Jet performance in ATLAS; First 13 TeV jet results

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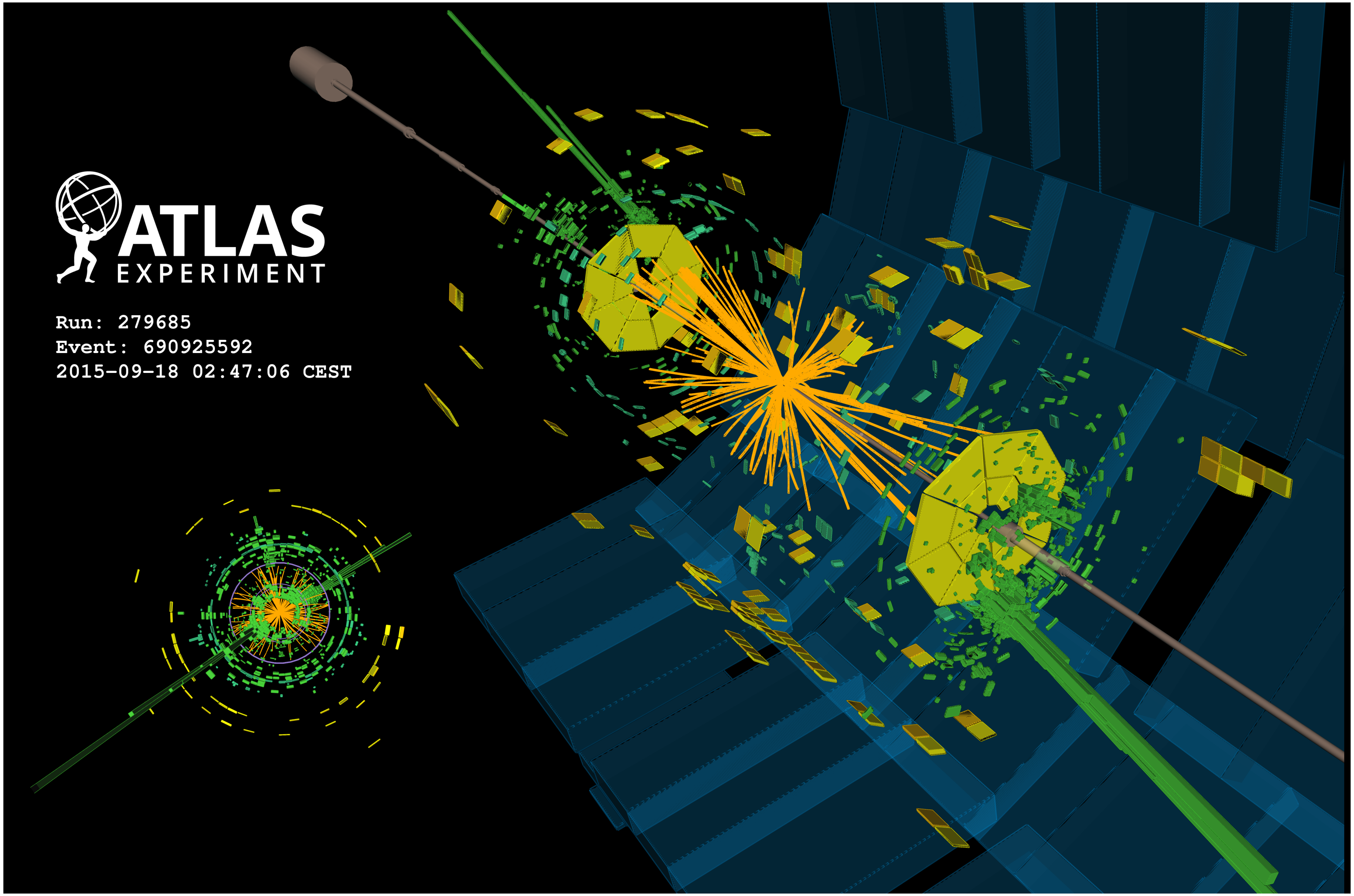
Particle Physics Seminar, University of Birmingham, 9th December 2015

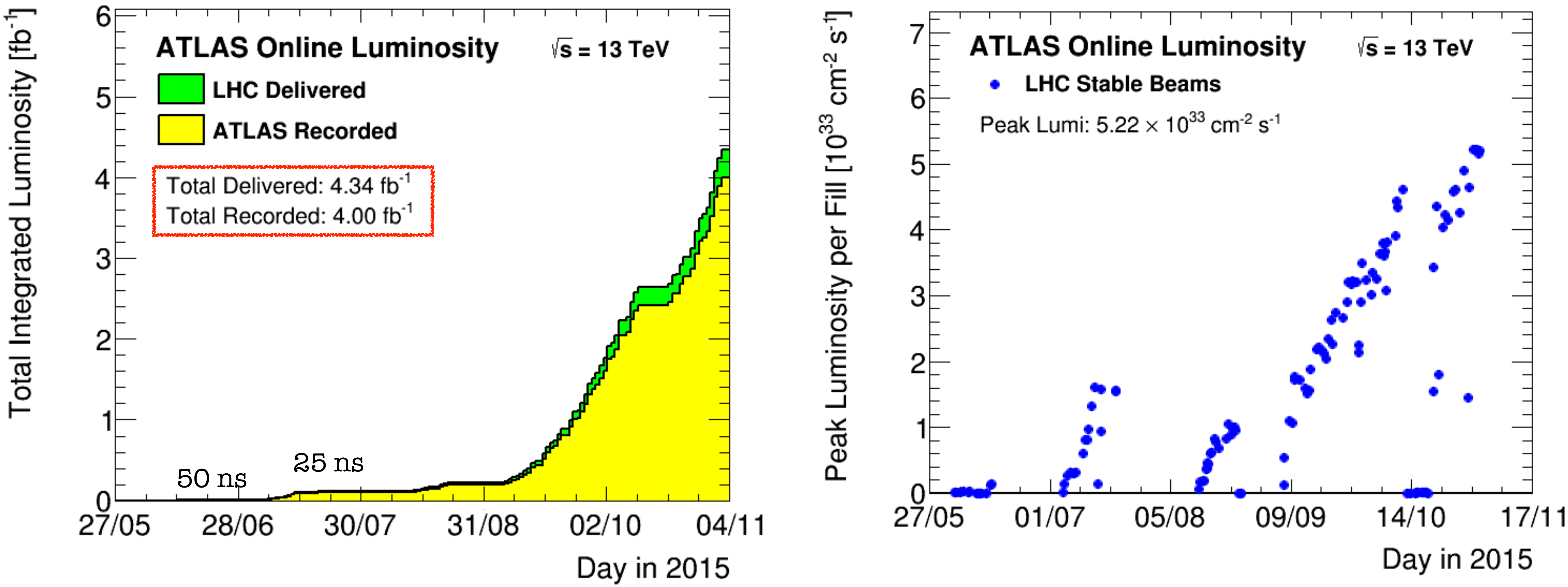
- **LHC Run 2 since June 2015: centre of mass energy at 13 TeV for the first time in particle physics history**

Unprecedented centre of mass energy



- A high-mass **dijet** event collected by ATLAS in September, 2015.
- The two central high-p_T jets have an **invariant mass of 8.8 TeV**

LHC Run 2, $\sqrt{s} = 13$ TeV

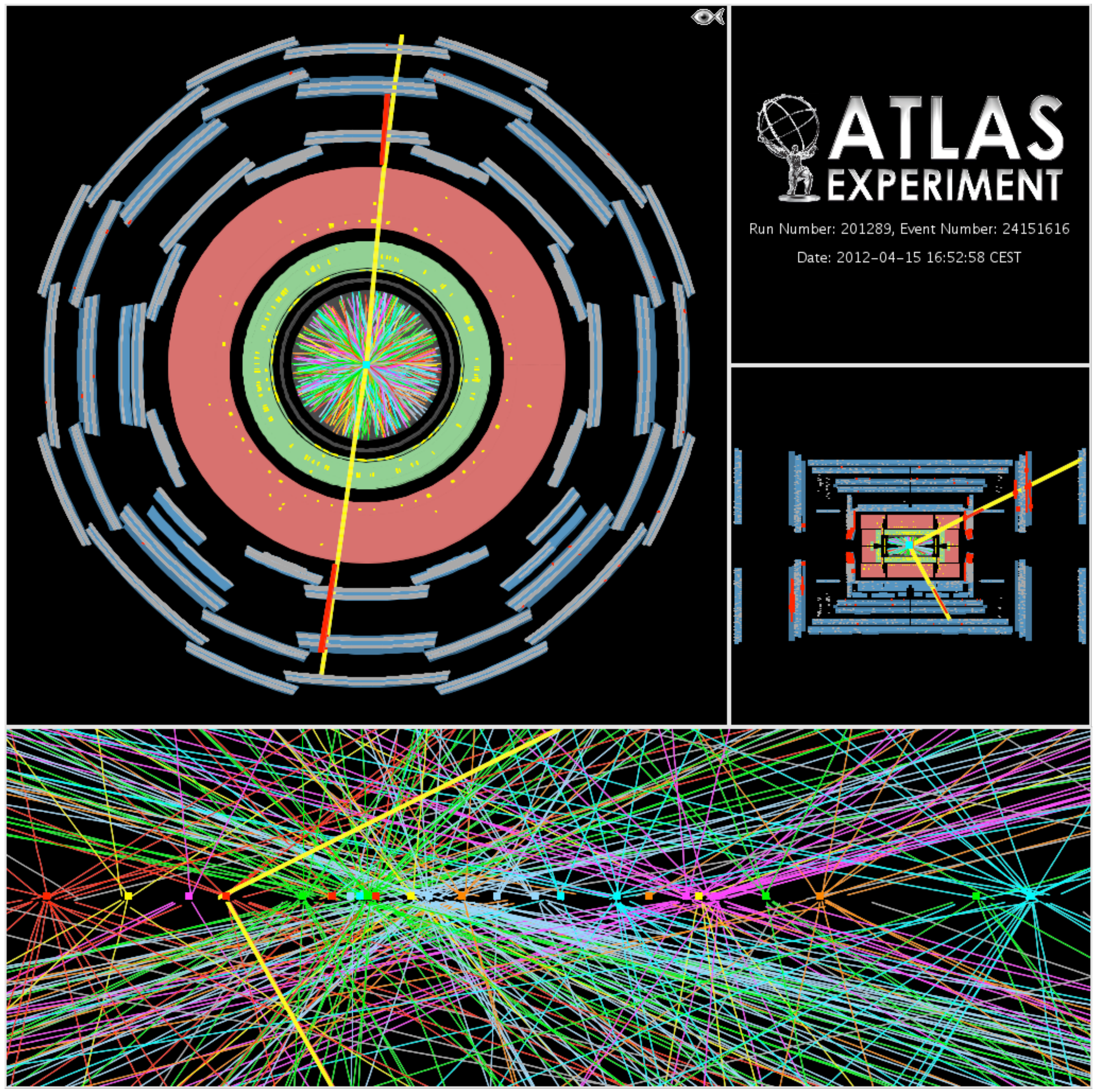


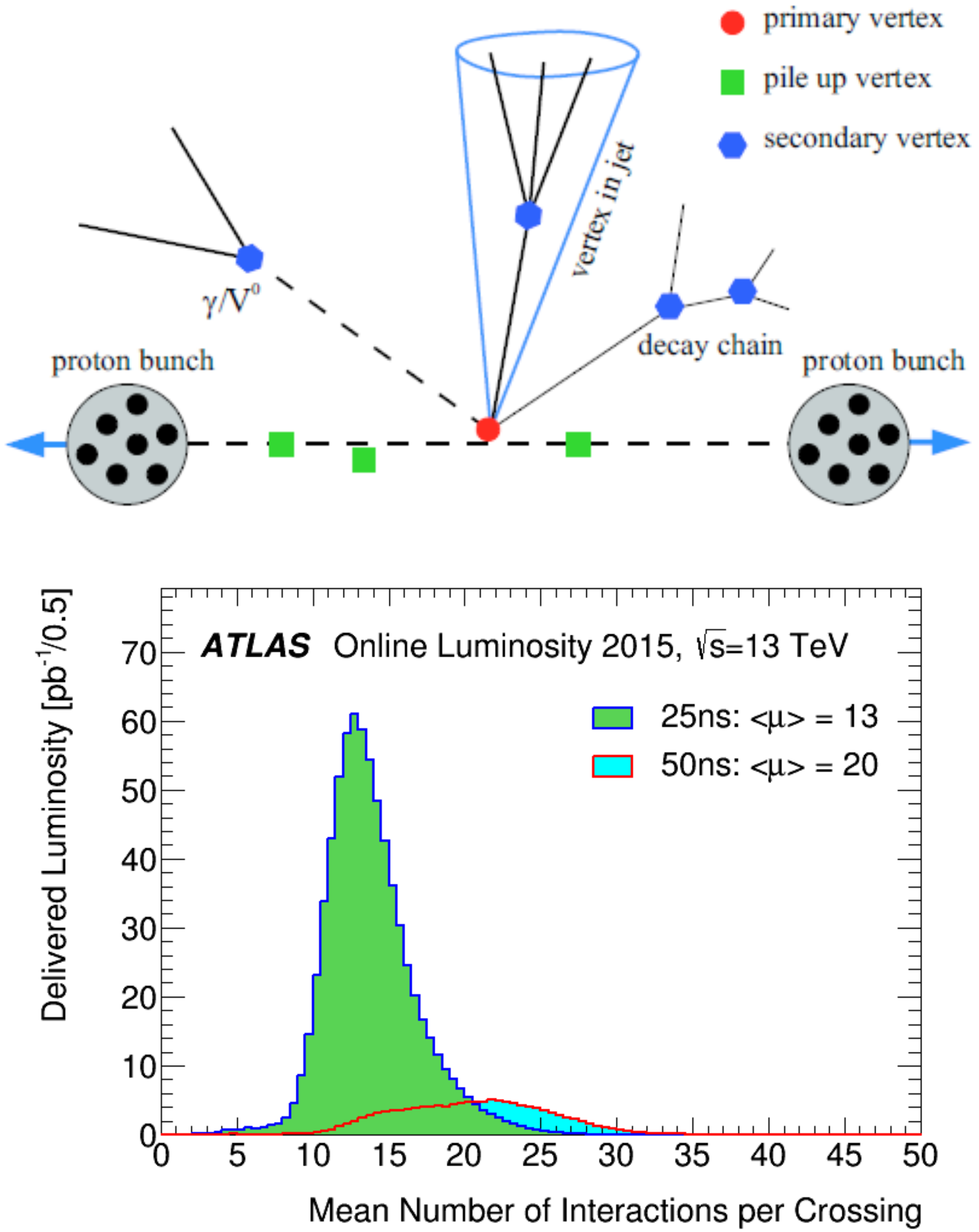
2015 peak luminosity 5.22 nb/s: ≃ 6 $Z \to ll$ events/s

- 50ns and 25ns bunch crossing data taking
- **Most of Run 2 Published results based on early 50ns data (~80 pb-1)**
- **25ns data results are around the corner** *(see end of the year CERN seminar on Tuesday 15th of December)*

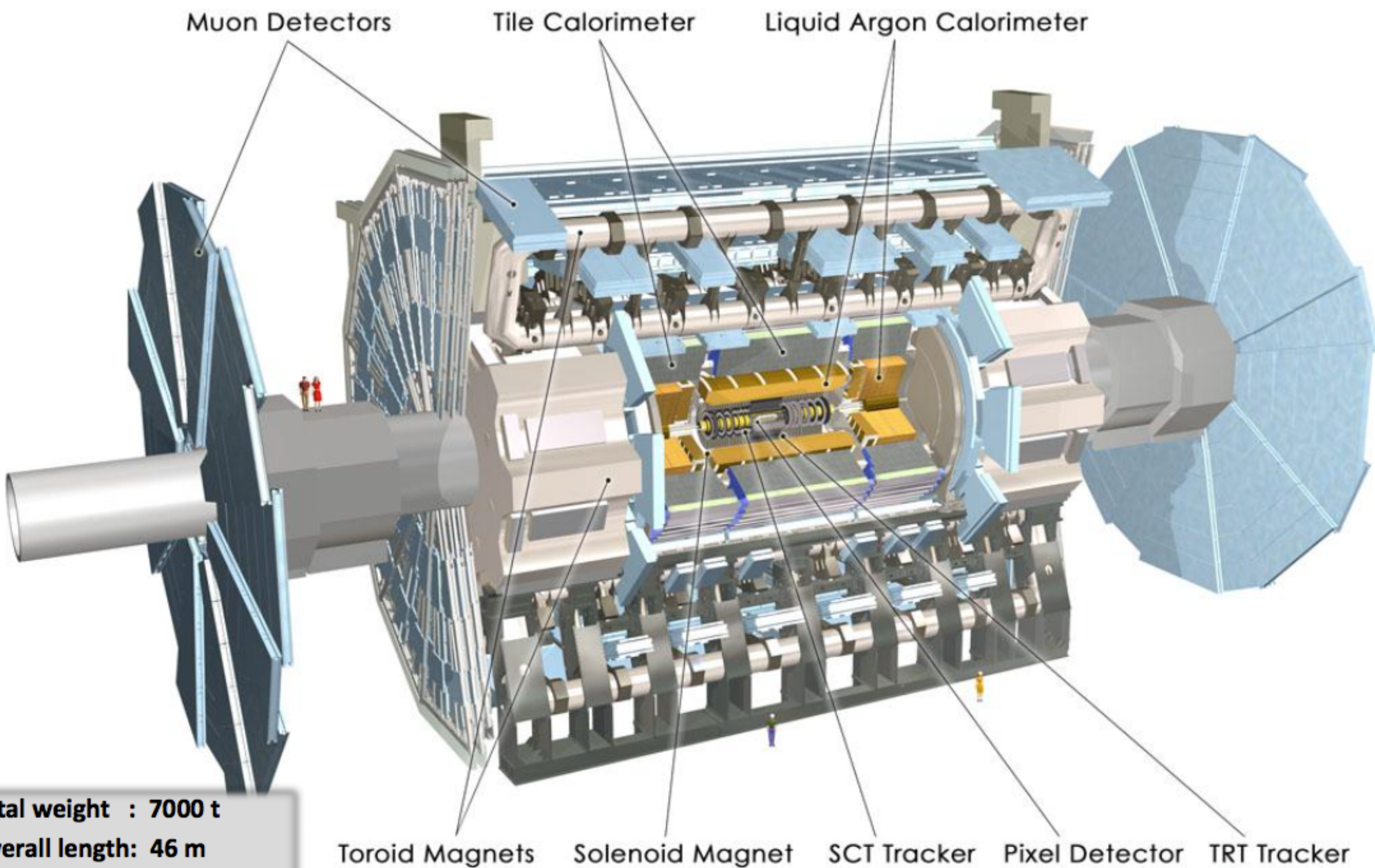
The price of high Luminosity: Pile-up

Z->μμ candidate event with 25 reconstructed vertices



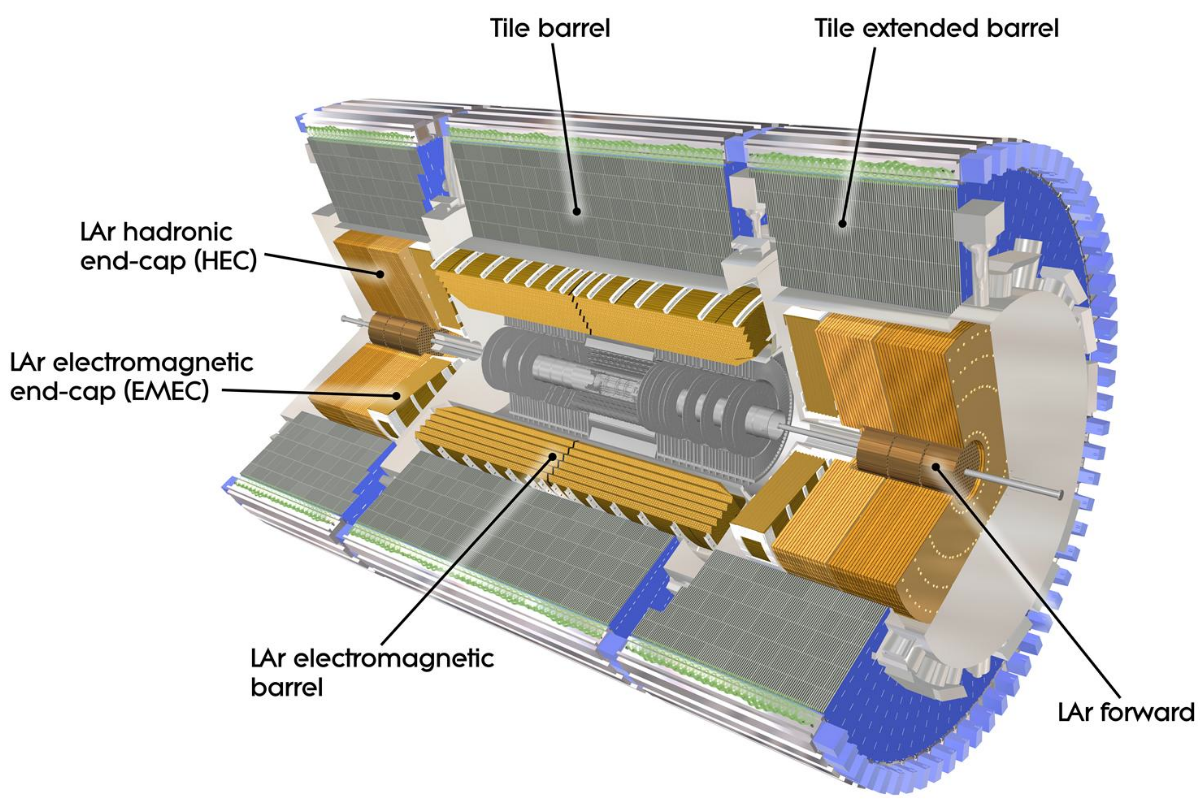


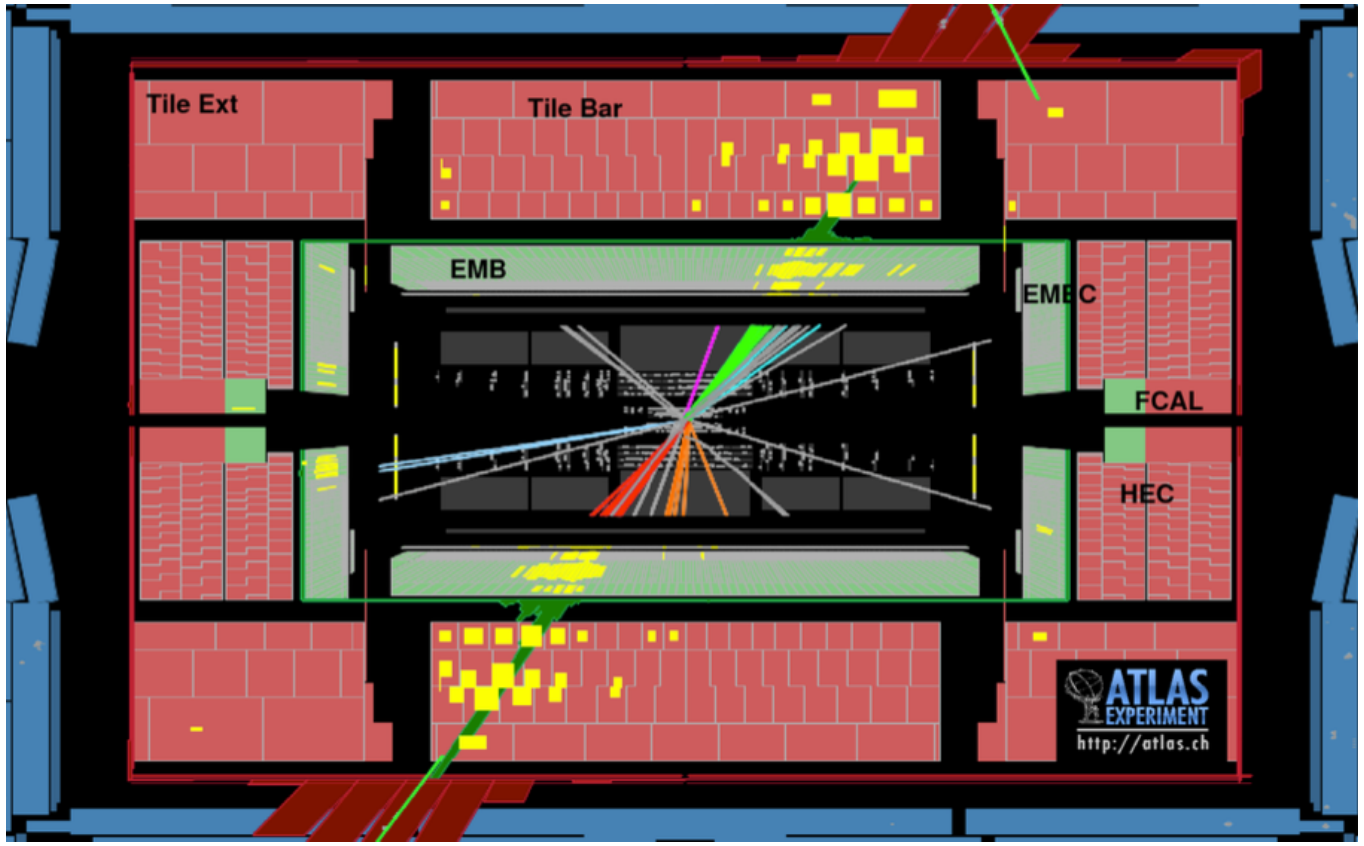
ATLAS



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

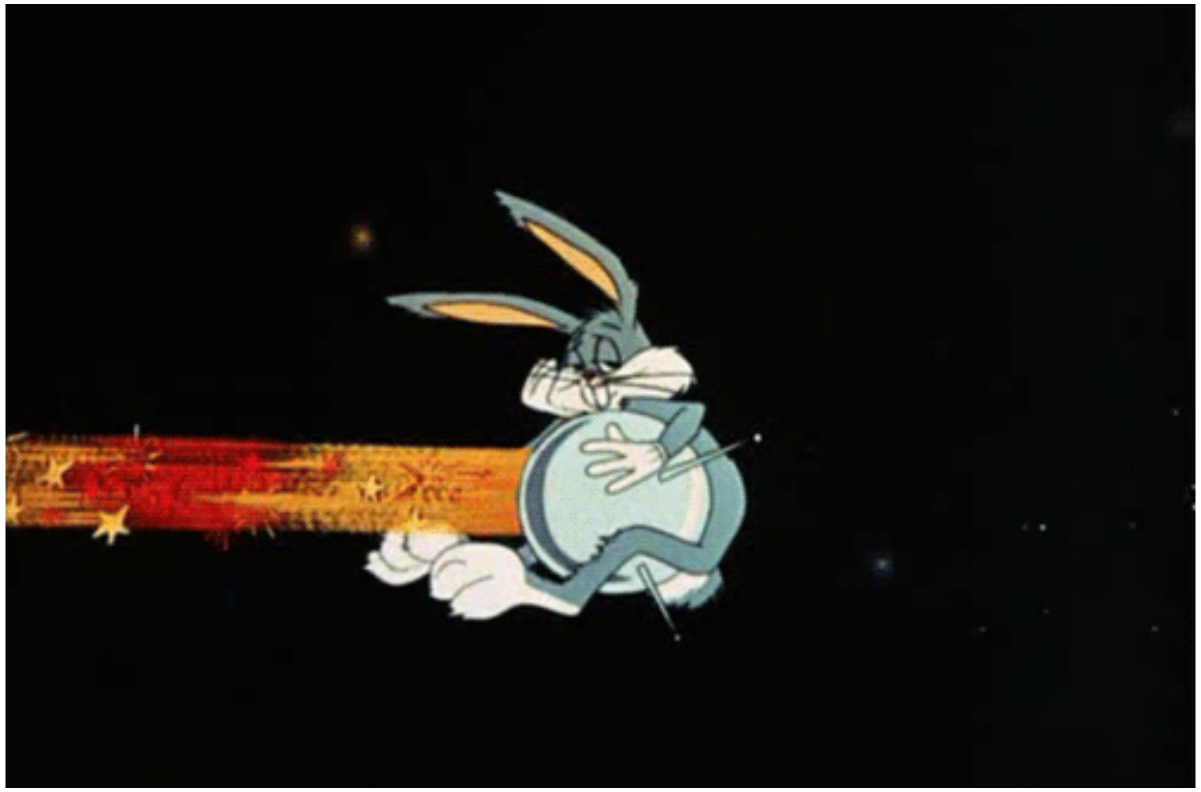
The ATLAS Calorimeter



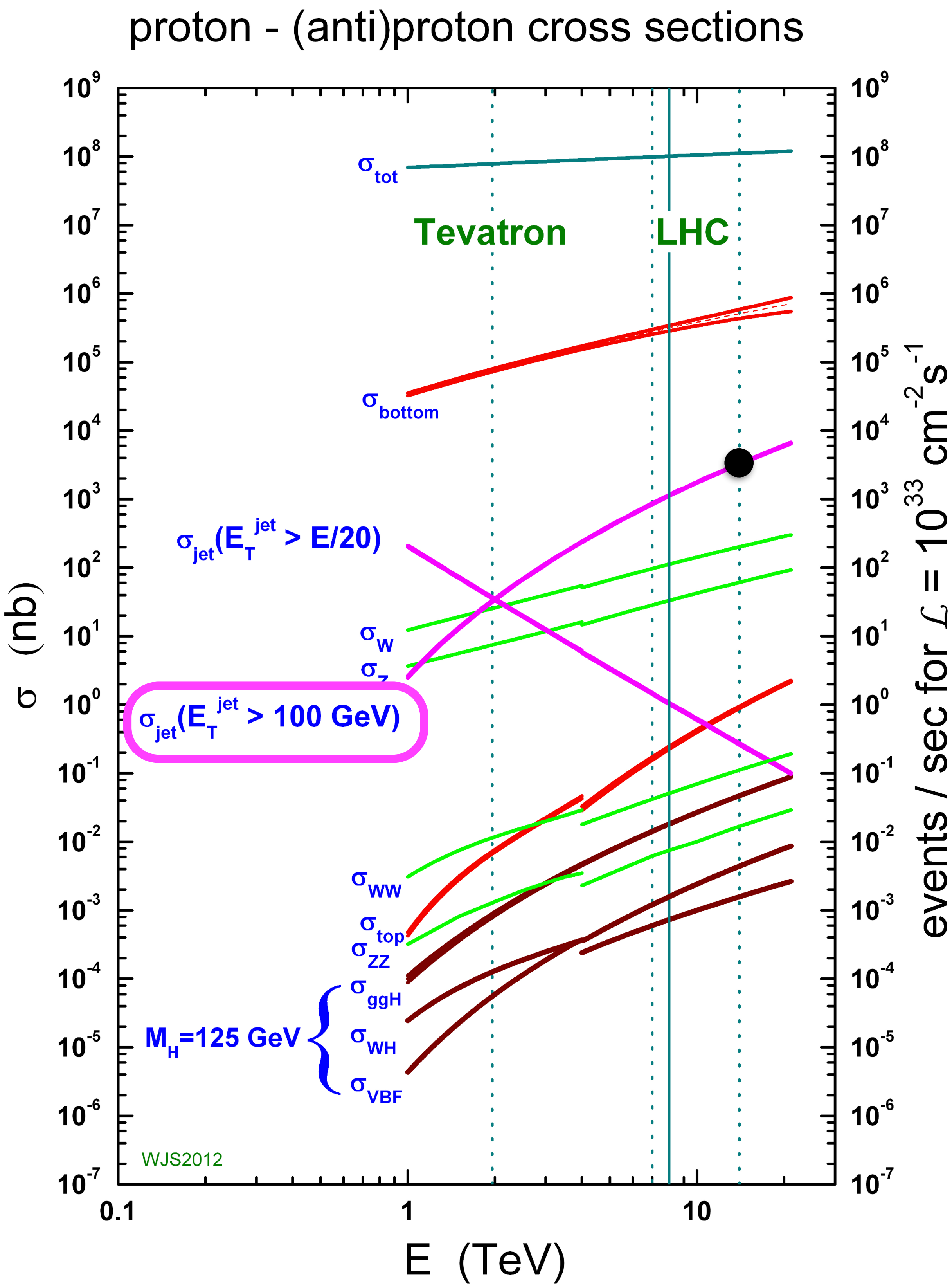


- **Large full coverage** calorimeter system: **|η|<4.9**
- Mixed technologies to match precision requirements
  - ✦ **Electromagnetic:** LAr/lead
  - ✦ **Hadronic central** iron/scintillator with tiled sampling structure - **Hadronic** LAr/copper
  - ✦ **Forward** LAr/copper-tungsten
- Highly granular detector: **~200k** readout channels

Jets and their performance

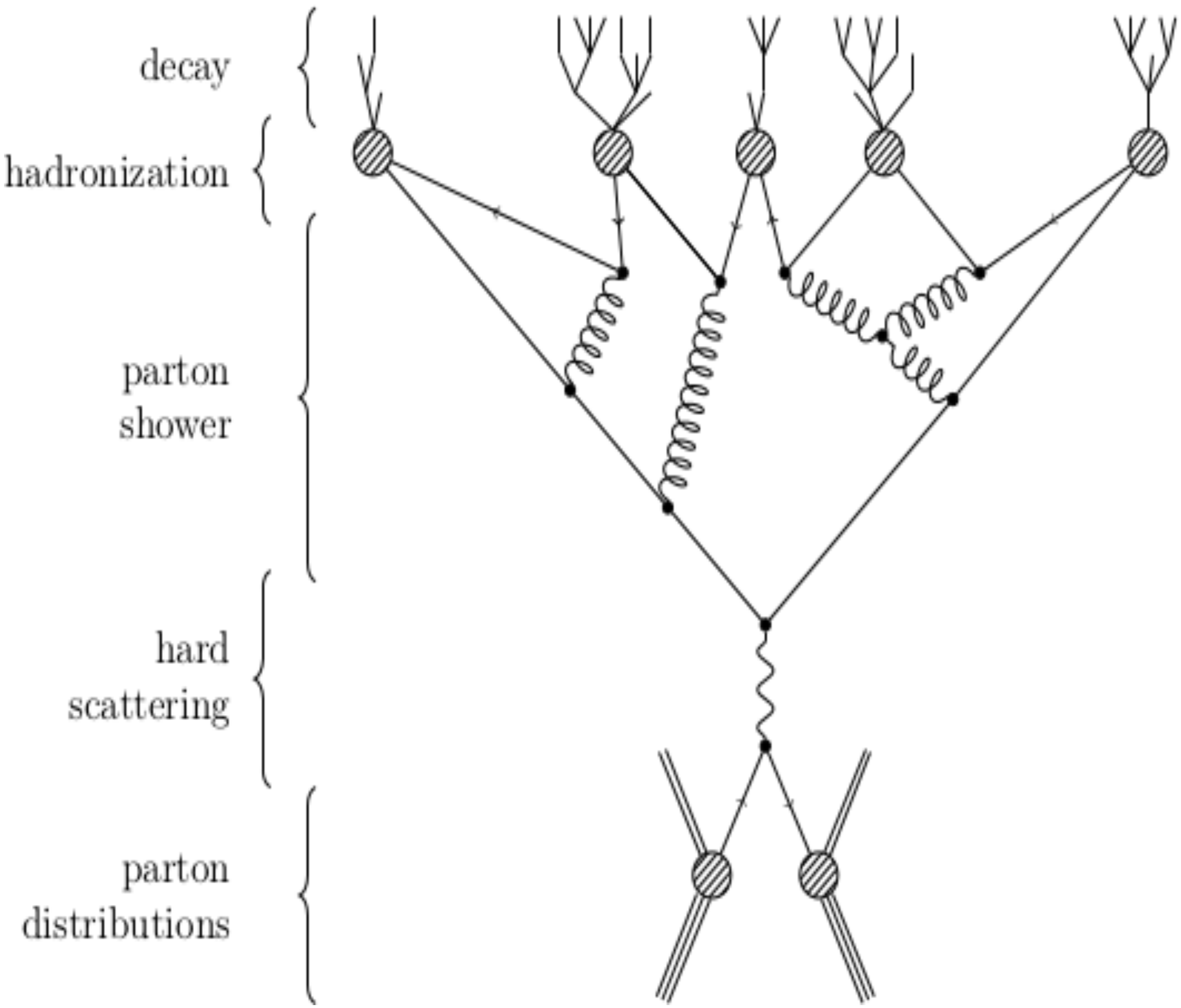


Jets introduction



- Energetic **jets** in LHC ***pp*** collisions are **produced abundantly**
  - Signal, **QCD prediction**
  - **Significant background** to other analyses
  - <u>**Indispensable element of almost all LHC analyses**</u>
- **A new energy regime and new tools for the analysis of hadronic final states from theorists**
  - New jet algorithms : anti-k_t
  - Jet substructure techniques
  - Unprecedented high luminosity environment: increase of pile-up
- **Excellent detector capabilities**
  - Calorimeter granularity and tracking enabling sophisticated clustering algorithms and calibration.
  - Combine information from sub-detectors (tracker +calorimeter + muon system)

What are jets?



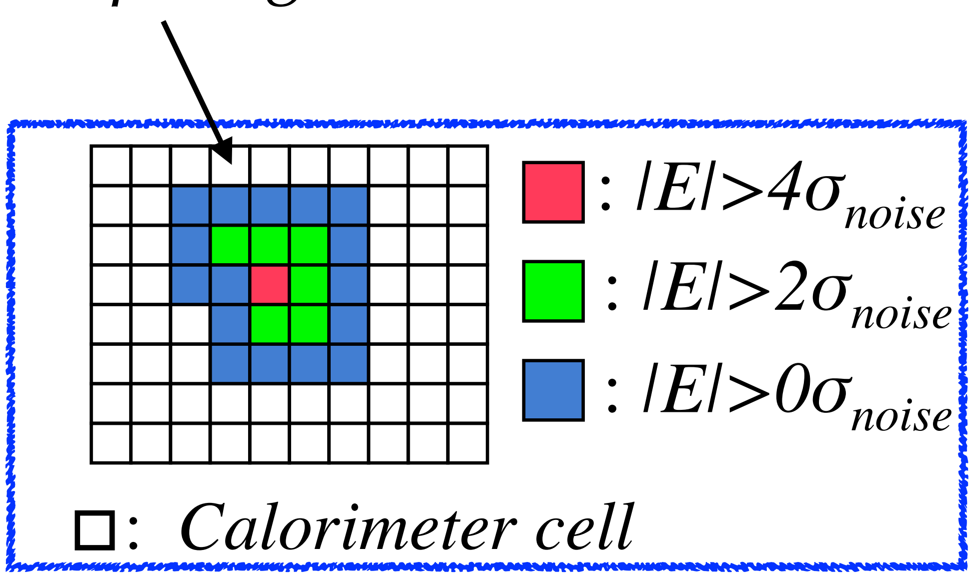
- The challenge (and opportunity!) of jets comes from physics of QCD: **parton shower** and **hadronization**
  - ✦ The particles we measure -π, K, *p*, *n*, etc- are **not** the particles from the hard scattering
- Jets are the outputs of the **clustering algorithms** that group **inputs** (truth particles or **calorimeter clusters**)
  - ✦ The goal: improve our ability to understand the event by providing **proxies for quarks and gluons**

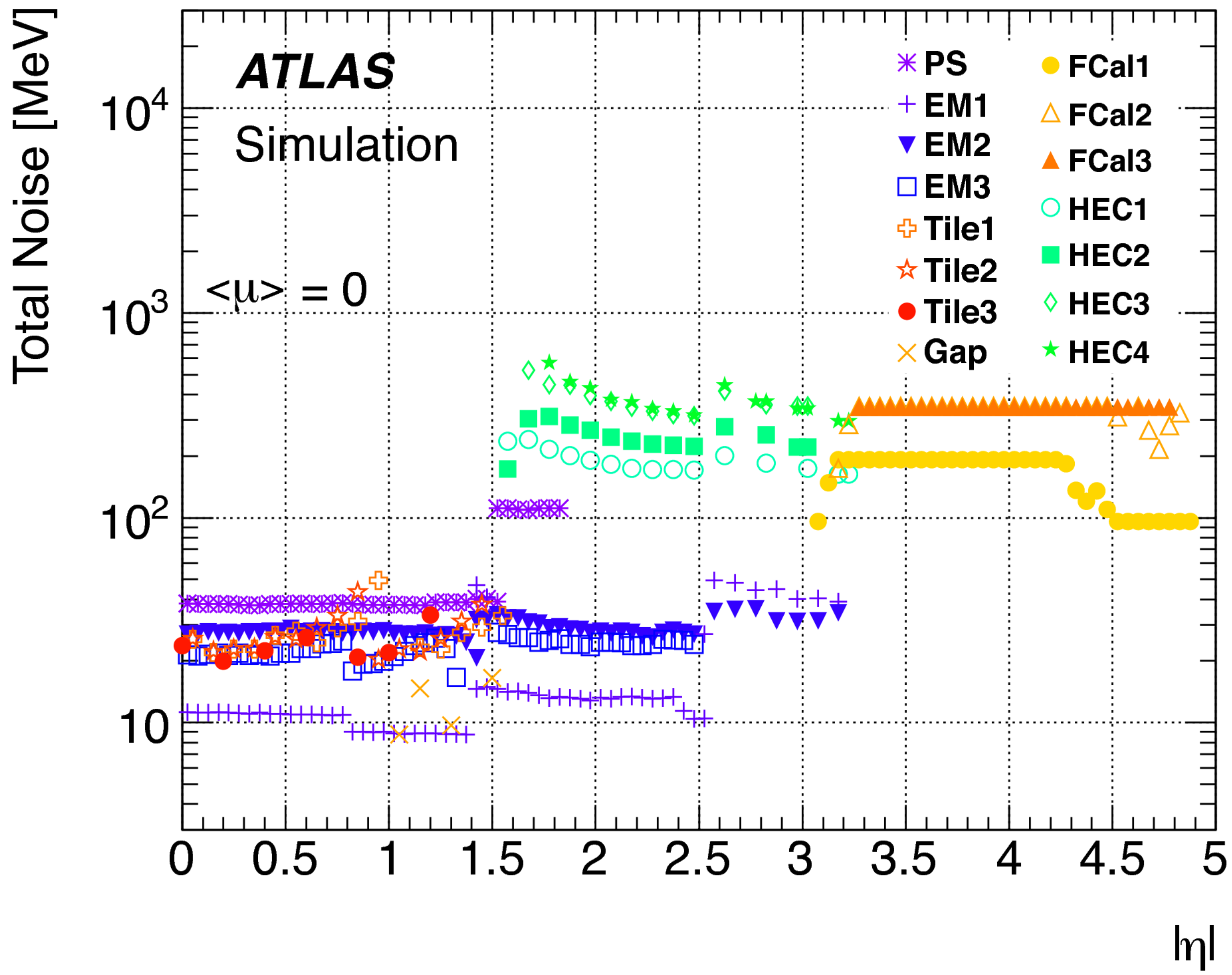
Jet inputs: calorimeter clusters

⇒Exploit high resolution of calorimeters and fine longitudinal segmentation

- **3-dimensional topological clustering of calorimeter read-out channels (cells)**
  - Optimise to follow the shower development in the calorimeter
  - **Noise suppression**
  - Ideal for jet substructure (constituent level calibration)

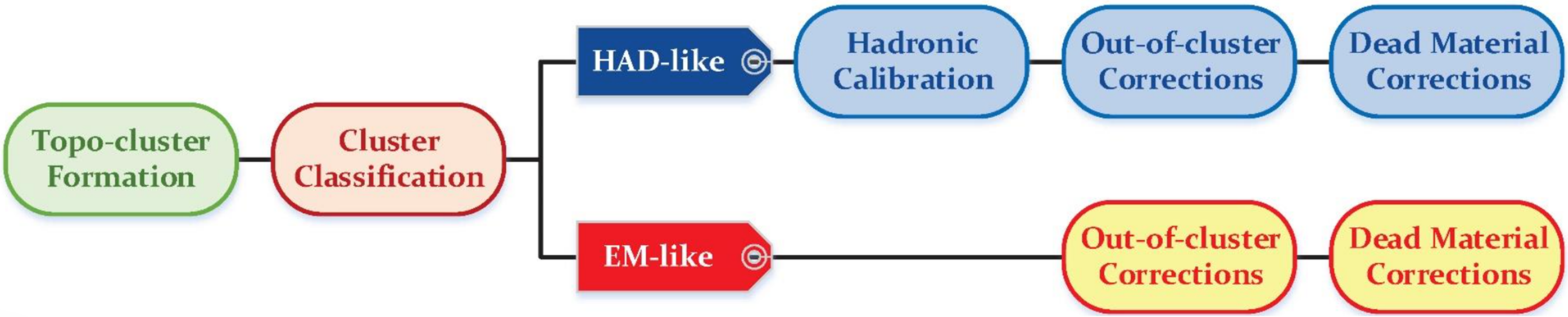
3D topological cluster

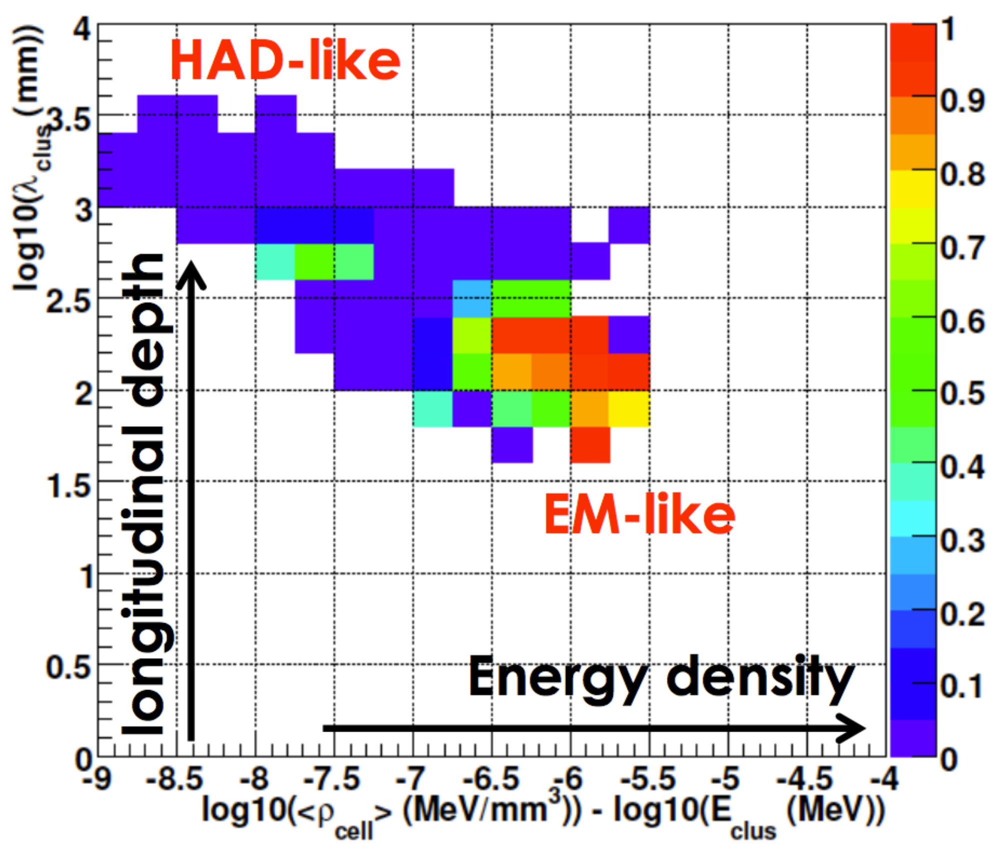


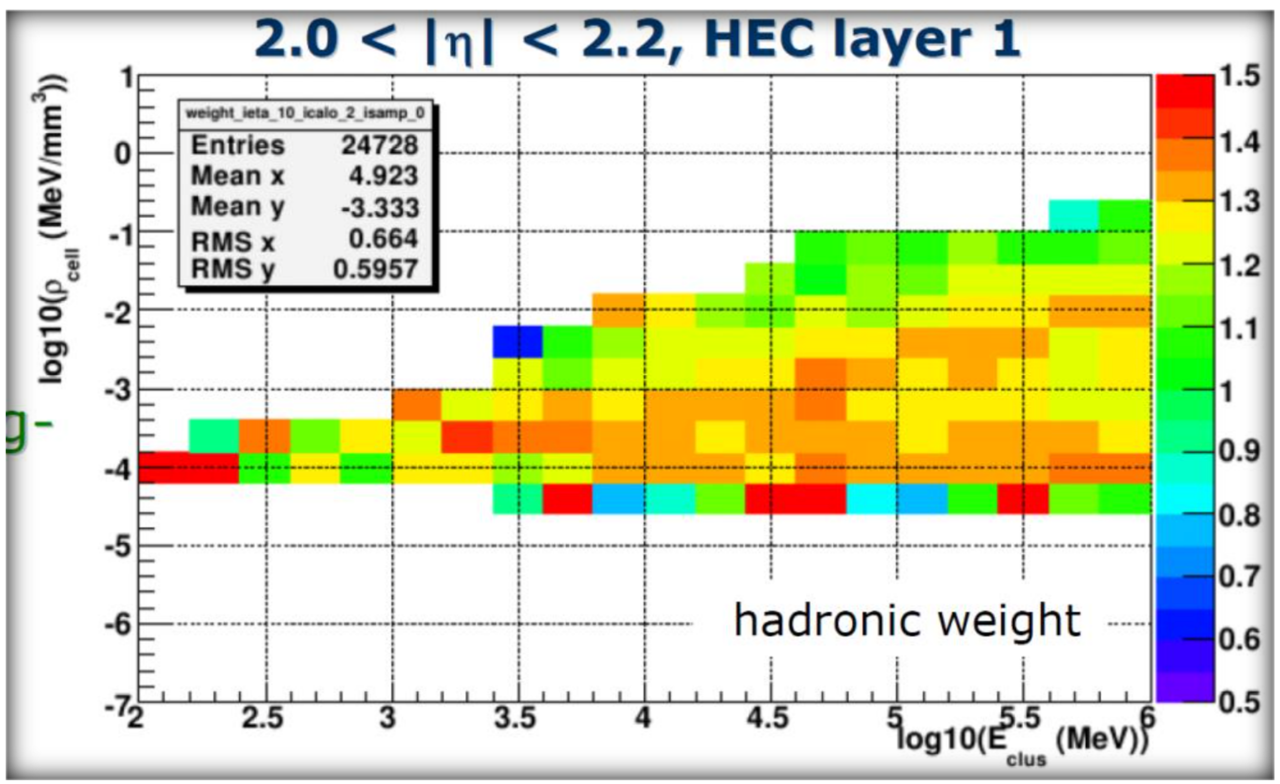


Jet inputs: calorimeter clusters

- **Two energy scale calibrations for topological clusters**
  - Electromagnetic (**EM**)
  - Local cluster weighting (**LCW**): Distinguish EM/HAD depositions







Jet algorithms

- Naively, jet algorithms are the inverse of the parton shower

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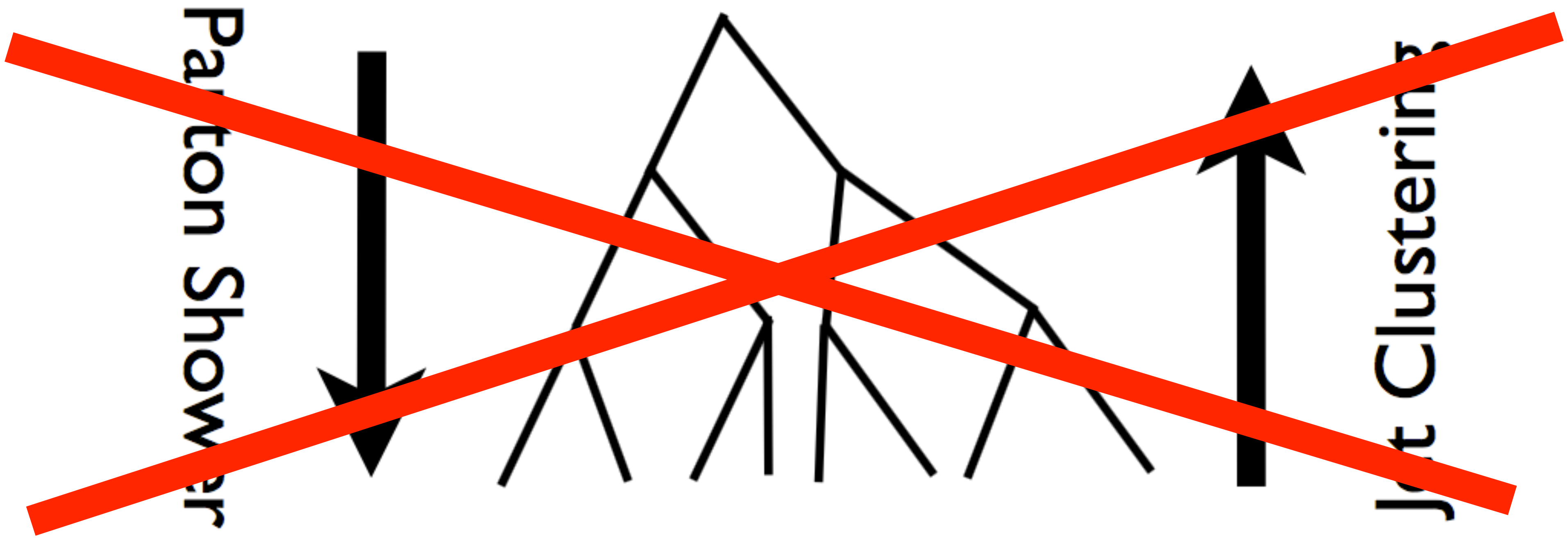
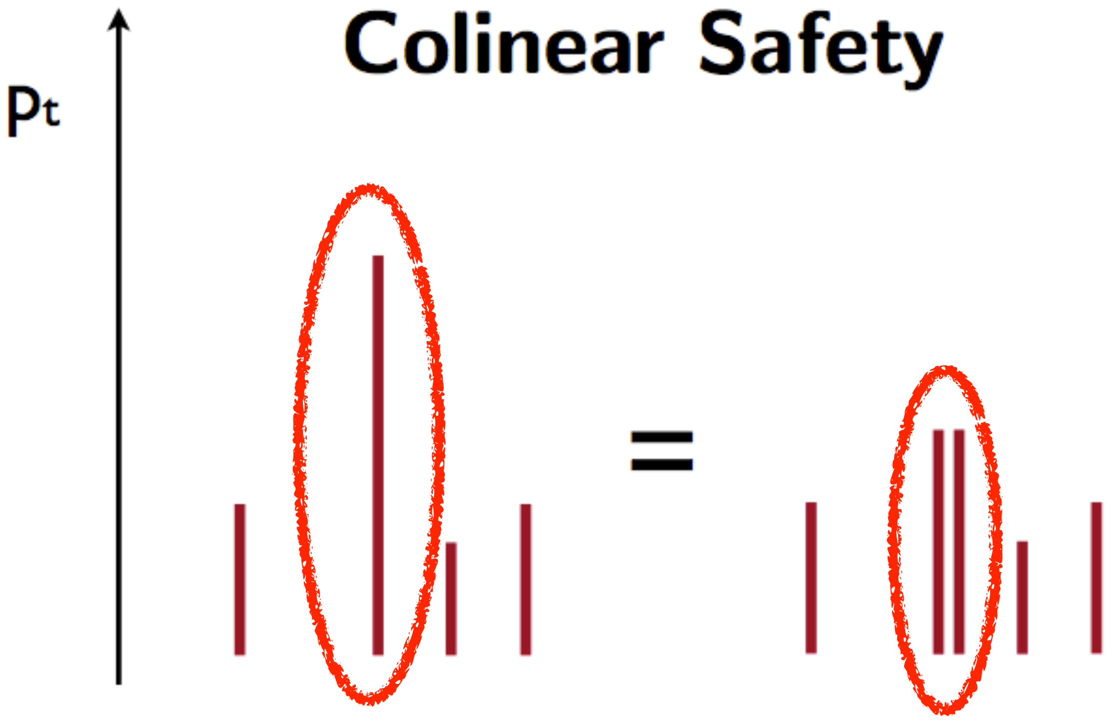


- <u>But the parton shower is actually not invertible!</u>

- There is no correct jet algorithm: only **better** or **worse**
- What are the metrics for useful algorithm?

IRC Safety

Colinear Safety



- Parton shower can **split particles**
- Clustering should not be sensitive to this!

Infrared Safety

- Parton shower can add **extra soft radiation**
- Also want to be insensitive to these effects!

- These are the main *theoretical* considerations on jet clustering

→ Can make comparisons to **calculations** much easier if these are followed!

Jet algorithms

- k_T algorithm

$$d_{ij} = \min(p_{Ti}^2, p_{Tj}^2)\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^2$$

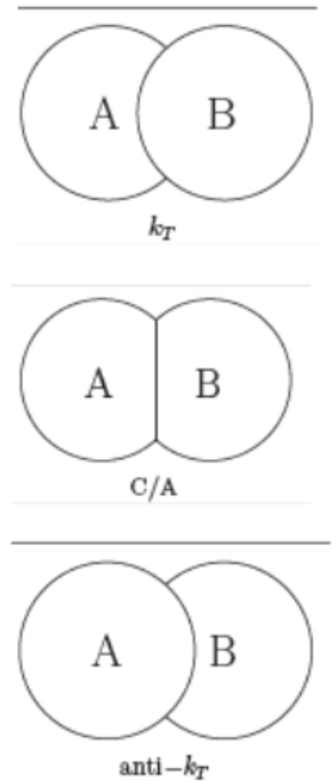
- C/A algorithm

$$d_{ij} = \left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = 1$$

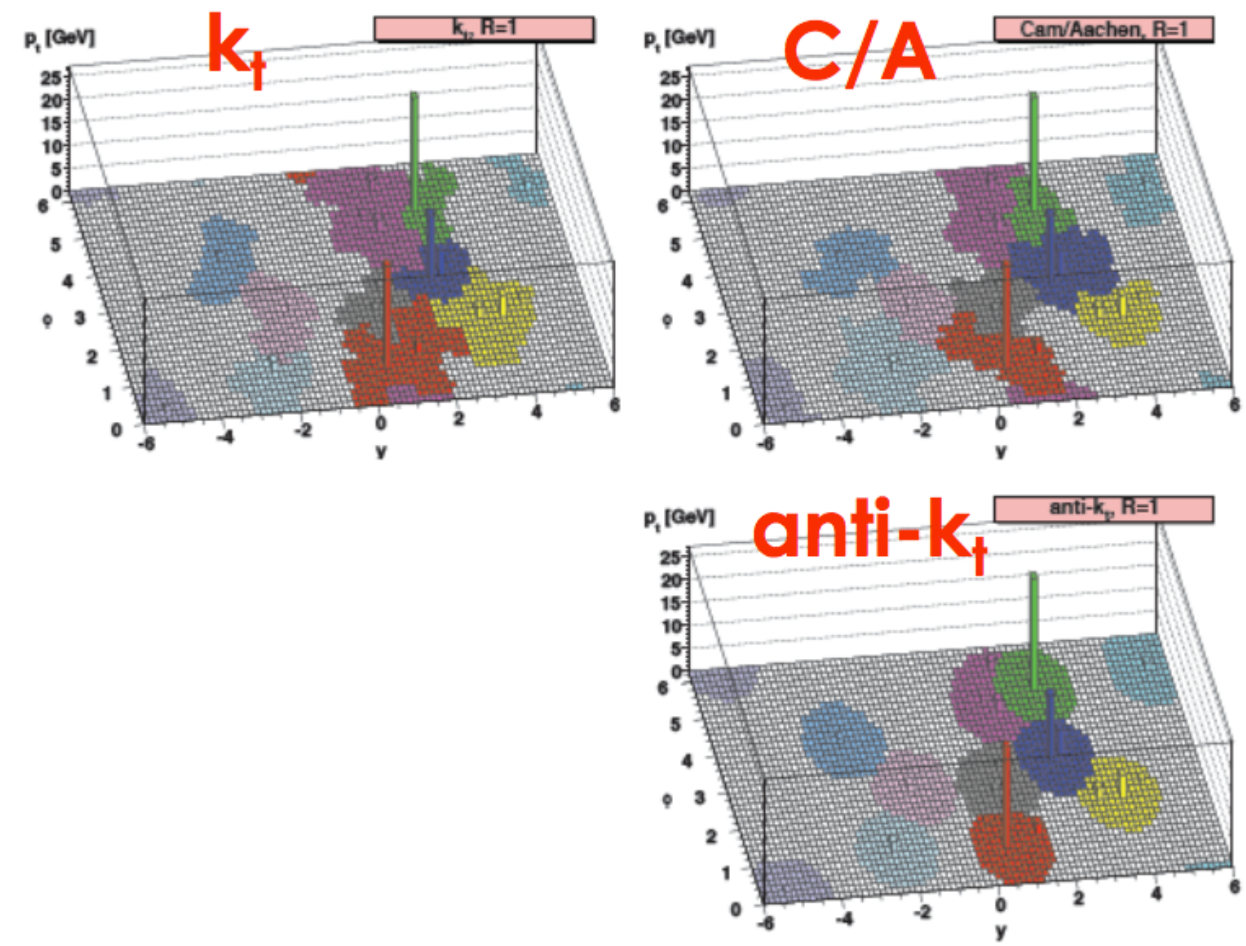
- anti-k_T algorithm

$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\left(\frac{\Delta R}{R_0}\right)^2, \; d_{iB} = p_{Ti}^{-2}$$

$$(\Delta R)^2 \equiv (\Delta\eta)^2 + (\Delta\phi)^2$$

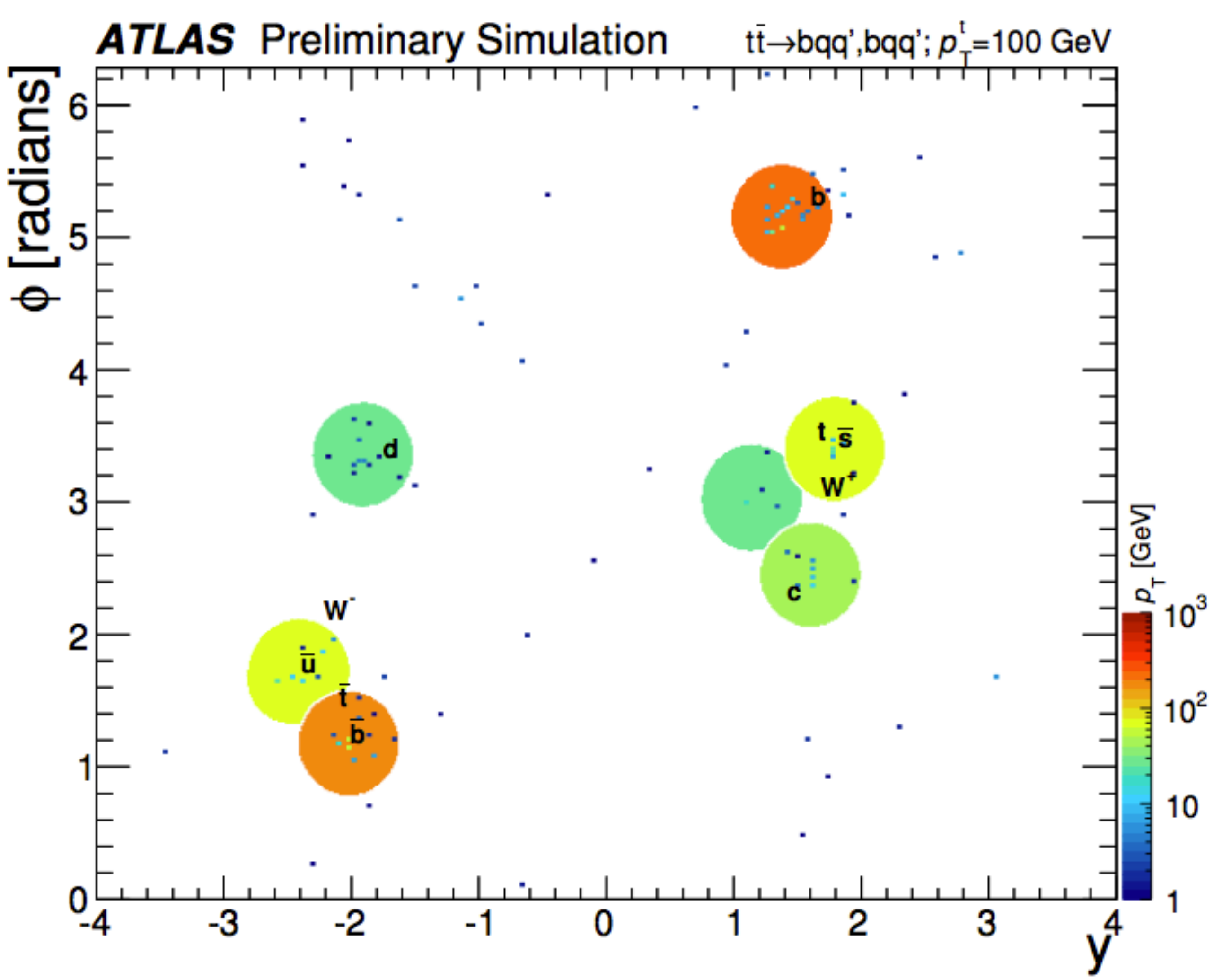


$$p_T^A > p_T^B$$



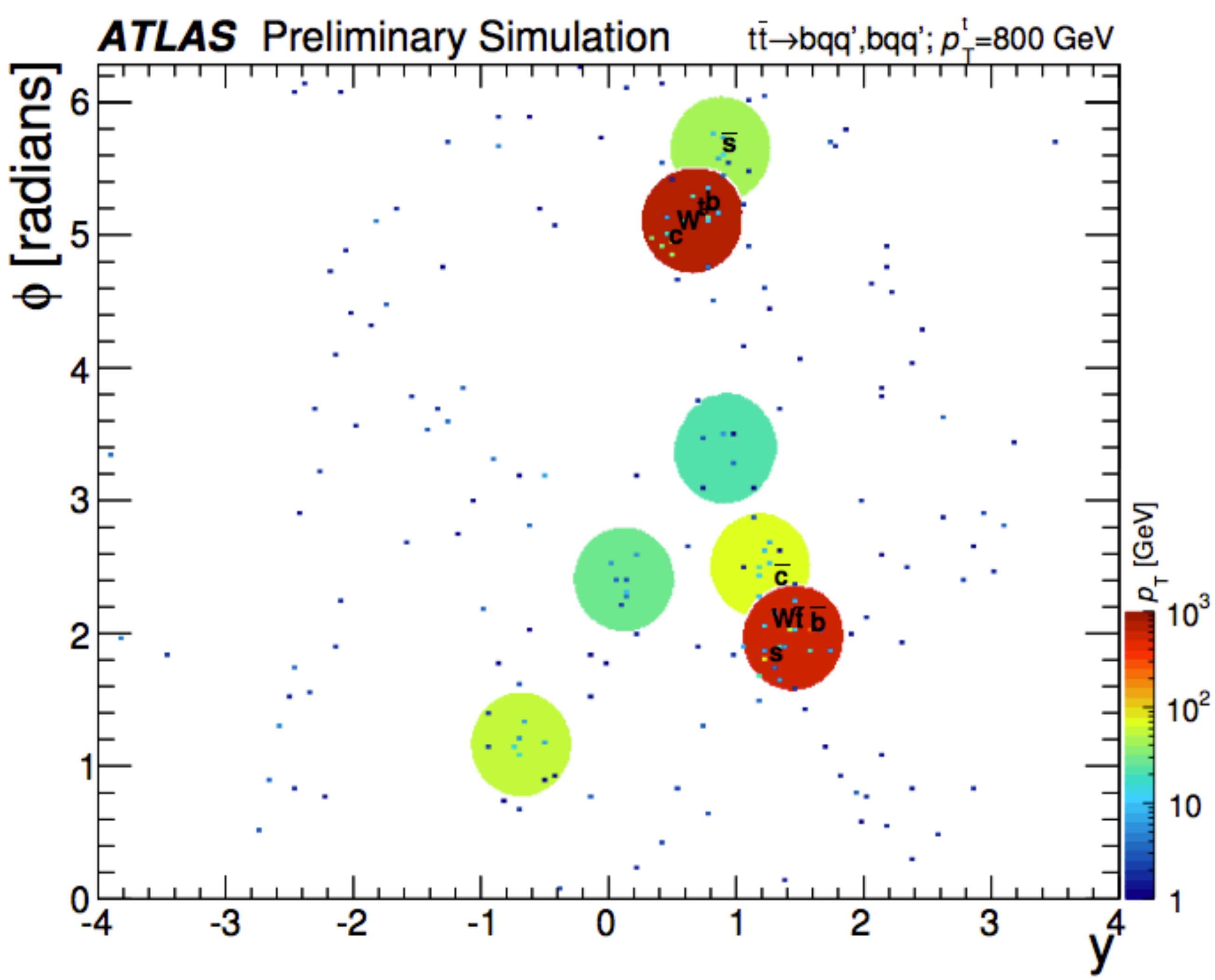
- Inputs: **energy of topological clusters**
- Anti-k_t family of jet algorithms are all IRC safe: the standard at LHC experiments
  - Regular shape objects (easy to calibrate, more resilient to pile-up)

R choice (jet size)



Top p_T =100 GeV

- jets fully resolved



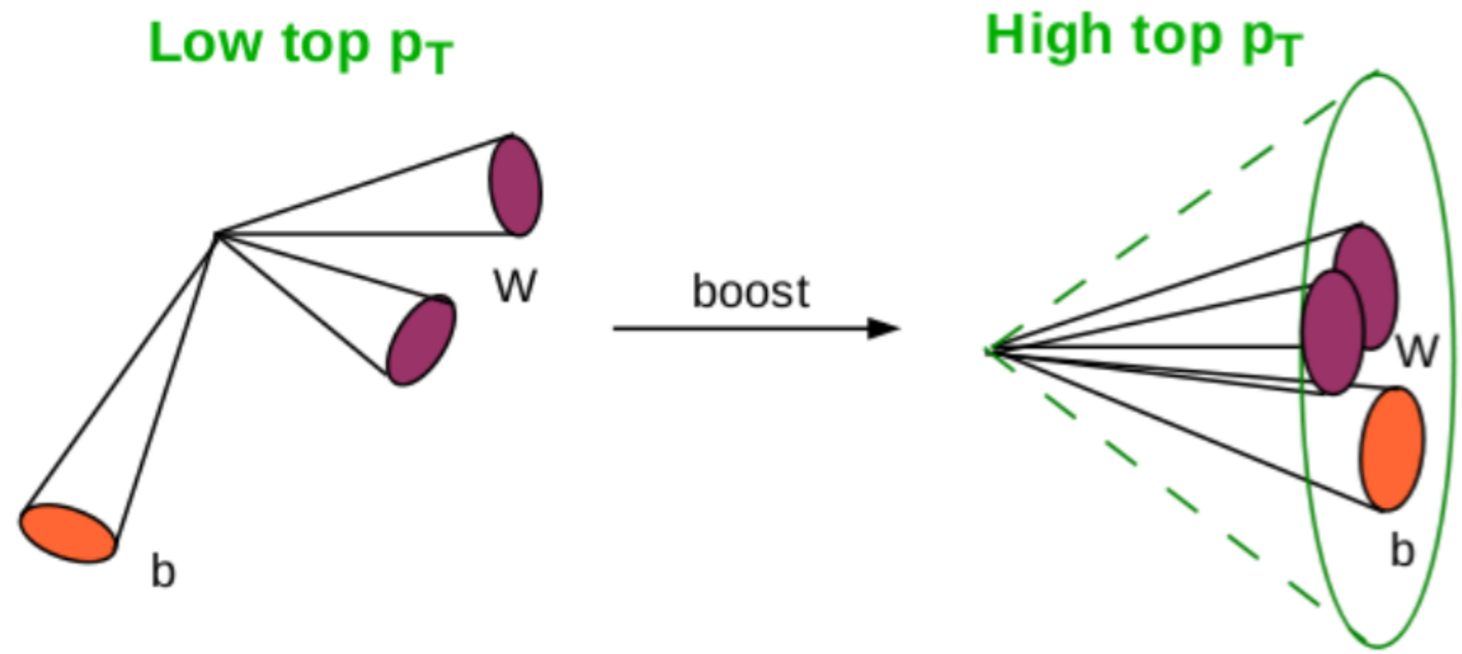
Top p_T =800 GeV

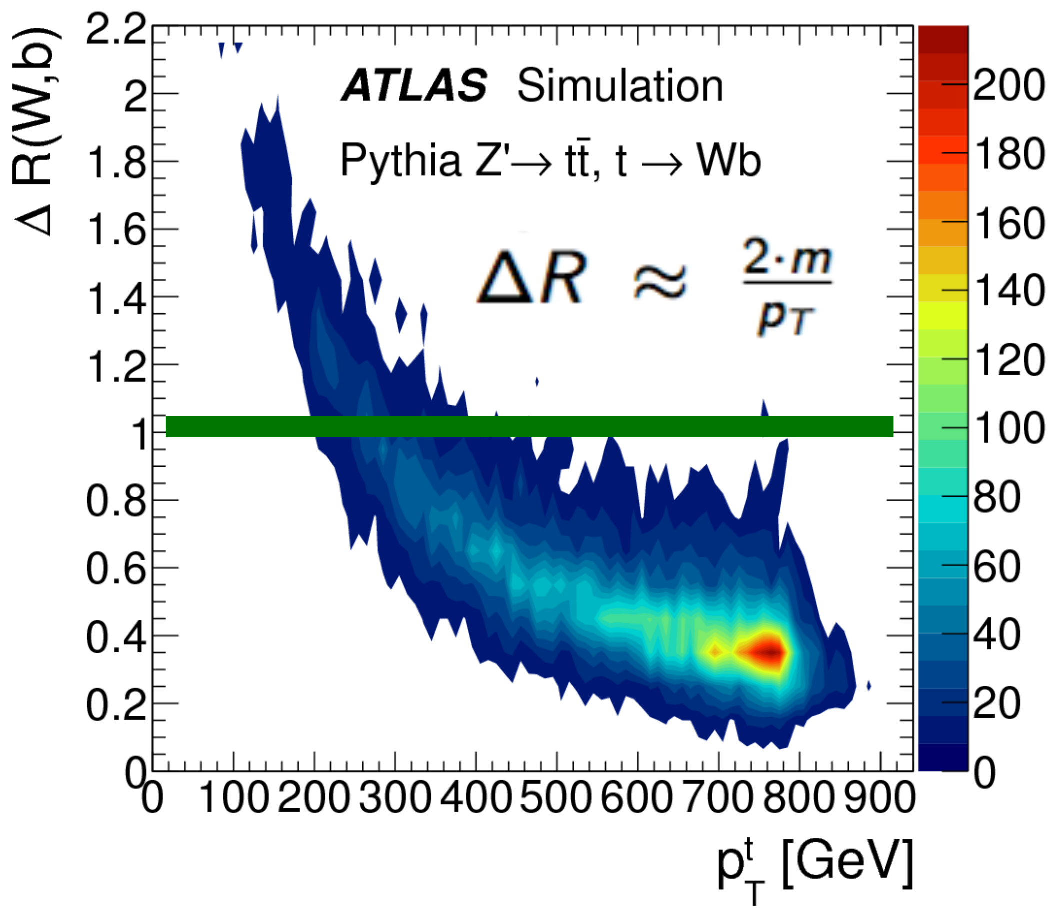
- jets fully merged

⇒ Use the R appropriate for the energy scale of the given signal

Boosted objects and large-R jets

- Decay products of a **boosted object** are **highly collimated** and can even **overlap**
- On the example of t→Wb
  - ✦ Decay products most likely within DR~1 for p_T^{top}>350 GeV
  - ✦ **Solution: use a single large jet containing all decay products**



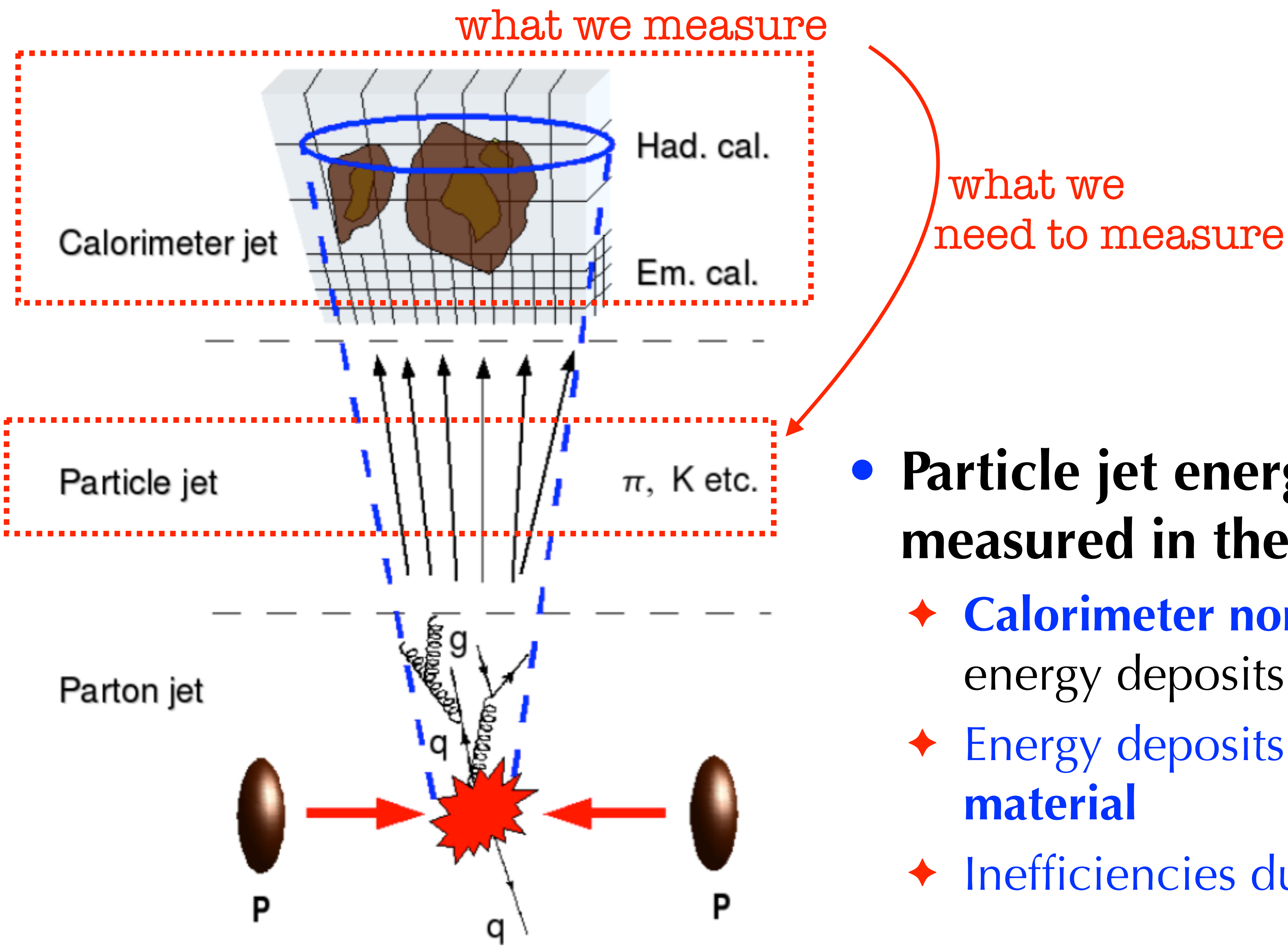


$R^{th,nnpdf}$ = **14TeV to 8 TeV xsec ratios**

Cross Section	$R^{\rm th,nnpdf}$	$\delta_{\rm PDF}(\%)$	δ_{α_s} (%)	$\delta_{\rm scales}$ (%)
$t\bar{t}/Z$	2.12	± 1.3	−0.8 − 0.8	−0.4 − 1.1
$t\bar{t}$	3.90	± 1.1	−0.5 − 0.7	−0.4 − 1.1
Z	1.84	± 0.7	−0.1 − 0.3	−0.3 − 0.2
W^+	1.75	± 0.7	−0.0 − 0.3	−0.3 − 0.2
W^-	1.86	± 0.6	−0.1 − 0.3	−0.3 − 0.1
W^+/W^-	0.94	± 0.3	−0.0 − 0.0	−0.0 − 0.0
W/Z	0.98	± 0.1	−0.1 − 0.0	−0.0 − 0.0
ggH	2.56	± 0.6	−0.1 − 0.1	−0.9 − 1.0
$t\bar{t}(M_{tt} \geq 1$ TeV)	8.18	± 2.5	−1.3 − 1.1	−1.6 − 2.1
$t\bar{t}(M_{tt} \geq 2$ TeV)	24.9	± 6.3	−0.0 − 0.3	−3.0 − 1.1
$\sigma_{\rm jet}(p_T \geq 1$ TeV)	15.1	± 2.1	−0.4 − 0.0	−1.9 − 2.4
$\sigma_{\rm jet}(p_T \geq 2$ TeV)	182	± 7.7	−0.3 − 0.2	−5.7 − 4.0

Jet calibration in ATLAS

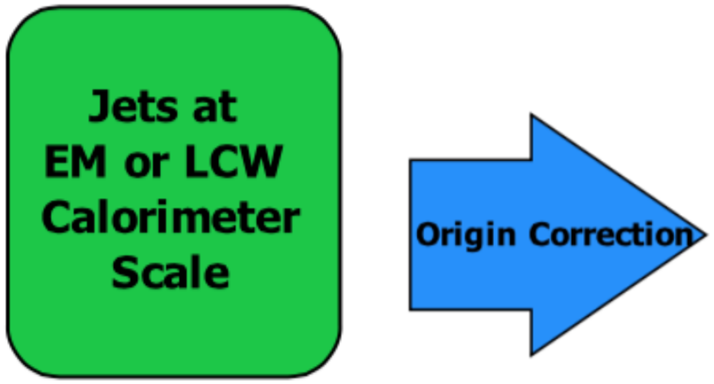
Why calibrate jets?



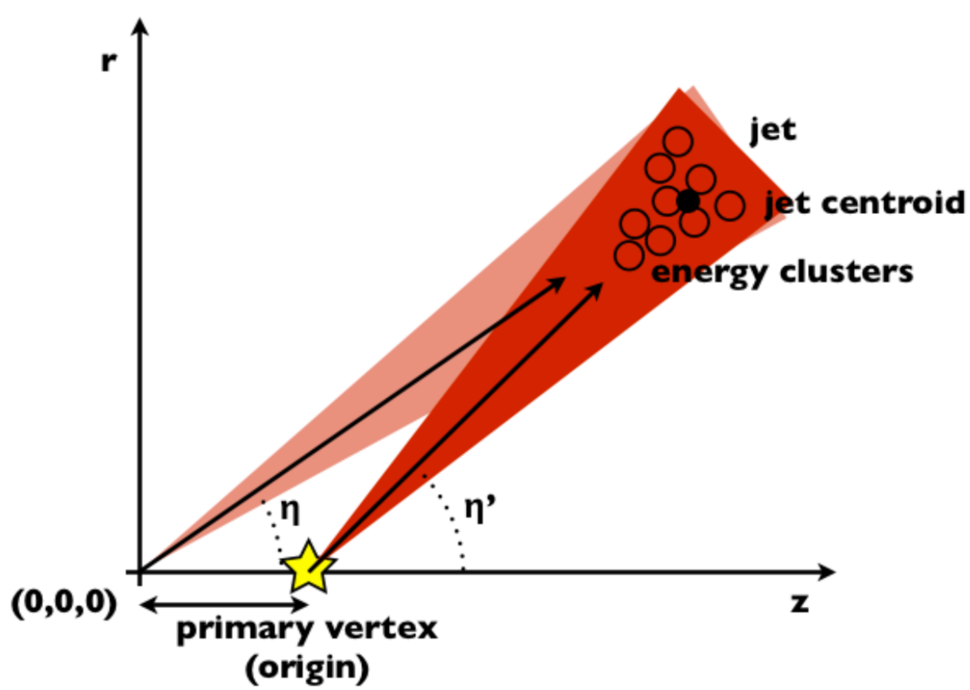
- **Particle jet energy different than energy measured in the calorimeter**
  - **Calorimeter non compensation** hadrons energy deposits are only partially measured
  - Energy deposits missed because of **dead material**
  - Inefficiencies due to **noise** and **pile-up**

➡ **Need a calibration to reach the particle jet energy level**

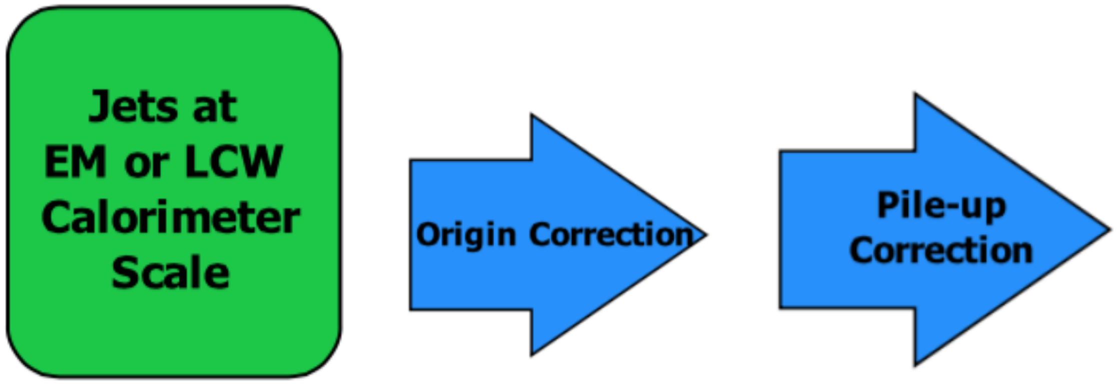
Jet calibration chain



- Start from calorimeter jets
  - **Origin correction:** to account for the hard scattering primary vertex. Changes the jet direction

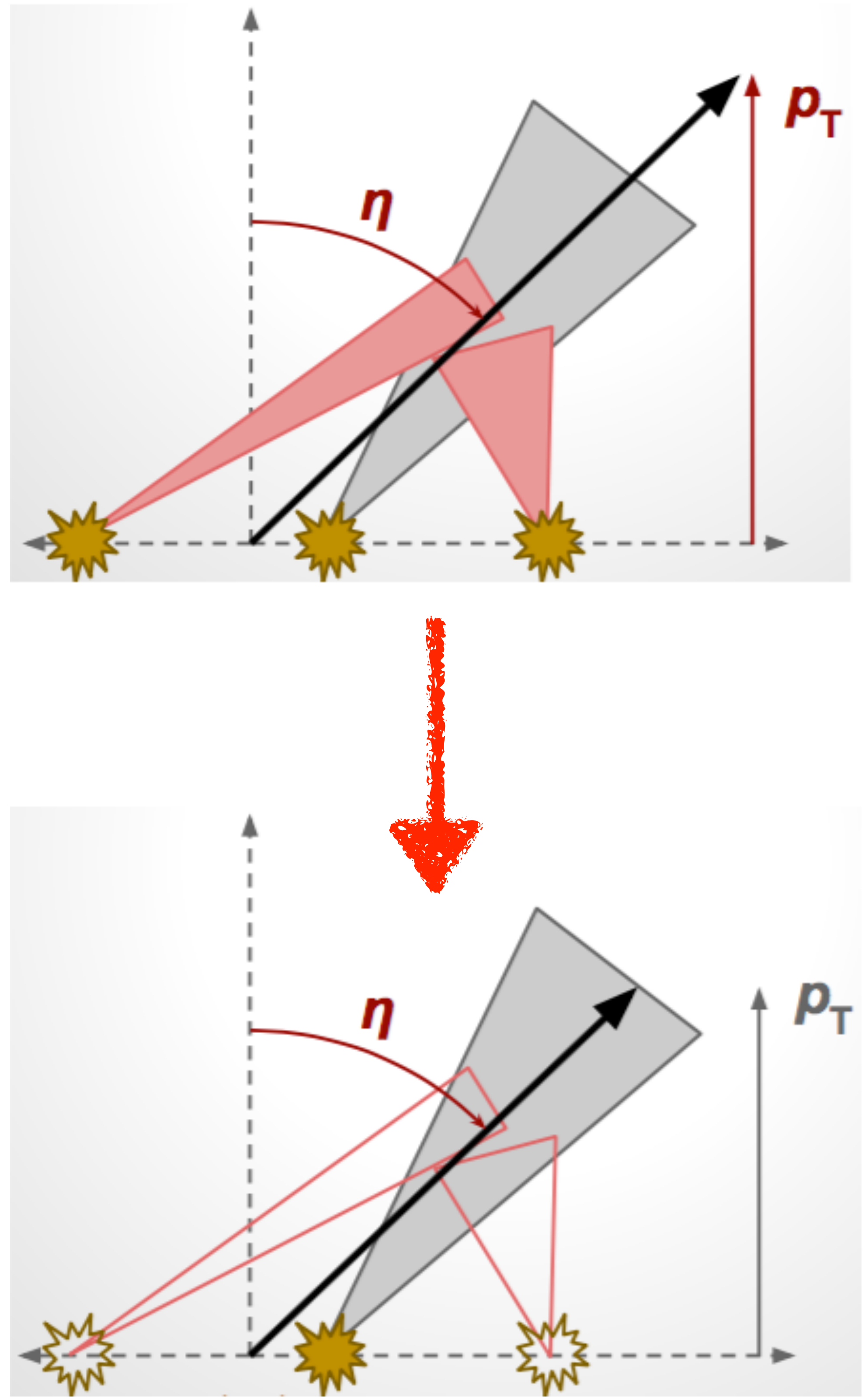


Jet calibration chain

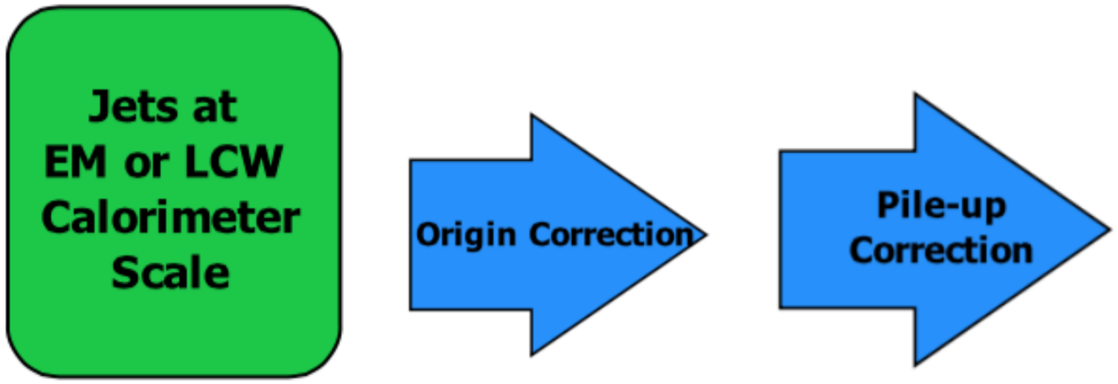


- Start from calorimeter jets

- **Origin correction:** to account for the hard scattering primary vertex. Changes the jet direction
- **Jet area and residual pileup corrections** to decrease pile-up contamination



Jet calibration chain



[ATLAS-PHYS-PUB-2015-015]

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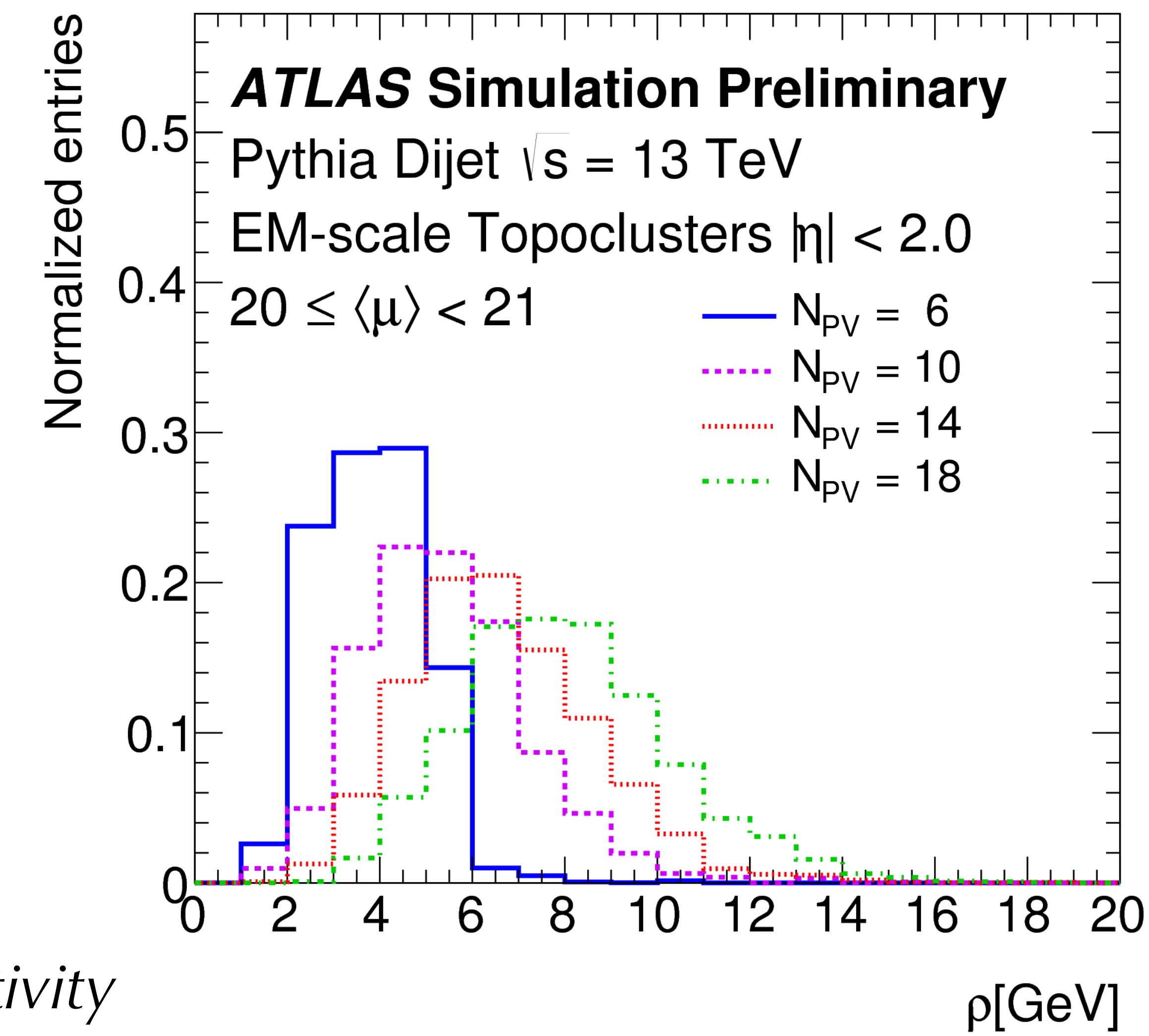


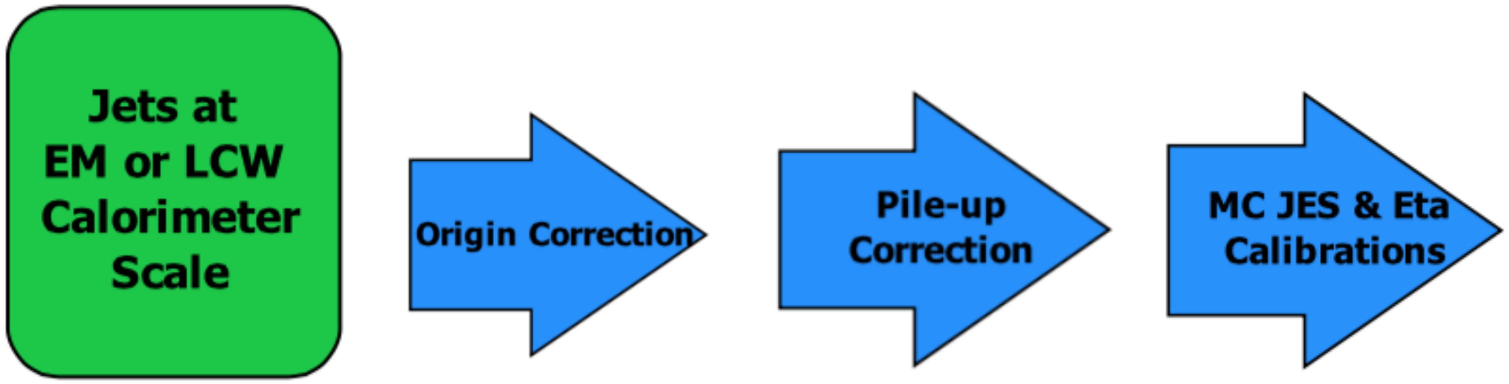
Jet-by-jet pile-up sensitivity

$$p_T^{corr} = p_T - \rho A_T - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle$$

*Event-by-event pile-up activity (**pile-up density**)*

$$\rho = \text{median}\left\{\frac{p_{T,i}^{\text{jet}}}{A_i^{\text{jet}}}\right\}$$

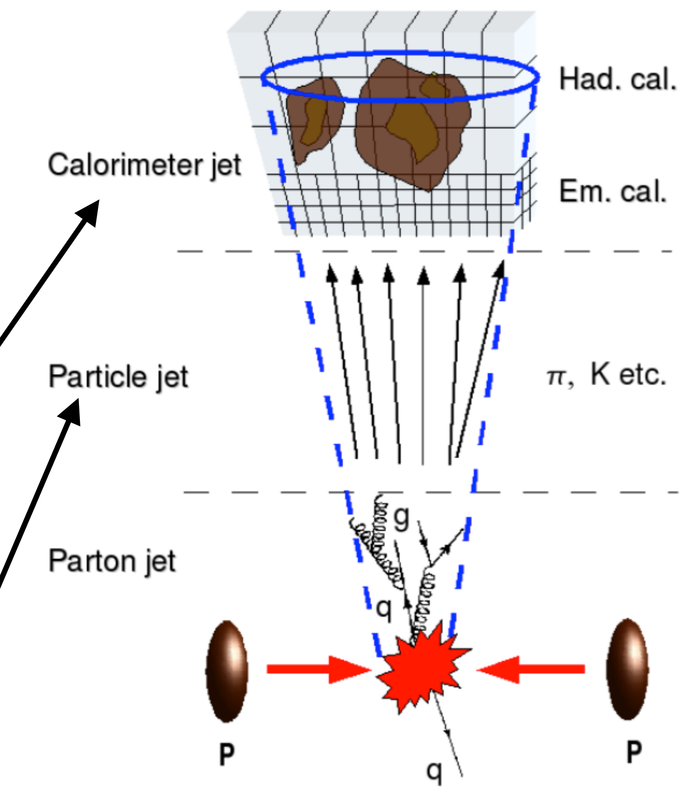
Jet calibration chain

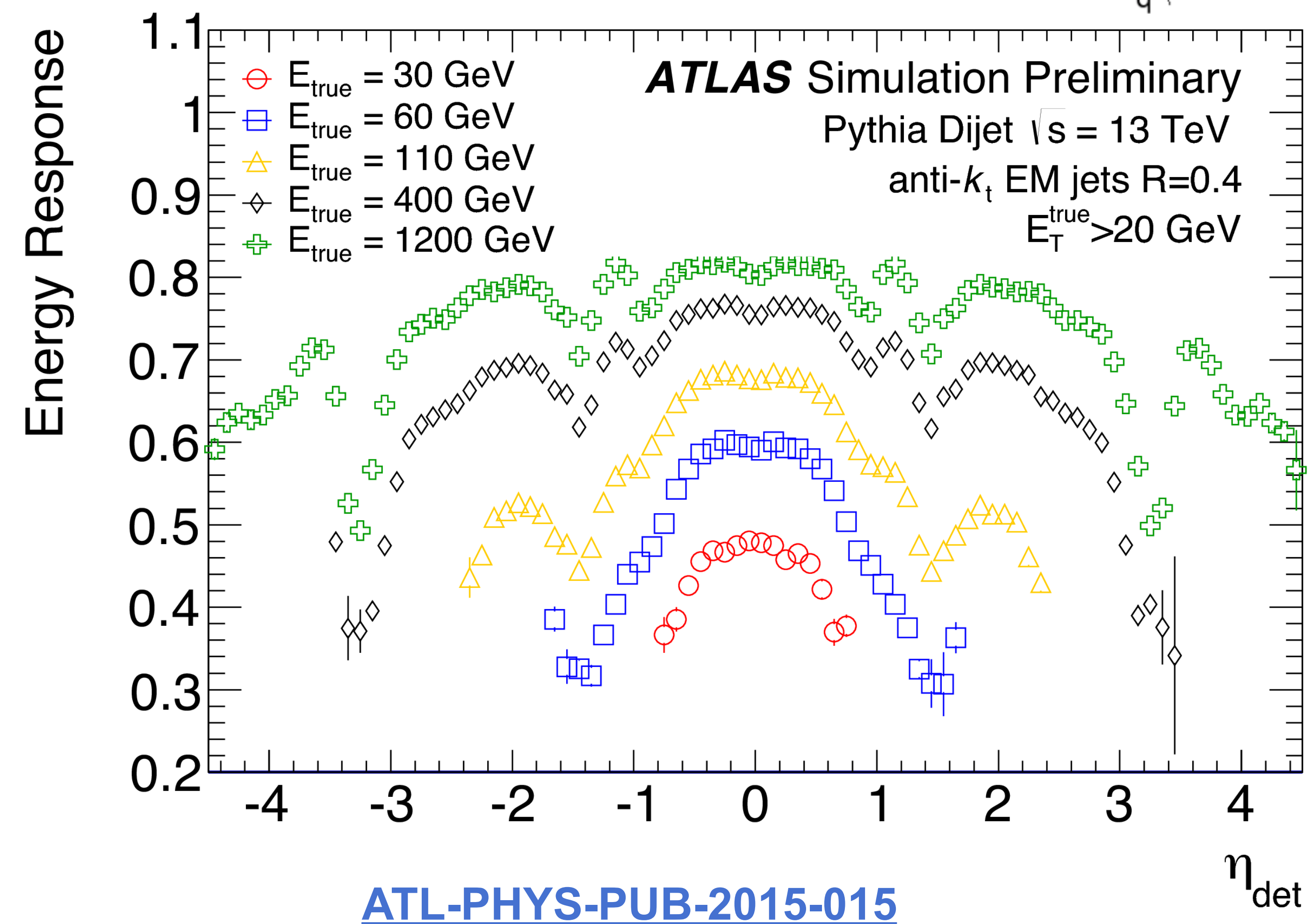


- Start from calorimeter jets

- **Origin correction:** to account for the hard scattering primary vertex. Changes the jet direction
- **Jet area and residual pileup corrections** to decrease pile-up contamination
- **MC JES:** Calibrates the jet energy and pseudo rapidity to the reference scale

$$E_{response} = \frac{E_{jet}^{calorimeter}}{E_{jet}^{particle}}$$





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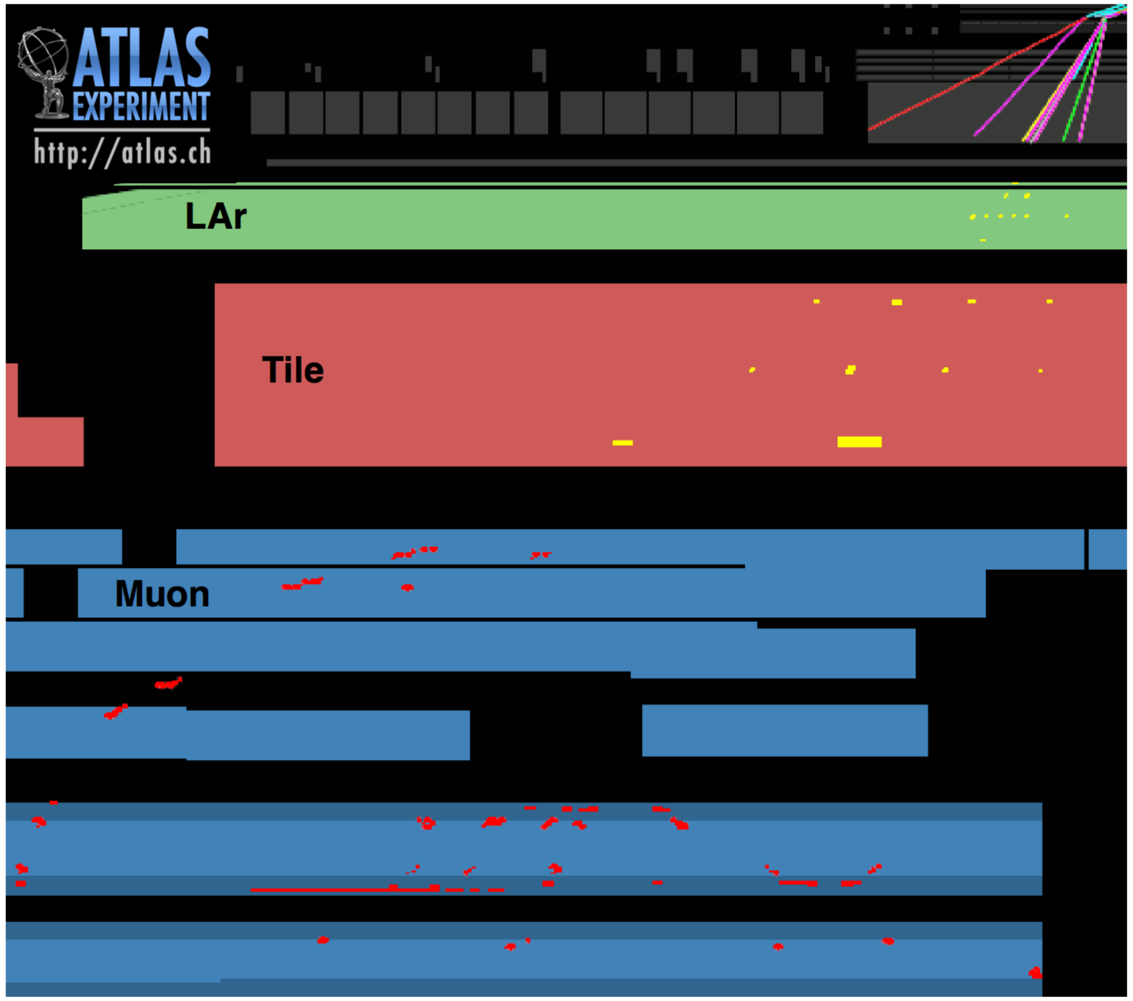
Jet calibration chain

ATLAS-CONF-2015-002

- Global sequential calibration (GSC): **reduce fluctuation effects**
  - Use jet-by-jet information to correct the response of each jet individually
  - Improves jet energy resolution



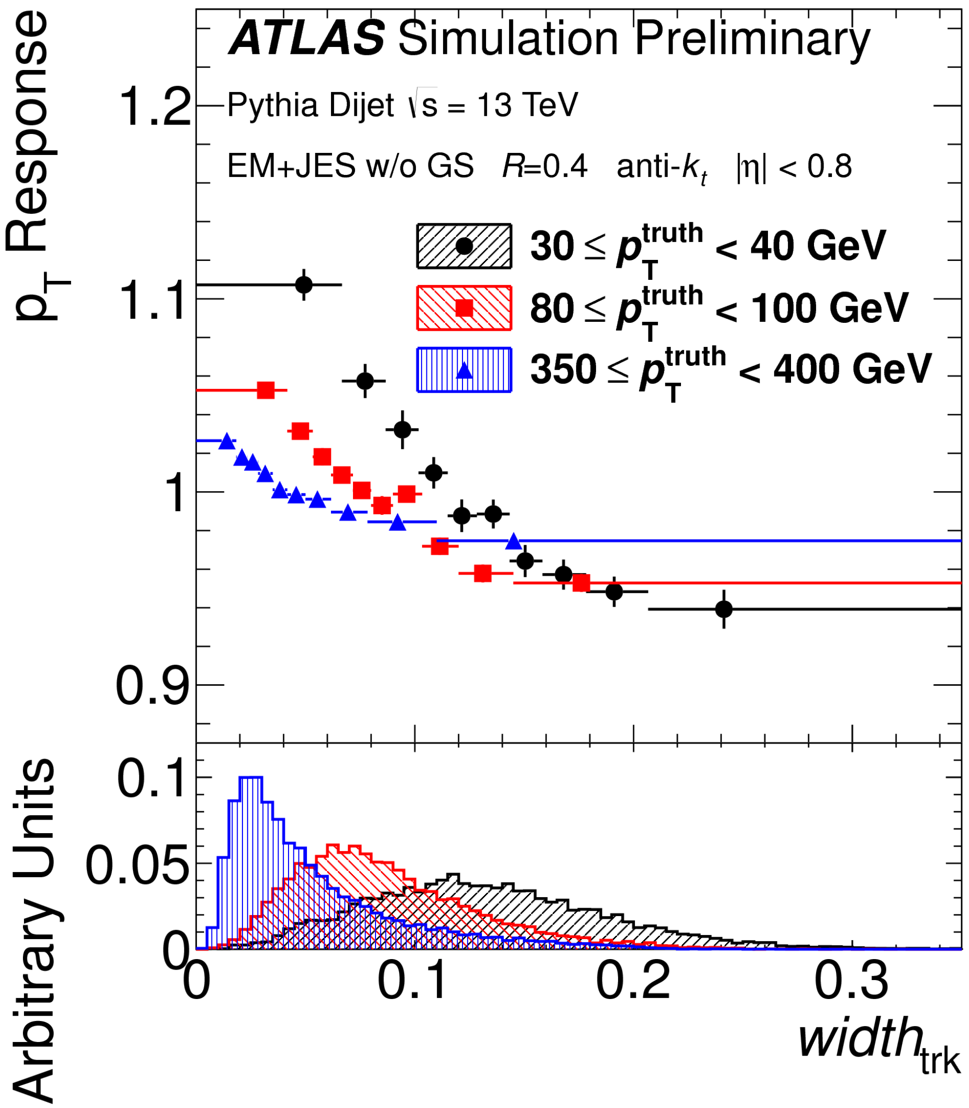
- GSC variables

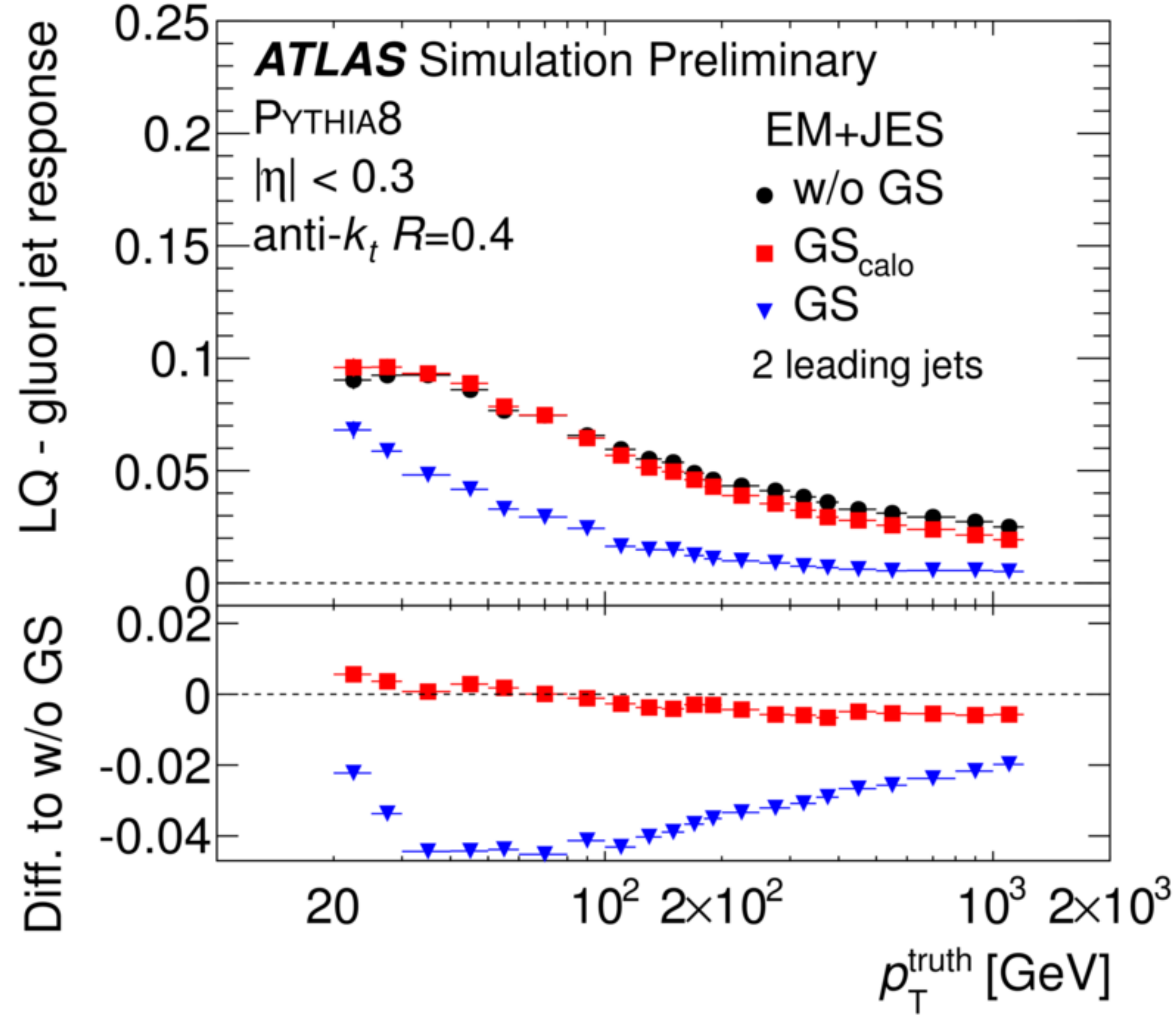
- Longitudinal structure of the **energy depositions** within the calorimeters
- **Track information** associated to the jet
- Information related to the activity in the muon chamber behind a jet (**muon segments**)
- Modelling of variables at 13 TeV already tested: **Good Data/MC agreement**

Global Sequential Calibration

ATLAS-CONF-2015-002
ATL-PHYS-PUB-2015-015

- Derived using MC, parametrised in p_T and η



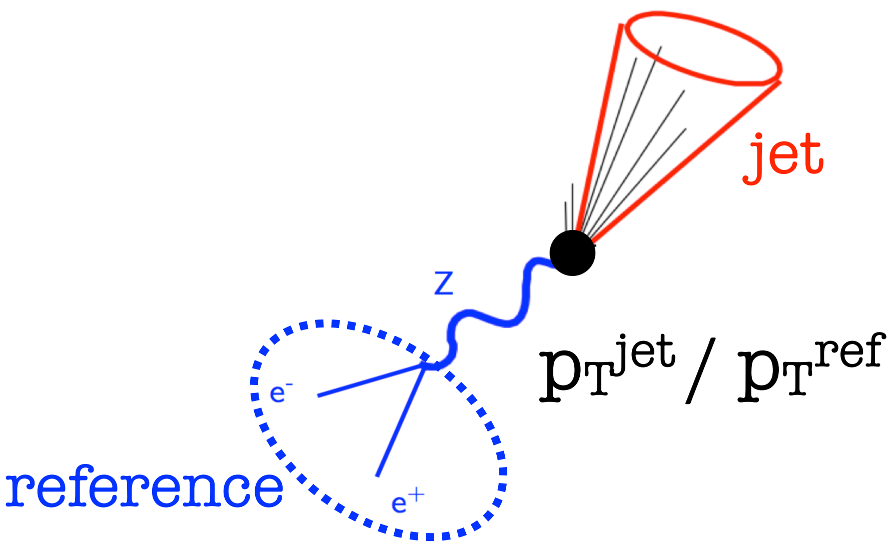


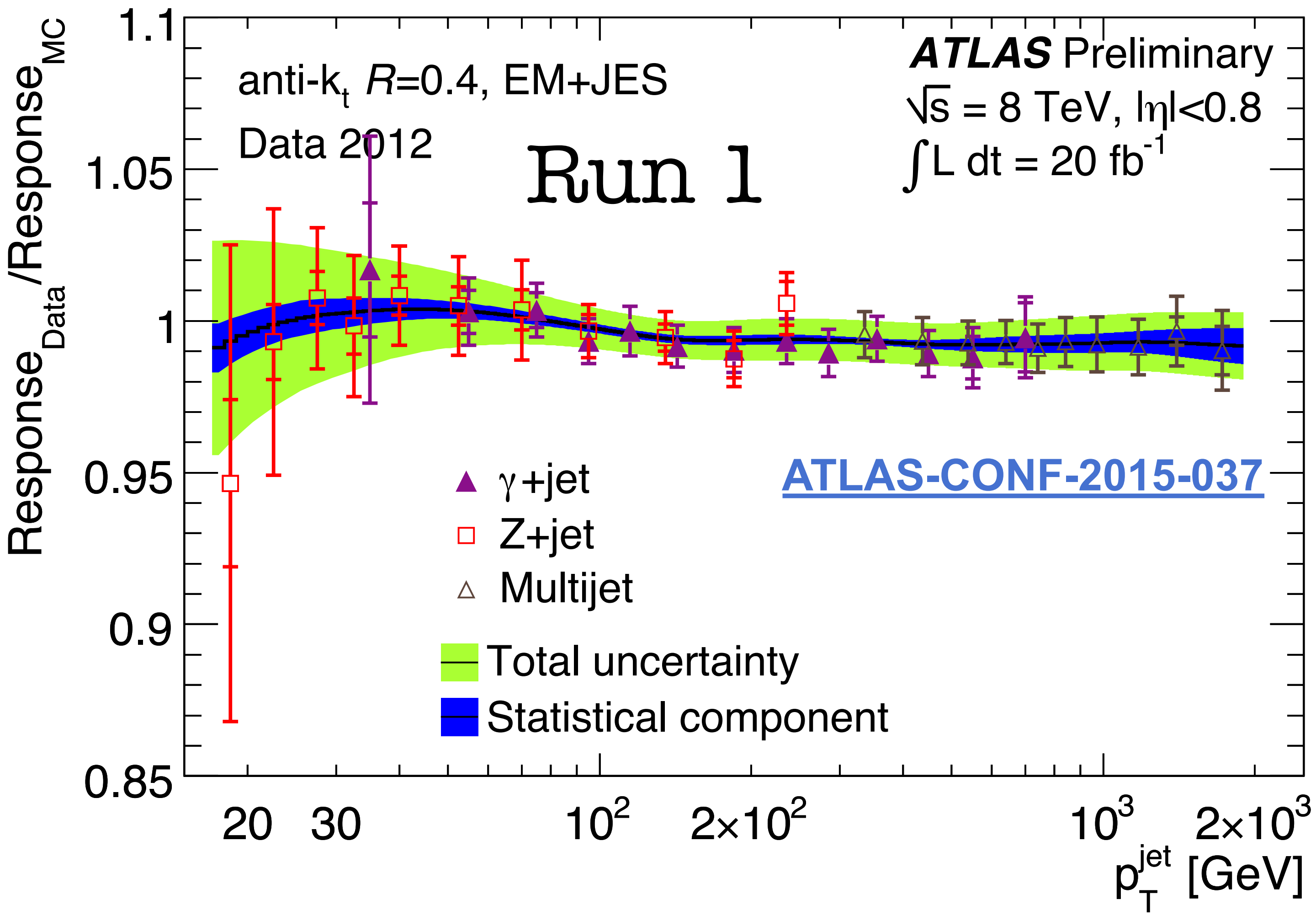
- Improves flavour uncertainties

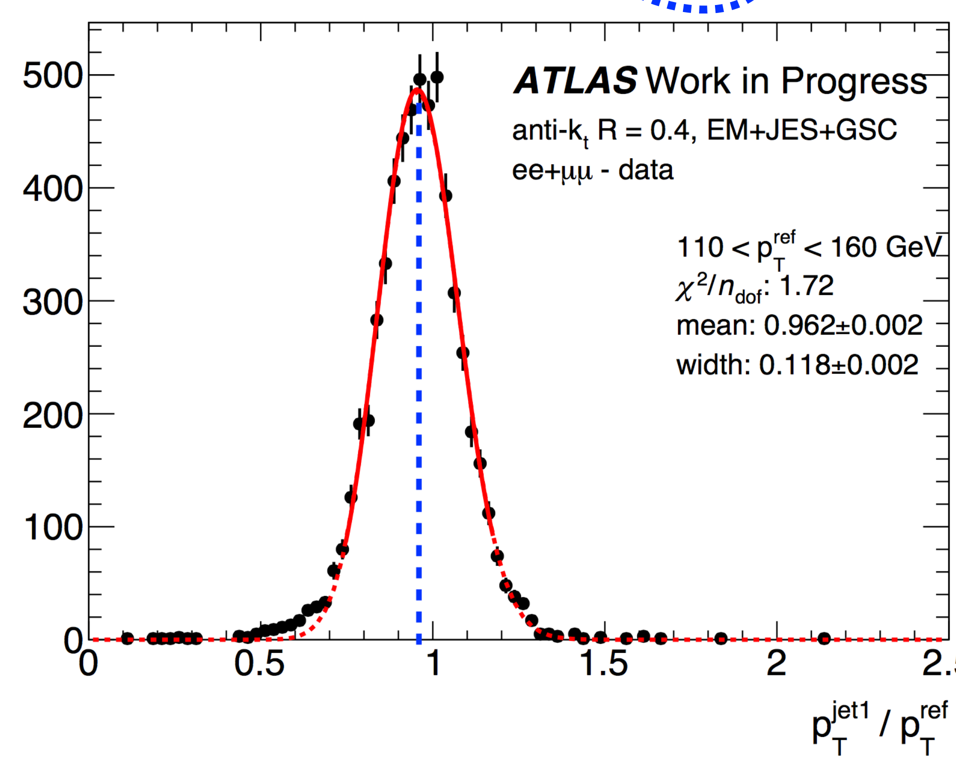
$$width_{\mathrm{trk}} = \frac{\sum_i p_T^i \Delta R(i,\mathrm{jet})}{\sum_i p_T^i},$$ average distance between tracks associated to jets and jet axis

In-situ corrections

- **In-situ** measurement using a **jet** recoiling against **well-calibrated** object as a **reference**
- Combination of 3 in-situ measurements

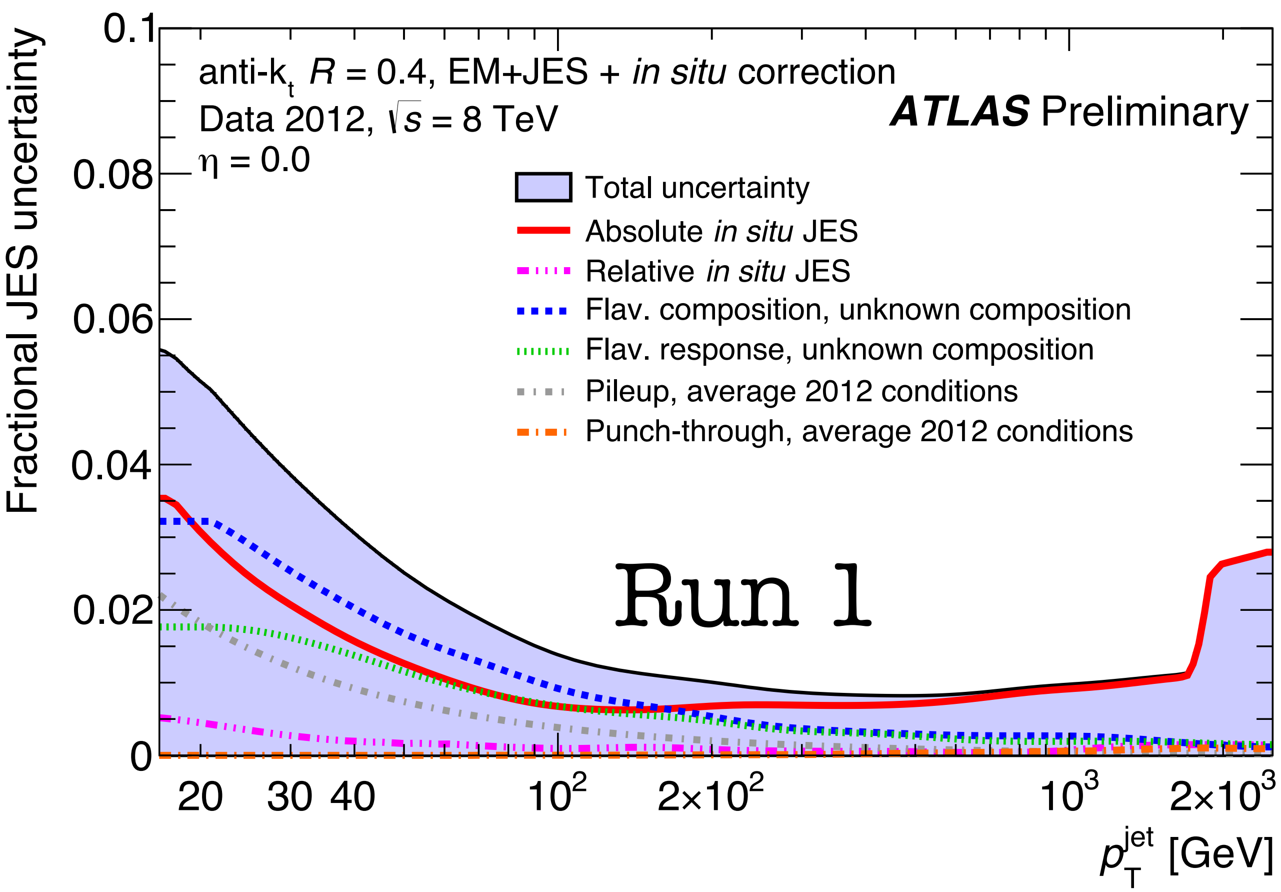


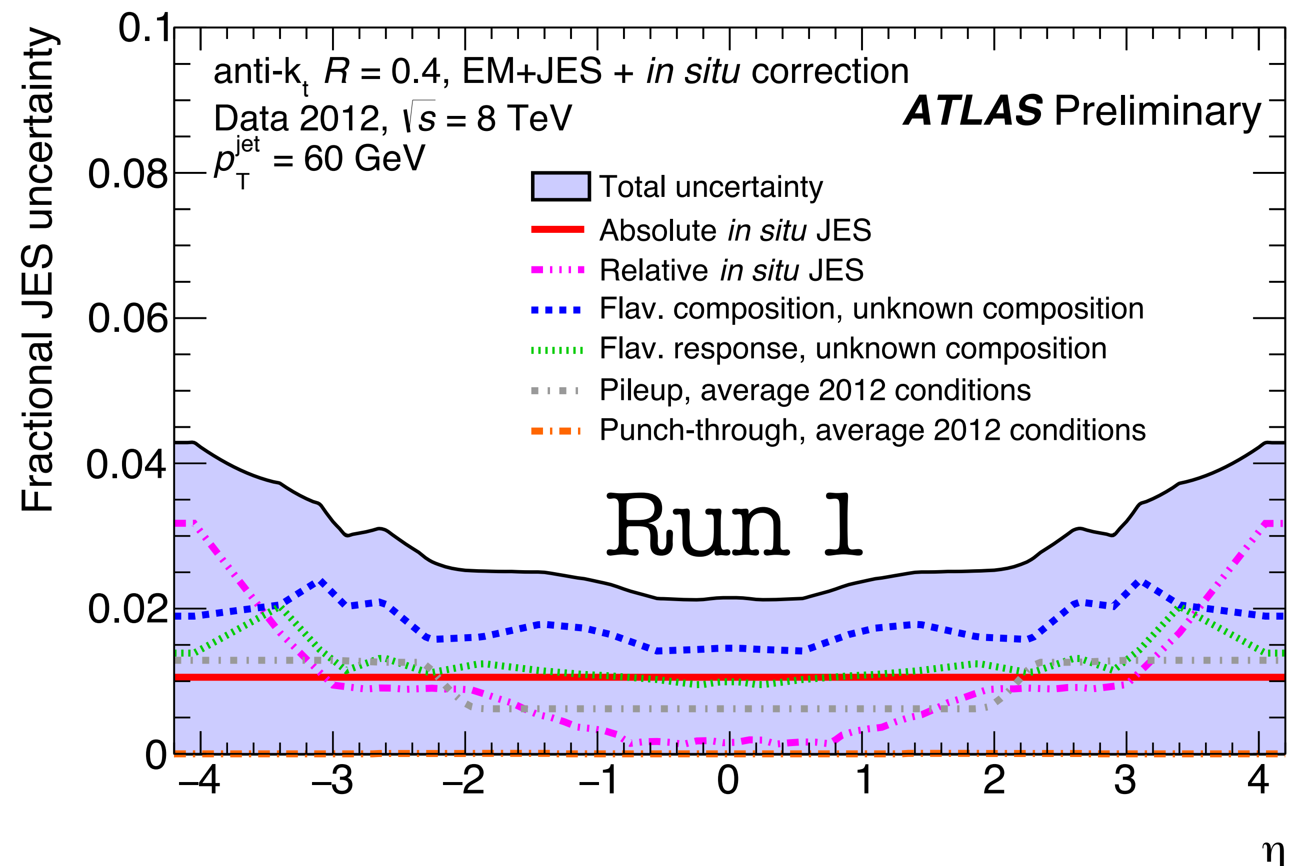




JES uncertainties in **Run 1**

ATLAS-CONF-2015-037





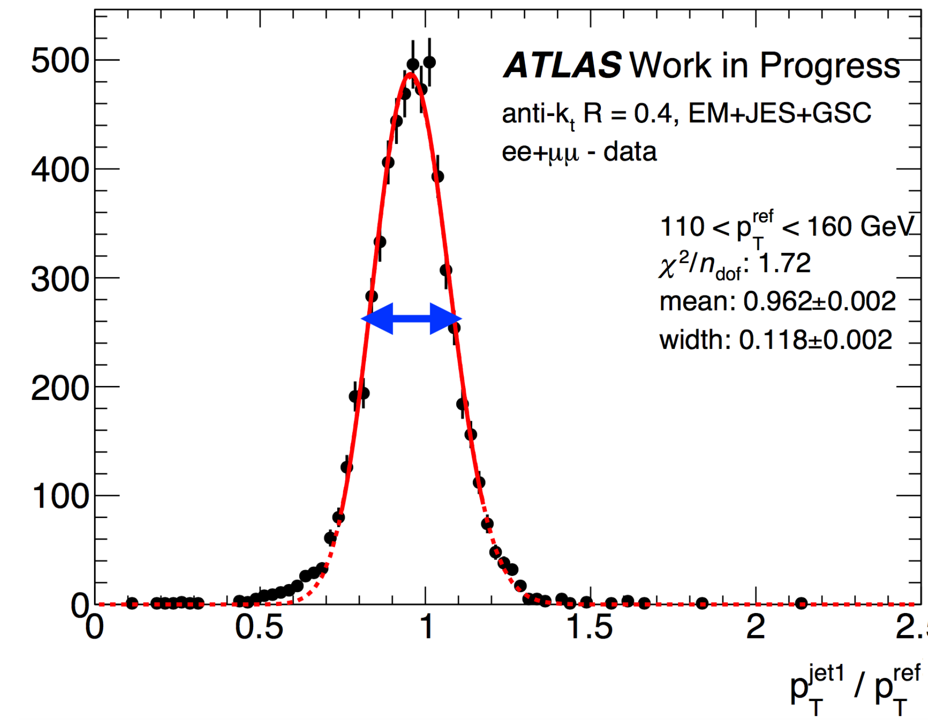
- Final JES uncertainties components **O(60)**, a combination of **in-situ** and **estimated upstream in calibration chain**
- Statistical methods have been developed to reduce the number of final components

Jet energy resolution (JER)

ATLAS-CONF-2015-037

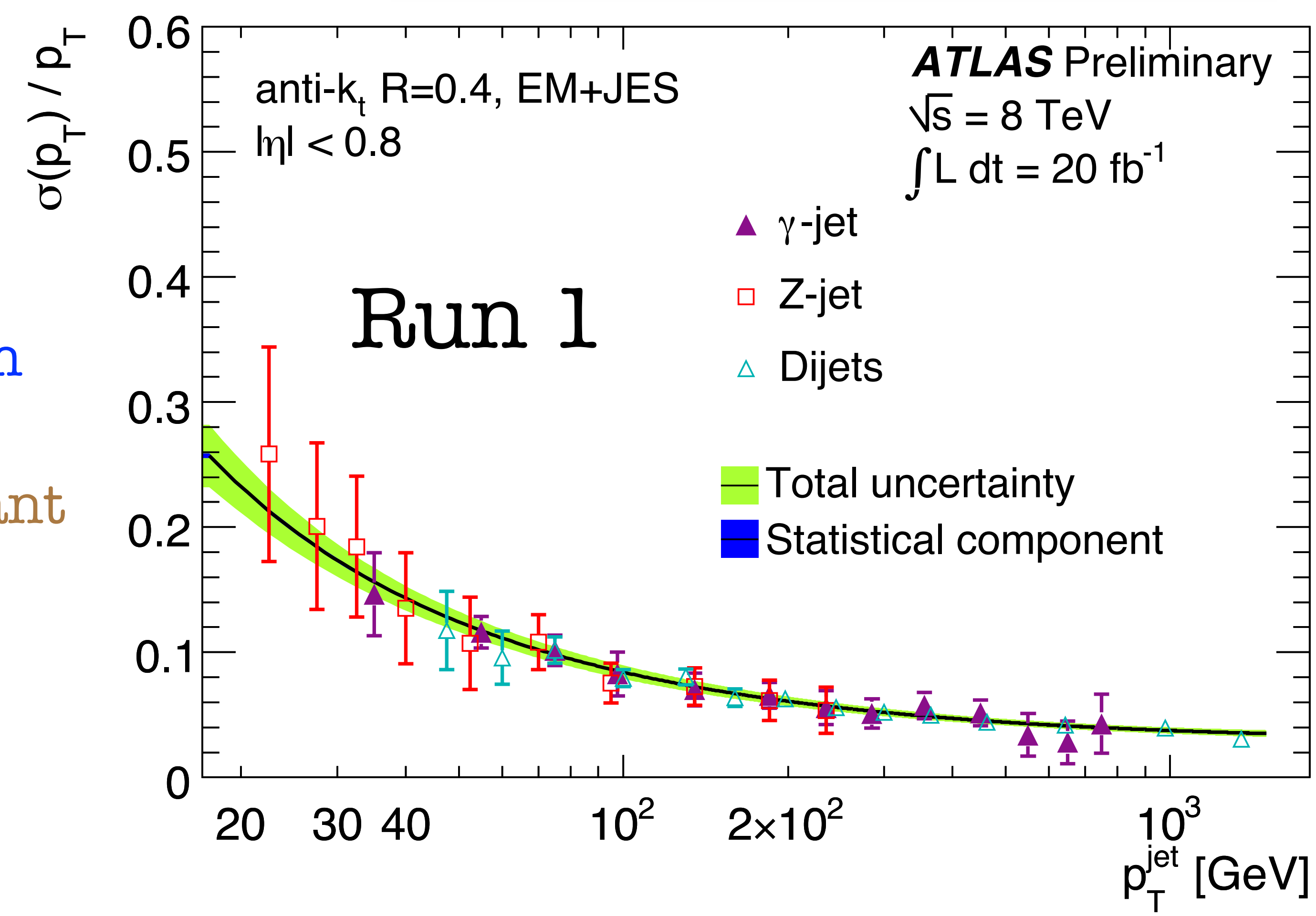
- Measure jet resolution combining Run 1 in-situ γ+jet, Z+jet and dijet **for the first time,** by performing a p_T global fit

- Constraint fit at low pT via an in-situ noise study

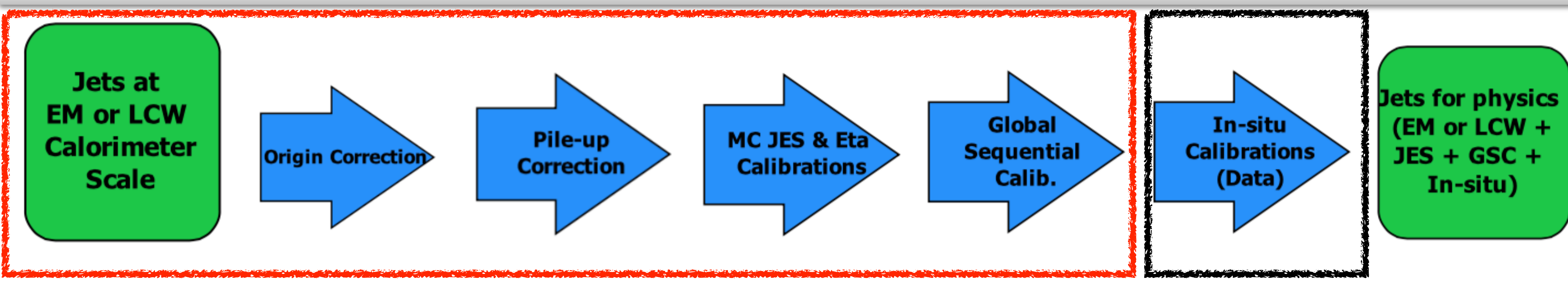


noise term, stochastic term, constant

$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$$



Jet uncertainties in **Run 2**



2015 MC Simulation

2012 data-based

- **The idea is to be based on the Run-I knowledge**
- Use the **2012** in-situ
- Need to apply a **correction/uncertainty** based on **2012→2015 simulation changes** to **maintain** the **applicability** of the 2012 in-situ corrections to **2015 data**
  - ***Detector:* IBL - added material because of IBL services, mainly in the forward region**
  - *Beam conditions*: 8→13 TeV ; 50→25 ns (pile-up)
  - …

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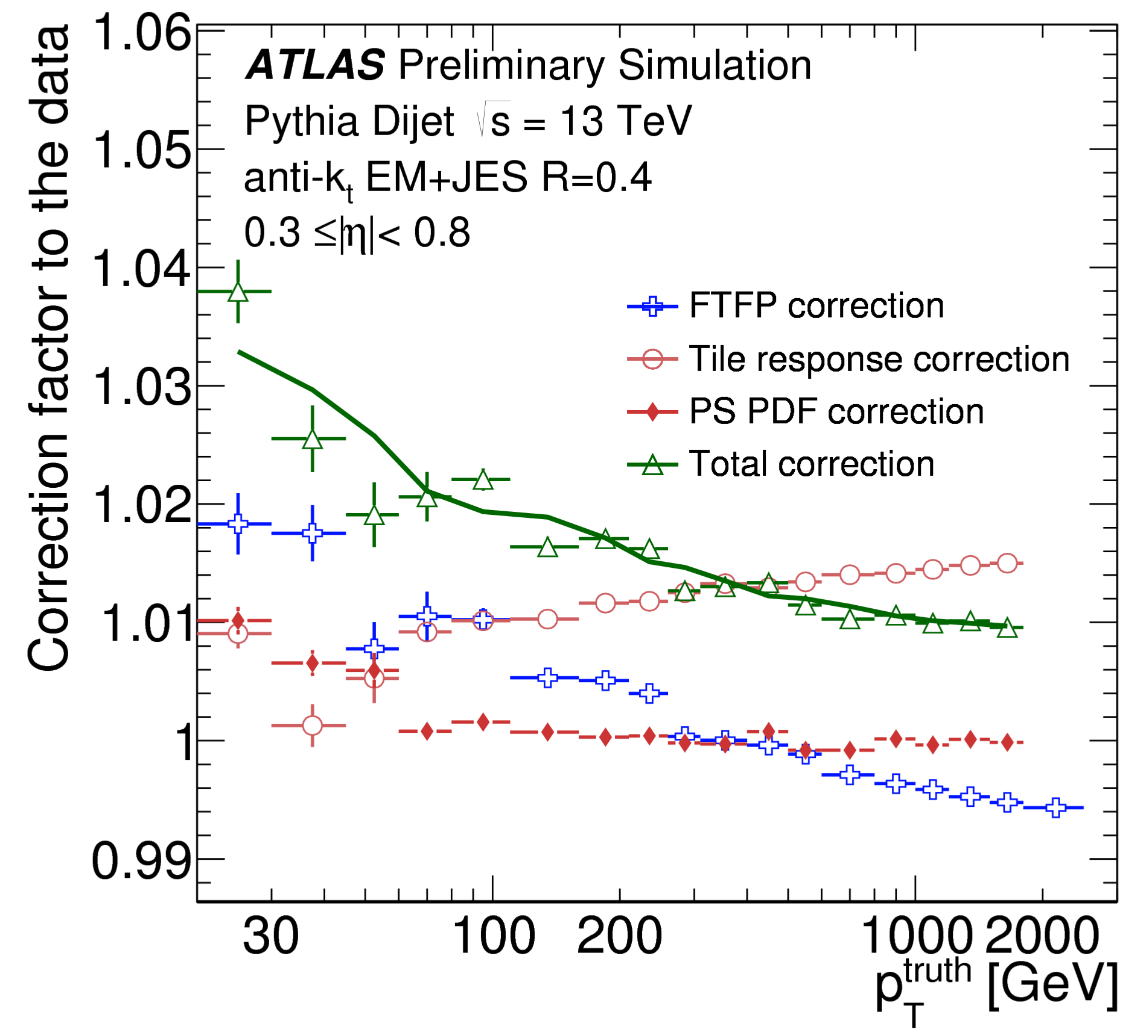

Jet energy uncertainties in Run 2

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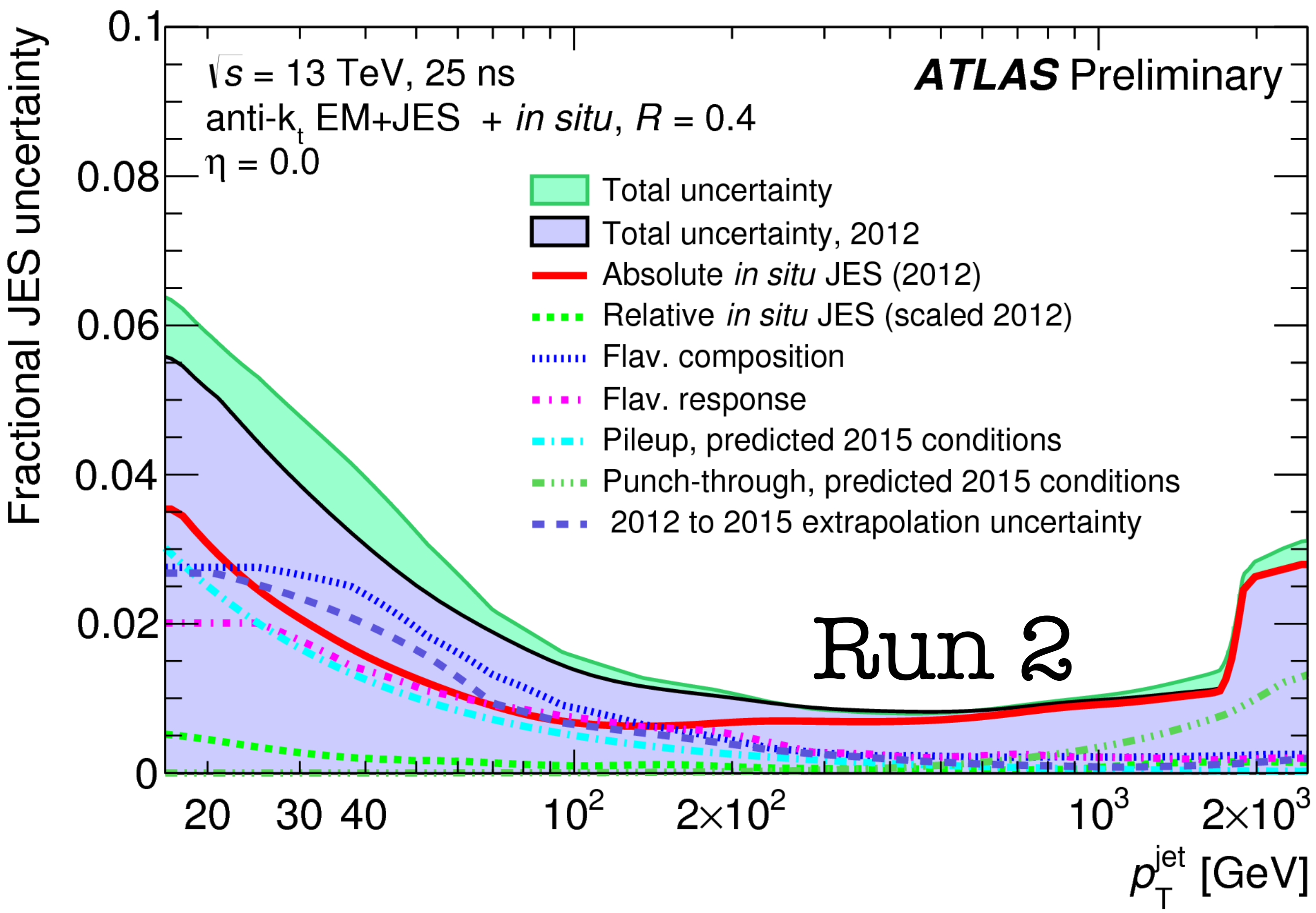
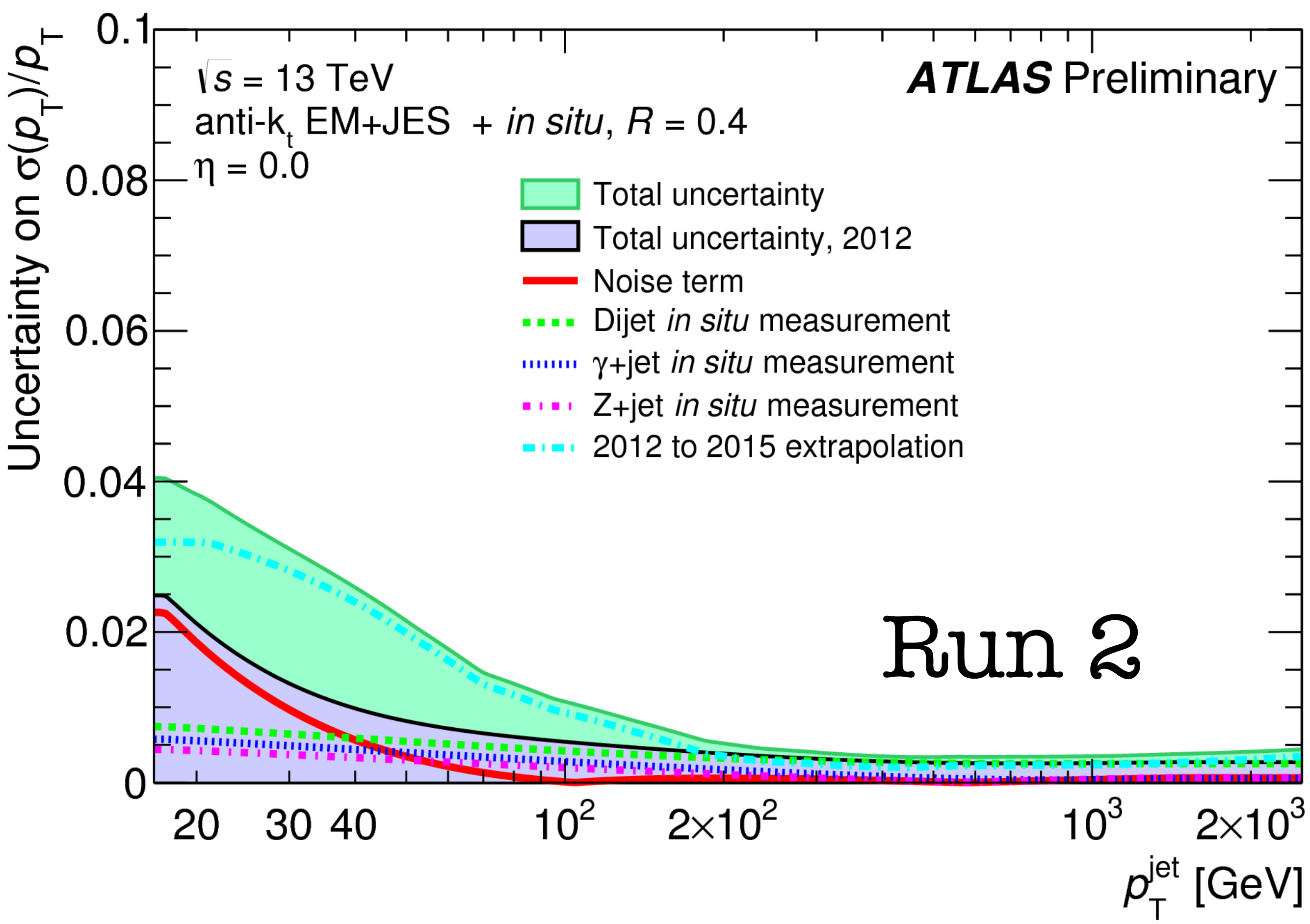




- **~3%** additional uncertainty **with respect to Run 1** at low p_T
  - Negligible for jet **p_T > 200 GeV**

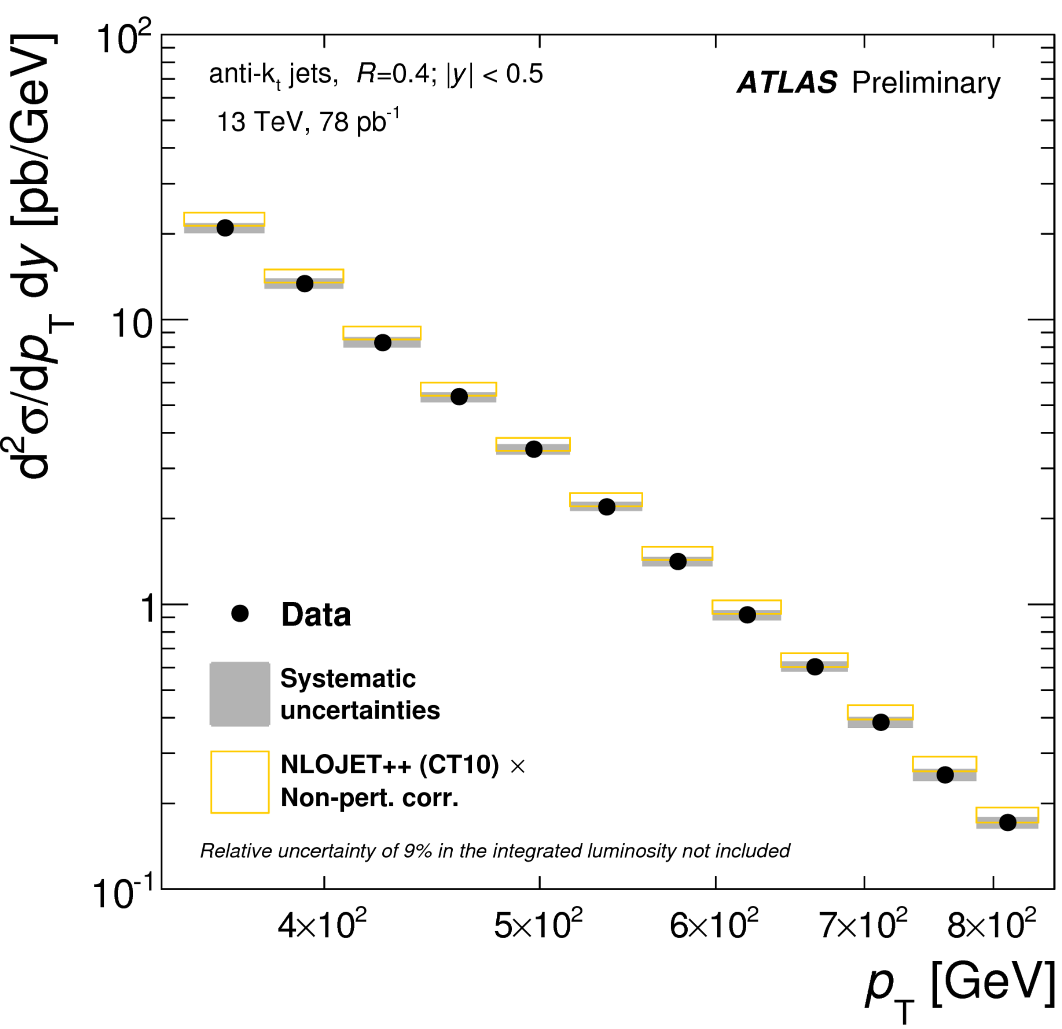
SM jet inclusive cross section measurement

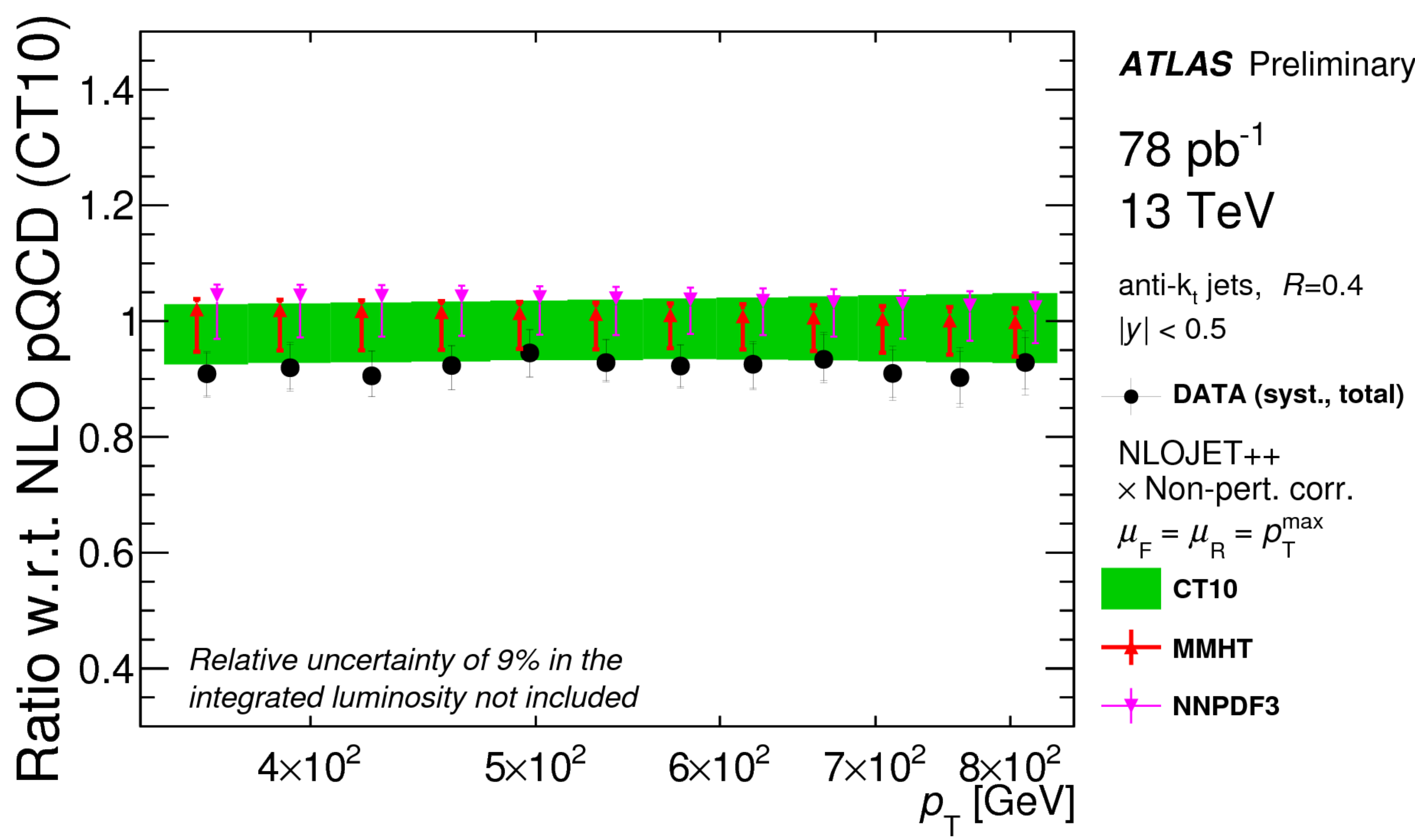
First inclusive jet x-section at 13 TeV

ATLAS-CONF-2015-034

- **Inclusive jets cross-section** measurement using the **first 13 TeV data**
  - ✦ $350 < p_T < 840$ GeV and $|y_{jet}|<0.5$
  - ✦ Single jet trigger, fully efficient above 300 GeV
  - ✦ Correct detector effets using unfolding
  - ✦ **Dominant systematic uncertainty: jet energy scale**

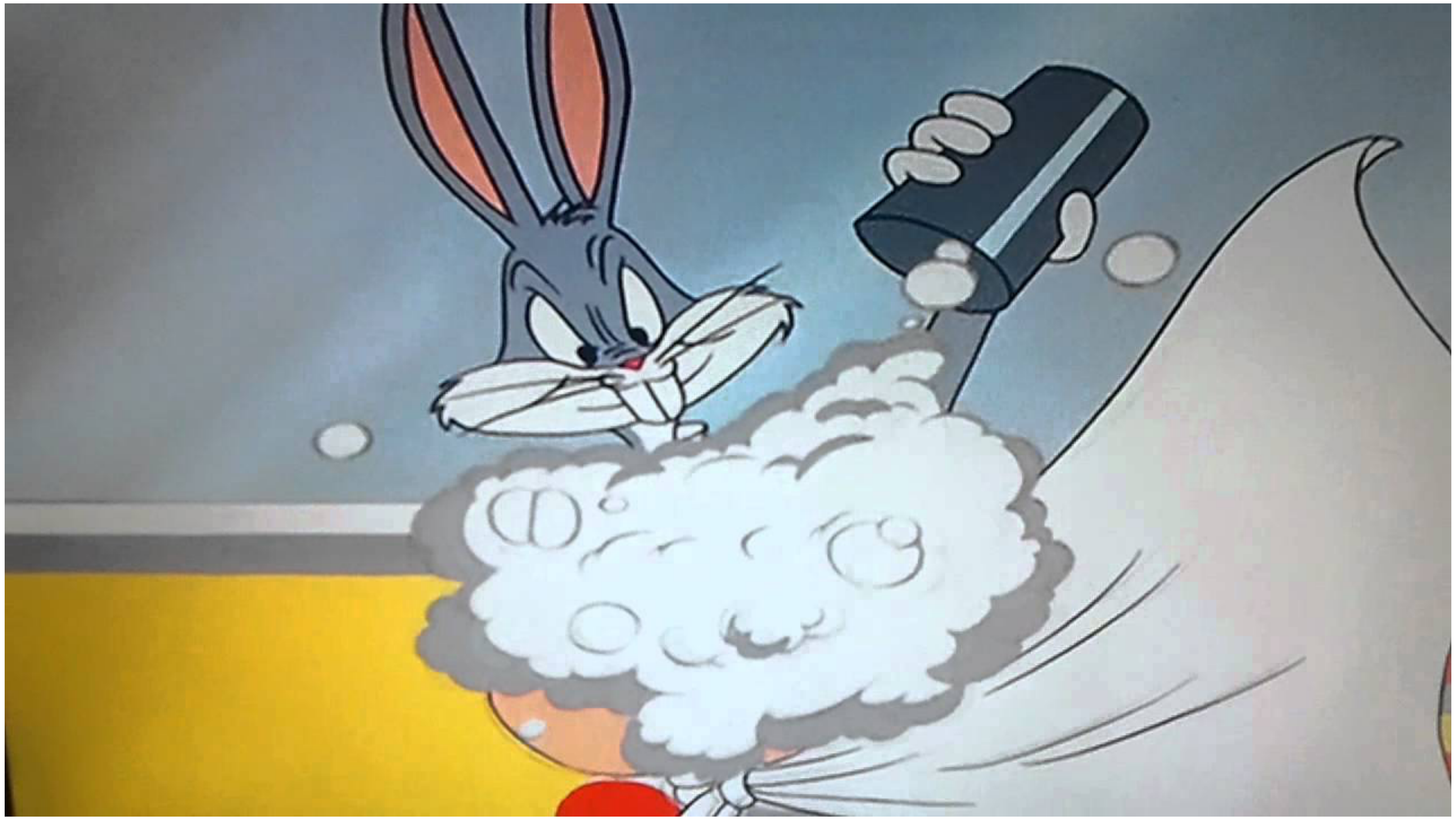
1st jet x-sec measurement in 13 TeV. Presented in EPS





NLO QCD predictions are consistent with the measured cross sections

Searches for New Physics in di-jet final states

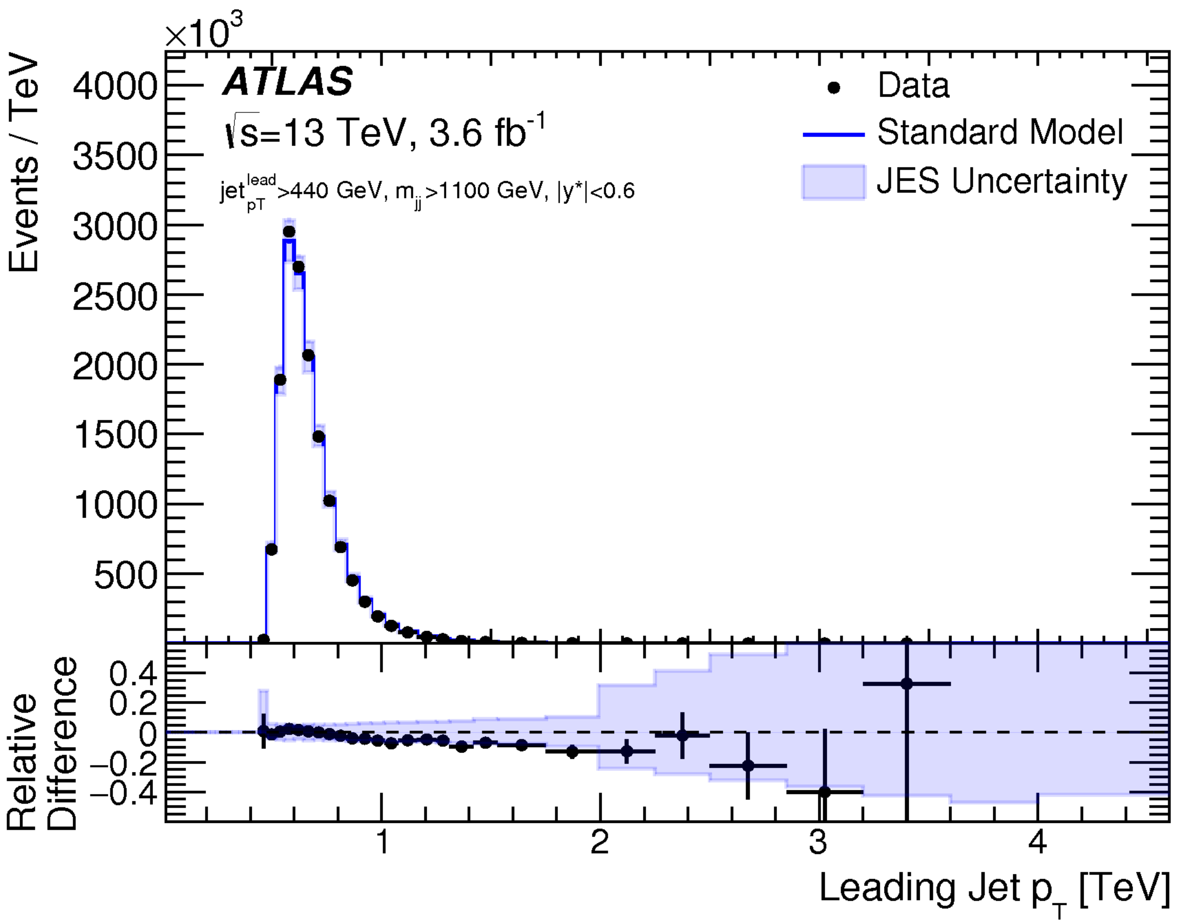


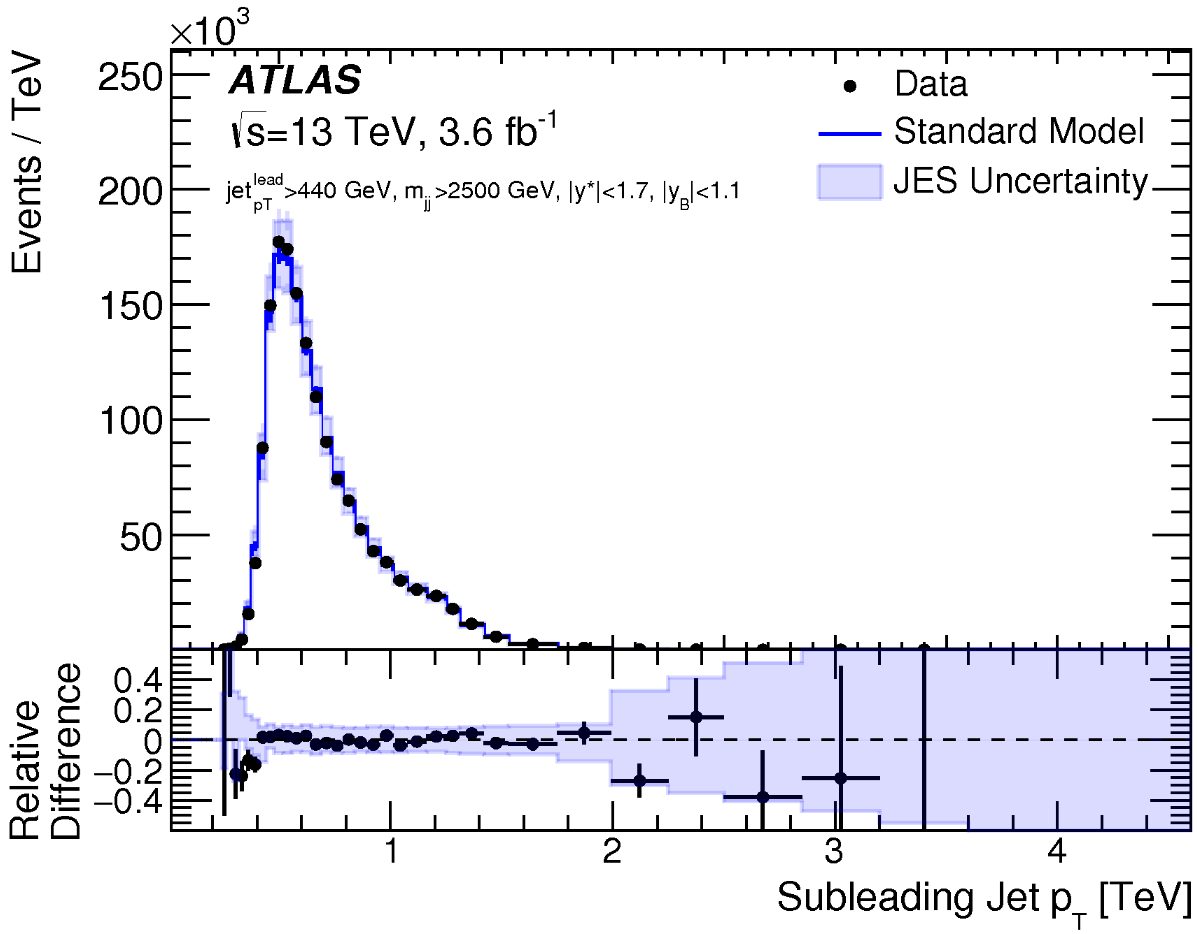
Searches of new physics

arXiv:1512.01530v2

- **Search for non-SM features in di-jet final, two analyses**
  - ✦ **New resonances in m_{jj} spectrum**
    - Select events with leading (subleading) jet p_T > 440(50) GeV
    - **Search for a bump in invariant mass m_{jj}**
  - ✦ Deviations in angular variables
    - Complementary analysis to m_{jj} resonance search
- **Full 2015 dataset has been analysed**

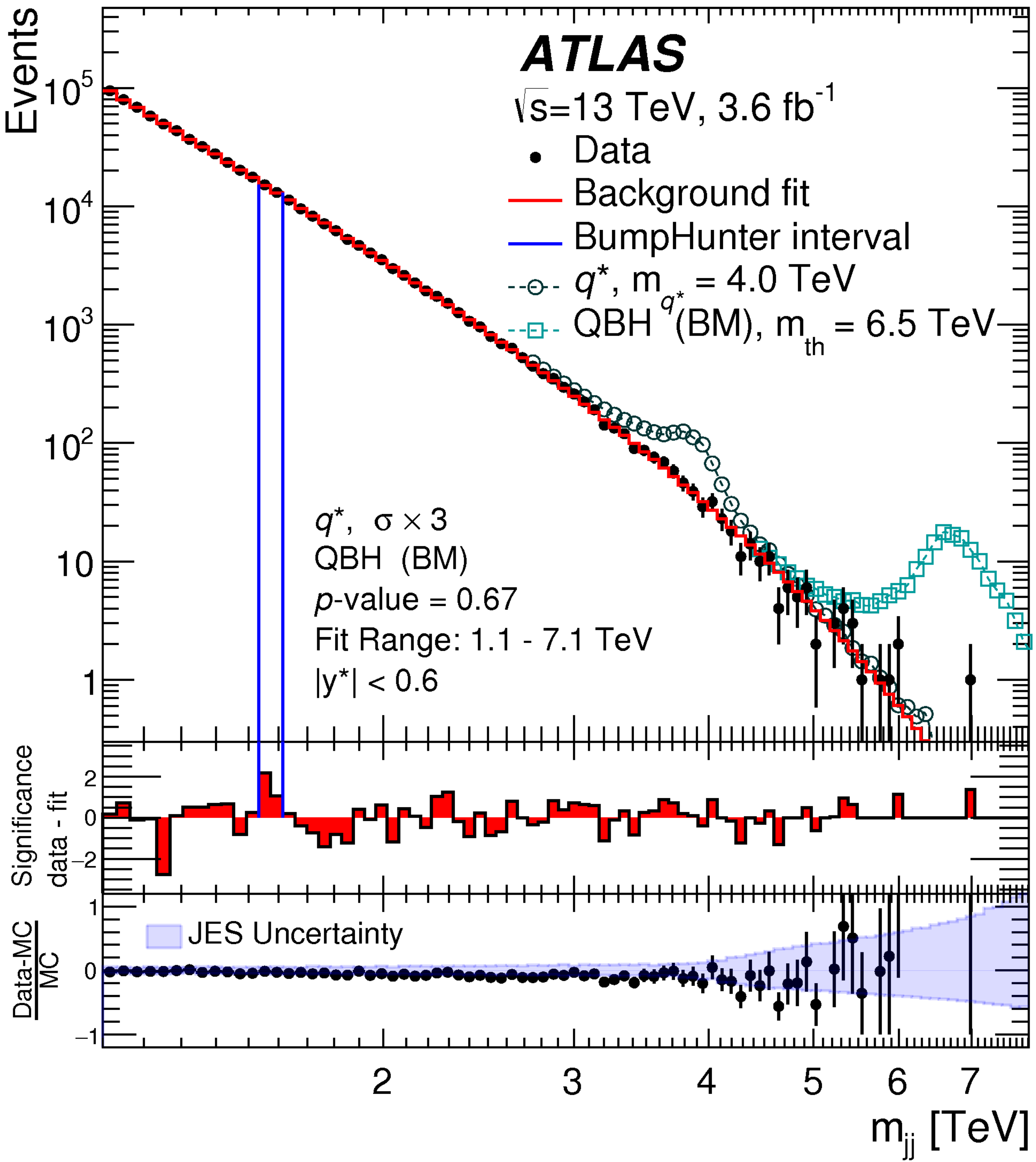
New!
7 Dec. 2015





Dijet resonance search

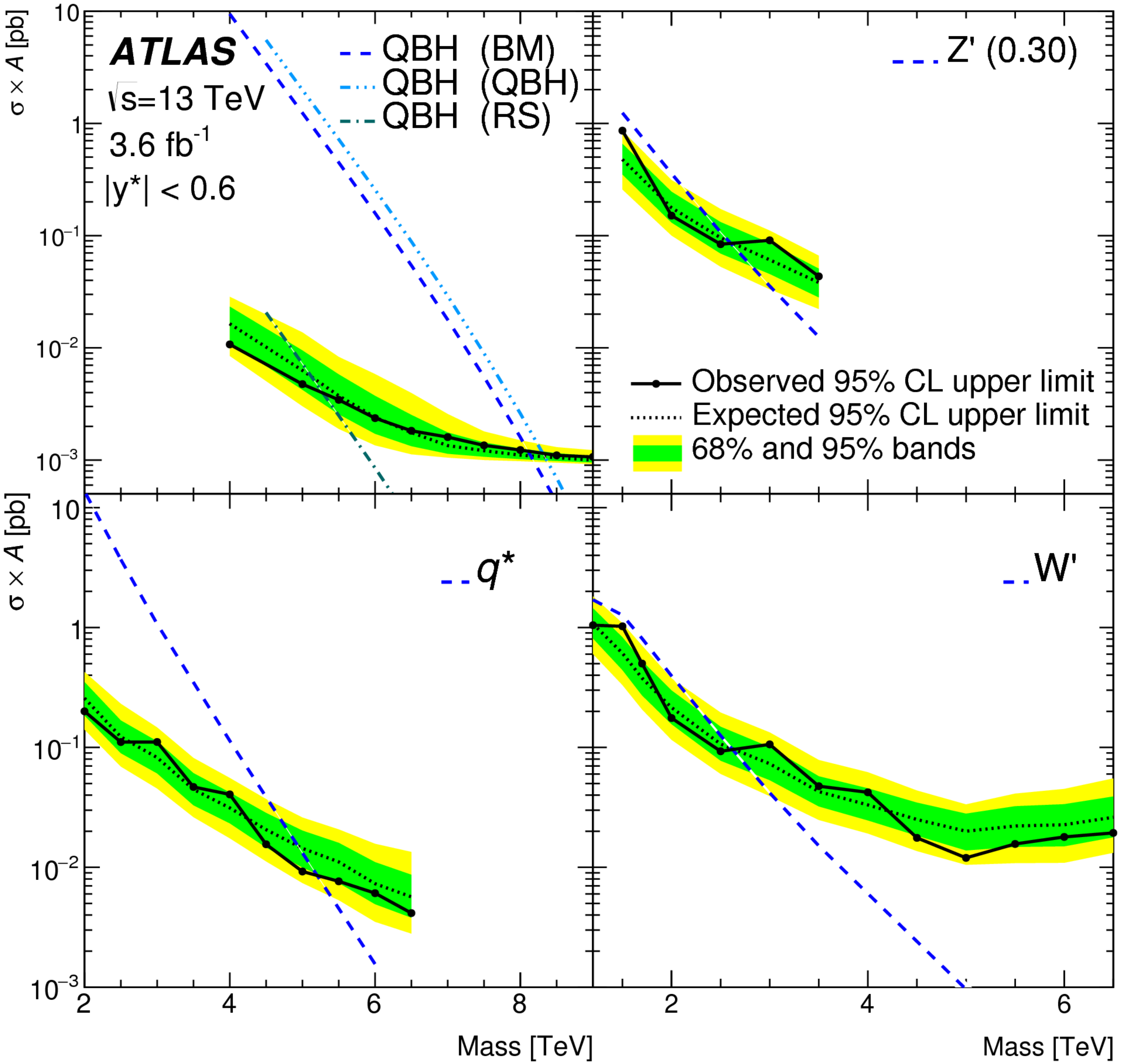
arXiv:1512.01530v2



- Fit m_{jj} distribution using analytic function
- Compare fit with observed data
- **No significant excess found, data are consistent with the background hypothesis**

Dijet resonance search

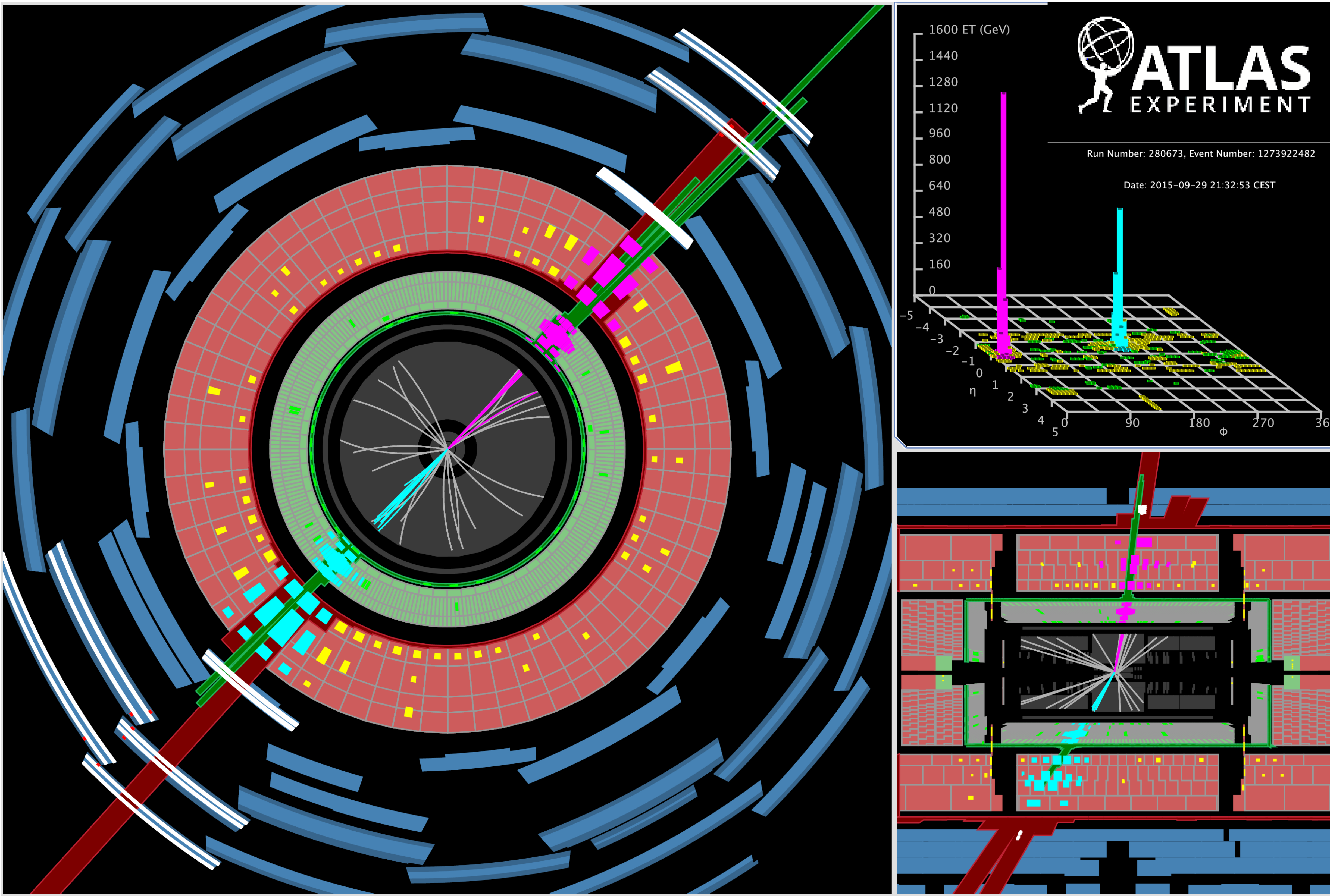
arXiv:1512.01530v2



- **No significant excess found, data are consistent with the background hypothesis**
  - QBH: M_{th} < 8.3 TeV excluded @ 95% CL
  - Significantly better than Run 1 sensitivity

Highest mass candidate, m_{jj}=6.9 TeV

arXiv:1512.01530



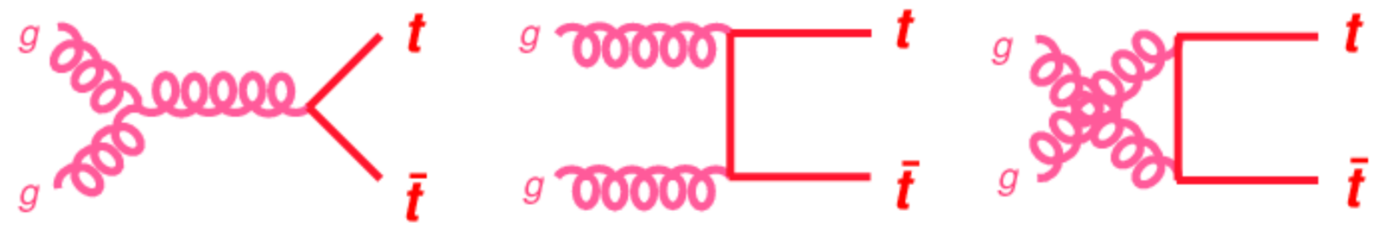
– Jet$_1$ p_T = 3.2 TeV, Jet$_2$ p_T = 3.2 TeV, E_T^{miss} = 46 GeV

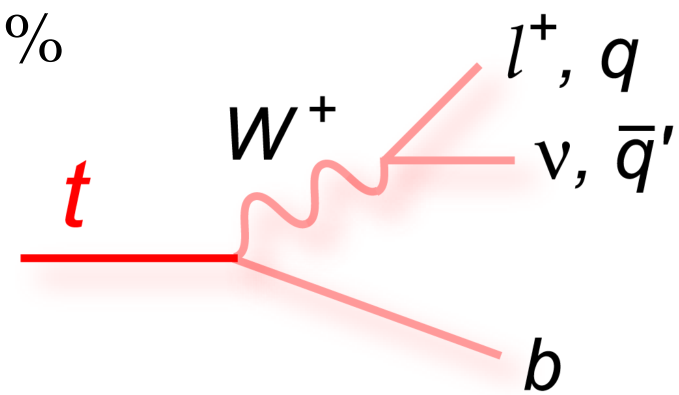
First $t\bar{t}$ cross section measurement at 13 TeV

Top quark trivia

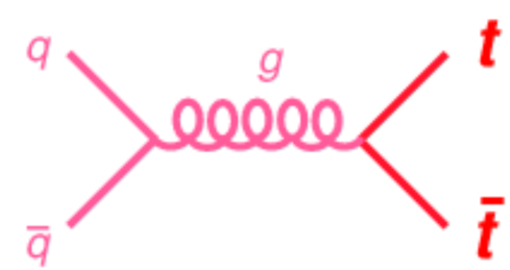
- **Heaviest elementary particle**
- Top pair decay channels
  - ✦ Dilepton (e/μ/τ) ~ 11%
  - ✦ l+jets (e/μ/τ) ~ 45%
  - ✦ All jets ~ 44%

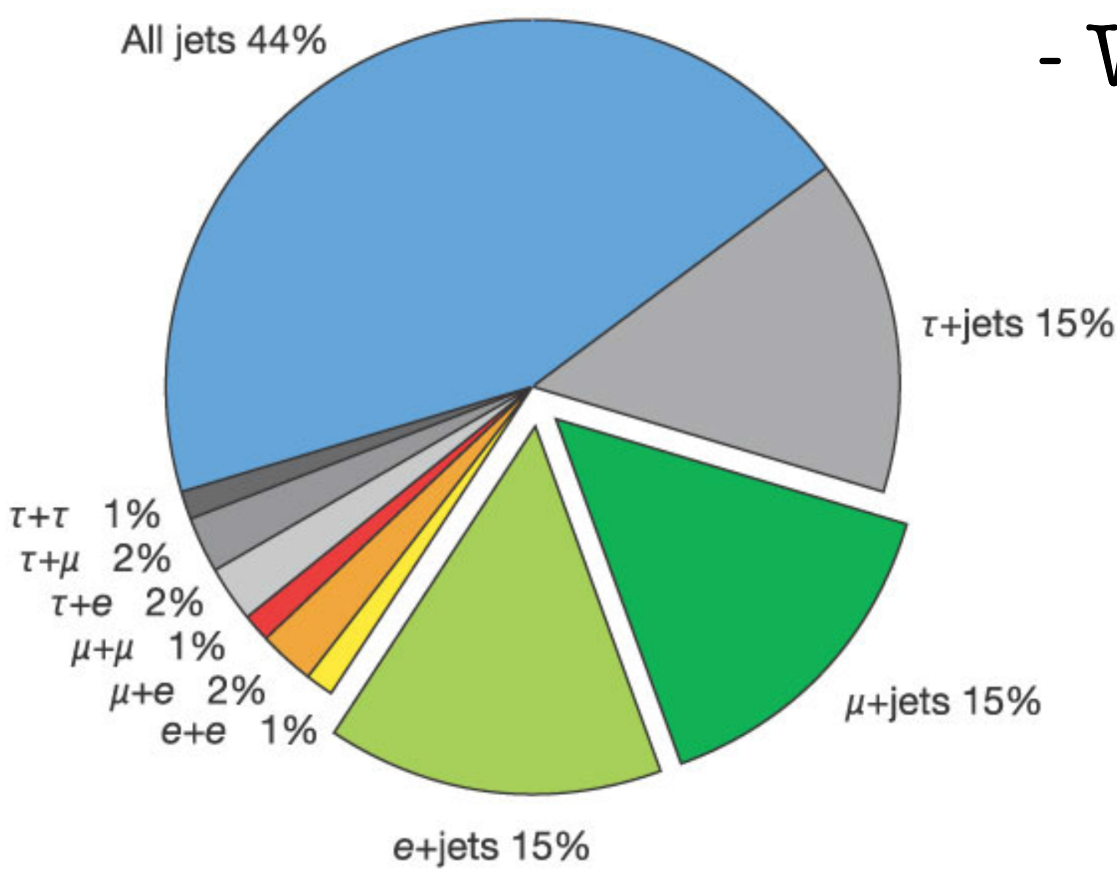
87%





13%





\- Why the top quark pair production?

- Cross section **increases** by a **factor of ~4** (8 → 13 TeV)
  - ✦ Excellent **precision tests** of **Standard Model**
  - ✦ Sensitive to **QCD effects**, **PDF**, **top quark mass**
  - ✦ **Probe of new physics**

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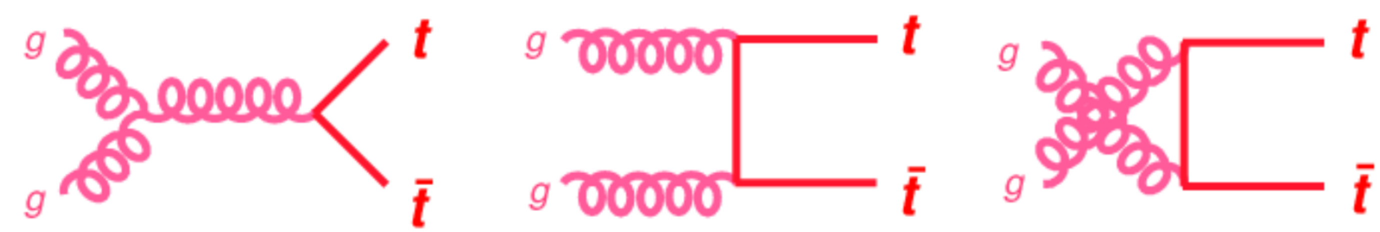
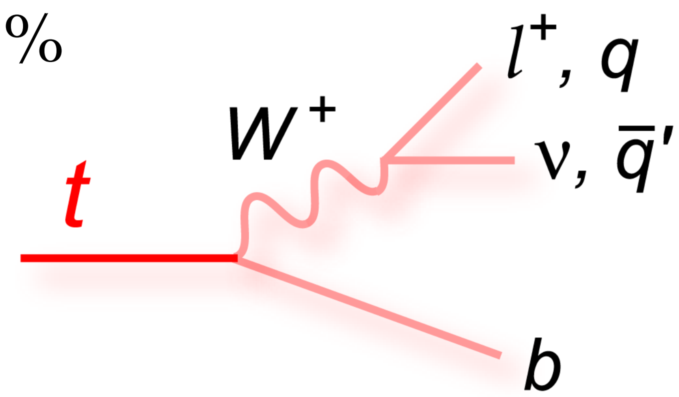
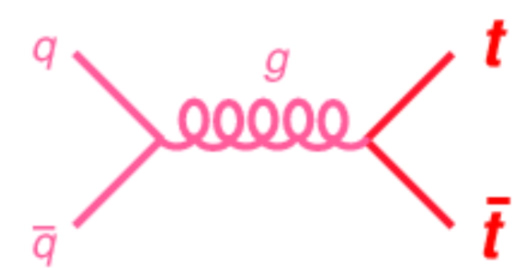
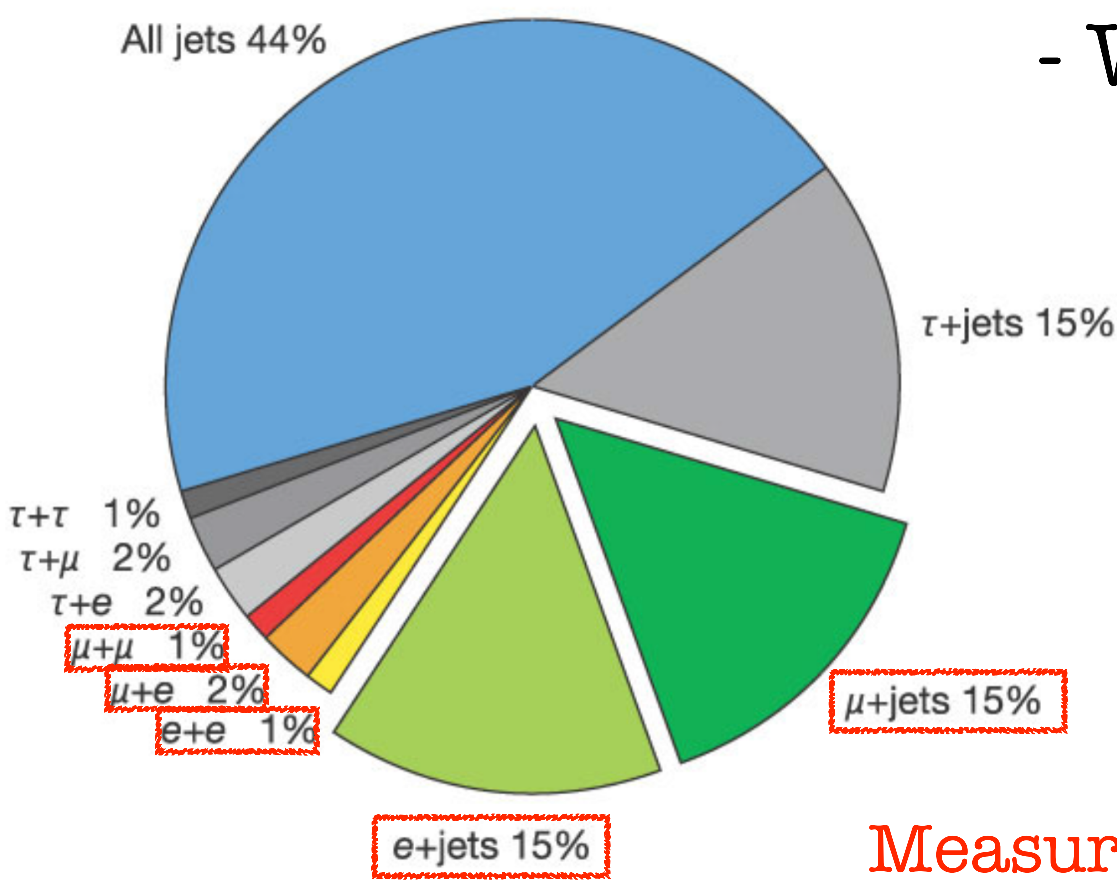




13%





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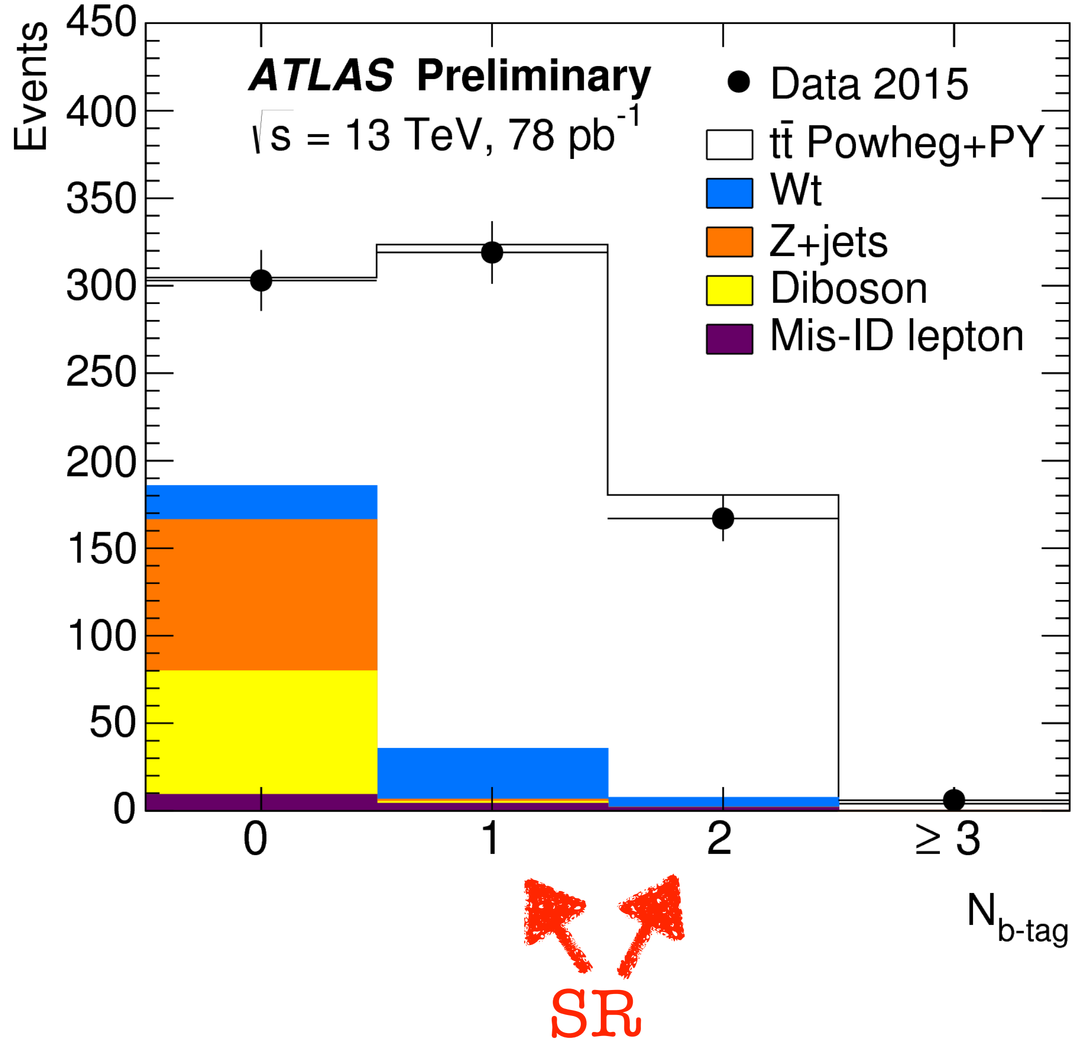
Measurements at 13 TeV

e/μ + b-jets at 13 TeV

ATLAS-CONF-2015-033



- Select **opposite-sign eμ pair**
- Two **signal regions** with $\mathbf{N_{b\text{-}tag\ jets} = 1\ or\ 2}$
- Dominant uncertainties
  - Luminosity 10%
  - Statistics 6%
  - Theory 5%
  - ➡ **13.5 % total uncertainty**
    - ➡ It was 4% for full Run-1 dataset analysis
  - ➡ **JES uncertainty subdominant**

Result

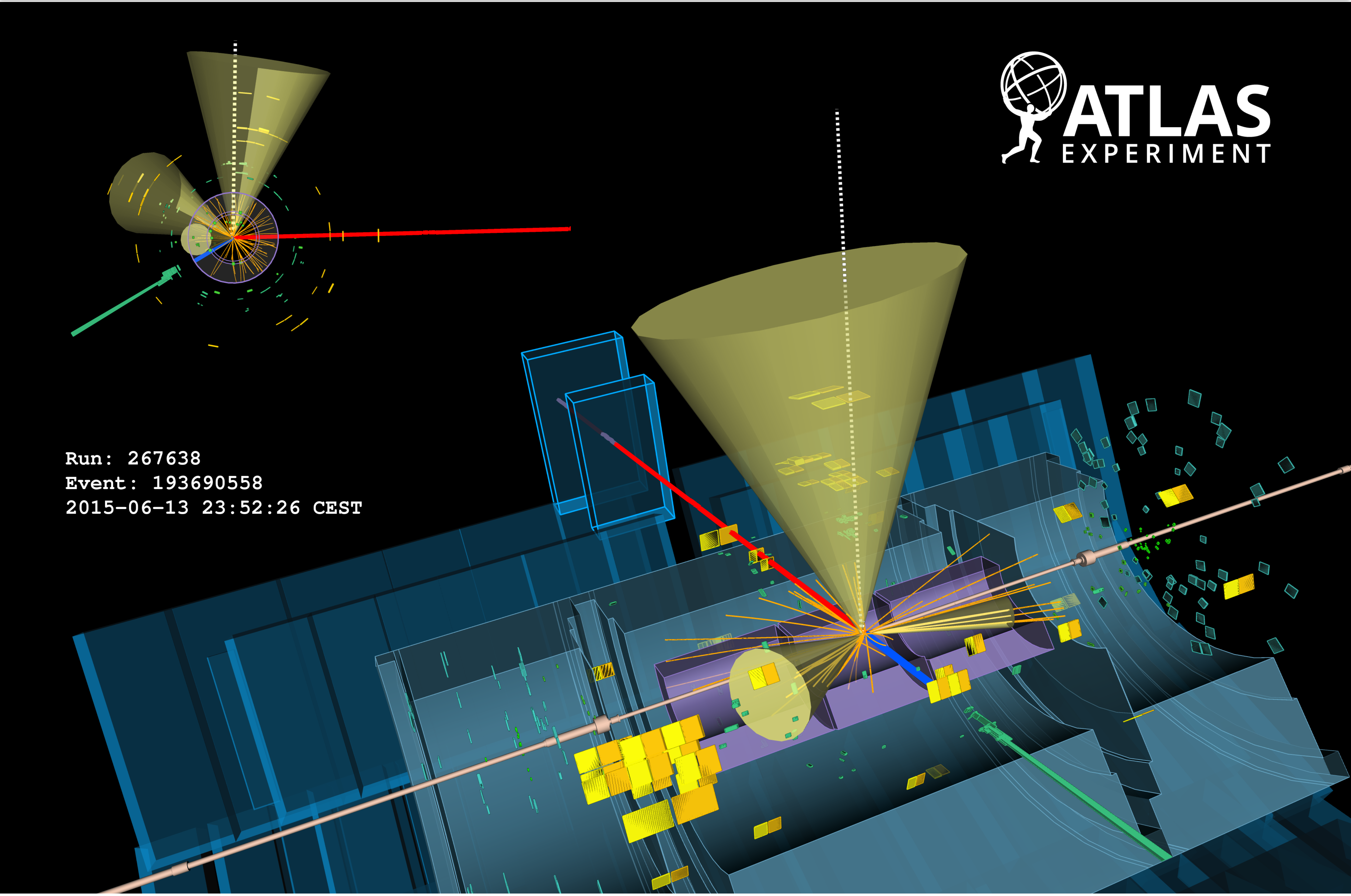
$$\sigma_{t\bar{t}} = 829 \pm 50\,(\mathrm{stat}) \;\pm 56\,(\mathrm{syst}) \;\pm 83\,(\mathrm{lumi})\;\;\mathrm{pb}$$

Theory NNLO+NNLL 832^{+40}_{-46} pb at $m_t = 172.5$ GeV

Czakon, Fiedler, Mitov
PRL 110 252004

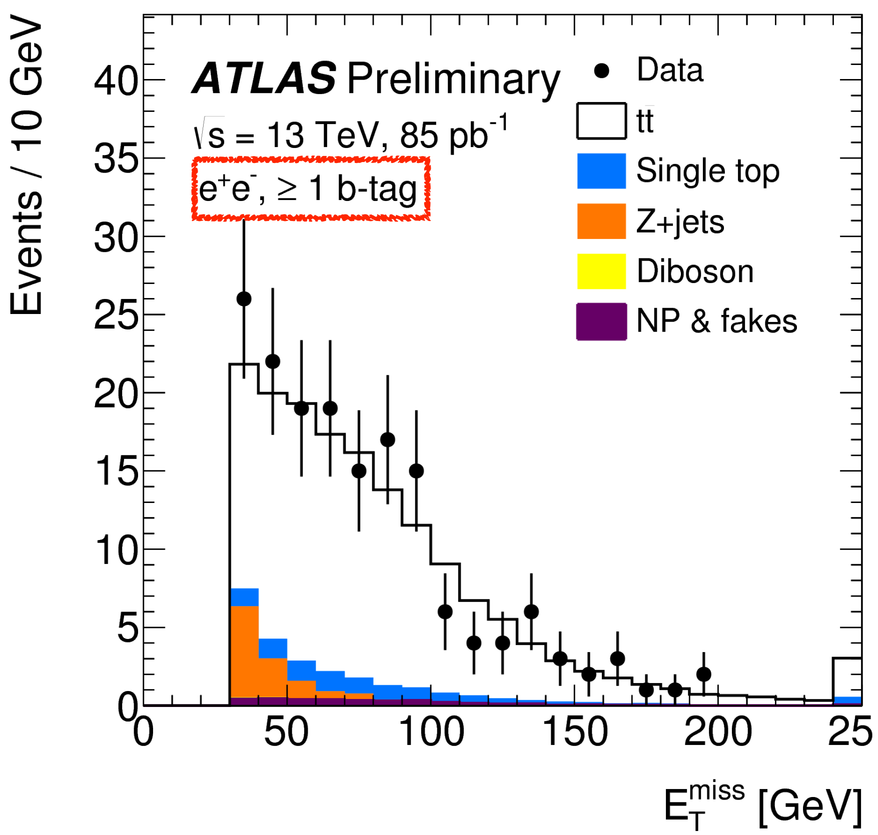
ATLAS-CONF-2015-033

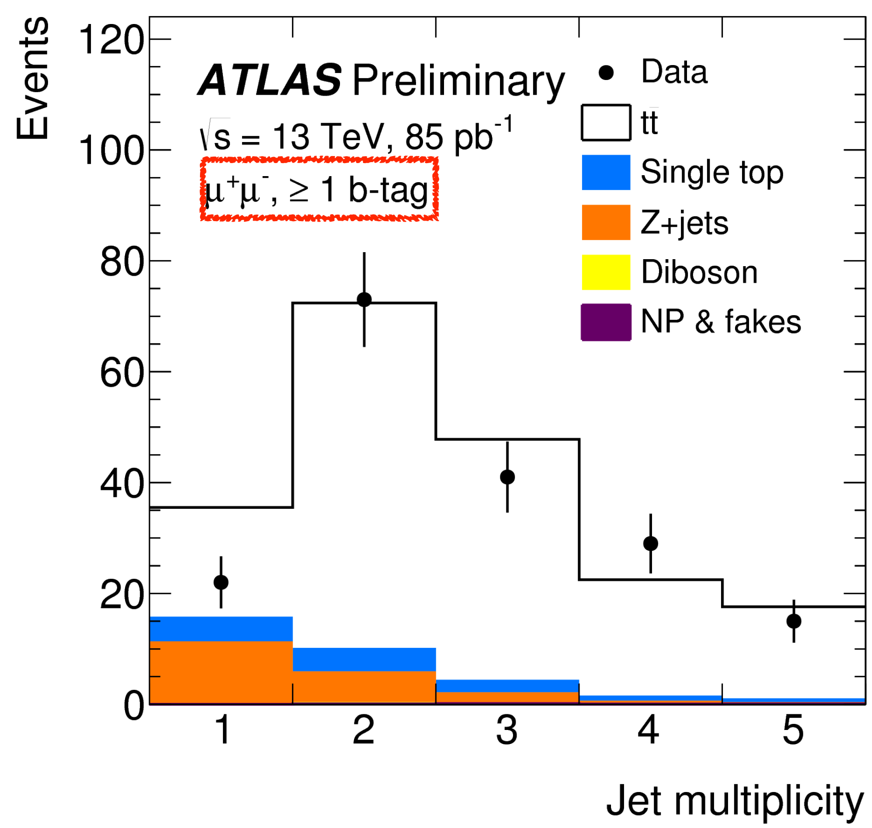
$t\bar{t}$ production at 13 TeV



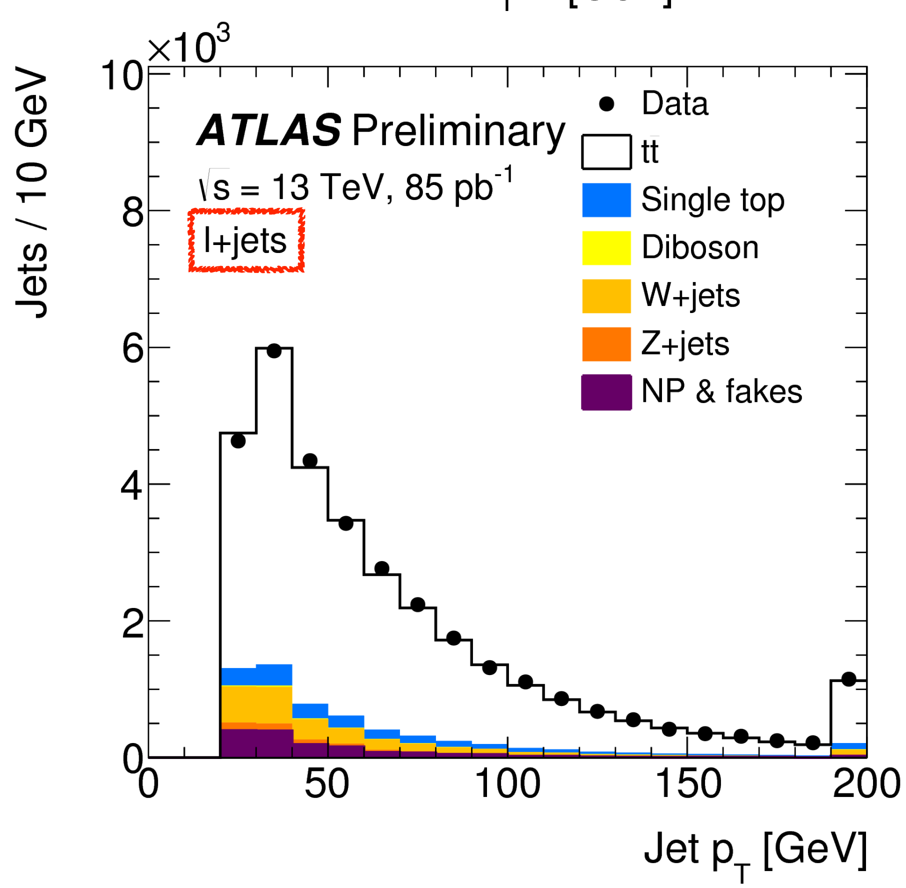
Lepton-jets at 13 TeV

ATLAS-CONF-2015-049





- **ee/μμ + b-jets**
  - Opposite sign ee/μμ
- **lepton + jets**
  - One e/μ
  - Four jets (1 b-tagged)



data — background

$$\sigma_{t\bar{t}} = \frac{(N - B)}{\varepsilon L}$$

efficiency — luminosity

Lepton-jets at 13 TeV: results

ATLAS-CONF-2015-049

ee/μμ + b-jets

Result

$\sigma_{t\bar{t}} = 749 \pm 57$ (stat) ± 79 (syst) ± 74 (lumi) pb — 16%

8% 11% 10%

Uncertainties

- Theory: 9%
- **Jet Energy Scale: 1.2%**

e/μ + 4-jets

Result

$\sigma_{t\bar{t}} = 817 \pm 13$ (stat) ± 103 (syst) ± 88 (lumi) pb

2% 13% 11% 17%

Uncertainties

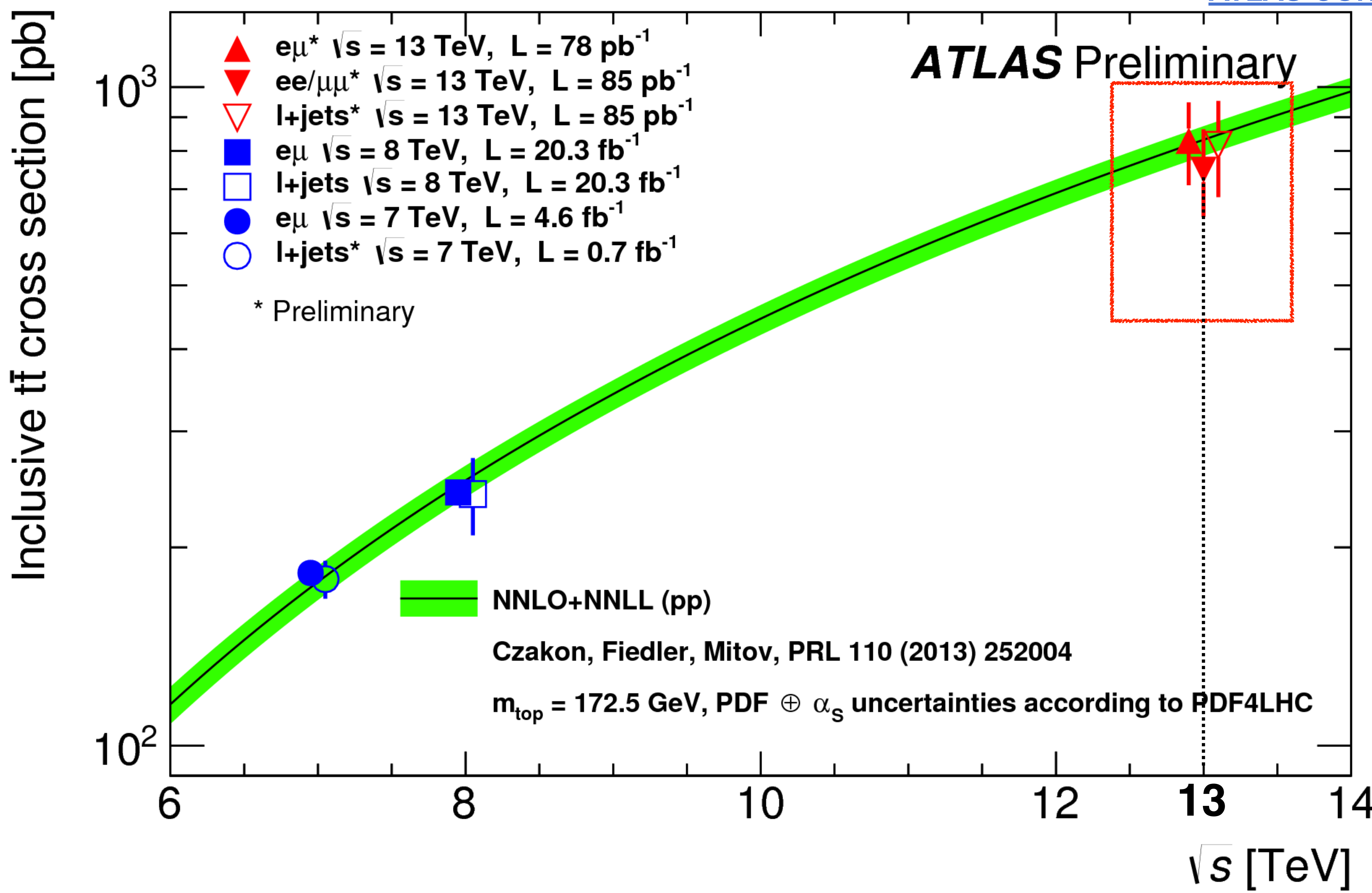
- **Jet Energy Scale, the dominant one: 9%**
- b-tagging: 4%
- Theory: 5%

Theory NNLO+NNLL prediction

832^{+40}_{-46} pb at $m_t = 172.5$ GeV

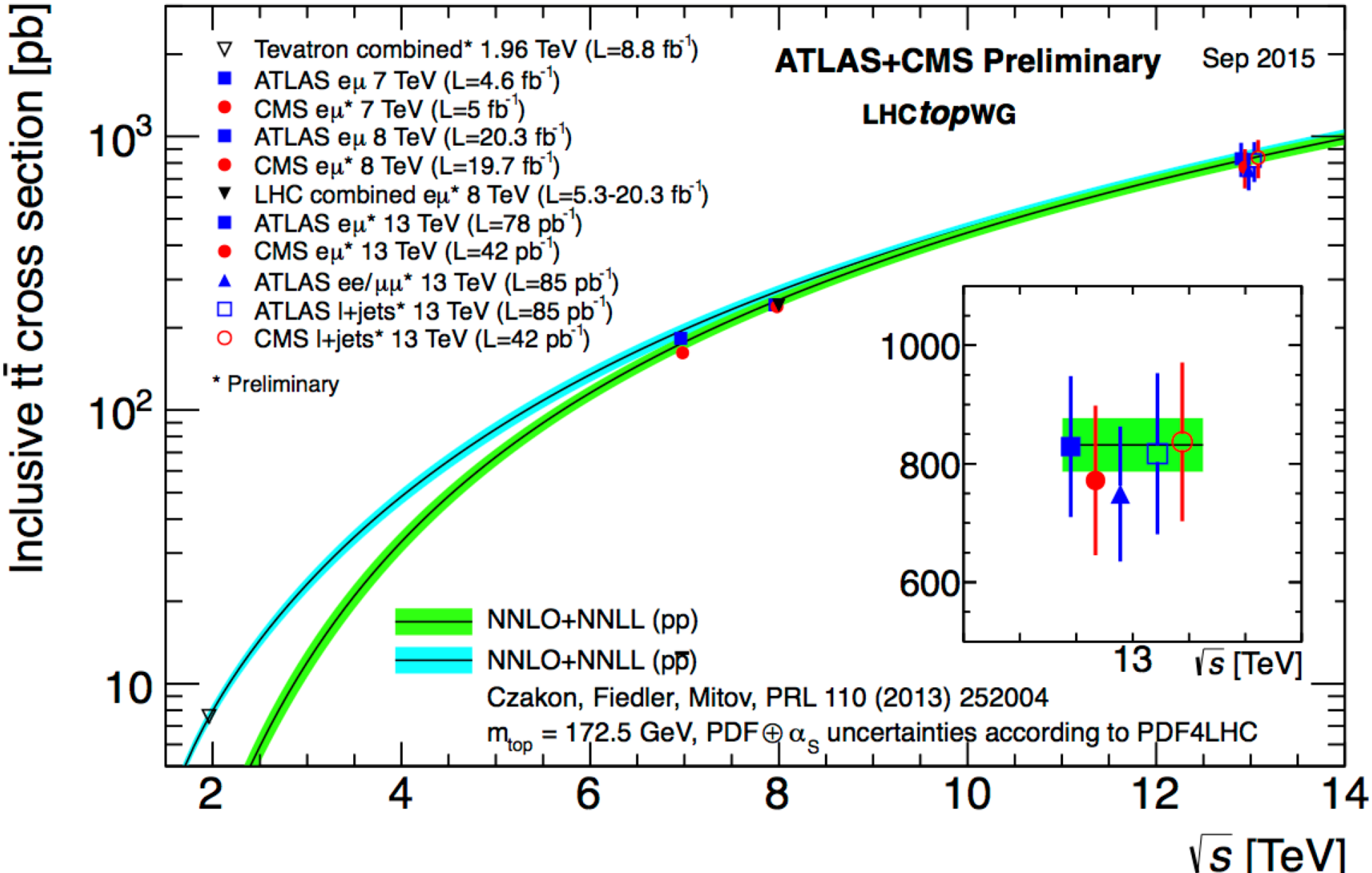
$t\bar{t}$ cross section in ATLAS

ATLAS-CONF-2015-049



- **NNLO+NNLL predictions consistent with 13 TeV measurements**

$t\bar{t}$ cross section in LHC



- **Five measurements already at 13 TeV from ATLAS and CMS**
- **All consistent with theory and within each other**

Conclusions

- **Jets in LHC: challenging but extremely interesting objects**
  - Huge amount of work optimising their energy calibration and performance

- **Run 2 (13 TeV) remarkable results already published challenging/exceeding Run 1 sensitivity**
  - ✦ Jet inclusive cross section measurement
    - ✤ Contributed to reveal and fix an important trigger issue
  - ✦ $t\bar{t}$ cross section measurements
  - ✦ Searches of New Physics in di-jet final states

- **Robust jet performance in Run 2: key ingredient for most ATLAS physics analyses**
  - ✦ Perform jet energy calibration and evaluate related uncertainties in a very short time scale during last summer

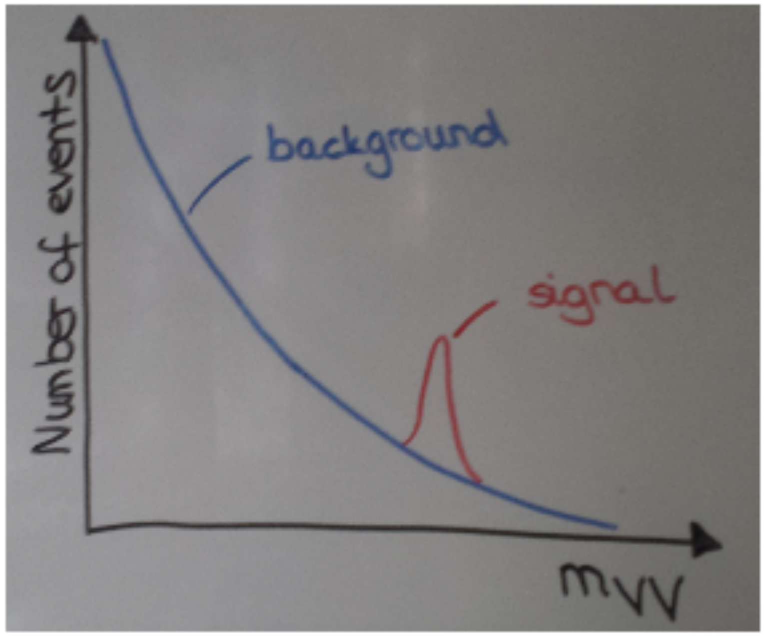
➡ **ATLAS Run 2 jets ready for ambitious physics program**

If time permits

A large-R analysis from 8 TeV: VV resonance

How to search for diboson resonances

- Observable:
  invariant mass of diboson system m_{VV}
- Here: search for narrow resonance on top of smoothly falling background distribution



Decay modes:

- **Semi-leptonic final state**
- **Full-hadronic final state:**
  - Large branching ratio:

$$\mathrm{BR}(W \to qq) \approx 3 \times \sum_{\ell=e,\mu} \mathrm{BR}(W \to \ell\nu)$$

$$\mathrm{BR}(Z \to qq) \approx 10 \times \sum_{\ell=e,\mu} \mathrm{BR}(Z \to \ell\ell)$$

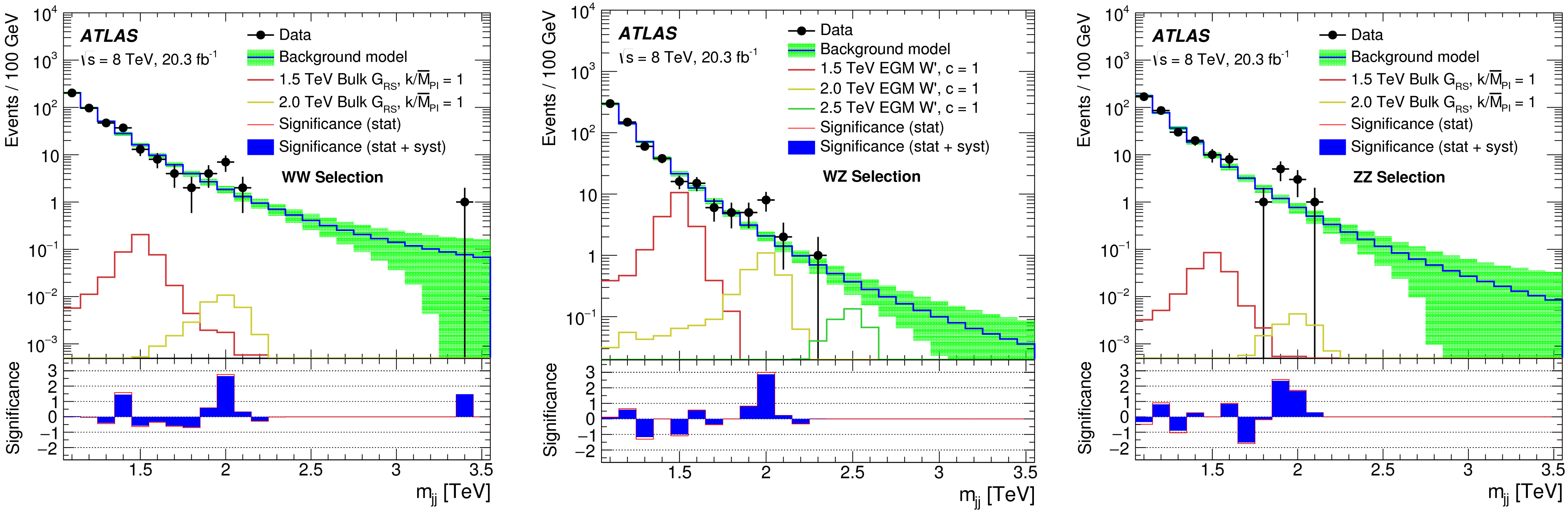
  - No MET
  - large dijet background

- **Full-leptonic final state**
  - Clean signature and low background
  - Small branching ratio
  - (Not considered here)

A large-R analysis from 8 TeV: VV resonance

arXiv:1506.00962

VV—> qq qq (2 large-R jets) m_{JJ} spectrum



- Good agreement between data and background model over full dijet mass range except for region around m_{JJ}=2 TeV
- Frequentist approach used to interpret data
  - Local significance: WZ: 3.4σ, WW: 2.6σ, ZZ: 2.9σ
  - Global significance: WZ: 2.5σ

Back-up