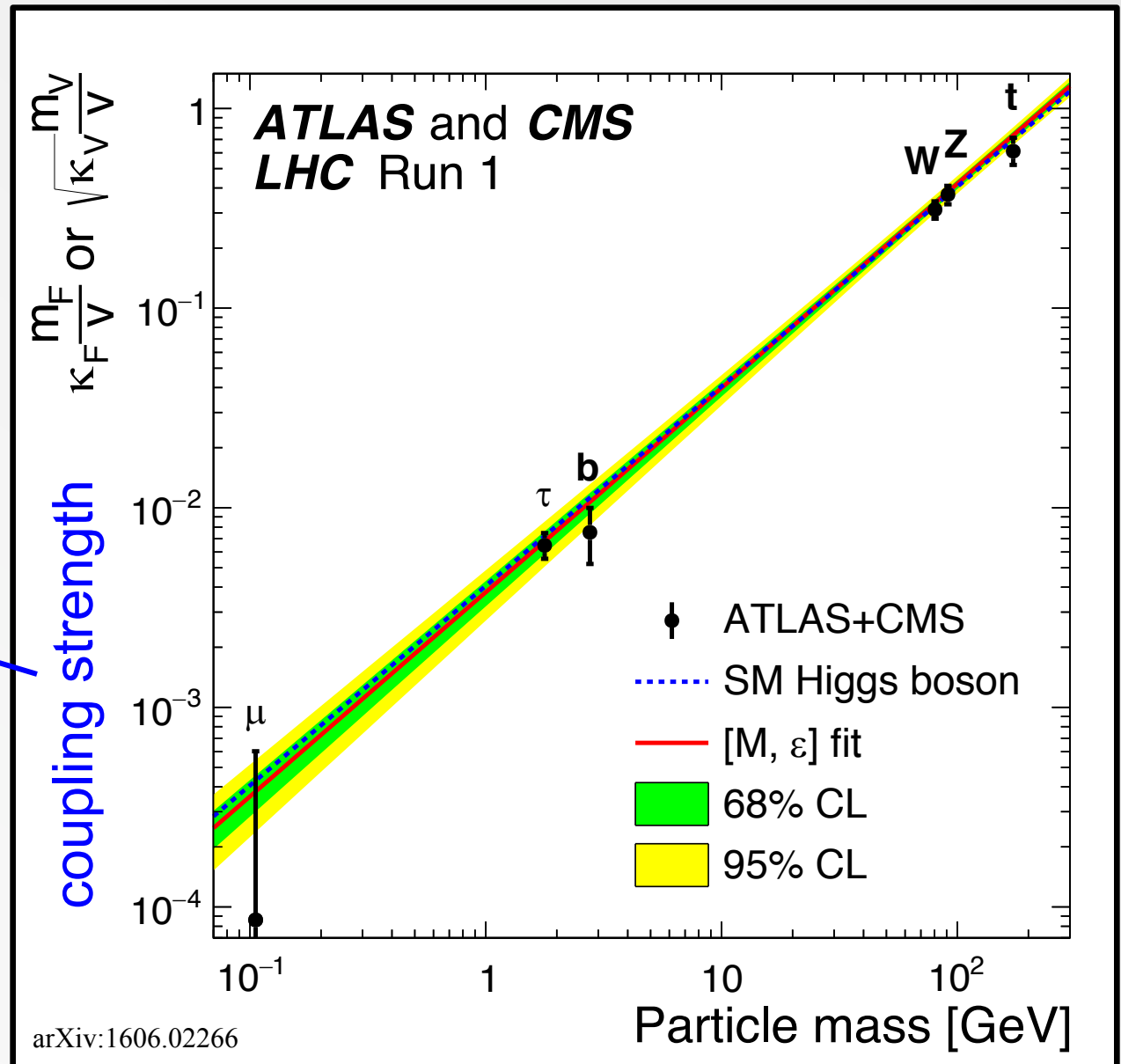
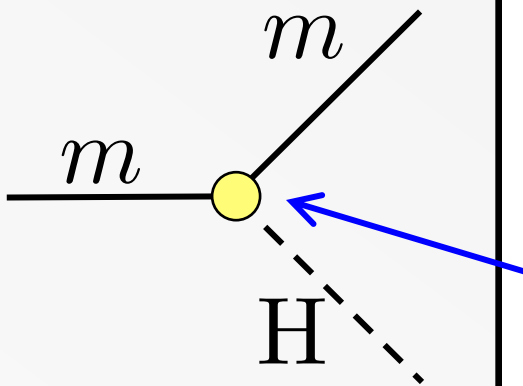
$$\mu = \frac{(\sigma \times \text{Br})_{\text{measured}}}{(\sigma \times \text{Br})_{\text{SM}}}$$



Global fit of coupling strengths

$$\kappa_V = \frac{g_{VH}^{\text{fit}}}{g_{VH}^{\text{SM}}}$$

$$\kappa_F = \frac{g_{FH}^{\text{fit}}}{g_{FH}^{\text{SM}}}$$



phenomenological global 2-parameter (M, ϵ) fit

$$\kappa_F \frac{M}{v} = \left(\frac{m_F}{M} \right)^\epsilon$$

$$\sqrt{\kappa_V} \frac{M}{v} = \left(\frac{m_V}{M} \right)^\epsilon$$

Standard Model:

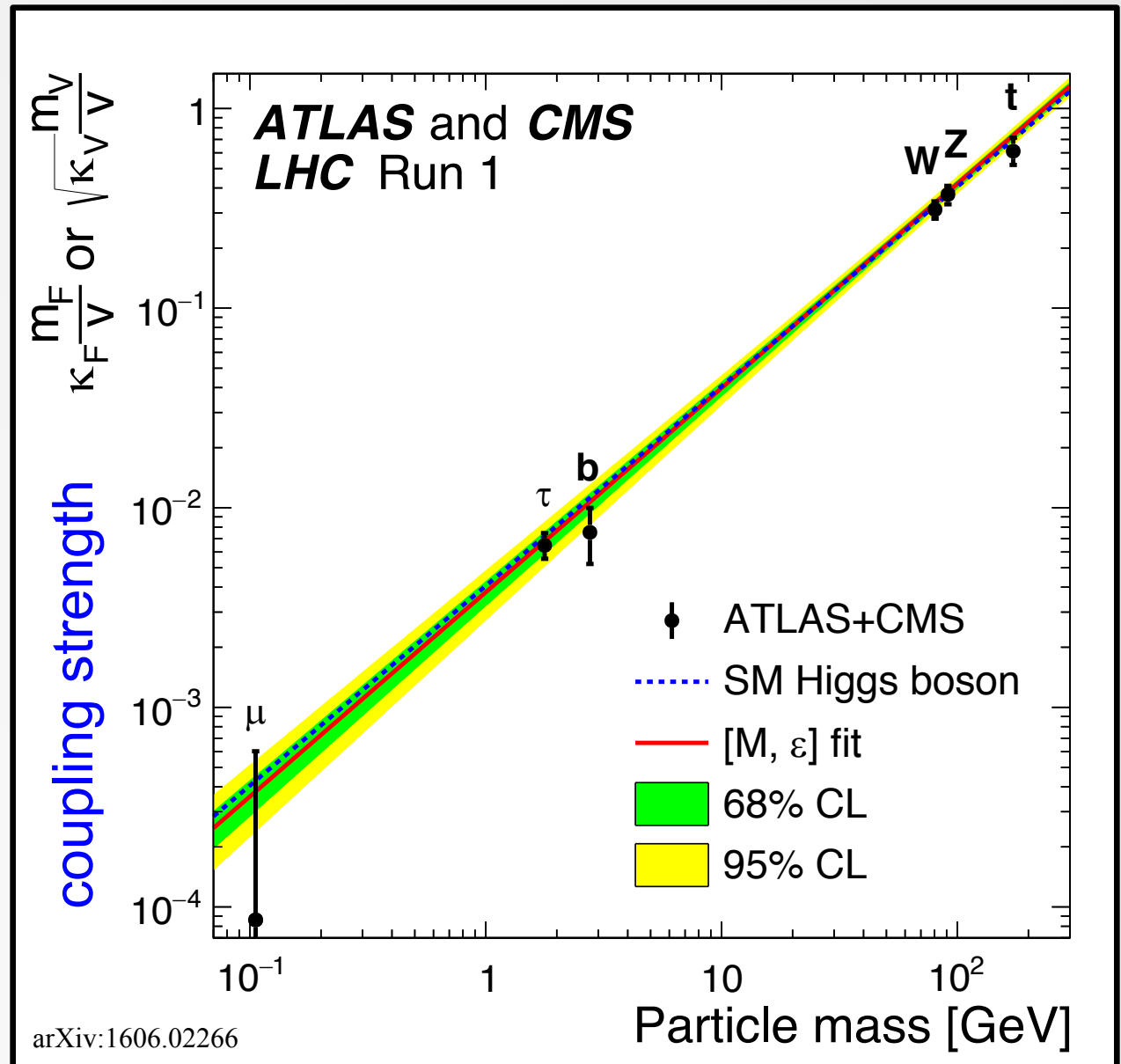
$$M = v$$

$$\epsilon = 0$$

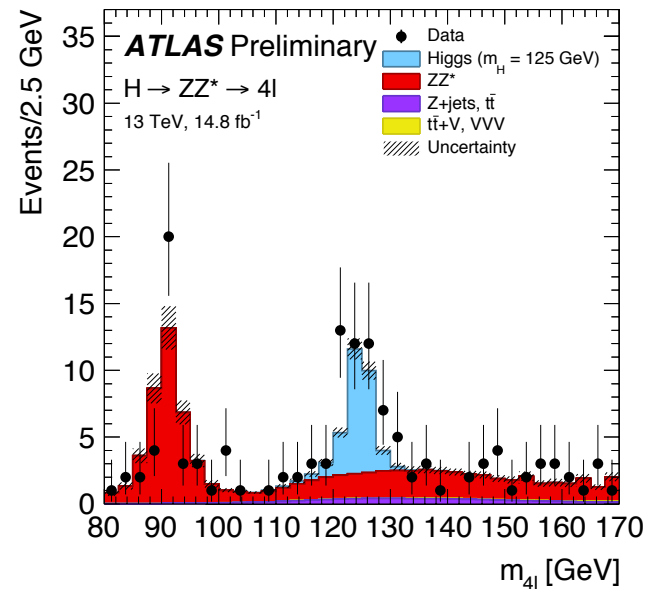
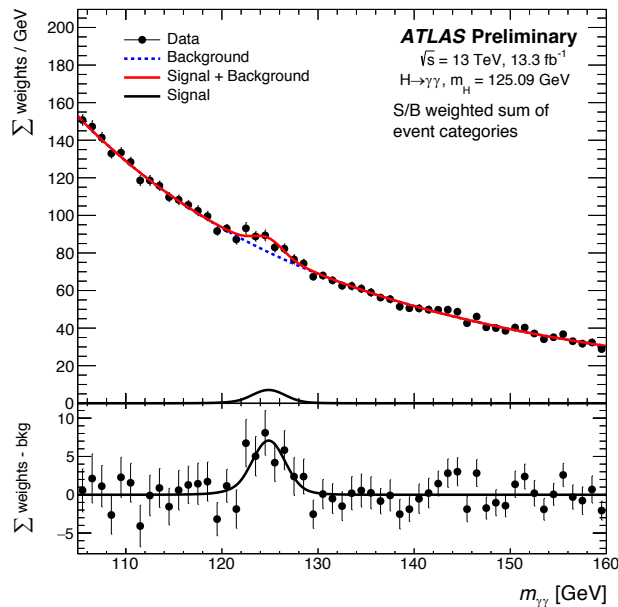
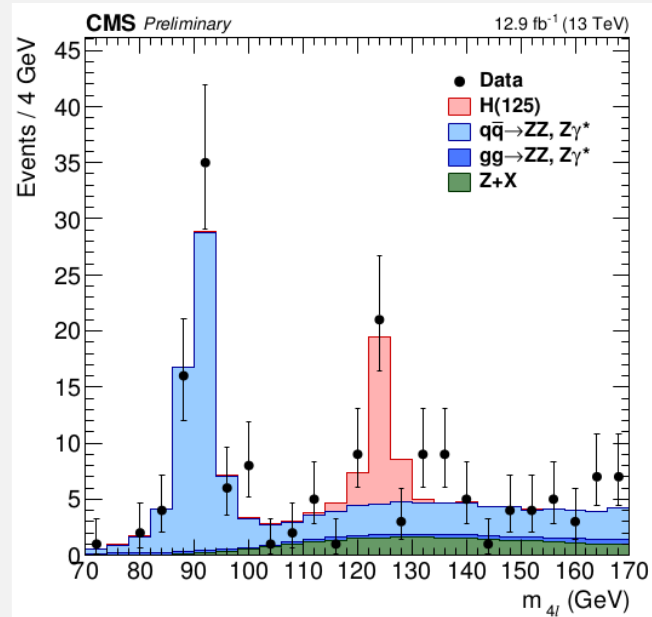
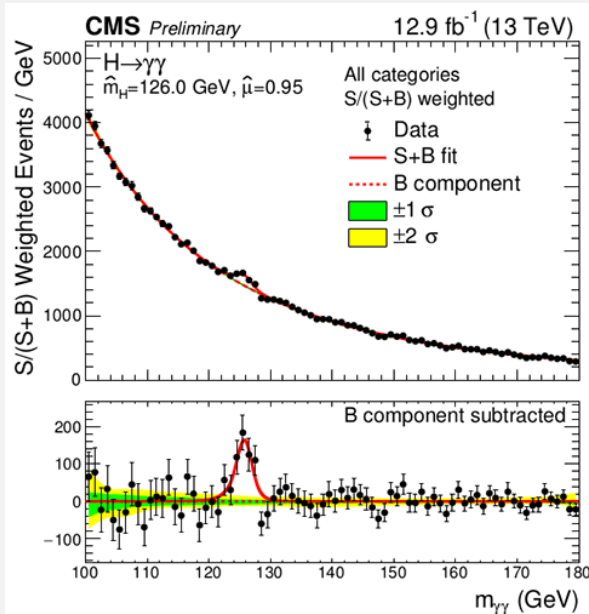
Fit:

$$M = 233^{+13}_{-12} \text{ GeV}$$

$$\epsilon = 0.023^{+0.029}_{-0.027}$$

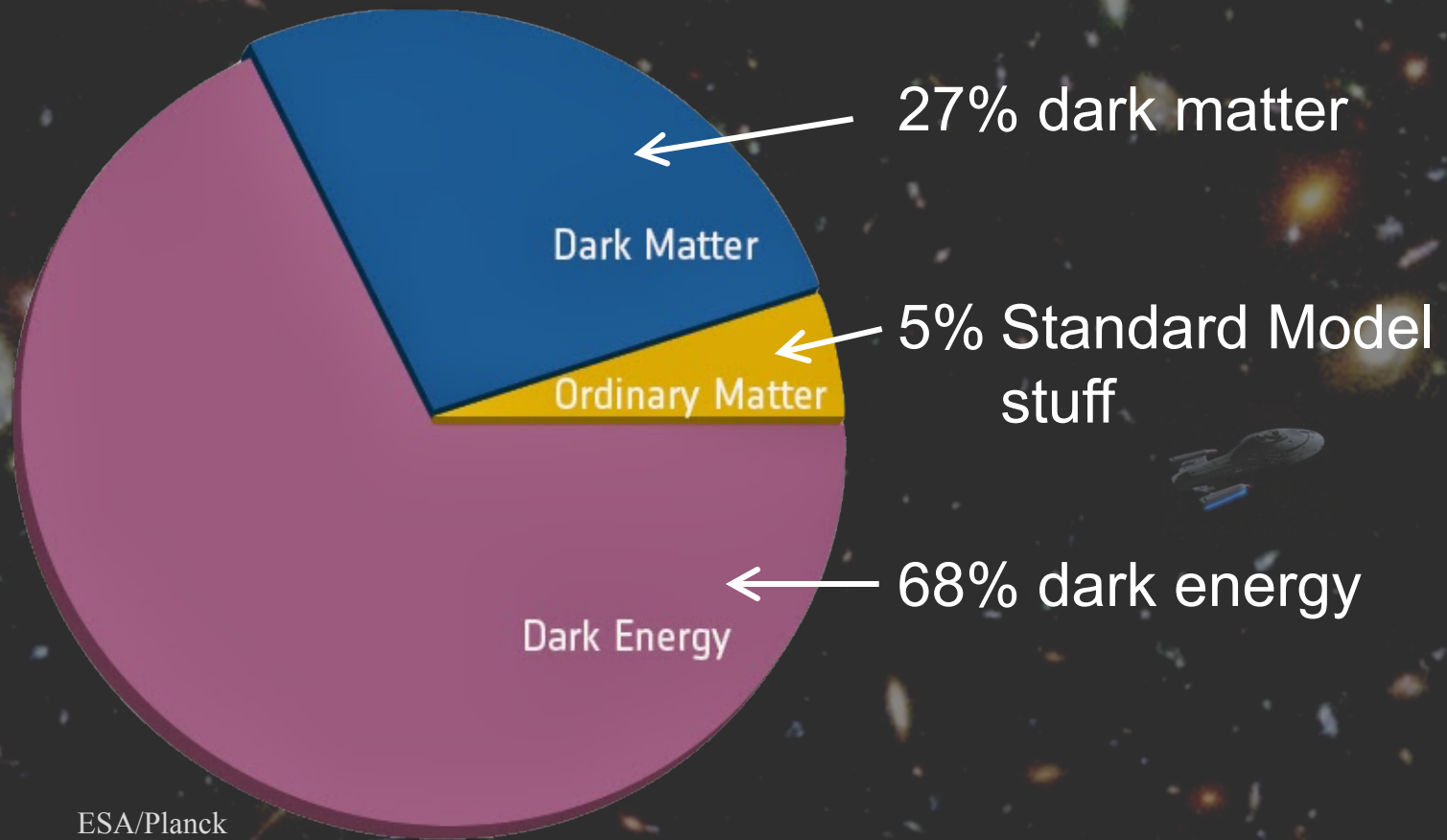


The signal is back at $\sqrt{s} = 13$ TeV



Is this it?

Is there nothing else out there?



Yes, there is! We understand(?) only 5%!

Standard Model today

u	c	t	γ
d	s	b	g
ν_e	ν_μ	ν_τ	Z
e	μ	τ	W
			H

World beyond the Standard Model

- Dark matter
- Dark energy
- Neutrino oscillations
- Neutrino masses
- Matter/antimatter ratio
- Grand unified force
- Quantum gravity
- >3 spatial dimensions
- Origin of (weird) SM parameter values
- Esthetics (fine-tuning)

Energy scale of the Standard Model: $v = 246 \text{ GeV}$

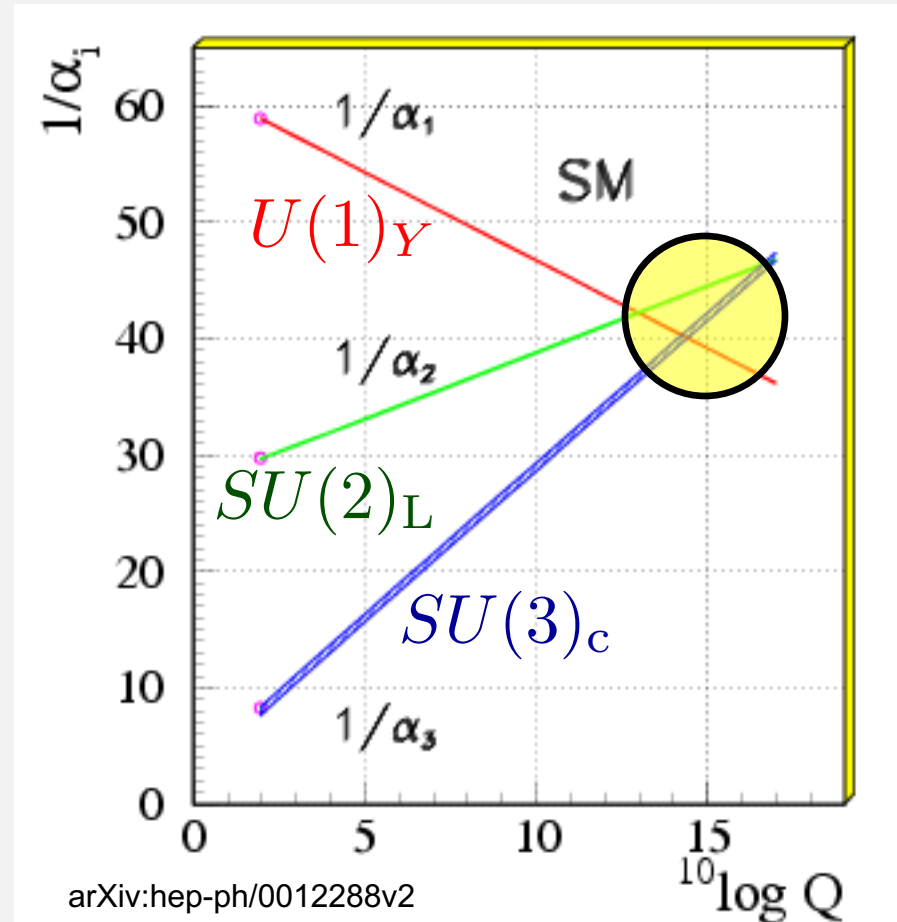
Assumption: there is another scale: $\Lambda \gg v$

Examples:

- Grand unification

$$\Lambda \sim 10^{15-16} \text{ GeV}$$

(GUT scale)



- Quantum gravity $\Lambda \sim 10^{19} \text{ GeV}$ (Planck scale)

Consequence:

$$\int^{\infty} d^4 k \text{ (diagram)} \longrightarrow \int^{\Lambda} d^4 k \text{ (diagram)}$$

The diagram shows a loop of fermions (blue circle with arrows) connected to two external wavy lines (red). The momentum of the loop is labeled k .

Why? Similar to this:

Fermi theory

$$\sigma \left[\begin{array}{c} \nu_e \searrow \quad \nearrow e^- \\ \quad \quad \quad \bullet \\ e^- \nearrow \quad \searrow \nu_e \end{array} \right] = \frac{G_F^2 s}{\pi}$$

The diagram shows a four-fermion contact interaction with a yellow vertex. The coupling is labeled G_F in pink.

violates unitarity bound at
 $\sqrt{s} \sim 300 \text{ GeV} \approx v$

Standard Model

$$\sigma \left[\begin{array}{c} \nu_e \searrow \quad \nearrow e^- \\ \quad \quad \quad \bullet \\ q \text{ (wavy)} \quad W \\ \quad \quad \quad \bullet \\ e^- \nearrow \quad \searrow \nu_e \end{array} \right] \rightarrow \frac{G_F^2 M_W^2}{\pi}$$

The diagram shows a t-channel exchange of a W boson between two fermion pairs. The vertices are labeled g in pink, and the propagator is labeled q in red.

propagator cut-off

$$\text{(wavy line)} \propto \frac{1}{q^2 - M_W^2}$$

New scale destabilizes the Standard Model:

effective Higgs mass (similar to effective charges)

Feynman diagram showing a self-energy correction to the Higgs mass. It consists of a red dashed line labeled 'H' on the left, followed by a plus sign, then another red dashed line labeled 'H' on the left, a loop of fermions 'f' with momentum 'k' and coupling 'g_{fH}' in the middle, another red dashed line labeled 'H' on the right, followed by a plus sign and an ellipsis '...'.

$$M_{\text{H}}^2 = -2\mu^2 + \delta M_{\text{H}}^2$$

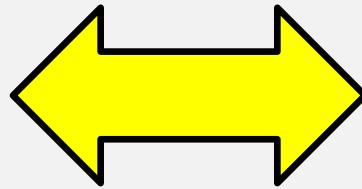
$$\delta M_{\text{H}}^2 \sim \int^{\Lambda} \frac{d^4 k}{k^2 - m_{\text{f}}^2} + \dots \sim \Lambda^2 + \dots$$

Without **extreme** fine-tuning $\Rightarrow$

$$M_{\text{H}} = \mathcal{O}(\Lambda) \gg 125 \text{ GeV}$$

Cancellation by new scalar particles?

Fermion $f_{L,R}$
spin $\frac{1}{2}$ (spinor)



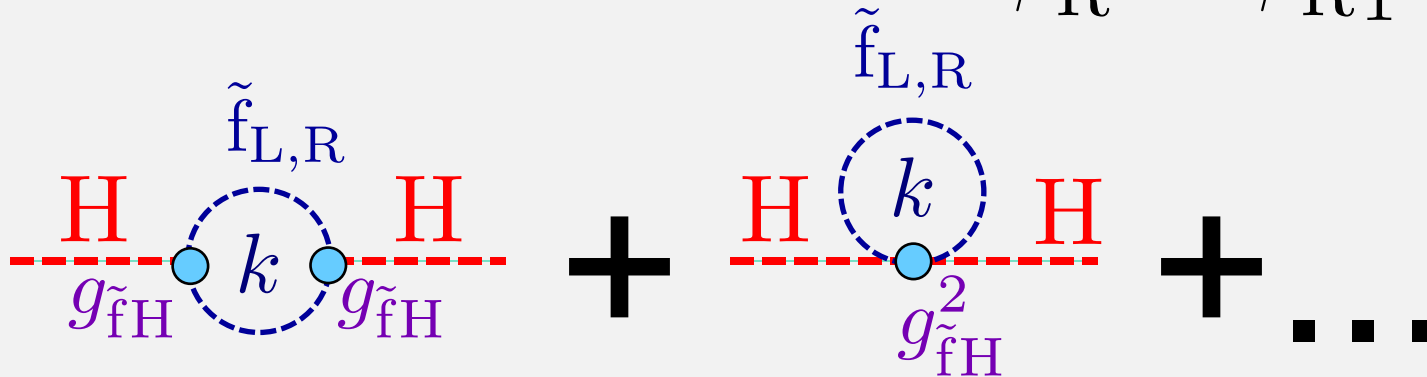
Boson $\tilde{f}_{L,R}$
spin 0 (complex scalar)

$$\psi^f = \psi_L^f + \psi_R^f$$

4 components

$$\phi_L^f = \phi_{L1}^f + i\phi_{L2}^f$$

$$\phi_R^f = \phi_{R1}^f + i\phi_{R2}^f$$



Cancellation $\Leftrightarrow g_{fH}^2 = g_{\tilde{f}H}^2 \Leftrightarrow$ new **symmetry**

Supersymmetry (SUSY)

Supersymmetry (SUSY)

Requirements:

- no scalar partners known $\Rightarrow$ SUSY must be **broken**

$$g_{fH}^2 = g_{\tilde{f}H}^2$$

$$m_{\tilde{f}}^2 = m_f^2 + \delta m_f^2$$

- mass splitting adds to effective Higgs mass
 $\Rightarrow$ SUSY must be **softly broken**

$$\delta m_f^2 = \mathcal{O}(v^2)$$

SUSY should be accessible at the LHC! ... (?)

- Standard Model needs to be extended:
at least 2 Higgs doublets required (separate for up- and down-type fermions)

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix} \quad \langle \phi_u \rangle_0 = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

$$\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix} \quad \langle \phi_d \rangle_0 = \begin{pmatrix} v_d \\ 0 \end{pmatrix} \quad \frac{v_u}{v_d} \equiv \tan \beta$$

$$4 \text{ charged fields} \begin{cases} 2 \text{ charged Goldstone bosons} \rightarrow M_{W^\pm} \\ 2 \text{ charged Higgs bosons } H^\pm \end{cases}$$

$$2 \text{ neutral fields} \begin{cases} 1 \text{ neutral Goldstone boson} \rightarrow M_Z \\ 3 \text{ neutral Higgs bosons } h, H, A \end{cases}$$

$$m_h \leq M_Z |\cos(2\beta)| + \text{loop corrections} \Rightarrow h \text{ is light}$$

(minimal) SUSY particle content

quarks	leptons	neutrinos	spin
$[u, d, c, s, t, b]_{L,R}$	$[e, \mu, \tau]_{L,R}$	$[\nu_e, \nu_\mu, \nu_\tau]_L$	$1/2$
$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R}$	$[\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R}$	$[\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau]_L$	0
squarks	sleptons	sneutrinos	

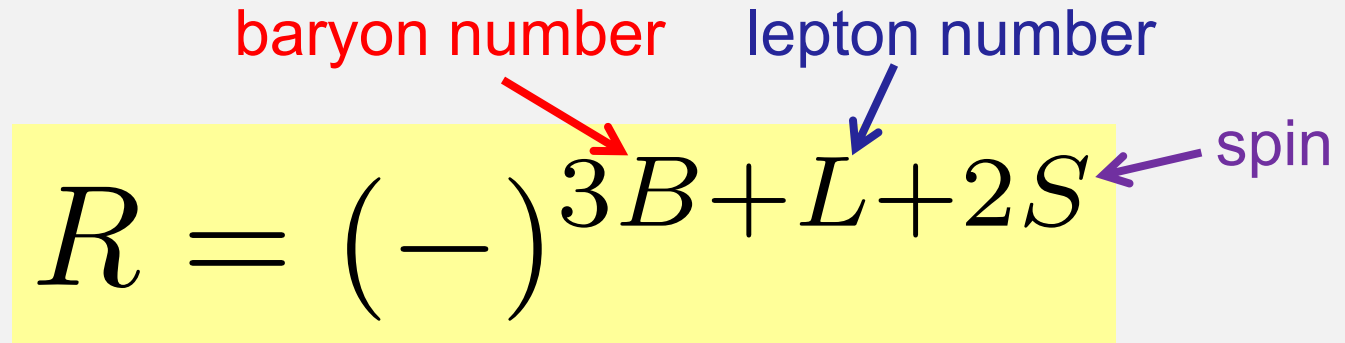
gluons		$\overbrace{h, H, A}$	
g	$W^\pm / H^\pm$	$\gamma, Z / H_1^0, H_2^0$	1/0
$\tilde{g}$	$\tilde{W}^\pm, \tilde{H}^\pm$	$\tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0$	$1/2$
gluinos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	
	charginos	neutralinos	

More symmetry in SUSY (minimal++)

Strictly conserved parity:

$$R = (-)^{3B + L + 2S}$$

baryon number lepton number spin

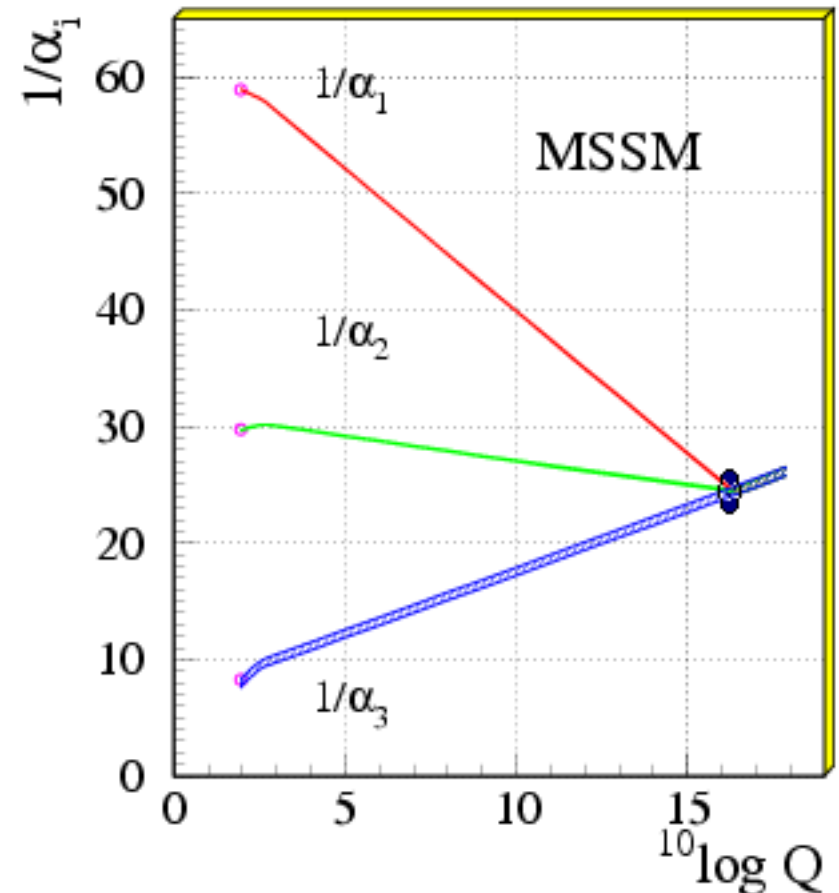
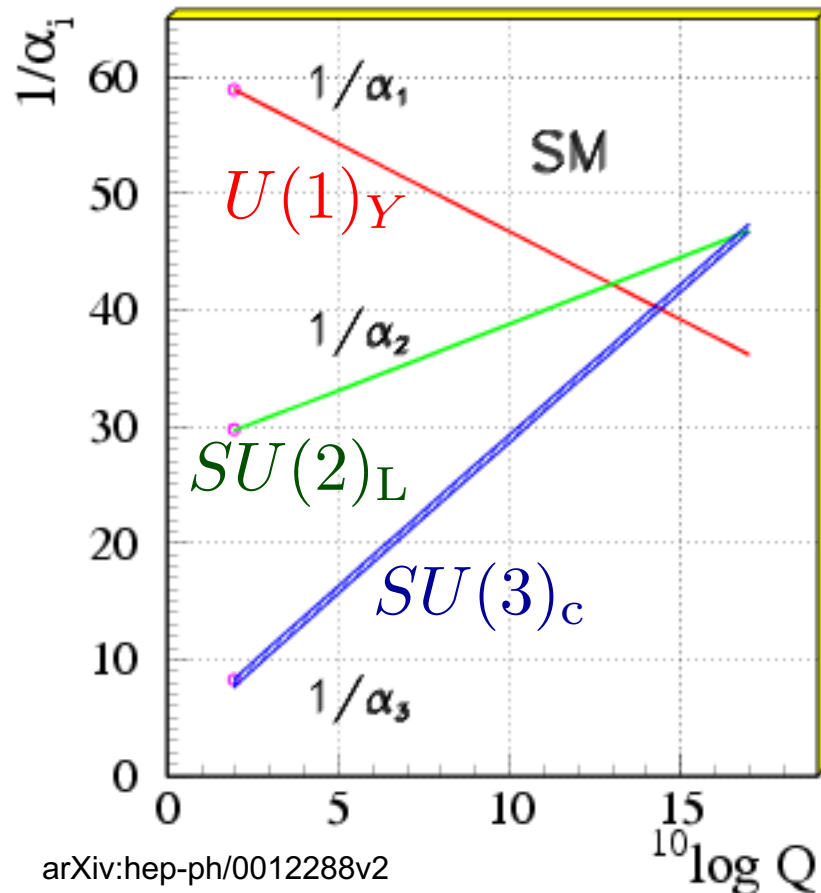


- Standard Model particles have $R = +$
- SUSY particles have $R = -$
- SUSY particles are created in pairs
- The lightest SUSY particle (LSP) is **stable**

Many SUSY versions have lightest neutralino as LSP

⇒ **dark matter candidate** $\tilde{\chi}_1^0$

SUSY makes the couplings unify



SUSY not yet detected

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\tau [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference		
Inclusive Searches	MSUGRA/CMSSM	0-3 $e, \mu/1-2 \tau$	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{q}$	1.35 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2016-078	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1604.07773	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$	1.86 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2016-078	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$	1.83 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2016-078	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	13.2	$\tilde{g}$	1.7 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2016-037	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$	1.6 TeV	$m(\tilde{\chi}_1^0) < 500 \text{ GeV}$	ATLAS-CONF-2016-037	
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV	-	1607.05979	
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	1606.09150	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$	1507.05493	
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0) > 680 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2016-066	
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$	1502.01518		
3 rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	$\tilde{g}$	1.89 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2016-052	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	14.8	$\tilde{g}$	1.89 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2016-052	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1407.0600	
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$	840 GeV	$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$	1606.08772	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$	325-685 GeV	$m(\tilde{\chi}_1^0) < 150 \text{ GeV}, m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 100 \text{ GeV}$	ATLAS-CONF-2016-037	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	170-200 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^\pm)=55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\nu}_\tau^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	90-198 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	1506.08616, ATLAS-CONF-2016-077	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	90-323 GeV	$m(\tilde{\chi}_1^0)-m(\tilde{\chi}_1^\pm)=5 \text{ GeV}$	1604.07773	
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$	290-700 GeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	ATLAS-CONF-2016-038	
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$	320-620 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1506.08616	
	EW direct	$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-335 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	1403.5294
		$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\tilde{\ell}\bar{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-475 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tilde{\tau}\bar{\nu})$		2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$	355 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350	
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}_L\nu_L(\tilde{\ell}\bar{\nu})$		3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	715 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029	
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^\pm Z\tilde{\chi}_1^0$		2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	425 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294, 1402.7029	
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^\pm h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$		e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^\pm)=0, \tilde{\ell}$ decoupled	1501.07110	
$\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0\tilde{\chi}_1^0$		4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \bar{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086	
GGM (wino NLSP) weak prod.		1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau < 1 \text{ mm}$	1507.05493	
GGM (bino NLSP) weak prod.		2 γ	-	Yes	20.3	$\tilde{W}$	590 GeV	$c\tau < 1 \text{ mm}$	1507.05493	
Long-lived particles		Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^\pm)-160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$	1310.3675
	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_1^\pm)-160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) < 15 \text{ ns}$	1506.05332	
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584	
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	1.58 TeV	-	1606.05129	
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	-	1604.04520	
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \bar{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, \tau > 10 \text{ ns}$	1411.6795	
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma G$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$10 < \tan\beta < 50$	1409.5542	
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$	displ. $e\bar{e}/\mu\bar{\mu}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1504.05162	
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ZG$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162	
								$6 < c\tau(\tilde{\chi}_1^0) < 480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$	1607.08079	
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$	1404.2500	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\bar{\nu}, \mu\bar{\nu}$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, \lambda_{12\pm} \neq 0 (k=1, 2)$	ATLAS-CONF-2016-075	
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\bar{\nu}_\tau, e\bar{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 m(\tilde{\chi}_1^\pm), \lambda_{133} \neq 0$	1405.5086	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	4-5 large- R jets	-	14.8	$\tilde{g}$	1.08 TeV	$\text{BR}(\tilde{t})=\text{BR}(\tilde{b})=\text{BR}(\tilde{c})=0\%$	ATLAS-CONF-2016-057	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	0	4-5 large- R jets	-	14.8	$\tilde{g}$	1.55 TeV	$m(\tilde{\chi}_1^0)=800 \text{ GeV}$	ATLAS-CONF-2016-057	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 e, μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)=800 \text{ GeV}$	ATLAS-CONF-2016-037	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$	410 GeV	$m(\tilde{\chi}_1^0)=800 \text{ GeV}$	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 e, μ	2 b	-	20.3	$\tilde{t}_1$	450-510 GeV	$m(\tilde{\chi}_1^0)=800 \text{ GeV}$	ATLAS-CONF-2015-015		
						0.4-1.0 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$			
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325	

*Only a selection of the available mass limits on new states or phenomena is shown.

10⁻¹

1

Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

10^{-1}

1

Mass scale [TeV]

Minimal version of SUSY is in trouble

The Standard Model is in great shape...
but we are not there yet

Thanks!