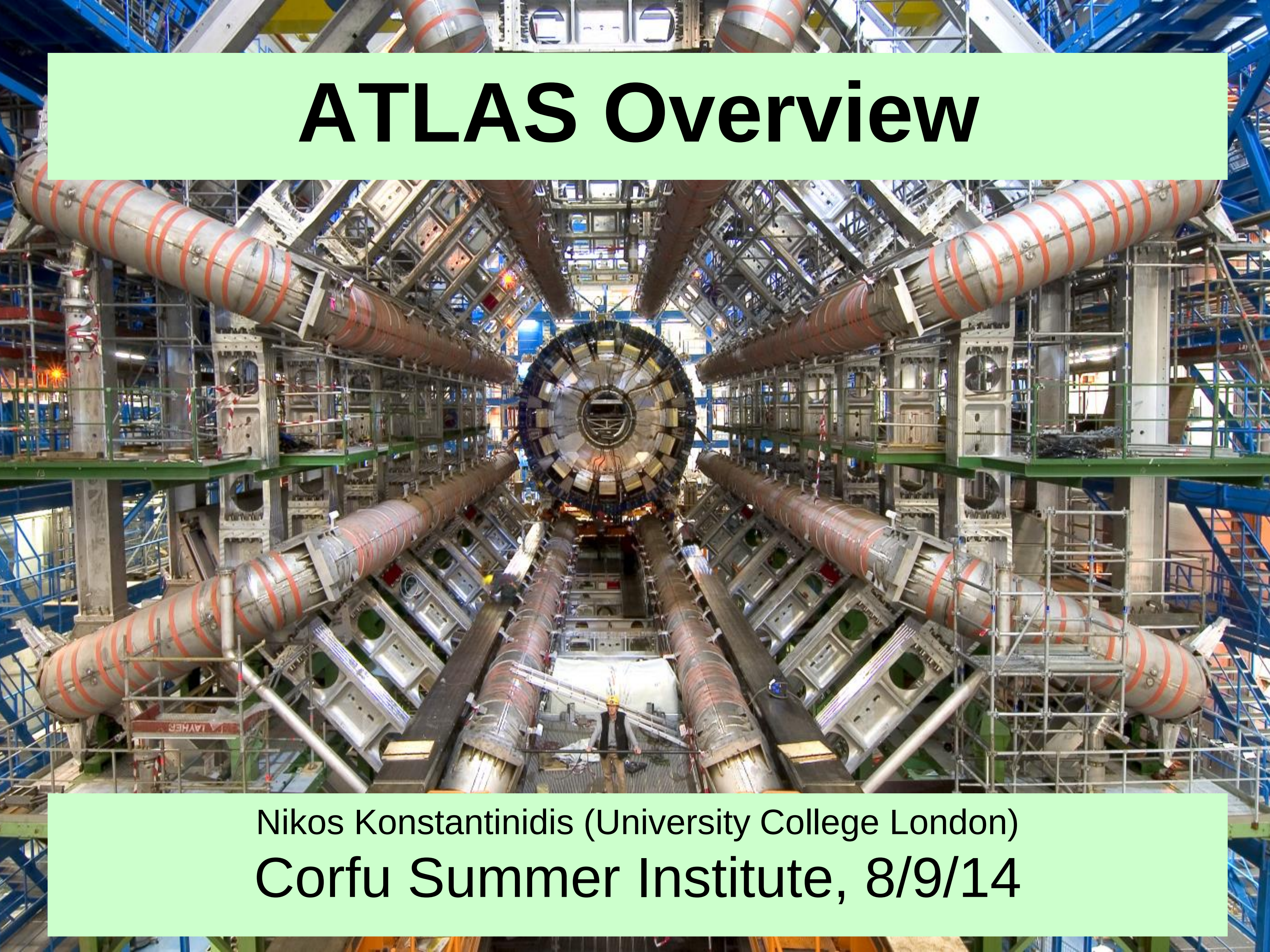
ATLAS Overview



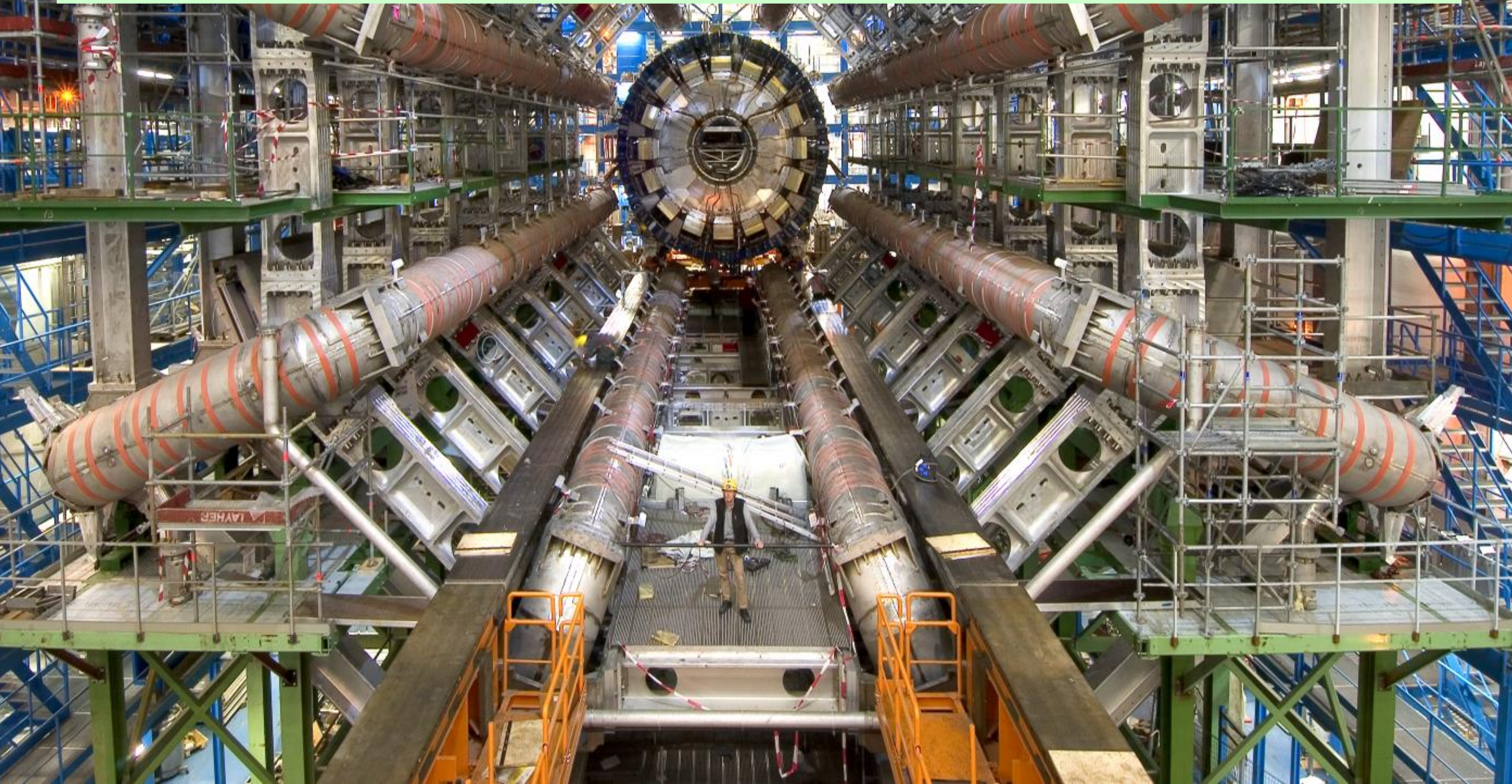
Nikos Konstantinidis (University College London)

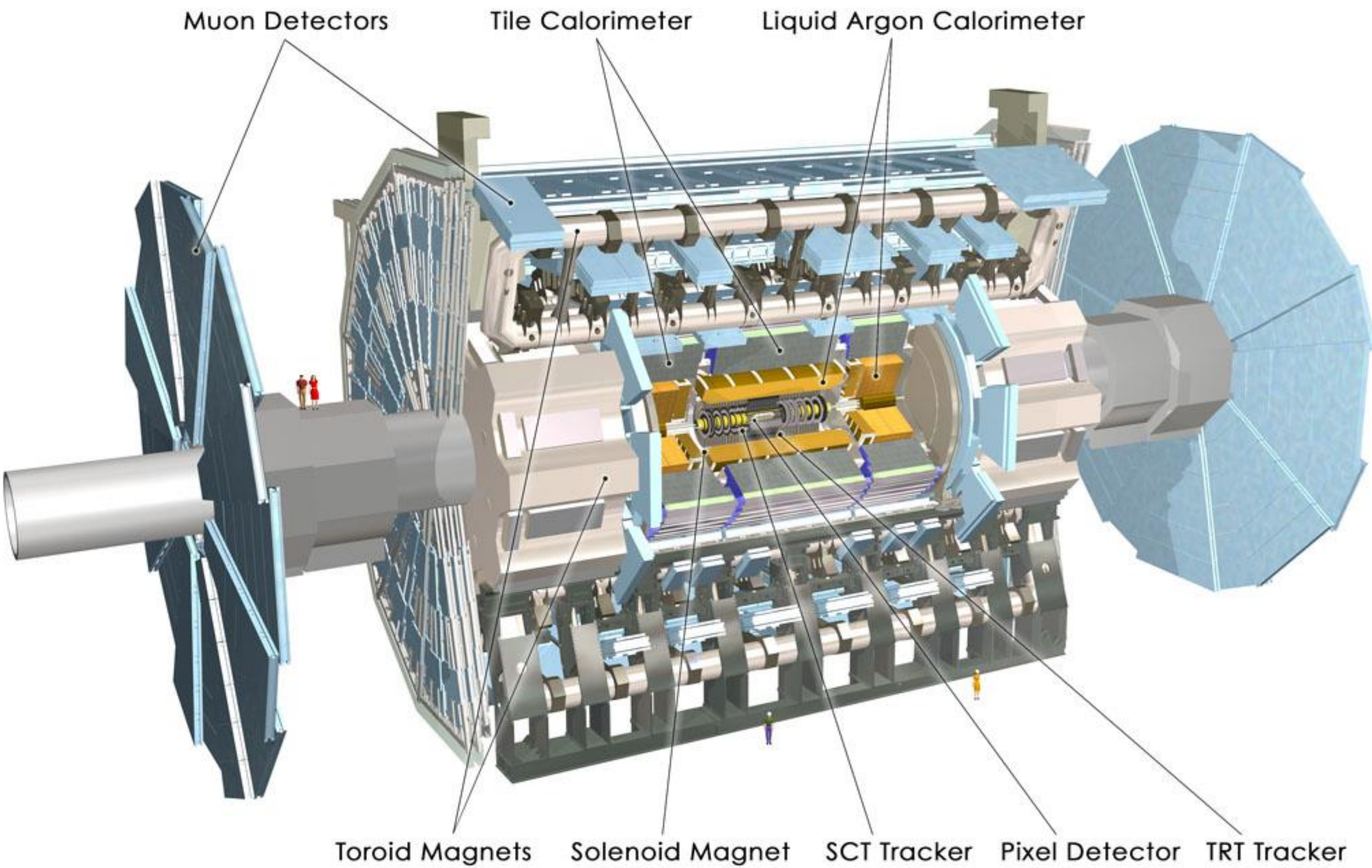
Corfu Summer Institute, 8/9/14

Outline

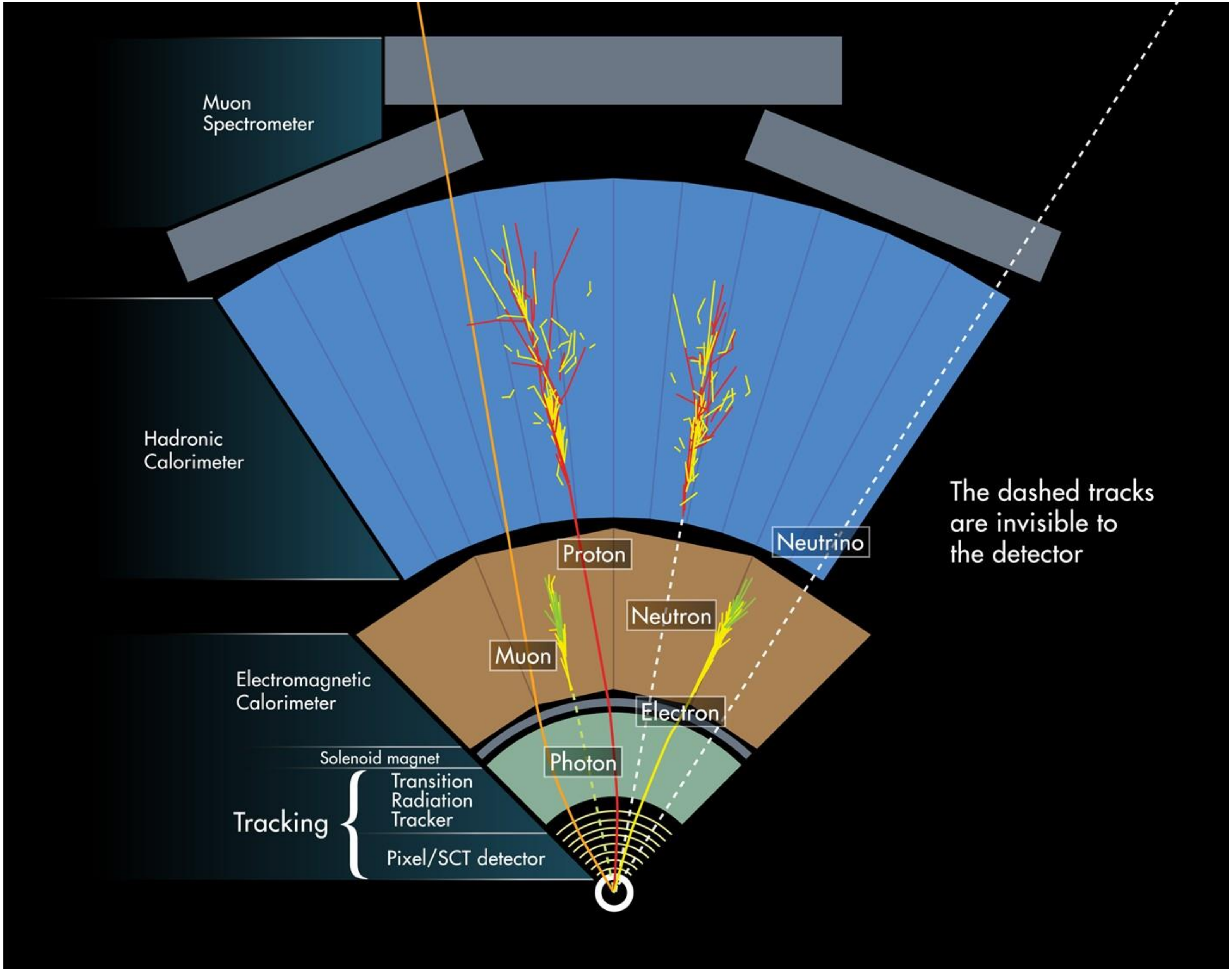
- Operation and performance overview in Run 1
- Highlights of recent results
- The future: upgrades for Run 2, 3, 4…
- Summary & Outlook

Detector overview and performance in Run 1



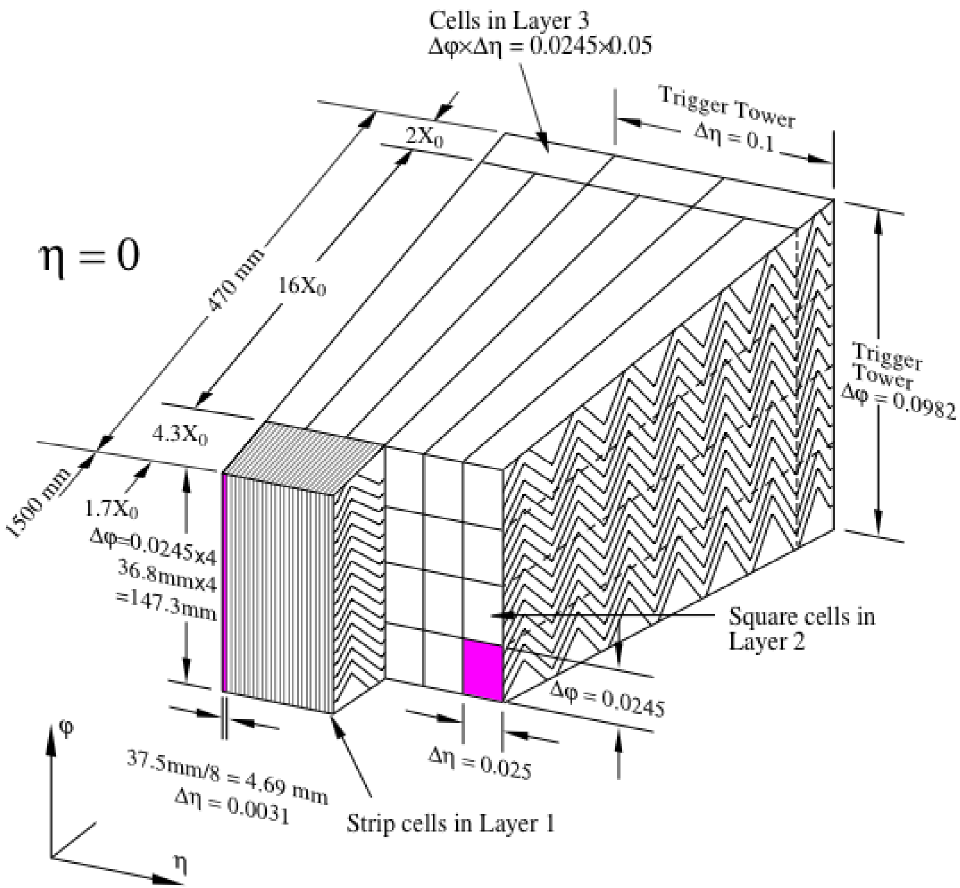

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

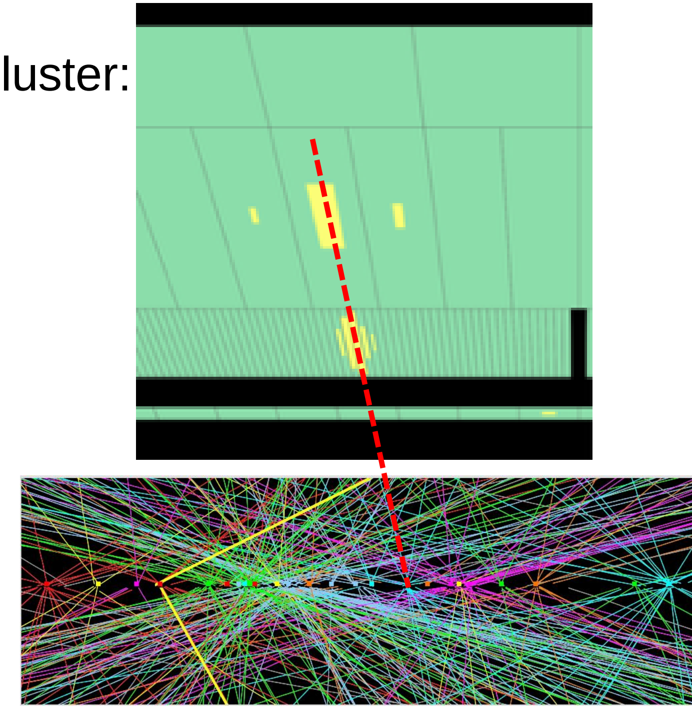
Detecting particles in ATLAS



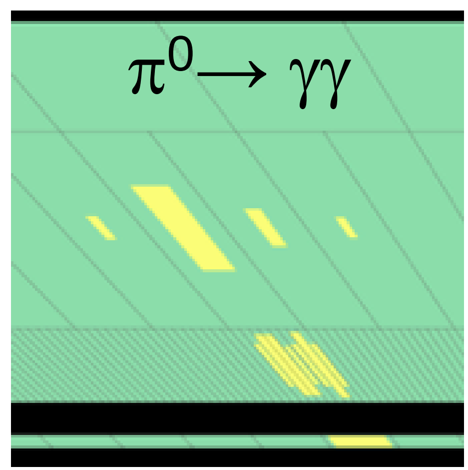
Calorimeters

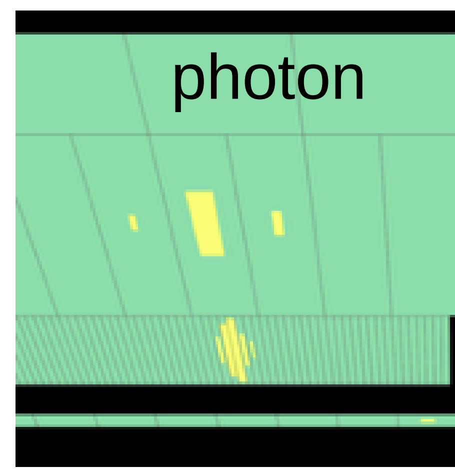
Depth granularity helps determine z-origin of an EM cluster:



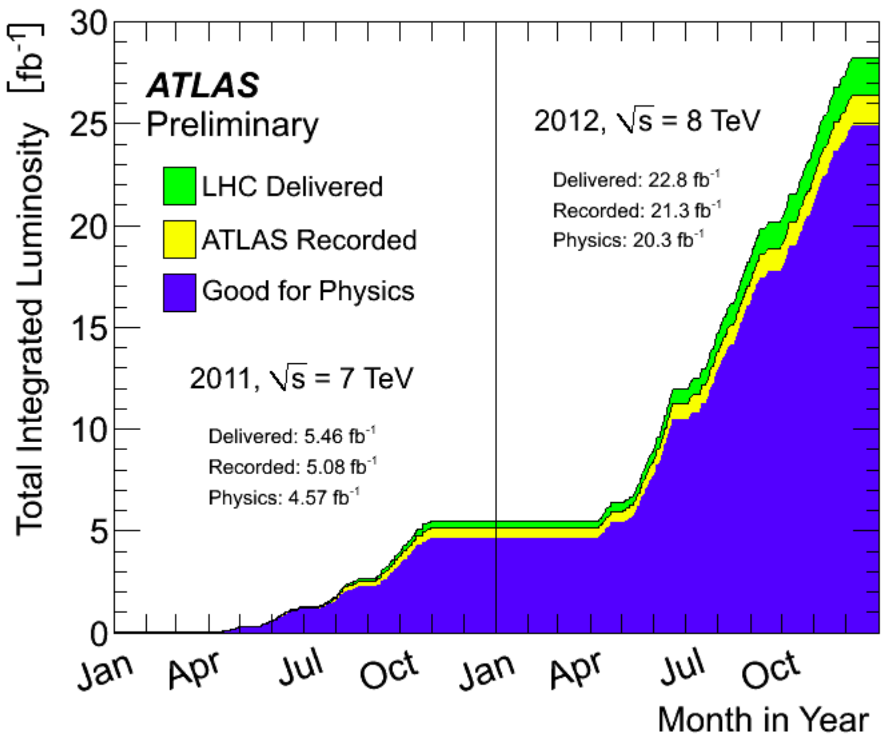


Eta segmentation of 1st sampling (strips) powerful for γ/π^0 separation:





ATLAS Run 1 data taking



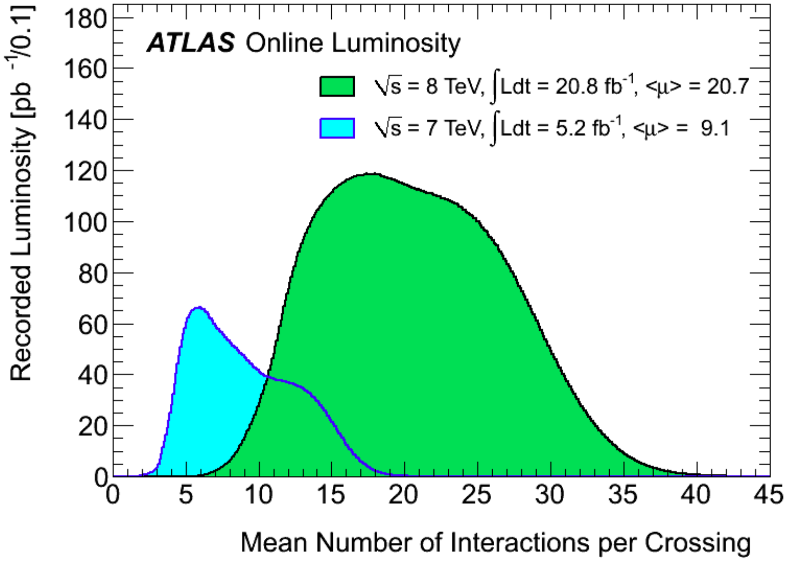
ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb⁻¹ of recorded data.										

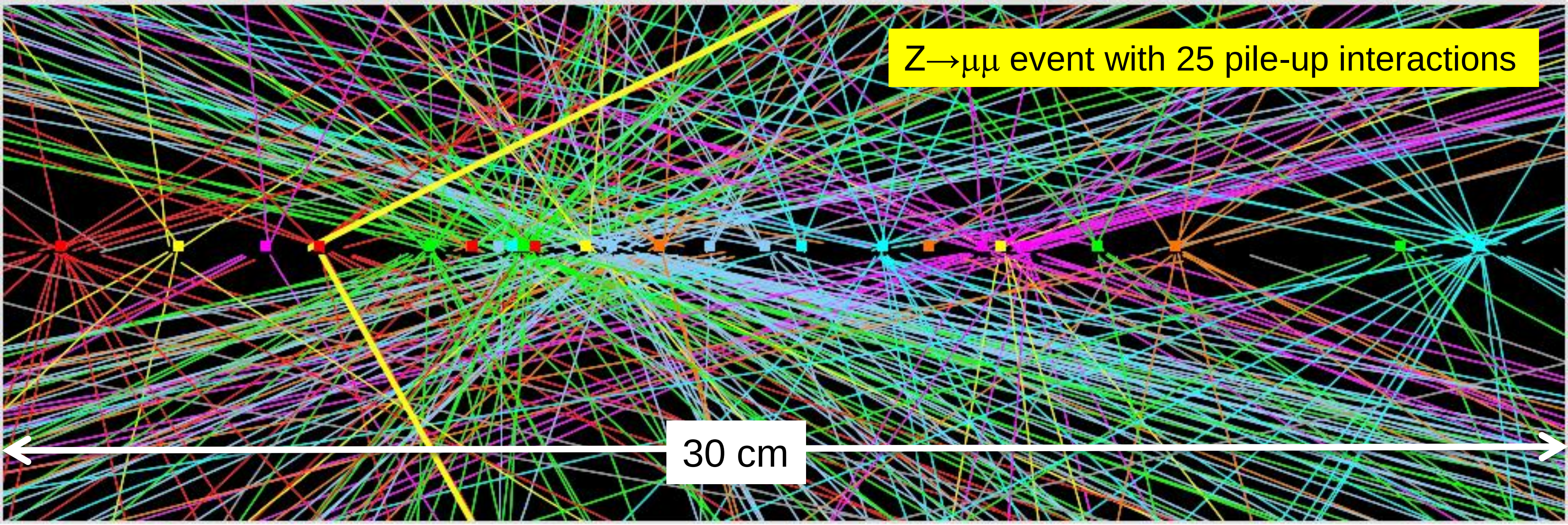
	√s [TeV]	Years	Lumi (rec.)
pp	7	2010-11	5.1 fb^{-1}
pp	8	2012	21.3 fb^{-1}
Pb+Pb	2.76	2010-11	160 μb^{-1}
Pb+p	5	2013	30 nb^{-1}

~90% of the luminosity delivered by LHC good for physics!

The pile-up challenge!

- Enormous effort to mitigate the impact of pile-up in physics!

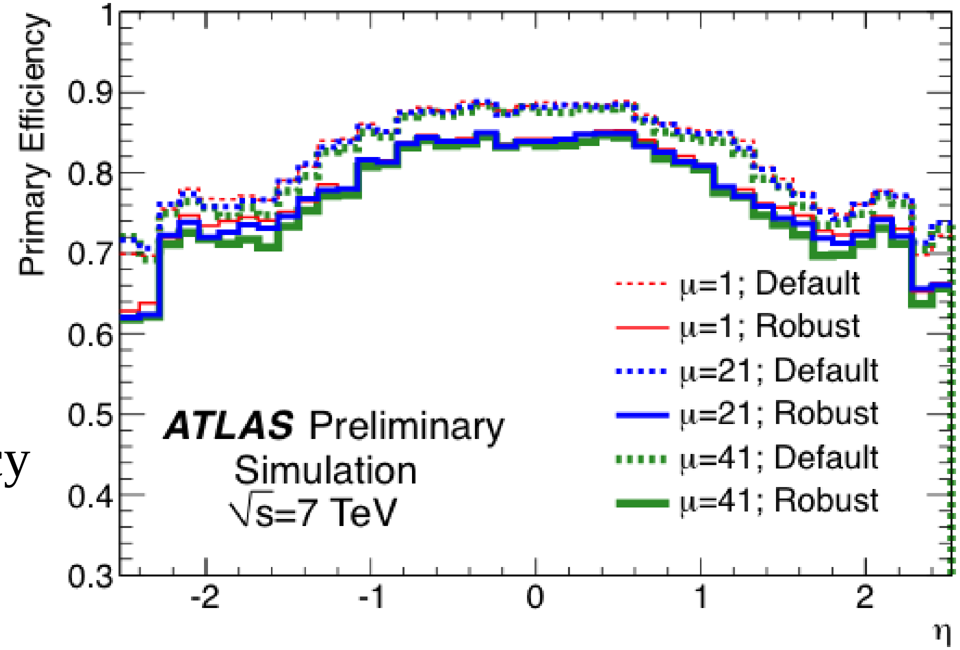


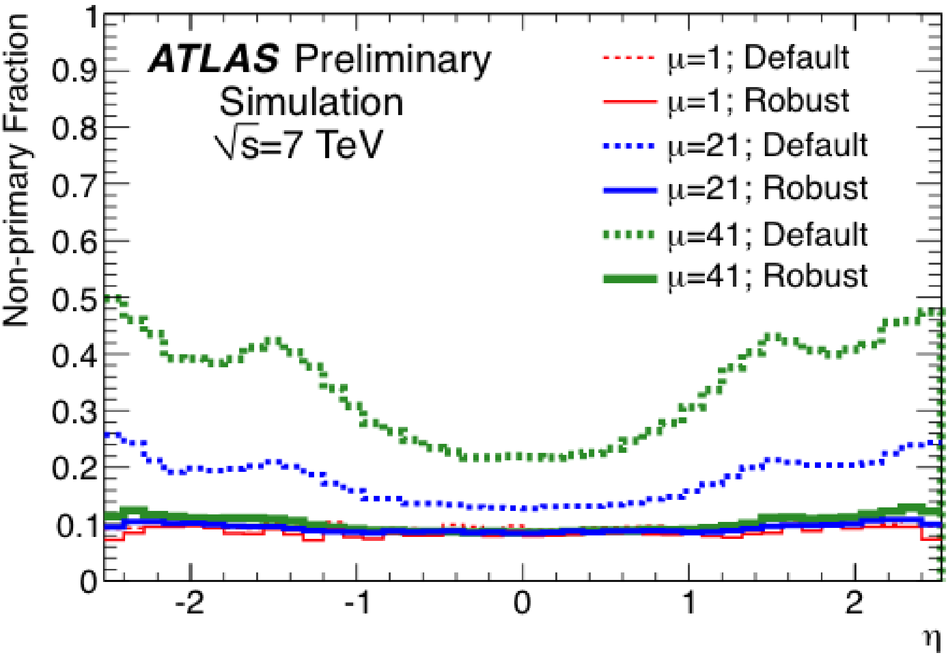


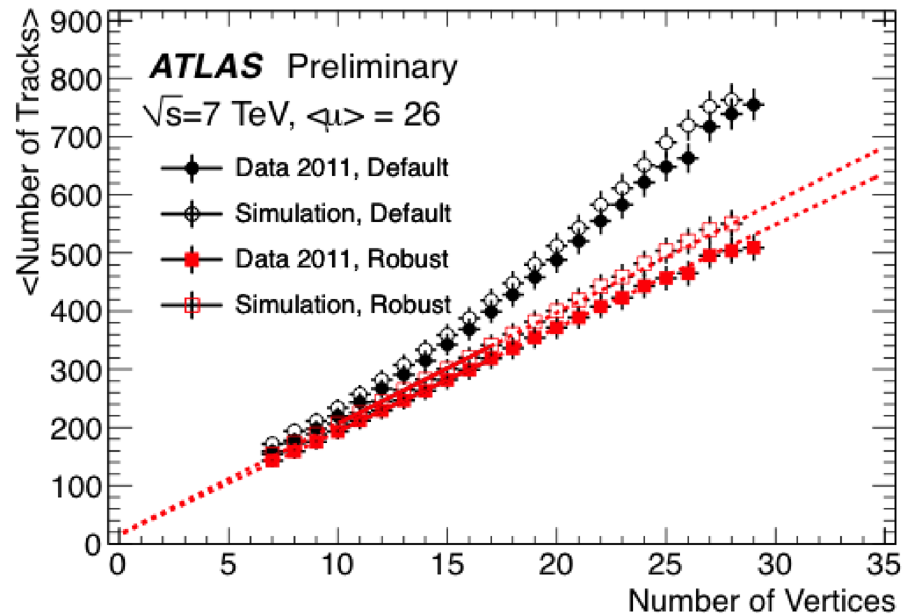
Track reconstruction at high pile-up

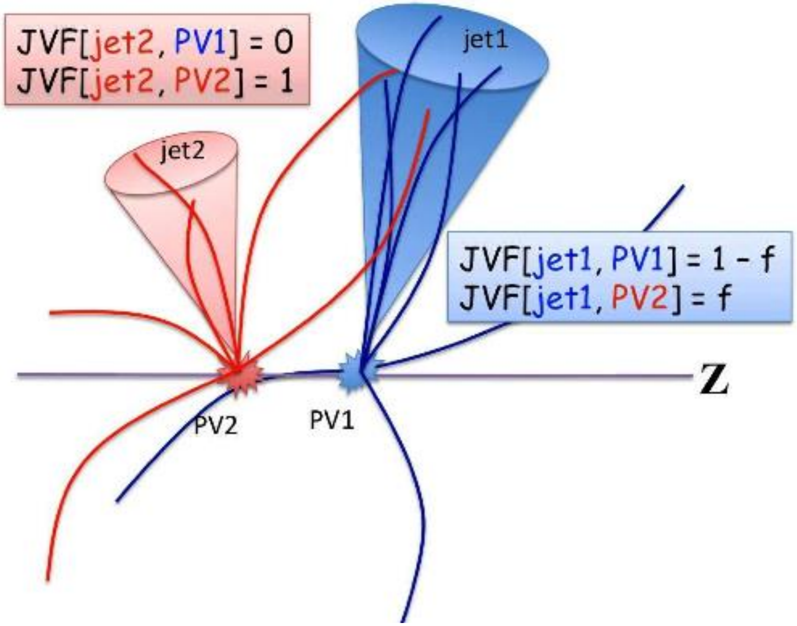
- Higher occupancy in tracking detectors
  ➔ higher combinatorics ➔ more fakes

- Tighten track quality requirements to control fakes, and achieve a linear behaviour vs. pile-up
  ➔ at a small price in good track efficiency





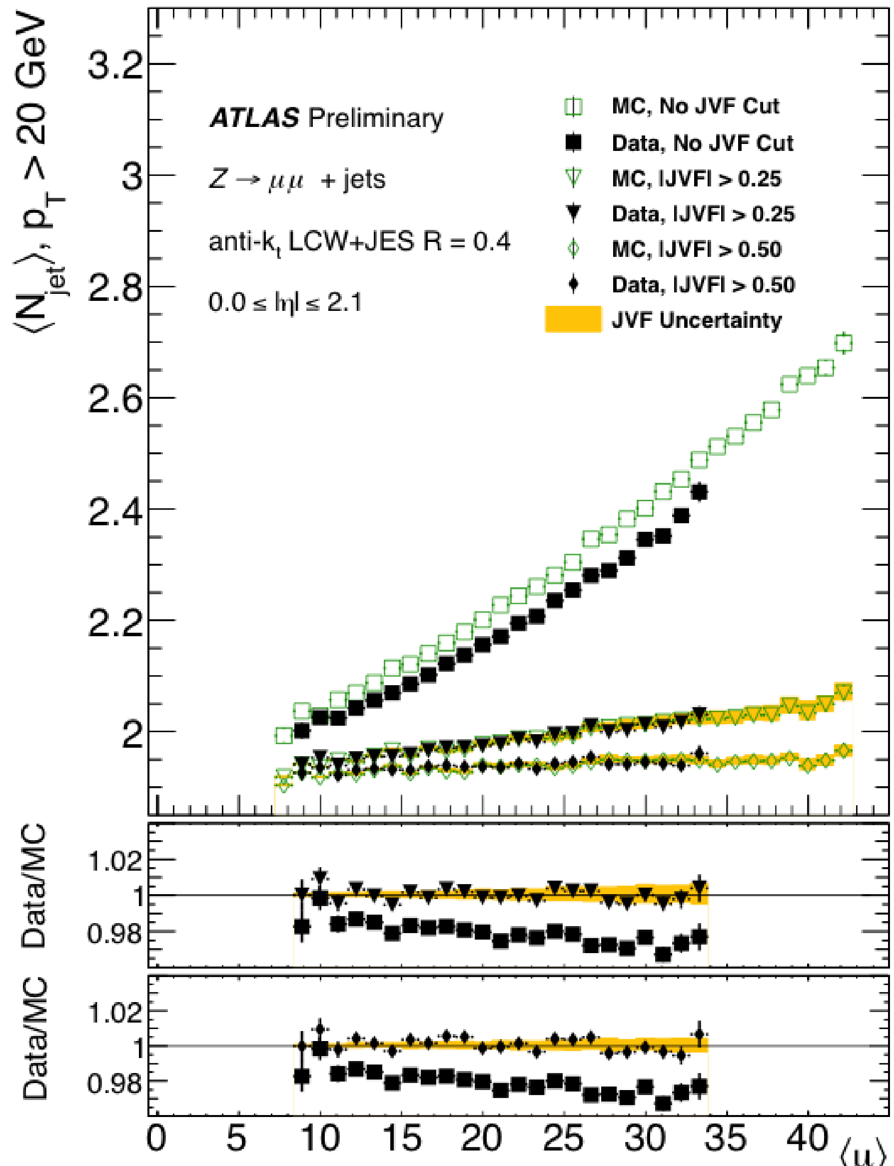




$$\mathrm{JVF} = \frac{\sum_{i \in \mathrm{PV0}} p_T^{\mathrm{track\ i}}}{\sum_j p_T^{\mathrm{track\ j}}}$$

PV0 is the hard-scatter (HS) vertex:

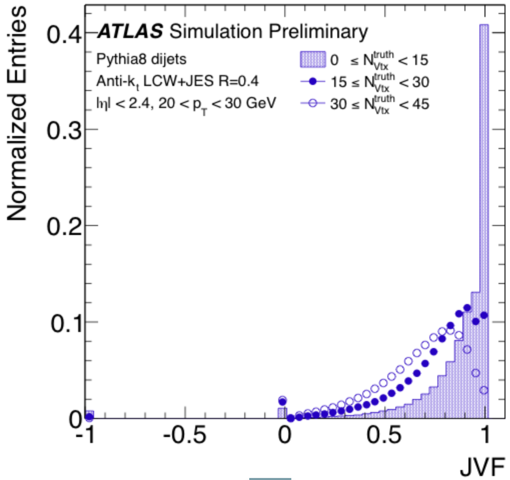
the one with highest $\sum_j \left(p_T^{\mathrm{track\ j}}\right)^2$



ATLAS-CONF-2013-083

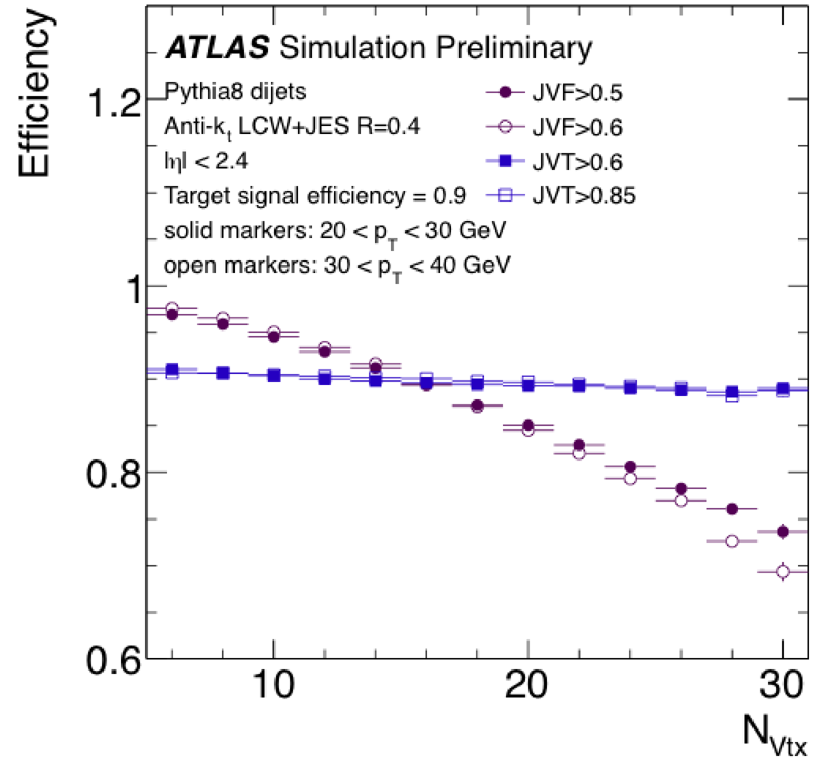
For Run 2: JVF → JV Tagger

JVF is pile-up dependent:



Jet Vertex Tagger: A likelihood-based combination of a pile-up-corrected revision of JVF and

$$R_{pT} = \frac{\sum_k p_T^{trk_k}(PV_0)}{p_T^{jet}}$$



JVT is a lot more robust against pile-up and offers ~2 times better pile-up rejection

ATLAS-CONF-2014-018

Pile-up and missing E_T

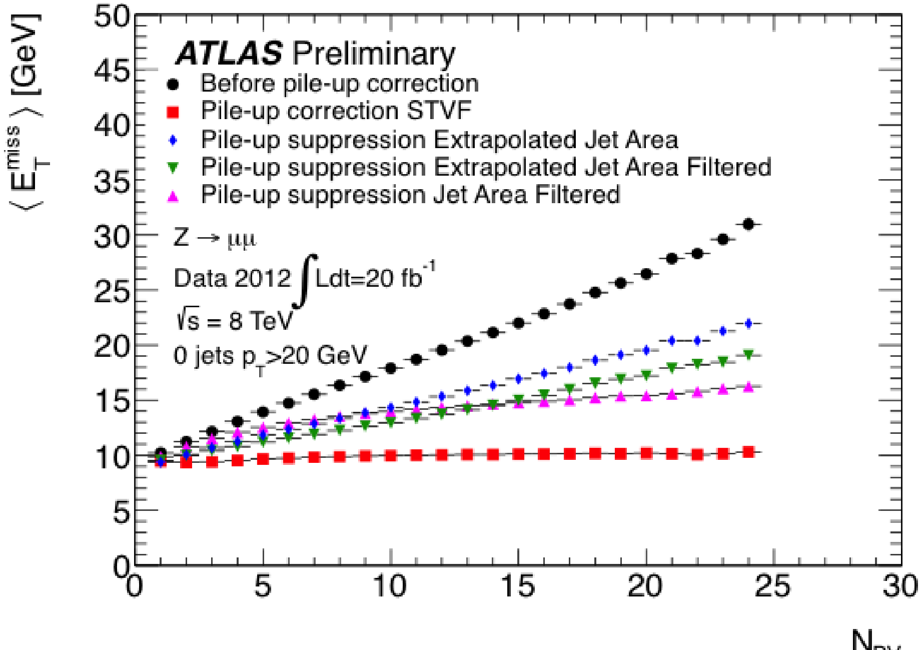
- E_T^{mis} based on momentum conservation in the transverse plane

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

$$E_{x(y)}^{\mathrm{miss}} = -\left(E_{x(y)}^{\mathrm{jets}} + E_{x(y)}^{e} + E_{x(y)}^{\gamma} + E_{x(y)}^{\tau} + E_{x(y)}^{\mu} + E_{x(y)}^{\mathrm{Soft\ Term}}\right)$$

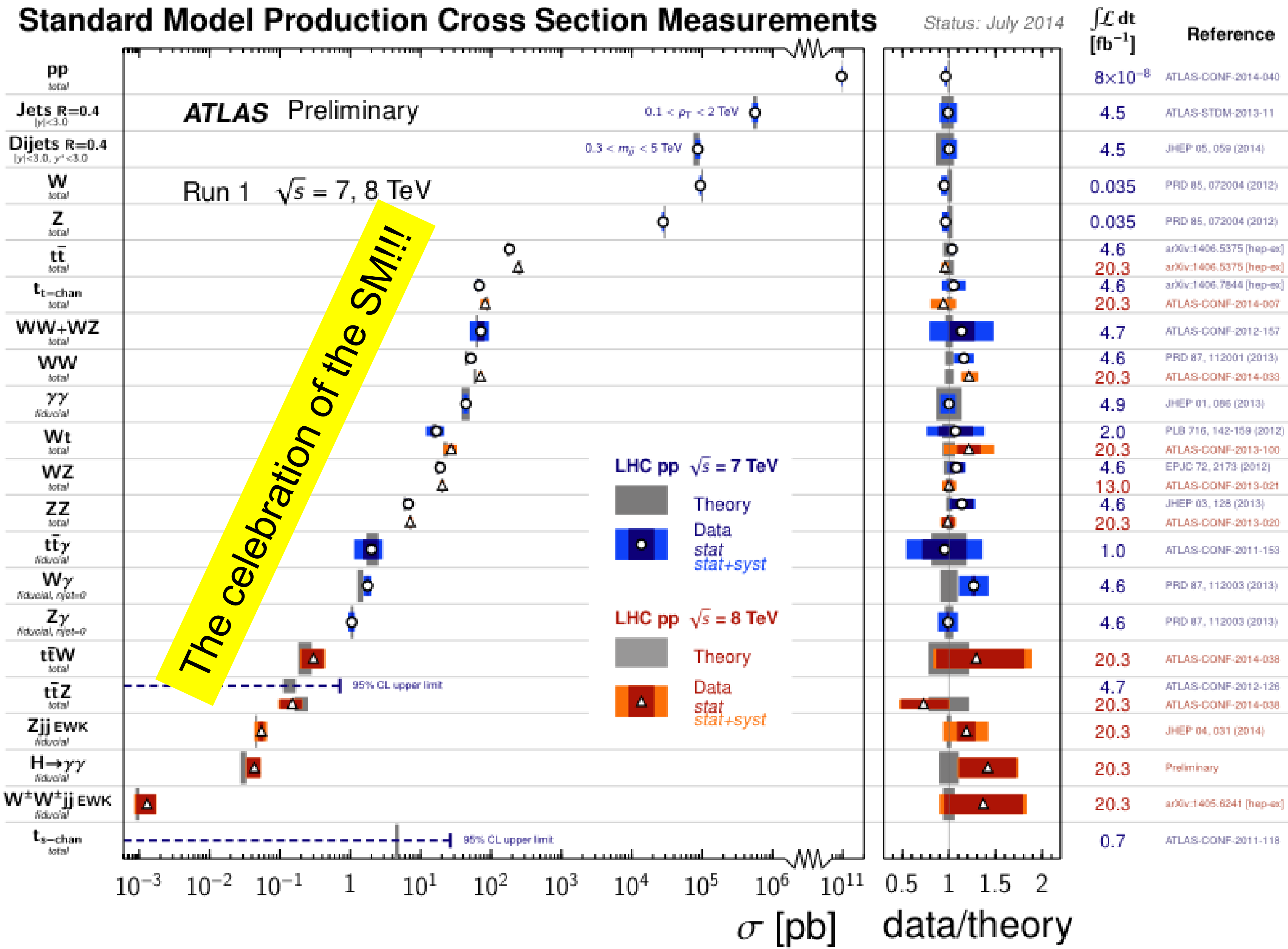
- Soft term is the energy sum of all energy clusters or tracks which are not associated with any of the identified physics objects
  - Most sensitive to pile-up
  - Corrected by multiplicative factor Soft Term Vertex Fraction:

$$\mathrm{STVF} = \frac{\sum_{\mathrm{i \in PV0}} \mathrm{p_T^{track\ i}}}{\sum_{\mathrm{j}} \mathrm{p_T^{track\ j}}}$$



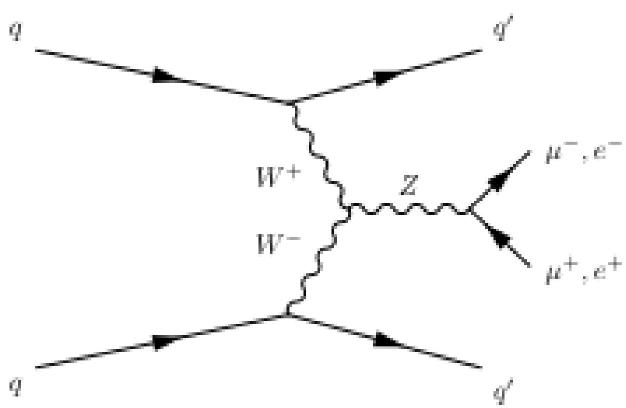
Highlights of recent results

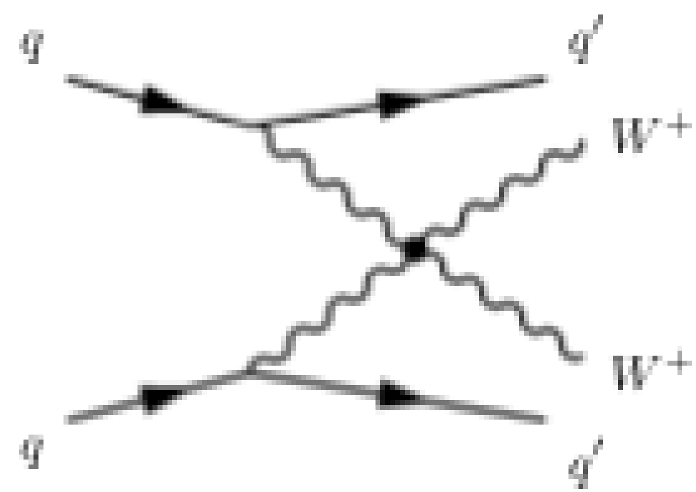
ATLAS Standard Model measurements



Vector Boson Fusion & Scattering

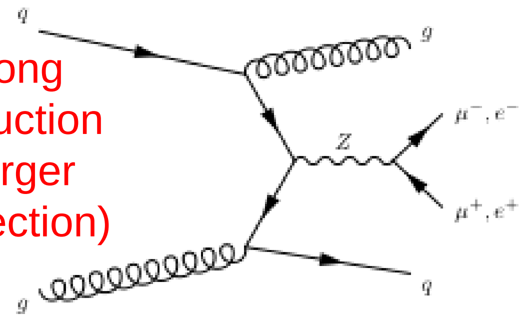
- In the SM, the Higgs plays the vital role of unitarising the longitudinal Vector Boson Scattering (VBS) cross section at high effective □s
  - An important test of the role of the Higgs
- Vector Boson Fusion: an important Higgs production mechanism
  - Useful to test theoretical modelling of VBF in non-Higgs channels
- Key feature of VBS/VBF topology: two high-p_T, forward jets
  - large dijet invariant mass
  - large rapidity gap between the two jets (no other jets in between)
- ATLAS has two recent measurements
  - VBF: Z production
  - VBS: same-sign WW production

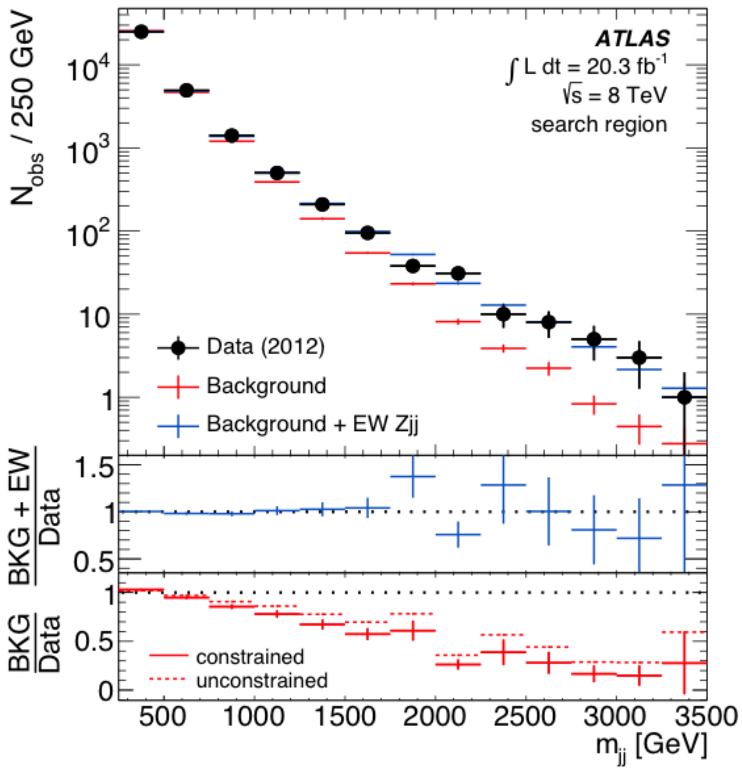


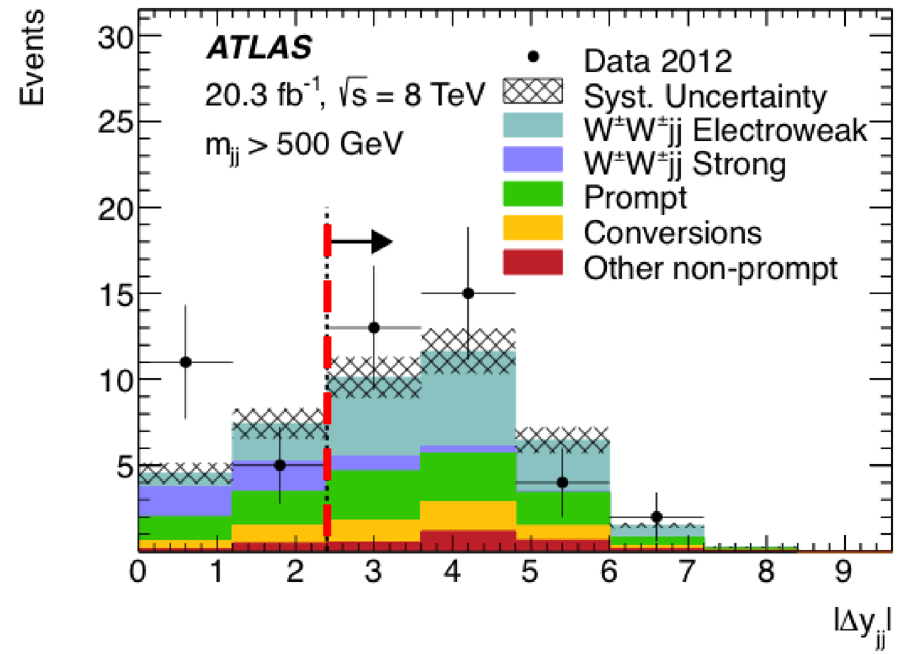


Vector Boson Fusion & Scattering

Bkg: strong Zjj production (x100 larger cross section)







Enhance EW $W^{\pm}W^{\pm}jj$ with $|\Delta y_{jj}|>2.4$ and $m_{jj}>500$GeV:

$\sigma^{EW} = 54.7 \pm 4.6(\mathrm{stat})^{+9.8}_{-10.4}(\mathrm{syst}) \pm 1.5(\mathrm{lumi})$ fb

SM NLO (Powheg) = 46.1±1.0 fb

$\sigma^{EW}_{fid} = 1.3 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})$ fb

$\sigma^{EW}_{SM} = 0.95 \pm 0.06$ fb

arXiv:1401.7610

arXiv:1405.6241

Vector Boson Fusion & Scattering

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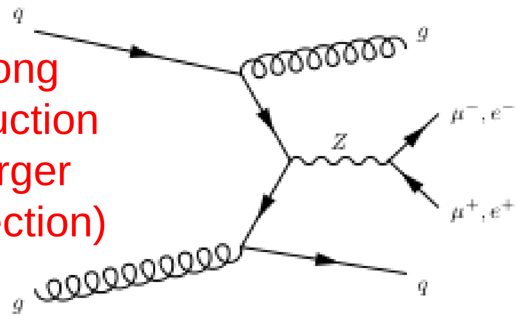

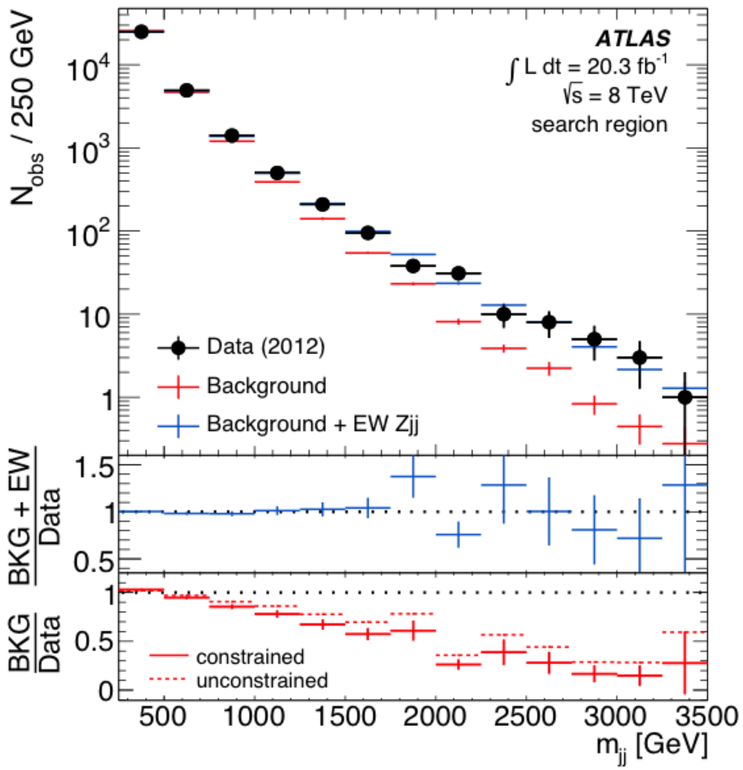

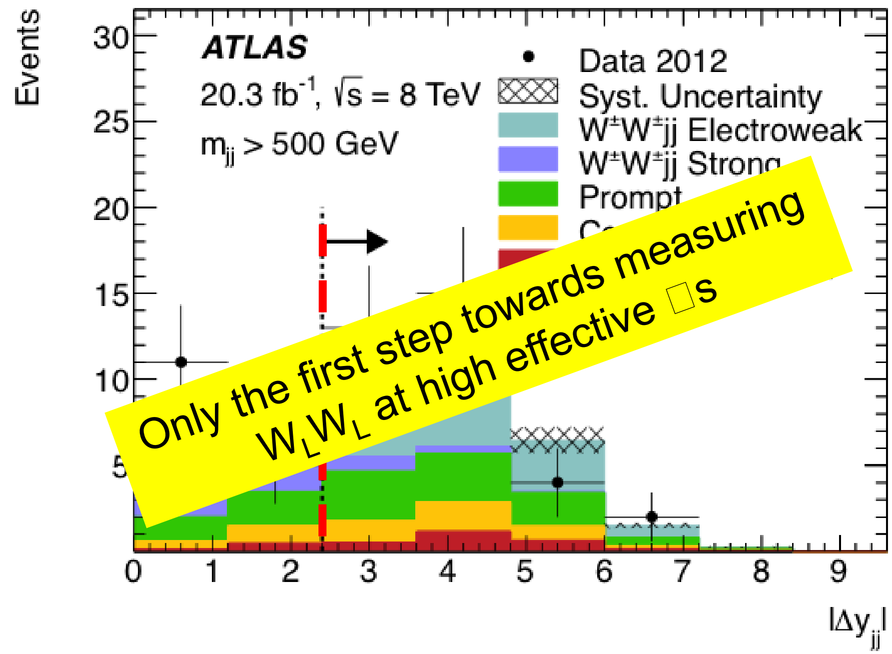

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arXiv:1401.7610

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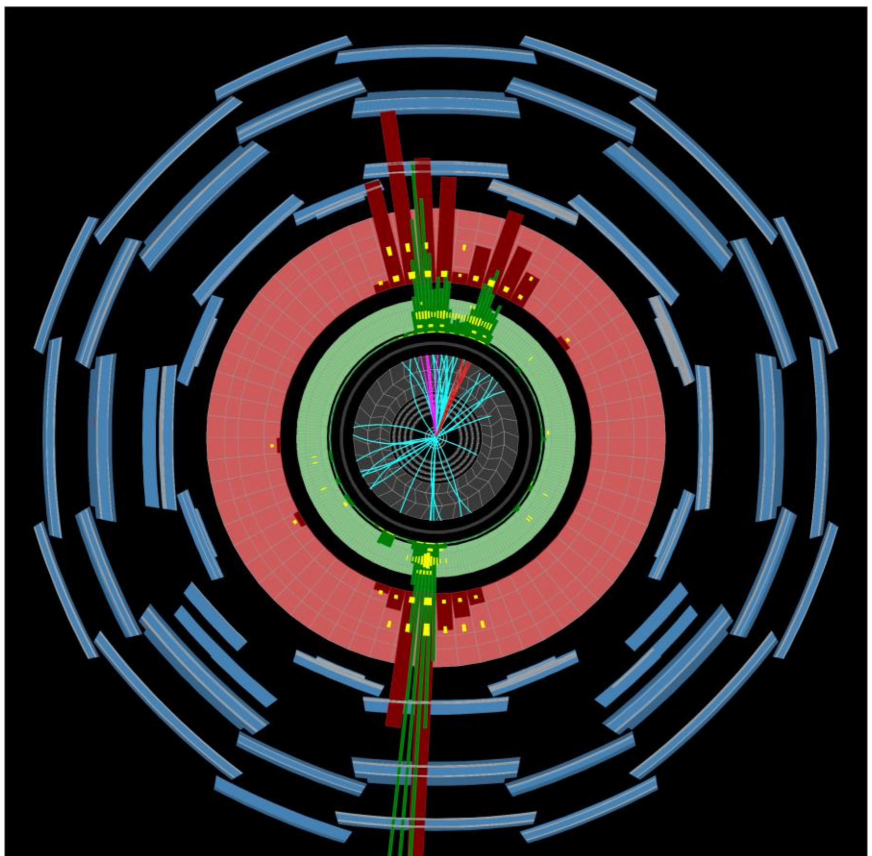
“Boosted” Z→bb production

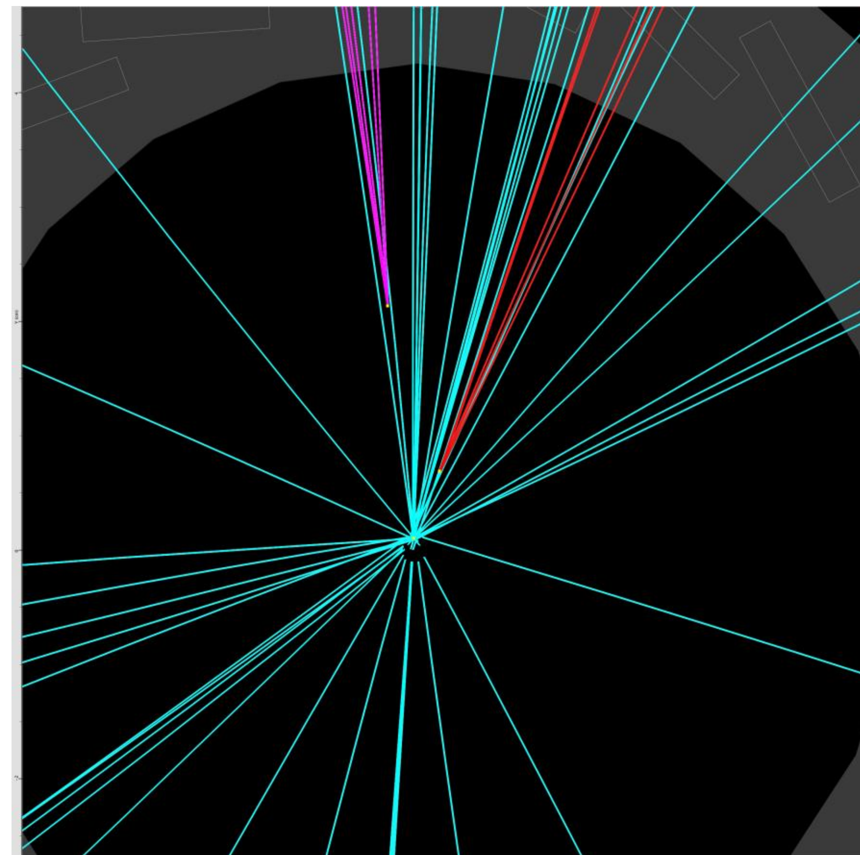
Z→bb candidate selection:

-2 b-tagged anti-k_t R=0.4 jets, $|\eta|<2.5$, $p_T>40$GeV

- ΔR(jet1,jet2)<1.2, dijet pT>200GeV

Data-driven estimate of the bkg (nearly all gluon→bb)





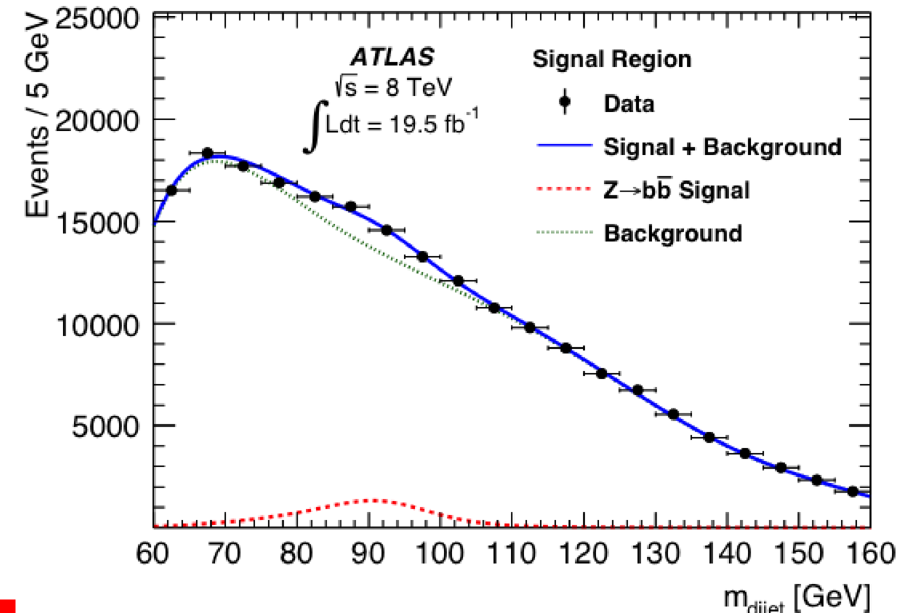
“Boosted” Z→bb production

Fit results:

$N_{\mathbf{signal}}$ = 6420±640 events

$\delta M_Z = -1.5 \pm 0.7^{+3.4}_{-2.5}$ GeV

(validation of b-jet energy scale in ATLAS)



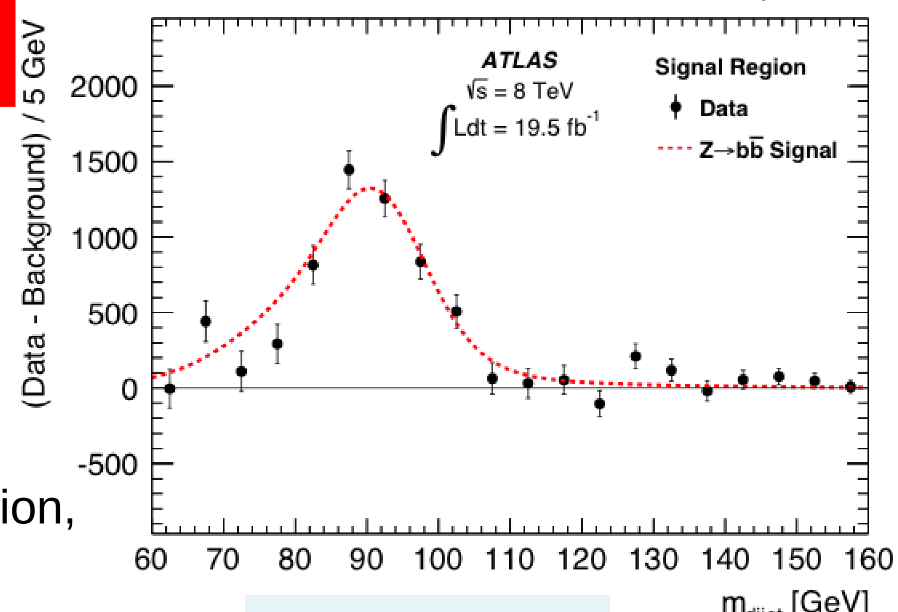
Result:

$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\ (\text{stat.})\ \pm 0.25\ (\text{syst.}) \pm 0.06\ (\text{lumi.})\ \text{pb}$$

NLO predictions:

$$\text{POWHEG}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02\ ^{+0.25}_{-0.19}(\text{scales})\ ^{+0.03}_{-0.04}(\text{PDF})\ \text{pb}$$

$$\text{aMC@NLO}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 1.98\ ^{+0.16}_{-0.08}(\text{scales}) \pm 0.03(\text{PDF})\ \text{pb}$$

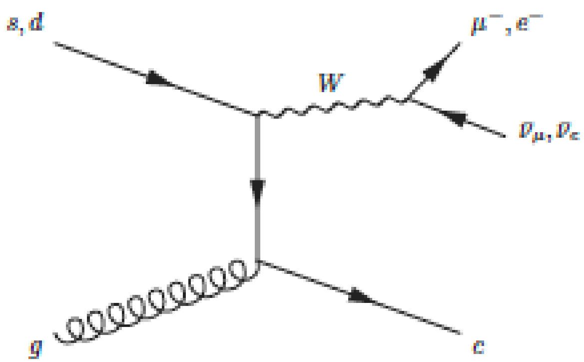


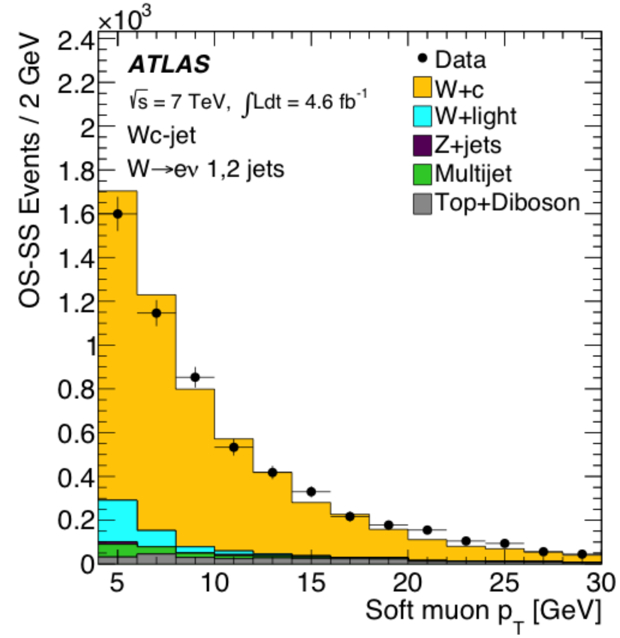
Dominant systematics: Jet energy scale/resolution, bkg shape modelling, trigger modelling

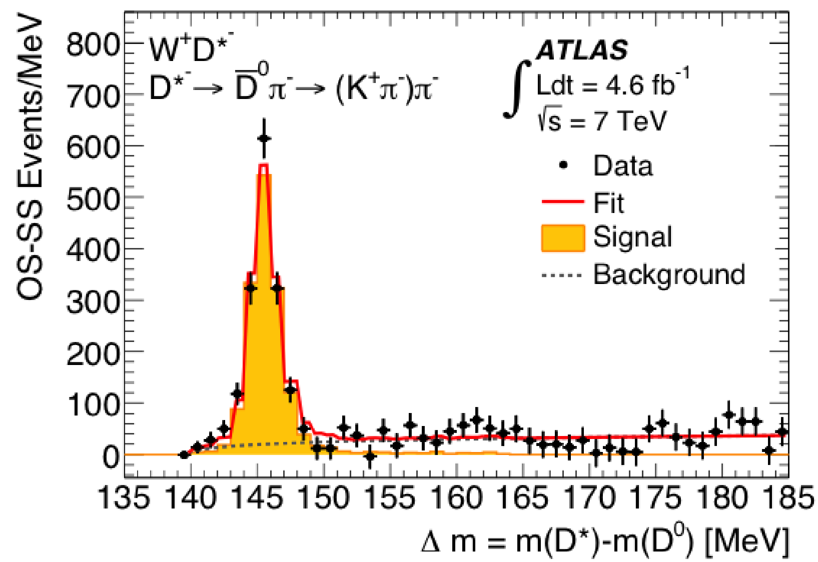
arXiv:1404.7042

- Improving our understanding of the proton's structure vital for the LHC physics programme

- s-content probed by W+c production (d-quark contribution ~10%)

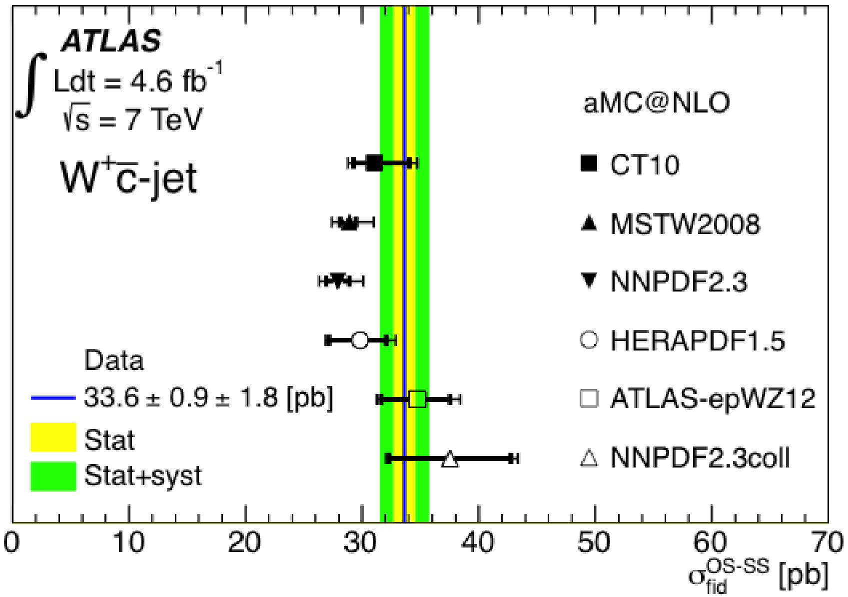


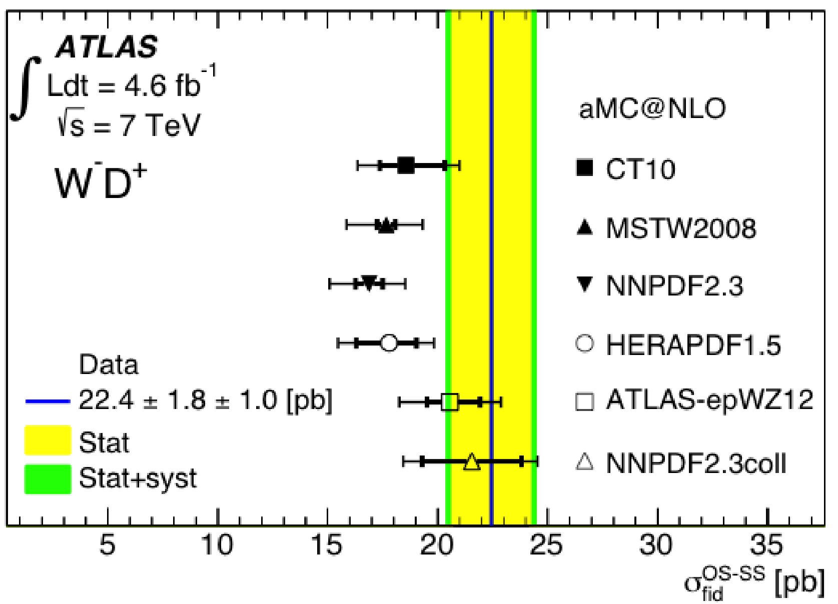




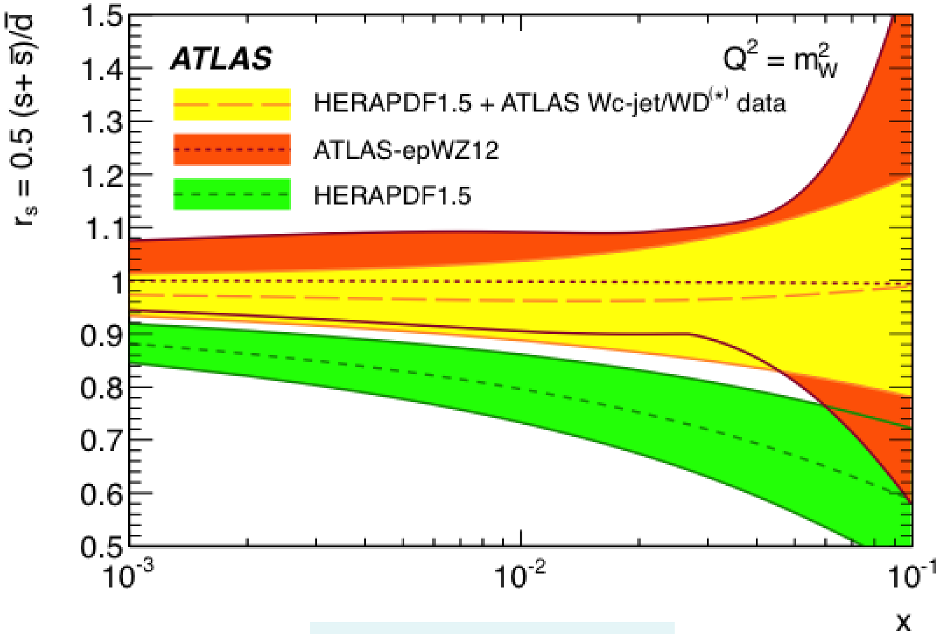
- ATLAS measurements using W plus
  - (a) jets with a reconstructed soft muon
  - (b) jets with a reconstructed D*

PDFs: W+c results





- Data consistent with all PDF sets, but favour no suppression of sbar over s density
- Also, data support no variation of s+sbar density relative to d-sea, in the range of the measurement.

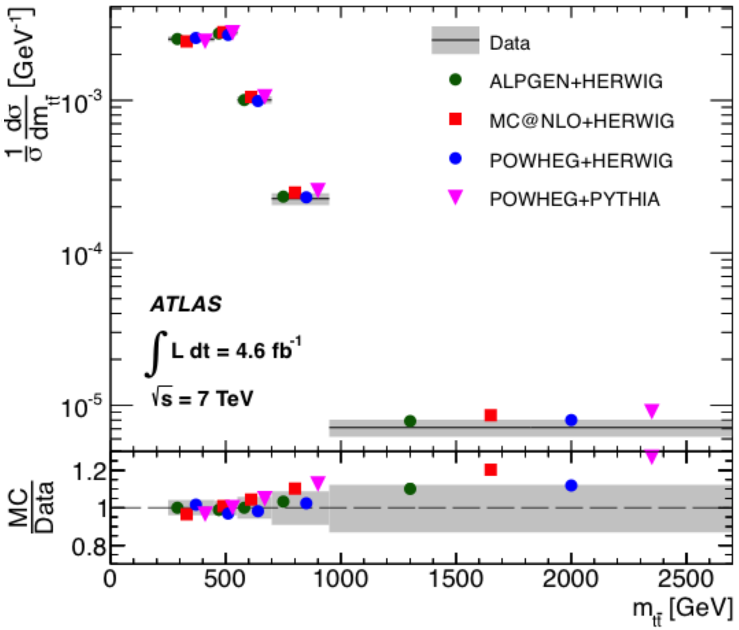


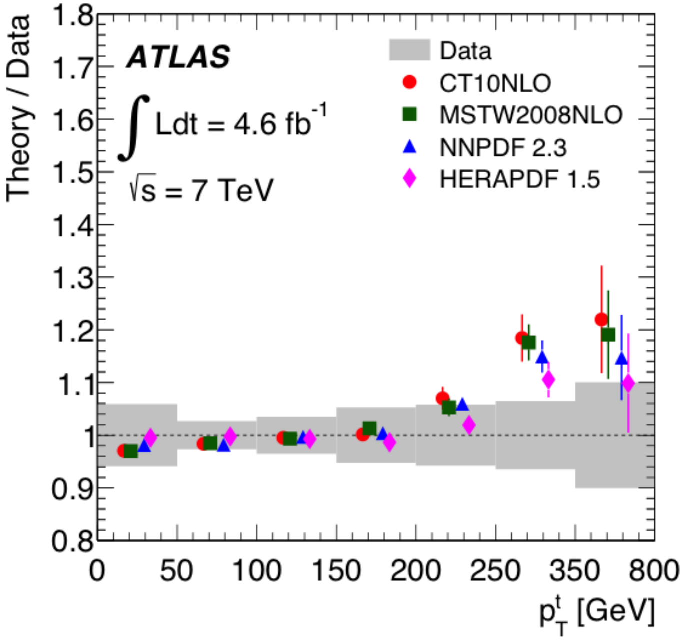
arXiv:1402.6263

Top-pair production cross section

- Measured differentially in semi-leptonic tt events (~80% pure) at 7TeV (4.6fb^{-1})
- Data unfolded to parton-level kinematics
- Cross section vs hadronic top p_T, m_{tt}, p^T_{tt}, y_{tt}
- Data appears to have softer spectrum than all MC programs
  - ➢ And mostly true for different PDF sets
  - ➢ Important in searches for high-mass ttbar resonances
  - ➢ Relevant for all analyses where tt is a big background
- Measurement is systematics limited, dominated by the unfolding dependence on MC generators

arXiv:1407.0371





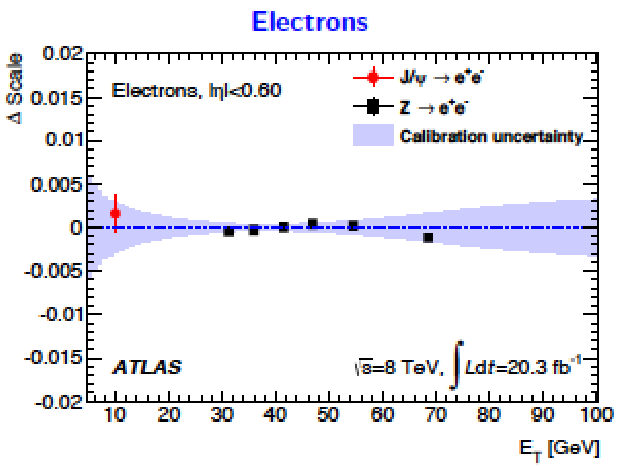
Improvements for Higgs mass measurement

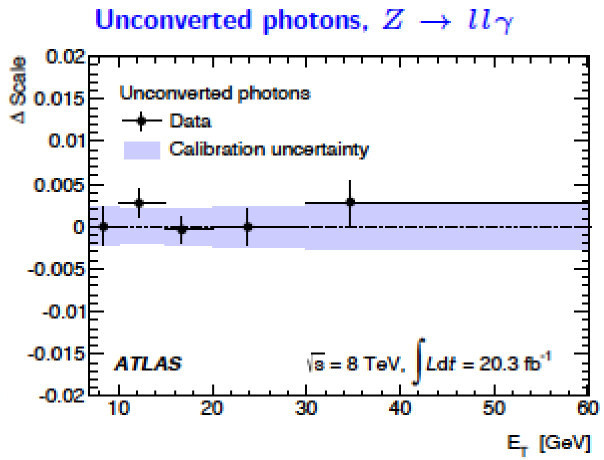
- From summer 2013 to summer 2014
  - Much improved calibration of photons, electrons and muons
    - Significant reduction of systematic uncertainties in Higgs mass measurement

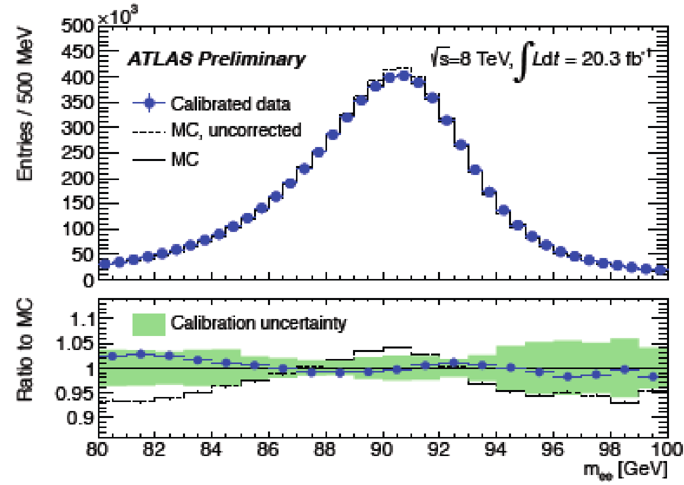
- Many improvements to the di-photon and 4-lepton analyses

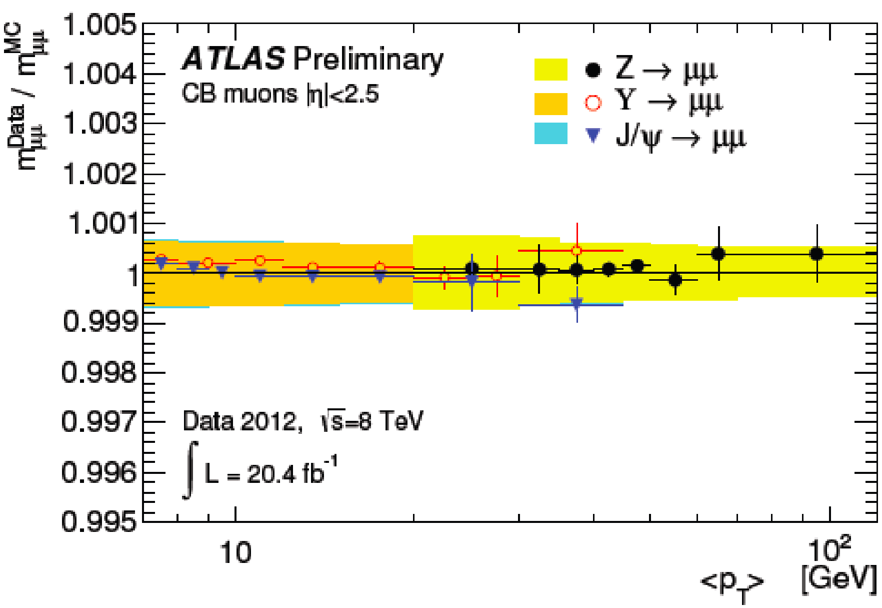
- In $H \to$ 4leptons
  - Moved from cut-based to MVA-based electron-ID
    - x2 better fake electron rejection for same eff
  - Combine track and cluster for electron energy for E_T<30GeV
  - MVA-based discriminant against ZZ* bkg
  - Better modelling of muon pT in the simulation

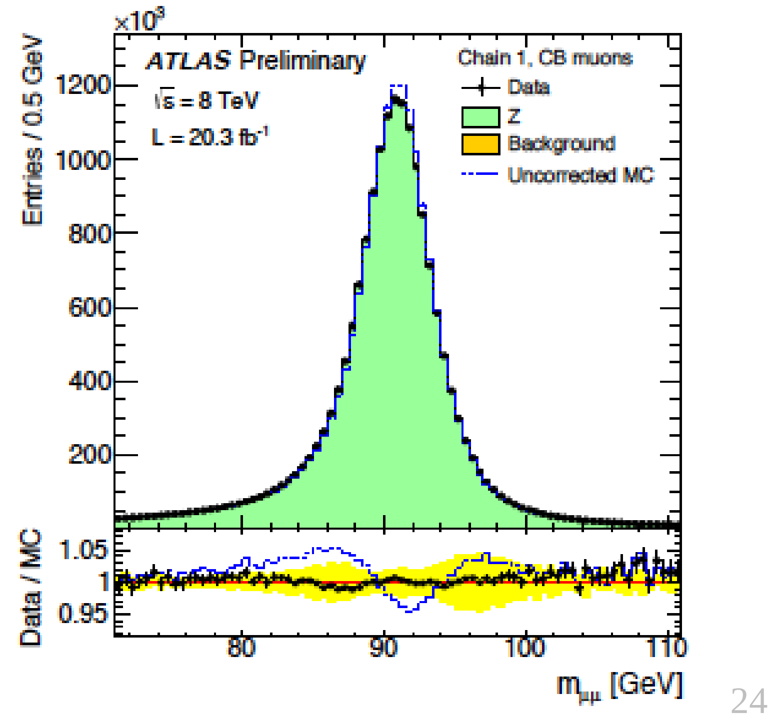
Improvements for Higgs mass measurement











ATLAS Run 1 Higgs mass

H → γγ

$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{sys})\ \text{GeV}$$
$$= 125.98 \pm 0.50\ \text{GeV}$$
$$\mu = 1.29 \pm 0.30$$

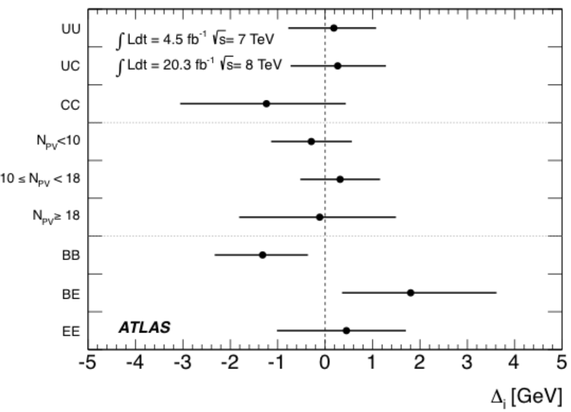
H → 4leptons

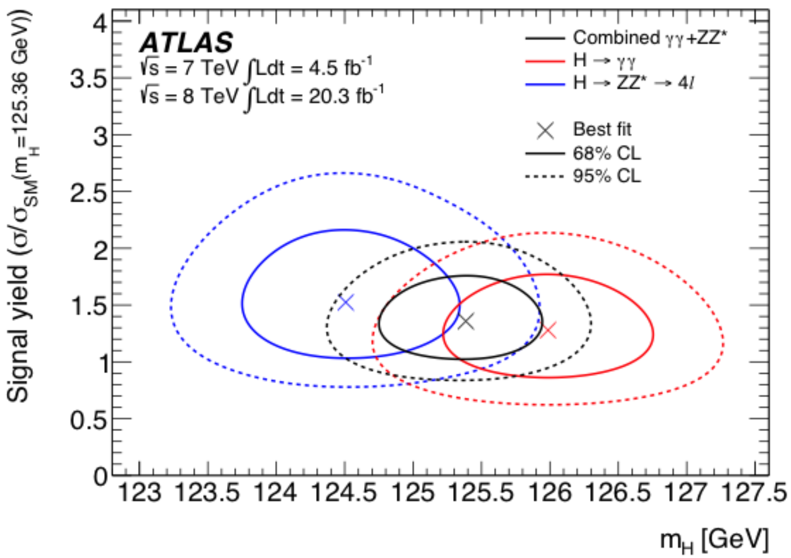
$$m_H = 124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{sys})\ \text{GeV}$$
$$= 124.51 \pm 0.52\ \text{GeV}$$
$$\mu = 1.66^{+0.45}_{-0.38}$$

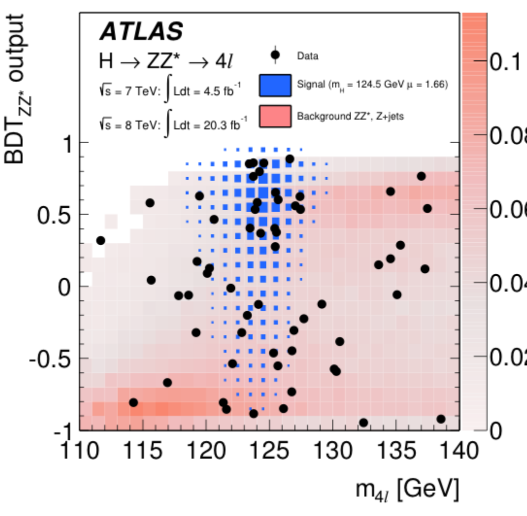
The two measurements are compatible at the 2σ level (p-value: 4.6%).

ATLAS Run 1 combined result:

$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}$$







arXiv:1406.3827

- For m_H= ~125GeV, the SM predicts Γ_H= ~4.2MeV
  - This is ~3 orders of magnitude smaller than the experimental resolution for the diphoton and 4leptons peaks (O(GeV)) ➔ impossible to measure

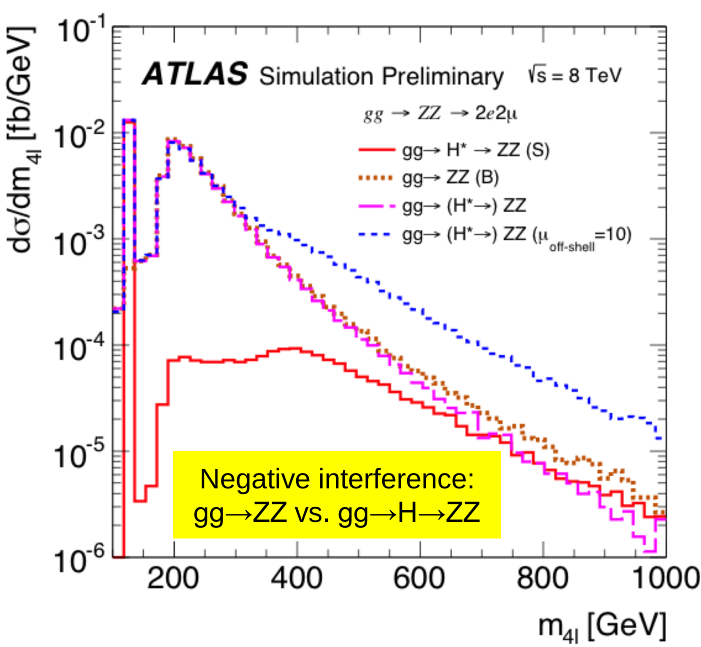
- Theorists to the rescue: Proposed by F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024), N. Kauer and G. Passarino, JHEP 08 (2012) 116, J. Campbell et al. (arXiv:1311.3589)
  - Determine Γ_H indirectly, by measuring on-shell/off-shell $\sigma(H\to ZZ)$!

$$\boxed{\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M^2_{4l}} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{(M^2_{4l}-m^2_H)^2+m^2_H\Gamma^2_H}}$$

Assuming couplings independent of M_{4l}

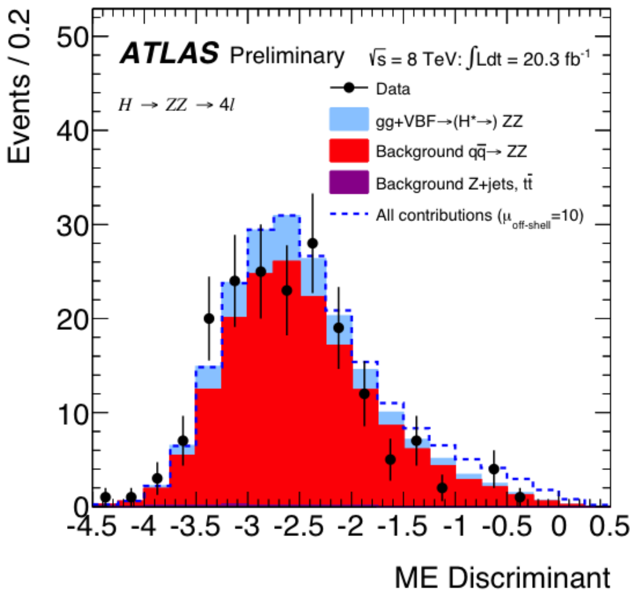
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \equiv \mu\cdot\sigma^{\text{on-peak}}_{gg\to H\to ZZ}(SM) \qquad r=\Gamma_H/\Gamma_H^{SM}$$

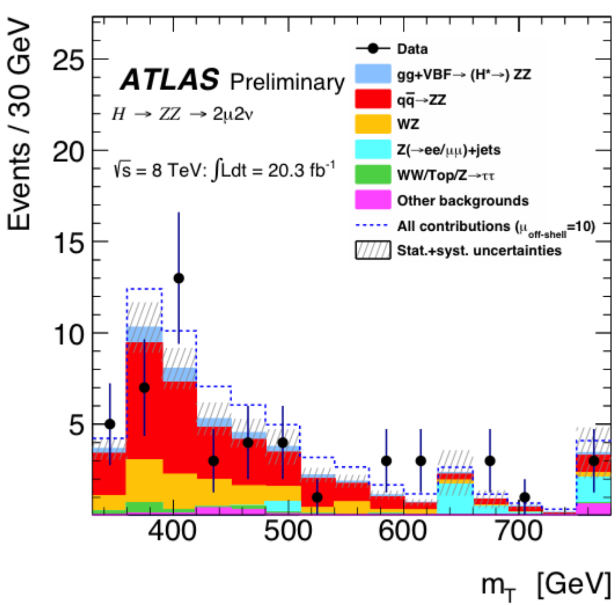
$$\frac{\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu\cdot r\cdot\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}(SM)}{dm_{ZZ}} \qquad \mu\equiv\frac{\sigma^{\text{on-peak}}_{gg\to H\to ZZ}}{\sigma^{\text{on-peak}}_{gg\to H\to ZZ}(SM)}$$



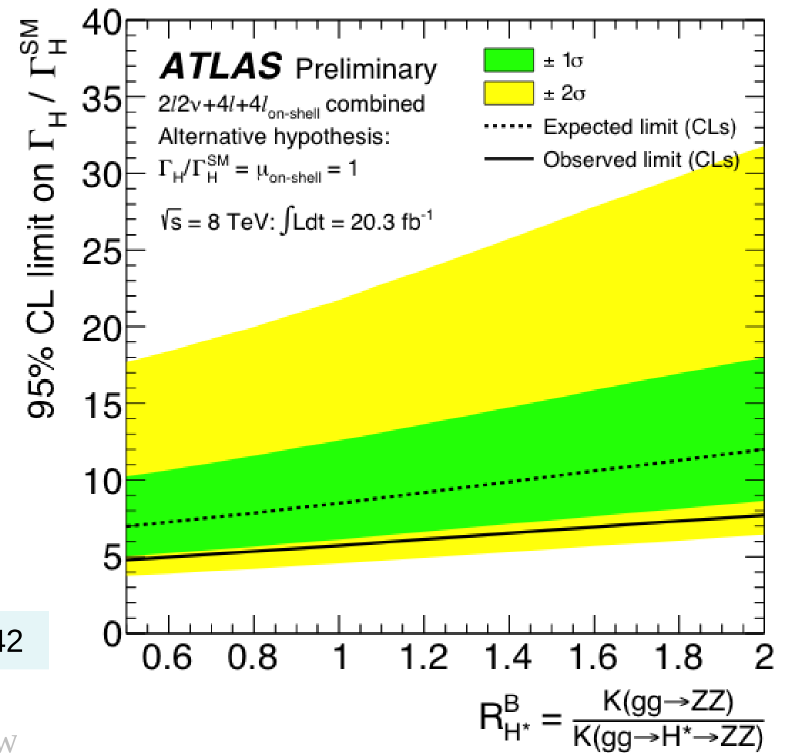
- 4ℓ channel uses Matrix Element based discriminant
- $2\nu2\ell$ channel uses transverse mass discriminant
- Results produced as function of the ratio of k-factors:

$$R^{B}_{H^*} = \frac{K(gg \to ZZ)}{K(gg \to H^* \to ZZ)} = \frac{K^{B}(m_{ZZ})}{K^{H^*}_{gg}(m_{ZZ})}$$

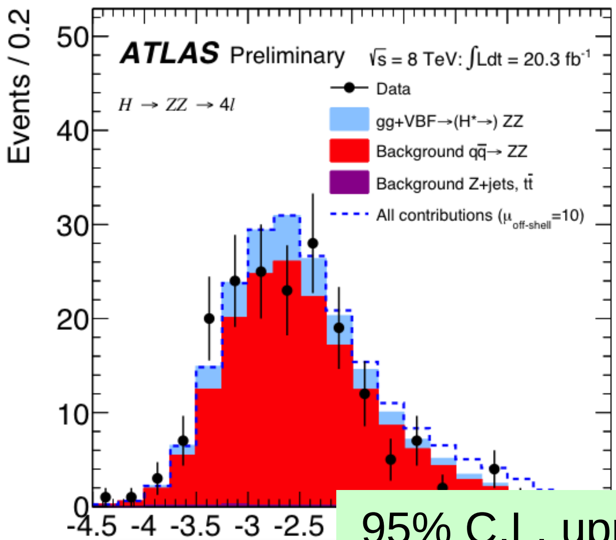




ATLAS-CONF-2014-042



Higgs width in ATLAS from off-shell ZZ



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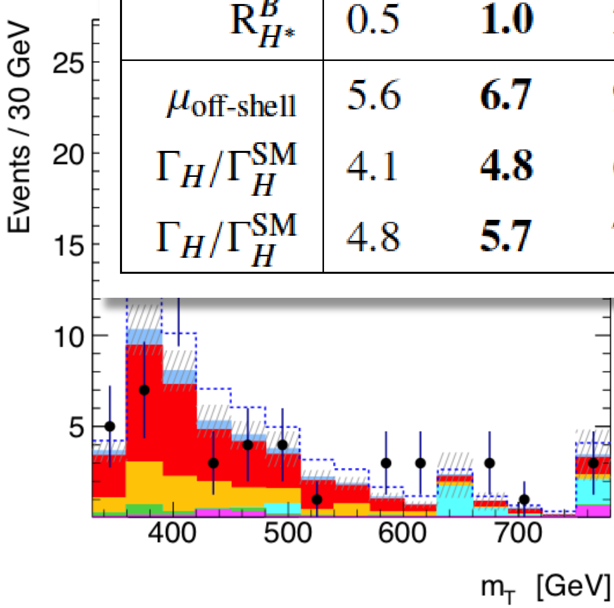
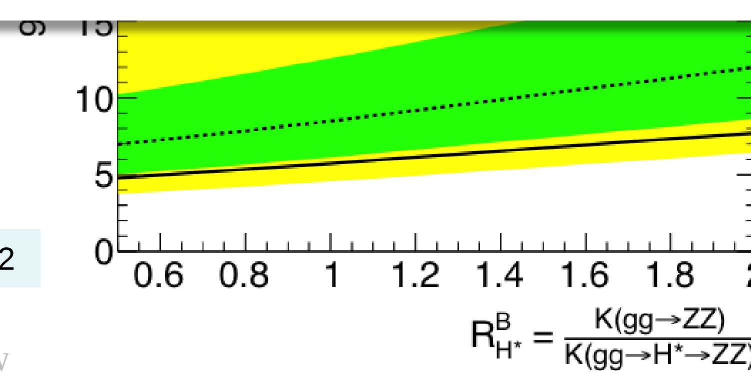
95% C.L. upper limits for various alternative hypotheses

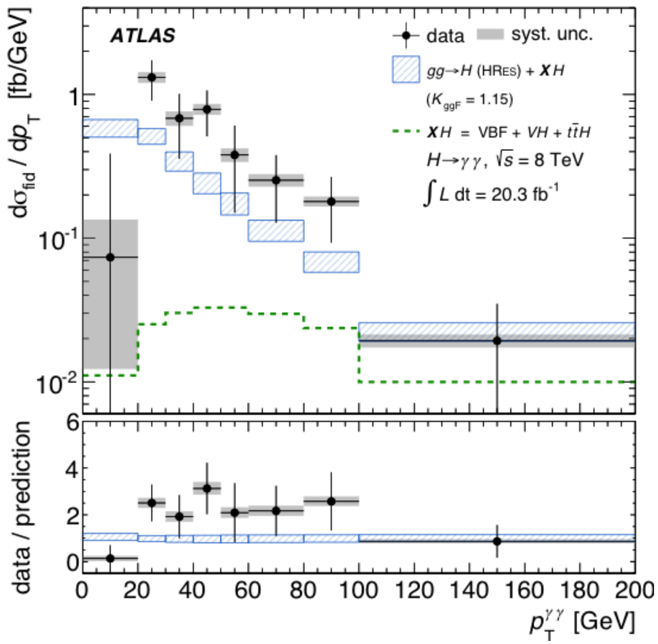
$R^B_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Alternative hypothesis
$\mu_{\text{off-shell}}$	5.6	**6.7**	9.0	6.6	**7.9**	10.7	$R^B_{H^*} = 1, \mu_{\text{off-shell}} = 1$
Γ_H/Γ_H^{SM}	4.1	**4.8**	6.0	5.0	**5.8**	7.2	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1.51$
Γ_H/Γ_H^{SM}	4.8	**5.7**	7.7	7.0	**8.5**	12.0	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1$



ATLAS-CONF-2014-042



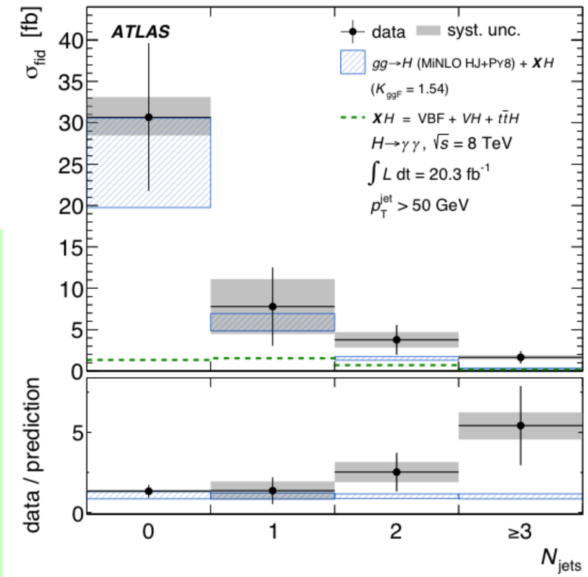
Higgs differential cross sections

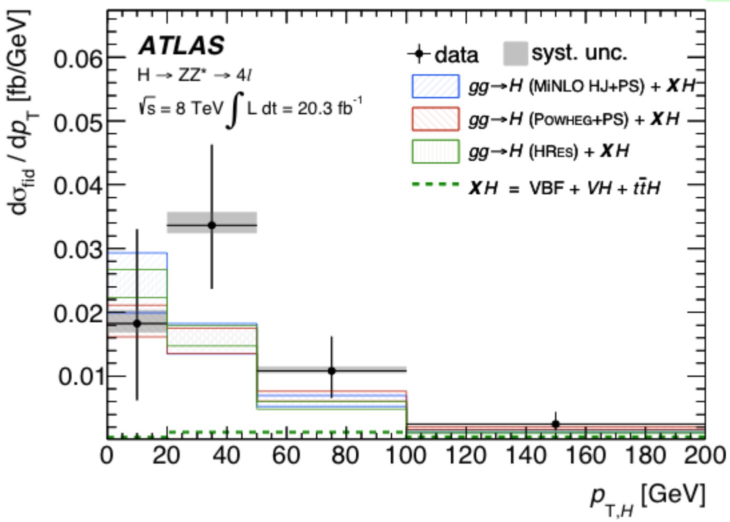


H → γγ
arXiv:1407.4222

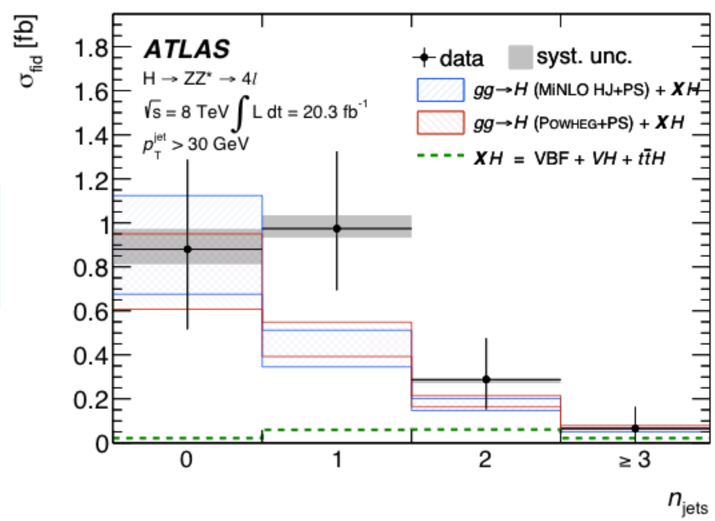
First differential, unfolded cross sections!

Stats-limited now, will become powerful tools for understanding the dynamics of Higgs production in the future





H → 4leptons
arXiv:1408.3226

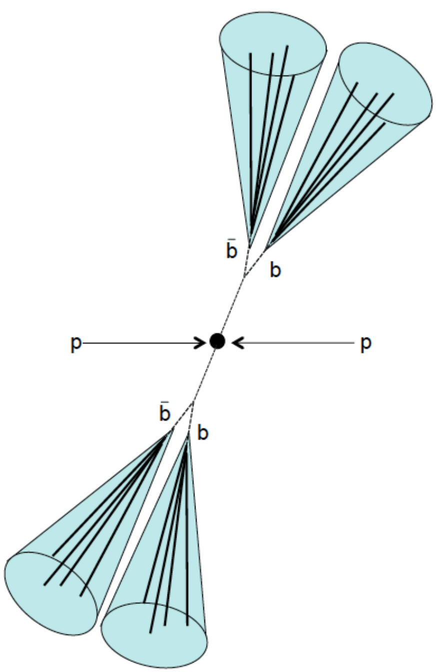


Resonance mass range: 500-1500GeV

Search for two back-to-back, boosted dijets, each with mass~125GeV

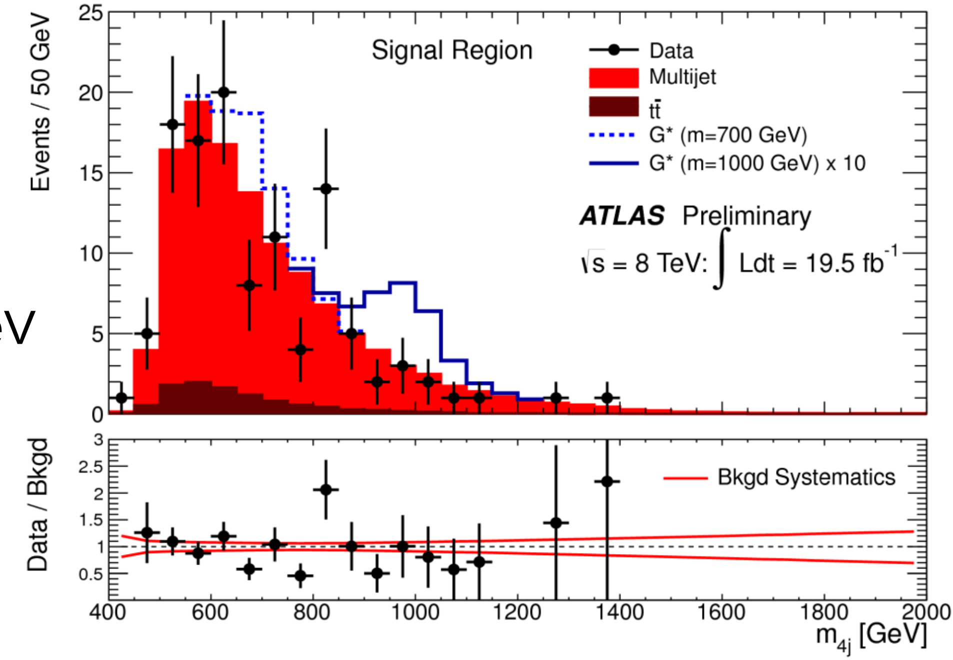
Jet requirements:
4 b-tagged anti-k_t (R=0.4) jets with p_T>40GeV

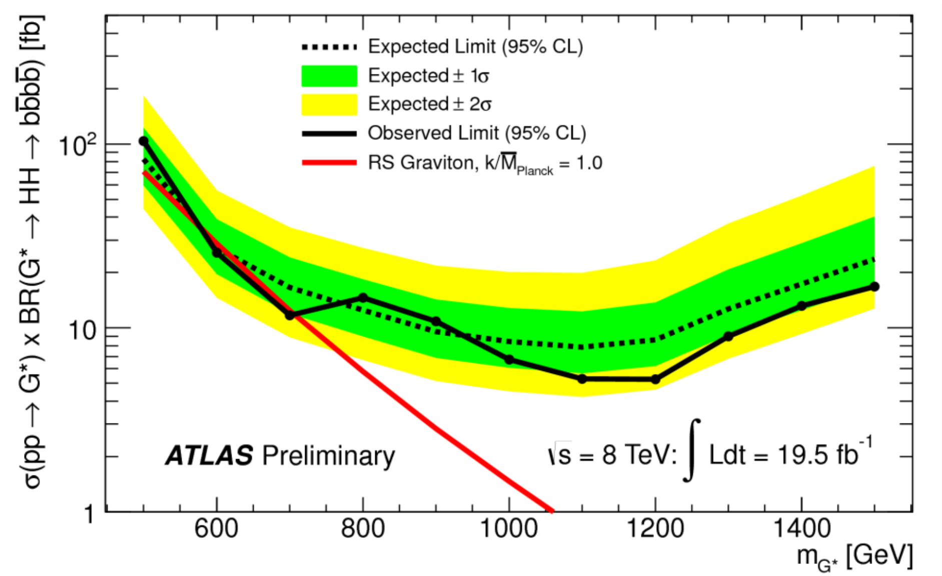
Dijet requirements:
p_T>200GeV, $\Delta R(b,b)<1.5$



Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114
G^* (m_{G^*} = 500 GeV)	12.5 ± 0.4
G^* (m_{G^*} = 700 GeV)	12.5 ± 0.2

ATLAS-CONF-2014-005





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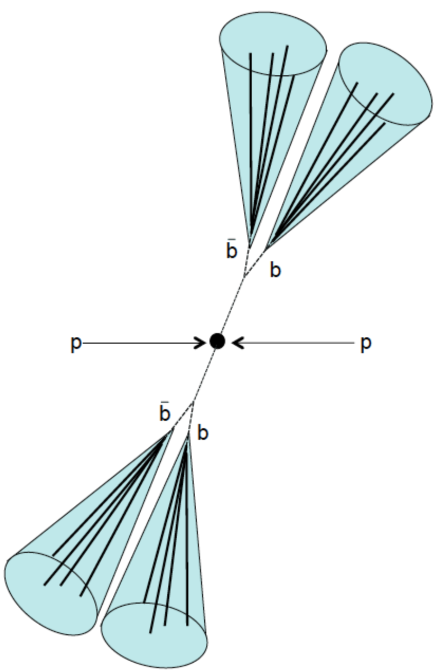

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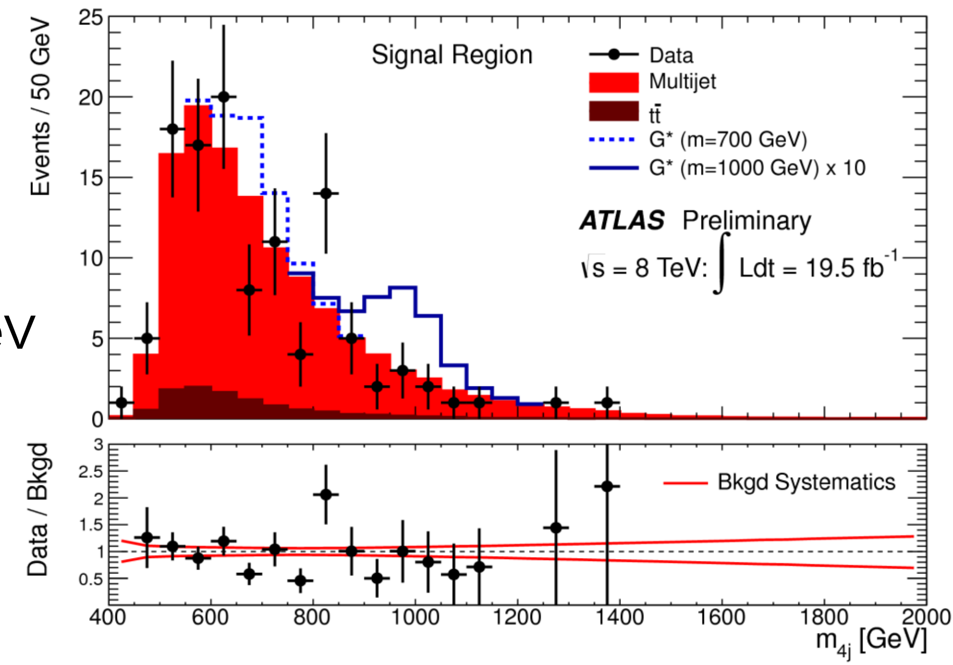
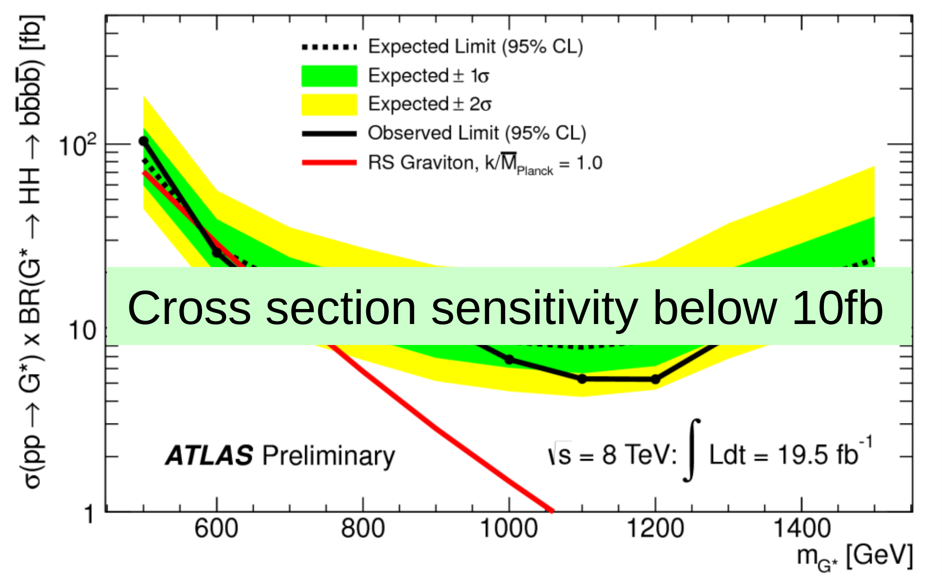
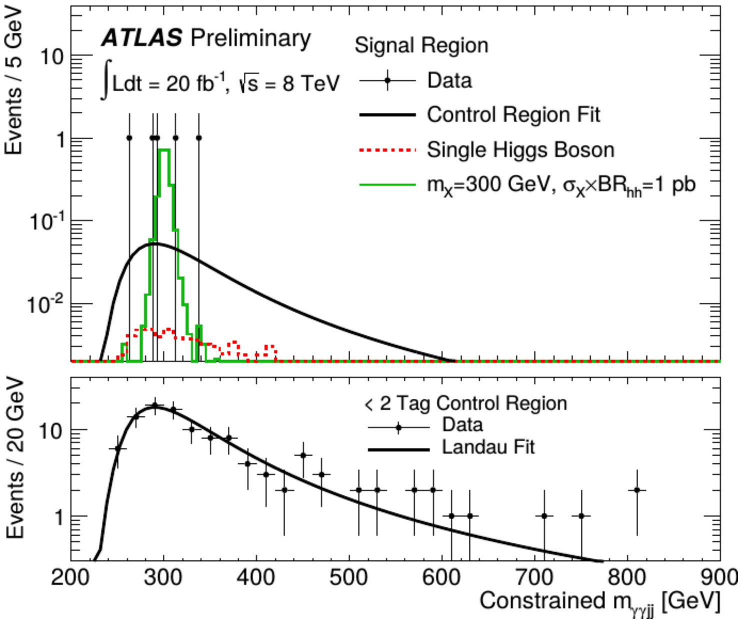
ATLAS-CONF-2014-005

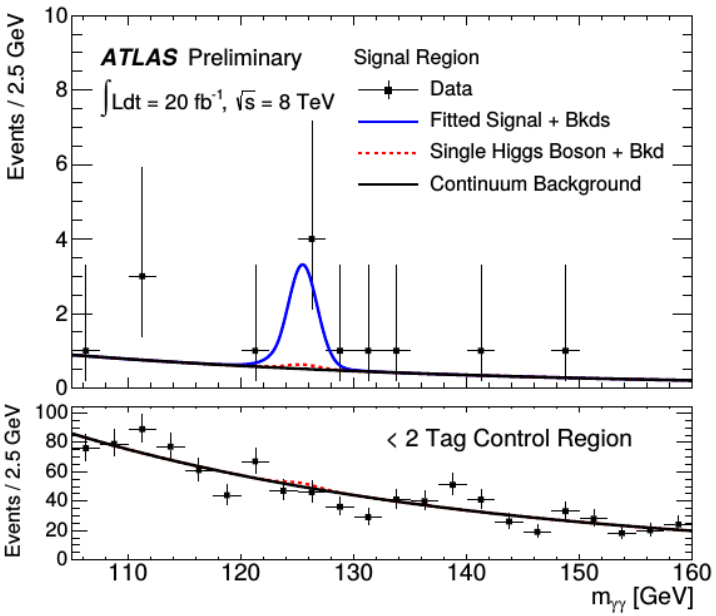




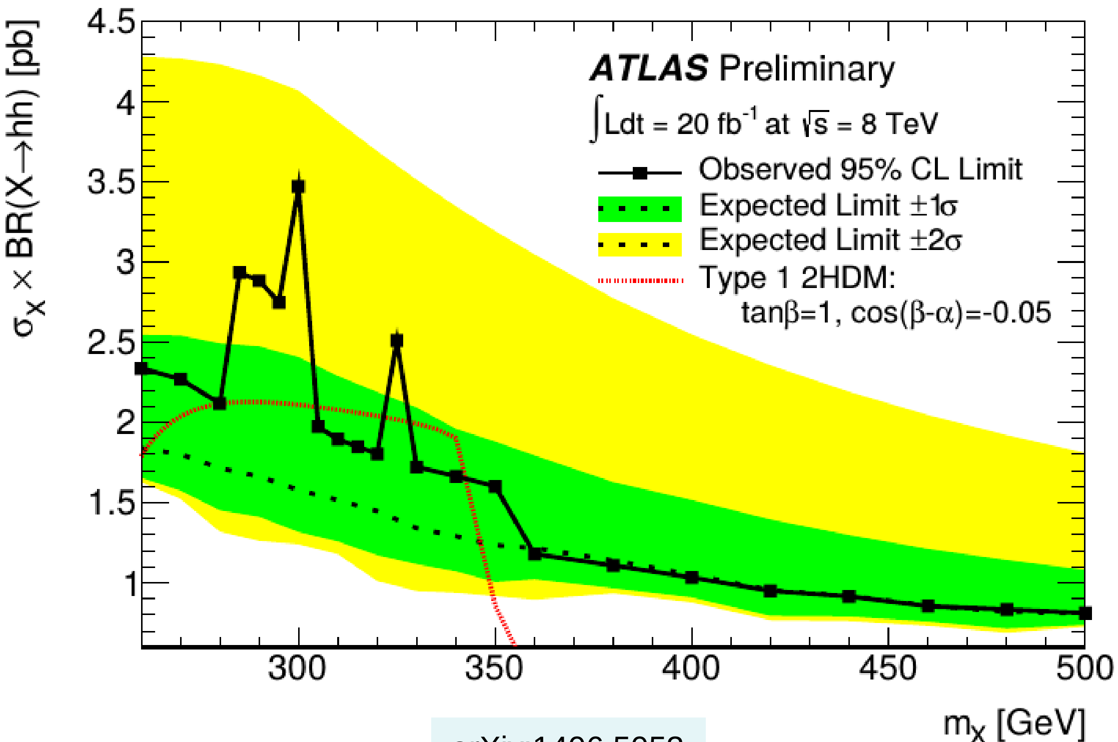
Cross section sensitivity below 10fb

X→HH→bbγγ





- Resonance mass range investigated: 260-500GeV
  - Look for excess in $m_{\gamma\gamma bb}$ spectrum
  - Data-driven bkg shape by relaxing b-tagging
- Looked also for non-resonant enhancement
  - Look for excess in $120<m_{\gamma\gamma}<130$GeV window
  - σ(non-res)<2.2(/1.0)pb obs.(/exp.) @95%CL



arXiv:1406.5053

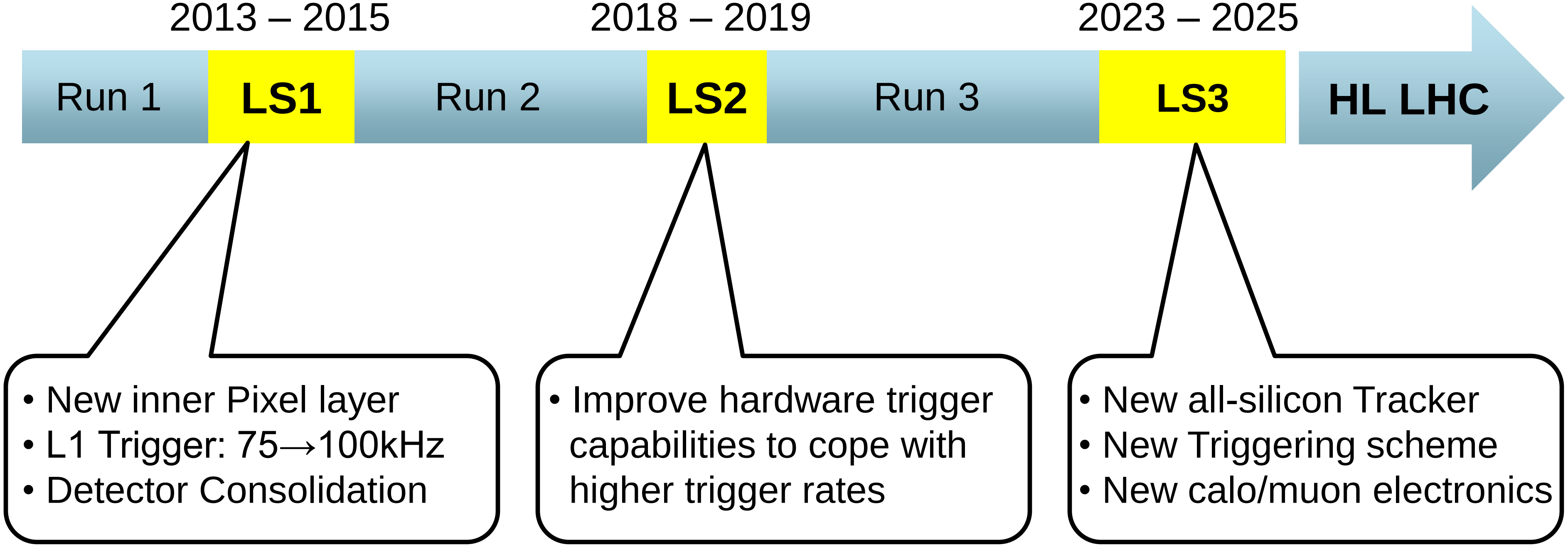
The future:
ATLAS upgrades for Run 2, 3, 4…

LHC Roadmap

Run 1	LS1	Run 2	LS2	Run 3	LS3	HL LHC
	2013 – 2015		2018 – 2019		2023 – 2025	
$\sqrt{s}$ = 7-8TeV		$\sqrt{s}$ = 13-14TeV		$\sqrt{s}$ = 14TeV		$\sqrt{s}$ = 14TeV
~$0.5 \times 10^{34} cm^{2} s^{-1}$		~$1 \times 10^{34} cm^{2} s^{-1}$		~$2 \times 10^{34} cm^{2} s^{-1}$		~$5\text{-}7 \times 10^{34} cm^{2} s^{-1}$
pile-up ~20		pile-up ~40		pile-up ~60		pile-up ~140-200
~$25 fb^{-1}$		~$100 fb^{-1}$		~$300 fb^{-1}$		~$3000 fb^{-1}$

- Increasing instantaneous luminosity make detector upgrades or replacements necessary
  - Improve trigger capabilities
  - Cope with higher occupancies (readout bandwidth)
  - Deal with radiation damage

ATLAS upgrades Roadmap



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  - Improve trigger capabilities
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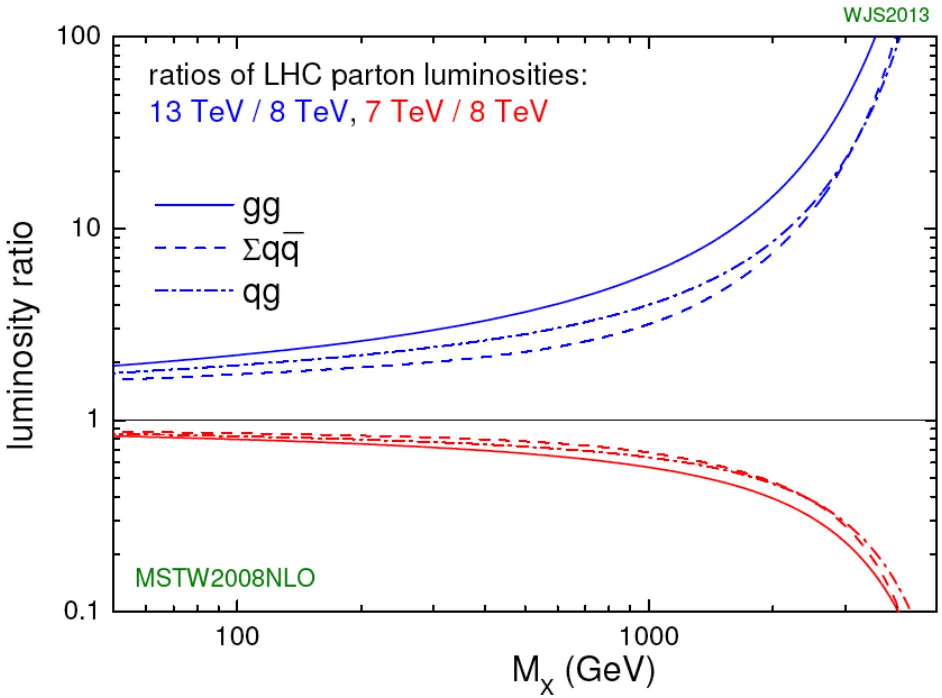
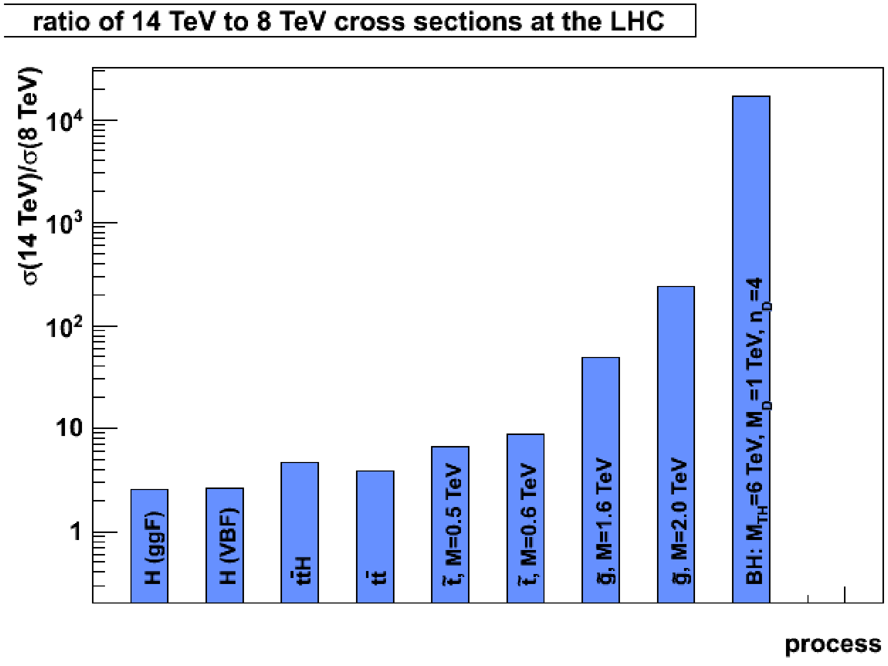
Run 2 prospects

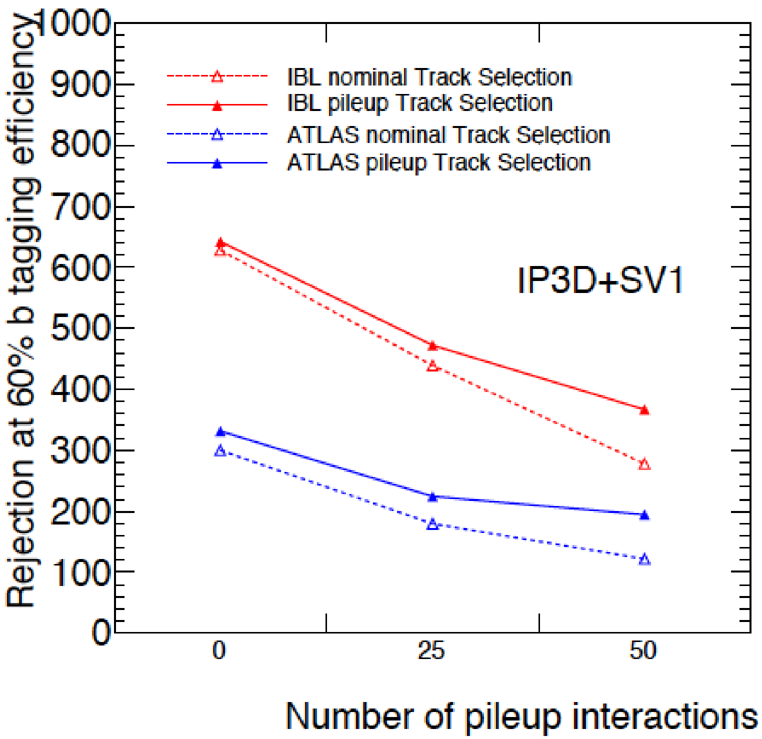


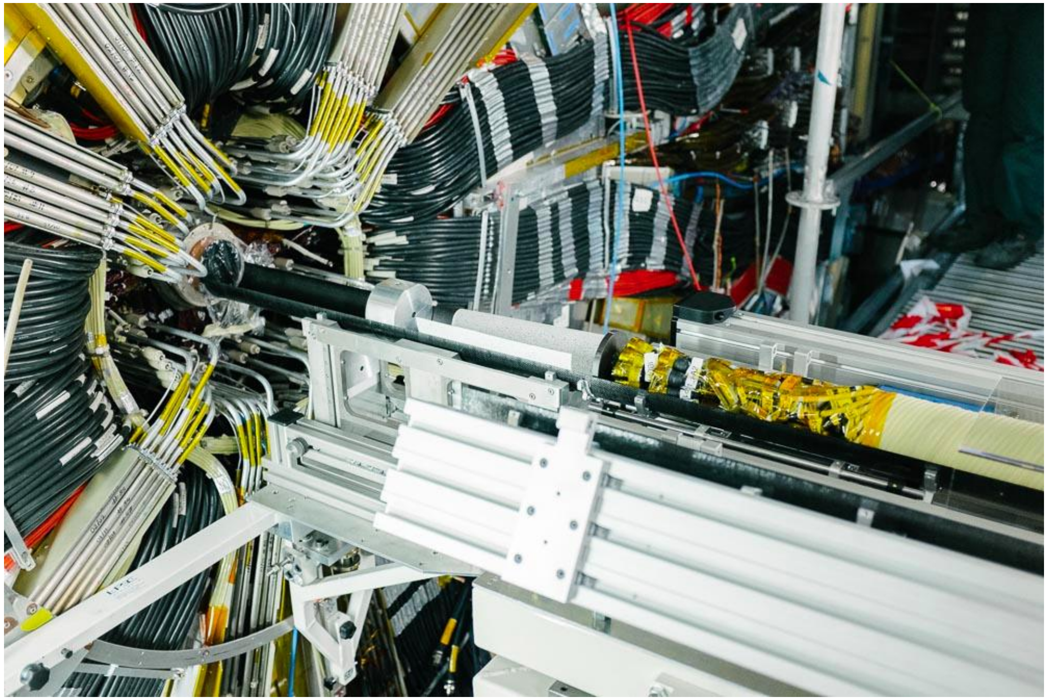


- Jump from 8TeV to 13TeV gives a huge boost in discovery potential at the multi-TeV energy range
  - Cross section increase by ~5 for M_X=1TeV, ~10 for M_X=2TeV
- Run 1 sensitivity for new physics will be surpassed in some cases after a few fb^{-1}!
  - Also, big improvements in the Higgs sector (e.g. H→bb, ttH, couplings, width)

Inner Pixel Layer for Run 2

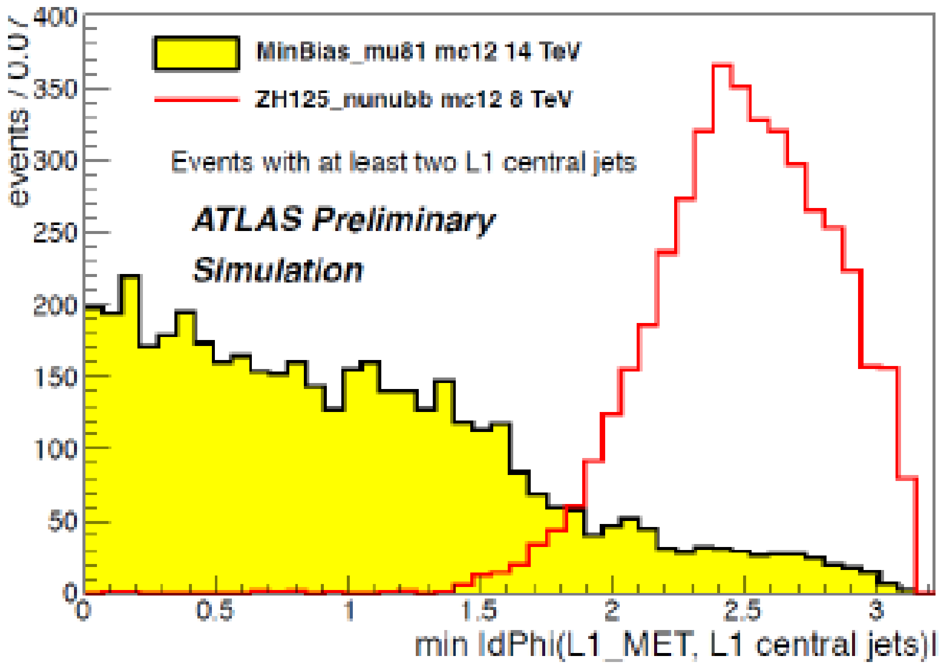
- New pixel barrel layer at radius ~3.5cm, already successfully installed
- Uses new front-end chip (FE-I4), 2 cm x 2 cm (130 nm CMOS process), which would be the basis for HL-LHC chip design
- b-tagging: x 2 better light-jet rejection



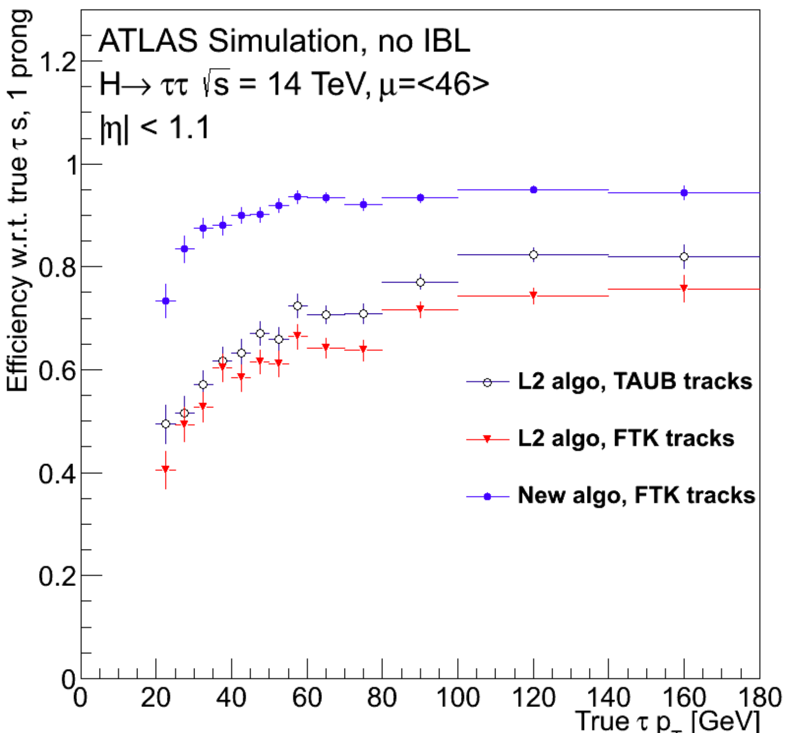


Upgrades for Runs 2-3

- L1Topo: topological info at L1
  - E.g. invariant masses or angular separation between L1 objects
  - Ready to be installed for the start of Run 2

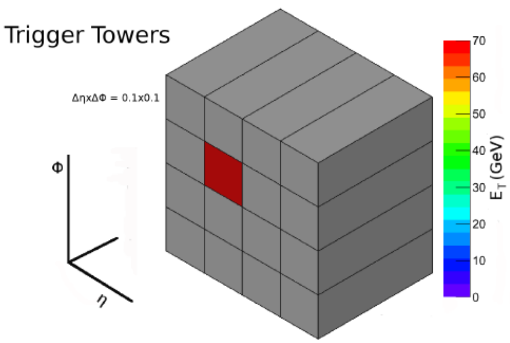


- FTK: a custom-hardware track reconstruction system
  - Full tracking with near-offline resolution, for all L1-accepted events, for use at the start of HLT
  - To be installed and commissioned during Run-2 (2015-16)



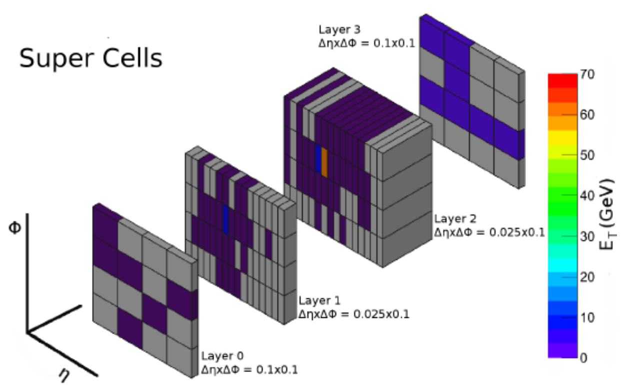
Upgrades for Run 3

- EM calorimeter readout
  - finer granularity for L1Calo
    - shower shapes & E resolution
  - keep Run 1 trigger thresholds for e, γ, τ, missing E_T…

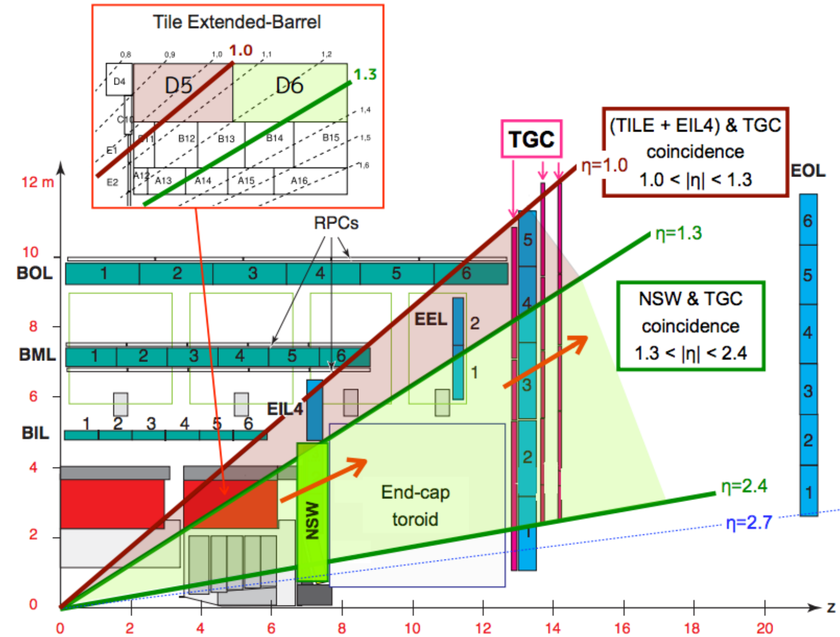


Run 1 Trigger Towers

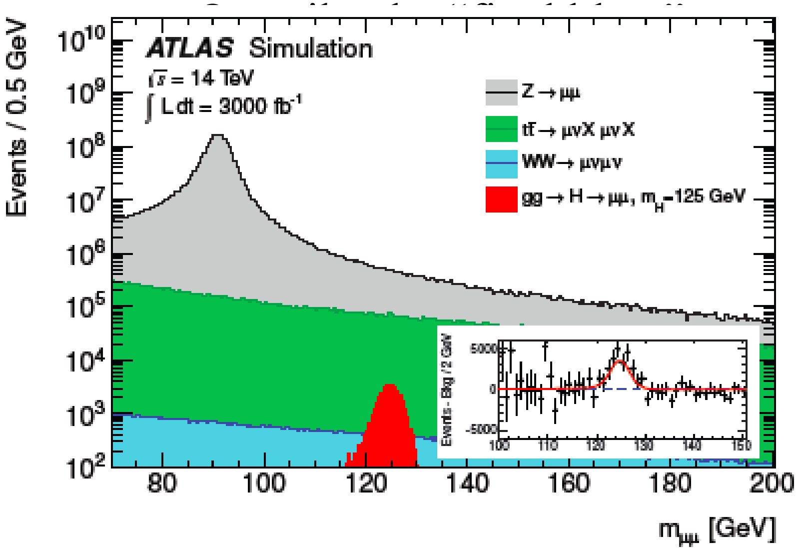
Run 3 Super Cells

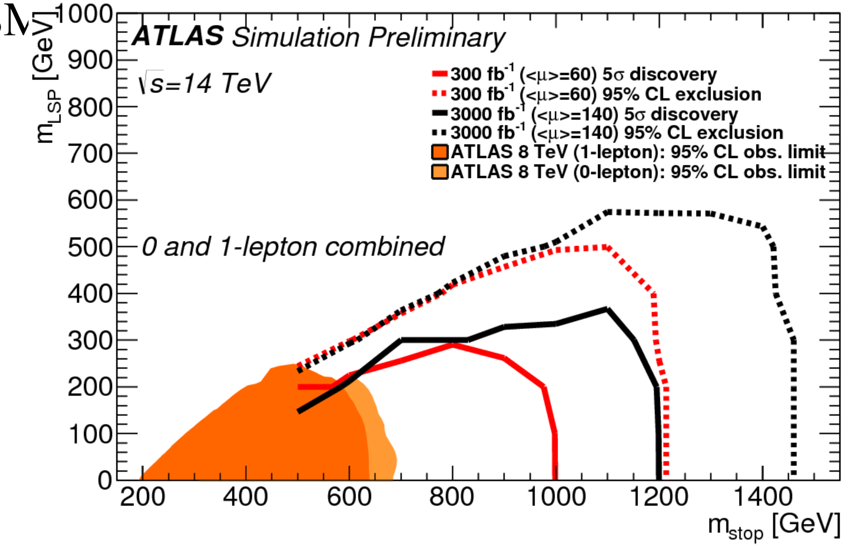


- New Muon Small Wheels
  - Micromegas and sTGCs
    - Improved tracking resolution
    - Much reduced L1 muon rates
- Add Tile-Cal info for L1 muon trigger in $1.0<|\eta|<1.3$



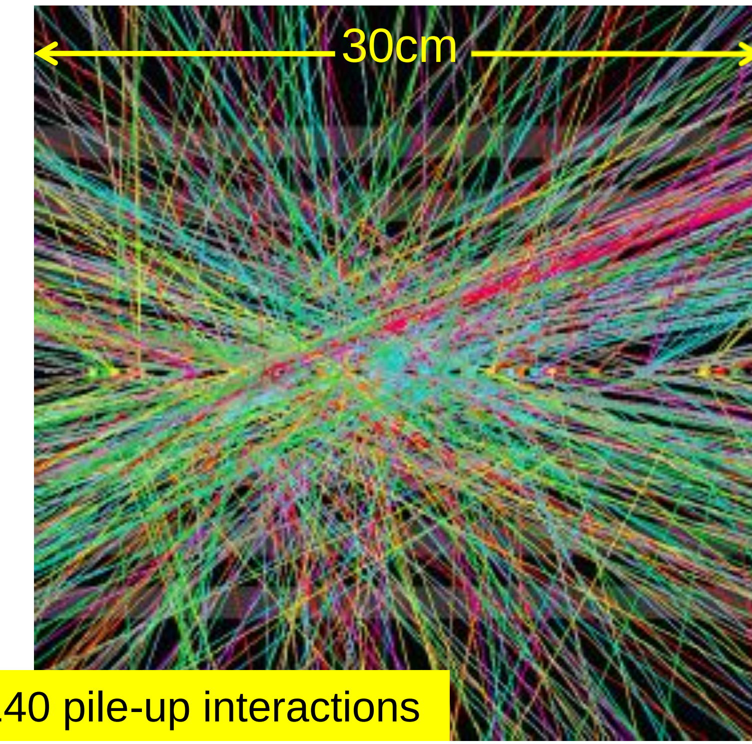
- From 300fb^{-1} to 3000fb^{-1} you get:
  - A much more extended & thorough exploration of the (multi-)TeV region
    - Much higher energy than any other collider could achieve in these timescales!
  - High-precision Higgs physics
    - Higgs couplings down to a few %; Higgs self-coupling
    - Observation of Higgs coupling to 2nd generation fermions (H→μμ)
    - More rare decays (e.g. H→Zγ) and details on the Higgs properties (e.g. ttH(μμ))
  - The chance to study thoroughly discoveries made in Run 2 or 3
    - any BSM





HL-LHC challenges

- Maintain (if possible, improve) today’s performance at 5-10 times higher pile-up and instantaneous luminosity
- Survive 10 years of extreme irradiation!



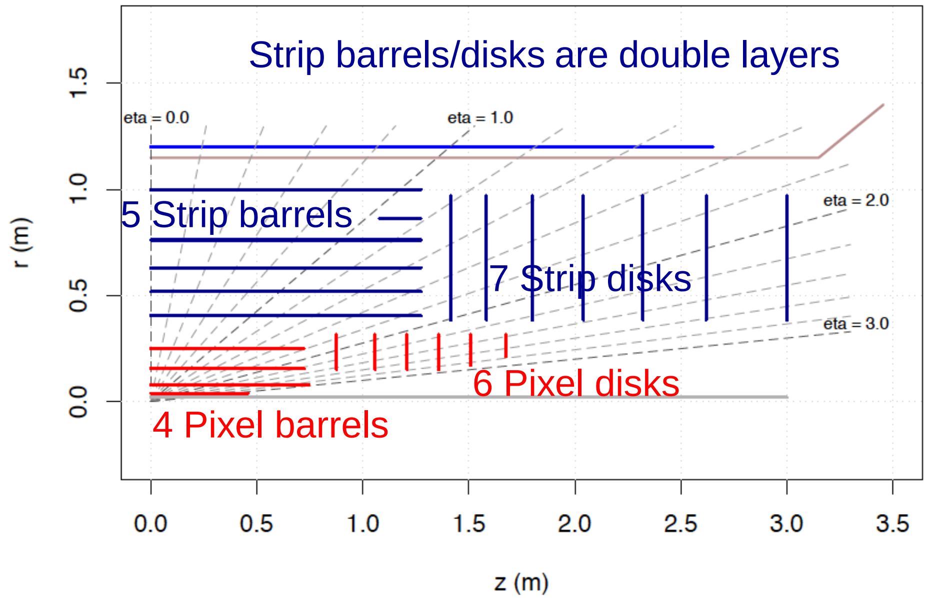
Top event in ATLAS with 140 pile-up interactions

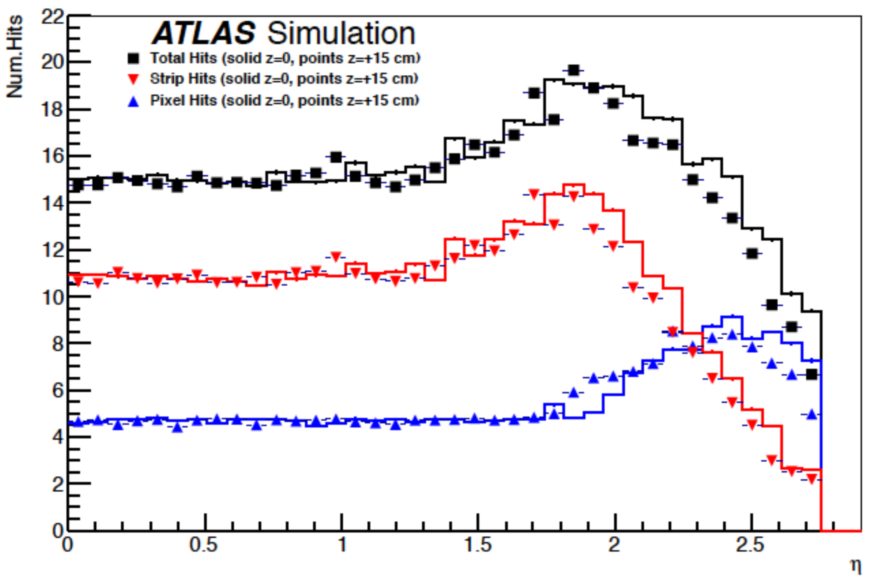
Many systems need upgrading, but most importantly the Tracker and Trigger

ATLAS Upgrades for HL-LHC: Tracker

- New, all-Si tracker
  - Radiation tolerant up to >3000fb^{-1}
  - Finer granularity (occupancy <1%)
  - Less material
  - Higher bandwidth
  - ~30% better curvature resolution and z_0 resolution for high p_T tracks than current tracker

	Silicon Area	Channels [10^6]
Pixel	8.2m^2	638
Strip	193m^2	74





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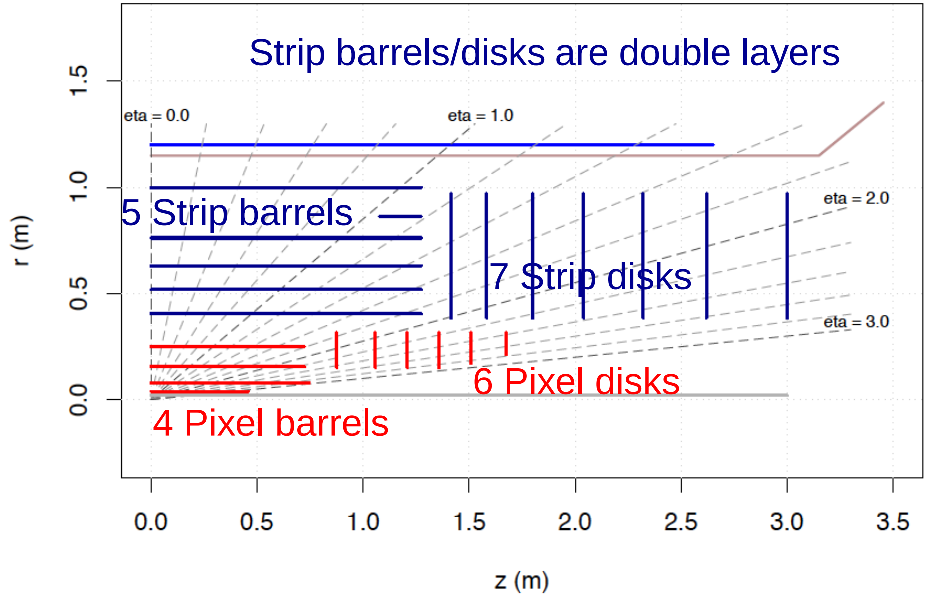

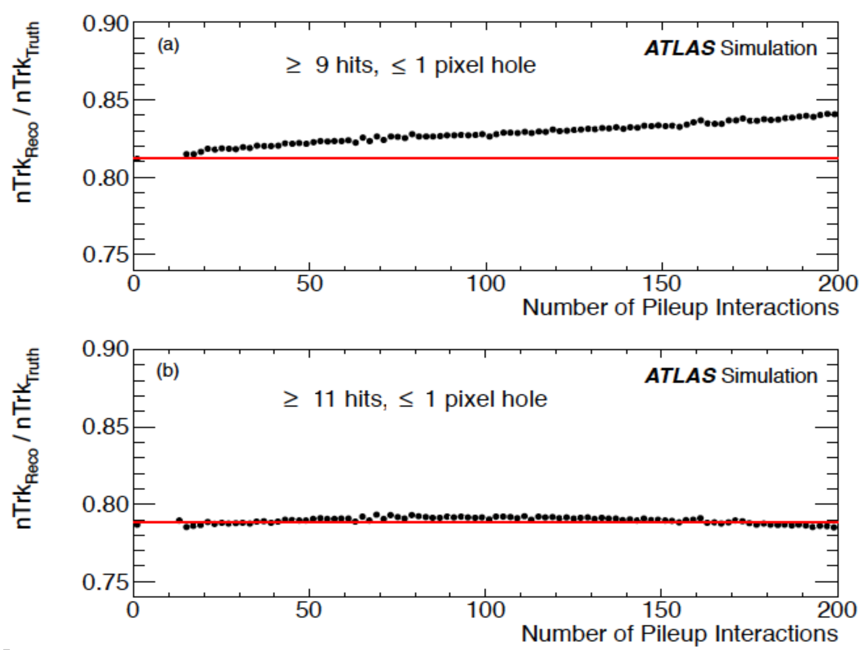

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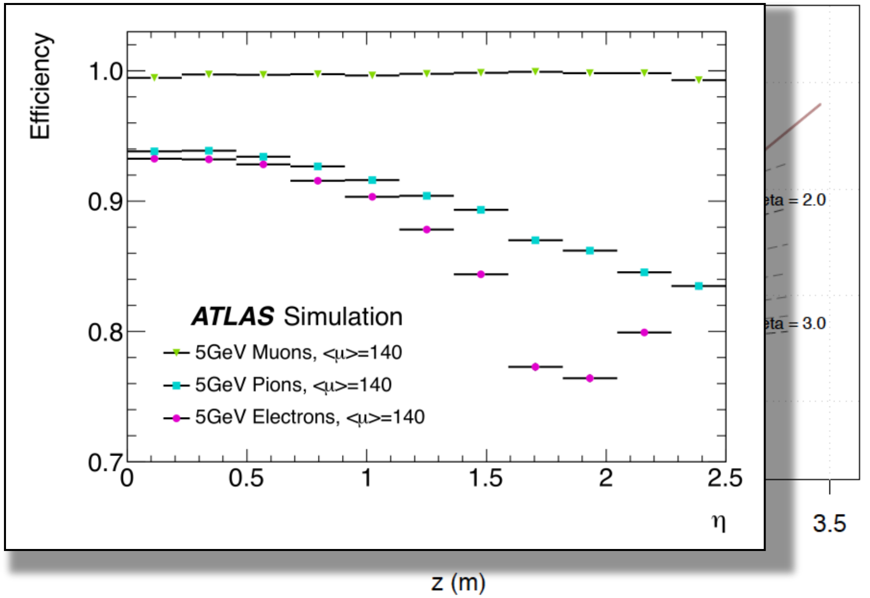

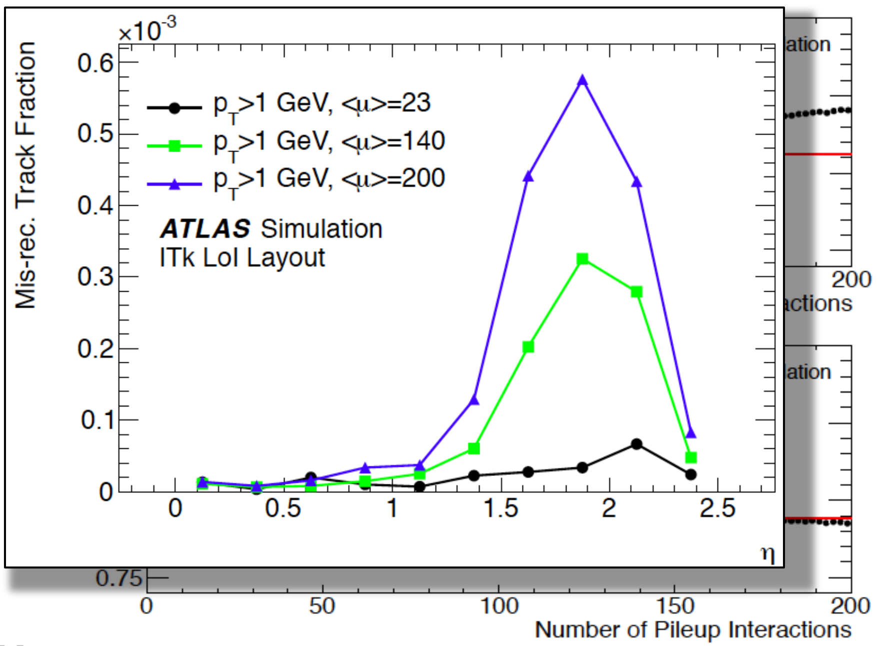

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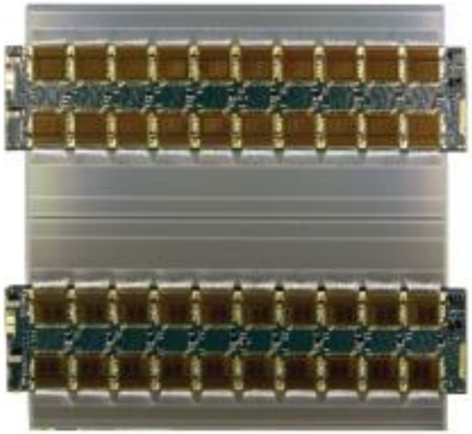
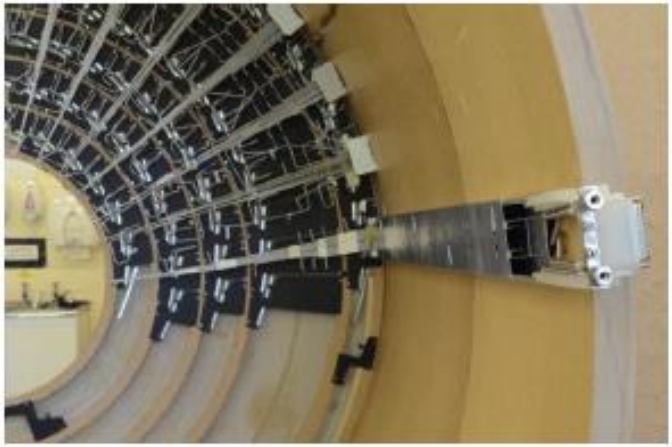
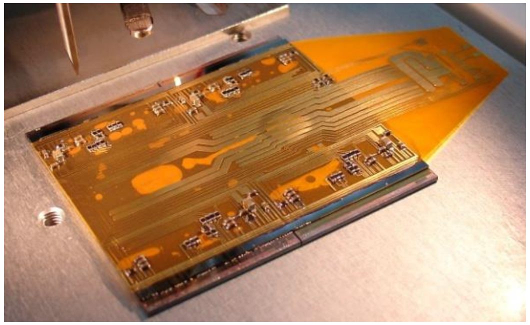
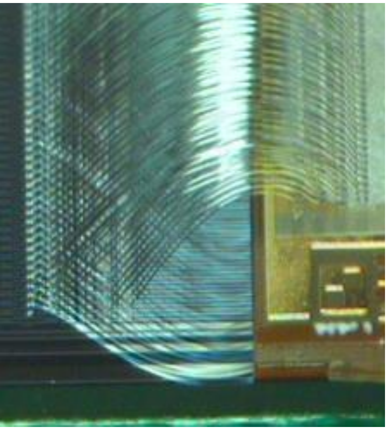
ATLAS Tracker Upgrade R&D

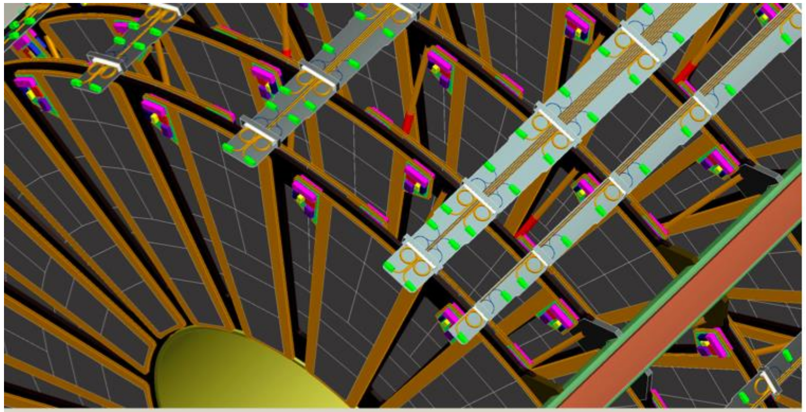


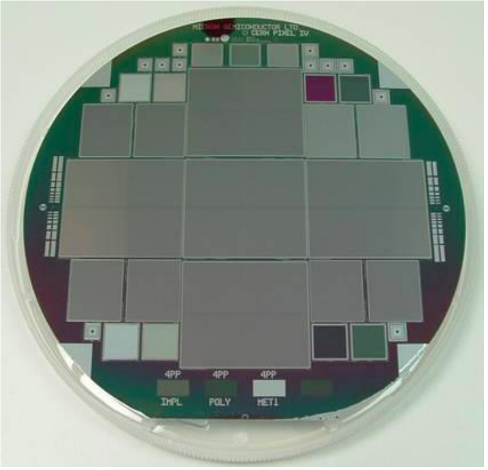


Huge amounts of work!
Good progress!
No show-stoppers!



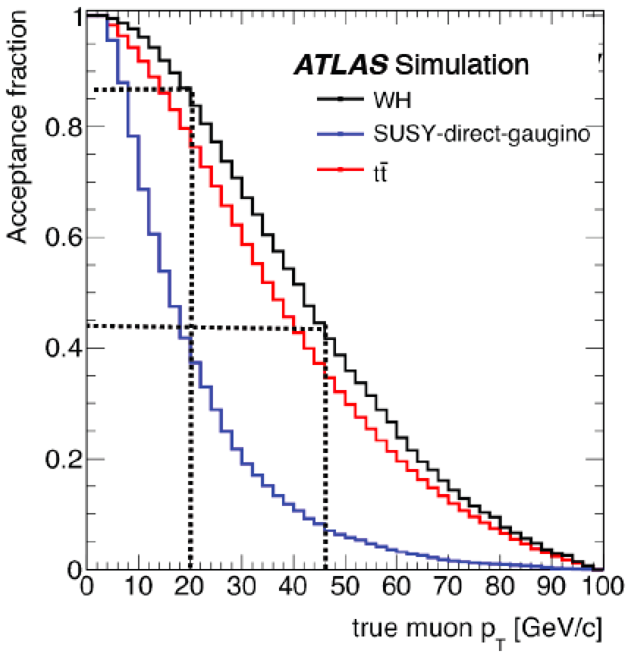






ATLAS Upgrades for HL-LHC: L1 Trigger

- To get the best physics out of HL-LHC we must maintain our current ability to trigger on electroweak scale objects
  - More true than ever since the discovery of the Higgs at ~125GeV!



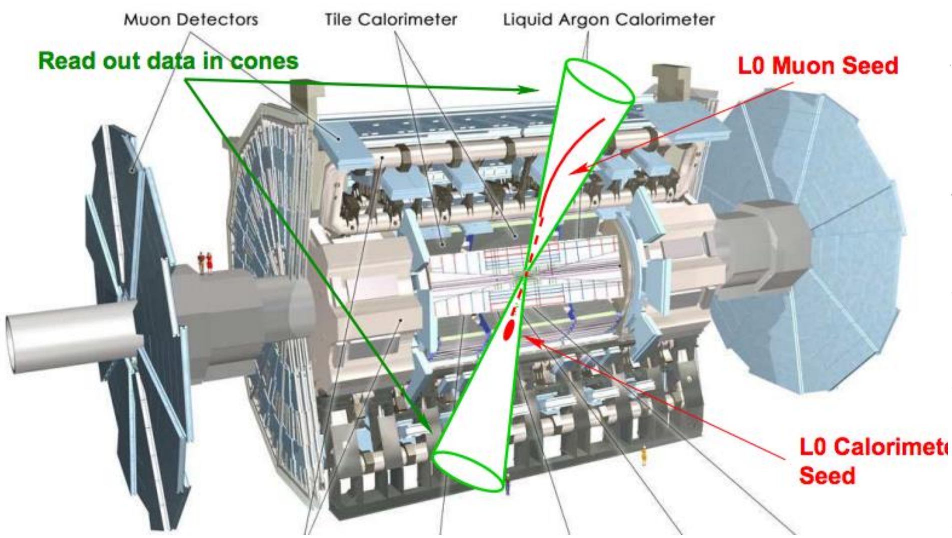
- L1 rates shoot up at high lumi and pile-up
  - Bear-impossible to keep L1 trigger thresholds at similar levels to those in Run 1 with L1Calo and L1Muon info only
  - Especially for single-lepton triggers

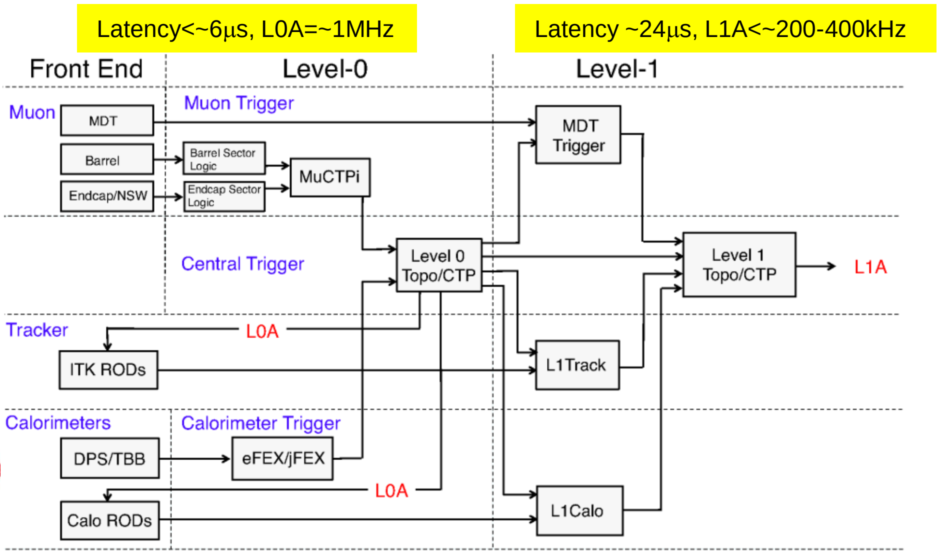
- Big idea for HL-LHC: use tracking at L1

ATLAS L1 strategy for HL-LHC: “L0/L1”

- Practically impossible to readout entire tracker at 40MHz!

- ATLAS strategy: a two-step hardware trigger
  - L0: the Run-3 L1Calo and L1Muon becomes L0 Trigger at HL-LHC
    - They bring the rate down from 40MHz to ~1MHz and identify Regions of Interest (RoIs) to seed Regional tracker readout and pattern recognition (L1Track)
  - L1: combines L1Track info with more refined Calo/Muon info
    - L1-Accept rate for full detector readout at 200-400kHz





Summary and Outlook

- Run 1 was an amazing success for the LHC and for ATLAS!
- Run 1 was triumph for the Standard Model!
- Run 1 gave us one of the biggest discoveries in fundamental science for decades!

Summary and Outlook

- Run 1 was an amazing success for the LHC and for ATLAS!
- Run 1 was triumph for the Standard Model!
- Run 1 gave us one of the biggest discoveries in fundamental science for decades!

- But…

- Run 1 only “scraped the surface” in the exploration of the TeV energy scale and left the biggest question unanswered:

Summary and Outlook

- Run 1 was an amazing success for the LHC and for ATLAS!
- Run 1 was triumph for the Standard Model!
- Run 1 gave us one of the biggest discoveries in fundamental science for decades!

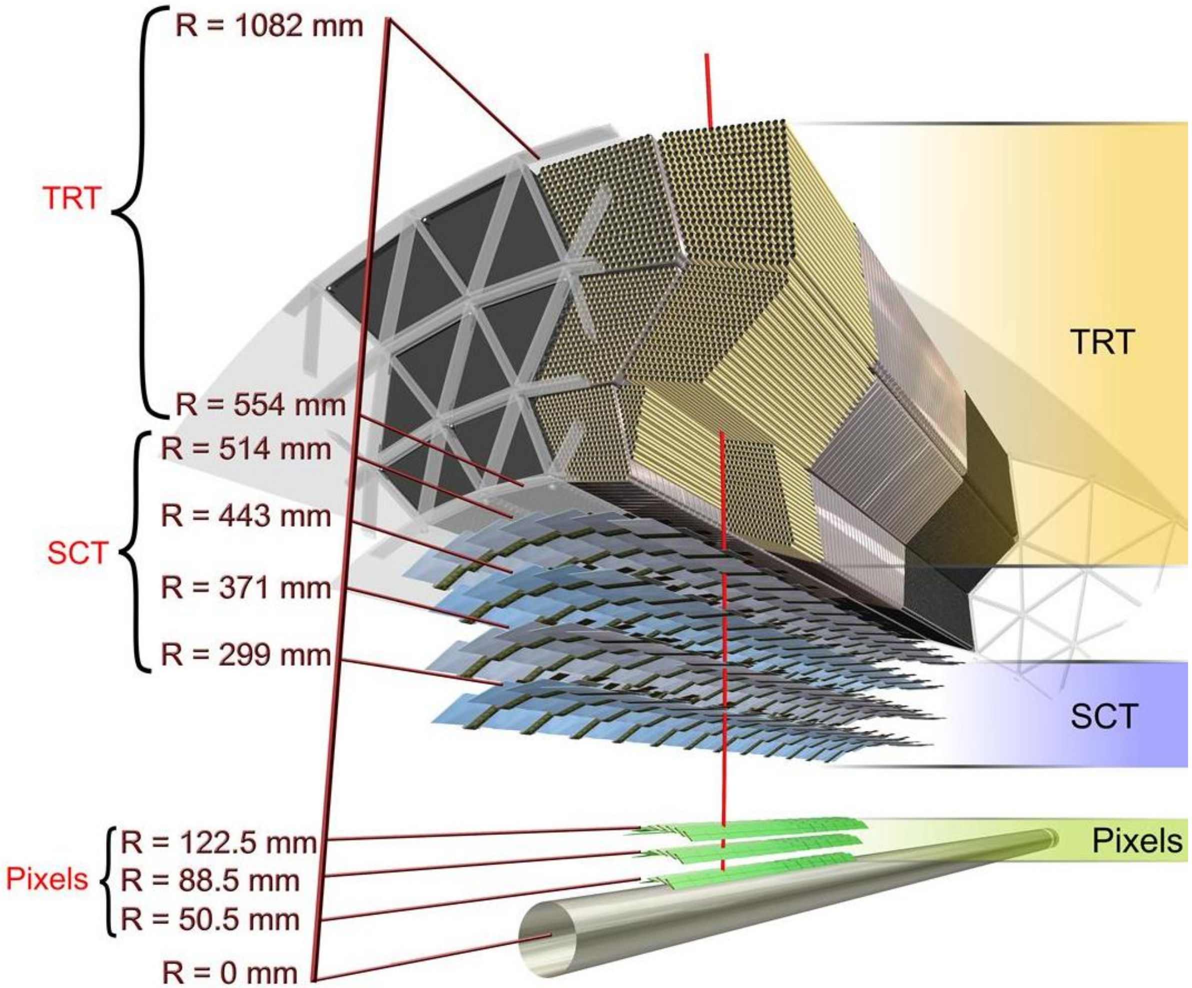
- But…

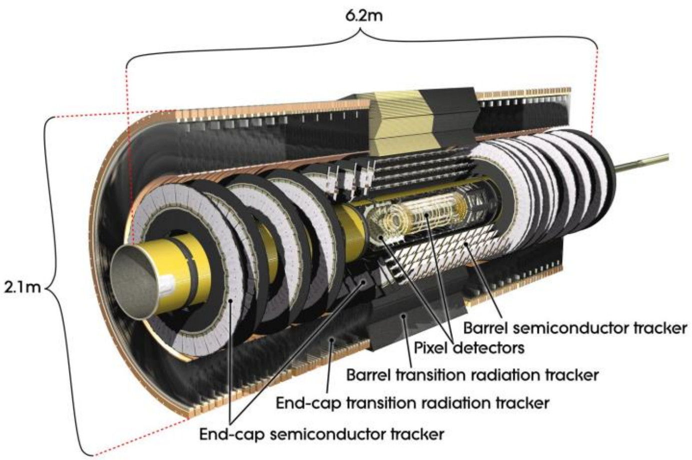
- Run 1 only "scraped the surface" in the exploration of the TeV energy scale and left the biggest question unanswered:

What lies beyond the Standard Model?

Lets hope that the LHC 14TeV running will shed light to this question!

Tracking system





Barrel track passes:

- 3 Pixel layers (50μm x 300μm)
- 4x2 strip layers (80μm x 6cm)
- 36 TRT straws (4mm x 1m)

Typical tracking resolutions

- d0 ~ 10μm
- z0 ~ 65μm
- p_T x s(1/p_T) ~ 0.02