Report from ATLAS Experiment (External Partner)

by Markus Elsing
CERN EP-ADP Group

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)

LHC ring at CERN:
27 km circumference

70 – 140 m depth

CMS

LHC control room

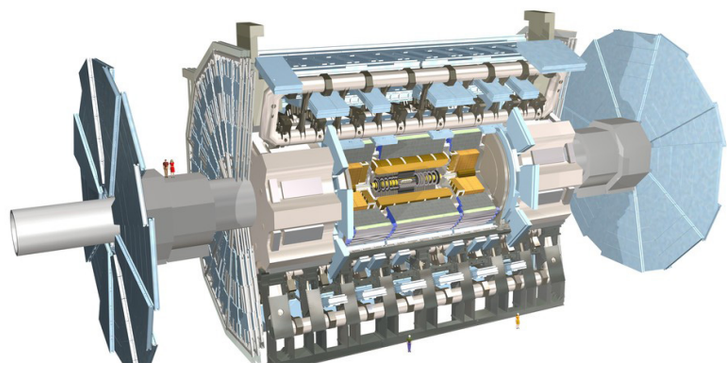
CERN (Prévessin site)

LHCb

SPS ring:
7 km circumference

ALICE

CERN (Meyrin site)



ATLAS: a large, sophisticated general purpose particle detector

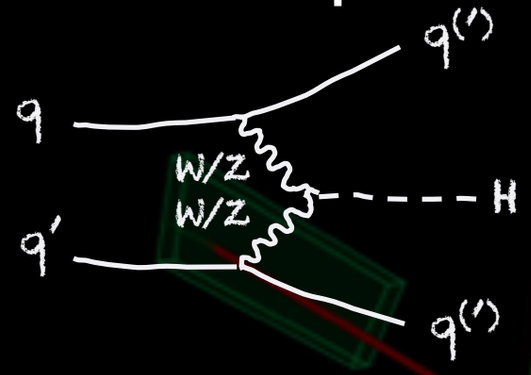
Introduction: LHC Physics Programme

- Proton-proton programme:
  - **I. Mass and electroweak symmetry breaking**
    - Precision measurements of the Higgs Boson properties (after the discovery in 2012)
  - **II. Electroweak unification and strong interactions**
    - Precision measurements (m_{top}, M_W) and tests of the Standard Model
    - Tests of perturbative QCD at the high-energy frontier
  - **III. Hierarchy** in the TeV domain
    - Search for new phenomena moderating the hierarchy problem
    - Search for the unexpected at the high-energy frontier
  - **IV. Flavour**
    - B-/D-mixing, rare decays and CP violation as tests of the Standard Model

- Heavy ion programme:
  - ➡ Study quark-gluon plasma in Pb-Pb collisions at 5 TeV per colliding nucleon

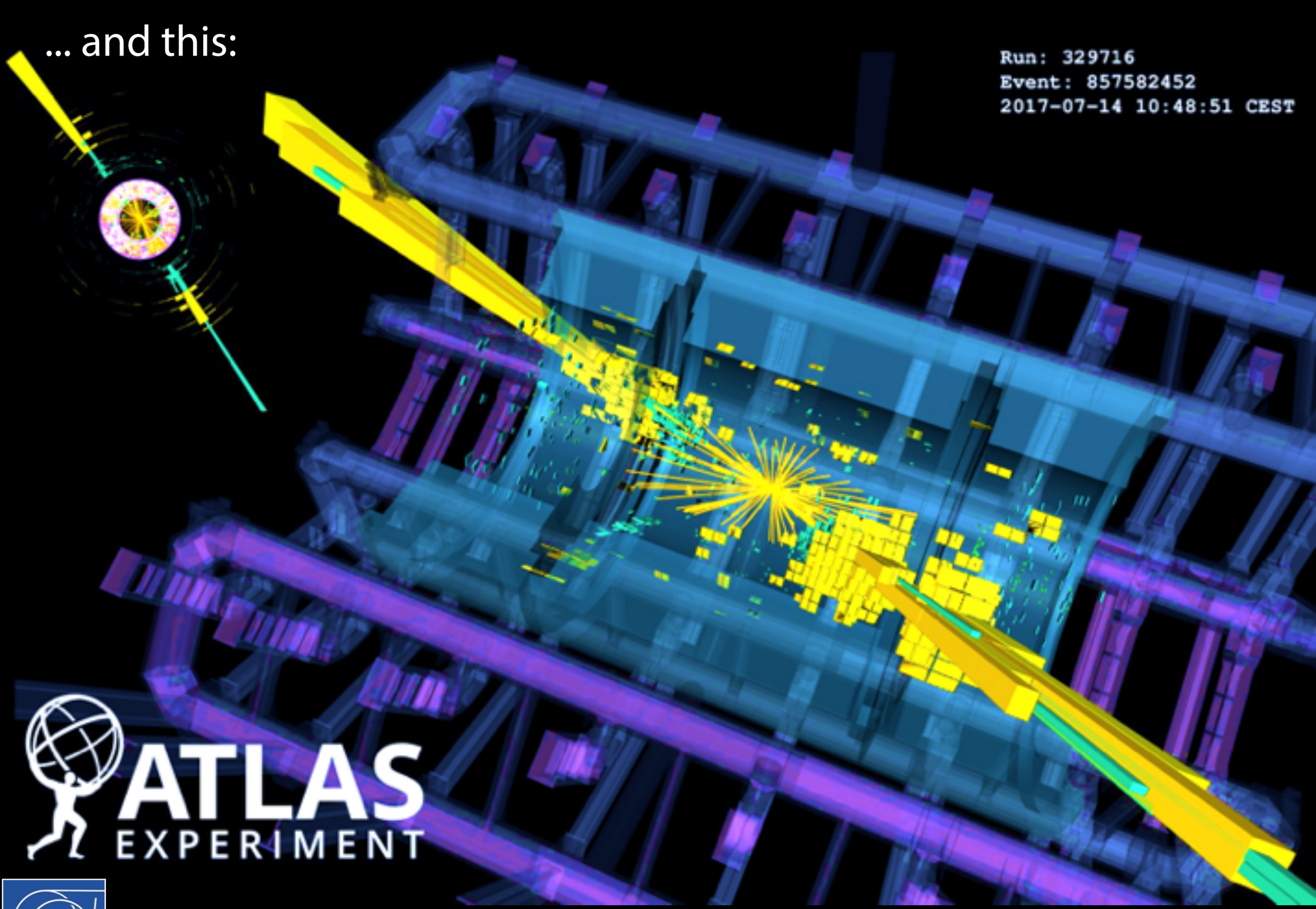
Peter Higgs visiting CERN in 2008

... we are producing events like this:



Display of VBF H → eeμμ + 2 jets candidate from 13 TeV pp collisions recorded in 2015.

... and this:



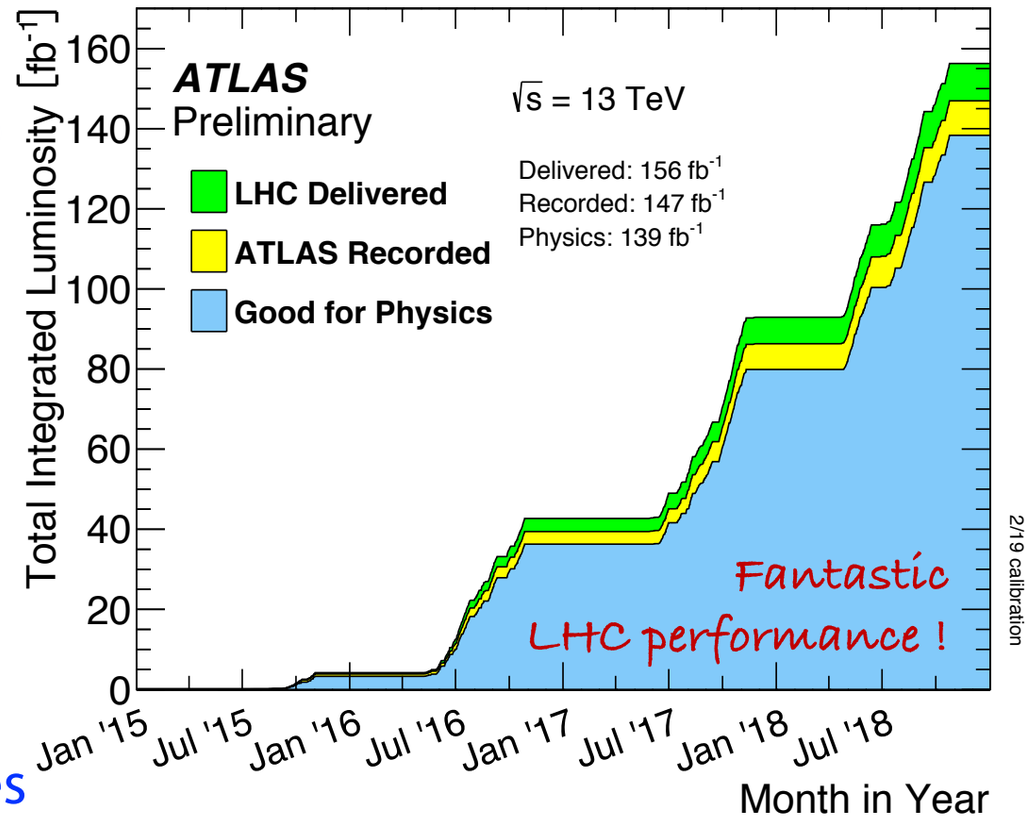
Display of di-jet event with mjj=9.3 TeV, produced in pp collisions at $\sqrt{s}$ = 13 TeV in 2017.
The two high-pT jets both have pT=2.9 TeV, one is at η=−1.2 and the other at η=0.9.

... in an pile-up environment like this:

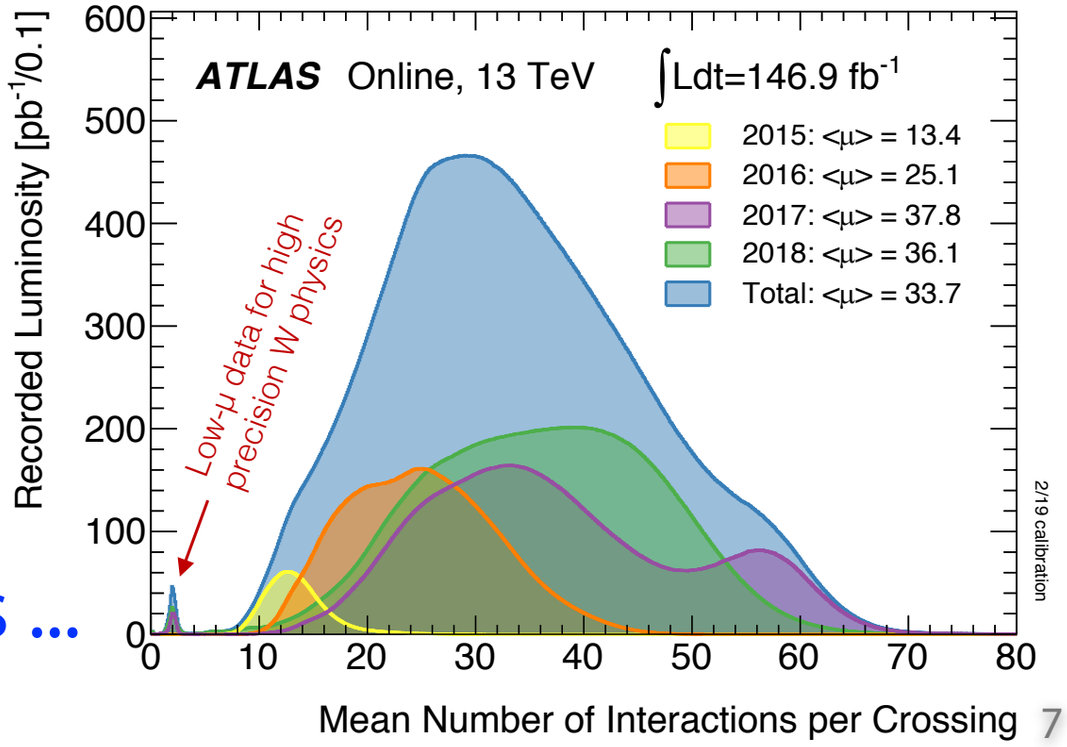
Event displays of the interaction region, showing a Z→ll candidate produced with 65 reconstructed proton-proton collisions. (top: 100 MeV tracks, bottom 1 GeV tracks)

ATLAS Run-2 (2015-2018) Datasets

- Run-2 Integrated pp luminosity
  - ➡ Excellent data taking (94%) and data quality (95%) efficiency
  - ➡ 139 fb^{-1} (!) of good pp data at $\sqrt{s}$ = 13 TeV
  - ➡ Luminosity measured to a precision of 1.7%
    ATLAS-CONF-2019-021
  - ➡ Excellent reconstruction performance based on precise detector calibrations



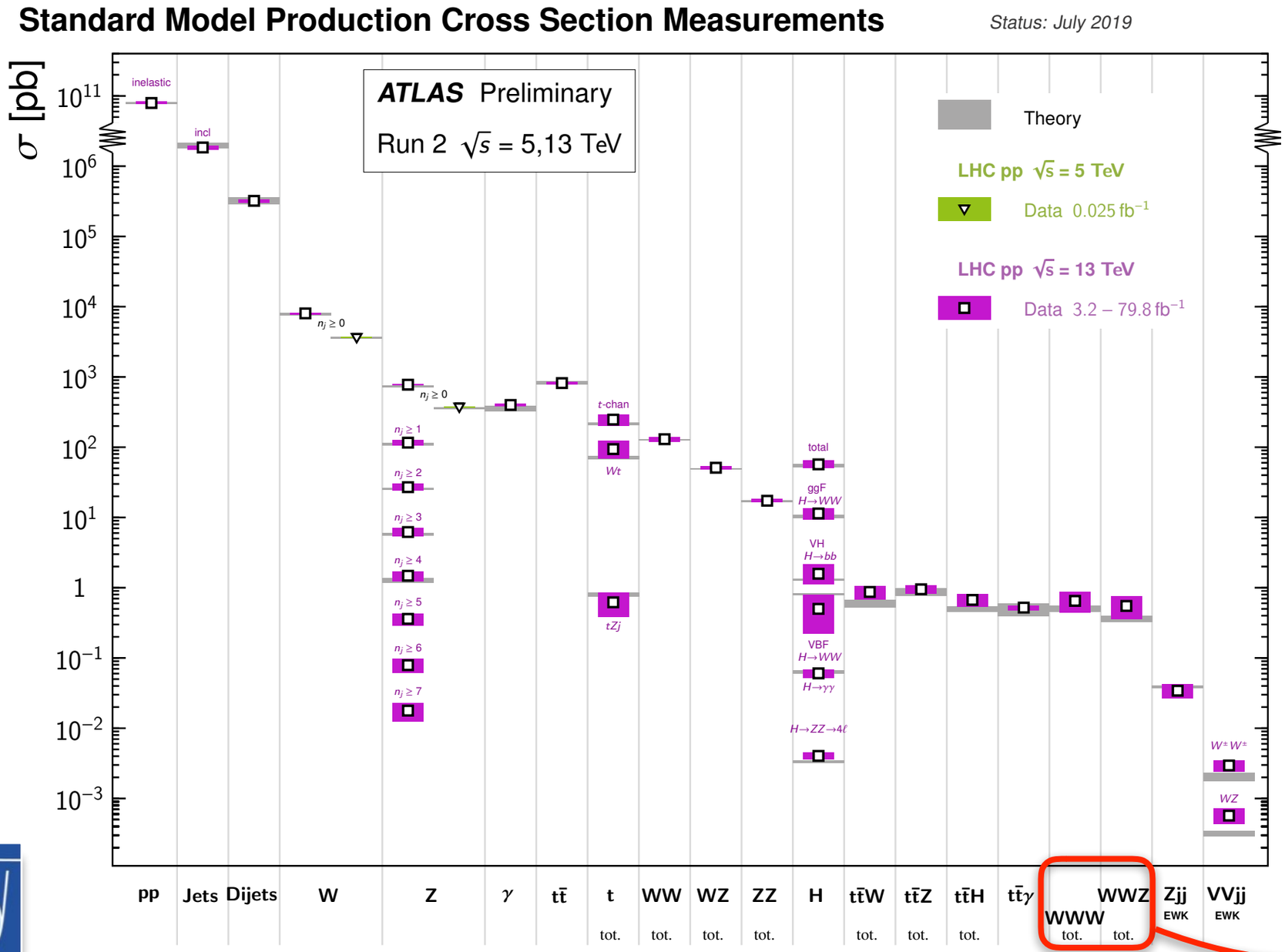
- LHC is a versatile machine
  - ➡ Dedicated setups with different beam energies and optics for diffractive physics
  - ➡ Low-μ data for precision W physics
  - ➡ Collected 2.3 nb^{-1} of 5 TeV Pb-Pb data, and p-Pb & Xe-Xe data

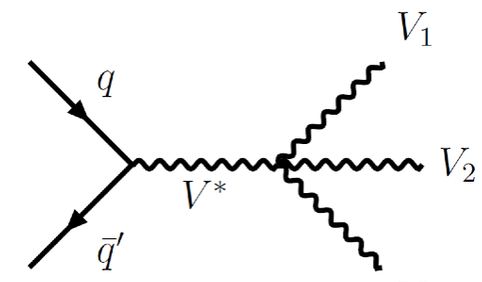


- Rich harvest of physics results based on (full) Run-2 datasets presented at summer conferences ...

Standard Model Production Cross Sections

- So far, all measured total cross sections agree with theory
  - ➡ Production cross sections span 14 orders of magnitude
  - ➡ Also thanks to huge progress on theoretical calculations (NNLO revolution)





> 4σ evidence for weak tri-boson production by ATLAS using 2015–2017 data

arXiv:1903.10415

Precision Top Cross Section Measurements

- Measure $t\bar{t}$ cross section
  - ➡ Final state: eμ and >= 1 b-tagged jet
  - ➡ Total:

2.4% uncert.

$$\sigma_{t\bar{t}} = 826.4 \pm 3.6 \pm 11.5 \pm 15.7 \pm 1.9\,\text{pb}$$

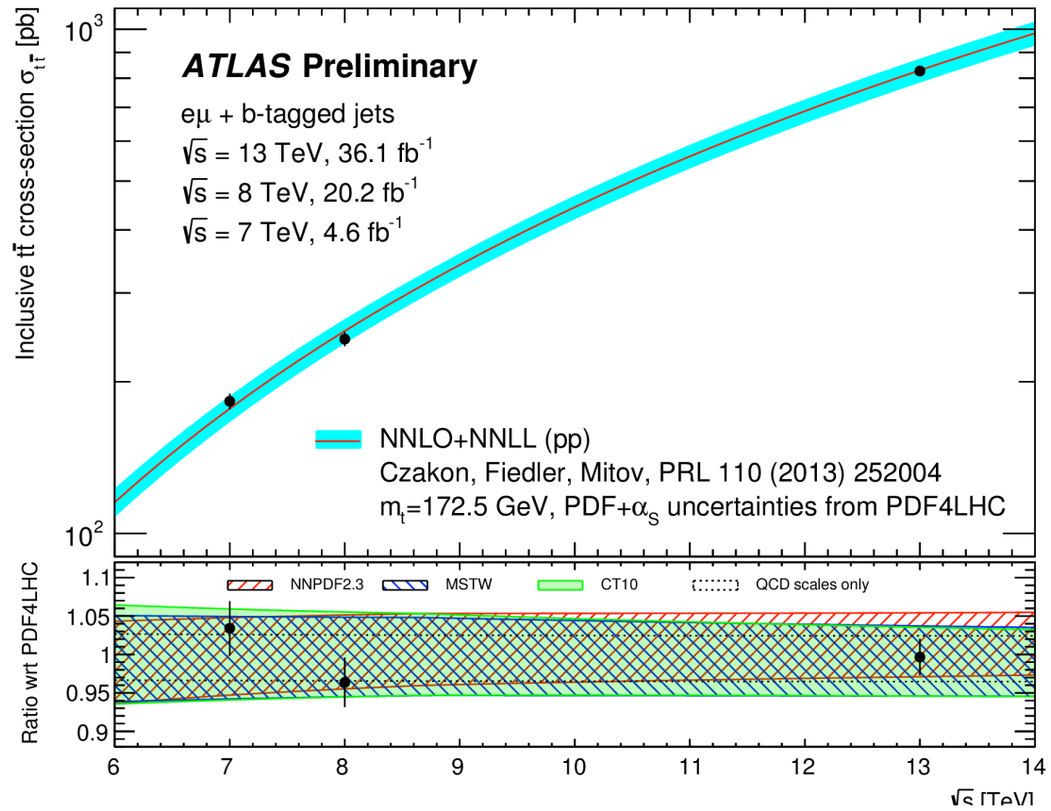
  - ➡ NNLO+NNLL prediction: $832 \pm 35^{+20}_{-29}\,\text{pb}$
  - ➡ Also fiducial and differential cross section provided

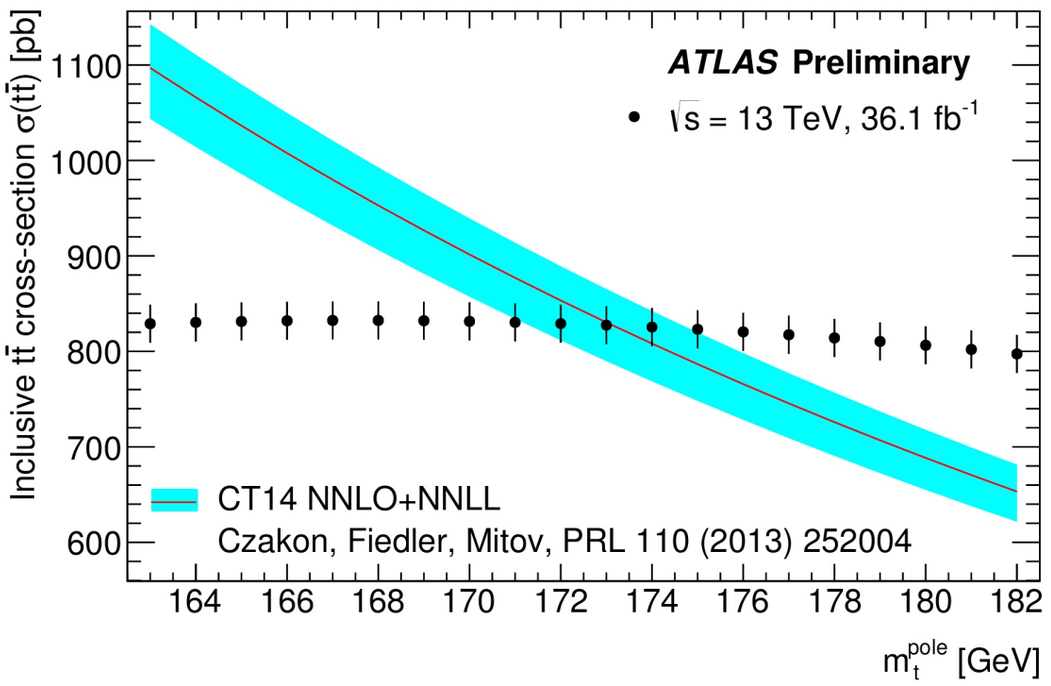
ATLAS-CONF-2019-014

  - ➡ Re-interpretation of $\sigma_{t\bar{t}}$ yields:

$$m_t^{\text{pole}} = 173.1^{+2.0}_{-2.1}\,\text{GeV}$$

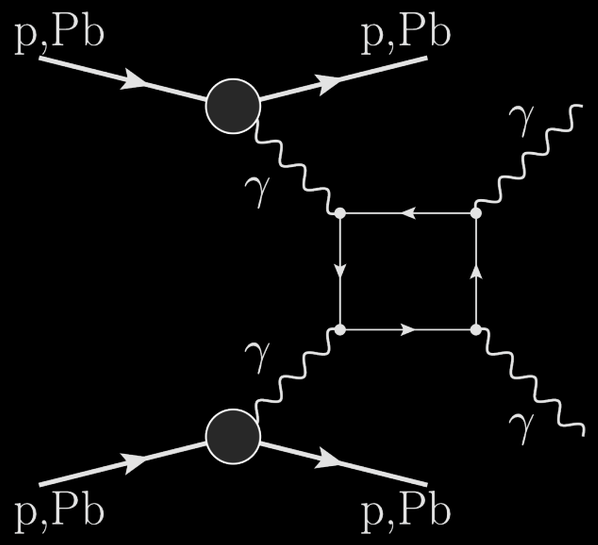
  - ➡ Compare to 172.69 ± 0.25 ± 0.41 GeV from ATLAS direct measurements

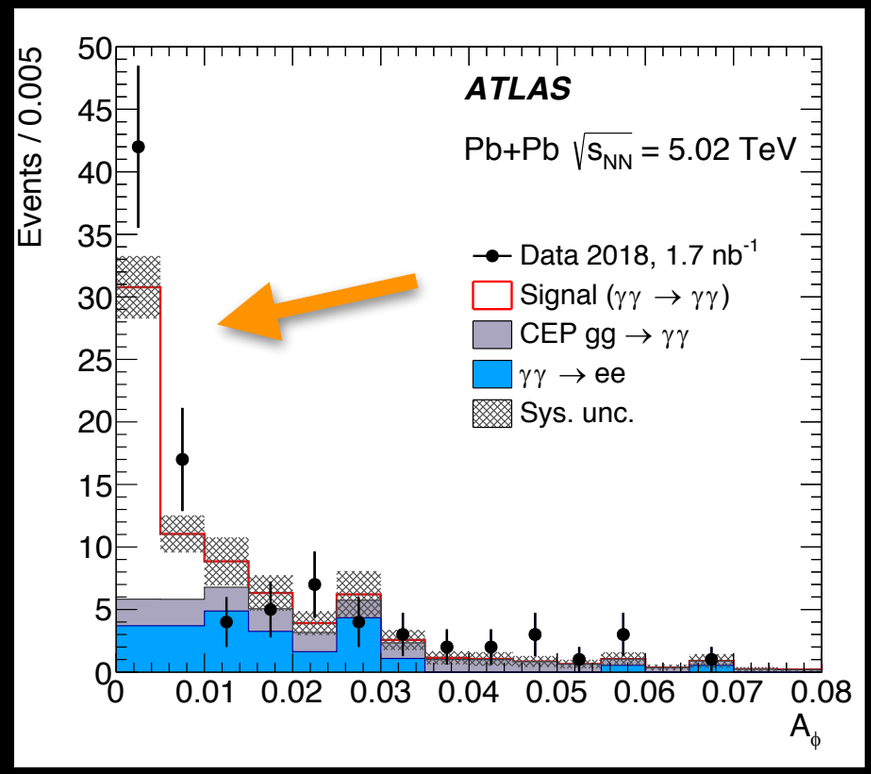




Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb-Pb collisions

[arXiv:1904.03536]



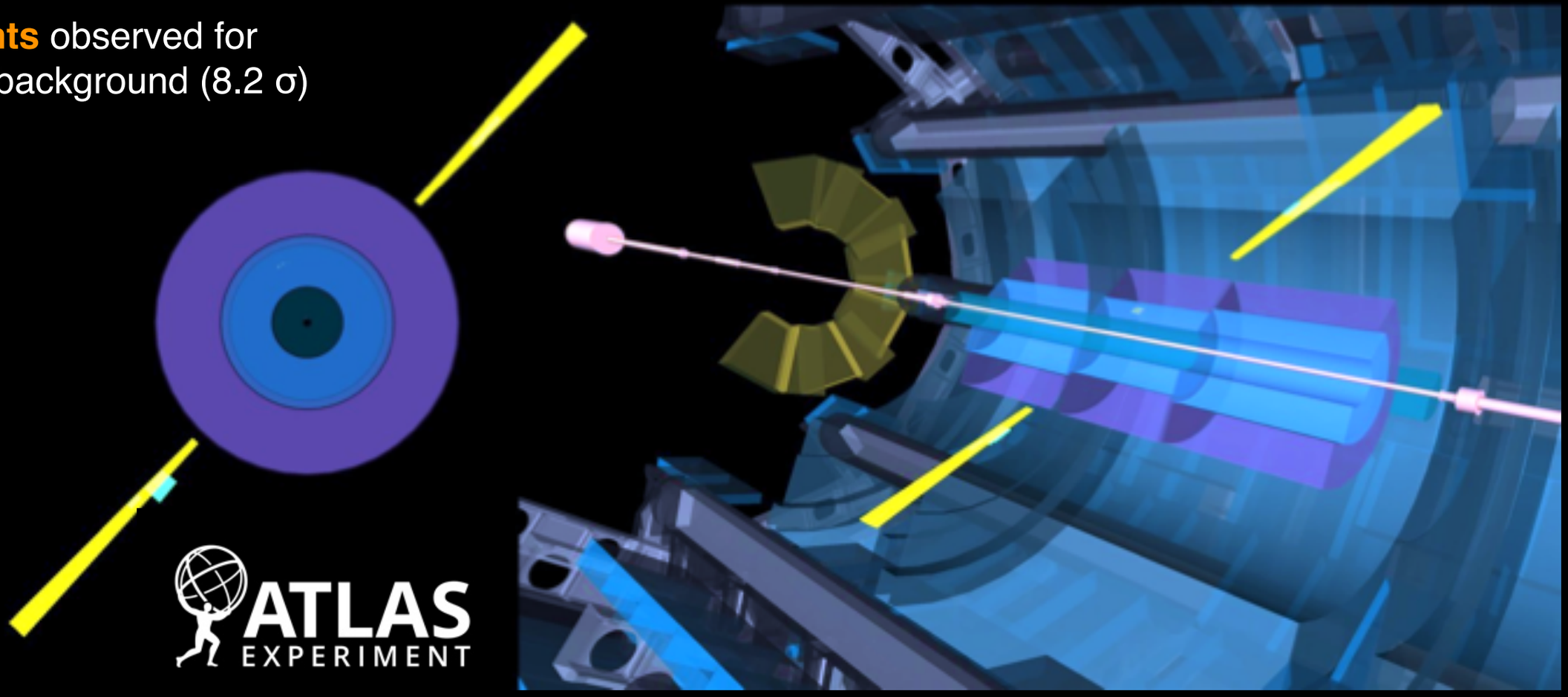


Field strength of up to 10^{25} V/m
γγ luminosity ~ Z^4 ~ $5*10^7$

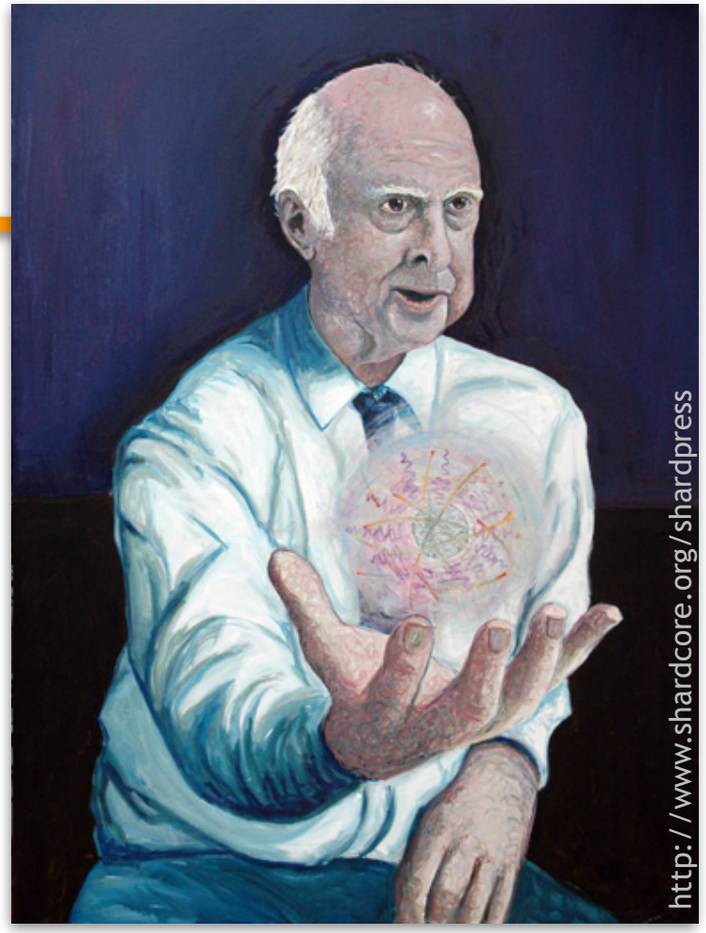
Look for low-energy back-to-back photons pairs with no additional activity in detector

59 γγ → γγ events observed for
12 ± 3 expected background (8.2 σ)

2018 Pb-Pb

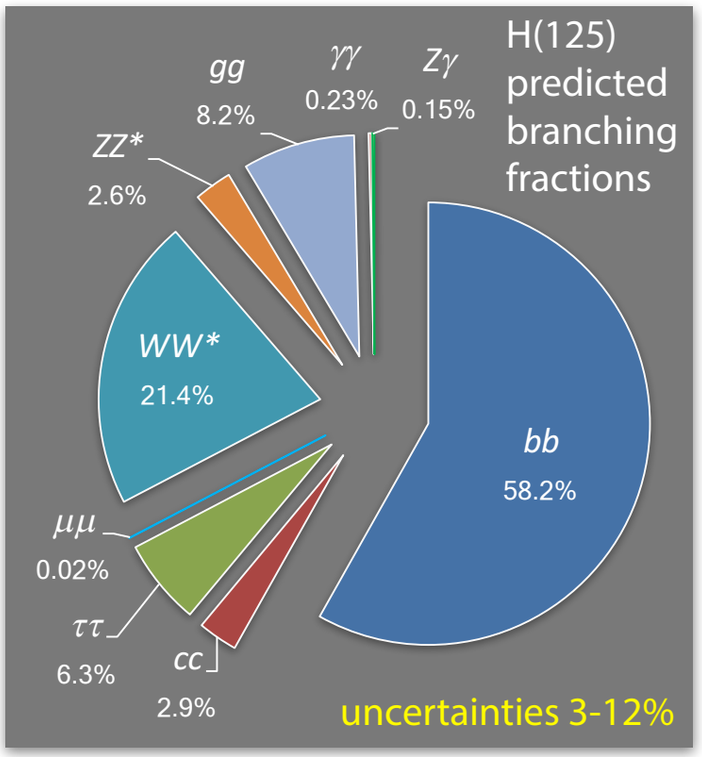


Higgs Boson Physics



- Access to a new sector of SM Lagrangian:
  - ➡ Only elementary scalar particle in the SM
  - ➡ Yukawa couplings (new types of interaction)
  - ➡ Gauge–scalar boson interactions
  - ➡ Higgs potential (incl. self coupling)
- Large sample of ~8M Higgs bosons produced
  - ➡ Allows to do precise test of SM predictions

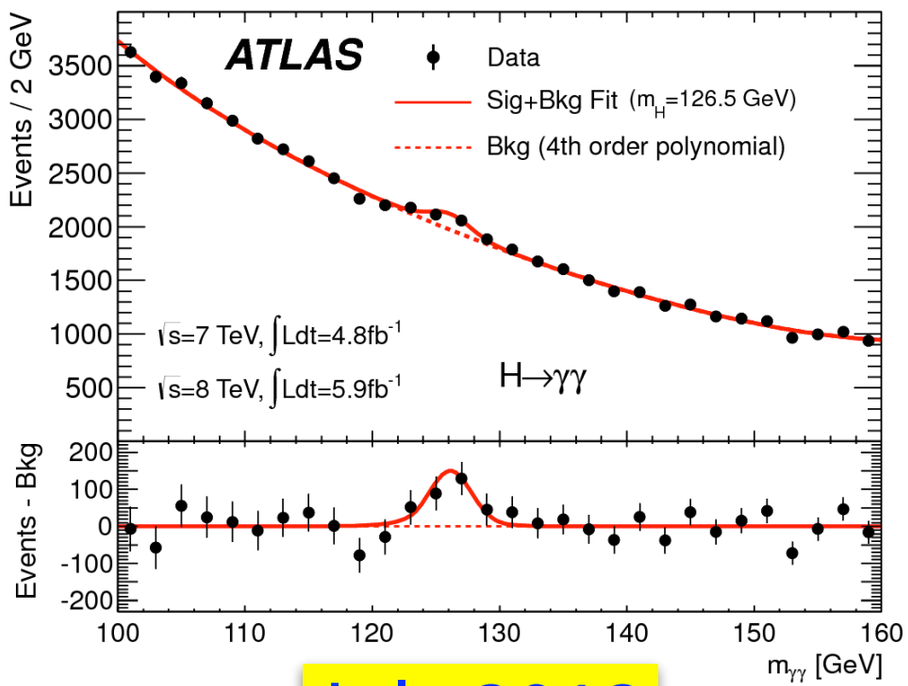
Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	($\to 4\ell$) 210	1–2%
$H \to WW^*$	1,680,000	($\to 2\ell 2\nu$) 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

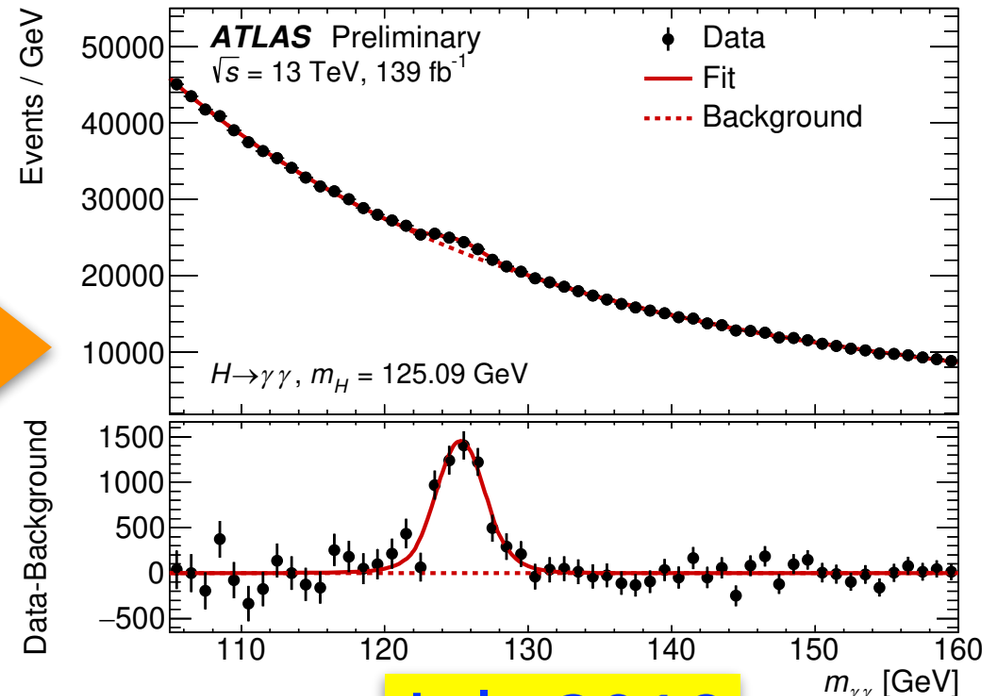


- Major progress over recent ~year
  - ➡ Observation of H→bb decay and of ttH and VH production
  - ➡ All major Higgs production and decay modes now observed
  - ➡ Detailed studies of cross sections, search for H→μμ etc., anomalous Higgs couplings and more

Higgs Boson: Now and Then

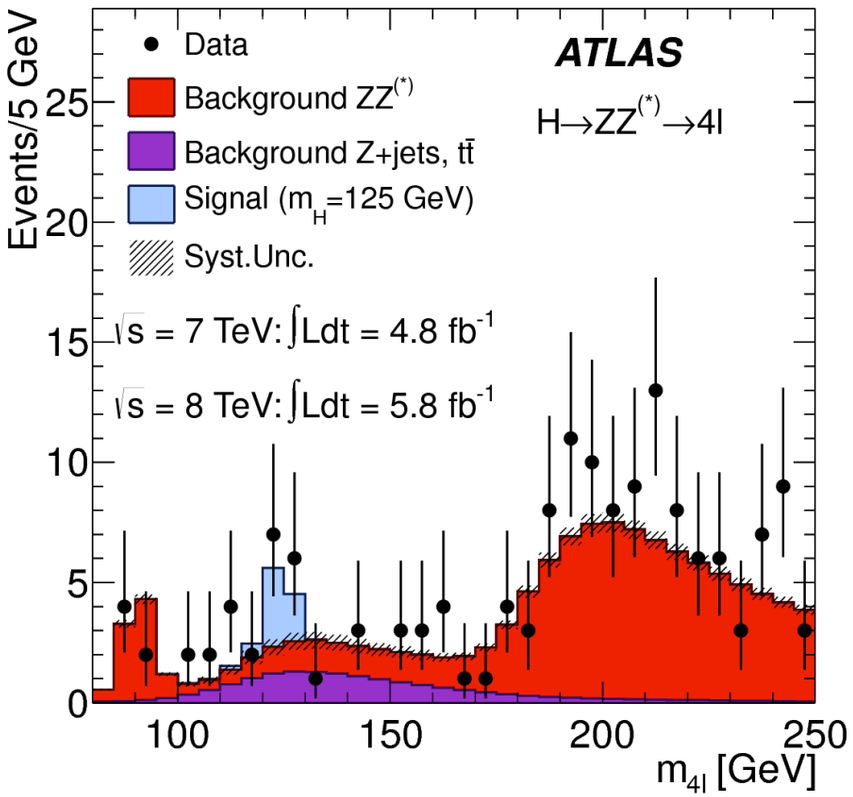
Full Run-2



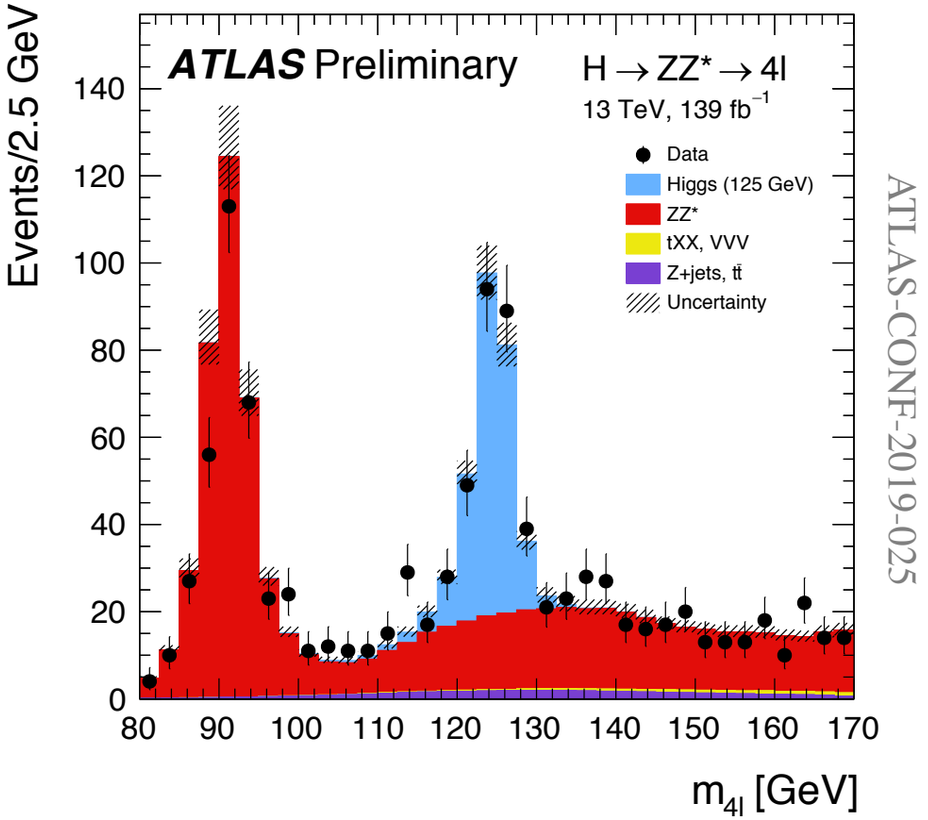


ATLAS-CONF-2019-029

July 2012



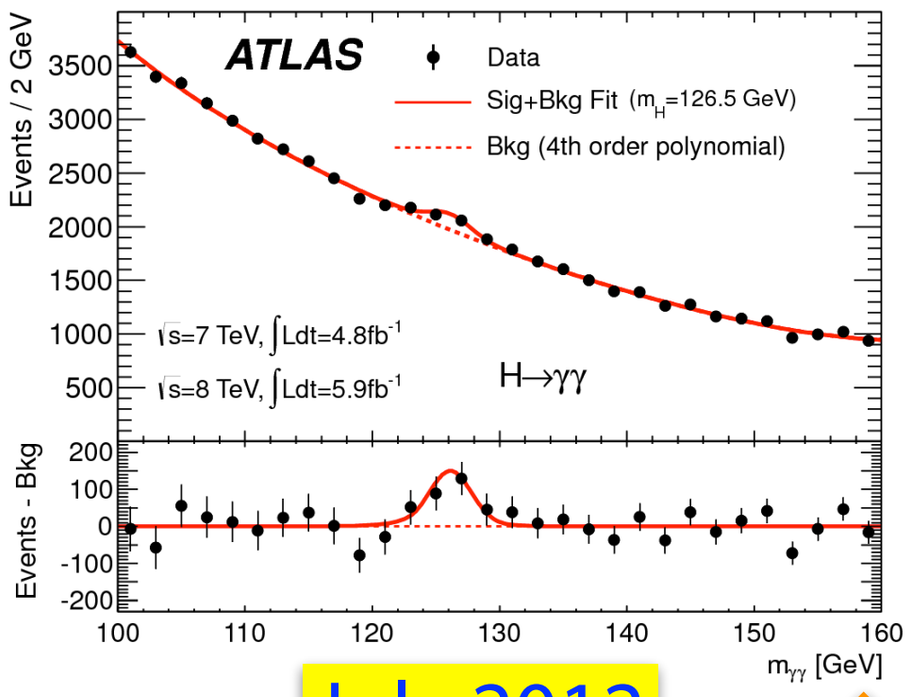
July 2019



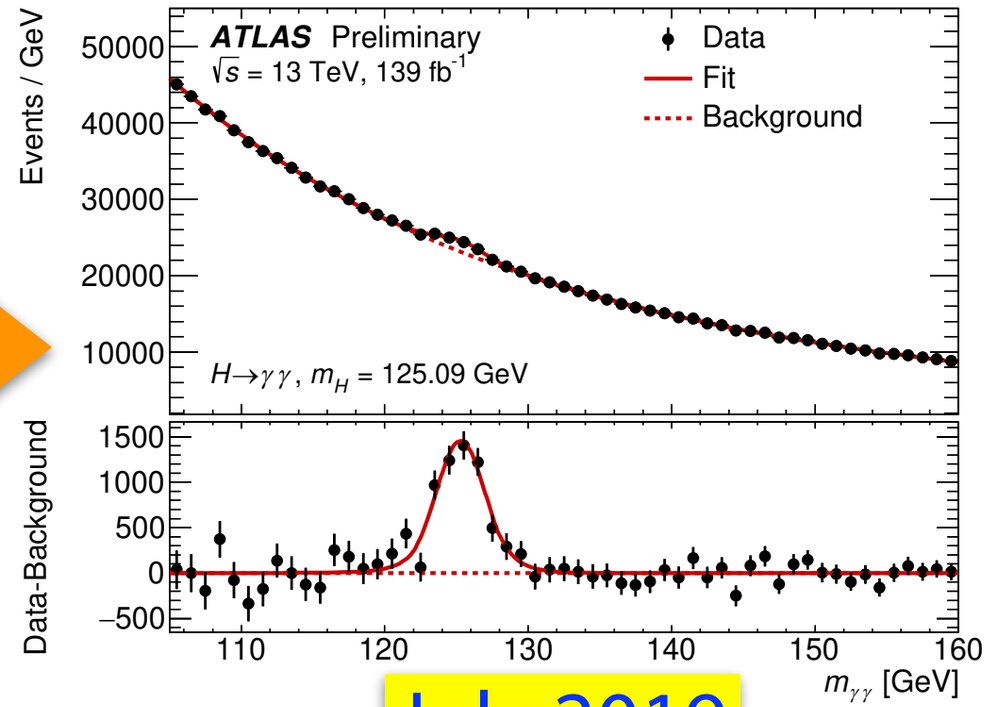
ATLAS-CONF-2019-025

Higgs Boson: Now and Then

Full Run-2



July 2012



ATLAS-CONF-2019-029

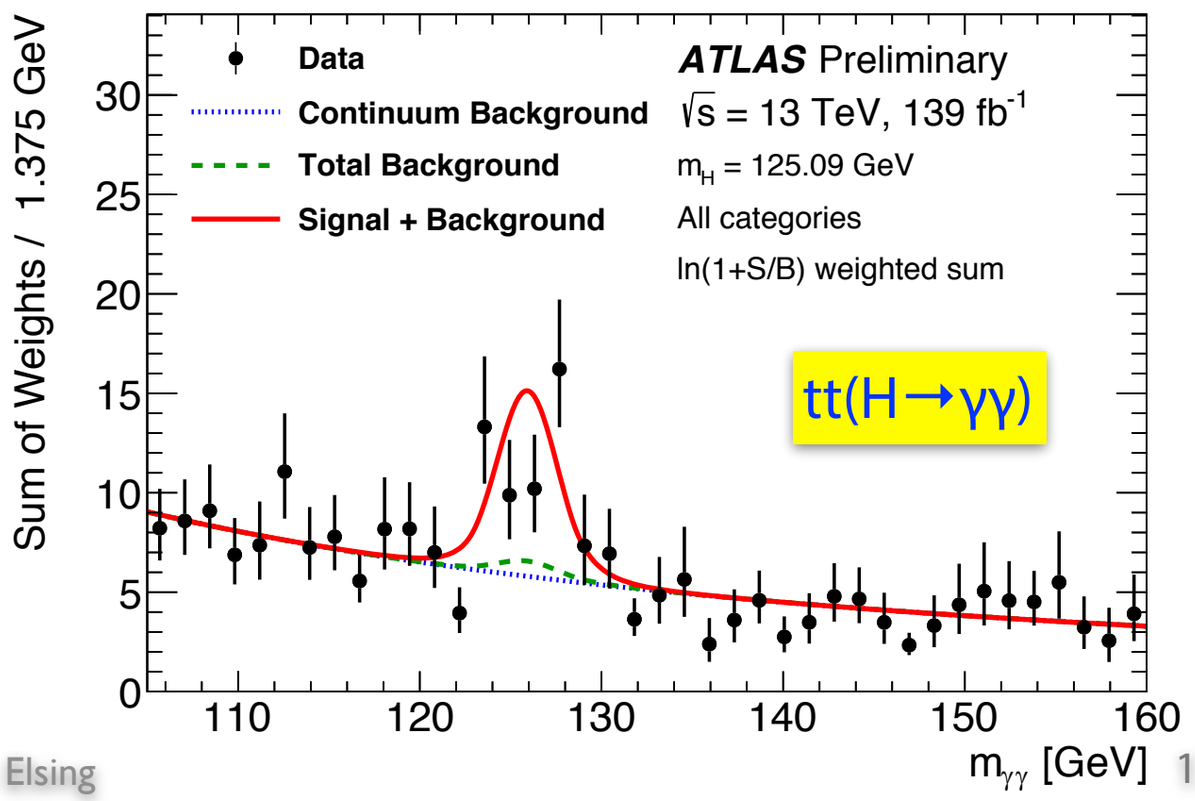
July 2019

- 4.9σ observation of H→γγ in rare ttH production channel

  (only ~1% of total Higgs cross section)

ATLAS-CONF-2019-004 Full Run-2

➡ Was 6.3σ in combined multi-channel analysis in 2018



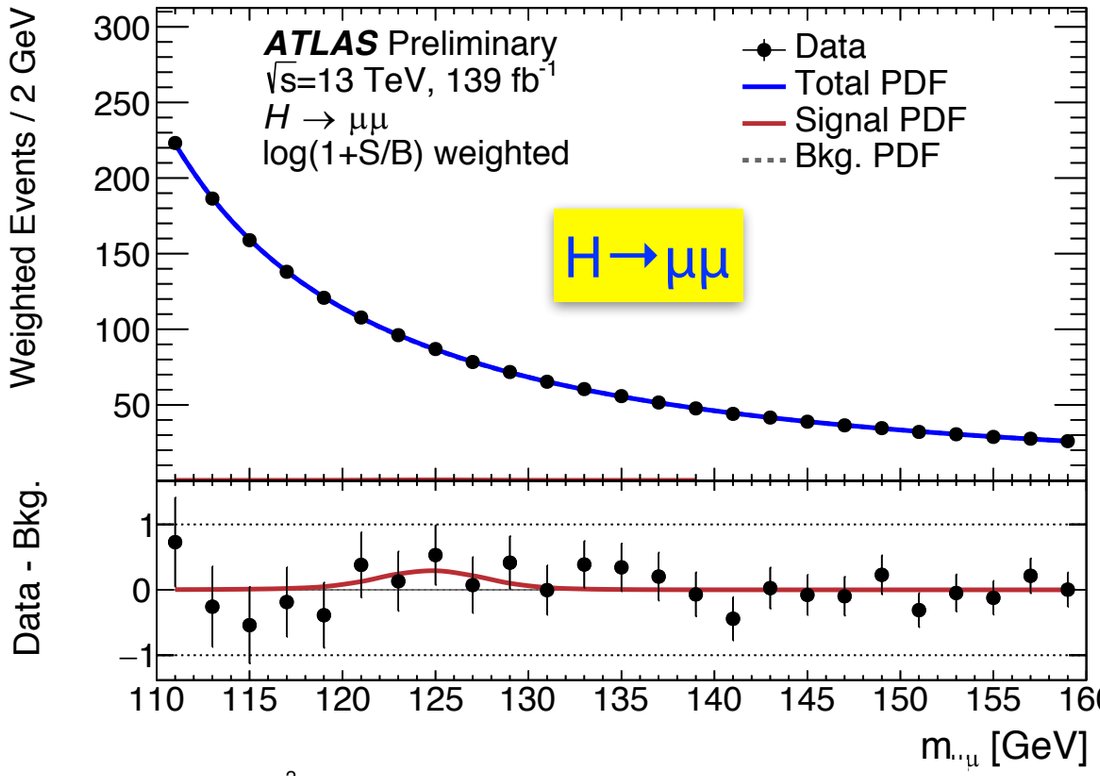
Higgs Boson Decay to Muons (and Electrons)

- H→μμ is challenging at LHC
  - ➡ Small coupling in SM and large backgrounds
  - ➡ Exploit expected event features in multi-variant analysis
  - ➡ Expected sensitivity: 1.5σ , observed: 0.8σ

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

ATLAS-CONF-2019-028

Full Run-2

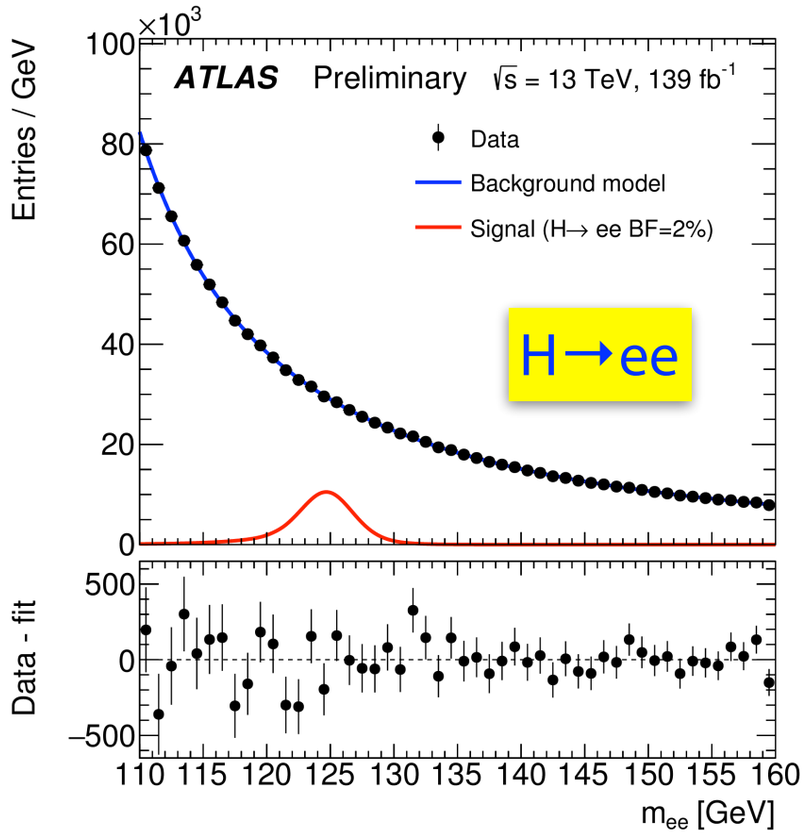


- Search for H→ee (1st generation)
  - ➡ No sensitivity to SM couplings at LHC
  - ➡ No excess observed, limit on branching ratio:

3.6×10^{-4} (3.5×10^{-4} exp.)

ATLAS-CONF-2019-037

Full Run-2



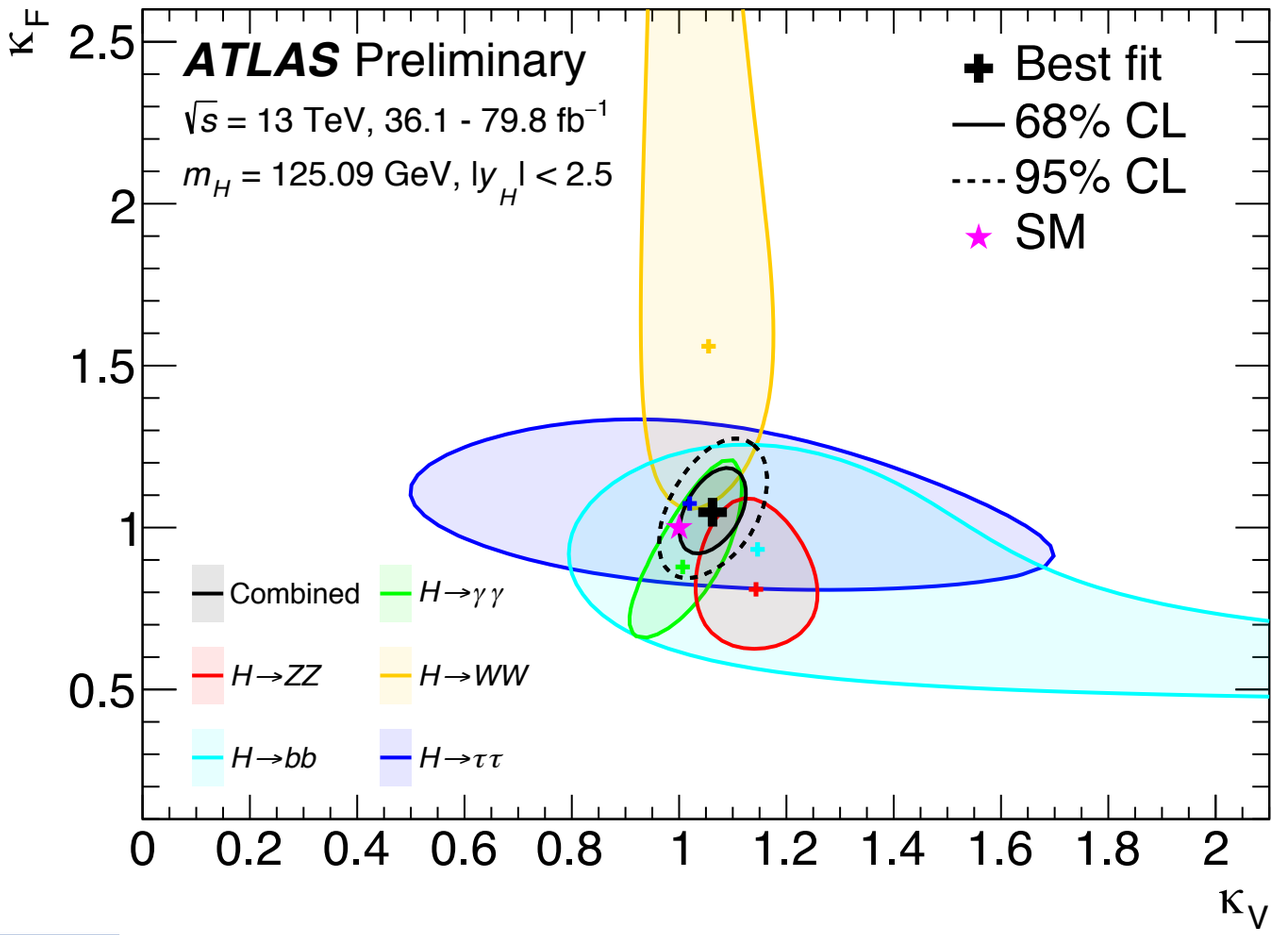
Combination of Higgs Results

➡ Kappa Framework assigns coupling modifiers to each interaction vertex (LO motivated)

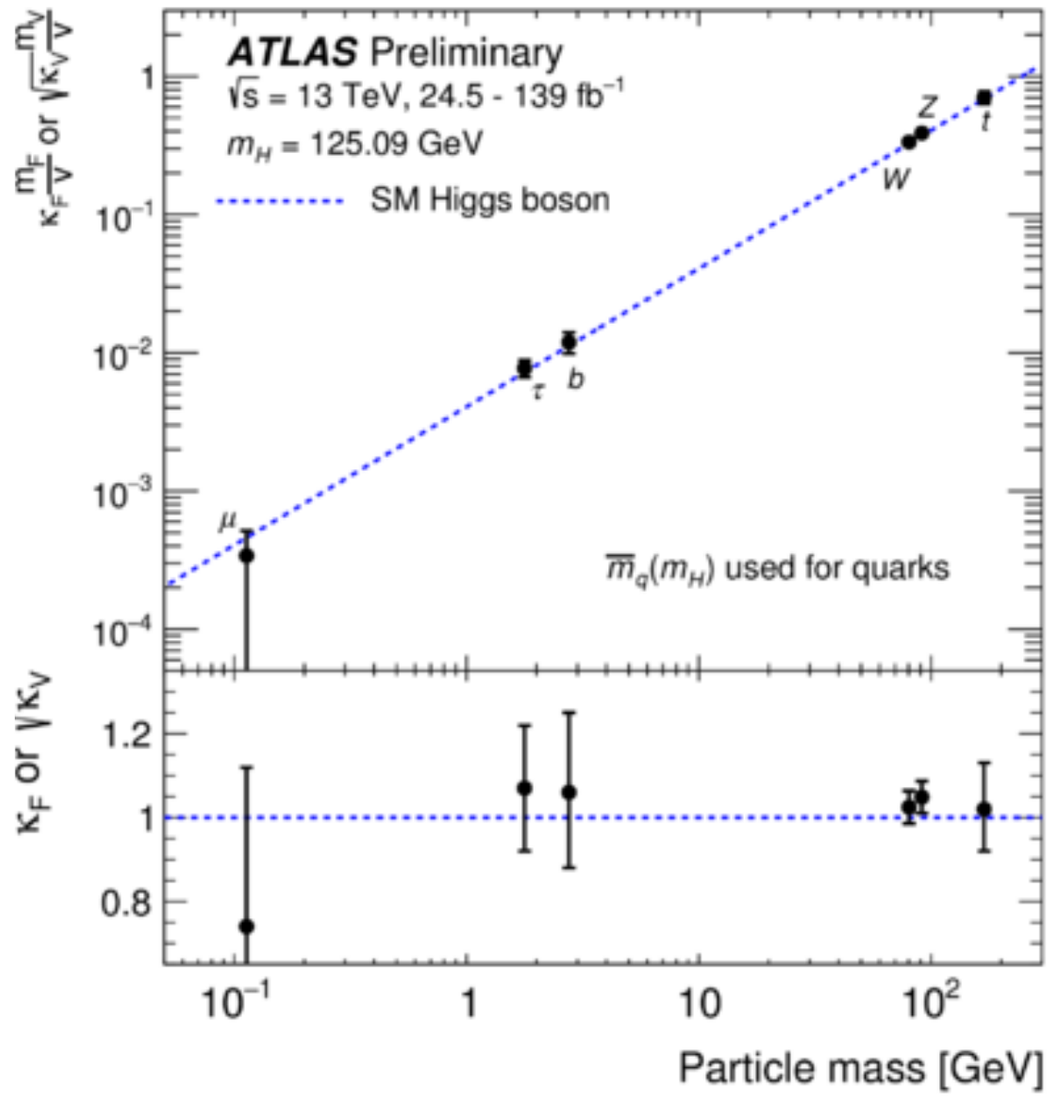
$$\sigma(i \to H \to f) = \kappa_i^2 \sigma_i^{\mathrm{SM}} \frac{\kappa_f^2 \Gamma_f^{\mathrm{SM}}}{\kappa_H^2 \Gamma_H^{\mathrm{SM}}}$$

Resolve loops, assume no BSM contribution in loops or total width

➡ $\kappa_V = \kappa_W = \kappa_Z$ VS $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$



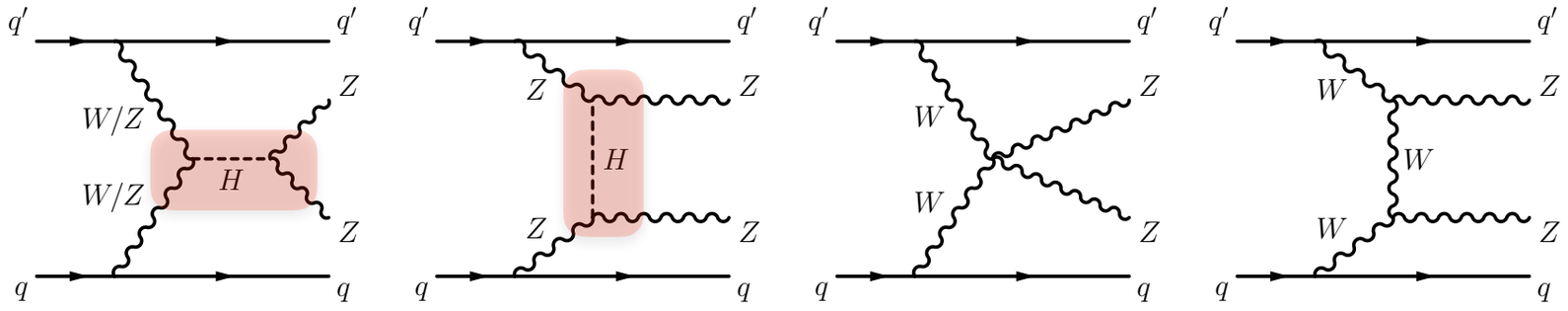
➡ linear version of the plot



Higgs Boson and Electroweak Section

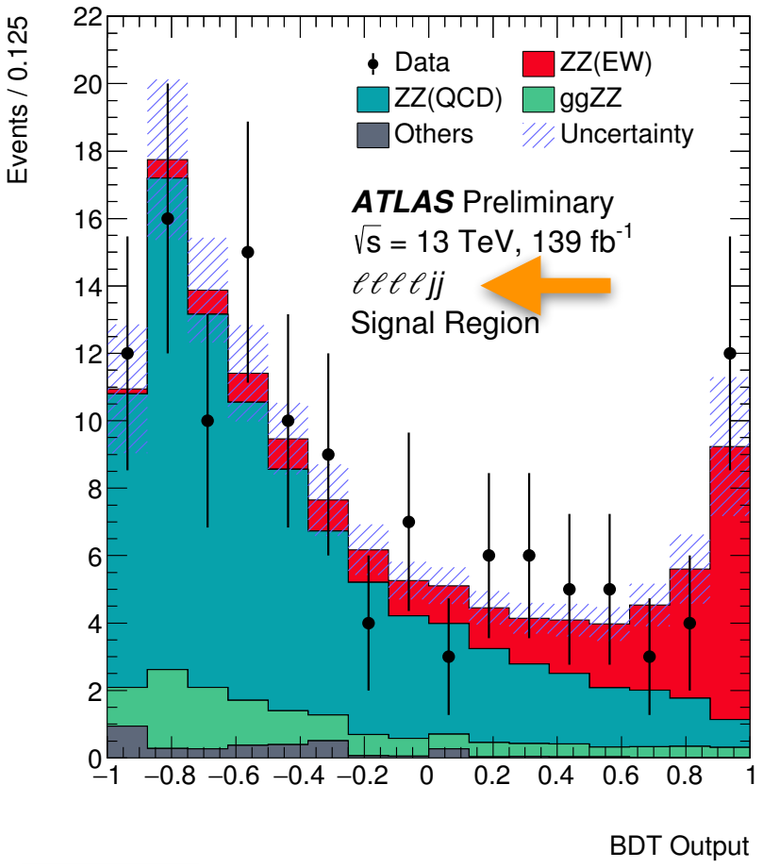
Higgs boson regularises the weak boson scattering cross section at high energies

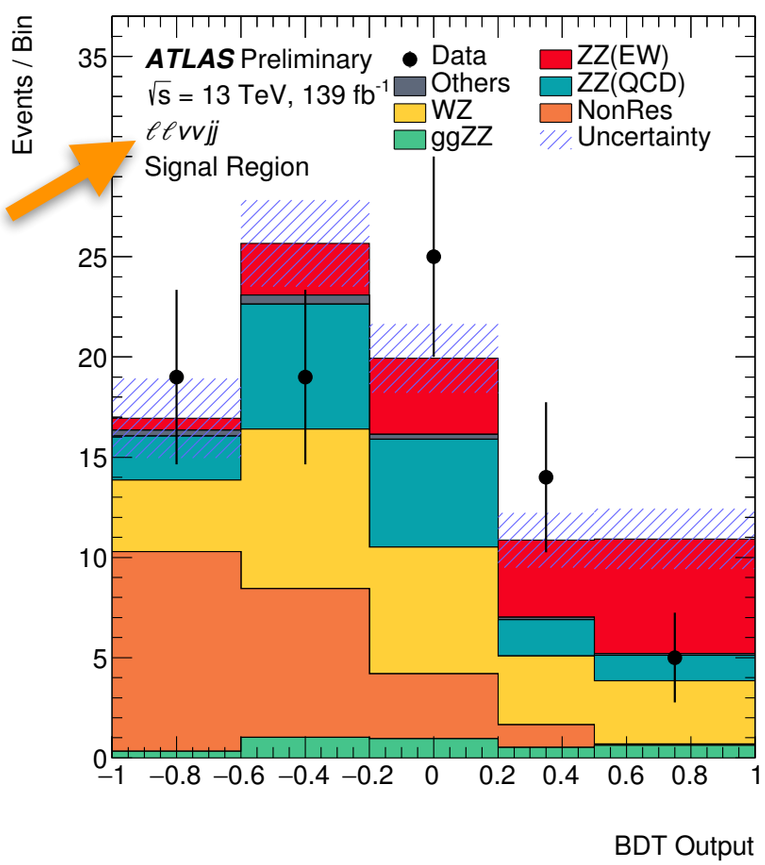
- Observation of vector boson scattering in rare channel ZZjj



➡ Analysis exploits decays to four charged leptons (ℓℓℓℓ) and (ℓℓνν)

➡ Multivariate analysis to separate EW signal from backgrounds (e.g. QCD ZZ)





➡ Observed (expected) significance for EW production: 5.5σ (4.3σ)

$\sigma_{fid}(EW) = 0.82 \pm 0.21$ fb

SM: 0.61 ± 0.03 fb

ATLAS also observed vector boson scattering at:

- 6.9σ in WW channel
- 5.3σ in WZ channel

in agreement with SM

arXiv:1906.03203, arXiv:1812.09740

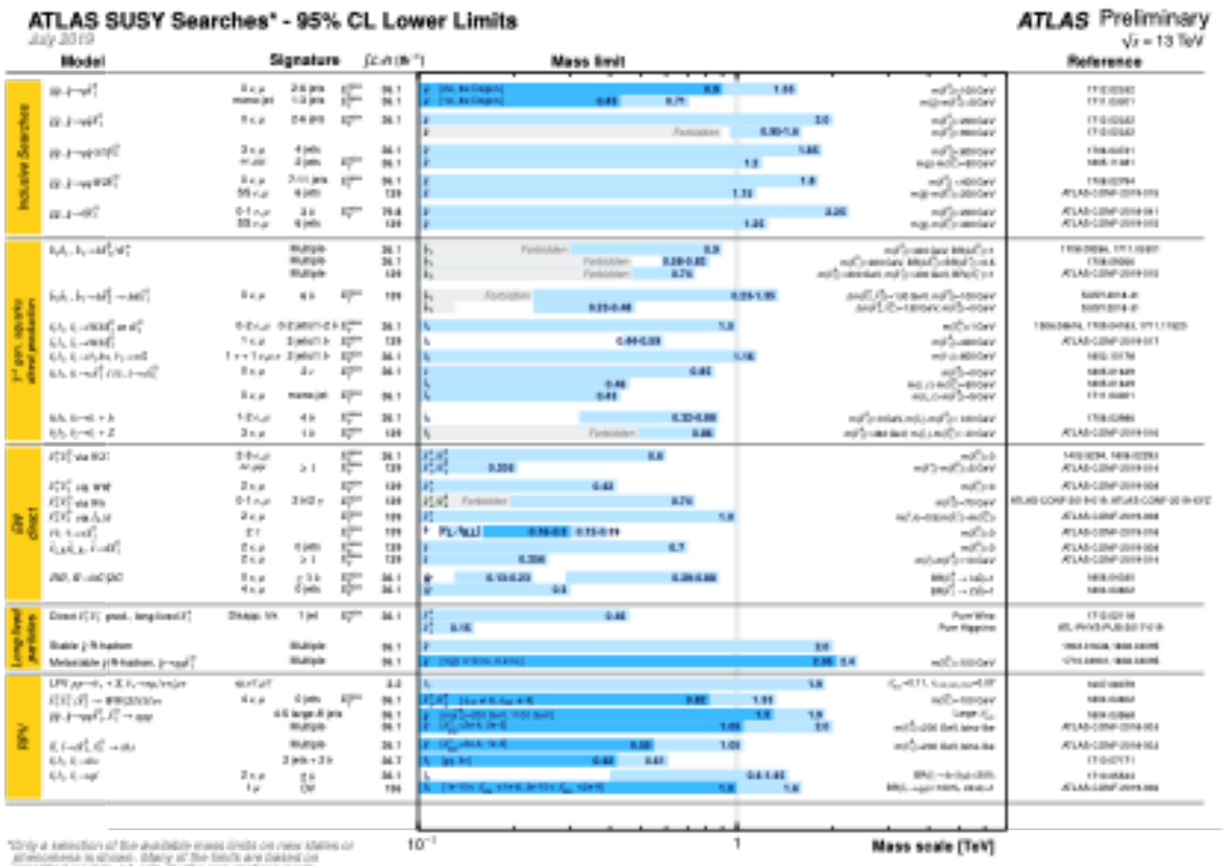
ATLAS-CONF-2019-033

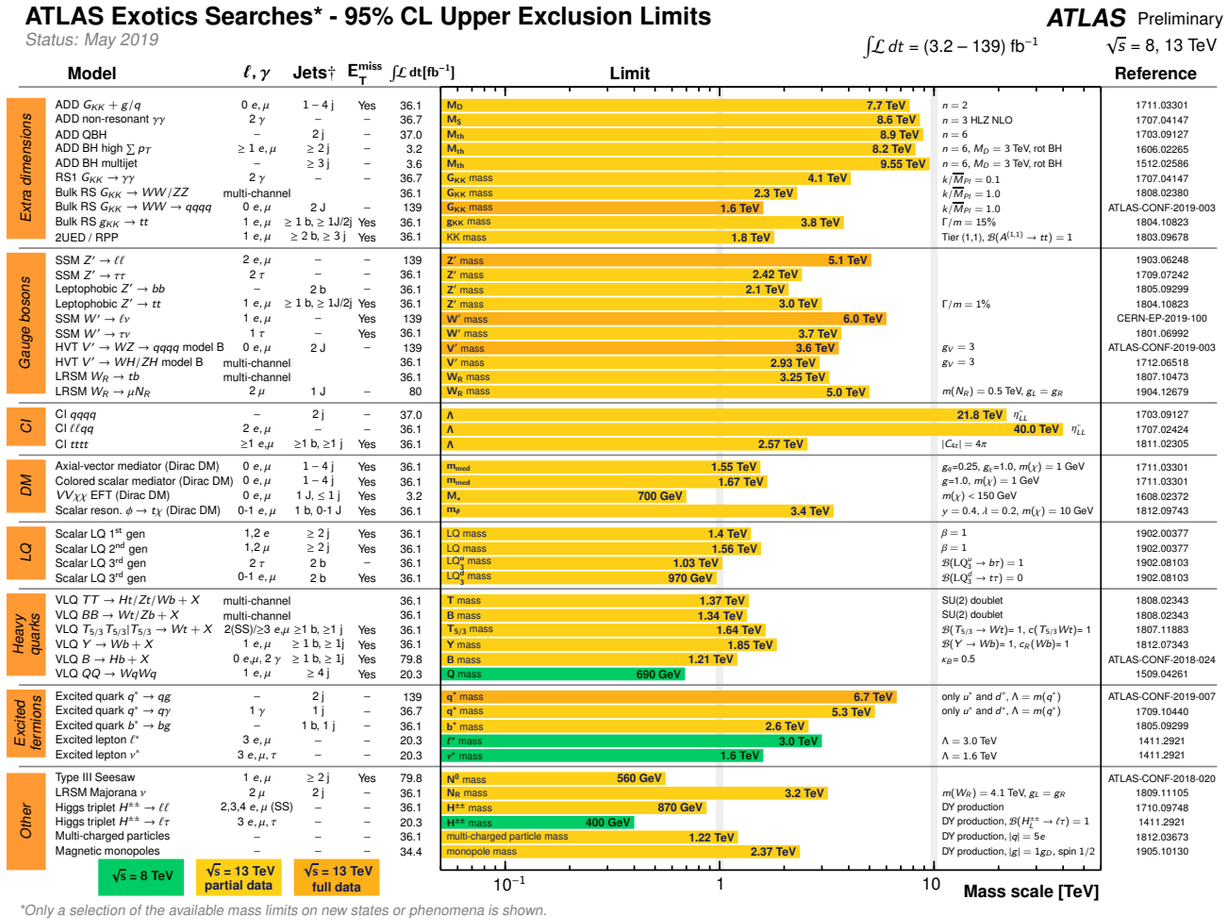
Full Run-2

Searching for Physics beyond the SM at the LHC: looking under the (many) lampposts

Searches for New Physics

- ATLAS running a vast programme that 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

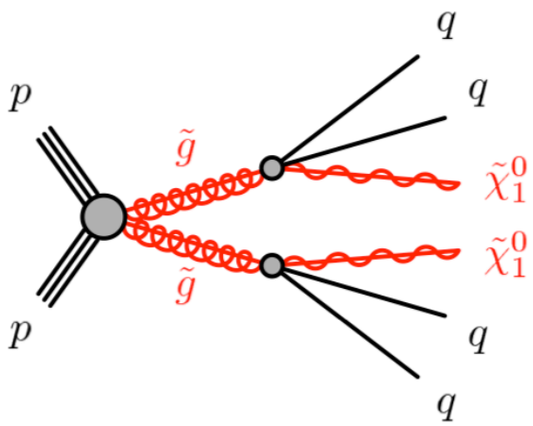


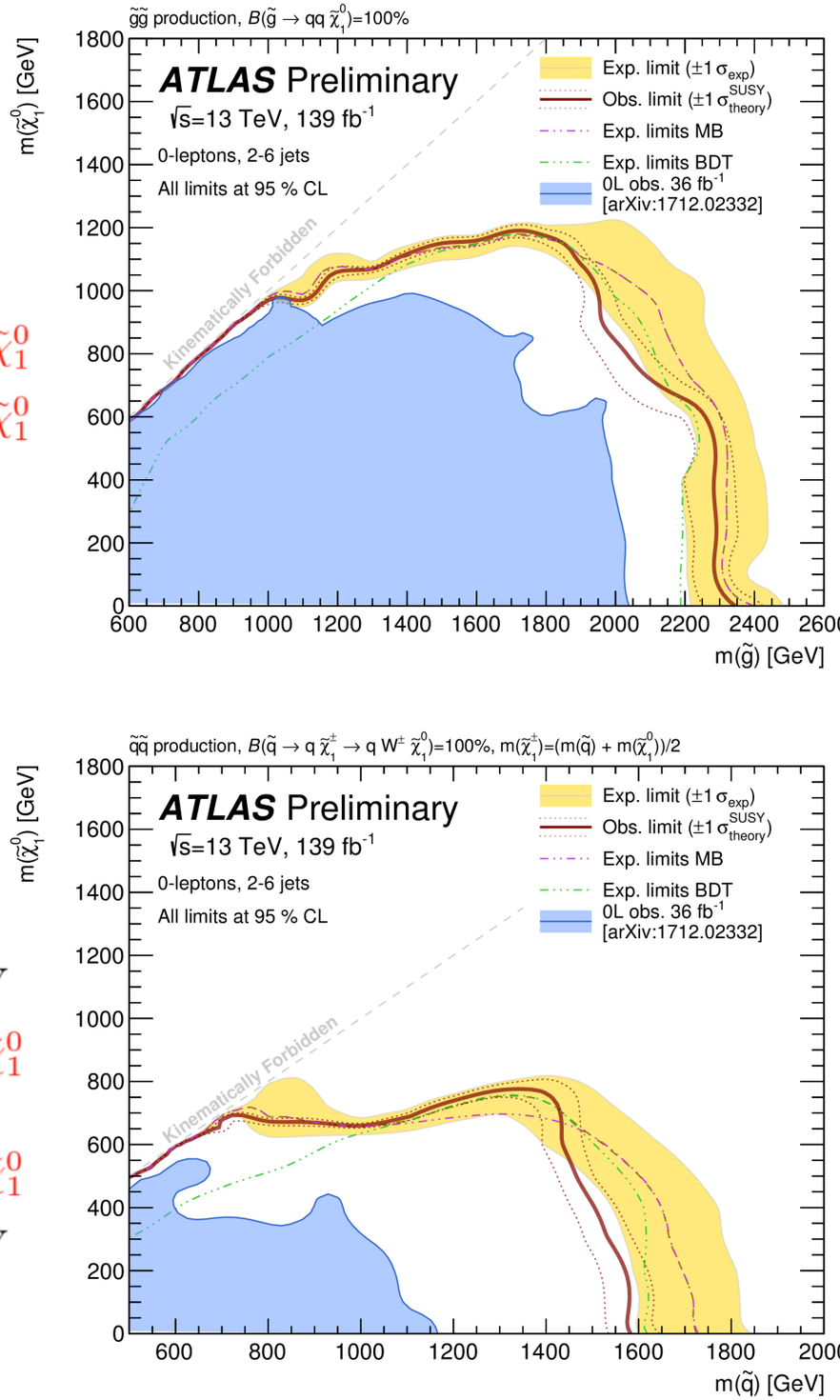


*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

SUSY: Strong Production

- Sensitive searches for squarks and gluinos
  - ➡ R-parity conserving scenarios with neutralino as LSP (no leptons)
  - ➡ High mass reach at LHC

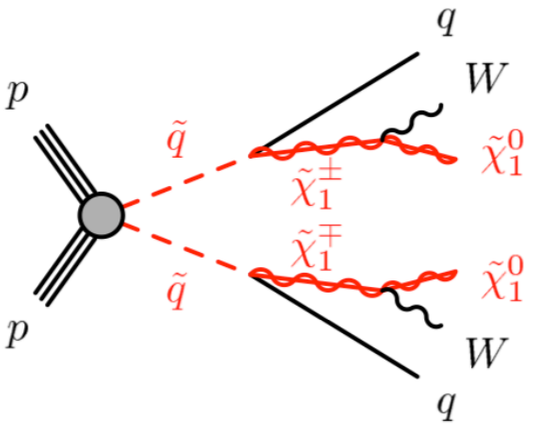




- Many different scenarios investigated, examples:
  - gluino decays to quarks and neutralino
  - squark decays to quarks, W boson, and neutralino
  - ➡ Significant improvement over previous limits

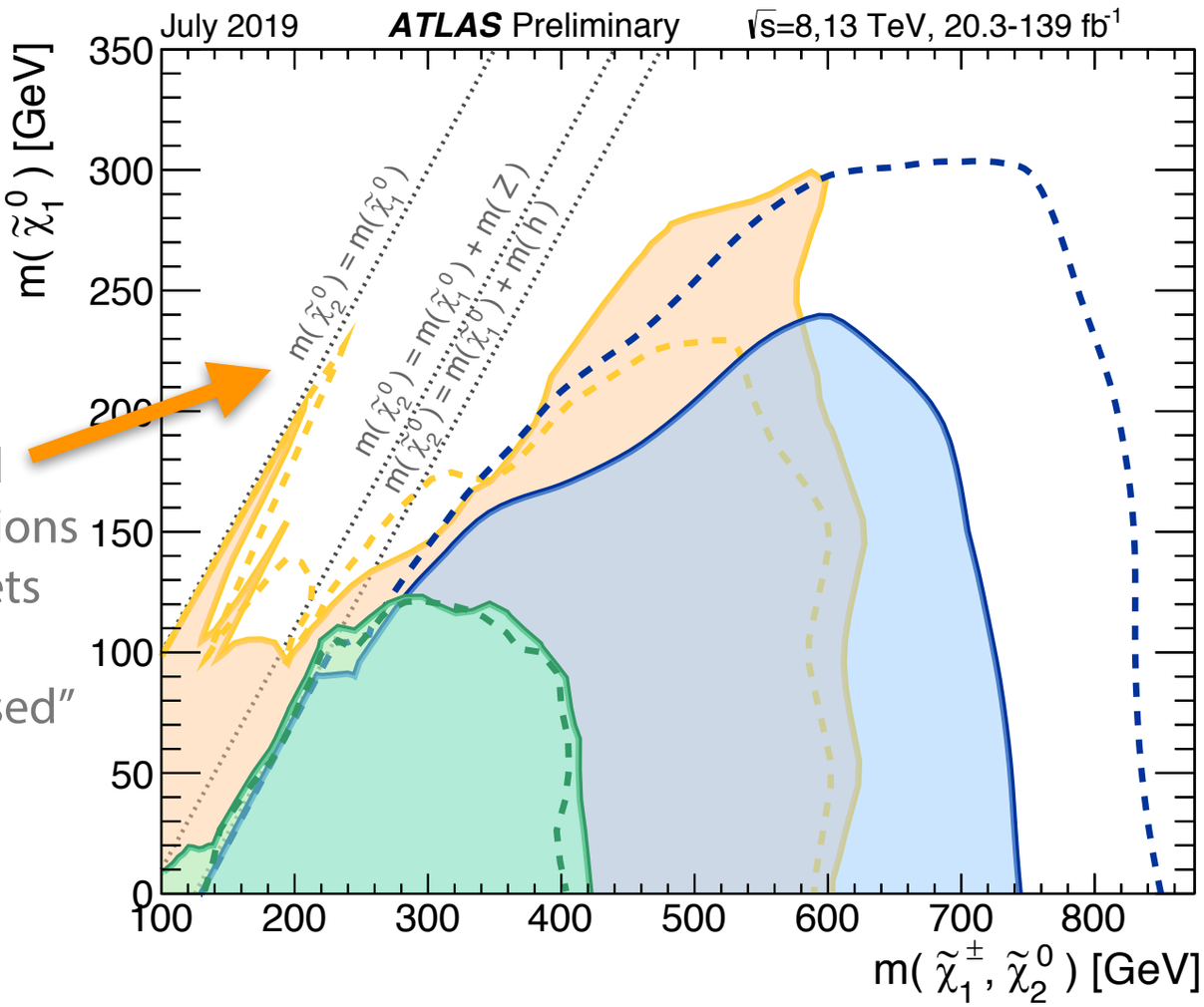
ATLAS-CONF-2019-040

Full Run-2

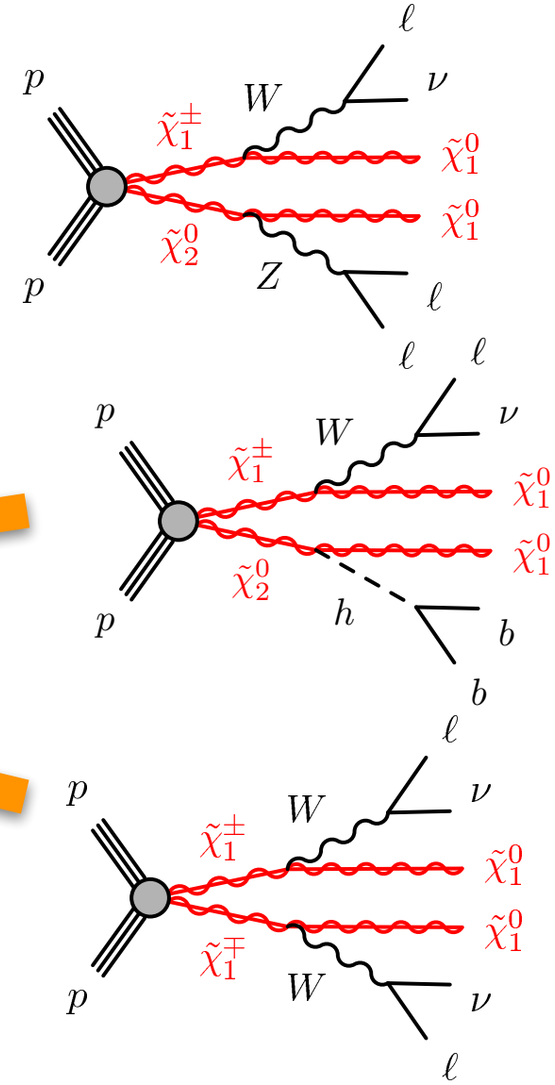


Electroweak SUSY Production

- If squarks and gluinos are very heavy, then electroweak production of SUSY particles could dominate
  - ➡ Much lower cross sections, challenging phase space to explore
  - ➡ Summary of recent ATLAS SUSY EWK results: Full Run-2



Dedicated signal regions with ISR jets targeting "compressed" spectra

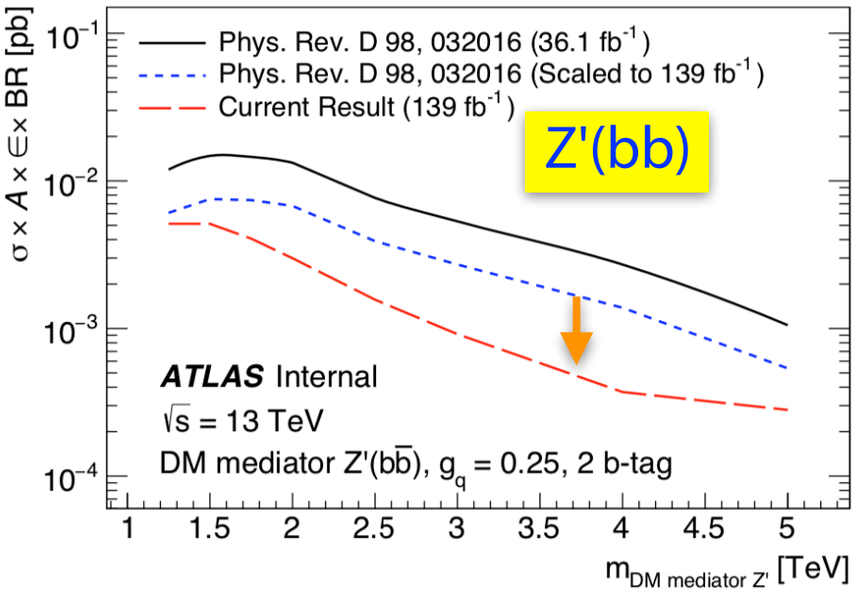


Most favourable case: electroweakino production with decays through light sleptons: exclusion reaches up to 1 TeV (not shown)

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

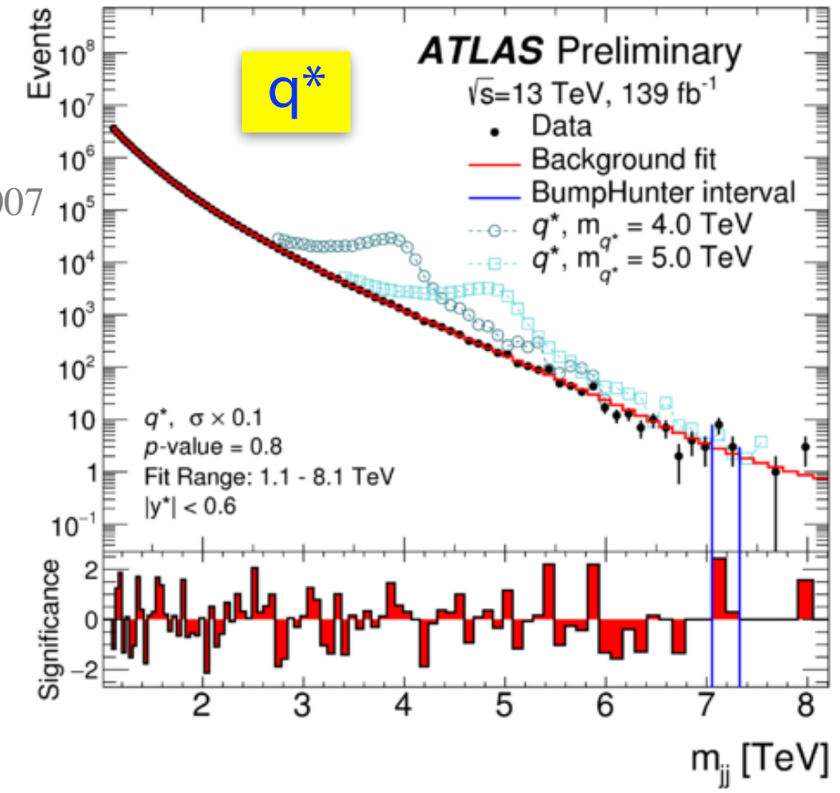
BSM Searches: Di-Jet Resonances, W', Z'

- Search for particles decaying to two jets, including two b-tagged jets:
  - q* : 6.7 TeV (obs), 6.4 (exp)
  - W': 4.0 TeV (obs), 4.2 (exp)
  - SSM Z'(bb): 2.8 TeV (obs), 2.0 (exp)
- Significant improvement in b-tagging performance at high-p_T:



CERN-EP-2019-162

Full Run-2



ATLAS-CONF-2019-007

Full Run-2

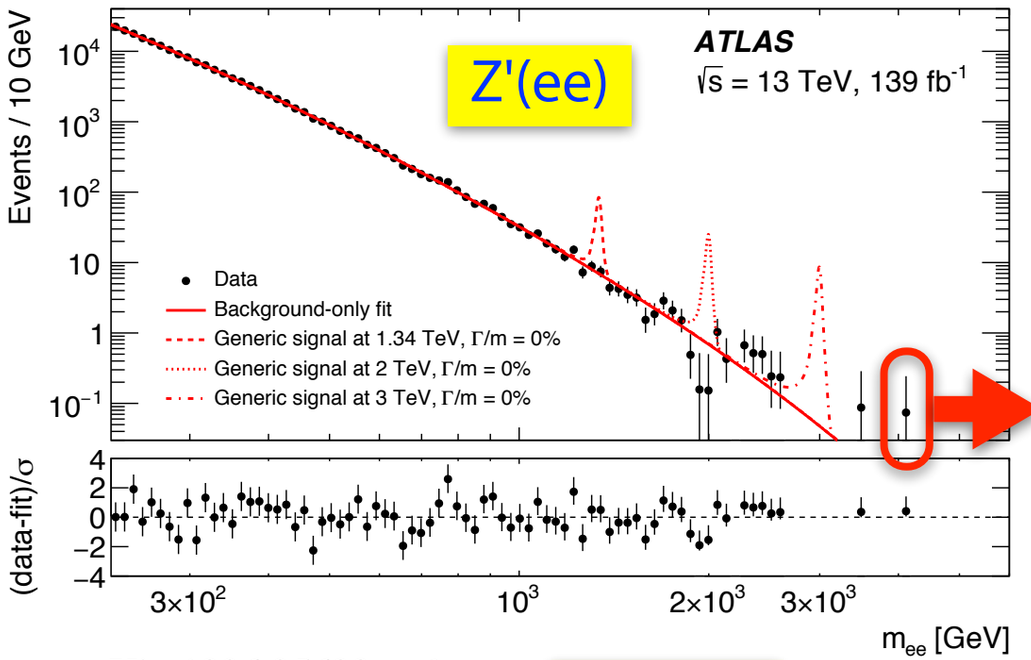
- Searches in di-lepton and lepton + $E_{T,mis}$ events:

Limits on SSM benchmark (95% CL):

Decay	$m(W')$ lower limit [TeV] Observed	Expected
$W' \to e\nu$	6.0	5.7
$W' \to \mu\nu$	5.1	5.1
$W' \to \ell\nu$	6.0	5.8

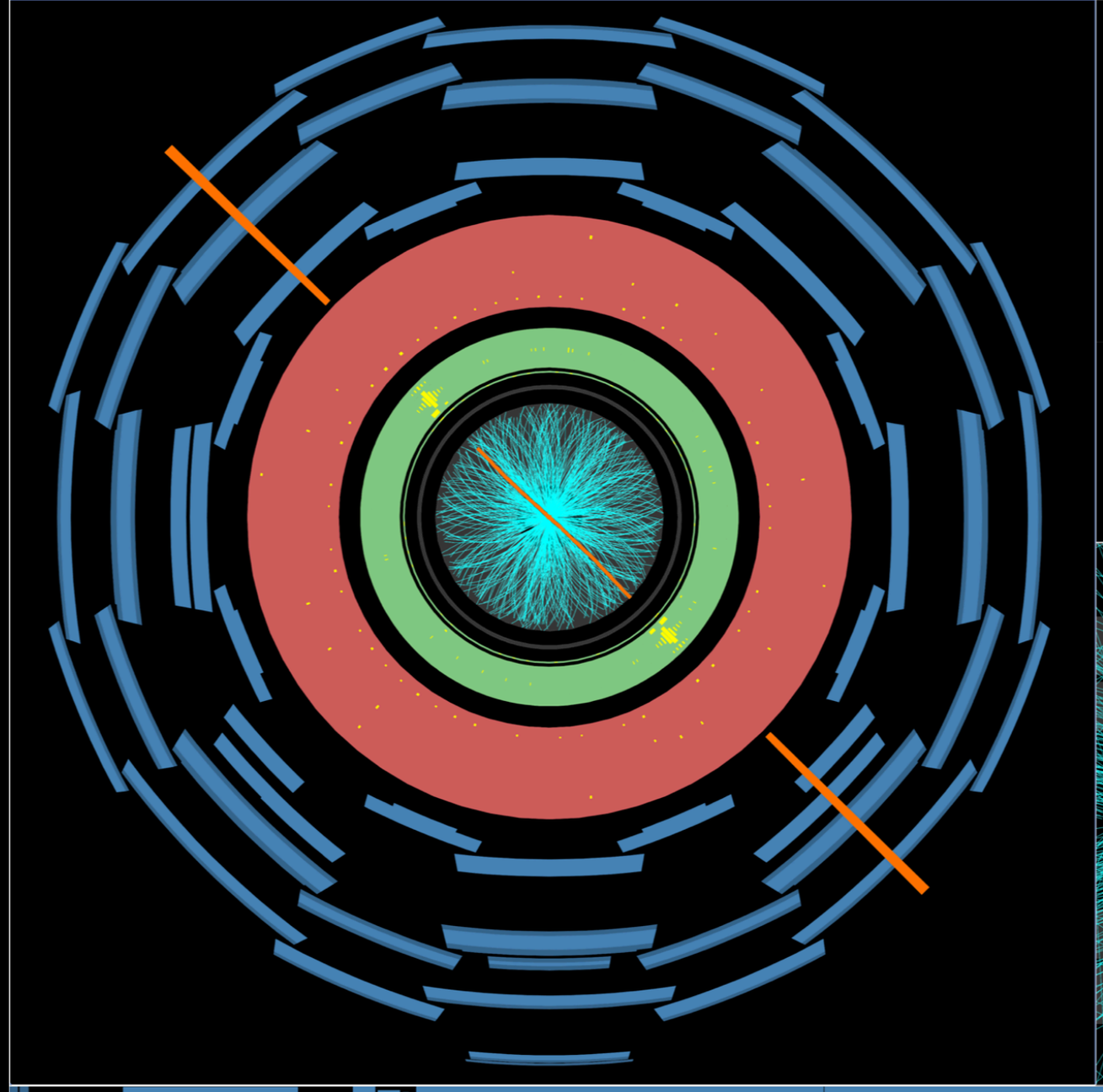
Limits on benchmark models (95% CL):

Model	Lower limits on $m_{Z'}$ [TeV] ee obs	ee exp	$\mu\mu$ obs	$\mu\mu$ exp	$\ell\ell$ obs	$\ell\ell$ exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1



arXiv:1906.05609 and
Phys. Lett. B 796 (2019) 68

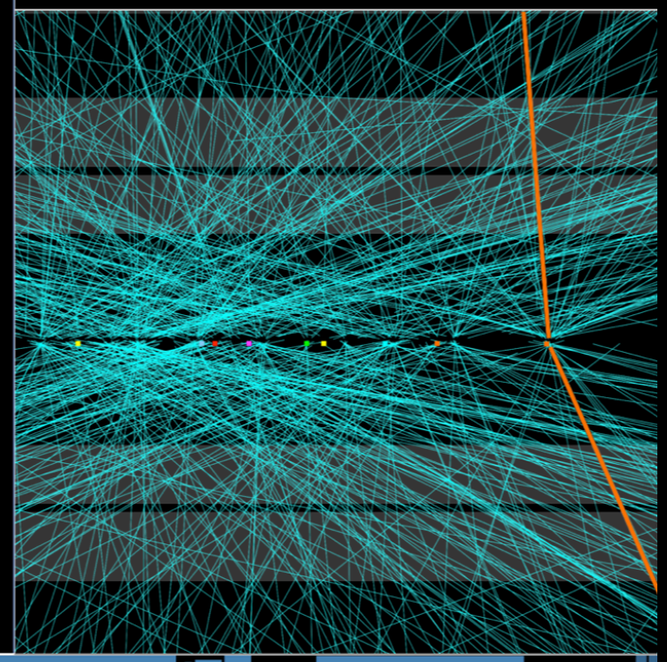
Full Run-2

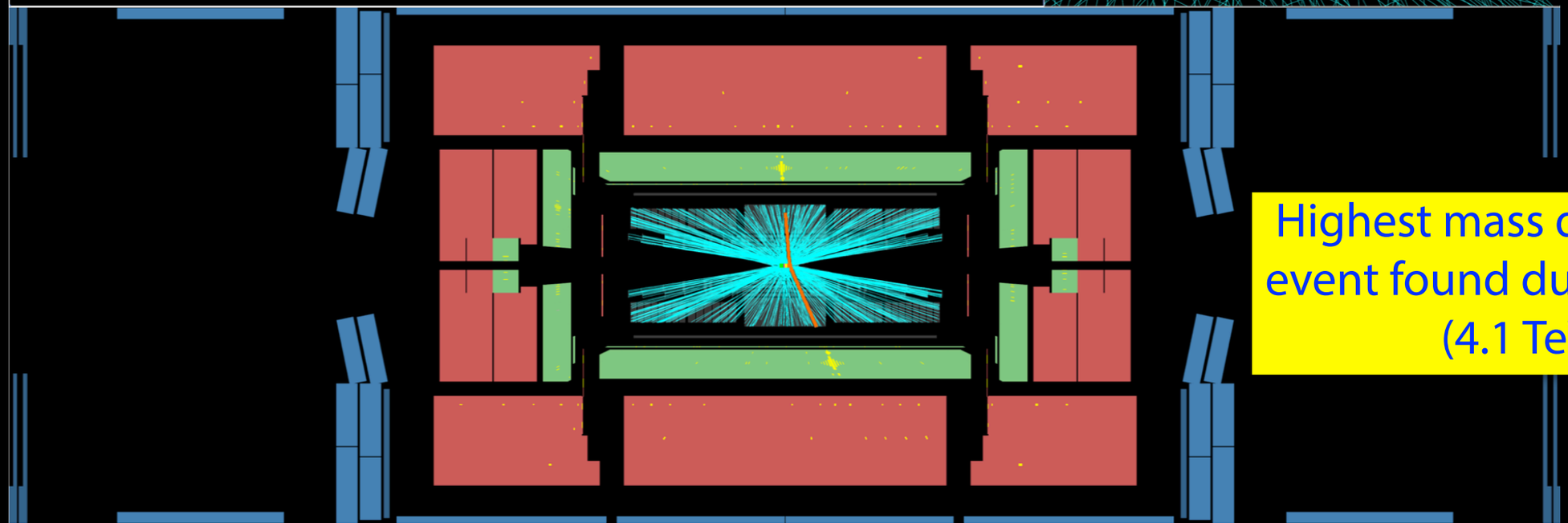


ATLAS EXPERIMENT

Run Number: 336852, Event Number: 1440436043

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



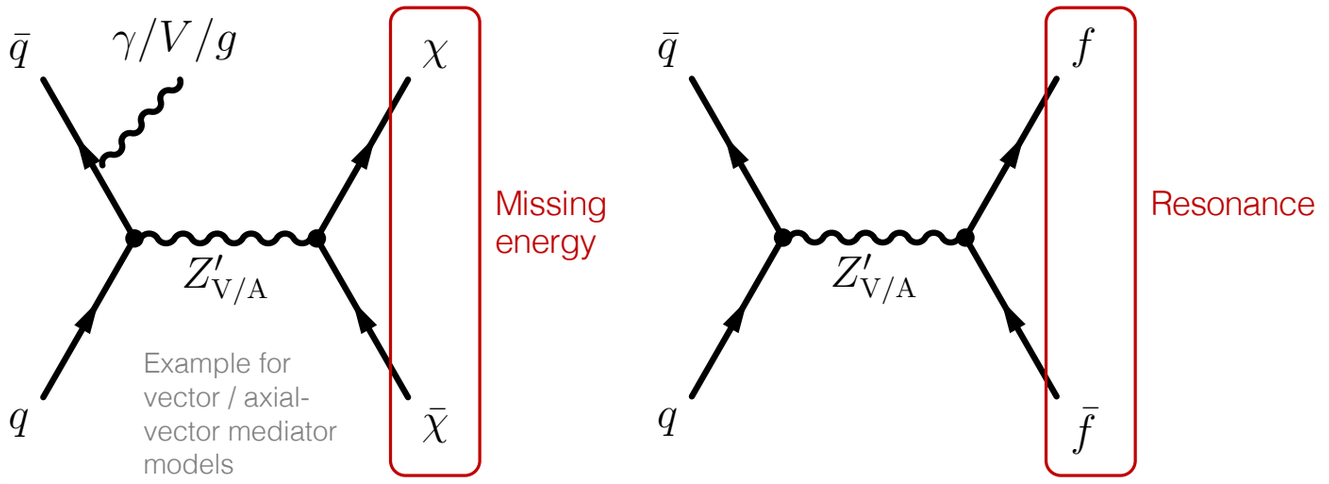


Highest mass di-electron event found during Run-2 (4.1 TeV)

CERN

Dark Matter Searches

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



- ATLAS released a combination of $E_{T,miss}$ based DM searches involving: $E_{T,miss}$ + X,

  X = jet, γ, W, Z, H, b(b), t(t)

  using large number of models

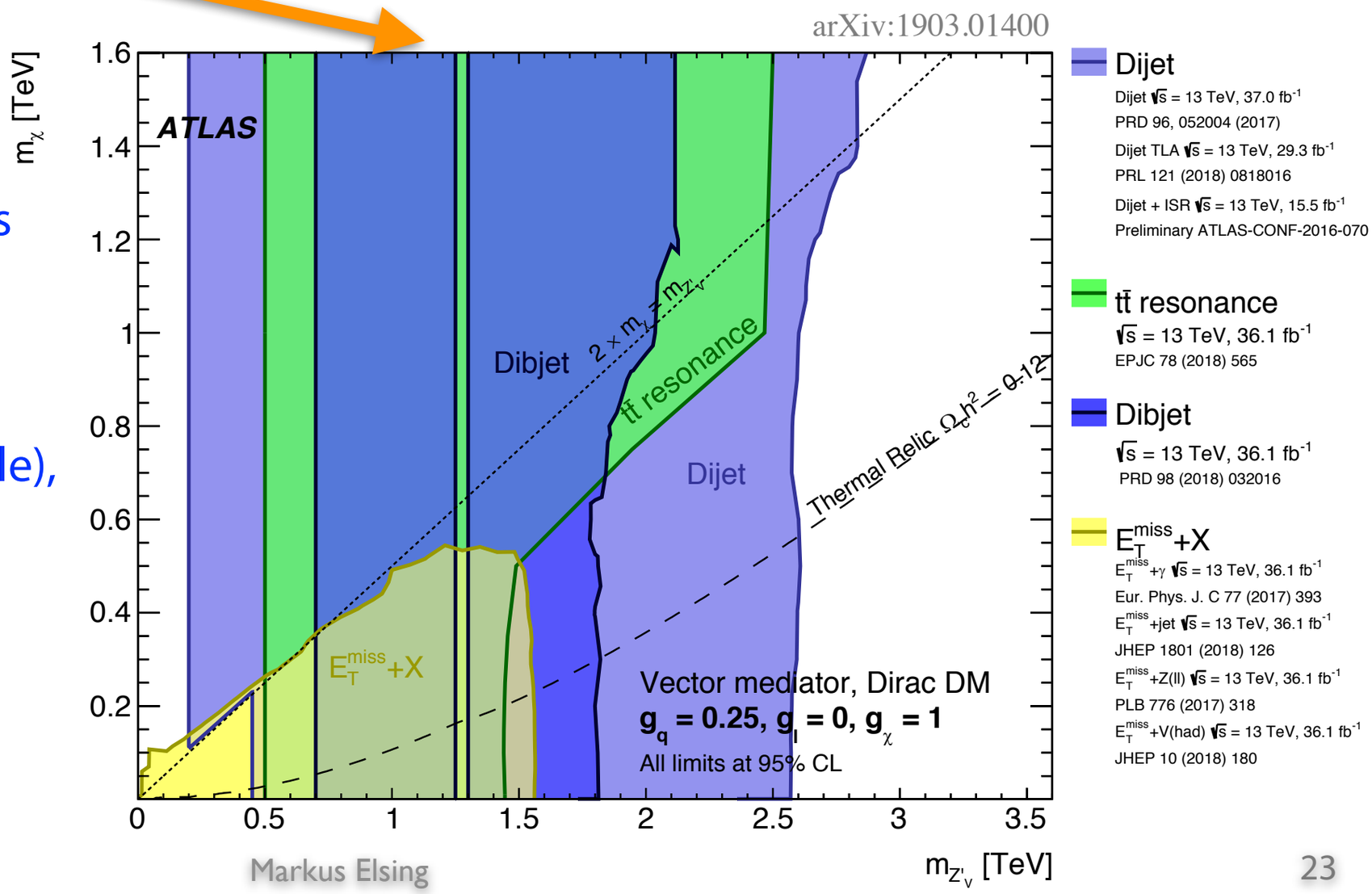
  arXiv:1903.01400, up to 37 fb^{-1}

- If light enough, Higgs boson can decay to DM (H → invisible), ATLAS combination:

  BR(H → invisible) < 0.26

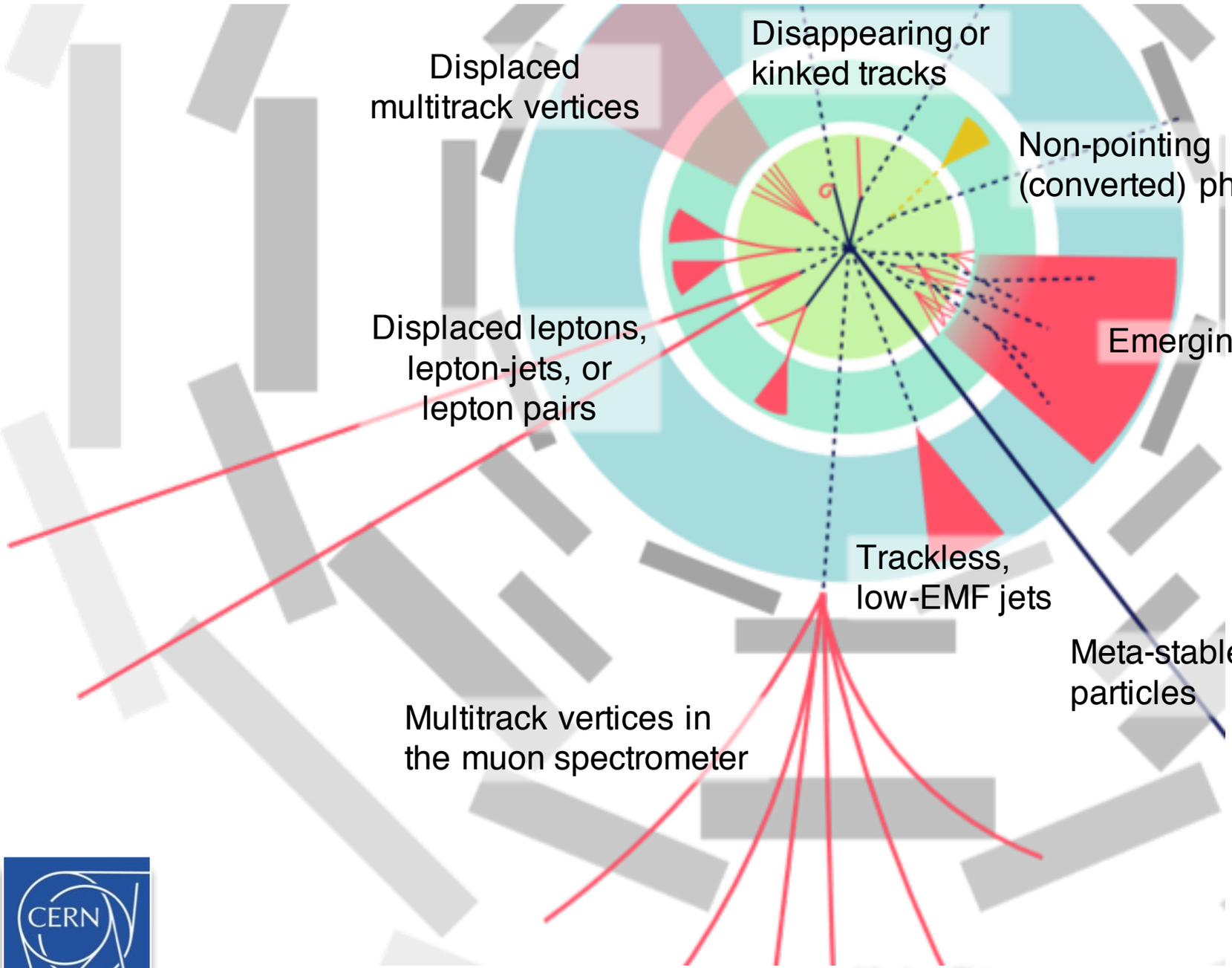
  (0.17 expected)

  arXiv:1904.05105, 36 fb^{-1}



And what if New Physics is all different ?

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

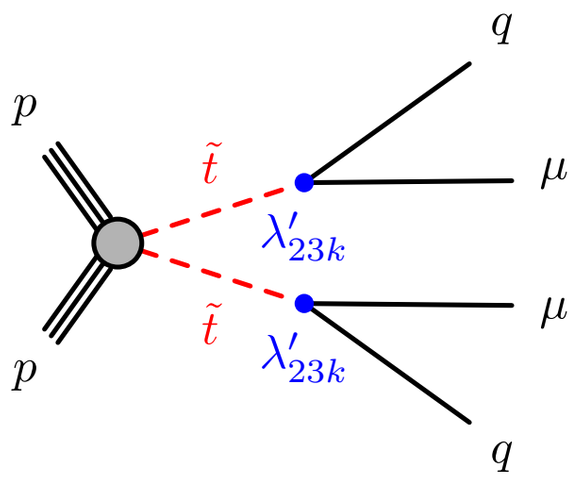


➡ Diverse set of signatures that are pursued by dedicated, usually non-standard analyses

➡ Experimental challenge, often requiring special triggers

Example for long-lived Particle Searches

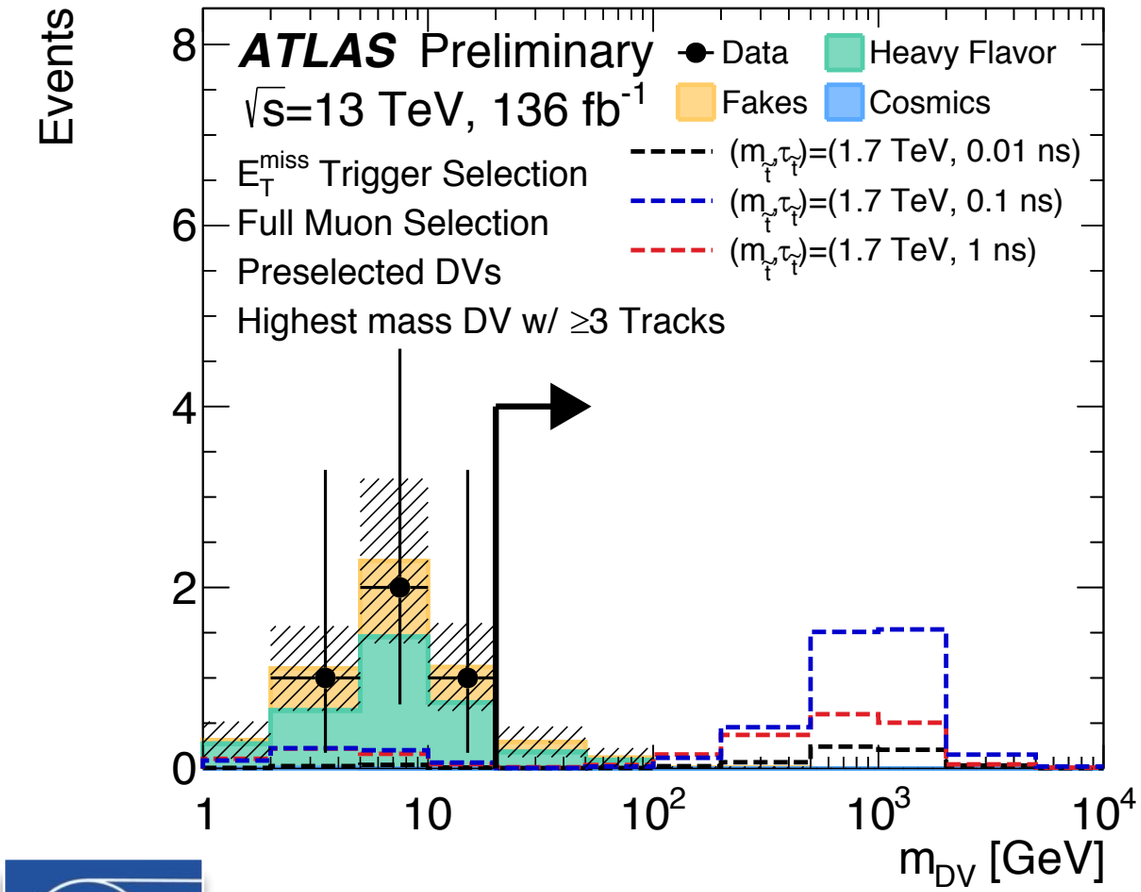
- Search for a long-lived particle with displaced vertex (DV) and muon
  - ➡ Clean signature of large track multiplicity and vertex mass

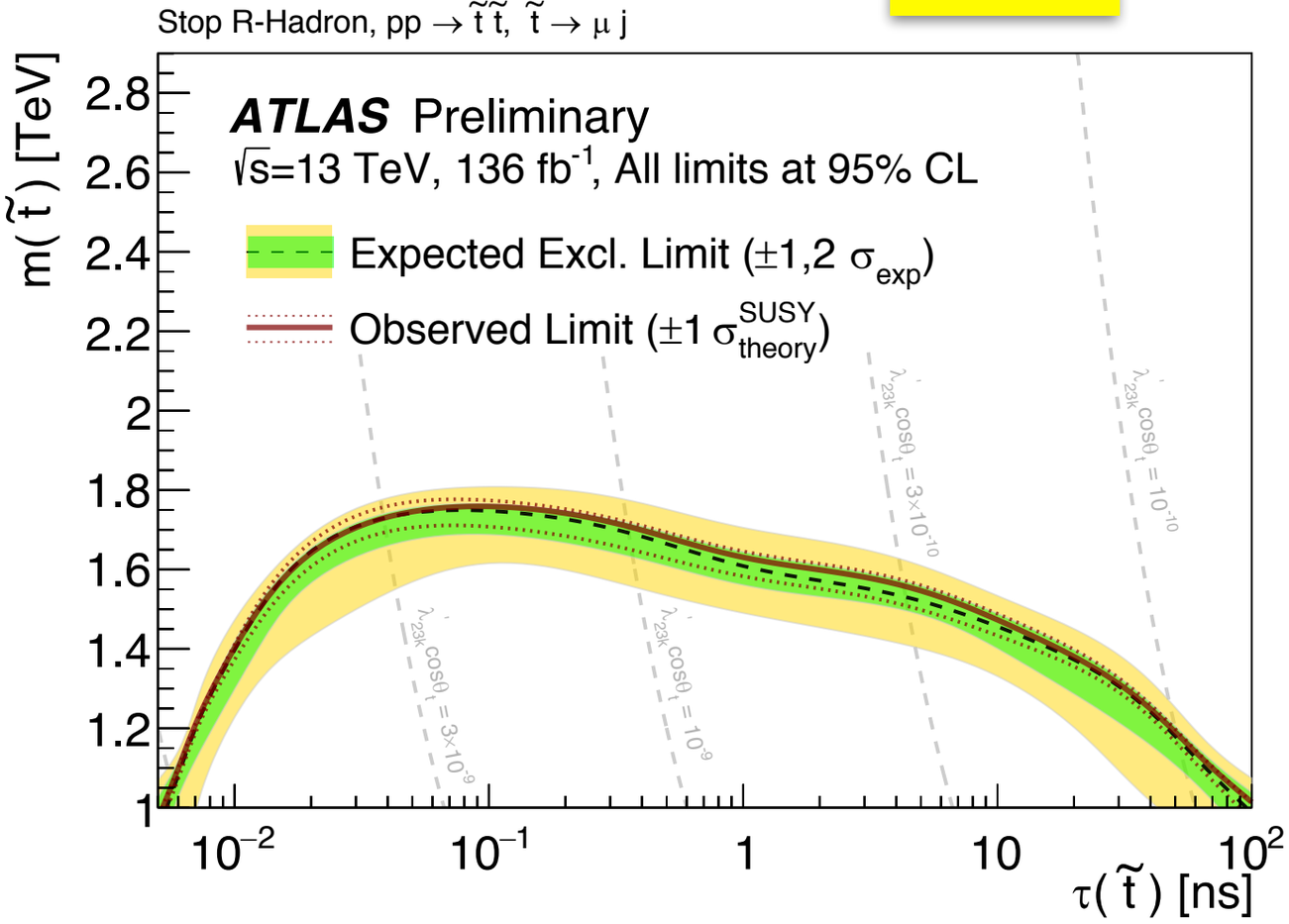


R-parity violating signature with long-lived stop

ATLAS-CONF-2019-006

Full Run-2

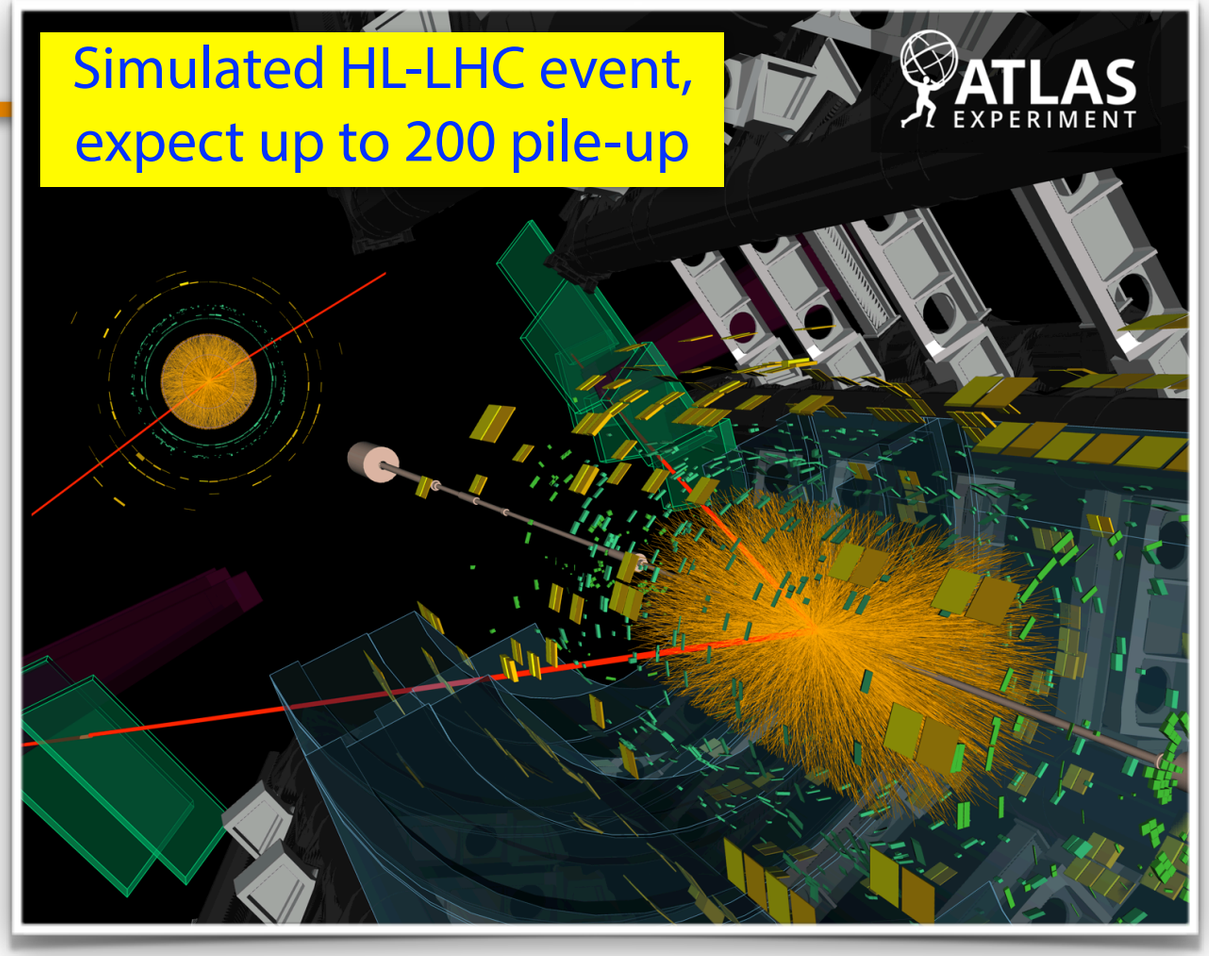


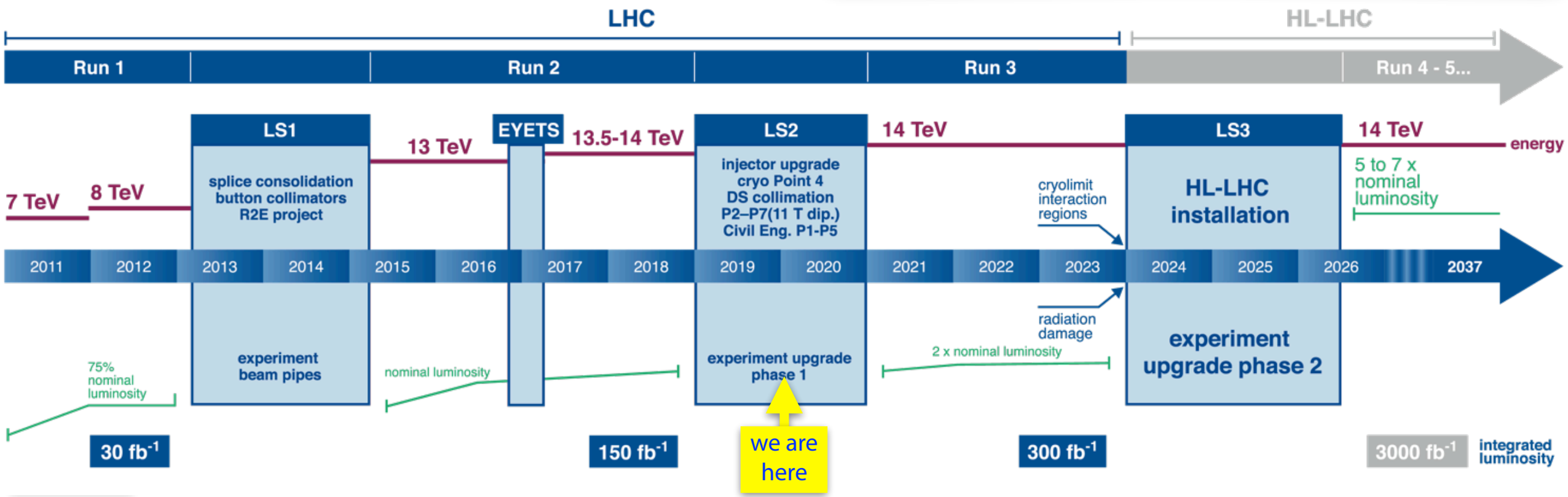


Preparing for the Future

- Current Long-Shutdown 2
  - ➡ Phase-1 upgrade
  - ➡ First set of upgrades for ATLAS
- Run-3 to collect 300 fb^{-1} at 14 TeV

- Long-Shutdown 3
  - ➡ Phase-2 upgrade
  - ➡ Major upgrade of ATLAS experiment
- High Luminosity LHC (3000 fb^{-1})





ATLAS Phase-I and Phase-II Upgrades

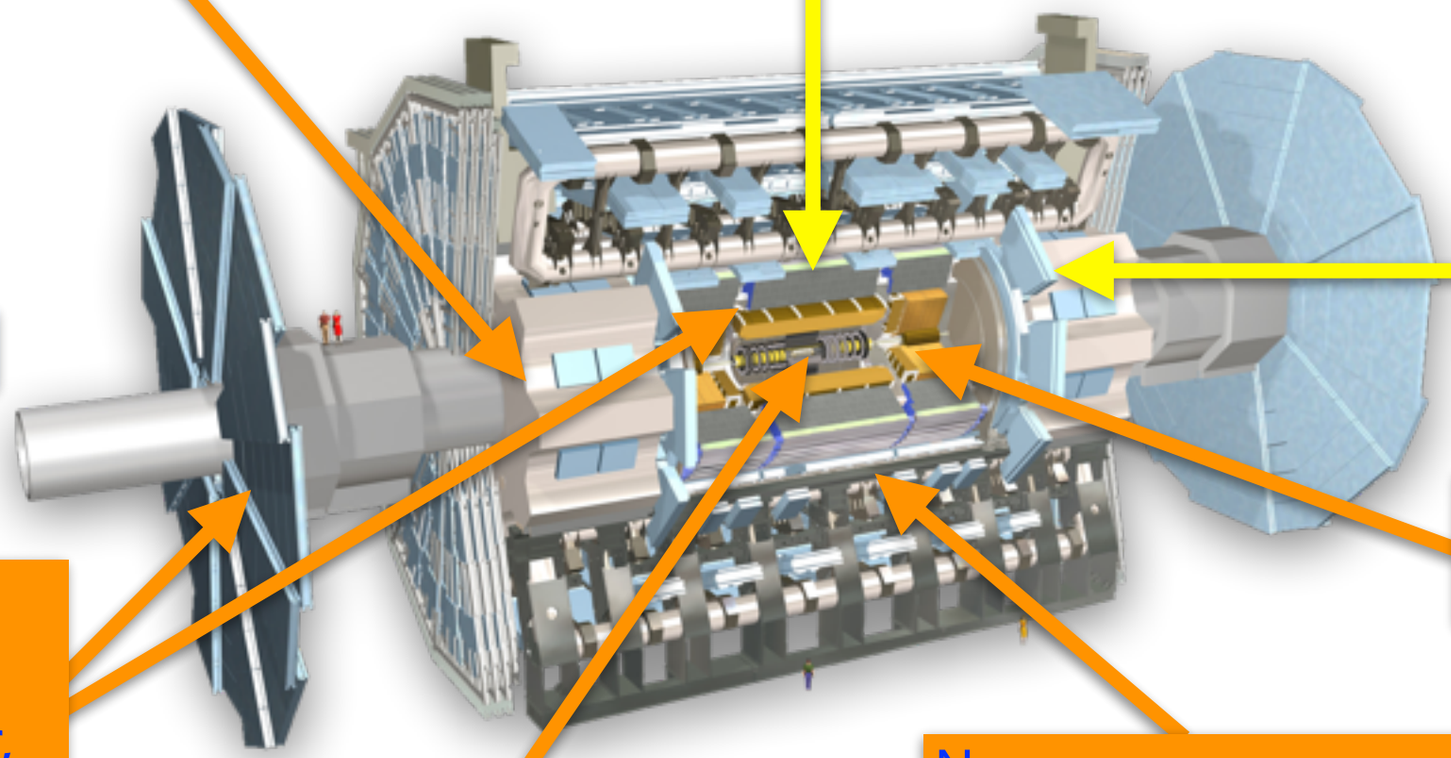
Options:
forward muon tagger

LAr calorimeter:
fine granularity readout
for Level-1

Level-1 trigger electronics

FTK trigger tracking

Upgrade of
Level-1 Trigger
and TDAQ System
(1 MHz readout)



Muon system:
New Small Wheel

HW trigger tracking

High Granularity
Timing Detector

Detector electronics
replacement:
LAr + Tile calorimeter,
Muon system

New inner
tracking system

New muon
chambers in the
inner barrel region

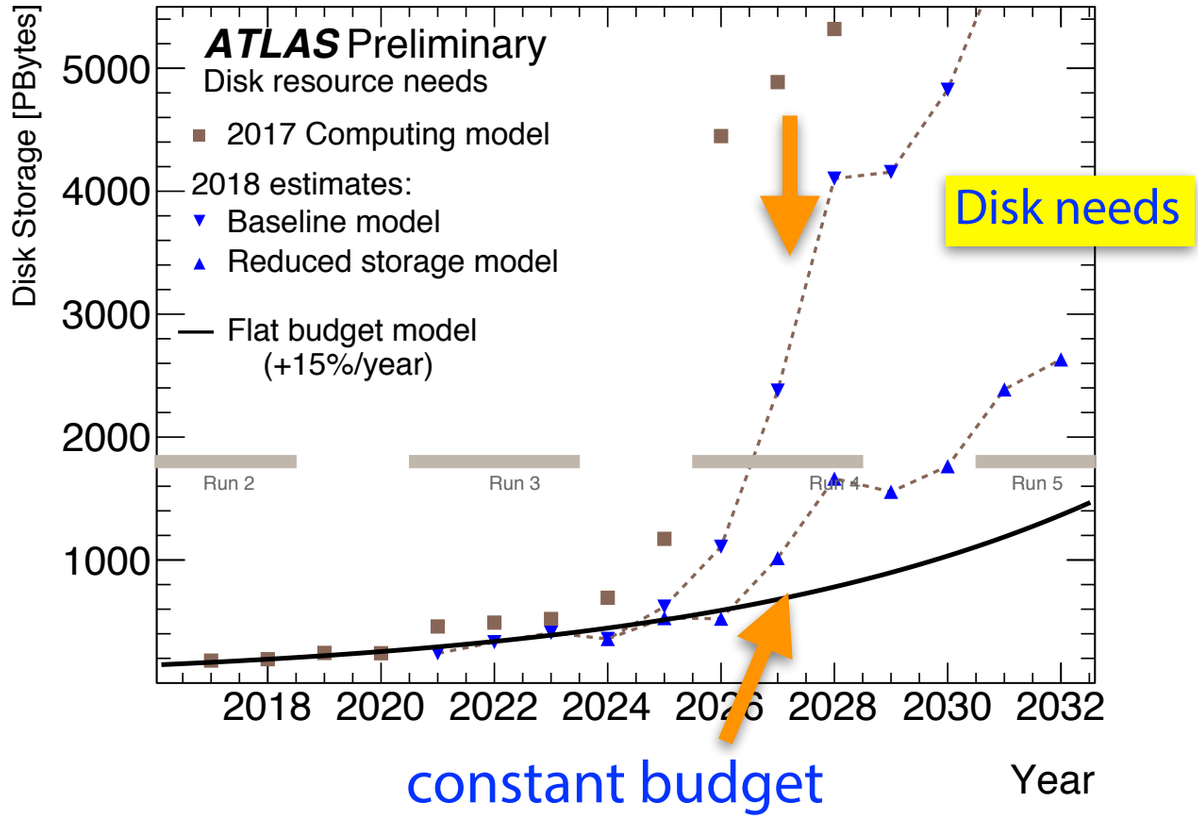
Phase-I

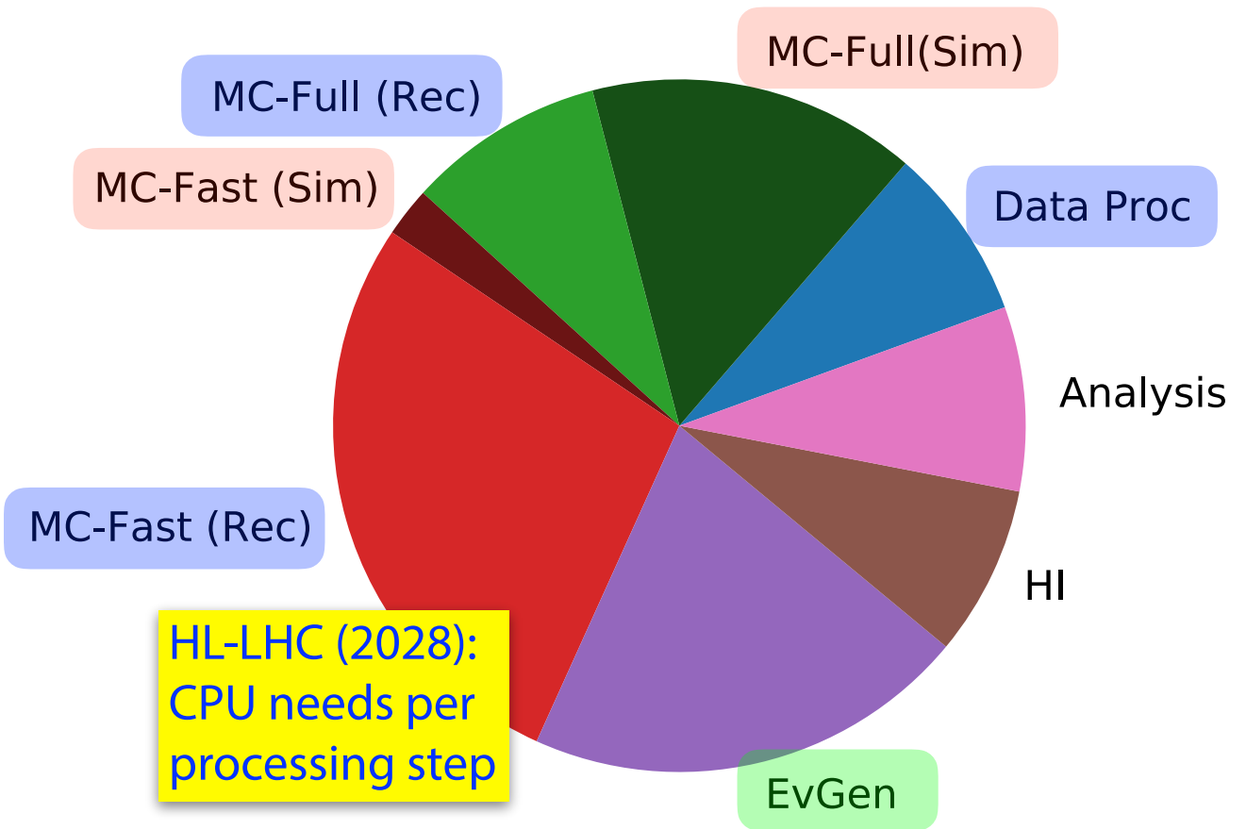
Phase-II

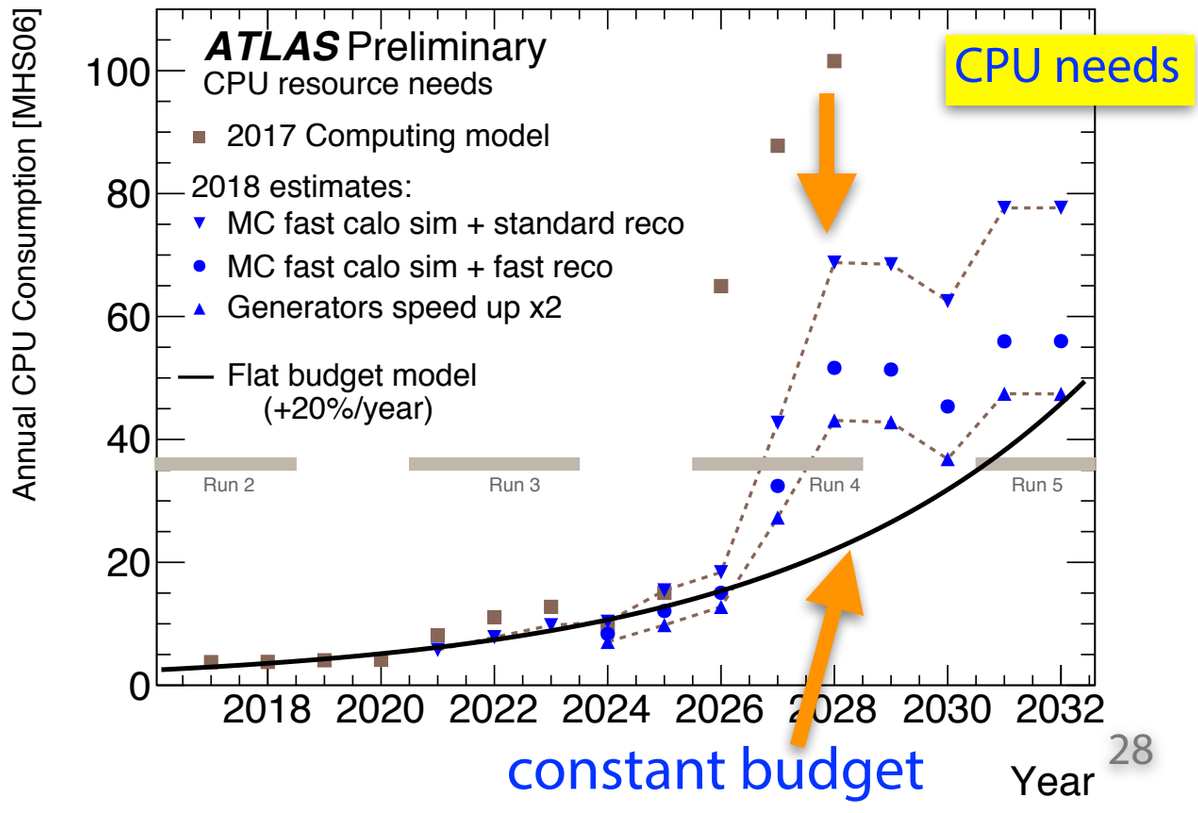
HL-LHC Computing Challenges...

- To explore high luminosity:
  - ➡ Increased event rate to 10 KHz (disk space)
  - ➡ Increased Monte Carlo statistics (disk and CPU)
  - ➡ Pile-up up to 200 (CPU for reconstruction)
  - ➡ Precision of event generators (CPU)

- Computing model extrapolations exceed current budget !
  - ➡ Explore all options to reduce computing costs

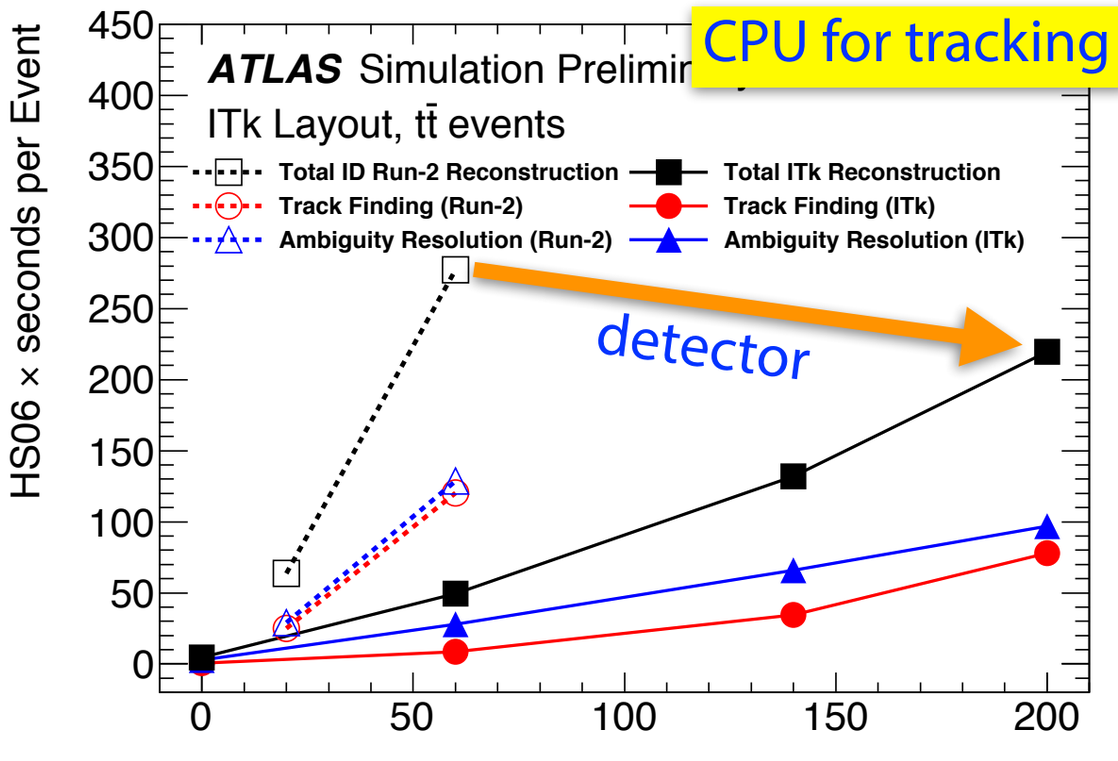


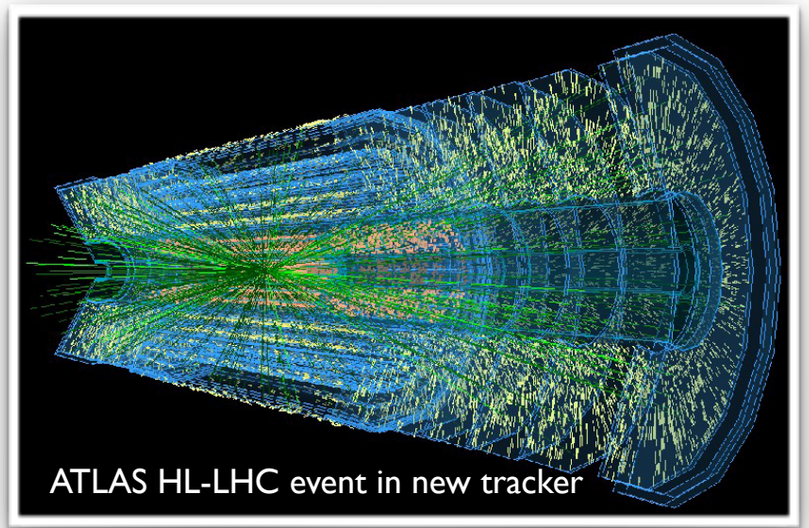


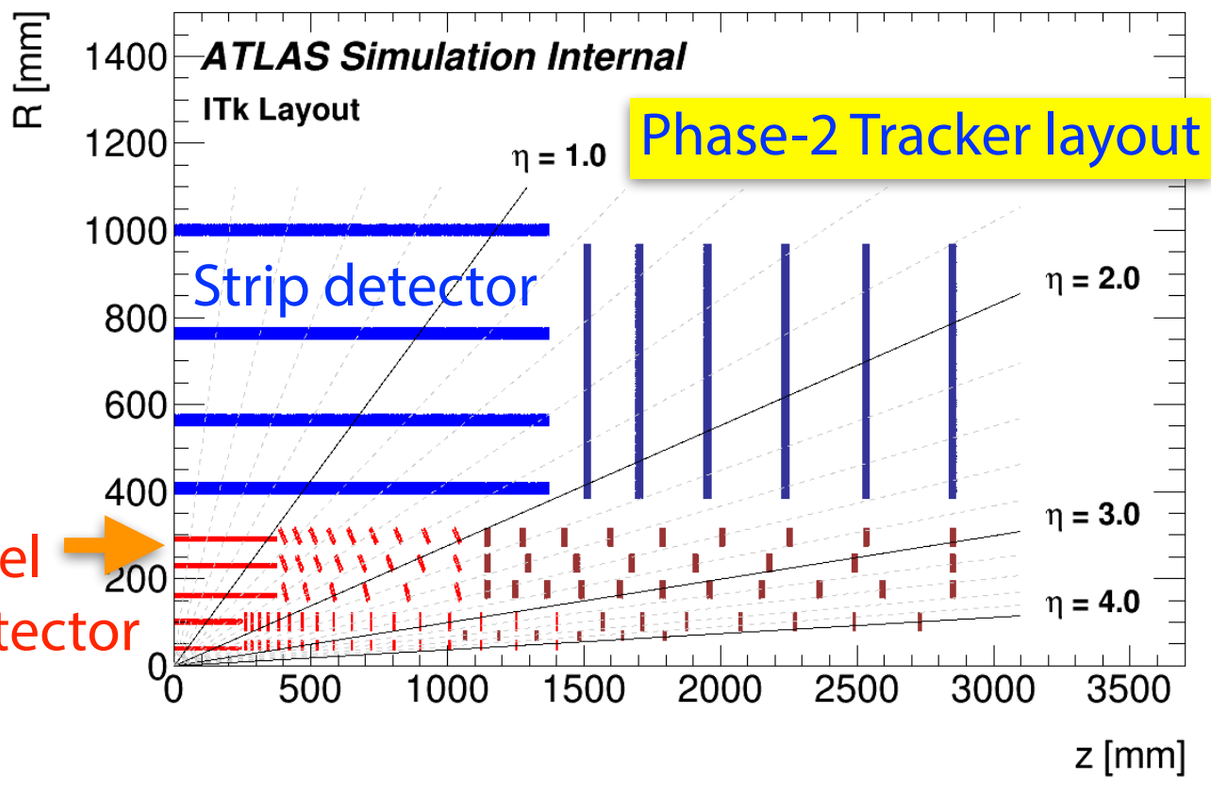


Phase-II Tracker Upgrade (ITk)

- Current Inner Detector will reach end-of-lifetime
  - ➡ To be replaced by all silicon tracker (ITk)
    - 4 layer (double sided) strip detector
    - 5 layer pixel system
  - ➡ Will extend coverage in |η| from 2.5 to 4
- ITk designed for precision tracking at 200 pile-up
  - ➡ Better resolutions and less fakes than for current detector during Run-2
  - ➡ Detector designed to also minimise CPU needs for track reconstruction

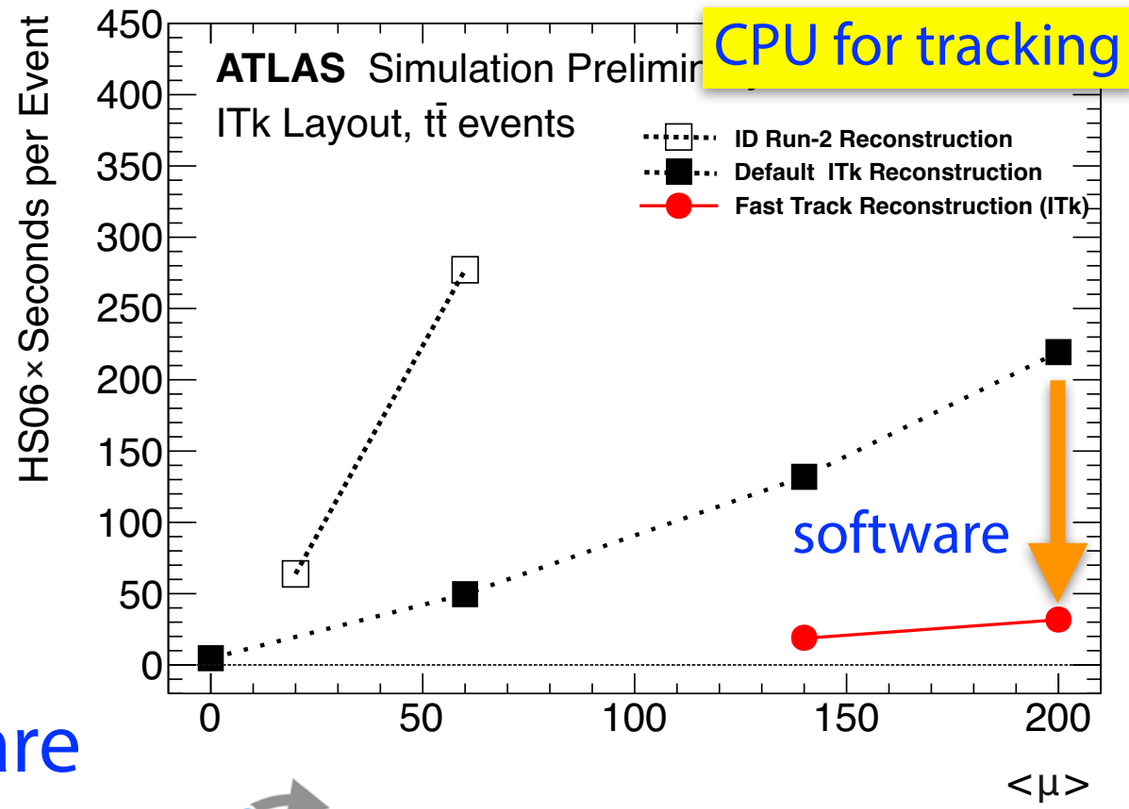






Phase-II and Algorithm Developments

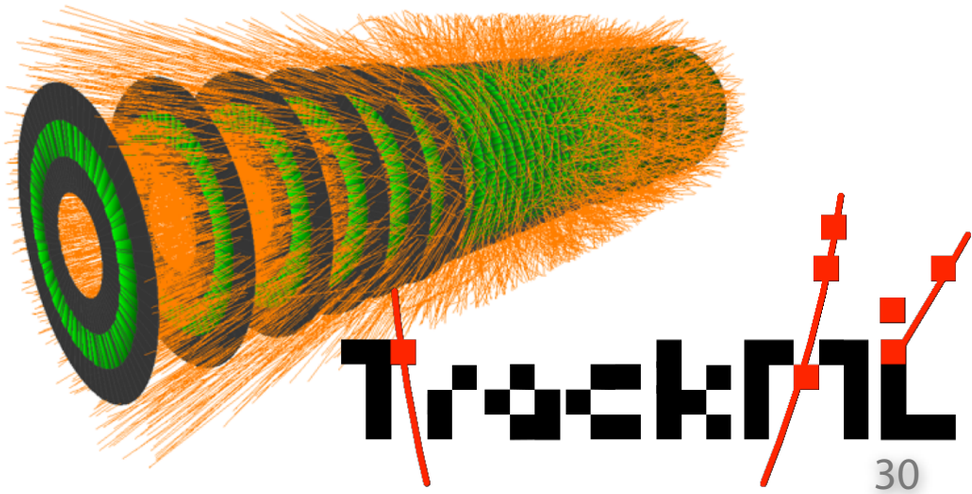
- Phase-II software upgrade program
  - ➡ Complements detector upgrades
- Algorithmic optimisation of track reconstruction
  - ➡ Prototype based on classical tracking techniques at 200 pile-up faster than current detector at 20 !
- Intensive R&D on algorithmic software
  - ➡ ACTS as an open source tracking project
    - "community" project ATLAS, Belle-II, FCC ...
  - ➡ Tracking community workshops (CTD/WIT)
  - ➡ R&D on support for GPUs and other co-processors
- Tracking Machine Learning Challenge
  - ➡ Reaching data science community (Kaggle/Codalab)
  - ➡ Machine learning and novel algorithmic approaches



acts.web.cern.ch

CTD/WIT 2019
Connecting the Dots and Workshop on Intelligent Trackers
IFIC, València, Spain
2nd - 5th April 2019

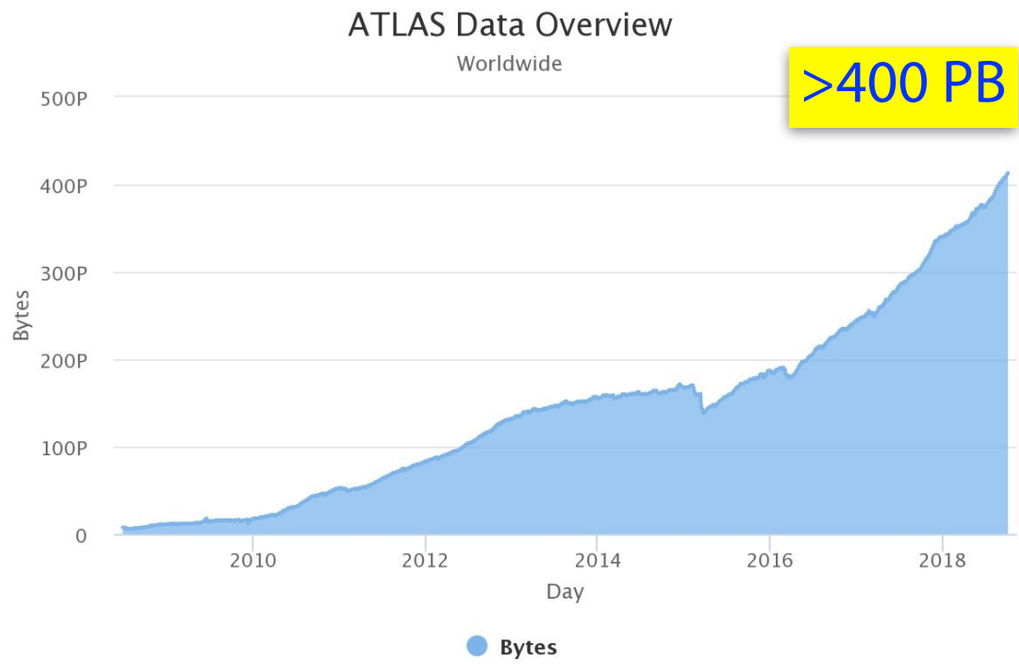
https://indico.cern.ch/e/ctdwit2019



Rucio Scientific Data Management

- Exa-scale data volumes for HL-LHC
  - ➡ Rucio is a generic service for large scale scientific data management
  - ➡ Supports heterogeneous computing infrastructures (GRID, CLOUD, HPC)
  - ➡ Developed originally for ATLAS experiment, became an open source community project

RUCIO
SCIENTIFIC DATA MANAGEMENT
rucio.cern.ch



- Rucio in ATLAS today:
  - more than 1 billion files
  - total >0.4 ExaByte
  - 2.5 M files (2.5 PetaByte) transferred per day
  - more than 150 computing centres
  - more than 1000 active users

- Rucio Community is growing fast...
  - ➡ Many experiments and science organisations within HEP and beyond ...
  - ➡ Community workshops every year
    https://indico.cern.ch/event/773489/

Summary

- Plenty of new ATLAS Run-2 results presented this summer
  - ➡ Gave a short overview of recent ATLAS SM, top and Higgs physics results
  - ➡ No signs for physics beyond the SM in full Run-2 dataset yet
- ATLAS is getting ready for Run-3 with Phase-I upgrades
  - ➡ And ATLAS is moving from pure GRID computing to inclusion of HPCs and clouds
- Detector, software and computing upgrades for HL-LHC
- Opportunities for collaboration within EuroPlex
  - ➡ Physics (of course)
  - ➡ Data science techniques and algorithmic software developments
    - Software development for heterogenous computing using co-processors (GPUs...)
  - ➡ Computing and HPC/HTC:
    - Middleware services for Scientific Data Management and alike