

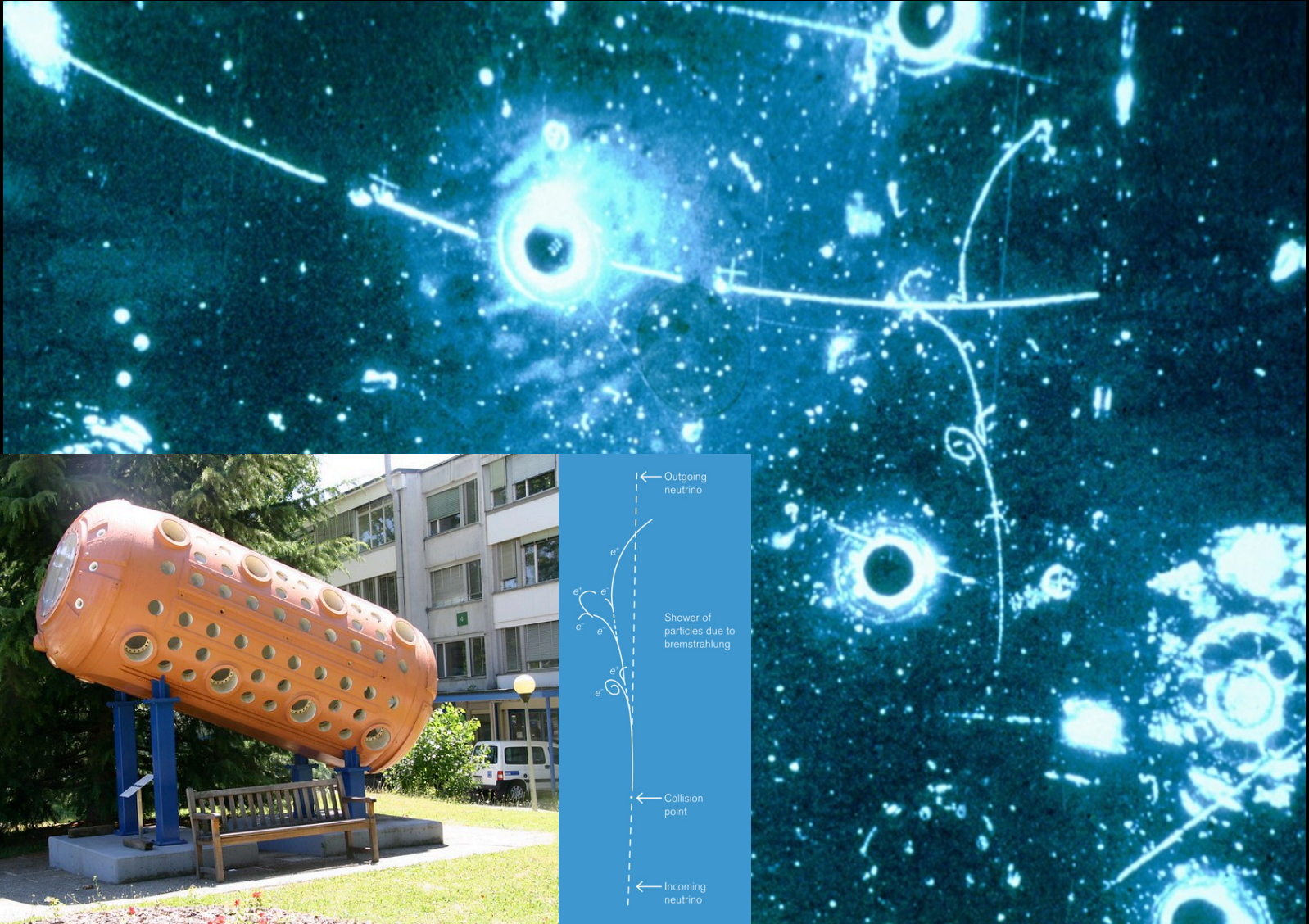
Highlights from the ATLAS experiment

Andreas Hoecker (CERN)

TIC-HEAP 2019, 19–21 October 2019, Constantine, Algeria

ATLAS
EXPERIMENT

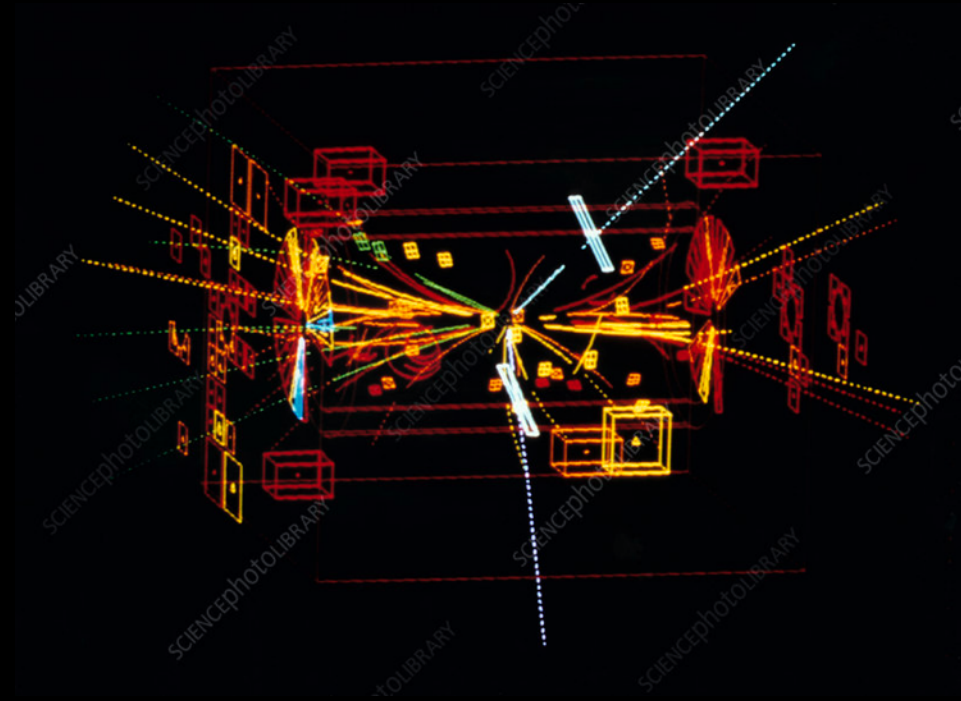
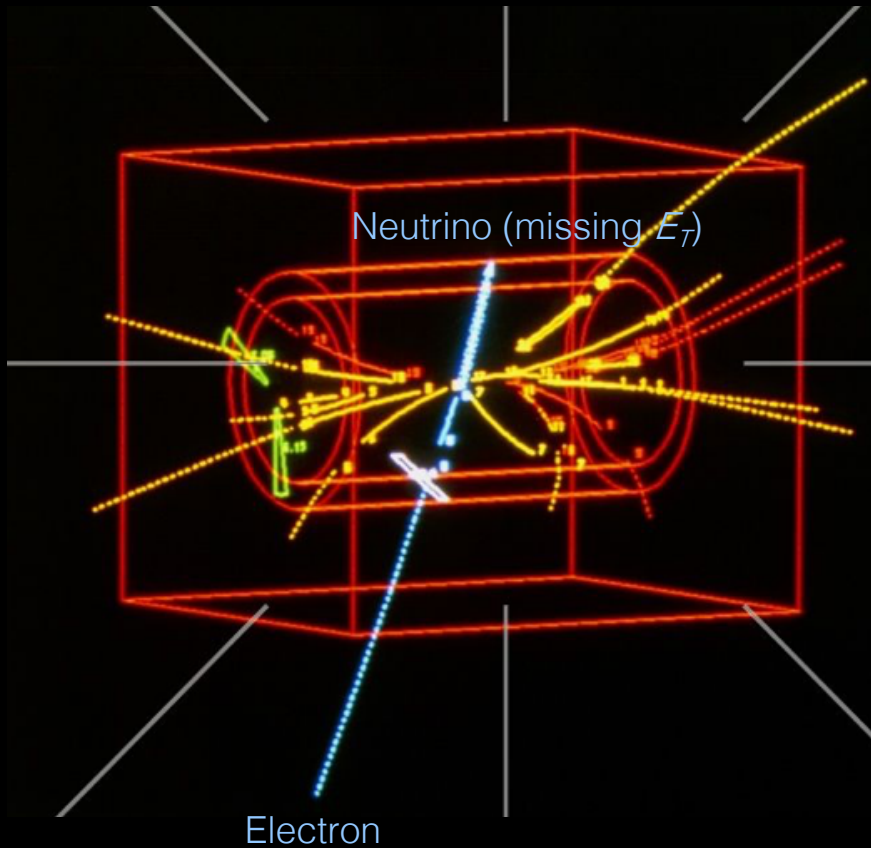
Experimental particle physics has come a long way...



Event shows tracks produced in the 1200 litre Gargamelle bubble chamber that provided the first direct evidence of a neutral current (Z boson) interaction in 1973. EPS High Energy and Particle Physics Prize in 2009.

Nobel prize for Glashow, Salam and Weinberg in 1979 for EW theory

... over discovering the W and Z bosons by UA1 & UA2 at CERN's SPS collider in 1983



Nobel prize for Rubbia and van der Meer in 1984 for their contributions to collider and experiments which led to the W and Z boson discovery

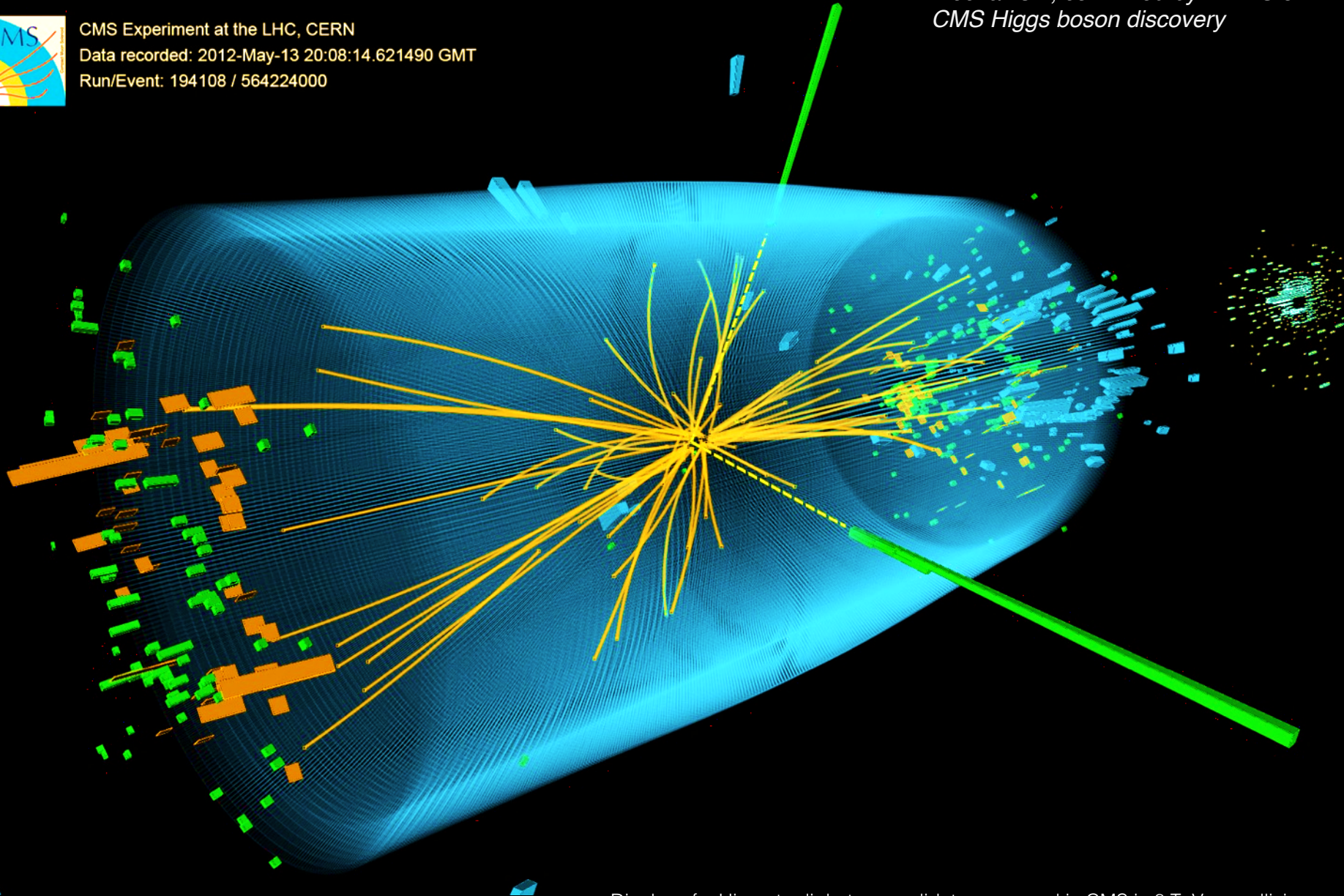
Displays show W (left) and Z (right) boson candidates from proton-antiproton collisions measured in the UA1 detector

... to produce and observe this:



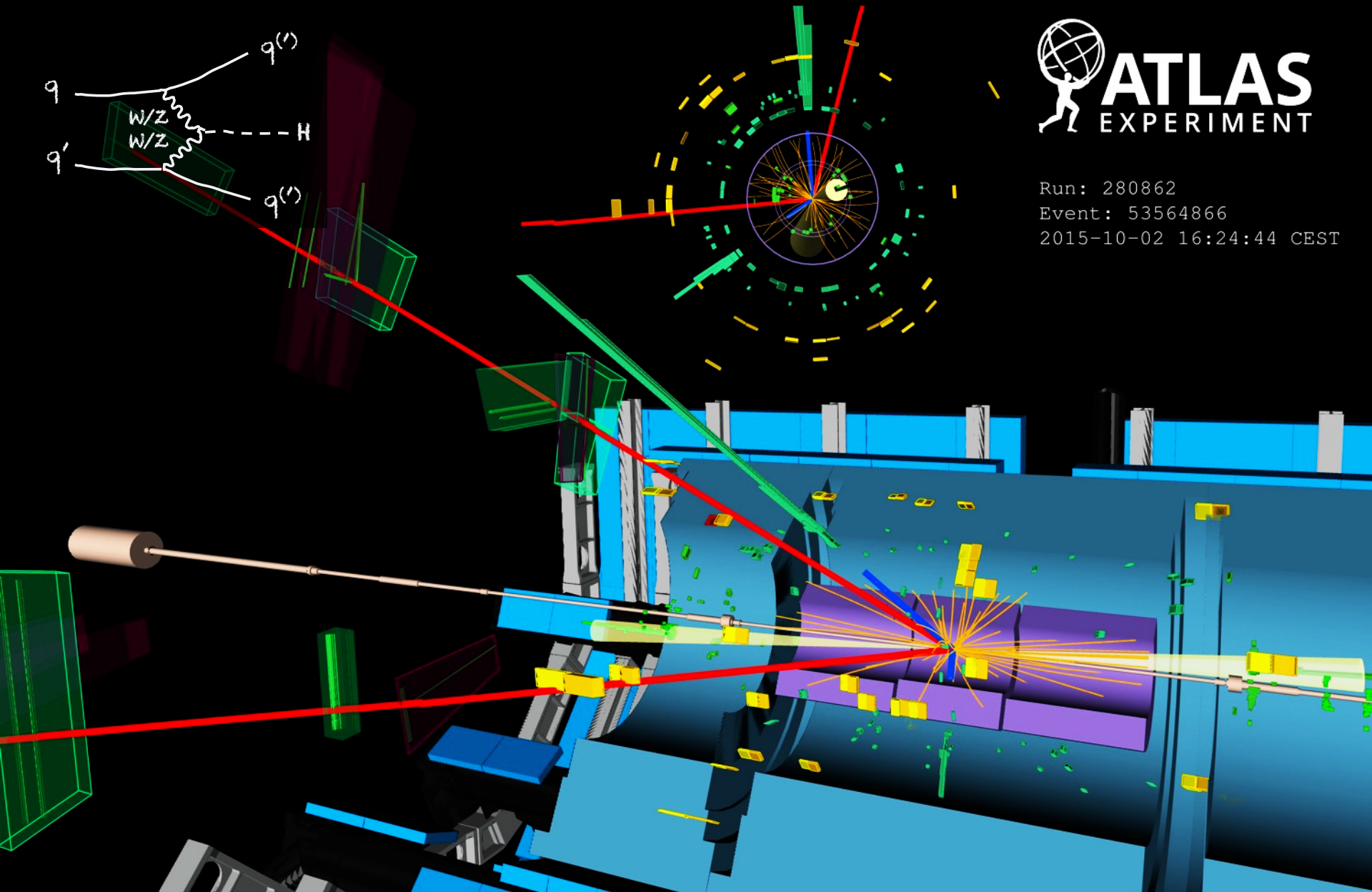
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

*Nobel prize for Englert & Higgs in
2013 for the development of the BEH
mechanism, confirmed by ATLAS &
CMS Higgs boson discovery*



Display of a Higgs to diphoton candidate measured in CMS in 8 TeV pp collisions

... to producing and observing this:



Display of VBF $H \rightarrow e\bar{e}\mu\mu + 2 \text{ jets}$ candidate from 13 TeV pp collisions recorded in 2015

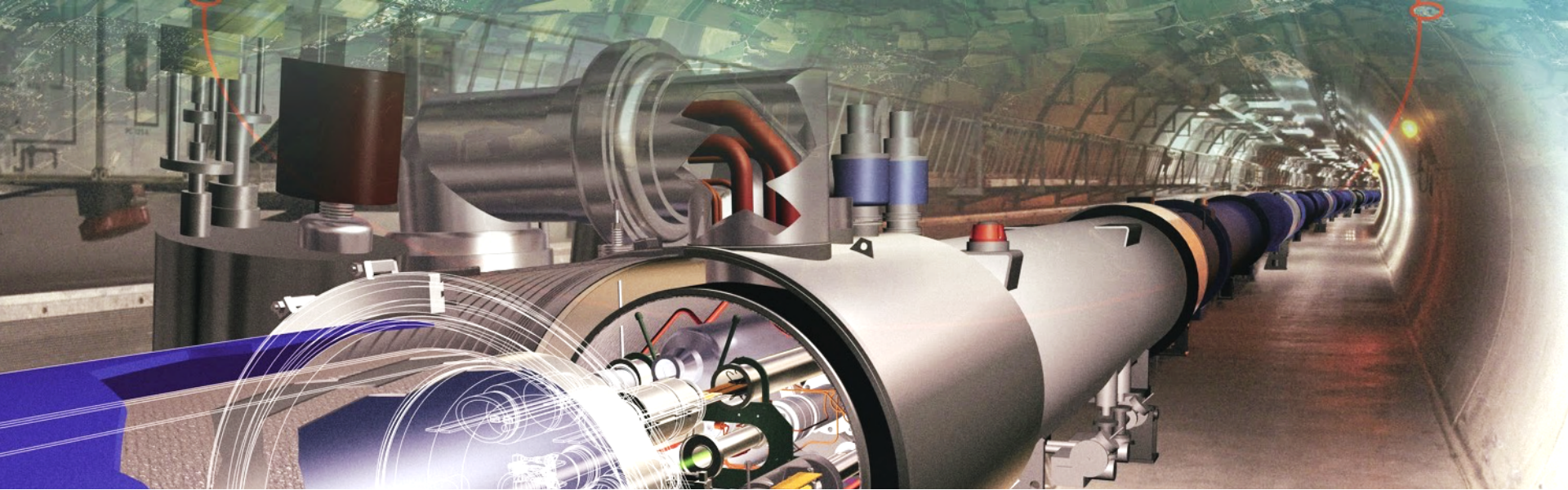
... and this:

Run: 329716
Event: 857582452
2017-07-14 10:48:51 CEST



ATLAS
EXPERIMENT

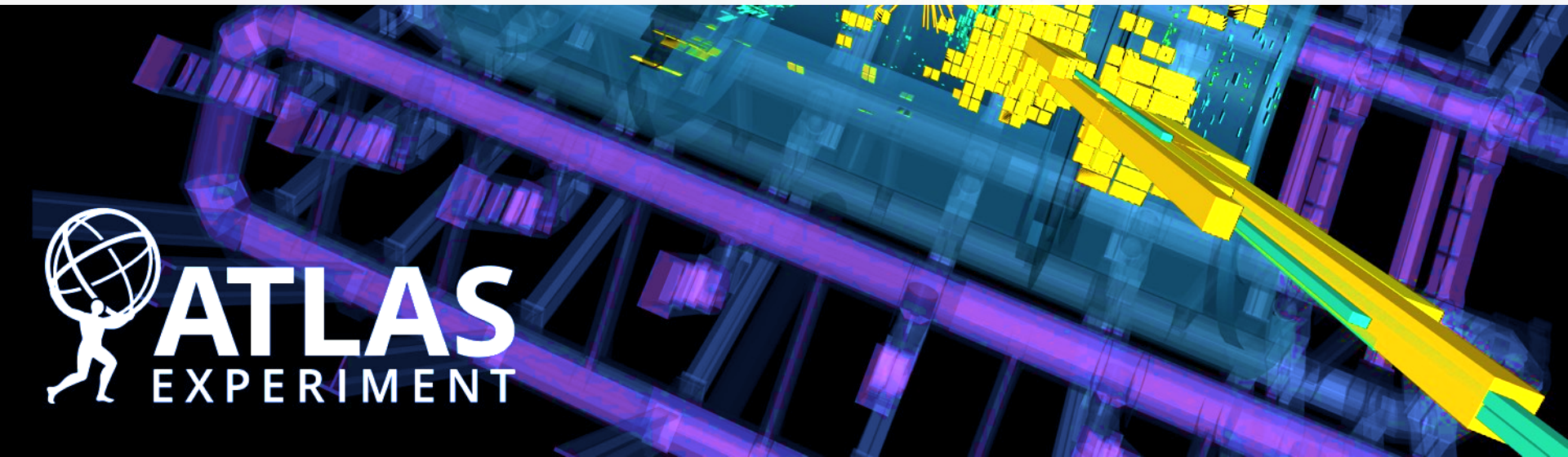
Display of di-jet event with $m_{jj}=9.3$ TeV, produced in pp collisions at $\sqrt{s} = 13$ TeV in 2017.
The two high- p_T jets both have $p_T=2.9$ TeV, one is at $\eta=-1.2$ and the other at $\eta=0.9$.



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



ATLAS
EXPERIMENT



LHC: Superconducting proton/ion accelerator & collider installed in 27 km circumference underground tunnel

LHC ring at CERN:
27 km circumference

70 – 140 m depth

CMS

LHC
control
room

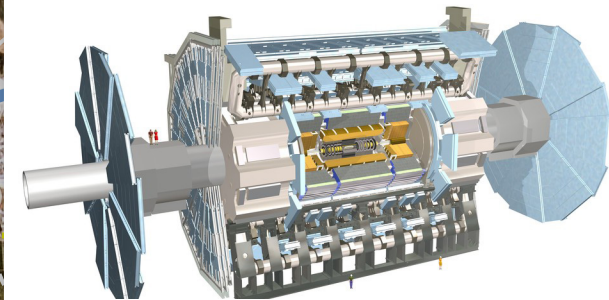
CERN (Prévessin site)

LHCb

SPS ring:
7 km circumference

ALICE

CERN (Meyrin site)

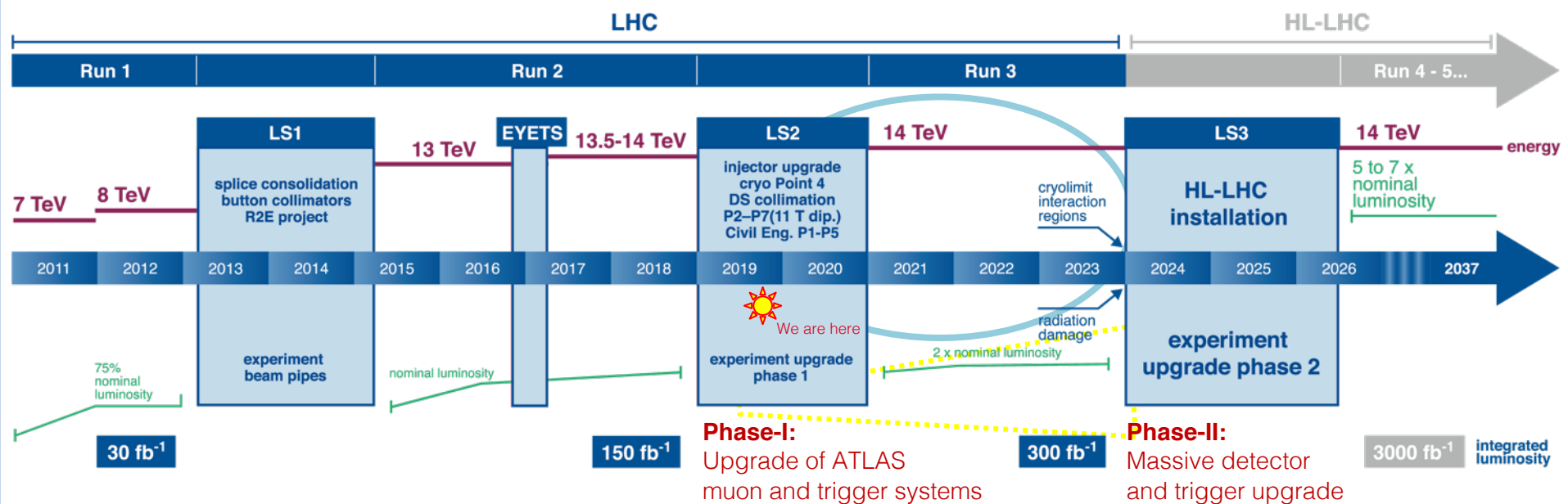


ATLAS: a large, sophisticated
general purpose particle detector

LHC: Superconducting proton/ion accelerator & collider installed in 27 km circumference underground tunnel

LHC ring at CERN:
27 km circumference

LHC / HL-LHC Plan

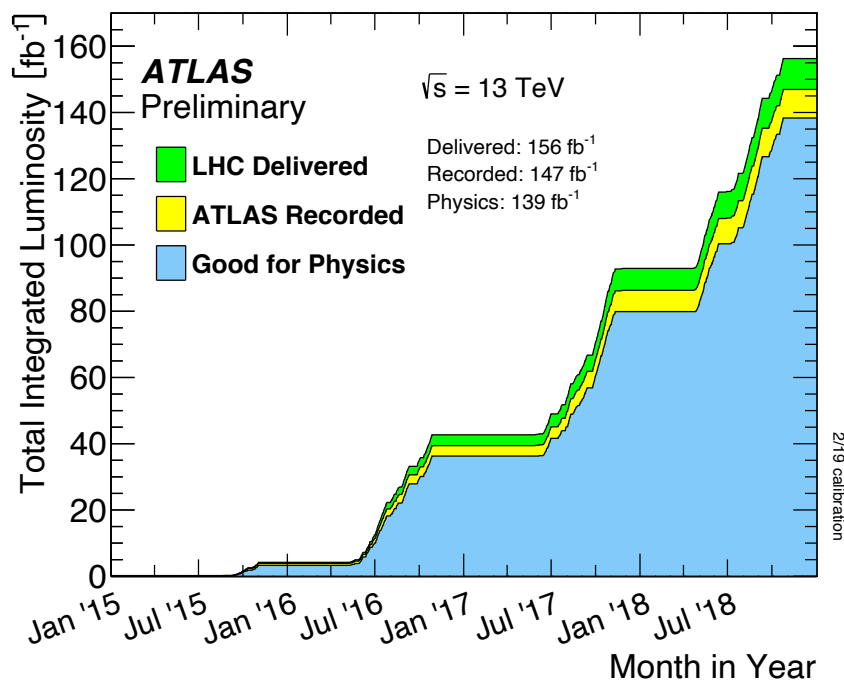


LHC Run-2 (2015–2018)

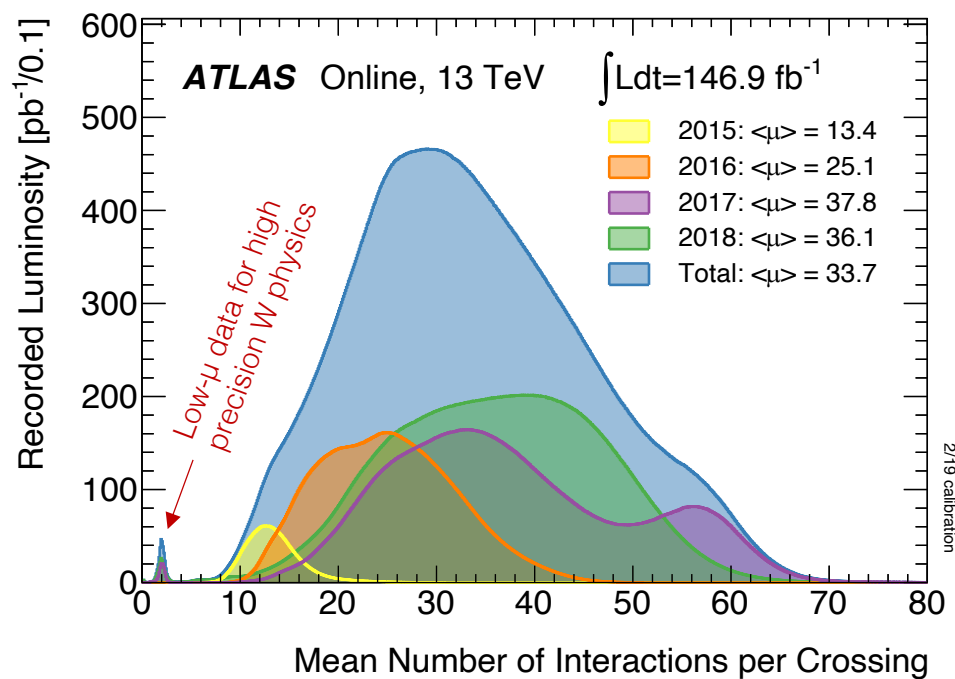
$\sqrt{s} = 13 \text{ TeV}$

Integrated pp luminosity during Run-2

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

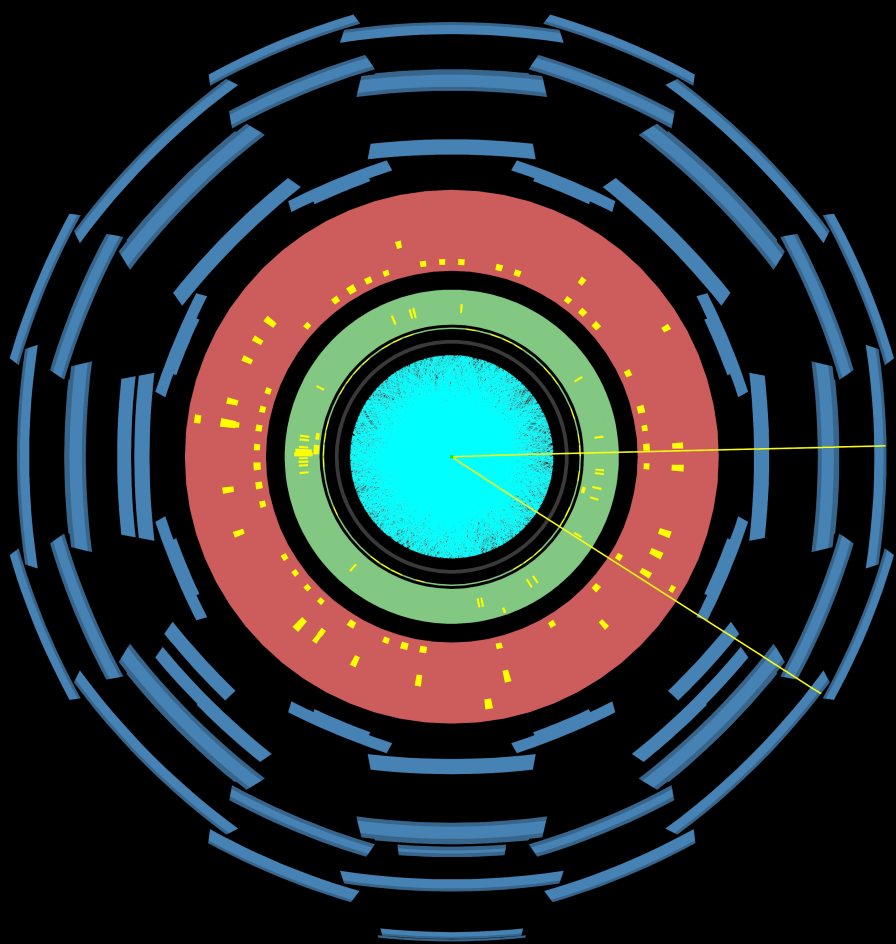


High-luminosity comes with a challenge



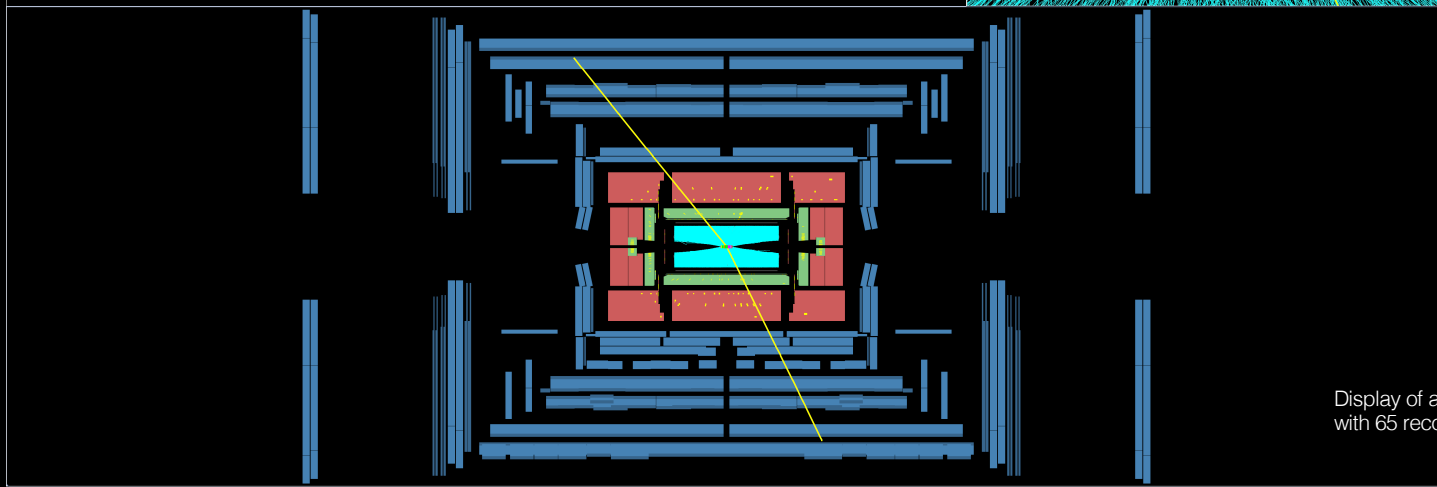
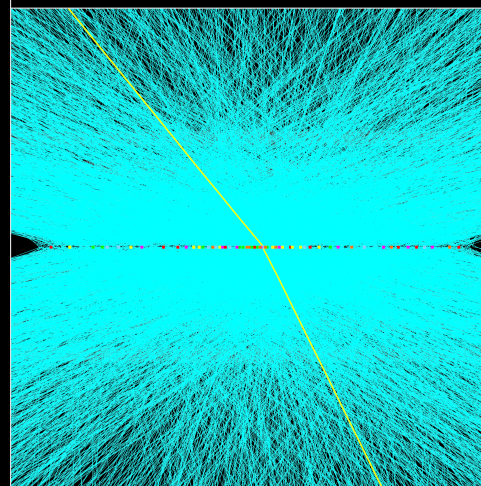
Exceptional data taking (94%) and data quality (95%) efficiencies thanks to highly committed ATLAS operator and shifter teams. Integrated luminosity in Run-2 measured to 1.7% precision

ATLAS-CONF-2019-021



Run Number: 336852, Event Number: 883966264

Date: 2017-09-29 09:19:23 CEST



Display of a $Z \rightarrow \mu\mu$ candidate event
with 65 reconstructed pileup vertices



Run Number: 336852, Event Number: 883966264

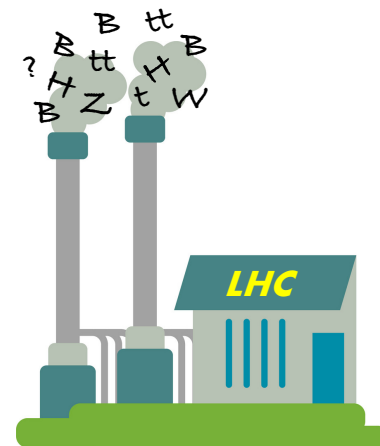
Date: 2017-09-29 09:19:23 CEST

LHC Run-2 (2015–2018)

$\sqrt{s} = 13 \text{ TeV}$

The LHC is an **everything** factory

Particle	Produced in 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$	
Higgs boson	7.8 million	
Top quark	275 million	
Z boson	8 billion	($\rightarrow \ell\ell$, 270 million per flavour)
W boson	26 billion	($\rightarrow \ell\nu$, 2.8 billion per flavour)
Bottom quark	~ 160 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

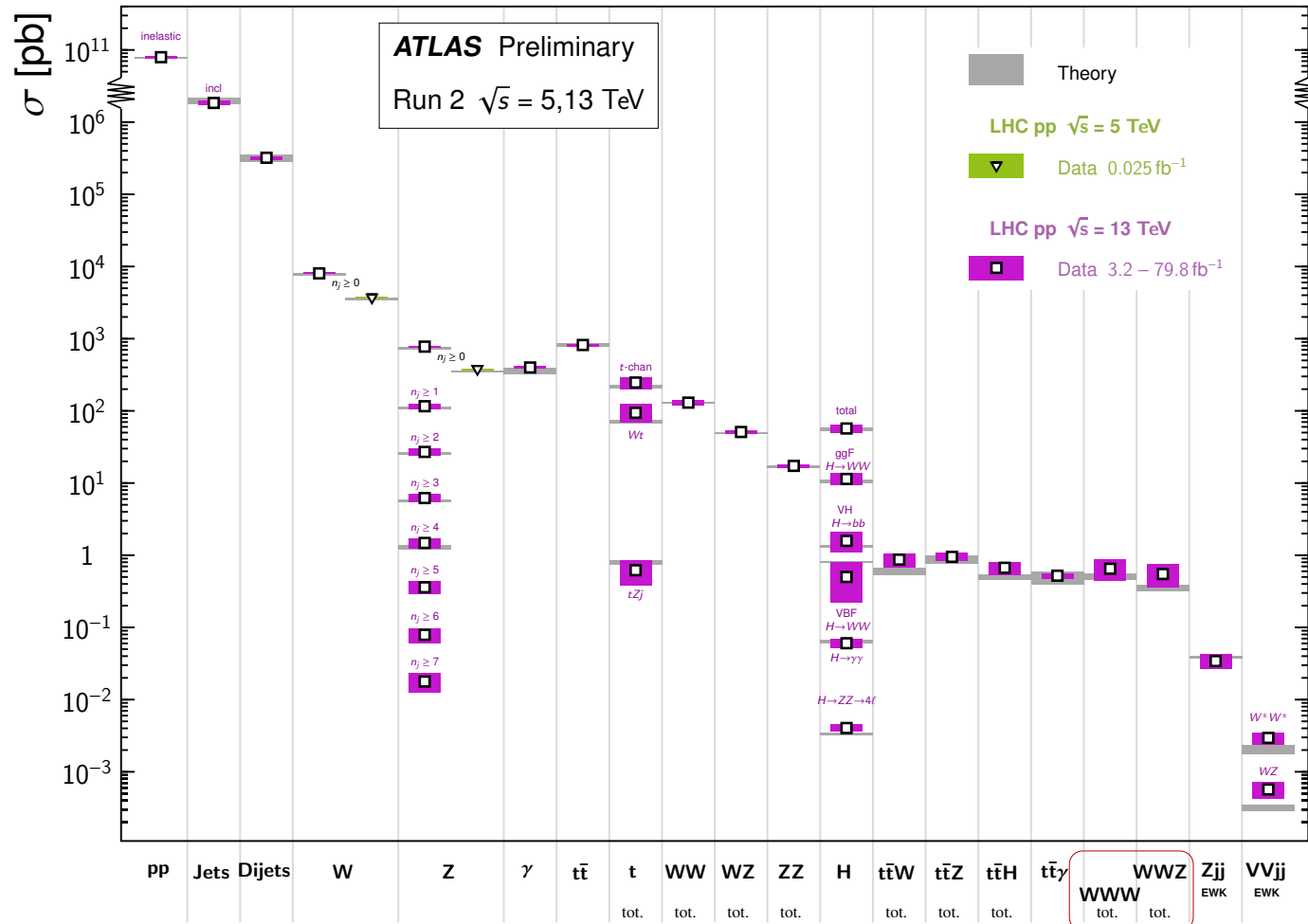
Widespread use of machine learning to increase event reconstruction performance and background suppression

Theory so far agrees with all measured cross sections

Across widely different processes

Standard Model Production Cross Section Measurements

Status: July 2019



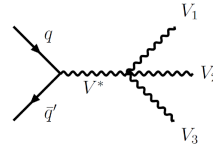
Harvest of ATLAS cross section measurements confirms the predictive power of the Standard Model

Also huge progress on theoretical calculations (NNLO revolution)

Many more detailed fiducial and differential cross section measurements

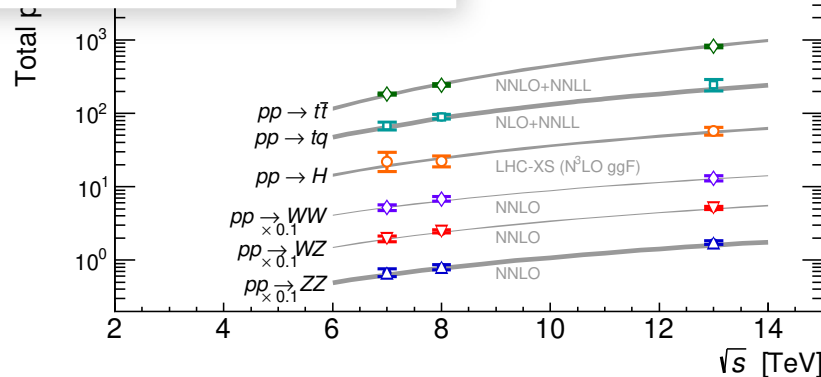
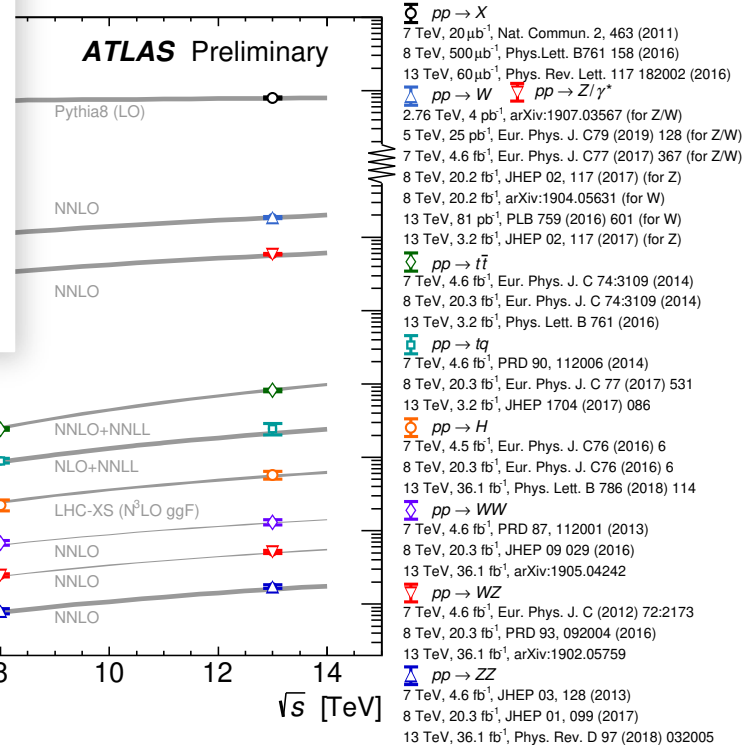
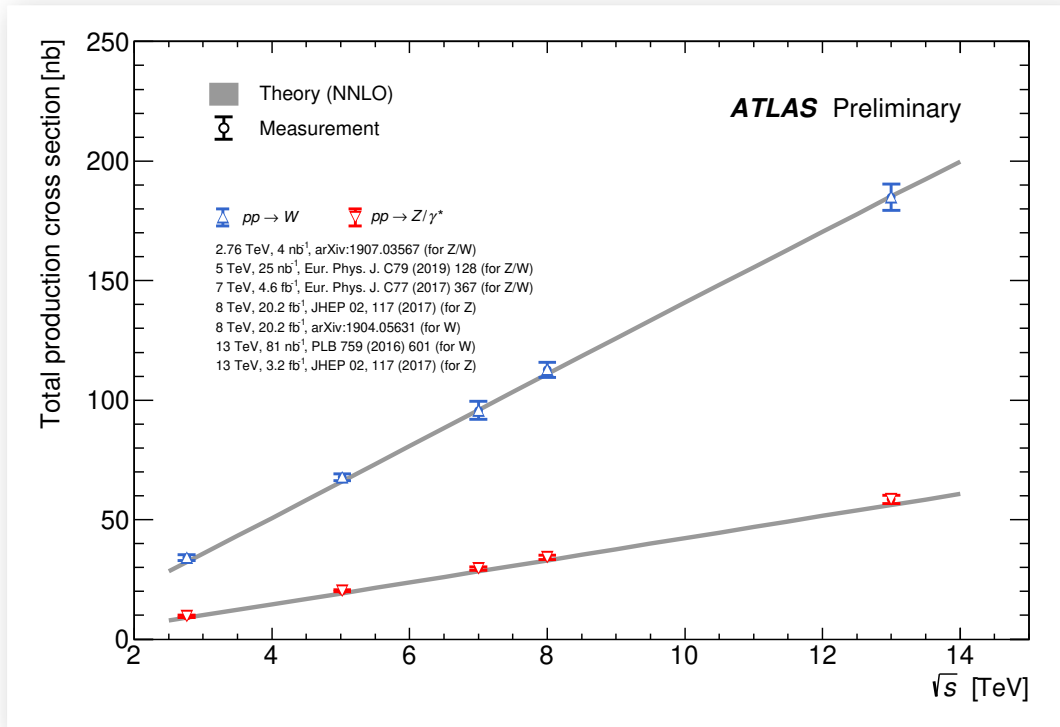
> 4 σ Evidence for weak triboson production by ATLAS using 2015–2017 data

arXiv:1903.10415



Theory so far agrees with all measured cross sections

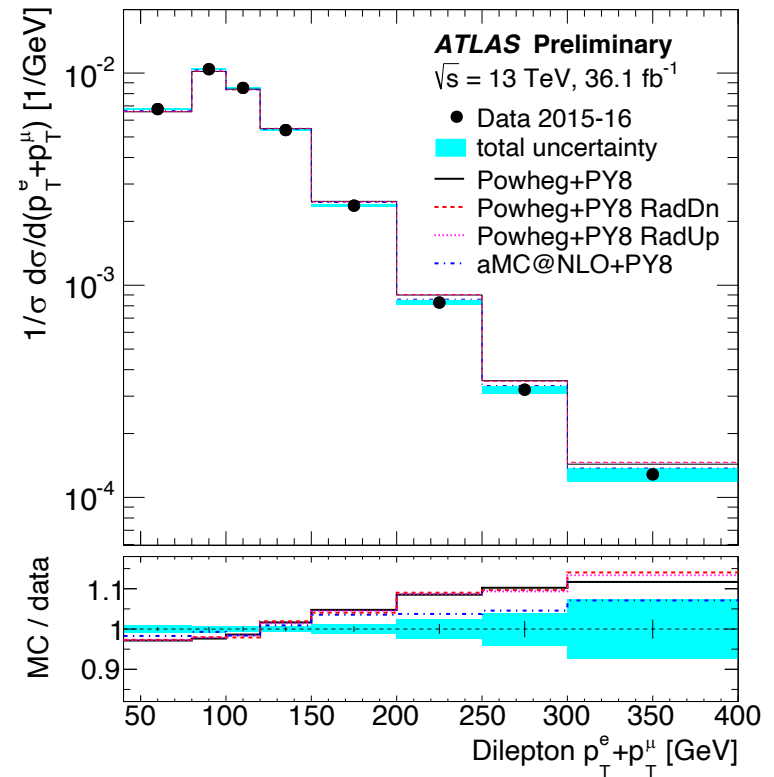
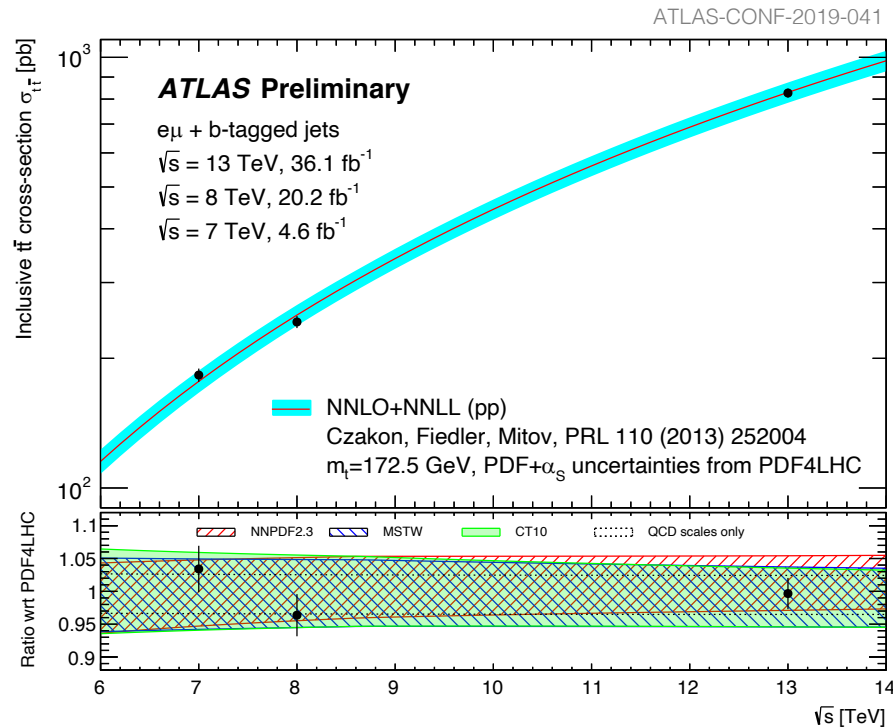
...and across centre-of-mass energies



Top-antitop production measurements

Huge top-antitop statistics at LHC allows to measure multidimensional differential cross sections

Analysis based on 36 fb^{-1} with high-precision in situ performance calibration



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

(1.9%)

NLO theoretical predictions insufficient,
improved by new NNLO calculations

High-statistics probes of top-quark charge asymmetry

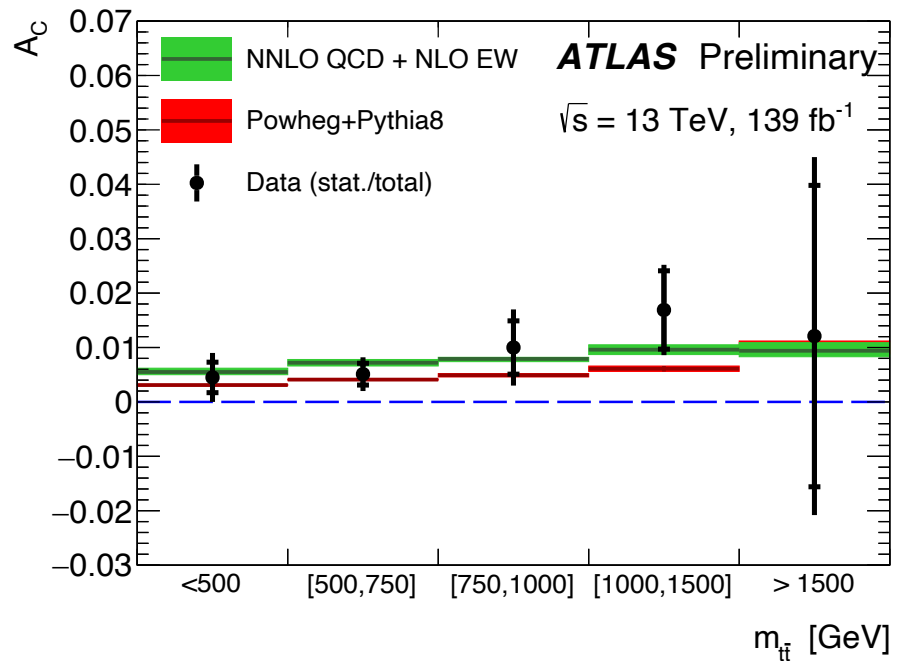
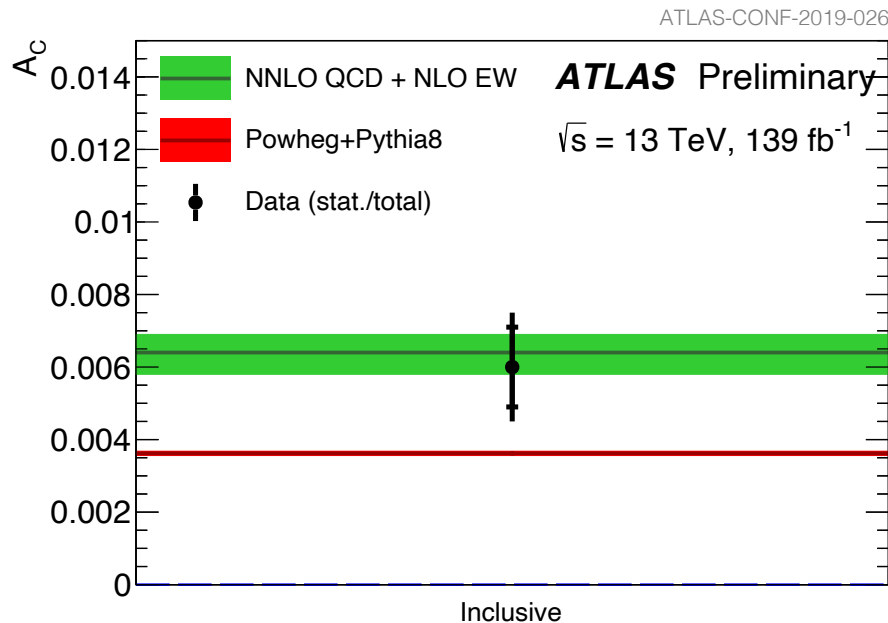
Higher order QCD effects generate charge asymmetry in pp collisions

Full Run-2

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



Consistent description in NNLO QCD with NLO EW corrections

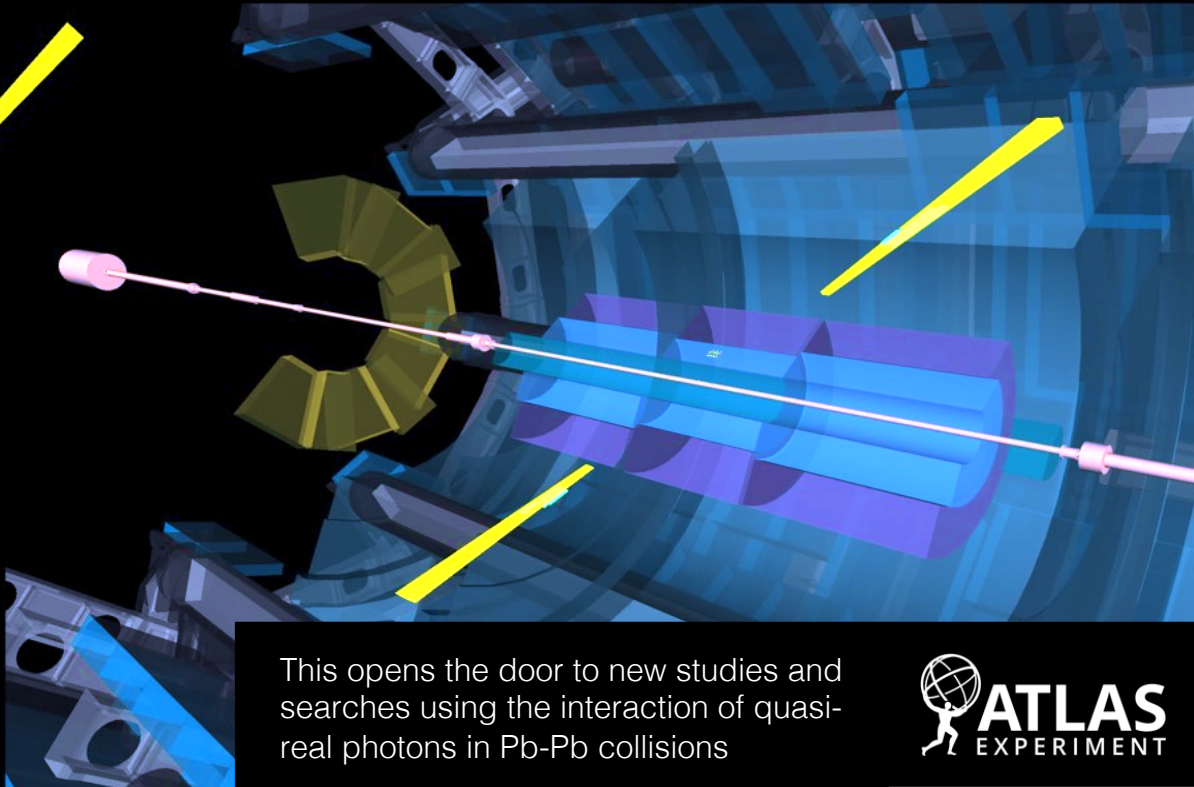
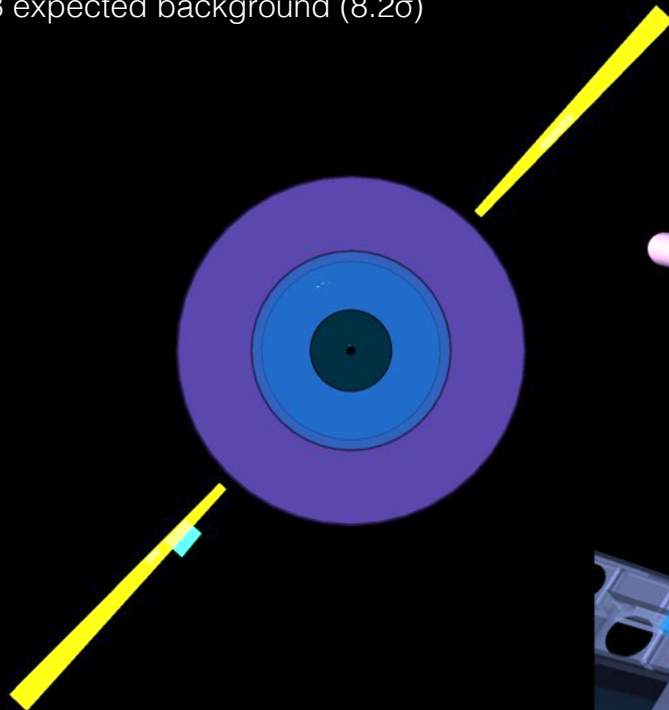
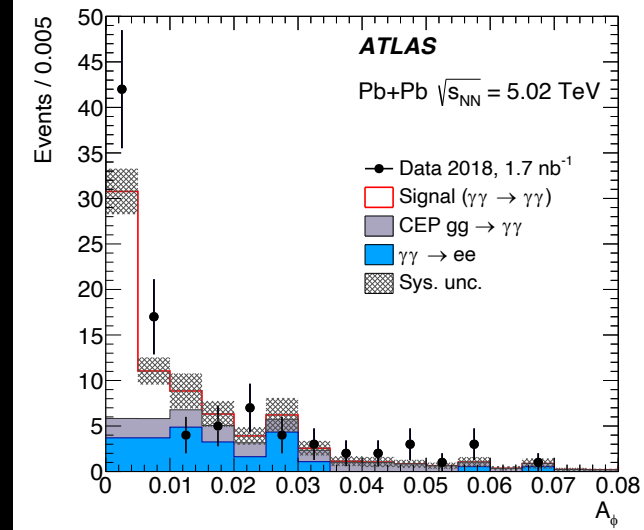
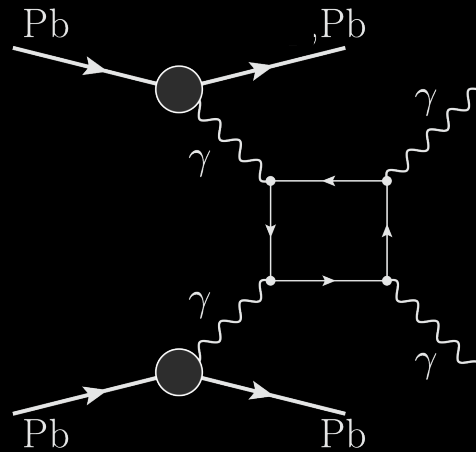
Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb+Pb collisions taken in 2018

[arXiv:1904.03536]

Field strength of up to 10^{25} V/m
 $\gamma\gamma$ luminosity $\sim Z^4 \sim 5 \cdot 10^7$

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

59 $\gamma\gamma \rightarrow \gamma\gamma$ events observed for
 12 ± 3 expected background (8.2σ)



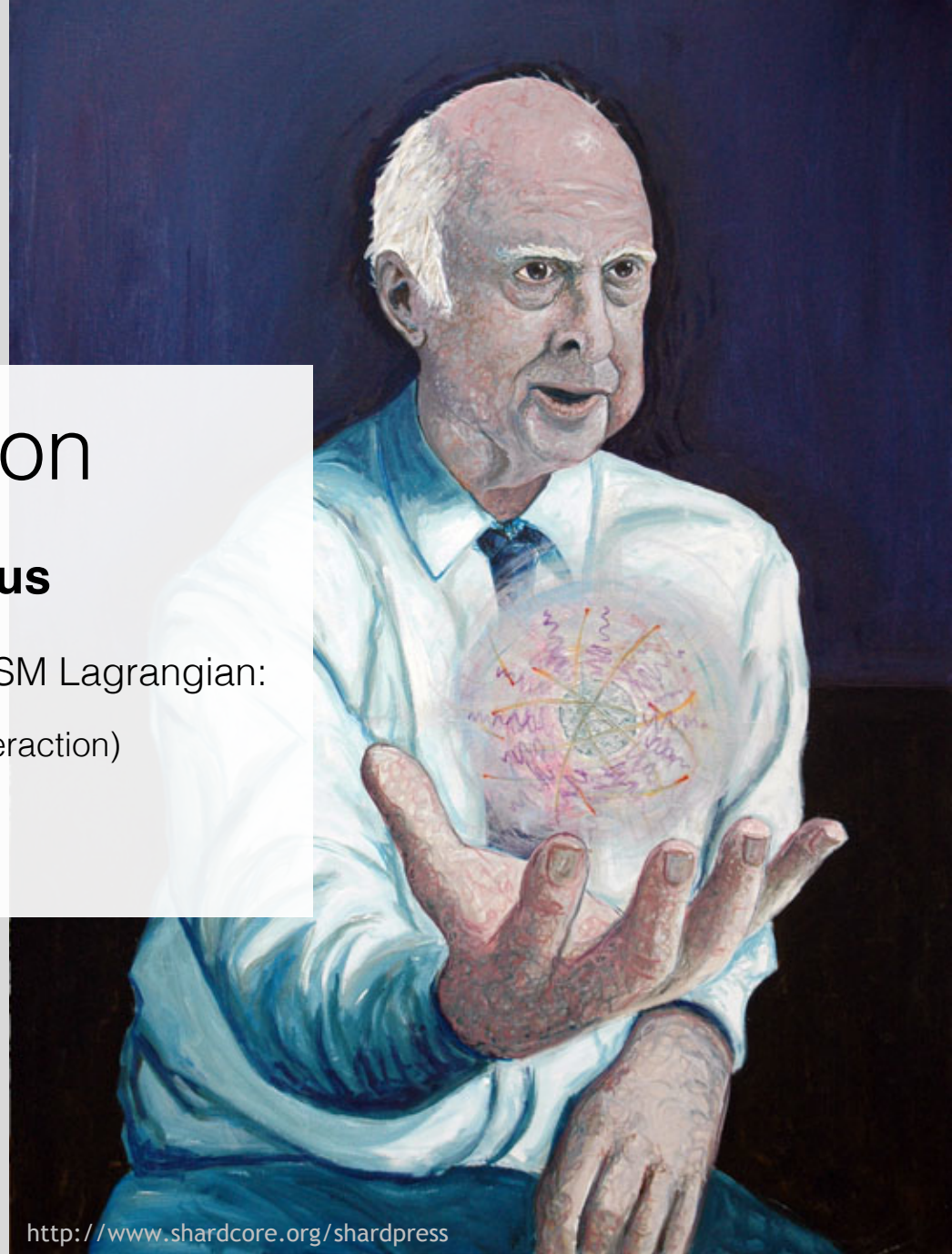
This opens the door to new studies and searches using the interaction of quasi-real photons in Pb-Pb collisions

The Higgs boson

The LHC's magnum opus

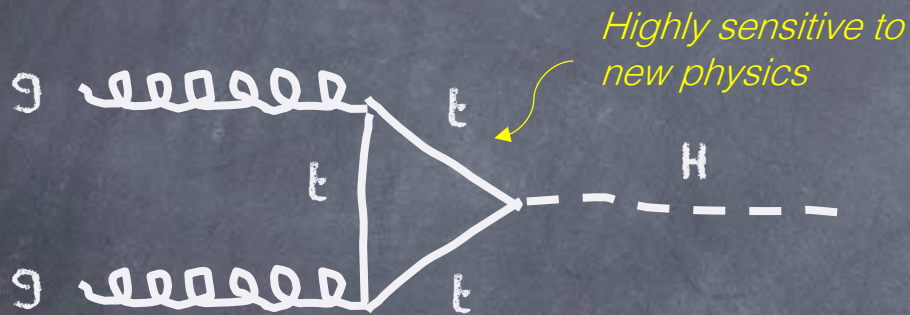
Discovery allows to access new sector of SM Lagrangian:

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



Higgs boson production at the LHC

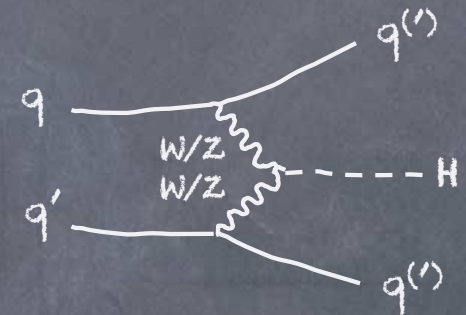
At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,\text{total}} = 56 \text{ pb}$ at $\sqrt{s} = 13 \text{ TeV}$ for $m_H = 125 \text{ GeV}$



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

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

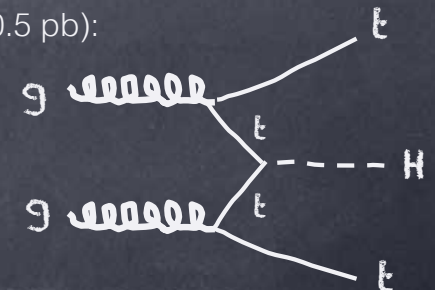
Weak boson fusion — VBF ($\sigma_{\text{VBF}} \sim 3.8 \text{ pb}$):



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



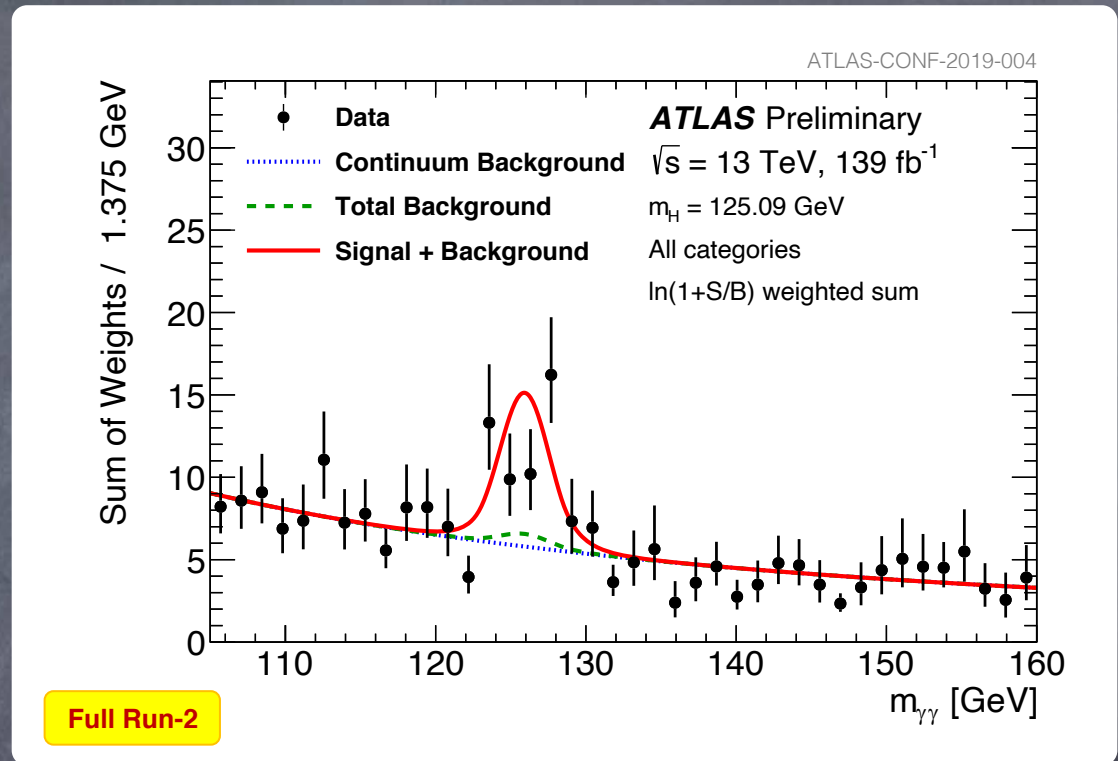
“ttH” production
($\sigma_{\text{ttH}} \sim \sigma_{\text{bbH}} \sim 0.5 \text{ pb}$):



**All major Higgs production modes
have been observed by ATLAS**

Higgs boson production at the LHC

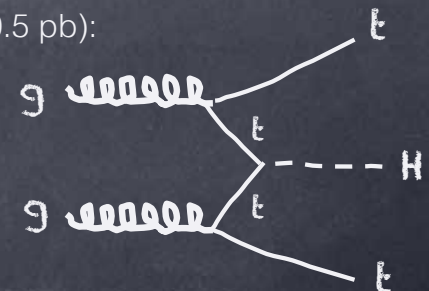
After the combined multi-channel observation of $t\bar{t}H$ with 6.3σ in 2018, ATLAS observes $t\bar{t}H$ in single diphoton channel at 4.9σ using full Run-2 dataset



$$\begin{aligned}\sigma_{t\bar{t}H} \cdot B_{H \rightarrow \gamma\gamma} &= 1.59^{+0.43}_{-0.39} \text{ fb} \\ &= 1.59^{+0.38}_{-0.36}(\text{stat})^{+0.15}_{-0.12}(\text{exp})^{+0.15}_{-0.11}(\text{theo}) \text{ fb}\end{aligned}$$

In agreement with SM prediction of $1.15 \pm 0.10 \text{ fb}$

" $t\bar{t}H$ " production
 $(\sigma_{t\bar{t}H} \sim \sigma_{b\bar{b}H} \sim 0.5 \text{ pb})$:



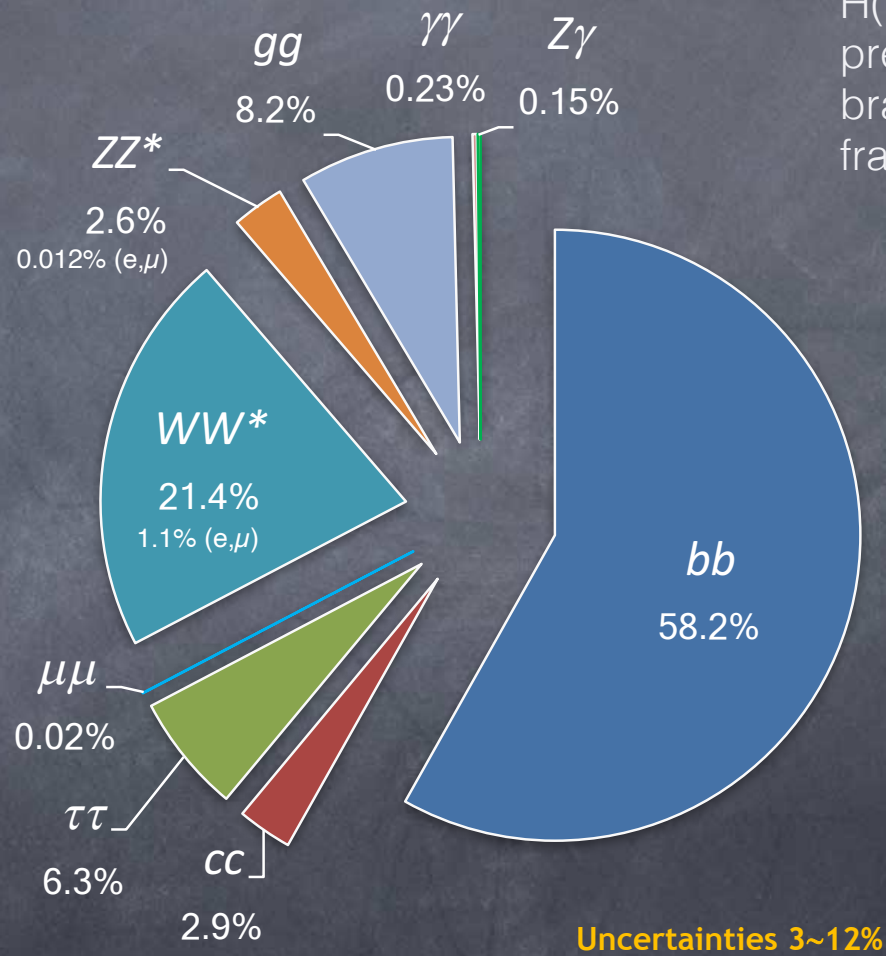
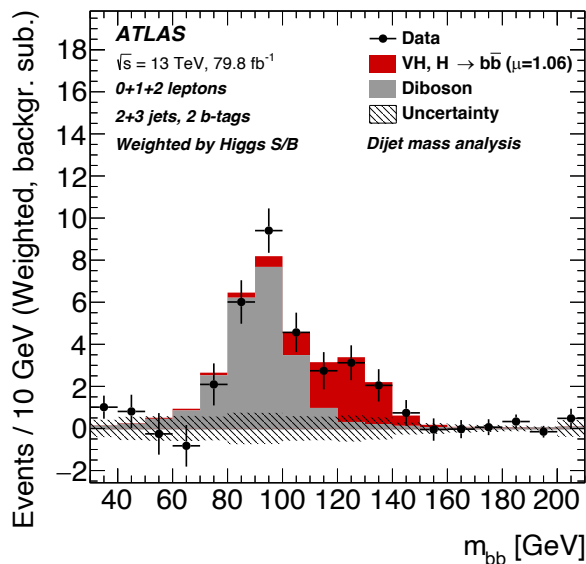
Higgs boson production at the LHC

Because Higgs boson couples to mass of particles:

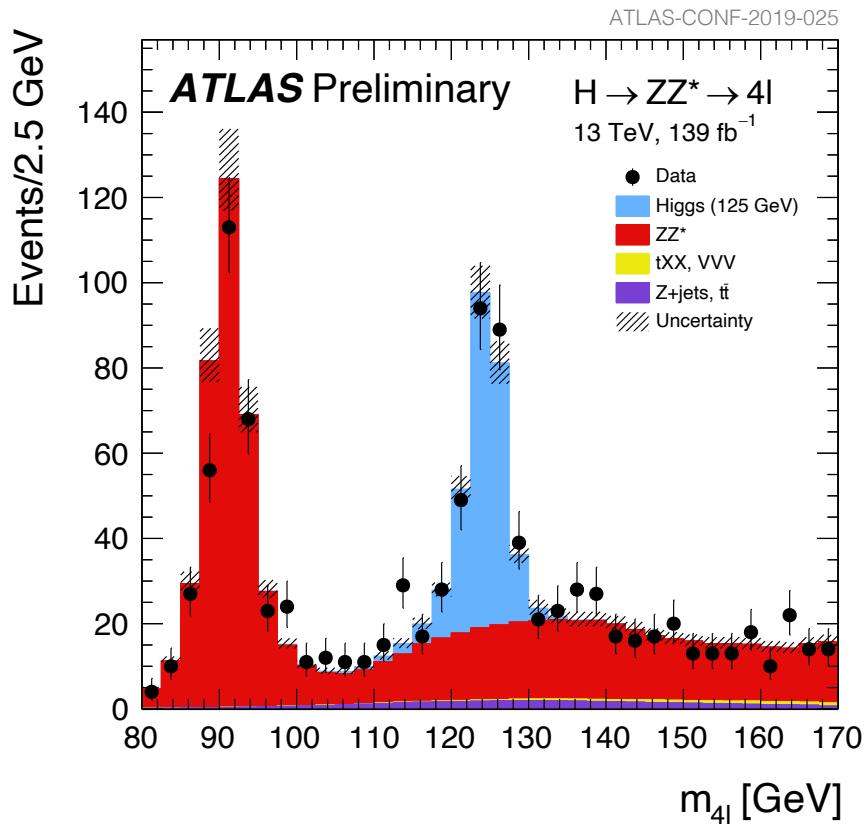
... the Higgs decays with preference to the heaviest particles allowed

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

Observation (5.3 σ) of $H \rightarrow b\bar{b}$ in 2018



Find ~ 210 $pp \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell$ 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

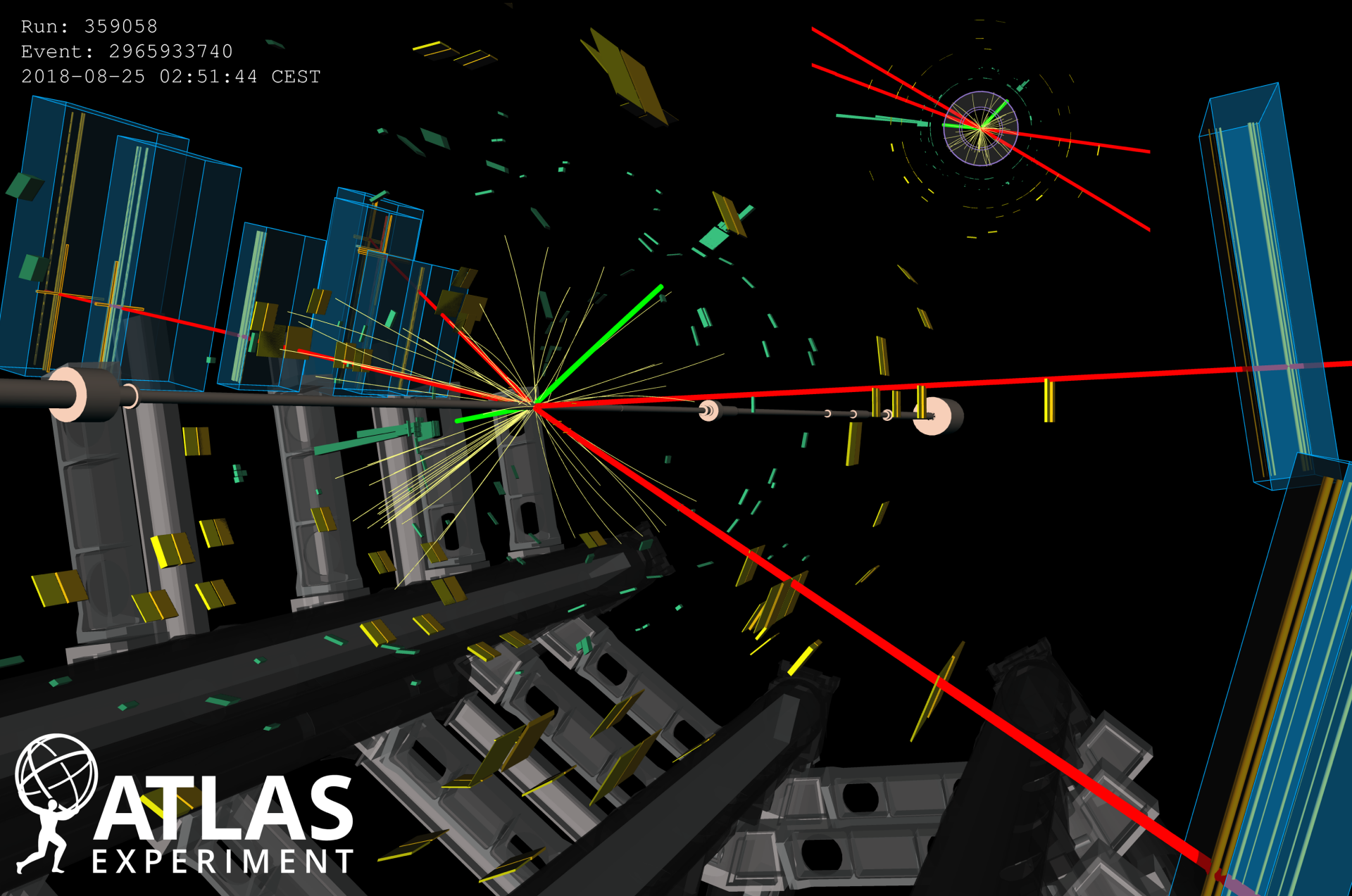


Overall $\sigma(\text{obs}) / \sigma(\text{SM})$

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

Also: Inclusive, fiducial, differential, and template cross section measurements

Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST



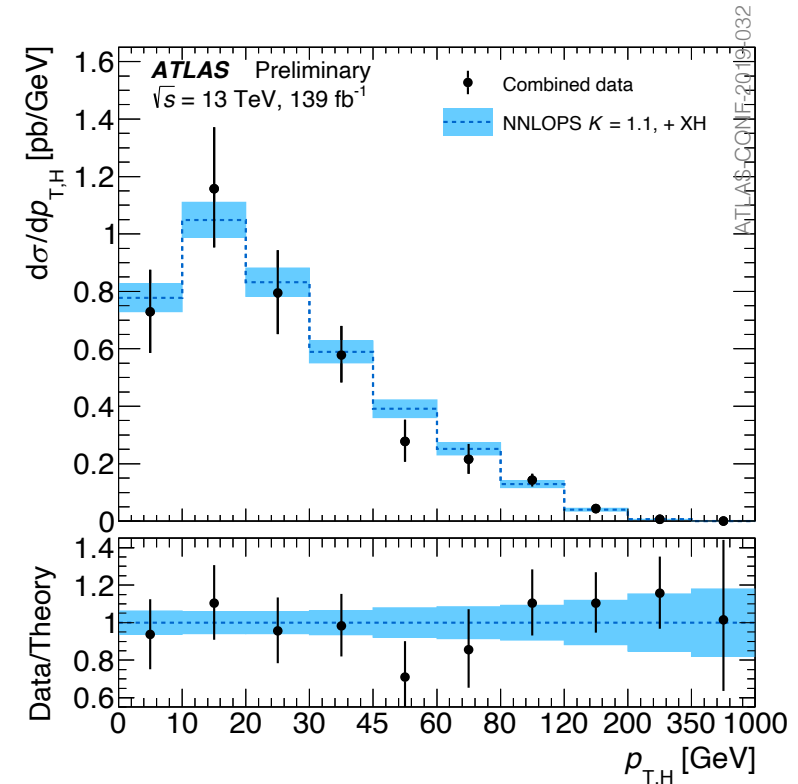
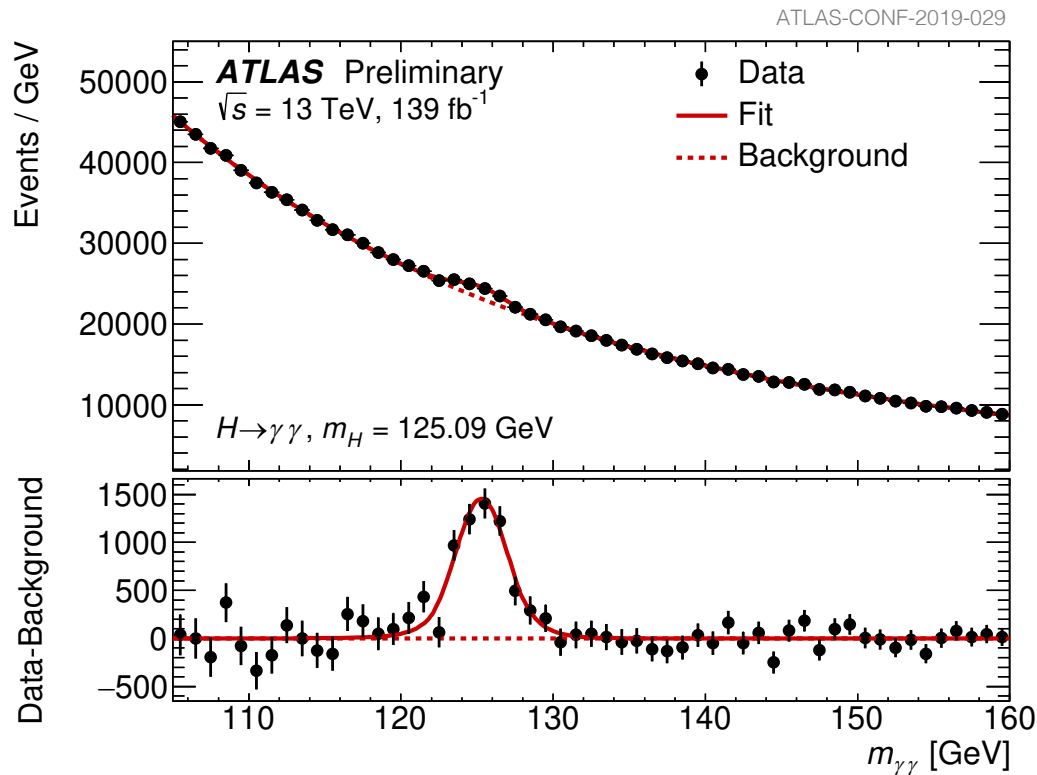
Find 6550 $pp \rightarrow H \rightarrow \gamma\gamma$ signal events in full Run-2 dataset

Rich sample to study details of Higgs production and constrain new physics

Combination of 4-lepton and diphoton channels

$$\sigma(pp \rightarrow H) = 56.7^{+6.4}_{-6.2} \text{ (comb) pb} \quad (7.8\%)$$

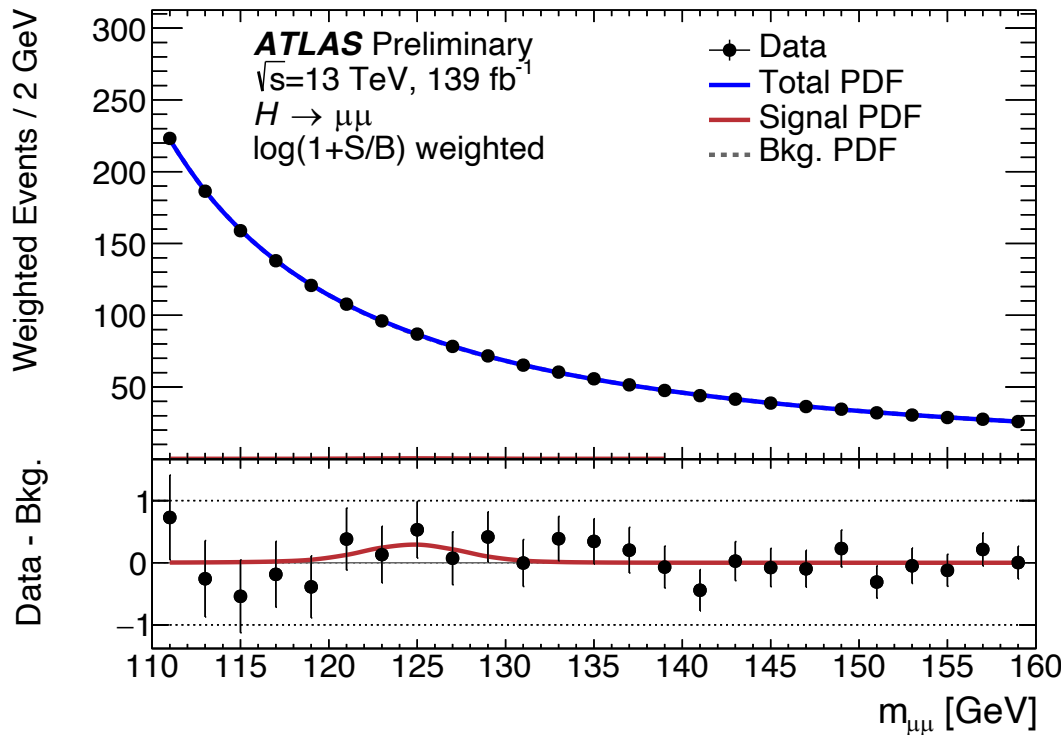
SM: 55.6 ± 2.5 pb (NLO-3NLO QCD, NLO EW)



Constraints from direct and indirect ATLAS searches for $H \rightarrow c\bar{c}$ sensitive to $\kappa_c \sim 10$
More promising: $H \rightarrow \mu\mu$, but challenging due to huge $pp \rightarrow Z/\gamma^* \rightarrow \mu\mu$ background

Analysis strongly exploits expected features of signal and background via specific categories and BDTs
Robust empirical background modelling, validated against “spurious signal” using large simulated 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

50% sensitivity improvement over 2018 (80 fb⁻¹) analysis

The Higgs boson as a *portal* to beyond the SM physics

Higgs is narrow: 4.1 MeV (SM)

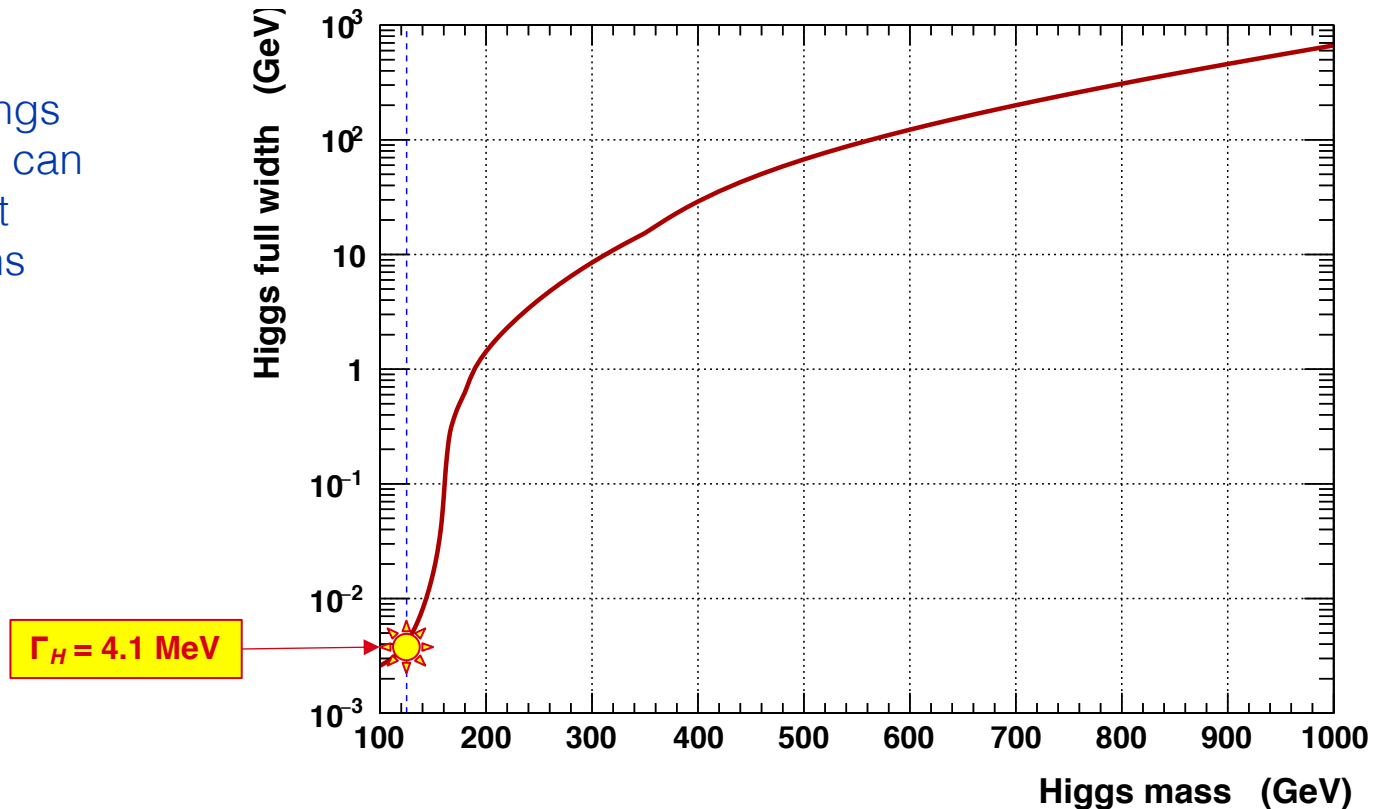
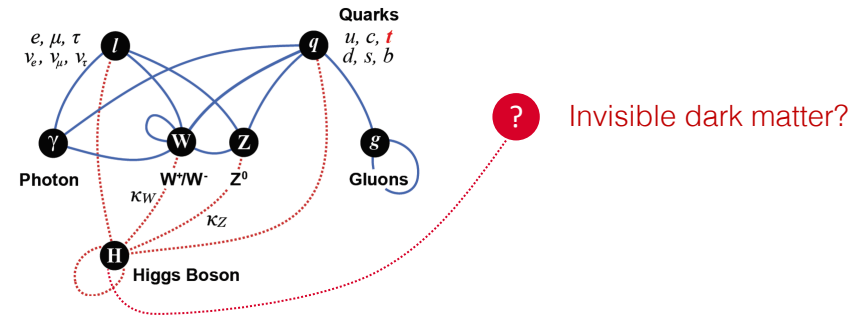
For comparison:

$$\Gamma_W = 2085 \text{ MeV}$$

$$\Gamma_Z = 2495 \text{ MeV}$$

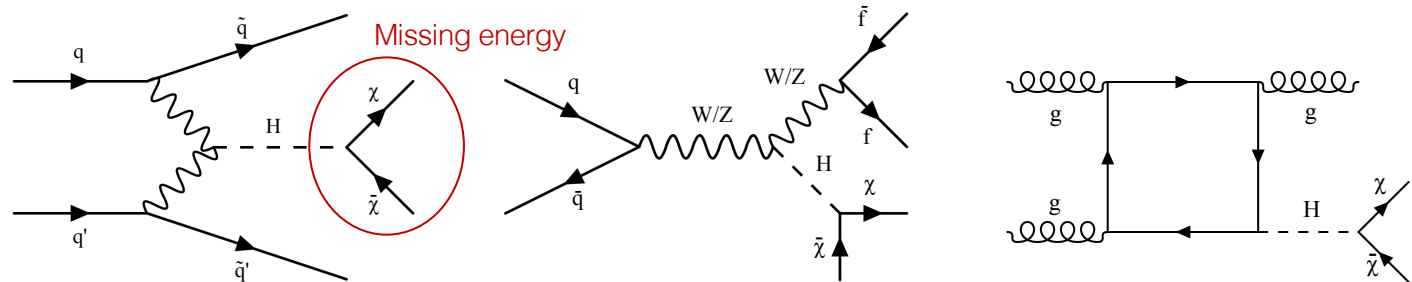
$$\Gamma_{\text{top}} = 1350 \text{ MeV}$$

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



Search for dark matter through invisibly decaying Higgs

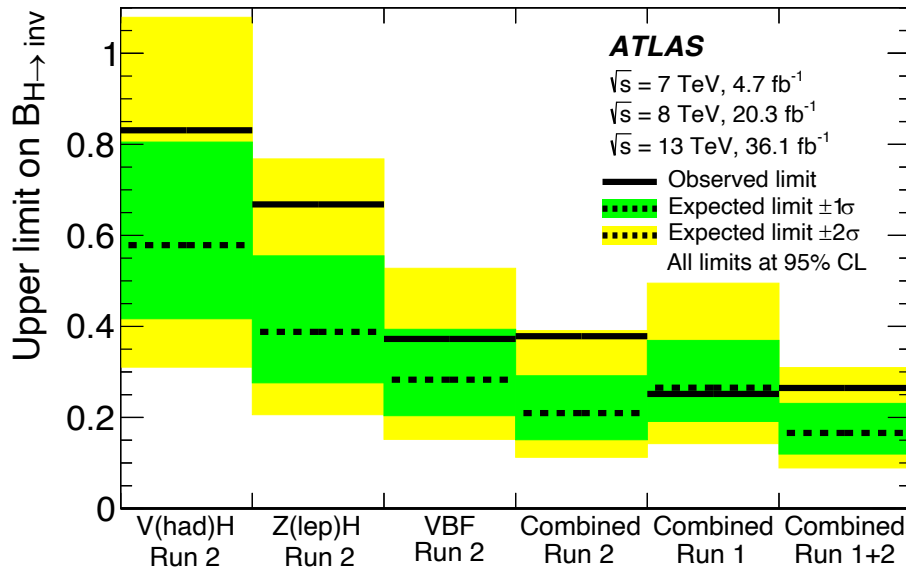
Invisible Higgs decays can be probed by associated production (VBF, VH, ...)



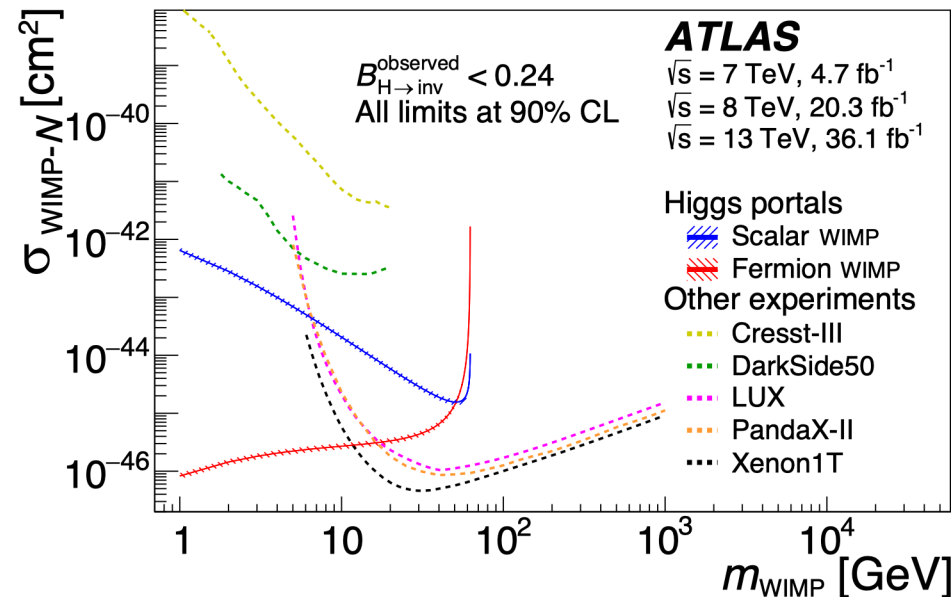
Sensitivity to WIMP mass $< m_H / 2$, complementary to direct dark matter searches
Also sensitivity to higher WIMP masses if mediated by heavy new particle (eg, Z')

ATLAS Run 1+2 combination:

arXiv:1904.05105

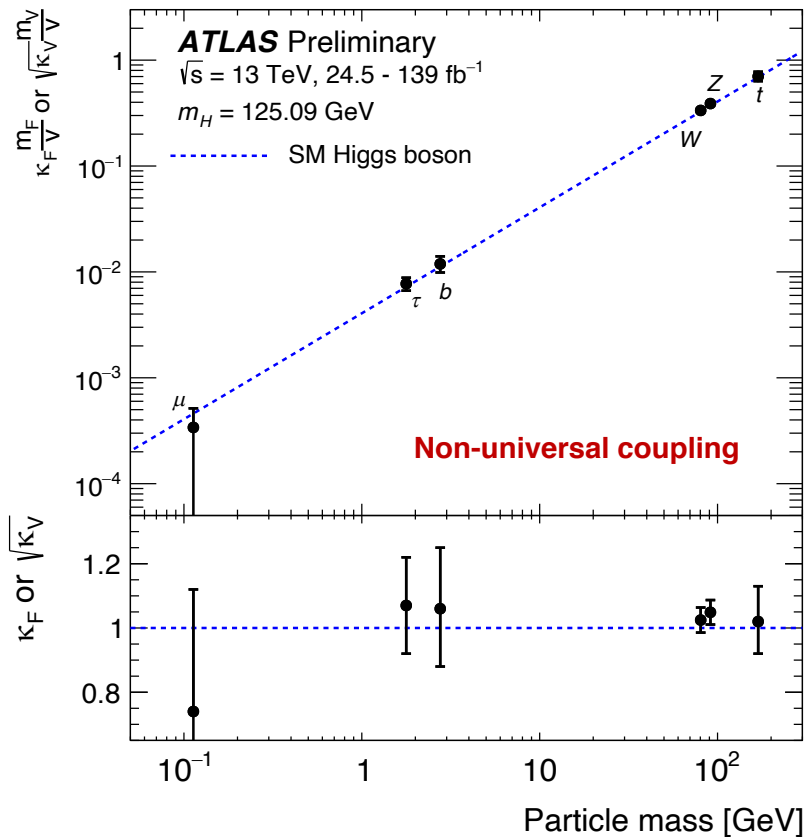


$\text{BR}(H \rightarrow \text{invisible}) < 0.26 \text{ (} 0.17^{+0.07}_{-0.05} \text{ expected)}$



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

The Brout-Englert-Higgs mechanism is real !



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

$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

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

The Brout-Englert-Higgs mechanism at work

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

Symmetric phase – early universe

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

The Brout-Englert-Higgs mechanism at work

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

At a phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s
after big bang, causal domain of few cm) the
Higgs field displaces the ground state
breaking gauge symmetry

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

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

→ Action of the Higgs field
creates “vacuum viscosity”
(not in the classical sense of friction)

Higgs quantum liquid in broken phase

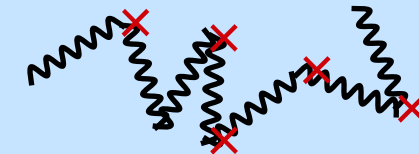
Gravity



Photon



Weak boson



Neutrinos



Electrons



Top quark



Interaction with Higgs
field alters chirality of
massive Dirac fermion

H. Murayama

The electroweak sector needs the Higgs boson

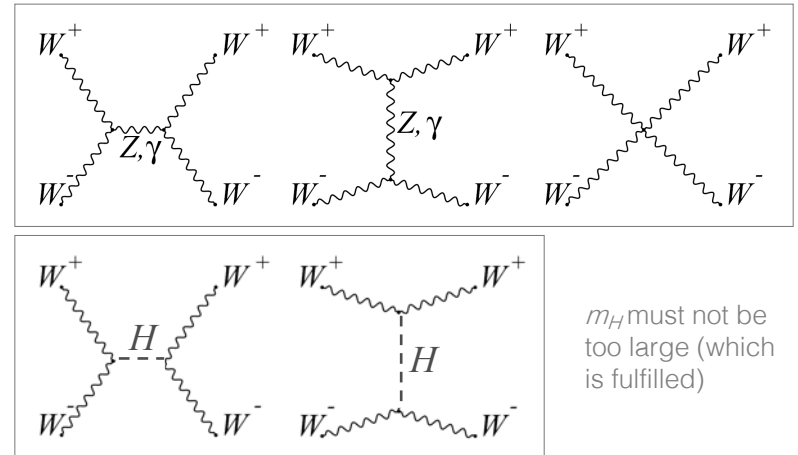
Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

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

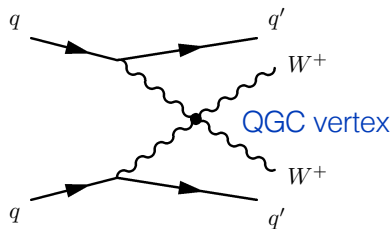
$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

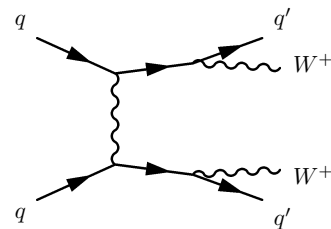
$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$



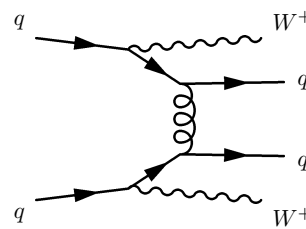
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

The electroweak sector needs the Higgs boson

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

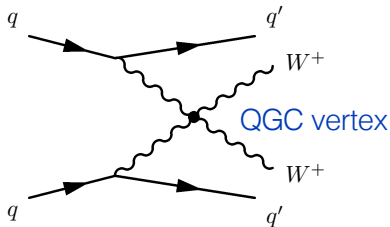
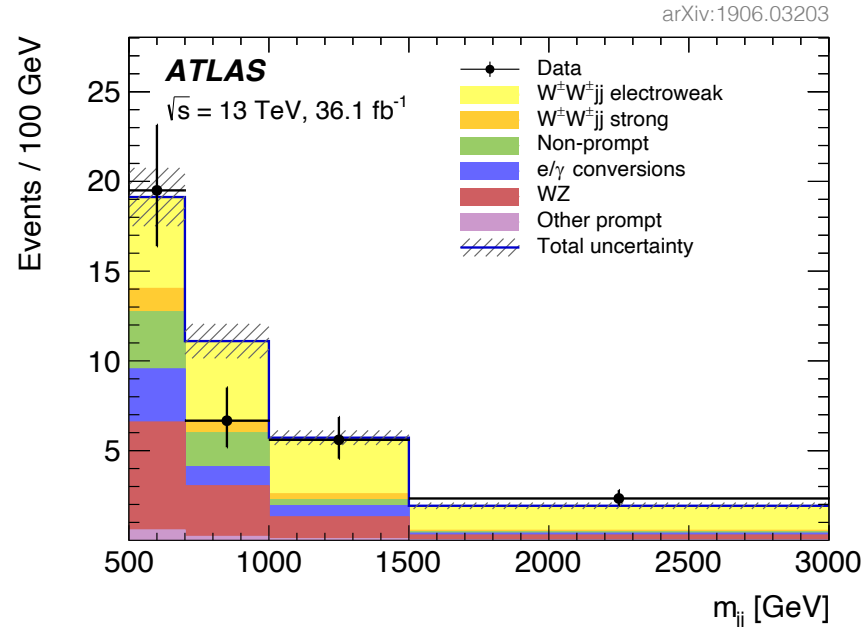
Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

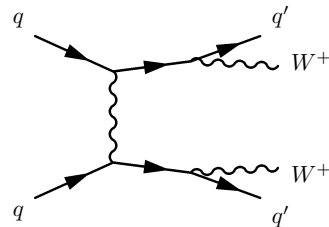
Higgs boson restores unitarity of total amplitude:

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

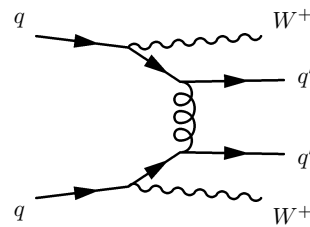
Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

ATLAS observed vector boson scattering at 6.9σ in WW, 5.3σ in WZ, and 5.3σ in ZZ channel in agreement with SM predictions

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

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

Model	ℓ, γ	Jets †	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit
Extra dimensions	ADD $G_{KK} \rightarrow g/q$	0 e, μ	1-4 j	Yes	36.1
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7
	ADD OBH	2 j	-	-	37.0
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2
	ADD BH multi-jet	-	$\geq 3 j$	-	3.6
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	0 e, μ	2 j	-	139
	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3 j$	Yes	36.1
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1
	Leptophobic $Z' \rightarrow bb$	-	2 b	-	36.1
	Leptophobic $Z' \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1 J/2$	Yes	36.1
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	Yes	139
	SSM $W' \rightarrow \tau\nu$	1 τ	-	Yes	36.1
	HVT $V' \rightarrow WZ \rightarrow qqqq$ model B	0 e, μ	2 j	-	139
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1
	LRSM $W'_K \rightarrow tb$	36.1	-	-	2.93
	LRSM $W'_K \rightarrow \mu N_R$	2 μ	1 j	-	80
CI	CI $qqqq$	-	2 j	-	37.0
	CI $\ell\ell qq$	2 e, μ	-	-	36.1
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1
					2.57 TeV
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4 j	Yes	36.1
	VV (x EFT (Dirac DM))	0 e, μ	1, 1, 1 j	Yes	3.2
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0-1 e, μ	1 b, 0-1 j	Yes	36.1
LQ	Scalar LQ 1 st gen	1, 2 e	$\geq 2 j$	Yes	36.1
	Scalar LQ 2 nd gen	1, 2 μ	$\geq 2 j$	Yes	36.1
	Scalar LQ 3 rd gen	2 τ	2 b	-	36.1
	Scalar LQ 3 rd gen	0-1 e, μ	2 b	Yes	36.1
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1
	VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1
	VLQ $V \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 j$	Yes	36.1
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	20.3
	Excited lepton ℓ^*	3 e, μ	-	-	20.3
Other	Excited lepton ν^*	3 e, μ, τ	-	-	20.3
	Type III Seesaw	1 e, μ	$\geq 2 j$	Yes	79.8
	LRSM Majorana ν	2 μ	2 j	-	36.1
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, 4 e, μ (SS)	-	-	20.3
Magnetic monopoles	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	3 e, μ, τ	-	-	20.3
	Multi-charged particles	-	-	-	36.1
	Magnetic monopoles	-	-	-	34.4

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2019

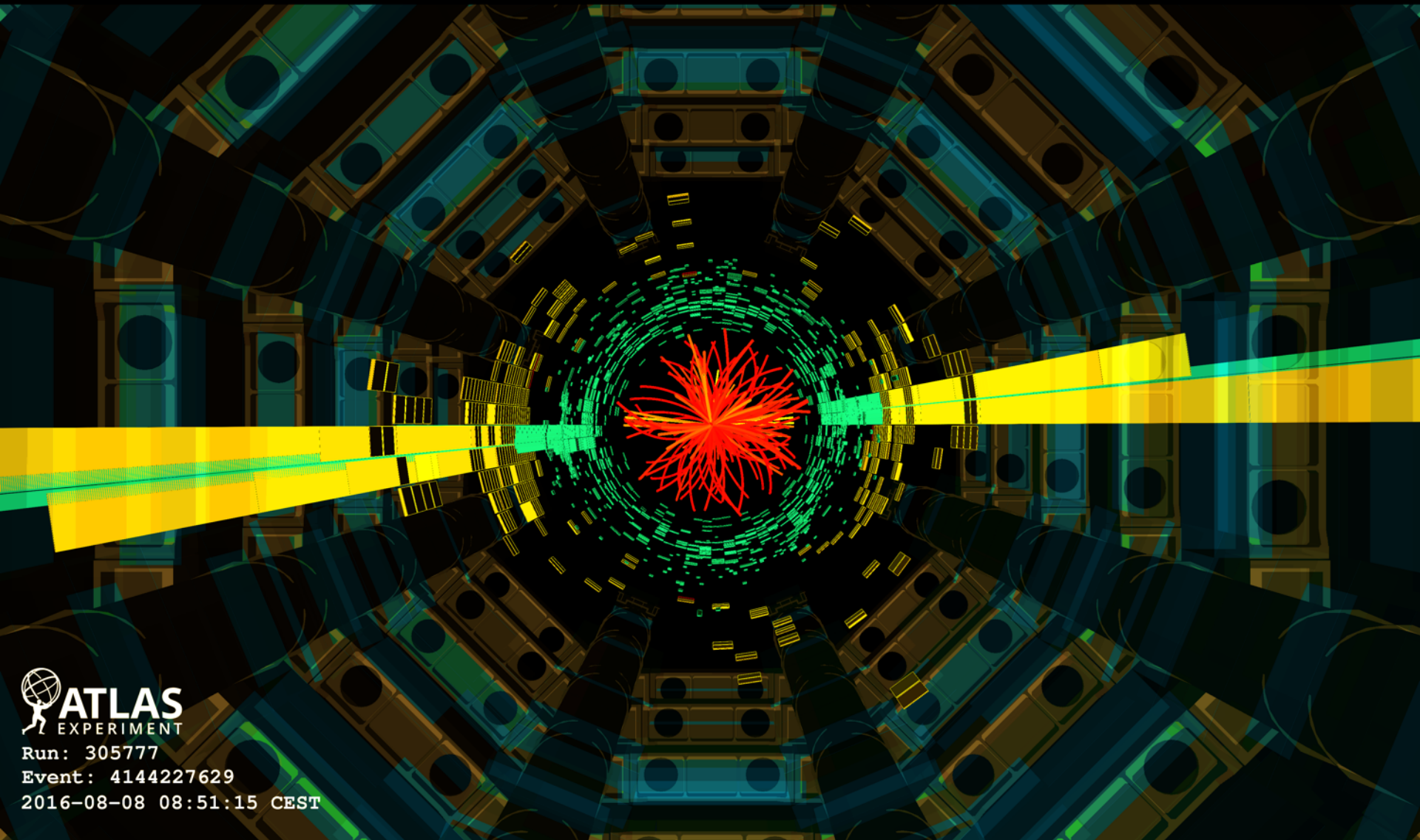
Model	Signature	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{q}^0$	0 e, μ	2-6 jets	36.1
	mono-jet	1-3 jets	E_T^{miss}	36.1
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	0 e, μ	2-6 jets	36.1
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	3 e, μ	4 jets	36.1
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	2 jets	E_T^{miss}	36.1
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	0 e, μ	7-11 jets	36.1
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	SS e, μ	6 jets	139
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	0-1 e, μ	3 b	79.8
	$\tilde{b}\tilde{b} \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0$	SS e, μ	6 jets	139
				1.25
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	Multiple	Forbidden	0.9
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	Multiple	Forbidden	0.59-0.82
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	Multiple	Forbidden	0.74
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0 e, μ	6 b	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0-2 e, μ	0-2 jets/1-2 b	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	1 e, μ	3 jets/1 b	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	1 $\tau + 1 e, \mu, \tau$	2 jets/1 b	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0 e, μ	2 c	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0 e, μ	mono-jet	E_T^{miss}
	$\tilde{b}_1\tilde{b}_1 \rightarrow b\tilde{b}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	1-2 e, μ	4 b	E_T^{miss}
EW direct	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2-3 e, μ	2 jets/1-2 b	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2 e, μ	2 jets/1 b	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0-1 e, μ	2 b/2 γ	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2 e, μ	2 jets/1 b	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2 e, μ	2 τ	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2 e, μ	0 jets	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	2 e, μ	≥ 1	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	0 e, μ	$\geq 3 b$	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	4 e, μ	0 jets	E_T^{miss}
				0.3
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1$	Disapp. trk	1 jet	E_T^{miss}
	Stable $\tilde{g}$ R-hadron	Multiple	Multiple	36.1
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{q}^0$	Multiple	Multiple	36.1
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.0
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.05
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.4
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.0
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.0
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.0
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		2.0
RPV	LFV $p\bar{p} \rightarrow \nu\bar{\nu} + X, \nu\bar{\nu} \rightarrow q\bar{q} + \nu\bar{\nu}$	0 e, μ	0 jets	E_T^{miss}
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	Multiple	Multiple	36.1
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2
	$\tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{t}\tilde{q}\tilde{q}^0/\tilde{q}\tilde{q}^0$	36.1		3.2

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

*Only a selection of the available mass limits on new states or phenomena is shown.

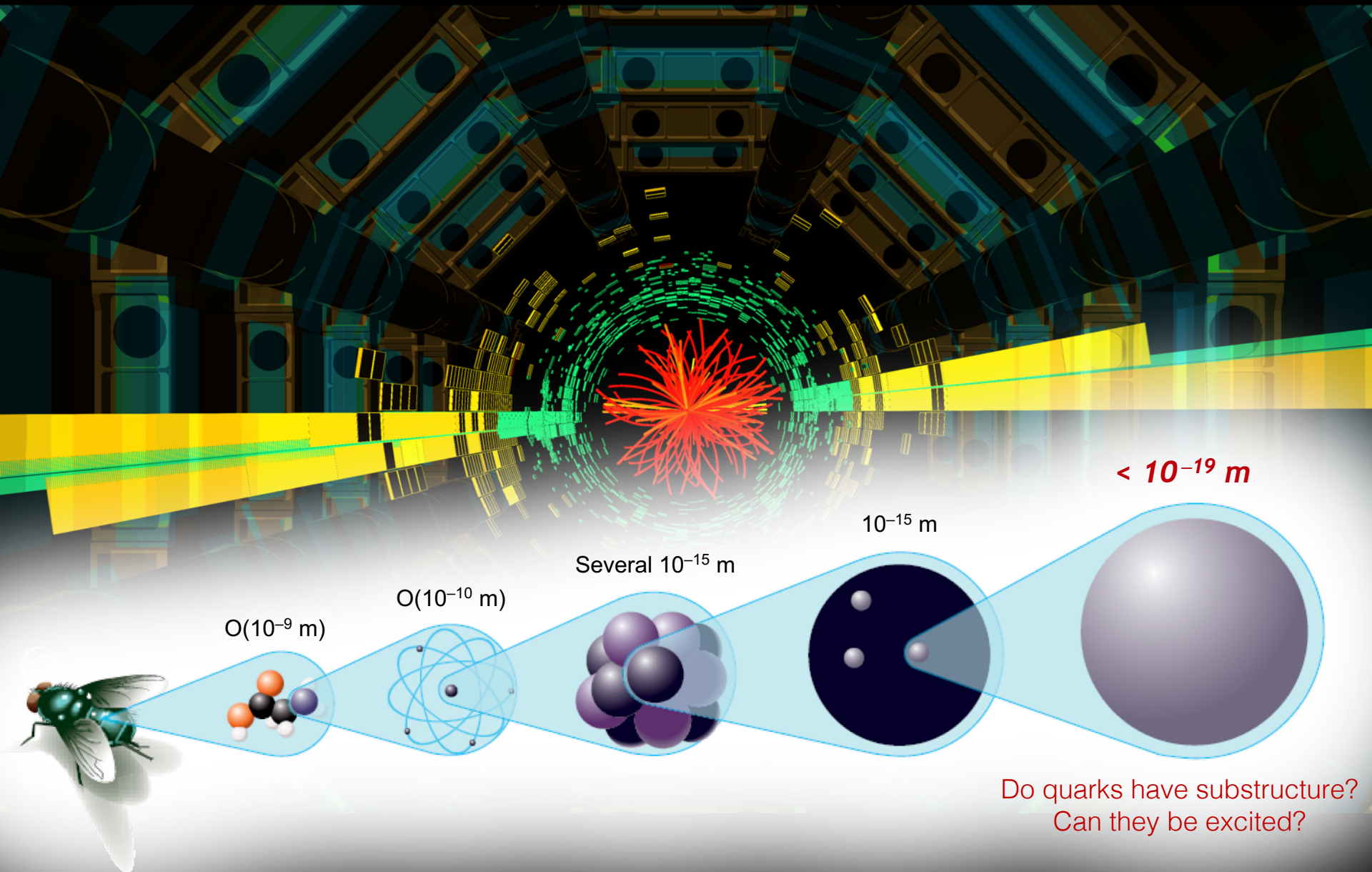
† Small-radius (large-radius) jets are denoted by the letter j (J).

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

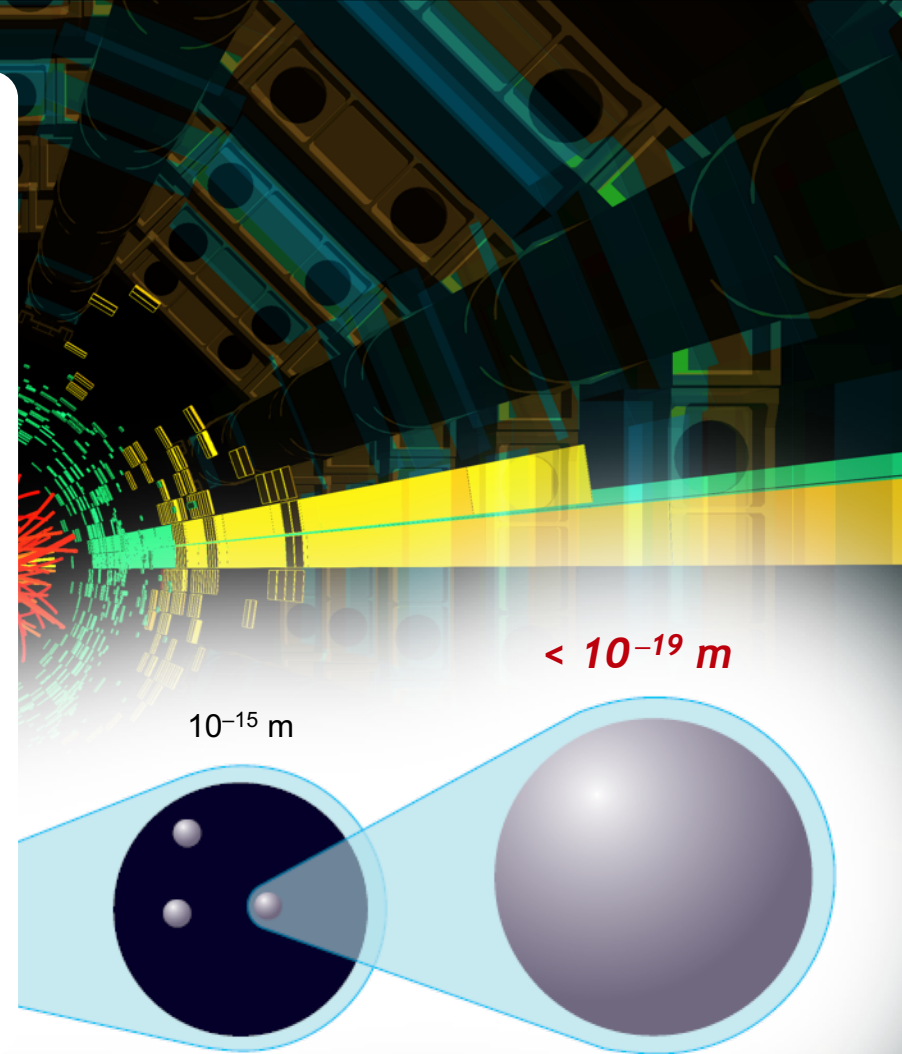
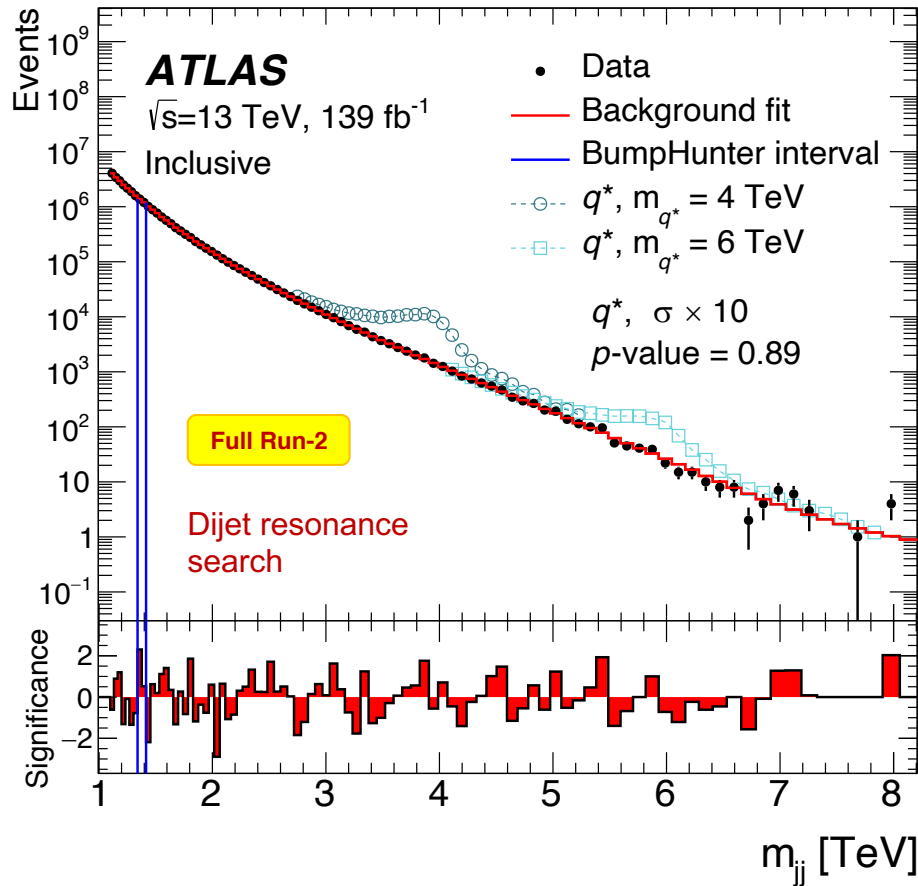


Highest-mass central dijet event of 8.0 TeV selected in resonance search

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



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

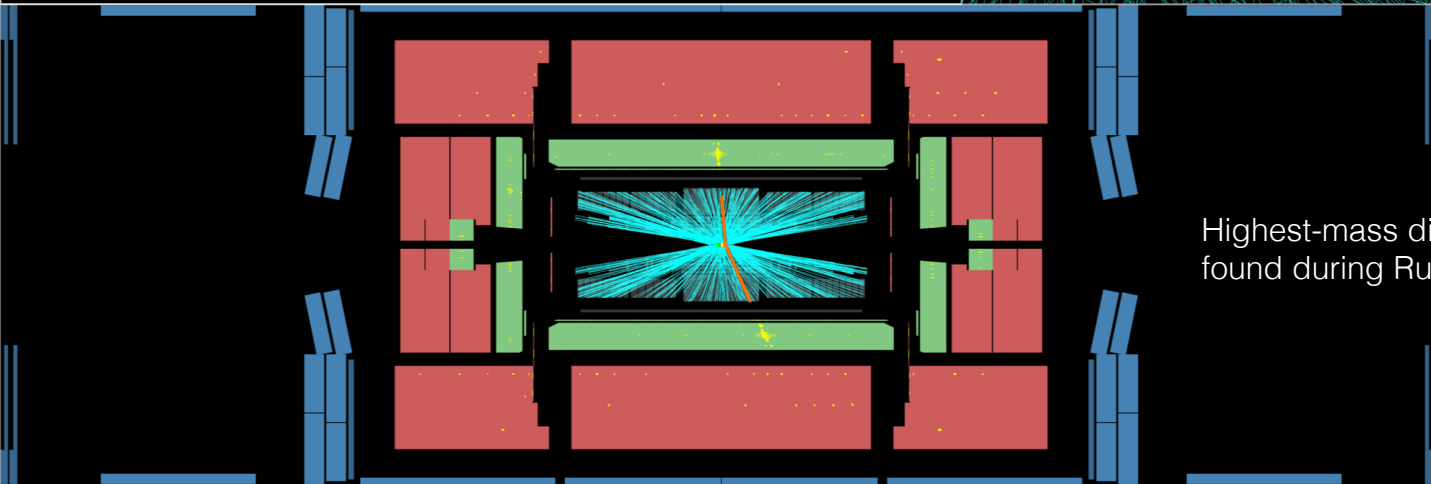
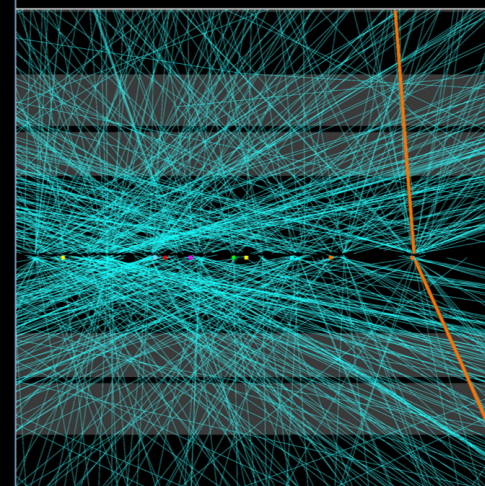
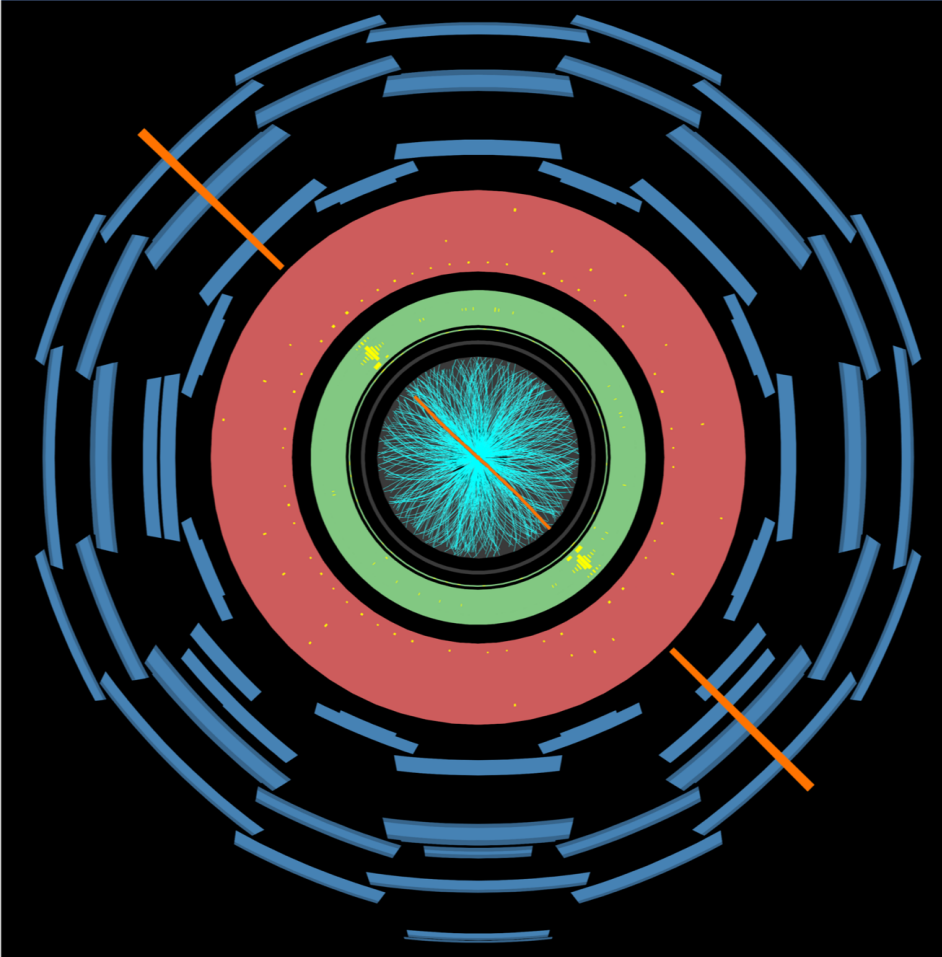


Do quarks have substructure?
Can they be excited?



Run Number: 336852, Event Number: 1440436043

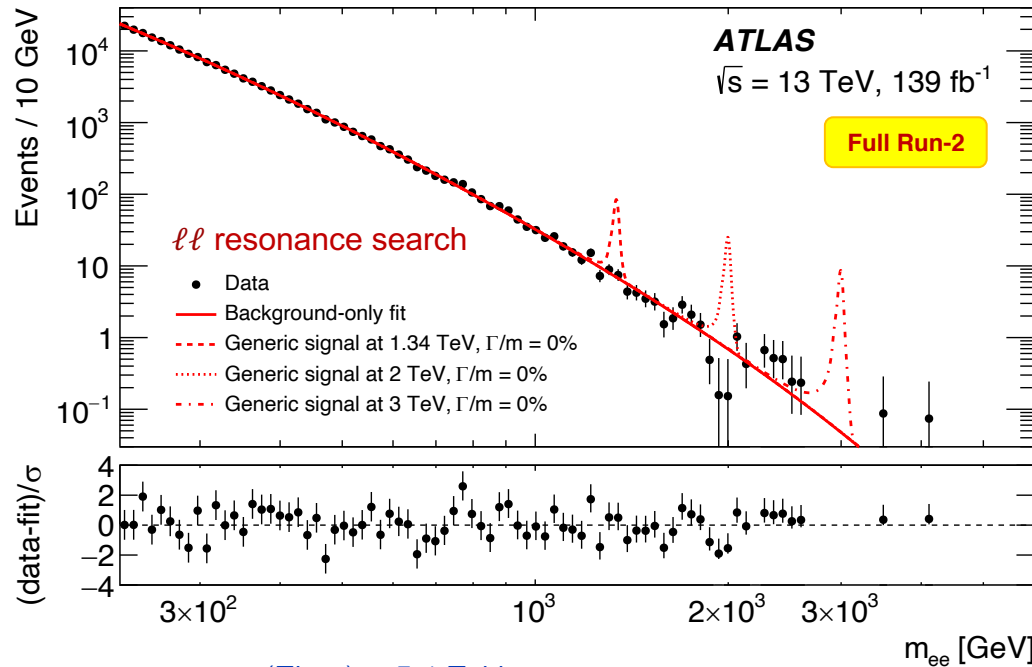
Date: 2017-09-29 11:44:35 CEST



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

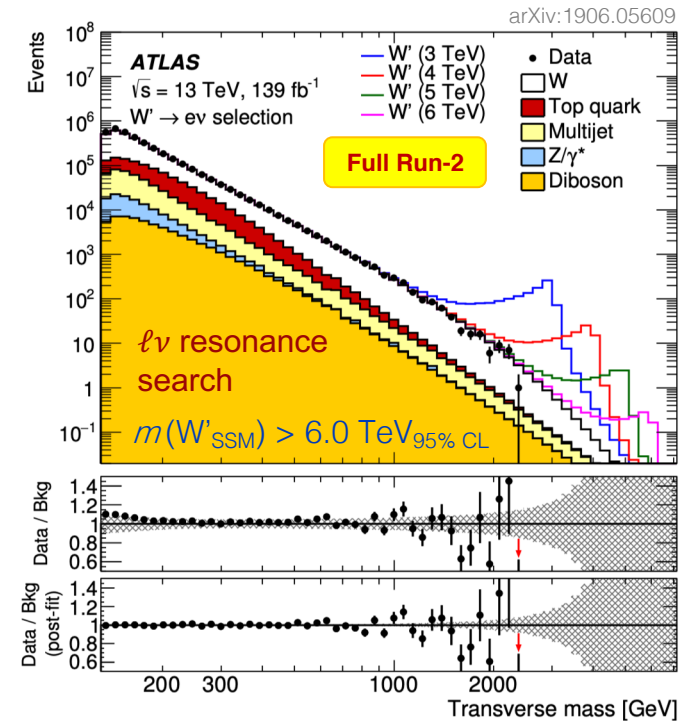
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Date: 2017-09-29 11:44:35 CEST



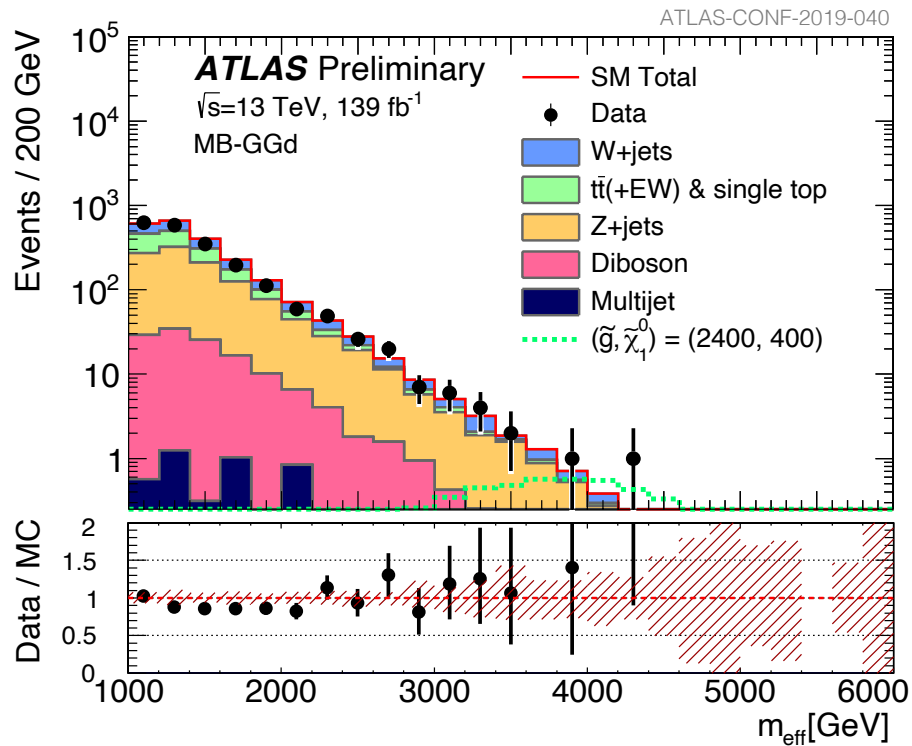
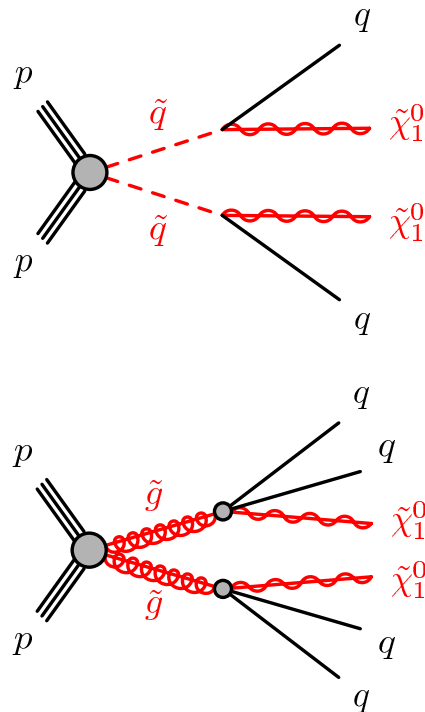
arXiv:1903.06248

$m(Z'_{\text{SSM}}) > 5.1 \text{ TeV}_{95\% \text{ CL}}$



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

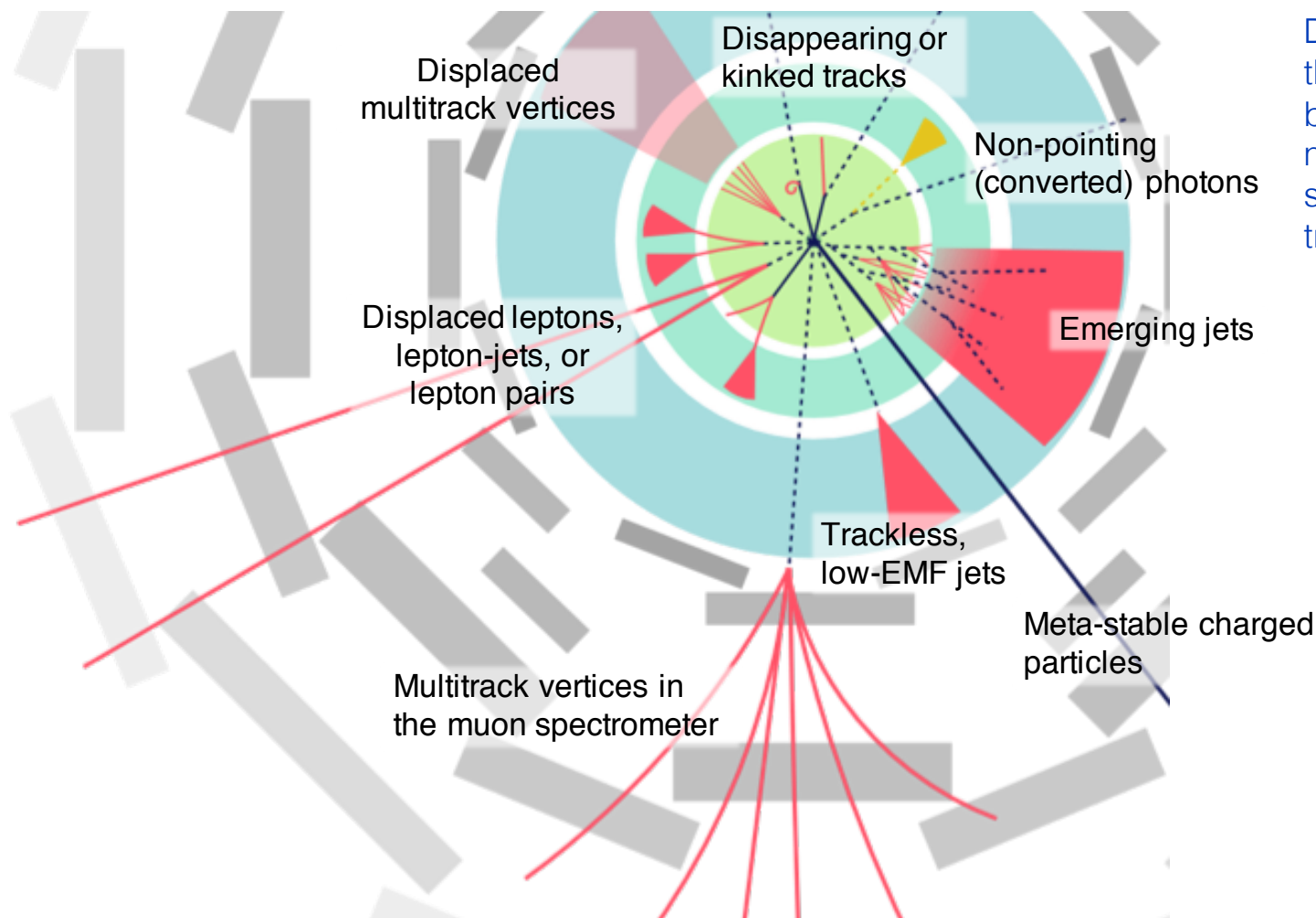
New search for squark & gluino production, reaching beyond 2 TeV mass sensitivity, increased use of machine learning



Also focus on naturalness-driven searches: direct electroweak production, 3rd generation squark production

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)



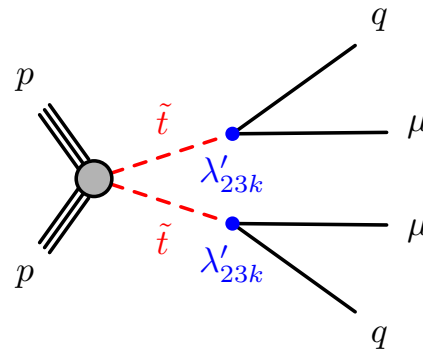
Diverse set of signatures that need to be pursued by dedicated, usually non-standard analyses, some requiring special triggers

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

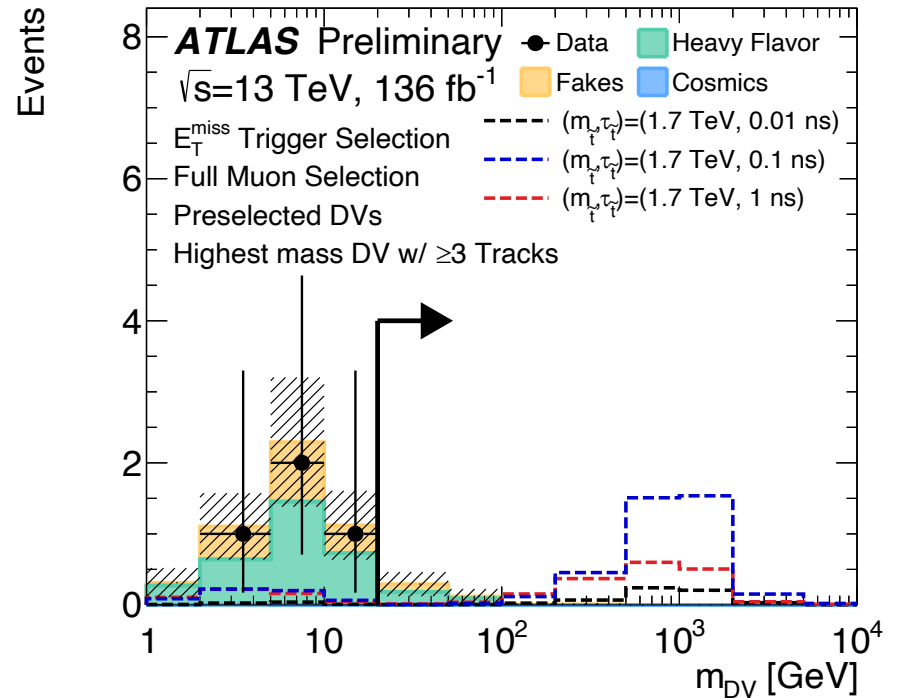
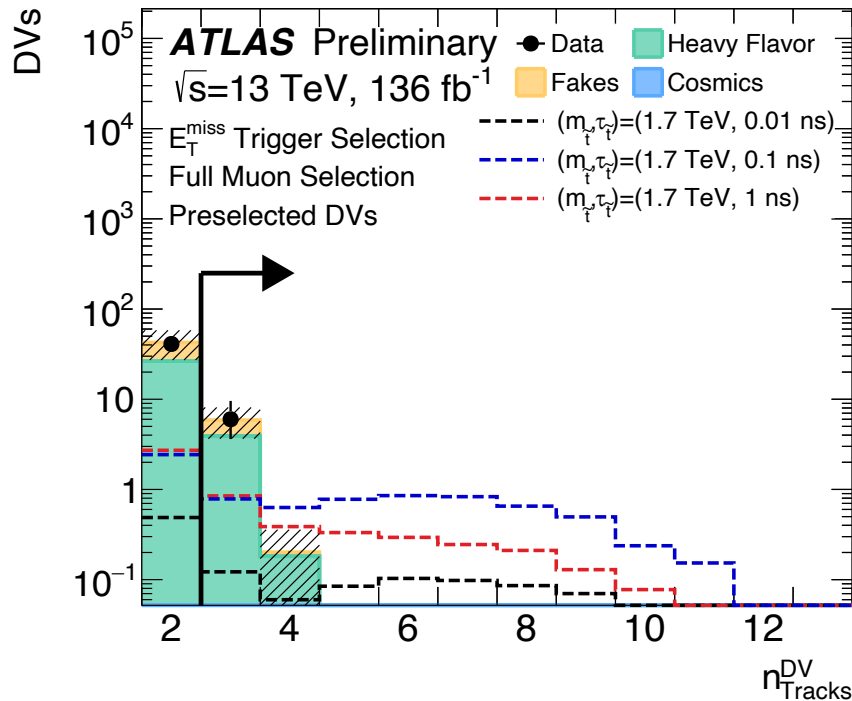
Full Run-2

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

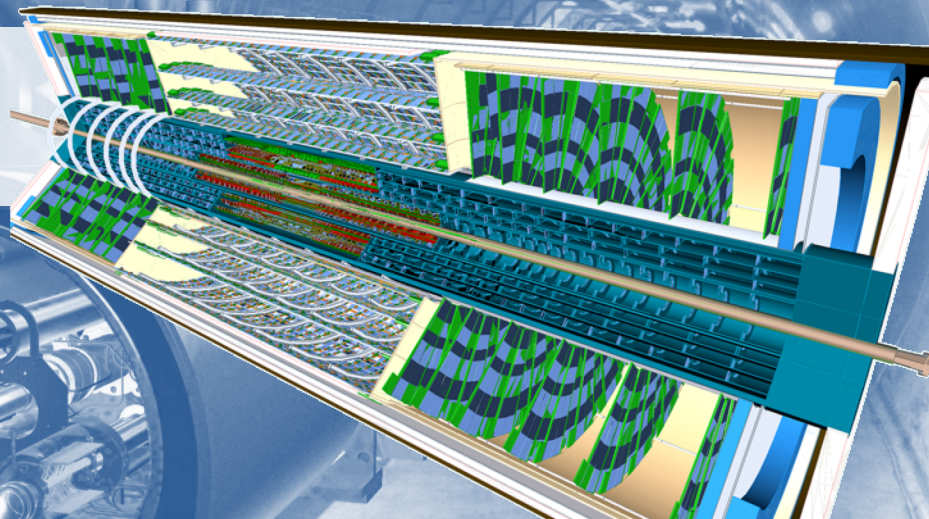
Clean signature of large track multiplicity and vertex mass



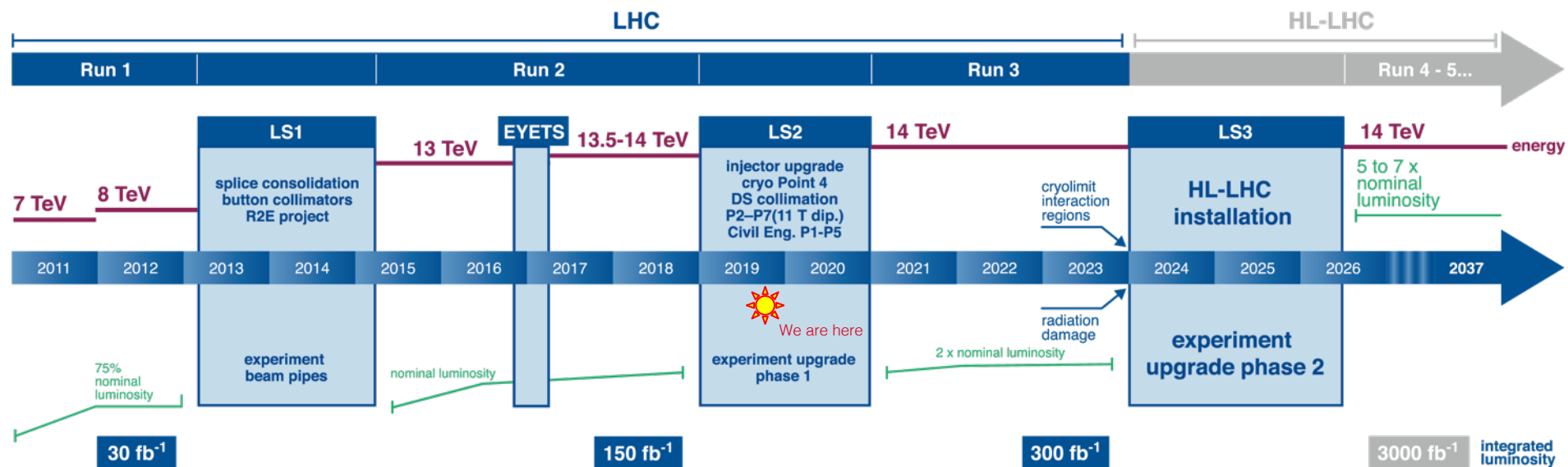
R-parity violating signature with long-lived stop



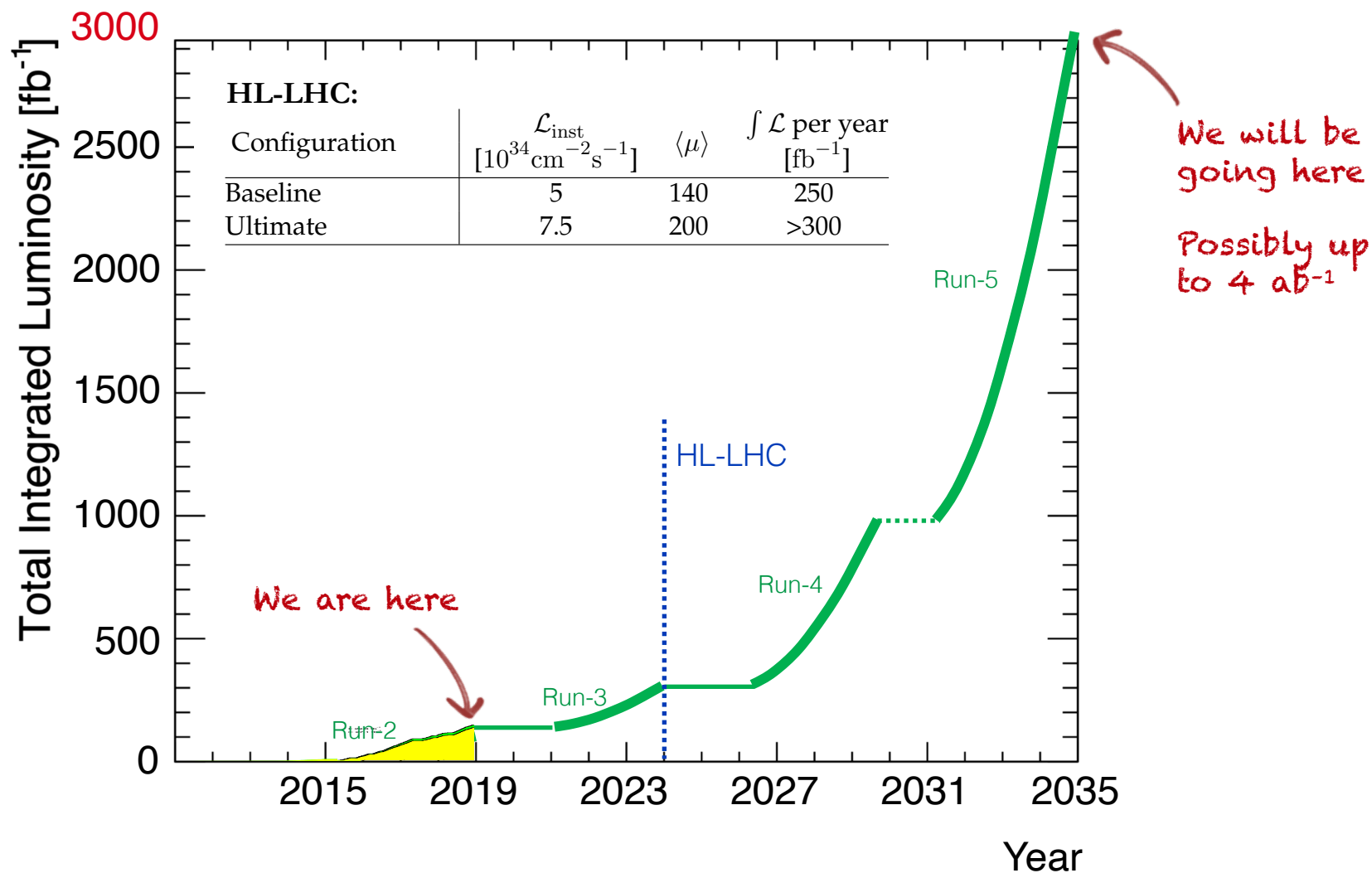
Phase-II: The High-Luminosity LHC



LHC / HL-LHC Plan



Expected integrated luminosity of LHC & HL-LHC



ATLAS Phase-II detector upgrade

Designed to recover current performance under high pileup ($\sim 35 \rightarrow 200$, $L_{\text{peak}} \sim 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)

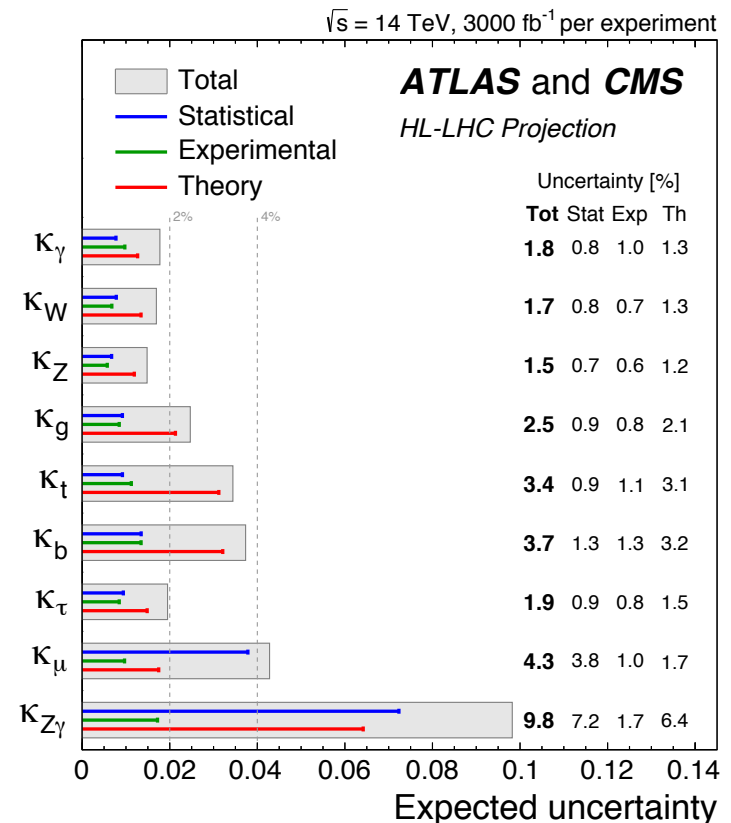
HL-LHC

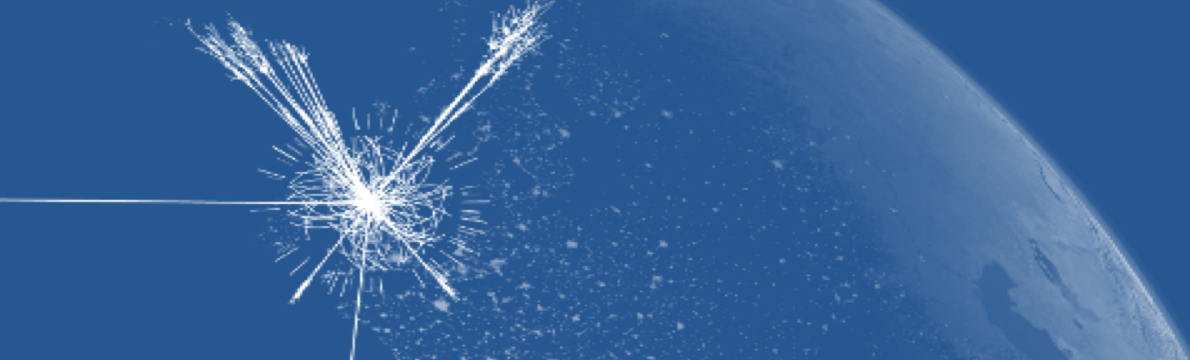
- Higgs factory for precision Higgs coupling measurements (see figure) and increased rare & new physics sensitivity
- Detector upgrades required for improved pileup and radiation robustness



ATLAS developed novel detection technologies at the forefront of speed, granularity and radiation hardness

- Silicon tracking detectors with $> 1\text{B}$ channels
- Timing detector based on fast silicon LGAD technology (30 ps timing resolution per layer)
- High granularity topological trigger and high-performance DAQ architecture
- New compute technologies and massive parallelisation: use of high-performance computing, possibly GPUs, machine learning
- 6 TDRs approved (1 more to come), MoUs being signed by funding agencies



A visualization of a particle collision, showing a central point from which numerous lines radiate outwards, representing the paths of particles. The background is a dark blue gradient with a faint, curved horizon line.

Challenges and opportunities

Particle physics has entered an era of uncertainty: we have a beautiful theory, and many proofs that it is incomplete. Contrary to the Fermi (electroweak) scale, we do not know the next new physics scale. Naturalness has been an important and successful guiding principle in physics, but it is challenged by the experimental data of the LHC (and elsewhere).

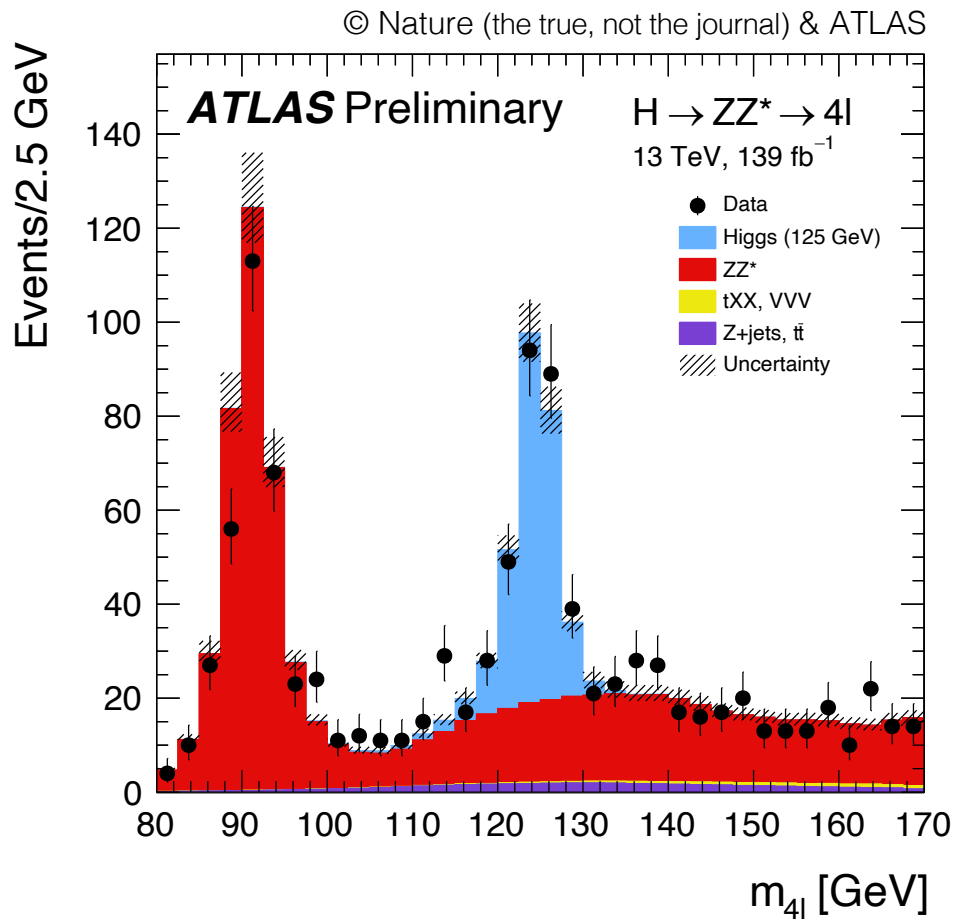
We have observed the Higgs boson, but in spite of precise SM predictions none of the properties of this most peculiar scalar particle can be taken for granted and must thus be probed by experiment.

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, ATLAS together with its cousin experiments represent the flagship of particle physics at the energy frontier for decades to come. The huge Run-2 and future data samples offer the opportunity to study matter and force in unprecedented detail and diversity.

ATLAS is up to take the challenge with 900 papers on collision data produced to date.

Follow us on: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ResultswithData2018>, <http://atlas.cern>



Thank you

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” ($\sigma_z \sim 4\text{--}6\text{ cm}$)



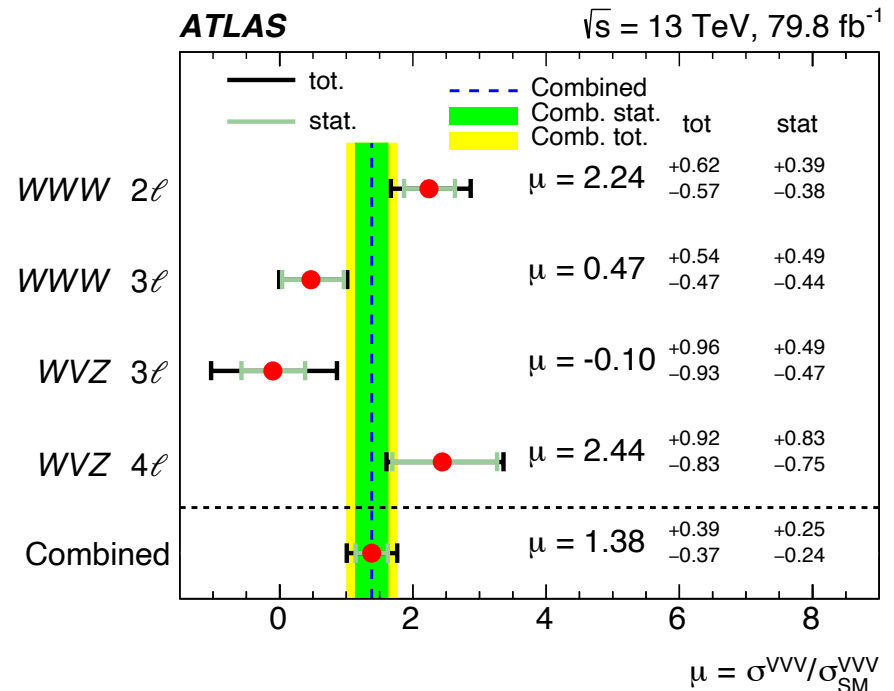
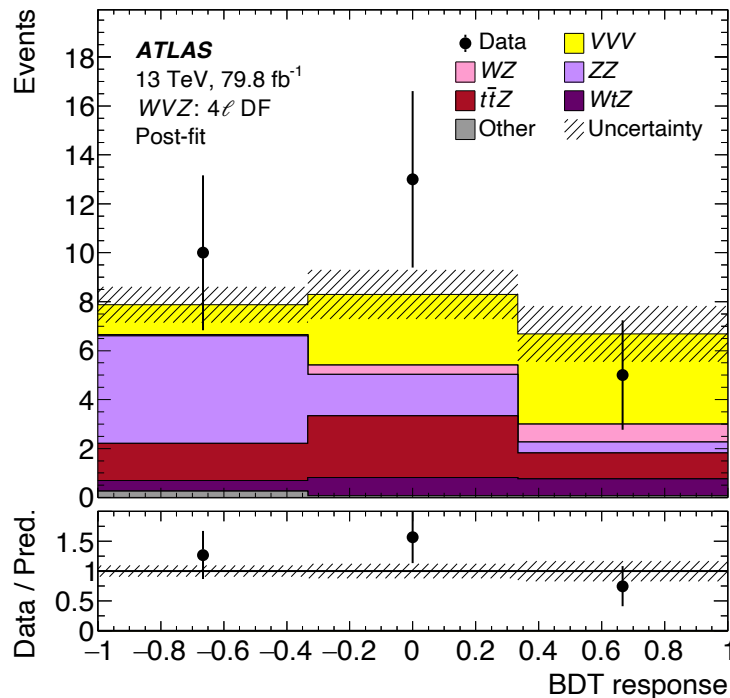
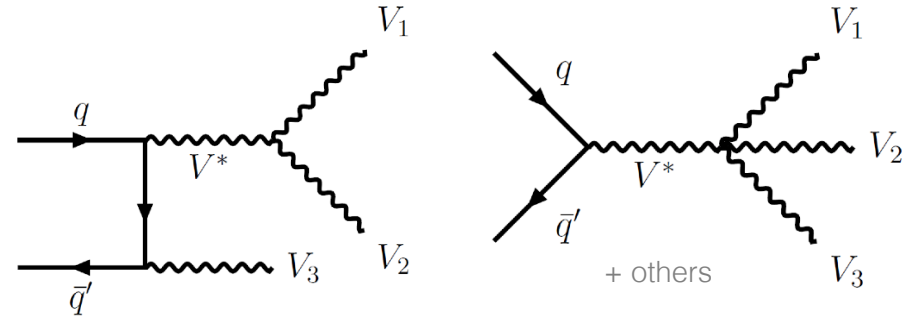
Reaching to low cross section electroweak processes

Sensitive to anomalous triple and quartic gauge couplings

arXiv:1903.10415

Evidence for production of WVW , $V = W, Z$

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



Ultimate precision is possible at the LHC

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

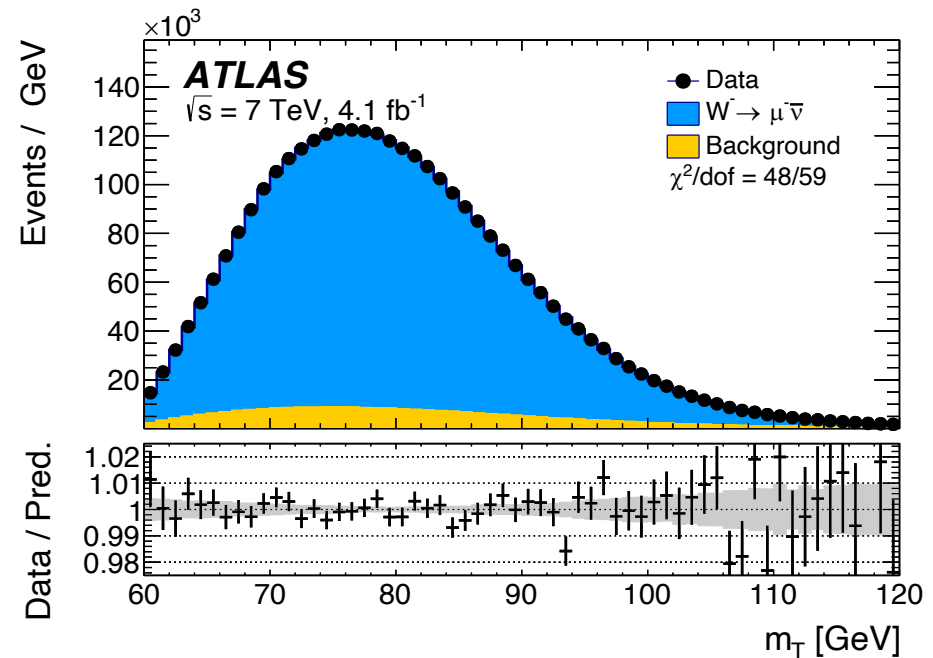
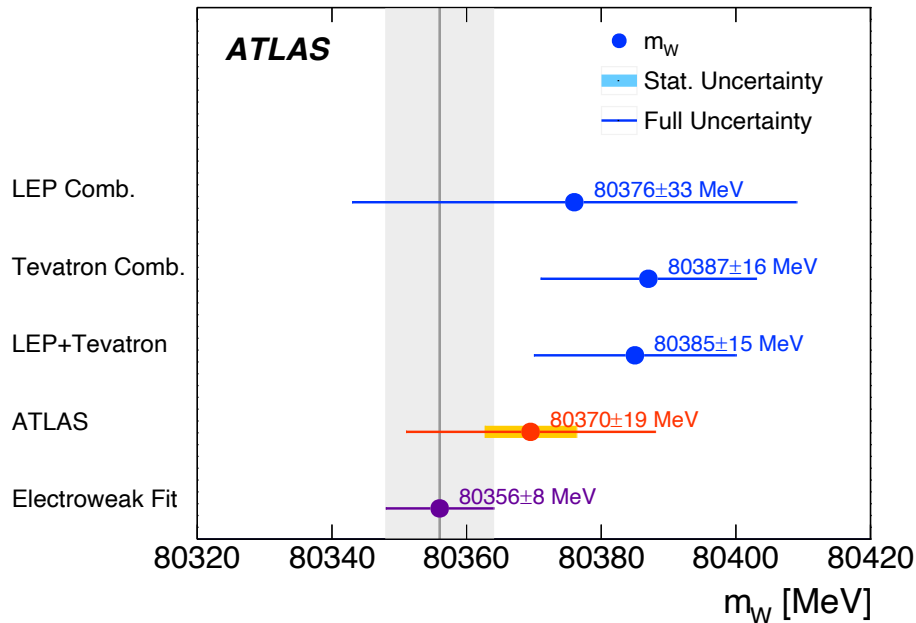
Measurement uses $W \rightarrow e\nu, \mu\nu$ events

Excellent agreement of results among e / μ channels, W^+ / W^- and $p_{T,\ell} / m_T$

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

W boson mass

arXiv:1701.07240



Higgs boson production at the LHC

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

H(125 GeV) — approximate numbers			
Channel	Produced	Selected	Mass resolution
$H \rightarrow \gamma\gamma$	18,200	6,440	1–2%
$H \rightarrow ZZ^*$	210,000	($\rightarrow 4\ell$) 210	1–2%
$H \rightarrow WW^*$	1,680,000	($\rightarrow 2\ell 2\nu$) 5,880	20%
$H \rightarrow \tau\tau$	490,000	2,380	15%
$H \rightarrow b\bar{b}$	4,480,000	9,240	10%

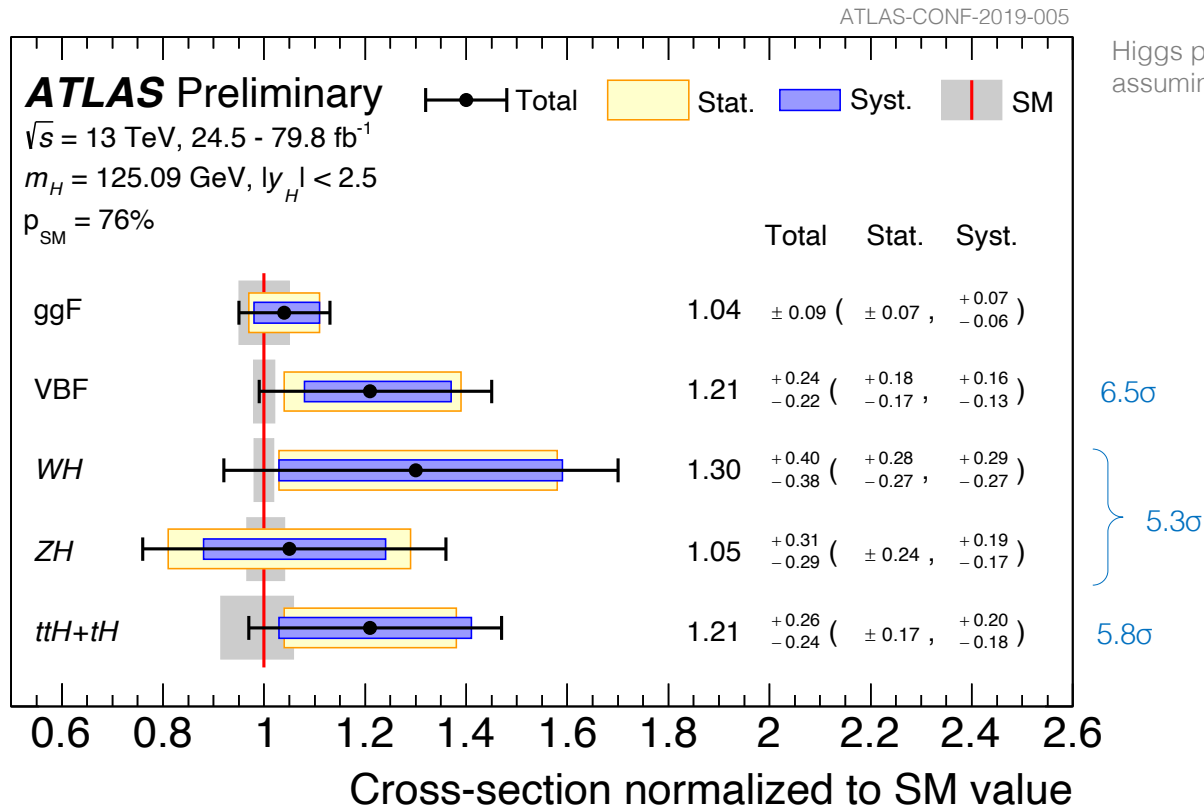
Our goal is to measure the couplings of the Higgs boson to all particles and their dependence of the event kinematics and topology as precisely as possible

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^* , $\mu\mu$, $VH(bb)$, $ttH(\gamma\gamma)$ with 80 fb⁻¹
- All other channels using 36 fb⁻¹



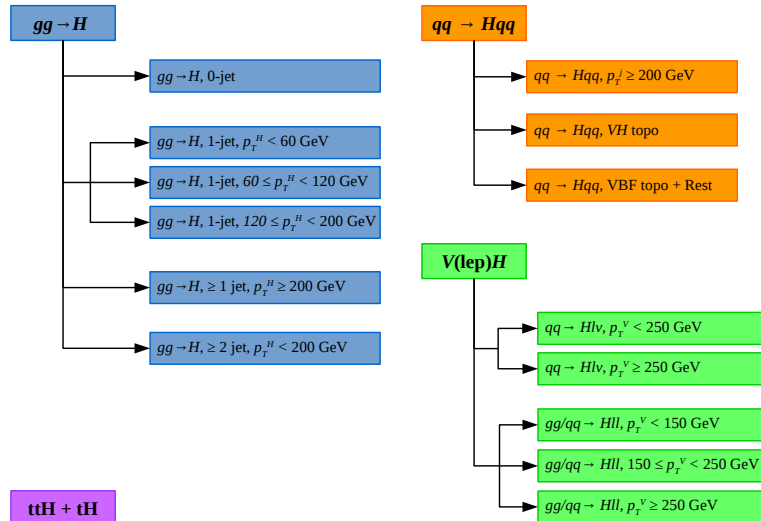
Higgs production processes, assuming decays to follow SM

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

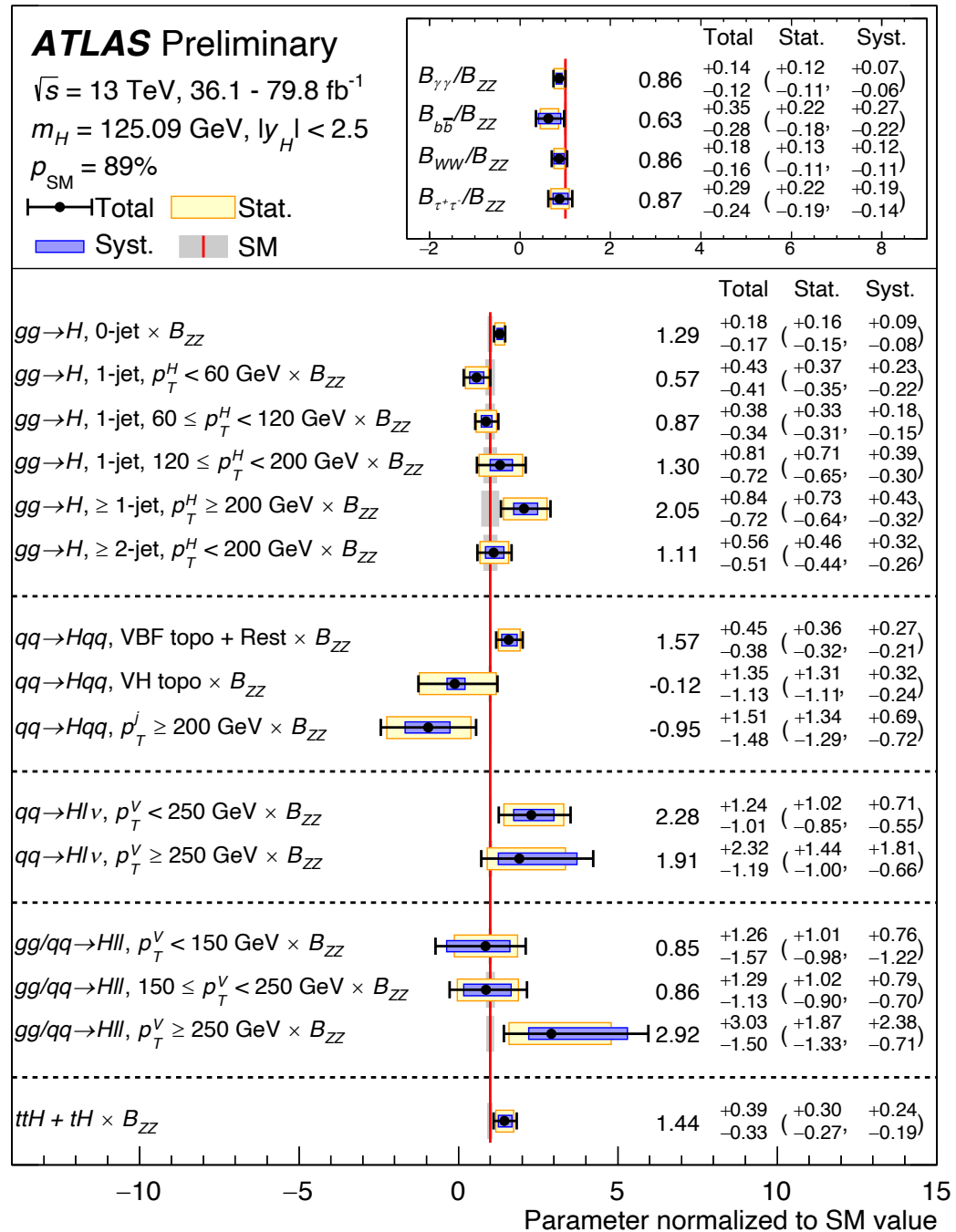
Combined measurement of simplified template cross sections (STXS)

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



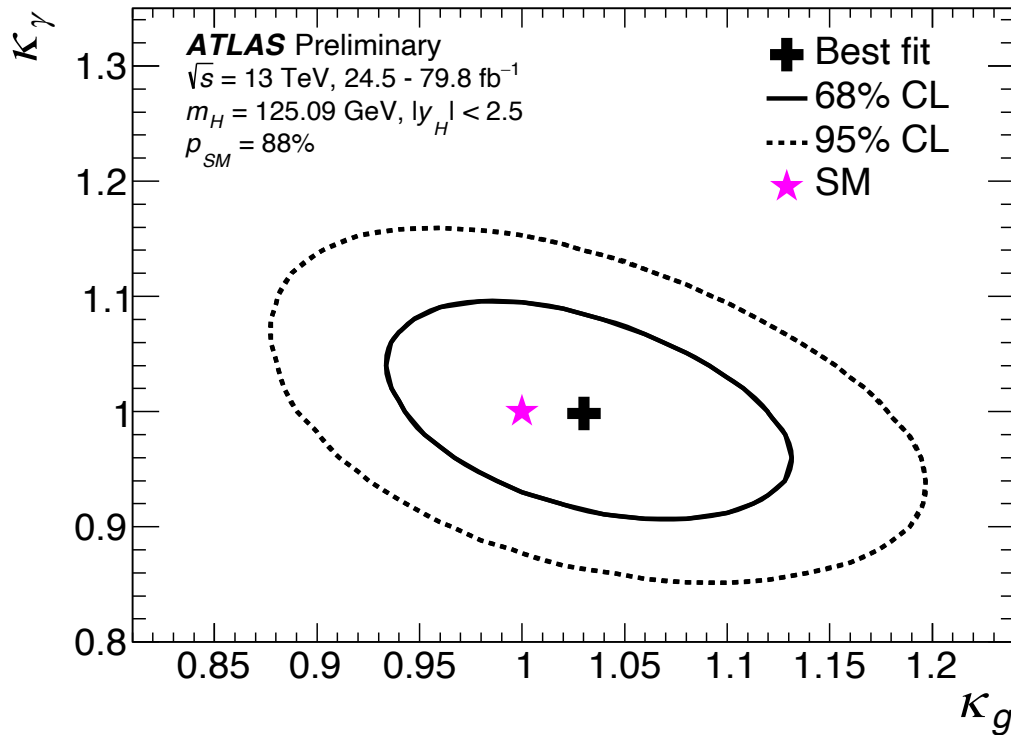
Definition of "Stage-1" STXS used in the analysis



Unprecedented precision on Higgs boson couplings

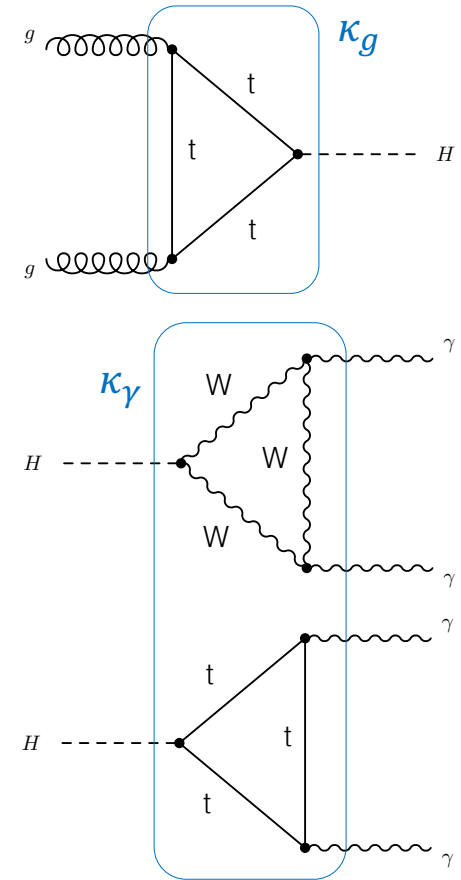
Strong constraints on new physics via loops

- Coupling modifiers: $\kappa = \kappa(\text{exp}) / \kappa(\text{SM})$, 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)

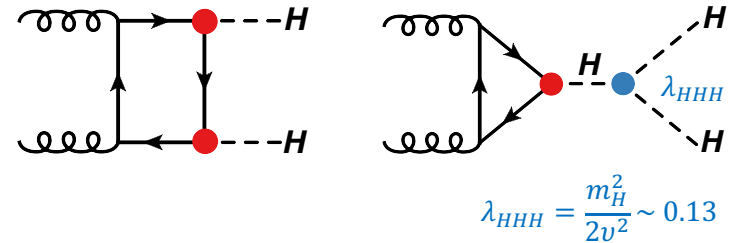
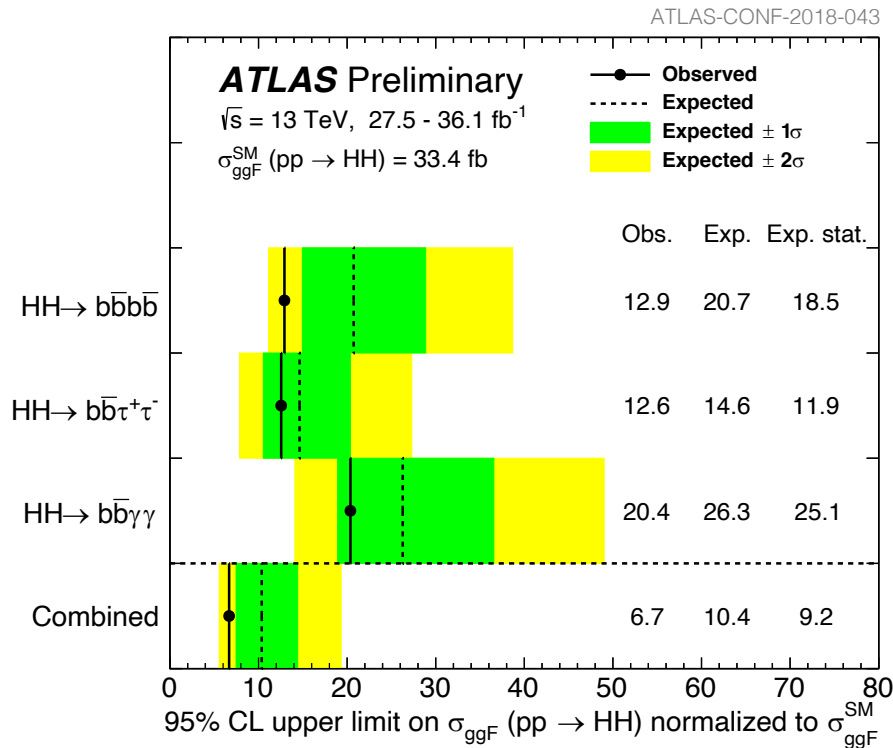
Di-Higgs production

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: $b\bar{b}\gamma\gamma$ (BR = 0.26%), $b\bar{b}\tau\tau$ (7.3%), $b\bar{b}b\bar{b}$ (34%)
→ combination

ATLAS combination using 36 fb⁻¹ analyses:



LO diagrams contributing with negative interference to SM HH production

Box diagram dominates inclusive production

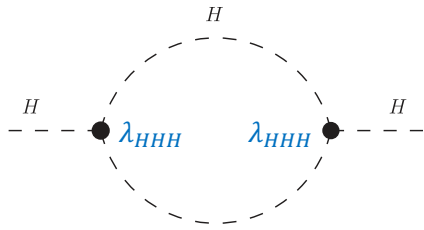
Sensitivity to H self-coupling rises at low m_{HH}

Combined fit yields 95% CL
allowed range:

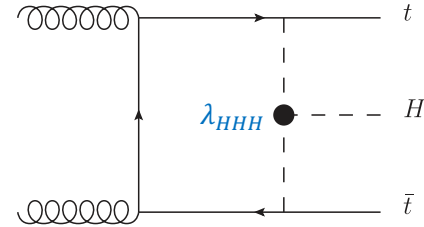
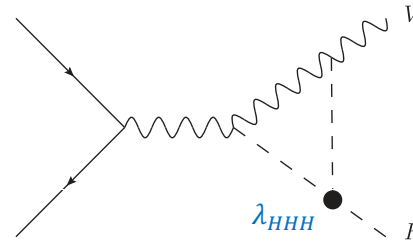
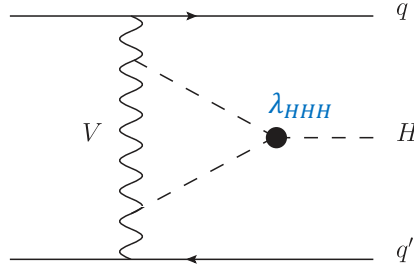
$$-5.0 < \frac{\lambda_{HHH}(\text{obs})}{\lambda_{HHH}(\text{SM})} < 12.1$$

Indirect constraints on Higgs self coupling through loops

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

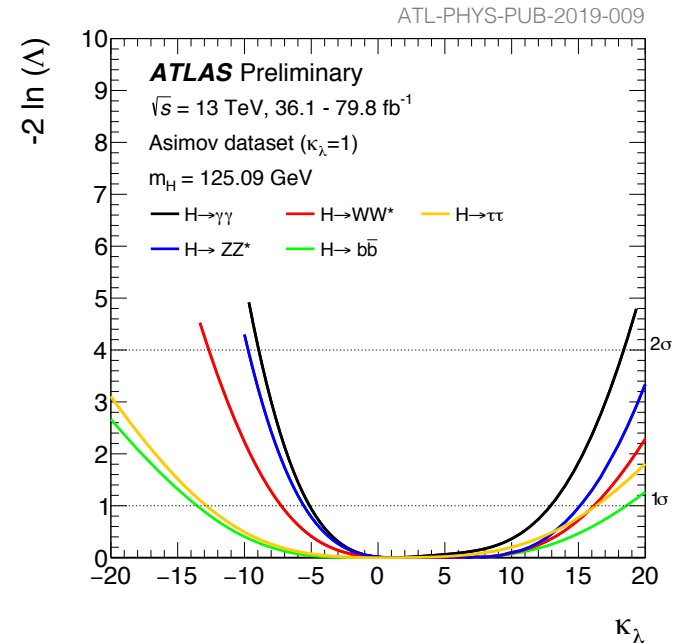
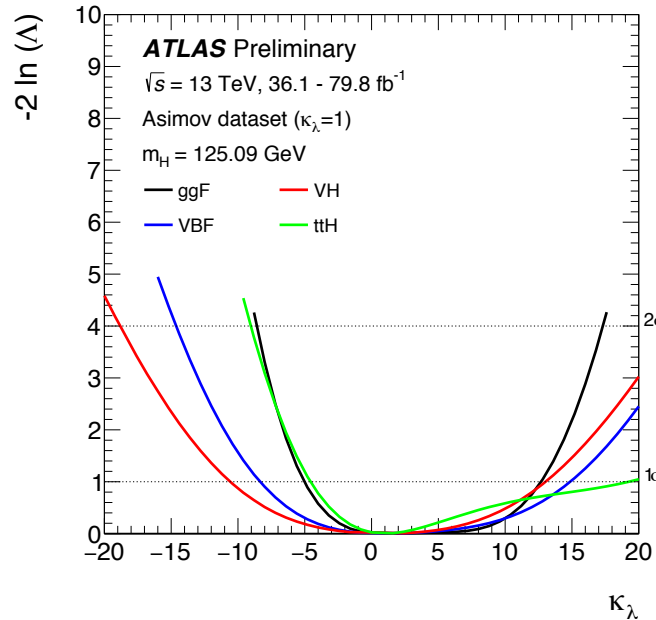


Higgs self energy contributing to, eg, ggF Higgs production



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

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



Particle physics at the dawn of the LHC Run-3

No new physics in direct searches
or studies of quantum fluctuations

QED tested to parts per million accuracy (*slight anomaly in muon $g-2$*)

Asymptotic freedom in strong interactions verified at % level

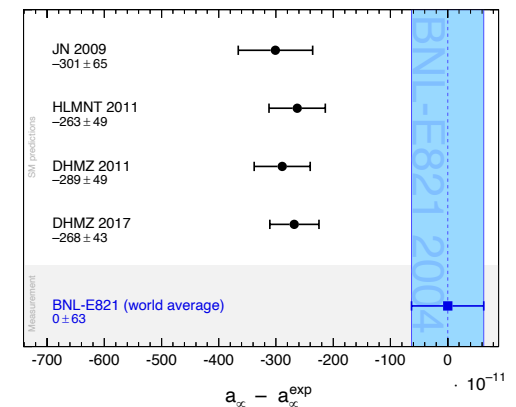
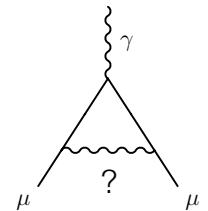
Electroweak unification tested to high precision

Higgs mechanism for electroweak symmetry breaking confirmed,
Higgs boson SM like

Quark sector: CKM picture for quark mixing & CP violation confirmed
(*some anomalies in flavour sector*)

Lepton sector: massive neutrinos, unknown nature, masses, CP
violation, sterile ν 's ? No flavour violation in charged lepton sector.
Lepton universality tested to per-mil level

No compelling sign of new physics found at high mass scales, or
anywhere else, yet. E.g.: no electric dipole moments (EDM), no dark
matter particles (gravitational hints only), no axions, no proton decay





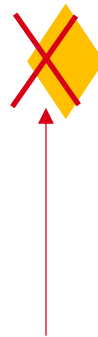
Two beautiful, extremely precise theories...

The Standard Model of EW and strong interactions

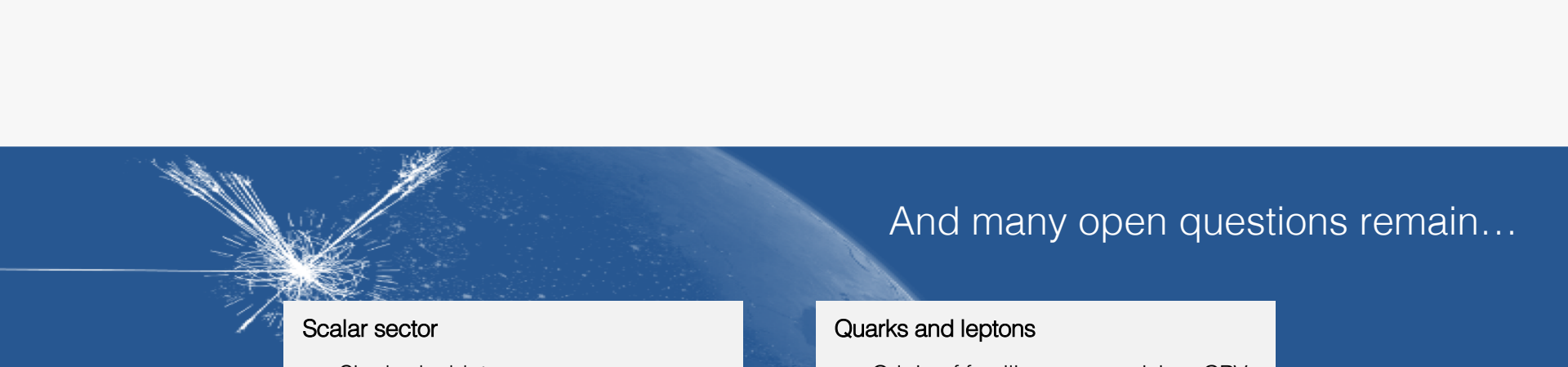
Predicting, e.g., the anomalous magnetic moment of the electron to a relative precision of better than 10^{-9} in agreement with experiment

General relativity — theory of gravitation

Tested up to an accuracy of order 10^{-5}
(Cassini probe [B Bertotti et al., Nature 425, 2003])



Unfortunately, the SM and general relativity don't work in regimes where both are important (ie, at very small scales)



And many open questions remain...

Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

Expansion of Universe

- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

High-scale physics

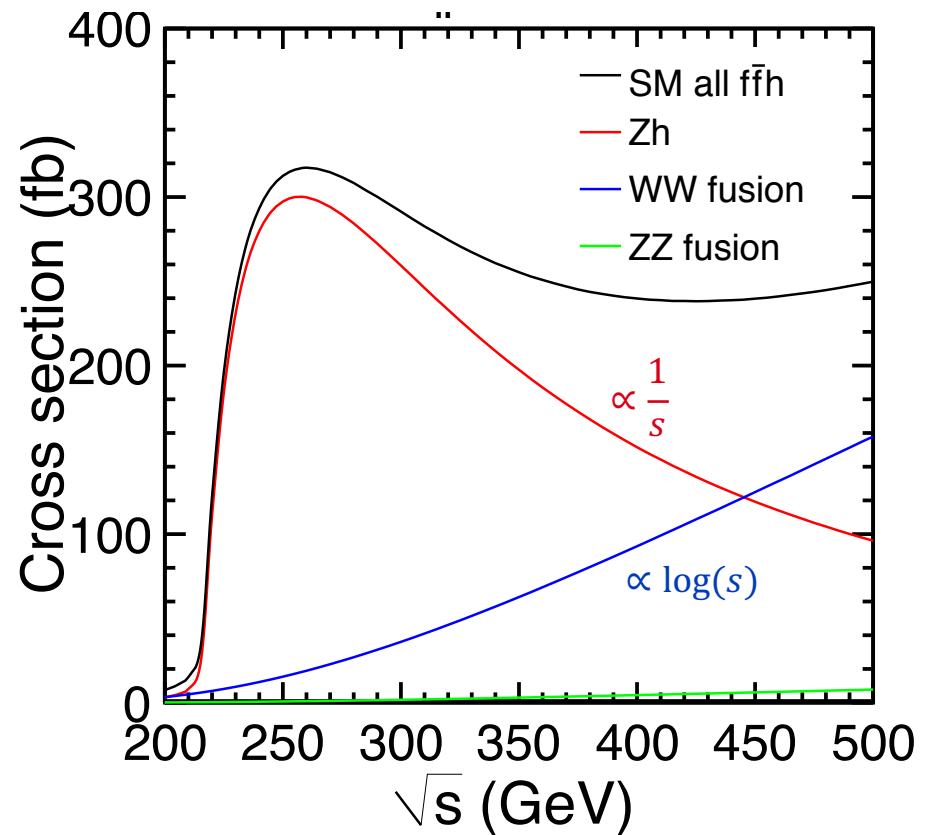
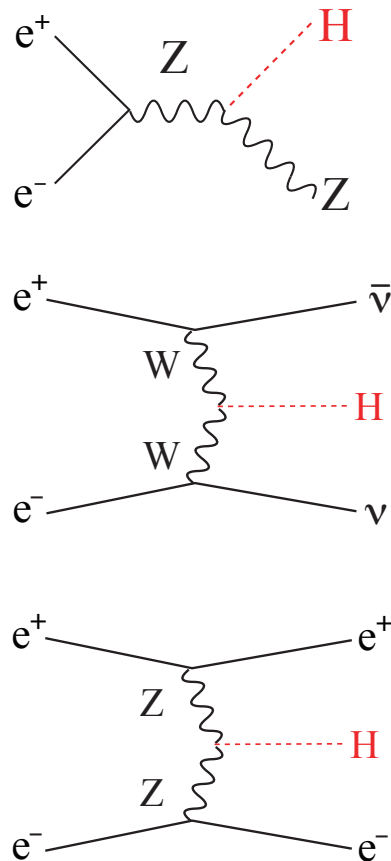
- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory

Strong CP problem

Future e^+e^- collider

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

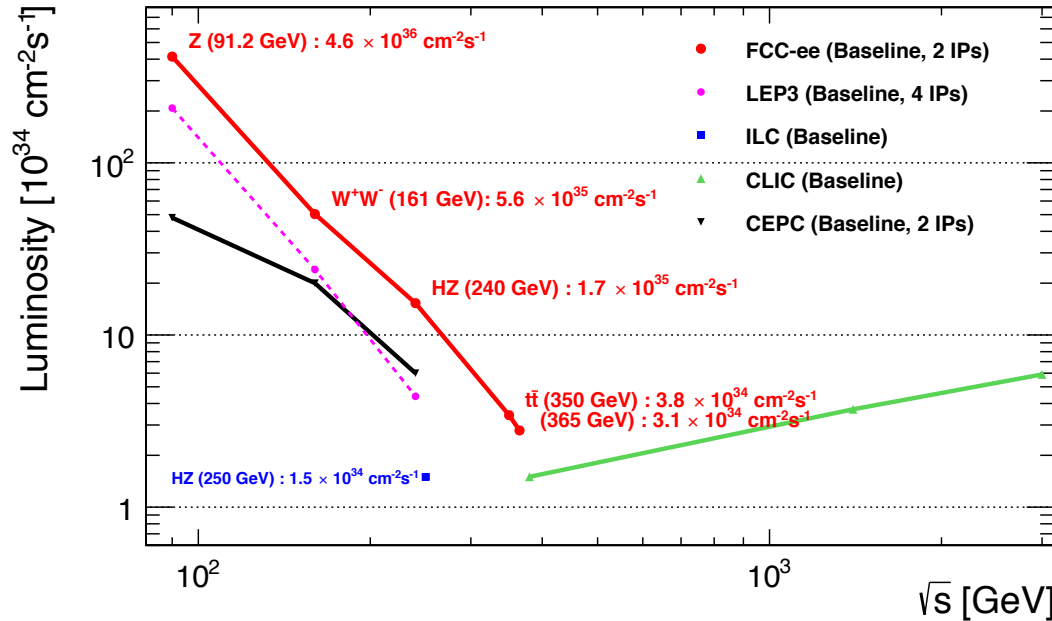
Dominant production mechanisms: $e^+e^- \rightarrow ZH$ (Higgsstrahlung), $\nu\nu H$ (W fusion), eeH (Z fusion)



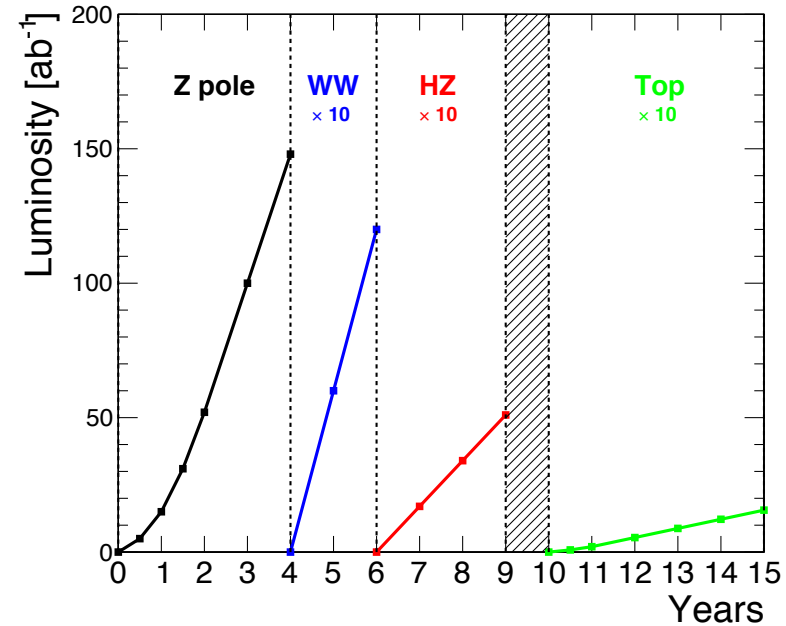
Future e⁺e⁻ collider

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	$> 10^5 \times \text{LEP}$ 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 tt events

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%