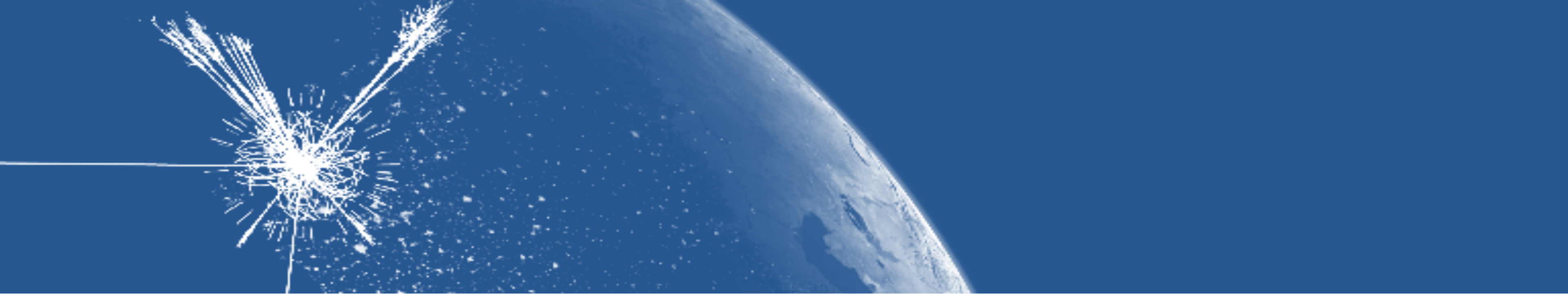


Physics at the LHC (1)

Andreas Hoecker (CERN)

Summer School on Symmetries and Fundamental Interactions
September 18–23, 2016, Abtei Frauenwörth, Germany

Outline

[2 × 1h30 lectures]

Today:

- Basic introduction
- Overview of the LHC experimental programme and methods
- A review of Run-1 physics highlights

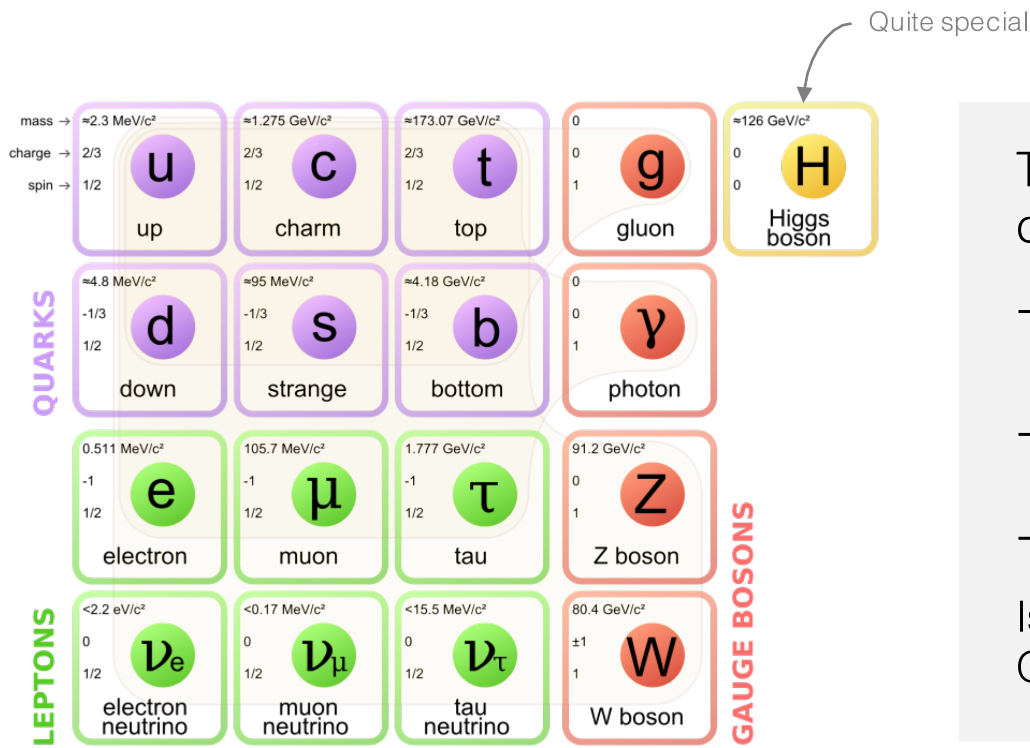
Tomorrow

- The LHC Run-2, results obtained so far
- The LHC Run-2 and beyond, expectations
- Outlook to future projects

Disclaimer: I sincerely apologise to show more results from ATLAS than the other LHC experiments, which is a choice solely driven by convenience. In those cases, the CMS results are almost always similar (and vice versa).

I also apologise for not covering heavy-ion physics in my lecture.

Everyday life, and particle physics, are described by the Standard Model (SM)



\+ gravitation

The SM is **the** legacy of 20th century particle physics

- It unifies quantum mechanics, special relativity and field theory
- It unifies electromagnetic and weak interactions
- It describes ~ all laboratory data

Is the SM the theory of everything? Or rather of almost everything? **No!**

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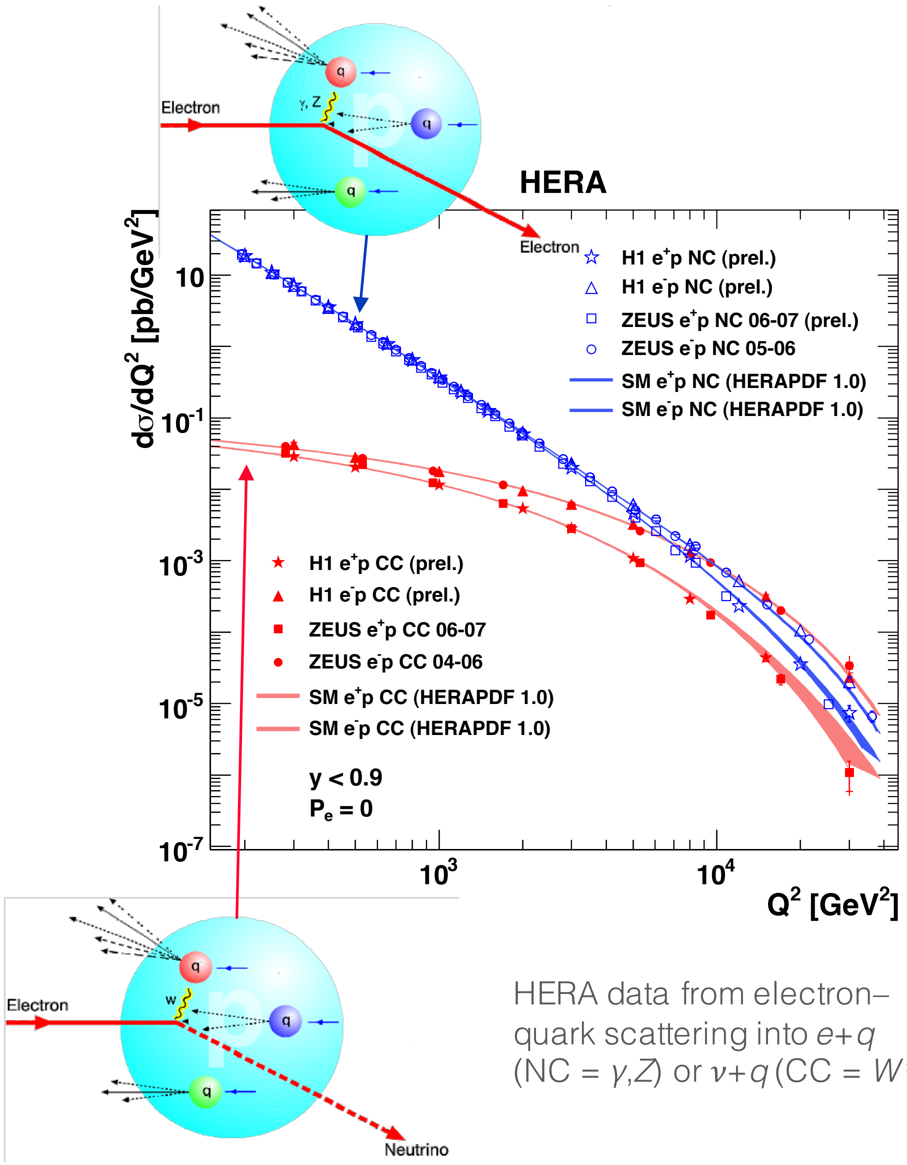

HERA data from electron–quark scattering into $e+q$ (NC = γ,Z) or $\nu+q$ (CC = $W^{\pm}$)

The SM is **the** legacy of 20th century particle physics

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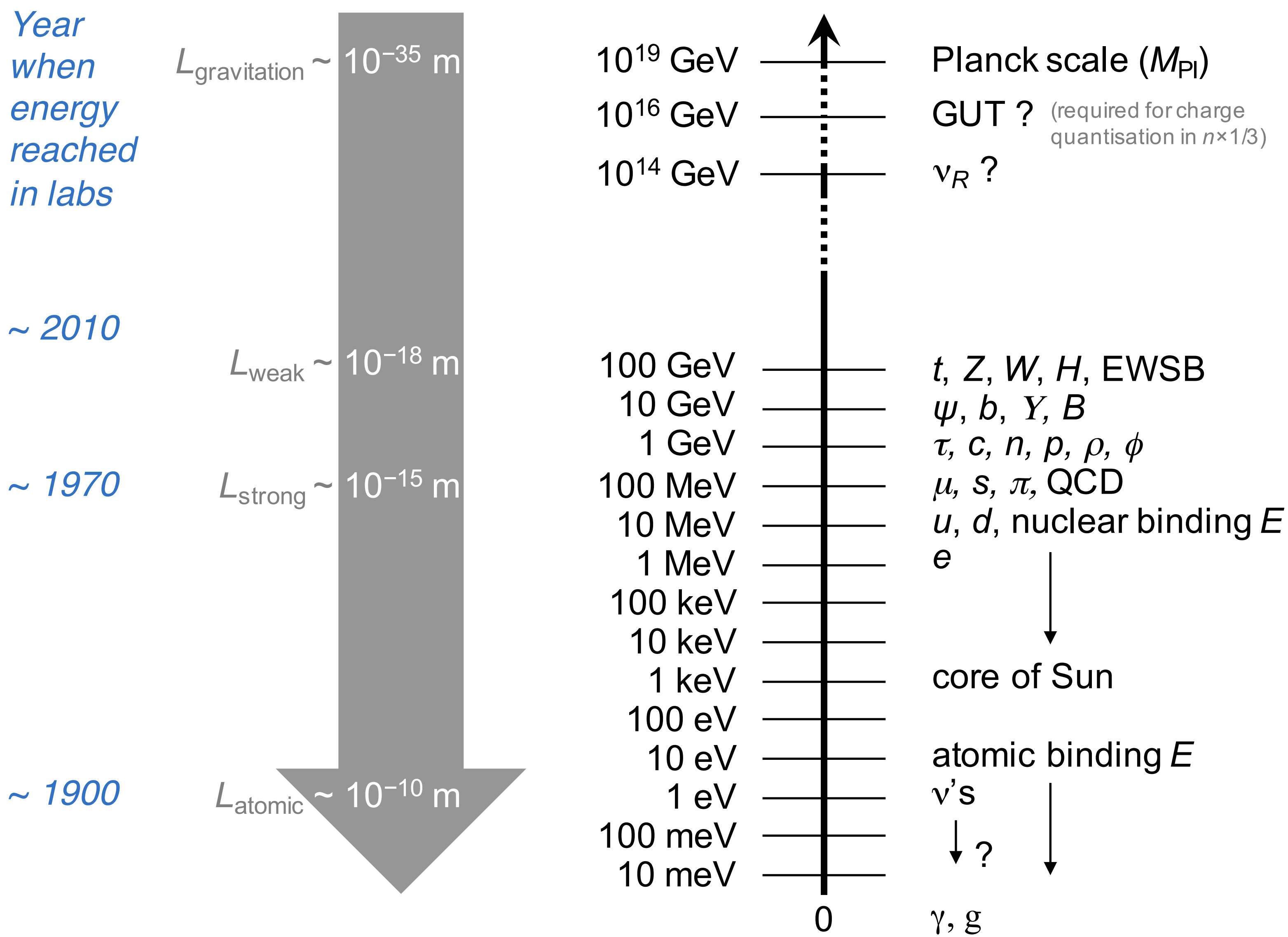
- It unifies electromagnetic and weak interactions
- It describes ~ all laboratory data

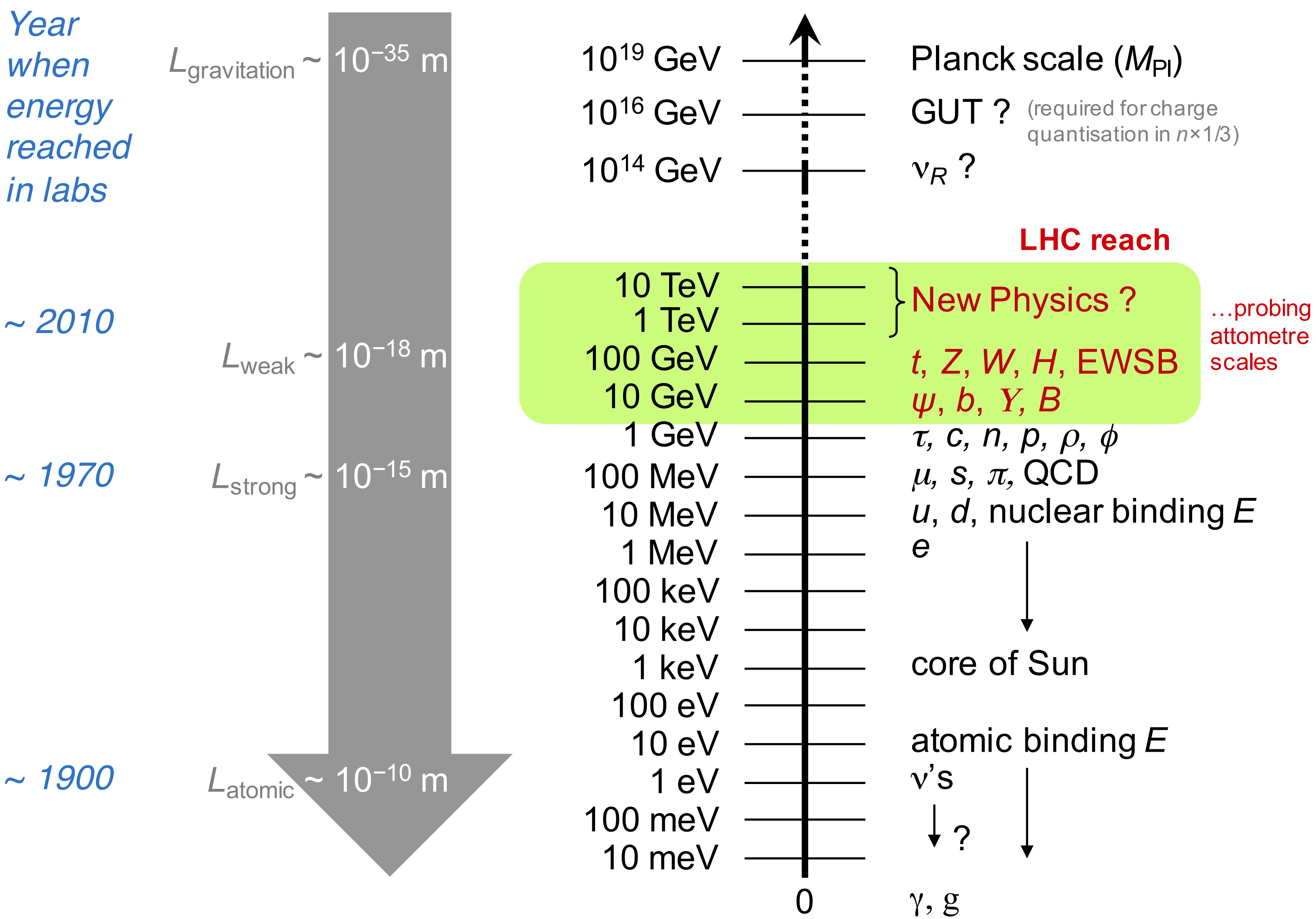
Is the SM the theory of everything? Or rather of almost everything? **Or …**

- Below ~100 GeV, weak interaction is weaker than electromagnetism
- Above ~100 GeV, electromagnetic and weak interactions are unified
- **Reduces 20 SM parameters to 19 (if ν = 0)**

Scales in particle physics



Scales in particle physics



The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

A problem: local gauge symmetry requires massless spin-1 "gauge" (=force) boson

This has been well verified for QED, with a massless photon (= infinite range)

However, the *W*, *Z* bosons are massive (→ finite range ~10^{-15} cm of weak interaction)

Only way to break gauge symmetry consistently is to spontaneously break the symmetry of the vacuum in the ground state:

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = v \neq 0$$

[non-zero vacuum expectation value]

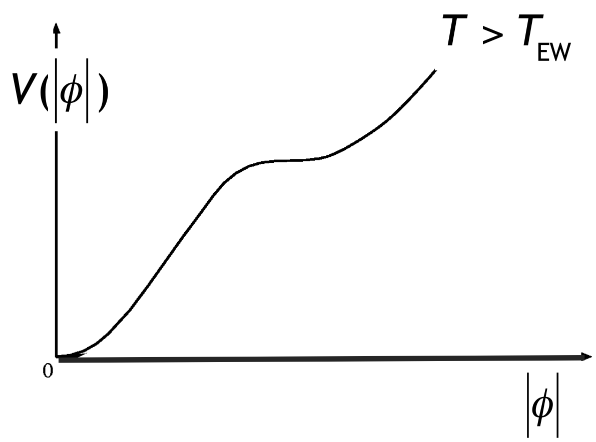
ϕ is a complex doublet field with non-zero vacuum expectation value.
three d.o.fs become Z, $W^{\pm}$ masses, fourth d.o.f is **massive scalar Higgs boson**

This is known as the "Brout-Englert-Higgs (BEH) mechanism"

The Standard Model

BEH mechanism

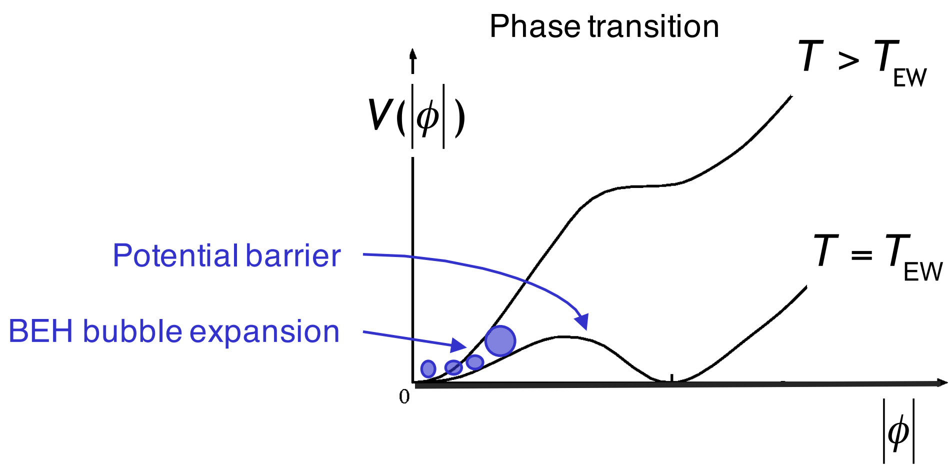
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)



The Standard Model

BEH mechanism

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ (~several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



Picture describes a 1st order phase transition that would require light Higgs, or new physics → currently disfavoured

The Standard Model

BEH mechanism

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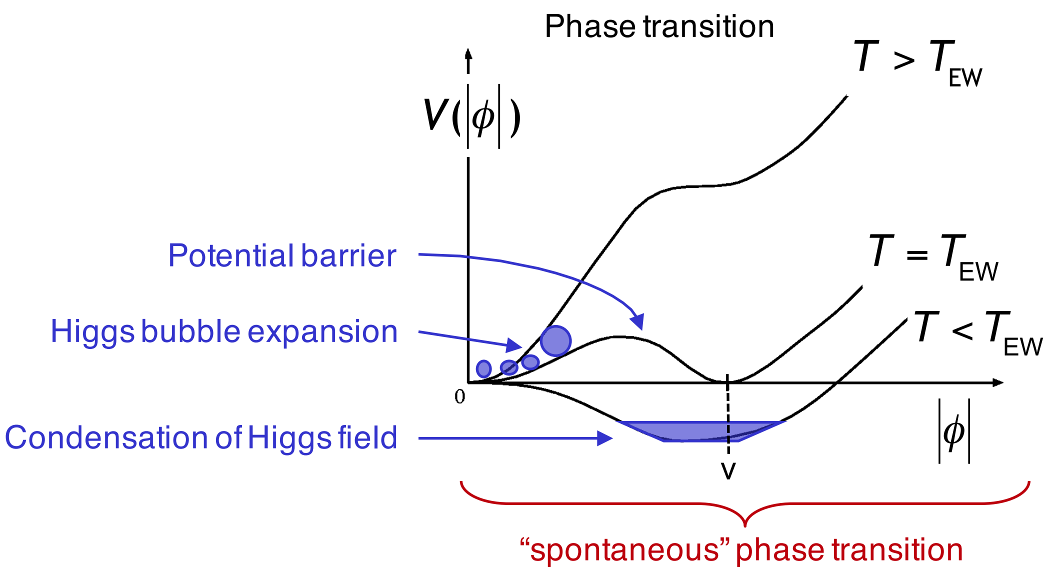


Higgs potential: $V(\phi) = \mu^2_{<0} |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi^i_L \psi^j_R \phi$

(μ, λ determined once Higgs mass known)

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds of new physics …

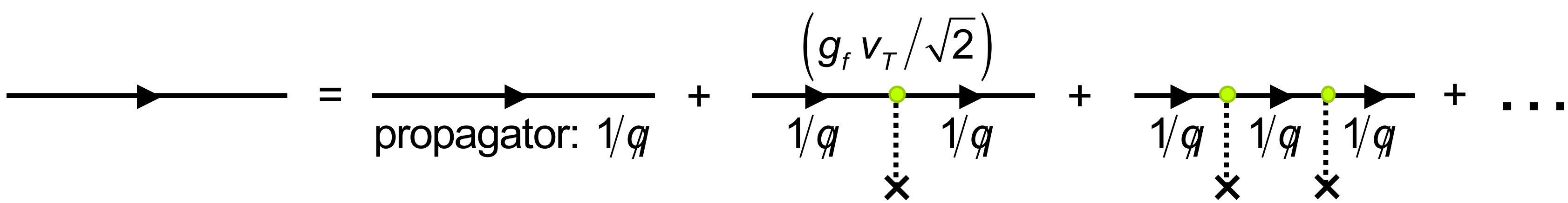
The Standard Model

BEH mechanism

"Mexican hat" BEH potential at $T \approx 0$: $V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 \quad , \quad \mu^2 < 0$

with vacuum expectation value: $\upsilon_{T=0} = \sqrt{-\frac{\mu^2}{2\lambda}} = \frac{1}{\sqrt{\sqrt{2} G_F}} = 246\ \text{GeV} \qquad \langle 0|\phi|0\rangle_{T=0} = \upsilon_{T=0}/\sqrt{2}$

At T < T_{EW}, the massless fermion fields interact with the non-vanishing BEH "condensate":



Geometric series yields massive propagator creating effective mass for fermion:

$$\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \ldots = \frac{1}{q}\sum_{n=0}^{\infty}\left(\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\right)^n = \frac{1}{q - m_f}$$

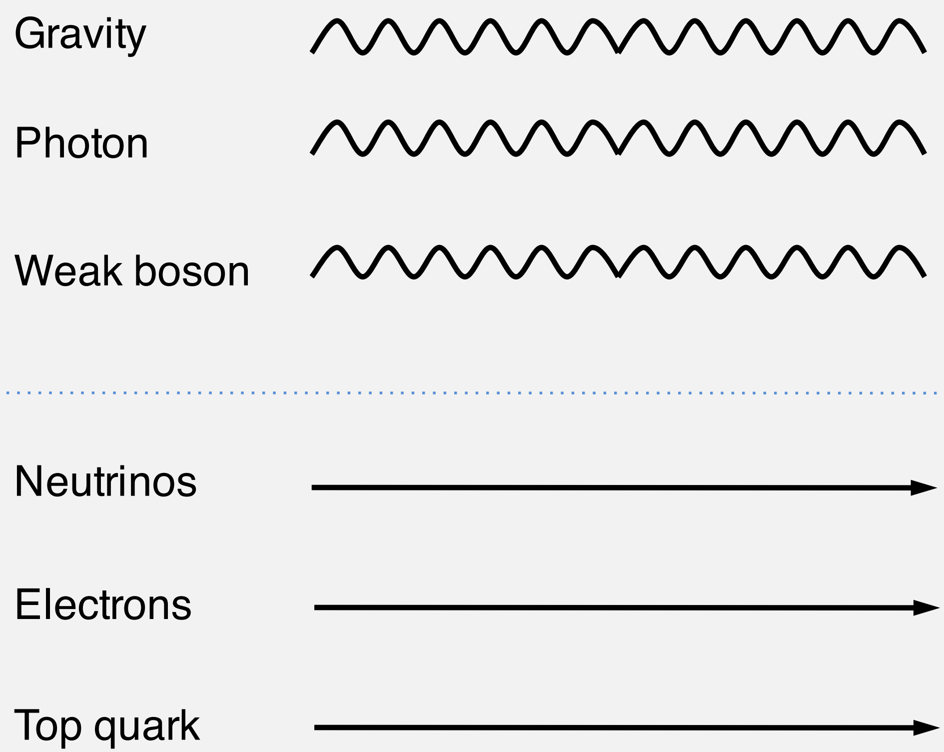
And similar for gauge bosons

The Standard Model

BEH mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase – early universe



H. Murayama

The Standard Model

BEH mechanism

Early universe: symmetric phase, fundamental particles are massless → gauge symmetry is respected

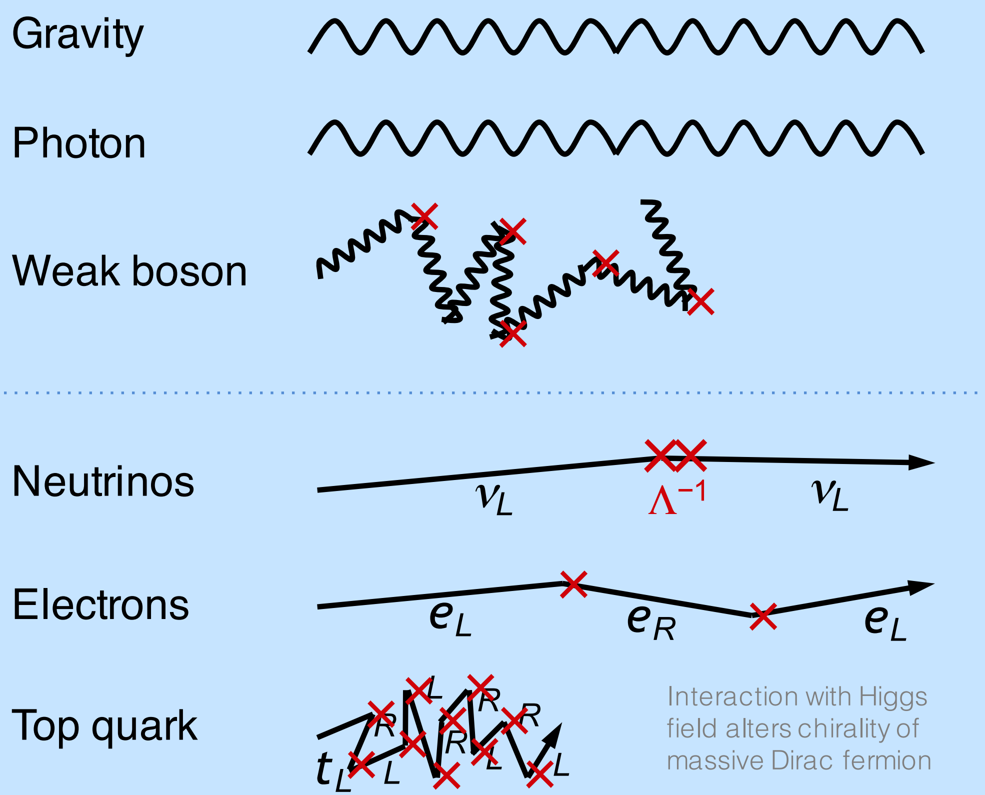
A Higgs field displaces ground state breaking gauge symmetry

It fills all space time (but without orientation as it has no spin)

Particles interact with Higgs field and effectively reduce their velocity. Acquired mass proportional to interaction strength

→ Action of the Higgs field creates “vacuum viscosity”

Higgs quantum liquid in broken phase

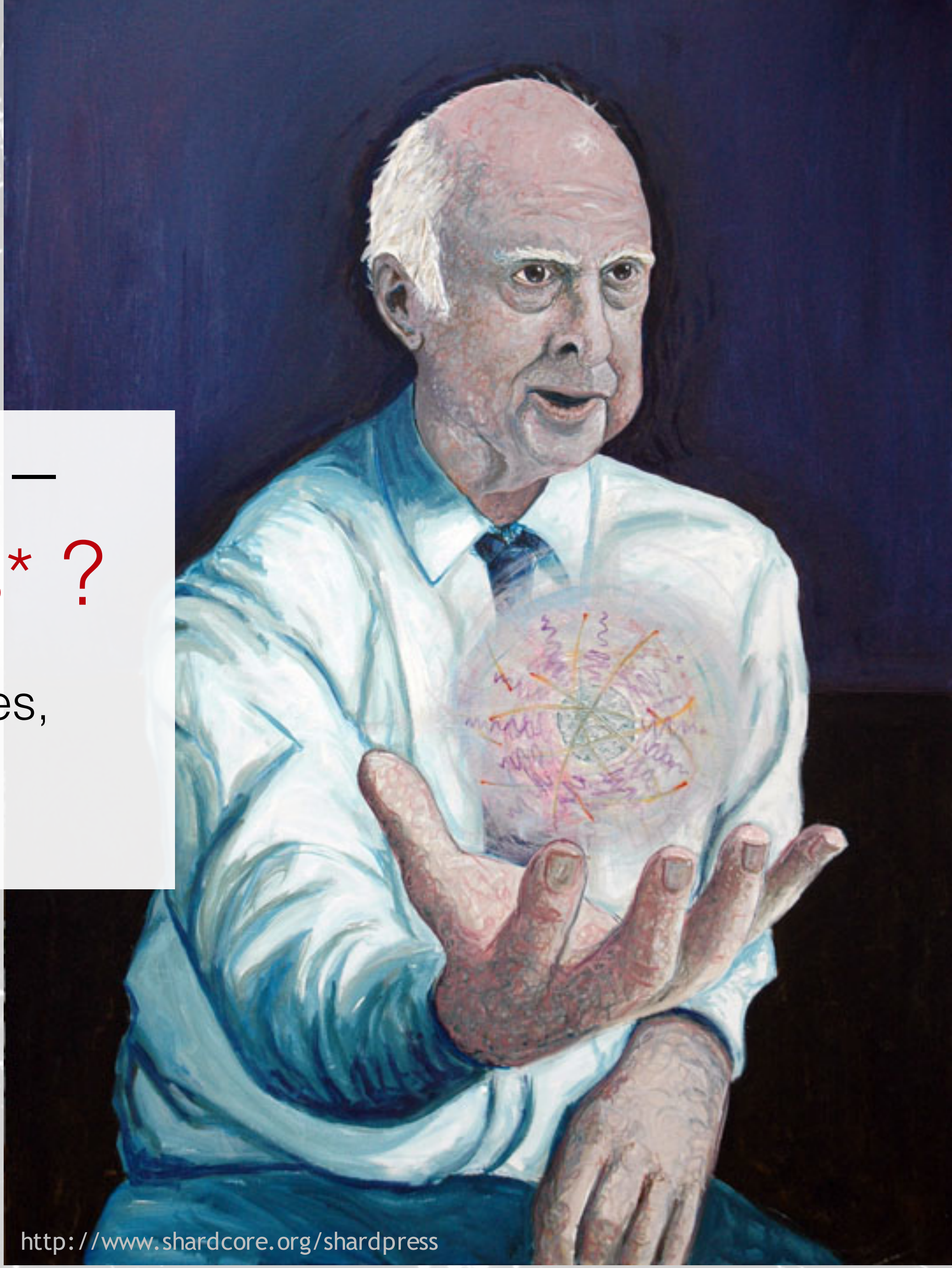


H. Murayama

The Higgs boson –
last of the particles* ?

The SM predicts all its properties, except for its mass

*No!



Full references for mechanism:

F. Englert and R. Brout, PRL 13 (1964) 321.
P.W. Higgs, PRL 13 (1964) 508.
G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

It should be noted that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the "Higgs mechanism" and predates it by several years.

Particle physics at the dawn of the LHC

LEP (& SLC) had ended their programmes, with among their main results:

- Three light active neutrino flavours
- Direct Higgs searches excluded $m_H < 114$ GeV

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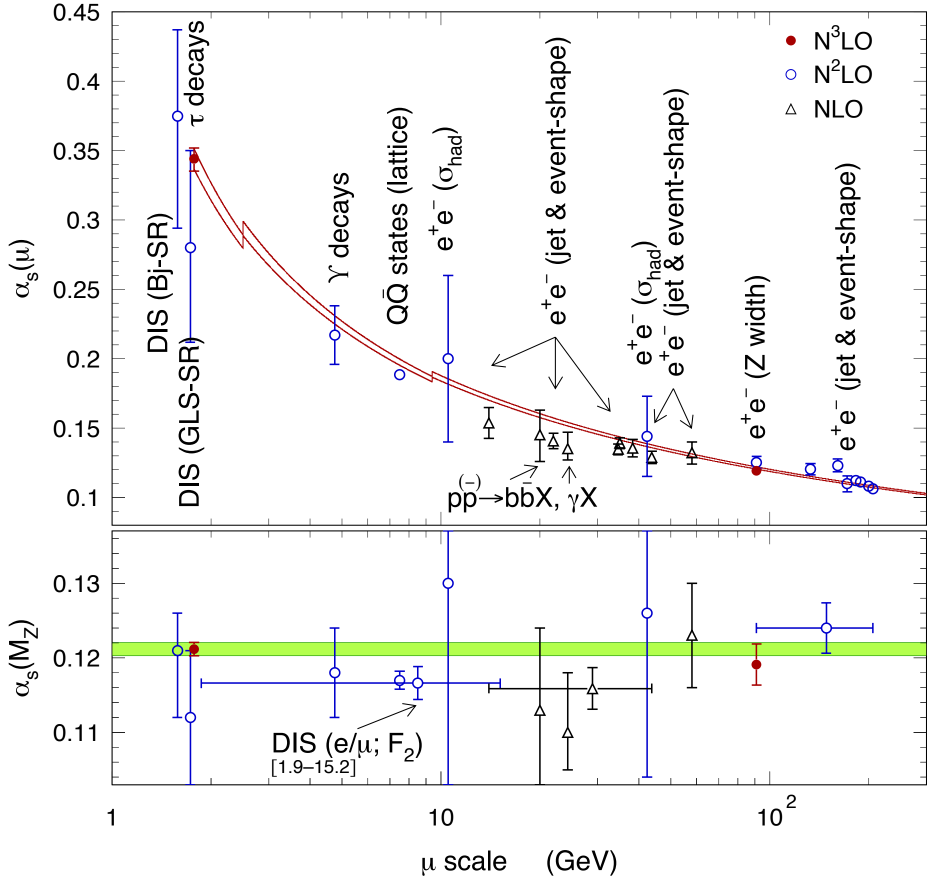
Asymptotic freedom of strong interaction has been verified at the percent level

$\alpha_S(\mu)$ extracted from R_τ, $R_\ell(Z)$ measurements using NNNLO (=3NLO) perturbative QCD

Ratio with respect to tau-based value



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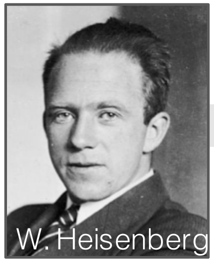

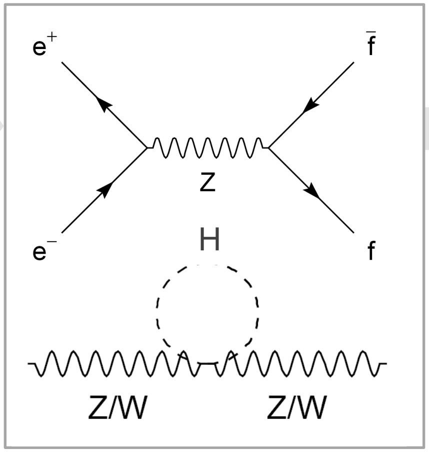

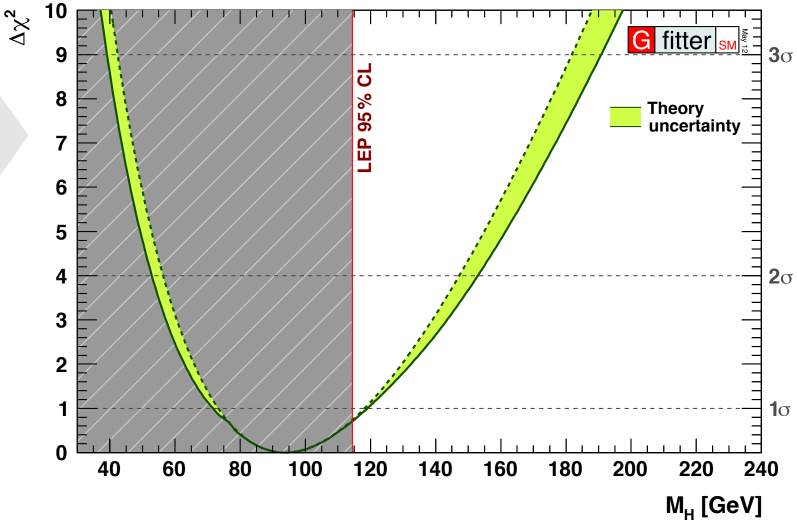

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- SM tests to unprecedented precision, no direct/indirect hint of BSM physics
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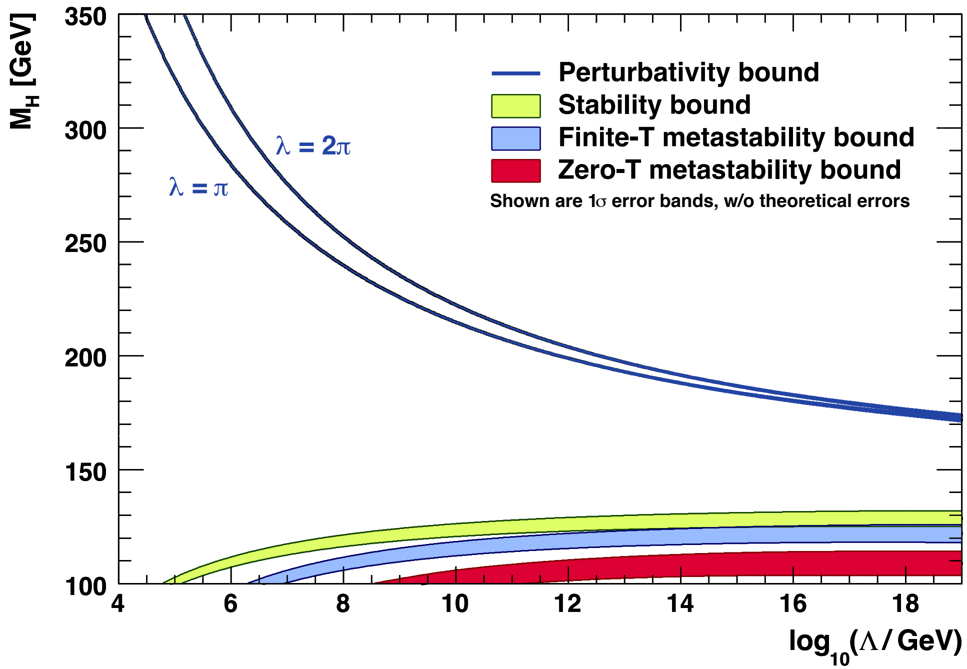
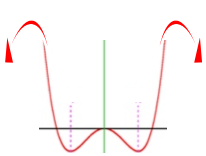
- There also were theoretical arguments in favour of a light Higgs moderating $W_L W_L$ scattering

Also: perturbativity and (meta)stability bounds versus the SM cut-off scale Λ

The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2\times10^{18}$ GeV





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Tevatron was still continuing Run-2

- Discovery of top-quark and < 1% mass measurement
- B_s mixing precisely measured, agreeing with SM
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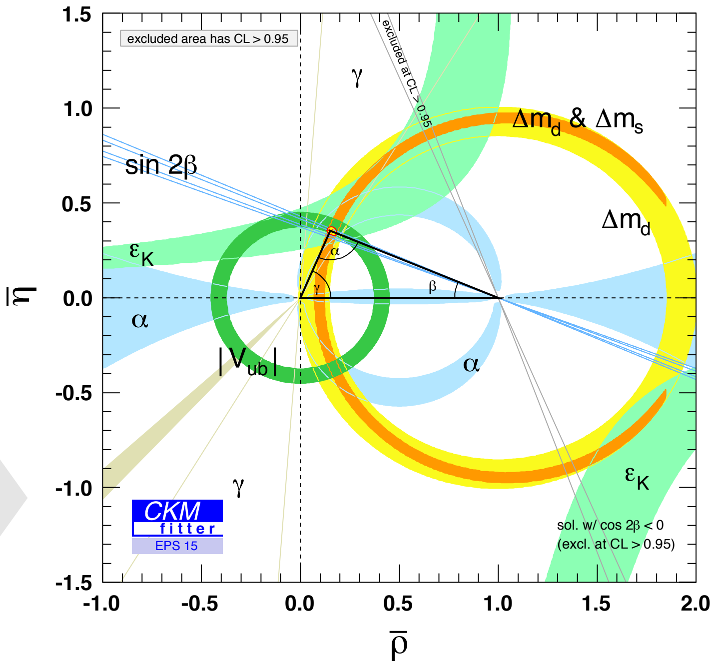
B-factories experiments BABAR & Belle about to end

- *CP* violation measurements in *B* system confirm CKM
- Despite ambiguous initial results, no hint of BSM



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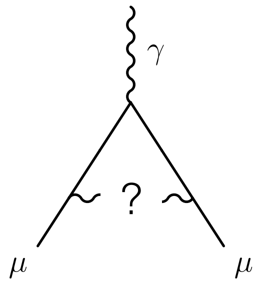

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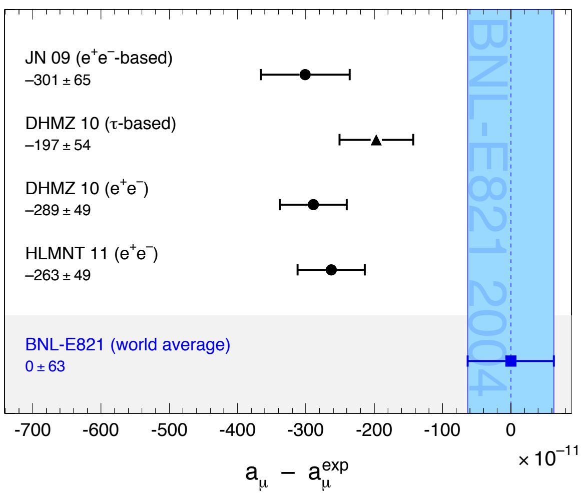

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Low-energy experiments: no signs of charged LFV, EDM, only muon g–2 showed anomaly

Neutrino revolution: massive neutrinos established, unknown matter nature and hierarchy

No signal for dark matter particles (only gravitational effects), no axions, no proton decay

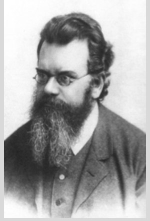
Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

Lawrence
(First cyclotron provided 80 keV proton acceleration)

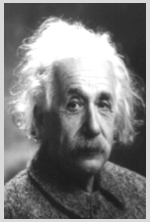
Particles accelerators:

- Look deeper into matter (size ~ $1/E$)
  ("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)

de Broglie

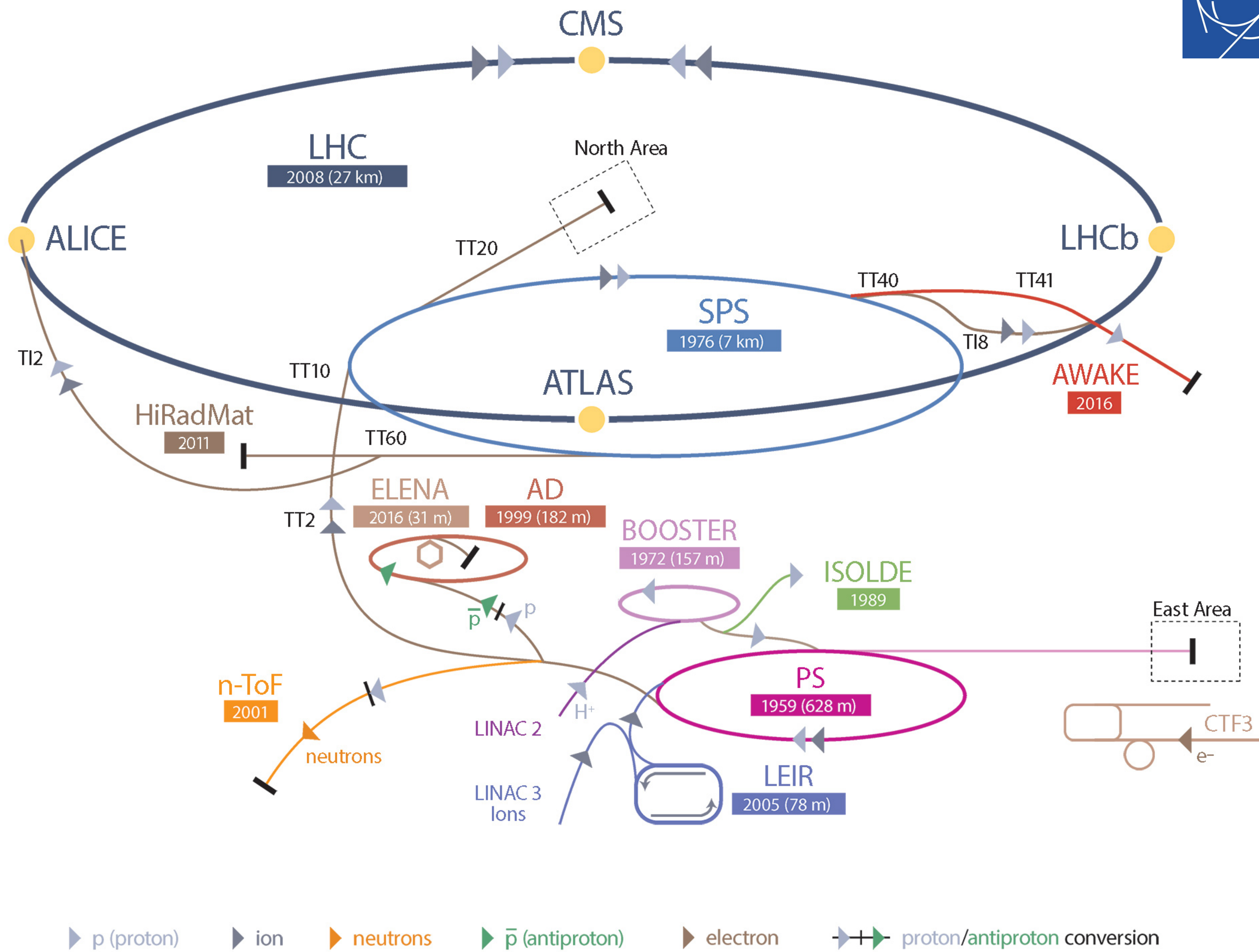


Boltzmann



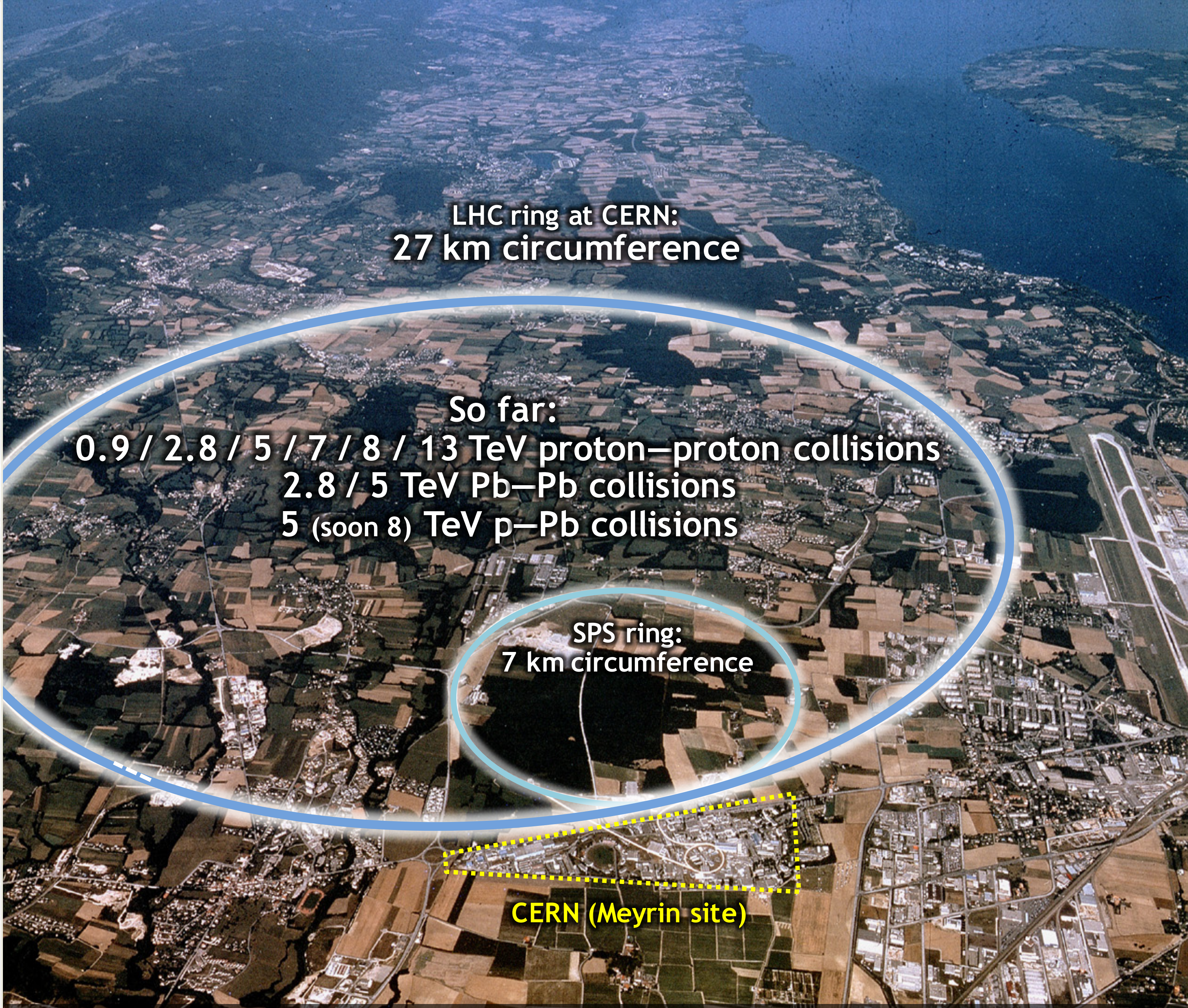
Einstein

CERN's Accelerator Complex



Superconducting proton/ion accelerator and collider installed in a 27 km circumference underground tunnel (4 m tunnel cross-section diameter)

7 TeV
LHC
450 GeV
SPS
26 GeV
PS
1.4 GeV
BOO-
STER
50 MeV
LIN-
AC2

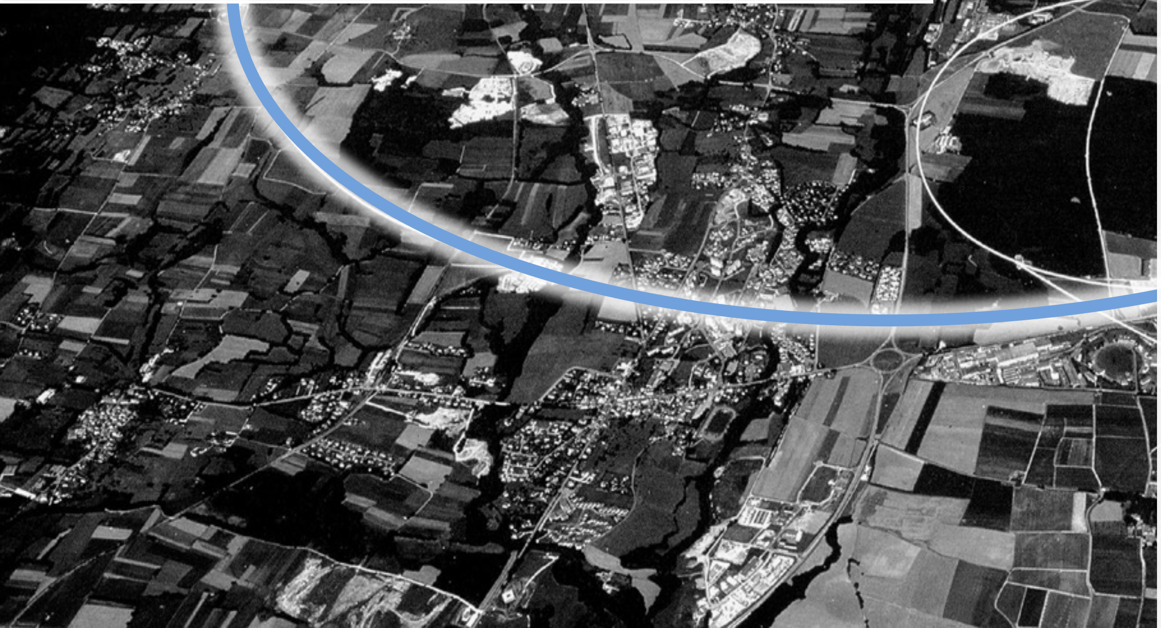


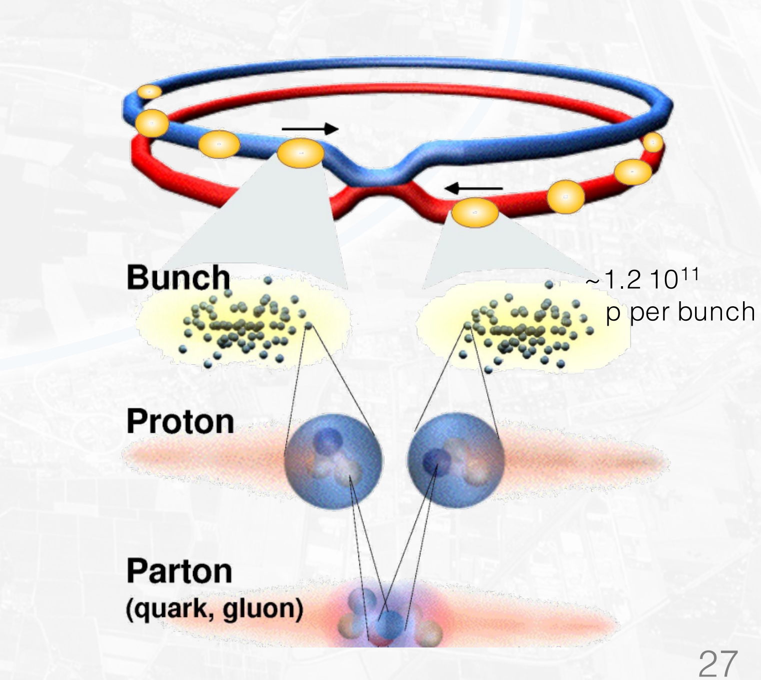
~20 minutes are required to accelerate the protons in the LHC from 450 GeV to 7 TeV

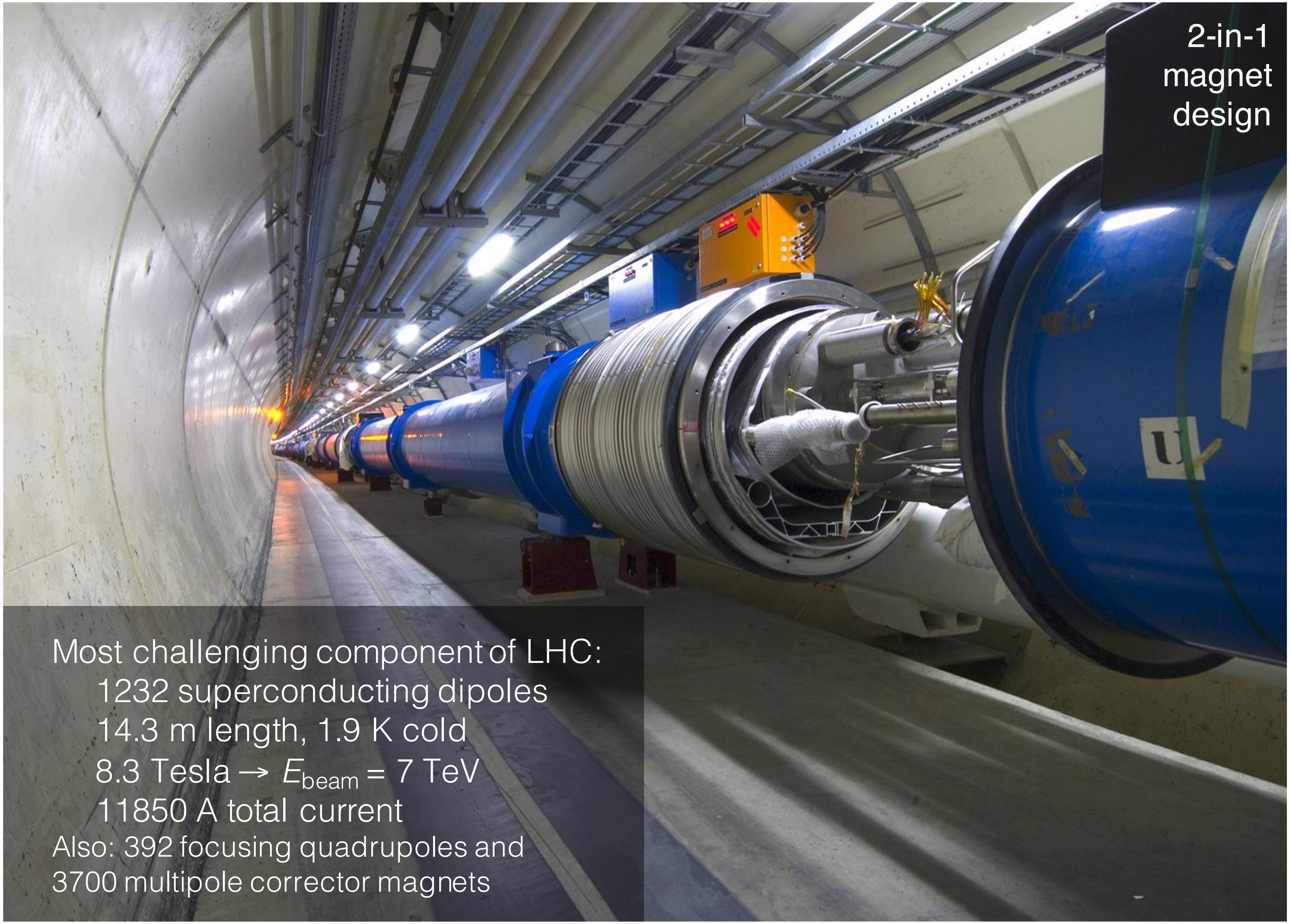

CMS
LHCb
ALICE
ATLAS

The search for new physics exploits smallest distances → largest energies

- Proton energy is limited by magnets that guide the circular beams
- $E_{proton} \sim 0.3 \cdot B \cdot r$: since radius is fixed (4.3 km), use as strong fields as possible (> 8 T)
- Length scale (am) ~ 200 GeV am / E (GeV)
  (am = atto-metre = 10^{-18} m)
- The LHC collides protons at E_{CM} = 14 TeV
  → probing a distance of 10^{-20} m ?
  Not quite, since protons are composites:
  the energy is distributed among its partons







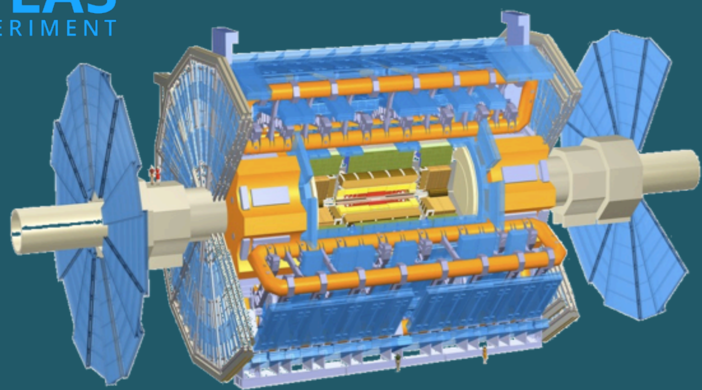
Most challenging component of LHC:

- 1232 superconducting dipoles
- 14.3 m length, 1.9 K cold
- 8.3 Tesla → E_{beam} = 7 TeV
- 11850 A total current

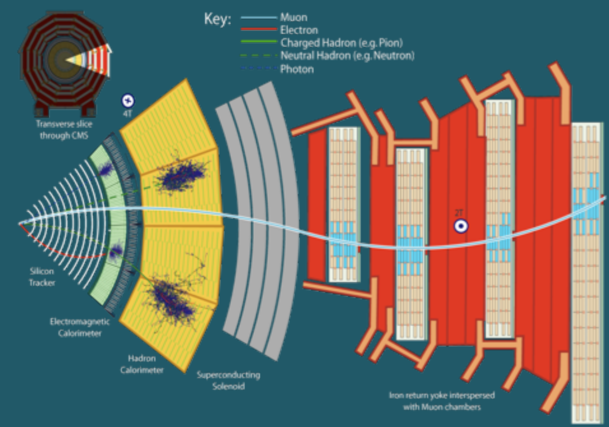
Also: 392 focusing quadrupoles and 3700 multipole corrector magnets

ATLAS & CMS: giant, ultra sophisticated particle detectors

ATLAS EXPERIMENT



CMS

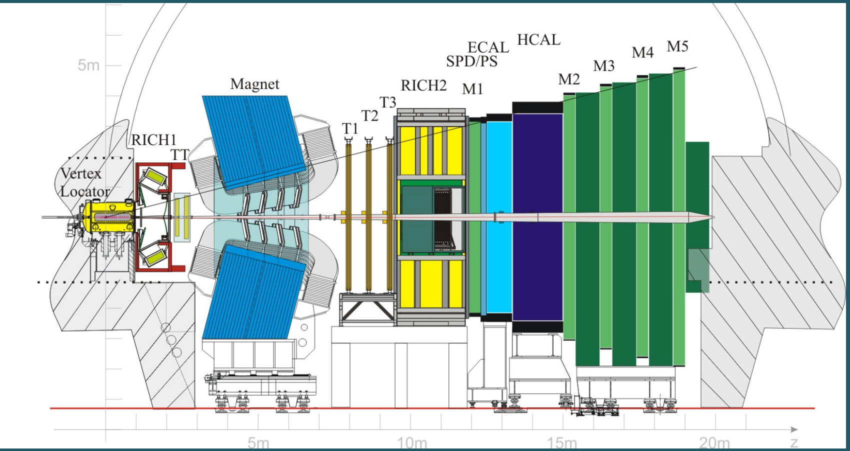


ATLAS: emphasis on excellent jet and missing-E_T resolution, particle identification, flavour tagging, and standalone muon measurement

CMS: emphasis on excellent electron/photon energy & track (muon) momentum resolution, and flavour tagging

Both: excellent hermeticity – very few "cracks"

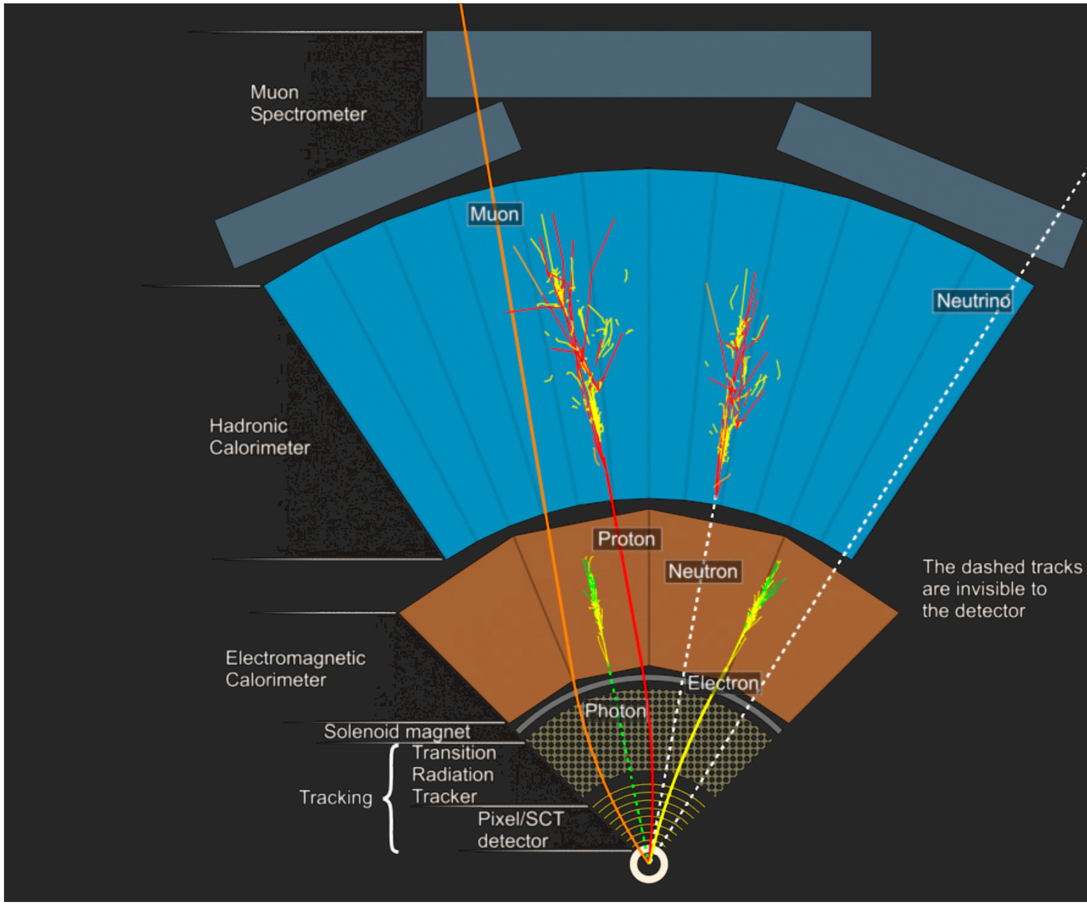
LHCb & ALICE: optimised for low-p_T physics



LHCb: forward spectrometer dedicated to *pp* flavour physics featuring hadronic trigger, excellent low-momentum track resolution, particle identification (π/K separation)

ALICE: dedicated to study of heavy-ion collisions and soft *pp* physics; ALICE features highly efficient track reconstruction in busy heavy-ion environment and particle identification

The detectors measure interaction of particles with active material

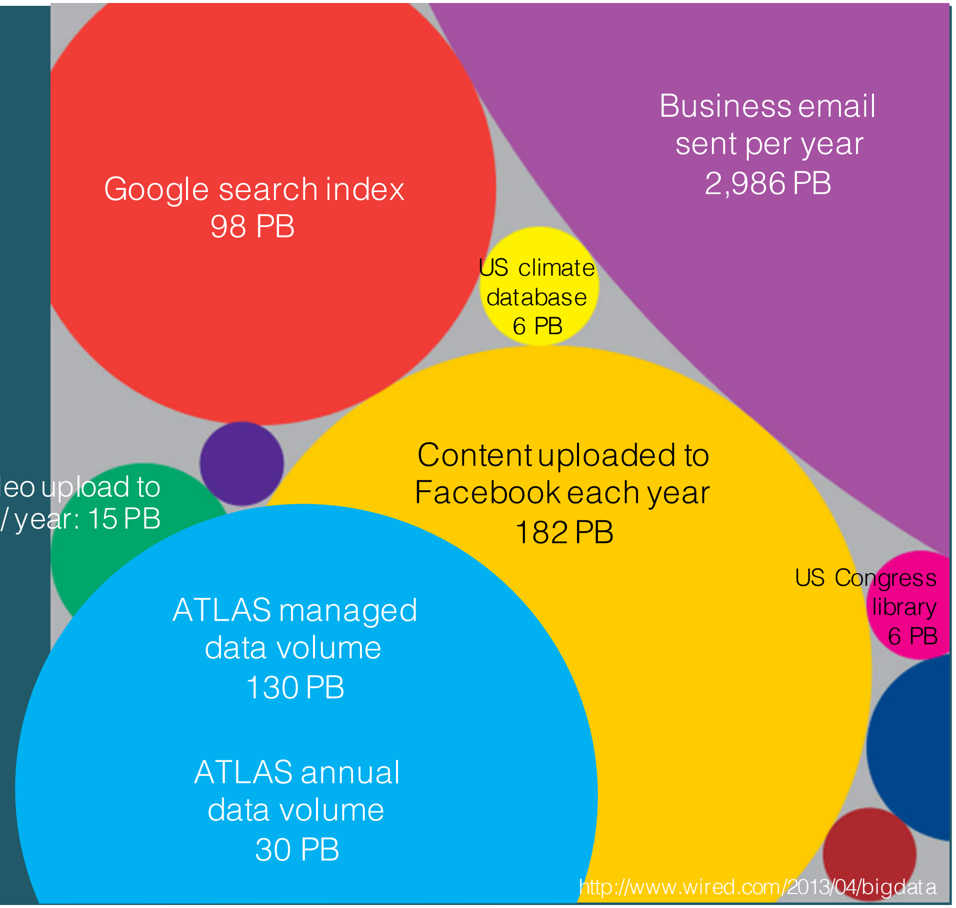


Ensemble of measured interactions in a given proton–proton bunch crossing makes up an "event"

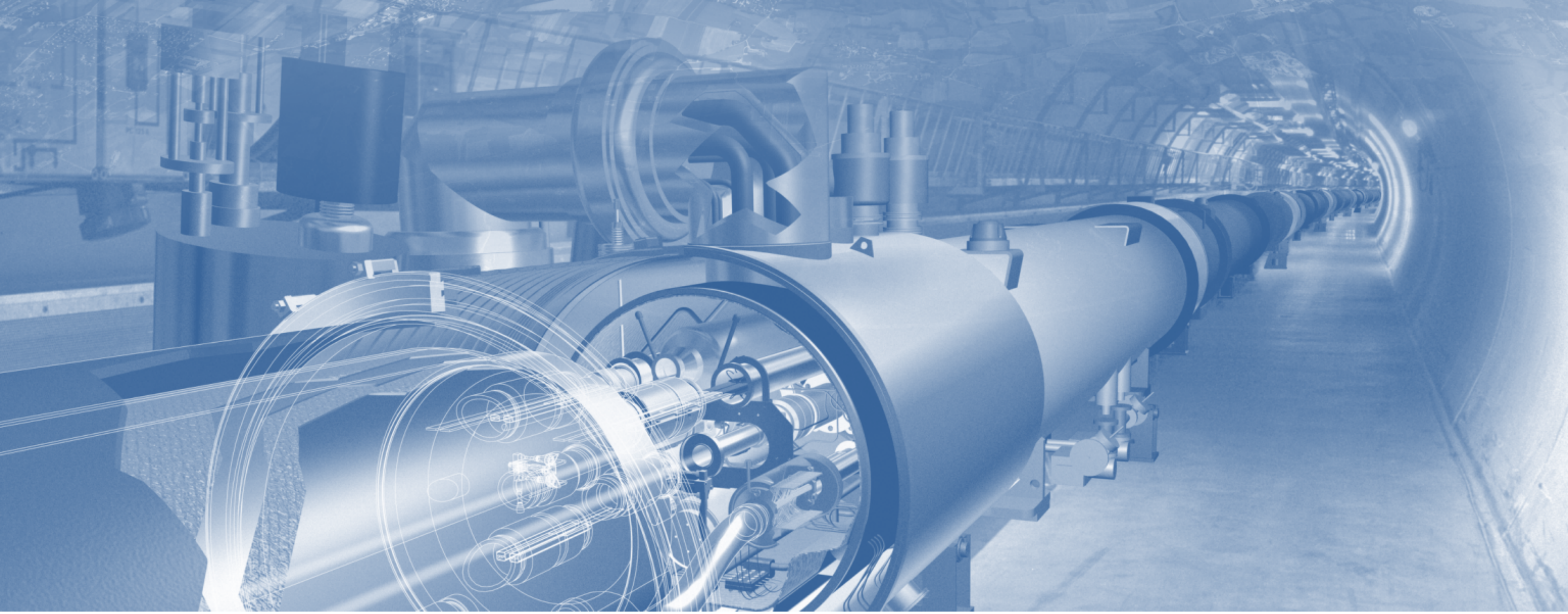
LHC computing is big data

LHC experiments started more than a decade ago with large scale computing — now big data is everywhere

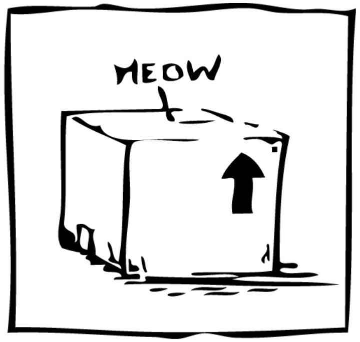
Note: LHC has a public science budget, unlike Google or Facebook

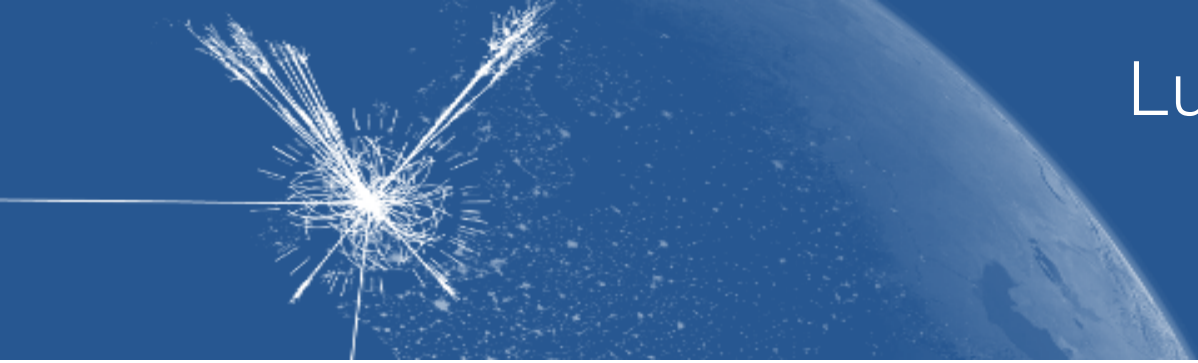


Largest data volume from simulated events, not from real collision data !



A few (basic) experimental concepts at the LHC





Luminosity — single most important quantity

- Luminosity is a function of the LHC beam parameters

$$L \sim \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{A} = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi\sigma_x\sigma_y} \qquad [L] = \frac{1}{\text{s} \cdot \text{cm}^2}$$

L_{max} ~ 1.6 × 10^{34} $s^{-1}cm^{-2}$

10 $nb^{-1}s^{-1}$ = 10^{34} $s^{-1}cm^{-2}$

~ 1 GHz interaction rate

- f_{rev} = 11245.5 Hz is the bunch revolution frequency
- n_{bunch} = 1…2808 is the number of bunches in the machine
- N_p = 1.1 × 10^{11} is the number of protons per bunch (“bunch intensity”)
- $\sigma_{x/y}$ = 12…50 µm is the transverse beam width characterising beam optics, $\sigma^2_{x/y} = \varepsilon_{x/y}\, \beta^*_{x/y}$

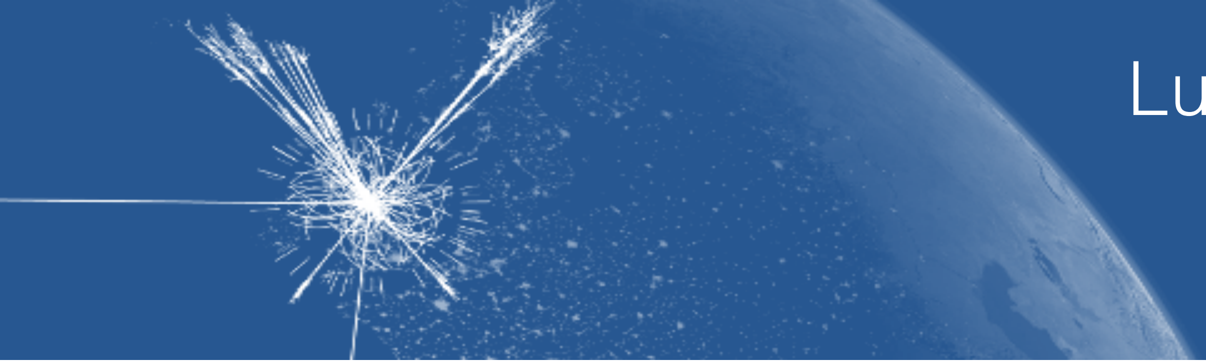
- Luminosity drives our ability to detect low cross-section processes

$$N_{\text{events}}^{\text{obs}} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt$$

“Cross section” given by Nature

“Efficiency” of detection optimised by experimentalist

Integrated luminosity delivered by LHC

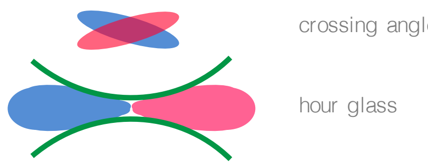


Luminosity — single most important quantity

- Maximising luminosity

Compensate reduction factor

Crossing angle (0.3 mrad) and "hourglass effect" (σ_z ~ 4–6 cm)



$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi\sigma_x\sigma_y} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z) = \frac{1}{4\pi} \cdot f_{\text{rev}}\, n_{\text{bunch}} N_p \cdot \frac{N_p}{\varepsilon_n} \cdot \frac{\gamma}{\beta^*} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

Maximise total beam current

Cryo-limit on maximum beam current anticorrelates N_p to n_{bunch}.

Collimation, cryogenics vacuum, protection improvements, … allow to increase limit.

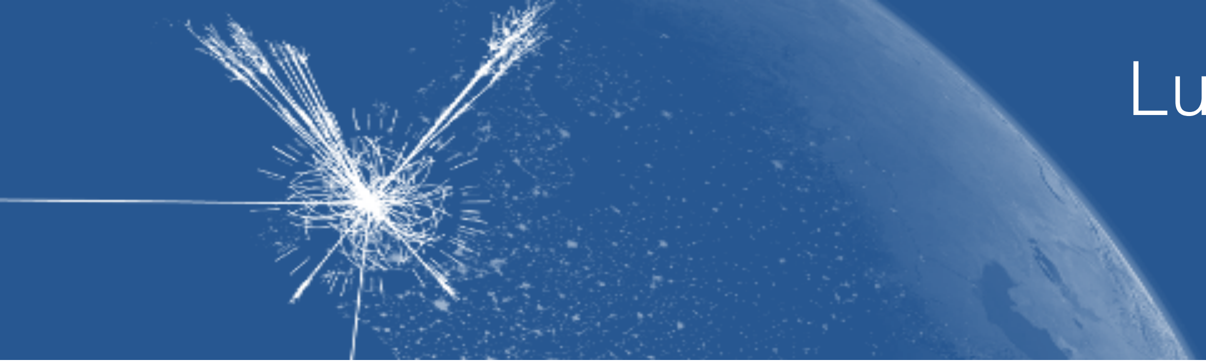
Maximise brightness & energy, minimise β^*

Beam size: $\sigma(s) = \sqrt{\beta(s)\varepsilon_n/\gamma}$, $\sigma^* = \sigma(0)$ ~ 17 μm at collision point

Emittance: $\varepsilon \times \pi =$ area in phase space occupied by beam (ε_n ~ 3.8 μm is normalised emittance, taken out gamma factor)

To reduce ("squeeze") β^* (distance from focus point where beam is twice as wide, 60 cm) need to respect quadrupole aperture limit

Beam "brightness": N_p/ε_n limited by beam–beam interactions (quadrupole defocusing effect), space charge tune shift (tune spread limited by resonances)

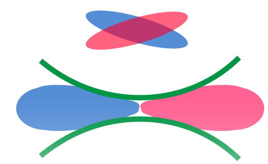


Luminosity — single most important quantity

- Maximising luminosity

Compensate reduction factor

Crossing angle (0.3 mrad) and "hourglass effect" (σ_z ~ 4–6 cm)



Great LHC tool to compute luminosity and other relevant beam parameters as a function of LHC settings:

http://lpc.web.cern.ch/lpc/lumi2.html

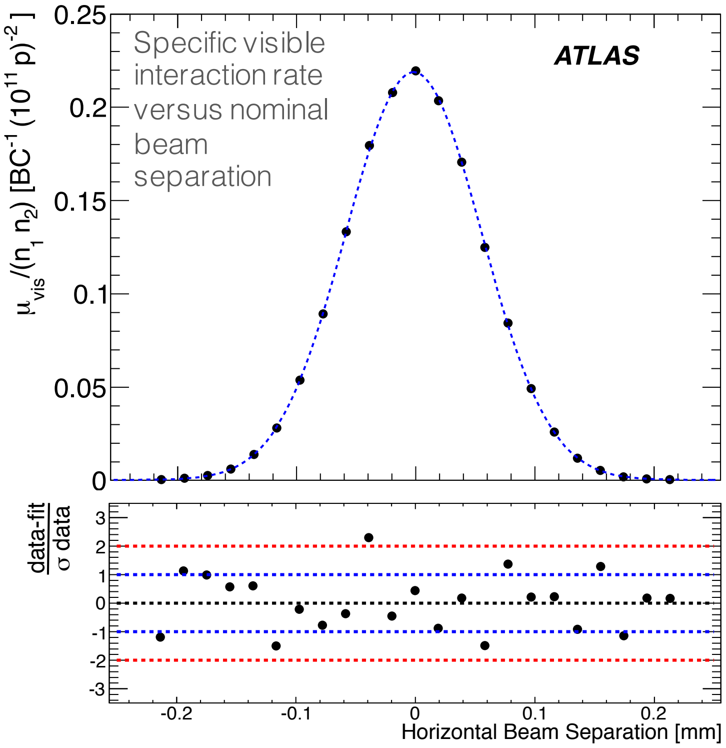
Beam "brightness": N_p/ε_n limited by beam–beam interactions (quadrupole defocusing effect), space charge tune shift (tune spread limited by resonances)

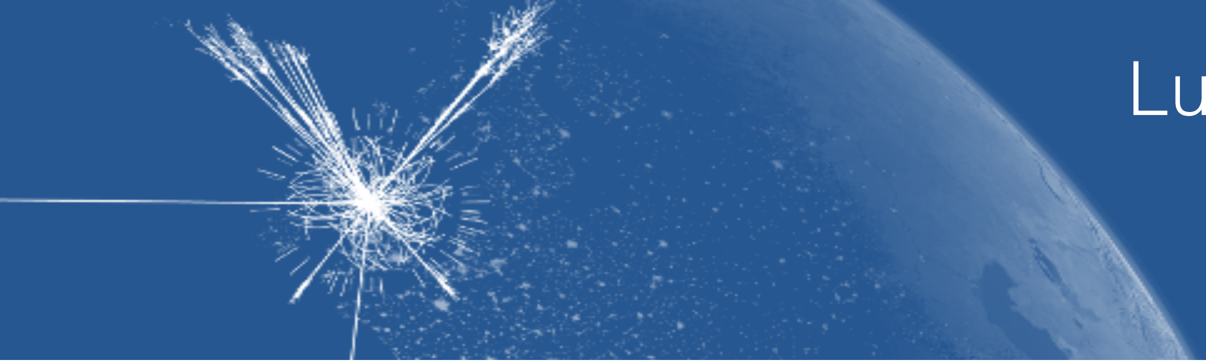
Luminosity — single most important quantity

- The luminosity detectors of the experiments are calibrated with beam-separation scans (the so-called "van-der-Meer method")

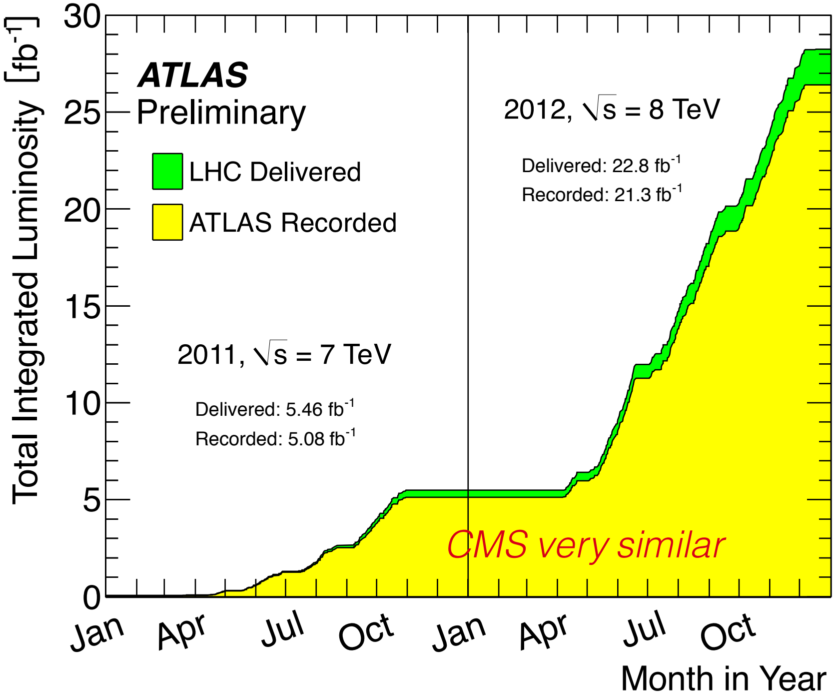
$$\sigma_{x/y} = \Sigma_{x/y} / \sqrt{2}$$

- $\Sigma_{x/y}$ = horizontal and transverse convolved beam widths directly determined from the scan
- The knowledge of L from the measured beam currents and beam widths allows to extract the ***visible cross section*** of a given luminosity detector
- During normal data taking the counts measured in that detector, together with the known visible cross section, allows to extract the luminosity





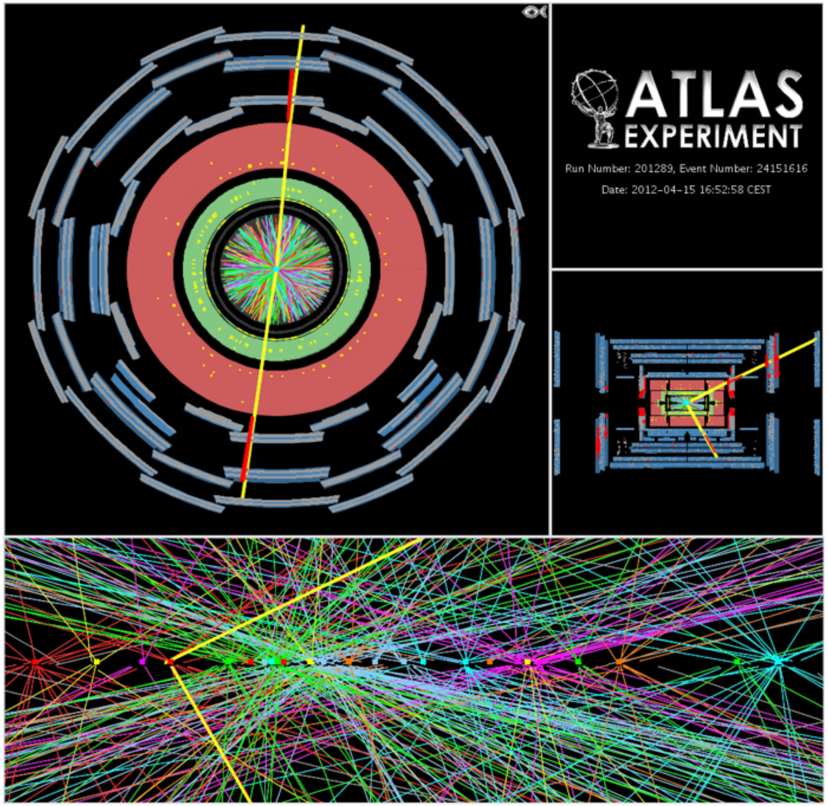
Luminosity — single most important quantity



Run-1 luminosity profile

- $L_{int,recorded}$ = 21 fb^{-1} at 8 TeV
- L_{peak} = 7.7 $\times 10^{33}$ cm^{-2}s^{-1}
- Max colliding bunches: 1380 with 50 ns bunch distance
- Max L_{int} / day: 286 pb^{-1}
- At L_{peak} every 45 min. 1 $H \rightarrow \gamma\gamma$, need ~2 typical 160 pb^{-1} fills to produced one $H \rightarrow 4l$

High luminosity comes at price of pileup interactions



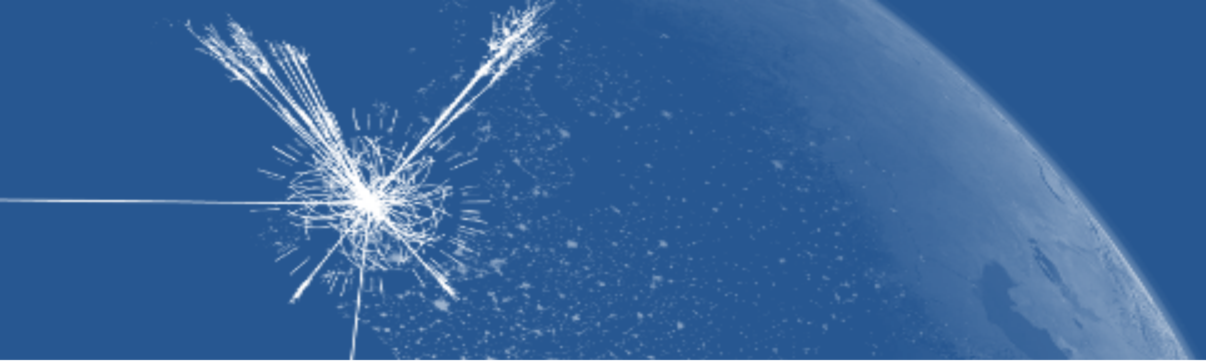
CMS very similar

Pileup interactions

- Average of 21 (peak: 40) interactions per crossing in 2012. Similar in 2016.
  LHC design value (14 TeV):

$$\mu = \frac{\sigma_{\mathrm{inel}} \cdot L}{f_{\mathrm{rev}} \cdot n_{\mathrm{bunch}}} \approx \frac{80\ \mathrm{mb} \cdot 10\ \mathrm{nb}^{-1}\mathrm{s}^{-1}}{11245\ \mathrm{s}^{-1} \cdot 2808} = 25$$

- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- However: higher trigger thresholds
  → low-p_T physics suffers

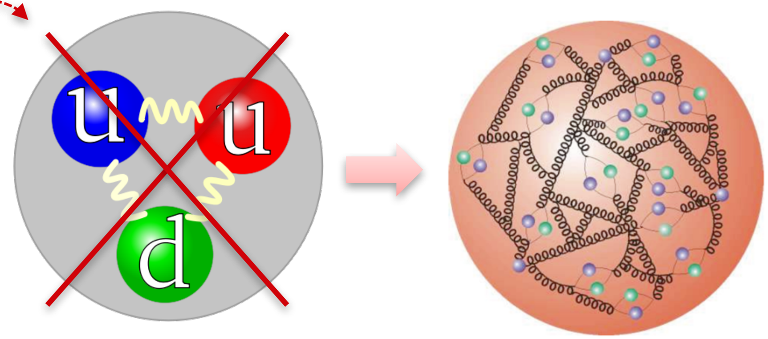


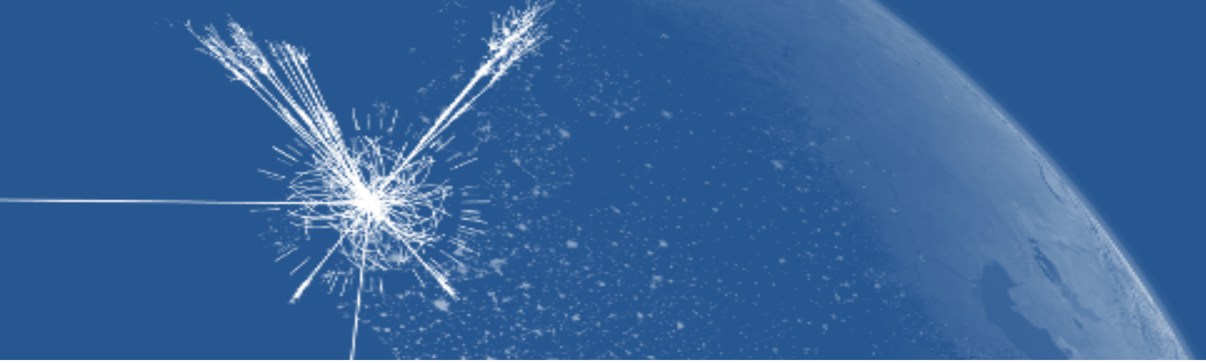
Proton–Proton Collisions

- For proton–proton collisions, cross section is **convolution of Parton Density Functions (PDF) with parton scattering Matrix Element**

Parton distribution functions

Representing structure of proton, extracted using experimental data and QCD properties





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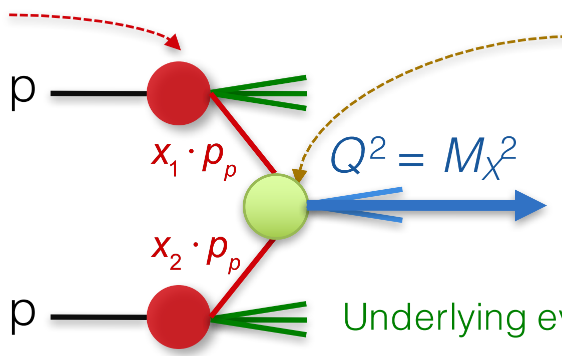
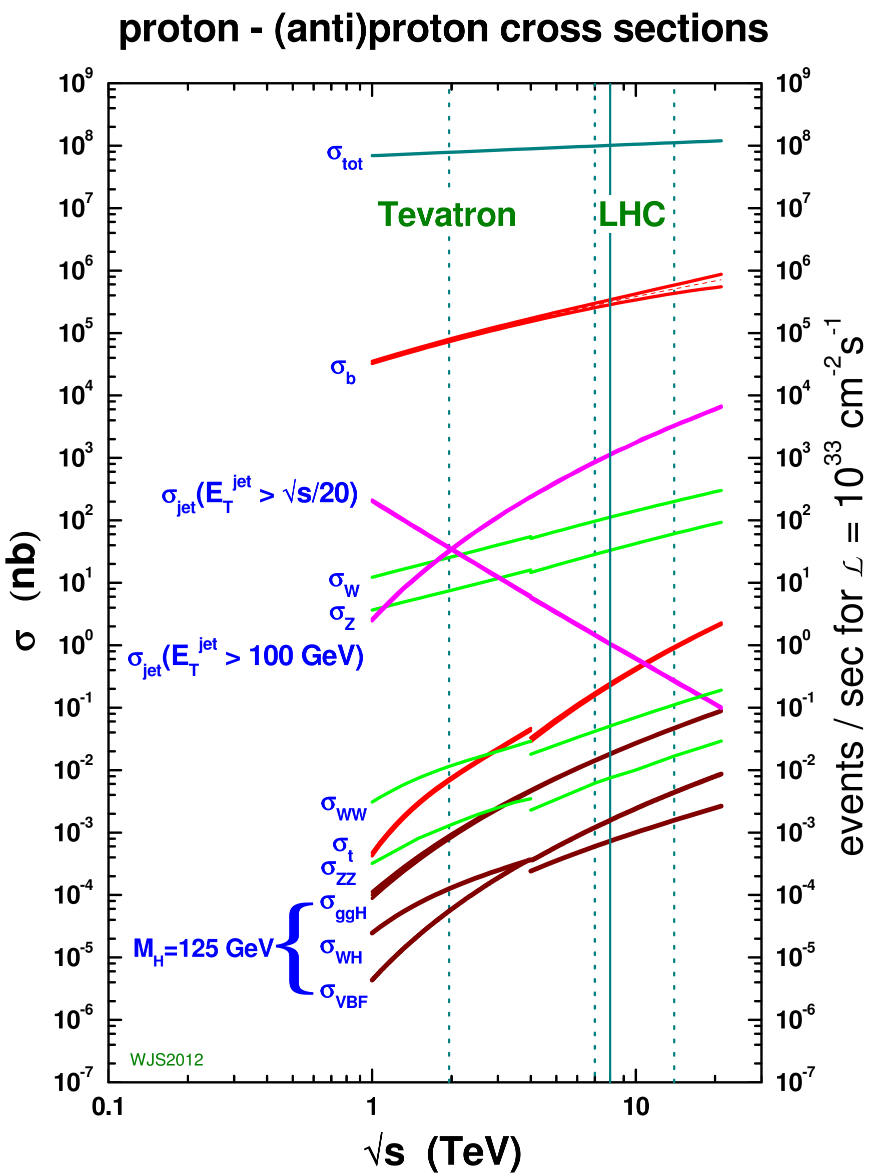


- CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\mathrm{LHC}}$
- The parton density functions rise dramatically towards low x:
  - — Higher cross section at higher proton–proton collision energy
  - — More luminosity also achieves higher achievable energy
  - — Low-x regime (eg, Higgs production) dominated by gluon–gluon collisions: “gluon collider”

Proton–Proton Collisions



- Cross-section fully dominated by inelastic strong interaction “minimum bias” events

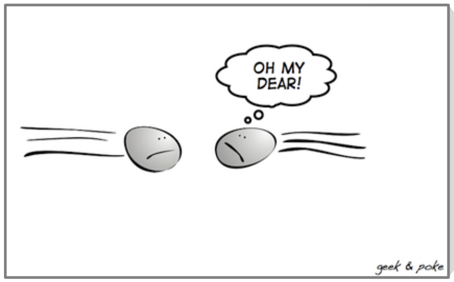
- Detectors cannot record 40 MHz event rate* (each event ~2 MB size → 80 TB / second)

- Online custom hardware and software “triggers” reduce rate to filter out events with a million & more times smaller cross-sections than minimum bias events

*LHCb phase-1 upgrade is preparing for exactly that!

The data path in a nutshell
(example ATLAS)

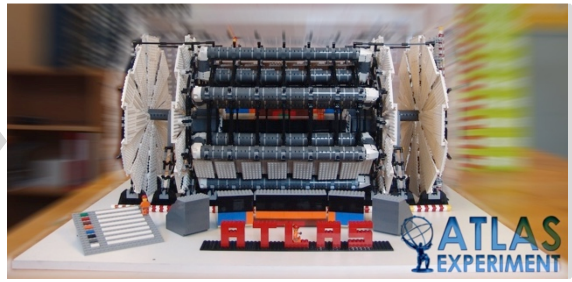
Large Hadron Collider



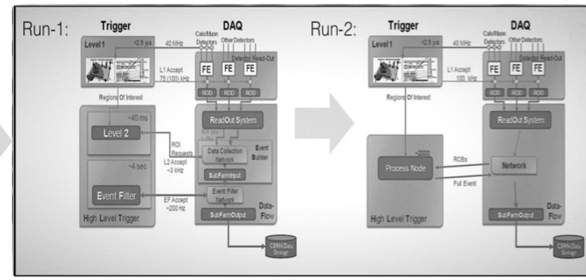
25/50 ns bunch distance

$L_{max} \sim 1 \times 10^{34}$ cm^{-2} s^{-1}

LHC Detector



Trigger & Online monitoring



L1 (HW, up to 100 kHz) + HLT (SW, 1 kHz)

Low-threshold single lepton triggers, single MET and jet triggers, and low-threshold di-object & topological triggers

Calibration & Reconstruction

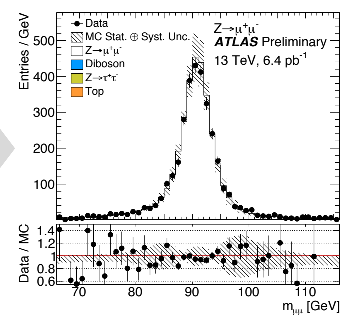
48h calibration & data quality processing, then prompt reconstruction of data in Tier-0

Distributed computing

Production of standardised derived datasets for physics and performance analysis

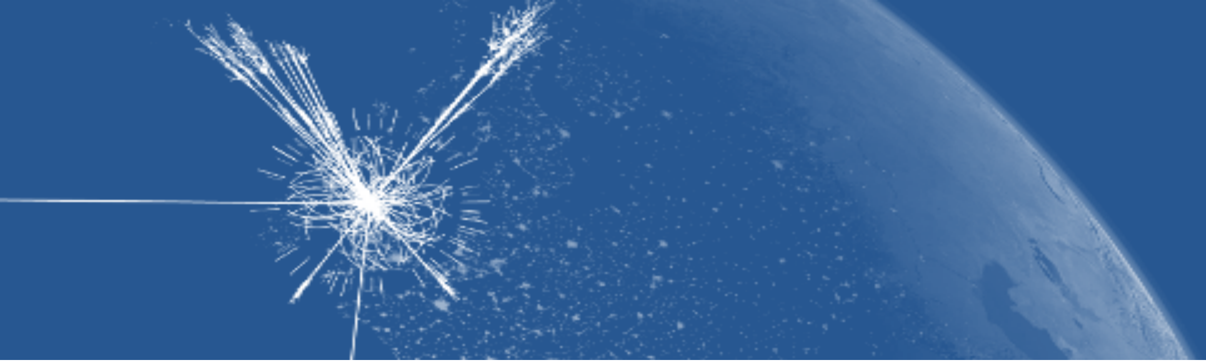
Also: MC production — O(4 billion) 13 TeV events produced per experiment

Analysis



Performance groups provide standard physics objects with calibrations and uncertainties, unified in analysis release

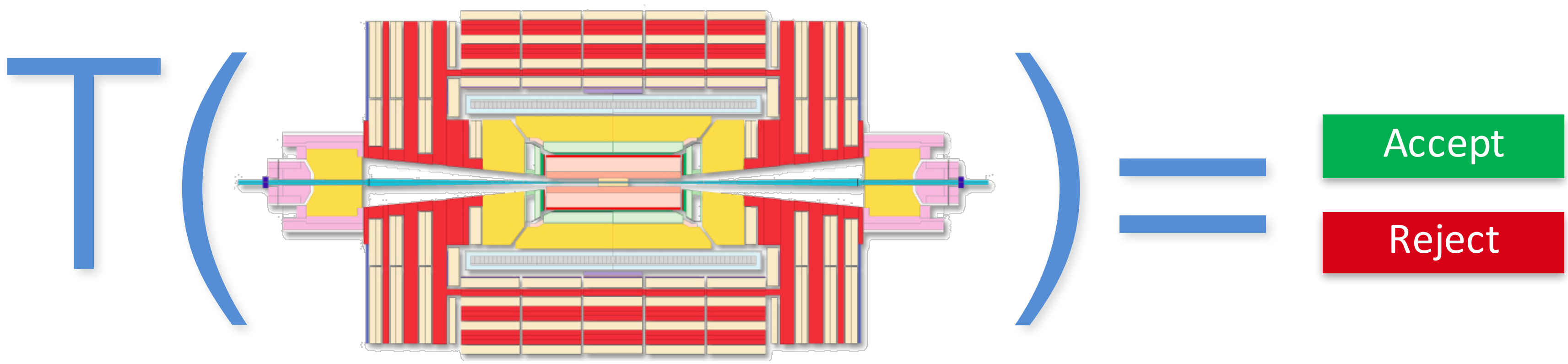
Analysis groups build physics analyses upon this ground work



Trigger

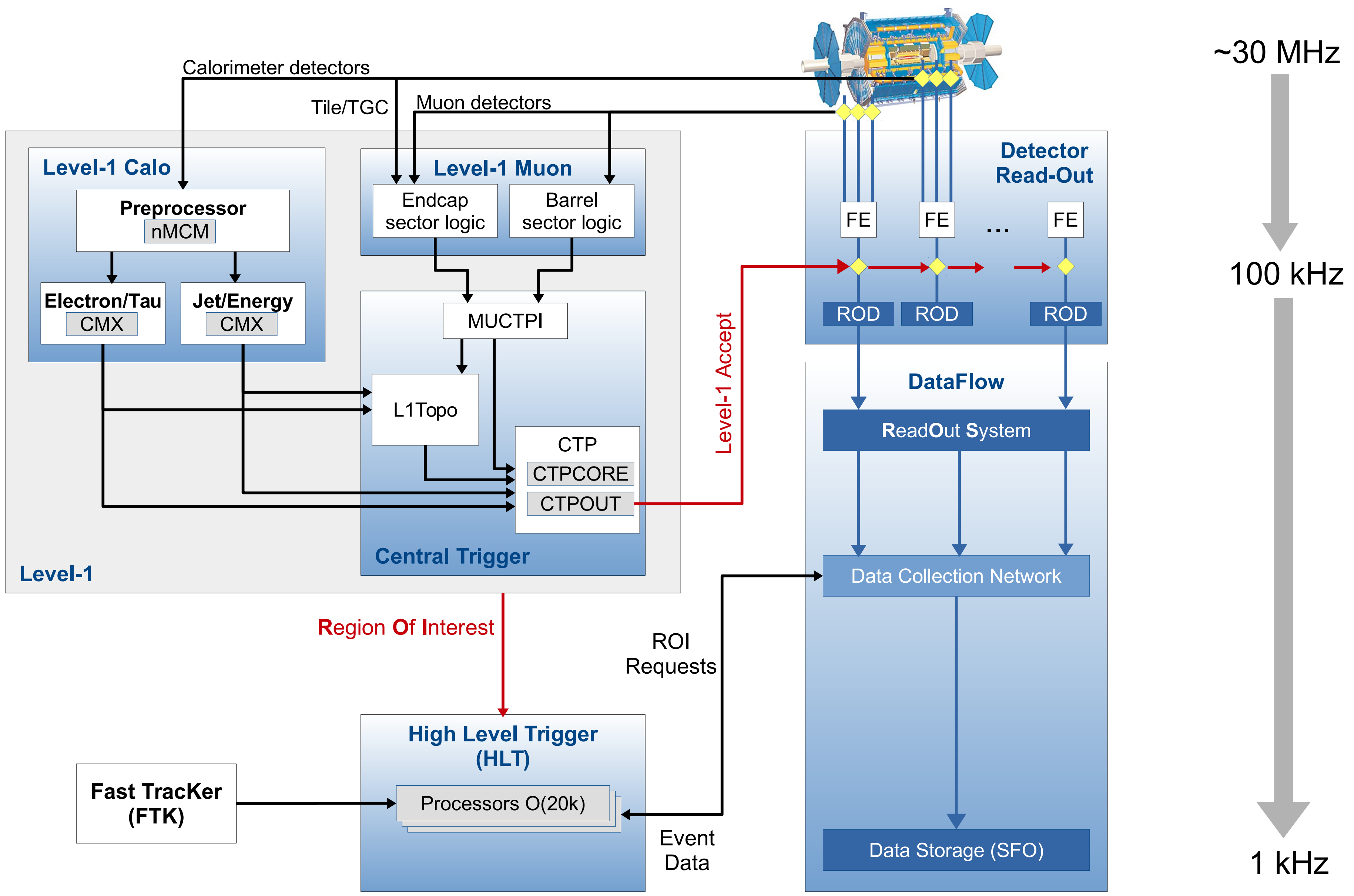
First selection filter: reduce initial event rate by factor of one million for recording.

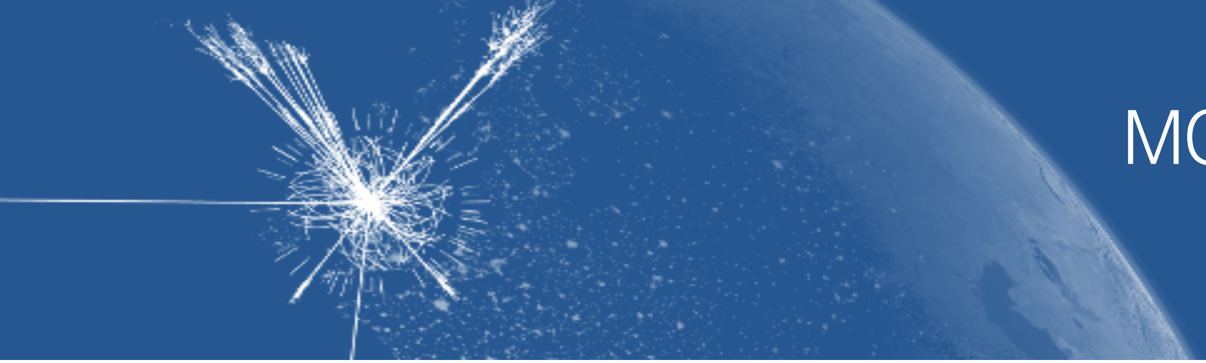
For each **event** the Trigger is a function of the event data, the apparatus, physics channel and parameters



Look at (almost) all bunch crossings, select most interesting one, collect all detector information and store it for offline analysis (do this with a reasonable amount of resources)

Schematic view of the ATLAS trigger / data acquisition system in Run-2





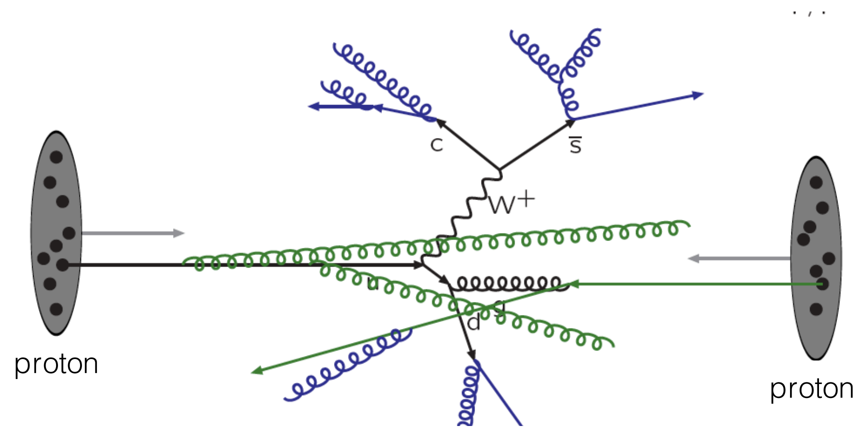
MC event simulation is key for analysis

Event generation → **Detector simulation** → **Digitisation** → **Reconstruction**

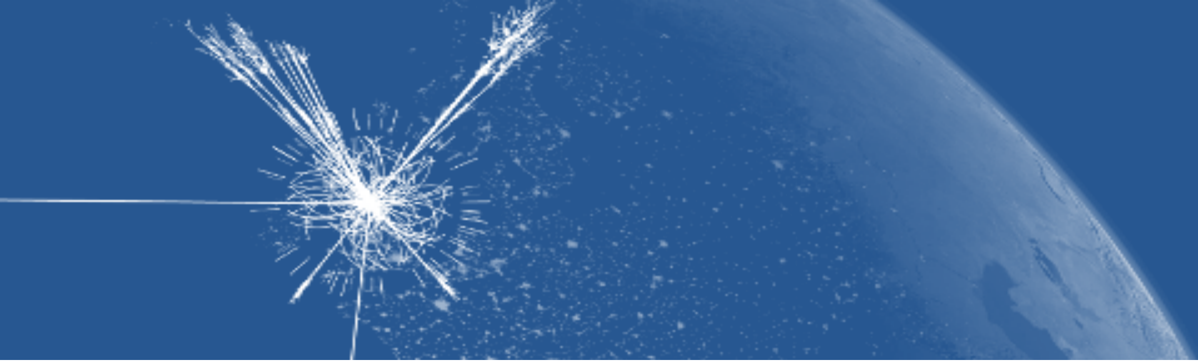
- Event generation: Hard scattering event
- Detector simulation: Geant4 or parameterised
- Digitisation: Mimics detector readout; "Mix-in" pileup events
- Reconstruction: Same as for real data

Physics modelling with event generators gives largest systematic uncertainty in many analyses

- Hard scattering convolved with parton densities
- Decays of the hard subprocesses, initial- and final-state radiation (ISR/FSR), multiple parton interactions (and their ISR/FSR)
- Use matrix elements as much as possible, but cannot fully avoid phenomenological parton showers, hadronisation, and underlying event
- State-of-the-art: NLO ME up to 2 partons, LO ME up to 5 partons, PS matching, non-perturbtive and electroweak corrections sometimes applied
- Fixed-order calculations known to higher order



Rough sketch of proton–proton scattering in LHC



Theoretical cross-sections and uncertainties

Beyond event simulation, theory needed for cross-section and acceptance calculations

- Inclusive jet production is known to NLO QCD (2→2 parton level) + nonperturbative corrections (particle to parton level cross-section ratio) + NLO electroweak corrections (up to 12% at large p_T)
- Inclusive W, Z production is known to full NNLO in QCD + NLO electroweak corrections
- W/Z + jets production known at particle level to NLO up to 2 jets (up to 5 jets for parton level), LO matrix elements for additional partons. Also approximate NNLO calculation for W/Z+1 jet.
- Diboson production, eg, WW: NNLO for quark annihilation, NLO for non-resonant gg → WW
- Higgs production is known to N3LO in QCD + NLO EW (gluon fusion), VH in NNLO QCD and NLO EW, VBF in approx. NNLO QCD and NLO EW, ggZH, $tt/bb_{4FS}H$, tH in NLO QCD
- Inclusive top-antitop production is known to full NNLO QCD + NNLL soft-gluon + EW corrections
- Most other relevant processes known to NLO in QCD, some like single top in approximate NNLO

Theoretical uncertainties usually estimated by adding in quadrature:

- Symmetrised renormalisation and factorisation scale variations (×2, /2), strong coupling and PDF variations (often maximum of uncertainty from main PDF used and comparison with alternative sets)
- In some cases (such as for parton shower and hadronisation) comparison between alternative generators

Theoretical cross-sections and uncertainties

Progress in theoretical calculations — **NNLO revolution**

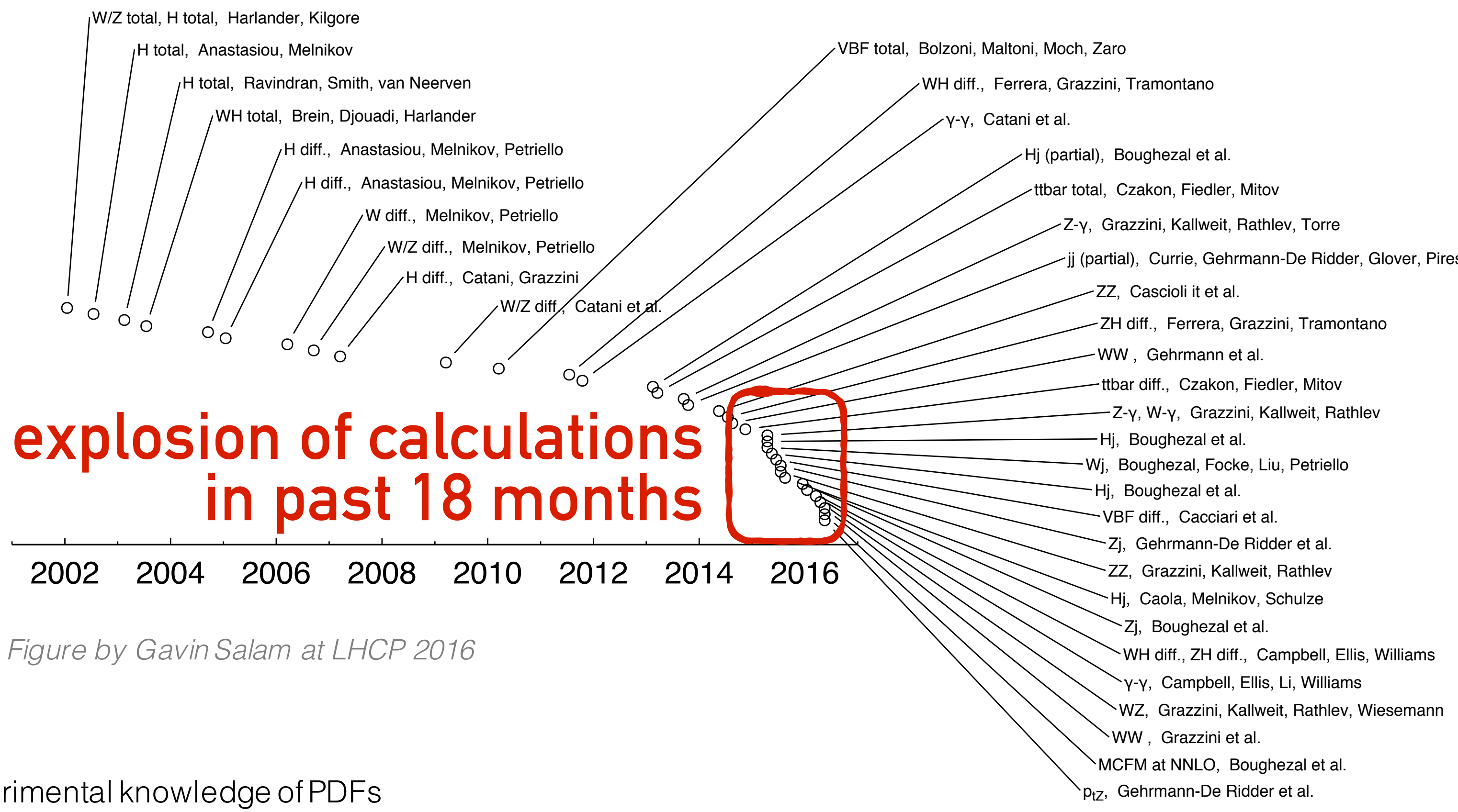
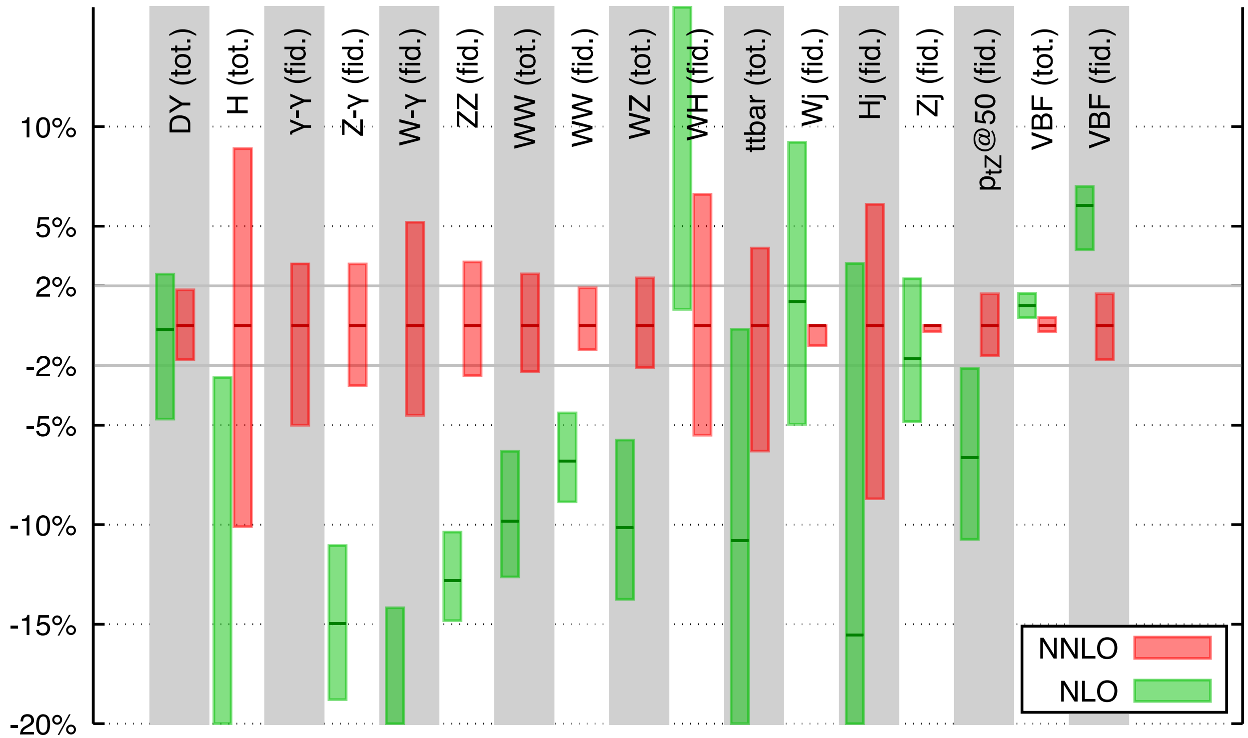


Figure by Gavin Salam at LHCP 2016

Also experimental knowledge of PDFs
limits precision in many LHC analyses !

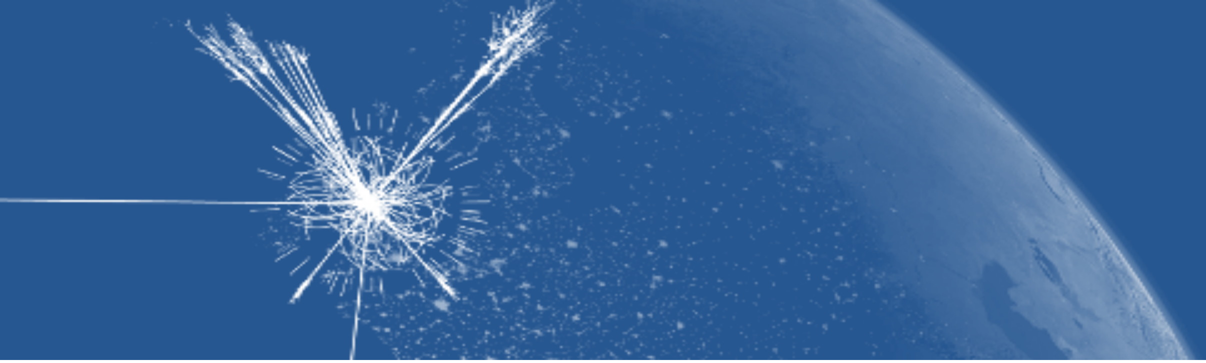
Theoretical cross-sections and uncertainties

Are NLO theoretical uncertainties estimated from scale variations conservative enough ?



Also experimental knowledge of PDFs is limiting precision in many LHC analyses !

For many processes NNLO scale band is ~±2%
But only in 3/17 cases is NNLO (central) within NLO scale band…



Testing theory via unfolded measurements

Unfold measured distributions from detector effects (resolution, reconstruction and identification efficiencies) to particle level fiducial cross section (least theory bias)

- Implement analysis in "Rivet" which allows to consistently apply cuts to HepMC formatted events

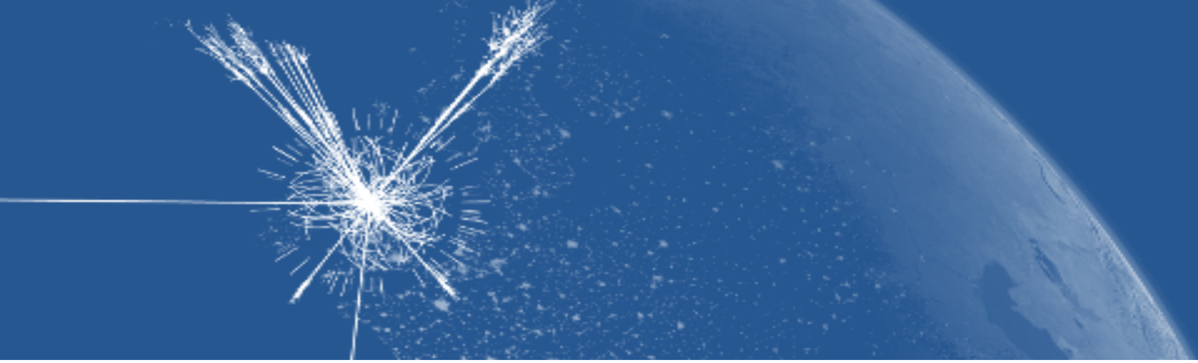
Main experimental measurement

$$\sigma^{tot}_{pp\to X} = \frac{1}{A_X} \boxed{\sigma^{fid}_{pp\to X}} = \frac{1}{A_X}\left(\frac{N_{\text{obs}} - N_{\text{background}}}{L \cdot C_X}\right)$$

A_X : acceptance factor= $N_{\text{gen,fiducial}} / N_{\text{gen}}$

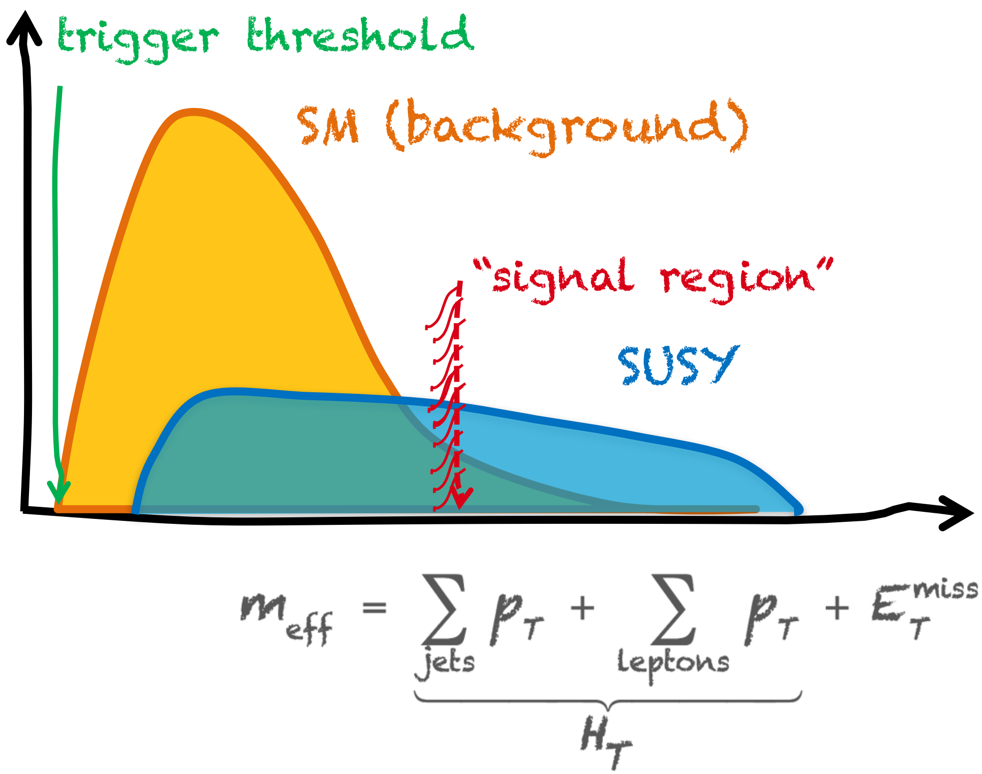
C_X : correction factor = $N_{\text{reco,selected}} / N_{\text{gen,fiducial}}$

- Acceptance factors are computed entirely from theory (use best available fixed order calculation)
- Correction factor depends on experiment, usually needs MC generator
- Differential cross section corresponds to binned fiducial cross section; requires unfolding due to bin-to-bin correlations. Mathematically unstable procedure needing regularisation



Background determination

Example SUSY search: analyses look for tails in distributions of observables sensitive to high produced event mass: m_{eff}



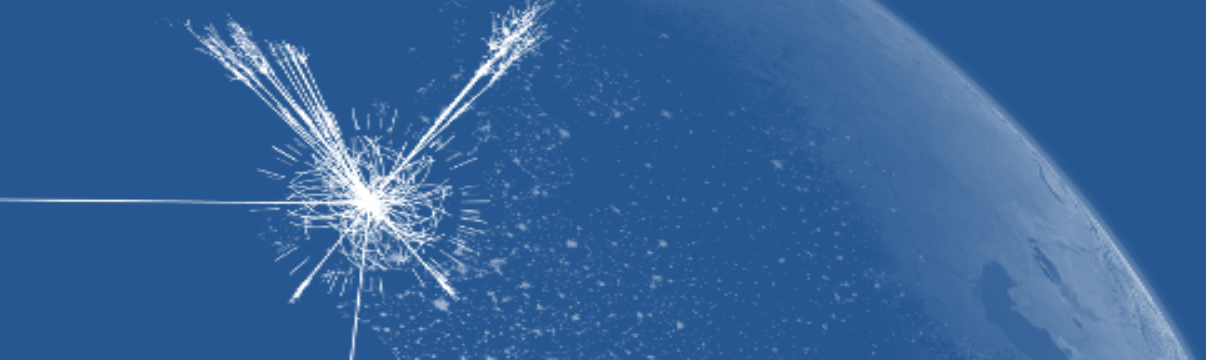
Requires **reliable** estimate of SM backgrounds in signal region

Main background sources:

- $tt \rightarrow W(\rightarrow \ell(\tau)\,\nu)b + W(\rightarrow qq)\,b$
- $W(\rightarrow \ell\,\nu)$ + jets
- $Z(\rightarrow \nu\,\nu)$ + jets
- WW, WZ, ZZ, $tt + W/Z$ (+ jets)
- QCD multijets, fake objects, …

Several estimation methods:

- MC simulation
- Data control regions + MC transfer
- Fully data-driven (sidebands, ABCD method, etc.)

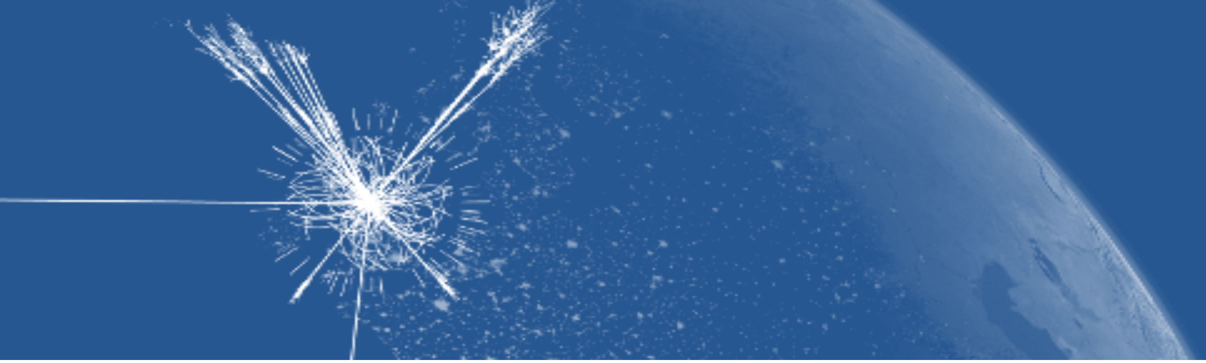


Basic physics objects

All LHC physics analyses use basic "physics objects" :

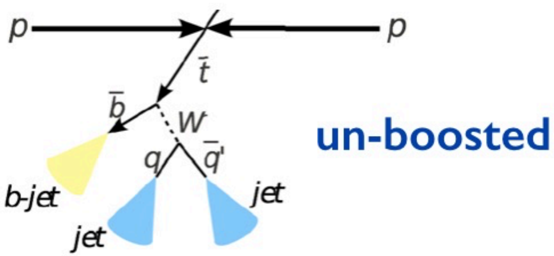
Object	Reconstructed how?	Calibrated how?
Tracks & vertices	Inner tracking systems	Hit residuals (alignment), hadrons, MC
Electron / photon	EM calorimeter cluster, track(s)	Z, $J/\psi \rightarrow ee(\gamma)$, $W \rightarrow e\nu$, π^0, MC(γ)
Muon	Inner tracker and muon system combined	Z, Υ, $J/\psi \rightarrow \mu\mu$
Tau (hadronic decay)	Inner tracker and EM & had calorimeters*	$Z \rightarrow \tau\tau$, E_{calo}/p
Jet	Inner tracker and EM & had calorimeters*	Di-/multijet balance, γ + jet, Z + jet
Missing E_T	Reconstructed objects + "soft" objects*	$Z \rightarrow \mu\mu$ (also ee) for soft term
***b*-jets (*c*-jets)**	Inner tracker (+ jet reconstruction)	Top pairs, muons, …, MC(high p_T)

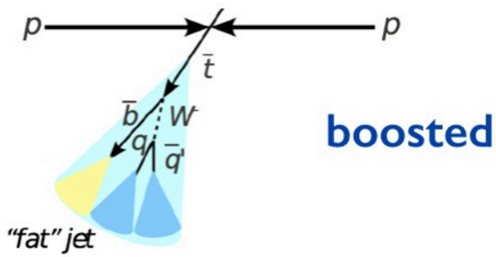
*CMS uses event-wise particle flow



Reconstructing boosted particles

LHC can produce highly boosted W / Z / H bosons or top quarks so that their decays into jets can be merged





$\Delta R \sim 2m / p_T$

Hence, for $X \to WW$ and m_X = 800 GeV (m_W = 80 GeV & p_T = 400 GeV) : $\Delta R \sim 0.4$

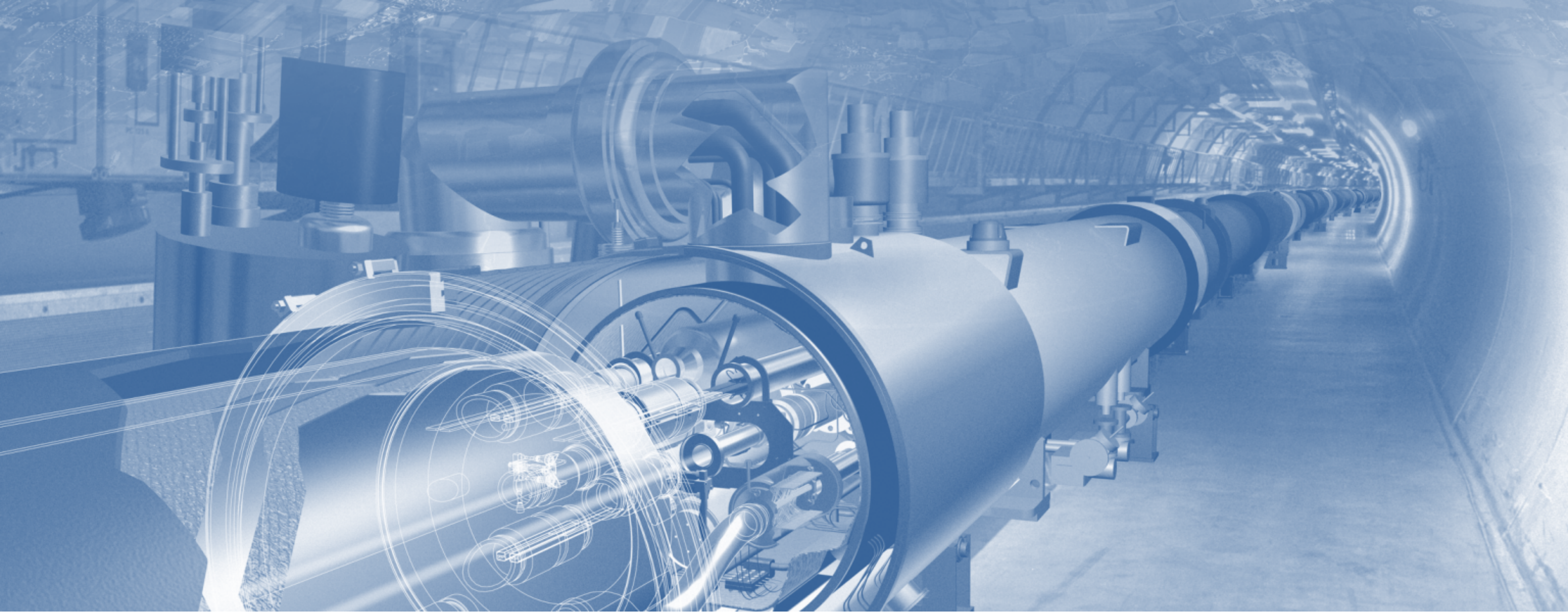
- Reconstruction as "fat jets" ($R \sim 1.2$, compared to standard $R = 0.4$ anti-k_t jets)
- Strategies to reconstruct substructure in fat jet (eg, jet mass), and to correct for pileup effects
- Boosted signatures (BS) occur in high-mass new physics searches
- BS can have better signal to background (multijet) ratio (eg, in $H \to bb$ / $\tau\tau$)
- BS via ISR jet can be used to render invisible modes accessible (eg, WIMPs, compressed spectra)

Systematic uncertainties

The **evil** in every measurement

- Well designed experiments minimise as much as possible systematic uncertainties (full coverage, measurement precision, homogeneity and linearity, λ depth, longevity of components, etc)
- Understanding, estimating and reducing remaining systematic uncertainties is often the main analysis challenge
- A high quality analysis stands out by its thoroughness on all relevant sources of systematic uncertainty
- It is important to distinguish relevant from irrelevant sources; in doubt → relevant
- For many uncertainty sources, in particular theoretical ones, estimating a “one-sigma” error is very difficult, or simply impossible → be conservative !

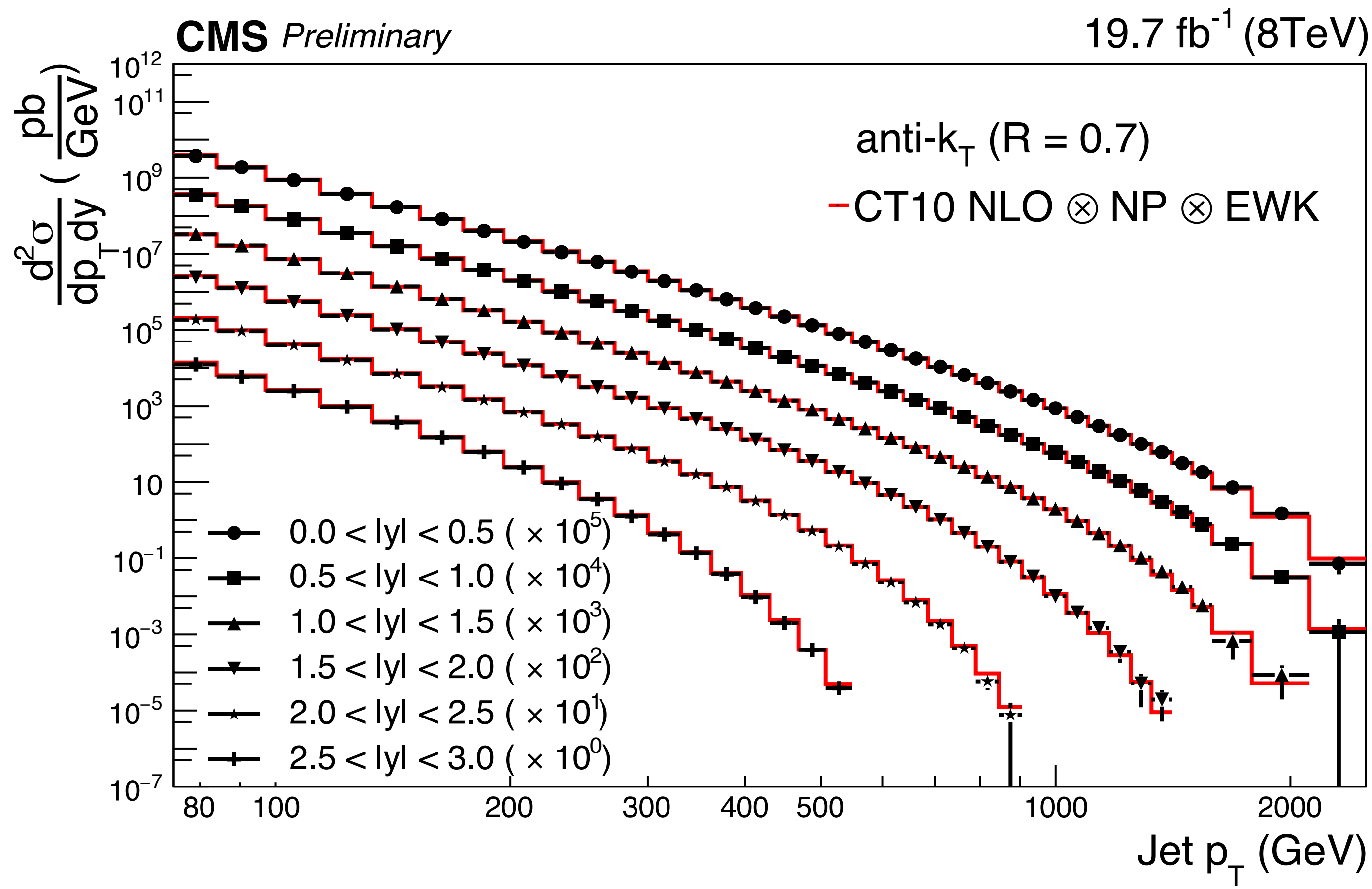
(Reasonably) conservative uncertainty estimates are a must! It is of <u>no use</u> for science to make over-aggressive statements that one cannot fully trust



The LHC Run-1: 7 & 8 TeV pp, 5 & 20 fb^{-1}

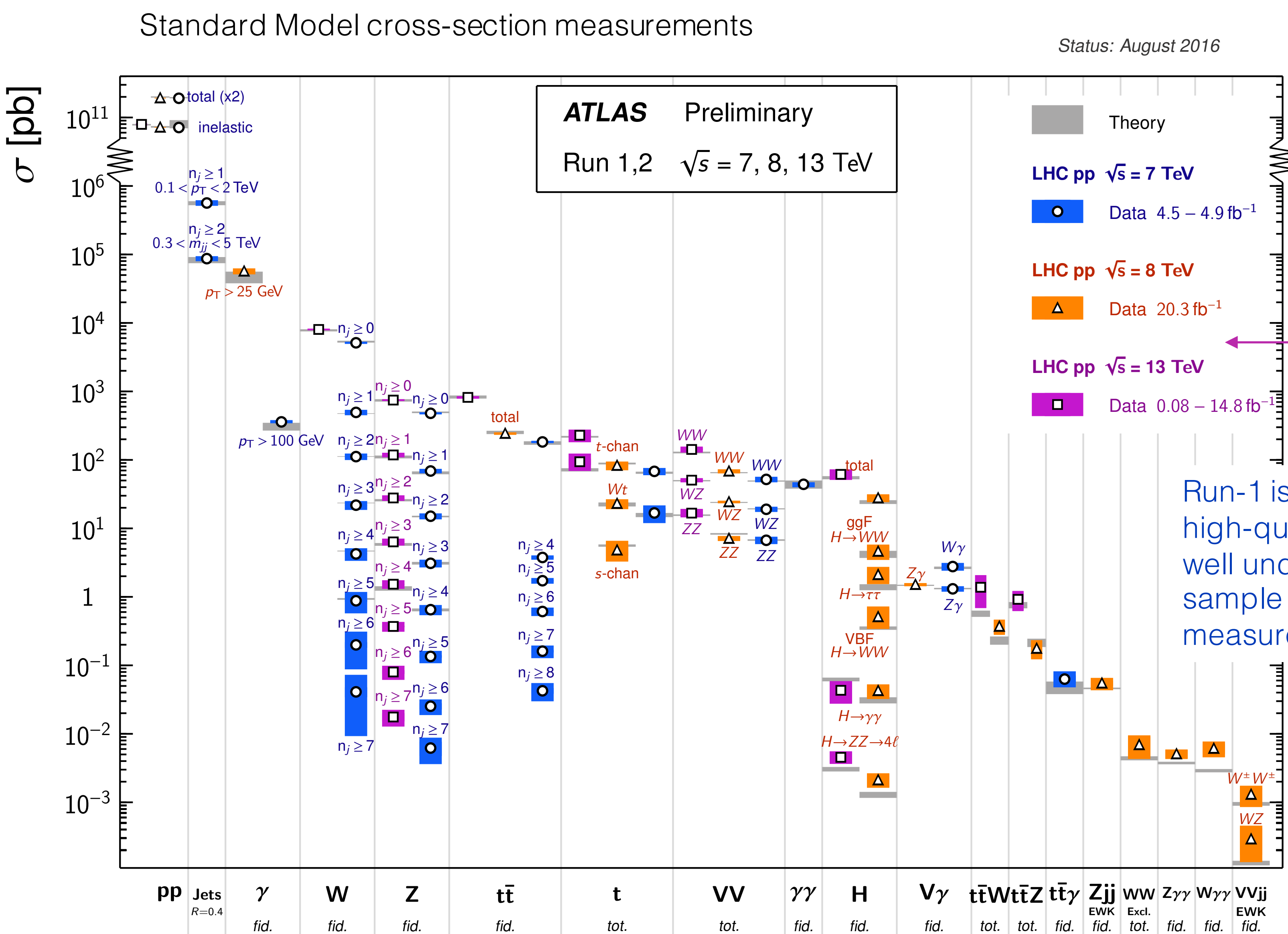
A brief history of selected highlights

Jet production [CMS-PAS-SMP-14-001]



Precision measurements & theory developments (includes nonperturbative and electroweak corrections) → new quality of QCD tests at hadron colliders

Harvest of Run-1 results (> 500 papers / exp) confirming predictive power of SM



Note !

Run-1 is not over yet: high-quality, extremely well understood data sample for precision measurements

Run-1 allowed critical first electroweak studies

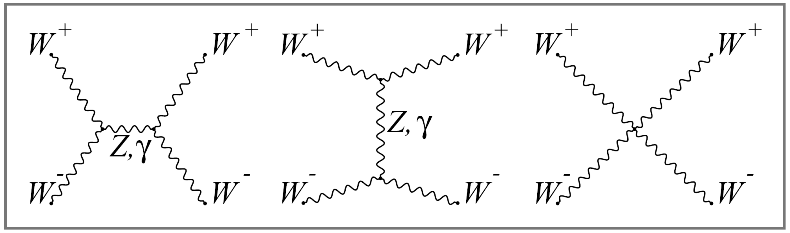
Higgs boson acts as "moderator" to unitarise high-energy longitudinal vector boson scattering

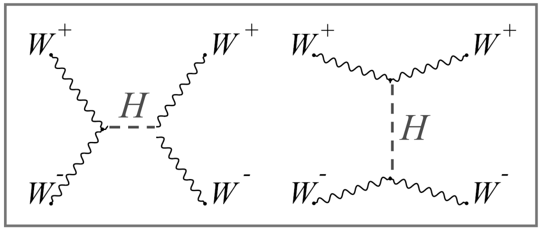
If only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering **violates unitarity**

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

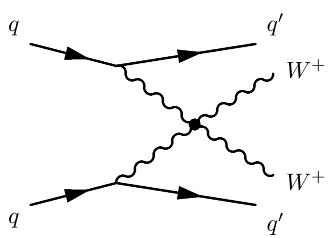
Higgs boson restores unitarity of total amplitude:

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

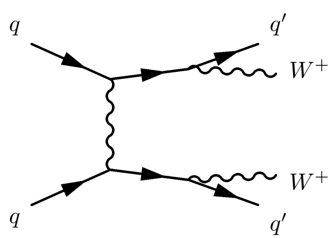




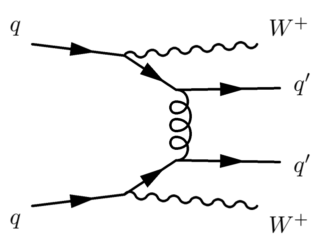
m_H must not be too large (which is fulfilled)



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

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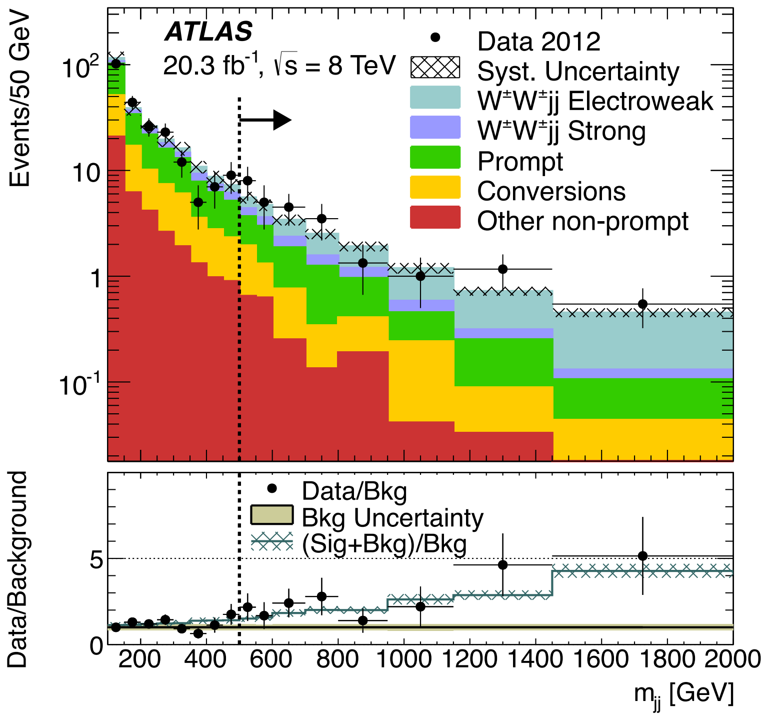
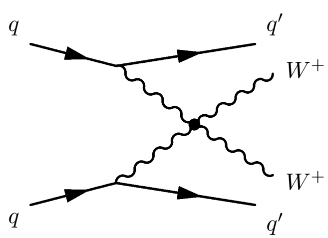
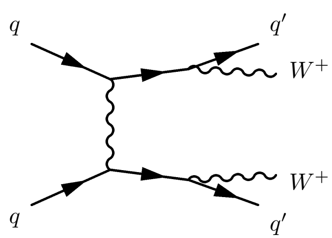
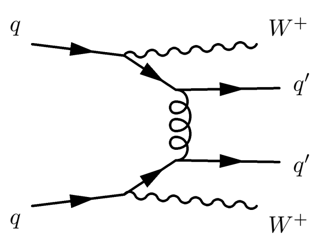




EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

Top quark production has been studies with unprecedented experimental precision

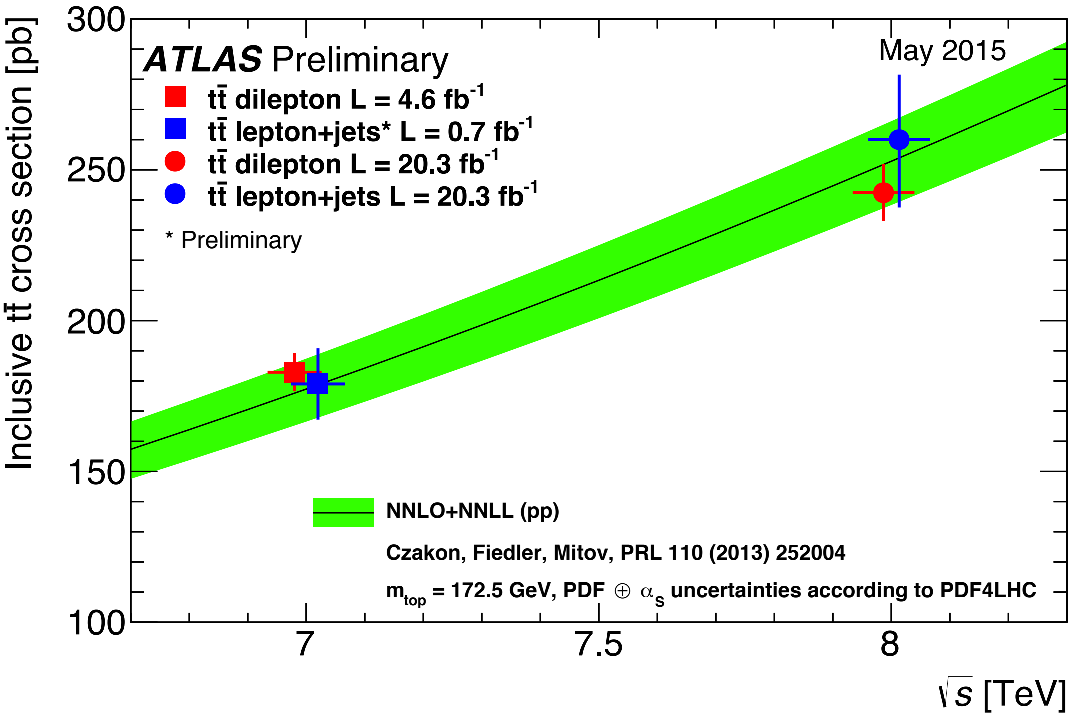
tt cross-section measurement

[ATLAS, EPJ C 74, 3109 (2014)]

Precision test of NNLO QCD, used to derive the top mass and new physics limits

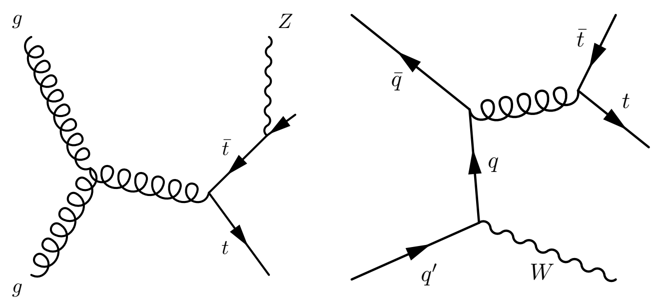
Many top properties measured

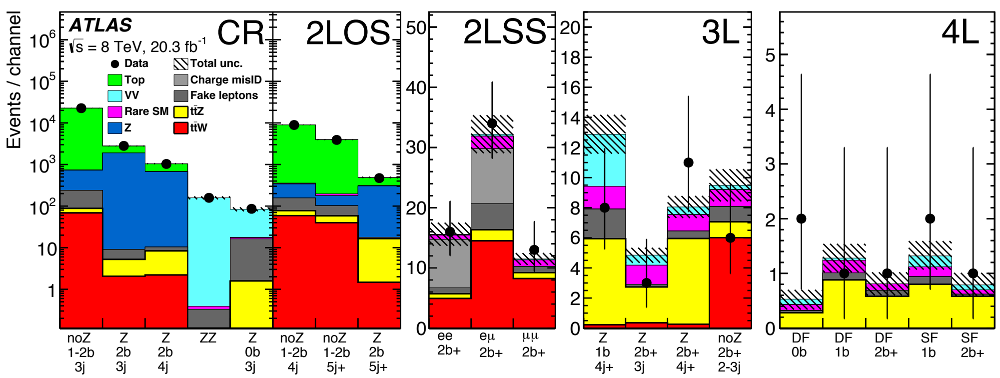
Luminosity and centre-of-mass energy open phase space to observe rare *tt* + vector-boson production



tt+W/Z: 7.1σ combined significance

[ATLAS 1509.05276]





Electoweak single top production

Top cross-sections significantly enhanced at LHC wrt Tevatron: at 8 TeV, factors of 42 (t-channel), 31 ($t\bar{t}$), but only 5 for s-channel
(ie, worse S/B at LHC)

t-channel already measured differentially

[ATLAS, 1406.7844, CMS 1511.02138]

Wt channel observed with 7.7σ

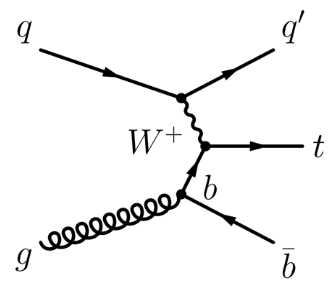
[ATLAS, 1510.03752, CMS 1401.2942]

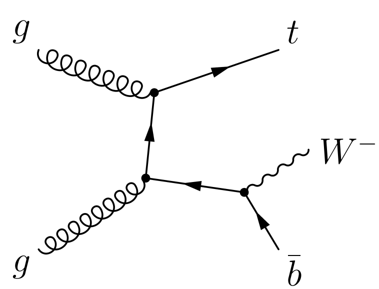
s-channel process first observed at Tevatron with 6.3σ in agreement with SM prediction

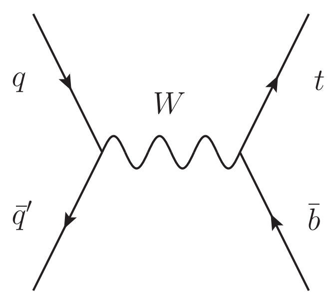
[CDF & D0, 1402.5126]

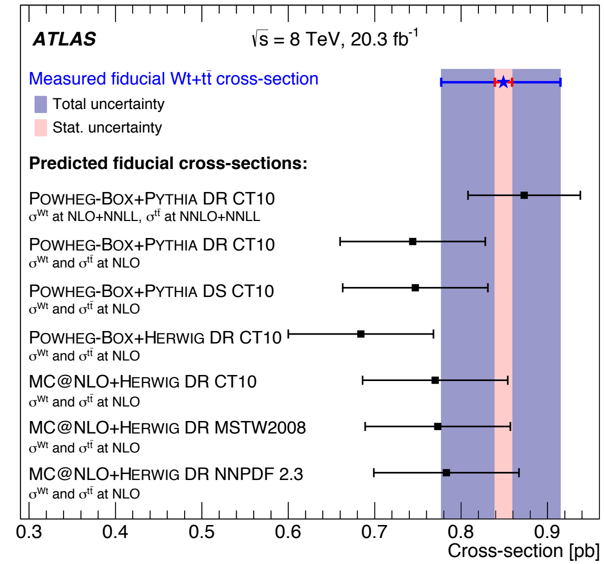
ATLAS reported 3.2σ (3.9σ exp.) evidence in agreement with SM

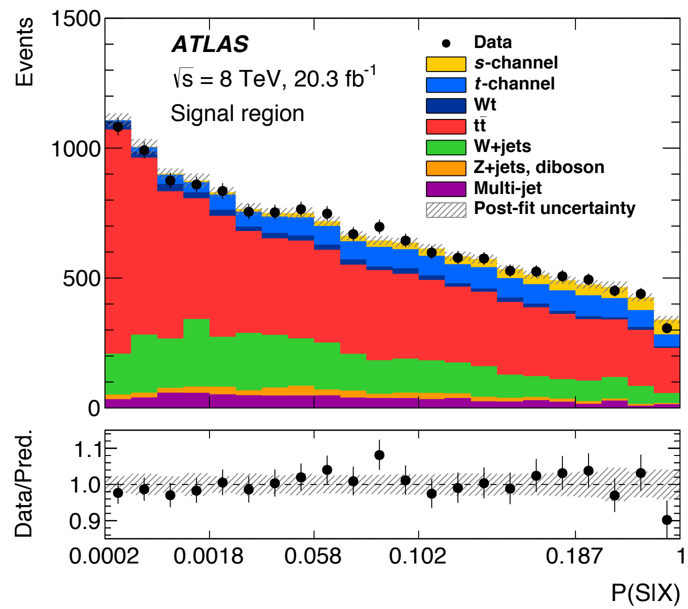
[ATLAS, 1511.05980]









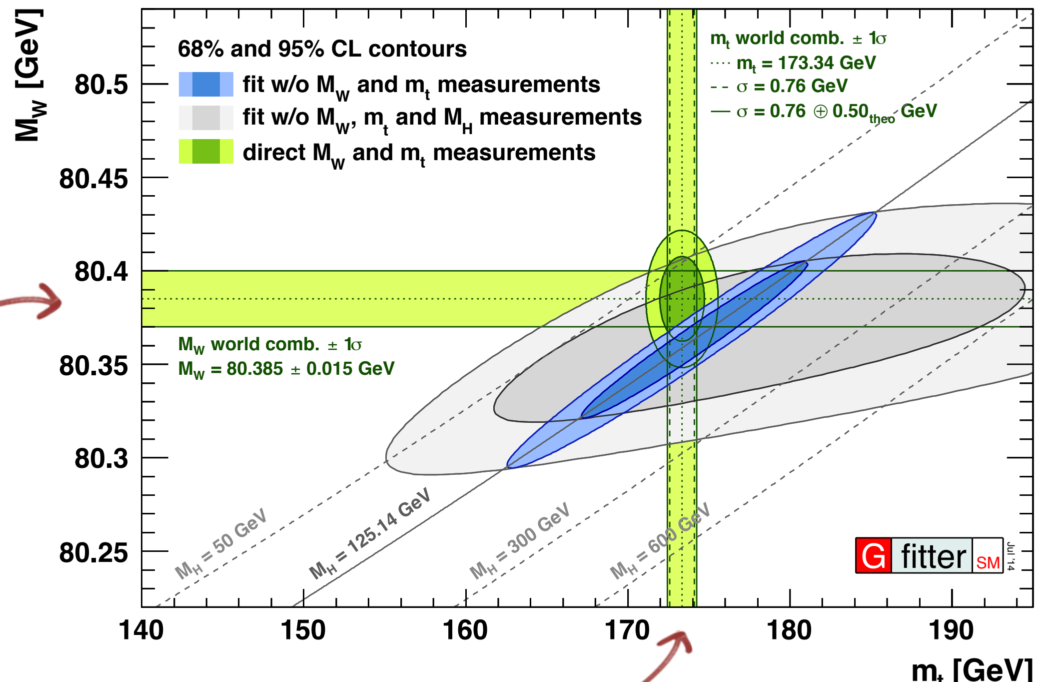


No LHC result yet

World average value dominated by Tevatron measurements : 80.387 ± 0.016 GeV

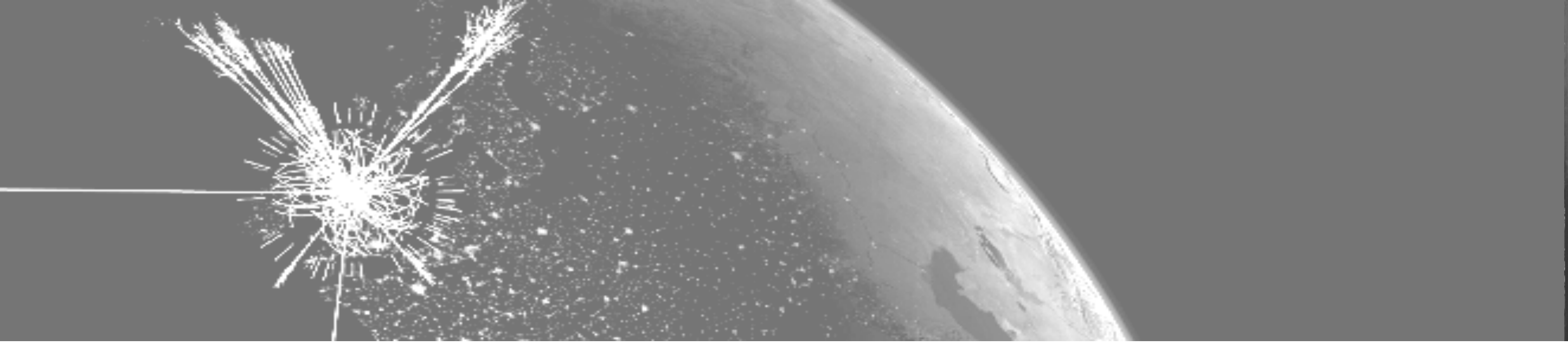
[CDF & D0, 1204.0042]

No W mass measurement from LHC yet

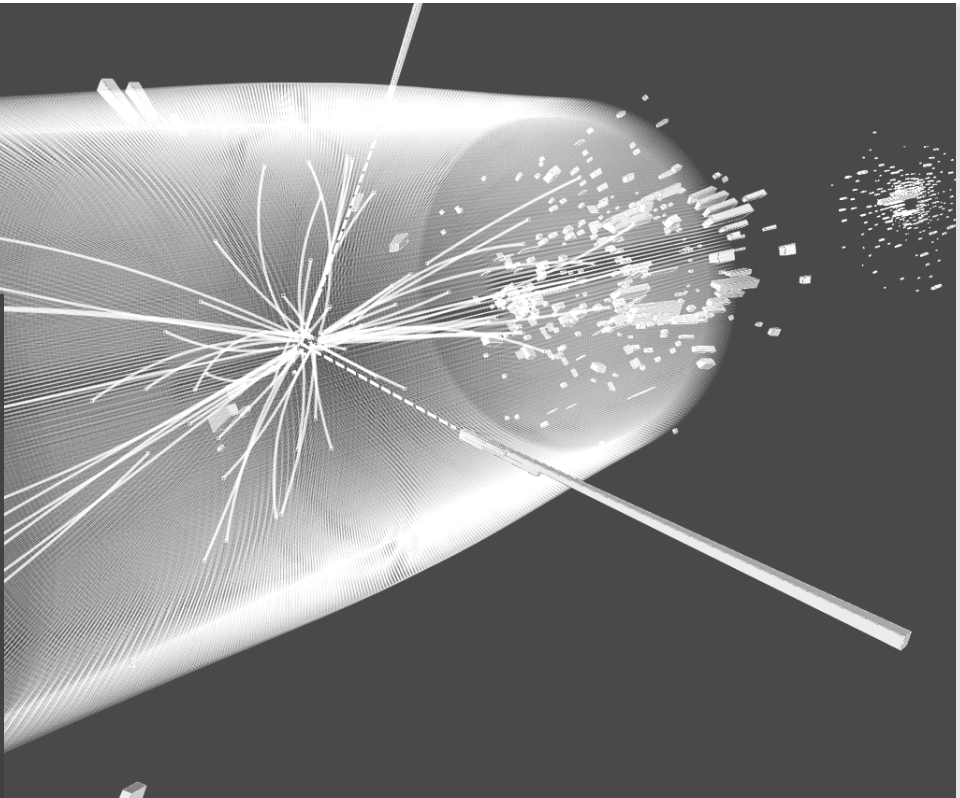


Global electroweak fit

Competitive top mass results from the LHC



Higgs Boson — Run-1 Masterpiece



The Higgs boson had been vainly searched for at many accelerators

Best non-LHC 95% CL limits from LEP (CERN, 1989—2000) and Tevatron (Fermilab, 1990—2011):

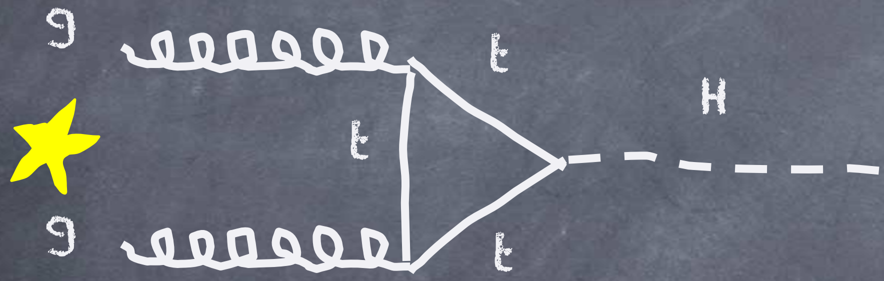
$m_H > 114$ GeV

147 GeV $< m_H >$ 179 GeV

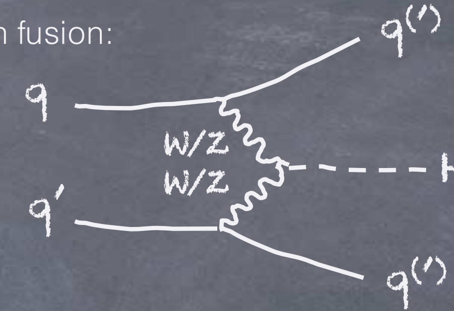
EW fit: $m_H < 153$ GeV

At the LHC, the Higgs boson is dominantly produced via gluon fusion $\sigma_{H,total}$ ~22 pb at 8 TeV for m_H = 125 GeV

Cross section steeply falling with Higgs mass

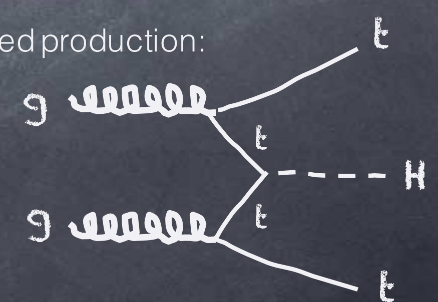


Vector boson fusion:



Higgs-strahlung:

"ttH" associated production:



Total production of ~470 thousand SM Higgs bosons of 125 GeV in 2012 in each ATLAS and CMS

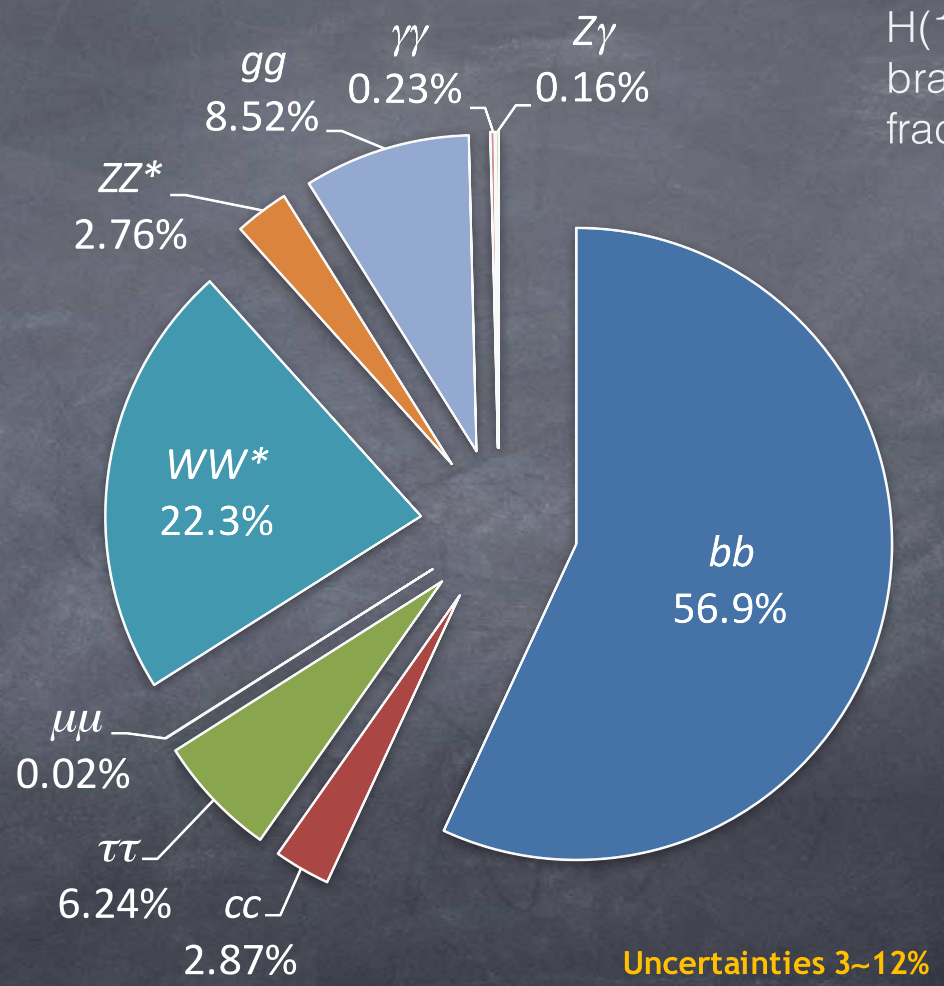
Higgs boson decay

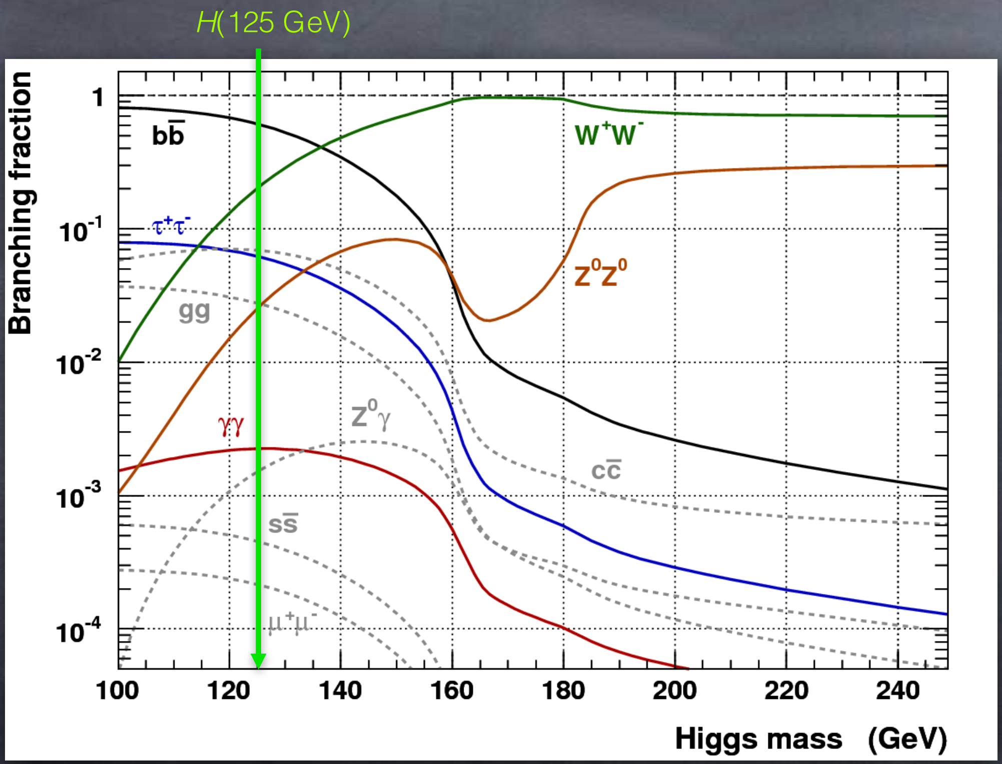
Because of the coupling to the mass of the decay particles:

… the Higgs will decay with preference to the heaviest particles allowed

… the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, *W*)

H(125 GeV) branching fractions:





For medium to heavy Higgs:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For light Higgs:

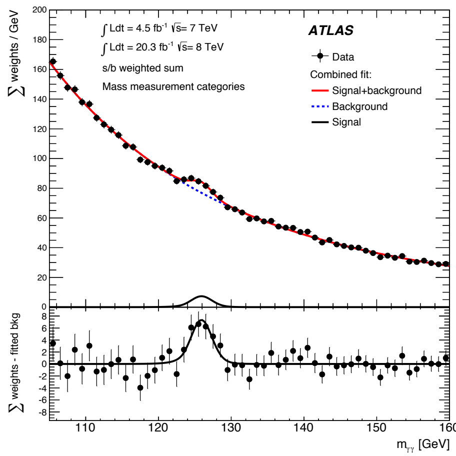
- Lepton final states via WW^*, ZZ^*
- Di-photon final state
- Di-tau final state

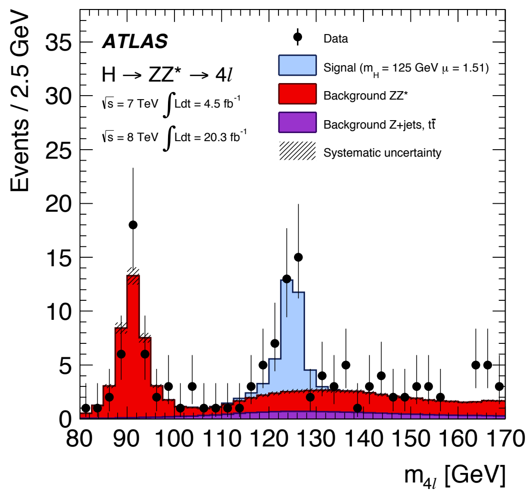
The dominant $H \to bb$ mode is only exploitable in association with W/Z or tt, also with strong Higgs boost

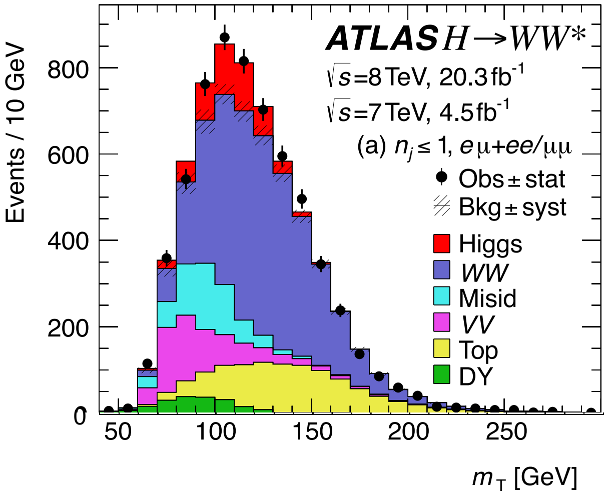
Associated leptons provide trigger signal as they help to reduce huge QCD background, $\sigma(bb) \sim O(100\ \mu b)$

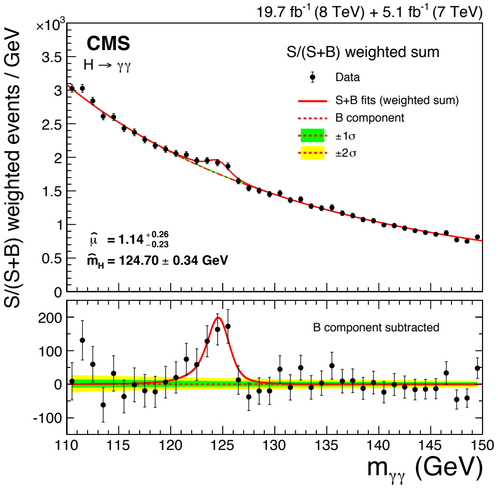
No doubt on H_{125} discovery in the bosonic channels

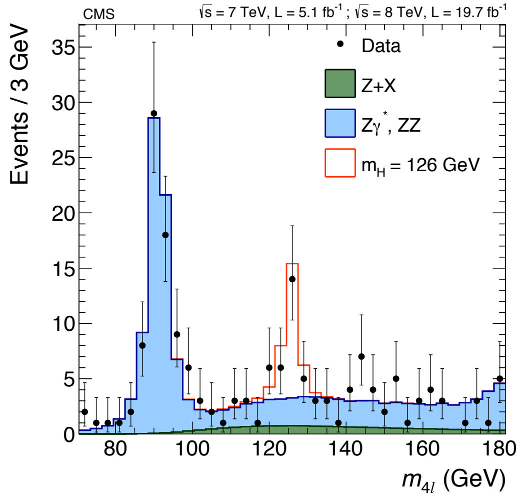
$H \to \gamma\gamma$	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to 2\ell 2\nu$

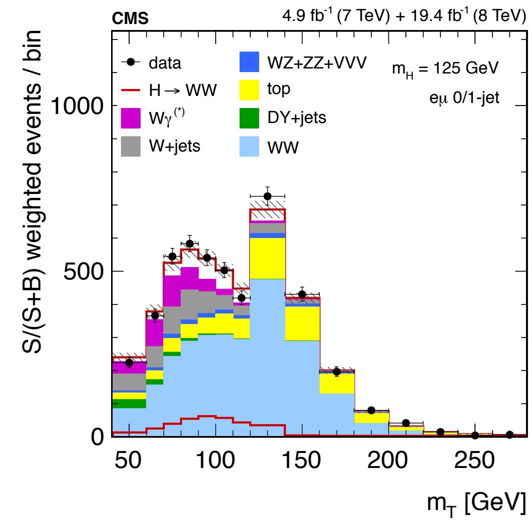












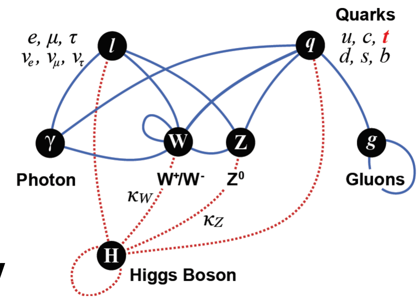
Very different experimental challenges in each of these discovery channels.
All analyses significantly improved since July 2012

Combined Higgs analysis and a flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

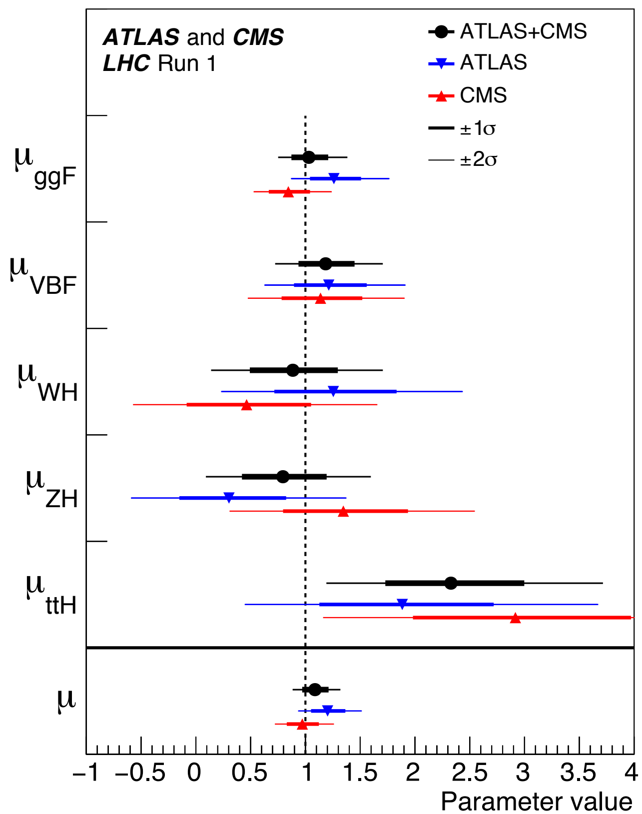
$m_H = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}$ **GeV**



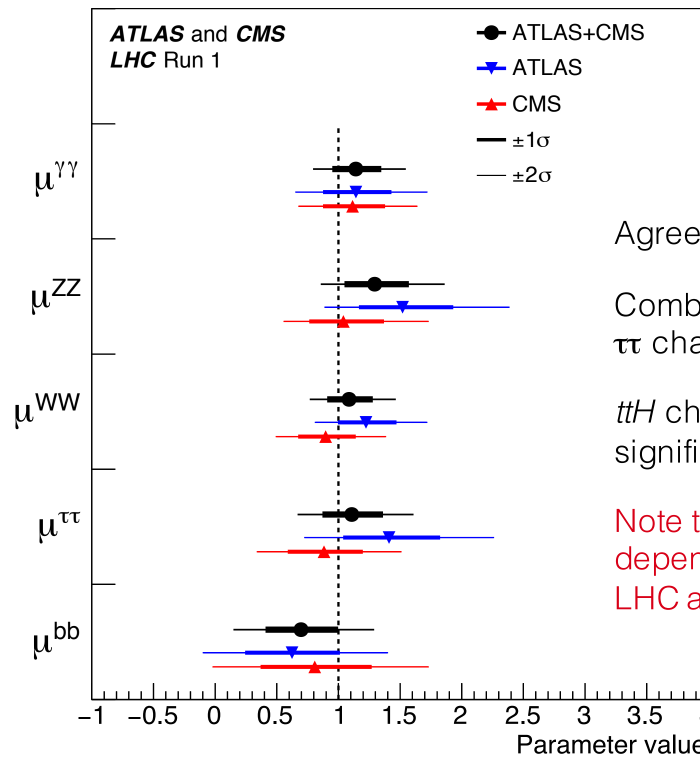
***Also*:**

- Differential cross-section measurements
- Limit on Γ_H from off-shell to on-shell coupling ratio
- Limit on invisible Higgs branching ratio of < 25% [1509.00672, 1404.1344]
- Constraints on anomalous off-shell coupling or spin/CP, forbidden decays (FCNC) and other scalar particles (BSM Higgs)

Higgs production processes



Higgs decay processes



Agreement among experiments

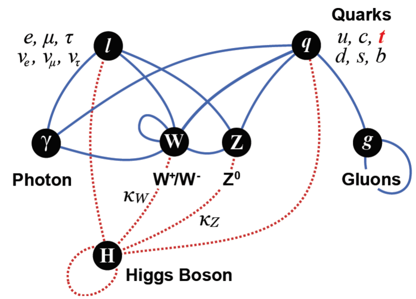
Combined observation of $H \rightarrow \tau\tau$ channel and VBF production

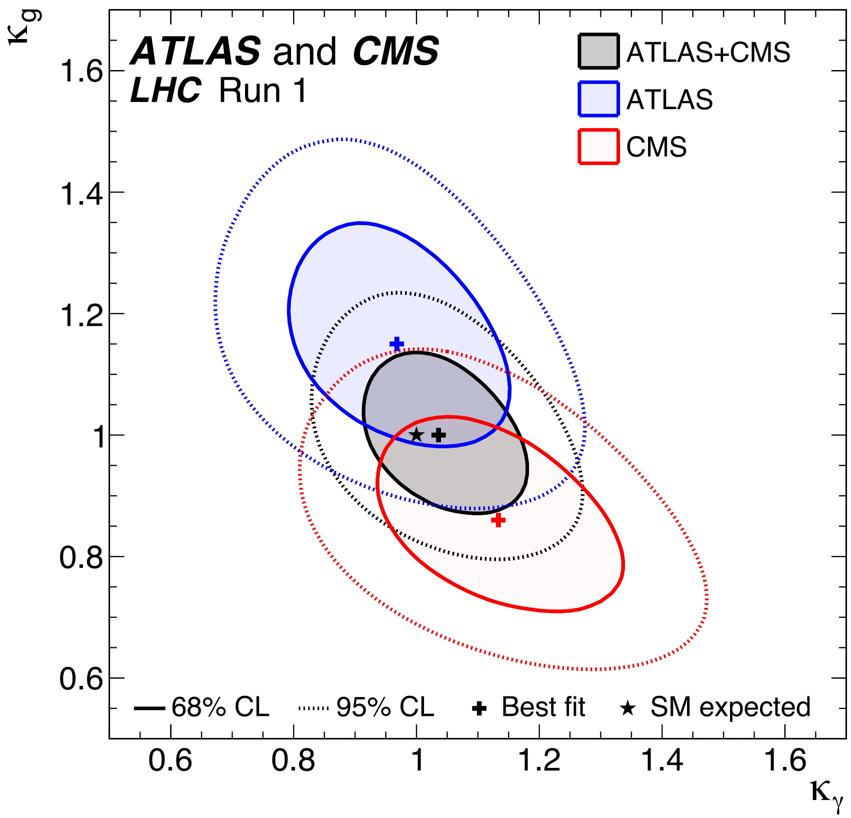
ttH channel a bit large: 4.4σ significance (2.0 exp), μ = 2.3

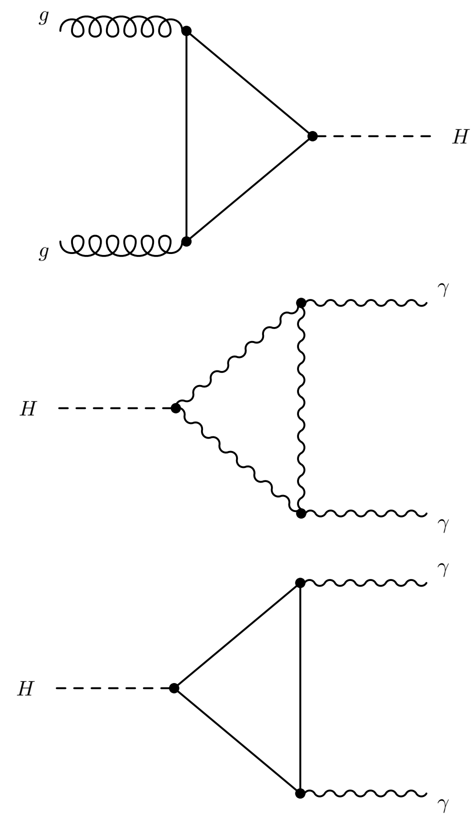
Note that the least model-dependent observables at the LHC are **ratios of couplings**

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]







Couplings to massless particles mediated by loops involving heavy particles

Powerful test for new physics (eg, excludes SM-like heavy 4th fermion generation)

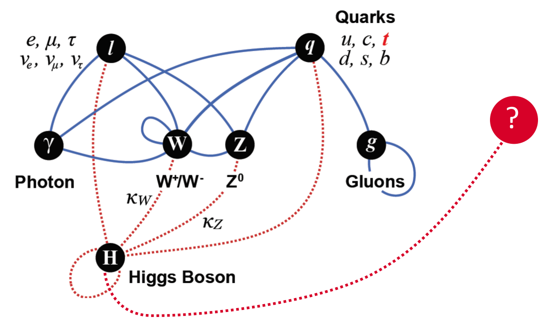
Higgs as BSM portal

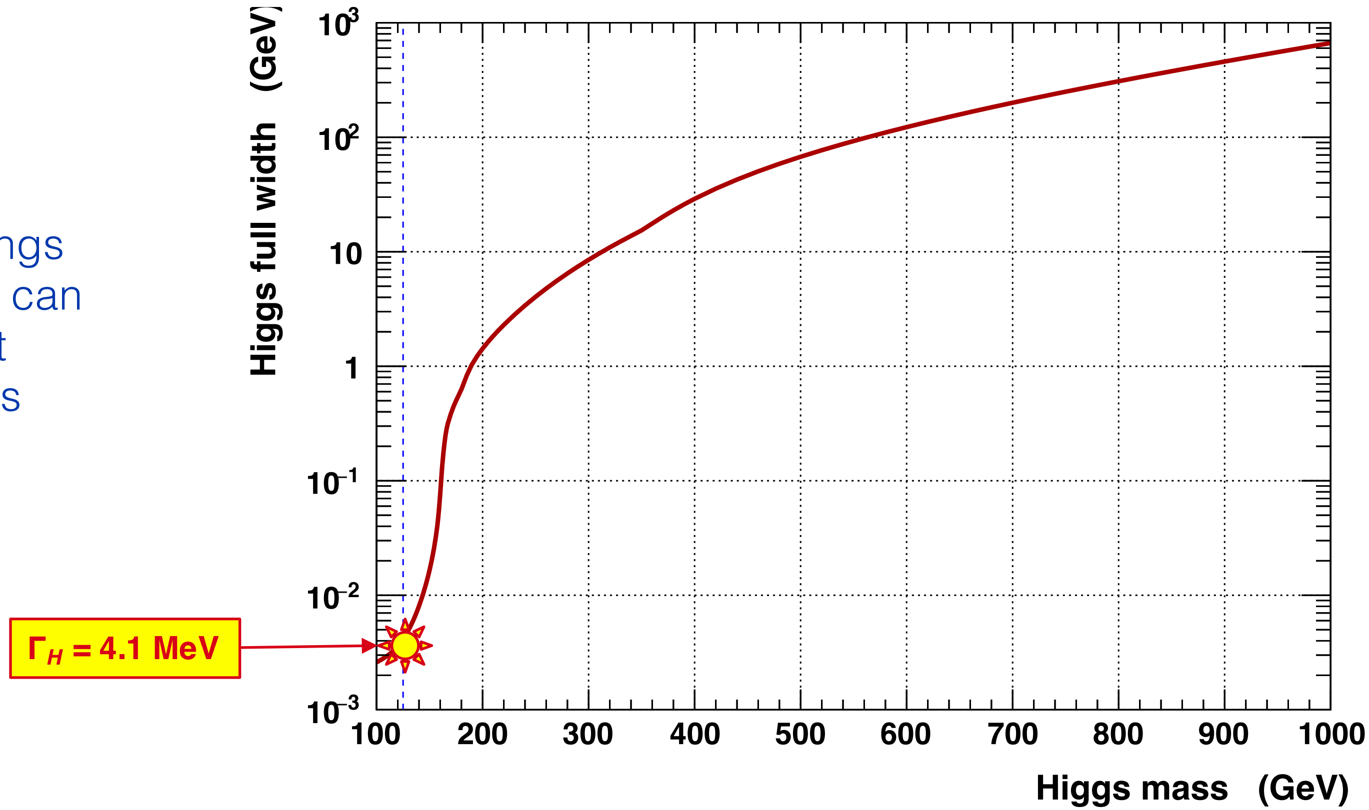
Higgs is narrow: 4.1 MeV

For comparison:

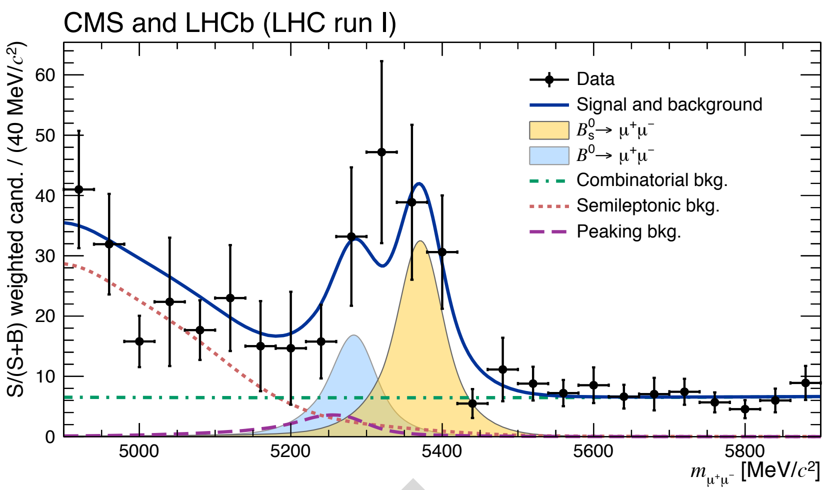
Γ_W = 2.1 GeV
Γ_Z = 2.5 GeV
Γ_{top} = 1.3 GeV

Even small couplings to new light states can measurably distort branching fractions





Flurry of results from LHCb [~300 papers to date]



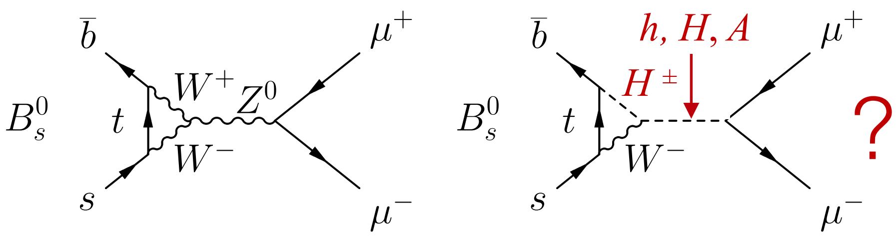
CMS & LHCb: observation of $B_s \to \mu\mu$

[Nat. 522 (2015) 68]

ATLAS Run-1 result ~2σ below SM

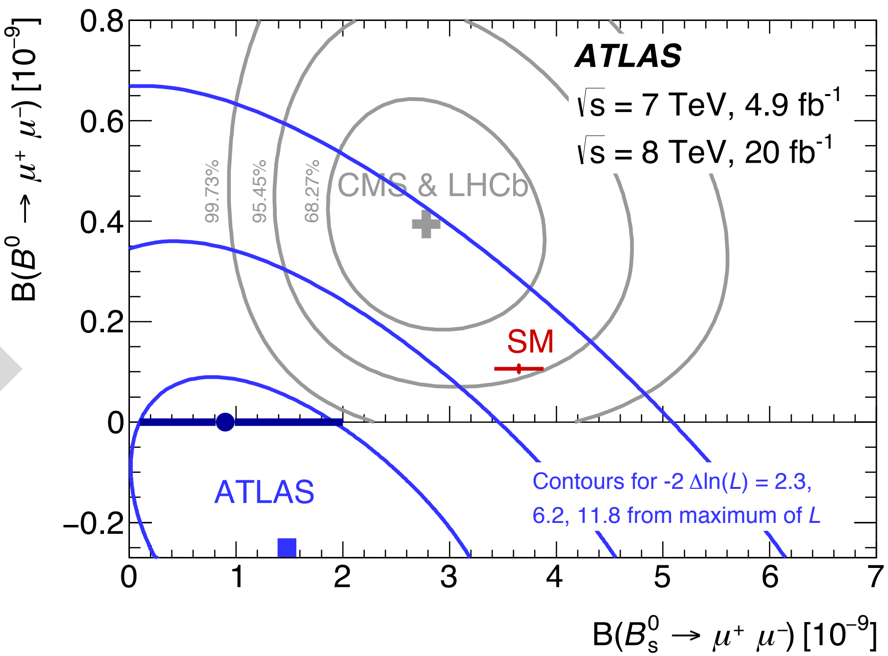
[1604.04263]

Does the Higgs boson has brothers and sisters?



$B_s \to \mu\mu$ is loop process (no tree-level FCNC) that is in addition CKM & helicity suppressed

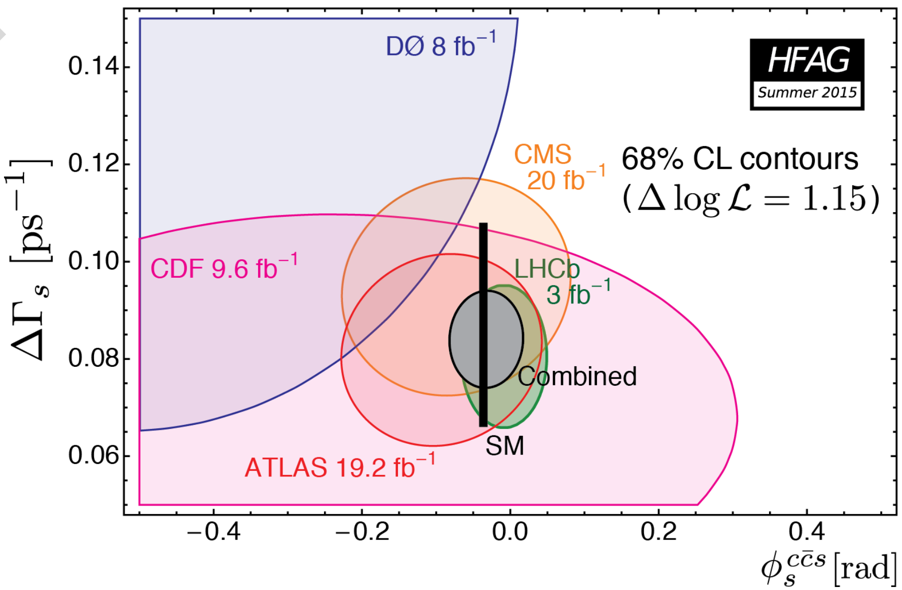
SM: $3.7 \pm 0.2 \times 10^{-9}$



Flurry of results from LHCb [~300 papers to date]

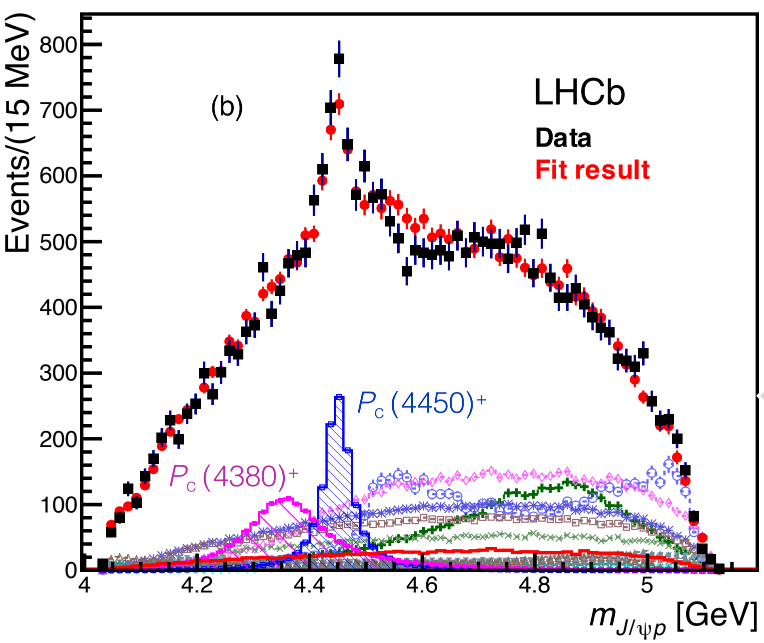
Precision measurement of ϕ_s

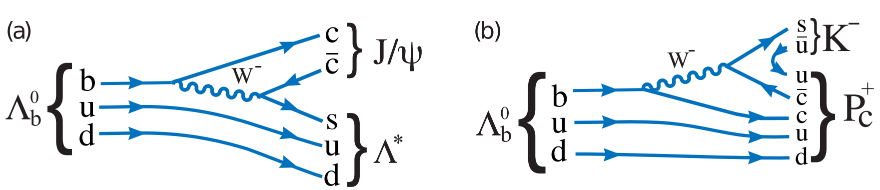
[PRL 114, 041801 (2015): $\phi_s = -0.010 \pm 0.039$]



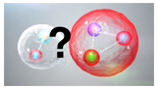
Observation of new states consistent with pentaquarks

[PRL 115, 072001 (2015)]

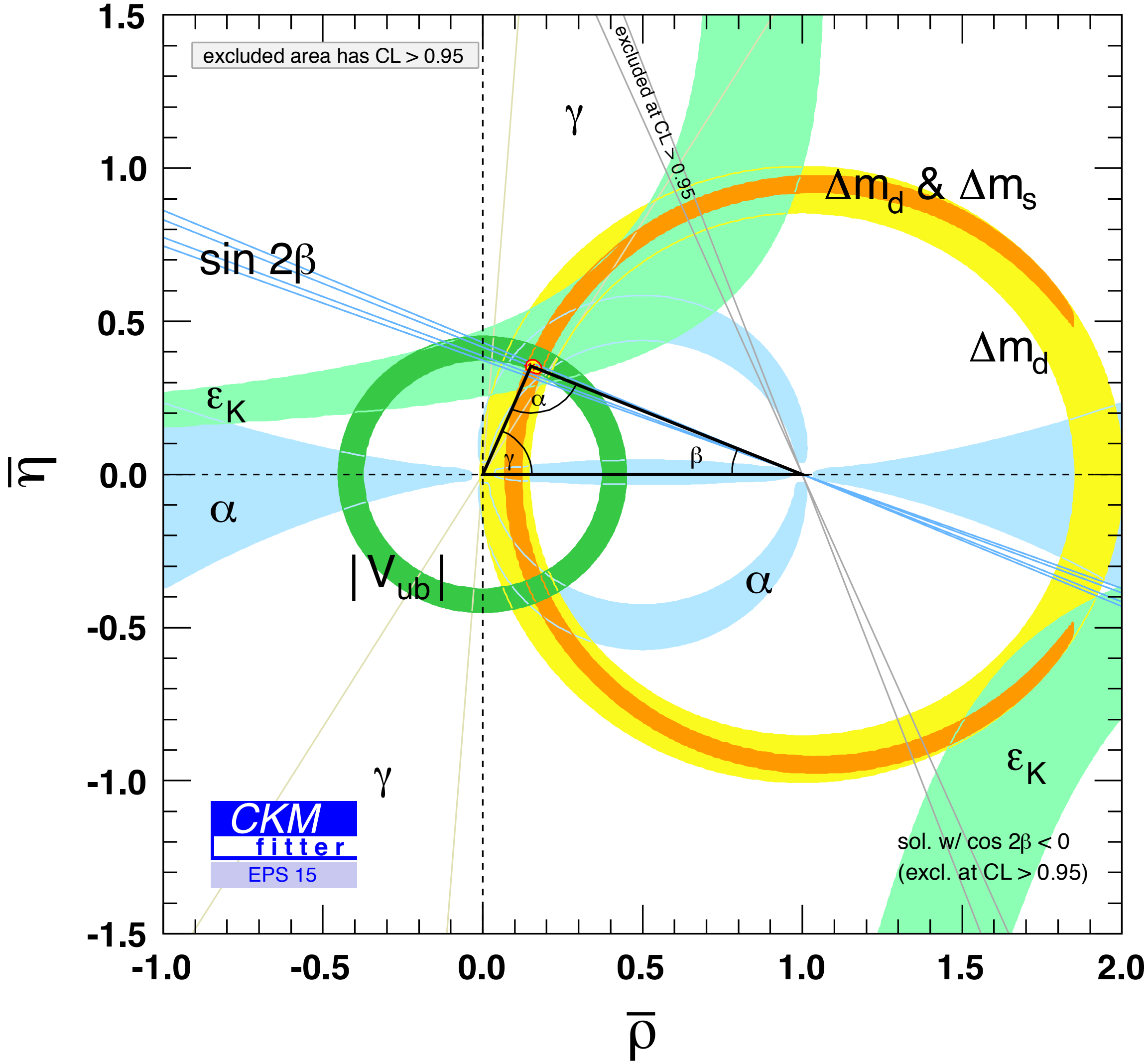




or



or … ?



Long-term effort to *overconstrain* CKM matrix continues (phase value itself "accident" of nature?).

Huge contributions from LHCb:

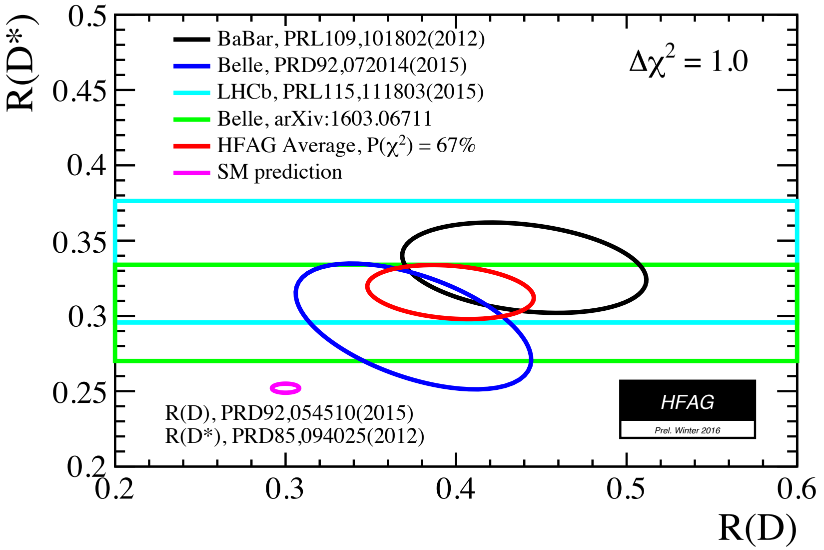
- Measurements of γ, $\sin(2\beta)$, $|V_{ub}|$, $\Delta m_{s/d}$ from LHCb
- World's best constraints on CP violation in $B^0_{(s)}$ mixing (a_{sl}^s, a_{sl}^d) in agreement with SM (D0 sees 3.6σ deviation)

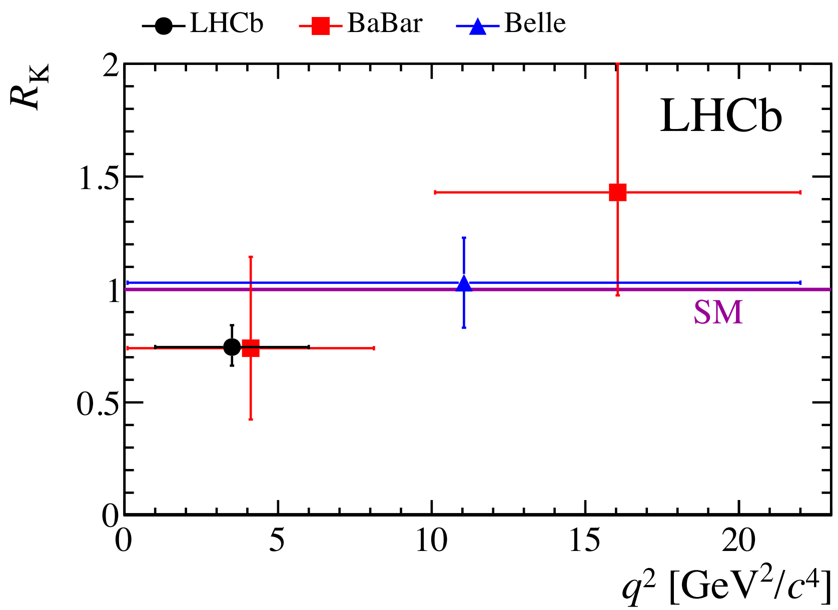
Is the CKM phase an "accident of nature"?

B-factories and LHCb measure ratios of semileptonic B decays. Robust SM predictions

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B^0 \to D^{(*)}\tau\nu)}{\mathrm{BR}(B^0 \to D^{(*)}\ell\nu)}$$

$$R_K = \frac{\mathrm{BR}(B^+ \to K^+\mu\mu)}{\mathrm{BR}(B^+ \to K^+ee)}$$





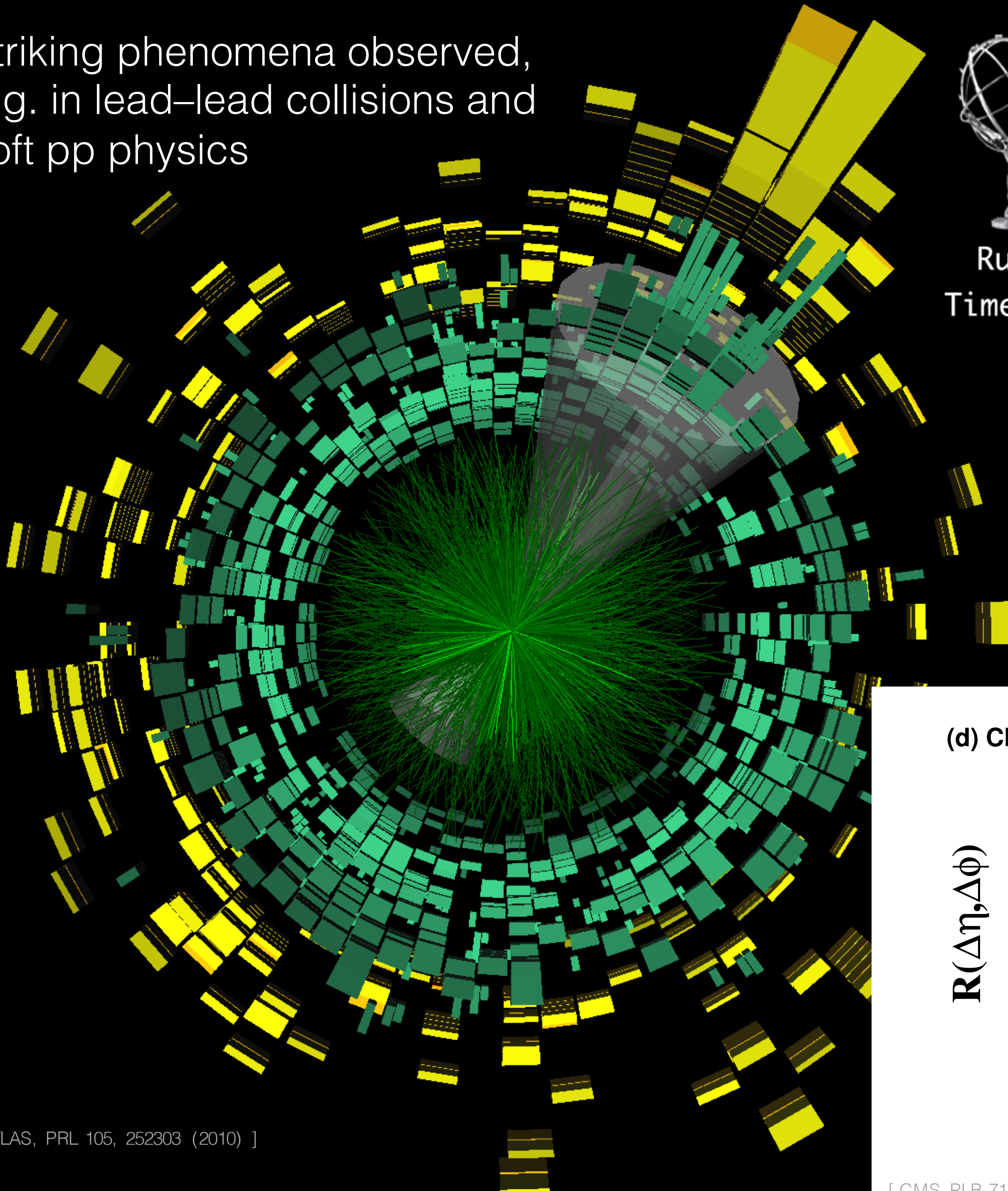
Latest measurement by Belle using semileptonic tagging of recoil B (Moriond EW):

$\boldsymbol{R_{D^*} = 0.302 \pm 0.030_{stat} \pm 0.011_{syst}}$ [SM: 0.252 ± 0.003, 1.6σ]

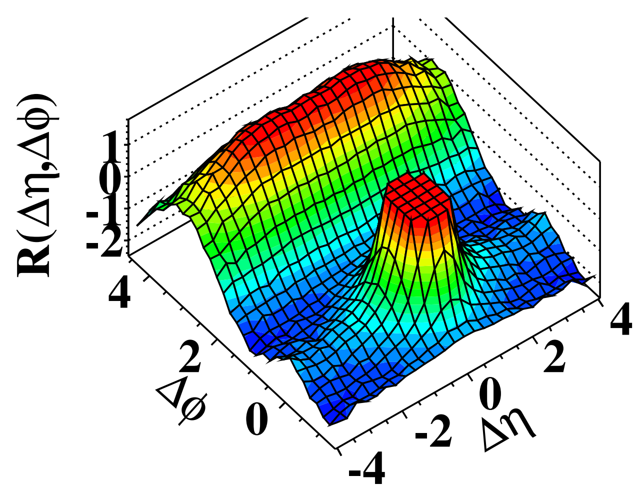
World average by HFAG: R_{D^*} = 0.316 ± 0.016 ± 0.010 (3.3σ from SM, combined R_{D^*} & R_D is 4.0σ)

http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

Striking phenomena observed, e.g. in lead–lead collisions and soft pp physics

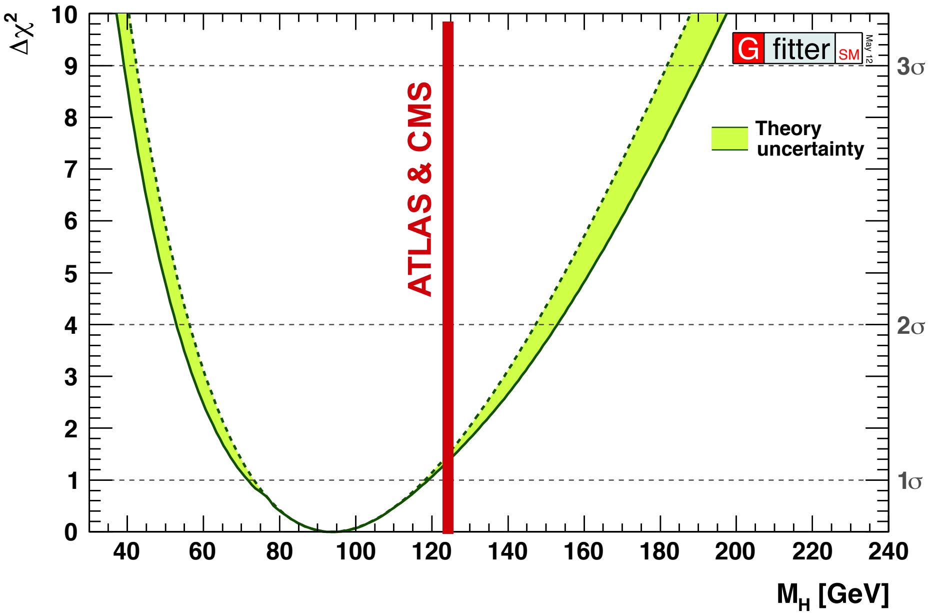


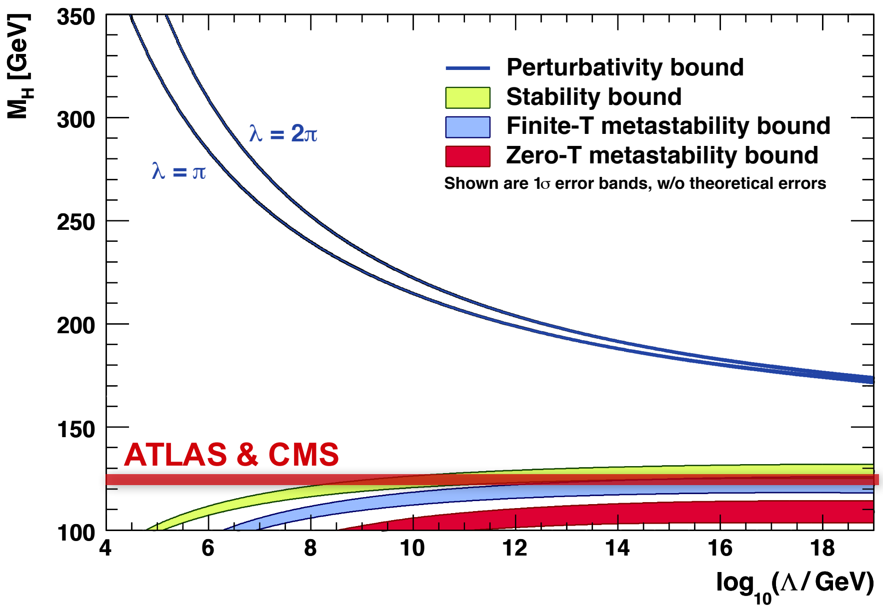
[ATLAS, PRL 105, 252303 (2010)]



[CMS, PLB 718 (2013) 795]

Since the LHC Run-1 the Standard Model is complete






Since the LHC Run-1 the Standard Model is complete

It is a triumph for the imagination and rigour of the scientific endeavour

It is a triumph for the greatest experimental undertaking ever:

- *Frontier of accelerator & detector technologies*
- *Global data sharing, analysis & collaboration*

It seems, however, that the SM isn't all there is

LHC may address

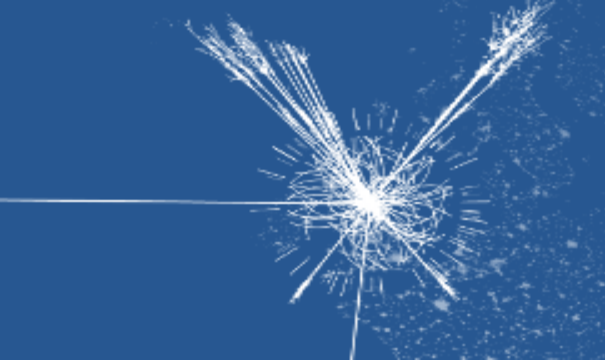
- Higgs is only fundamental scalar
  neither matter, nor force, – all known scalars are composite states
- Huge mass hierarchy between matter particles
- Gauge hierarchy / apparent lack of naturalness
  No separation of scales
- Dark matter
- Unification of SM forces
- Massive neutrinos
- Matter-antimatter asymmetry in universe

Inflation

Dark energy (Λ)

Strong CP problem

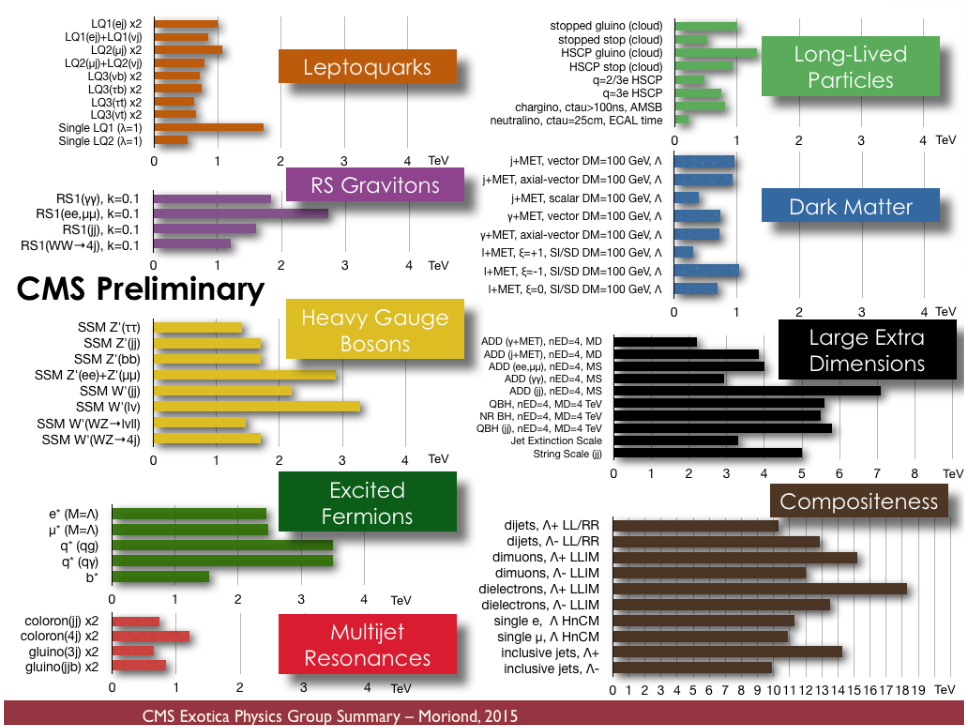
Quantum gravity

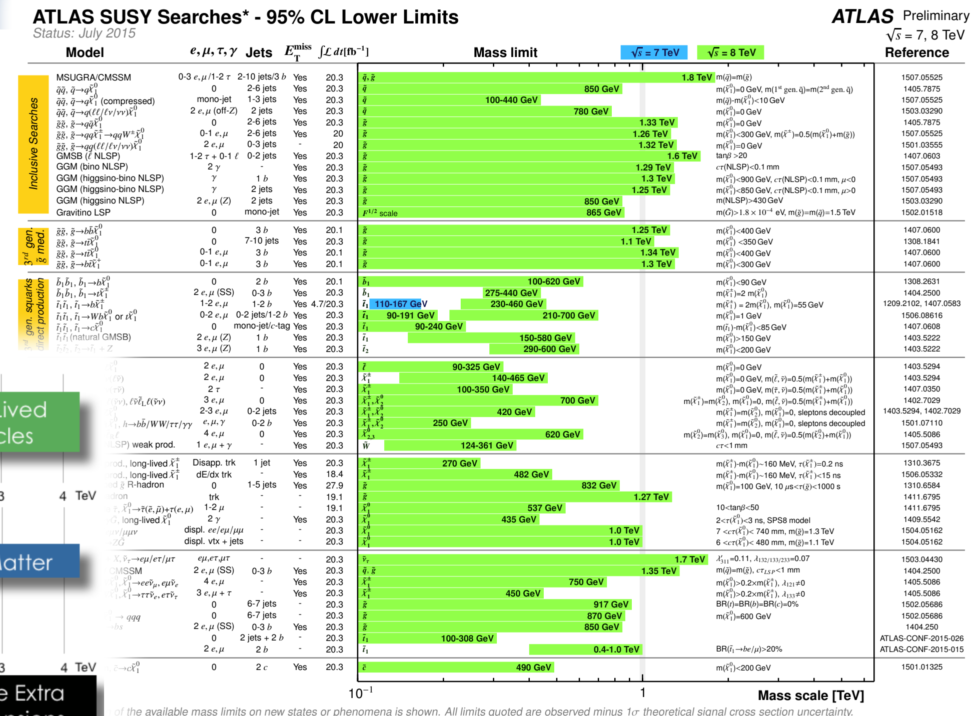


It seems, however, that the SM isn't all there is

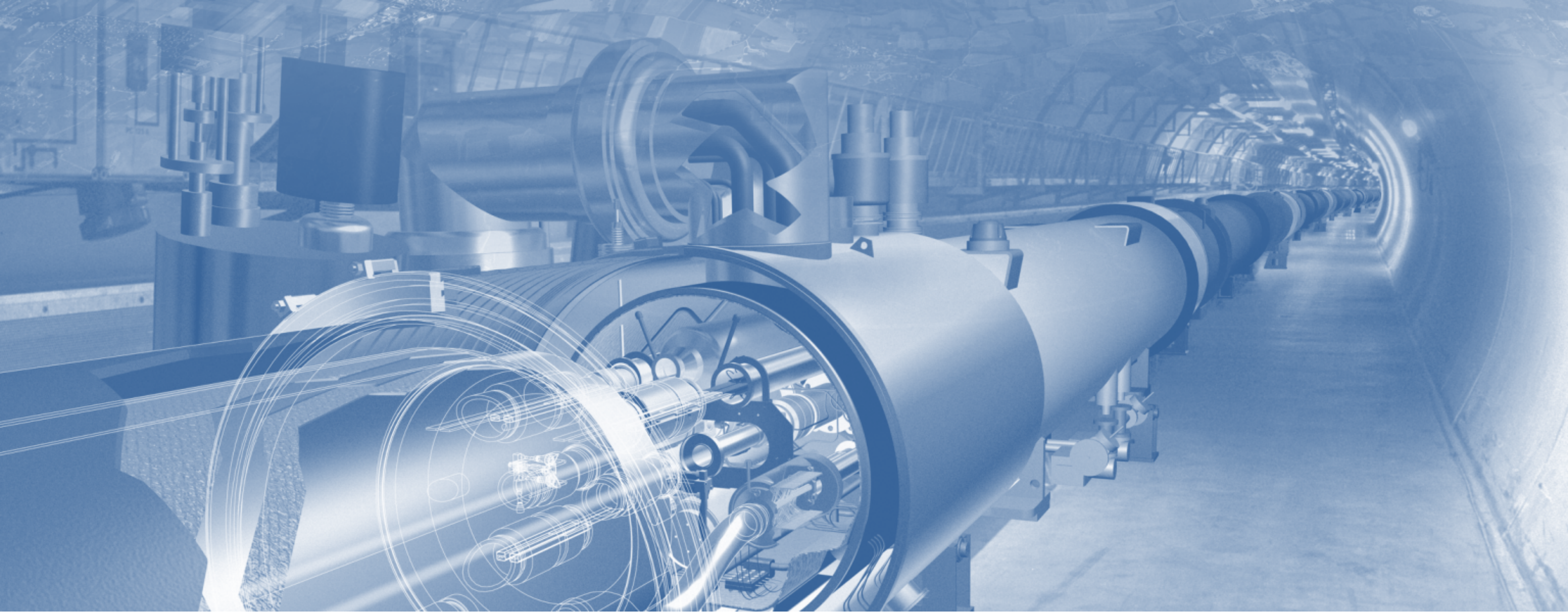
Vast amount of BSM searches

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

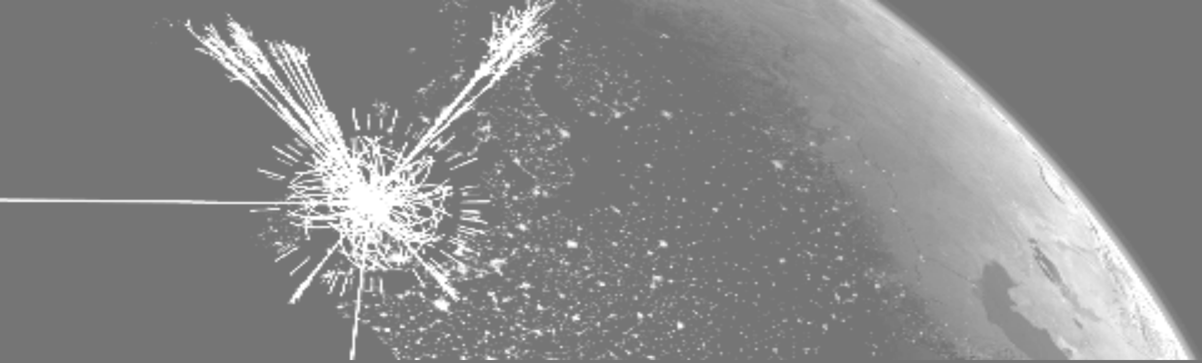




No significant anomaly seen so far



Tomorrow: the LHC Run-2 at 13 TeV and beyond



Extra slides

The Standard Model is ***the*** *legacy of 20th century particle physics*

Standard Model (36+1 particles, 3 forces)

Selected Nobel Prizes since 1957 (incomplete!)

Gauge group = $SU(3)_C \times SU(2)_L \times U(1)_Y$

$SU(3)_C \times U(1)_{EM}$

EWSB

Courtesy: Pascal Pralavorio

Broad search coverage — not only the standard signatures

Run-1 "tour de force" analysis of pMSSM

[ATLAS, 1508.06608, CMS 1606.03577]

Combined use of 22 separate ATLAS SUSY searches in addition to external constraints (m_H, EWPO, flavour, LEP searches, dark matter) to probe 19 parameter pMSSM

Distinction of LSP types: *bino*, *wino*, *higgsino*

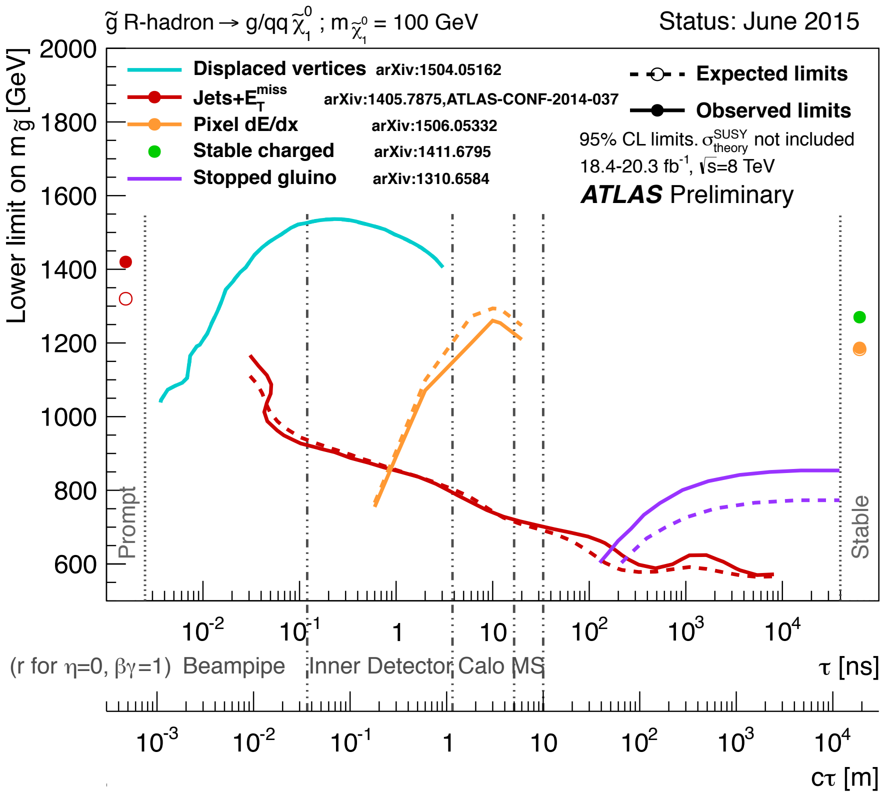
Analysis overall reproduces simplified models picture

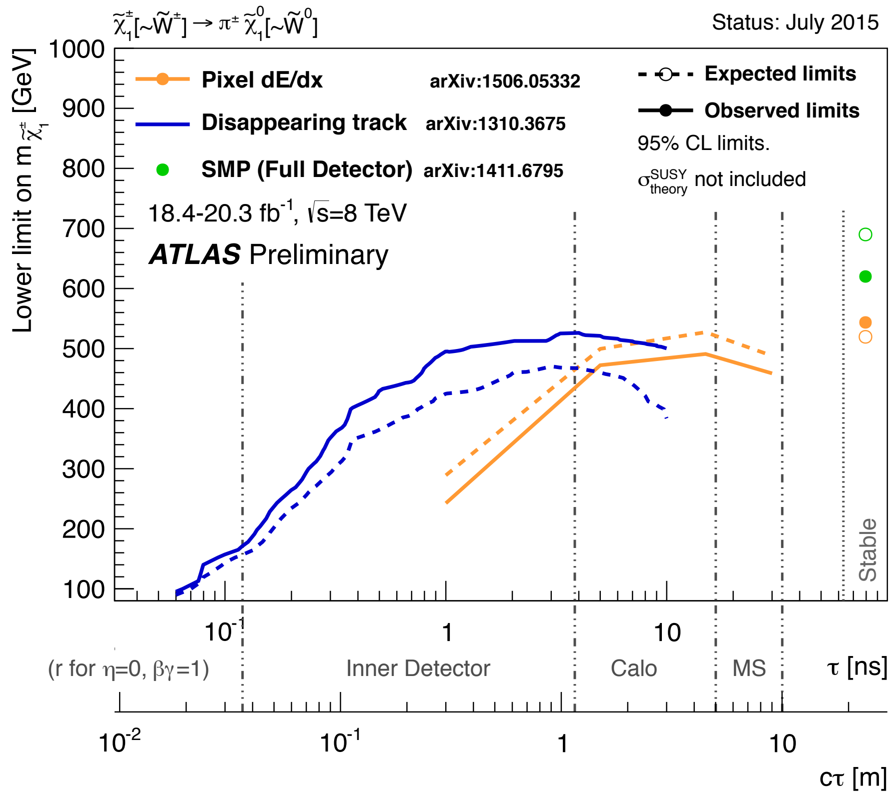
Higgsino/wino scenarios biggest challenge →

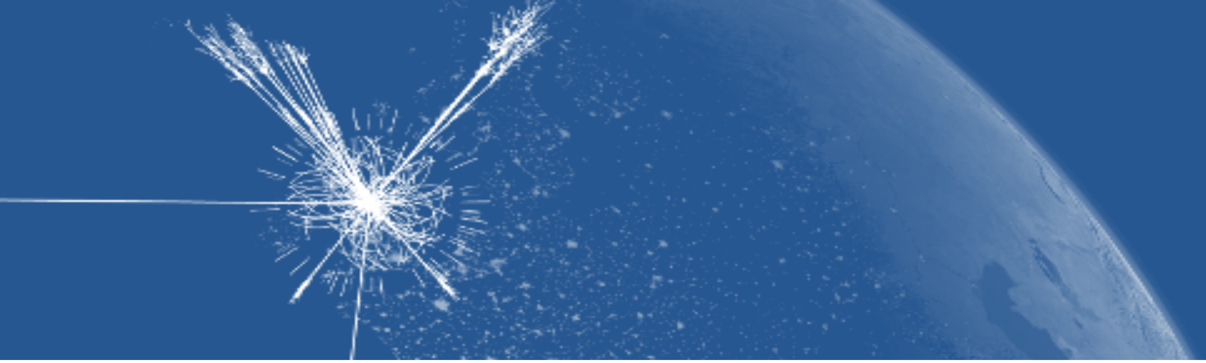
Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+E_T^{miss}, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

Broad search coverage — not only the standard signatures

All experiments looked for various types of long-lived massive particles







SM predictions in Monte Carlo simulations

Parton level examples (often require “hadronisation” and soft “parton shower” corrections):

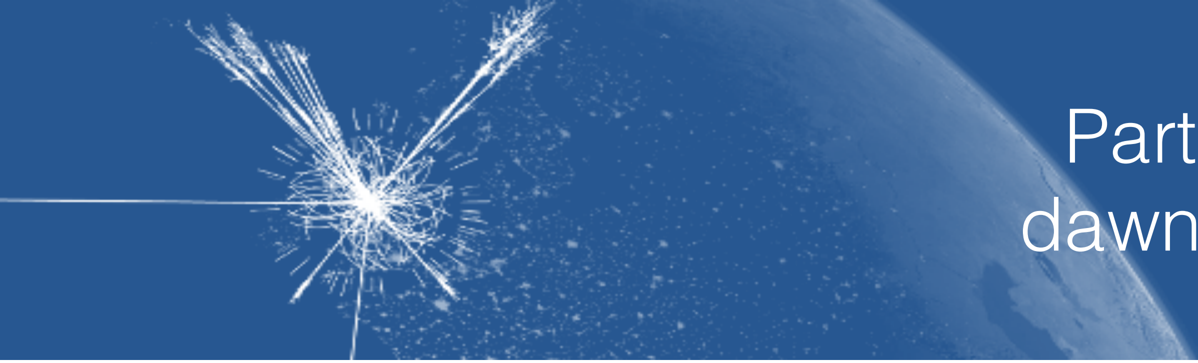
- MCFM: fixed-order NLO → vector bosons etc.
- BLACKHAT+SHERPA: NLO fixed order pQCD (up to 4p) → vector bosons etc.
- Jetphox: fixed-order NLO QCD → photons
- PeTeR: resummed NNLO (NNNLL accuracy) → photons, etc.
- NLOjets++: fixed-order NLO QCD → jets
- FEWZ, DYNNLO, Njetti etc. – NNLO calculations for vector bosons

Event generators at hadron/particle level, examples:

- PYTHIA8, HERWIG++: LO ME with parton showers (PS) – general-purpose generator, hadronisation and PS tools
- ALPGEN: LO matrix element (ME) multipartons (up to 5p)
- SHERPA: LO/NLO multipartons (up to 5/2p) + PS (internal)
- MadGraph/MG5_aMC@NLO: LO/NLO MEmultiparton (5/2p)
- POWHEG, MC@NLO: NLO

State of the art is:

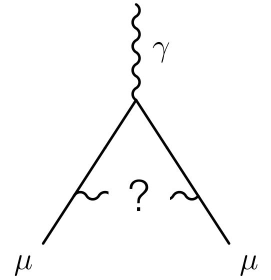
- **Parton level**: NNLO with resummed logs
- **Hadron level**: NLO + PS, LO multiparton + PS

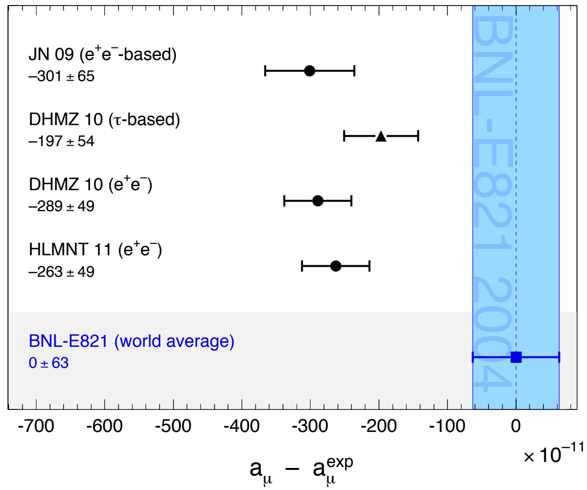


Particle physics at the dawn of the LHC Run-2

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)