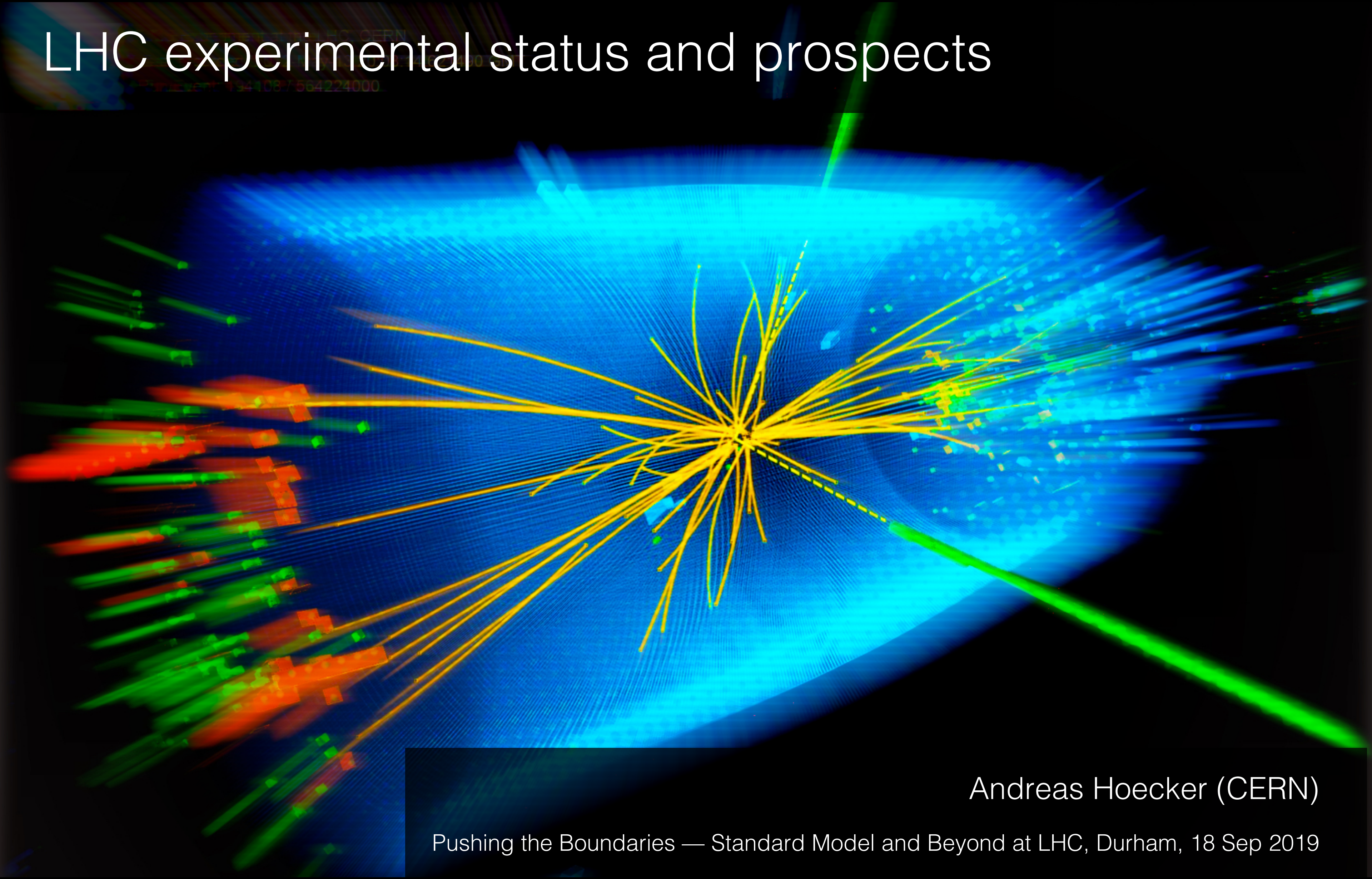
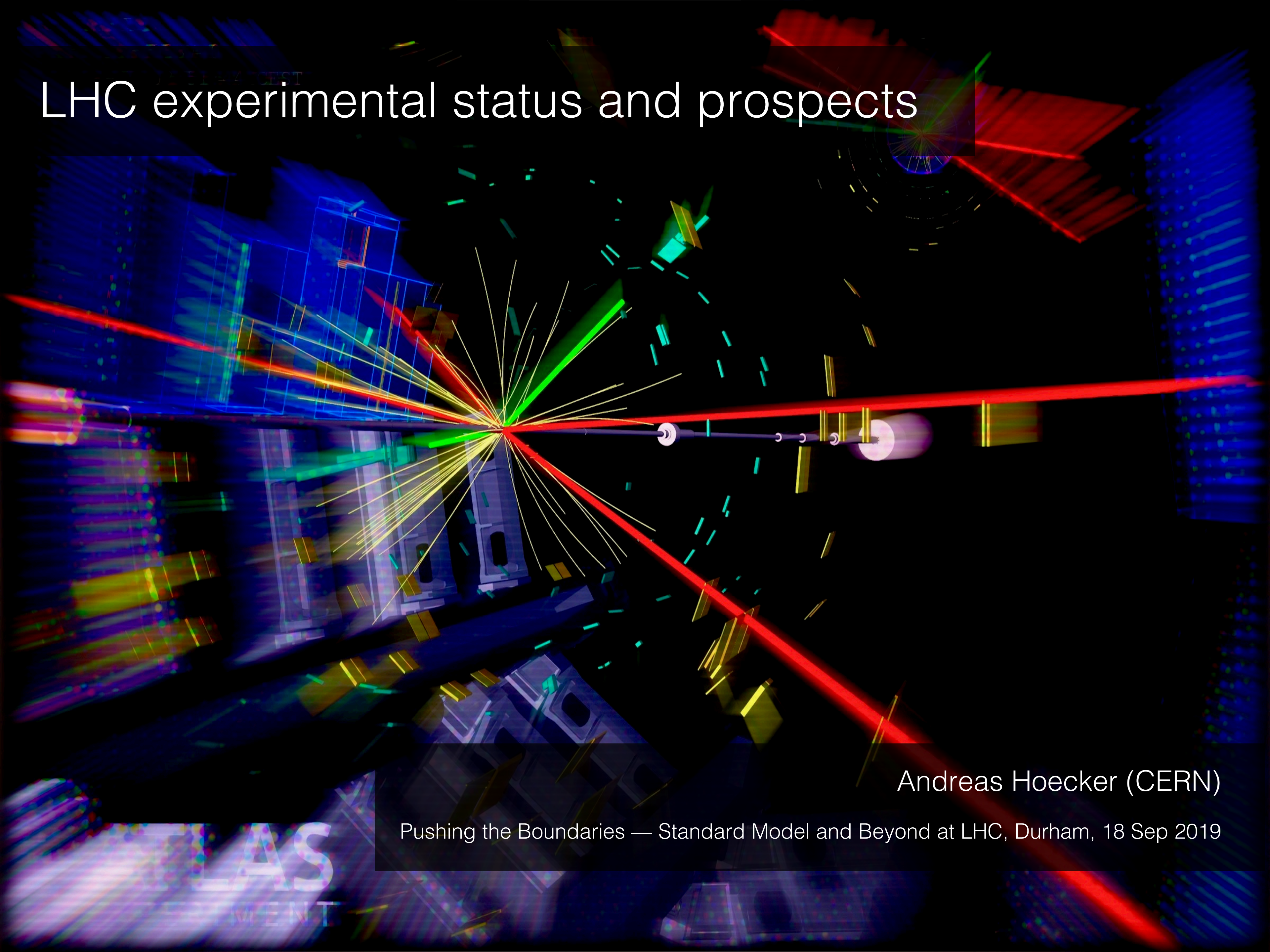
LHC experimental status and prospects



Andreas Hoecker (CERN)

Pushing the Boundaries — Standard Model and Beyond at LHC, Durham, 18 Sep 2019



LHC experimental status and prospects

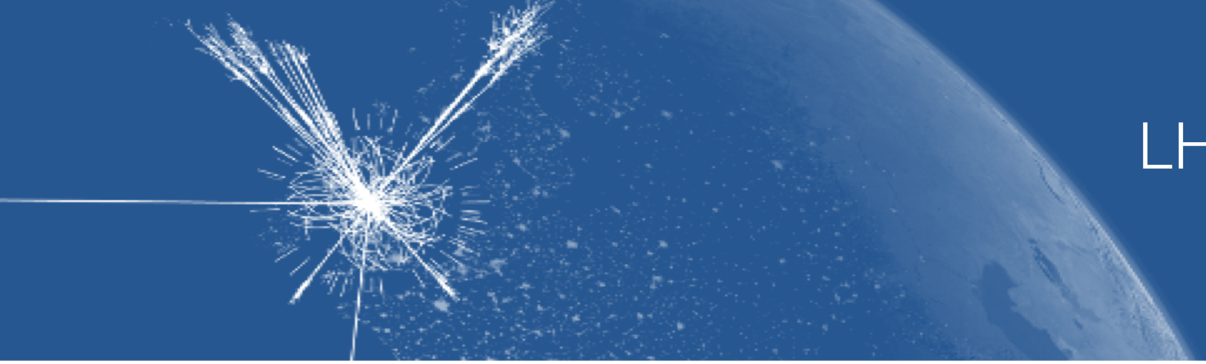
Andreas Hoecker (CERN)

Pushing the Boundaries — Standard Model and Beyond at LHC, Durham, 18 Sep 2019

LHC experimental status and prospects

A few preliminary remarks on this talk:

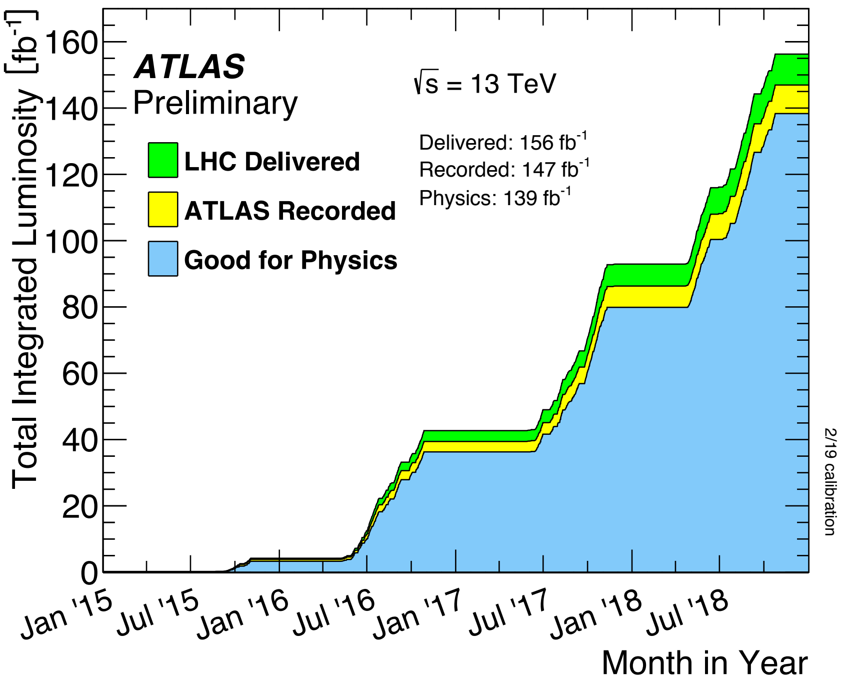
- Focus on newest results and full Run-2 data analyses
- ATLAS heavy – mostly due to convenience (apologies for this!): in most cases equivalent results from CMS
- Only brief coverage of heavy ion results, where relevant for particle physics



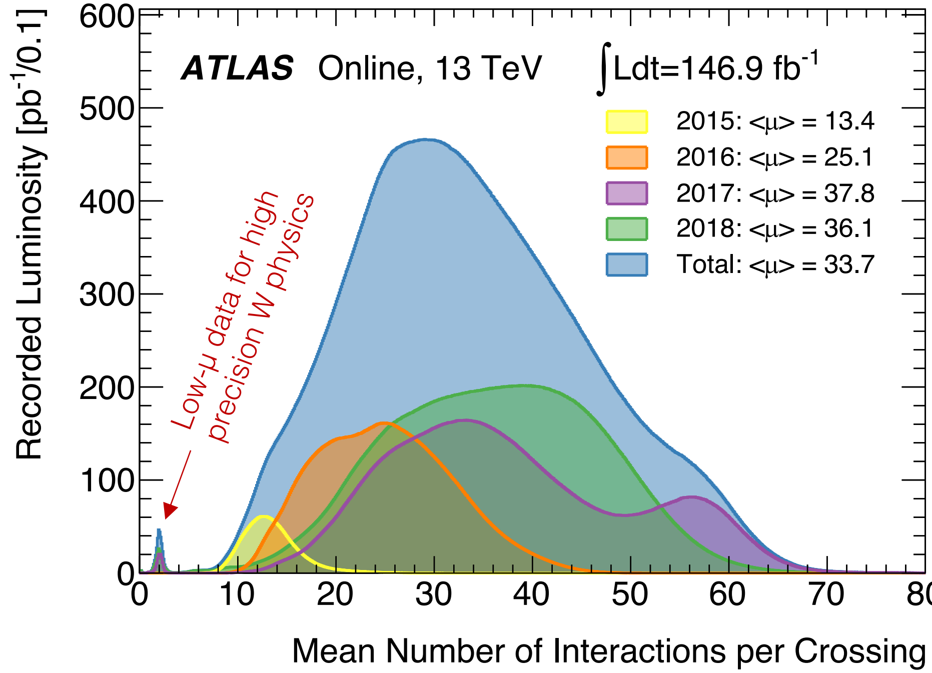
LHC Run-2 (2015–2018)
$\sqrt{s}$ = 13 TeV

Integrated pp luminosity during Run-2

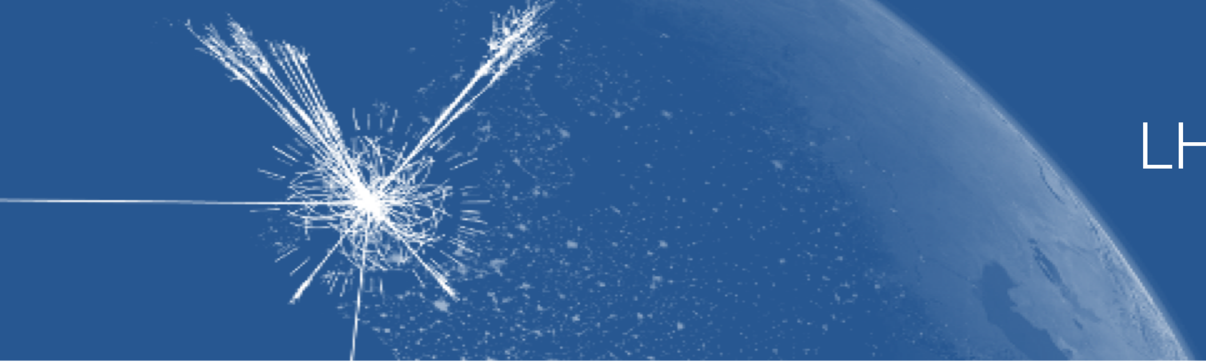
Also collected 2.3 nb^{-1} of 5 TeV Pb-Pb data, and p-Pb & Xe-Xe data



High-luminosity comes with a challenge



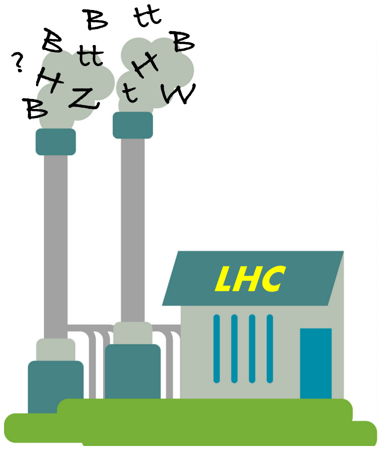
Exceptional data taking (94%) and data quality (95%) efficiencies, similar for CMS and ATLAS.
Integrated luminosity in Run-2 measured to 1.7% precision (ATLAS) ATLAS-CONF-2019-021



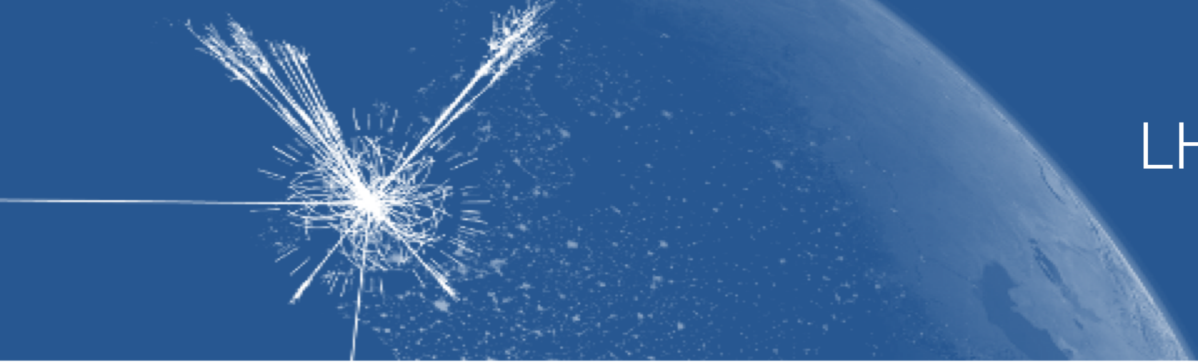
LHC Run-2 (2015–2018)
$\sqrt{s}$ = 13 TeV

The LHC is an **everything** factory

Particle	Produced in 140 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 million	
Top quark	275 million	
Z boson	2.8 billion	($\rightarrow \ell\ell$, 290 million)
W boson	12 billion	($\rightarrow \ell\nu$, 3.7 billion)
Bottom quark	~40 trillion	(significantly reduced by acceptance)



Broad physics potential by probing with high-precision Higgs and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements



LHC Run-2 (2015–2018) $\sqrt{s}$ = 13 TeV

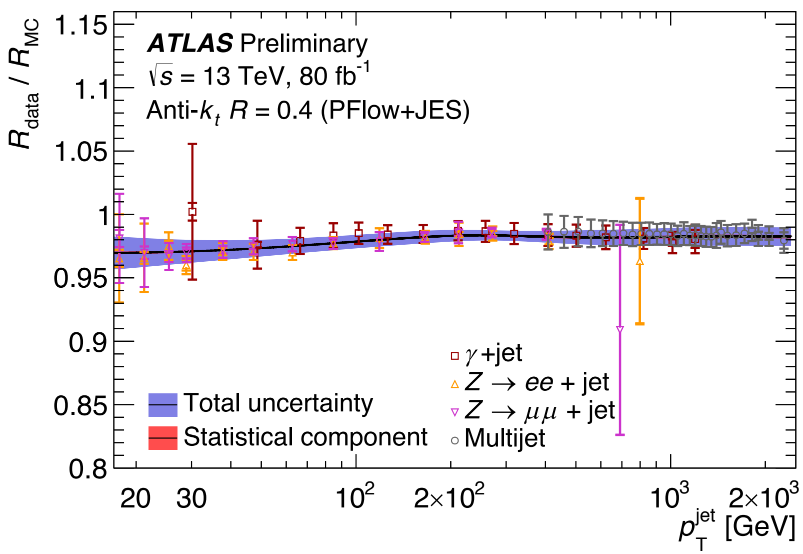
Excellent reconstruction performance, validated in data up to very large pileup values (> 60, design was 25)

Coherent data and MC sample for all of Run-2

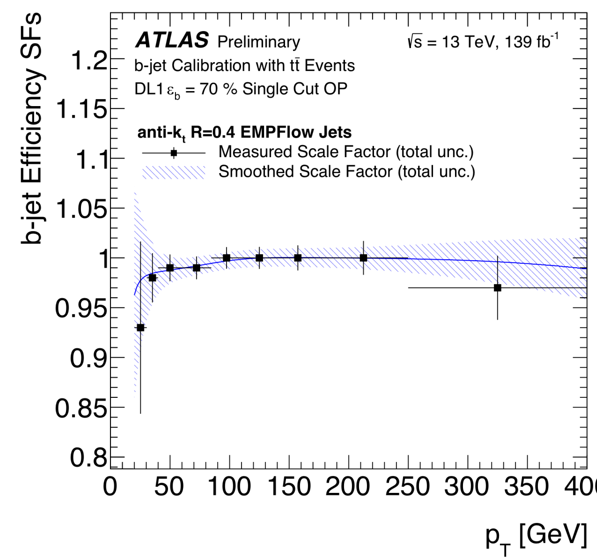
Widespread use of machine learning techniques for particle reconstruction & identification

Dedicated improvements and calibrations of low-momentum leptons, hadronic taus, low & high momentum b-tagging, boosted hadronic objects, …

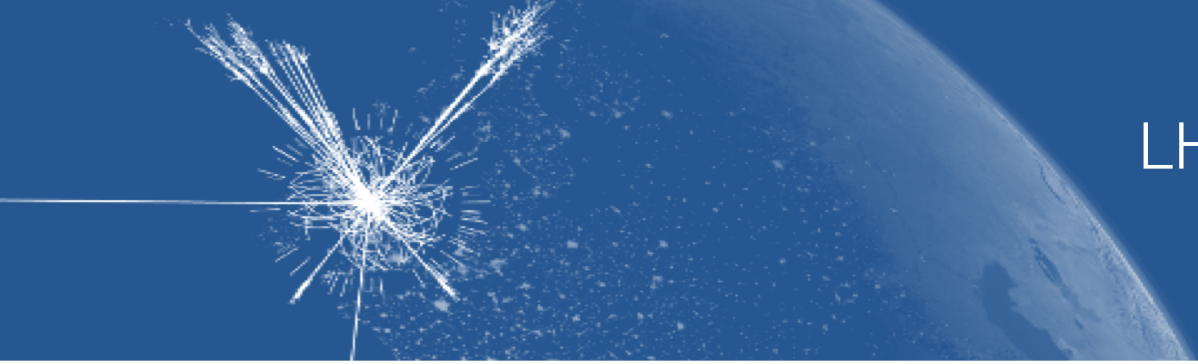
Data-driven energy calibration of standard particle flow jets.



Data-driven energy calibration of b-jet tagging efficiency



Percent precision reached for both hadronic objects



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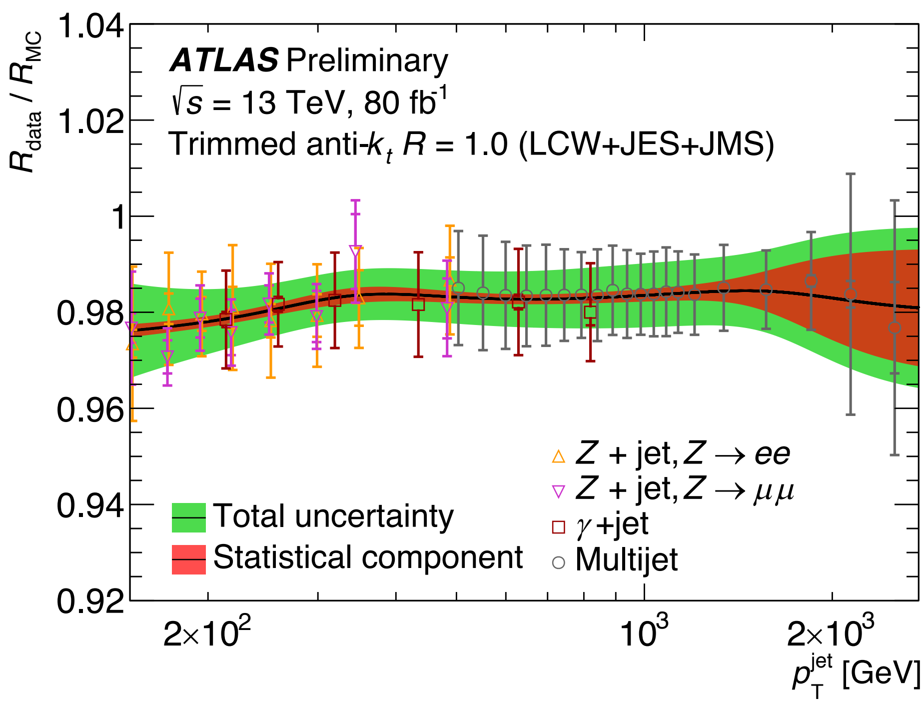
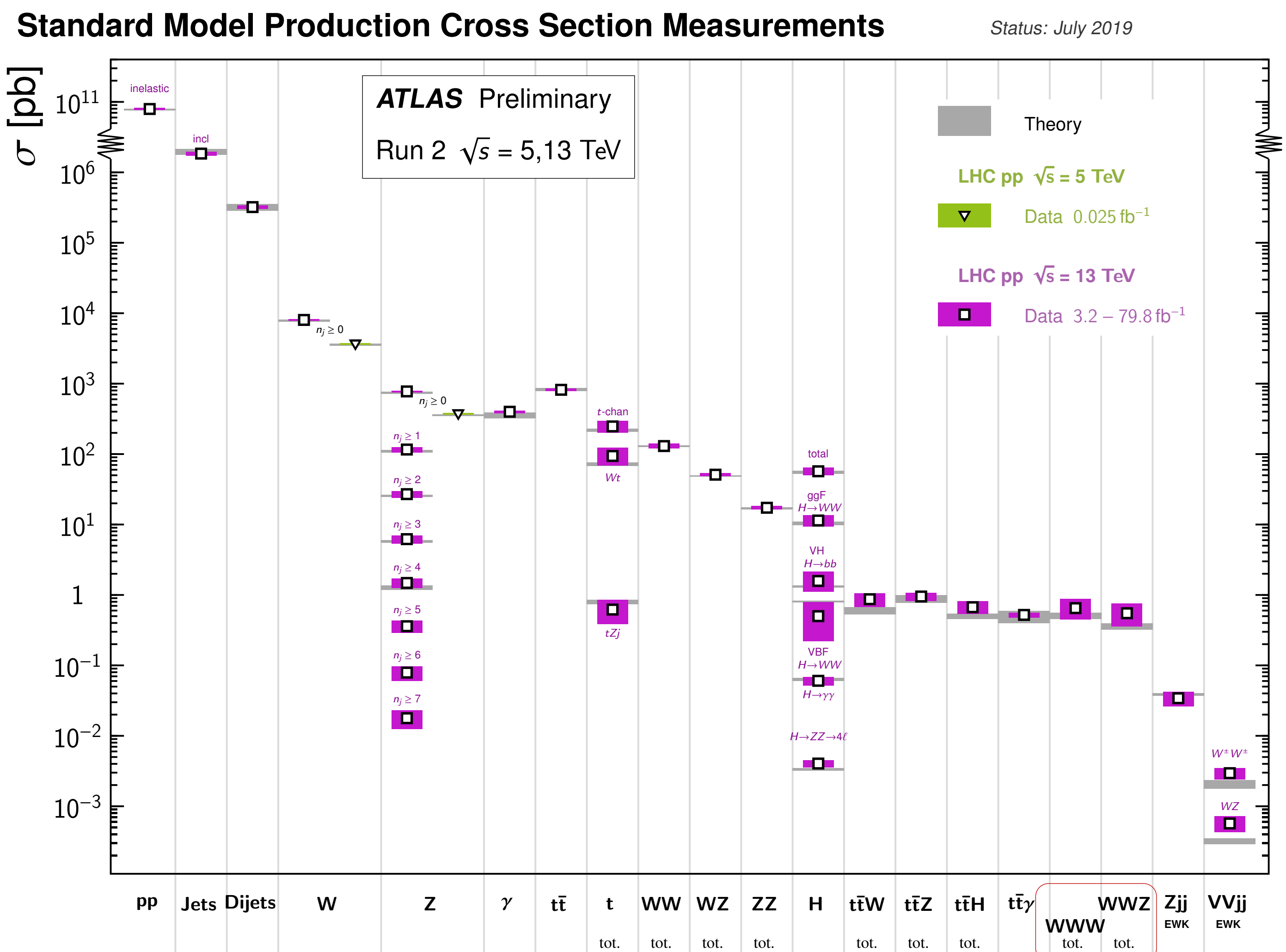


Percent-level precision also for data-driven calibration of large-R jets

Theory so far agrees with all measured cross sections

Across widely different processes



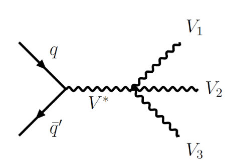
Harvest of CMS & ATLAS cross section measurements confirms the predictive power of the Standard Model

Also huge progress on theoretical calculations (NNLO revolution)

Many more detailed fiducial and differential cross section measurements

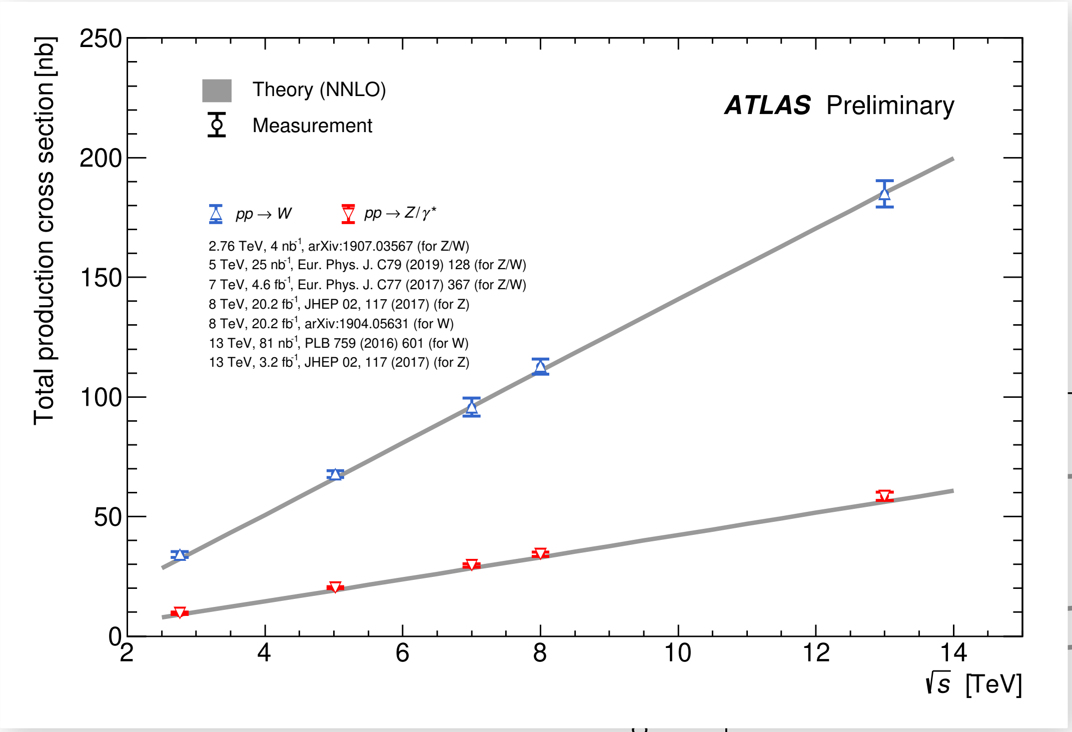
> 4σ Evidence for weak triboson production by ATLAS using 2015–2017 data

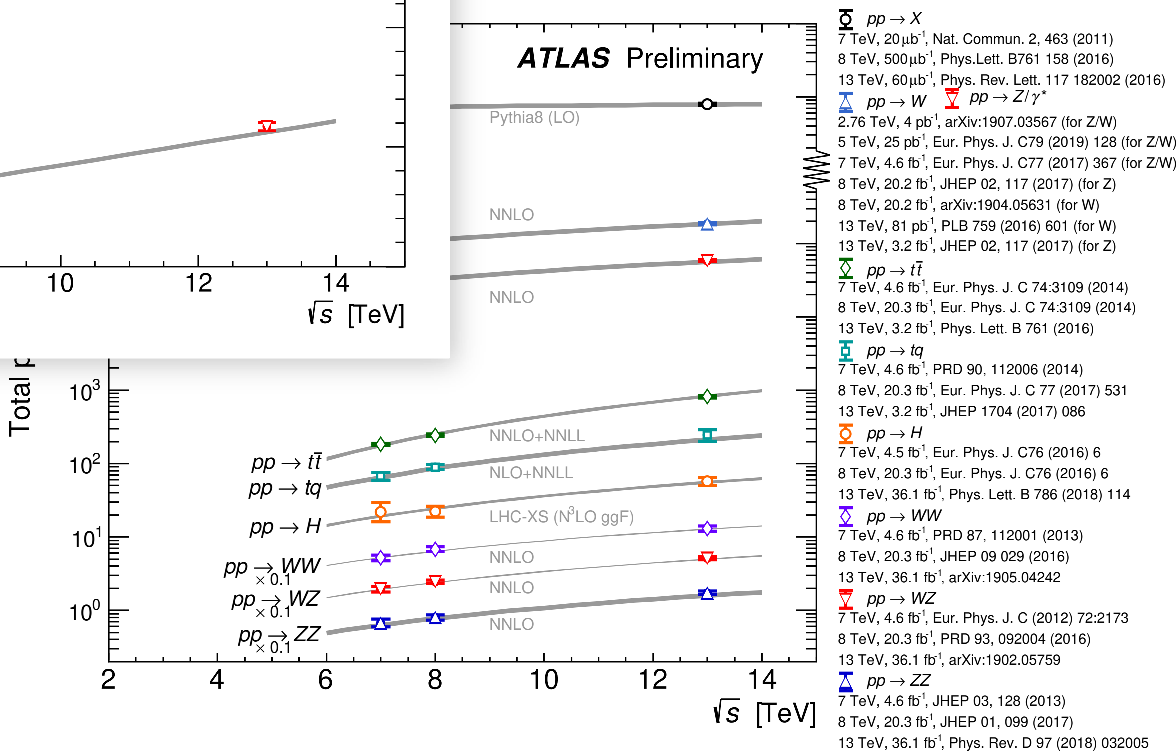
arXiv:1903.10415



Theory so far agrees with all measured cross sections

…and across centre-of-mass energies



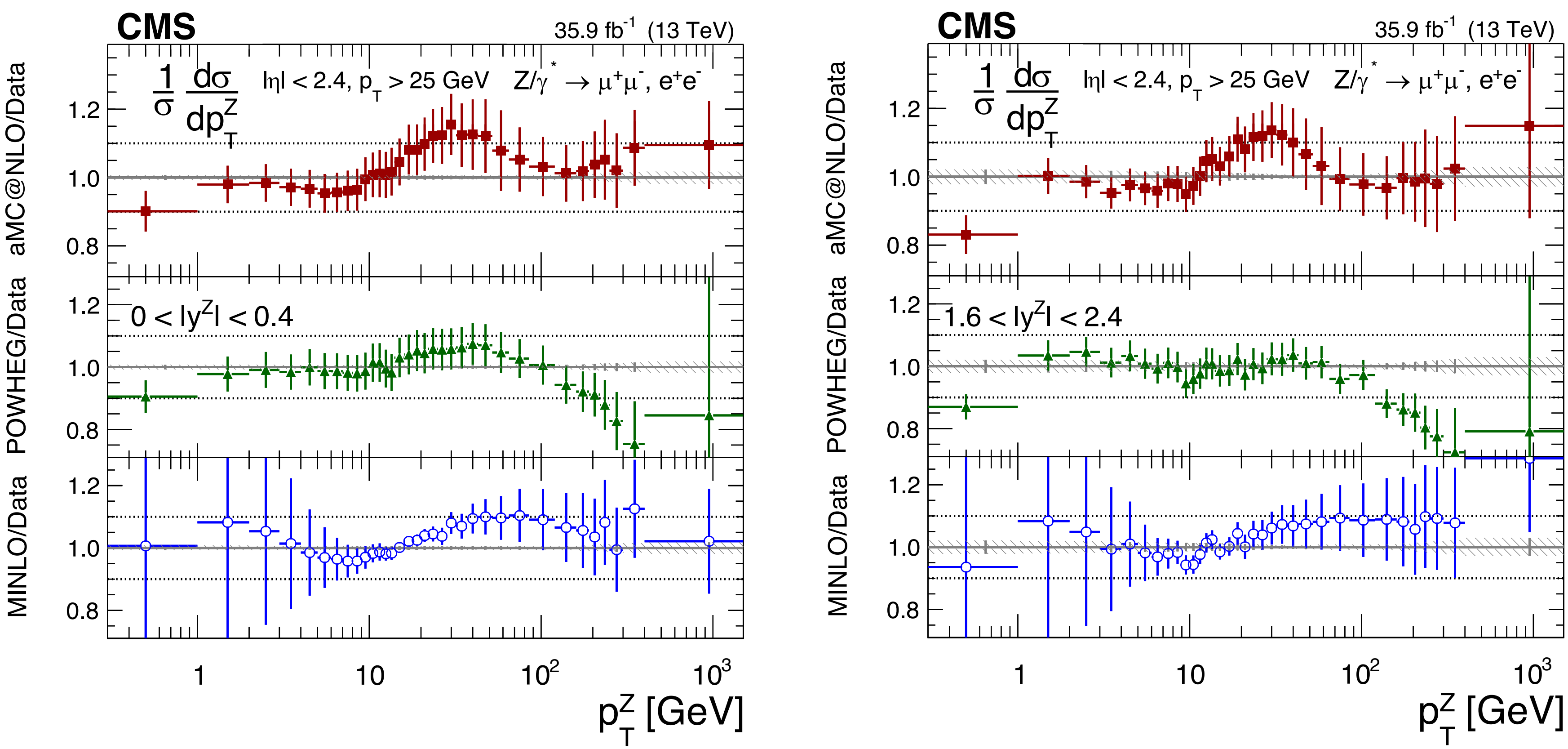


Precise measurements of boson production

Exploring differential spectra

arXiv:1909.04133

High-precision study of Z production at 13 TeV compared to state-of-the-art predictions



Also comparisons with resummed & FO predictions. None provides fully satisfying agreement yet.

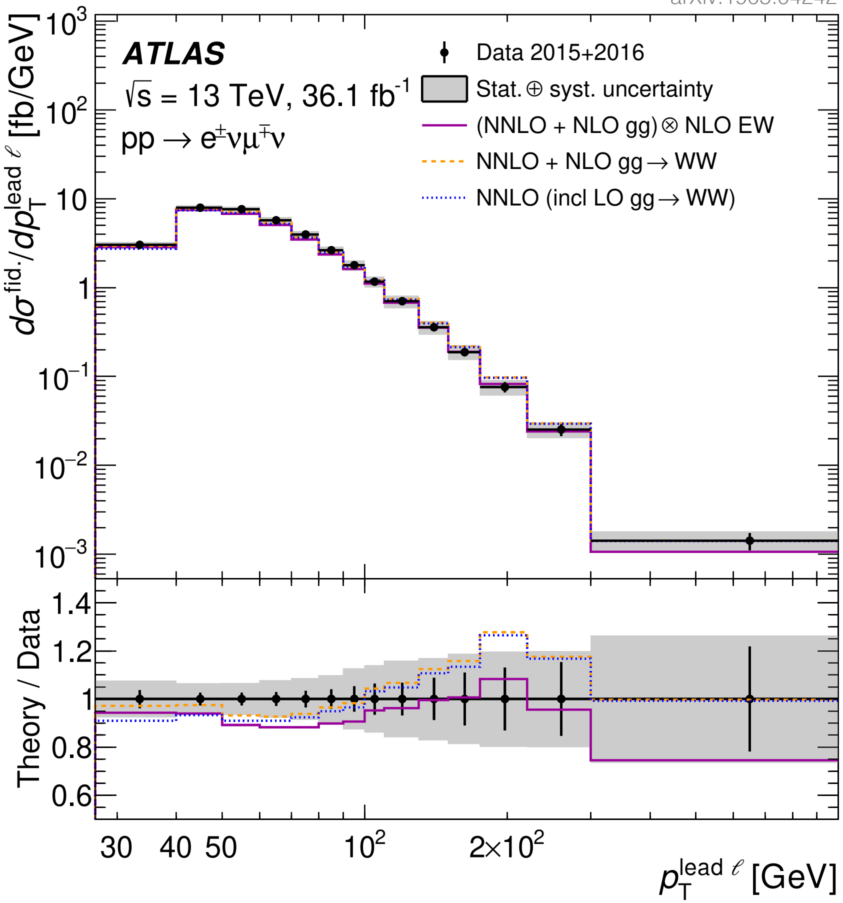
Understanding of p_T(V) spectrum and W–Z correlation important for W mass measurement

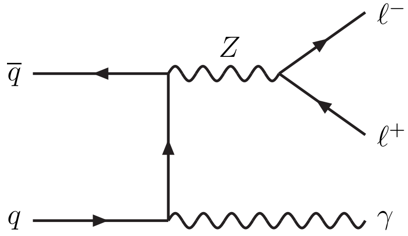
High-statistics probes of diboson production

Exploring differential spectra

New high-precision measurement of differential W^+W^- (left) and $Z\gamma$ (right) diboson cross sections, probing EW gauge structure of SM and tests QCD

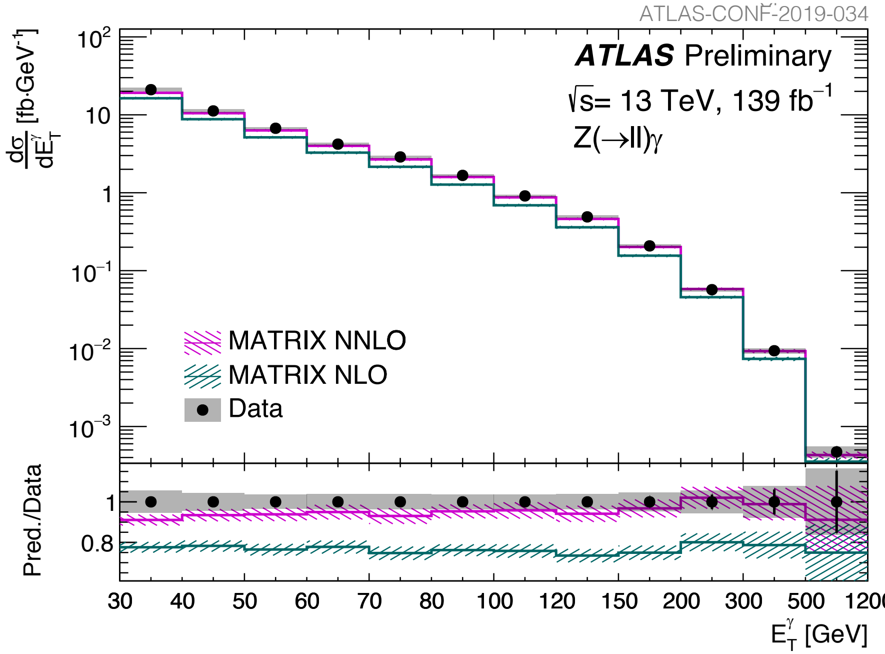
arXiv:1905.04242





FSR and quark/gluon fragmentation processes removed

ATLAS-CONF-2019-034

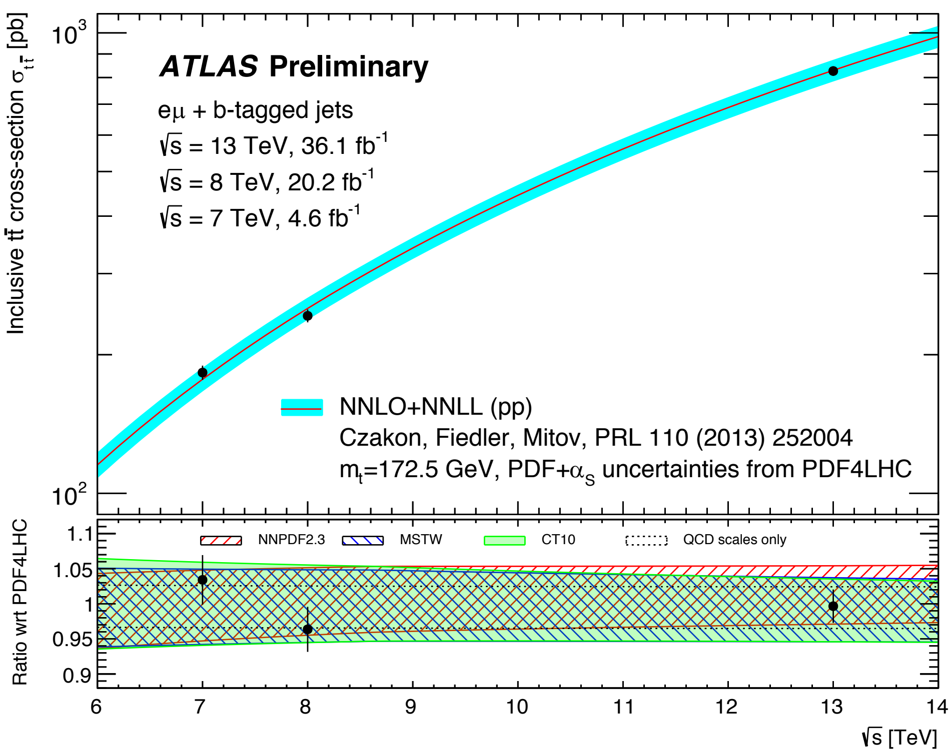


Top–antitop production measurements

Huge ttbar statistics at LHC allows to measure multidimensional differential cross sections

Analysis based on 36/fb with high-precision in situ performance calibration

ATLAS-CONF-2019-041

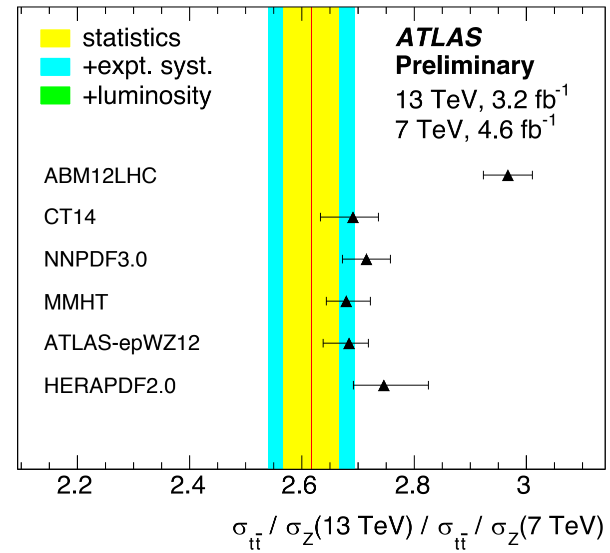


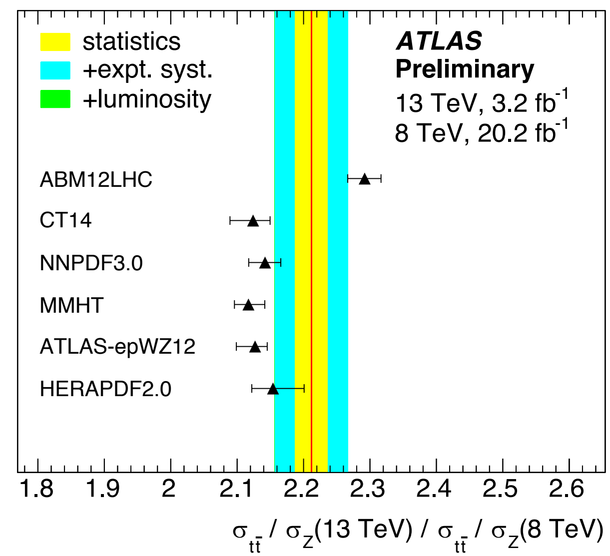
$\sigma(tt) = 826.4 \pm 3.6_{stat} \pm 11.5_{syst} \pm 15.7_{lumi} \pm 1.9_{beam}$ pb (2.4%)

(1.9%)

$m(t) = 173.1\,^{+2.0}_{-2.1}$ GeV (at pole)

Uncertainty dominated by PDF, QCD scale, experimental



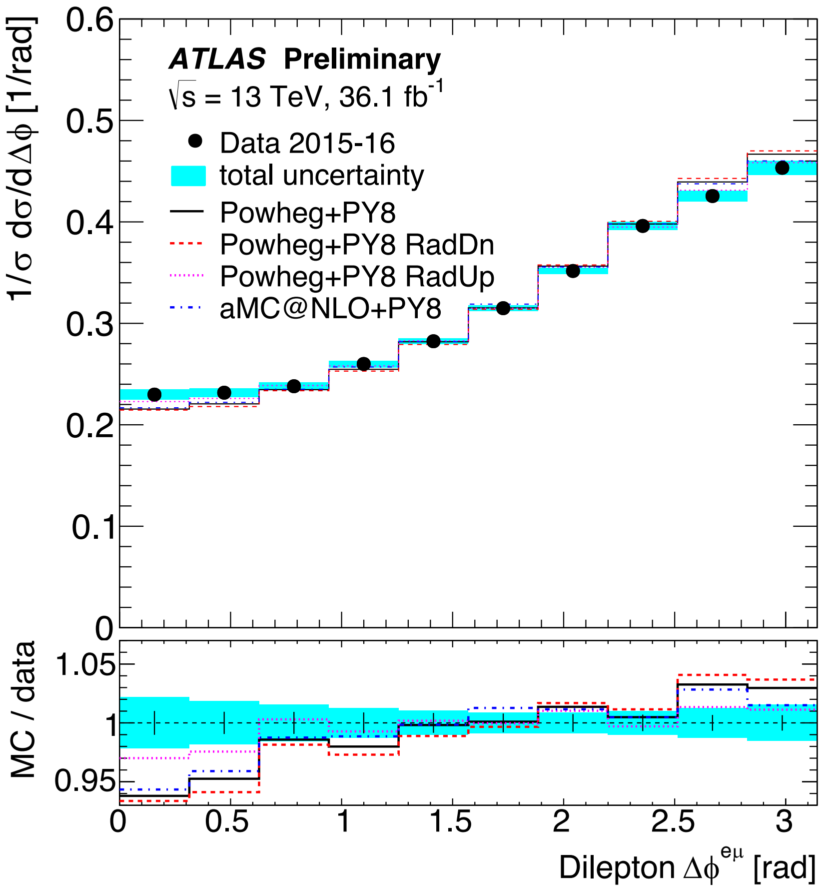


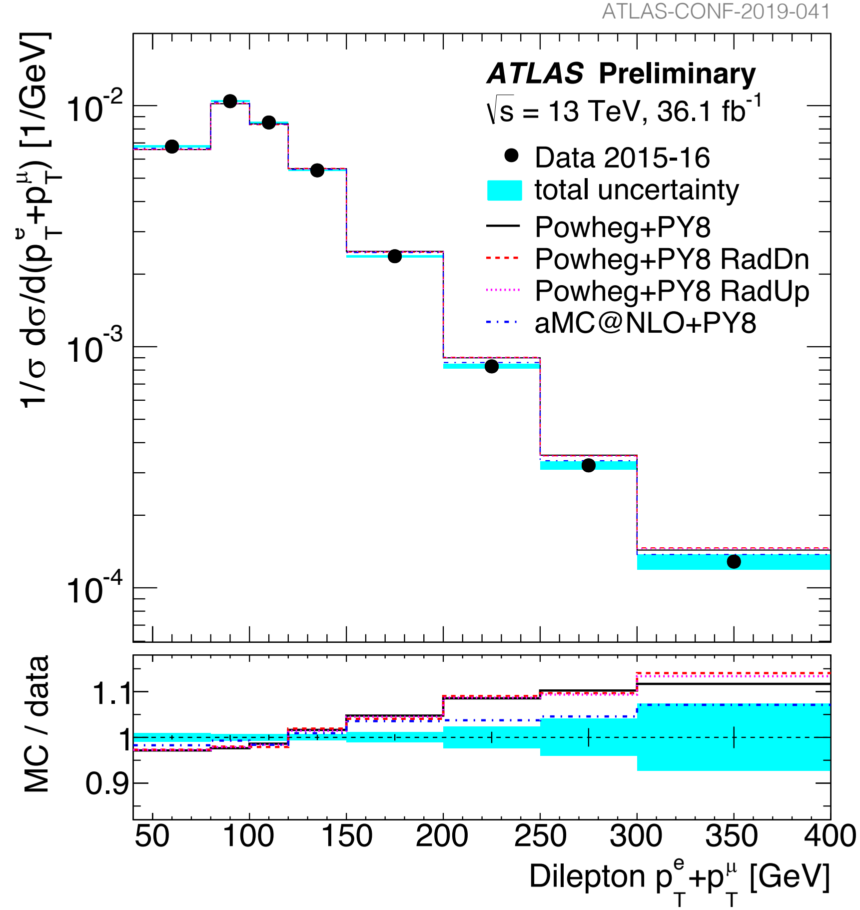
Top–antitop production measurements

Huge ttbar statistics at LHC allows to measure multidimensional differential cross sections

Detailed differential cross-section measurements exhibit known modelling problems, examples below

ATLAS-CONF-2019-041



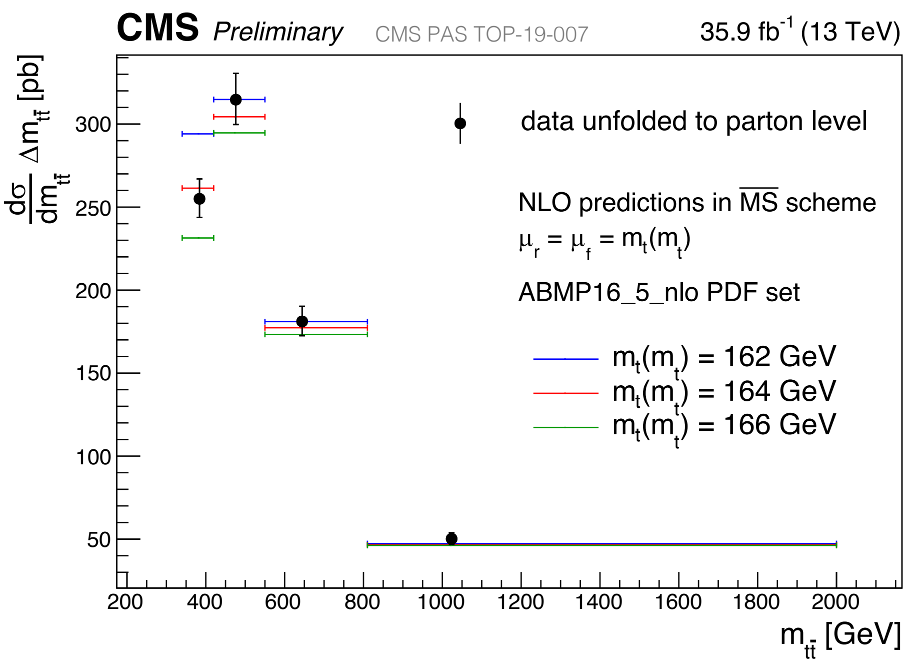


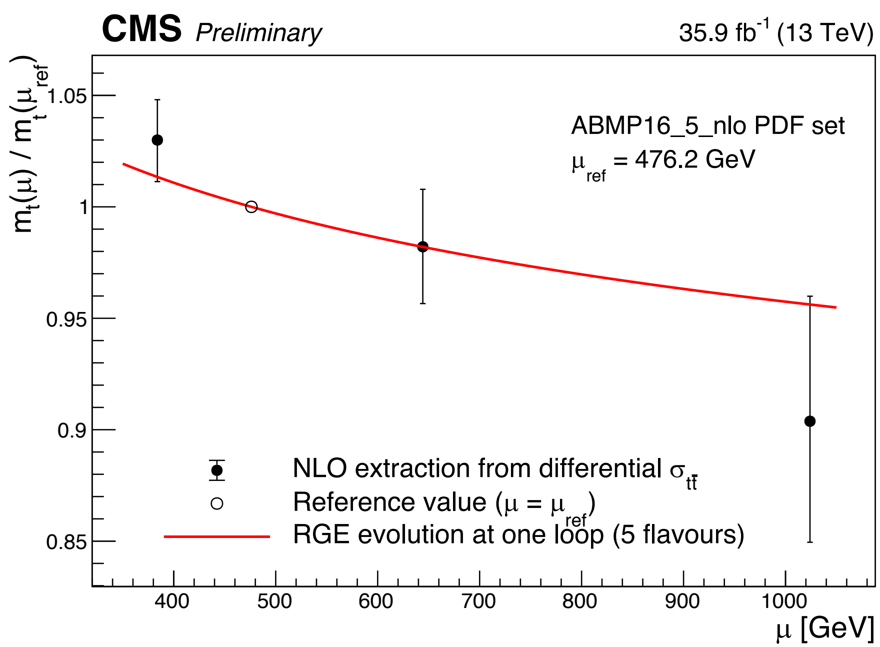
Top production measurements

Differential cross section versus ttbar mass can be exploited to probe running top mass

Interpret measurement in eμ channel in terms of running MS mass

- m(tt) derived at parton level from fit to event kinematics





- Observed running is compatible with scale dependence predicted by RGE at NLO
- p-value of 2.6σ for no-running hypothesis

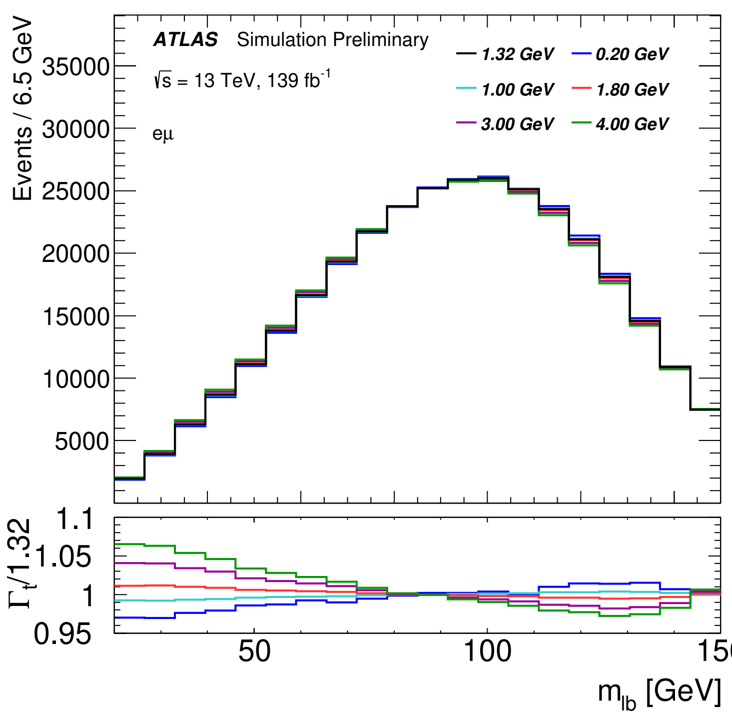
Top decay width

Top quark, shortest-lived matter known (~5×10^{-25} s)

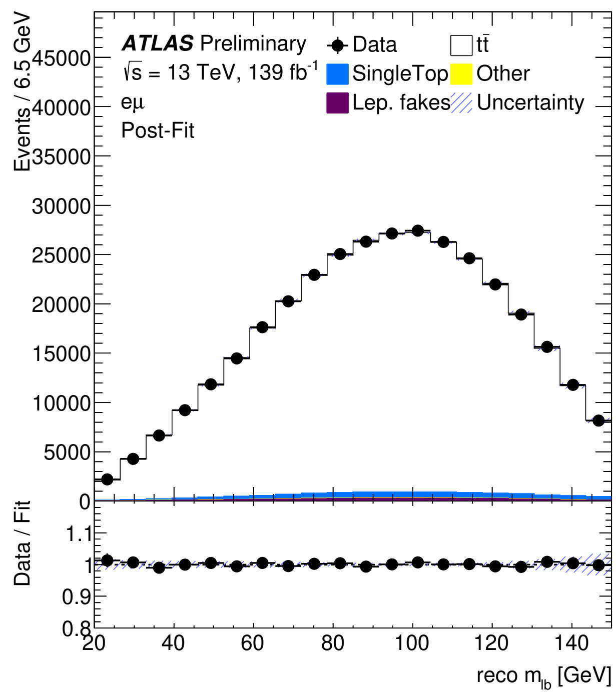
Top much broader than QCD bound states, width governed by weak decay:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right] \sim 1.32\ \text{GeV (for } m_t = 172.5\ \text{GeV)}$$

New measurement from ATLAS in dilepton channel (280k candidates) using full Run-2 dataset



ATLAS-CONF-2019-038



Measurement relies on in situ constraints of systematic uncertainty parameters

Result:

Γ_t = 1.9 ± 0.5 GeV

(0.2_{stat})

Dominant systematics:

- Jet reconstruction
- Signal and bkg modelling
- MC statistics

High-statistics probes of top-quark charge asymmetry

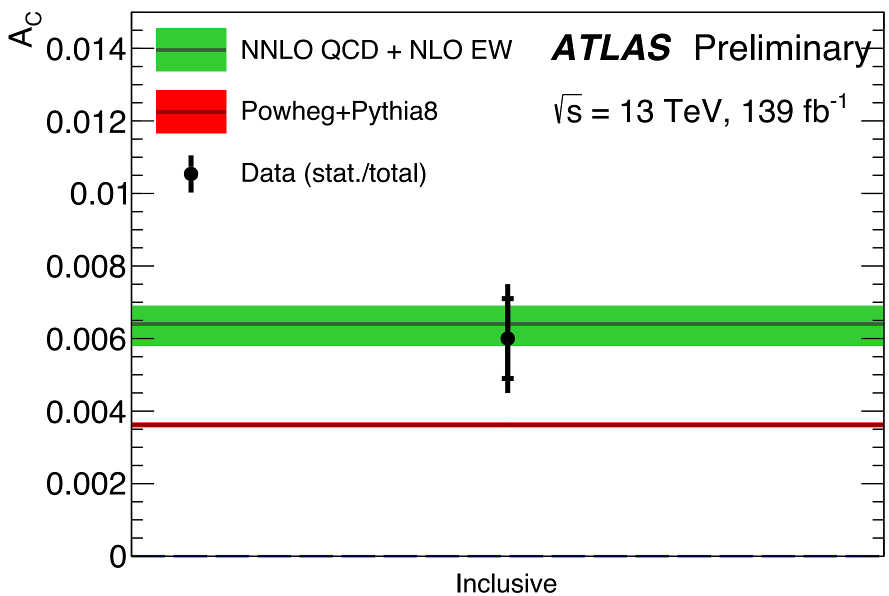
Higher order QCD effects in qq and qg collisions generate charge asymmetry (gg symmetric)

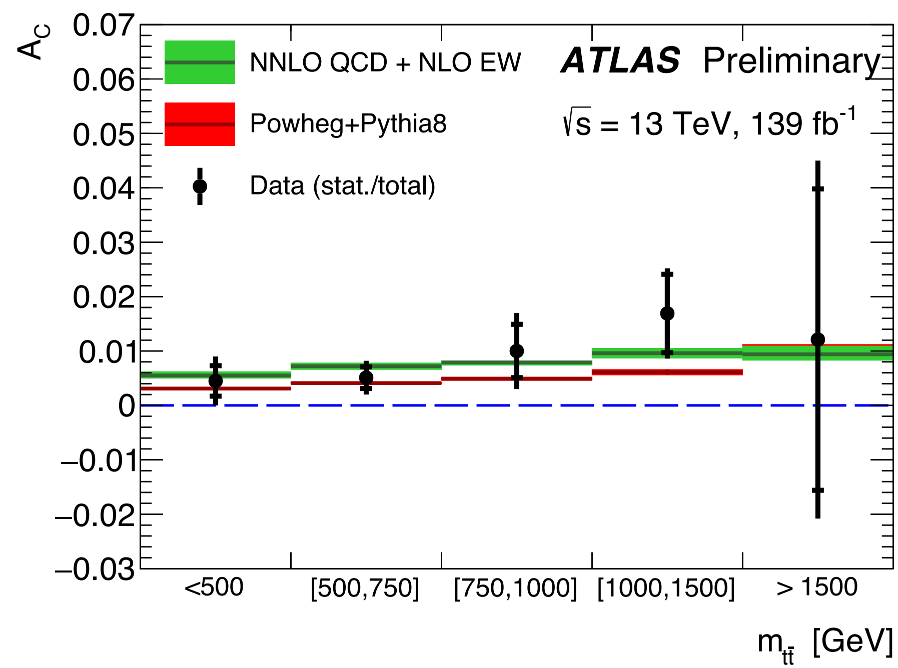
Charge asymmetry measurement in top-antitop system using resolved and boosted top-quark decays in lepton+jets events

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} = 0.0060 \pm 0.0011_{\text{stat}} \pm 0.0010_{\text{sys}}$$

Non-zero at 4σ — first evidence at LHC

ATLAS-CONF-2019-026

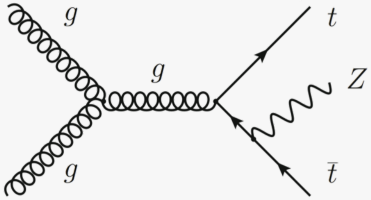




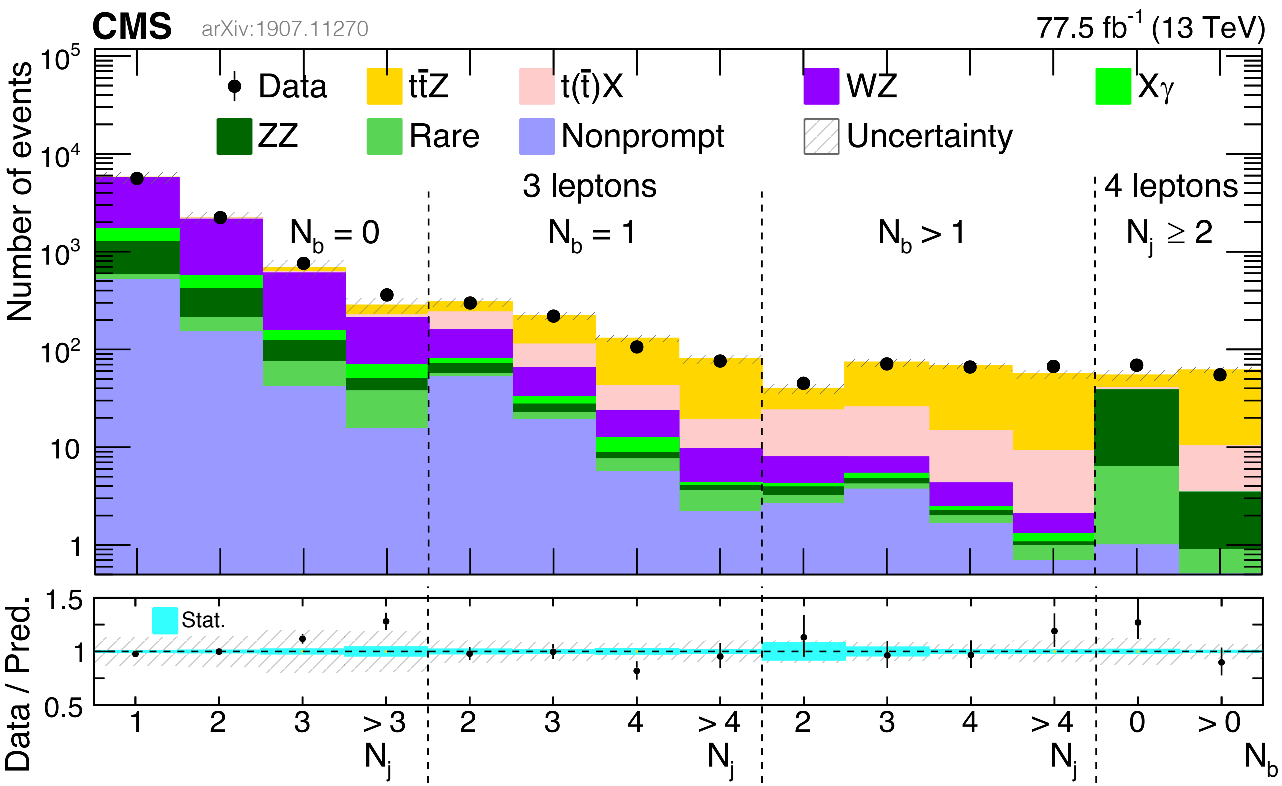
Consistent description in NNLO QCD with NLO EW corrections

Associated production of ttbar with bosons

ttZ cleanest channel, allows differential cross section measurements



Very interesting measurement from CMS using 78/fb in 3 and 4-lepton channels



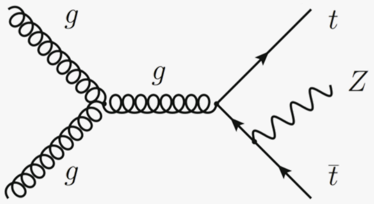
Very clean signal regions. Total cross section measured:

$\sigma(ttZ) = 0.95 \pm 0.05_{stat} \pm 0.06_{syst}$ pb

SM(NLO): 0.84 ± 0.10 pb

Associated production of ttbar with bosons

ttZ cleanest channel, allows differential cross section measurements



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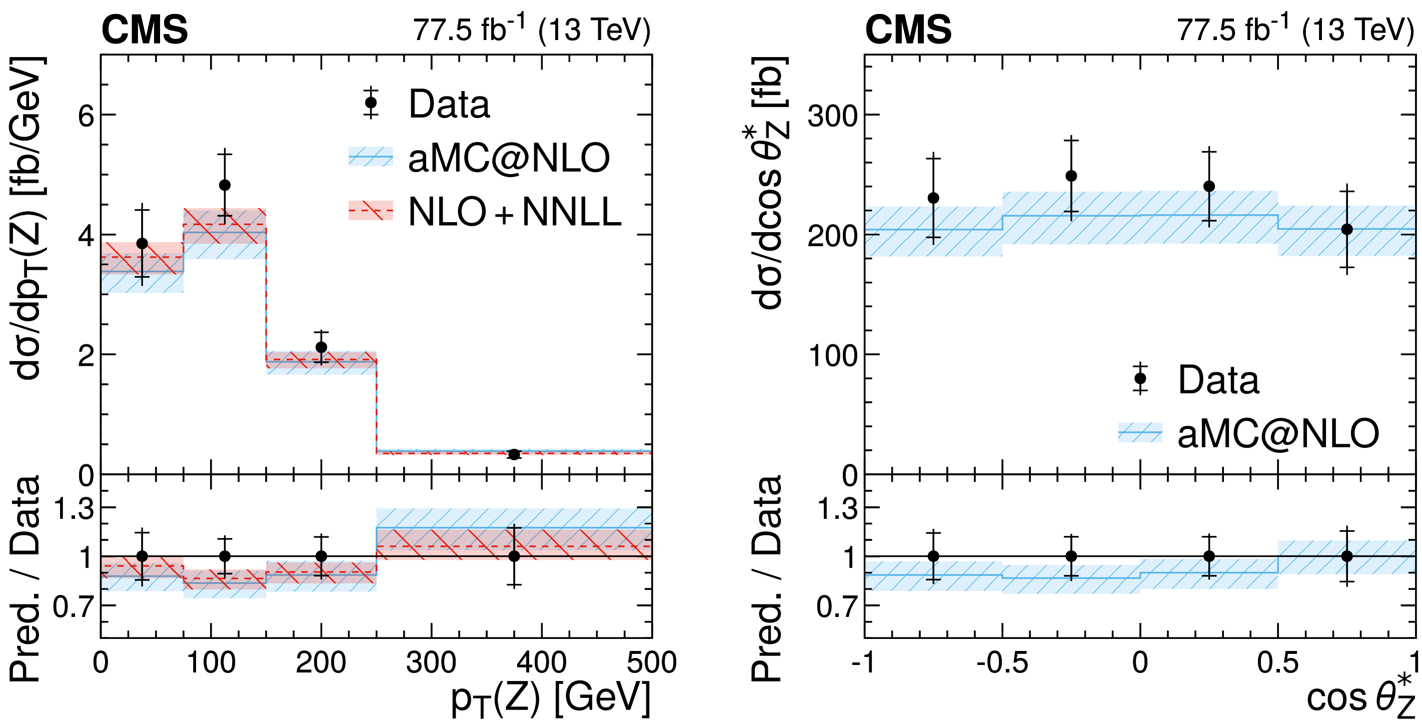


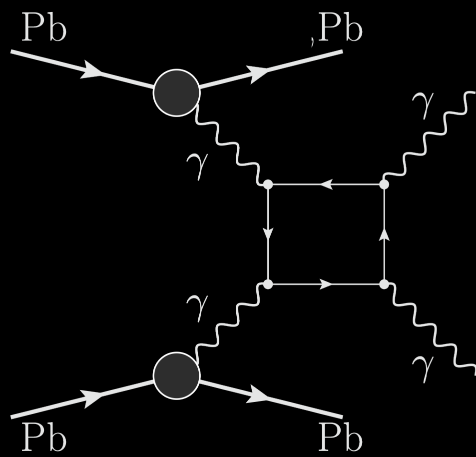
arXiv:1907.11270

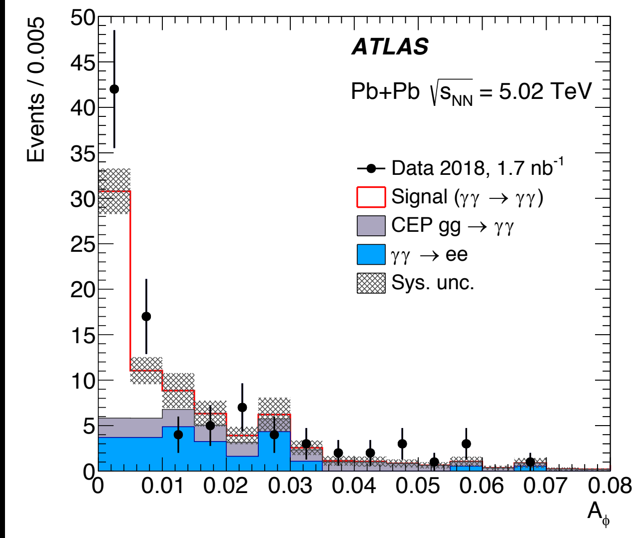
Used differential cross sections to constrain anomalous top-Z vector/axial-vector couplings and electroweak magnetic and electric dipole interaction couplings (the latter are only radiatively present in SM, ie, very small)

Alternative interpretation in SMEFT (constraints on effective Wilson coefficients)

Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb+Pb collisions taken in 2018

[arXiv:1904.03536]



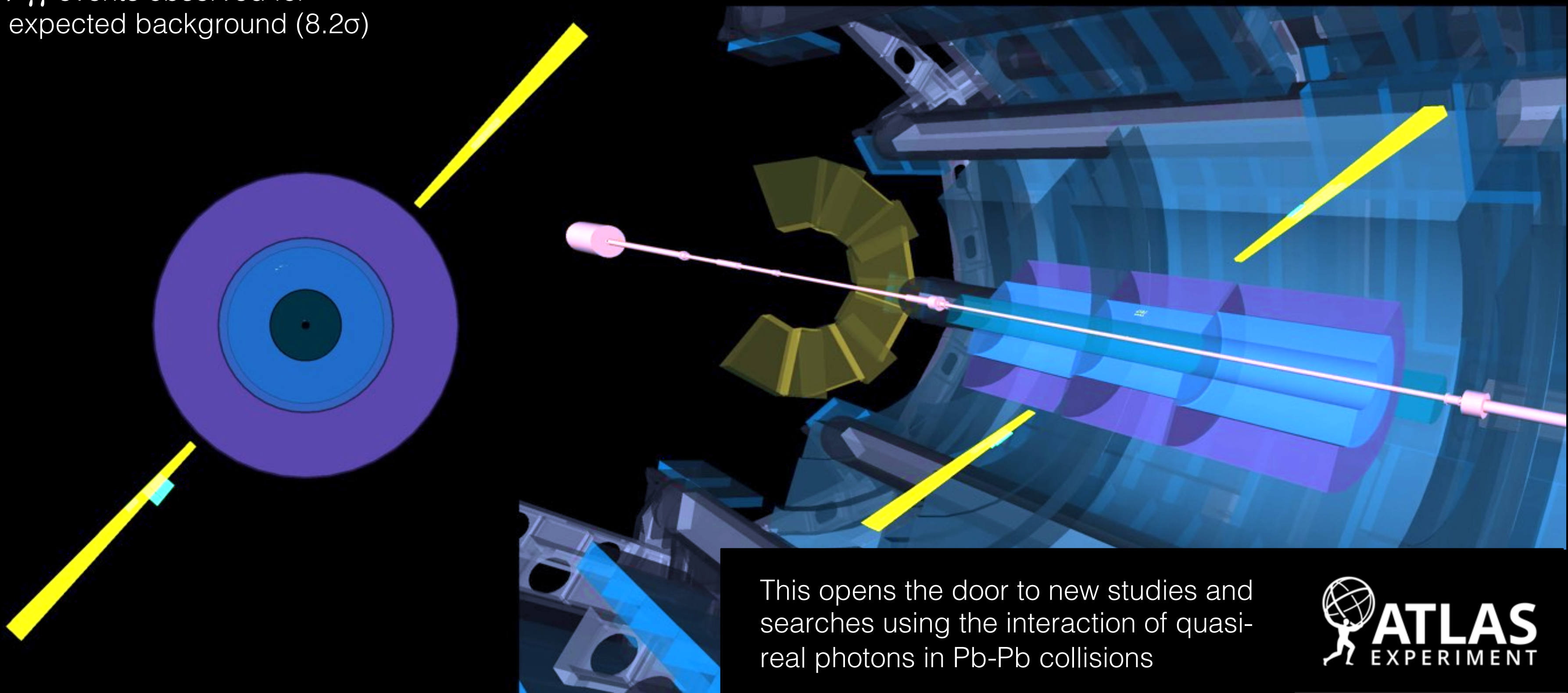


Field strength of up to 10^{25} V/m

$\gamma\gamma$ luminosity ~ Z^4 ~ 5×10^7

Look for low-energy back-to-back photon pair with no additional activity in detector

59 $\boldsymbol{\gamma\gamma \to \gamma\gamma}$ events observed for 12 ± 3 expected background (8.2σ)



This opens the door to new studies and searches using the interaction of quasi-real photons in Pb-Pb collisions

ATLAS EXPERIMENT

Ultraperipheral PbPb collisions are rich source of photons

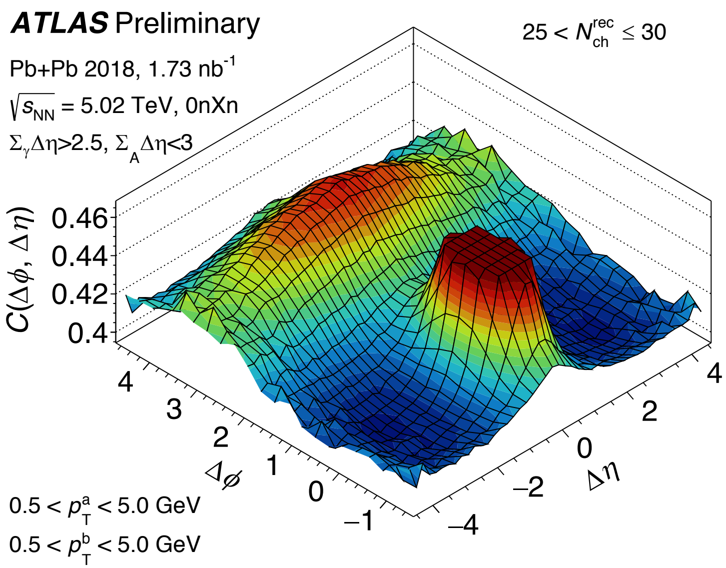
Look for two-particle correlations in γ+Pb scattering (selected by dedicated photo-nuclear trigger)

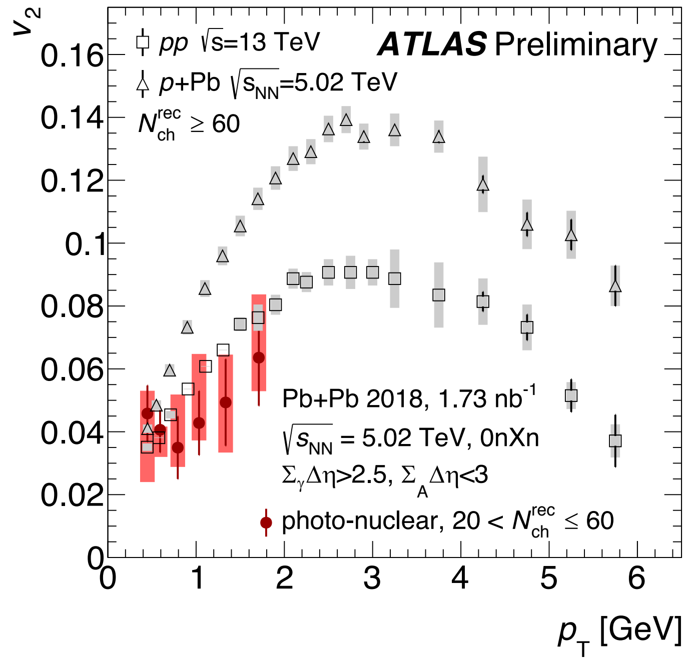
Two-particle correlations observed in non-UPC Pb+Pb, p+Pb in pp collisions:

- Long-range azimuthal correlations ("ridge") due to collective behavior in "quark-gluon plasma", quantified via Fourier decomposition of yields in ϕ (v_2 is the leading term, called elliptic flow)

Can such an effect occur in photo-nuclear collisions?

ATLAS-CONF-2019-022





Ridge in small systems like p+Pb or pp still open to new interpretations and more experimental studies

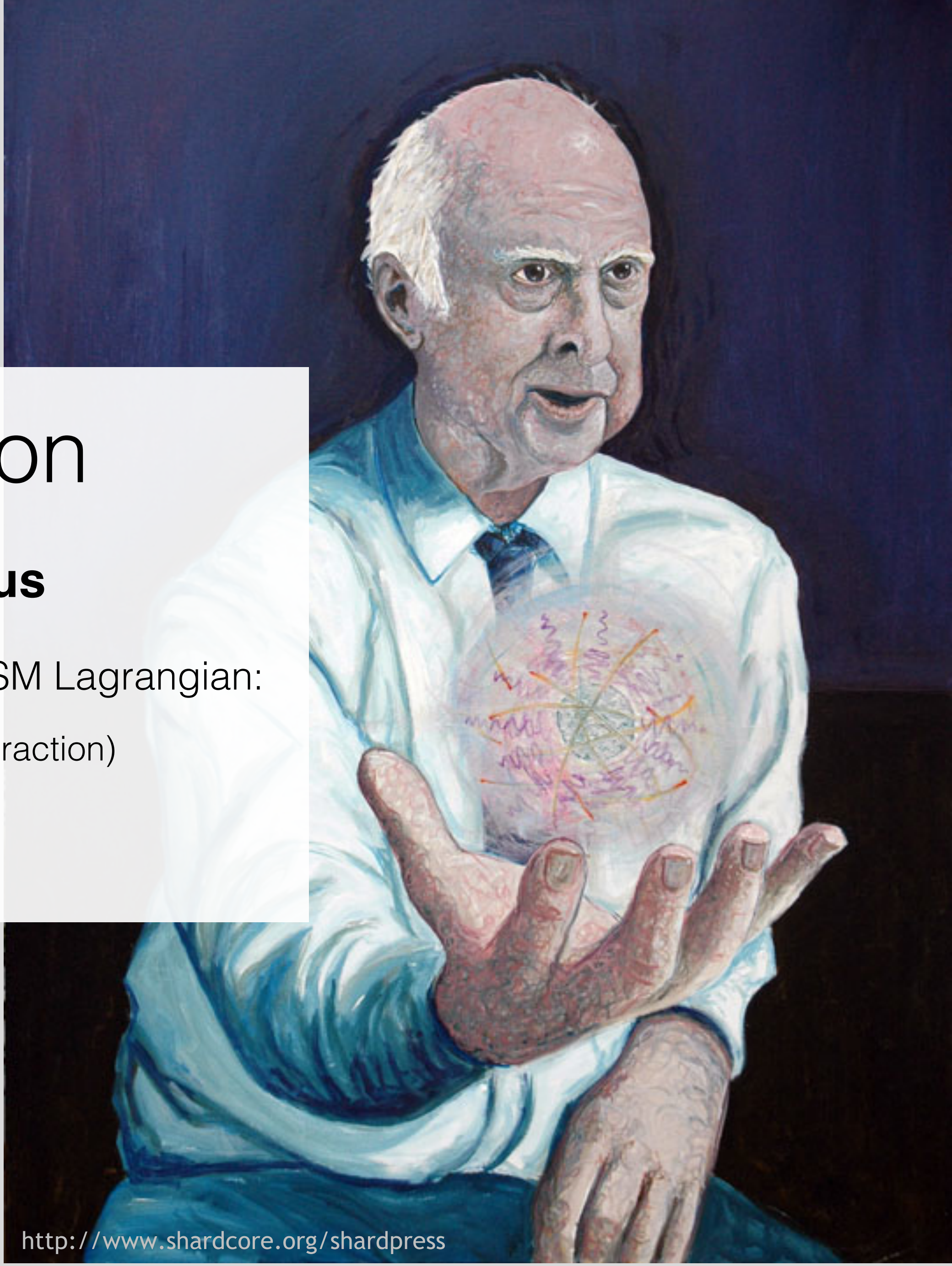
- Vector-meson dominance: photon fluctuates to vector meson γ+Pb ⇔ ρ+Pb

The Higgs boson

The LHC's magnum opus

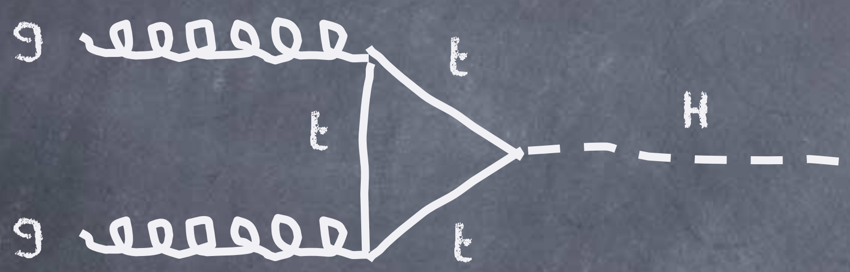
Discovery allows to access new sector of SM Lagrangian:

- Yukawa couplings (new types of interaction)
- Gauge–scalar boson interactions
- Higgs potential (incl. self coupling)



Higgs boson production at the LHC

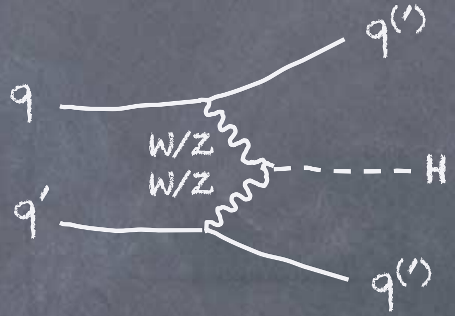
At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,total}$ = 56 pb at $\sqrt{s}$ = 13 TeV for m_H = 125 GeV



$\sigma_{H,ggF}$ ~ 49 pb at 13 TeV

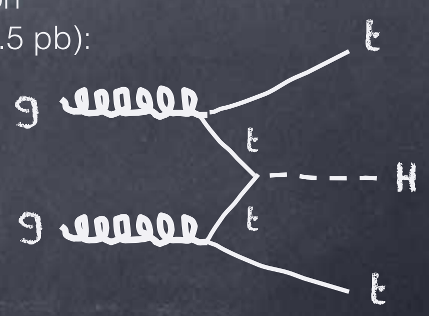
Yukawa coupling: $y_t = \upsilon / (m_t \sqrt{2}) \sim 1$

Weak boson fusion — VBF (σ_{VBF} ~ 3.8 pb):



Higgs-strahlung ($\sigma_{W/Z+H}$ ~ 1.4/0.9 pb):

“ttH” production
(σ_{ttH} ~ σ_{bbH} ~ 0.5 pb):



All major Higgs production modes observed at LHC

Higgs boson production at the LHC

Total production of almost 8 million Higgs bosons expected in each CMS & ATLAS during Run-2 — that's huge, but …

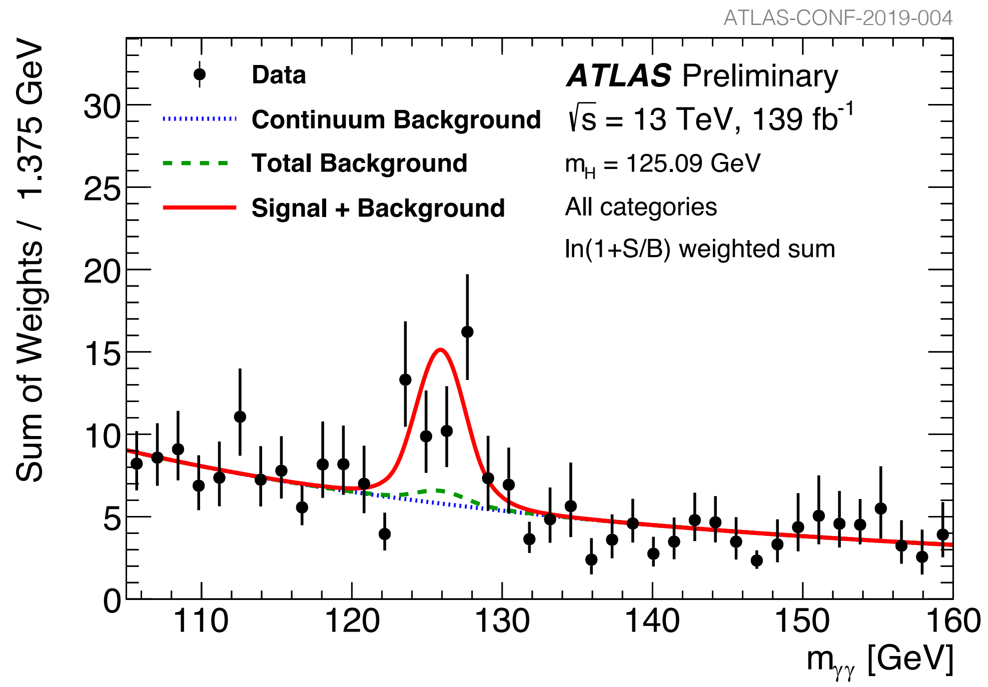
H(125 GeV) — approximate numbers

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,500	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

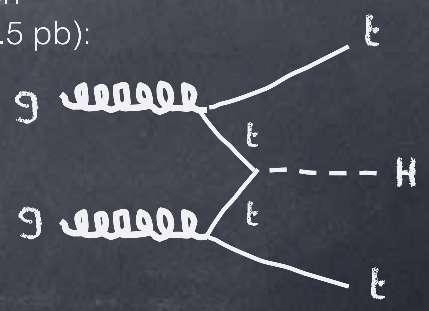
Our goal is to measure the couplings of the Higgs boson to all particles and their dependence of the event kinematics and topology as precisely as possible

Higgs boson production at the LHC

After the combined multi-channel observation of ttH with 6.3σ in 2018, ATLAS observes ttH in single diphoton channel at 4.9σ using full Run-2 dataset



"ttH" production ($\sigma_{ttH} \sim \sigma_{bbH} \sim 0.5$ pb):



$$\sigma_{ttH} \cdot B_{H\to\gamma\gamma} = 1.59\,^{+0.43}_{-0.39}\ \text{fb}$$
$$= 1.59\,^{+0.38}_{-0.36}(\text{stat})\,^{+0.15}_{-0.12}(\text{exp})\,^{+0.15}_{-0.11}(\text{theo})\ \text{fb}$$

In agreement with SM prediction of 1.15 ± 0.10 fb

Higgs boson production at the LHC

Because Higgs boson couples to mass of particles:

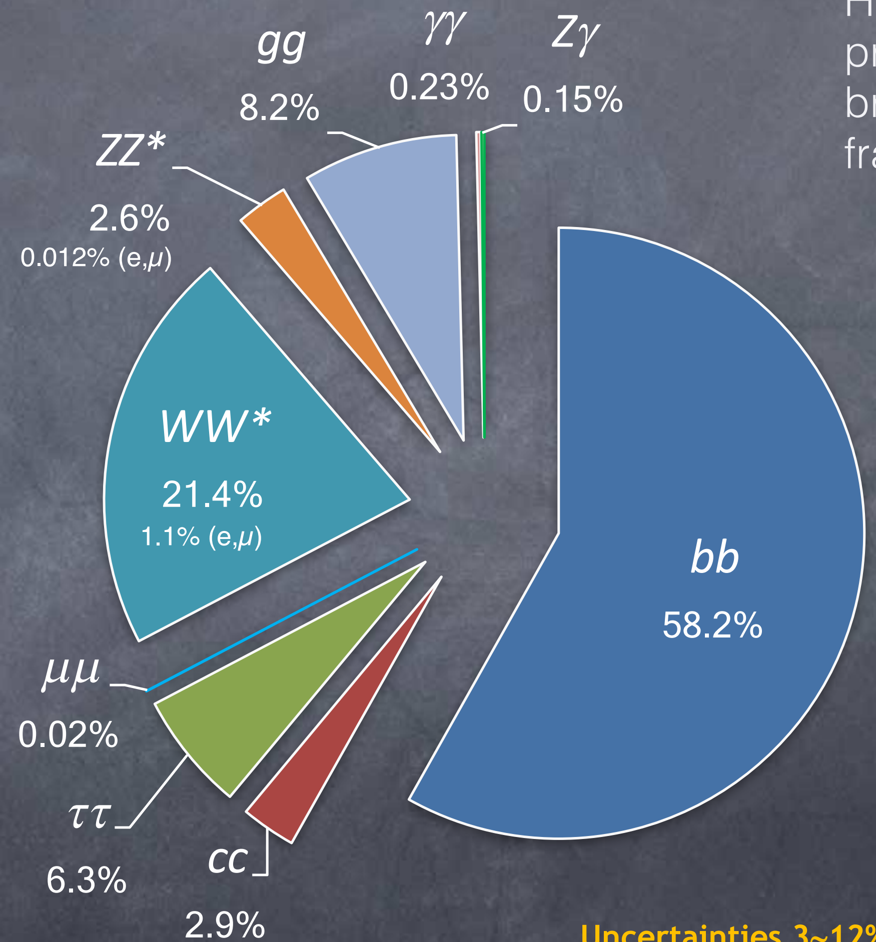
- … the Higgs decays with preference to the heaviest particles allowed
- … and couples only via "loops" involving preferentially heavy particles (e.g., top, W) to photons and gluons

At the LHC we measure:

$$\text{Rate}(pp \to H \to f) \propto \sigma_H \cdot \frac{\Gamma_{H\to f}}{\Gamma_H}$$

- Higgs boson width Γ_H not directly accessible (except using tricks)
- Absolute coupling measurement requires extraction of $\sigma_H \cdot \Gamma_{H\to f}$
- Therefore, only coupling ratios model-independent at LHC

H(125 GeV) predicted branching fractions:



Uncertainties 3~12%

Higgs boson production at the LHC

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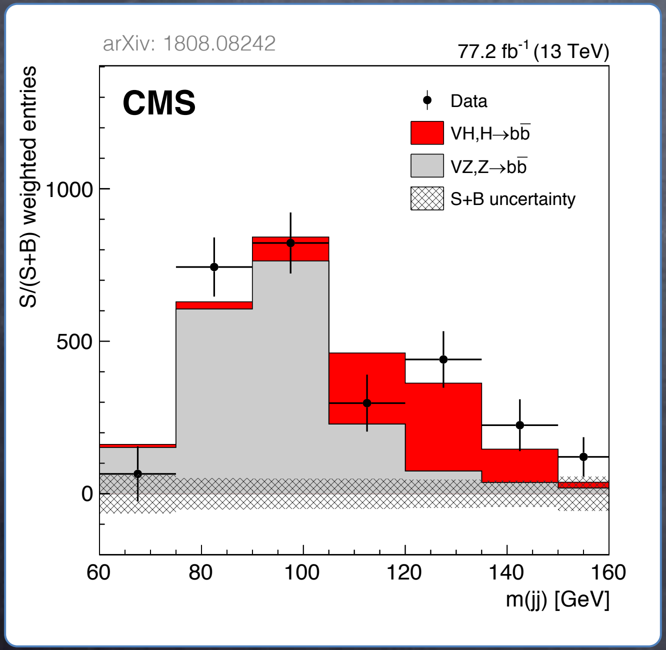
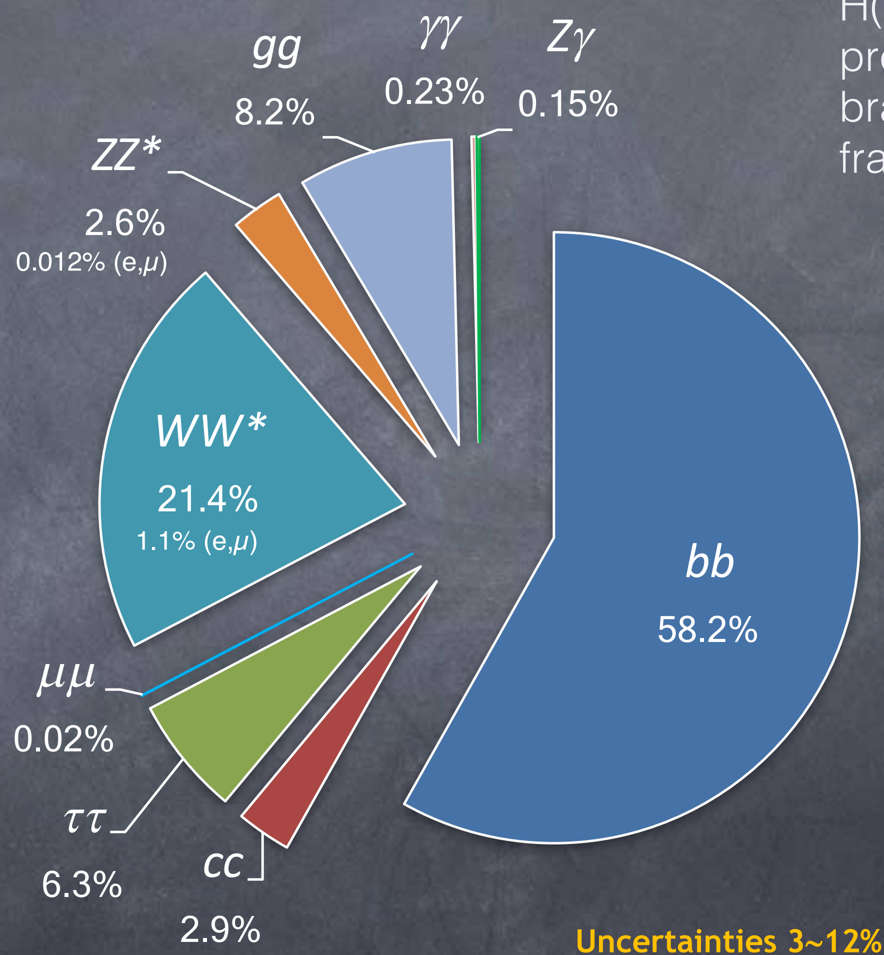
… the Higgs decays with preference to the heaviest particles allowed

… and couples only via “loops” involving preferentially heavy particles (e.g., top, W) to photons and gluons

Observation of H → bb in 2018

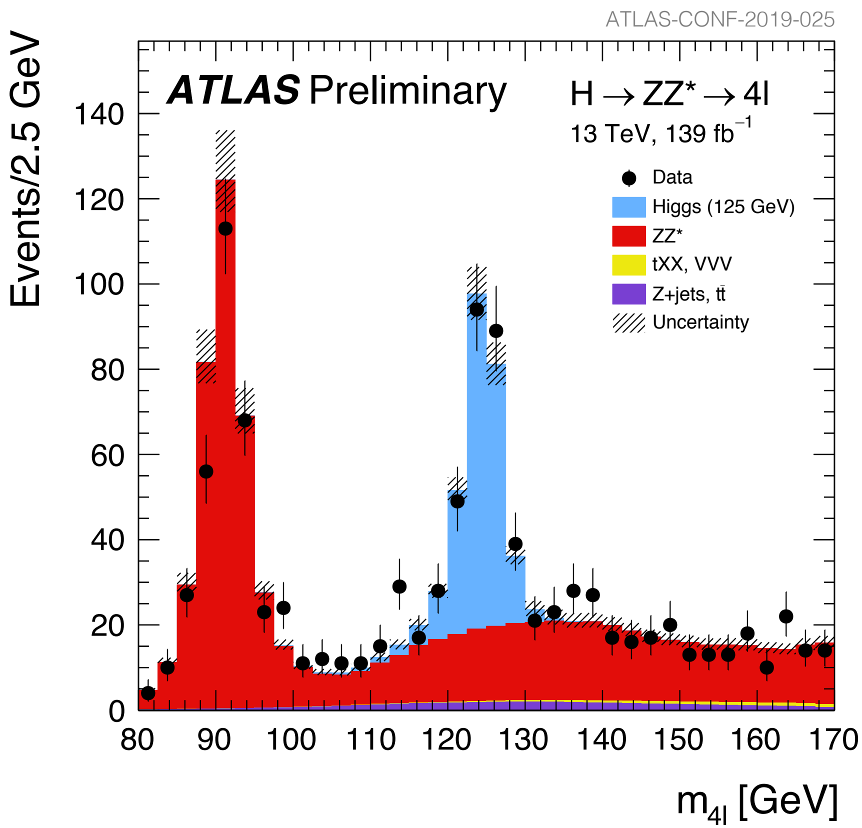


H(125 GeV) predicted branching fractions:

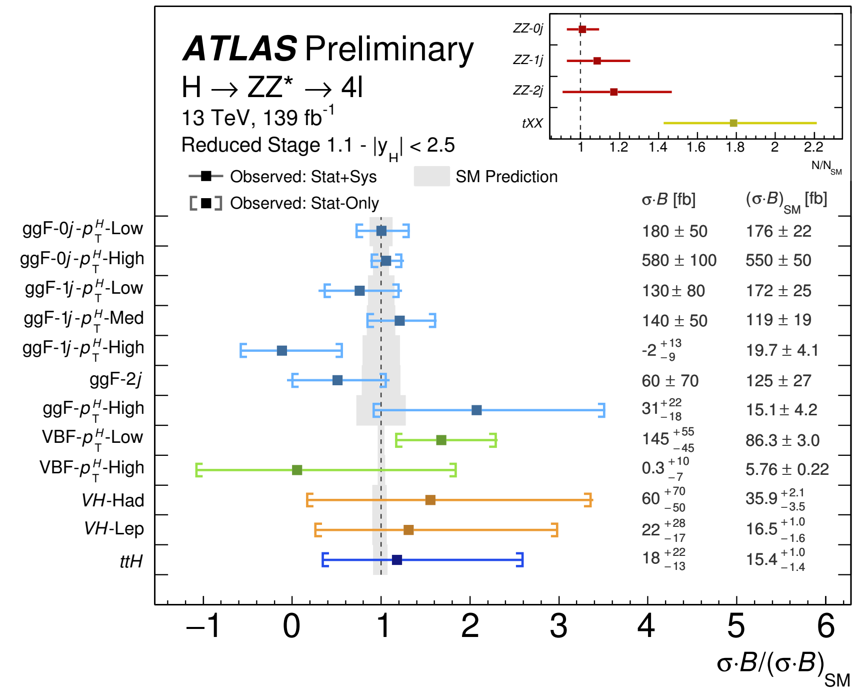


Cross section measurements in 4-lepton channel

Find ~210 pp → H → ZZ* → 4ℓ signal events within 115 < $m_{4\ell}$ < 130 GeV in full Run-2 dataset
Clean separation in production channels using NNs. Main ZZ background from sideband fit

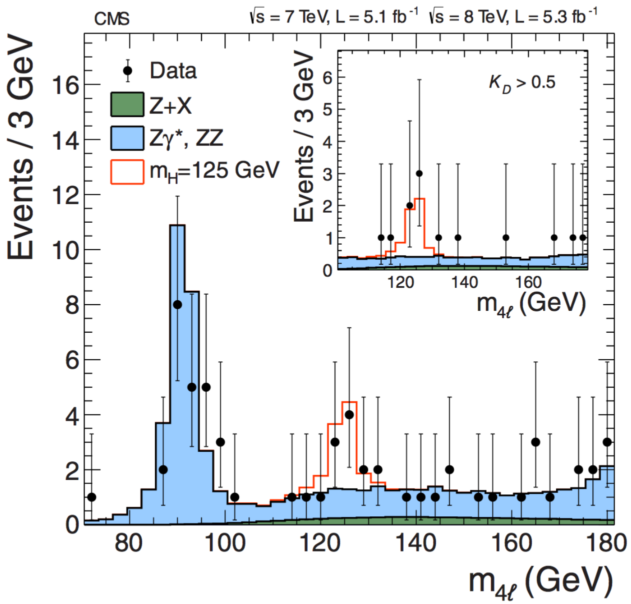


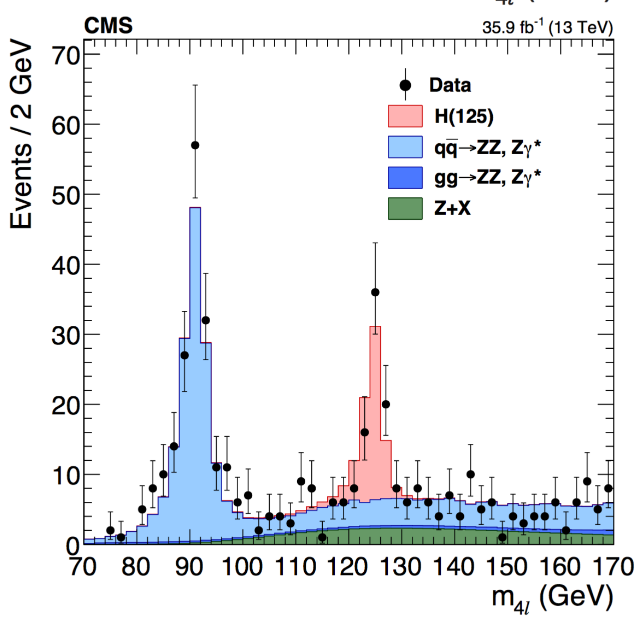
Inclusive, fiducial, differential, and
template cross section measurements

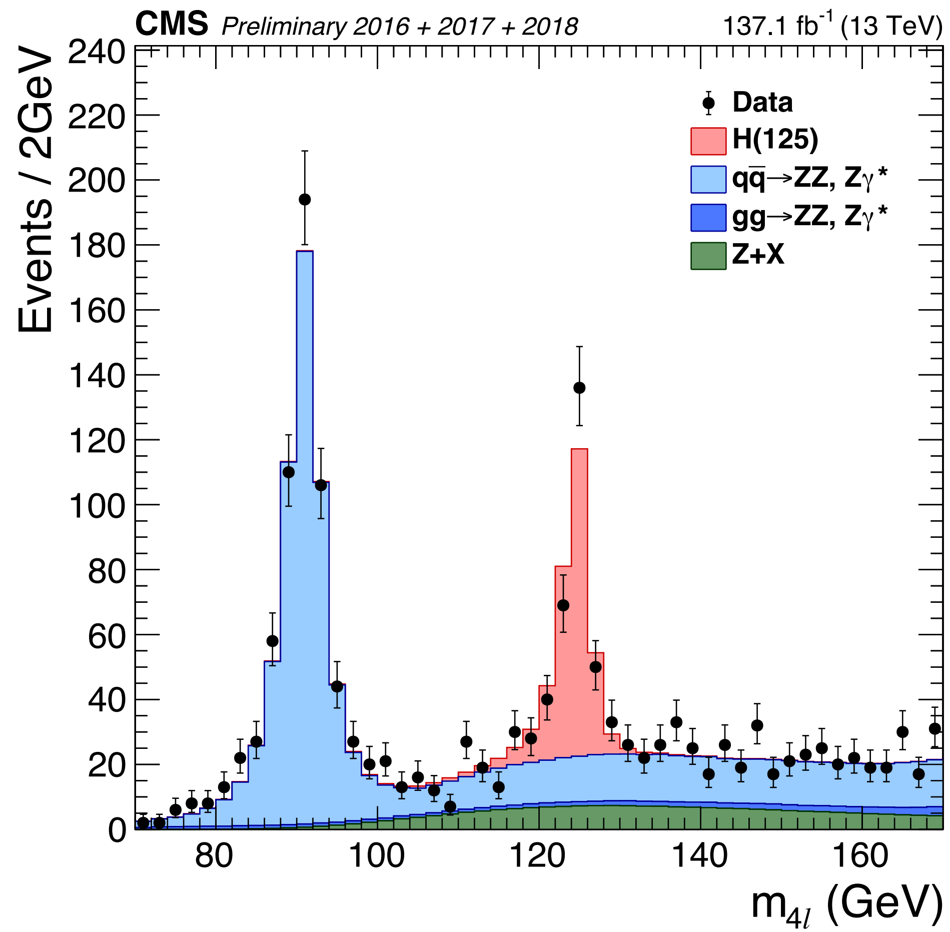


Overall σ(obs) / σ(SM) $= 1.04^{+0.09}_{-0.08}(\text{stat.})^{+0.04}_{-0.03}(\text{exp.})^{+0.06}_{-0.05}(\text{th.}) = 1.04^{+0.12}_{-0.10}$

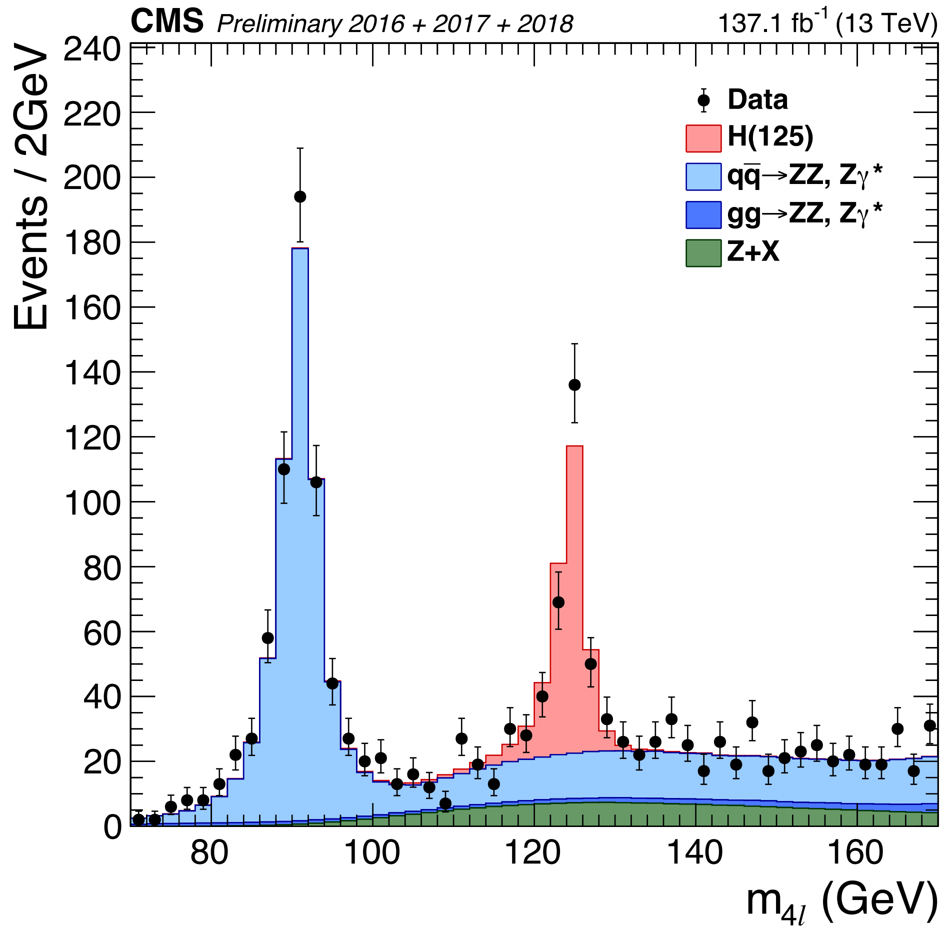
…and since it is so beautiful

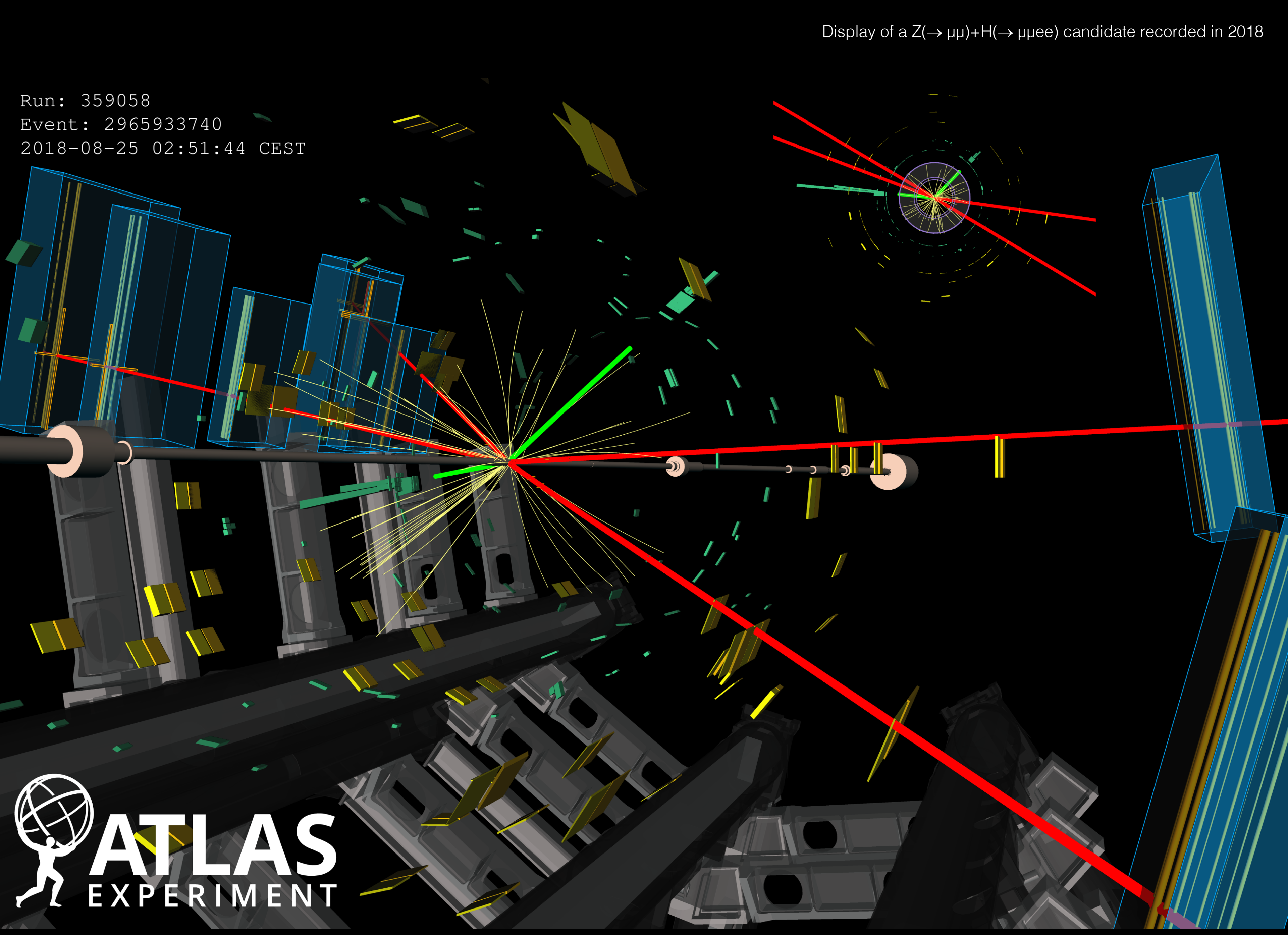




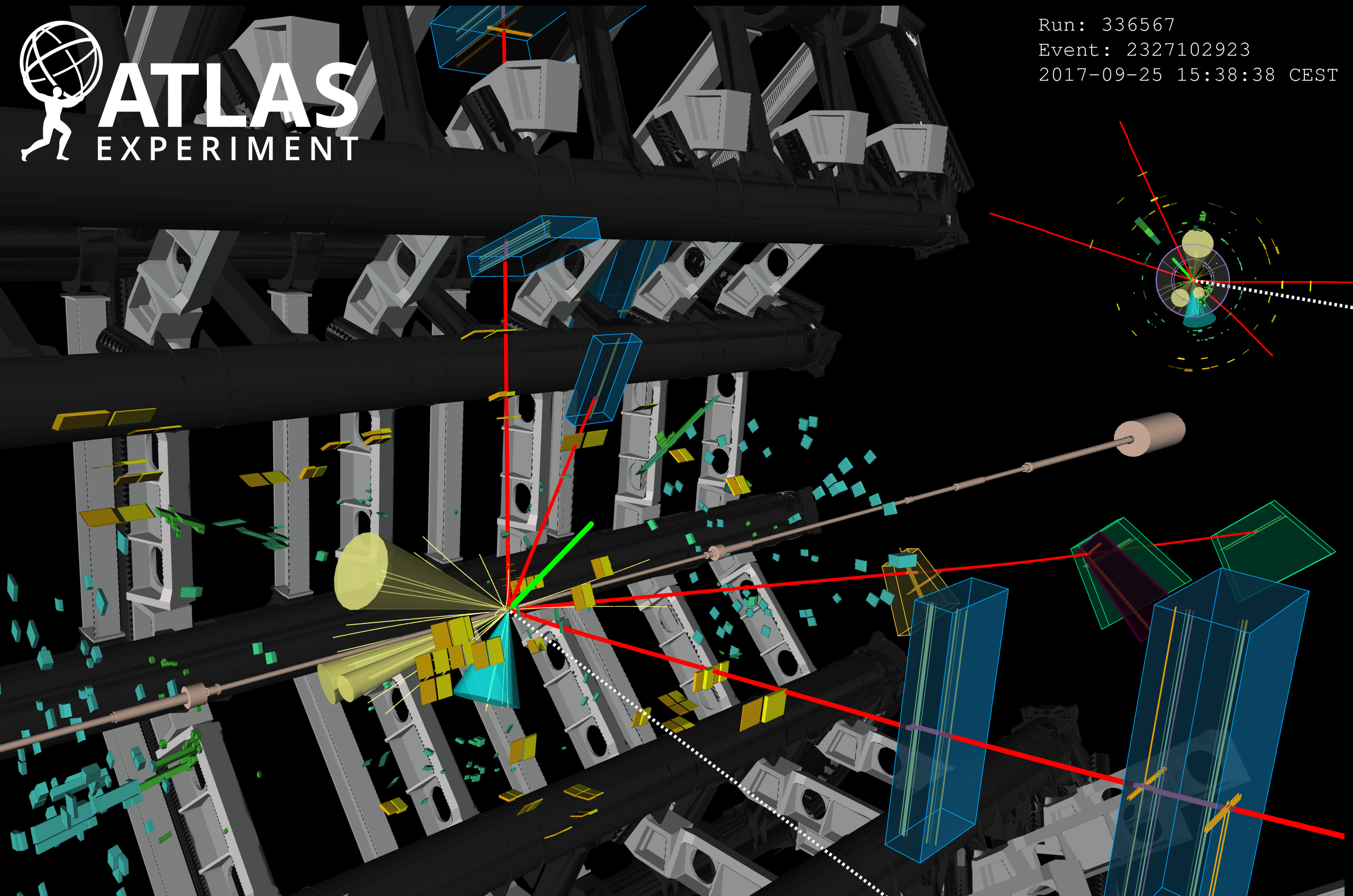


CMS: HIG-19-001




Display of a Z(→ μμ)+H(→ μμee) candidate recorded in 2018
Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST
ATLAS
EXPERIMENT

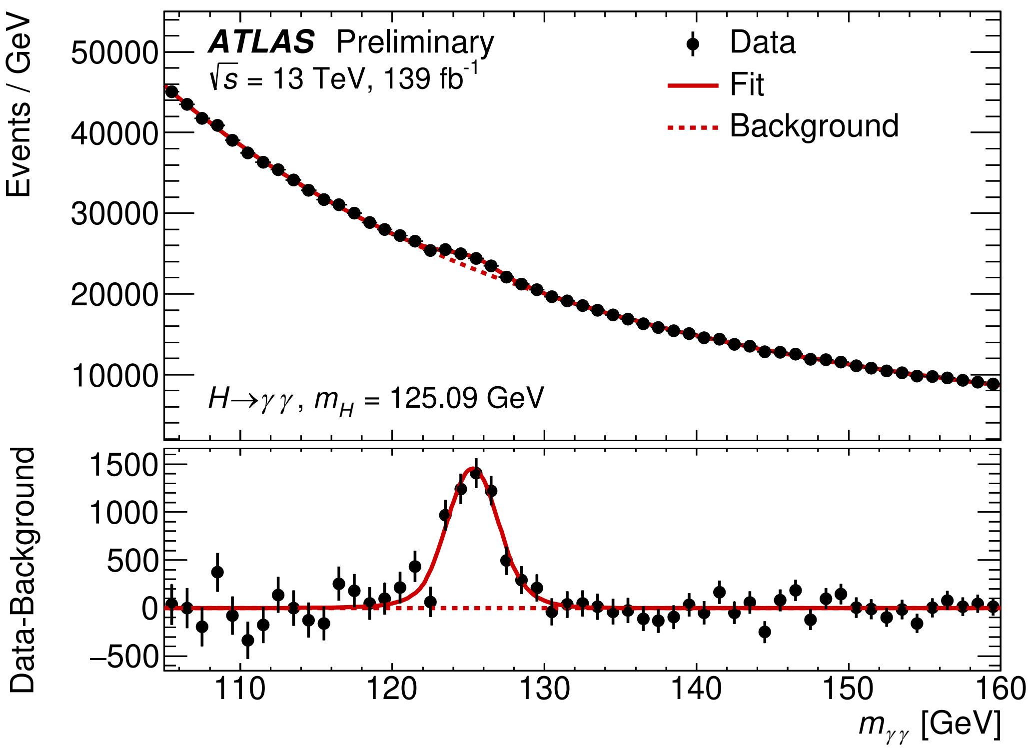
Display of a tt(→ e+jets)+H(→ μμμμ) candidate recorded in 2017
Expected S/B of ~ 30



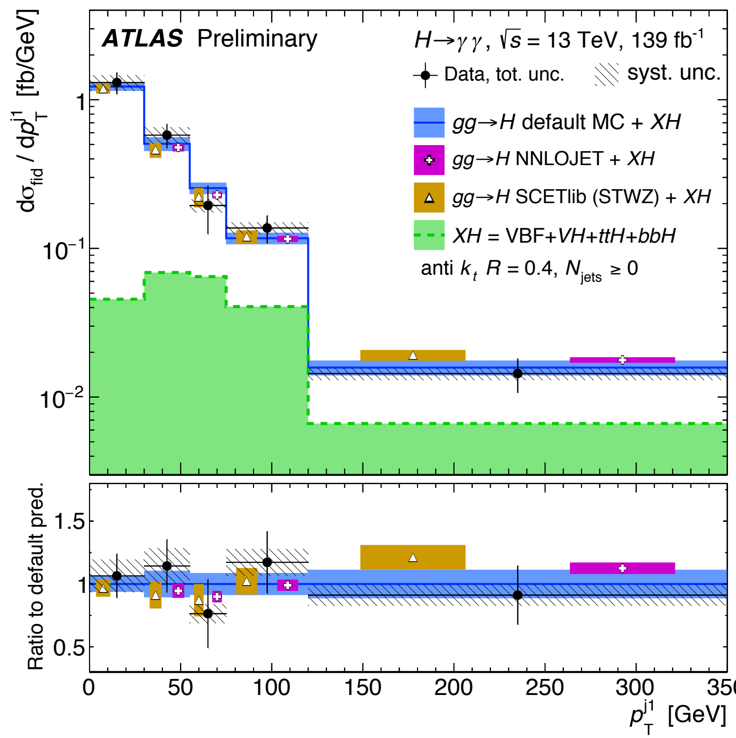
Cross section measurements in diphoton channel

Find 6550 pp → H → $\gamma\gamma$ signal events in full Run-2 dataset
Rich sample to study details of Higgs production and constrain new physics

ATLAS-CONF-2019-029



Raw spectrum, no categories, no weighting — beautiful Higgs boson signal

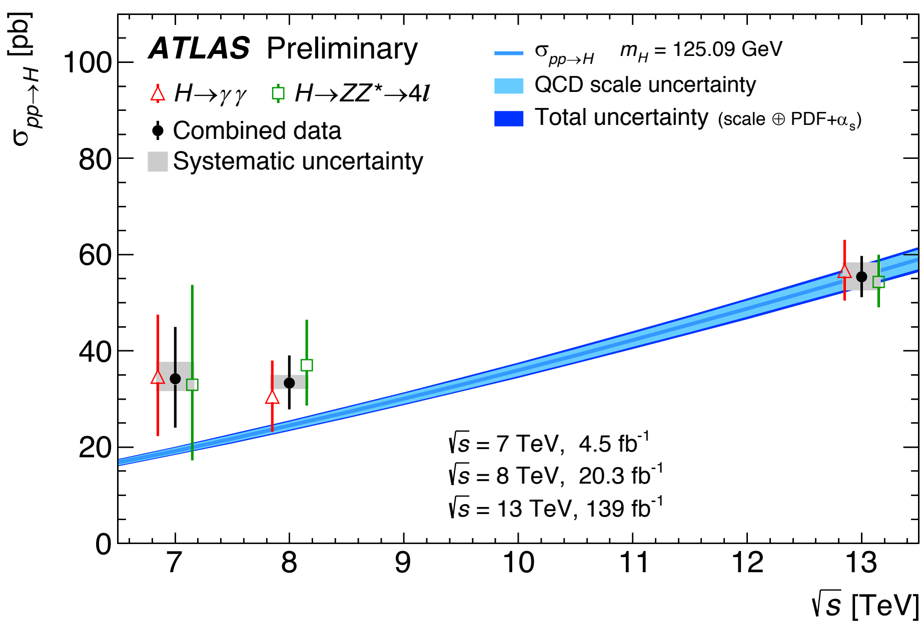


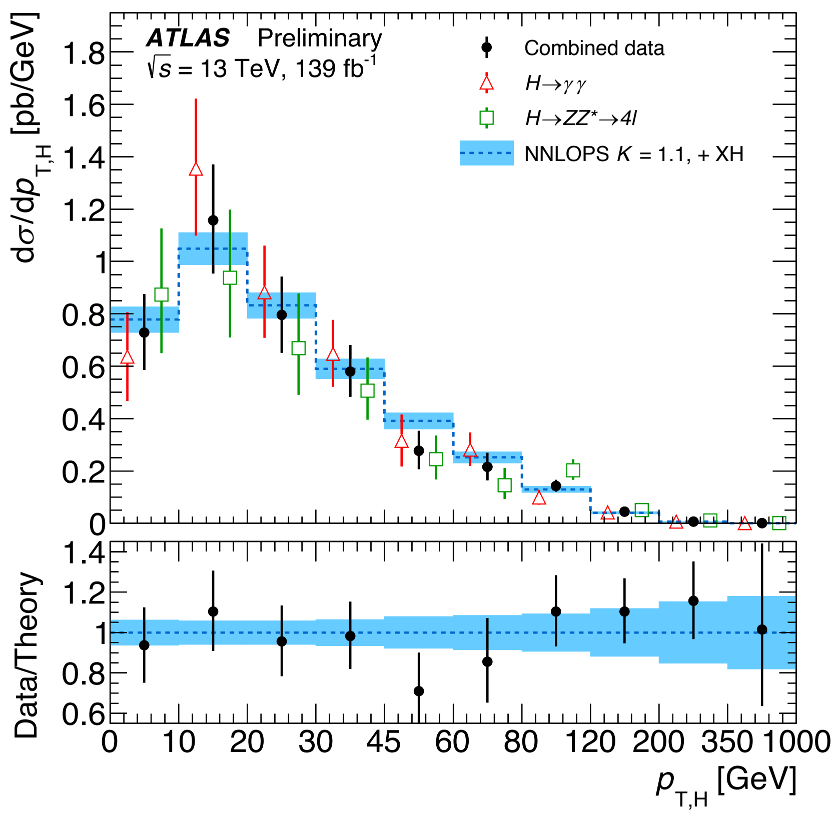
Differential cross section measurement. Results used to constrain EFT parameters and charm Yukawa coupling

Fiducial cross section $\sigma_{fid} = 65.2 \pm 4.5_{stat} \pm 5.6_{syst} \pm 0.3_{theo}$ fb (SM: 63.6 ± 3.3 fb)

Statistical combination for total and differential cross section measurements

ATLAS-CONF-2019-032





Combined inclusive pp → H + X cross section:

$$\sigma(pp \to H) = 56.7\,^{+6.4}_{-6.2}(\gamma\gamma),\ 54.4\,^{+5.6}_{-5.4}(4\ell),\ 55.4\,^{+4.3}_{-4.2}(\text{comb})\ \text{pb}$$

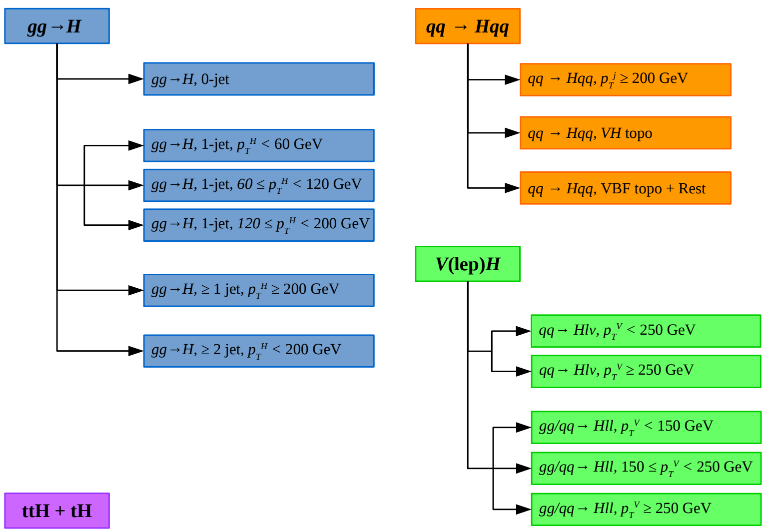
(7.8%)

SM: 55.6 ± 2.5 pb (NLO–3NLO QCD, NLO EW)

Combined measurement of simplified template cross sections (STXS)

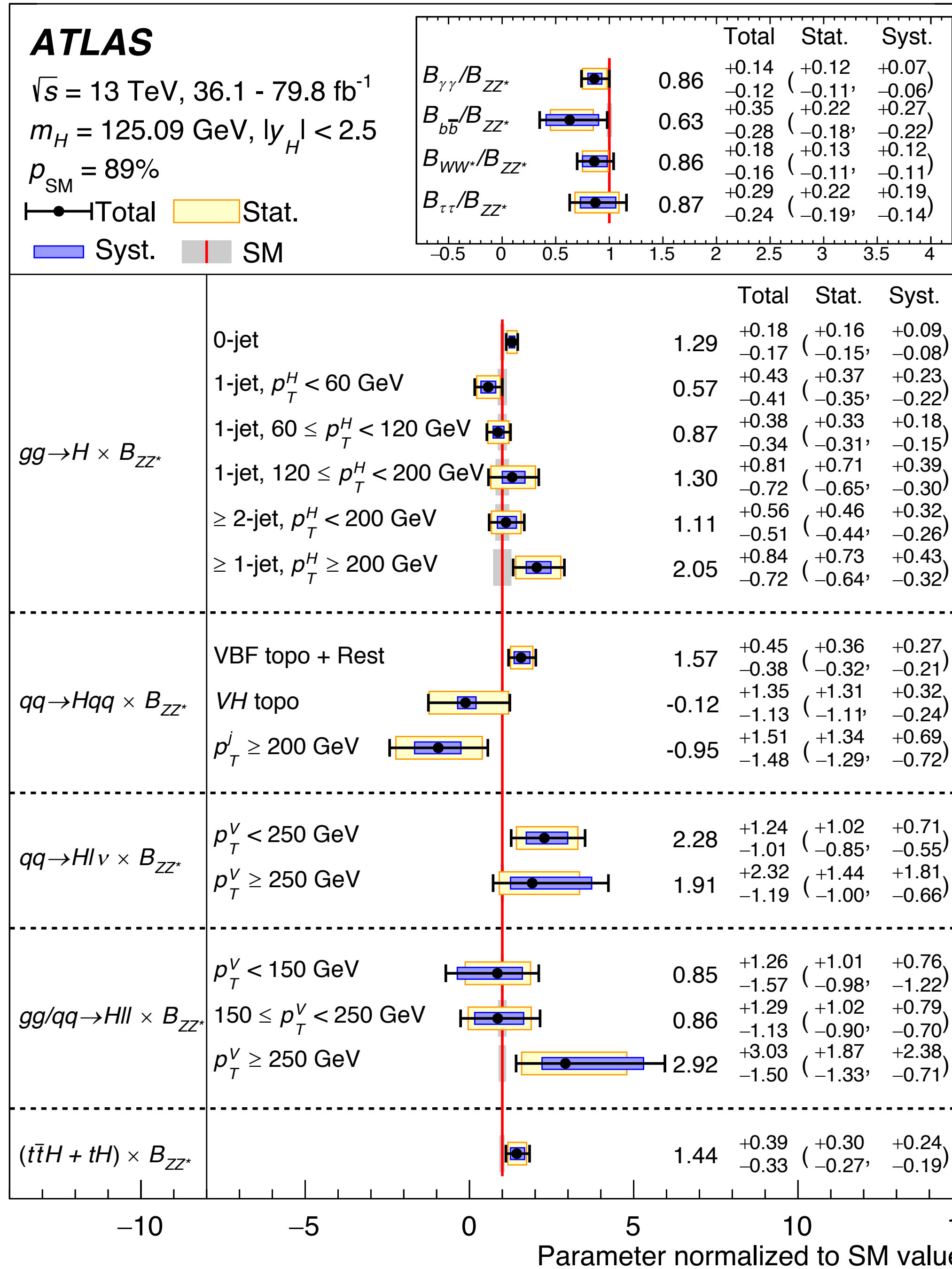
STXS allow to combine different channels in well defined phase space regions* with reduced theory input

*incl. regions sensitive to new physics (such as high p_T) that might not manifest itself in total cross-section



Definition of "Stage-1" STXS used in the analysis

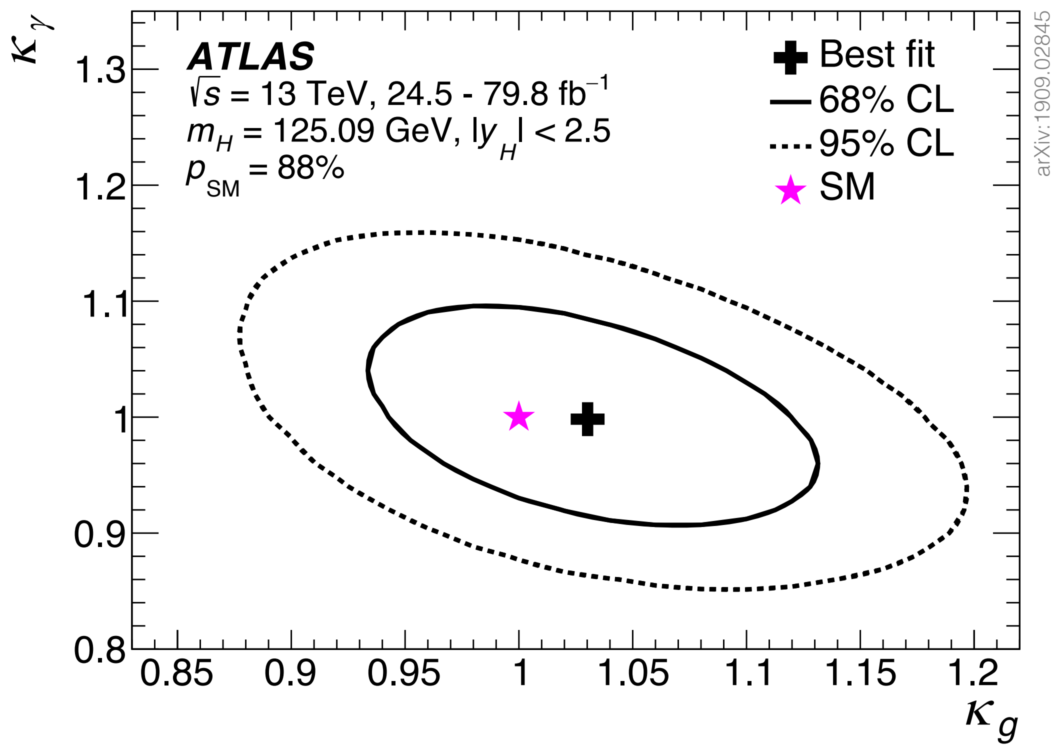
arXiv:1909.02845

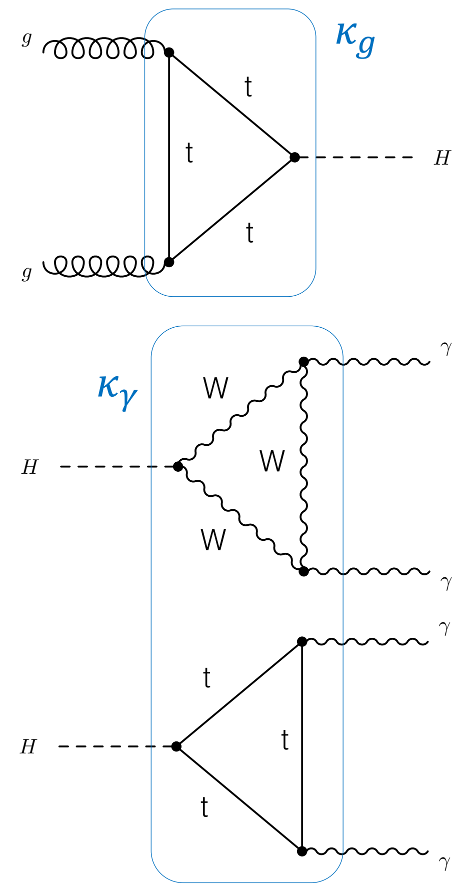


Note: 36–80/fb analyses here and next page !

Strong constraints on new physics via loops

- Coupling modifiers: κ = κ(exp) / κ(SM), modifier ratios: $\lambda_{ab} = \kappa_a / \kappa_b$





Most model-independent coupling ratios, independent of Higgs width

λ_{tg}	$1.10^{+0.15}_{-0.14}$	$\lambda_{\gamma Z}$	0.94 ± 0.07
λ_{Zg}	$1.12^{+0.15}_{-0.13}$	$\lambda_{\tau Z}$	0.95 ± 0.13
λ_{WZ}	0.95 ± 0.08	λ_{bZ}	$0.93^{+0.15}_{-0.13}$

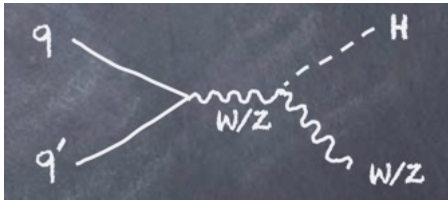
Couplings to massless particles mediated by loops involving heavy particles

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

Higgs boson coupling to (lighter) 2nd generation fermions

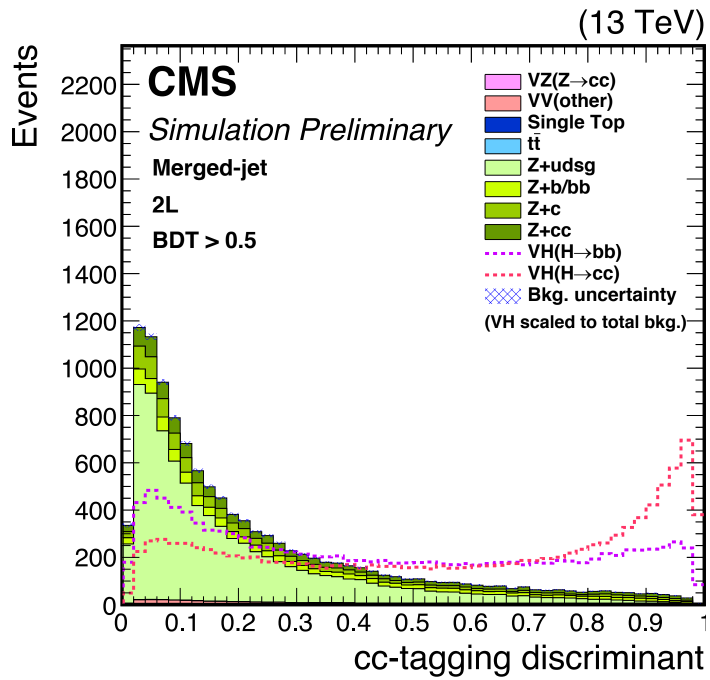
Search for VH(→ cc), new result from CMS, significantly improved over previous ATLAS limit

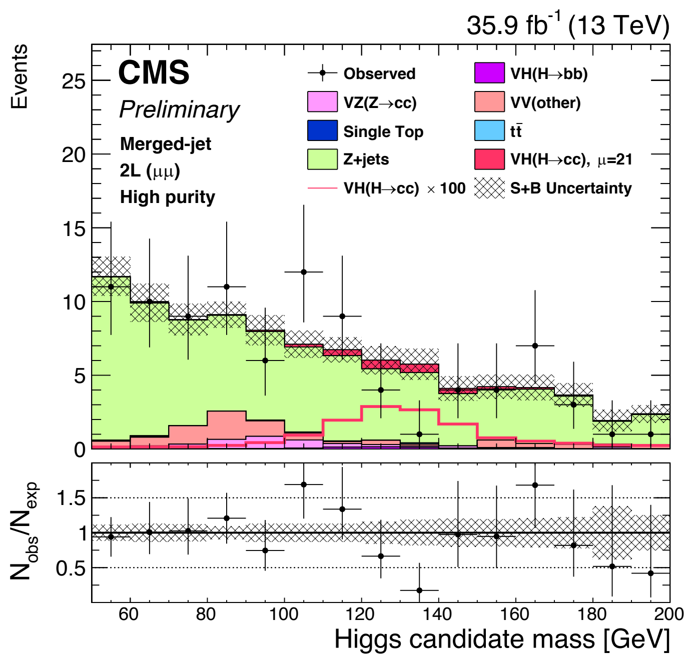
BR: 2.9% → 20 times smaller than bb, so need to worry about H → bb background



Challenging due to low cross section and need for c-tagging

- Categorisation according to charged-lepton multiplicity of V decays (0,1,2L)
- Use and combination of of resolved (2c) and merged (1 large-R cc) jets
- Use of ML and jet substructure for tagging and classification





CMS-PAS-HIG-18-031

Combined 95% CL upper limit:

$\sigma \times BR / SM < 70$

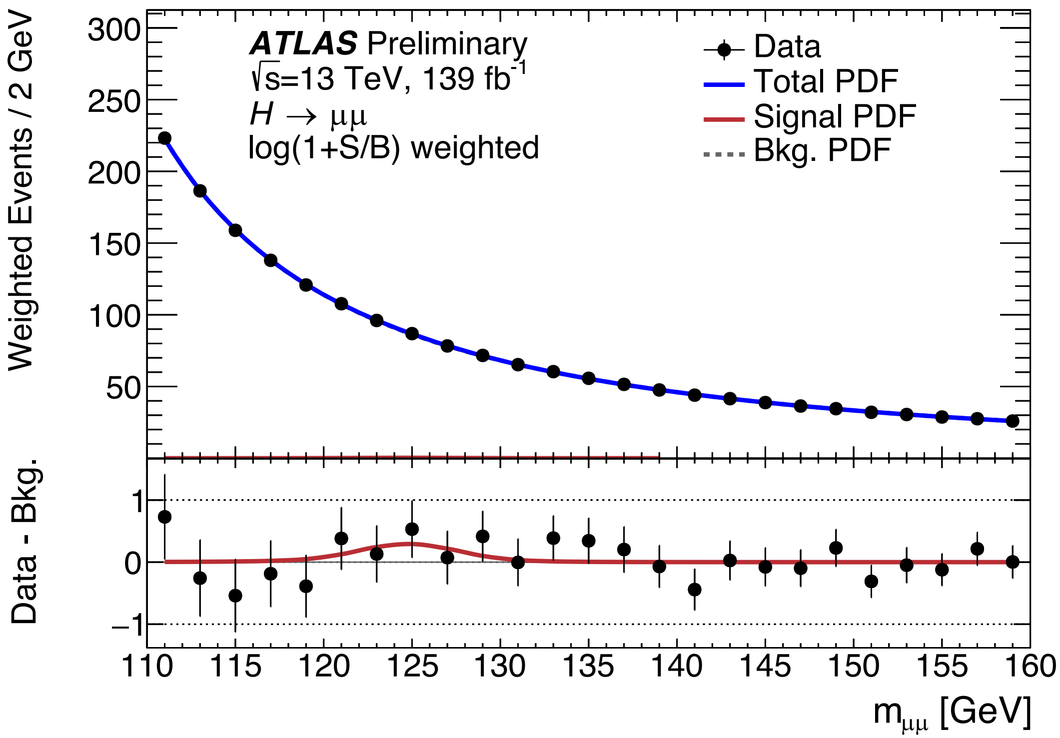
(37^{+16}_{-11} expected)

Higgs boson coupling to (lighter) 2nd generation fermions

More promising than charm: $H \to \mu\mu$, but challenging due to huge $Z/\gamma^* \to \mu\mu$ background

Analysis strongly exploits expected features of signal and background via specific categories and BDTs
Robust empirical background modelling, “spurious signal” systematics using huge MC samples

ATLAS-CONF-2019-028



$\sigma(\text{obs}) / \sigma(\text{SM}) = 0.5 \pm 0.7$
< 1.7 at 95% CL

Sensitivity: 0.8σ, for 1.5σ expected

Current sensitivity from CMS (36/fb):
0.9σ observed for 1.0σ expected
arXiv:1807.06325

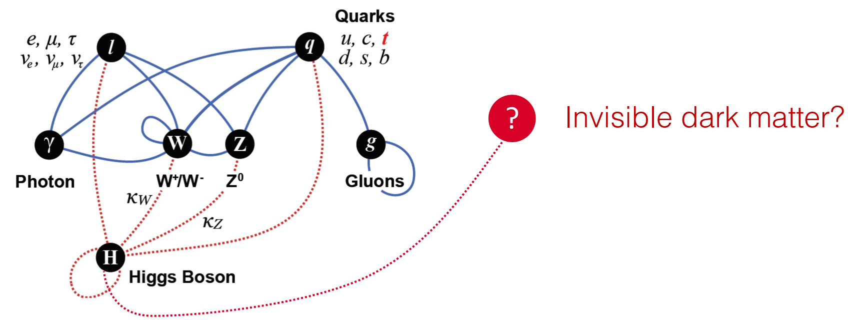
Expect roughly 1.4 times better sensitivity for CMS owing to stronger solenoid field

50% sensitivity improvement over 2018 (80 fb^{-1}) analysis

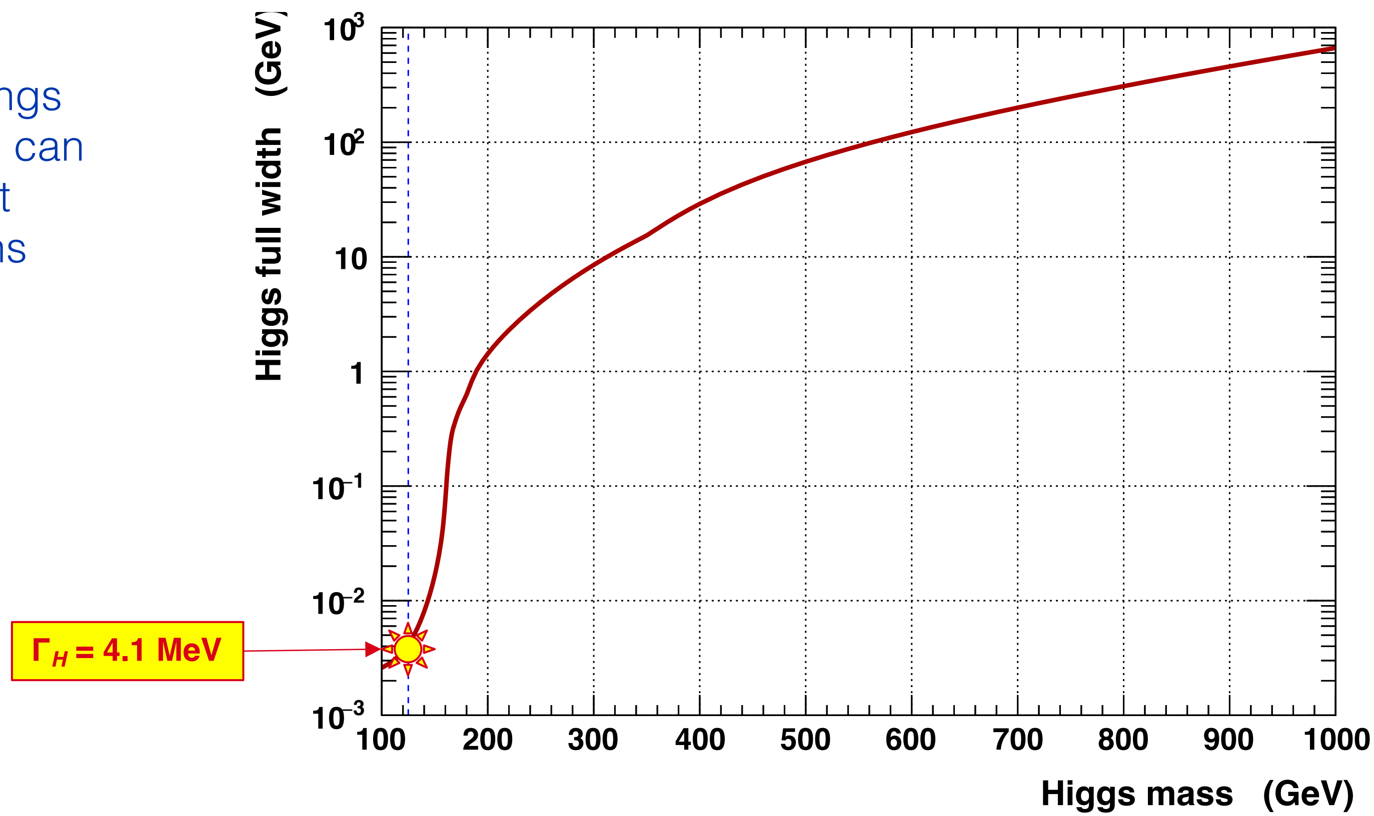
Higgs is narrow: 4.1 MeV

For comparison:

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

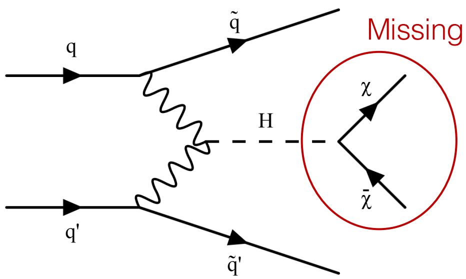


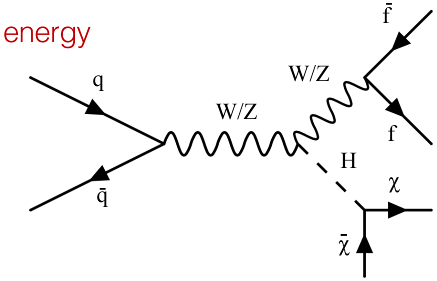
Even small couplings to new light states can measurably distort branching fractions

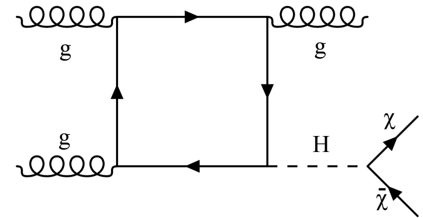


Search for dark matter through invisibly decaying Higgs

Invisible Higgs decays can be probed by associated production (VBF, VH, …)



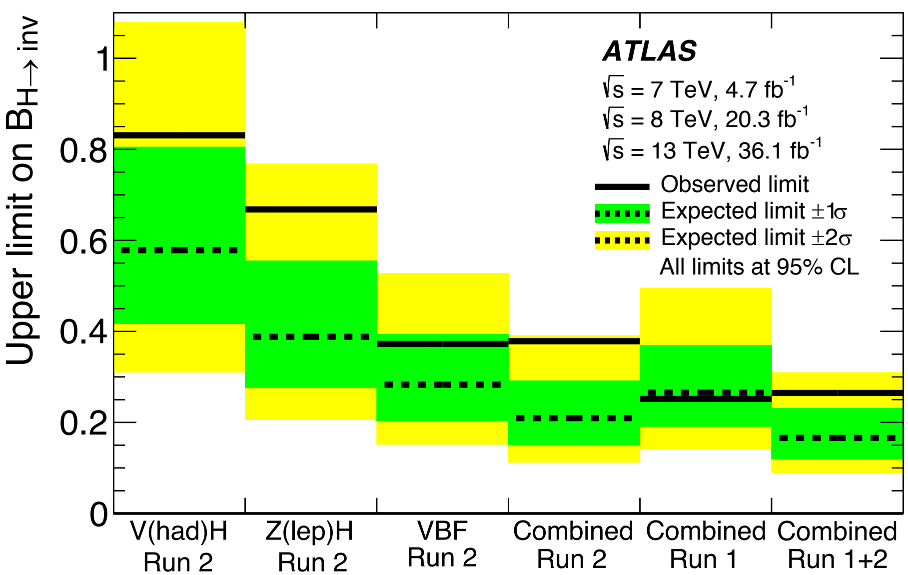




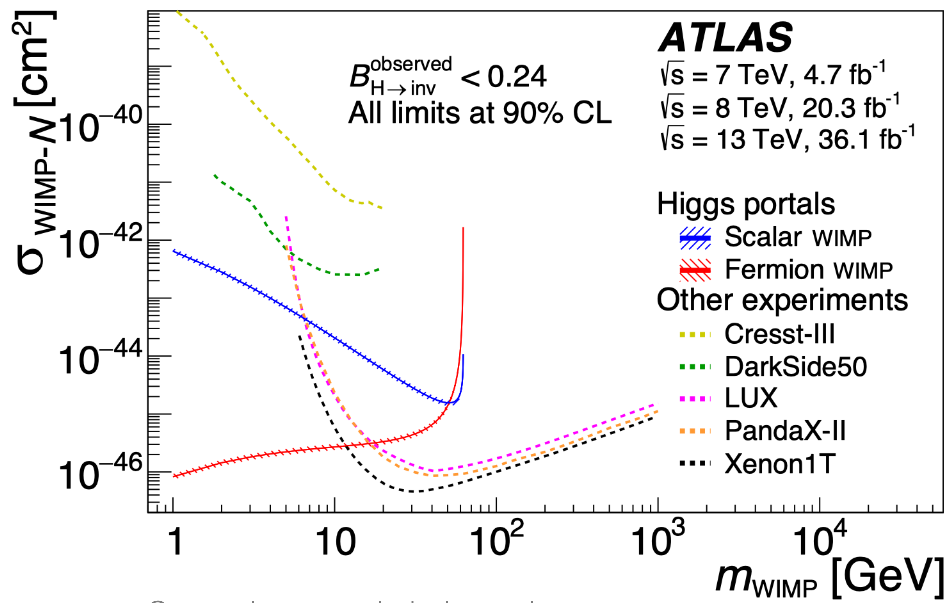
Sensitivity to WIMP mass < m_H / 2, complementary to direct dark matter searches

ATLAS Run 1+2 combination:

arXiv:1904.05105



BR(H → invisible) < 0.26 (0.17 $^{+0.07}_{-0.05}$ expected)

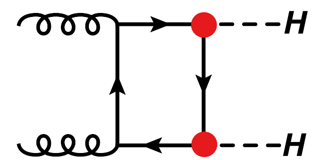


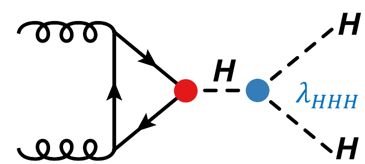
Constraints on spin-independent WIMP-nucleon scattering cross section (used: f_N = 0.308 ± 0.018)

Di-Higgs production

HH ggF cross section predicted to 34 fb at 13 TeV, >1000 times smaller than single Higgs production

Sophisticated analyses needed, room for innovation
Best channels: bb$\gamma\gamma$ (BR = 0.26%), bb$\tau\tau$ (7.3%), bbbb (34%)
$\rightarrow$ combination





$$\lambda_{HHH} = \frac{m_H^2}{2v^2} \sim 0.13$$

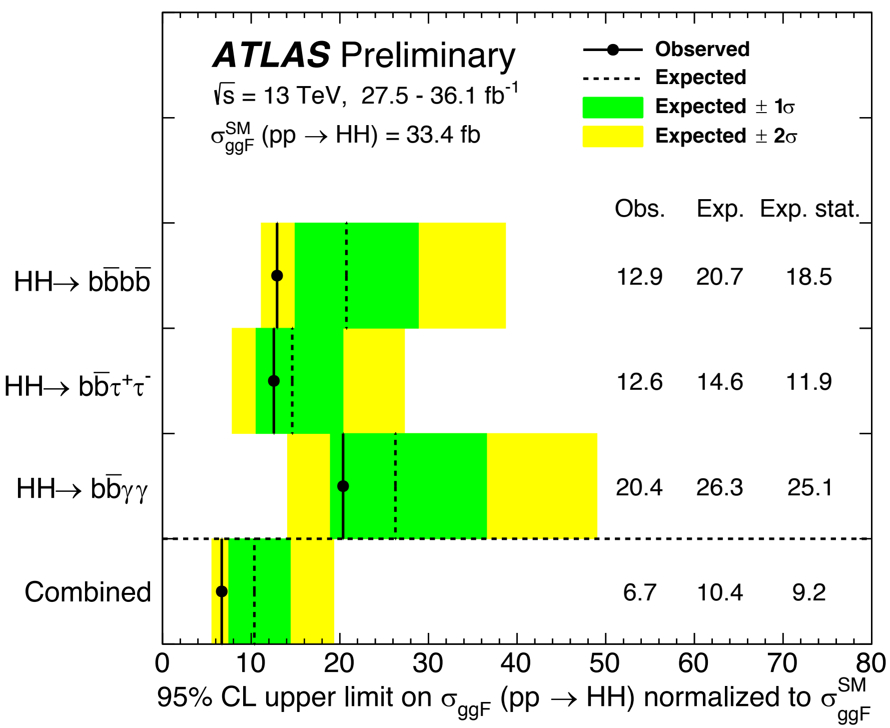
LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

Sensitivity to H self-coupling rises at low m_{HH}

ATLAS combination using 36 fb^{-1} analyses:

ATLAS-CONF-2018-043

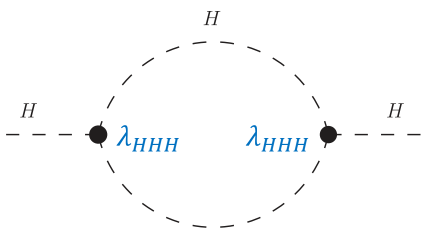


Combined fit yields 95% CL allowed range:

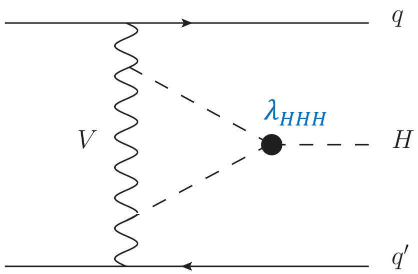
$$-5.0 < \frac{\lambda_{HHH}(\mathrm{obs})}{\lambda_{HHH}(\mathrm{SM})} < 12.1$$

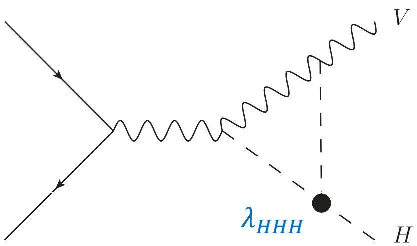
Indirect constraints on Higgs self coupling through loops

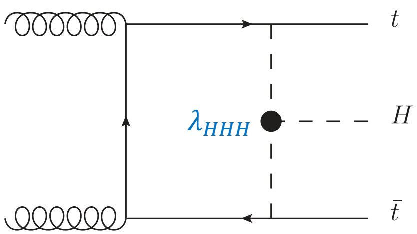
Higgs self coupling also occurs in electroweak loops contributing to Higgs production



Higgs self energy contributing to, eg, ggF Higgs production



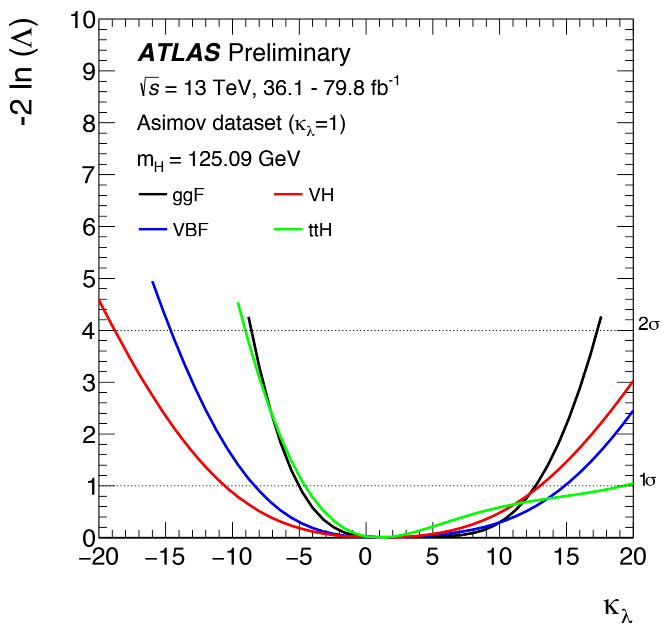


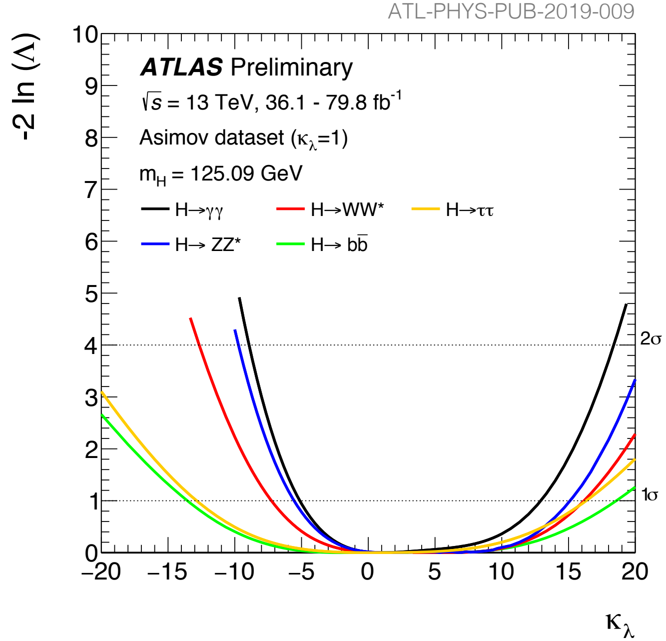


ATL-PHYS-PUB-2019-009

Gobal fit of λ_{HHH} in NLO corrections to combined Higgs STXS measurements assuming no other new physics present

$$-3.2 < \frac{\lambda_{HHH}(\text{obs})}{\lambda_{HHH}(\text{SM})} < 11.9$$

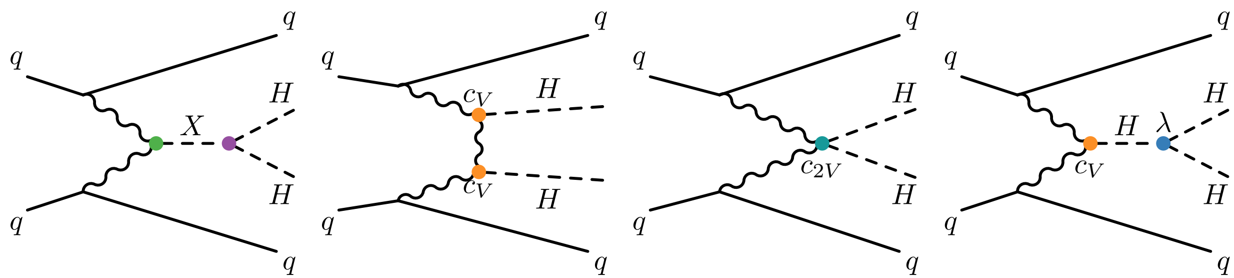




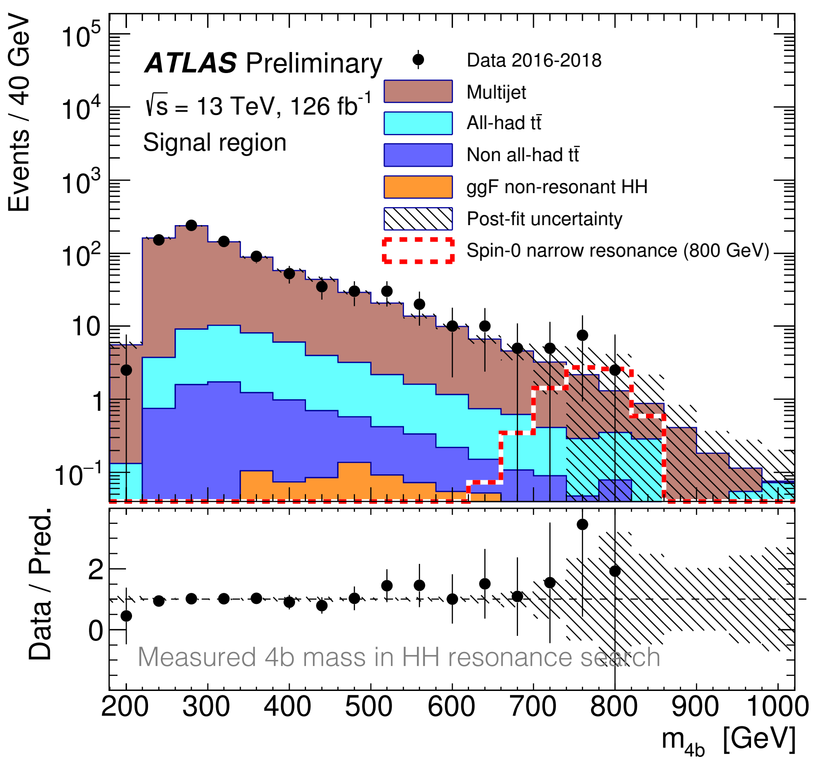
Constraining the VVHH coupling

Search for HH production in 4b channel through VBF

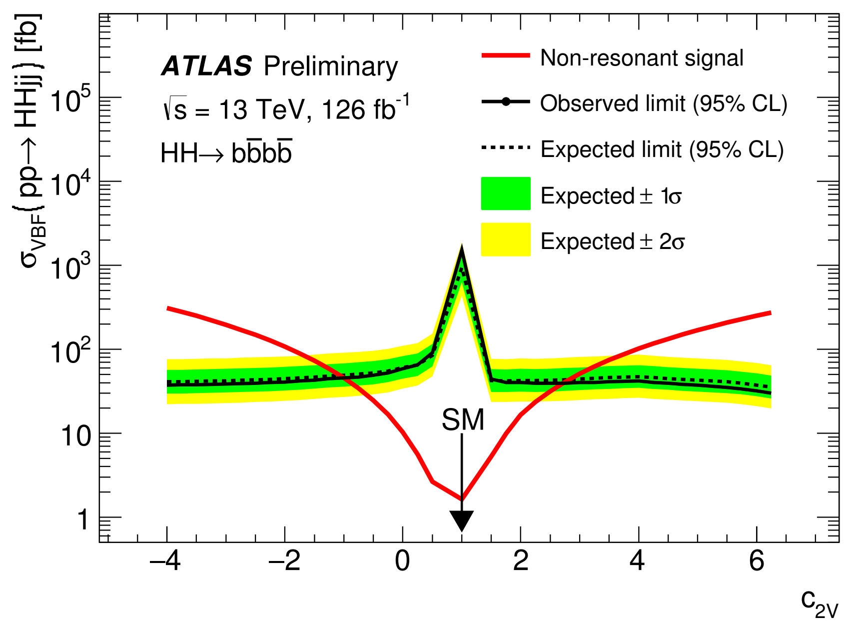
Backgrounds from data using m_{bb} sidebands



ATLAS-CONF-2019-030



SM: $\lambda = c_V = c_{2V} = 1$



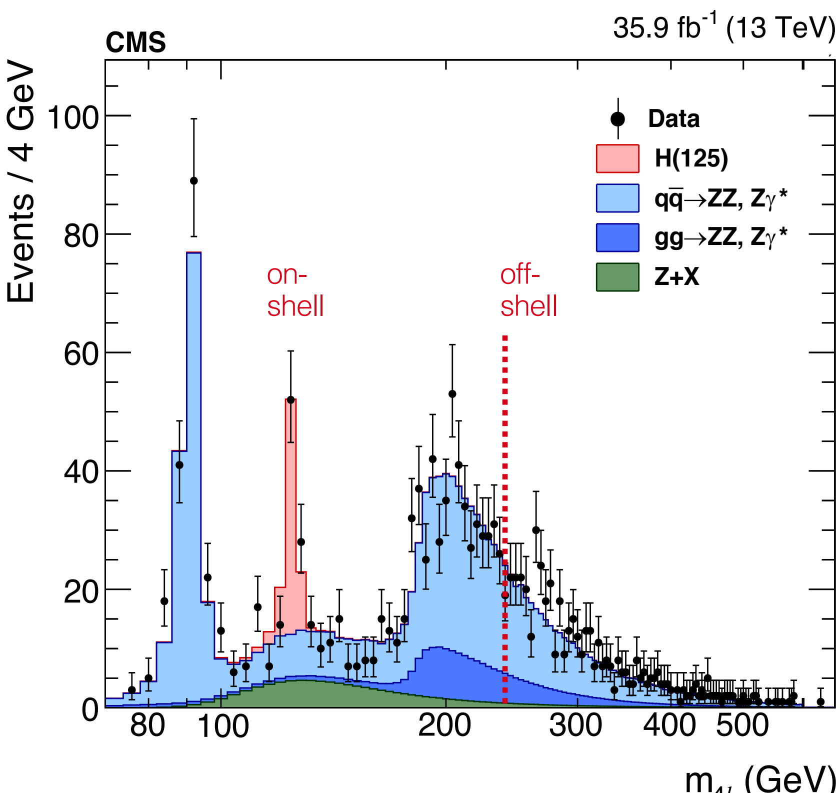
95% CL limits $-1.0 < c_{2V} < 2.7$ (non-resonant search)

Limit on non-resonant search of 2.0 pb (SM: 1.7 fb)

Constraining the Higgs boson width

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 from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



arXiv:1706.09936
(for illustration only, not the measurement reported here)

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

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

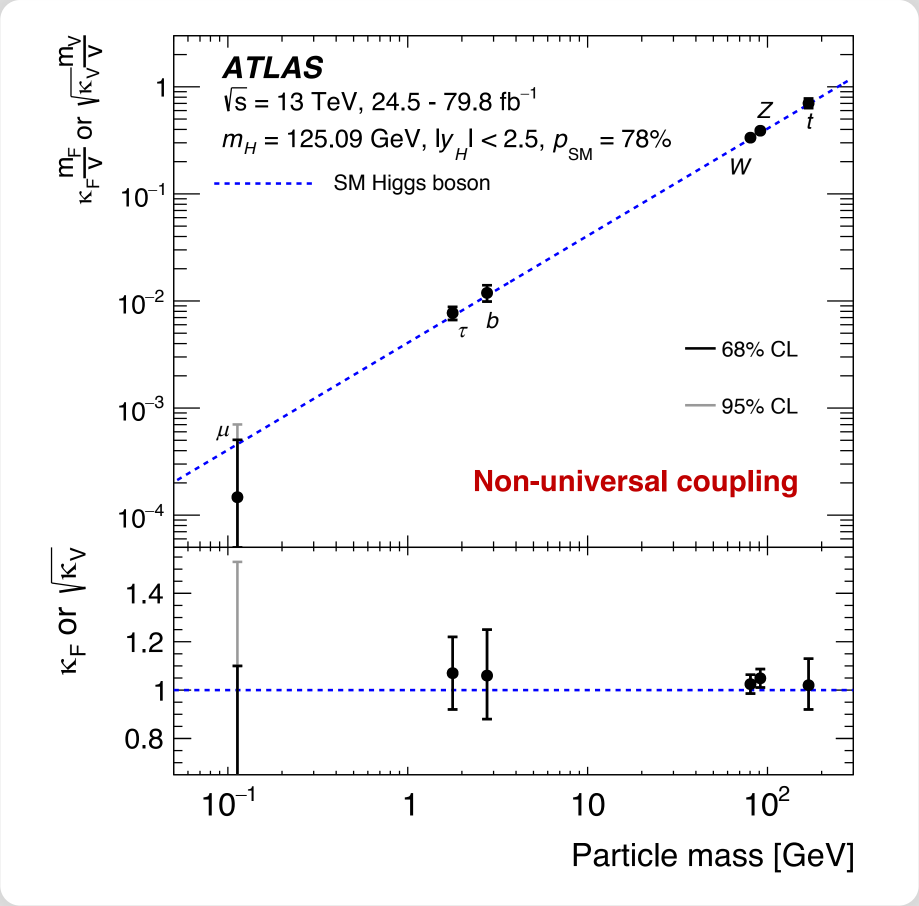
Newest result from CMS using 80/fb and exploiting matrix element techniques to separate production modes yields: arXiv:1901.00174

$\Gamma_H < 9.2$ MeV at 95% CL ($\Gamma_{H,SM} = 4.1$ MeV)

Best fit: $\Gamma_H = 3.2\ ^{+2.8}_{-2.2}$ MeV

Theory uncertainty from gg → ZZ prediction

The Brout-Englert-Higgs mechanism is real !



The scalar sector is directly connected with profound questions: naturalness, vacuum stability & energy, flavour

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

The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades

And the Higgs boson does more …

The electroweak sector needs the Higgs boson

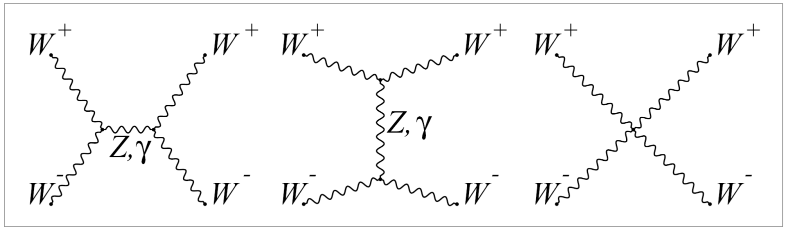
Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

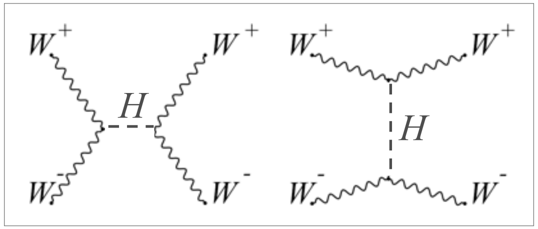
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

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

Higgs boson restores unitarity of total amplitude:

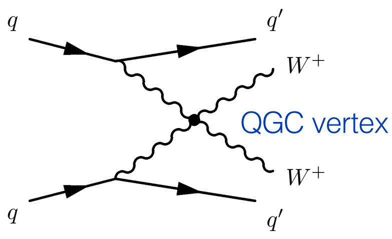
$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$



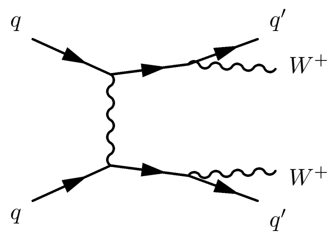


m_H must not be too large (which is fulfilled)

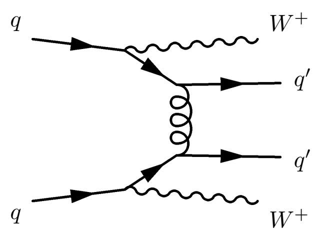
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

The electroweak sector needs the Higgs boson

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

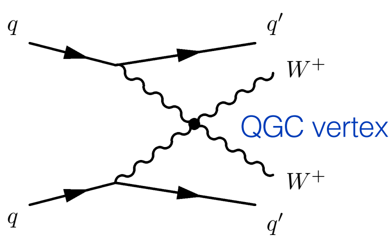
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

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

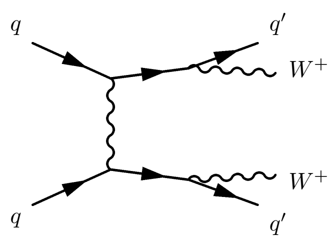
Higgs boson restores unitarity of total amplitude:

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

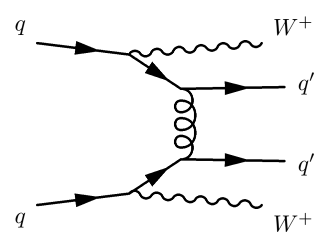
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



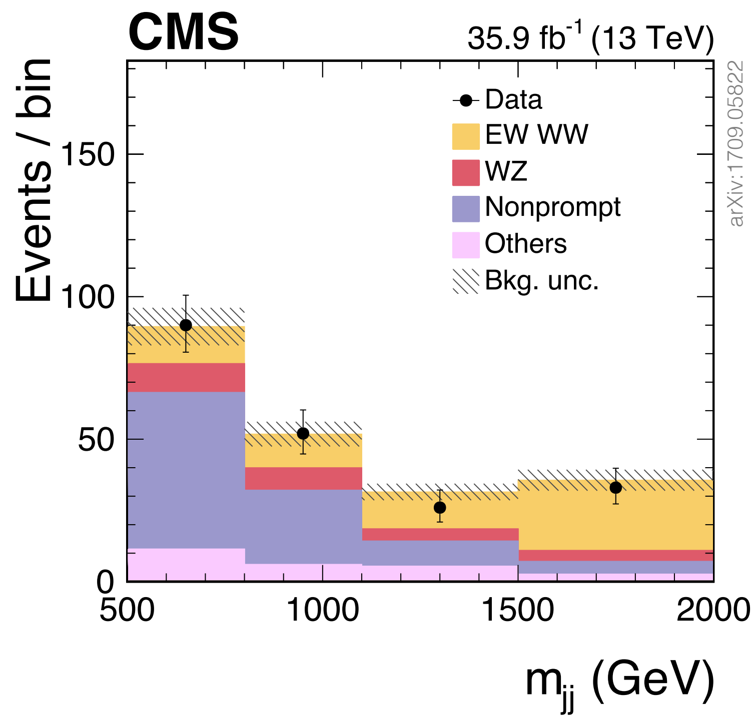
EW VBS production



Non-VBS production



Strong production



Look for VBS scattering in high dijet invariant mass distributions

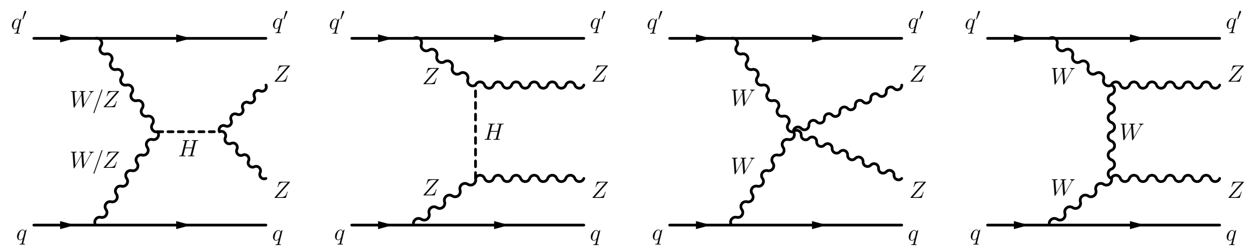
CMS & ATLAS observed vector boson scattering in WWjj at > 5σ (ATLAS also in WZ channel)

arXiv:1906.03203, arXiv:1812.09740

Observation of Electroweak ZZ+jj production

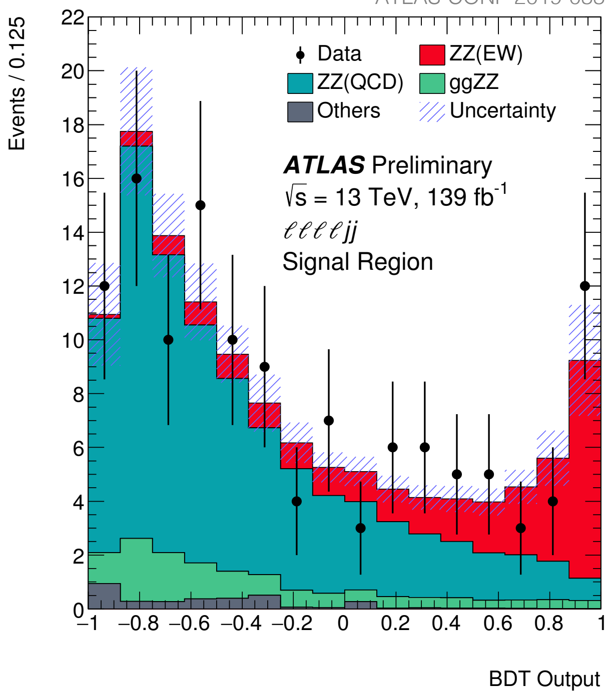
This completes observation of weak boson scattering, and sparks new ways to test EWSB

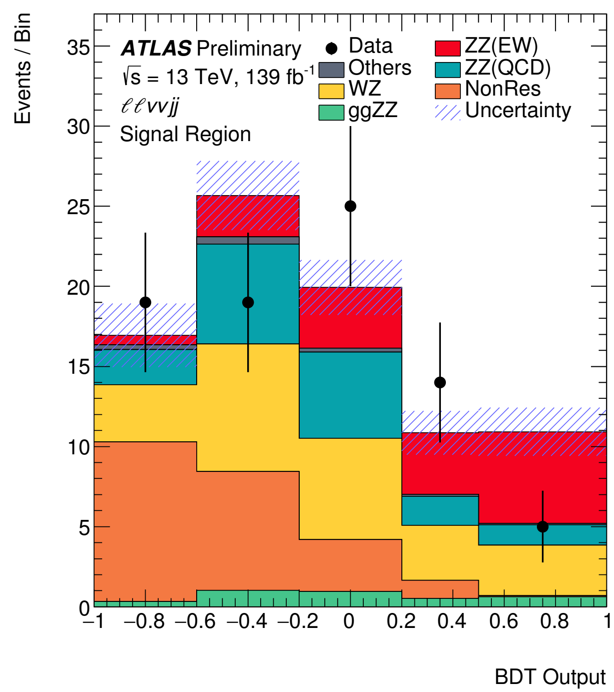
Very rare but clean mode using Z decays to charged leptons; exploit also Z $\rightarrow \nu\nu$ decay



Multivariate analysis to separate EW signal from strong interaction background

ATLAS-CONF-2019-033





Observed (expected) significances for EW production: 5.5σ (4.3σ), dominated by 4ℓ channel

σ_{fid}(EW) = 0.82 ± 0.21 fb

SM: 0.61 ± 0.03 fb

CMS observes electroweak $Z\gamma$ + 2jets production in 36/fb with 4.7σ (5.5σ expected)

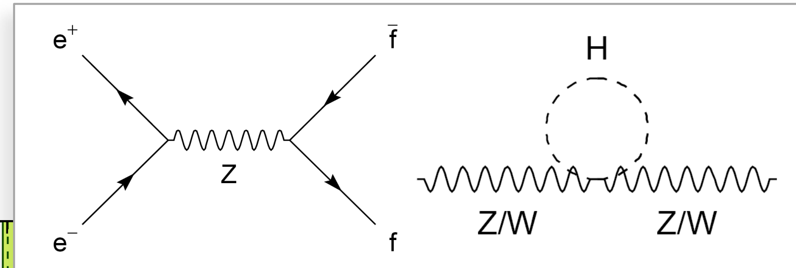
CMS-PAS-SMP-18-007

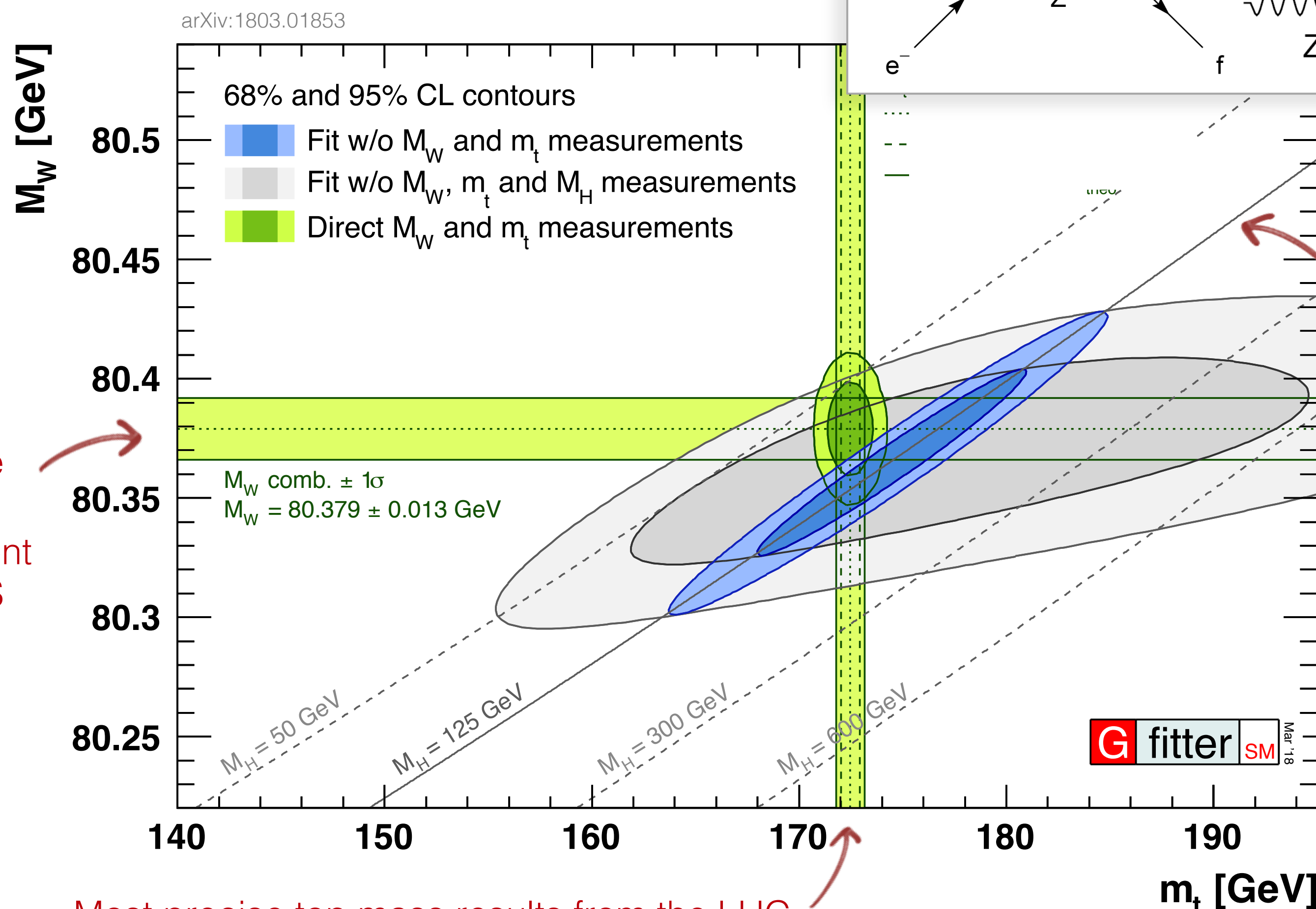
ATLAS-CONF-2019-039

The electroweak sector needs the Higgs boson

Global electroweak fit was masterpiece of LEP/SLD (e^+e^-) era

Discovery of Higgs over-constrains the fit and dramatically improves predictability





Competitive W mass measurement from ATLAS

Higgs boson mass from LHC

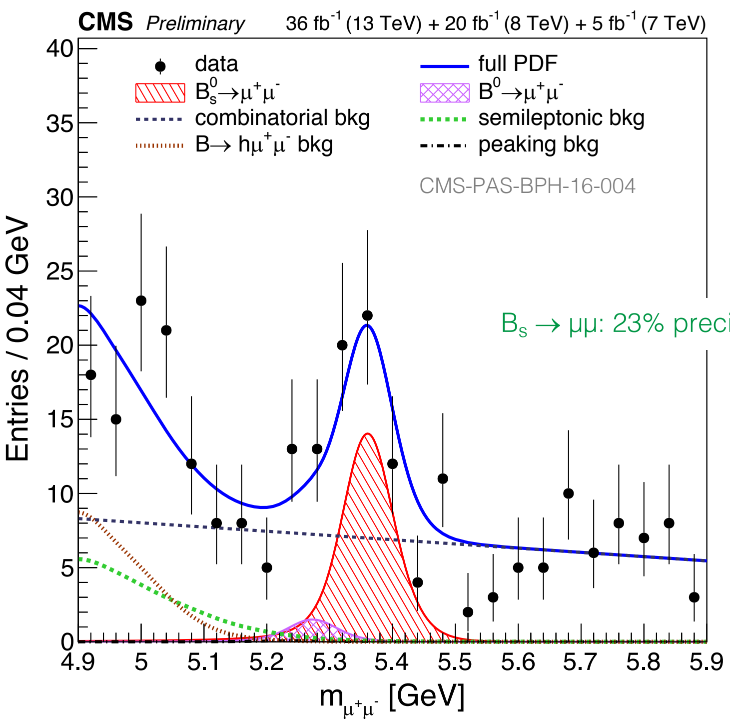
Also: precise measurement of $\sin^2\theta_{\text{eff}}$ (new result by ATLAS in 2018)

Most precise top mass results from the LHC

Flavour physics

Extremely rich spectrum of results from LHC — will not discuss spectroscopy here

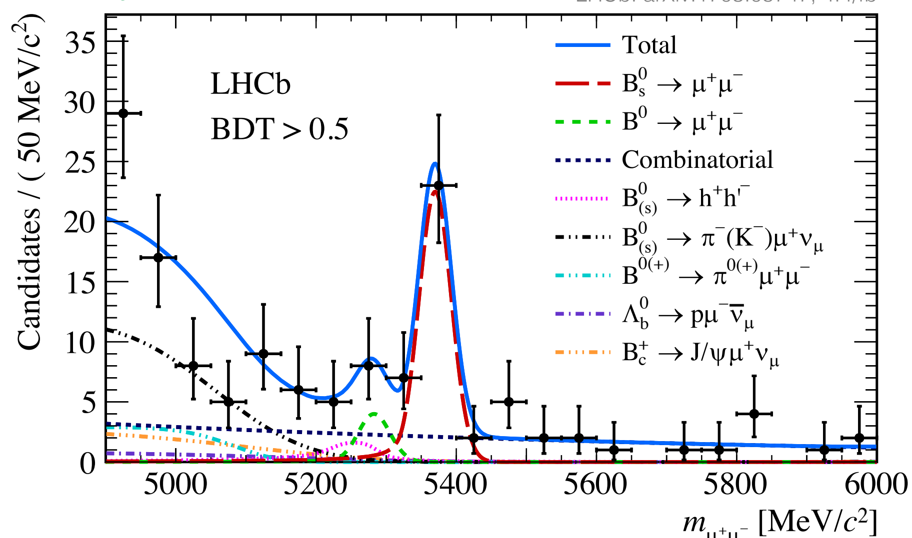
$B_{(s)} \to \mu\mu$ — recent result from CMS using 36/fb + reanalysis of and combination with Run-1



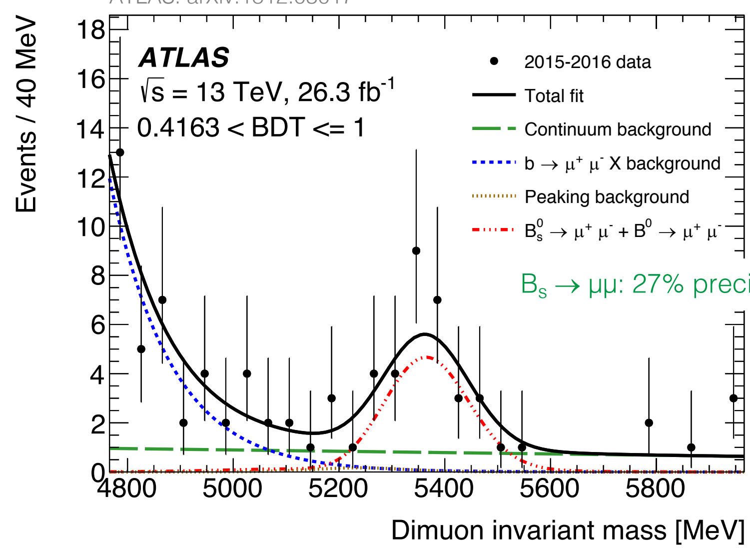
$B_s \to \mu\mu$: 23% precision

$B_s \to \mu\mu$: 22% precision

LHCb: arXiv:1703.05747, 4.4/fb



ATLAS: arXiv:1812.03017



$B_s \to \mu\mu$: 27% precision

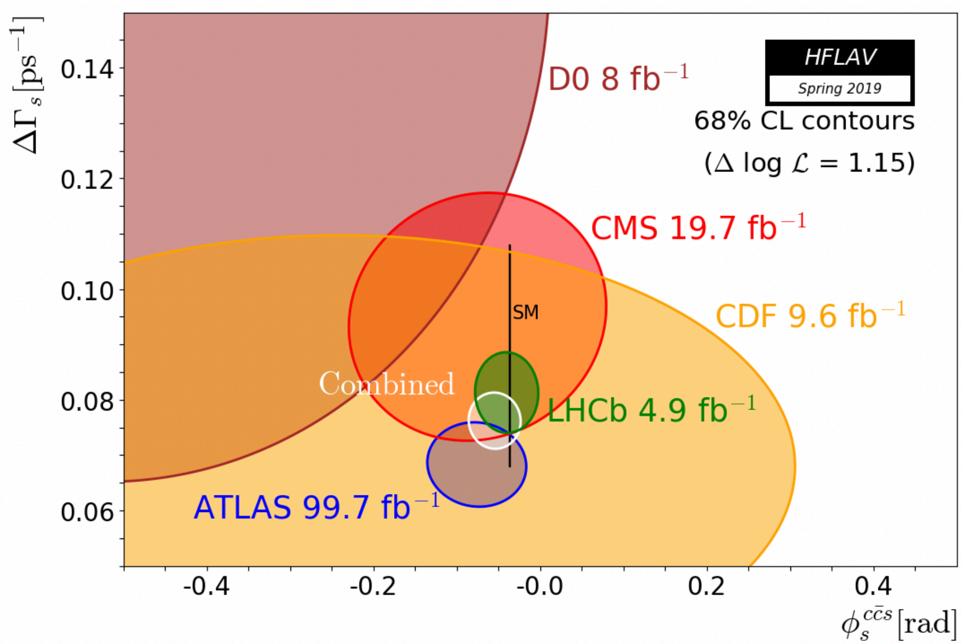
Plots show highest purity MVA bins

Branching faction results for both B flavours in agreement with SM predictions (for B_s: $3.6 \pm 0.2 \times 10^{-9}$)

Flavour physics

Extremely rich spectrum of results from LHC — will not discuss spectroscopy here

Recent ATLAS result on ϕ_s from $B_s \to J/\psi\phi$ (80/fb)



Combination (HFLAV group):

- ϕ_s = −0.055 ± 0.021 rad
- $\Delta\Gamma_s$ = 0.0764 ± 0.0034 ps^{-1}

SM prediction: ϕ_s = −0.036 ± 0.002 rad

Also: beautiful observation of CP violation in charm by LHCb, but hard to interpret (cf. ε'/ε)

Status of flavour anomalies:

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

(possible NP in charged current in tree diagram)

Anomaly reduced after recent Belle result [1904.08794] in agreement with SM

Remaining tension (HFLAV): 3.1σ

Corresponding $R_{J/\psi|\tau/\mu}$ ~2σ above SM [LHCb: 1711.05623]

$$R_{K^{(*)}} = \frac{B(B \to K^{(*)}\mu\mu)}{B(B \to K^{(*)}ee)} \cong 1$$

Exps measure double ratio involving J/ψ

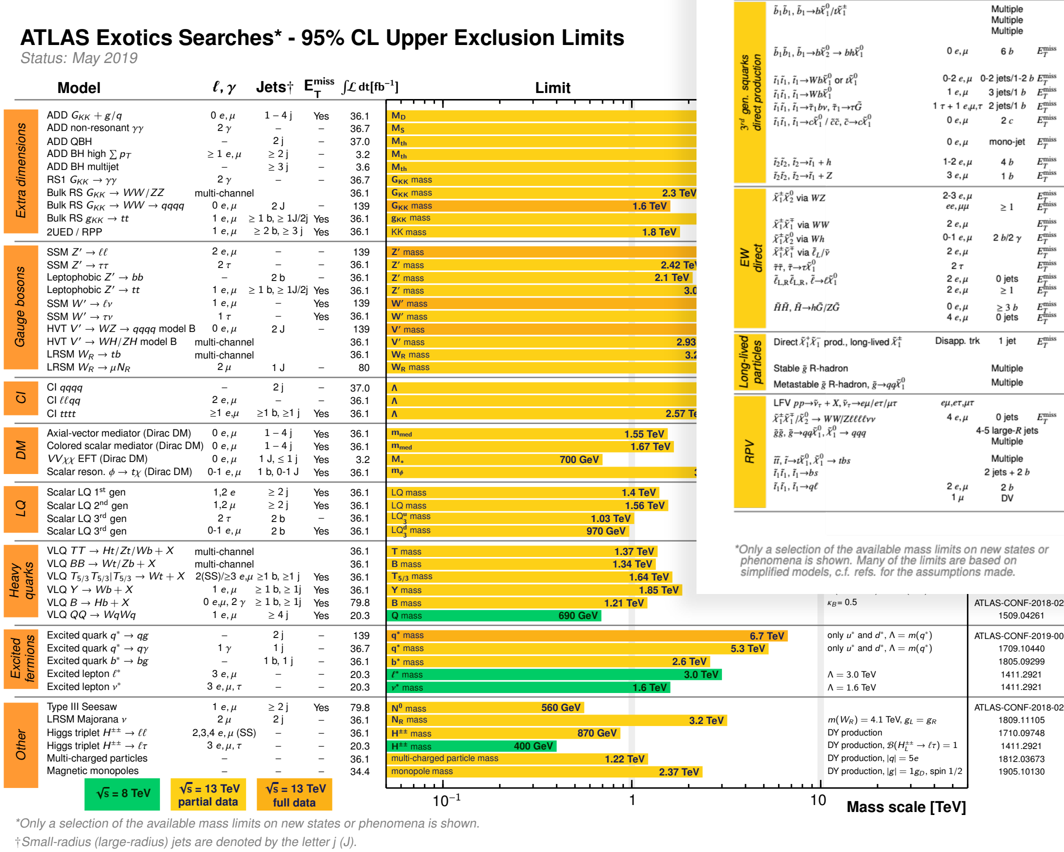
R_K: LHCb most precise, Run-2 ~SM, combination with Run-1: 2.5σ < SM

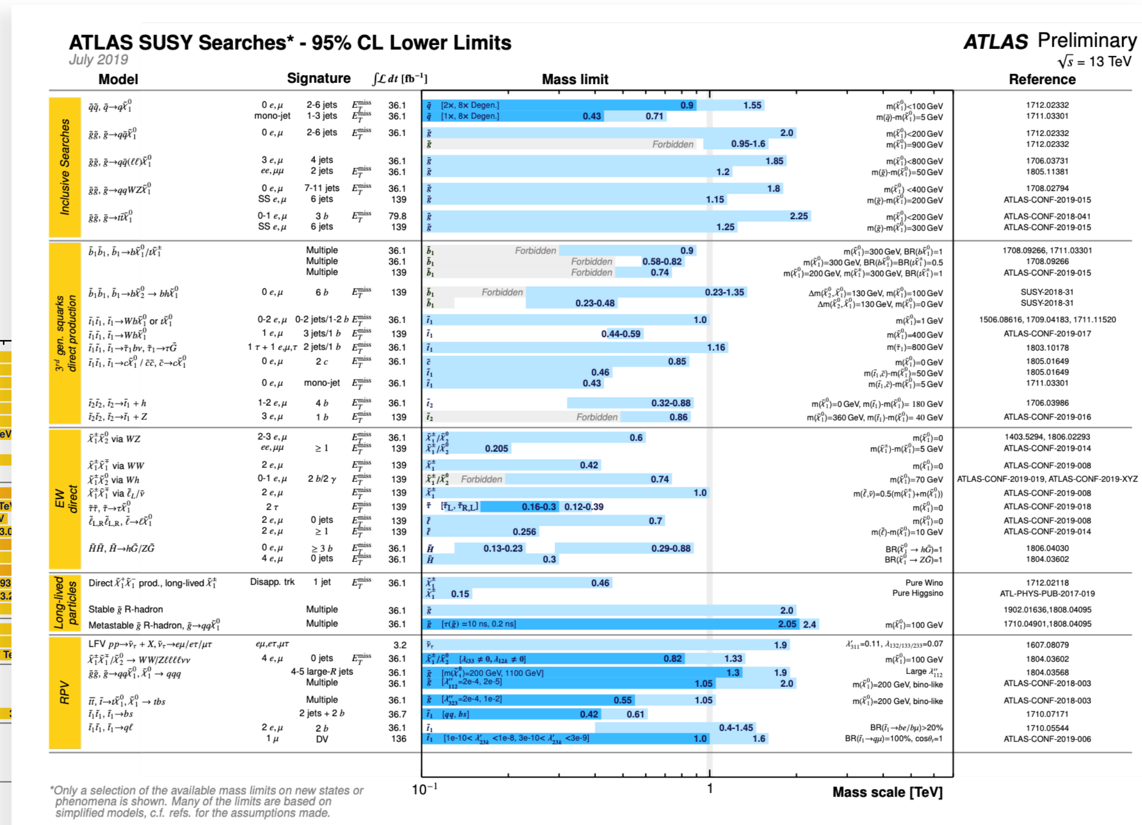
R_{K^*}: LHCb somewhat low at low q^2

Searches for new physics

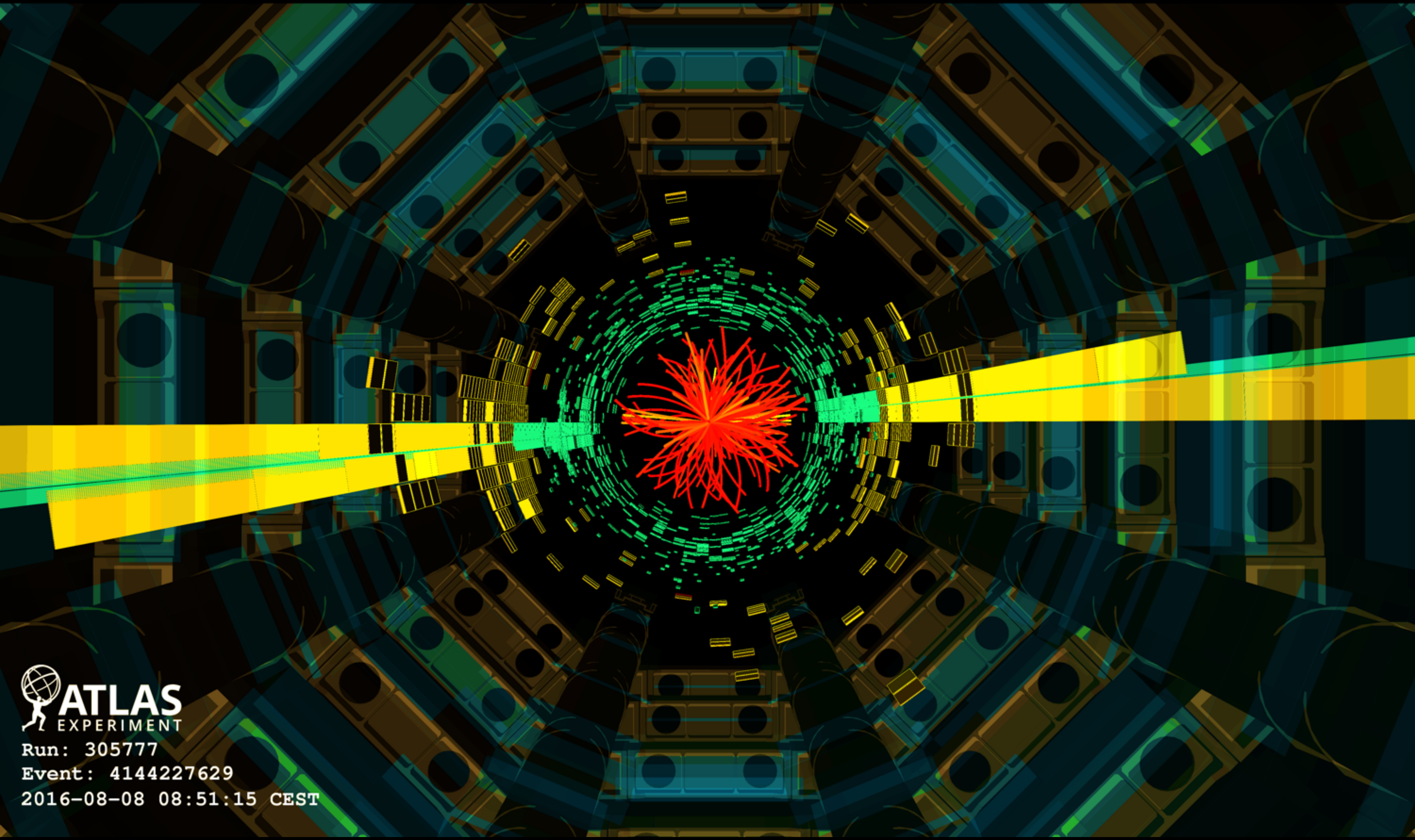
Cover all areas: high mass, electroweak production, long-lived particles, forbidden decays, …

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



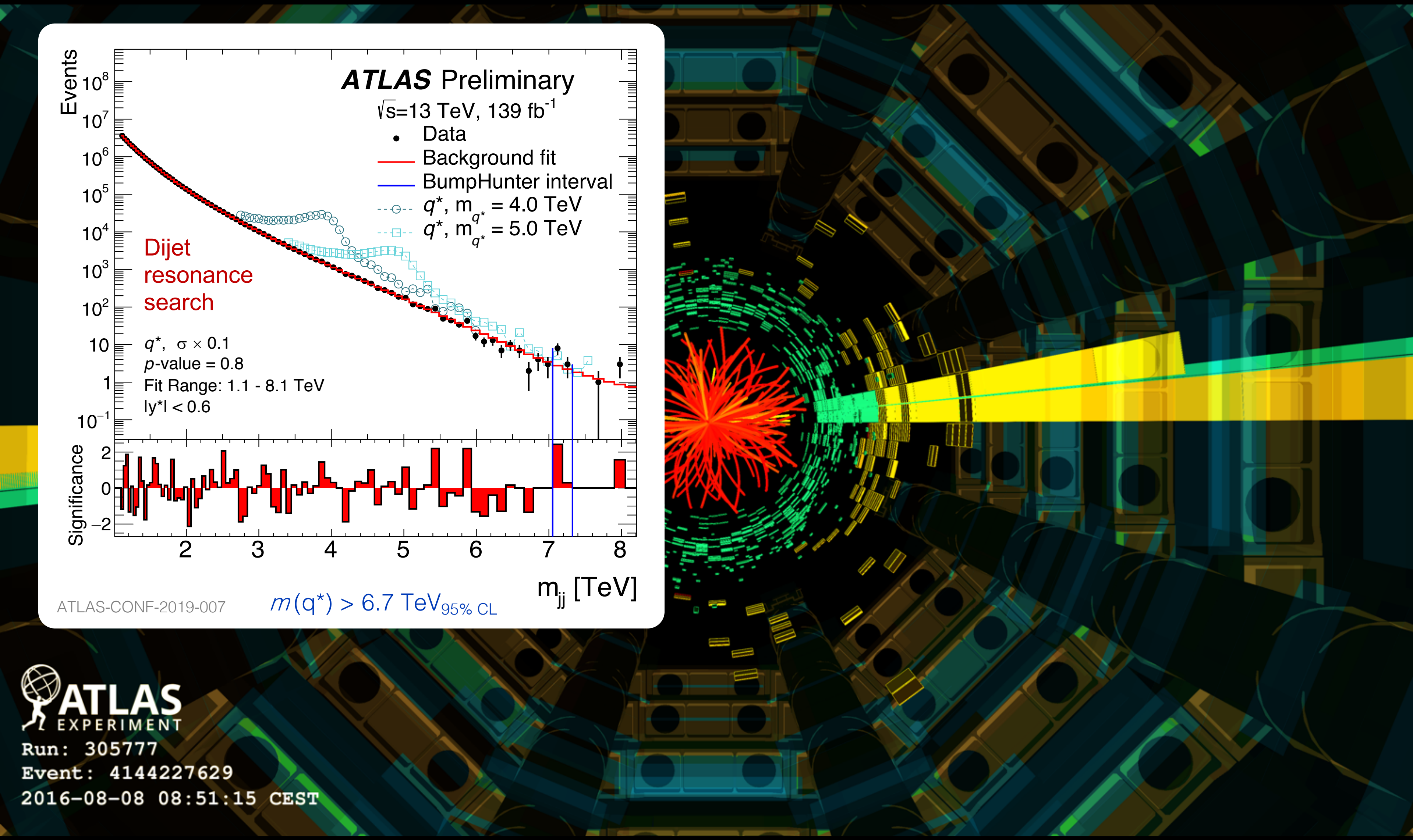


High-mass resonance searches to probe new TeV scale symmetries or forces

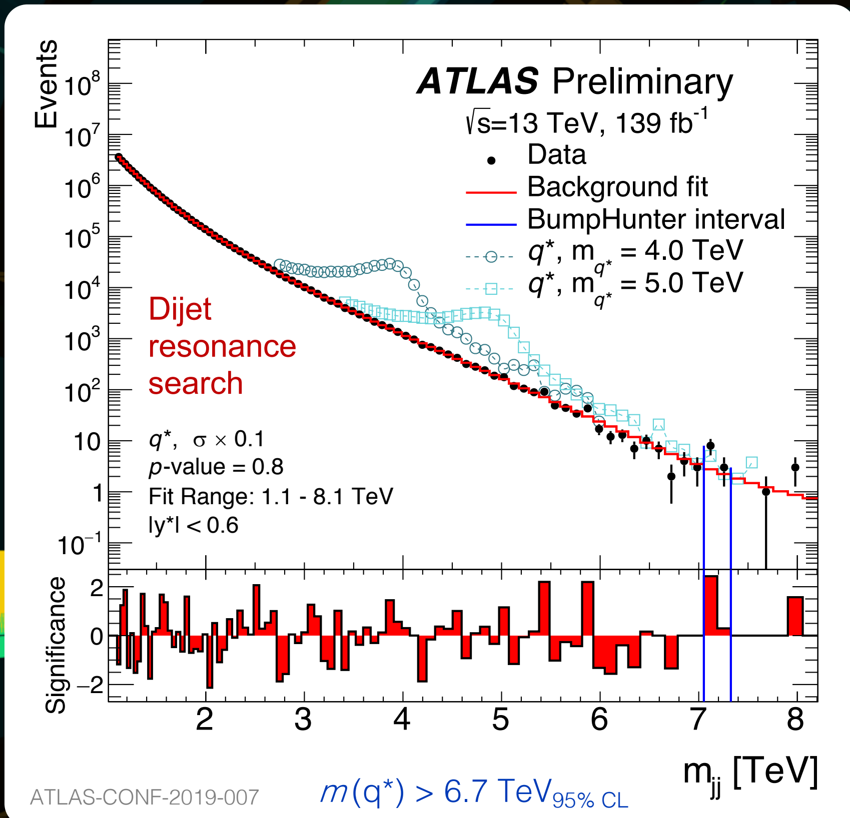


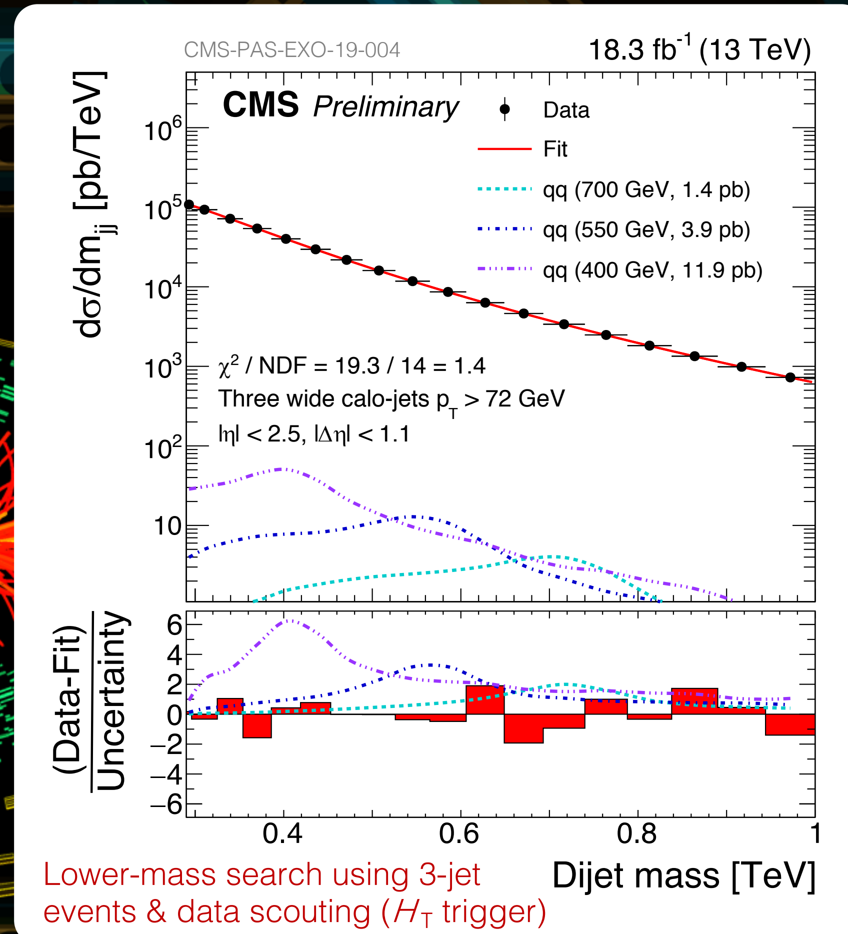
Highest-mass central dijet event of 8.0 TeV selected in resonance search

High-mass resonance searches to probe new TeV scale symmetries or forces



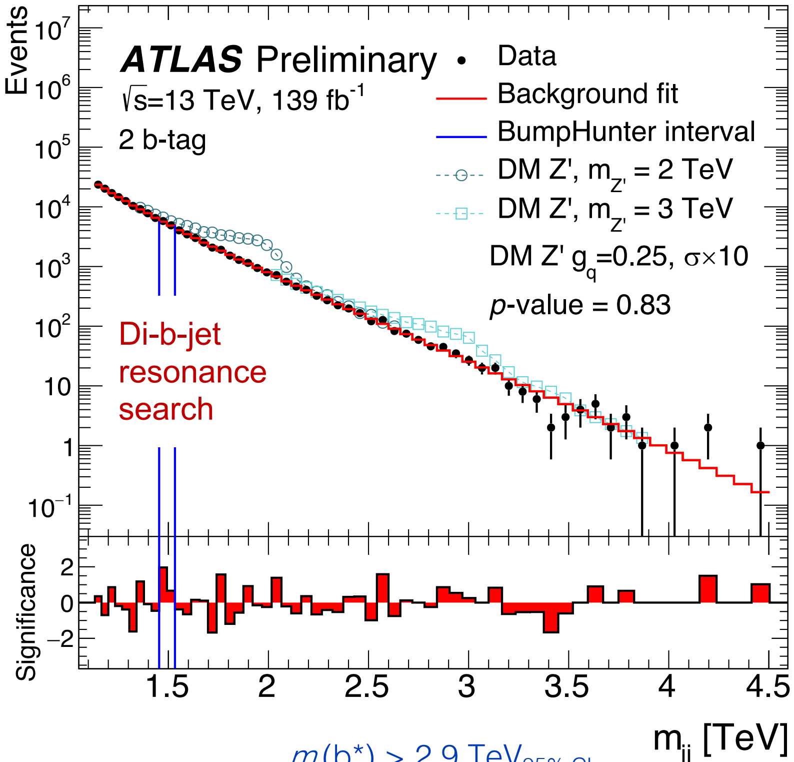
High-mass resonance searches to probe new TeV scale symmetries or forces



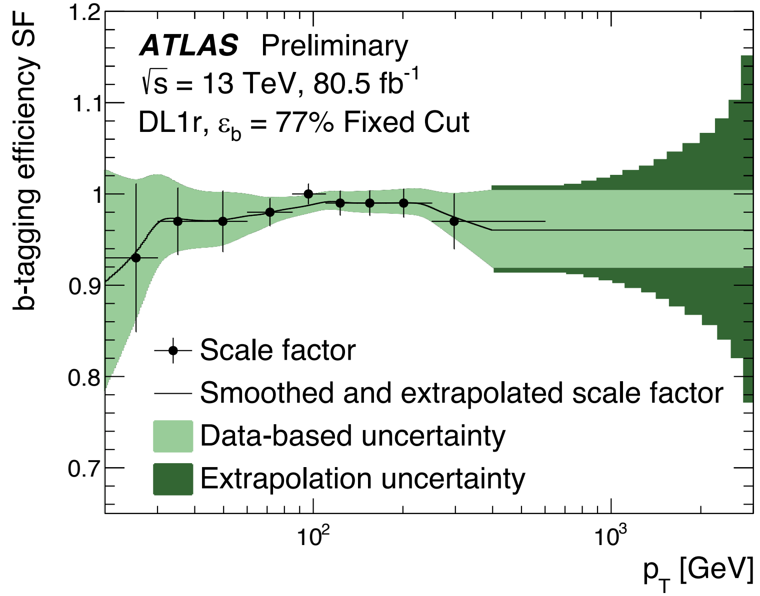


ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

High-mass resonance searches to probe new TeV scale symmetries or forces



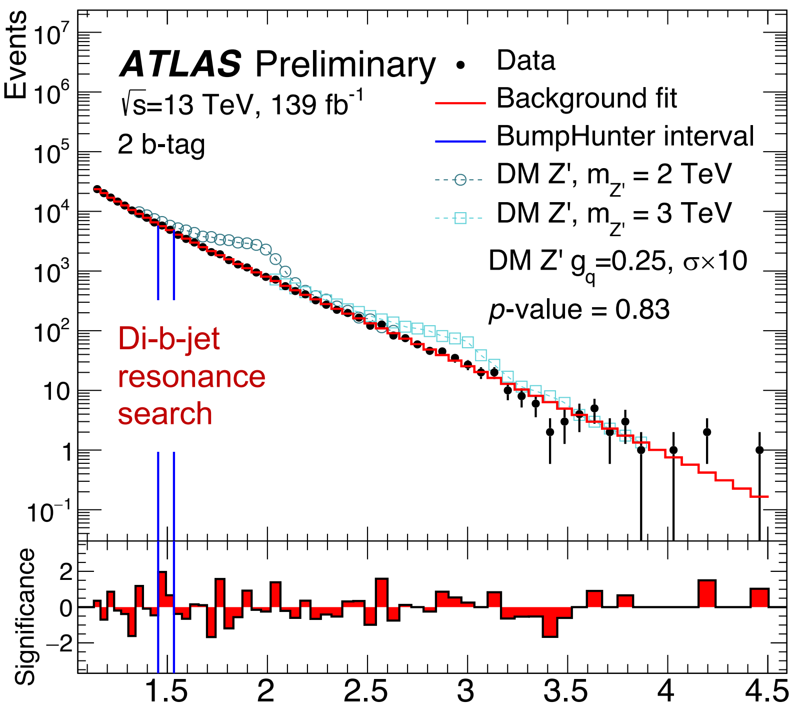
$m(b^{*}) > 2.9$ TeV$_{95\%\ CL}$



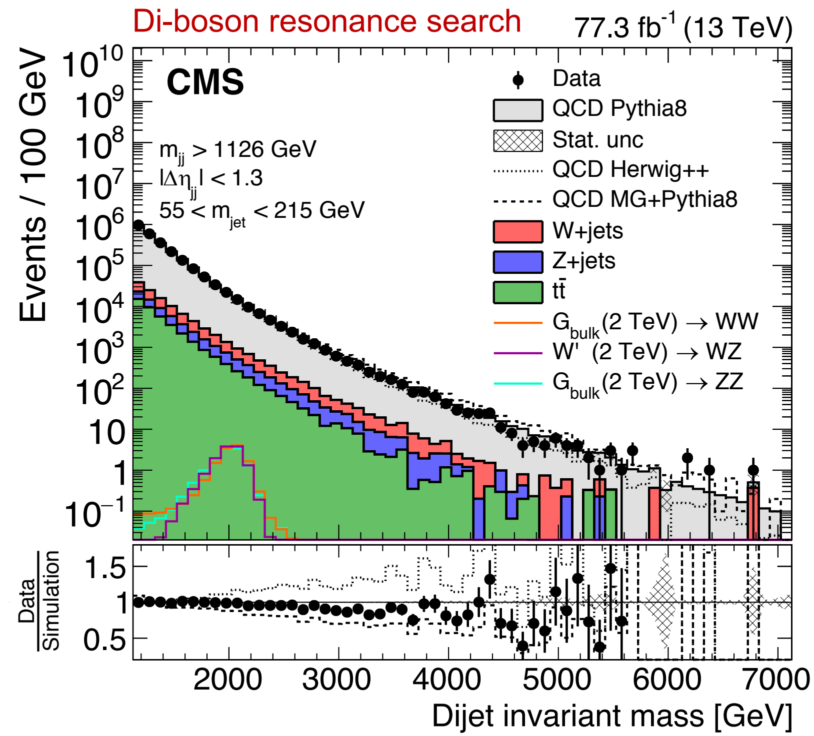
Data/MC scale factor vs. b-jet p_T for the DL1r algorithm (77% eff WP). Data driven information stems from ttbar events, which is extrapolated to high p_T

ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

High-mass resonance searches to probe new TeV scale symmetries or forces



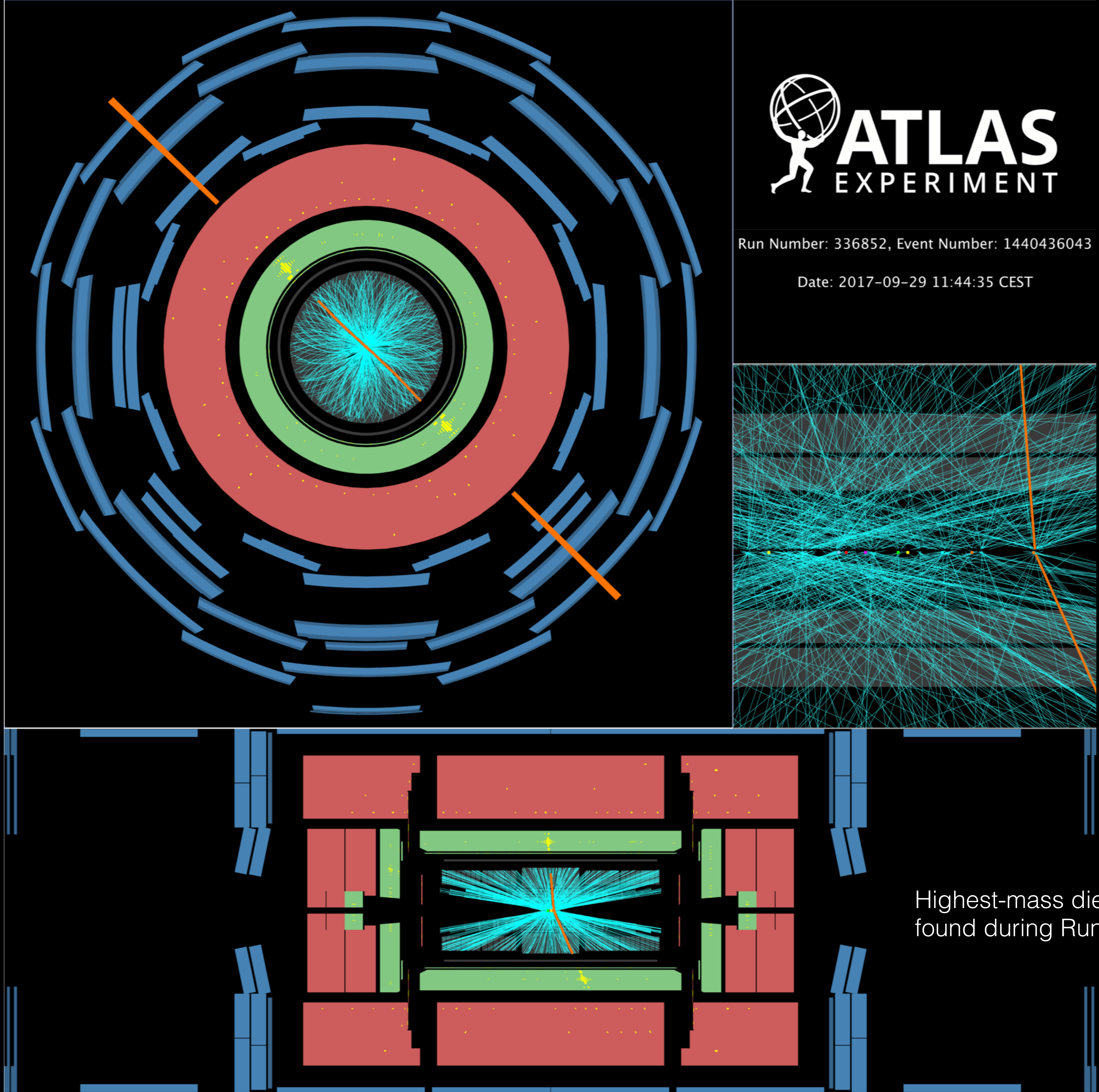
$m(b^*) > 2.9$ TeV$_{95\%\ CL}$



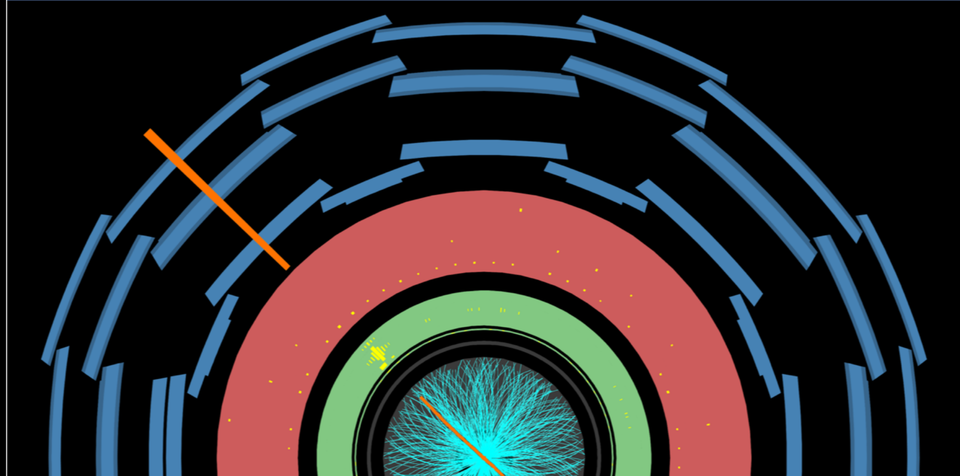
Exploit 3D likelihood fit to jet and dijet masses (30% improvement). In heavy vector triplet model, exclude Z' (W') below 3.5 (3.8) TeV

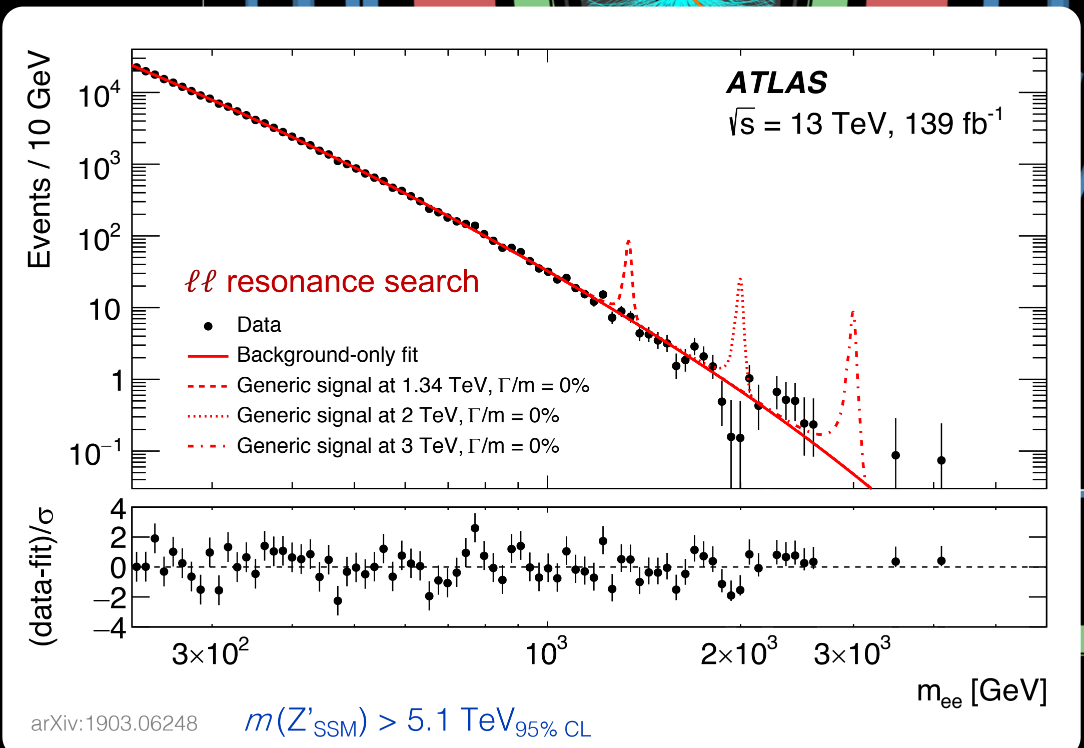
arXiv:1906.05977

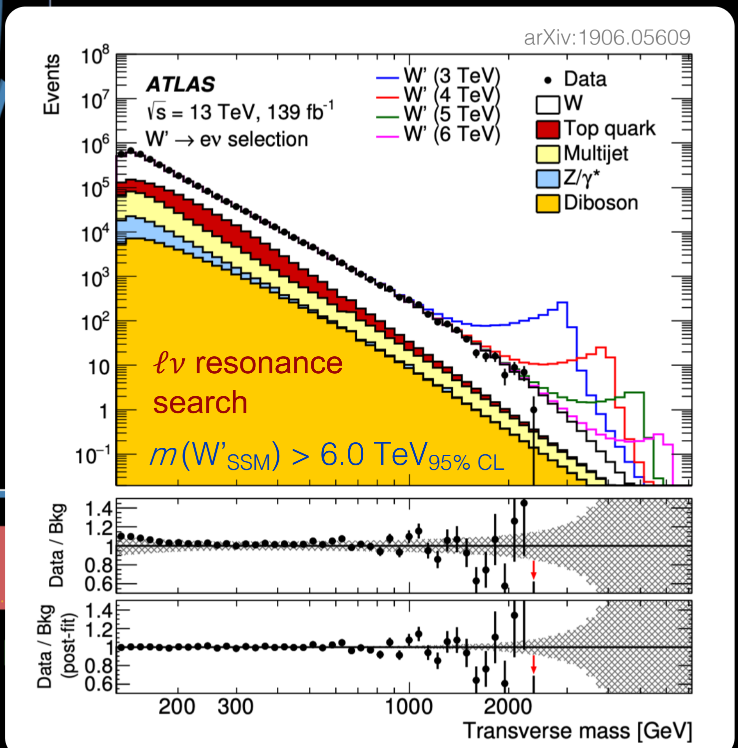
ATLAS EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST



Highest-mass dielectron event found during Run-2: 4.1 TeV.

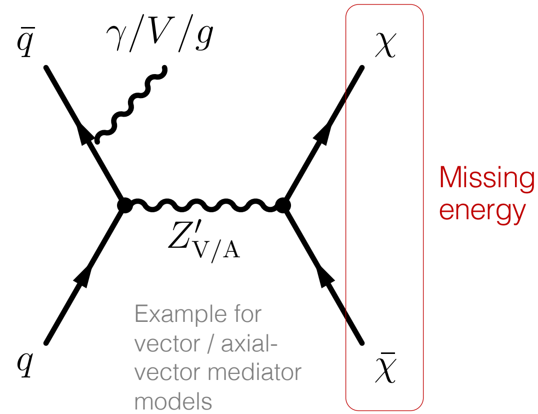

ATLAS
EXPERIMENT
Run Number: 336852, Event Number: 1440436043
Date: 2017-09-29 11:44:35 CEST

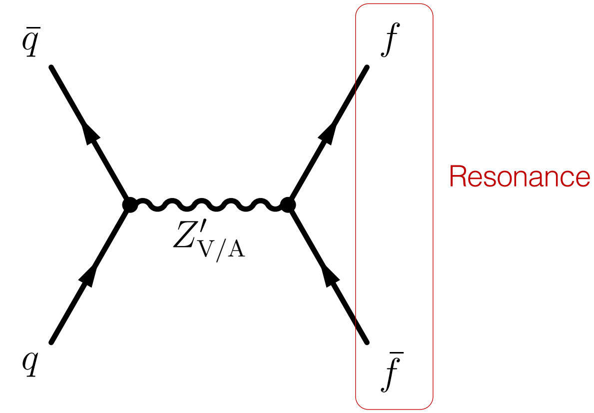

ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$\ell\ell$ resonance search
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m = 0%
Generic signal at 2 TeV, Γ/m = 0%
Generic signal at 3 TeV, Γ/m = 0%
Events / 10 GeV
(data-fit)/σ
m_{ee} [GeV]
arXiv:1903.06248
$m(Z'_{SSM}) > 5.1\ \mathrm{TeV}_{95\%\ CL}$


arXiv:1906.05609
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
W' → eν selection
W' (3 TeV)
W' (4 TeV)
W' (5 TeV)
W' (6 TeV)
Data
W
Top quark
Multijet
Z/γ*
Diboson
Events
$\ell\nu$ resonance
search
$m(W'_{SSM}) > 6.0\ \mathrm{TeV}_{95\%\ CL}$
Data / Bkg
Data / Bkg (post-fit)
Transverse mass [GeV]

Dark Matter (DM)

If produced at the LHC, DM interactions will be mediated by particles that can also be directly searched for
— complementarity



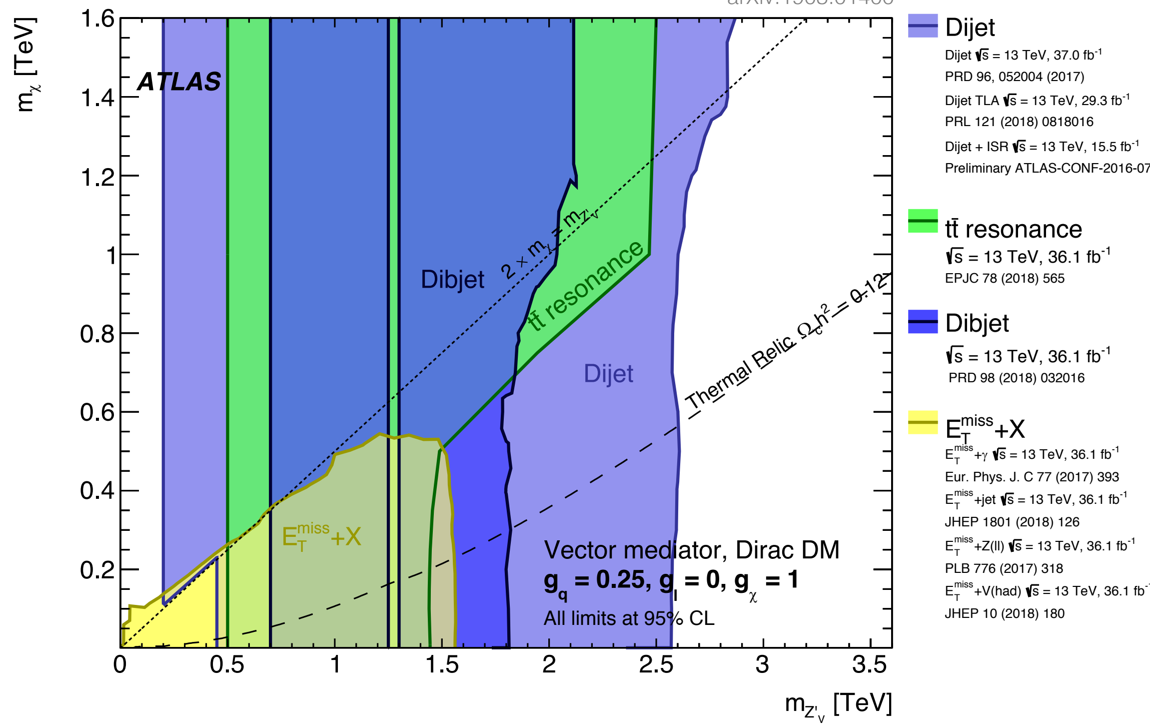


ATLAS released combination of $E_{T,\mathrm{miss}}$ based DM searches involving $E_{T,\mathrm{miss}}$ + X, X = jet, γ, W, Z, H, b(b), t(t) using large number of models

arXiv:1903.01400, up to 37 fb^{-1}

Interpretation in WIMP-nucleon cross section plane highly model dependent

arXiv:1903.01400

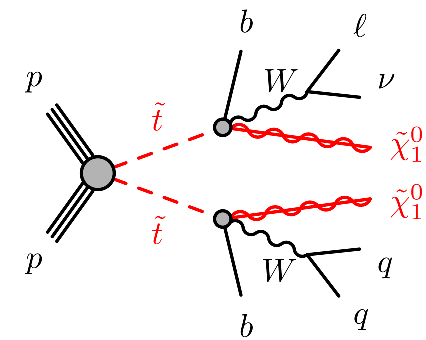


Elusive supersymmetry (could solve naturalness problem, unification, dark matter)

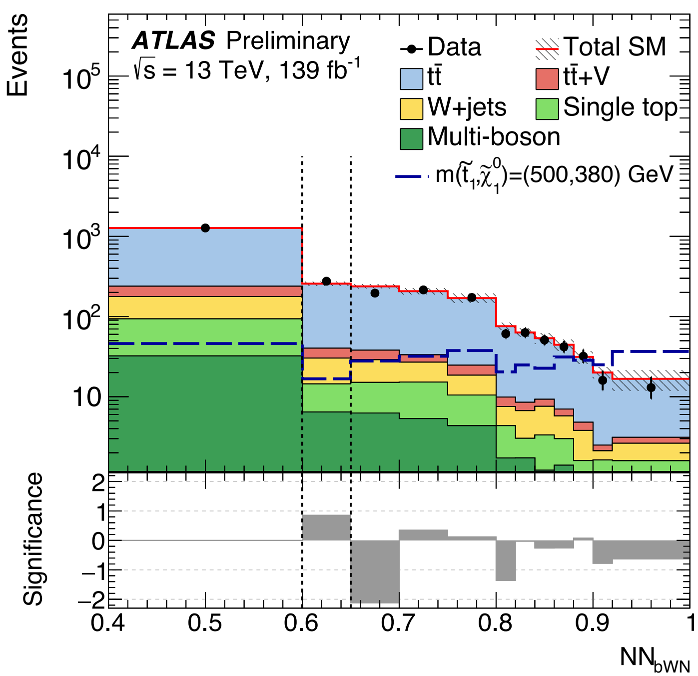
Very diverse signatures. Missing-E_T based searches for scenarios with R-parity conservation, Exotics-like signatures otherwise

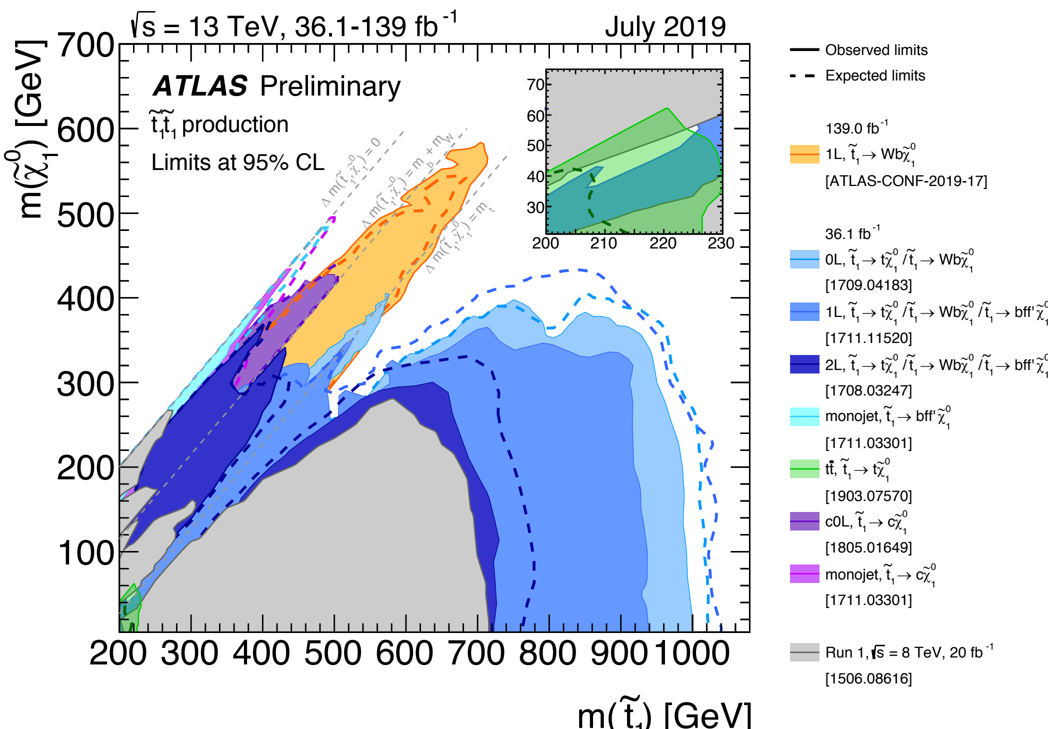
Limits on gluinos reach up to >2 TeV, focus on naturalness-driven searches for early analyses of full Run-2 dataset. More complex approaches (MVA, multi-binned fits)

New search addresses specific soft ("3-body") region of stop-pair production



ATLAS-CONF-2019-017





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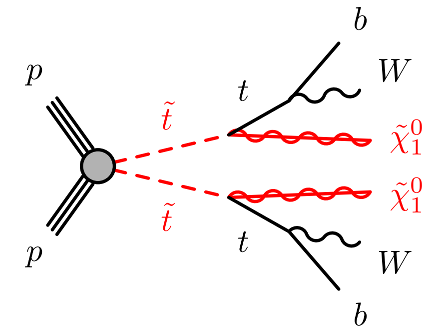
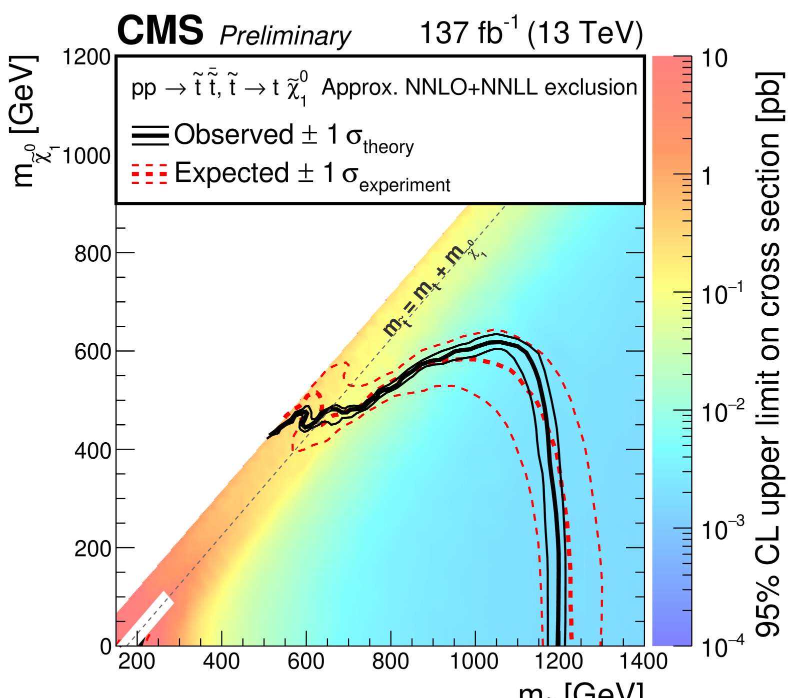
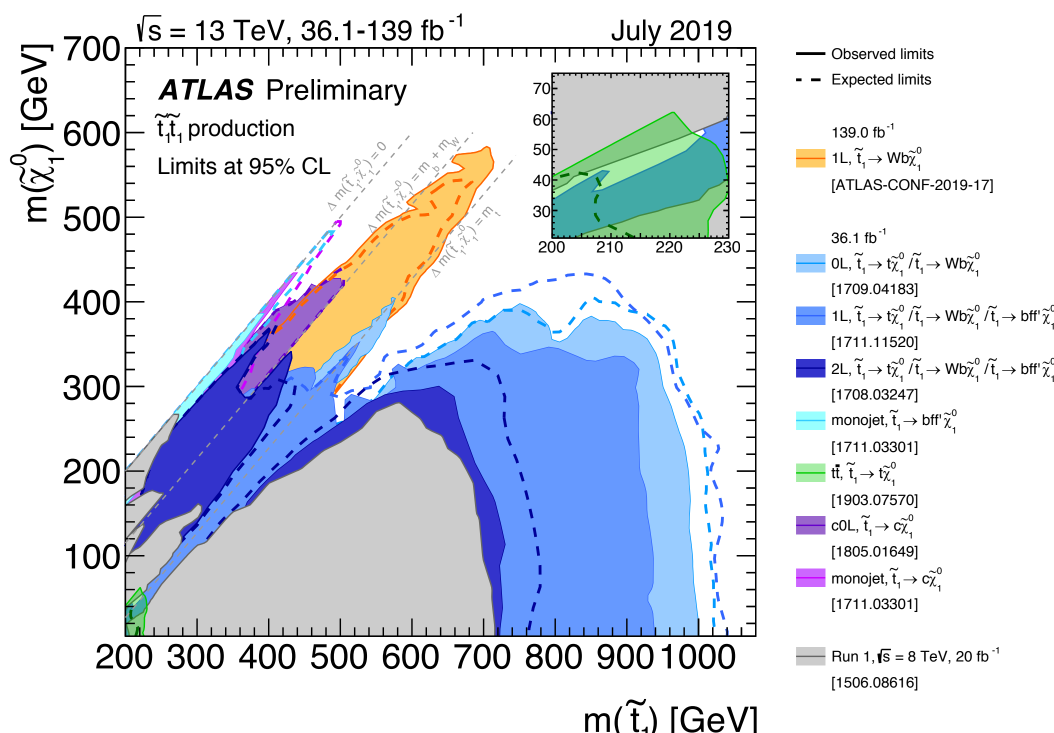


CMS full Run-2 search for direct stop production



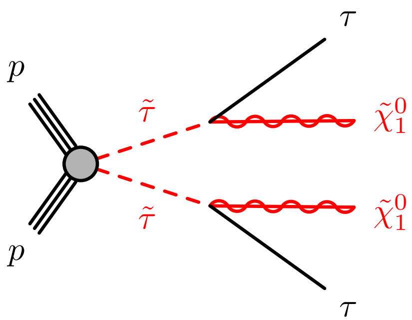
CMS-PAS-SUS-19-009

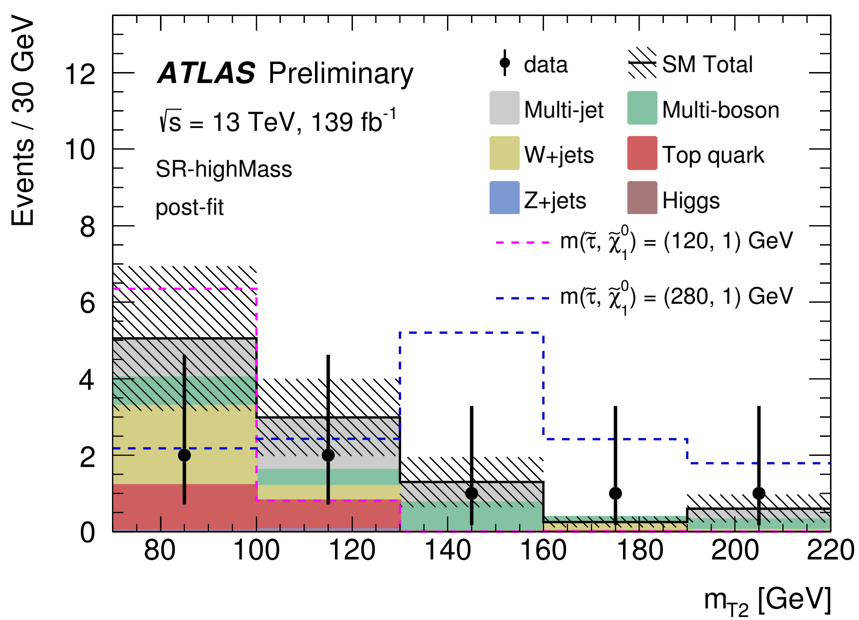


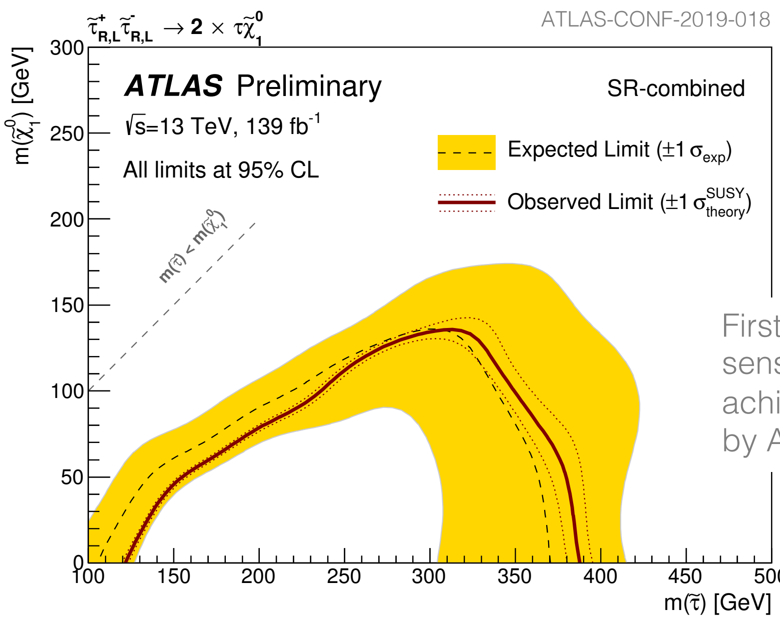
Elusive supersymmetry (could solve naturalness problem, unification, dark matter)

Electroweak SUSY production,
not because it is easy …

Stau pair production







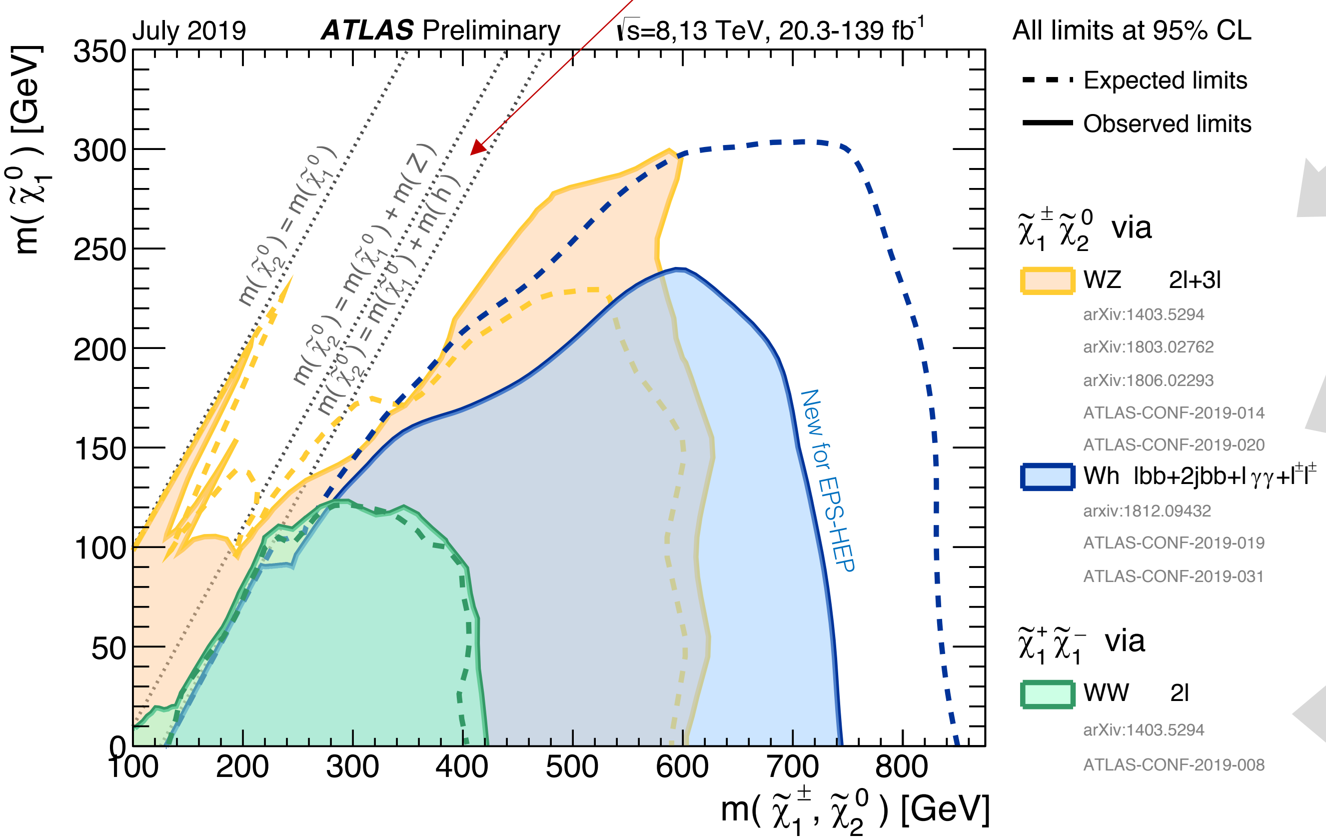
First time sensitivity achieved by ATLAS

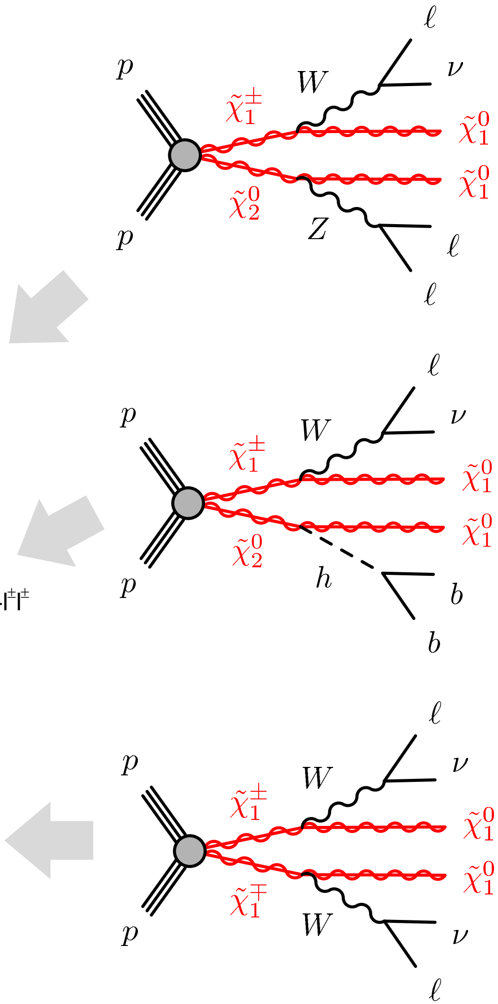
Elusive supersymmetry (could solve naturalness problem, unification, dark matter)

Electroweak SUSY production, not because it is easy …

Dedicated signal regions with ISR jets targeting "compressed" spectra

Summaries



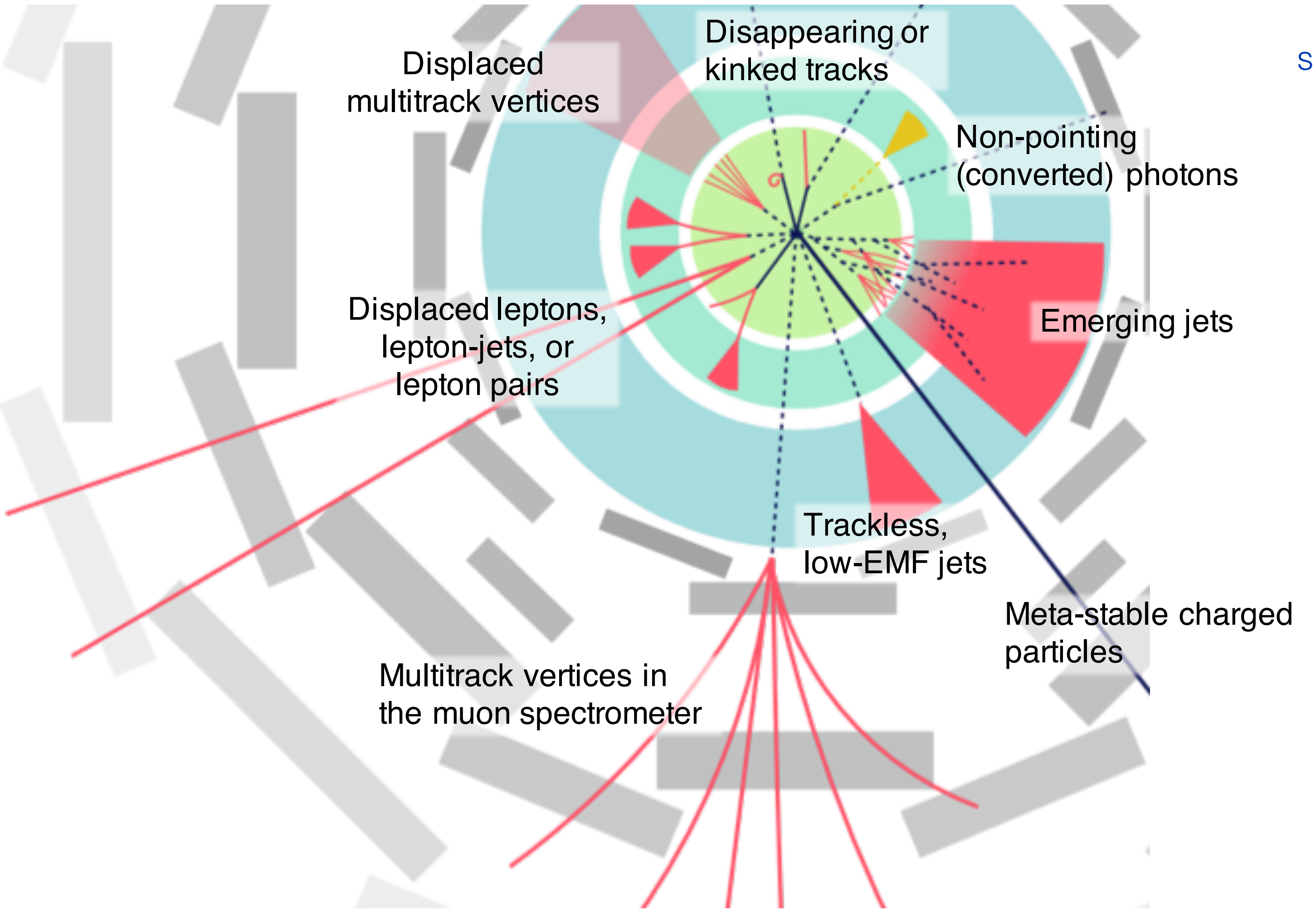


Most favorable case: EWk-ino production with decays through light sleptons not shown: exclusion reaches up to 1.1 TeV

Direct slepton production excluded up to 700 GeV mass ATLAS-CONF-2019-008

And what if new physics is all different? For example long-lived?

Long-lived particles can occur in case of weak couplings, small phase space (mass degeneracy), high virtuality (scale suppression)

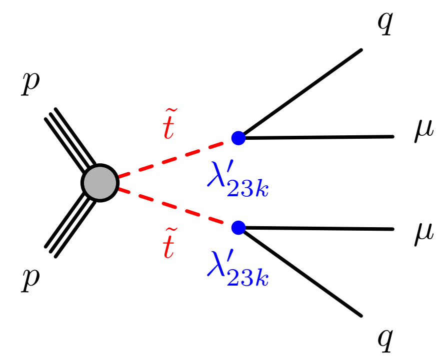


Diverse set of signatures that need to be pursued by dedicated, usually non-standard analyses, some requiring special triggers

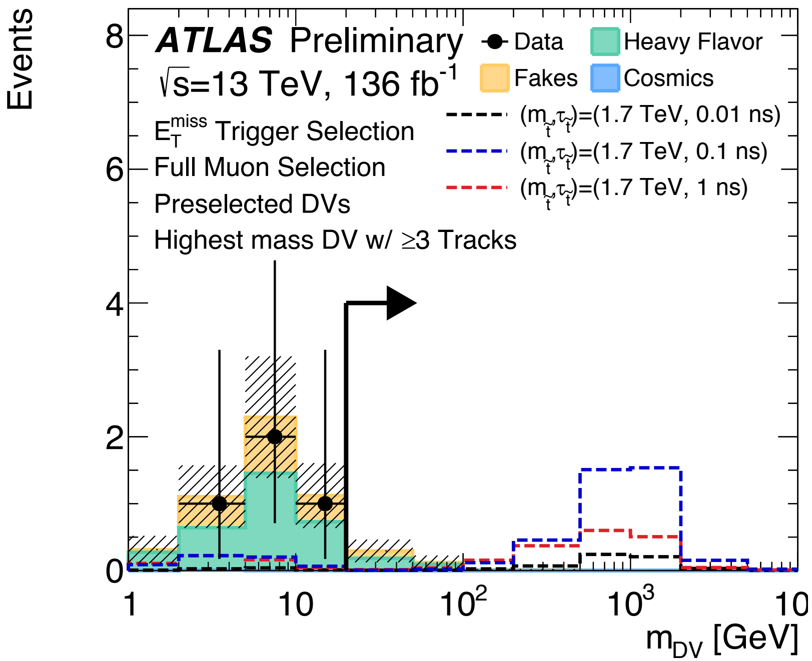
And what if new physics is all different? For example long-lived?

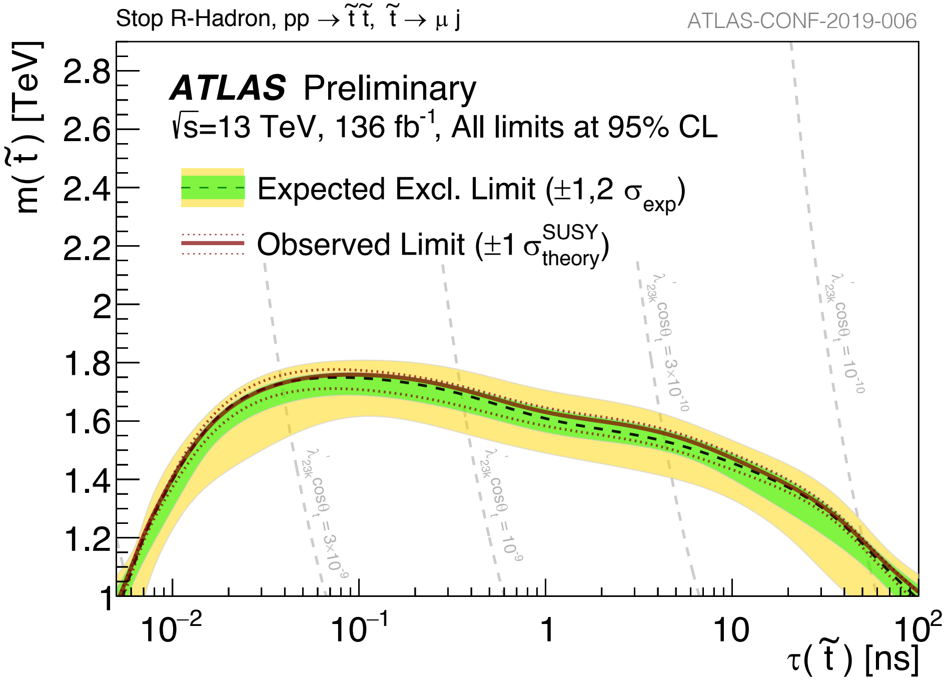
Search for a long-lived particle with displaced vertex and muon

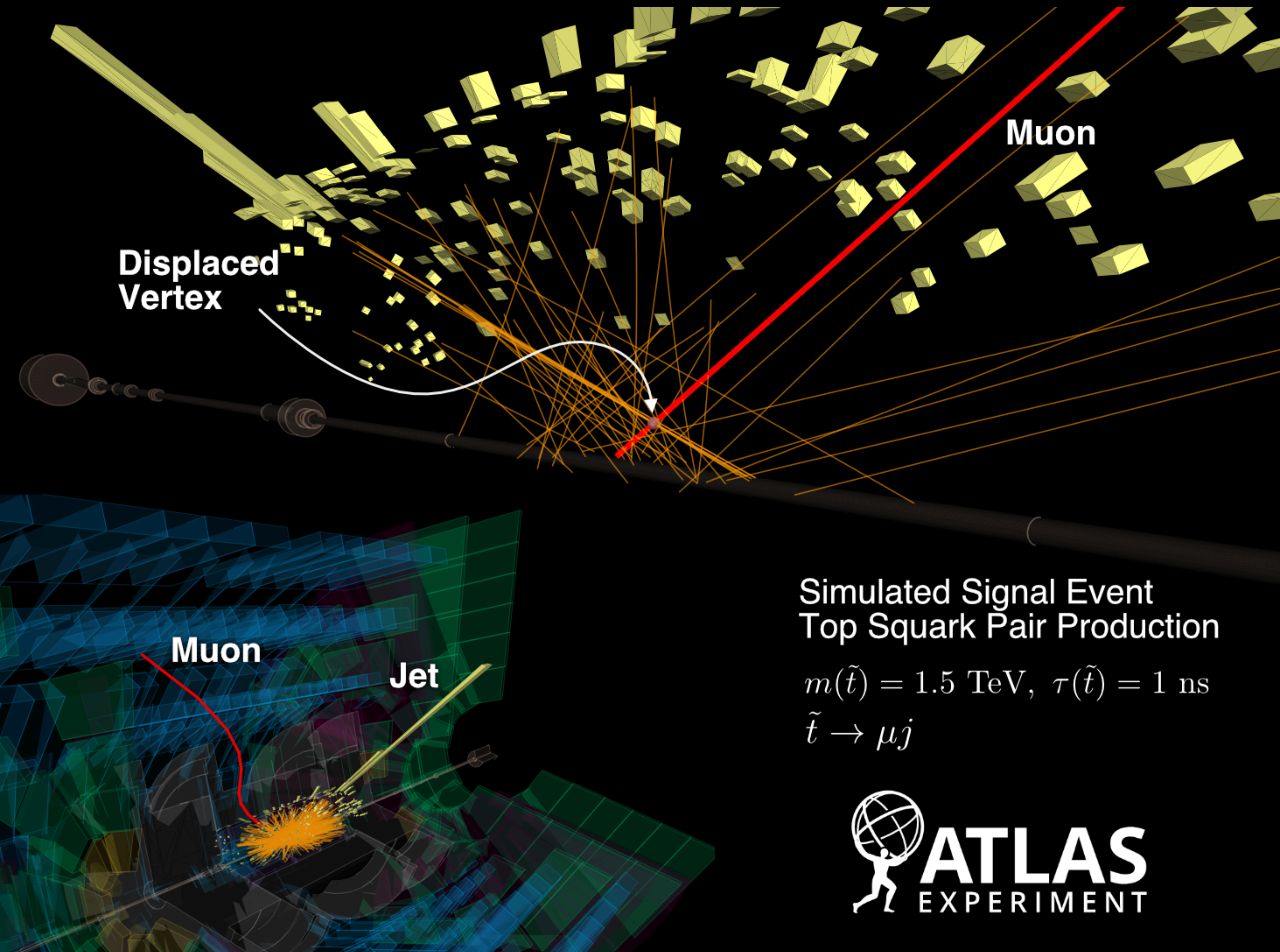
Clean signature of large track multiplicity and vertex mass



R-parity violating signature with long-lived stop





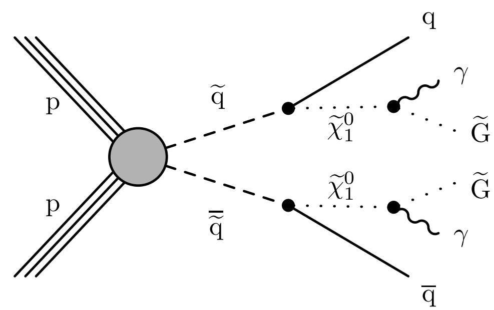

Muon
Displaced Vertex
Muon
Jet
Simulated Signal Event
Top Squark Pair Production
$m(\tilde{t}) = 1.5$ TeV, $\tau(\tilde{t}) = 1$ ns
$\tilde{t} \rightarrow \mu j$
ATLAS
EXPERIMENT

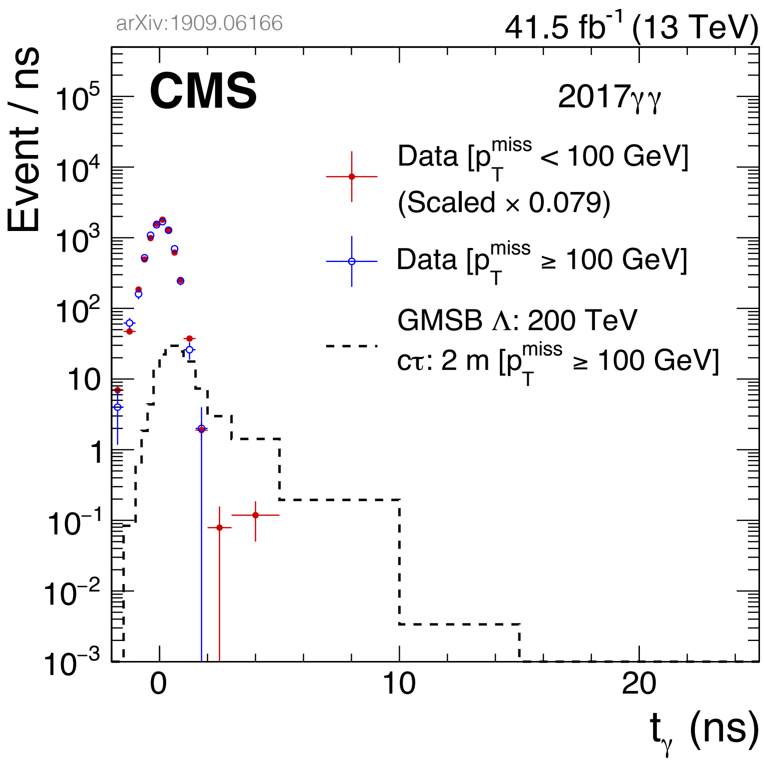
And what if new physics is all different? For example long-lived?

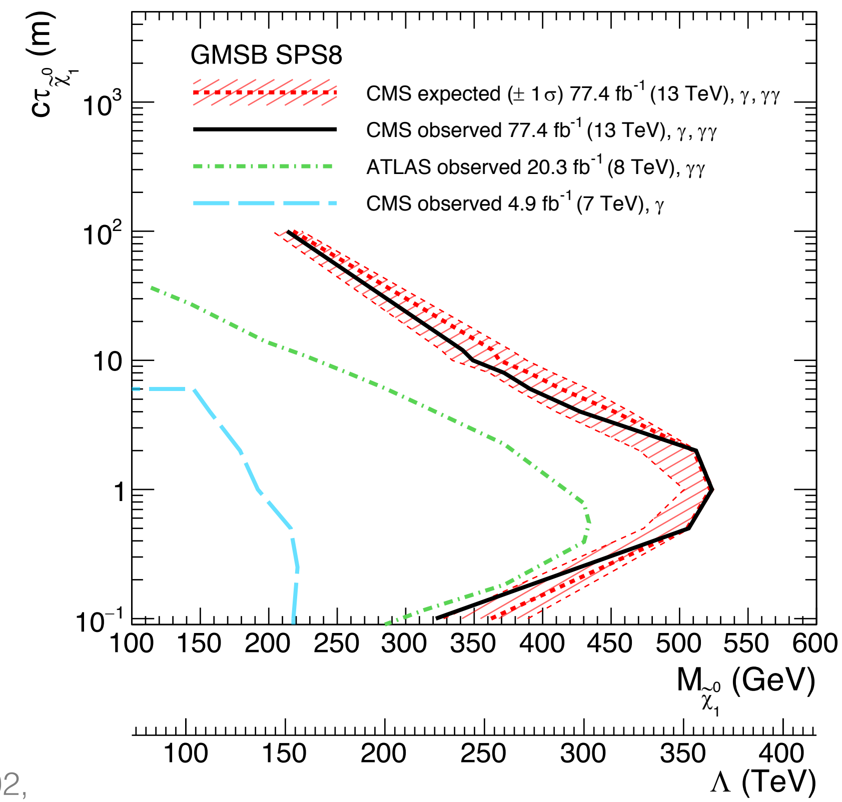
Search for a long-lived neutralinos with delayed photons

Exploit $E_{T,miss}$ and photon timing using ECAL (precise calibration required)

→ Background estimate from 'ABCD' method

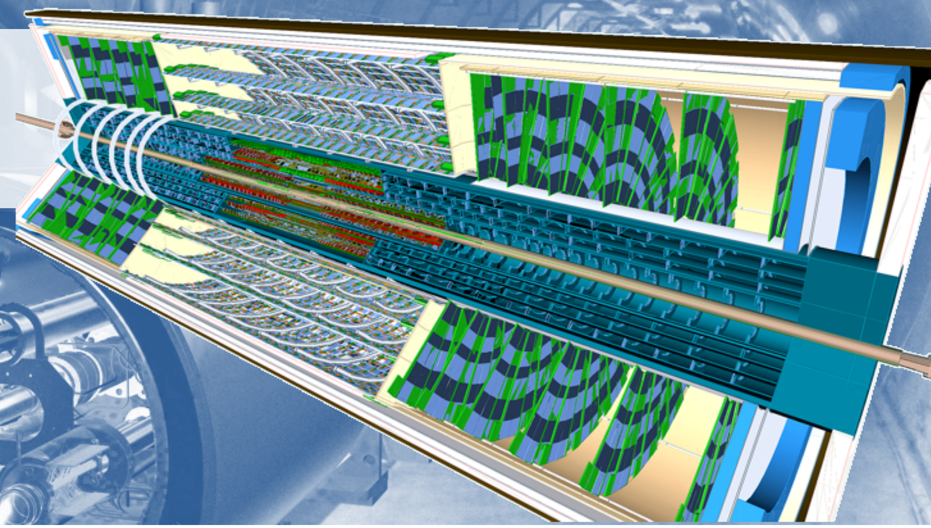




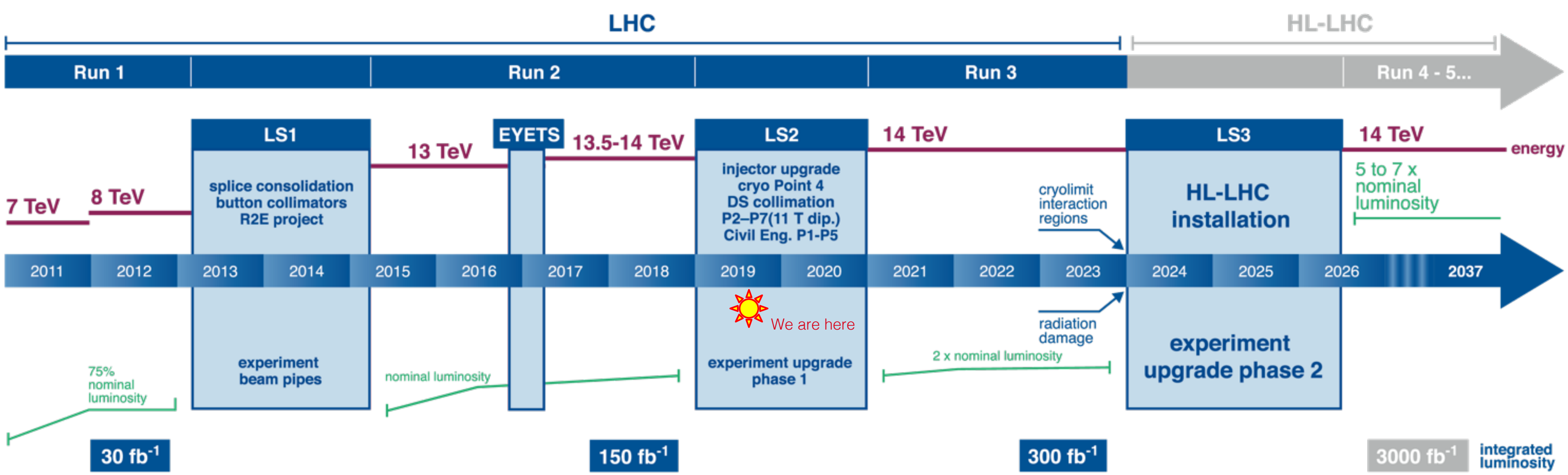


SPS8 benchmark: for neutralino decay lengths of 101, 102, 103, 104 cm, masses below 320, 525, 360, 215 GeV are excluded at 95% CL

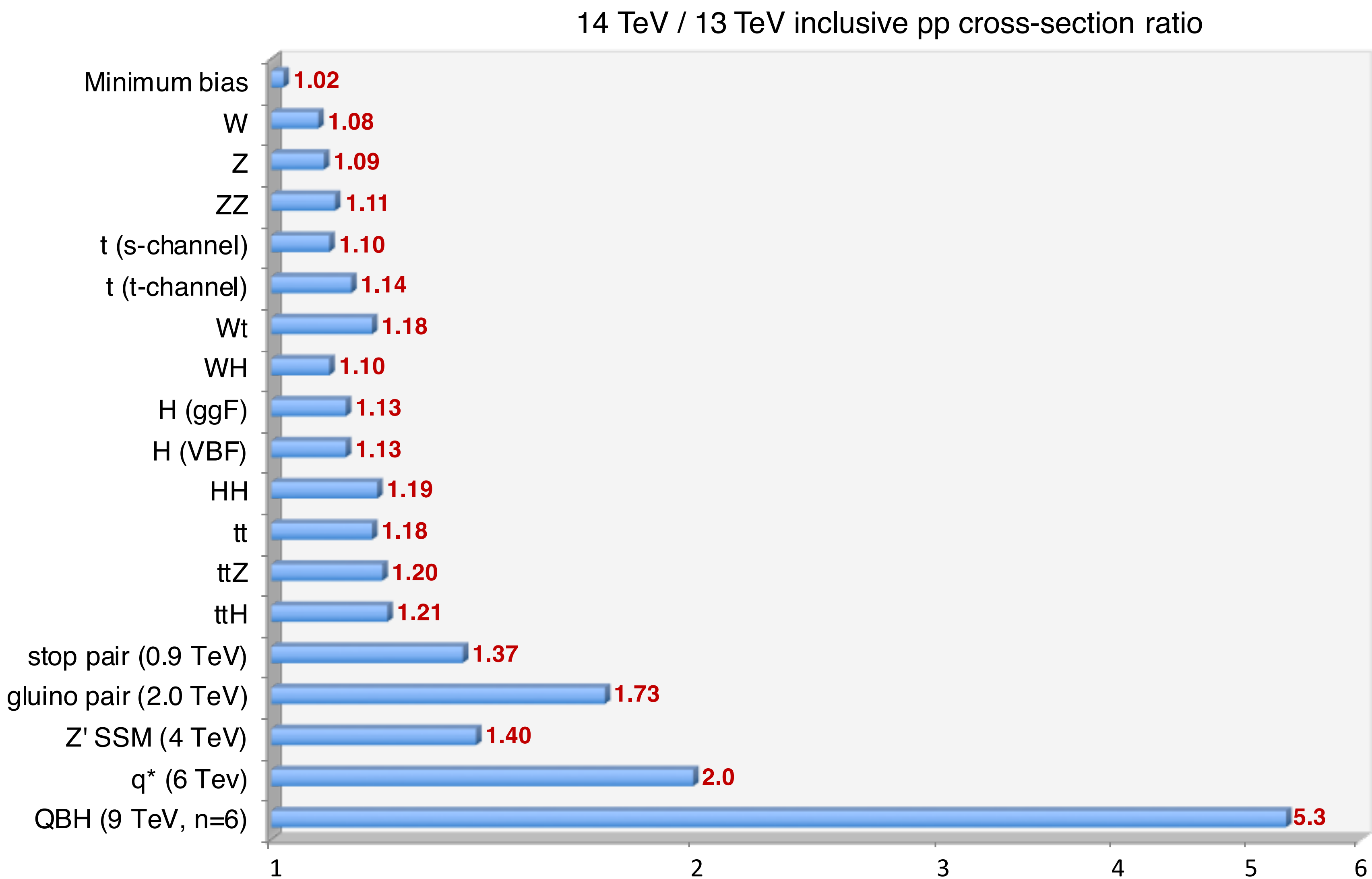
Phase-II:
The High-Luminosity LHC



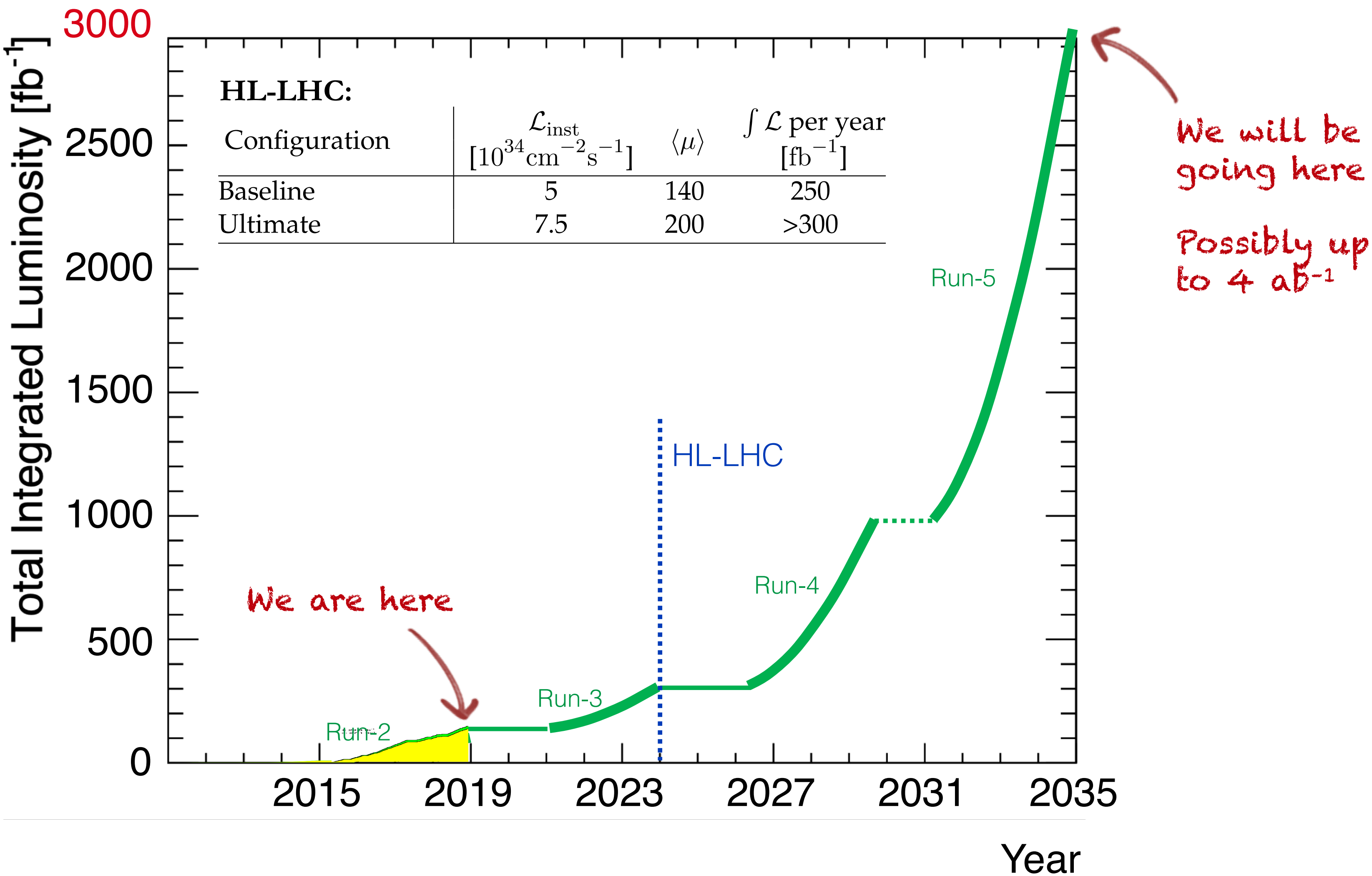
LHC / HL-LHC Plan



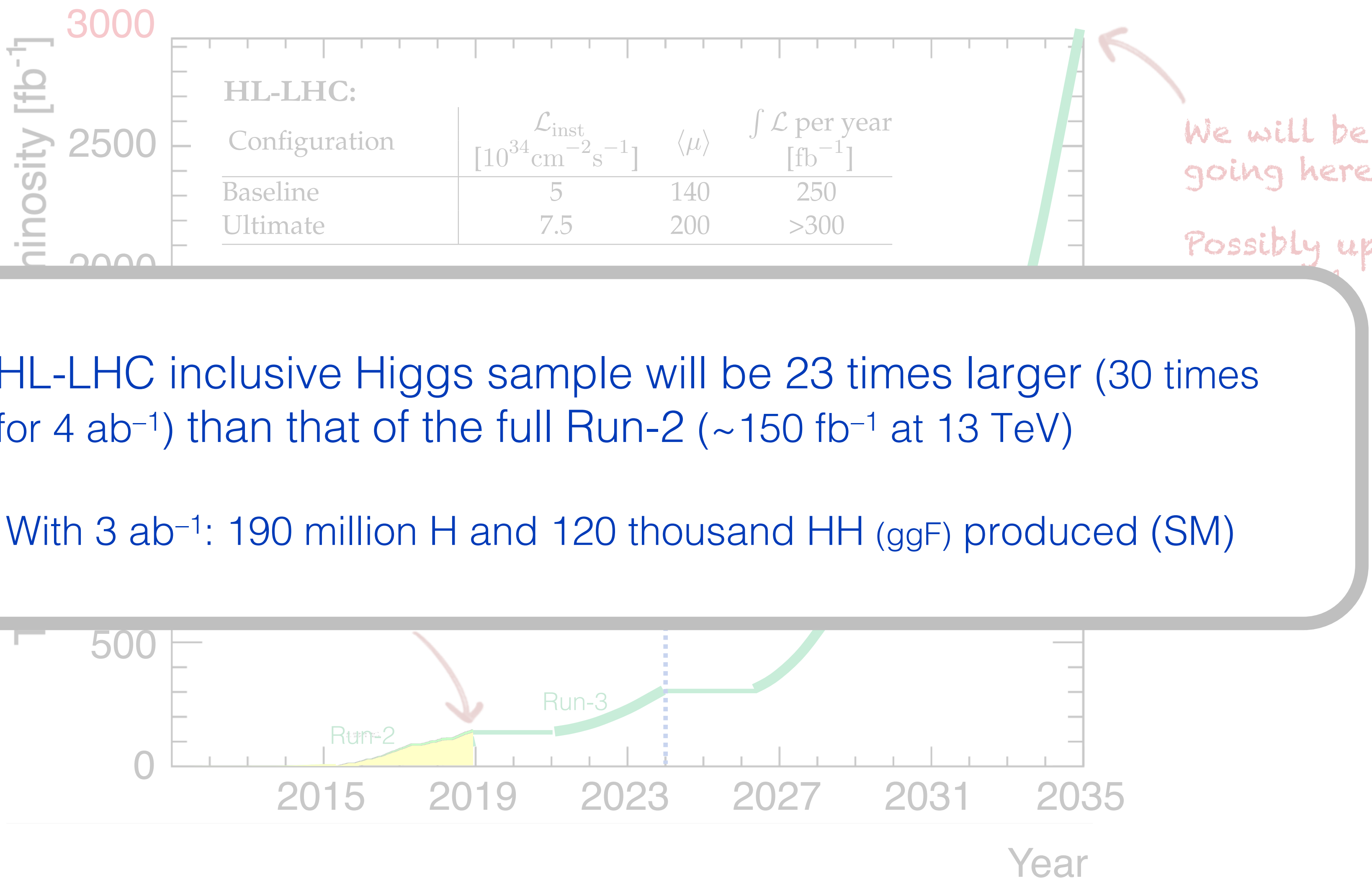
14 TeV proton–proton centre-of-mass energy



Expected integrated luminosity of LHC & HL-LHC



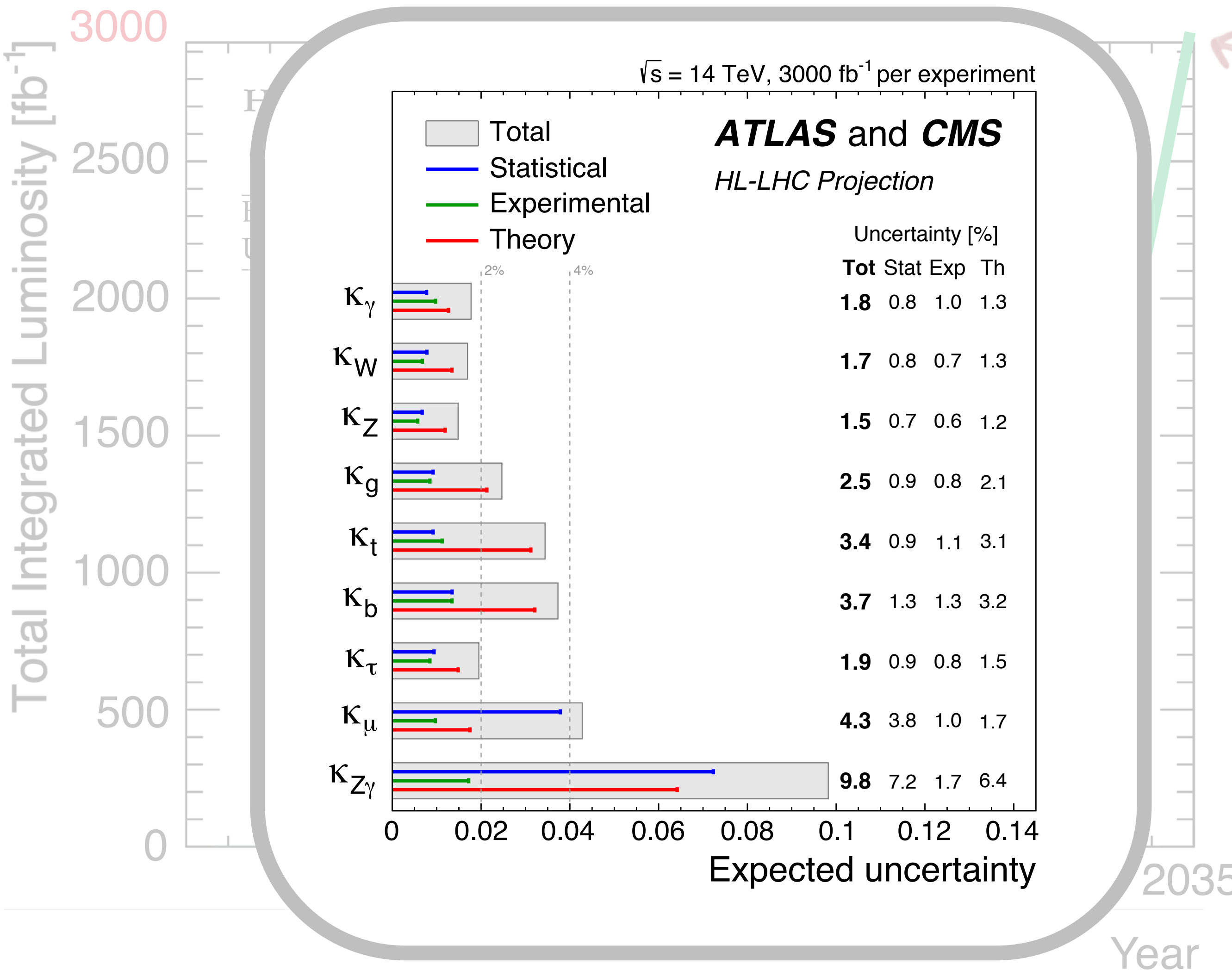
Configuration	$\mathcal{L}_{\text{inst}}$ [10^{34}cm^{-2}s^{-1}]	$\langle\mu\rangle$	$\int\mathcal{L}$ per year [fb^{-1}]
Baseline	5	140	250
Ultimate	7.5	200	>300



HL-LHC inclusive Higgs sample will be 23 times larger (30 times for 4 ab^{-1}) than that of the full Run-2 (~150 fb^{-1} at 13 TeV)

With 3 ab^{-1}: 190 million H and 120 thousand HH (ggF) produced (SM)

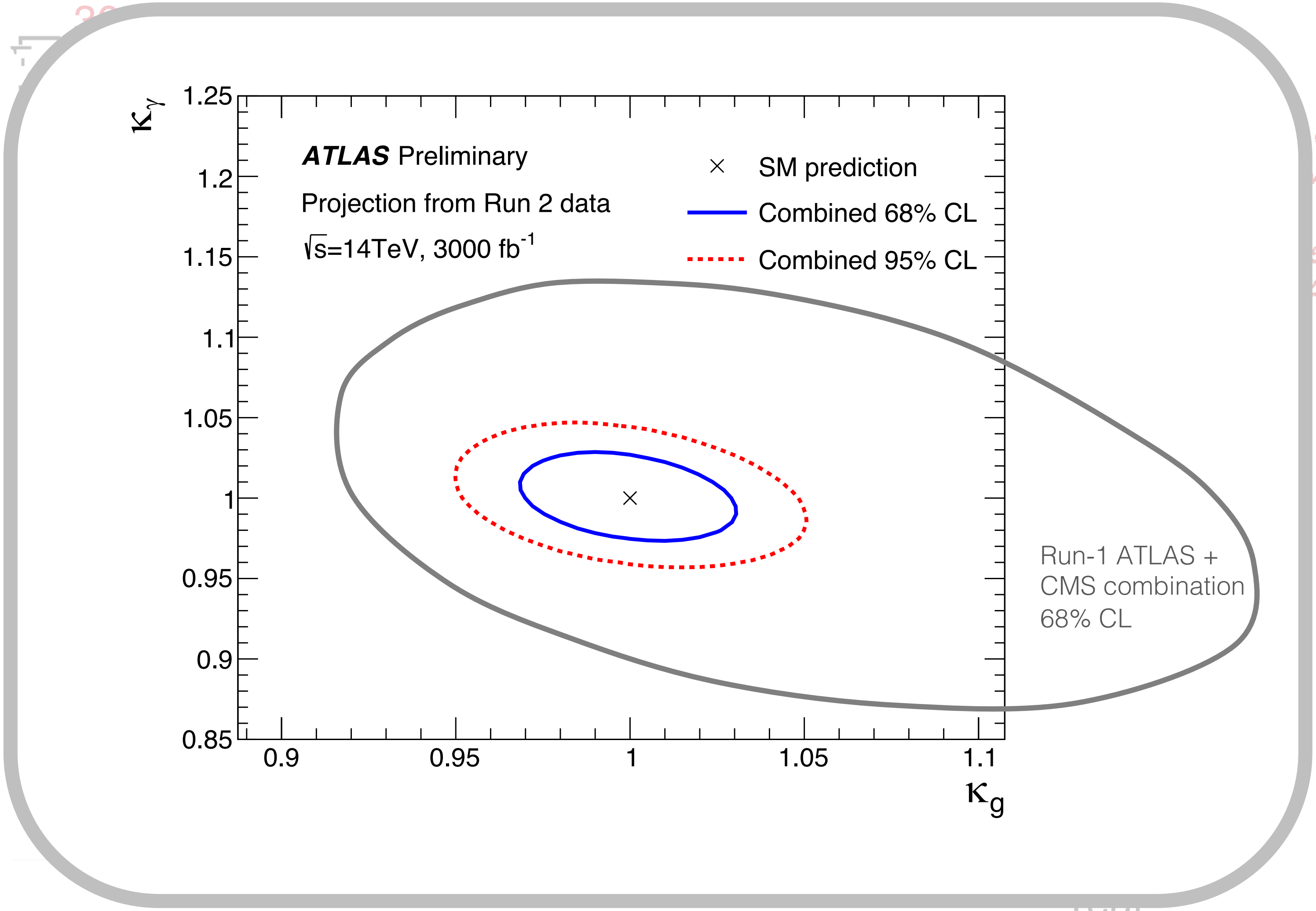
Expected integrated luminosity of LHC & HL-LHC

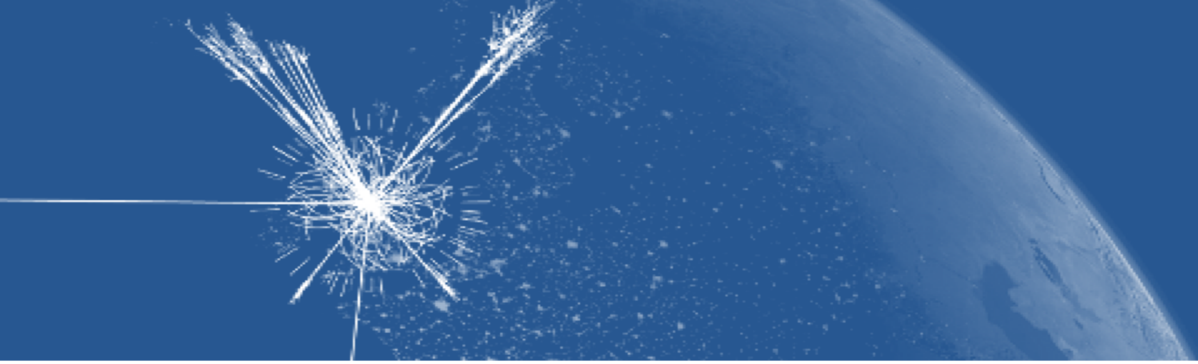


We will be going here

Possibly up to 4 ab^{-1}

Expected integrated luminosity of LHC & HL-LHC





Challenges and opportunities

LHC experiments are in full swing analysing their (up to) 140 fb^{-1} Run-2 datasets

- High-precision measurements of multi-boson and top properties.
  Limitation by theoretical modelling uncertainties — needs theoretical guidance.
- Observation of all WWjj, WZjj, ZZjj electroweak (incl. vector boson scattering) processes.
- Precise Higgs cross-section measurements, progress in rare decay searches, first constraint on VVHH coupling.
  None of the properties of the scalar sector can be taken as granted and must thus be measured.
- New physics searches continue to improve their sensitivity and probe new signatures.
  We do not know the next new physics scale. Naturalness has been a successful guiding principle, but it is challenged by the data from the LHC (and elsewhere). However, there are still unexplored scenarios and parameter regions that must be studied.

We live in data-driven times, experiment must guide us to the next stage.
This requires a broad and diverse particle physics research programme.

The LHC and its experiments represent the flagship of particle physics for decades to come.
The huge Run-2 data sample offers the opportunity to study particle interactions in unprecedented detail and diversity.

Reserved slides …

Higgs physics programme at the HL-LHC in a nutshell

Higgs properties:

- mass (well known, expect to improve to ~33 MeV in $H \to 4\mu$), width (through interference measurements)
- spin (0^+ established), CP (odd admixture possible) — not discussed today

Rare Higgs decays:

- Observation of $H \to \mu\mu$, $H \to Z\gamma$, HH production (constraint on Higgs self coupling)
- Search for very rare (eg, $H \to M\gamma$, $M=J/\psi$, ϕ, ρ), difficult ($H \to cc$) or anomalous decays (invisible or new particles, or flavour violating)

Higgs couplings:

- Study of Higgs production and anomalous couplings by differential cross-section measurements
- Global and partially global coupling fits: experiments moving from “kappa” interpretation to EFT

New physics in Higgs production or other scalar states

- Search for anomalous FCNC through top decays, Higgs production via SUSY cascades, etc.
- Search for additional scalar particles

Luminosity — single most important quantity

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

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

"Cross section" given by Nature

"Efficiency" of detection optimised by experimentalist

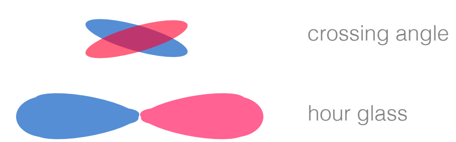
Integrated luminosity delivered by LHC

- Luminosity is a function of the LHC beam parameters

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

Reduction factor

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



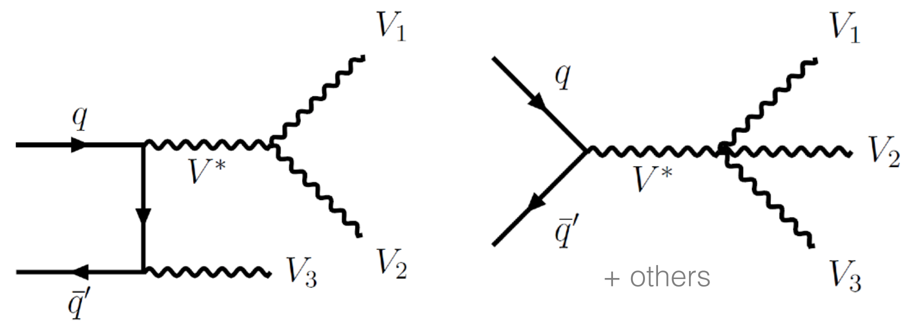
Reaching to low cross section electroweak processes

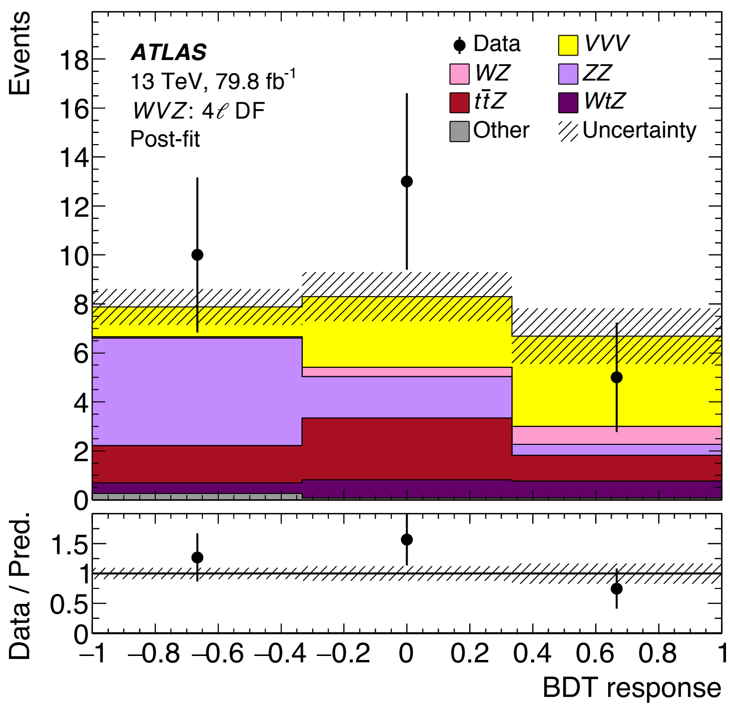
Sensitive to anomalous triple and quartic gauge couplings

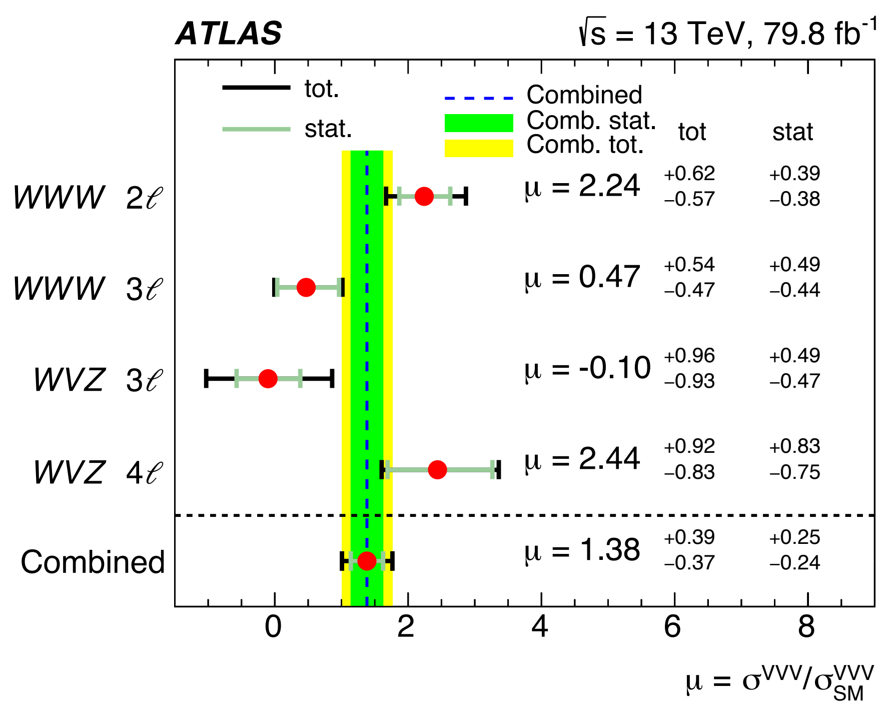
arXiv:1903.10415

Evidence for production of WVV, V = W, Z

- Requires combination of many different final states involving 2–4 leptons
- Use BDT to suppress large backgrounds
- 4.0σ (3.1 σ) observed (expected) sensitivity





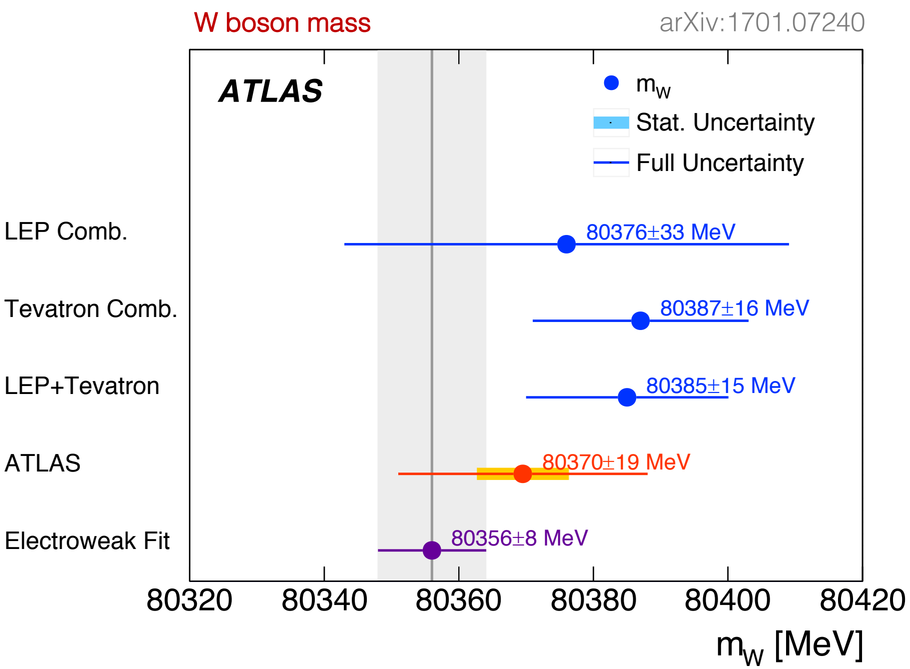


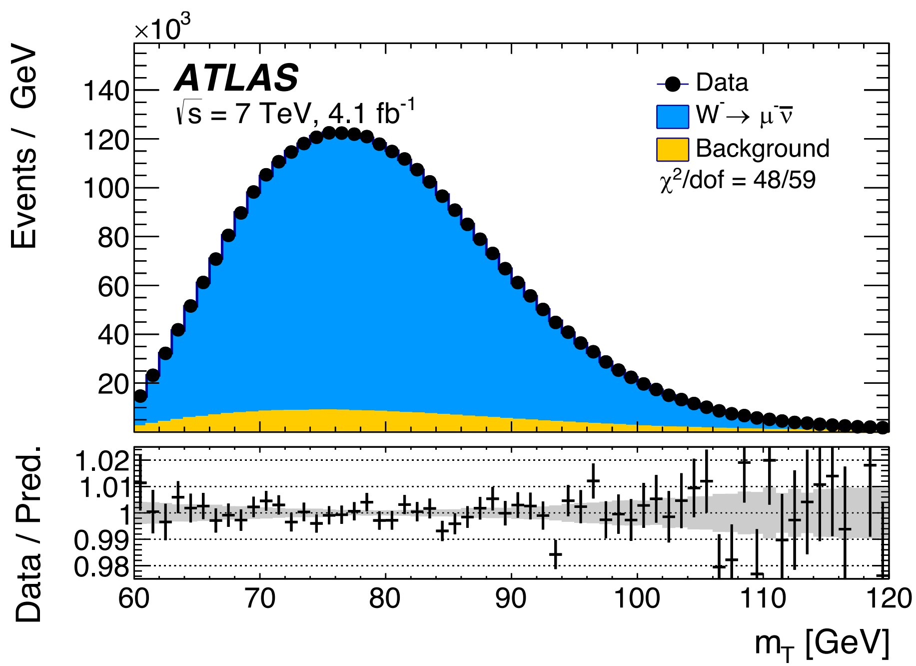
Ultimate precision is possible at the LHC

W boson mass to 0.02% and top quark mass to 0.3% precision

Measurement uses $W \to e\nu$, $\mu\nu$ events
Excellent agreement of results among e / μ channels, W^+ / W^- and $p_{T,\ell}$ / m_T

$$m_W\,(\text{ATLAS}) = 80370 \pm 7_{\text{stat}} \pm 11_{\text{exp syst}} \pm 14_{\text{mod syst}}\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV}$$





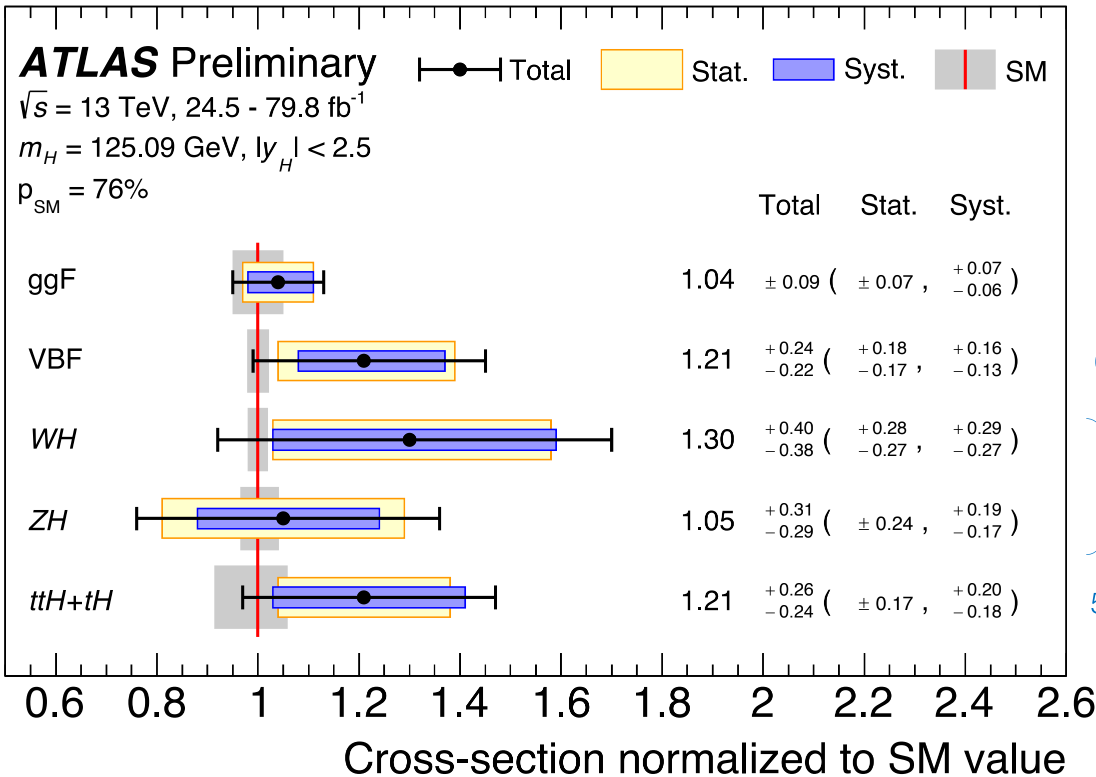
New ATLAS Higgs combination, including data up to 80 fb^{-1}

New ATLAS combination establishes observation of all major production modes

Not yet including latest ttH($\gamma\gamma$) result

- Includes $\gamma\gamma$, ZZ*, μμ, VH(bb), ttH($\gamma\gamma$) with 80 fb^{-1}
- All other channels using 36 fb^{-1}

ATLAS-CONF-2019-005



Higgs production processes, assuming decays to follow SM

6.5σ

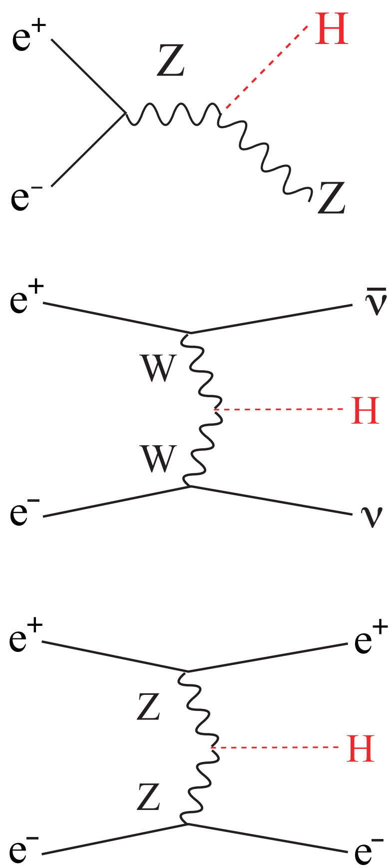
5.3σ

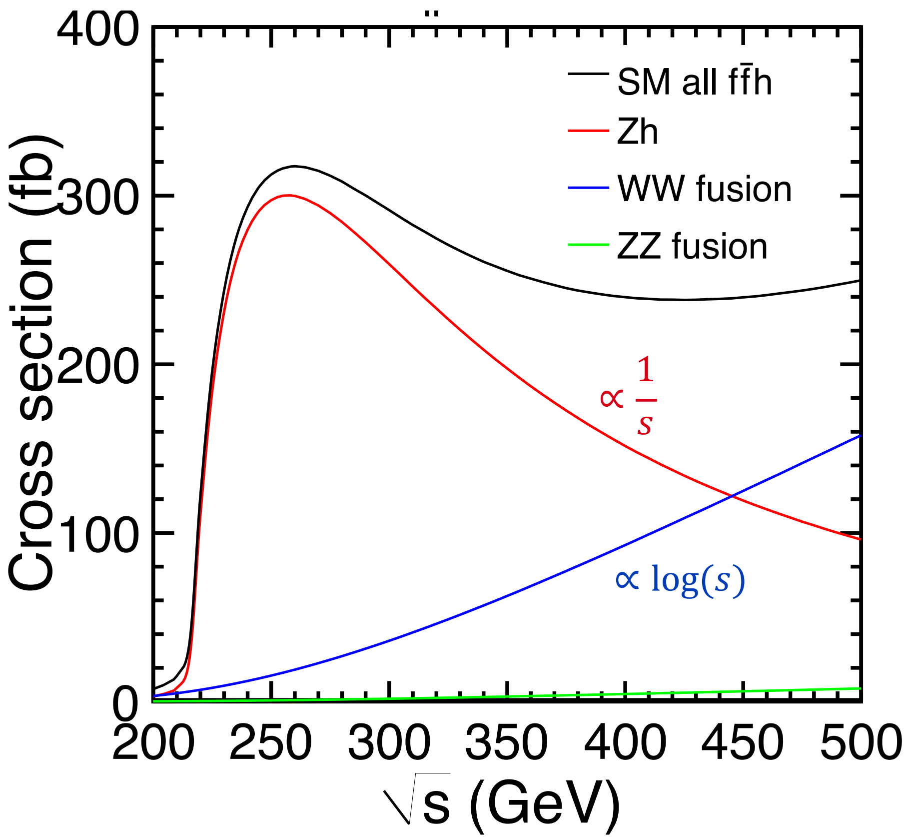
5.8σ

Overall σ(exp) / σ(SM) $= 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$

Several future e^+e^- collider options: linear (ILC, CLIC), circular (FCC-ee, CEPC)

Dominant production mechanisms: $e^+e^- \to ZH$ (Higgsstrahlung), $\nu\nu H$ (W fusion), eeH (Z fusion)

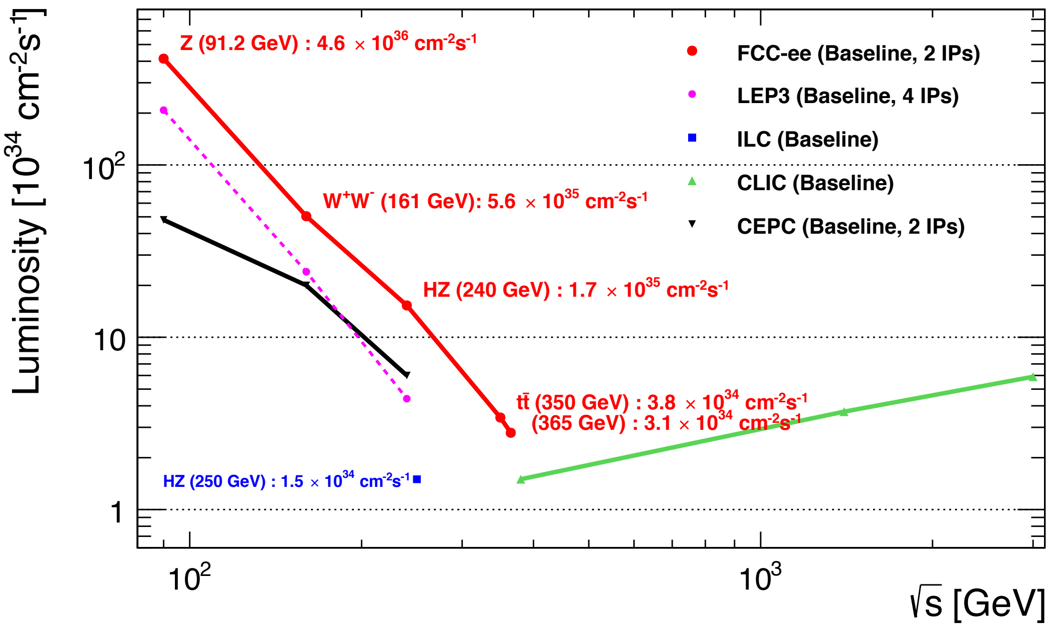




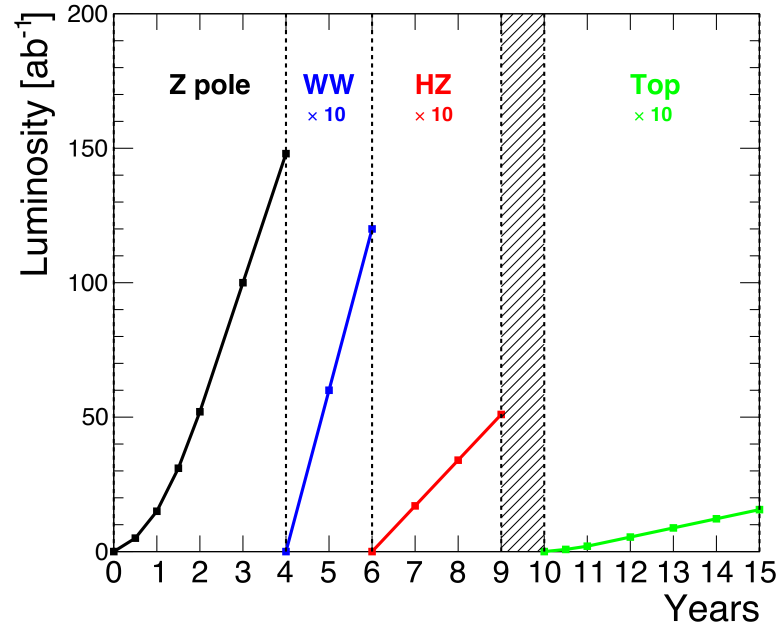
Future e+e– collider

Several future e⁺e⁻ collider options: linear (ILC, CLIC), circular (FCC-ee, CEPC)

Baseline luminosity scenarios



Operational model for FCC-ee



Run plan for FCC-ee baseline configuration with two experiments

Phase	Run duration (years)	Centre-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^{8} WW events
FCC-ee-H	3	240	5	10^{6} ZH events
FCC-ee-tt	5	345-365	1.5	10^{6} $t\bar{t}$ events

> 10^5 × LEP

Comparison among colliders

Numbers taken from Nov 2018 FCC CDR (Physics case)

Uncertainties in %

Coupling	HL-LHC	ILC 240 GeV, 2 ab^{-1}	FCC-ee 240 GeV, 5 ab^{-1}	FCC-ee → 365 GeV, 6.5 ab^{-1}	Comments
κ_γ	1.8	6.4	4.7	3.8	All e$^+$e$^-$ uncertainties are statistical only **Experimental systematic uncertainties expected to be small, unlike at LHC** **BR$_{inv}$ sensitivity ten times better at lepton colliders than LHC** FCC-ee numbers taken from recent CDR CEPC numbers similar to FCC-ee[240]
κ_W	1.7	1.7	1.3	0.5	
κ_Z	1.5	0.35	0.25	0.22	
κ_g	2.5	2.2	1.7	1.0	
κ_t	3.4	~5% @ ILC-500	–	–	
κ_b	3.7	1.8	1.4	0.7	
κ_c	UL	2.3	1.8	1.2	
κ_τ	1.9	1.9	1.4	0.8	
κ_μ	4.3	13	10	9	
$\kappa_{Z\gamma}$	9.8	–	–	–	
Γ_H	~50% (model dep.)	3.8	1.8	1.6	
λ_{HHH}	~60%	~30% @ ILC-500	~40% through loops + EFT		FCC-hh: ~5%, CLIC: 10~15%