Electroweak precision measurements

$\sin^2\theta_W$ and Z asymmetries from hadron colliders

CDF, D0, and also LHC have extracted weak mixing angle from Z/γ^* asymmetry measurements

Uncertainties at Tevatron dominated by statistical uncertainties, LHCb equally, ATLAS & CMS by PDF uncertainties.

Data-driven "PDF replica rejection" method applied by CDF

Complex measurements (in particular physics modelling) that are important to pursue, but precision of hadron colliders not yet competitive with LEP/SLD

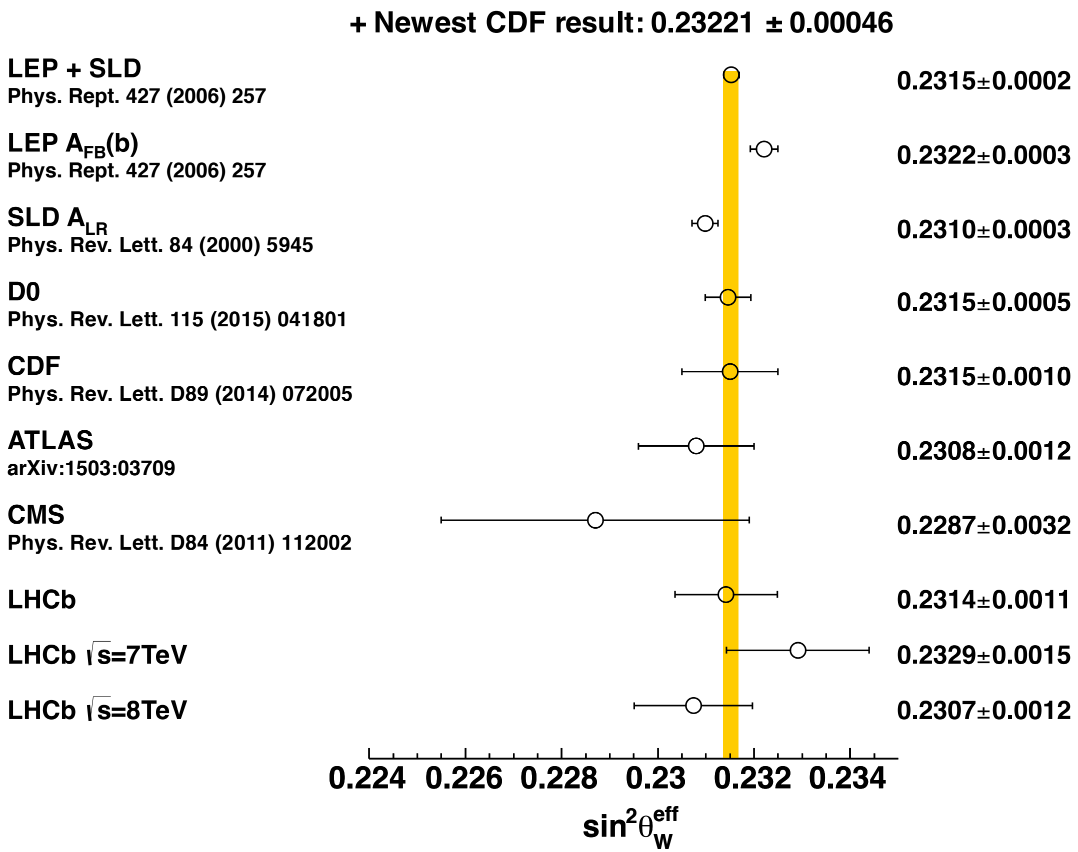


Figure from LHCb 1509.07645

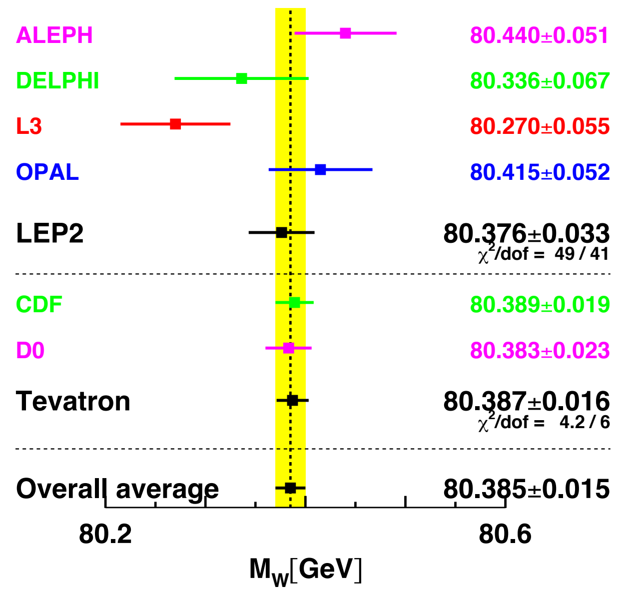
Electroweak precision measurements

W mass: towards a first measurement at the LHC via decay to lepton + neutrino

Brief history of W mass measurements:

- 1983 CERN SPS: W discovery
- 1983 UA1: m_W = 81 ± 5 GeV
- 1992 UA2 (with m_Z from LEP): 80.35 ± 0.37 GeV
- 2013 LEP: 80.376 ± 0.033 GeV
- 2013 Tevatron: 80.387 ± 0.016 GeV
- World average: 80.385 ± 0.015 GeV

Current experimental picture for m_W



Quite a surprise that WA is dominated by hadron collider, which was not built with that goal in mind.

Hardest measurement in HEP: O(7) years to accomplish it

LHC also not built for W mass, but to discover new particles

Unfavorable environment at LHC compared to e^+e^- or proton–antiproton colliders

At Tevatron, W production dominated by valence quarks. At LHC sea & heavy quarks much more important

This difference affects all aspects of the measurement: detector calibration, transfer from Z to W, PDF uncertainties, W polarisation, modelling of p_T W

Very challenging — but also very interesting: **a lot** to learn on the way !

Electroweak precision measurements

W mass: towards a first measurement at the LHC via decay to lepton + neutrino

ATLAS and CMS are progressing towards the m_W measurement at the LHC

Measurement relies on excellent understanding of **final state**

Observables: $p_{T,\ell}$, $p_{T,\nu}$, m_T as probes of m_W

Challenges, high-precision:

- Momentum/energy scale (incl. had. recoil) calibration: Z, J/ψ, Y
- Signal efficiency and background modelling
- Physics modelling:
  - Production governed by PDF & initial state interactions (pert & non-pert): use W^+, W^-, Z, W+c data for calibration, and NNLO QCD calculations + soft gluon resummation
  - EW corrections well enough known
  - Probes very sensitive to W polarisation (and hence to PDF, including its strange density)

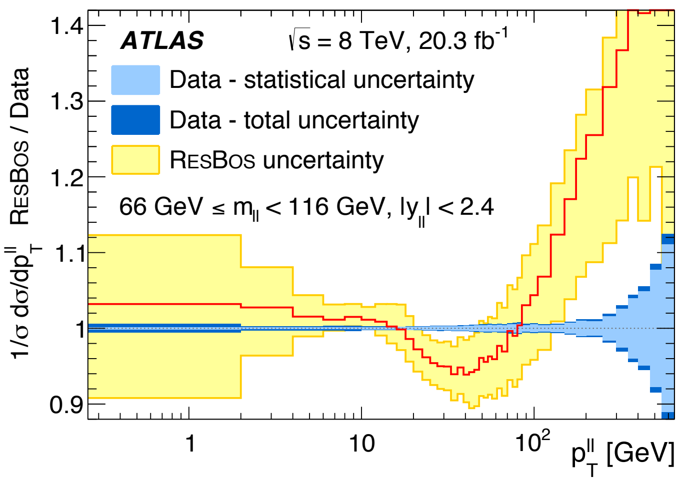
Project: Experiments are in a vigorous process of addressing the above issues. Many precision measurements (differential Z, W + X cross sections, polarisation analysis, calibration performance, …) produced on the way. Also theoretical developments mandatory. **Long-term effort.**

Electroweak precision measurements

Comprehensive Z p_T and polarisation measurements done by both CMS and ATLAS

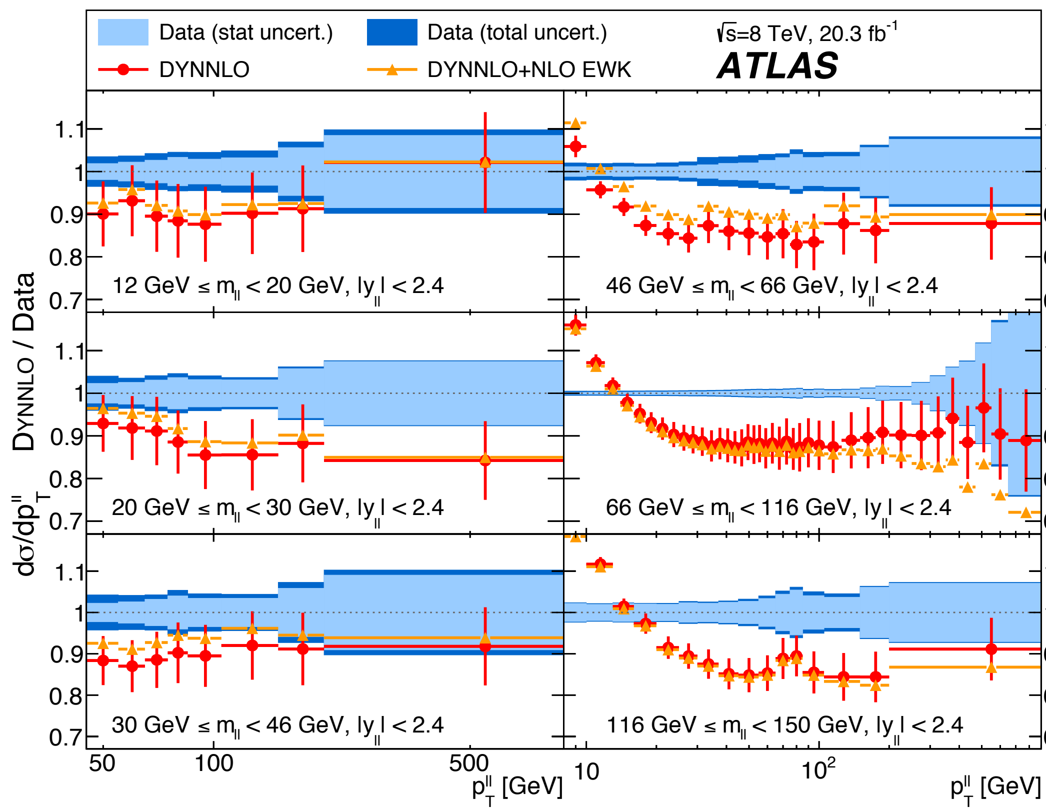
ATLAS and CMS use precise measurements of $p_T(Z)$ to tune $p_T(W)$ modelling, which relies on NNLO and NNLL/resummed calculations. But: different generators predict different transfers from Z to W.

Also: PDFs play different roles in Z and W production.



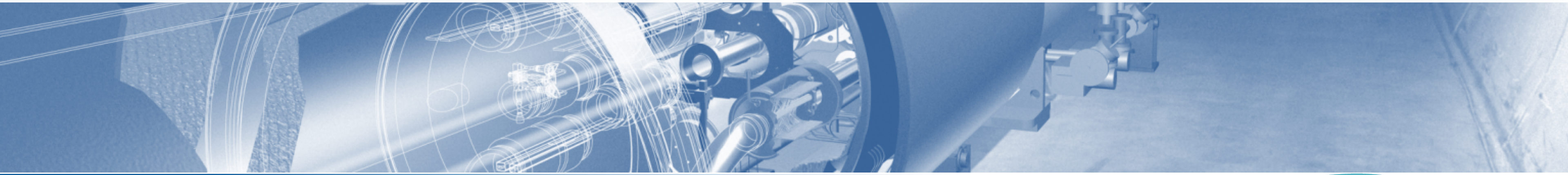
RESBOS: ISR at approximate NNLO, γ*–Z interference at NLO, NNLL soft-gluon resummation, no FSR or hadronic event activity, CT14 PDF.

DYNNLO: QCD production at NNLO, no soft-gluon resummation, CT10 PDF.

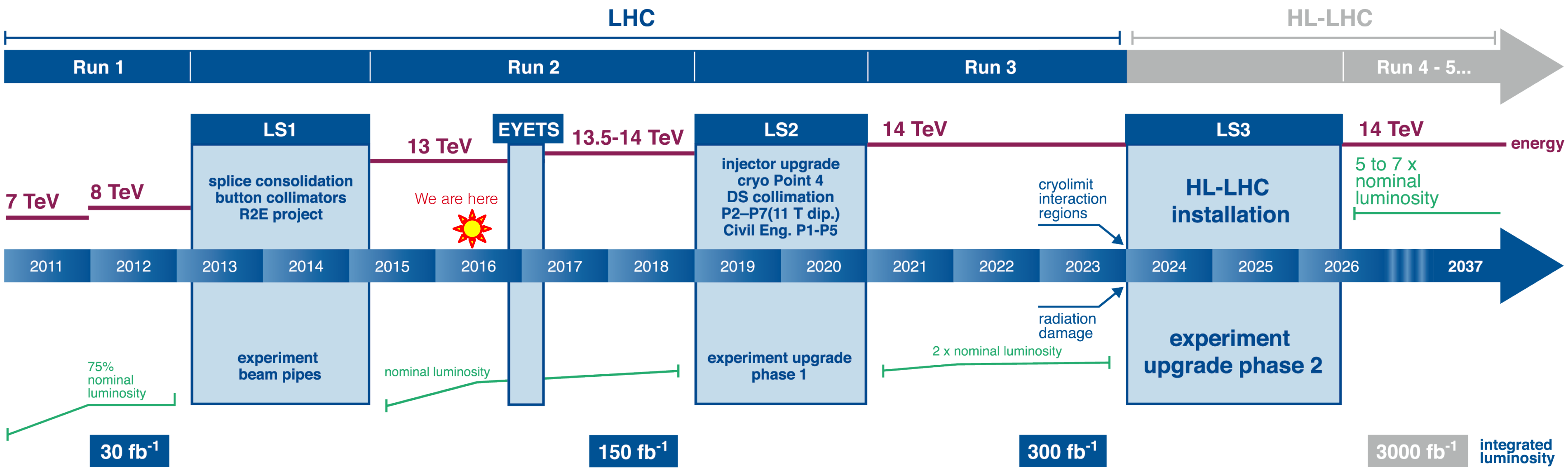


The road to the future

The LHC Run-2 and beyond

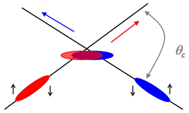


LHC / HL-LHC Plan



How can these LHC luminosity improvements be achieved ?

Crab crossing:
(deflects head and tail in opposite direction)



Run-1

- E_{beam} = 0.45–4 TeV
- L_{max} = 0.8 ×10^{34} $cm^{-2}s^{-1}$
- Δt_{bunch} = 50 ns
- $N_{bunches,max}$ = 1380
- β^* = 60 cm
  [recall: $L \propto (\sigma_x \sigma_y)^{-1} = (\varepsilon_n \beta^*/\gamma)^{-1}$]
- Norm. emittance ε_n ~ 2.3 μm
- $N_{protons\ /\ bunch}$ ≤ 1.7 · 10^{11}
- <μ> ~ 21
  (note: μ_{peak} much larger)

Run 2 & 3 (13–14 TeV)

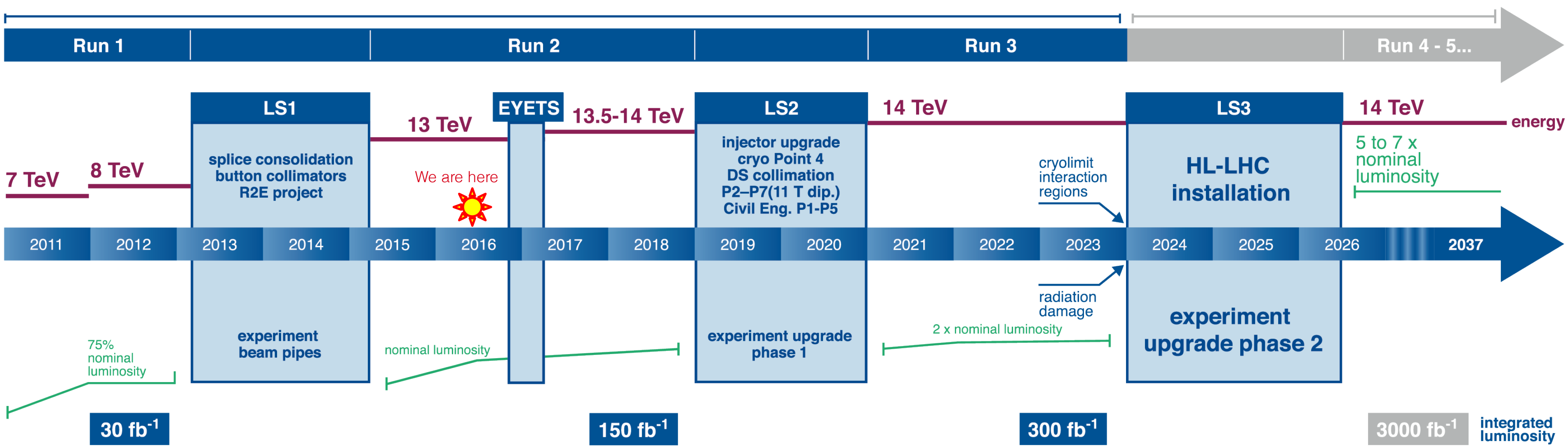
- E_{beam} = 6.5–7 TeV
- L_{max} = 0.7–2 ×10^{34} $cm^{-2}s^{-1}$
- Δt_{bunch} = 25 ns
- $N_{bunches,max}$ = 2028~2748 (?)
- β^* = 40 cm
- ε_n = 3.5–2.5 μm (2.3 μm with BCMS)
- $N_{protons\ /\ bunch}$ ~ 1.2 · 10^{11}
- <μ> ~ 21~50

LS2: injector upgrade for increased beam brightness (batch compression in PS, new optics in SPS, collimator upgrades)

HL-LHC (14 TeV)

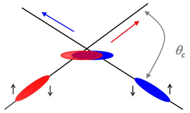
- E_{beam} = 7 TeV
- L_{max} ~ 5 ×10^{34} $cm^{-2}s^{-1}$
- Δt_{bunch} = 25 ns
- $N_{bunches,max}$ = 2748
- β^* = 15 cm
- ε_n = 2.5 μm
- $N_{protons\ /\ bunch}$ = 2.2 · 10^{11}
- <μ> ~ 140

LS3: new triplet design (low-β^* quadrupoles, crab cavities), injector upgrades for luminosity levelling



How can these LHC luminosity improvements be achieved ?

Crab crossing:
(deflects head and tail
in opposite direction)



Run-1	Run 2 & 3 (13–14 TeV)	HL-LHC (14 TeV)

Also significant detector, in particular trigger (goal: keep current thresholds) and inner tracker, upgrades to cope with increased LHC luminosity:

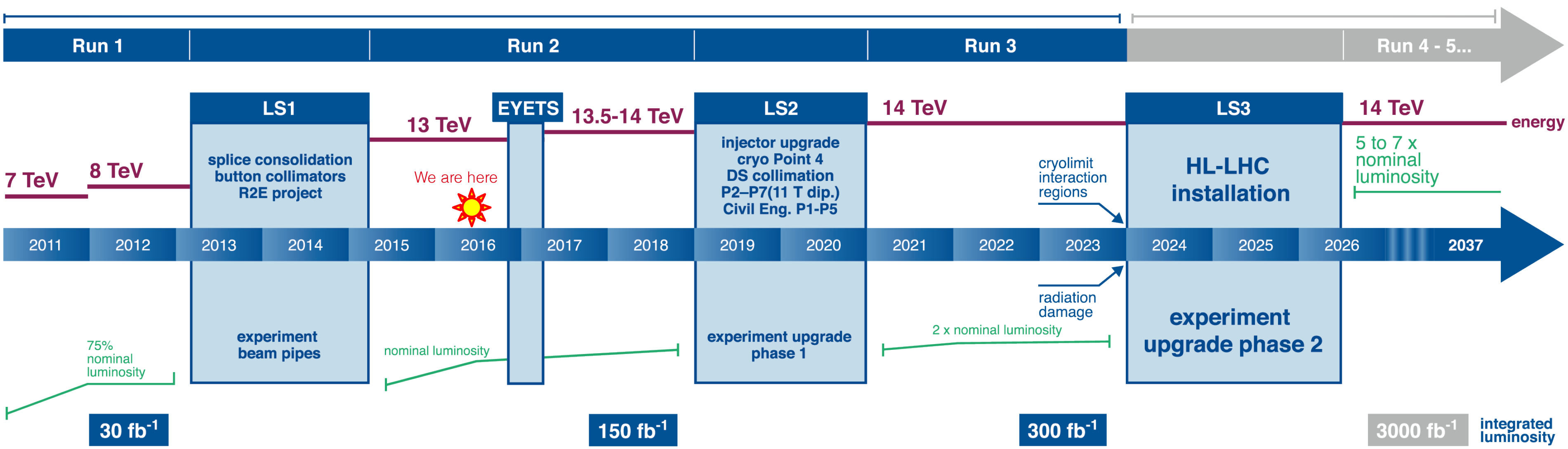
- Phase-1 during LS2 preparing for high-brightness Run-3
- Phase-2 during LS3 preparing for HL-LHC

No time for a discussion here, but happy to follow up during discussion sessions

(note: β_{peak} much larger)

brightness (batch compression in PS, new optics in SPS, collimator upgrades)

quadrupoles, crab cavities), injector upgrades for luminosity levelling



The main proton–proton physics goals in a nutshell

Run 1 (8 TeV)

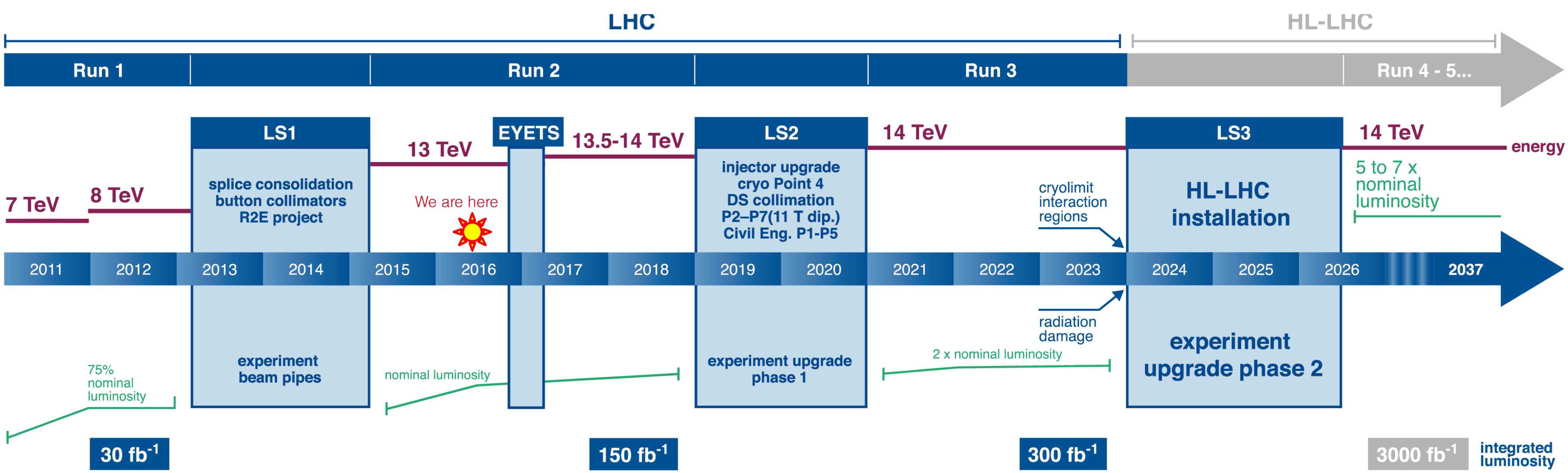
- Discovery of Higgs boson
- Searches for additional new physics (negative)
- Observation of rare processes, such as $B_s \to \mu\mu$
- Precision measurements of Standard Model processes
- Study of *CP* asymmetries in B_s sector

Run 2 & 3 (13–14 TeV)

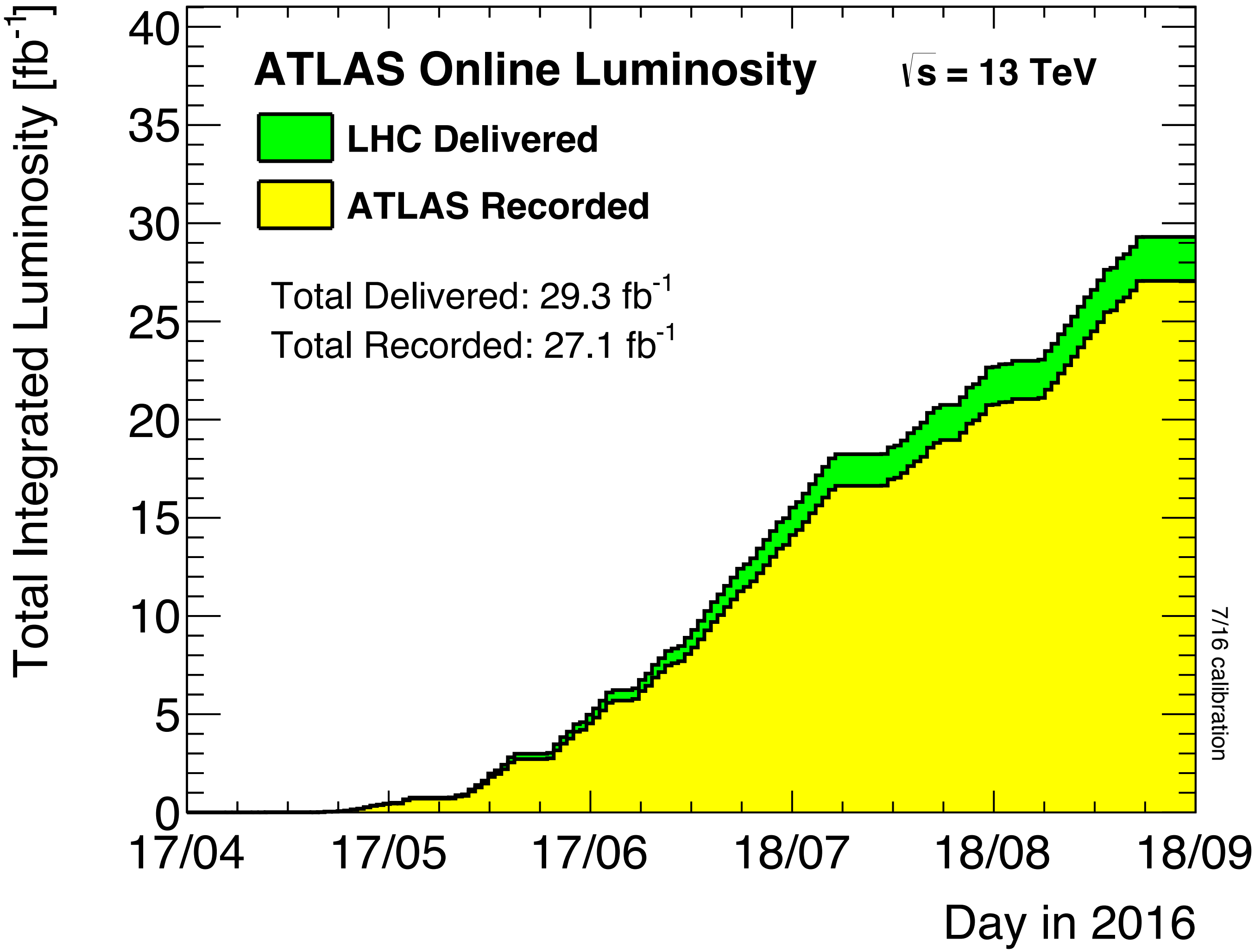
- Searches for new physics
- Improved measurements of Higgs couplings in main channels
- Consolidation / observation of Higgs channels
- Measurement of rare Standard Model processes & more precision
- Improved measurements of rare *B* decays and *CP* asymmetries

HL-LHC (14 TeV)

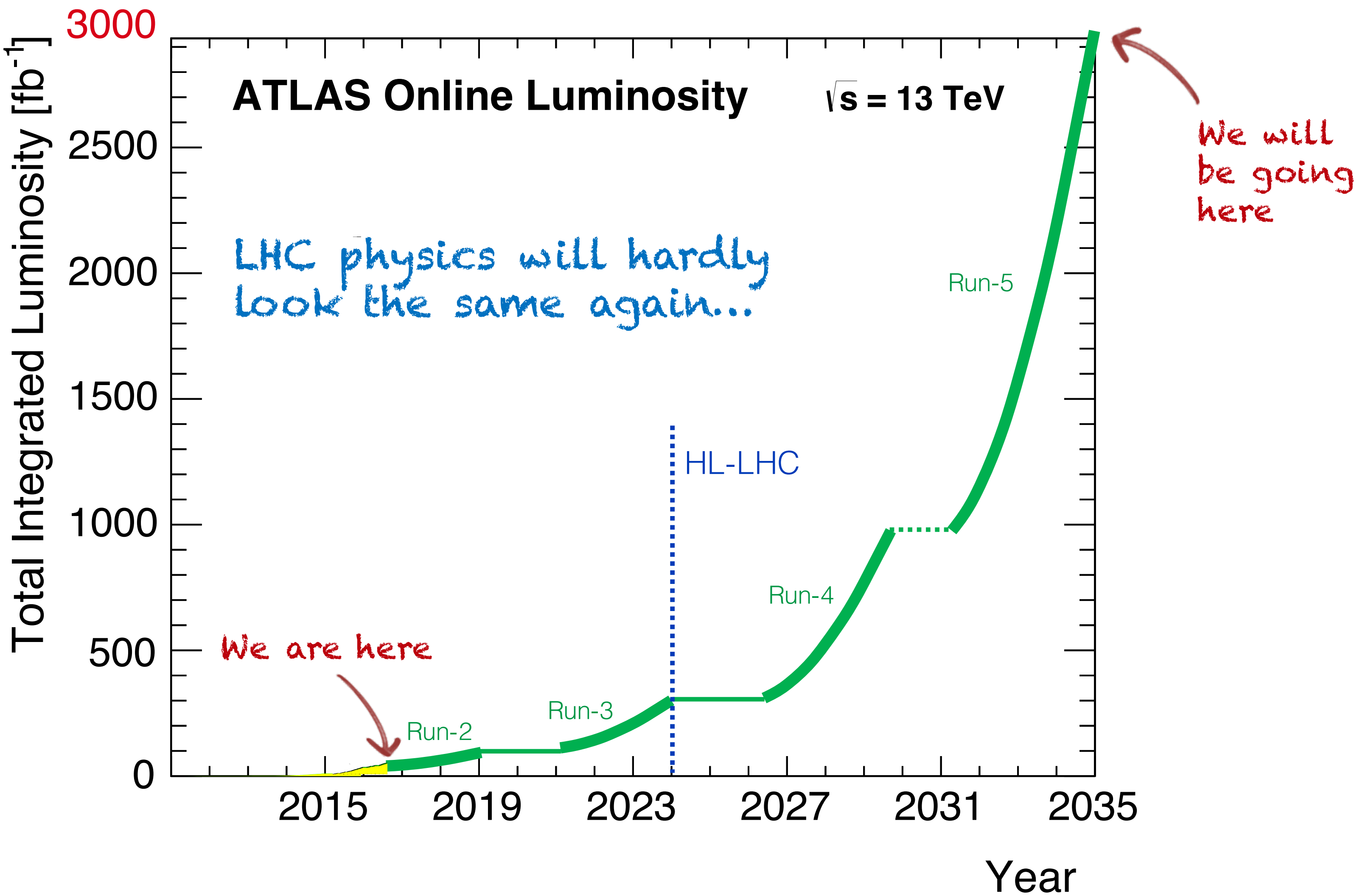
- Precision measurements of Higgs couplings
- Observation of very rare Higgs modes
- Ultimate new physics search reach (on mass & forbidden decays, eg, FCNC)
- Ultimate SM & HF physics precision for rare processes (VBS, aT/QGC, etc)

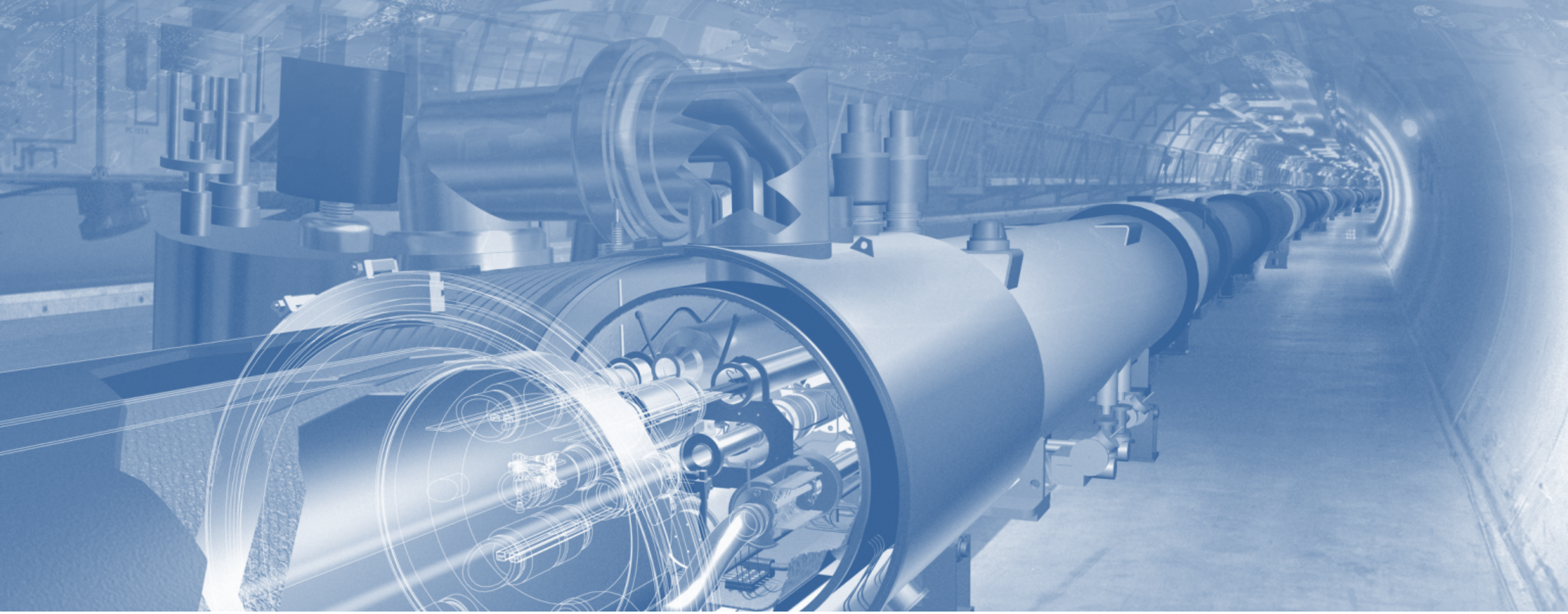


Status of Run-2 (19 Sep 2016)



Expected integrated luminosity of LHC & HL-LHC





Prospects for the LHC Run-2/3 and beyond (HL-LHC)

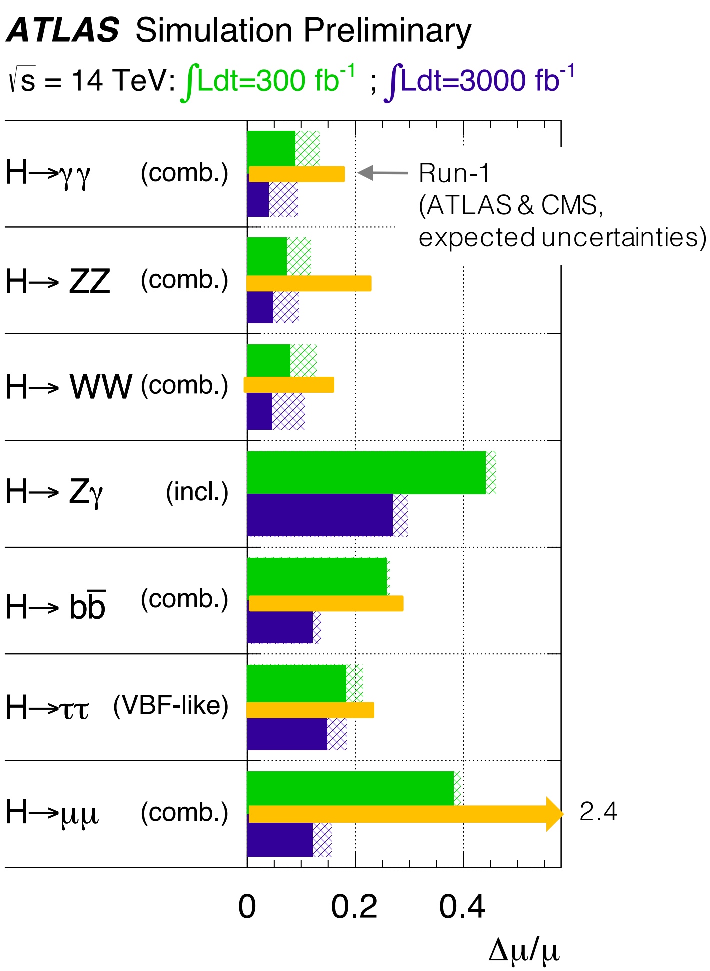
VERY brief set of example plots

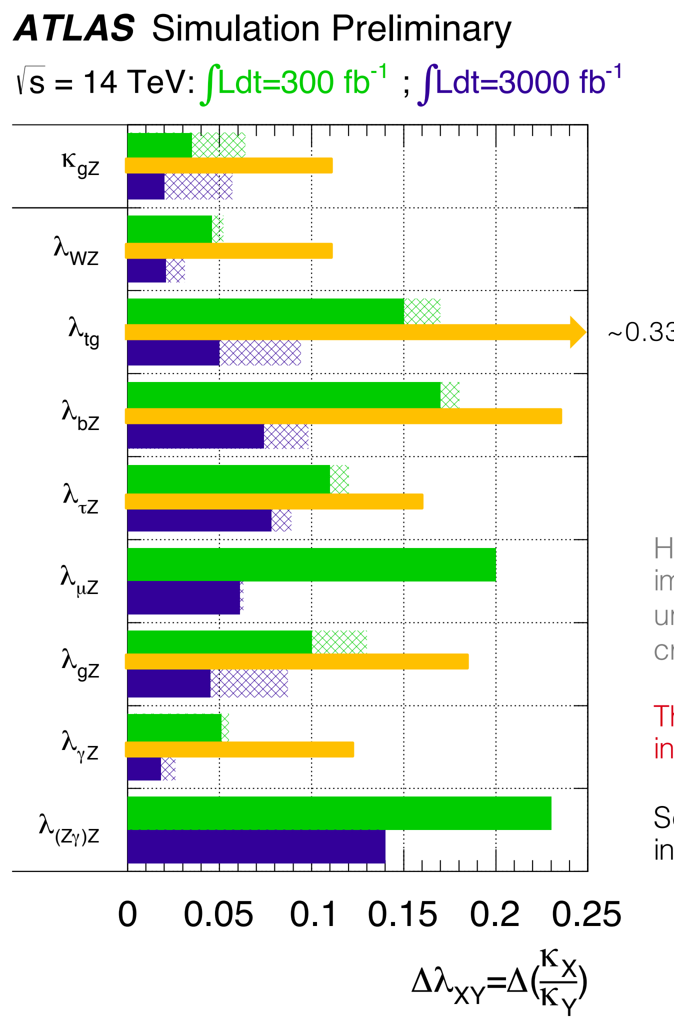
Any detection of new physics would likely be a game changer !

Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange)





$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Hatched areas indicate impact of theoretical uncertainties on expected cross-sections

Theory uncertainty limiting in several cases

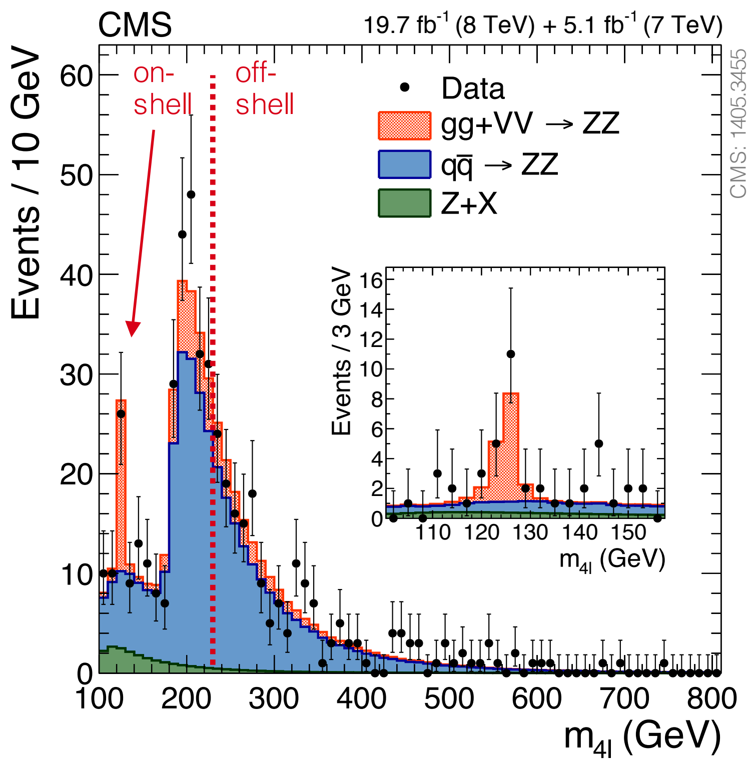
Some uncertainties cancel in ratios

Higgs boson physics

Constraining the Higgs off-shell coupling

Both CMS and ATLAS have constrained the Higgs off-shell coupling and through this obtained upper limits on the Higgs total width Γ_H

The method uses the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings. One can then determine Γ_H (=4.2 MeV in SM) from the measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

With Run-1, limits of the order of $5 \times \Gamma_H^{\text{SM}}$ obtained

With L_1 = 300 fb^{-1} and L_2 = 3000 fb^{-1}, one may find:

$$\mu^{(L1)}_{\text{off-shell}} = 1.00^{+0.80}_{-0.97}\ \text{(stat+sys)}$$

$$\mu^{(L2)}_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}\ \text{(stat+sys)}$$

$$\Rightarrow \quad \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}$$

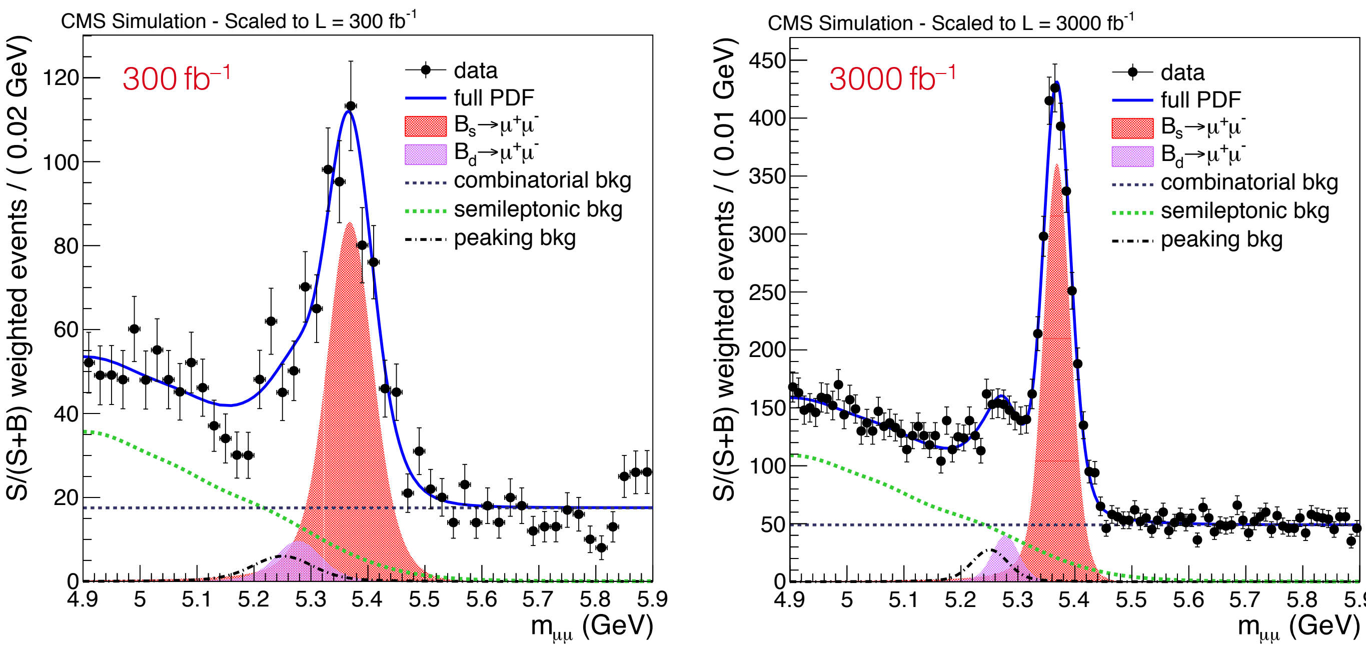
ATLAS: ATL-PHYS-PUB-2015-024

More Standard Model and Flavour physics

Continuous gain in precision and reach for rare or suppressed processes

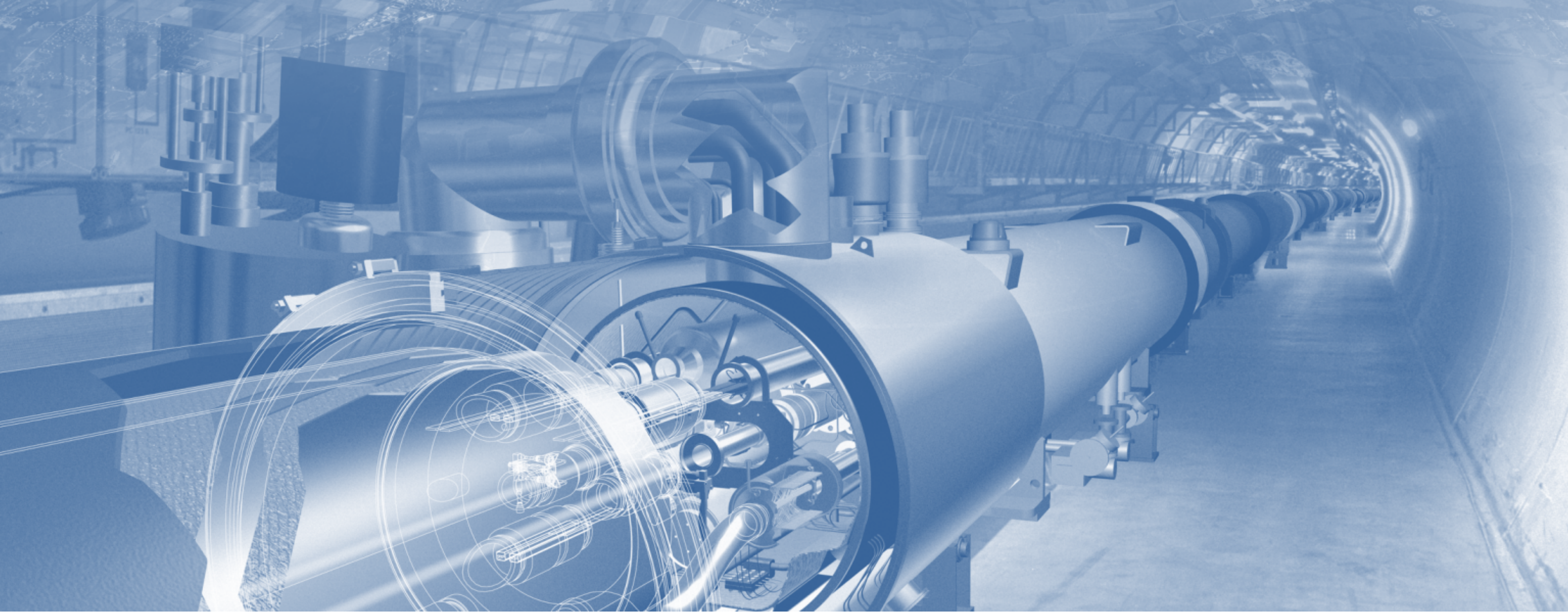
High-profile flavour physics measurements (slower Run-2 luminosity rise for LHCb due to luminosity levelling, but upgrade to 40 MHz trigger readout during LS2 will increase, eg, the annual muonic B rate by factor of ten)

- Rare decays: $B_{(s)} \to \mu\mu$ and similar and $b \to s$ transitions: $B \to K^*\mu\mu$ and similar (LHCb, CMS, ATLAS)
- CP violation: ϕ_s (LHCb, CMS, ATLAS), γ and other CKM parameters (LHCb), also CPV in charm sector
- Lepton universality tests (LHCb)
- Spectroscopy (LHCb, CMS, ATLAS)



Prospective study by CMS for the rare $B_s \to \mu\mu$ decay

CMS-PAS-FTR-13-022



Conclusions

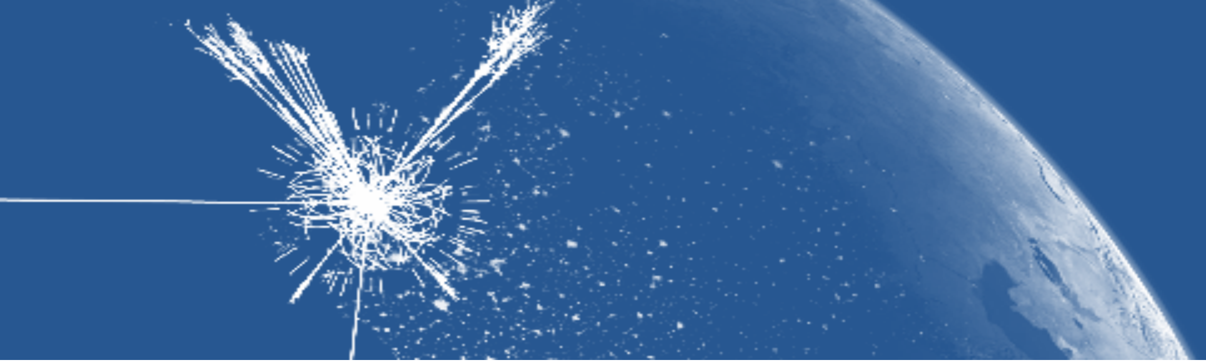
Conclusions

The LHC Run-2 is a key period for particle physics

- High CM energy and first 100 fb^{-1} are critical for searches for new physics in all signatures
- Further consolidation of Higgs sector with observation and measurement of $H \rightarrow \tau\tau$ & bb, and ttH, as well as much more precise coupling and fiducial & differential cross section measurements
- The luminosity of Run-2 will hugely increase the amount of interesting Standard Model and flavour physics measurements that can be performed

Watch out:

- New physics does not necessarily appear at high mass, need to continue to search everywhere
- High precision measurements are key for a better knowledge of the Standard Model
- It is thereby extremely important to measure the detector performance in data as precisely as possible
  (This can often have priority over further improving the performance, example: b-tagging.)
- Many results are dominated by theoretical uncertainties. Need to produce measurements that allow to test theory, to improve PDFs, and that motivate theorists to improve calculations and event generators



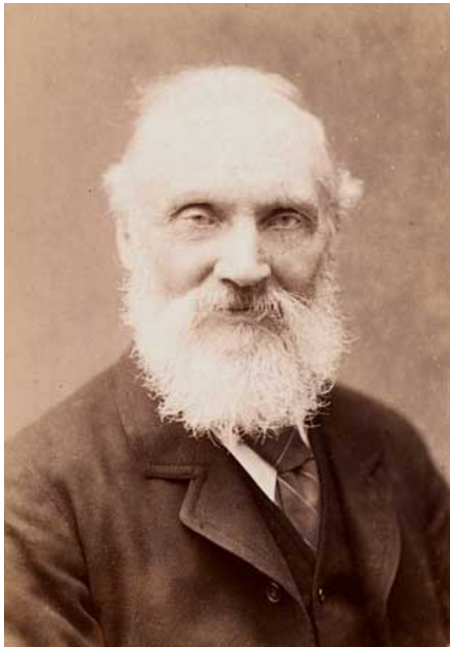
Conclusions

Accurate and minute measurement seems to the non-scientific imagination, a less lofty and dignified work than looking for something new.

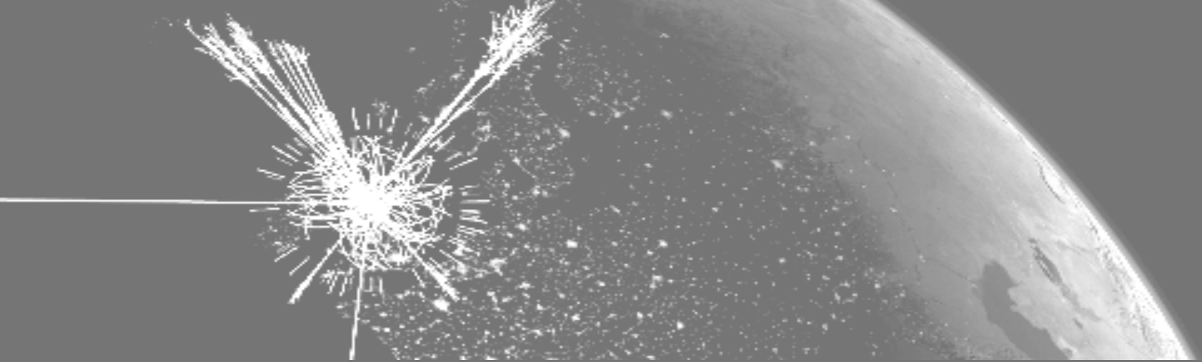
But [many of] the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labour in the minute sifting of numerical results.

William Thomson Kelvin

2 Aug 1871 in a speech to the British Association for the Advancement of Science



Lord Kelvin

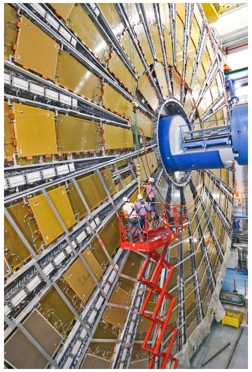


Extra slides

ATLAS improvements for Run-2

Huge consolidation & improvement programme for detector, online, offline, computing

Replacement of TGC chambers

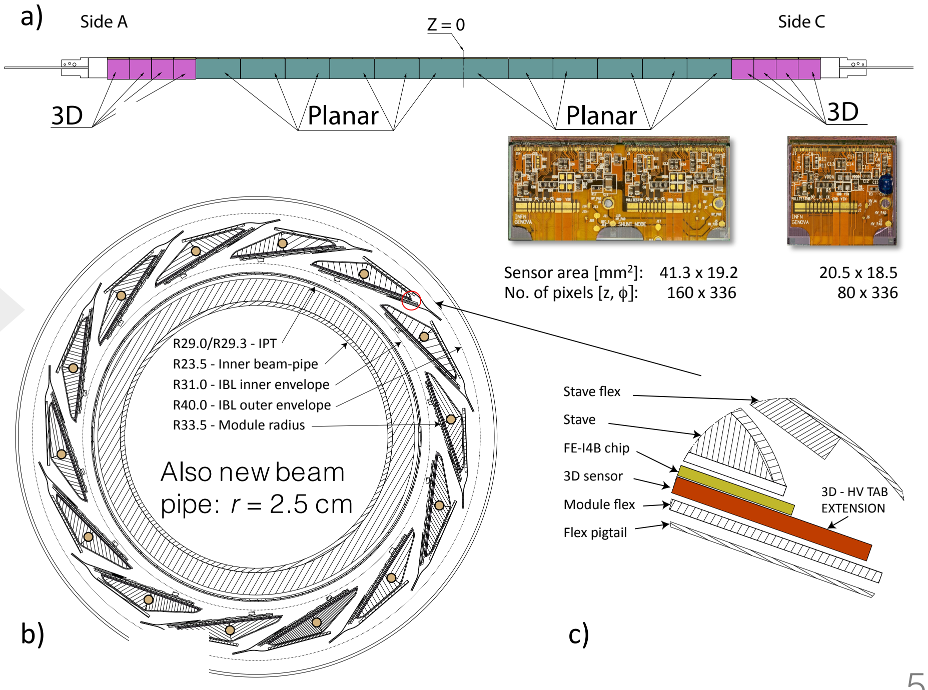


Infrastructure upgrades: magnet & cryogenic systems, additional muon chamber shielding, new beam pipes

Detector consolidation: muon chamber completion ($1.0 < |\eta| < 1.3$) & replacements, calorimeter electronics repairs, improved inner detector read-out capability to cope with 100 kHz L1 trigger rate, new pixel detector services and module repairs

New topological L1 trigger and new central trigger processor, restructured high-level trigger

New *Insertable B-layer*: fourth pixel layer at 3.3 cm from beam, consisting of planar & 3D (forward) silicon sensors, smaller pixels



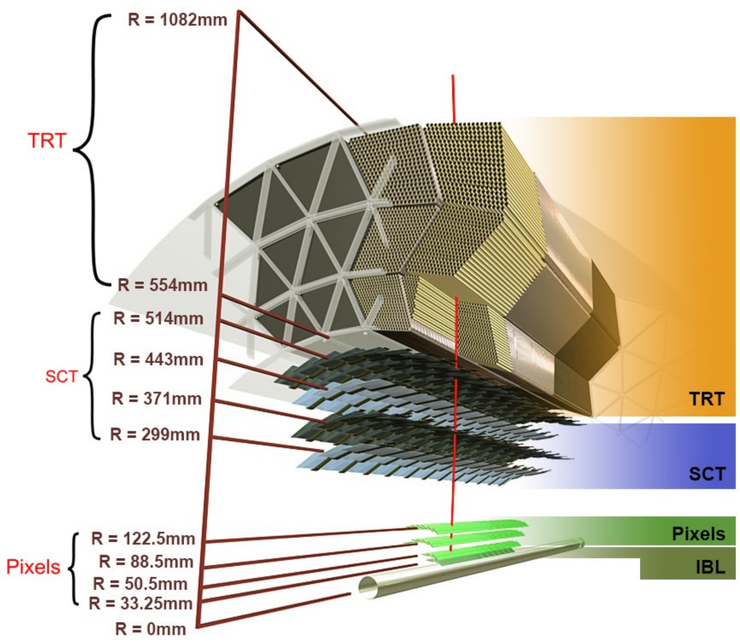
New software, new production system, new analysis model, …

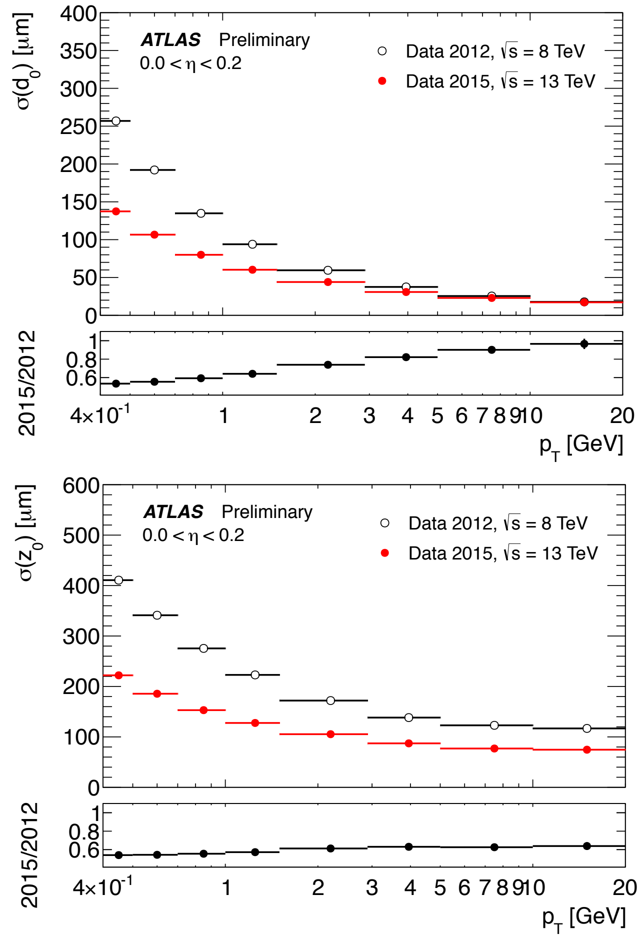
ATLAS inner tracking performance

[ATL-PHYS-PUB-2015-018]

ATLAS tracking in Run-2 features the new IBL, reduced material within acceptance, and algorithmic improvements (eg, huge speed-up, *tracking in dense environment* [ATL-PHYS-PUB-2015-006])

Sketch of ATLAS inner tracking detectors



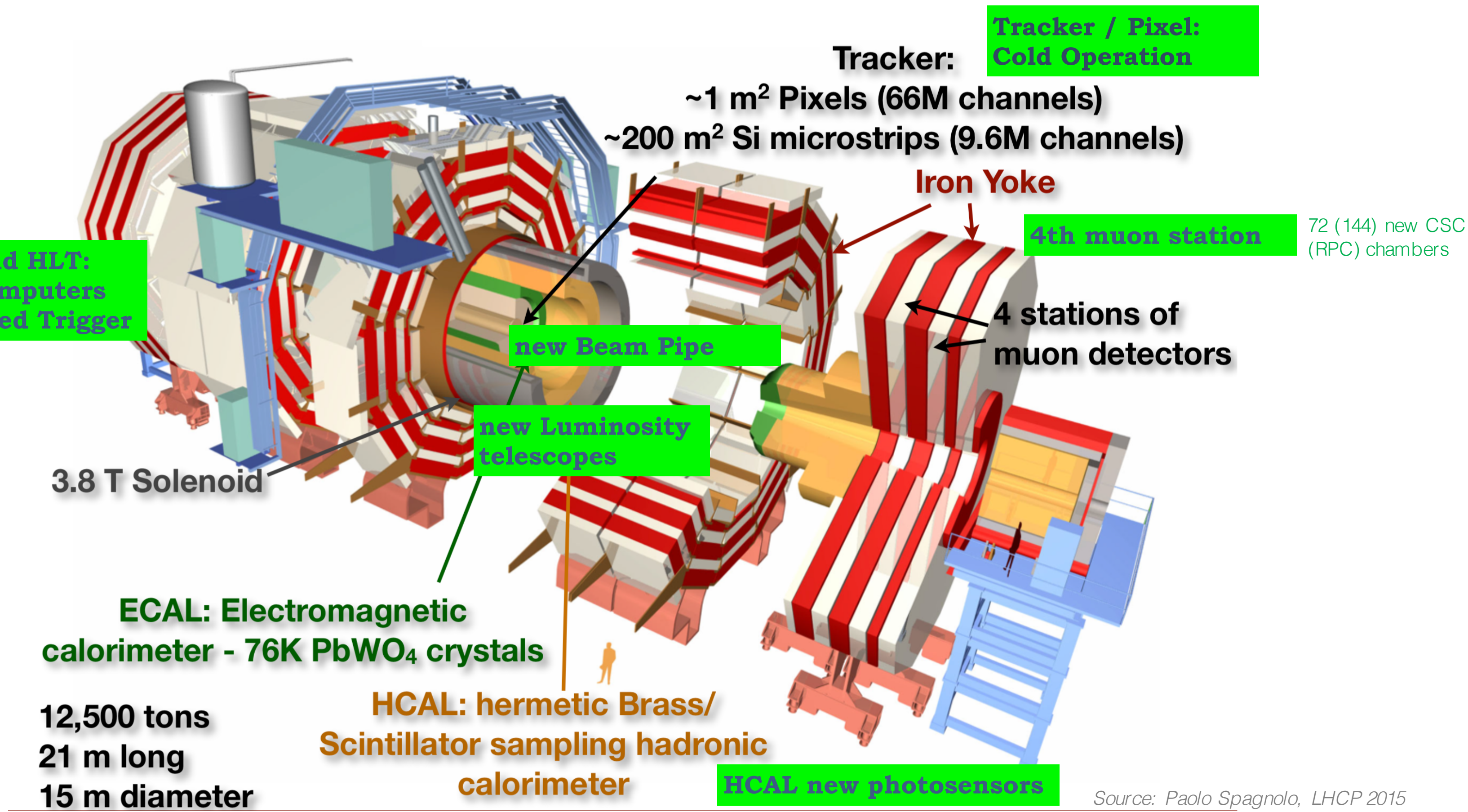


Impact parameter resolution improvement from IBL

Measured improvement of impact parameter resolution with IBL depending on track p_T

CMS improvements for Run-2

Also significant updates and improvements



Source: Paolo Spagnolo, LHCP 2015

Also:
- Multithreaded and more efficient reconstruction at CERN and Tier-1
- New compact mini-AOD format (~10% of AOD)
- Large efforts on improved (out-of-time) pileup mitigation

LHCb improvements for Run-2

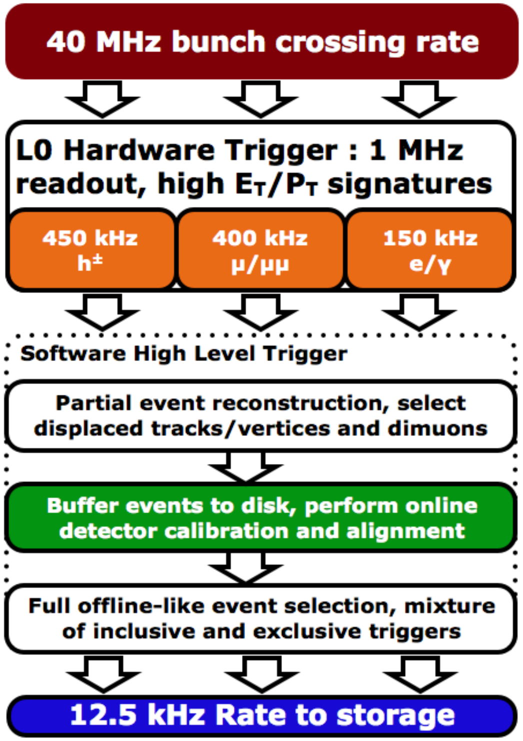
Big effort in trigger area (among others)

Detector consolidation: muon HV and grounding, 15% PMTs replace in HCAL, ECAL monitoring fibres replaced, module repairs in OT, HPD exchange in RICH, fixes in cooling, gas, power, shielding, …

HeRSCheL: new scintillating counters to extend LHCb coverage to high rapidity (CEP, diffraction, …)

Trigger upgrade — split trigger:

- All 1st stage (HLT1) output stored on disk
- Used for real-time calibration and alignment
- 2nd stage (HLT2) uses offline-quality calibration
- 5 kHz of 12 kHz to Turbo stream:
  - Objects produced by trigger are stored
  - No raw event → smaller event size
  - Used for high-yield channels (charm, J/ψ, ...)

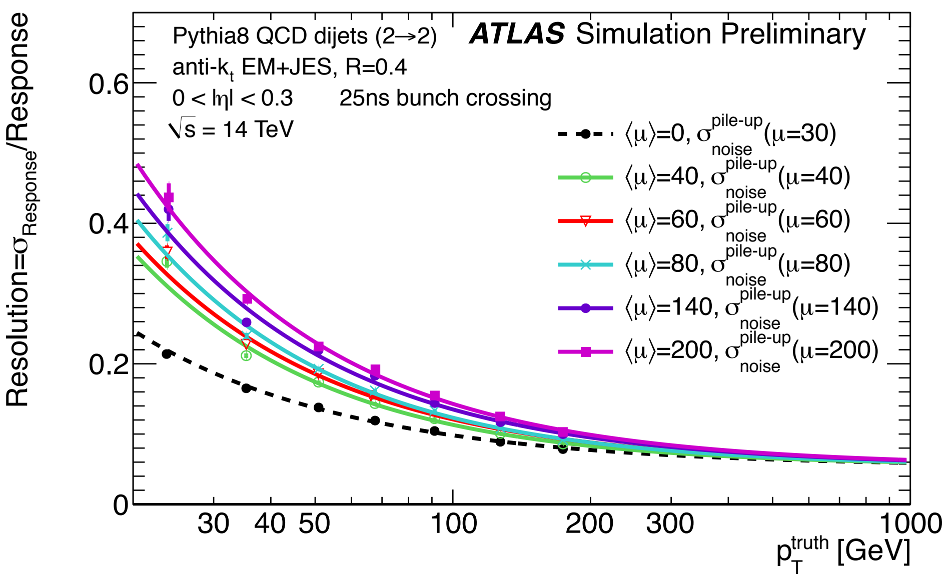


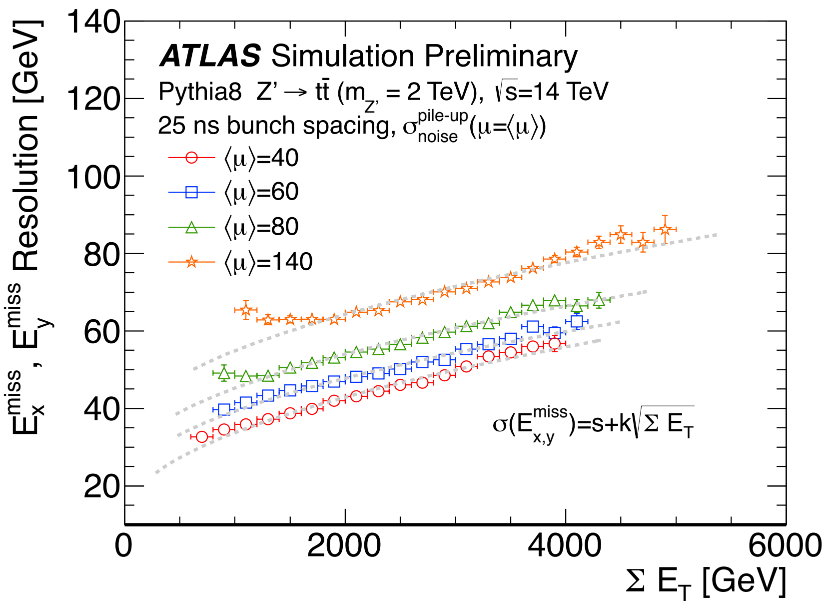
Detector performance

The performance of physics object reconstruction degrades with pileup

Pileup dependence mitigated by dedicated methods, but expect moderate decrease of electron/photon efficiency and resolution, and increase of fake rate. Muons less affected (main impact on trigger).

More difficult for tau ($H \rightarrow \tau\tau$), jets and missing transverse momentum:





The jet substructure can be resolved (eg, jet mass) with "grooming" techniques in high-pileup scenarios

Overall, no significant performance degradation expected during Run-2, some effects in Run-3

Higgs boson physics

Run-2 should increase Higgs sample by factor of ~10, ttH by factor of ~20

Higgs mass already well known (0.2%), but further improvement and – important – cross-check needed

Higgs width (SM: 4.2 MeV) cannot be directly measured; indirect constraints possible

Higgs spin & parity established as 0^+, but need to investigate possible *CP*-odd admixtures

Higgs couplings can be overconstrained from channel-wise (categorised) measurements

What is left to complete after Run-1 ?

- Complete observation of $H \to \tau\tau$
- Observe $H \to bb$
- Observe ttH and W/Z+H production (at large luminosity $H \to \gamma\gamma$ will be best for ttH, ATL-PHYS-PUB-2014-012)

What are long-term developments ?

- Search for $H \to \mu\mu$ (Run-1 limit: ~$7.5 \times \sigma_{SM}$)
- Search for $H \to Z\gamma$ (Run-1 limit: ~$9.5 \times \sigma_{SM}$)
- Search for di-Higgs production

And always with high priority:

- Improve global coupling constraints
- Fiducial and differential cross-section measurements
- Searches for CPV, and for rare (eg, $H \to J/\psi\ \gamma$), forbidden (eg, $H \to \tau\mu$) and invisible decays (eg, VBF+E_T^{miss})

Higgs boson physics

Run-2 should increase Higgs sample by factor of ~10, ttH by factor of ~20

Higgs mass already well known (0.2%), but further improvement and – important – cross-check needed

Higgs width (SM: 4.2 MeV) cannot be directly measured; indirect constraints possible

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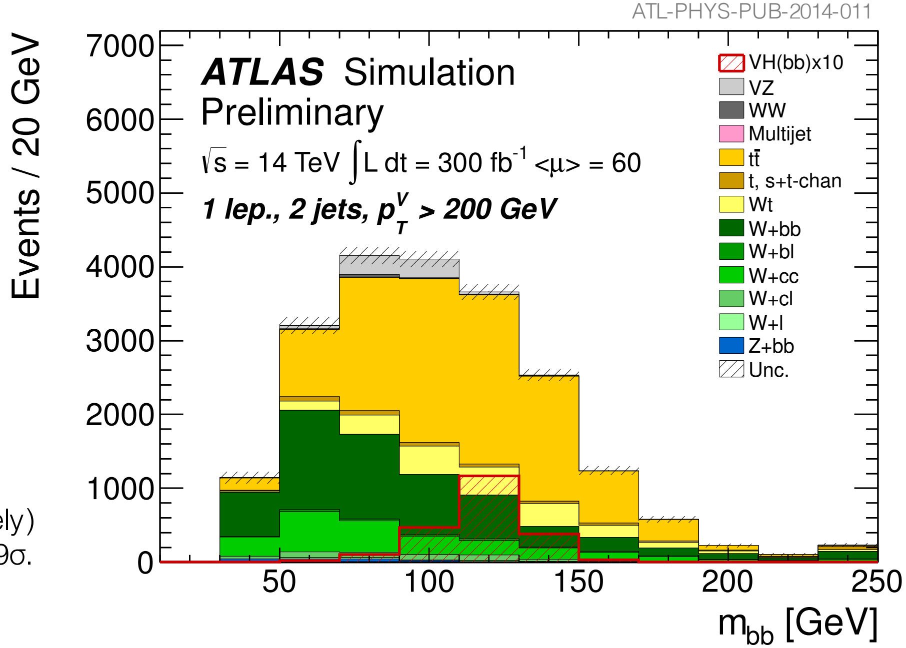
- Complete observation of $H \to \tau\tau$
- Observe $H \to bb$
- Observe ttH and W/Z+H production

ATL-PHYS-PUB-2014-011



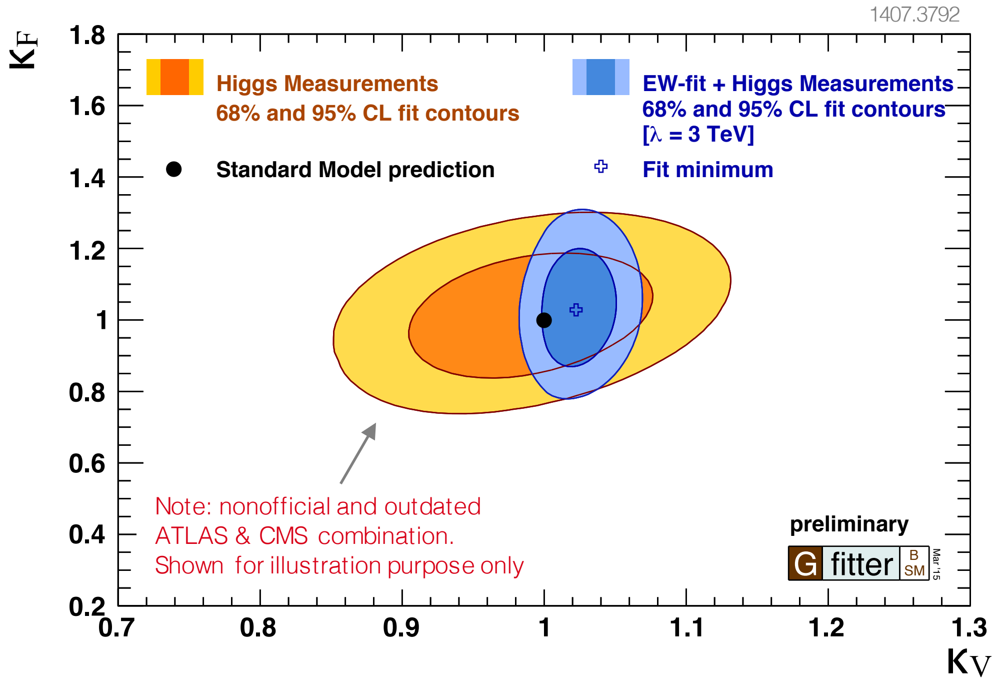
Extrapolated m_{bb} distribution in WH channel at 300 fb^{-1} and $\langle\mu\rangle$ = 60. The (conservatively) estimated significance for this analysis is 3.9σ.

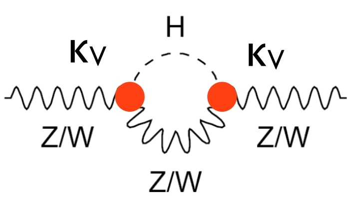
Higgs boson physics

Can combine LHC measurement with constraints on κ_V from electroweak precision data

Constraints on global fermion versus vector-boson coupling modifiers

Constraints from global EW fit through "oblique parameters" S, T (SM: S = T = 0), parameterizing new physics contributions to electroweak observables through loop diagrams involving massive W and Z bosons





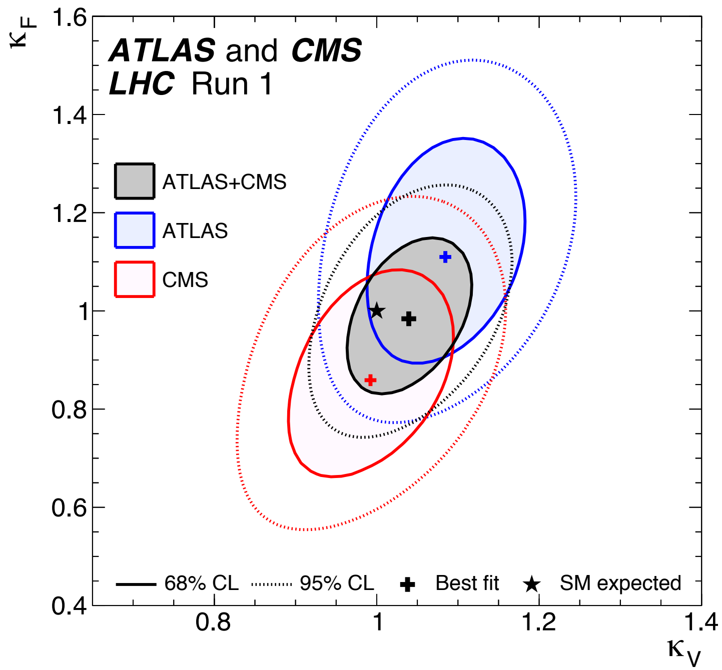
$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}\,, \quad T = -\frac{3}{16\pi\cos^2\theta_{\rm eff}^\ell}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}\,, \quad \Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$$

λ is cut-off parameter, set arbitrarily to 3 TeV

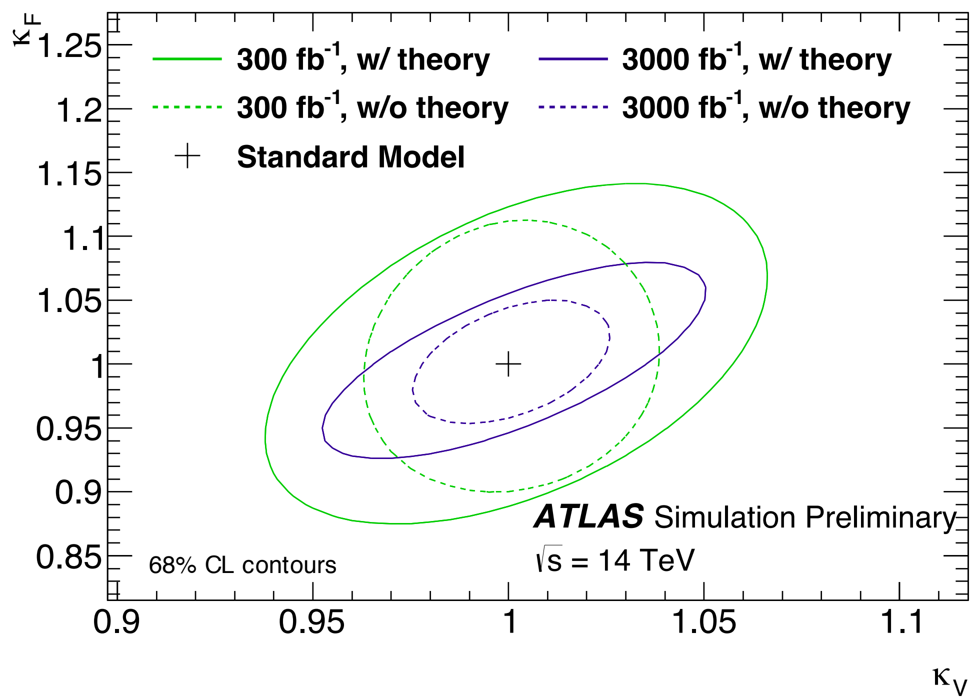
(Conservative) extrapolation of Higgs coupling measurements

Constraints on global fermion versus vector-boson coupling modifiers

Current (Run-1):



Extrapolation:

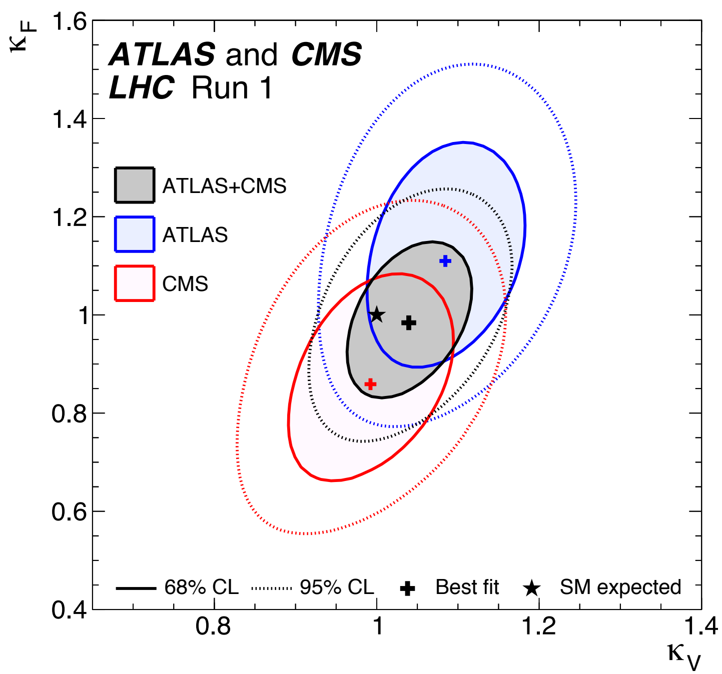


Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

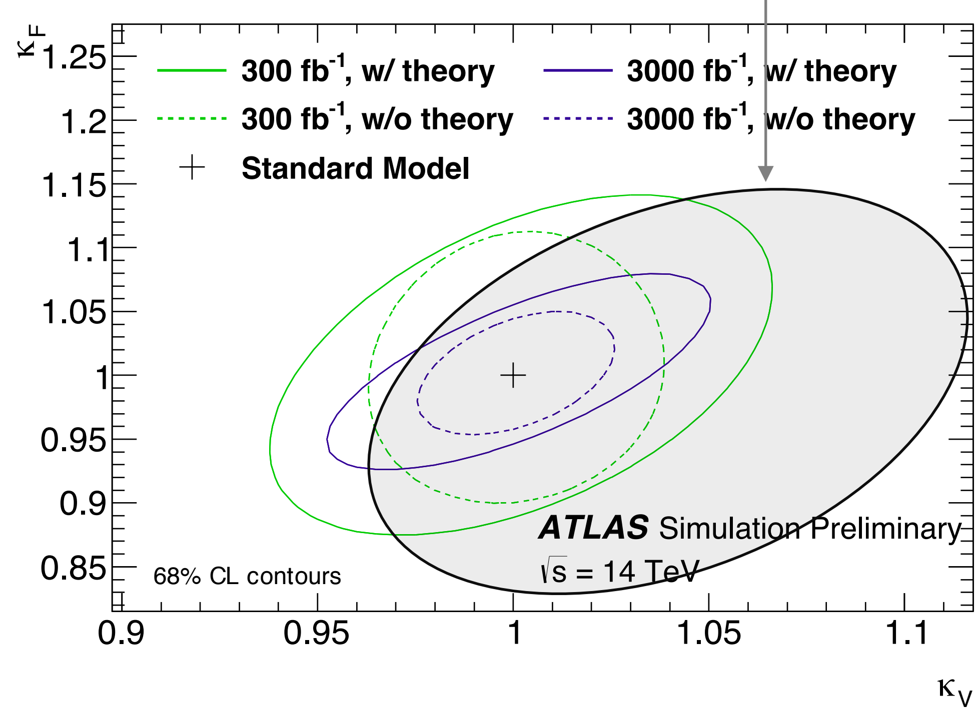
Constraints on global fermion versus vector-boson coupling modifiers

Current (Run-1):



Extrapolation:

Run-1 (ATLAS & CMS, observed 68% CL contour)

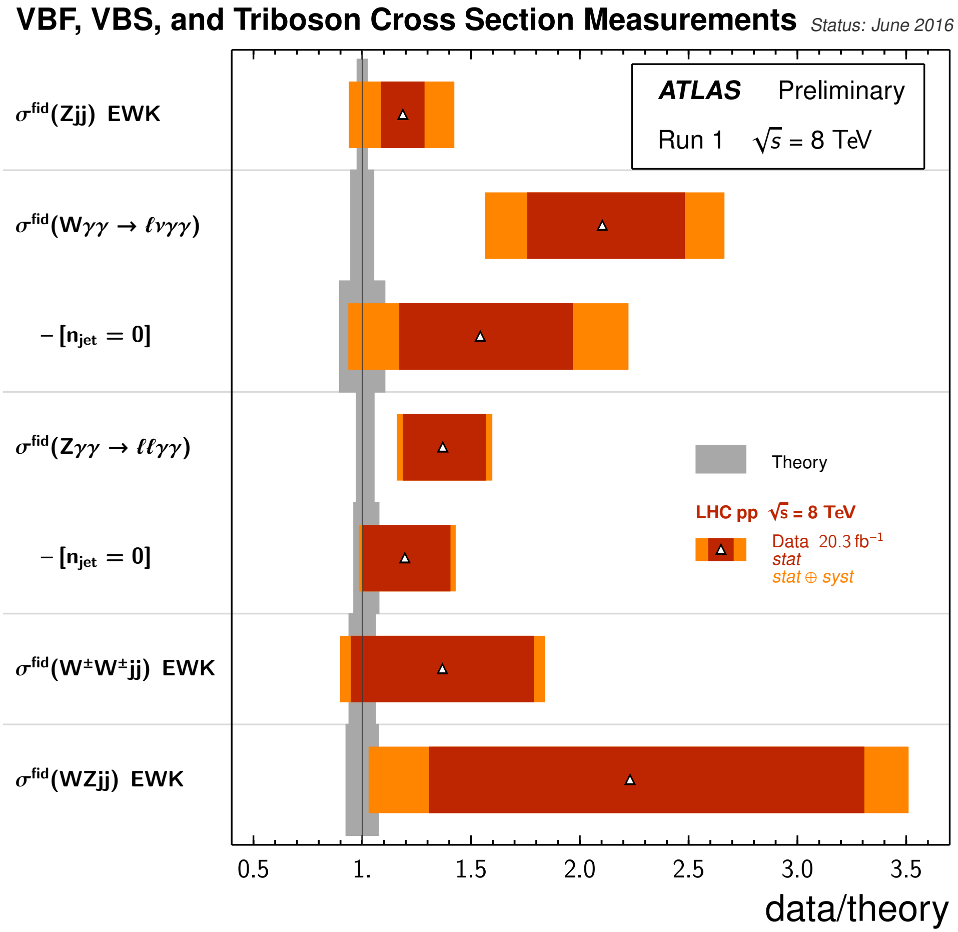


More Standard Model physics

Continuous gain in precision and reach for rare or suppressed processes

High-profile measurements:

- M_W and $\sin^2\theta_W$: *discussed before* *(work on reduction of physics modelling uncertainties required)*
- Triple (TGC) and quartic (QGC) gauge boson couplings in diboson and triboson events also via differential cross-section measurements especially at high p_T and mass. This includes VBF and **VBS diboson production**
- QCD tests with further precision differential cross-sections measurements of Z/W/γ + jets, also detailed studies of V + qq VBF production.
- PDF constraints from high-precision fiducial and differential Z/W/γ cross-section measurements



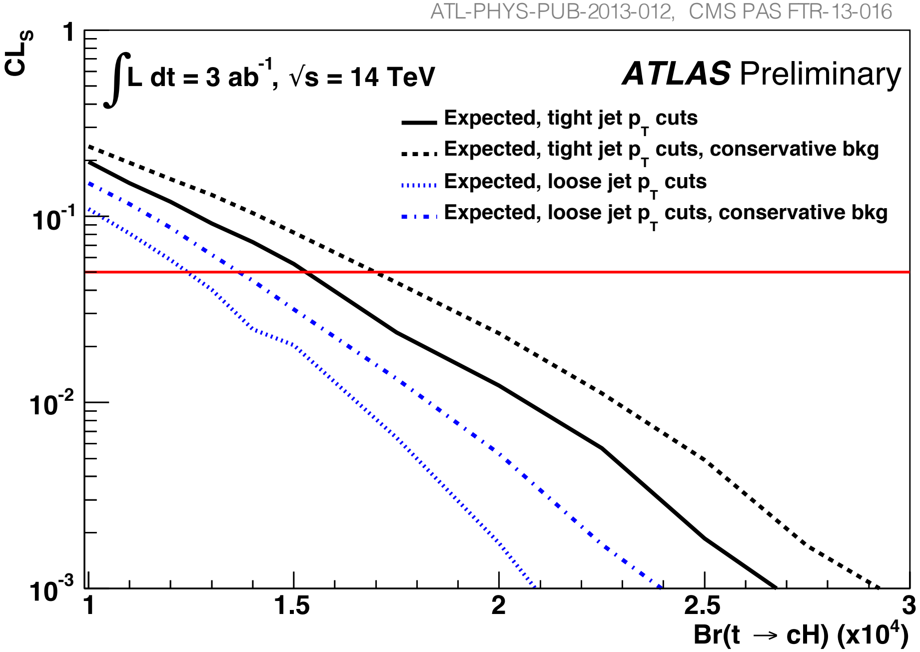
Top physics

Continuous gain in precision and reach for rare or suppressed processes

High-profile measurements:

- Mass: *discussed before*
- Differential cross-sections of top charge asymmetry, spin correlations, H_T, etc. are important theory tests
- Rare processes such as tb, ttZ, ttW, ttγ inclusively & differentially, constraints on anomalous couplings
- Forbidden processes such as the FCNC transitions t → qH, qZ, qγ, qg (q = u,c), also t → d/s+W

ATL-PHYS-PUB-2013-012, CMS PAS FTR-13-016



Numbers: at 100 fb^{-1}, LHC will have produced (13 TeV numbers, summed over charges):

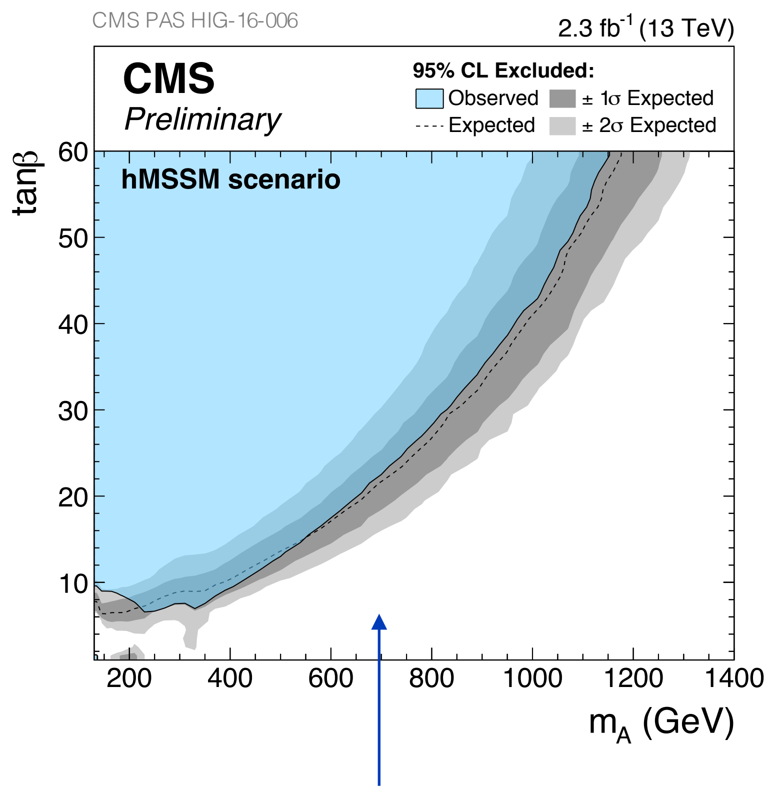
- → 83M top pairs,
- → 22M t-channel top, 7M Wt, 1M s-channel top,
- → 70k tZ, 6k tH,
- → 170k ttγ, 80k ttZ, 60k ttW, …

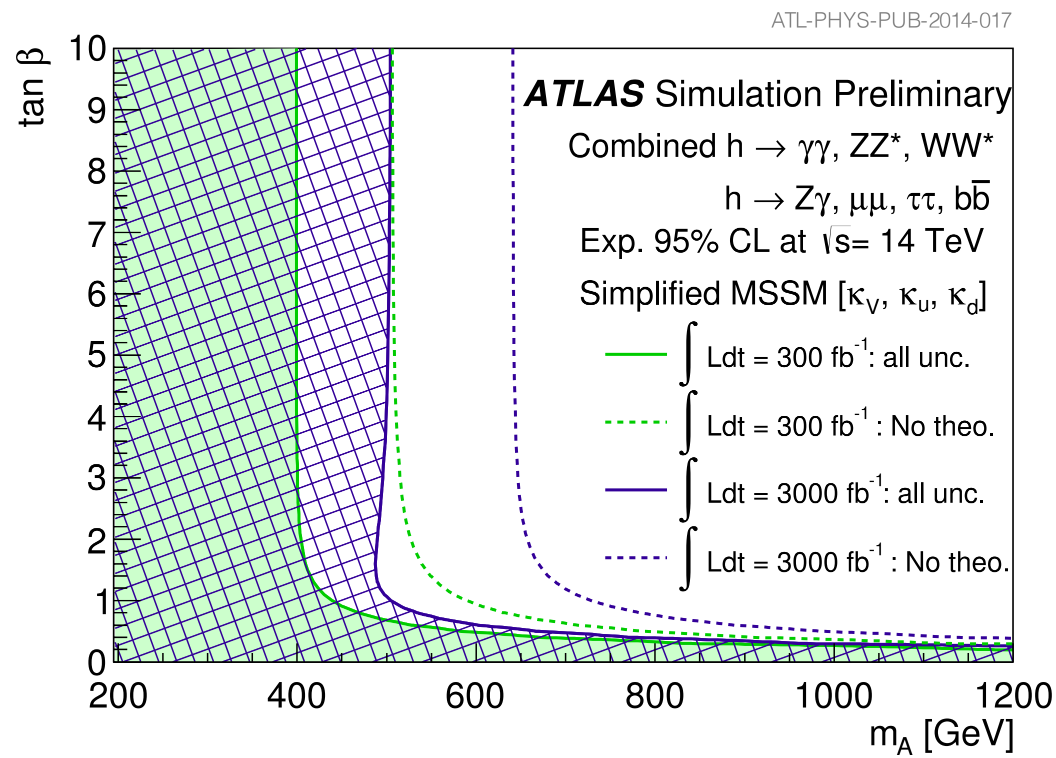
Limit on t → cH(→ γγ) branching ratio estimated for the full HL-LHC: ~0.015% (current 8 TeV: < 0.46%)

CMS for t → cZ: current/300/3000 fb^{-1} limit: < 0.10% / 0.027% / 0.010%

Example application for constraint on MSSM Higgs from Higgs coupling fit

Constraints on m_A and tanβ in simplified MSSM model from direct H/A → ττ searches (left – current constraint), and from an extrapolation of global Higgs coupling measurements (right)





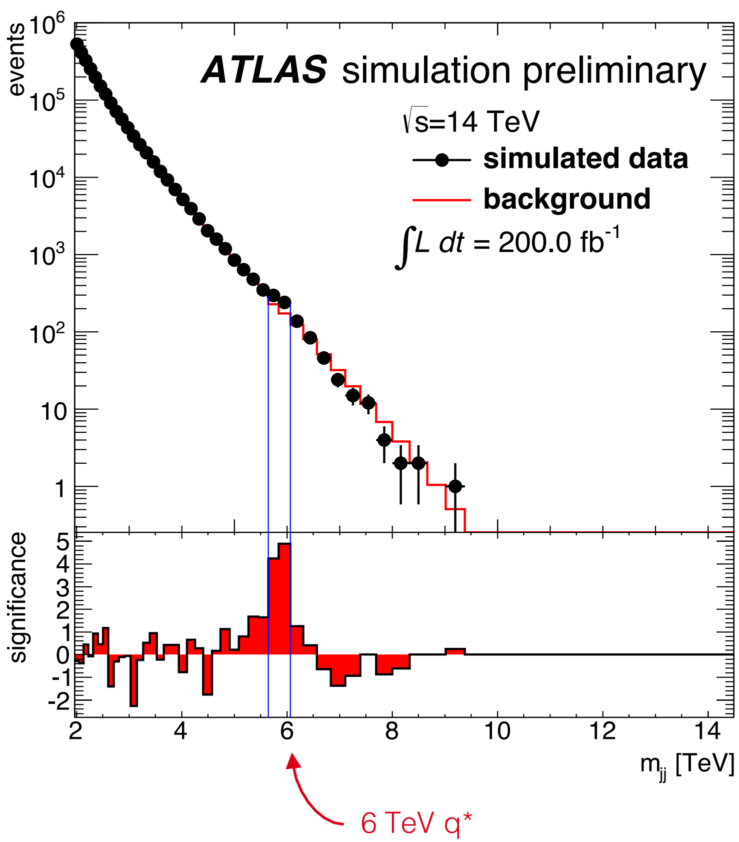
A → tt is dominant decay beyond top-pair production threshold and for low tanβ.
Very difficult channel due to interference with the continuum top pair contribution deteriorating the (broad) tt mass peak

Searches

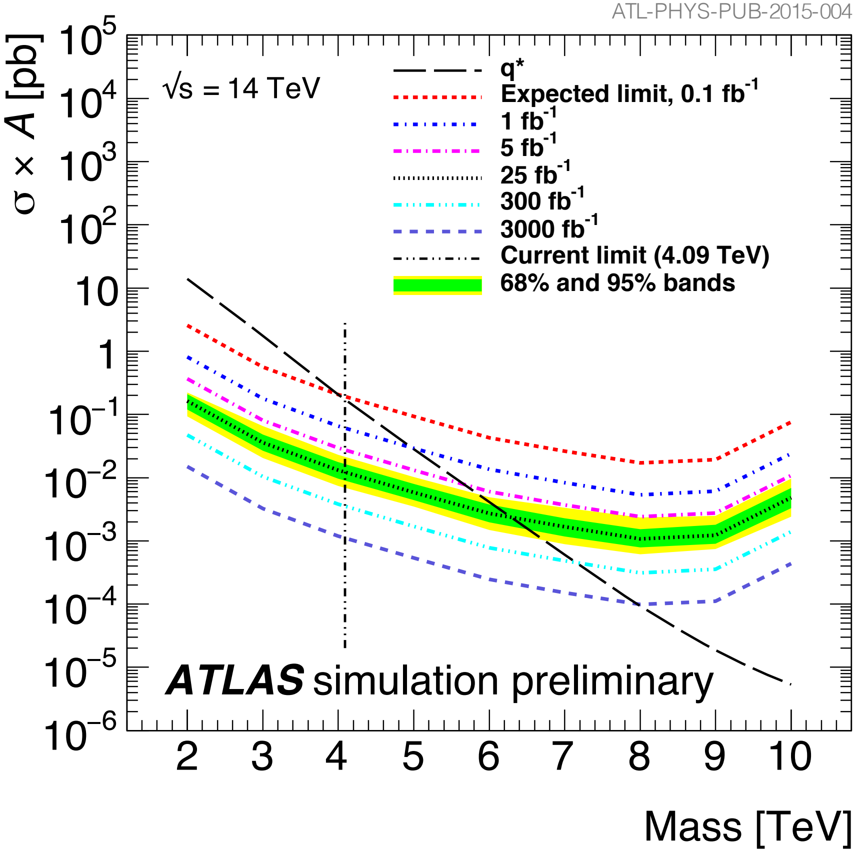
Will always stay a central piece of the LHC physics programme as a discovery machine

Still huge sensitivity increase this year, but will slow down with the progress of Run-2 and after.
Searches gradually move from highest masses to lower cross-sections and difficult phase space regimes

Example: dijet resonance search (interpretation with excited u & d quarks $q^* \to qg$)



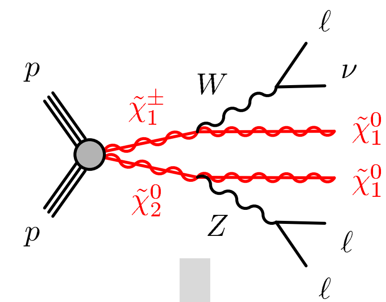
ATL-PHYS-PUB-2015-004



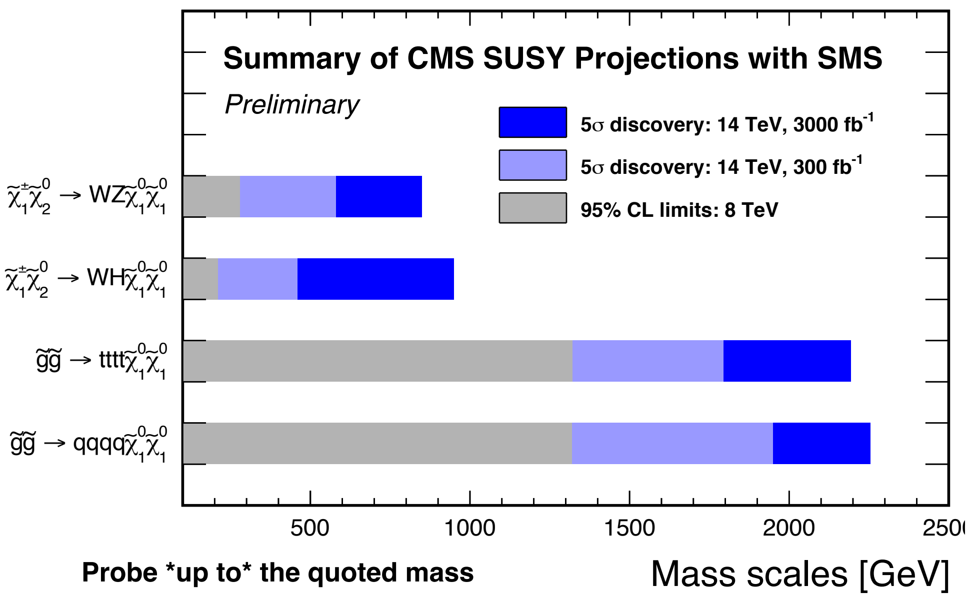
Searches

Will always stay a central piece of the LHC physics programme as a discovery machine

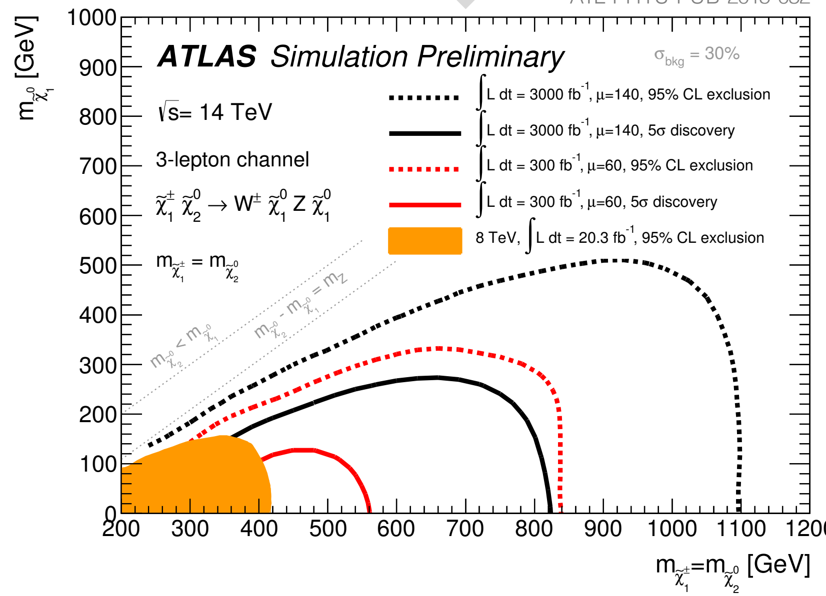
SUSY searches will move to low cross-section electroweak production and compressed scenarios



CMS-PAS-SUS-14-012



ATL-PHYS-PUB-2015-032



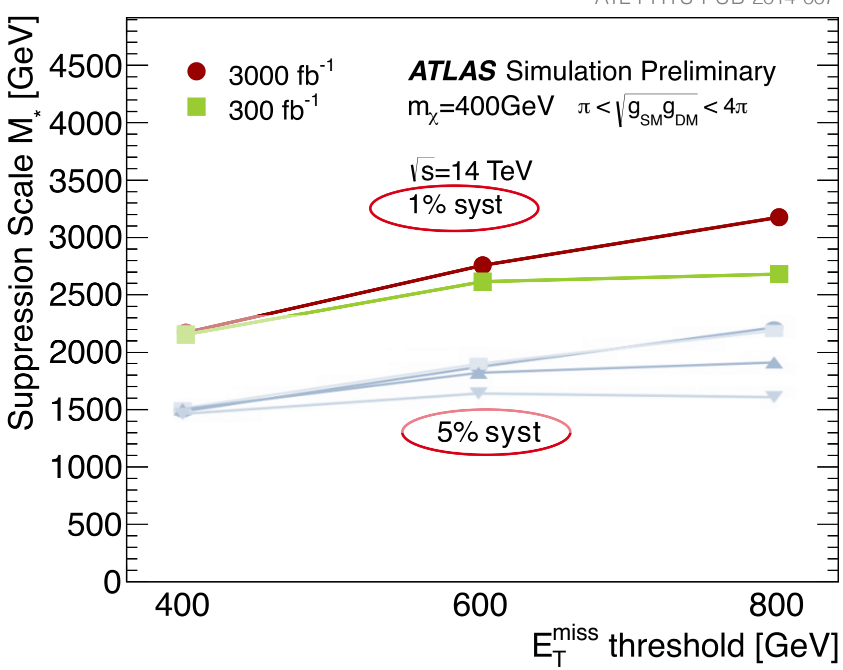
Searches

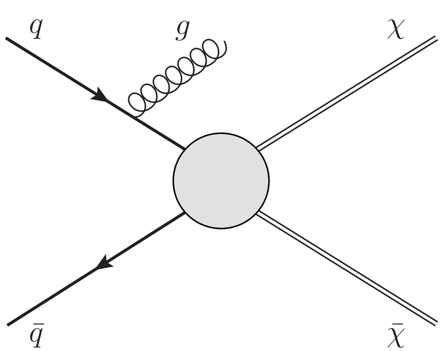
Will always stay a central piece of the LHC physics programme as a discovery machine

The sensitivity of dark matter searches looking for an excess in the high E_T^{miss} tail depends strongly on the systematic uncertainty achieved for the irreducible background → meets SM analysis efforts

D5 vector operator: $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$

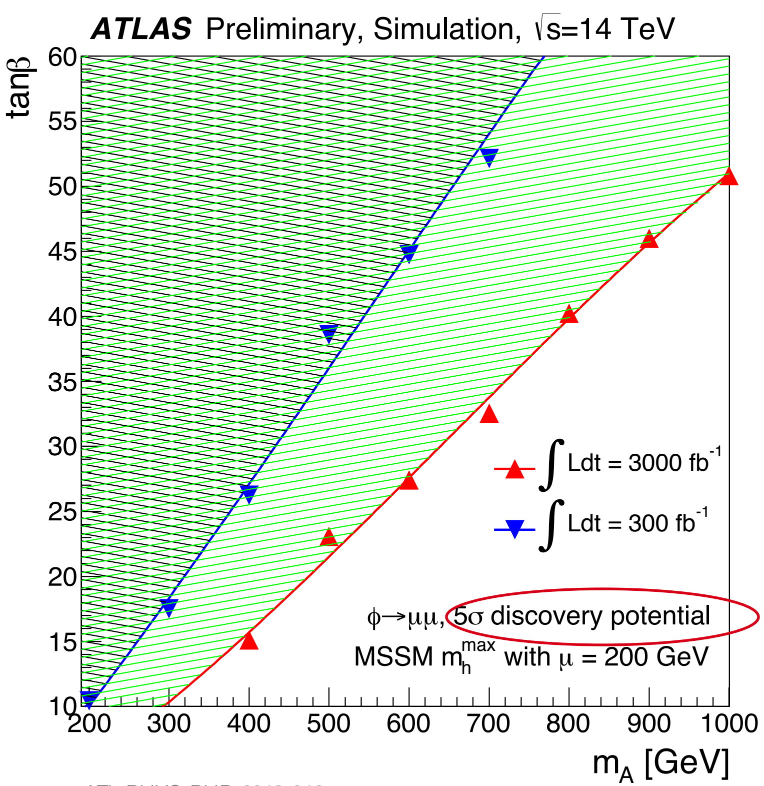
ATL-PHYS-PUB-2014-007





The discovery potential for H/A → ττ is compromised for large m_A and low tanβ where the H/A decays predominantly to top pairs with a deteriorating interference pattern with the continuum top pair contribution

Production of gg → A → Z(→ℓℓ) h(→bb) in the 2HDM can be discovered for low tanβ and at least moderate |cos(β – α)| up to and beyond m_A = 700 GeV



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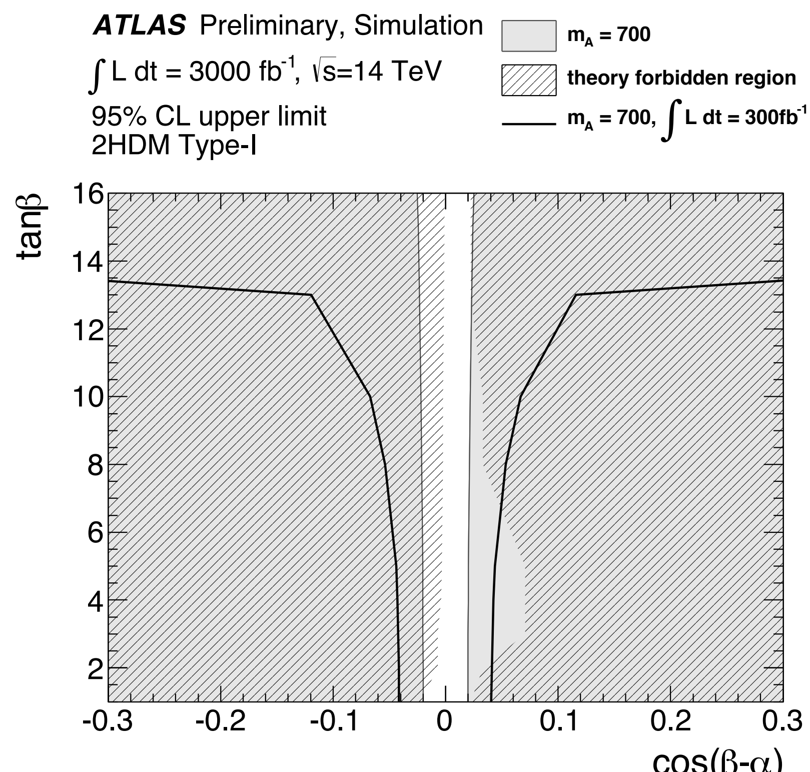
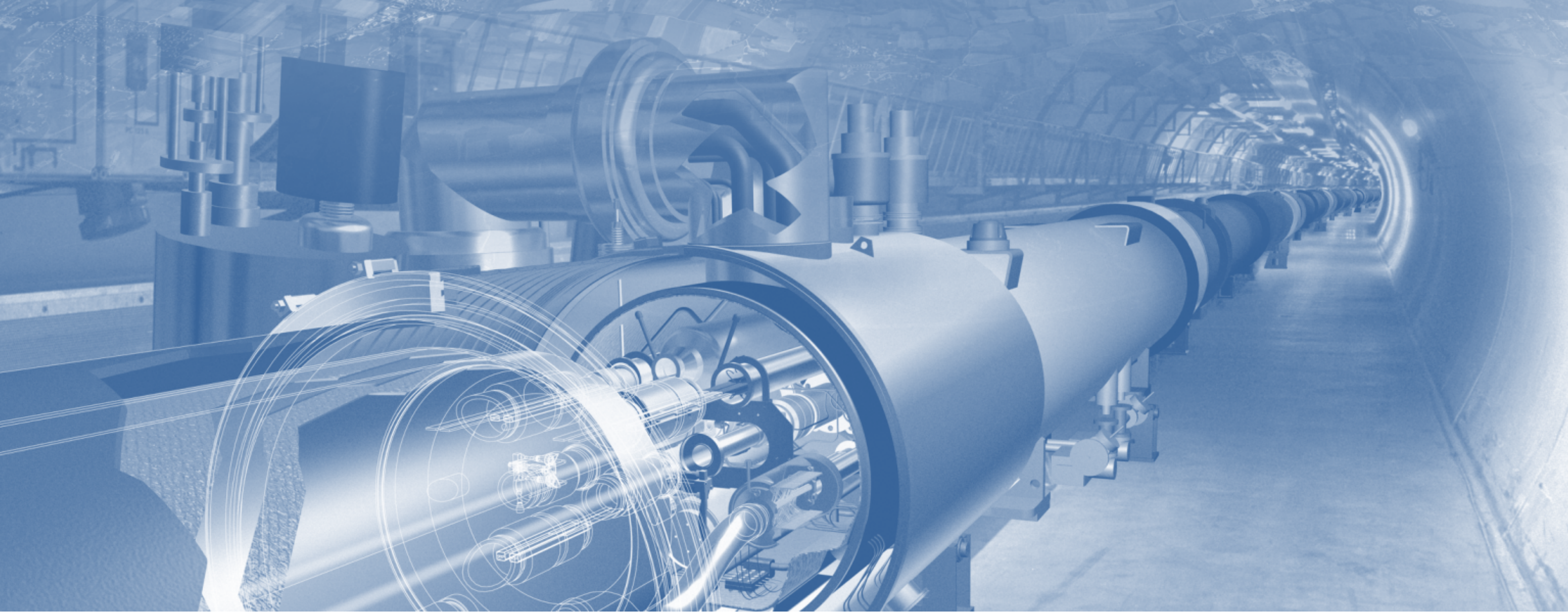


ATL-PHYS-PUB-2013-016



Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

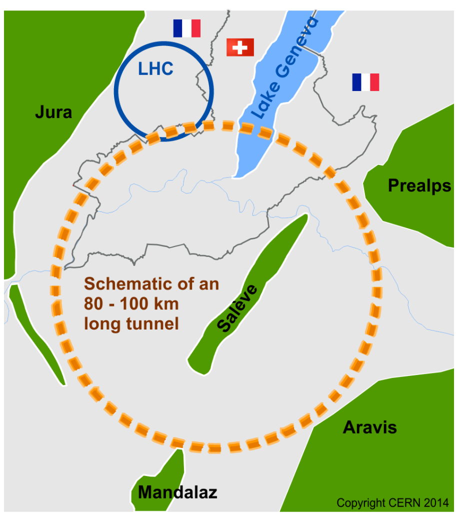
HL-LHC: E_{CM} = 14 TeV, 3 ab^{-1}, 2026~2035… (formally approved as *project* by CERN council)

Future Circular Collider FCC-hh (CERN):

- E_{CM} ~ 100 TeV in 100 km ring, $L \sim 2 \times 10^{35}$ s^{-1}cm^{-2}
- ~16 T magnets, possibly HE-LHC (E_{CM} ~ 28 TeV) as intermediate stage
- Huge detectors for muon p_T measurement
- Possible start of physics ~ 2035
- Includes HE-LHC as project step

SppC (China):

- E_{CM} ~ 71 TeV in 55 km ring, $L \sim 1 \times 10^{35}$ s^{-1}cm^{-2}
- Requires very high gradient dipole magnets ~ 20 T
- Possible start of physics ~ 2042



Parameter	FCC-hh		SppC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main + 2		2	2 main + 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} cm^{-2}s^{-1}]	5	~25	12	1	5
events/bunch crossing	170	~850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
E-loss/turn synchrotron radiation/beam	5 MeV 3 MW		2 MeV 5.8 MW	7 keV 5.4 kW	7 keV 9.5 kW

Future e^-e^+ collider projects in a nutshell

Measure EW & EWSB sector to highest precision

International Linear Collider ILC (host candidate: Japan)

- 20 years of R&D, mature technology, ~32 MV/m accelerating gradient ~ xFEL at DESY (45 MV/m for 1 TeV)
- E_{CM} ~ 500–1000 GeV in 31–45 km total length, $L \sim 1.8 \times 10^{34}$ s^{-1}cm^{-2}, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

*A low energy, high current, "drive" beam is decelerated in power extraction structures and the RF power is transferred to the cavities that accelerate the main beam

- High-gradient 2-beam scheme*: 100 MV/m gradient
- E_{CM} ~ 380–3000 GeV, 11–50 km total length, $L \sim$ a few $\times 10^{34}$ s^{-1}cm^{-2}, only one interaction region
- 0.5 ns bunch distance, nm beam size, large beamstrahlung, physics ~ 2035

Future Circular Collider FCC-ee (CERN):

- E_{CM} ~ 90–350 GeV in 2 rings (90k bunches), $L \sim 70–1.3 \times 10^{34}$ s^{-1}cm^{-2}
- Synchrotron power (E^4/R up to 7.5 GeV/turn): 100 MW (LEP-2: 22 MW)

Circular EP collider CEPC (China):

- E_{CM} ~ 240 GeV, $L \sim 2 \times 10^{34}$ s^{-1}cm^{-2}
- Single ring, 50 bunches
- Possible start of physics ~ 2028

parameter	FCC-ee			CepC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	**100**			**103**	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5