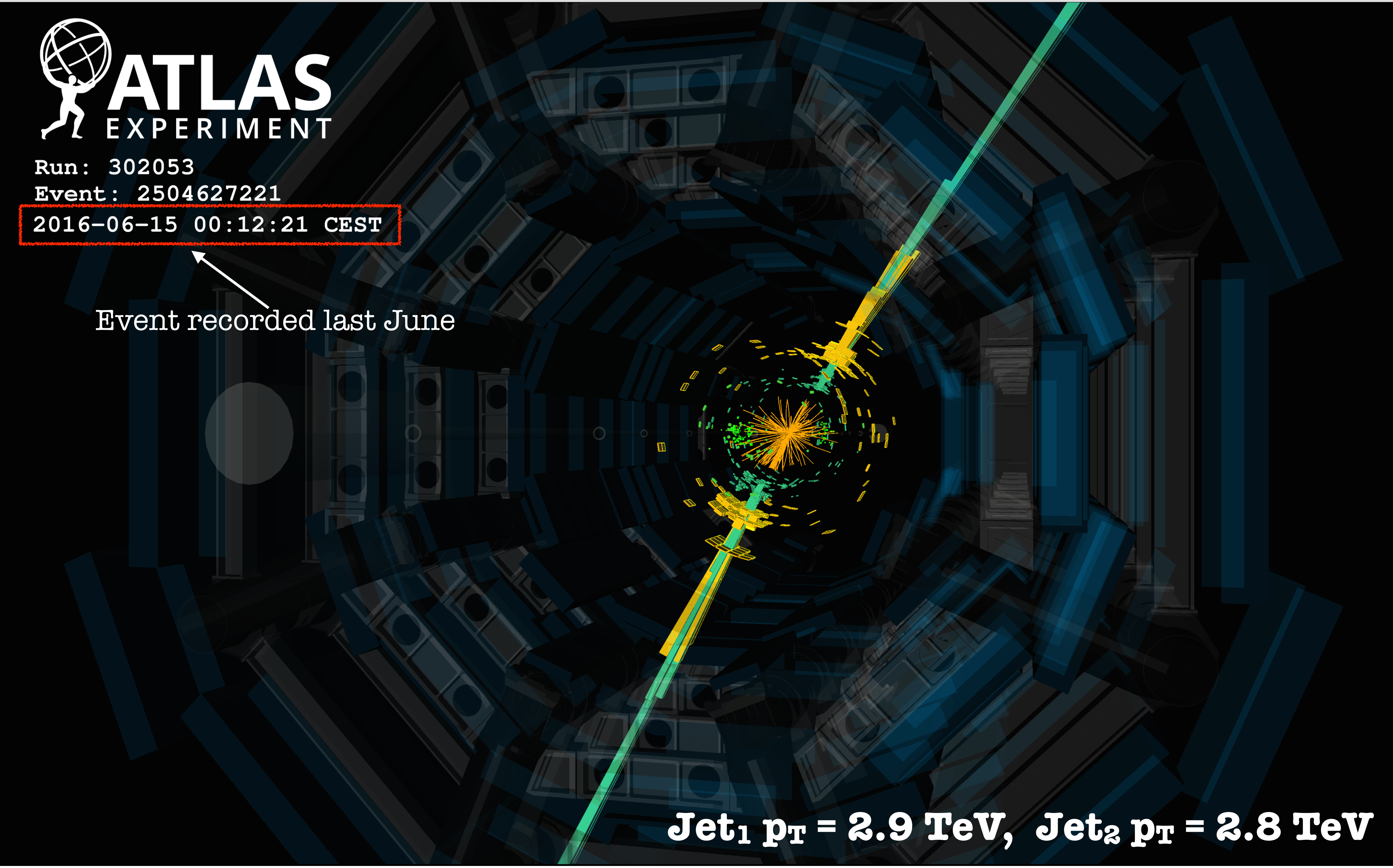
Jet calibration in ATLAS

Dimitris Varouchas

GDR Terascale, Paris, France, 24th November 2016

Collisions at 13 TeV: very energetic jets!

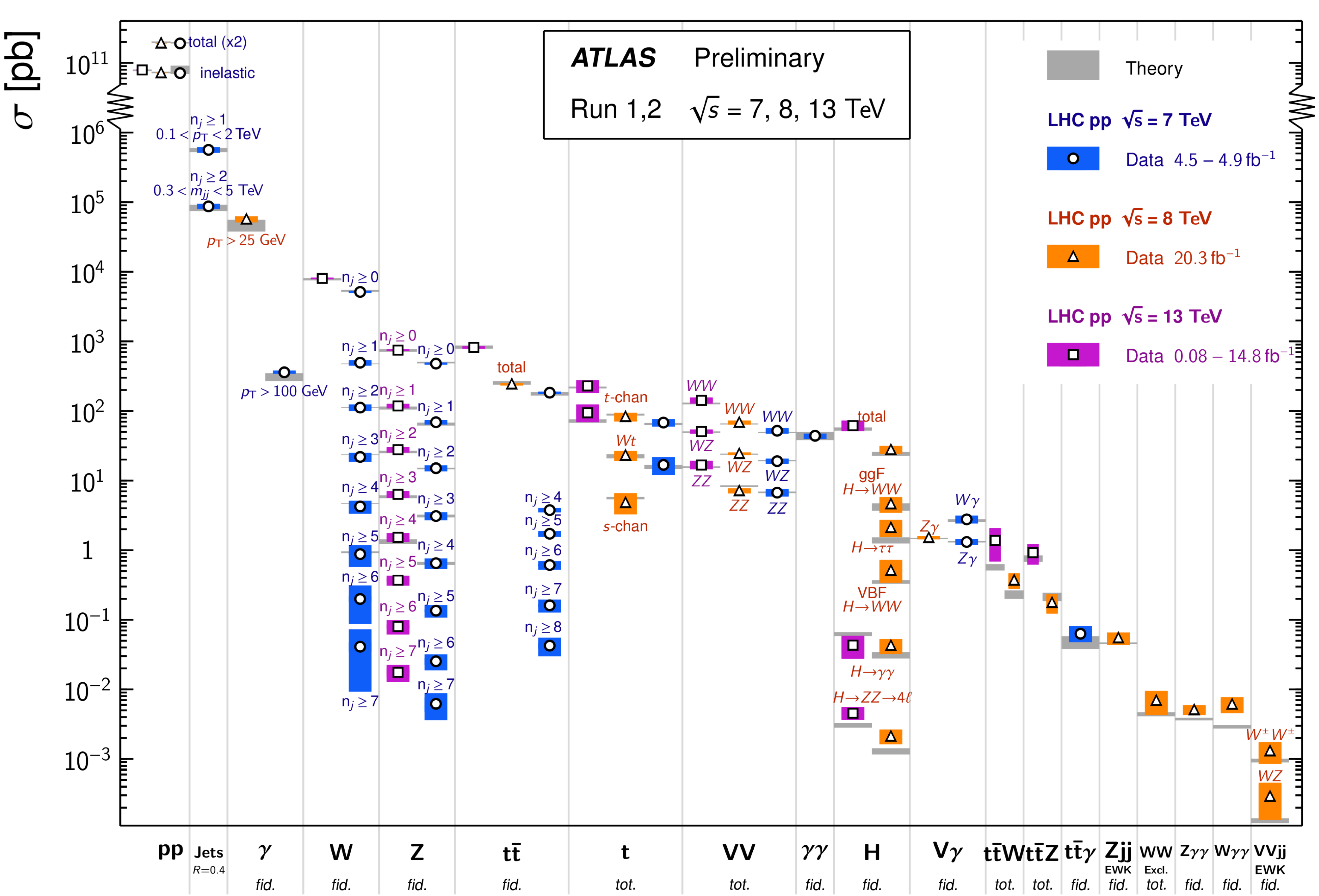


Event recorded last June

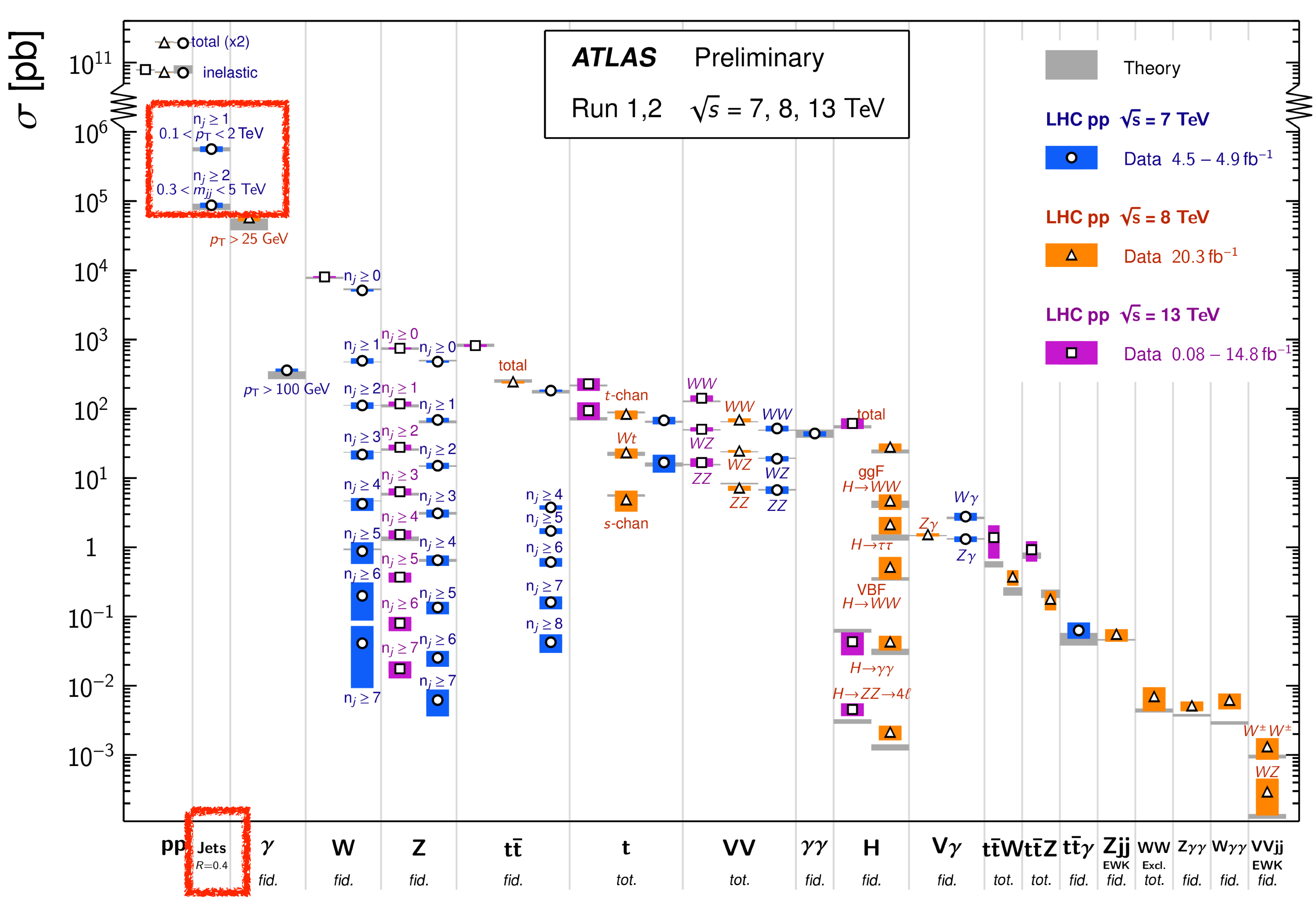
Jet$_1$ p_T = 2.9 TeV, Jet$_2$ p_T = 2.8 TeV

- The two central high-p_T jets with **invariant mass of 6.5 TeV**

Why care about jets?

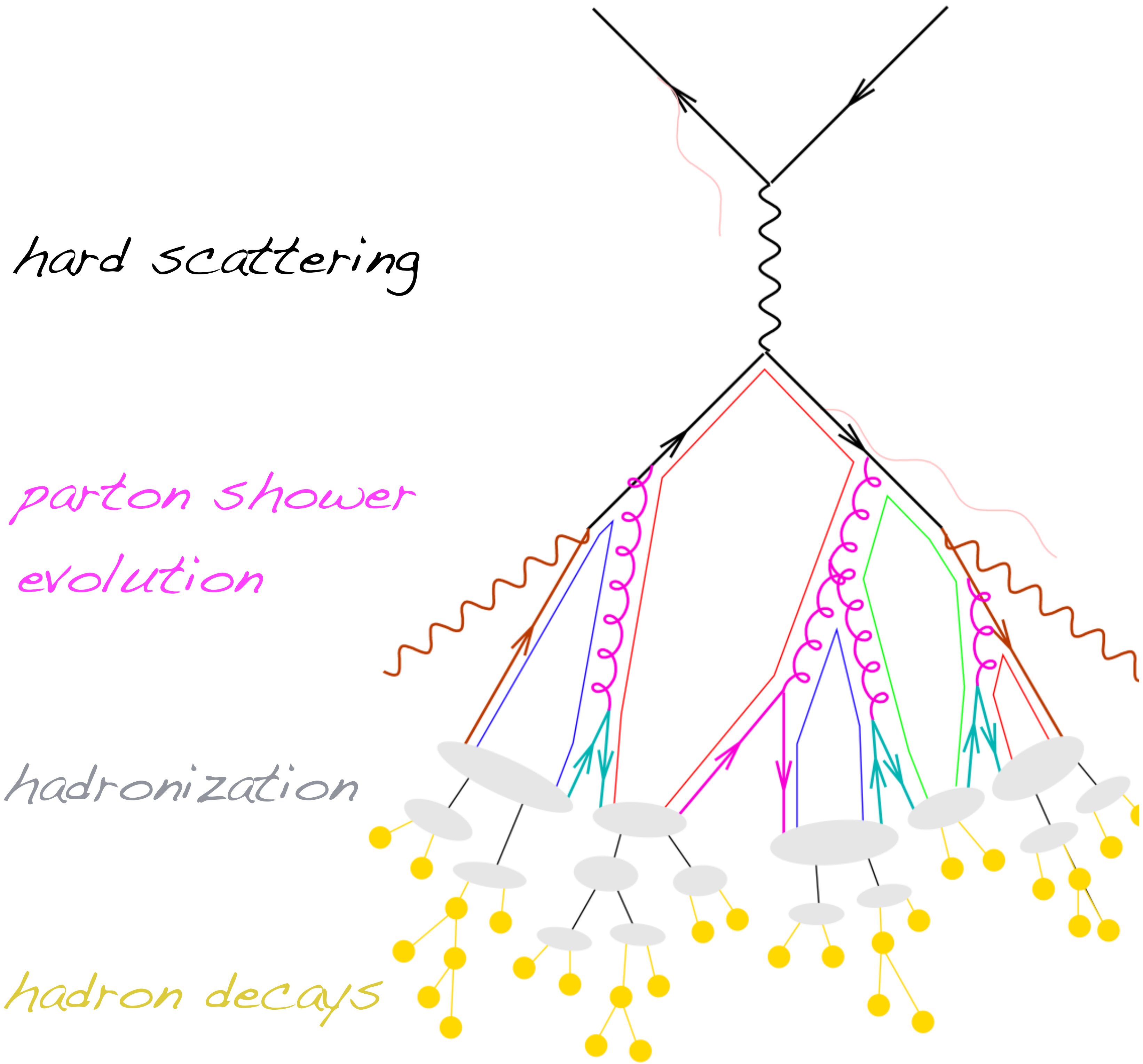


Why care about jets?



- Energetic **jets** in LHC ***pp*** collisions are **produced abundantly**
  - ✦ Signal, **QCD prediction**
  - ✦ **Significant background** to other analyses
  - ✦ **Jets are present in almost all LHC analyses**

What are jets?



- Jets are the outputs of **clustering algorithms** that group **inputs**
  - Truth particles (stable particles)
  - Particle-flow objects **(CMS)**, or calorimeter energy clusters **(ATLAS)**
- The challenge of jets comes from **QCD physics**: **parton shower** and **hadronization**
  - The particles we measure -π, K, *p*, *n*, etc- are **not** the particles from the hard scattering
- **Jets are proxy to the hard scattered parton (quark or gluon)**

Jet algorithms

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

Jet algorithms

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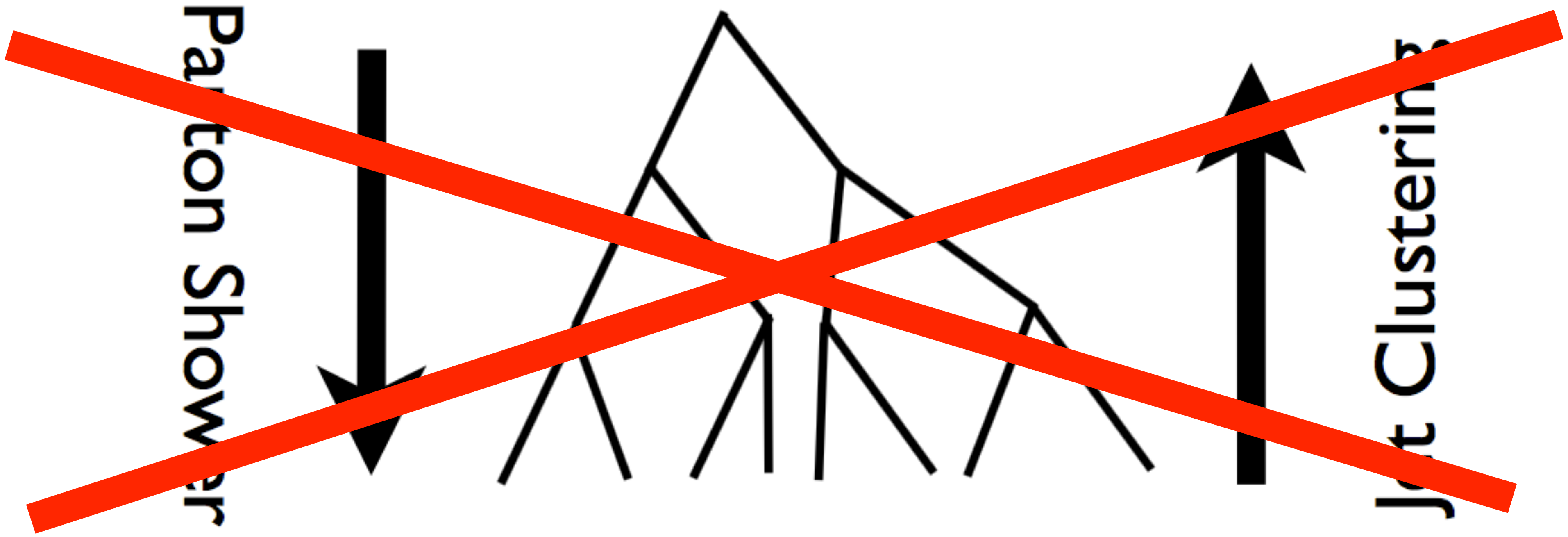
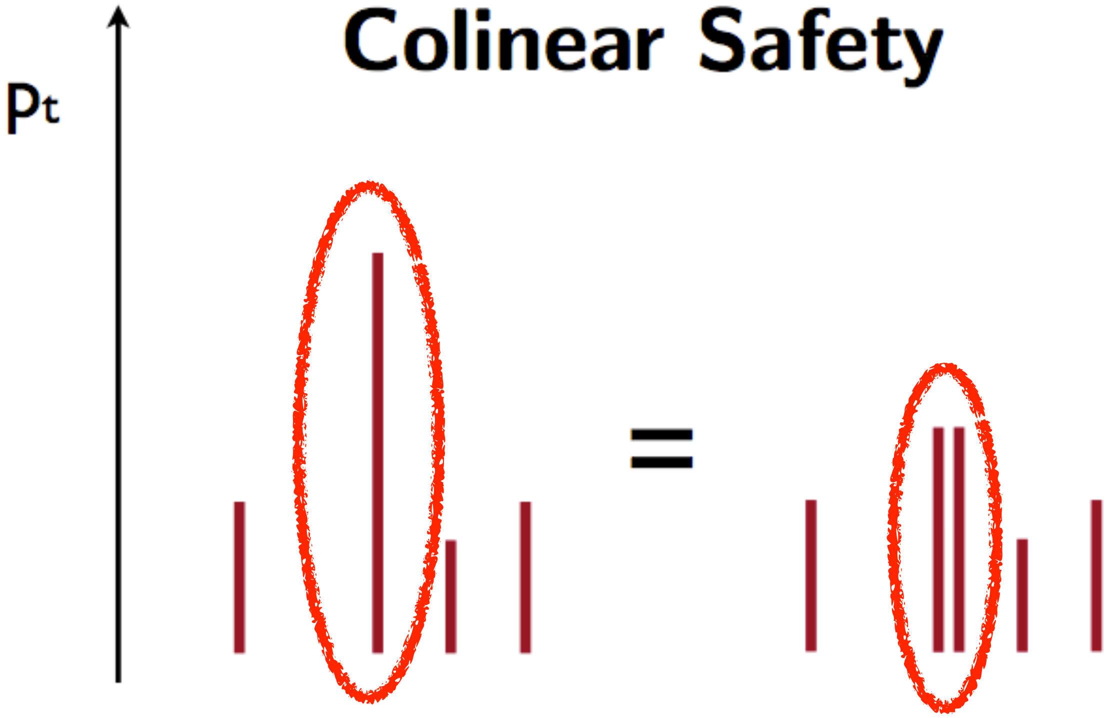


- <u>But the parton shower is actually not invertible!</u>
- There is no correct jet algorithm. Choice depends on the physics case

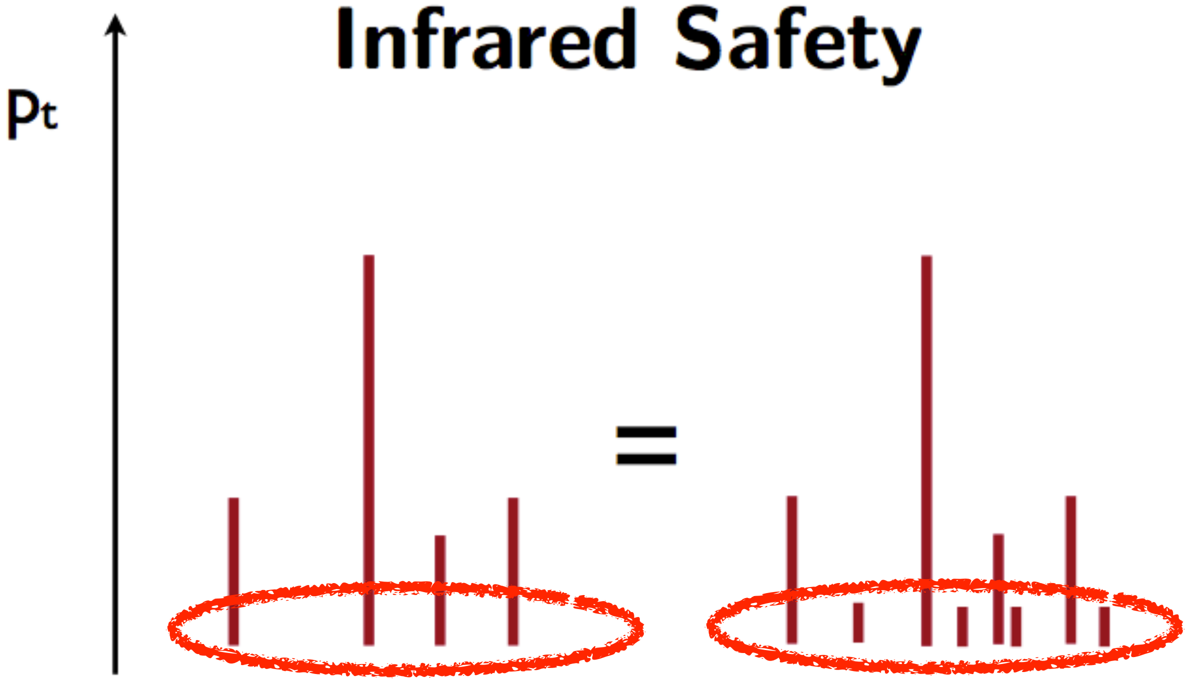
IRC Safety

Colinear Safety



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

Infrared Safety

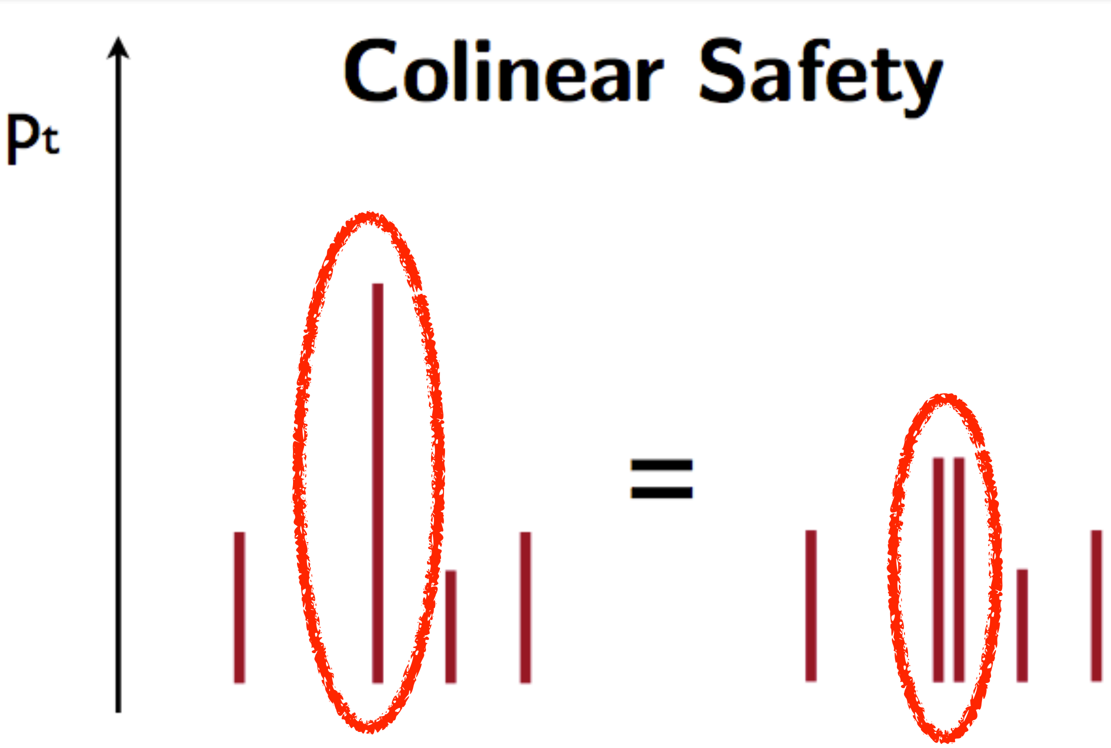


- Parton shower can add **extra soft radiation**
- Also want to be insensitive to these effects!

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

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

IRC Safety


Colinear Safety

- Parton shower can **split particles**
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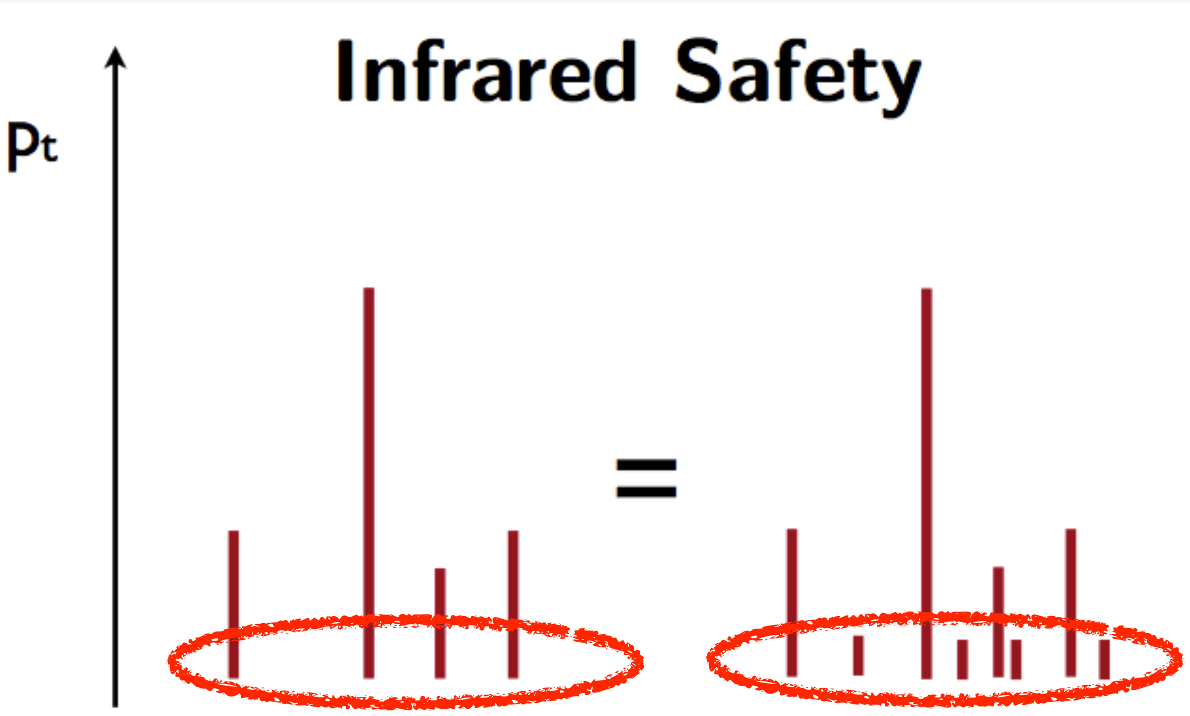
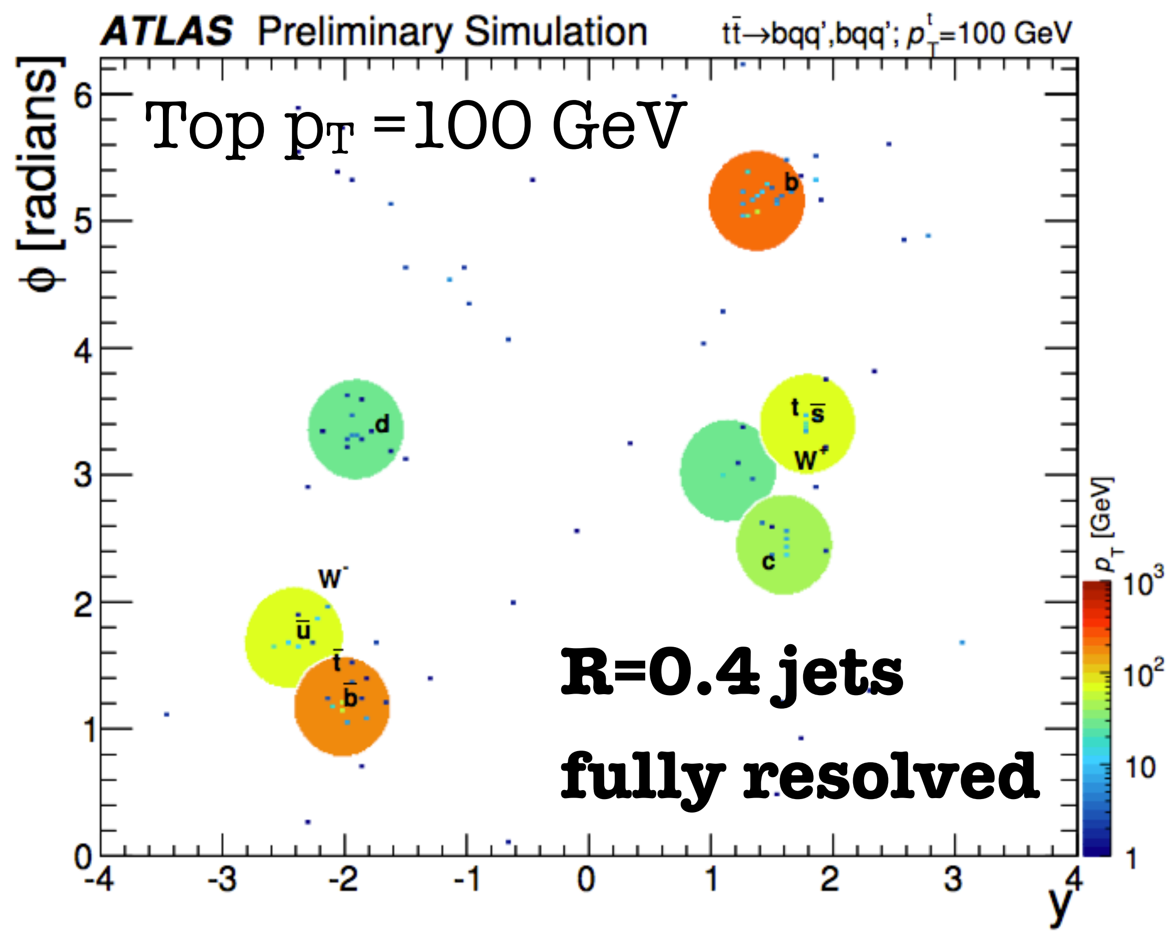

Infrared Safety

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

- **Anti-k$_T$** family of jet algorithms: the **standard** at **LHC** experiments
  - ✦ Regular shape objects, **easy to calibrate** and **more resilient to pile-up**
  - ✦ Typical jet size for **resolved objets** R=0.4 or 0.5 , where $R=\sqrt{(\Delta\eta^2+\Delta\varphi^2)}$

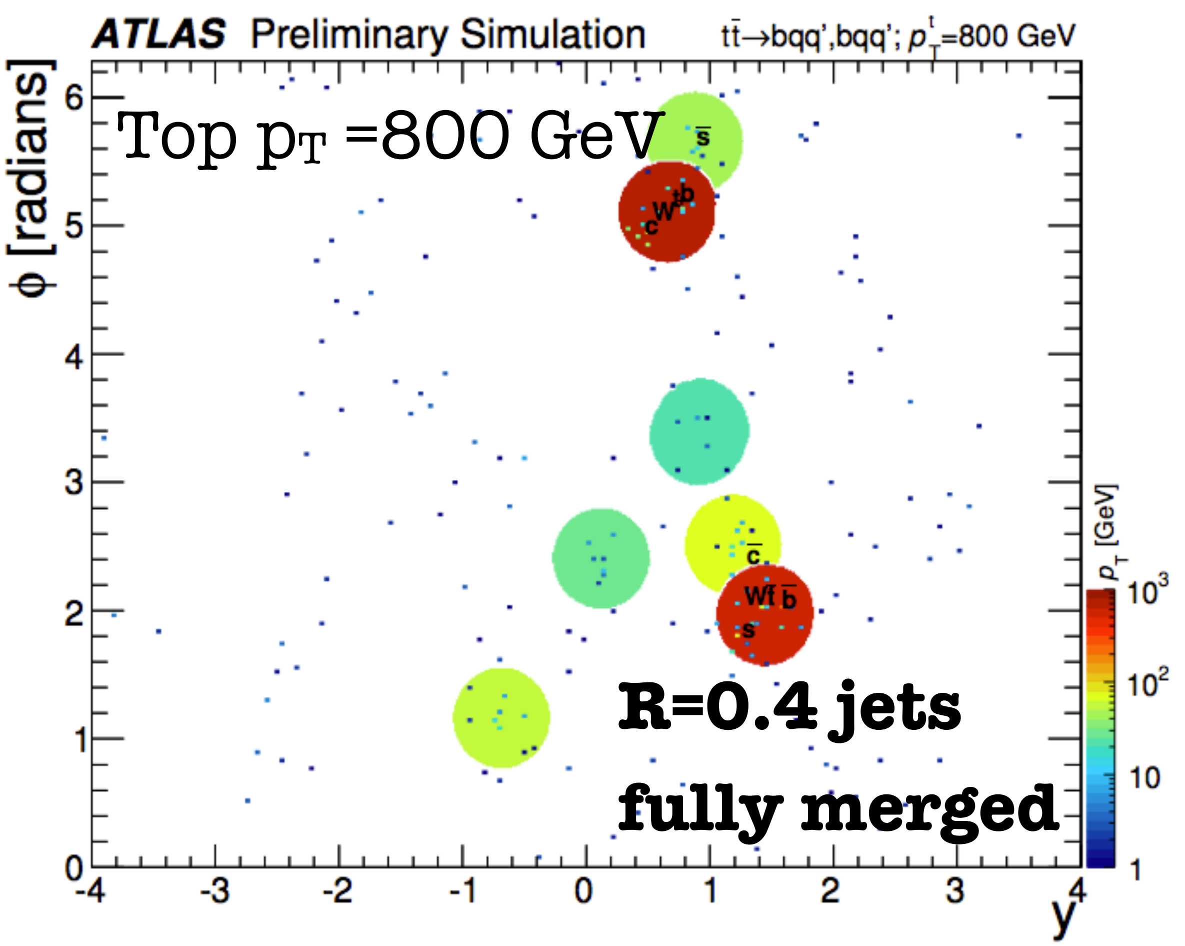
R choice (jet size)



Top p_T =100 GeV

R=0.4 jets

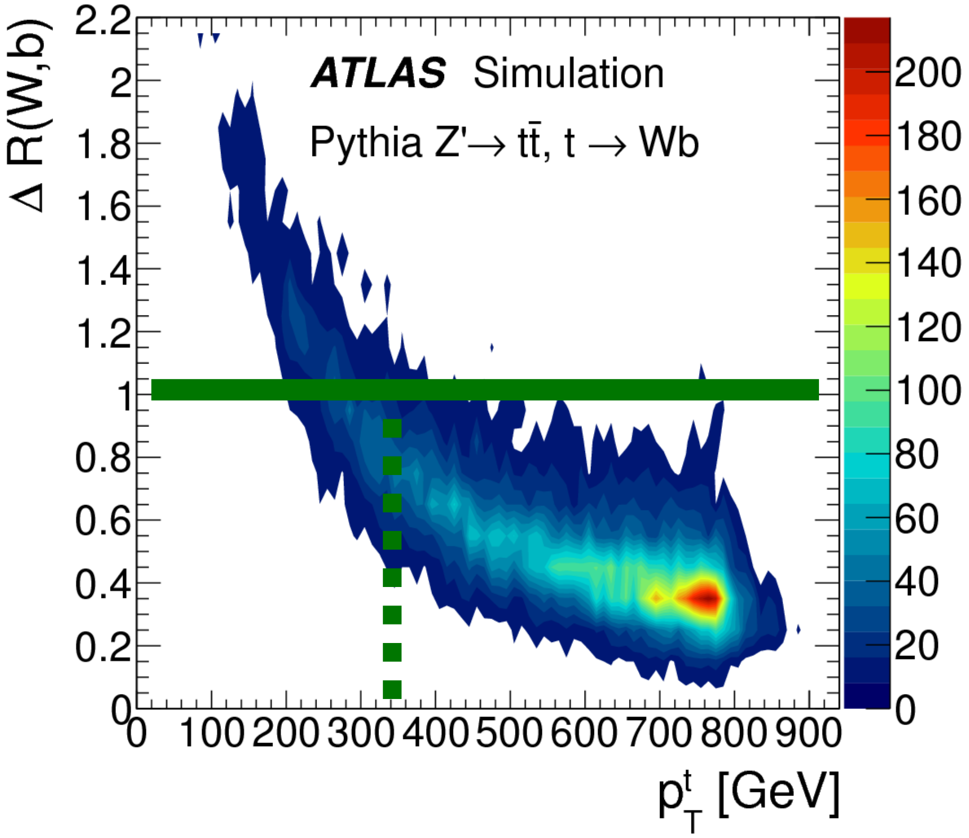
fully resolved



Top p_T =800 GeV

R=0.4 jets

fully merged



- Decay products of a **boosted object** are **highly collimated** and can even **overlap**
- On the example of the hadronic top decay
  - ✦ Decay products most likely within DR~1 for p_T^{top}>350 GeV, $\Delta R \approx \frac{2\cdot m}{p_T}$

⇒ Use the appropriate R based on the energy scale of the given signal

Jet energy calibration

or

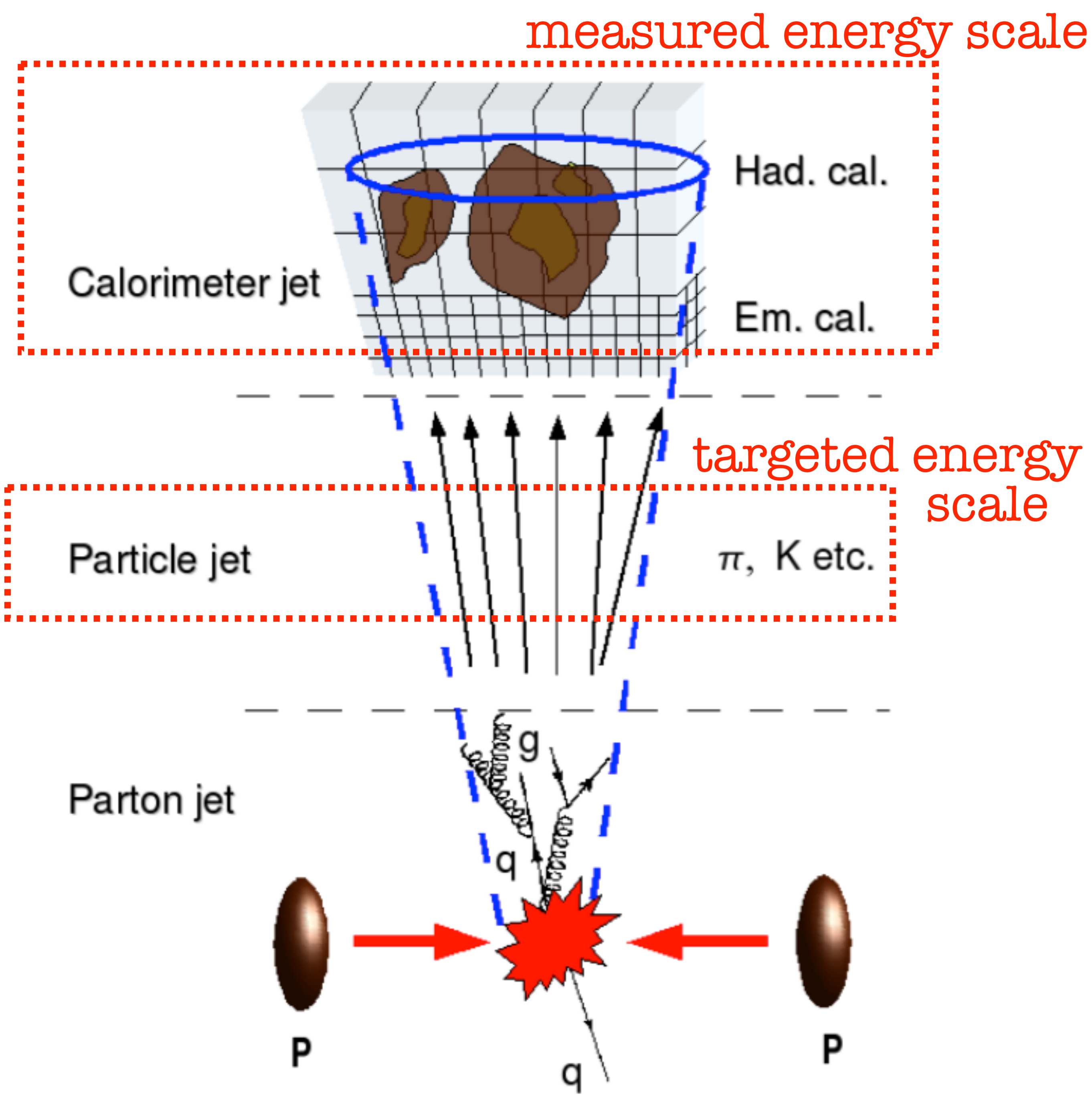
Jet energy scale

or

Jet energy correction

Focusing on ATLAS from now on...

Why calibrate jets?



- **Calorimeter** jet energy **different** than the **particle** jet energy
  - ✦ **Sampling calorimeter:** cannot measure energy deposited in the absorber
  - ✦ **Calorimeter non compensating:** 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**

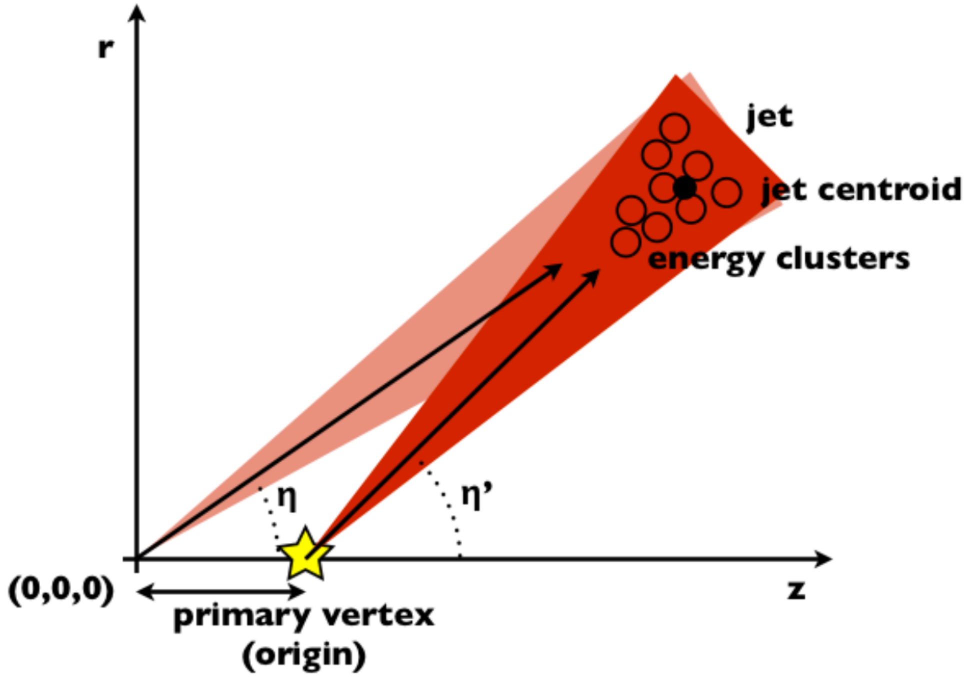
- **All detector capabilities have to be exploited**
  - ✦ **Combine information** from sub-detectors (tracker + calorimeter + muon system)

Jet calibration chain

Jets at Calorimeter Scale

Origin Correction

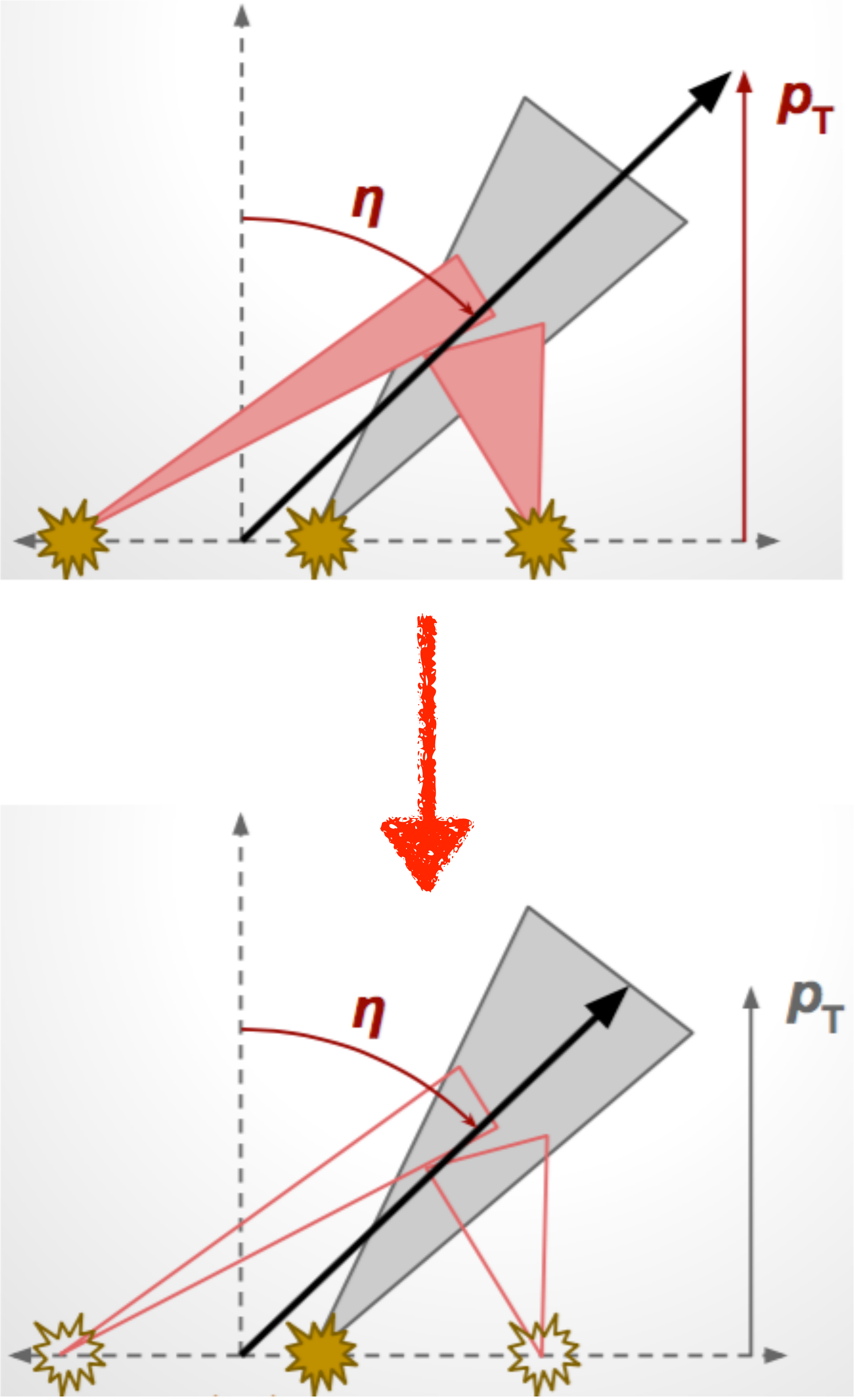
- Start from calorimeter jets
  - **Origin correction:** to account for the hard scattering primary vertex. Changes the jet direction



Jet calibration chain

Jets at Calorimeter Scale → **Origin Correction** → **Pile-up Correction**

- 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

Jets at Calorimeter Scale → **Origin Correction** → **Pile-up Correction**

ATLAS-PHYS-PUB-2015-015

Pile-up paper submitted to EPJC

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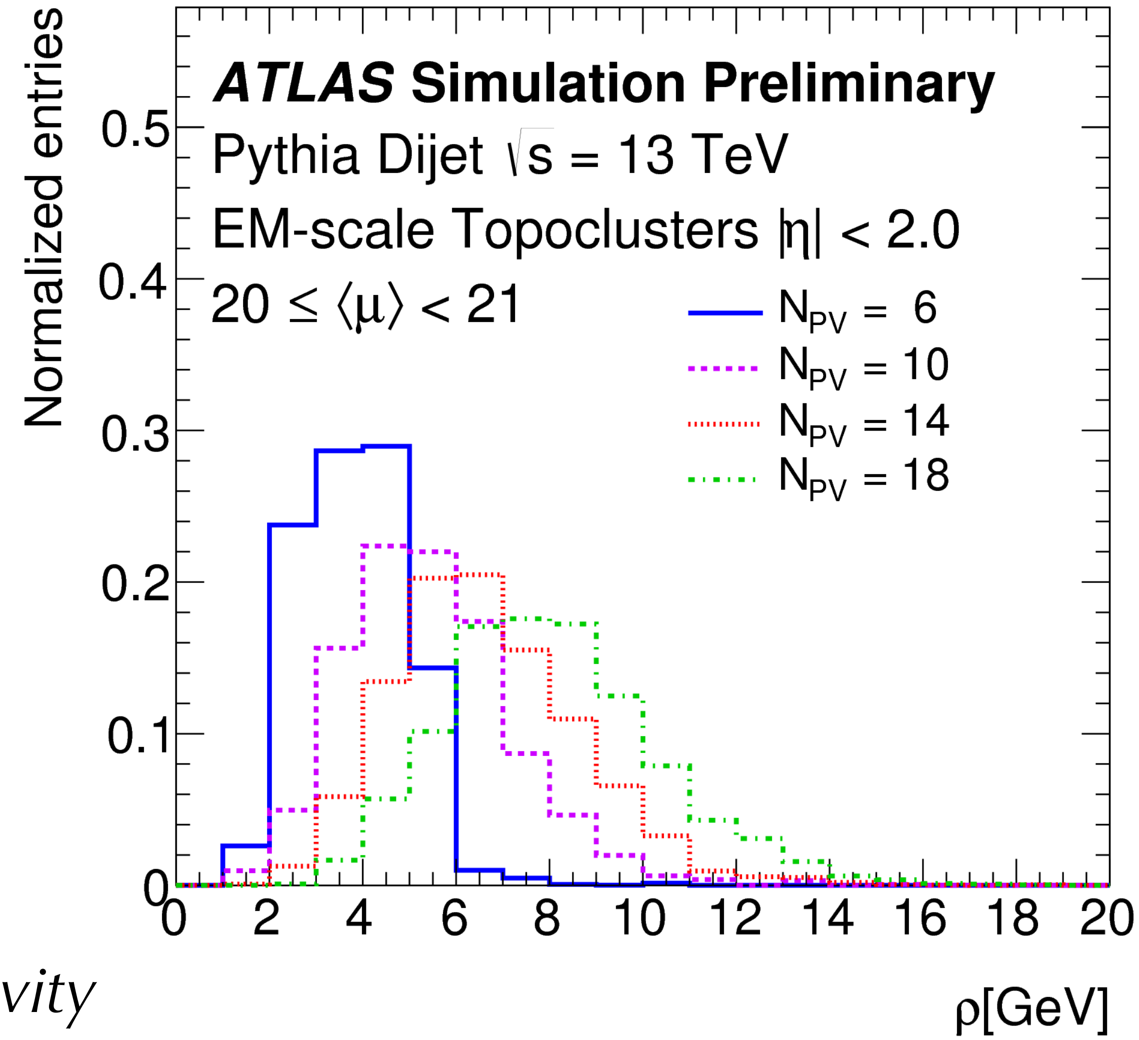


Jet-by-jet pile-up sensitivity

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

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

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

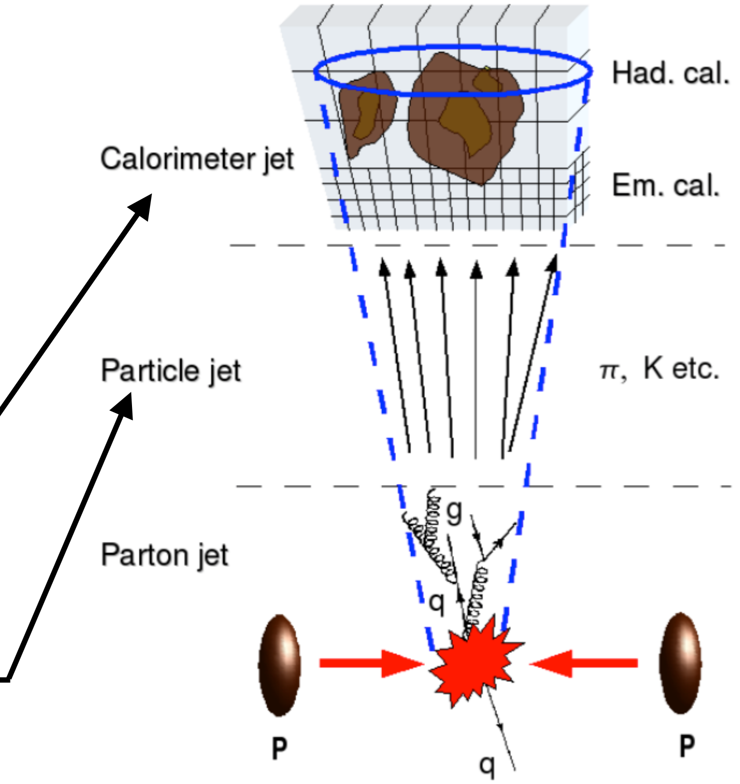
constructed with no minimum p_{T} threshold

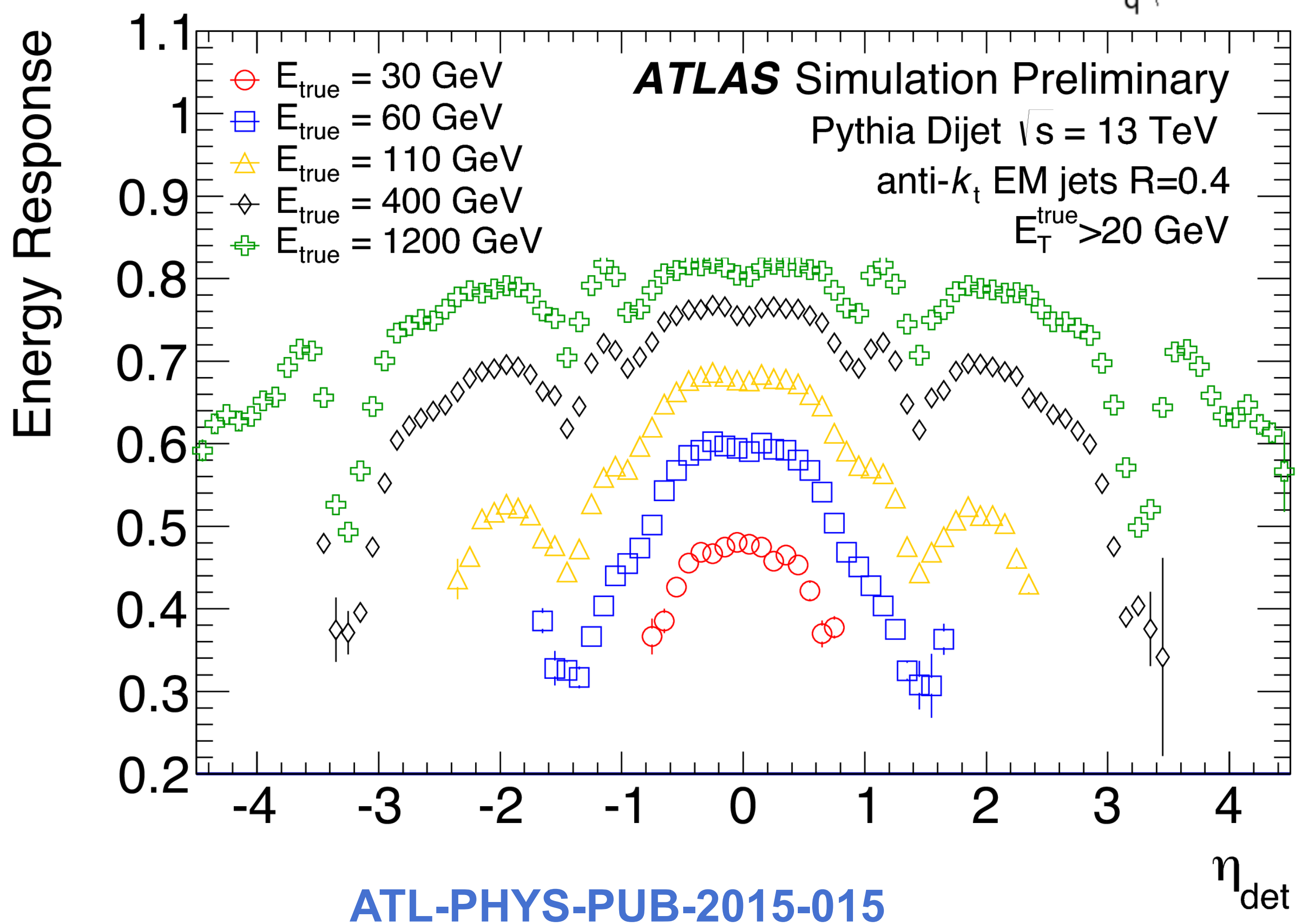
Jet calibration chain

Jets at Calorimeter Scale → **Origin Correction** → **Pile-up Correction** → **MC JES & Eta Calibrations**

- 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

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





ATL-PHYS-PUB-2015-015

Jet calibration chain

ATLAS-CONF-2015-002

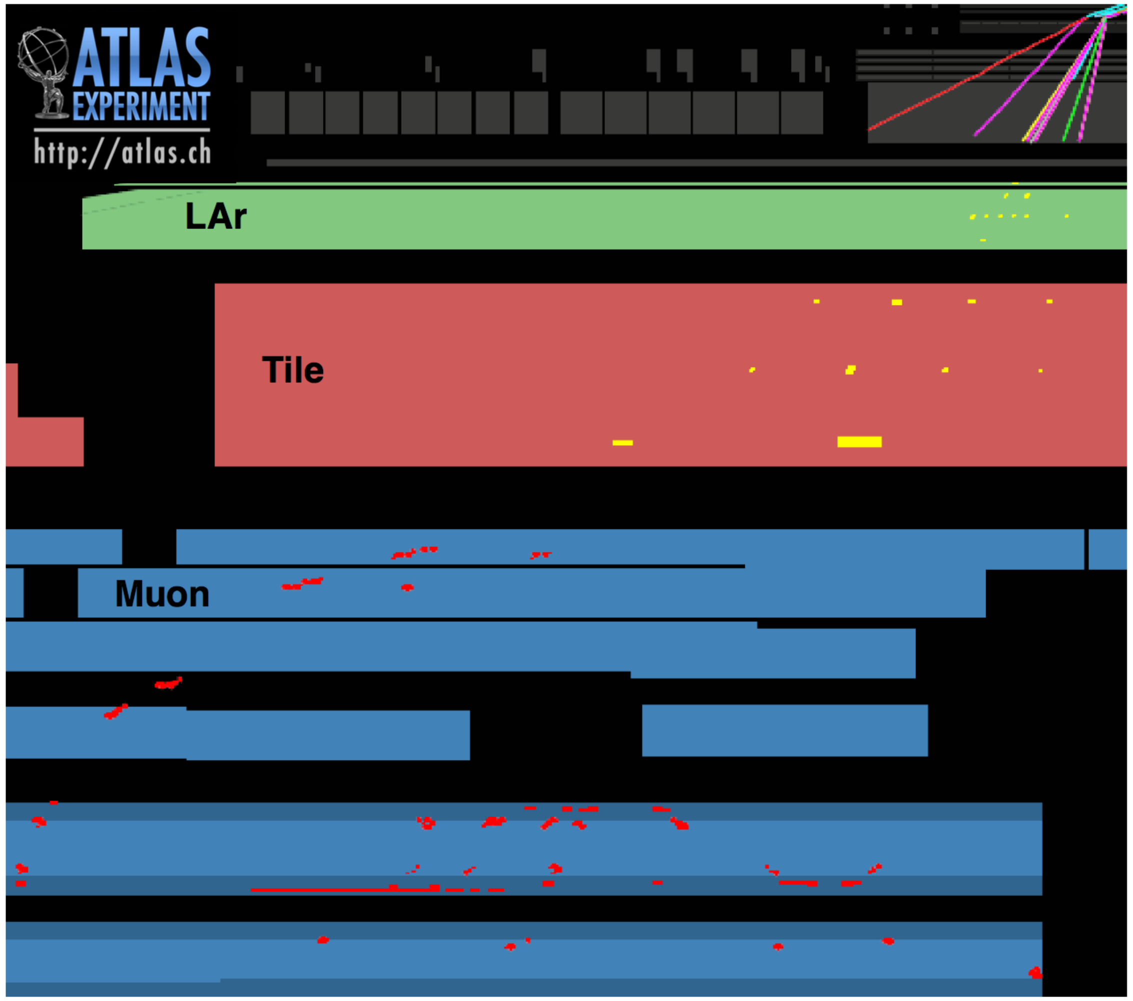
Jets at Calorimeter Scale

Origin Correction

Pile-up Correction

MC JES & Eta Calibrations

Global Sequential Calib.



- 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 an energetic jet (**muon segments**)

η relative in-situ corrections

Jets at Calorimeter Scale

Origin Correction

Pile-up Correction

MC JES & Eta Calibrations

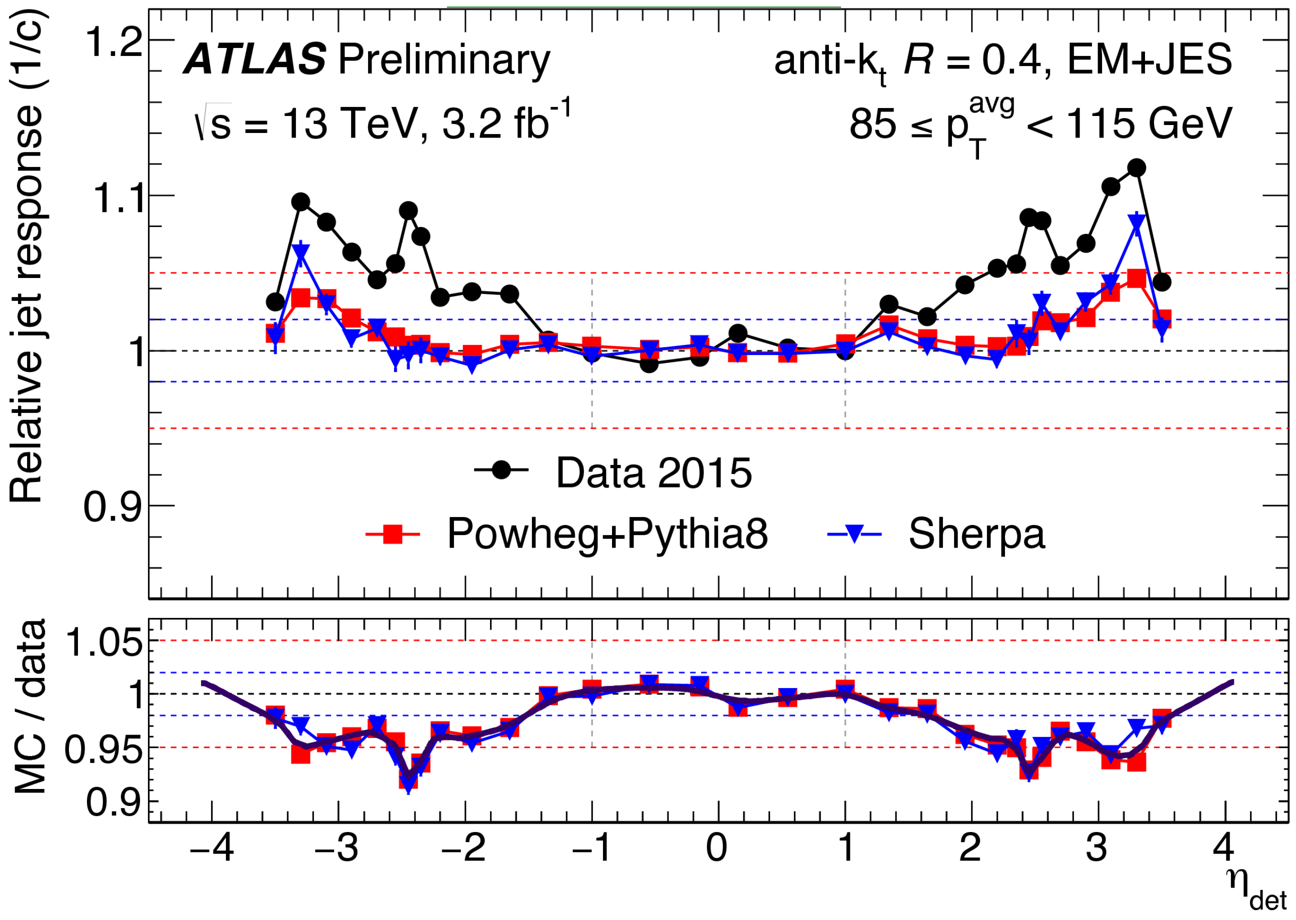
Global Sequential Calib.

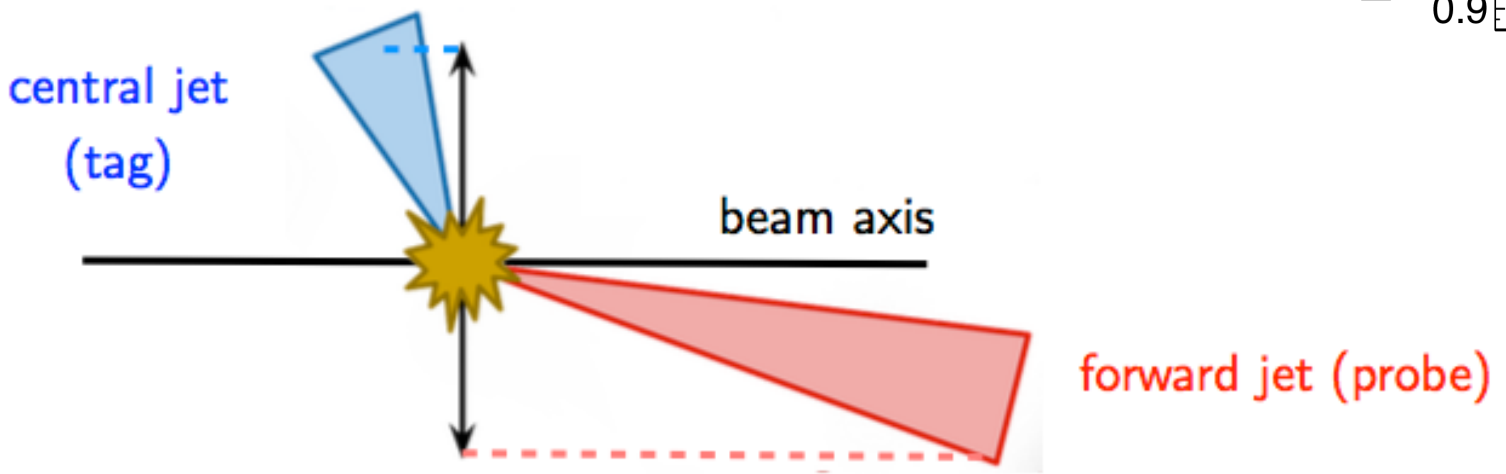
In-situ Calibrations (Data)

Jets for physics

- **MC simulation** typically describes the **data** to within about **10%**
- More adequate calibration for forward region is performed: **η inter-calibration** in **data** dijet events to **correct η dependence of jet response**

JETM-2016-002

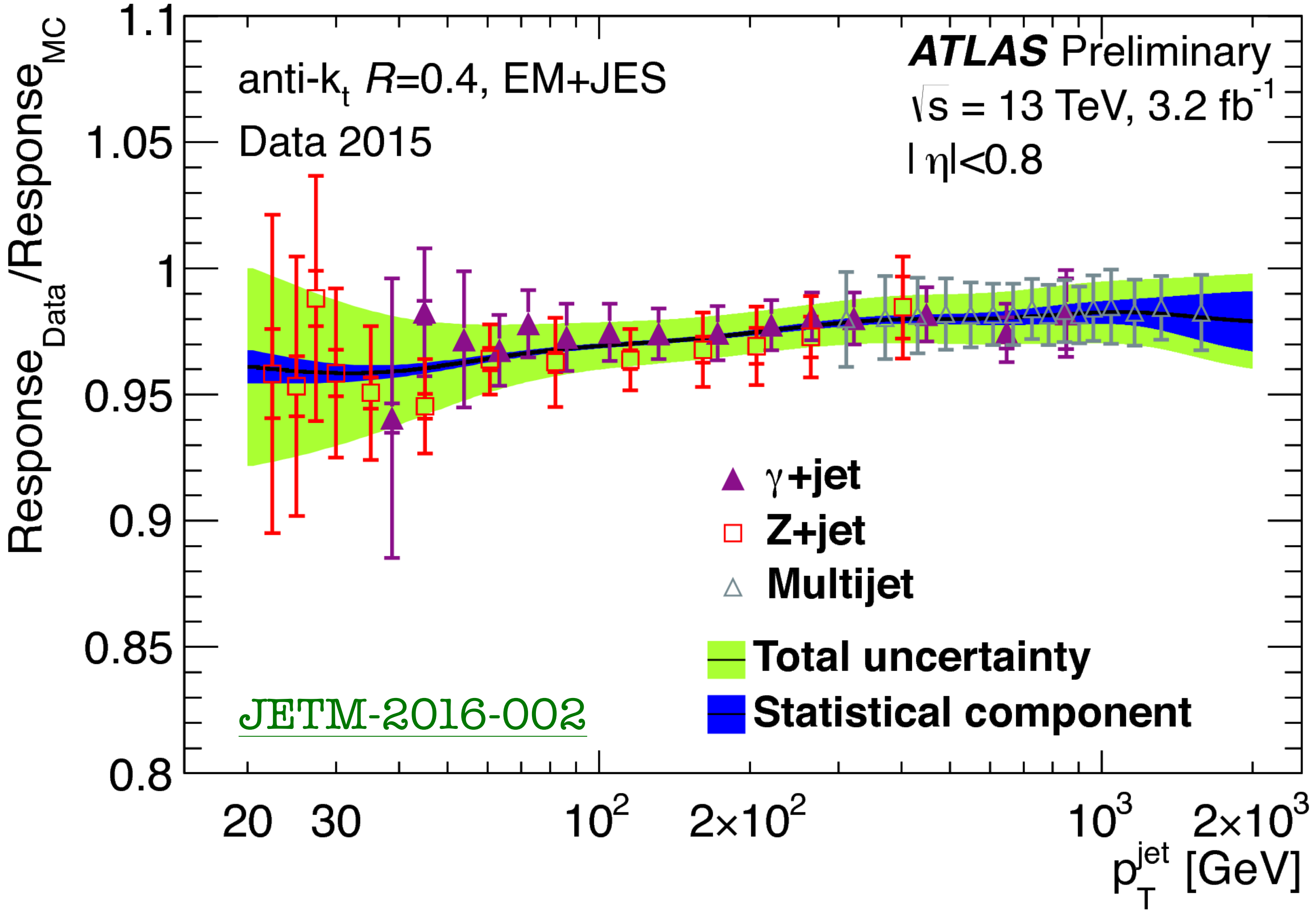




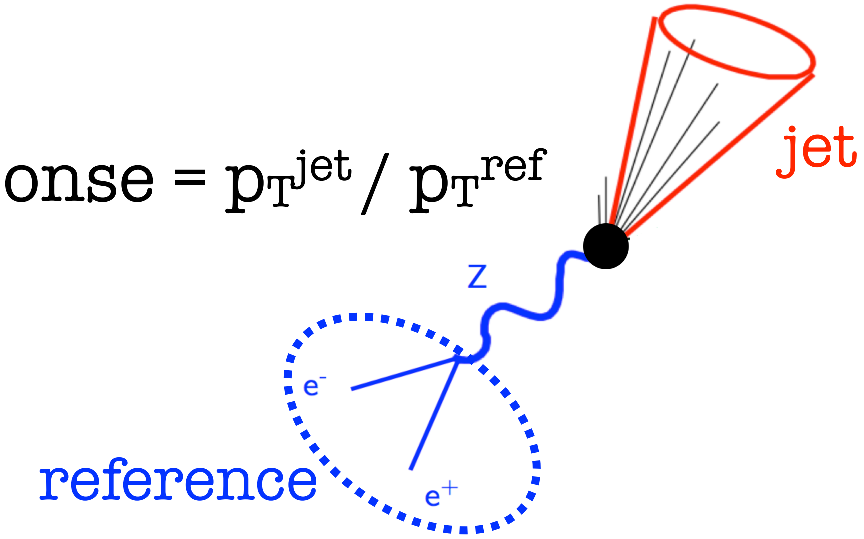
Absolute in-situ corrections

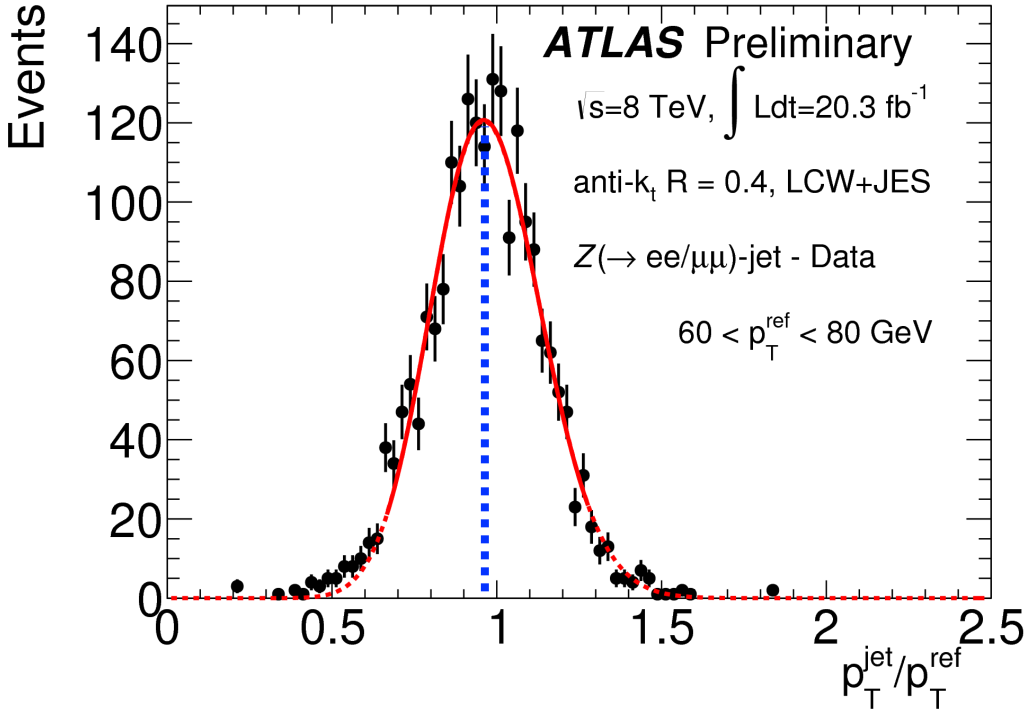
Jets at Calorimeter Scale → Origin Correction → Pile-up Correction → MC JES & Eta Calibrations → Global Sequential Calib. → In-situ Calibrations (Data) → Jets for physics

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

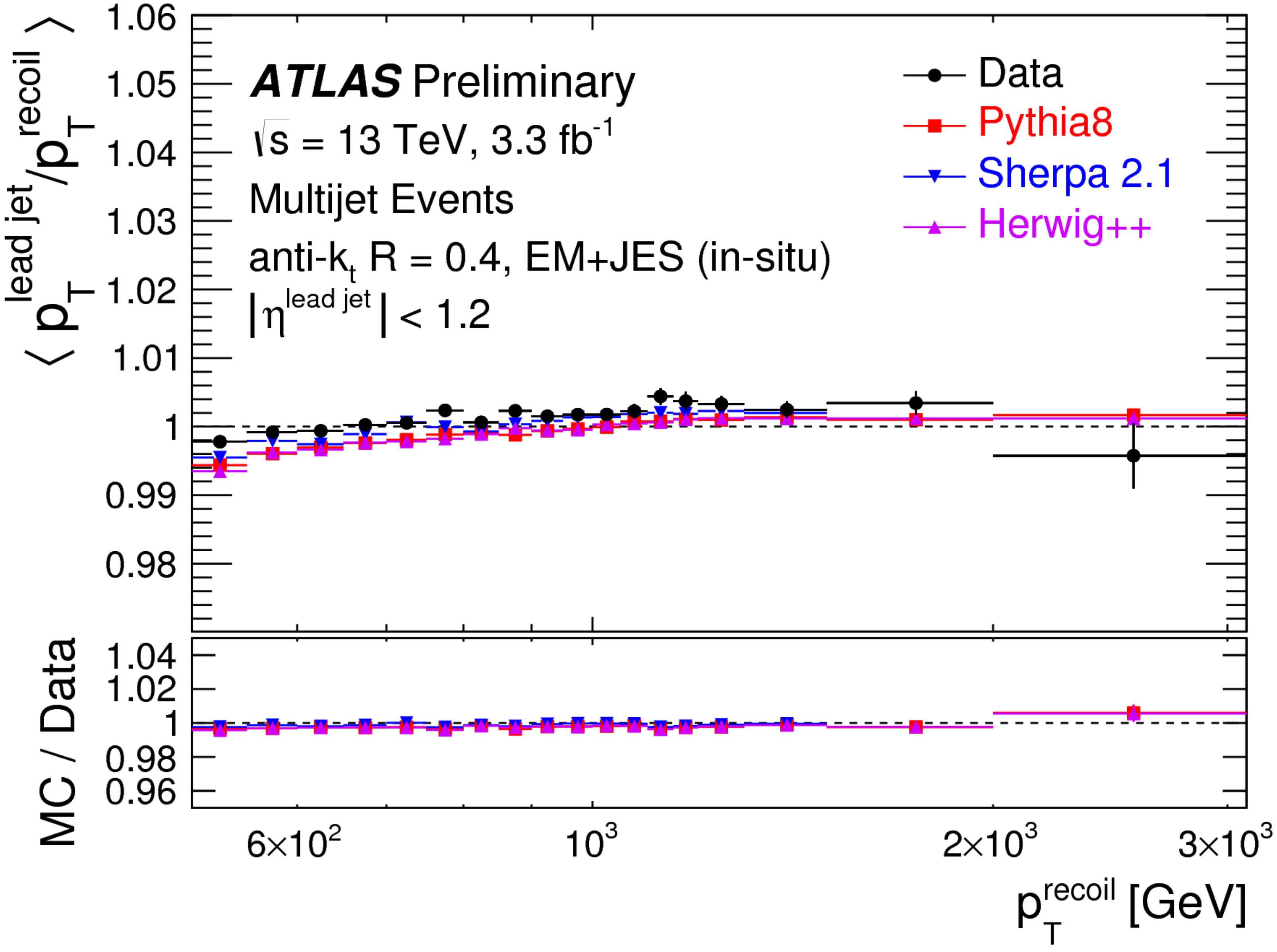


Response = p_T^{jet} / p_T^{ref}





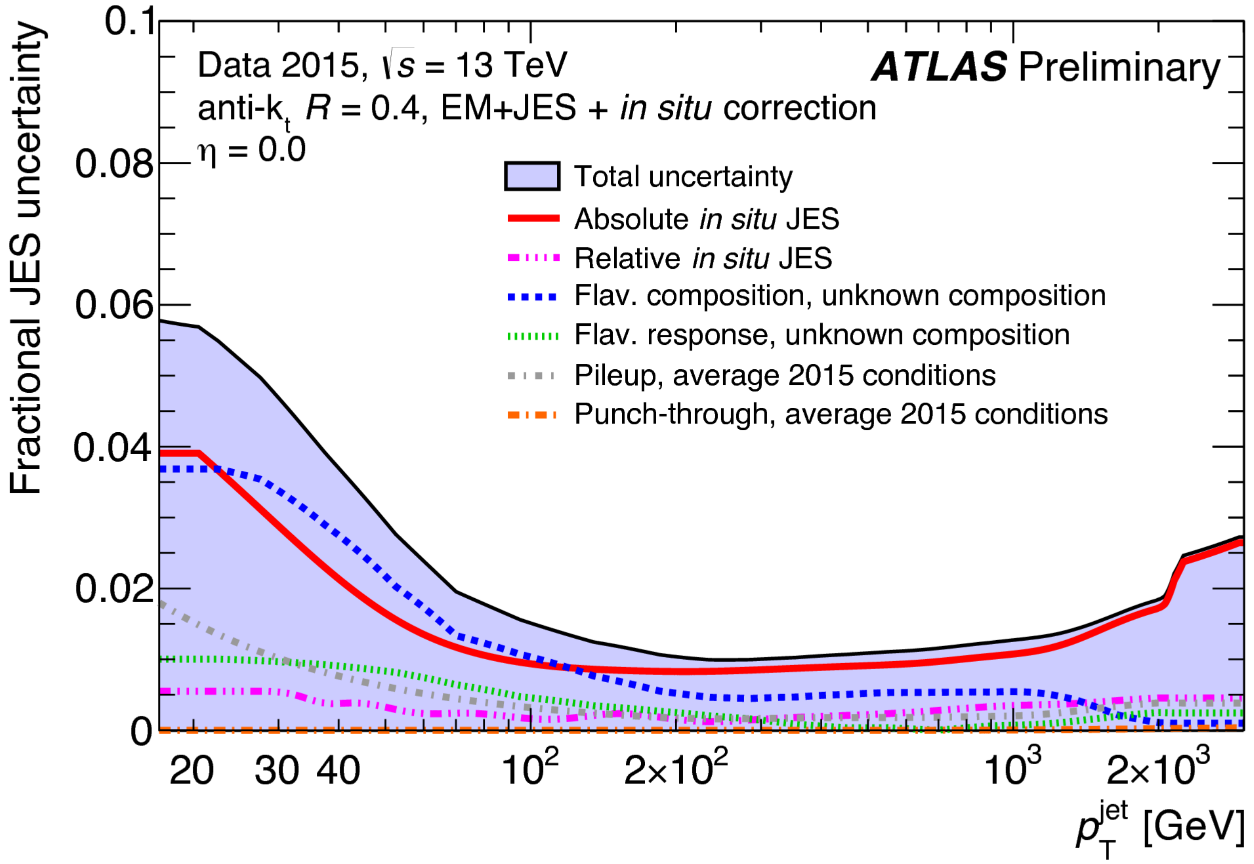
Jet calibration performance in Run-2

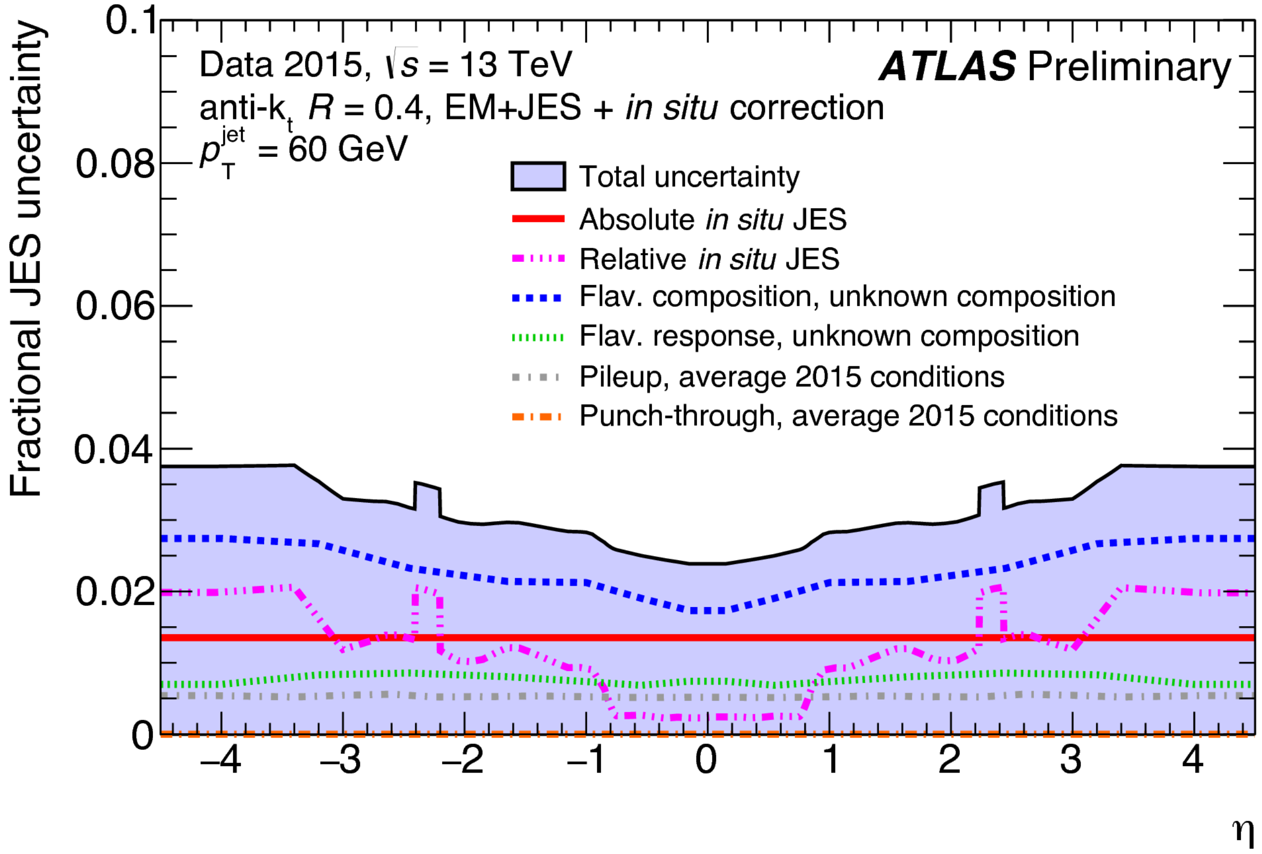


- Many checks with Run-2 data
  - ✦ Jet response in events of high p_T jet balancing against lower p_T jets
  - ✦ Jet response in events of photon - jet balance
- **Remarkable agreement** between Data and MC

JES uncertainties

JETM-2016-002





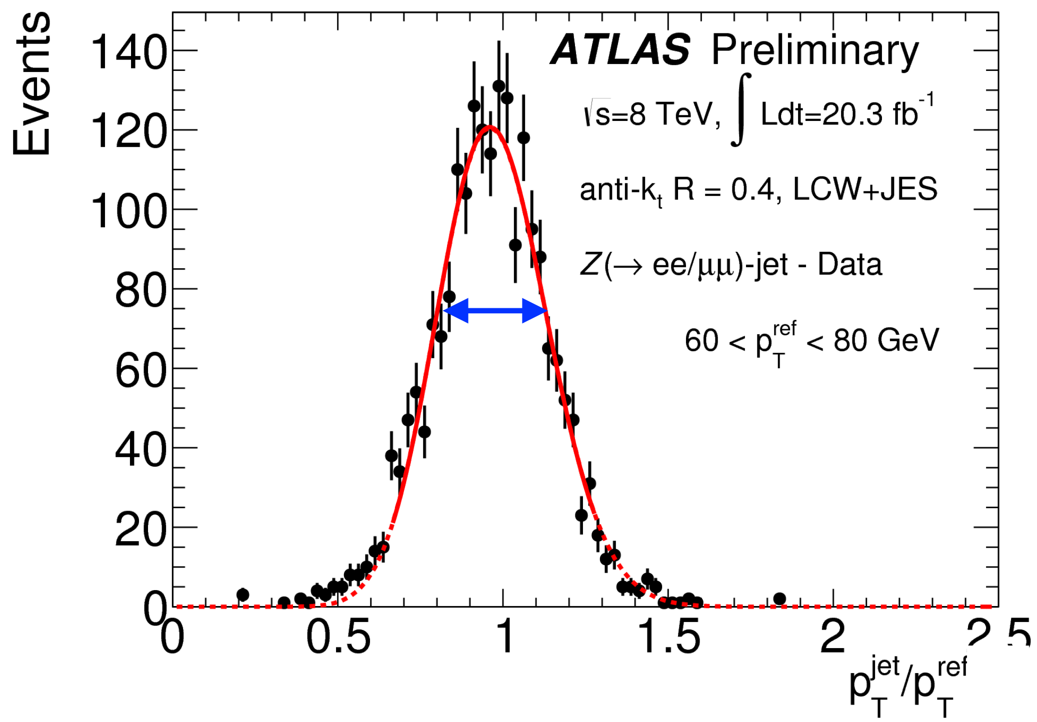
- Final JES uncertainties components **O(80)**, a combination of **in-situ** and **estimated upstream in calibration chain**
- Dedicated statistical tools to reduce the number of components maintaining the relevant correlations
- Performance in Run-2 almost comparable to the Run-1 one

Jet energy resolution

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 p_T** via an in-situ **noise study**

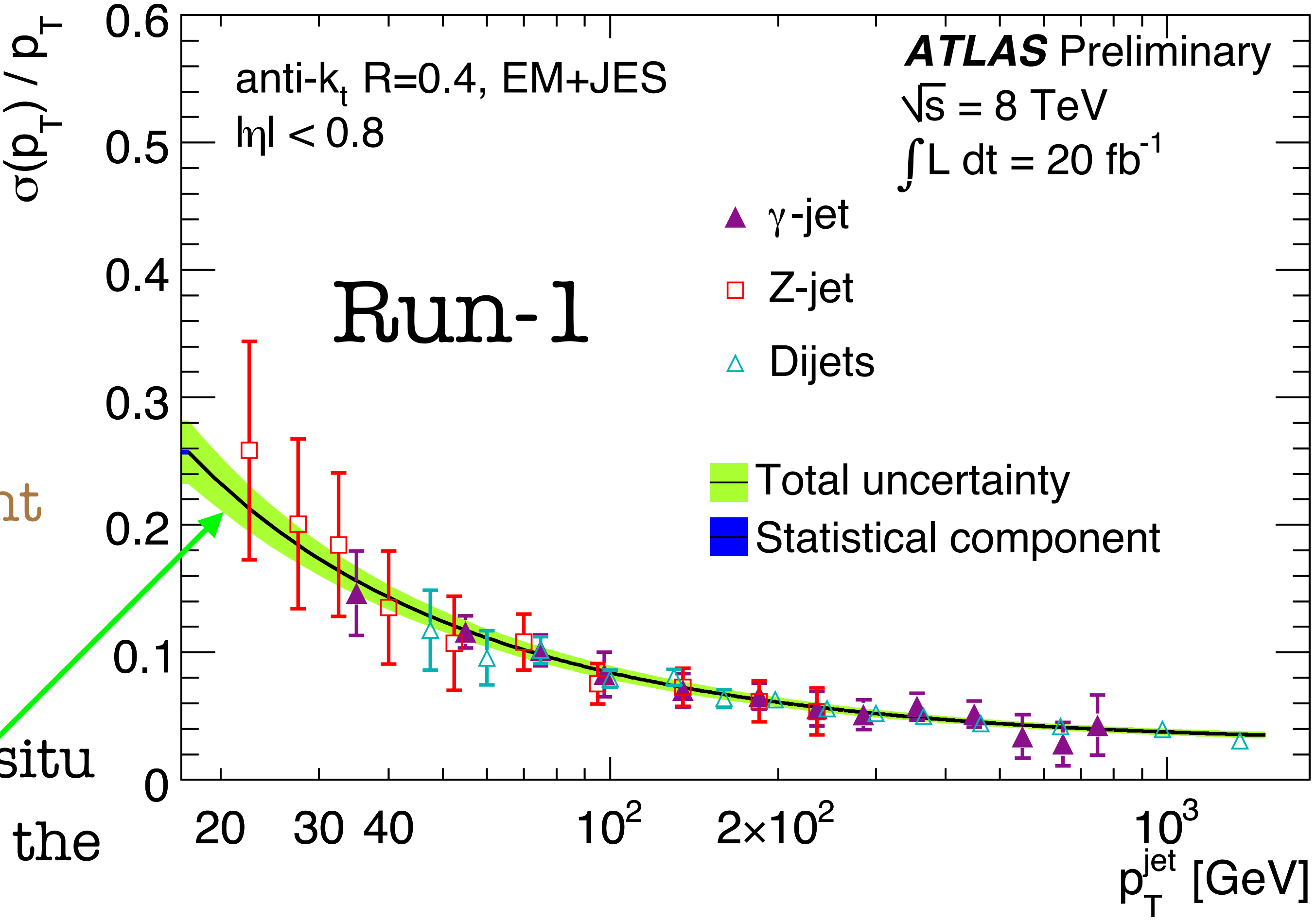


noise term

stochastic term

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

constant



Uncertainties evaluated via the in-situ measurements taking into account the correlations

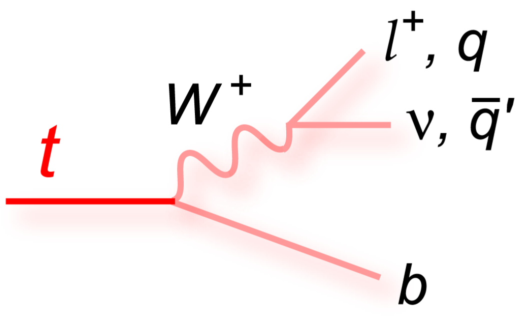
Jet perfromance in physics analyses

- Jets are extremely complicated objects
- Their energy calibration relays on every single part of the detector
  - ✦ Accurate sub-detector calibration is needed
- They are very sensitive to pile-up
- Several QCD physics effects are present that are hard to model

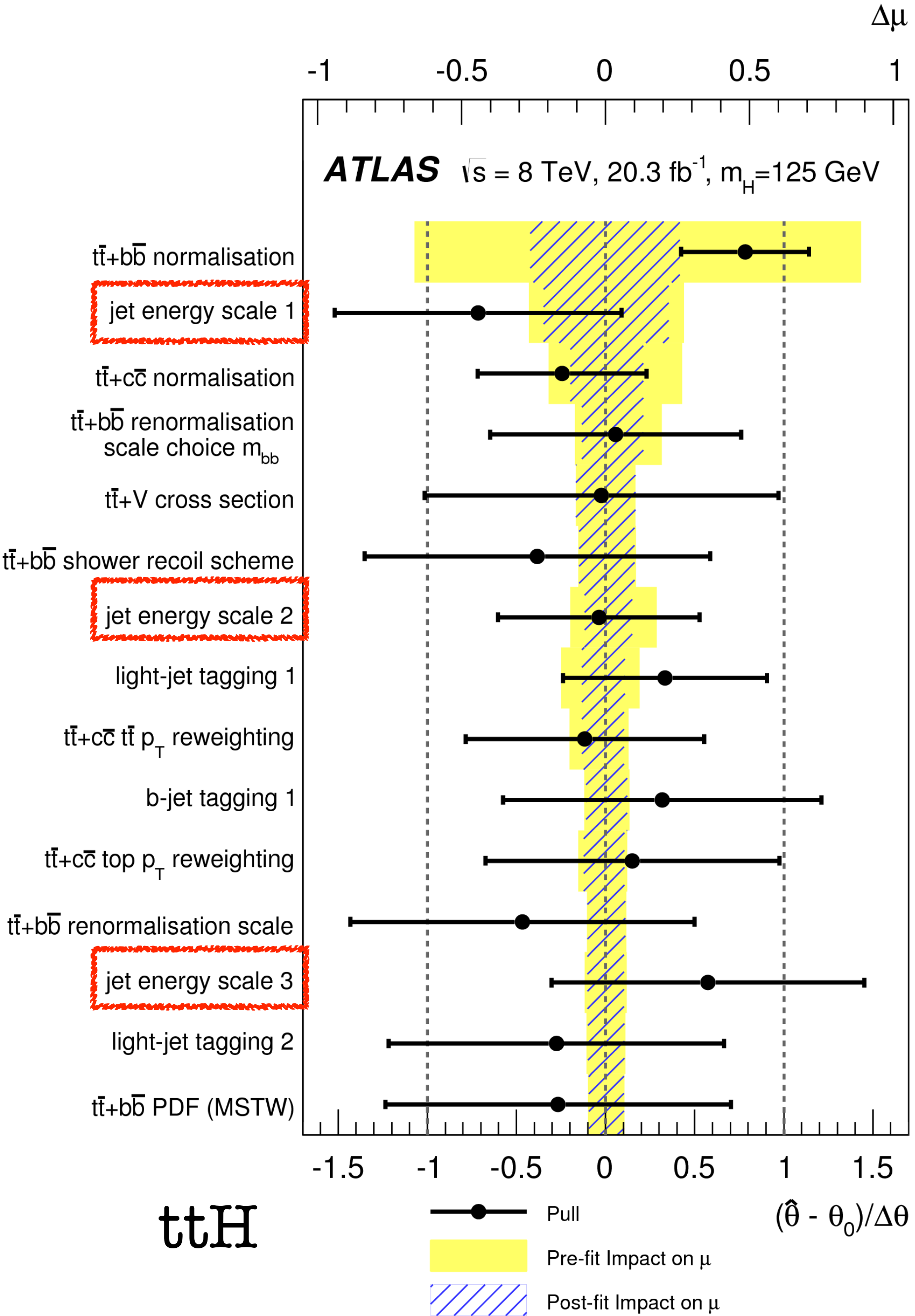
➡ Jet related uncertainties are often the **dominant detector related** uncertainties in physics analyses

- ✦ *A few examples in the following slides*

Jets and tops

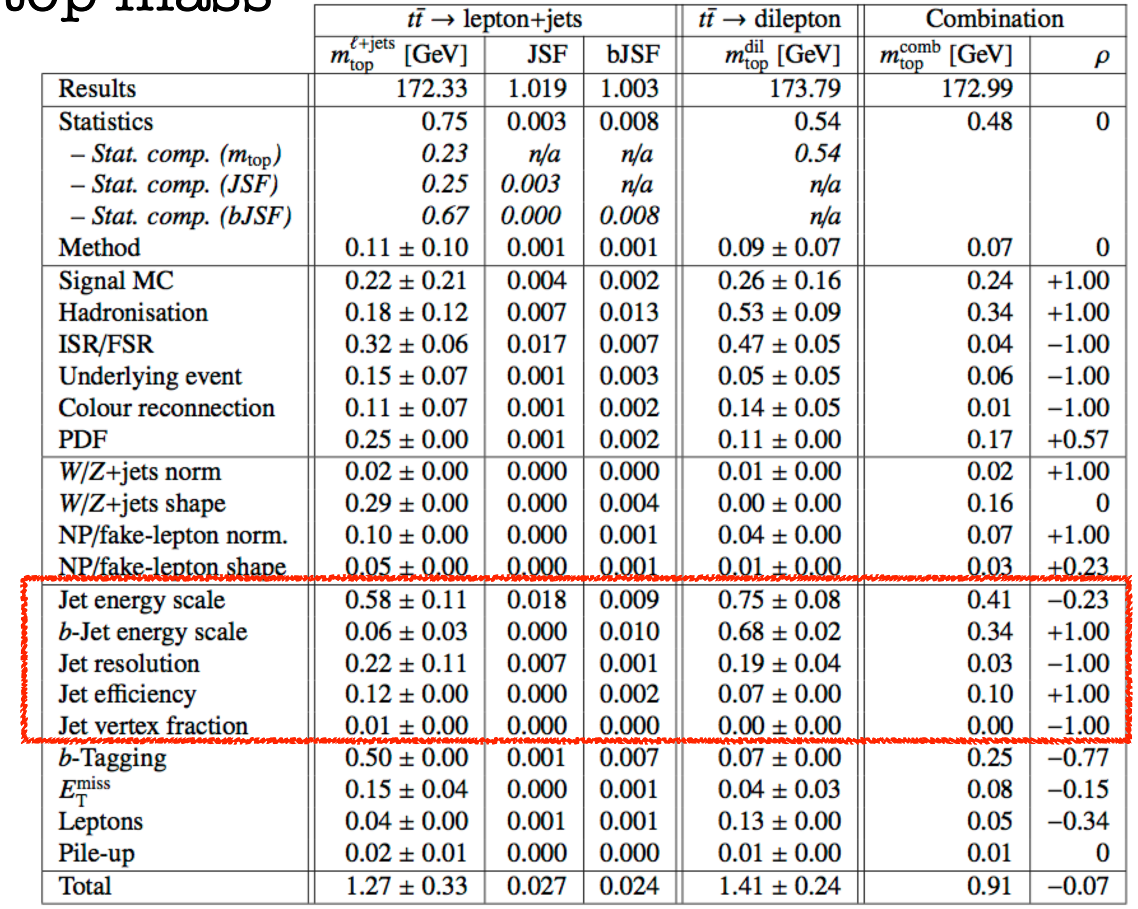


- $t\bar{t}$ branching ratios
  - **All hadronic: ~44%**
  - **Lepton+jets: ~45%**
  - Dilepton: ~11%



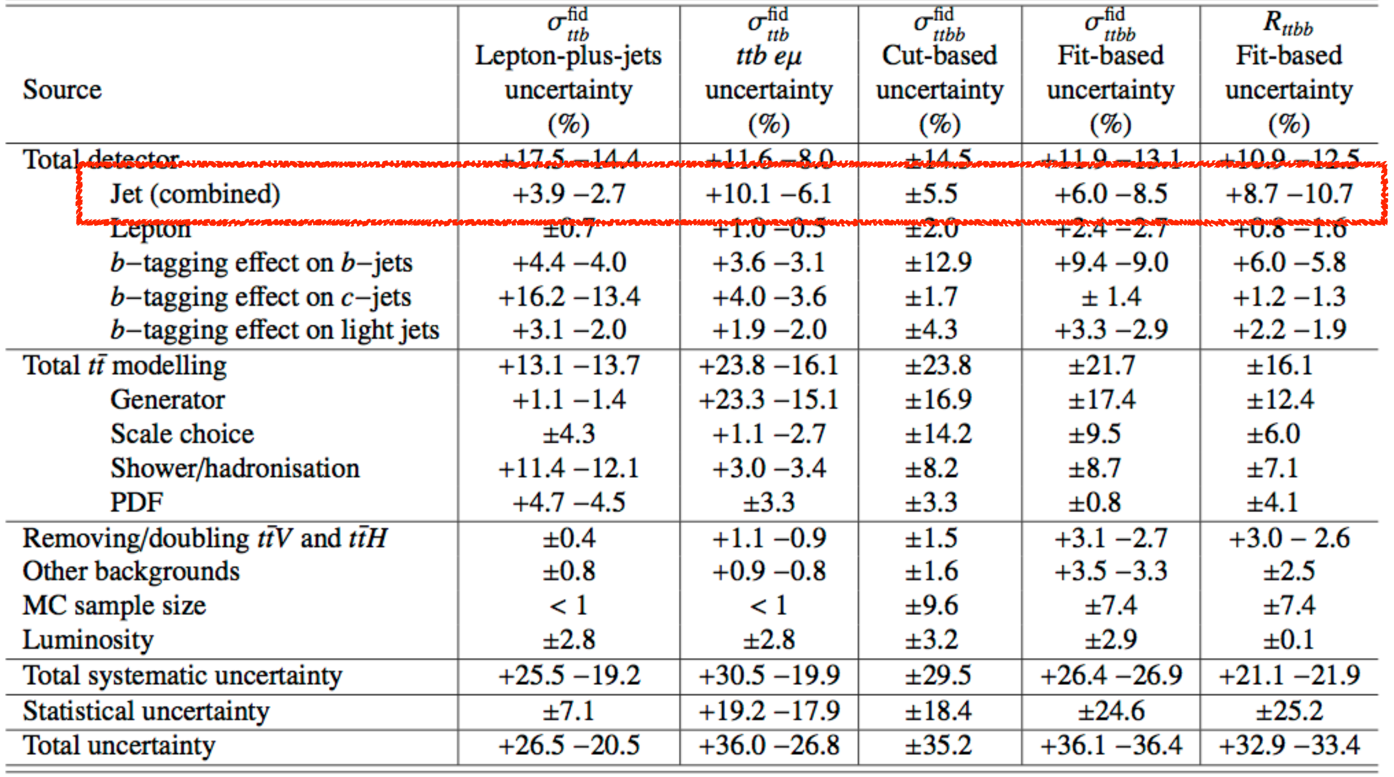
ttH

top mass



	$t\bar{t}$ → lepton+jets			$t\bar{t}$ → dilepton	Combination	
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	JSF	bJSF	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{comb}}$ [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– Stat. comp. (m_{top})	*0.23*	*n/a*	*n/a*	*0.54*		
– Stat. comp. (JSF)	*0.25*	*0.003*	*n/a*	*n/a*		
– Stat. comp. (bJSF)	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-Tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

tt fiducial cross section

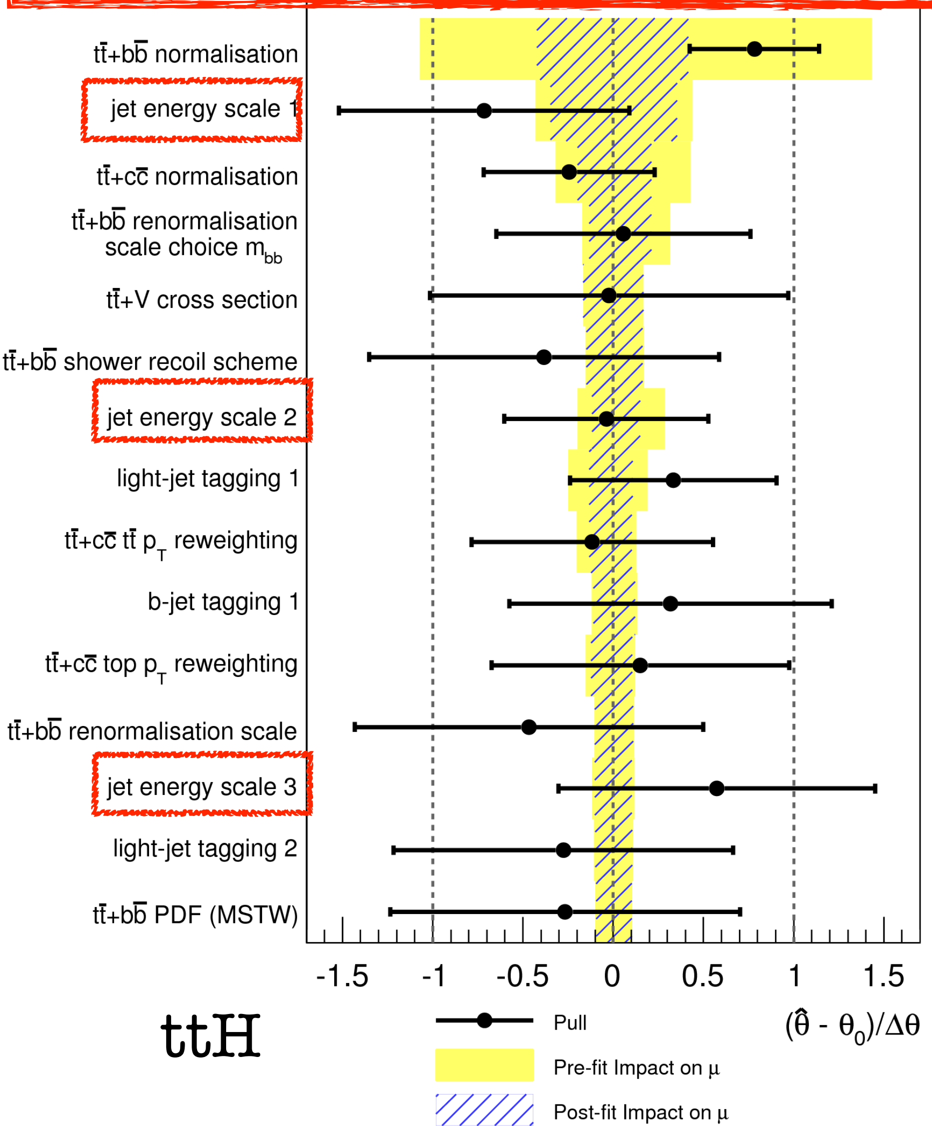


Source	$\sigma_{ttb}^{\text{fid}}$ Lepton-plus-jets uncertainty (%)	$\sigma_{ttb}^{\text{fid}}$ *ttb eμ* uncertainty (%)	$\sigma_{ttbb}^{\text{fid}}$ Cut-based uncertainty (%)	$\sigma_{ttbb}^{\text{fid}}$ Fit-based uncertainty (%)	R_{ttbb} Fit-based uncertainty (%)
Total detector	+17.5 −14.4	+11.6 −8.0	±14.5	+11.9 −13.1	+10.9 −12.5
Jet (combined)	+3.9 −2.7	+10.1 −6.1	±5.5	+6.0 −8.5	+8.7 −10.7
Lepton	±0.7	+1.0 −0.5	±2.0	+2.4 −2.7	+0.8 −1.6
b−tagging effect on *b*−jets	+4.4 −4.0	+3.6 −3.1	±12.9	+9.4 −9.0	+6.0 −5.8
b−tagging effect on *c*−jets	+16.2 −13.4	+4.0 −3.6	±1.7	± 1.4	+1.2 −1.3
b−tagging effect on light jets	+3.1 −2.0	+1.9 −2.0	±4.3	+3.3 −2.9	+2.2 −1.9
Total $t\bar{t}$ modelling	+13.1 −13.7	+23.8 −16.1	±23.8	±21.7	±16.1
Generator	+1.1 −1.4	+23.3 −15.1	±16.9	±17.4	±12.4
Scale choice	±4.3	+1.1 −2.7	±14.2	±9.5	±6.0
Shower/hadronisation	+11.4 −12.1	+3.0 −3.4	±8.2	±8.7	±7.1
PDF	+4.7 −4.5	±3.3	±3.3	±0.8	±4.1
Removing/doubling $t\bar{t}V$ and $t\bar{t}H$	±0.4	+1.1 −0.9	±1.5	+3.1 −2.7	+3.0 – 2.6
Other backgrounds	±0.8	+0.9 −0.8	±1.6	+3.5 −3.3	±2.5
MC sample size	< 1	< 1	±9.6	±7.4	±7.4
Luminosity	±2.8	±2.8	±3.2	±2.9	±0.1
Total systematic uncertainty	+25.5 −19.2	+30.5 −19.9	±29.5	+26.4 −26.9	+21.1 −21.9
Statistical uncertainty	±7.1	+19.2 −17.9	±18.4	±24.6	±25.2
Total uncertainty	+26.5 −20.5	+36.0 −26.8	±35.2	+36.1 −36.4	+32.9 −33.4

Jets and tops

- **Jet related uncertainties are one of the dominant detector uncertainties in the majority of top measurements**

- **Profound understanding of the jet energy calibration/correction and the related uncertainties will result in more precise top measurements**



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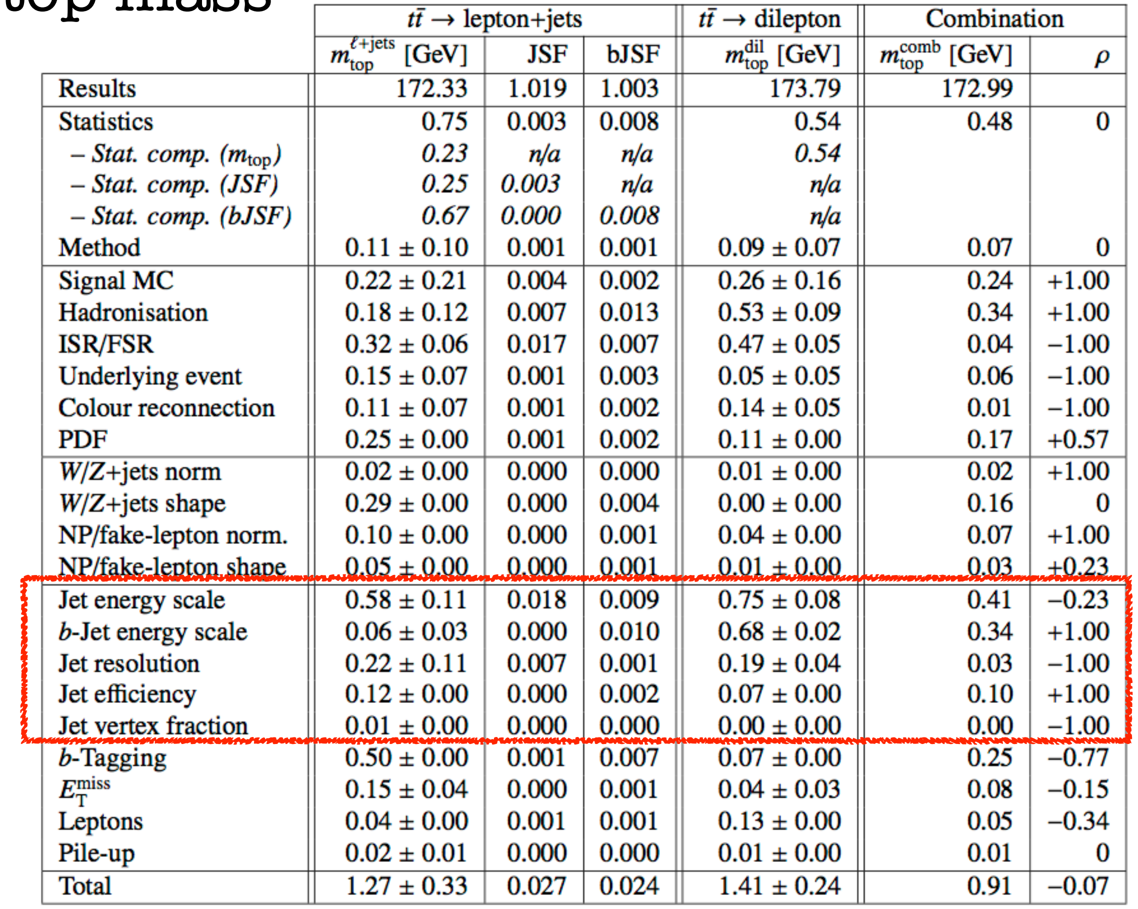
top mass



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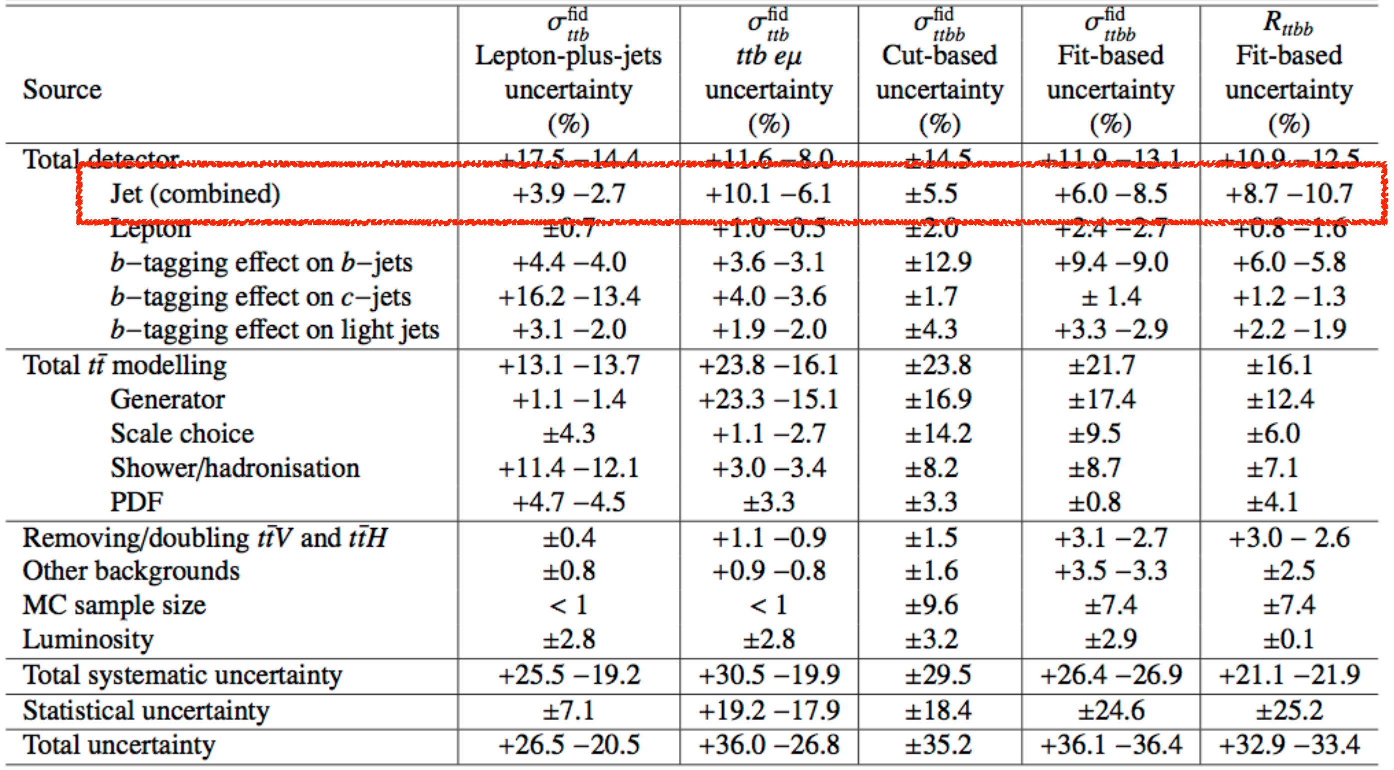
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– *Stat. comp.* (m_{top})	*0.23*	*n/a*	*n/a*	*0.54*		
– *Stat. comp. (JSF)*	*0.25*	*0.003*	*n/a*	*n/a*		
– *Stat. comp. (bJSF)*	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-Tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
E_T^{miss}	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

tt fiducial cross section

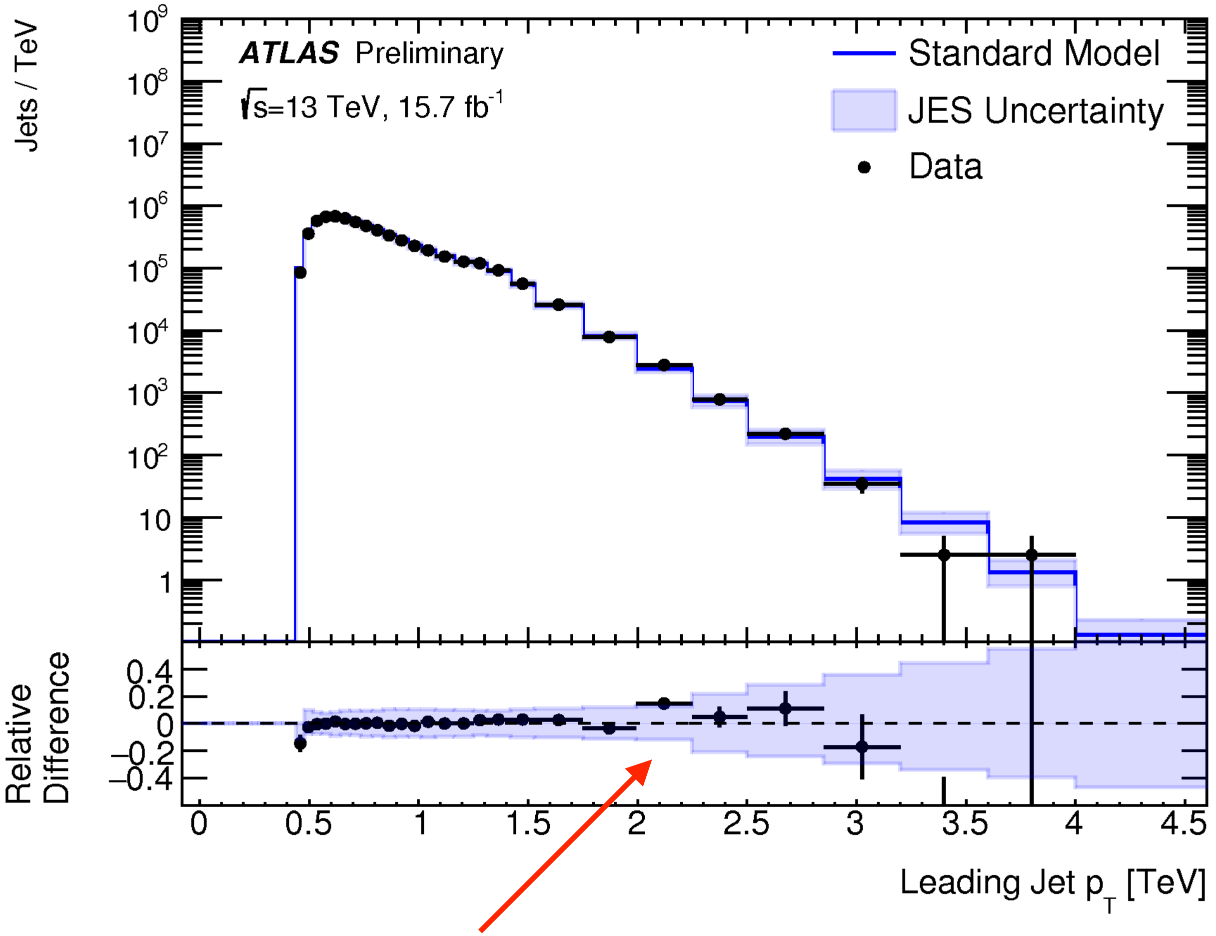


Source	σ_{ttb}^{fid} Lepton-plus-jets uncertainty (%)	σ_{ttb}^{fid} *ttb eμ* uncertainty (%)	σ_{ttbb}^{fid} Cut-based uncertainty (%)	σ_{ttbb}^{fid} Fit-based uncertainty (%)	R_{ttbb} Fit-based uncertainty (%)
Total detector	+17.5 −14.4	+11.6 −8.0	±14.5	+11.9 −13.1	+10.9 −12.5
Jet (combined)	+3.9 −2.7	+10.1 −6.1	±5.5	+6.0 −8.5	+8.7 −10.7
Lepton	±0.7	+1.0 −0.5	±2.0	+2.4 −2.7	+0.8 −1.6
b−tagging effect on *b*−jets	+4.4 −4.0	+3.6 −3.1	±12.9	+9.4 −9.0	+6.0 −5.8
b−tagging effect on *c*−jets	+16.2 −13.4	+4.0 −3.6	±1.7	± 1.4	+1.2 −1.3
b−tagging effect on light jets	+3.1 −2.0	+1.9 −2.0	±4.3	+3.3 −2.9	+2.2 −1.9
Total $t\bar{t}$ modelling	+13.1 −13.7	+23.8 −16.1	±23.8	±21.7	±16.1
Generator	+1.1 −1.4	+23.3 −15.1	±16.9	±17.4	±12.4
Scale choice	±4.3	+1.1 −2.7	±14.2	±9.5	±6.0
Shower/hadronisation	+11.4 −12.1	+3.0 −3.4	±8.2	±8.7	±7.1
PDF	+4.7 −4.5	±3.3	±3.3	±0.8	±4.1
Removing/doubling $t\bar{t}V$ and $t\bar{t}H$	±0.4	+1.1 −0.9	±1.5	+3.1 −2.7	+3.0 − 2.6
Other backgrounds	±0.8	+0.9 −0.8	±1.6	+3.5 −3.3	±2.5
MC sample size	< 1	< 1	±9.6	±7.4	±7.4
Luminosity	±2.8	±2.8	±3.2	±2.9	±0.1
Total systematic uncertainty	+25.5 −19.2	+30.5 −19.9	±29.5	+26.4 −26.9	+21.1 −21.9
Statistical uncertainty	±7.1	+19.2 −17.9	±18.4	±24.6	±25.2
Total uncertainty	+26.5 −20.5	+36.0 −26.8	±35.2	+36.1 −36.4	+32.9 −33.4

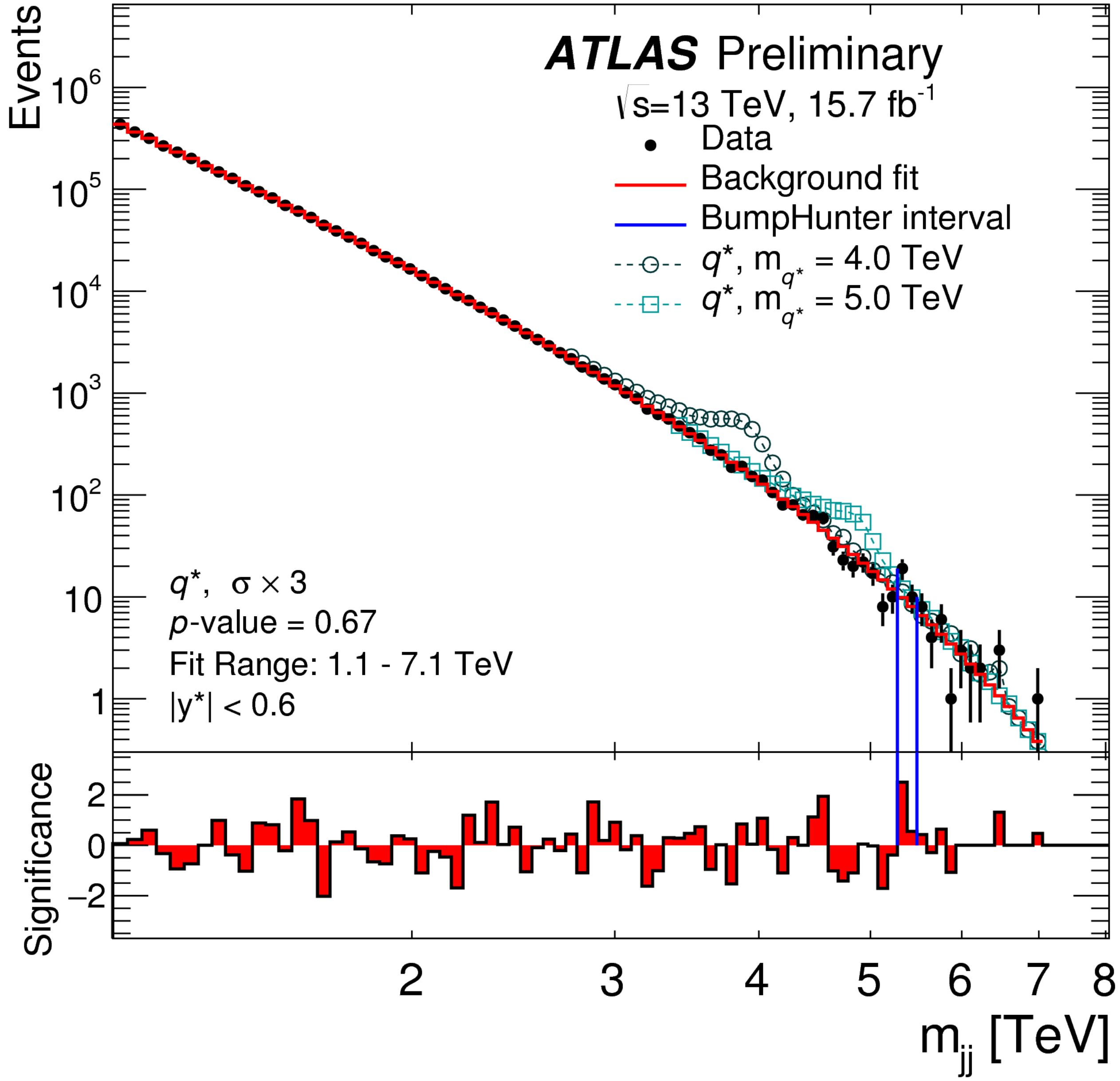
Dijet resonance searches

ATLAS-CONF-2016-069

- **Search for non-SM features in di-jet final**
  - **New resonances in m_{jj} spectrum**
    - Select events with leading (subleading) jet $p_T > 440(60)$ GeV
    - **Search for a bump in invariant mass m_{jj}**
- ~16 fb^{-1} analysed, preliminary result shown in ICHEP

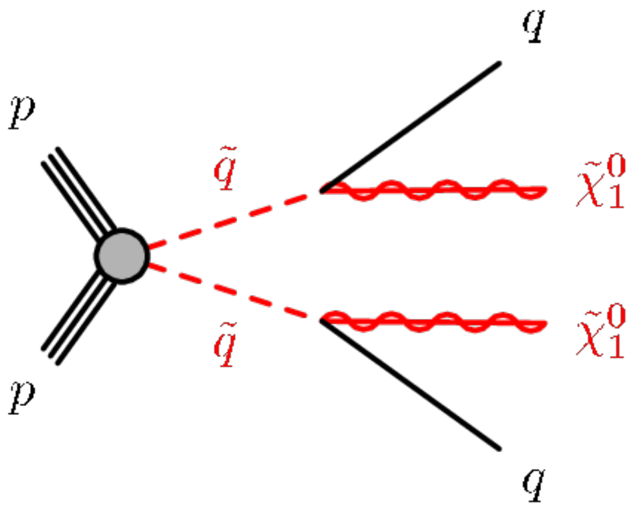


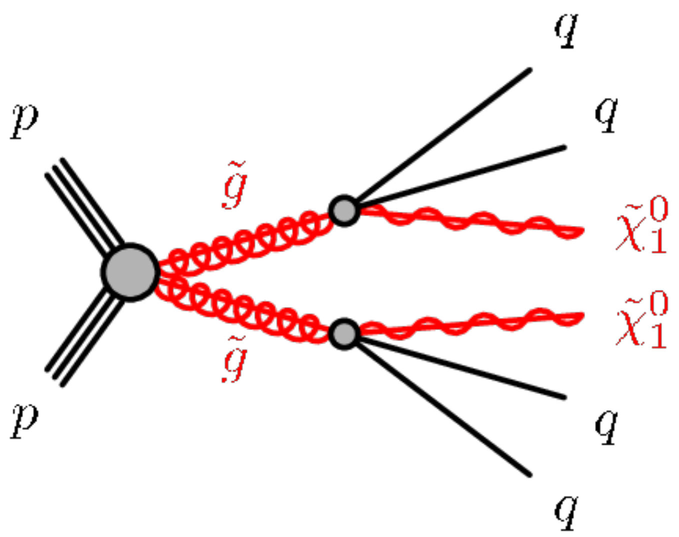
JES uncertainty being the dominant one



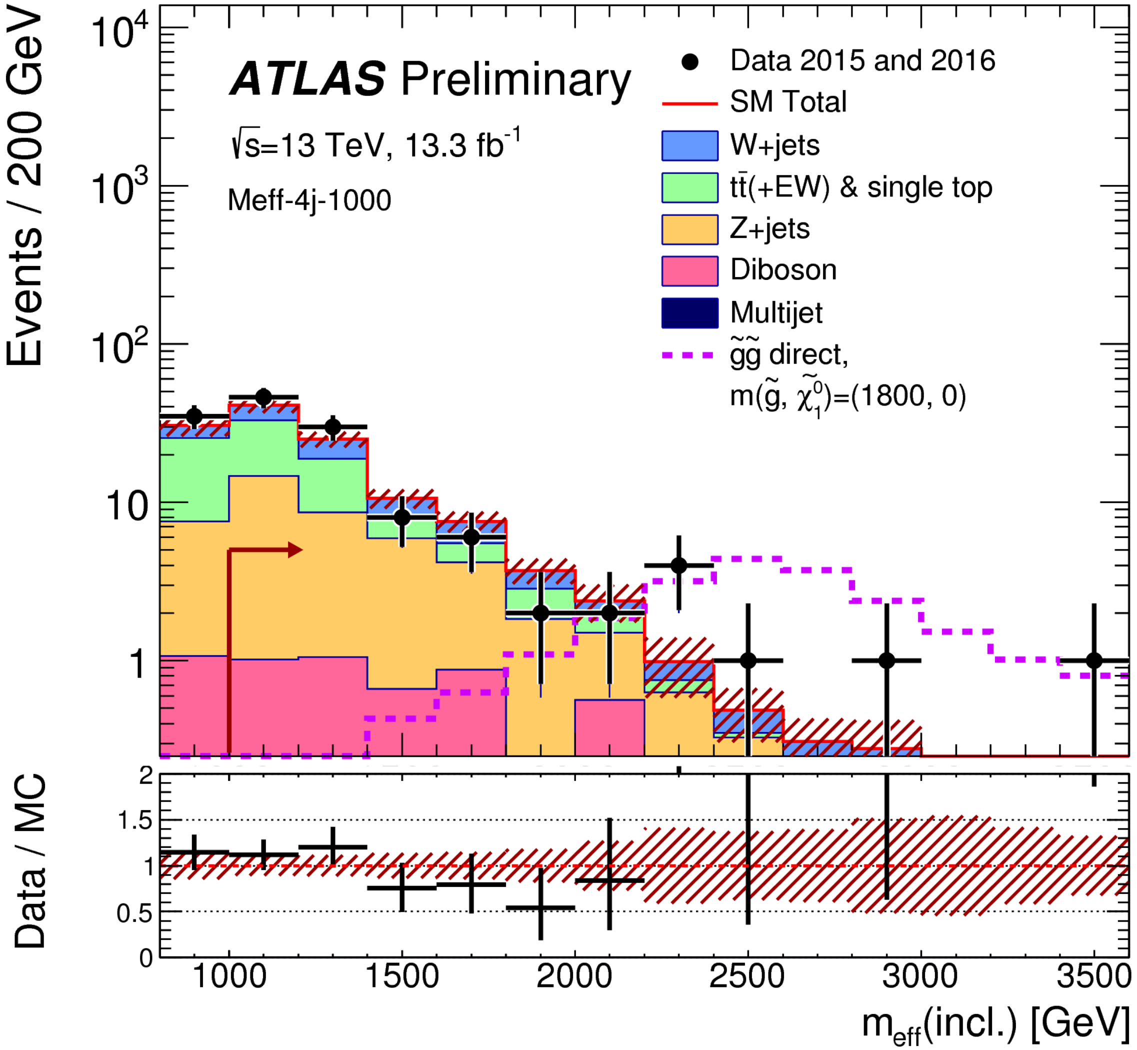
SUSY searches with jets and E_T^{miss}

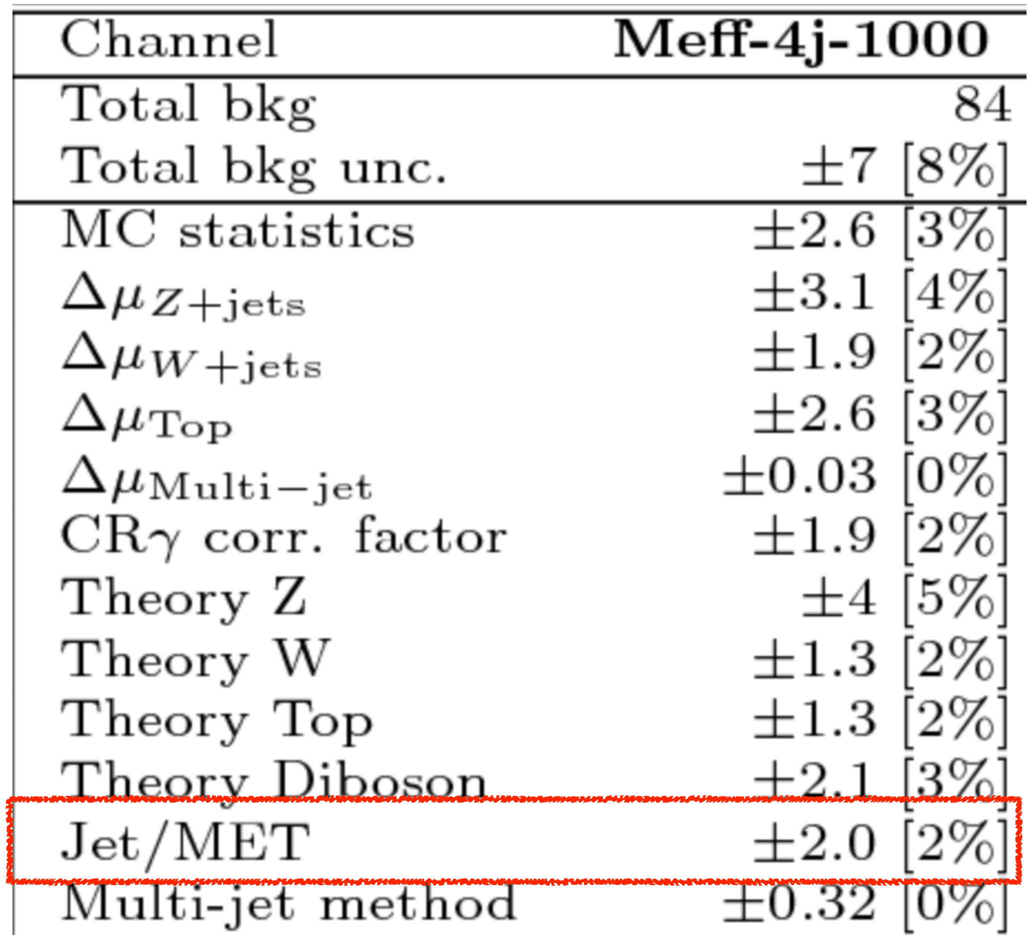
ATLAS-CONF-2016-078





- Search for squarks and gluinos in final states with **jets** and **E_T^{miss}**
- Effective mass (scalar sum of **jets p_T** and **E_T^{miss}**) the discriminating variable
- ~13 fb^{-1} analysed, preliminary result shown in ICHEP





Channel	**Meff-4j-1000**
Total bkg	84
Total bkg unc.	± 7 [8%]
MC statistics	± 2.6 [3%]
$\Delta\mu_{Z+\text{jets}}$	± 3.1 [4%]
$\Delta\mu_{W+\text{jets}}$	± 1.9 [2%]
$\Delta\mu_{\text{Top}}$	± 2.6 [3%]
$\Delta\mu_{\text{Multi-jet}}$	± 0.03 [0%]
CRγ corr. factor	± 1.9 [2%]
Theory Z	± 4 [5%]
Theory W	± 1.3 [2%]
Theory Top	± 1.3 [2%]
Theory Diboson	± 2.1 [3%]
Jet/MET	± 2.0 [2%]
Multi-jet method	± 0.32 [0%]

Jet/MET the only relevant detector - related uncertainty

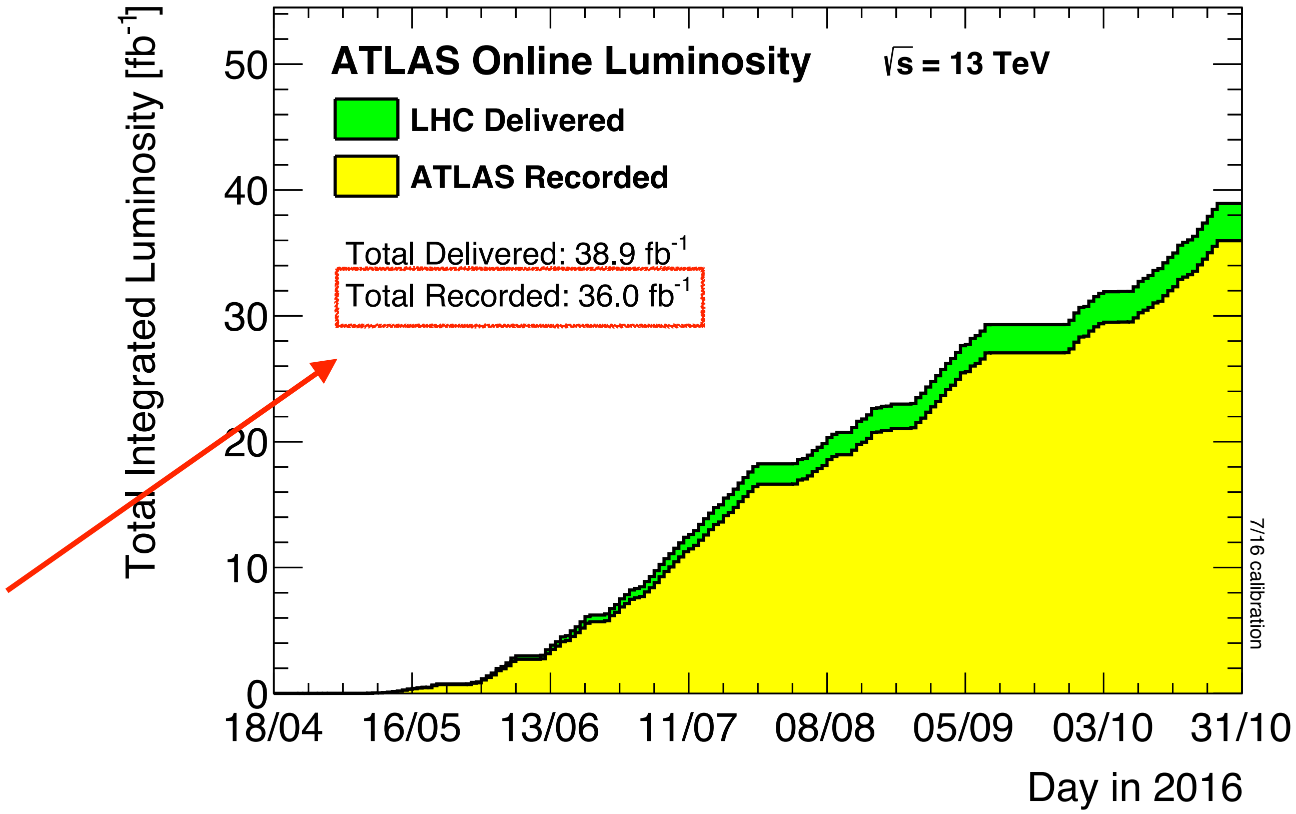
Conclusions

- Jets in LHC: challenging but extremely interesting objects
  - ✦ Huge amount of work optimising their energy calibration and performance and minimise the related uncertainties
  - ✦ **Key ingredient for many analyses**

- Jet Run-2 performance in ATLAS, already comparable to the one of Run-1
  - ✦ We should (and will) do better in the years to come

➡ **ATLAS Run-2 jets are ready for an ambitious physics programme**

- ➡ Stay tuned for the full **2015+2016 datasets results**



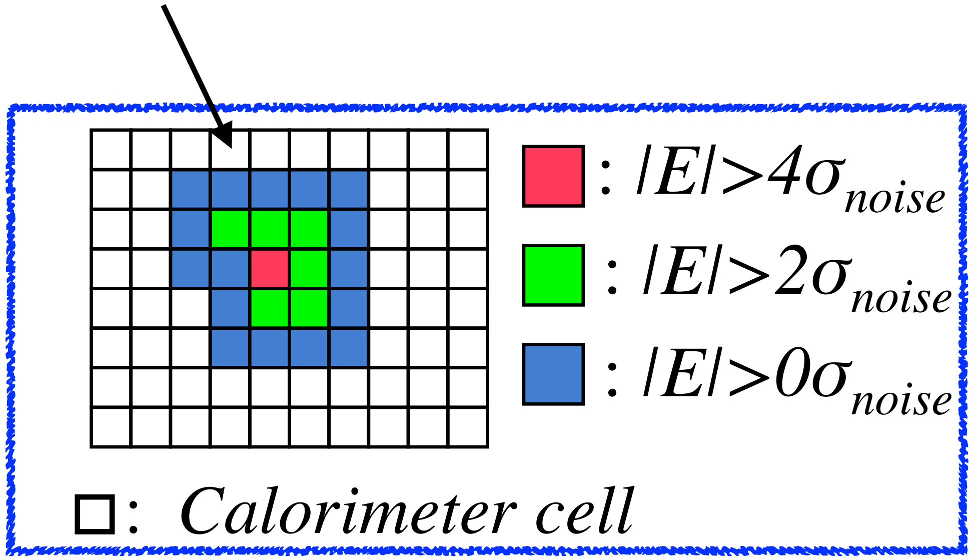
Back-up

Jet inputs in ATLAS: 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

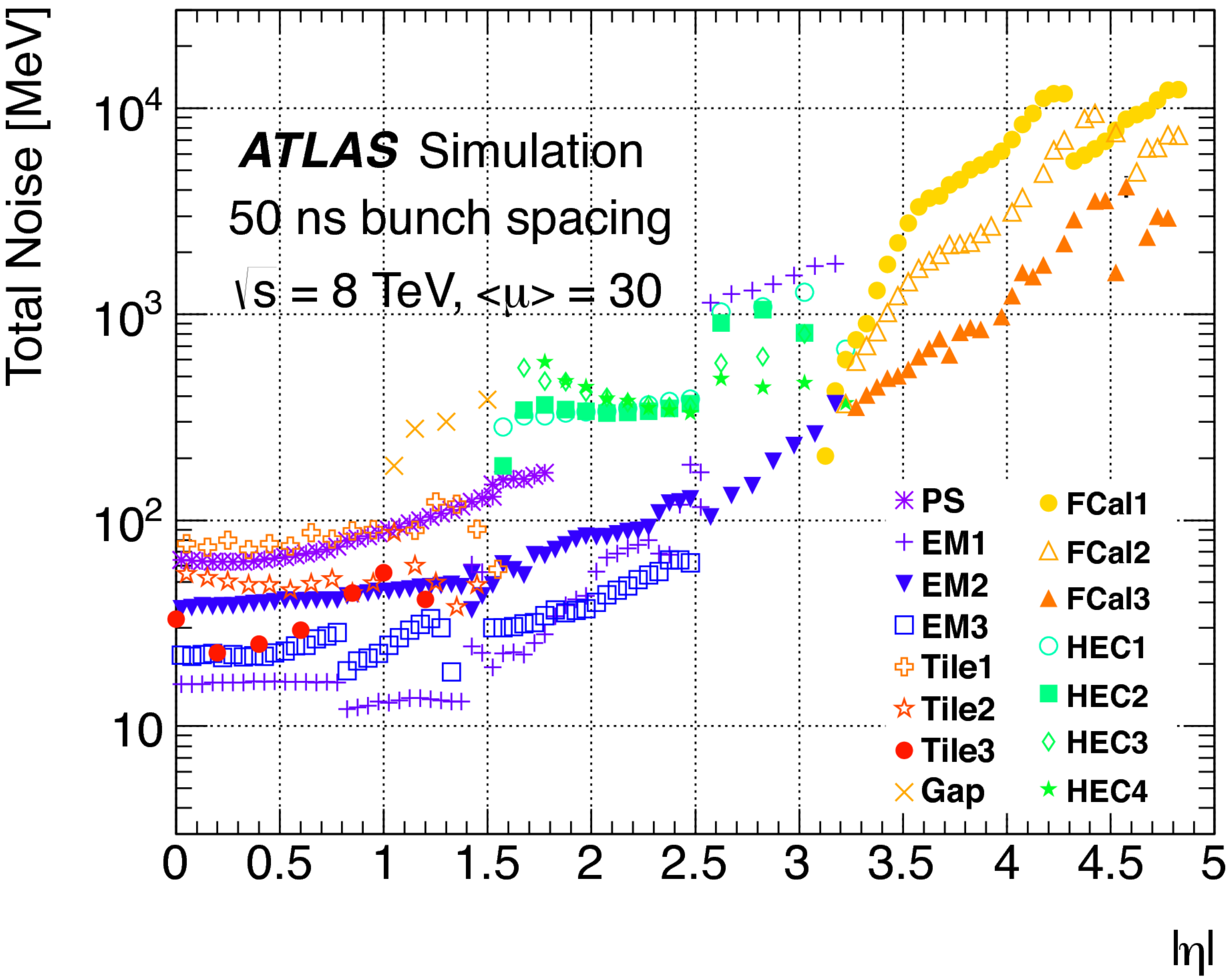


🟥 : $|E|>4\sigma_{noise}$

🟩 : $|E|>2\sigma_{noise}$

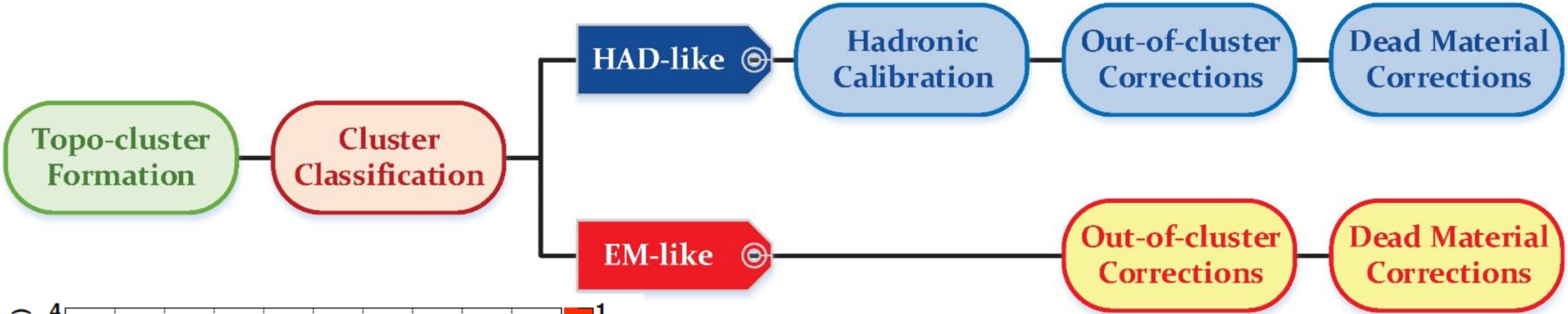
🟦 : $|E|>0\sigma_{noise}$

☐ : *Calorimeter cell*



Jet inputs: calorimeter clusters

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



Topo-cluster Formation

Cluster Classification

HAD-like

Hadronic Calibration

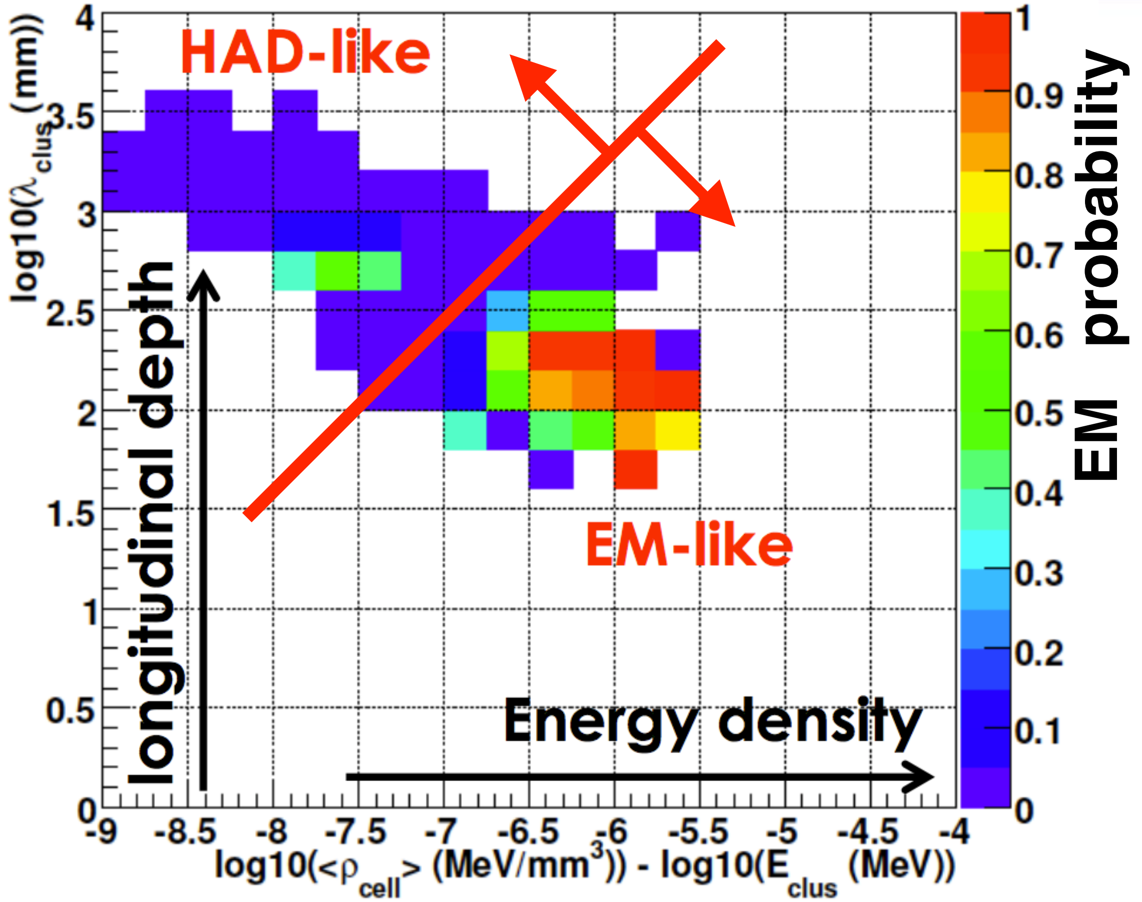
Out-of-cluster Corrections

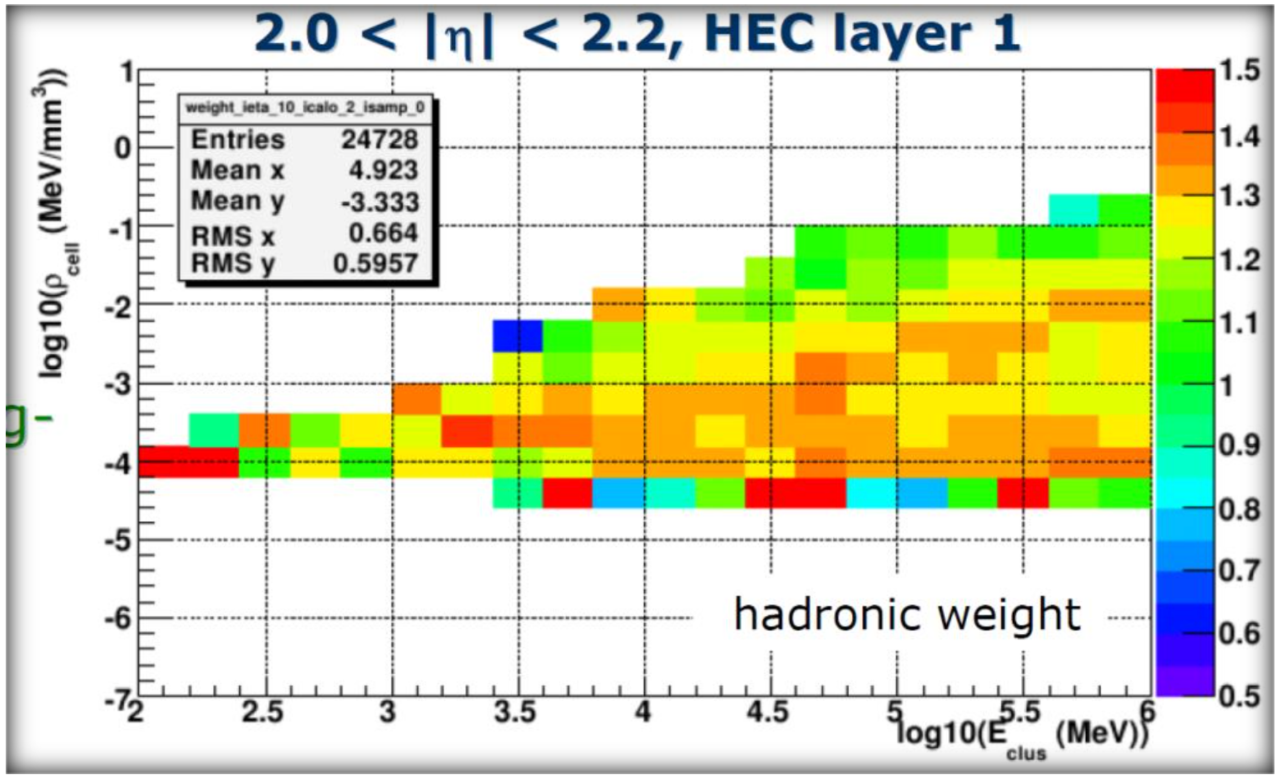
Dead Material Corrections

EM-like

Out-of-cluster Corrections

Dead Material Corrections





Jet algorithms

- k_T algorithm

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

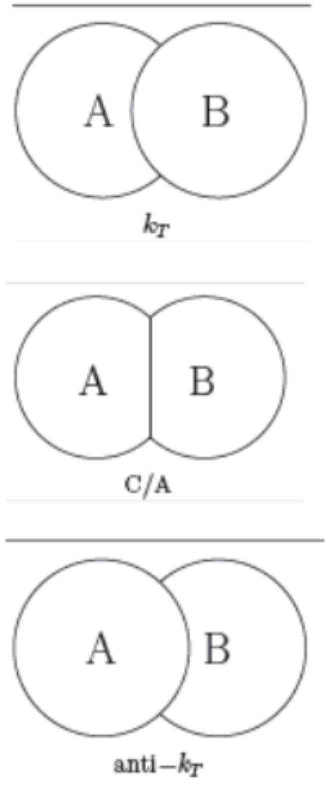
- C/A algorithm

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

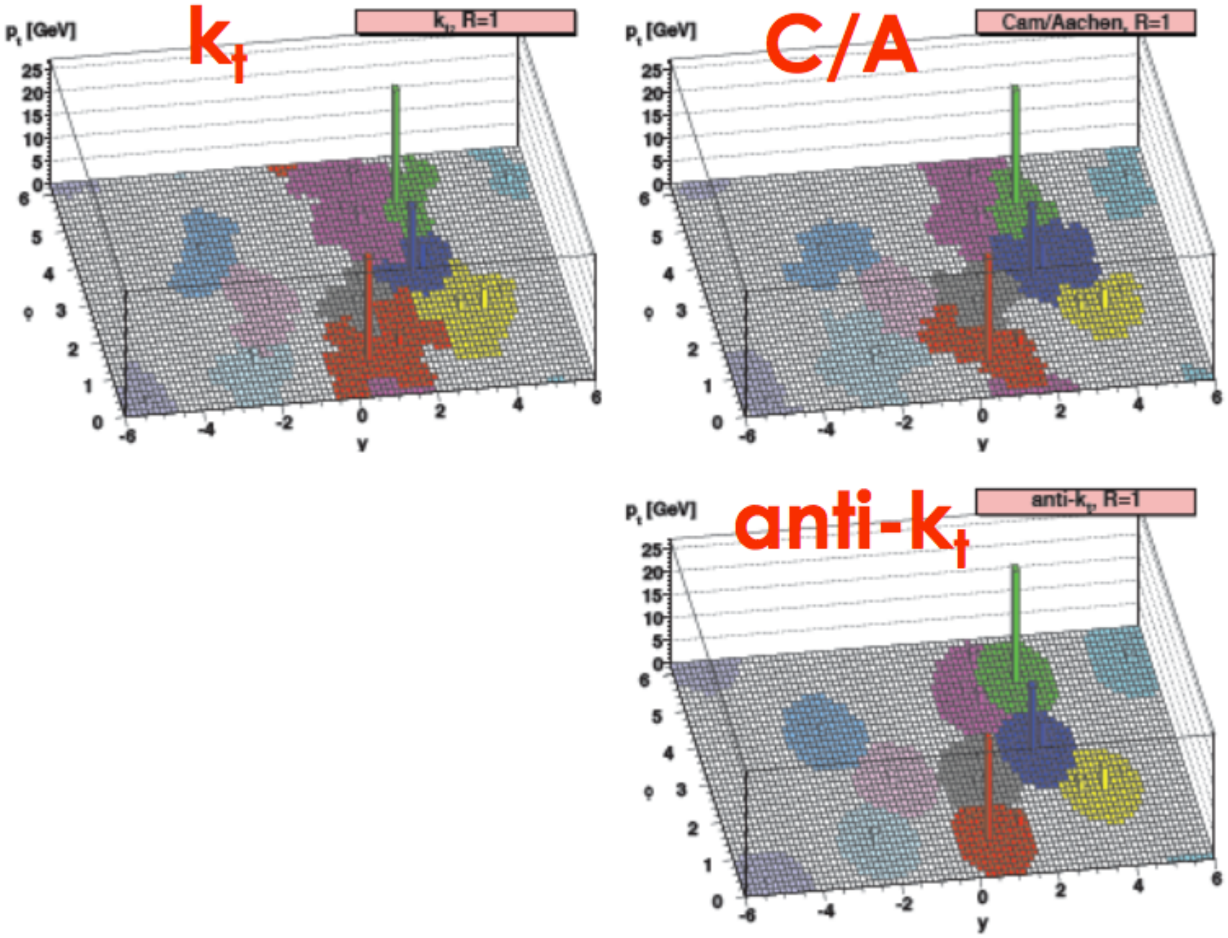
- anti-k_T algorithm

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

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

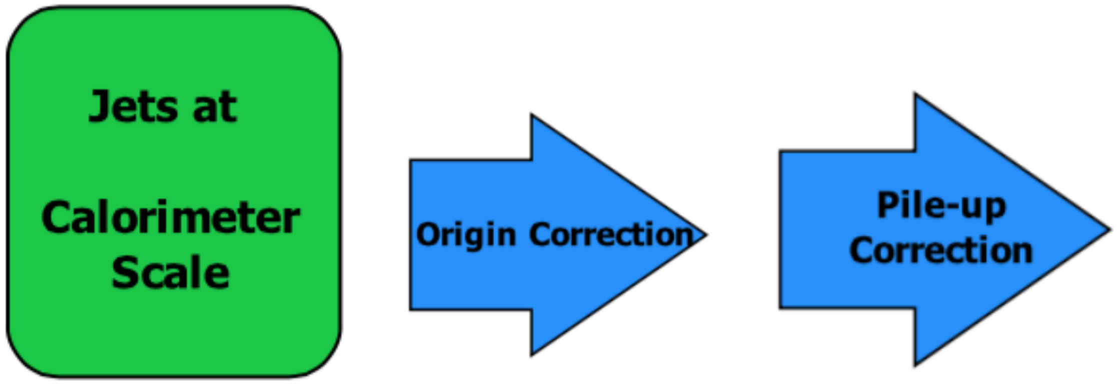


$$p_T^A > p_T^B$$



- **Anti-k_T** family of jet algorithms: the **standard** at **LHC** experiments
  - ✦ Regular shape objects (**easy to calibrate**, **more resilient to pile-up**)
  - ✦ Typical jet size for **resolved objets** R=0.4 or 0.5 , where $R=\sqrt{(\Delta\eta^2+\Delta\varphi^2)}$

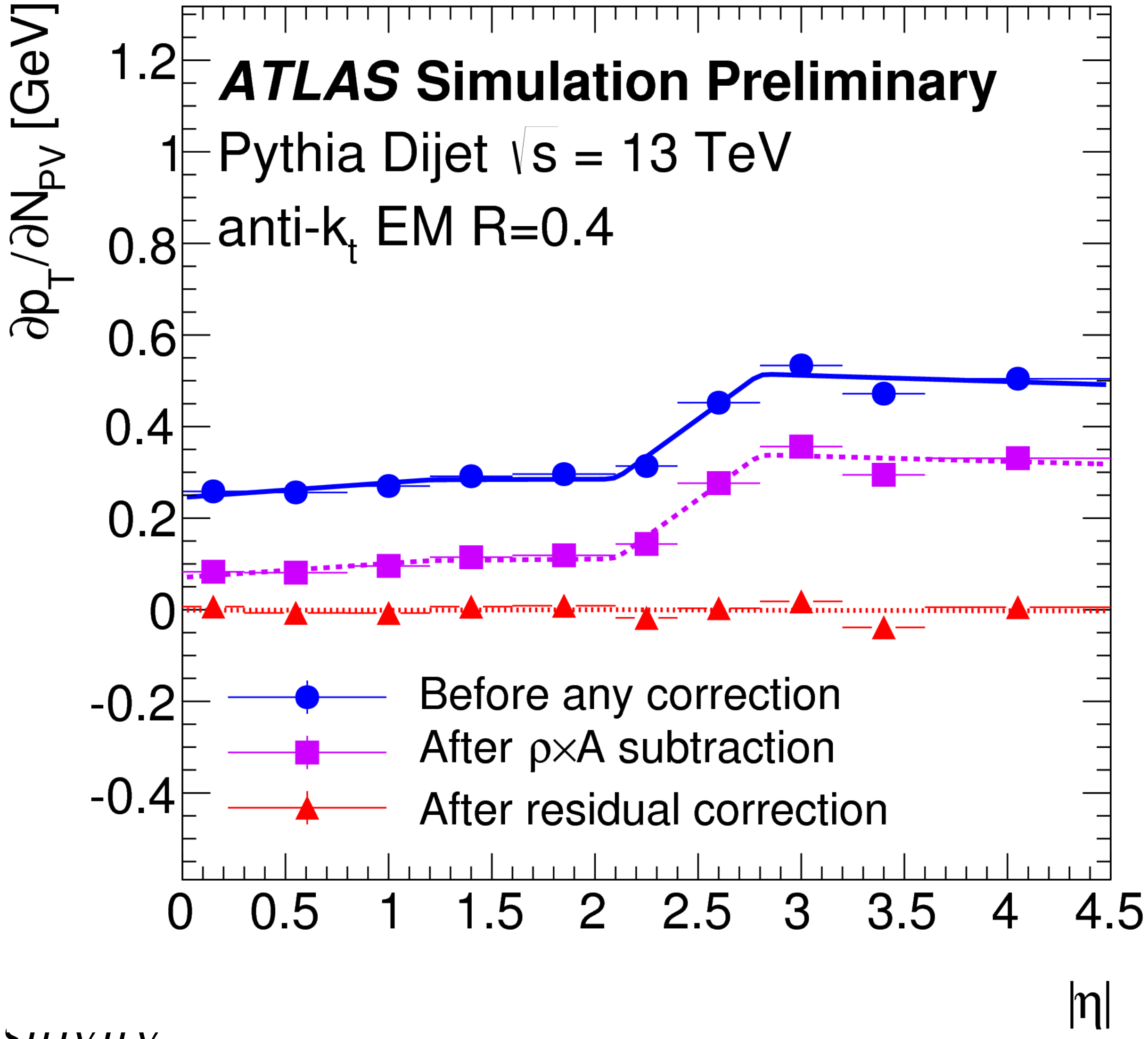
Jet calibration chain



ATLAS-PHYS-PUB-2015-015

Pile-up paper submitted to EPJC

- 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-by-jet pile-up sensitivity

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

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

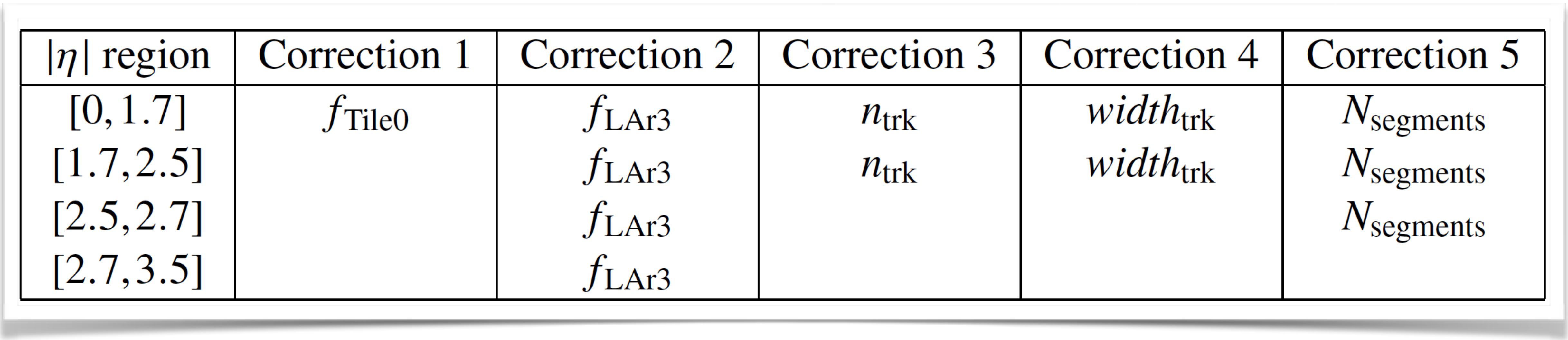
$$\rho = \text{median}\left\{\frac{p_{T,i}^{\text{jet}}}{A_i^{\text{jet}}}\right\}$$

constructed with no minimum p_{T} threshold

Jet calibration chain

ATLAS-CONF-2015-002

- **Global sequential calibration (GSC)**: to **reduce** fluctuation **effects**
  - ✦ Use jet-by-jet information to correct the response of each jet individually
- MC JES (one step before) corrects jets to particle level reference on **average**
- 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**)

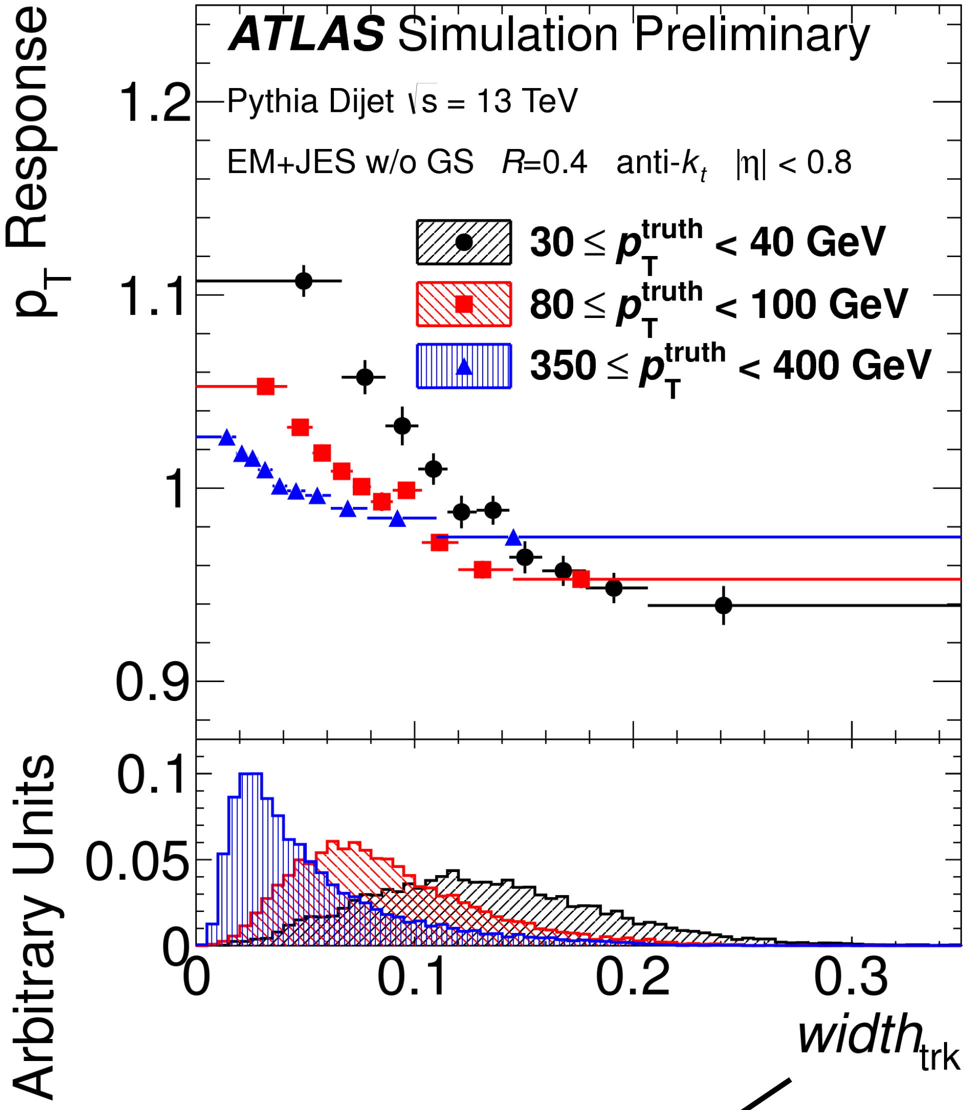


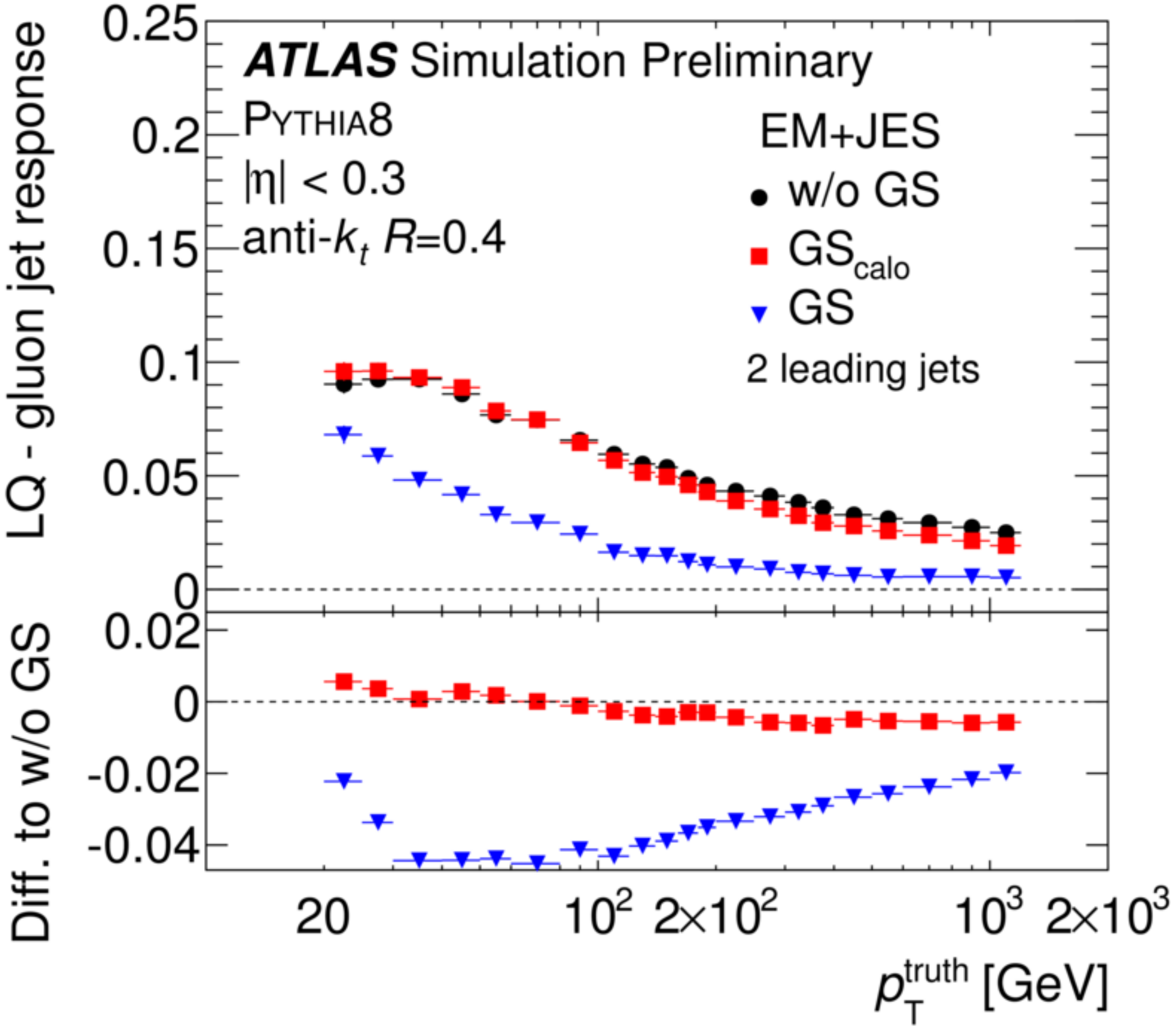
$\lvert\eta\rvert$ region	Correction 1	Correction 2	Correction 3	Correction 4	Correction 5
$[0,1.7]$	f_{Tile0}	f_{LAr3}	n_{trk}	$width_{\mathrm{trk}}$	N_{segments}
$[1.7,2.5]$		f_{LAr3}	n_{trk}	$width_{\mathrm{trk}}$	N_{segments}
$[2.5,2.7]$		f_{LAr3}			N_{segments}
$[2.7,3.5]$		f_{LAr3}			

Global Sequential Calibration

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

- Derived using MC, parametrised in p_T and η



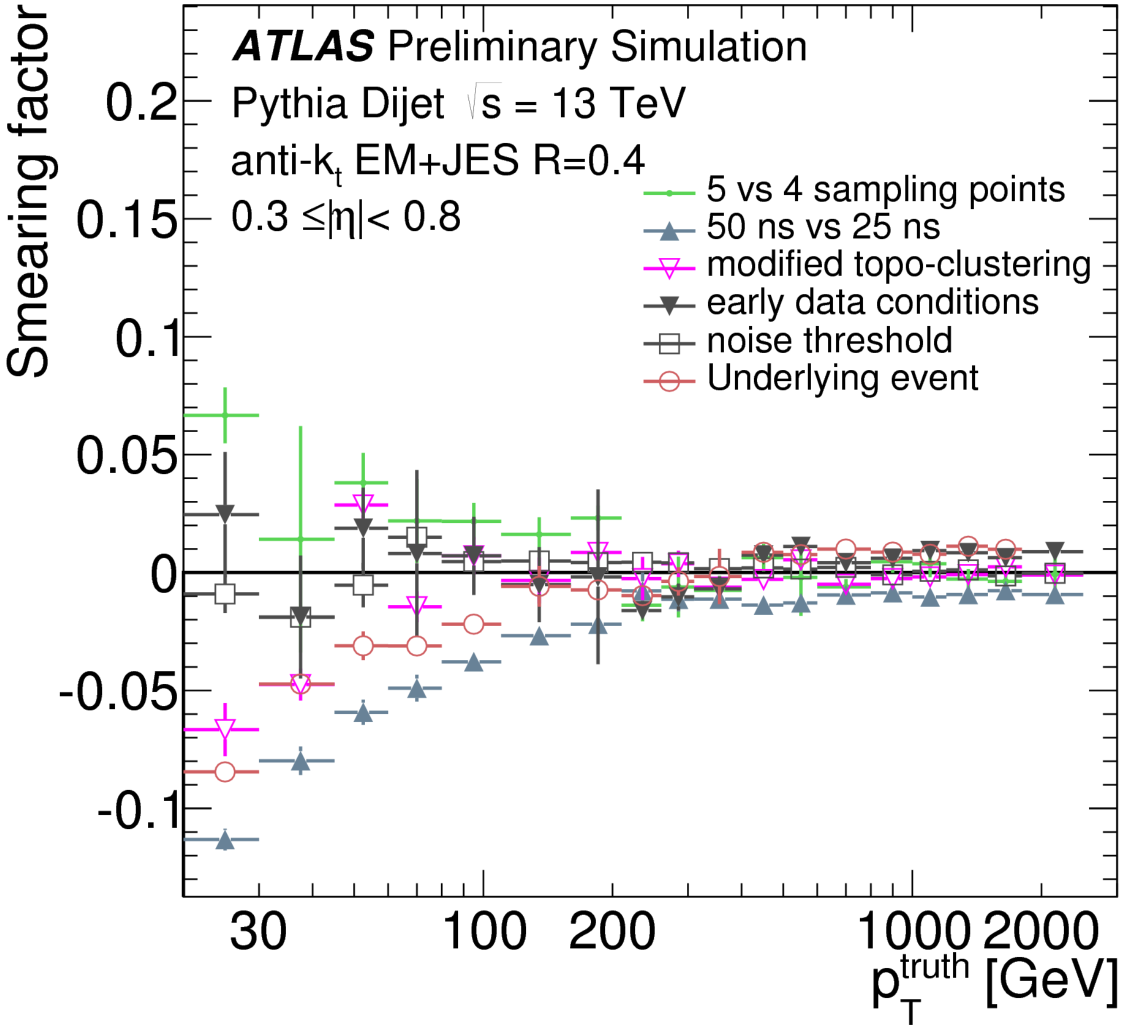


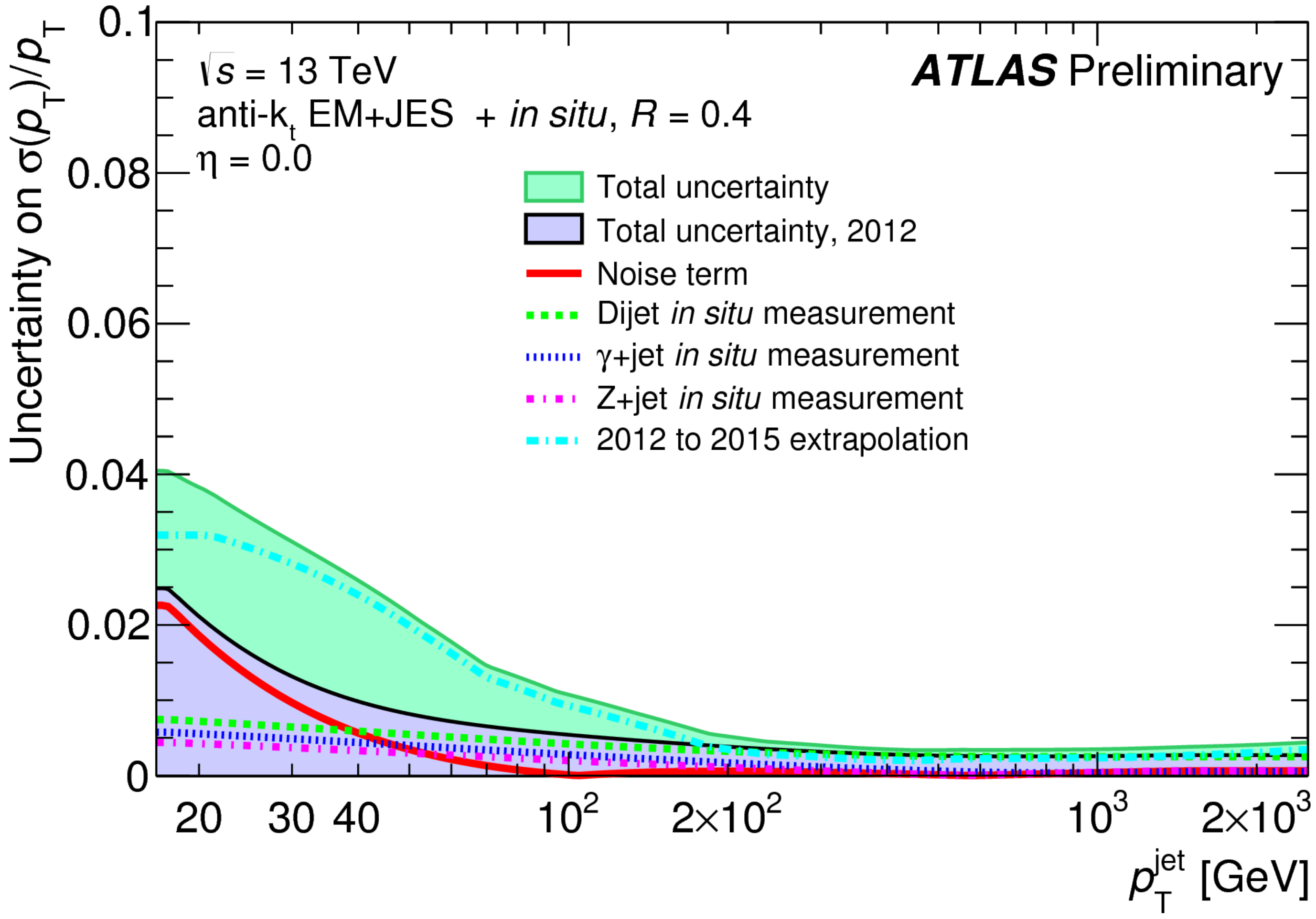
✦ **Improves flavour uncertainties**

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

JER uncertainties in Run 2

ATL-PHYS-PUB-2015-015





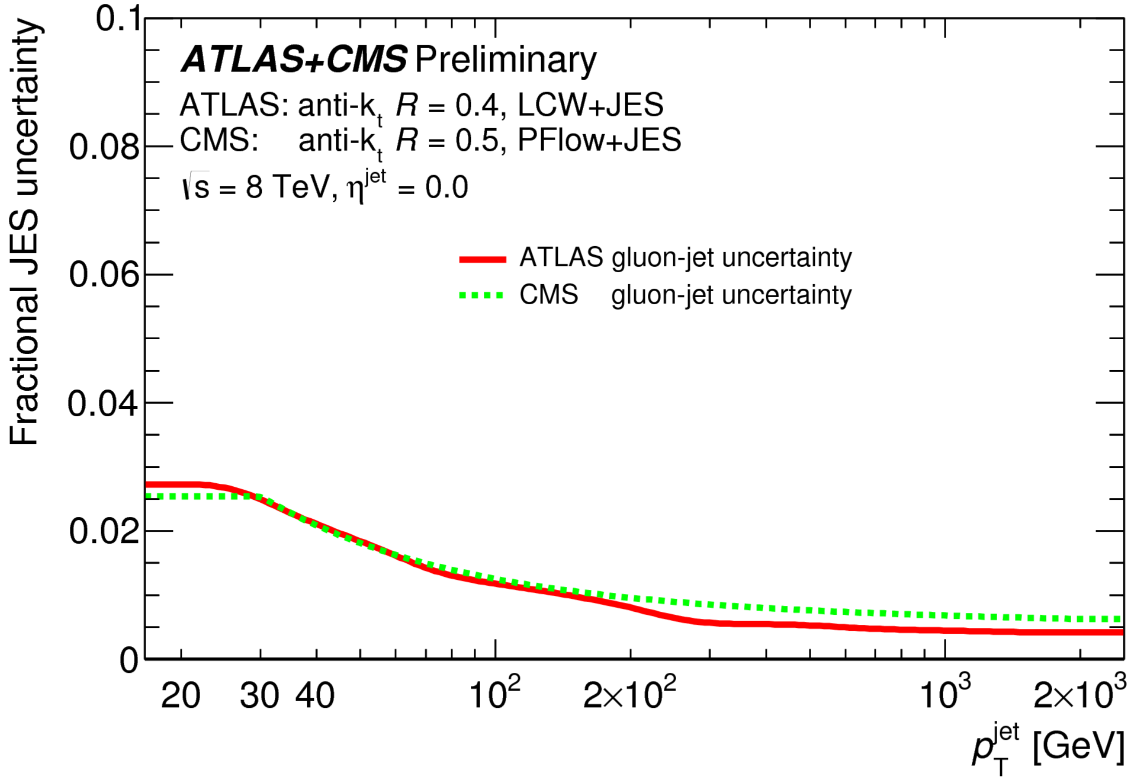
- Current **2015** JER measurement, based on a **2012** JER measurement **extrapolation** (pre-recommendations)
- In-situ **2015** measurement ongoing, **target to have it done in 1-2 months timescale**. It will be the base of the 2016 JER recommendations
- JER uncertainties correlations are now taken into account coherently
  - We provide an implementation with 9NPs, smearing the MC and Data. See here for details
  - This will be supported in 2016 recommendations

JES ATLAS and CMS

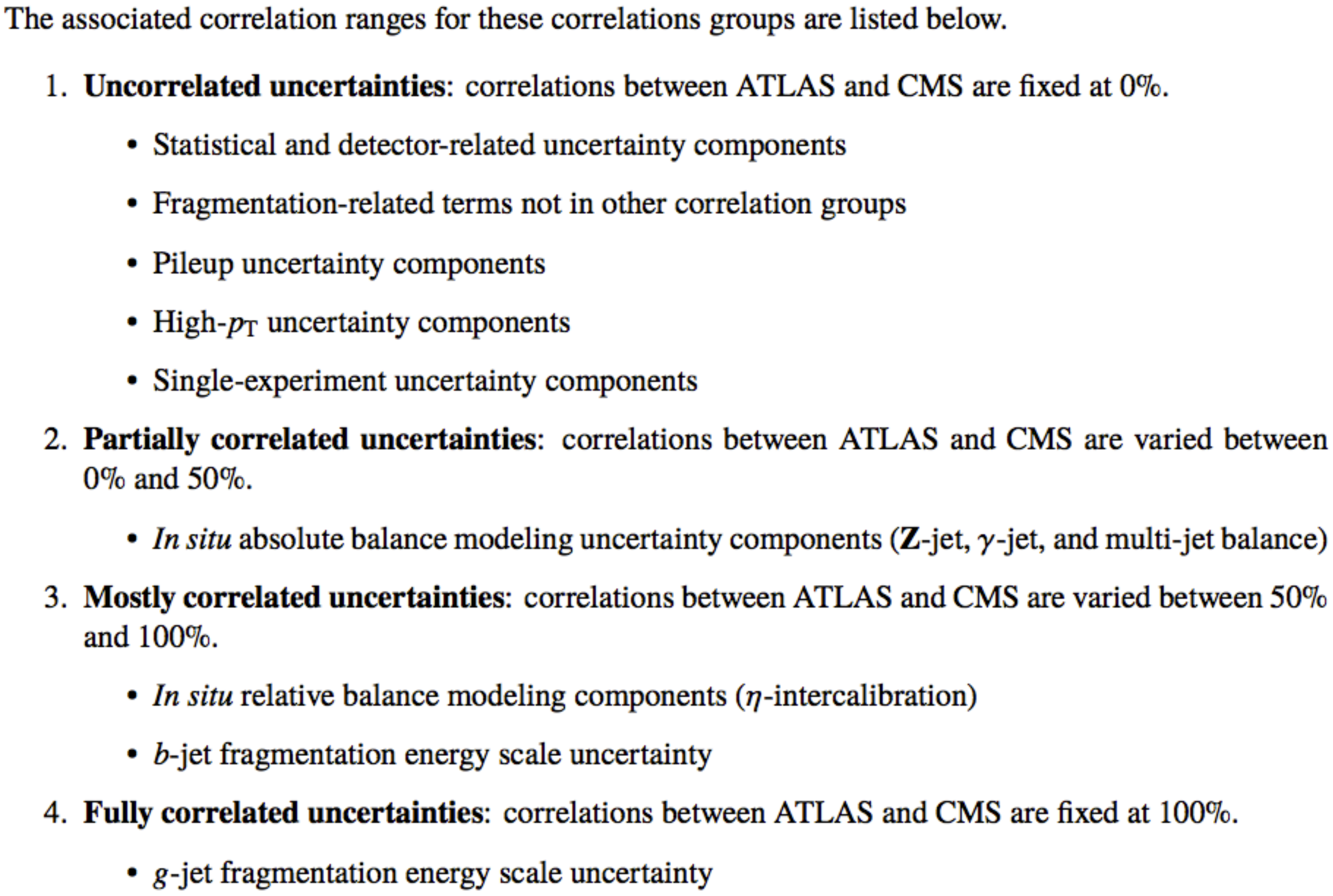
- Understand the source of the uncertainty
- Correlations are driven by the methods to derive them

- **Detector related —-> non correlated**
- **Theory related (use simulation) —-> correlated**
- **Others in between**

- **Gluon flavour uncertainty**
- ATLAS and CMS derive an uncertainty from the difference between Pythia and Herwig++,
- same generator difference is used, and then evaluated in a given topology (for a given gluon fraction), they are expected to be strongly → correlated.
- This, combined with the nearly identical resulting uncertainty between experiments **fully correlated**.



JES ATLAS and CMS

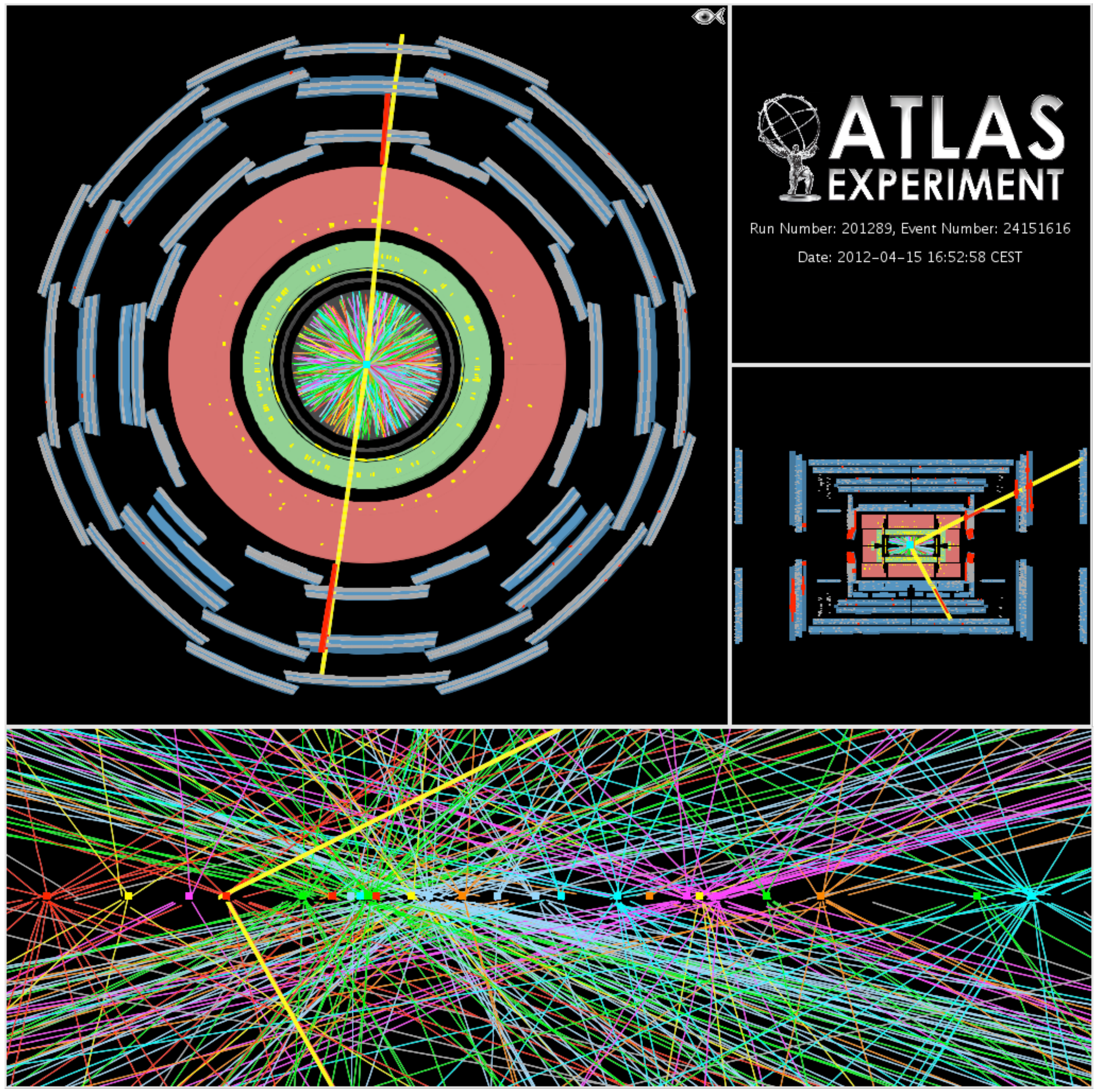


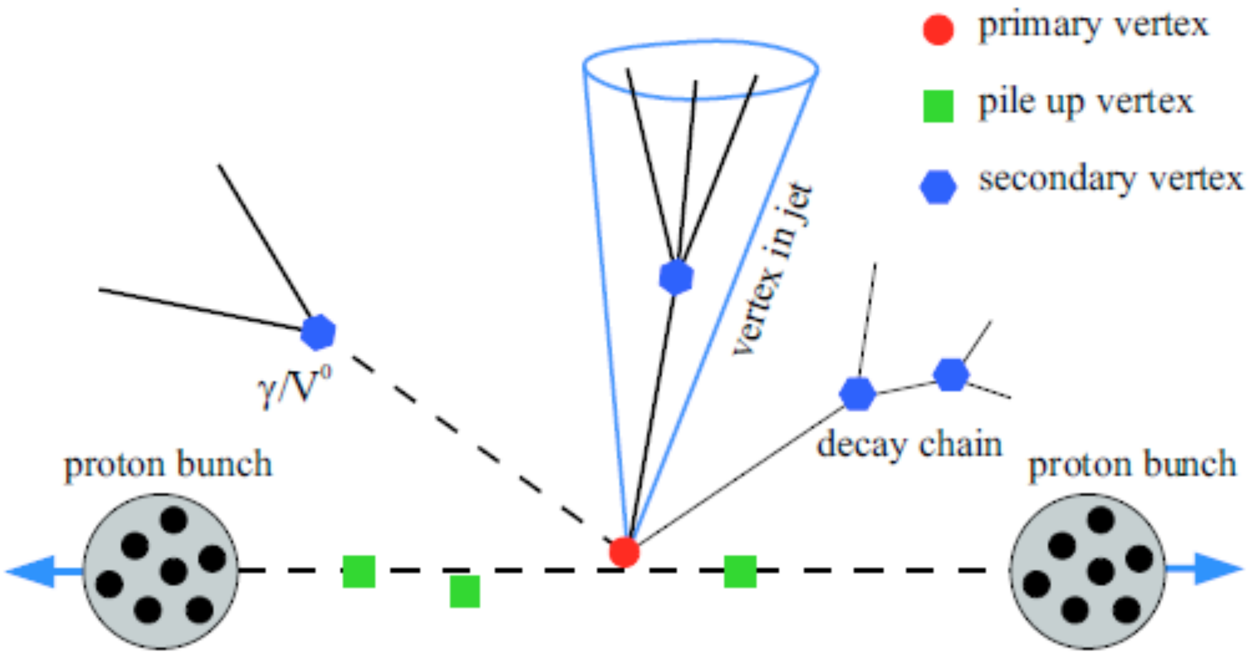
The associated correlation ranges for these correlations groups are listed below.

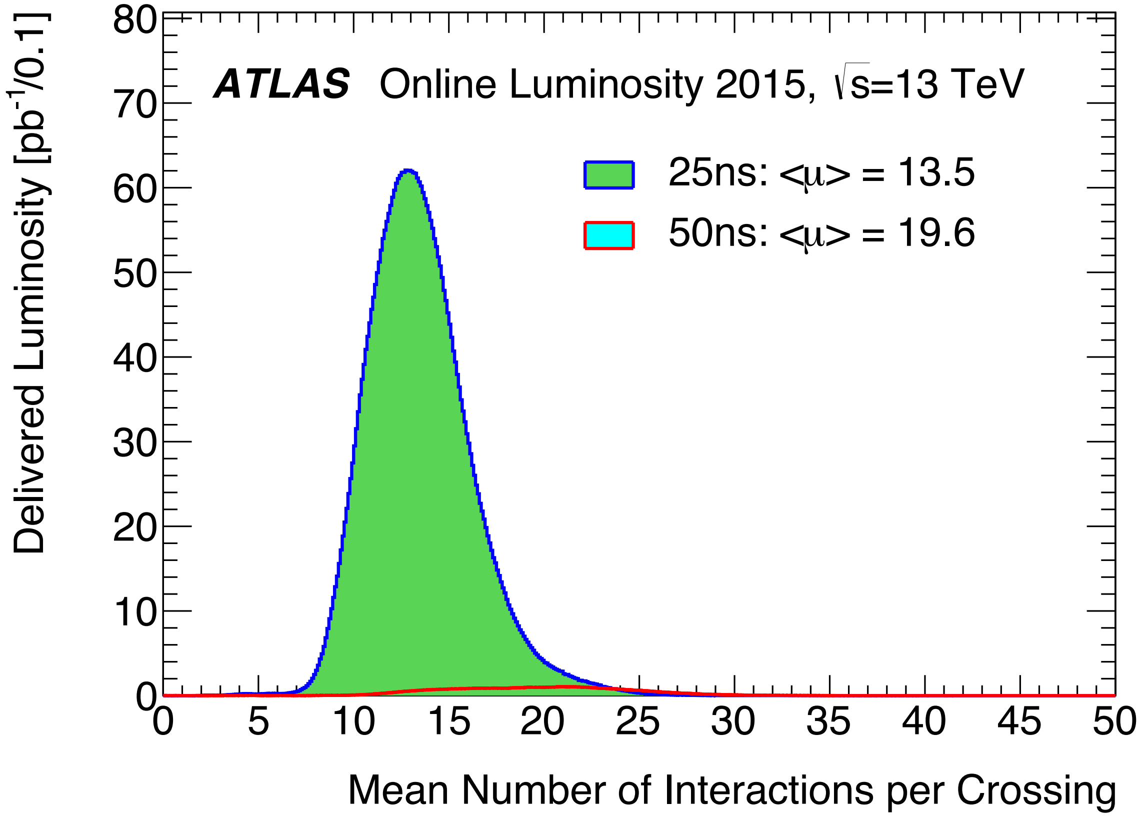
1. **Uncorrelated uncertainties**: correlations between ATLAS and CMS are fixed at 0%.
    - Statistical and detector-related uncertainty components
    - Fragmentation-related terms not in other correlation groups
    - Pileup uncertainty components
    - High-p_T uncertainty components
    - Single-experiment uncertainty components
2. **Partially correlated uncertainties**: correlations between ATLAS and CMS are varied between 0% and 50%.
    - *In situ* absolute balance modeling uncertainty components (**Z**-jet, γ-jet, and multi-jet balance)
3. **Mostly correlated uncertainties**: correlations between ATLAS and CMS are varied between 50% and 100%.
    - *In situ* relative balance modeling components (η-intercalibration)
    - b-jet fragmentation energy scale uncertainty
4. **Fully correlated uncertainties**: correlations between ATLAS and CMS are fixed at 100%.
    - g-jet fragmentation energy scale uncertainty

The price of high Luminosity: Pile-up

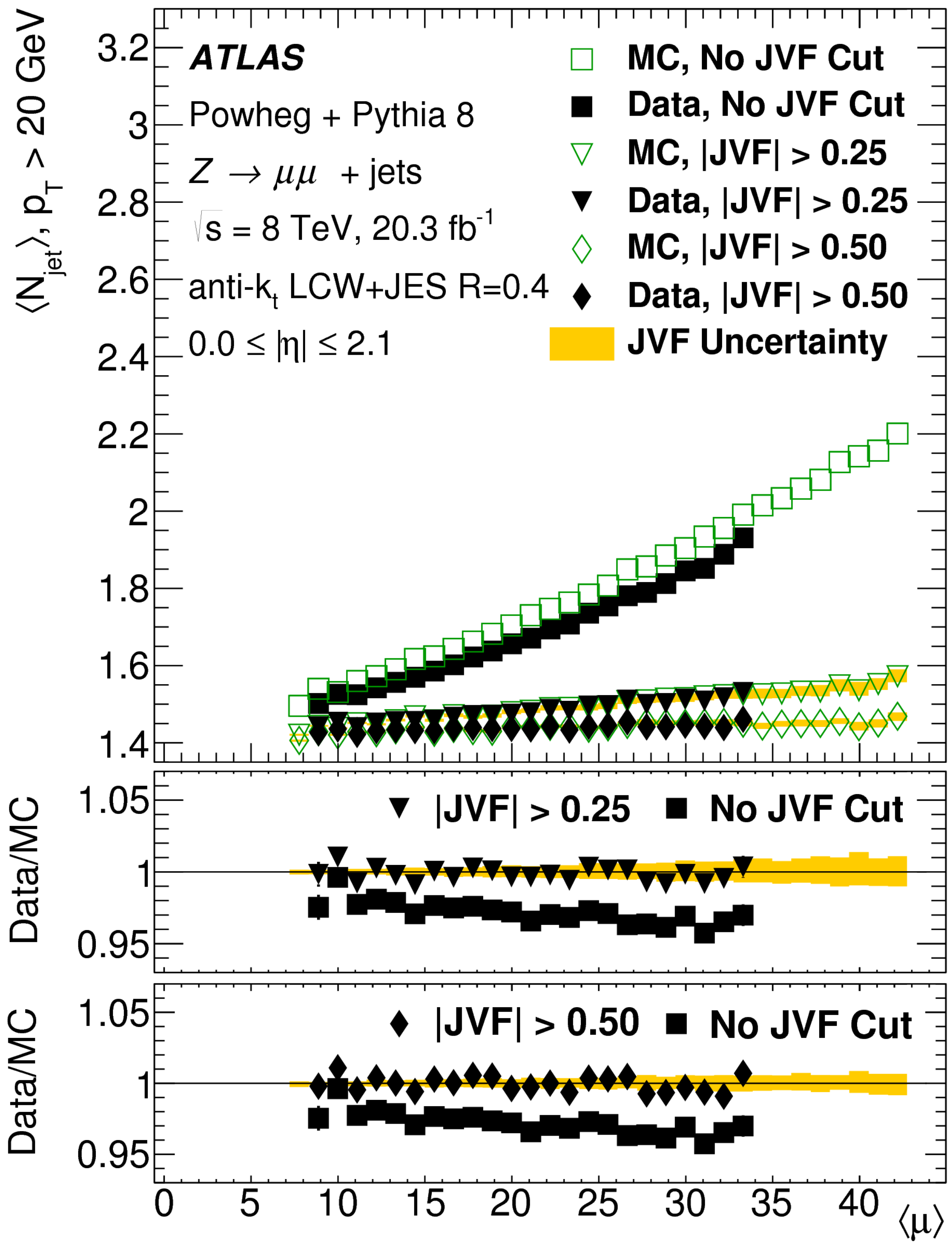
Z->μμ candidate event with 25 reconstructed vertices



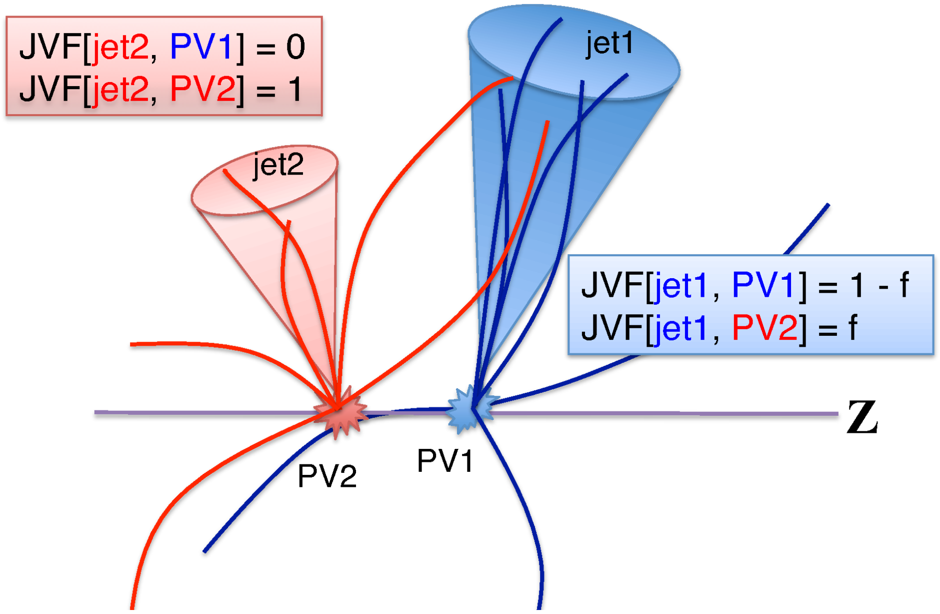


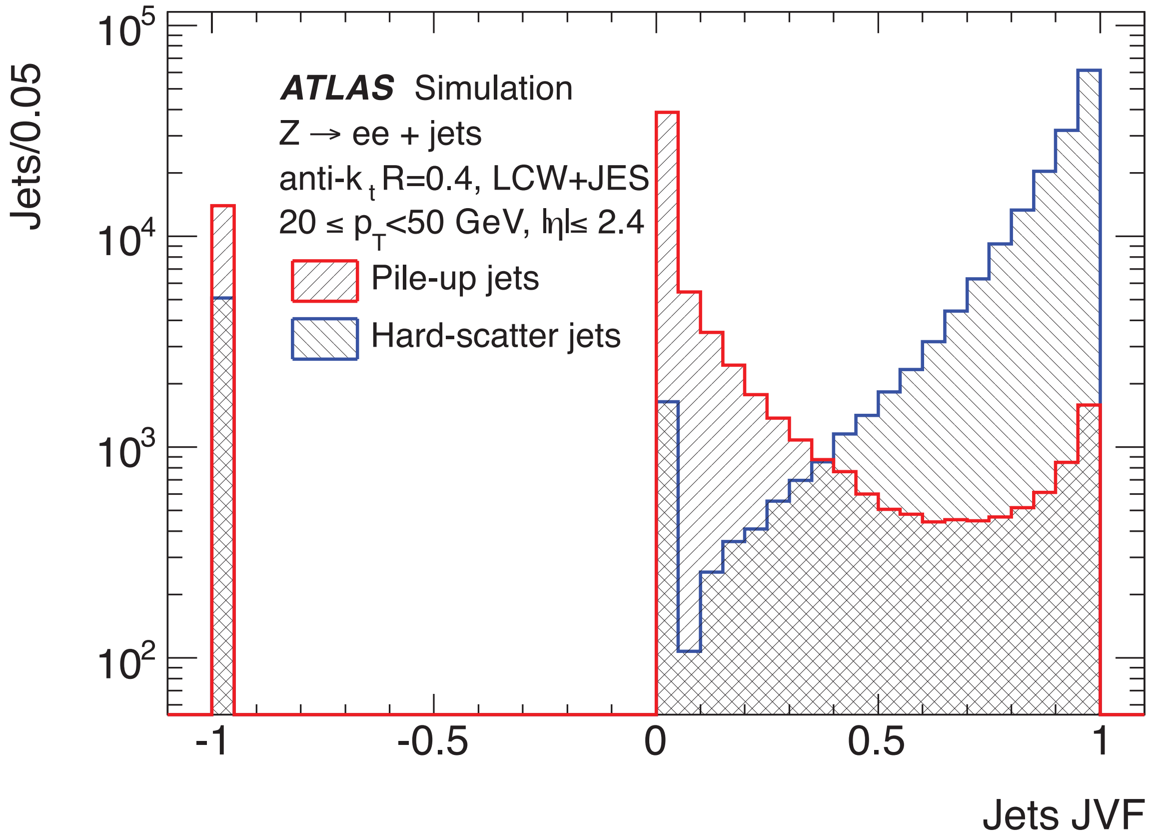


Tracks and vertexing against pile-up



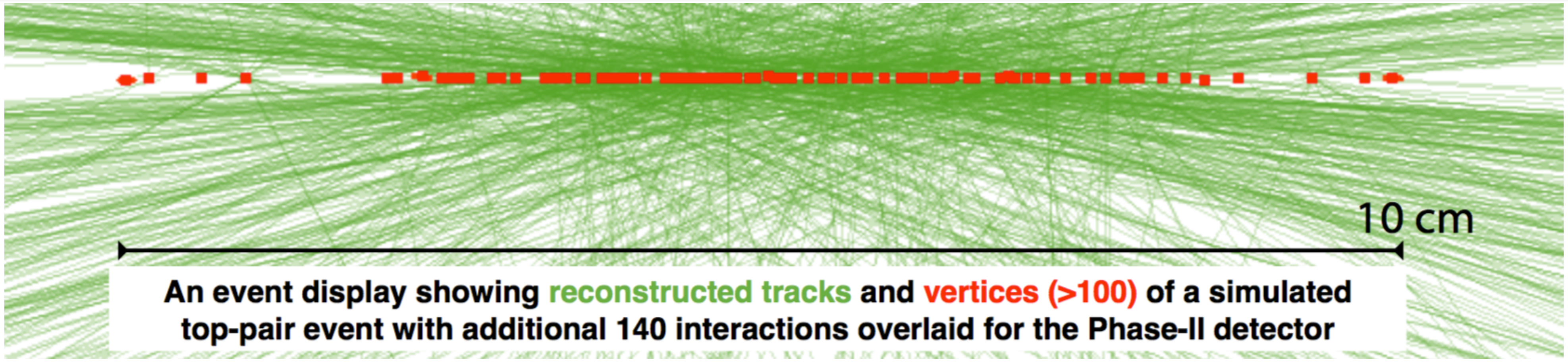
$$f_{\mathrm{JVF}}(\mathrm{jet}|\mathrm{vtx}) = \frac{\sum p_T^{\mathrm{trk}|\mathrm{vtx}}}{\sum p_T^{\mathrm{trk}}}$$





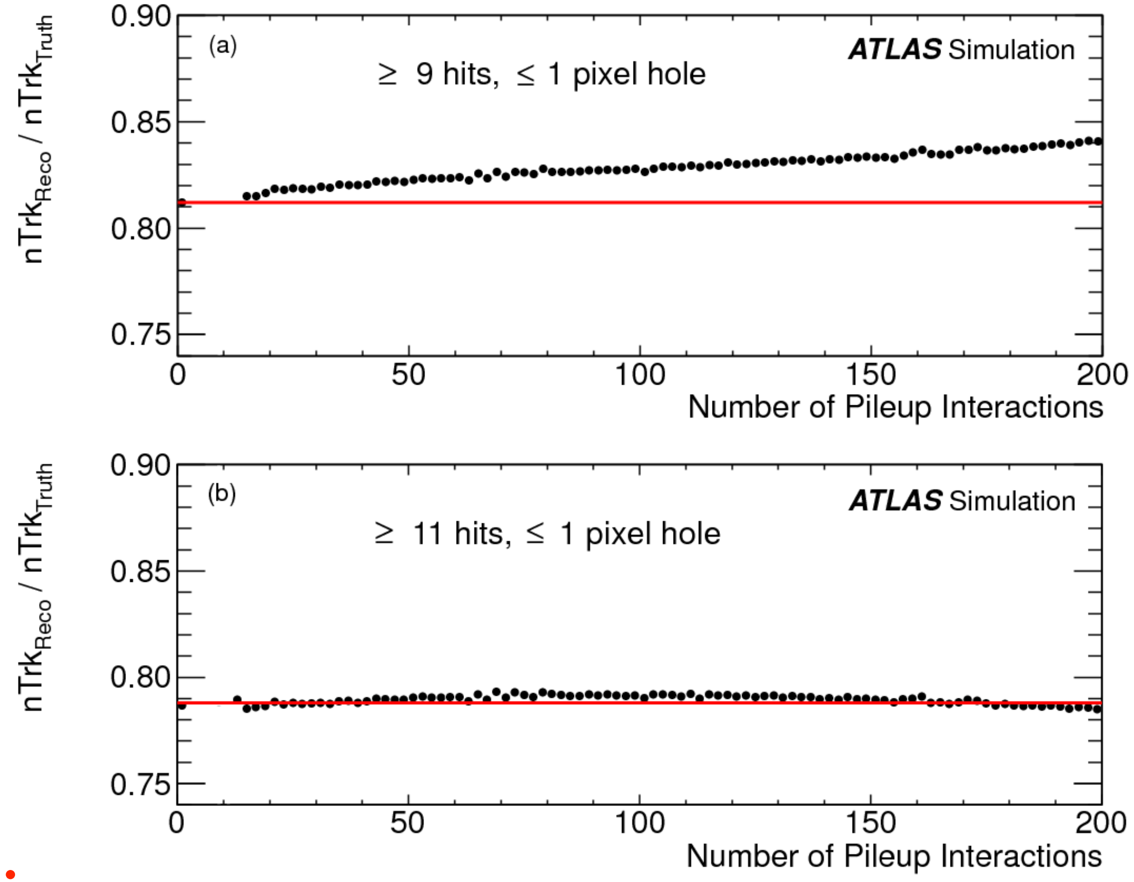
- **Robust** and **efficient tracking** performance is **of paramount importance** to **mitigate** the **pile-up** fluctuations affecting hard scattered jets

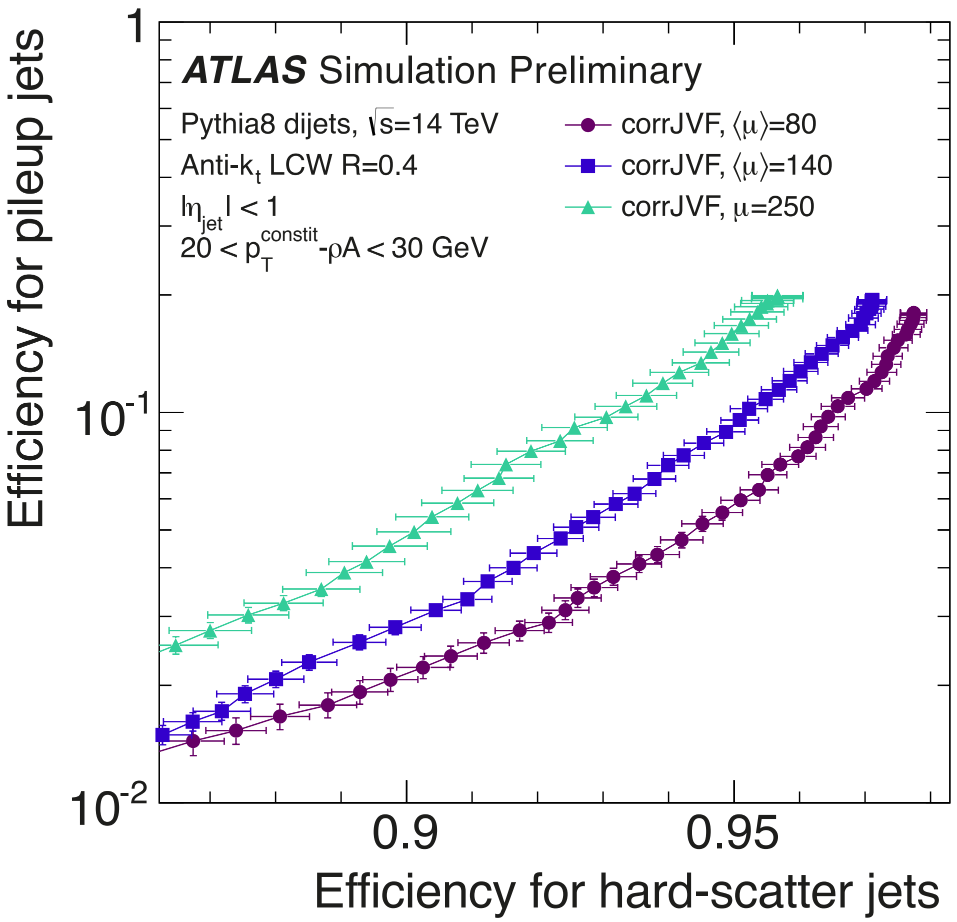
Pile-up at HL-LHC



An event display showing reconstructed tracks and vertices (>100) of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector

- Coping with **140-200** expected **pile-up interactions, a tremendous challenge in HL-LHC**





Solution

- Choose relevant detector capabilities
- Develop sophisticated pile-up mitigation techniques

- Important component of ongoing R&D

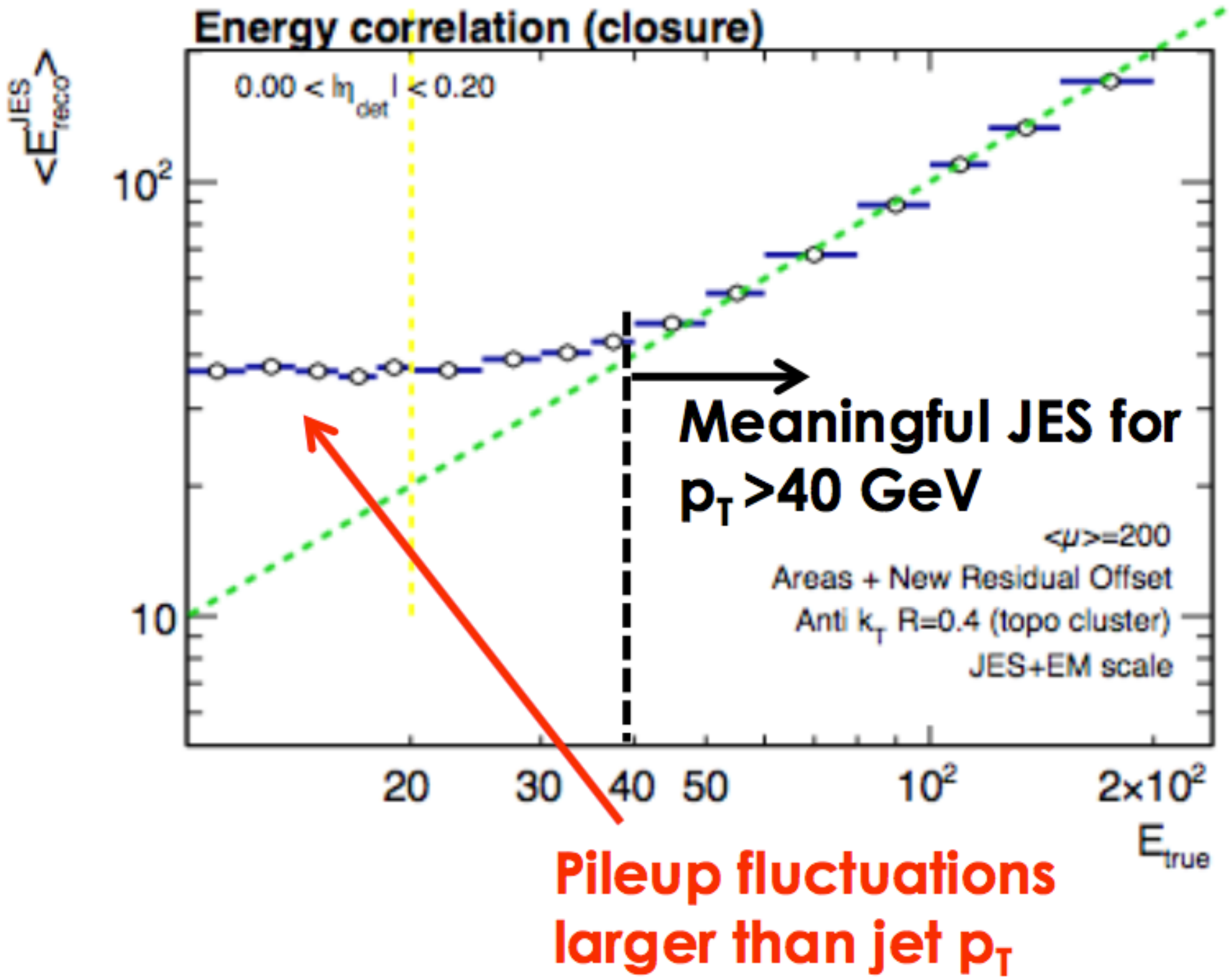
- ITk η coverage will play a crucial role

Jet performance at HL-LHC

- The size of **pile-up fluctuations** become of the **same order** as the hard scatter **jets at low p_T**

- Jet p_T measurement is only meaningful when it is significantly above the pile-up noise
  - ✦ Key for jet calibration at high luminosity: reduce pile-up fluctuations!

- Lower jet p_T thresholds are important for several physics processes, e.g. jet veto in **VBF Higgs processes, single top, t-tbar, etc**



Meaningful JES for p_T>40 GeV

Pileup fluctuations larger than jet p_T