

New Results from the LHC (3)

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September 26–28, 2016 in Freudenstadt, Germany

Outline

[3 × 1h lectures]

Before yesterday:

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

Yesterday:

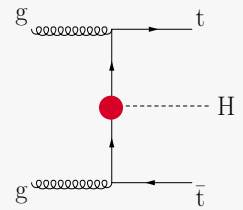
- A review of Run-1 physics highlights
- SM results from the LHC Run-2

Today

- Higgs and BSM searches from the LHC Run-2
- Digression on precision measurements
- Short outlook to HL-LHC

First search for ttH production at 13 TeV by CMS

Most interesting of the SM Higgs channels at current luminosity



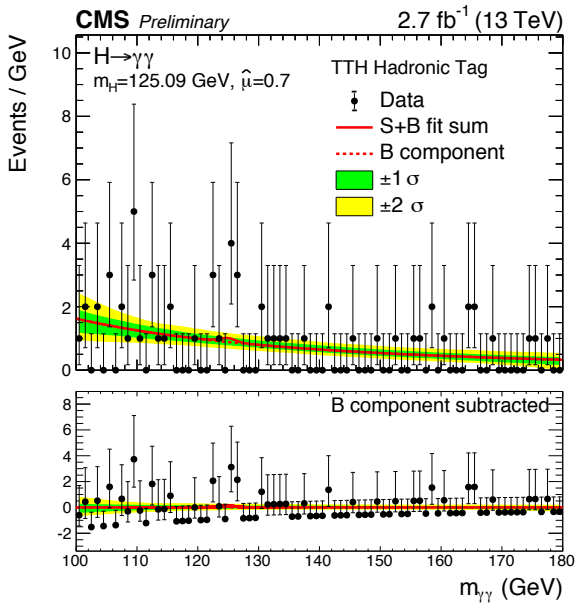
CMS showed preliminary results for ttH in all major Higgs decay channels: **H** → **γγ**, **multi-leptons**, **bb**

Highly complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)

H → **γγ**,
tt → 0 & 1 leptons

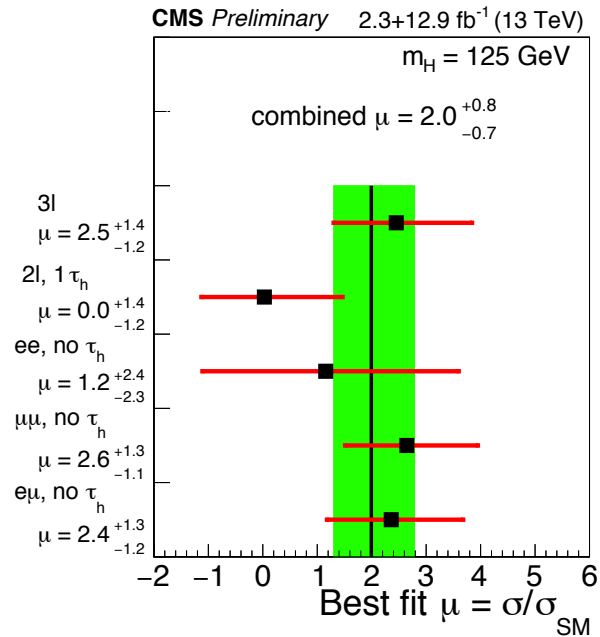
ttH → **multi-leptons**
2 same charge (+ τ) / 3 leptons

H → **bb**
tt → 1 & 2 leptons



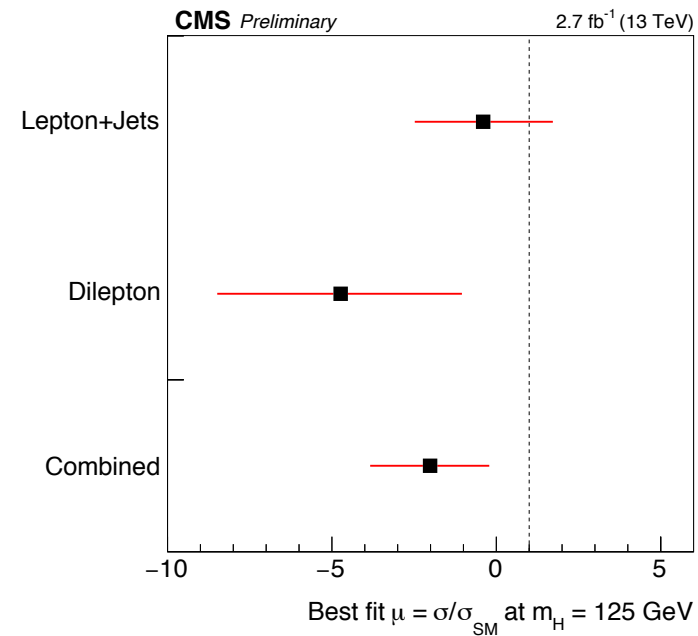
$$\mu = 3.8^{+4.5}_{-3.6}$$

CMS-PAS-HIG-15-005



$$\mu = 2.0^{+0.8}_{-0.7}$$

CMS-PAS-HIG-16-022

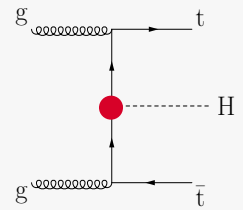


$$\mu = -2.0 \pm 1.8 < 2.6 \text{ (95\% CL)}$$

CMS-PAS-HIG-16-004

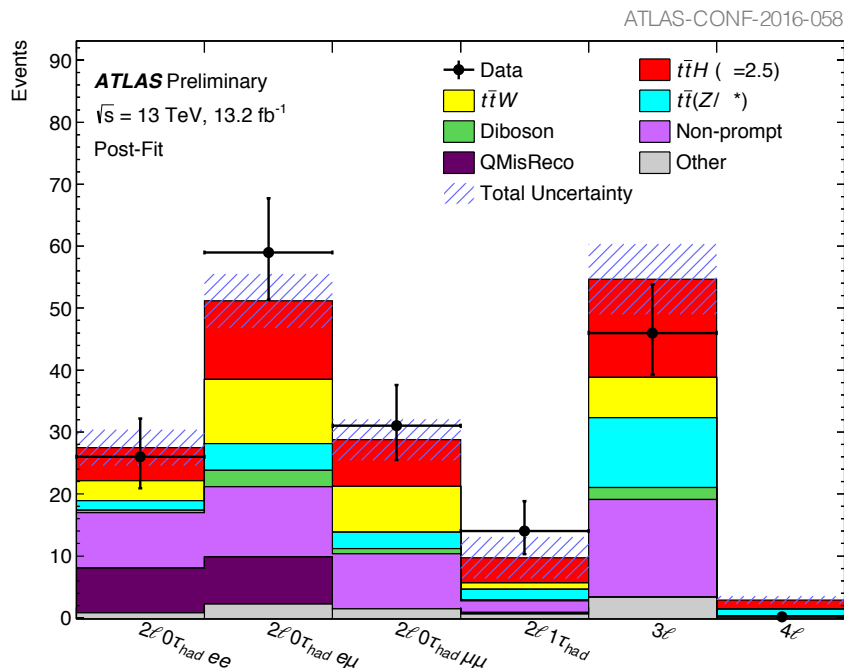
First search for ttH production at 13 TeV by ATLAS

Most interesting of the SM Higgs channels at current luminosity



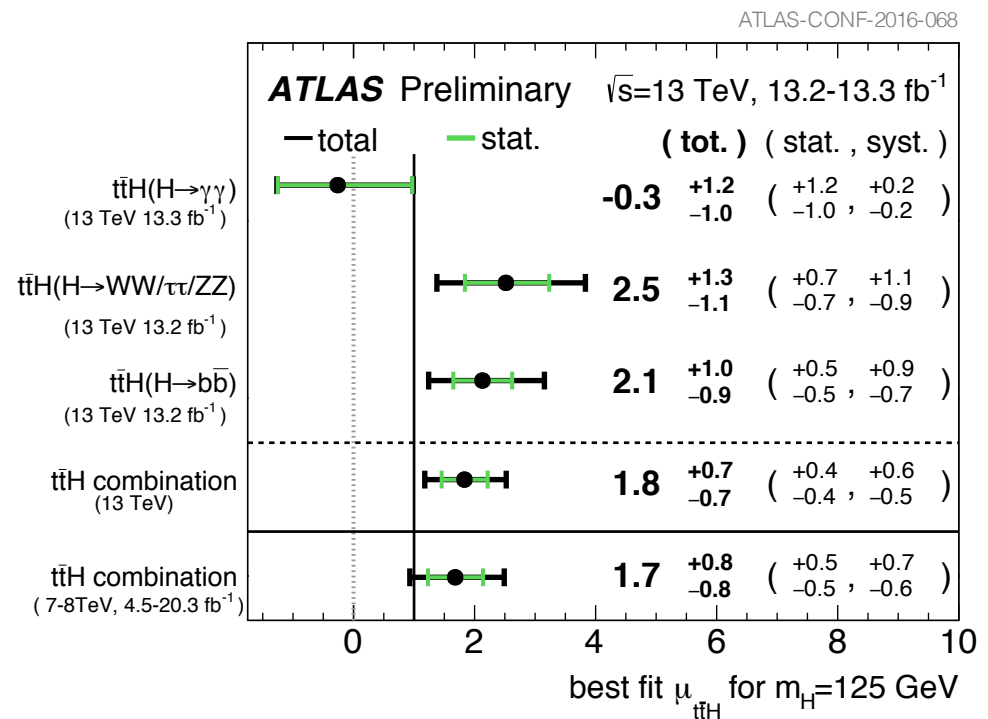
ATLAS showed preliminary results for ttH in all major channels and their combination at ICHEP 2016

ttH → multi-leptons



$$\mu = 2.5^{+1.3}_{-1.1}$$

Individual channels and combination



LHC-13

BSM searches — a fresh start

Will cover:

- BSM Higgs (briefly)
- Heavy resonances
- Supersymmetry
- Long-lived particles
- Dark matter (WIMPs)

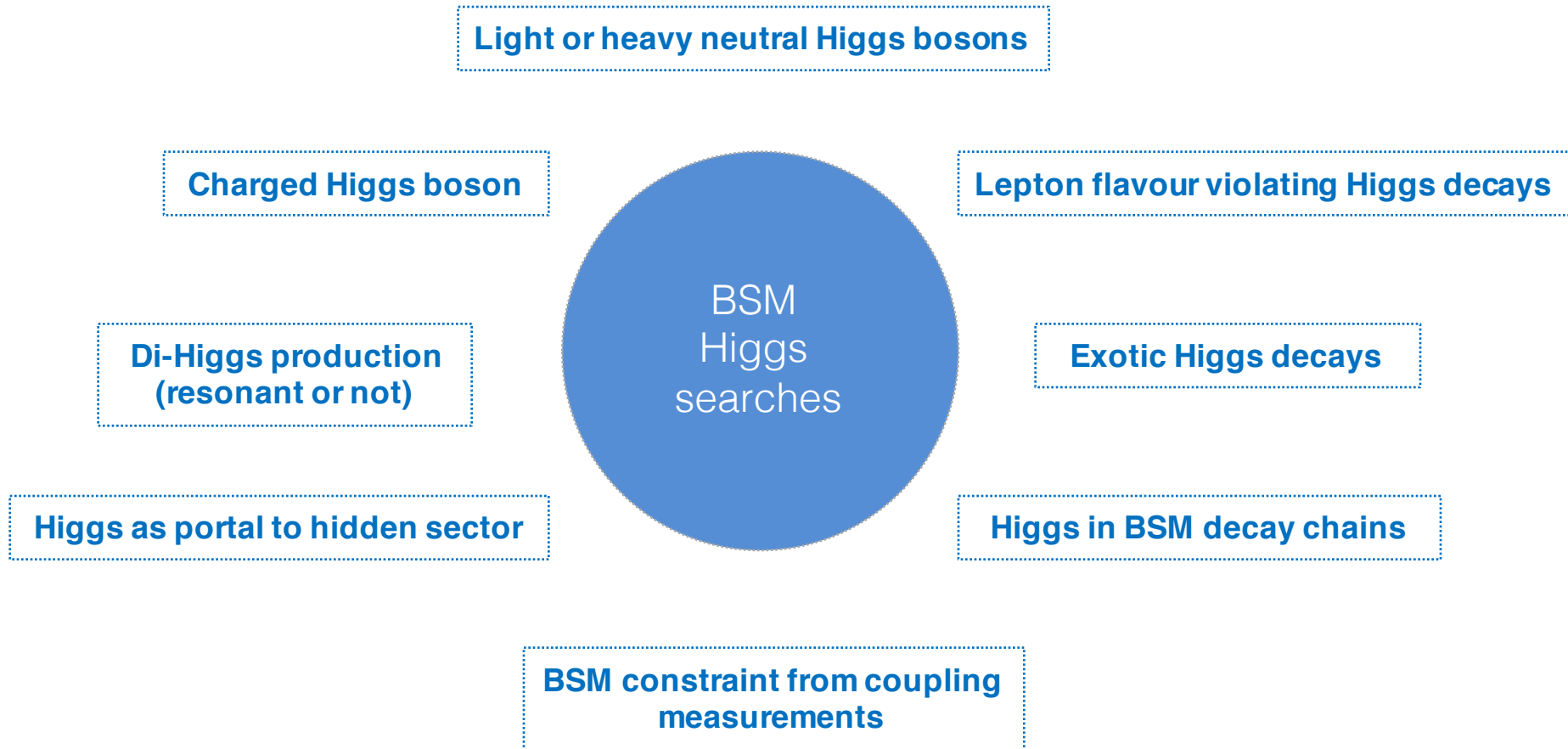
Heavy resonance searches benefit the most and fastest from increase in centre-of-mass energy. Slow improvement with increasing luminosity



Beyond the Standard Model Higgs physics

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

Diverse search programme:



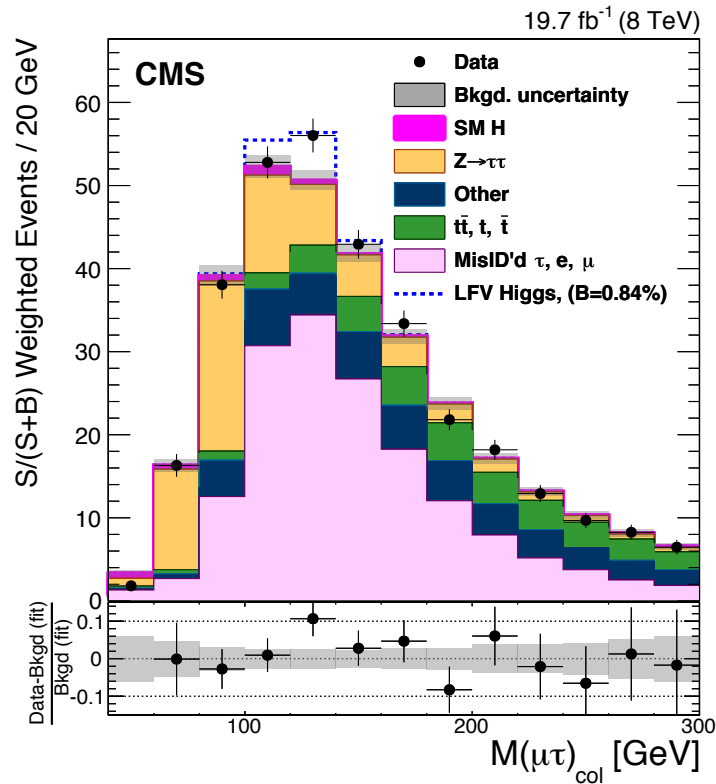
One word on lepton flavour violation in Higgs decays

Both experiments have finalised their Run-1 LFV analyses

While $H \rightarrow \mu e$ is severely constrained from flavour physics, $H \rightarrow \tau\mu$, τe are not ($\sim 10\%$ limits)

CMS released early 2015 a $H \rightarrow \tau\mu$ search finding a slight (2.4σ) excess

Not confirmed by ATLAS in the full Run-1 analysis



$H \rightarrow \tau\mu$:

ATLAS:

$$\text{BR} = 0.53 \pm 0.51\% < 1.43\% \text{ (95\% CL)}$$

CMS:

$$\text{BR} = 0.84^{+0.39}_{-0.37} \% < 1.51\% \text{ (95\% CL)}$$

$H \rightarrow \tau e$:

ATLAS:

$$\text{BR} = -0.3 \pm 0.6\% < 1.04\% \text{ (95\% CL)}$$

One word on lepton flavour violation in Higgs decays

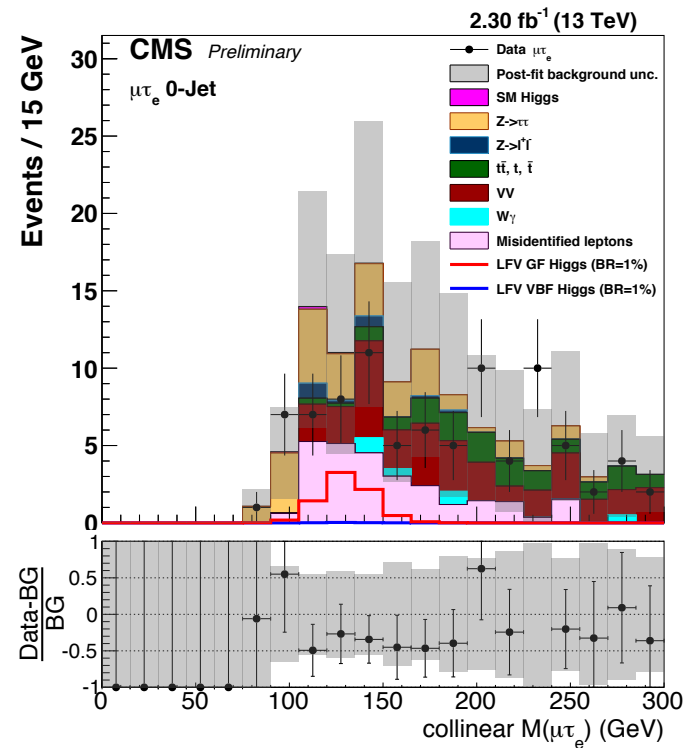
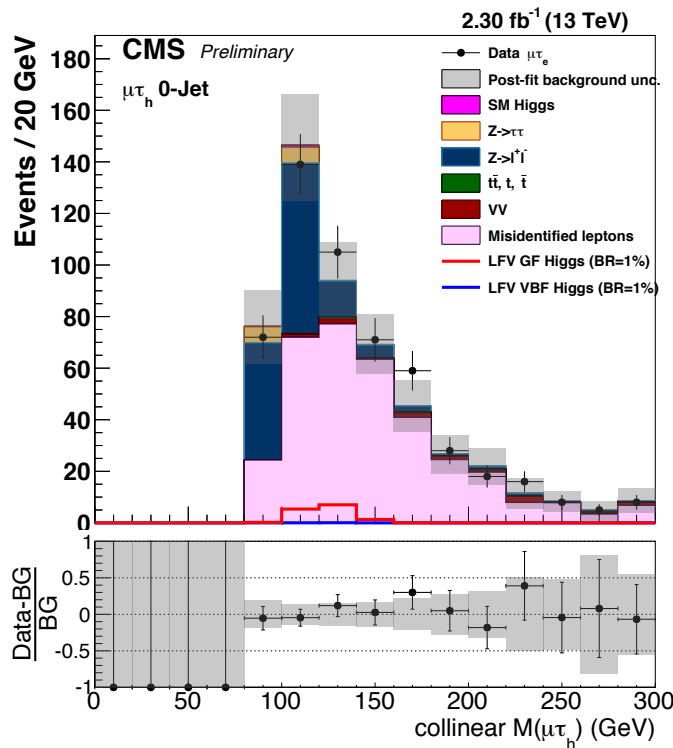
Both experiments have finalised their Run-1 LFV analyses

New preliminary result with 13 TeV from CMS [CMS-PAS-HIG-16-005]

Six categories considered: $(\mu\tau_h, \mu\tau_e) \times (0, 1, 2 \text{ jets})$

No significant excess, combined limit: $BR = -0.8 \pm 0.8 \%$ ($< 1.2\%$ at 95%CL, expected: $< 1.6\%$)

Limit on non-diagonal Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$



BSM Higgs boson searches

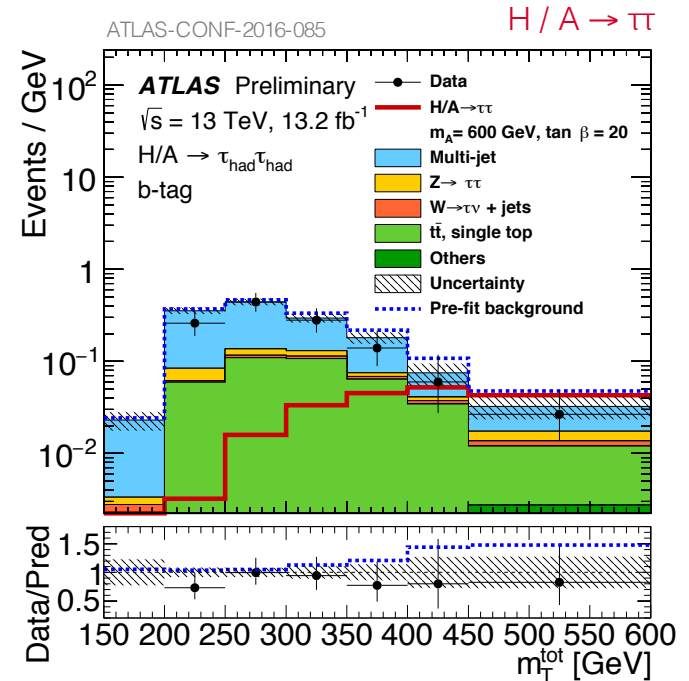
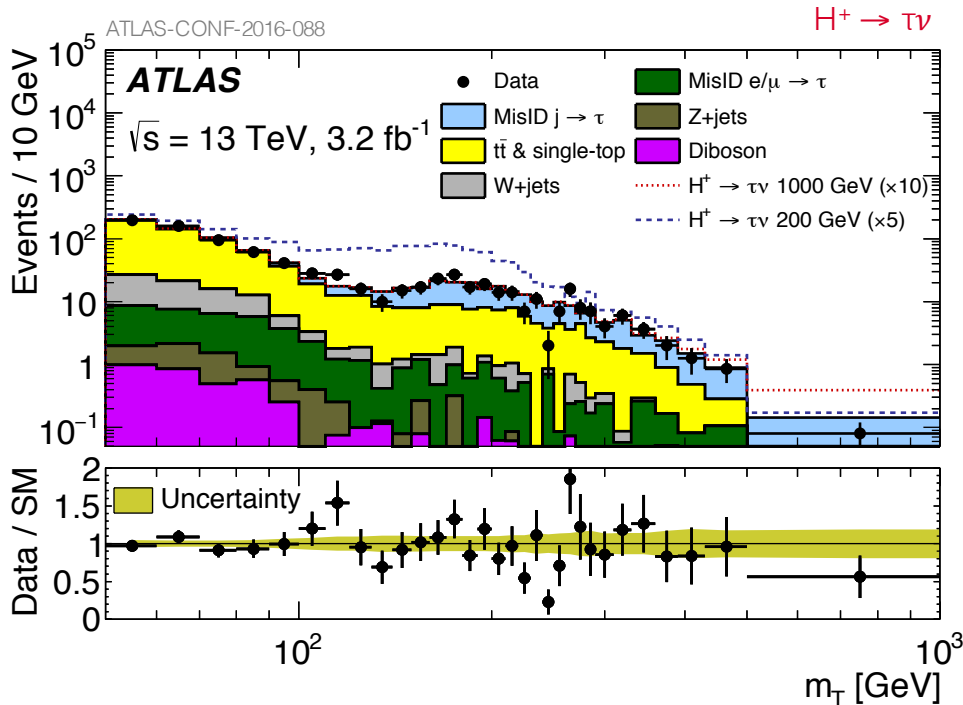
Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

Beyond the SM “Higgs zoo”

[Will Davey, LHCP 2014]



Higgs coupling to mass, look for decays to tau leptons or weak bosons, for example:

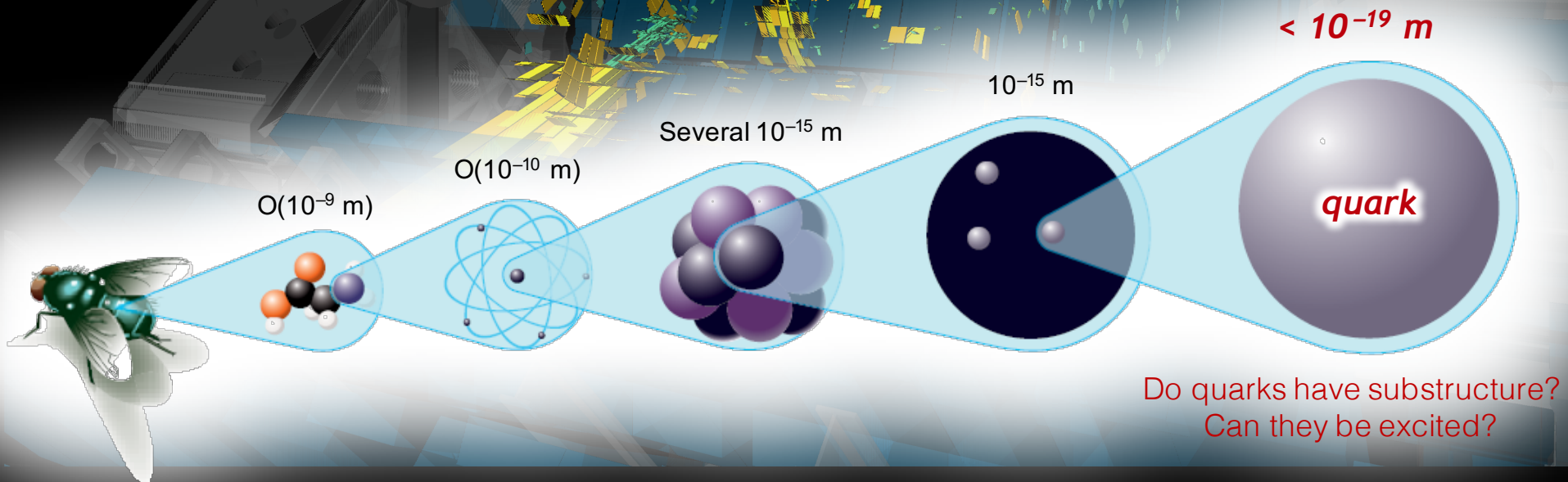


New physics in events with jets ?

Run: 280464

Event: 478442529

2015-09-27 22:09:07 CEST



Searches in high- p_T multijet final states at 13 TeV

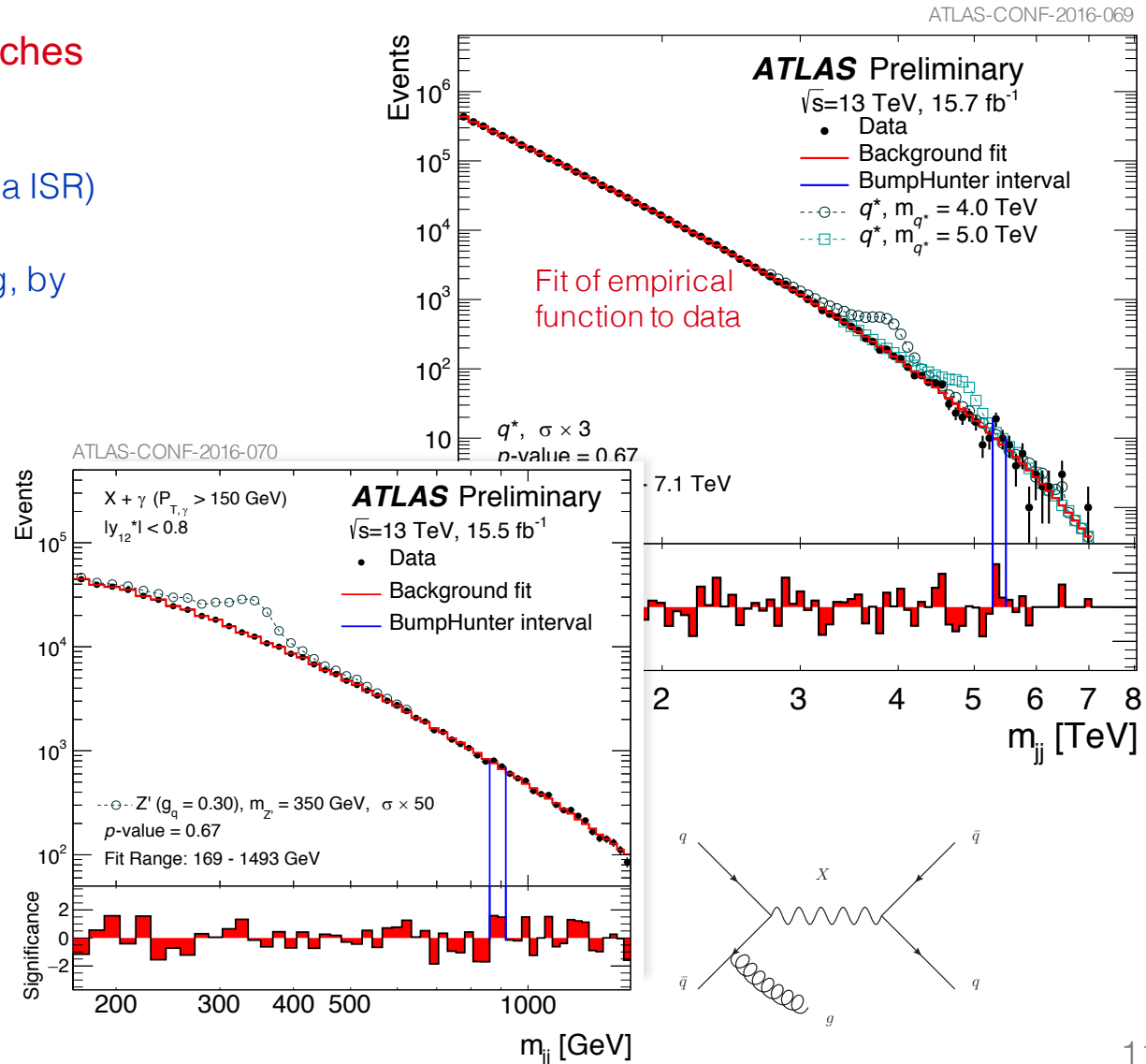
Processes with large cross-sections, sensitivity to highest new physics scales

High priority early 13 TeV searches

- Dijet resonance and angular distribution (incl. lower mass via ISR)
- High- p_T multijets produced, eg, by strong gravity
- High- p_T lepton + jets (strong gravity)
- Second generation scalar lepto-quark pair production (μq - μq final state, excl. < 1.2 TeV)

None of these searches showed an anomaly so far

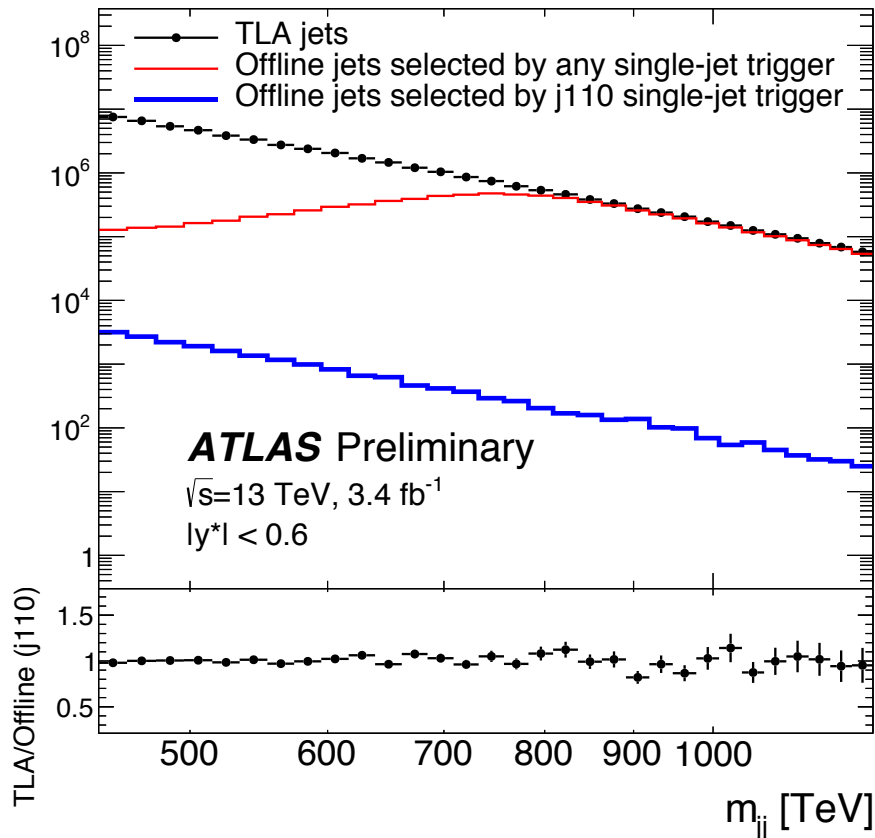
Limits on excited quarks (for example) at 5.6 TeV



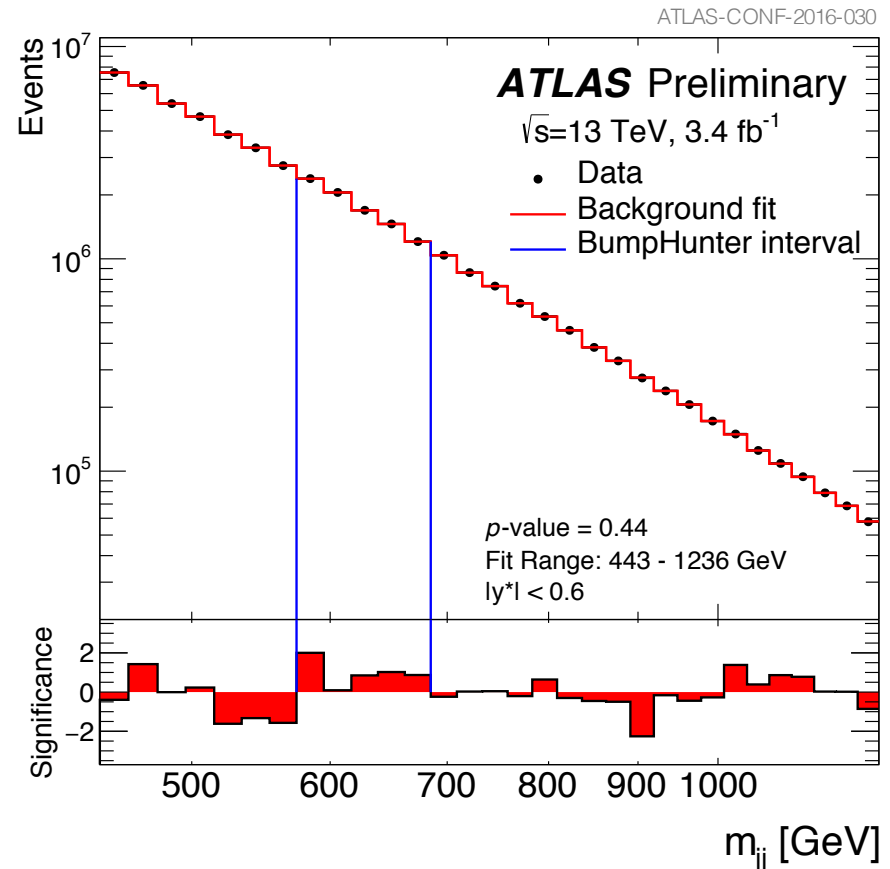
Searches in high- p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

A “trigger level analysis” allows to reduce trigger threshold



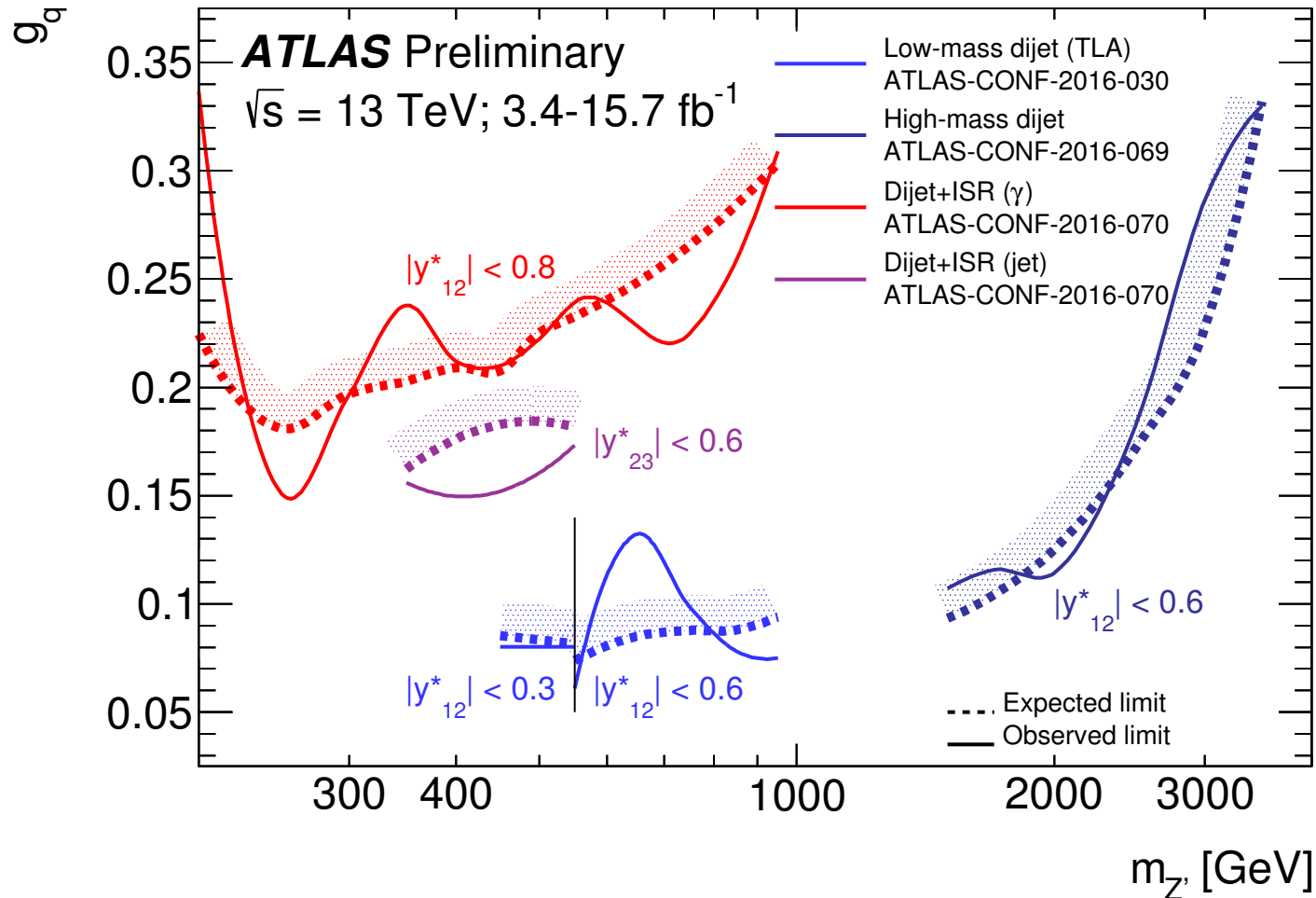
$$y^* = \frac{1}{2}(y_1 - y_2)$$



Searches in high- p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

ATLAS bounds in the coupling-vs-mass plane for leptophobic Z' model from dijet searches



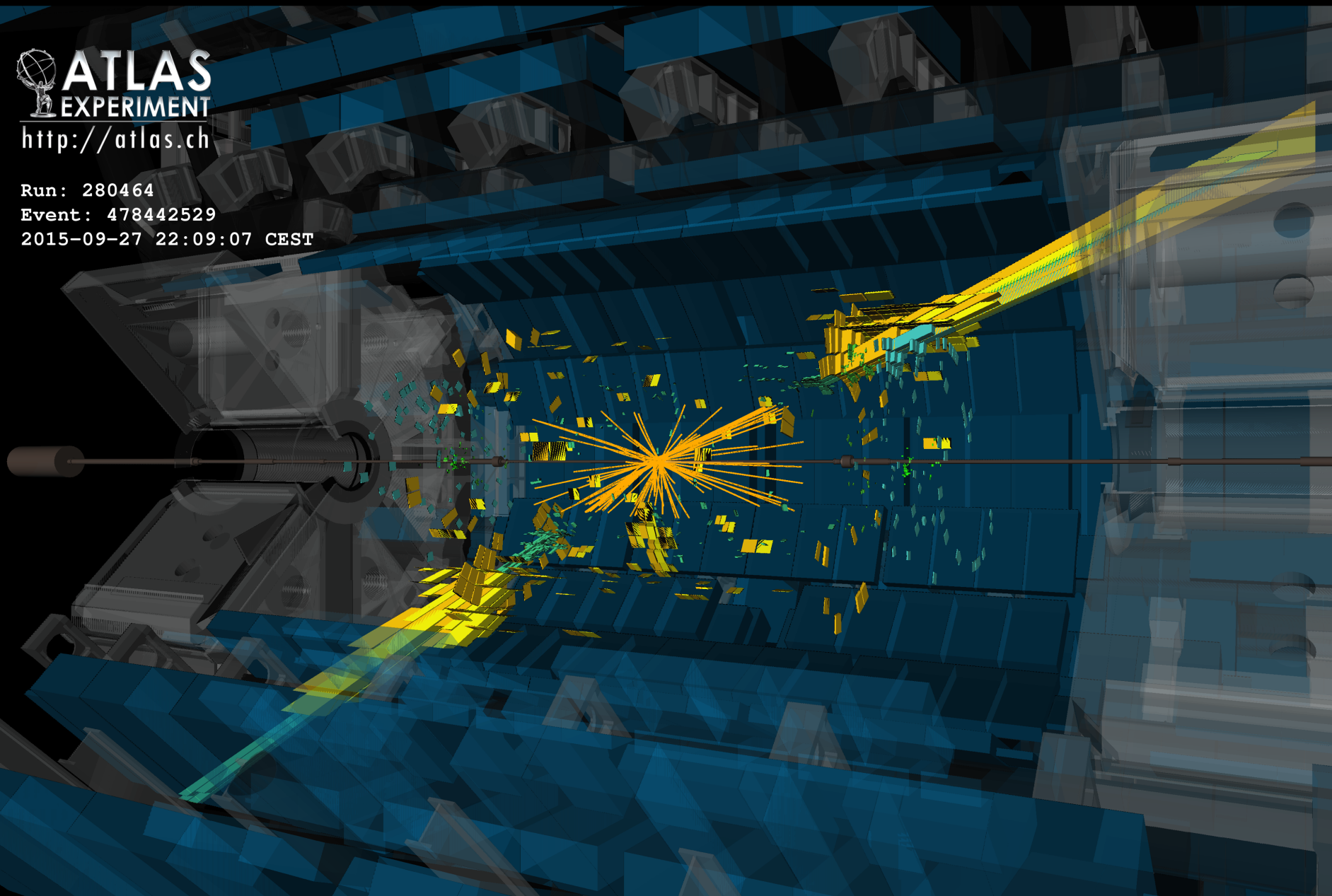
Highest mass dijet event measured by ATLAS in 2015 ($\sqrt{s} = 13 \text{ TeV}$): $m_{jj} = 7.9 \text{ TeV}$

 **ATLAS**
EXPERIMENT
<http://atlas.ch>

Run: 280464

Event: 478442529

2015-09-27 22:09:07 CEST



Highest mass *central* dijet event measured by ATLAS in 2015 ($\sqrt{s} = 13$ TeV): $m_{jj} = 6.9$ TeV

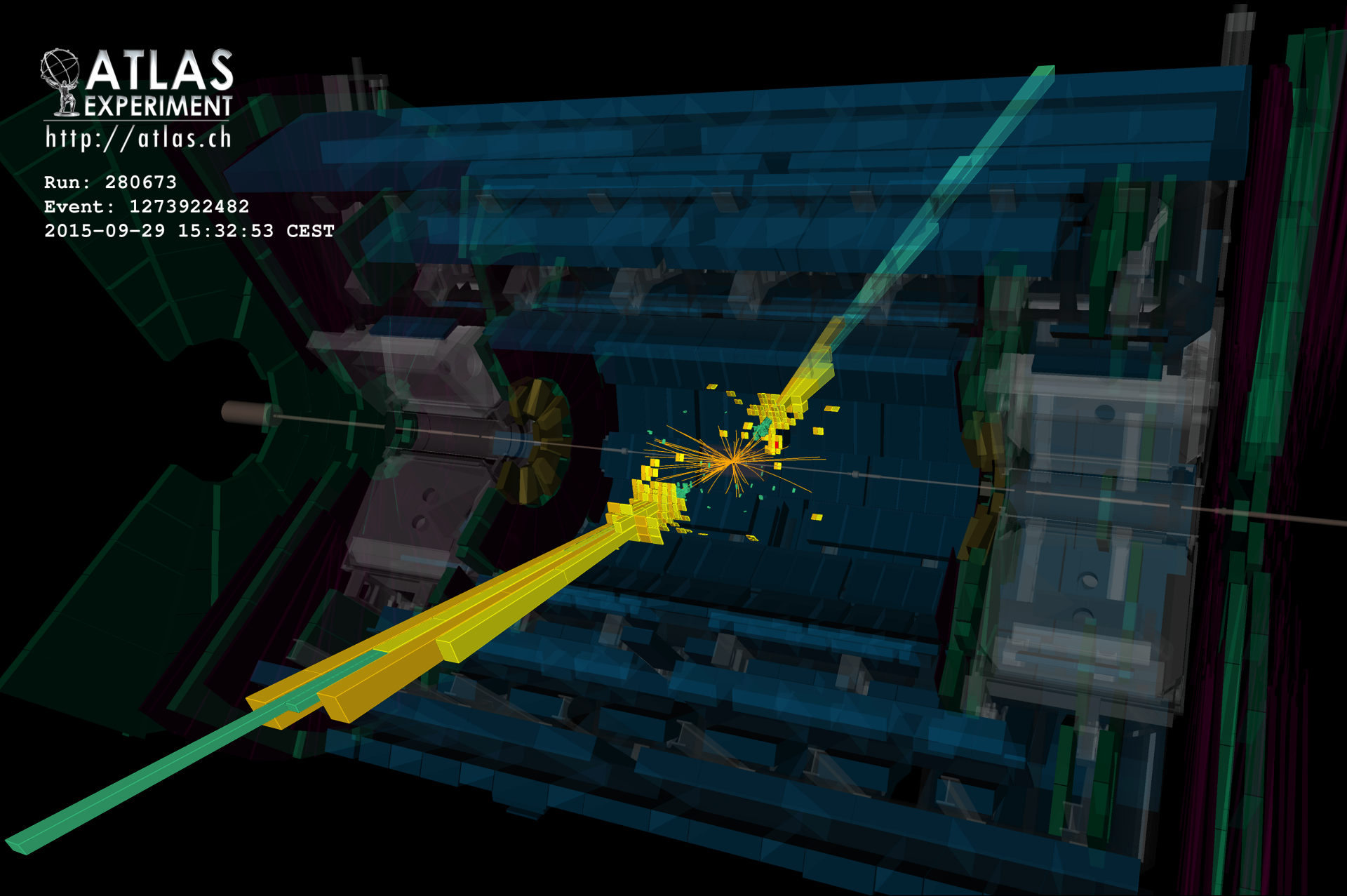


<http://atlas.ch>

Run: 280673

Event: 1273922482

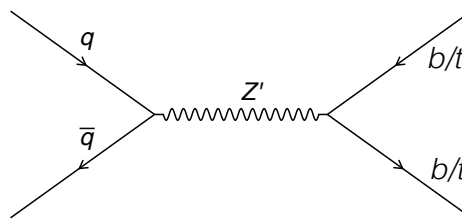
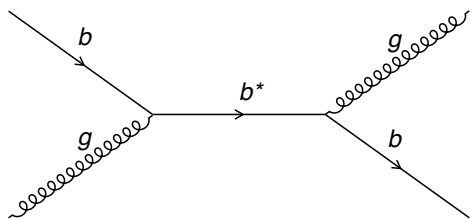
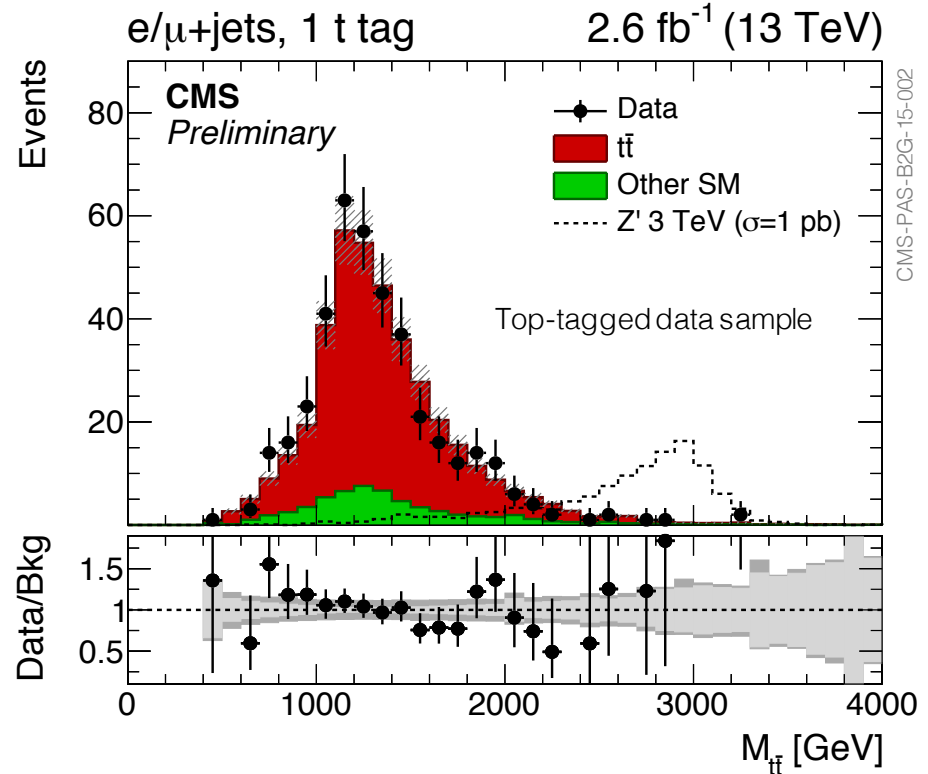
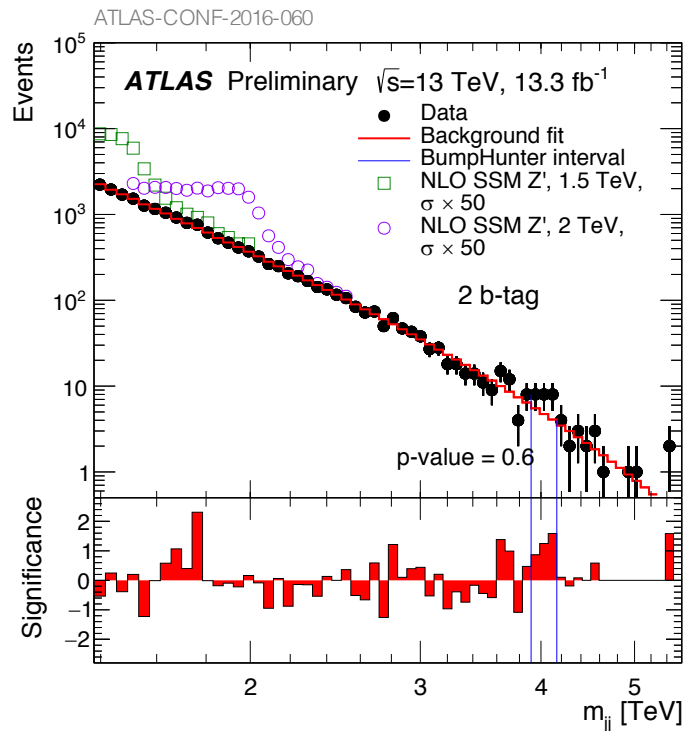
2015-09-29 15:32:53 CEST



Searches in high- p_T heavy-flavour final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

Also searches for a b -anti- b and top-antitop resonance



Need to understand detector performance at highest momentum scales with practically no control samples

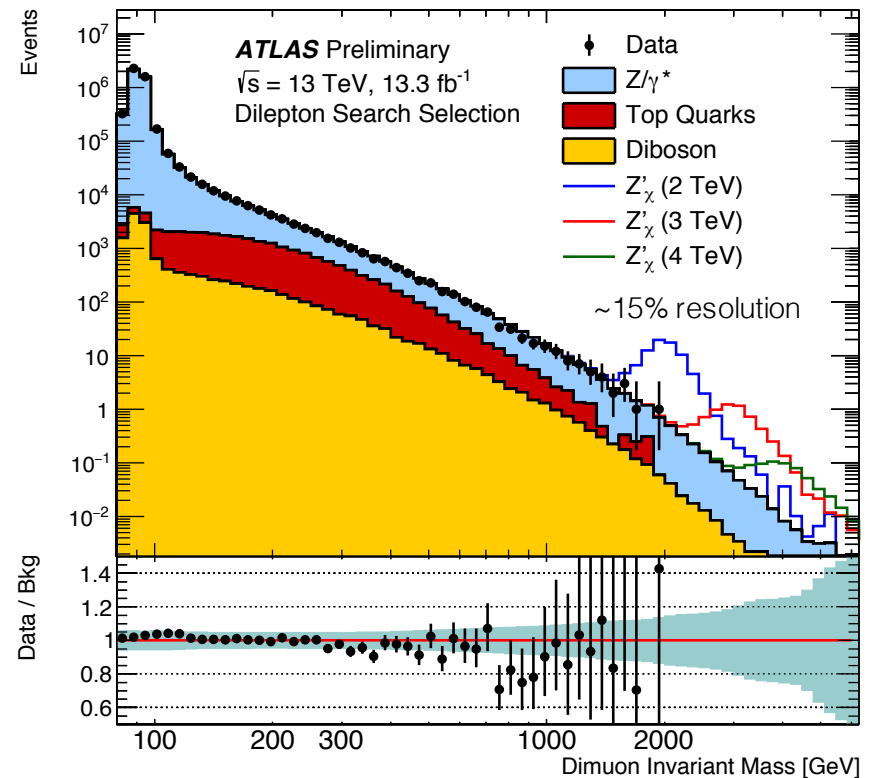
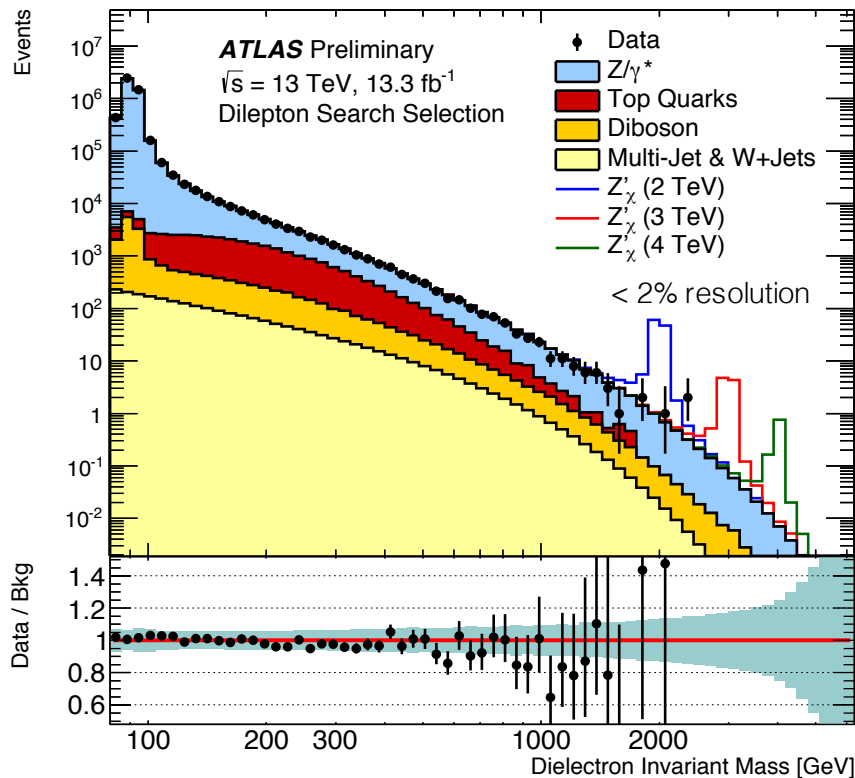
Searches in leptonic final states

Canonical searches for new physics in high-mass Drell-Yan production ($Z' \rightarrow \ell^+\ell^- / W' \rightarrow \ell\nu$)

Good Drell-Yan modelling crucial $\rightarrow$ SM diff. cross-section measurements paired with searches

High- p_T muons challenge detector alignment (30 μm in ATLAS), $\sim$ no charge information from electrons

No anomaly found. SSM Z' / W' benchmark limits set at 4.0 / 4.7 TeV (2.9 / 3.3 TeV at 8 TeV)



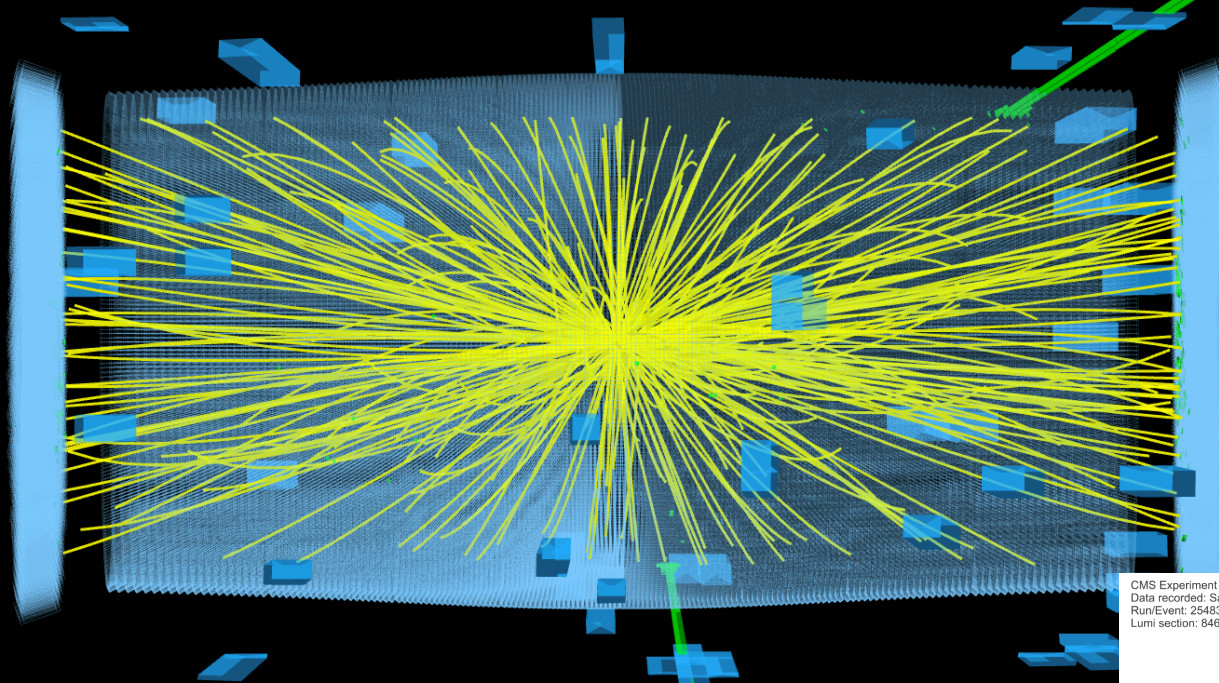
ATLAS & CMS also looked into high-mass $e\mu$ (LFV) production. Main background here: top-antitop.



CMS Experiment at the LHC, CERN

Data recorded: 2015-Aug-22 02:13:48.861952 GMT

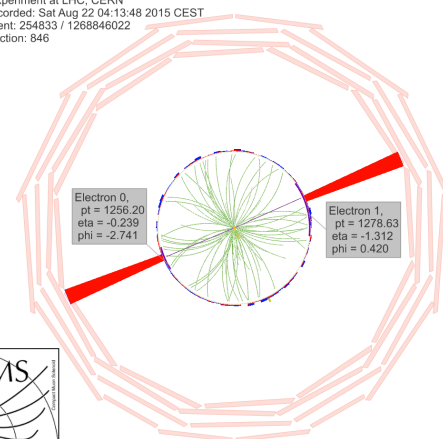
Run / Event / LS: 254833 / 1268846022 / 846



- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV ($\mu\mu$)

CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846



Heavy resonance searches

Corollary: future improvements in reach will take more time

Historical data and future extrapolation (lower limits given in TeV):

95% CL limit (TeV)	CDF	Run-1 '12	Moriond '16	ICHEP '16	300 fb ⁻¹ 14 TeV	3000 fb ⁻¹ 14 TeV
$Z' \rightarrow \ell\ell$	1.1	2.9	3.4	4.1	6.5	7.8 (?)
$q^* \rightarrow qg$	0.9	4.1	5.2	5.6	7.4	8
$Z' \rightarrow t\bar{t}$ (1.2% width)	0.9	1.8	2.0		3.3	5.5

ATLAS upgrade:
ATL-PHYS-PUB-2013-003,
ATL-PHYS-PUB-2015-004

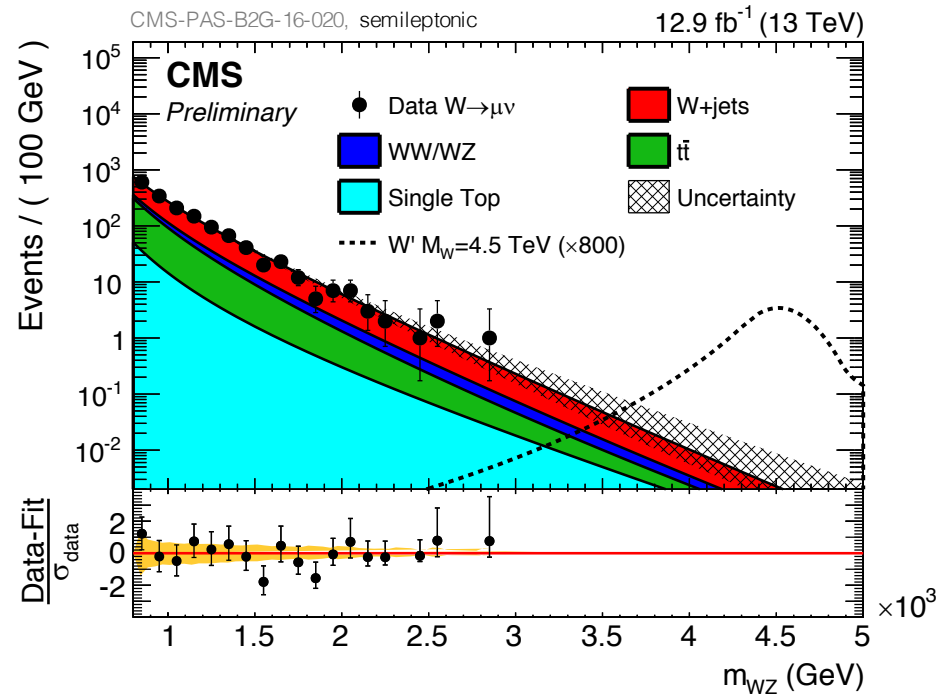
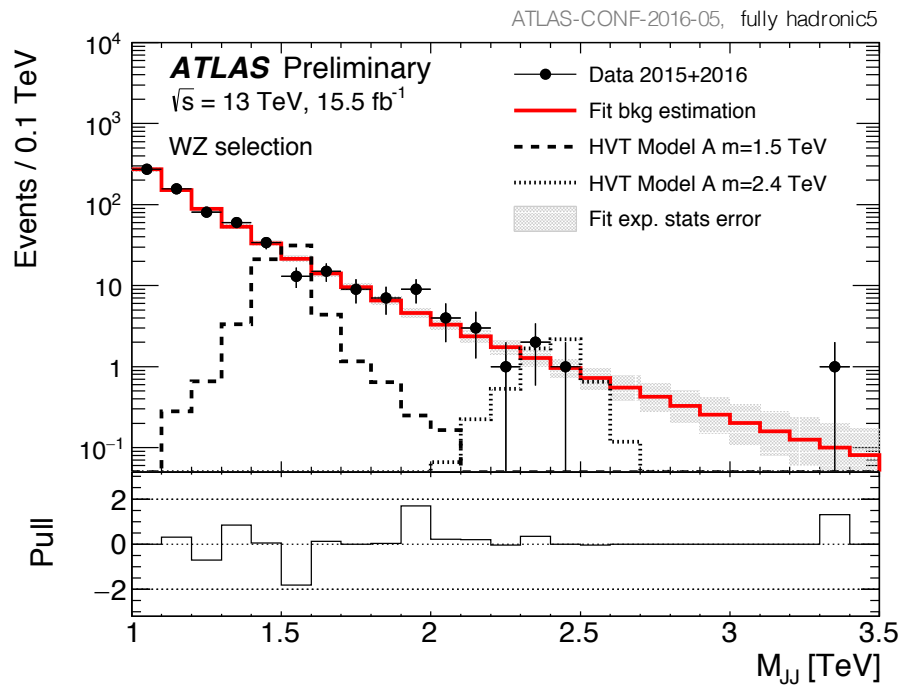
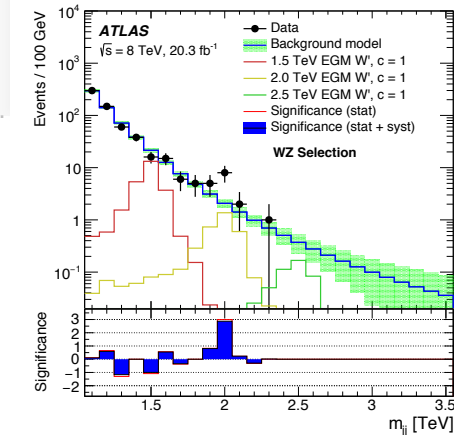
CDF:
<http://arxiv.org/abs/1101.4578> (4.6 fb⁻¹)
<http://journals.aps.org/prd/abstract/10.1103/PhysRevD.83.031102> (5.3 fb⁻¹)
<http://prd.aps.org/abstract/PRD/v79/i11/e112002> (1.1 fb⁻¹)
<http://arxiv.org/abs/1211.5363> (9.5 fb⁻¹)

Searches for diboson resonances (hh, Vh, VV)

High- p_T of bosons boosts hadronic decay products into merged jets

Hadronic decay modes use jet substructure analysis to reconstruct bosons. Important strong interaction backgrounds

Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen at 8 TeV in VV in fully hadronic channel, not seen in the other decay channels (eg, $lvqq$)



Light quanta



First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand, Nov 1895
[First Nobel price of physics, 1901]



Used since forever
as detection probe

Recent example: $H \rightarrow \gamma\gamma$
Other example:

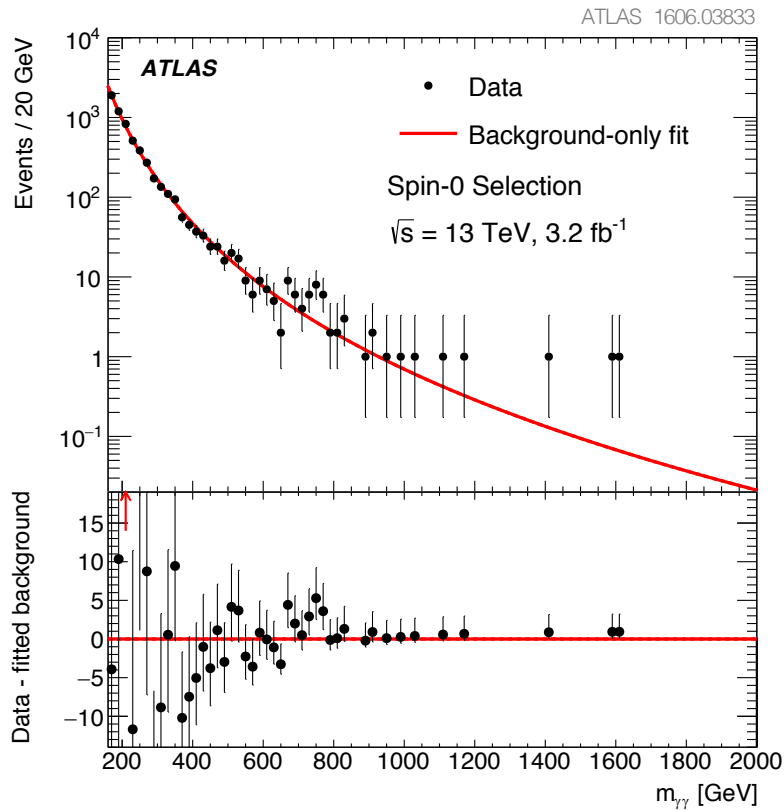


Picture of a mirage

Diphoton resonance searches, the 2015 data

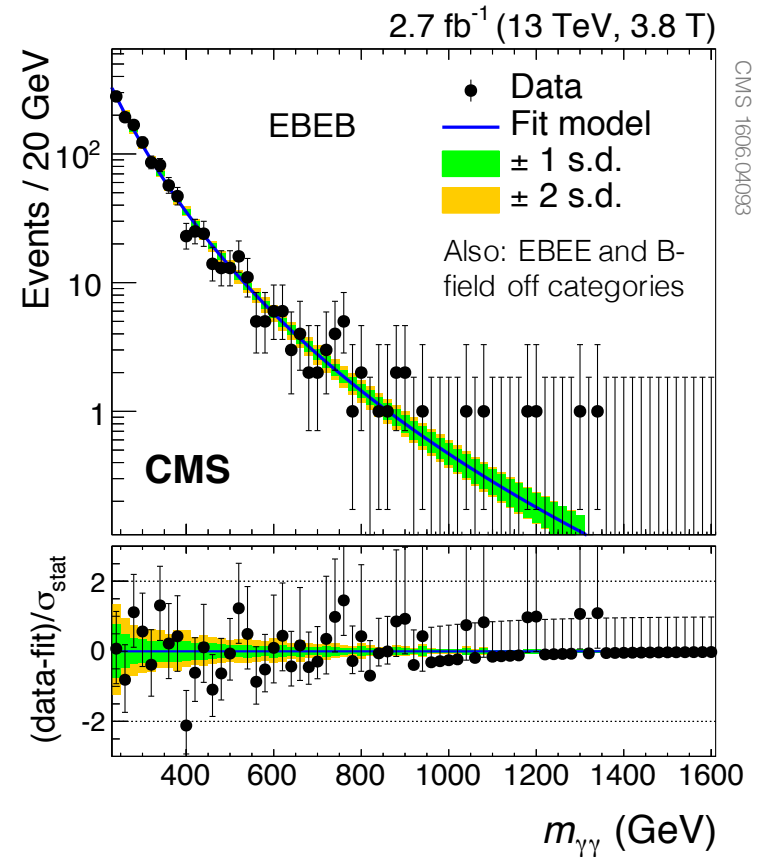
Dedicated searches for a spin-0 and a spin-2 diphoton resonance

- Photons are tightly identified and isolated. Typical purity $\sim 94\%$, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)



Lowest p-value at $\sim 750 \text{ GeV}$, $\Gamma \sim 45 \text{ GeV}$ (6%)

Local / **global** $Z = 3.9 / 2.1\sigma$



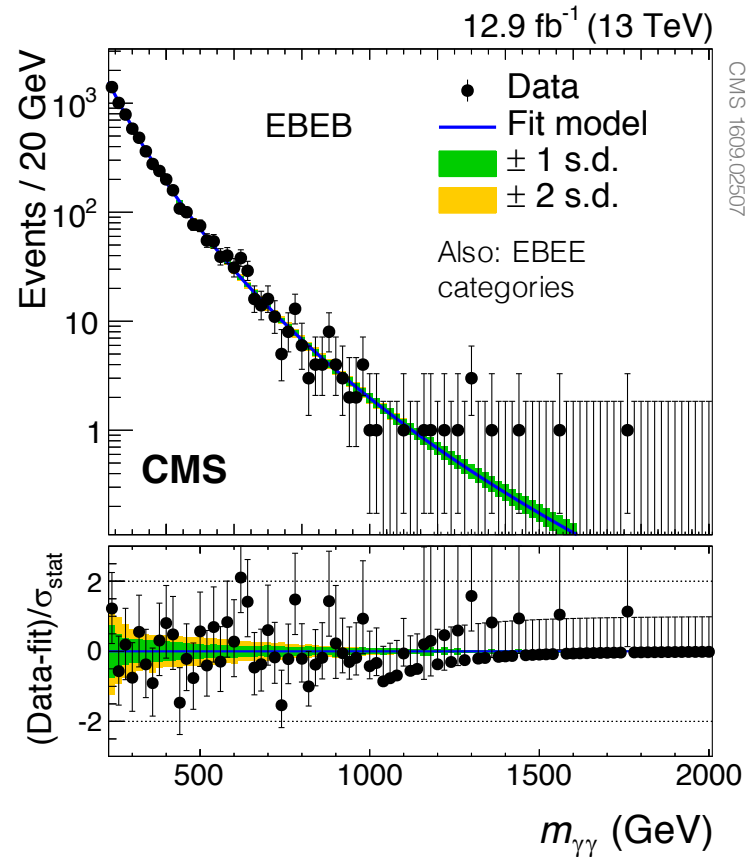
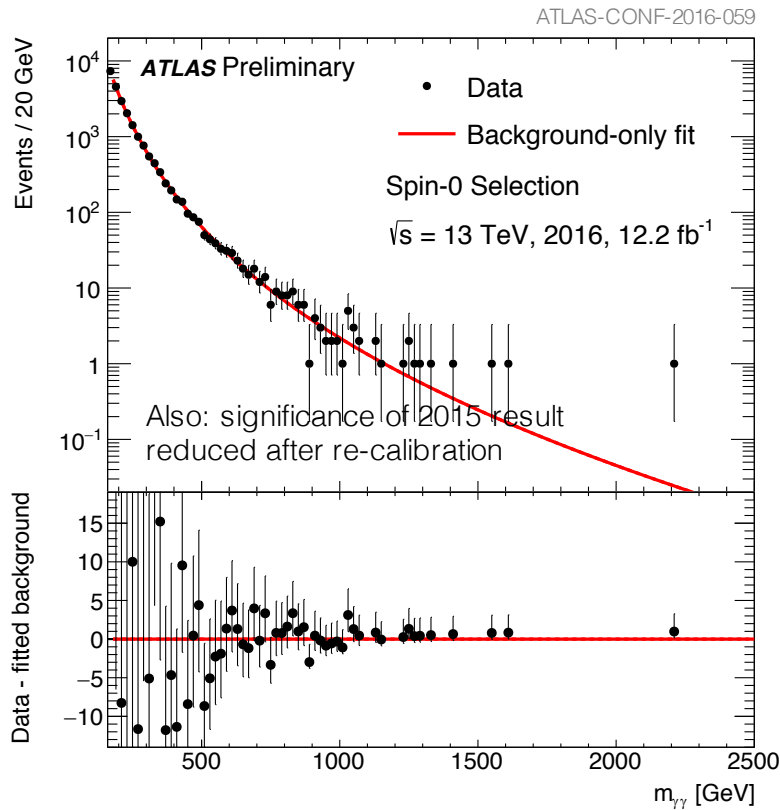
Lowest p-value at $\sim 750 \text{ GeV}$, narrow width

Local / **global** $Z = 3.4\sigma / 1.6\sigma$ (Run-1+2 combination)

Diphoton resonance searches, the 2016 results

Repeated ~unchanged analyses with 2016 data

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)

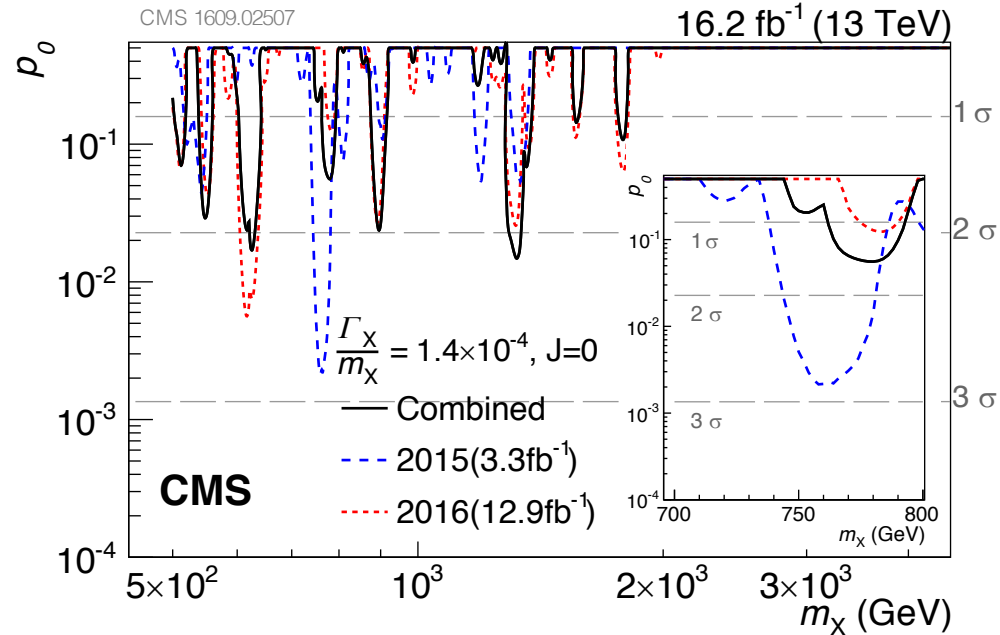
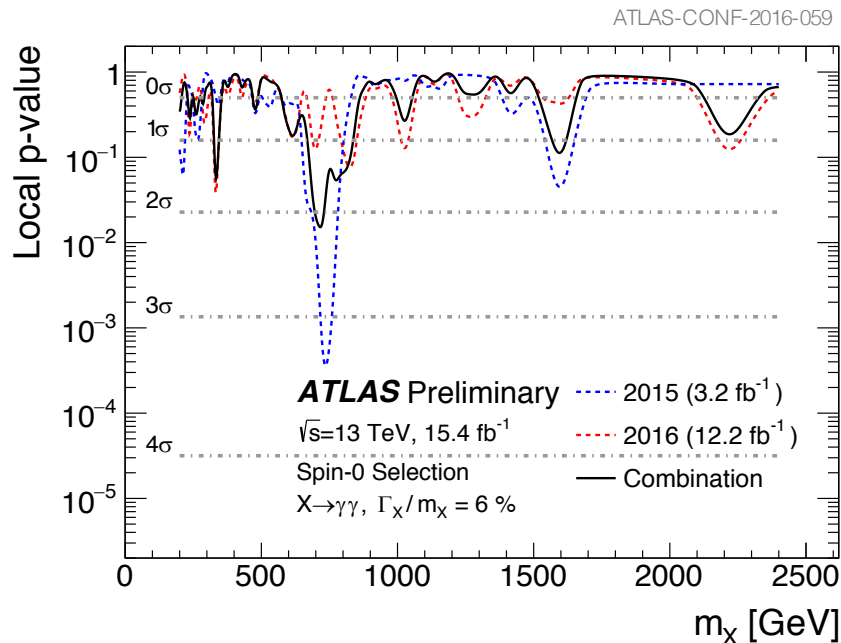


No noticeable excess in 2016 data

Diphoton resonance searches, the 2016 results

Comparison of 2015 and 2016 p-values

Resulting background-only p-values



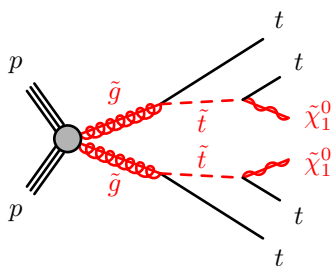
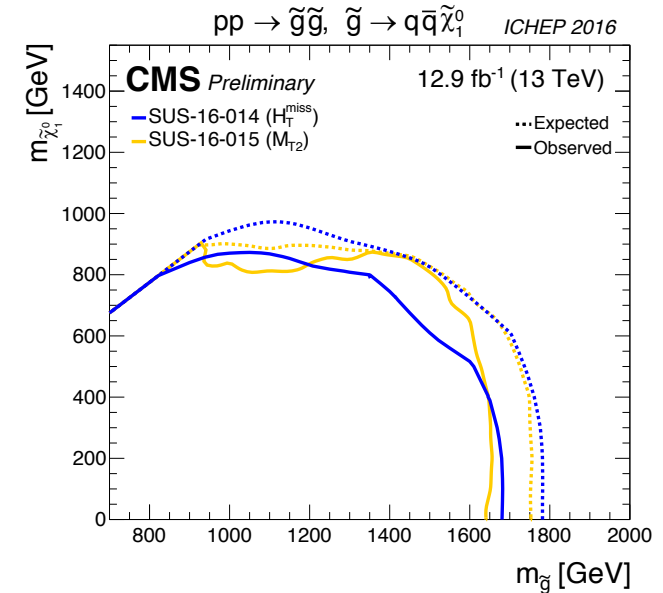
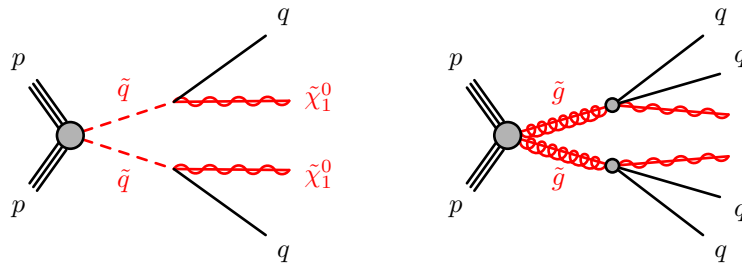
Lesson? Statistical fluctuation. Can happen, nothing wrong.

Actual trials factor larger than global factor quoted, as very many signatures probed by experiments (hard to estimate, but keep in mind!). Having a second experiment with a similar non-significant excess does not remove trials factor if you keep both. Removing 2015 data, and looking at 750 GeV in 2016 does remove trials factor.

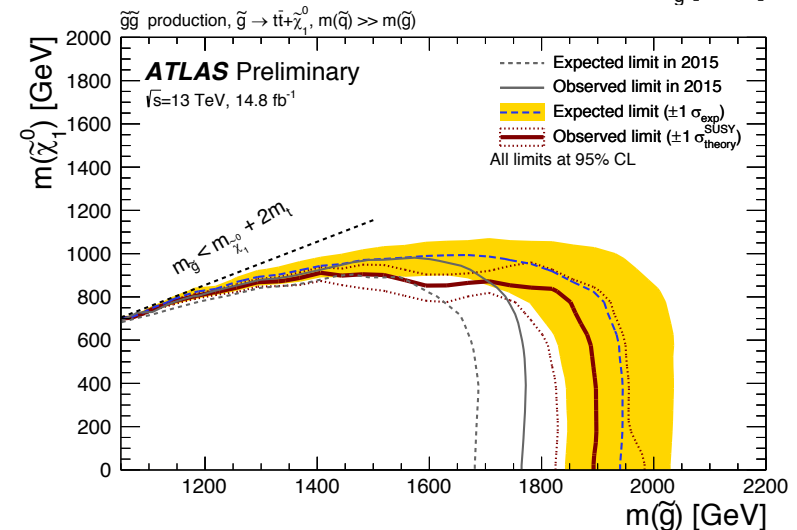
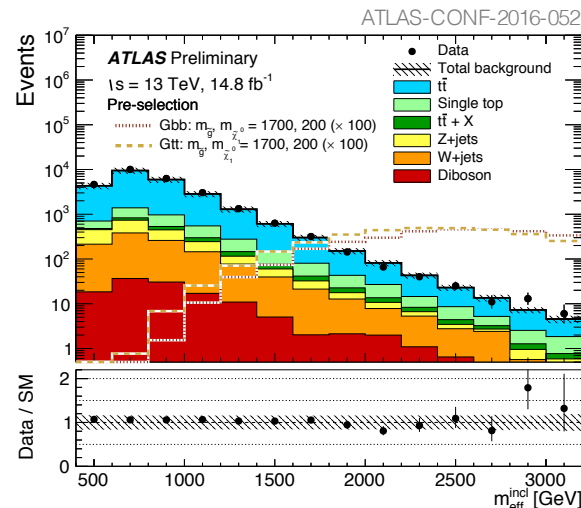
Supersymmetry

Still among the most popular SM extensions: hierarchy problem, unification, dark matter

Very diverse signatures. Highest cross-section events produce gluino / squark pairs with decays to jets and missing transverse momentum



No significant anomaly seen in many different analyses

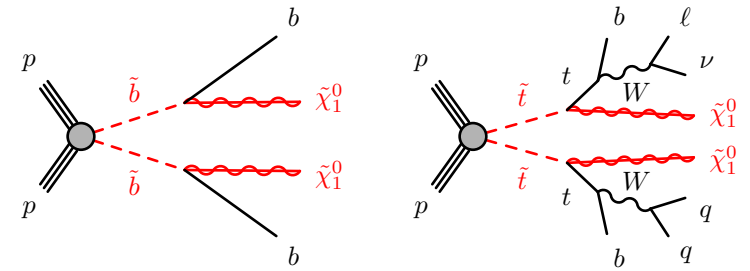


Third generation quark partners

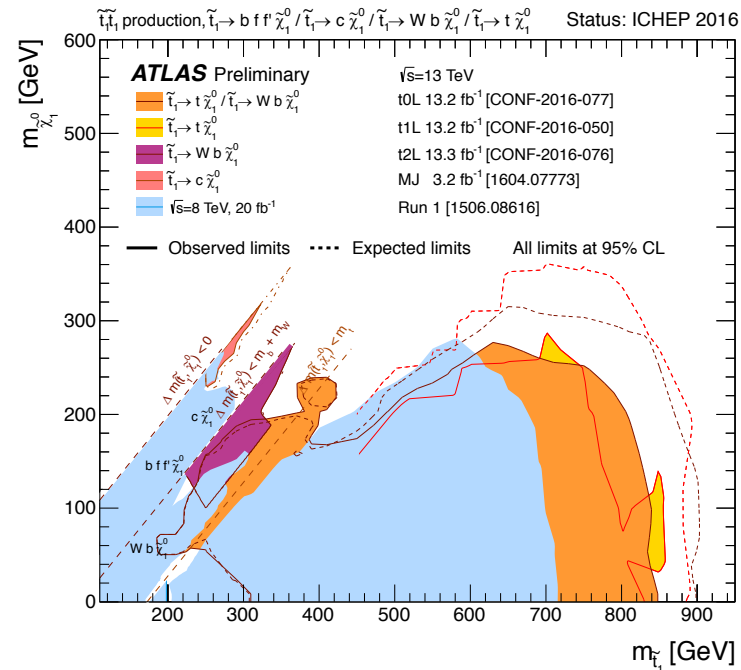
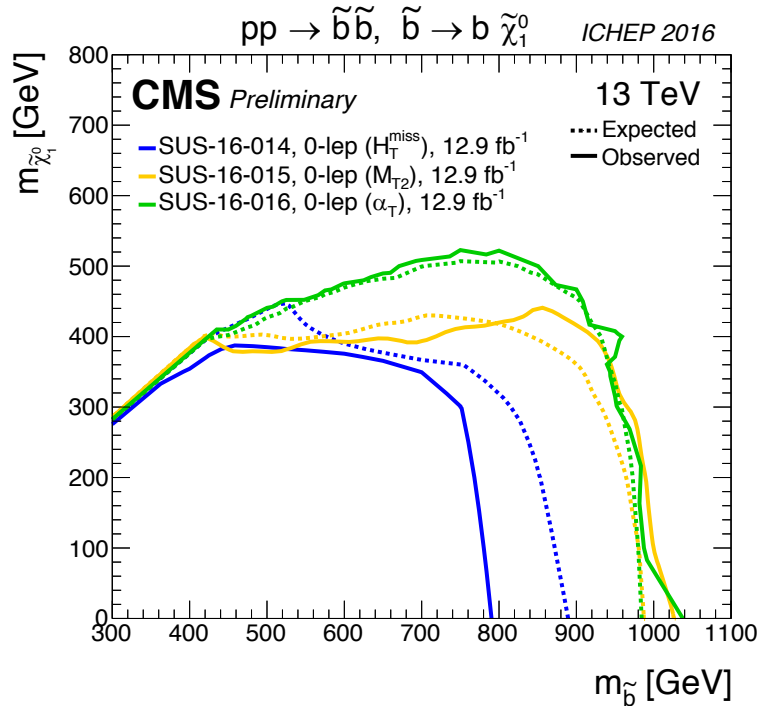
Searches for direct production

SUSY stop and sbottom may be the lightest sfermions. They have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Vector-like quarks* (VLQ) singly or pair produced decay to bW , tZ or tH . Also exotic $X_{5/3} \rightarrow tW$ possible



Signatures are b-jets, jets, possibly leptons and MET



No anomaly seen

Sensitivity improved over Run-1

Similar for VLQ searches

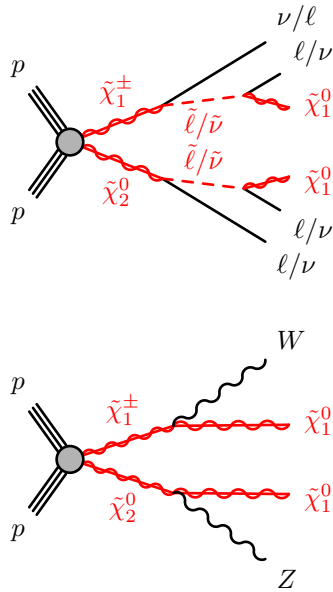
*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Electroweak supersymmetry production

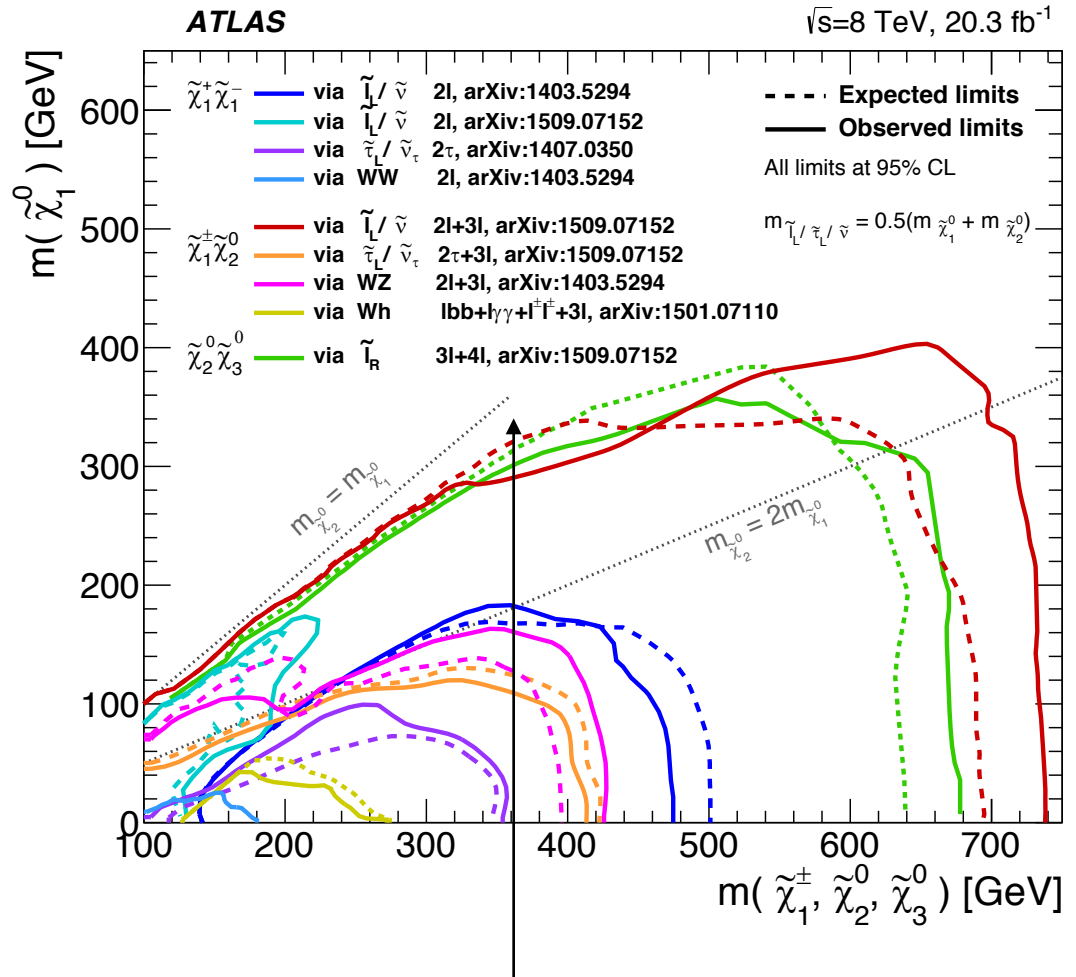
Searches for direct production

“**Electroweak-inos**” may be the lightest fermions. They also have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Signatures are leptons, few or no jets, MET



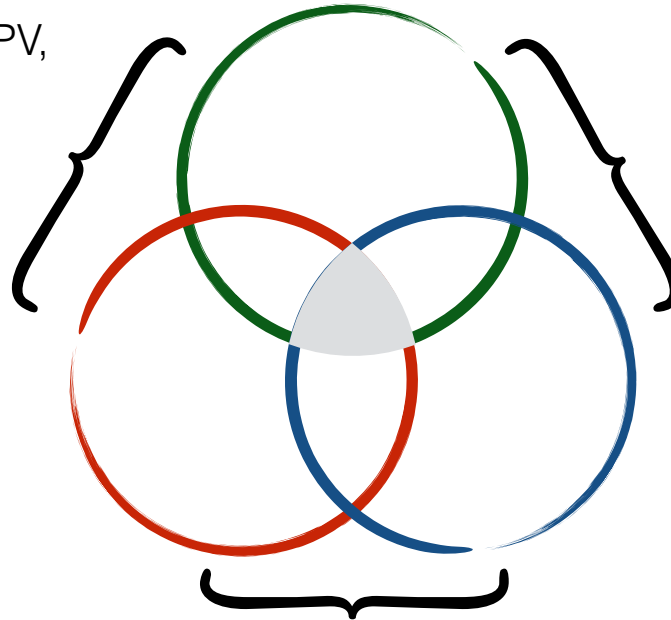
Example diagrams



Compressed region (“higgsino” case)

Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>



Naturalness & Dark Matter

- Additional states near weak scale (sgluon, KK resonances, ...)
- Higgs properties
- <Your idea here>

Unification & Dark Matter

- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Good idea ?

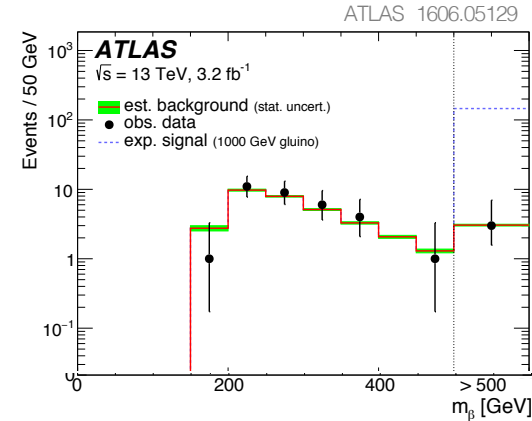
Long-lived particles predicted in many new physics models

Reason: large virtuality in decay, low coupling, or mass degeneracy

Multitude of signatures depending on lifetime, charge, decay: highly ionising, slow, out-of-time decay, displaced vertex, kinked or disappearing track, lepton-jets, ...

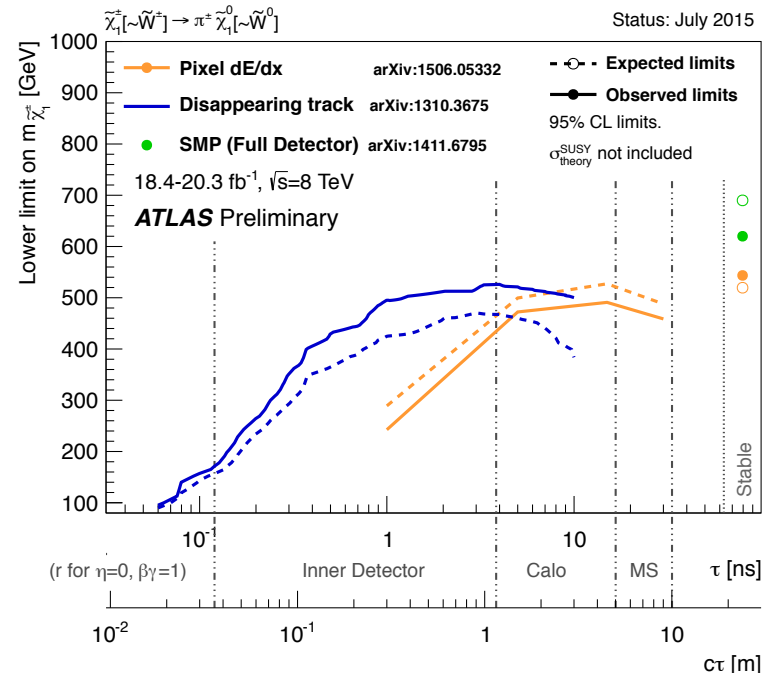
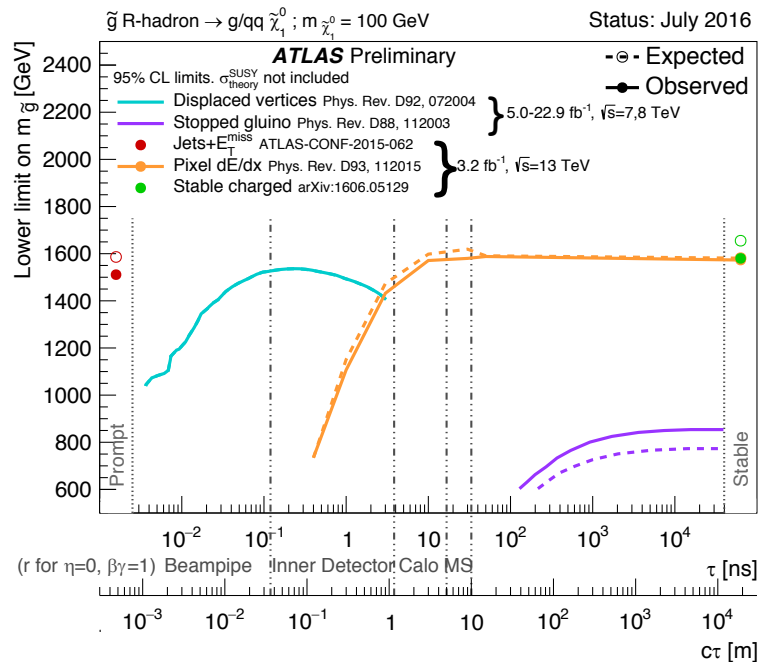
Some signatures require dedicated triggers, most requiring dedicated analysis strategies.

Standard searches sometimes sensitive to signatures with long-lived particles as well



Particle mass from velocity via time-of-flight measured in Tile calorimeter

Similar analysis from CMS uses tracker dE/dx and TOF from muon system



Summaries of mass limits versus lifetime of new particle

Searches for dark matter production at the LHC

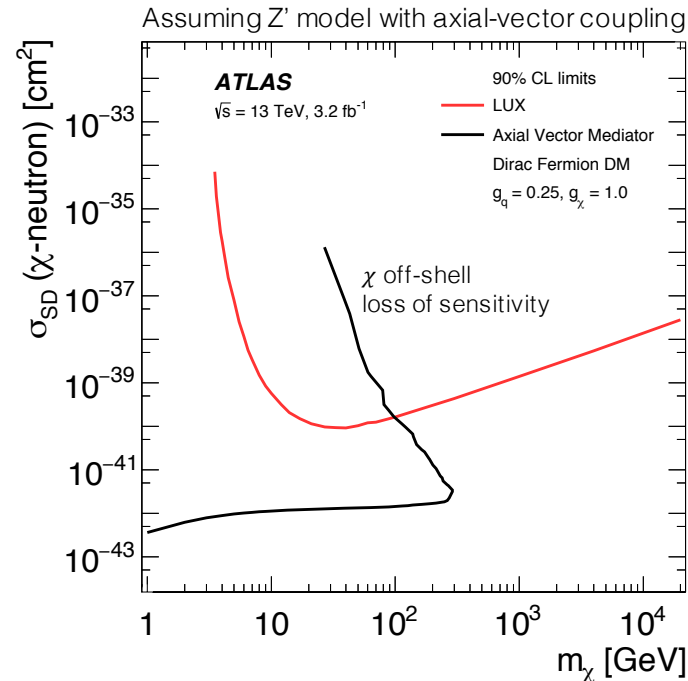
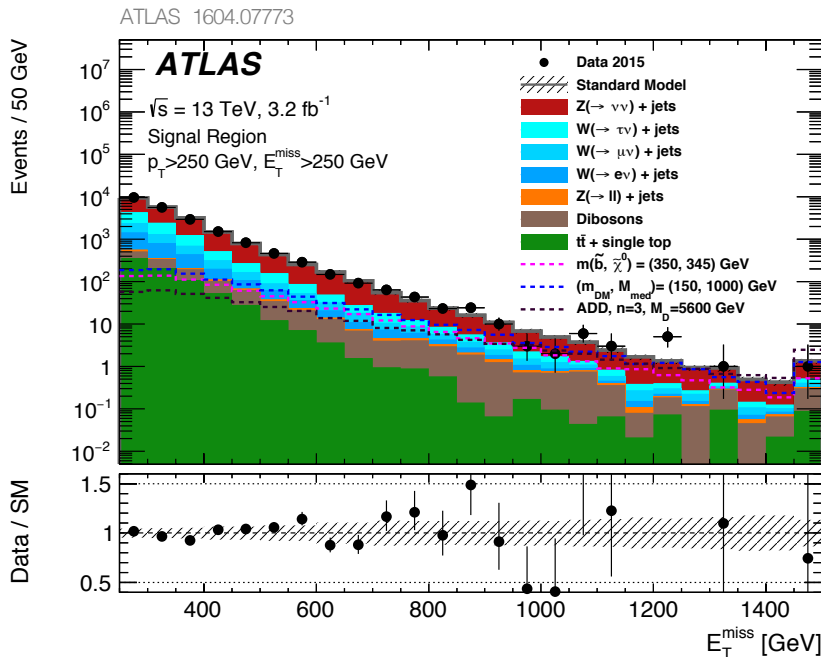
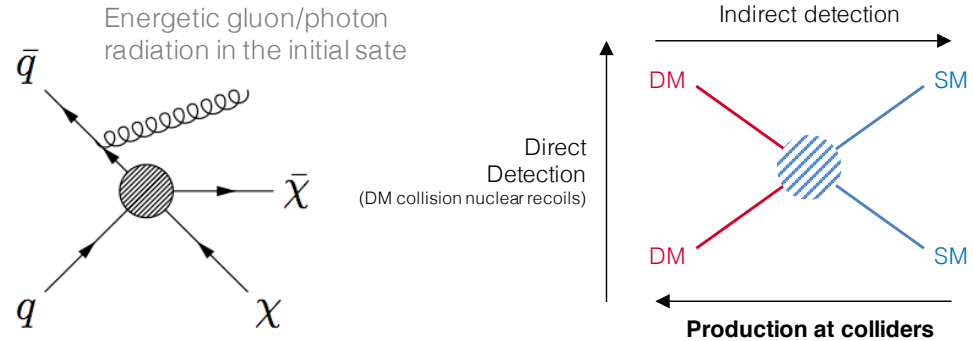
Canonical signature is 'X+MET' with large variety of 'X'

May not be able to
prove at LHC that a
signal is dark matter

Direct dark matter production at the LHC

Requires boost for triggering. Depending on coupling it can be made by different objects.

Experimentally challenging to control Z/W+jets background. Theory input needed.

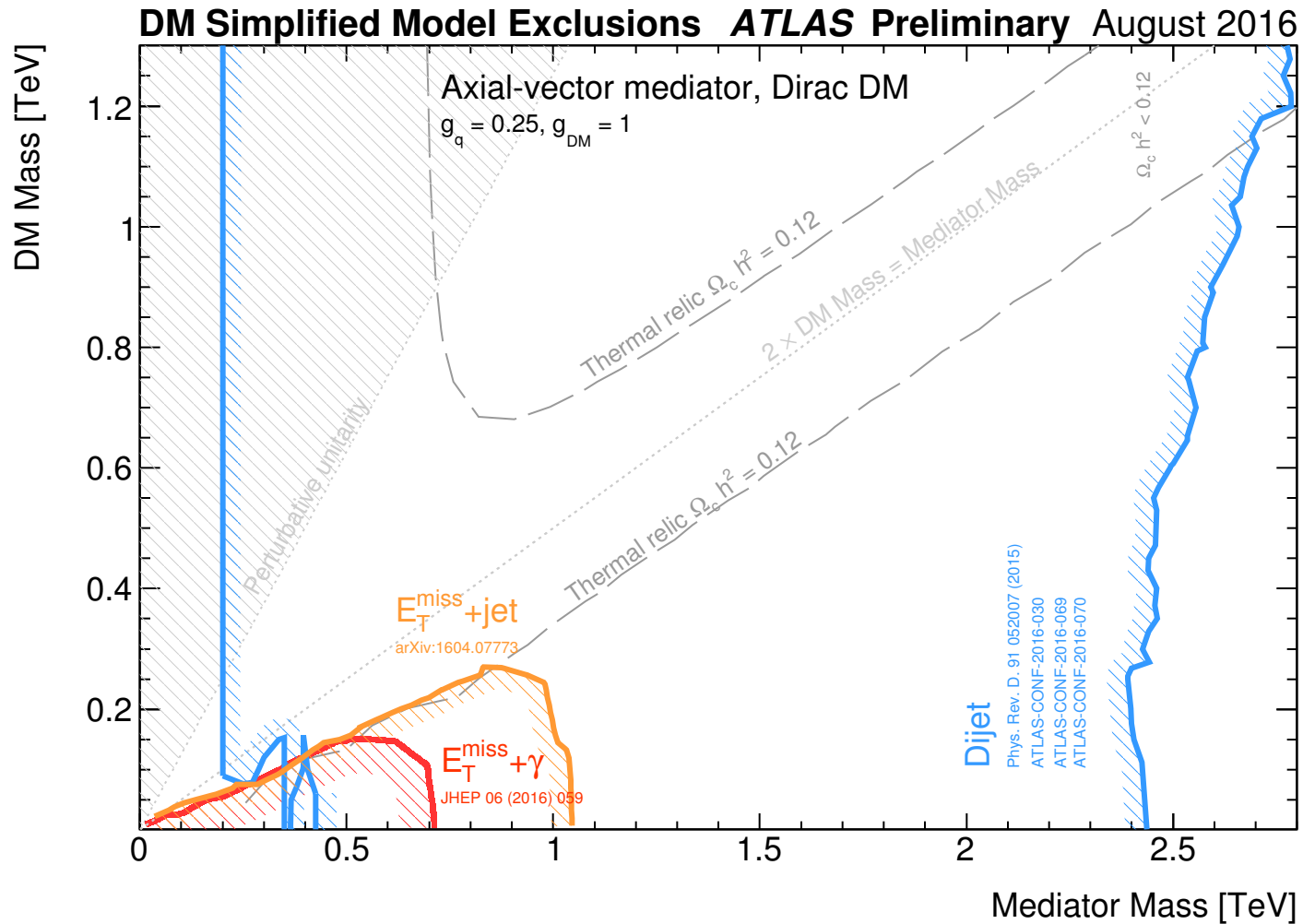


Many other
13 TeV results
available:

- jets + MET
- γ + MET
- V + MET
- $b\bar{b}/t\bar{t}$ + MET

No anomaly
seen so far

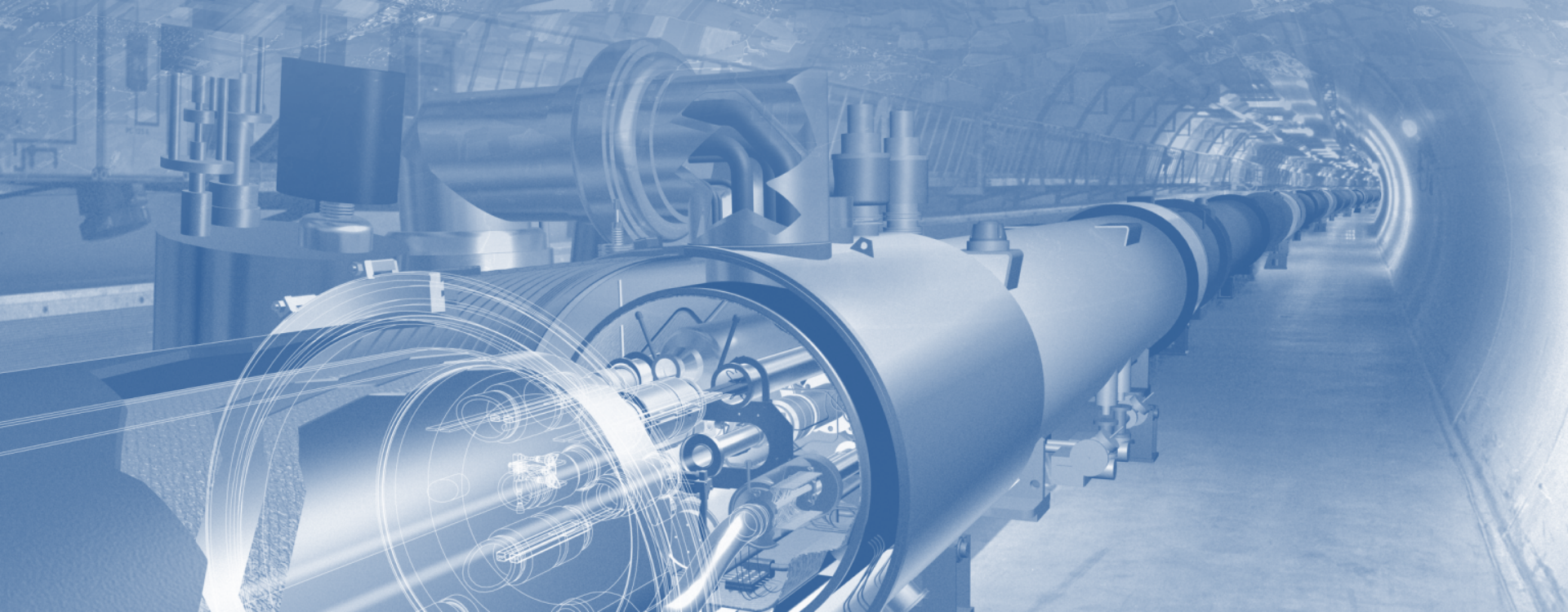
Exclusion regions for simplified models with heavy particle mediating interaction between initial state quarks and final state WIMPs



This was a very incomplete extraction of all the available 13 TeV searches only

The return of the limits ...

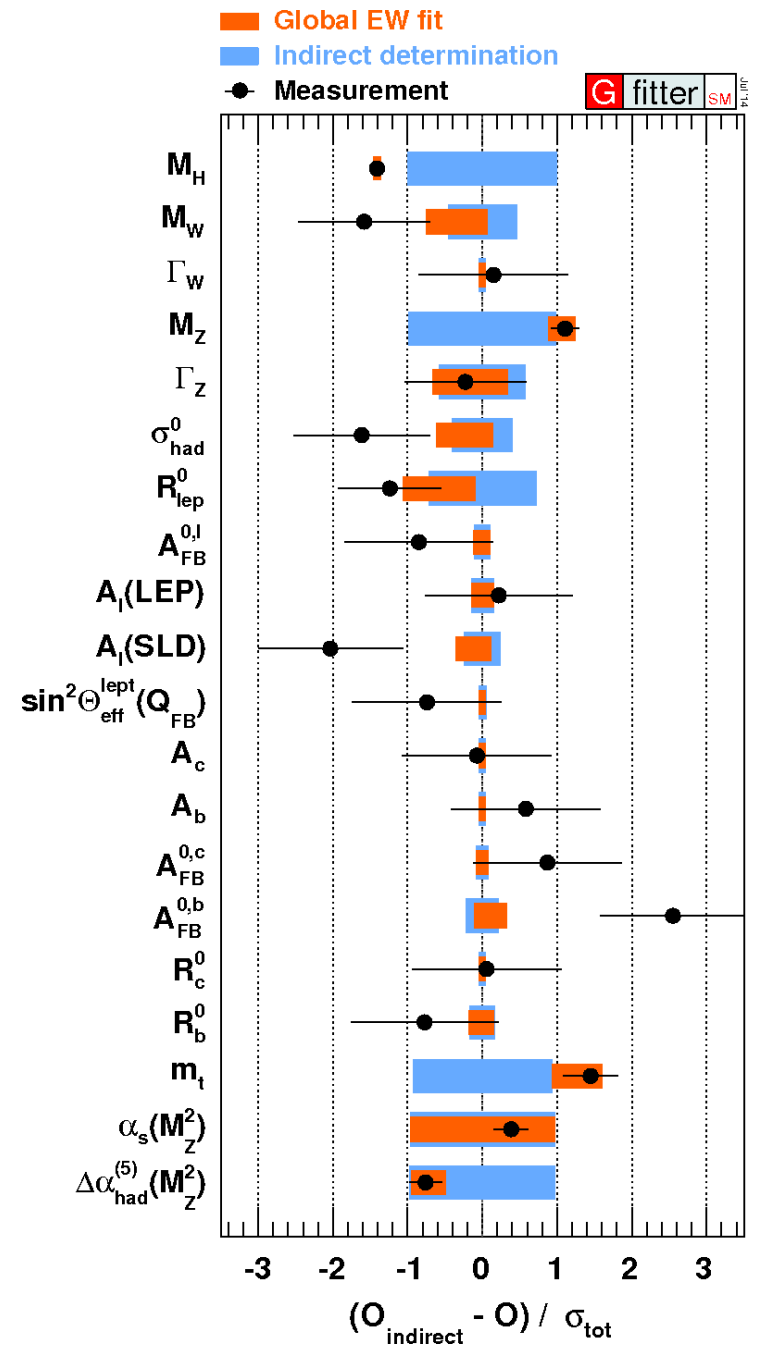
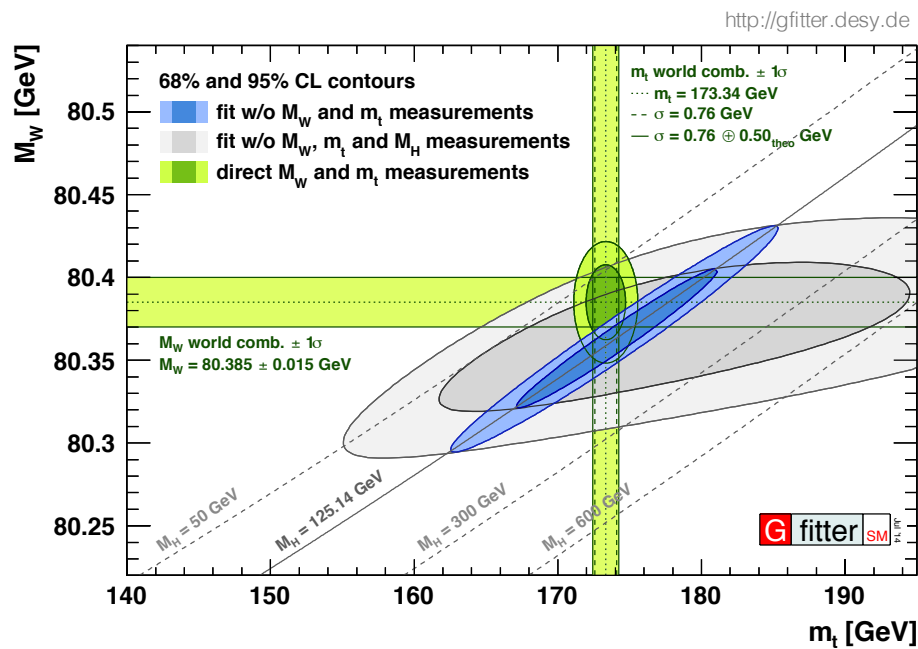




Digression on Precision Measurements

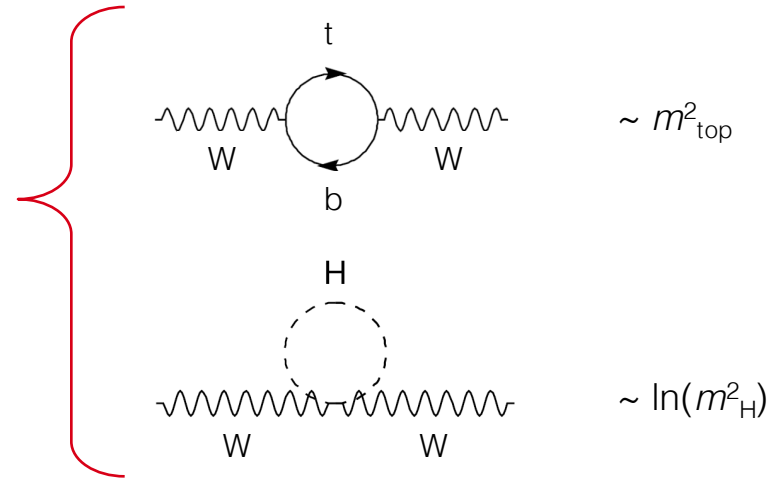
Electroweak precision physics

Global electroweak fit was masterpiece of LEP/SLD era.
Discovery of Higgs over-constrains the fit and dramatically improves predictability



Electroweak sector relates M_W to α , G_F , M_Z

$$M_W^2 = \frac{M_Z^2}{2} \left(1 + \sqrt{1 - \frac{\sqrt{8} \pi \alpha (1 - \Delta r)}{G_F M_Z^2}} \right)$$



SM Predictions [1407.3792, EW fit]

$$M_W = 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\text{theo}} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta \alpha_{\text{had}}} \\ \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\text{theo}} M_W} \text{ GeV ,}$$

$$= 80.358 \pm 0.008_{\text{tot}} \text{ GeV . [exp WA: } \sigma = 15 \text{ MeV]}$$

$$\sin^2 \theta_{\text{eff}}^\ell = 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\text{theo}} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta \alpha_{\text{had}}} \\ \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\text{theo}} \sin^2 \theta_{\text{eff}}^f} ,$$

$$= 0.23149 \pm 0.00007_{\text{tot}} , \quad [\text{exp WA: } \sigma = 0.00016]$$

Electroweak precision measurements

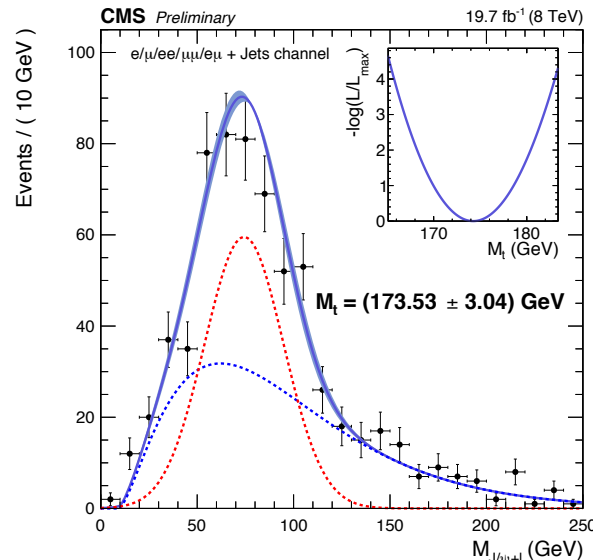
Best top mass from LHC: $172.44 \pm 0.13 \pm 0.47$ GeV (CMS), $172.84 \pm 0.34 \pm 0.61$ GeV (ATLAS, not yet all 8 TeV)

Traditional kinematic top mass measurement method approaches systematic limit of b modelling

Possible ways to improve (a lot of pioneering work by CMS):

- Choose more robust observables (eg, wrt. b fragmentation)
- Select charmed mesons (rare but very clean signature)
- Use dilepton kinematic endpoint (clean but large theoretical uncertainties)
- Use cross-sections or differential variables (promising but difficult to achieve competitive precision)

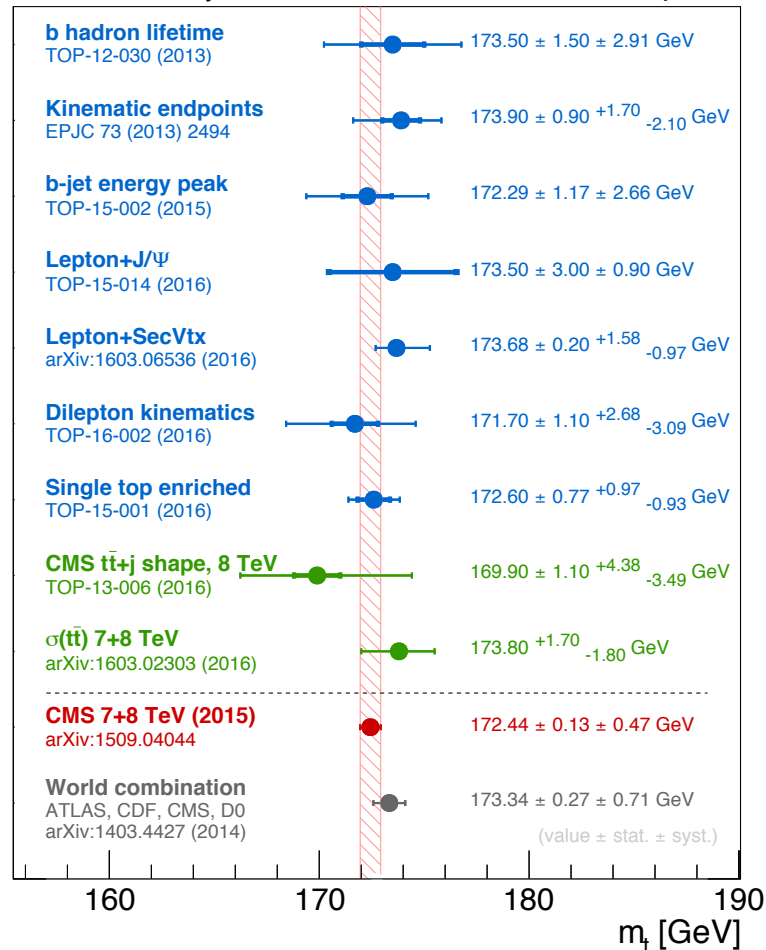
Currently best result(CMS): 1.7 GeV uncertainty



CMS alternative top mass measurements:

CMS Preliminary

May 2016



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

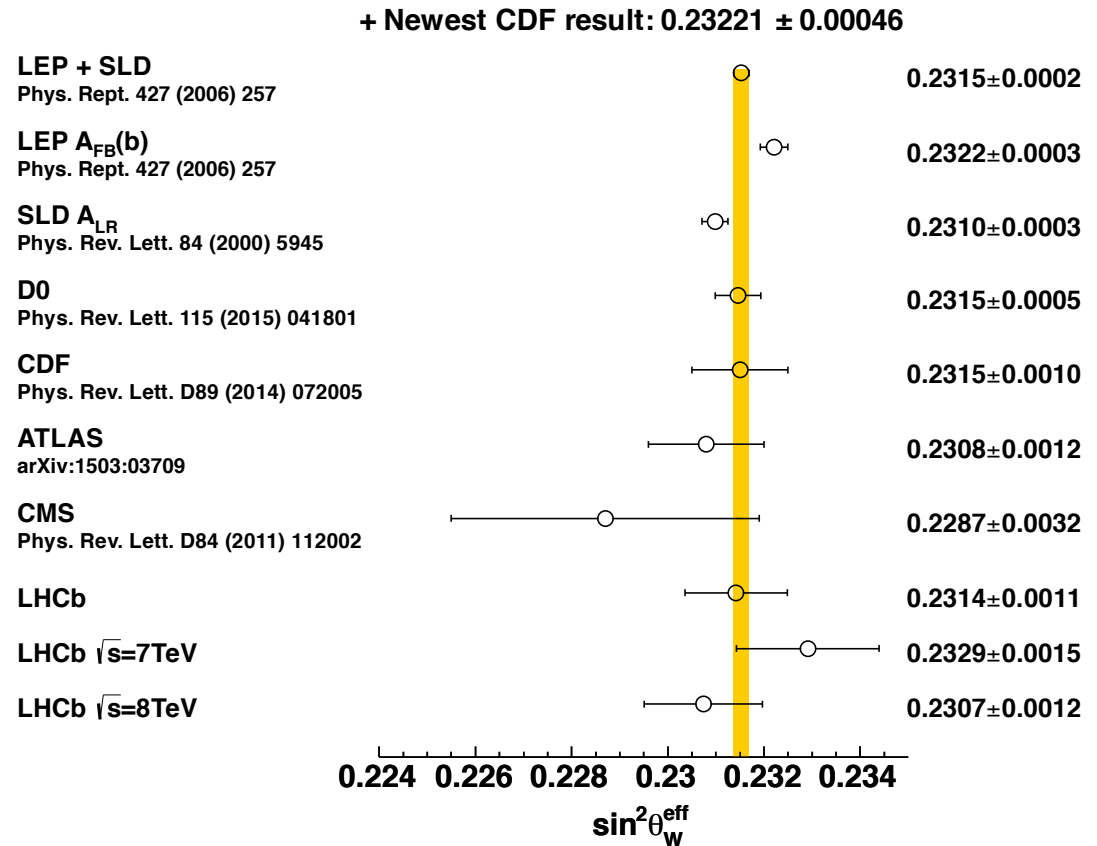


Figure from LHCb 1509.07645

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: $m_W = 81 \pm 5$ 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**

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

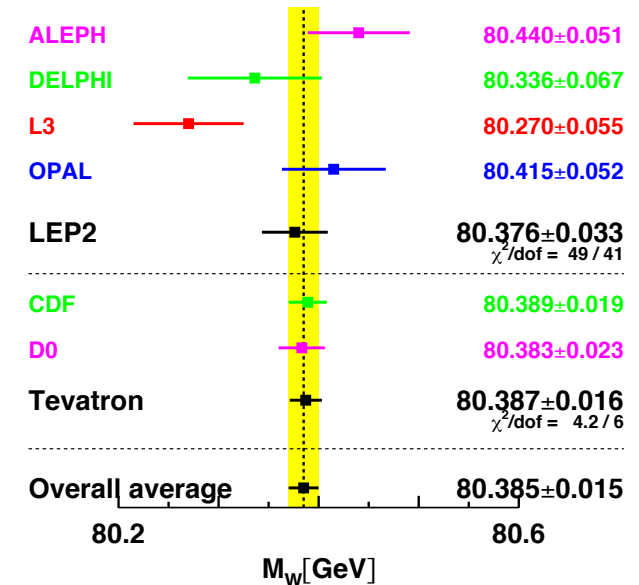
Unfavorable environment at LHC compared to e^+e^- or proton–antiproton colliders

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 !

Current experimental picture for m_W



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)

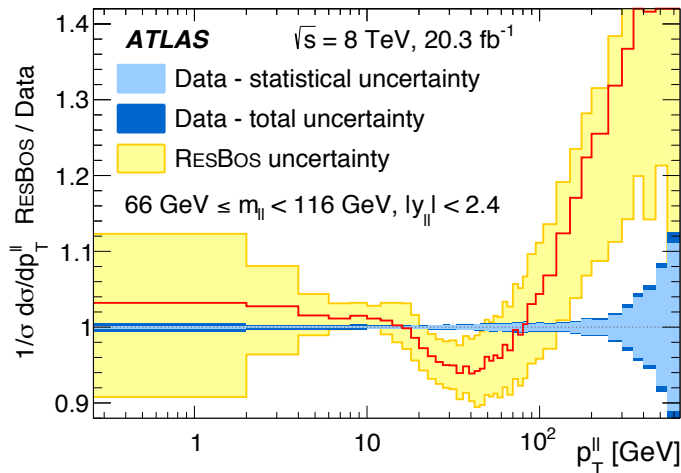
Project: Experiments are in a vigorous process of addressing the above issues. Many precision measurements (differential Z, W + X cross sections, polarisation analysis, calibration performance, ...) produced on the way. **Also theoretical developments mandatory. Long-term effort.**

Electroweak precision measurements

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

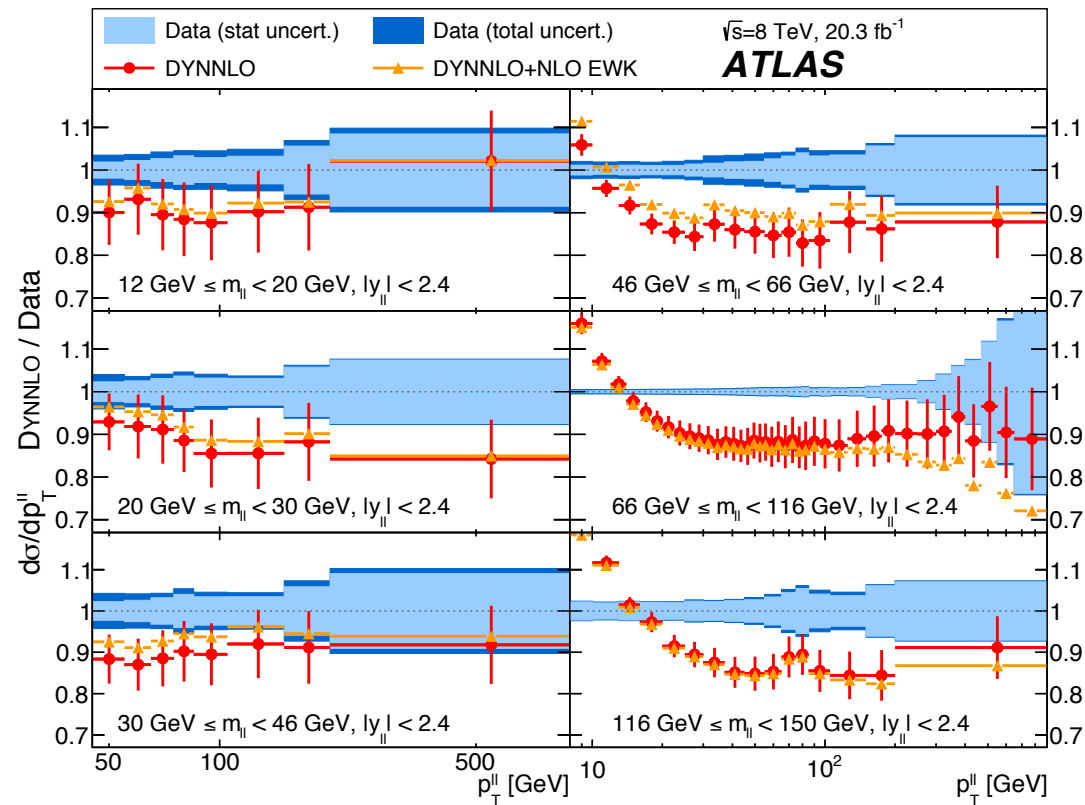
ATLAS and CMS use precise measurements of $p_T(Z)$ to tune $p_T(W)$ modelling, which relies on NNLO and NNLL/resummed calculations. But: different generators predict different transfers from Z to W .

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



RESBOS: ISR at approximate NNLO, $\gamma^* \text{--} Z$ interference at NLO, NNLL soft-gluon resummation, no FSR or hadronic event activity, CT14 PDF.

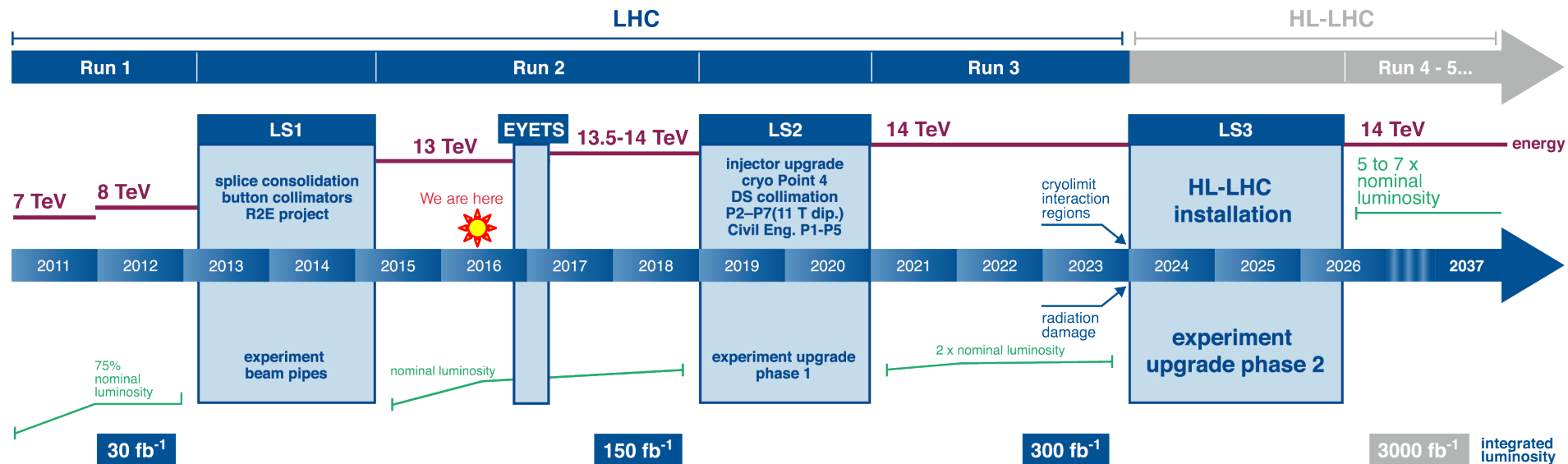
DYNNLO: QCD production at NNLO, no soft-gluon resummation, CT10 PDF.



The road to the future

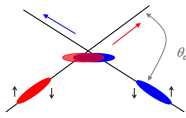
The LHC Run-2 and beyond

LHC / HL-LHC Plan



How can these LHC luminosity improvements be achieved ?

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



Run-1

- $E_{\text{beam}} = 0.45\text{--}4\text{ TeV}$
- $L_{\text{max}} = 0.8 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 50\text{ ns}$
- $N_{\text{bunches,max}} = 1380$
- $\beta^* = 60\text{ cm}$
[recall: $L \propto (\sigma_x \sigma_y)^{-1} = (\varepsilon_n \beta^* / \gamma)^{-1}$]
- Norm. emittance $\varepsilon_n \sim 2.3\text{ }\mu\text{m}$
- $N_{\text{protons / bunch}} \leq 1.7 \cdot 10^{11}$
- $\langle \mu \rangle \sim 21$
(note: μ_{peak} much larger)

Run 2 & 3 (13–14 TeV)

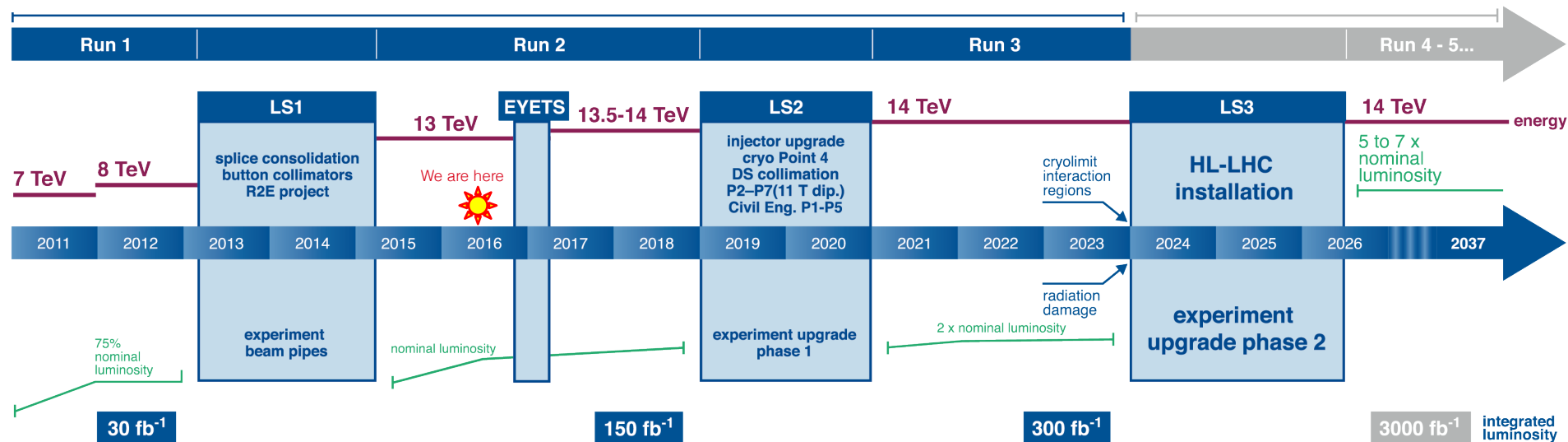
- $E_{\text{beam}} = 6.5\text{--}7\text{ TeV}$
- $L_{\text{max}} = 0.7\text{--}2 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 25\text{ ns}$
- $N_{\text{bunches,max}} = 2028\text{--}2748(?)$
- $\beta^* = 40\text{ cm}$
- $\varepsilon_n = 3.5\text{--}2.5\text{ }\mu\text{m}$ (2.3 μm with BCMS)
- $N_{\text{protons / bunch}} \sim 1.2 \cdot 10^{11}$
- $\langle \mu \rangle \sim 21\text{--}50$

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

HL-LHC (14 TeV)

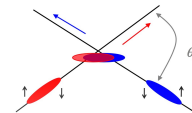
- $E_{\text{beam}} = 7\text{ TeV}$
- $L_{\text{max}} \sim 5 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 25\text{ ns}$
- $N_{\text{bunches,max}} = 2748$
- $\beta^* = 15\text{ cm}$
- $\varepsilon_n = 2.5\text{ }\mu\text{m}$
- $N_{\text{protons / bunch}} = 2.2 \cdot 10^{11}$
- $\langle \mu \rangle \sim 140$

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:

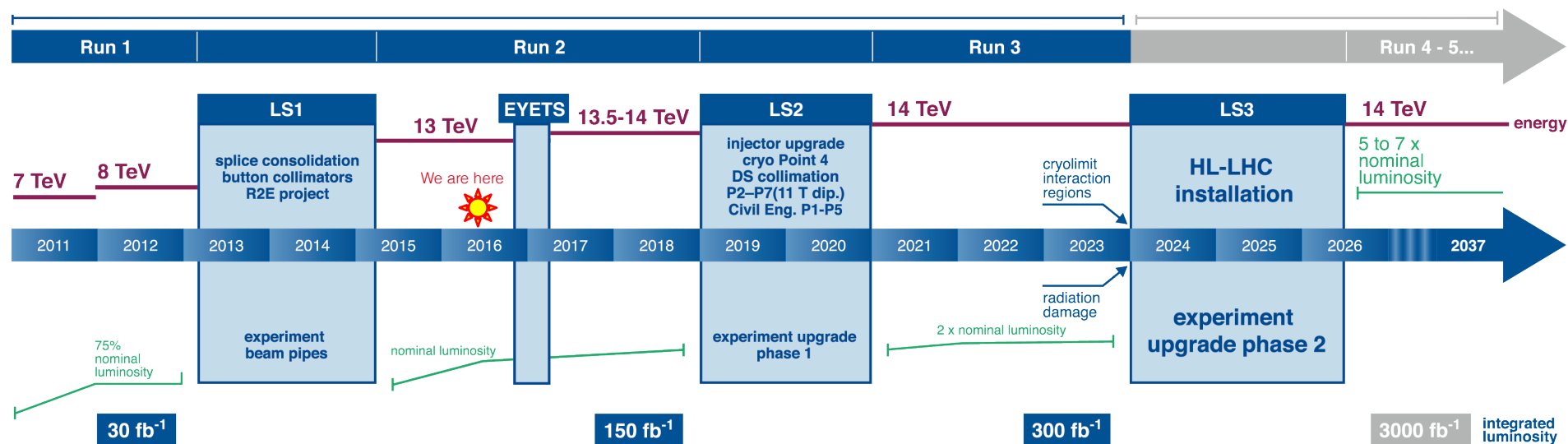
- Phase-1 during LS2 preparing for high-brightness Run-3
- Phase-2 during LS3 preparing for HL-LHC

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

(note: p_{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)

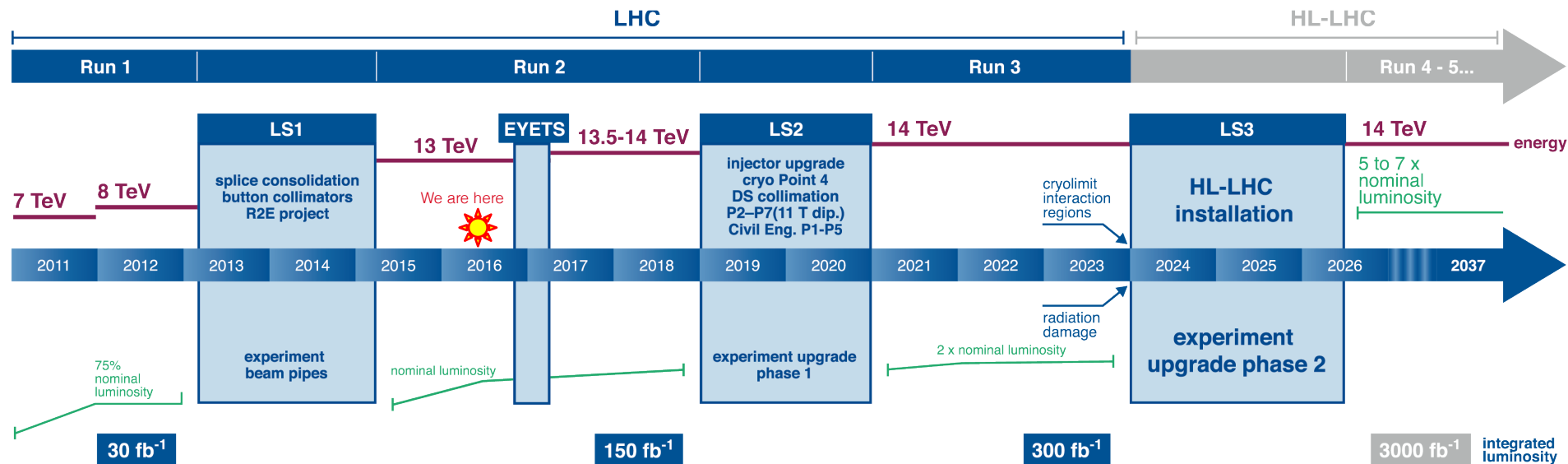
- Discovery of Higgs boson
- Searches for additional new physics (negative)
- Observation of rare processes, such as $B_s \rightarrow \mu\mu$
- Precision measurements of Standard Model processes
- Study of CP asymmetries in B_s sector

Run 2 & 3 (13–14 TeV)

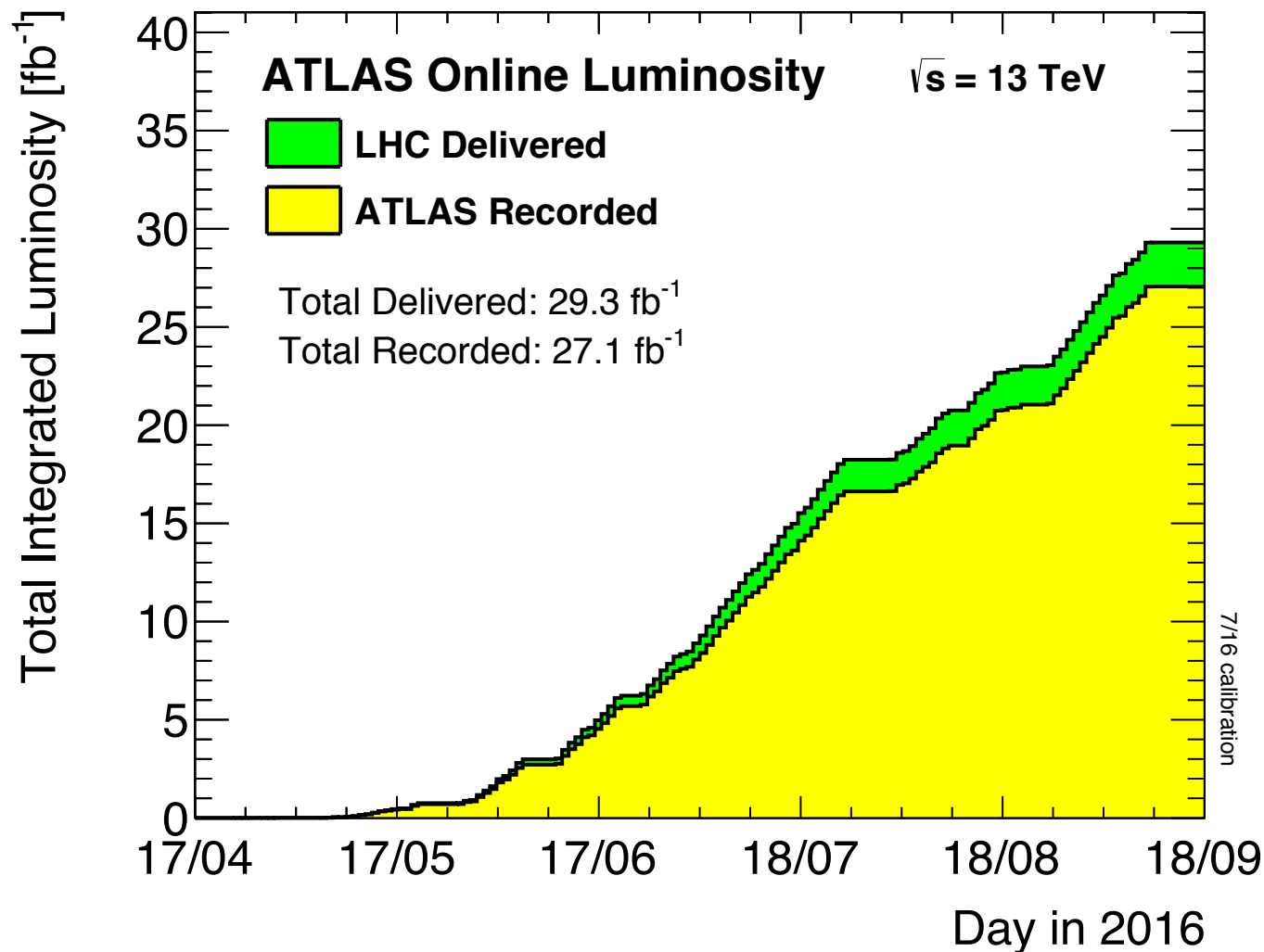
- Searches for new physics
- Improved measurements of Higgs couplings in main channels
- Consolidation / observation of Higgs channels
- Measurement of rare Standard Model processes & more precision
- Improved measurements of rare B decays and CP asymmetries

HL-LHC (14 TeV)

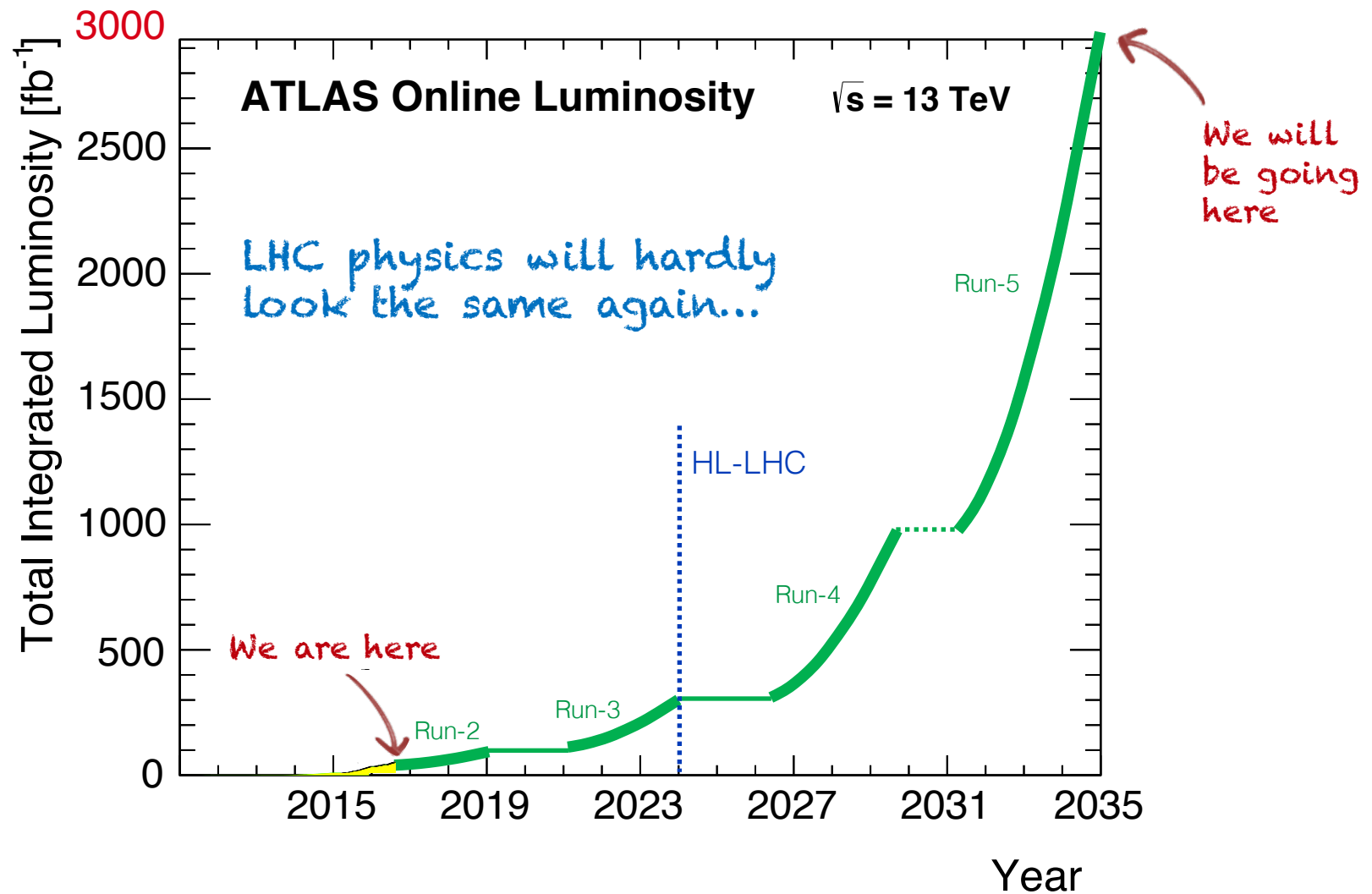
- Precision measurements of Higgs couplings
- Observation of very rare Higgs modes
- Ultimate new physics search reach (on mass & forbidden decays, eg, FCNC)
- Ultimate SM & HF physics precision for rare processes (VBS, aT/QGC, etc)

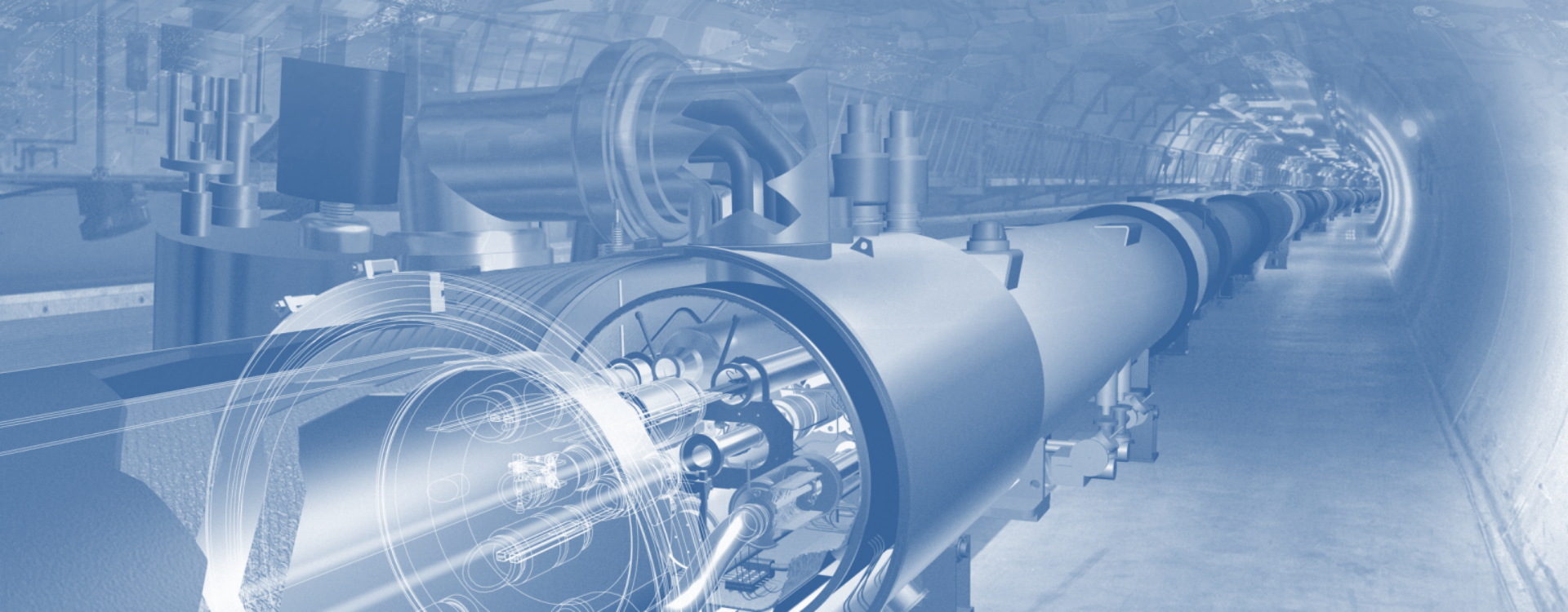


Status of Run-2 (19 Sep 2016)



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 !

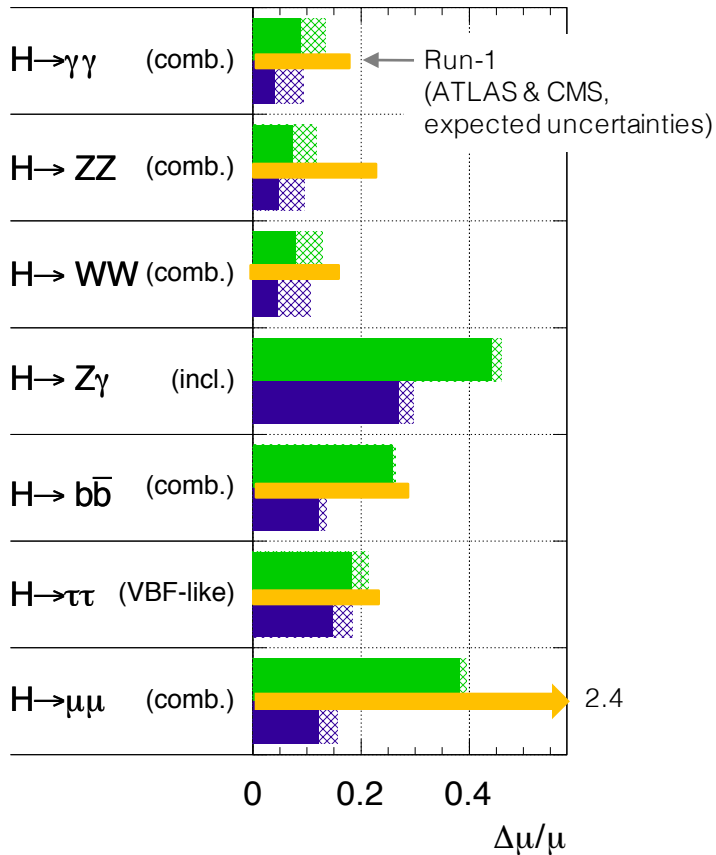
Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

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

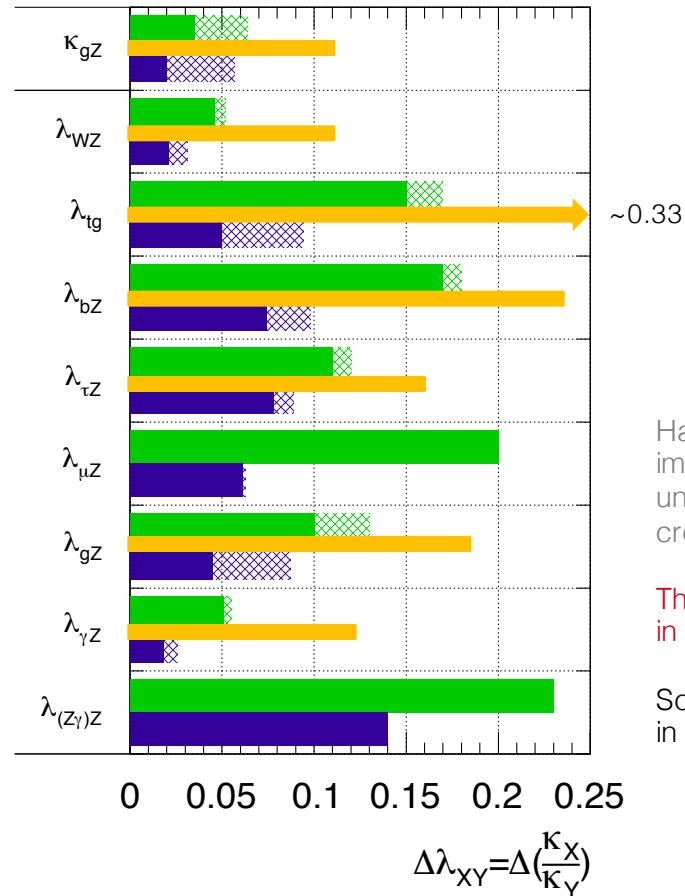
ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



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

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

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

Theory uncertainty limiting in several cases

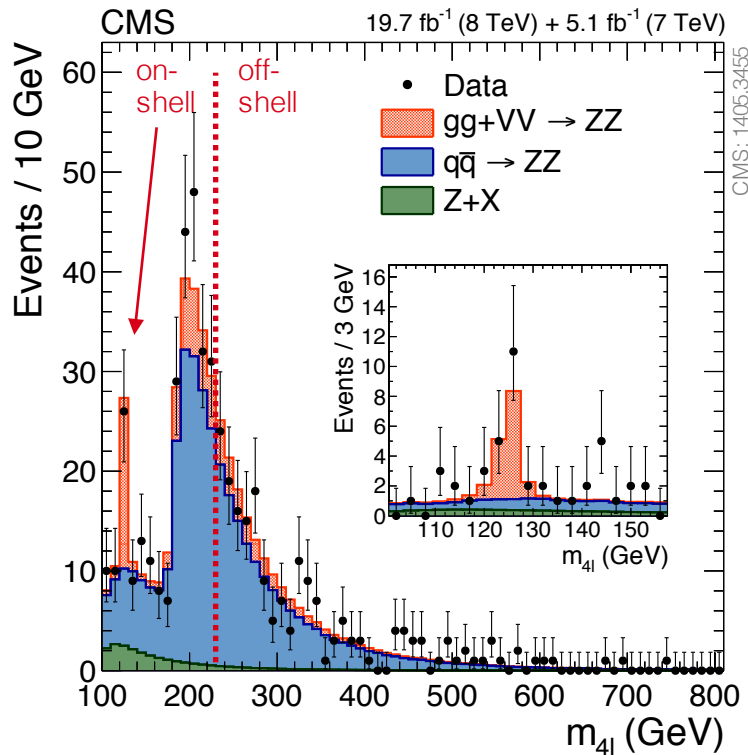
Some uncertainties cancel in ratios

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 $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})}{\sigma_{\text{off-shell, SM}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})} = \kappa_{g, \text{off-shell}}^2(\hat{s}) \cdot \kappa_{V, \text{off-shell}}^2(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ}}{\sigma_{\text{on-shell, SM}}^{gg \rightarrow H \rightarrow ZZ}} = \frac{\kappa_{g, \text{on-shell}}^2 \cdot \kappa_{Z, \text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

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

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

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

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

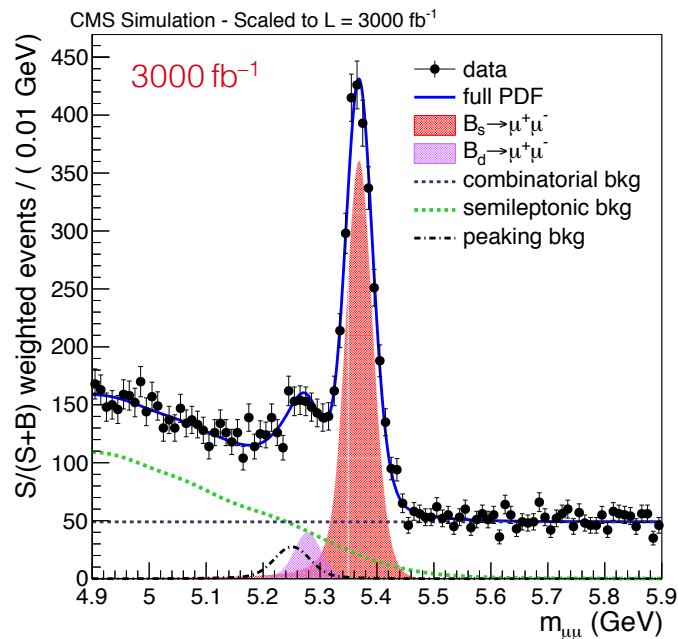
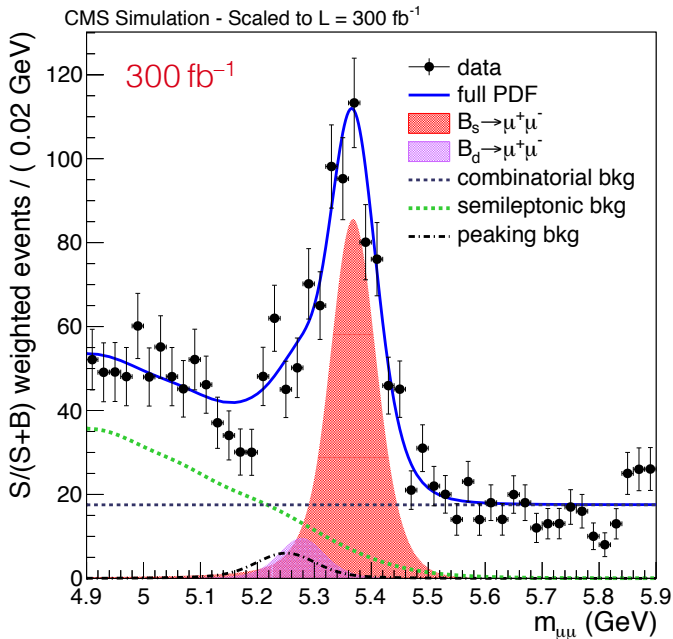
$$\Rightarrow \Gamma_H^{(L2)} = 4.2_{-2.1}^{+1.5} \text{ MeV (stat+sys)}$$

More Standard Model and Flavour physics

Continuous gain in precision and reach for rare or suppressed processes

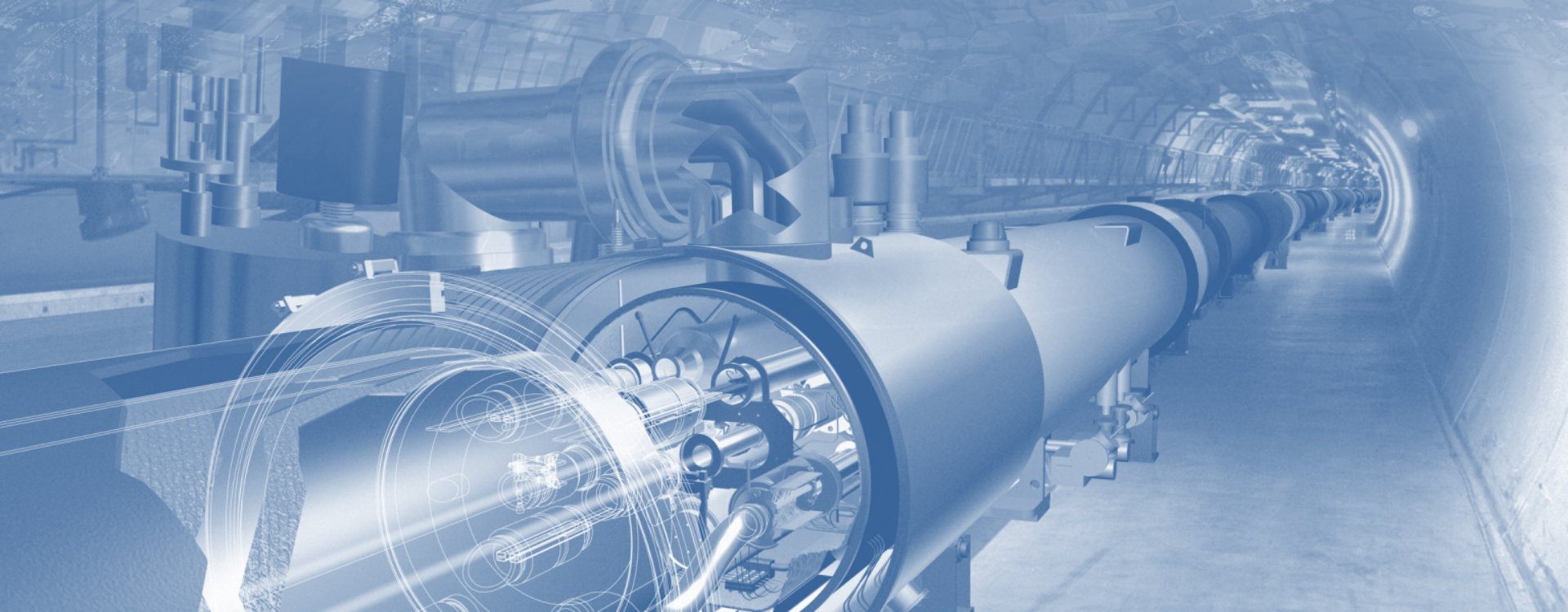
High-profile flavour physics measurements (slower Run-2 luminosity rise for LHCb due to luminosity levelling, but upgrade to 40 MHz trigger readout during LS2 will increase, eg, the annual muonic B rate by factor of ten)

- **Rare decays:** $B_{(s)} \rightarrow \mu\mu$ and similar and **b $\rightarrow$ s transitions:** $B \rightarrow K^*\mu\mu$ 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 $B_s \rightarrow \mu\mu$ decay

CMS-PAS-FTR-13-022



Conclusions

A visualization of a particle collision, likely from the LHC, showing a central point of impact with numerous tracks radiating outwards, set against a blue background with a curved horizon line.

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

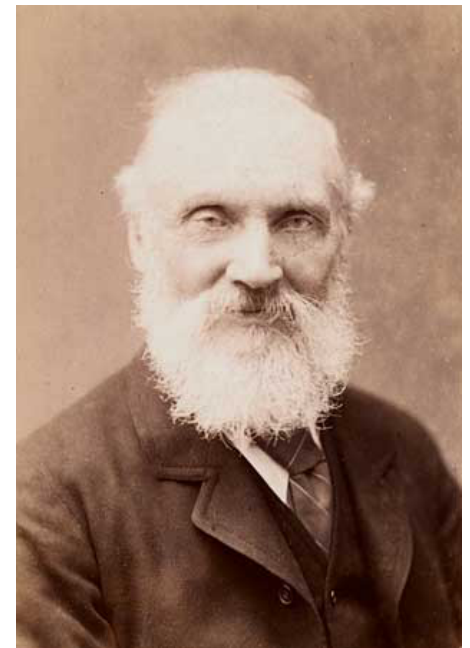
Conclusions

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

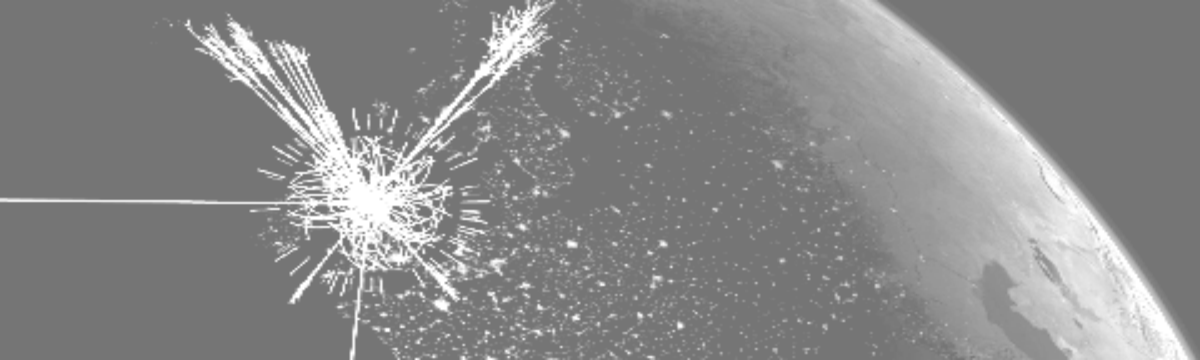
But [many of] the grandest discoveries of science have been but the rewards of accurate measurement and patient long-continued labour in the minute sifting of numerical results.

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

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

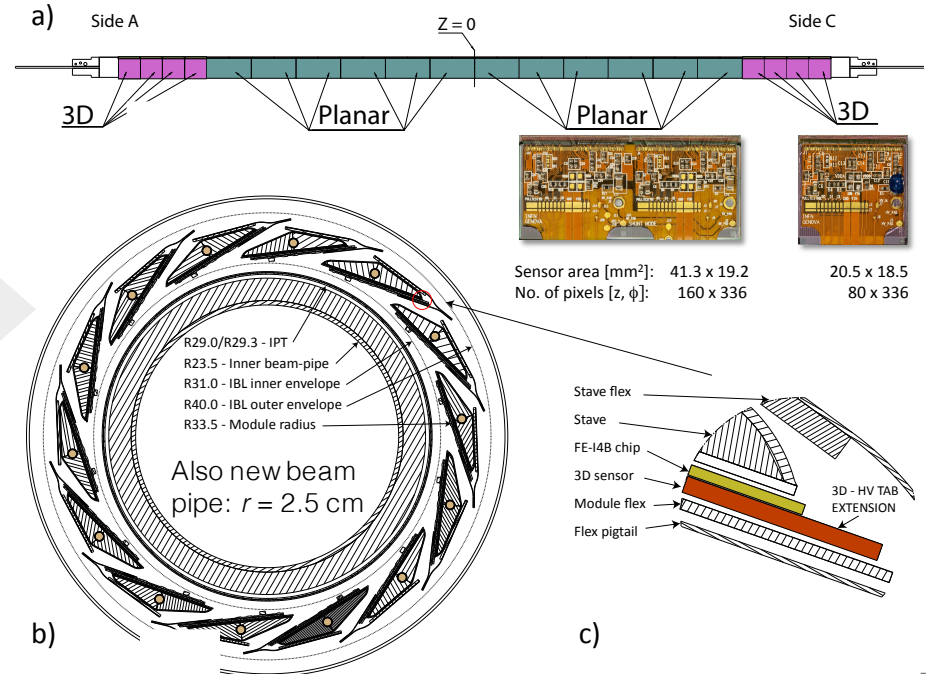
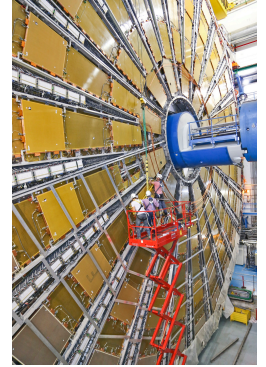
Detector consolidation: muon chamber completion ($1.0 < |\eta| < 1.3$) & replacements, calorimeter electronics repairs, improved inner detector read-out capability to cope with 100 kHz L1 trigger rate, new pixel detector services and module repairs

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, ...

Replacement of TGC chambers

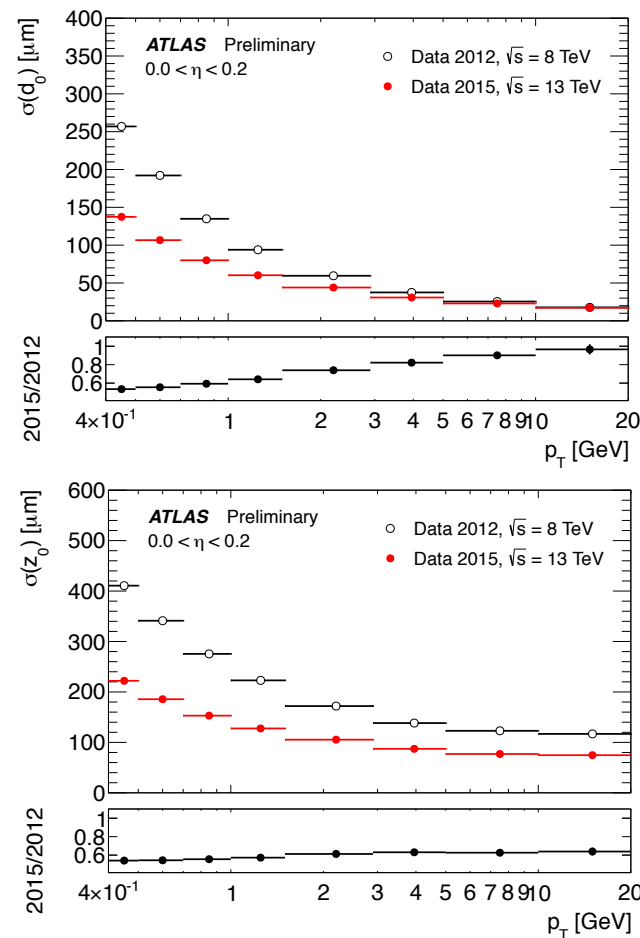
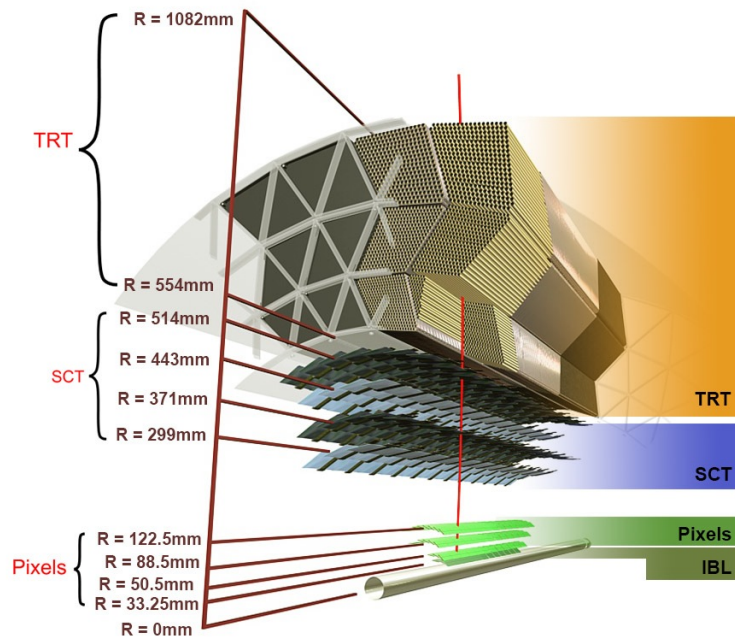


ATLAS inner tracking performance

[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

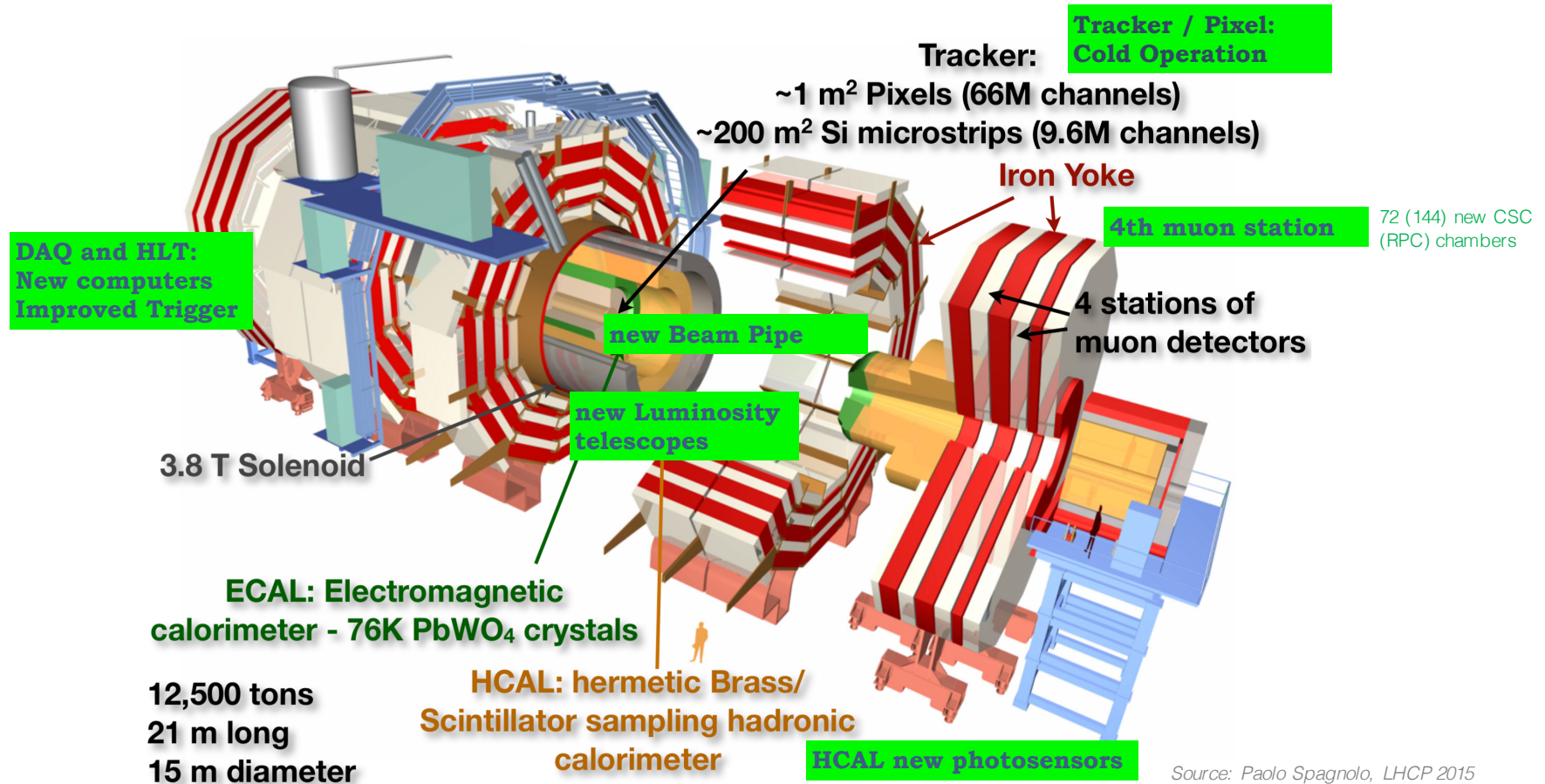


Impact parameter resolution improvement from IBL

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

CMS improvements for Run-2

Also significant updates and improvements



- 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

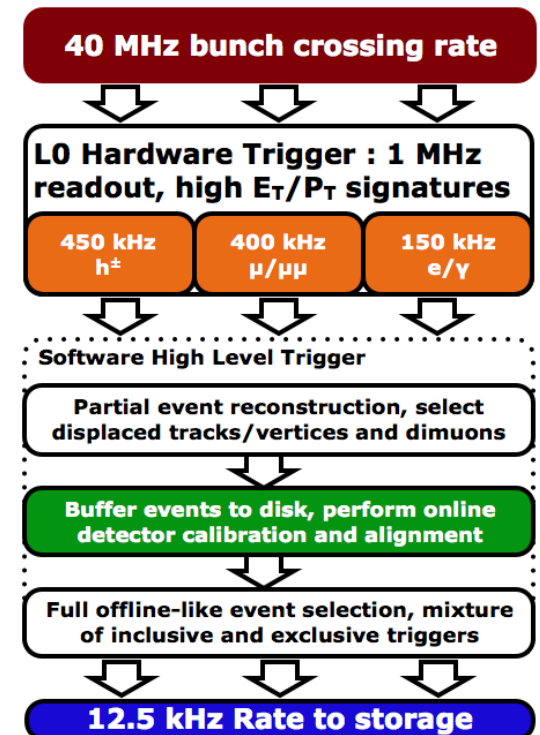
Big effort in trigger area (among others)

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 , ...)

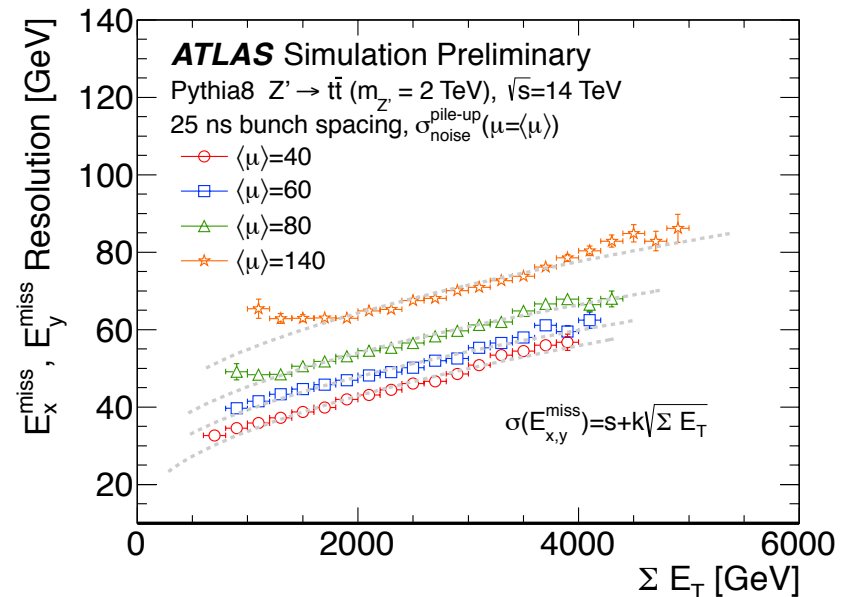
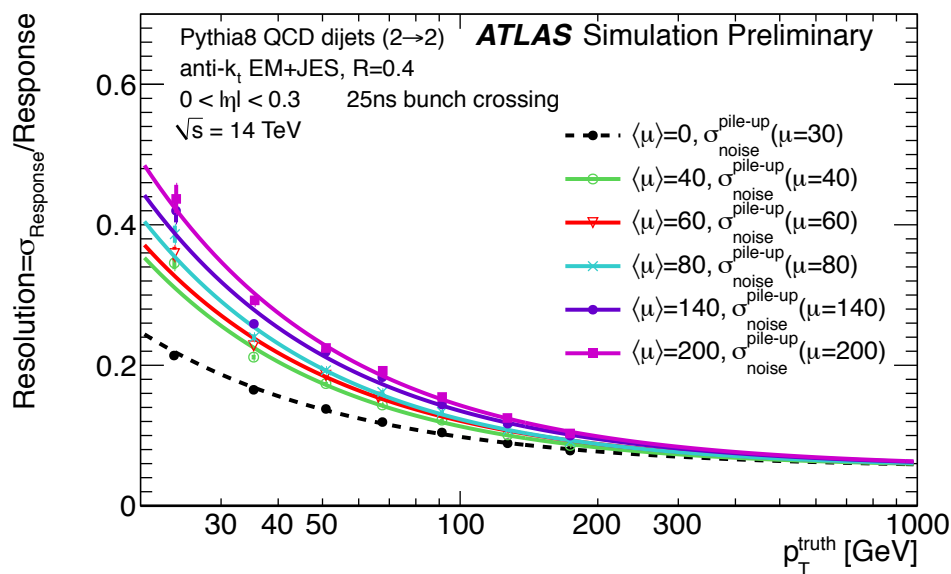


Detector performance

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 $H \rightarrow \tau\tau$
- Observe $H \rightarrow b\bar{b}$
- Observe ttH and W/Z+H production
(at large luminosity $H \rightarrow \gamma\gamma$ will be best for ttH,

ATL-PHYS-PUB-2014-012)

What are long-term developments ?

- Search for $H \rightarrow \mu\mu$ (Run-1 limit: $\sim 7.5 \times \sigma_{\text{SM}}$)
- Search for $H \rightarrow Z\gamma$ (Run-1 limit: $\sim 9.5 \times \sigma_{\text{SM}}$)
- 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, $H \rightarrow J/\psi \gamma$), forbidden (eg, $H \rightarrow \tau\mu$) and invisible decays (eg, VBF+ E_T^{miss})

Higgs boson physics

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

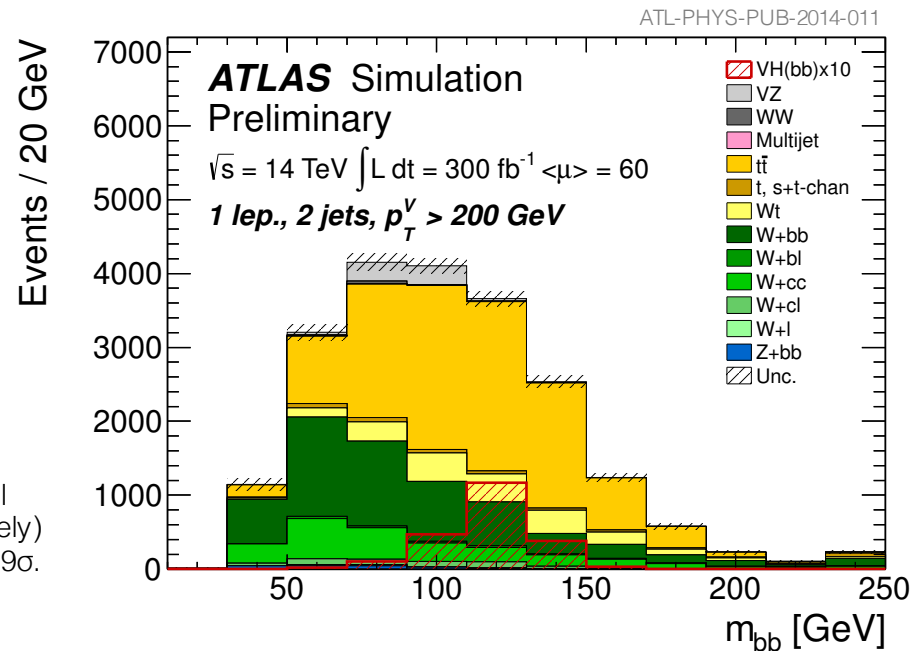
Higgs spin & parity established as 0^+ , but need to investigate possible CP -odd admixtures

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

What is left to complete after Run-1 ?

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

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 .

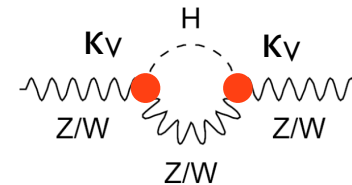
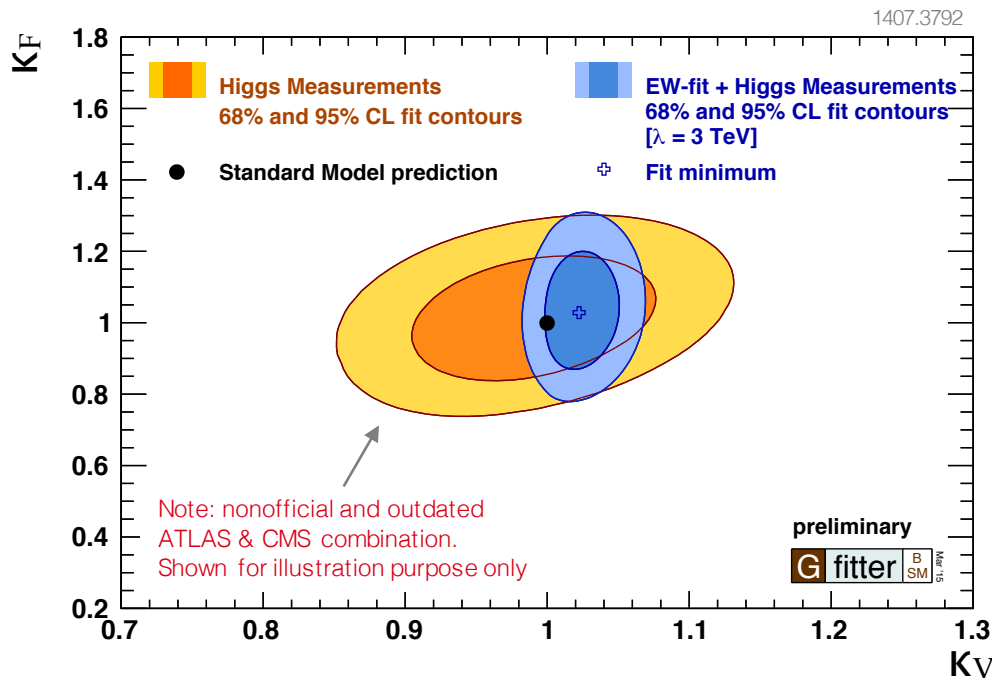


Higgs boson physics

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: $s = \tau = 0$), parameterizing new physics contributions to electroweak observables through loop diagrams involving massive W and Z bosons



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

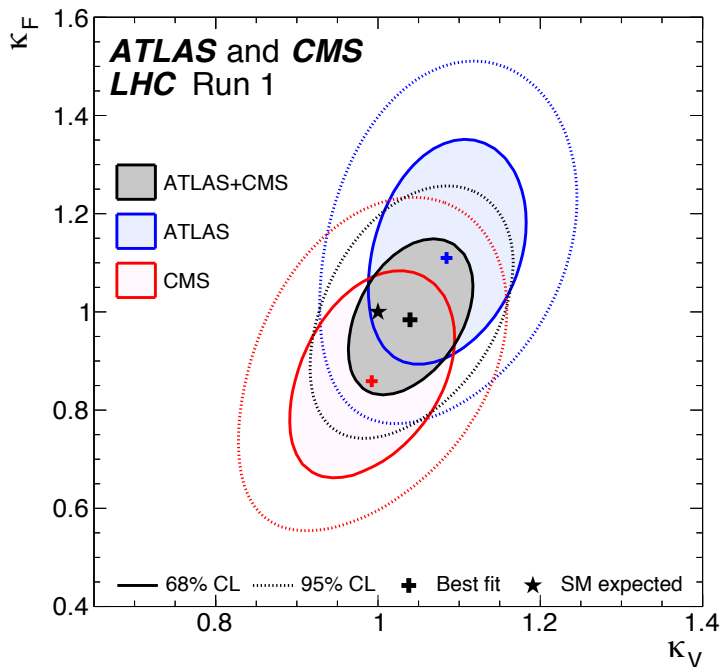
λ is cut-off parameter, set arbitrarily to 3 TeV

Higgs boson physics

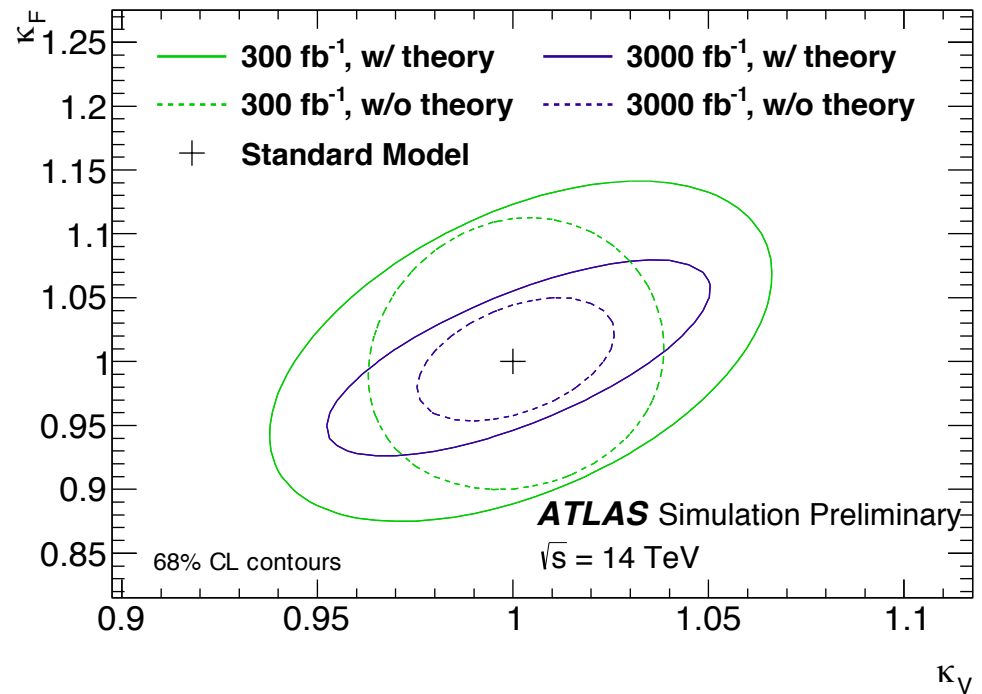
(Conservative) extrapolation of Higgs coupling measurements

Constraints on global fermion versus vector-boson coupling modifiers

Current (Run-1):



Extrapolation:

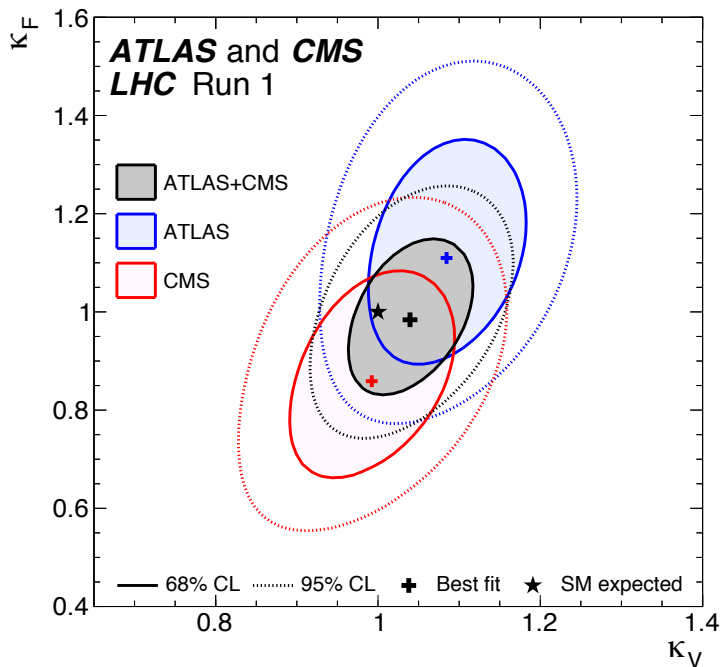


Higgs boson physics

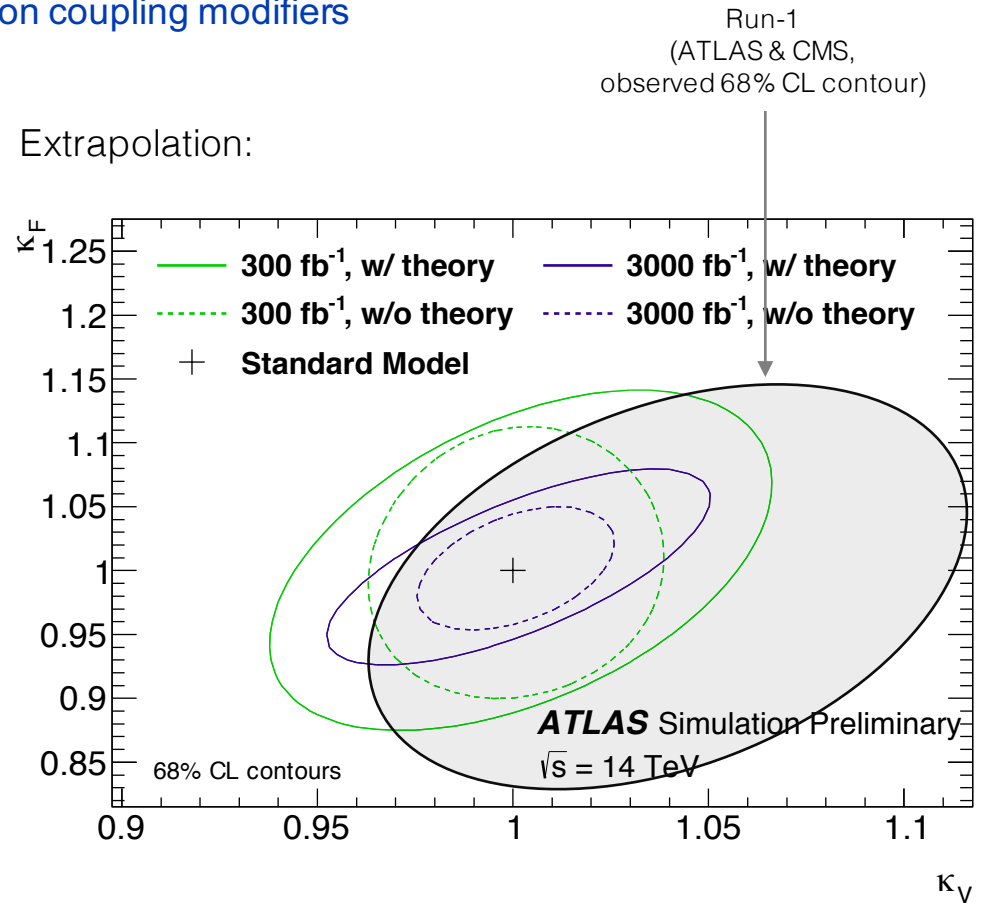
(Conservative) extrapolation of Higgs coupling measurements

Constraints on global fermion versus vector-boson coupling modifiers

Current (Run-1):



Extrapolation:



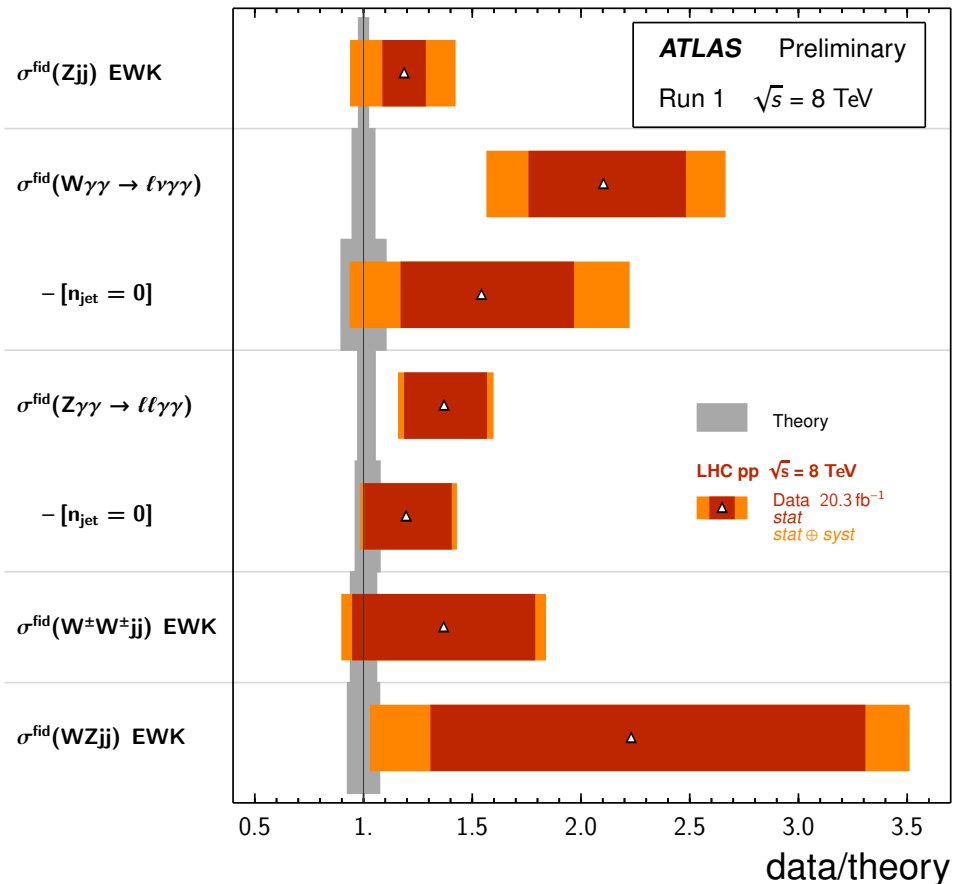
More Standard Model physics

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

VBF, VBS, and Triboson Cross Section Measurements Status: June 2016

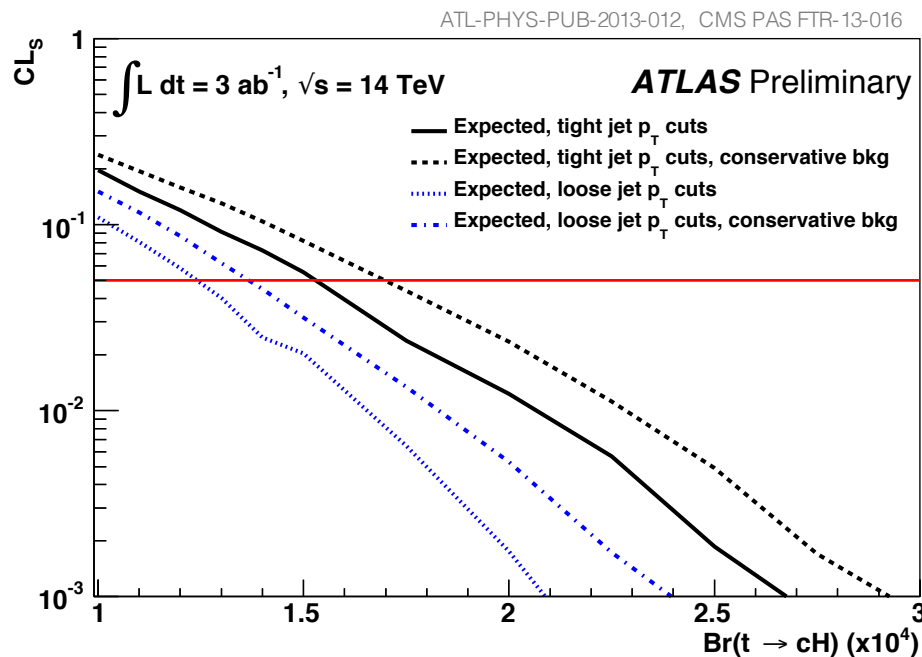


Top physics

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 $t\bar{b}$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$ inclusively & differentially, constraints on anomalous couplings
- **Forbidden processes** such as the FCNC transitions $t \rightarrow qH$, qZ , $q\gamma$, qg ($q = u, c$), also $t \rightarrow d/s+W$



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 $t\bar{t}\gamma$, 80k $t\bar{t}Z$, 60k $t\bar{t}W$, ...

Limit on $t \rightarrow cH(\rightarrow \gamma\gamma)$ branching ratio
estimated for the full HL-LHC: $\sim 0.015\%$
(current 8 TeV: $< 0.46\%$)

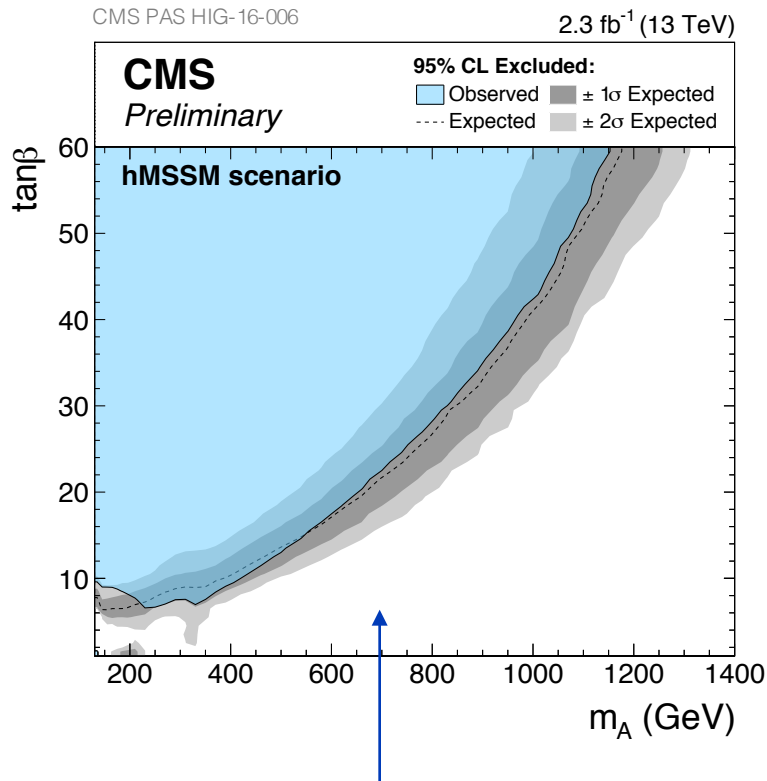
CMS for $t \rightarrow cZ$: current/300/3000 fb^{-1} limit:
 $< 0.10\% / 0.027\% / 0.010\%$

Higgs boson physics

Constraints on new physics from coupling measurements

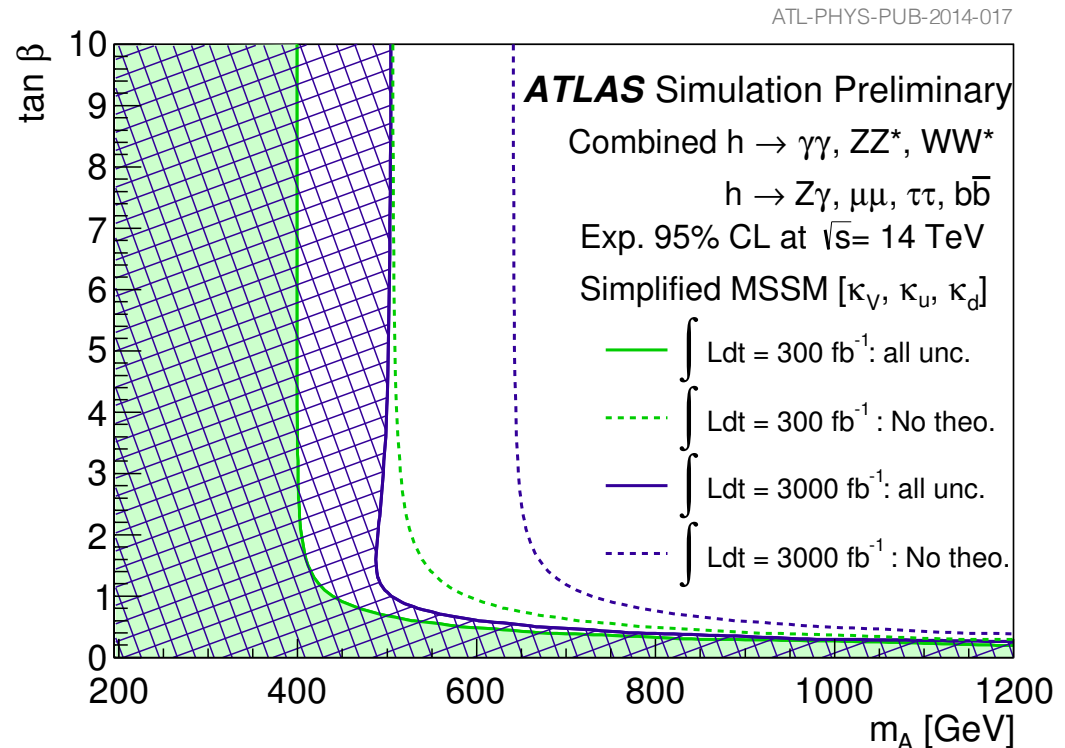
Example application for constraint on MSSM Higgs from Higgs coupling fit

Constraints on m_A and $\tan\beta$ in simplified MSSM model from direct $H/A \rightarrow \tau\tau$ searches (left – current constraint), and from an extrapolation of global Higgs coupling measurements (right)



$A \rightarrow t\bar{t}$ is dominant decay beyond top-pair production threshold and for low $\tan\beta$.

Very difficult channel due to interference with the continuum top pair contribution deteriorating the (broad) $t\bar{t}$ mass peak

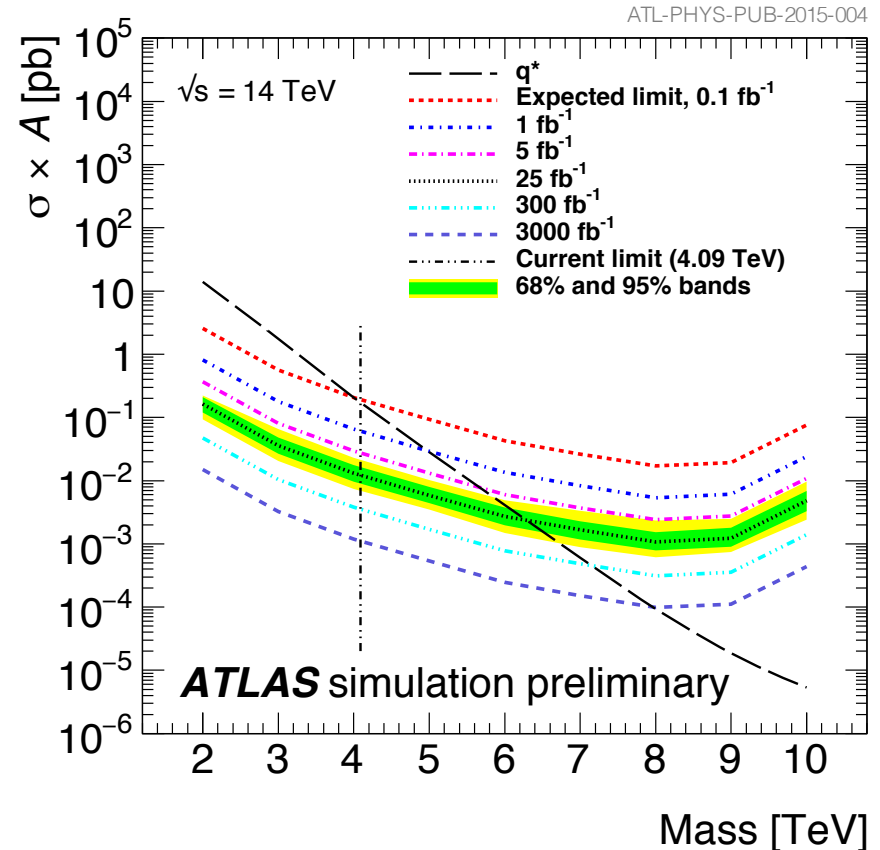
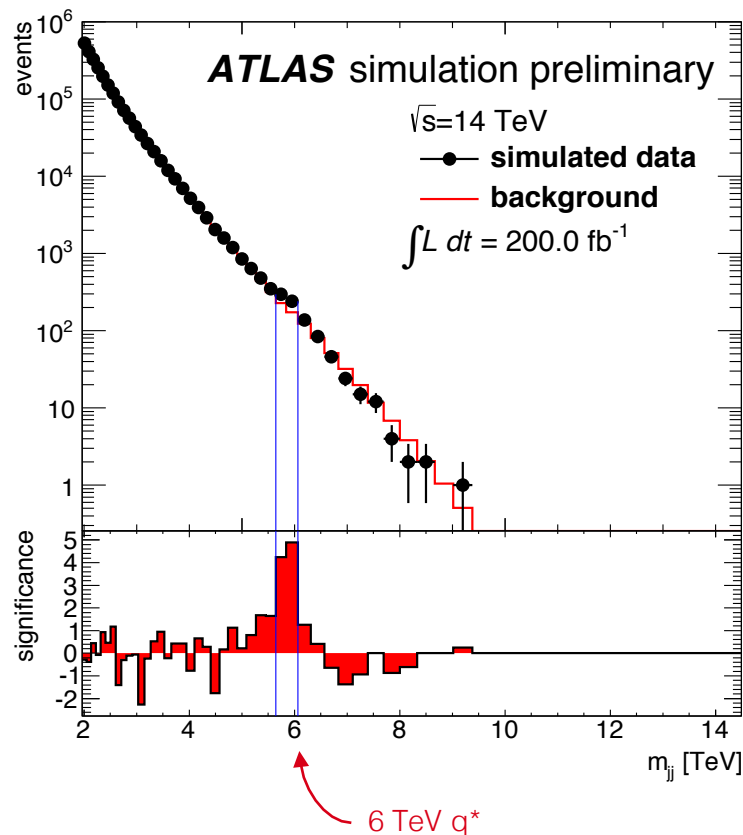


Searches

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 $q^* \rightarrow qg$)

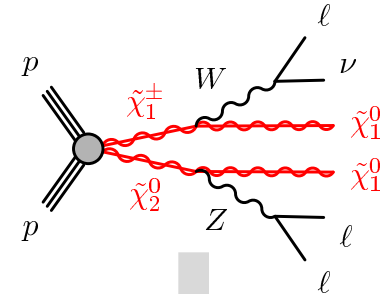
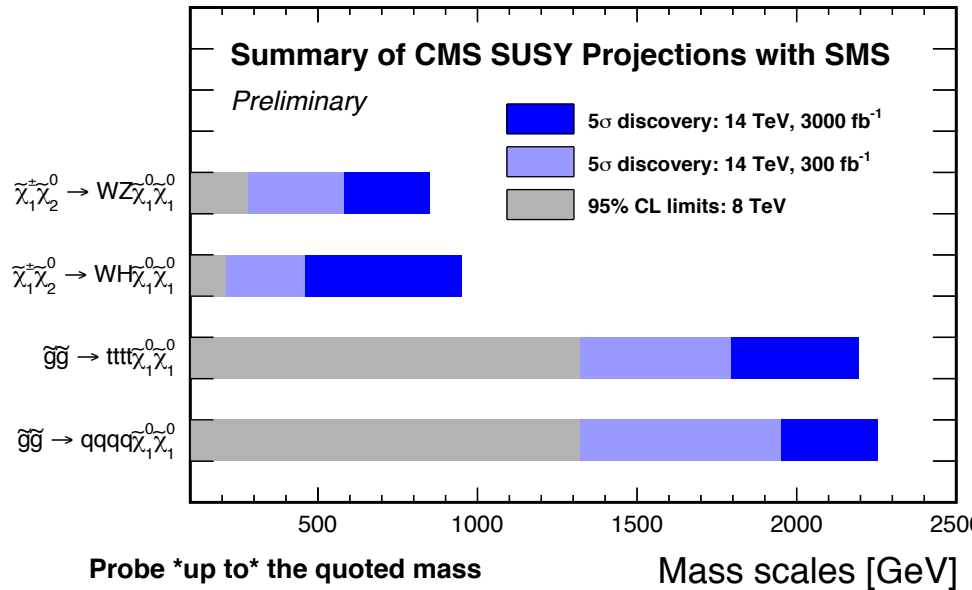


Searches

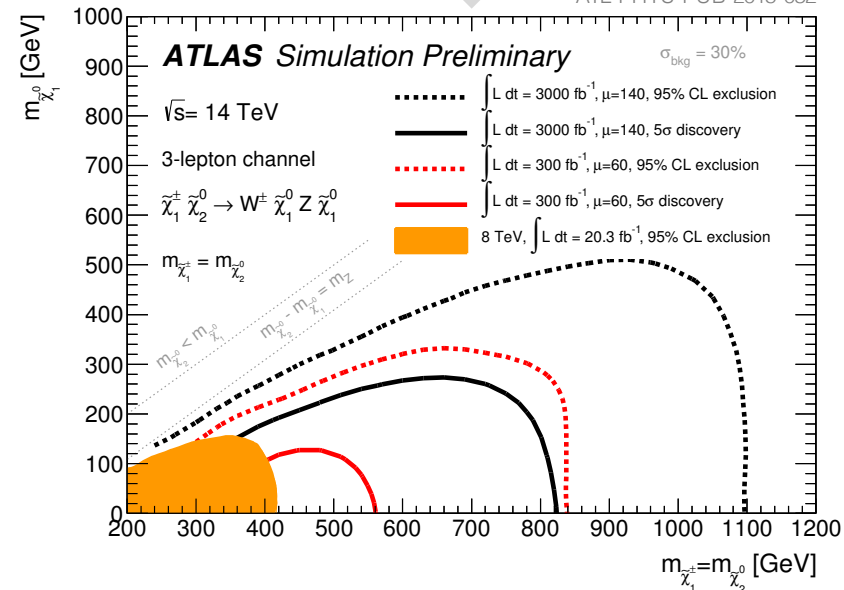
Will always stay a central piece of the LHC physics programme as a discovery machine

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

CMS-PAS-SUS-14-012



ATL-PHYS-PUB-2015-032

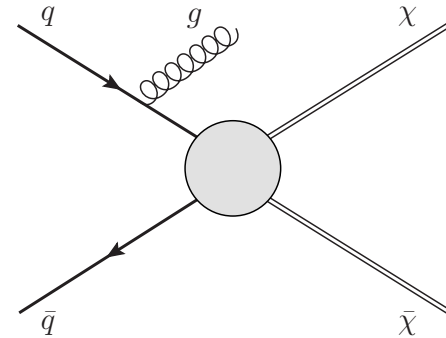
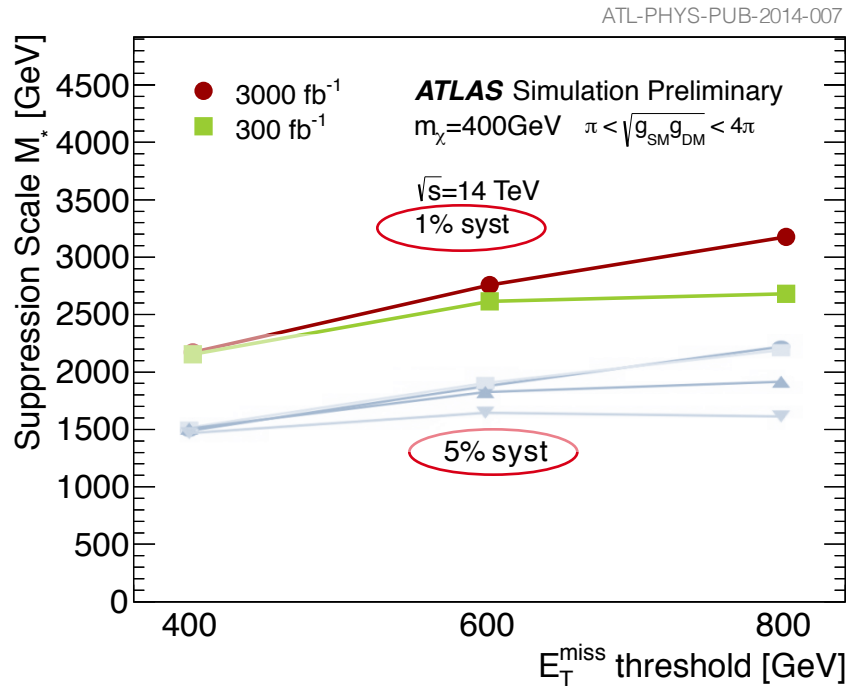


Searches

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

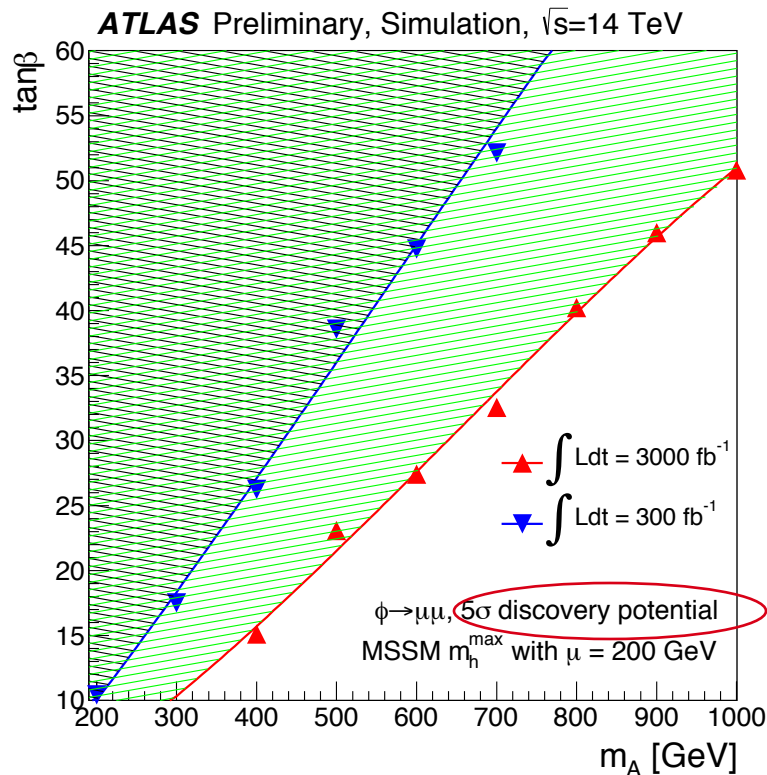


Higgs boson physics

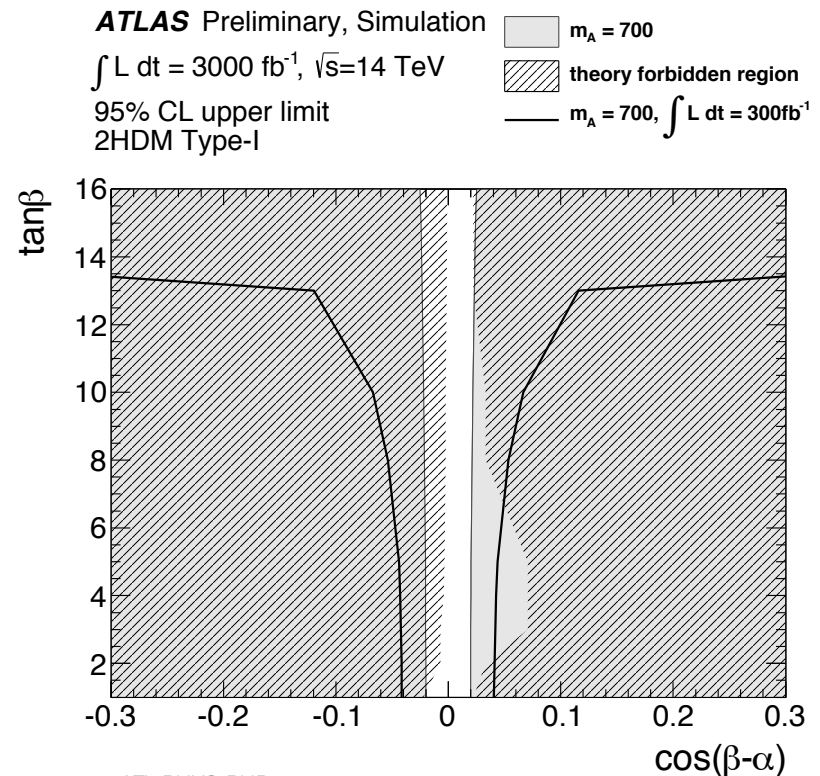
Searches for additional Higgs bosons

The discovery potential for $H/A \rightarrow \tau\tau$ is compromised for large m_A and low $\tan\beta$ where the H/A decays predominantly to top pairs with a deteriorating interference pattern with the continuum top pair contribution

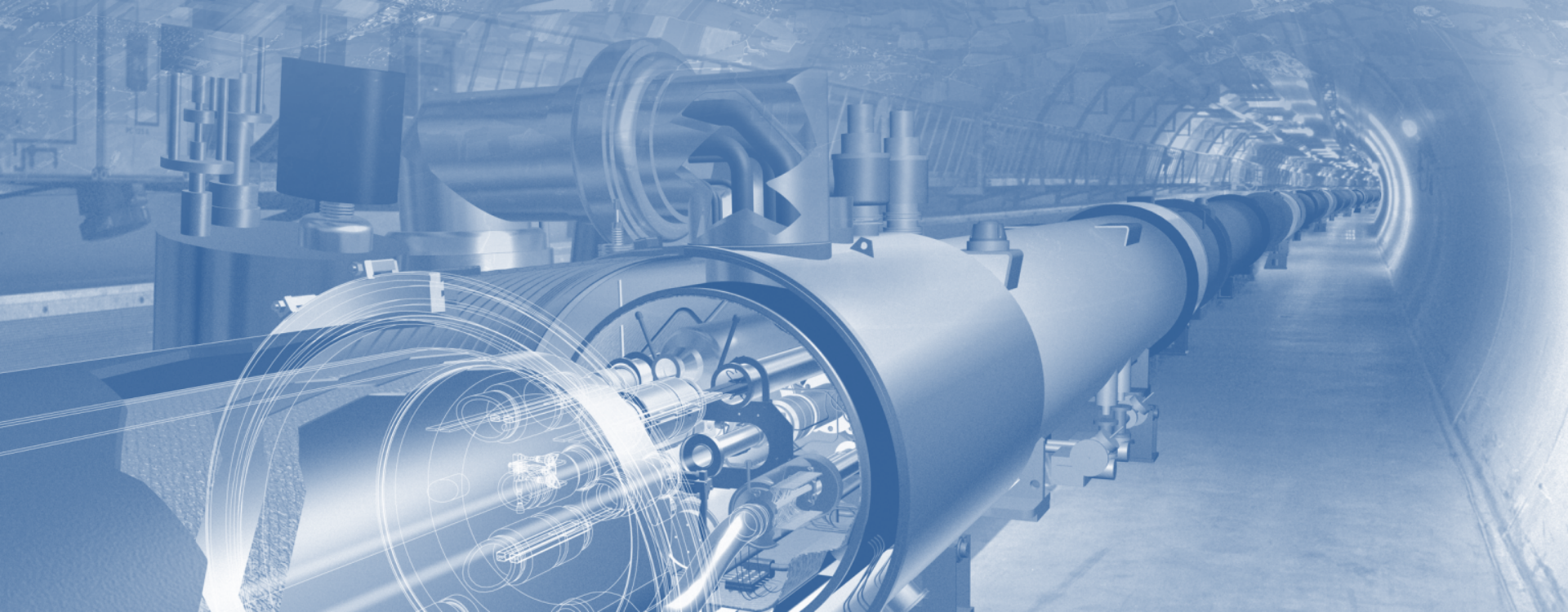
Production of $gg \rightarrow A \rightarrow Z(\rightarrow \ell\ell) h(\rightarrow bb)$ in the 2HDM can be discovered for low $\tan\beta$ and at least moderate $|\cos(\beta - \alpha)|$ up to and beyond $m_A = 700$ GeV



ATL-PHYS-PUB-2013-016



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Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

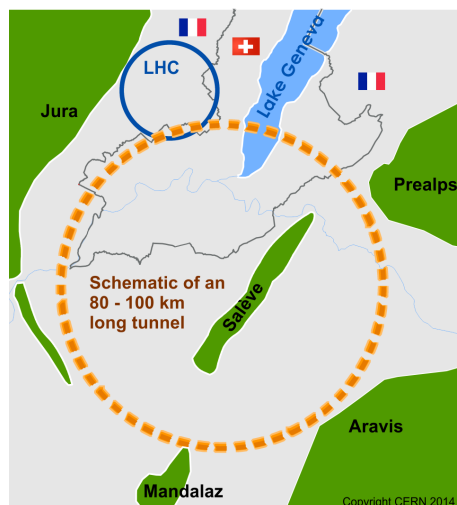
HL-LHC: $E_{\text{CM}} = 14 \text{ TeV}$, 3 ab^{-1} , 2026~2035... (formally approved as *project* by CERN council)

Future Circular Collider FCC-hh (CERN):

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

SppC (China):

- $E_{\text{CM}} \sim 71 \text{ TeV}$ in 55 km ring, $L \sim 1 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- Requires very high gradient dipole magnets $\sim 20 \text{ T}$
- 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/lp [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	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	5 MeV		2 MeV	7 keV	7 keV
synchrotron radiation/beam	3 MW		5.8 MW	5.4 kW	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)
- $E_{\text{CM}} \sim 500\text{--}1000$ GeV in 31–45 km total length, $L \sim 1.8 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

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

*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

Future Circular Collider FCC-ee (CERN):

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

Circular EP collider CEPC (China):

- $E_{\text{CM}} \sim 240$ GeV, $L \sim 2 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- 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 $10^{34} \text{ cm}^{-2}\text{s}^{-1}$	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