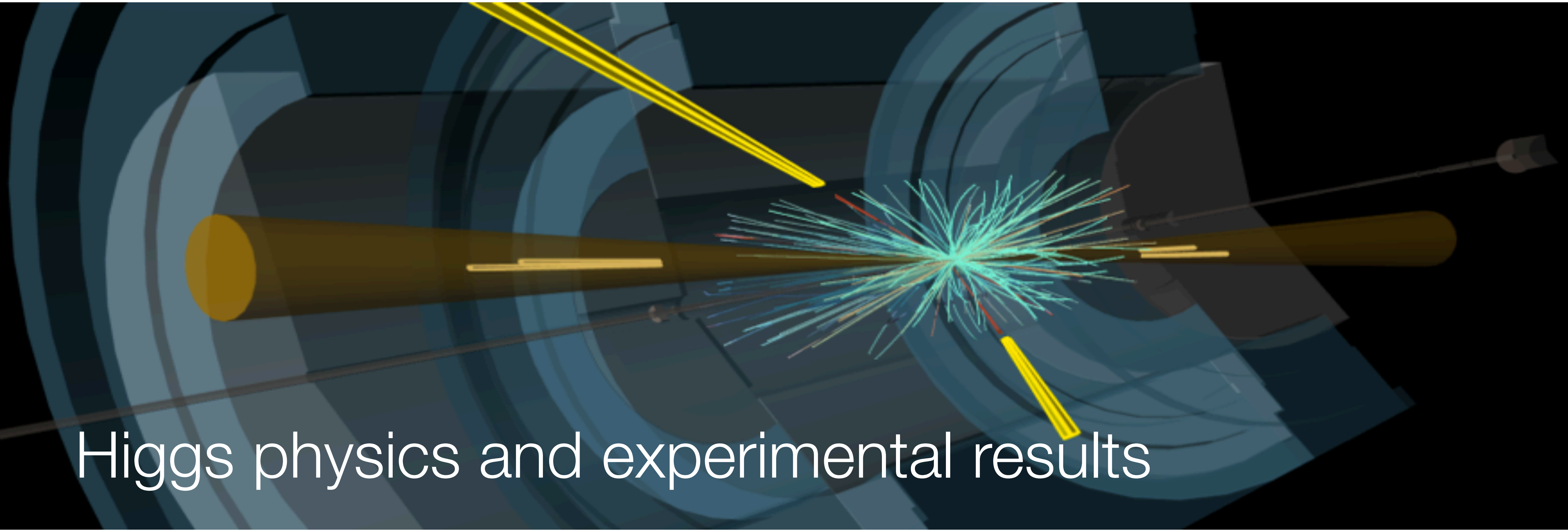


Higgs physics and experimental results

Bruno Lenzi

New Trends in High Energy Physics and QCD School, Natal, Brazil

21/10/2014

Outline

- Historical and theoretical aspects
- Brief introduction to LHC, ATLAS, CMS
- Main decay channels with focus on $H \rightarrow \gamma\gamma$
- Combined results and prospects

July 4 2012 at CERN

After half a century, the discovery!

and a few hours before...

http://blogs.discovermagazine.com/cosmicvariance/2012/07/03/live-blogging-the-higgs-seminar/#.VDZdG-evRBY

http://blackholekevinearthdestroyer.blogspot.ch/2012/07/higgs-dependence-day.html

Press coverage after July 4 2012

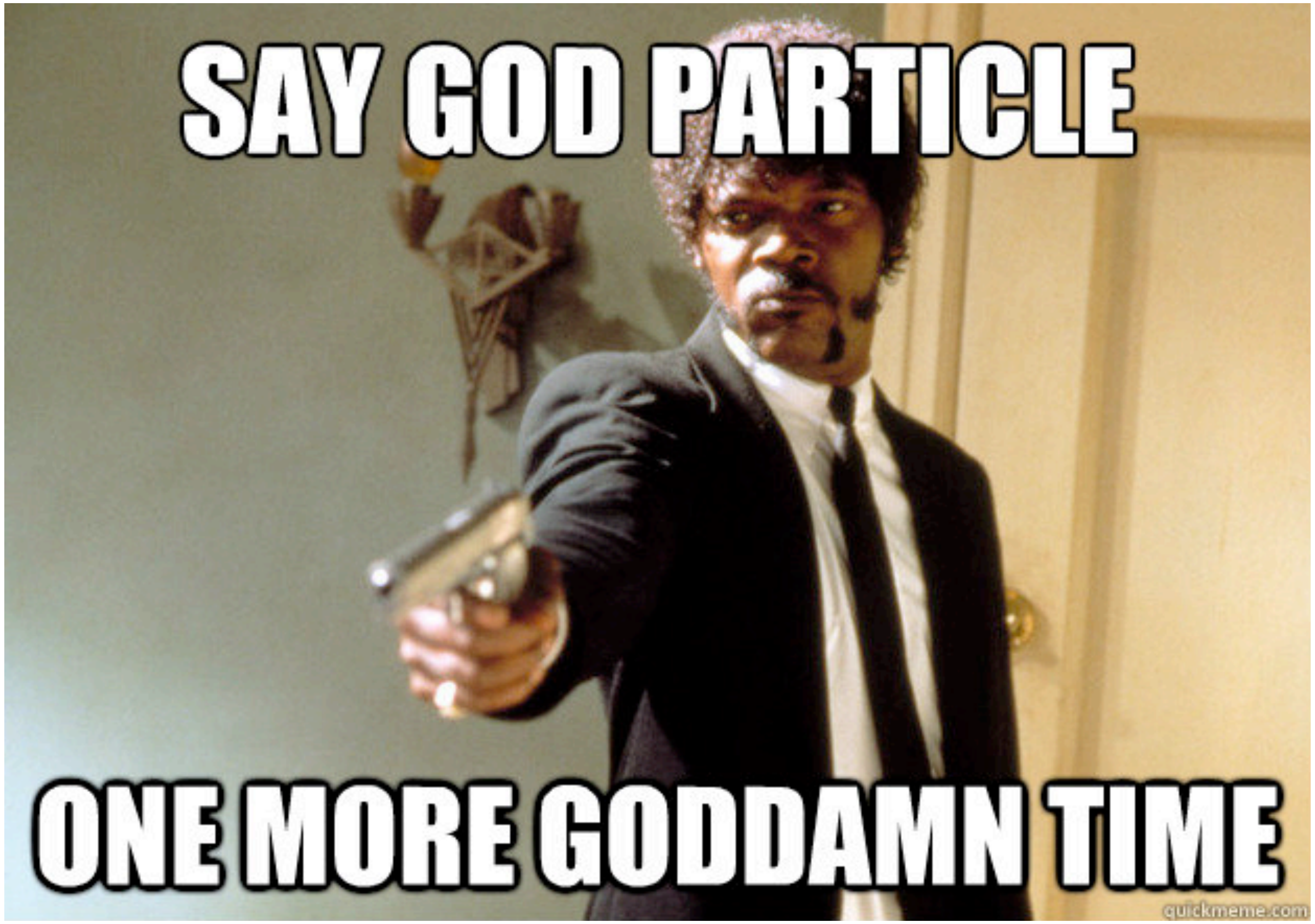
[Andreas Hoecker]

Reactions to the discovery

The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Reactions to the discovery

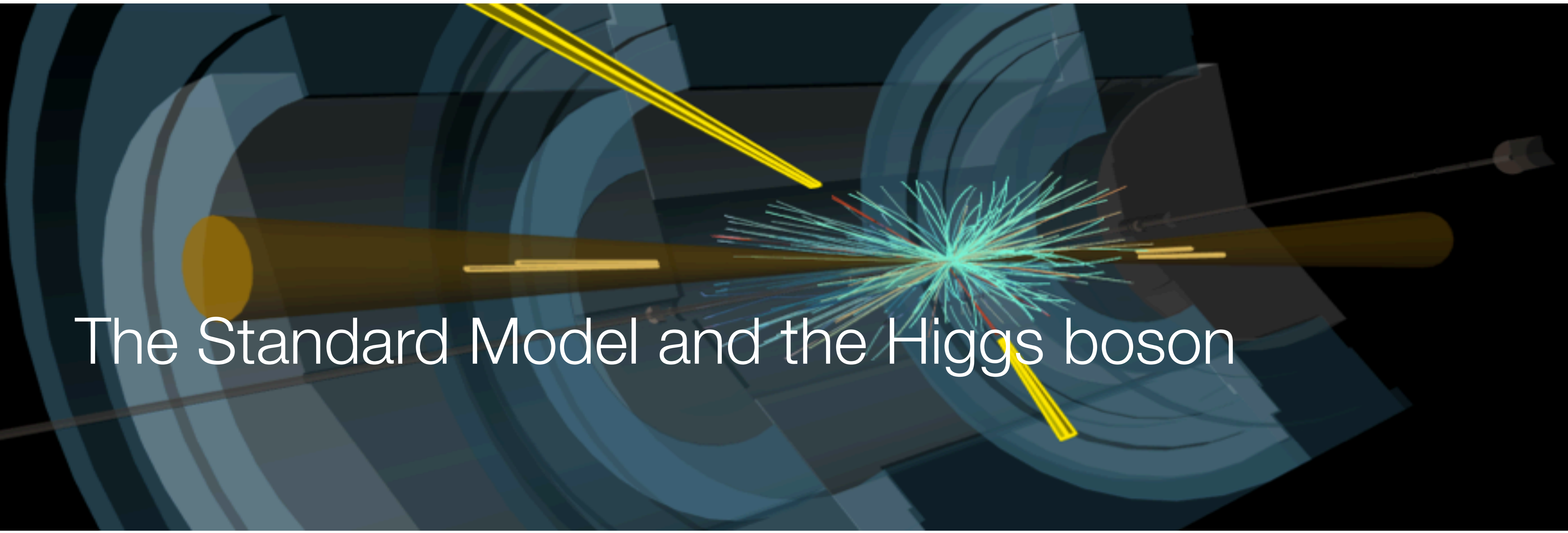


Reactions to the discovery

- Massless electron → infinite Bohr radius, atoms lose integrity
  - No chemistry, no life

Reactions to the discovery

- Massless electron → infinite Bohr radius, atoms lose integrity
  - No chemistry, no life
- 98% of the mass of the proton comes from binding energy
  - QCD confinement



The Standard Model and the Higgs boson

Higgs pre-history: summary

1964 The “BEH mechanism”

Brout, Englert ; Higgs ; Guralnik, Hagen, Kibble

1967 “BEH mechanism” included in the EW theory (SM)

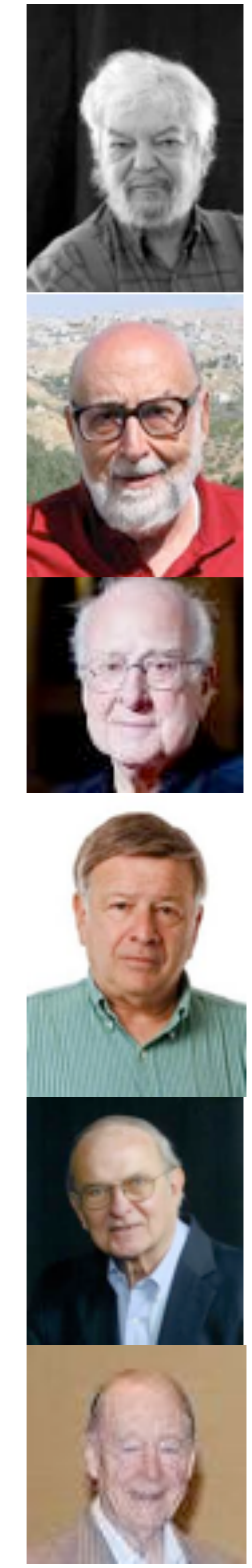
1973 Neutral current interactions observed at Gargamelle (CERN)

1983 W and Z bosons discovered at CERN SppS

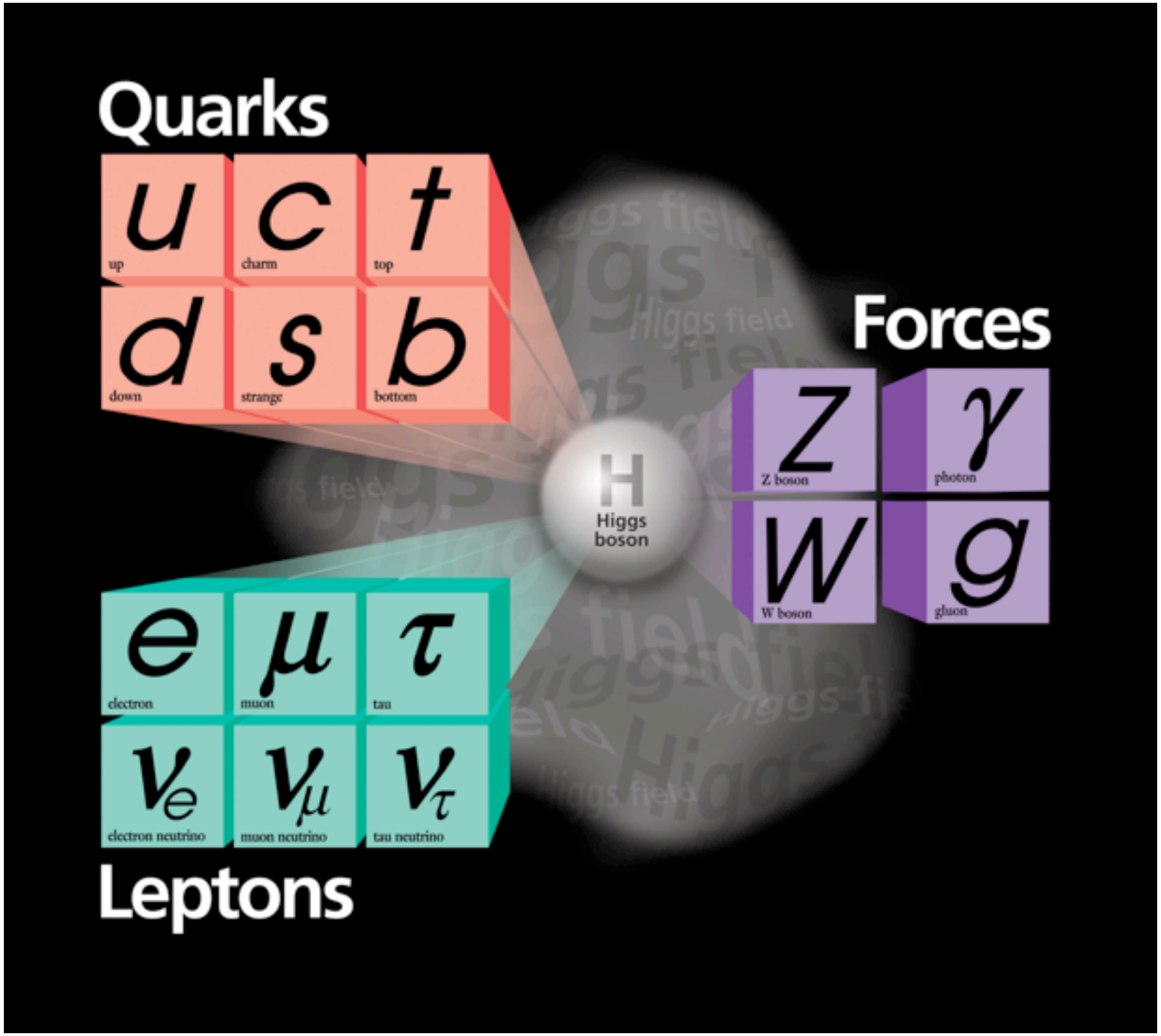
2000 LEP excludes m_H < 114.4 GeV

2011 Tevatron: 156-175 GeV excluded, LHC: hints around 125 GeV

2012 A new particle discovered at the LHC



The Standard Model (SM) of particle physics



- Unifies special relativity, quantum mechanics and field theory
- Describes electroweak and strong interactions between all known particles
- BEH mechanism gives mass to W,Z bosons (+ fermions)
- Survived last decades of experimental verification
    - Higgs boson was (?) the only missing piece

Gauge principle: Quantum electrodynamics (QED)

- Matter particles (fields) are fermions, obey Dirac equation:

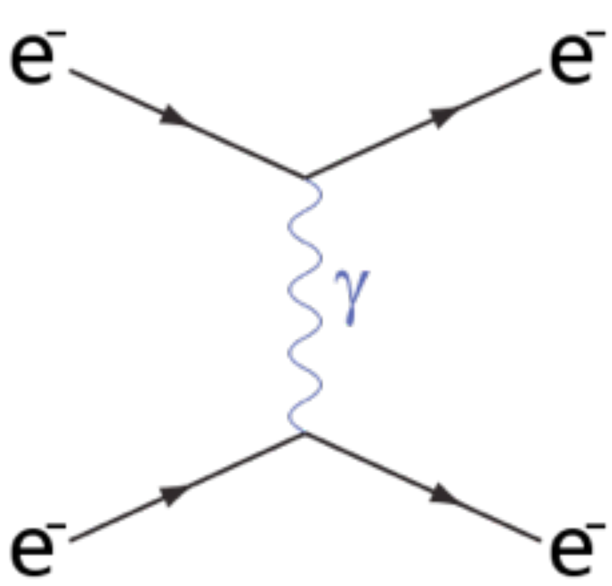
$$\mathscr{L} = \bar{\psi}(x)\,(i\gamma^\mu \partial_\mu - m)\,\psi(x)$$

- Gauge principle: $\mathscr{L}$ invariant under local phase transformations

$$\psi(x) \to e^{iq\alpha(x)}\psi(x)$$
$$A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x)$$
$$D_\mu \equiv \partial_\mu + iqA_\mu(x)$$

$$\begin{aligned}\mathscr{L} &= \bar{\psi}\,(i\gamma^\mu D_\mu - m)\,\psi \\ &= \bar{\psi}\,(i\gamma^\mu D_\mu - m)\,\psi - iqA_\mu \bar{\psi}\gamma^\mu\psi \\ &= \mathscr{L}_{\text{free}} - J^\mu A_\mu\end{aligned}$$

$$\mathscr{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$



Gauge principle: Quantum electrodynamics (QED)

- Fermion masses allowed

- Gauge-boson mass forbidden

  - Photon mass term violates gauge invariance

$$\frac{1}{2}m_\gamma^2 A^\mu A_\mu \neq \frac{1}{2}m_\gamma^2 \left(A^\mu - \partial^\mu \alpha\right)\left(A_\mu - \partial_\mu \alpha\right)$$

  - Massless photon “predicted” → consistent with observations: $m_\gamma < 10^{-18}$ eV (PDG)

Gauge principle vs. masses in the SM

- Gauge group of the SM: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ and Lagrangian:

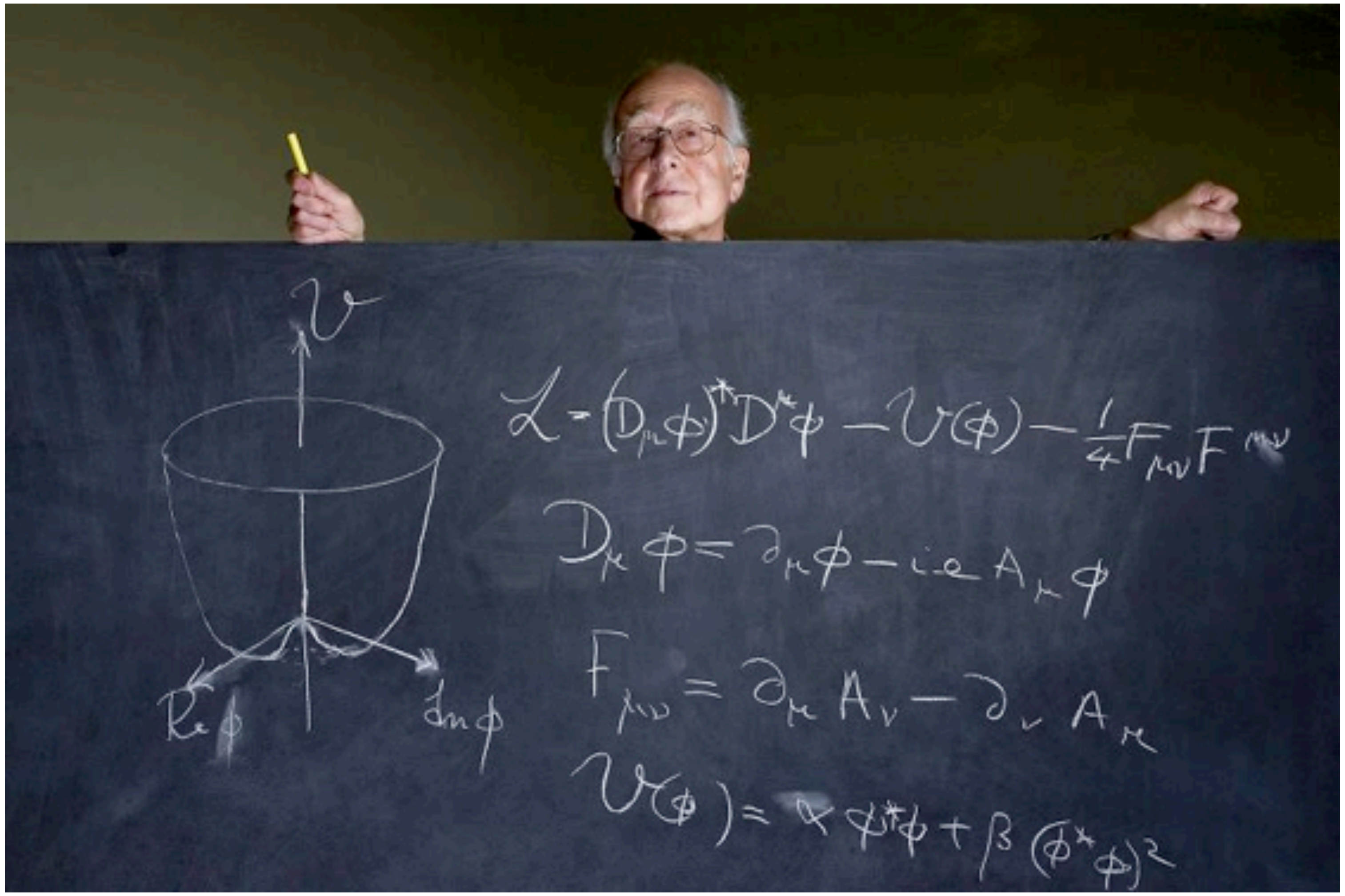
$$\mathscr{L}_{\text{gauge+fermions}} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - \frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_f i\bar{f}\not{D}f$$

- Weak interactions short-ranged → massive gauge bosons ($W^{\pm}$, Z)
  - But mass terms break gauge invariance: $m^2 W^a_{\mu\nu}W^{\mu\nu}_a \rightarrow \Delta\mathscr{L} \neq 0$
- Mass terms for fermions not allowed by $SU(2)_L \otimes U(1)_Y$

Break symmetry explicitly and abandon gauge principle ???

Spontaneous symmetry breaking: BEH mechanism

- Only way to break gauge symmetry consistently is to spontaneously break the symmetry of the vacuum:
  - Scalar field + potential with non-trivial minimum
- Goldstone theorem: SSB ↔ massless (Nambu-Goldstone) bosons
  - But no bosons observed!
  - Things work differently in gauge theories...

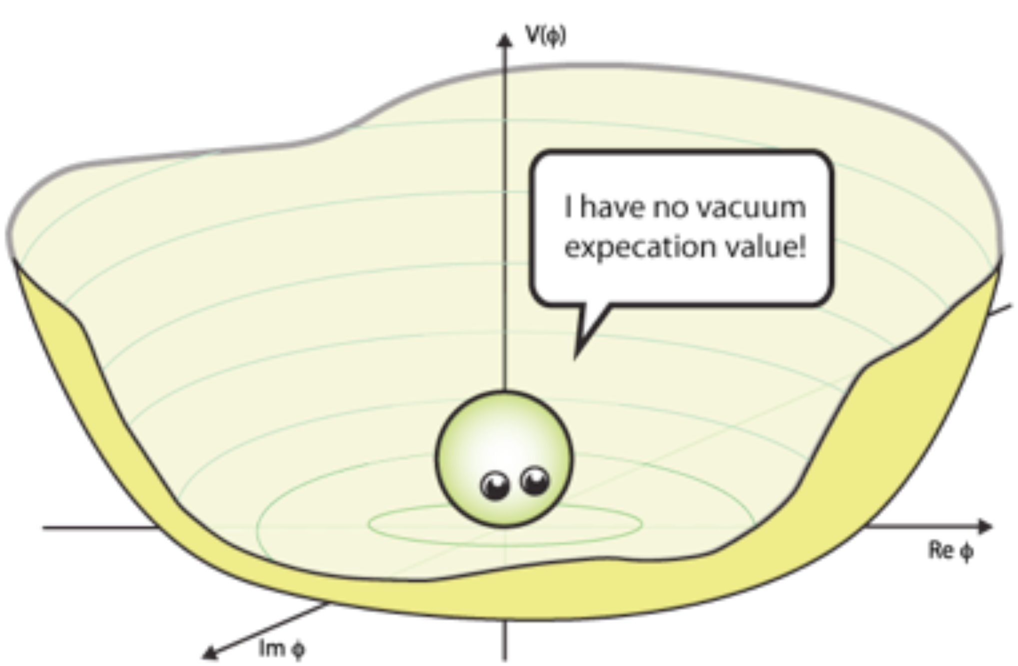


Spontaneous symmetry breaking: BEH mechanism

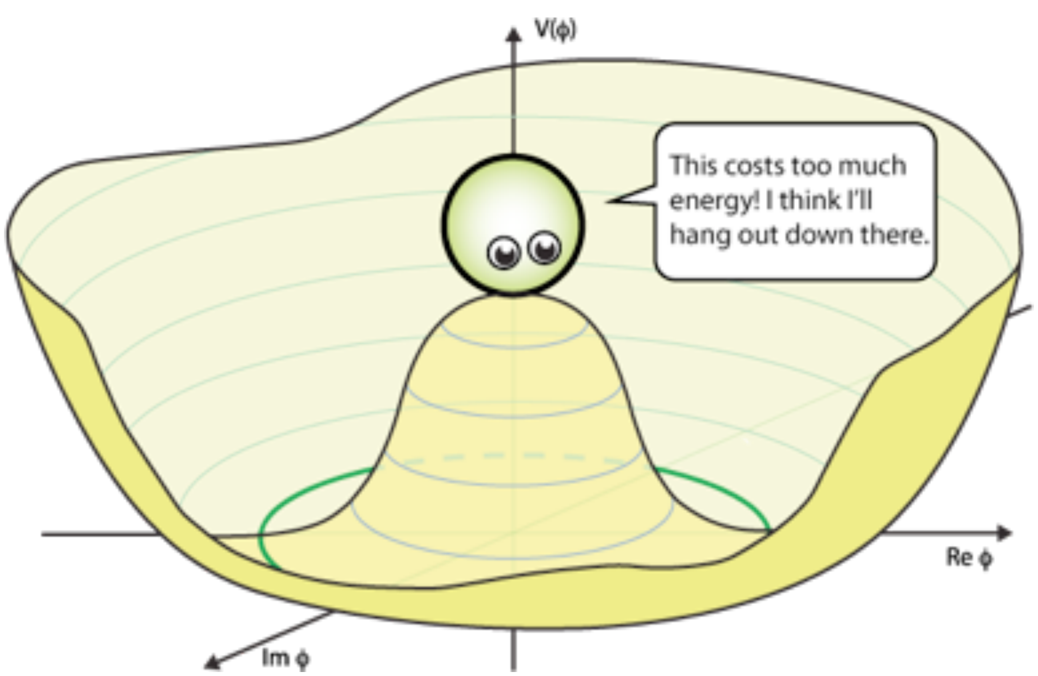
- Only way to break gauge symmetry consistently is to spontaneously break the symmetry of the vacuum:
  - Scalar field + potential with non-trivial minimum

$$V(\Phi) \quad = \quad \mu^2\, \Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$

$\mu^2 > 0$



$\mu^2 < 0$



http://www.quantumdiaries.org/2011/11/21/why-do-we-expect-a-higgs-boson-part-i-electroweak-symmetry-breaking/

Spontaneous symmetry breaking: BEH mechanism

- Develop the theory around a point of minimum:

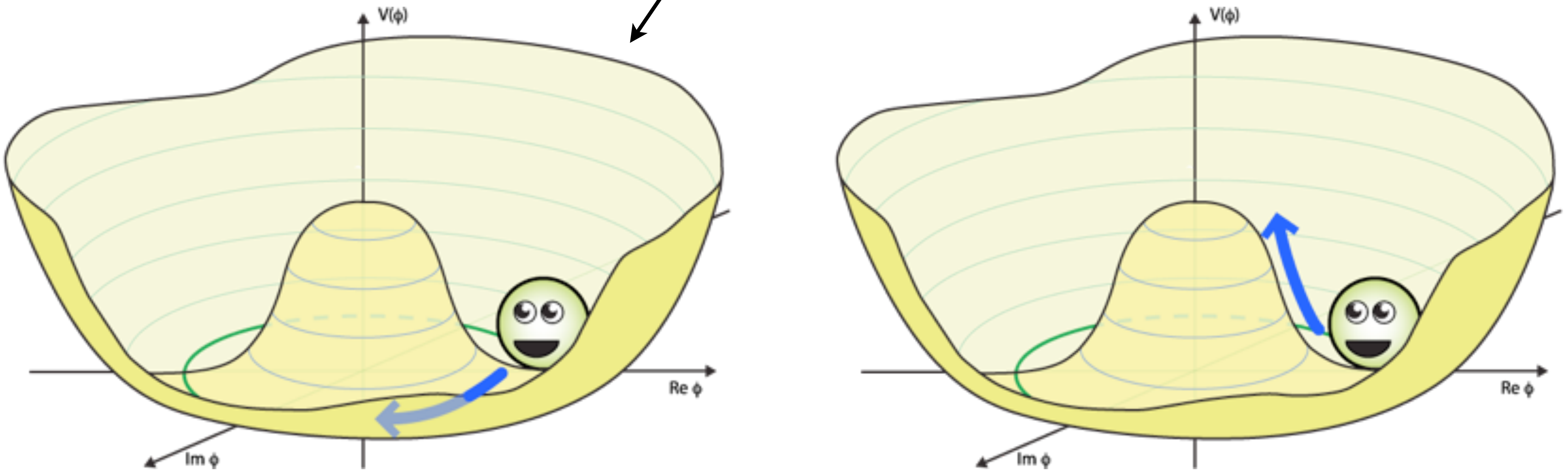
Doublet of complex fields (4 degrees of freedom)

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} e^{i\frac{\sigma_a}{2}\theta_a(x)} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

Nambu-Goldstone bosons (massless)

246 GeV (from muon decay)

Higgs boson (massive)



http://www.quantumdiaries.org/2011/11/21/why-do-we-expect-a-higgs-boson-part-i-electroweak-symmetry-breaking/

Spontaneous symmetry breaking: BEH mechanism

- Unitary gauge:
  - 3 NB bosons "eaten" by $W^{\pm}$, Z bosons that become massive

$$(D_\mu\Phi)^\dagger D^\mu\Phi \rightarrow \frac{1}{2}(\partial_\mu H)(\partial^\mu H) + (v+H)^2\left[\frac{g^2}{4}W_\mu^\dagger W^\mu + \frac{g^2}{8\cos^2\theta_W}Z_\mu Z^\mu\right]$$

  - Higgs boson (1 d.o.f) with $m_H^2 = -2\mu^2 = 2\lambda v$ (free parameter) remains
    - Was the only unknown parameter of the SM
- Mass terms for fermions allowed via Yukawa couplings (but not predicted)

$$\mathscr{L}_Y = -\frac{1}{2}(v+H)\lambda_f \bar{f} f$$

Spontaneous symmetry breaking: BEH mechanism

Four tasks of the Higgs boson / BEH mechanism in the SM:

- Hide electroweak symmetry (distinguish EM, weak interactions)
- Give masses to $W^{\pm}$, Z (predicted)
- Give masses and mixings to fermions (free parameters)
- Keep EW theory from misbehaving
    - Would break perturbative unitarity at ~1 TeV (WW scattering)

Higgs profile and hunting (pre-history)

Higgs hunting: 1976

Ellis, Gaillard, Nanopoulos, Nucl. Phys. B106, 292

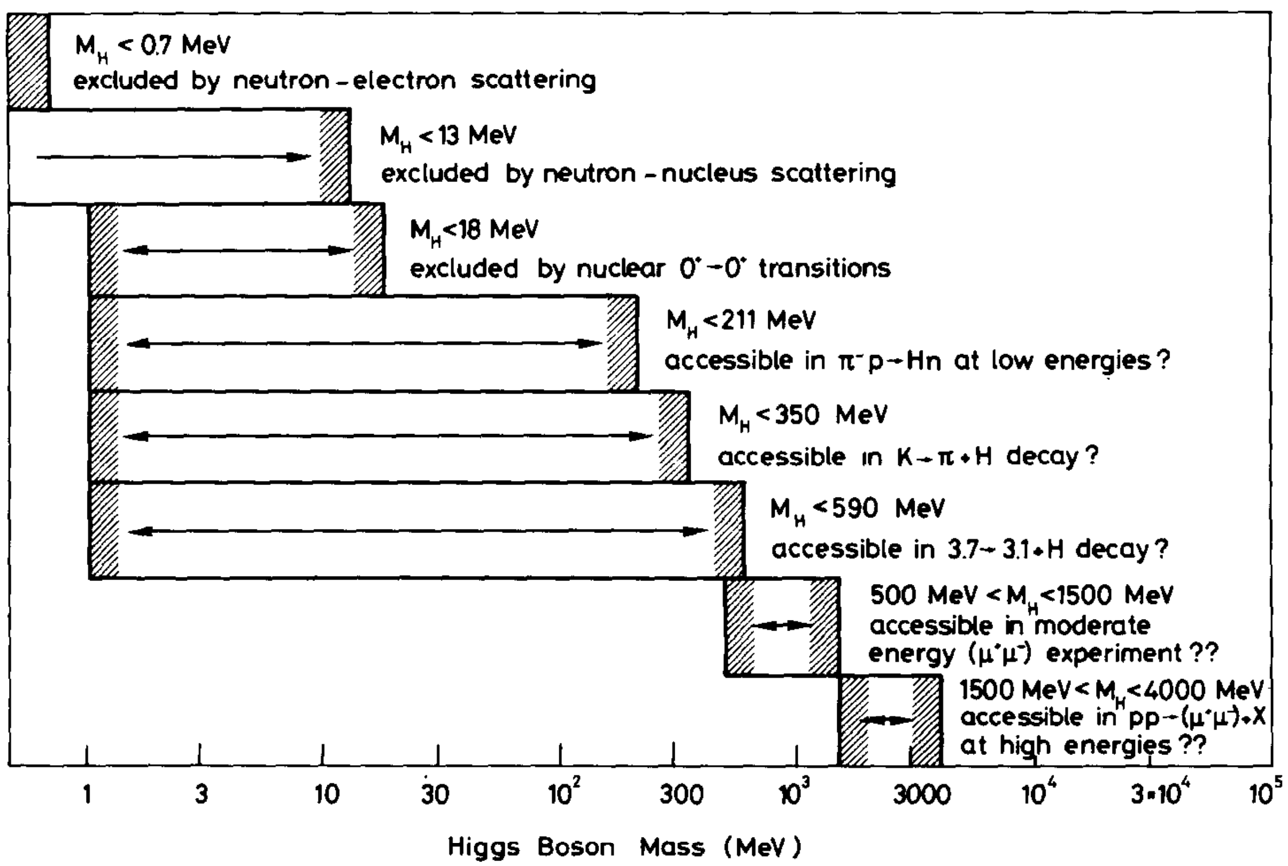


Fig. 3. Present and possible future limits on the Higgs boson mass.

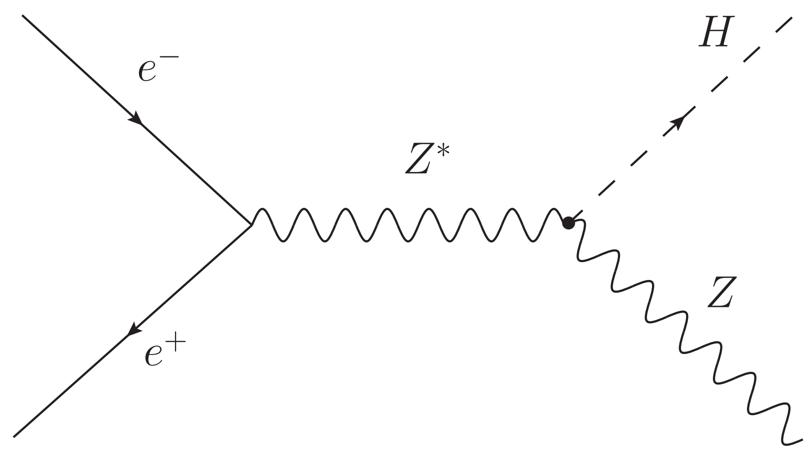
"We apologize to experimentalists for having no idea what is the mass of the Higgs boson [...]
For these reasons we do not want to encourage big experimental searches for the Higgs boson [...]"

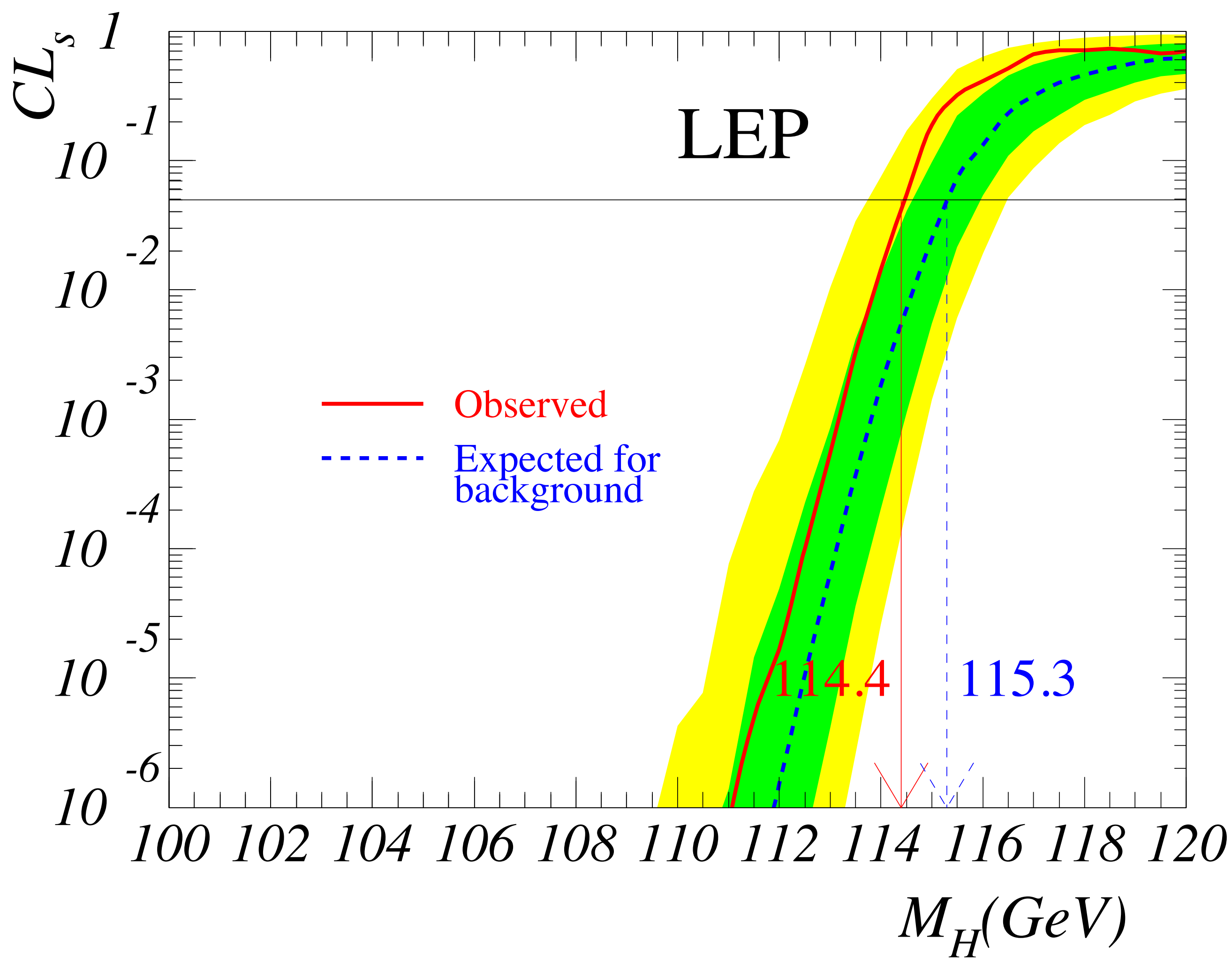
Higgs hunting: LEP (1989 - 2000)

- Running at Z pole mass, LEP-I excluded $m_H < 58$ GeV

$$(Z \rightarrow \bar{f} f + H)$$

- LEP-II ran up to 209 GeV and excluded $m_H < 114.4$ GeV

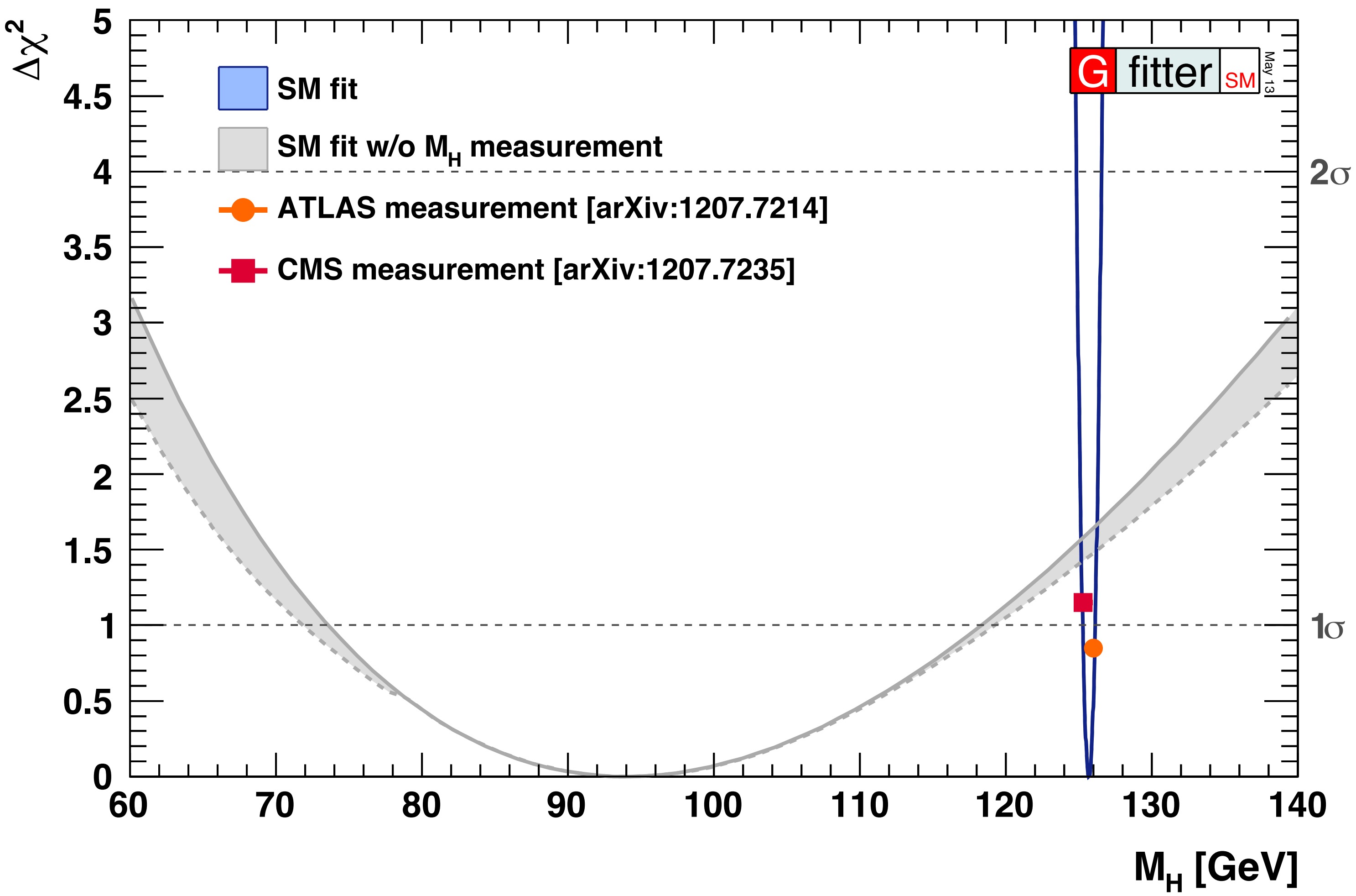


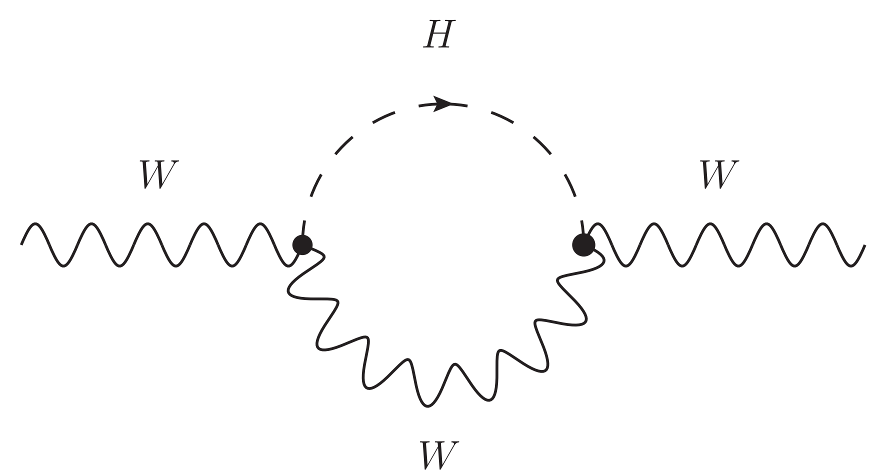


Higgs mass @ LHC start: precision EW data

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

$$\Delta r \sim \log\frac{M_H}{M_W}$$





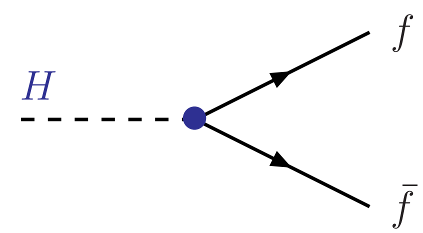
Best-fit @ 68% CL:

$$m_{\rm H}=93^{+25}_{-21}\ \mathrm{GeV}$$

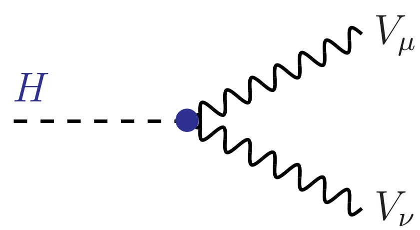
Higgs found just above 1σ!

SM Higgs couplings

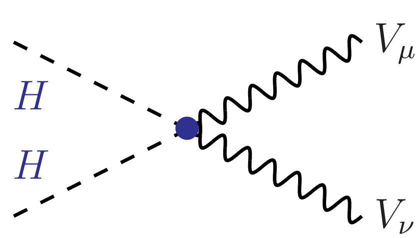
- Higgs couplings predicted:



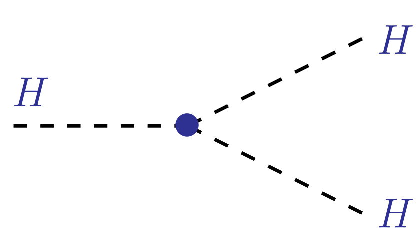
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2}\, m_f \qquad \times\ (i)$$



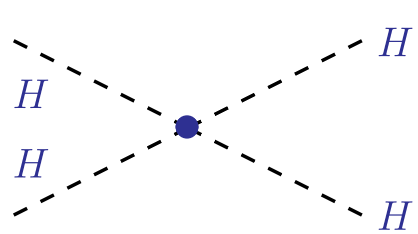
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2}\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu\, M_V^2 \qquad \times\ (-ig_{\mu\nu})$$



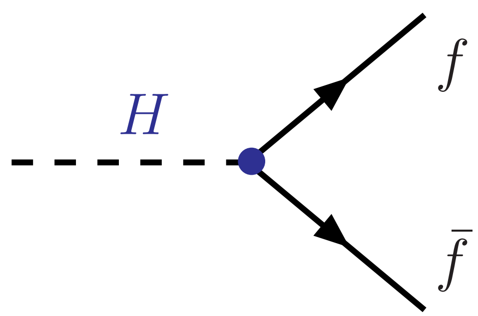
$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2}\, M_H^2 \qquad \times\ (i)$$



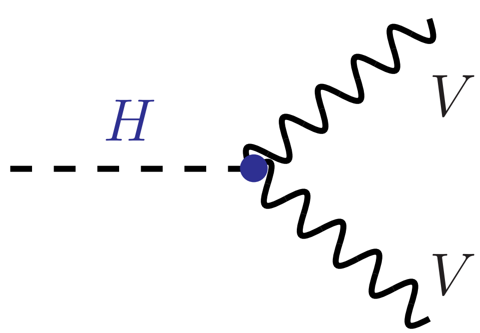
$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu\, M_H^2 \qquad \times\ (i)$$

SM Higgs couplings

- Higgs couplings predicted:
  - Trick: (1 + h / v) in mass terms (not true for derivatives)



$$m_f \bar{f}_L f_R \rightarrow m_f \left(1 + \frac{h}{v}\right) \bar{f}_L f_R \rightarrow \frac{m_f}{v}$$

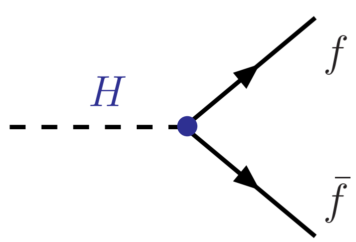


$$M_V^2 V^\mu V^\mu \rightarrow M_V^2 \left(1 + \frac{h}{v}\right) V^\mu V^\mu \rightarrow \frac{M_V^2}{v}$$

SM Higgs partial decay widths

- Couplings proportional to mass → decays to heaviest particles kinematically accessible (with many exceptions)

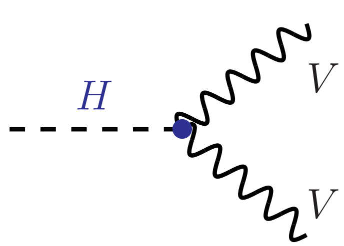
- Tree-level decays to fermions (N_C = 3 for quarks, 1 for leptons):
  - Threshold effect depend on velocity: β^3 for scalar, β for pseudo-scalar



$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F}{4\sqrt{2}\pi} m_{\rm H}\, m_f^2\, \beta^3 \ , \ \beta = \left(1 - 4m_f^2/m_{\rm H}^2\right)^{1/2}$$

$$\Gamma(H \to f\bar{f})/m_{\rm H} \sim (m_f/v)^2 \to \mathcal{O}\left(10^{-5}\right) \text{ for b-quarks (few MeV)}$$

- Tree-level decays to (on-shell) gauge-bosons (N_V = 2 for W, 1 for Z):

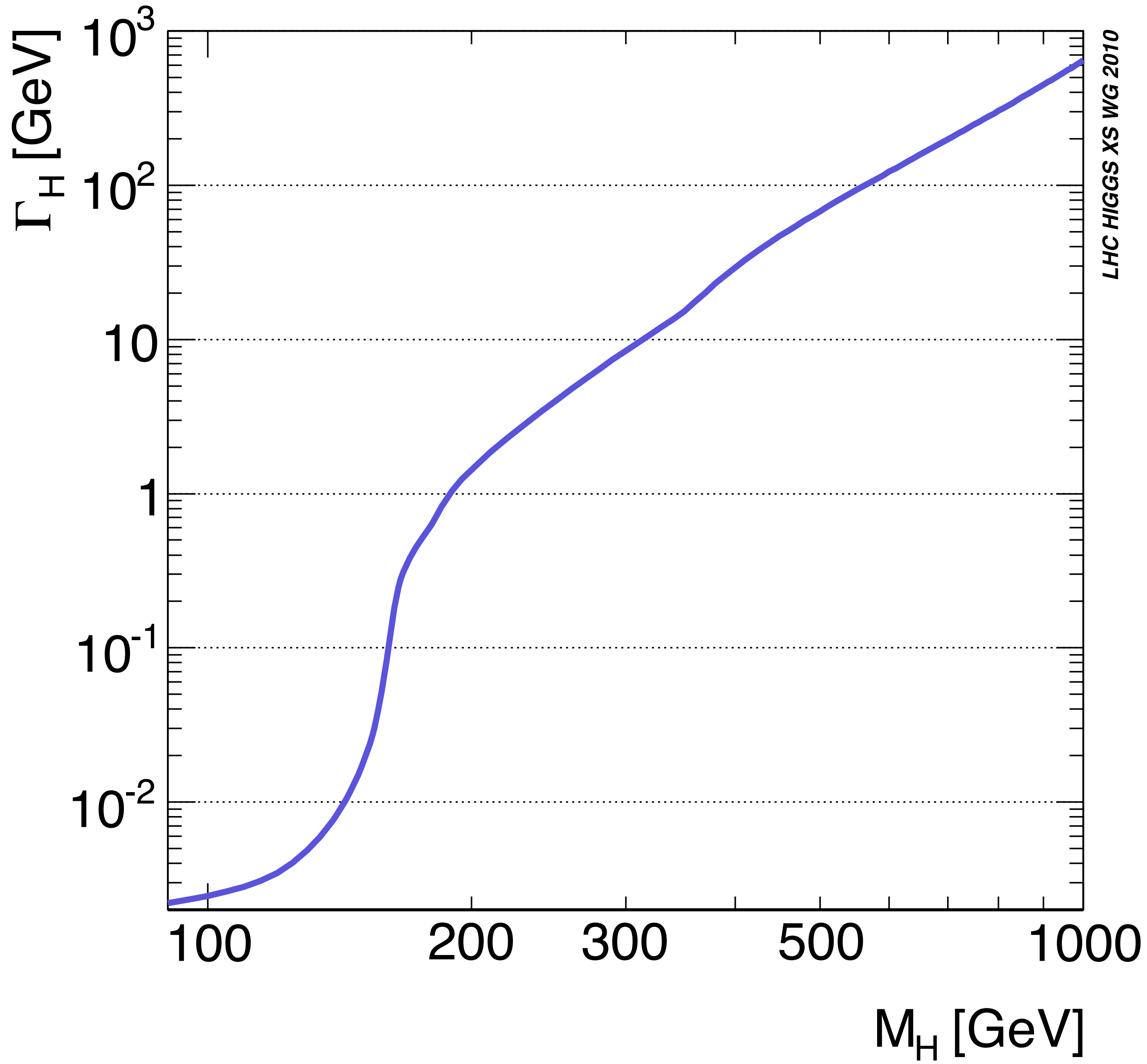


$$\Gamma(H \to VV) = N_V \frac{G_F}{16\sqrt{2}\pi} m_{\rm H}^3 \,(1-4x)^{1/2}\left(1 - 4x + 12x^2\right) \ , \ x = \left(\frac{M_V}{m_{\rm H}}\right)^2$$

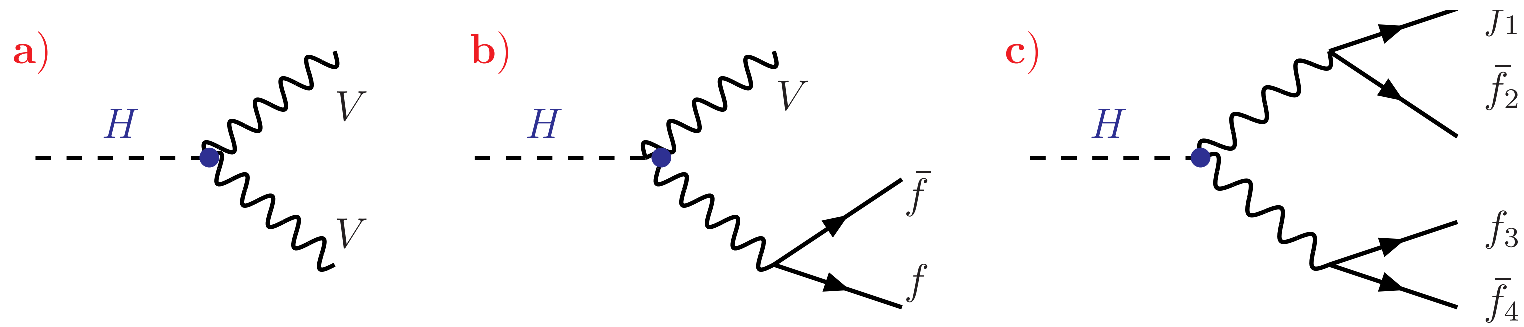
$$\Gamma(H \to VV) \sim m_{\rm H}^3 \to \text{dominate at high masses, Higgs become “obese”}$$

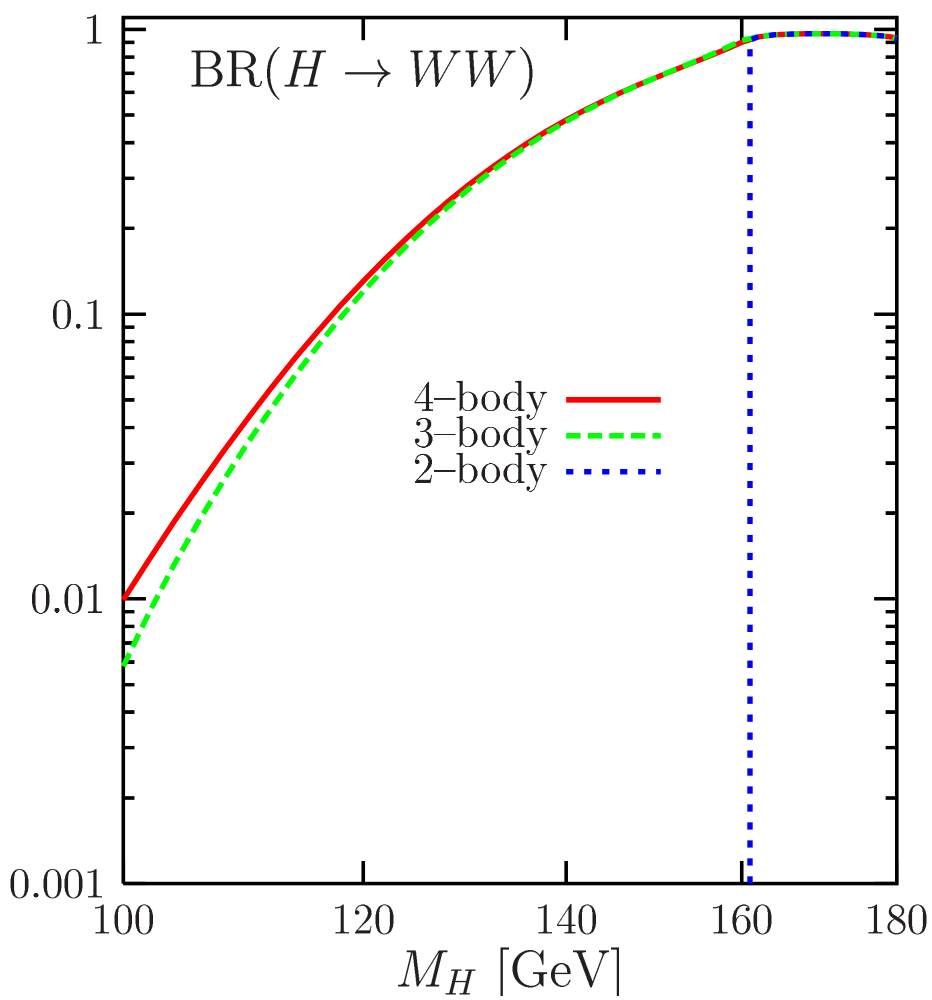
SM Higgs width

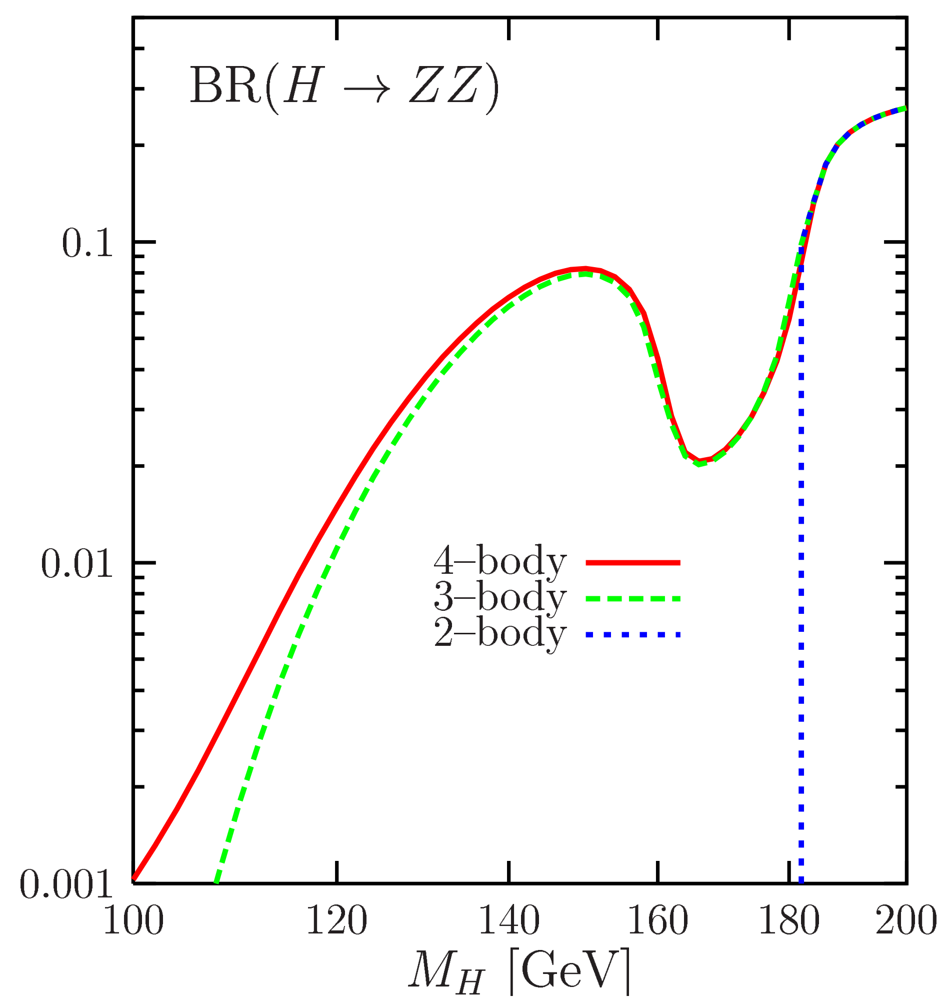
~4 MeV @ 125.5 GeV, grows when decays to on-shell gauge bosons open-up



Important for low mass Higgs (two of the main discovery channels)

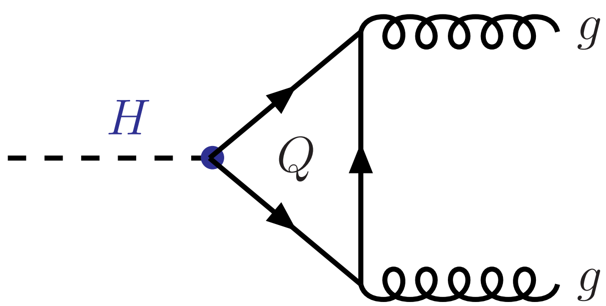




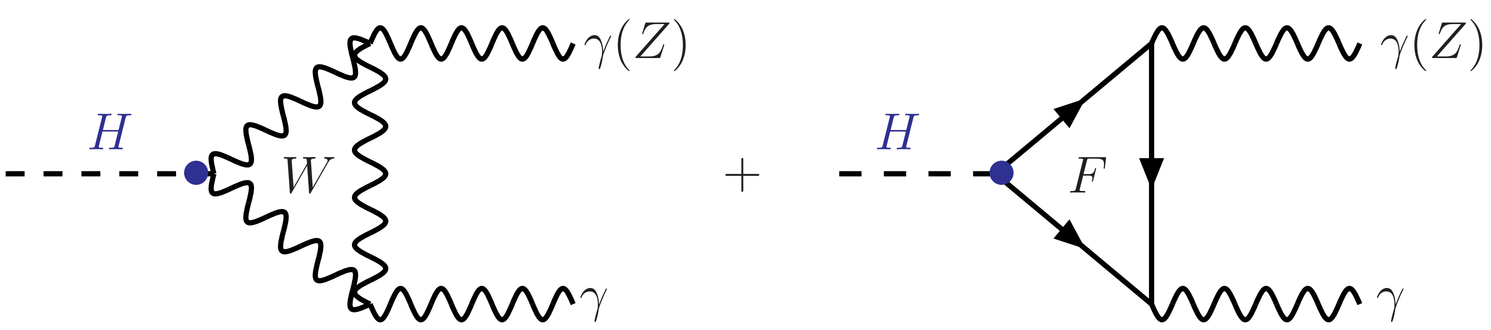


SM Higgs decays: loop-induced processes

- H → gg: completely dominated by top-quark (in the SM)
  - Hopeless as a decay at the LHC, but important for production



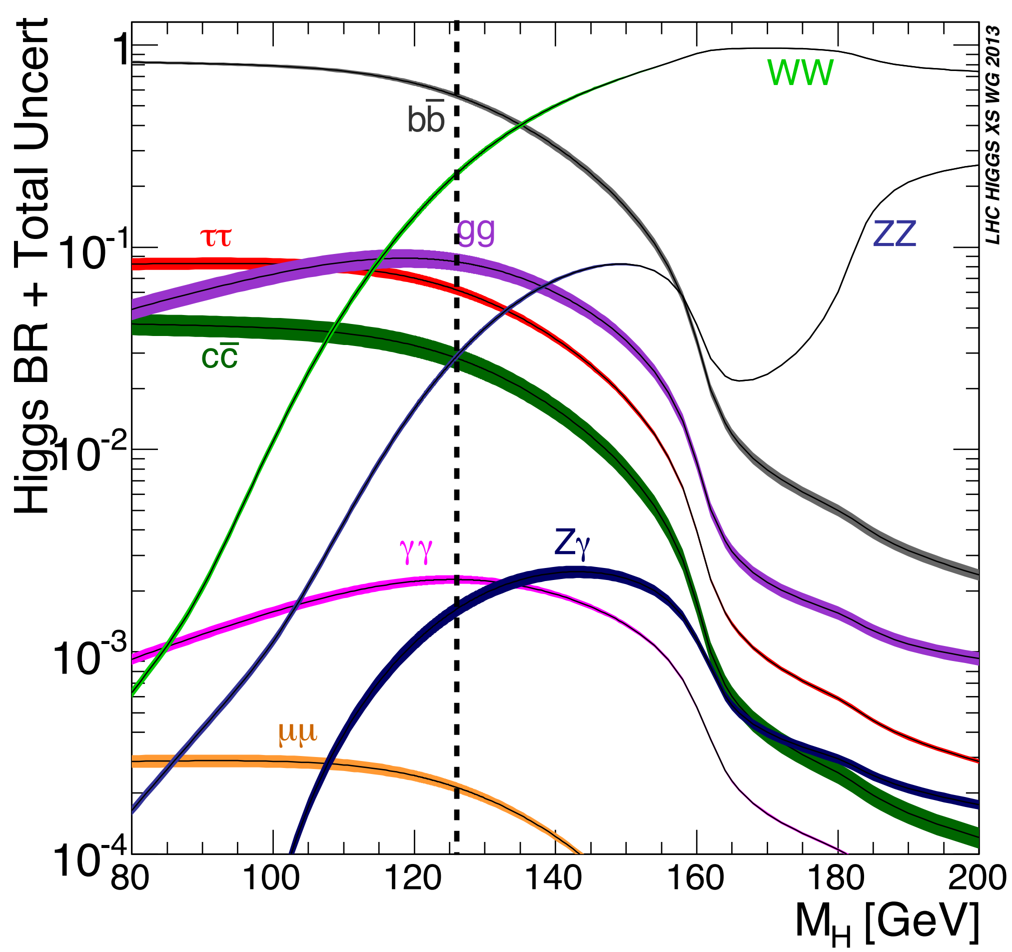
- H → γγ and Zγ: destructive interference between W (dominant) and top-quark
  - H → γγ is one of the cleanest decays at the LHC



SM Higgs boson decay branching-ratios

Couplings proportional to mass → decays to particles with heaviest particles accessible (with many exceptions)

@ 125.5 GeV, most decay modes accessible experimentally!



NLO calculations, uncertainties around 5%, dominated by m_b

@ m_H = 125.5 GeV:

bb: 57%

WW*: 22%

τ τ : 6.2%

ZZ*: 2.8%

γγ: 0.23%

Zγ: 0.16%

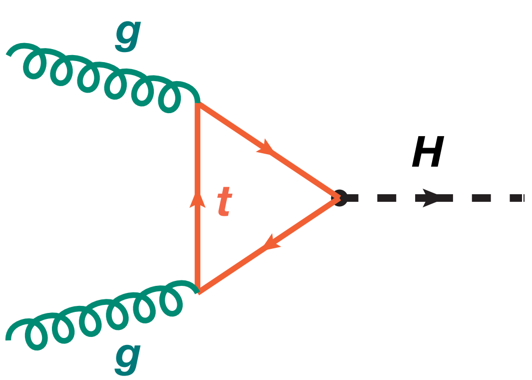
μμ: 0.02%

LHC Higgs Cross Section Working Group

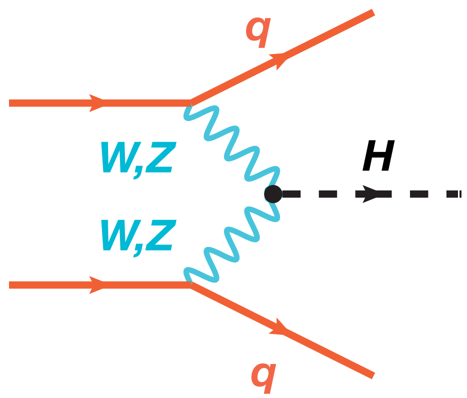
SM Higgs production modes at the LHC

Production mechanisms

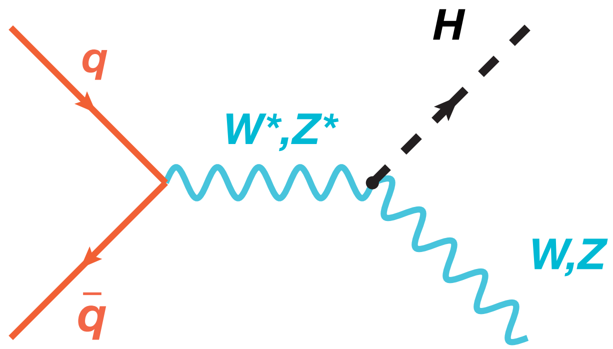
Gluon-fusion



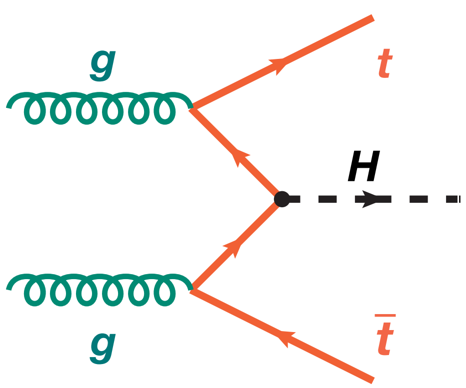
Vector boson fusion (VBF)

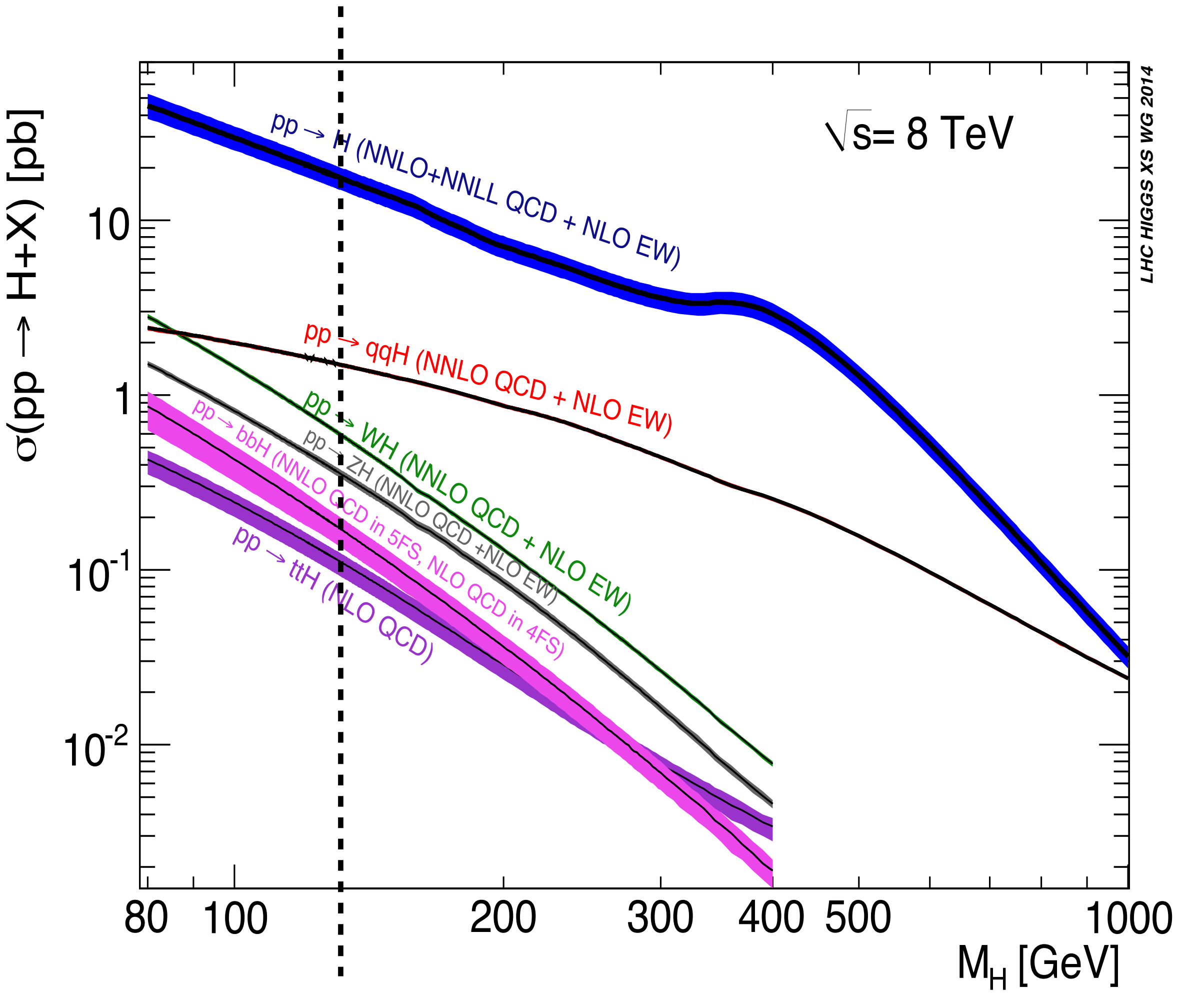


Associated with W / Z



Associated with tt (or bb)

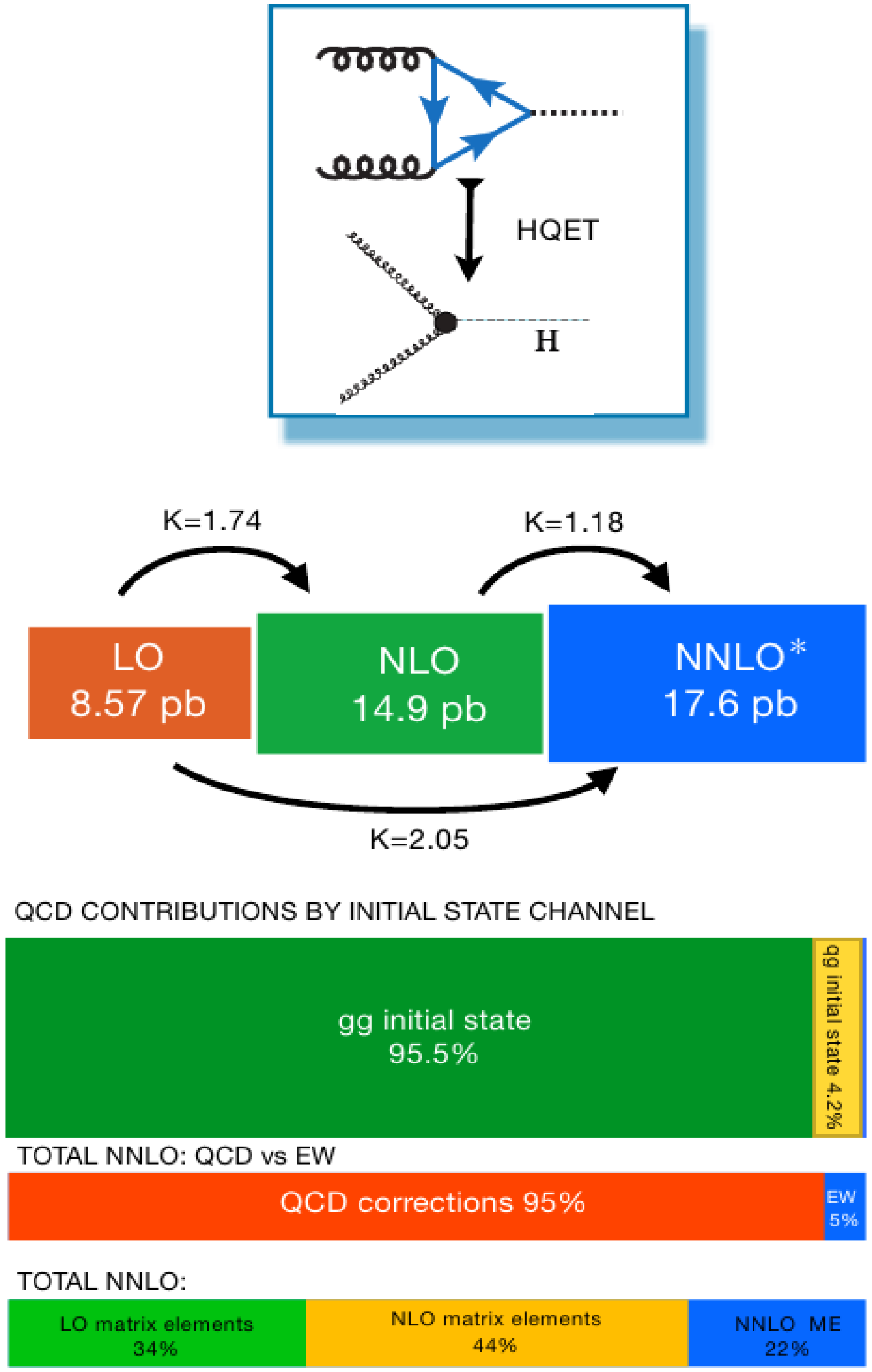




Huge effort to calculate cross-sections at (N)NLO

Gluon fusion cross section

[graphics by A.Lazopoulos]

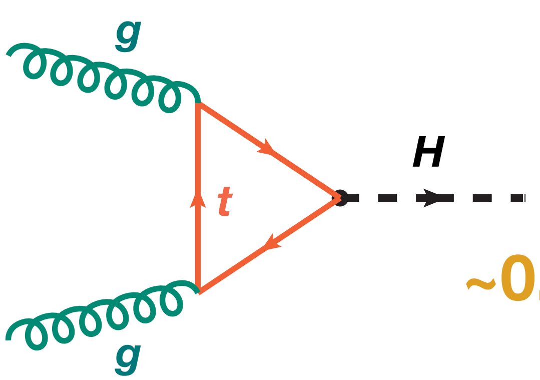


- Corrections ~100%!
- Scale (missing higher orders) and parton distribution function (gluon) uncertainties around 7-8% each
- NNLL re-summation of soft QCD radiation included
- N3LO on the way (first of a kind), could give additional ~5-15% increase

The SM Higgs boson at the LHC

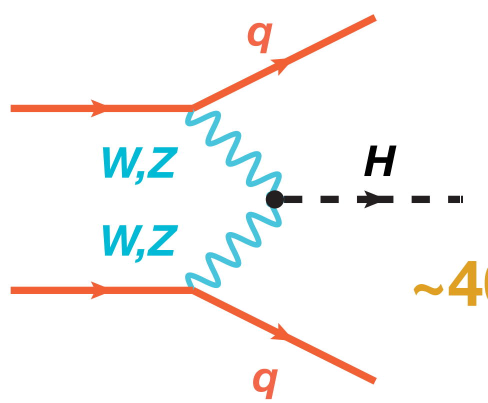
Production mechanisms (events produced)

Gluon-fusion



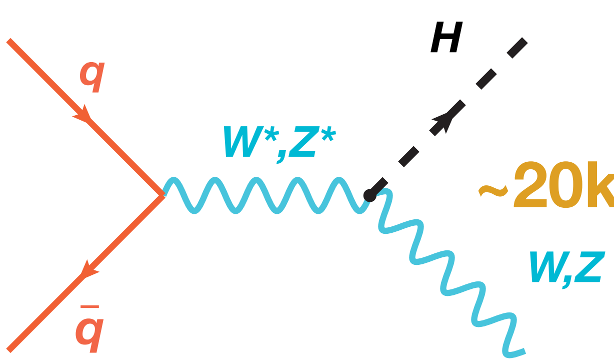
~0.5M

Vector boson fusion (VBF)



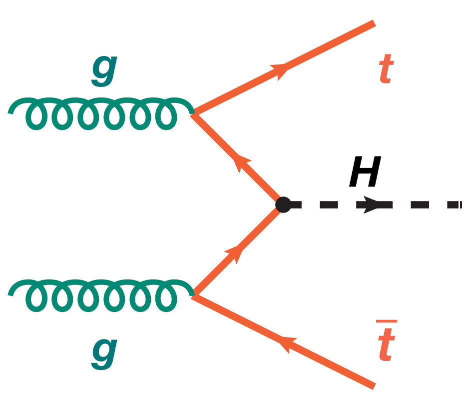
~40k

Associated with W / Z



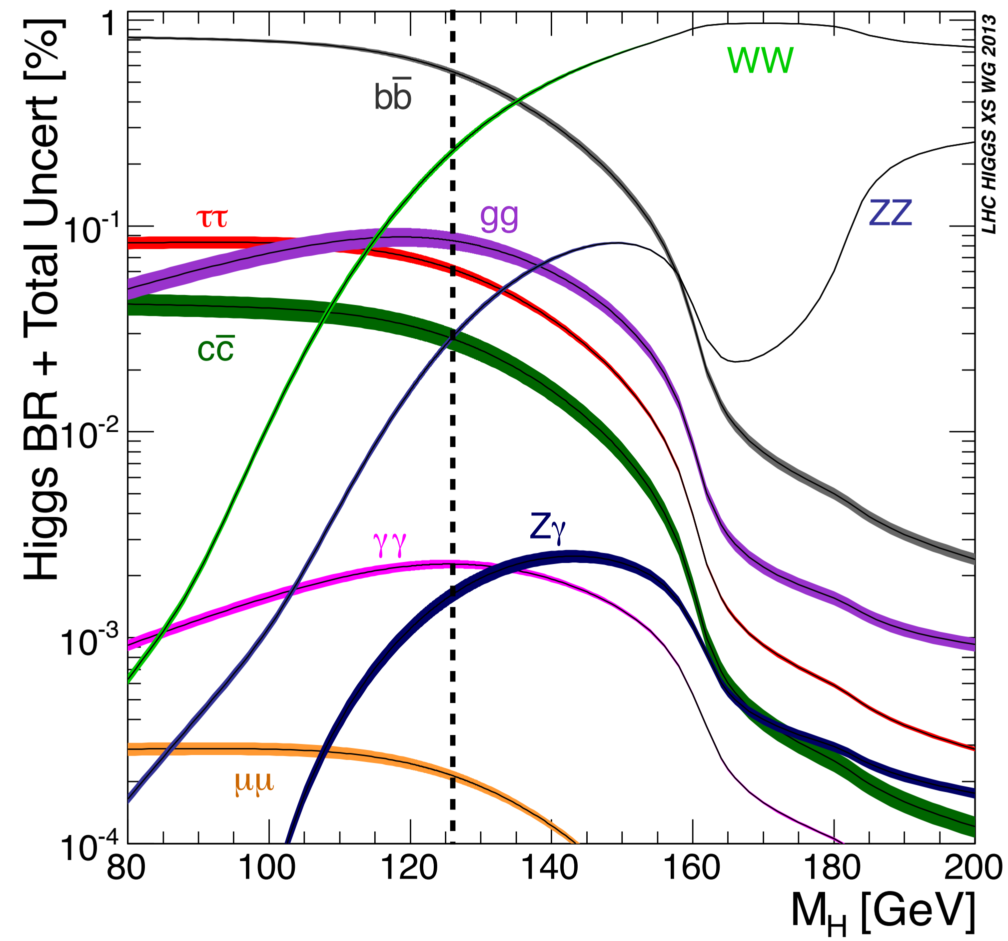
~20k/10k

Associated with tt (or bb)



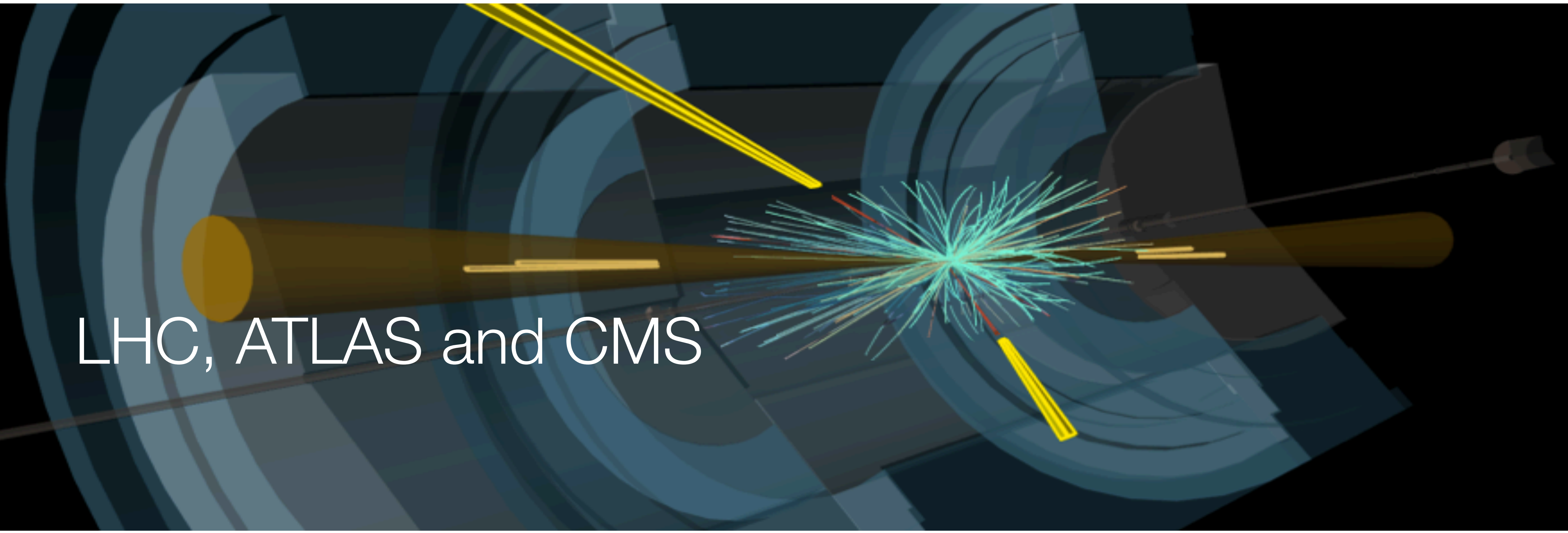
~3k/5k

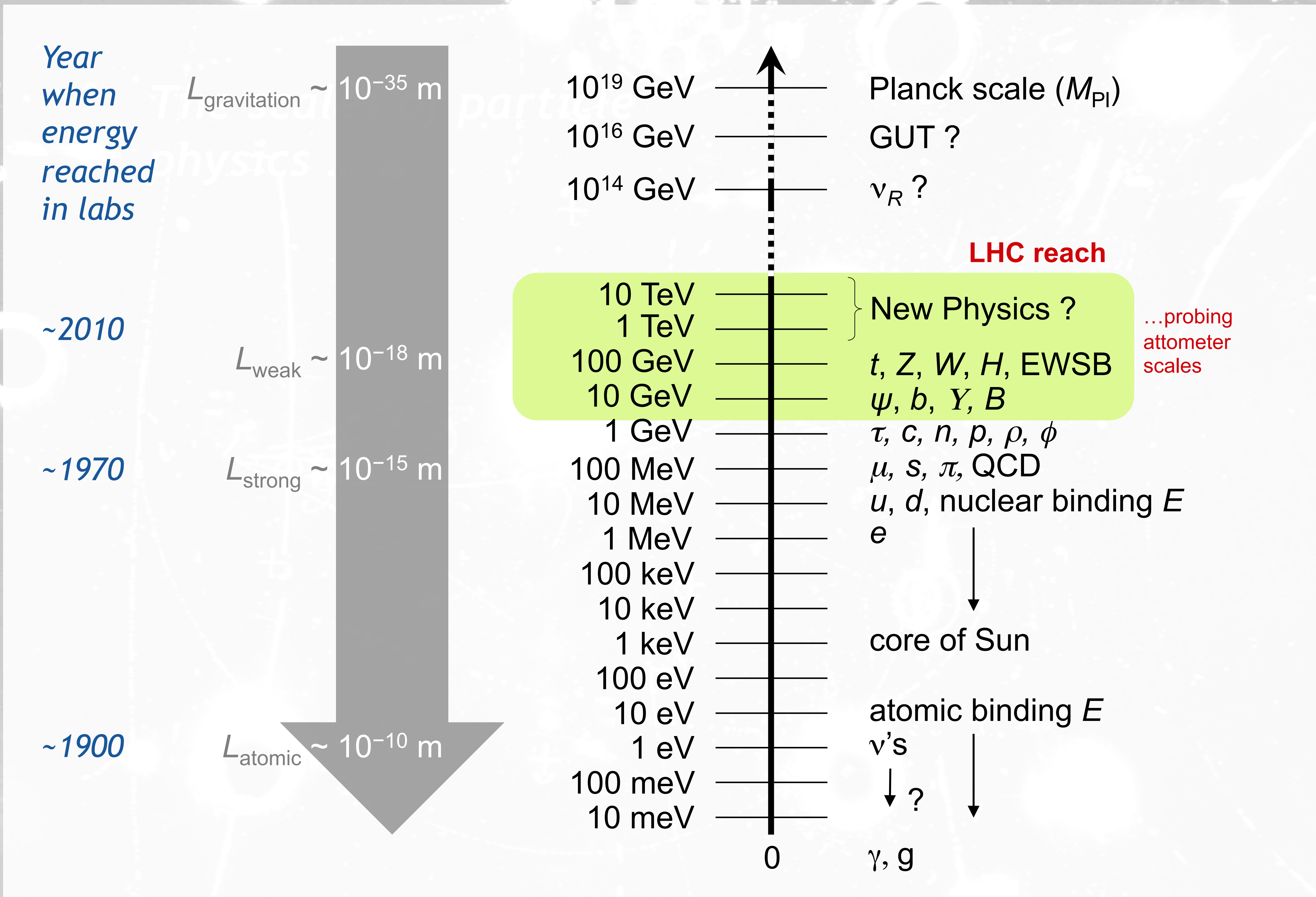
Decay modes



- Main channels (bosonic): H → γγ, H → ZZ* → 4ℓ, H → WW* → ℓνℓν
- Fermionic modes (associated production): (VBF) H → ττ, (W/Z) H → bb
- Rare decays: H → Zγ, H → μμ

LHC, ATLAS and CMS



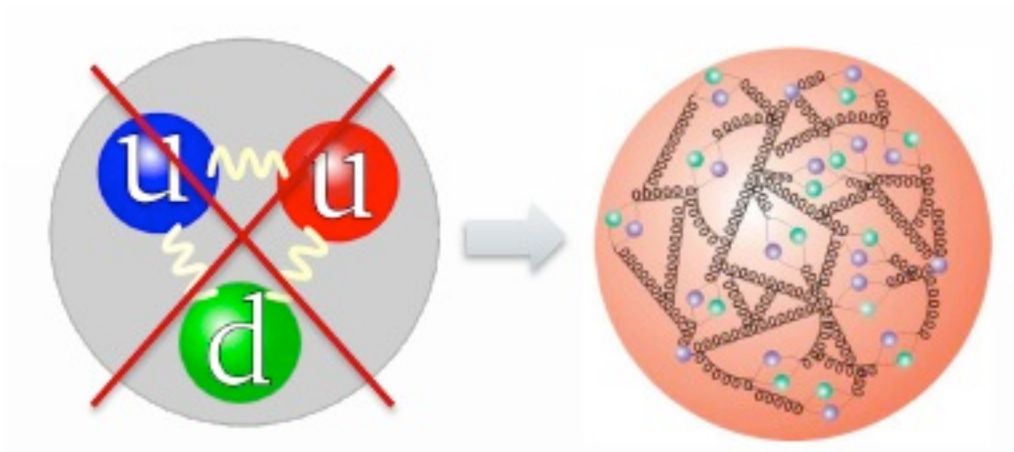


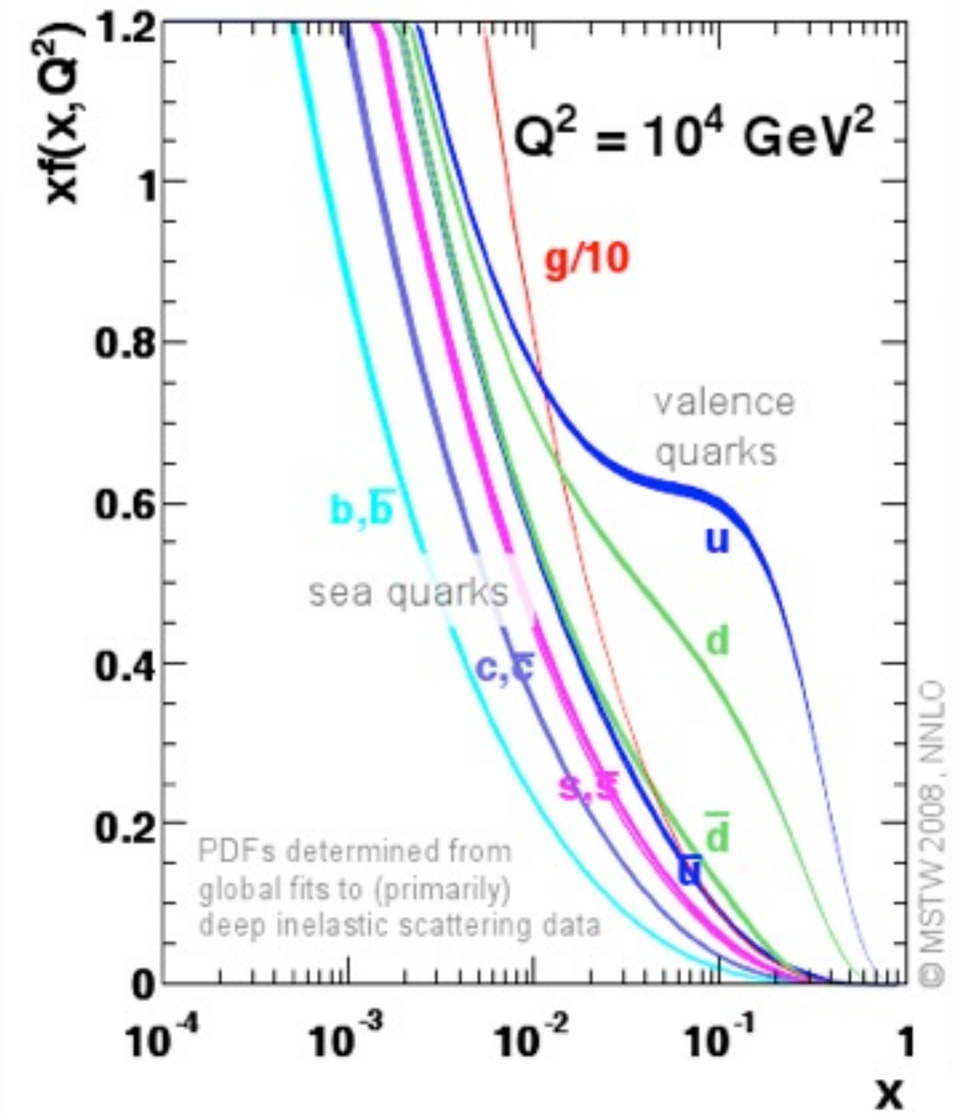
Andreas Hoecker

p+p collisions

- Hadron colliders are (usually) good discovery machines...
  - Easier to achieve higher energies than with e^+e^- (synchrotron radiation ~ m^{-4})
  - "Automatic" energy scanning
    - Partons carry a fraction of the proton energy
    - Gluons dominate at intermediate x

The large gluon collider





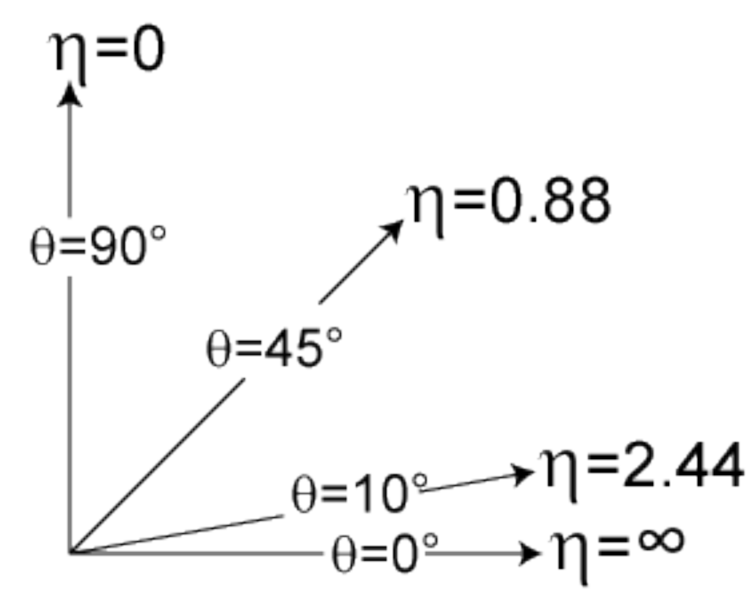
p+p collisions

- ...with some drawbacks
  - Only part of the energy available for collisions
  - Unknown boost along beam-axis
  - Low energy collisions dominate
  - Huge QCD background and large theoretical uncertainties

p+p collisions: kinematics

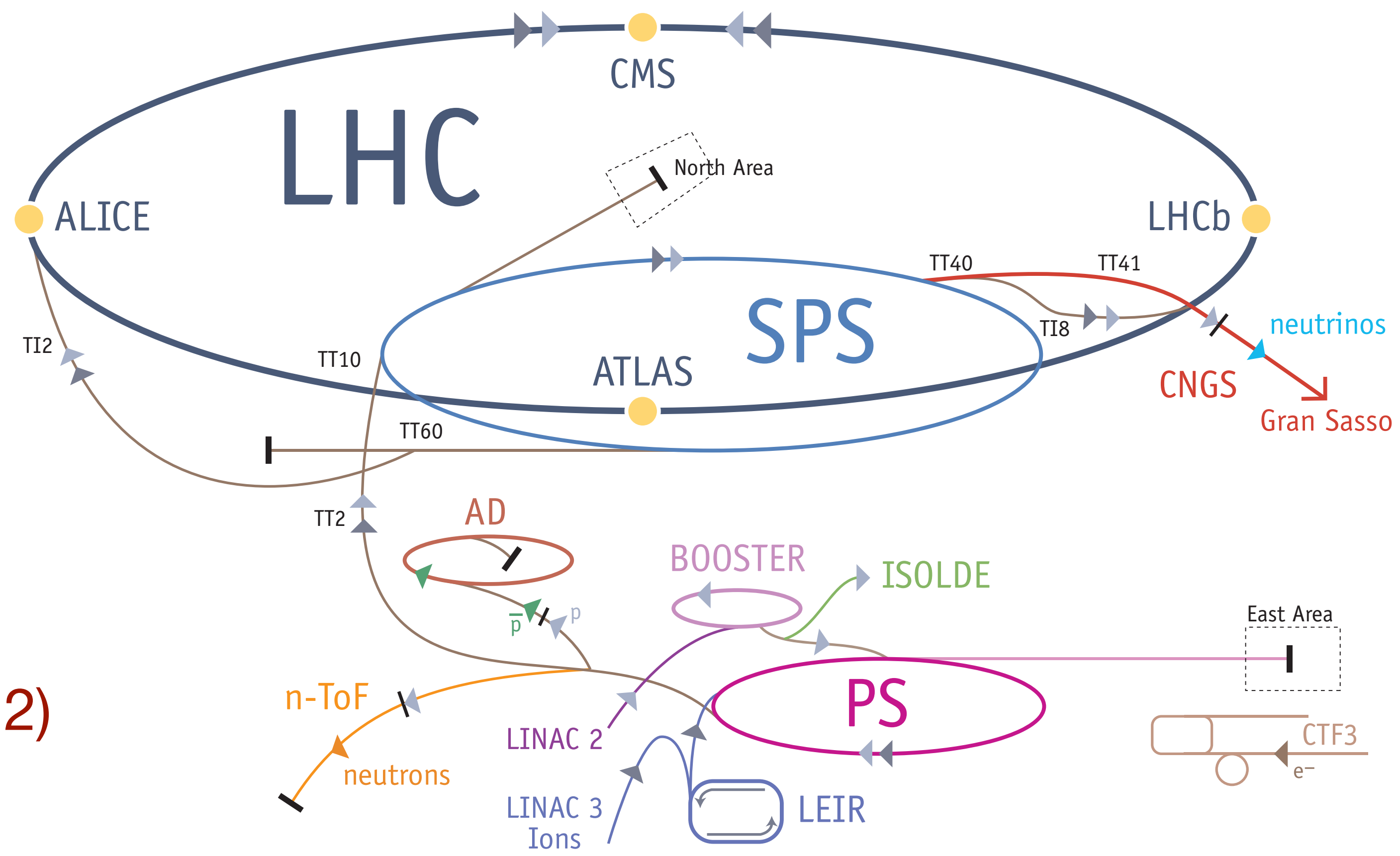
- Momentum conserved in transverse plane: $\sum \vec{p_T} + \vec{E}_T^{\mathrm{miss}} = 0$
- Directions expressed in pseudo-rapidity η and ϕ
  - Particle production ~ constant in rapidity y
  - Δy is invariant under boosts along z

$$y \xrightarrow{m=0} \eta = -\log\left(\frac{\tan\theta}{2}\right)$$

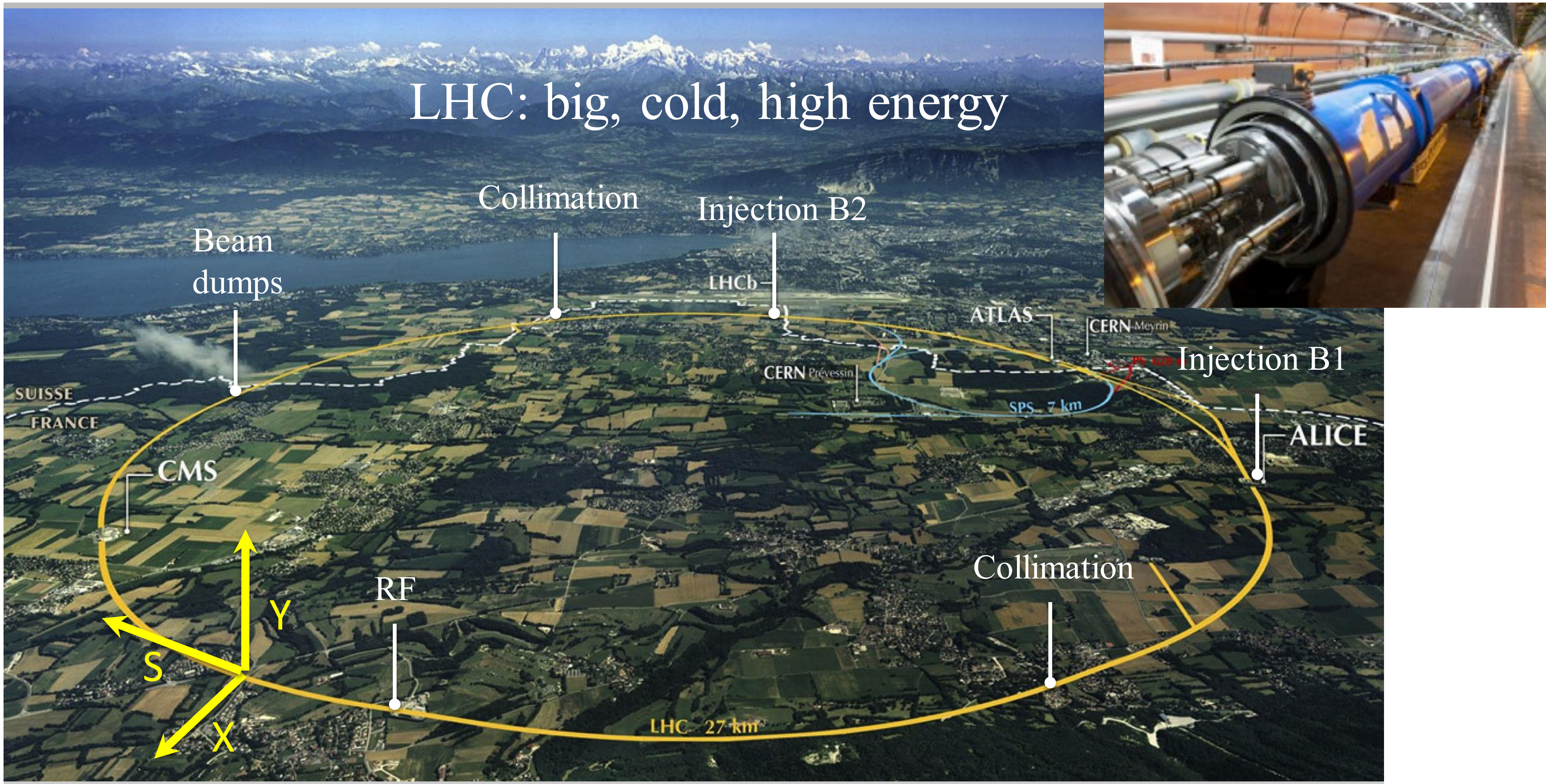


The Large Hadron Collider (LHC)

- Large accelerator complex, 27 km ring
  - LEP tunnel (1985) ~100m underground
  - Circular collider: energy increased at each turn (limited by bending power)
  - 2-3h to recover beams on a good day
- p+p collisions up to 14 TeV @ 40 MHz (nominal)
  - 7-8 TeV @ 20 MHz in run-1 (2010 - 2012)
  - Also Pb+Pb and p+Pb
- Multi-purpose (ATLAS, CMS) and specialized experiments (ALICE, LHCb, ...)



The Large Hadron Collider (LHC)

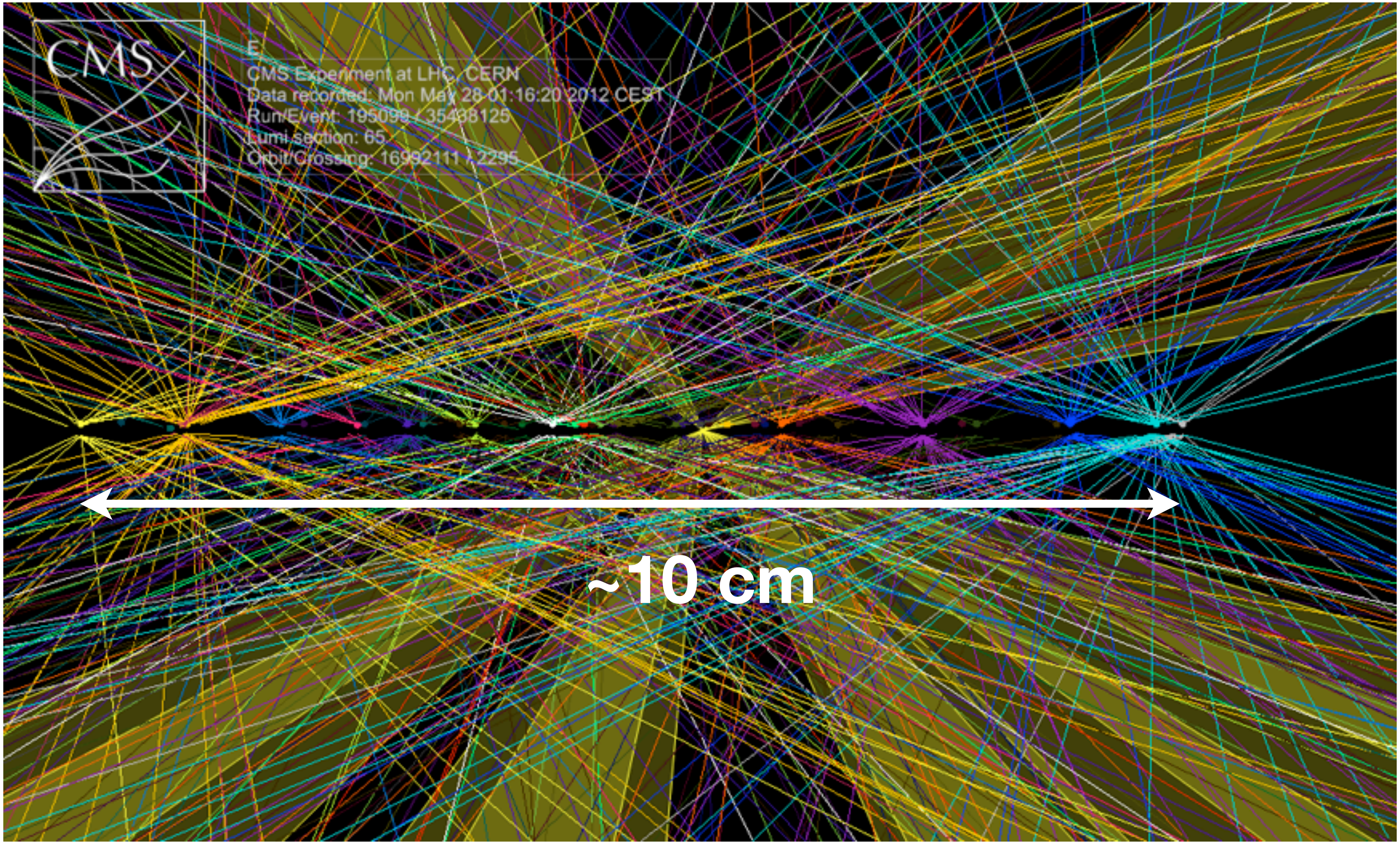


1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV

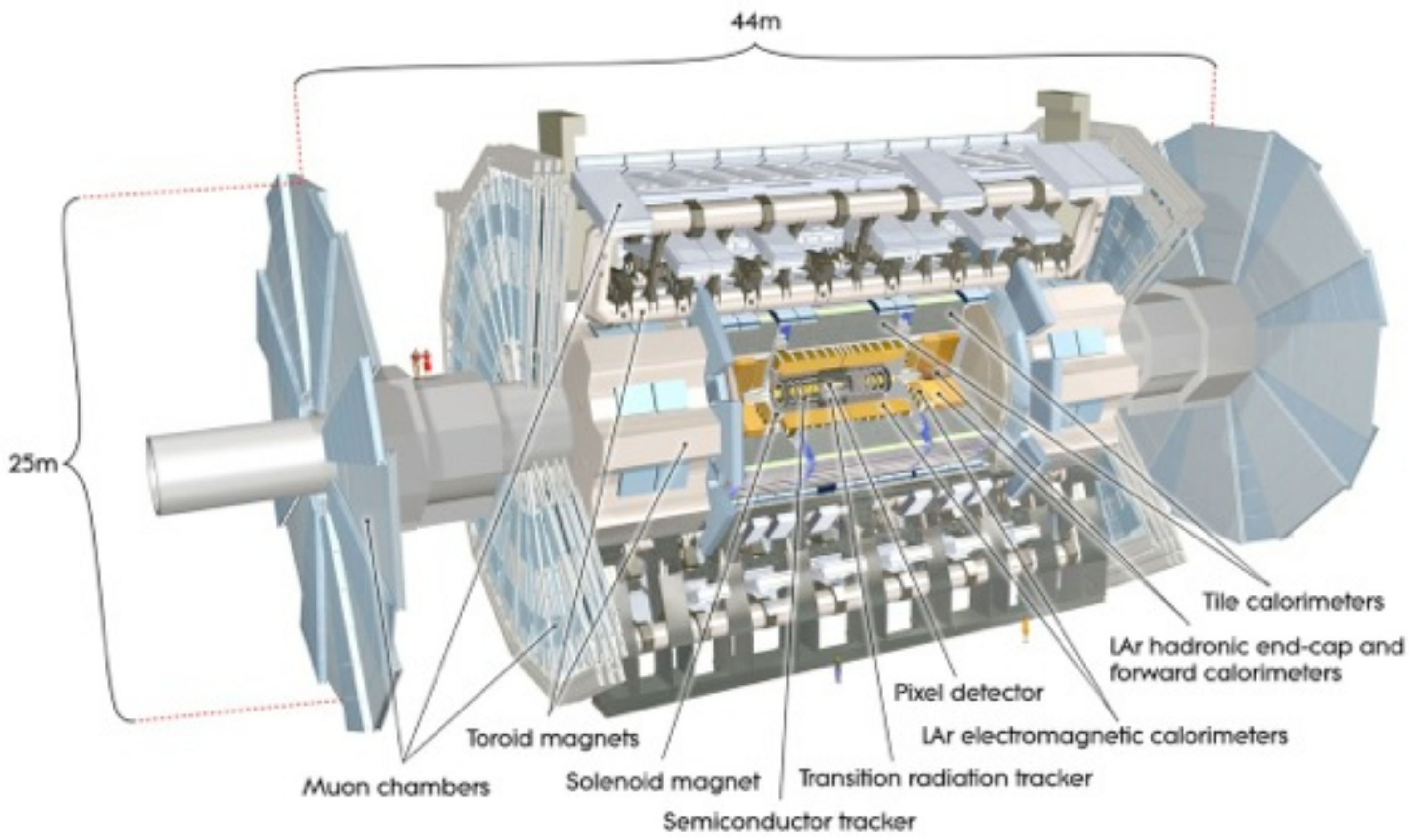
Mike Lamont 2

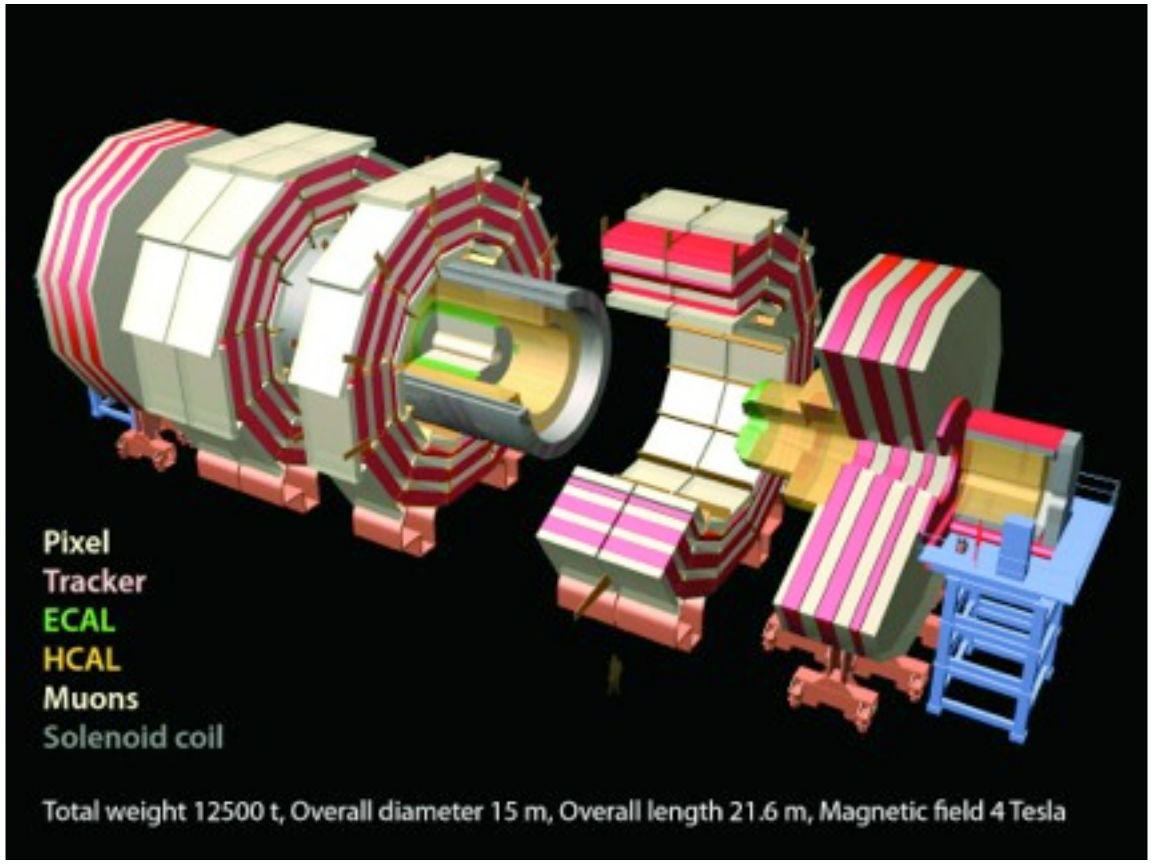
LHC collision, another one coming in 25 ns...



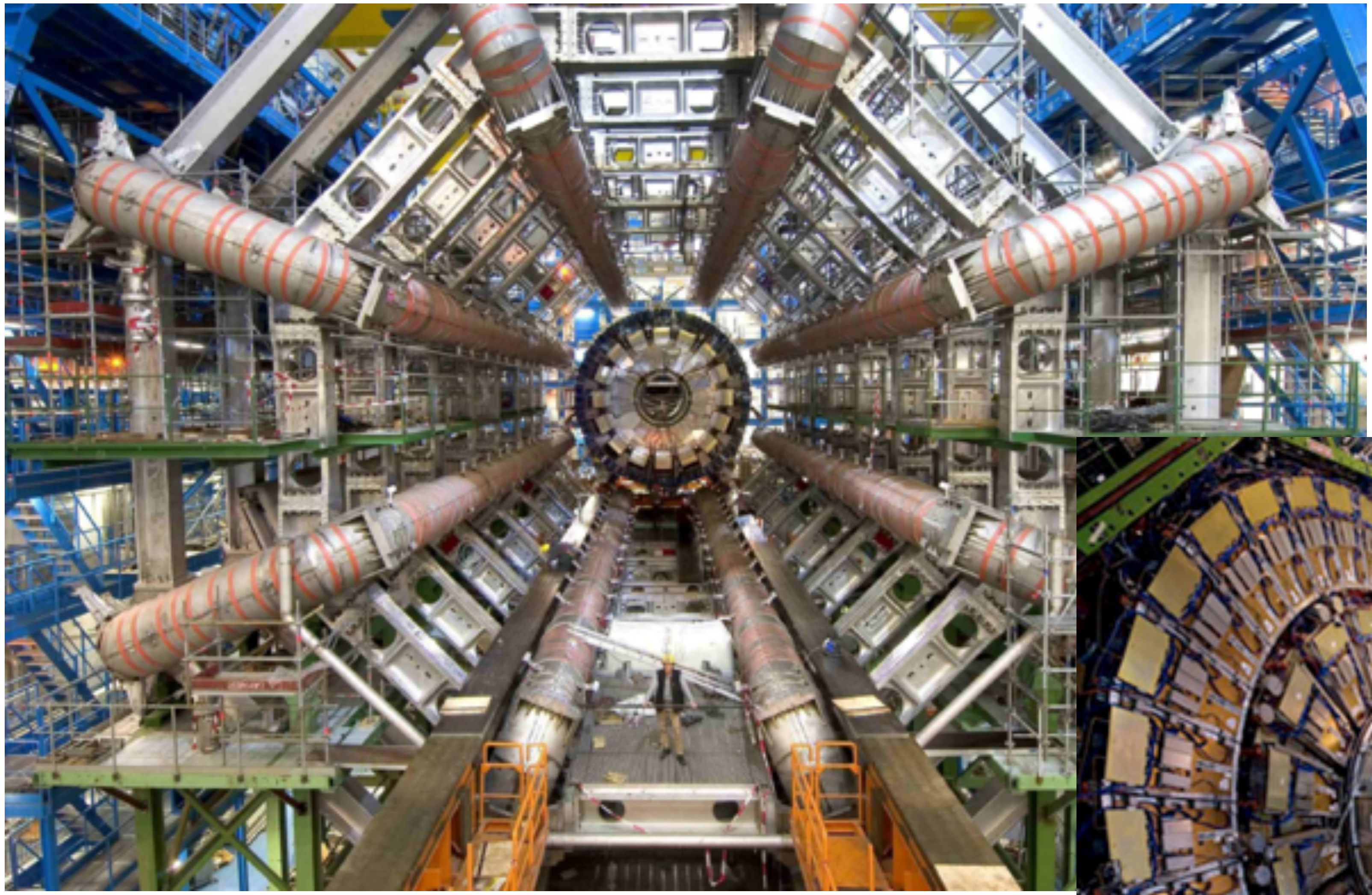
The ATLAS and CMS experiments

- More than 3000 people from ~40 countries in each collaboration
- Detector design and construction with Higgs search in mind (+SM and BSM searches)

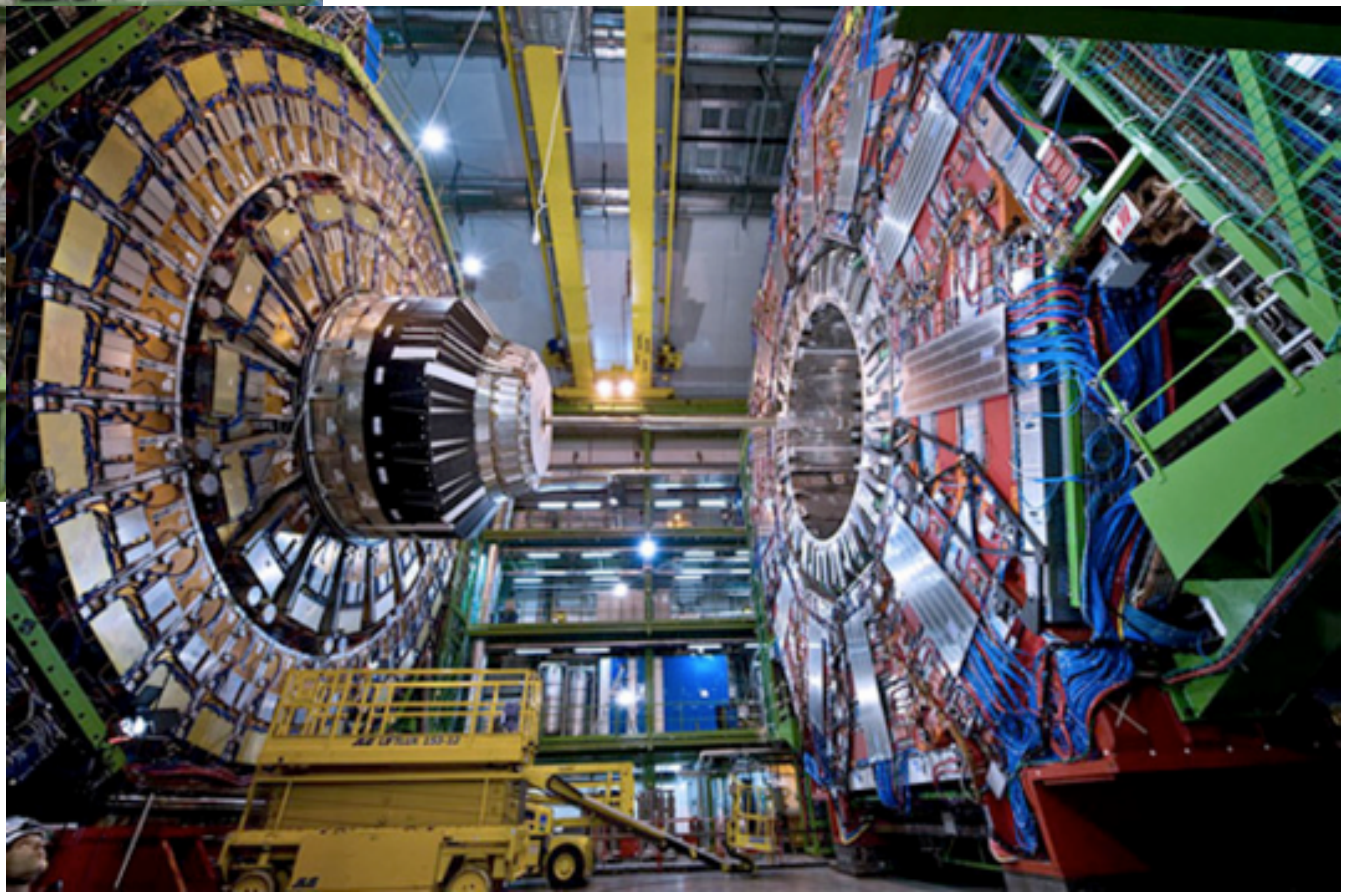




The ATLAS and CMS experiments



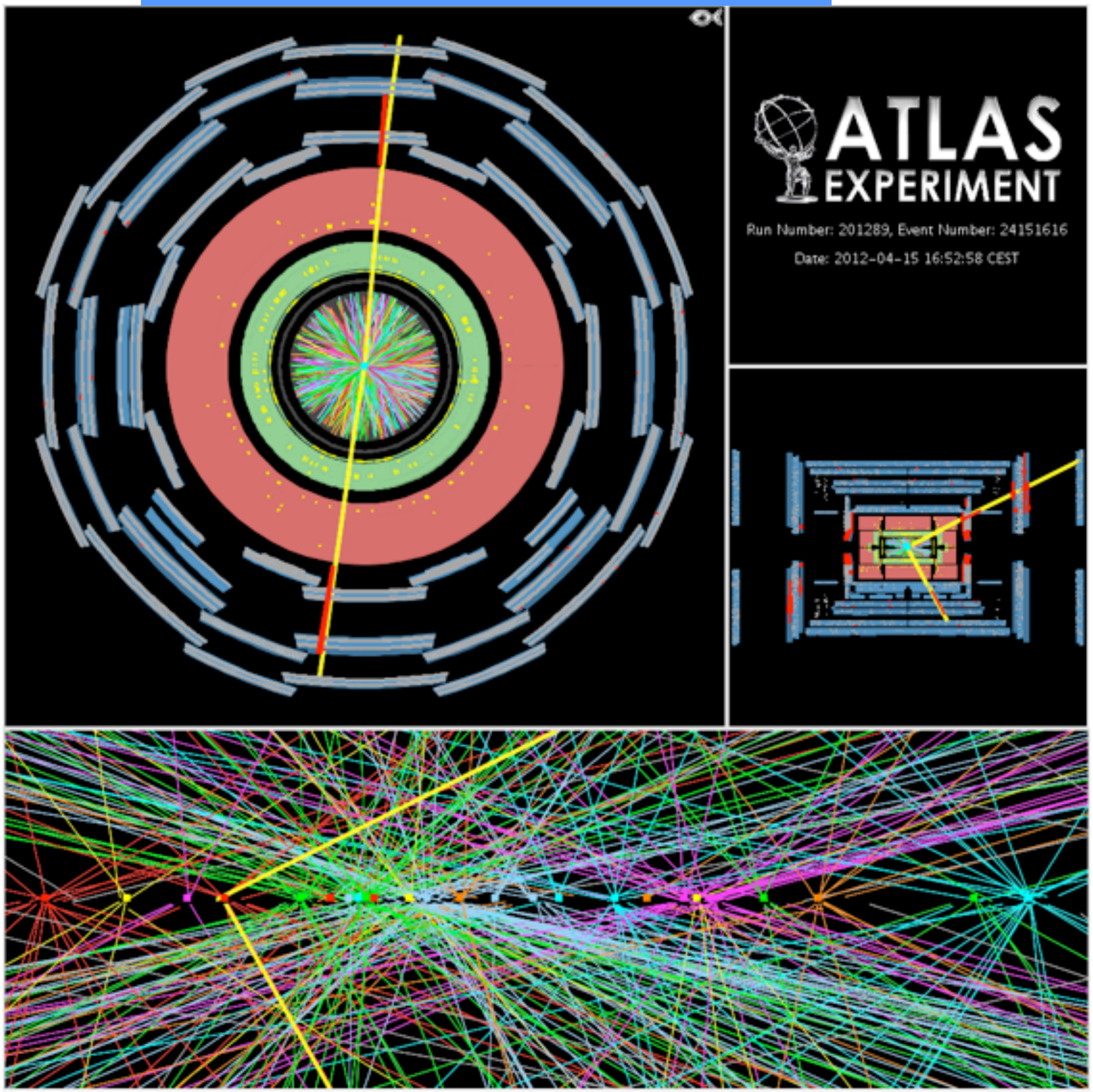
80 Mpixel cameras...



...taking 40M pictures / s
(storing ~300)

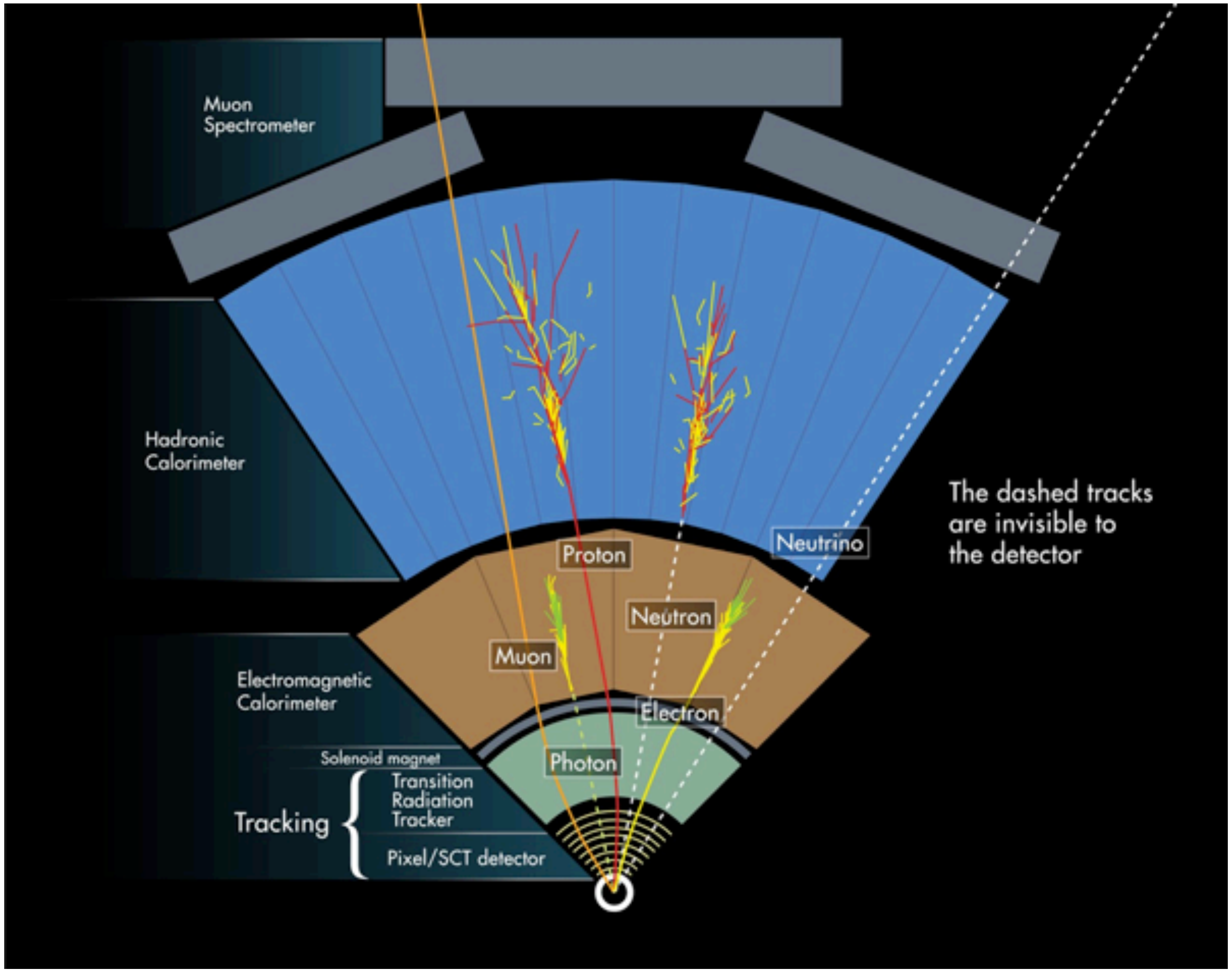
LHC collisions and pile-up

$Z \rightarrow \mu\mu$ + ~25 interactions



- Collisions at 40 MHz, events recorded @ ~300 Hz, ~90% used for analyses
- Multiple collisions per LHC bunch crossing (~20 in 2012)
- Experimental conditions beyond detector design capabilities
- Clean signatures: leptons (e,μ) and photons
- Increasingly difficult: (b-)jets, taus, missing transverse energy

LHC collisions and pile-up



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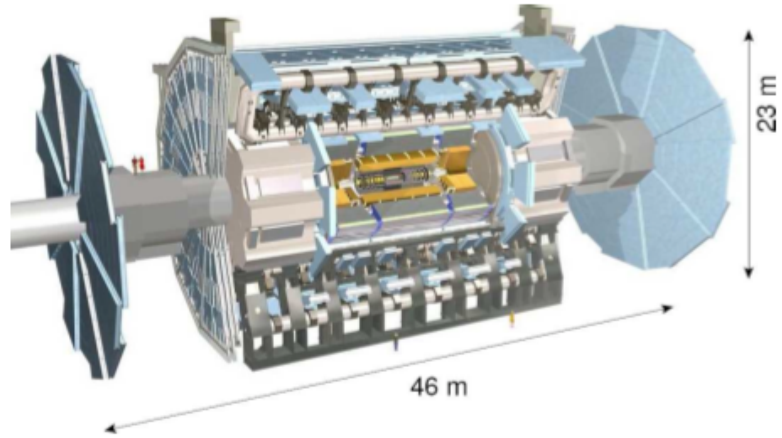
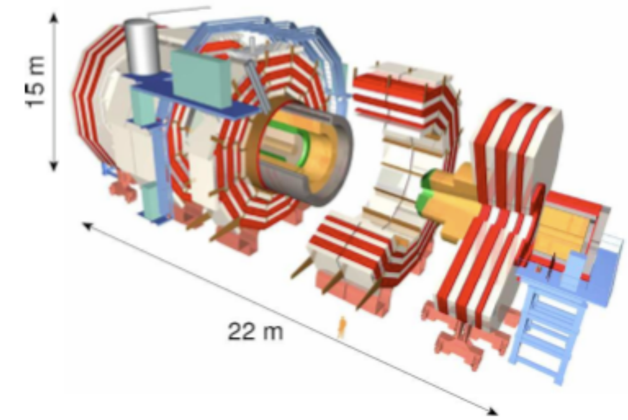
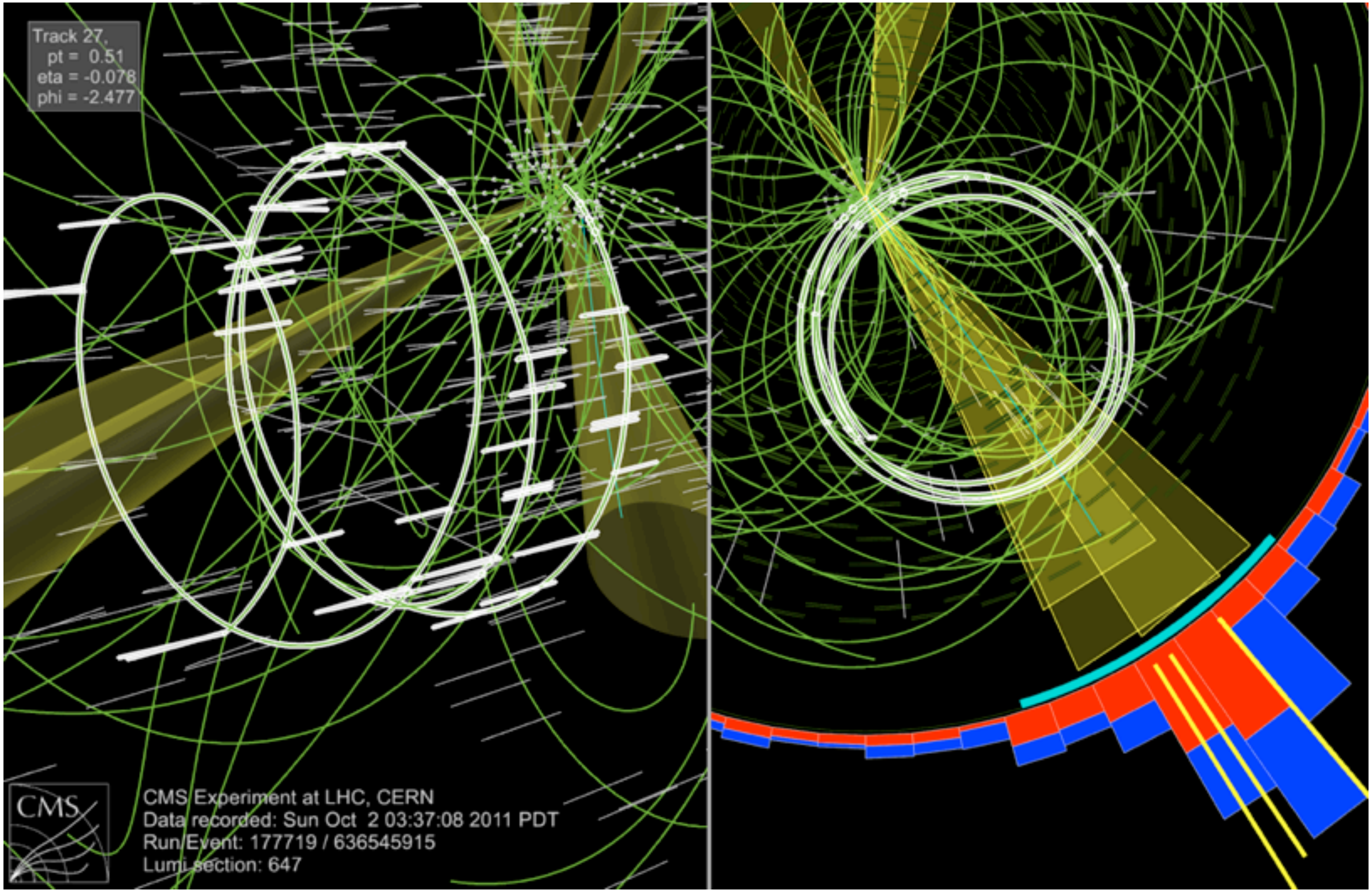
The ATLAS and CMS experiments

Marumi Kado

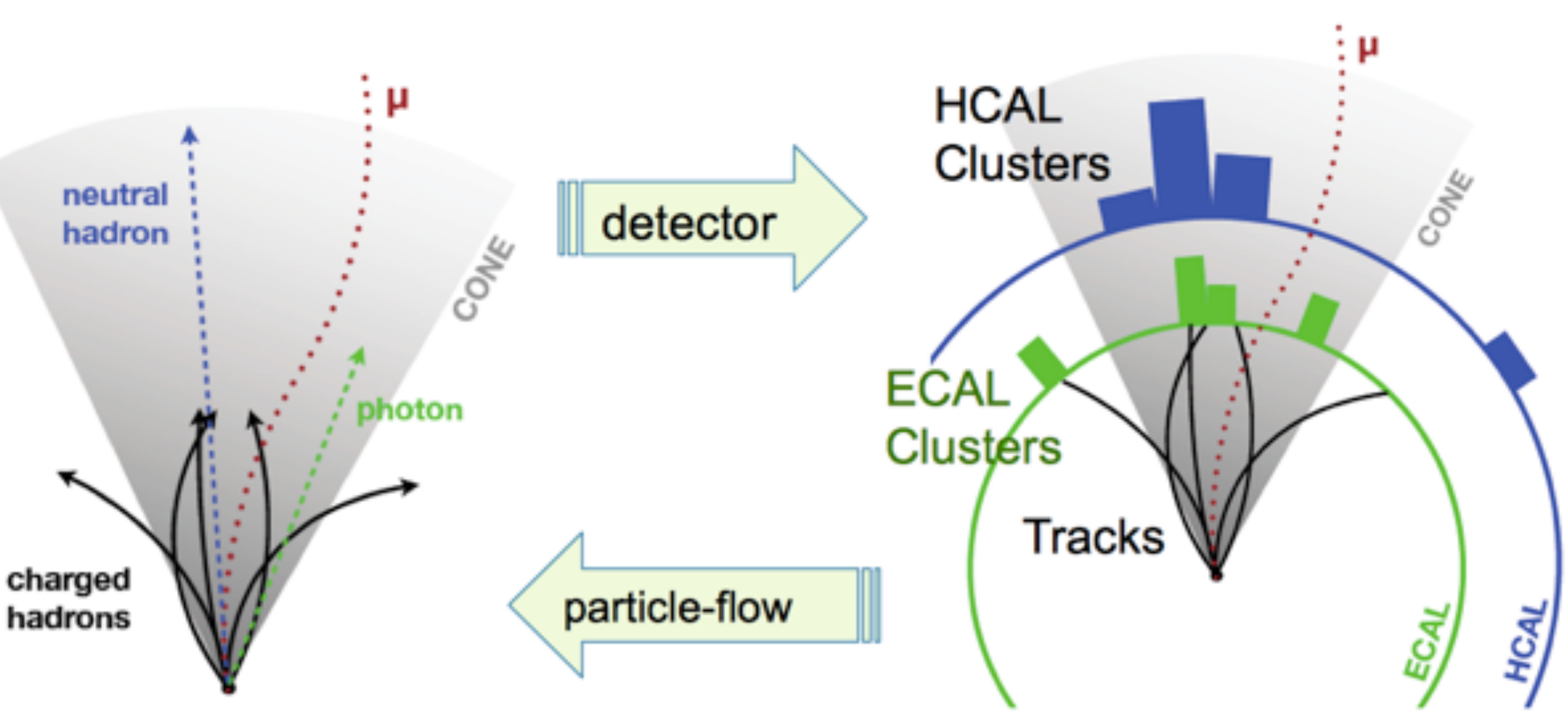
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

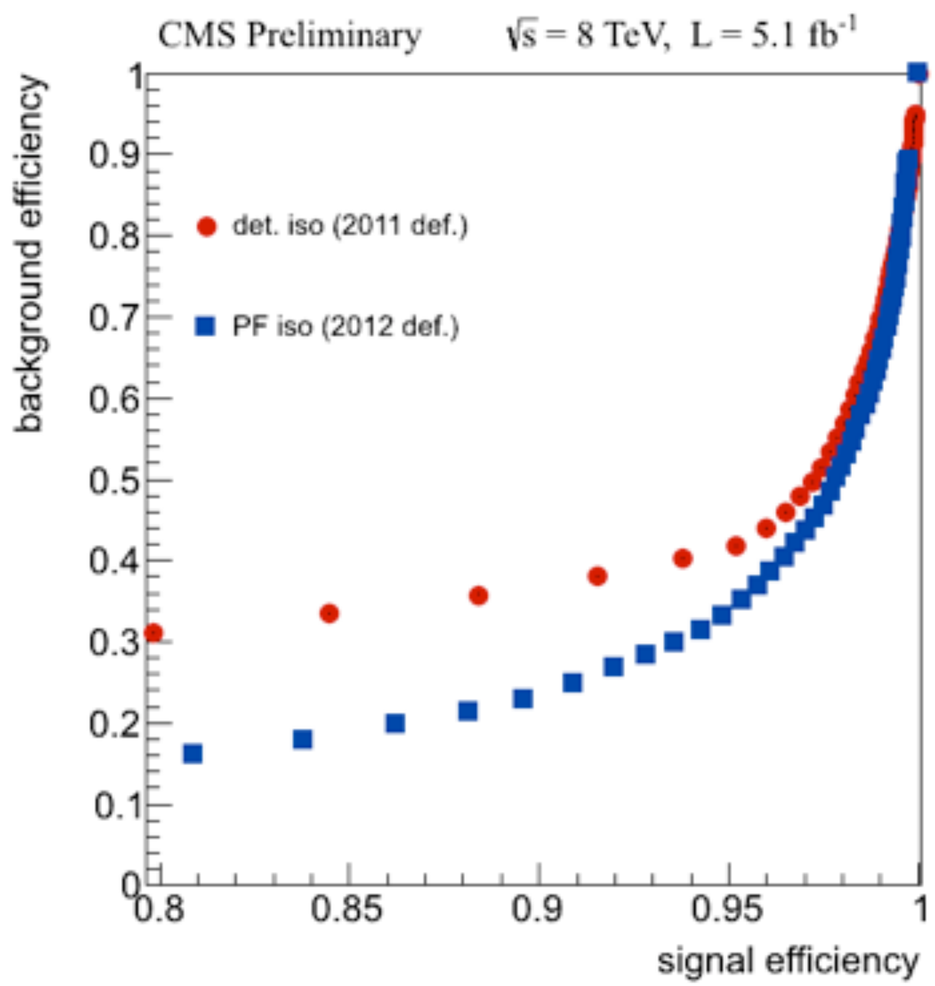
Detector challenges: low P_T charged particles

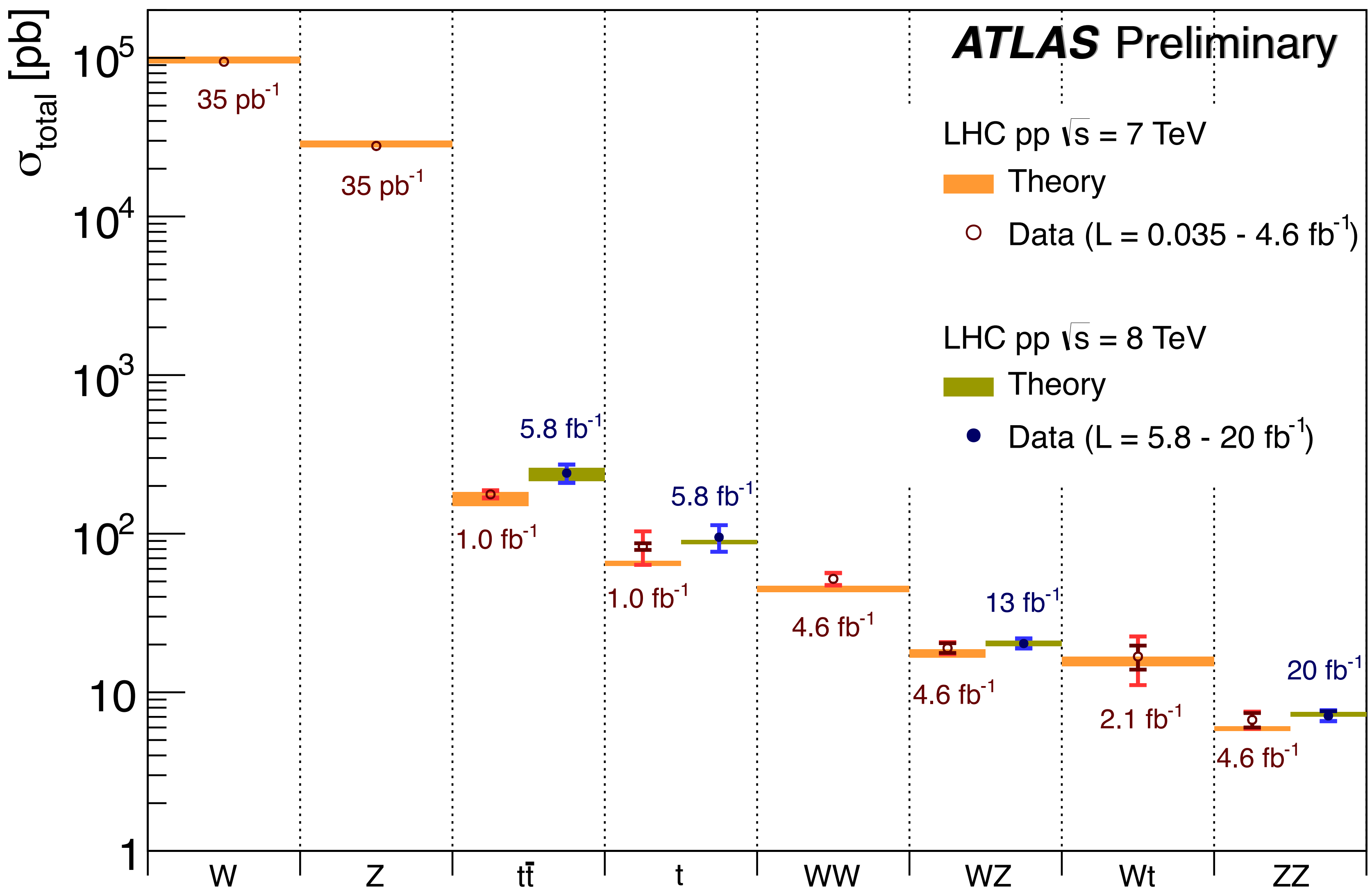


Techniques: particle-flow and isolation

- Particle-flow: combine the information from several detectors
  - Can improve resolution and pileup rejection
- Isolation: activity around the particle
  - Leptons and photons from H, W, Z decays vs. jets







1 Higgs boson produced every 10^{10} events
...and many others look-alike