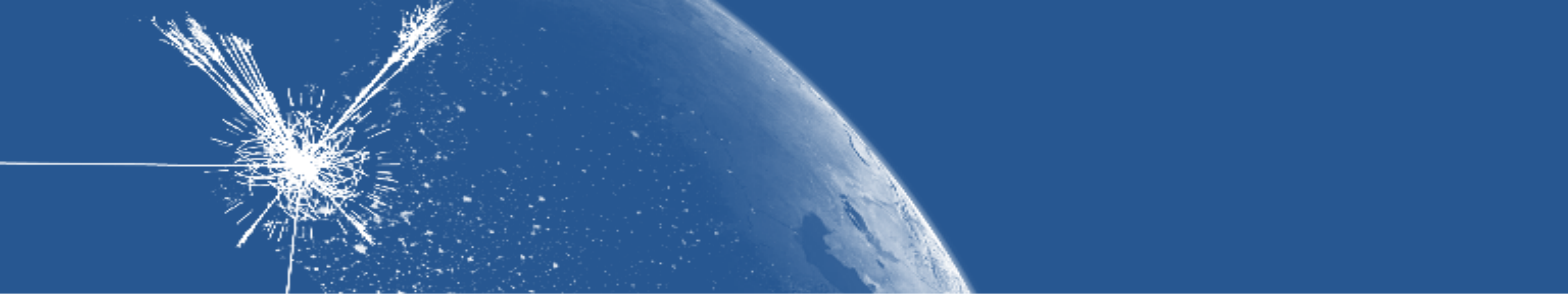


New Results from the LHC (1)

Andreas Hoecker (CERN)

September 26–28, 2016 in Freudenstadt, Germany

Outline

[3 lectures]

Today:

- Basic introduction
- Overview of the LHC experimental programme and methods

Tomorrow

- A review of Run-1 physics highlights
- The LHC Run-2, results obtained so far

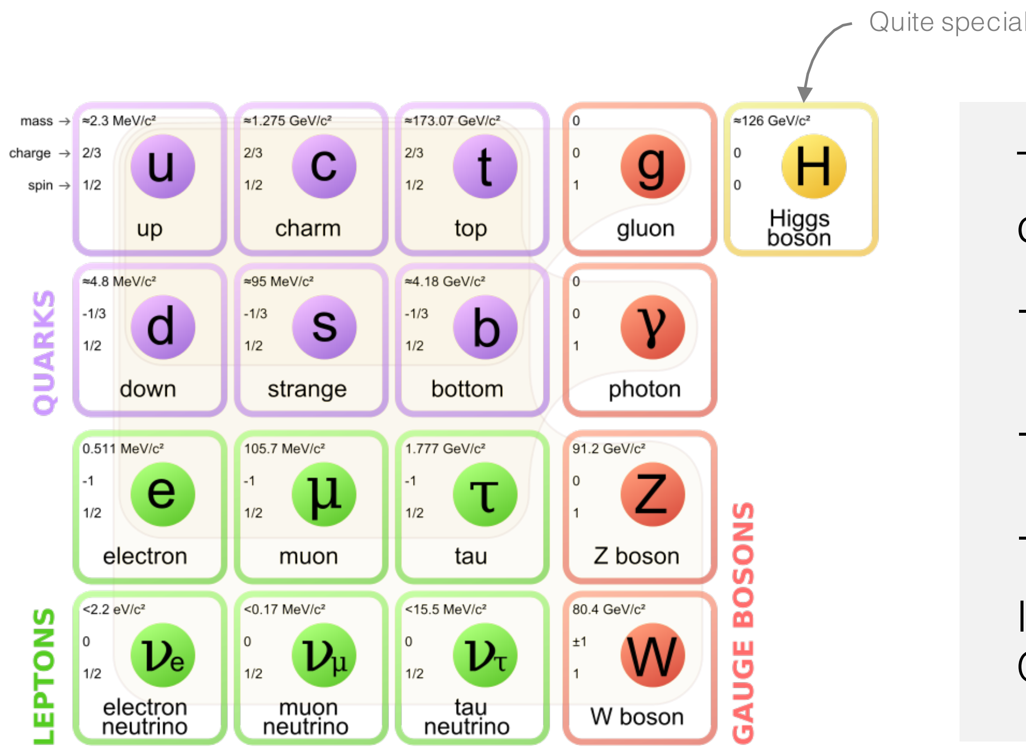
After tomorrow

- LHC Run-2 results 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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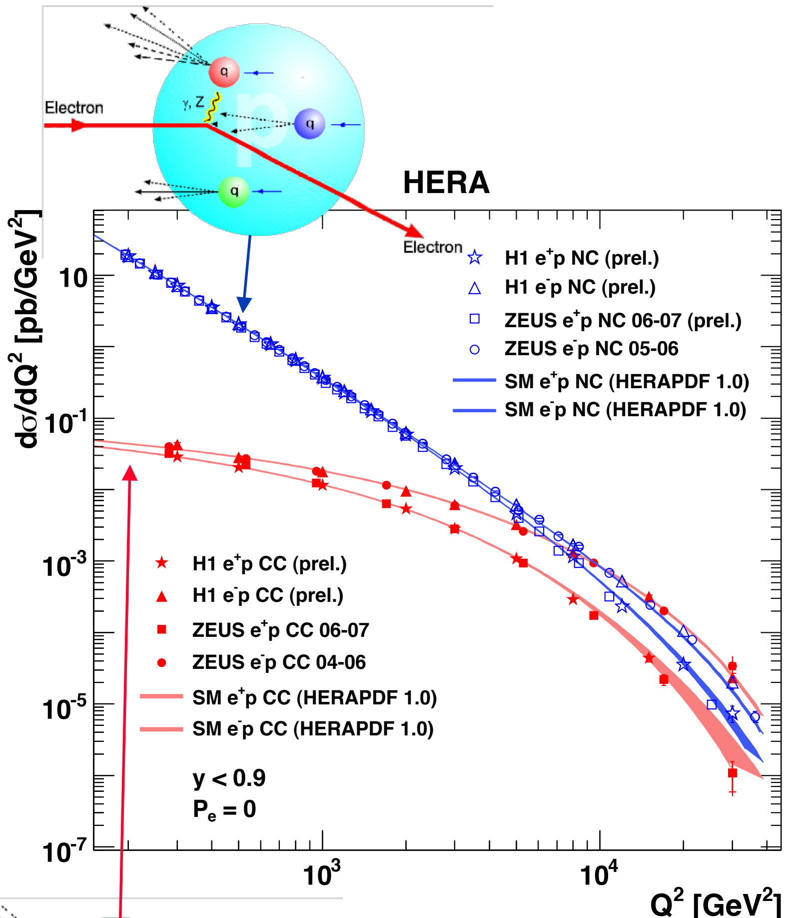
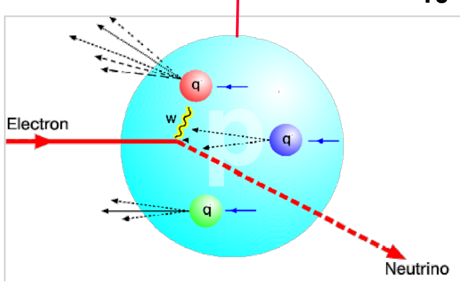




HERA data from electron–quark scattering into $e+q$ (NC = γ,Z) or $\nu+q$ (CC = $W^{\pm}$)

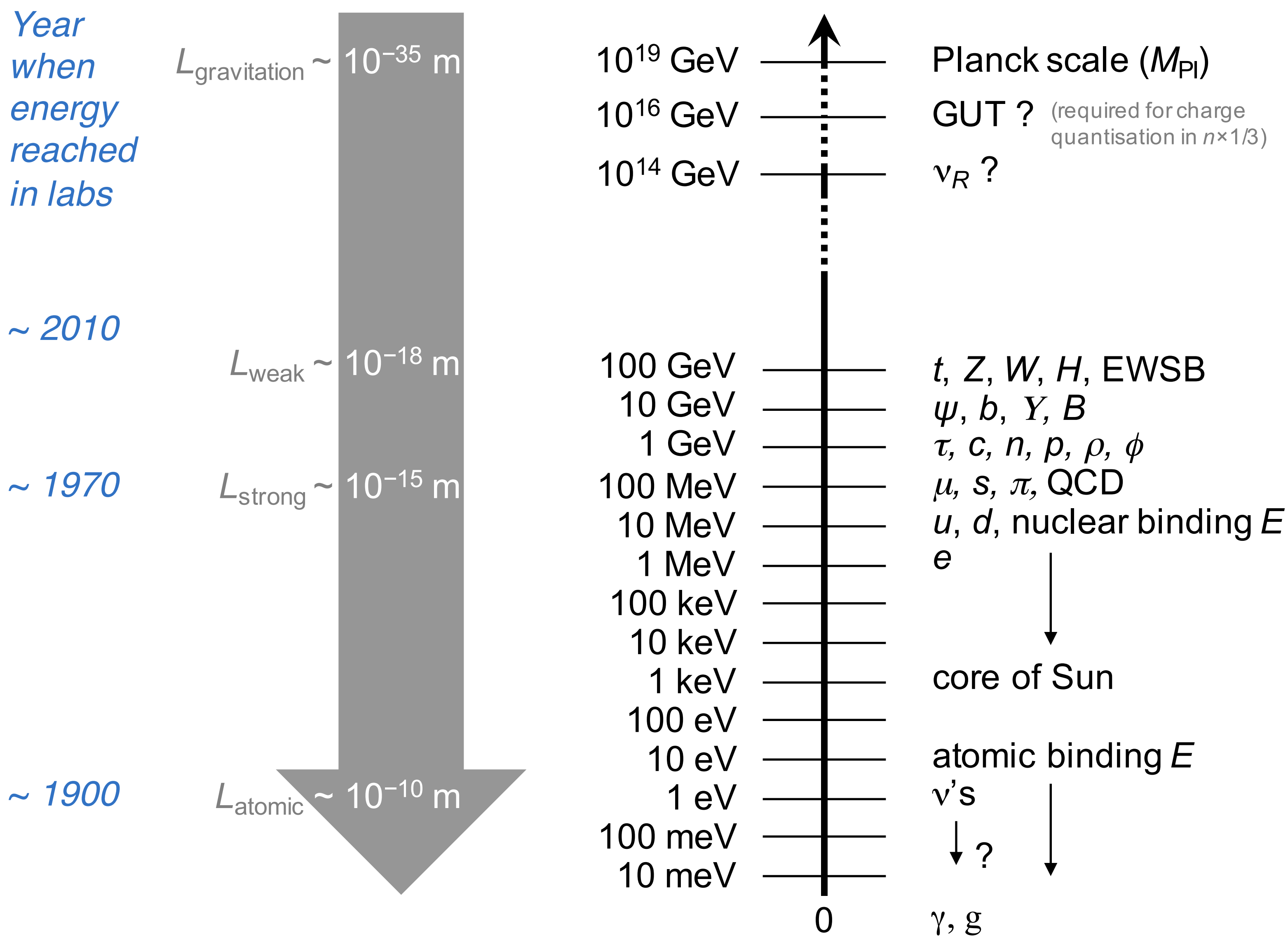
The SM is **the** legacy of 20th century particle physics

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

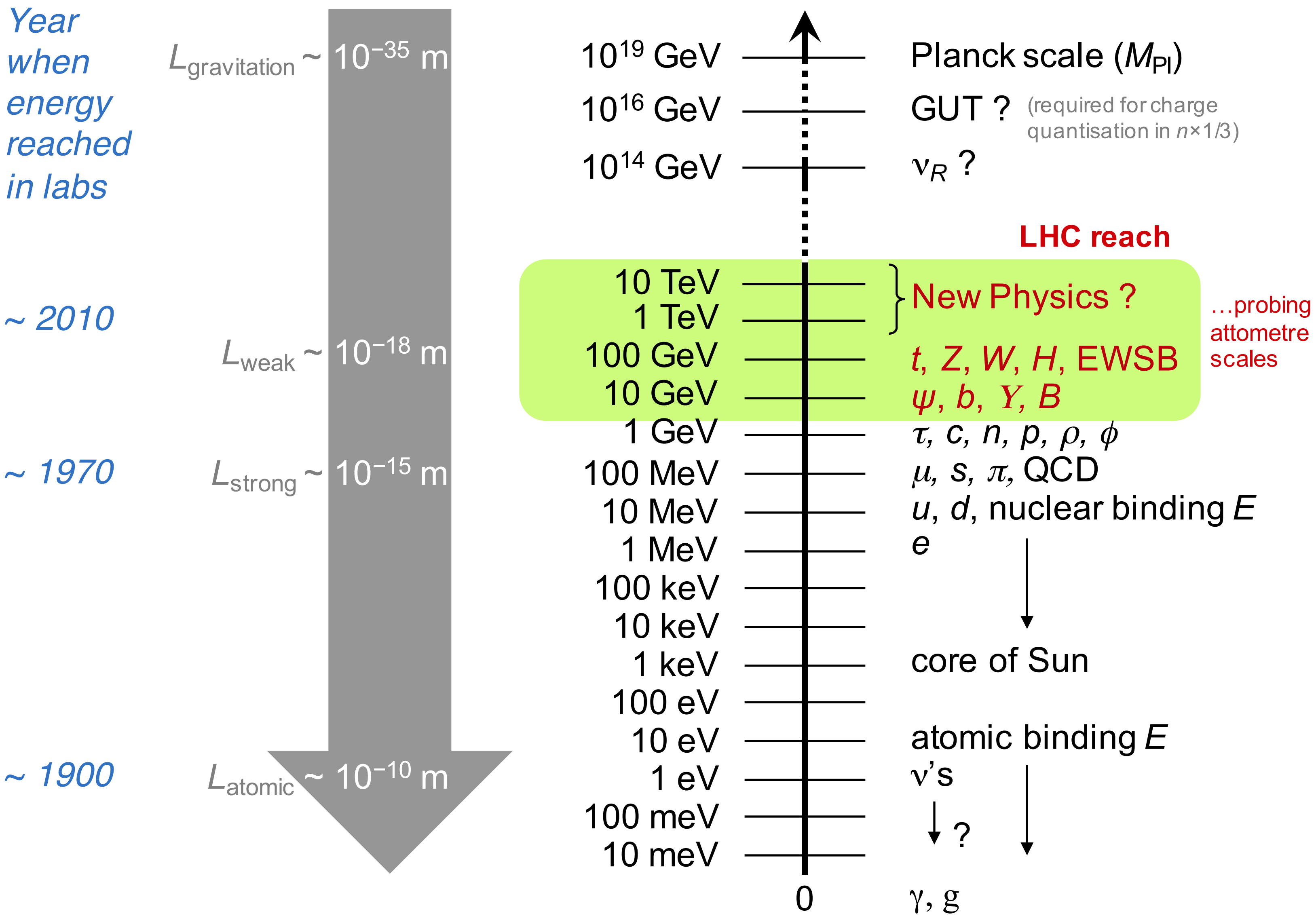
Is the SM the theory of everything? Or rather of almost everything? **Or …**

- 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 $\nu = 0$)**

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:

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 \,|\, \phi \,|\, 0 \rangle = \upsilon \neq 0$$ [non-zero vacuum expectation value]

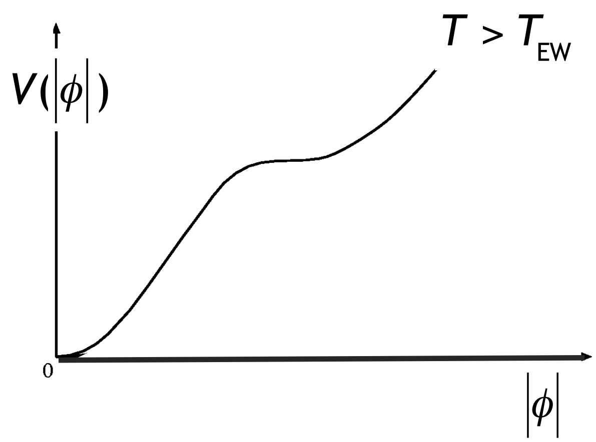
ϕ is a complex doublet field with non-zero vacuum expectation value.
three d.o.fs become Z, $W^{\pm}$ masses, fourth d.o.f is **massive scalar Higgs boson**

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

The Standard Model

BEH mechanism

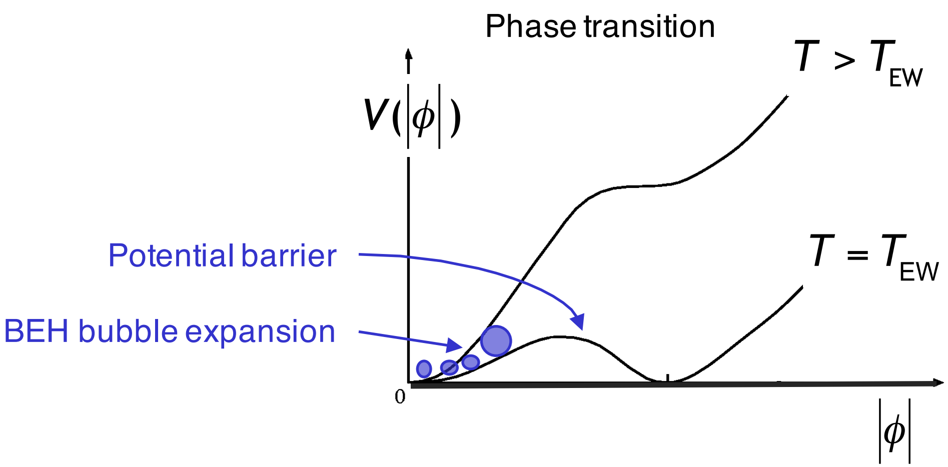
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)



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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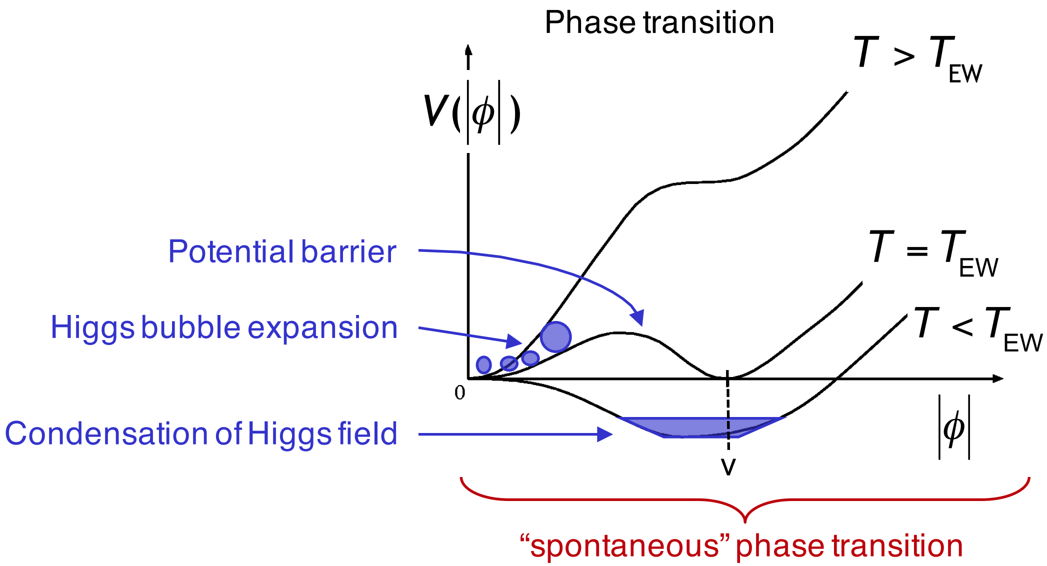


Higgs potential: $V(\phi) = \mu^2_{<0} |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$

(μ, λ determined once Higgs mass known)

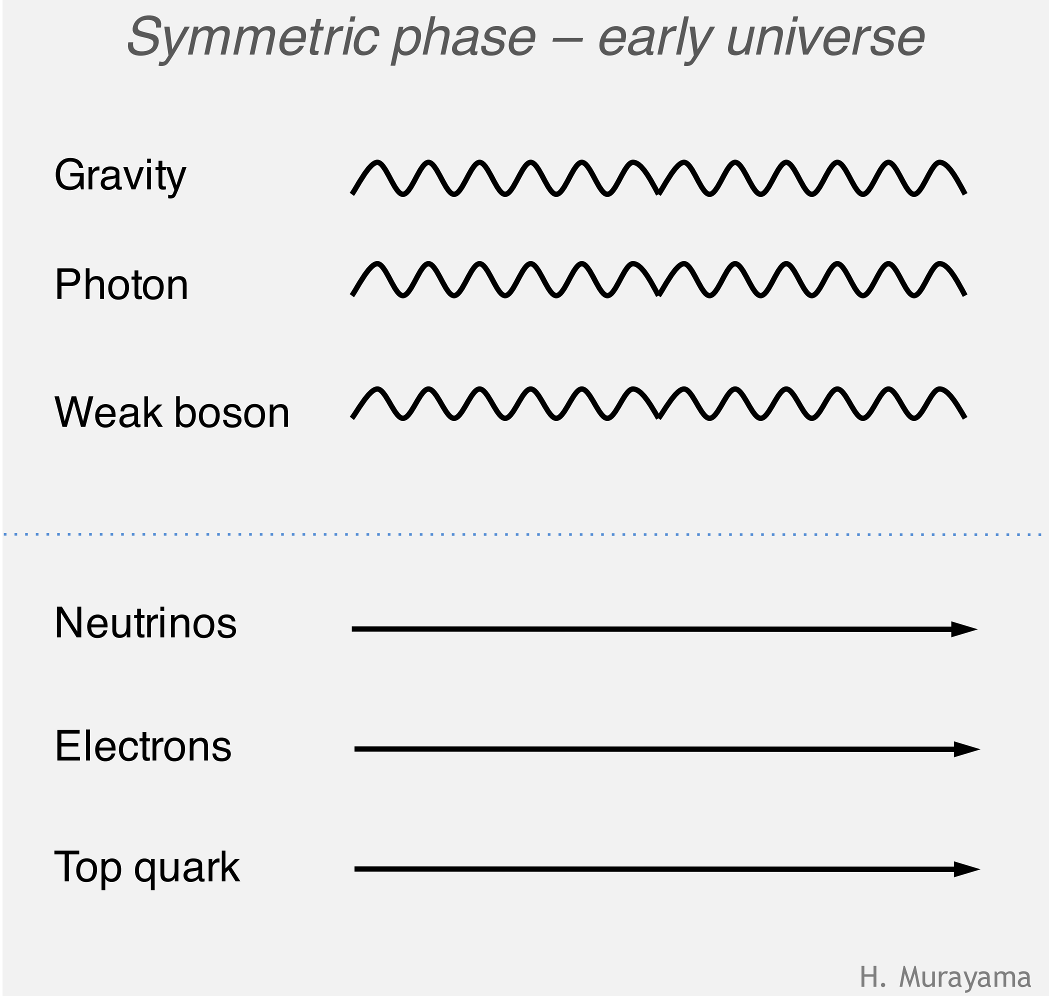
Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds of new physics …

The Standard Model

BEH mechanism

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



The Standard Model

BEH mechanism

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

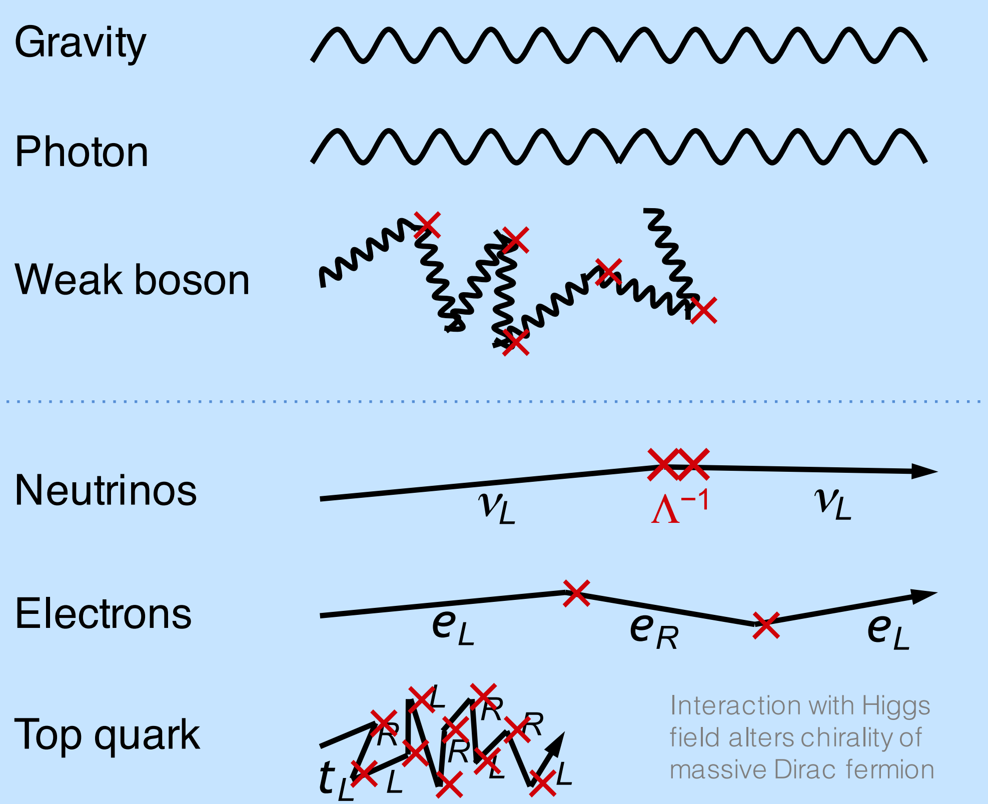
A Higgs field displaces ground state breaking gauge symmetry

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* ?

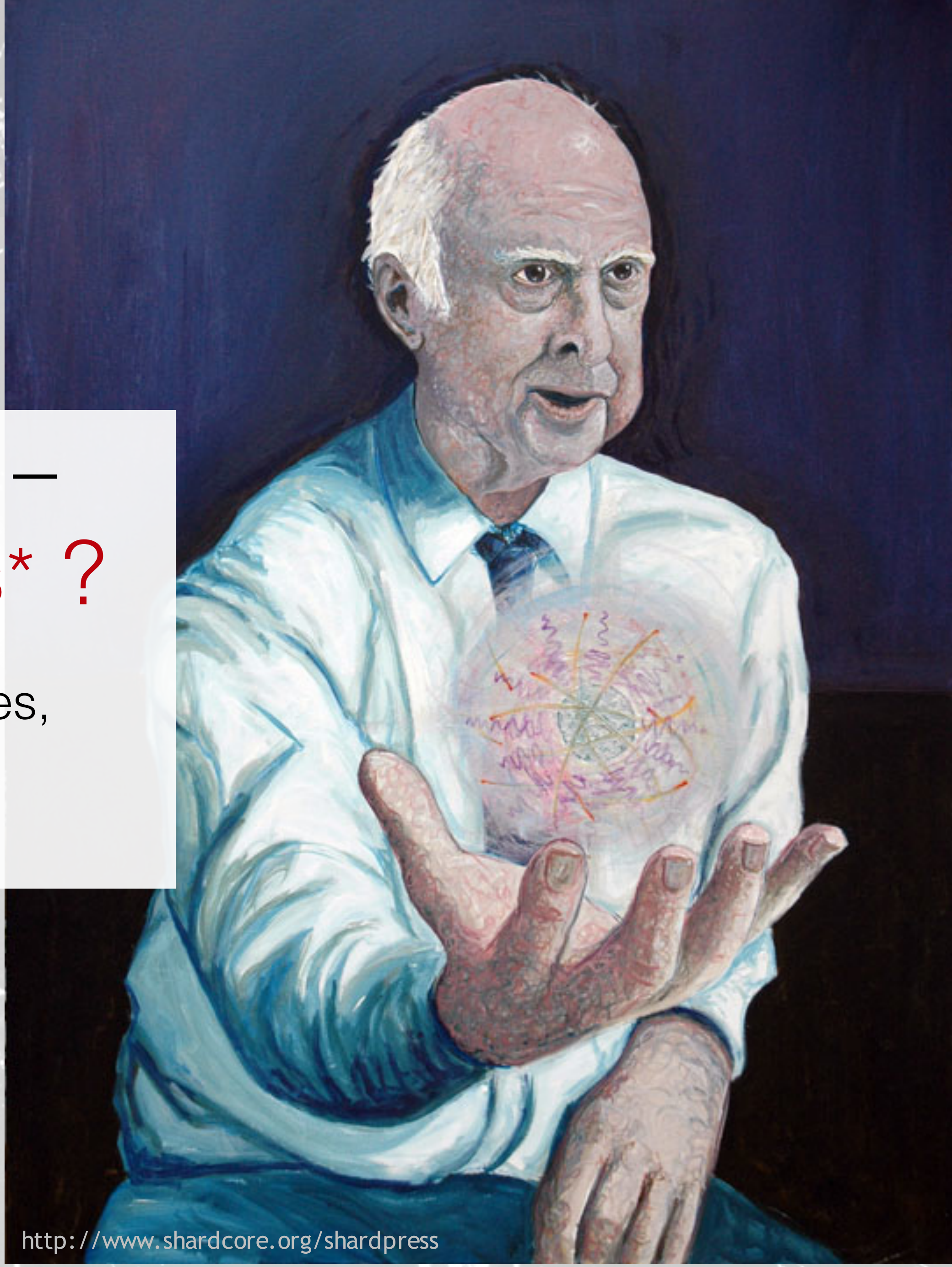
The SM predicts all its properties, except for its mass

*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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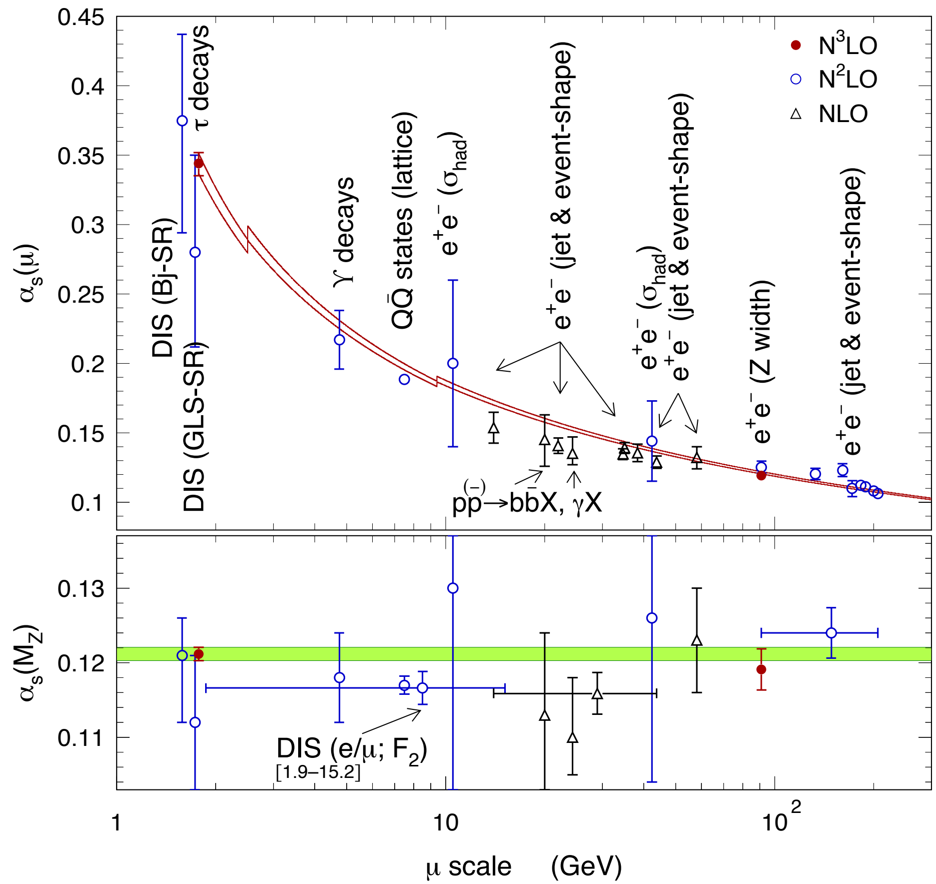
- SM tests to unprecedented precision, no direct/indirect hint of BSM physics

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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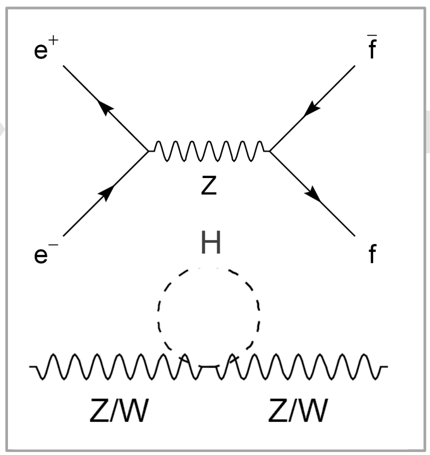

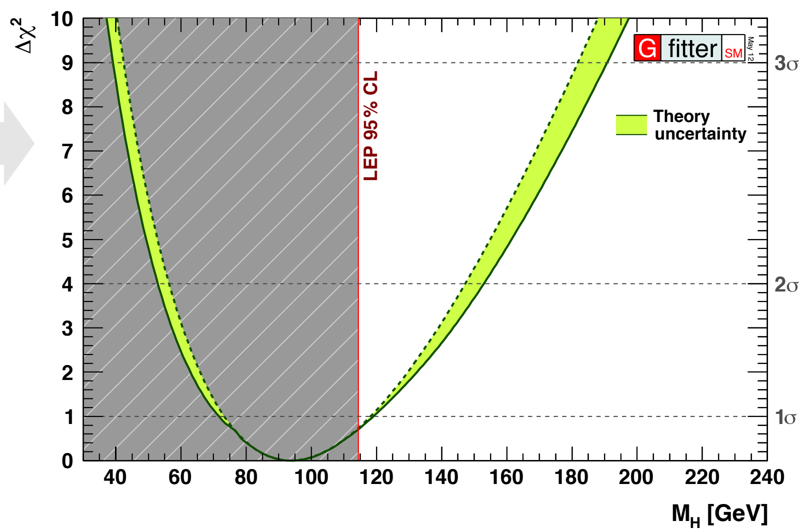

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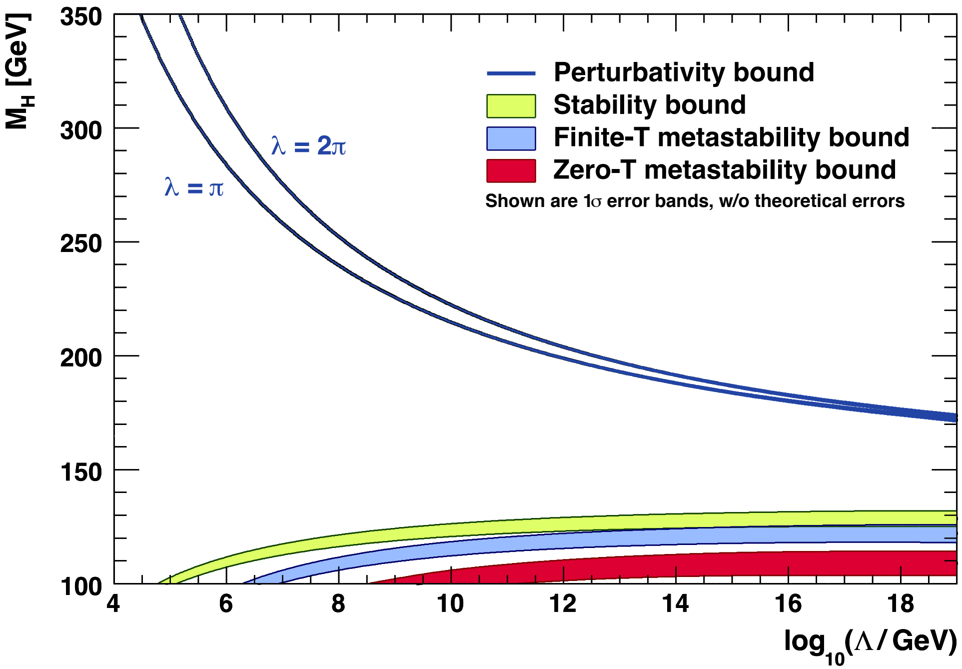
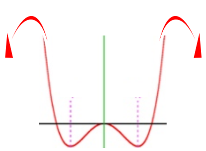
- There also were theoretical arguments in favour of a light Higgs moderating $W_L W_L$ scattering

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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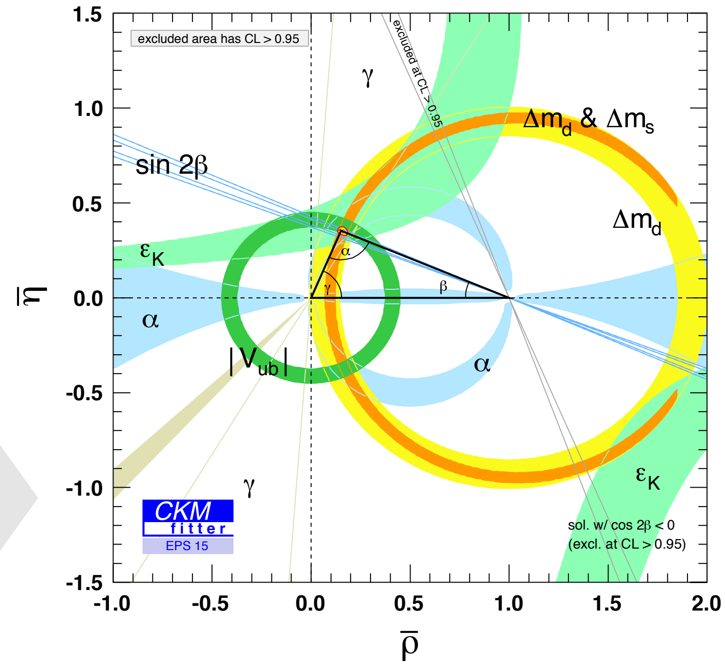
B-factories experiments BABAR & Belle about to end

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



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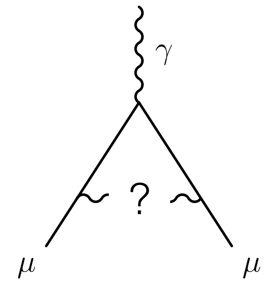

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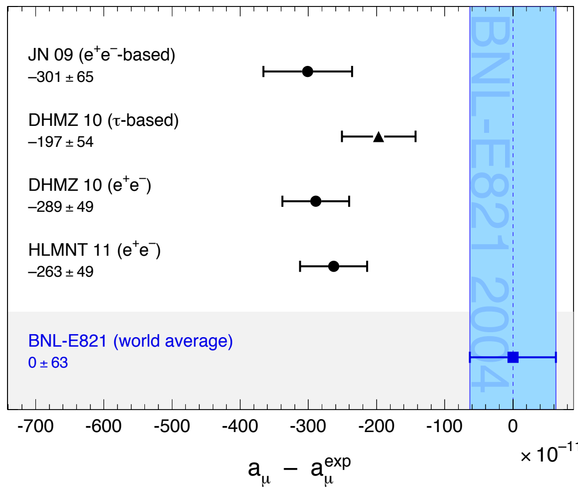

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Low-energy experiments: no signs of charged LFV, EDM, only muon g–2 showed anomaly

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

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

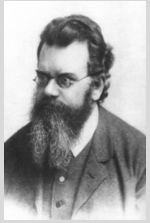
Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

Lawrence
(First cyclotron provided 80 keV proton acceleration)

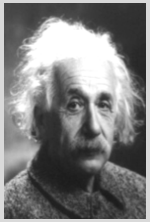
Particles accelerators:

- 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

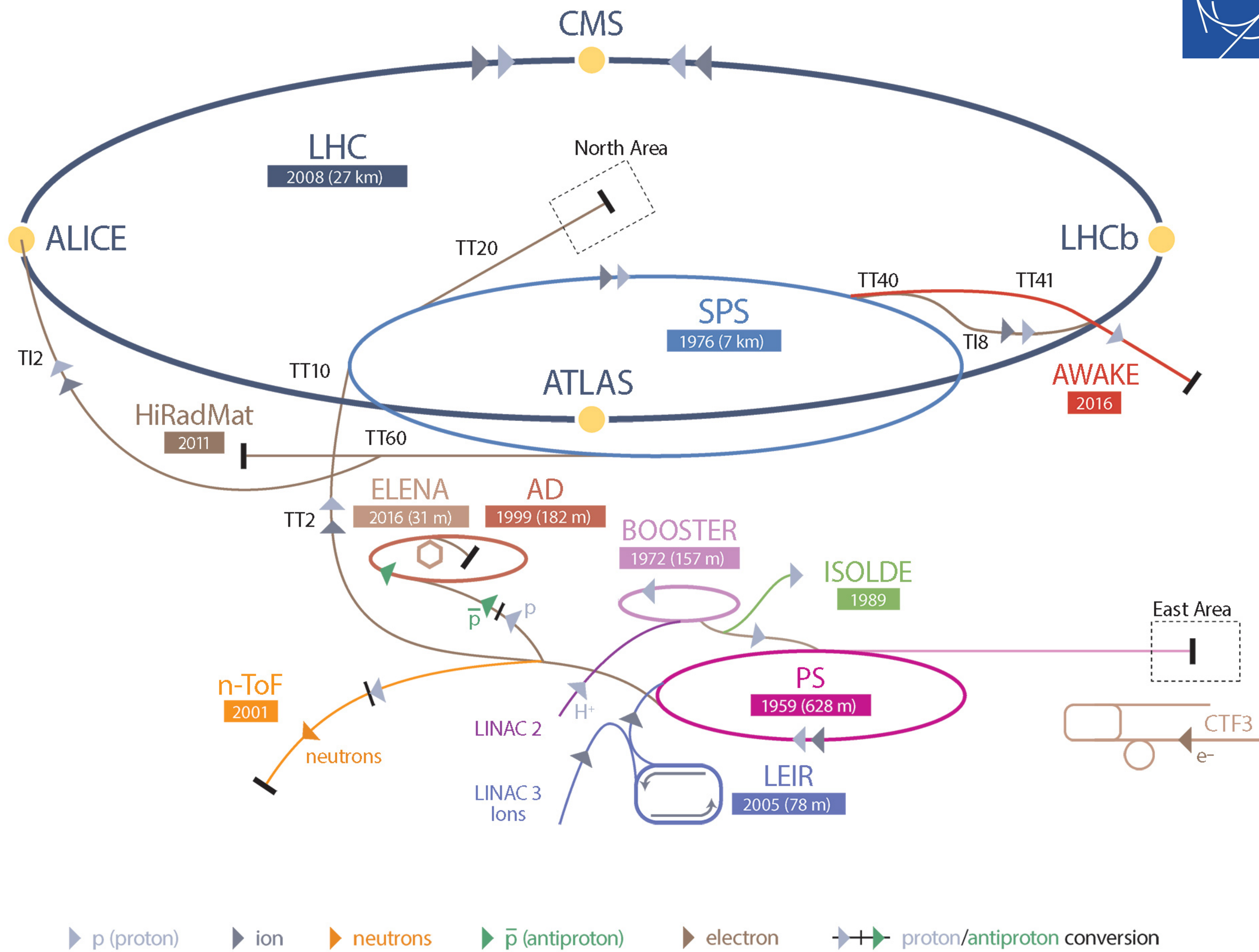


Boltzmann



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

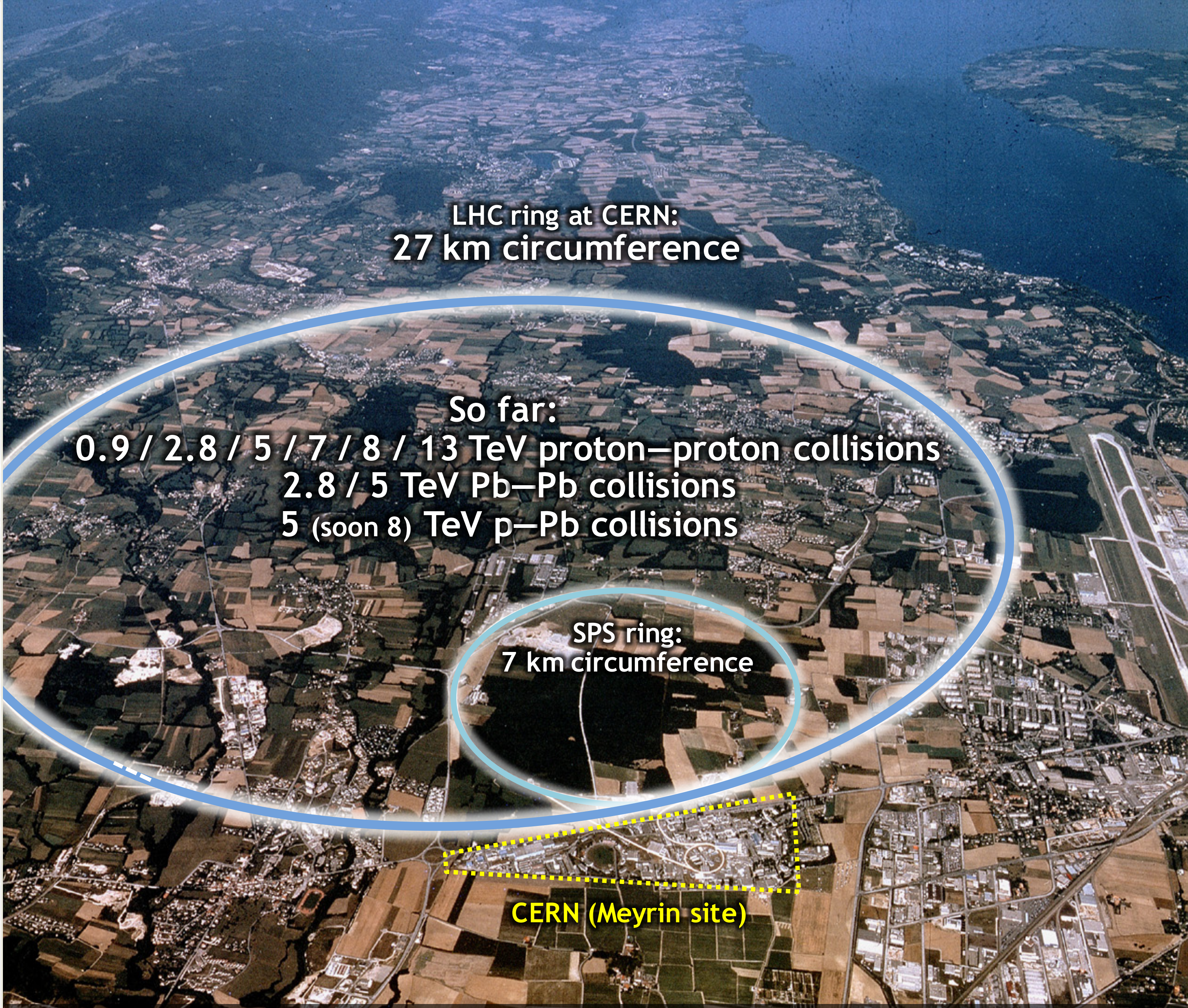
PS

1.4 GeV

BOO-
STER

50 MeV

LIN-
AC2

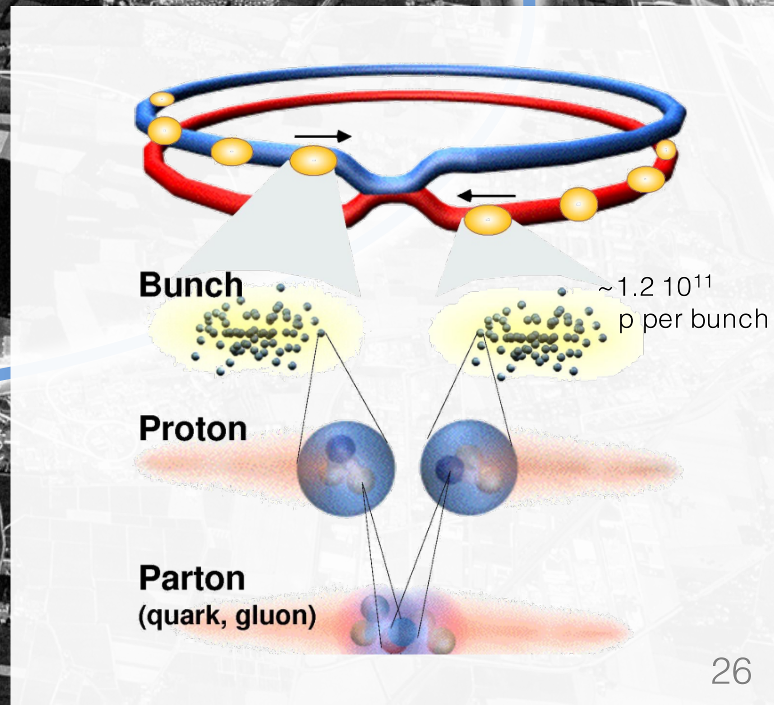


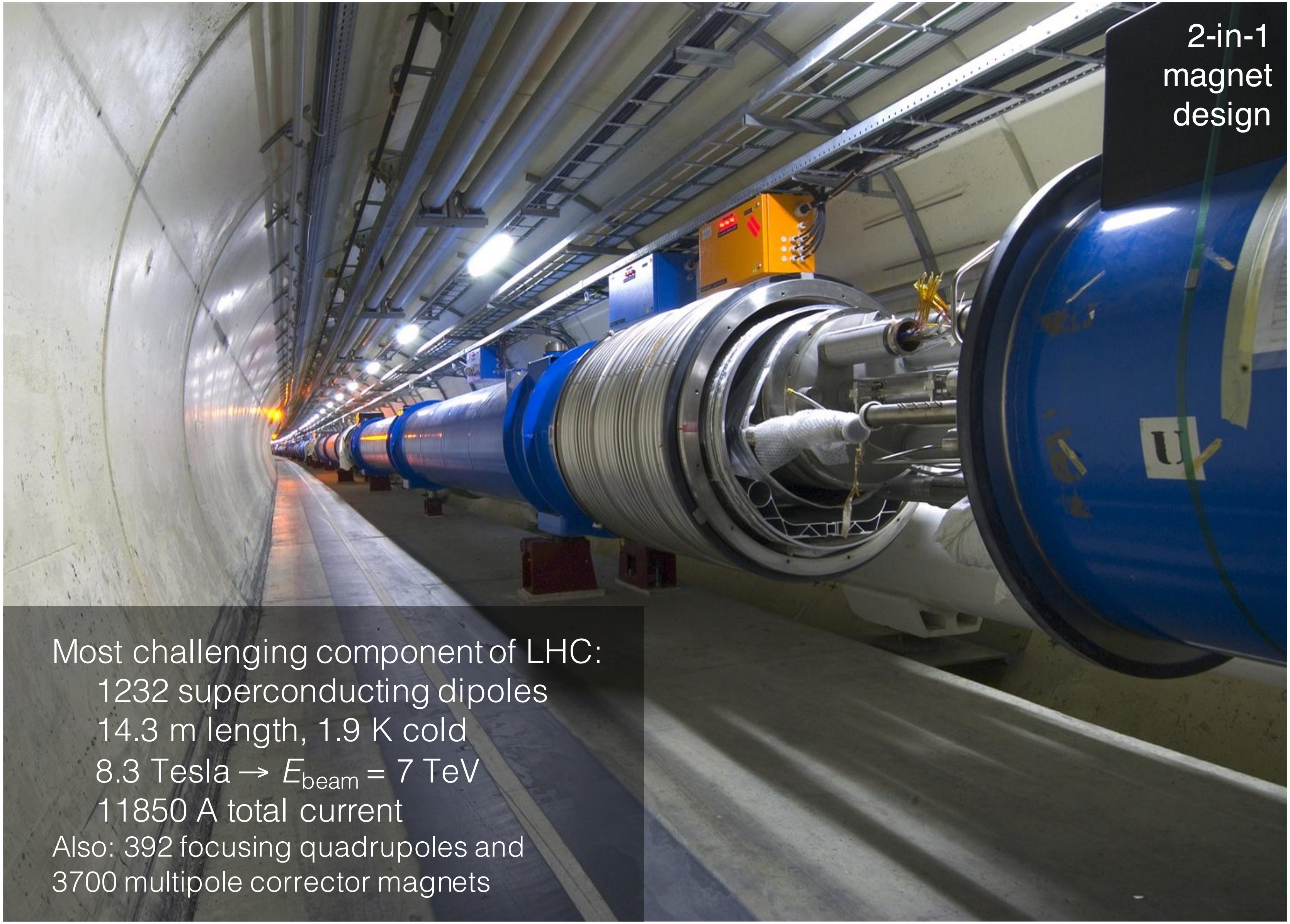
~20 minutes are required to accelerate the protons in the LHC from 450 GeV to 7 TeV


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



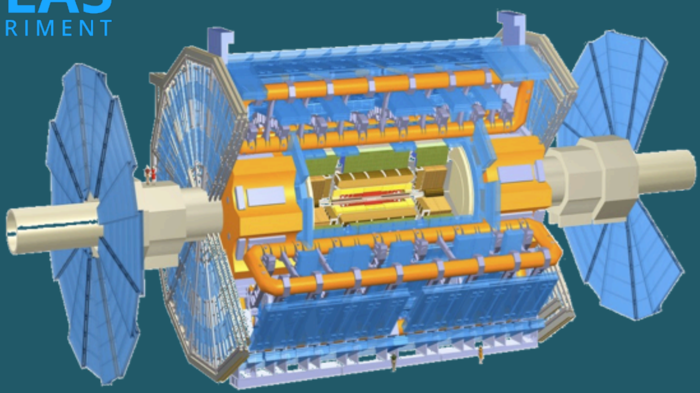


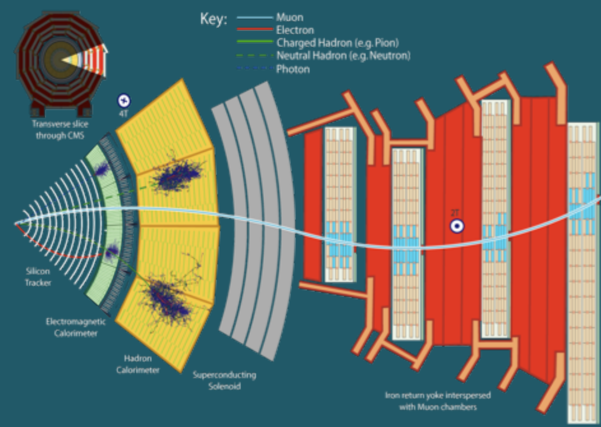
Most challenging component of LHC:

- 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



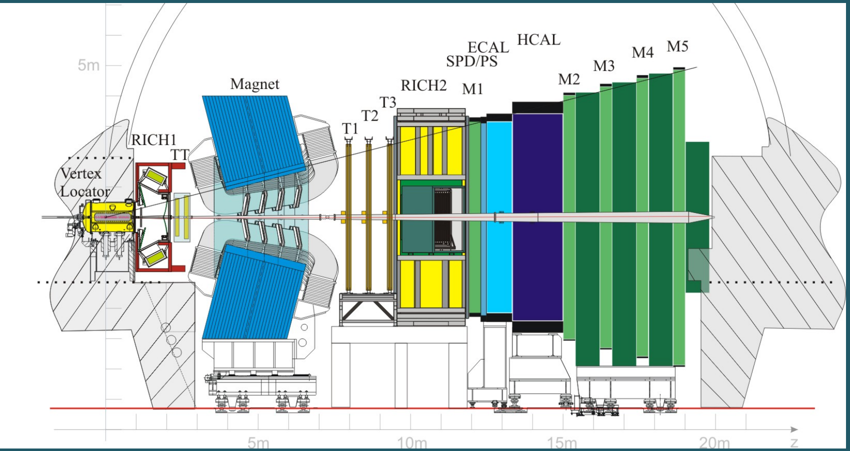


ATLAS: emphasis on excellent jet and missing-E_T resolution, particle identification, flavour tagging, and standalone muon measurement

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

Both: excellent hermeticity – very few "cracks"

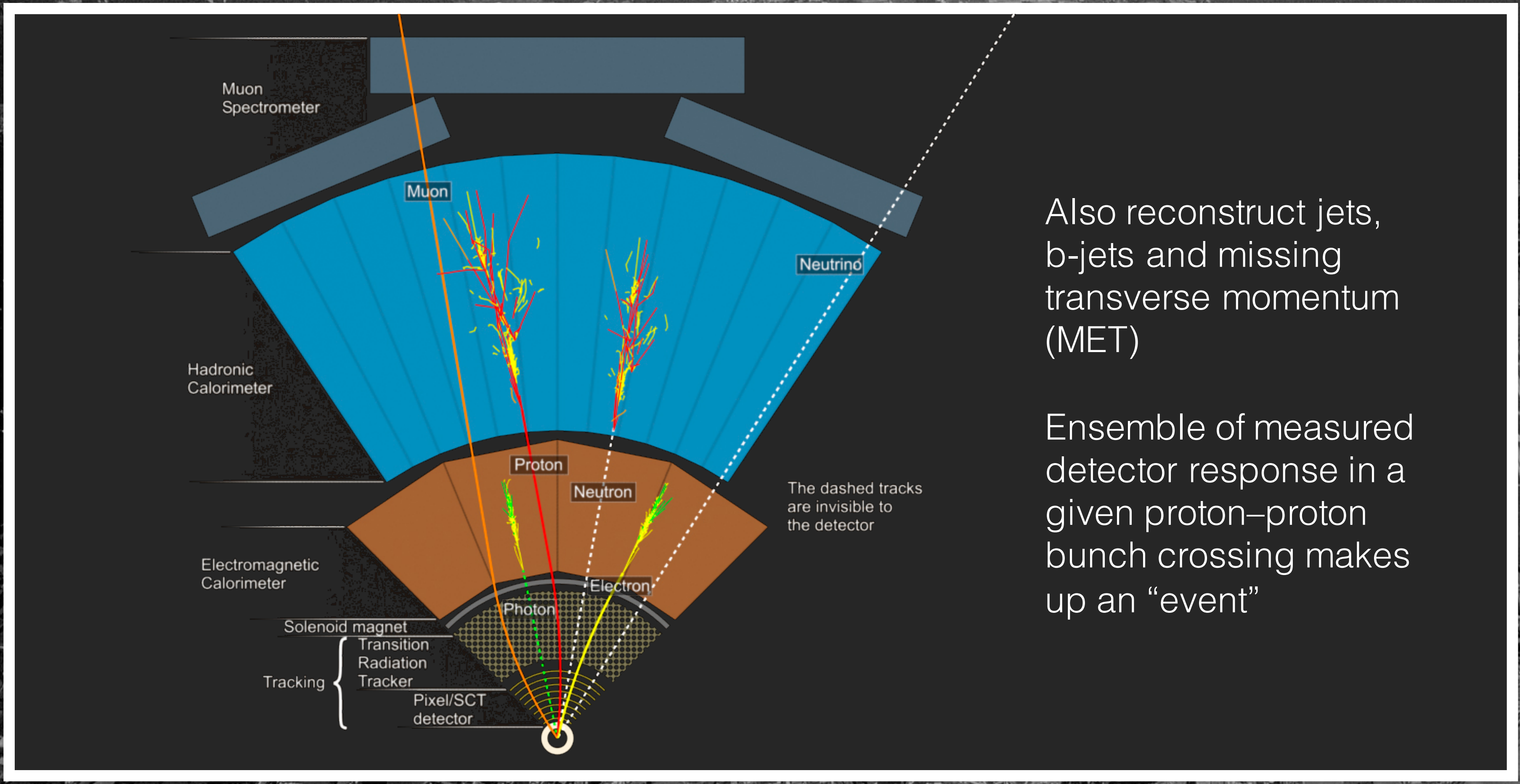
LHCb & ALICE: optimised for low-p_T physics



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



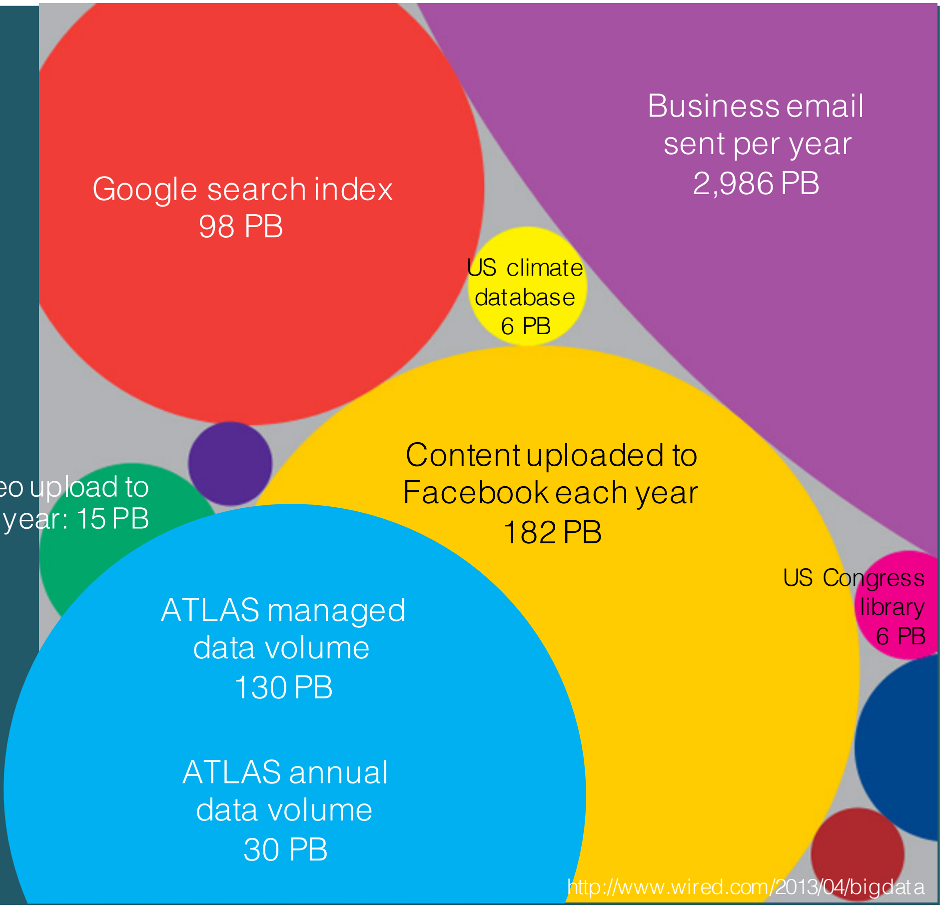
Also reconstruct jets, b-jets and missing transverse momentum (MET)

Ensemble of measured detector response in a given proton–proton bunch crossing makes up an “event”

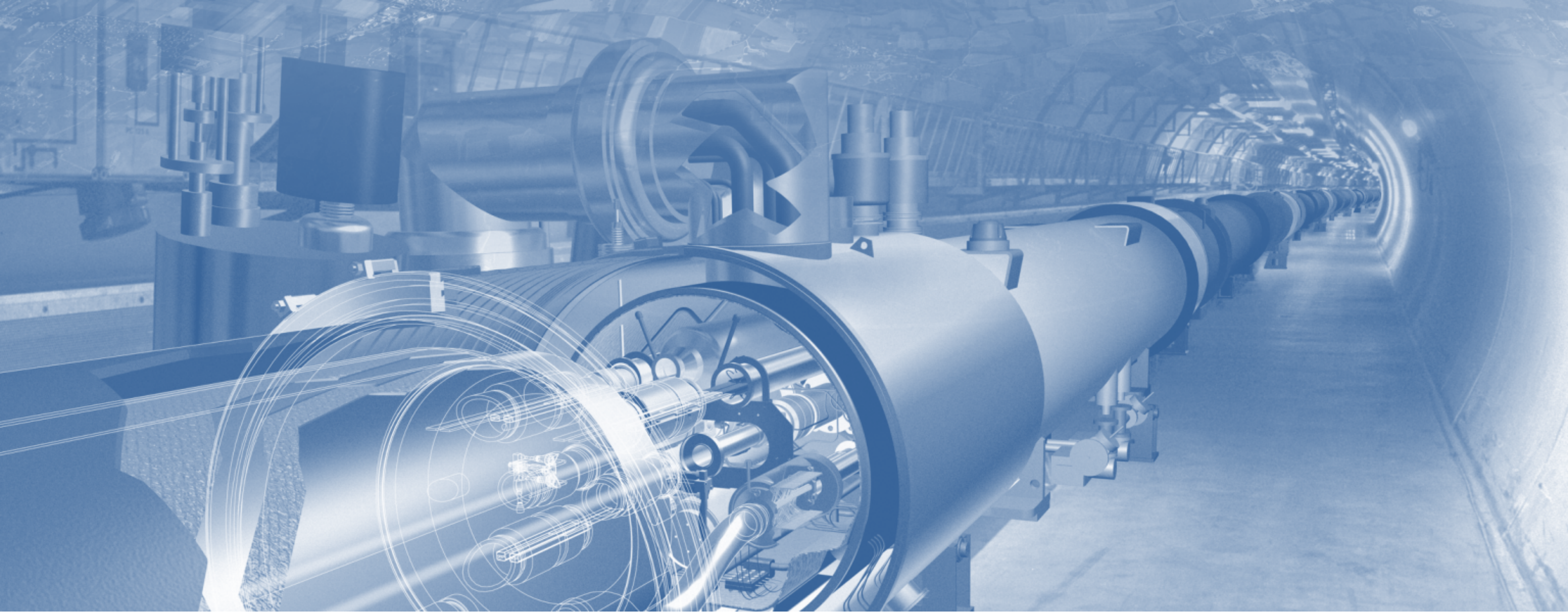
LHC computing is big data

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

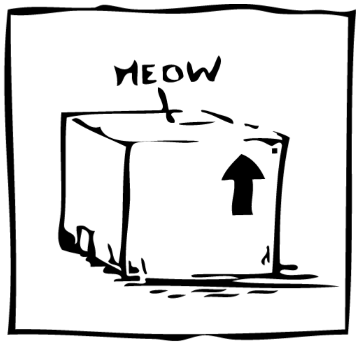
Note: LHC has a public science budget, unlike Google or Facebook

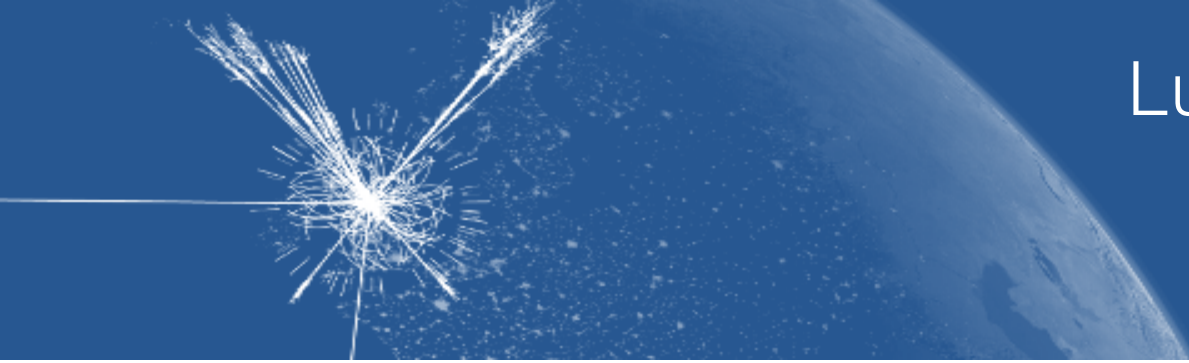


Largest data volume from simulated events, not from real collision data !



A few (basic) experimental concepts at the LHC





Luminosity — single most important quantity

- Luminosity is a function of the LHC beam parameters

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

$L_{\text{max}} \sim 1.6 \times 10^{34}\ \text{s}^{-1}\text{cm}^{-2}$

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

$\sim$ 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, $\sigma^2_{x/y} = \varepsilon_{x/y}\,\beta^*_{x/y}$

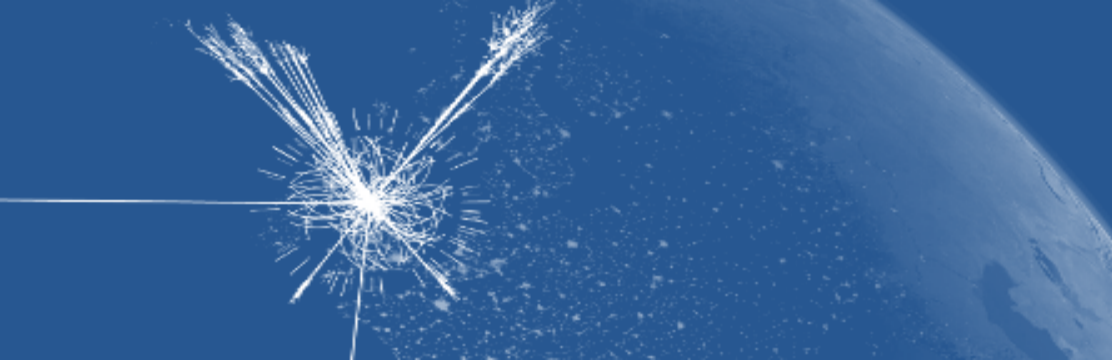
- Luminosity drives our ability to detect low cross-section processes

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

“Cross section” given by Nature

“Efficiency” of detection optimised by experimentalist

Integrated luminosity delivered by LHC

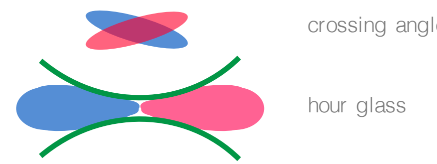


Luminosity — single most important quantity

- Maximising luminosity

Compensate reduction factor

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



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

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.

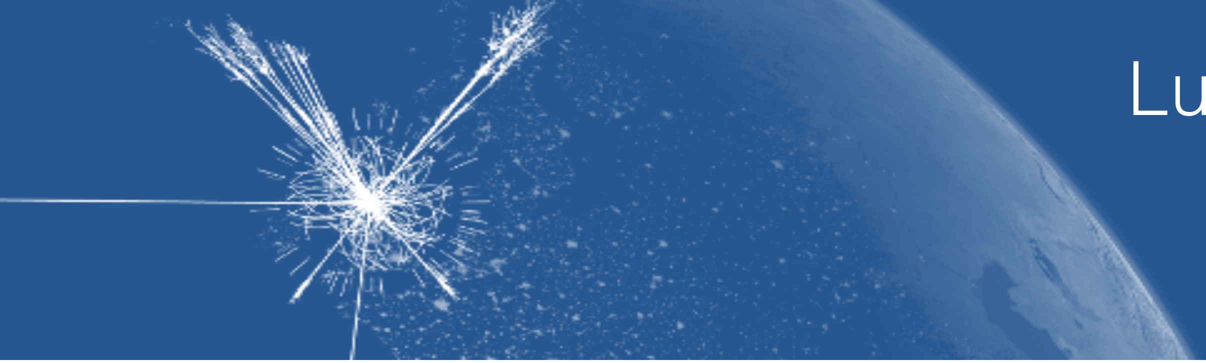
Maximise brightness & energy, minimise β^*

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

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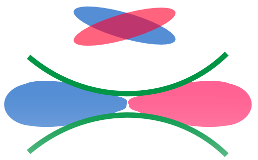
Crossing angle (0.3 mrad) and "hourglass effect" (σ_z ~ 4–6 cm)



crossing angle

hour glass

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

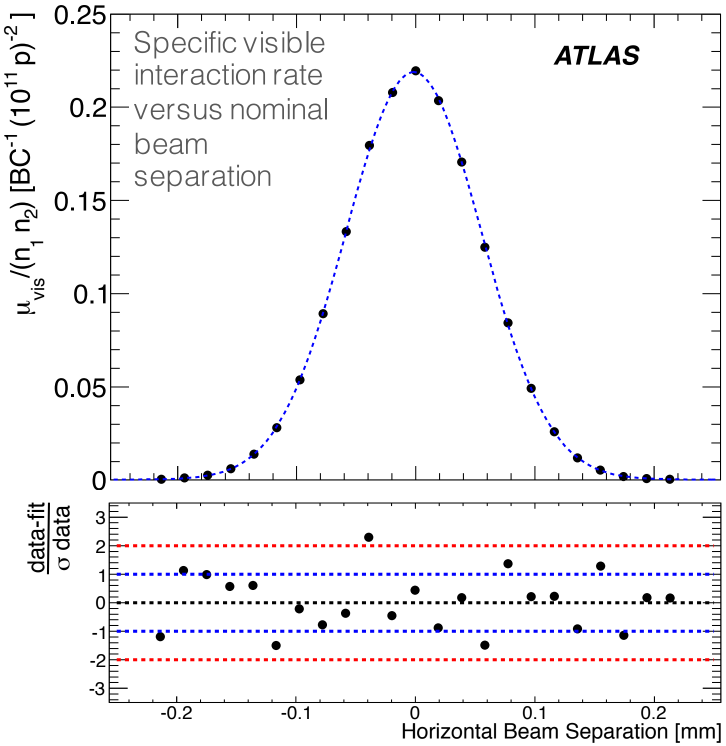
- The luminosity detectors of the experiments are calibrated with beam-separation scans (the so-called "van-der-Meer method")

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

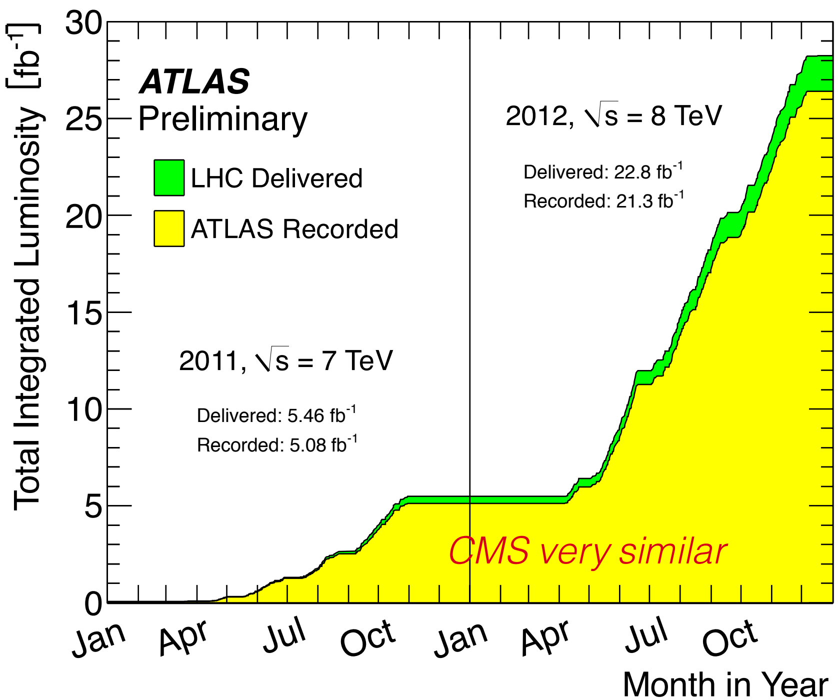
- $\Sigma_{x/y}$ = horizontal and transverse convolved beam widths directly determined from the scan

- 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



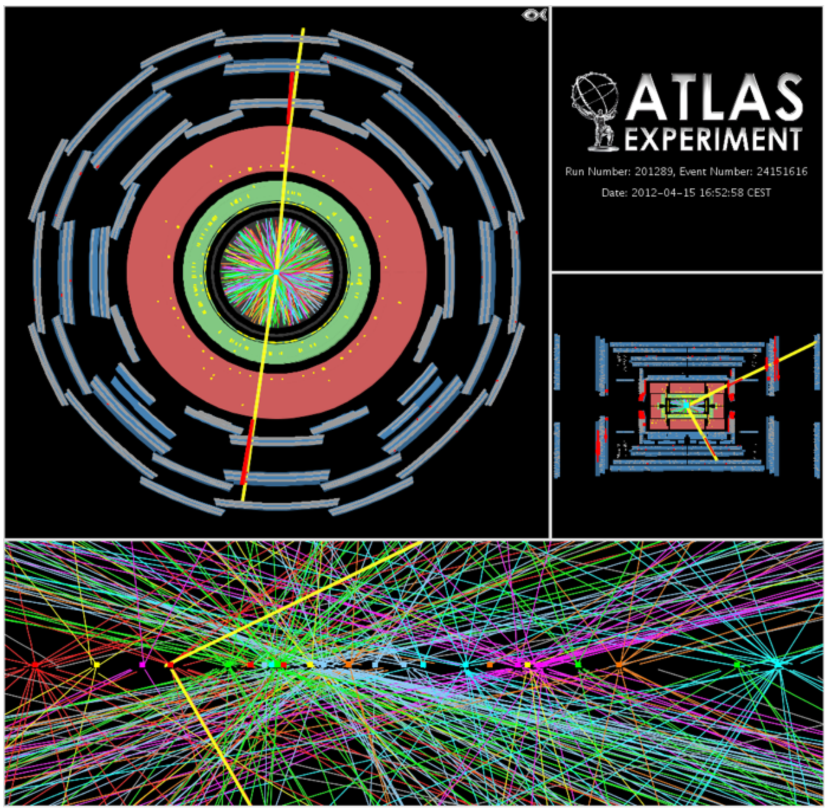
Luminosity — single most important quantity



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):

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

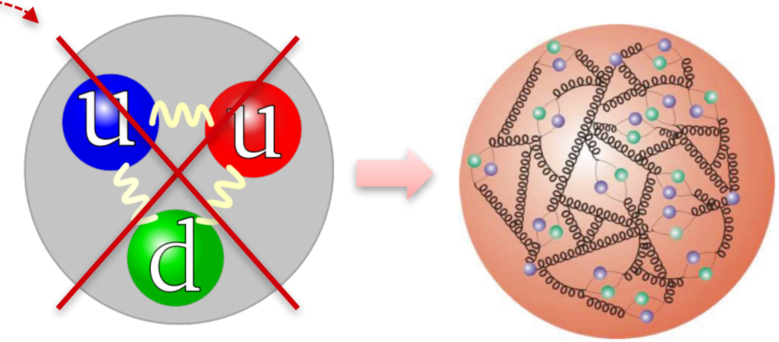
- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- However: higher trigger thresholds
  → low-p_T physics suffers

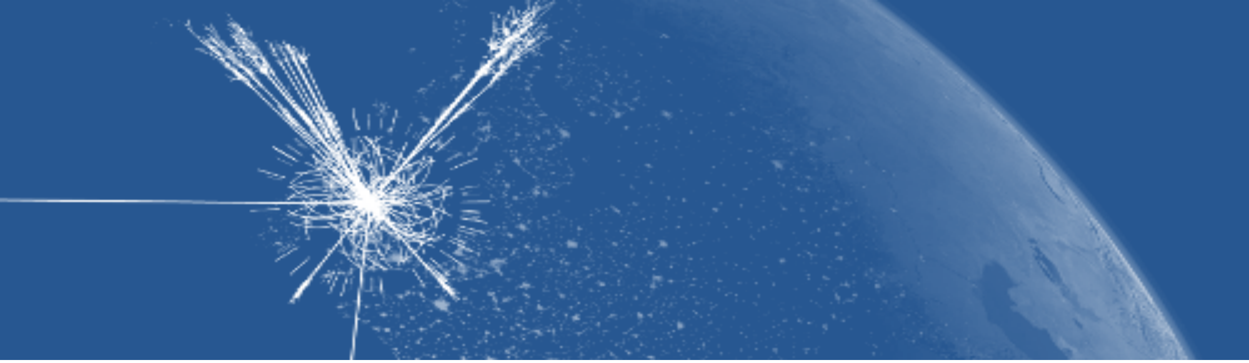
Proton–Proton Collisions

- 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





Proton–Proton Collisions

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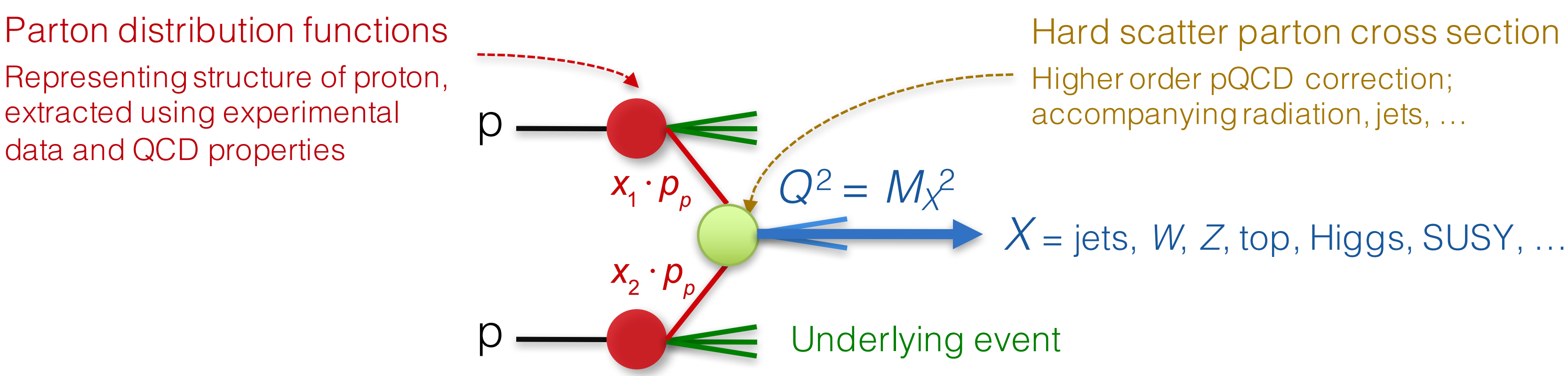
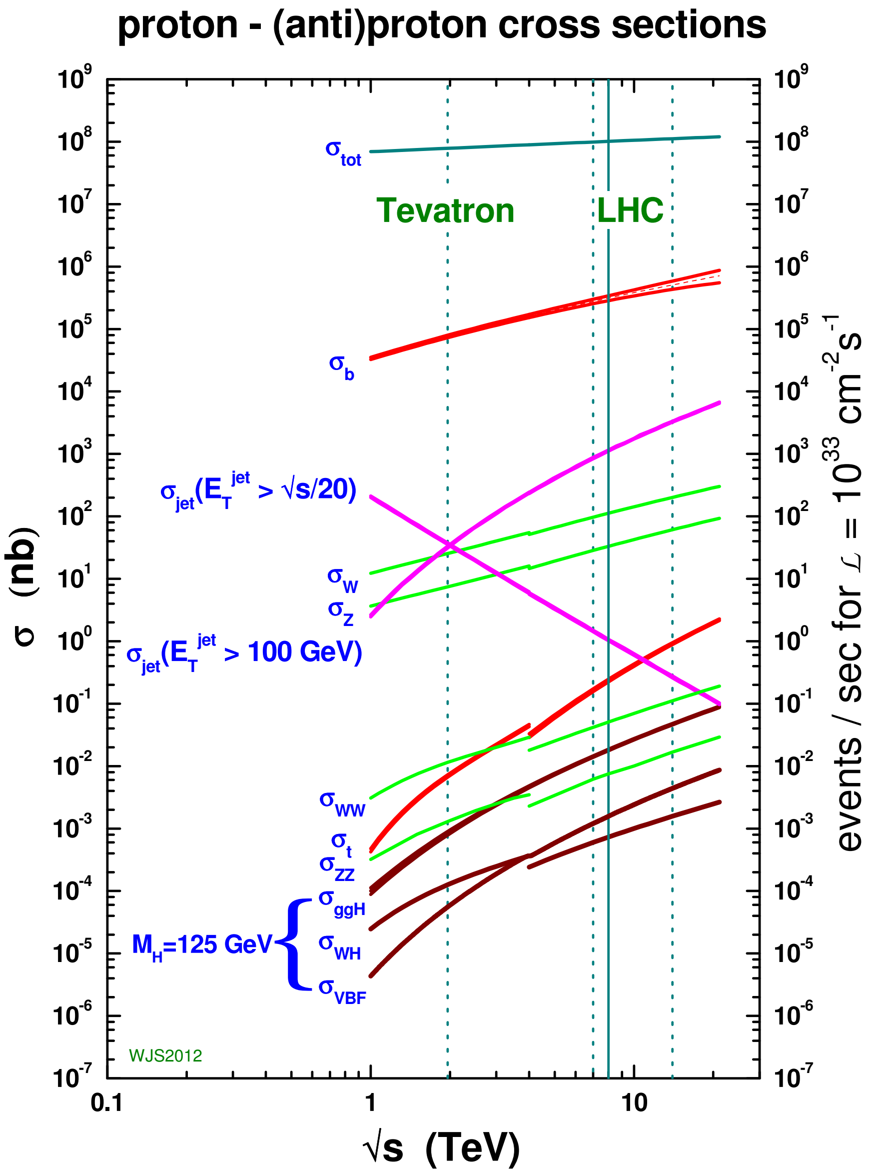


- CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\mathrm{LHC}}$
- The parton density functions rise dramatically towards low x:
  - Higher cross section at higher proton–proton collision energy
  - More luminosity also achieves higher achievable energy
  - Low-x regime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

Proton–Proton Collisions

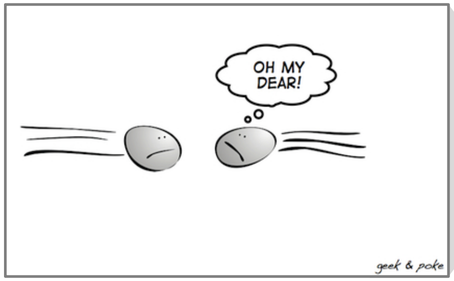


- Cross-section fully dominated by inelastic strong interaction "minimum bias" events
- Detectors cannot record 40 MHz event rate* (each event ~2 MB size → 80 TB / second)
- Online custom hardware and software "triggers" reduce rate to filter out events with a million & more times smaller cross-sections than minimum bias events

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

The data path in a nutshell
(example ATLAS)

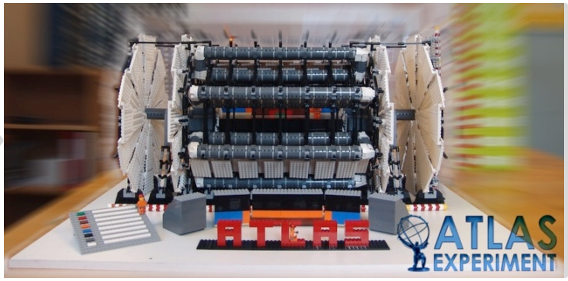
Large Hadron Collider



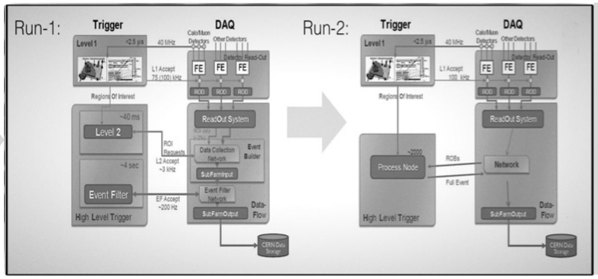
25/50 ns bunch distance

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

LHC Detector



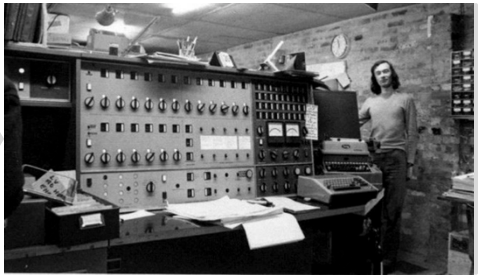
Trigger & Online monitoring



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



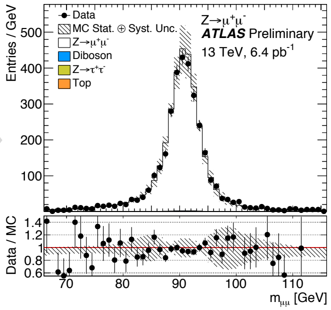
48h calibration & data quality processing, then prompt reconstruction of data in Tier-0

Distributed computing

Production of standardised derived datasets for physics and performance analysis

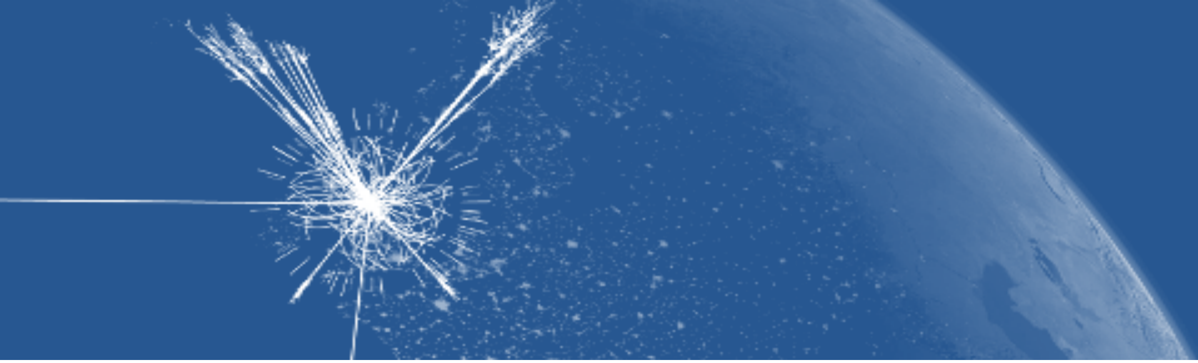
Also: MC production — O(4 billion) 13 TeV events produced per experiment

Analysis



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

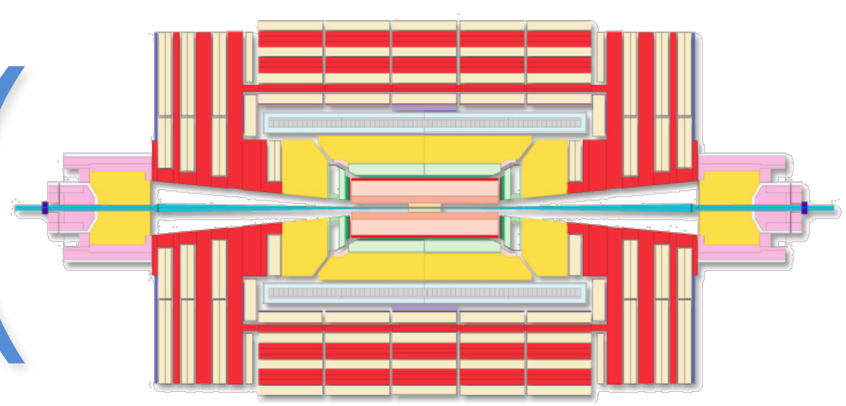
Analysis groups build physics analyses upon this ground work



Trigger

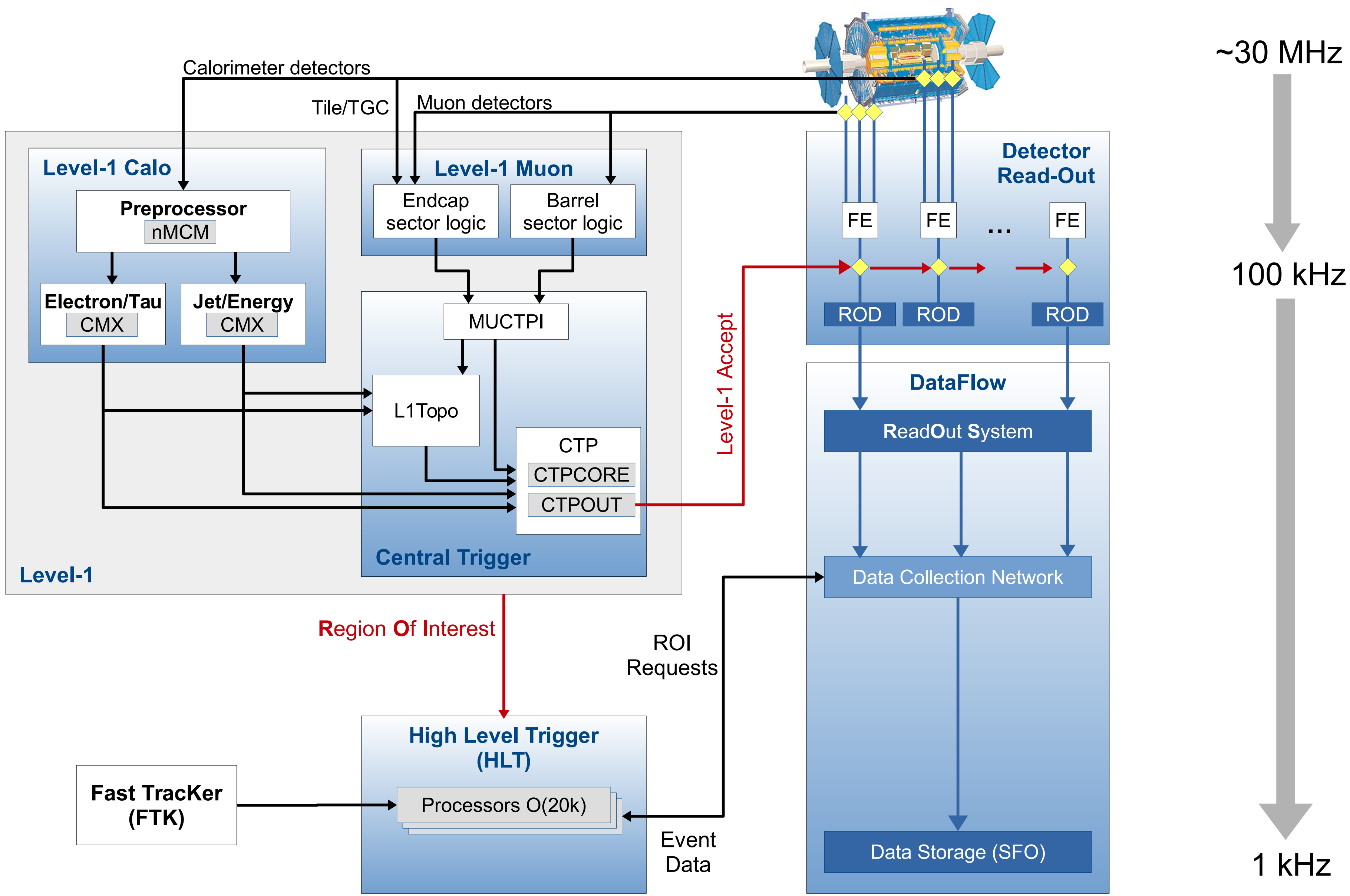
First selection filter: reduce initial event rate by factor of one million for recording.

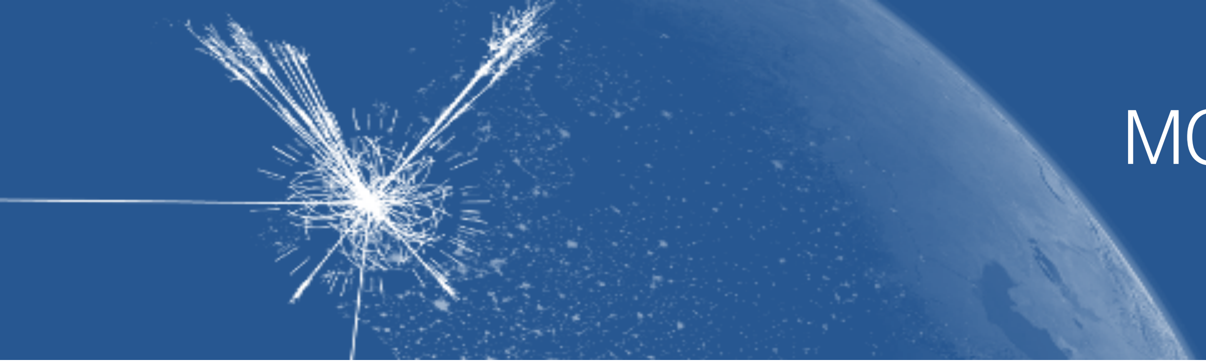
For each **event** the Trigger is a function of the event data, the apparatus, physics channel and parameters

T() = Accept / Reject

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





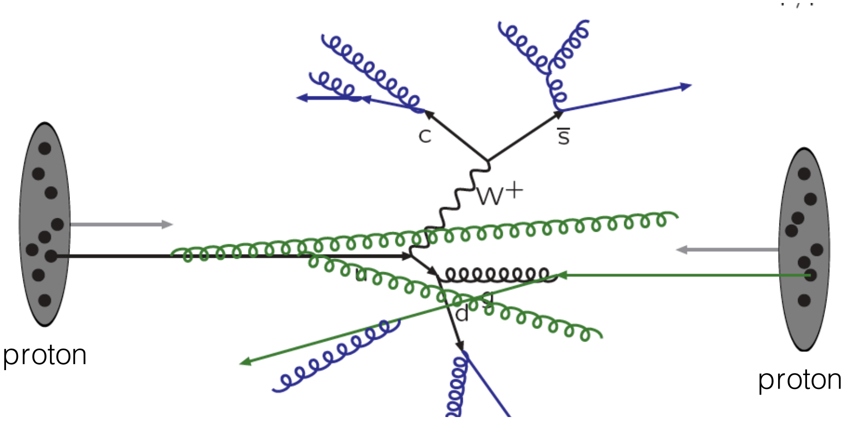
MC event simulation is key for analysis

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

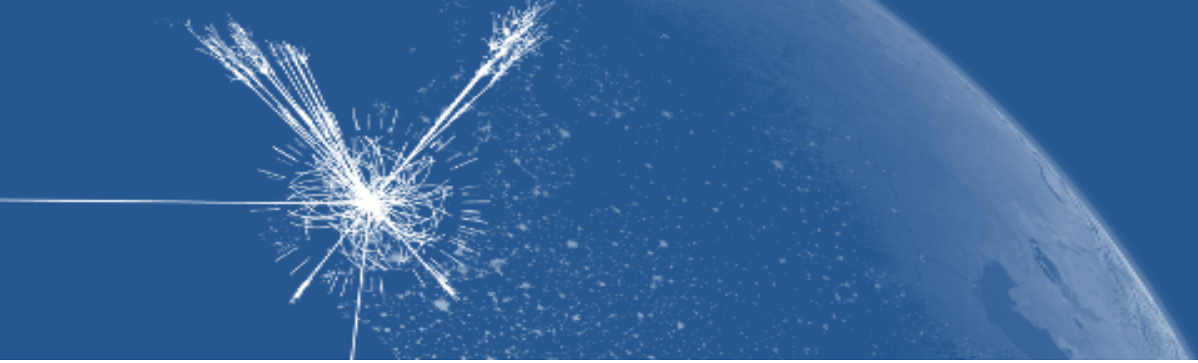
- Event generation: Hard scattering event
- Detector simulation: Geant4 or parameterised
- Digitisation: Mimics detector readout; "Mix-in" pileup events
- Reconstruction: Same as for real data

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

Progress in theoretical calculations — **NNLO revolution**

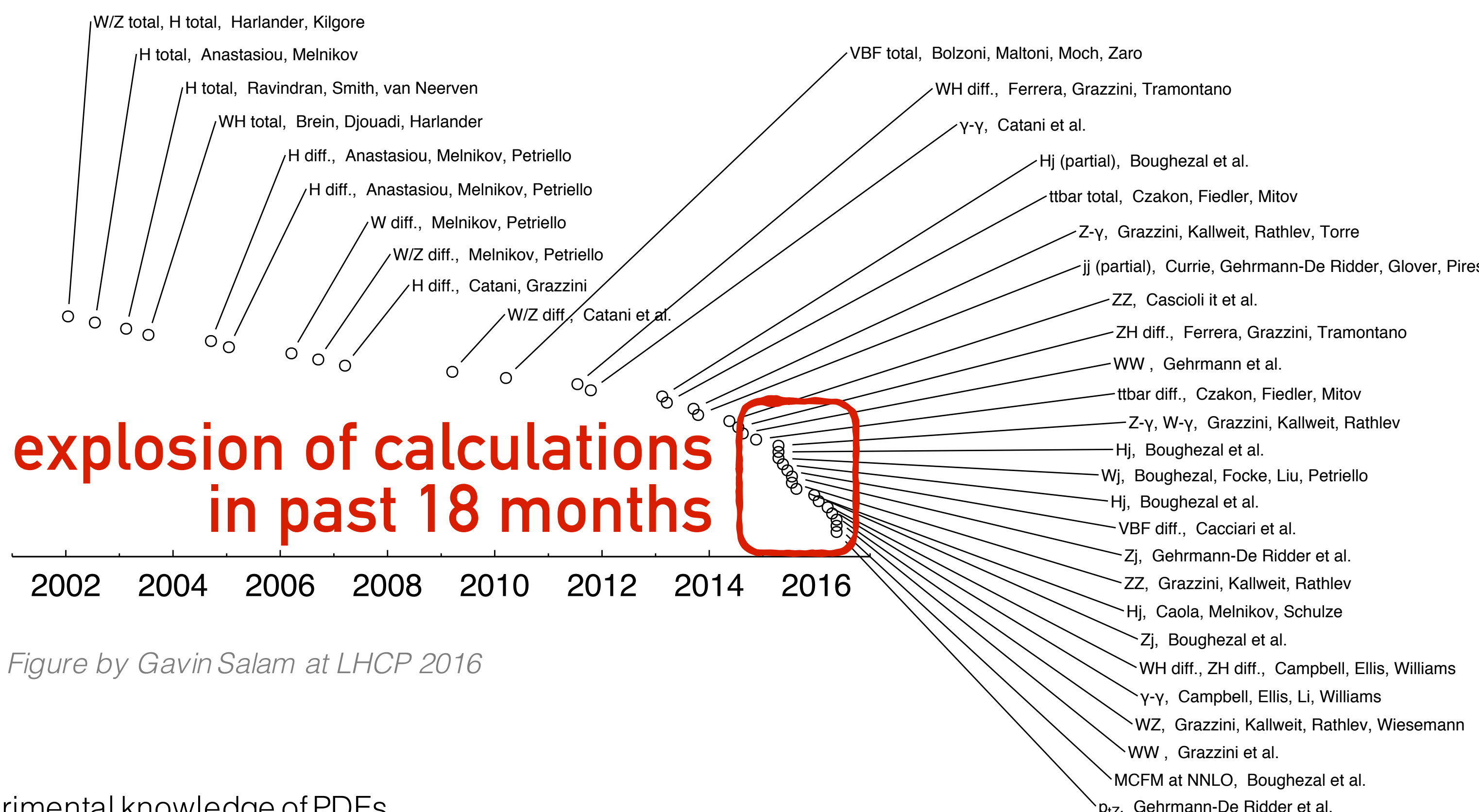
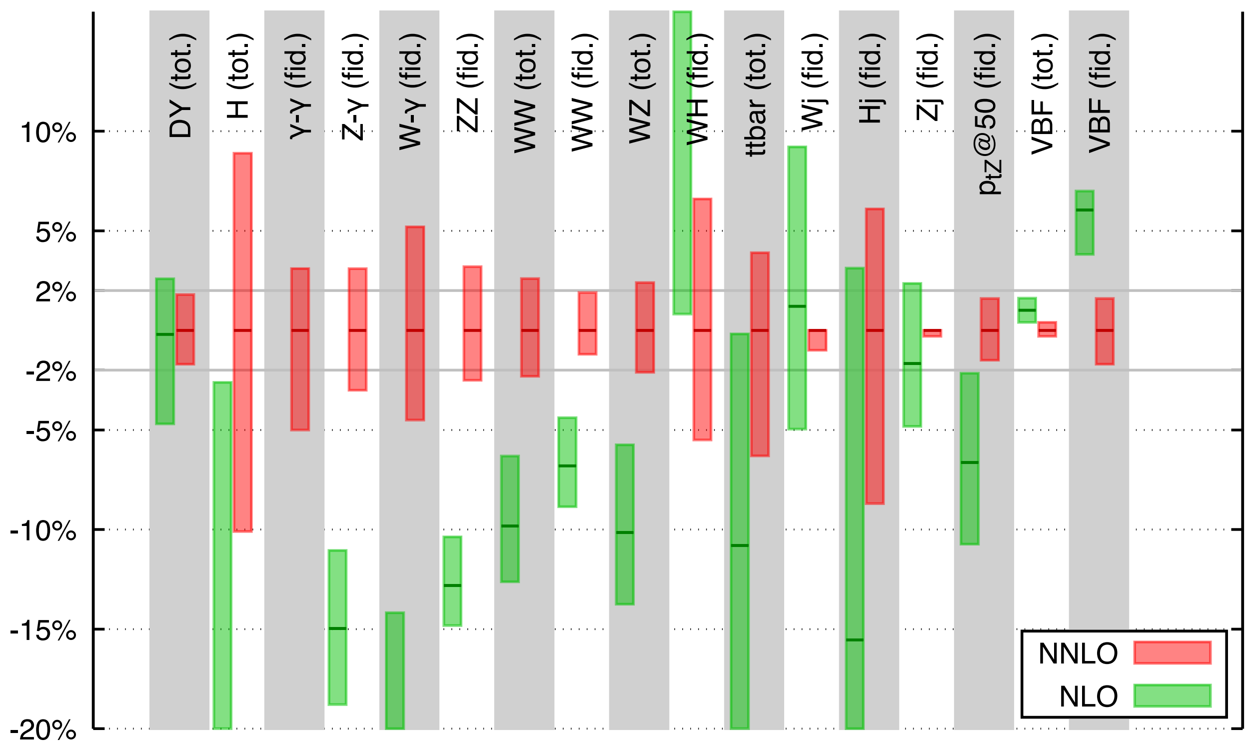


Figure by Gavin Salam at LHCP 2016

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

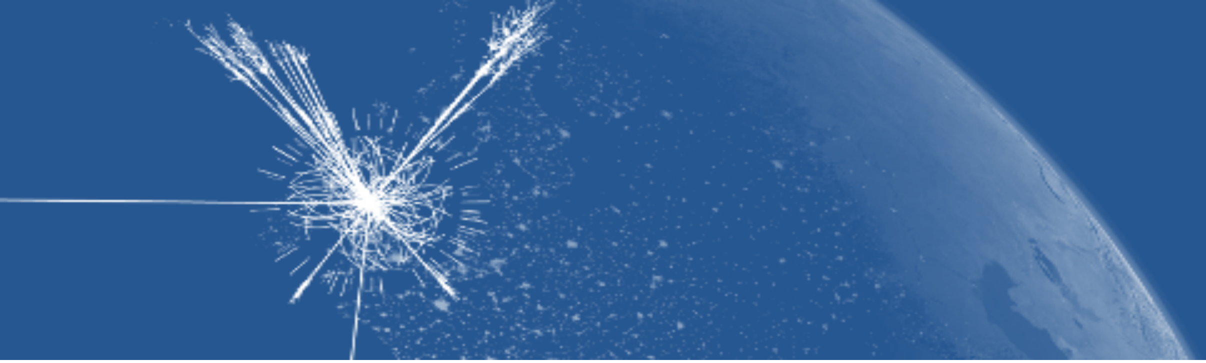
Theoretical cross-sections and uncertainties

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

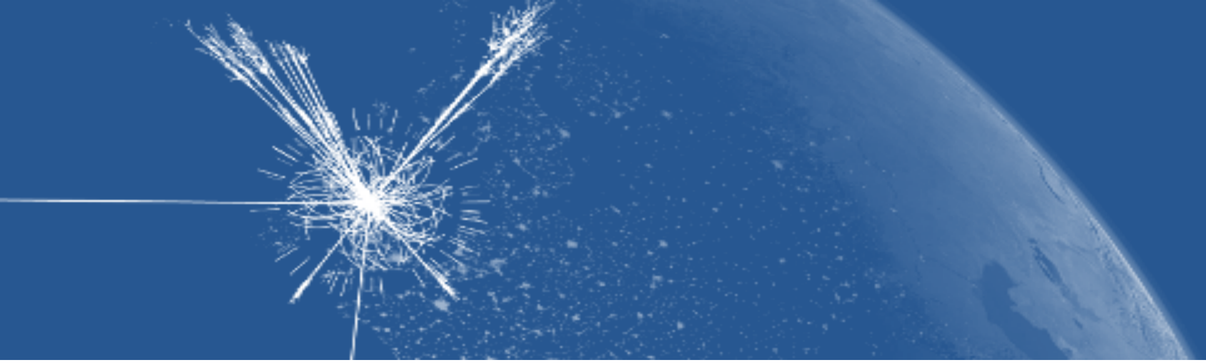
Main experimental measurement

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

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

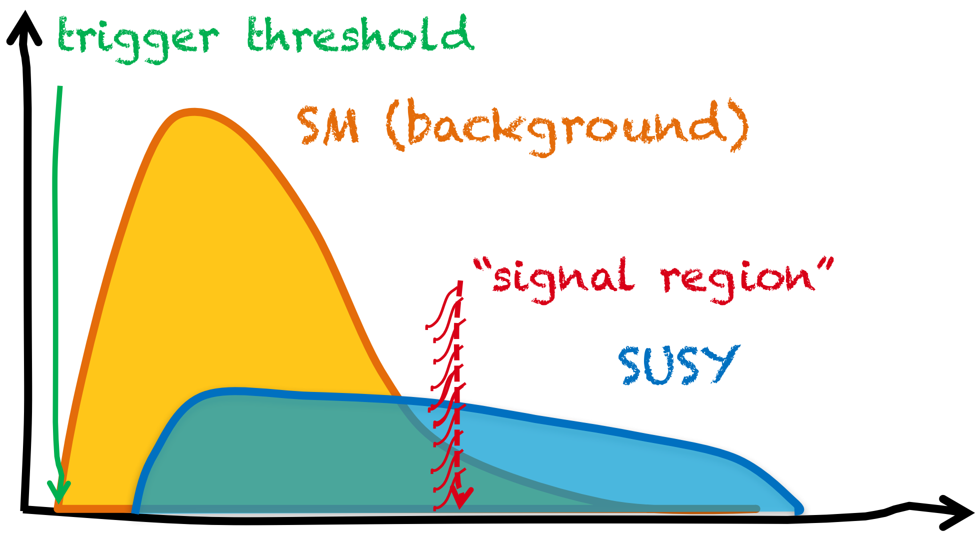
C_X : correction factor = $N_{\mathrm{reco,selected}}$ / $N_{\mathrm{gen,fiducial}}$

- 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}



$$m_{\text{eff}} = \underbrace{\sum_{\text{jets}} p_T + \sum_{\text{leptons}} p_T}_{H_T} + E_T^{\text{miss}}$$

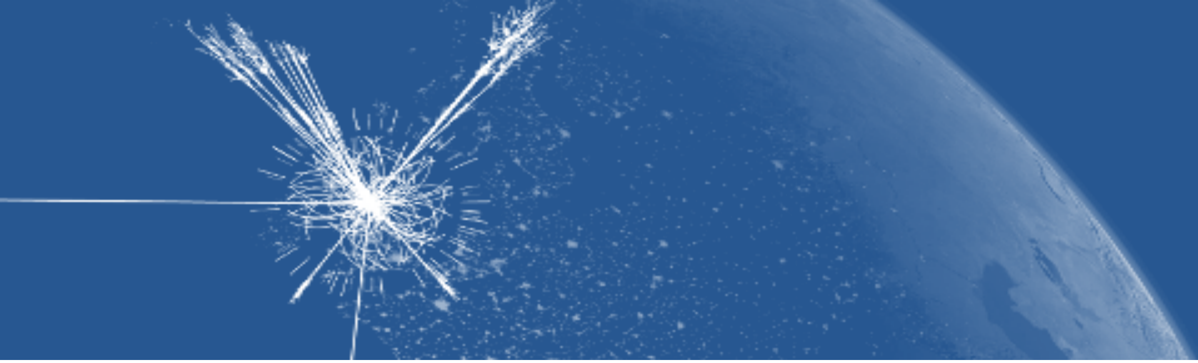
Requires **reliable** estimate of SM backgrounds in signal region

Main background sources:

- $tt \to W(\to \ell(\tau)\,\nu)b + W(\to qq)\,b$
- W($\to \ell\,\nu$) + jets
- Z($\to \nu\,\nu$) + 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.)

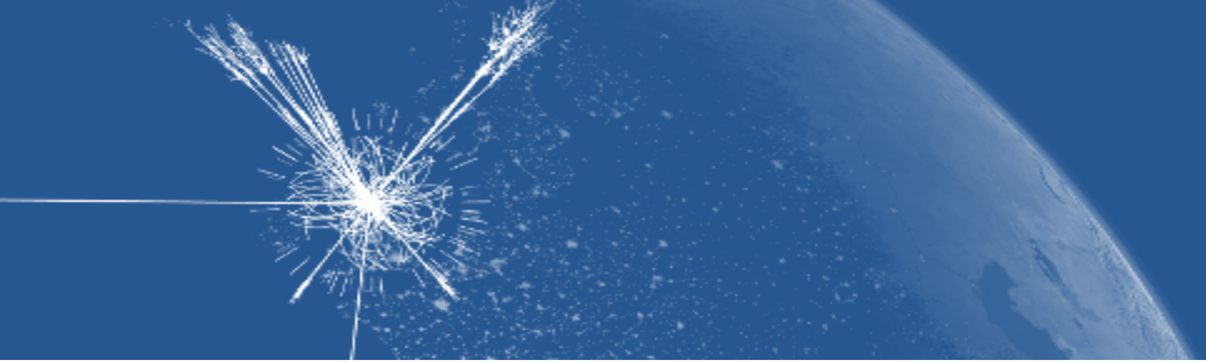


Basic physics objects

All LHC physics analyses use basic “physics objects” :

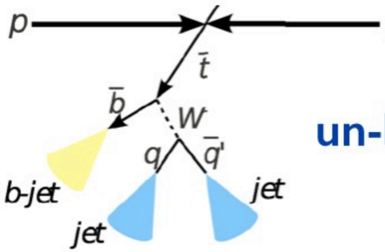
Object	Reconstructed how?	Calibrated how?
Tracks & vertices	Inner tracking systems	Hit residuals (alignment), hadrons, MC
Electron / photon	EM calorimeter cluster, track(s)	Z, $J/\psi \to ee(\gamma)$, $W \to e\nu$, π^0, MC(γ)
Muon	Inner tracker and muon system combined	Z, Y, $J/\psi \to \mu\mu$
Tau (hadronic decay)	Inner tracker and EM & had calorimeters*	$Z \to \tau\tau$, E_{calo}/p
Jet	Inner tracker and EM & had calorimeters*	Di-/multijet balance, γ + jet, Z + jet
Missing E_T	Reconstructed objects + “soft” objects*	$Z \to \mu\mu$ (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

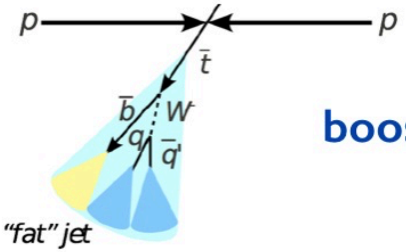


Reconstructing boosted particles

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



un-boosted

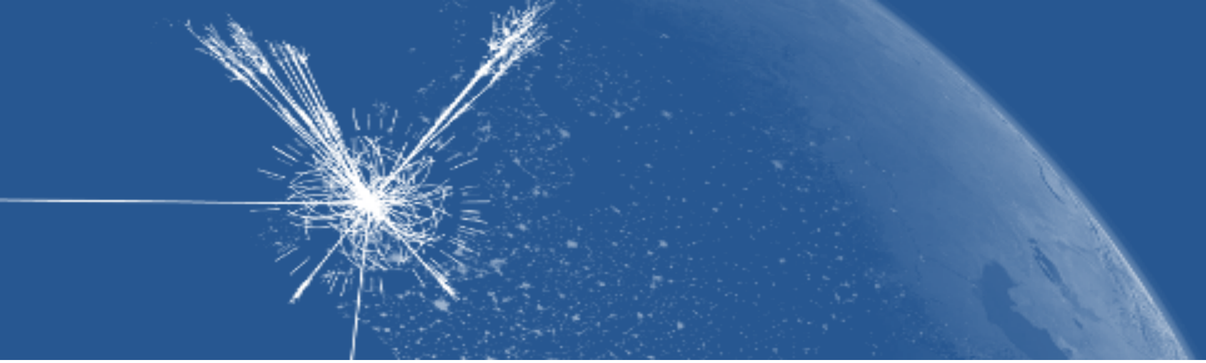


boosted

$\Delta R \sim 2m\,/\,p_T$

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)

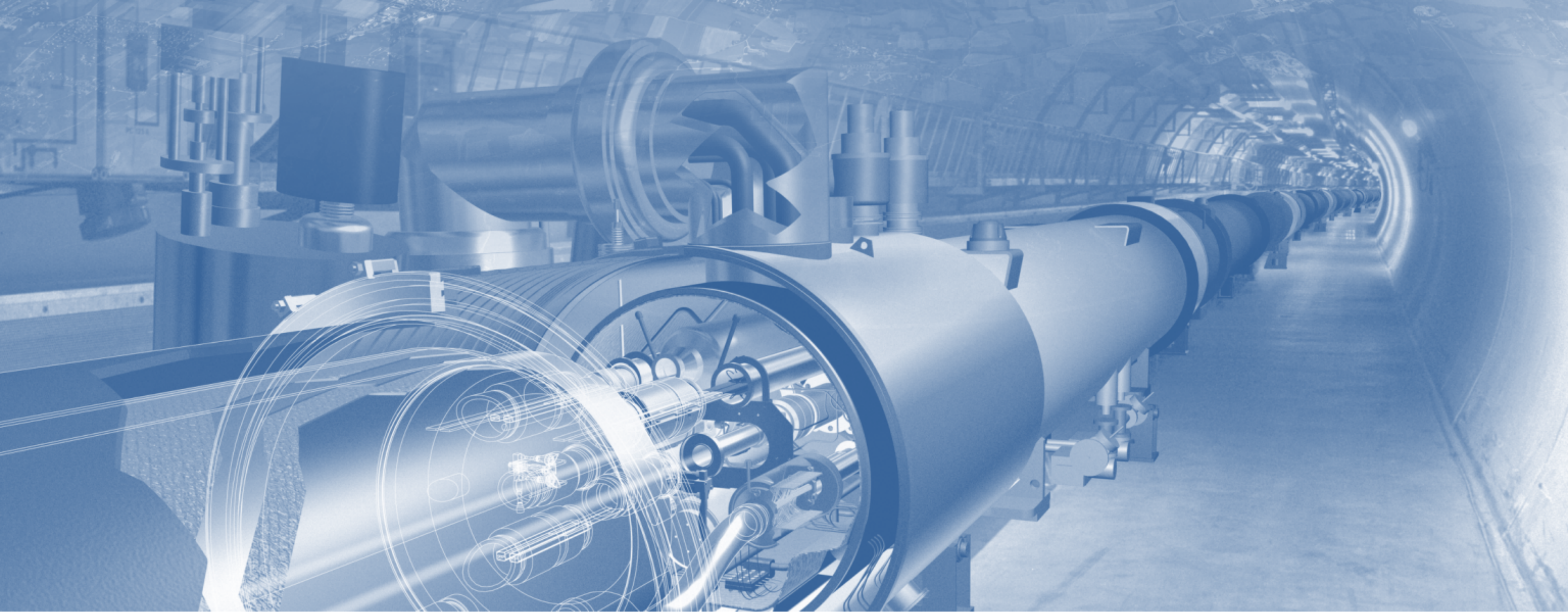


Systematic uncertainties

The **evil** in every measurement

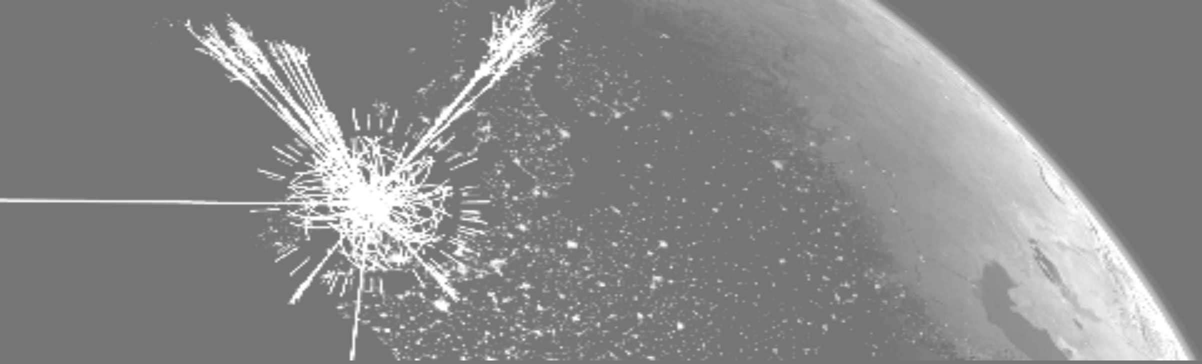
- Well designed experiments minimise as much as possible systematic uncertainties (full coverage, measurement precision, homogeneity and linearity, λ depth, longevity of components, etc)
- Understanding, estimating and reducing remaining systematic uncertainties is often the main analysis challenge
- 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.



Tomorrow:

Highlights from LHC’s Run-1 and results from Run-2



Extra slides

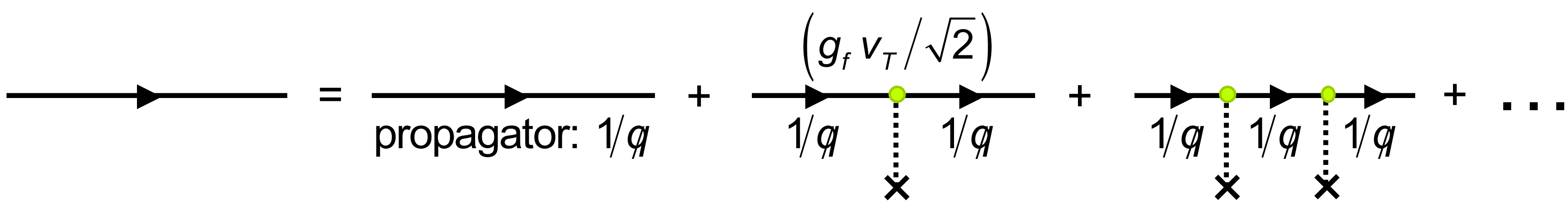
The Standard Model

BEH mechanism

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

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

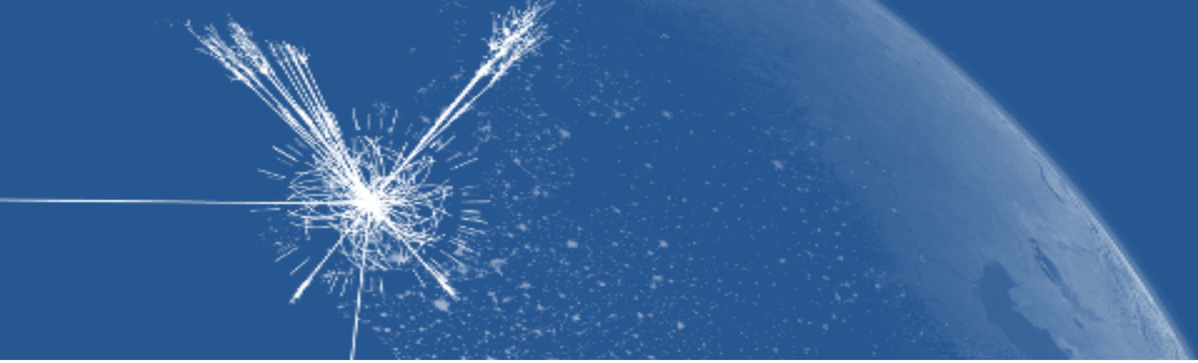
At T < T_{EW}, the massless fermion fields interact with the non-vanishing BEH “condensate”:



Geometric series yields massive propagator creating effective mass for fermion:

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

And similar for gauge bosons



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