An introduction to Hadron Collider Physics

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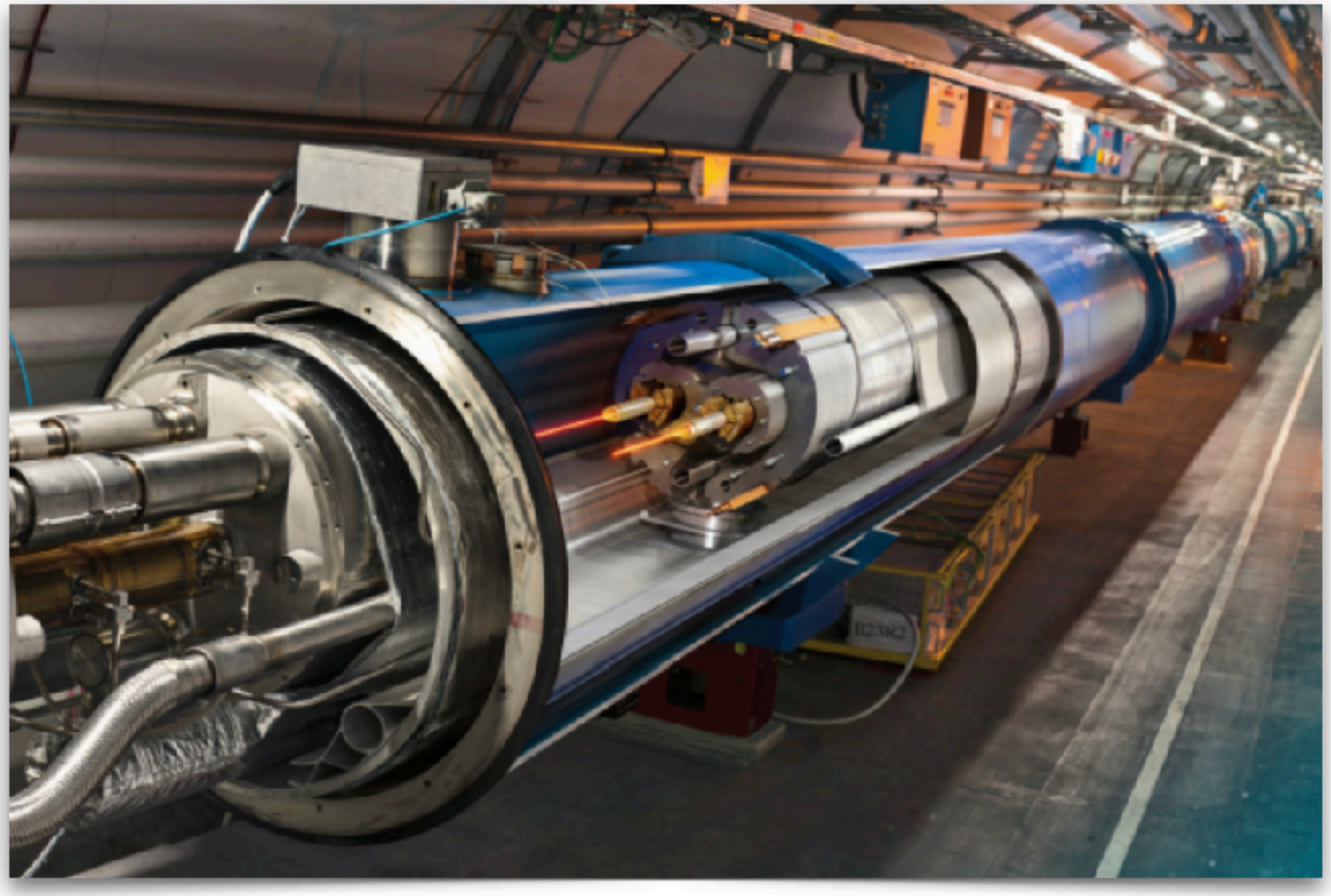
What are these lectures about ?

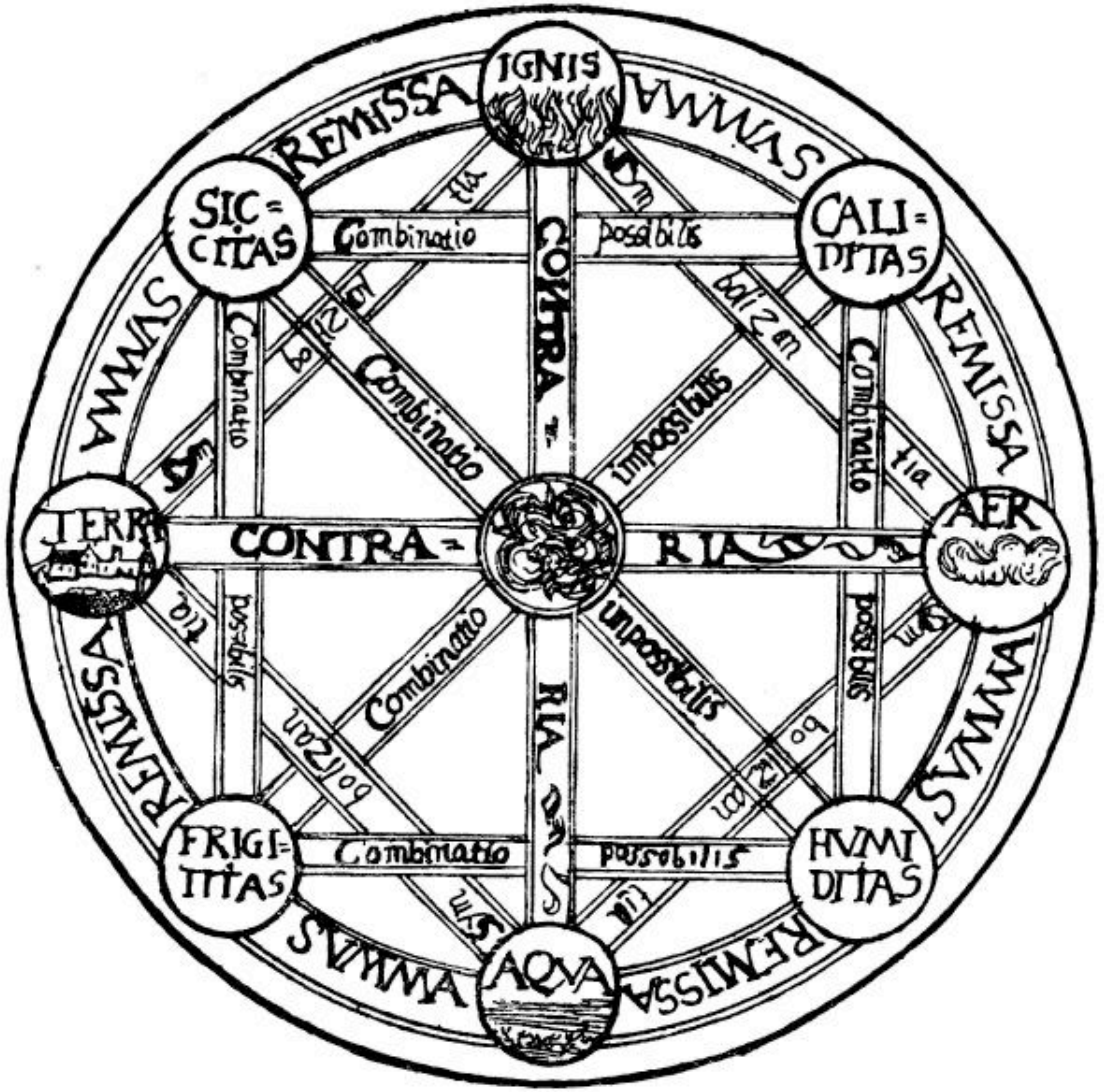
Main goals of these lectures are:

- A brief overview of the theory of elementary particles and interactions
- Provide the essential elements to understand the LHC physics program, with a few specific and representative examples



The building blocks of reality

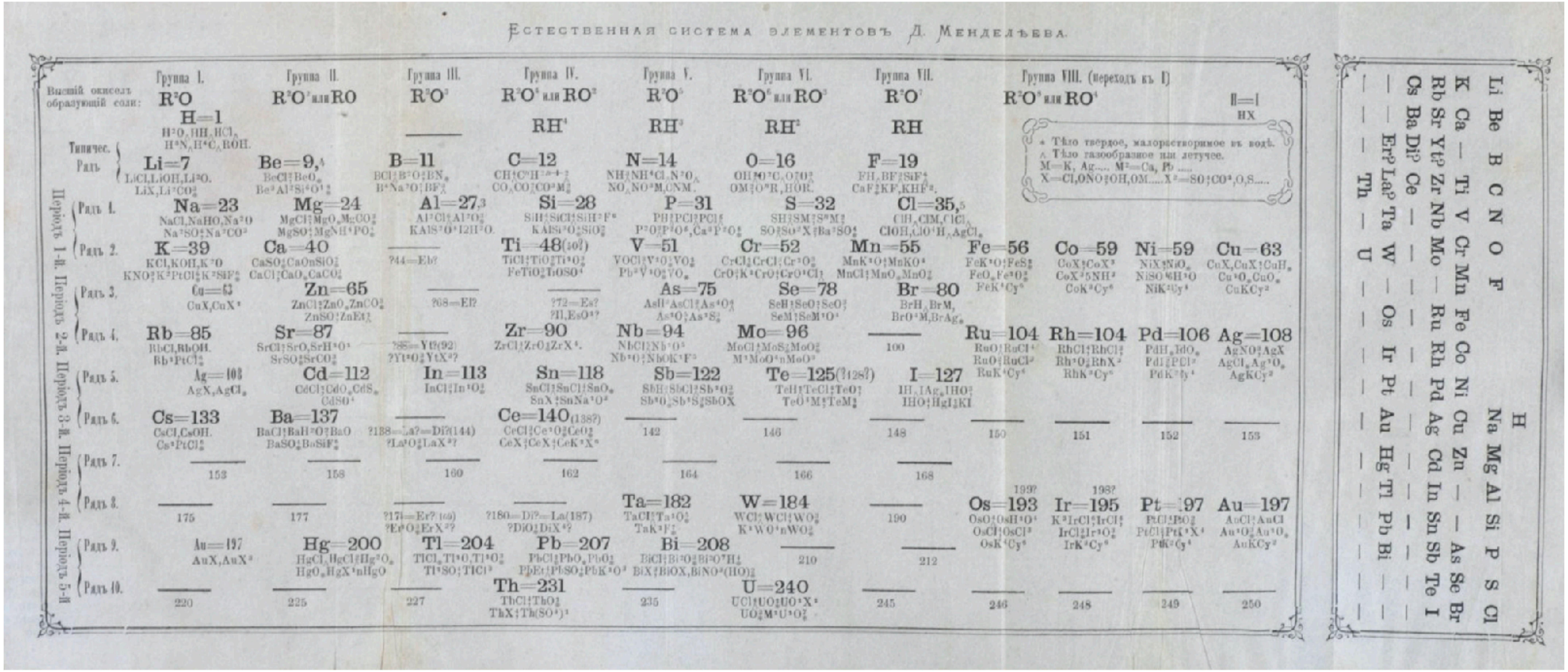
What are we made of ?



Leibniz representation of the universe resulting from the combination of the Aristotelian four elements (earth, water, air, fire)

What are we made of ?

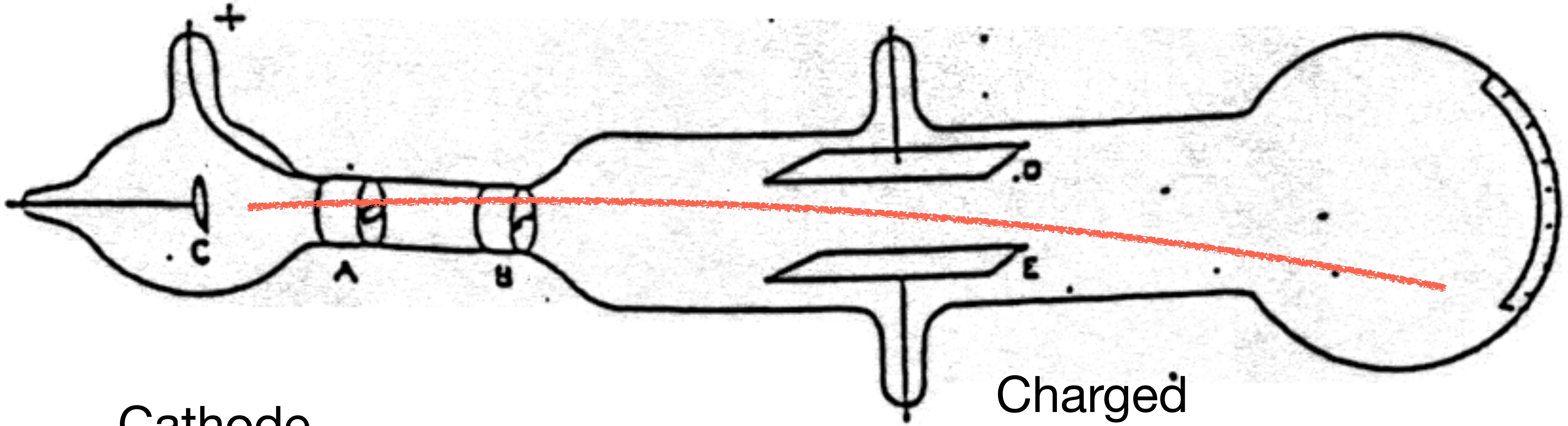
- In 1869 Russian chemist Dimitry Mendeleev published the periodic table, arranging all known chemical elements by their atomic mass
- ~80 elements - why so many? Why is there a structure?



The electron

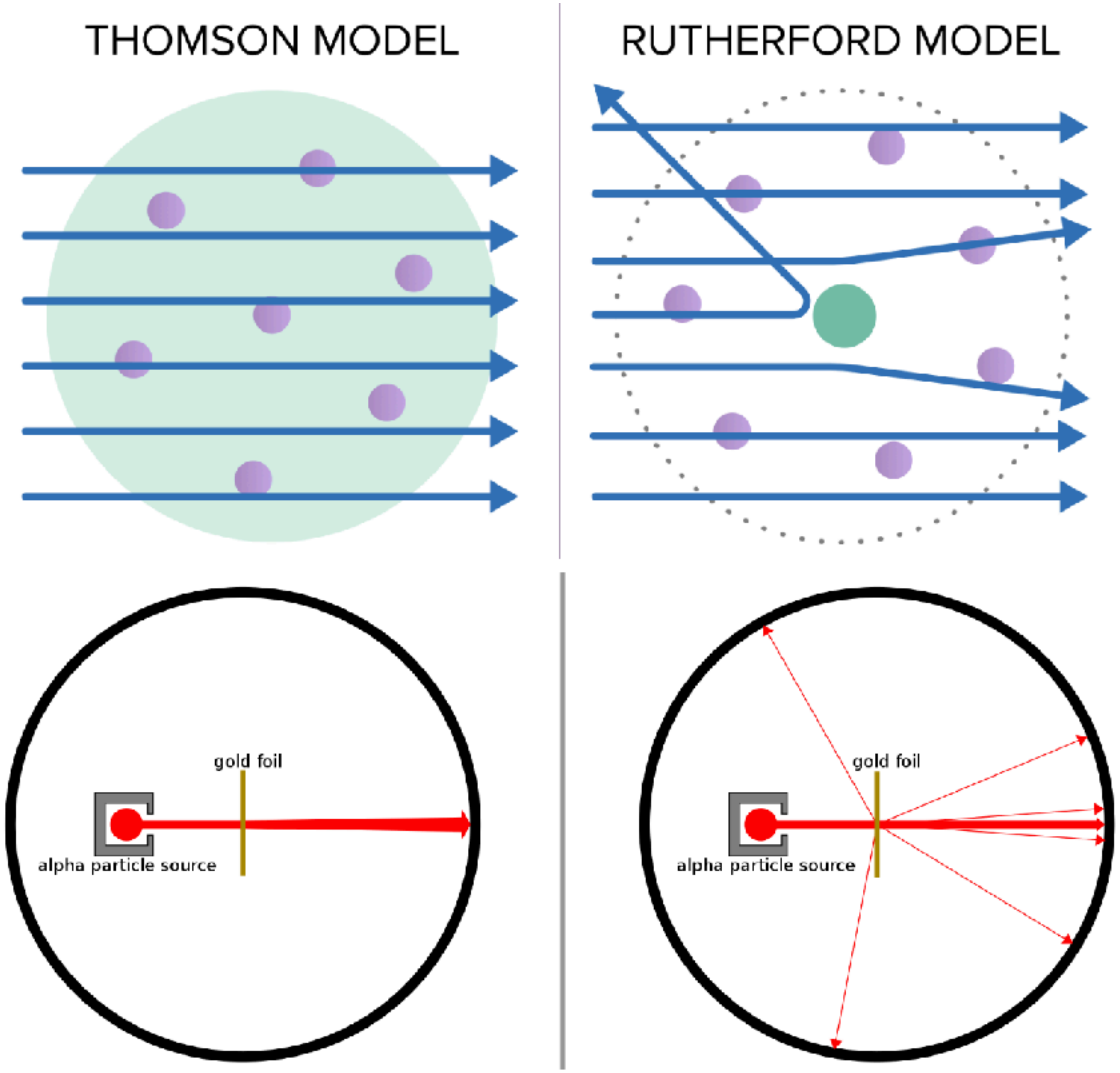
1897 electron discovered by J.J. Thompson

As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.



The nucleus

1911 nucleus discovered by Rutherford



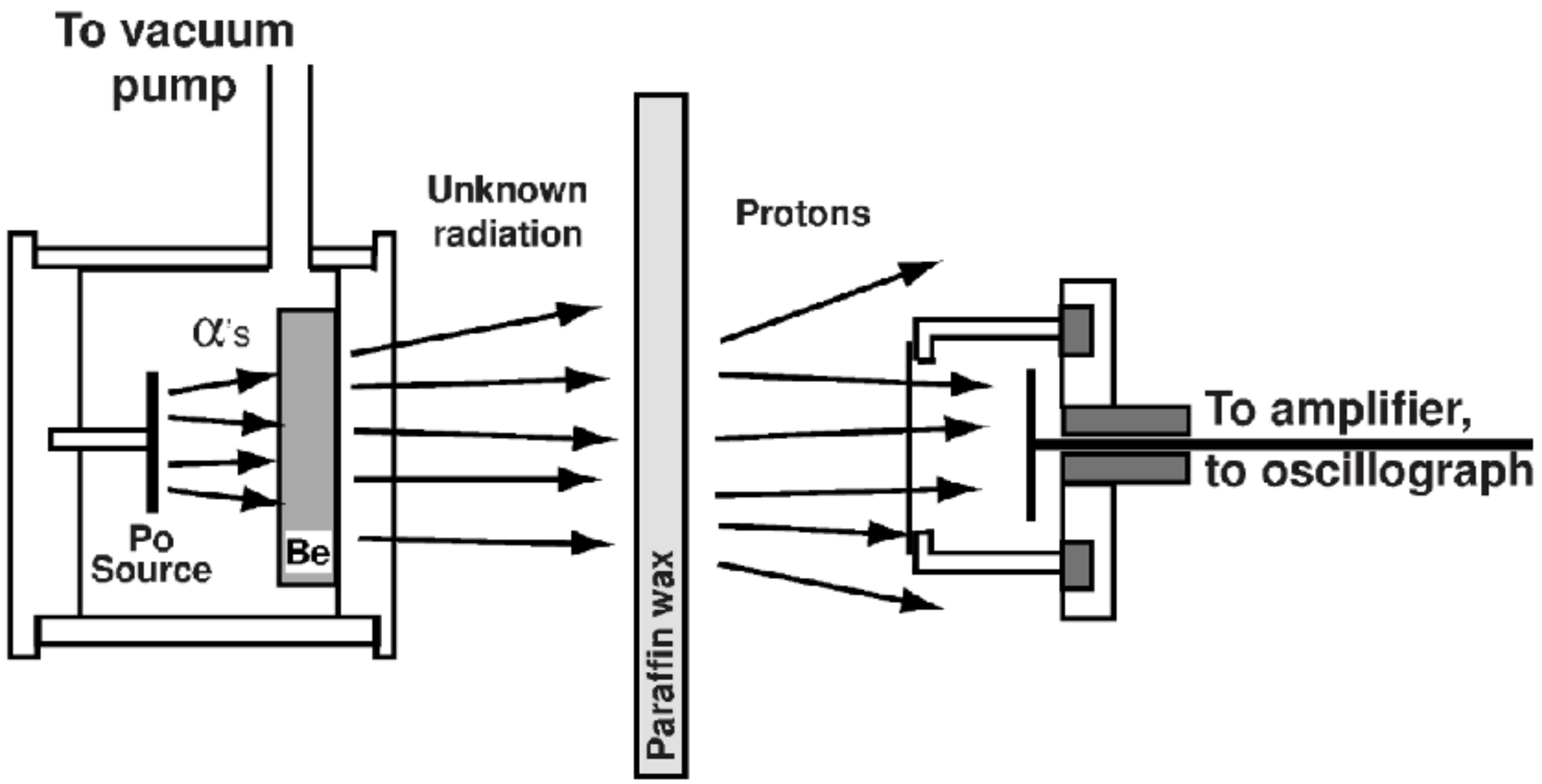
1911 - atomic nucleus by Rutherford

1919 proton discovery by Rutherford

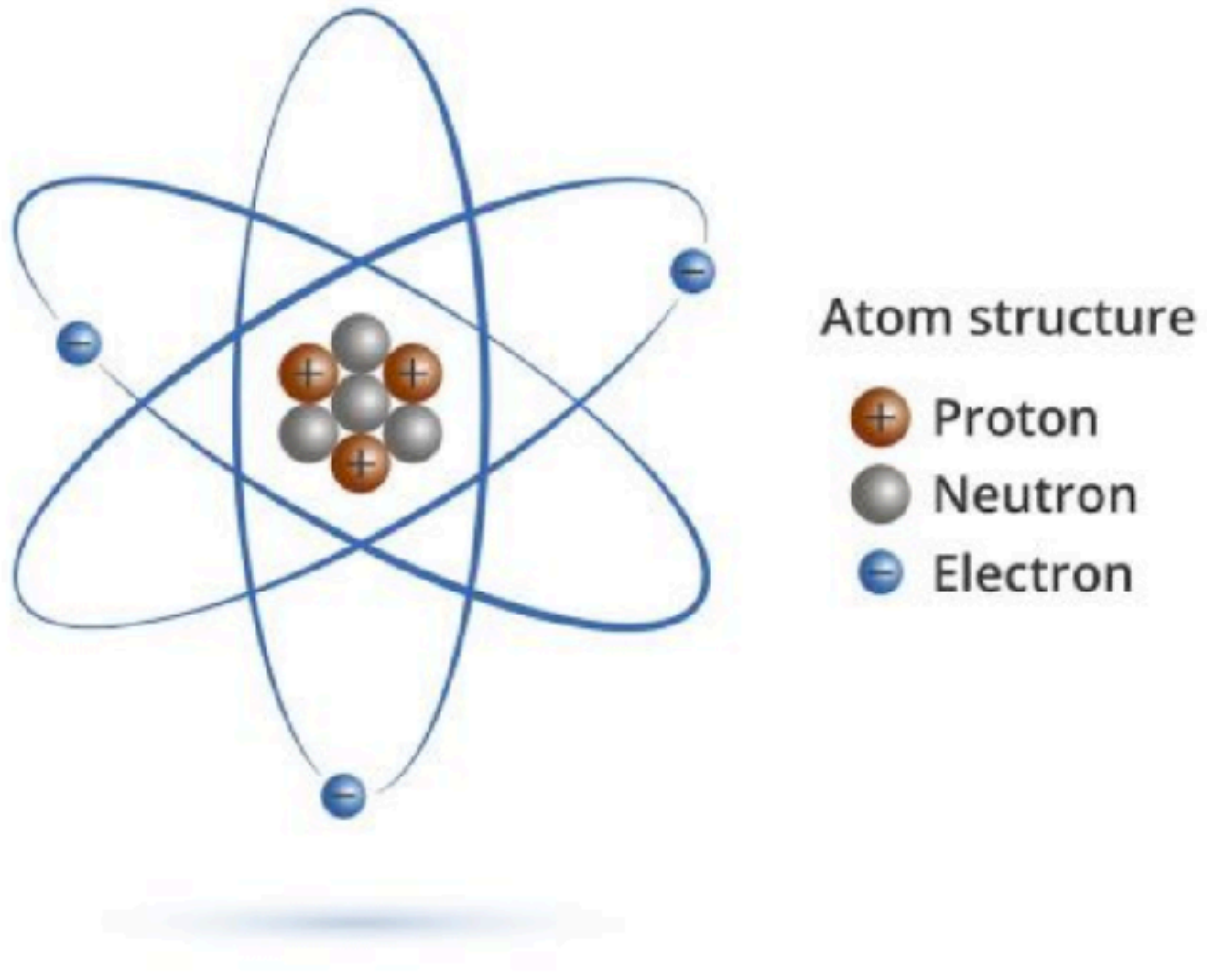
- Shot alpha particles at nitrogen gas and got hydrogen.
  Hypotheised the hydrogen came from the nitrogen
  Suggested hydrogen nucleus to be an elementary particle, named it proton

1932 neutron discovered by Chadwick

- Determined the mass of neutral radiation produced in Beryllium hit by alpha particles.
  Measured that the energy of the proton leaving the hydrogen and worked backwards
  ~1.006 times larger than that of a proton



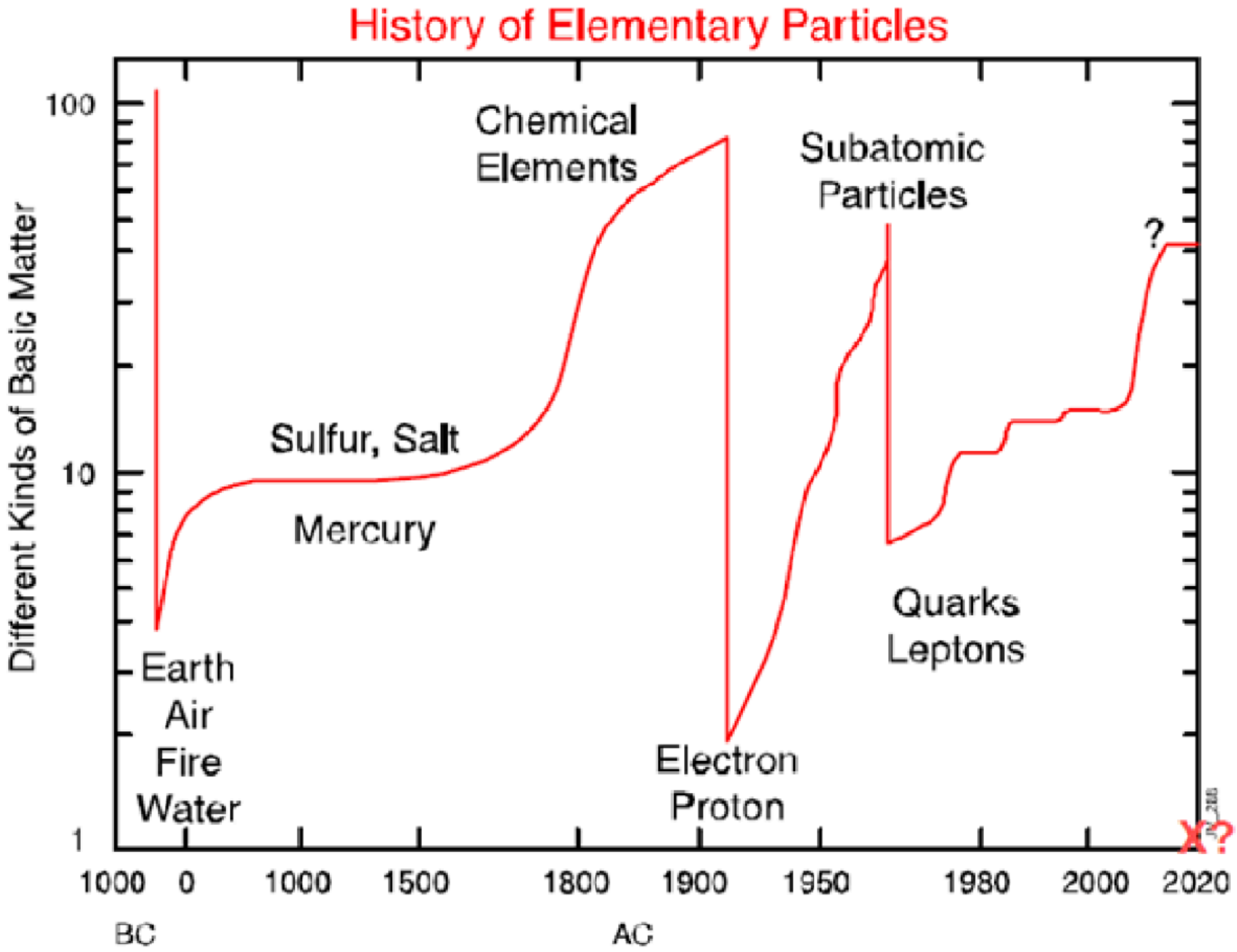
Particle physics ~1930



"If we consider protons and neutrons as elementary particles,
we would have three kinds of elementary particles [p,n,e]....
This number may seem large but, from that point of view,
two is already a large number."

Paul Dirac 1933 Solvay Conference

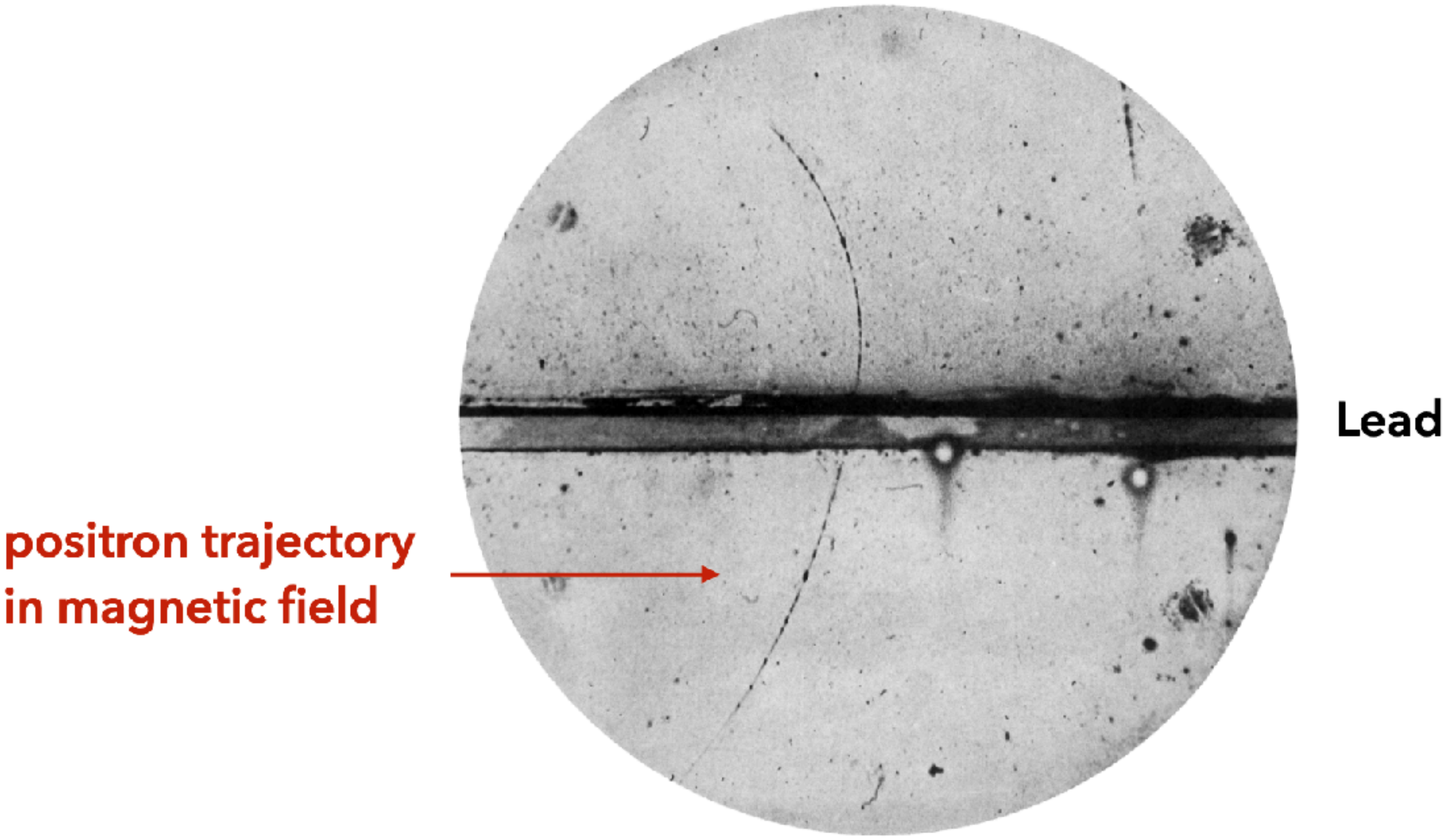
What are we made of ?



Discovery of antimatter

1932 Discovery of the positron

- Predicted by Dirac in 1928



Anti-particle:
a subatomic particle having the same mass as a given particle but opposite electric or magnetic properties

Photo Credit: Carl D. Anderson, Physical Review Vol.43, p491 (1933)

More and more particles appear

Other particle not part of the atom seemed to appear!

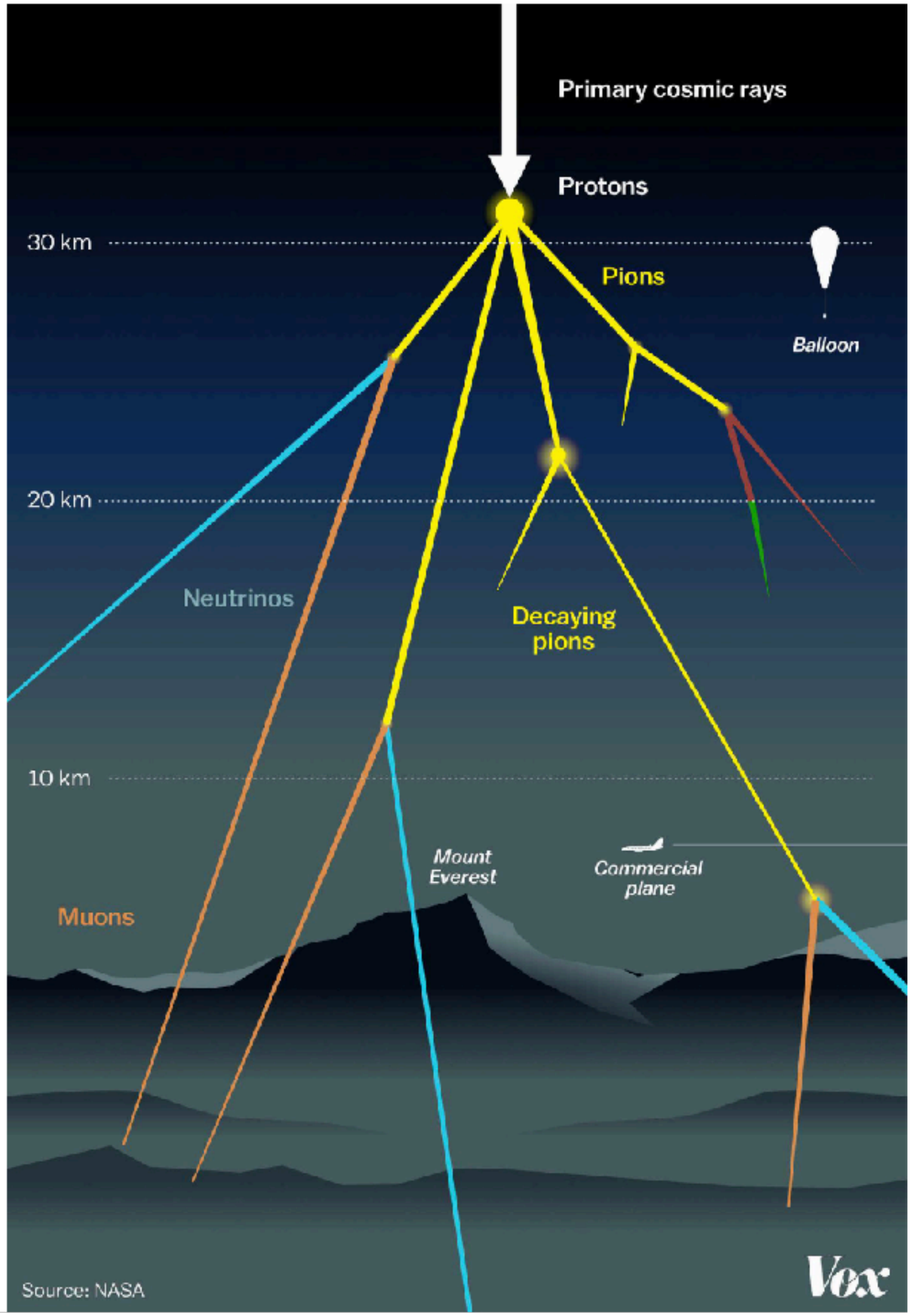
1919 V. Hess discover cosmic rays

- With a hot air balloon flew above 2Km observing the amount of radiation increased instead of decreasing (radiation from the sky)

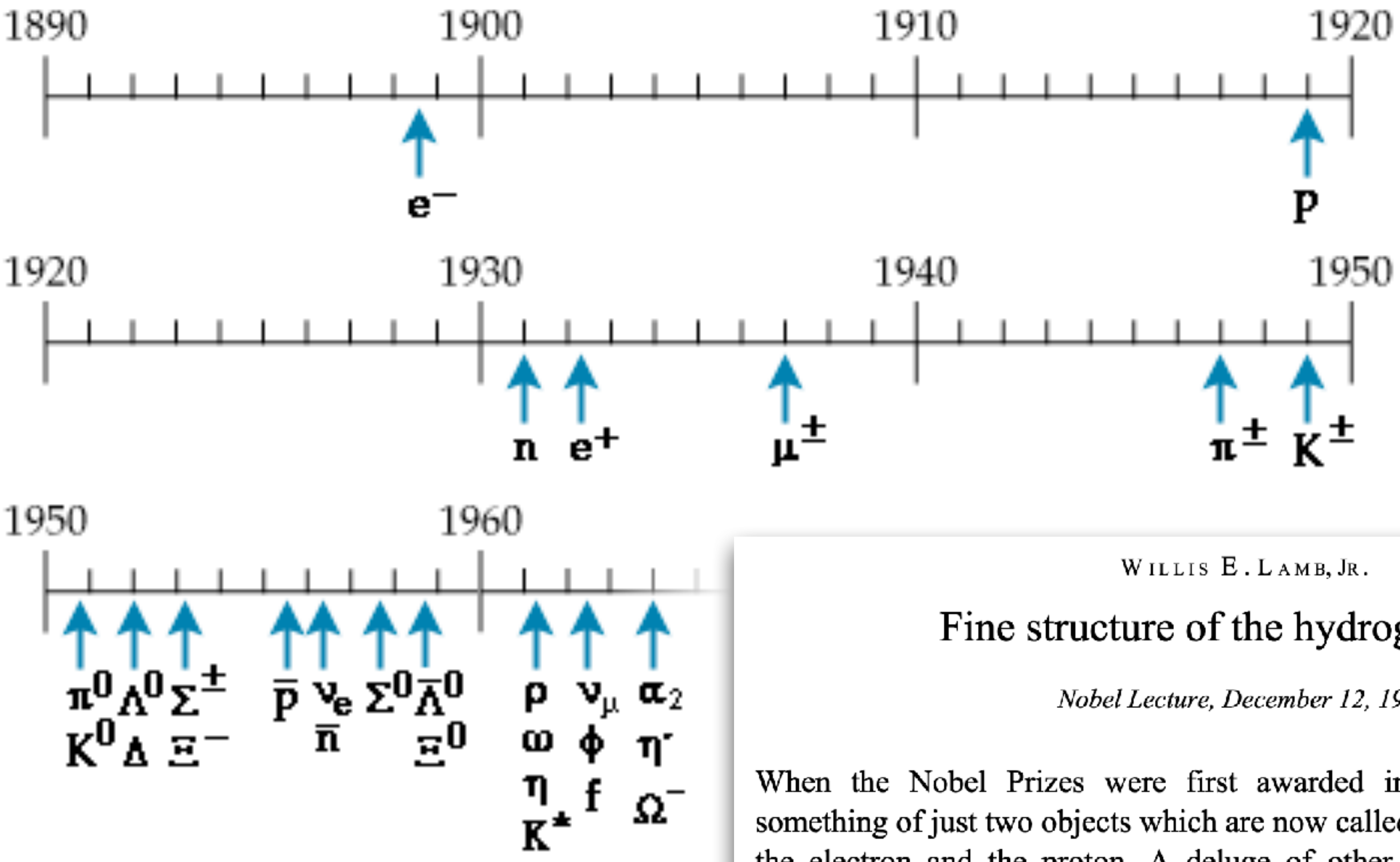
1937 Discovery of muons in cosmic rays

- Negatively charged particles which in a magnetic field curve less than an electron but more than a proton, for particles with the same velocity -> mass between electron and proton

1947 Discovery of the pion and Kaon



The particle Zoo (~1960)



- With the advent of accelerators the particle zoo quickly grew to more than 200 "elementary particles"
- Why so many?
- Can we make some order ?

WILLIS E. LAMB, JR.

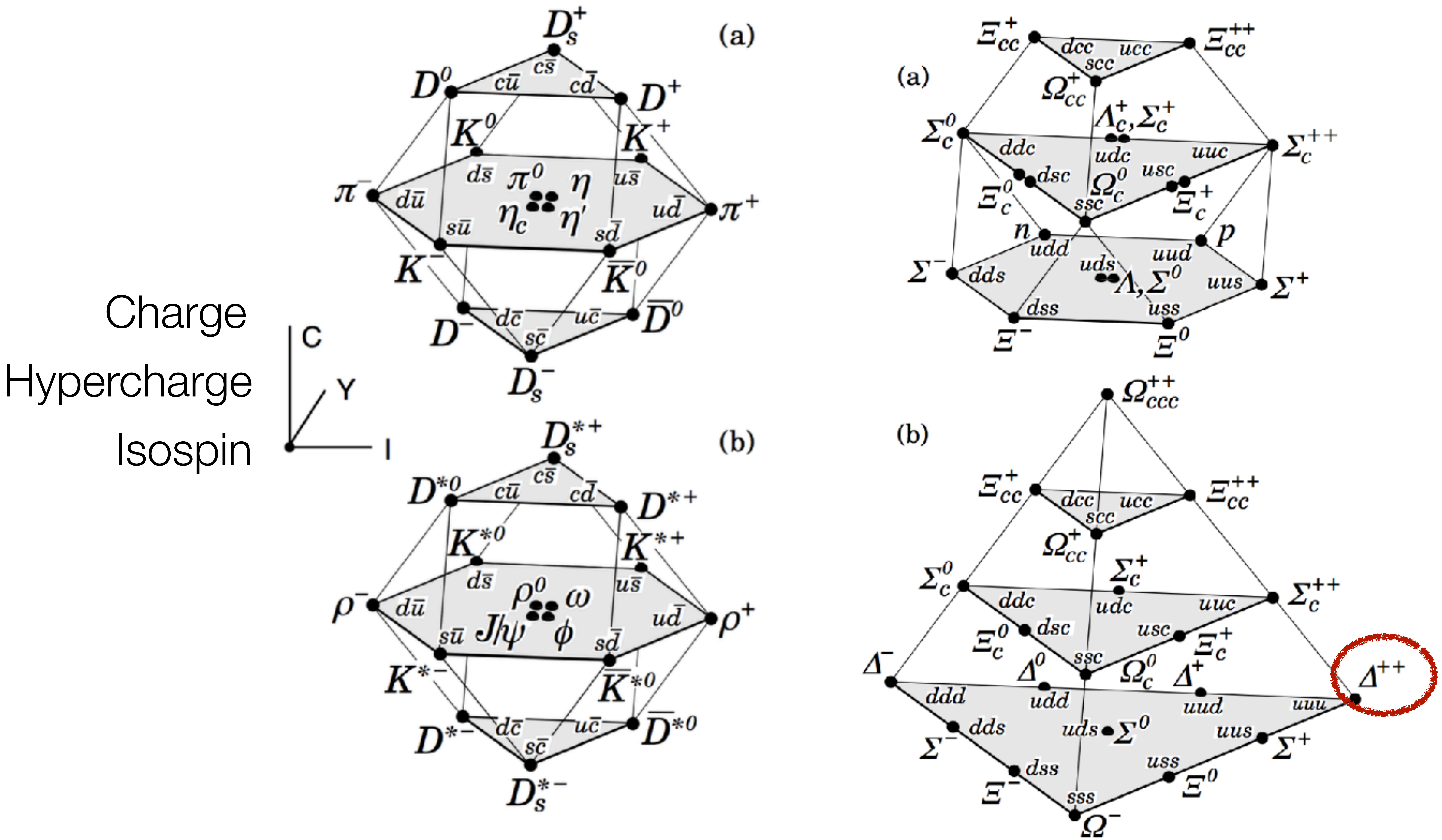
Fine structure of the hydrogen atom

Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».

Patterns begin to emerge

1960s M. Gell-Mann and G. Zweigh explained the pattern of particles by hypothesizing fundamental particles inside them. Gell-Mann named them “quarks”

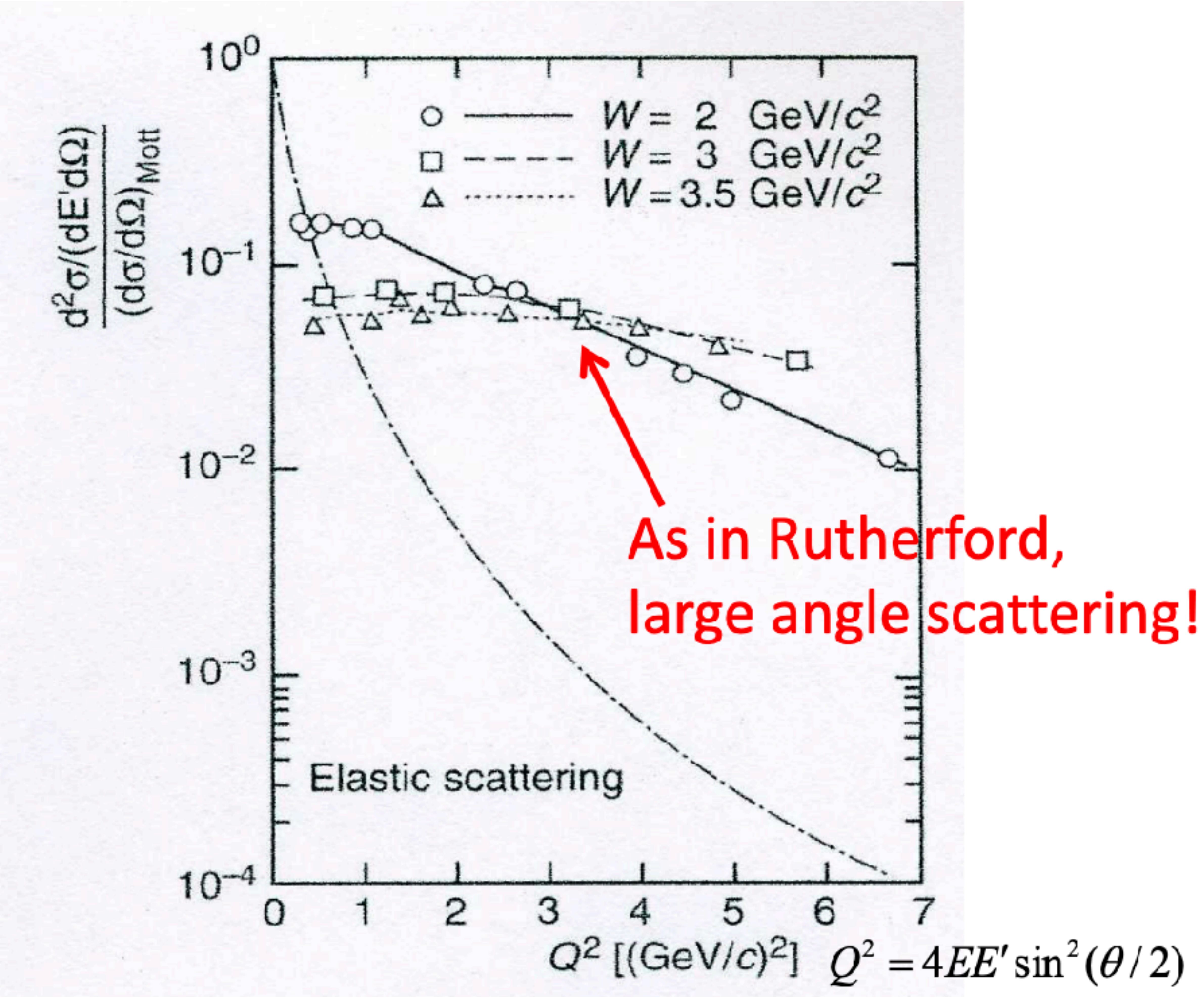


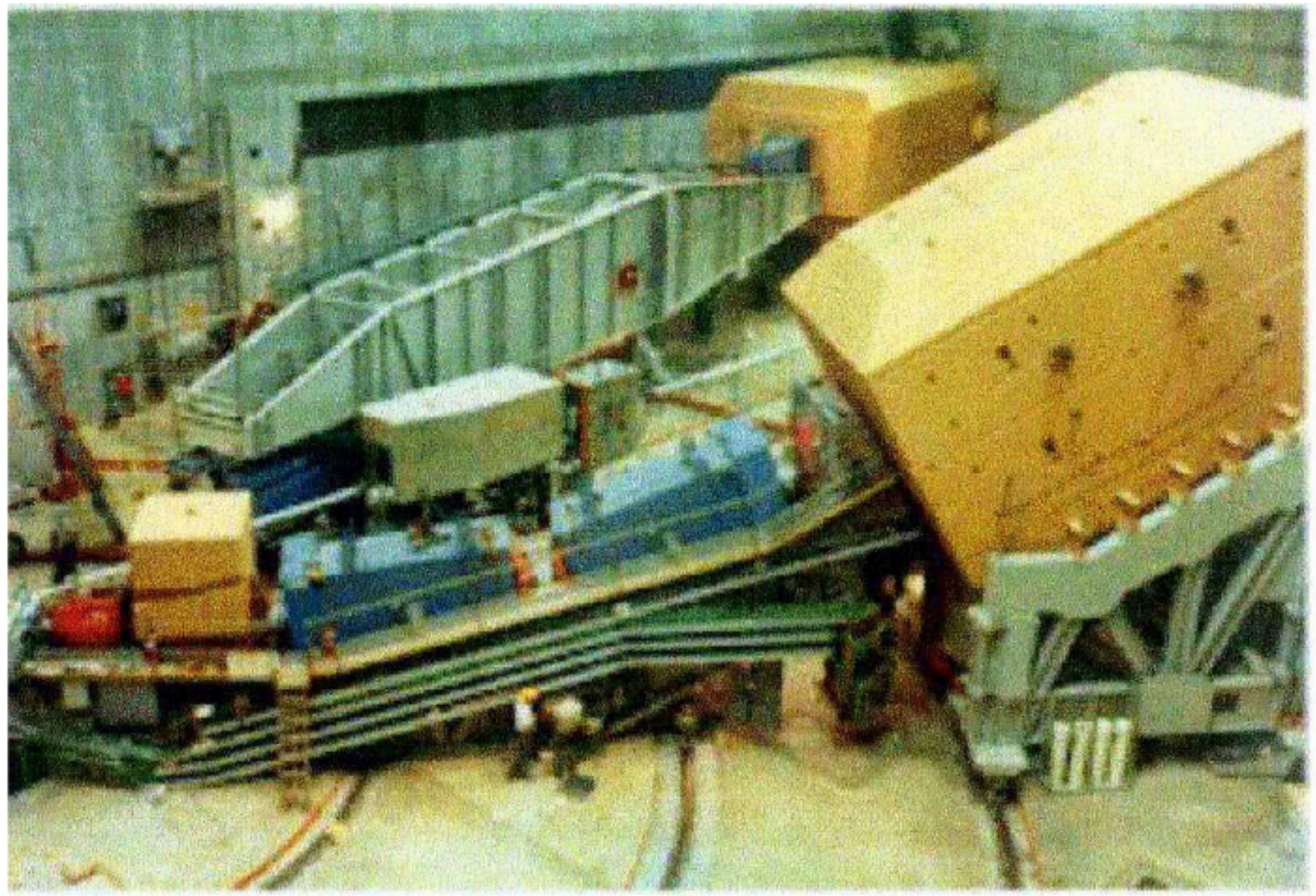
Patterns suggestive of some substructure: fundamental building blocks?

The structure of the proton

1968 confirmation of the quark model of the proton (Kendall, Friedman, Taylor)

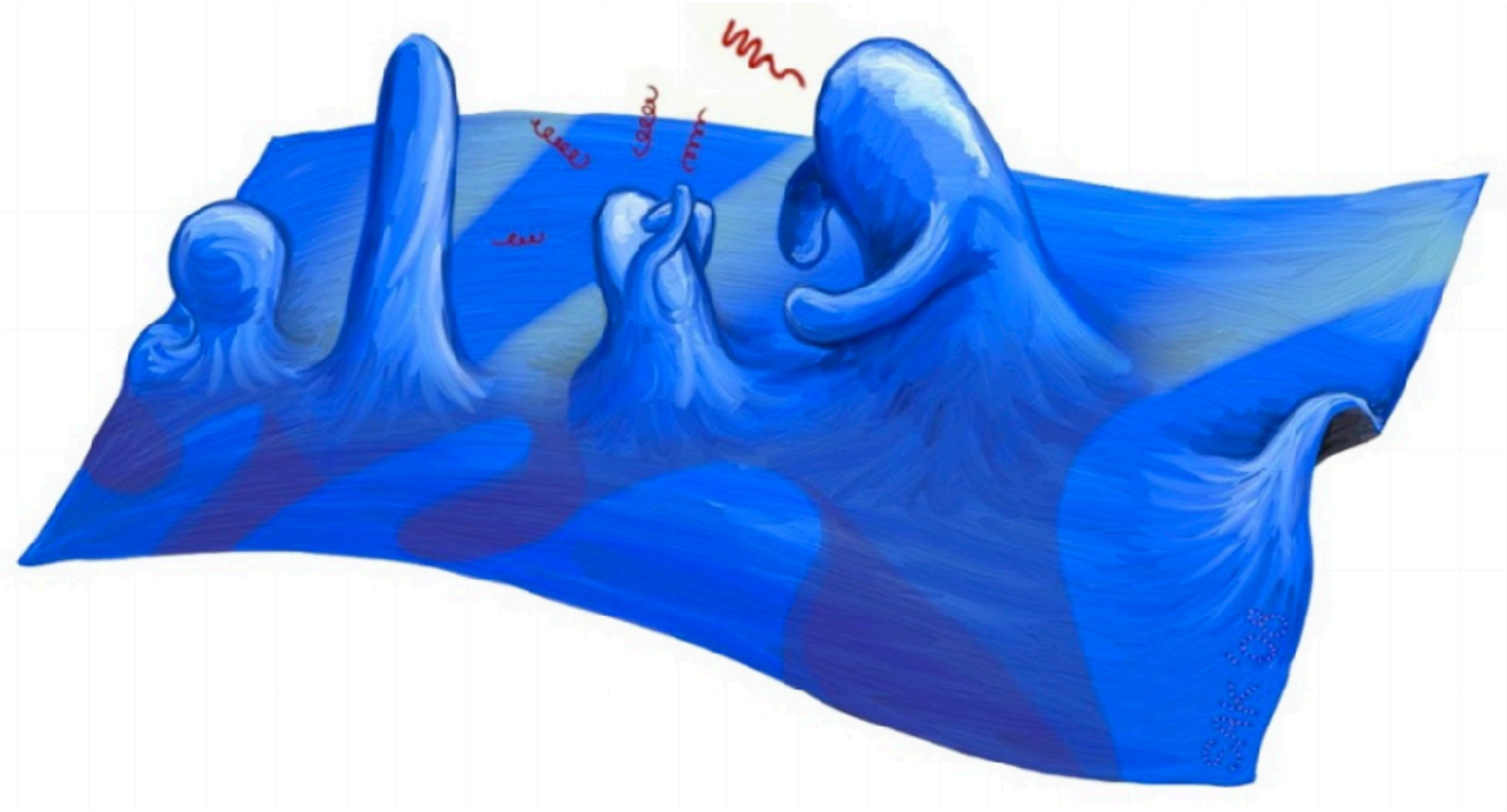
Rutherford like scattering experiment at SLAC shooting 20 GeV electrons into protons





Consistent with the diffusion of electrons from point-like particles inside the proton

What is matter made of ?



Particles: excitations of underlying quantum fields

Forces: also due to fields and have associated particles
Consequence of enforcing symmetries to be local (gauge)

The Standard Model

Standard Model (36+1 particles, 3 forces)

Selected Nobel Prizes since 1957 (incomplete!)

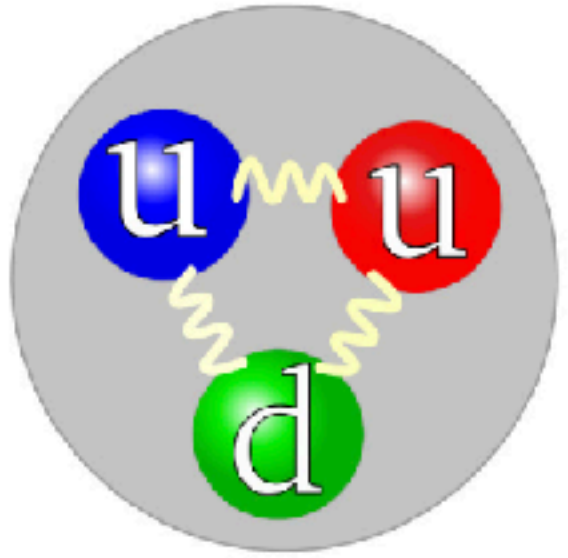
What are we made of ?

Almost all the matter in the universe is made up from just four of the fermions.

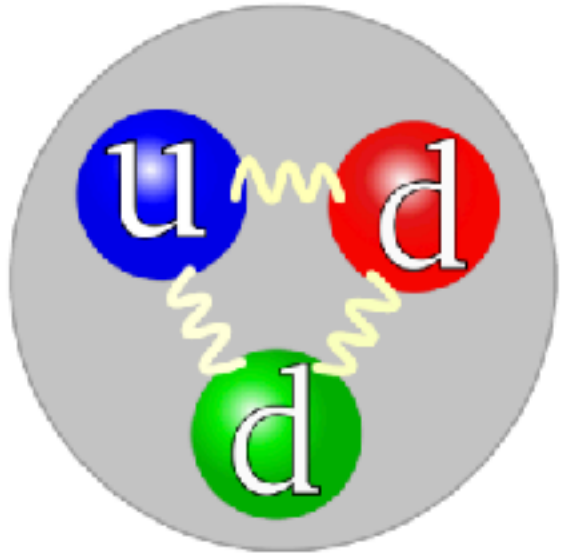
Particle	Symbol	Type	Charge [e]
Electron	e^-	lepton	-1
Neutrino	ν_e	lepton	0
Up quark	u	quark	$+\frac{2}{3}$
Down quark	d	quark	$-\frac{1}{3}$

The proton and neutron are simply the lowest energy bound states of a system of three quarks: essentially all an atomic or nuclear physicist needs.

Proton (p)



Neutron (n)



The 3 fermion families

Nature is not so simple.

There are 3 generations/families of fundamental fermions (and only 3).

1^{st} generation		2^{nd} generation		3^{rd} generation	
Electron	e^-	Muon	μ^-	Tau	τ^-
Electron Neutrino	ν_e	Muon Neutrino	ν_μ	Tau Neutrino	ν_τ
Up quark	u	Charm quark	c	Top quark	t
Down quark	d	Strange quark	s	Bottom quark	b

Each generation is a replica of (e^-, ν_e, u, d).

The mass of the particles increases with each generation:

the first generation is lightest and the third generation is the heaviest.

The generations are distinct

i.e. μ is not an excited e, or $\mu^- \rightarrow e^-\gamma$ would be allowed – this is not seen.

Quarks

Quarks experience all the forces (strong, electromagnetic, weak).

Flavour	Charge [e]	Mass	Strong	Weak	EM
1^{st} generation					
u	$+\frac{2}{3}$	$2.3\ \mathrm{MeV}/c^2$	✓	✓	✓
d	$-\frac{1}{3}$	$4.8\ \mathrm{MeV}/c^2$	✓	✓	✓
2^{nd} generation					
c	$+\frac{2}{3}$	$1.3\ \mathrm{GeV}/c^2$	✓	✓	✓
s	$-\frac{1}{3}$	$95\ \mathrm{MeV}/c^2$	✓	✓	✓
3^{rd} generation					
t	$+\frac{2}{3}$	$173\ \mathrm{GeV}/c^2$	✓	✓	✓
b	$-\frac{1}{3}$	$4.7\ \mathrm{GeV}/c^2$	✓	✓	✓

- Spin $\frac{1}{2}$ fermions
- 6 distinct flavours
- Fractional charge:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} +\frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$$

- Antiquarks $\bar{u}$, $\bar{d}$ etc
- Quarks are confined within hadrons, e.g. $p=(uud)$, $\pi^+=(u\bar{d})$

- Quarks come in three colours (colour charge) Red, Green, Blue.
  Colour is a label for the charge of the strong interaction.
  Unlike the electric charge ($+-$), the strong charge has three orthogonal colours (RGB).

Hadrons

Single, free quarks have never been observed. They are always confined in bound states called hadrons.

Mesons ($q\bar{q}$): Bound states of a quark and an antiquark.
Mesons have integer spin 0, 1, 2... bosons.

e.g. $\pi^+ \equiv (u\bar{d})$, charge $= (+\frac{2}{3} + +\frac{1}{3})e = +1e$

$\pi^- \equiv (\bar{u}d)$, charge $= (-\frac{2}{3} + -\frac{1}{3})e = -1e$; antiparticle of π^+

$\pi^0 \equiv (u\bar{u} - d\bar{d})/\sqrt{2}$, charge $= 0$; is its own antiparticle.

Baryons (qqq): Bound states of three quarks.
Baryons have half-integer spin $\frac{1}{2}$, $\frac{3}{2}$... fermions.

e.g. $p \equiv (udu)$, charge $= (+\frac{2}{3} + -\frac{1}{3} + +\frac{2}{3})e = +1e$

$n \equiv (dud)$, charge $= (-\frac{1}{3} + +\frac{2}{3} + -\frac{1}{3})e = 0$

Antibaryons e.g. $\bar{p} \equiv (\bar{u}\bar{d}\bar{u})$, $\bar{n} \equiv (\bar{d}\bar{u}\bar{d})$

Leptons

Leptons are fermions which do not interact via the strong interaction.

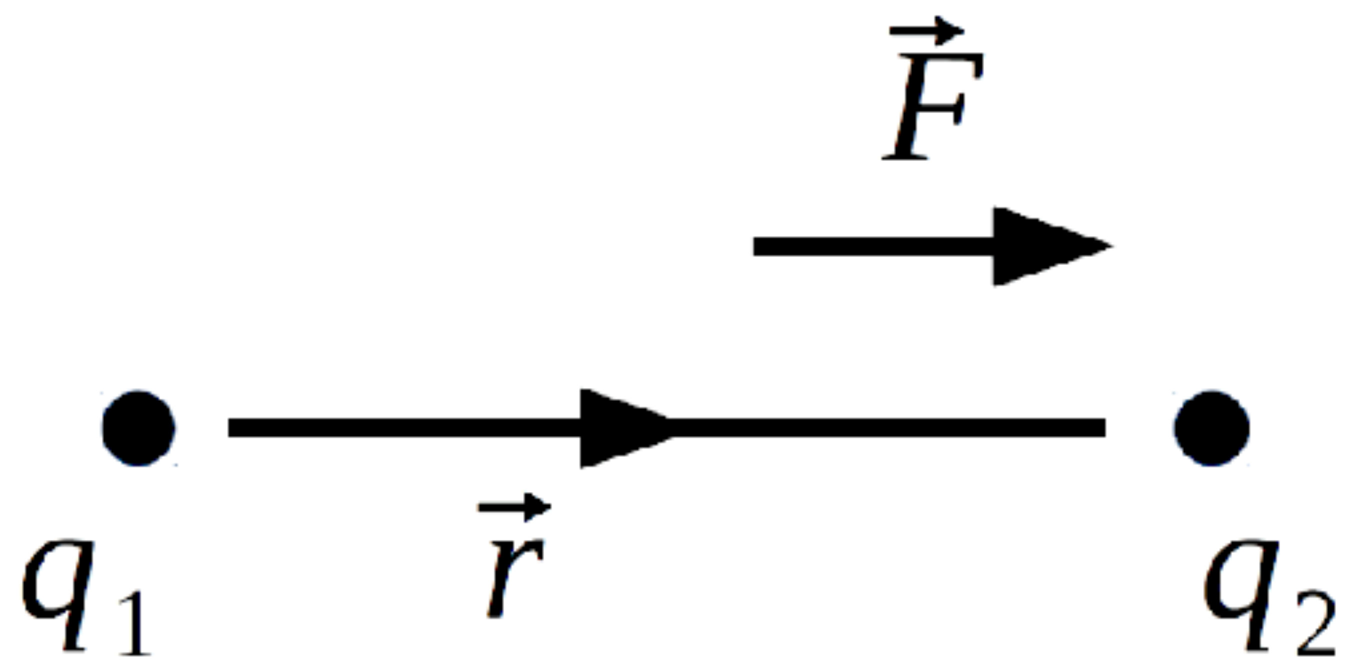
Flavour	Charge [e]	Mass	Strong	Weak	EM
1^{st} generation					
e^-	-1	$0.511\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_e	0	$< 2\ \mathrm{eV}/c^2$	✗	✓	✗
2^{nd} generation					
μ^-	-1	$105.7\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_μ	0	$< 0.19\ \mathrm{MeV}/c^2$	✗	✓	✗
3^{rd} generation					
τ^-	-1	$1777.0\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_τ	0	$< 18.2\ \mathrm{MeV}/c^2$	✗	✓	✗

- Spin $\frac{1}{2}$ fermions
- 6 distinct flavours
- 3 charged leptons: e^-, μ^-, τ^-.
  3 neutral leptons: ν_e, ν_μ, ν_τ.
- Antimatter particles $e^+, \bar{\nu}_e$ etc
- e is stable,
  μ and τ are unstable.

- Neutrinos are stable and almost massless. Only know limits on ν masses, but have measured mass differences to be $< 1\ \mathrm{eV}/c^2$. *Not completely true, see later...*
- Charged leptons experience only the electromagnetic & weak forces.
- Neutrinos experience only the weak force.

Forces - classical

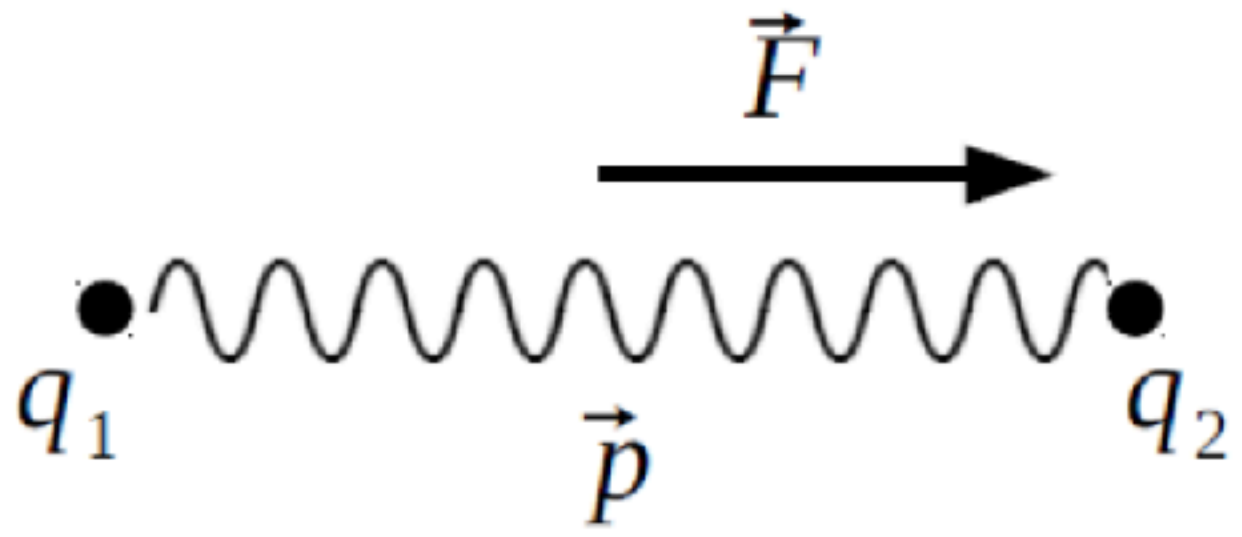
In classical physics, the electromagnetic forces arise via action at a distance through the electric and magnetic fields, $\vec{E}$ and $\vec{B}$.



$$\vec{F} = \frac{q_1 q_2 \vec{r}}{r^2}$$

Newton: "...that one body should act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has, in philosophical matters, a competent faculty of thinking, can ever fall into it. Gravity must be caused by an agent, acting constantly according to certain laws, but whether this agent be material or immaterial, I leave to the consideration of my reader."

Forces arise through the exchange of virtual field quanta called **Gauge Bosons**.



This process is called "second quantisation".

This process violates energy/momentum conservation *(more later)*. However, this is permissible for sufficiently short times owing to the Uncertainty Principle

The exchanged particle is "virtual" – meaning it doesn't satisfy $E^2 = p^2c^2 + m^2c^4$.

Uncertainty principle: $\Delta E \Delta t \sim \hbar \quad \Rightarrow \quad$ range $R \sim c\Delta t \sim \hbar c/\Delta E$

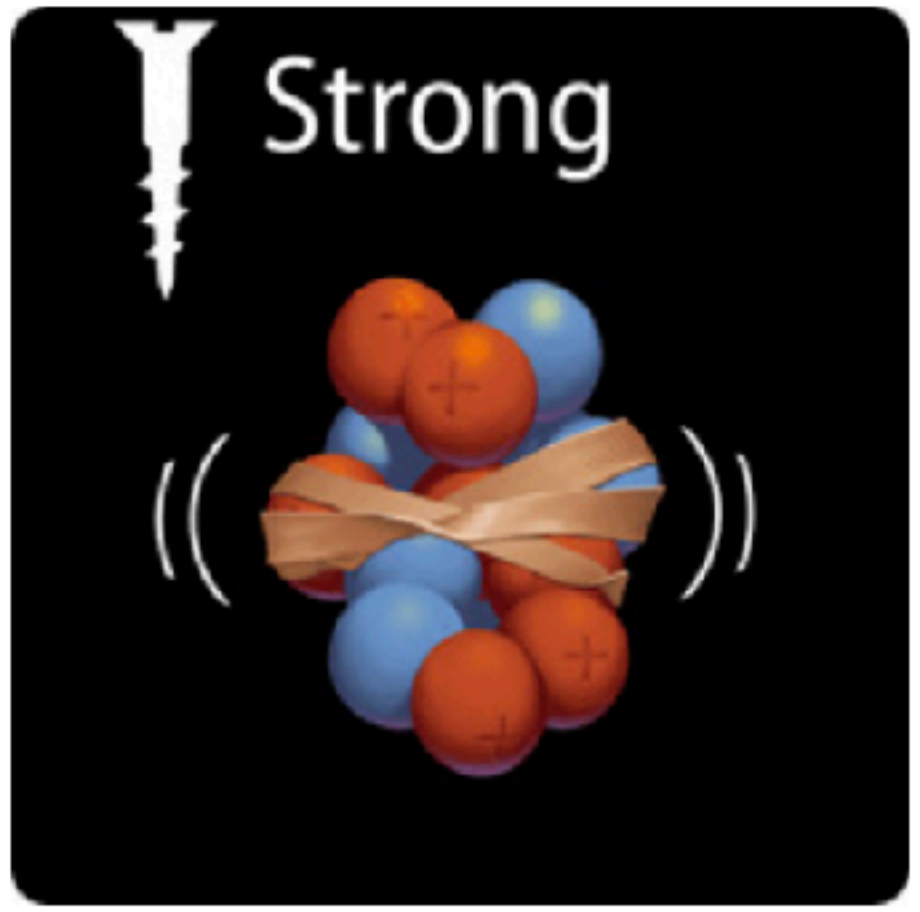
i.e. larger energy transfer (larger force) $\leftrightarrow$ smaller range.

Prob(emission of a quantum)$\propto q_1$, Prob(absorption of a quanta)$\propto q_2$

Coulomb's law can be regarded as the resultant effect of all virtual exchanges.

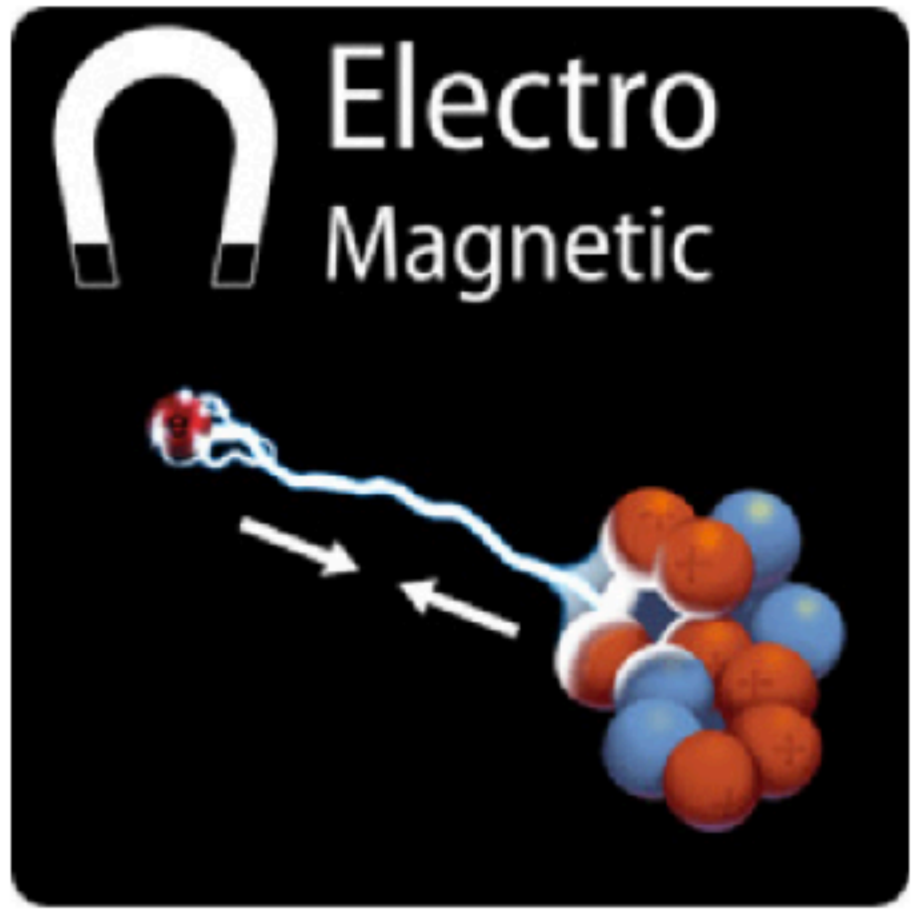
The four known forces

$SU(3)_{color} \times SU(2)_L \times U(1)_Y$



Carried by the gluon. Holds atomic nuclei together.

Carried by the W and Z bosons. Responsible for radioactive decay.



Carried by the photon. Acts between charged particles.

Carried by the graviton. Acts between massive particles.

Forces - Mediators

Gauge bosons mediate the fundamental forces

- They are spin-1 particles (vector bosons)
- Interact in a similar way with all fermion generations
- They exact mode of interaction determines the nature of the fundamental force

Force	Boson		Spin	Strength	Mass
Strong	8 gluons	g	1	1	massless
Electromagnetic	photon	γ	1	10^{-2}	massless
Weak	W and Z	W^+, W^-, Z	1	10^{-7}	80, 91 GeV
Gravity	graviton	?	2	10^{-39}	massless

N.B. Gravity is not included in the Standard Model

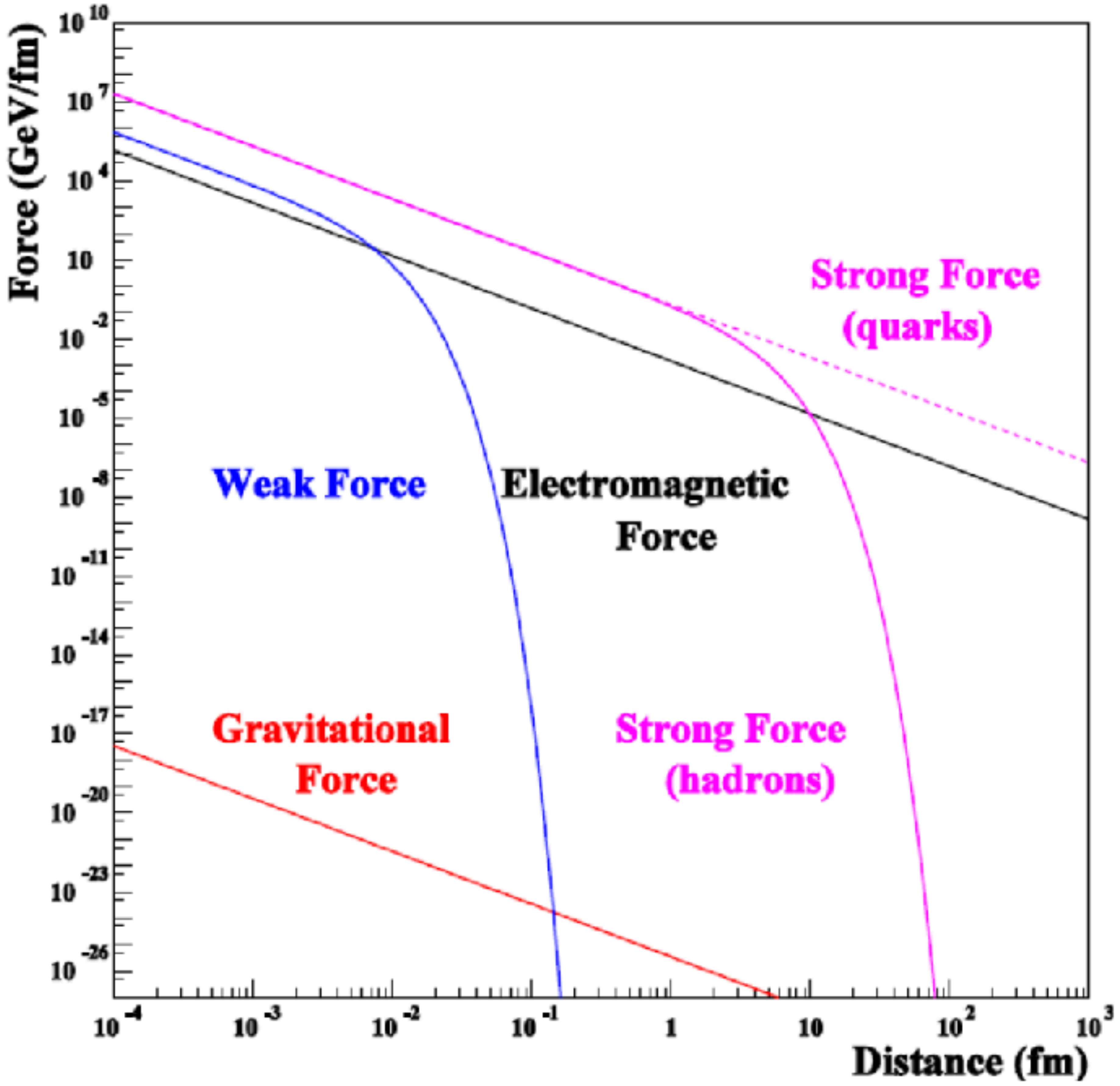
Forces - range

The range of a force is inversely related to the mass of the exchanged bosons

$$\Delta E \Delta t \sim \hbar, \qquad E = mc^2$$

$$\Rightarrow mc^2 \sim \frac{\hbar}{\Delta t} \sim \frac{\hbar c}{r} \quad \Rightarrow r \sim \frac{\hbar}{mc}$$

Force	Range [m]
Strong	inf
Strong (nuclear)	10^{-15}
Electromagnetic	inf
Weak	10^{-18}
Gravity	inf



Due to quark confinement, nucleons start to experience the strong force at ~ 2 fm

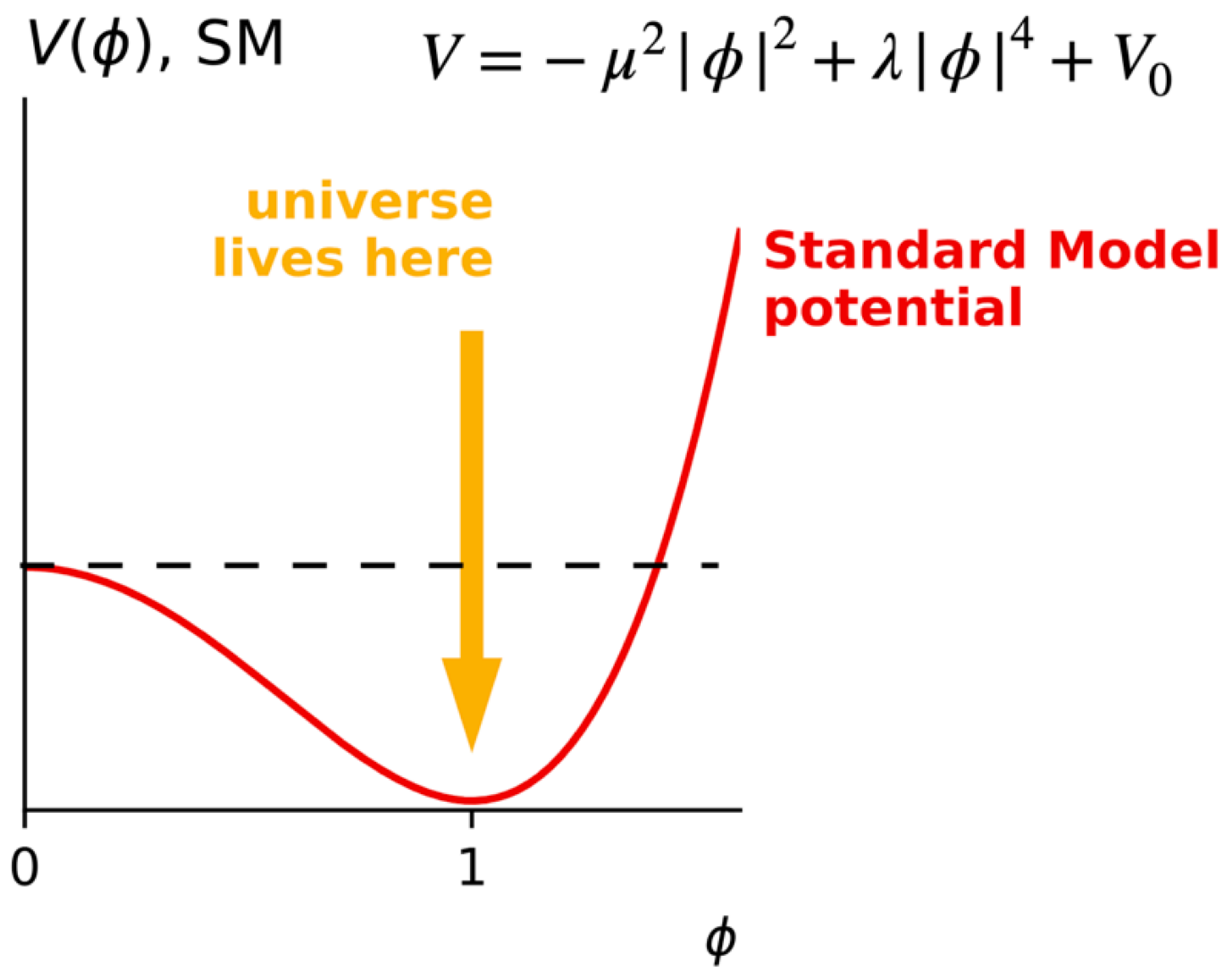
How do particles get their mass

The SM Lagrangian does not include a mass term for the gauge bosons or the fermions

- If we introduce it by-hand for the gauge fields, we violate gauge invariance
- For the fermions, a mass term would couple states of different chiralities, and violate weak isospin

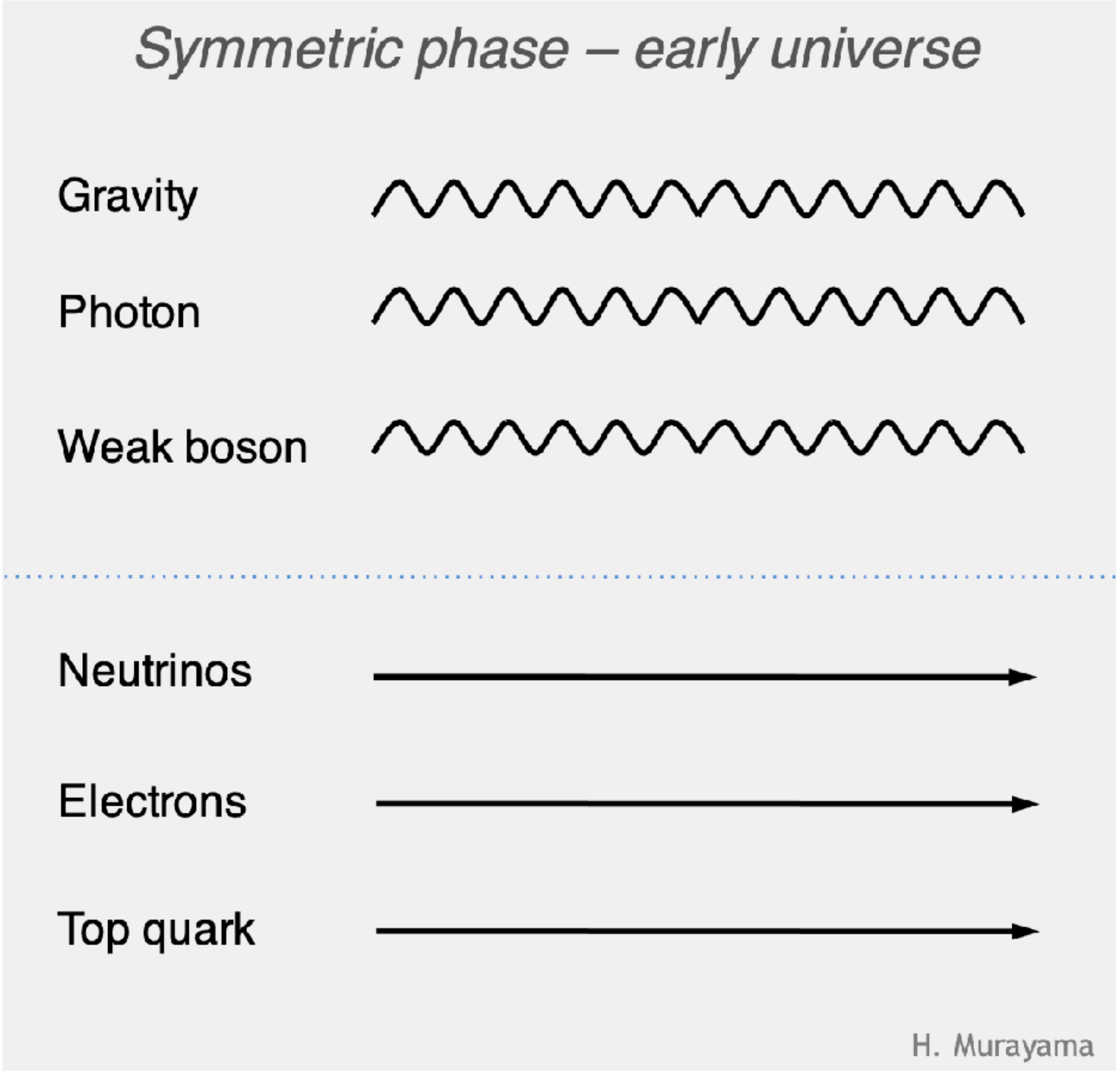
Spontaneous Symmetry Breaking

- Introduce a new field with self-interactions
- These induce a non-zero vacuum expectation value (VEV)
- Reparametrising the fields in terms of physical states we can introduce masses



Higgs boson

- Early universe: symmetric phase, fundamental particles are massless
 -> gauge symmetry is restored
- A Higgs field displaces the ground state, breaking gauge symmetry
- It fills all space-time
(but no orientation as spin-0)
- Particles interact with the Higgs field and effectively reduce their propagation speed
-> they acquire a mass proportional to their interaction strength
- Action of the Higgs field creates a "viscosity of the vacuum"



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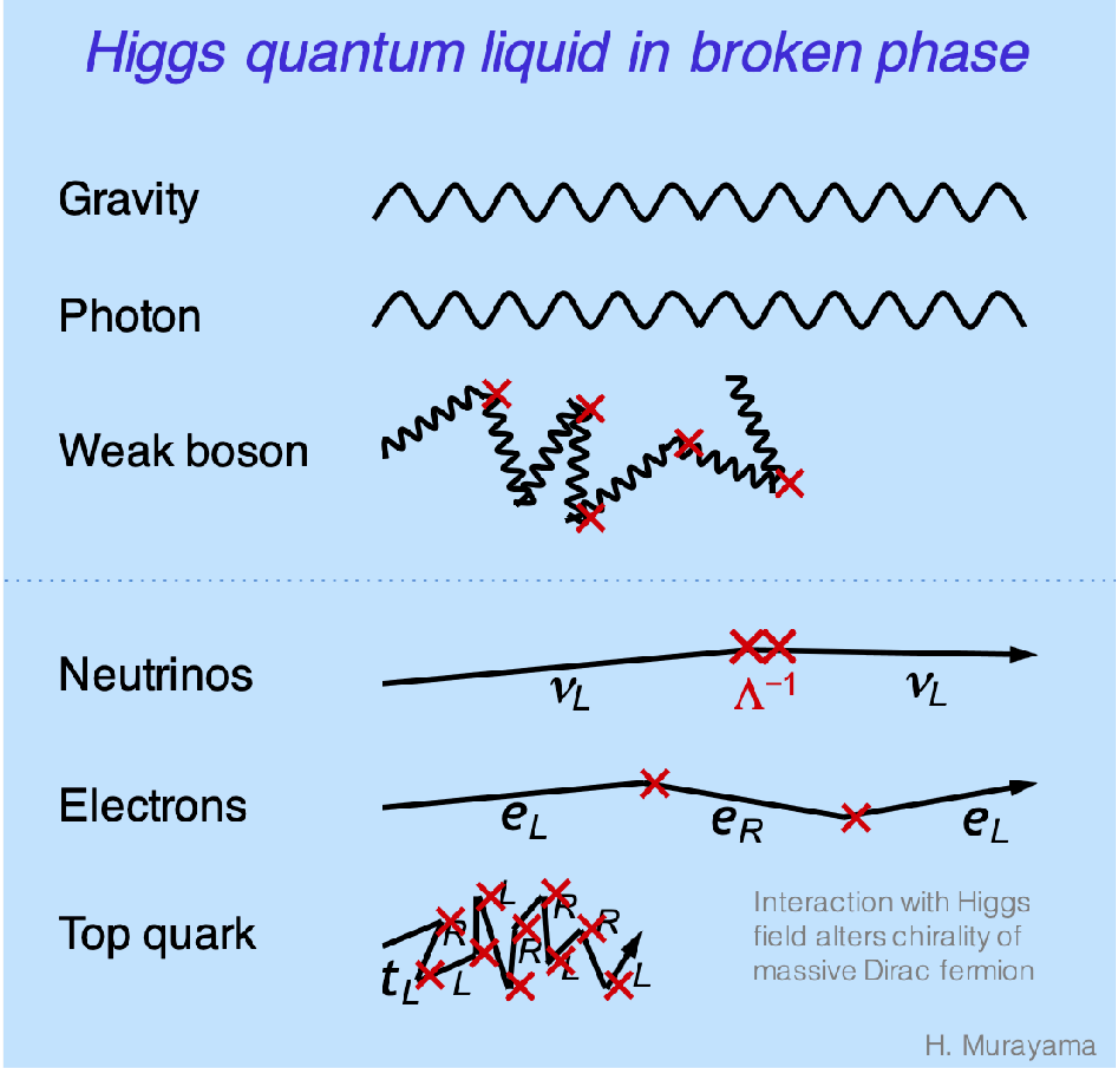


THE FATE OF SYMMETRIES IN THE SM

Several possible realization of symmetries

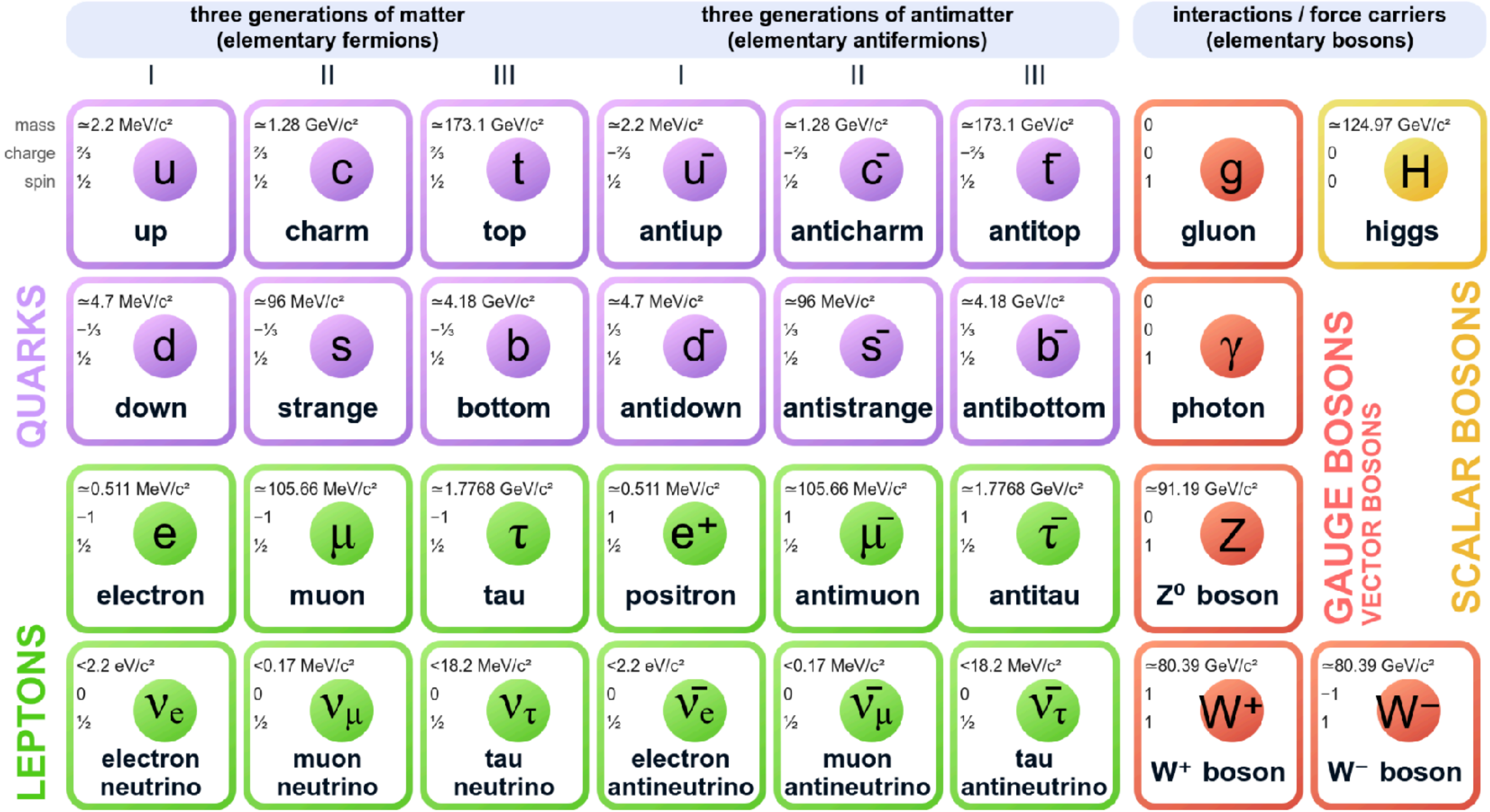
- Symmetries may remain exact
  → $U(1)_{em}$, $SU(3)_{color}$, B-L number

- They may be good symmetries of the classical action,
  but broken by quantum loop corrections (anomalies)
  → global U(1) axial symmetry

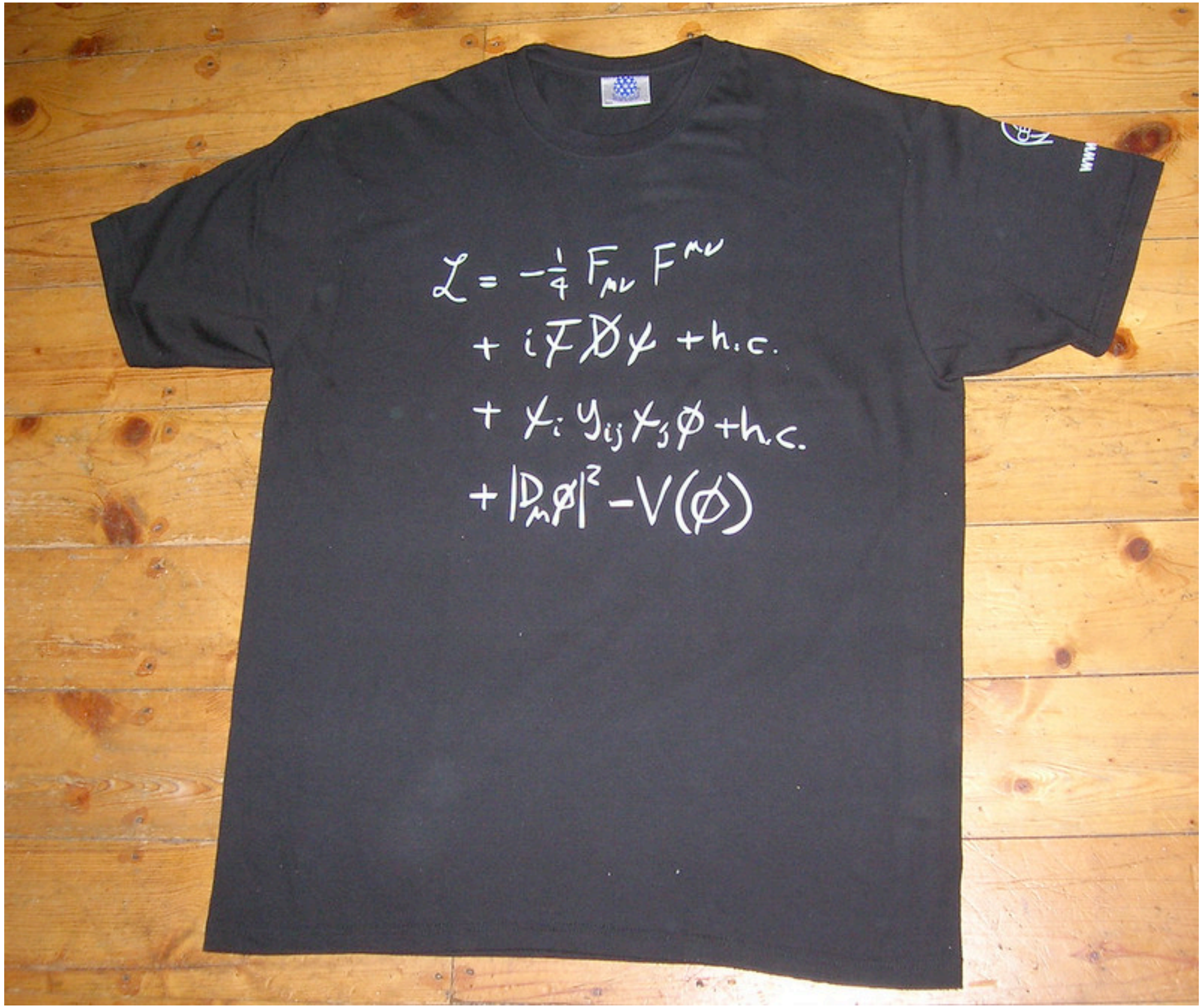
- They may be explicitly broken by terms in the lagrangian
  → $SU(2)_{Isospin}$ broken by EM interactions and non-zero quark masses

- Hidden (spontaneously broken) symmetries
  symmetries of the action but not of its ground state

The Standard Model



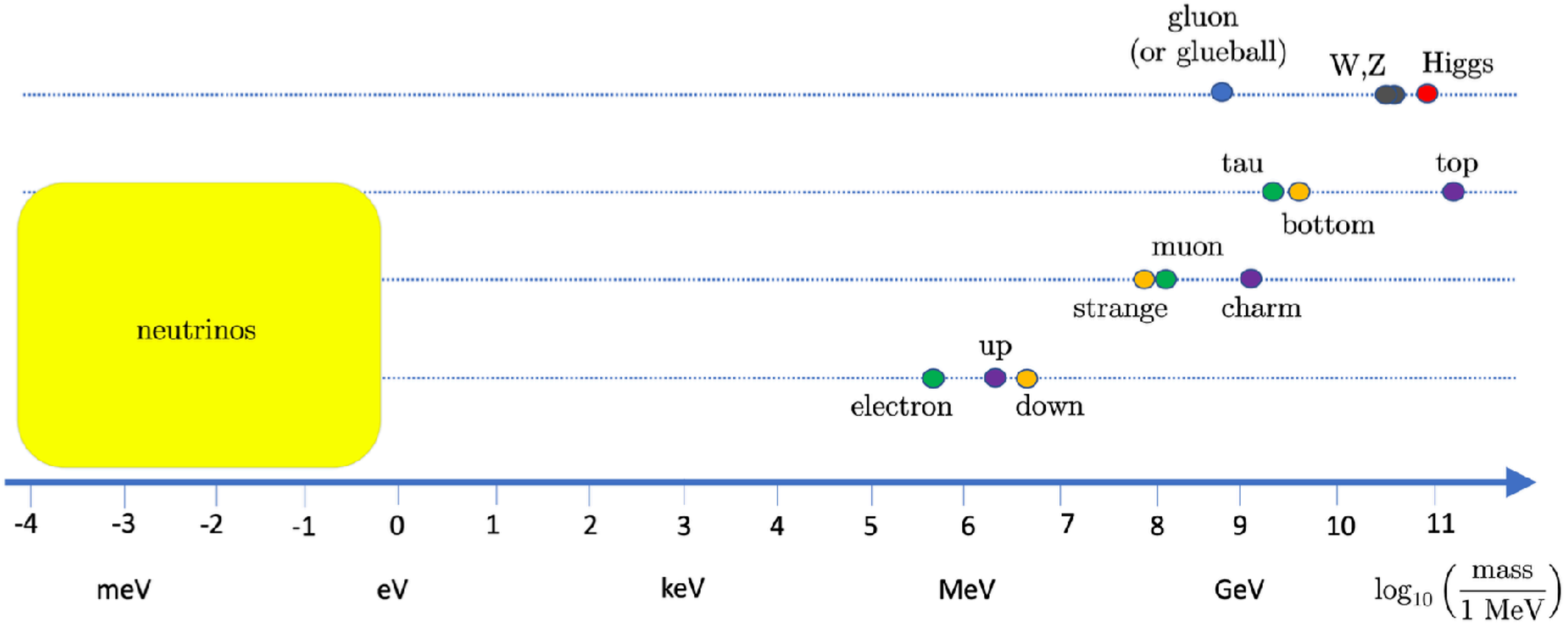
Compact enough to fit on a t-shirt



... ALMOST

$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H -$$
$$\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) -$$
$$\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial+m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial+m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial+$$
$$m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial+m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)d^\lambda_j) +$$
$$(\bar u^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2+\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) -$$
$$\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \frac{1}{4}\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa -$$
$$\frac{1}{4}\overline{\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa} + \frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) -$$
$$\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar G^a G^b g^c_\mu +$$
$$\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- -$$
$$\partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 -$$
$$\partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) - \frac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H\right) + \frac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) +$$
$$\frac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) +$$
$$\frac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).$$

Particle masses



Note: photon and graviton massless

Units

Choose energy as the basic unit of measurement...		...and simplify by choosing $\hbar = c = 1$
Energy	GeV	GeV
Momentum	GeV/c	GeV
Mass	GeV/c^2	GeV
Time	$(\mathrm{GeV}/\hbar)^{-1}$	GeV^{-1}
Length	$(\mathrm{GeV}/\hbar c)^{-1}$	GeV^{-1}
Cross-section	$(\mathrm{GeV}/\hbar c)^{-2}$	GeV^{-2}

Reintroduce "missing" factors of $\hbar$ and c to convert back to SI units.

$\hbar c = 0.197\ \mathrm{GeV\,fm} = 1$ Energy $\longleftrightarrow$ Length

$\hbar = 6.6 \times 10^{-25}\ \mathrm{GeV\,s} = 1$ Energy $\longleftrightarrow$ Time

$c = 3.0 \times 10^{8}\ \mathrm{ms}^{-1} = 1$ Length $\longleftrightarrow$ Time

Units

The usual practice in particle and nuclear physics is to use Natural Units.

- Energies are measured in units of eV:

  Nuclear $\mathrm{keV}(10^3\ \mathrm{eV}),\ \ \mathrm{MeV}(10^6\ \mathrm{eV})$

  Particle $\mathrm{GeV}(10^9\ \mathrm{eV}),\ \ \mathrm{TeV}(10^{12}\ \mathrm{eV})$

- Masses are quoted in units of MeV/c^2 or GeV/c^2 (using $E = mc^2$)

  e.g. electron mass $m_e = 9.11 \times 10^{-31}\,\mathrm{kg} = (9.11 \times 10^{-31})(3 \times 10^8)^2\,\mathrm{J}/c^2$

  $= 8.20 \times 10^{-14}/1.602 \times 10^{-19}\ \mathrm{eV}/c^2 = 5.11 \times 10^5\ \mathrm{eV}/c^2 = 0.511\ \mathrm{MeV}/c^2$

- Atomic/nuclear masses are often quoted in unified (or atomic) mass units

  1 unified mass unit (u) = (mass of a ${}^{12}_{6}\mathrm{C}$ atom) / 12

  $1\,\mathrm{u} = 1\,\mathrm{g}/\mathrm{N}_A = 1.66 \times 10^{-27}\mathrm{kg} = 931.5\ \mathrm{MeV}/c^2$

- Cross-sections are usually quoted in barns: $1\mathrm{b} = 10^{-28}\,\mathrm{m}^2$.

Units - examples

1. **cross-section $\sigma = 2 \times 10^{-6}$ GeV^{-2} change into standard units**

   Need to change units of energy to length. Use $\hbar c = 0.197\ \mathrm{GeV fm} = 1$.

   $\mathrm{GeV}^{-1} = 0.197\,\mathrm{fm}$

   $\mathrm{GeV}^{-1} = 0.197 \times 10^{-15}\,\mathrm{m}$

   $\mathrm{GeV}^{-2} = 3.89 \times 10^{-32}\,\mathrm{m}^2$

   $$\sigma = 2 \times 10^{-6} \times (3.89 \times 10^{-32}\,\mathrm{m}^2)$$
   $$= 7.76 \times 10^{-38}\,\mathrm{m}^2$$

   And using $1\,\mathrm{b} = 10^{-28}\,\mathrm{m}^2$, $\sigma = 0.776\,\mathrm{nb}$

2. **lifetime $\tau = 1/\Gamma = 0.5$ GeV^{-1} change into standard units**

   Need to change units of energy^{-1} to time. Use $\hbar = 6.6 \times 10^{-25}\ \mathrm{GeV\,s} = 1$.

   $\mathrm{GeV}^{-1} = 6.6 \times 10^{-25}\,\mathrm{s}$

   $$\tau = 0.5 \times (6.6 \times 10^{-25}\,\mathrm{s}) = 3.3 \times 10^{-25}\,\mathrm{s}$$

Also, can have Natural Units involving electric charge: $\epsilon_0 = \mu_0 = \hbar = c = 1$

3. **Fine structure constant** (dimensionless)

   $\alpha = \frac{\mathrm{e}^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}$ becomes $\alpha = \frac{\mathrm{e}^2}{4\pi} \sim \frac{1}{137}$ i.e. $e \sim 0.30(n.u.)$

Making predictions - Feynman diagrams

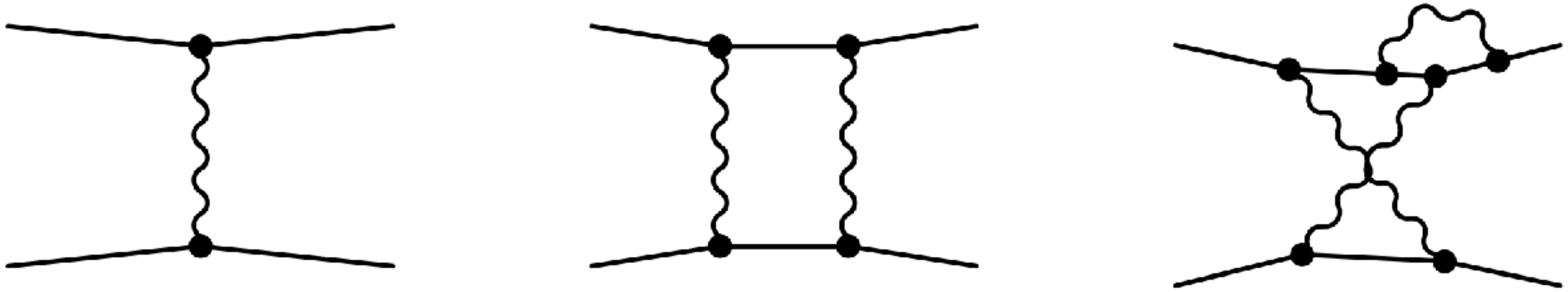
Each Feynman diagram represents a term in the perturbation theory expansion of the matrix element for an interaction.

Normally, a full matrix element contains an infinite number of Feynman diagrams.

Total amplitude $M_{fi} = M_1 + M_2 + M_3 + ...$

Total rate $\Gamma_{fi} = 2\pi |M_1 + M_2 + M_3 + ...|^2 \rho(E)$ Fermi's Golden Rule

But each vertex gives a factor of g, so if g is small (i.e. the perturbation is small) only need the first few. *(Lowest order = fewest vertices possible)*



g^2 g^4 g^6

QED $g = e = \sqrt{4\pi\alpha} \sim 0.30, \quad \alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$

Ingredients of Feynman diagrams - legs

External lines (visible real particles)

Spin 1/2	Particle		Incoming
			Outgoing
	Antiparticle		Incoming
			Outgoing
Spin 1	Particle		Incoming
			Outgoing

Internal lines (propagators; virtual particles)

Spin 1/2	Particle/antiparticle		Each propagator gives a factor of $\frac{1}{q^2 - m^2}$
Spin 1	γ, $W^{\pm}$, Z		
	g		

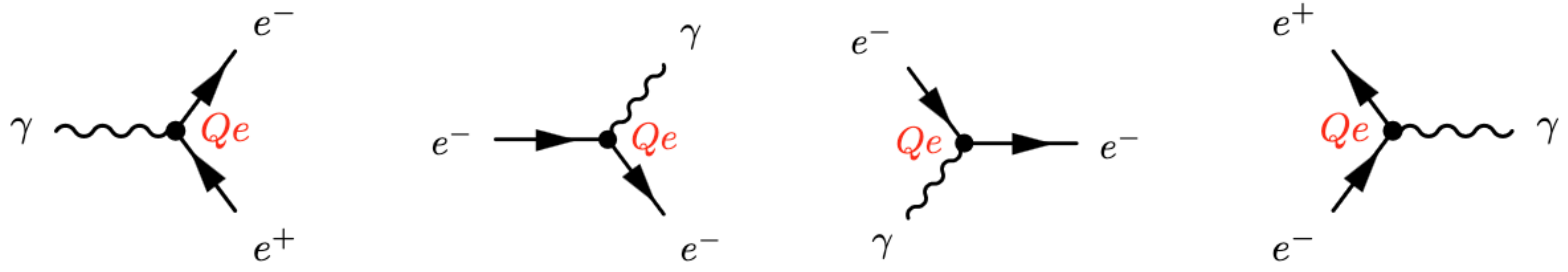
Ingredients of Feynman diagrams - vertices

A vertex represents a point of interaction: either EM, weak or strong.

The strength of the interaction is denoted by g

- EM interaction: $g = Qe$ (sometimes denoted as $Q\sqrt{\alpha}$, where $\alpha = e^2/4\pi$)
- Weak interaction: $g = g_W$
- Strong interaction: $g = \sqrt{\alpha_s}$

A vertex will have three (in rare cases four) lines attached, e.g.

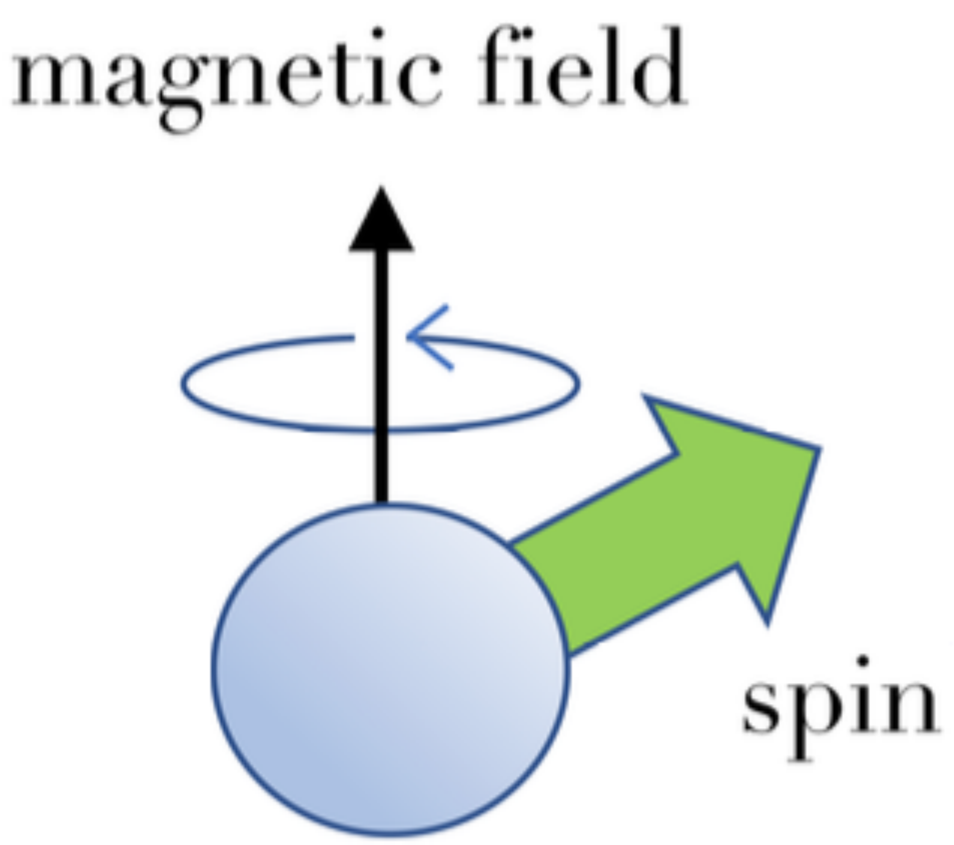


At each vertex, conserve energy, momentum, angular momentum, charge, lepton number ($L_e = +1$ for e^-, ν_e, $= -1$ for $e^+, \bar{\nu}_e$, similar for L_μ, L_τ), baryon number ($B = \frac{1}{3}(n_q - n_{\bar{q}})$), strangeness ($S = -(n_s - n_{\bar{s}})$) & parity – except in weak interactions.

Does the Standard Model get anything wrong?

Does the Standard Model get anything wrong?
No.

Anomalous magnetic moment



For the electron:

$$g_{\text{expt}} = 2.0023193043617 \pm 3$$

$$g_{\text{theory}} = 2.00231930436\ldots$$

For the muon:

$$g_{\text{expt}} = 2.00233184122$$

$$g_{\text{theory}} = 2.00233183602$$

So, are we done?

Despite being the greatest theory of all times the Standard Model remains unsatisfactory

Several important questions are left unanswered

Aesthetics

- Fine-tuning of the Higgs mass
- Hierarchy of scales in particle masses
- Number of free parameters

Empirical

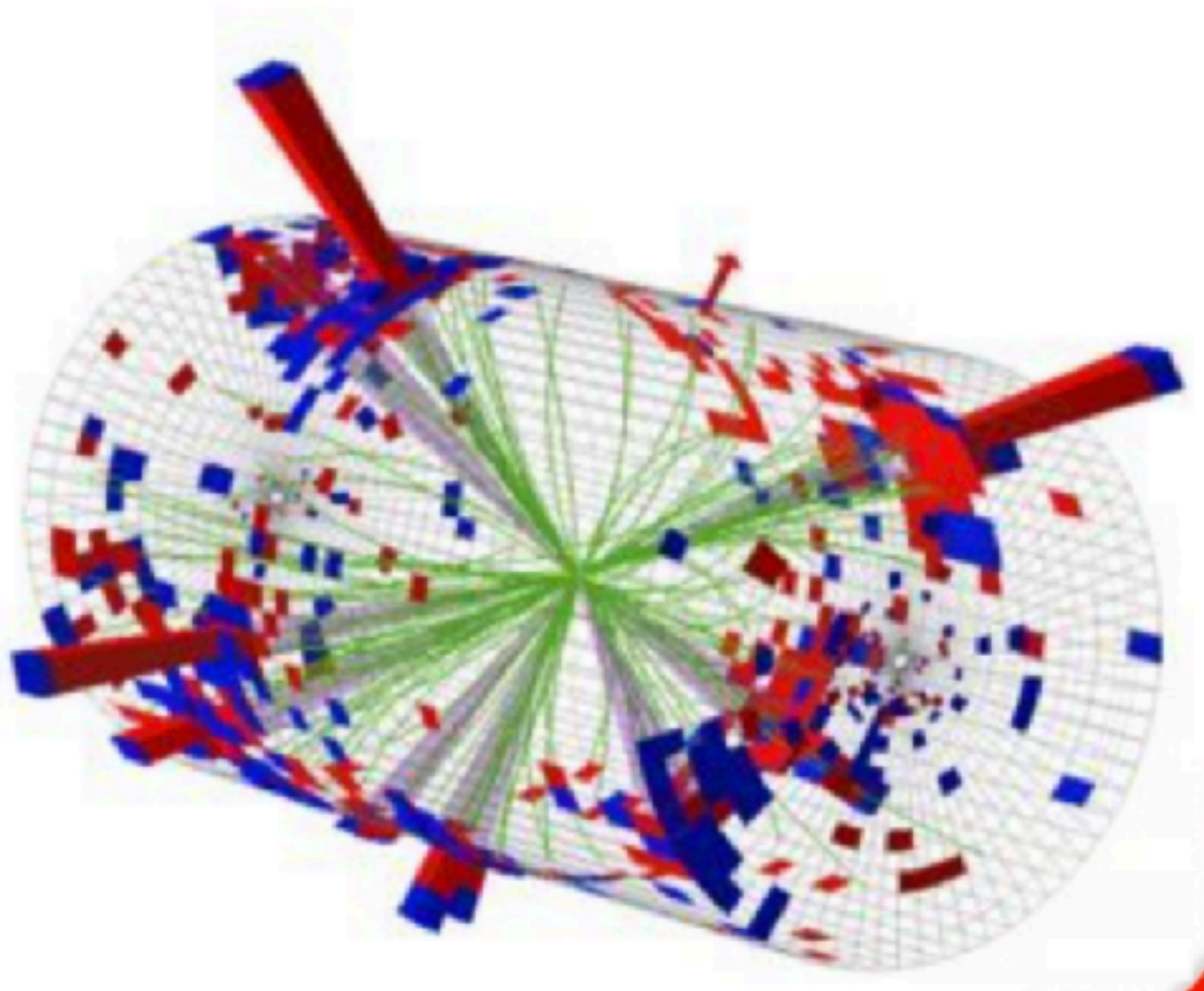
- Dark-Matter
- Dark-Energy
- Baryon asymmetry
- Gravity

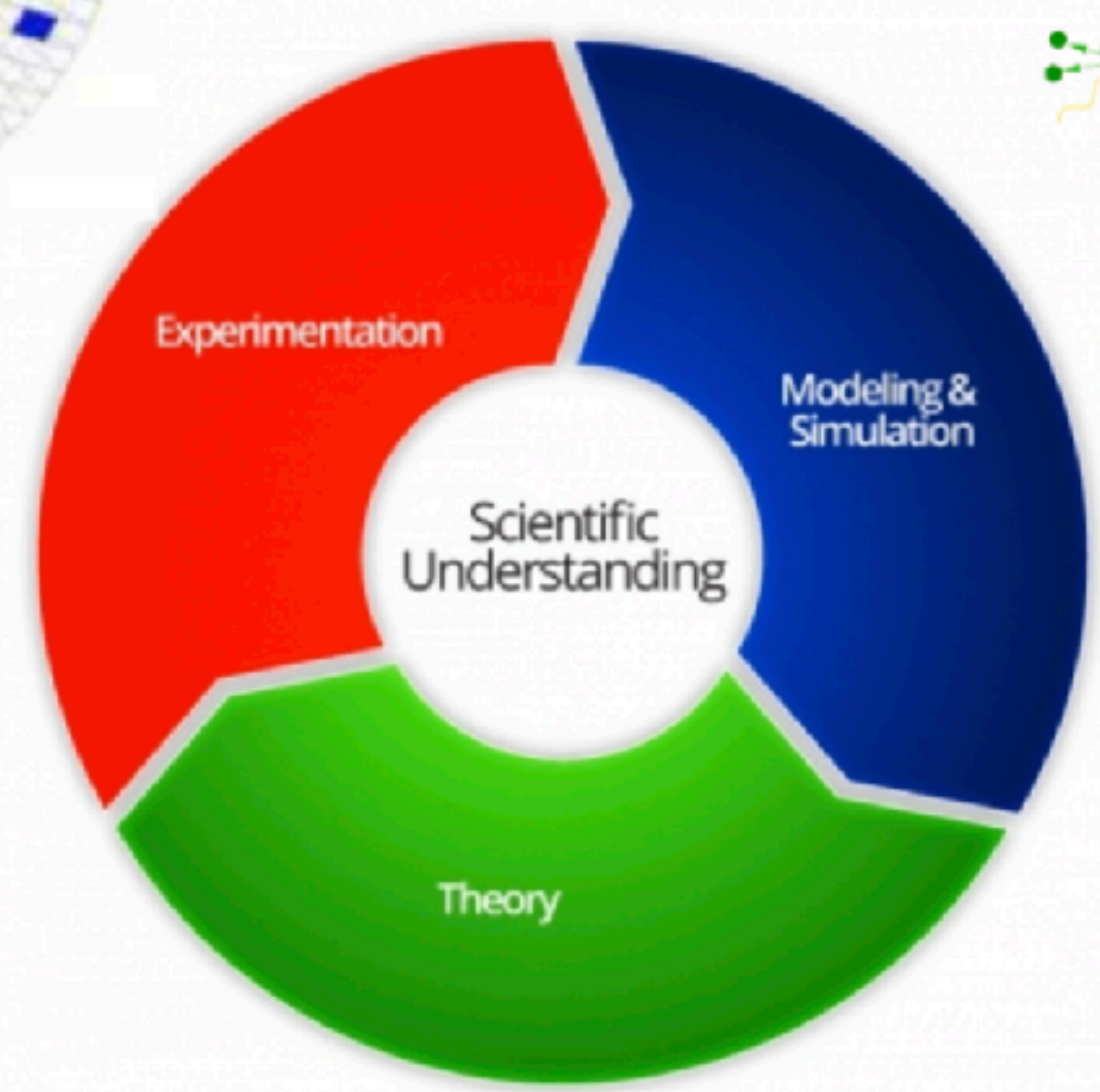
Some arguments to think the new physics to be around the weak scale ~ 1 TeV

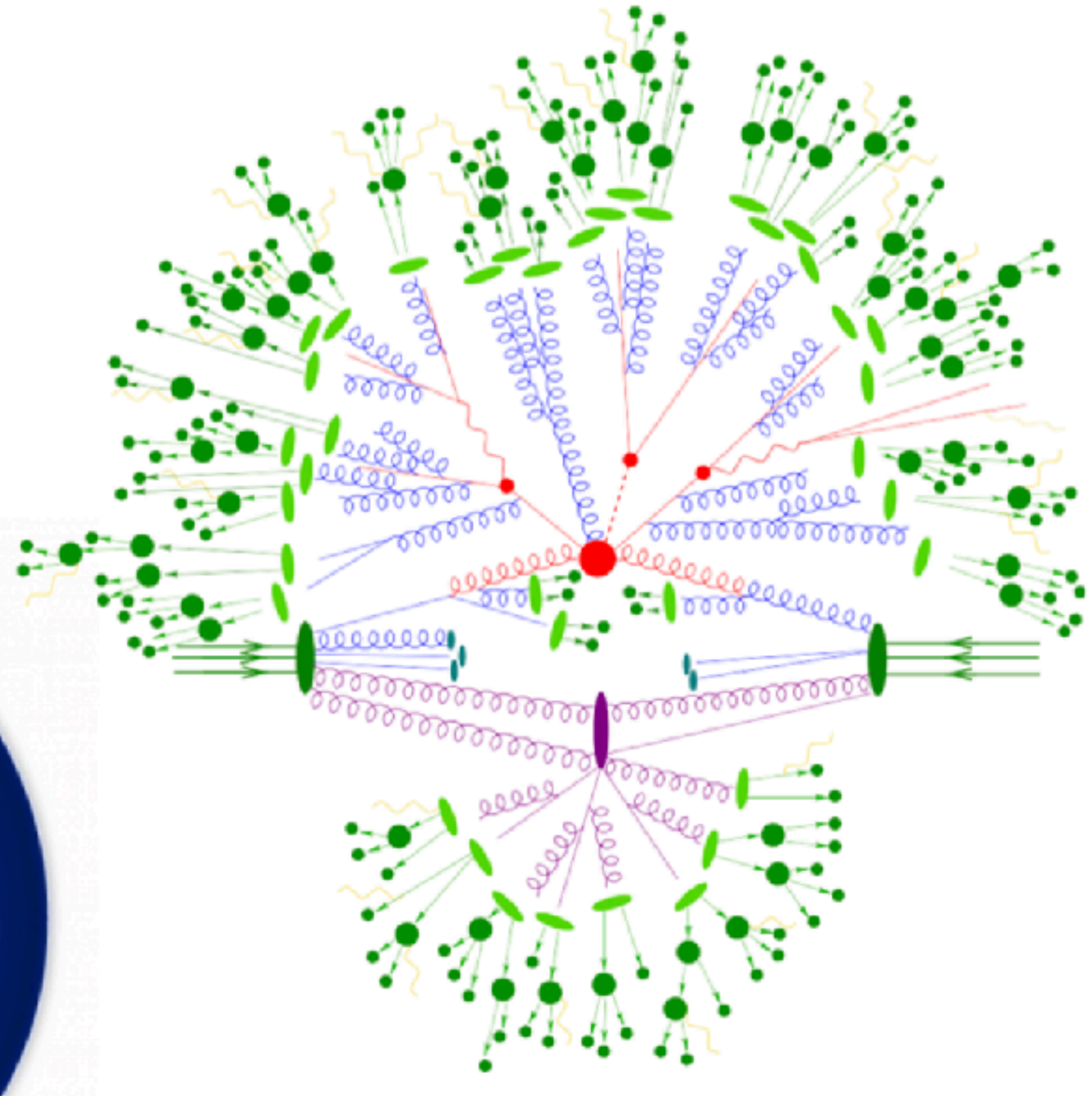
Strong motivation for a comprehensive exploration of the TeV-scale

Collider experiments

Connecting theory and experiment





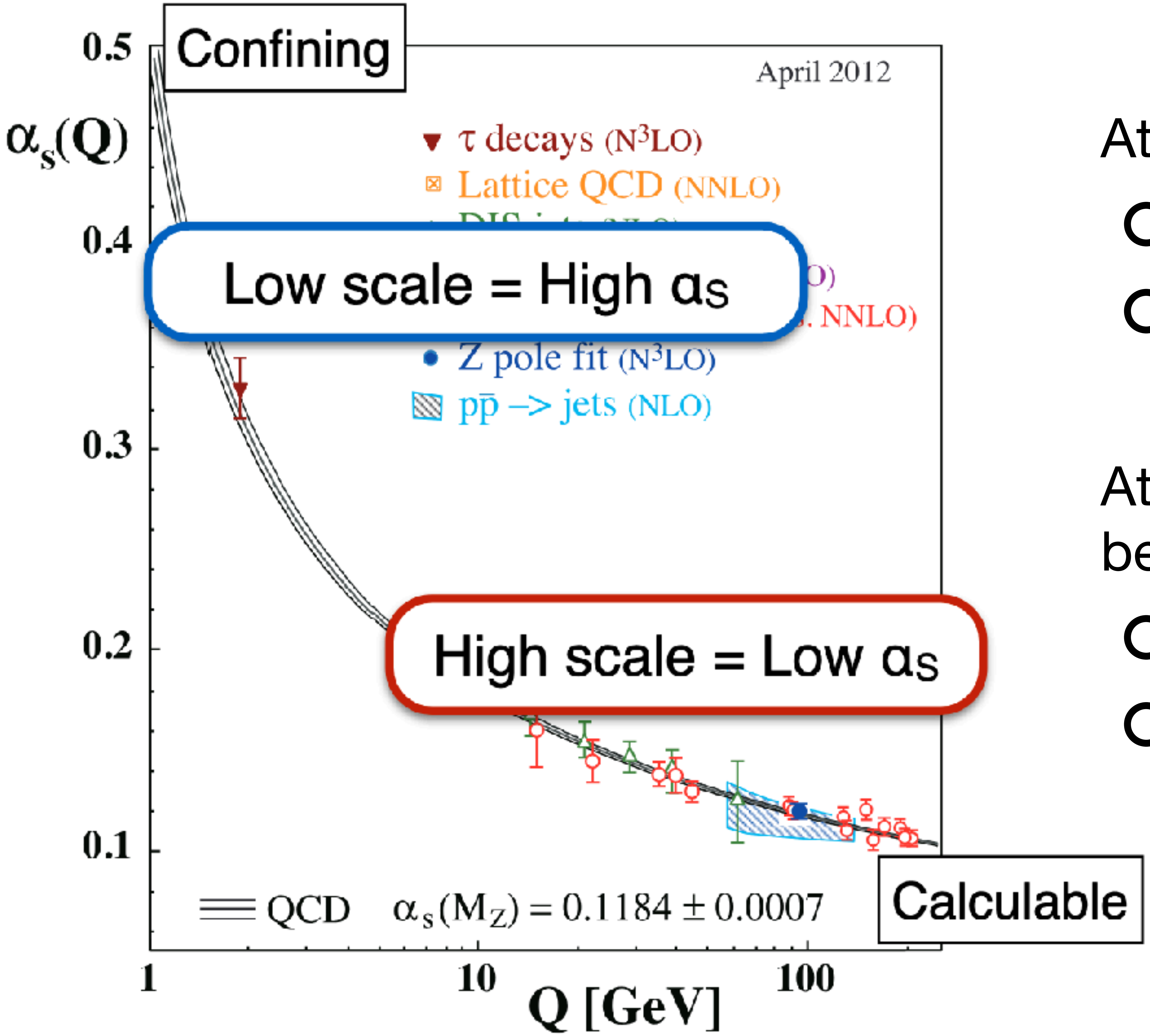


How can we get from the Standard Model lagrangian to simulated collision events?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + h.c.$$

An hierarchy of scales

- At hadron colliders most of the interesting dynamics due to the asymptotic freedom of Quantum Chromodynamics



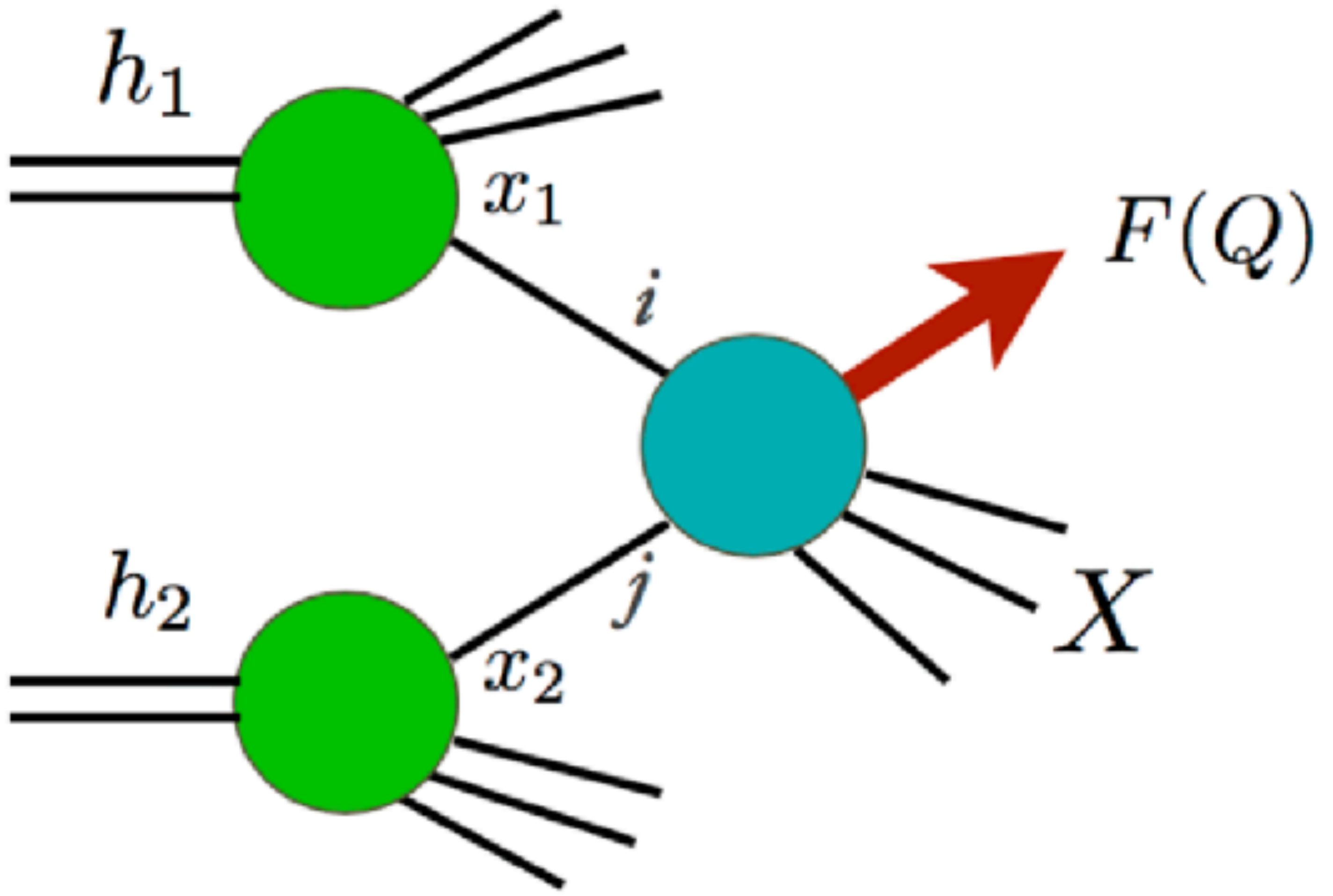
At low energy scales the strong coupling diverges

- Impossible to perform analytical calculations
- Physical degrees of freedom are the hadrons

At large momentum transfer the coupling strength becomes vanishingly small

- Allows the usage of perturbation theory
- Quarks and gluons are acceptable degrees of freedom

Collinear factorisation

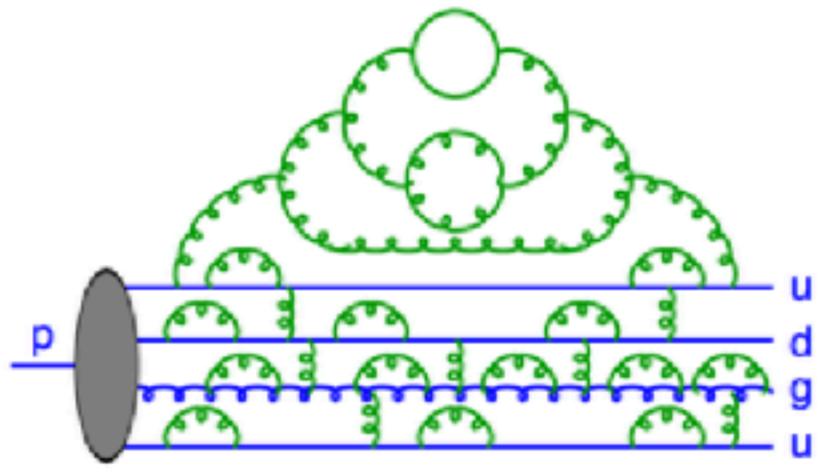


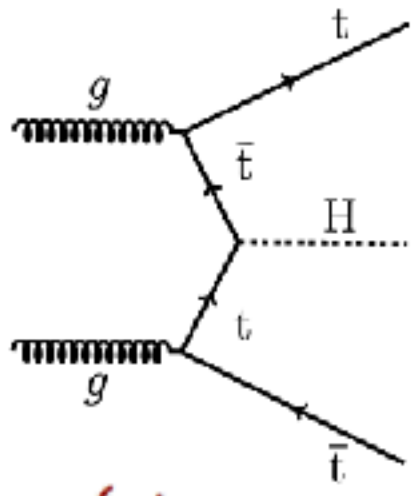
QCD is formulated in terms of quarks and gluons, but the protons we collide are composite objects, with a non-perturbative dynamic

The high-p_T interactions we are interested in are however characterised by the presence of a hard scale Q

⇨ They can be controlled through the ***factorisation theorem***

- The corresponding cross-section can be written as:





renormalisation scale

$$\sum_{a,b}\int dx_1 dx_2 d\Phi_{FS}\, f_a(x_1,\mu_F)\, f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral

Parton density functions

Parton-level cross section

factorisation scale

Predictions for hadronic cross section depend on knowledge of both σ_{ab} and $f(x,\mu_F)$

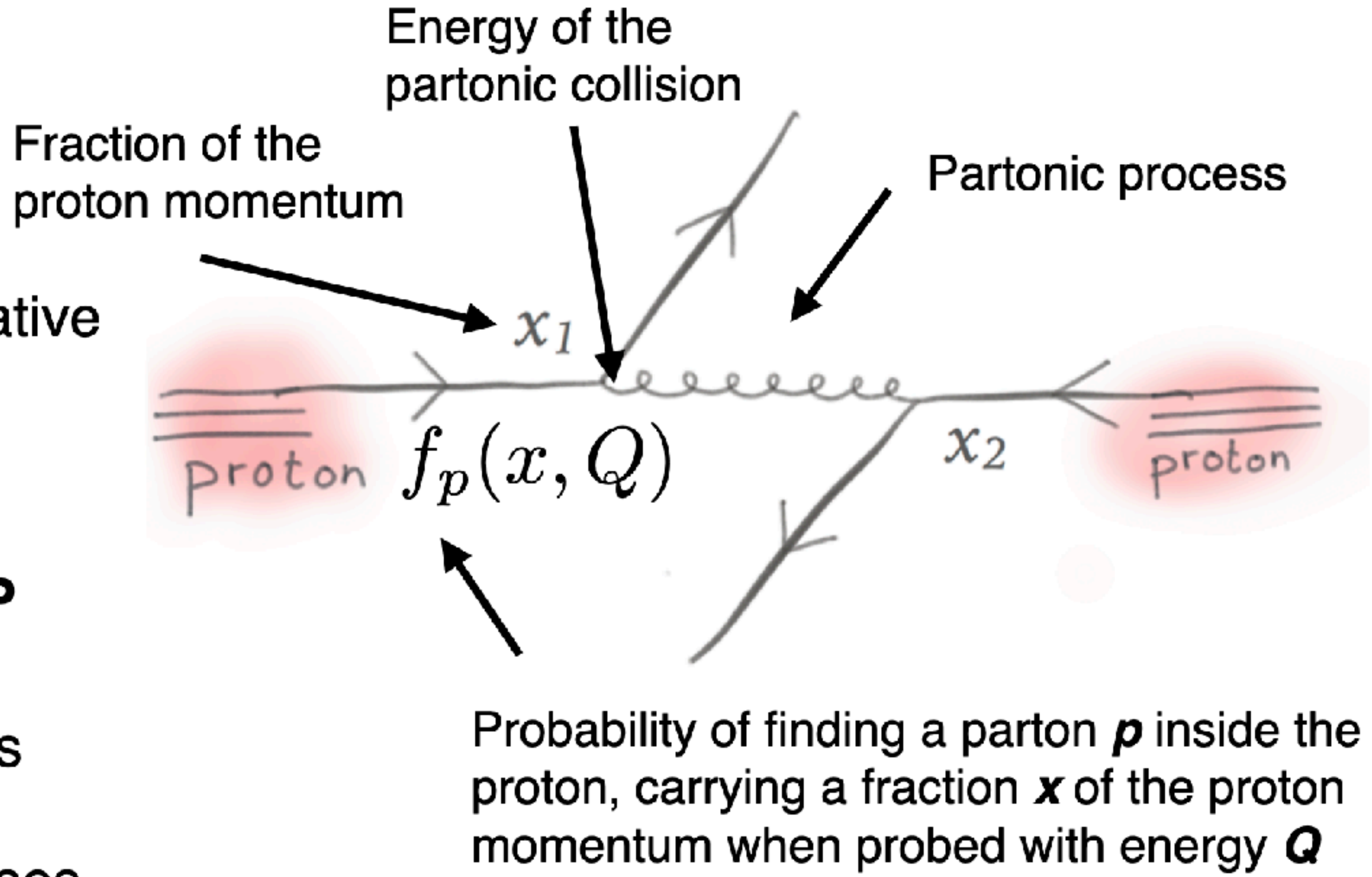
4

The Parton distribution functions

- ***Parton distribution functions*** parametrize our ignorance of what happens inside the proton below a given scale, μ_F
- How many quarks and gluons are there carrying a fraction *x* of the proton momentum?

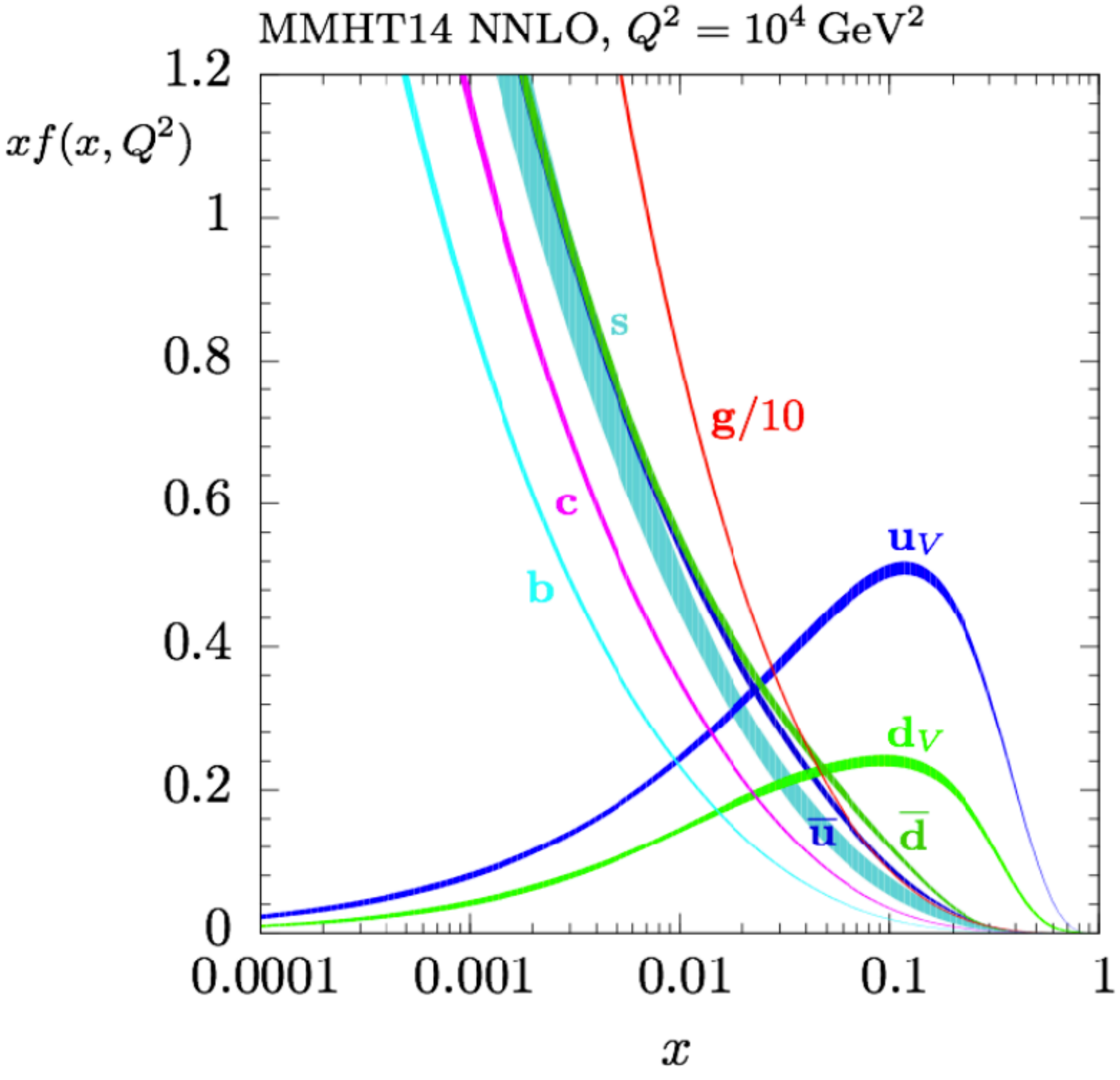
$$\sigma \propto f_{q/p}(x_1,\mu^2)\, f_{q/p}(x_2,\mu^2)$$

- The parton distributions are non-perturbative objects, they cannot be calculated analytically but need to be fitted to data
- However their scale evolution can be computed in perturbation theory (**DGLAP** equations)
- And the factorisation theorem guarantees universality: the PDFs extracted from a process can be used for different processes



The Parton distribution functions

- Valence u and d PDFs dominate at large x, about ~30 % of the proton momentum
- Sea quark takes ~20%, while remaining ~50% is in the gluons



PDFs Sum rules

Momentum sum rule

$$\sum_i \int_0^1 dx\, x f_i(x, Q^2) = 1$$

Flavour conservation sum rules

$$\int_0^1 (f_u(x, Q^2) - f_{\bar{u}}(x, Q^2))dx = 2$$

$$\int_0^1 (f_d(x, Q^2) - f_{\bar{d}}(x, Q^2))dx = 1$$

$$\int_0^1 (f_s(x, Q^2) - f_{\bar{s}}(x, Q^2))dx = 0$$

Hard cross-sections

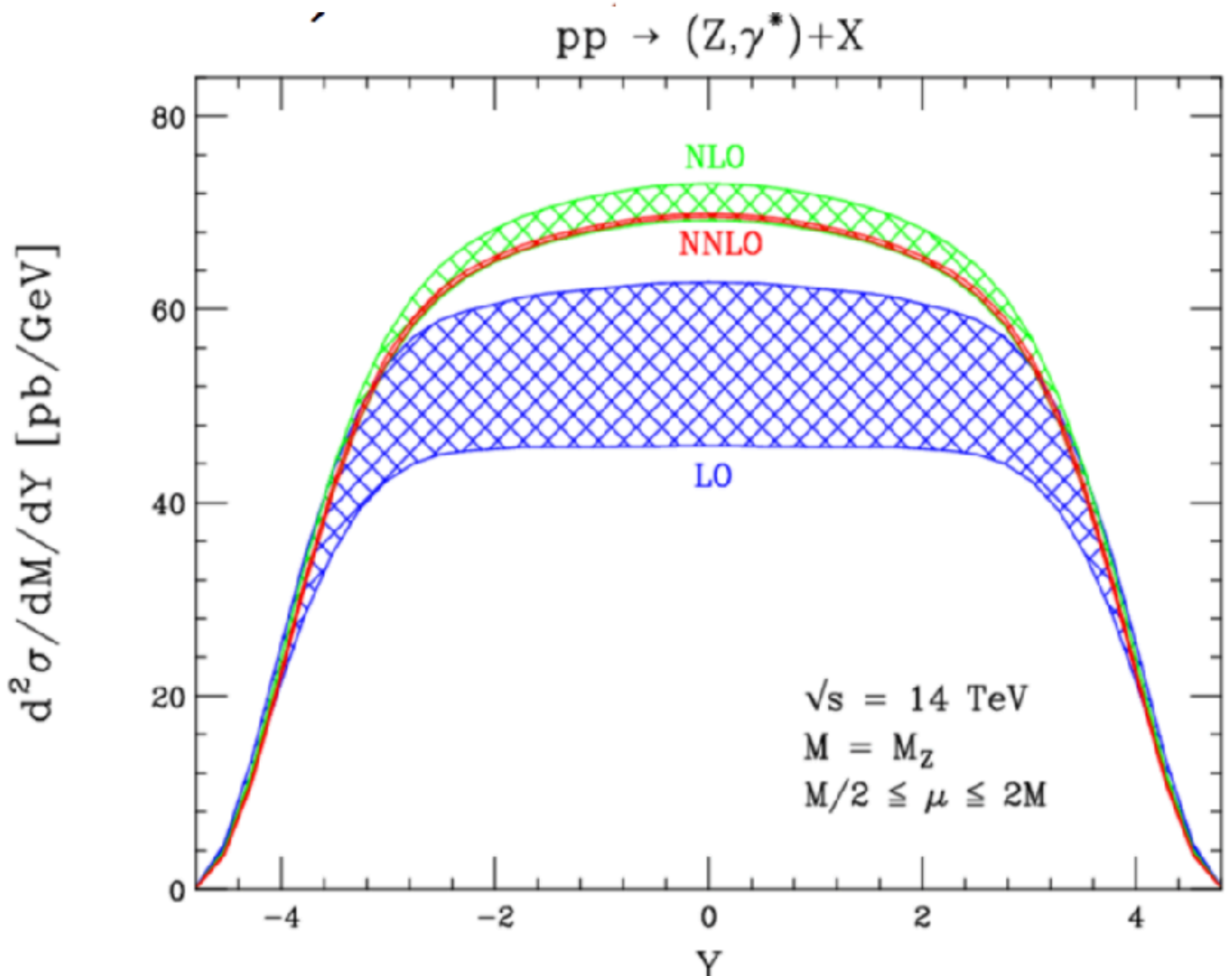
The ***partonic cross-section*** can be expressed as a series in powers of the strong coupling

$$\hat{\sigma} = \alpha_S^k \left(\hat{\sigma}^{(0)} + \frac{\alpha_S}{\pi} \hat{\sigma}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \hat{\sigma}^{(2)} + \dots \right)$$

The first non zero term in the series is the **Leading Order** (LO) which gives a first estimate of the cross-section

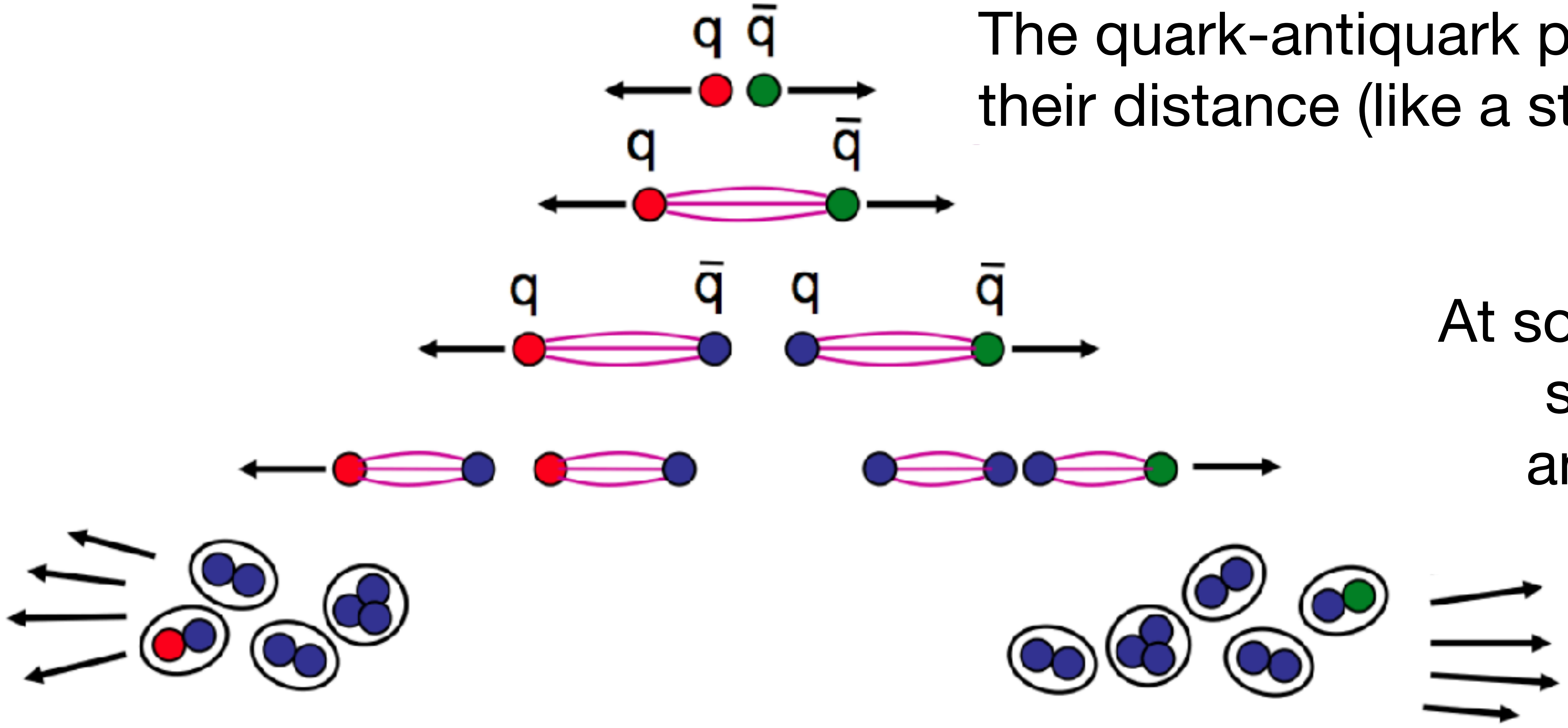
Next-to-Leading-Order (NLO): reduced dependence on the scale. First estimate of normalisation and shape of distributions

NNLO: percent level precision on the cross-section. Test the convergence of the perturbative series. Only available for few processes



Confinement and hadronization

- Quarks are not observed as free states: confinement



The quark-antiquark potential grows linearly with their distance (like a string being pulled)

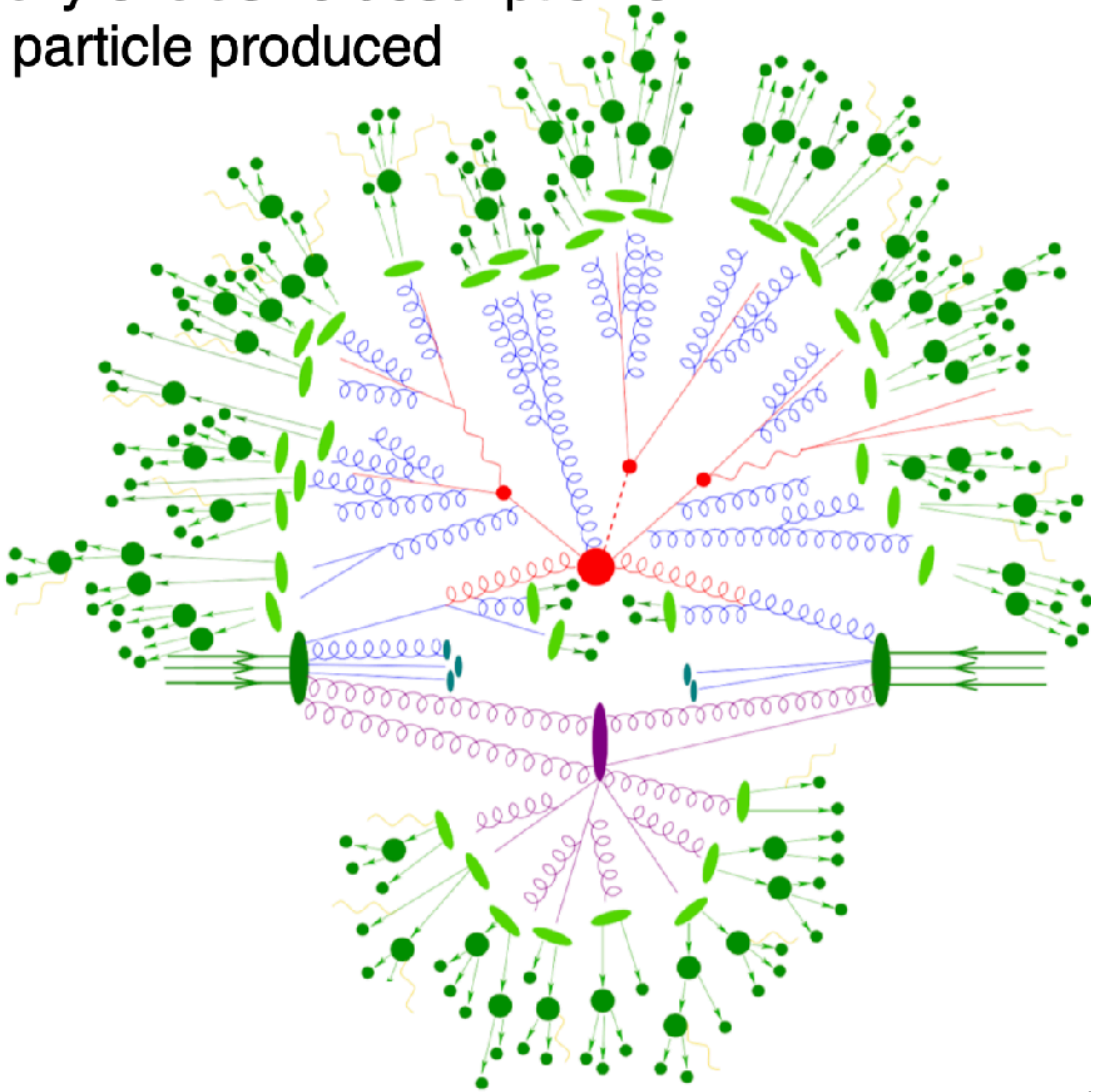
At some point the tension in the string is sufficient to release another quark-antiquark pair from the vacuum

The quark-antiquark pairs of low momentum form hadron bound states until all energy of the original quark is employed

This process is called hadronisation

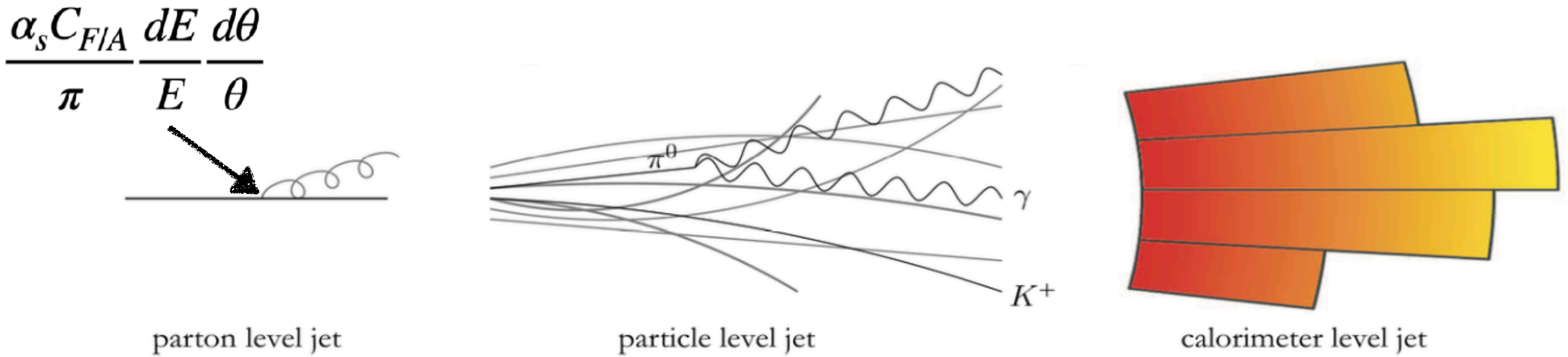
The anatomy of a collider event

Monte Carlo event generators provide a fully exclusive description of a collision event in terms of the final state particle produced

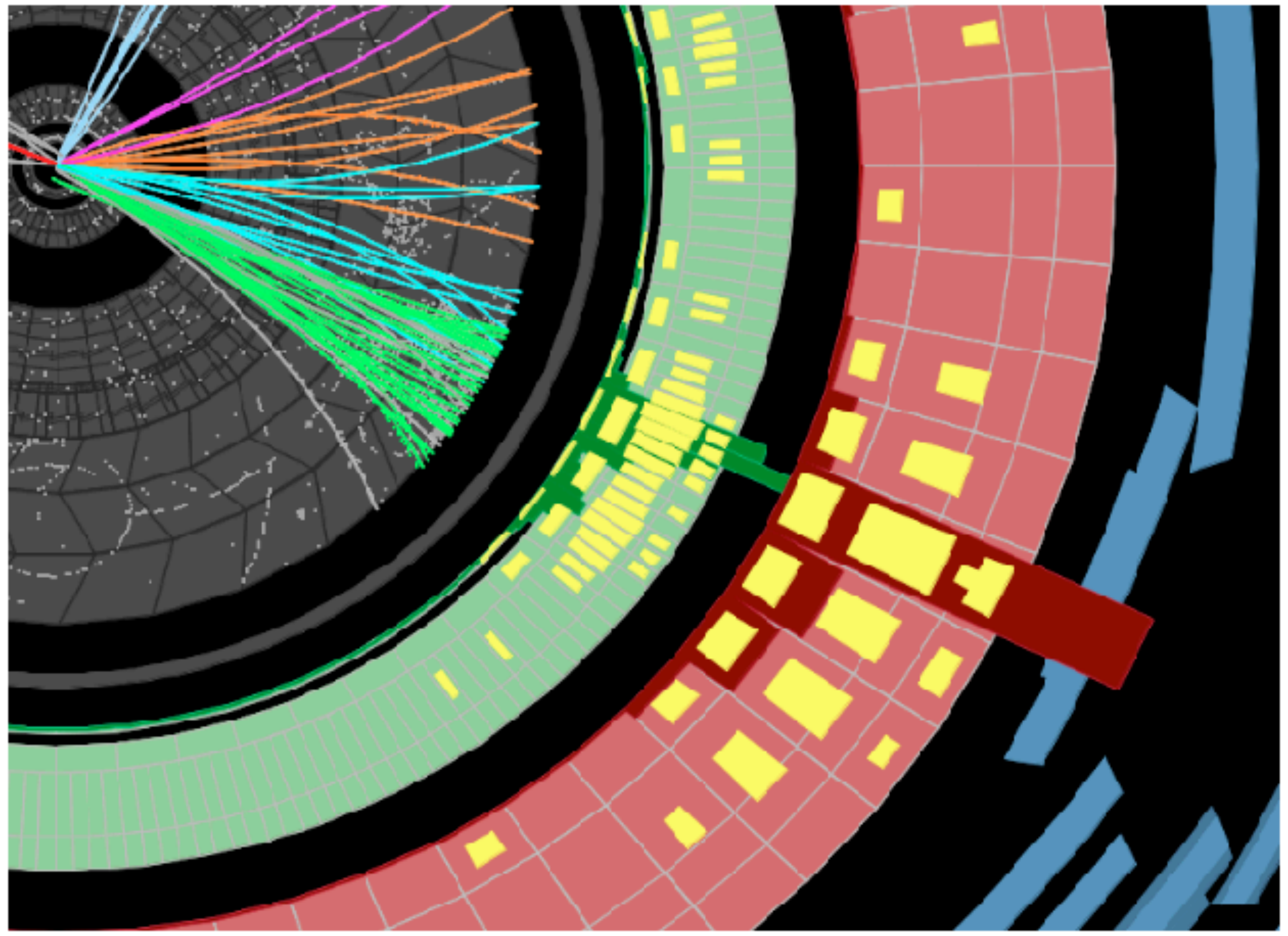


- Matrix Element (ME) generators simulate the central part of the event
- Parton Showers (PS) produce additional soft and collinear QCD radiation
- Multiple Interaction (MPI) models produce secondary hard interactions
- Fragmentation models the transition from QCD partons to the visible hadrons
- Hadrons can further decay into other detector stable particles
- Photon Emission generators simulate additional QED radiation

HADRONIC ACTIVITY AND JETS

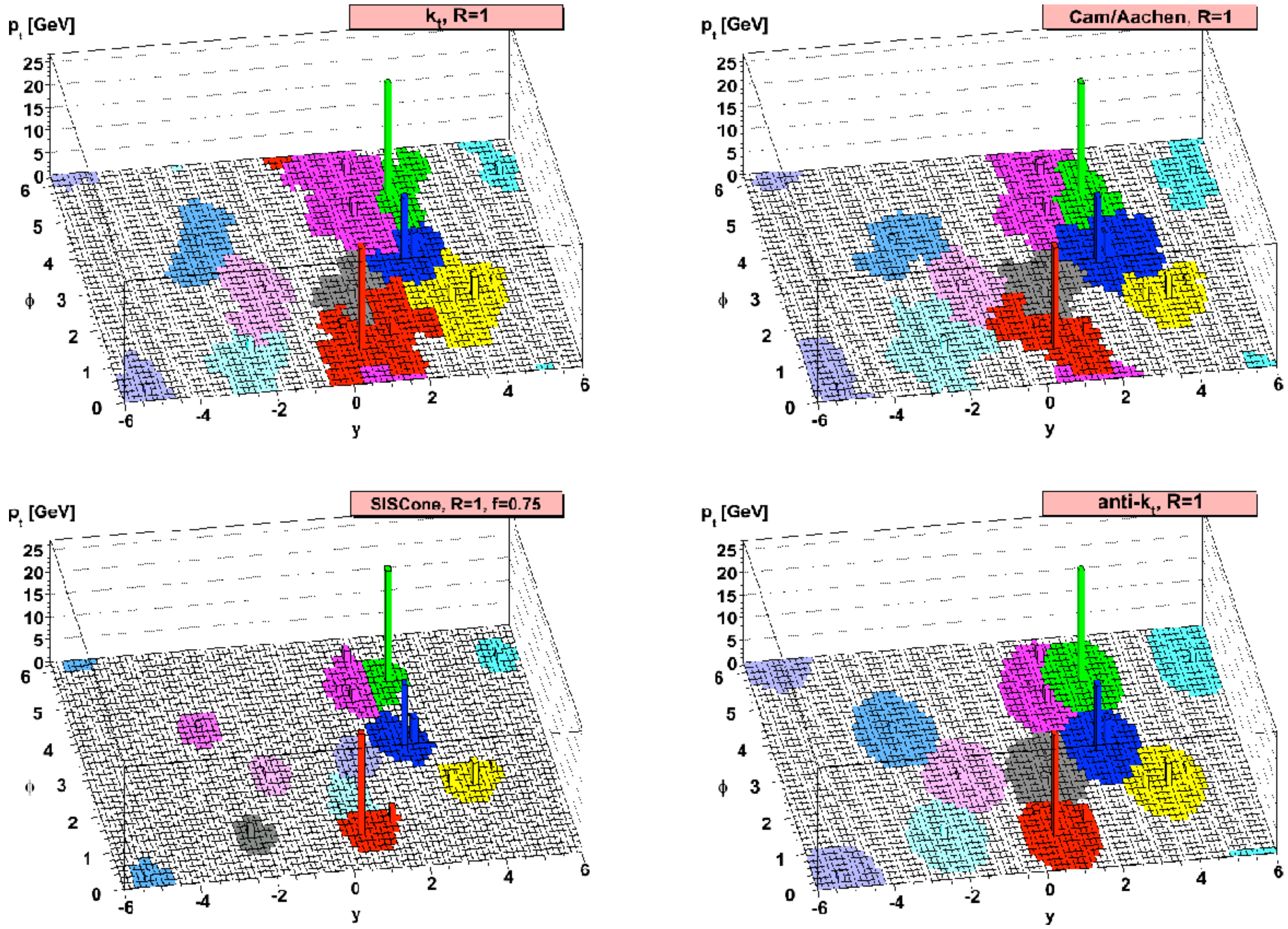


- Starting from an energetic quark a cascade of low energy and small angle gluons are produced, given a collimated spray of partons
- At the energy of the parton decreases, they will confine into hadrons keeping their overall direction
- We call this object an **hadronic jet**, essential to interpret hadronic final states



Jet algorithms comparison

- Require an operational definition that can be applied to theory calculation and to experimental data: a **jet algorithm**
- At the LHC, use the anti-kT algorithm, due to the circular jets it produces and being insensitive to pile-up



Monte Carlo event generators

PYTHIA (begun 1978)

Originated in hadronisation studies: Lund String model

Still significant emphasis on soft/non-perturbative physics

HERWIG (begun 1984)

Originated in coherence studies: angular-ordered showers

Cluster hadronisation as simple complement

SHERPA (begun ~2000)

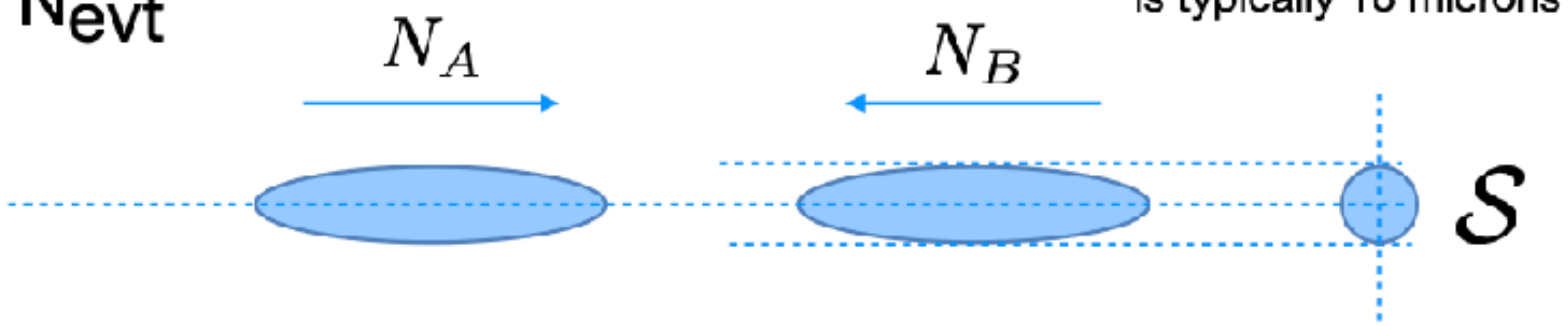
Originated in ME/PS matching (CKKW-L)

Own variant of cluster hadronisation

Cross-section and event rates

In HC experiments: measure the rate of events of a defined type N_{evt}

At LHC the transverse size is typically 16 microns



At LHC the longitudinal size is typically 5.6 cm

The rate of events can be predicted by:
- knowing the beam conditions
- Estimating the (hard scattering) cross section
- Estimating the reconstruction (experimental) efficientcy

The probability for a random particle A to collide with a random particle B yielding the defined type of event is: $\sigma/\mathcal{S}$

If NA and NB particles crossing each other per second within dt:

$$\frac{dN_{evts}}{dt} = N_A N_B \frac{\sigma}{\mathcal{S}} = \sigma\mathcal{L}$$

When beam collide with a revolution frequency f, the luminosity for two bunches colliding (always the same)

$$\mathcal{L} = \frac{f N_p^2}{4\pi\sigma_x\sigma_y}$$

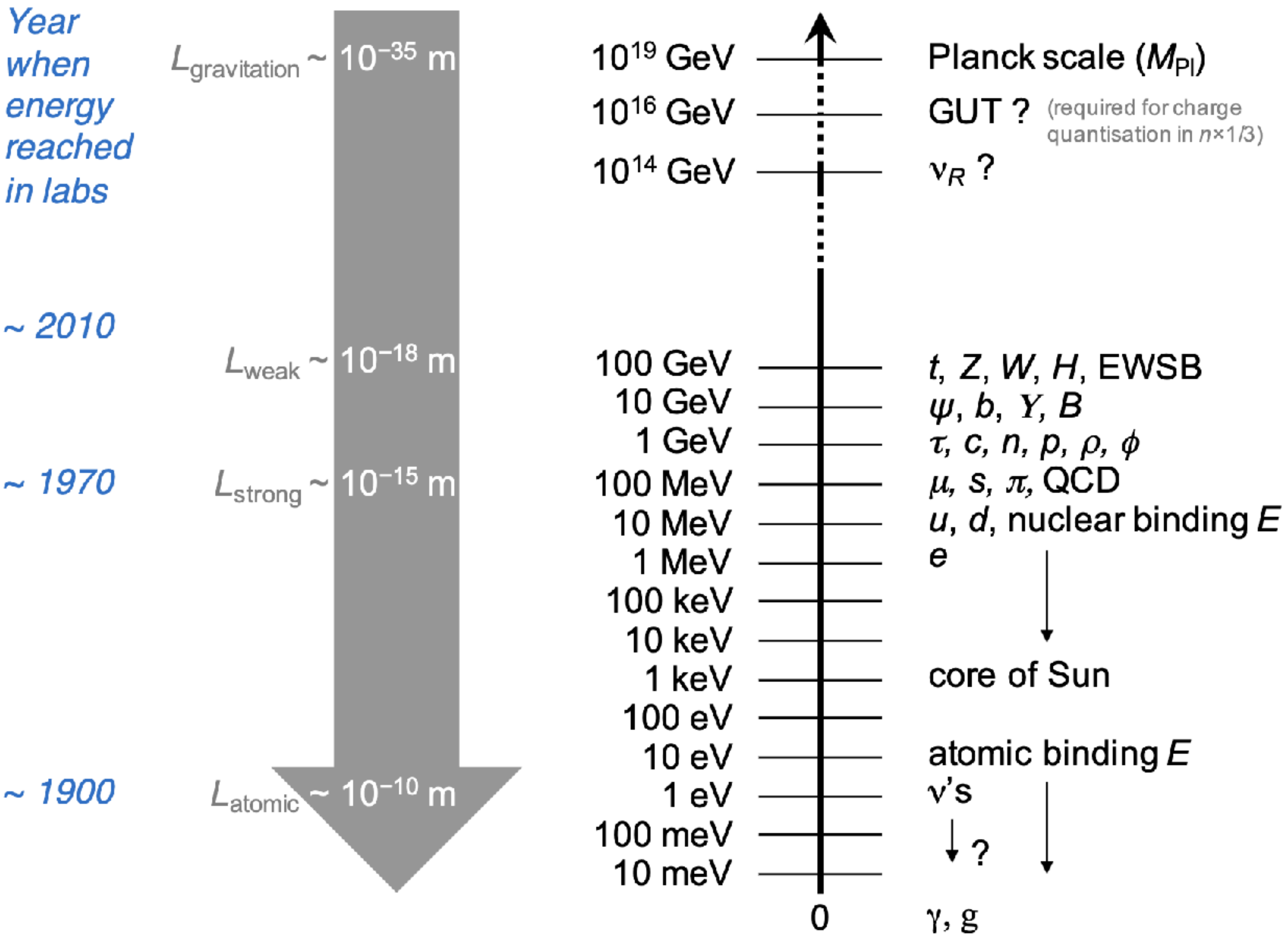
Not trivial (comes from the double integral of gaussian profiles)

σ_x and σ_y are the transverse dimensions of the beam at the interaction point. At the LHC the beams are symmetric with a size of 16 μm.

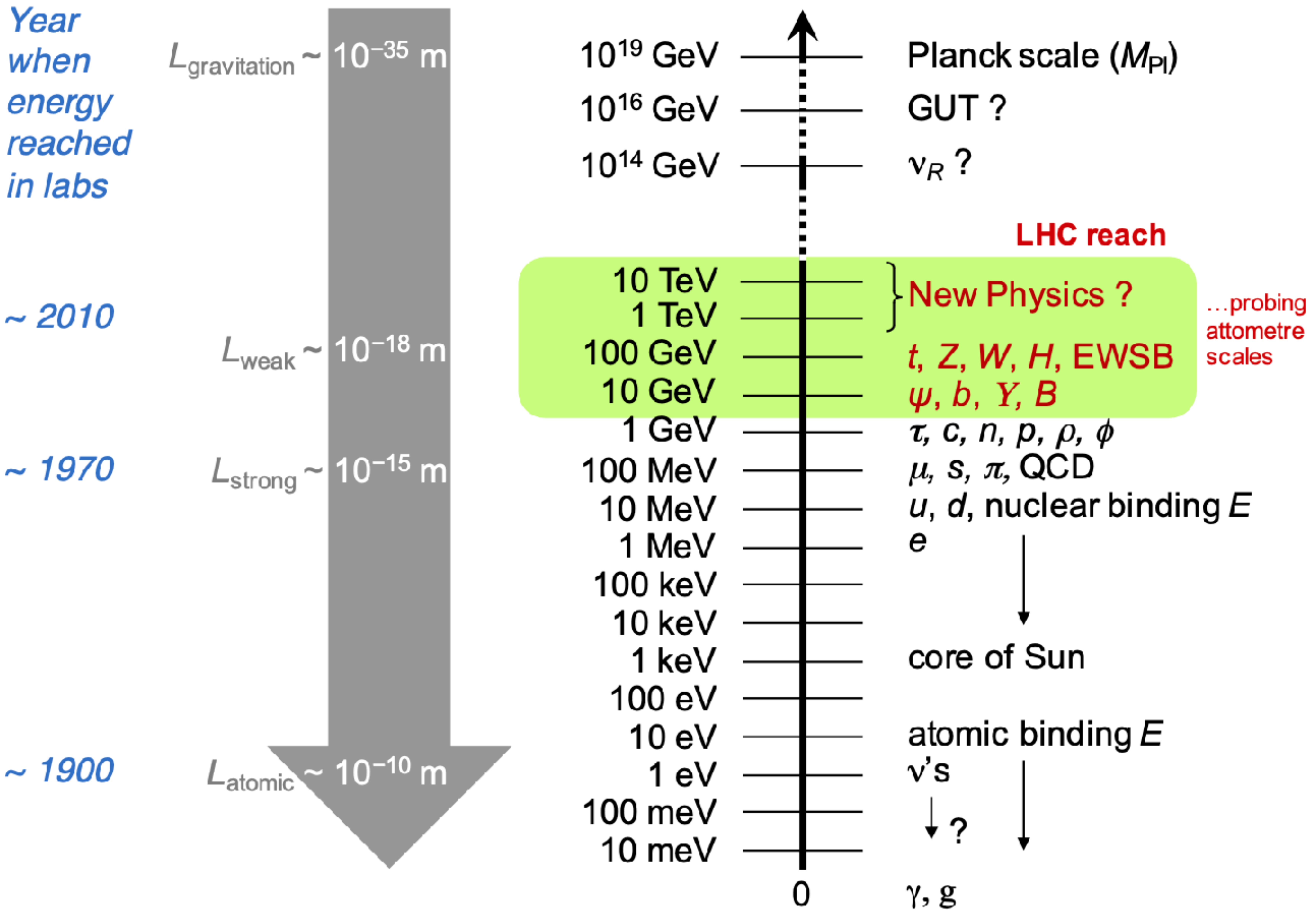
For bunches with equal average number of protons per bunch (Np)

- f is precisely known.
- Np is known precisely through beam current measurements

Energy Scales

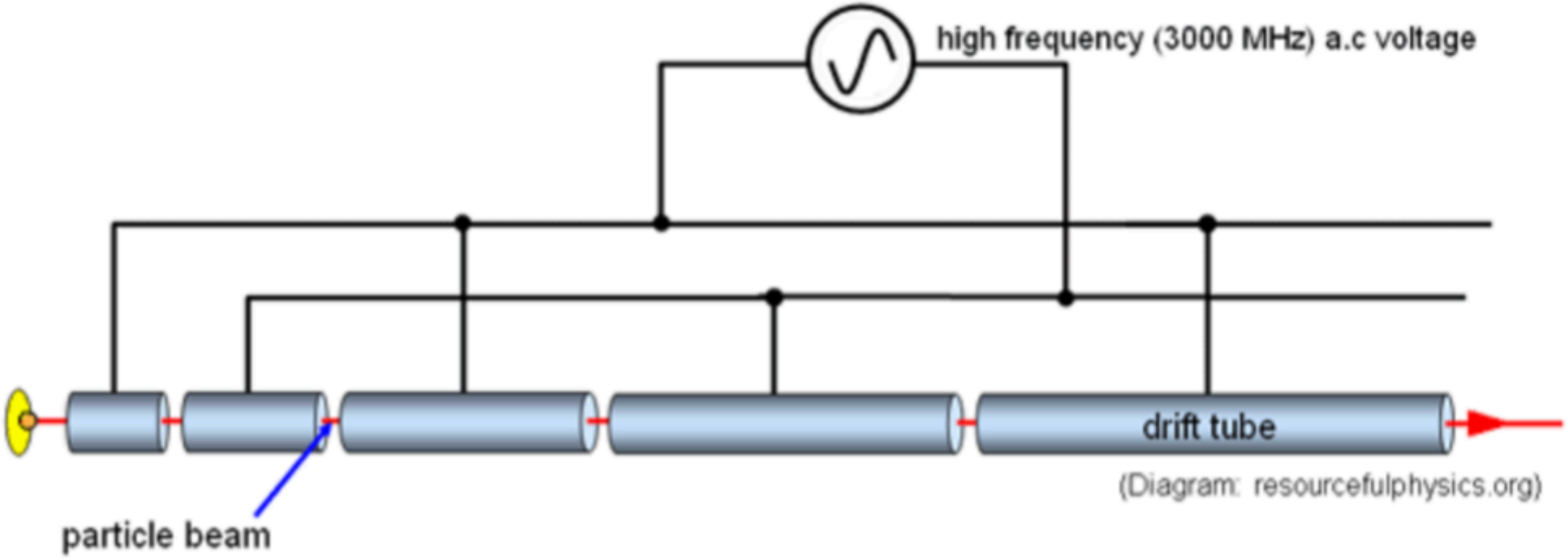


Energy Scales



Linear Colliders

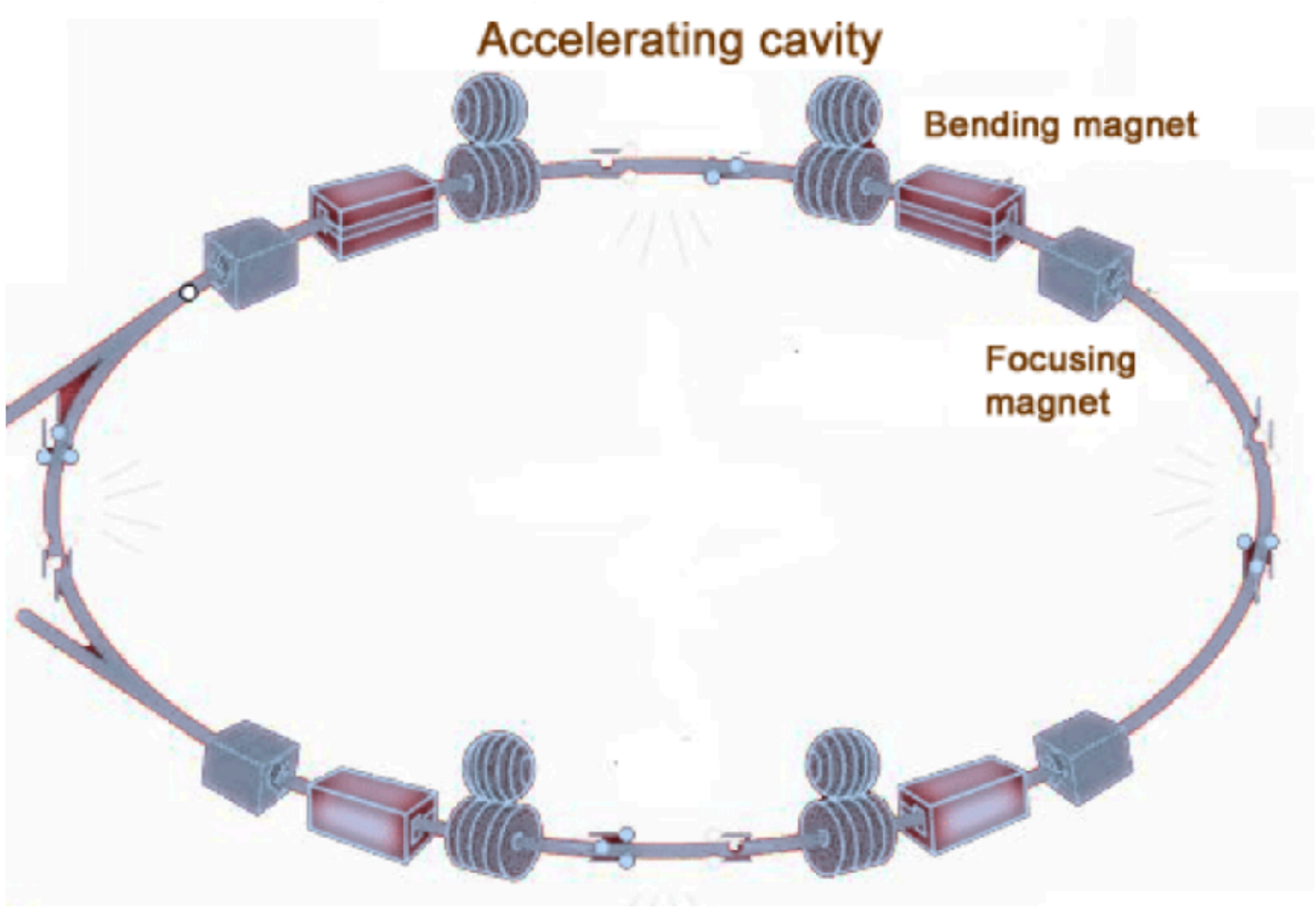
- To produce and discover heavy new particles, we need high E_{CM}
  Need to collide massive particles at high energies!
- Accelerate charged particles using RF high-voltage



- Energy gained at each application of the electric field $\Delta E = qV$
- Limited by physical space! SLAC 3.2 Km long, reached E_e=50 Gev

Circular Colliders

- Accelerate charged particles using RF high-voltage
- Curve the beam trajectory using bending magnets



High power magnets needed

$$B = \frac{p[\,\mathrm{GeV}]}{0.3r[\mathrm{m}]}$$

Limited by synchrotron radiation

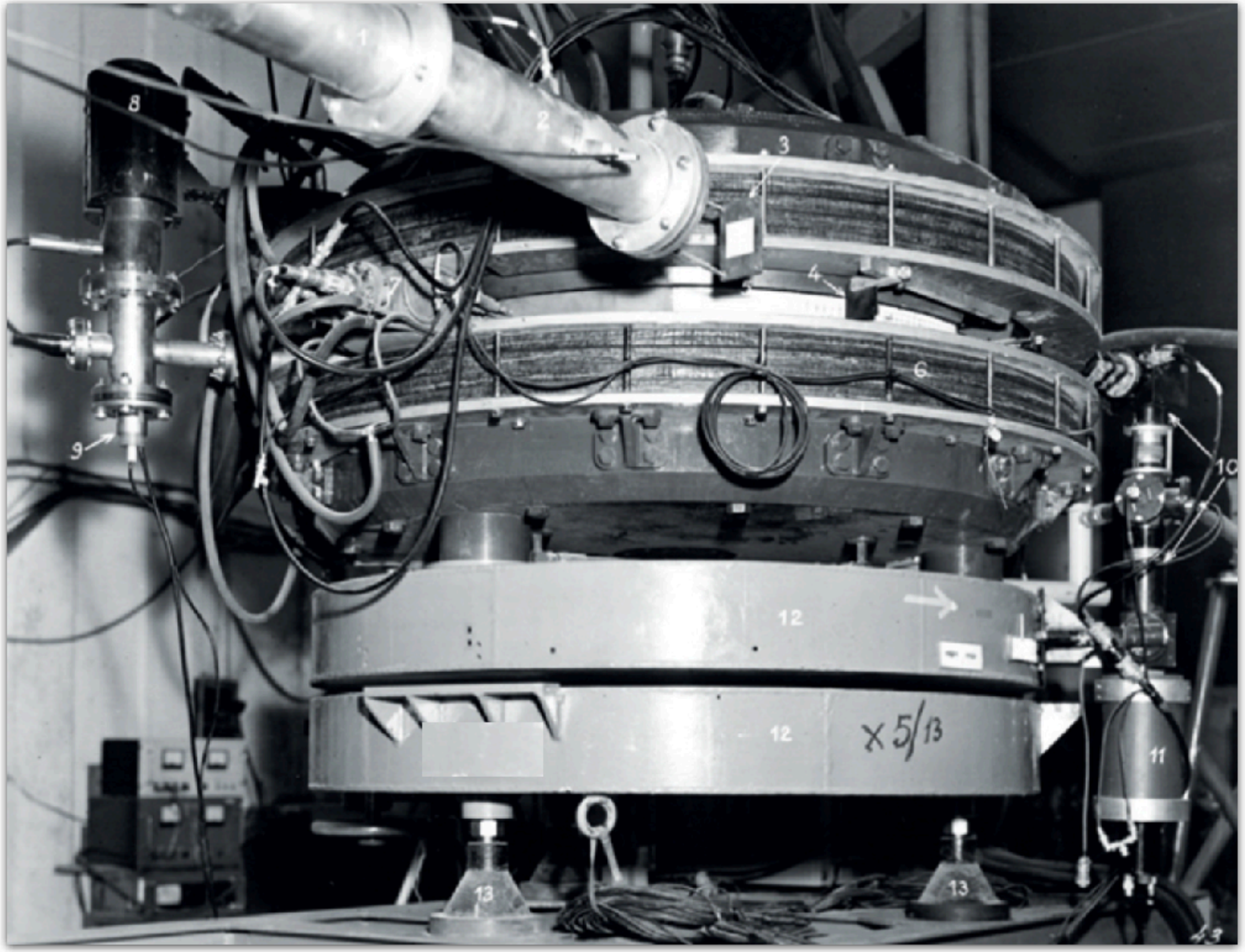
$$\text{radiated energy per orbit} = \frac{E^4}{m^4 r}$$

Circular Colliders

$$10^{-19}\ \mathrm{m}$$

Our **direct** knowledge of nature at the smallest scales relies mostly on colliders.

The first collider (AdA – Anello di Accumulazione) was built in 1961 in Frascati (then at LAL), had a radius of 3 meters and collided electrons and positrons at a centre-of-mass energy of 500 MeV.

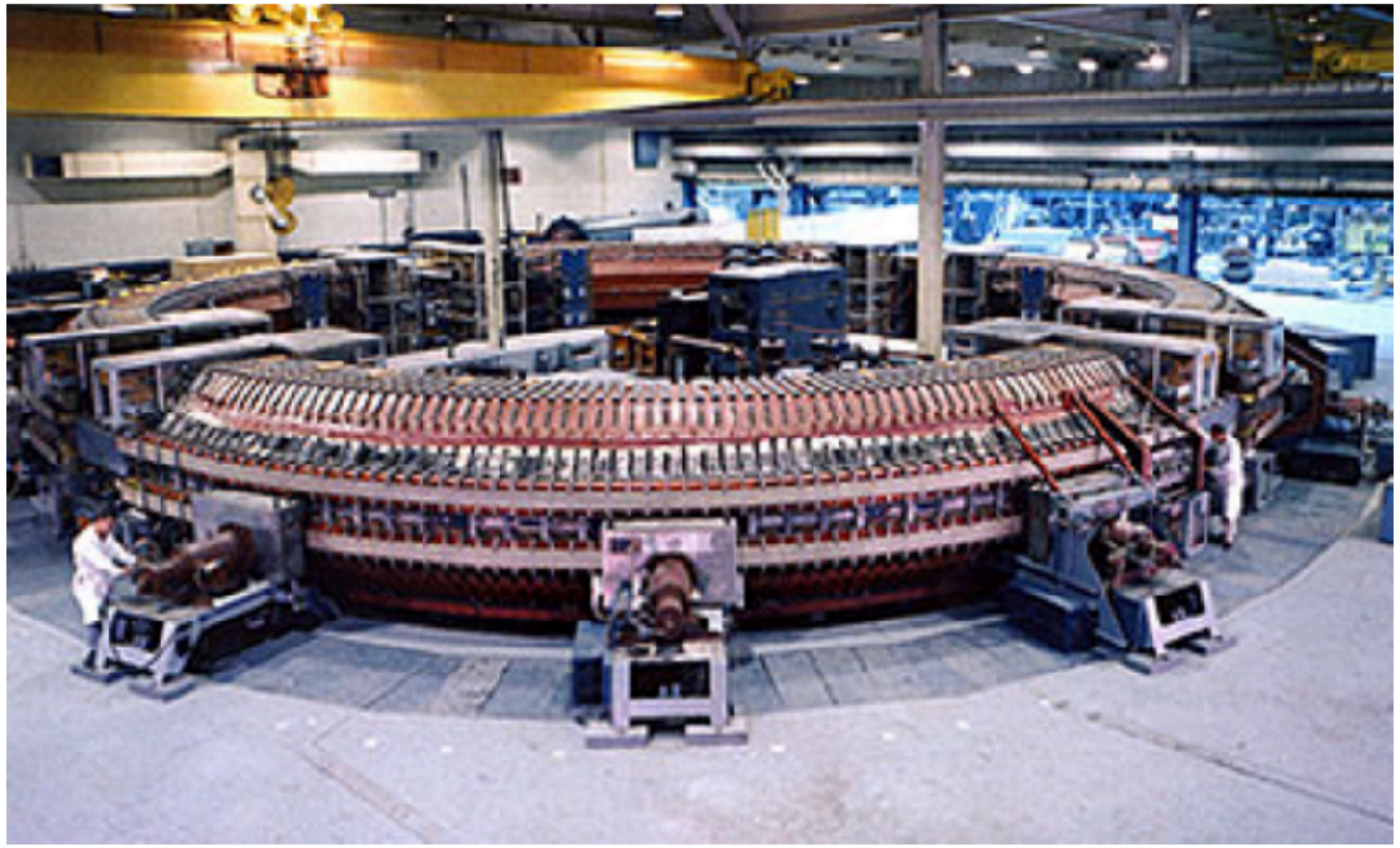


The Standard Model of particle physics and colliders started approximately at the same time.

The birth of the Standard model can be roughly dated in 1957-1959, and required 5 decades to be really completed.

The precursors

Cosmotron - BNL - 1952-1966
First accelerator beyond the GeV scale



Bevatron - LBNL - 1954-1993
Billions of electron volts (6.5 GeV/beam)

But only colliding in fixed-target modes

Colliders kinematics

Fixed Target Collision

$$\overset{\longrightarrow}{p_1 = (E_1, \vec{p}_1)} \quad \overset{\cdot}{p_2 = (m_2, 0)}$$

$$s = m_1^2 + m_2^2 + 2E_1 m_2$$

$$\text{For } E_1 \gg m_1, m_2$$

$$s \sim 2E_1 m_2 \quad \Rightarrow \quad \sqrt{s} \sim \sqrt{2E_1 m_2}$$

e.g. 450 GeV proton hitting a proton at rest:

$$\sqrt{s} \sim \sqrt{2 \times 450 \times 1} \sim 30 \text{ GeV}$$

Collider Experiment

$$\overset{\longrightarrow}{p_1 = (E_1, \vec{p}_1)} \quad \cdot \quad \overset{\longleftarrow}{p_2 = (E_2, \vec{p}_2)}$$

$$s = m_1^2 + m_2^2 + 2(E_1 E_2 - |\vec{p}_1||\vec{p}_2| \cos\theta)$$

$$\text{For } E_1 \gg m_1, m_2 \quad |\vec{p}| = E, \quad \theta = \pi$$

$$s = 2(E^2 - E^2 \cos\theta) = 4E^2 \Rightarrow \sqrt{s} = 2E$$

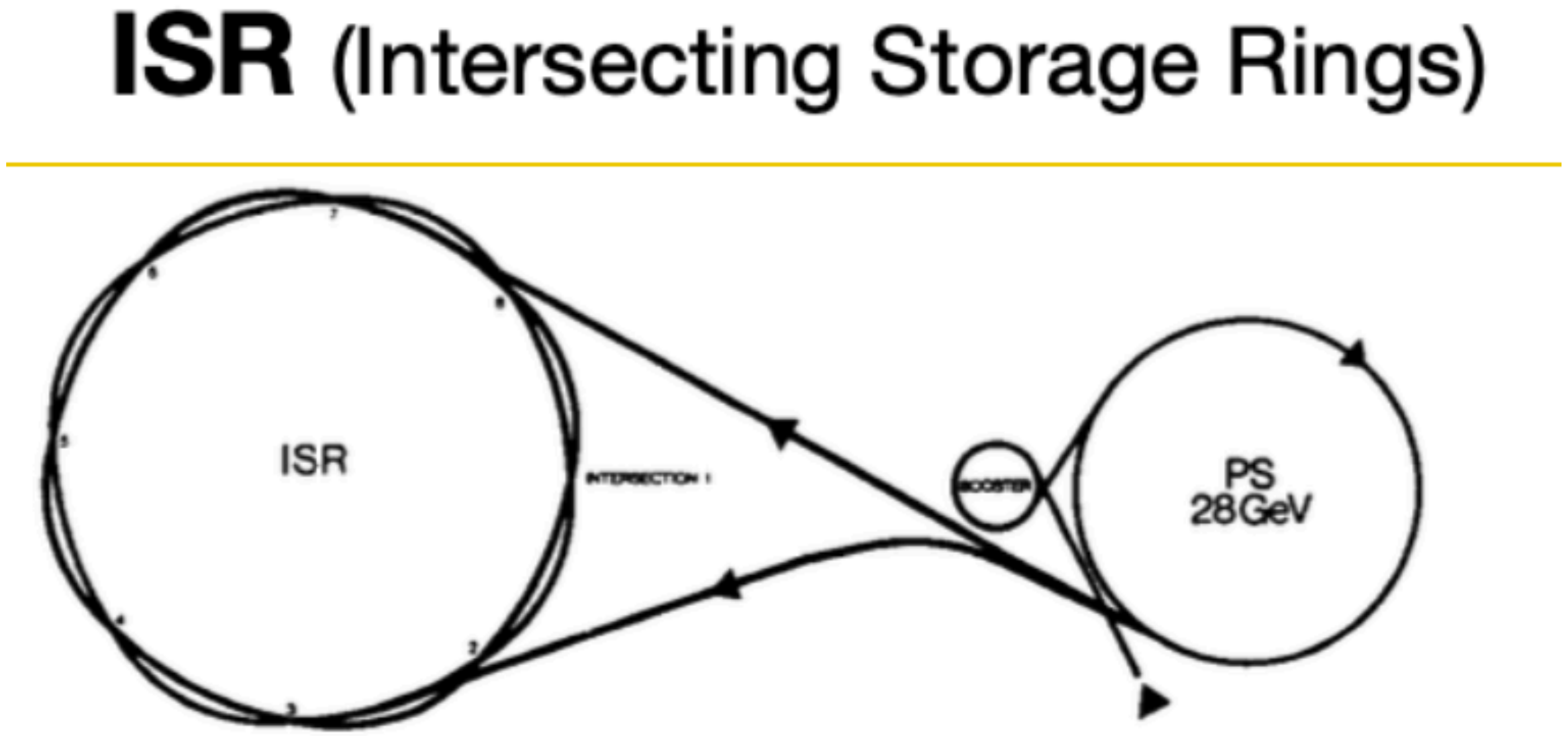
e.g. 450 GeV proton colliding with a 450 GeV proton:

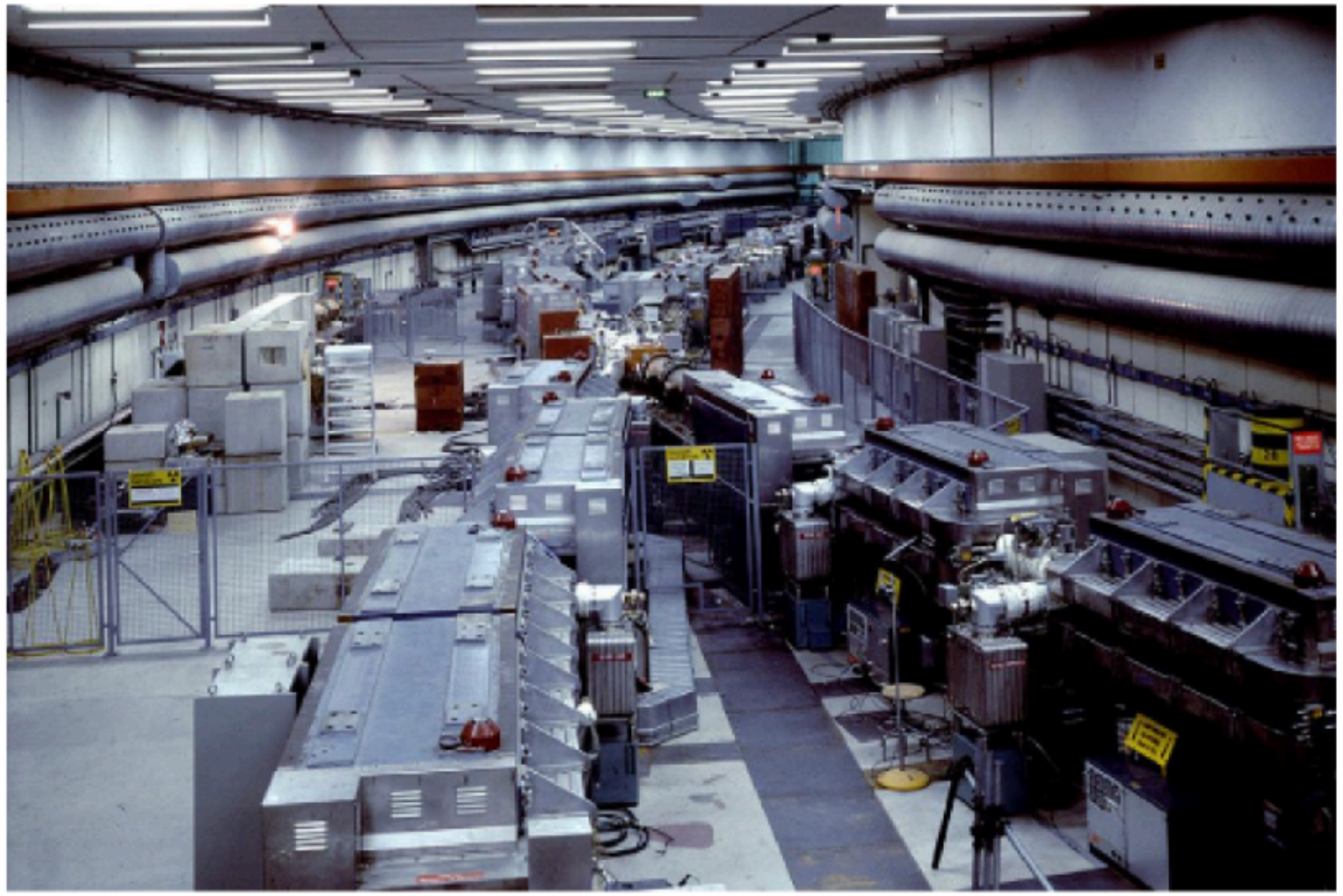
$$\sqrt{s} \sim 2 \times 450 = 900 \text{ GeV}$$

In a fixed-target experiment most of the proton's energy is wasted to boost the final state rather than being converted into interesting particles

Intersecting Storage Rings

CERN 1971 - 1984
proton-proton collisions at 62 GeV





Enough energy to produce the J/ψ and hadronic jets,
but experiments were instrumenting only the forward region

Hadron colliders

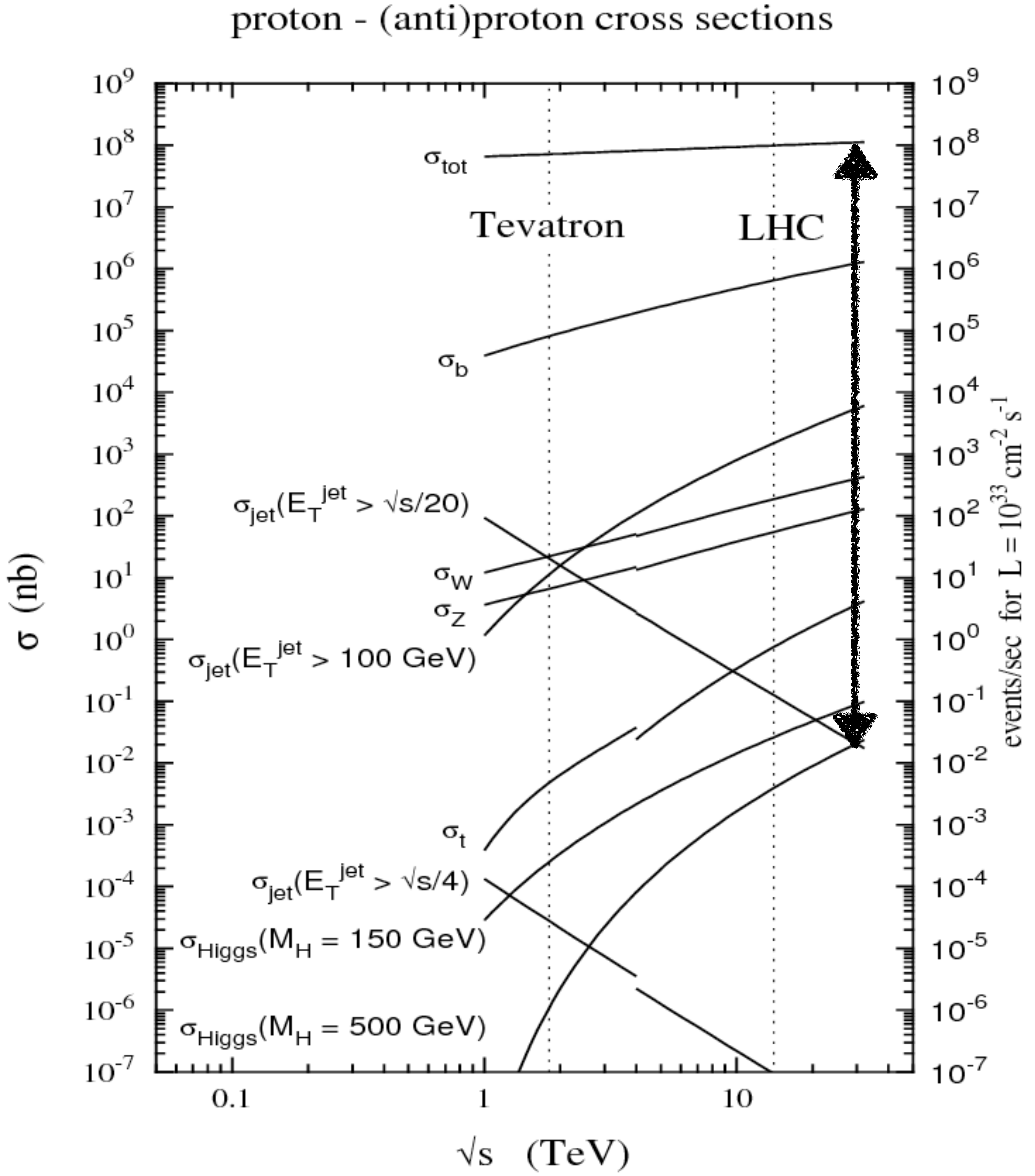
Accelerator	Location	Operations	Characteristics	Beam E	Highlights/discoveries
ISR	CERN	1971-1984	Circular rings 948m	31 GeV	Sufficient COM but not sufficient EXP coverage to observe J/Psi and Upsilon (unfortunately)
SPS-SppS	CERN	1981-1984	Circular 6.9km proton/anti-proton	315 GeV	W and Z bosons (1981)
TeVatron	Fermilab	1992-2011	Circular 6.3km proton/anti-proton	900 GeV	Top quark (1994)
RHIC	Brookhaven	Since 2001	Hexagonal rings 3.8km	100 GeV	Probing QGP
LHC	CERN	Since 2008	LEP Tunnel	8500 GeV	Higgs boson 2012

Cross-sections at Hadron colliders

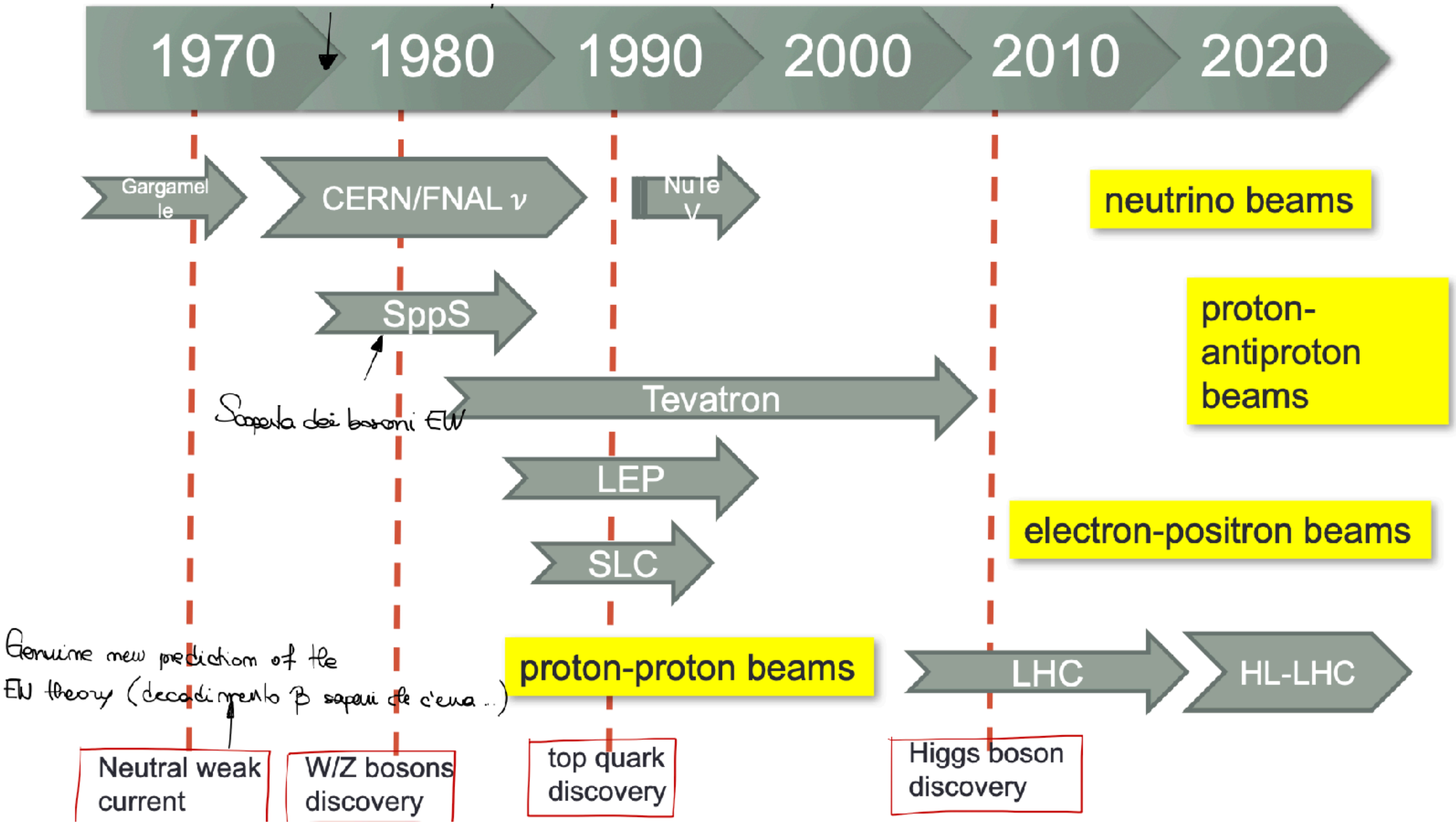
At the design luminosities (10^{34} cm^{-2} s^{-2}) the LHC produces

- Any event: 109/second
- W bosons: 103/second
- Top quarks: 10/second
- Higgs: 0.1/second

Need to detect and reconstruct the product of the collision to deduce the process

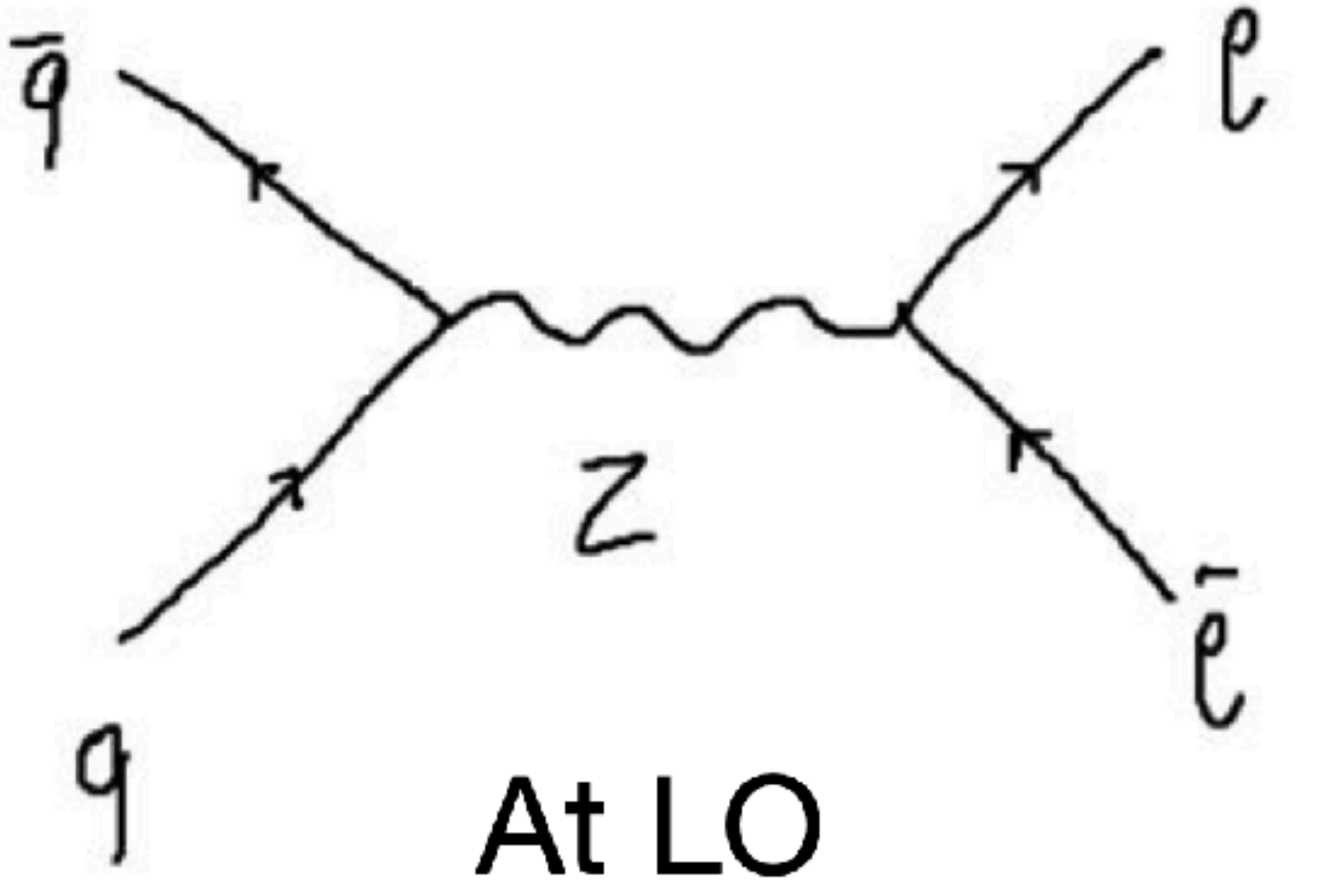


Testing the SM at colliders



Discovering the W and Z bosons

Production of W and Z at a $p\bar{p}$ collider proceeds as a result of $q\bar{q}$ annihilation $\bar{d}u \to W^+$, $d\bar{u} \to W^-$, $u\bar{u} \to Z$, $d\bar{d} \to Z$



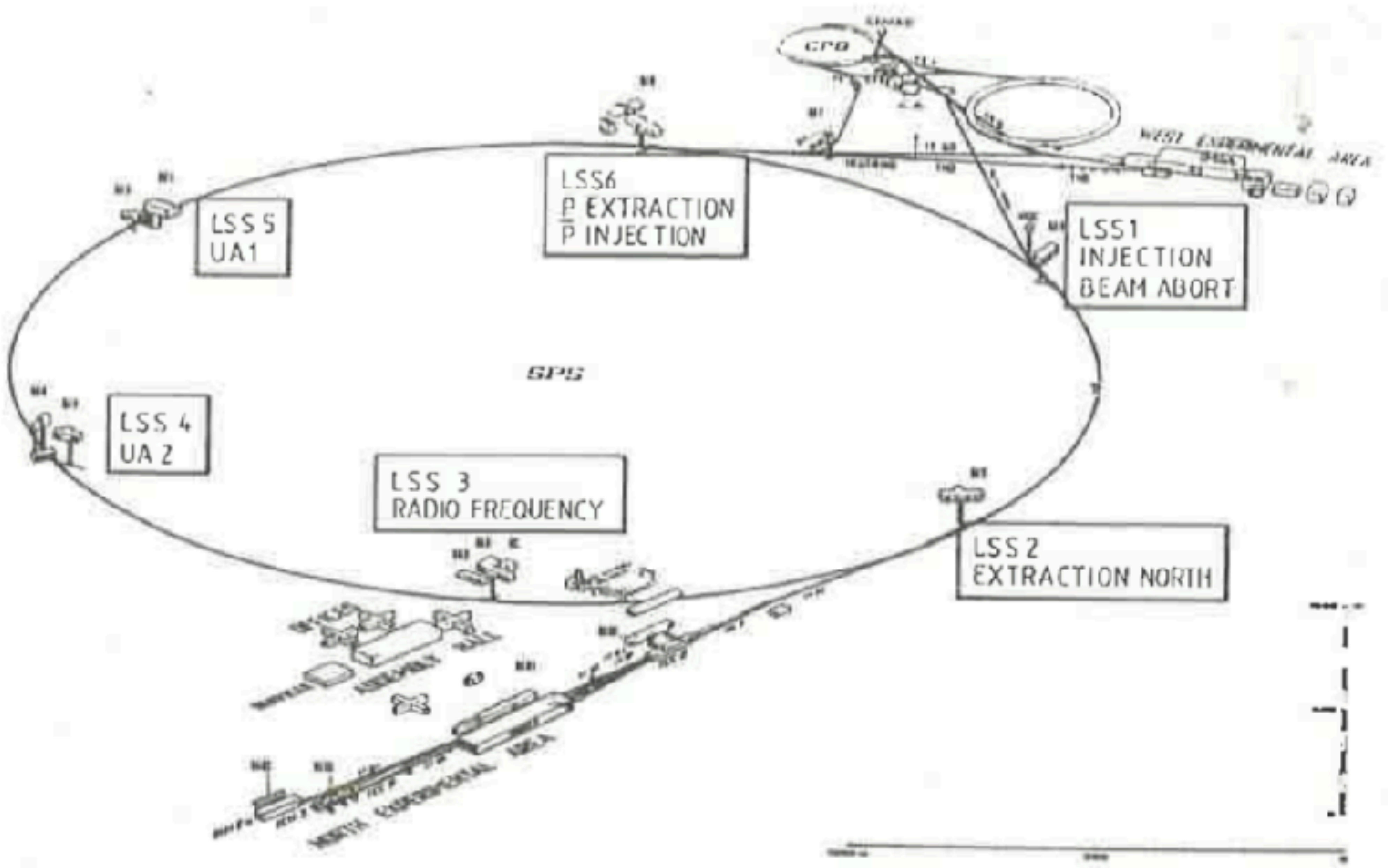
- ~ 50% of the momentum of a high-energy proton is carried, by three valence quarks, the remainder by gluons. A valence quark carries about 1/6 of the proton momentum
- W and Z production require a pp collider with a centre-of-mass energy of about six times the boson mass: 500–600 GeV

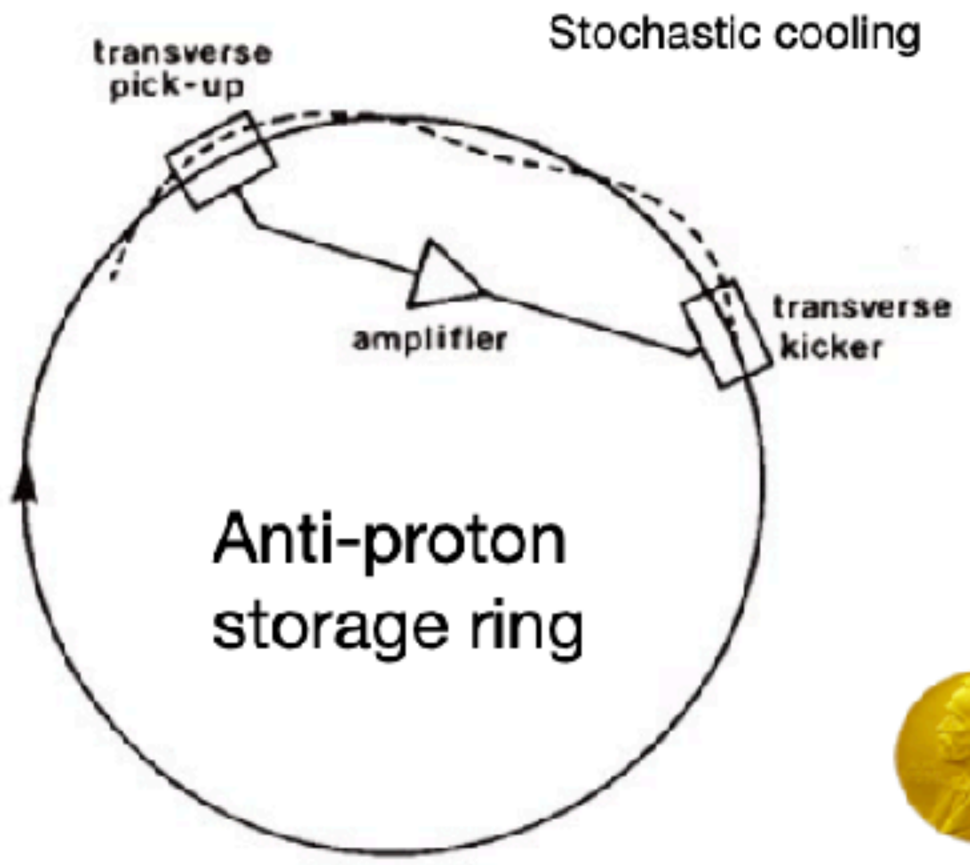
Need to detect $Z \to e^+e^-$ decays determines the minimal collider luminosity: the cross-section for inclusive Z production at ~600 GeV is ~1.6 nb

- The fraction of $Z \to e^+e^-$ decays is ~3%, hence a luminosity L = 2.5×10^{29} cm^{-2} s^{-1} would give an event rate of ~1per day. To achieve such luminosities one would need an antiproton source capable of delivering daily ~3×10^{10} $\bar{p}$

The SppS

The Sp$\bar{p}$S (Super Proton anti-Proton Synchrotron) operated with collisions at 900 GeV from 1981 to 1991.



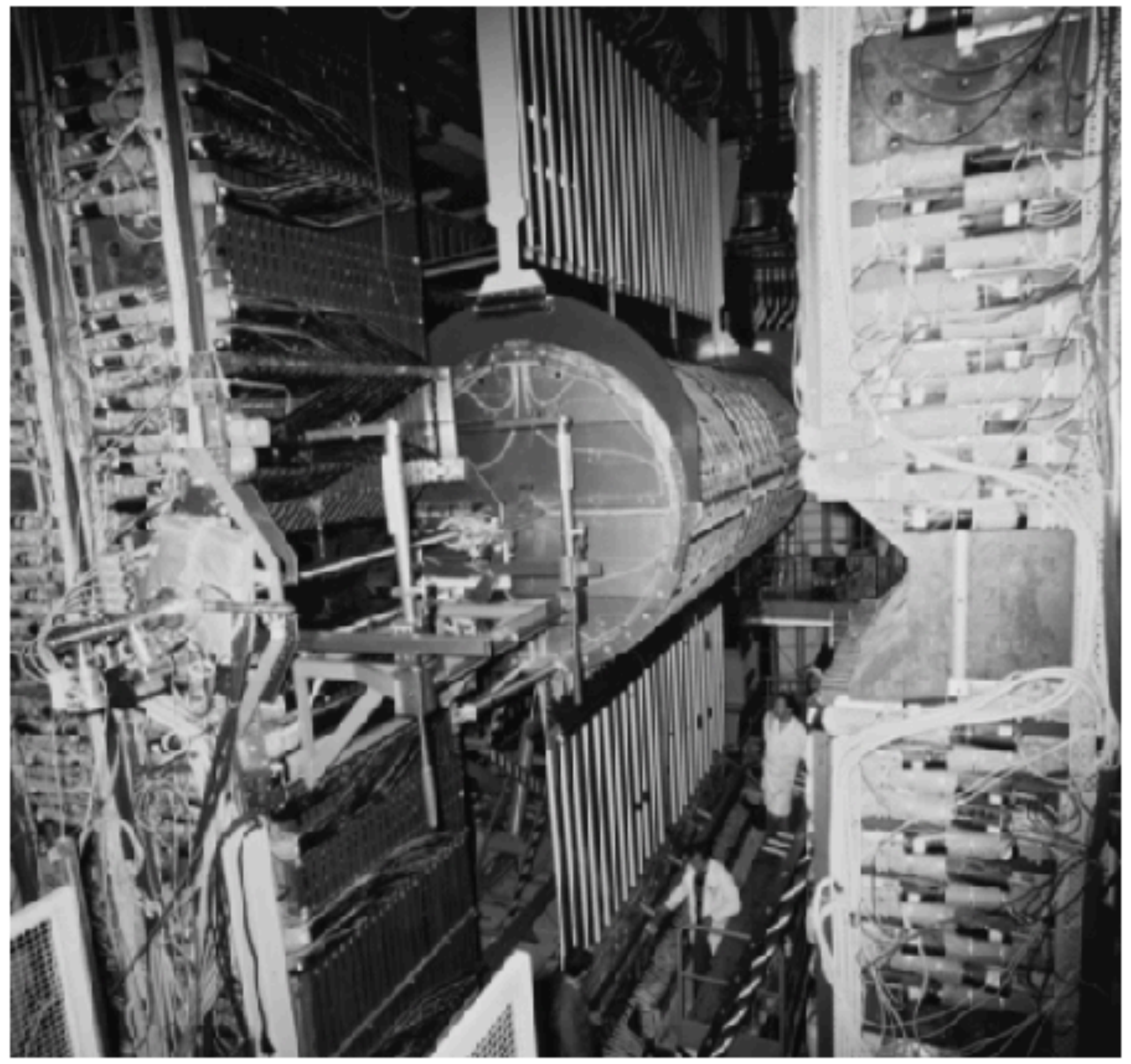


1984

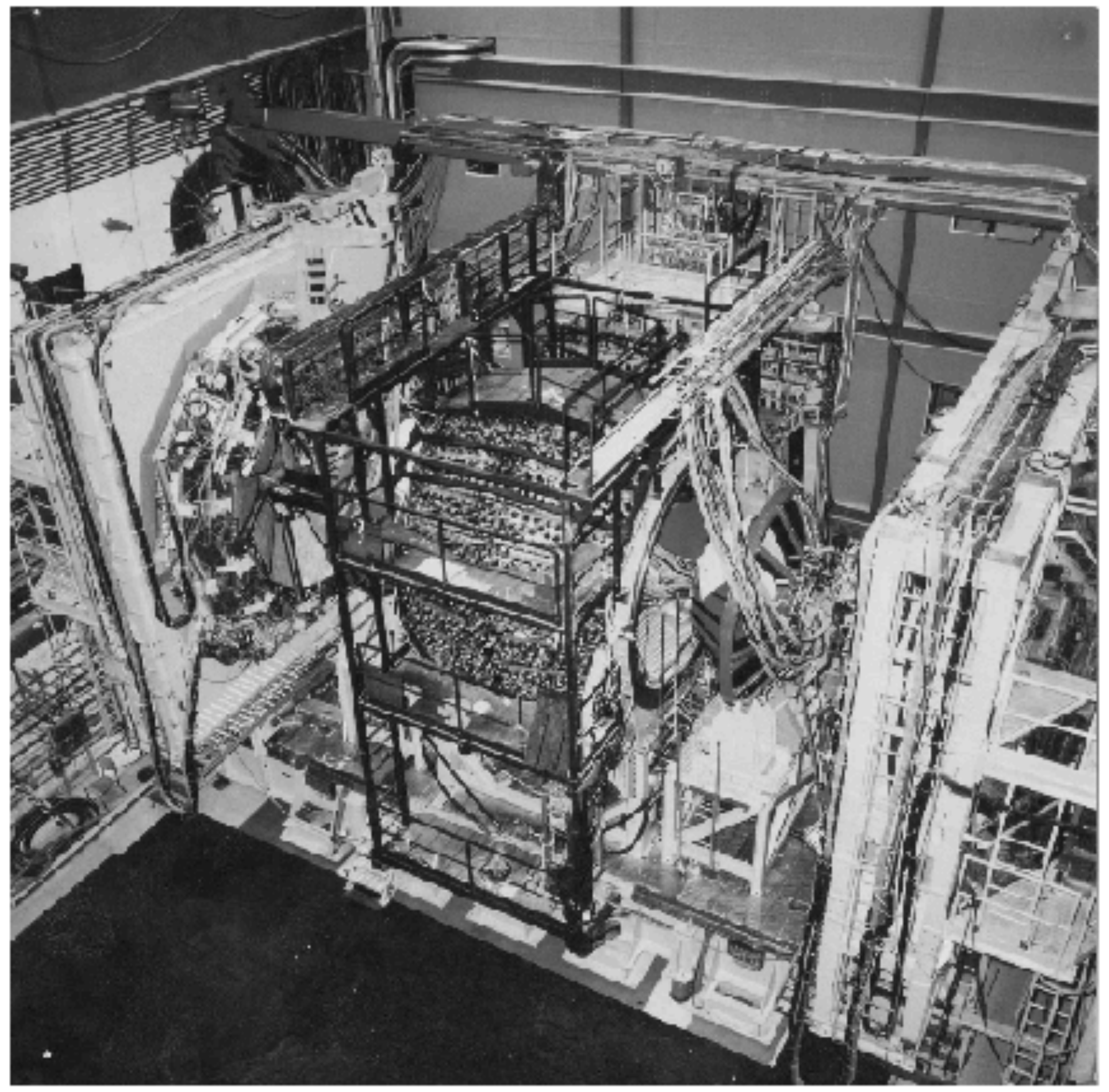
Discovery of the W and Z bosons

Carlo Rubbia, Simon Van der Meer

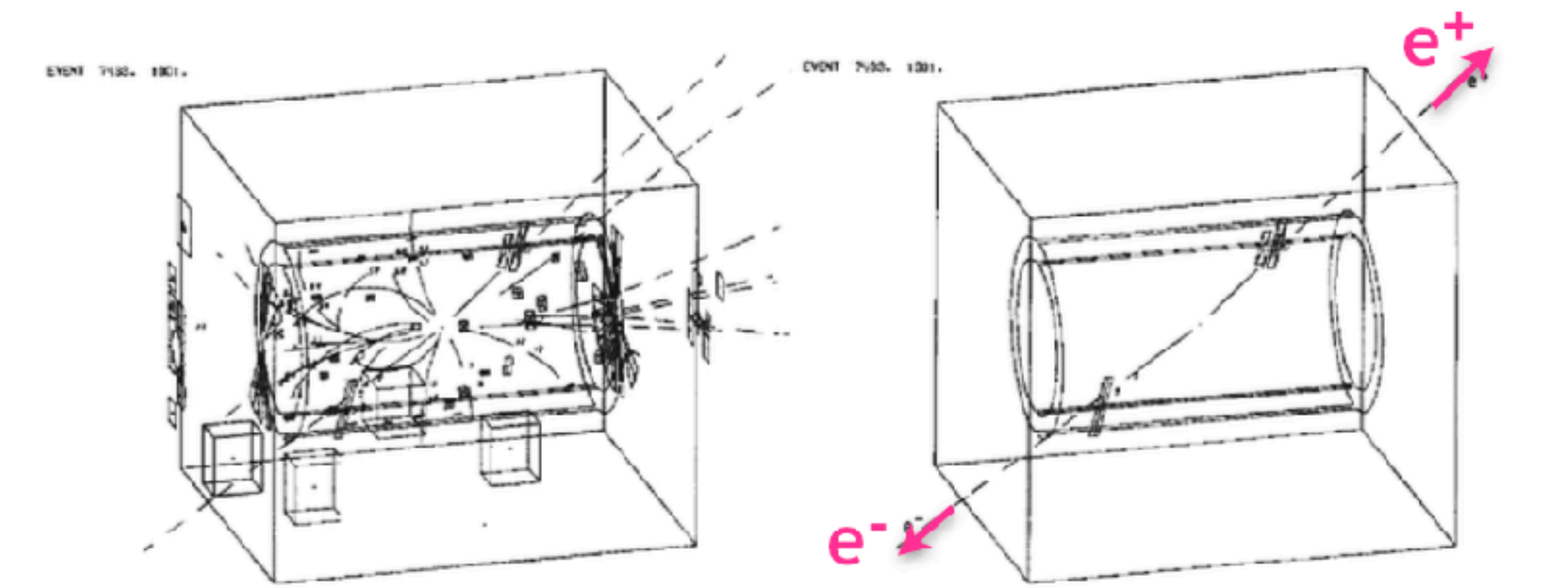
UA1



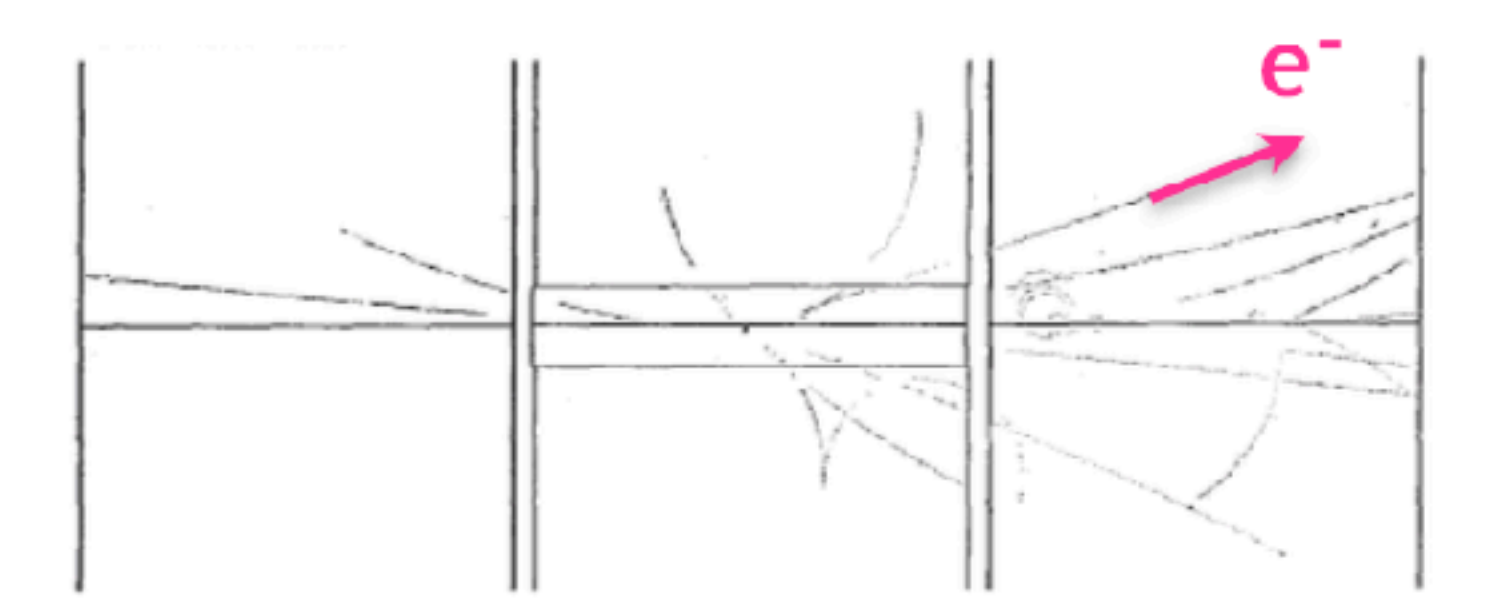
UA2



The legacy of the SppS

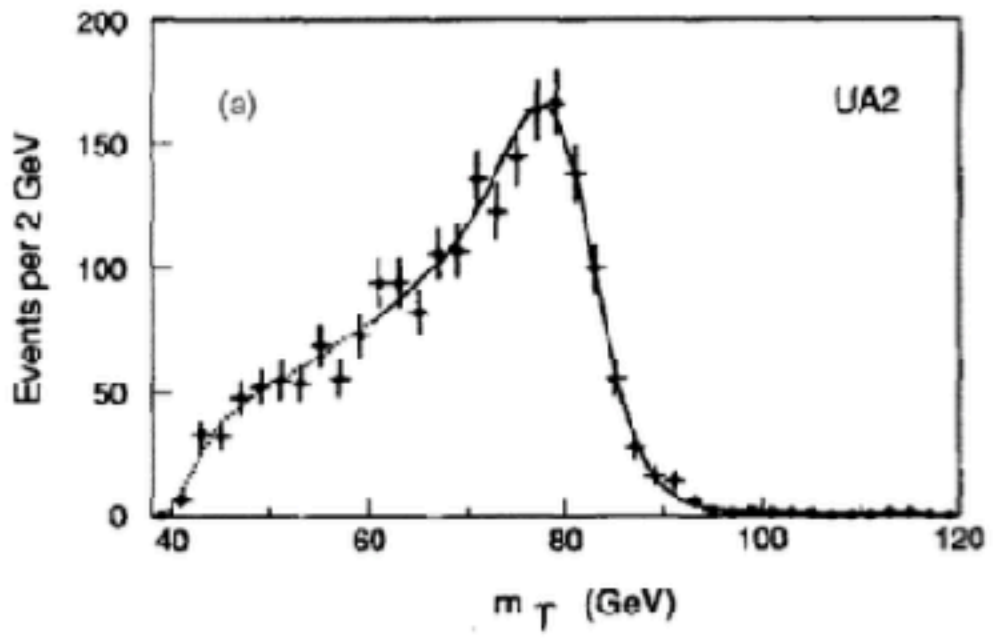


Z candidate in UA2 Track cleaning pT > 2GeV



W candidate in UA1

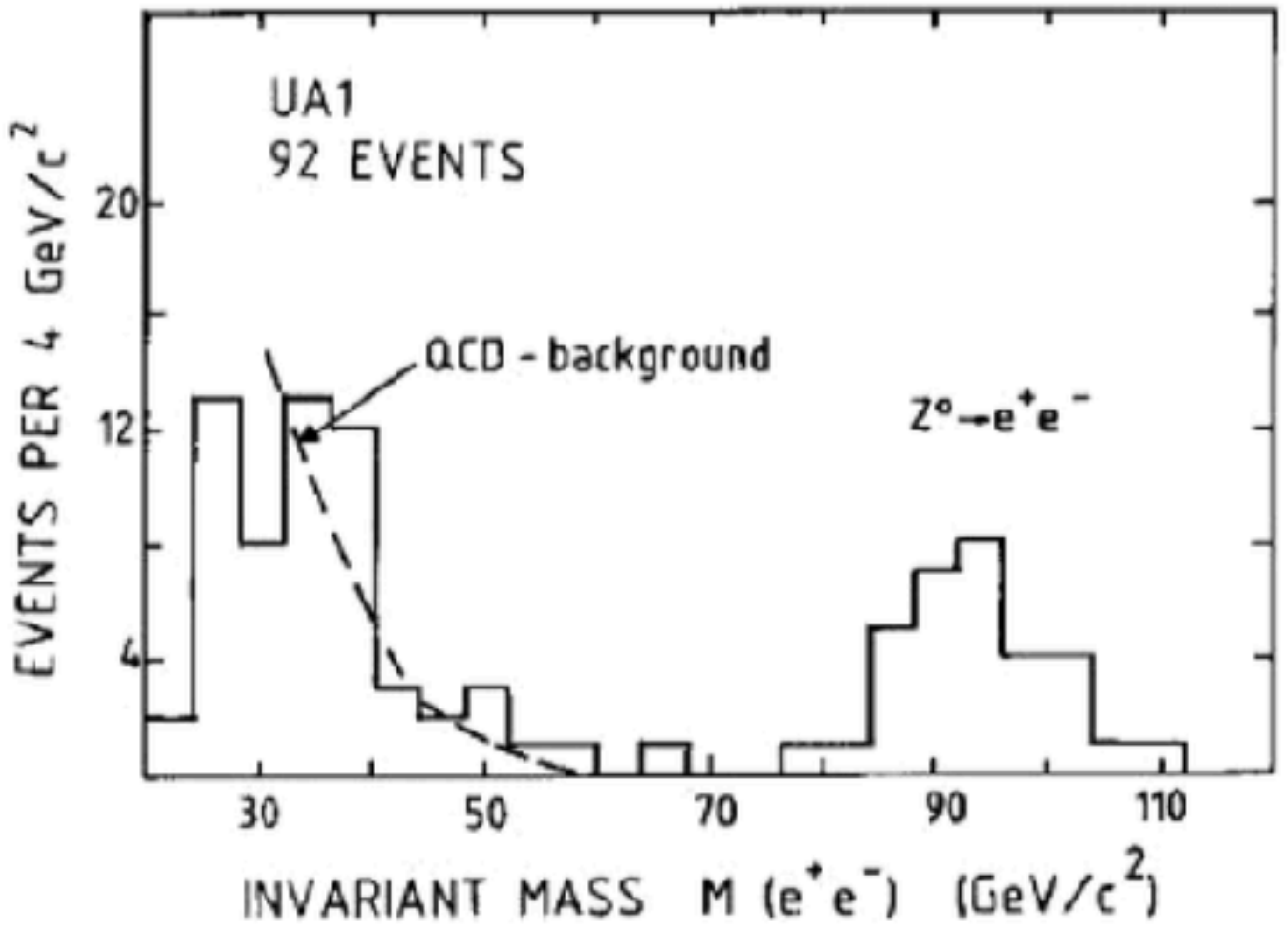
Transverse Mass distribution in UA2



$$m_T^2 = m^2 + p_x^2 + p_y^2$$

Altogether O(100) Z events

Altogether O(1000) W events



$$M_Z = 91.5 \pm 1.2 \pm 1.7\,(\mathrm{GeV}) \quad \textit{(UA1)}$$

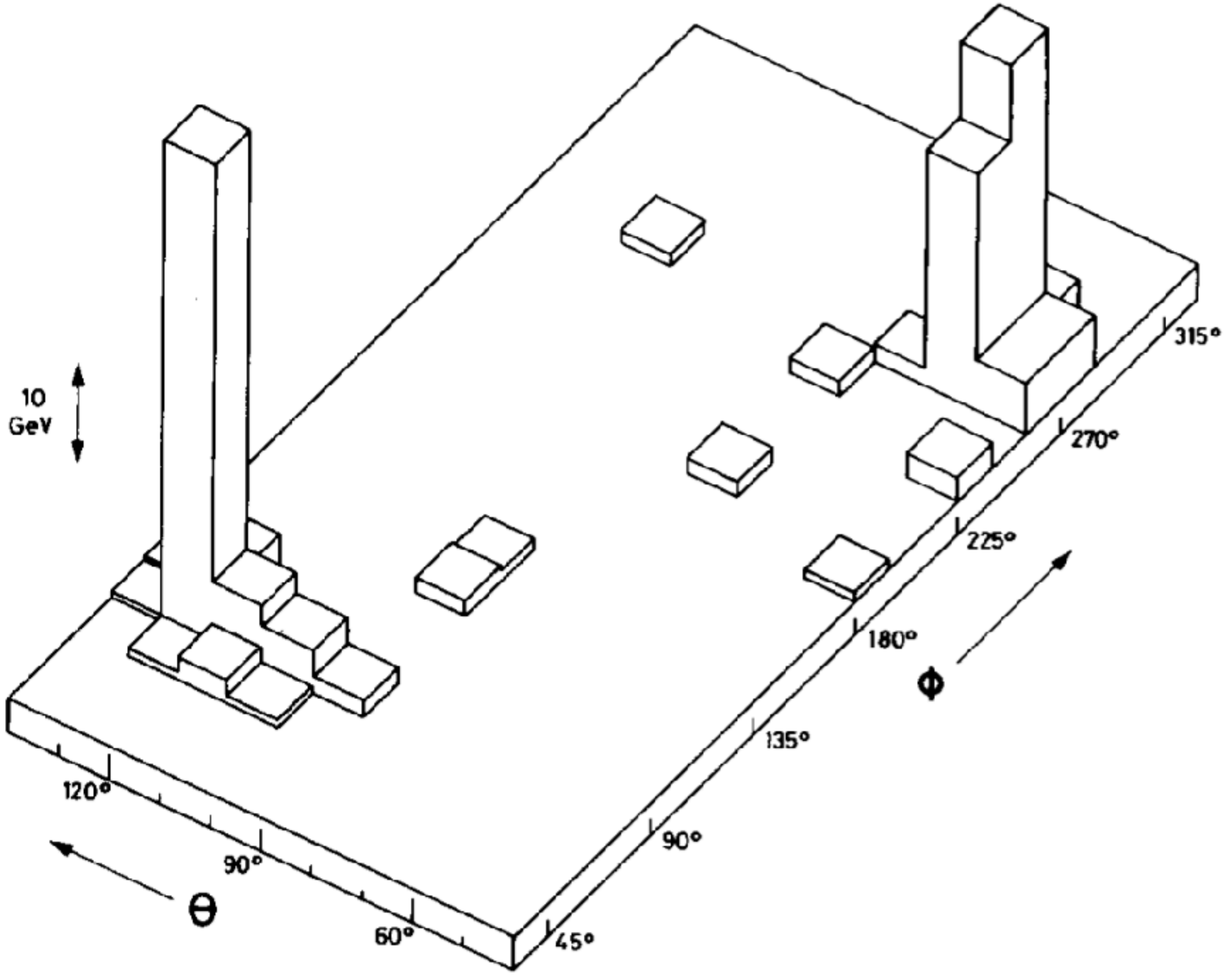
$$M_W = 81.0 \pm 0.8 \pm 1.3\,(\mathrm{GeV}) \quad \textit{(UA2)}$$

$$\rho = 1.004 \pm 0.052 \quad \textit{(UA1)}$$

$$\sin^2\theta_W = 0.226 \pm 0.014 \quad \textit{(UA1)}$$

First jets in hadronic collisions

Dijet event with separate energy deposits



Jet algorithm based on calorimeter cells structure

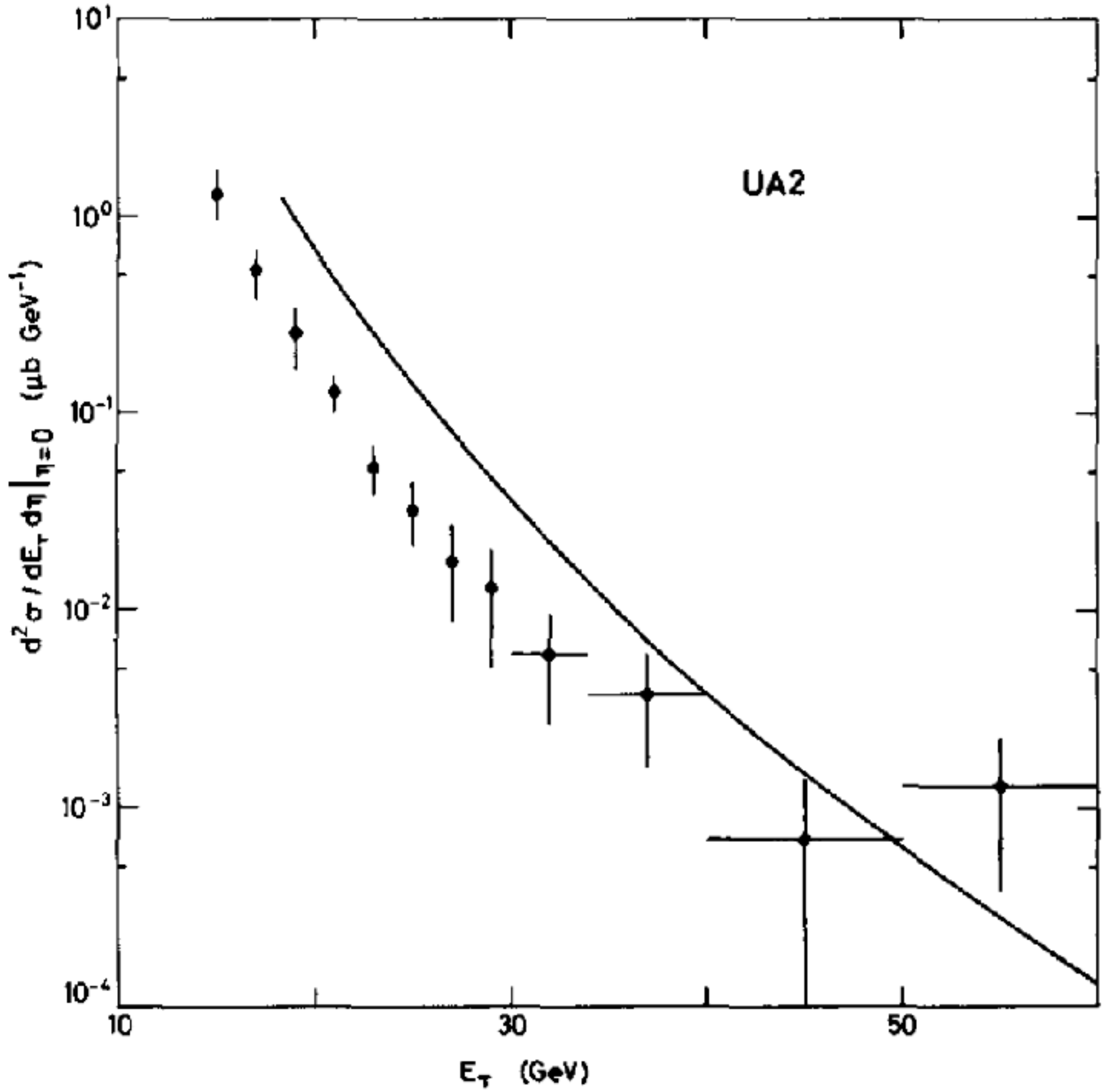


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

The Tevatron Collider

$p\bar{p}$ collider:

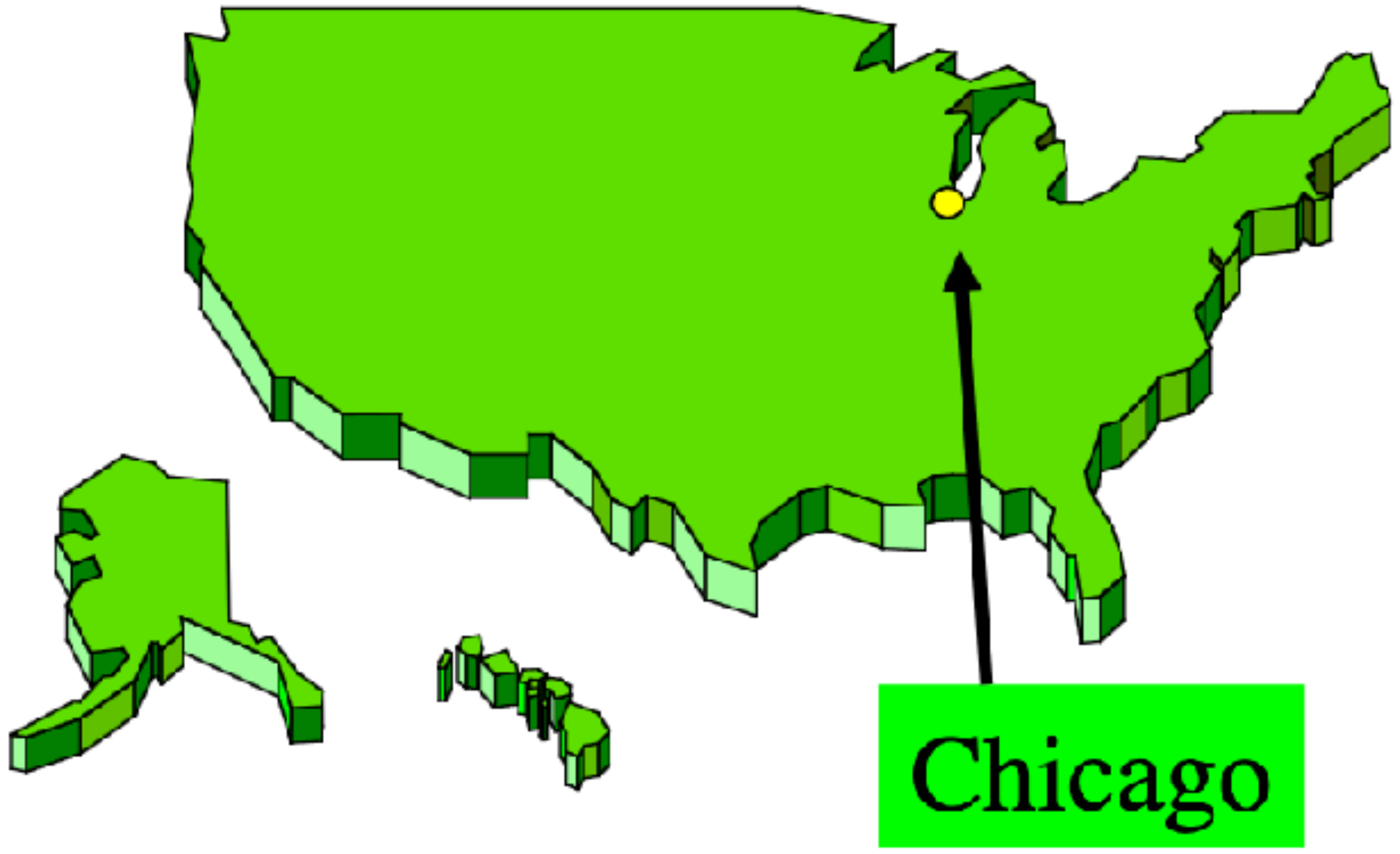
- 6.5 km circumference
- Beam energy: 980 GeV
  - $\sqrt{s}$=1.96 TeV
- 36 bunches:
  - Time between bunches: Δt=396 ns

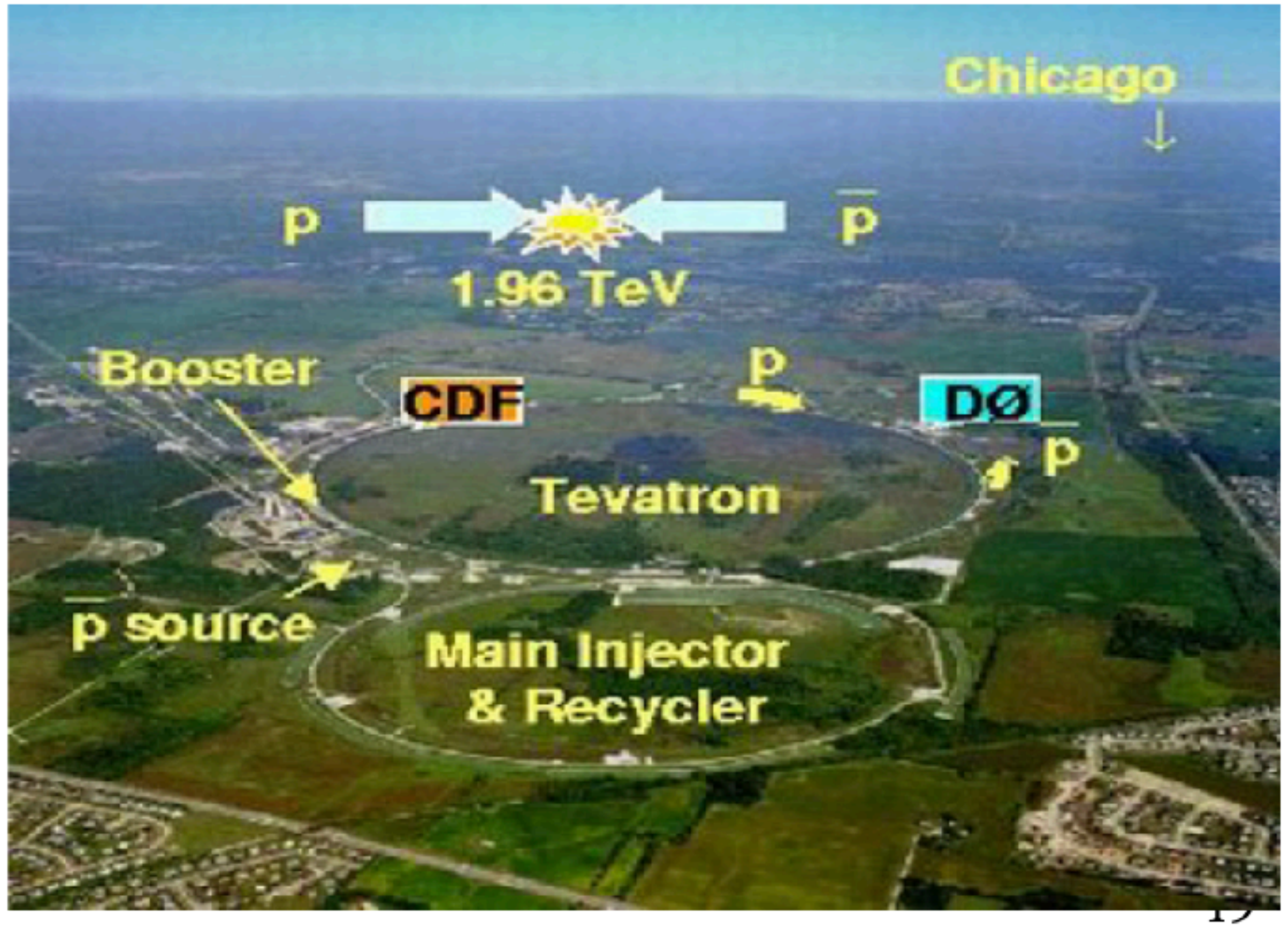
Main challenges:

- Anti-proton production and storage
- Irregular failures:
  - Quenches

CDF and DØ experiments:

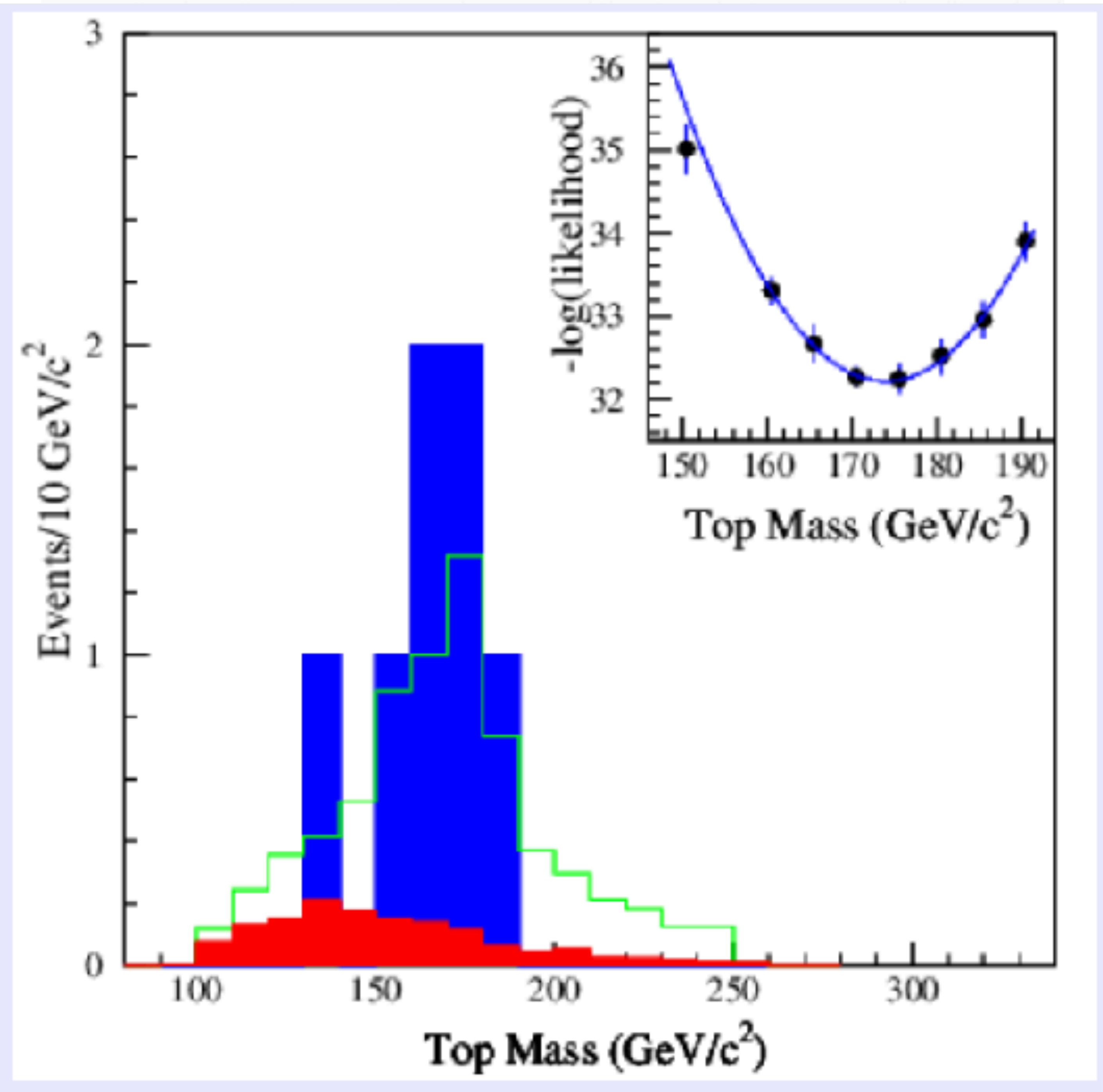
- 700 physicists/experiment

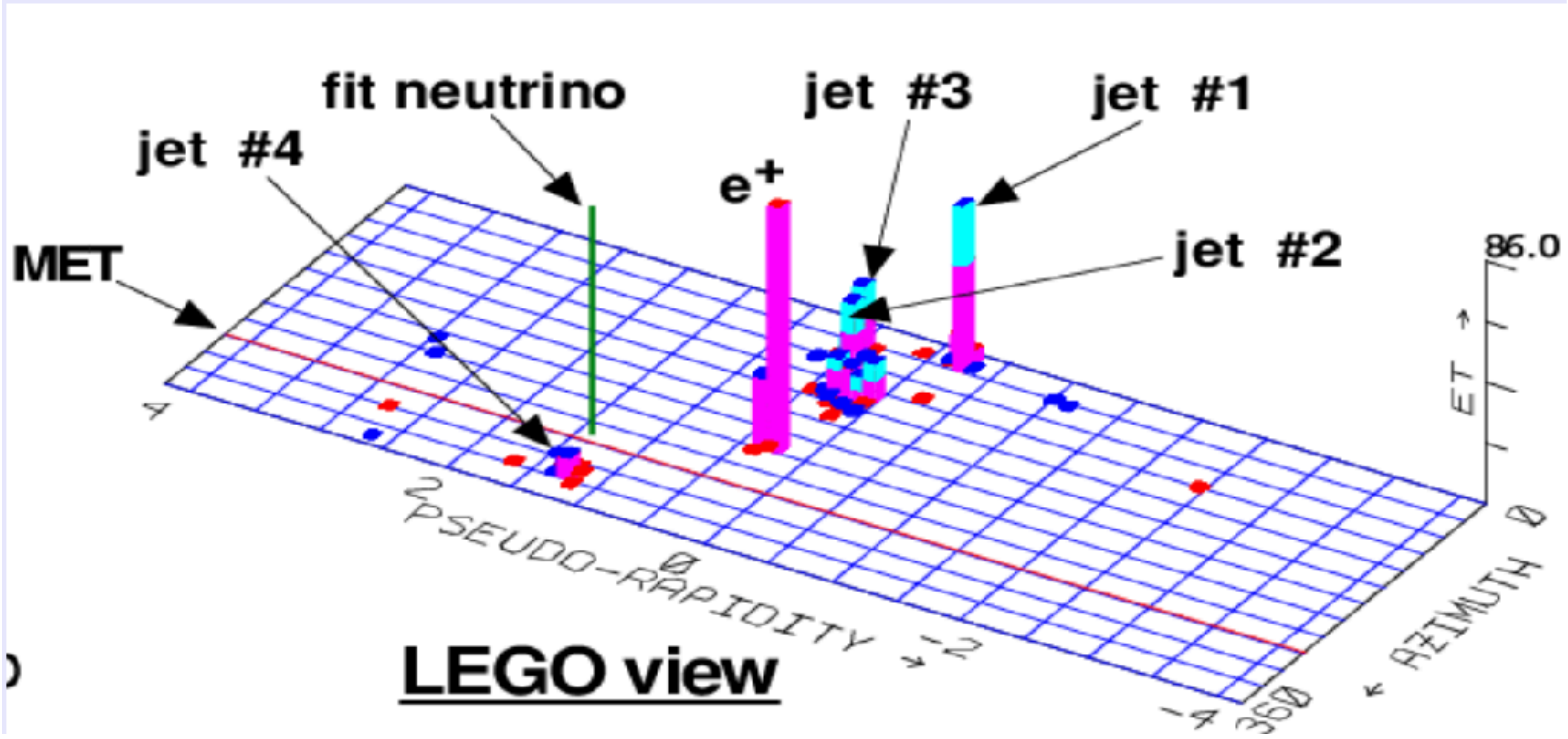


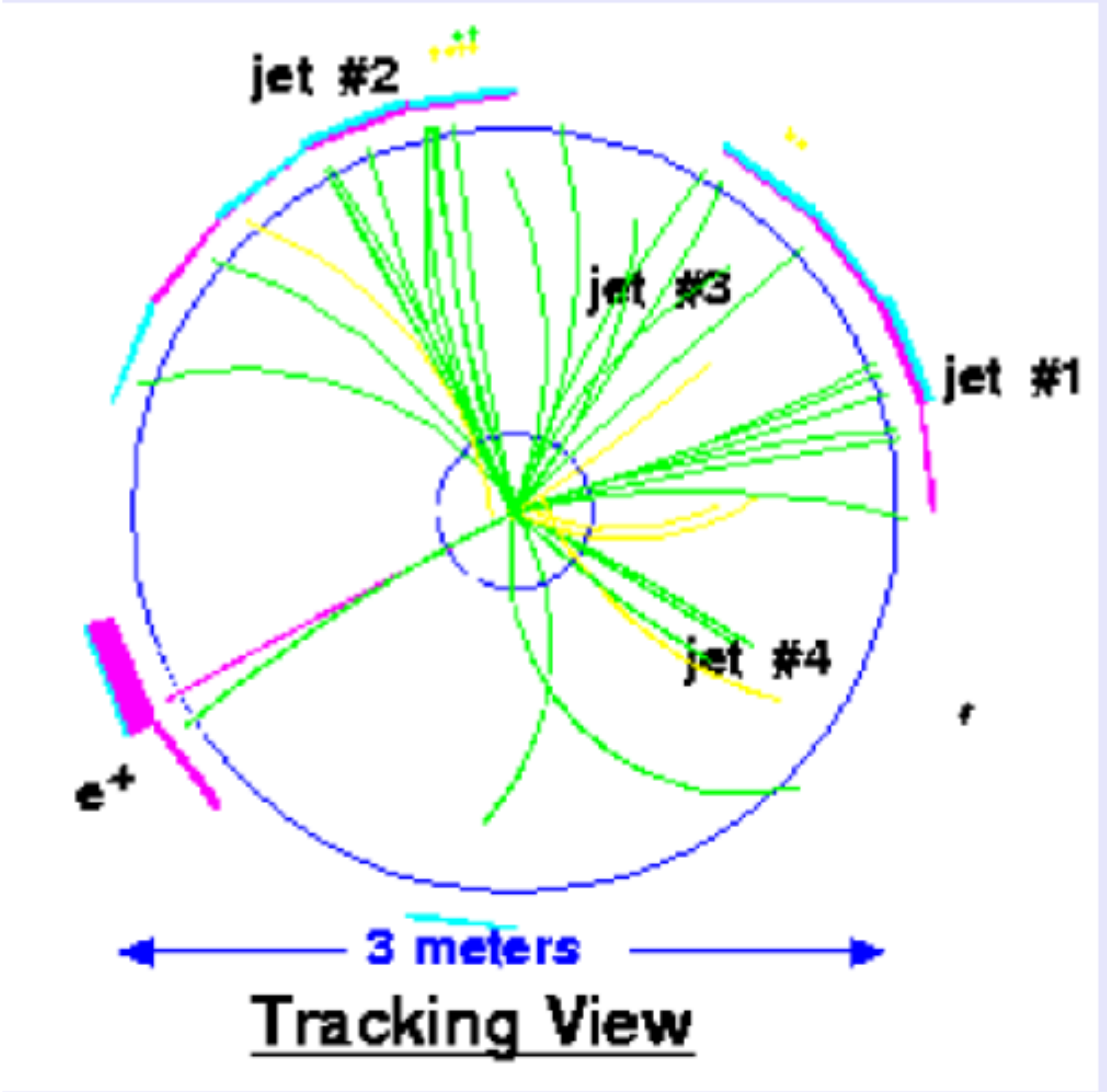


The discovery of the top quark

- Event found by CDF in September 1992
- Reconstructed tracks consistent with decay products of a pair of top quarks
- One clean event not enough to claim discovery!
- It took about three years before the top-quark discovery was later announced







What can we expect increasing collider energy?

Take a simple Z' model (a new Z-like boson with a larger mass) as simple example

Tevatron
$p\bar{p}$, 1.96 TeV, 10 fb^{-1}

Exclusion limit ~ 1.2 TeV

(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, μμ only)

→ × 4

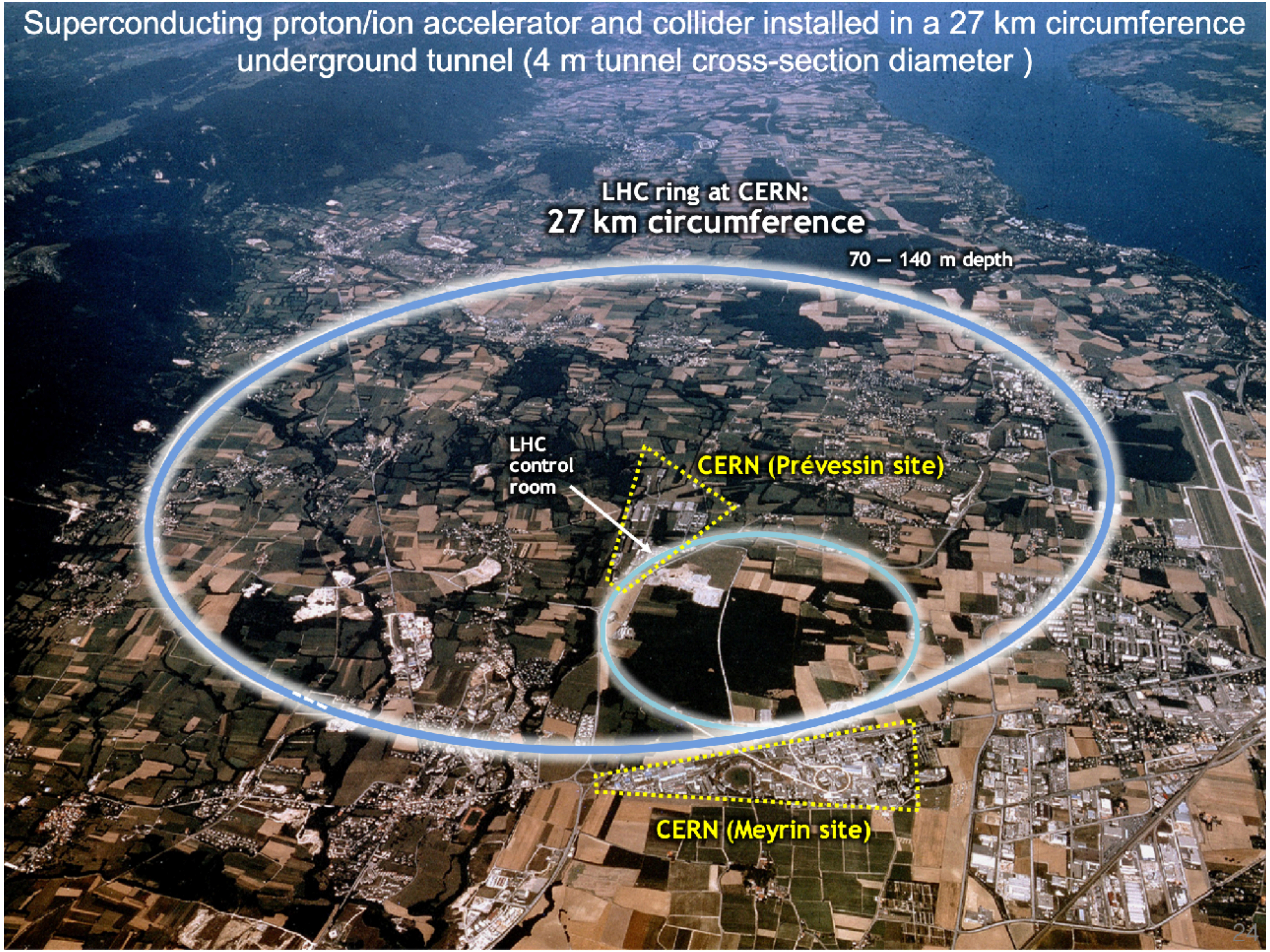
LHC
pp, 13.6 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

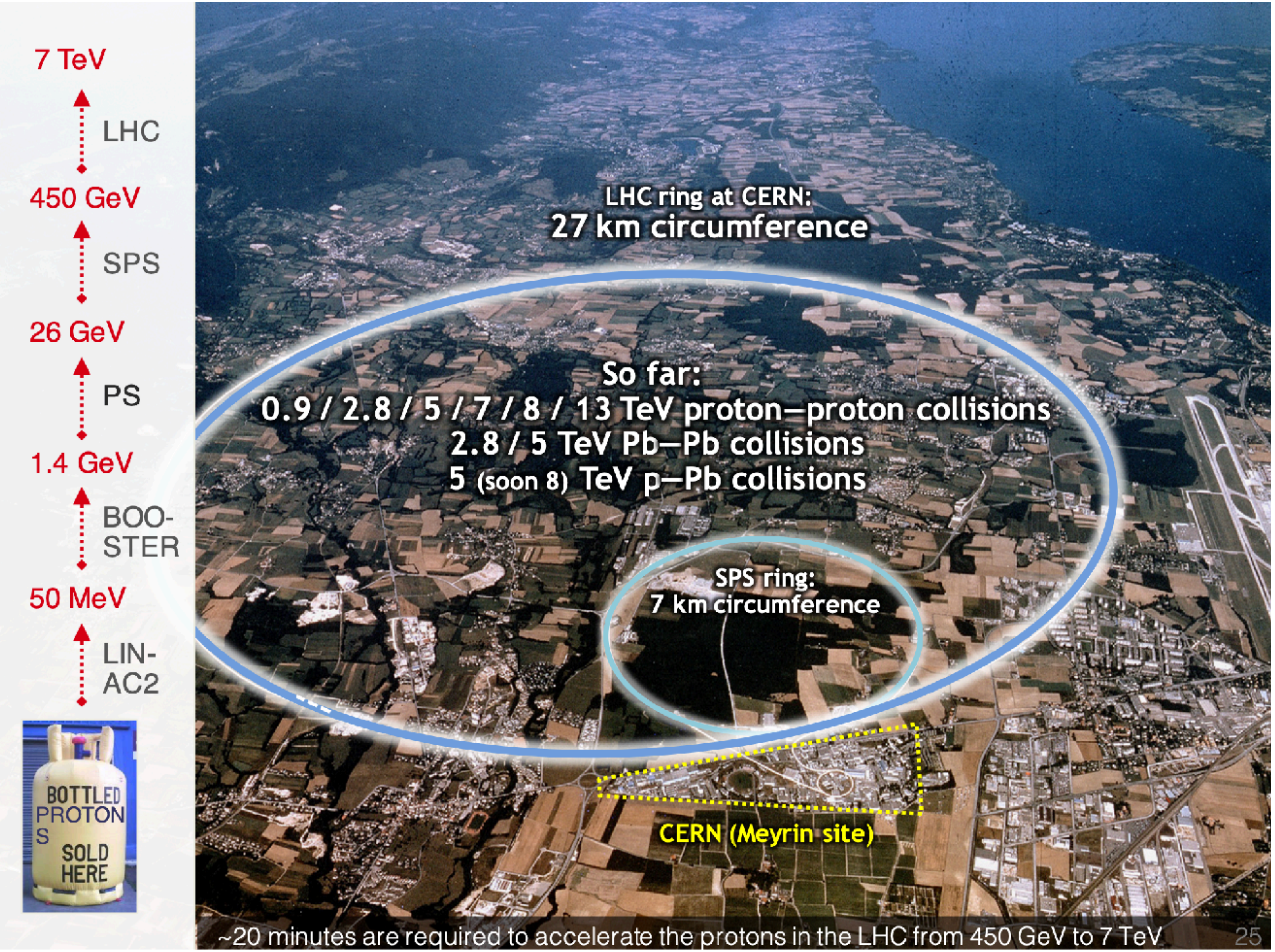
(electron and muon channels, single experiment)

Hadron colliders are "discovery" machines!

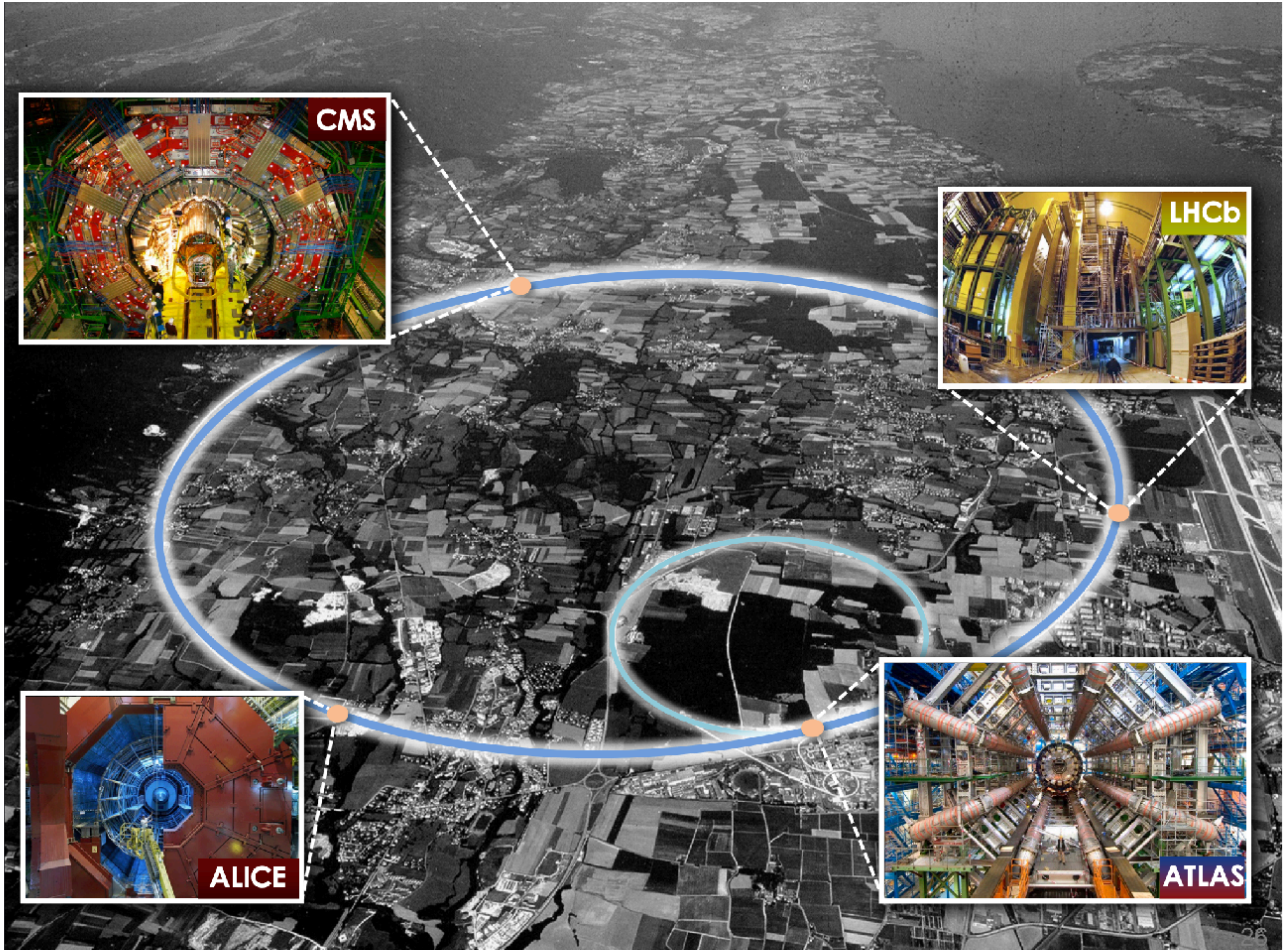
THE LARGE HADRON COLLIDER

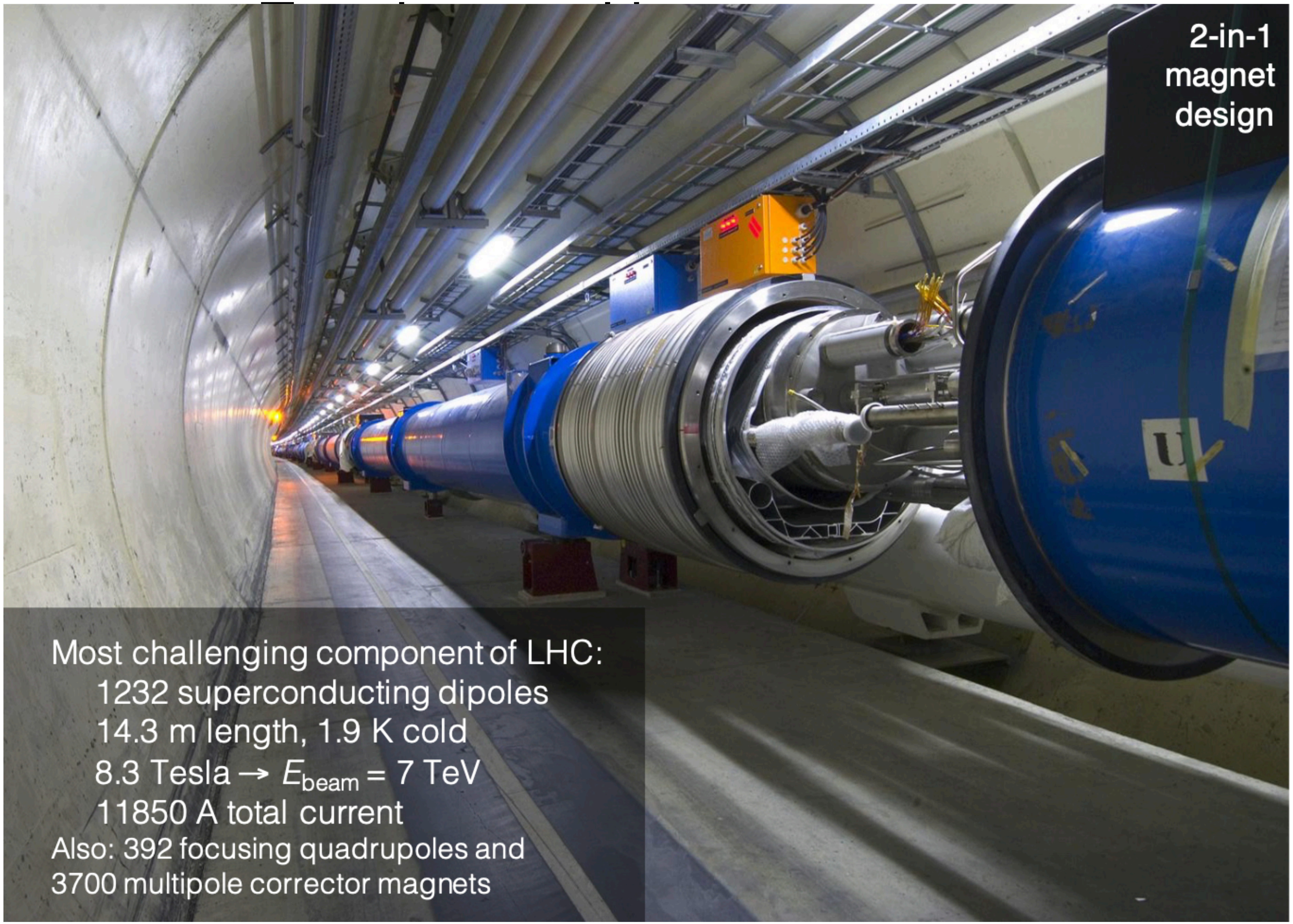


The Large Hadron collider

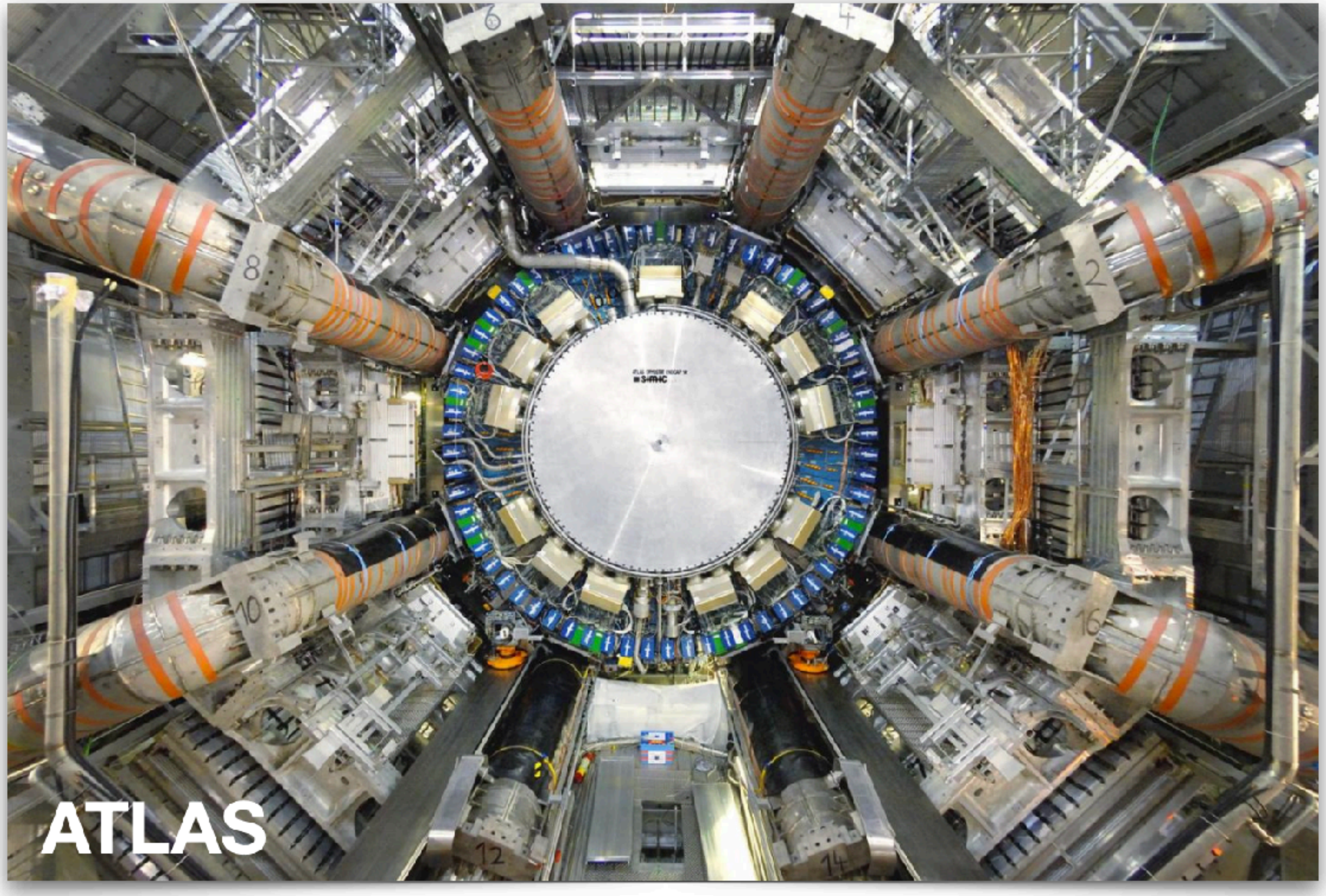


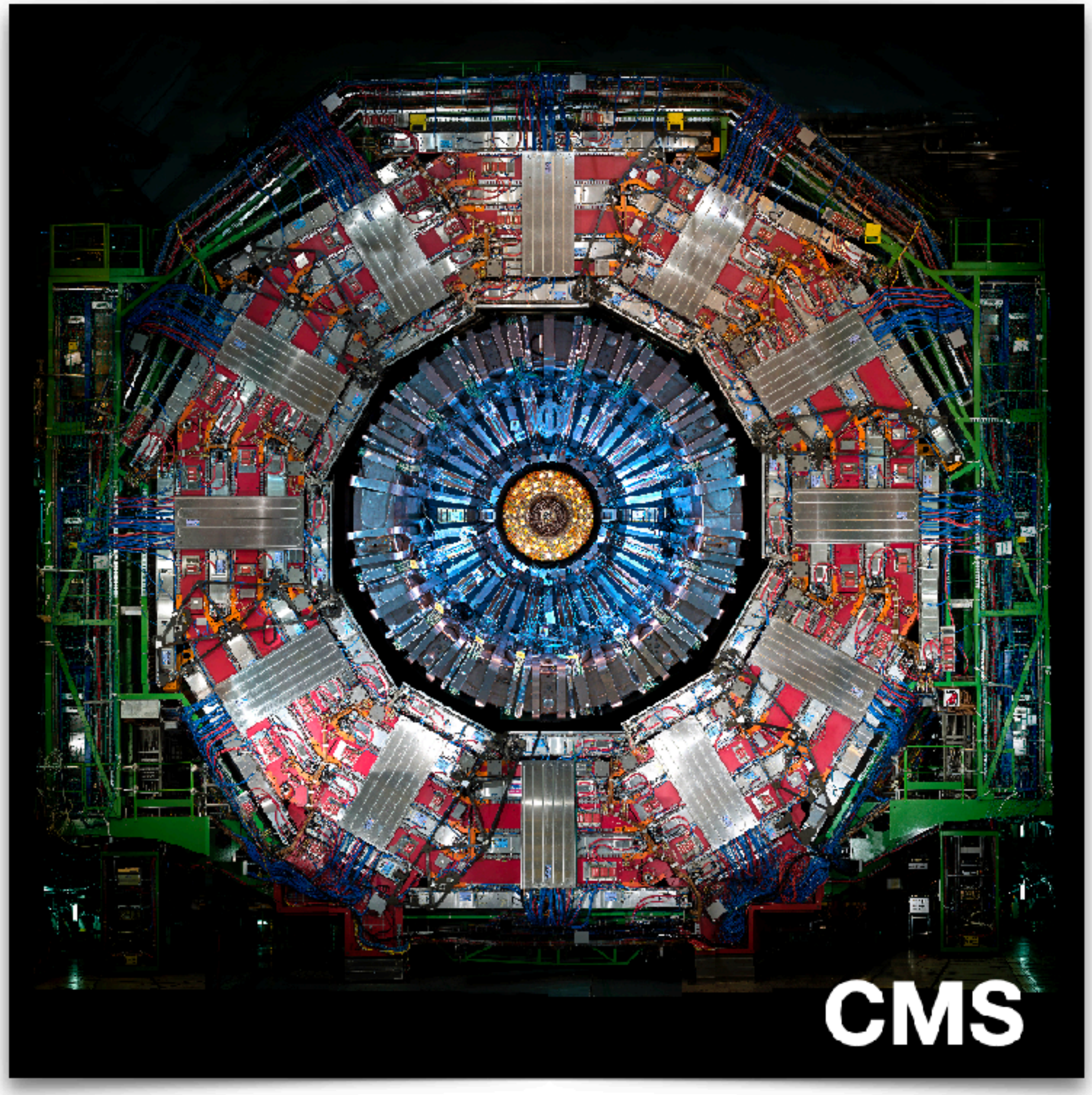
The Large Hadron collider



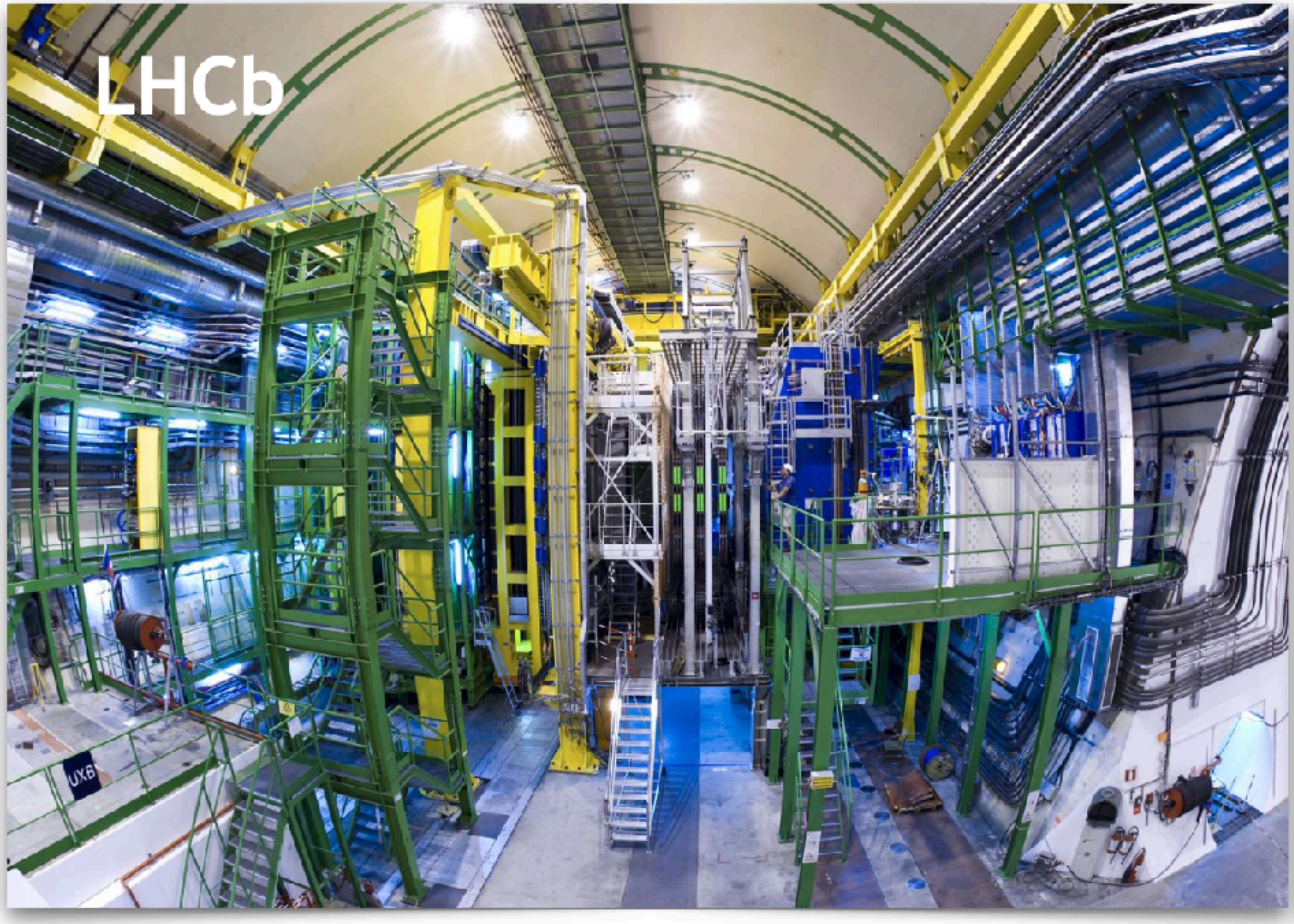

2-in-1
magnet
design
Most challenging component of LHC:
1232 superconducting dipoles
14.3 m length, 1.9 K cold
8.3 Tesla → E_{beam} = 7 TeV
11850 A total current
Also: 392 focusing quadrupoles and
3700 multipole corrector magnets

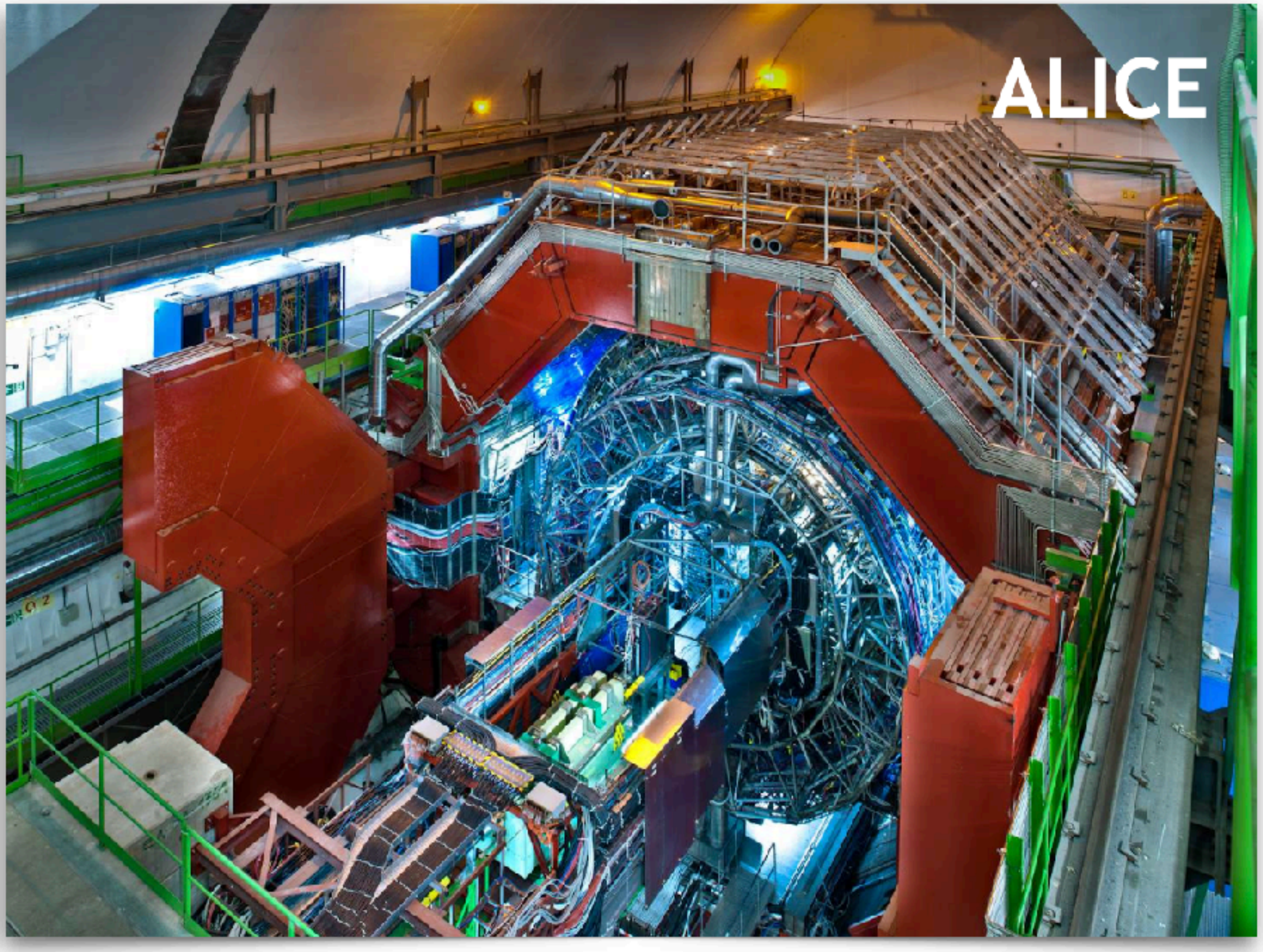
General purpose experiments



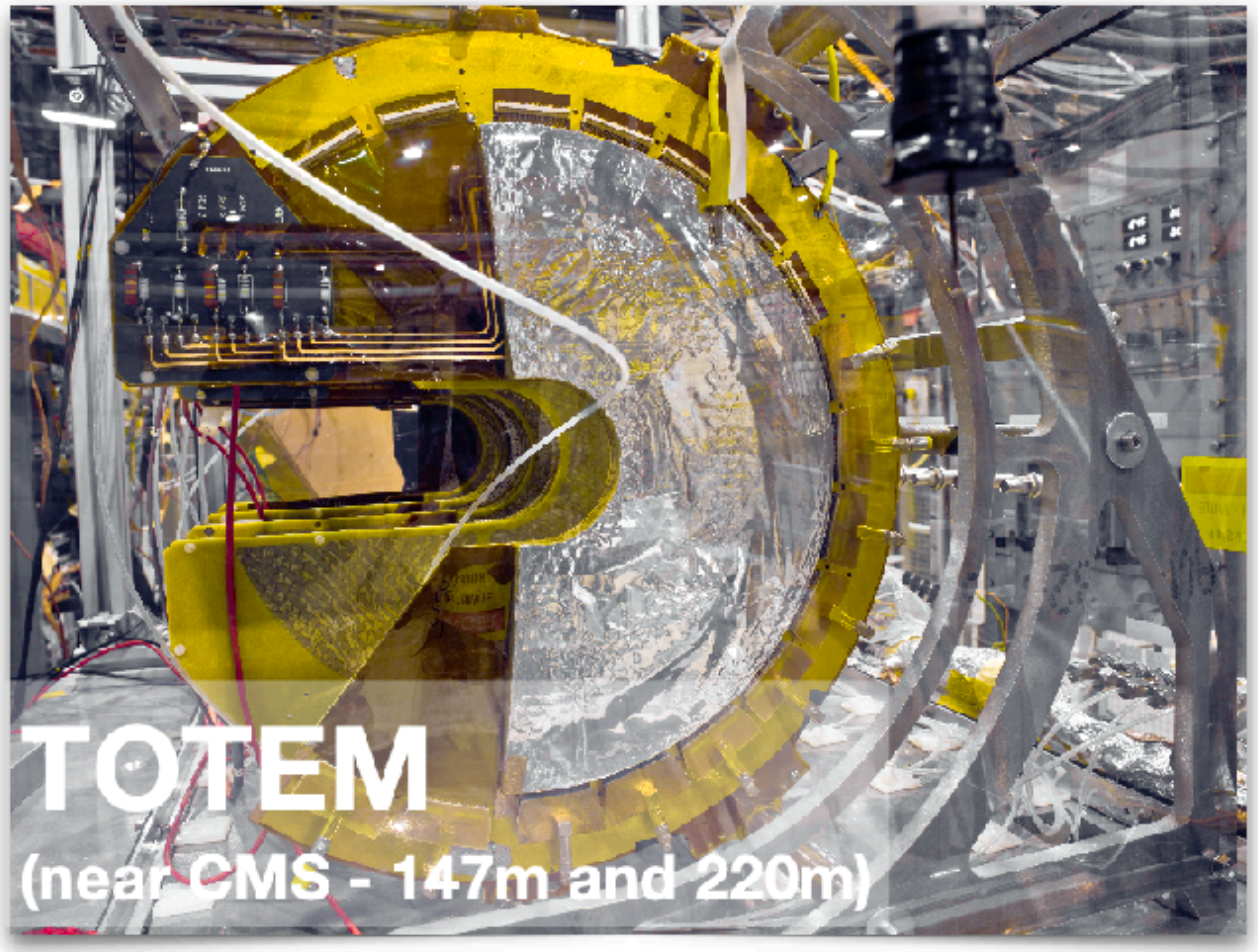


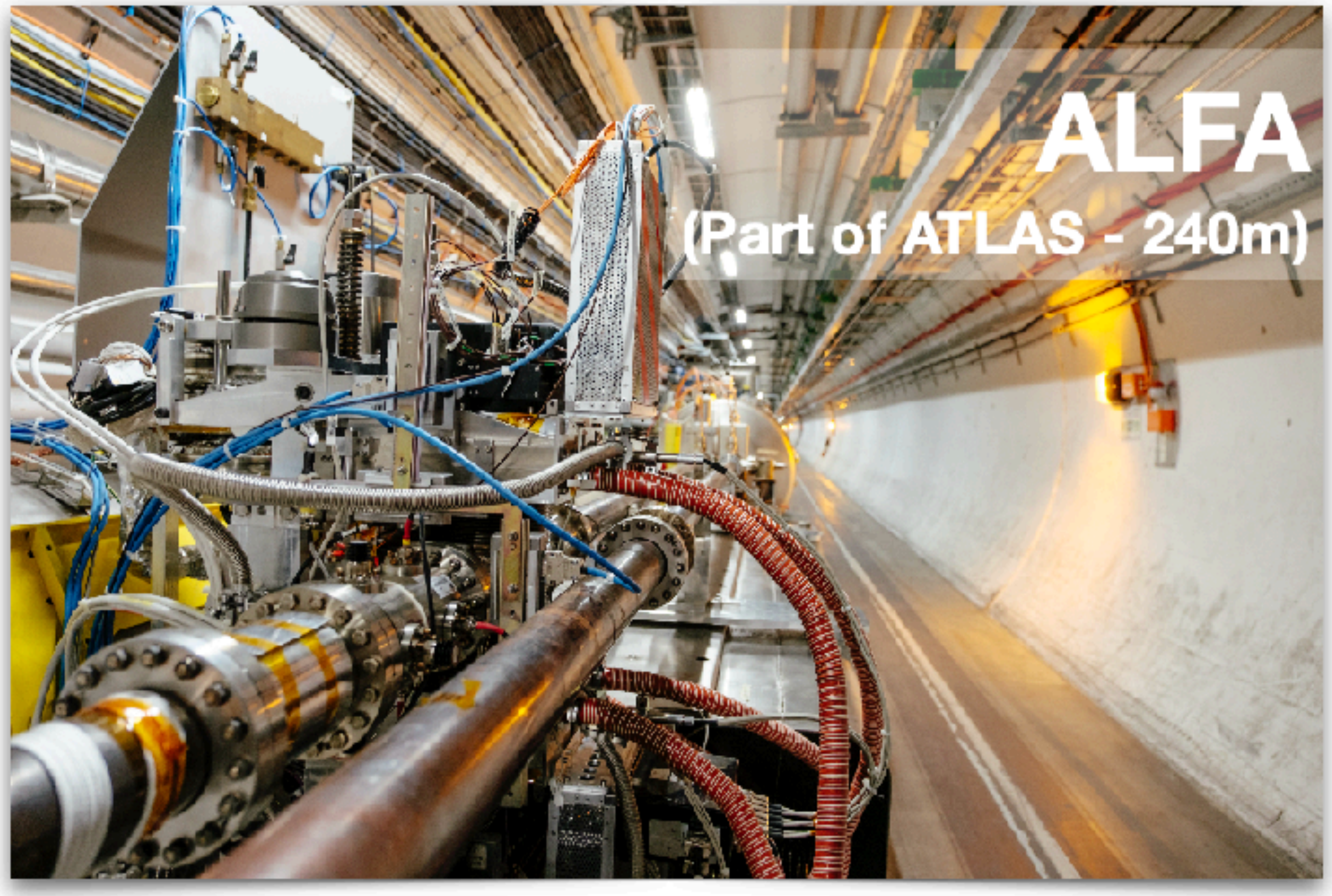
Specialized detectors

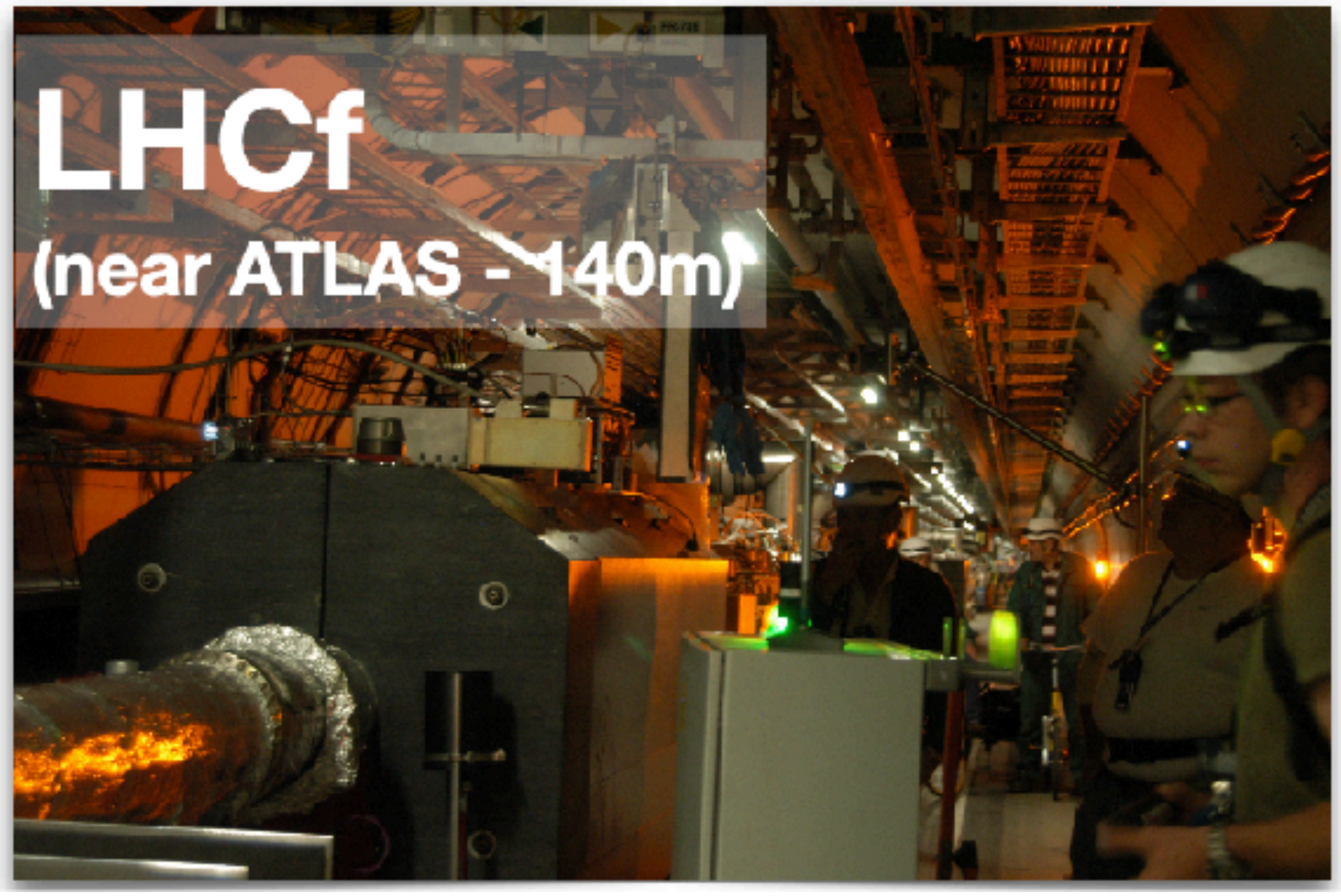


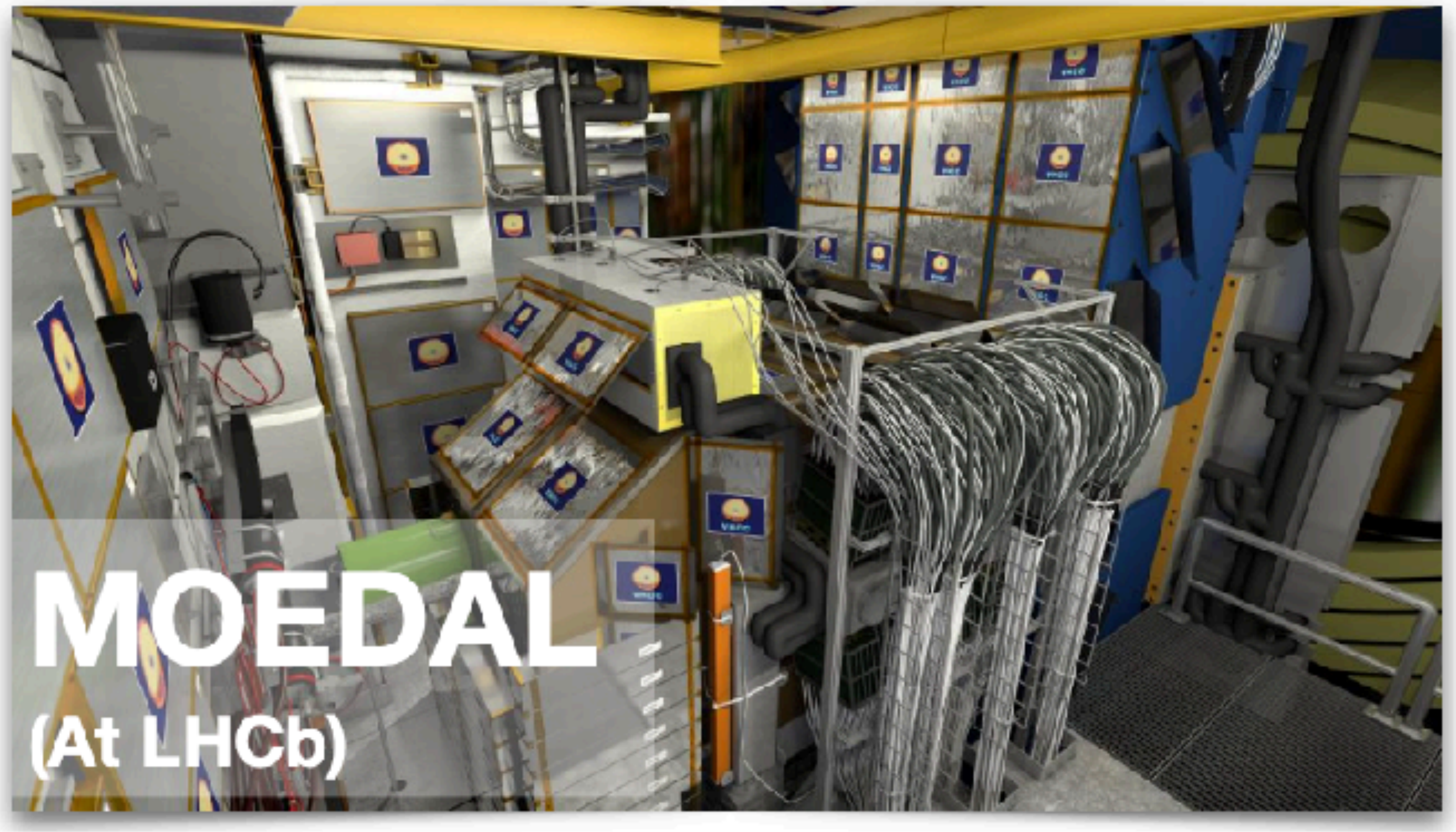


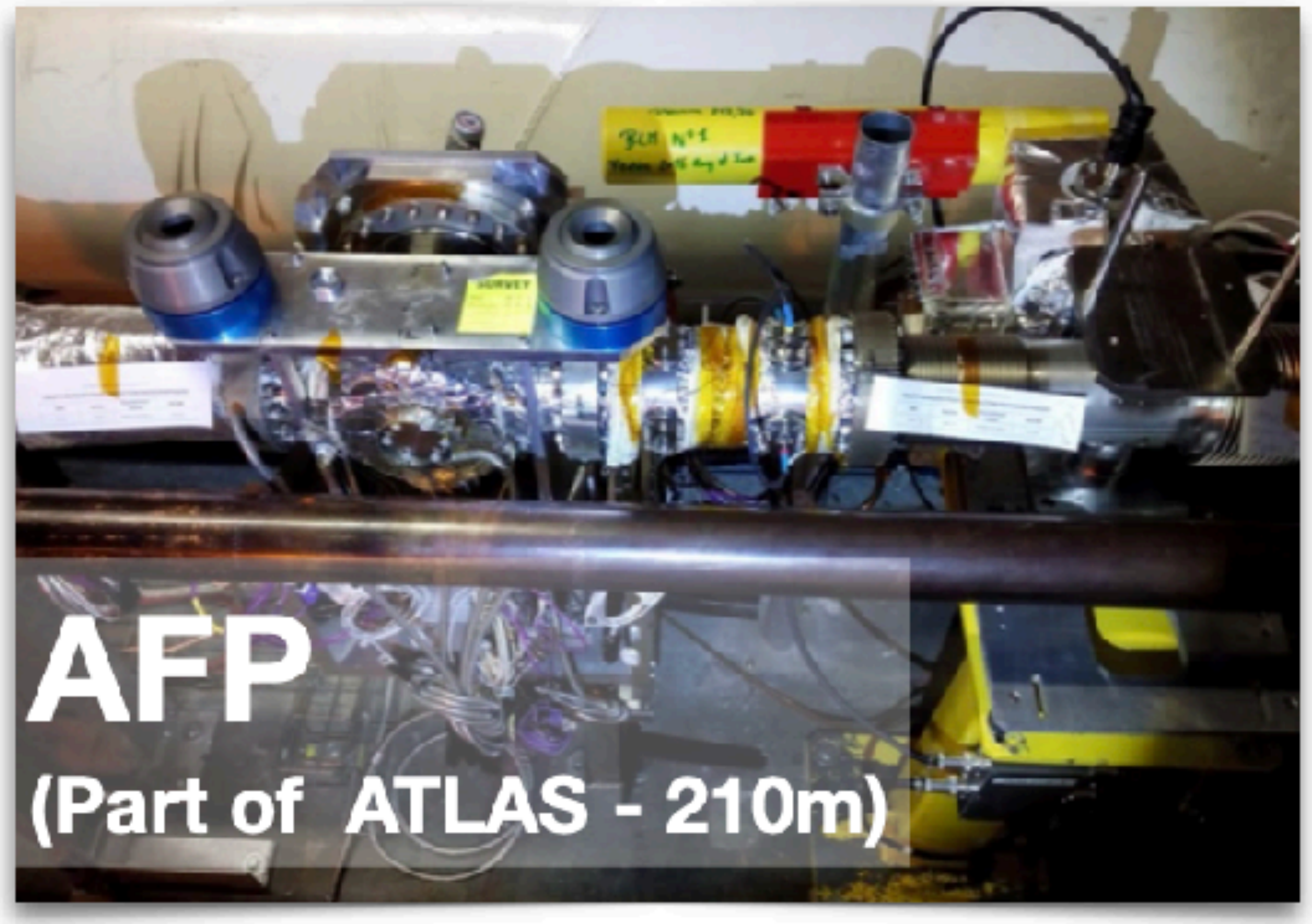
And even more specialized detectors











What do we actually "see" in a collision?

- **Stable particles**, which can be directly observed

$$p, \bar{p}, e^{\pm}, \gamma$$

- **Quasi-stable particles**, with a long lifetime can also be directly seen

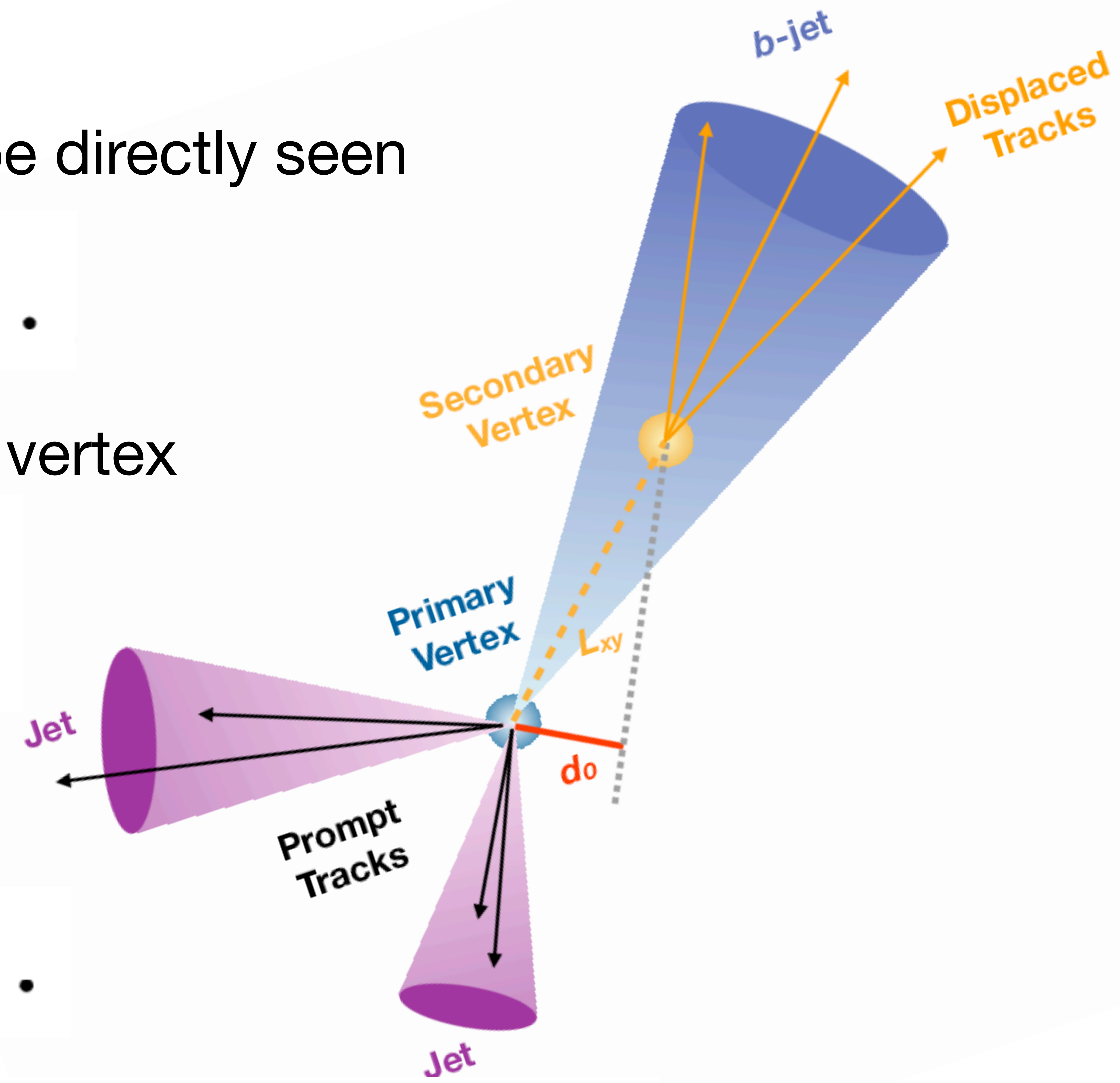
$$n, \Lambda, K_L^0, \ldots, \mu^{\pm}, \pi^{\pm}, K^{\pm}, \ldots$$

- **Short-lived particles** may display a secondary decay vertex

$$\tau \sim 10^{-12} \qquad B^{0,\pm}, D^{0,\pm}, \tau, \ldots$$

- Short lived particles which are not directly seen, may be reconstructed from their decay products

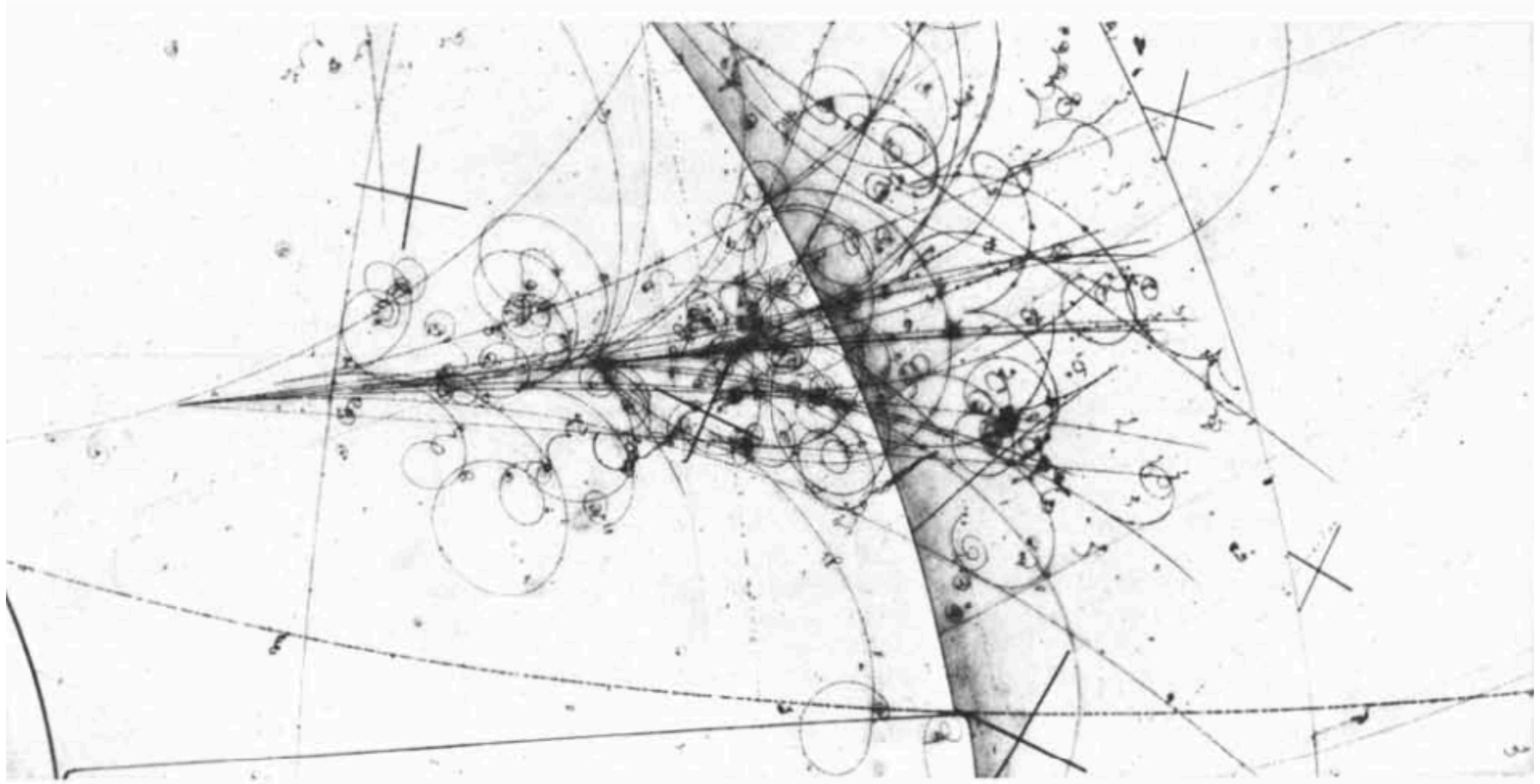
$$\pi^0, \rho^{0,\pm}, \ldots, Z, W^{\pm}, t, H, \ldots$$

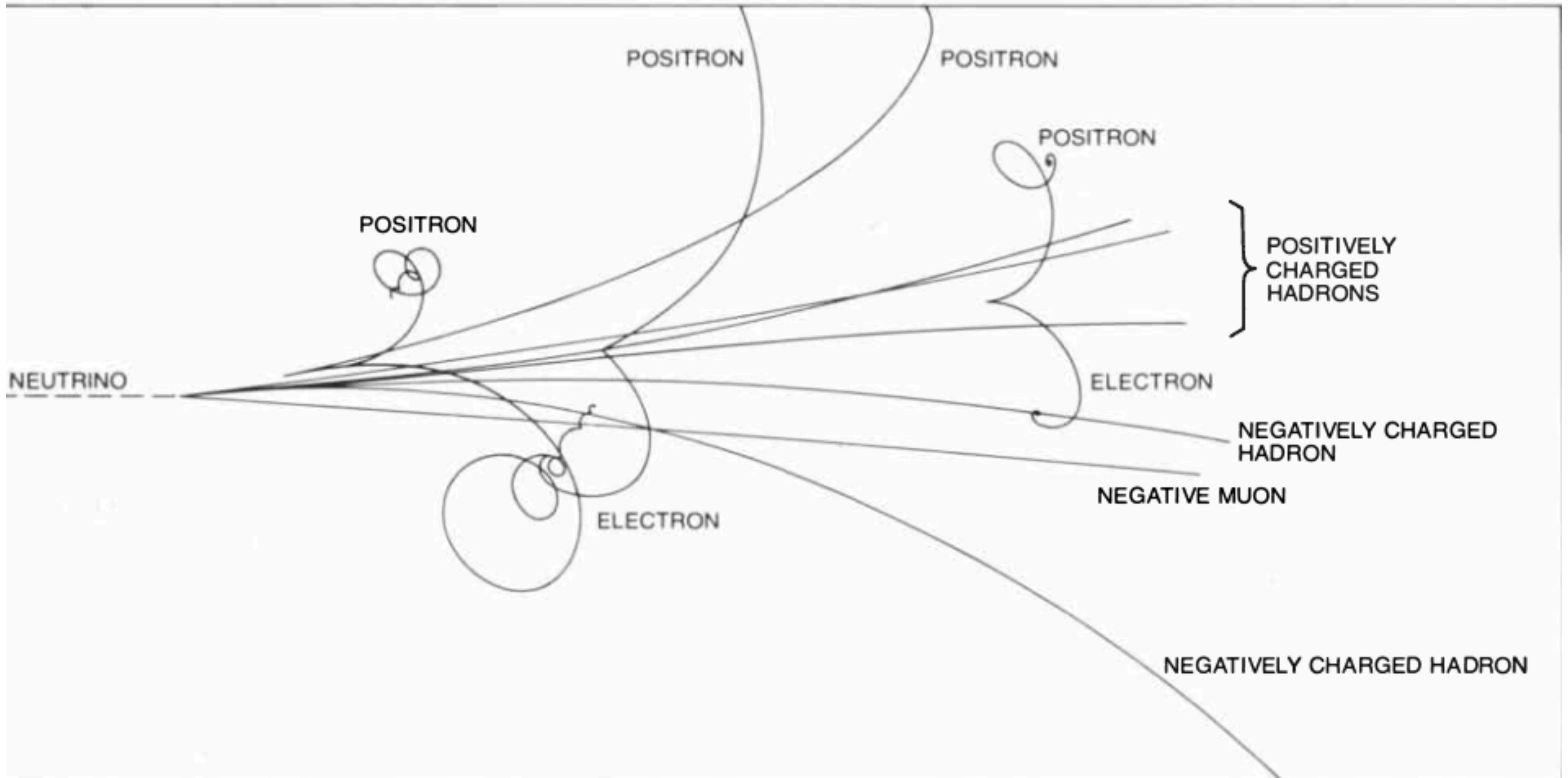


- **Missing particles**, neutral and weakly interacting that escape the detector

$$\nu, \tilde{\chi}^0, G_{KK}, \ldots$$

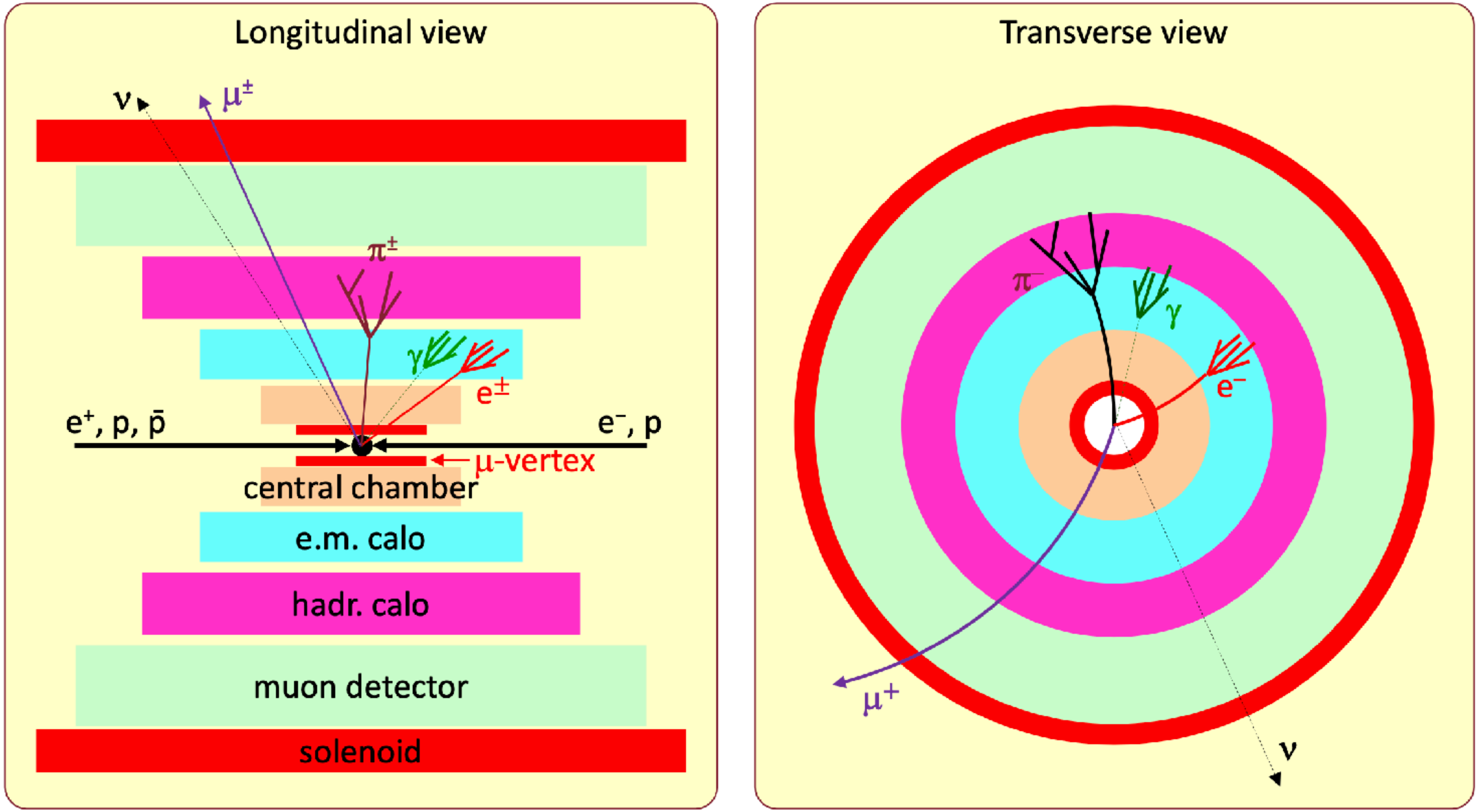
Detecting particles





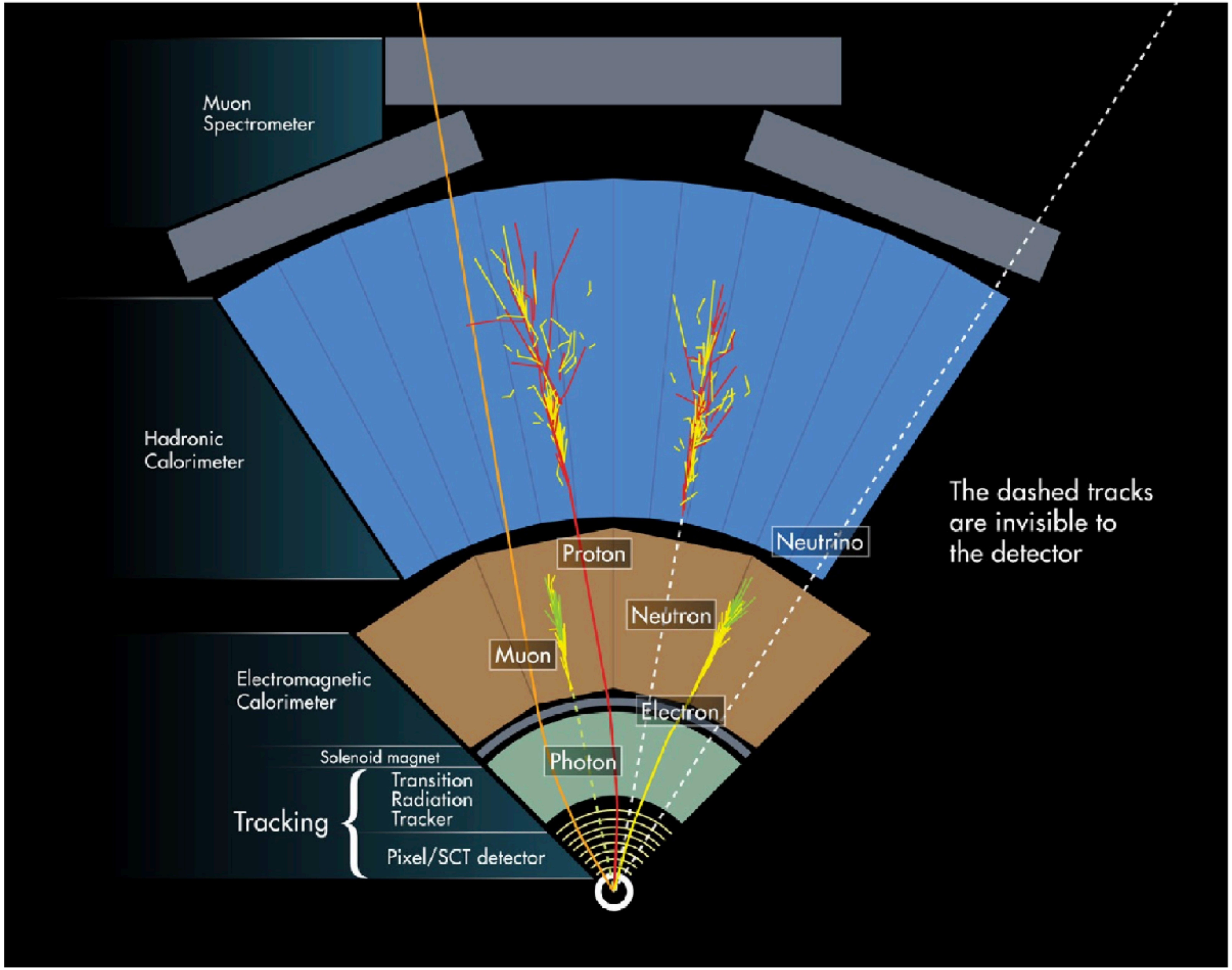
Collider detectors

A typical detector of LEP / Tevatron / LHC (ATLAS is the only remarkable exception)



A typical experiment: CMS

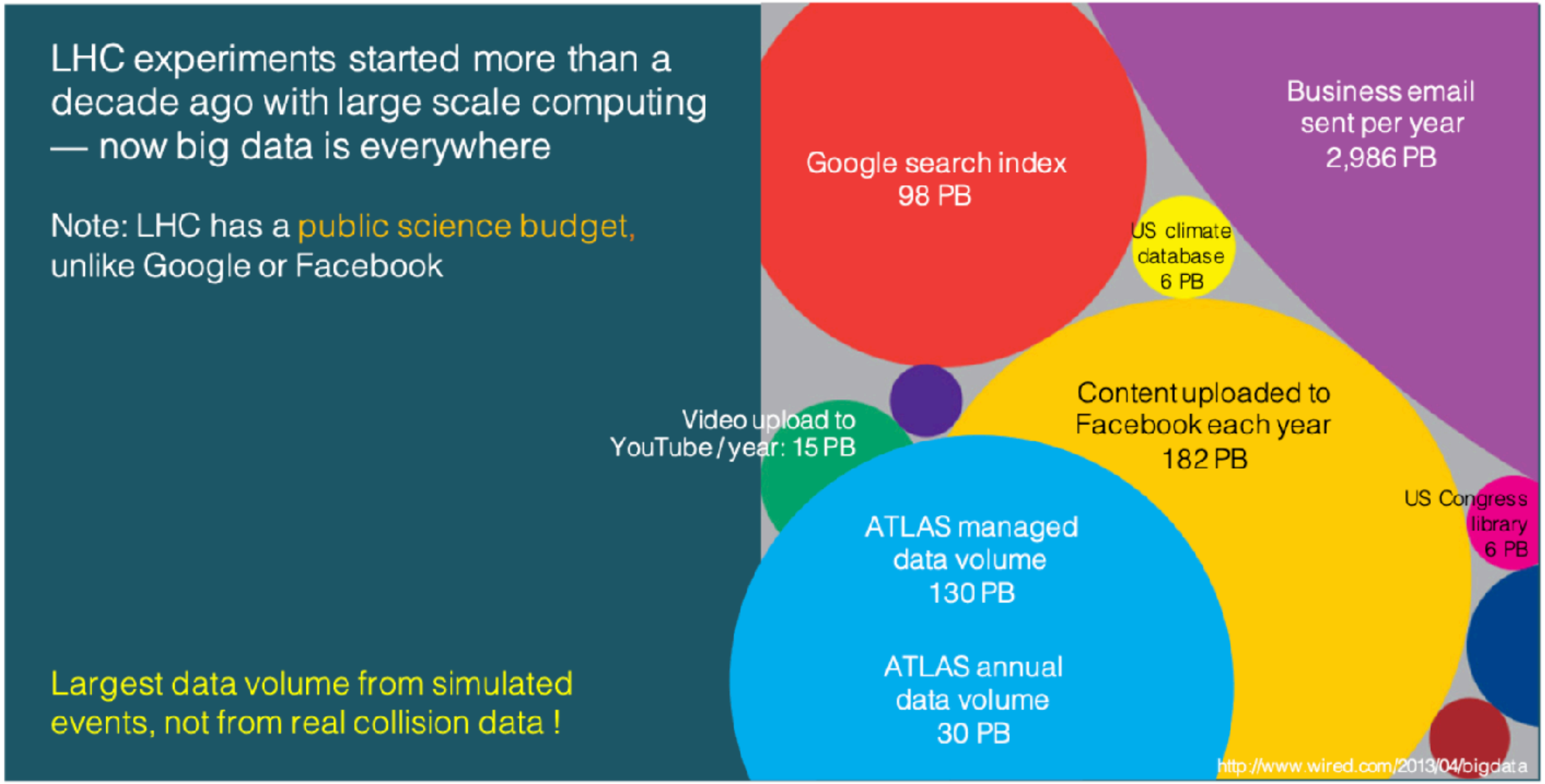
Detecting particles



An event display

The Data volume

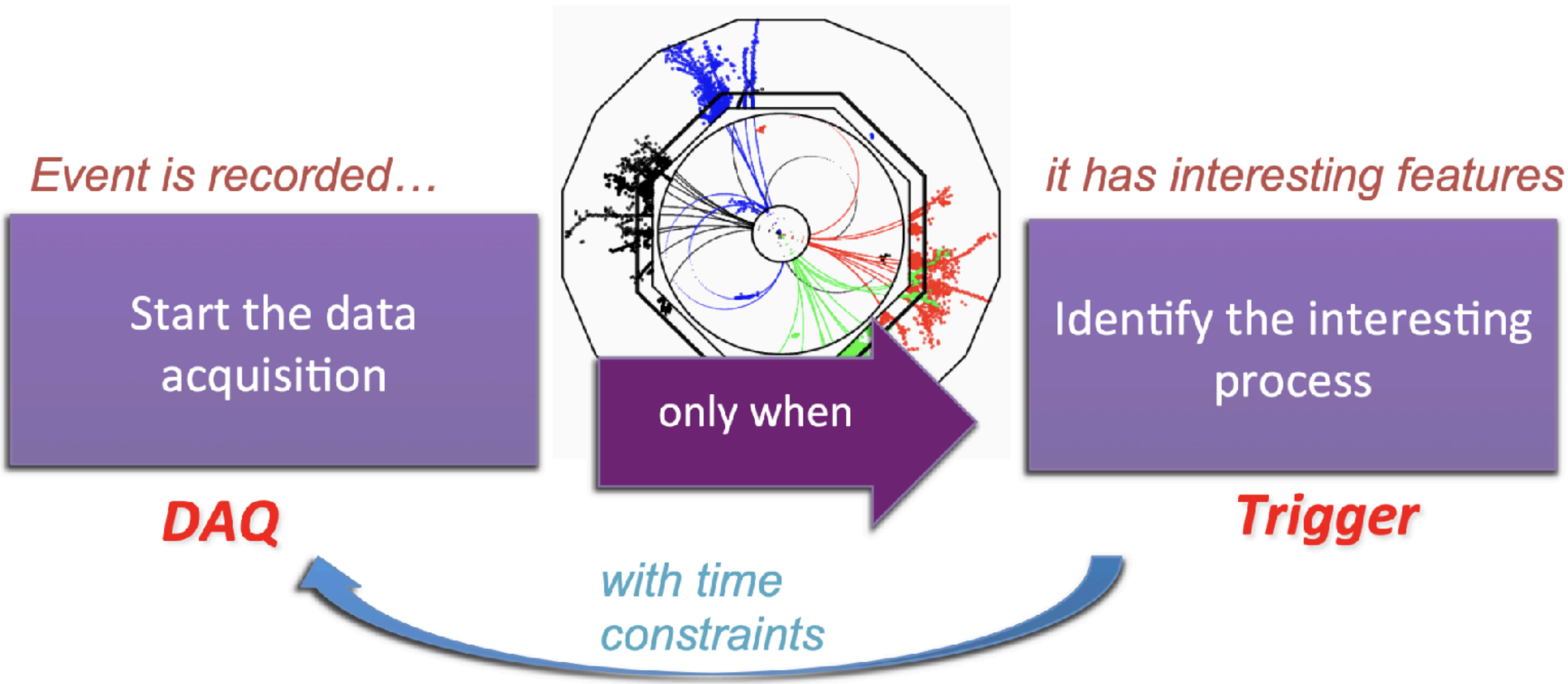
- ATLAS is designed to observe up to 1.7 billion proton-proton collisions per second, with a combined data volume of more than 60 million megabytes (MB) per second



- A picture on an iPhone is ~3Mb —> equivalent to 20000 pictures/second

Triggering

At the LHC we cannot (and do not want to) record all events



Computing challenges

Read out and reconstruct approximately **O(100M)** electronics channels at ~1 kHz.

Trigger Challenge : select ~400-1000 out of 20M events per second while keeping the interesting (including unknown) physics

Computing Challenge : reconstruct, store and distribute 1000 complex events per second and the very large amount of simulation (over 100 PB per experiment - Several farms of over 200k Cores).

Analysis Challenge : Maintain high (and as much as possible stable) reconstruction and identification efficiency.

CERN Computing Center

- **Machine Learning** : Ideal environment to develop Machine Learning techniques: in particular in areas such as trigger, reconstruction, object identification, calibration and Pile up Mitigation.

Kinematics

In pp collisions the longitudinal momentum of the system is not known a priori
However the transverse momentum should vanish
Event kinematics described by variables invariant under boosts in the z-axis

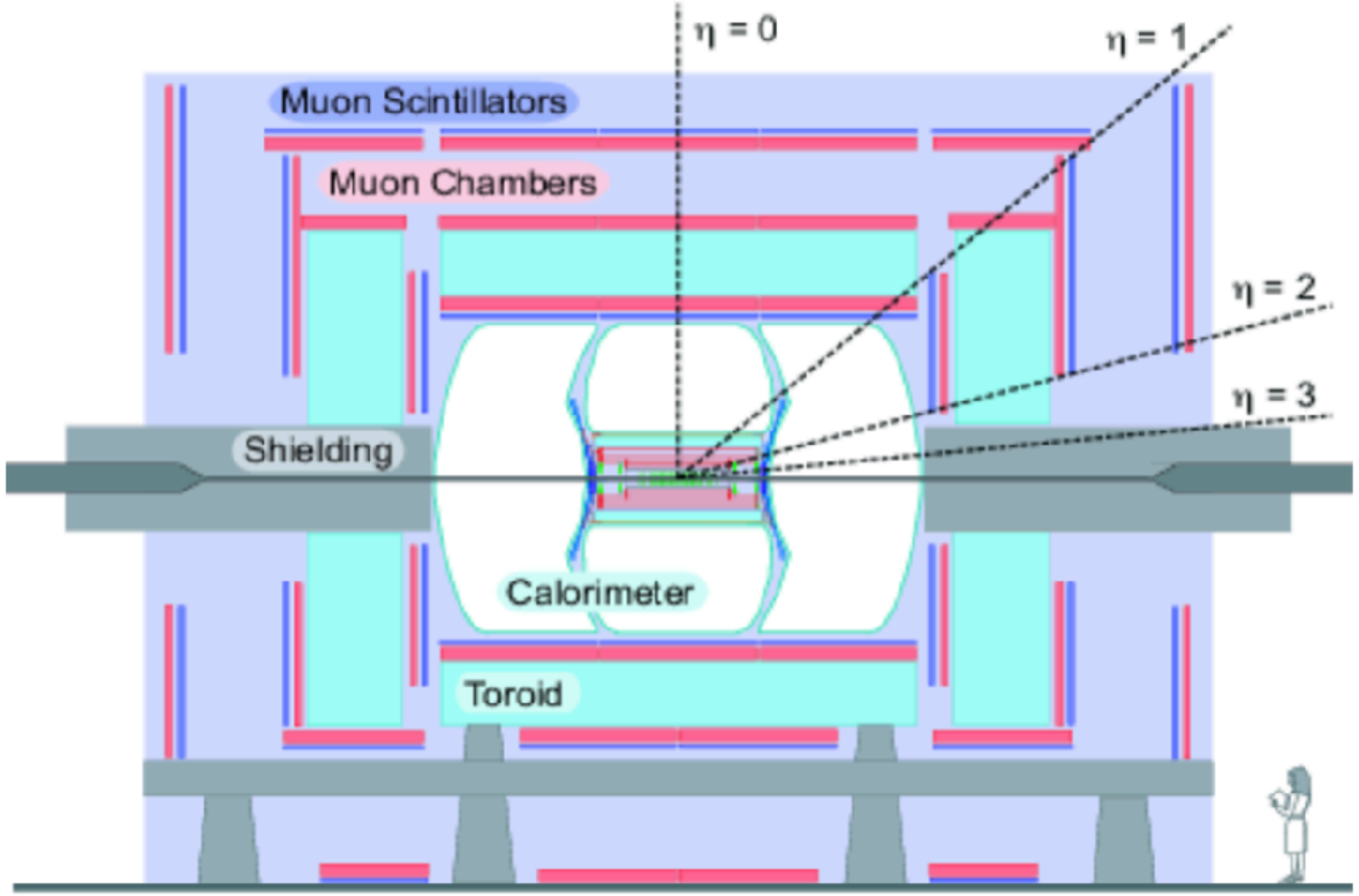
Rapidity

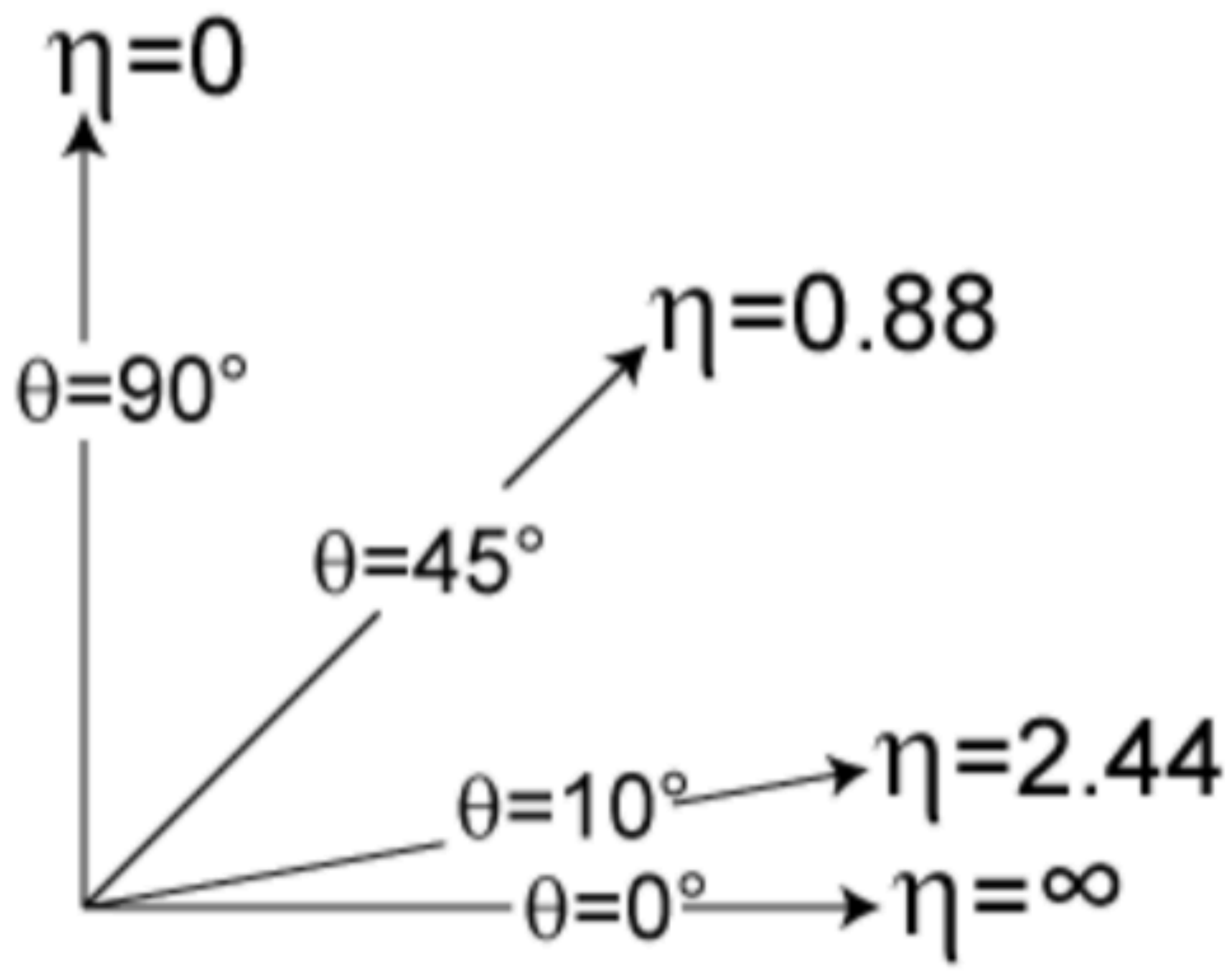
Not Lorenz invariant, but differences are

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

Pseudorapidity
for massless particles

$$\eta = -\ln\tan\frac{\theta}{2}$$

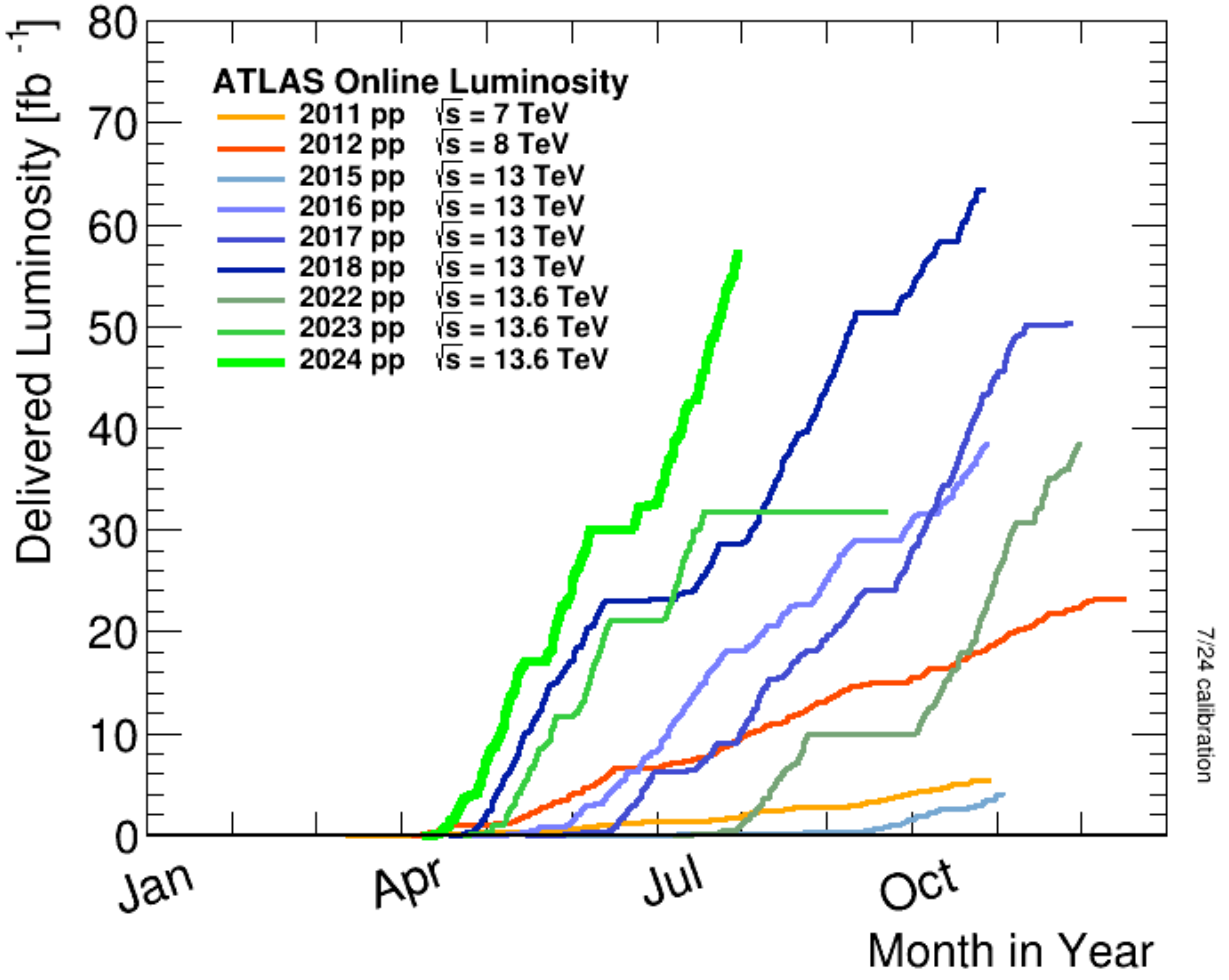




Transverse momentum p_T
momentum perpendicular to the beam direction

LHC operations

- The goal of a collider experiment is to collect the highest possible integrated luminosity in the best possible conditions for the experiments



- The LHC has delivered ~ 20 fb^{-1} in Run1 and ~150 fb-1 in Run2 to the experiments
- Outstanding performances over time
- Short turn-around time and stable conditions

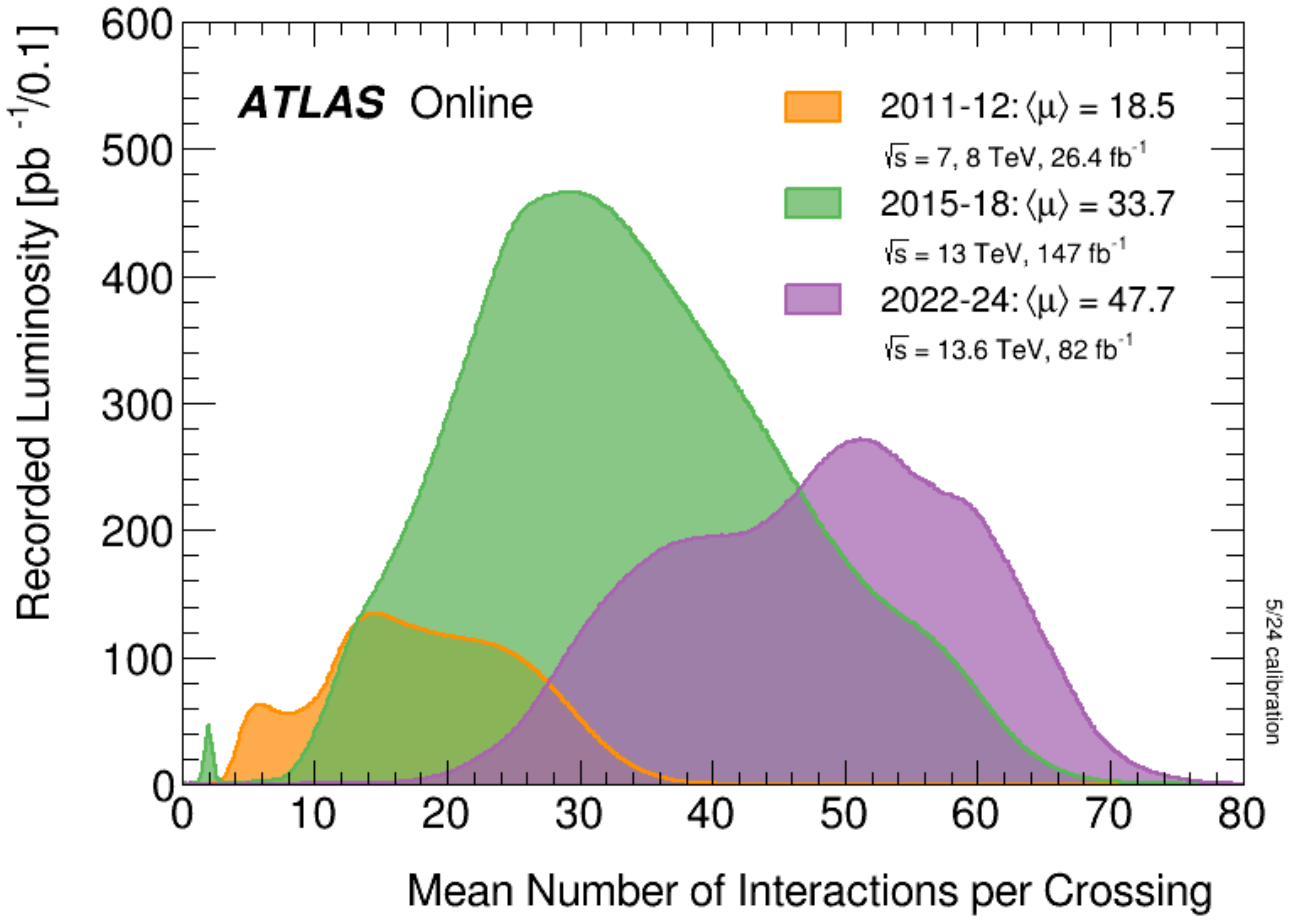
Pile-up

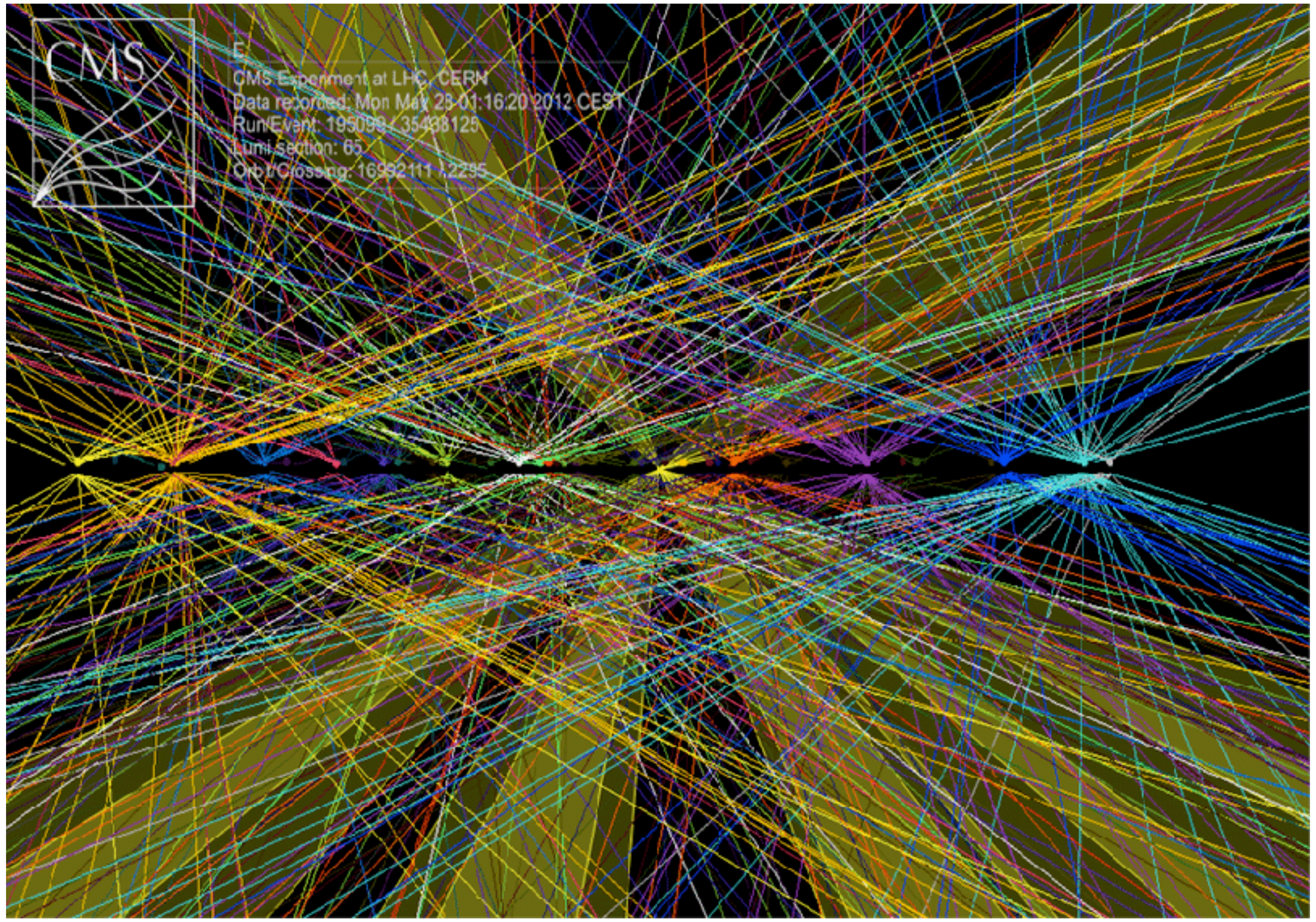
But increasing the instantaneous luminosity comes at a cost:
pile-up, number of inelastic collisions per bunch crossing

Bunch crossing frequency ~30 MHz, a collision of bunches every 25 ns

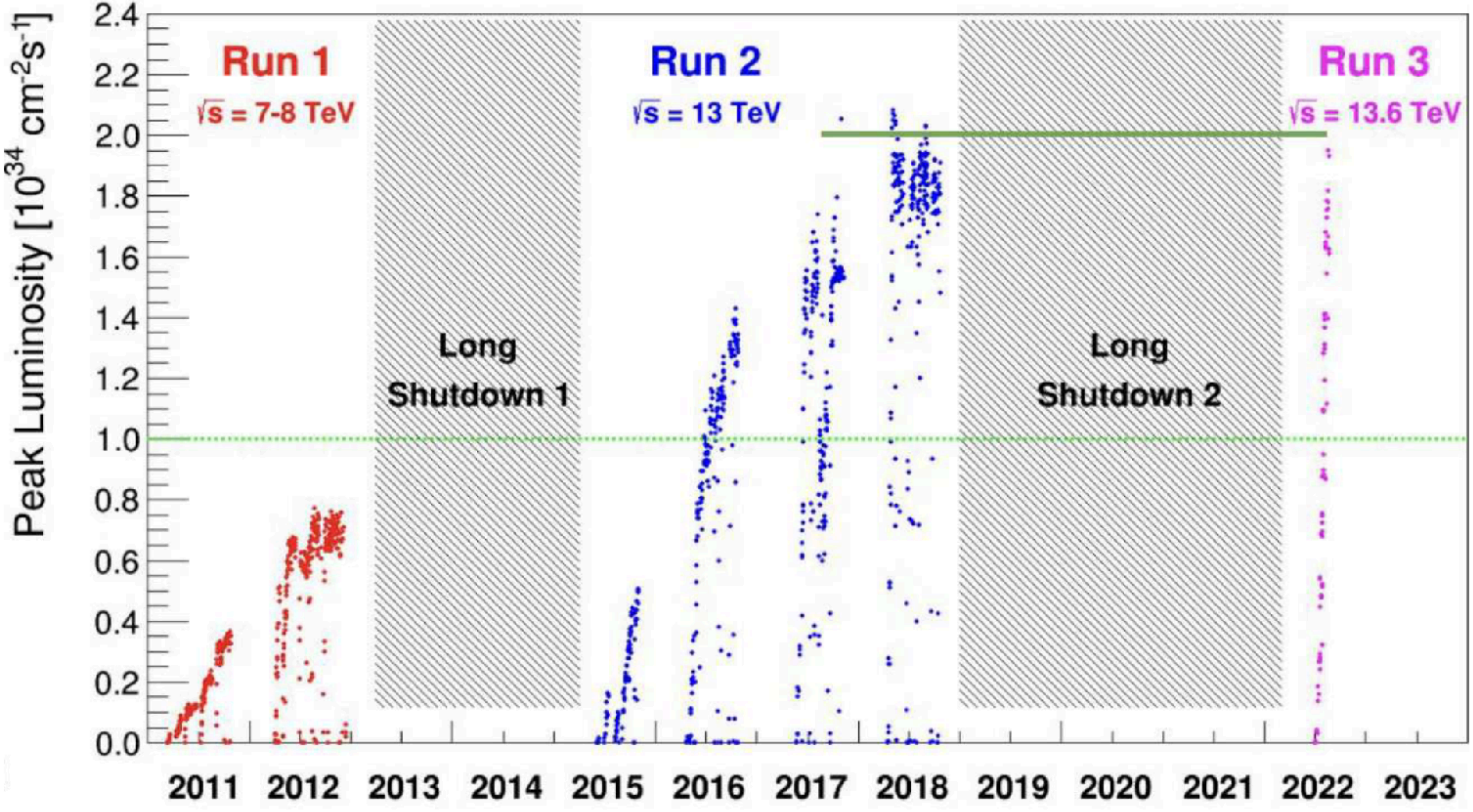
Up to 2808 proton bunches per beam, each with 10^{11} protons

- LHC reached average number of pile-up interactions of 40-60



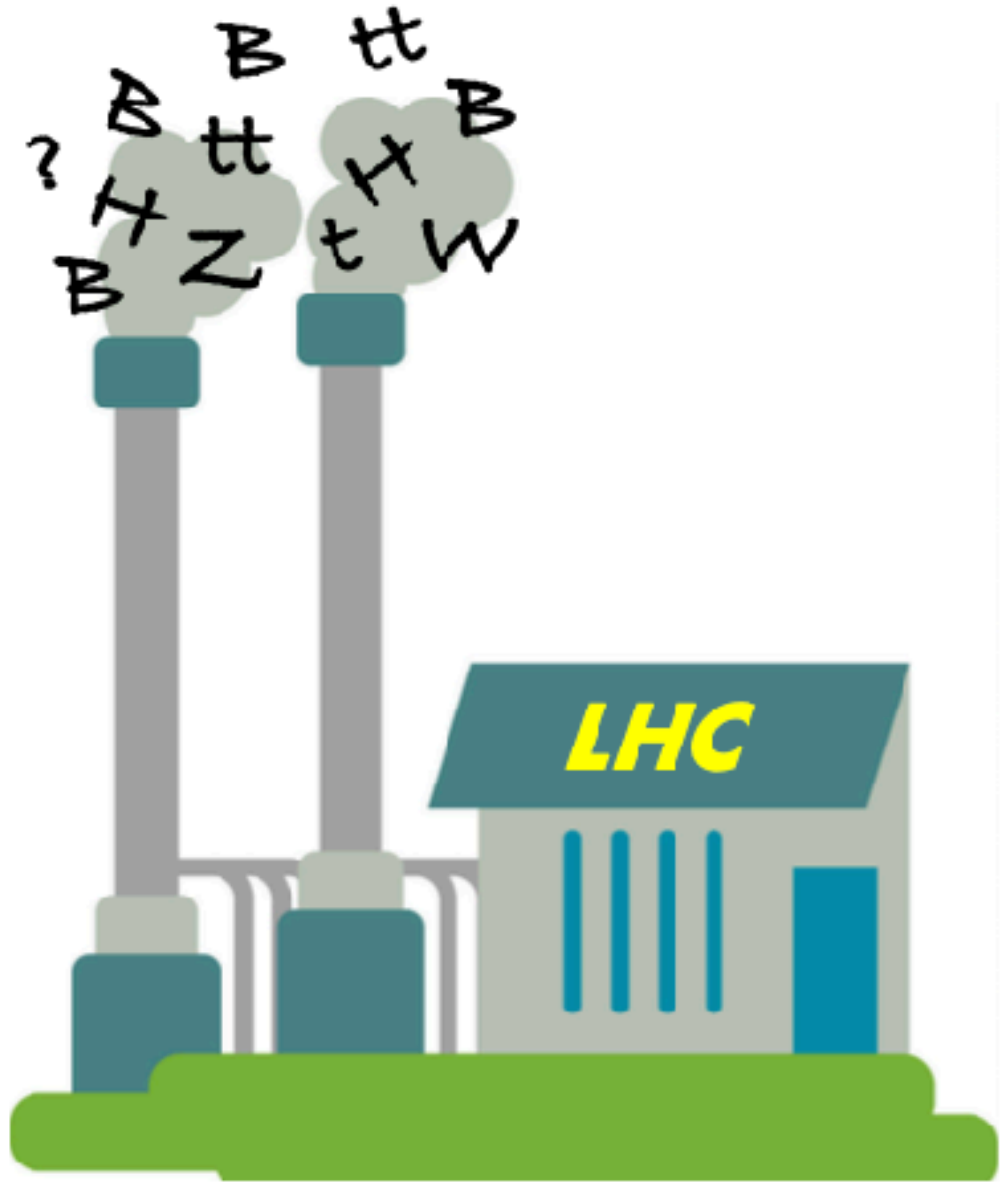


STATUS OF THE LHC



The LHC is an "everything factory"

Particle	Produced in 140 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\rightarrow \ell\ell$, 290 million)
W boson	12 billion	($\rightarrow \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)



The LHC "mission"

- **The no-loose theorem:** Either discover the Higgs boson or reveal new strong dynamics in vector boson scattering

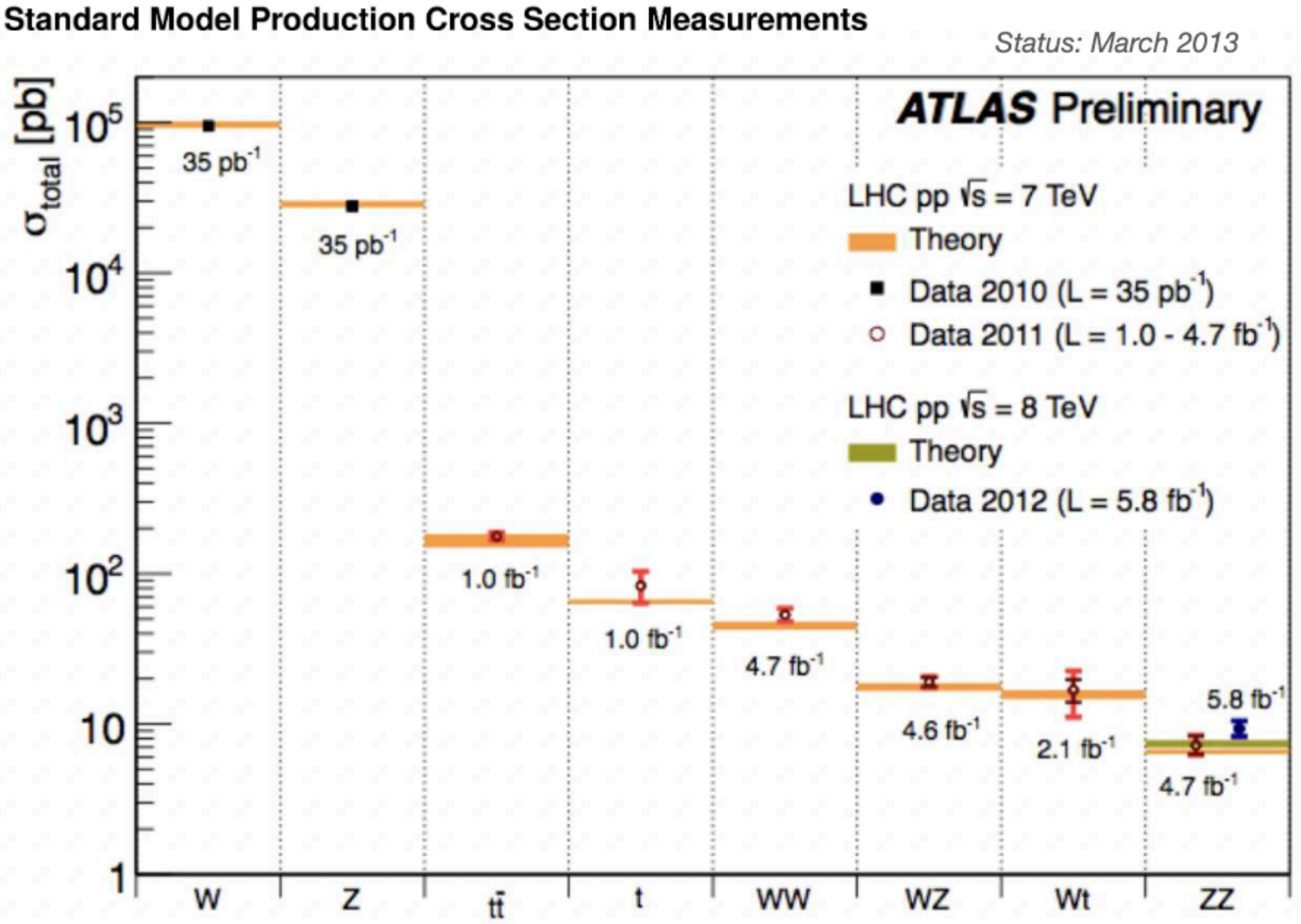
- **Probe the electroweak scale** with direct searches for new particles and forces beyond the Standard Model

- **Prove the Standard Model at higher scales** through indirect searches: CP-violation in Heavy Flavors, precision measurements of Higgs couplings, EW parameters, …

- **Study strongly interacting matter** at extreme energy densities in proton and heavy-ion collisions

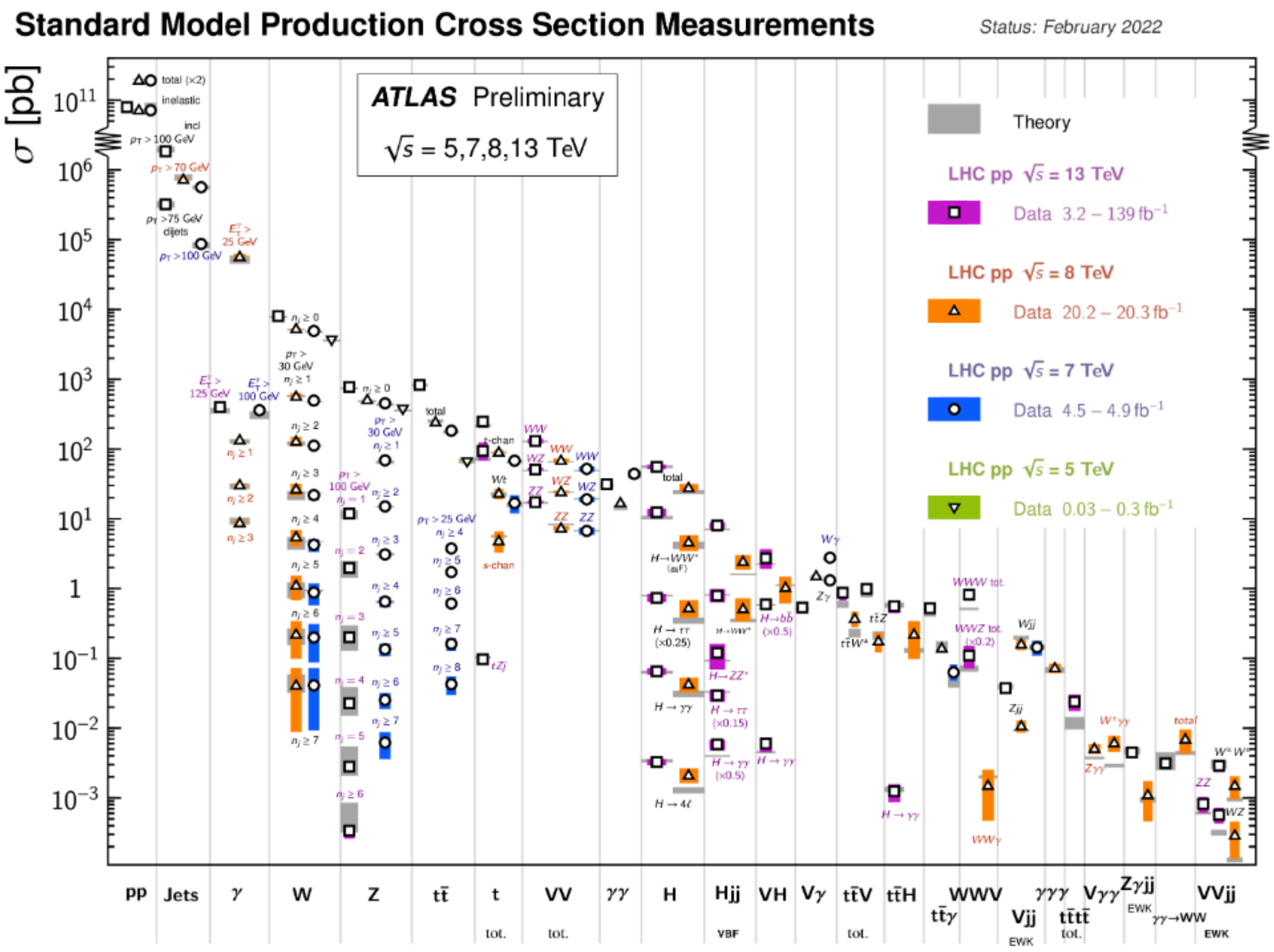
In all these areas the LHC is already an immense success

The Standard Model at the LHC



- **Discovery of the Higgs**
- **Precision measurements** of QCD and EW processes
- Exploration of **BSM physics** via direct and indirect searches

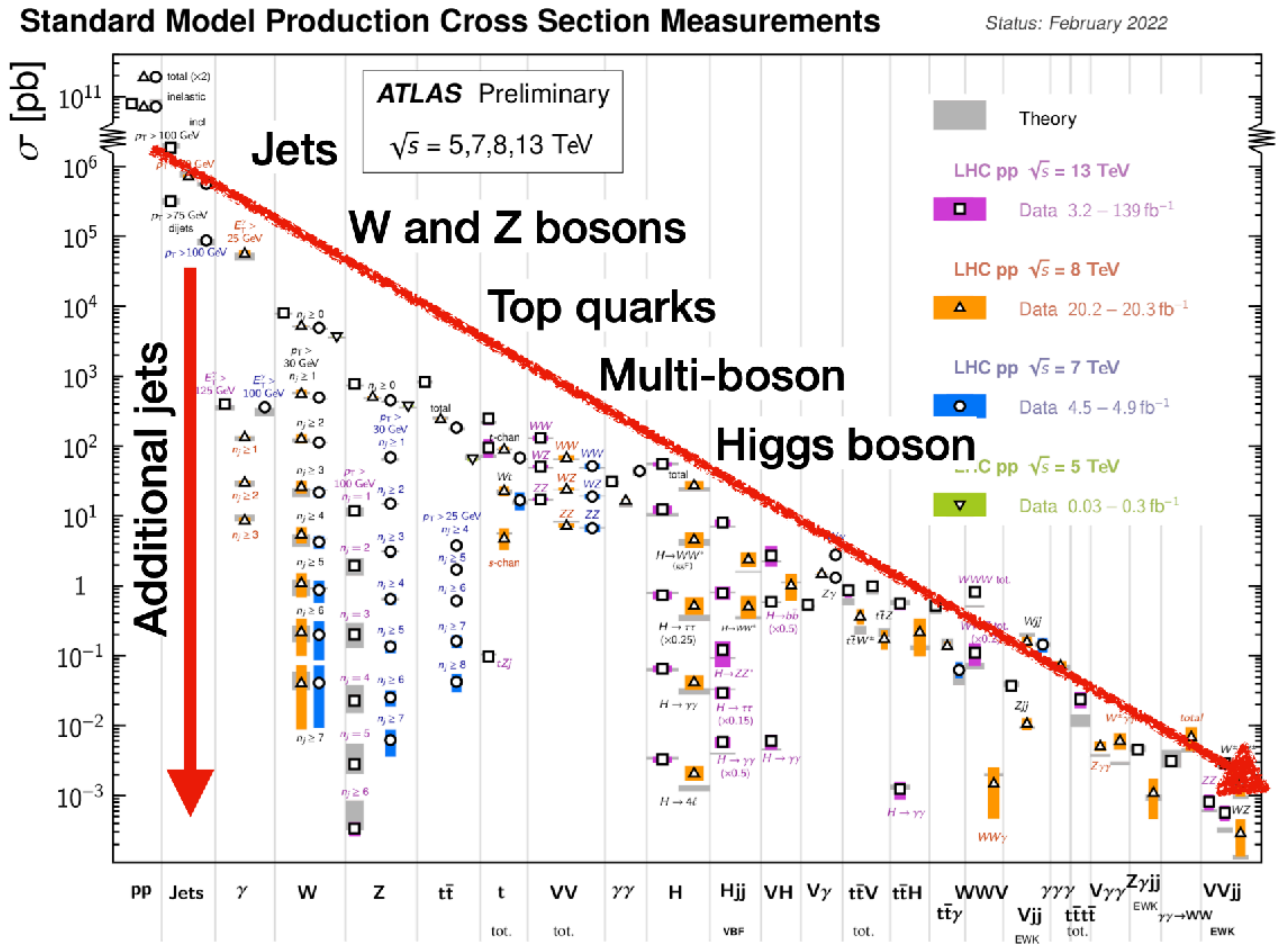
The Standard Model at the LHC



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

- **Precision measurements** of Higgs and Standard Model processes
- Observation of very **rare SM processes**
- Direct BSM searches
- Indirect BSM searches through precision measurements

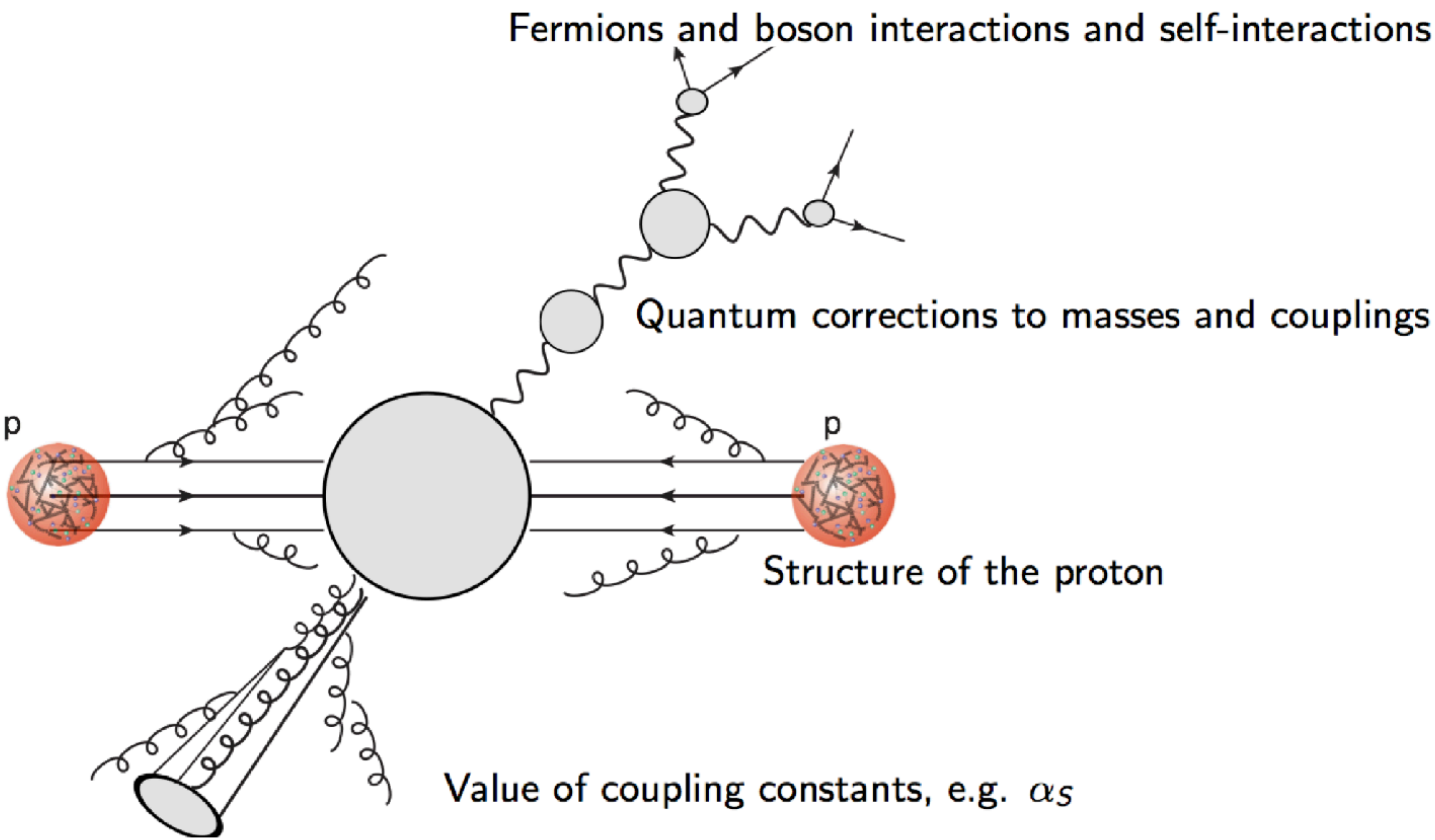
The Standard Model at the LHC



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

- Precision measurements of Higgs and Standard Model processes
- Observation of very rare SM processes
- Direct BSM searches
- Indirect BSM searches through precision measurements

SM measurements at the LHC



Hadronic jet Production

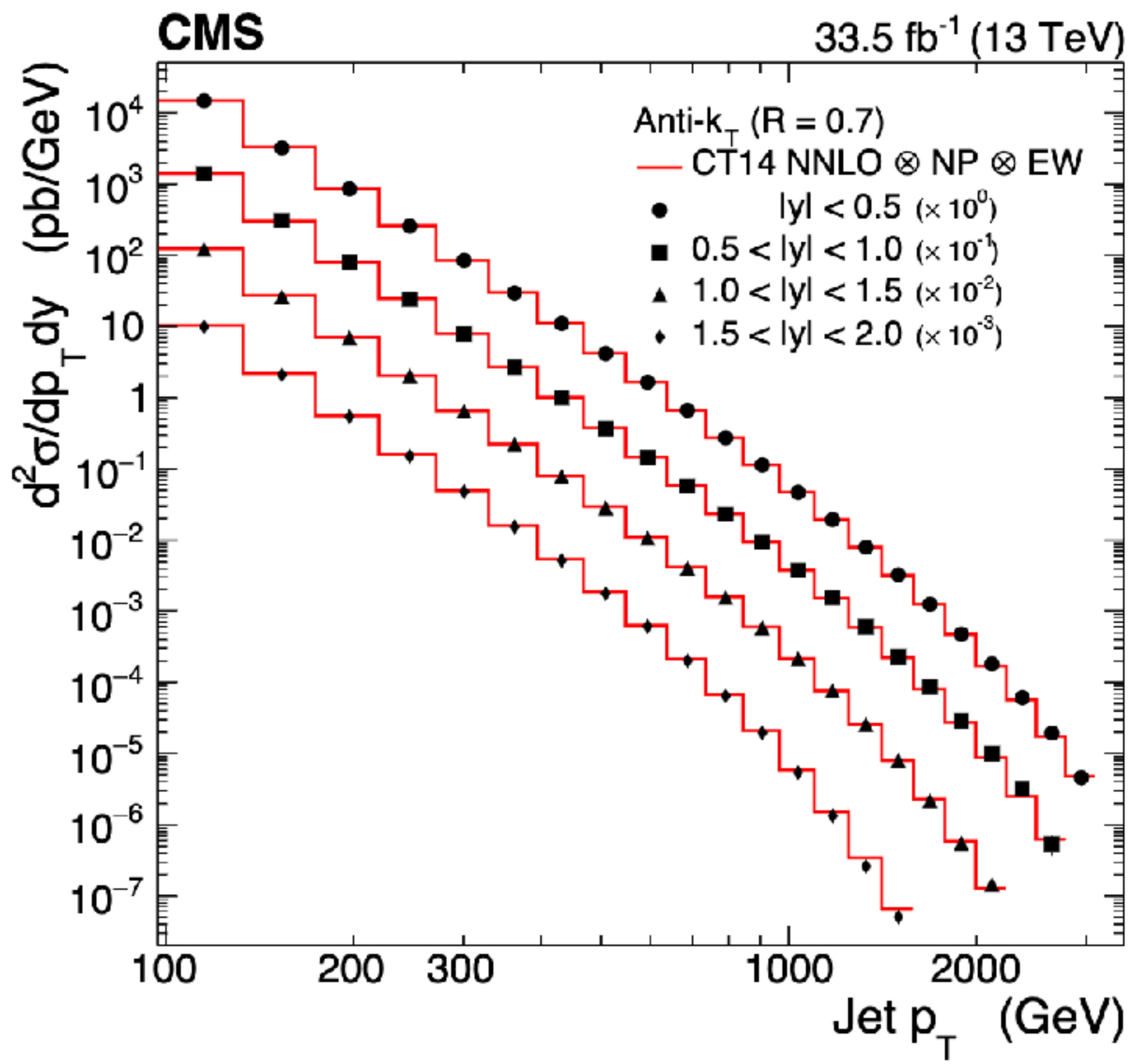
Display of a two jet event in CMS

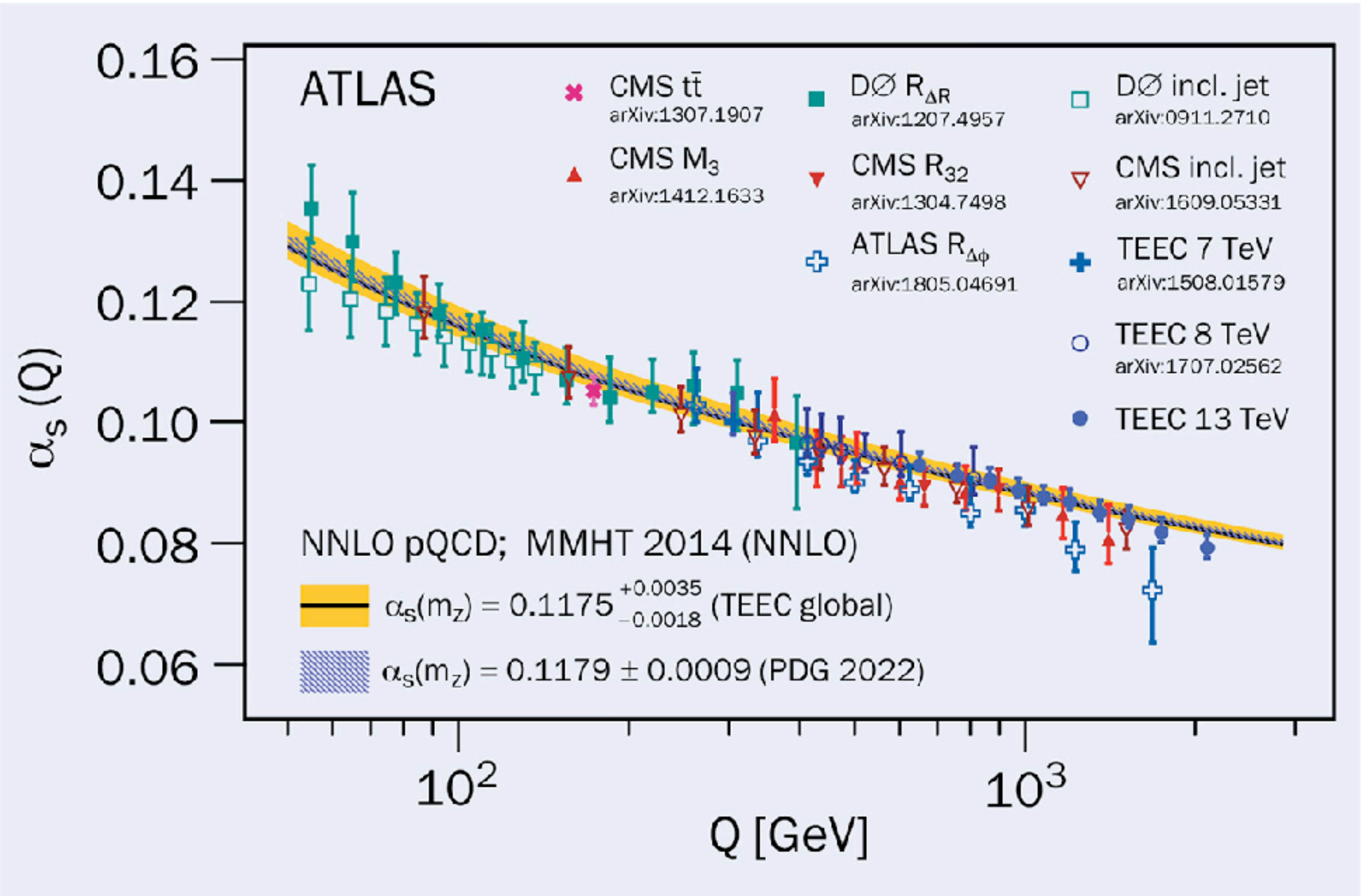
CMS Experiment at the LHC, CERN
Data recorded: 2016-Sep-27 14:40:45.336640 GMT
Run / Event / LS: 281707 / 1353407816 / 851

Inclusive jet cross-sections

- Measure the cross-section for the production of jets above a given transverse momentum
- N.B. jet-level and not event level quantity
- Sensitive to the strong coupling and its running

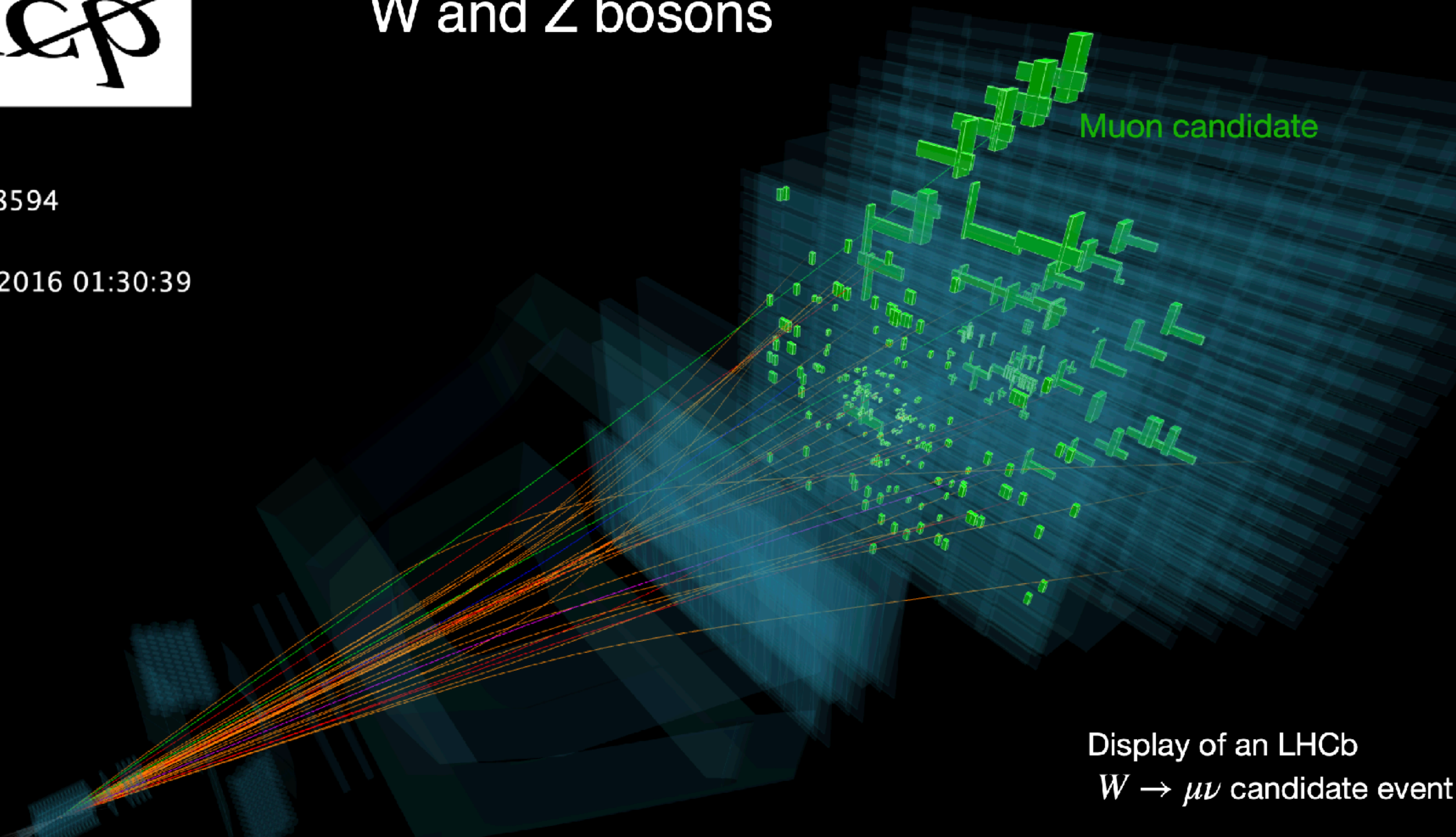
$$\frac{d^2\sigma}{dp_T\, dy} = \frac{1}{\epsilon \mathcal{L}_{\text{int}}^{\text{eff}}} \frac{N_{\text{jets}}}{\Delta p_T \Delta |y|}$$





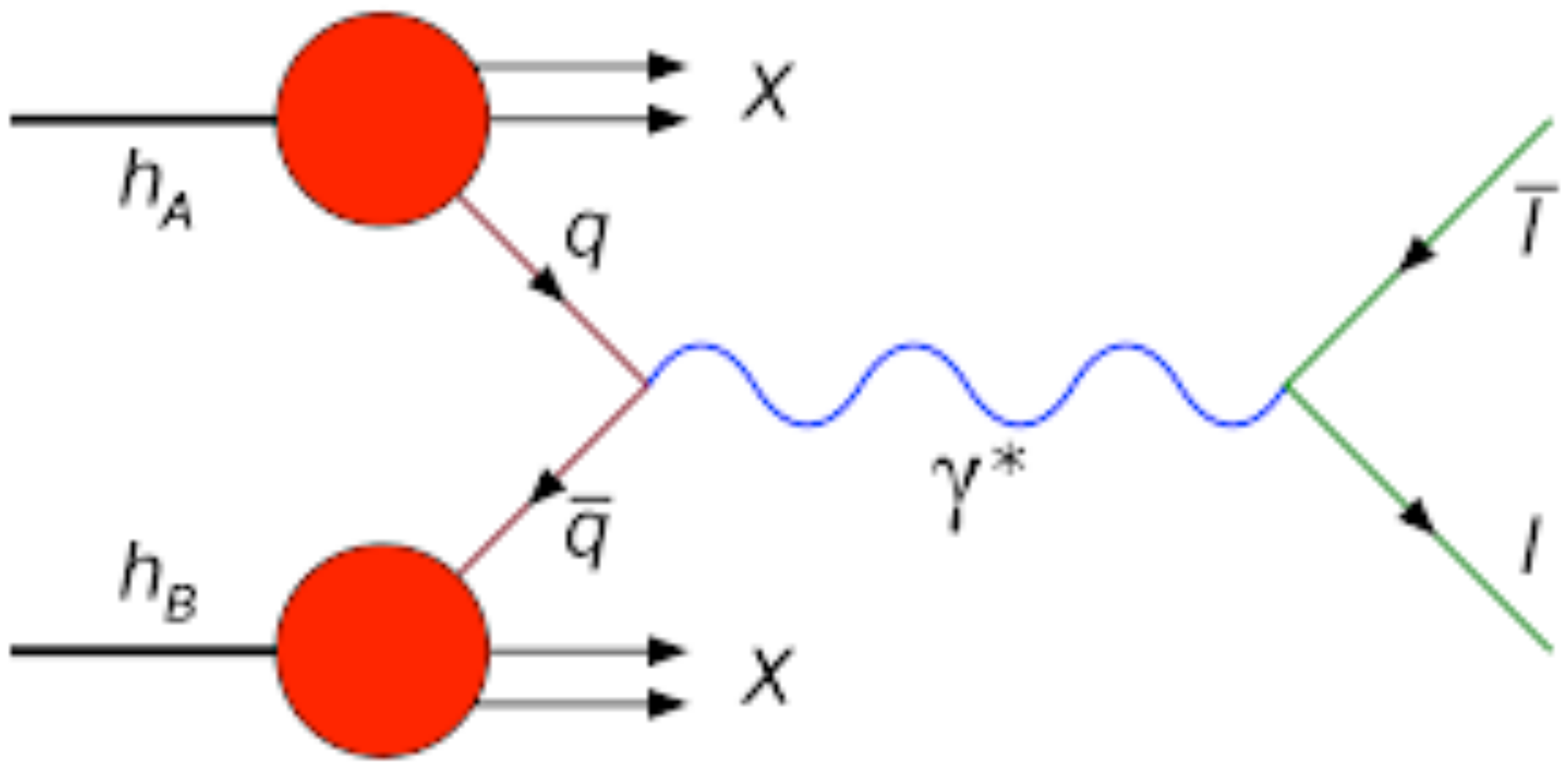
W and Z bosons

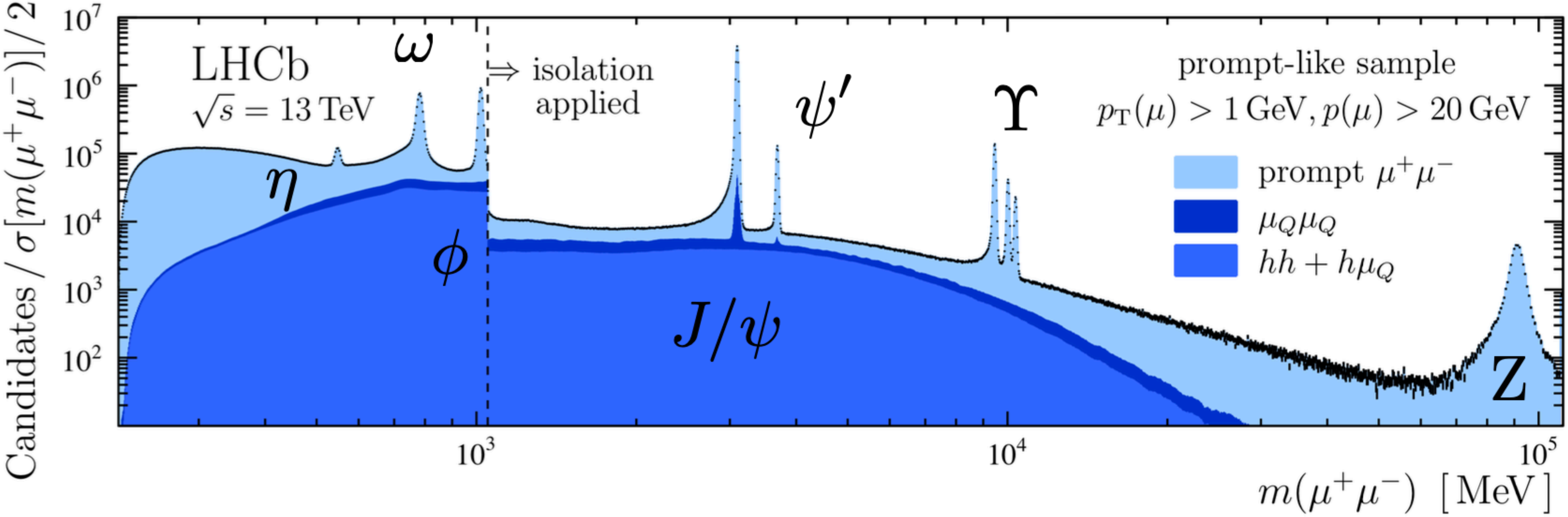
Event 506568594
Run 182153
Sun, 21 Aug 2016 01:30:39



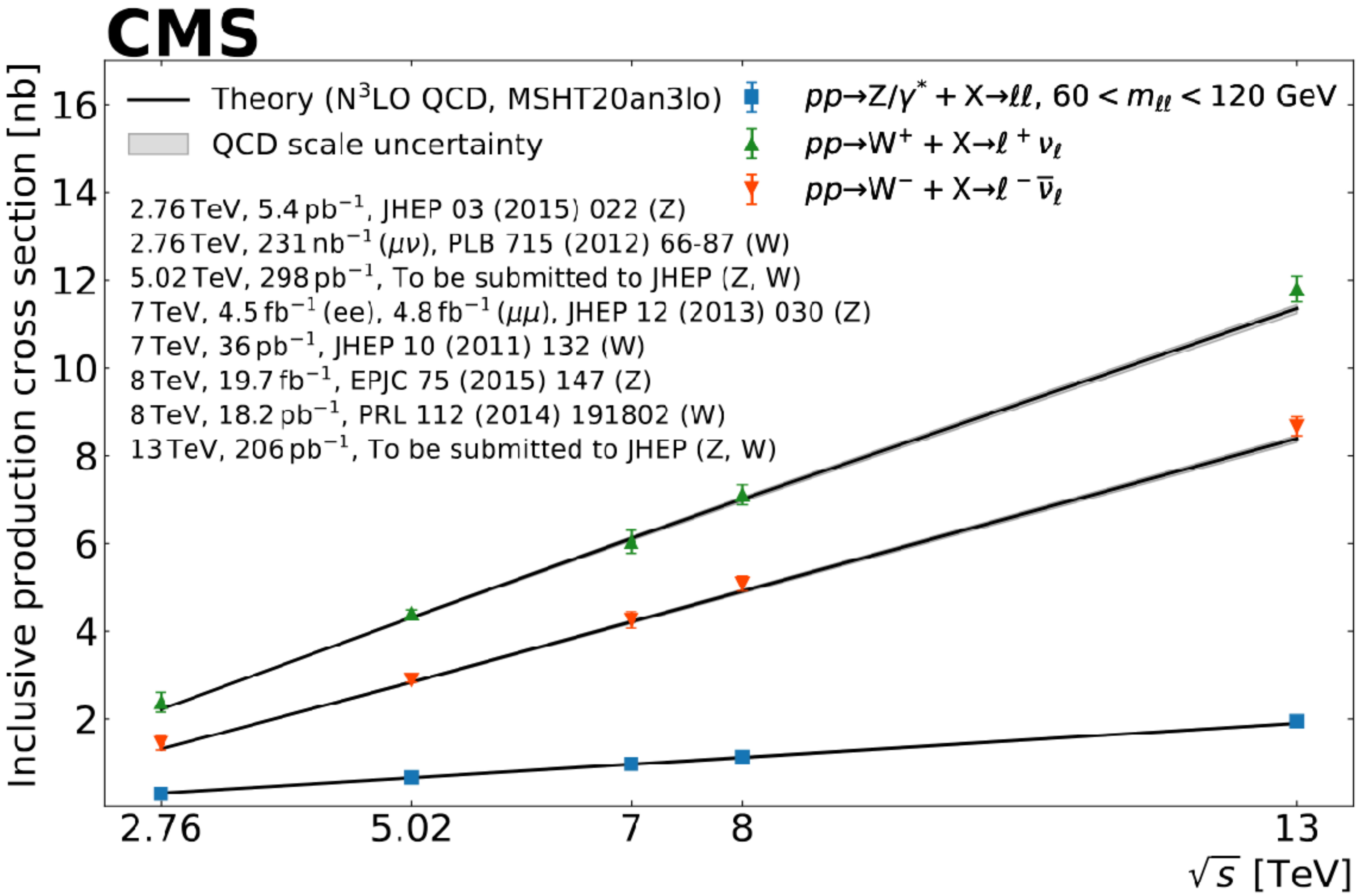
Display of an LHCb
$W \to \mu\nu$ candidate event

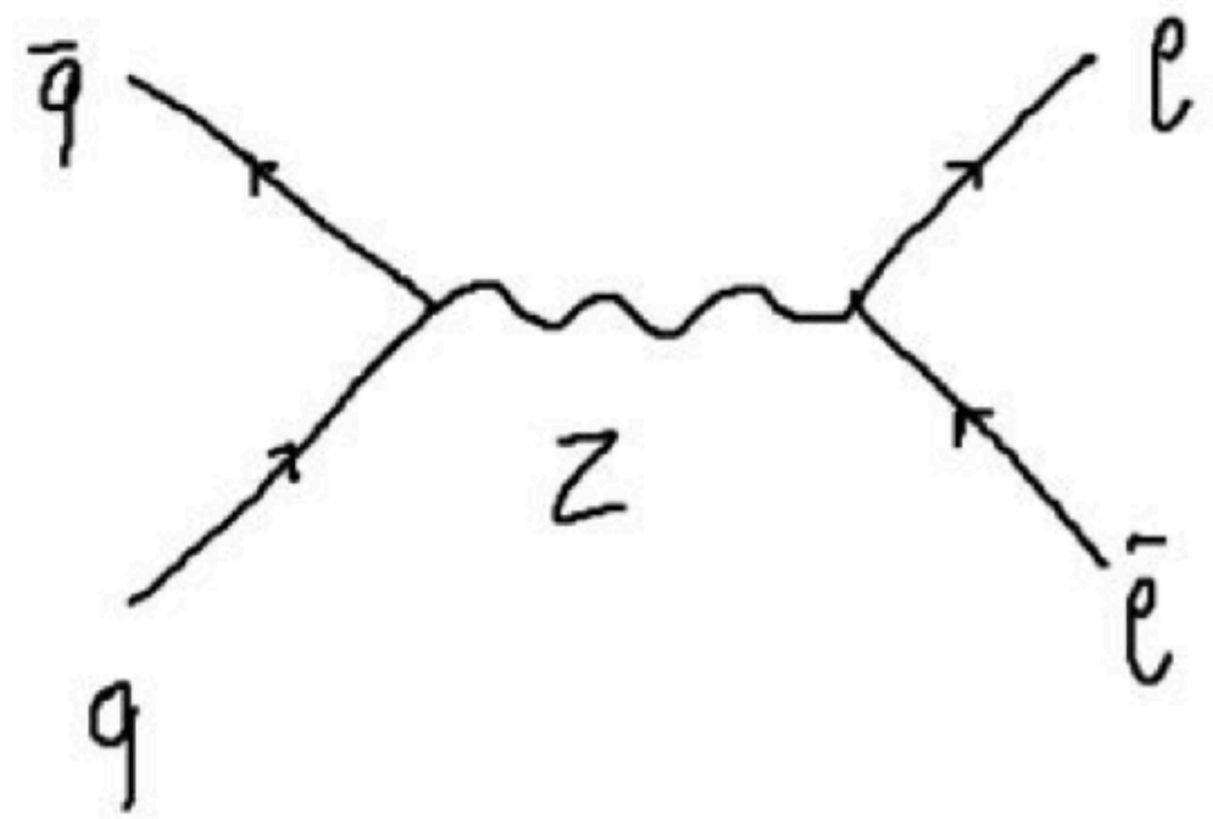
The dilepton mass spectrum at the LHC





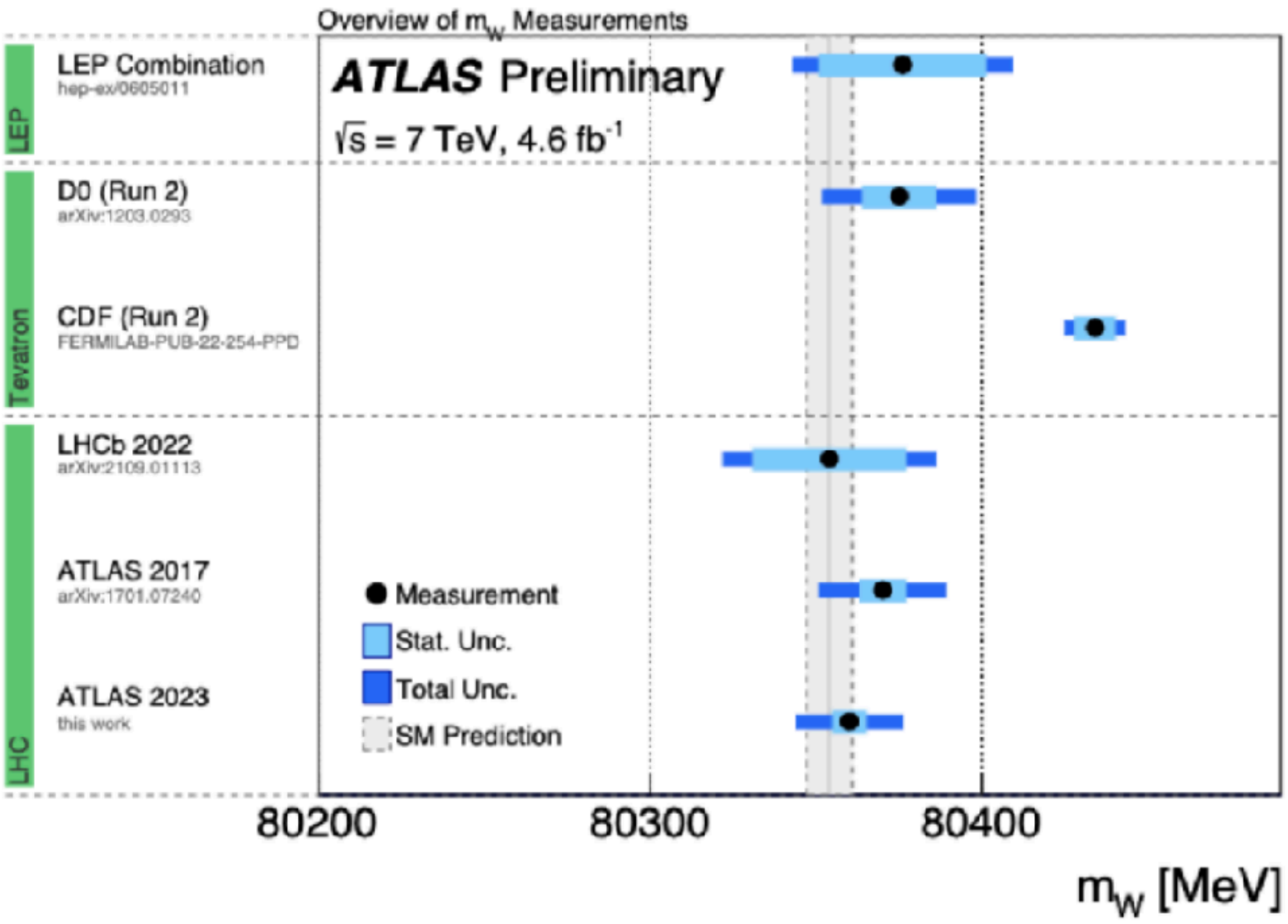
Drell-Yan measurements at the LHC

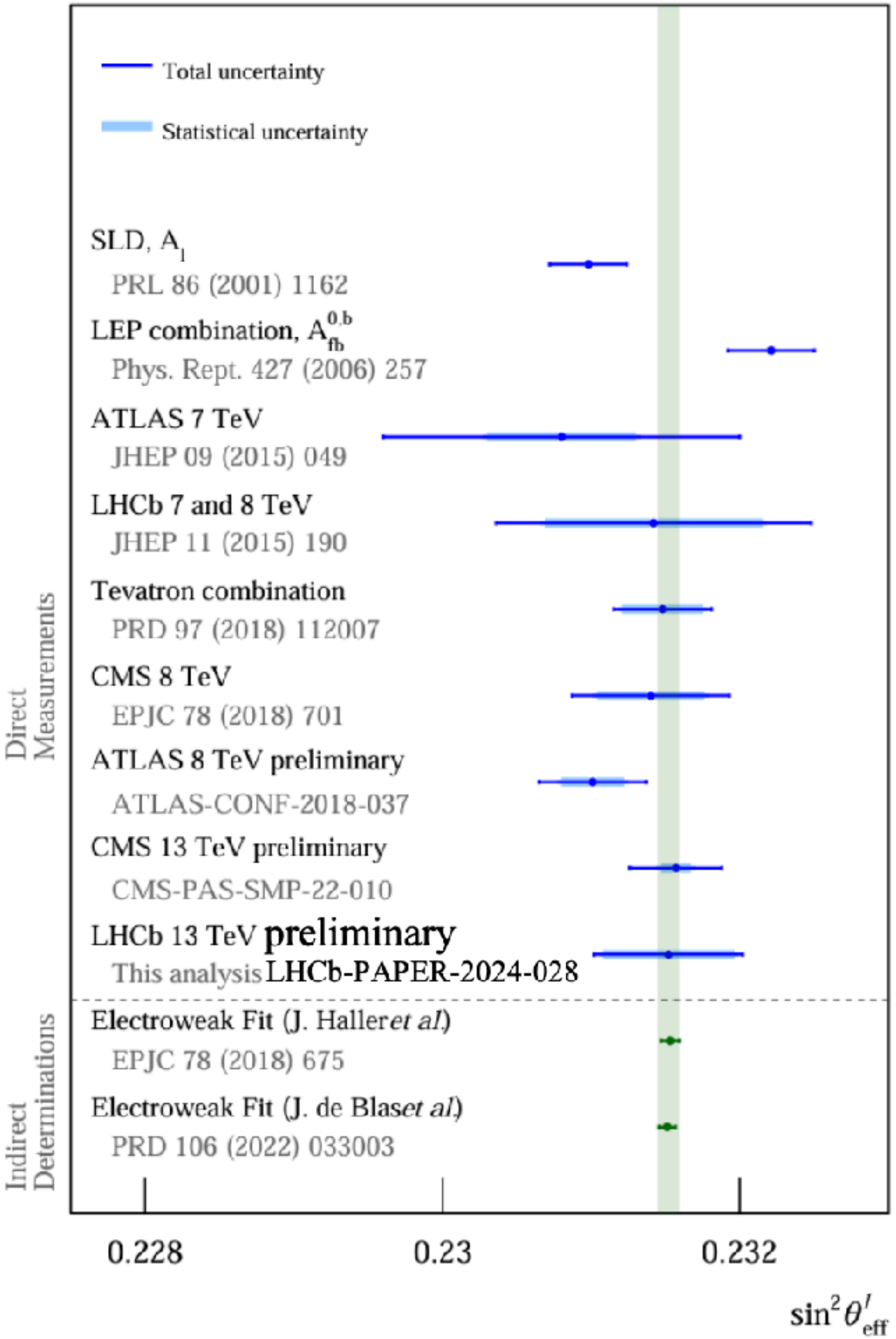




- Provide plenty of statistics for precise lepton calibrations
- Measured inclusively and differentially over a wide phase-space and at different collision energies
- Can now be predicted up to N3LO in QCD and NLO in EW

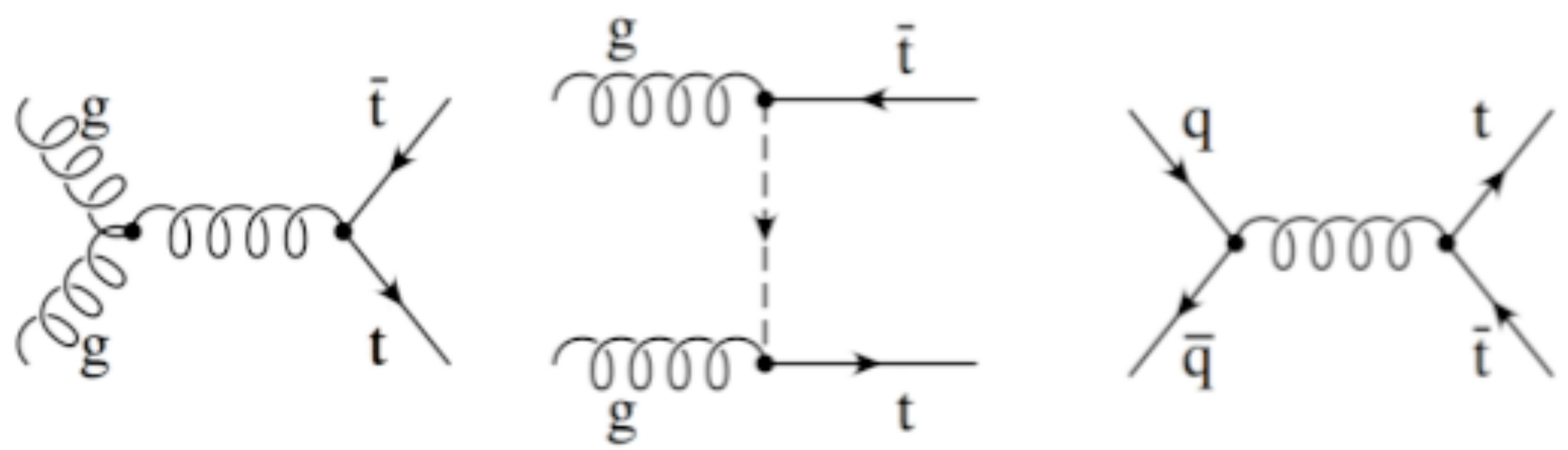
Potential for very precise measurements

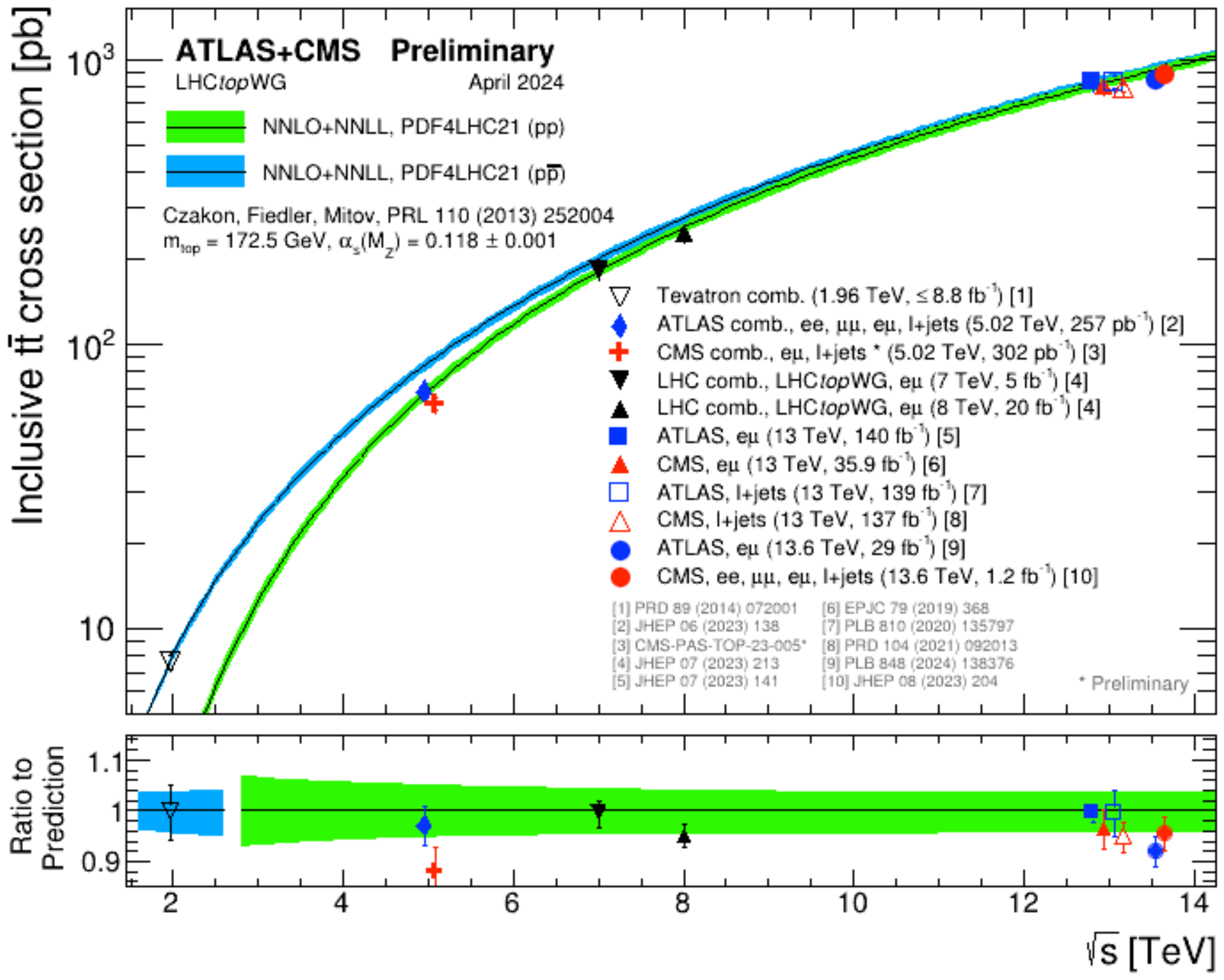


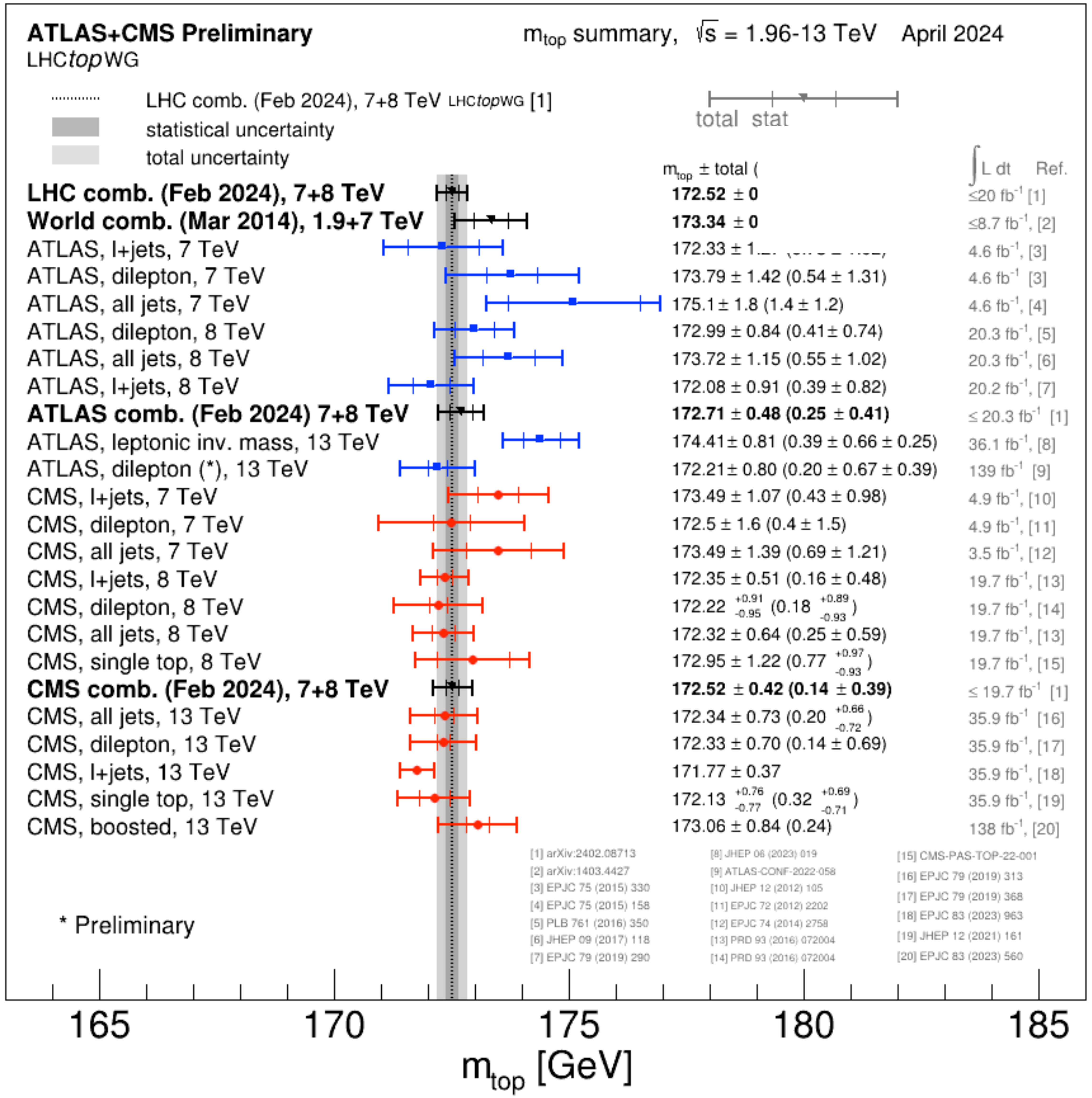



ATLAS EXPERIMENT
Top quark production
Run: 311071
Display of an ATLAS
top anti-top event in

Top pair cross-sections and mass



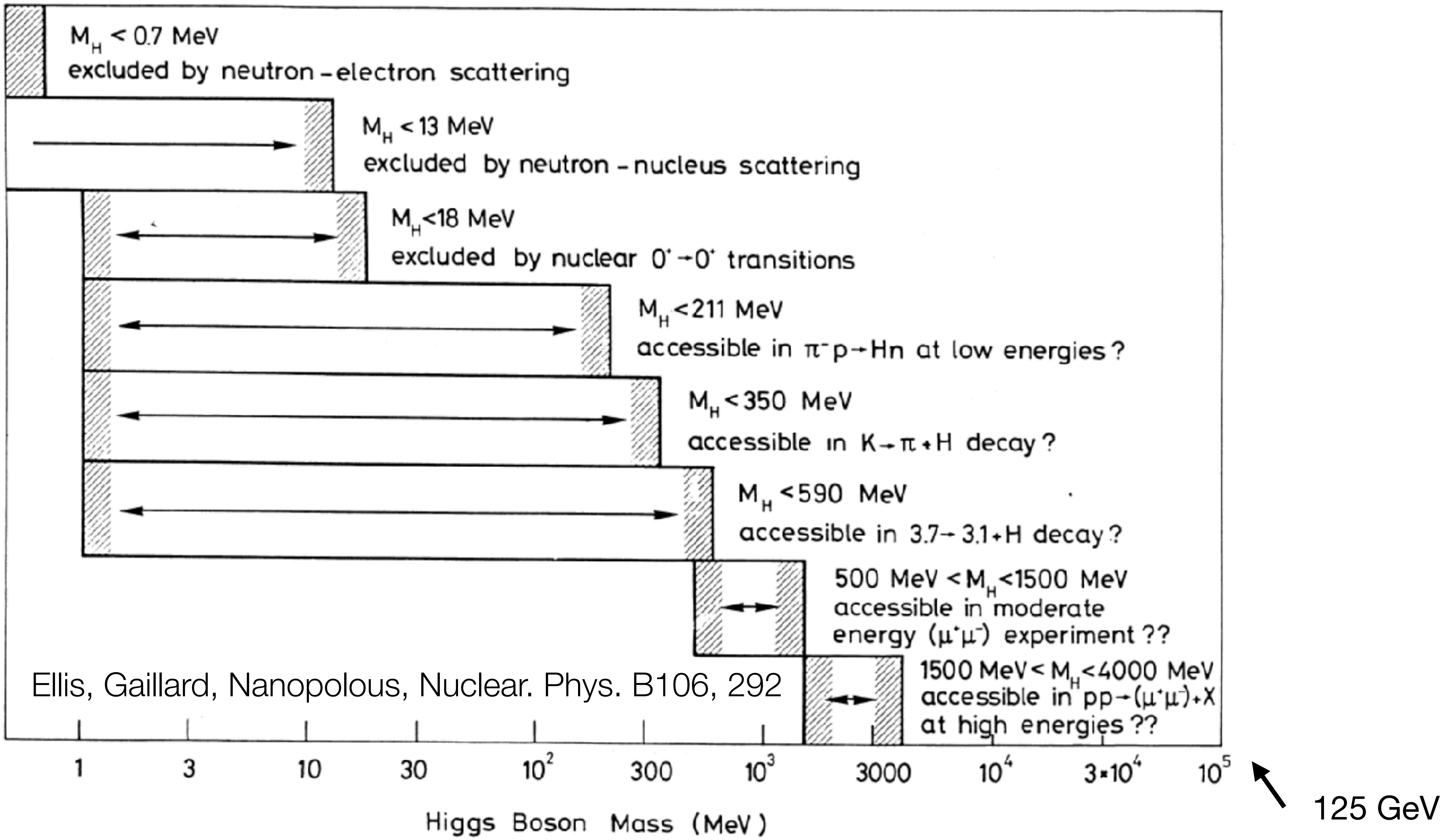




Higgs production

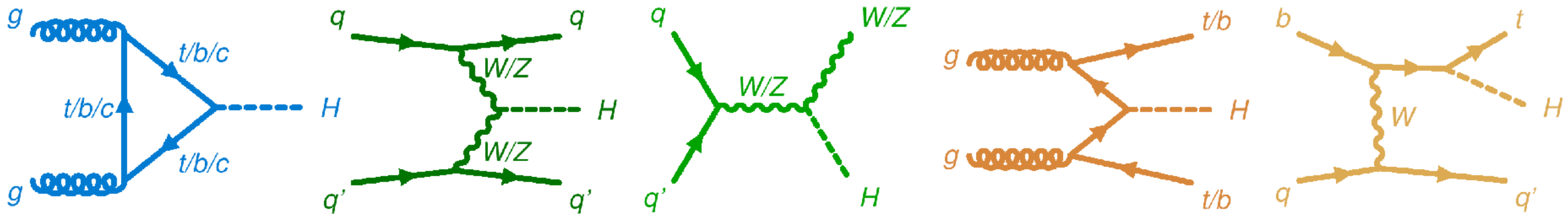
Display of an ATLAS candidate Higgs event decaying into four electrons

Higgs Searches: 1975

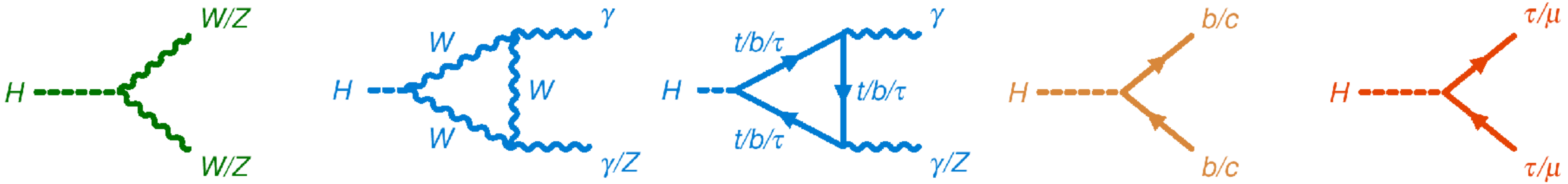


Higgs production and decay

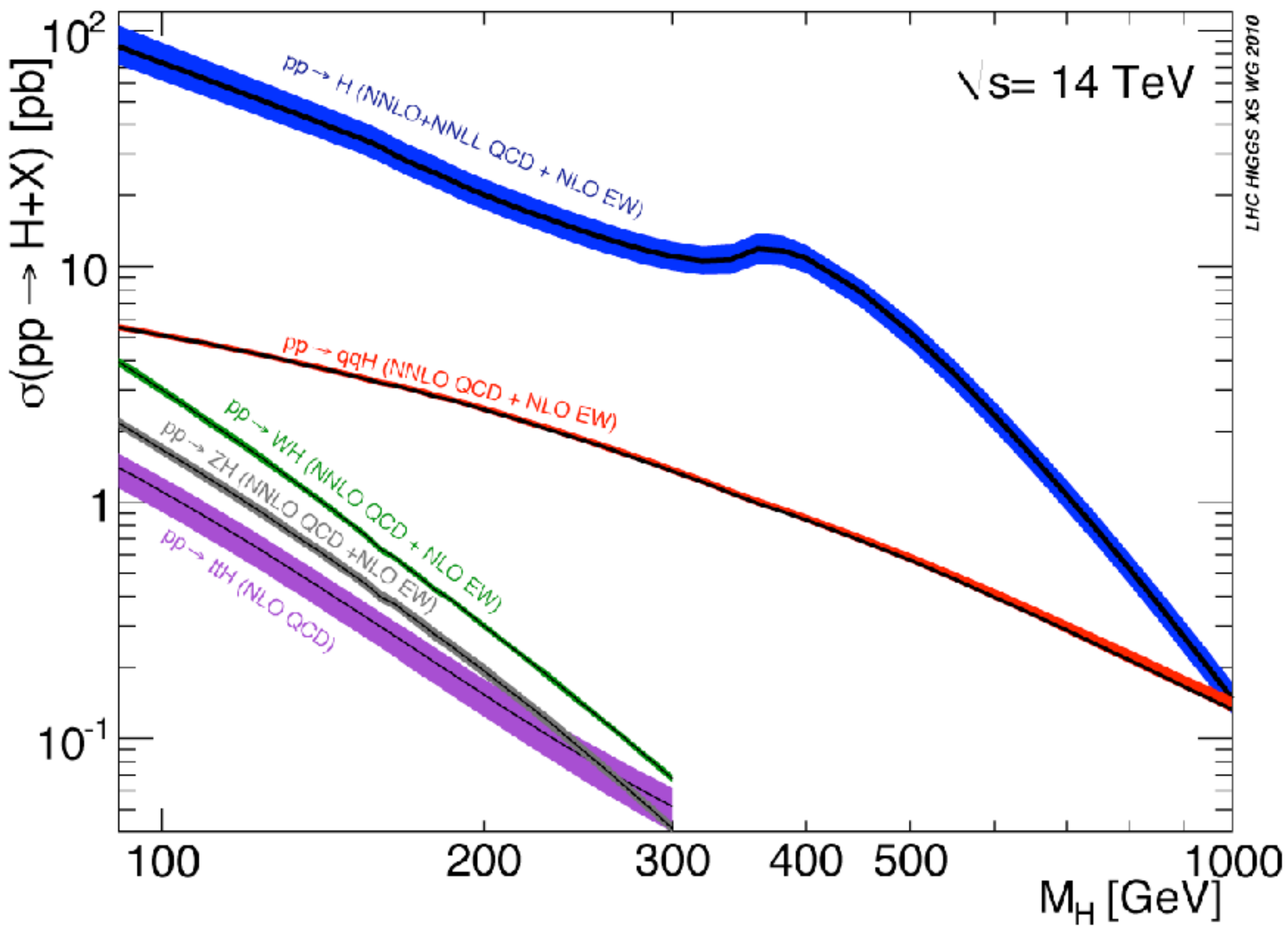
Production modes

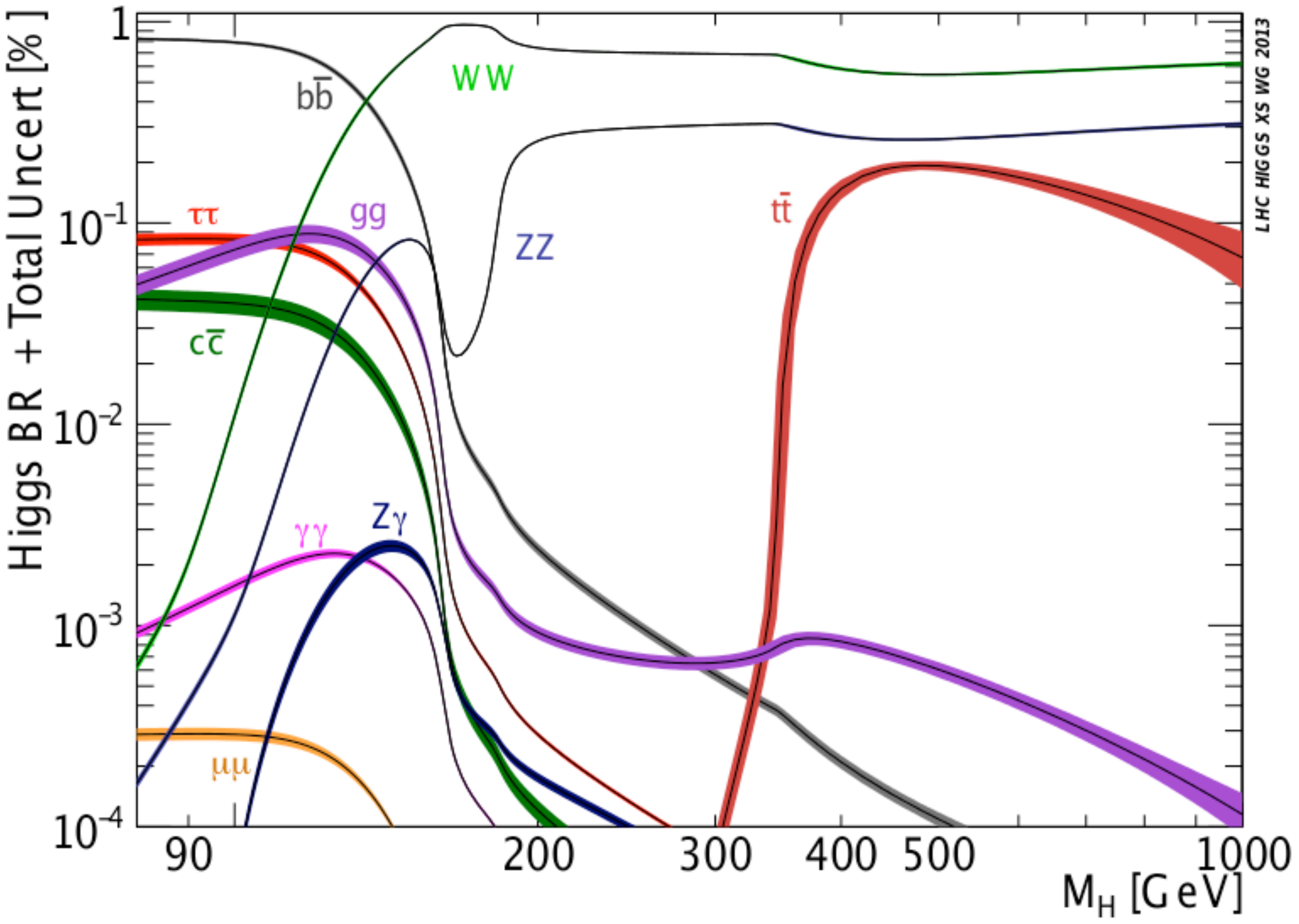


Decay modes



Higgs production and decay





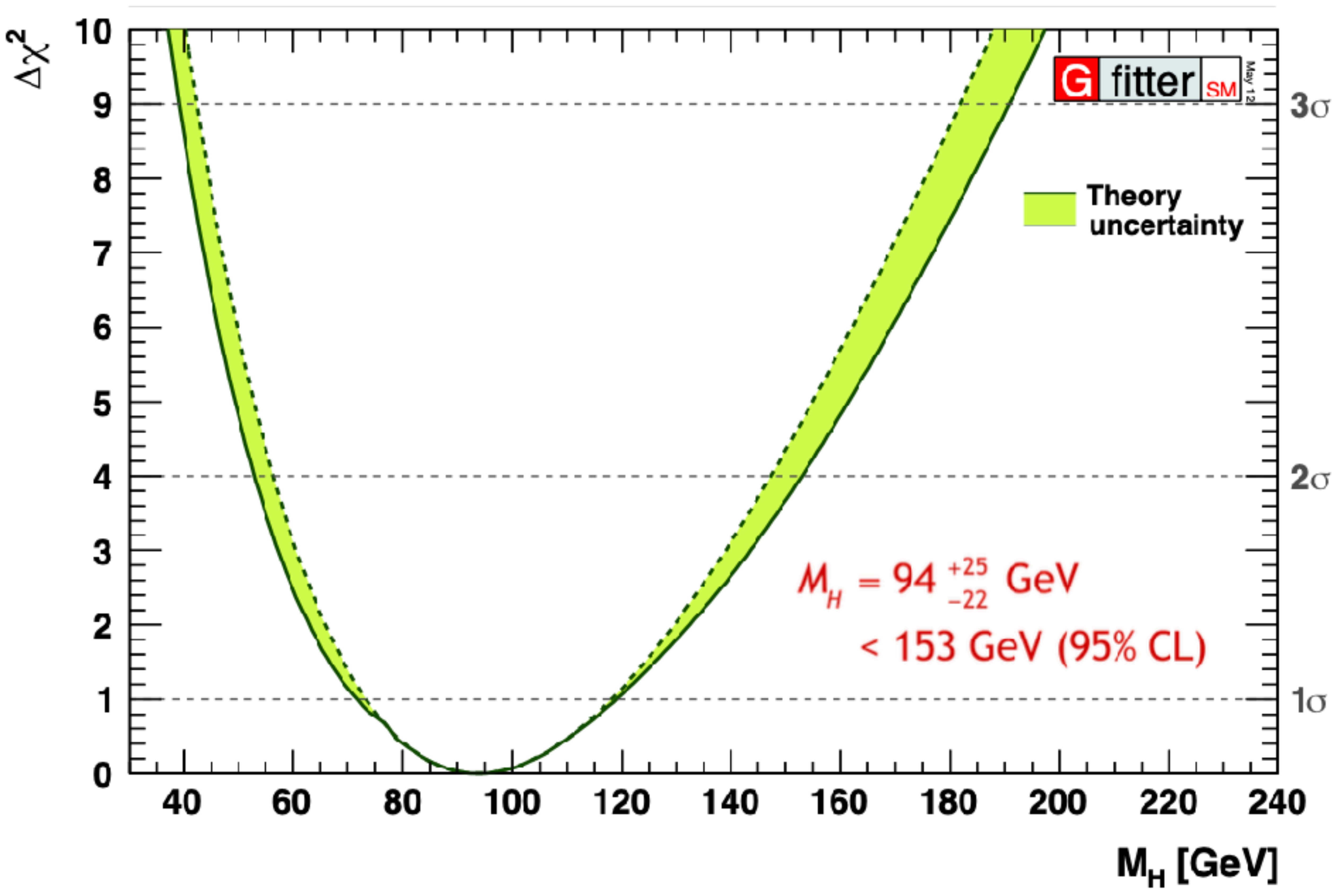
What was known about m_H before the LHC ?

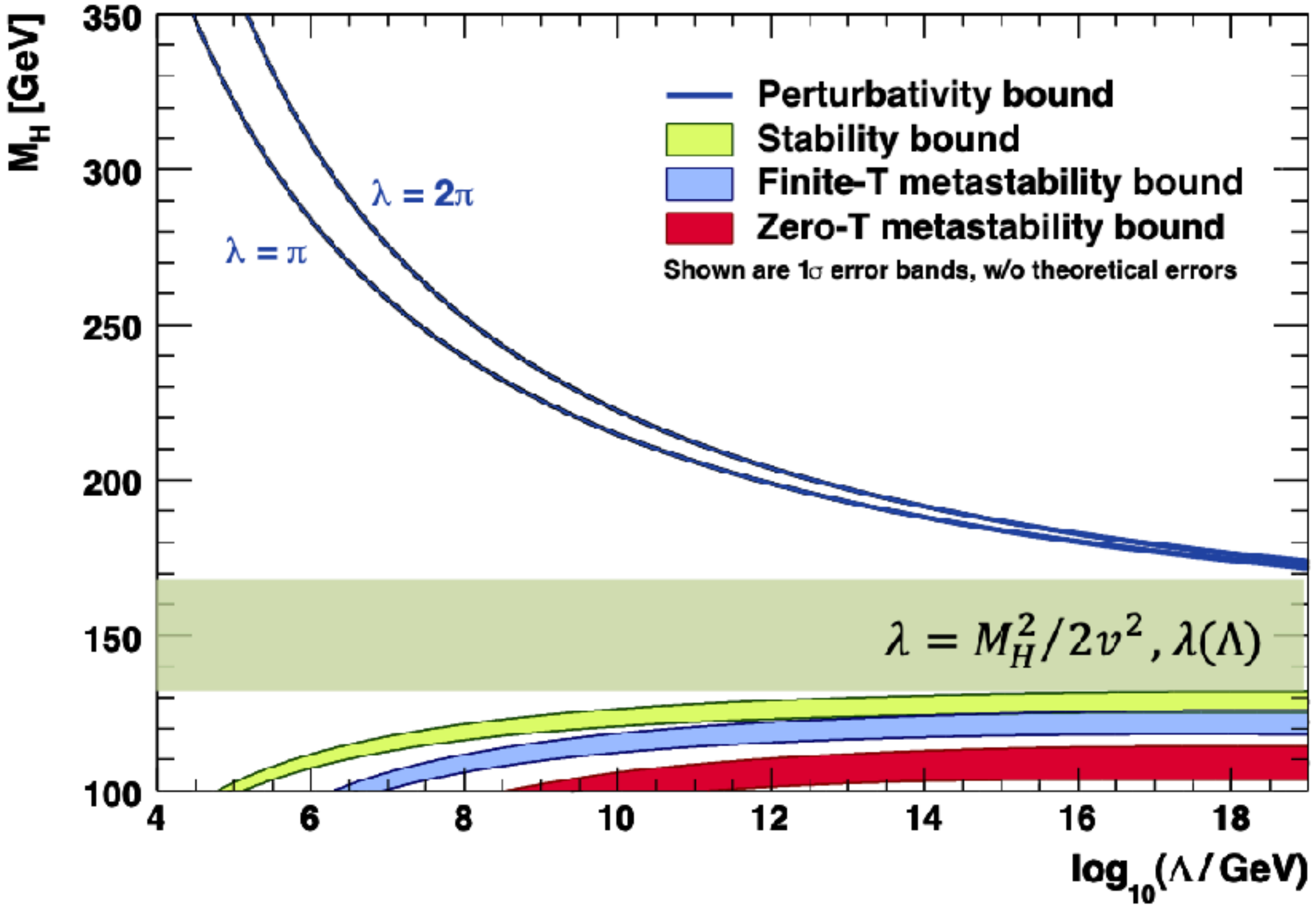
Direct searches at LEP excluded m_H < 114.4 GeV

Tevatron excluded m_H ~ 160 GeV

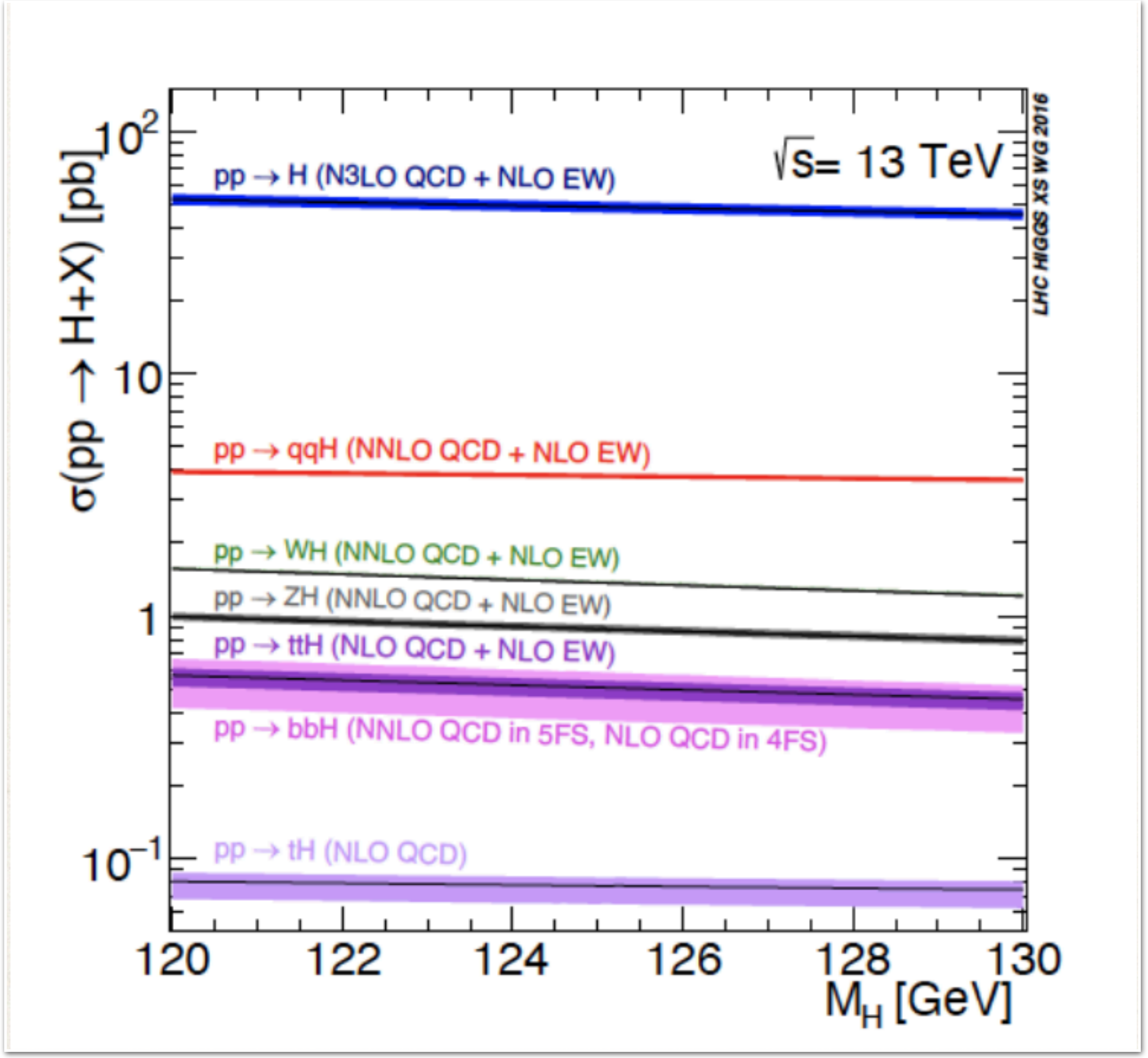
Indirect constraints from SM fit to EW precision data

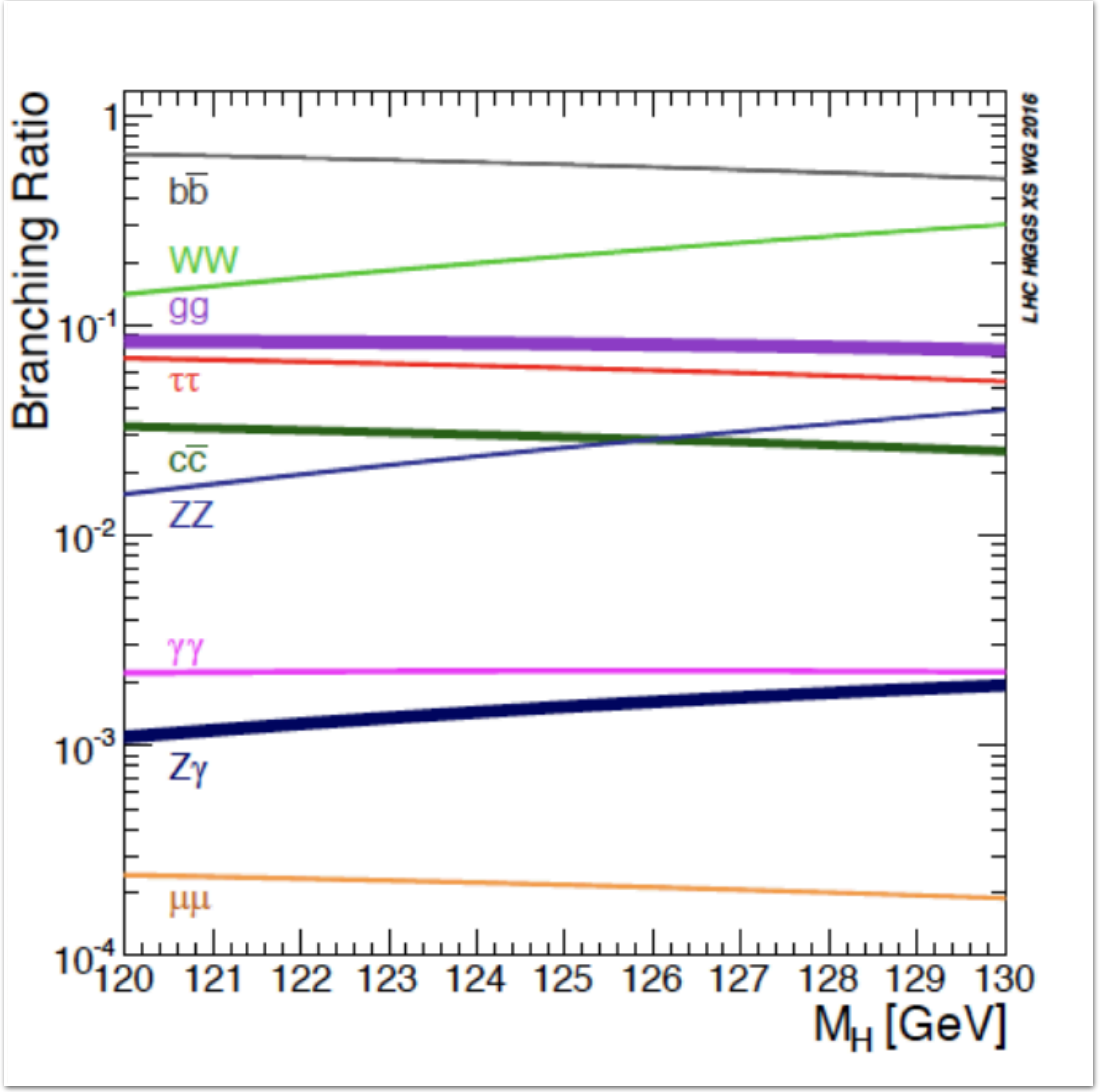
Indirect constraints from vacuum stability





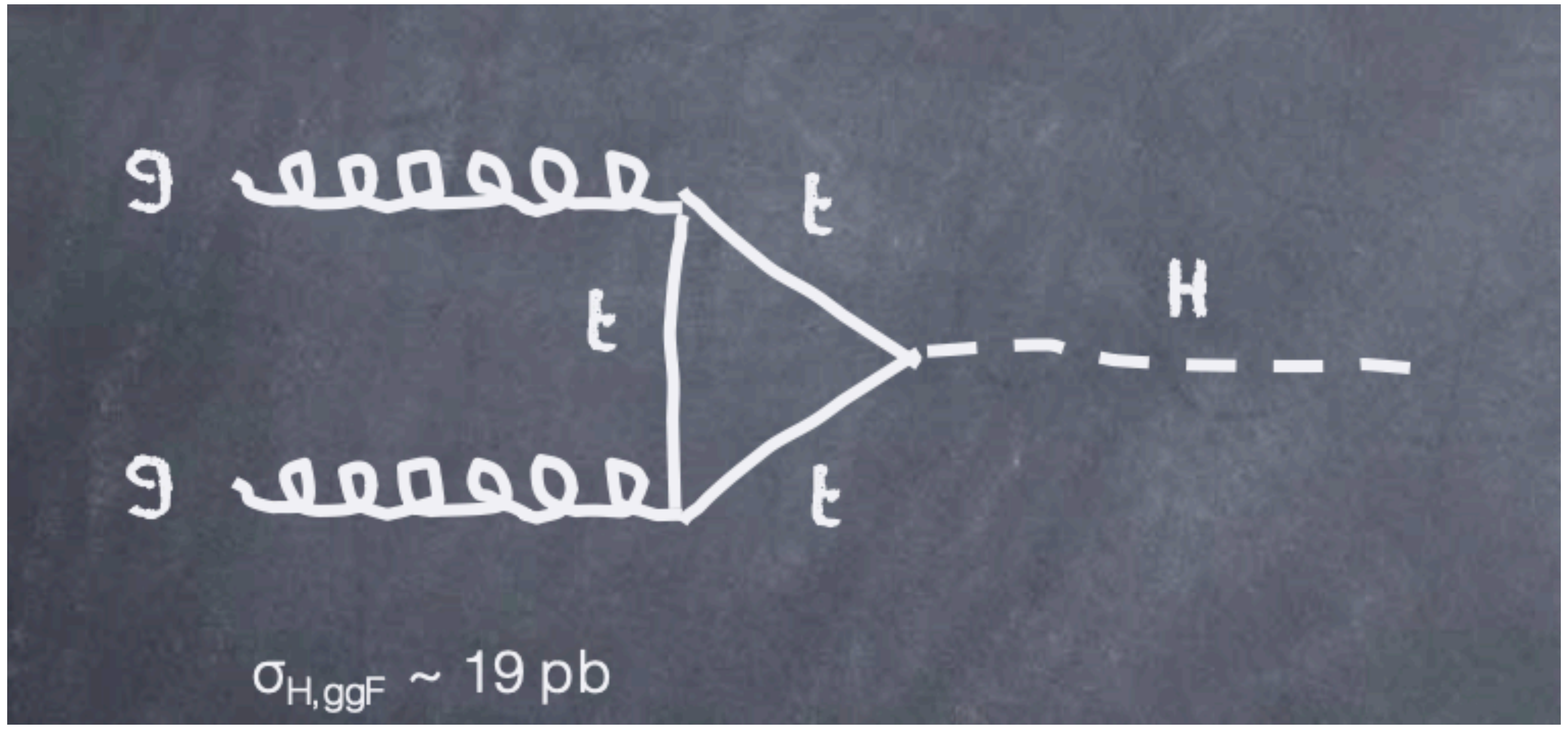
Higgs production and decay



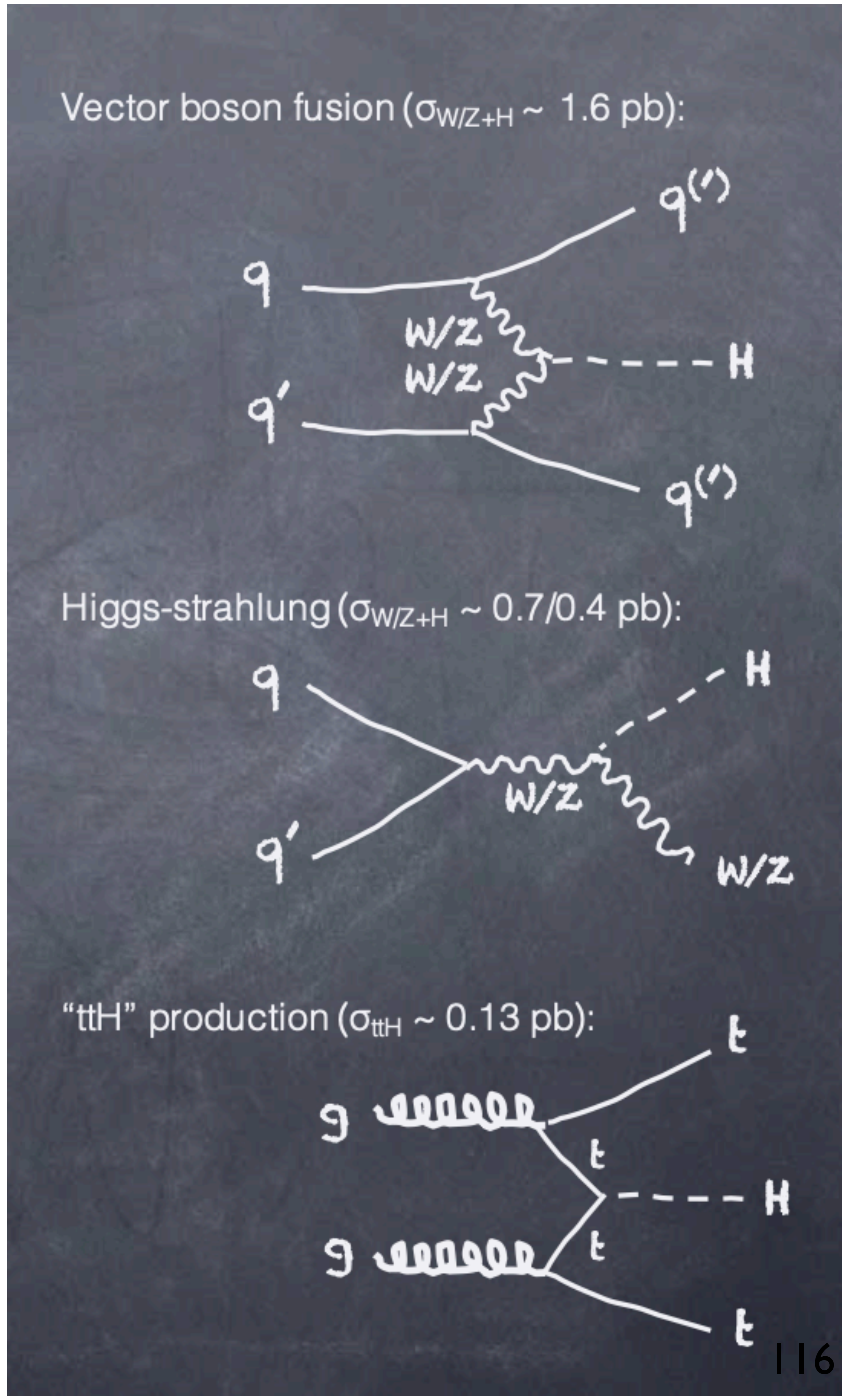


Higgs production and decay

At the LHC, Higgs boson is dominantly produced via gluon fusion: $\sigma_H \sim 22\text{pb}$ at 8 TeV
Cross section decays drastically with the Higgs mass



Other important production modes



Production of ~470K Higgs boson for each ATLAS and CMS in 2012

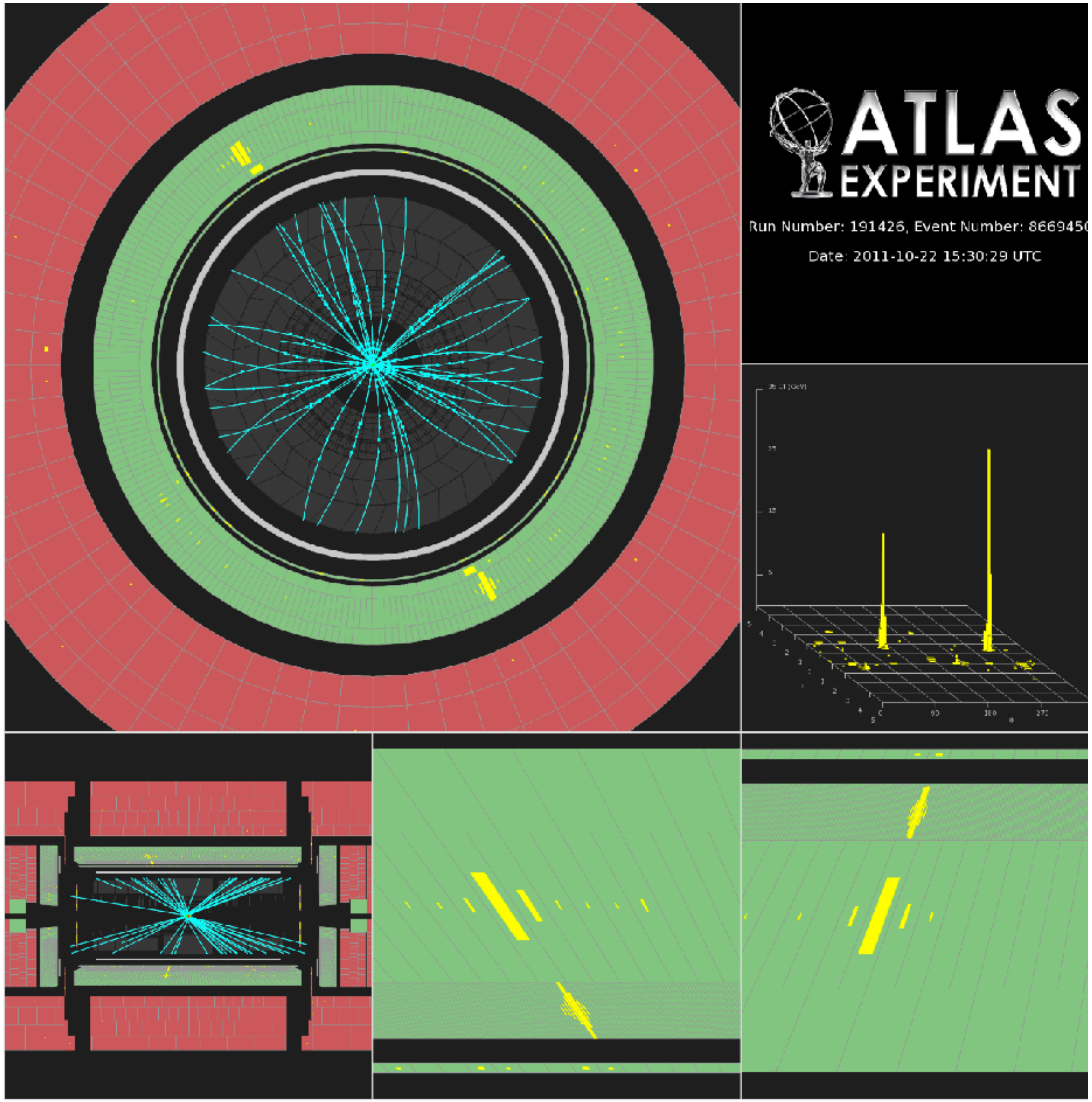
The Higgs will then decay preferentially to the heaviest particle allowed

It does not couple directly to photons or gluons, but can decay into them through loop diagrams involving heavy particles (top, W)

A Higgs candidate event

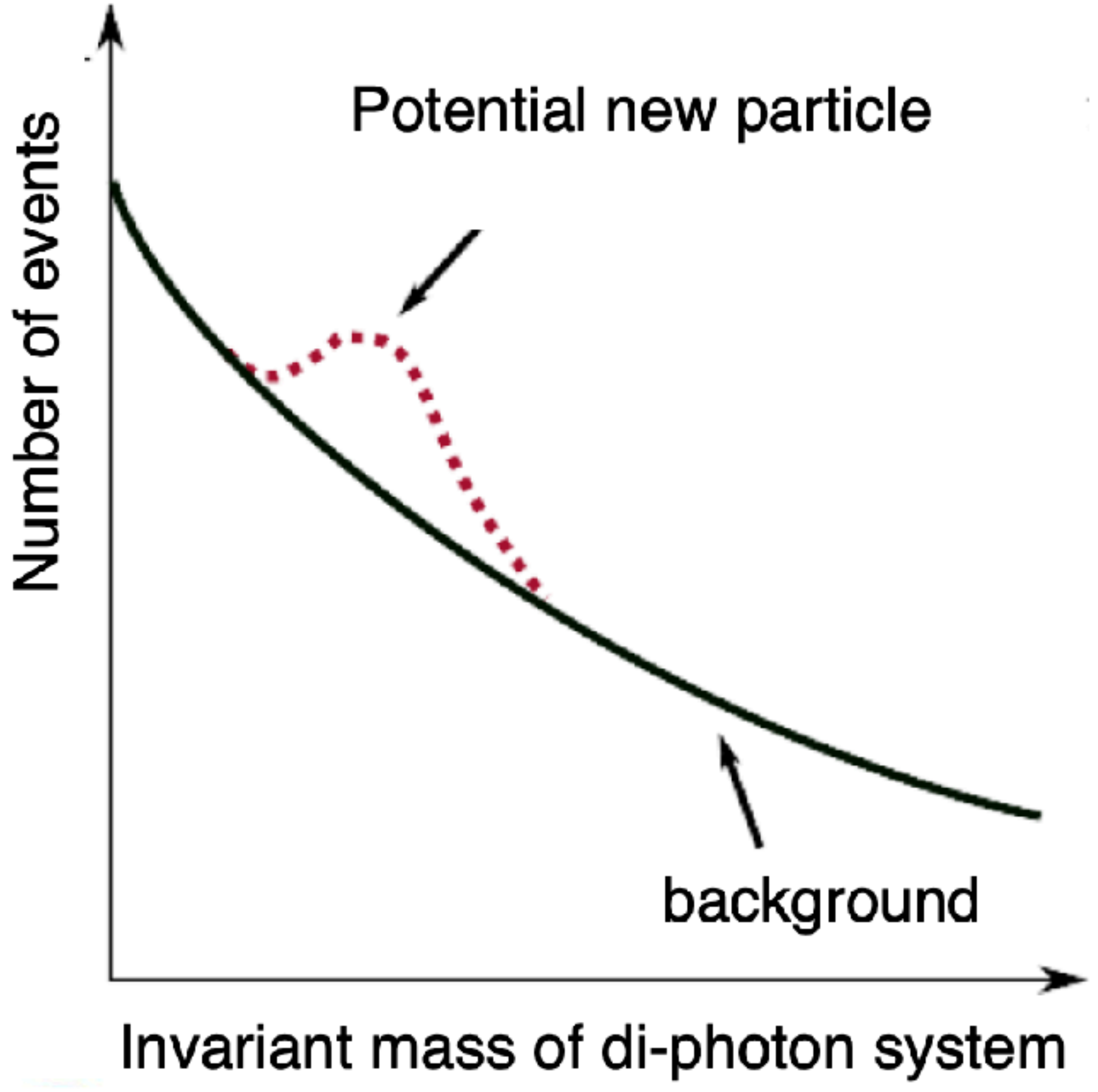
E_T =64.2 GeV
E_T=61.4 GeV

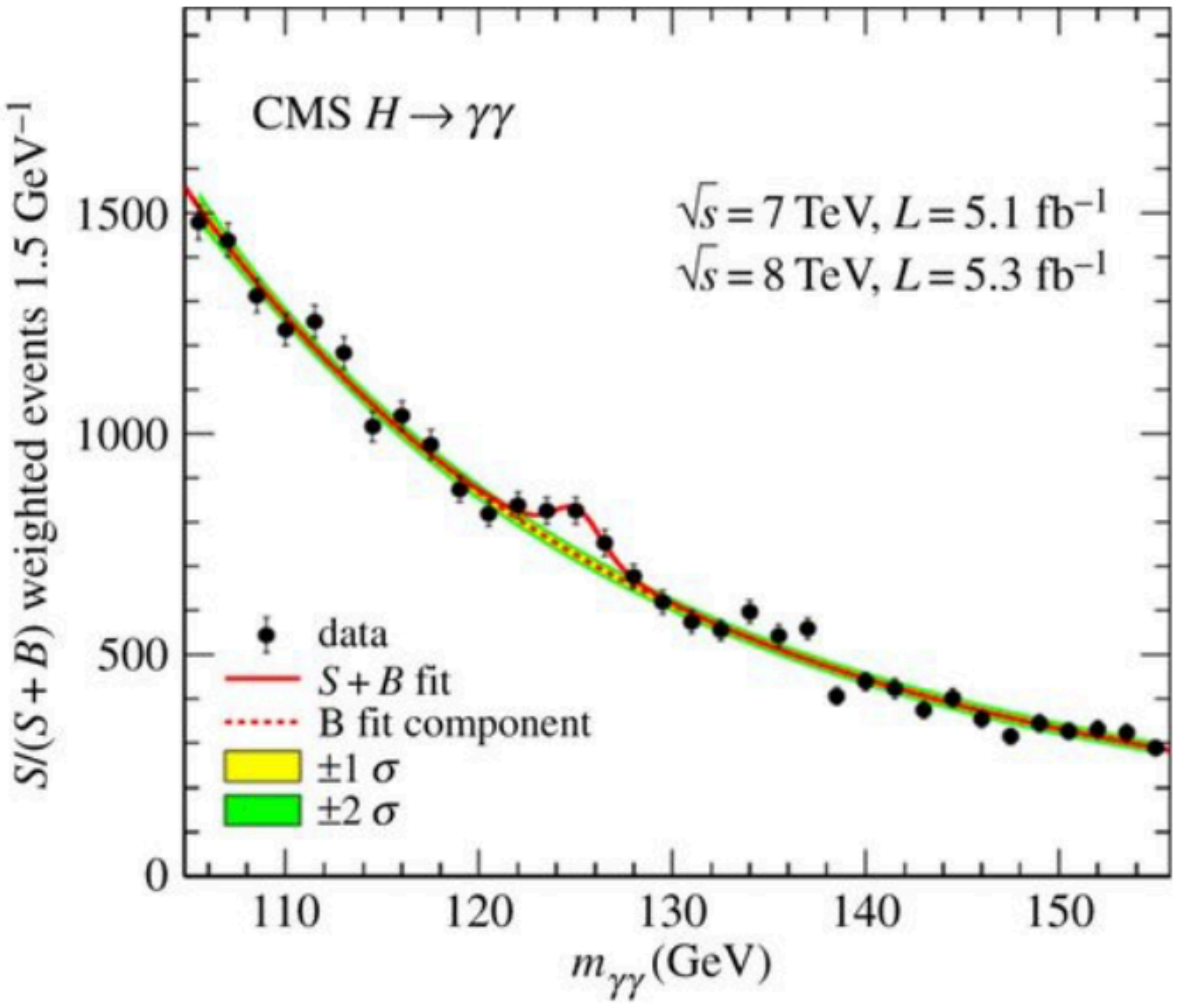
$m_{\gamma\gamma}$ = 126.6 GeV



How to discover a new particle

After having selected the interesting events, look for resonances in the invariant mass of the Higgs decay products



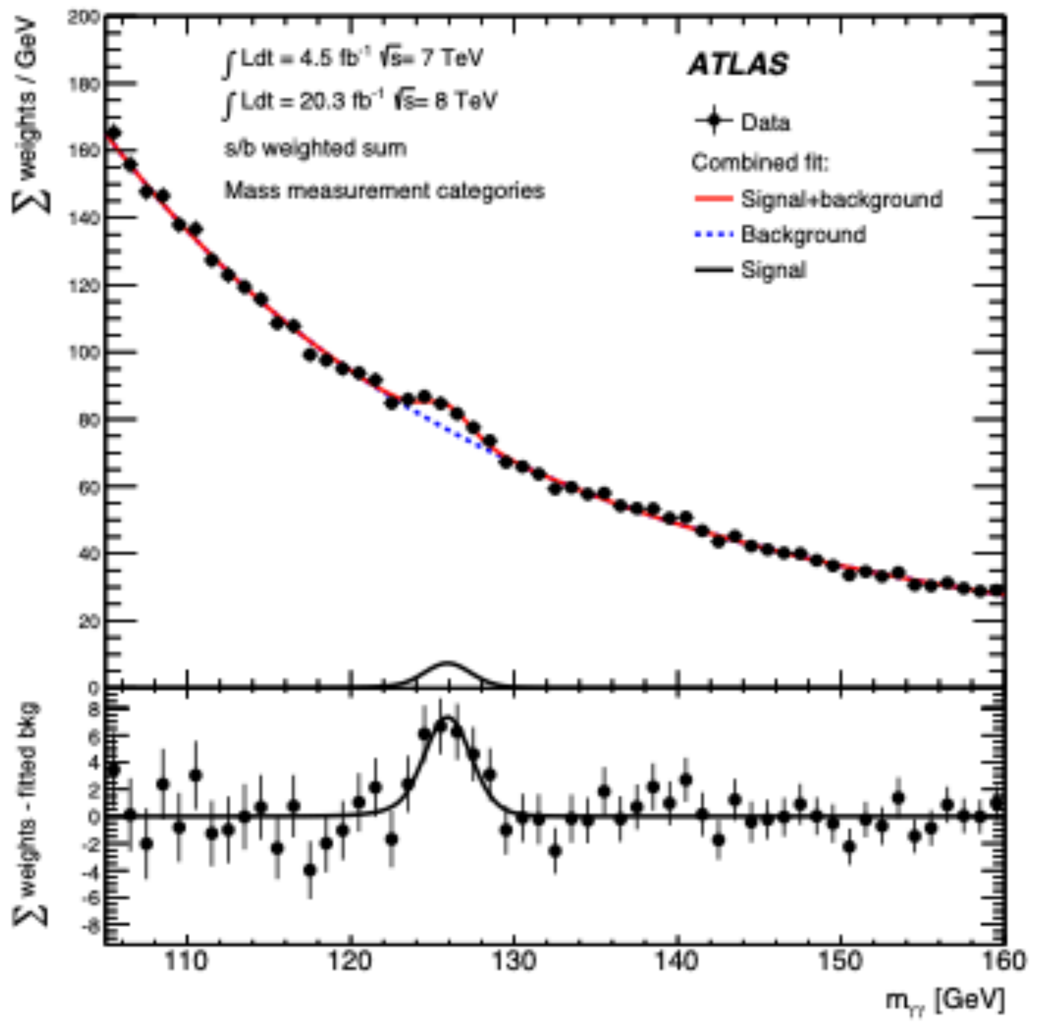


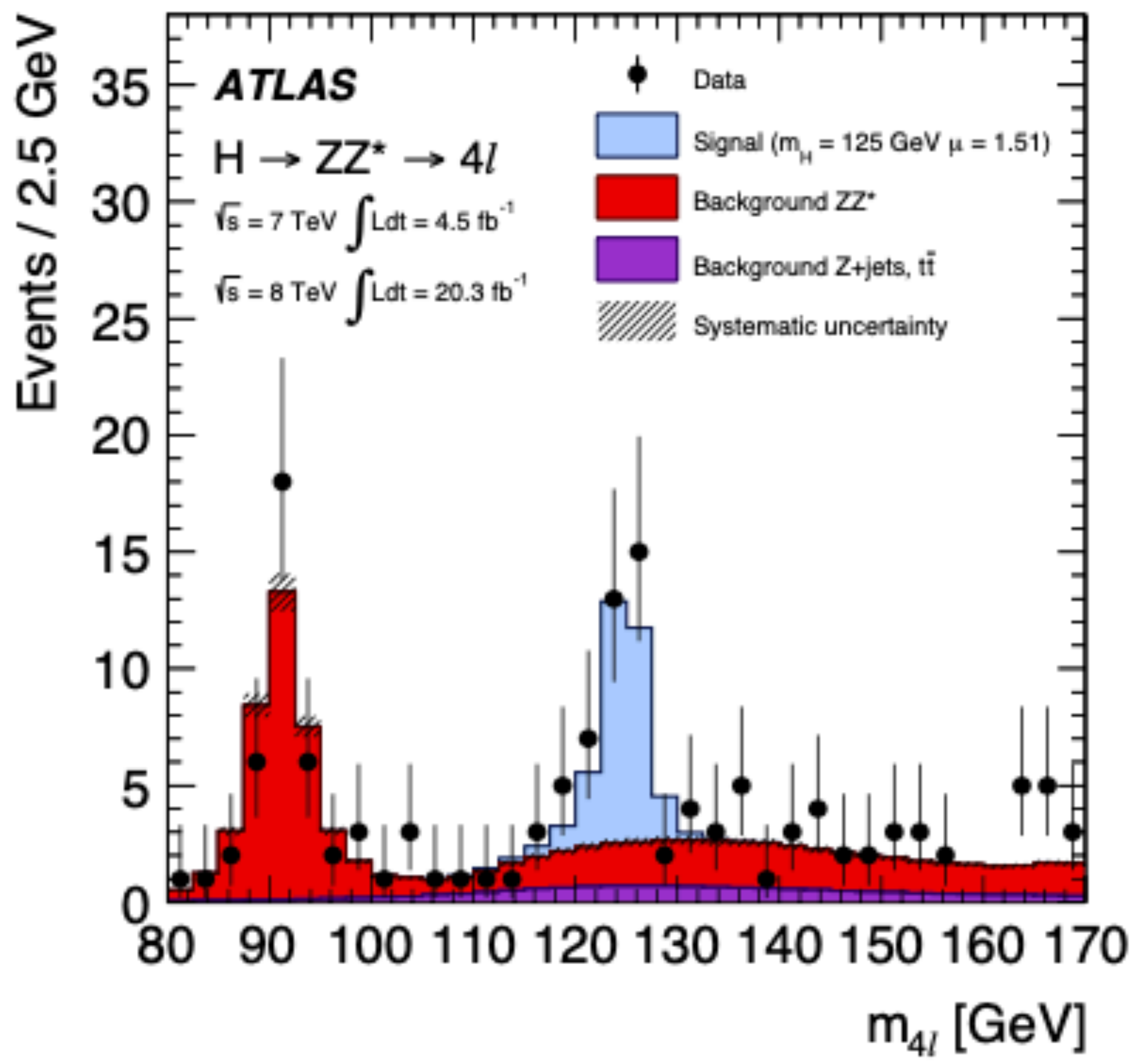
The Higgs discovery

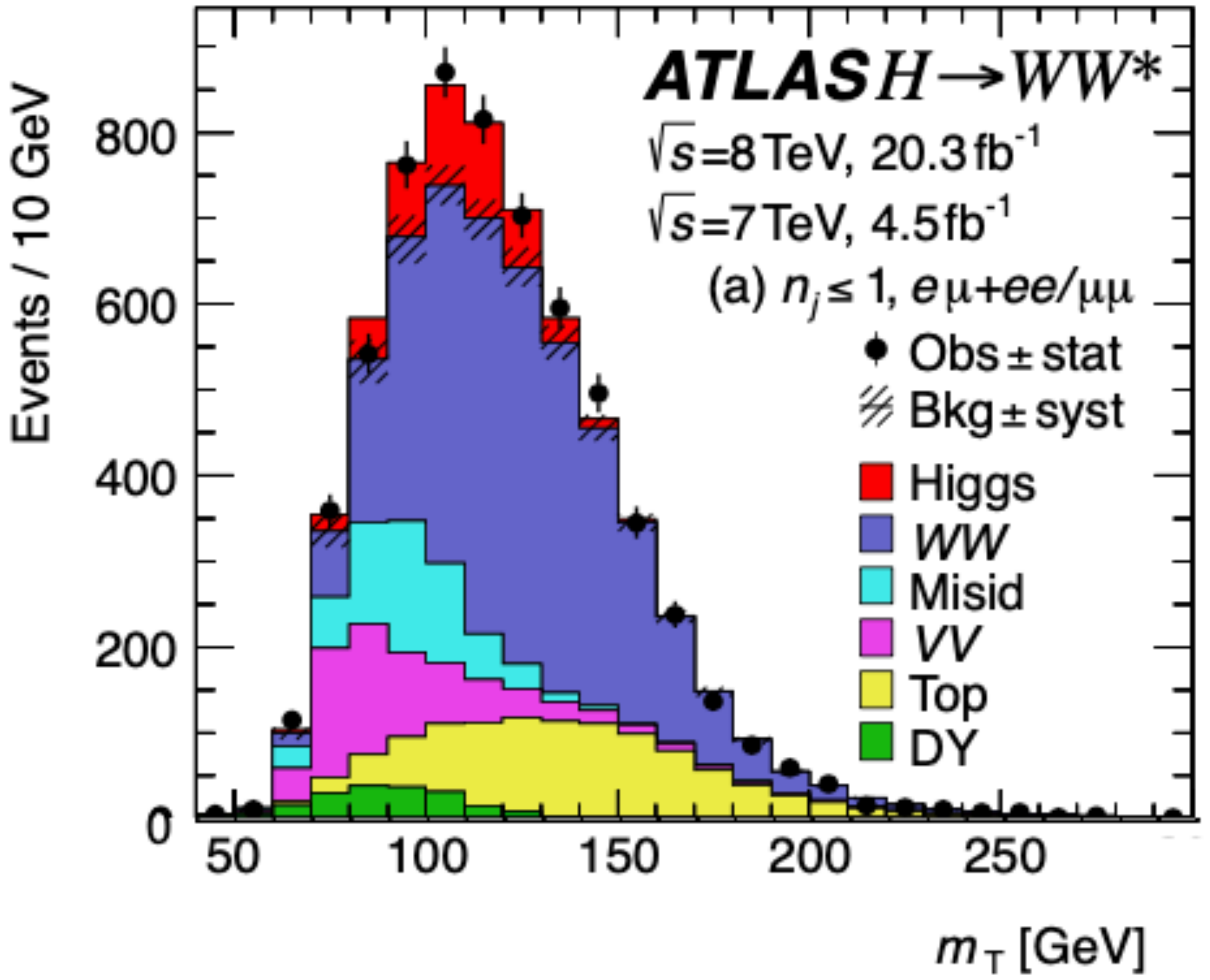
$H \to \gamma\gamma$ σ(m) ~ 1–2%

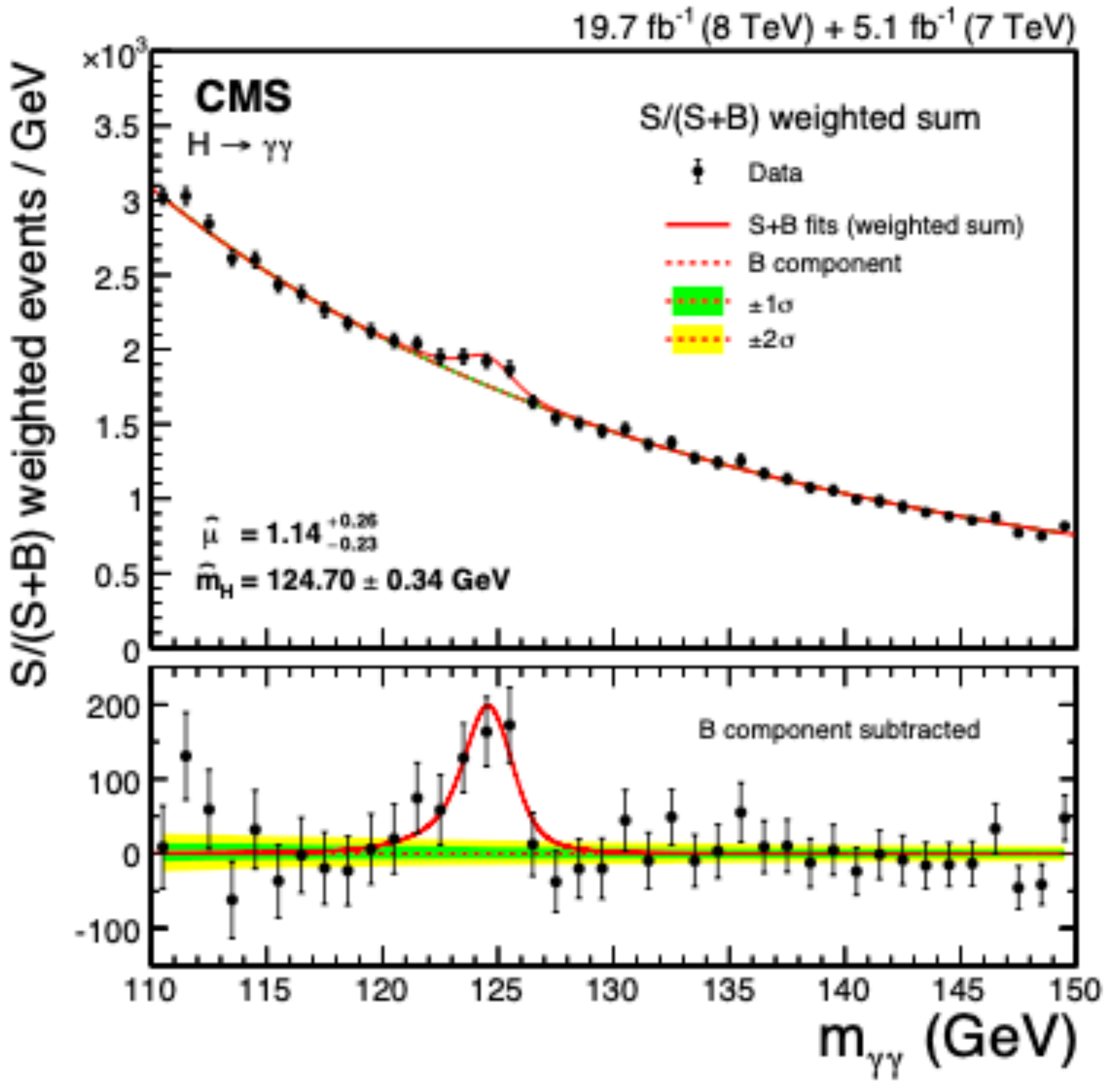
$H \to ZZ^{(*)} \to 4\ell$ σ(m) ~ 1–2%

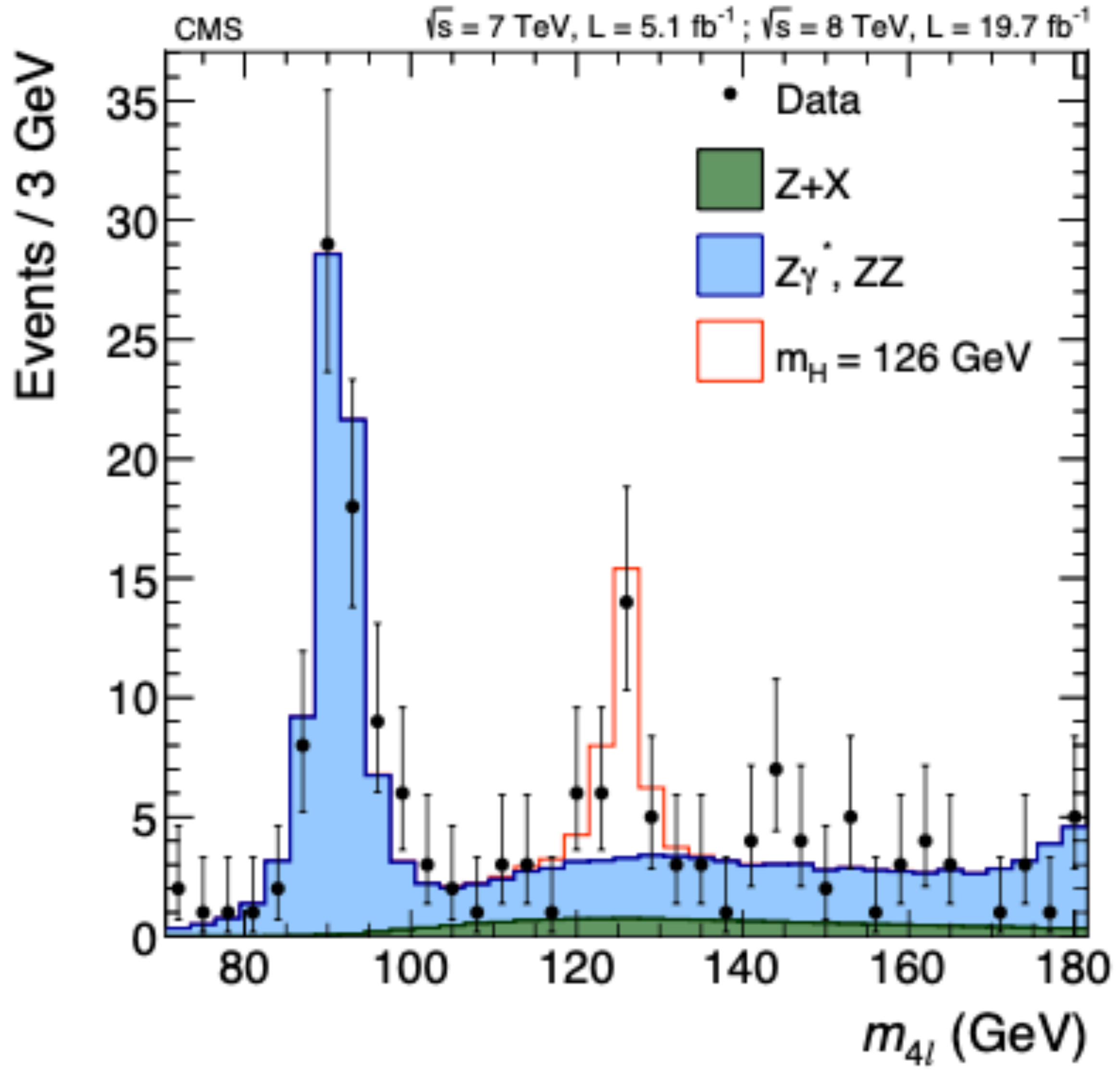
$H \to WW^{(*)} \to 2\ell 2\nu$ σ(m) ~ 20%

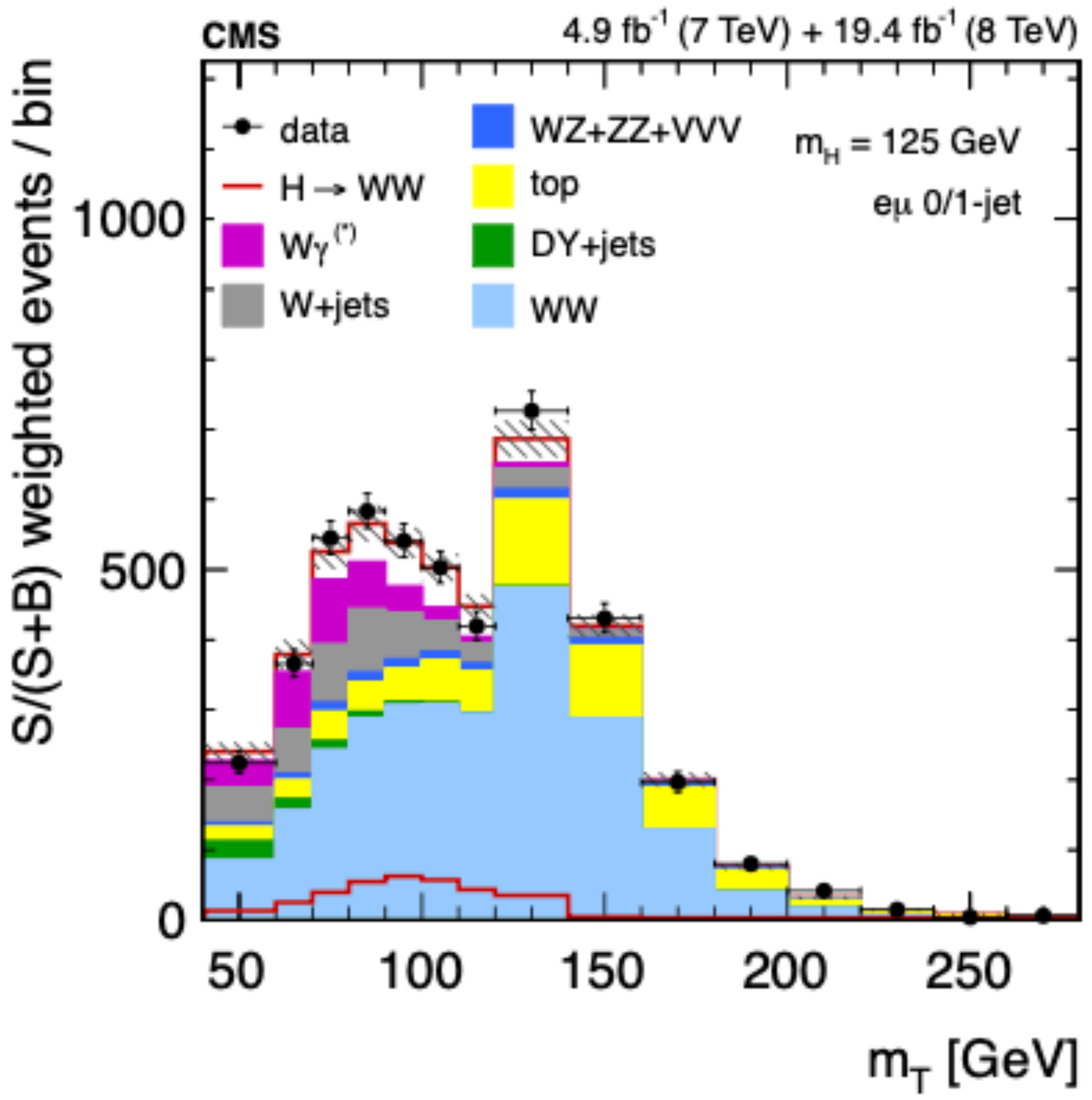




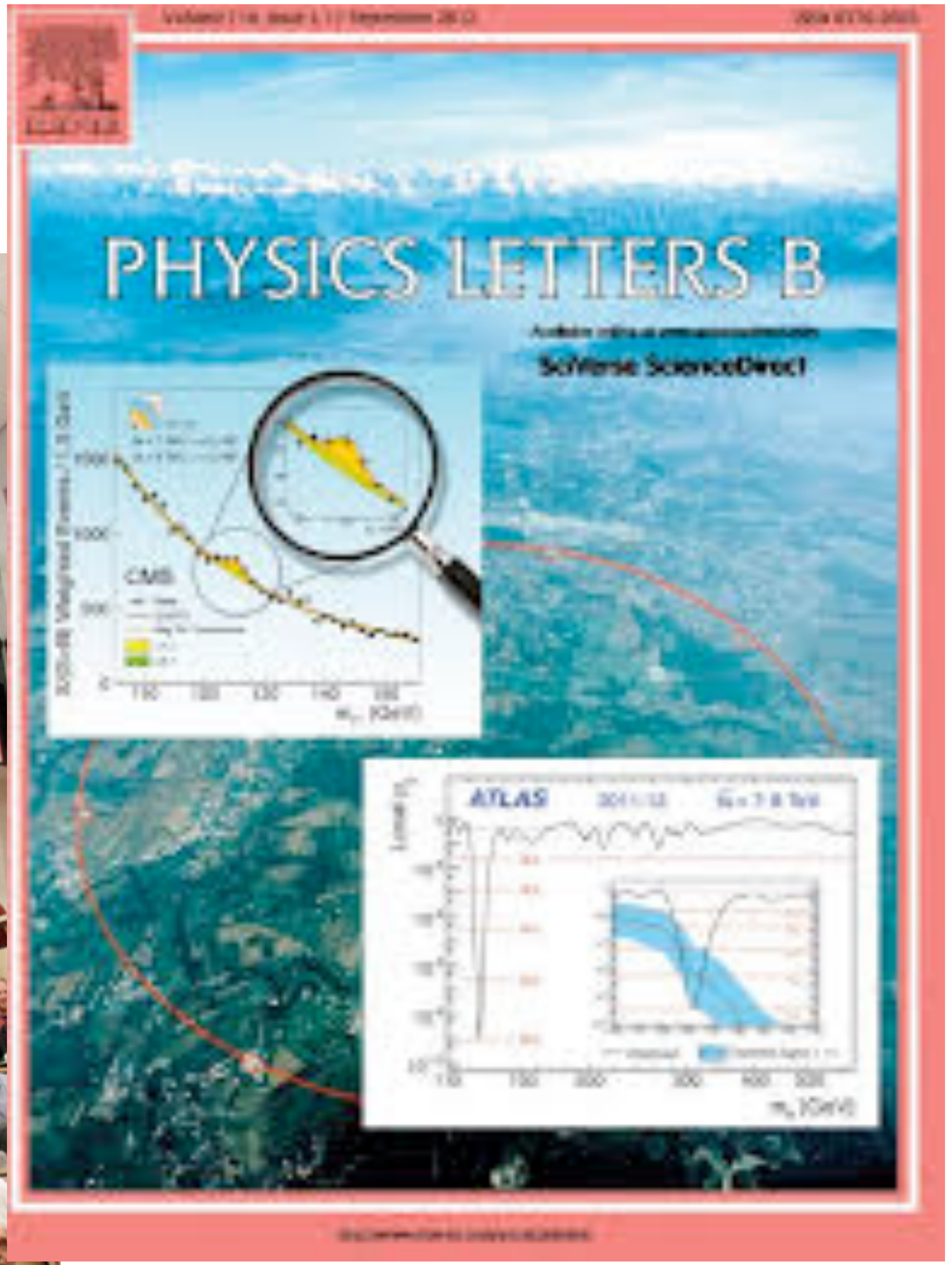








The Higgs discovery



ATLAS

$$m_H = 126.0 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{sys})$$

CMS

$$m_H = 125.3 \pm 0.4(\mathrm{stat}) \pm 0.5(\mathrm{sys})$$

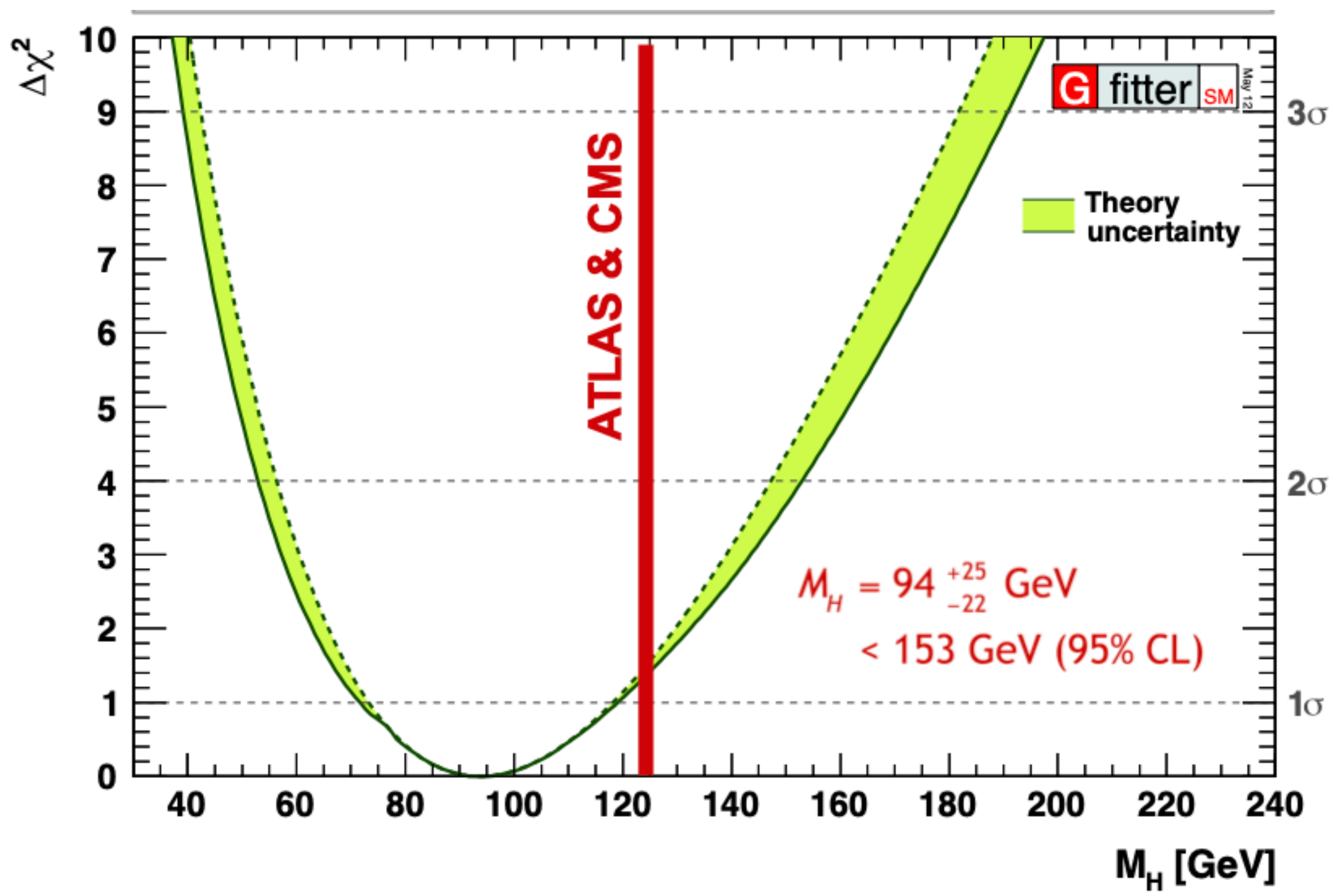
Does m_H agrees with our expectations?

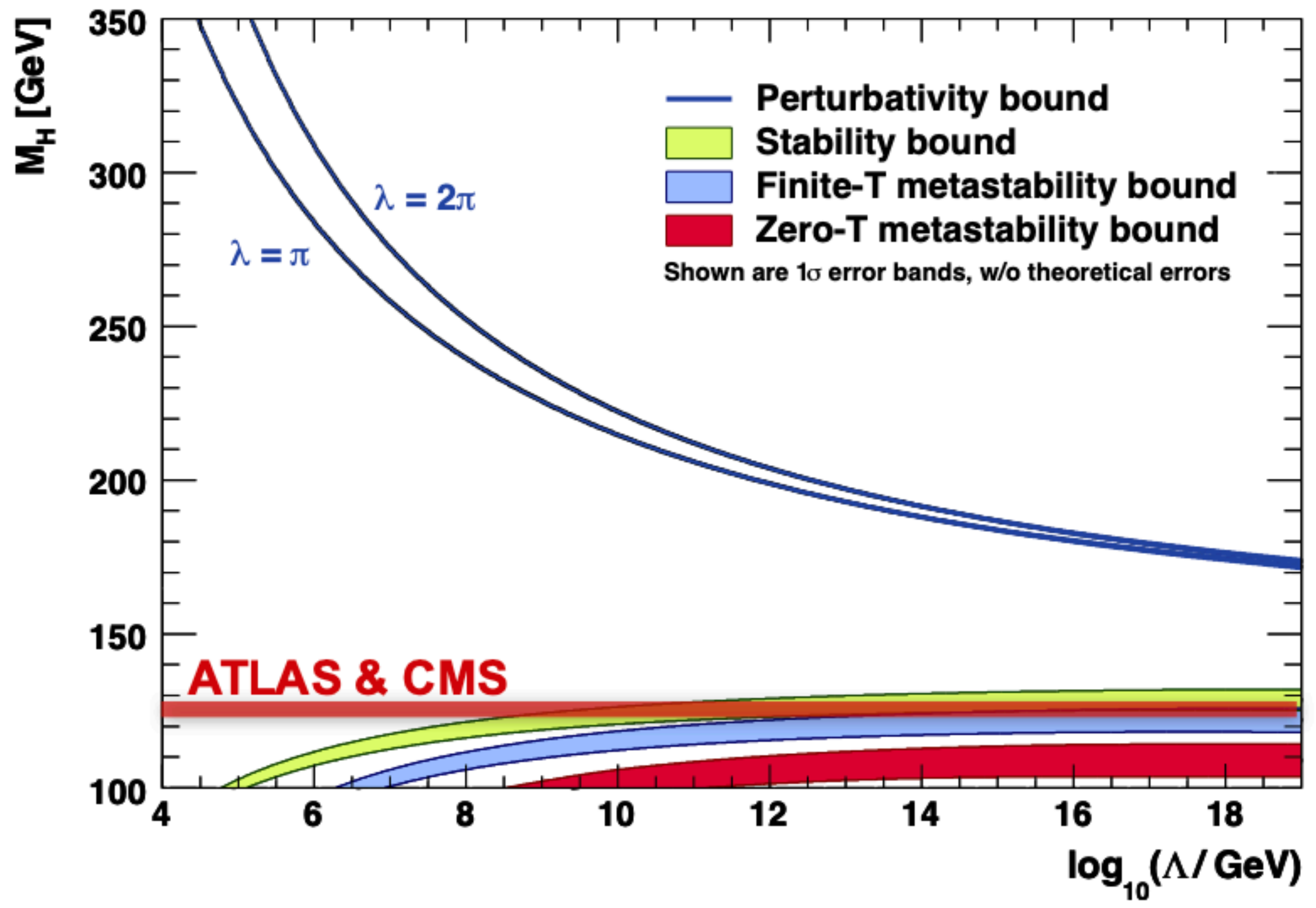
Direct searches at LEP excluded $m_H < 114.4$ GeV

Tevatron excluded $m_H \sim 160$ GeV

Indirect constraints from SM fit to EW precision data

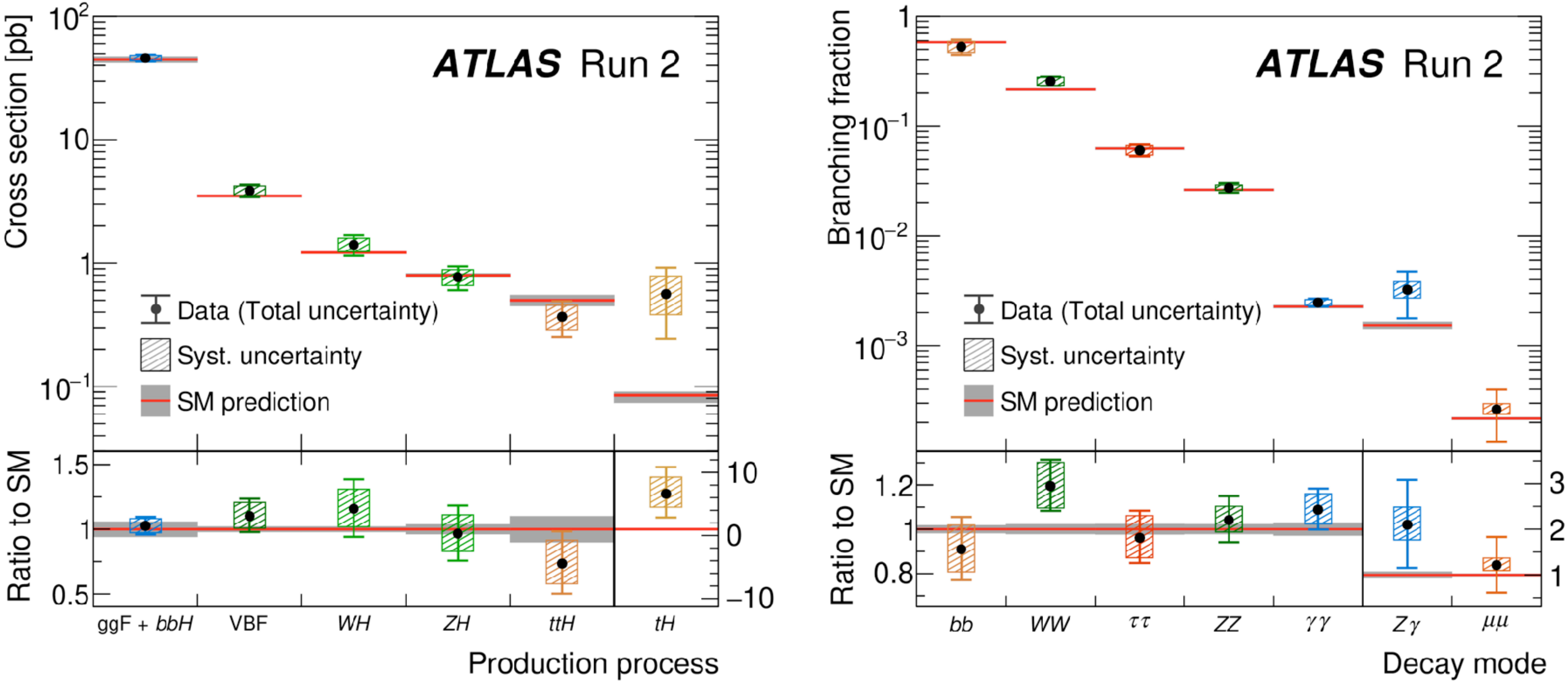
Indirect constraints from vacuum stability



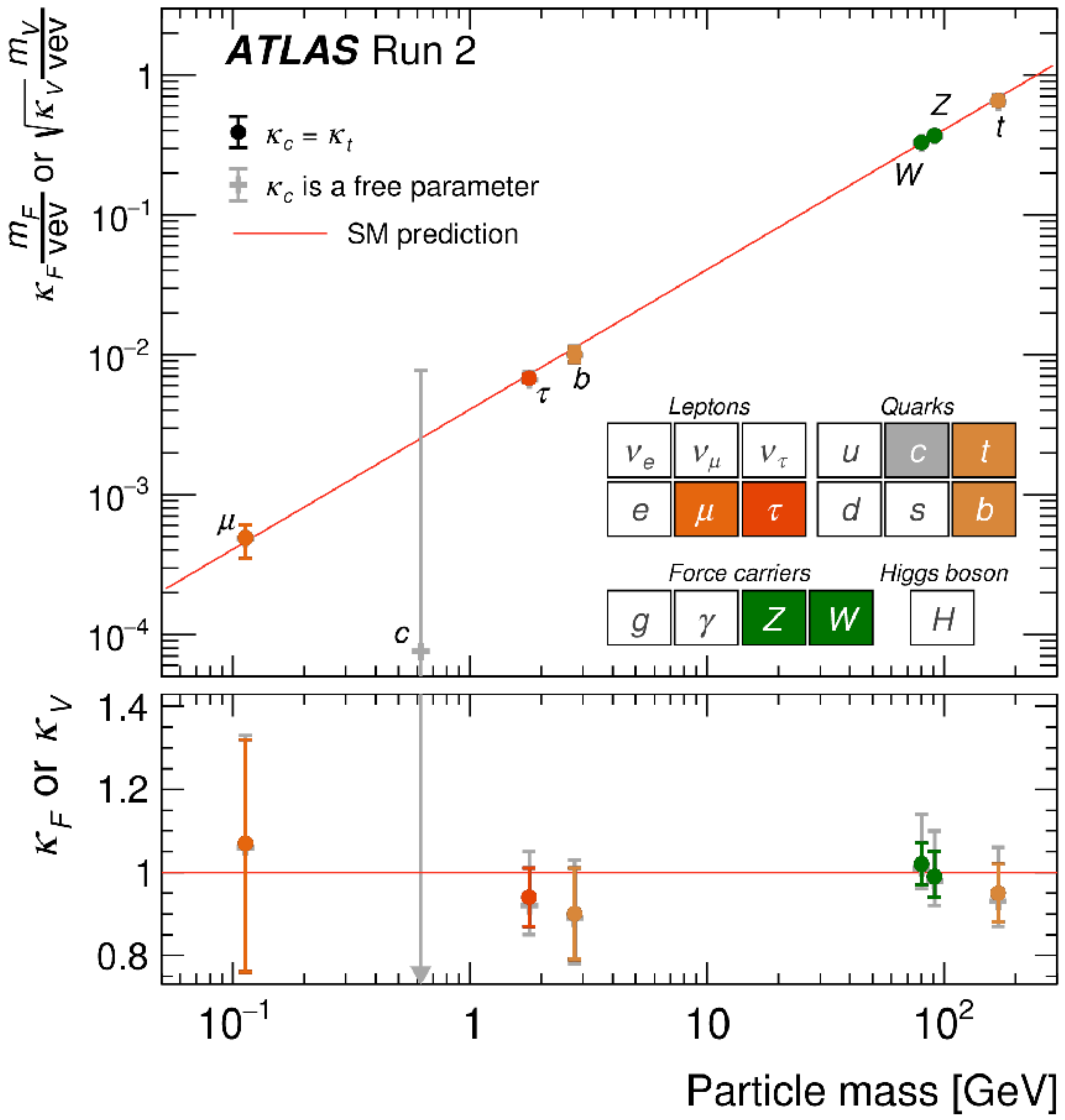


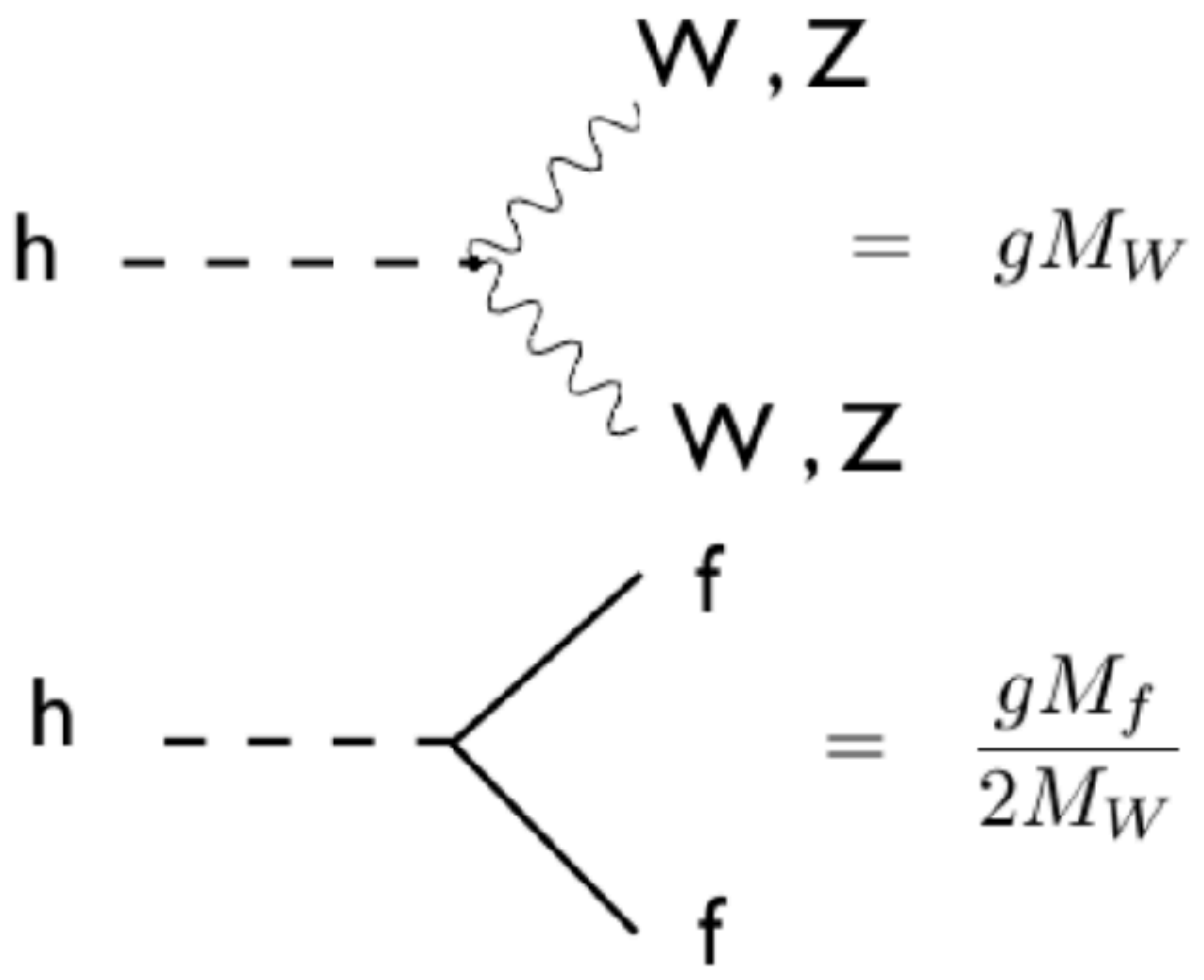
Higgs production and decay

Since then, tests of the Higgs boson properties - Is it the SM Higgs ?



Higgs couplings to fermions

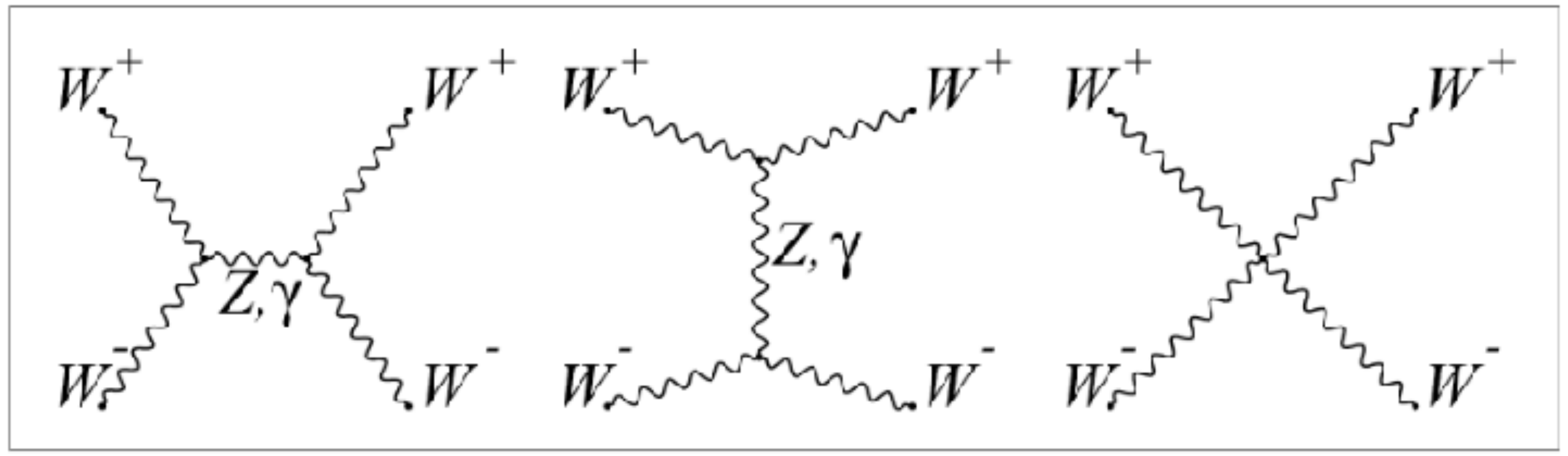




Electroweak symmetry breaking

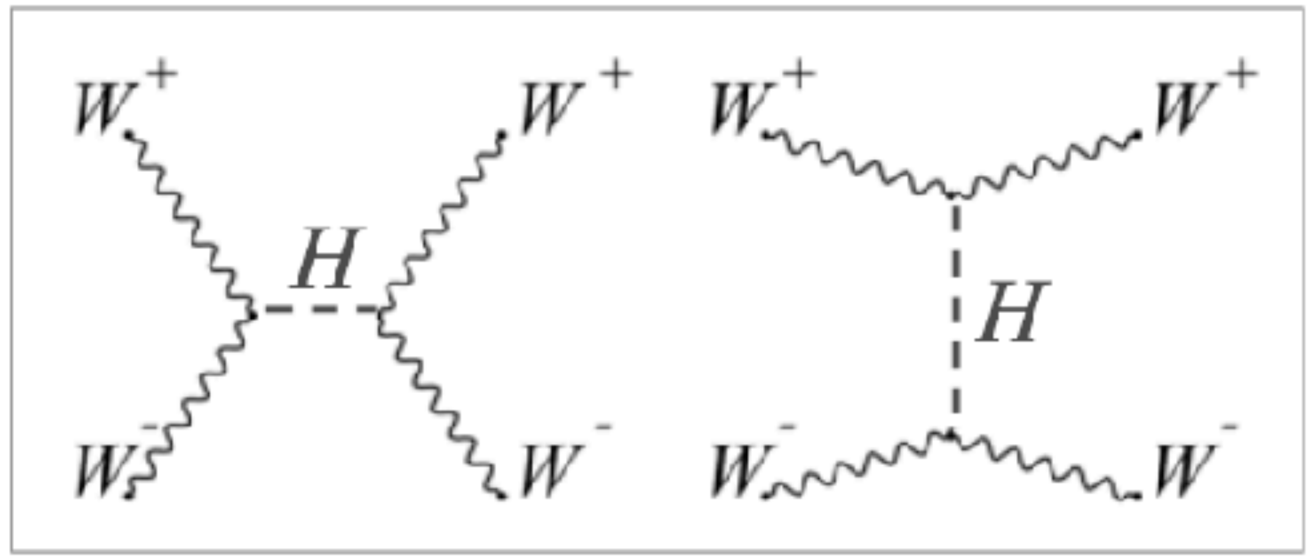
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$



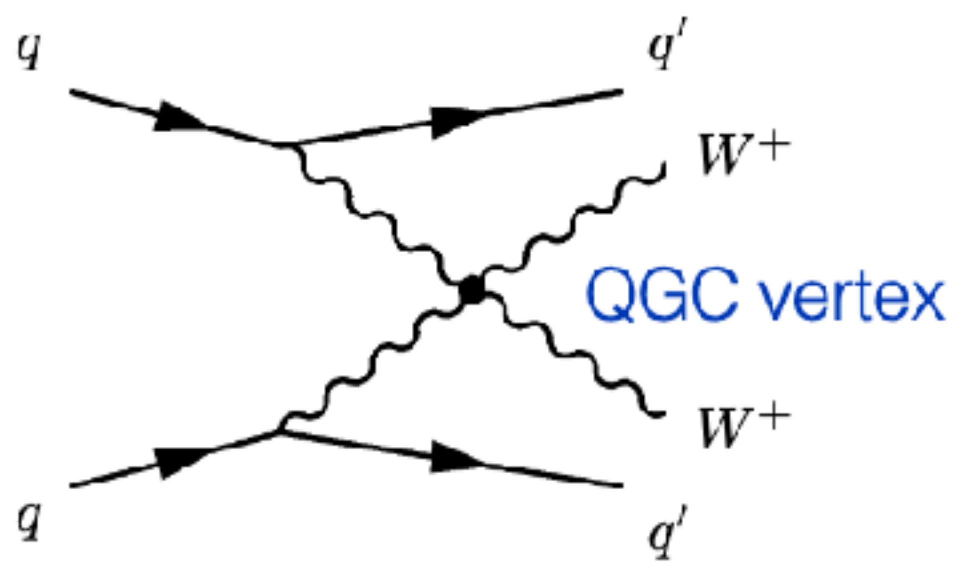
Higgs boson restores unitarity of total amplitude:

$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$

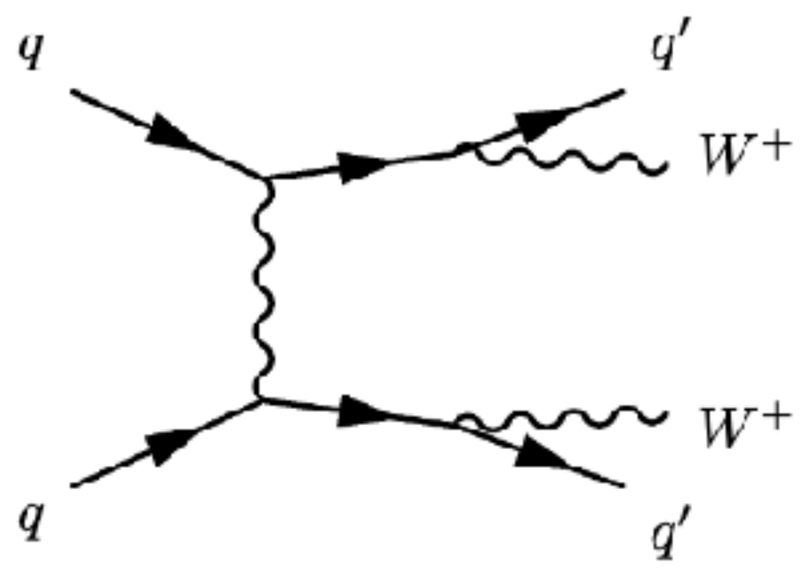


m_H must not be too large (which is fulfilled)

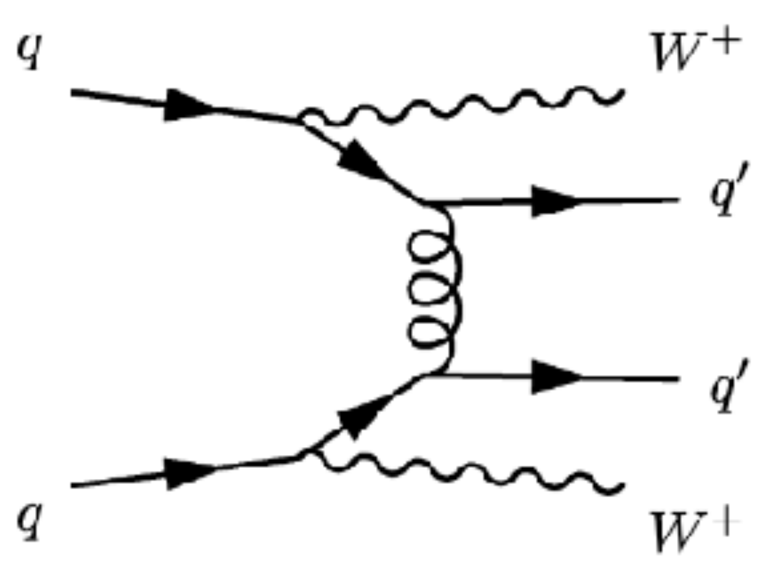
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

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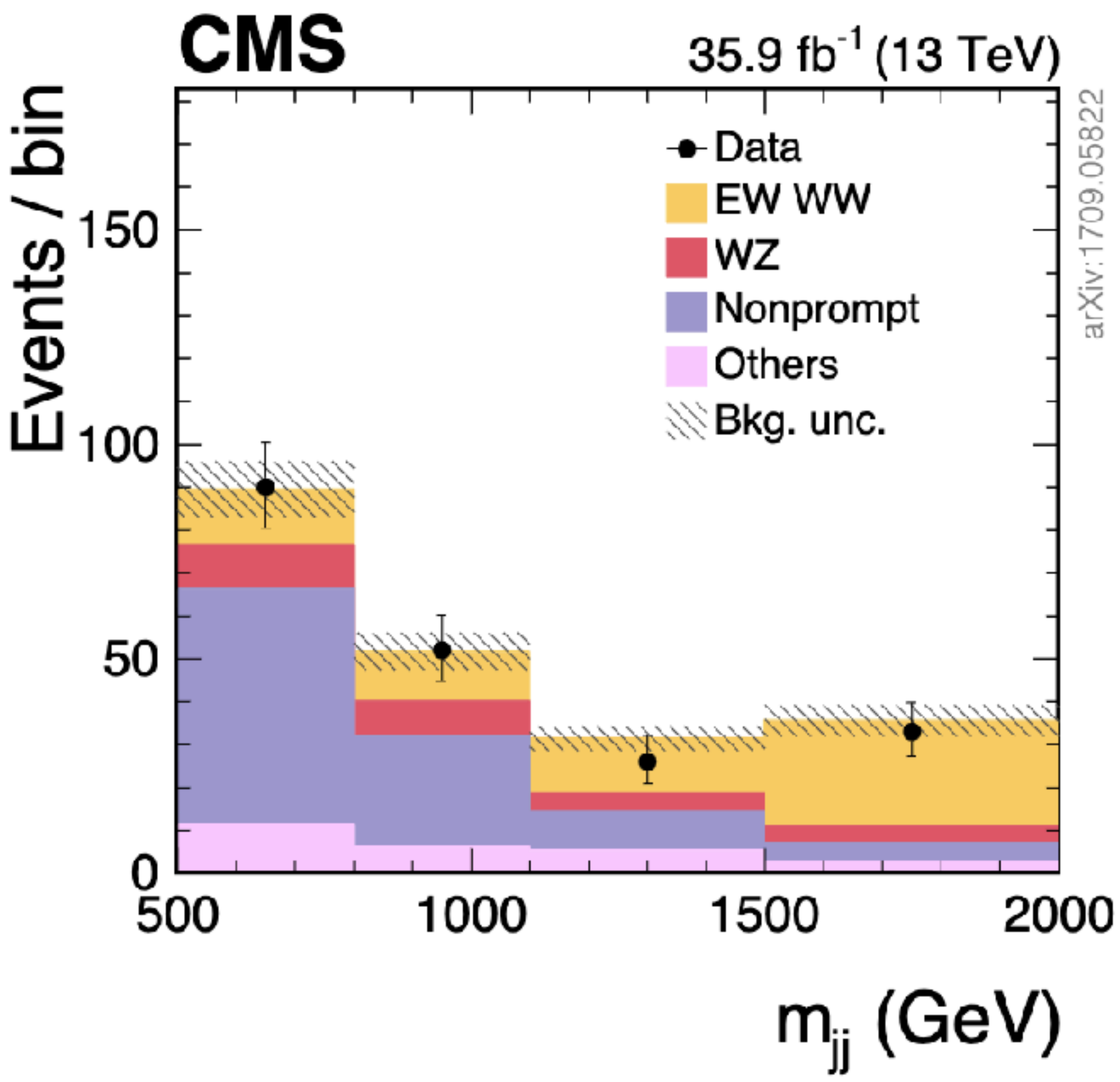
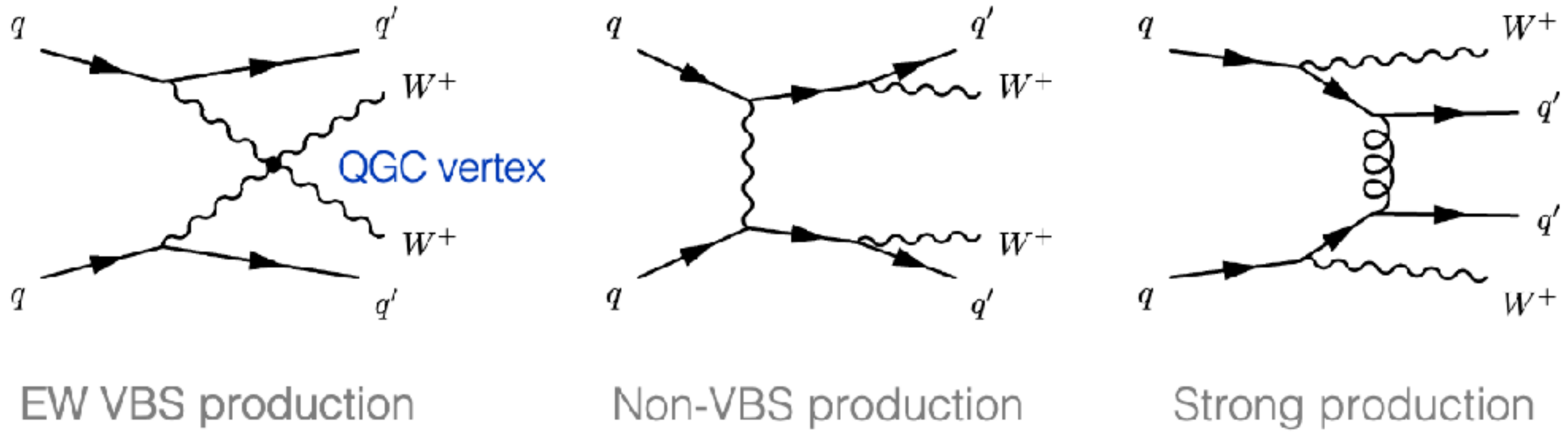


Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



Look for VBS scattering in high dijet invariant mass distributions

CMS & ATLAS observed vector boson scattering in WWjj at > 5σ (ATLAS also in WZ channel)

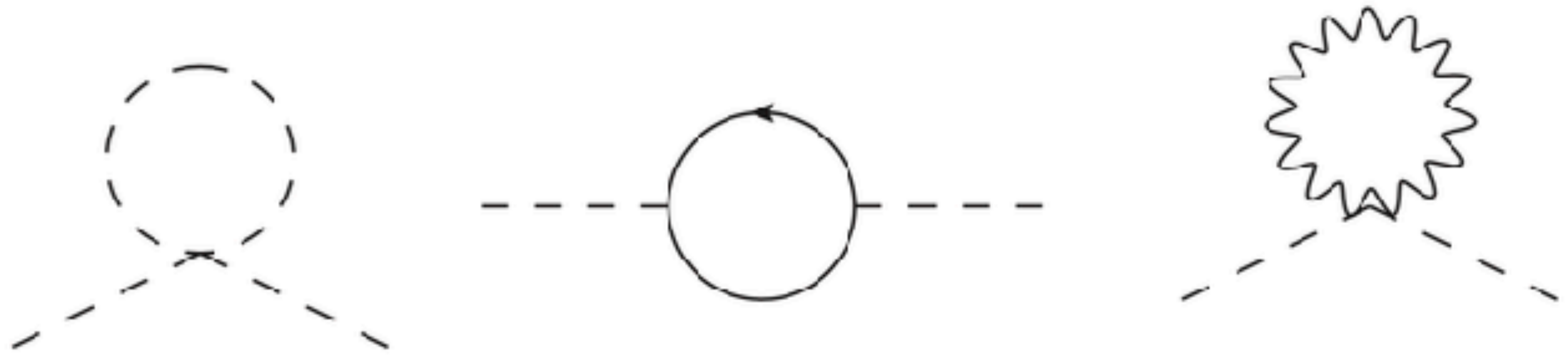
arXiv:1906.03203, arXiv:1812.09740

Searches for new physics

Display of an ATLAS candidate gluing event decaying into hadronic jets

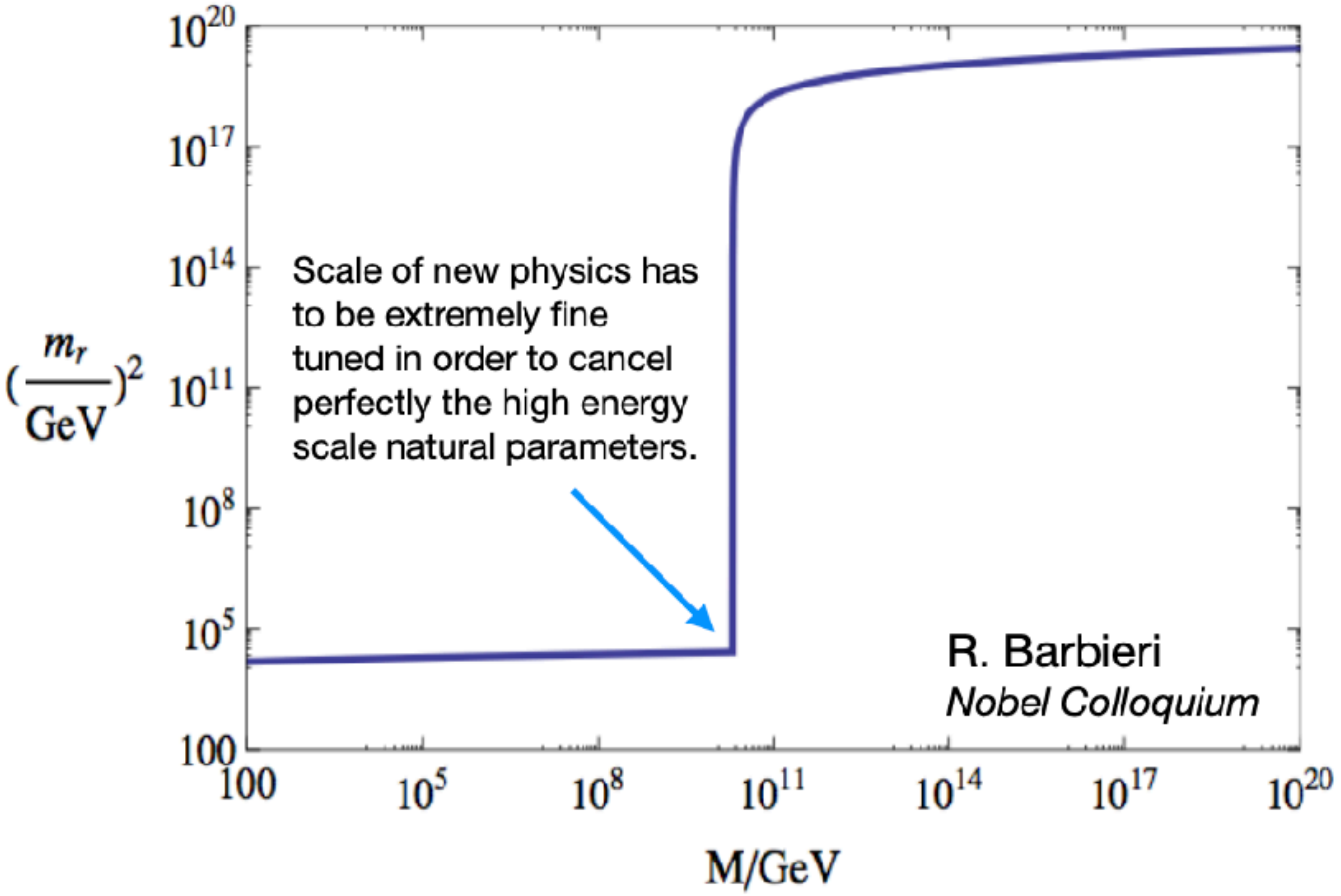
The hierarchy problem and weak scale new physics

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi}$$

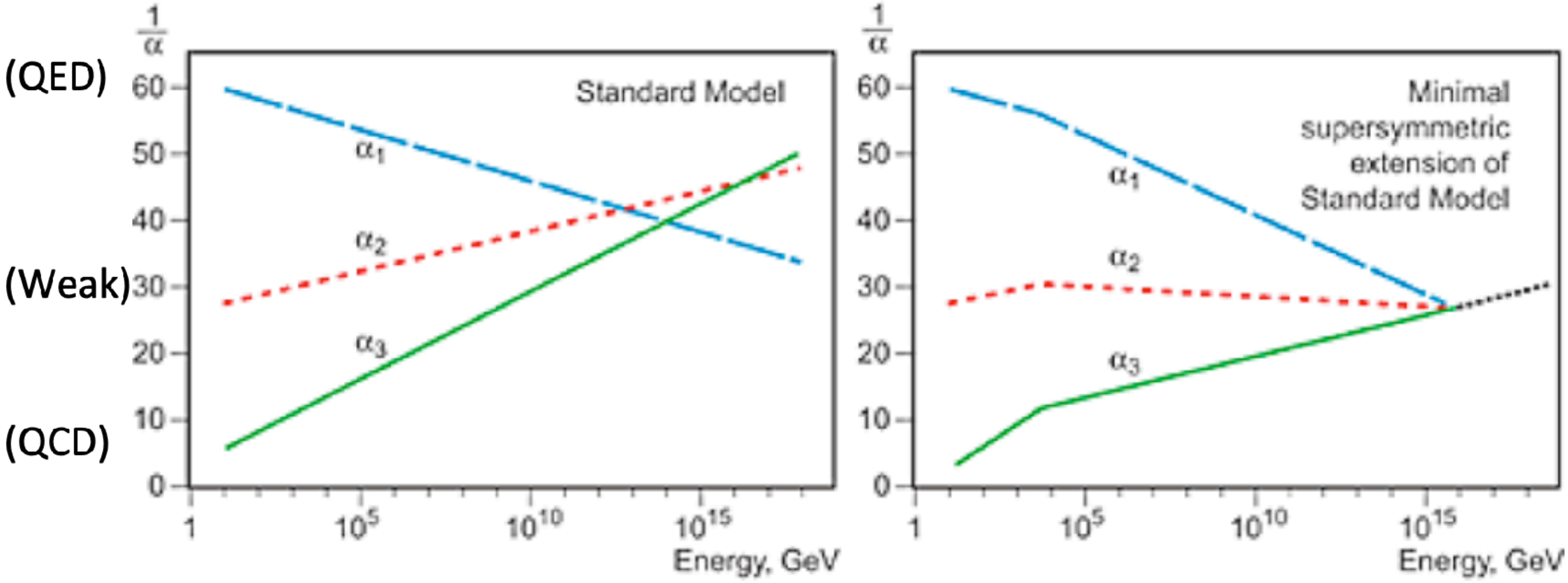
The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:



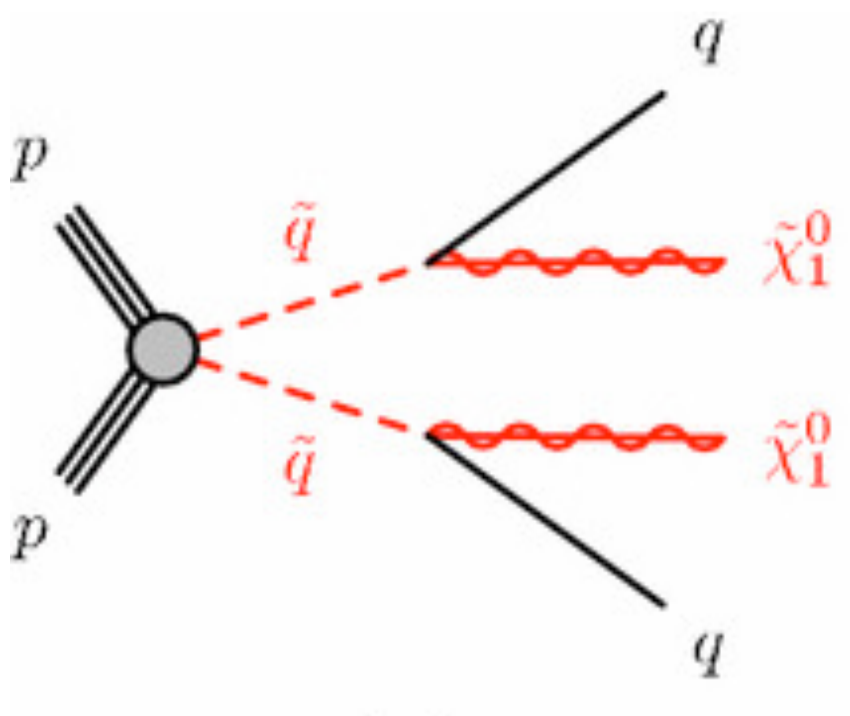
- Supersymmetry is a new symmetry between fermions and bosons which cancels these quadratic divergences
- Predicts “superpartners” for all known particles
- Supersymmetry must be broken: gives rise to complex phenomenology

Unification

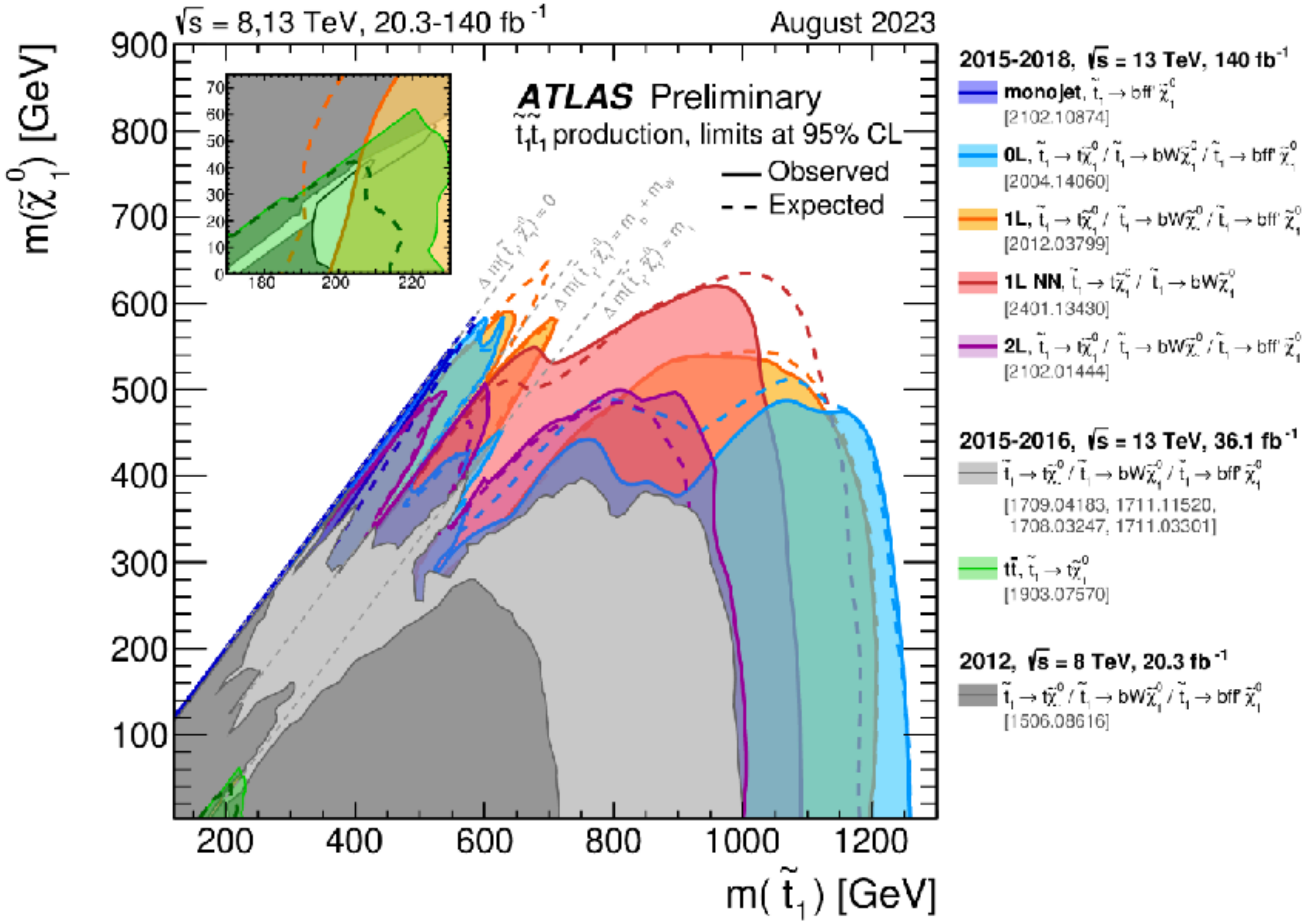
- Can we embed the SM symmetries into a larger group to obtain a Grand Unified Theory (GUT) of elementary interactions ?
- Turns out Supersymmetry could do just that

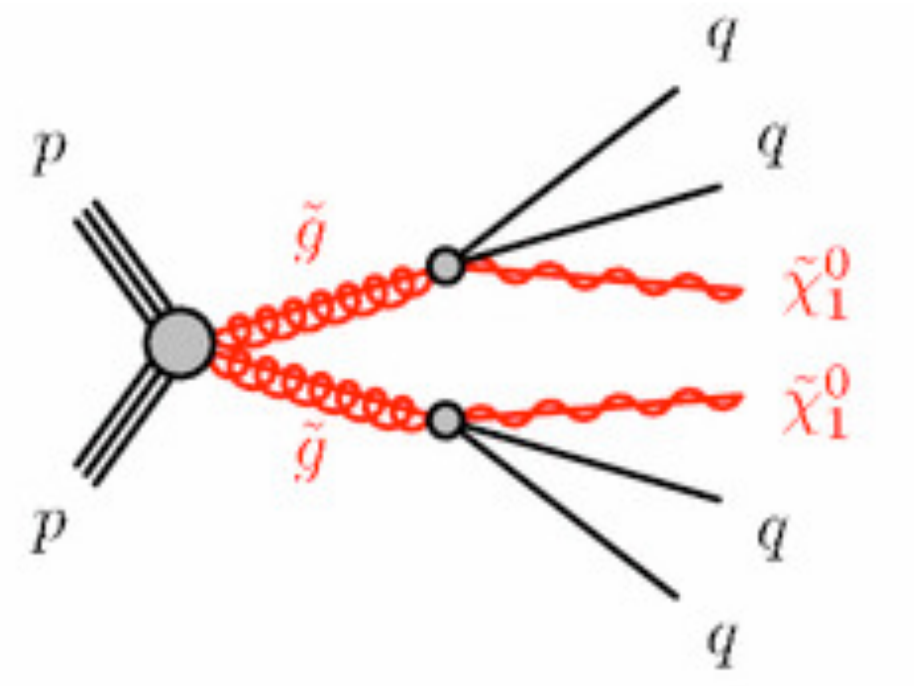


Searching for supersymmetry

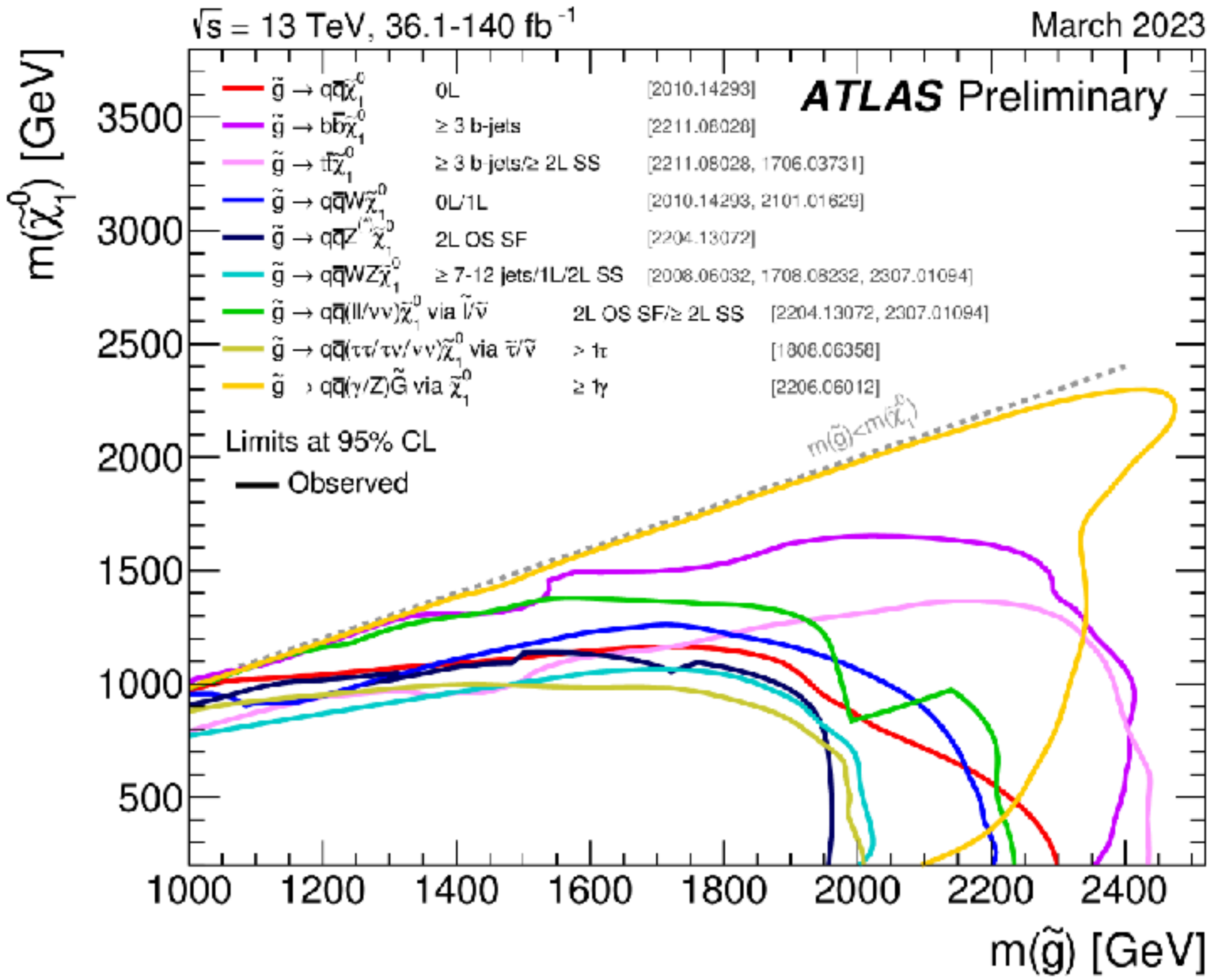


Stop searches

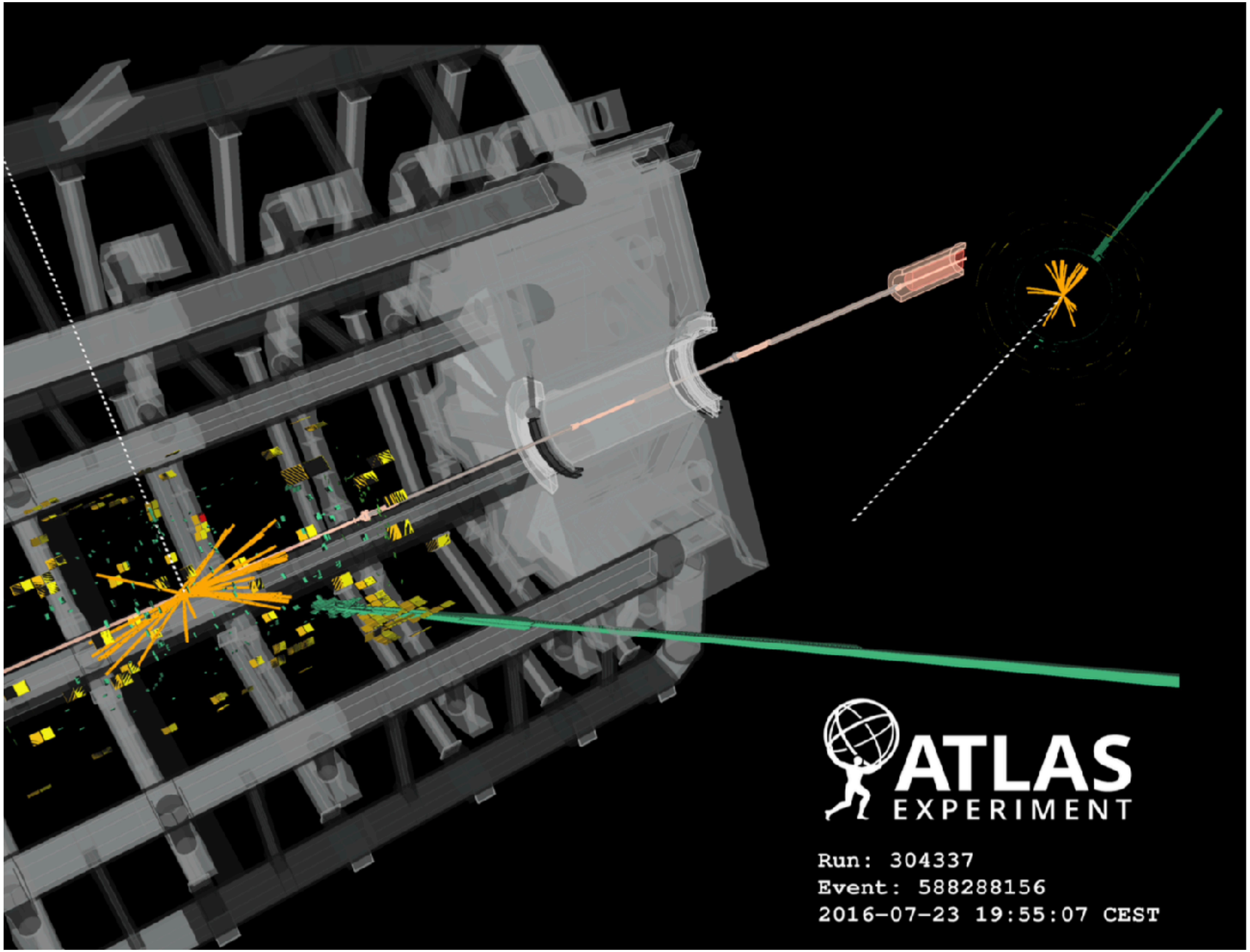




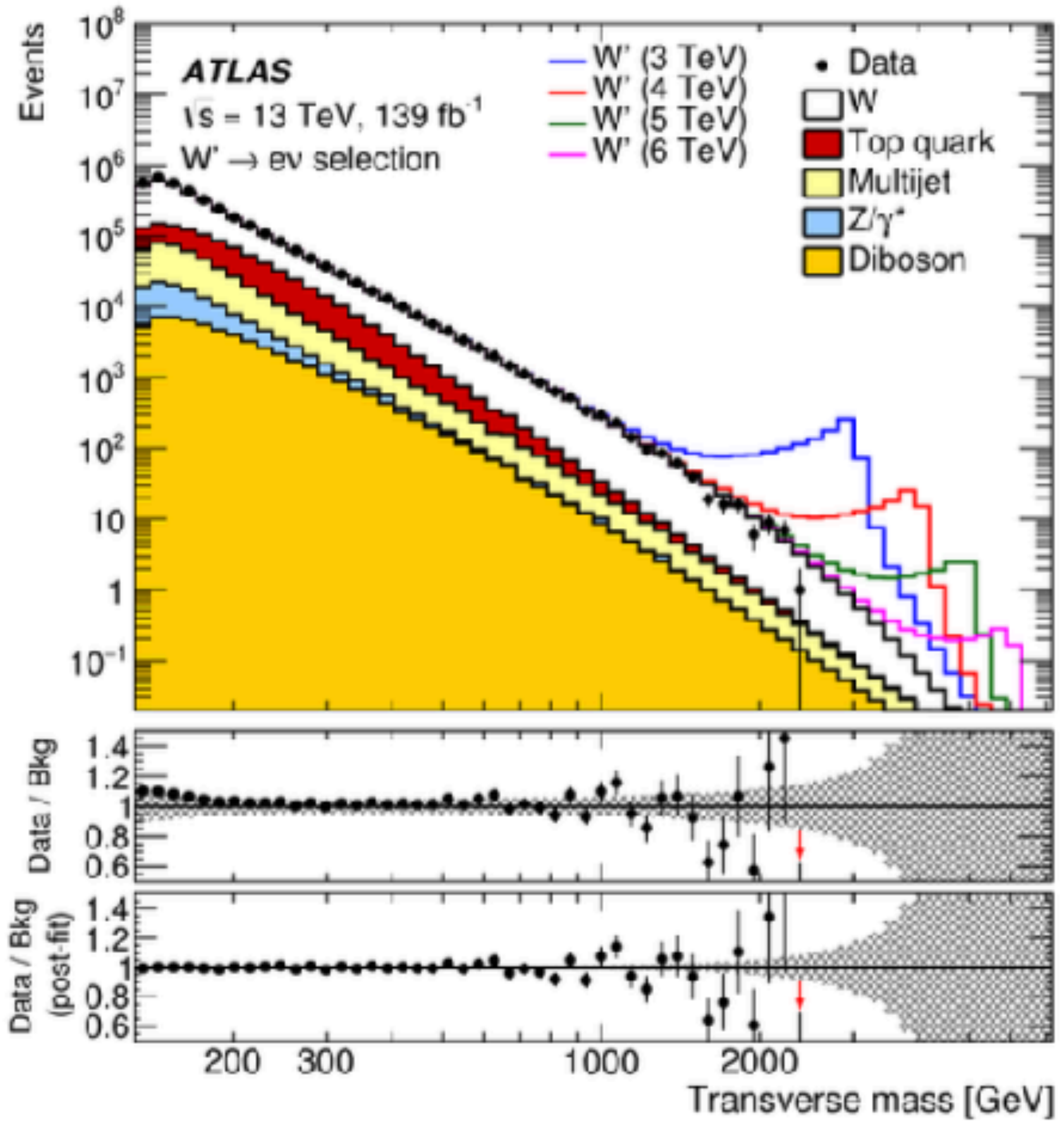
Gluino searches



Searching for new resonances



Transverse mass
(in lepton-MET search)



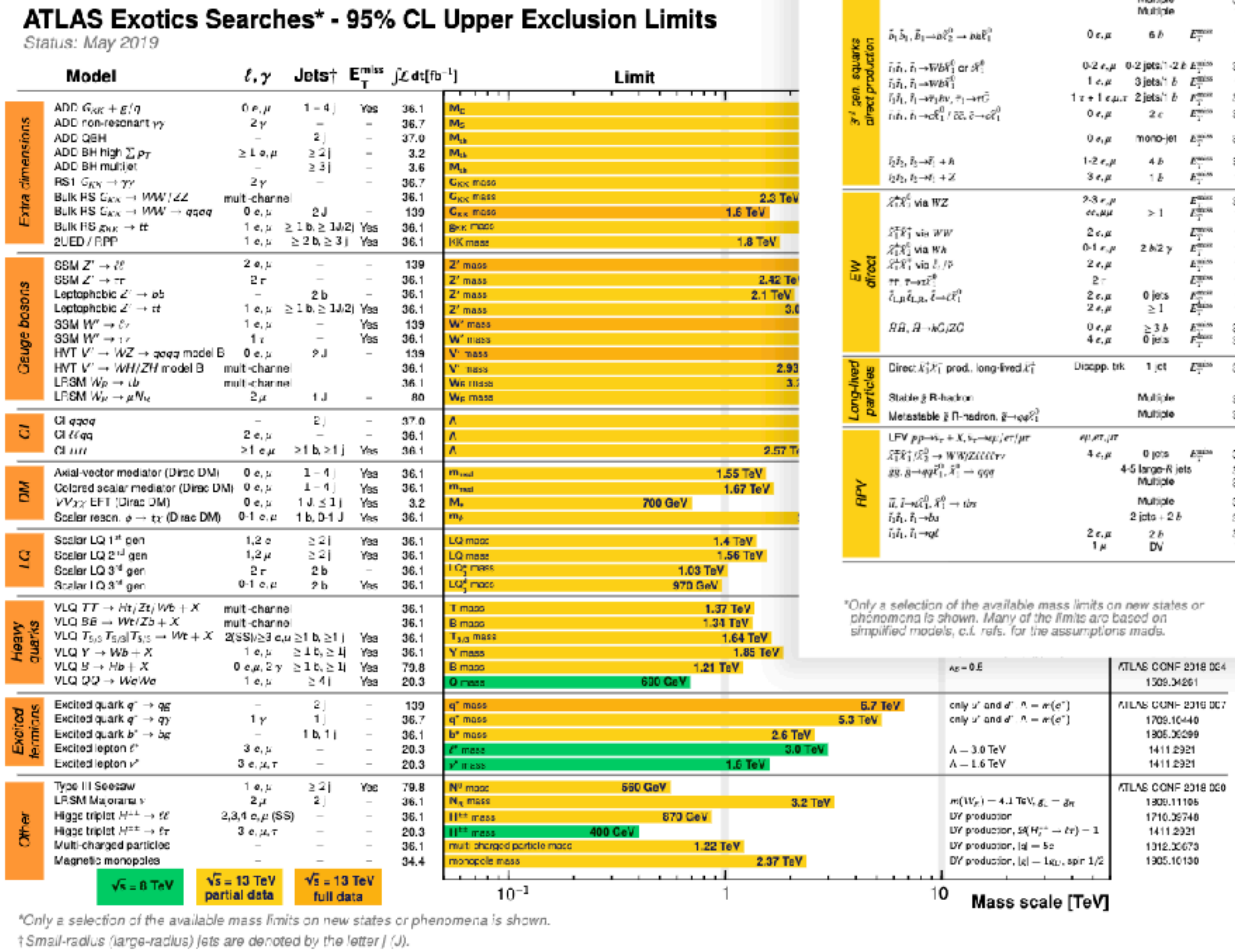
Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

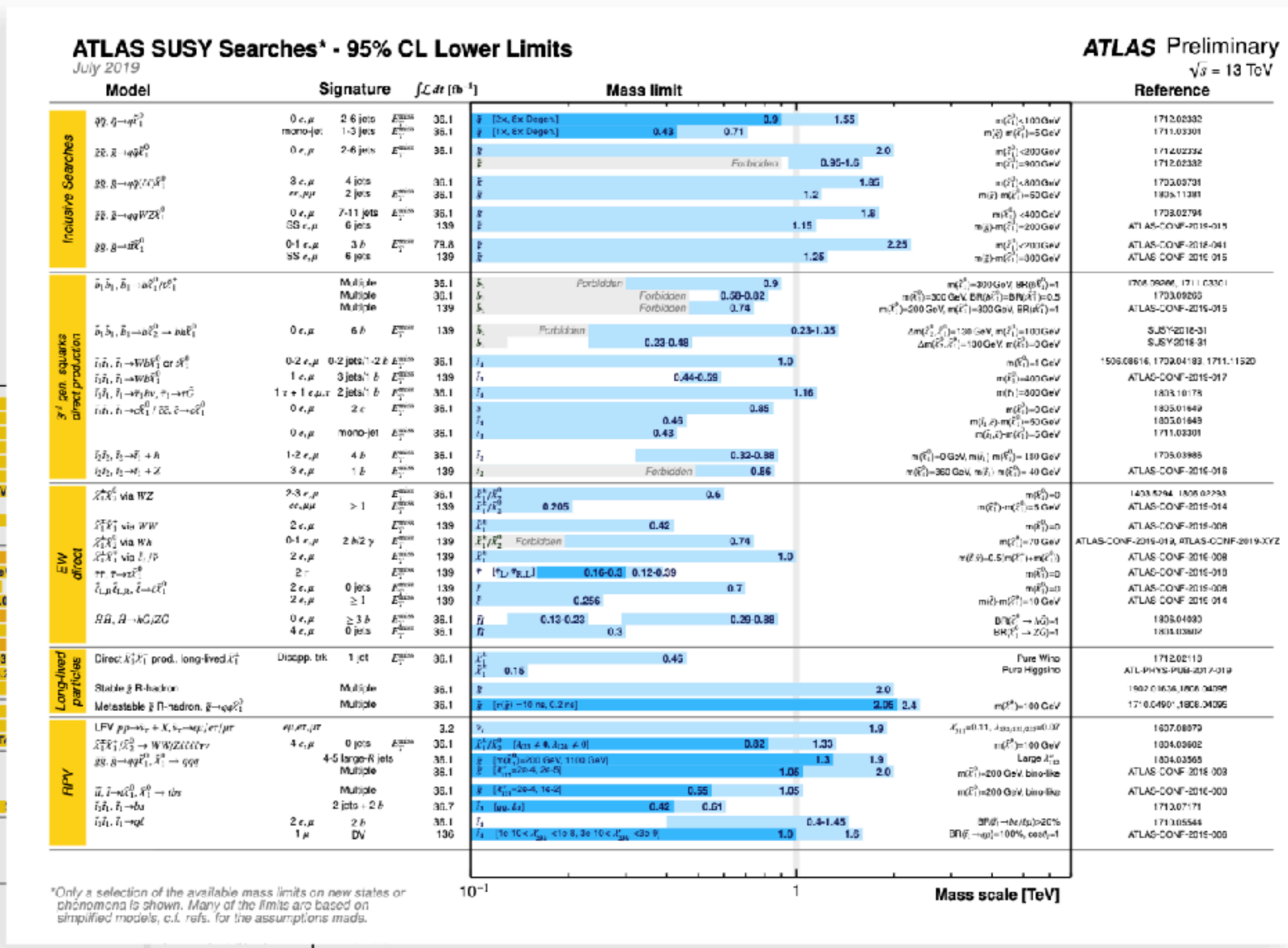
Electron pT = 1.1 TeV
MET = 1.16 TeV

Searches for New physics

- Cover all possibilities and leave no stone unturned

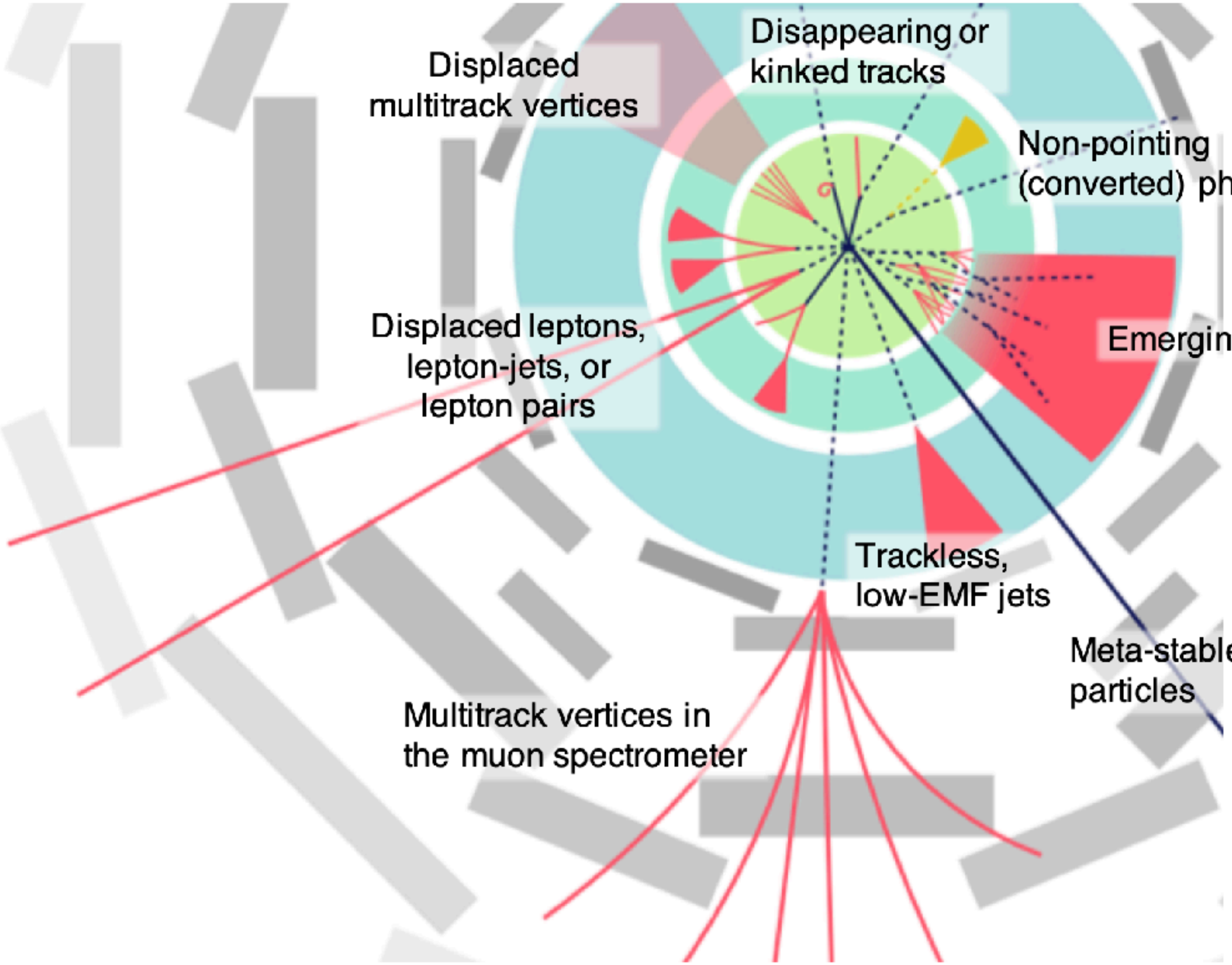
Theory-agnostic, signature based searches, as well as highly targeted model-dependent ones





Exotic exotica

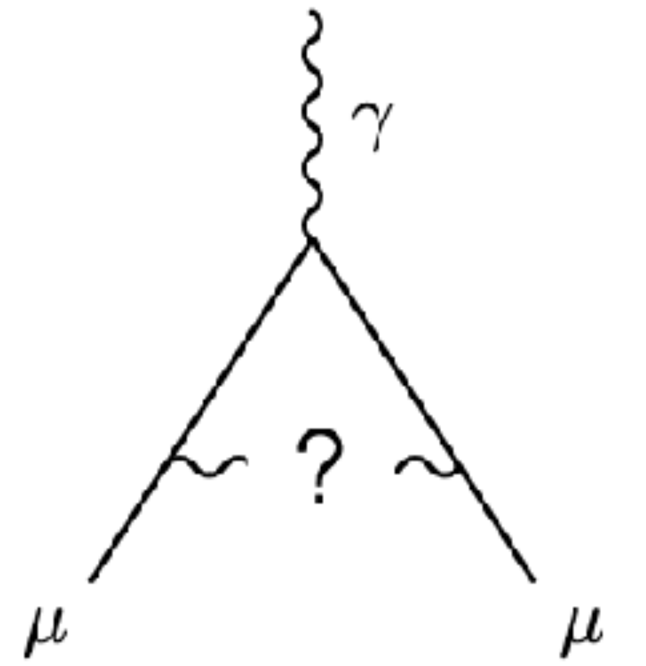
Long-lived particles can occur in case of weak couplings, ce
small phase-space (mass degeneracies) or high virtuality



Diverse set of signatures that need to be pursued by dedicated, usually non-standard analyses, some requiring special triggers

Confirmation of mass generation through spontaneous symmetry breaking in BEH potential. Scalar sector SM-like so far (but lacking precision)

QED tested to parts per million accuracy (slight anomaly in muon g–2)

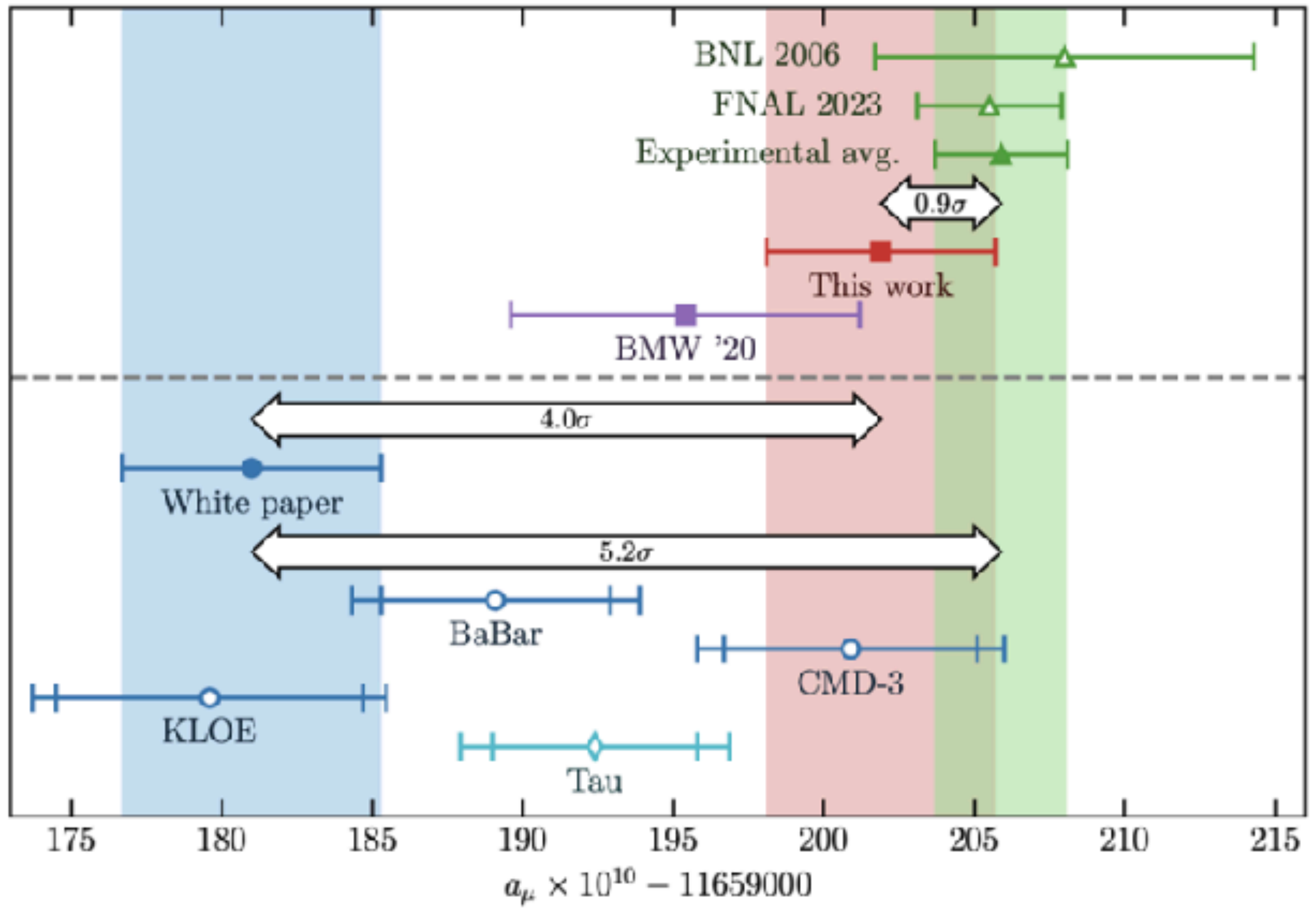


Asymptotic freedom in strong interactions verified at % level

Electroweak unification tested to high precision

Quark sector: CKM picture for quark mixing & CP violation confirmed

Lepton sector: massive neutrinos, unknown masses, nature, CP violation, sterile ν's ? No flavour violation in charged lepton sector. Lepton universality tested to per-mil level



No compelling sign of new physics found at high mass scales, or anywhere else, eg: no electric dipole moments (EDM), no dark matter particles (only gravitational hints), no axions (strong CP problem), no proton decay (GUT)

Hadron colliders - the future

What remains to be done ?

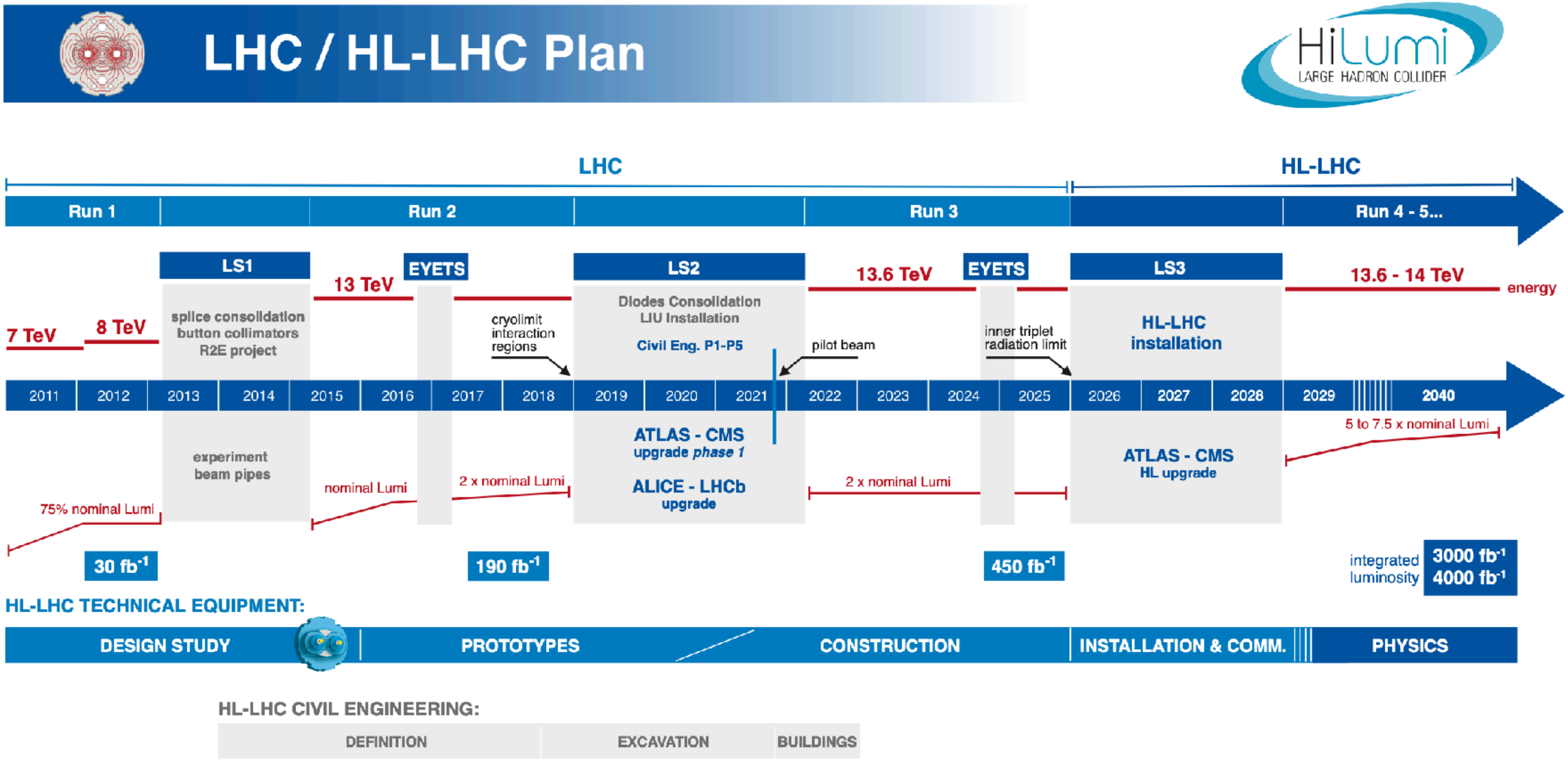
Almost every problem of the Standard Model originates from Higgs interactions

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour (y) — *naturalness* (μ^2) — *stability* (λ) — *cosmological constant* (V_0)

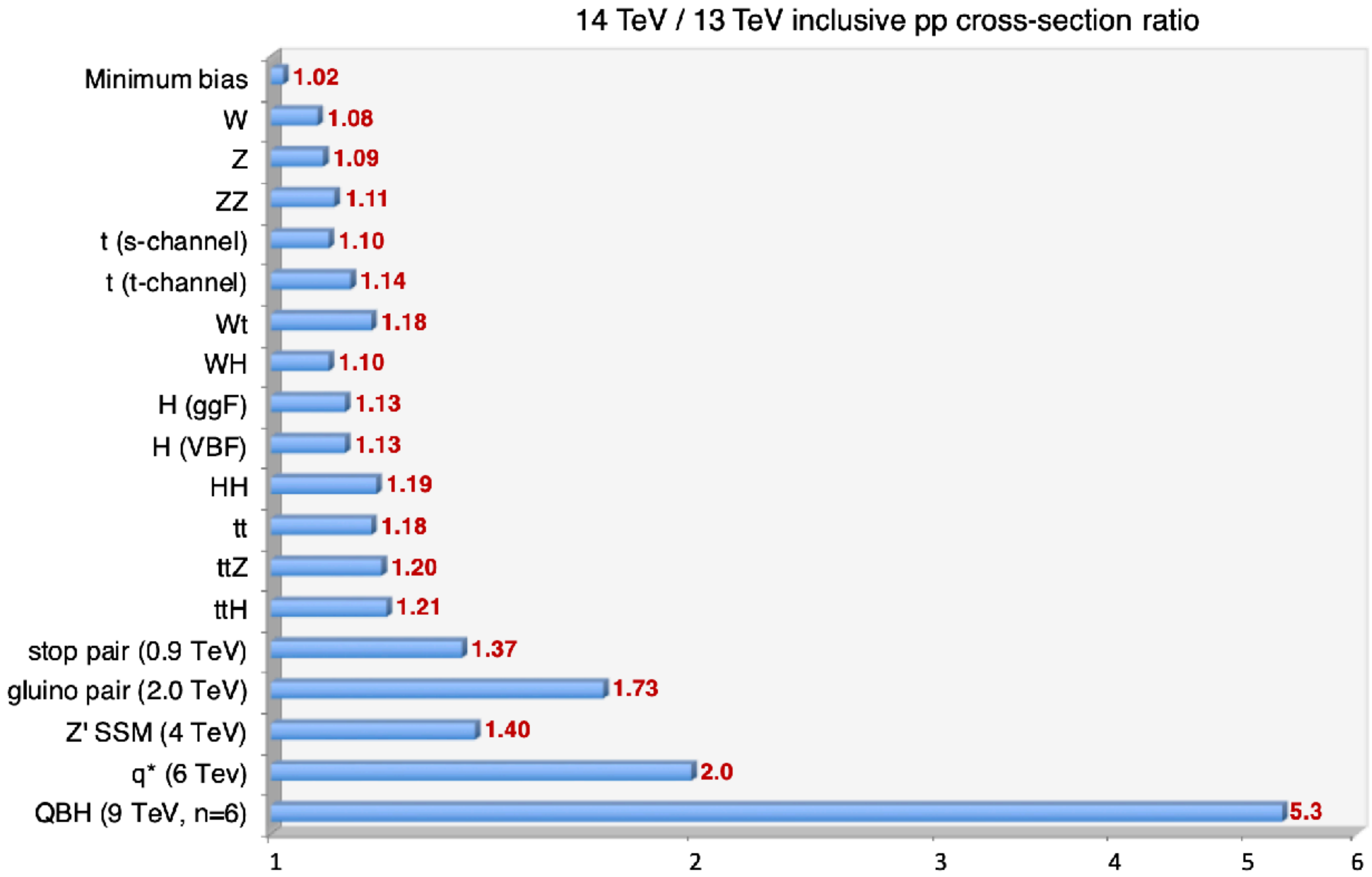
From Gavin Salam

The high-luminosity LHC



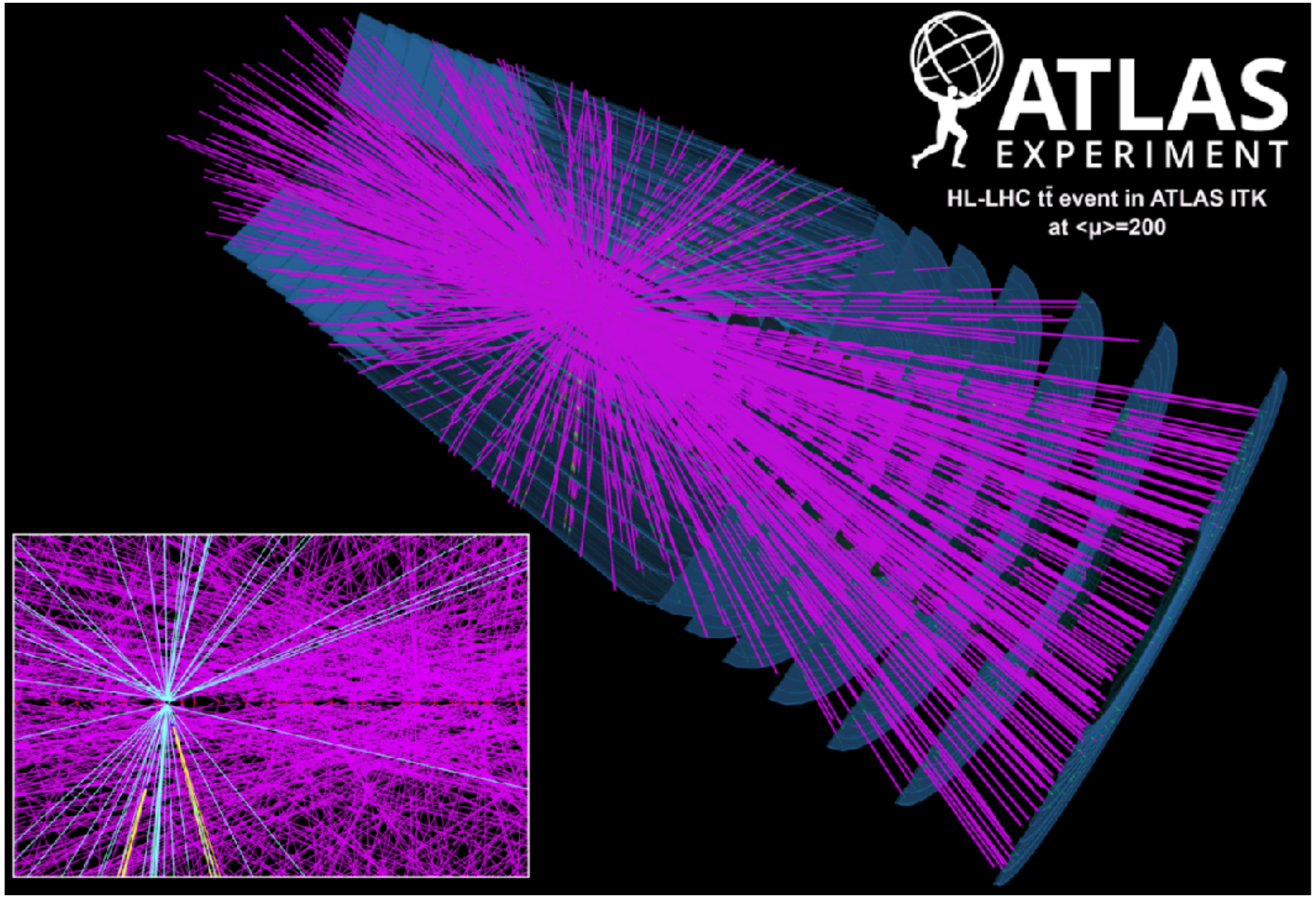
Hadron colliders: The HL-LHC

Hadron colliders: The HL-LHC



- The High-luminosity inclusive Higgs sample will be 23 times larger than that of the Run2
- 190M single Higgs and 120K di-Higgses produced in 3 ab^{-1}

Hadron colliders: The HL-LHC



- To collect data faster increase in number of collisions per bunch crossing. Average pile-up of ~200
- High particle fluency's challenge for detectors
- All experiments plan significant upgrades (mainly of traking systems)
- Novel reconstruction algorithms required (extensive usage of machine learning)

Hadron colliders: The HL-LHC

A new ATLAS for the high-luminosity era
18 January 2023 | By Stefan Guindon, Christian Ohm, Caterina Vernieri

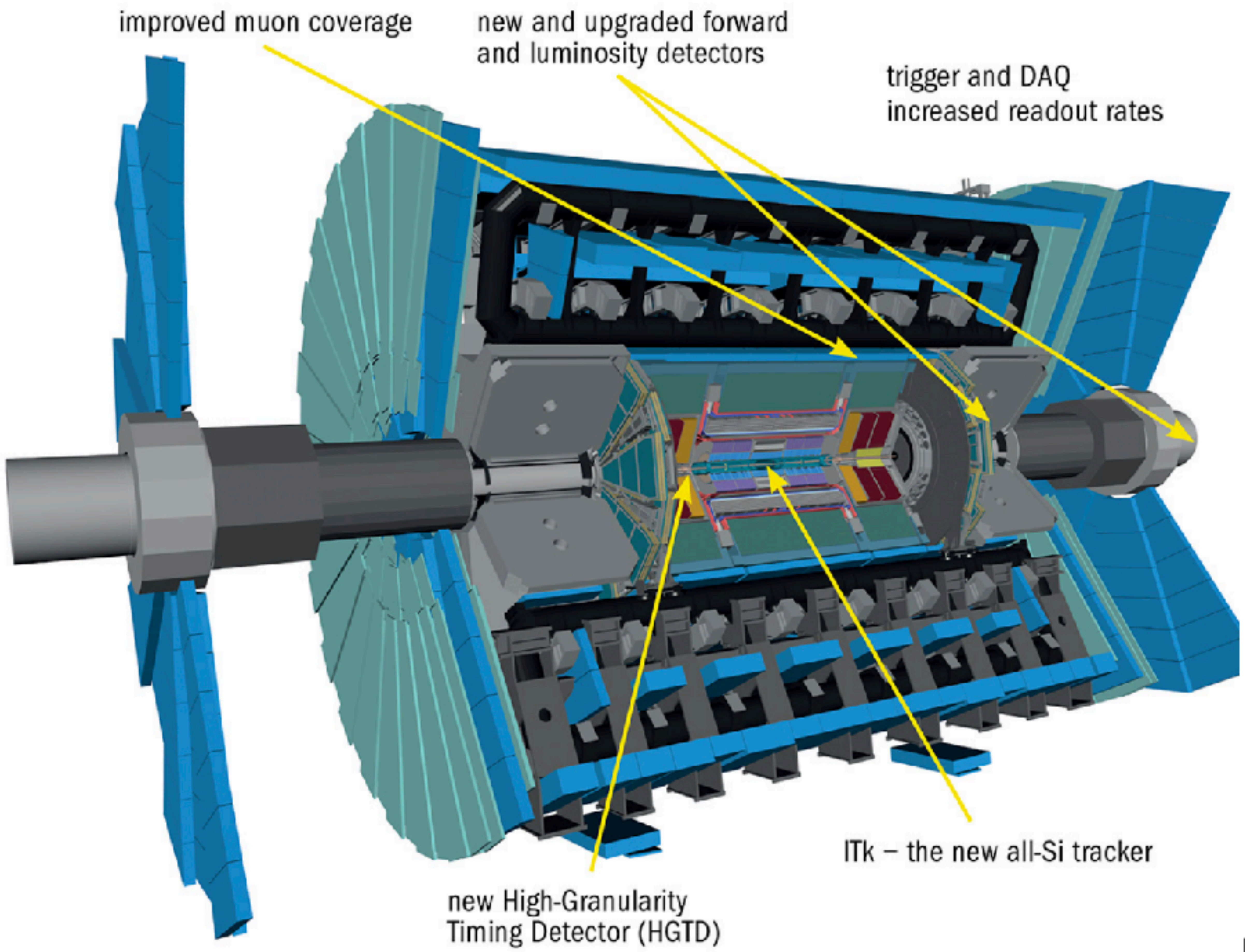
Feature link

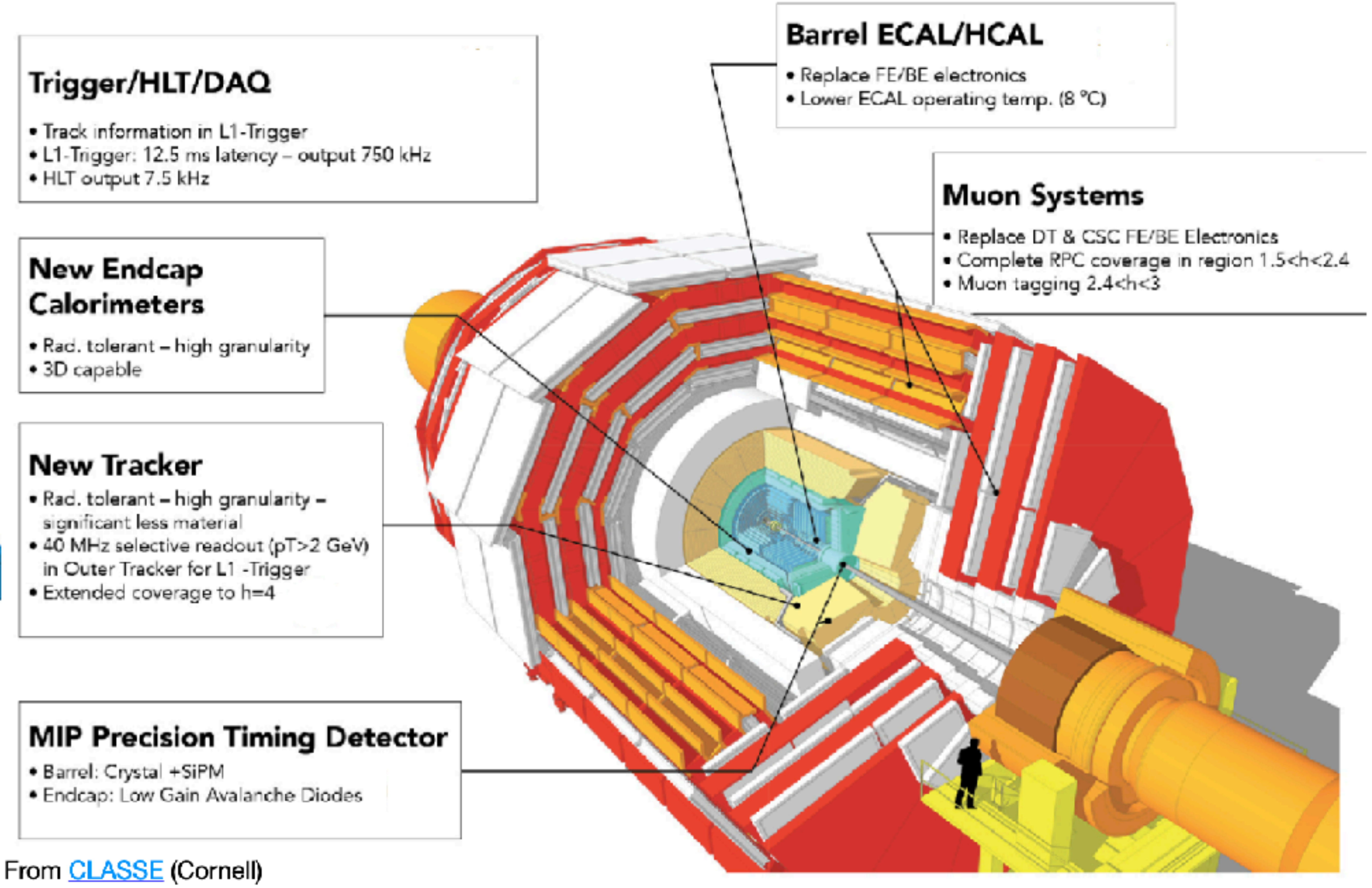
ACCELERATORS | FEATURE

CMS prepares for Phase II

9 January 2023

CERN Courier article link

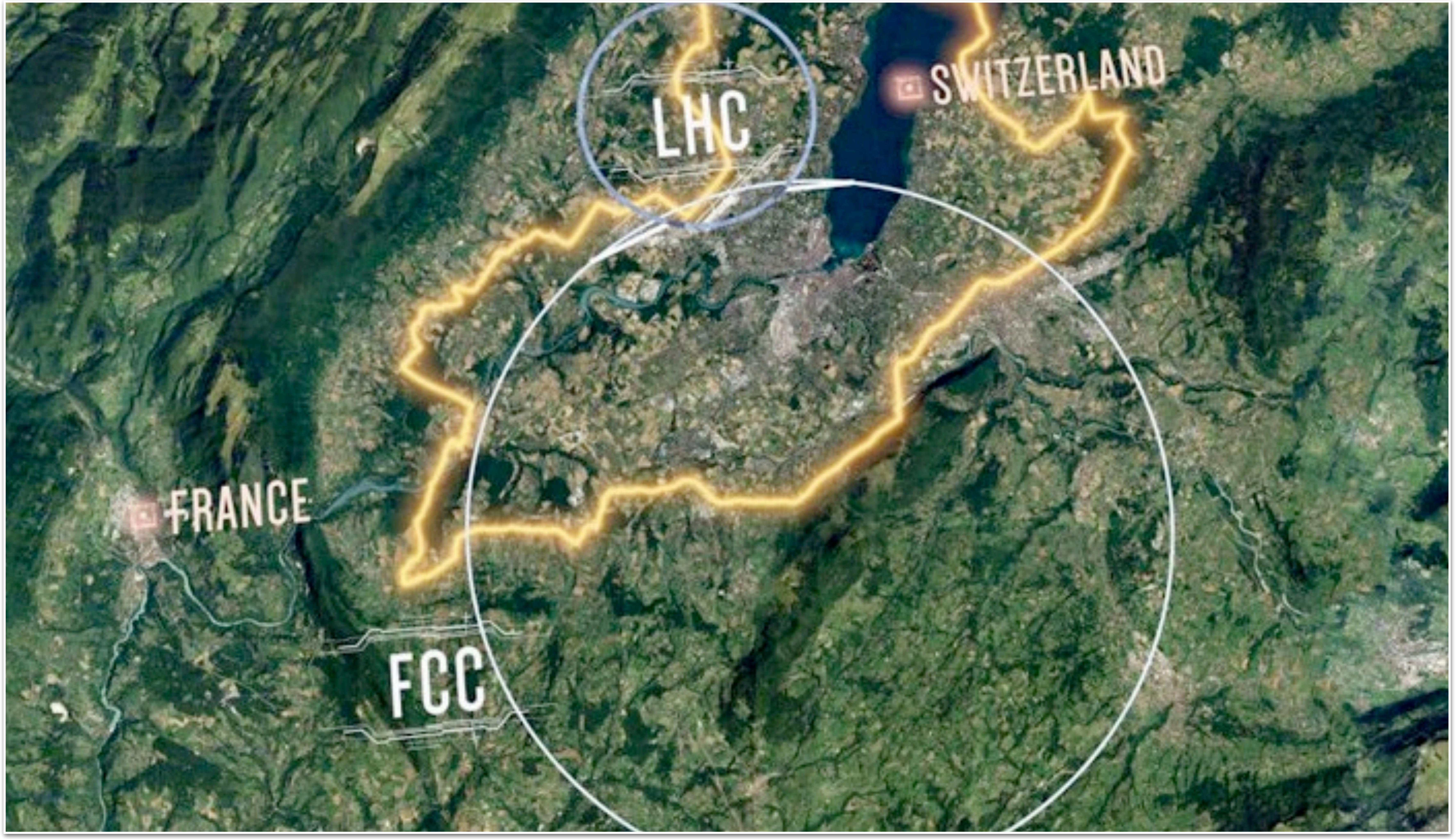




From CLASSE (Cornell)

The far future

- New generation high-energy lepton/hadron colliders being studied by CERN and China
- Aim to study with high precisionnthe Higgs properties an its potential



The far future

The FCC reach

Take a simple Z’ model (a new Z-like boson with a larger mass) as simple example

LHC

pp, 13 TeV, 139 fb^{-1}

Exclusion limit ~ 5.1 TeV

(electron and muon channels, single experiment)

× 7.8 →

FCC-hh

pp, 100 TeV, 20 ab^{-1}

Exclusion limit ~ 41 TeV

(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

This situation is not new

Glashow reveals that several of Harvard's most talented graduate students recently defected to Wall Street. "Goldman, Sachs loves theoretical physicists," he confides. Georgi notes that even before the SSC was terminated, the slumping economy and the influx of physicists from Eastern Europe had created a shortage of physics jobs in the U.S. "I don't understand why, but we still get fantastic young people entering the field," he comments. "Well, I do understand why, because the questions this field addresses are so interesting."

Faraday expressed as well as anyone why it is so difficult to abandon the hope that a single force rules nature. "If the hope should prove well-founded," the British scientist wrote, "how great and mighty and sublime in its hitherto unchangeable character is the force I am trying to deal with, and how large may be the new domain of knowledge that may be opened to the mind of man?"

"Experiment is the source of scientific imagination," he remarks. "All the philosophers in the world thinking for thousands of years couldn't come up with quantum mechanics."

Samuel C. Ting, a professor at the Massachusetts Institute of Technology and head of the largest detector at CERN's LEP collider, agrees. He points out that in this century, advances in physics "almost always come from a totally unexpected experimental result." The discoveries of antimatter (predicted by P.A.M. Dirac in 1930) and of the *Z* and *W* particles (predicted by Weinberg and others) were exceptions to this rule. More typical was the discovery in the 1950s of a subtle asymmetry in the behavior of certain particles that was not only unexpected but was thought to be prohibited by the known rules of physics.

Scientific American, ~1990

“Nuclear physics has put into the hands of mankind formidable power. We are still struggling with the problem of how to use nuclear energy efficiently and safely, we are rightly alarmed at the accumulation of nuclear weapons of annihilation. Until mankind has shown that it can deal wisely with nuclear power, it is not prepared for something entirely new. Until the last nuclear warhead has either been dispatched to outer space or quitely burnt up as fuel in an energy-producing reactor, I would not welcome an entirely new development. I have often said that I am in favor of supporting high energy physics, provided that the high energy physicists can promise not to produce applicable results within the next twenty-five years. I am usually not taken seriously when I make such remarks. I do, however, mean them very seriously.”

H.B.G. Casimir,

The 25th Anniversary Ceremony,

CERN Courier,

September 1979,

The end