Tau Physics at ATLAS: recent results and prospects

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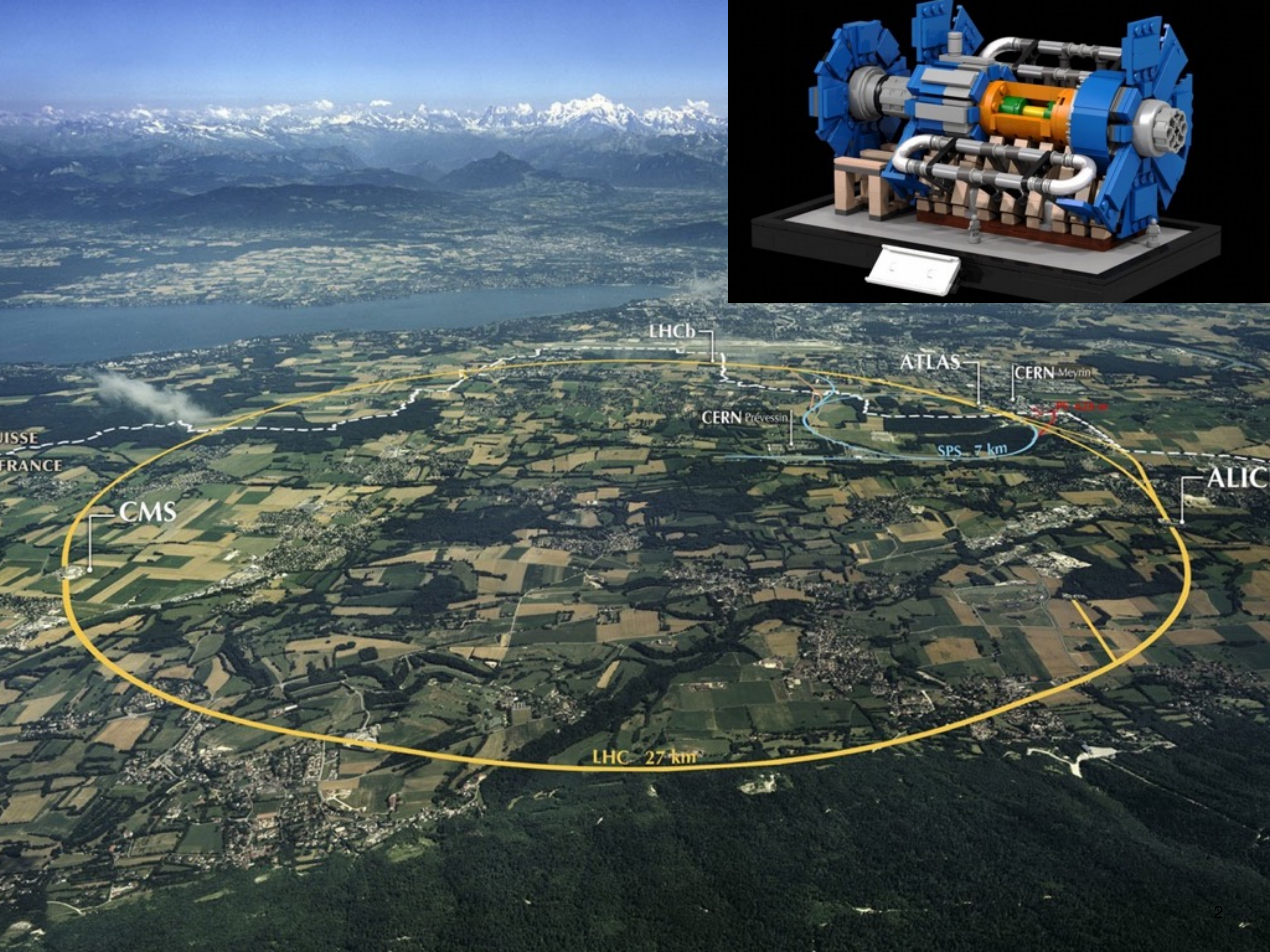
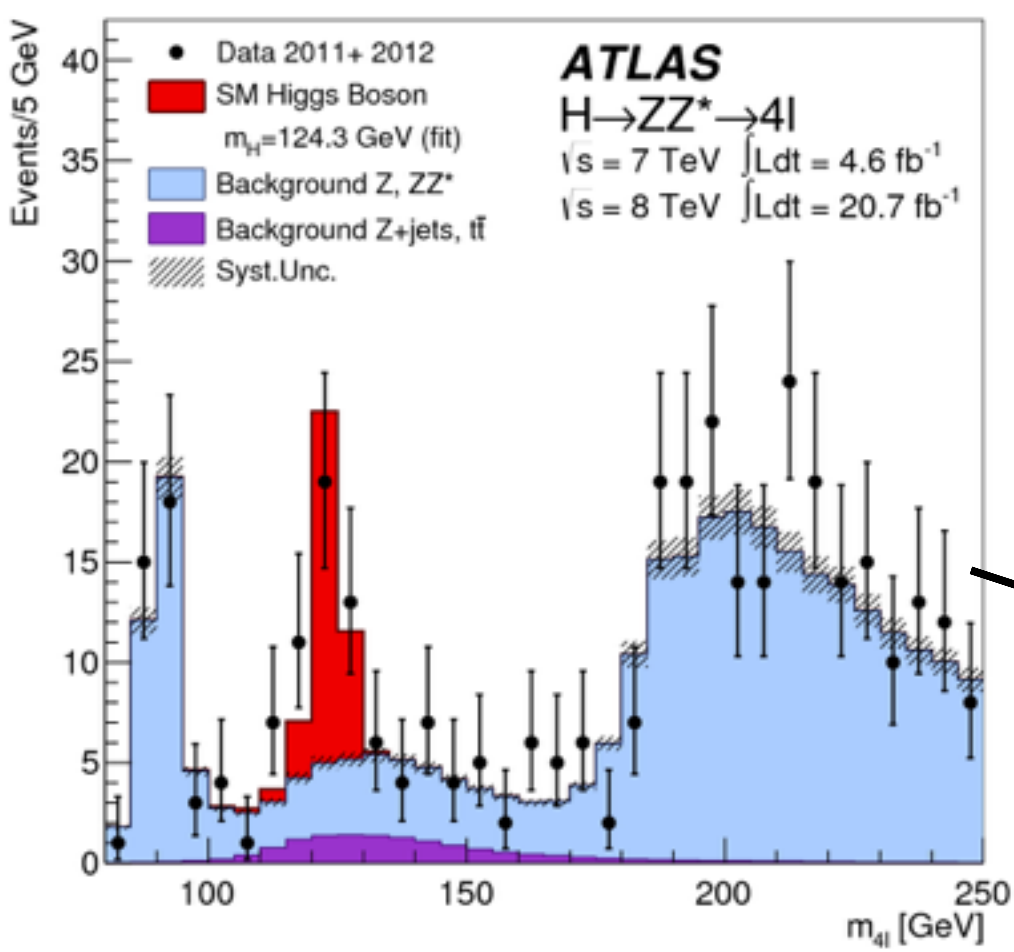
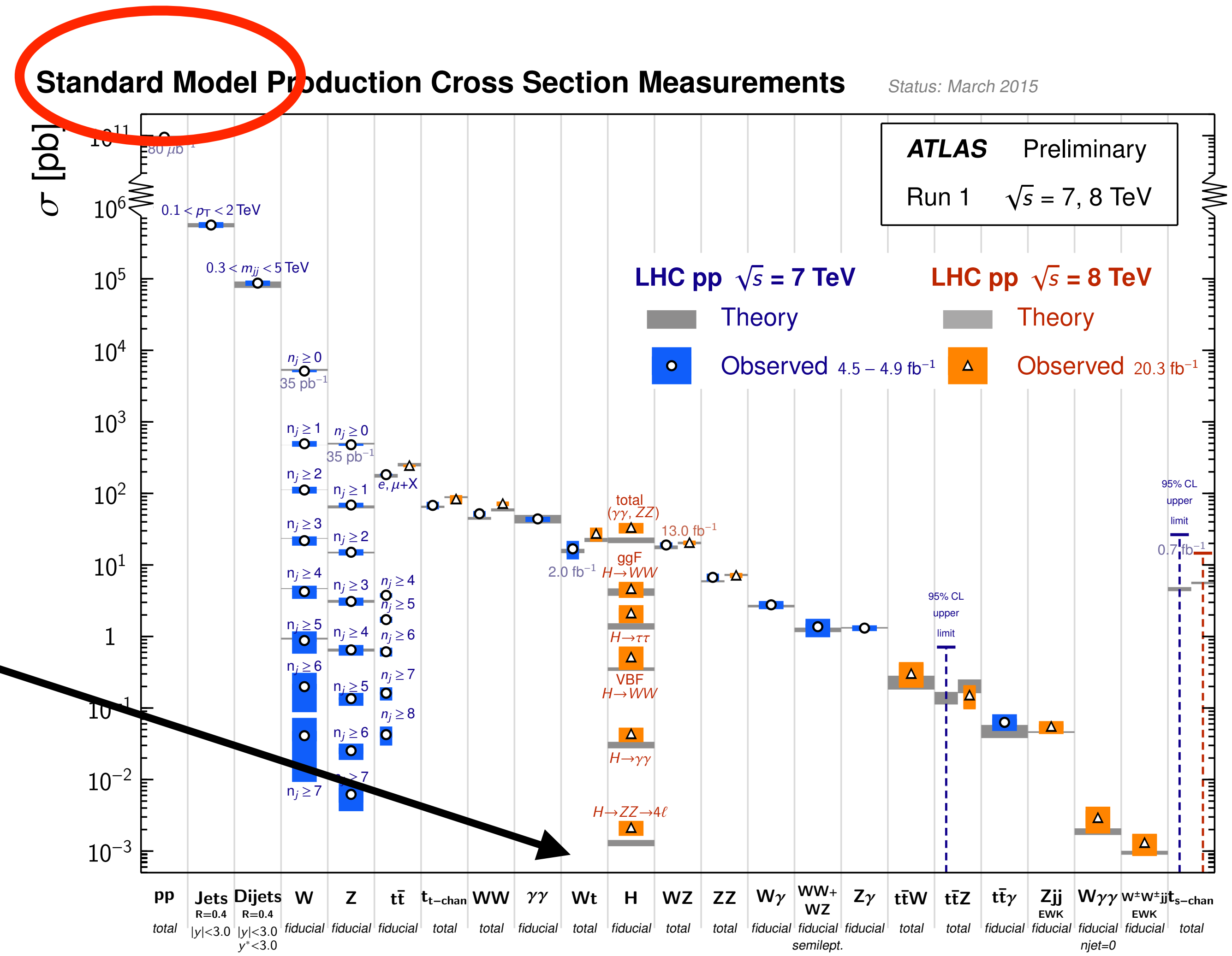
Séminaires du LAL - February 2nd, 2016


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
UISSE
FRANCE
ALIC
CMS
LHC 27 km

Run1 legacy: success of the Standard Model

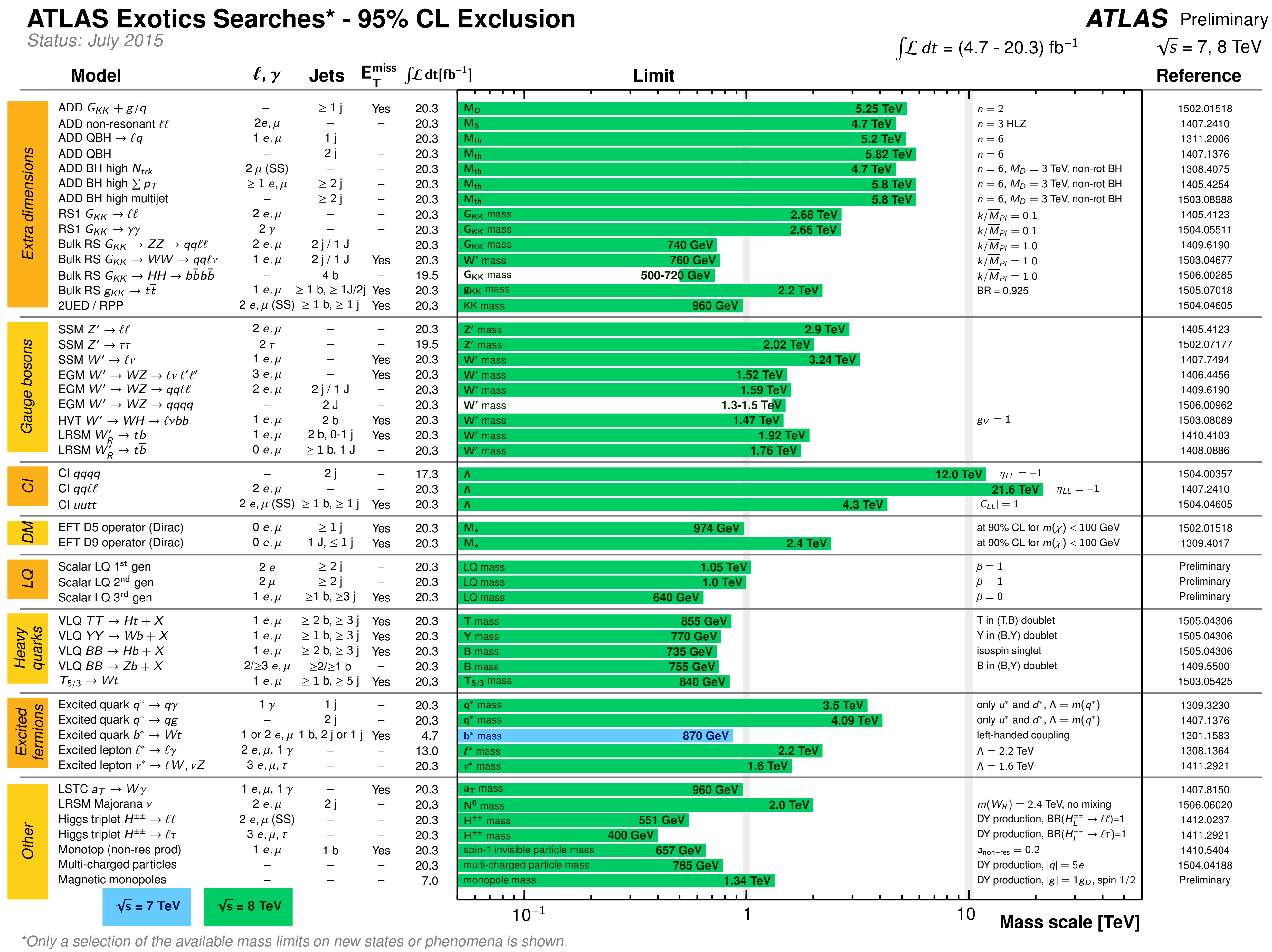




- Discovery of the Higgs boson by ATLAS and CMS, driven by the bosonic final states
- Couplings and CP measurements confirm agreement with the SM expectations

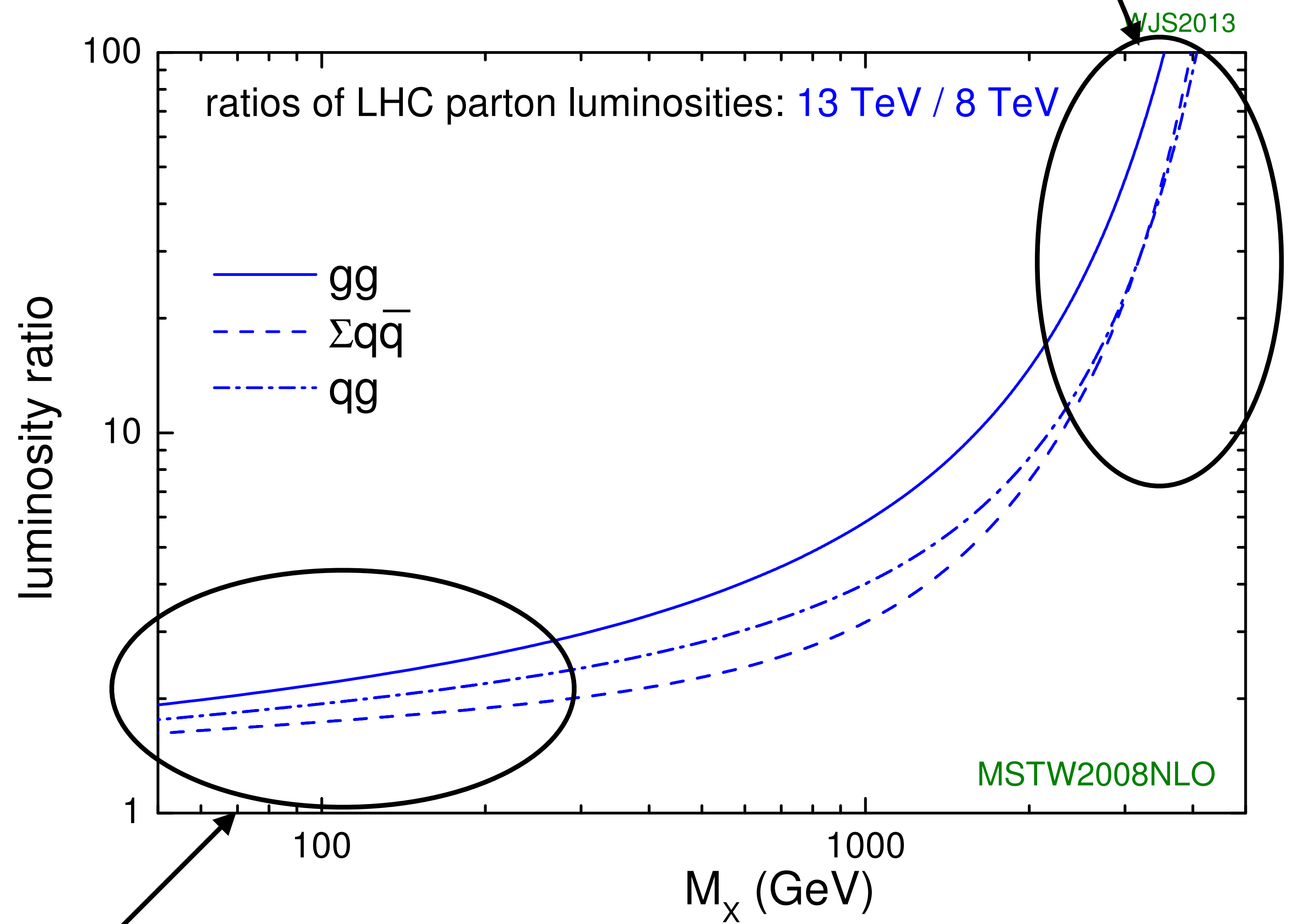
Run1 legacy: beyond the Standard Model?

No new physics, lot of constraints on models at the TeV scale



Run2: 8 TeV → 13 TeV

Very large gain for High-mass states

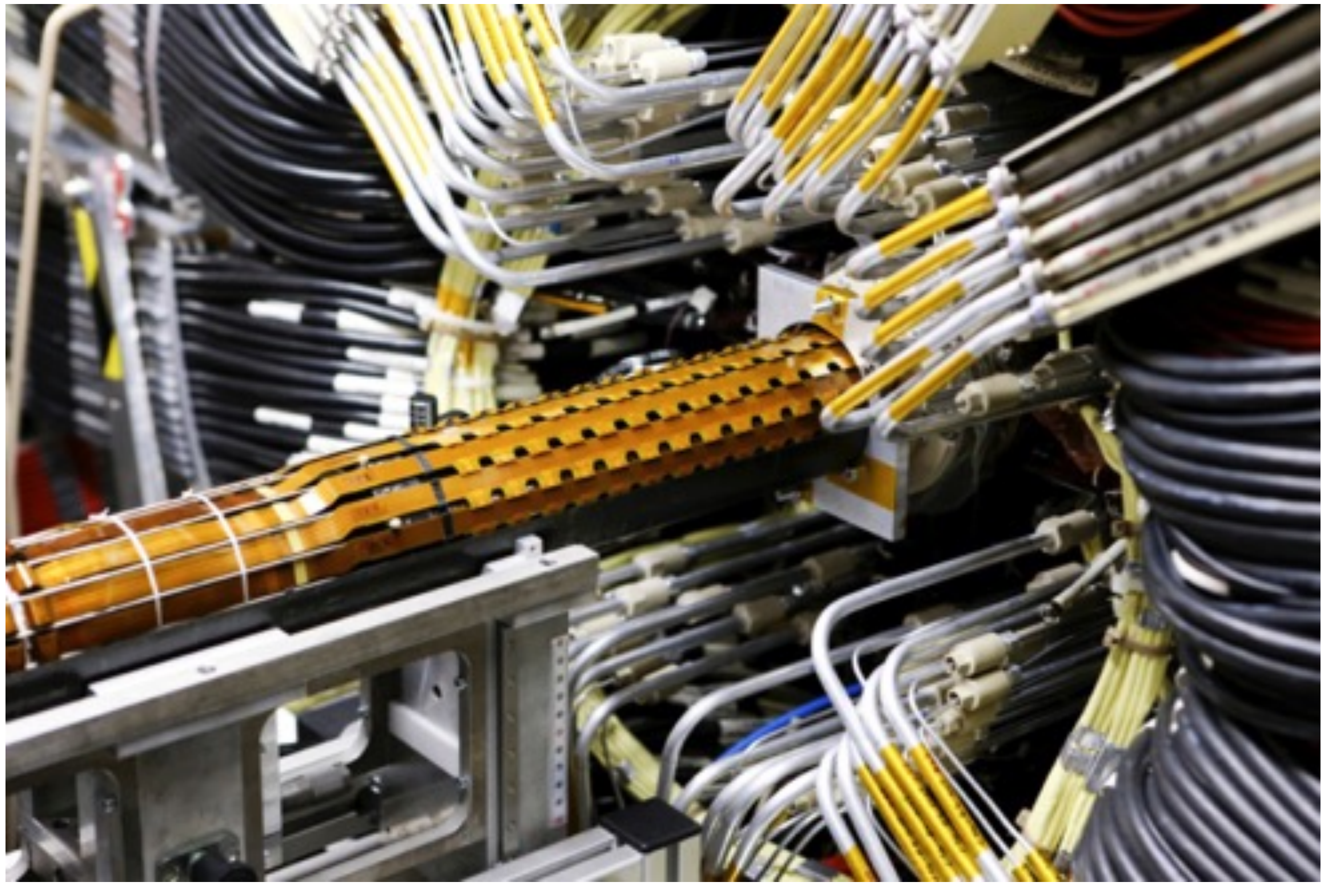


Increase of ~2 for ‘common’ processes, drives the trigger rates

Upgrading for two years

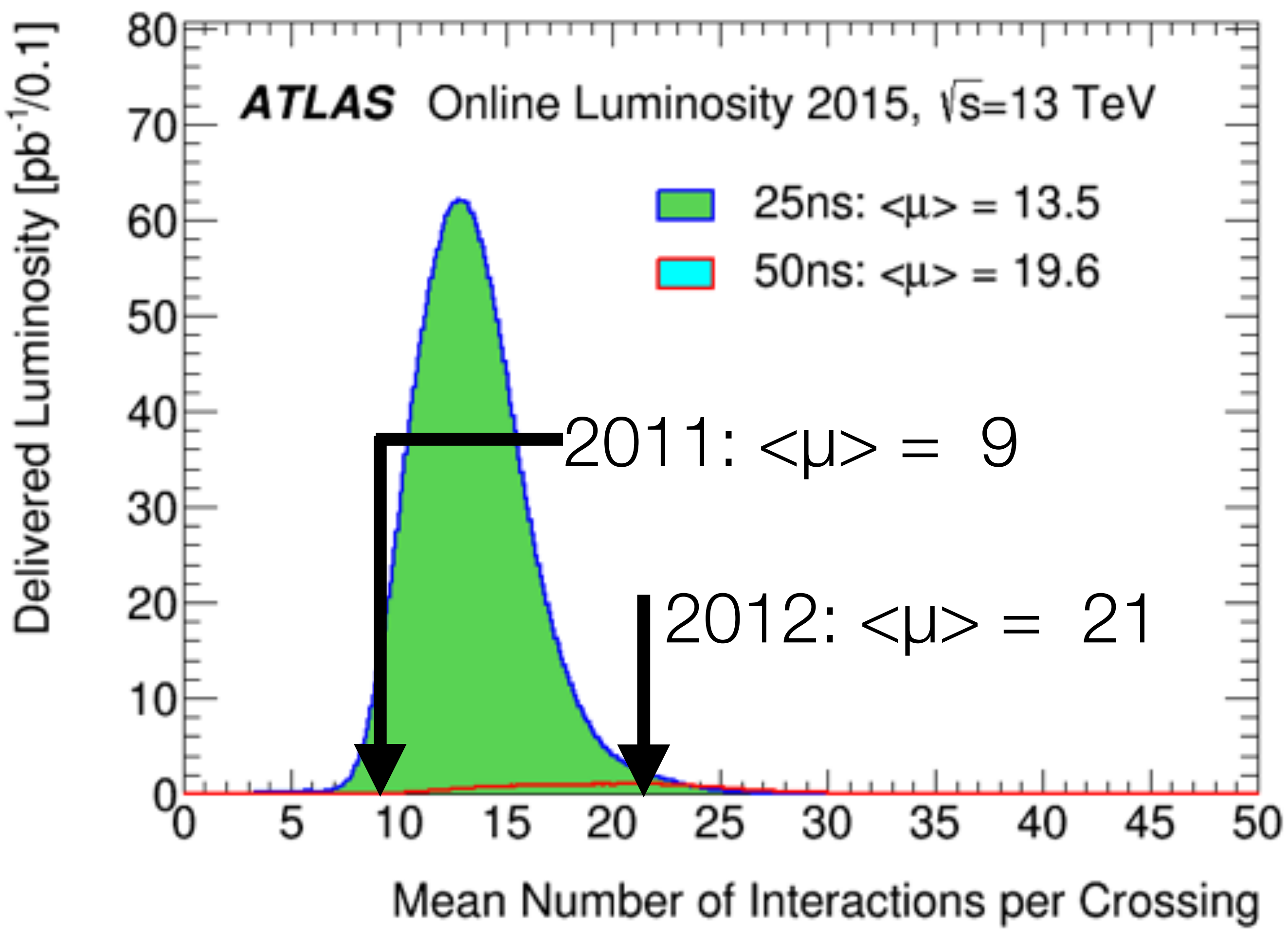
- New inner detector
  - Closest layer to the beam pipe.
- Trigger system upgrade
  - Increase L1 output rate from 75 to 100 kHz
  - New Central Trigger Processor
  - Merge L2 and HLT farms and additional ressources to increase output rate
- Various other upgrade/consolidation

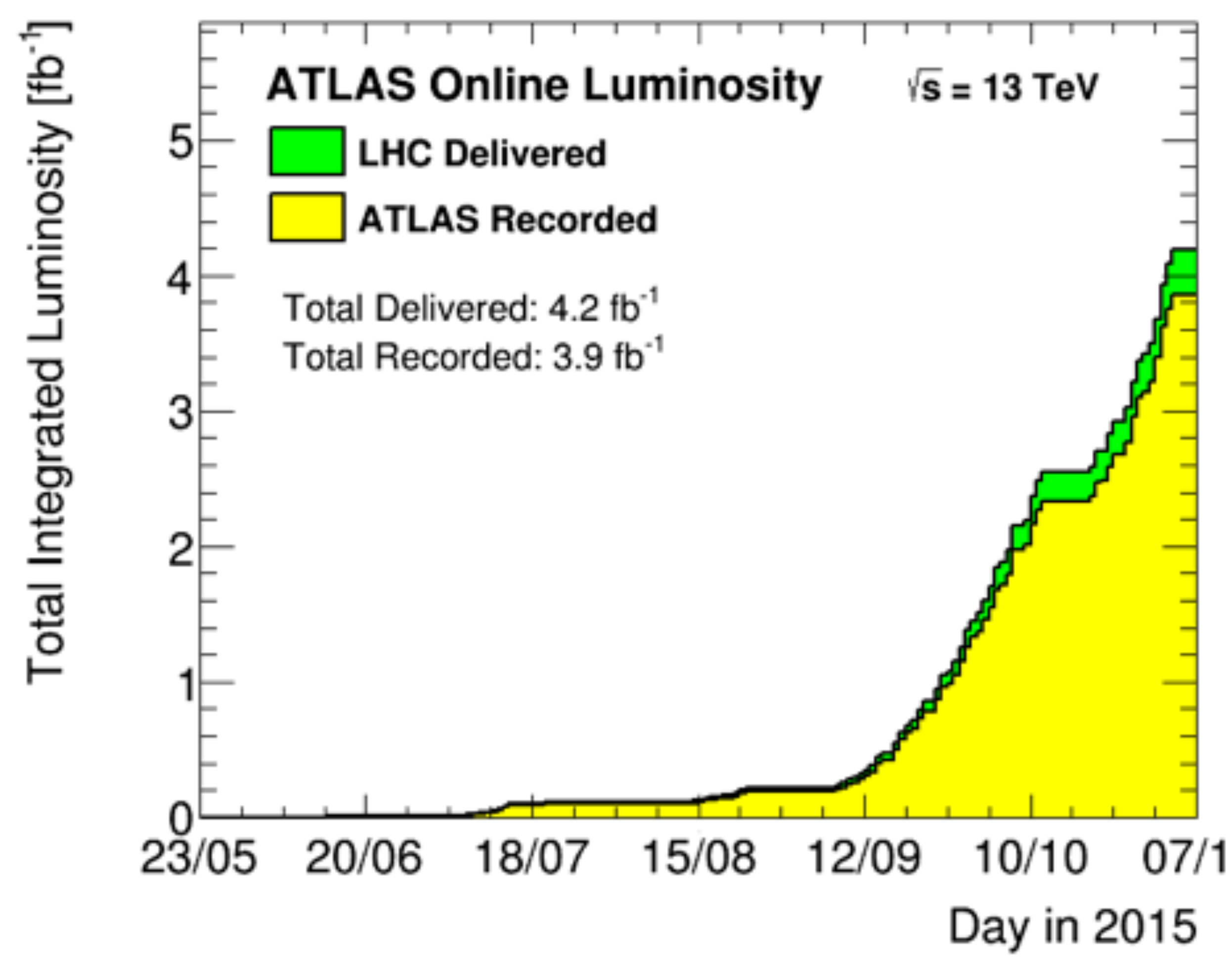
Insertable B Layer (IBL)



Back in business!

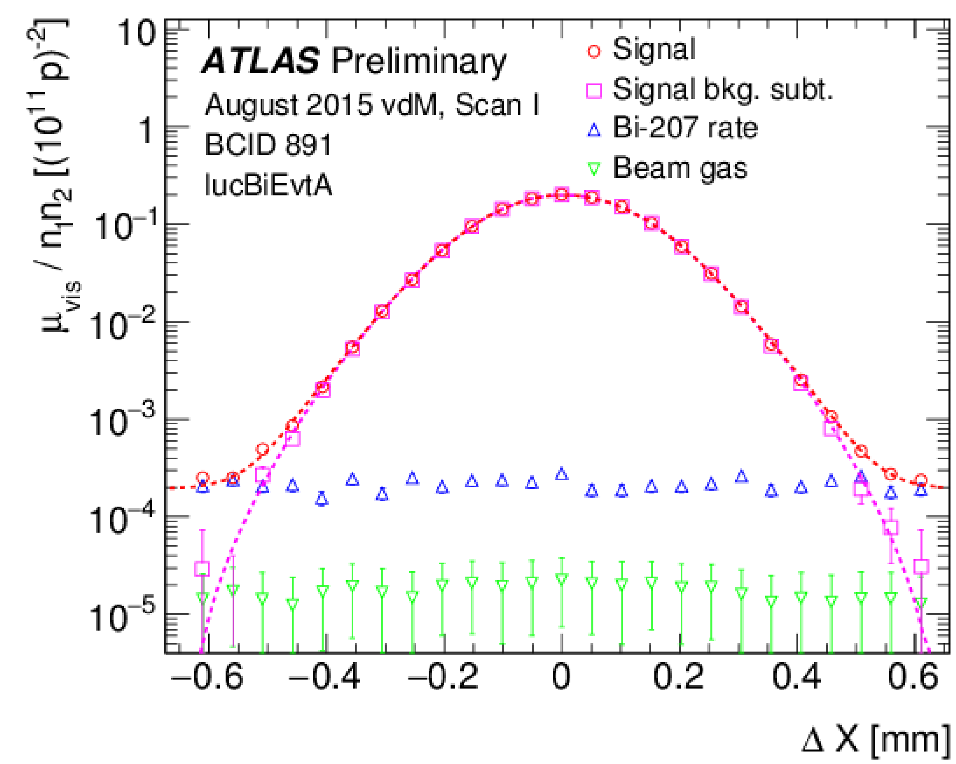
- Recorder 4.2fb^{-1} of pp collisions, peak luminosity of 5.10^{33}cm^{-2}s^{-1}
- Very smooth operations, smaller dataset than expected



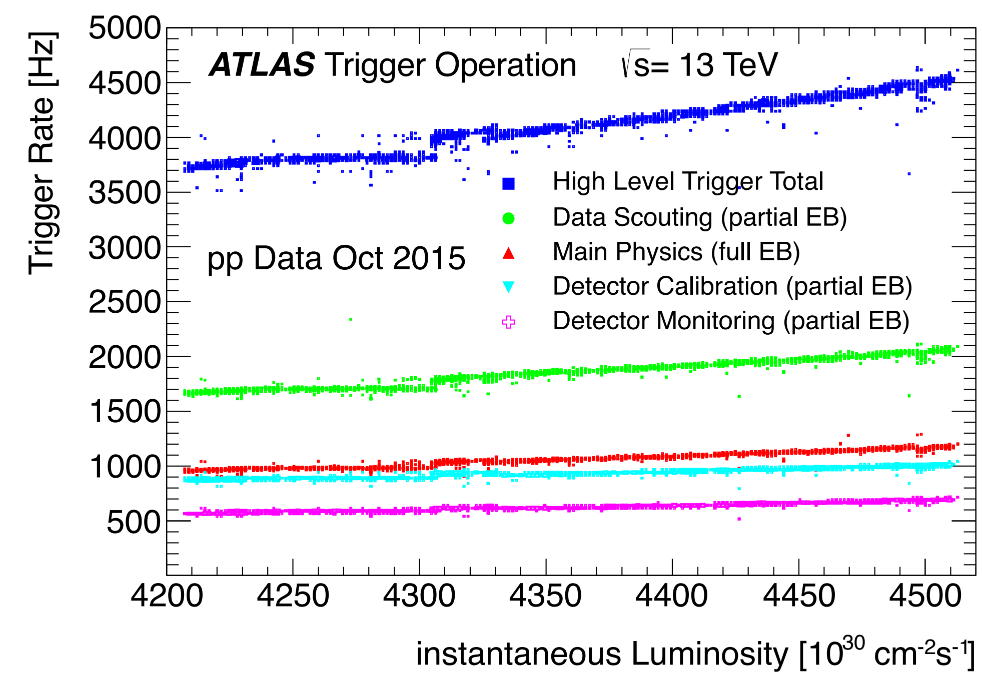


DAQ, Trigger

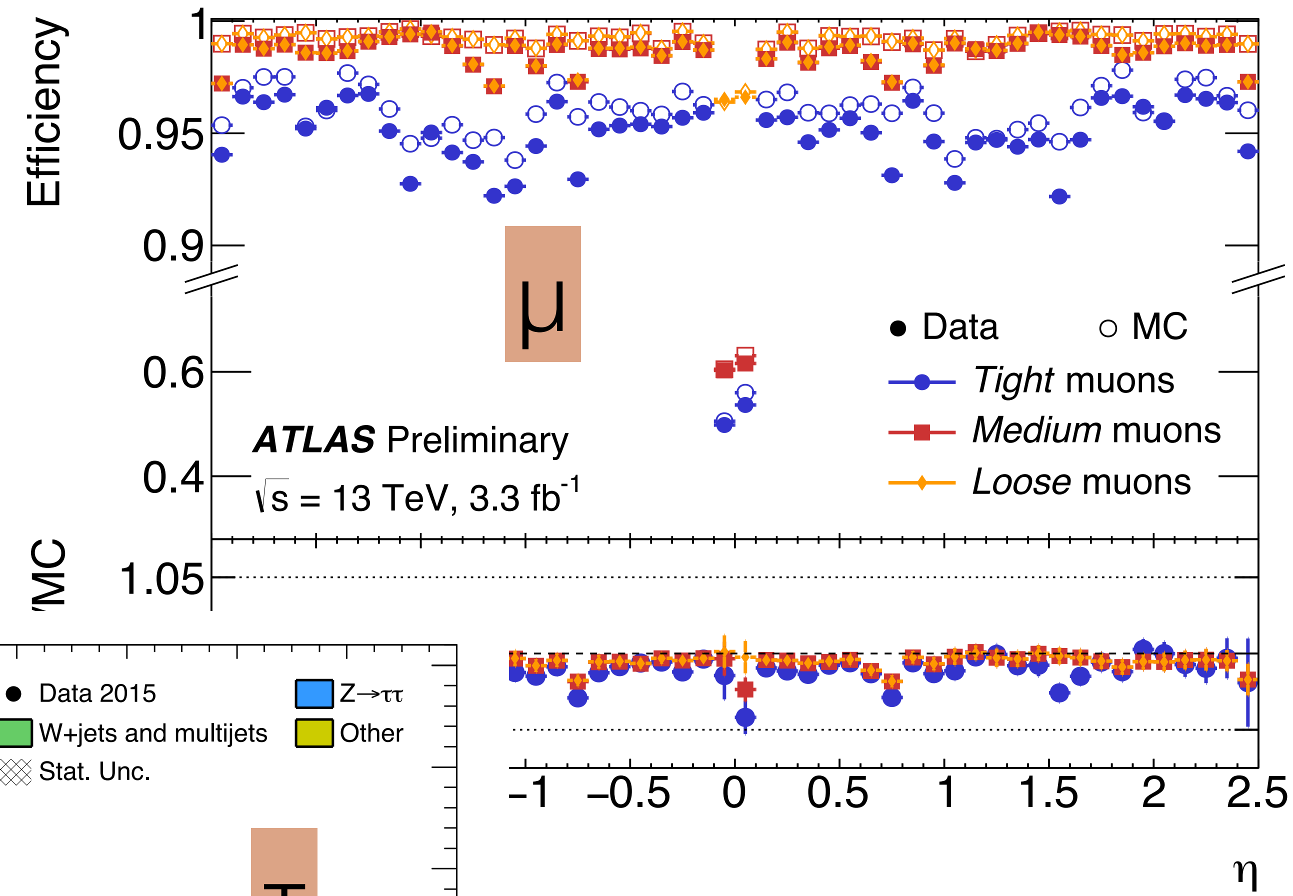
- DQ efficiency: 87%
    - main loss due to IBL off in 2 runs for safety reasons
- Luminosity: 3.2±0.2 fb^{-1}
    - Measured with vdM scans
- Very smooth trigger operations

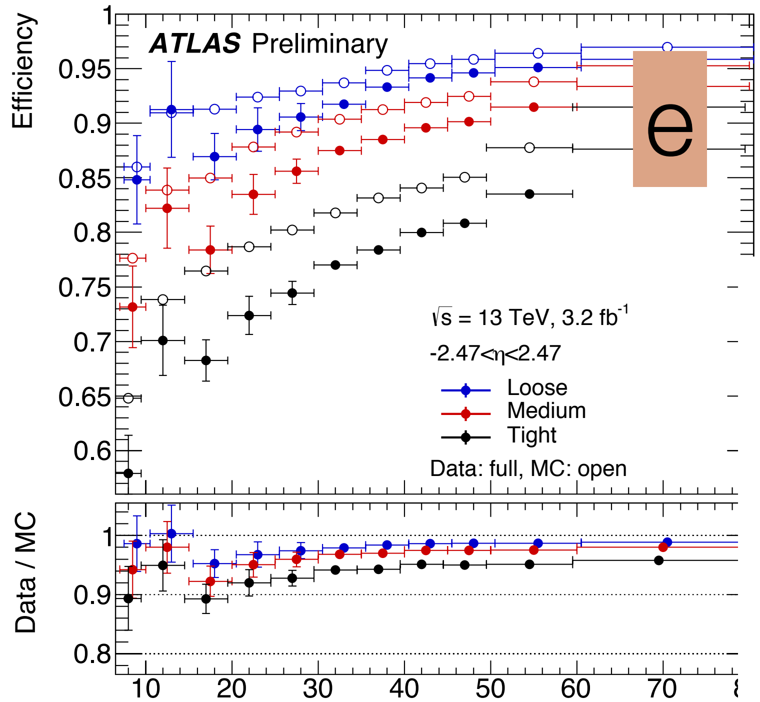


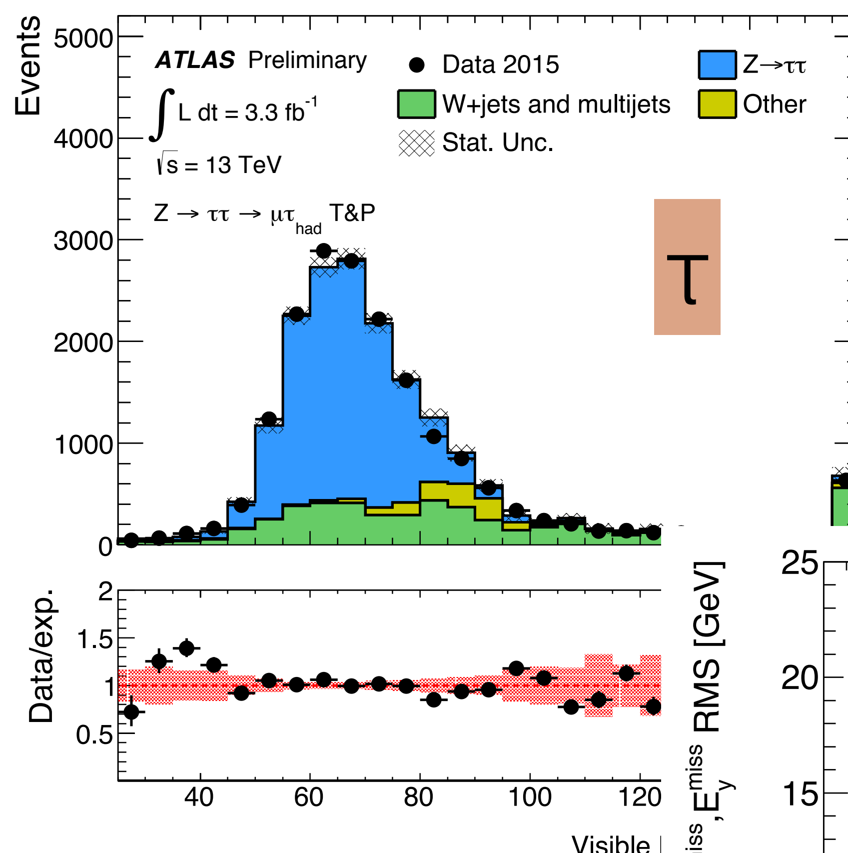
Trigger	p_T Threshold (GeV)		Rate (Hz) *	
	Run 1	Run 2	Run 1	Run 2
Inclusive e	24	24	70	97
Inclusive μ	24	20	45	130
E_T^{mis}	80	70	18	55

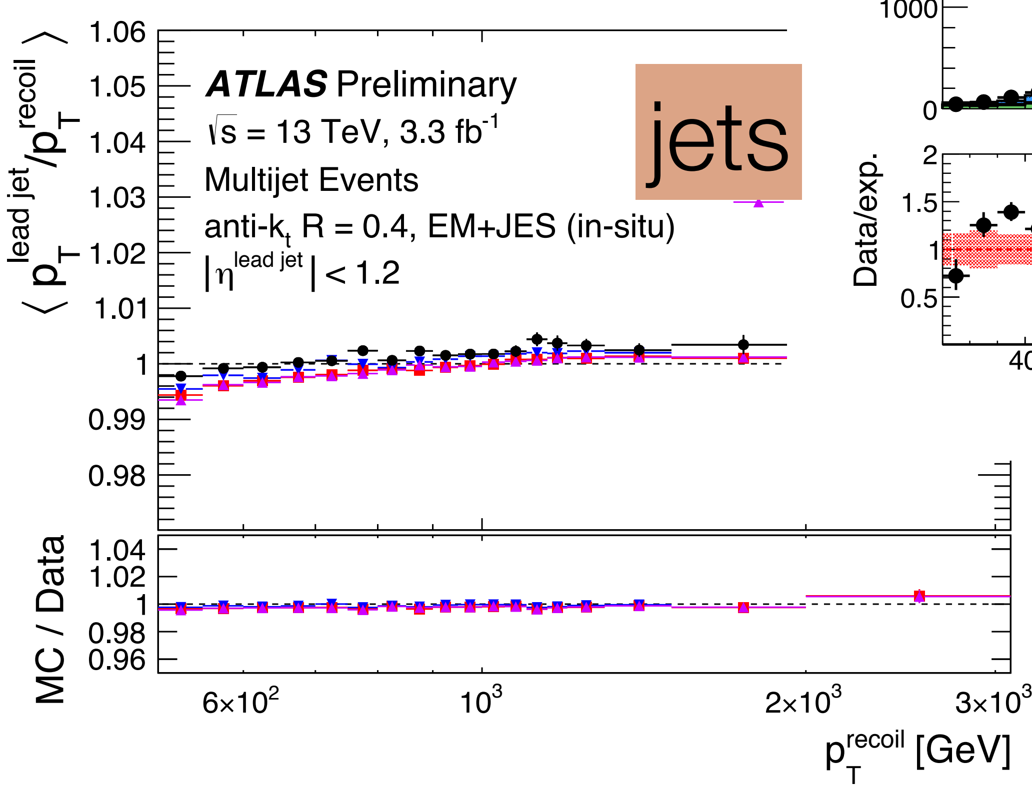


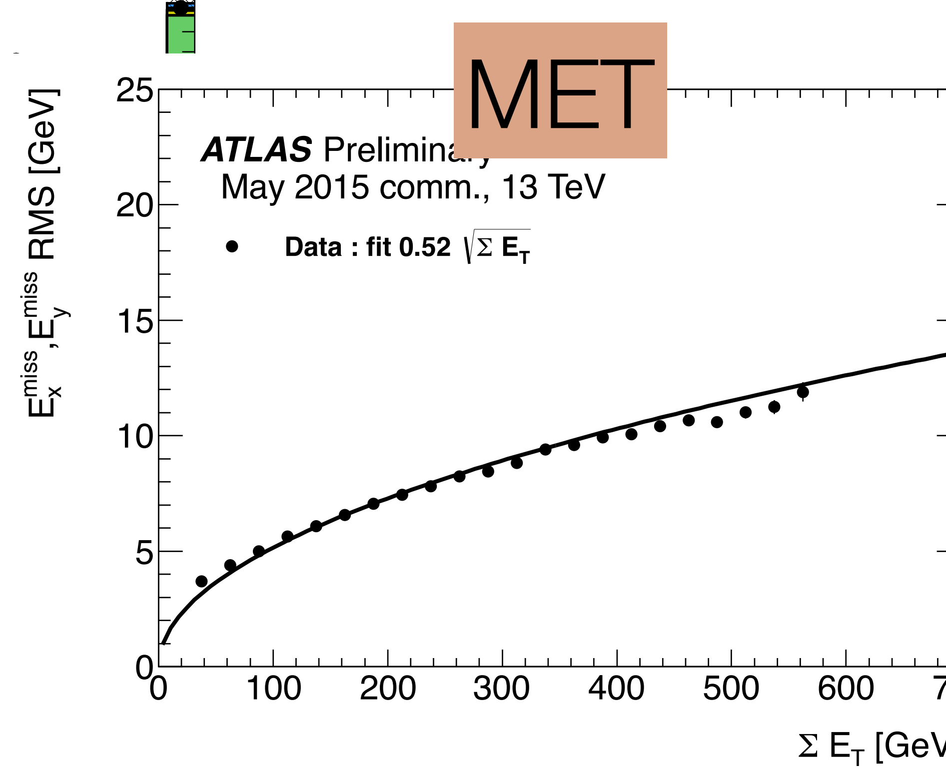
Performances











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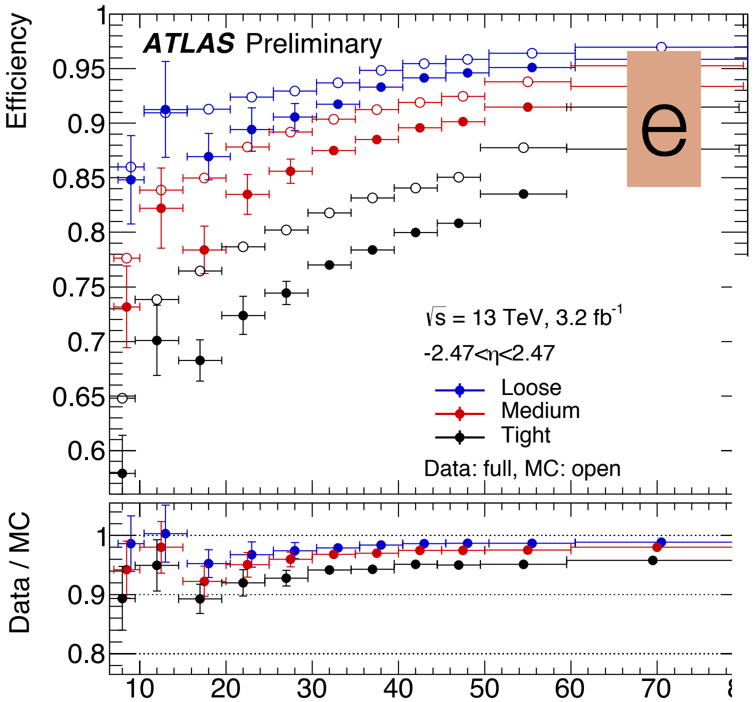
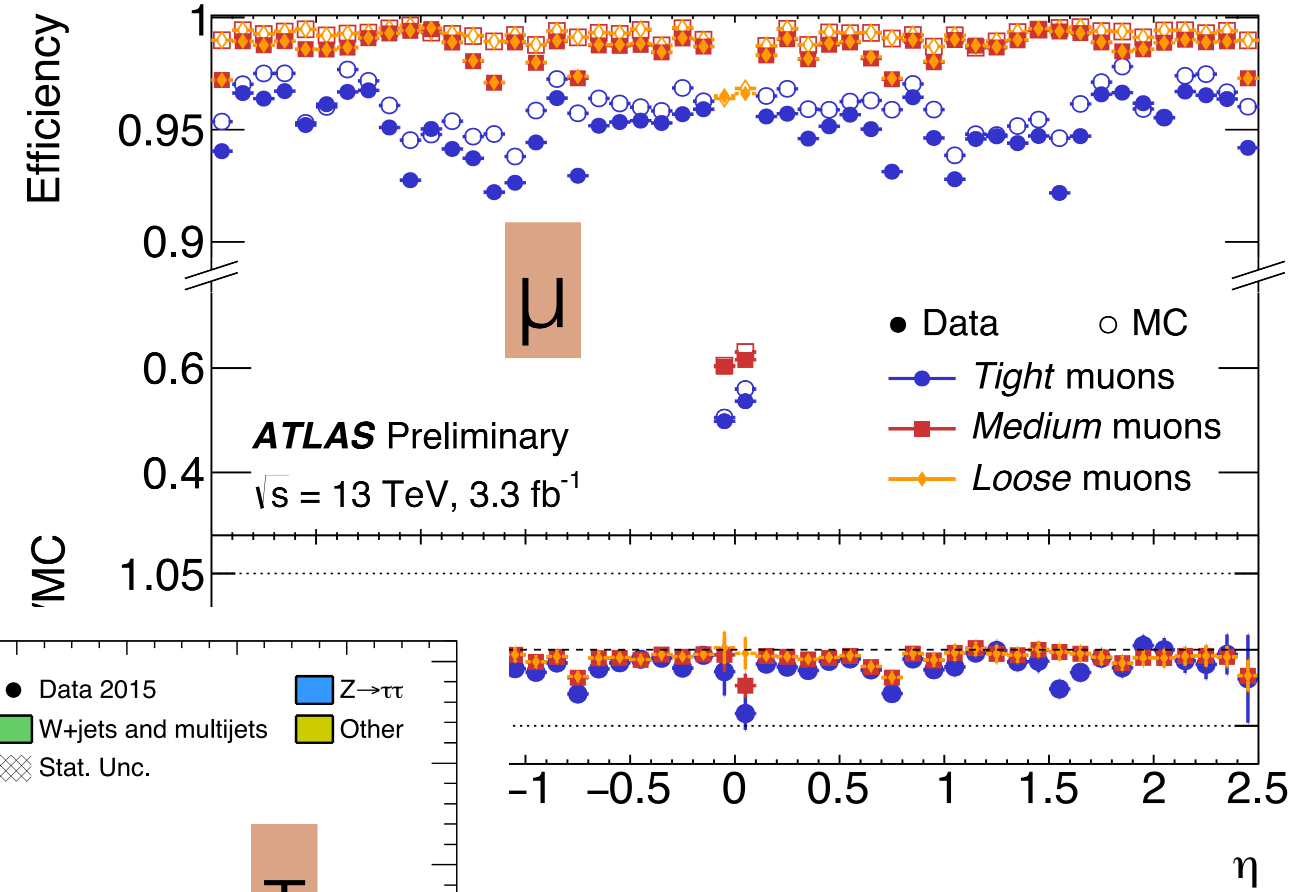
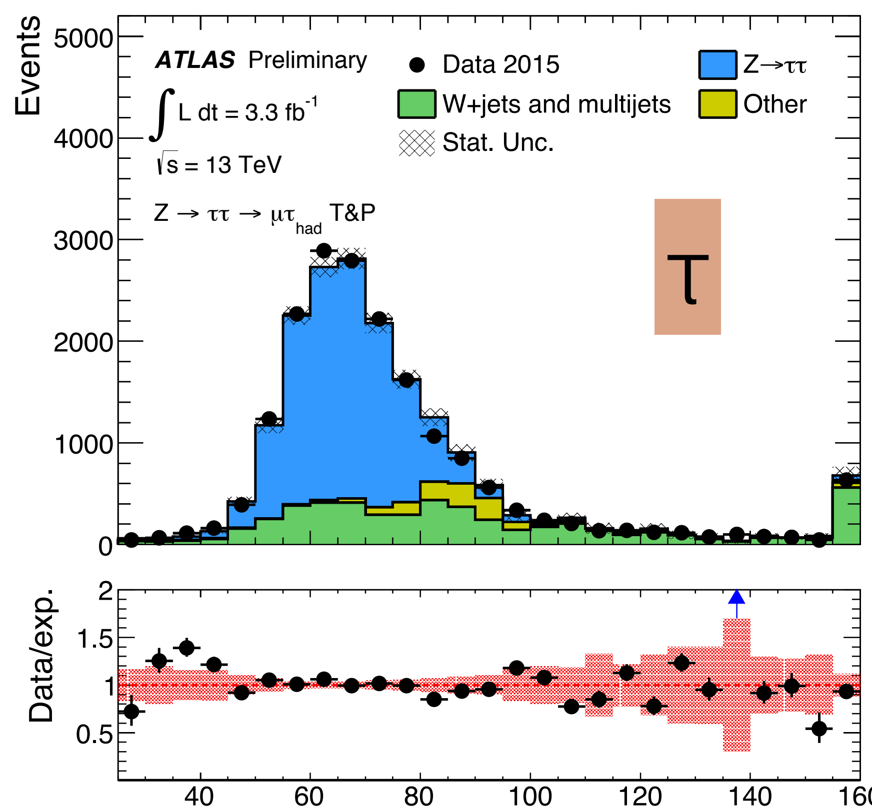
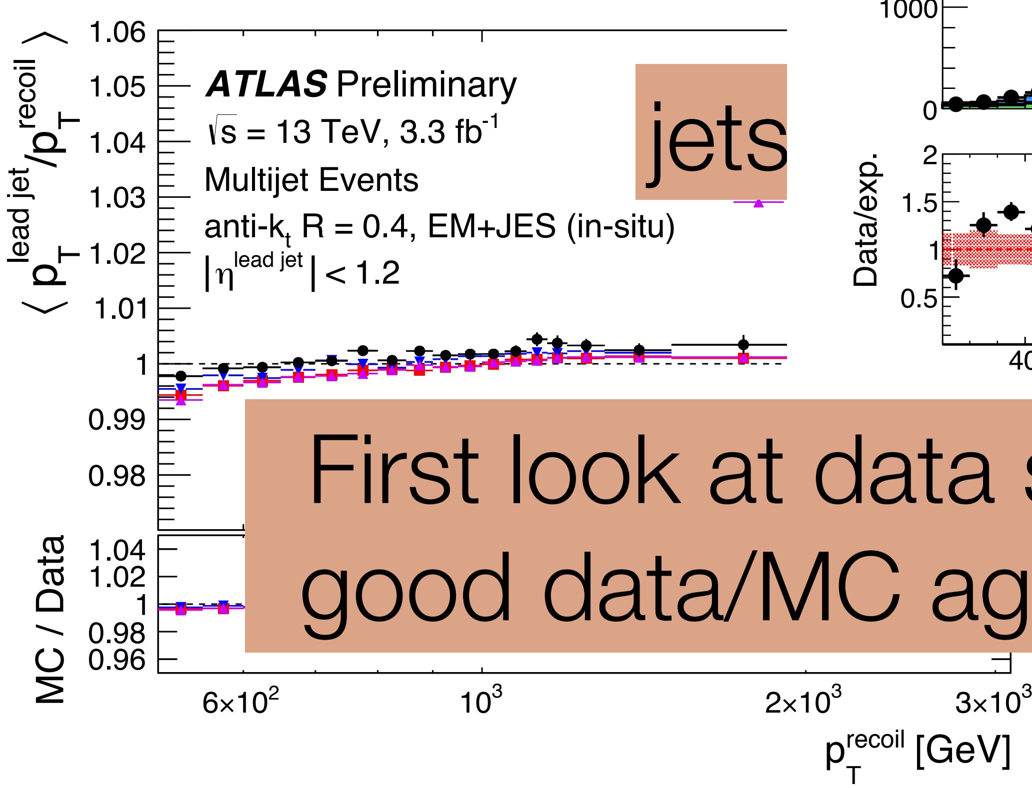
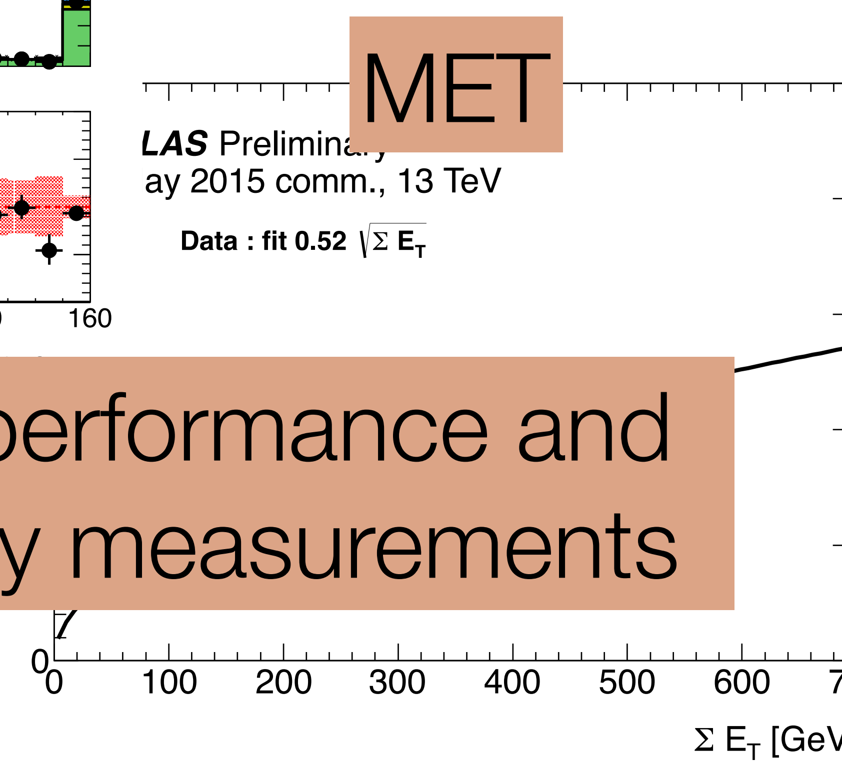










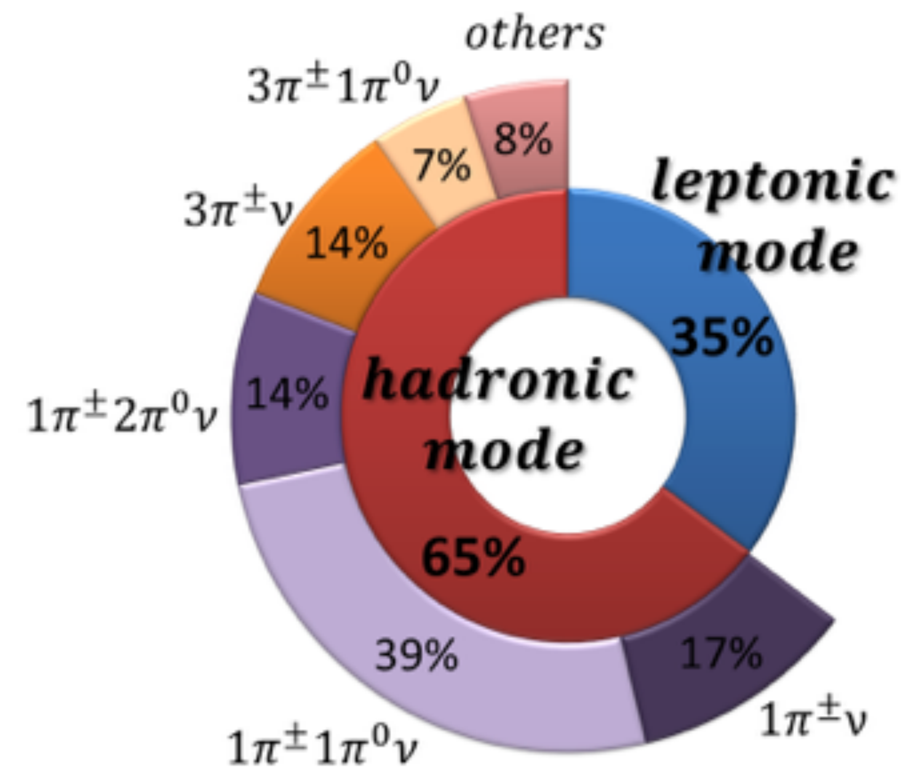
First look at data shows good performance and good data/MC agreement in key measurements

Tau Physics at the LHC

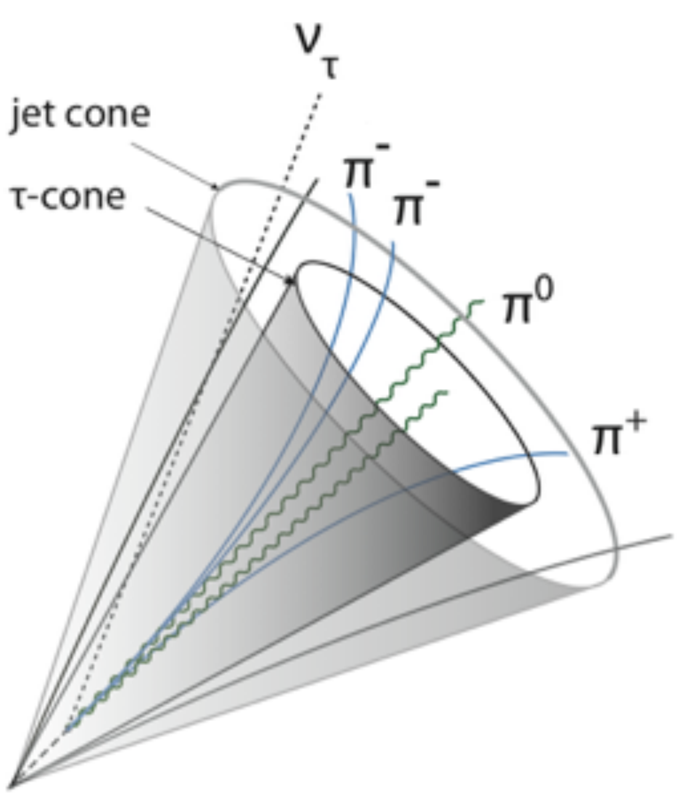
- The LHC is **not** a place to make precision measurements of the tau lepton
- As the heaviest lepton in the SM, the tau is a very useful probe of the EWSB mechanism:
  - Direct coupling the Higgs boson
  - Establishing the tau polarization in W/Z decays
  - Lepton Flavour Violation
- Many exotica and SUSY signatures involve taus, their discovery potential is usually weaker than signatures with light leptons (e/mu)

In this talk, instead of a broad review of the O(30) tau-related ATLAS results, I want to discuss the ATLAS strategy to detect hadronically-decaying taus and highlight a few recent results

Tau lepton at ATLAS



- m_{τ} = 1.777 GeV, $c\tau$ = 87 µm , decays: $\tau \to l\nu$ (35%), $\tau \to$ hadron(s) + ν (65%)
- Leptonic tau decays are nearly indistinguishable from prompt light lepton
- Hadron collider vocabulary: tau = hadronic decay ≈ collection of $\pi^{\pm}$ and π^{0}



- Signature: calorimeter deposit associated with 1 or 3 tracks
- Reconstruction seeded by an anti-k_T jet algorithm with a radius of 0.4:
  - Core within 0.2, isolation ring [0.2, 0.4]
  - Tracks associated to the core or the isolation ring

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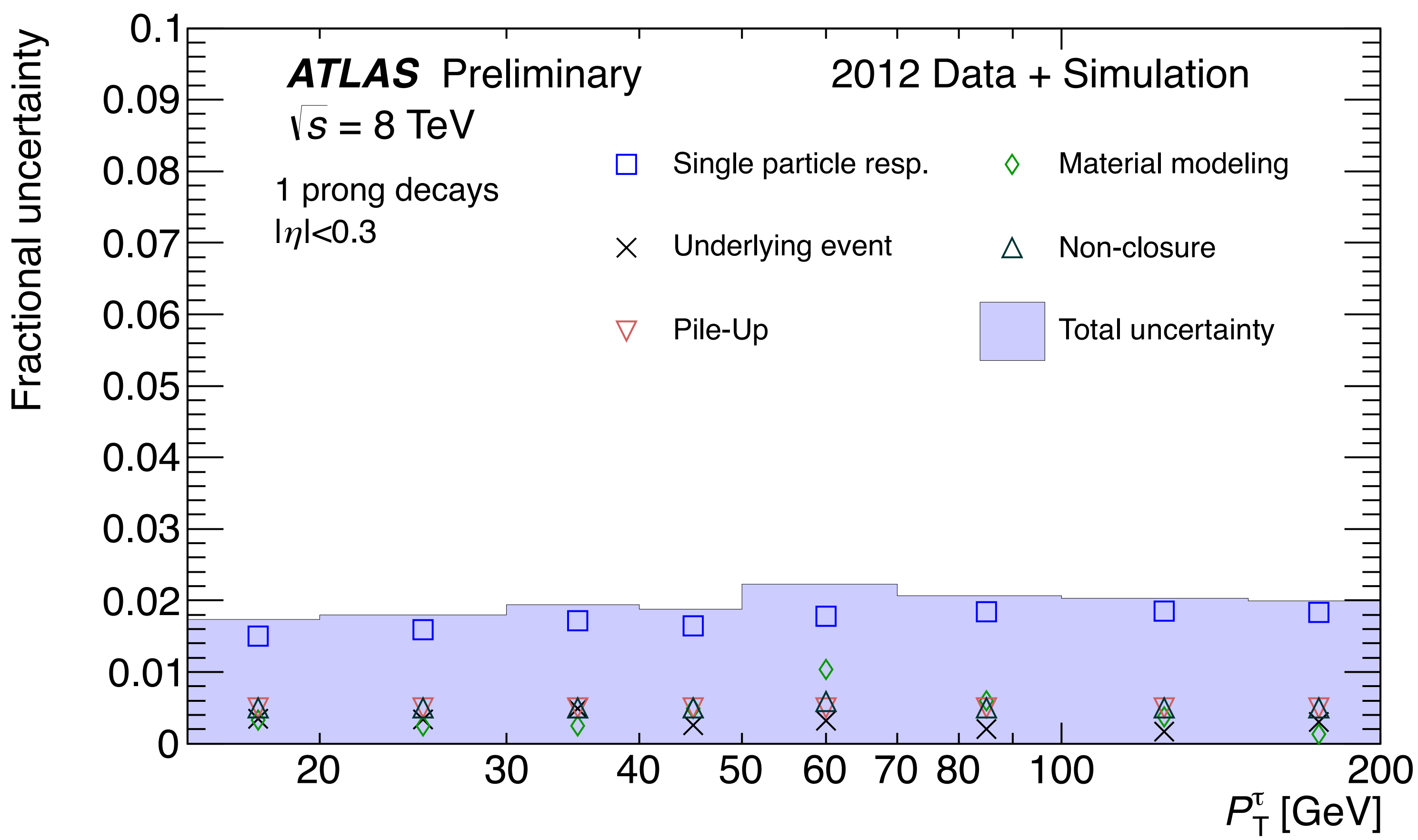
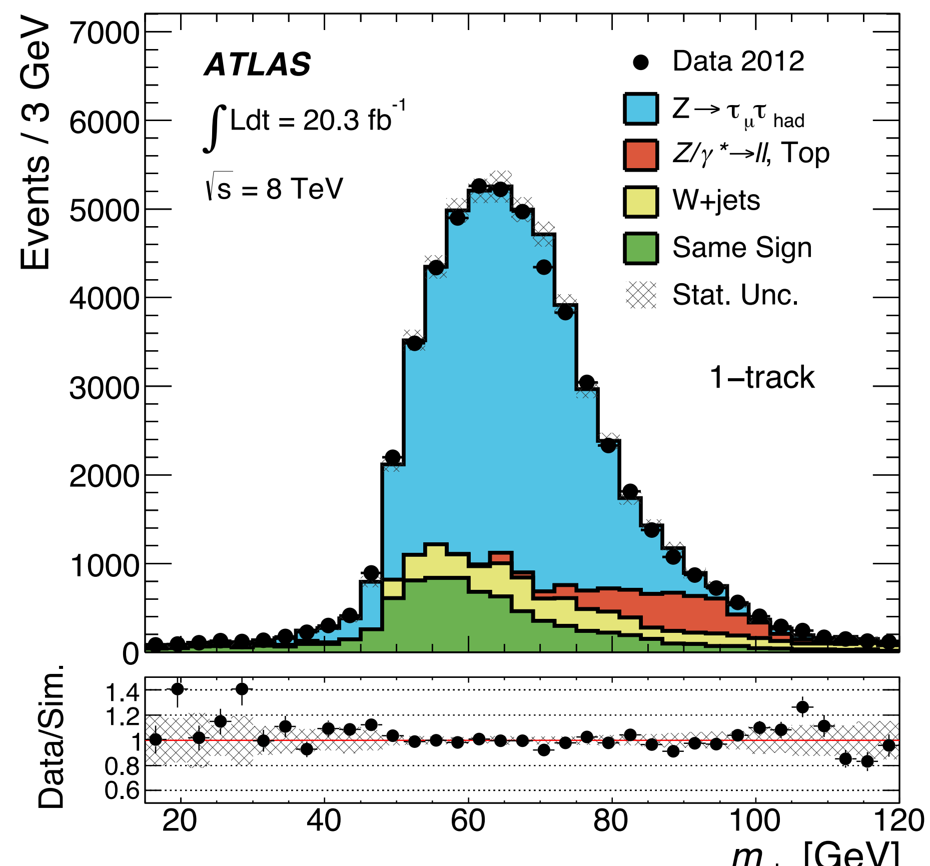
Tau Energy Scale

- Seeded with an anti-k_T jet (dR=0.4) at the LC scale.
- MC-driven corrections to agree with the simulated true visible E_T
- Deconvolution method and in-situ $Z\rightarrow\tau\tau$ measurement to provide a final ~1% correction and assert the systematic uncertainties:
  - ~2-3% for 1prong taus and 3-4% for 3prongs taus





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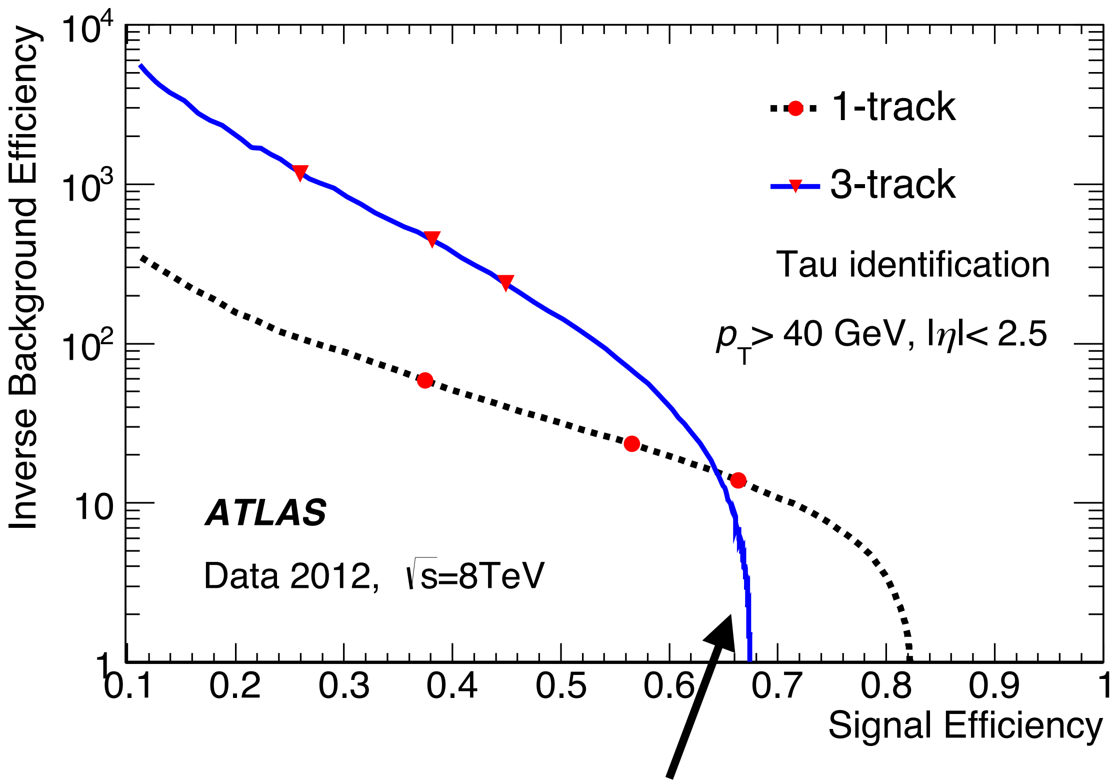
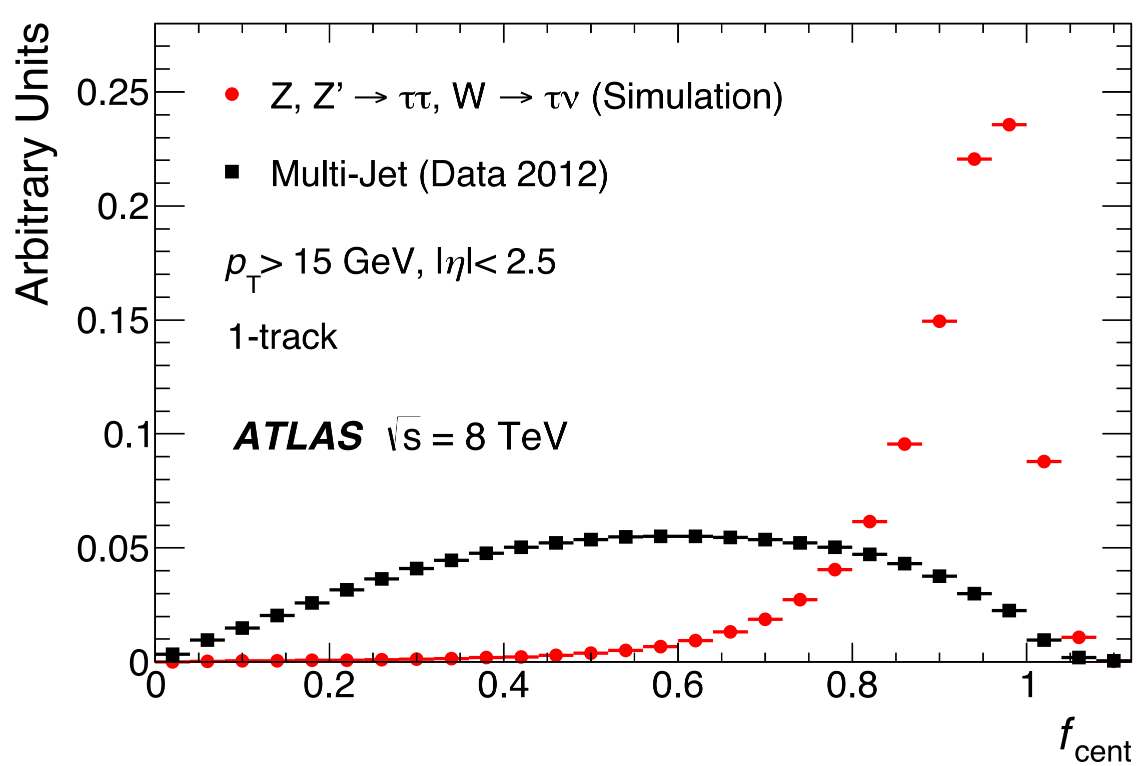
Tau Identification

- Multivariate discriminant (BDT) based on a combinaison of calorimetric and track-based variables.
- Two discriminants trained separately for 1prong and 3prongs candidates
  - Very different calorimetric response, usage of displaced vertex possible in 3prongs
  - Achieve an efficiency of 40% for a rejection of 60 (medium working point)

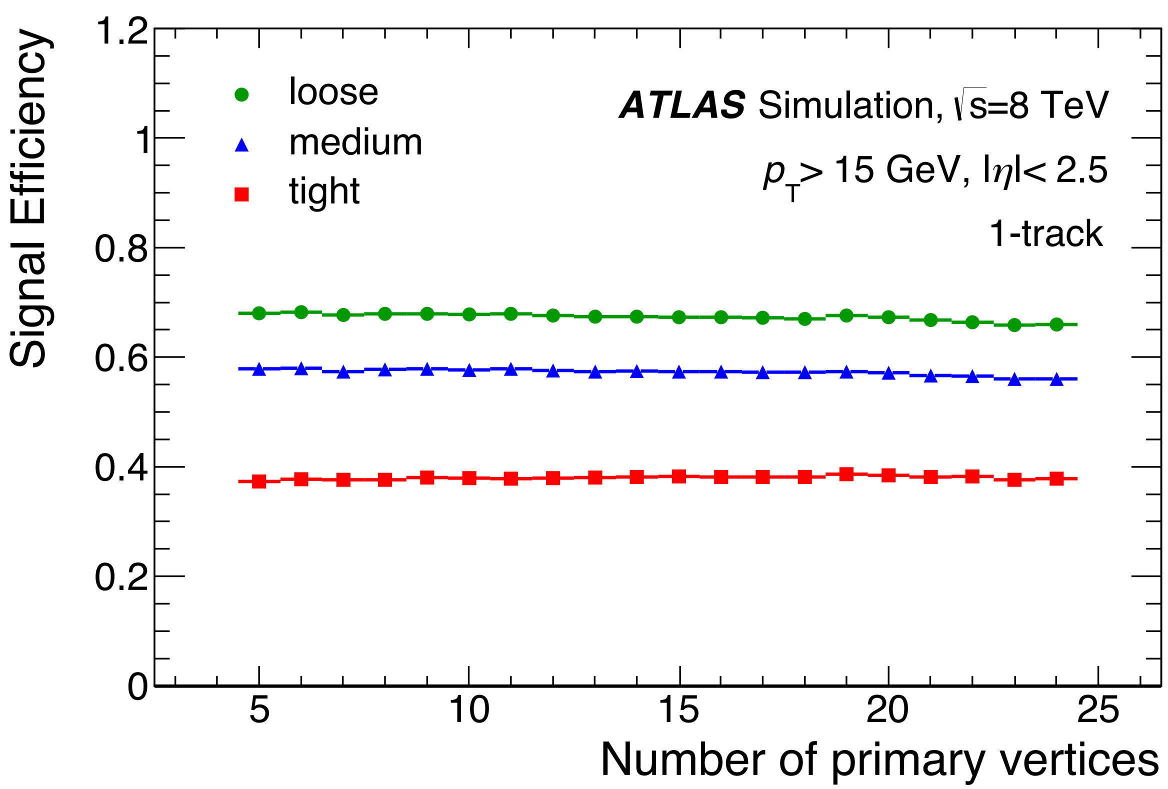


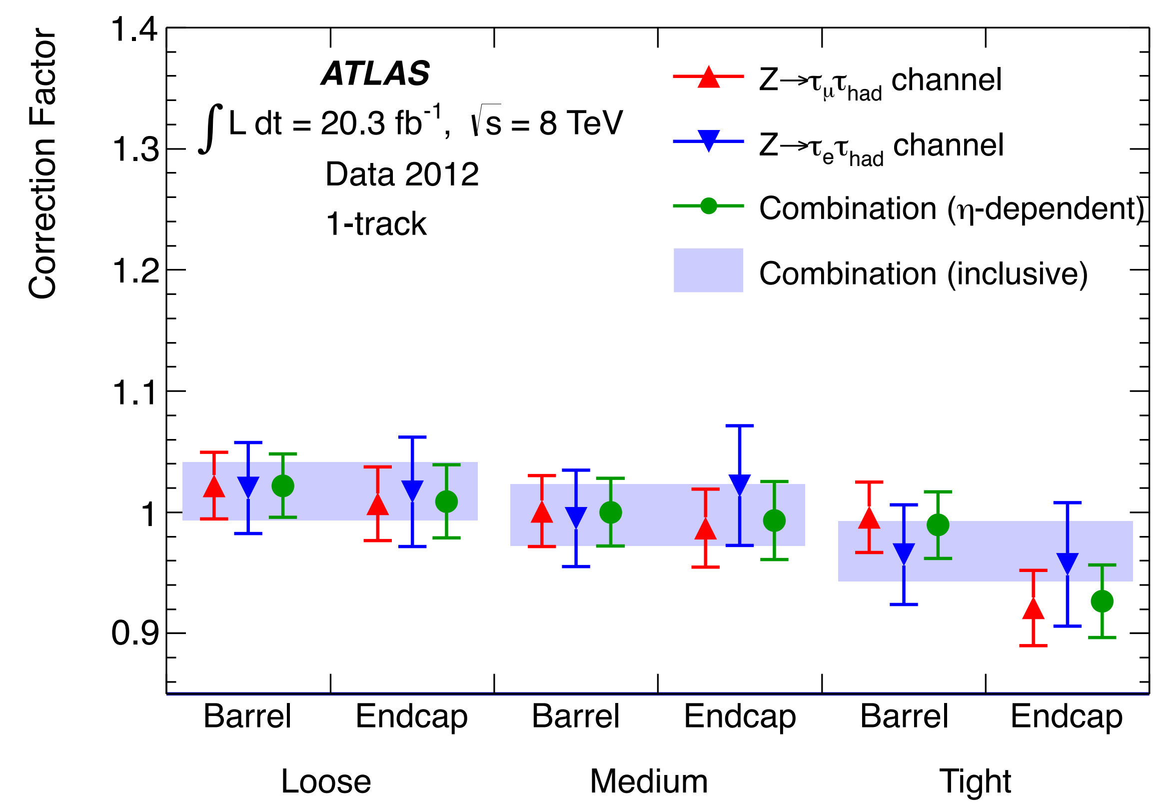


Efficiency includes track reconstruction

Tau Identification

- Very robust response agains pile-up obtained by explicitly correcting the input variables using n_{vtx}
- Agreement with data checked in $Z \to \tau\tau \to \mu\tau_h$ events
  - Scale factor deviates from unity by a few %





Triggering with taus?

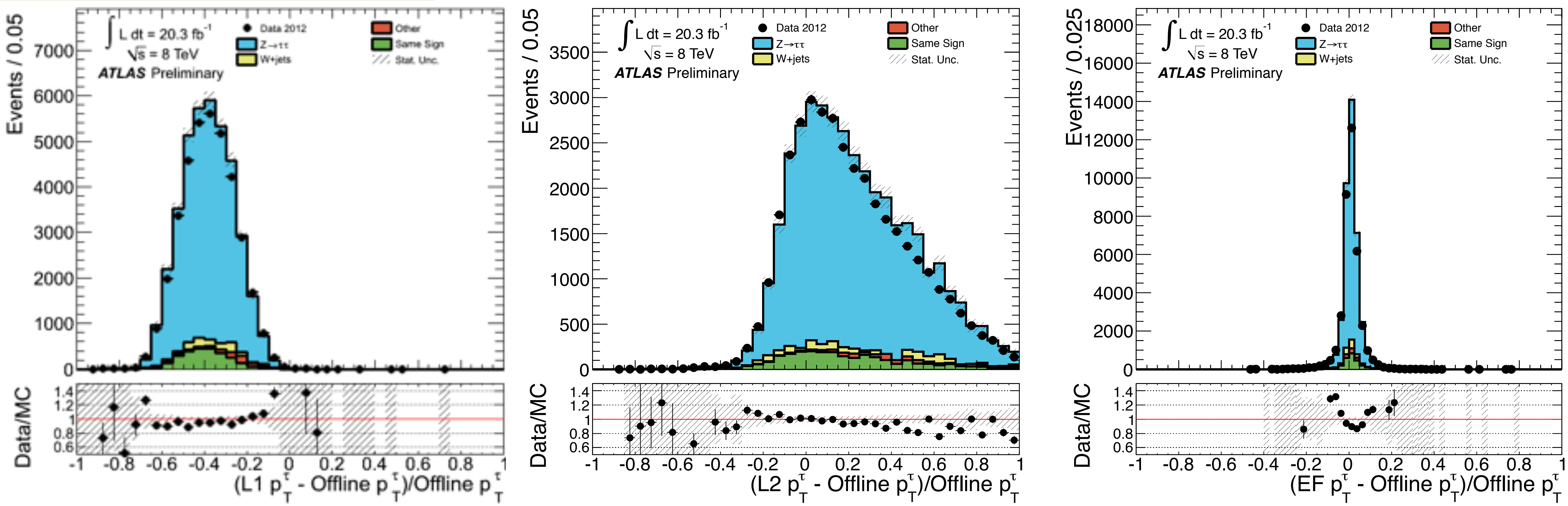
- We try to avoid it but it is required for key signatures.
- Fully Hadronic final state: BR($X \rightarrow \tau_h \tau_h$) = 42%
  - Hadronic taus are the best trigger handle available
- Semi leptonic final state: BR($X \rightarrow \tau_h \tau_l$) = 46%
  - At low instantaneous luminosity, most searches can rely on the single lepton triggers
  - With the nominal Run2 setup, combined lepton + tau triggers will be required

ATLAS (Tau) Trigger System: Run1

75 kHz — 3 kHz — 600 Hz

Level 1	Level 2	Event Filter
Calorimeter + Muon System (coarse granularity)	**Seeded by L1 Region Of Interest. Fast tracking**	**Full granularity, full tracking in the Region of Interest**

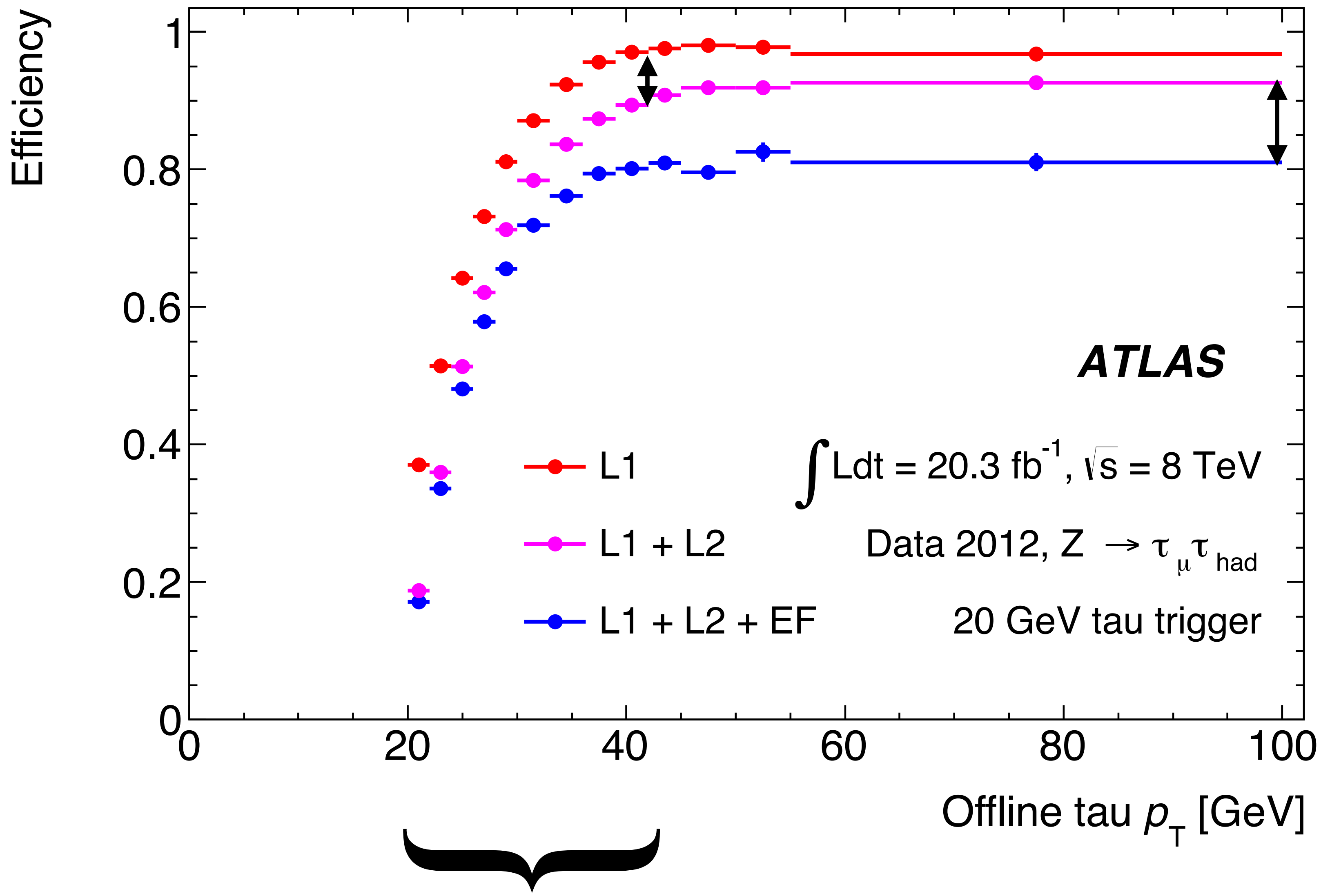
Tau Energy Resolution



Tau Trigger Run1 Performances

Efficiency wrt offline identified taus

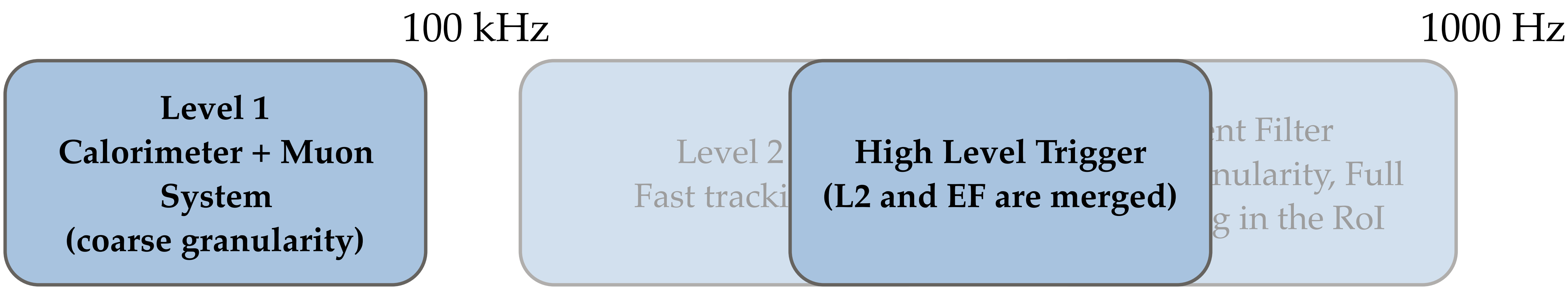
L2 ID ≠ Offline ID



HLT ID ≠ Offline ID

L1: very slow turn-on

ATLAS Trigger System: Run2 upgrade



- L1Topo:
  128 items available
  for combination

- L1Calo:
  Relative isolation cut

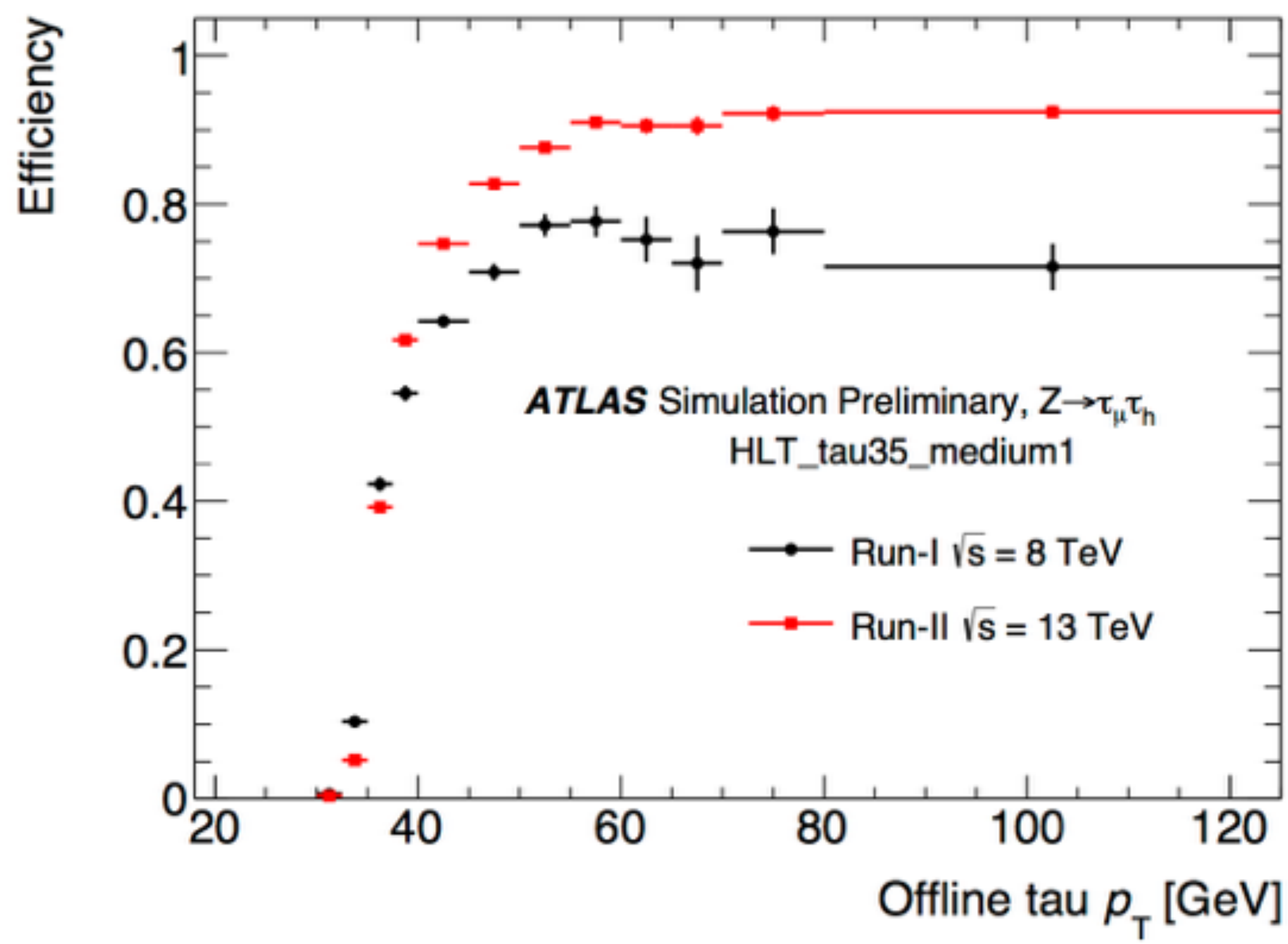
- L2/EF merger:
  - Topo-clustering available right at the L1 output.
  - Full tracking limited to the RoI
    - usually not fast enough to be run right at the L1 output (need a L2-like preselection)

- FTK:
  - Full scan of the tracking system right at the L1 output. Available in 2016…

Tau Trigger Run2 Performances

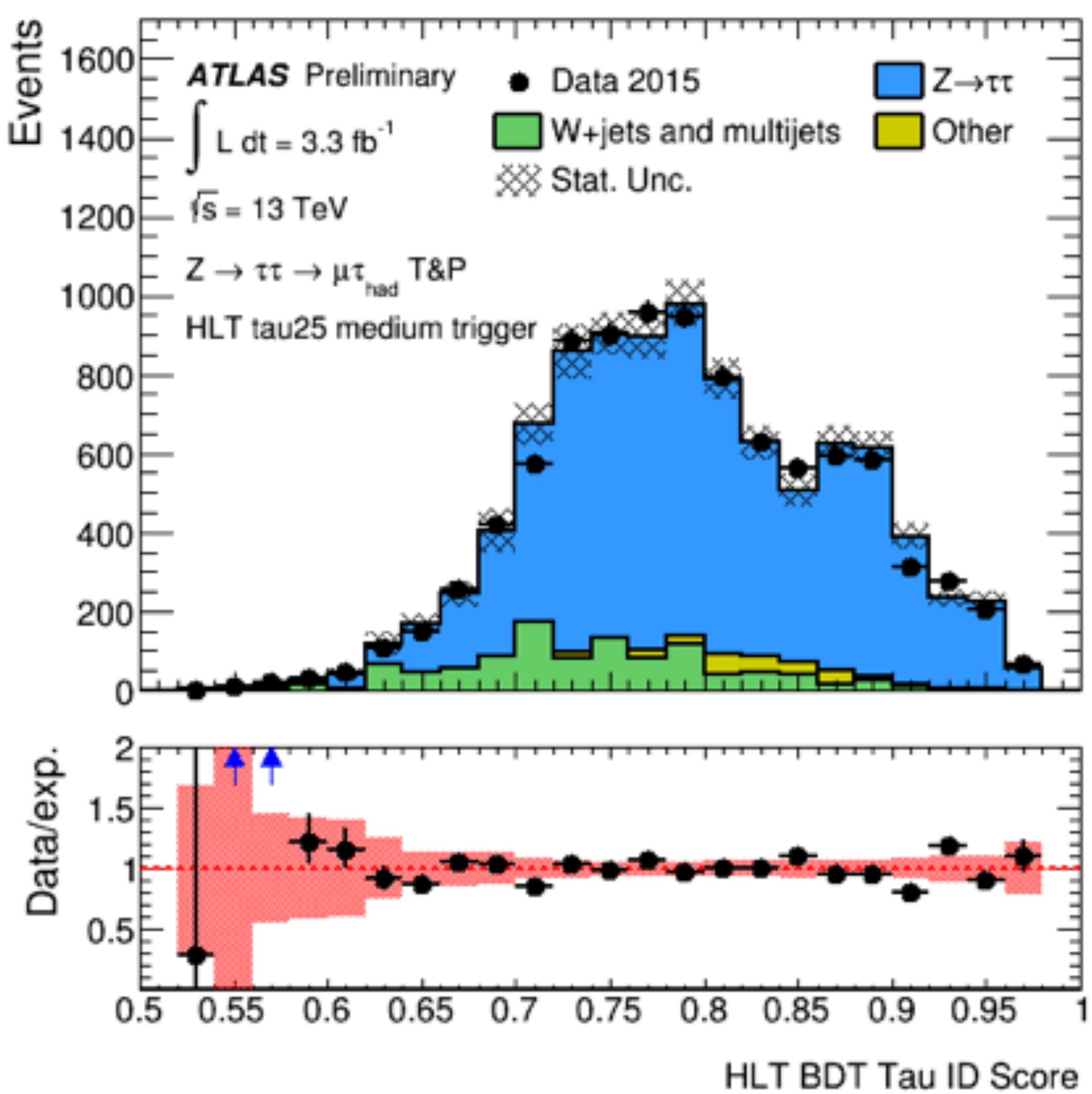
- Better performances than Run1
  - Relative Isolation at the L1
  - Cell-level precision available at the L1 output rate (EF/L2 merged)
  - HLT/offline ID menu harmonized

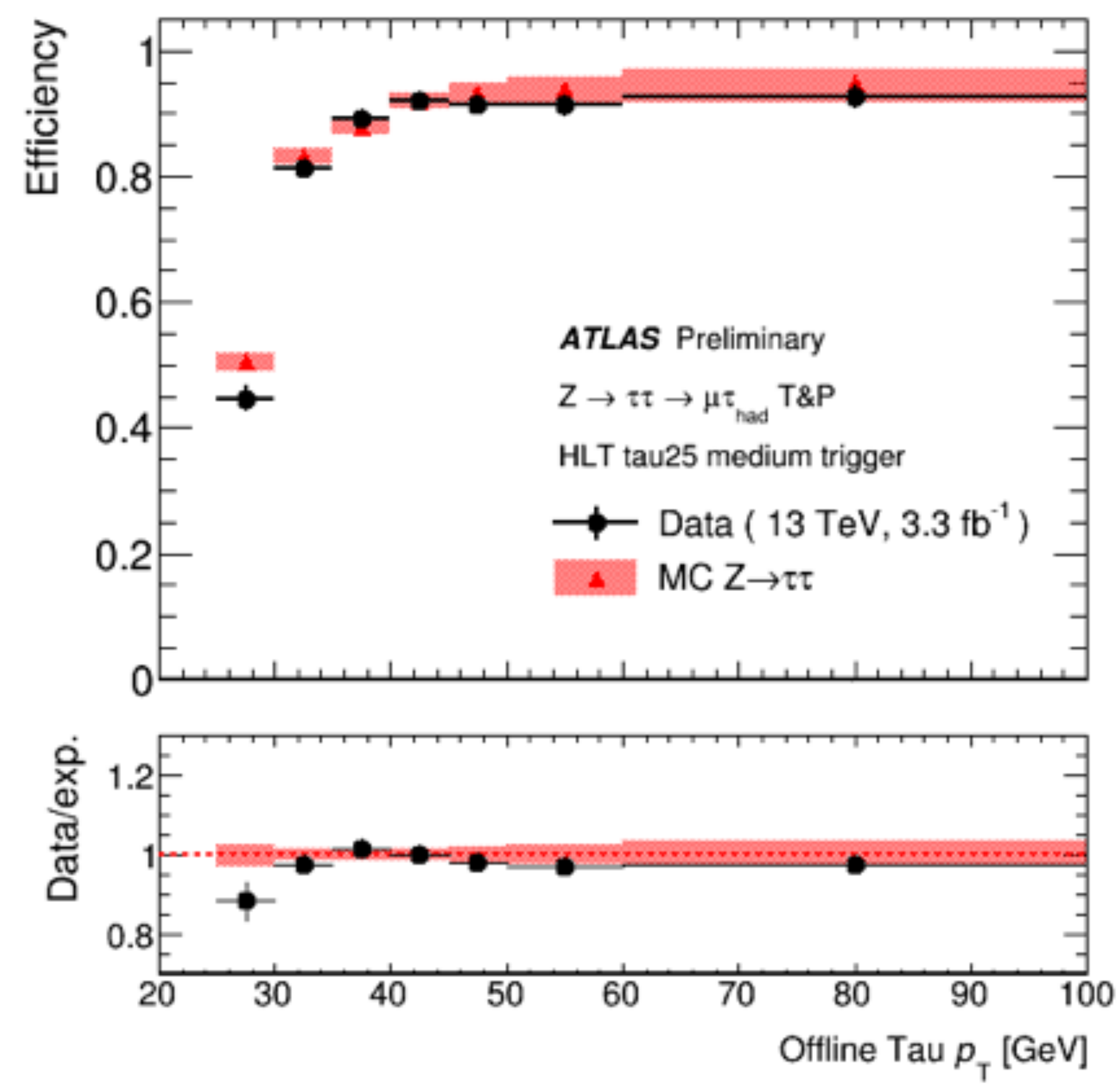
Efficiency wrt offline identified taus



Tau Trigger Run2: Efficiency Measurement

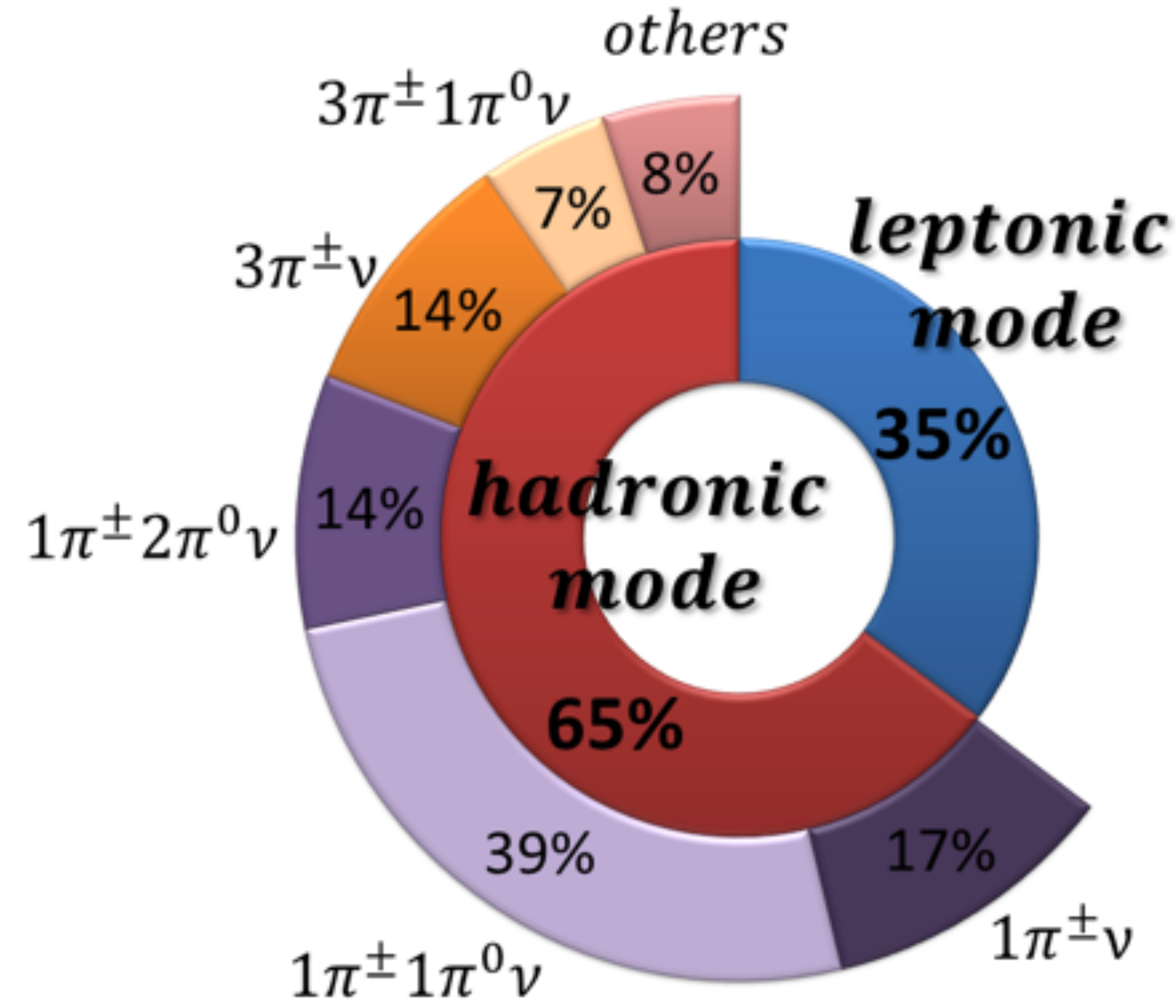
- Tag&Probe analysis using $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ events: very good agreement with simulation
- Data/simulation scale-factors measured close to unity.





Tau Particle Flow

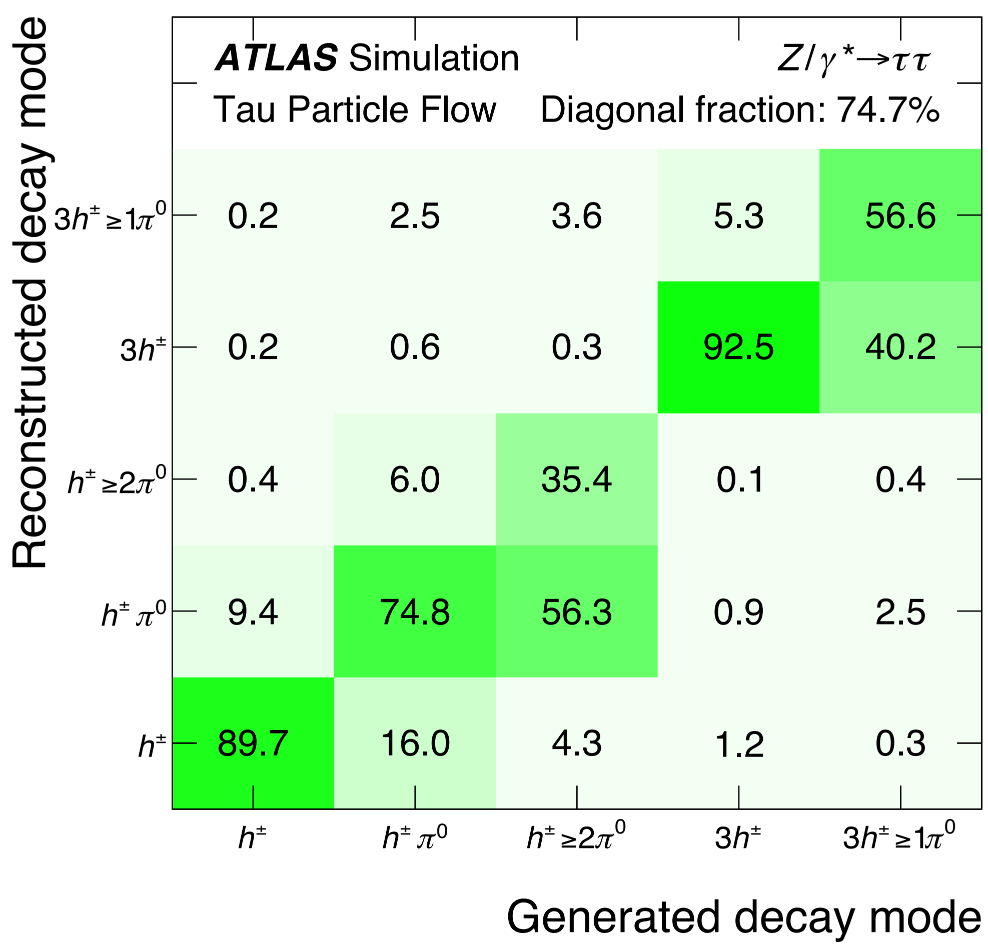
- Identify and classify the different hadronic decay modes:
  - Crucial information for decay-dependent measurements
  - Improve the energy resolution

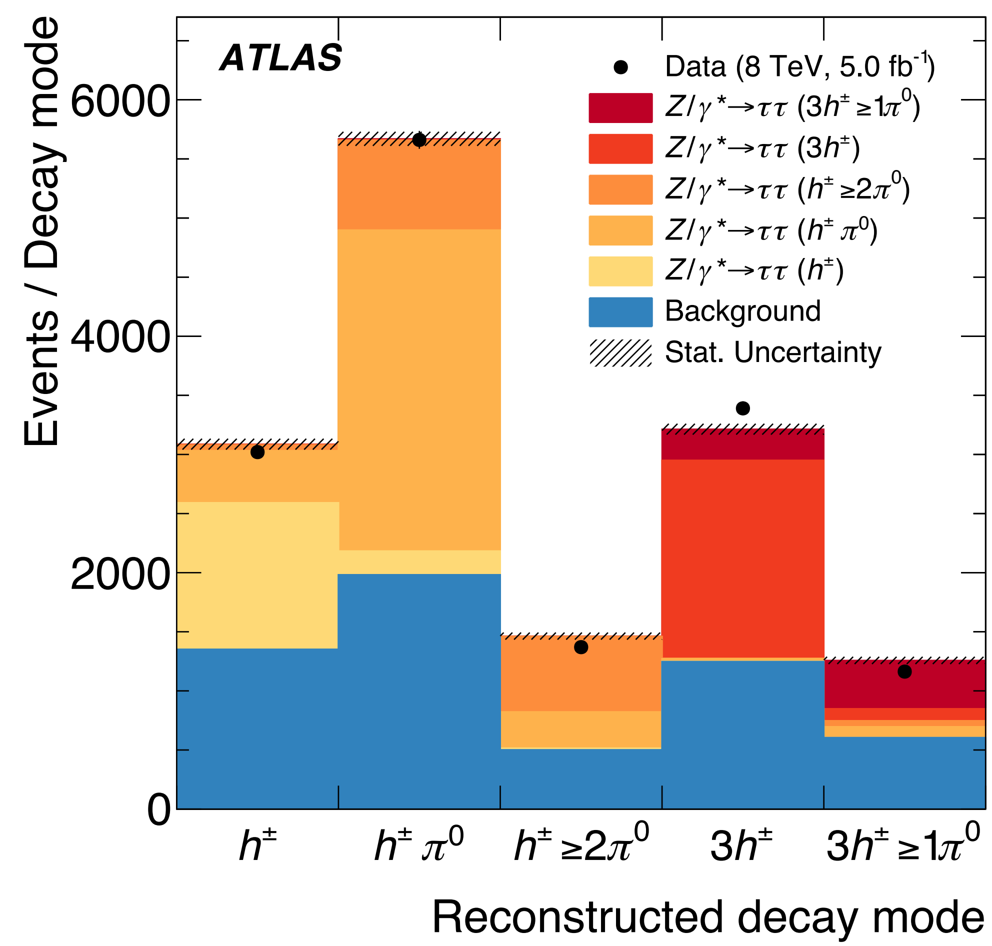


1. Reconstruct and identify individual neutral pions within the tau energy deposit:
   - Estimate EM energy from charged pions using E_{trk}-E_{HAD}. Combine EM shower shape variables into a BDT do discriminate π_0 from pile-up and h± remnants cluster.
2. Using the first layer of the ECAL, attempt to disentangle cases where two neutral pions share the same cluster.
3. Combine with the charged information from the tracking system to classify the tau and measure its kinematic properties

Tau Particle Flow: Classification

- Efficient separation of decays with and without neutral pions
- A lot of 1p2n to 1p1n migration

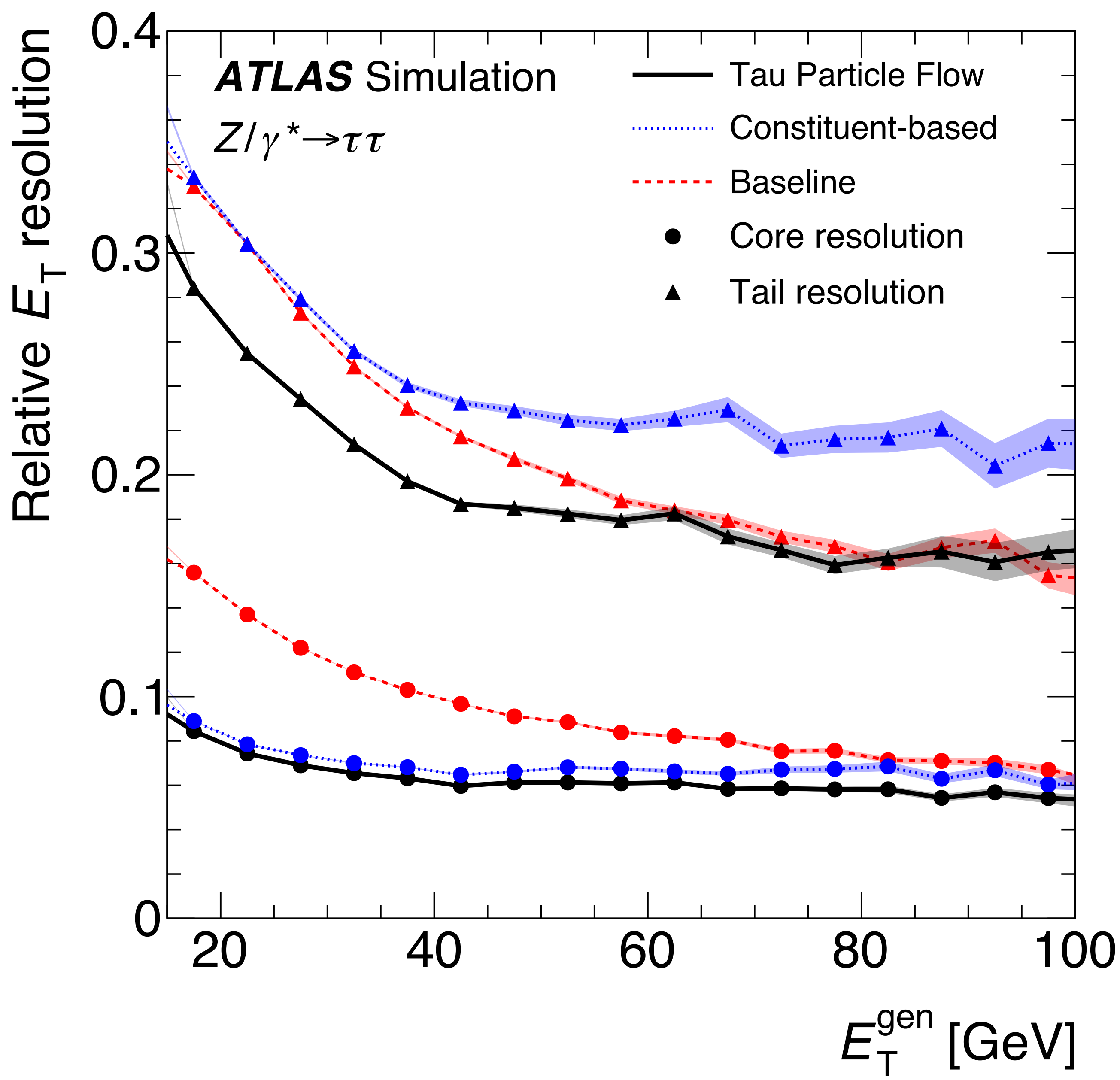




arXiv:1512.05955

Tau Particle Flow: Energy Resolution

- Decay classification allows a more reliable use of the tracking information to measure pT
- Huge gain in the core of the distribution
- Poor resolution in mis-classified decays, need to combine with calo-only (run1 approach) method

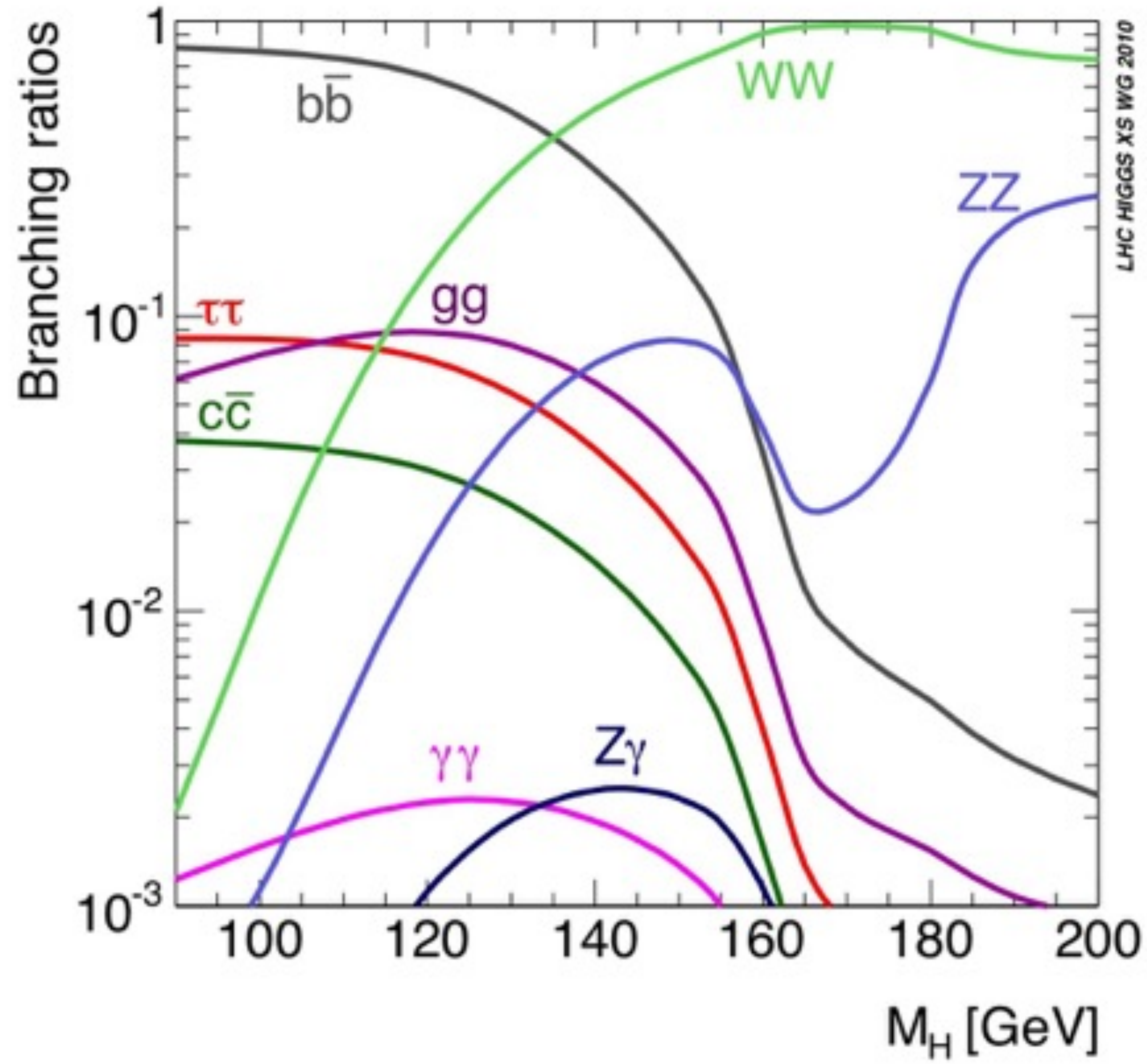


Tau detection at ATLAS

- Run1 tau reconstruction was very successful and used for key ATLAS analysis
- Tau Energy Scale is measured within a few %
- Tau Identification algorithms have a good efficiency of (60% for the medium WP) with a powerful jet suppression allowing for tau final states to be detected
- Run2 tau reconstruction:
  - Successful commissioning (both offline and trigger)
  - Target to validate and use the new Tau Particle Flow strategy in 2016

Higgs coupling to fermions: H→ττ

- Large branching ratio
- Presence of leptons in the Final States (less background than H→bb)
- Only leptonic decay reachable by the LHC (H→μμ should be visible in HL-LHC)
- All the production modes reachable by the LHC



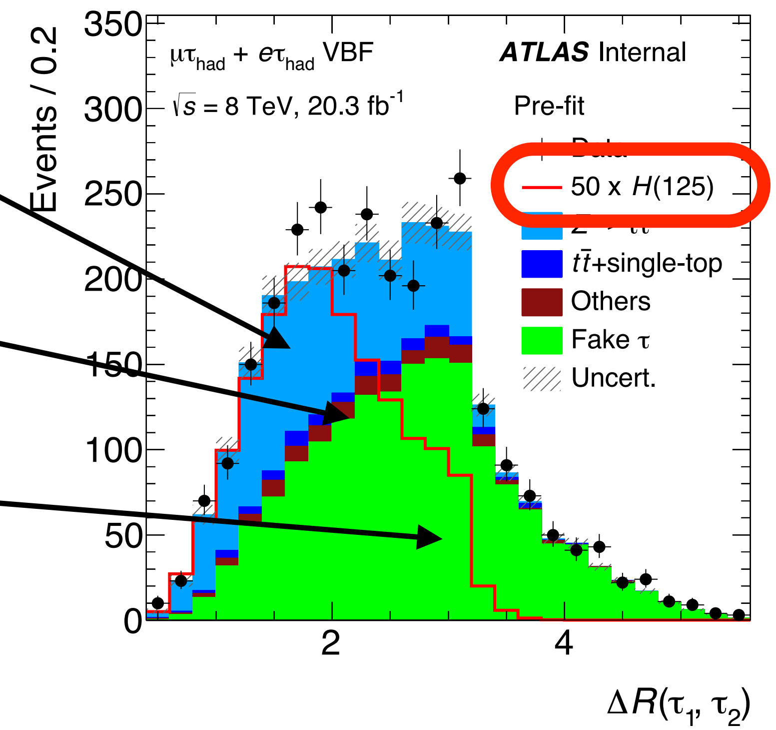
Does the 125 GeV boson decay to τ-lepton pairs ?

- Event categorized to target VBF and ggH production modes separately, all tau-decays considered
- MVA analysis to exploit most of the kinematic properties:
  - Boosted Decision Trees trained to separate the background from H(125)$\rightarrow\tau\tau$
  - Particularly powerful in the VBF category

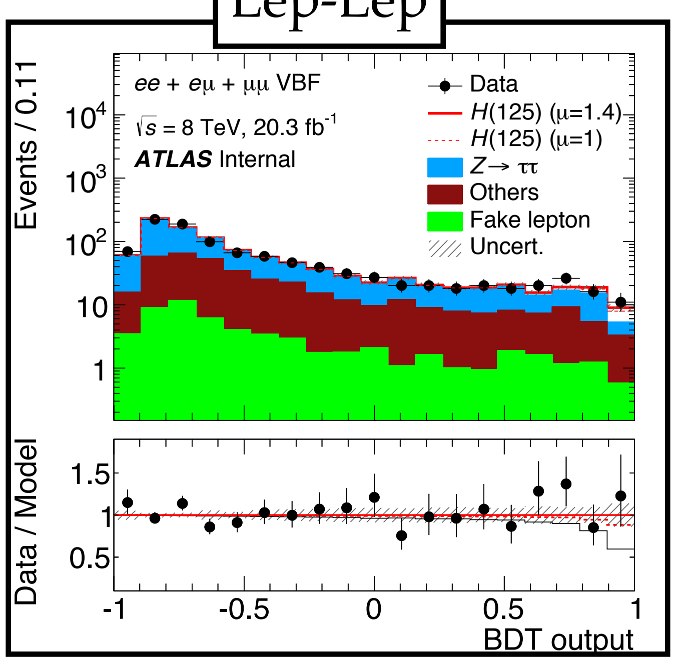
$Z\rightarrow\tau\tau$:
τ-embedded $Z\rightarrow\mu\mu$ data

Top+EWK:
MC simulations

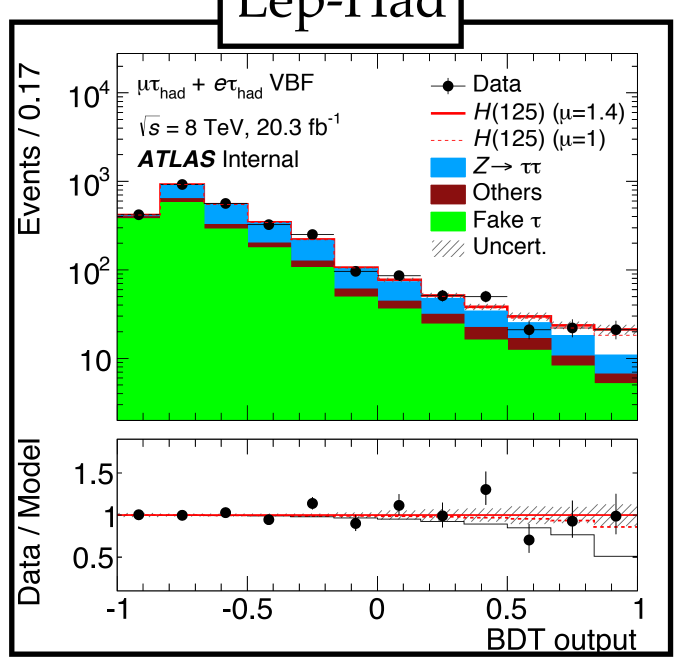
jet-faking-τ_h:
Data Driven



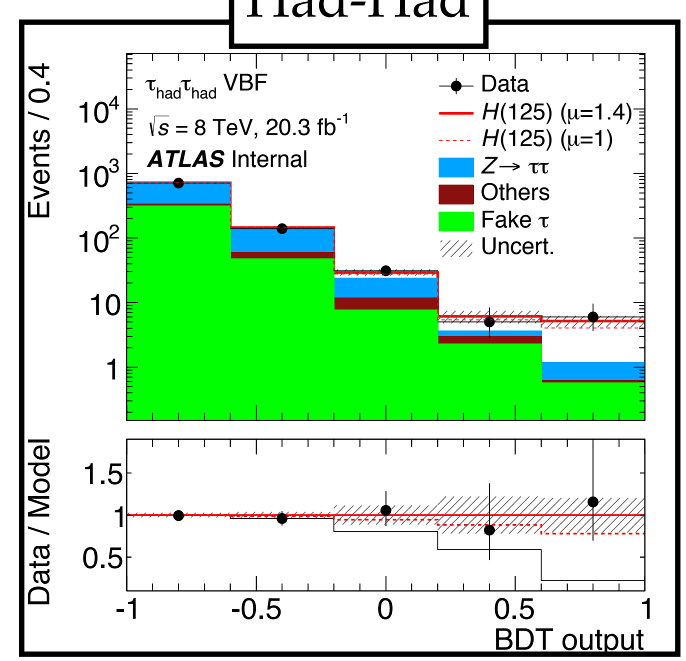
Lep-Lep



Lep-Had

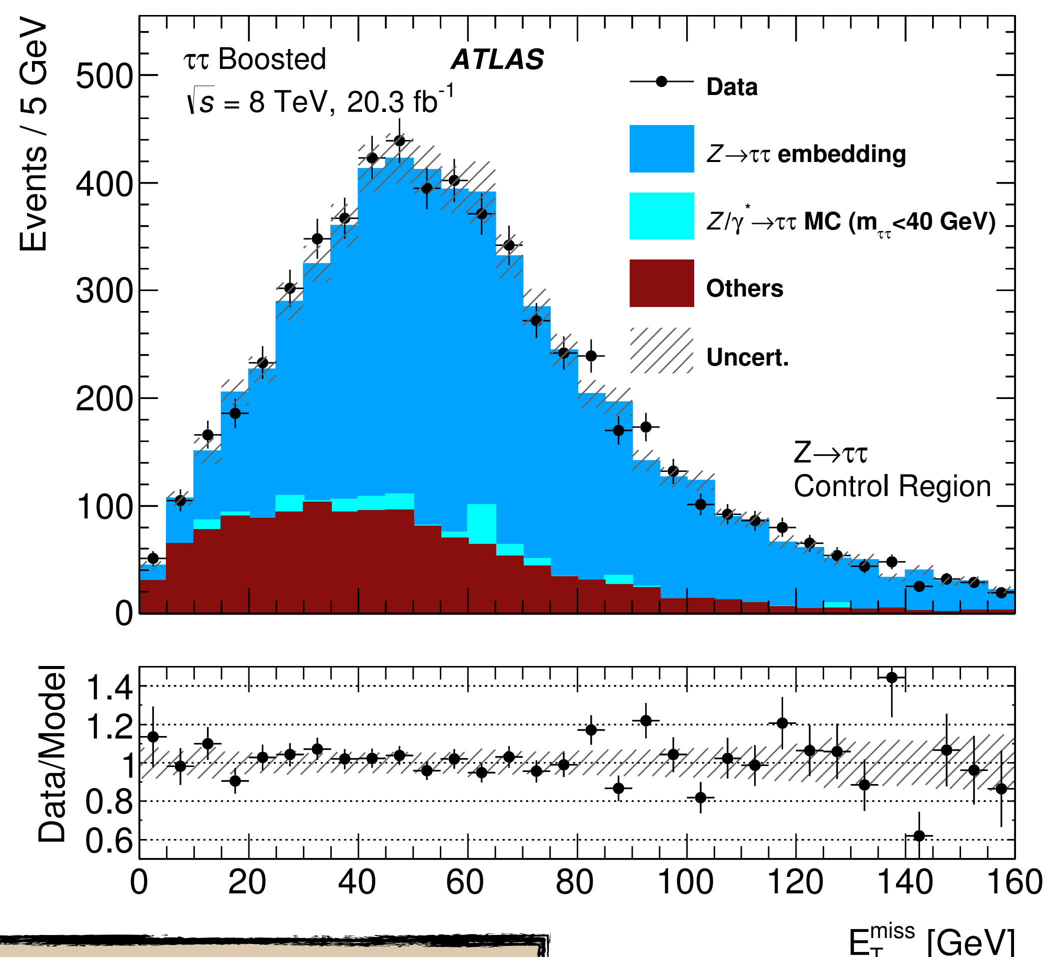


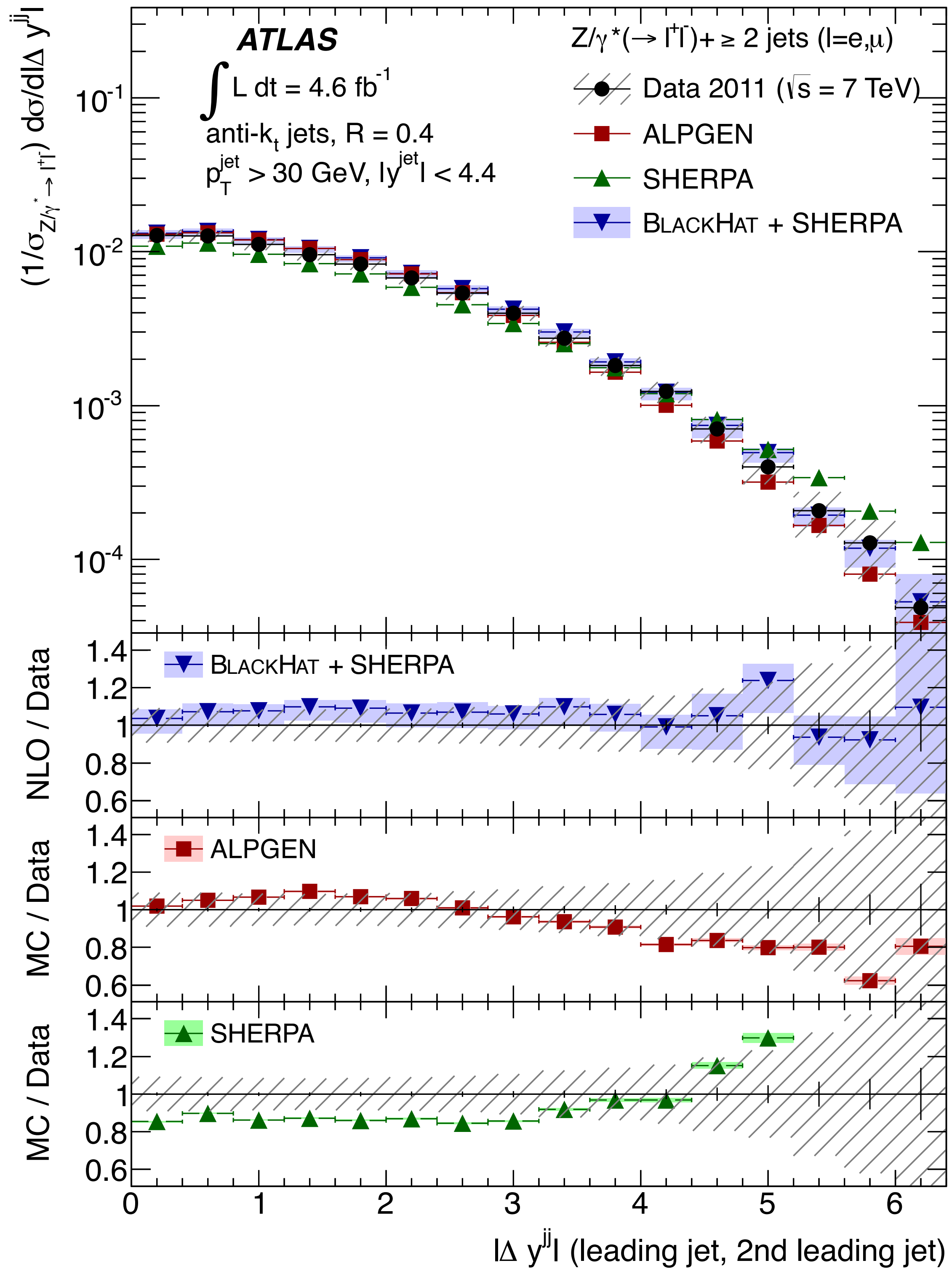
Had-Had



τ-embedded data

- Z(→ll)+jets measurements: large data/MC modelling
  - Require a sophisticated reweighing to model Z(→ττ)+jets
- Using τ-embedded Z(→μμ)+jets data:
  - very good modelling





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MVA

- Run1 $H \rightarrow \tau\tau$ heavily relies on MVA techniques
  - Improves the sensitivity from 2.5σ (cut-based) to 3.5σ
  - BDT trained to separate H(125) from the background, but also MissingMassCalculator, offline (and online!) BDT for tau ID, …
- Higgs ML challenge
- New techniques could be investigated:
  - Deep Neural Networks are becoming more and more popular (winner of the Higgs ML challenge).
    - Potential applications in ATLAS: energy calibration, particle ID, jet substructure, sig/bkg separation…
  - Matrix Element techniques: expensive computing needs are becoming reachable with GPU clusters

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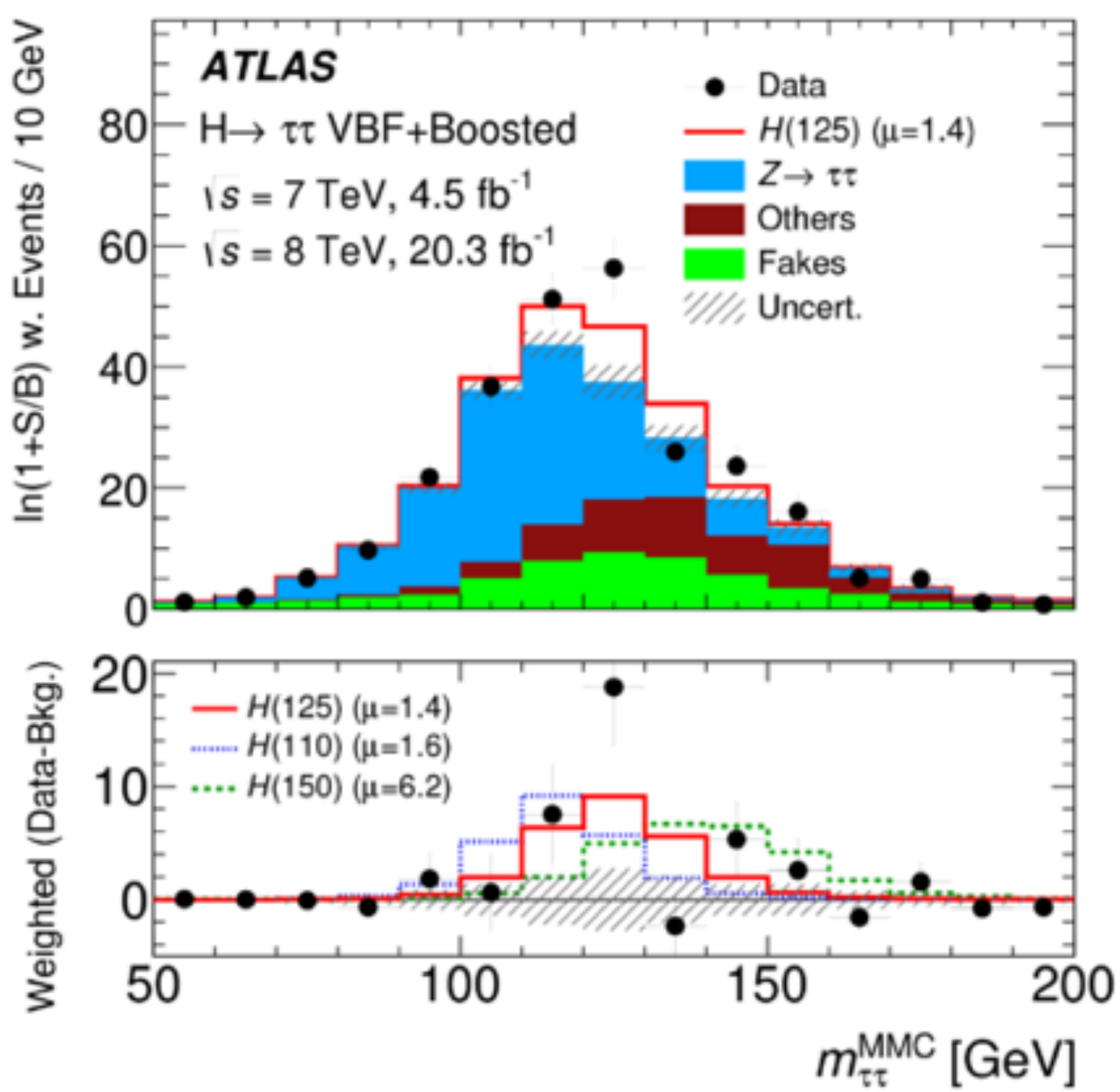
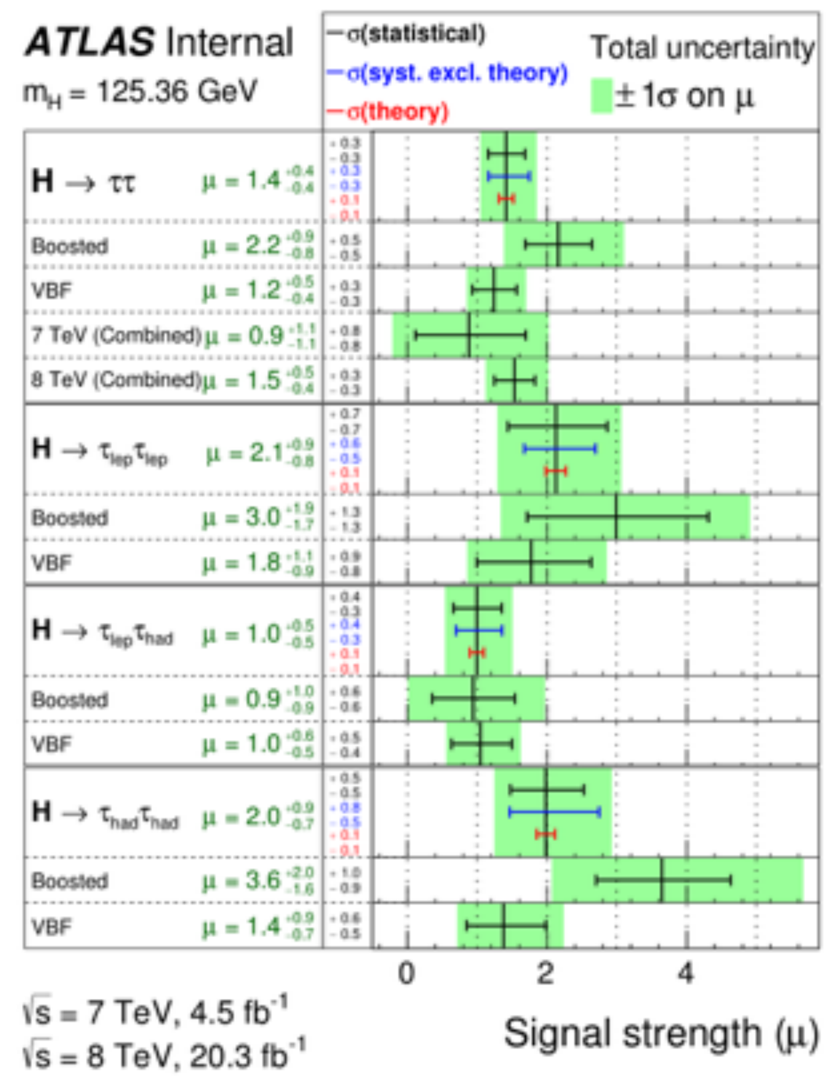
Run 1 Analysis: results

$$\mu = 1.42\,^{+0.27}_{-0.26}\,(\text{stat.})\,^{+0.33}_{-0.25}\,(\text{syst.}) \pm 0.1\,(\text{theory syst.})$$

- Observed (expected) significance: 4.5 (3.5)σ
- Measured signal strength consistent with the SM in all channels/categories

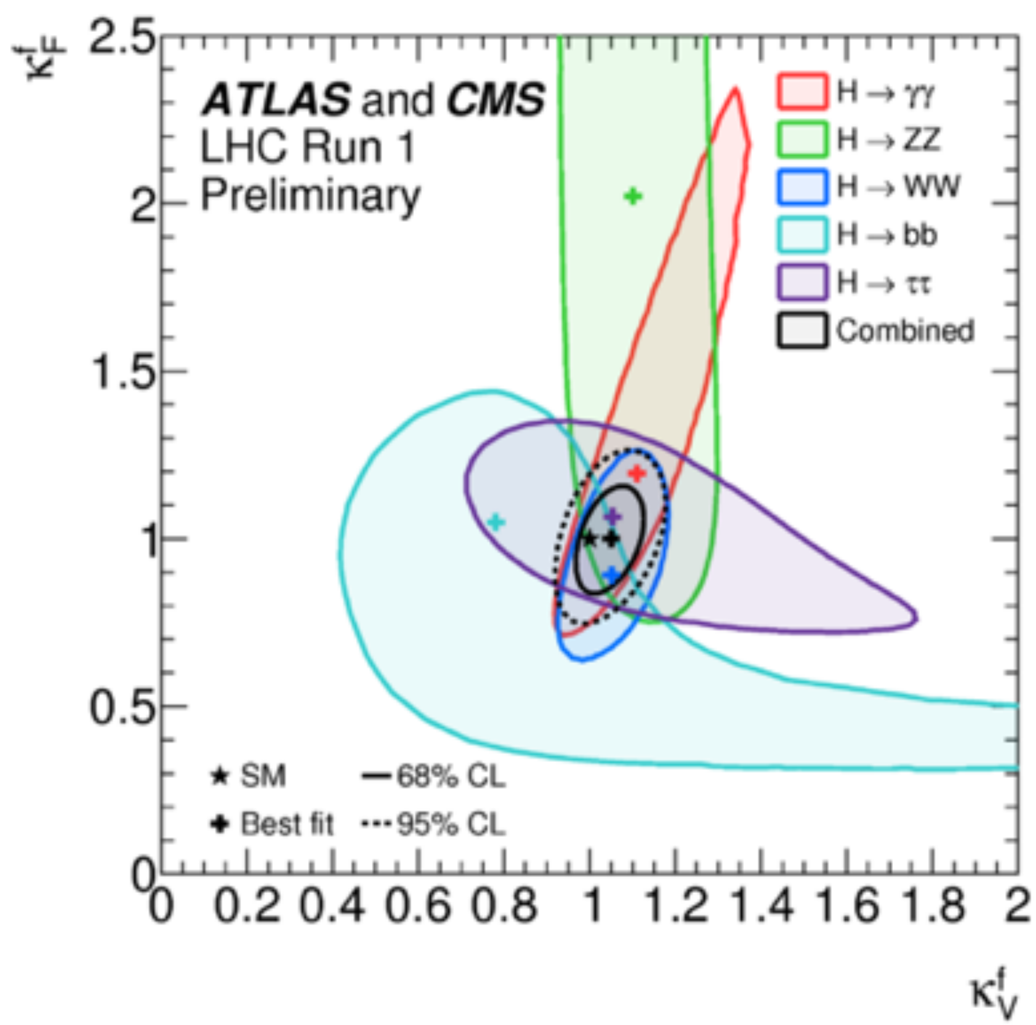


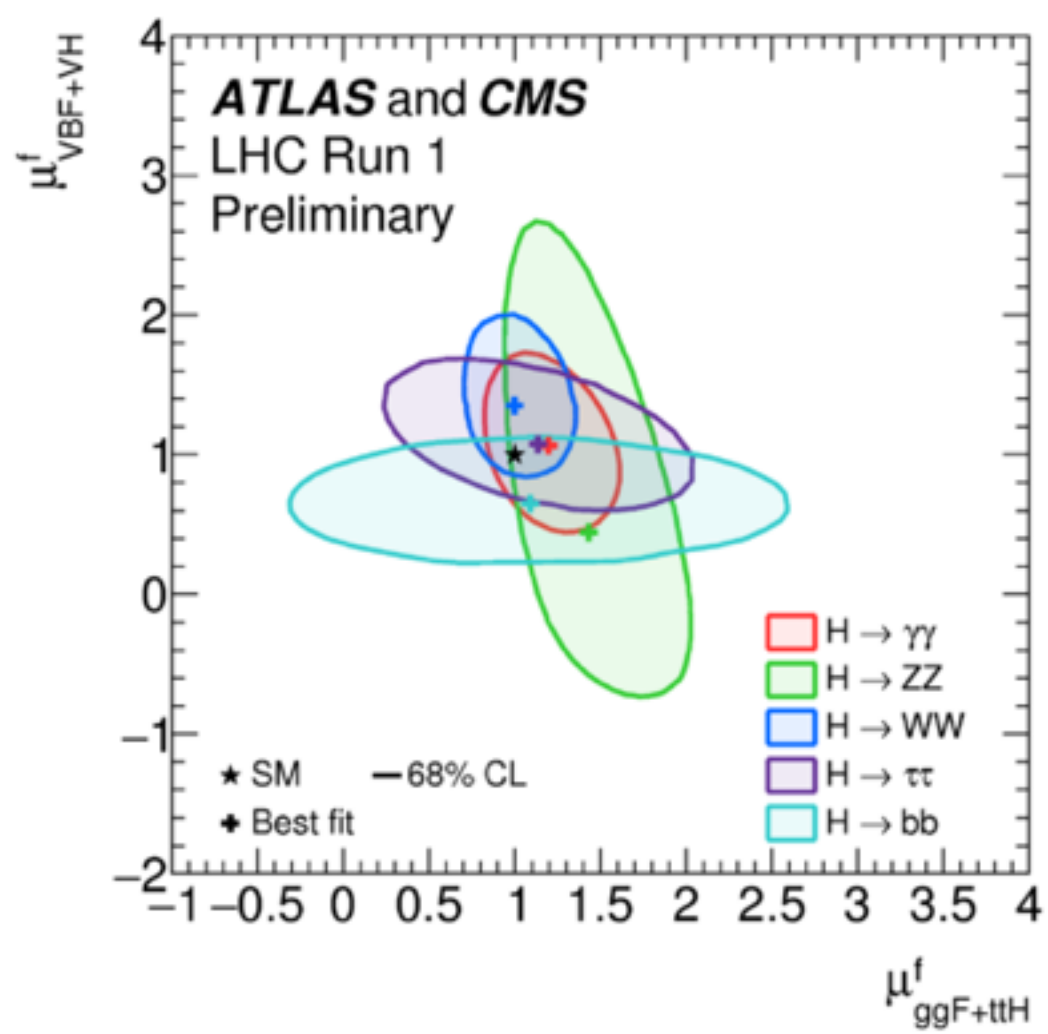


ATLAS-CONF-2015-044

ATLAS+CMS Higgs combination

- Combining with CMS, claim discovery (>5σ) of the tau coupling to the 125 GeV Higgs
- $H \rightarrow \tau\tau$ brings strong constraints on k_F
- Similar constraint to $H \rightarrow WW$ to the VBF production mode.





H→ττ prospectives: Run2 and beyond

- Extension of the SM:
    - high mass search in the ττ final states
    - Lepton Flavour Violation
- Test the SM with **new** and **more precise** Higgs property measurements
    - Observation of the VH production mode
    - Inclusive and differential cross-section
    - Hff CP quantum numbers
    - HVV and ggH couplings in VBF
- Higgs self-coupling

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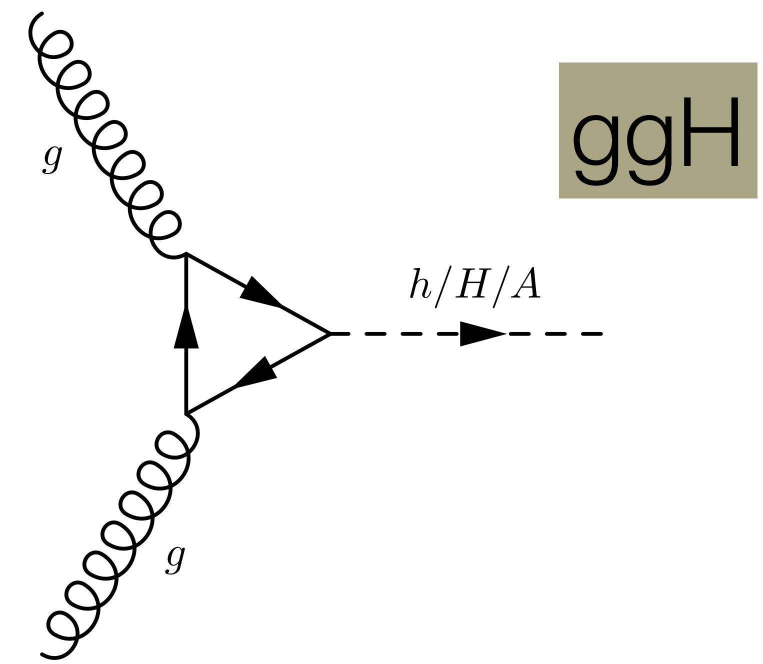
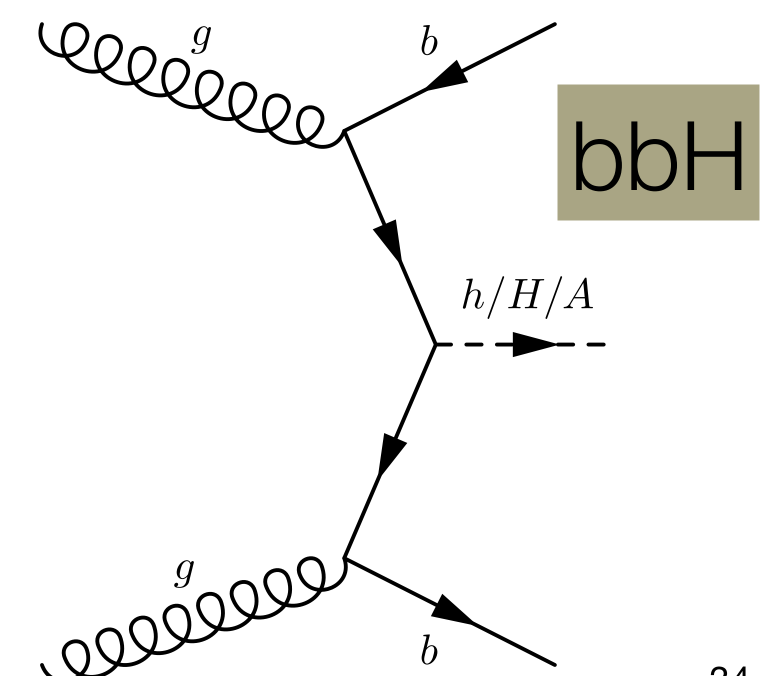
ATLAS-CONF-2015-061

Search for High Mass Neutral Higgs

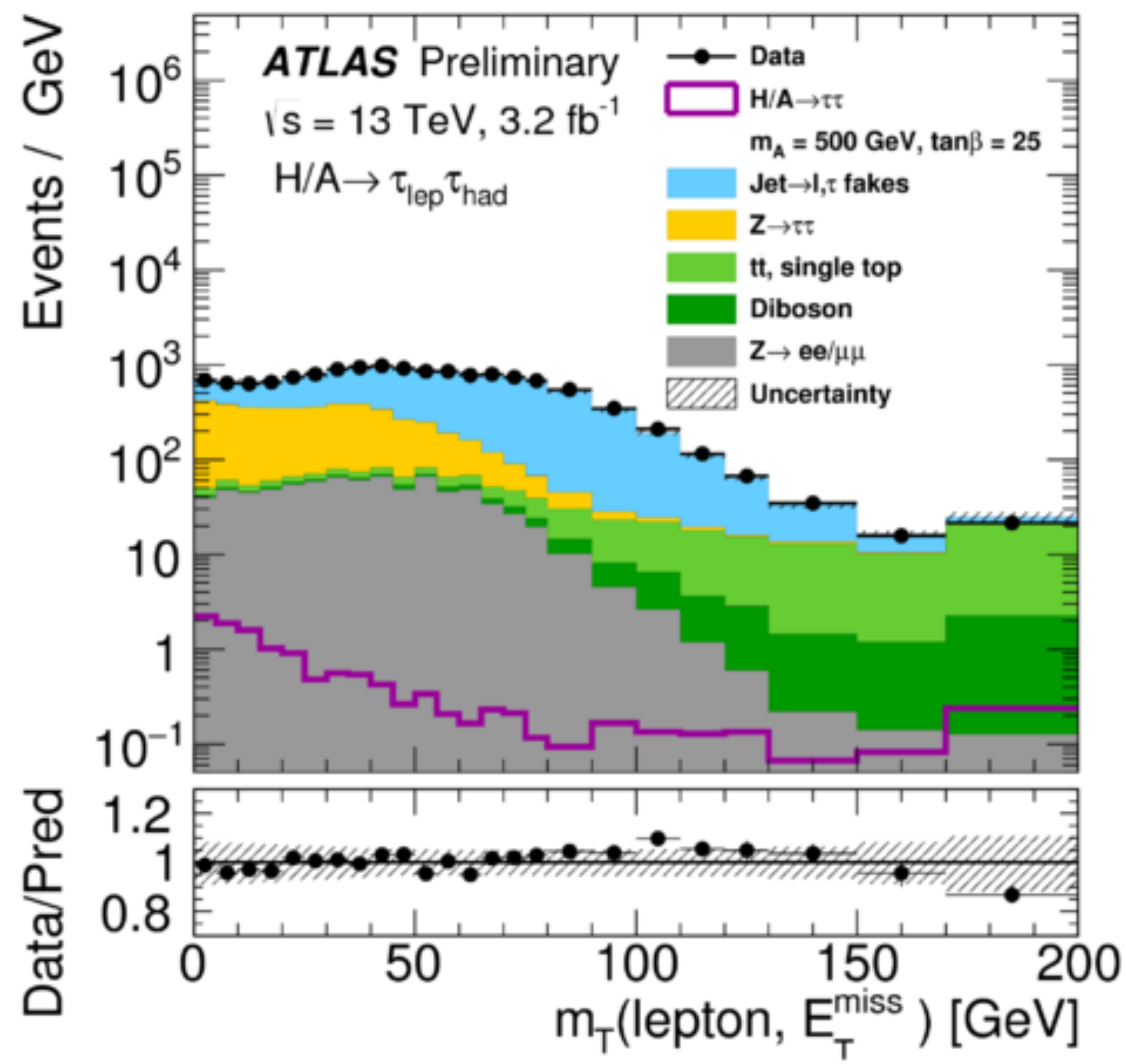
- First ATLAS run2 results with taus
- Many extensions of the SM predict an extended Higgs sector
- MSSM favours down-type fermion couplings at high tanβ
- ggH and associated-b productions are considered in this search





Search for High Mass Neutral Higgs

- Search performed in the hadronic channels
- Fake background estimated using data-driven techniques
- Z+jets, top and diboson from simulation



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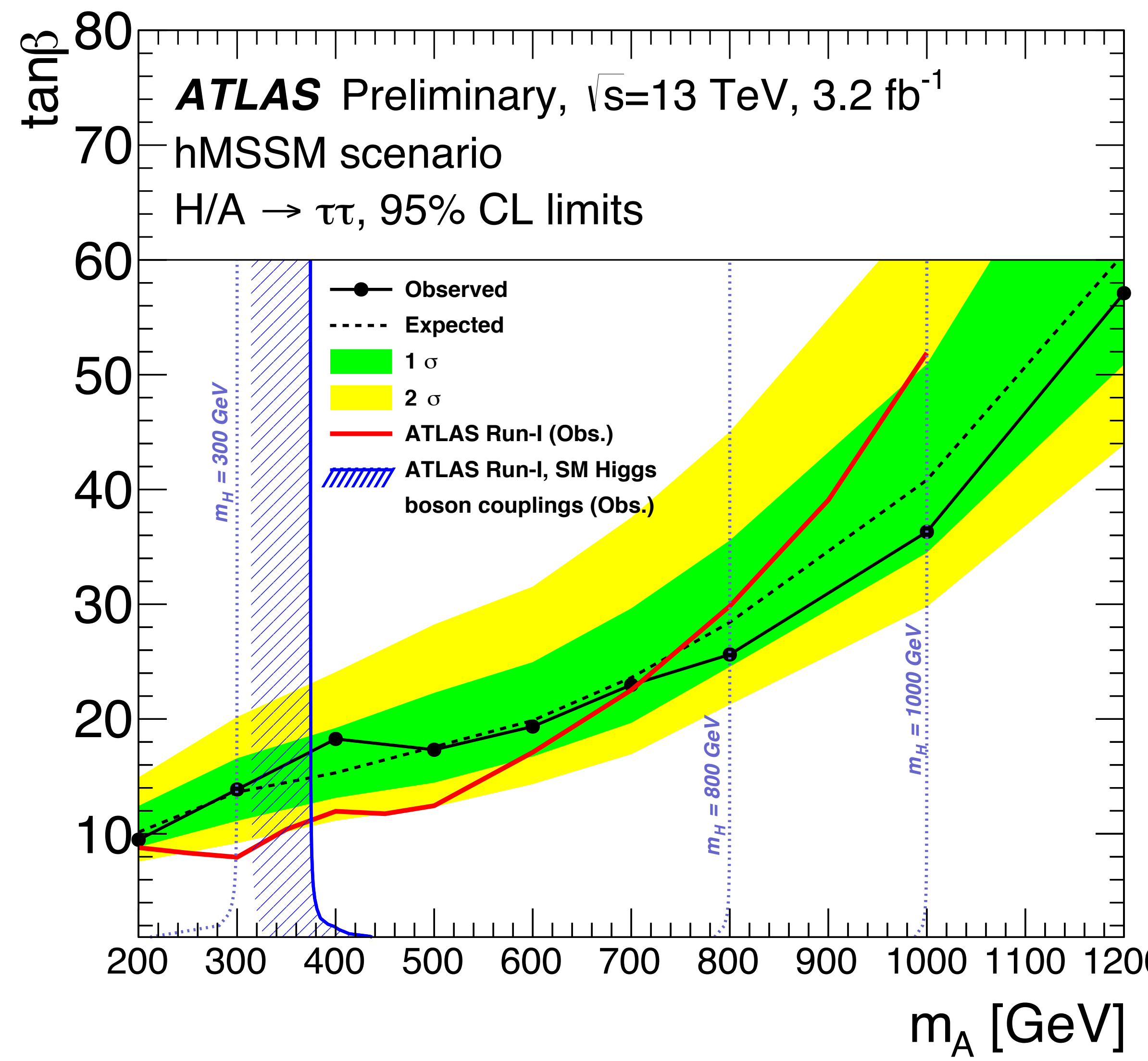
Search for High Mass Neutral Higgs

- In MSSM m_h^{mod+}, the strongest constraint is tanβ>10 for m_A = 200 GeV
- For m_A > 700 GeV, the run1 result is superseded.



Lepton Flavour Violation: $H \to \tau\mu$

- LFV couplings can occur in many SM extensions
- $BR(H \to e\mu) < O(10^{-8})$: strong constraints from $\mu \to e\gamma$ searches
- $BR(H \to \tau\mu) < O(10\%)$: loosely constrained from $\tau \to \mu\gamma$ searches
- CMS $H \to \tau\mu$ search has a slight excess of 2.4σ. They exclude $BR(H \to \tau\mu) < 1.57\%$ at 95% CL

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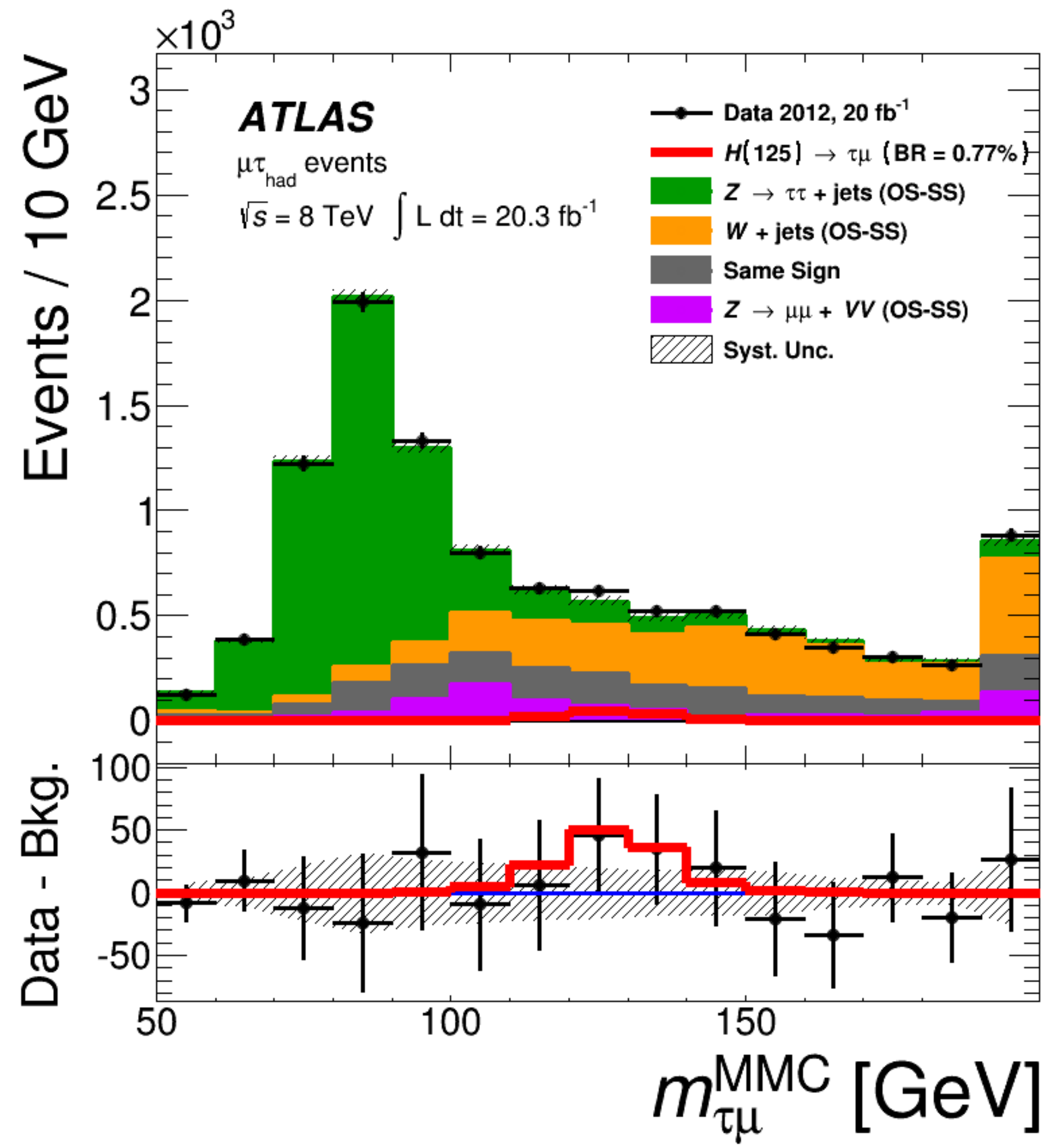
Lepton Flavour Violation: H→τμ

- Analysis performed in the $\tau_h\mu$ final state
- Background estimation similar to the H→ττ analysis, dedicated tune of the mass estimator
- Slight excess corresponding to 1.3σ
- BR(H→τμ) < 1.85% at 95% CL. Weaker than CMS limit but no combination (yet) with the eμ channel.



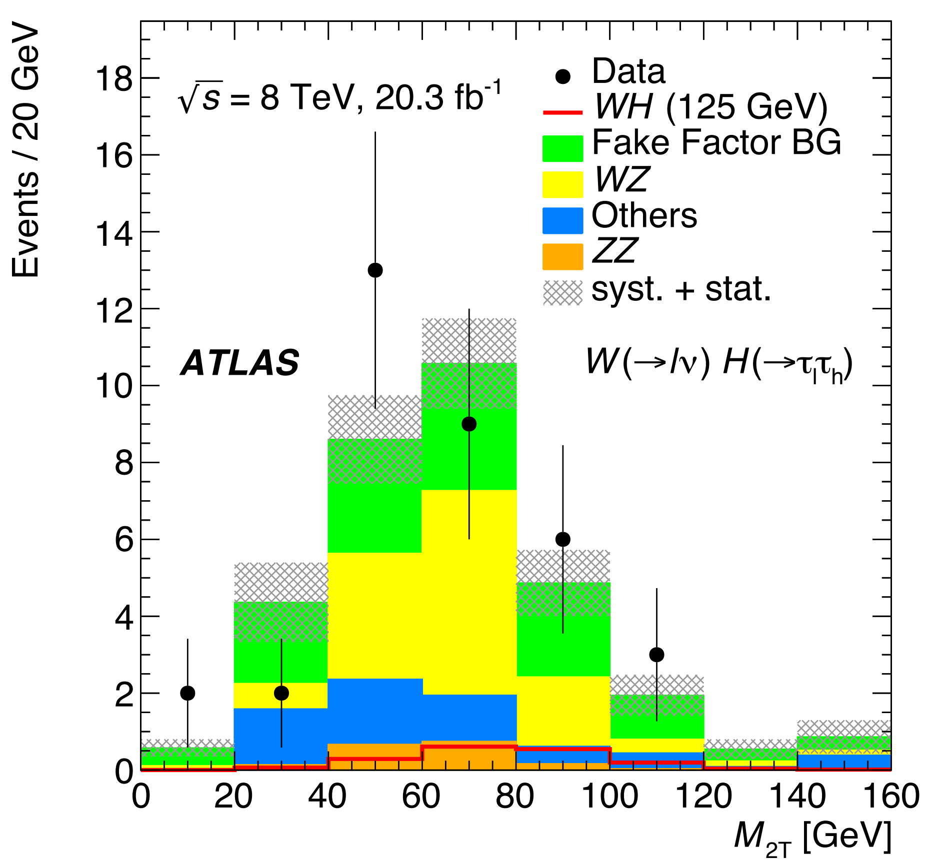
$H \rightarrow \tau\tau$ prospectives: Run2 and beyond

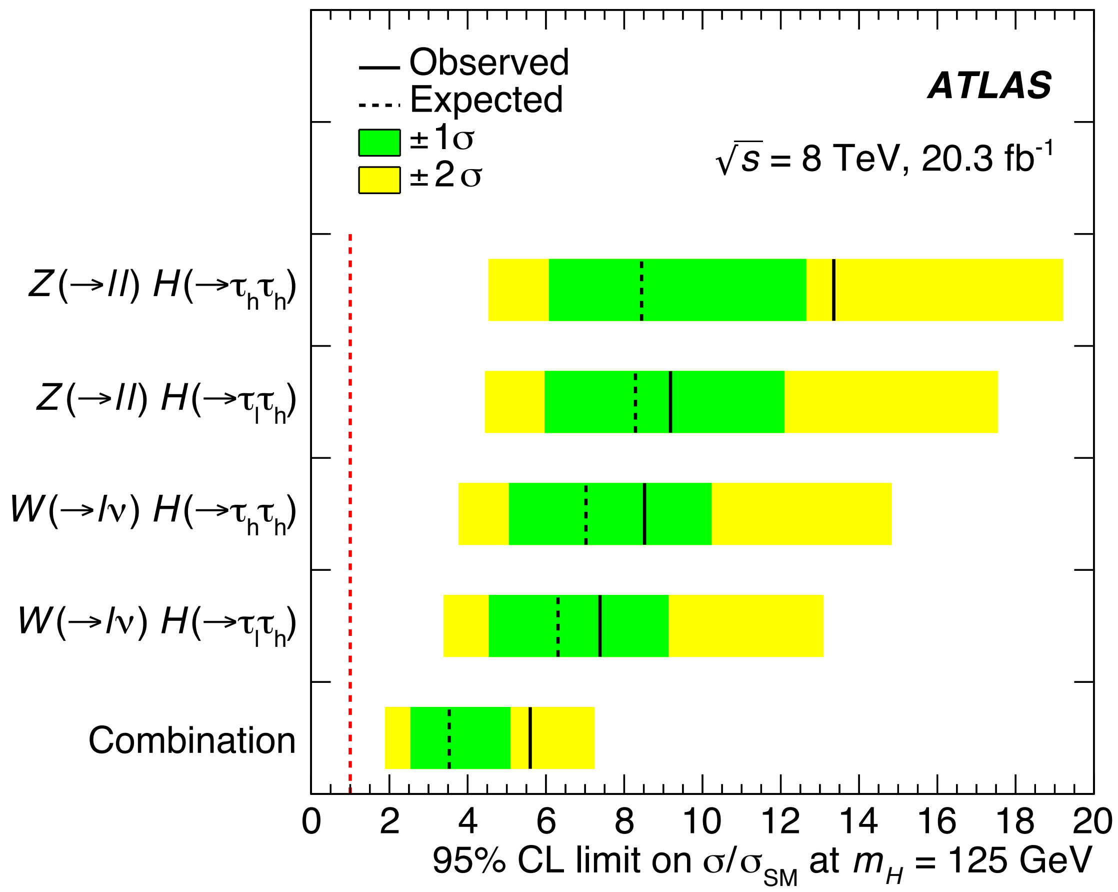
- Extension of the SM:
  - high mass search in the $\tau\tau$ final states
  - Lepton Flavour Violation
- Test the SM with **new** and **more precise** Higgs property measurements
  - Observation of the VH production mode
  - Inclusive and differential cross-section
  - Hff CP quantum numbers
  - HVV and ggH couplings in VBF
- Higgs self-coupling

arXiv:1511.08352

Higgs properties: VH→ττ

- Search carried in hadronic channels VH→ττ, still completely stat-dominated
- WH→$\tau_h\tau_l$ is the most sensitive channel (also the least affected by Fakes)
- Run2 dataset should provide observation/exclusion of VH→ττ at the SM expected rate

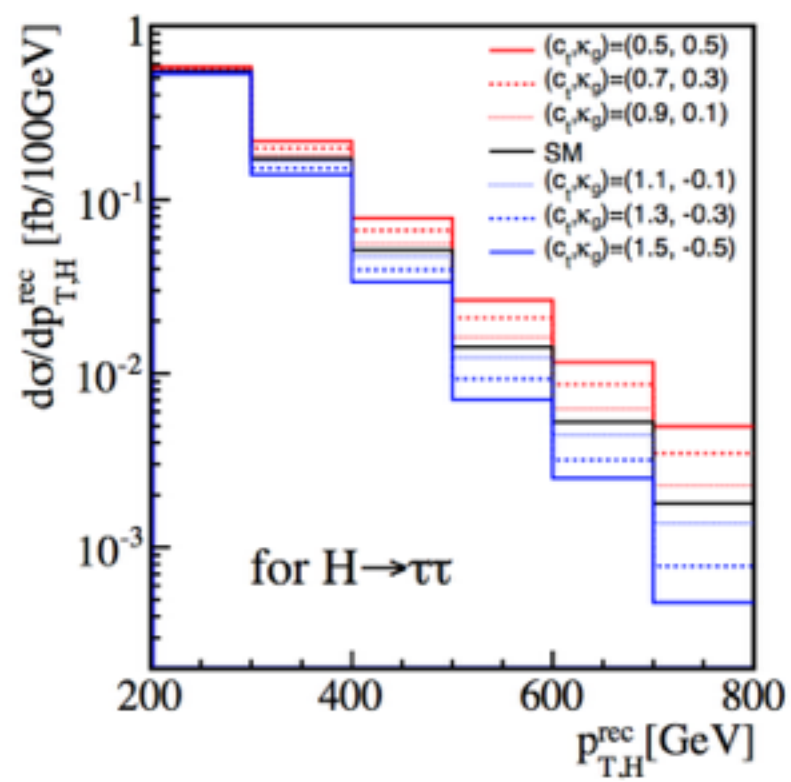




Higgs properties: incl. and diff. cross-sections

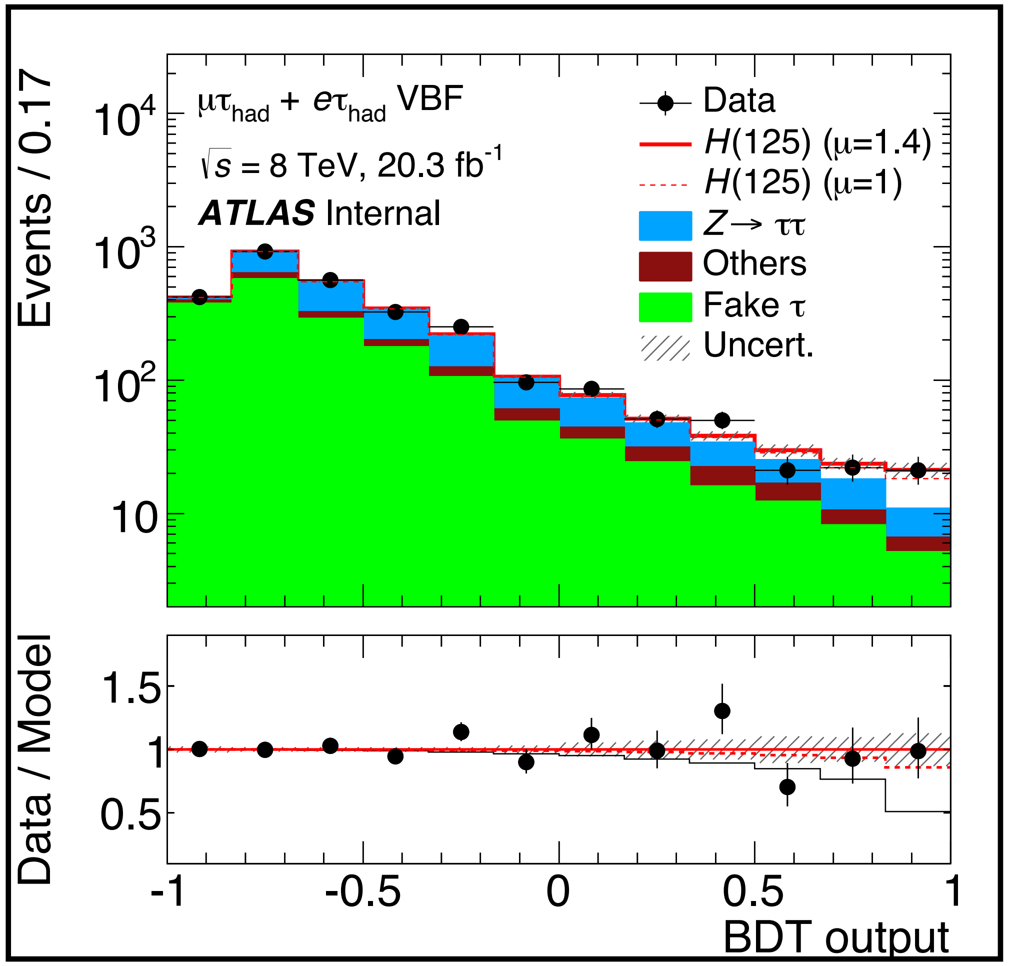
- Get the 5σ (inclusively and per production mode)!
- Strong VBF signal in H→ττ
  - Good place to measure fiducial corrections that still have large O(6-10%) systematic uncertainties
- Probe High pT regime of the Higgs boson
- H+jets: Break degeneracy with a high-pt jet that resolves the top loop but not the NP-loop

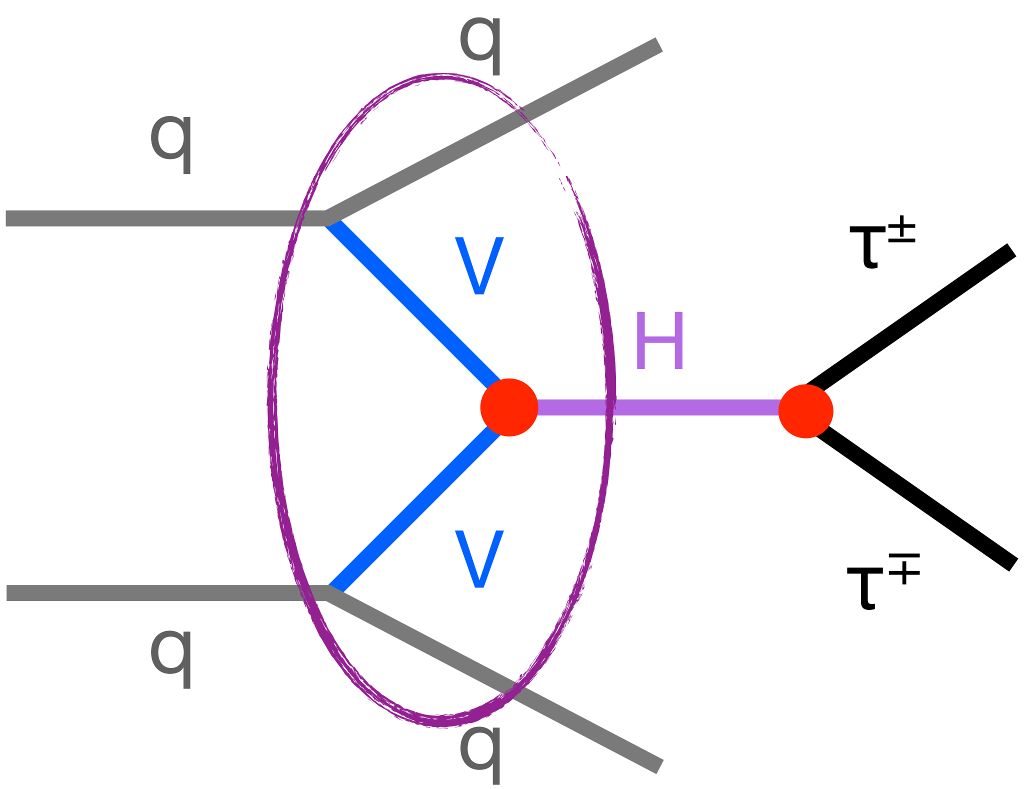
arxiv:1405.4295



Higgs properties: HVV vertex

- Probe HVV tensor structure by exploiting large VBF signal
- Run1 analysis in preparation:
  - Cut on the BDT score to select high VBF Higgs purity events

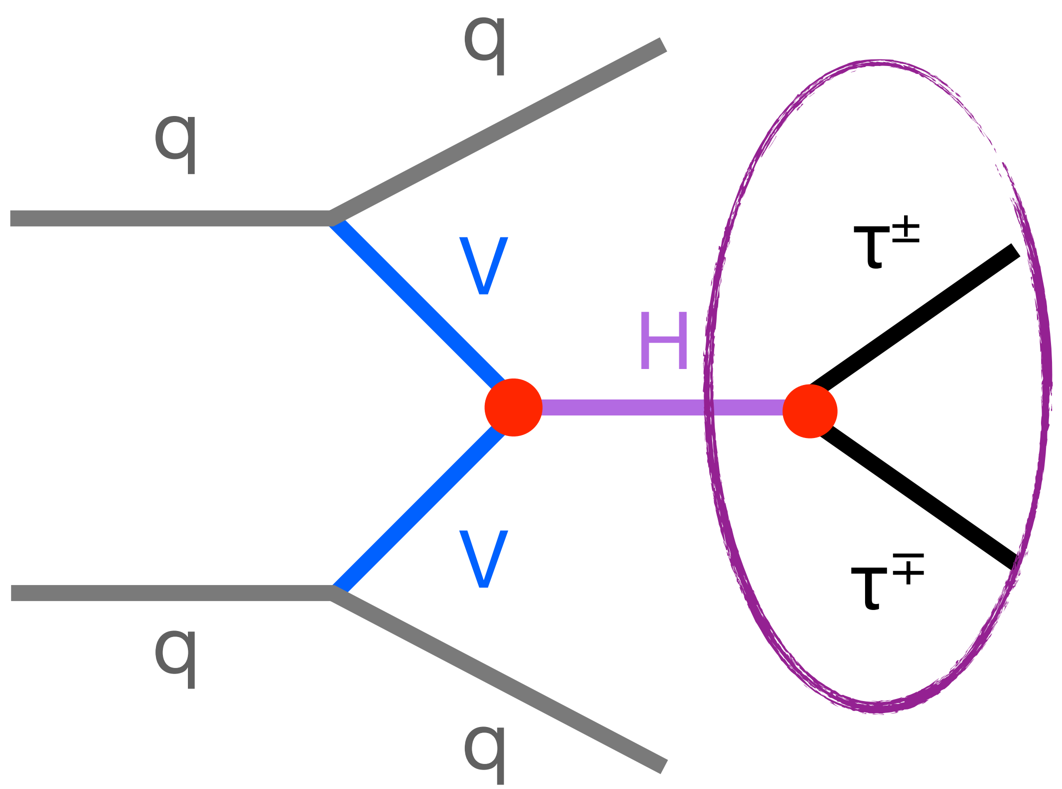


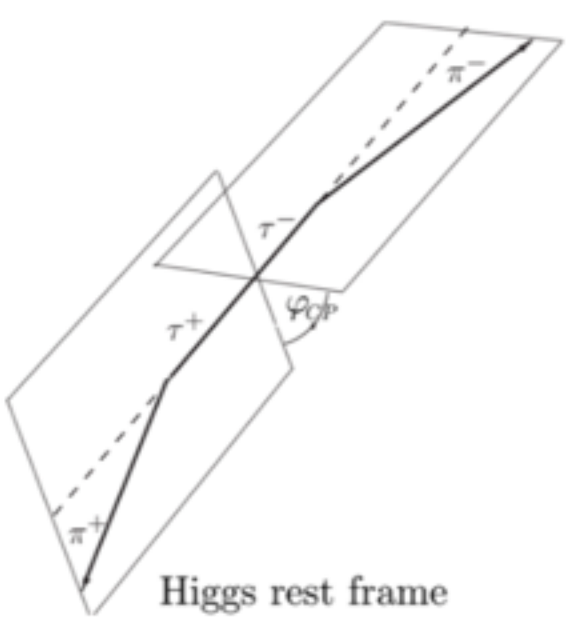


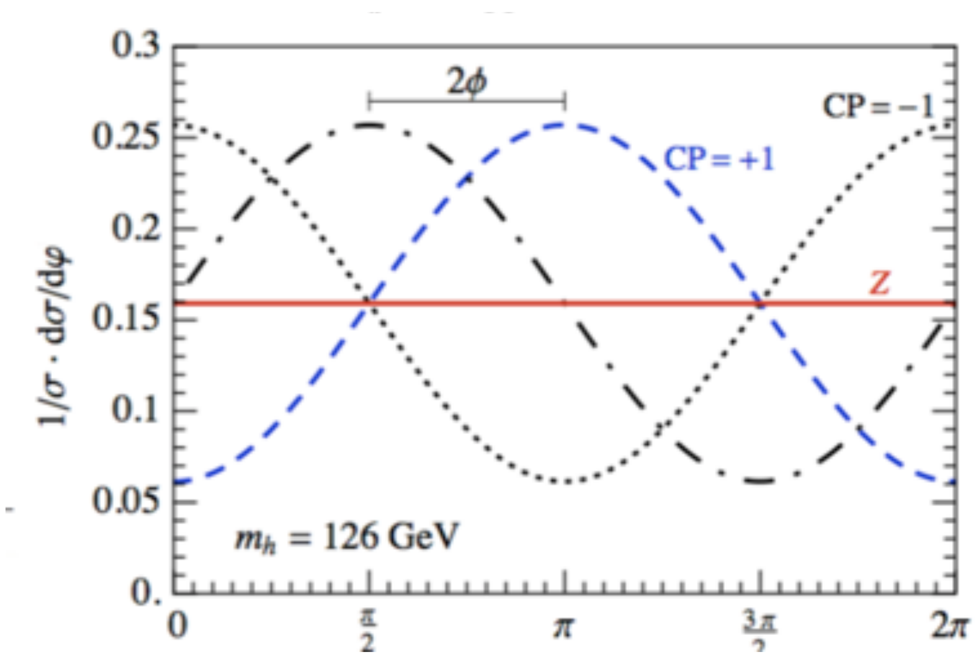
Proof of principle, analysis to be repeated with Run2 data

Higgs properties: Hff vertex

- Test CP of the Yukawa Hff coupling
- Access through spin correlation and angular distribution of tau decay products
- New Tau Particle flow will bring:
    - Mode-specific angle calculation. For example exploit the τ→ρ decay mode







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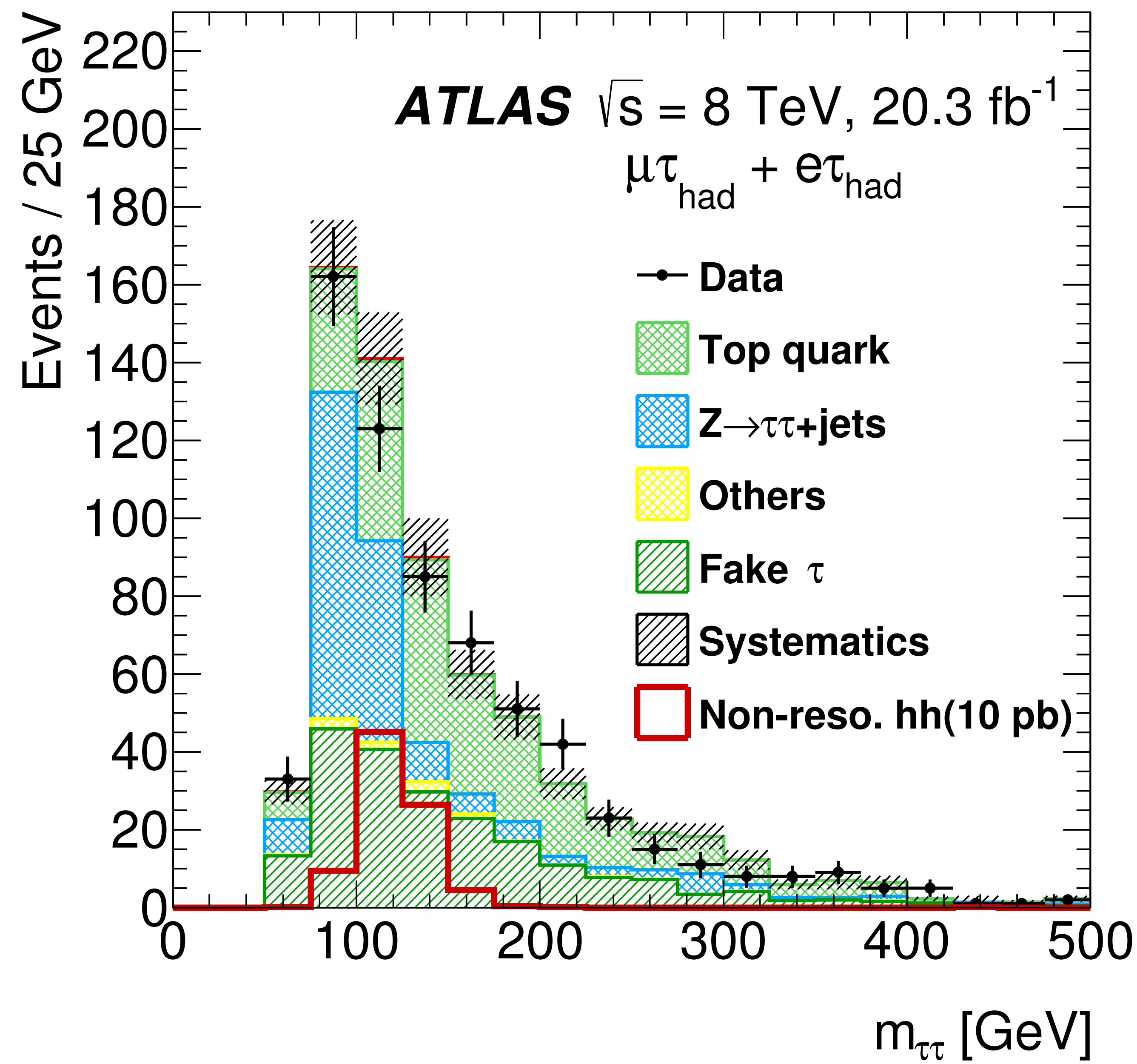
DiHiggs: HH→bbττ

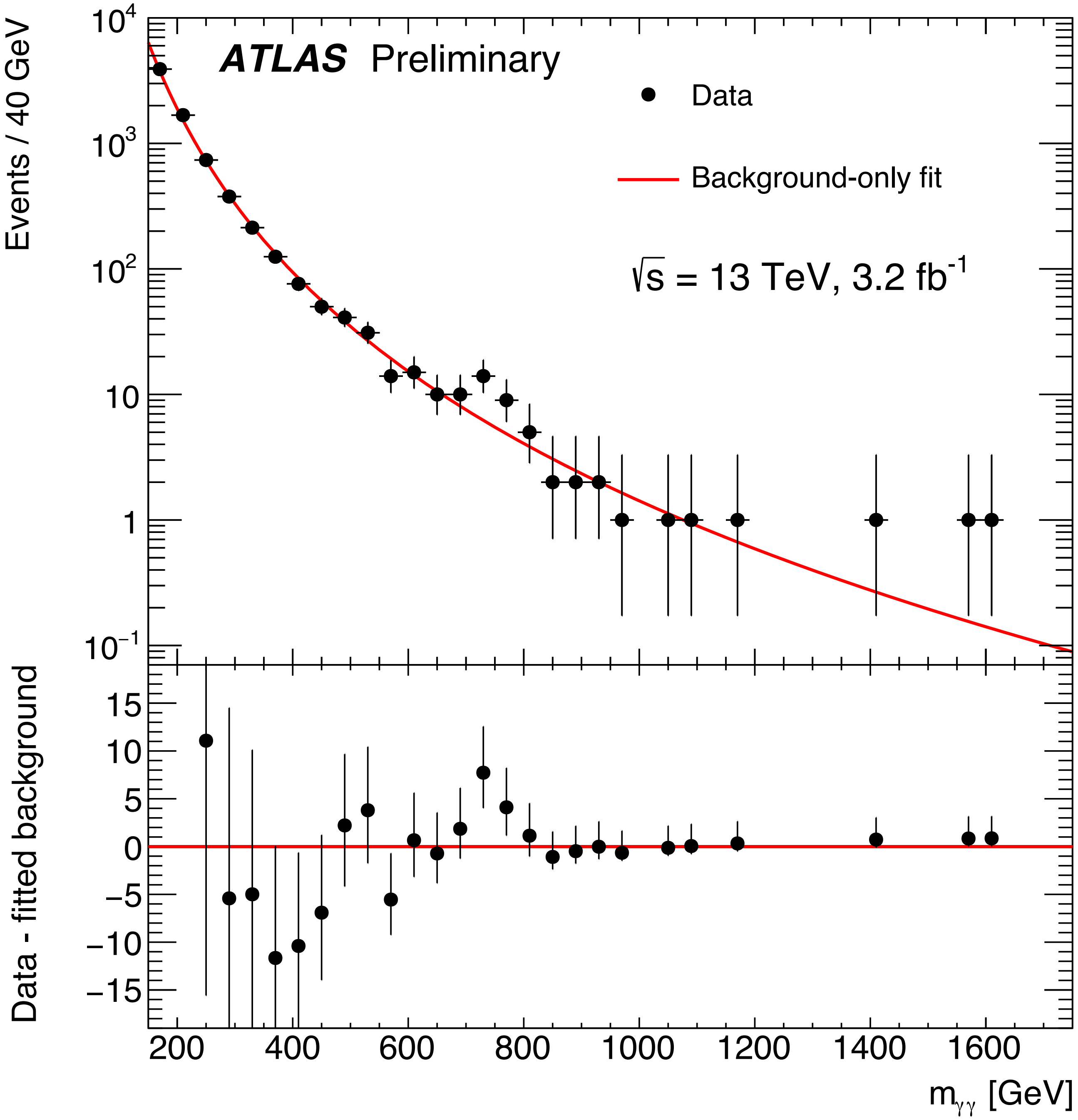
- Sensitivity to the SM not expected before HL-LHC dataset
- DiHiggs search carried in bbWW, bbγγ, bbττ and bbbb final states
- Still room for a lot of improvements with HL-LHC upgrade
  - 1MHz L0, L1 tracking
  - High eta coverage



Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

Things that go bump in the light*

- Deviation from the SM expectations observed around 750 GeV in the diphoton spectrum
- Using a narrow width resonance, the local p_0 is estimated at 3.6σ (2.0σ global)
- Width ~ 45 GeV
- Can we see it in the ditau final state?



*In Particular

Conclusion

- LHC Run1 program was very successful for tau physics
    - Observation of Higgs coupling to the tau lepton by ATLAS and CMS
- Successful energy upgrade of the LHC in 2015
    - Commissioning the tau trigger, validating the offline/online algorithms
    - Preliminary results supersede the Run1 limits on the MSSM Higgs at high $\tan\beta$
- The 2016 dataset will allow for more precise measurements in $H\rightarrow\tau\tau$
    - Stay tuned!

Additional Material

Tau Energy Scale Uncertainties

- Tau Energy Scale uncertainties are calculated using the deconvolution method

- Uncertainties on particle energies taken from E/p measurements in low mu runs, test beam studies and simulation are propagated to the constituents of hadronic tau decays

Source	Uncertainty [%]
Response	1.2–2.5
Detector model	0.3–2.5
UE	0.2–2.4
Pile-up	0.5–2.0
Non-closure	0.5–1.2
Shower model	0.0–2.0
Total	1.8–3.9