GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

Particle Physics

Thomas Lohse
Schule für Astroteilchenphysik 2016
Universität Erlangen-Nürnberg

SAT Astroteilchenphysik Schule für

HUMBOLDT-UNIVERSITÄT ZU BERLIN

The Plan

Part 1: Standard Model & experimental techniques

Part 2: Theory basics and precision tests

Part 3: Physics at the LHC

Part I

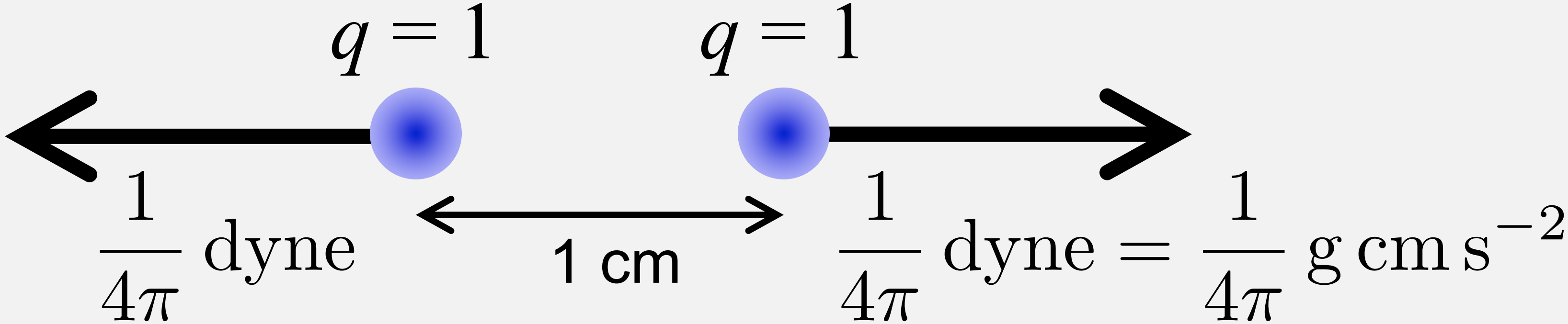
- Elements of the Standard Model: Matter & Forces
- Accelerators
- Detectors

Preliminary remarks: units

$$\hbar = c = 1$$

Heaviside-Lorentz units $\quad \epsilon_0 = 1$

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



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:

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

products: $$ab \equiv a_\mu b^\mu = a^\mu b_\mu = a^0 b^0 - \vec{a}\,\vec{b}$$

are invariant under Lorentz transformations

Examples:

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

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

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

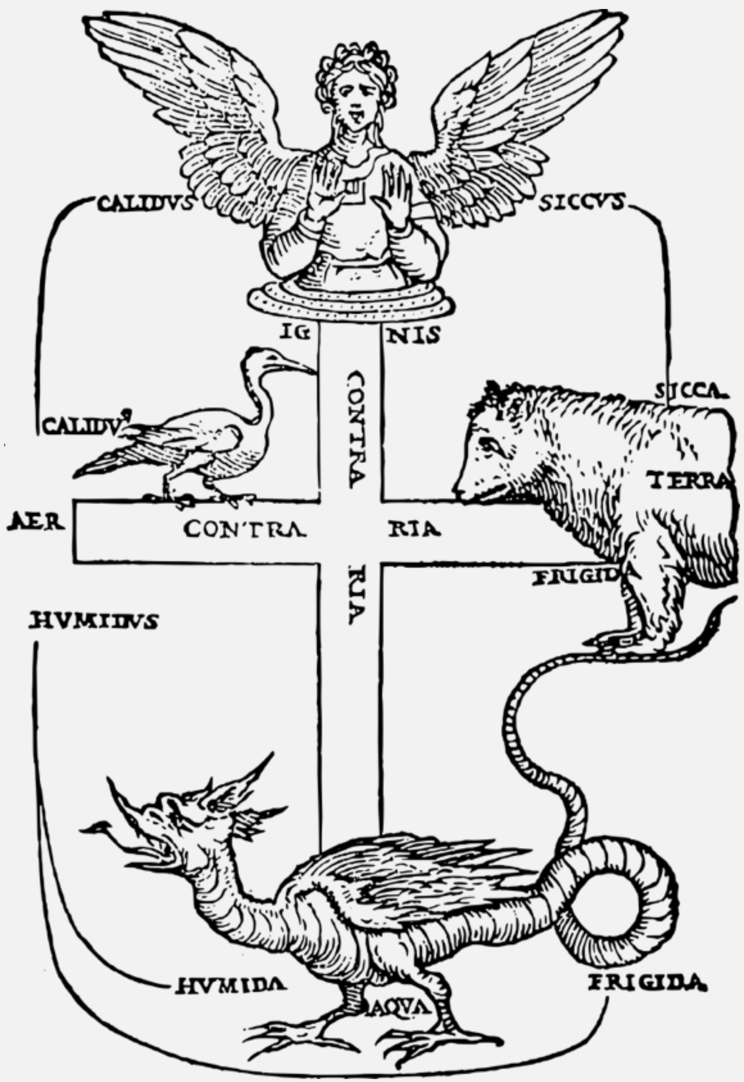
$$(j^\mu) = (\rho, \vec{j})$$ electromagentic 4-current

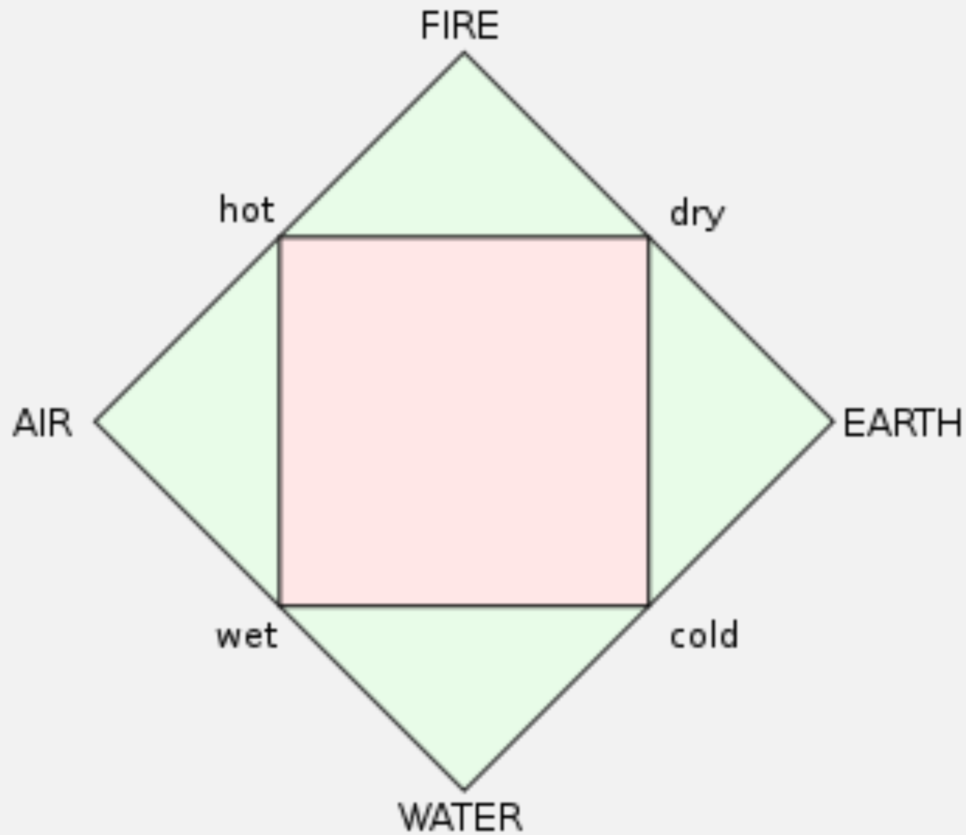
$$(p^\mu) = (E, \vec{p})$$ 4-momentum

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

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

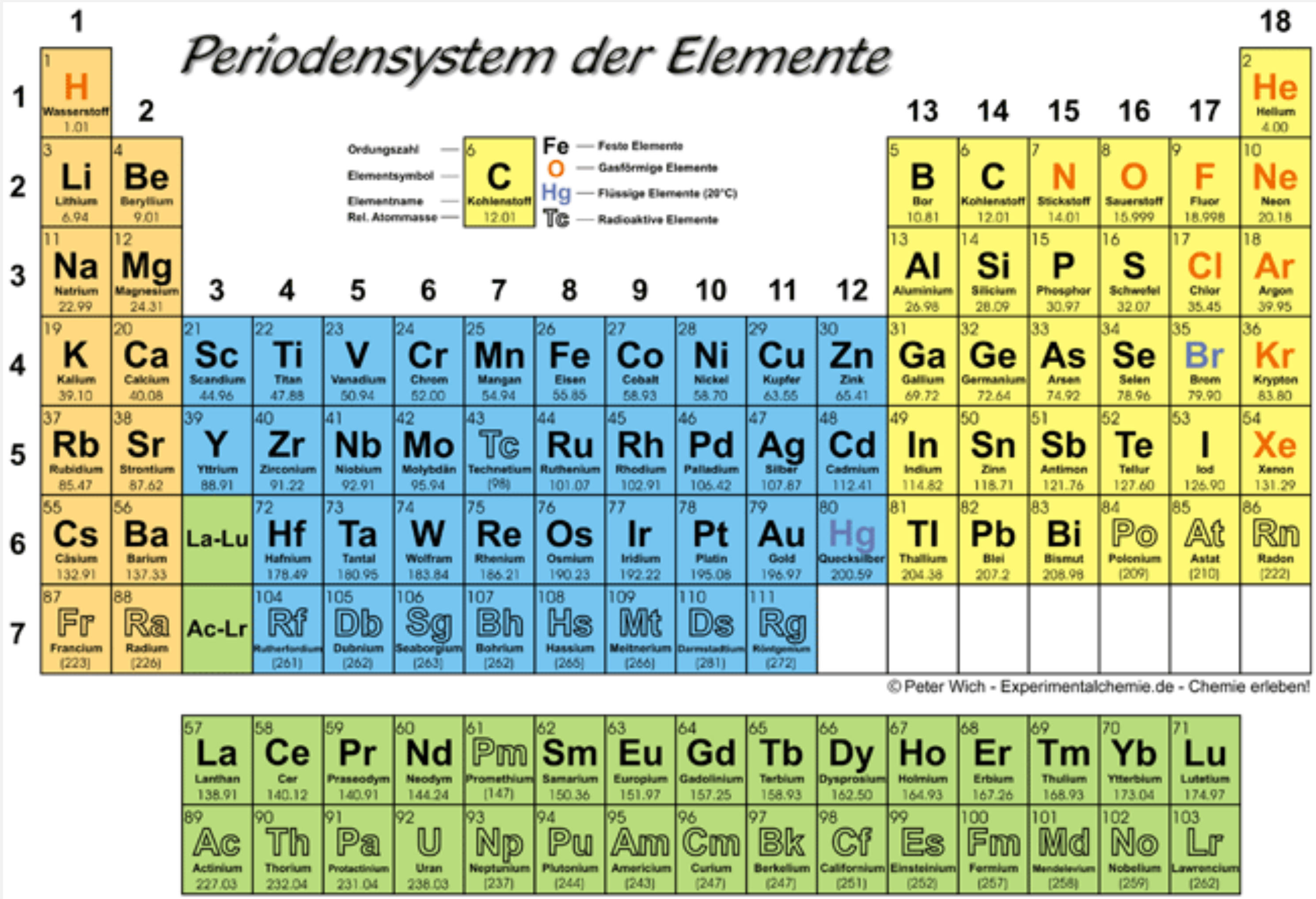
Structure of Matter (Empedokles et al., ≈ 500 b.C.)





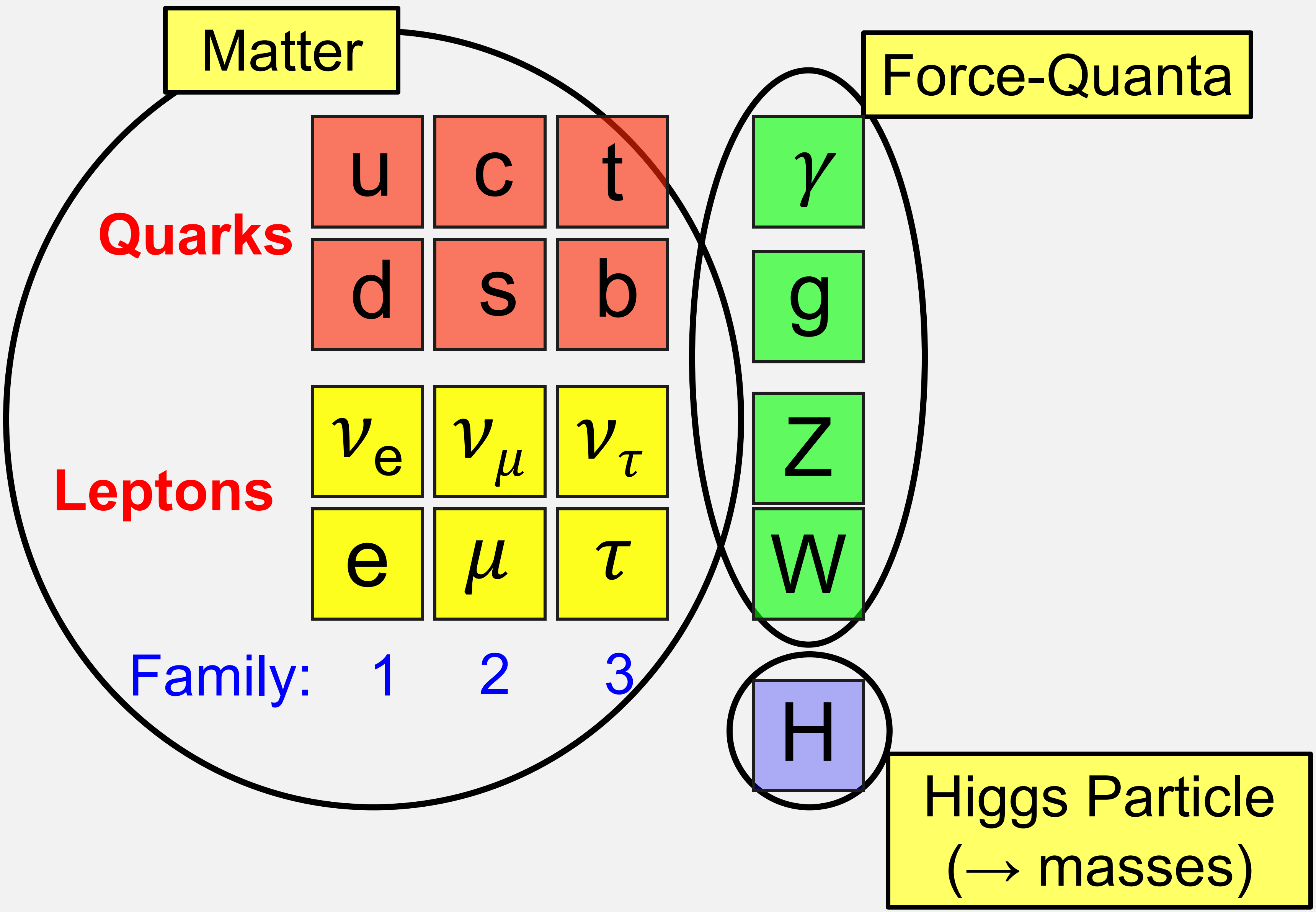
- quite successful
- lots of applications
- … somewhat coarse

Structure of Matter (Mendelejev, Meyer, 1869)

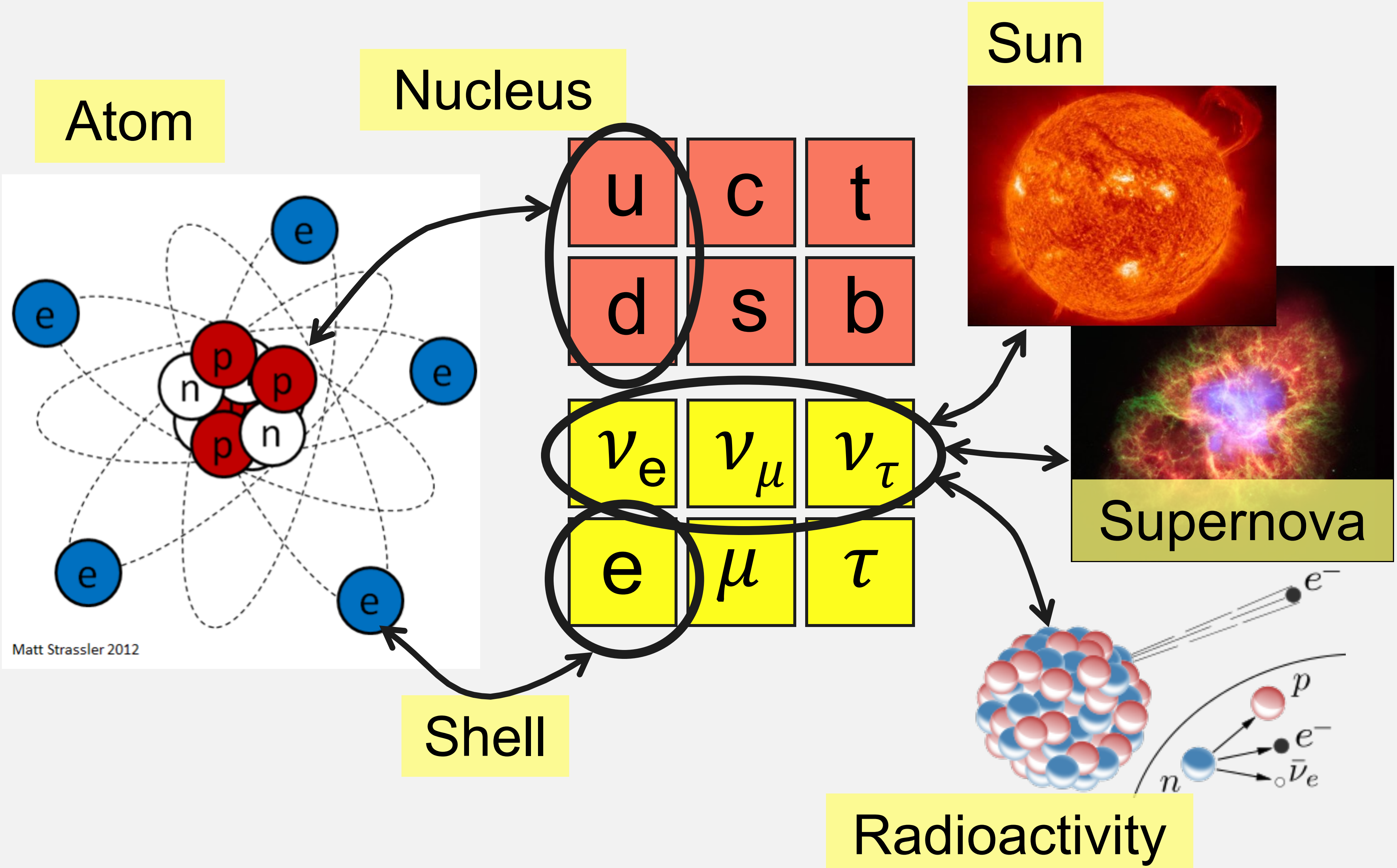


- basis of modern Chemistry
- … sub-atomic/sub-nucleonic phenomena not covered

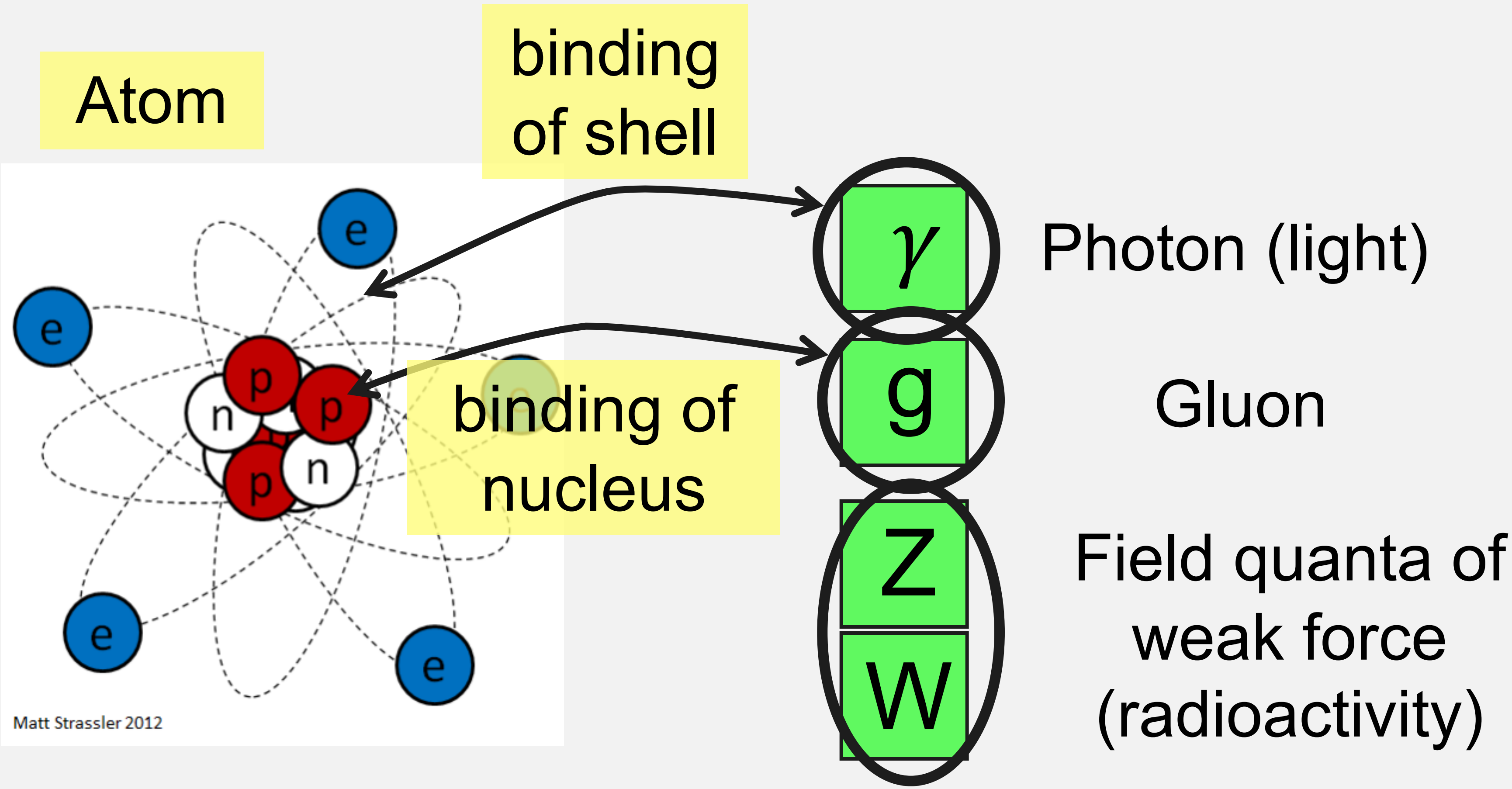
Structure of Matter (CERN et al., 2012)



Matter Particles



Force Particles



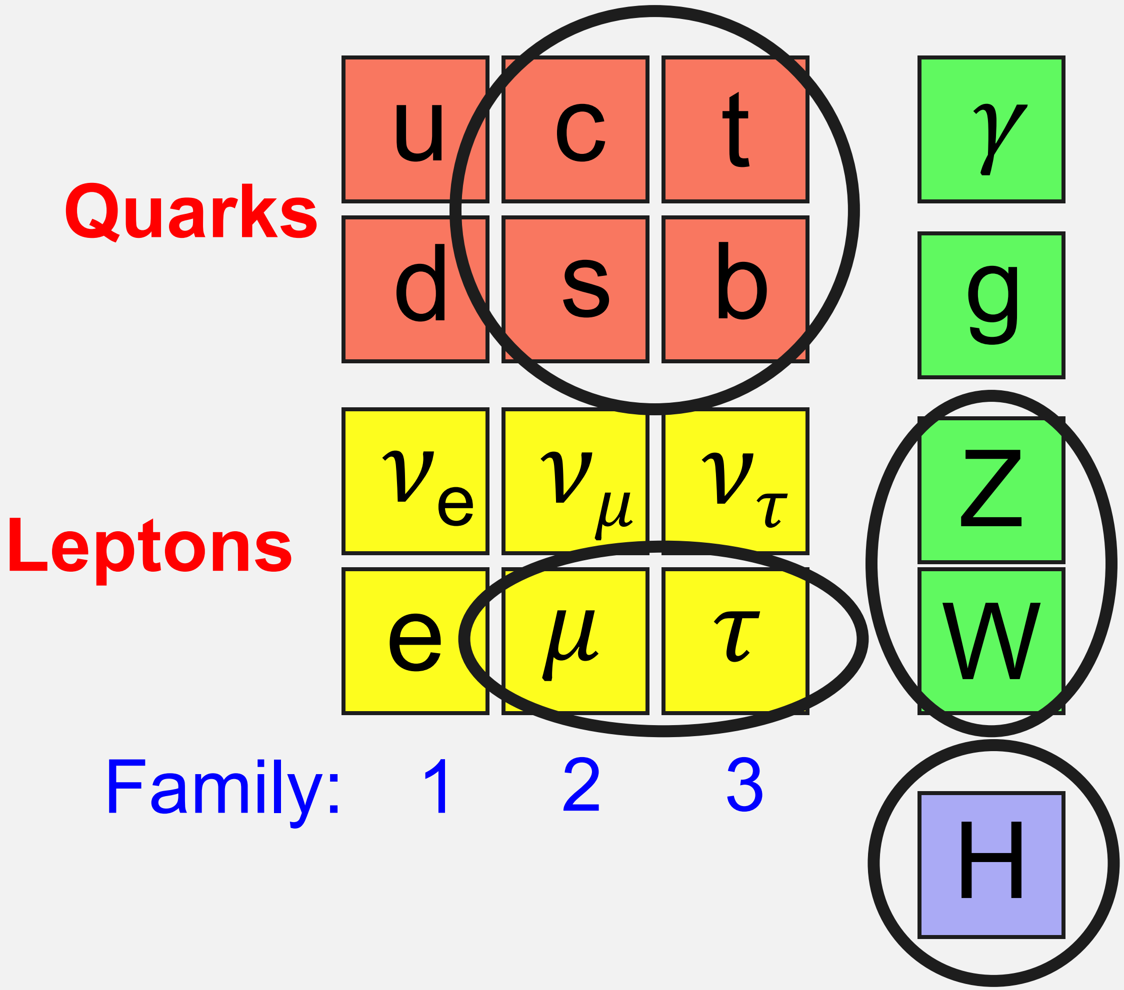
Mass Creation Particles

H

Higgs Boson

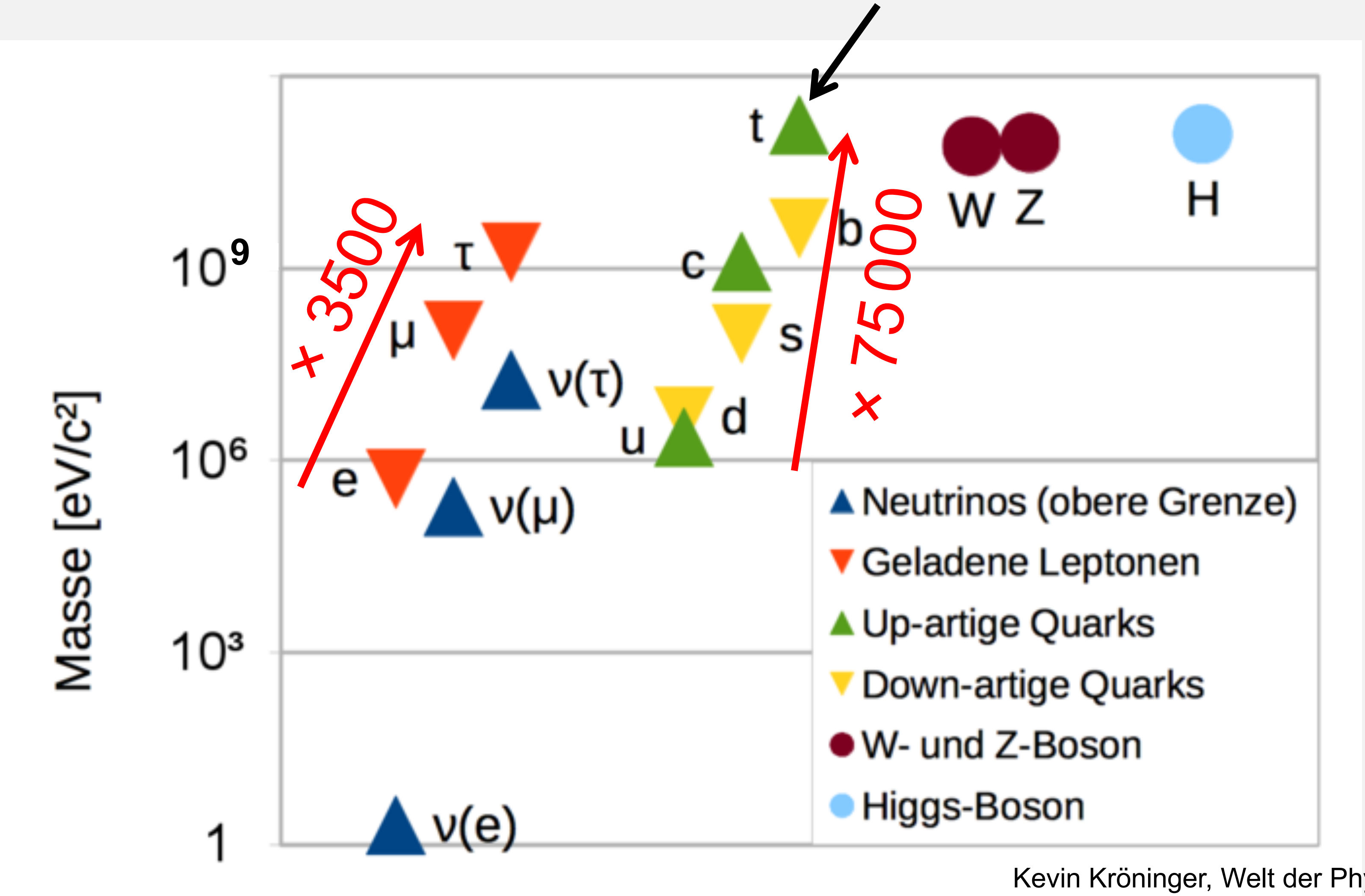
Heavy particles are very unstabe ...

but can be made at accelerators for short times



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

m(t-Quark) ≈ 180·m(Proton)



Kevin Kröninger, Welt der Physik

Quarks / Gluons (**partons**): confined in **hadrons**

you'll never walk alone

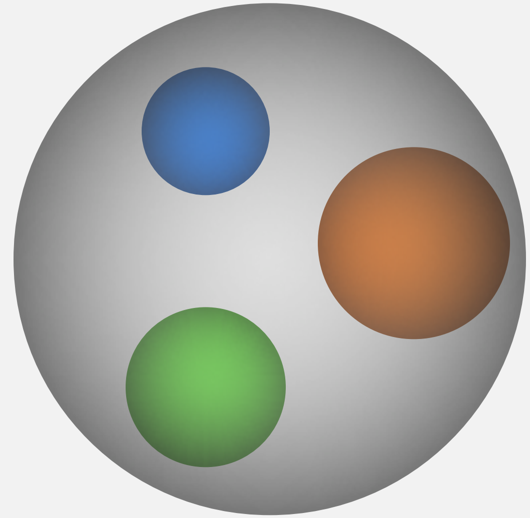
Quarks

u	c	t
d	s	b

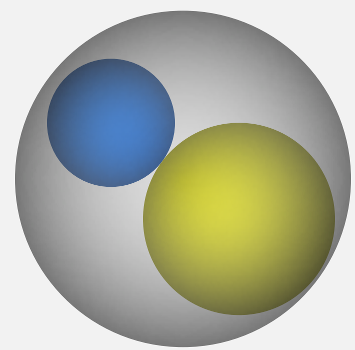
Gluons g

Anti-quarks

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

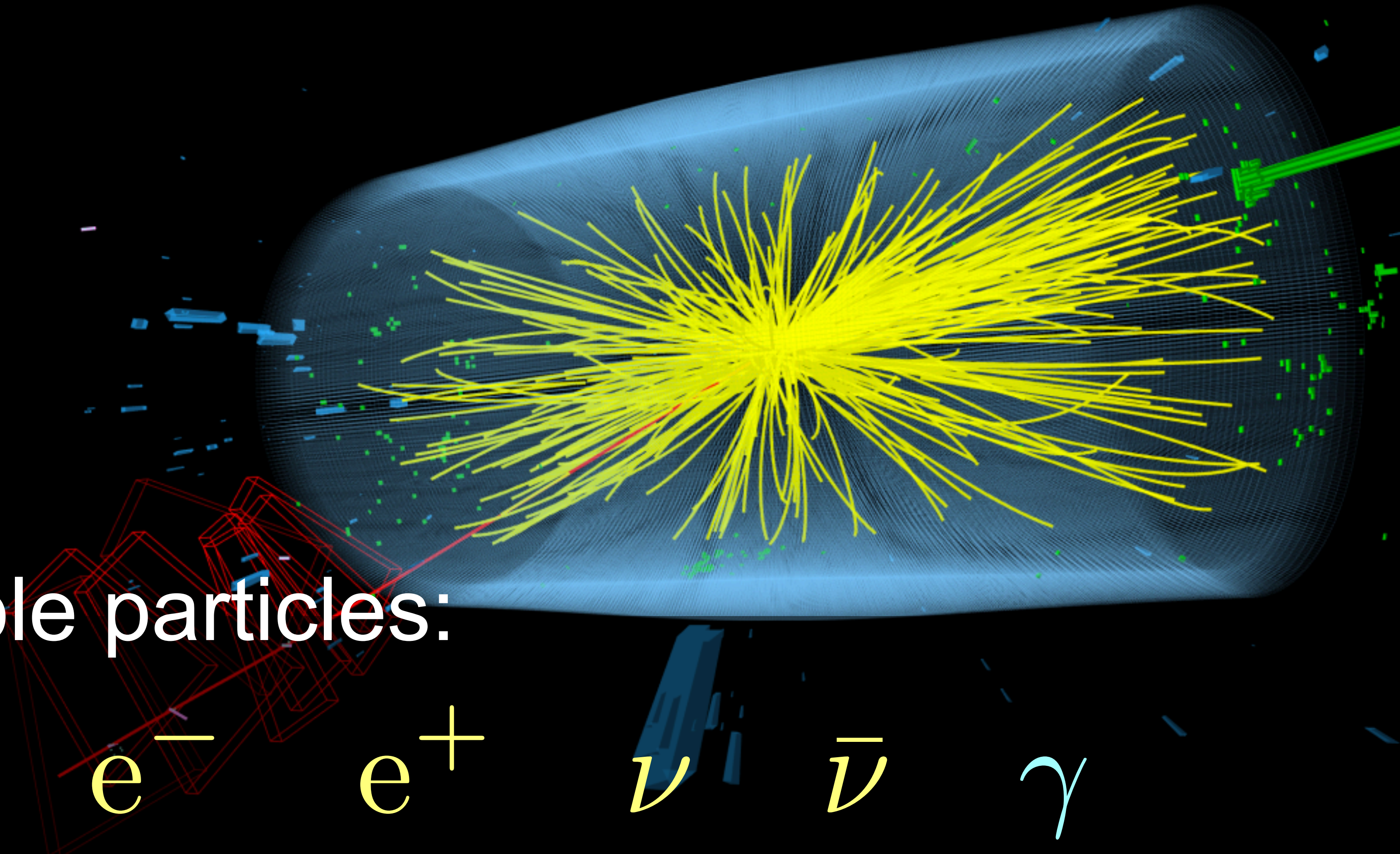


Baryon: 3 (valence) quarks



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

What is the stuff going through the detector?



Stable particles:

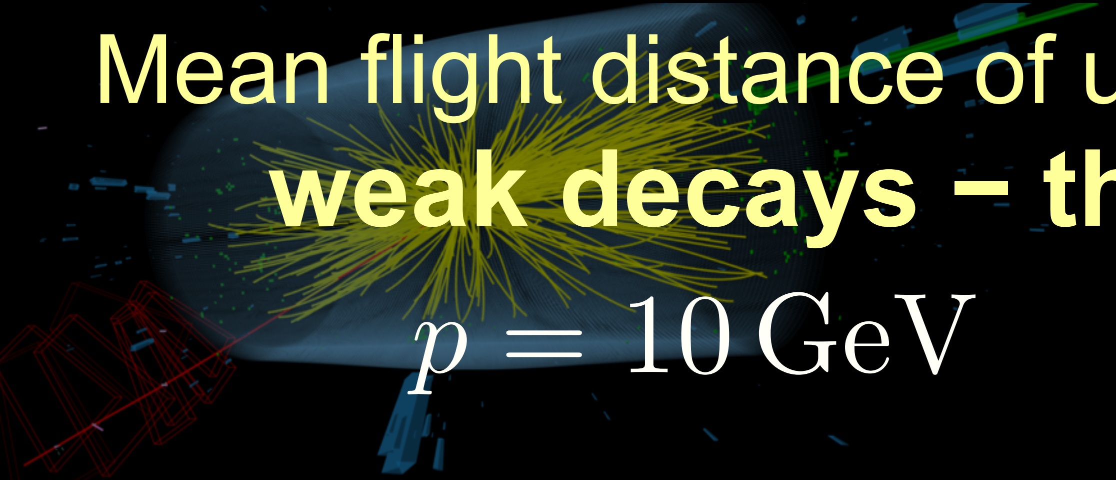
$$e^- \quad e^+ \quad \nu \quad \bar{\nu} \quad \gamma$$

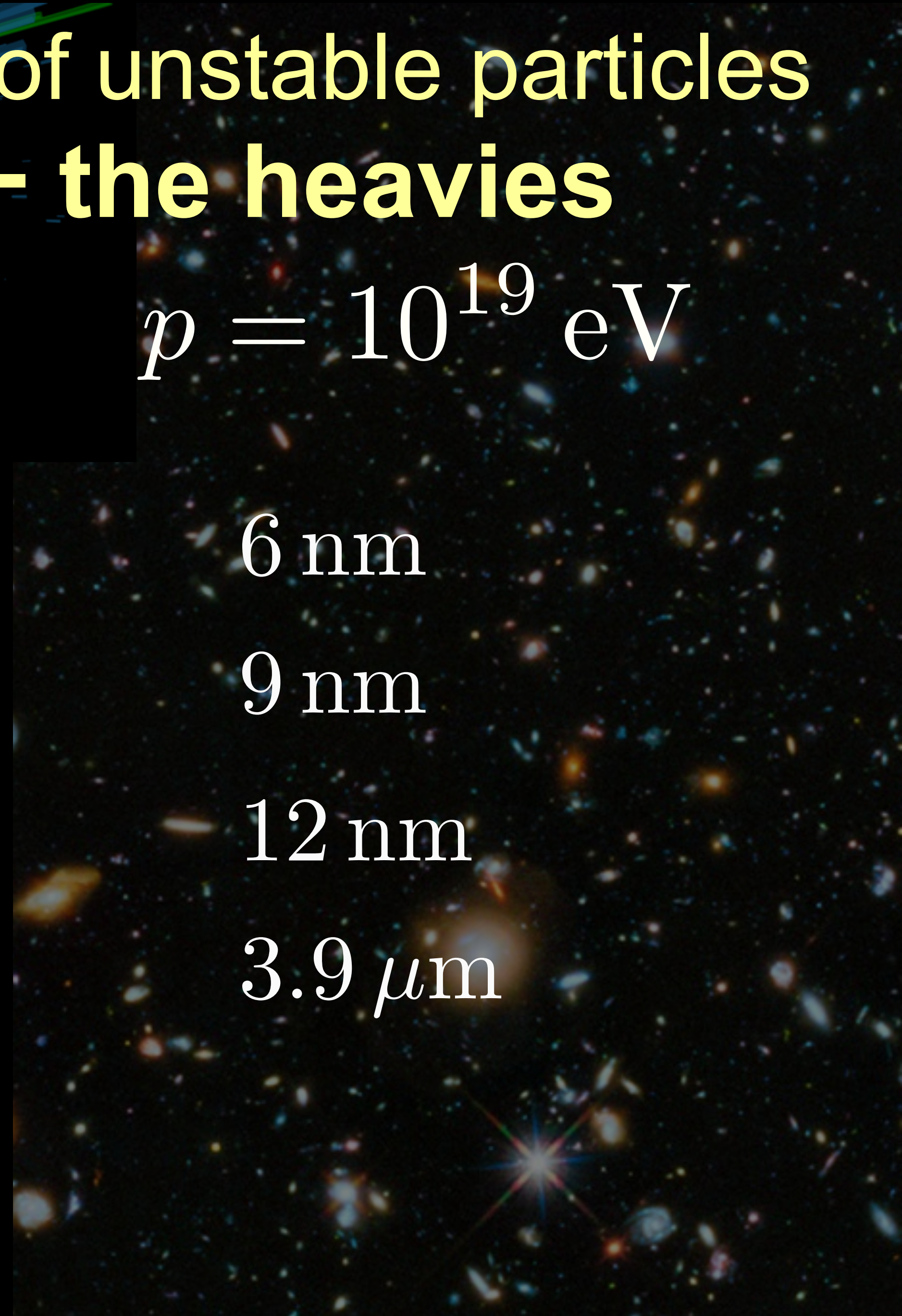
$$\mathrm{p} \quad \bar{\mathrm{p}} \quad (+\ \text{some nuclei})$$

Mean flight distance of unstable particles

weak decays

	$p = 10\,\mathrm{GeV}$	$p = 10^{19}\,\mathrm{eV}$
$\mathrm{n},\ \bar{\mathrm{n}}$	$19\,\mathrm{au}$	$91\,\mathrm{kpc}$
$\pi^\pm$	$560\,\mathrm{m}$	$3.8\,\mathrm{au}$
strange	$\lesssim 300\mathrm{m}$	$\lesssim 0.5\,\mathrm{au}$
charm	$\mathcal{O}(2\,\mathrm{mm})$	$\mathcal{O}(2000\,\mathrm{km})$
bottom	$\mathcal{O}(1\,\mathrm{mm})$	$\mathcal{O}(1000\,\mathrm{km})$
$\mu^\pm$	$58\,\mathrm{km}$	$390\,\mathrm{au}$
$\tau^\pm$	$0.5\,\mathrm{mm}$	$500\,\mathrm{km}$

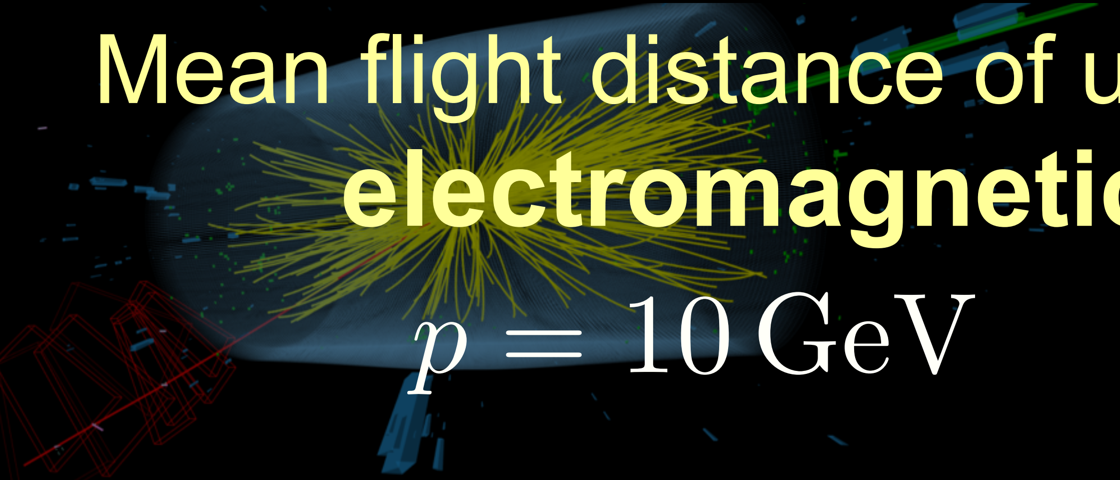


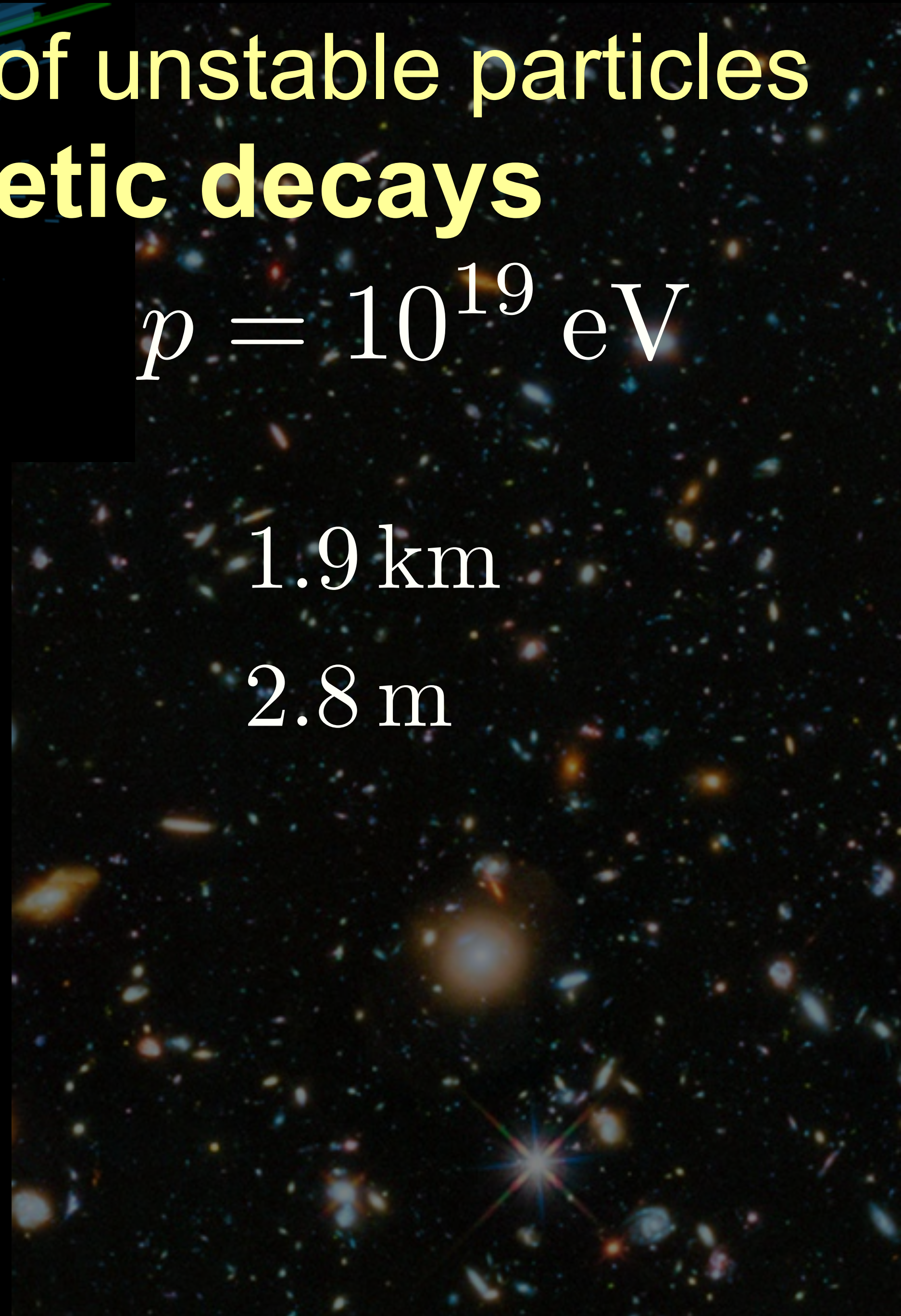


Mean flight distance of unstable particles

weak decays – the heavies

	$p = 10\,\mathrm{GeV}$	$p = 10^{19}\,\mathrm{eV}$
$\mathrm{t-quark}$	$0.006\,\mathrm{fm}$	$6\,\mathrm{nm}$
Z	$0.009\,\mathrm{fm}$	$9\,\mathrm{nm}$
$\mathrm{W}^{\pm}$	$12\,\mathrm{fm}$	$12\,\mathrm{nm}$
H	$3.9\,\mathrm{fm}$	$3.9\,\mu\mathrm{m}$





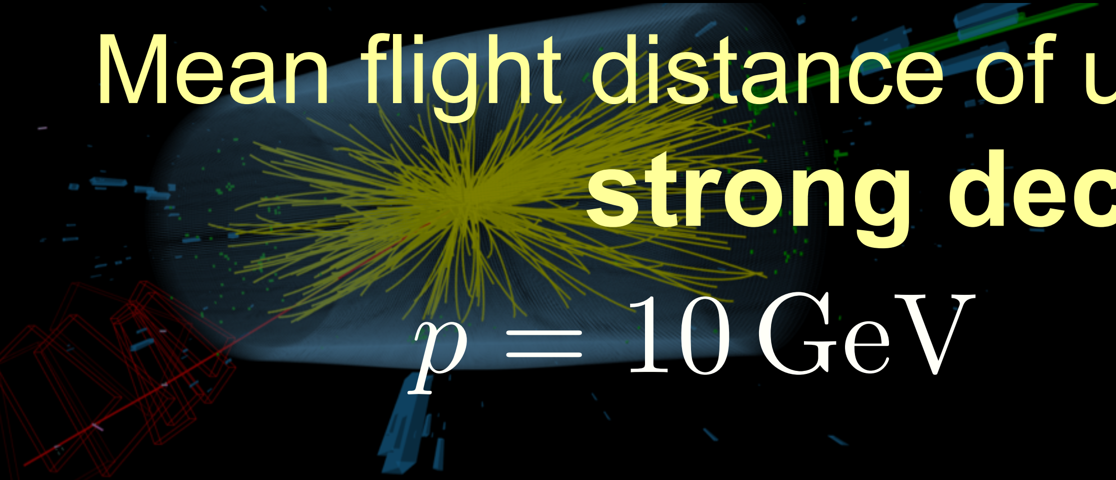
Mean flight distance of unstable particles

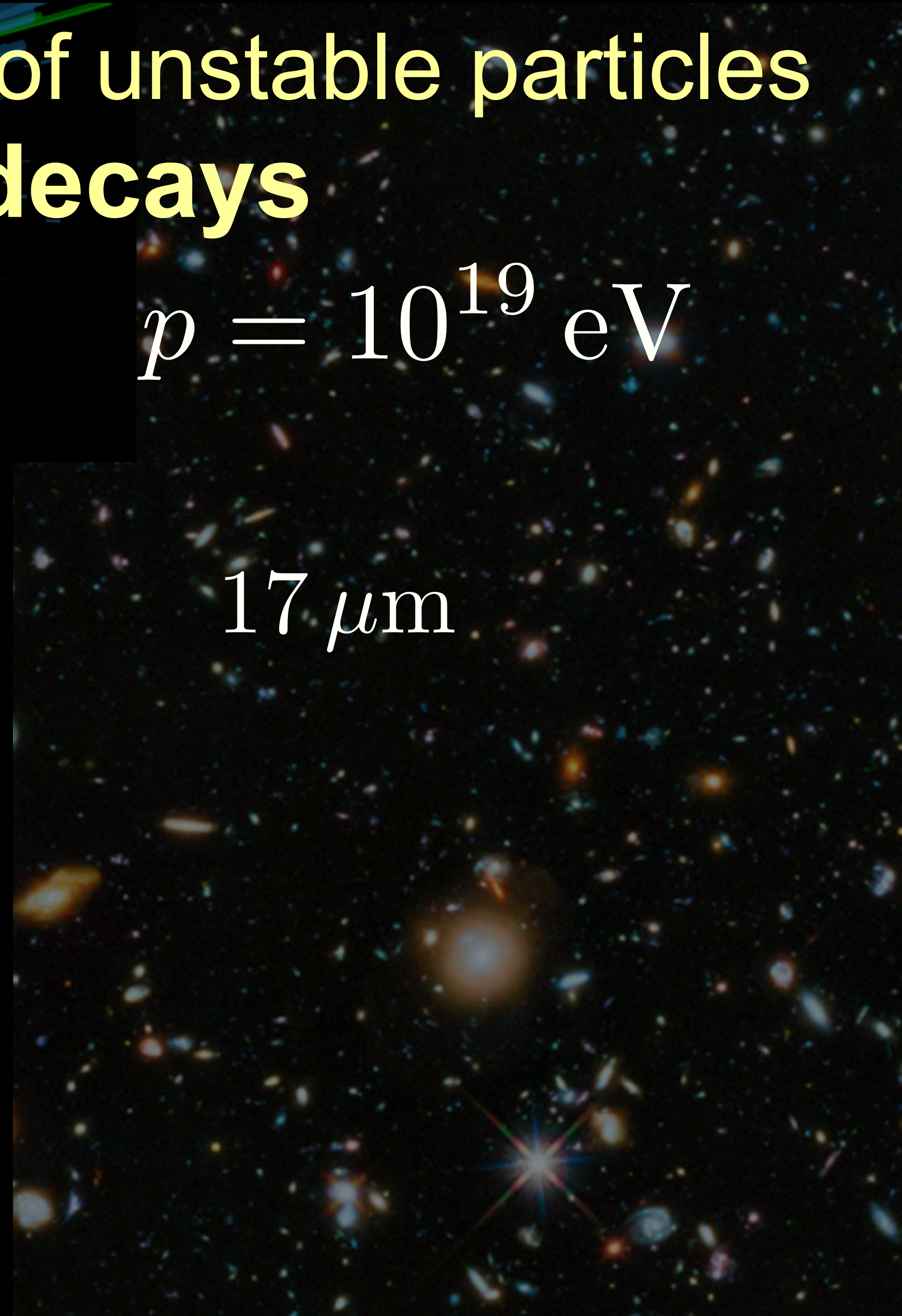
electromagnetic decays

	$p = 10\,\mathrm{GeV}$	$p = 10^{19}\,\mathrm{eV}$
π^0	$1.9\,\mu\mathrm{m}$	$1.9\,\mathrm{km}$
η	$2.8\,\mathrm{nm}$	$2.8\,\mathrm{m}$
$\vdots$		

Mean flight distance of unstable particles

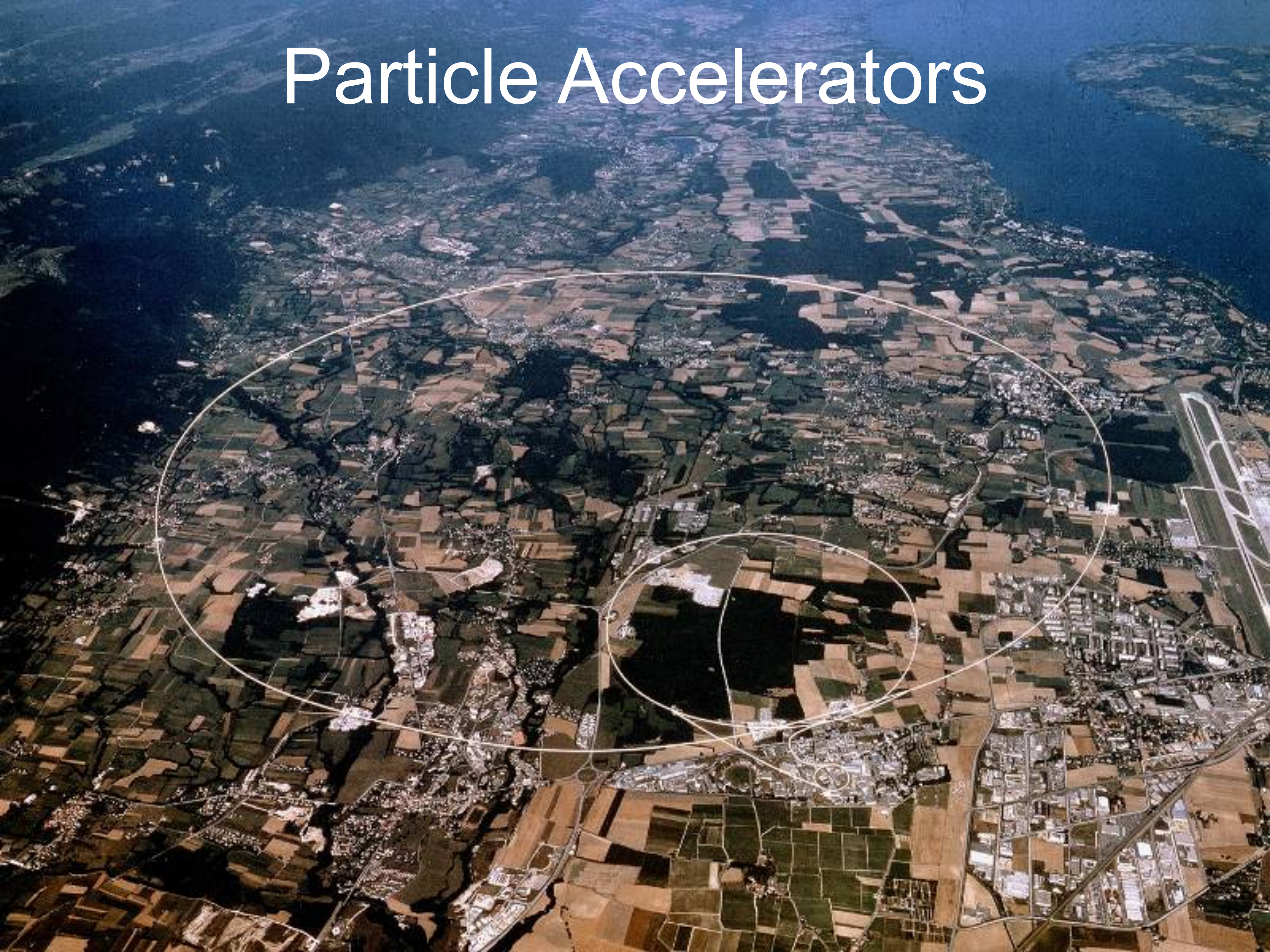
strong decays





	$p = 10\,\mathrm{GeV}$	$p = 10^{19}\,\mathrm{eV}$
ρ^0	$17\,\mathrm{fm}$	$17\,\mu\mathrm{m}$
$\vdots$		

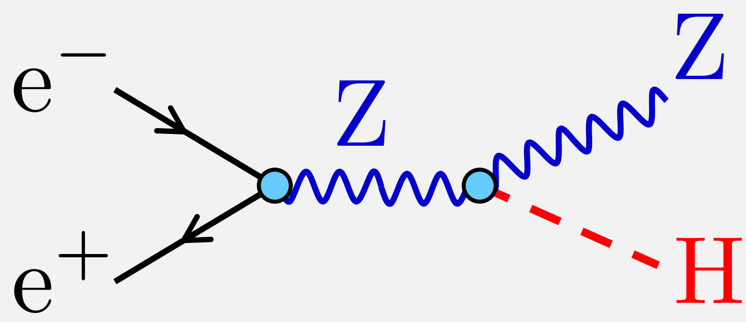
Particle Accelerators



Why do we need them?

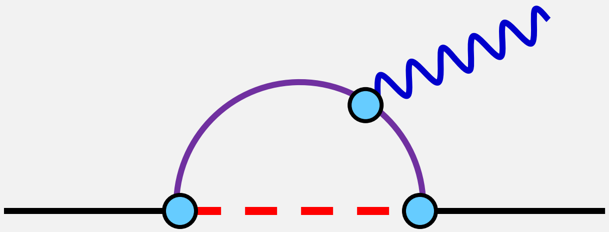
➢ Discover new heavy particles / field quanta

1. Create them



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

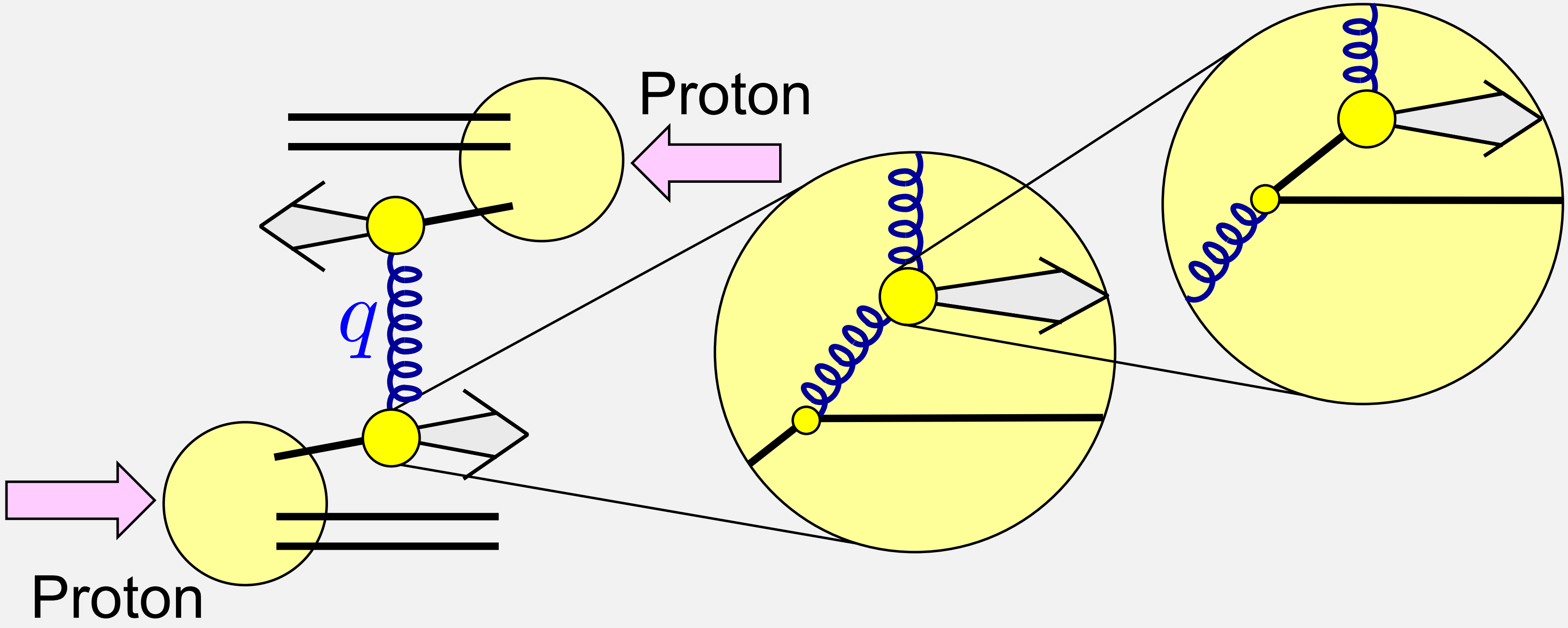
2. Measure their contributions in quantum fluctuations



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

$\Rightarrow$ needs high precision $\Rightarrow$ **high luminosity**

➢ Resolve structure / test small distances



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

$$\lambda \ll 1\,\mathrm{fm} \quad \Rightarrow \quad |q^2| \gg m_{\mathrm{p}}^2$$

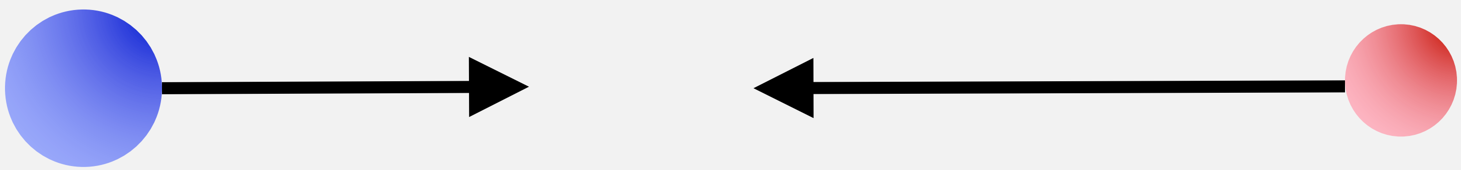
$\Rightarrow$ needs **high momentum transfer**

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

How do we design them?

beam particle e.g. proton

beam/target particle e.g. proton



$$p_1 = (E_1, \vec{p}_1) \qquad p_2 = (E_2, \vec{p}_2)$$

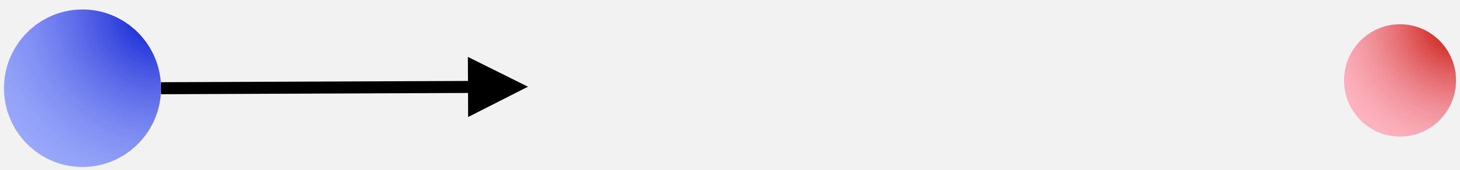
Centre of mass energy:

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

Case 1: Fixed target configuration

beam particle
e.g. proton

target at rest



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

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

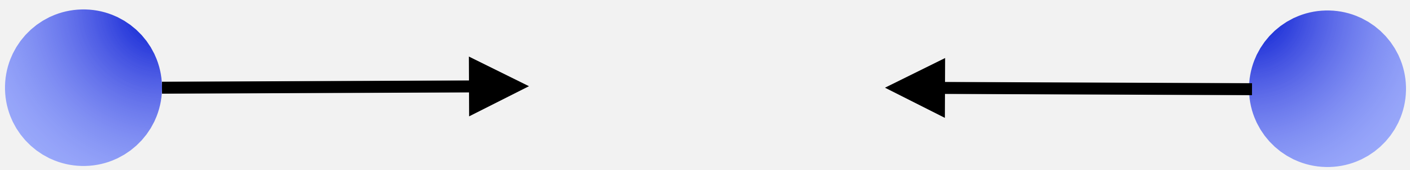
Centre of mass energy:

$$\sqrt{s} = \sqrt{(p_1 + p_2)^2} = \sqrt{m_1^2 + m_2^2 + 2p_1p_2}$$

$$= \sqrt{m_1^2 + m_2^2 + 2m_2E_1} \approx \sqrt{2m_2E_1}$$

Case 2: Colliding beams

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

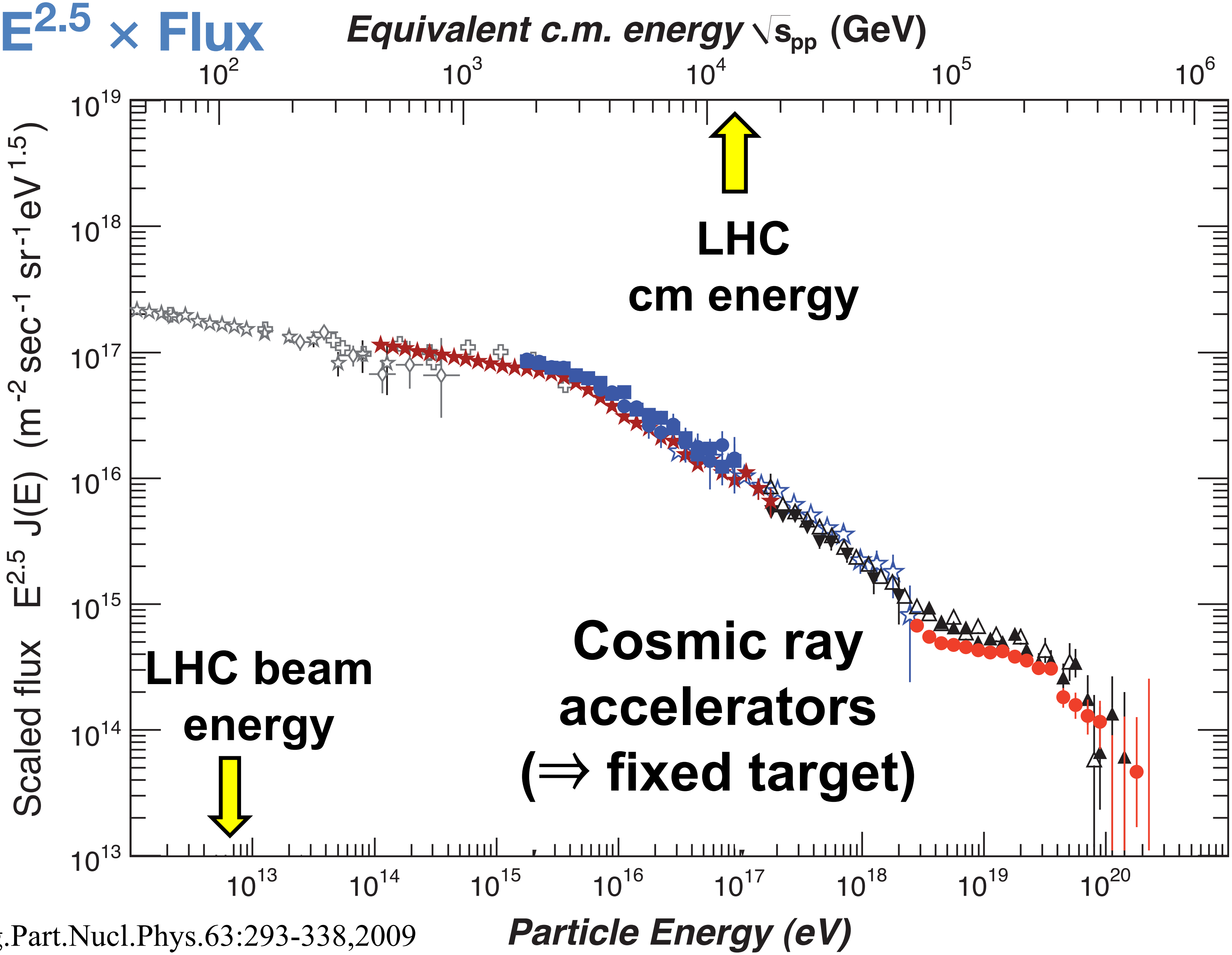


$p_1 = (E, \vec{p})$ $\qquad$ $p_2 = (E, -\vec{p})$

Centre of mass energy:

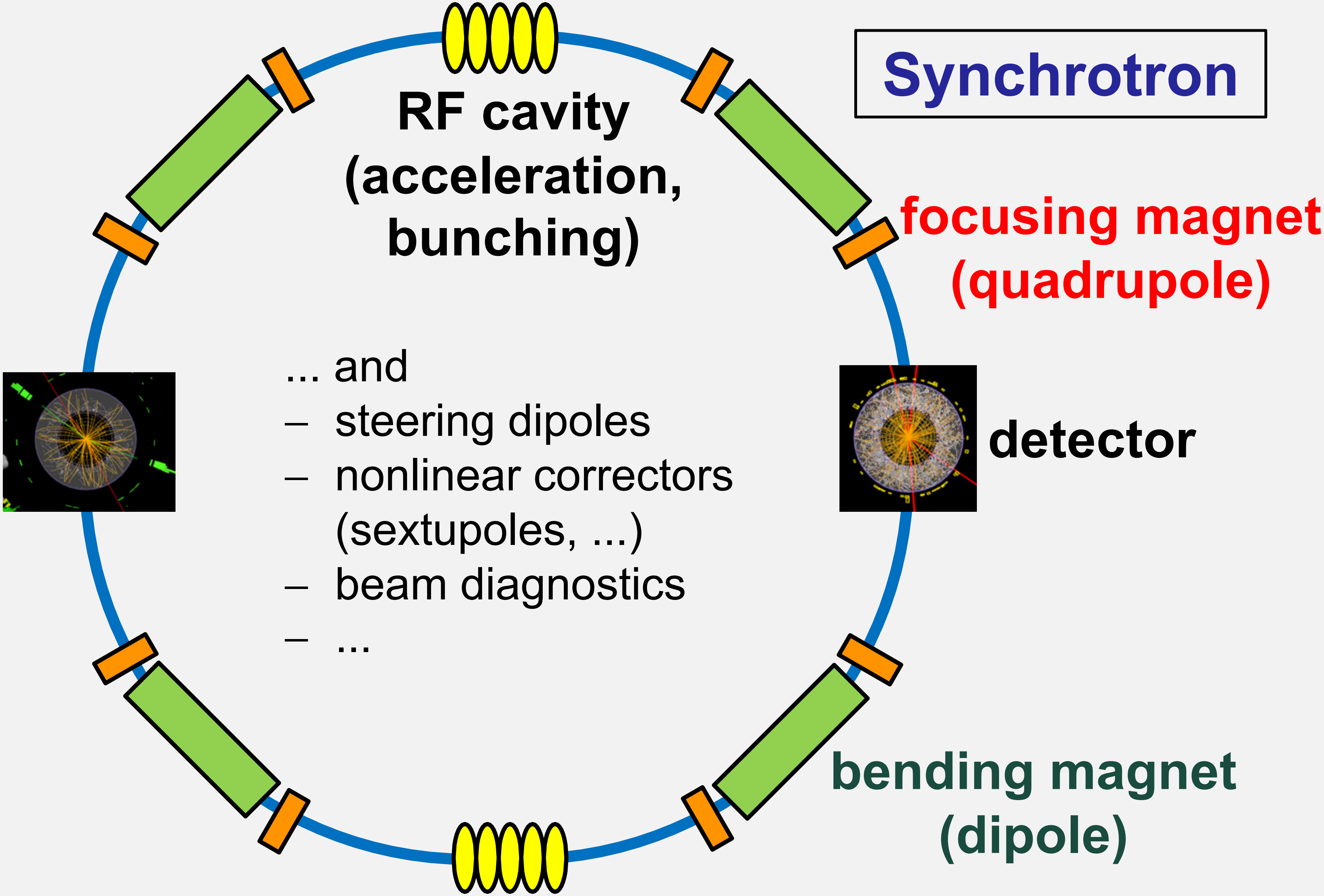
$$\sqrt{s} = \sqrt{(p_1 + p_2)^2} = \sqrt{(2E)^2} = 2E$$

$E^{2.5} \times$ Flux



Prog.Part.Nucl.Phys.63:293-338,2009

Storage Ring(s): fixed target or collider



... and

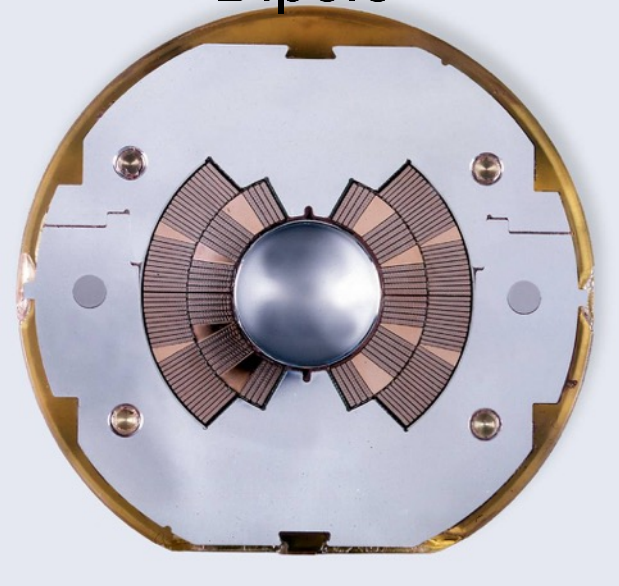
- steering dipoles
- nonlinear correctors (sextupoles, ...)
- beam diagnostics
- ...

Example: LHC

all super-conducting

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

Dipole



Quadrupoles

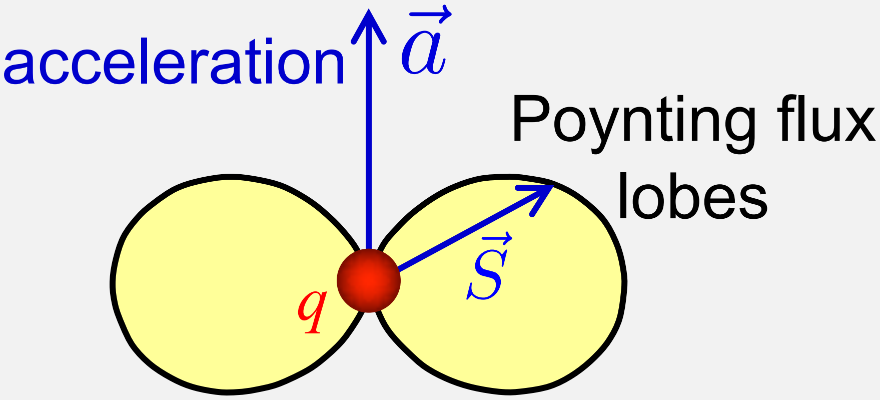
Sextupoles

bending beams around the arcs

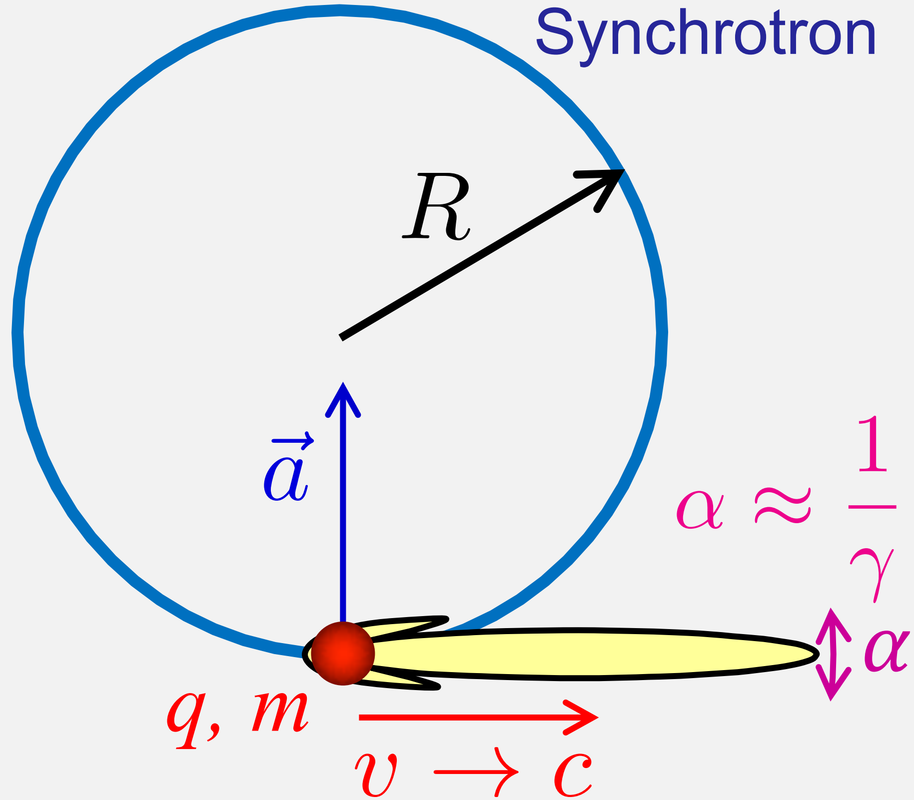
beam focusing

correct nonlinear aberrations

Radiation: accelerate electrons or protons?



rest system



synchrotron radiation

radiation loss (1 particle)

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

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

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

Example: LHC (pp)

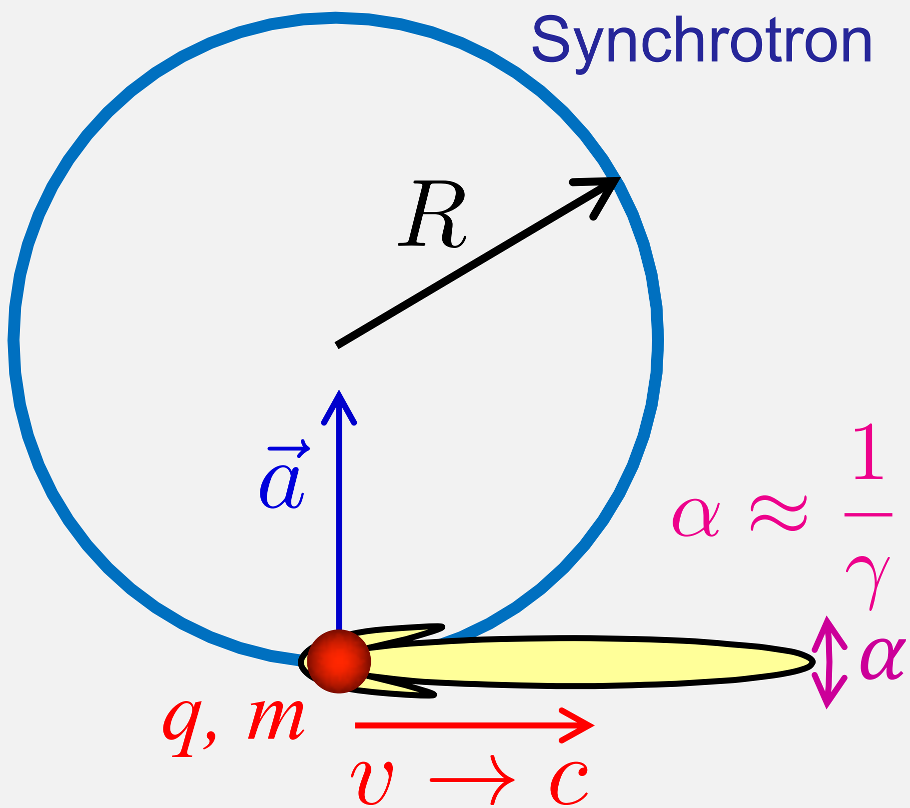
bunches: 2808 (per beam)

particles: 1.15×10^{11}

bending field: 8.33 T = 83.3 kG

beam energy: 7 TeV

$$R = \frac{\gamma m v}{eB} \overset{v\approx c=1}{\approx} \frac{\gamma m}{eB}$$



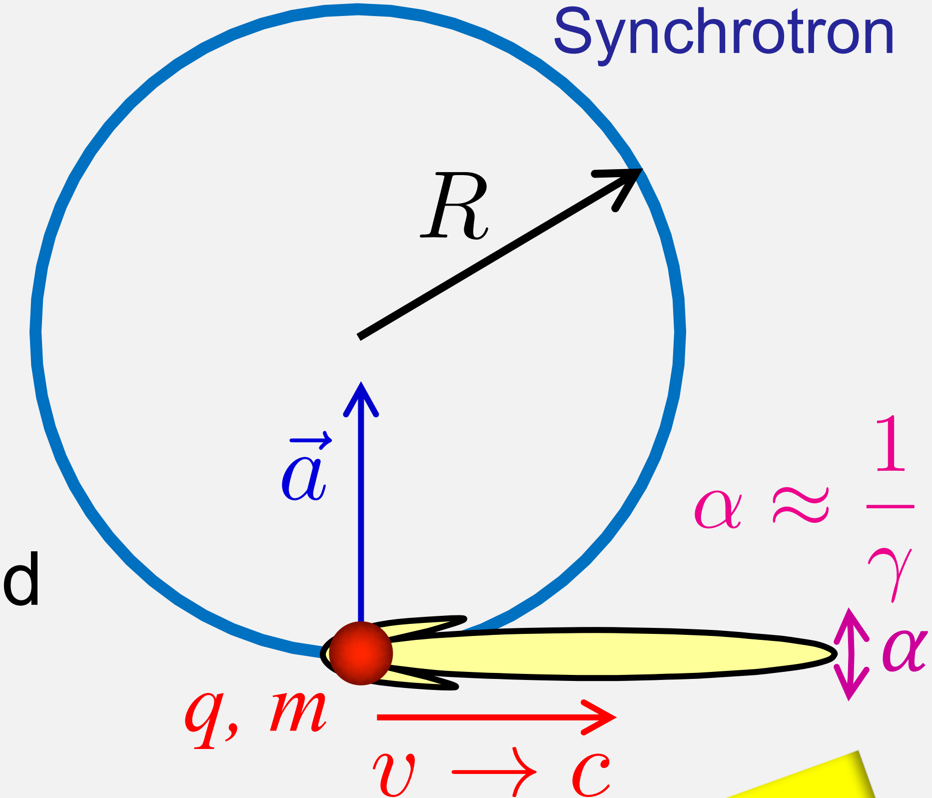
radiation power per proton beam:

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

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

LHC with $e^{\pm}$?

$$R = \frac{\gamma m v}{eB} \overset{v \approx c = 1}{\approx} \frac{\gamma m}{eB}$$



tunnel (R), magnets (B) fixed

$$\Rightarrow \quad \gamma_{\rm e} m_{\rm e} = \gamma_{\rm p} m_{\rm p}$$

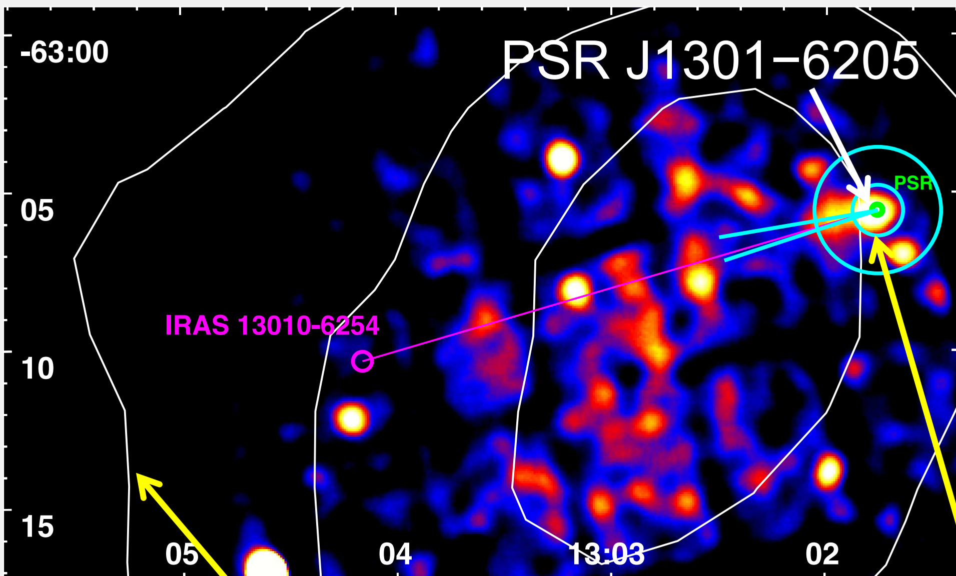
$$\Rightarrow \quad \frac{\gamma_{\rm e}}{m_{\rm e}} = \frac{\gamma_{\rm p}}{m_{\rm p}} \left(\frac{m_{\rm p}}{m_{\rm e}} \right)^2$$

$$\Rightarrow \quad P_{\rm e} = \left(\frac{m_{\rm p}}{m_{\rm e}} \right)^4 P_{\rm p} \approx 1.14 \times 10^{13} P_{\rm p}$$

hopeless

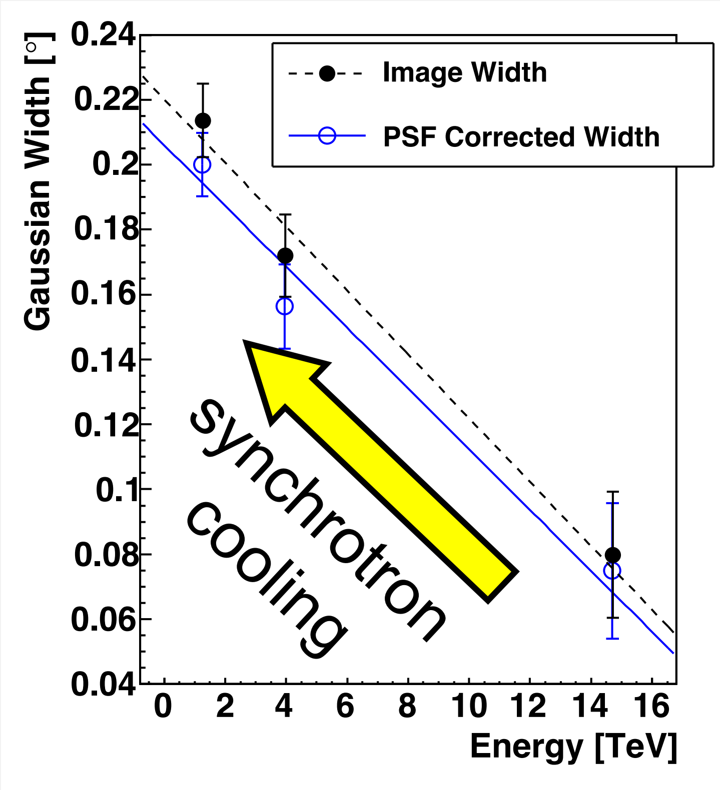
Conclusion: electron/positron beams radiate strongly ... also in astrophysical accelerators

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



A&A 548, A46 (2012)

H.E.S.S. J1303−631 size



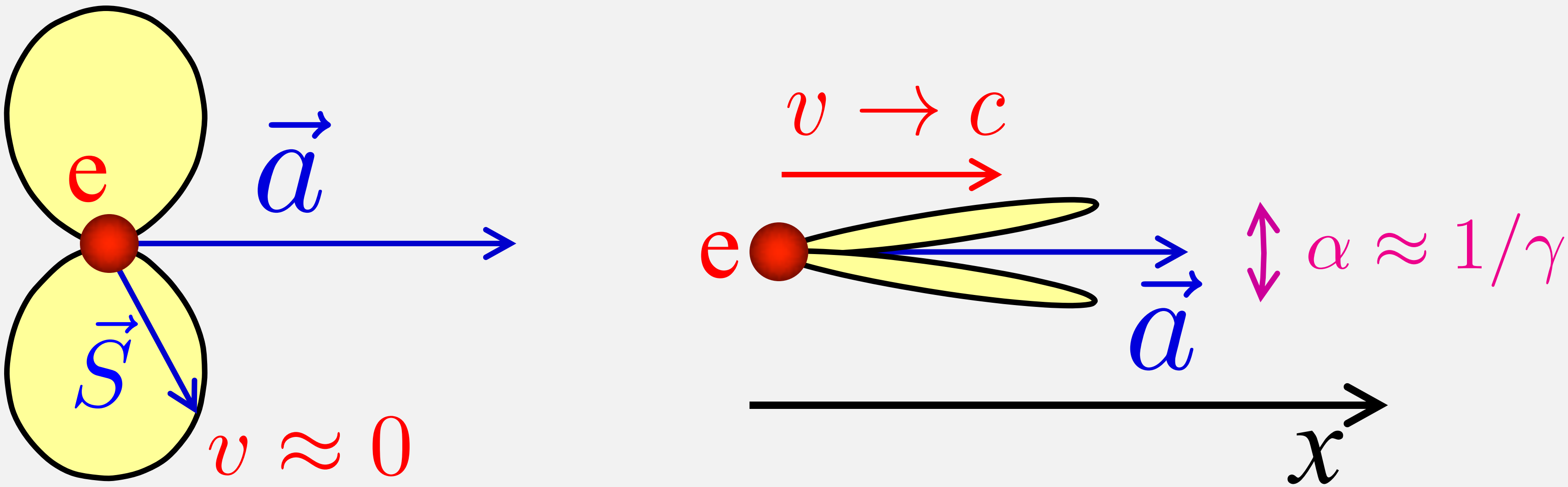
$E_\gamma > 700\,\mathrm{GeV}$

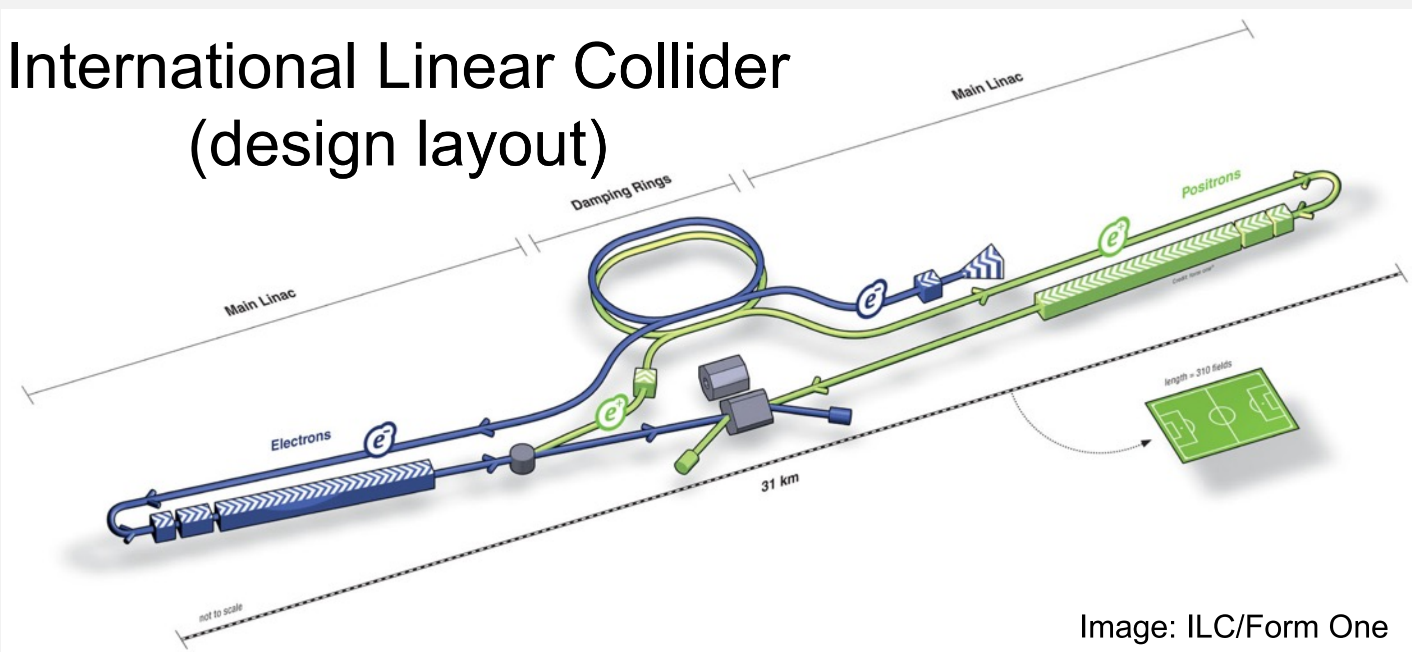
Inverse Compton scattering of synchrotron cooled electrons

$2\,\mathrm{keV} < E_\gamma < 8\,\mathrm{keV}$

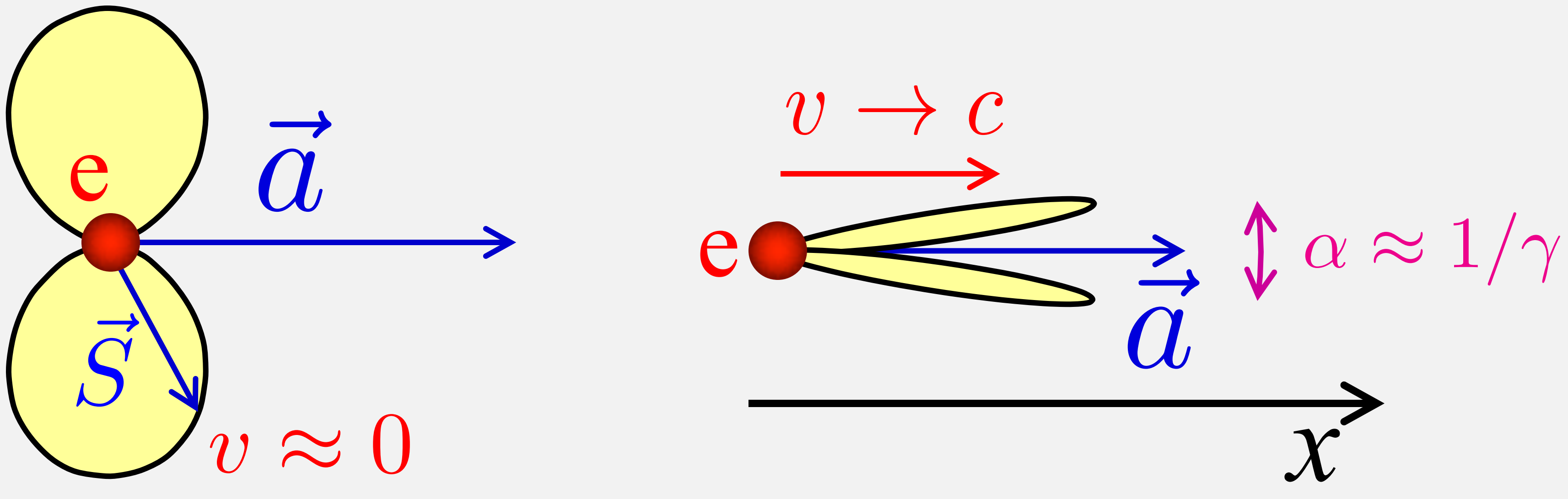
X-ray synchrotron nebula (XMM Newton)

Go linear! Towards TeV electron beams





Go linear! Towards TeV electron beams



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

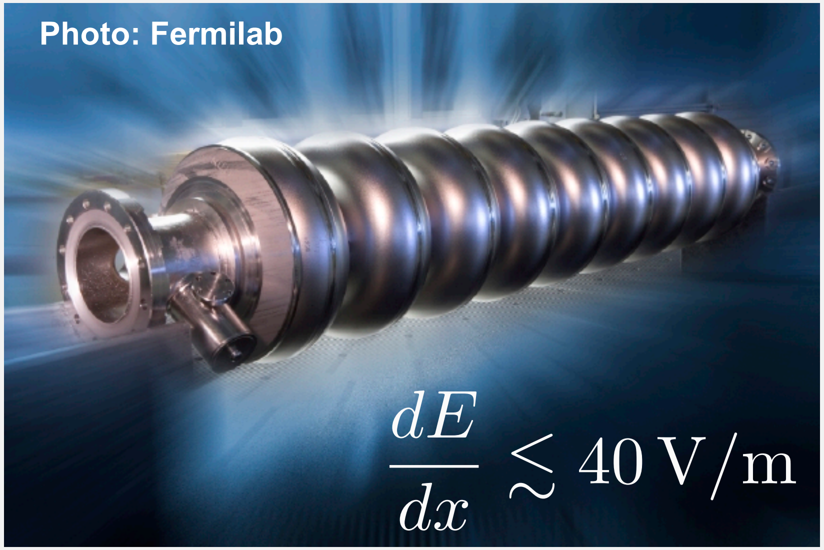
$$= 3.7 \times 10^{-15} \left. \frac{dE}{dx} \right|_{\frac{\mathrm{MeV}}{\mathrm{m}}}$$

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

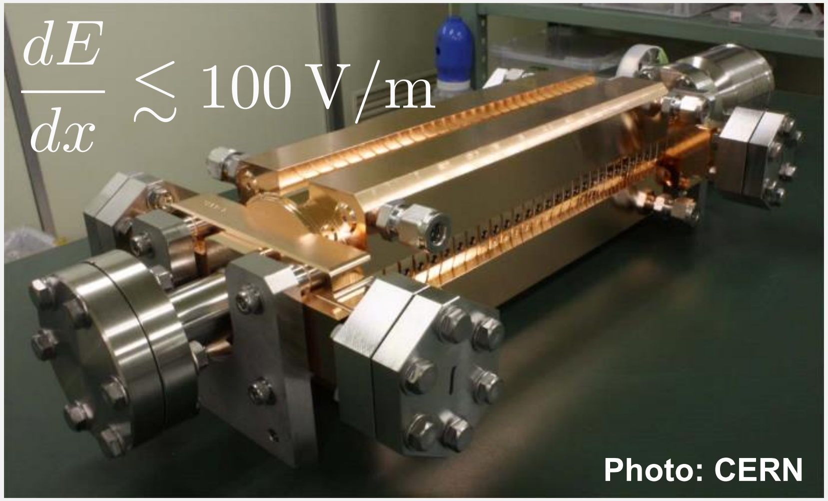
$$\left.\frac{P_{\rm rad}}{P_{\rm acc}}\right|_{\rm ILC} \lesssim 1,5 \times 10^{-13}$$

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

Radiation losses are totally negligible!

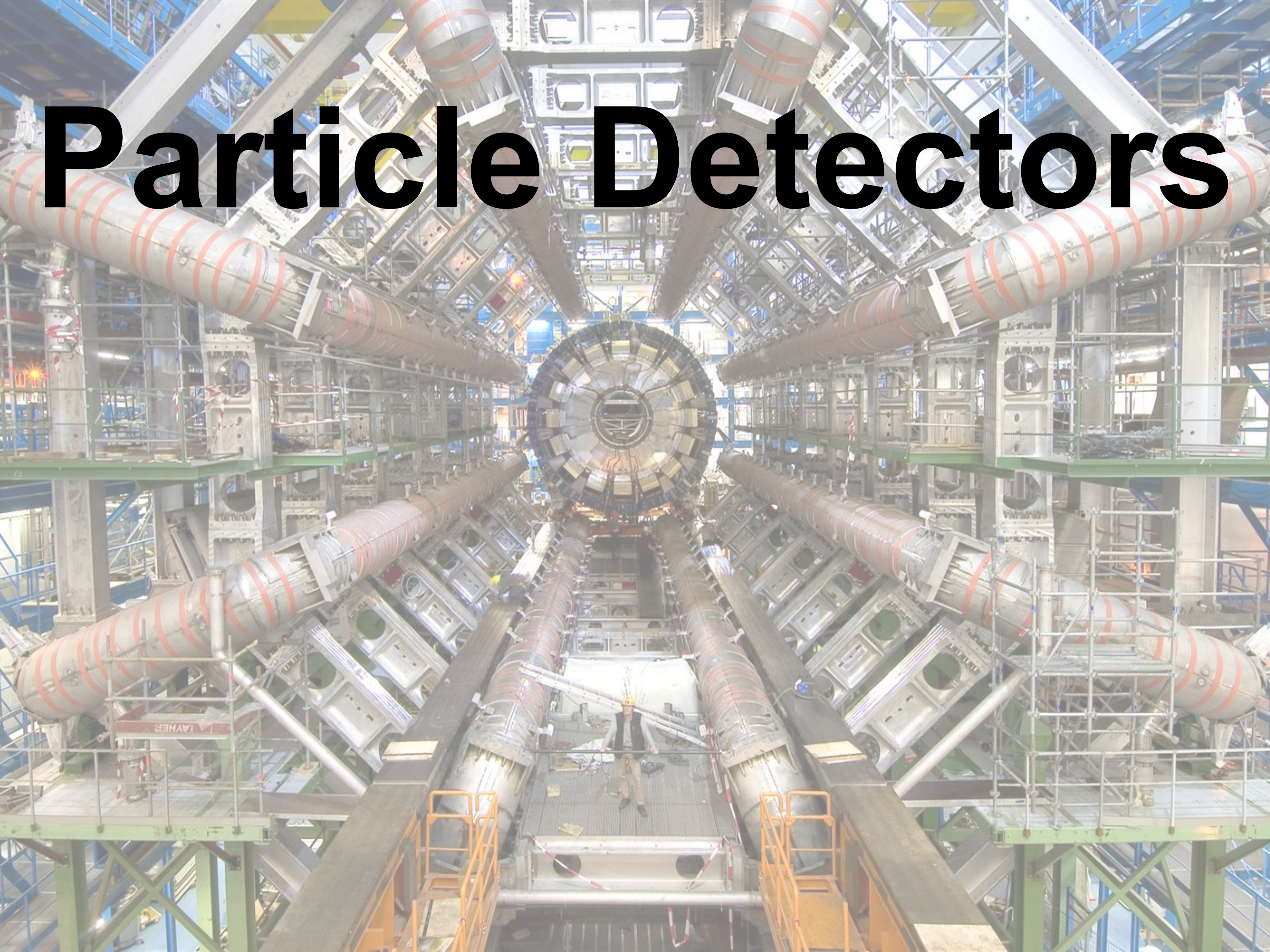


ILC: 9 cell Niobium cavity (superconducting)

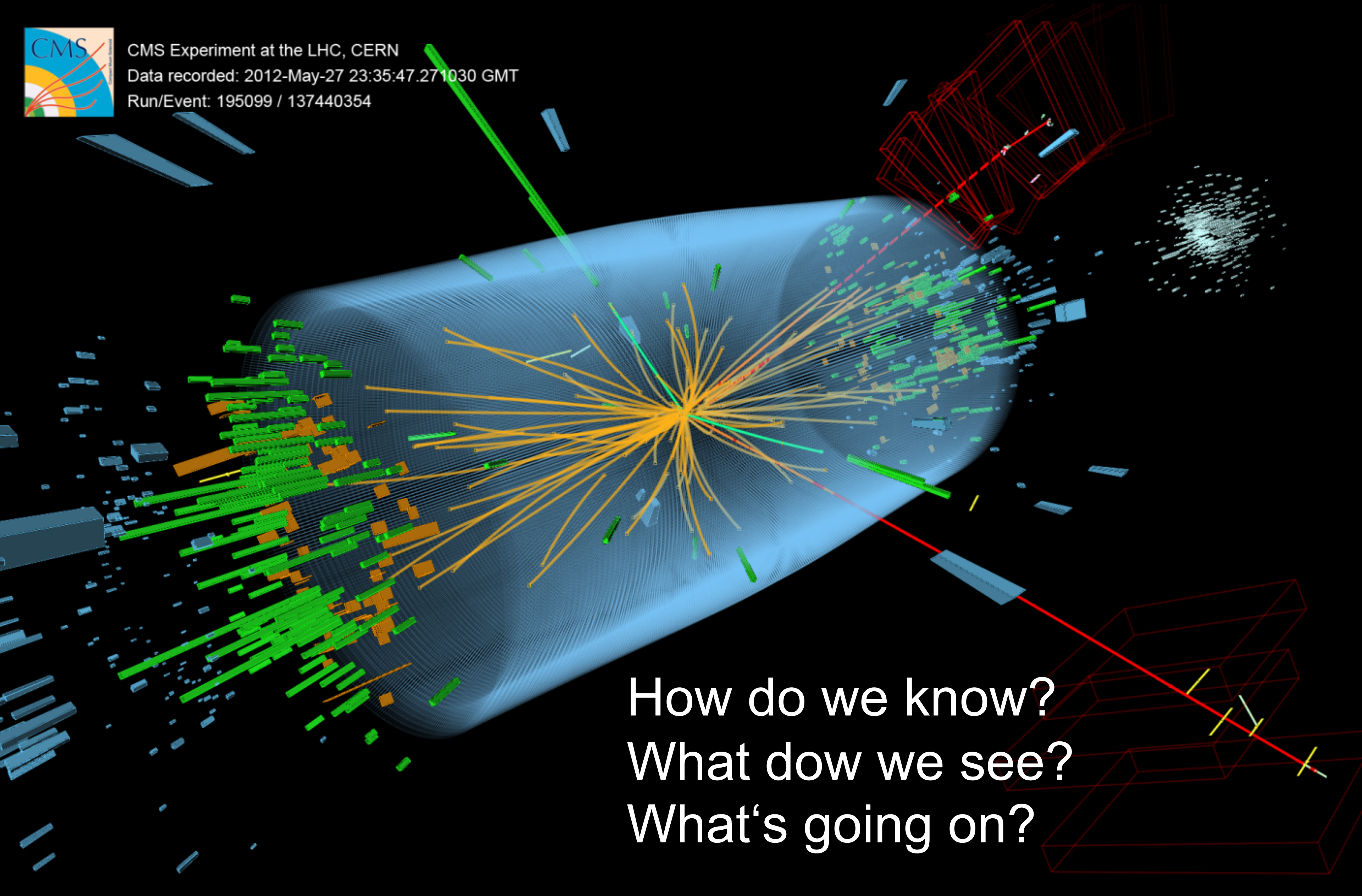


CLIC: copper accelerating structure (beam driven)

Particle Detectors



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



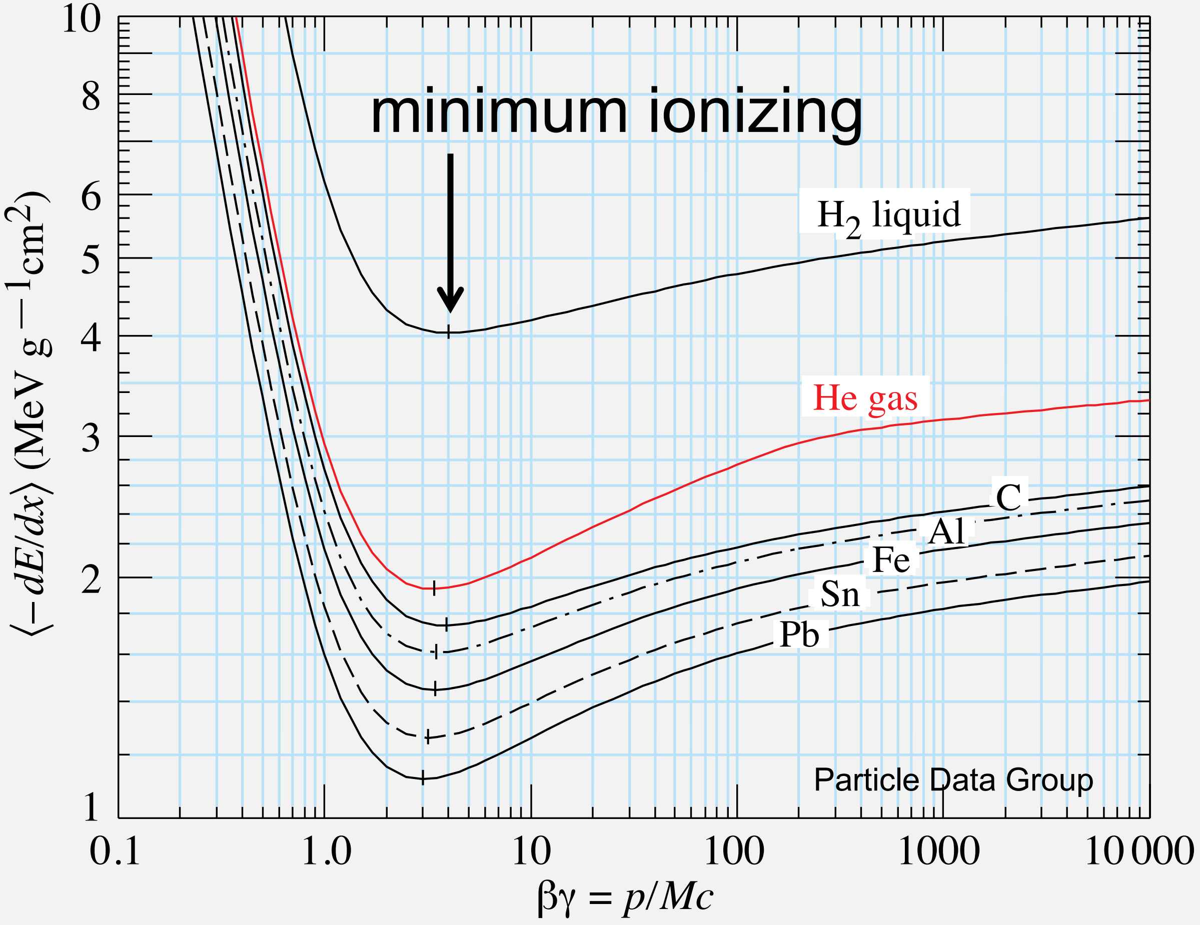
How do we know?
What dow we see?
What‘s going on?

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

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

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

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



- particles are relativistic ⇒ ionization close to minimum
- energy loss due to ionization is insignificant

Example: Argon gas

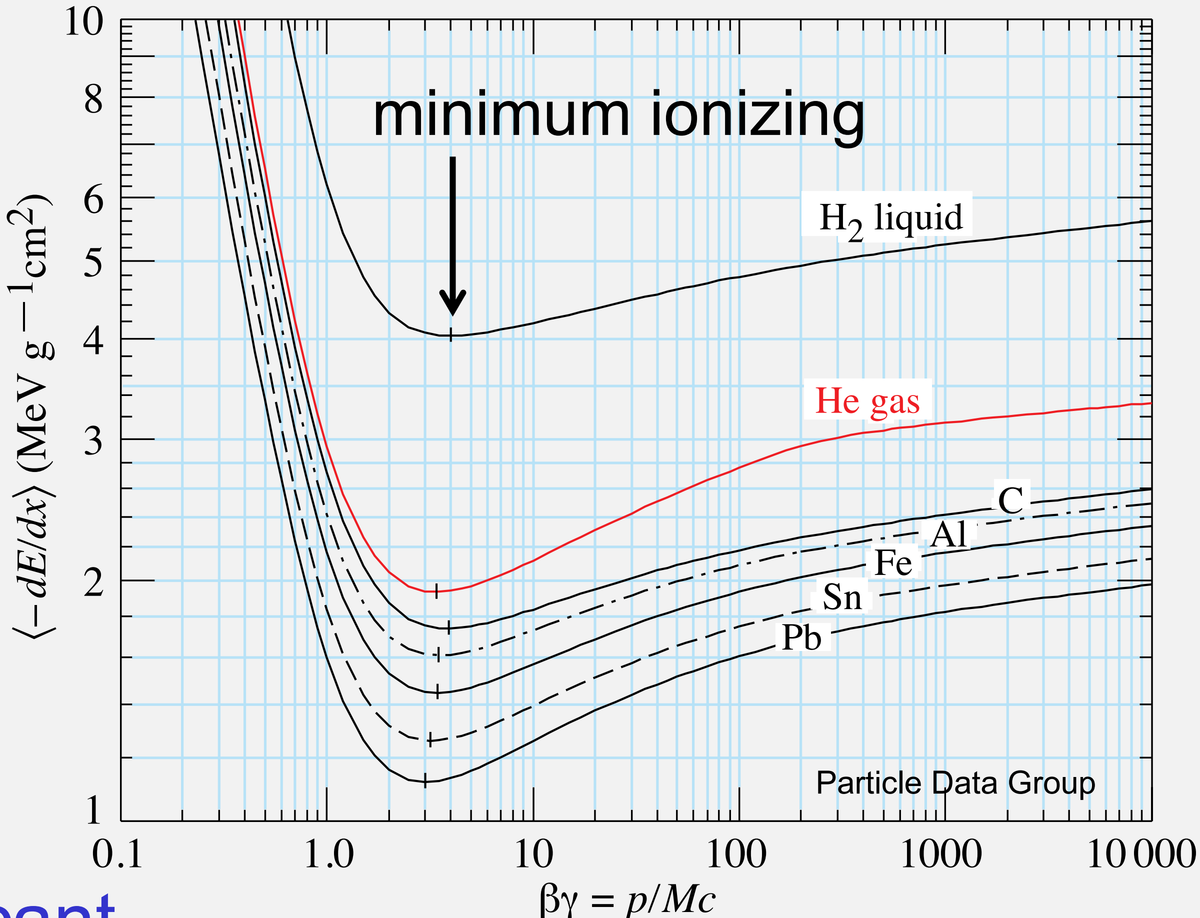
$$\frac{dE}{dx} \approx 2.5\,\mathrm{keV/cm}$$

ionisation energy:

$$E_\mathrm{I} = 15.7\,\mathrm{eV}$$

e^--ion-pairs:

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



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

Example: Silicon wafers (thickness 300 μm)

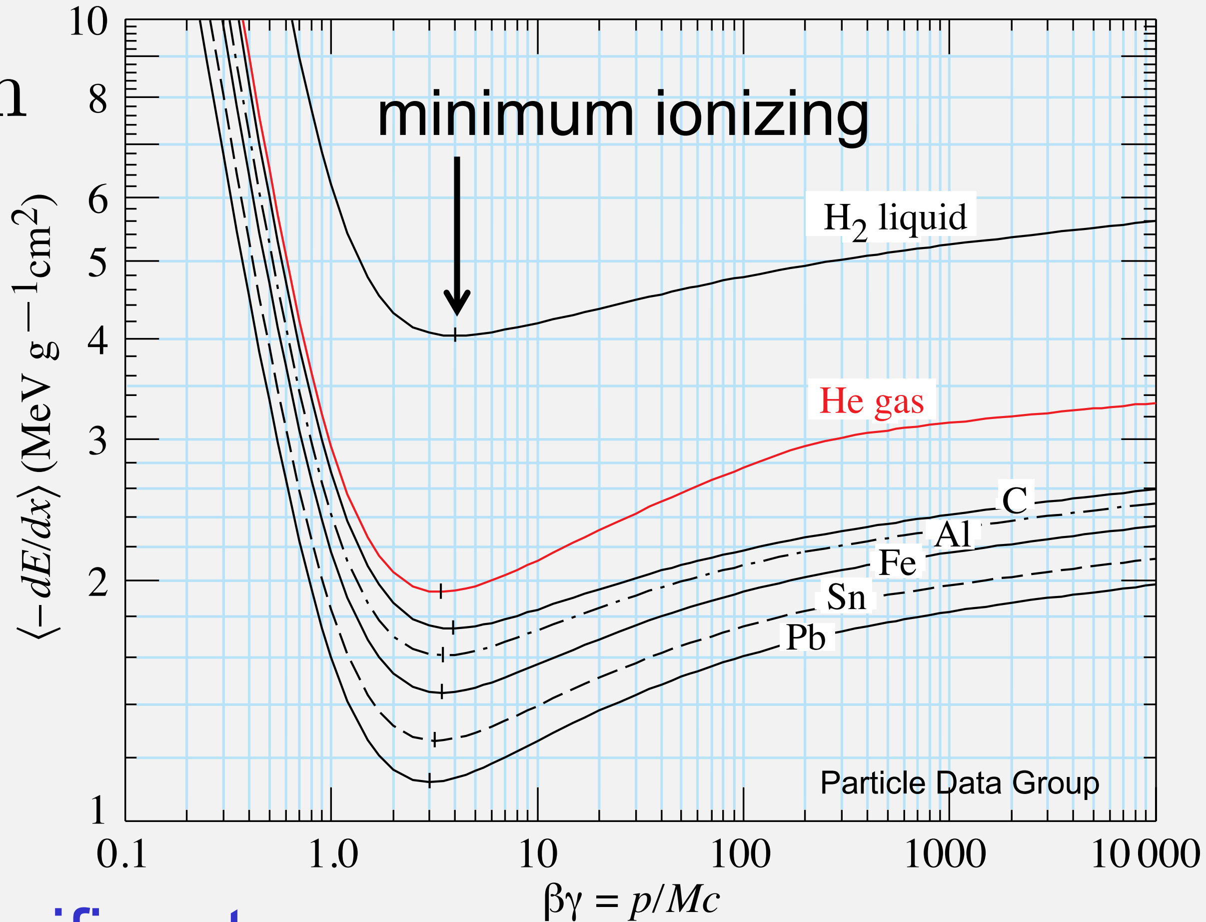
$$\frac{dE}{dx} \approx 1.7\,\mathrm{MeV/cm}$$

band gap:

$$E_{\mathrm{gap}} = 1.1\,\mathrm{eV}$$

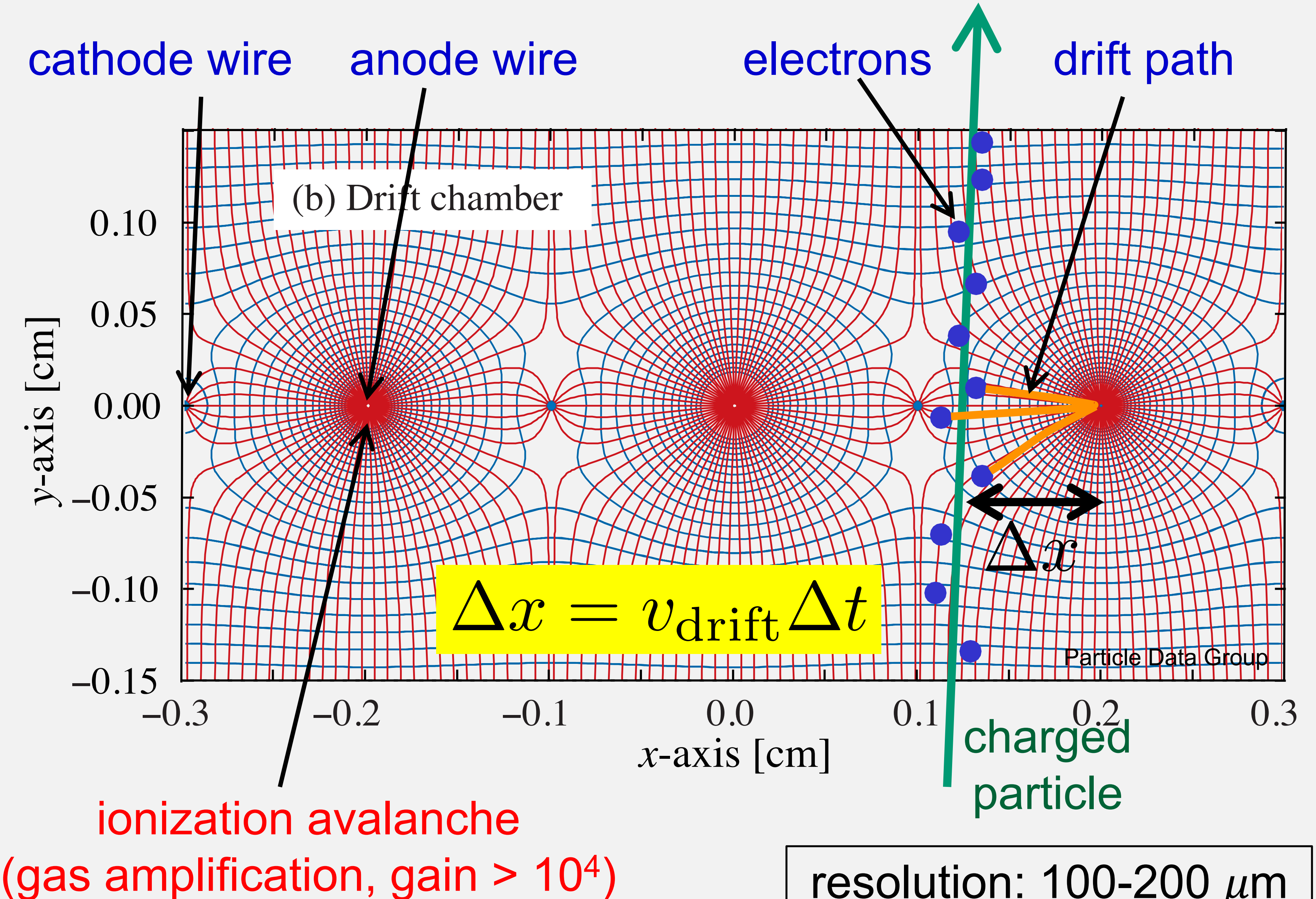
e^--hole-pairs:

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



- charge creation significant
- 100 μm-length scales needed
- sufficient charge for pre-amplification (S/N>10)

Example: drift chamber (gaseous detector)



$$\Delta x = v_{\mathrm{drift}} \Delta t$$

resolution: 100-200 μm

Installing the CDF drift chamber

Photo: Fermilab

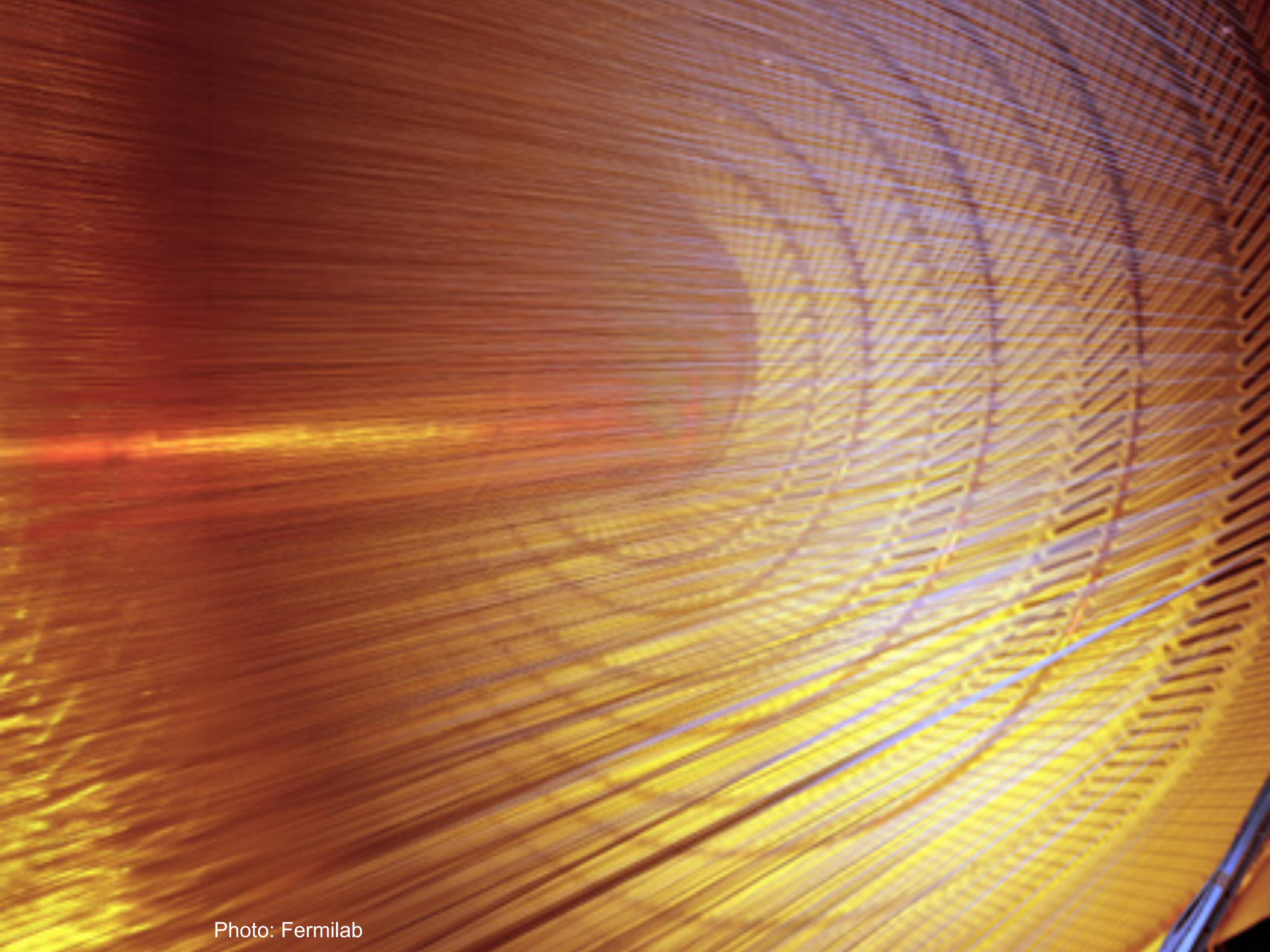
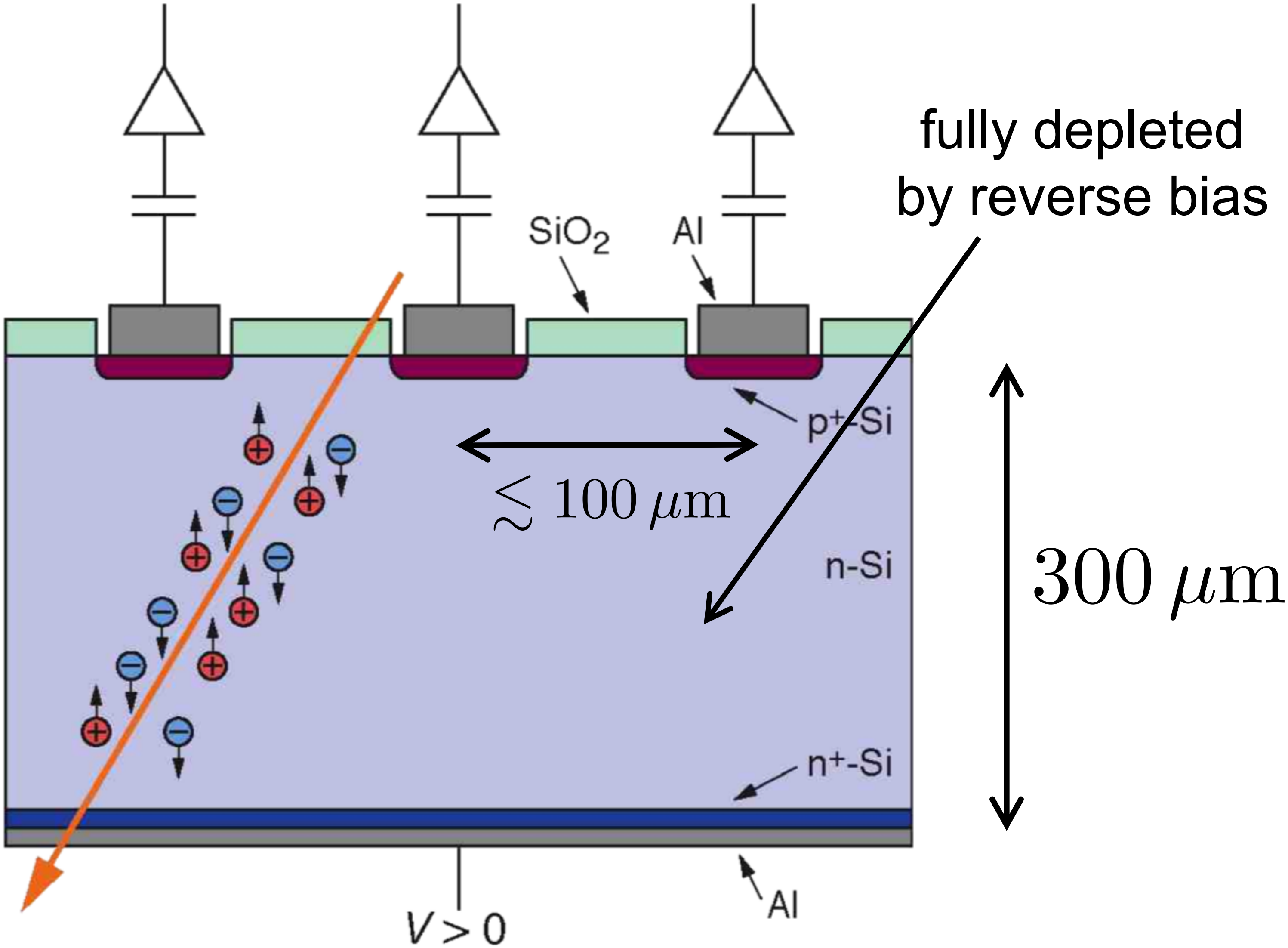


Photo: Fermilab

Example: silicon strip/pixel detector



typical resolution: 10 μm

Inside the CMS silicon tracker

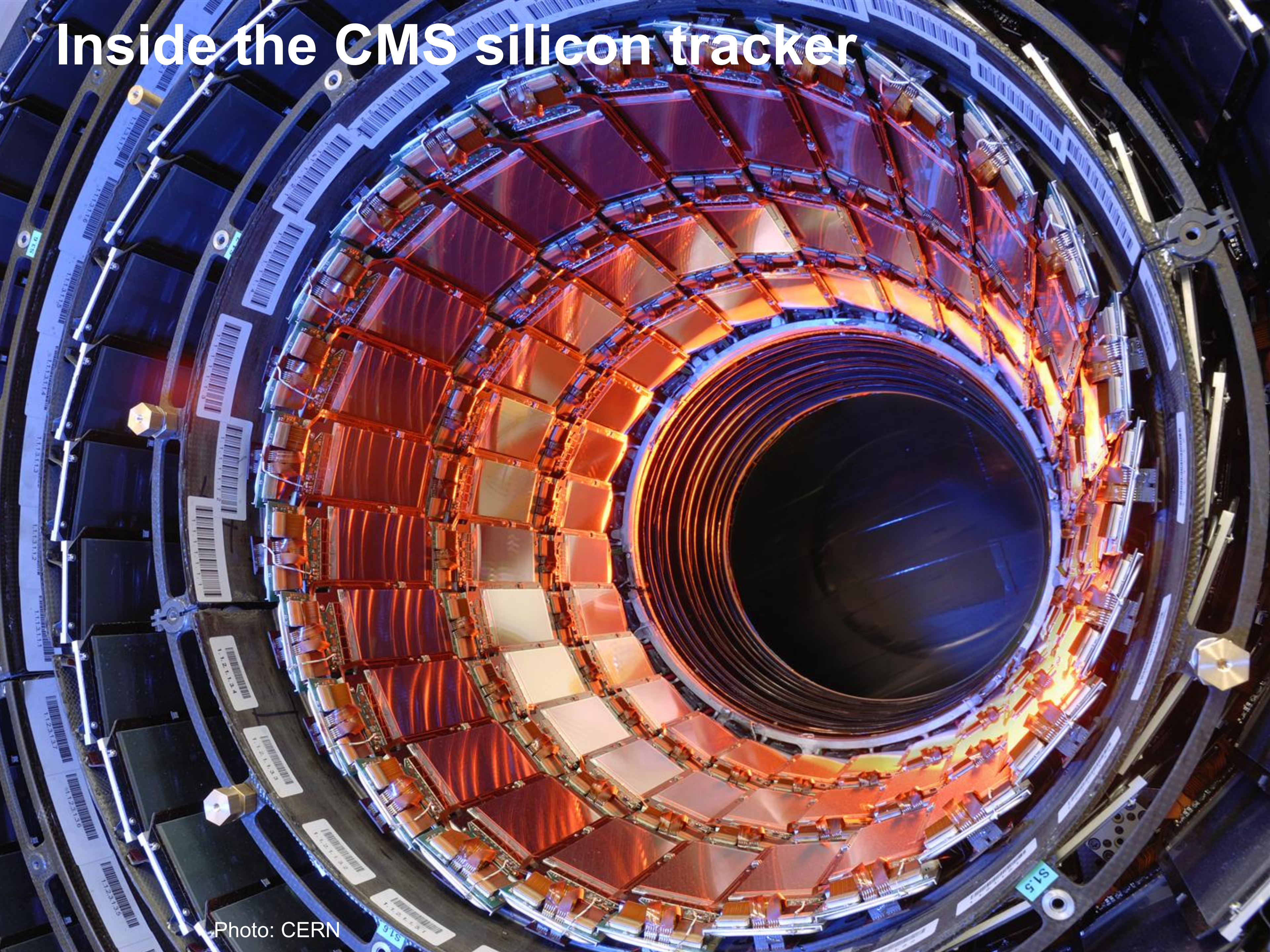
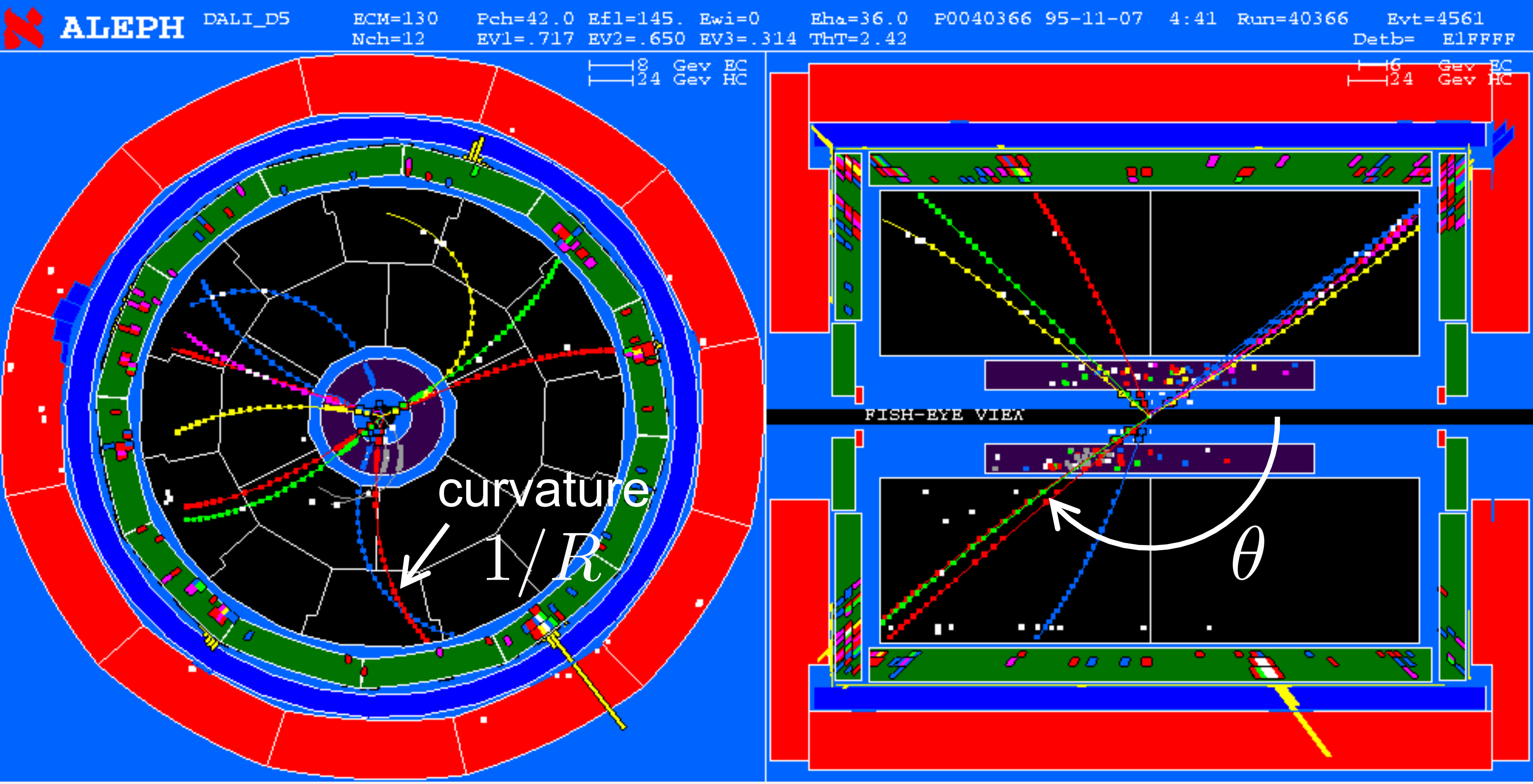


Photo: CERN

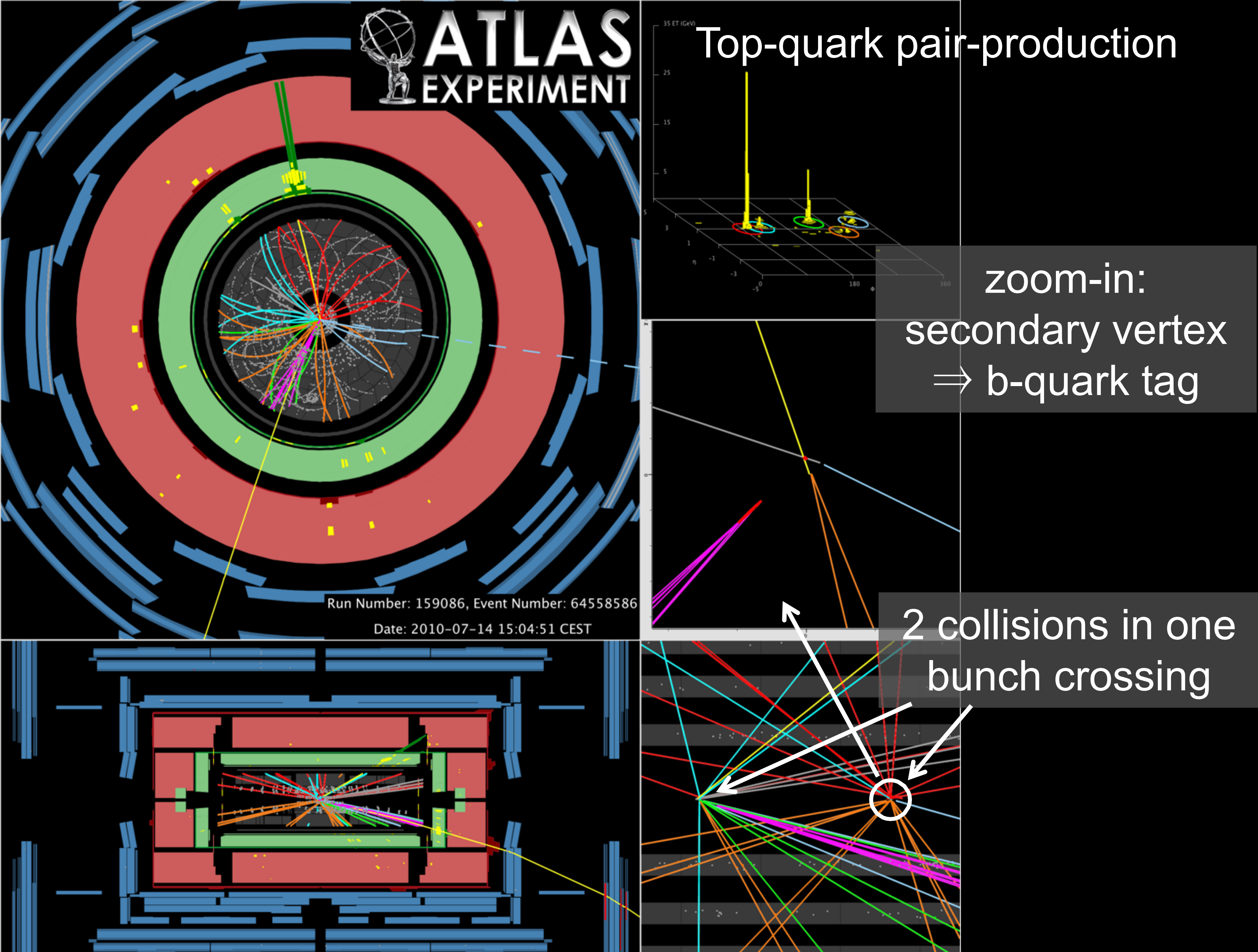


Curvature of ionization tracks in solenoidal magnetic field:

$$p_T = \pm eRB$$ sign of charged measured

$$p_L = p_T \cot\theta$$

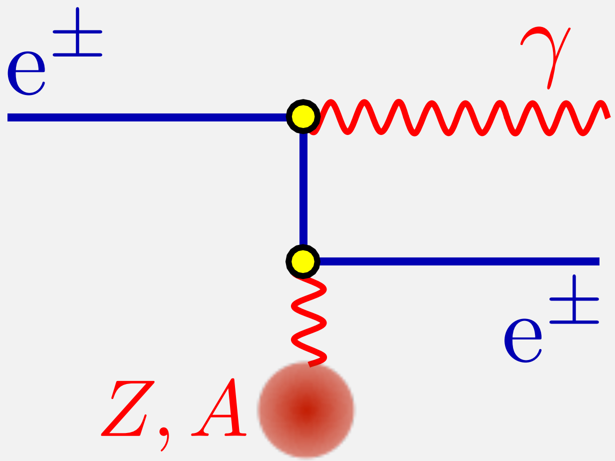
$$E = \sqrt{\vec{p}^{\,2} + m^2}$$ m assumed or from particle id.


Top-quark pair-production
ATLAS
EXPERIMENT
Run Number: 159086, Event Number: 64558586
Date: 2010-07-14 15:04:51 CEST
zoom-in:
secondary vertex
⇒ b-quark tag
2 collisions in one
bunch crossing

2) Radiation: $e^{\pm}$, γ

time →

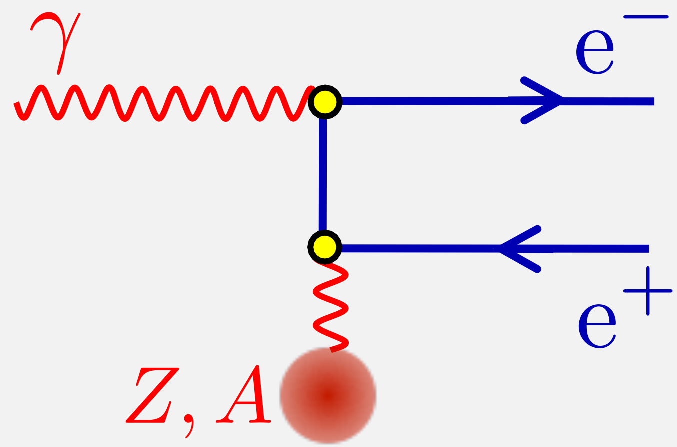
Bremsstrahlung:



nucleus
(detector medium)

attenuation length: X_0

Pair creation:



nucleus
(detector medium)

mean free path: $\frac{9}{7} X_0$

Radiation length:

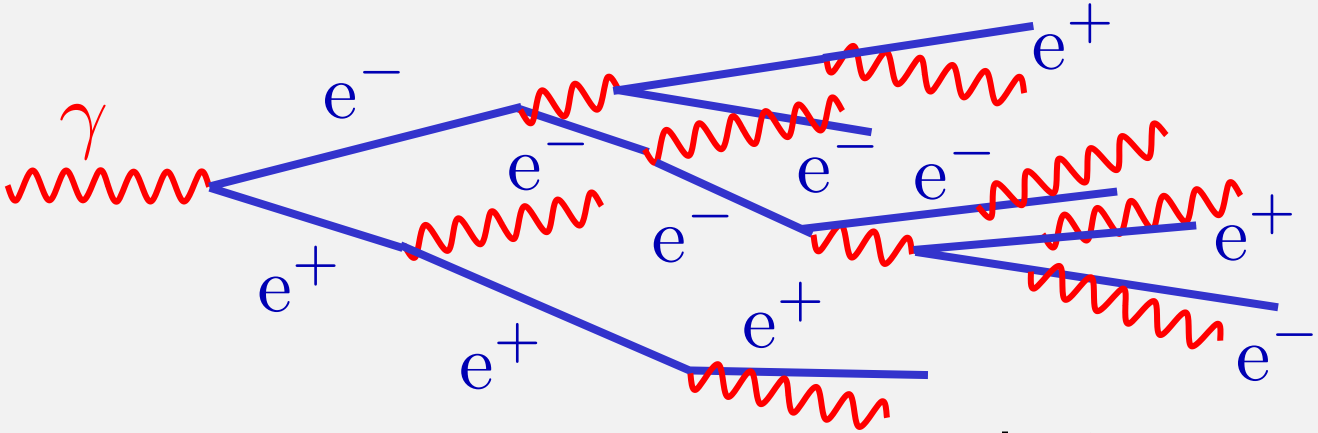
$$X_0 = \frac{1}{4\alpha^3} \frac{A}{N_A \rho} \frac{m^2}{Z^2 \ln \frac{183}{Z^{\frac{1}{3}}}}$$

Application: electromagnetic calorimeters

only dominant for electrons/positrons

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

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



electromagnetic shower

Photo: CERN

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

$$\frac{\sigma_E}{E} \approx \frac{3\%}{\sqrt{E/\mathrm{GeV}}}$$

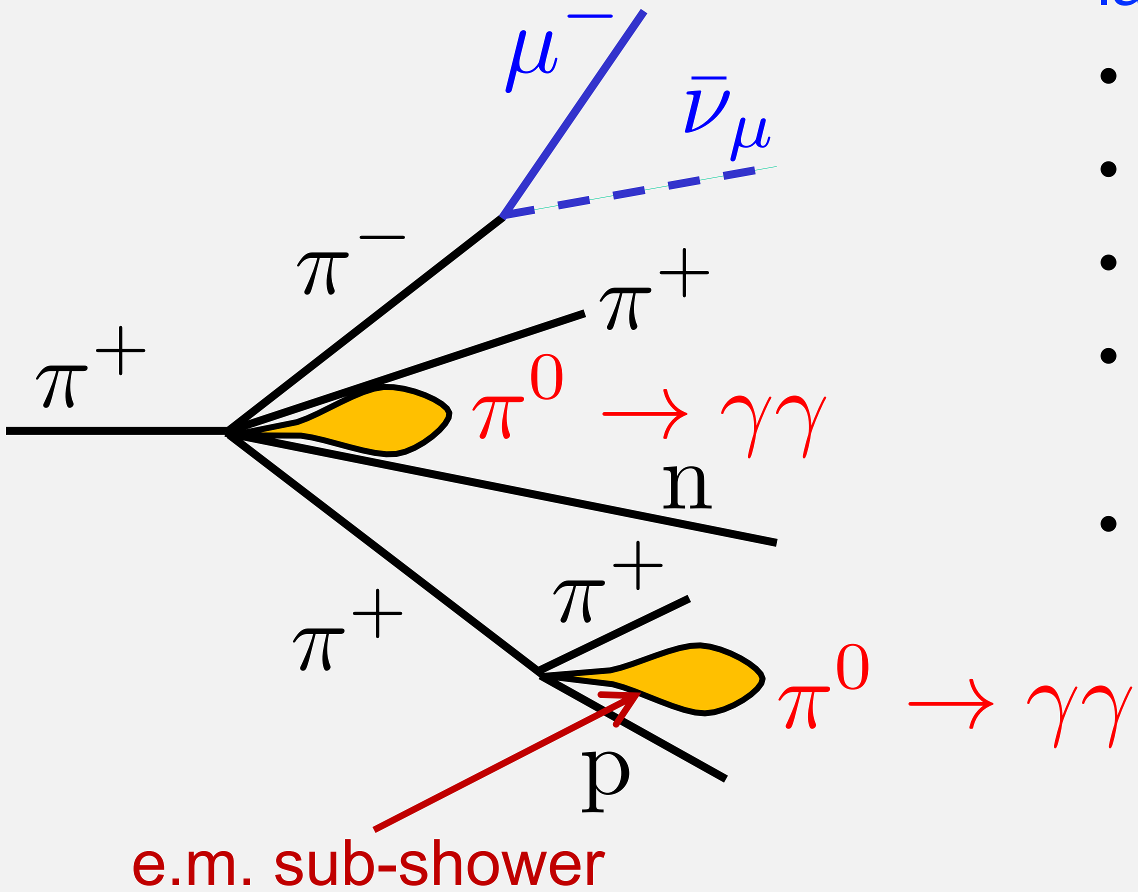
(at high energies)

Photo: CERN

2) Absorbing hadrons (charged and neutral):

strong interaction ⇒ attenuation length scale $\lambda_\mathrm{I} \propto A^{-1}$

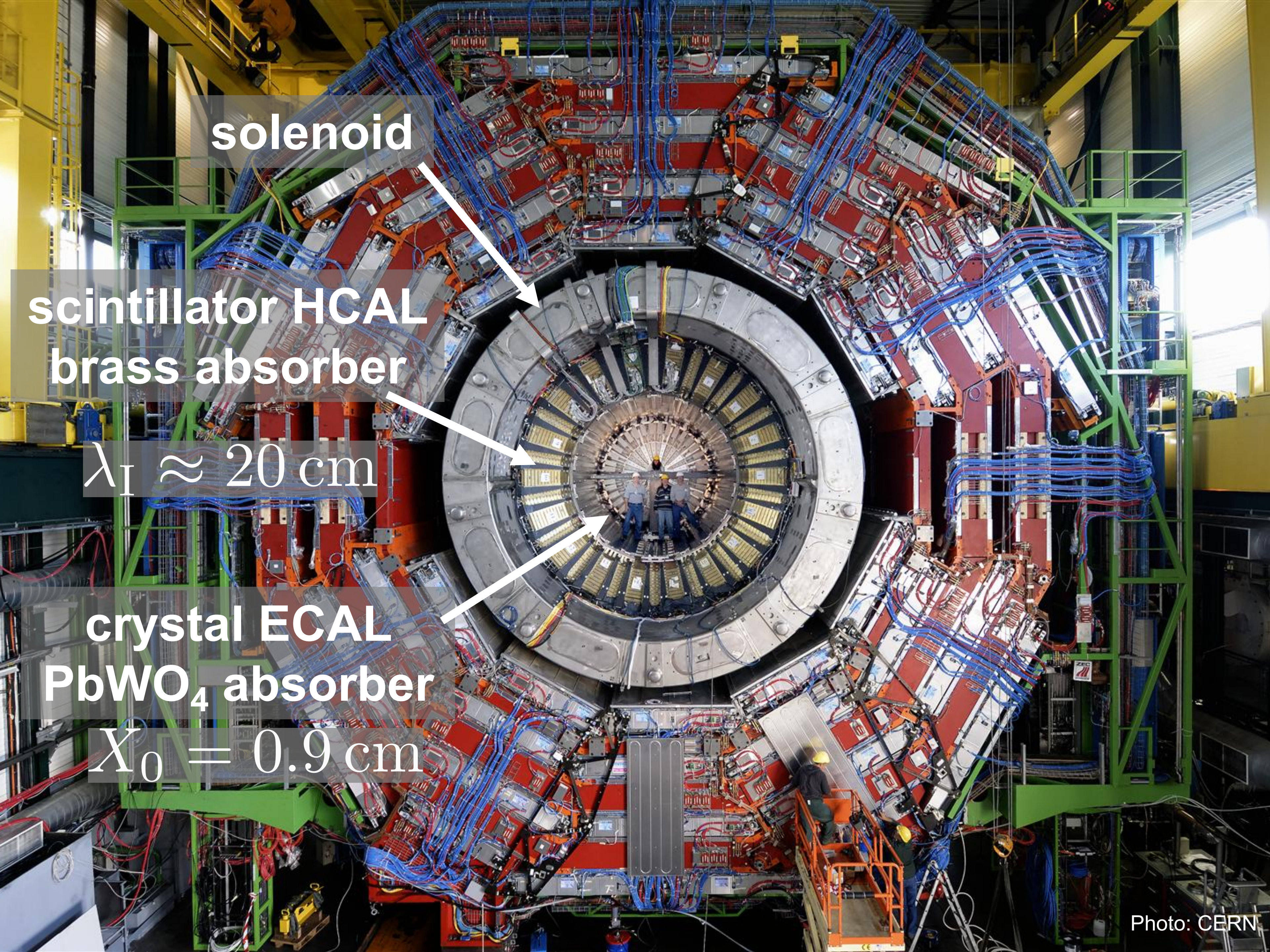
⇒ use material of large mass density (e.g. iron yoke of magnet)



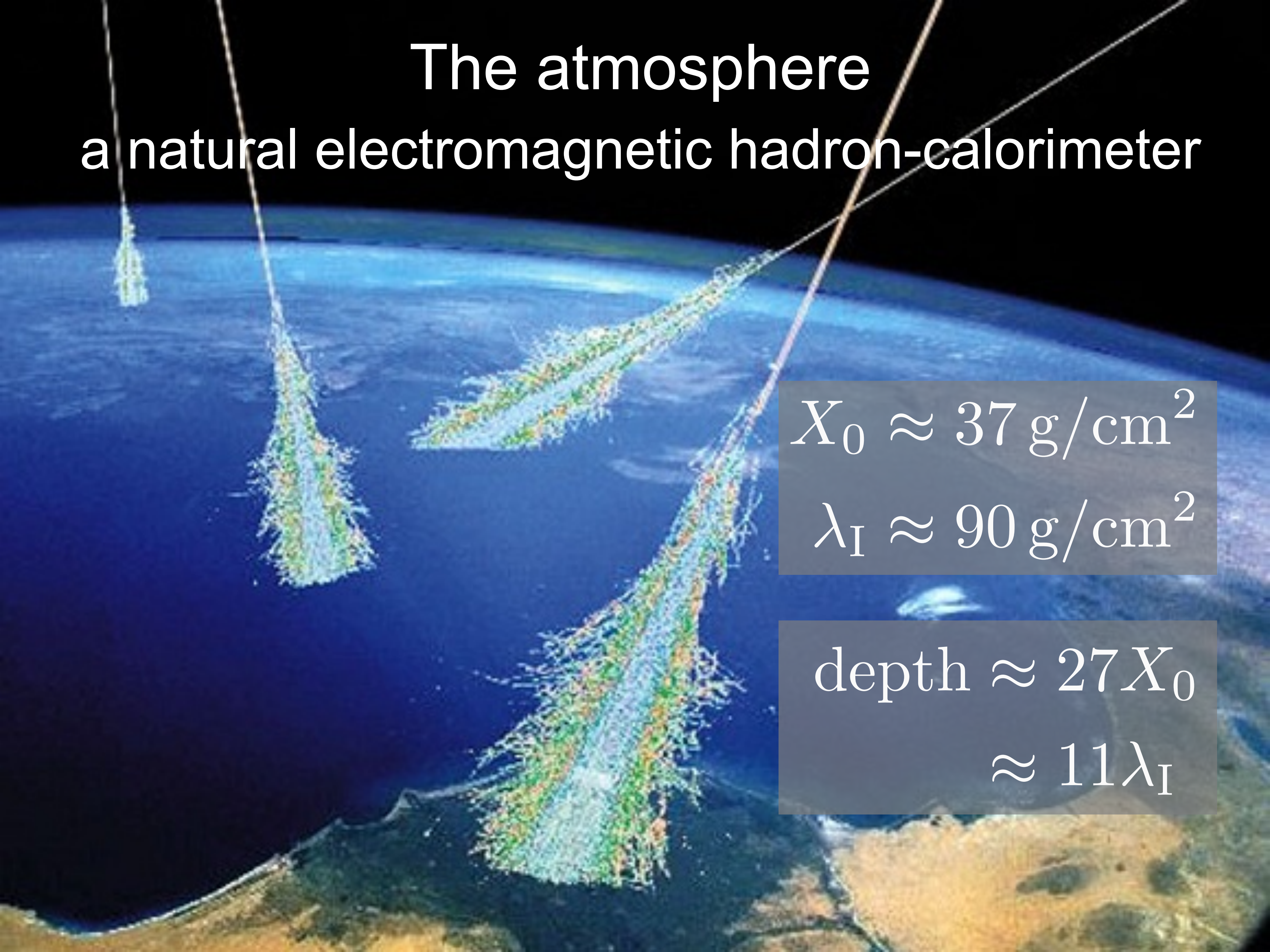
large fluctuations

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

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


solenoid
scintillator HCAL
brass absorber
$\lambda_I \approx 20\,\mathrm{cm}$
crystal ECAL
$PbWO_4$ absorber
$X_0 = 0.9\,\mathrm{cm}$
Photo: CERN

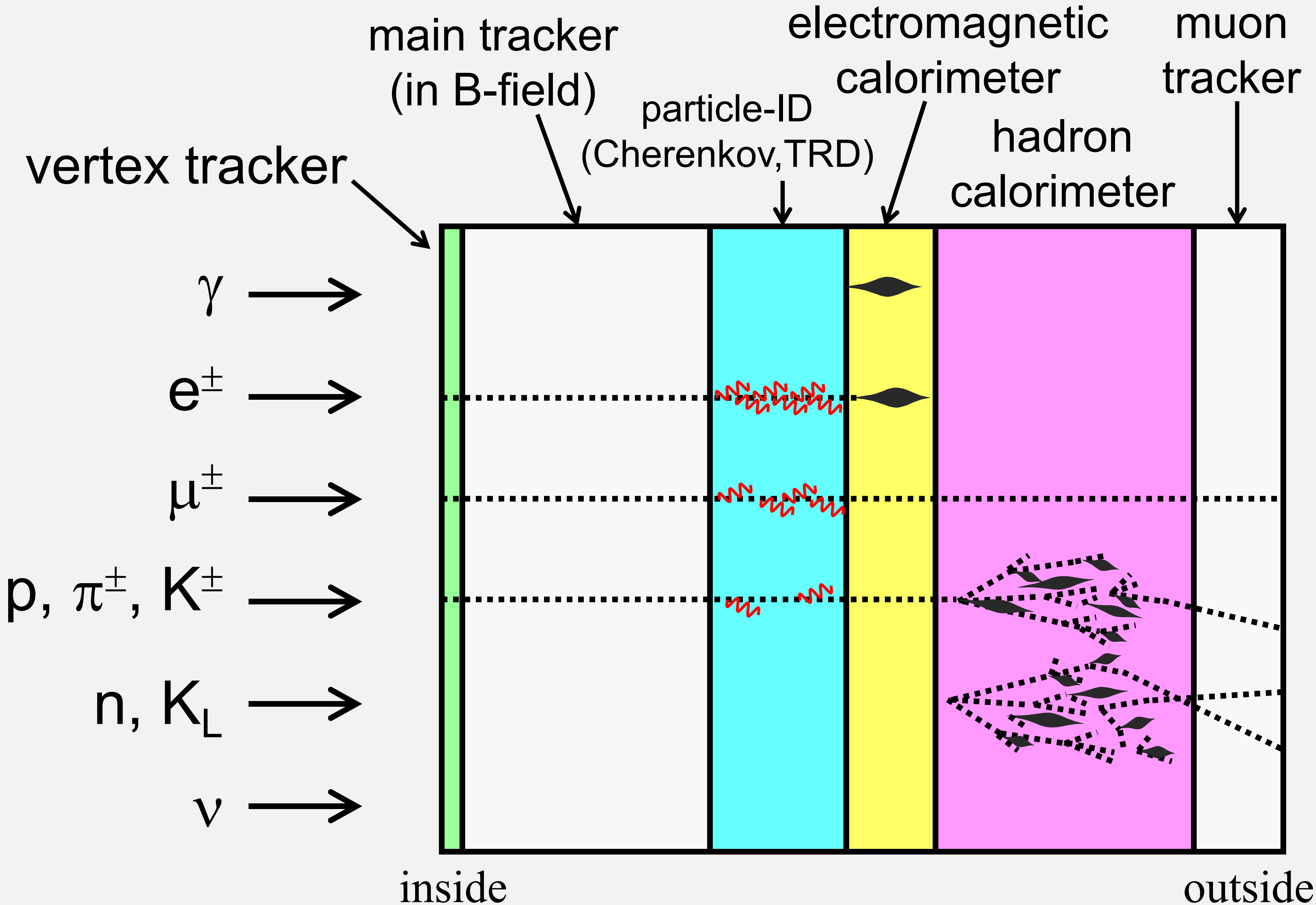
The atmosphere
a natural electromagnetic hadron-calorimeter



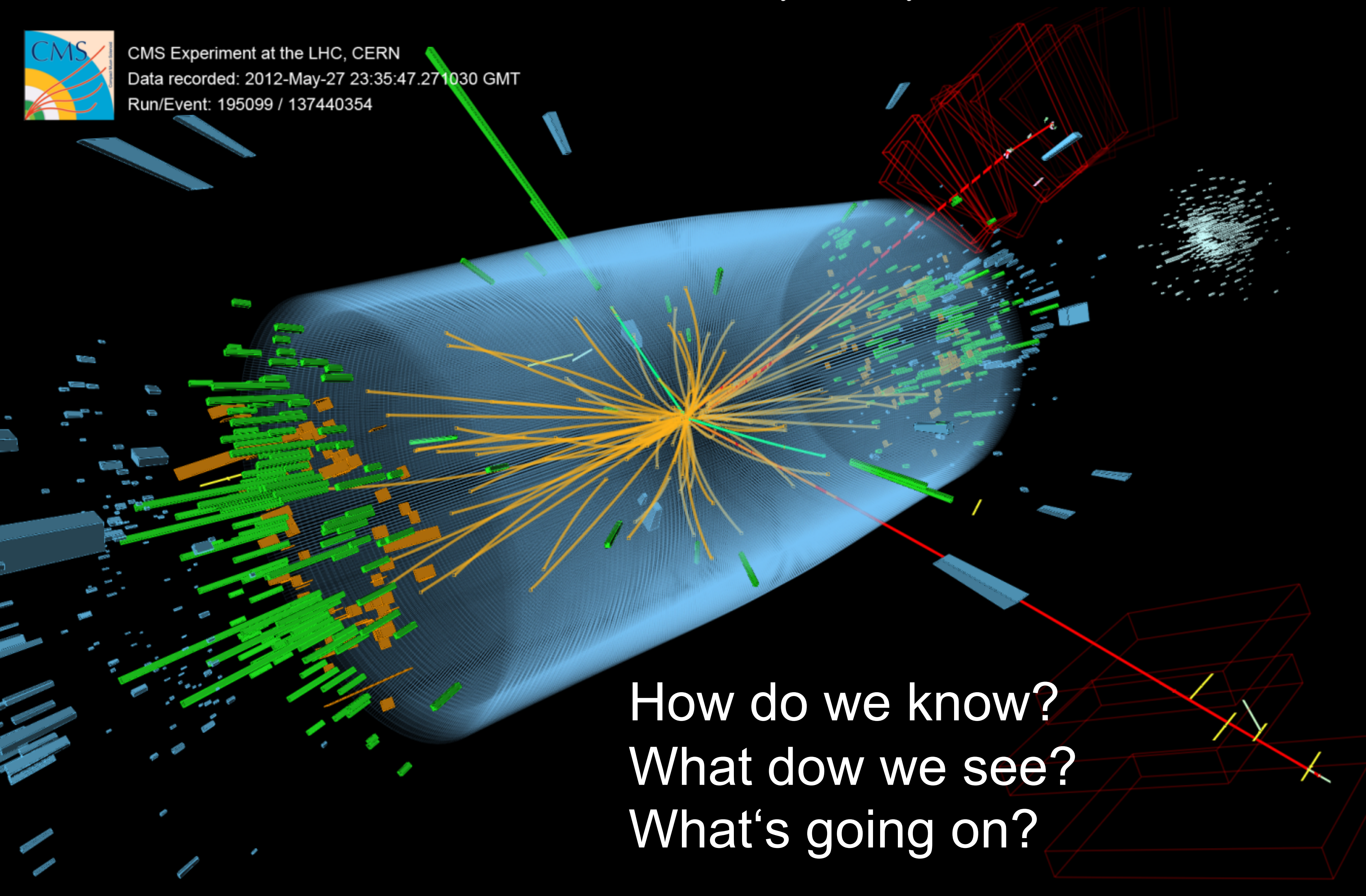
$$X_0 \approx 37\,\mathrm{g/cm^2}$$
$$\lambda_\mathrm{I} \approx 90\,\mathrm{g/cm^2}$$

$$\mathrm{depth} \approx 27 X_0$$
$$\approx 11 \lambda_\mathrm{I}$$

The fingerprints of ”stable“ particles

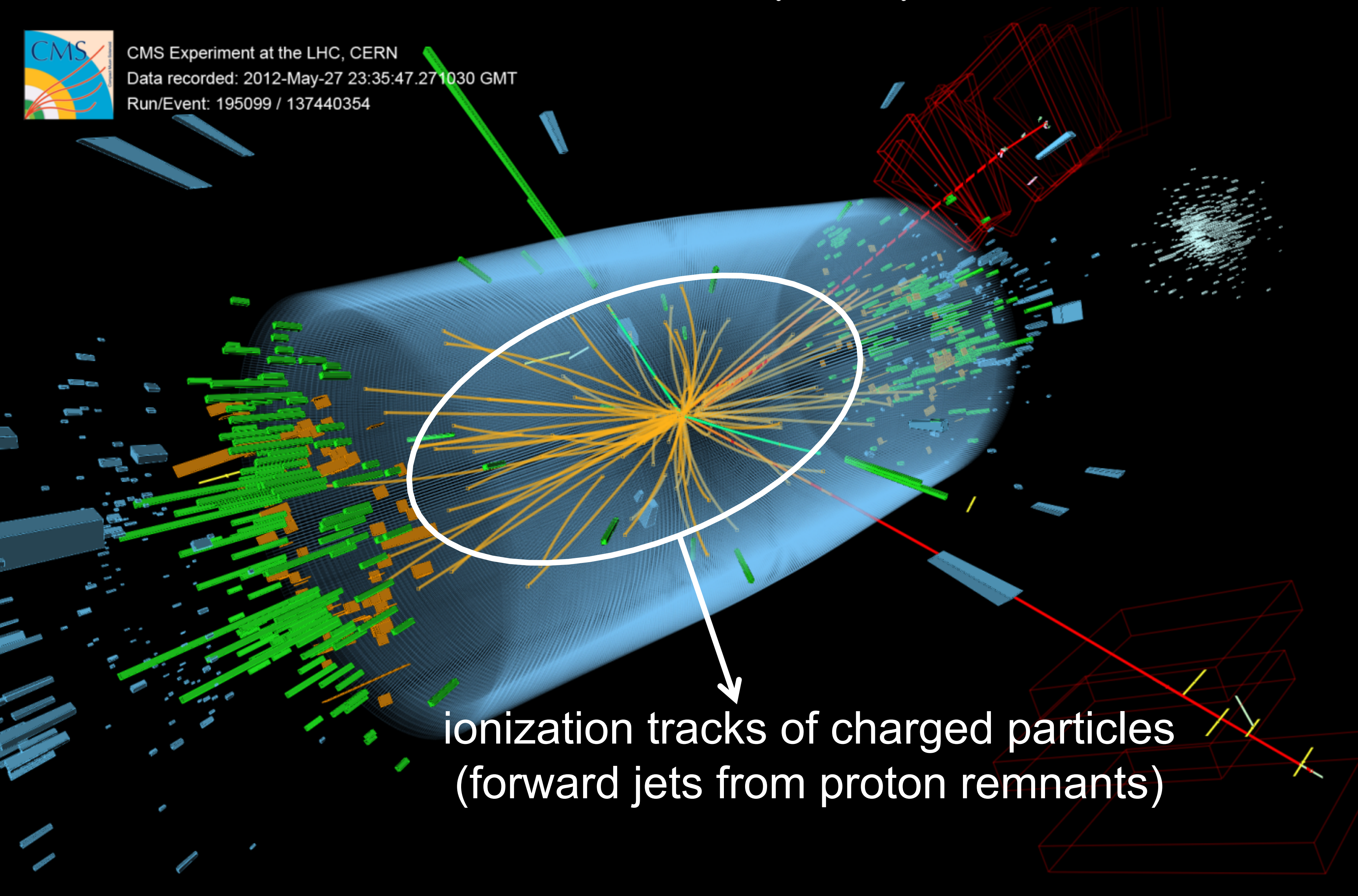


$H \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^-$

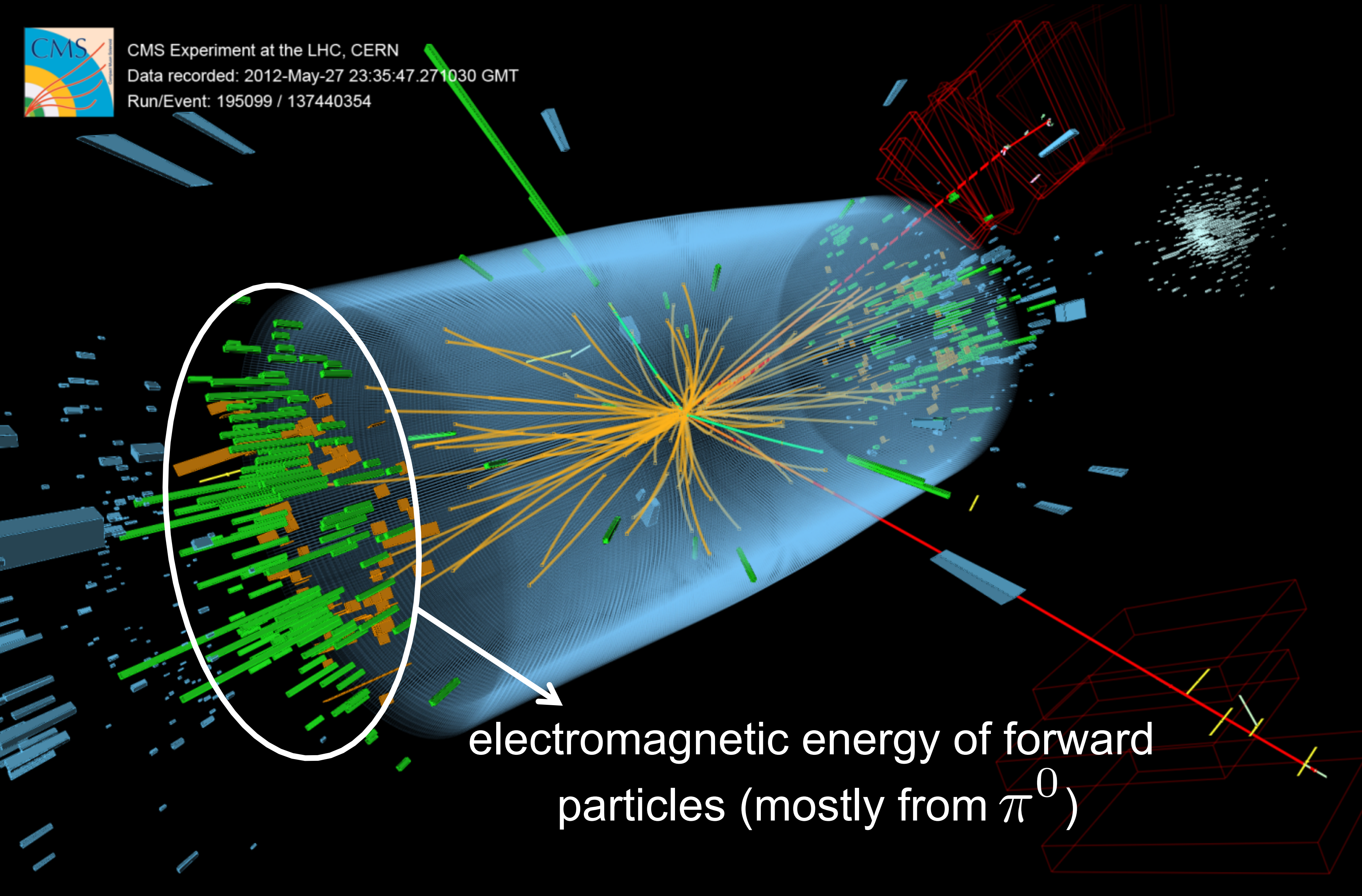


How do we know?
What dow we see?
What‘s going on?

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

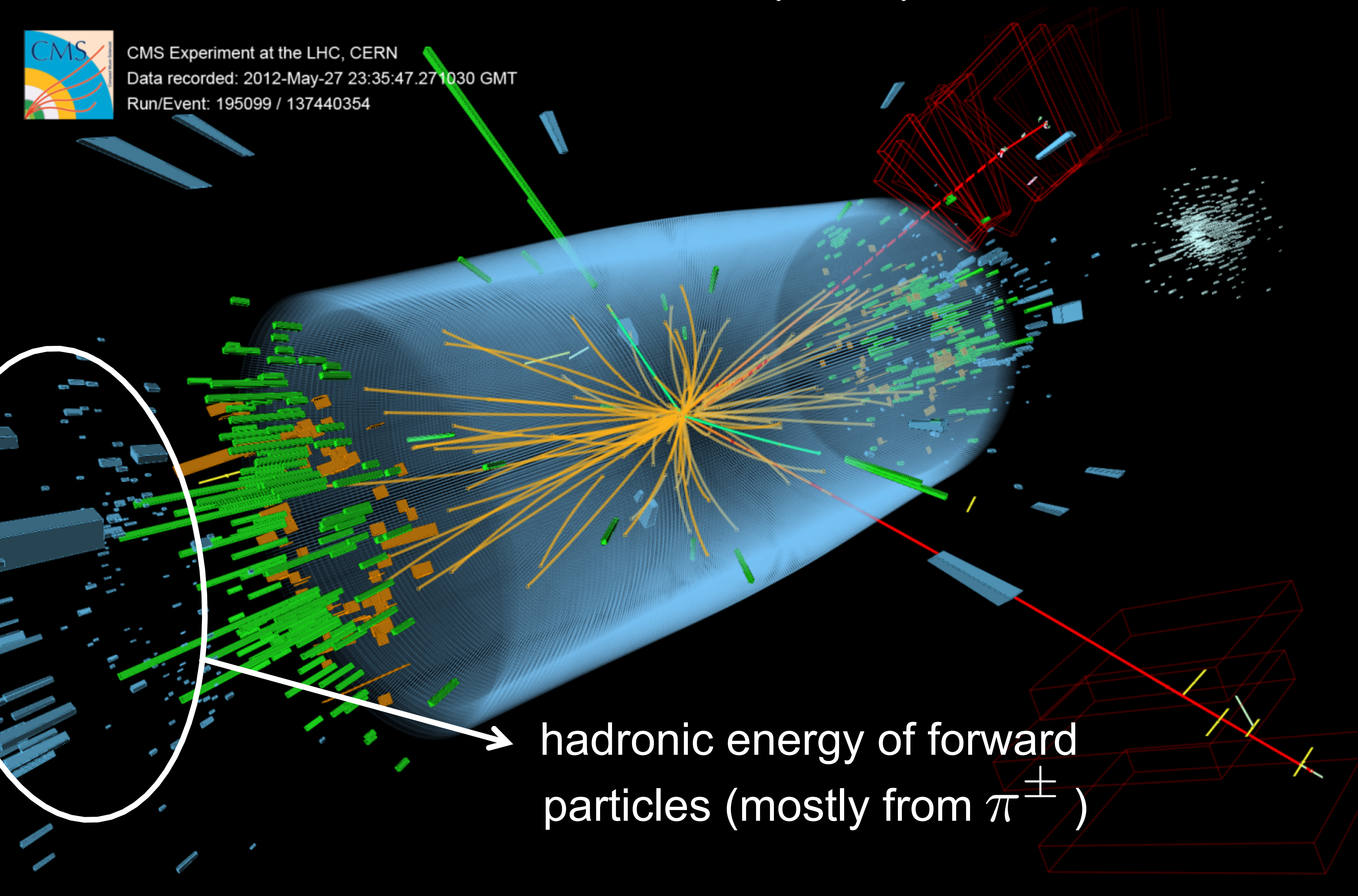


$H \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^-$

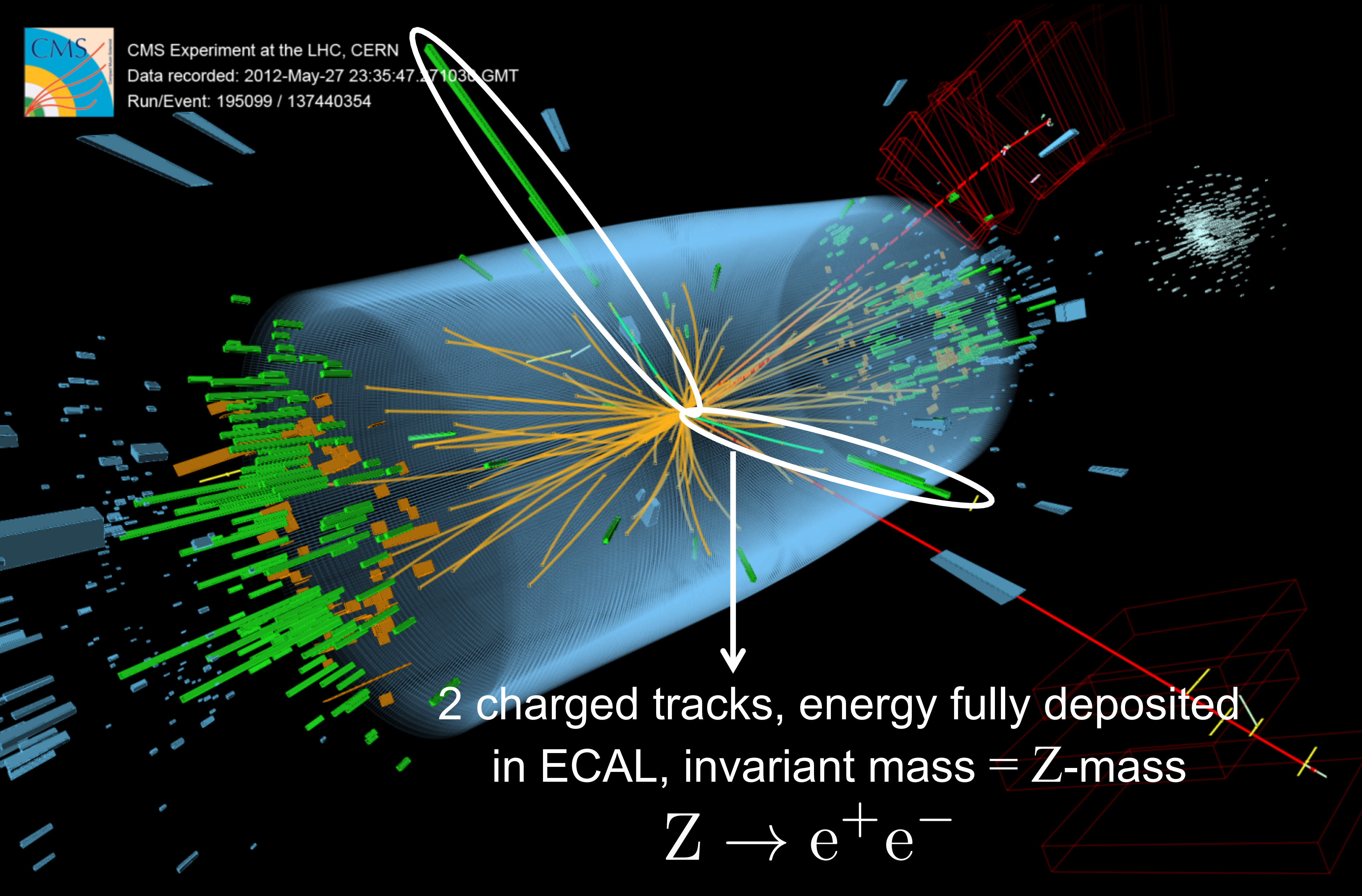


electromagnetic energy of forward particles (mostly from π^0)

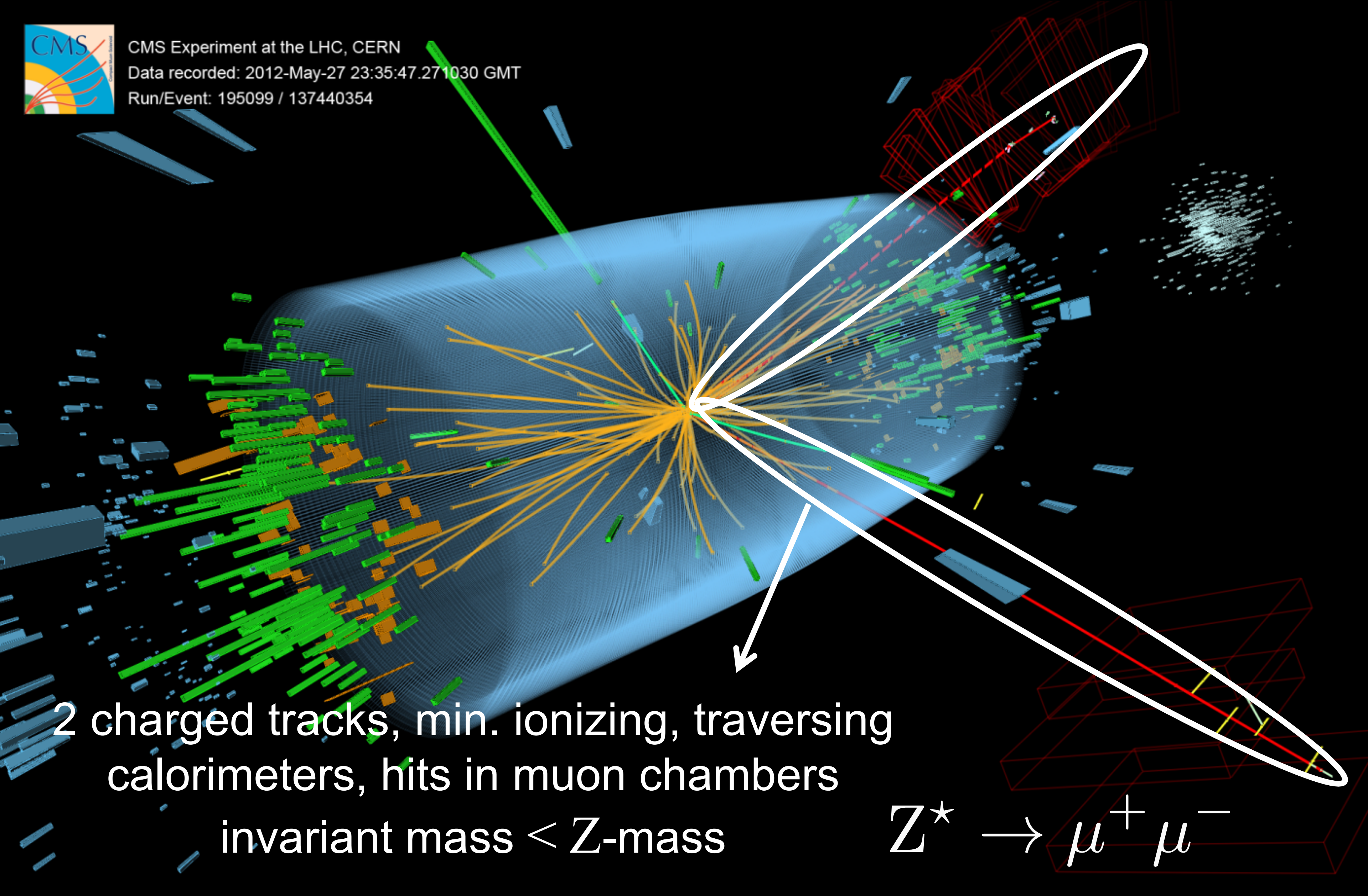
$H \to ZZ \to \mu^+\mu^-e^+e^-$



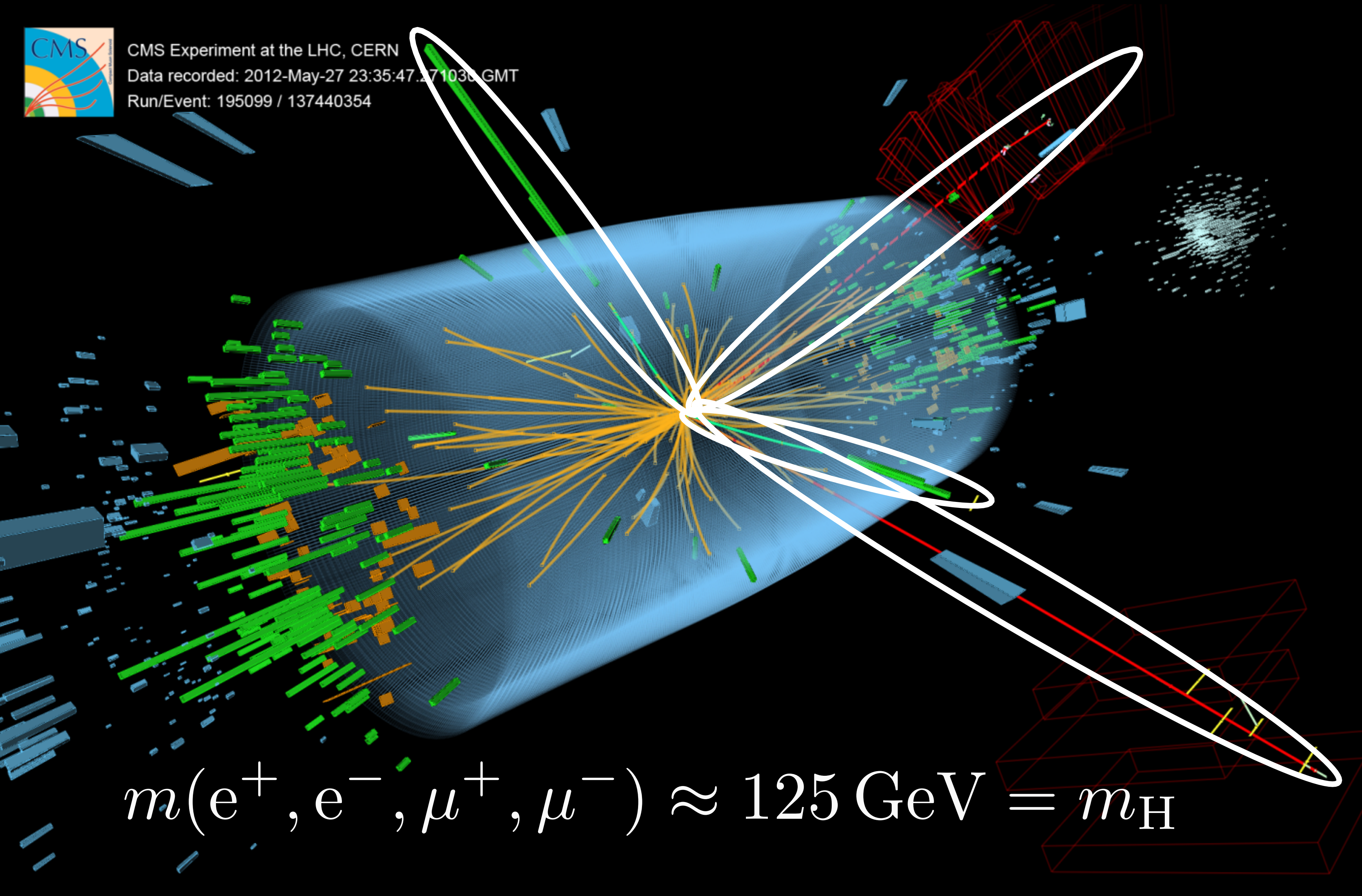
$H \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^-$



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

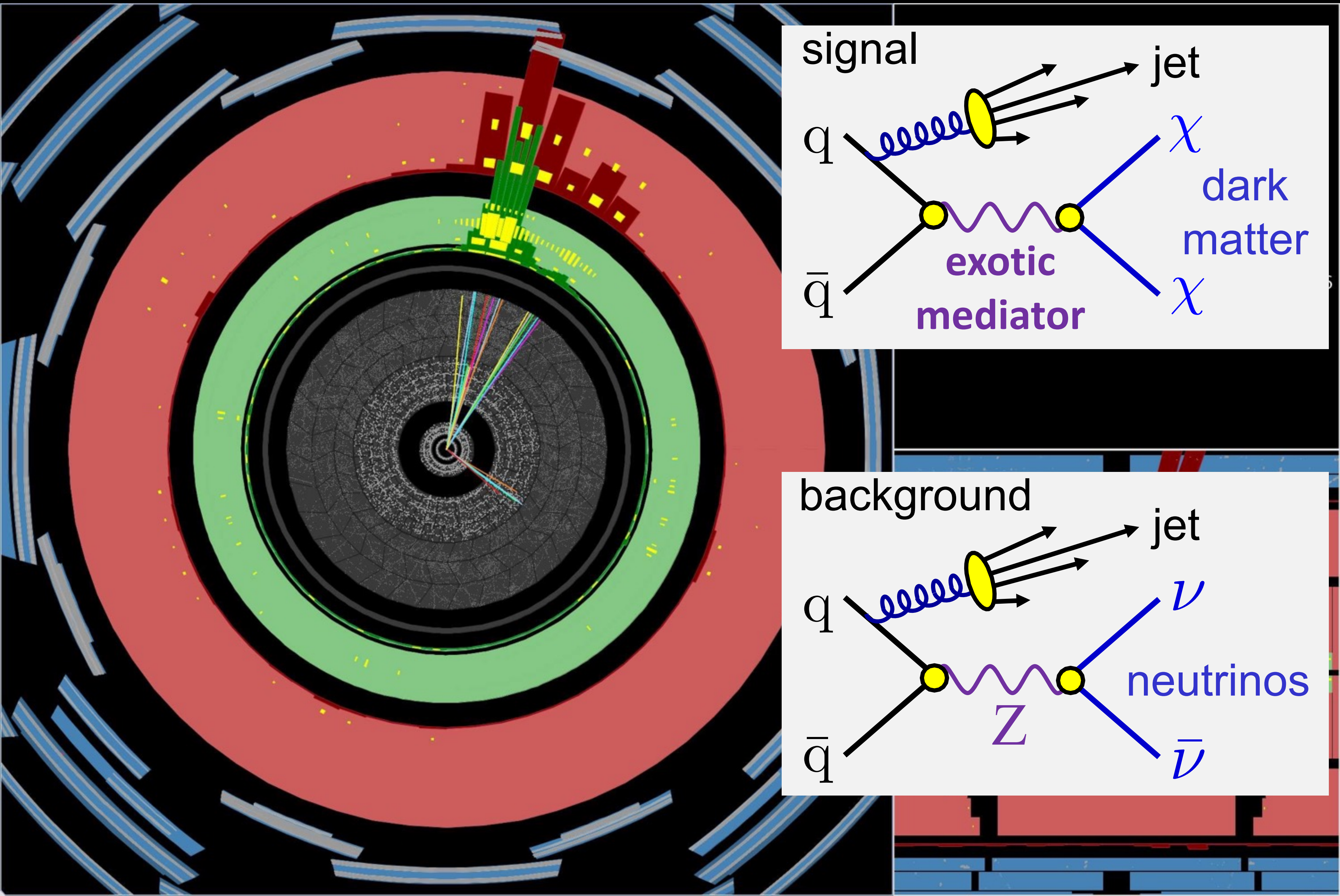


$$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$$



$$m(\mathrm{e}^+, \mathrm{e}^-, \mu^+, \mu^-) \approx 125\,\mathrm{GeV} = m_\mathrm{H}$$

The relevance of missing (transverse) energy



Part II

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

Reminder: examples of 4-vectors

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

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

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

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

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

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

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

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

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

particle mass: m

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

$$-\partial_\mu \partial^\mu \phi = m^2 \phi$$

wave function (ϕ)

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

Formulation via Lagrange density:

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

mass term (↔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-½ particle

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:

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

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

ψ	4 independent degrees of freedom
$\overline{\psi} \equiv \psi^\dagger \gamma^0$	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-½ 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:

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

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

Towards Quantum Field Theorie

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

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

Examples:

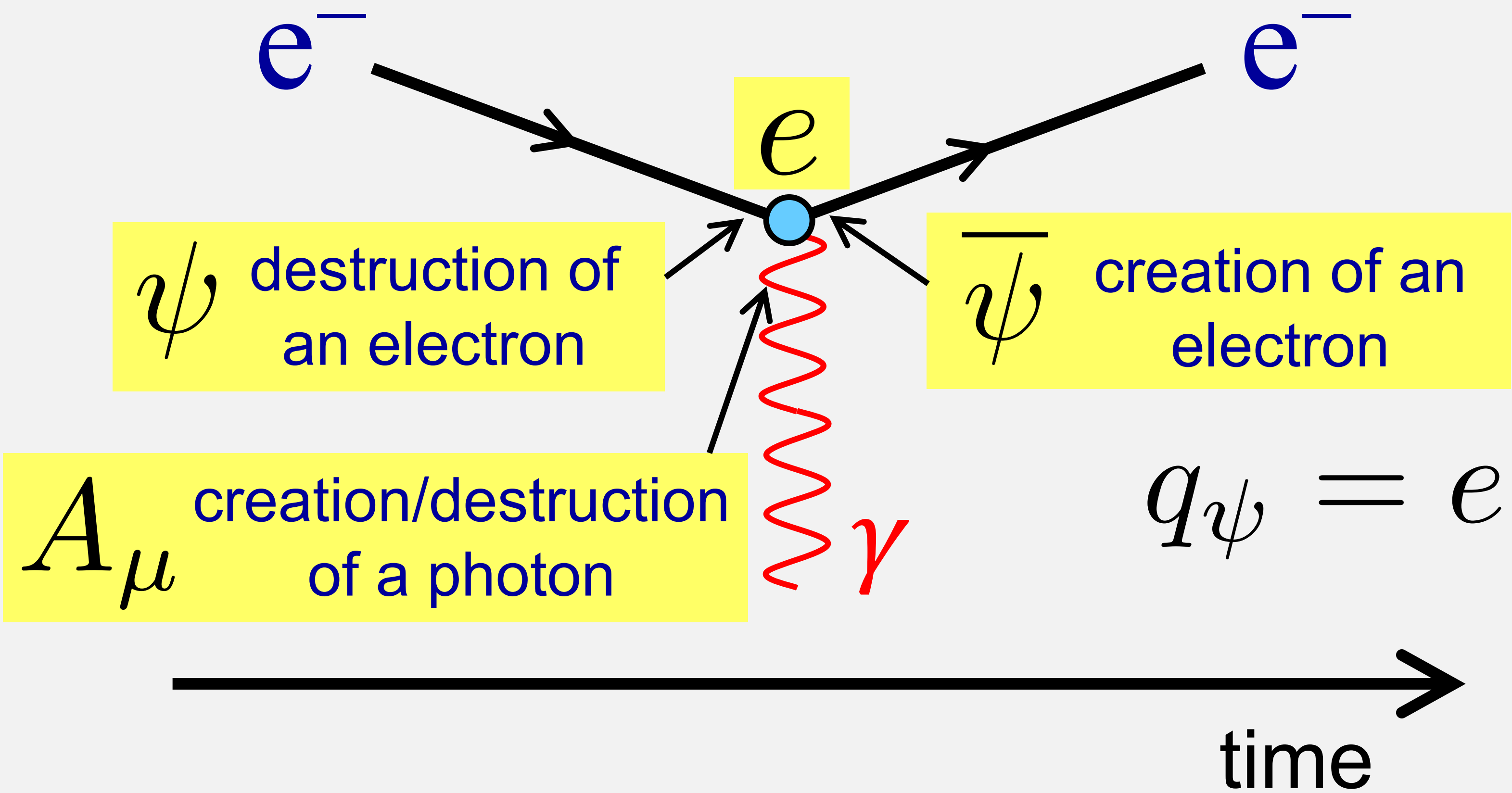
ψ_{e} destruction of an electron
creation of a positron

$\overline{\psi}_{\mathrm{e}}$ creation of an electron
destruction of a positron

A_μ creation / destruction of a photon

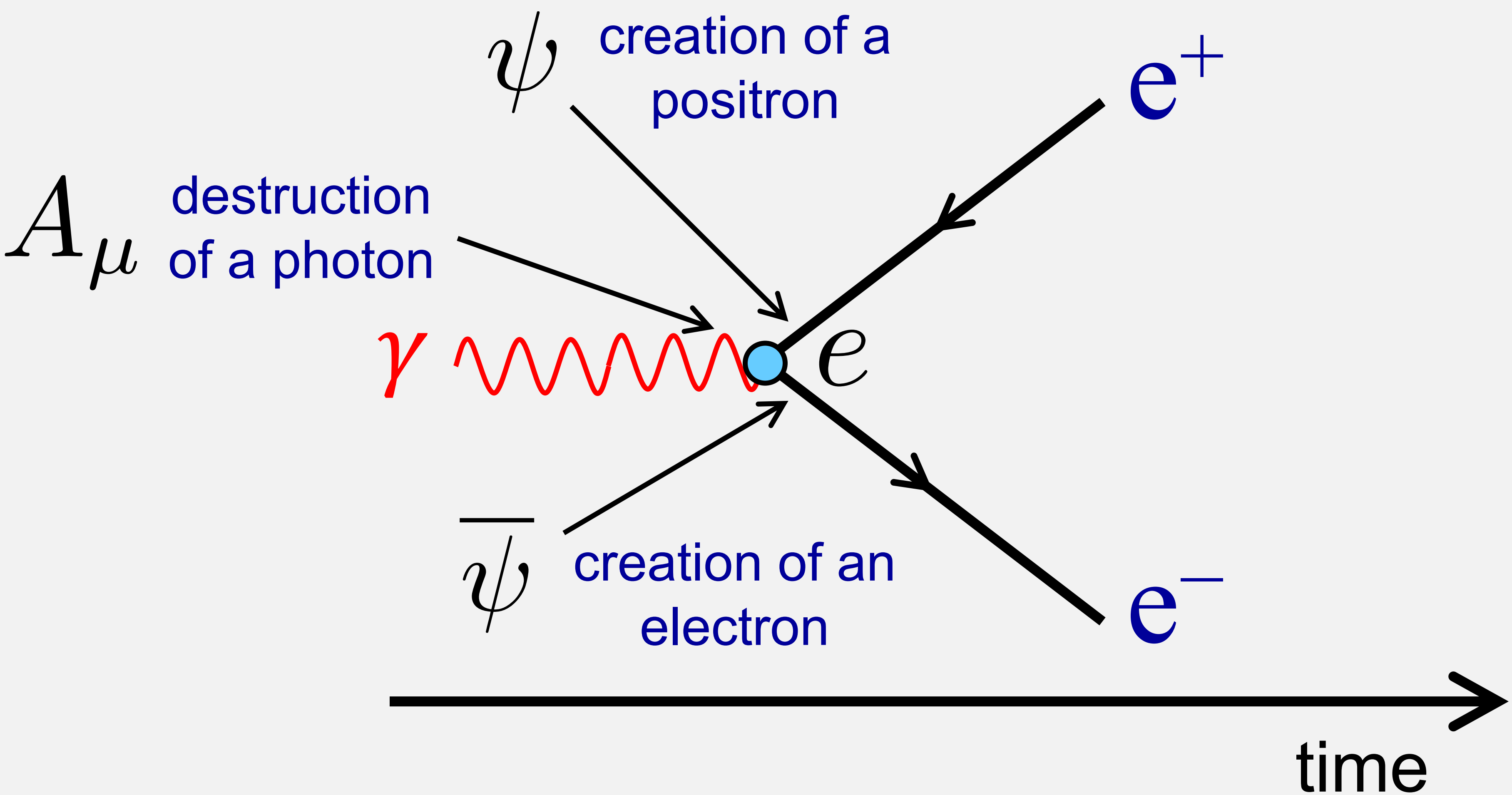
$\mathcal{L}_{\text{int}}$ and fundamental couplings (vertices)

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



$$q_\psi = e$$

… turn it any way you like ...

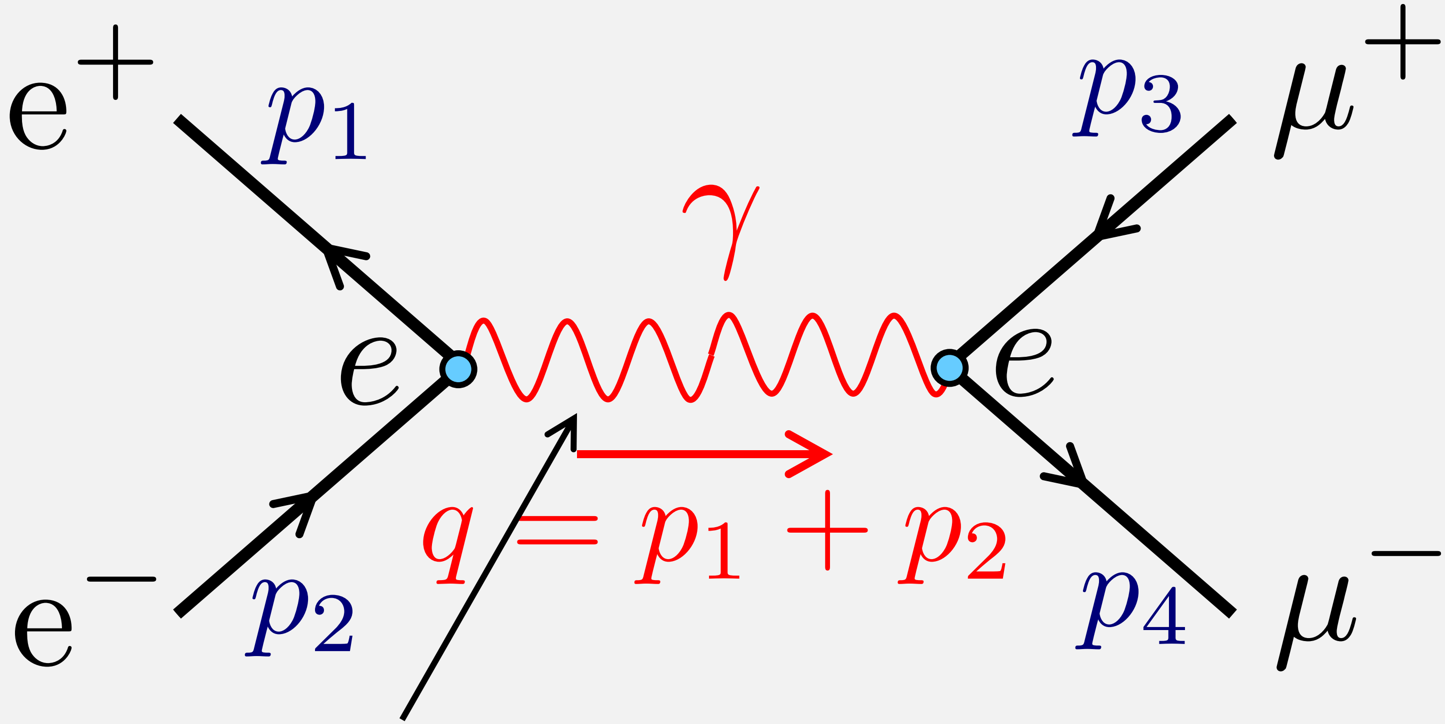


- anti-fermion ≙ fermion moving backwards in time
- fermion lines never end (e.m. current)

building Feynman diagrams

pronounced like “fine man“

→ scattering amplitudes in perturbative expansion in powers of $\boldsymbol{e}$



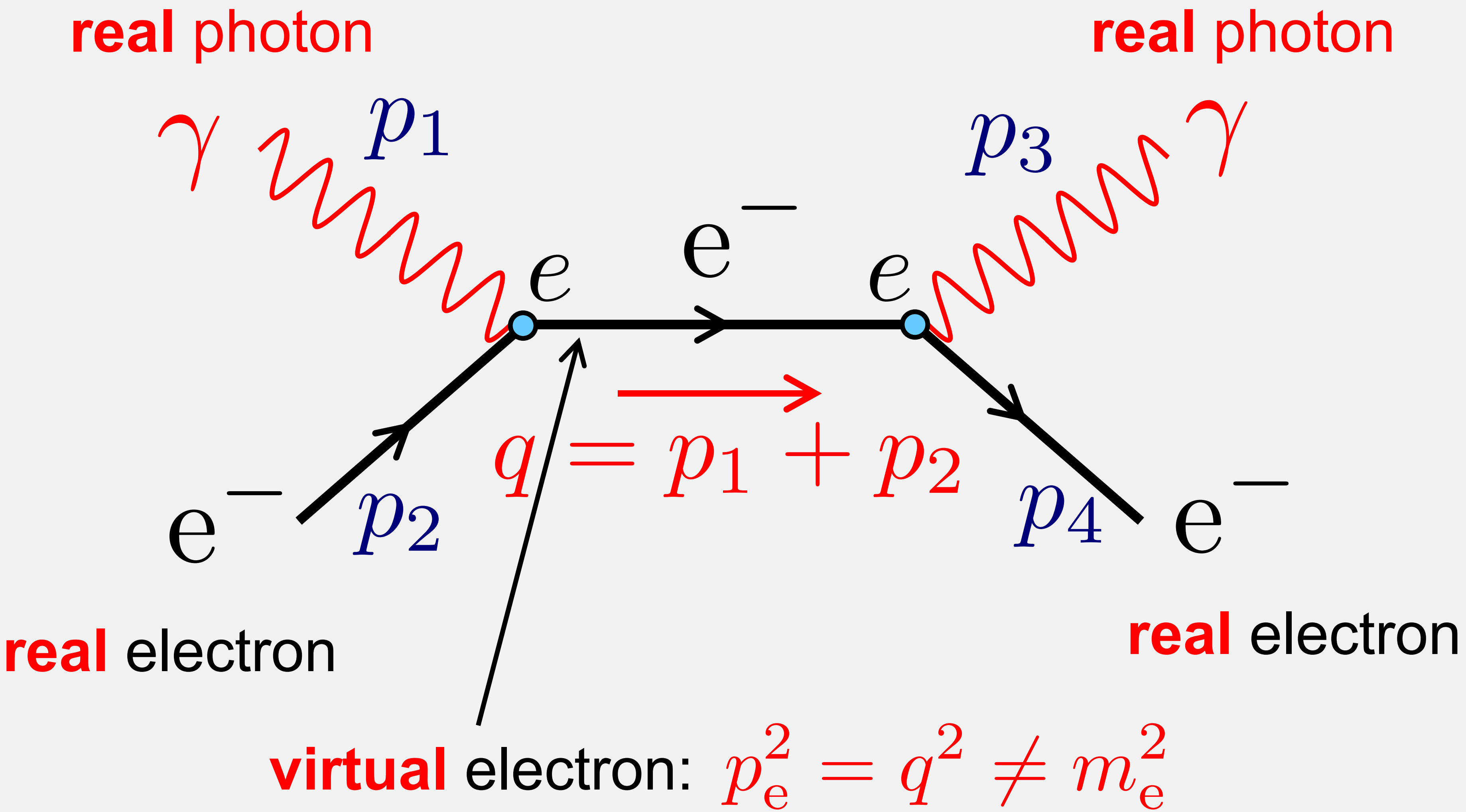
virtual photon (≙ potential in momentum space)

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

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

... anybody can go virtual ...

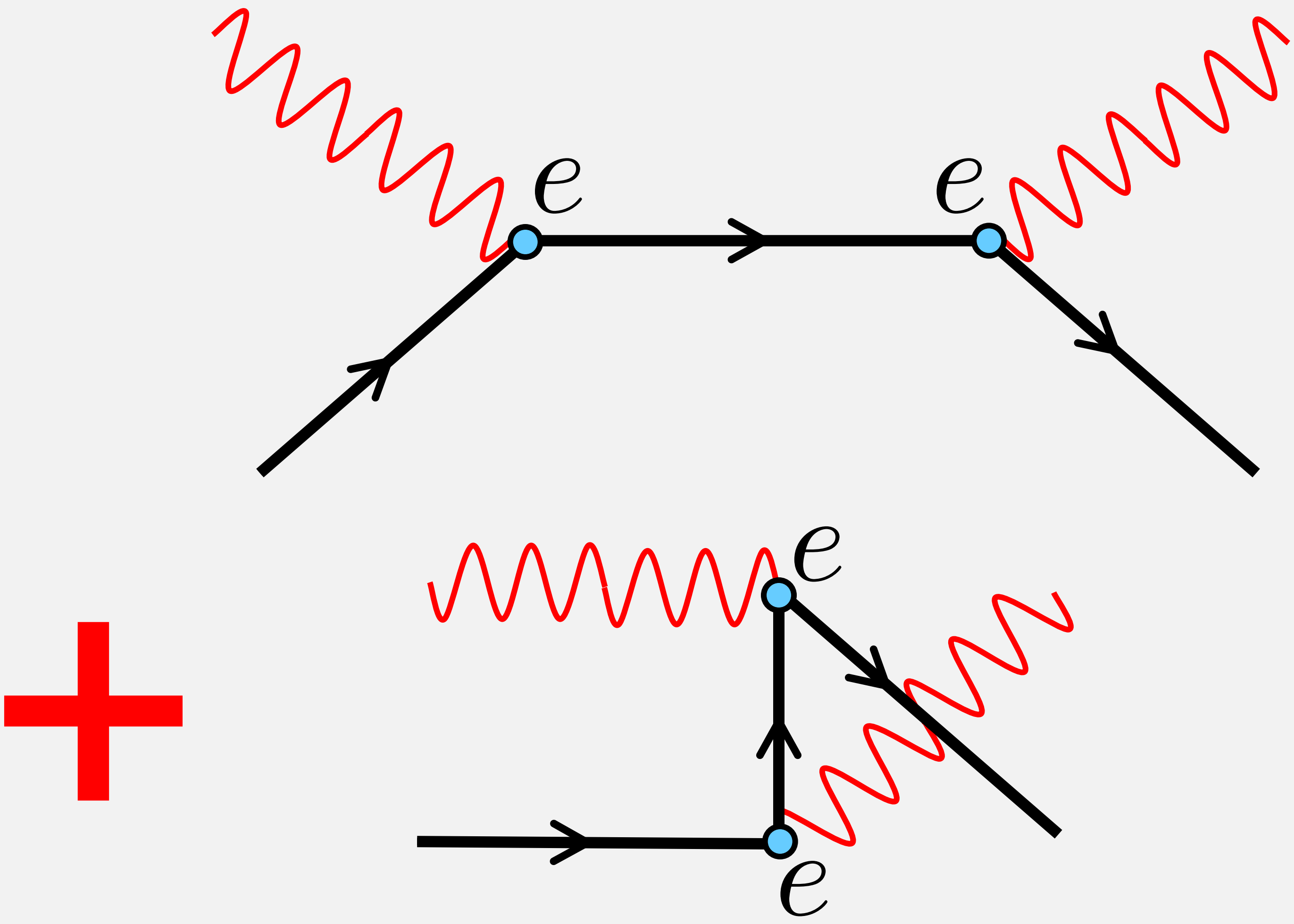
e.g. (inverse) Compton scattering



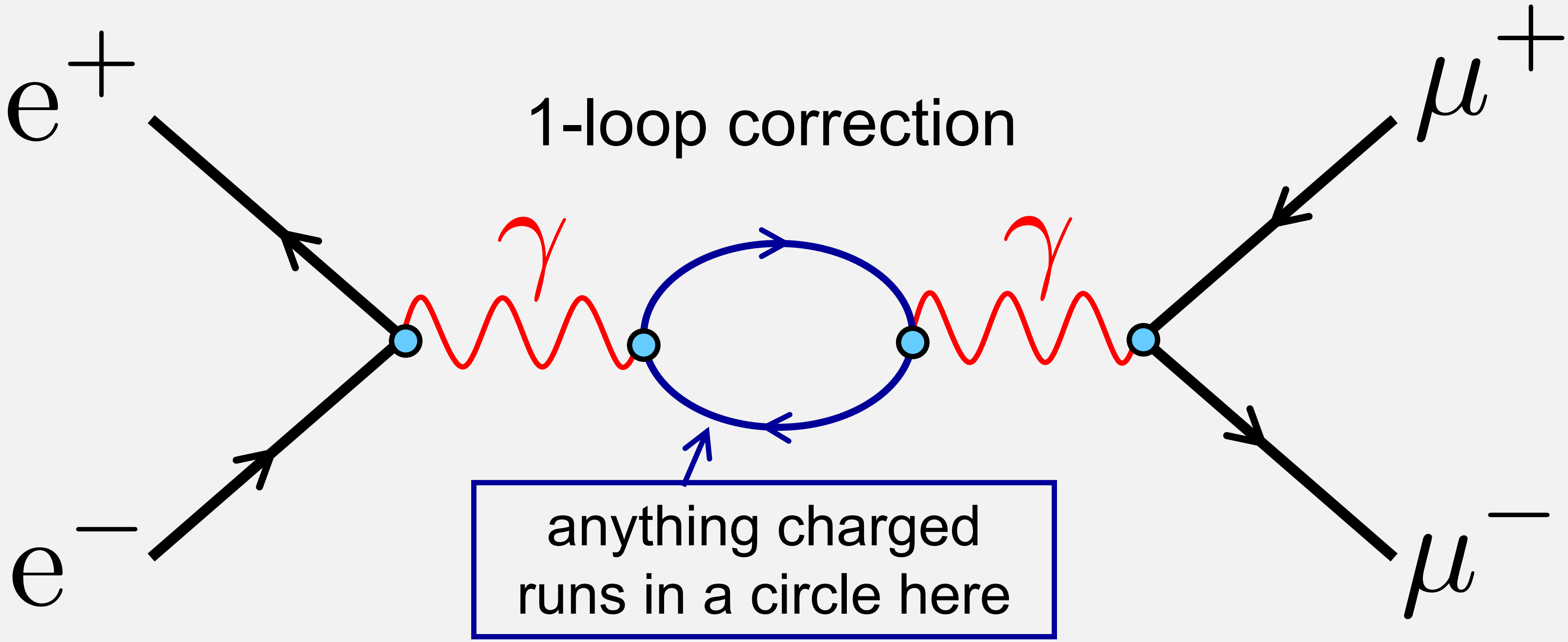
QFT: anything possible happens (all at once)

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

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

But this only works for global phase (α = const.)

3) Quantum electrodynamics:

local phase transformation $\psi \rightarrow e^{i\alpha(x)}\psi$

changes free particle Lagrangian, e.g.

$$\mathcal{L} = \overline{\psi}(i\gamma_\mu\partial^\mu - m)\psi$$

$$\rightarrow \mathcal{L} - (\overline{\psi}\gamma_\mu\psi)\partial^\mu\alpha(x)$$

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 $$D_\mu = \partial_\mu + ieQA_\mu$$

Local gauge transformation

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

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

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

Quantum electrodynamics (gauge invariant)

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

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

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

amplitudes of color-components

3×3 matrices

Why 8 phases?

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

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	$SU(3)$ symmetry
1 photon $A_\mu(x)$	8 gluons $A^a_\mu(x)$
gauge transformation:	gauge transformation:
$\psi \to e^{iQ\alpha(x)}\psi$	$\psi \to e^{iT^a\alpha^a(x)}\psi$
$D_\mu\psi \to e^{iQ\alpha(x)}D_\mu\psi$	$D_\mu\psi \to e^{iT^a\alpha^a(x)}D_\mu\psi$
covariant derivative:	covariant derivative:
$D_\mu = \partial_\mu + ieQA_\mu$	$D_\mu = \partial_\mu + ig_s T^a A^a_\mu$
e: electric unit charge (coupling strength)	g_s: unit color charge (coupling strength of strong force)

Dynamics of the $SU(3)$ gluons:

$U(1)$ symmetry	$SU(3)$ symmetry
1 photon $A_\mu(x)$	8 gluons $A_\mu^a(x)$
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$	$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{a\,\mu\nu}$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$	$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f^{abc} A_\mu^b A_\nu^c$ (gauge invariance $\Rightarrow$)
$[Q, Q] = 0$	$[T^a, T^b] = i f^{abc} T^c$ (f^{abc}: real numbers)
$U(1)$ is abelian	$SU(3)$ is non-abelian

Quantum Chromodynamics

quark ↓ gluons in here ↓ gluon dynamics ↓

$$\mathcal{L} = \overline{\psi}\,(i\gamma^{\mu} D_{\mu} - m)\,\psi - \frac{1}{4} F^{a}_{\mu\nu} F^{a\,\mu\nu}$$

$$= \quad \mathcal{L}_{g_{\rm s}=0}$$ free propagation of quarks/gluons

$$- g_{\rm s}\left(\overline{\psi}\gamma^{\mu} T^{a}\psi\right) A^{a}_{\mu}$$ qg-interaction

$$+ \mathcal{L}_{\rm ggg} \qquad \sim g_{\rm s} f^{abc} A^{a} A^{b} A^{c}$$

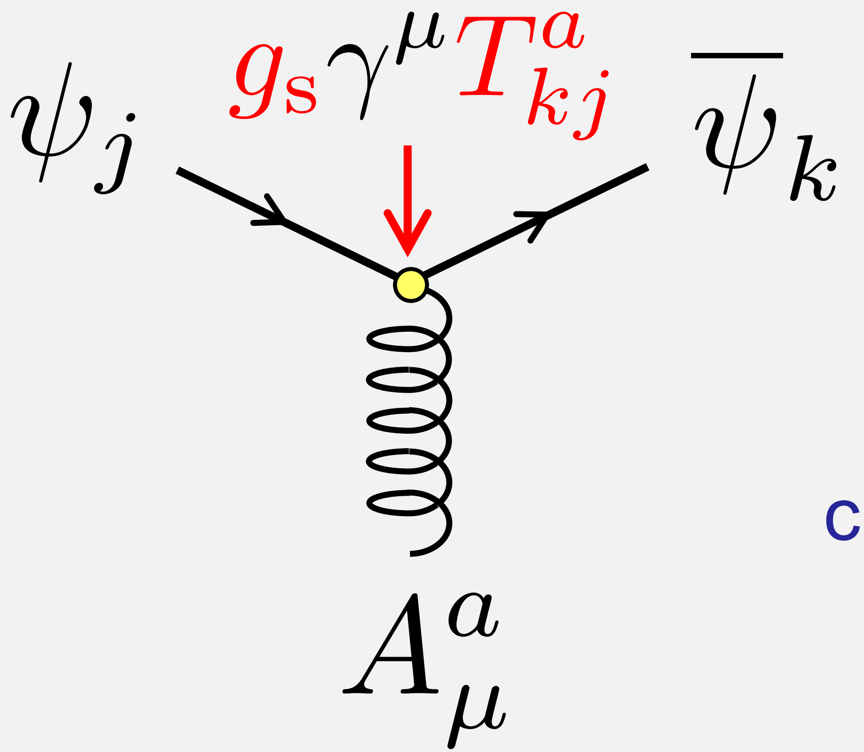
$$+ \mathcal{L}_{\rm gggg} \qquad \sim g_{\rm s}^{2} f^{abc} f^{ade} A^{b} A^{c} A^{d} A^{e}$$

$SU(3)$ non-abelian ⇔ gluons self-interact

⇔ gluons are colored ⇔ gluons modify quark color

quark-gluon interaction

$$g_{\mathrm{s}}\left(\overline{\psi}\gamma^{\mu}T^{a}\psi\right)A_{\mu}^{a}=g_{\mathrm{s}}\left(\overline{\psi}_{k}\gamma^{\mu}T_{kj}^{a}\psi_{j}\right)A_{\mu}^{a}$$

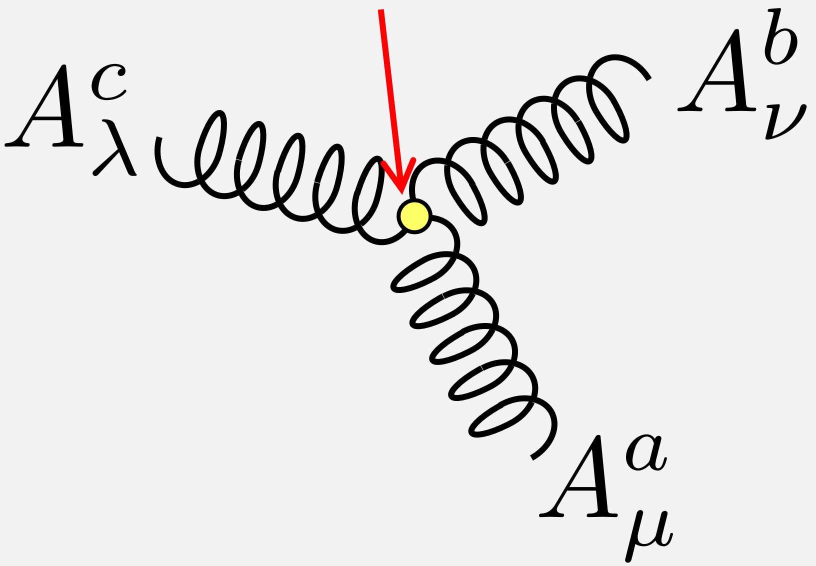


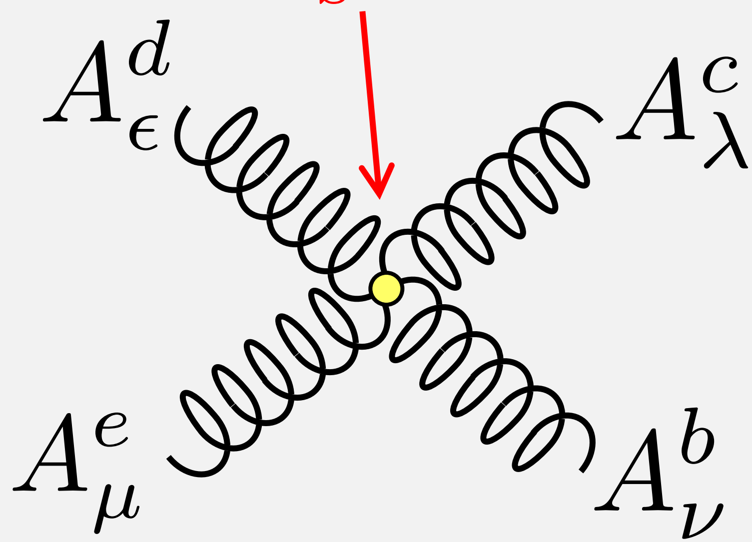
quark color
changes from j to k

gluon-gluon interactions

$$\sim g_{\rm s} f^{abc} A^a A^b A^c \qquad \sim g_{\rm s}^2 f^{abc} f^{ade} A^b A^c A^d A^e$$

$$\sim g_{\rm s} f^{abc} \qquad \sim g_{\rm s}^2 f^{\cdots} f^{\cdots}$$





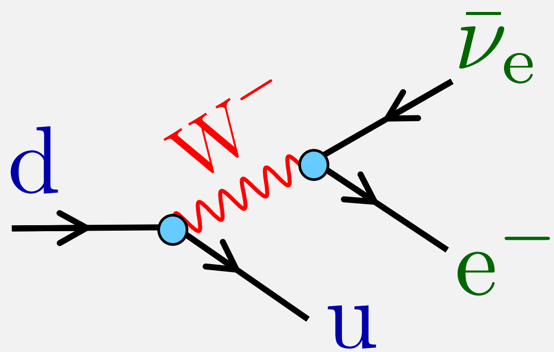
$\Rightarrow$ much more (highly non-trivial) dynamics to be verified experimentally

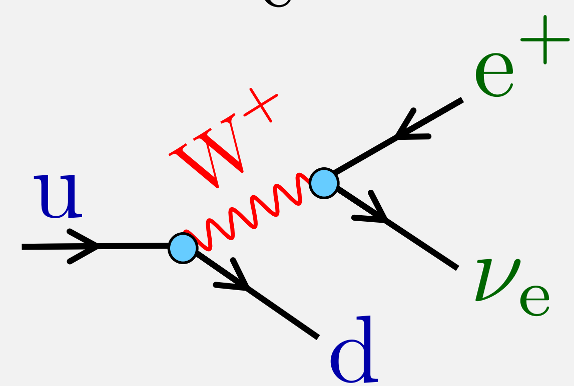
The same procedure for the weak force?

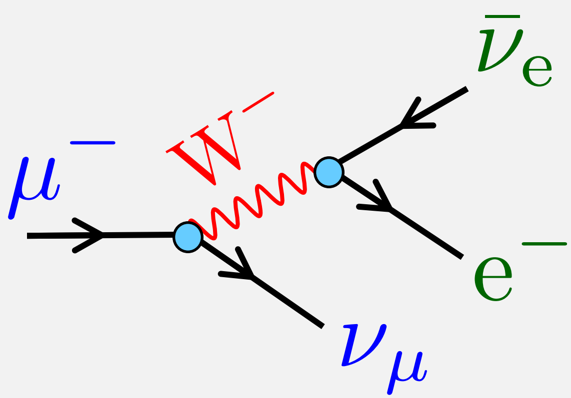
Guess a phase-symmetry!

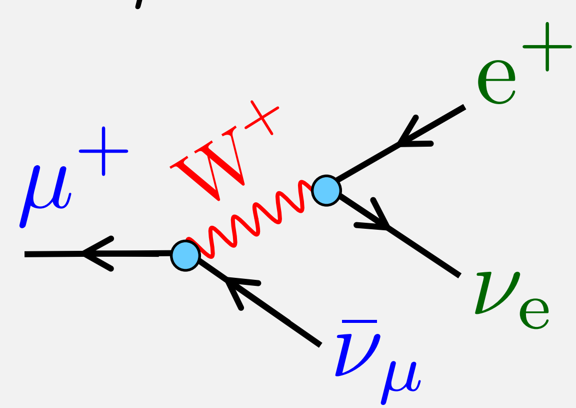
Observation 1: radioactive β-decay

β^--decay	β^+-decay
$n \to p\, e^- \, \bar{\nu}_e$	$p \to n\, e^+ \, \nu_e$
$\mu^- \to \nu_\mu\, e^- \, \bar{\nu}_e$	$\mu^+ \to \bar{\nu}_\mu\, e^+ \, \nu_e$



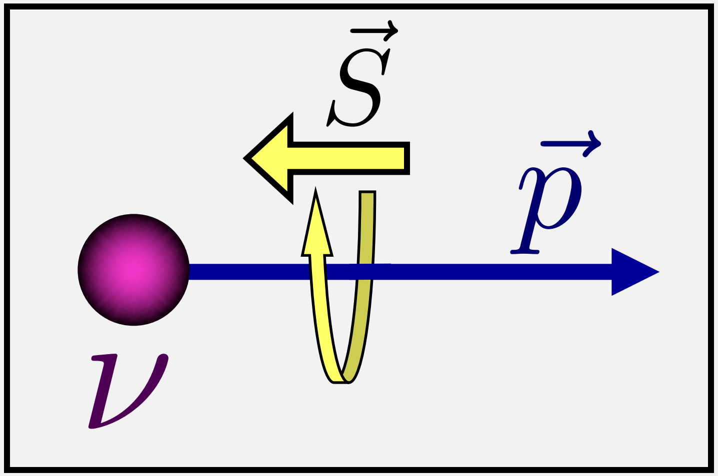




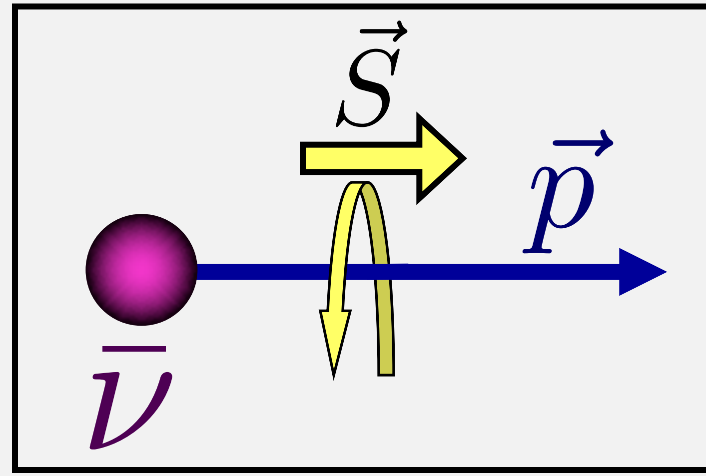


Surprise: β-decay fermions have handedness

Visualization of handedness for massless particles:



left-handed fermion



right-handed antifermion

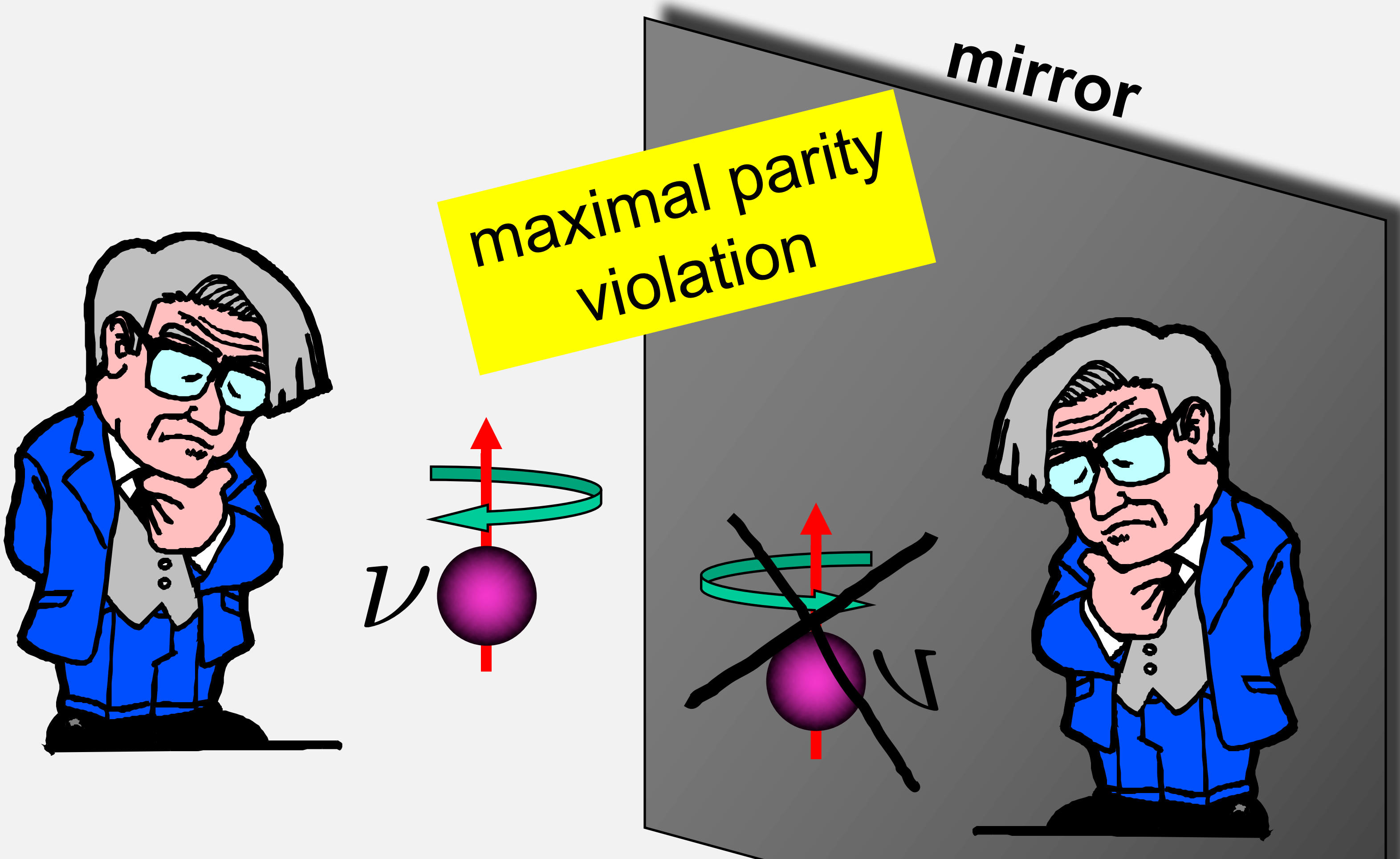
Dirac fermion: $$\psi = \psi_{\mathrm{L}} + \psi_{\mathrm{R}}$$

photons
gluons

$\mathrm{W}^{\pm}$ bosons

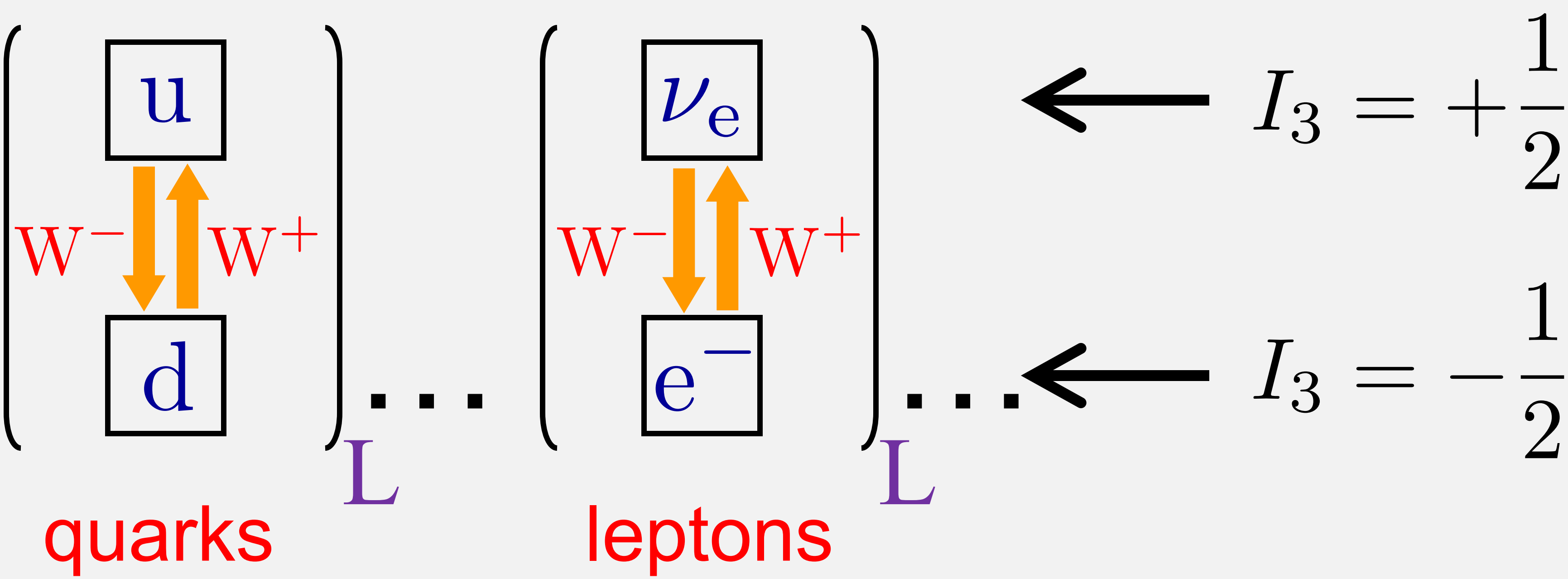
<u>Conclusion:</u> Weak force is different $\rightarrow \mathrm{W}^{\pm}$ bosons are only coupling to left-handed fermions and right-handed anti-fermions

Consequence:



➔ left-handed fermions carry weak charge I_3

➔ left-handed fermions live in weak doublets

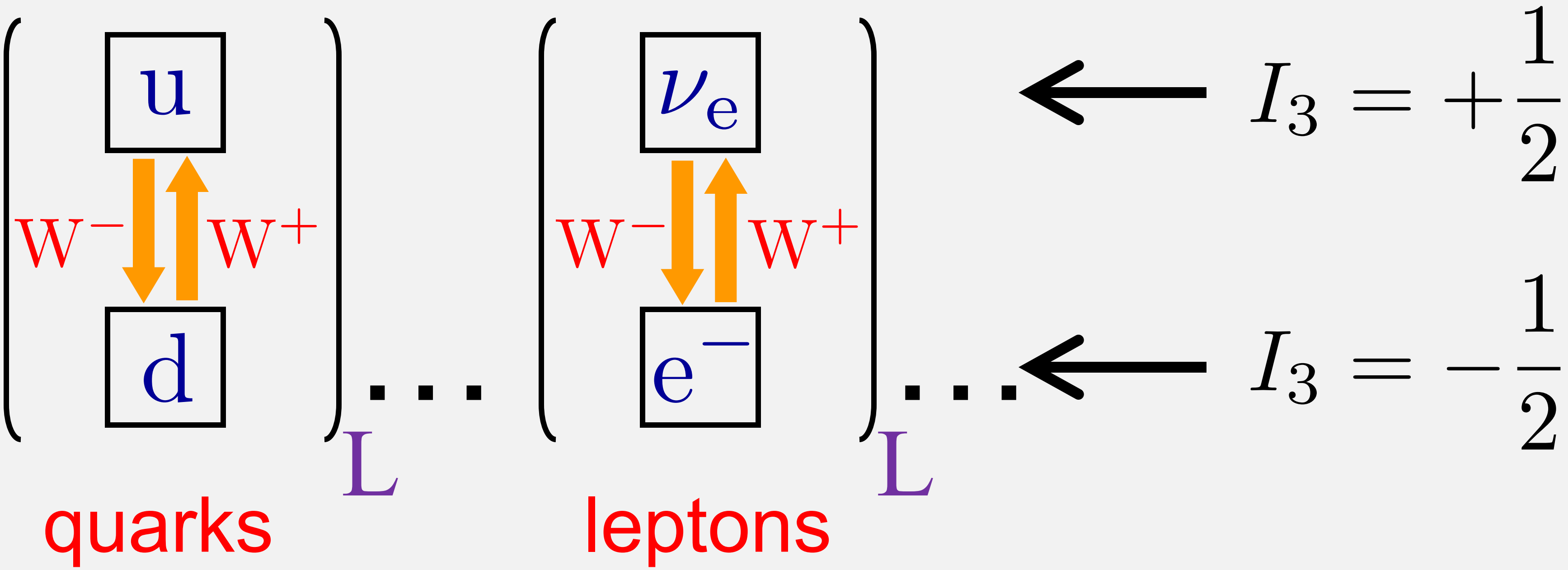


➔ W-bosons carry weak charge $I_3(W^{\pm}) = \pm 1$

➔ ... and electric charge $Q(W^{\pm}) = \pm 1$

➔ right-handed fermions are I_3-neutral

$$e^-_R,\ u_R,\ d_R,\ \ldots : \quad I_3 = 0$$



- 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 $SU(2)_{\mathrm{L}}$ ← left-handed

$$\psi_{\mathrm{L}} = \begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}_{\mathrm{L}} \rightarrow e^{i(T^1\alpha^1(x)+T^2\alpha^2(x)+T^3\alpha^3(x))}\begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}_{\mathrm{L}}$$

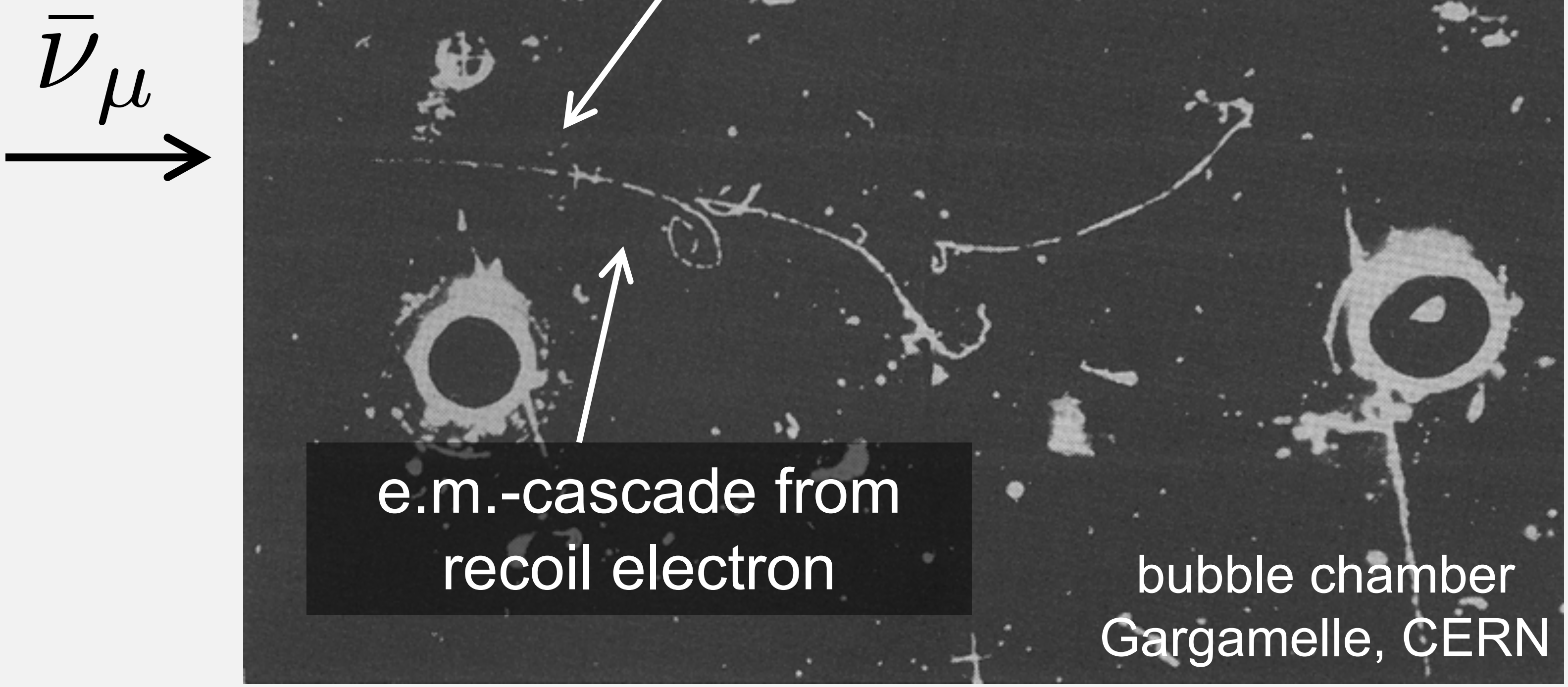
Charge number operators: $T^j = \frac{1}{2}\tau^j$ ← Pauli matrices

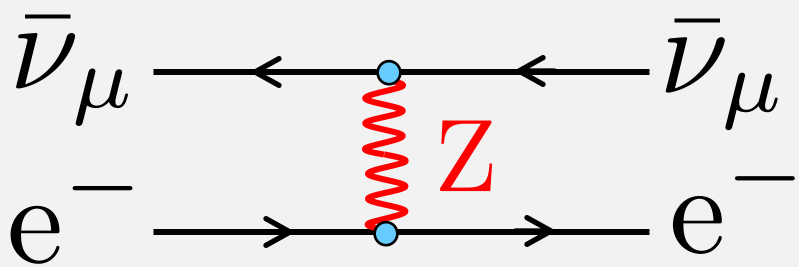
Gauge bosons:

		I_3	Q
$I = 1$	W^+	$+1$	$+1$
	W^0	0	0
	W^-	-1	-1

there must be a neutral boson (→ $Q = 0$)

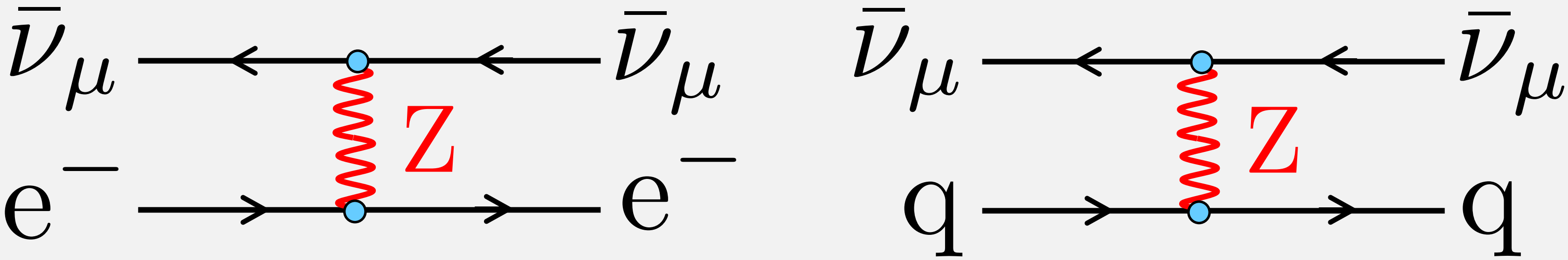
Discovery of neutral weak gauge bosons





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 ... somwhere between an $SU(2)$-boson and a $U(1)$-photon!

Try more complicated gauge symmetry

$$SU(2)_\mathrm{L} \times U(1)_Y$$

$U(1)$-charge, called **weak hypercharge** members of $SU(2)_\mathrm{L}$-multipletts must have identical Y

$I = 1/2$	I_3	Q
u_L	$+1/2$	$+2/3$
d_L	$-1/2$	$-1/3$

$I = 1/2$	I_3	Q
$\nu_{\mathrm{e},\mathrm{L}}$	$+1/2$	0
e^-_L	$-1/2$	-1

$I = 1$	I_3	Q
W^+	$+1$	$+1$
W^0	0	0
W^-	-1	-1

$$Y(\mathrm{W}) = 0$$

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

Convention:

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

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

Standard Model of electro-weak interactions

	$SU(2)_\mathrm{L}$	$U(1)_Y$
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

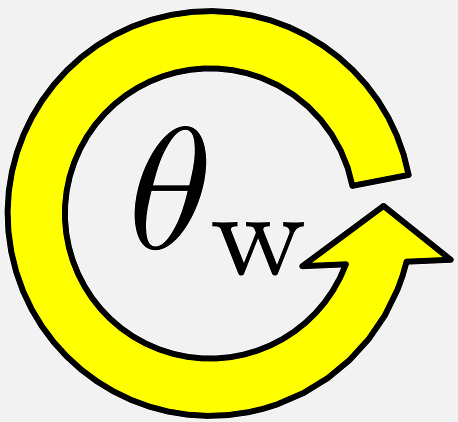
	$SU(2)_{\mathrm{L}}$	$U(1)_Y$
unit charge (convention)	g	$g'/2$

gauge bosons

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

physical force particles

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



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

identify this as photon

$\Rightarrow$ electro-weak unification $g \sin\theta_{\mathrm{w}} = g' \cos\theta_{\mathrm{w}} = e$

Electro-weak unification $g \sin\theta_{\mathrm{w}} = g' \cos\theta_{\mathrm{w}} = e$

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 $(A^\nu) = (\phi, \vec{A})$

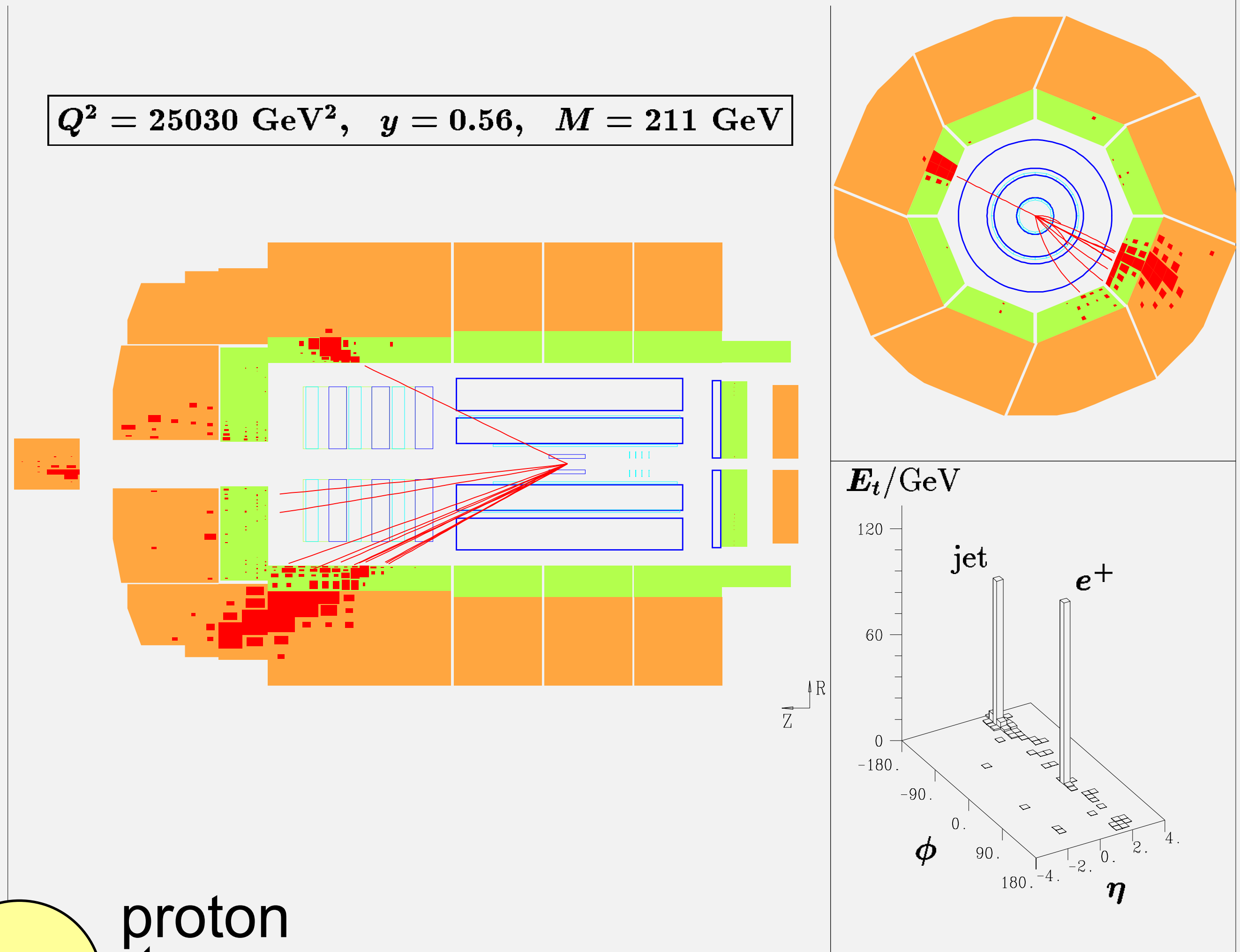
Yukawa potential $$\phi \propto \frac{e^{-mr}}{r}$$

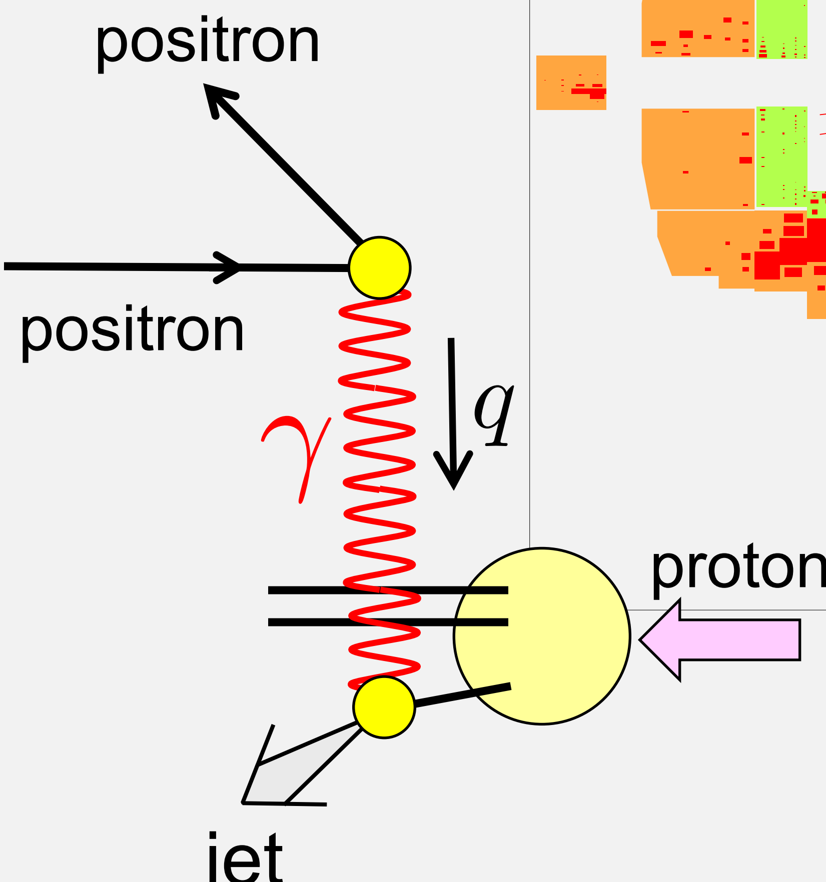
range $$\bar{r} = \frac{1}{m}$$

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

it is a simple mass-effect

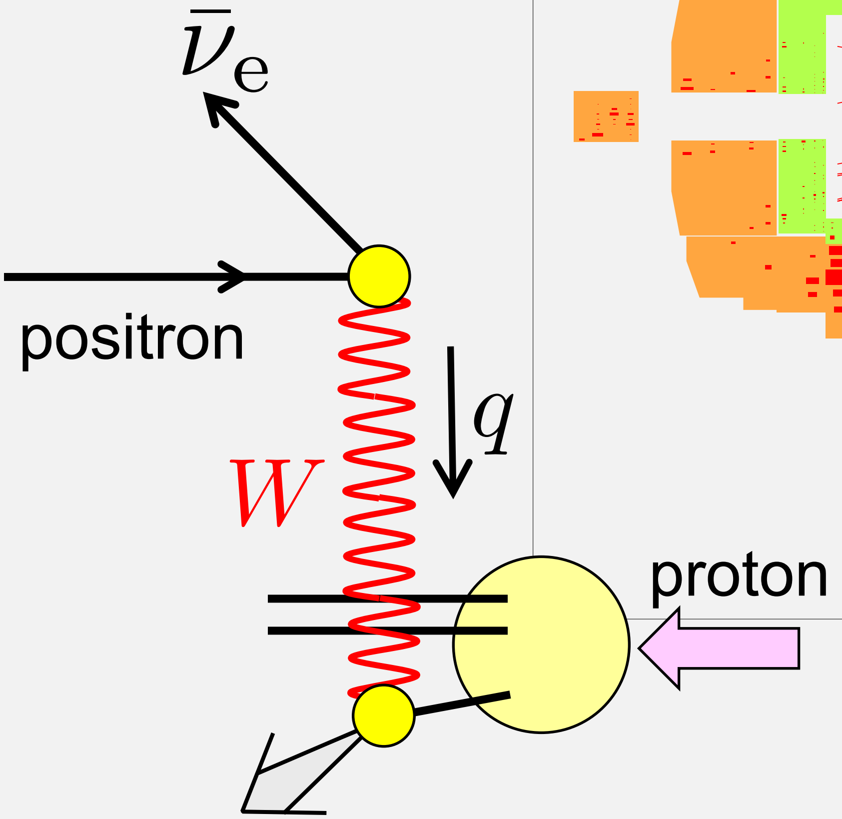
Photon in action at ep-collider HERA (DESY)

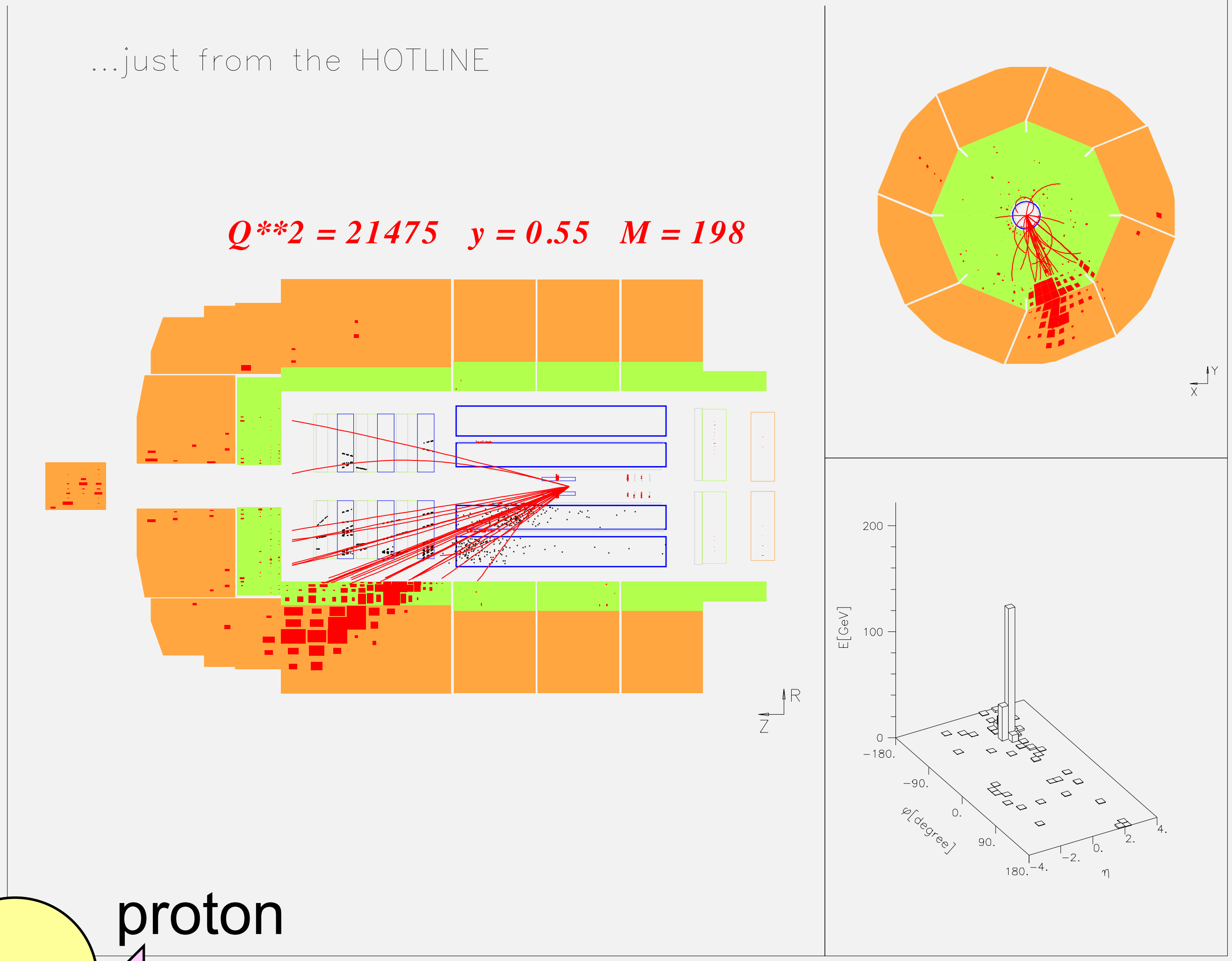




$$q^2 \equiv -Q^2$$

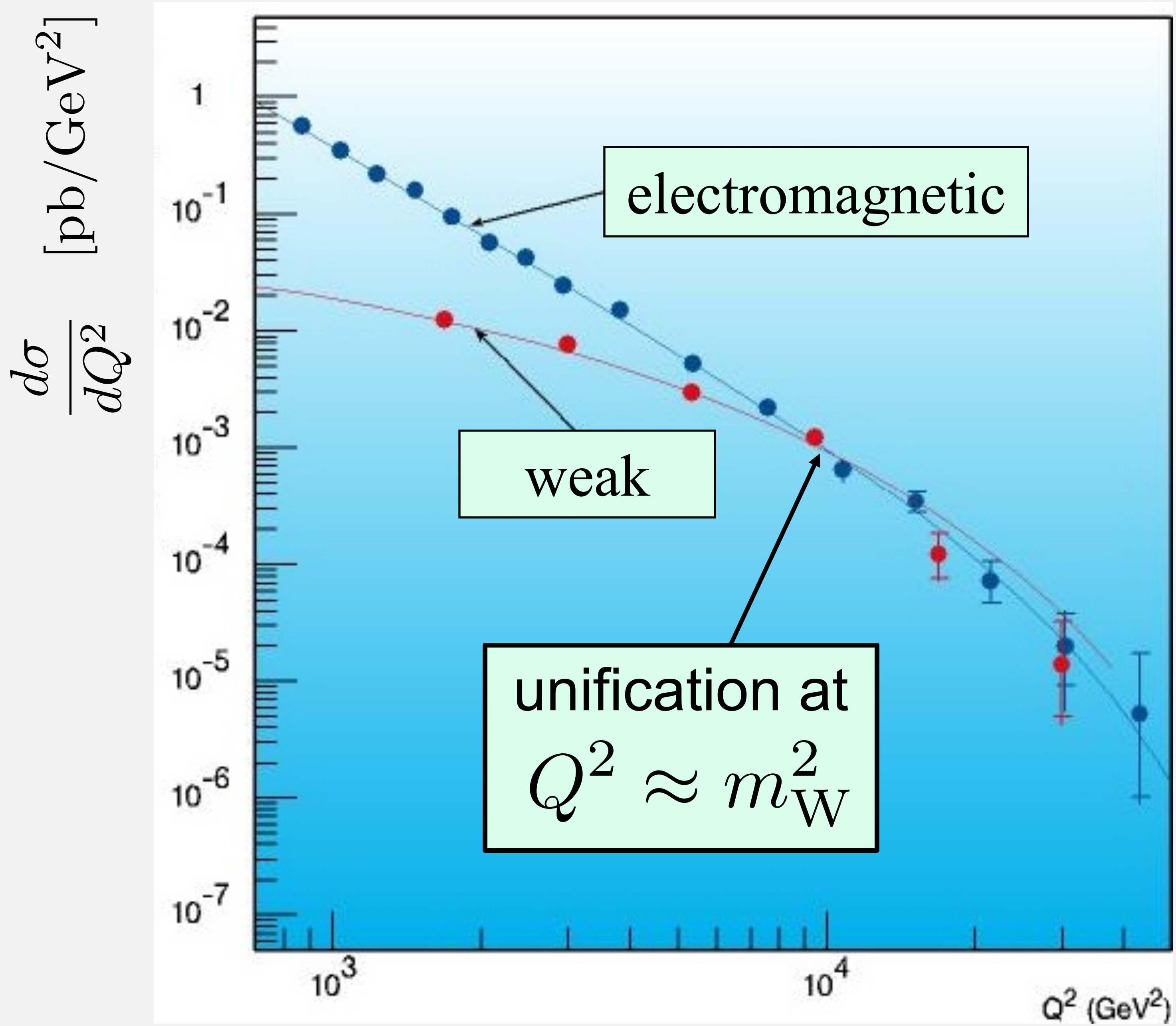
Weak interaction at ep-collider HERA (DESY)



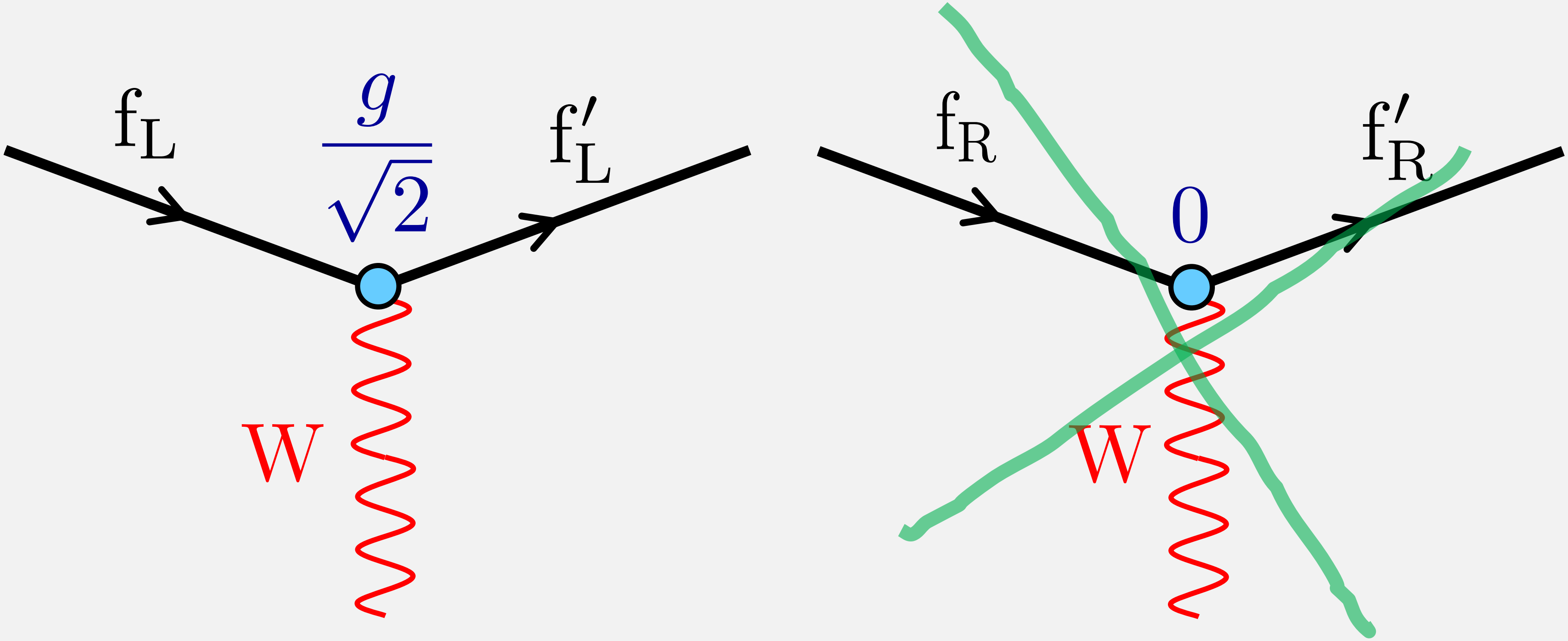


$$q^2 \equiv -Q^2$$

Compare forces at ep-collider HERA (DESY)

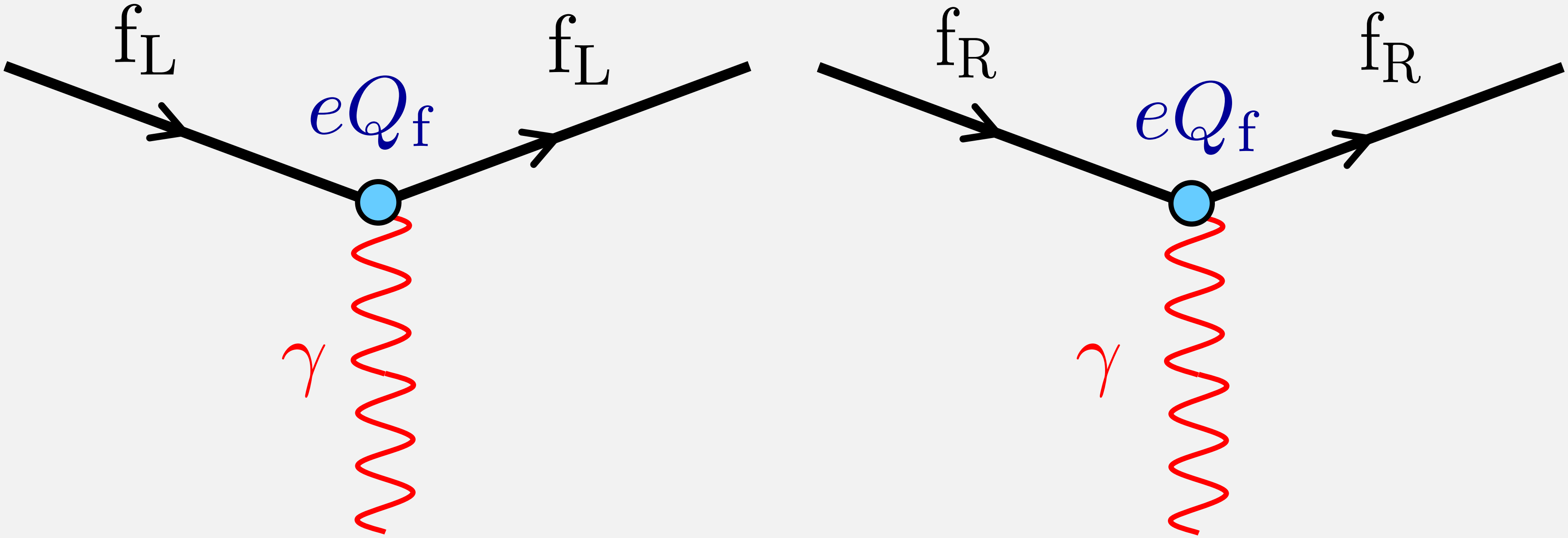


Electroweak couplings to fermions: $W^{\pm}$



purely left-handed

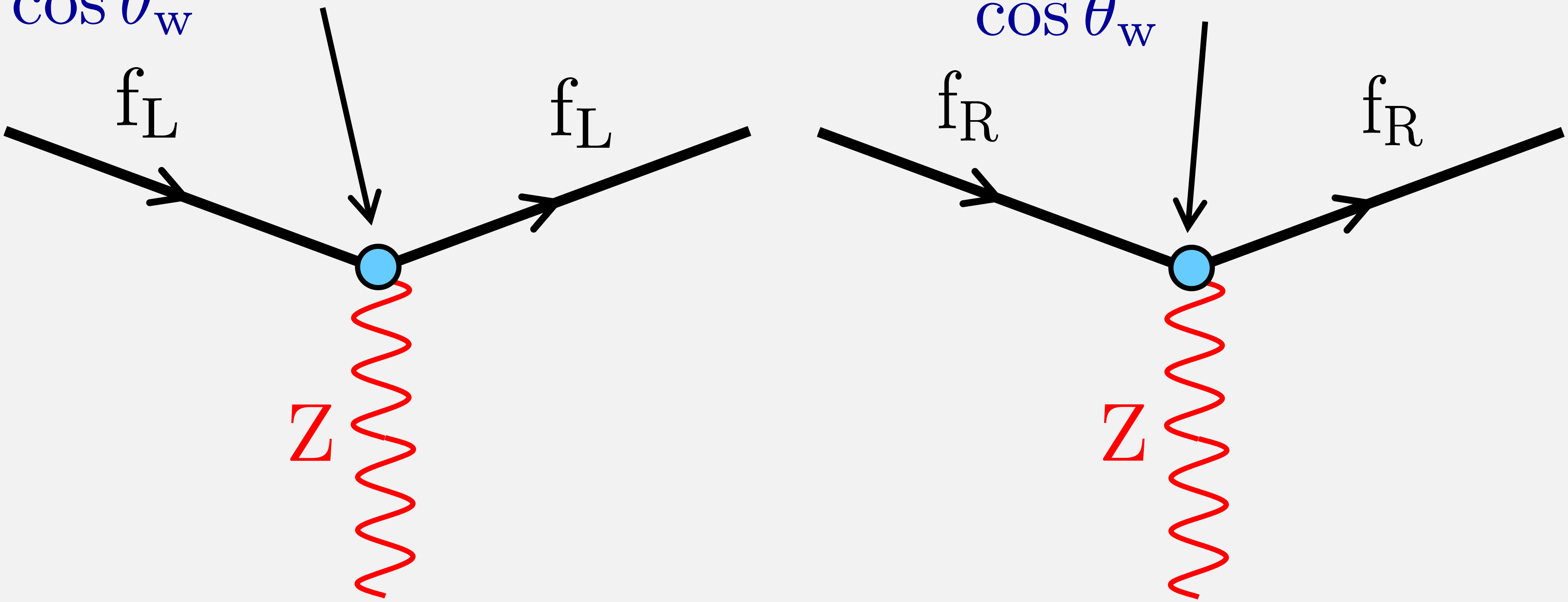
Electroweak couplings to fermions: γ



left-right symmetric

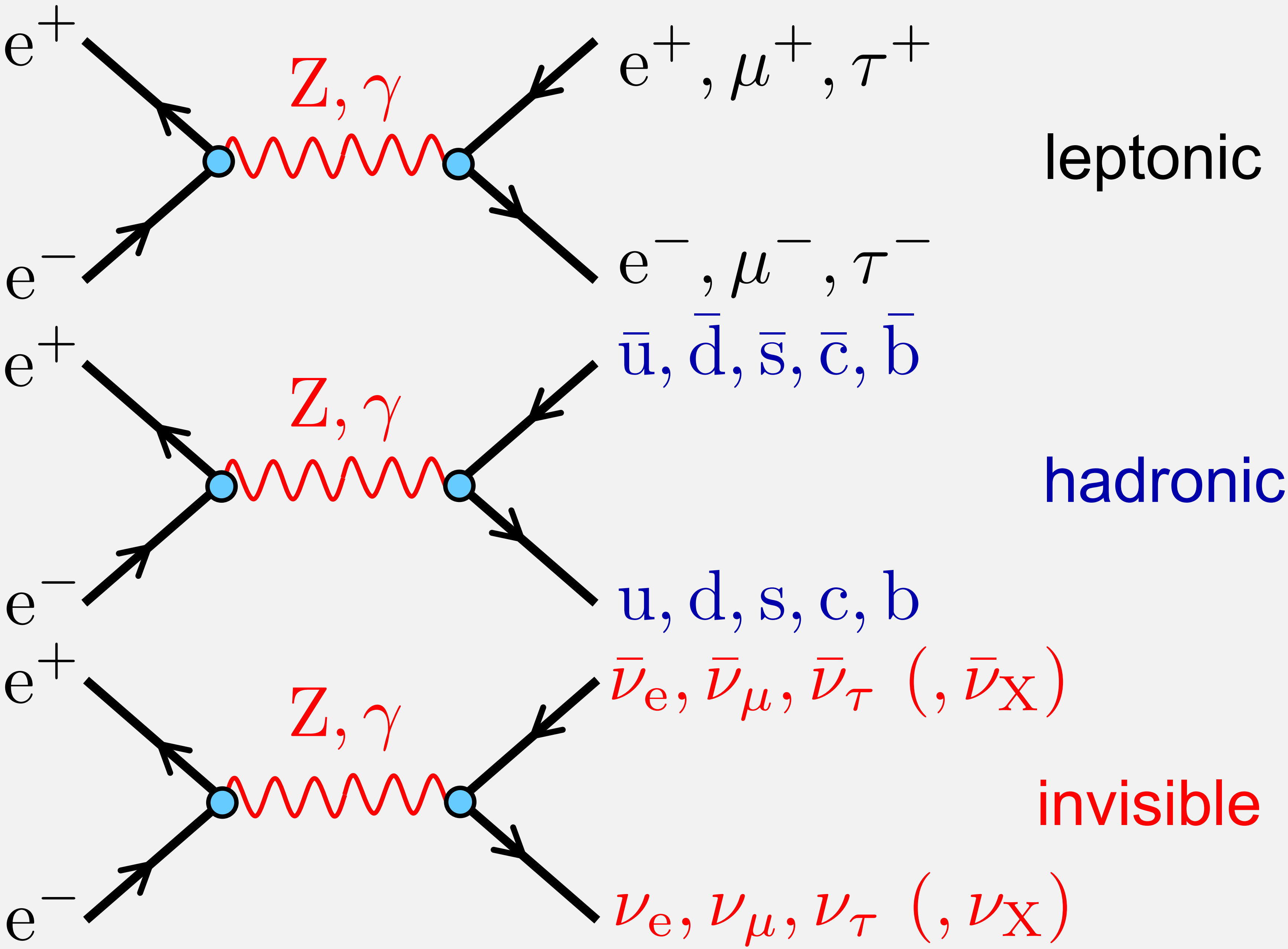
Electroweak couplings to fermions: Z

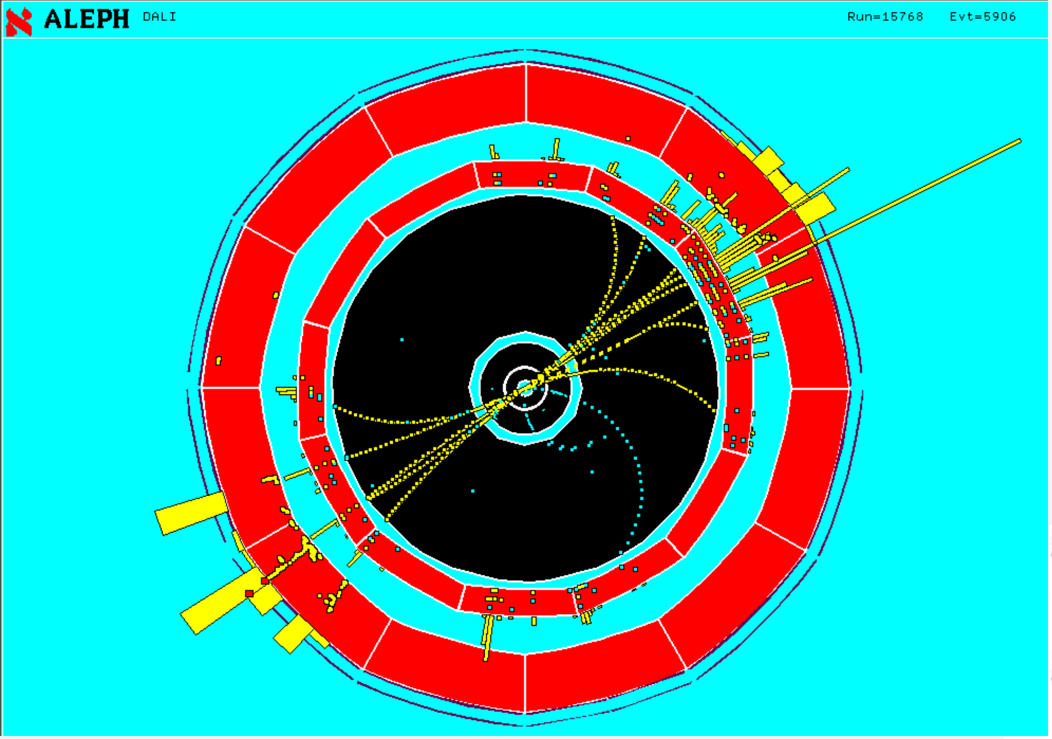
$$\frac{g}{\cos\theta_{\mathrm{w}}}\left(I_3^{\mathrm{f}} - Q_{\mathrm{f}}\sin^2\theta_{\mathrm{w}}\right) \qquad -\frac{g}{\cos\theta_{\mathrm{w}}}Q_{\mathrm{f}}\sin^2\theta_{\mathrm{w}}$$

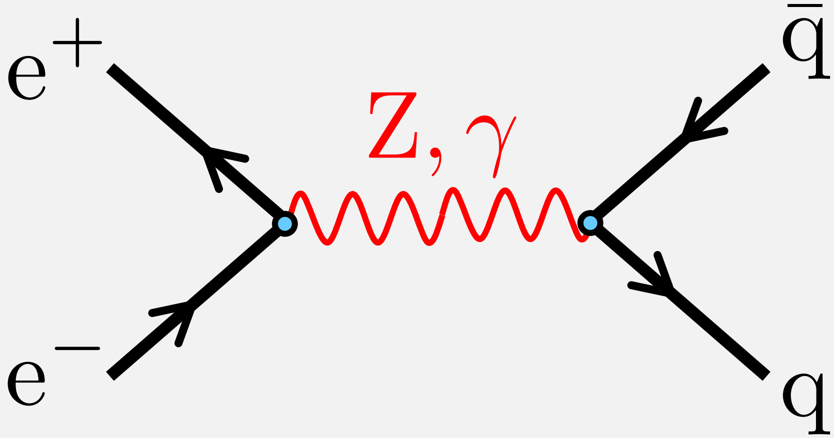


left and right, but not symmetric

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

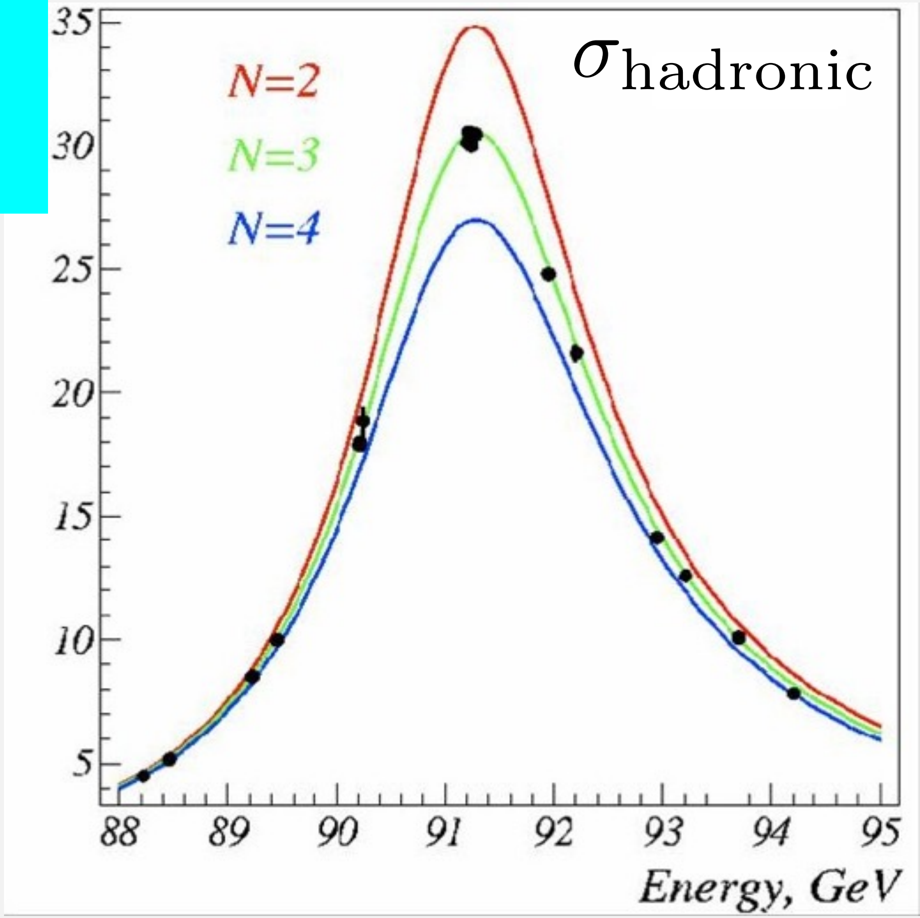




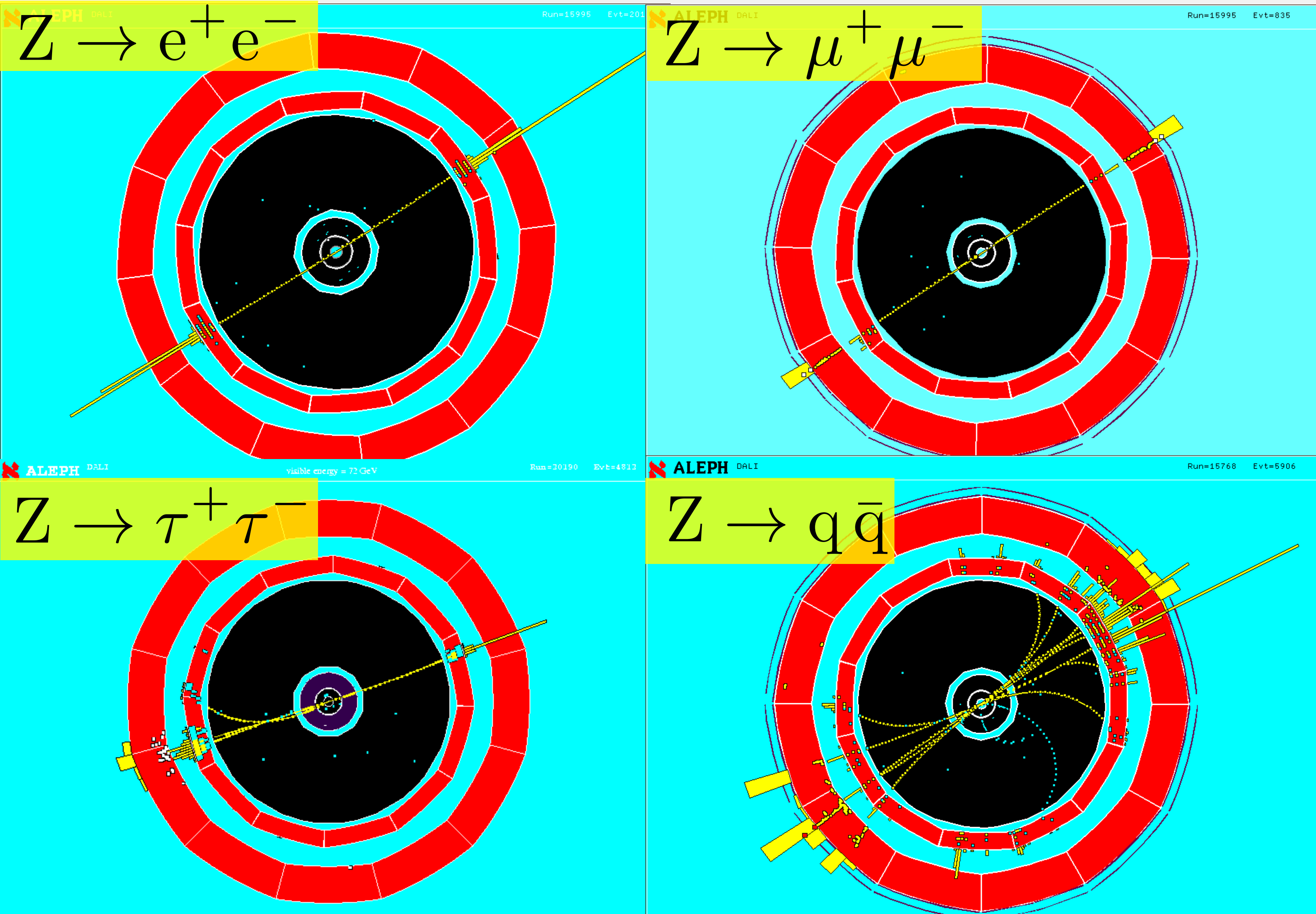


Z-resonance curve ⇒

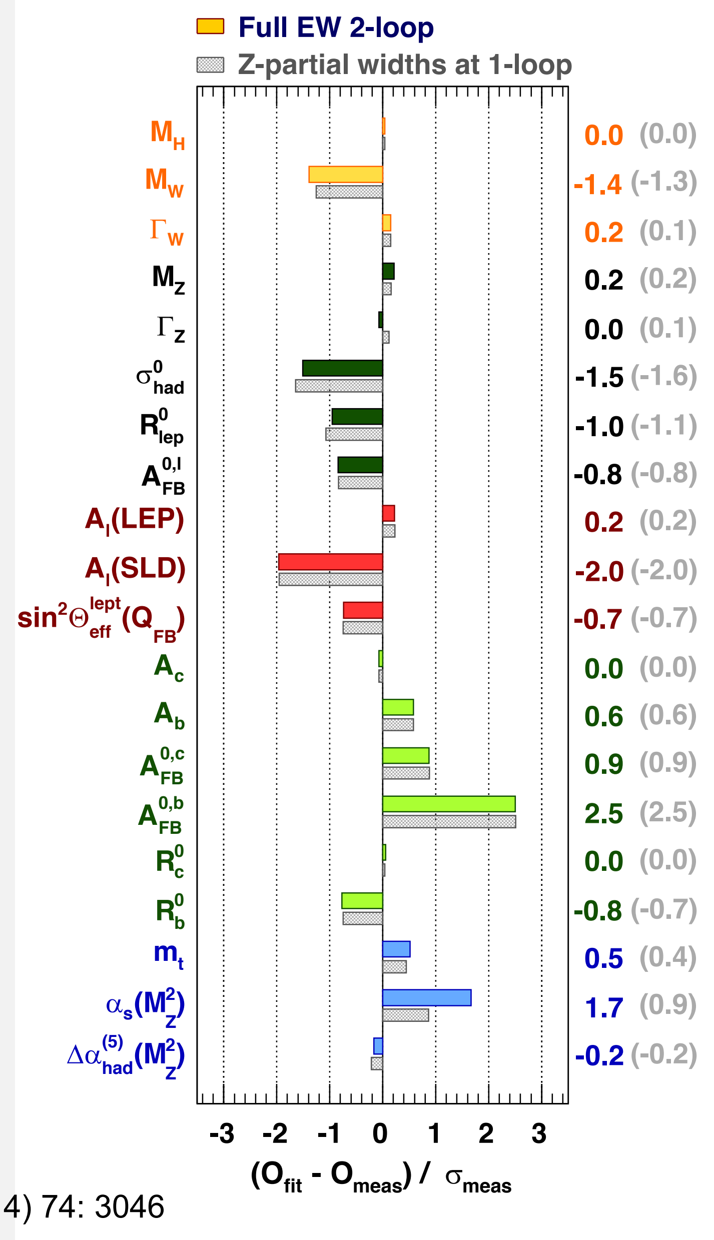
- mass
- width
- exactly three families
- overall coupling strengths

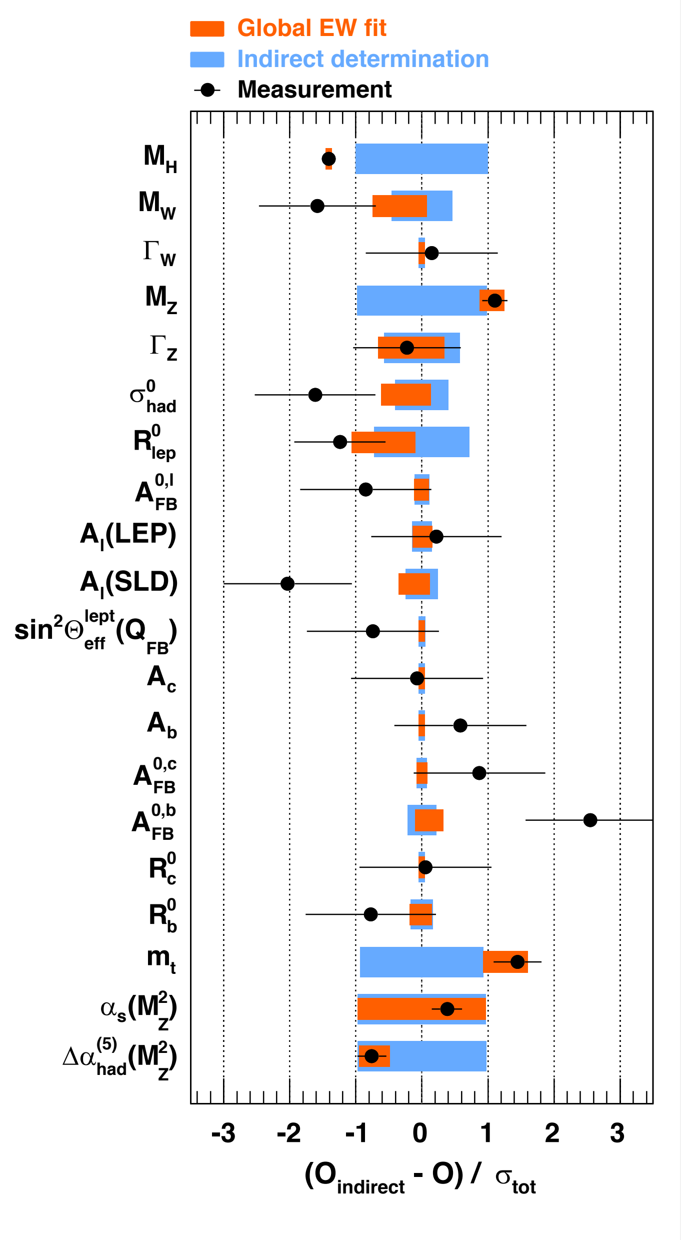


Couplings: branching fractions / angular distributions of...



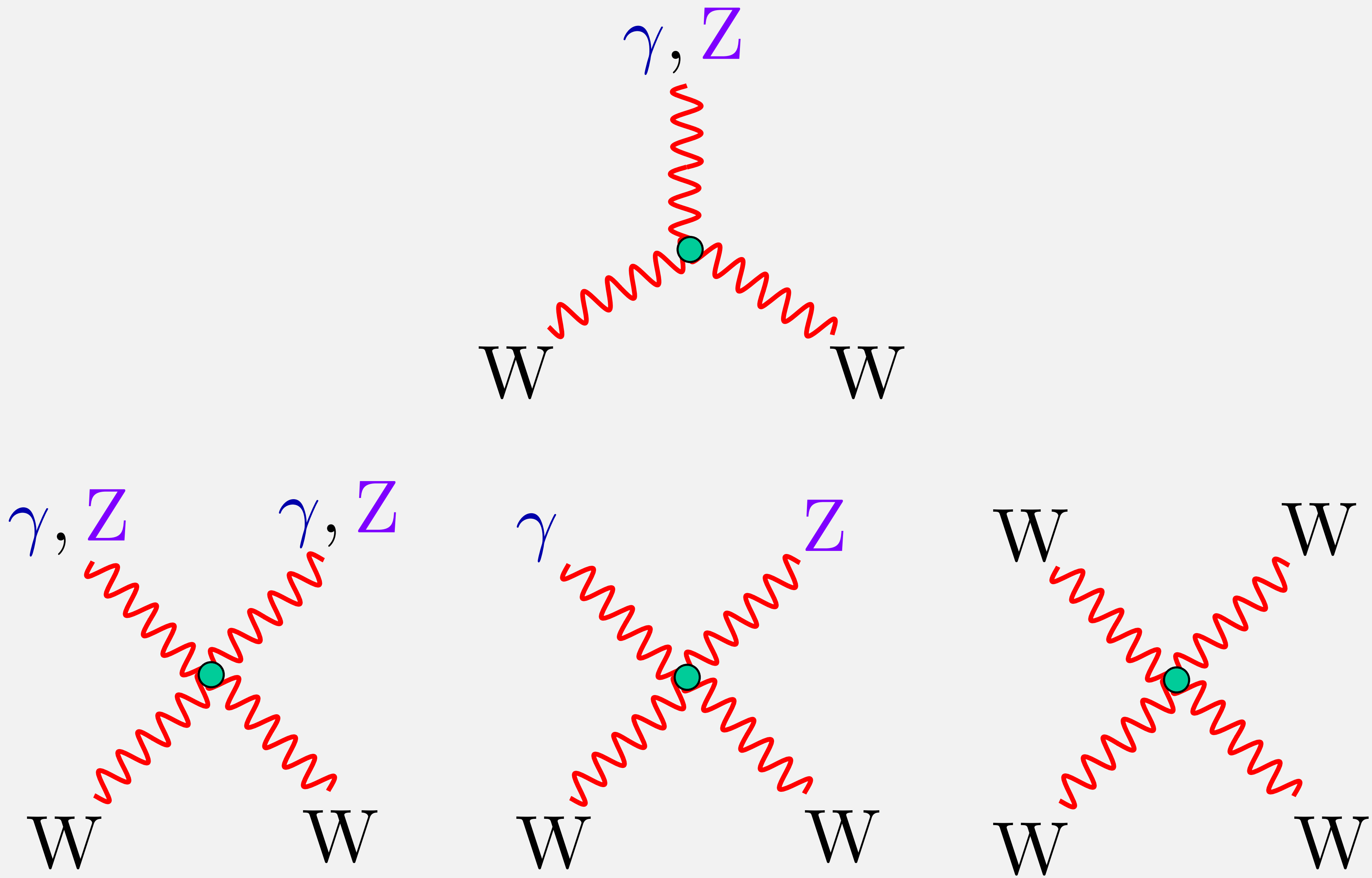
Electroweak fits prove highest level of internal consistency at quantum loop level





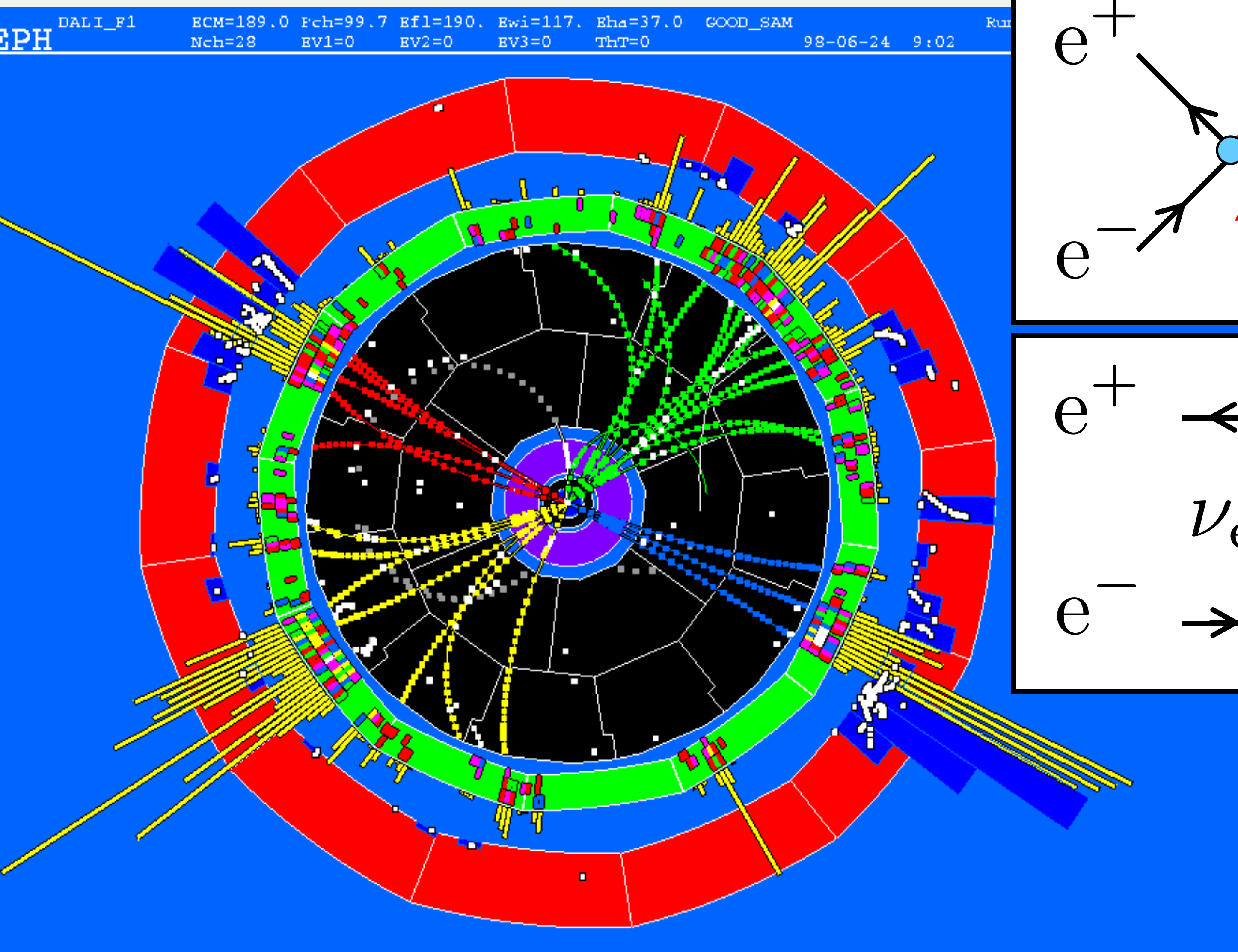
EPJ C (2014) 74: 3046

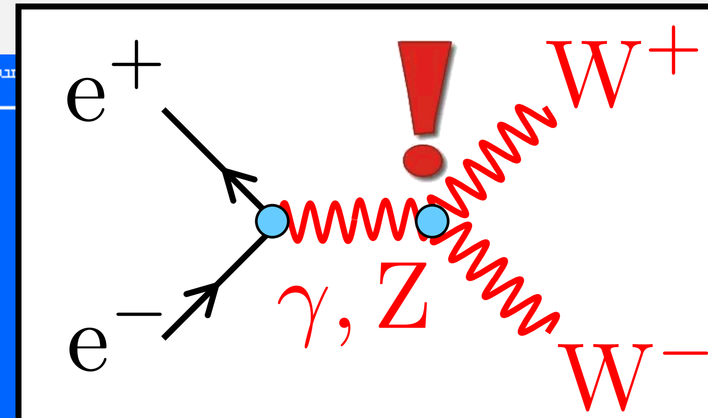
$SU(2)_\mathrm{L}$ is non-abelian ⇒ self-couplings

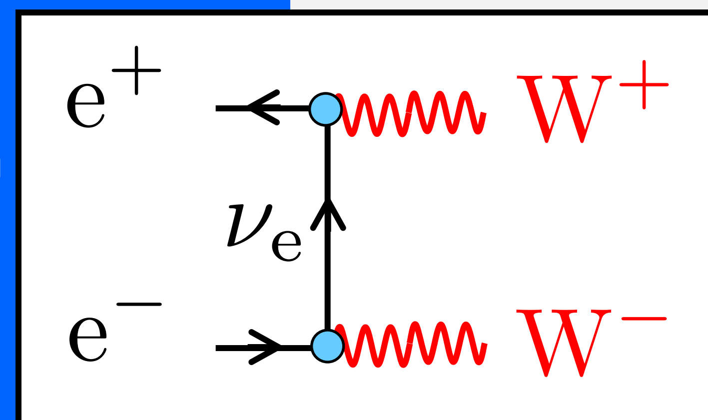


Example:

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

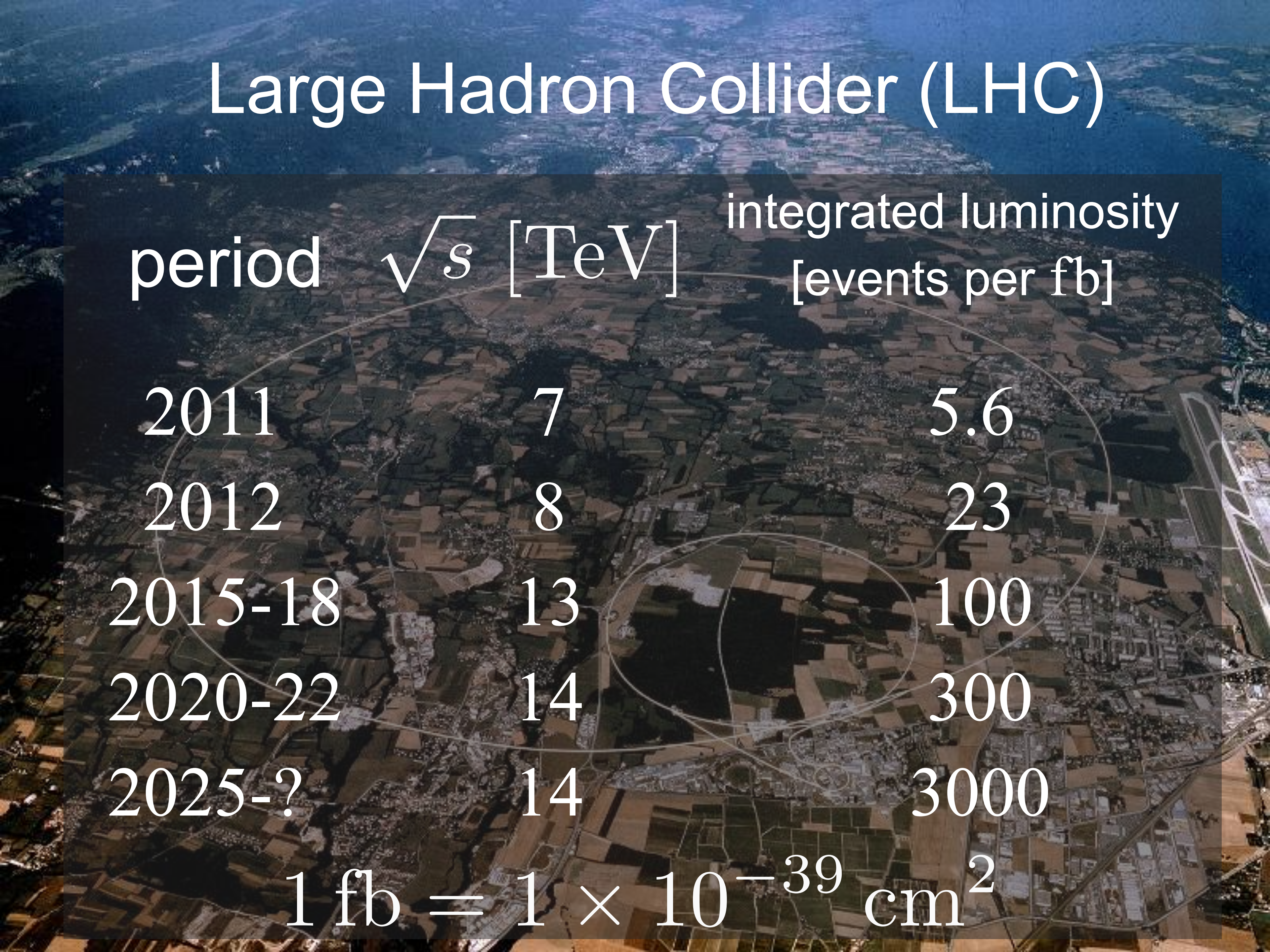






Part III

- 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)

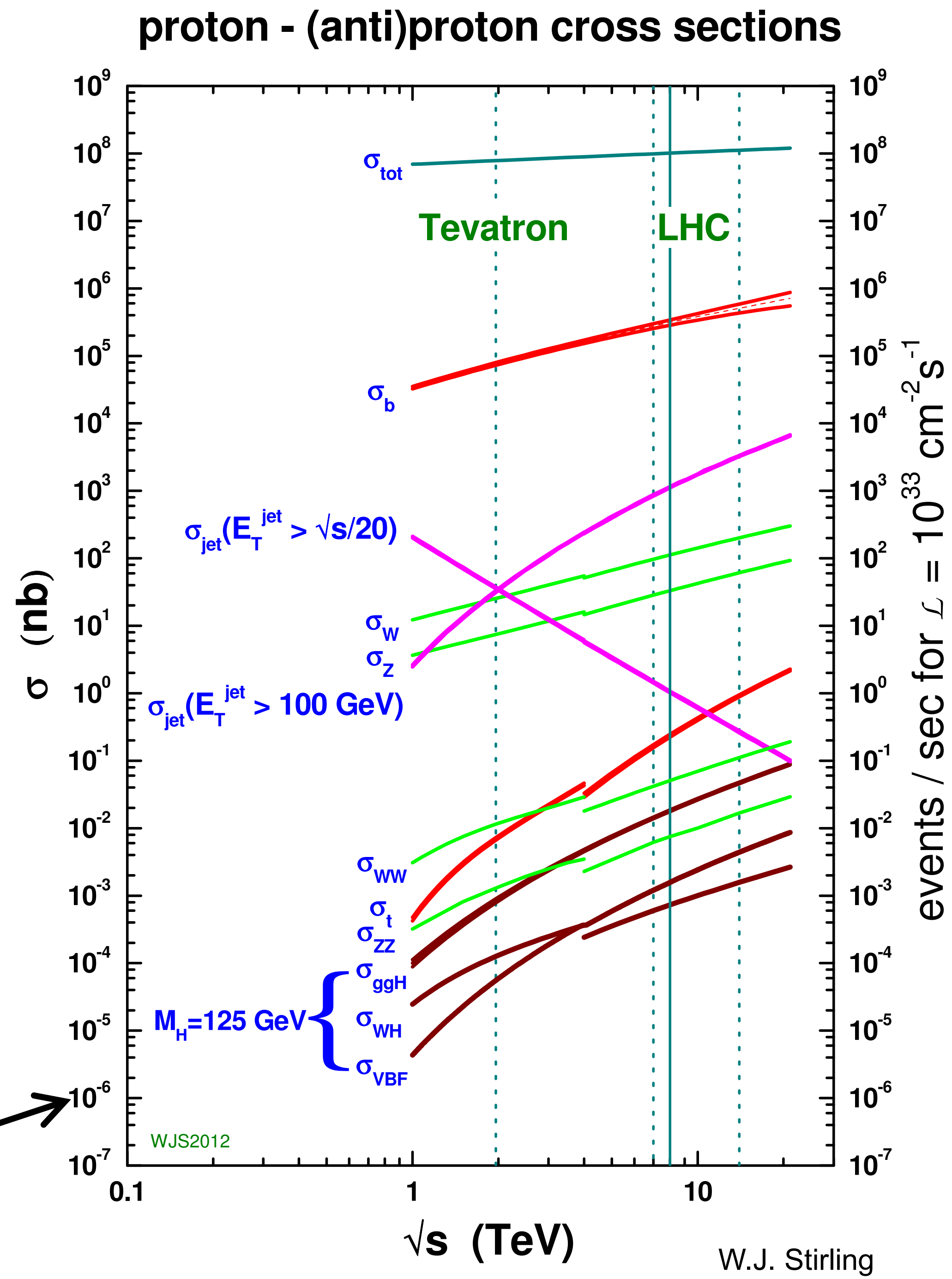
period	$\sqrt{s}$ [TeV]	integrated luminosity [events per fb]
2011	7	5.6
2012	8	23
2015-18	13	100
2020-22	14	300
2025-?	14	3000

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

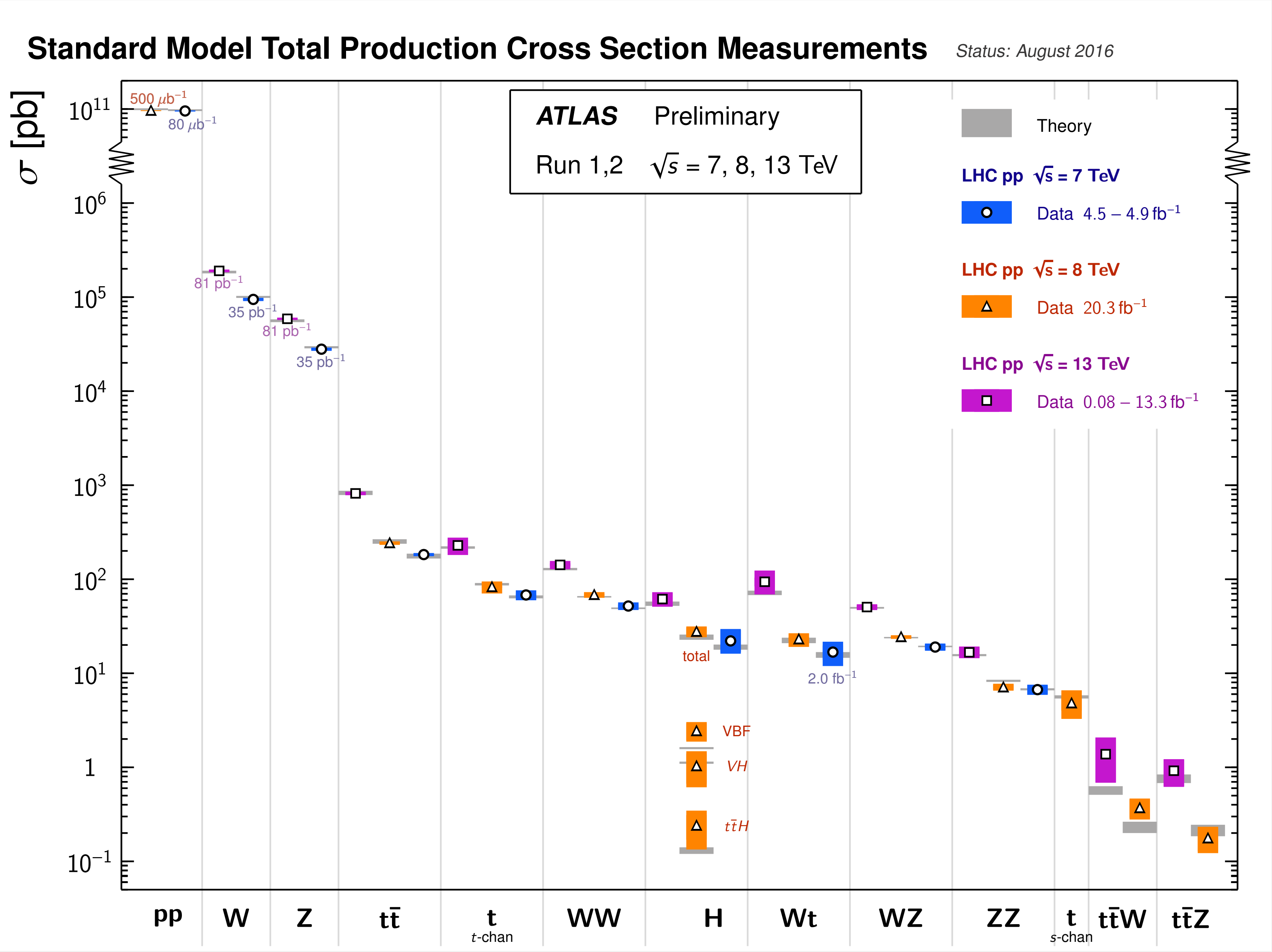
Cross sections

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}

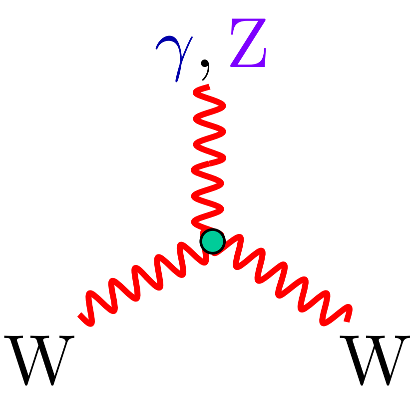
1 fb

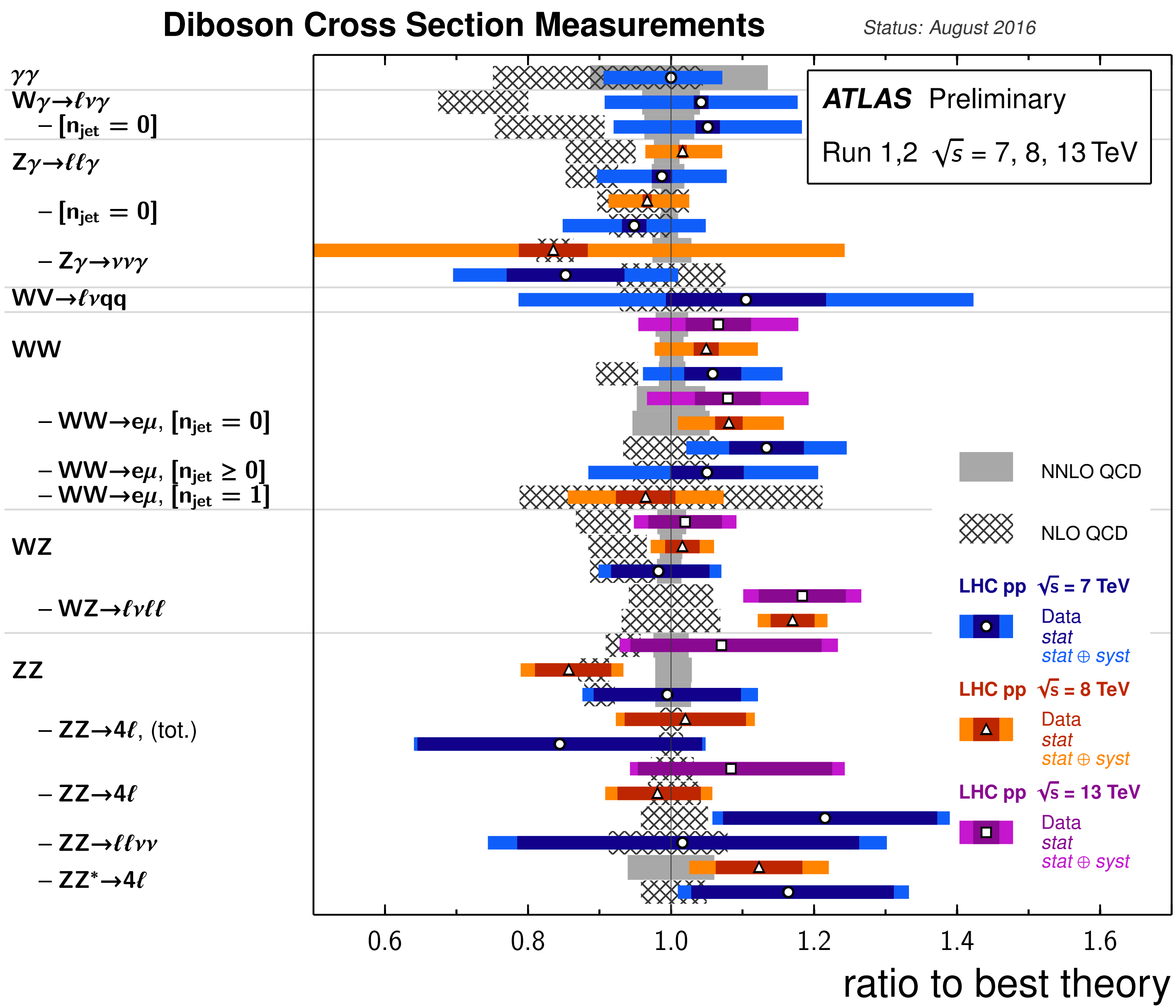


Wonderful agreement with measurements!

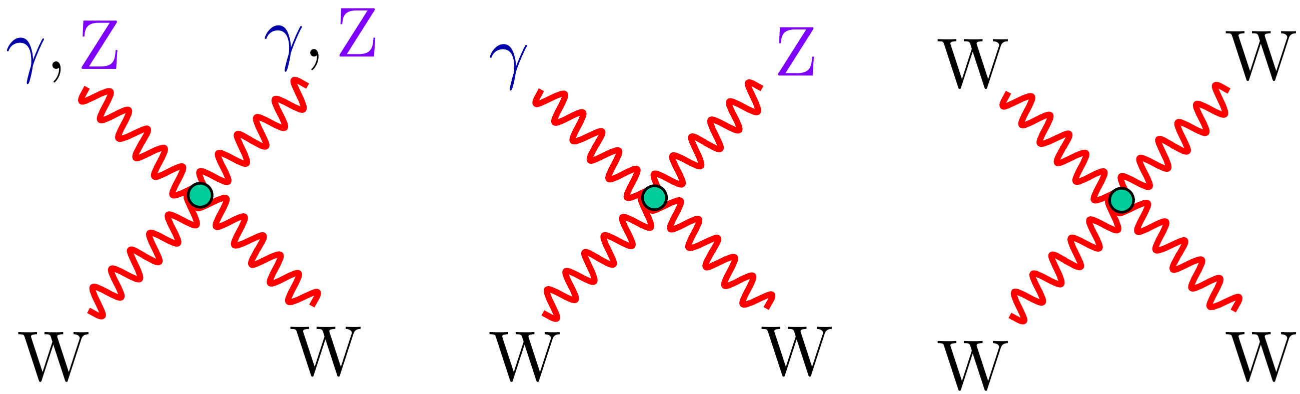


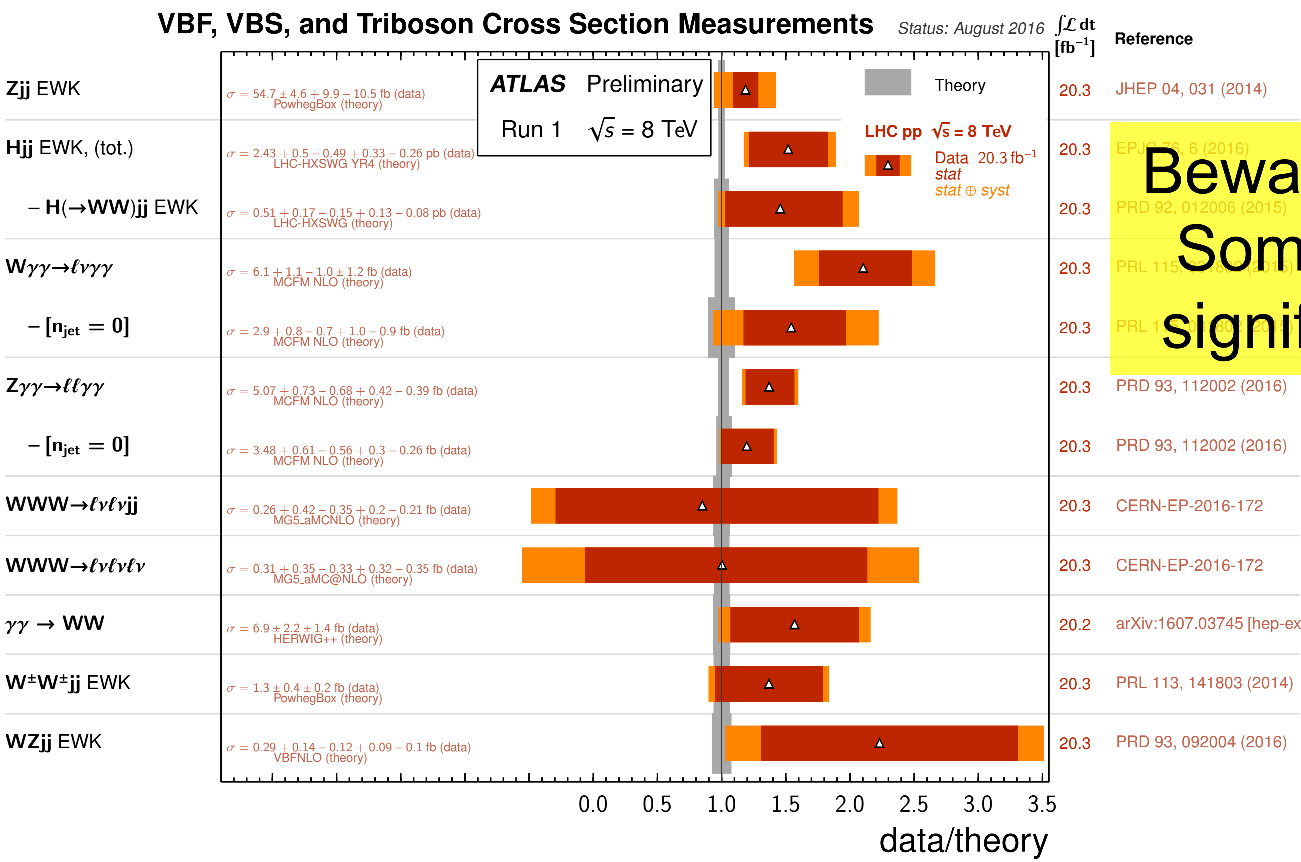
A closer look at Diboson production:





First look at processes sensitive to quartic couplings

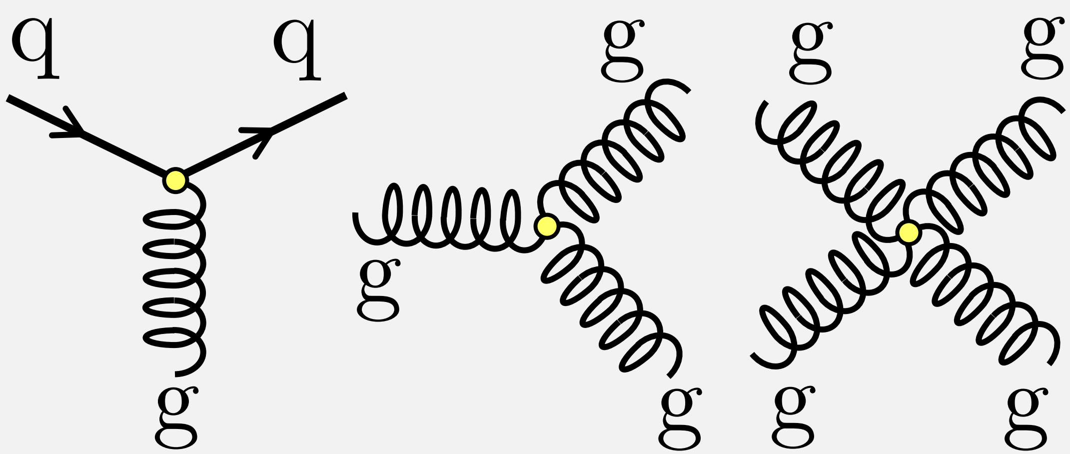


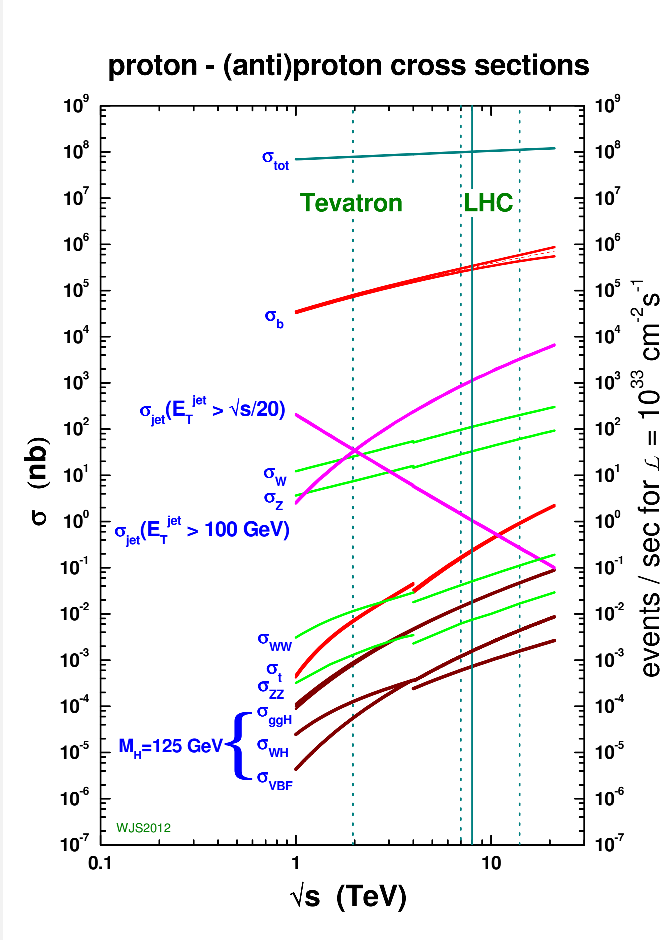


Beware! Low statistics!
Some processes not
significantly detected!

How to compute these cross-sections?

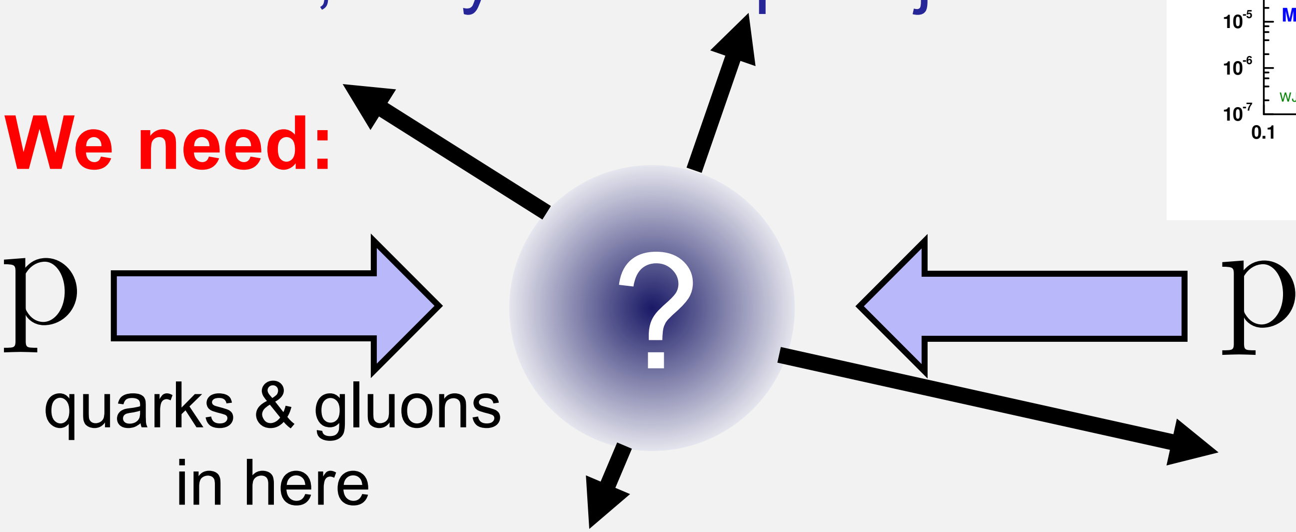
Quantum Chromodynamics ⇒





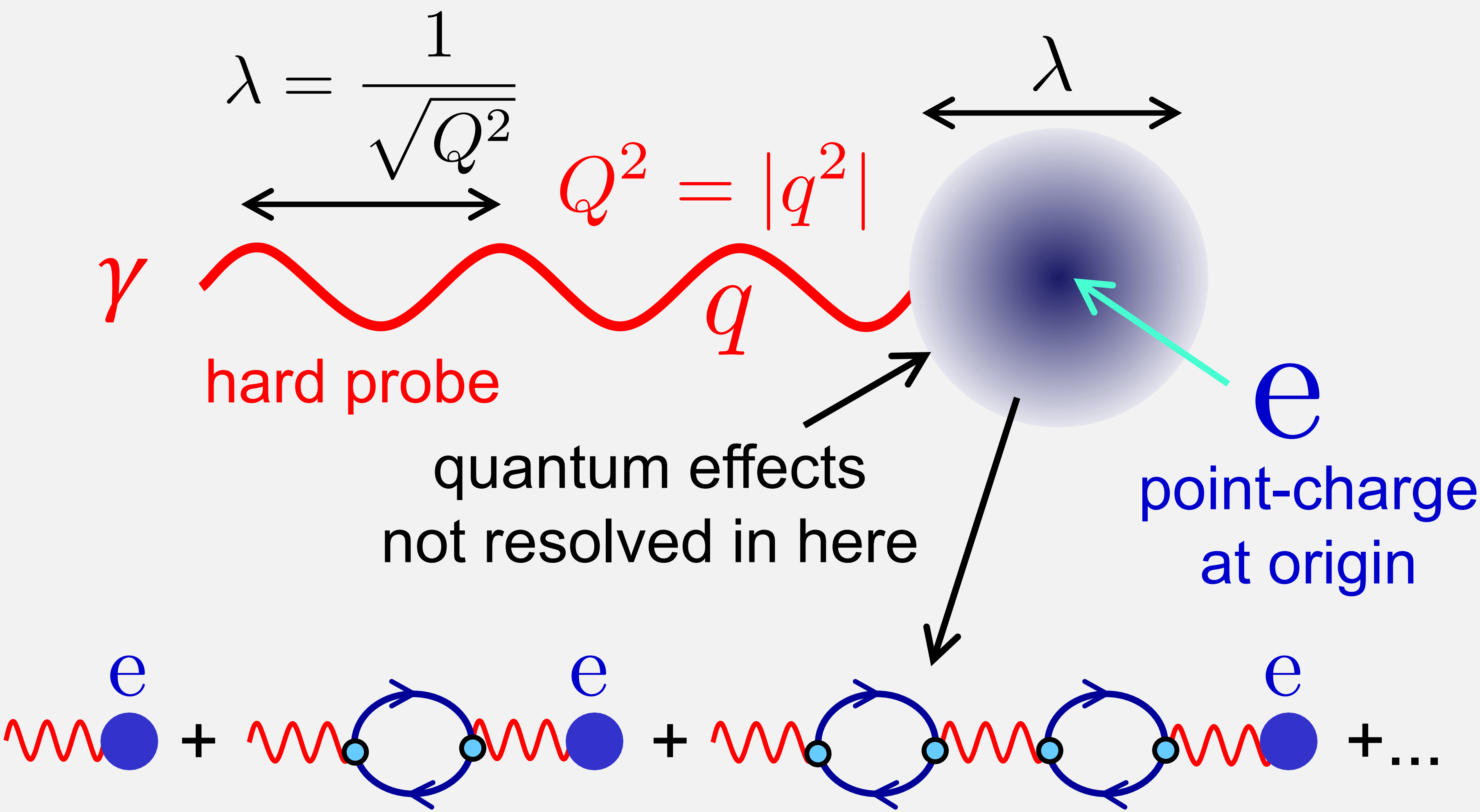
but free quarks and gluons are not observed; they show up as jets!

We need:

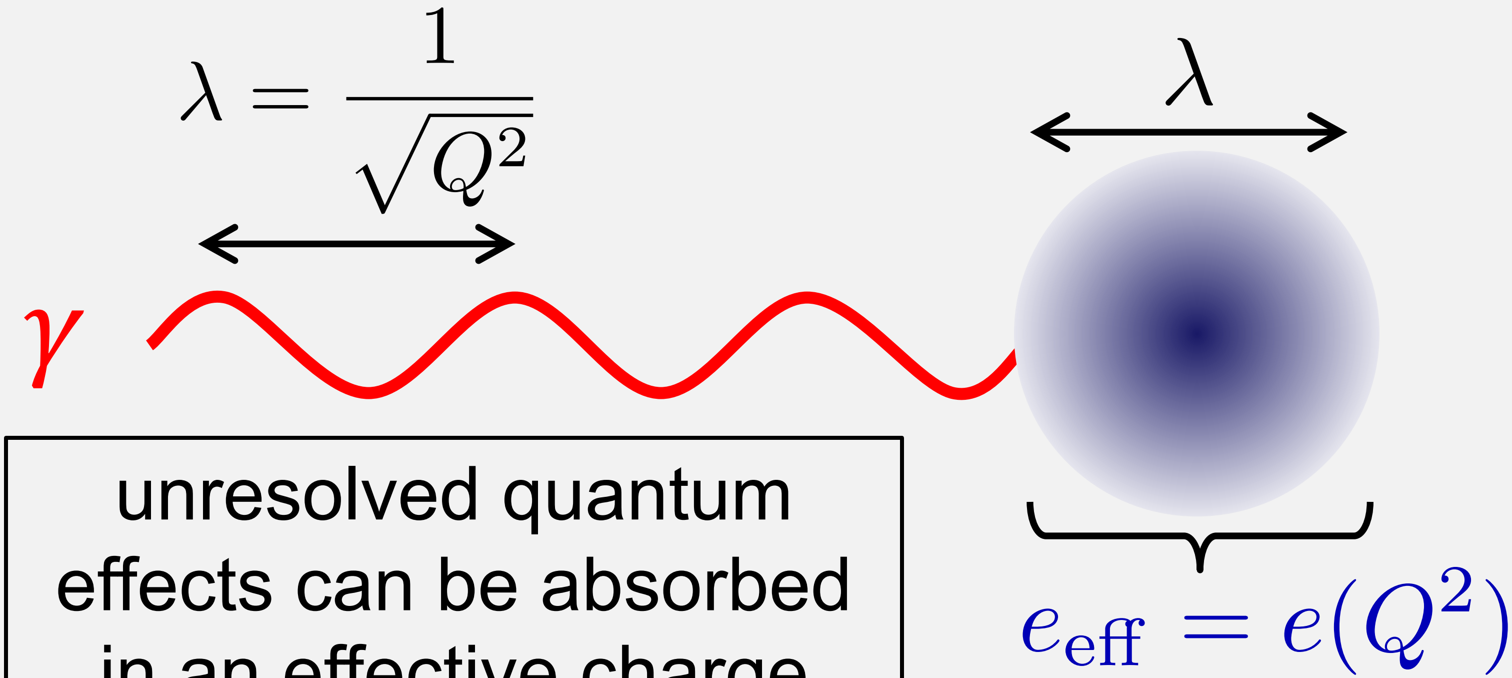


(1) Why are quarks and gluons never free?

First look at a positron – this can be free



$\Rightarrow$ screening of (unphysical) naked charge



unresolved quantum effects can be absorbed in an effective charge

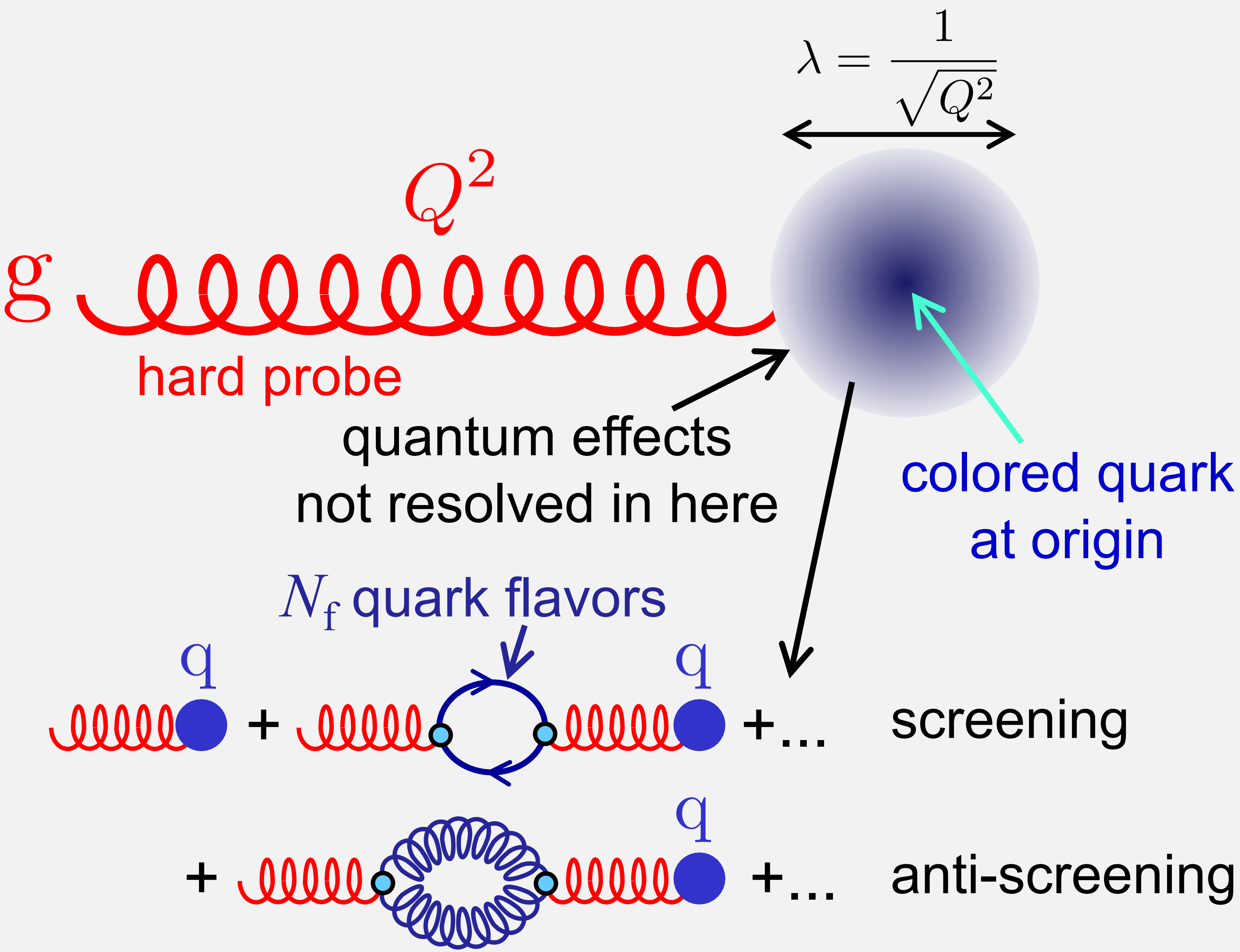
summing up the leading loops $\Rightarrow$

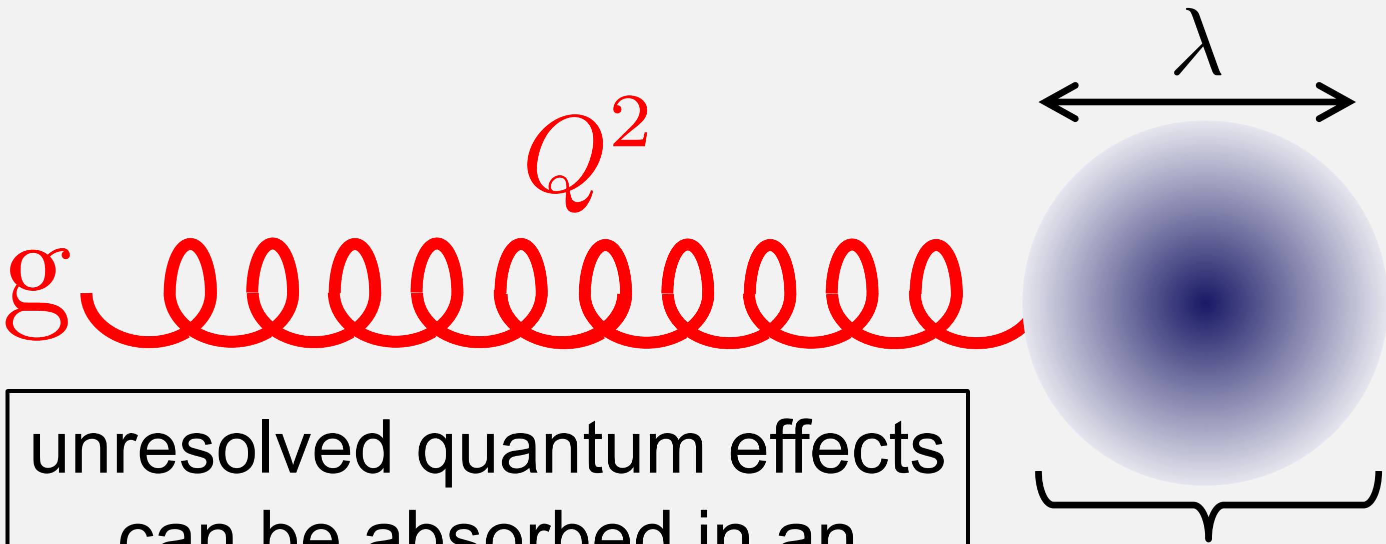
$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \log\left(\frac{Q^2}{\mu^2}\right)}$$

reference scale

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

Now look at a quark with a unit color charge





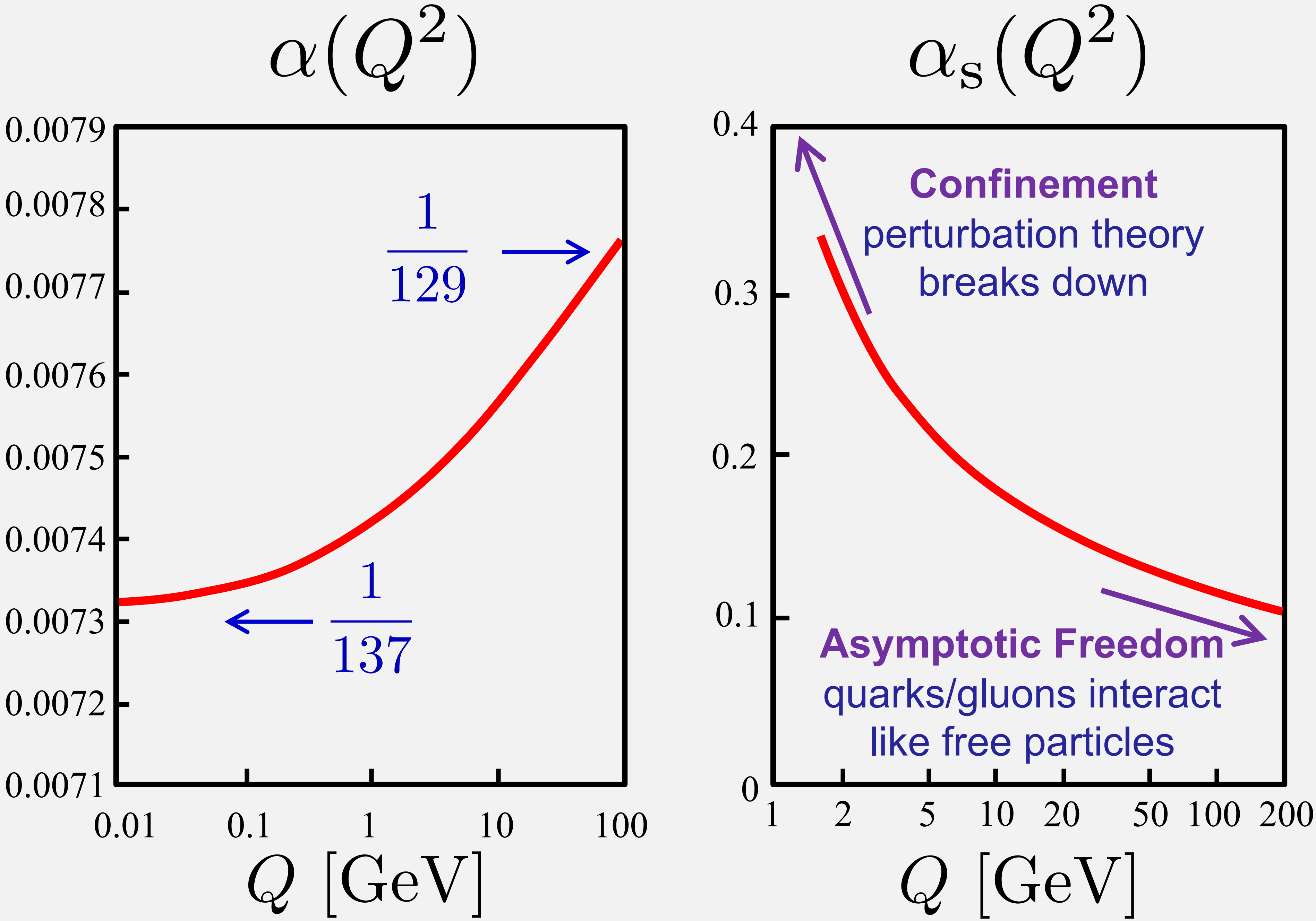
$$\alpha_s = \frac{g_s^2}{4\pi}$$

unresolved quantum effects can be absorbed in an effective color charge

$$g_{s\,\mathrm{eff}} = g_s(Q^2)$$

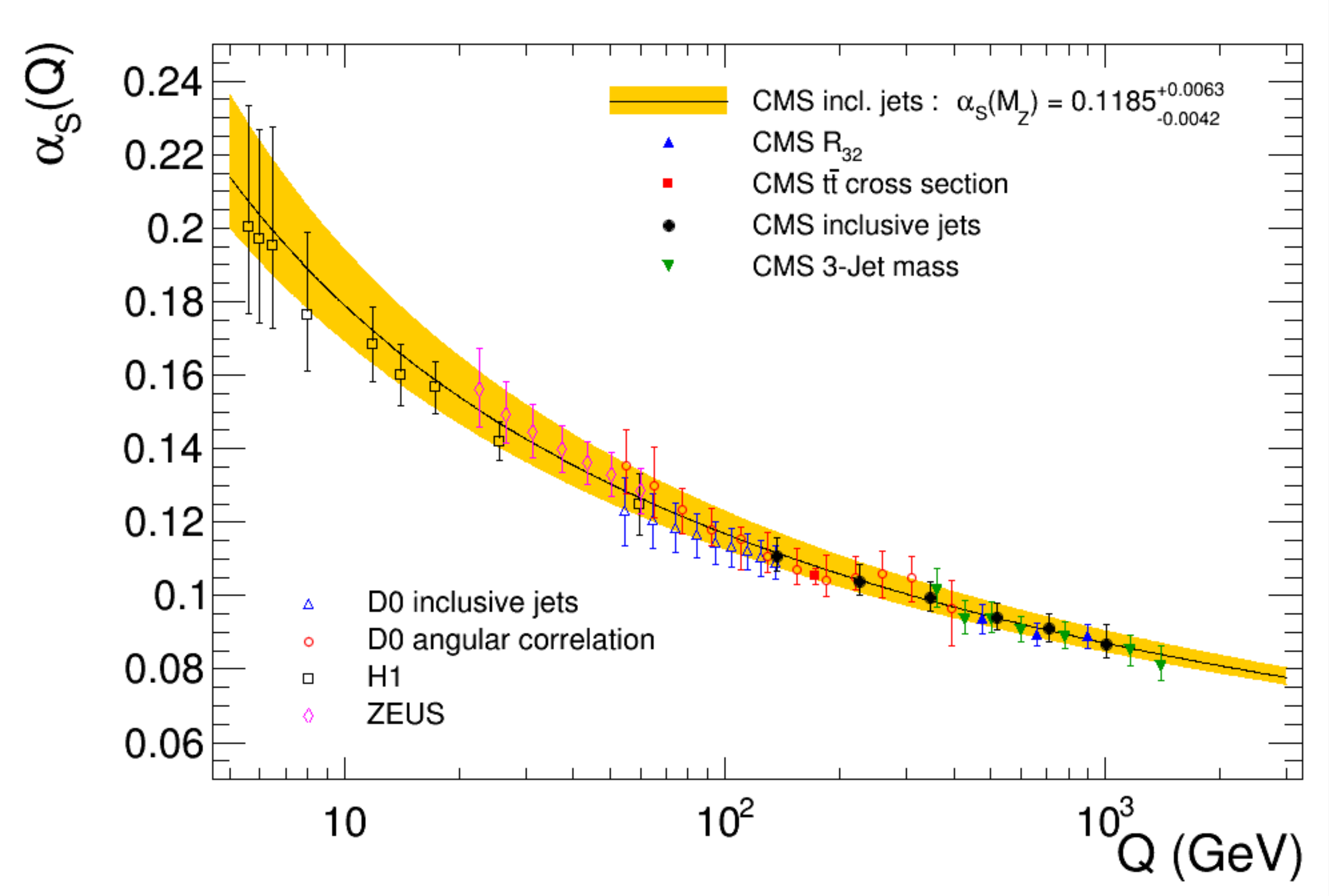
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{(33-2N_f)\alpha_s(\mu^2)}{12\pi}\log\left(\frac{Q^2}{\mu^2}\right)}$$

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

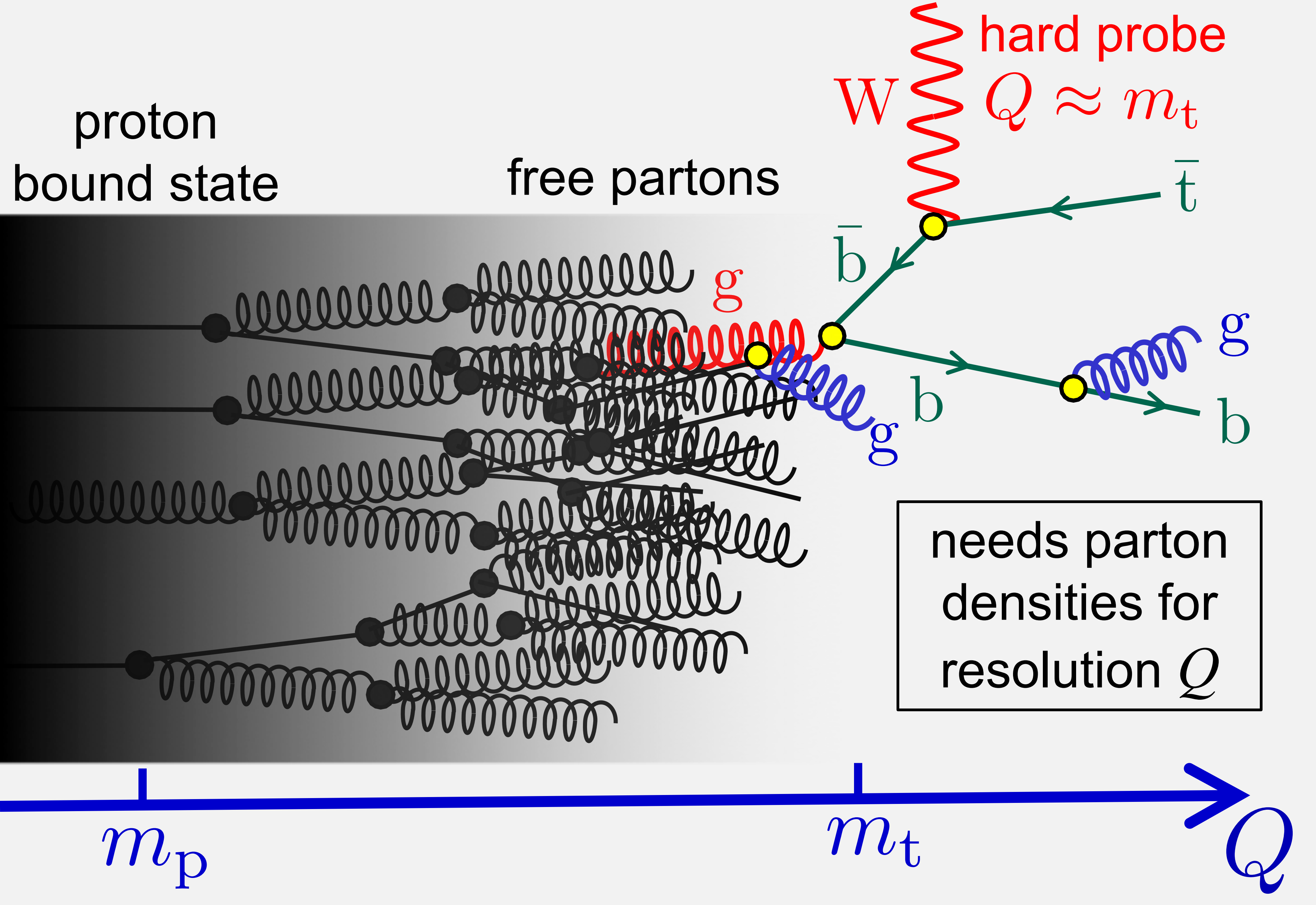


$\alpha(Q^2)$
$\alpha_s(Q^2)$
0.0079
0.0078
0.0077
0.0076
0.0075
0.0074
0.0073
0.0072
0.0071
$\frac{1}{129}$
$\frac{1}{137}$
0.01
0.1
1
10
100
Q [GeV]
0.4
0.3
0.2
0.1
0
1
2
5
10
20
50
100
200
Confinement
perturbation theory
breaks down
Asymptotic Freedom
quarks/gluons interact
like free particles
Q [GeV]

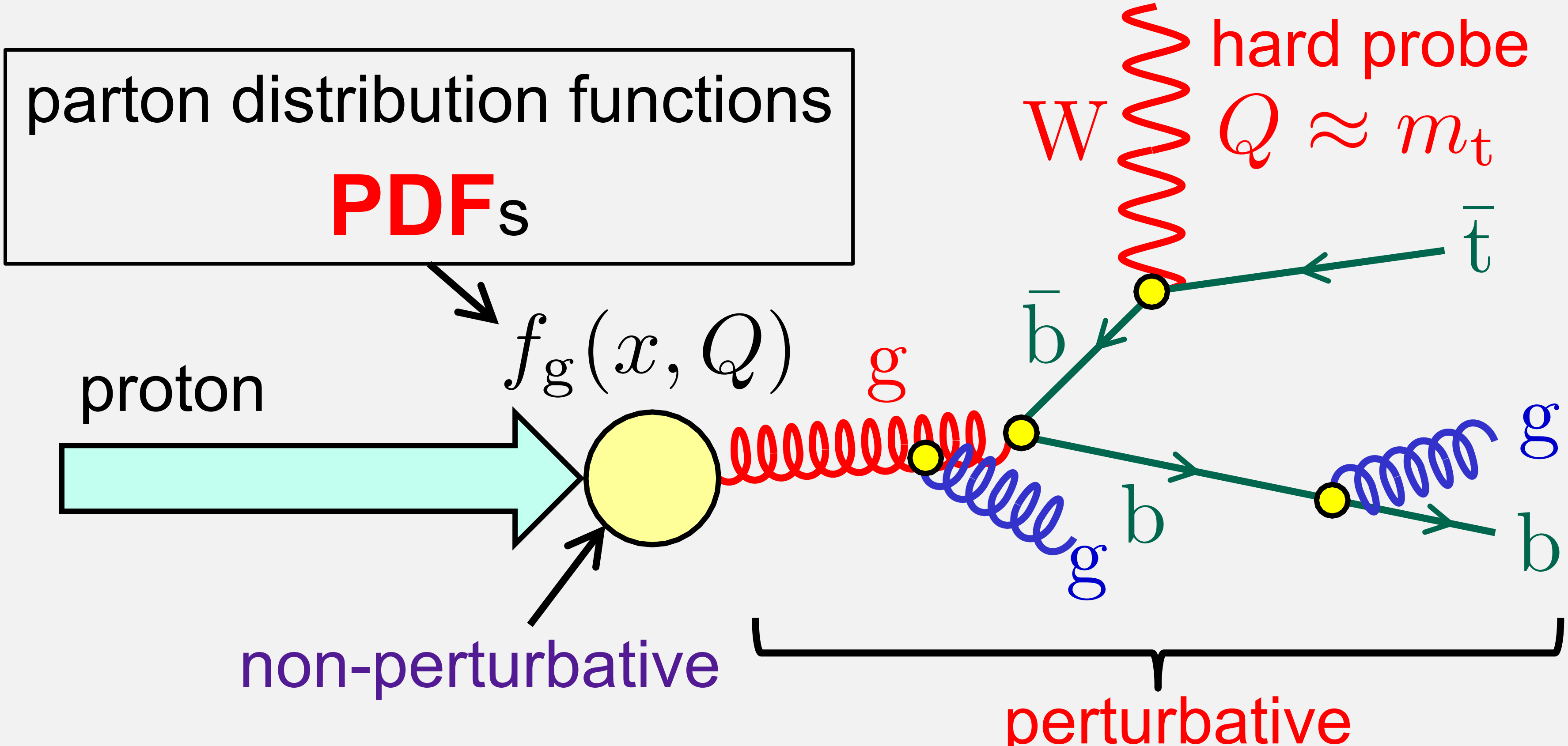
Experimentally accessible, e.g. $\alpha_s \sim \frac{\sigma(X+1\,\mathrm{jet})}{\sigma(X)}$



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



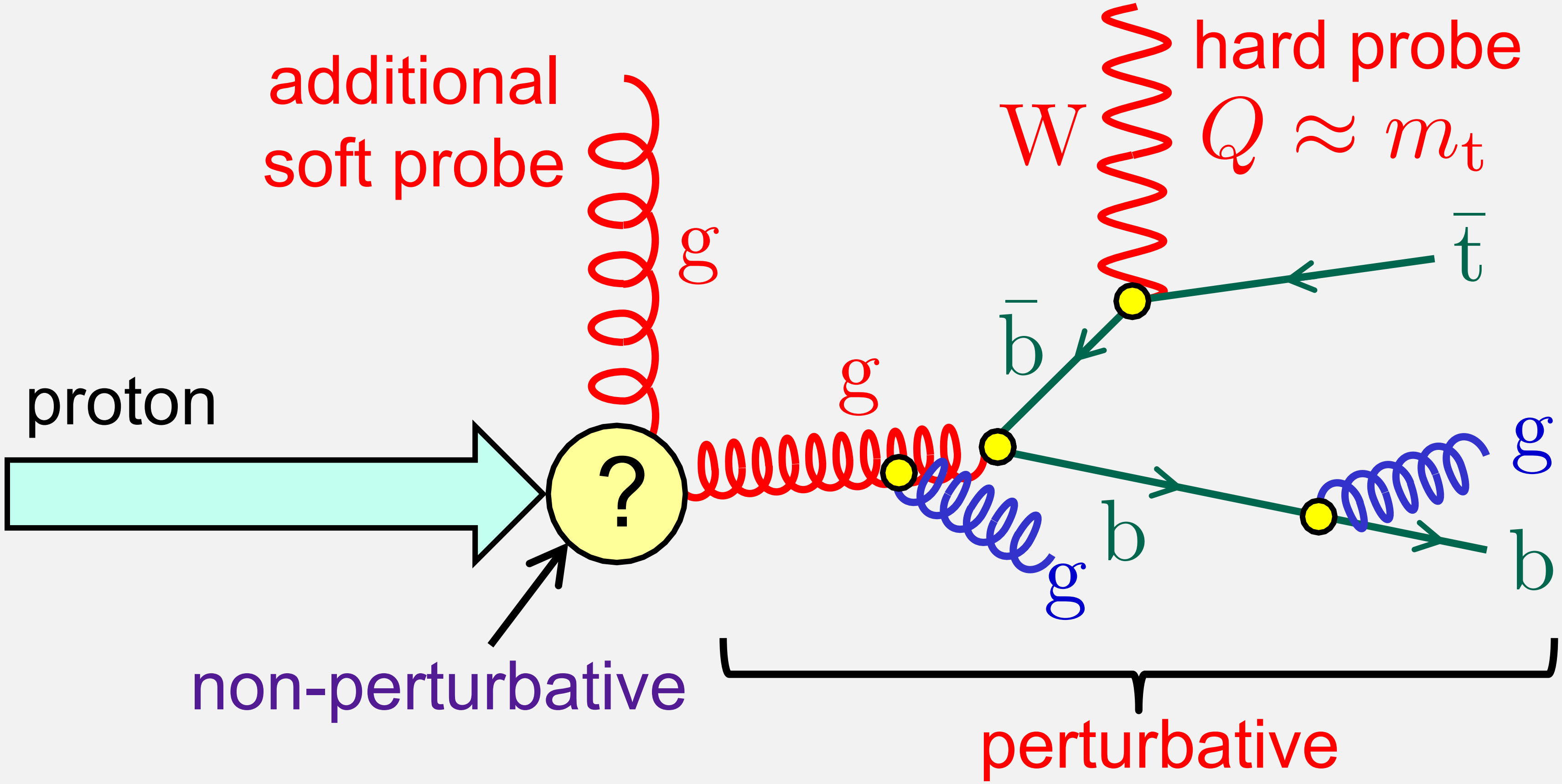
(2) How to treat the quarks/gluons in the protons



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

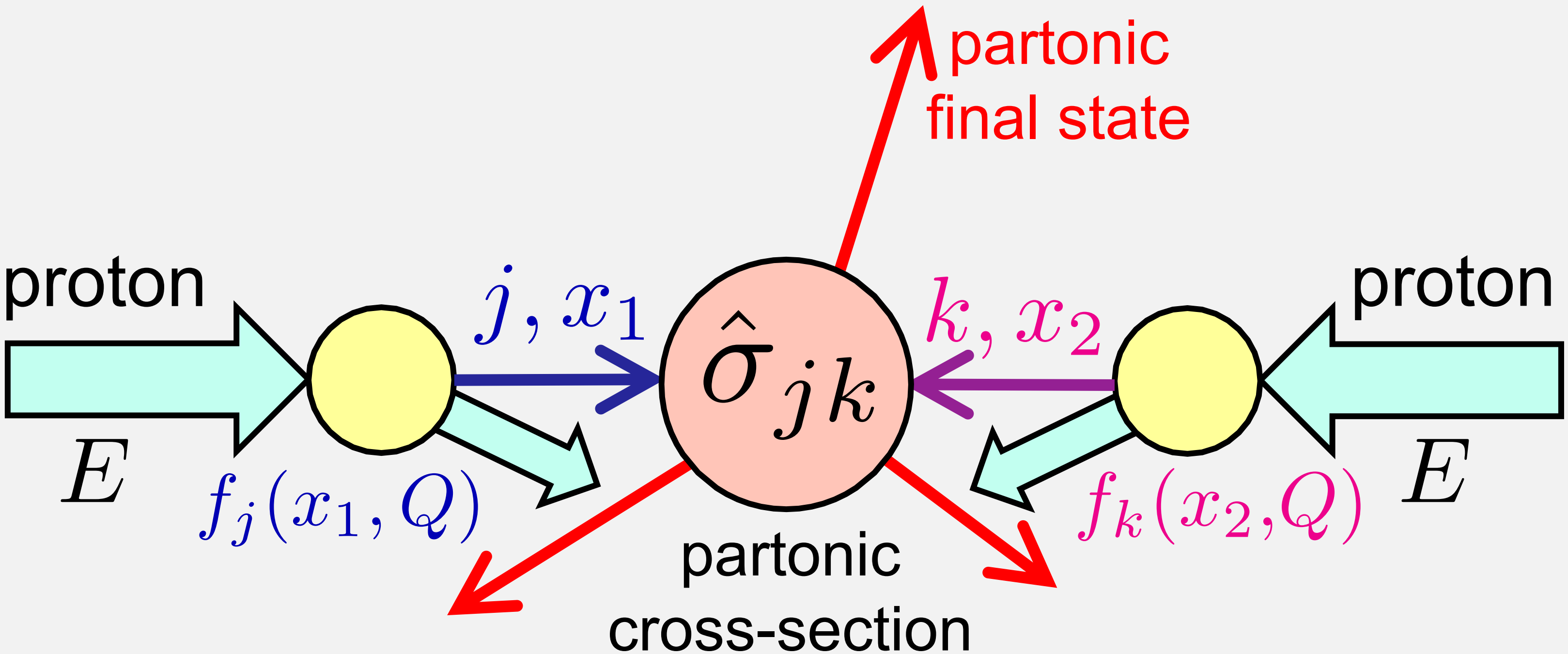
$f_j(x, Q)\, dx$ = number of partons of type j (probed with resolution Q) with momentum fraction in $[x, x + dx]$

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



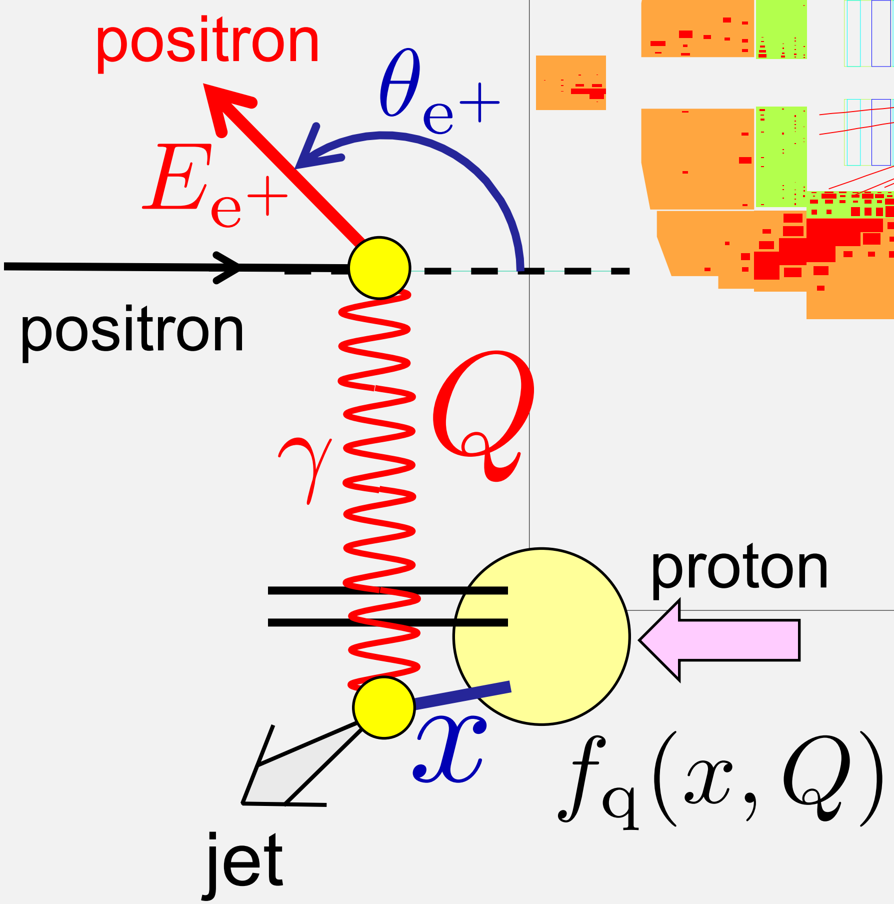
$$\sigma = \sum_{j,k} \int dx_1\, f_j(x_1, Q) \int dx_2\, f_k(x_2, Q) \times \hat{\sigma}_{jk}(\hat{s}, Q)$$

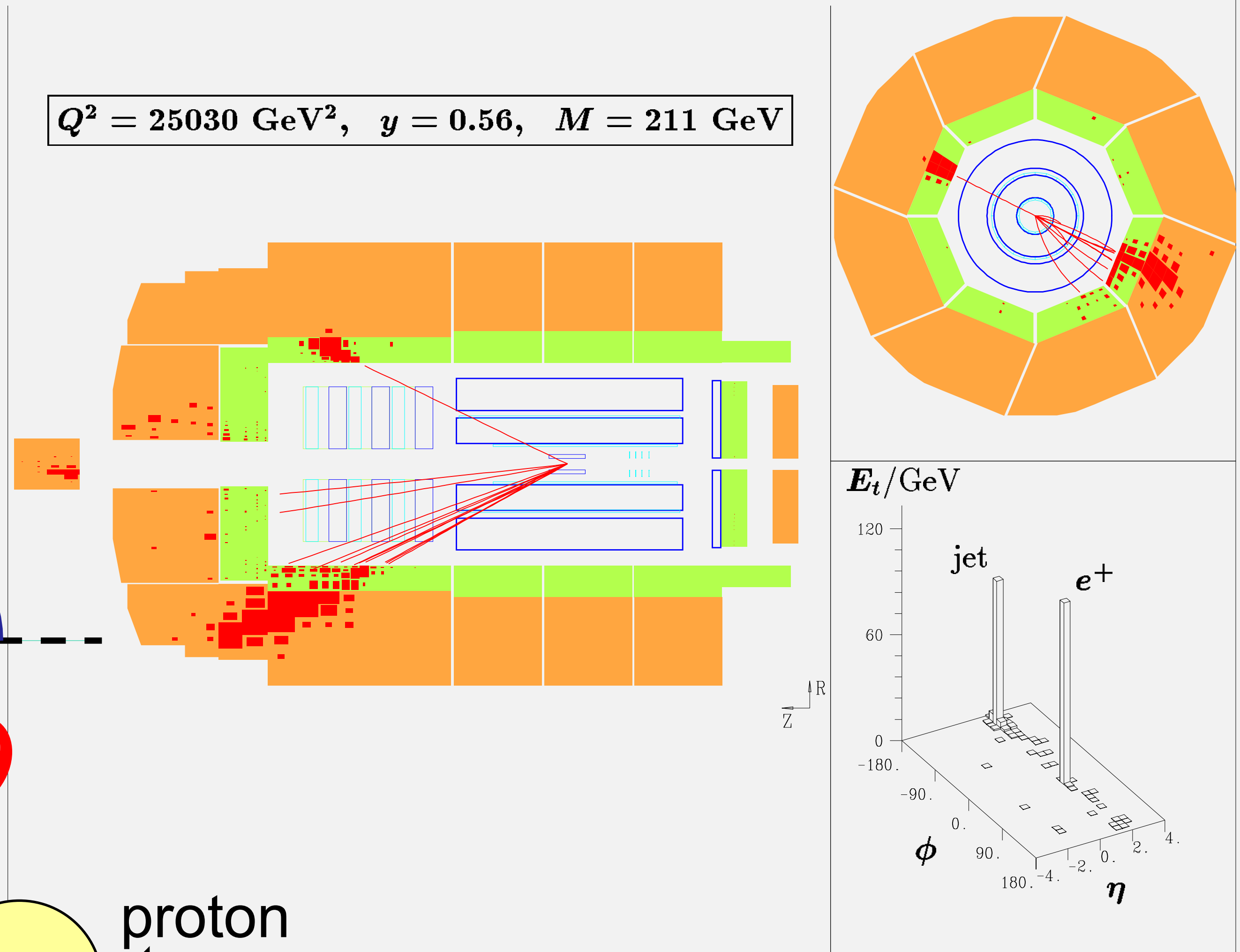
partonic center of mass energy

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

coupling strengths depend on Q

Measurement of PDFs at ep-collider HERA (DESY)

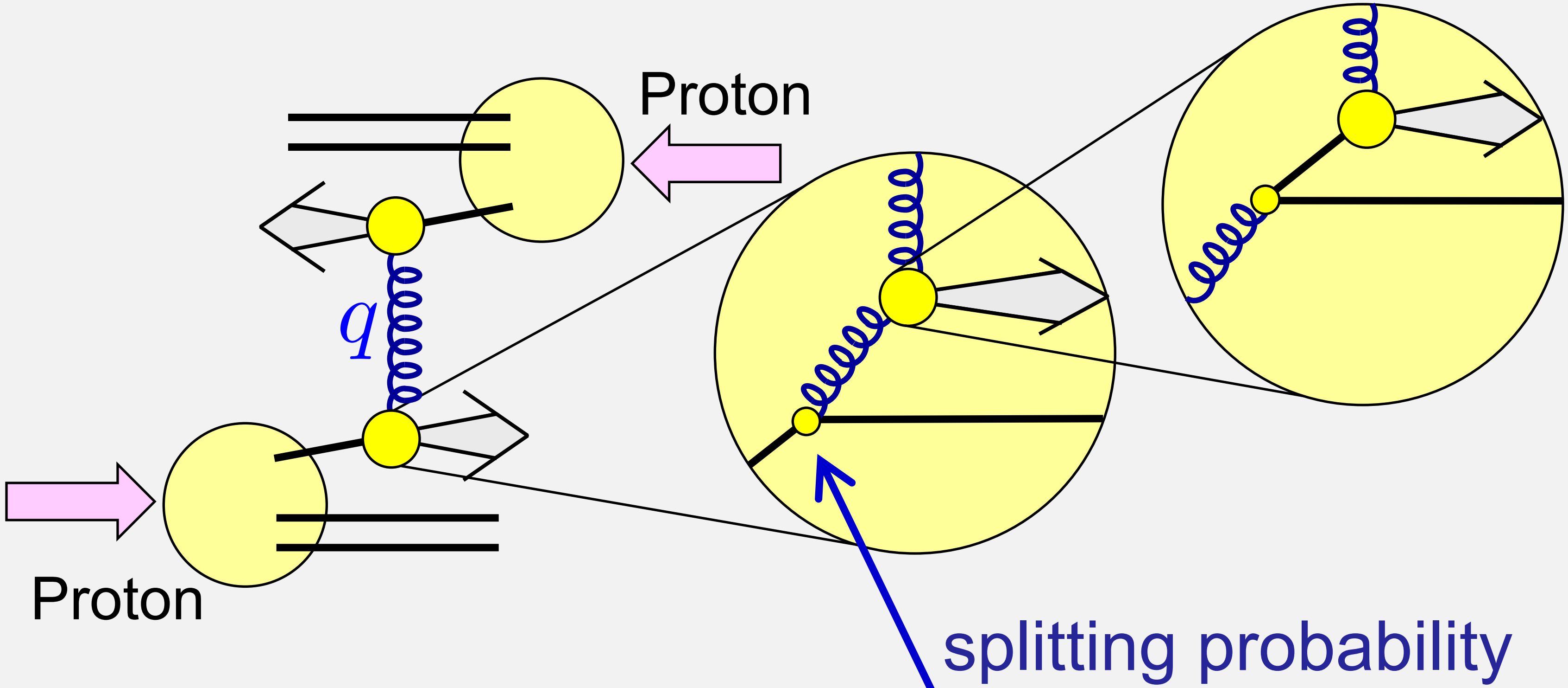




$$E_{e^+}, \theta_{e^+} \quad \Rightarrow \quad x, Q$$

measured

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

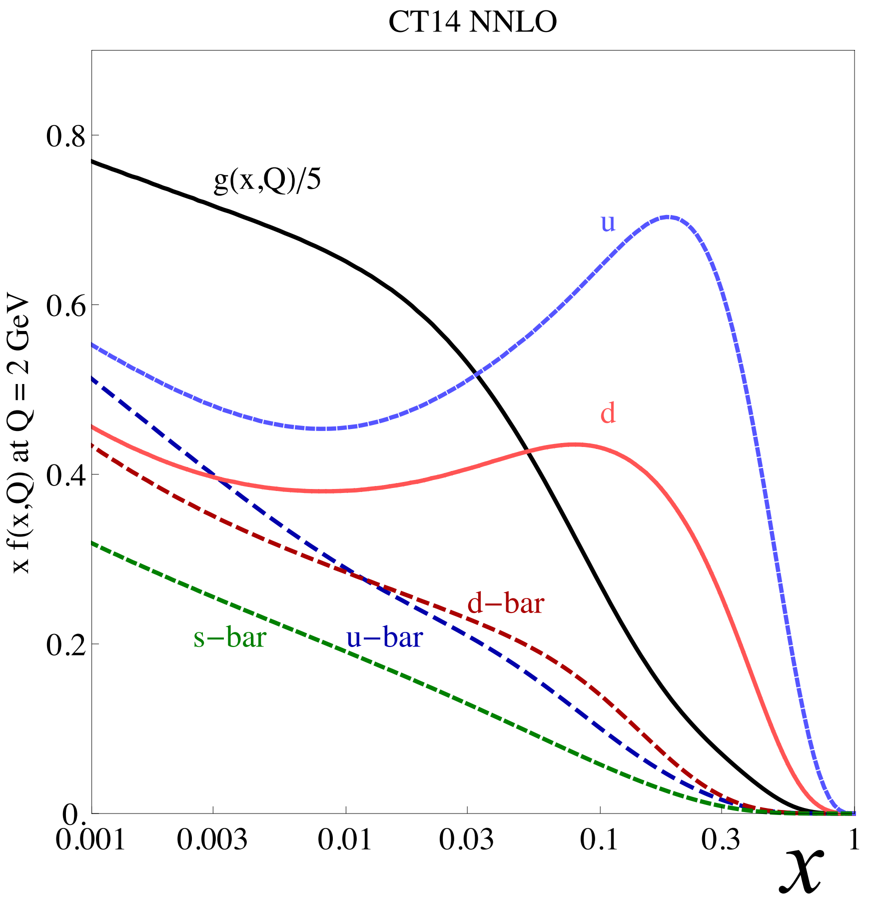


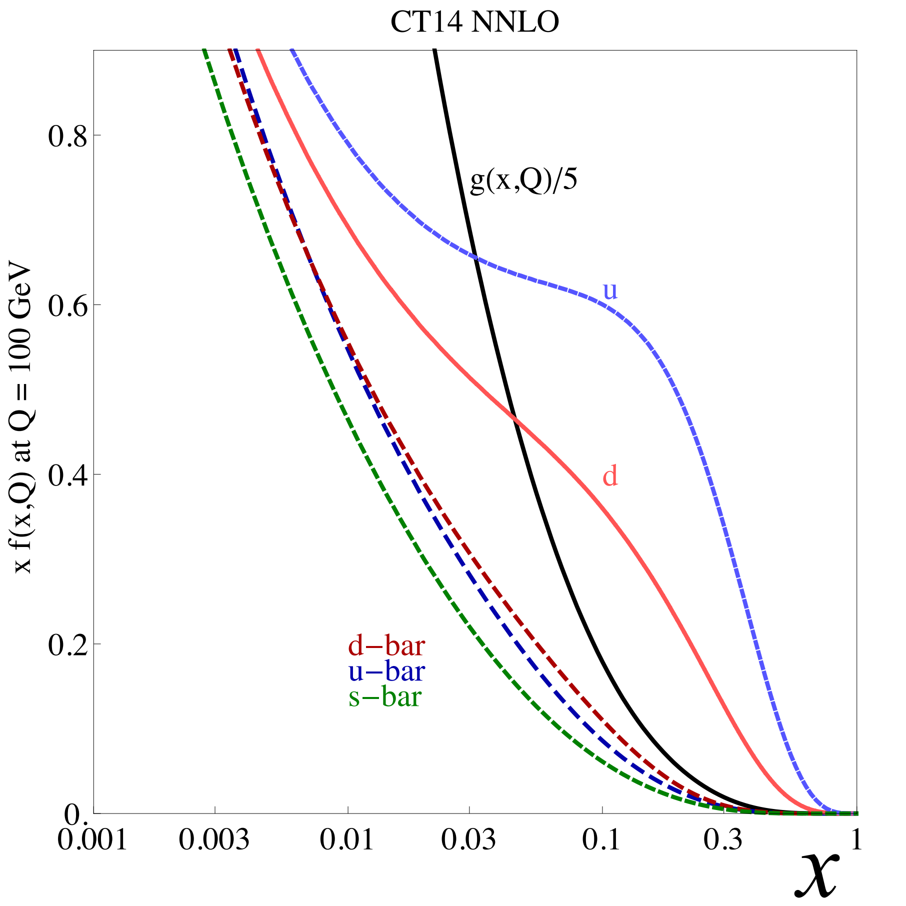
Self-similarity of the quark/gluon structure of the proton:

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

Analytical fits of parton distribution functions

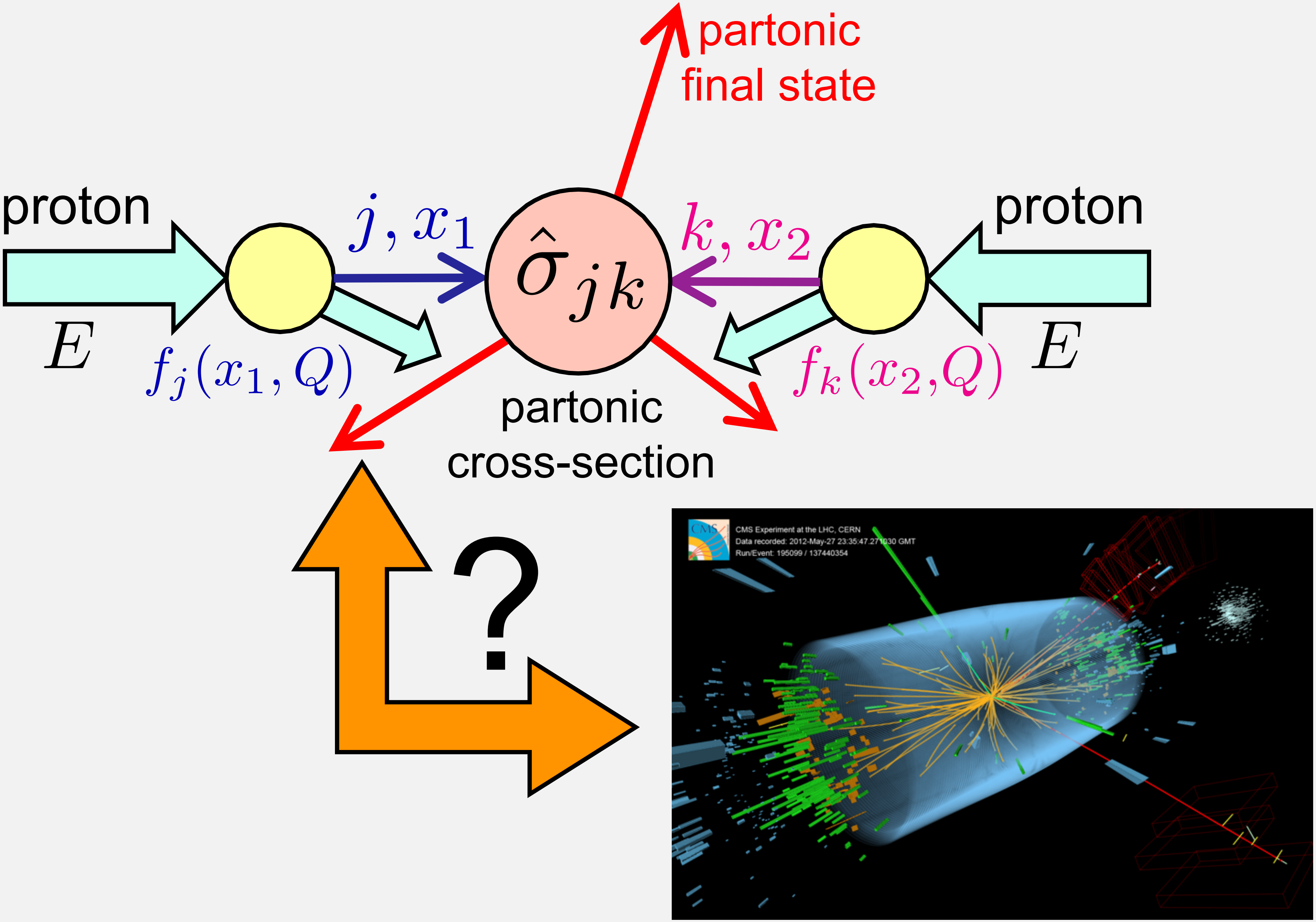
$Q = 2\,\mathrm{GeV}$ $\quad xf(x,Q) \quad$ $Q = 100\,\mathrm{GeV}$

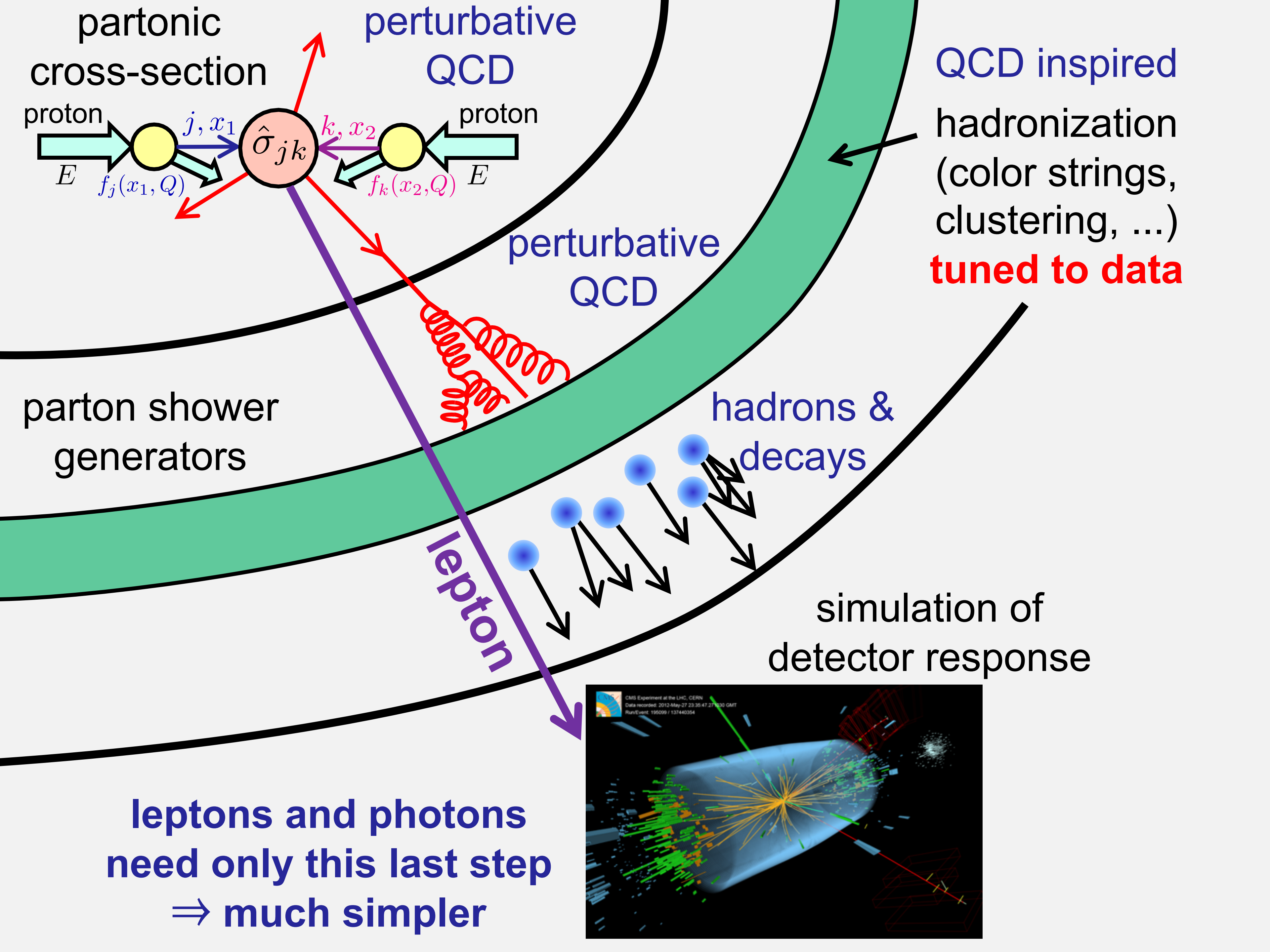




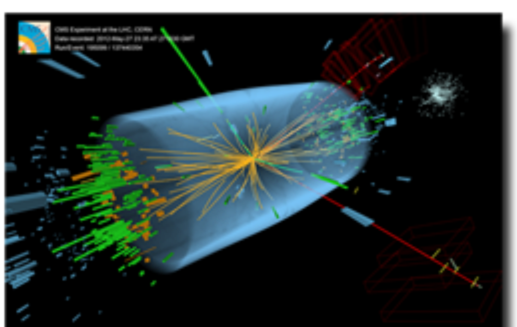
CT14: S. Dulat et al., PRD 93 (2016) 3, 033006

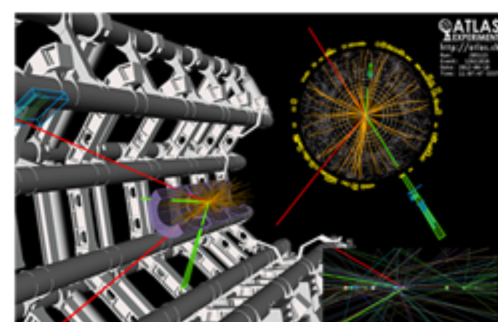
(3) How to connect to final states on hadron level?




partonic
cross-section
perturbative
QCD
QCD inspired
proton
proton
j, x_1
k, x_2
$\hat{\sigma}_{jk}$
E
E
$f_j(x_1, Q)$
$f_k(x_2, Q)$
hadronization
(color strings,
clustering, ...)
tuned to data
perturbative
QCD
parton shower
generators
hadrons &
decays
lepton
simulation of
detector response
leptons and photons
need only this last step
⇒ much simpler

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: $A_\mu \to A_\mu - \partial_\mu f(x)$

$$M_Z \approx 91\,\mathrm{GeV}$$
$$M_W \approx 80\,\mathrm{GeV}$$

?

b) Massive fermion:

$$\mathcal{L} = \overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi + \mathcal{L}_{\text{int}}$$
$$= \underbrace{i\overline{\psi}\gamma^\mu\partial_\mu\psi + \mathcal{L}_{\text{int}}}_{\text{gauge invariant}} - \underbrace{m(\overline{\psi}_{\text{L}}\psi_{\text{R}} + \overline{\psi}_{\text{R}}\psi_{\text{L}})}_{\text{not gauge invariant}}$$

with gauge transformation:

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

$$\psi_{\text{R}} \rightarrow e^{iY\beta(x)}\psi_{\text{R}}$$

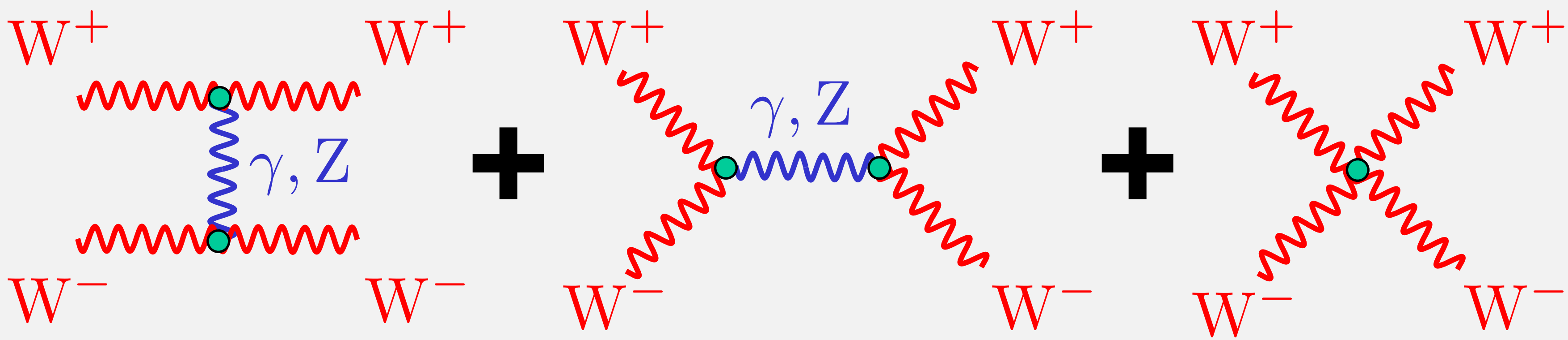
$$m_\tau \approx 1.8\,\text{GeV}$$
$$m_{\text{t}} \approx 173\,\text{GeV}$$

?

Fundamental problem 2 (ignoring problem 1)

Theory is misbehaved at (very) large energies!

Scattering of two W-bosons:



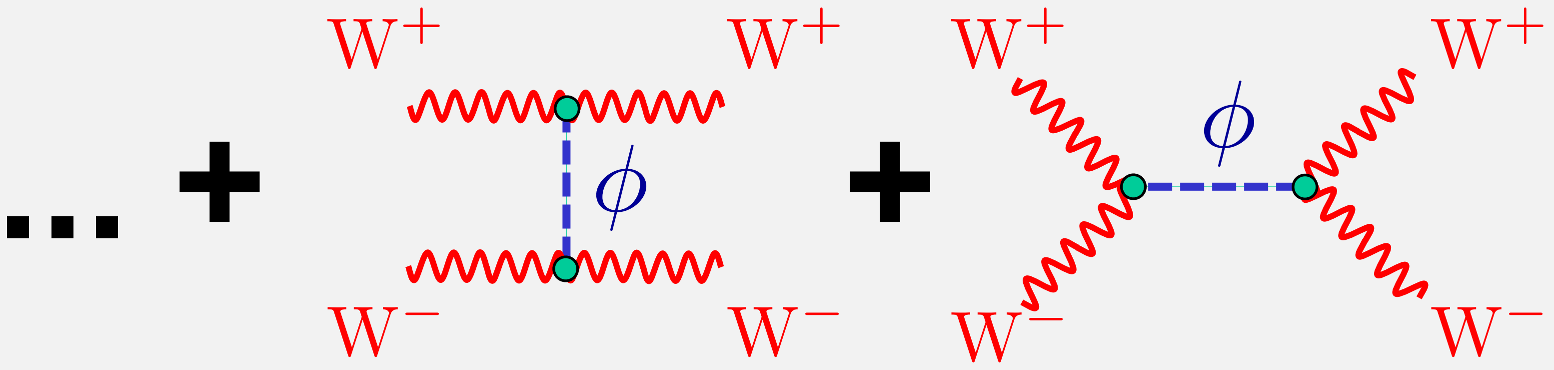
$$\propto \frac{s}{M_{\mathrm{W}}^2} \quad \text{for} \quad s \to \infty$$

$\Rightarrow$ scattering probability > 1 at high enough energies

$\Rightarrow$ violation of **unitarity** bound

... this can be fixed by additional amplitudes

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



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

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

Note:

Such cancellations work because of gauge **symmetry**

Solution:

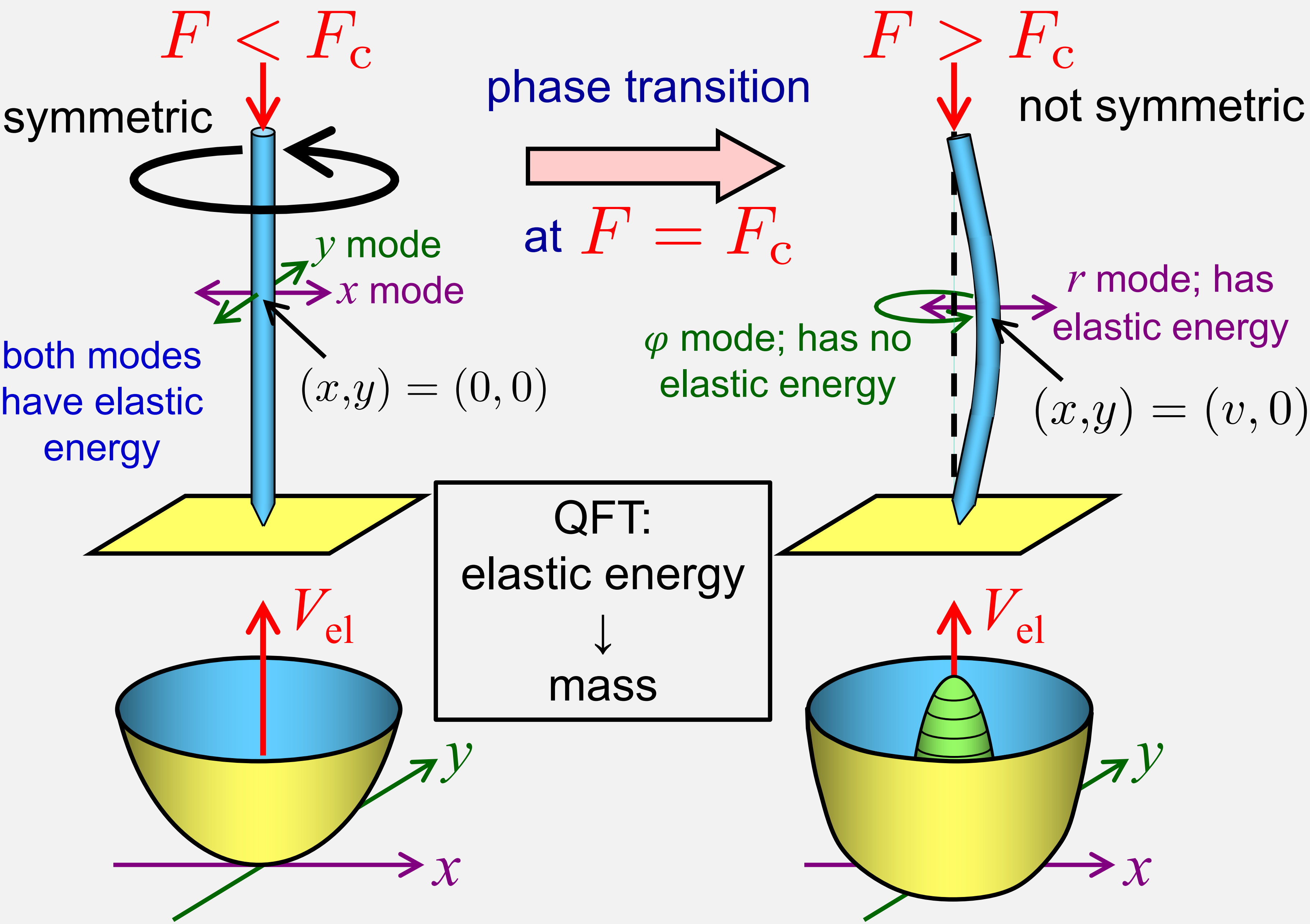
Spontaneous breaking of the

$$SU(2)_{\mathrm{L}} \times U(1)_Y$$

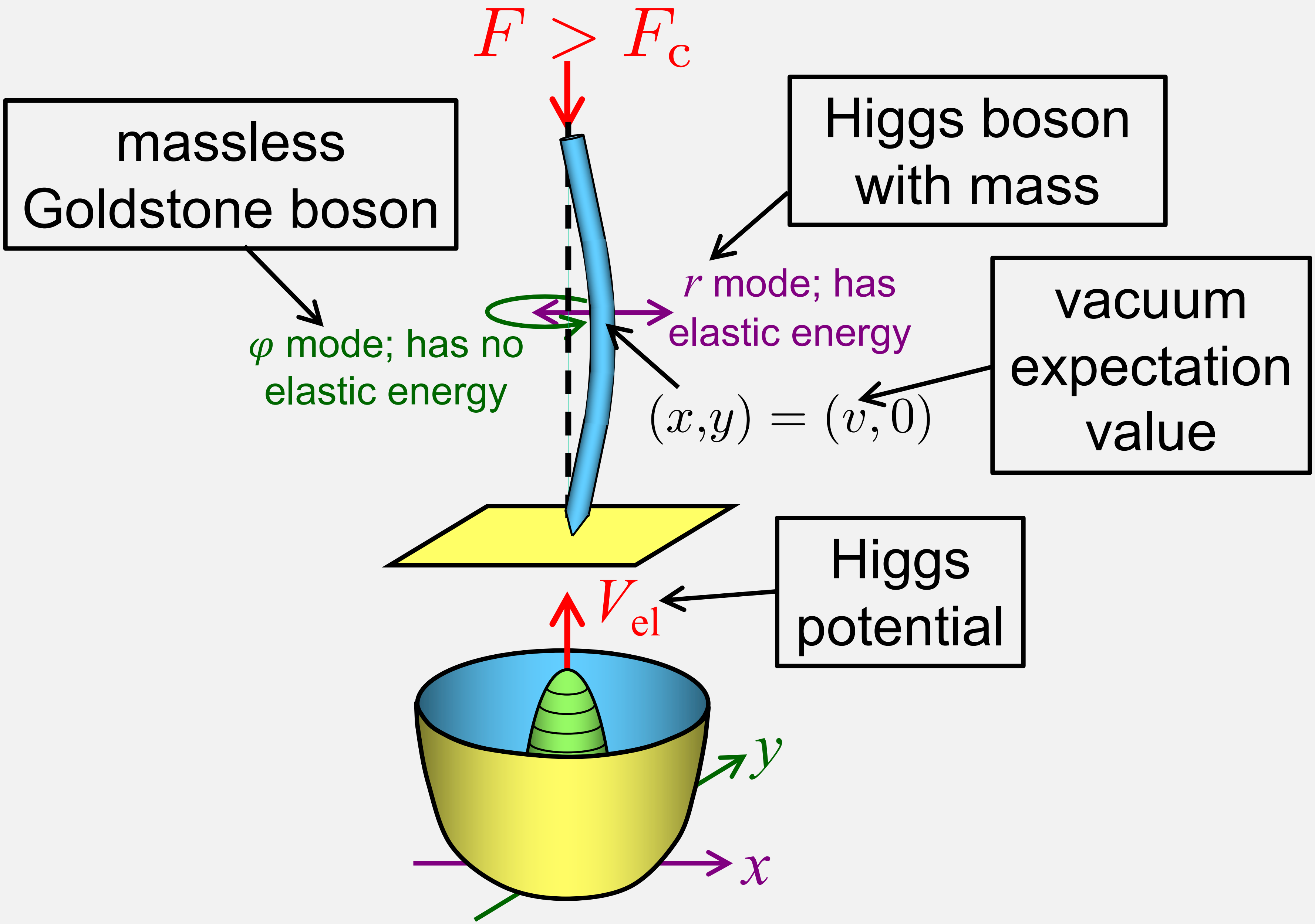
gauge symmetry

involving an additional scalar field

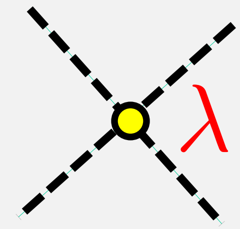
Classical example: buckling of an elastic rod



Correspondence with QFT (somewhat rough):



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



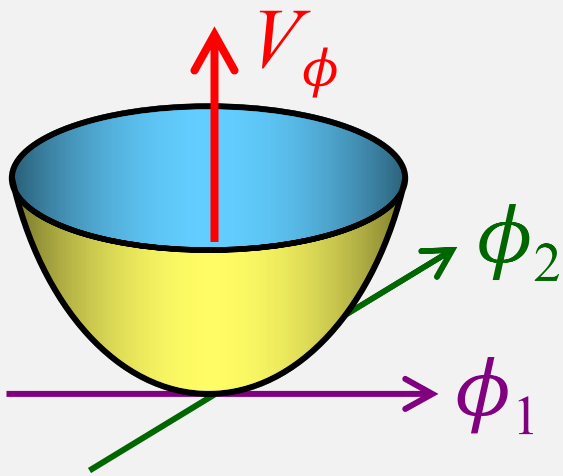
mass term

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

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

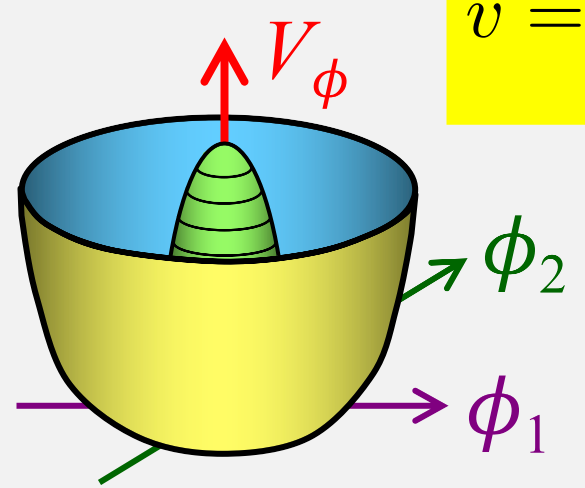
Higgs potential V_ϕ

$\mu^2 > 0$



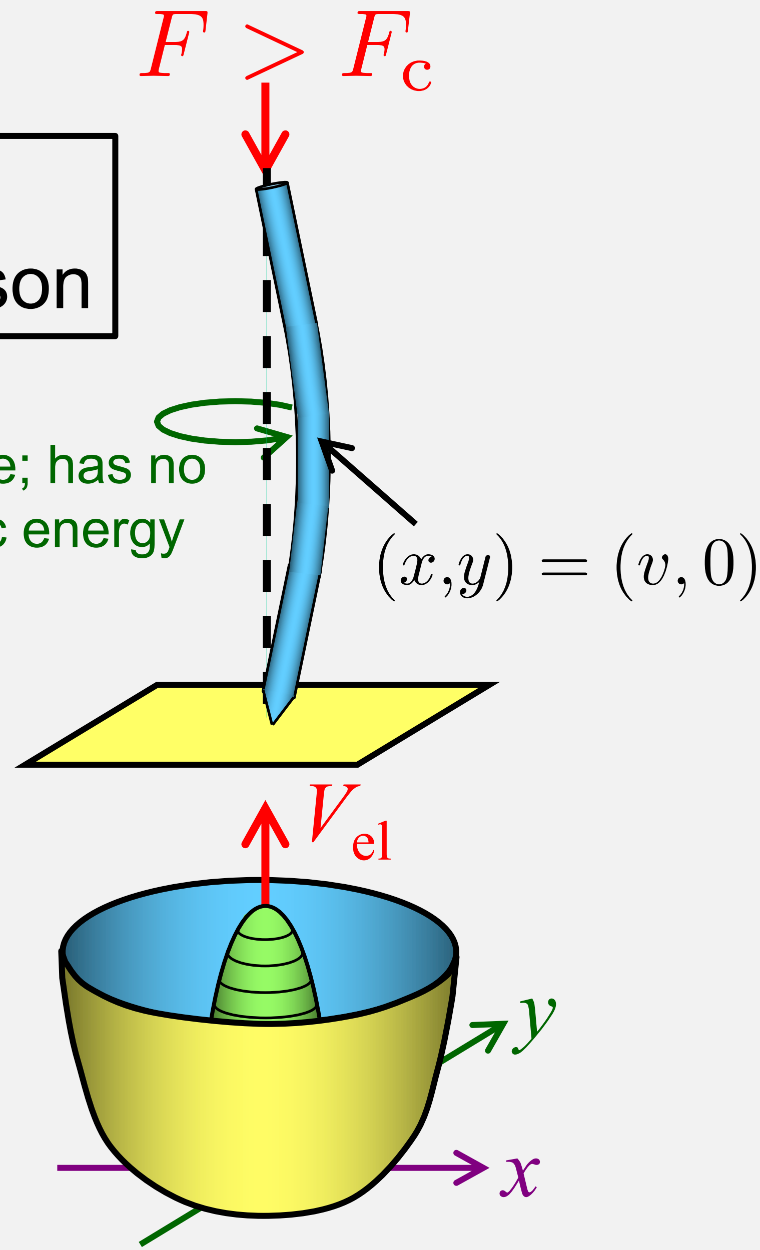
$\mu^2 < 0$

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



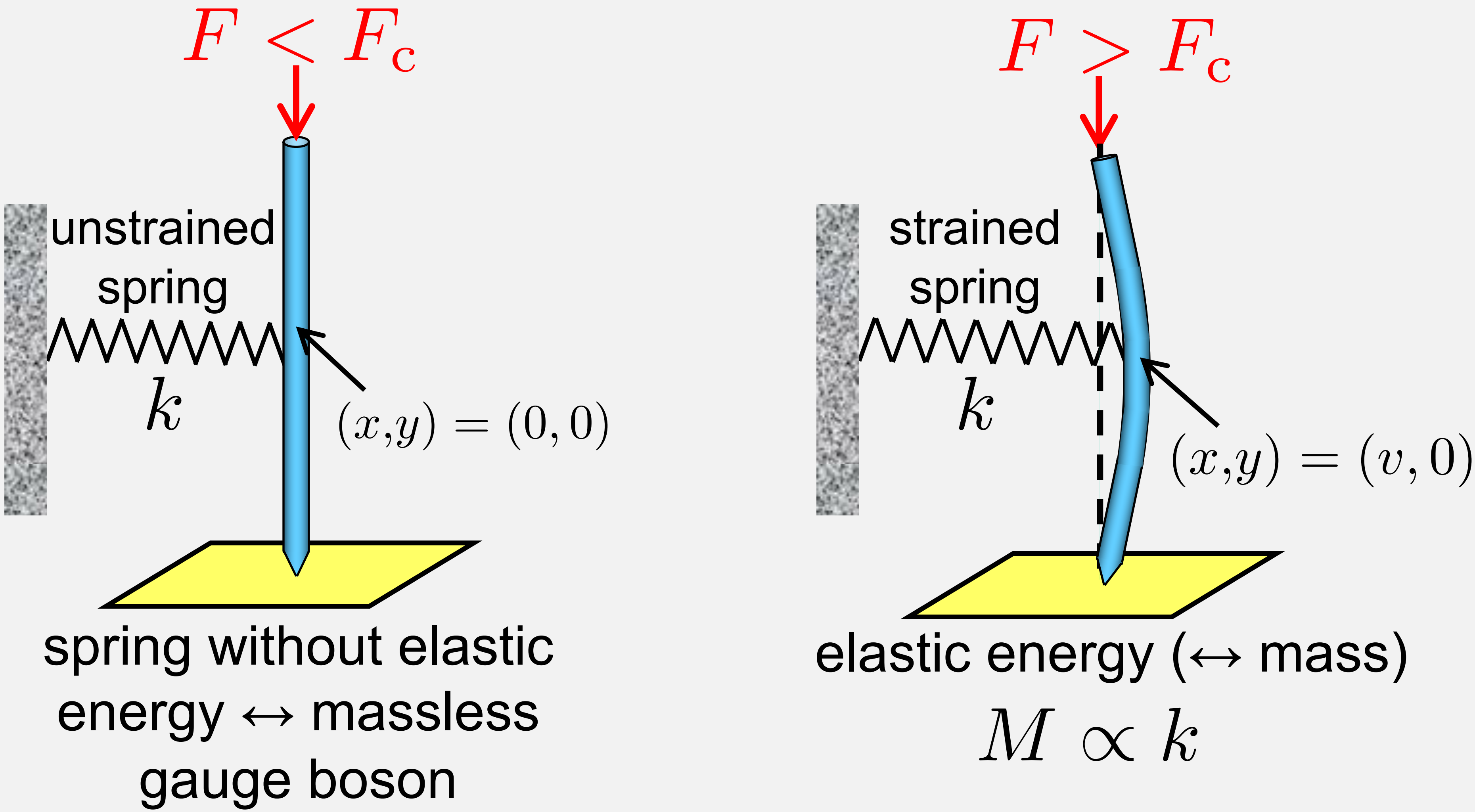
But: there are no (known) massless scalars in nature

massless
Goldstone boson



eliminate this mode by a transformation into the rotating system
(↔ gauge transformation)

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

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

$\mu^2 < 0 \Rightarrow$ 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 ↯

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

T^2 ↯

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

T^3 ↯

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

Y ↯

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

Q ✓

$$M_{\rm W} > 0,\ M_{\rm Z} > 0,\ M_\gamma = 0$$

!

1 Higgs H

Numbers

$$M_{\mathrm{W}} = \frac{1}{2} v g \qquad = 80.4\,\mathrm{GeV}$$

$$M_{\mathrm{Z}} = \frac{1}{2} v \sqrt{g^2 + g'^2} = 91.2\,\mathrm{GeV}$$

$$v = \qquad = 246\,\mathrm{GeV}$$

Predicted: $M_\gamma = 0 \;, \quad M_{\mathrm{Z}} = \dfrac{M_{\mathrm{W}}}{\cos\theta_{\mathrm{w}}}$

Not predicted: M_{W}

$$M_{\mathrm{H}} = \sqrt{2\lambda}\, v$$

Implementation of fermion masses

Example: electron

invariant under $SU(2)_\mathrm{L}$

$$\mathcal{L}_\mathrm{eH} = -\frac{m_\mathrm{e}}{v}\left[(\bar{\nu}_\mathrm{e}, \bar{e})_\mathrm{L}\begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix} e_\mathrm{R} + \mathrm{h.c.}\right]$$

$$Y = 1 + 1 - 2 = 0$$

invariant under $U(1)_Y$

Expanded around vacuum:

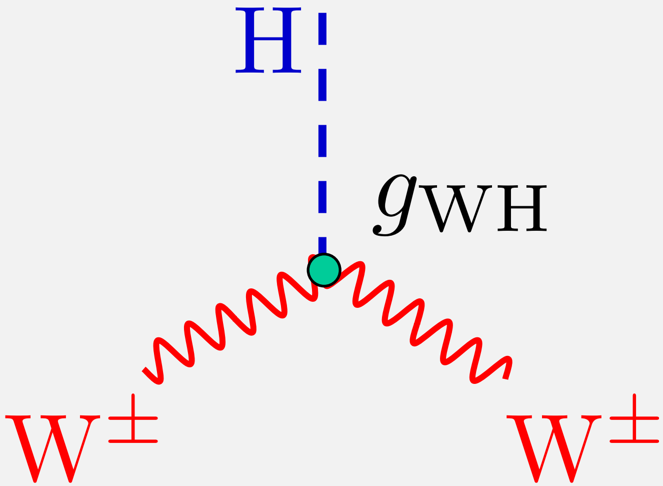
$$\mathcal{L}_\mathrm{eH} = -m_\mathrm{e}\bar{e}e - \frac{m_\mathrm{e}}{v}\bar{e}eH$$

mass term
(mass value not predicted)

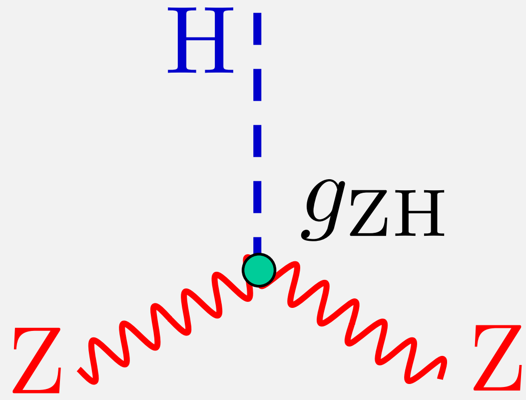
Yukawa coupling

Higgs coupling strength is proportional to mass

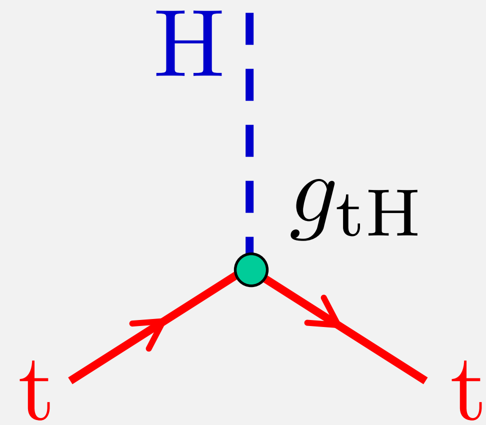
examples:



$$\propto g M_{\mathrm{W}} = \frac{2M_{\mathrm{W}}^2}{v}$$



$$\propto \frac{g}{\cos\theta_{\mathrm{w}}} M_{\mathrm{Z}} = \frac{2M_{\mathrm{Z}}^2}{v}$$



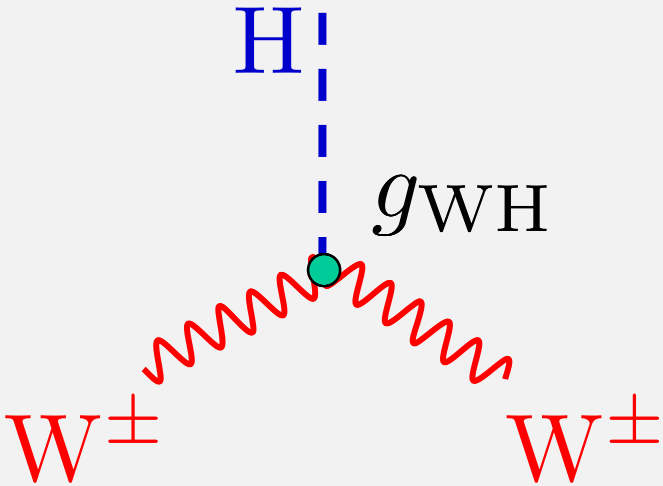
$$\propto g \frac{m_{\mathrm{t}}}{2M_{\mathrm{W}}} = \frac{m_{\mathrm{t}}}{v}$$

note: $$\frac{m_{\mathrm{t}}}{v} = \frac{173\,\mathrm{GeV}}{246\,\mathrm{GeV}} = 0.70 = \mathcal{O}(1)$$

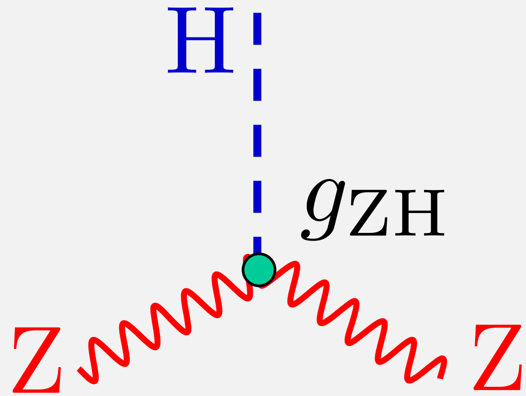
The top-quark is a golden key for testing the Higgs sector

Higgs coupling strength is proportional to mass

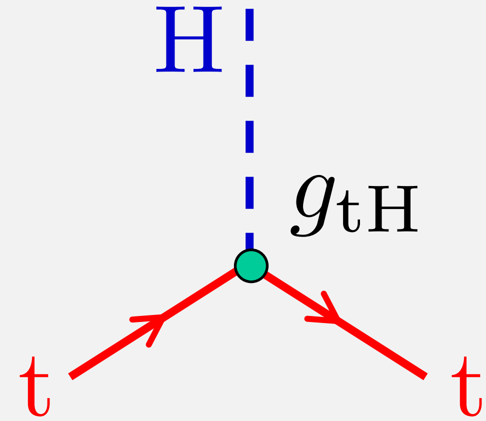
examples:



$$\propto gM_{\mathrm{W}} = \frac{2M_{\mathrm{W}}^2}{v}$$



$$\propto \frac{g}{\cos\theta_{\mathrm{w}}} M_{\mathrm{Z}} = \frac{2M_{\mathrm{Z}}^2}{v}$$



$$\propto g\frac{m_{\mathrm{t}}}{2M_{\mathrm{W}}} = \frac{m_{\mathrm{t}}}{v}$$

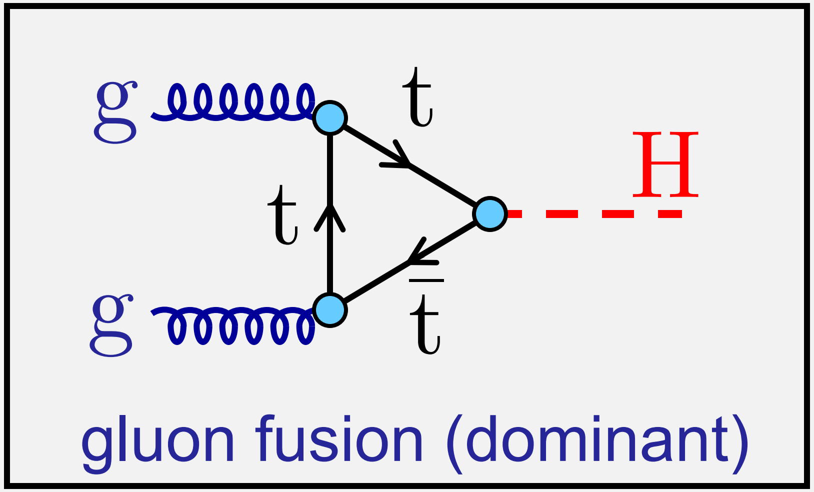
note:

$$\frac{M_{\mathrm{V}}}{v} = \sqrt{\frac{|g_{\mathrm{VH}}|}{2v}}\,, \qquad \frac{m_{\mathrm{F}}}{v} = |g_{\mathrm{FH}}|$$

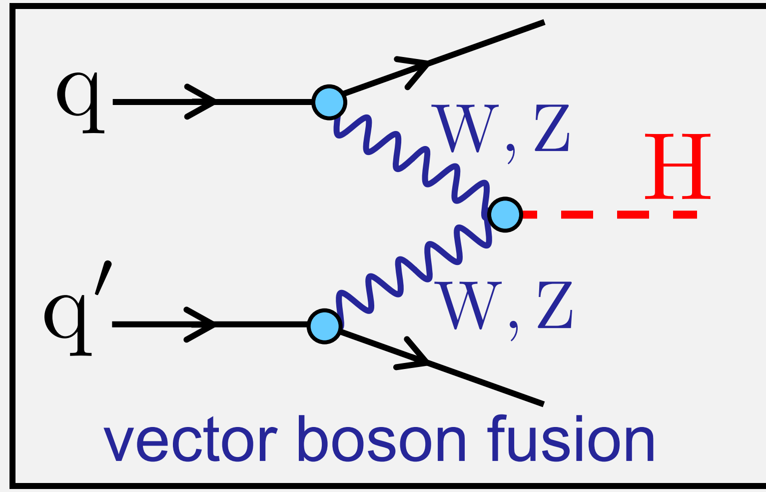
$\mathrm{V} = \mathrm{W}, \mathrm{Z}$

$\mathrm{F} = \mathrm{fermion}$

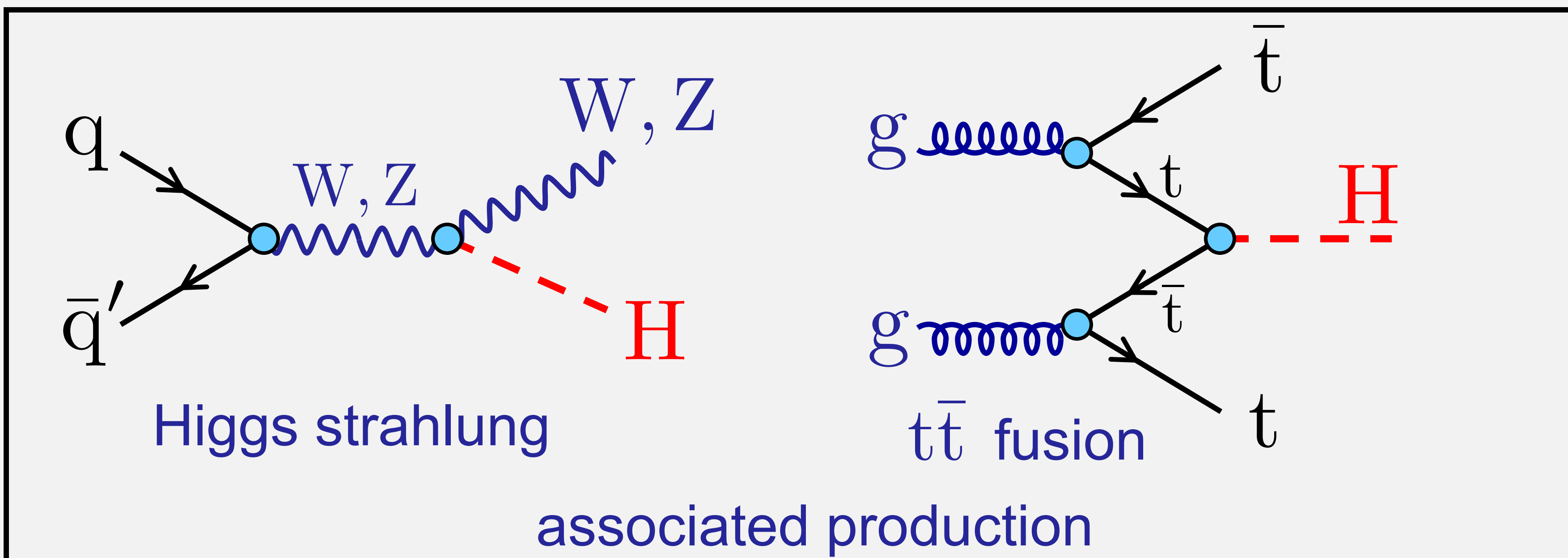
Higgs production at the LHC



gluon fusion (dominant)



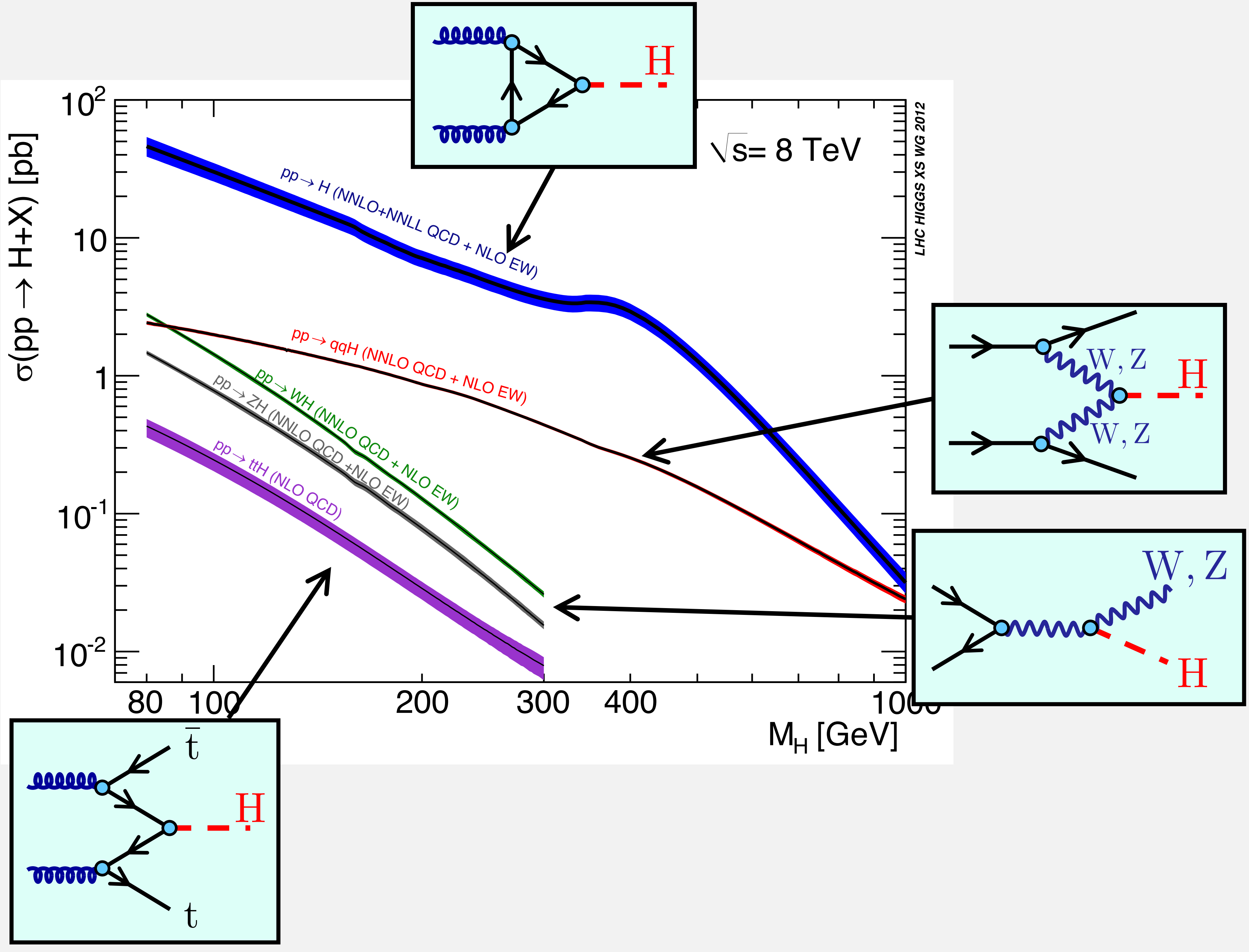
vector boson fusion



Higgs strahlung

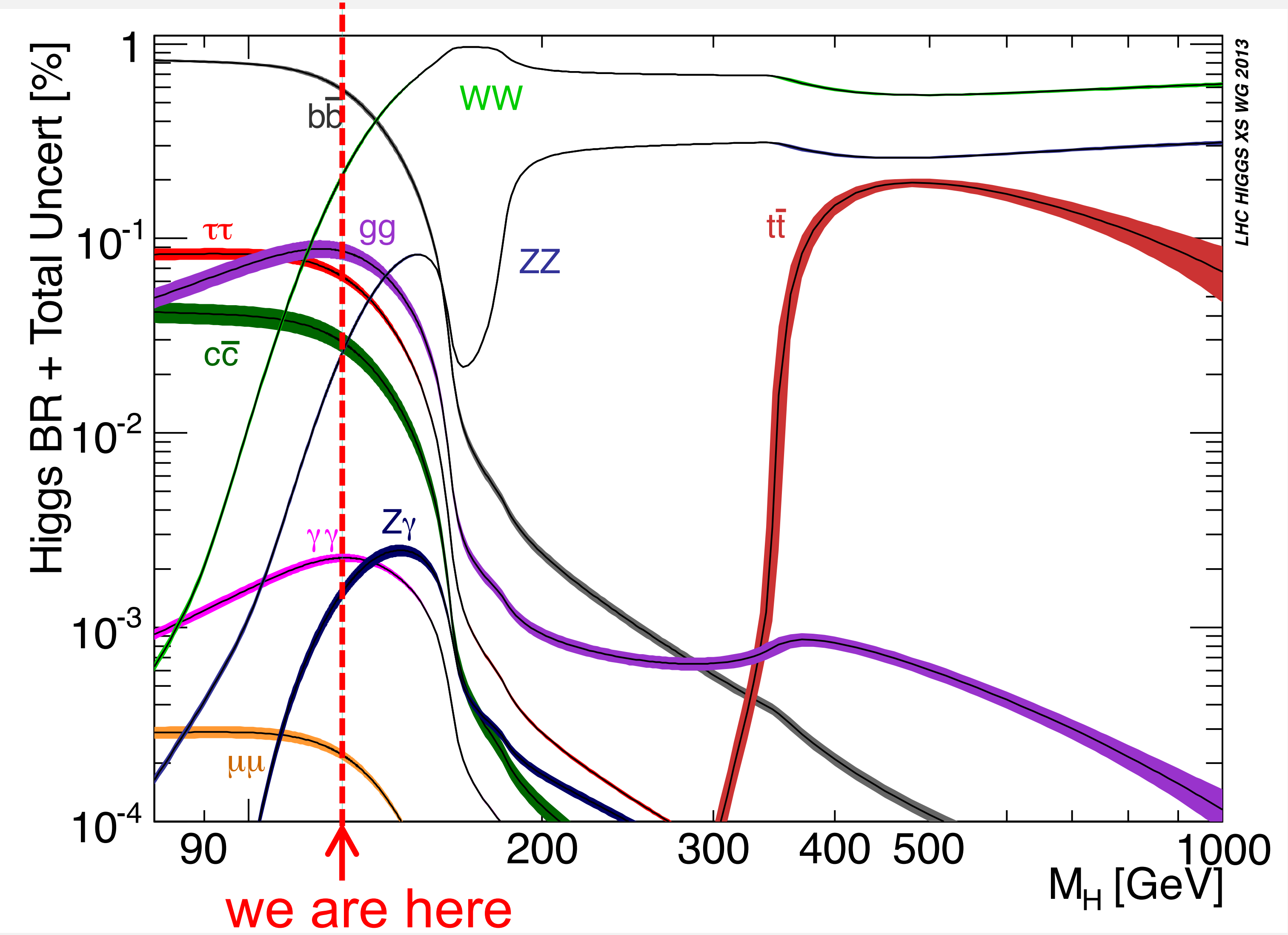
$t\bar{t}$ fusion

associated production



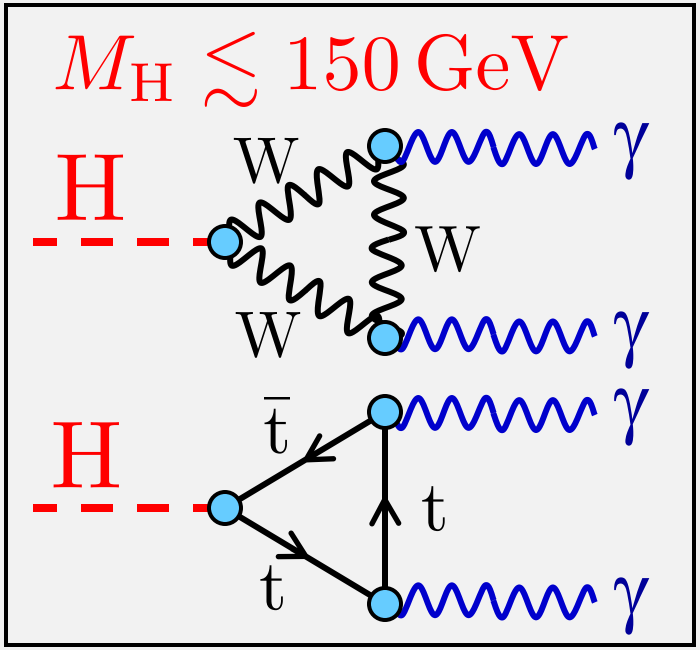
H
√s= 8 TeV
LHC HIGGS XS WG 2012
σ(pp → H+X) [pb]
pp→ H (NNLO+NNLL QCD + NLO EW)
pp→ qqH (NNLO QCD + NLO EW)
pp→ WH (NNLO QCD + NLO EW)
pp→ ZH (NNLO QCD +NLO EW)
pp→ ttH (NLO QCD)
W, Z
H
W, Z
W, Z
H
M_H [GeV]
t̄
H
t

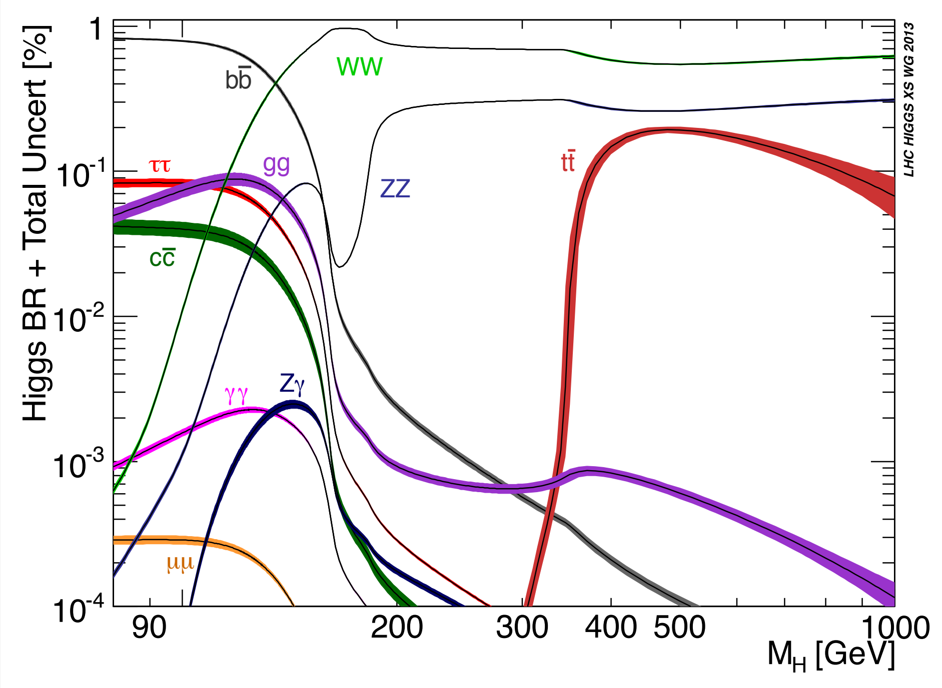
Higgs decay fractions vs. mass

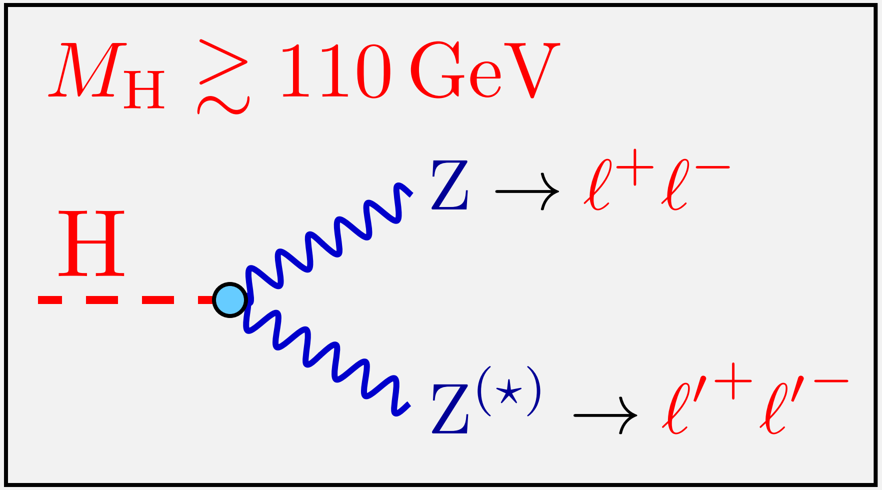


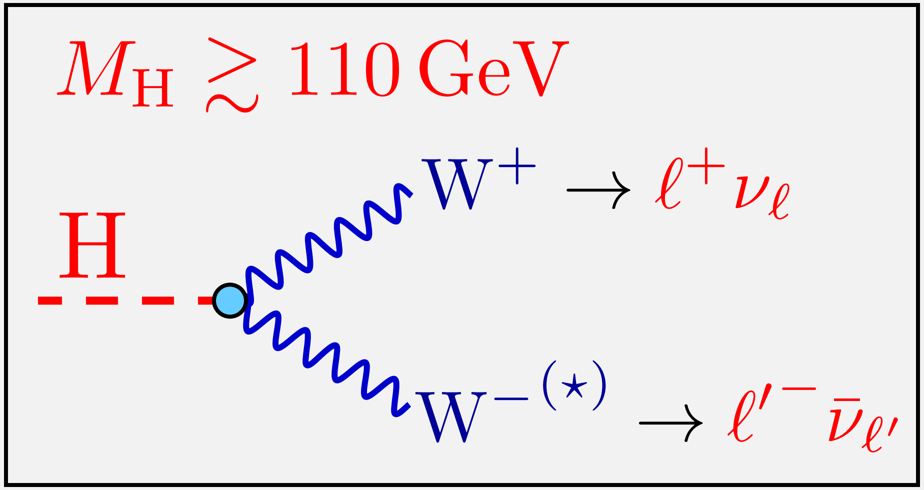
125 GeV Higgs sits in sweet-spot: all but ~11% $(gg, c\bar{c})$ of decays observable at LHC

Prime decay channels for detection:

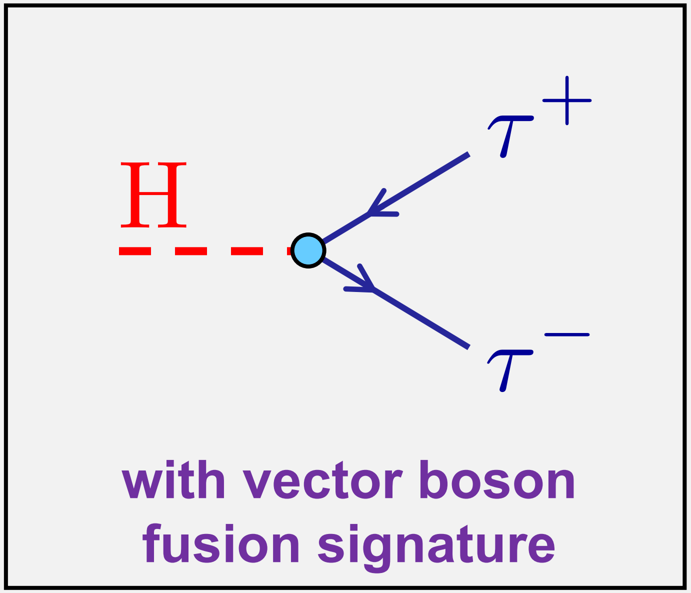


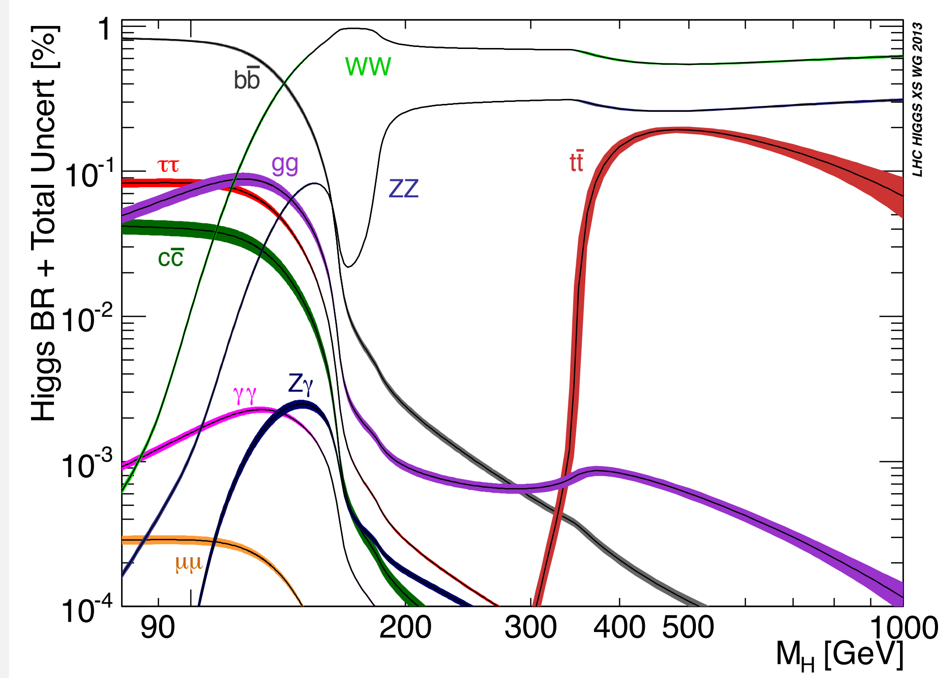


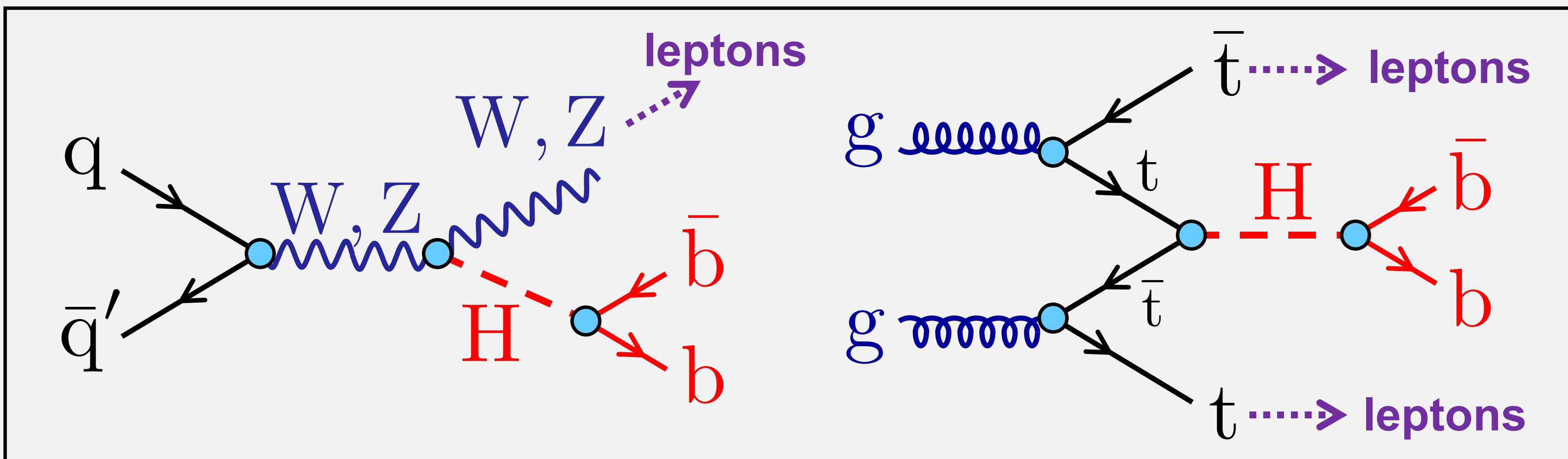




Decays to fermions (important but more difficult)

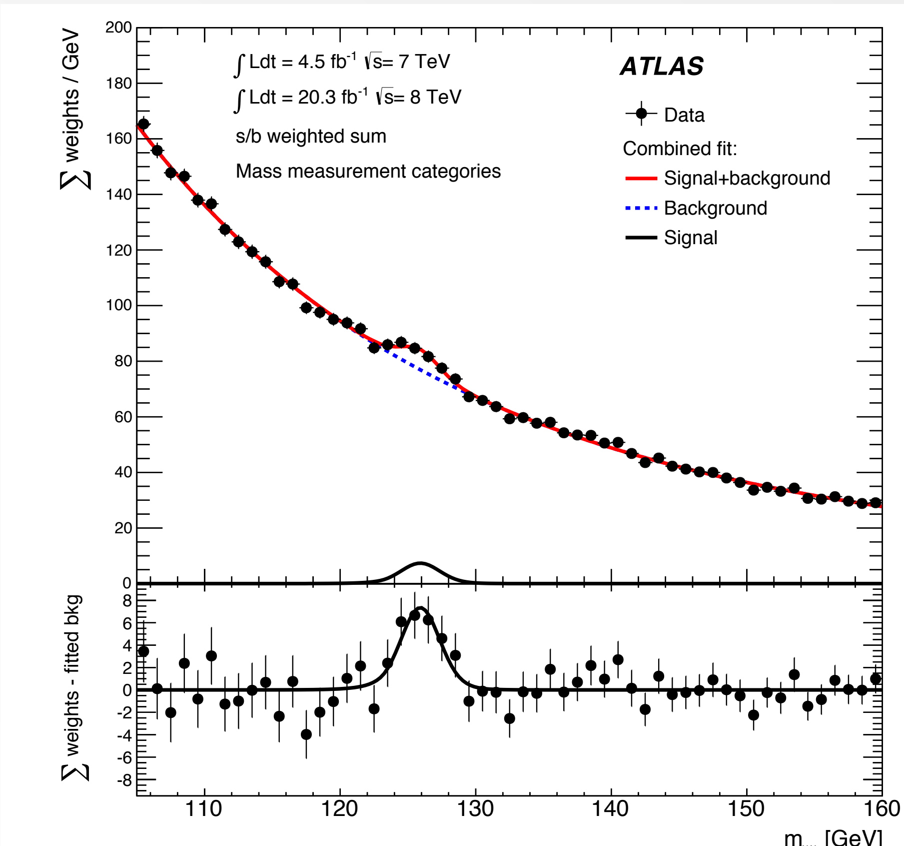




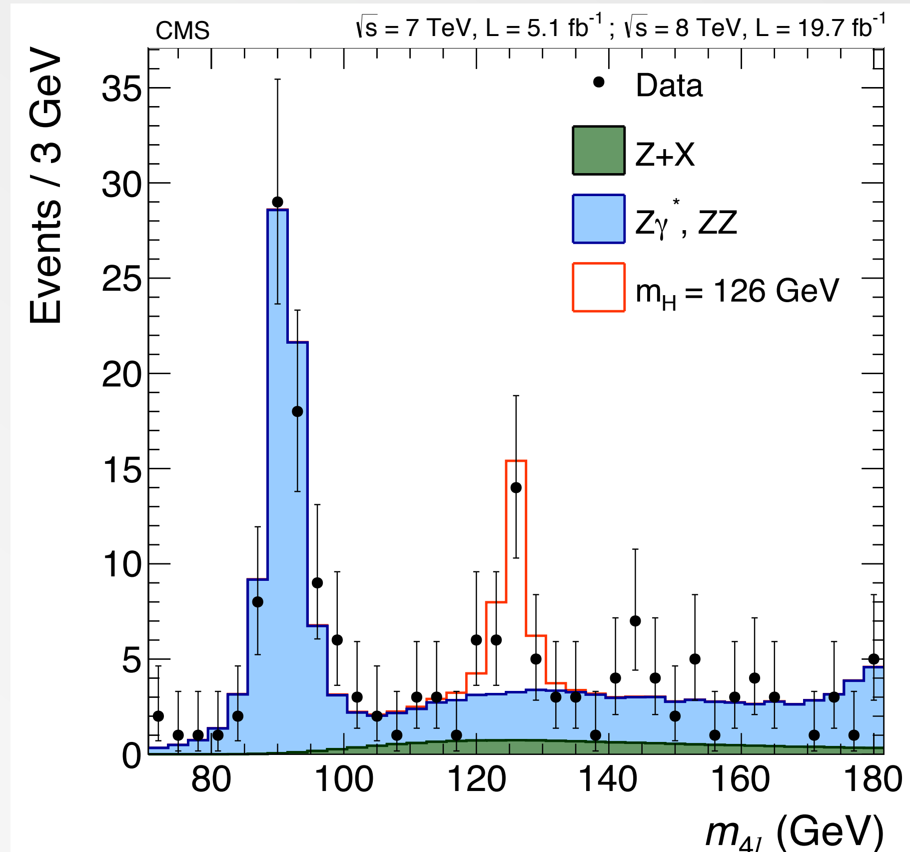


Discovery

$\mathrm{H} \to \gamma\gamma$ $\qquad$ $\mathrm{H} \to \mathrm{ZZ}^{\star} \to 4\ell$



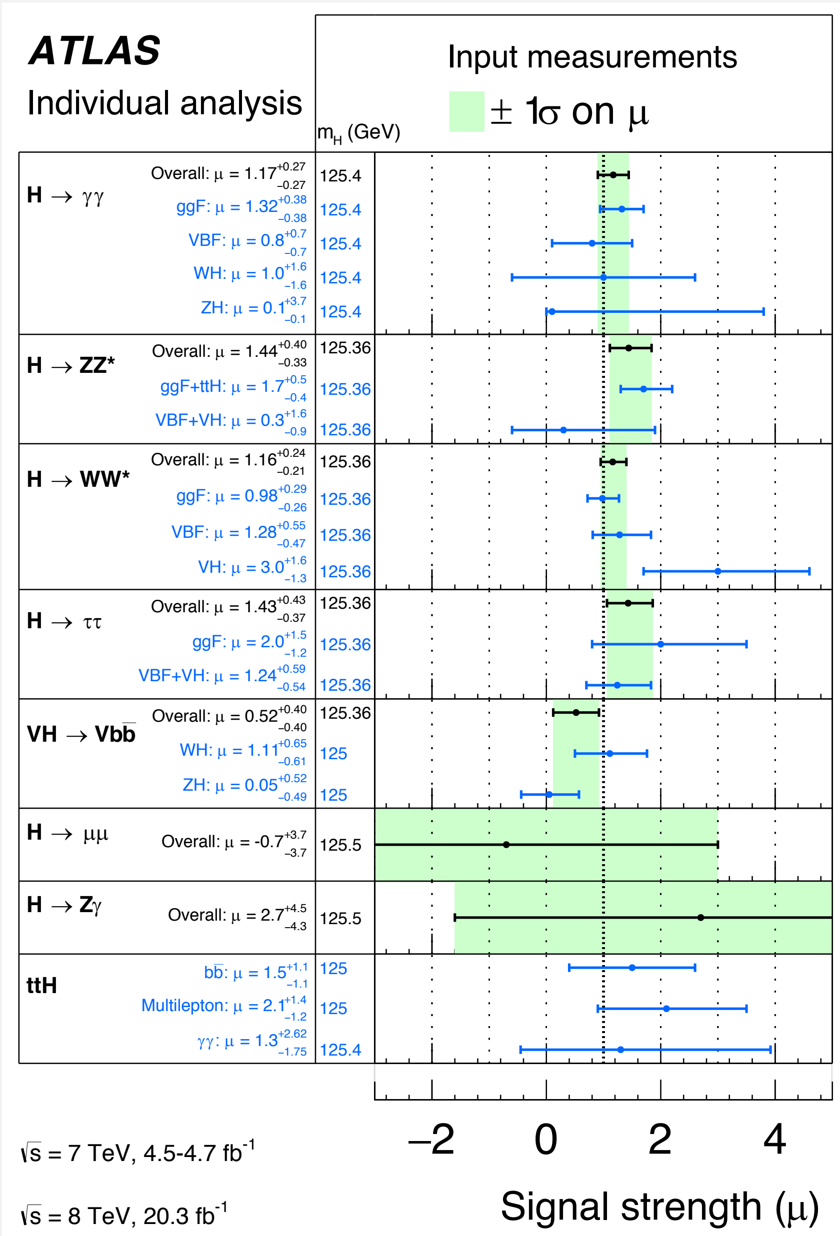
Phys. Rev. D90 (2014) 112015



Phys. Rev. D89 (2014) 092007

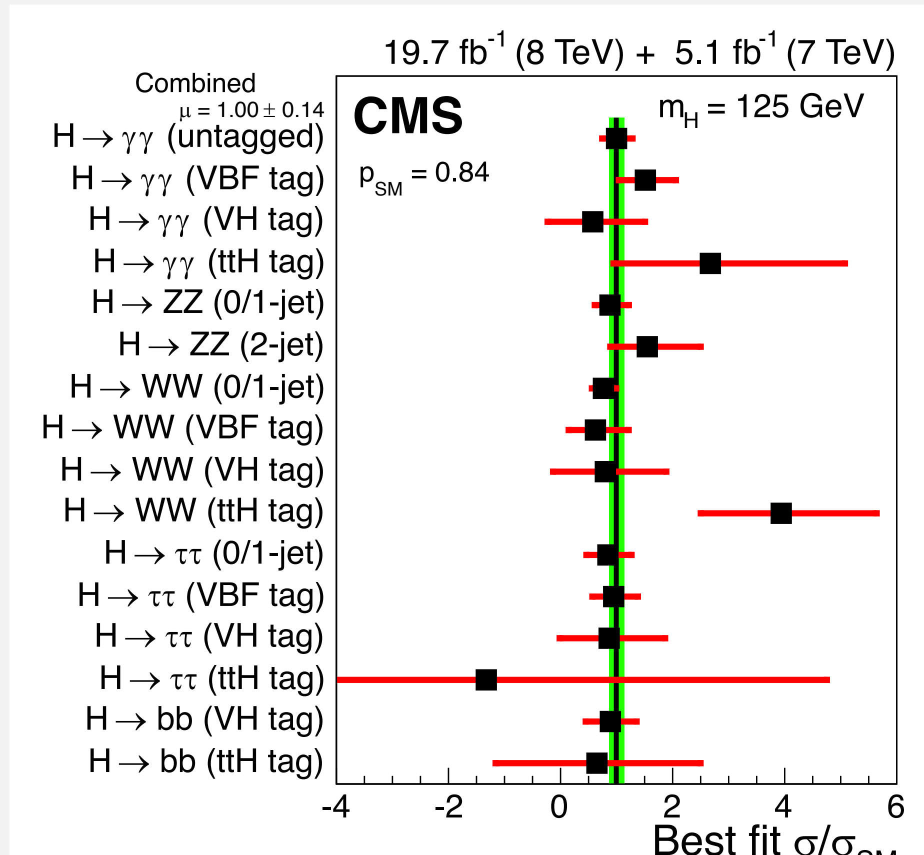
$M_{\mathrm{H}} \approx 125\,\mathrm{GeV}$; angular distributions confirm: $J^P = 0^+$

Measurement of production and decay rates



EPJ C76 (2016) 6

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

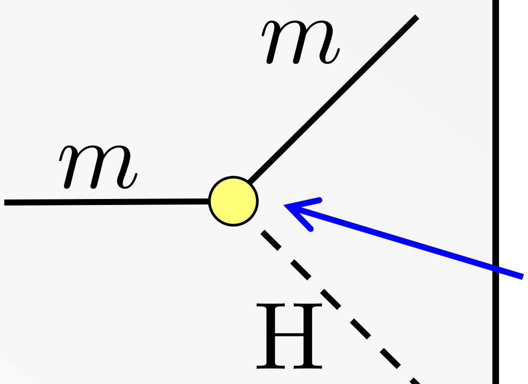


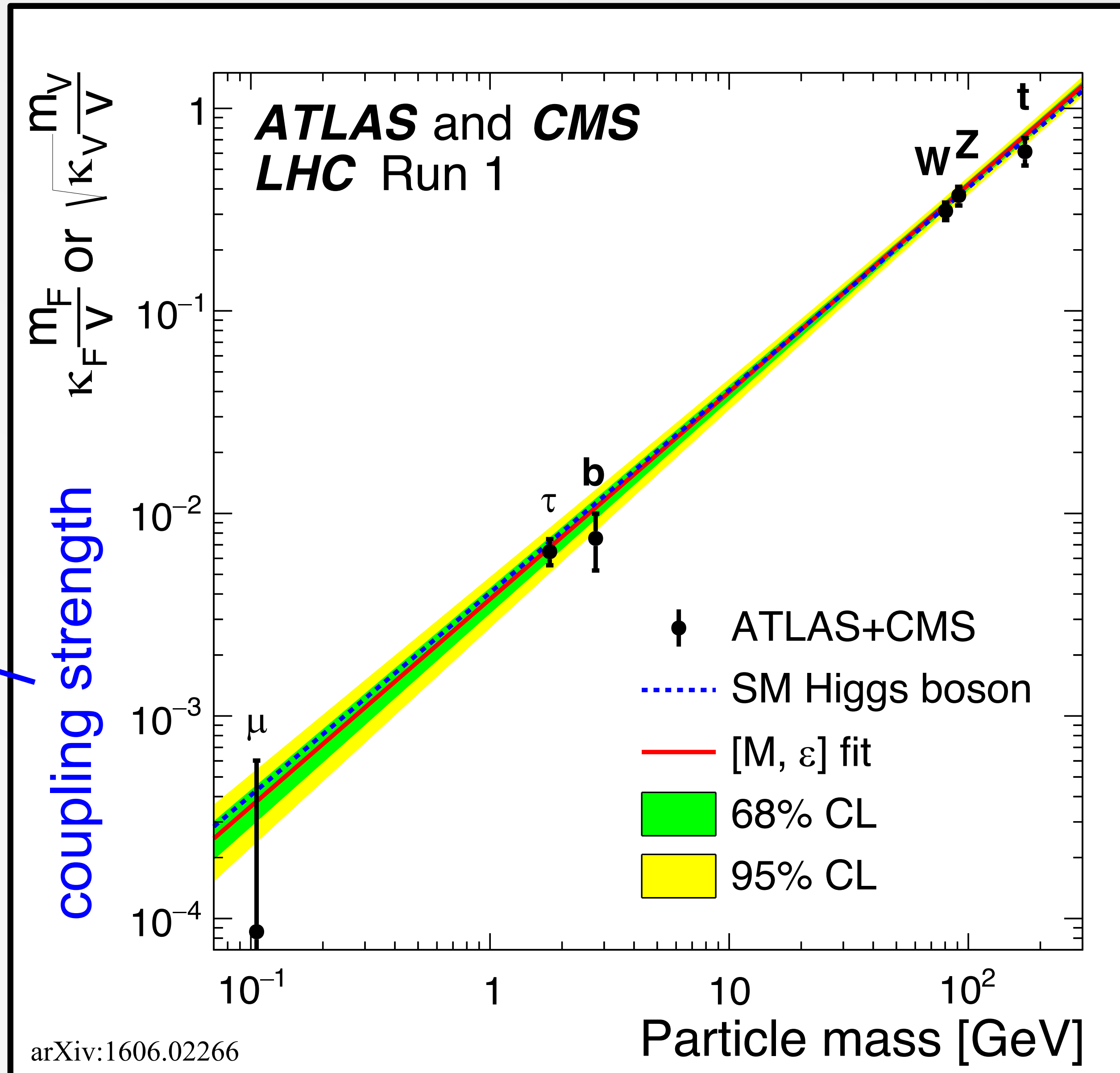
EPJ C75 (2015) 212

Global fit of coupling strengths

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

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





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:

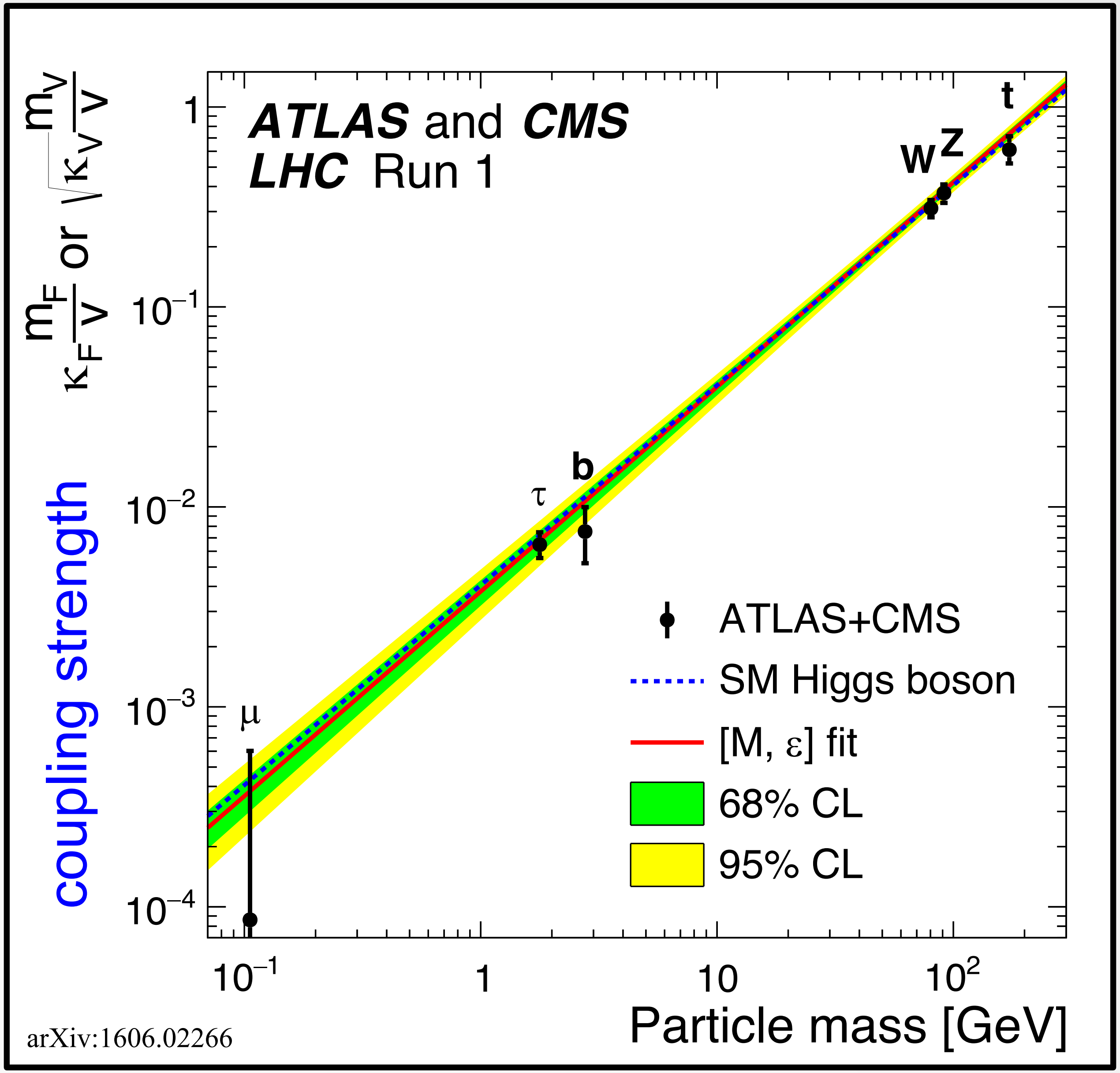
$$M = v$$

$$\epsilon = 0$$

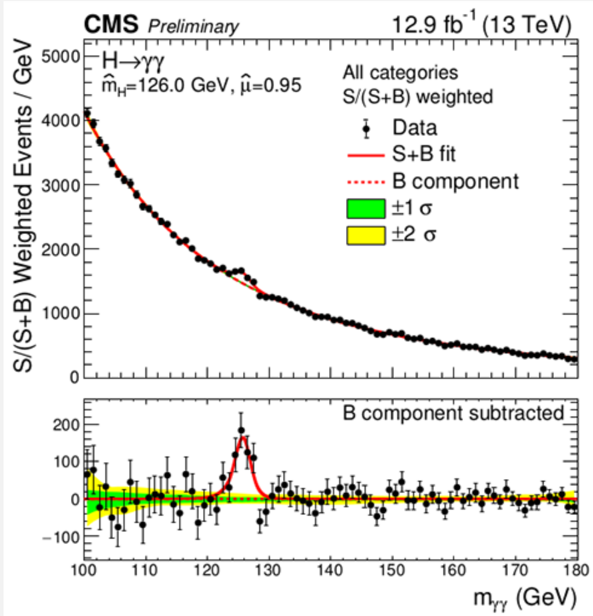
Fit:

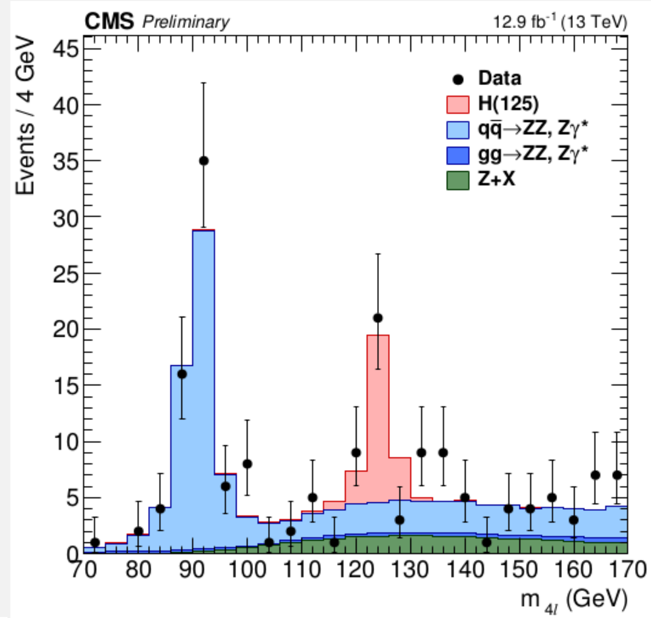
$$M = 233^{+13}_{-12}\,\mathrm{GeV}$$

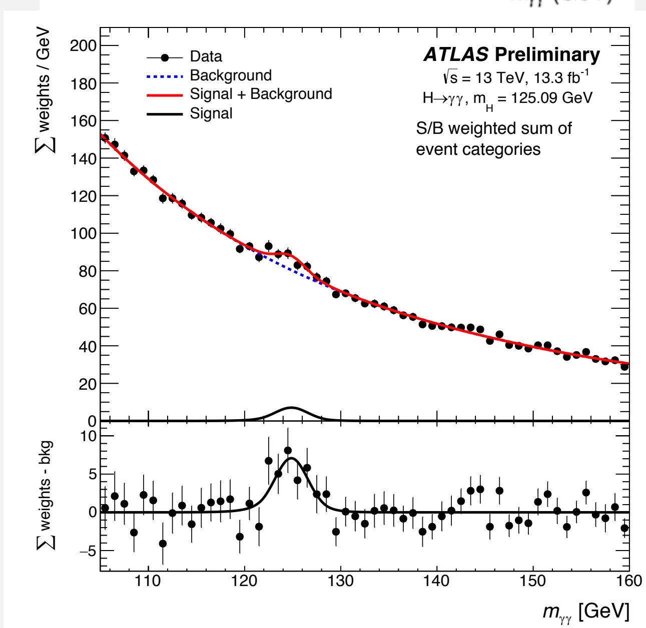
$$\epsilon = 0.023^{+0.029}_{-0.027}$$

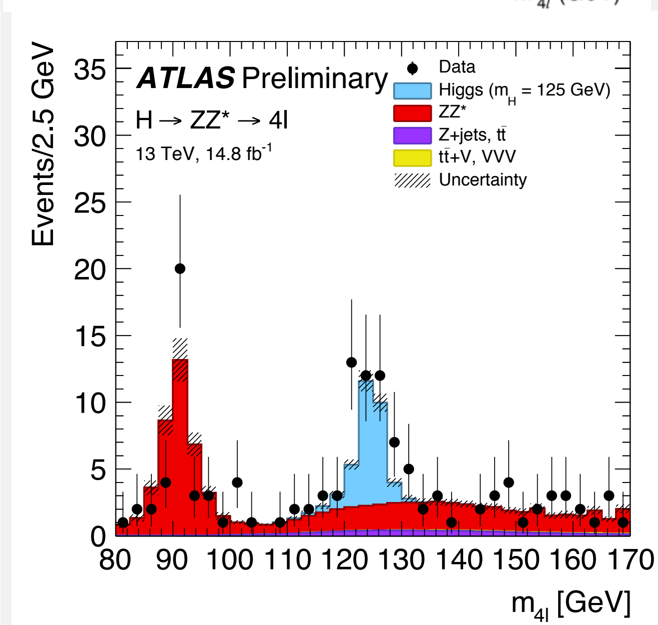


The signal is back at $\sqrt{s} = 13\,\mathrm{TeV}$





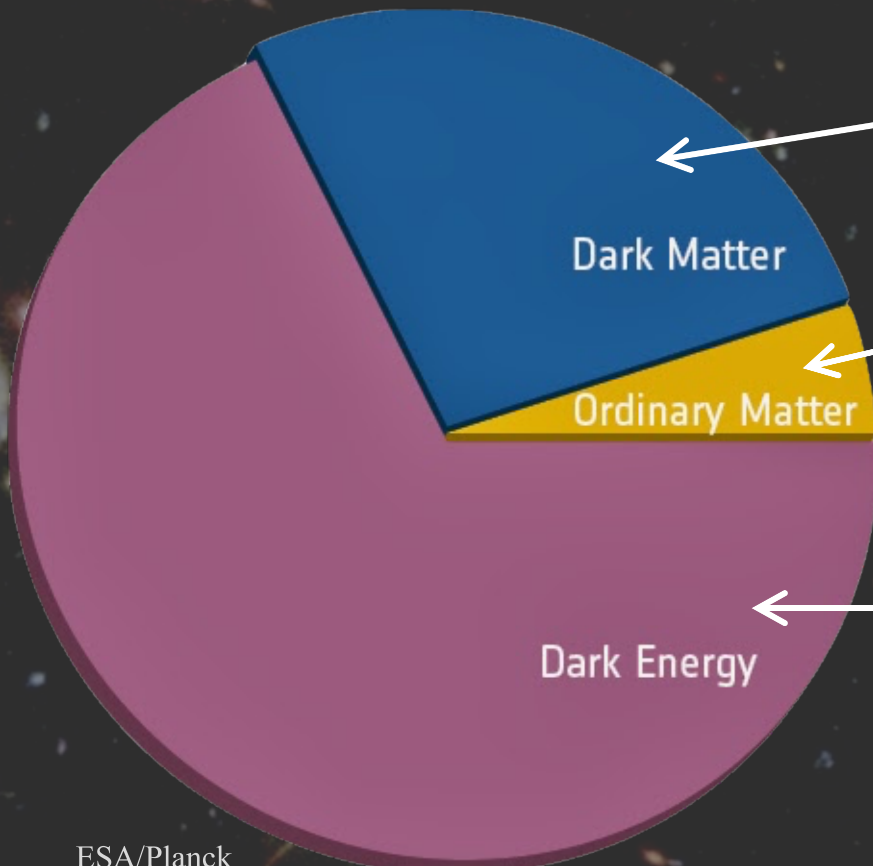




presented at
ICHEP 2016

Is this it?

Is there nothing else out there?



27% dark matter

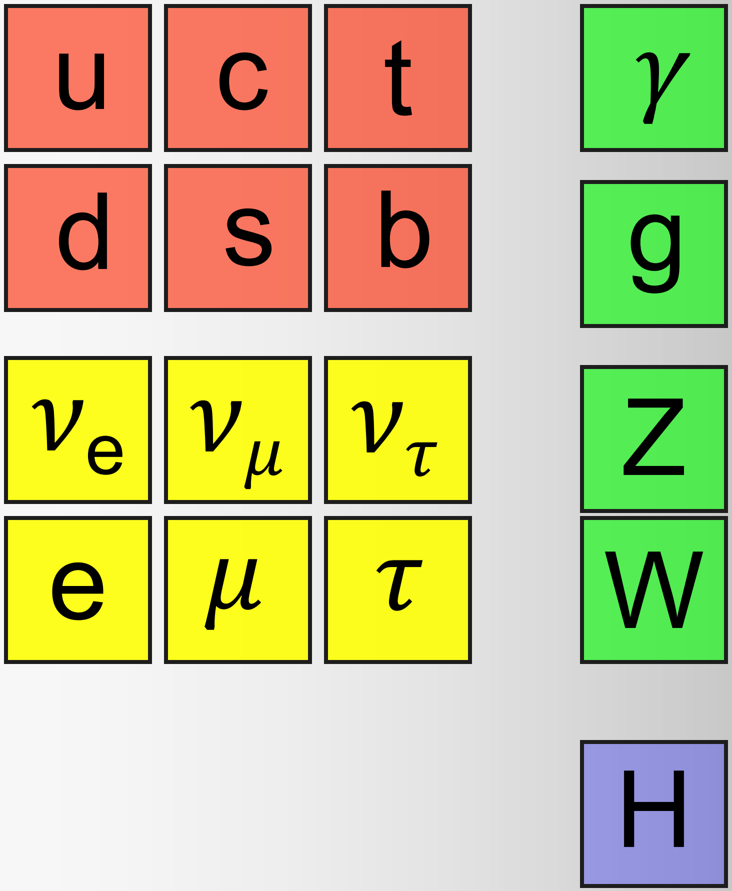
5% Standard Model stuff

68% dark energy

ESA/Planck

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

Standard Model today



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: $v = 246\,\mathrm{GeV}$

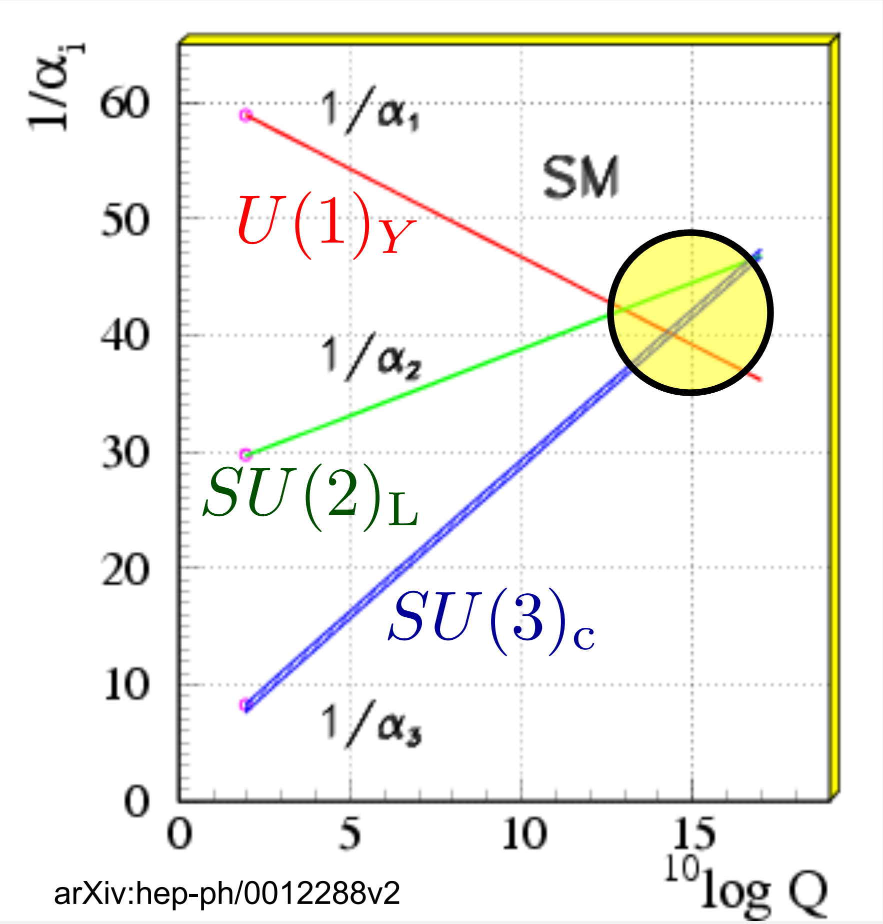
Assumption: there is another scale: $\Lambda \gg v$

Examples:

- Grand unification

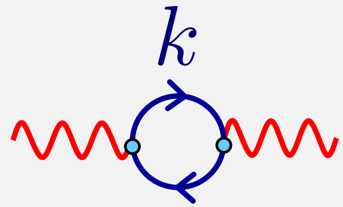
$$\Lambda \sim 10^{15-16}\,\mathrm{GeV}$$

(GUT scale)

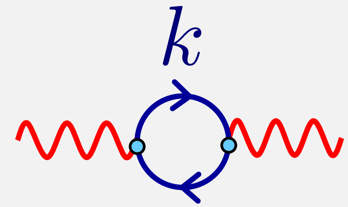


- Quantum gravity $\Lambda \sim 10^{19}\,\mathrm{GeV}$ (Planck scale)

Consequence:

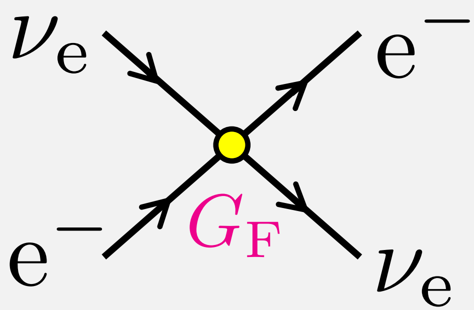
$$\int^{\infty} d^4k$$ 

$\Rightarrow$

$$\int^{\Lambda} d^4k$$ 

Why? Similar to this:

Fermi theory

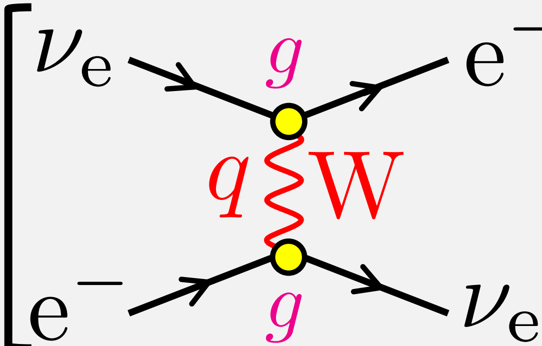
$\sigma\Big[$ 

$\Big] = \dfrac{G_F^2 s}{\pi}$

violates unitarity bound at

$$\sqrt{s} \sim 300\,\mathrm{GeV} \approx v$$

Standard Model

$\sigma\Big[$ 

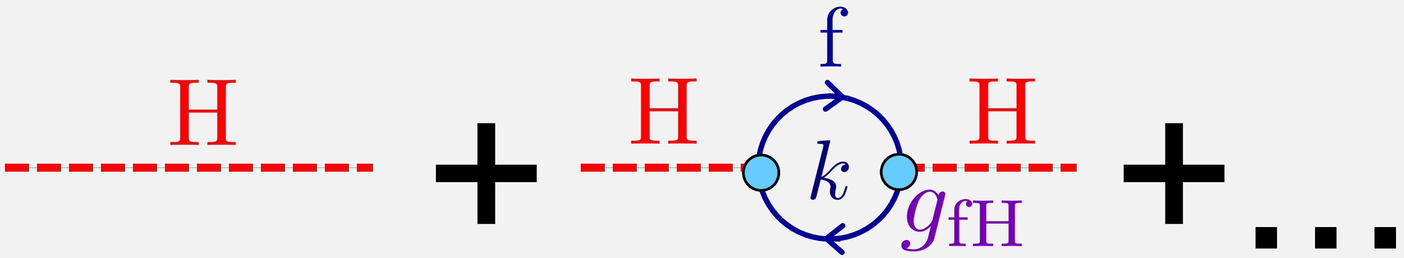
$\Big] \to \dfrac{G_F^2 M_W^2}{\pi}$

propagator cut-off

 $\propto \dfrac{1}{q^2 - M_W^2}$

New scale destabilizes the Standard Model:

effective Higgs mass (similar to effective charges)



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

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

Without extreme fine-tuning $\Rightarrow$

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

Cancellation by new scalar particles?

Fermion $\mathrm{f}_{\mathrm{L,R}}$ ⇔ **Boson** $\tilde{\mathrm{f}}_{\mathrm{L,R}}$

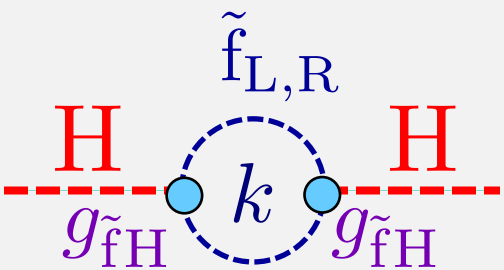
spin ½ (spinor) — spin 0 (complex scalar)

$$\psi^{\mathrm{f}} = \psi^{\mathrm{f}}_{\mathrm{L}} + \psi^{\mathrm{f}}_{\mathrm{R}}$$

4 components

$$\phi^{\mathrm{f}}_{\mathrm{L}} = \phi^{\mathrm{f}}_{\mathrm{L}1} + i\phi^{\mathrm{f}}_{\mathrm{L}2}$$

$$\phi^{\mathrm{f}}_{\mathrm{R}} = \phi^{\mathrm{f}}_{\mathrm{R}1} + i\phi^{\mathrm{f}}_{\mathrm{R}2}$$



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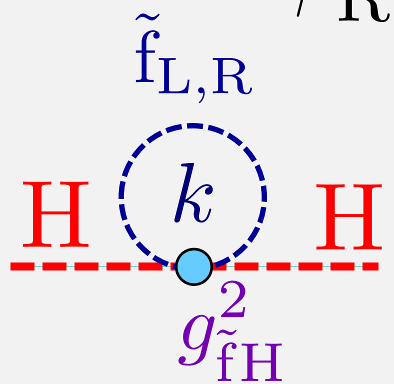


+ ...

Cancellation ⇔ $g^2_{\mathrm{fH}} = g^2_{\tilde{\mathrm{f}}\mathrm{H}}$ ⇔ new **symmetry**

Supersymmetry (SUSY)

Supersymmetry (SUSY)

Requirements:

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

$$g_{\mathrm{fH}}^2 = g_{\tilde{\mathrm{f}}\mathrm{H}}^2$$
$$m_{\tilde{\mathrm{f}}}^2 = m_{\mathrm{f}}^2 + \delta m_{\mathrm{f}}^2$$

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

$$\delta m_{\mathrm{f}}^2 = \mathcal{O}(v^2)$$

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)

$$\phi_\mathrm{u} = \begin{pmatrix} \phi_\mathrm{u}^+ \\ \phi_\mathrm{u}^0 \end{pmatrix} \quad \langle \phi_\mathrm{u} \rangle_0 = \begin{pmatrix} 0 \\ v_\mathrm{u} \end{pmatrix}$$

$$\frac{v_\mathrm{u}}{v_\mathrm{d}} \equiv \tan\beta$$

$$\phi_\mathrm{d} = \begin{pmatrix} \phi_\mathrm{d}^0 \\ \phi_\mathrm{d}^- \end{pmatrix} \quad \langle \phi_\mathrm{d} \rangle_0 = \begin{pmatrix} v_\mathrm{d} \\ 0 \end{pmatrix}$$

4 charged fields {
- 2 charged Goldstone bosons $\rightarrow M_{\mathrm{W}^\pm}$
- 2 charged Higgs bosons $\mathrm{H}^\pm$

2 neutral fields {
- 1 neutral Goldstone boson $\rightarrow M_\mathrm{Z}$
- 3 neutral Higgs bosons $\mathrm{h}, \mathrm{H}, \mathrm{A}$

$m_\mathrm{h} \leq M_\mathrm{Z} \, |\cos(2\beta)| + \text{loop corrections}$ $\Rightarrow$ h is light

(minimal) SUSY particle content

quarks	leptons	neutrinos	spin
$[\mathrm{u}, \mathrm{d}, \mathrm{c}, \mathrm{s}, \mathrm{t}, \mathrm{b}]_{\mathrm{L,R}}$	$[\mathrm{e}, \mu, \tau]_{\mathrm{L,R}}$	$[\nu_{\mathrm{e}}, \nu_{\mu}, \nu_{\tau}]_{\mathrm{L}}$	½
$[\tilde{\mathrm{u}}, \tilde{\mathrm{d}}, \tilde{\mathrm{c}}, \tilde{\mathrm{s}}, \tilde{\mathrm{t}}, \tilde{\mathrm{b}}]_{\mathrm{L,R}}$	$[\tilde{\mathrm{e}}, \tilde{\mu}, \tilde{\tau}]_{\mathrm{L,R}}$	$[\tilde{\nu}_{\mathrm{e}}, \tilde{\nu}_{\mu}, \tilde{\nu}_{\tau}]_{\mathrm{L}}$	0
squarks	sleptons	sneutrinos	

---

gluons		h, H, A	
g	$\mathrm{W}^{\pm} / \mathrm{H}^{\pm}$	$\gamma, \mathrm{Z} / \mathrm{H}_1^0, \mathrm{H}_2^0$	1/0
$\tilde{\mathrm{g}}$	$\tilde{\mathrm{W}}^{\pm}, \tilde{\mathrm{H}}^{\pm}$	$\tilde{\gamma}, \tilde{\mathrm{Z}}, \tilde{\mathrm{H}}_1^0, \tilde{\mathrm{H}}_2^0$	½
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:

baryon number — lepton number — spin

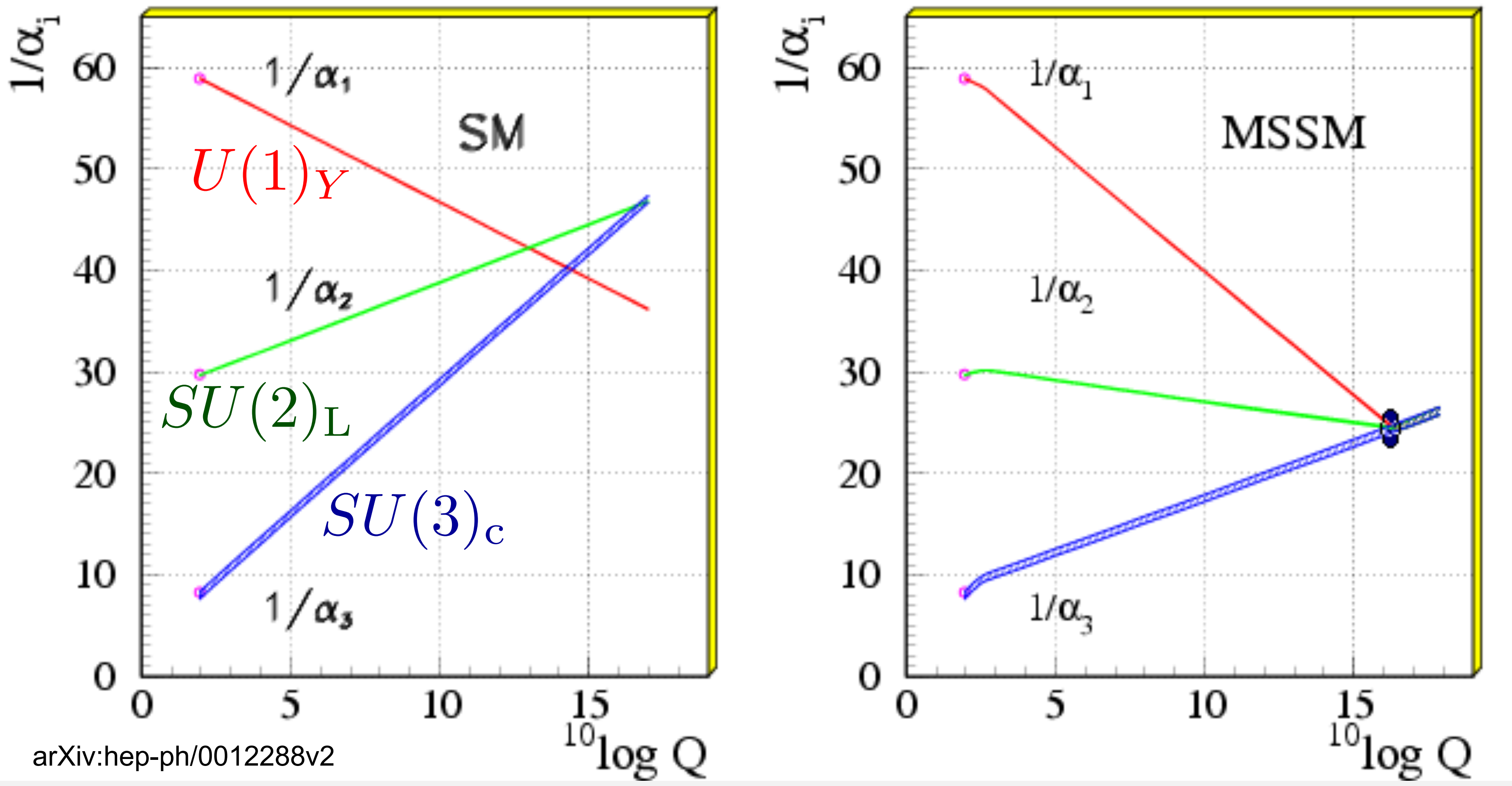
$$R = (-)^{3B+L+2S}$$

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

Many SUSY versions have lightest neutralino as LSP

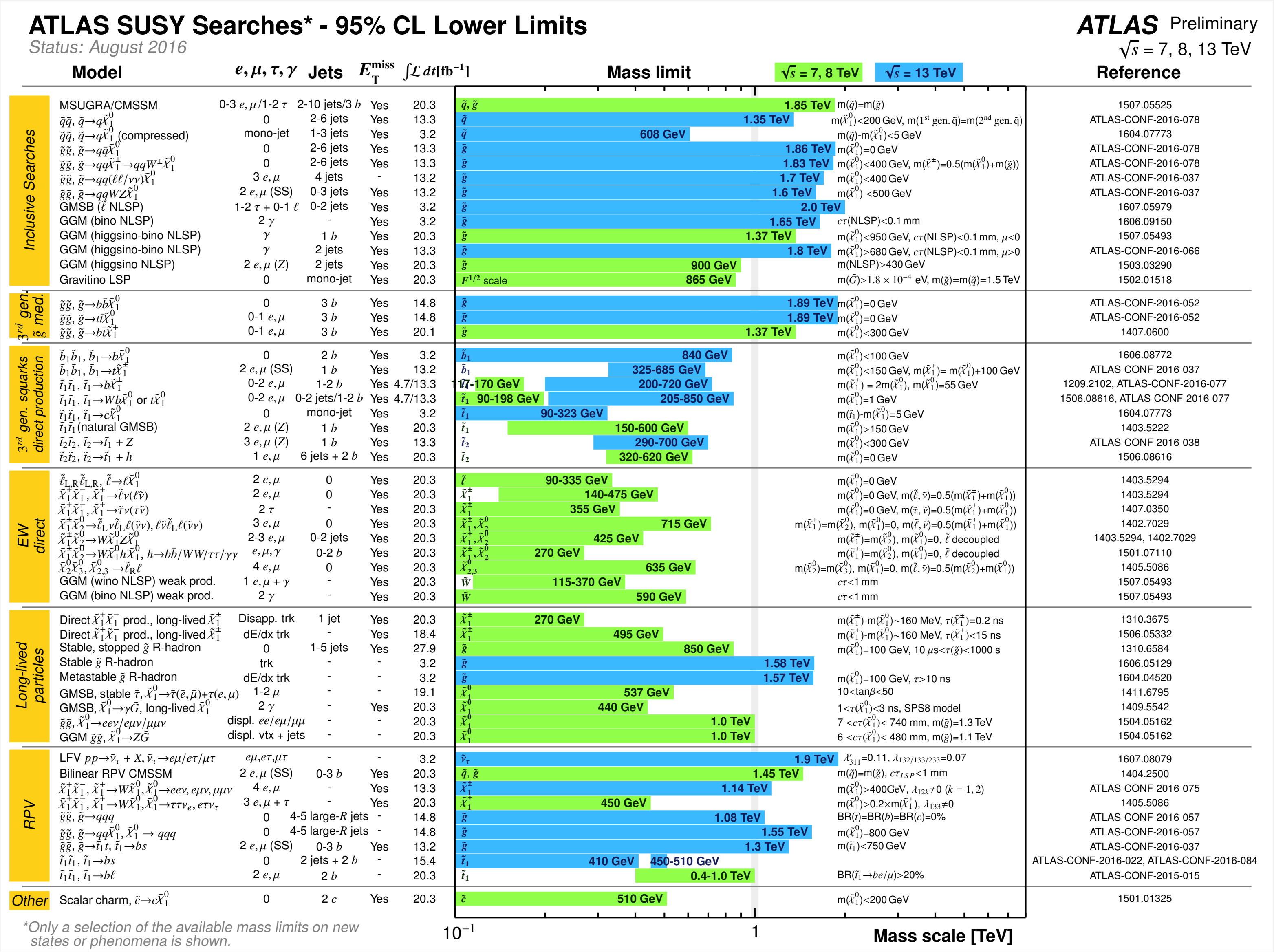
$\Rightarrow$ **dark matter candidate** $\tilde{\chi}_1^0$

SUSY makes the couplings unify



arXiv:hep-ph/0012288v2

SUSY not yet detected



Minimal version of SUSY is in trouble

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

Thanks!