

Physics at the LHC

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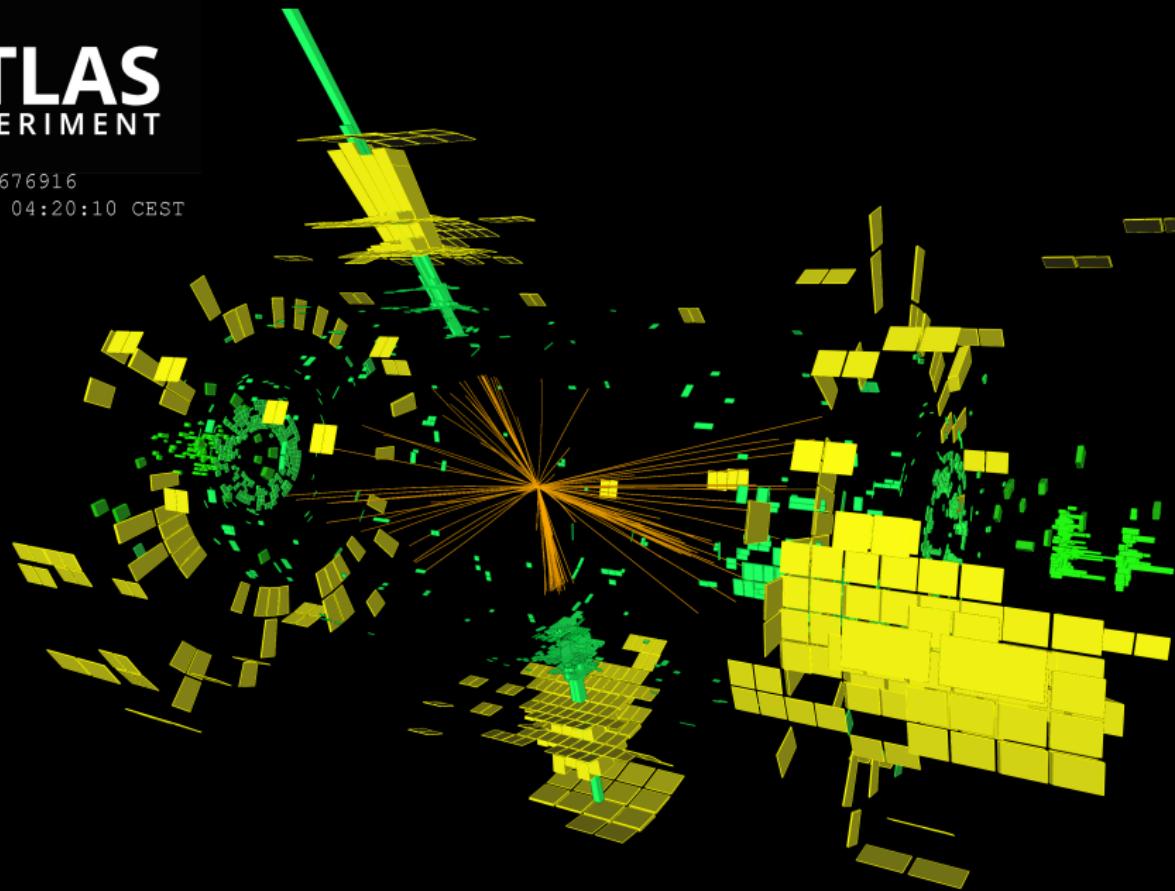
November 27, 2019







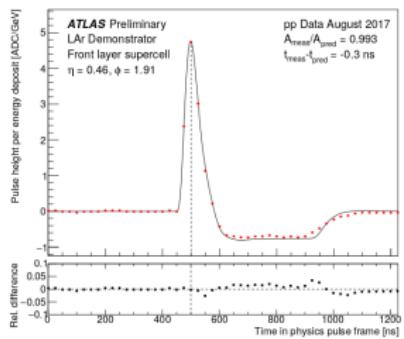
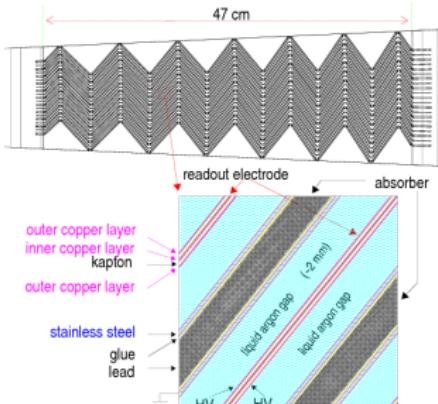
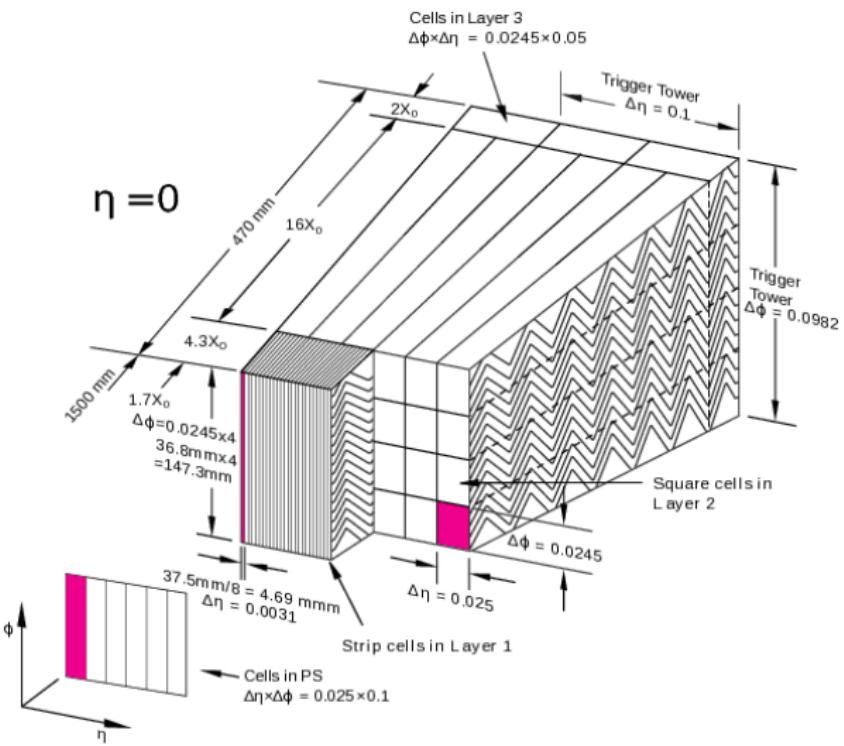
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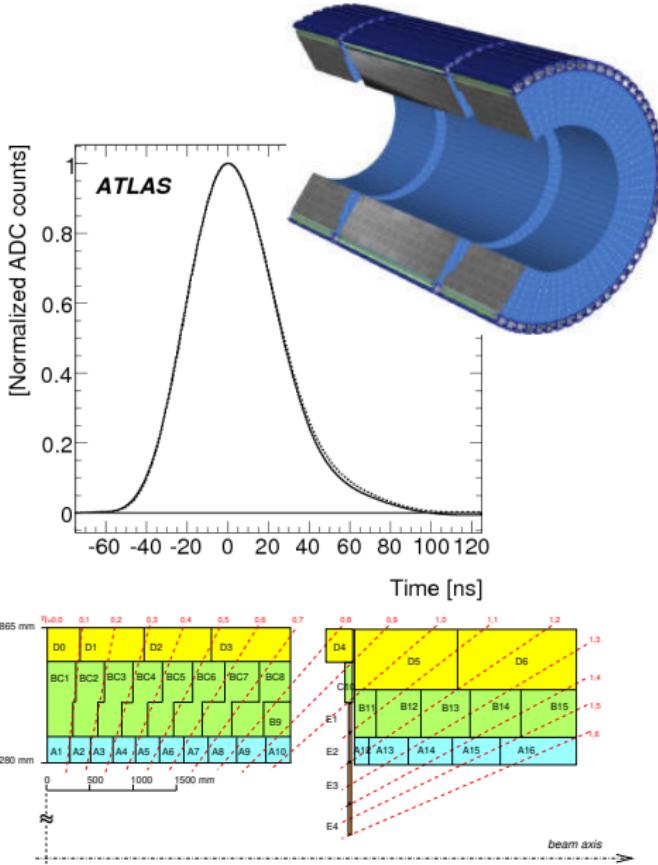
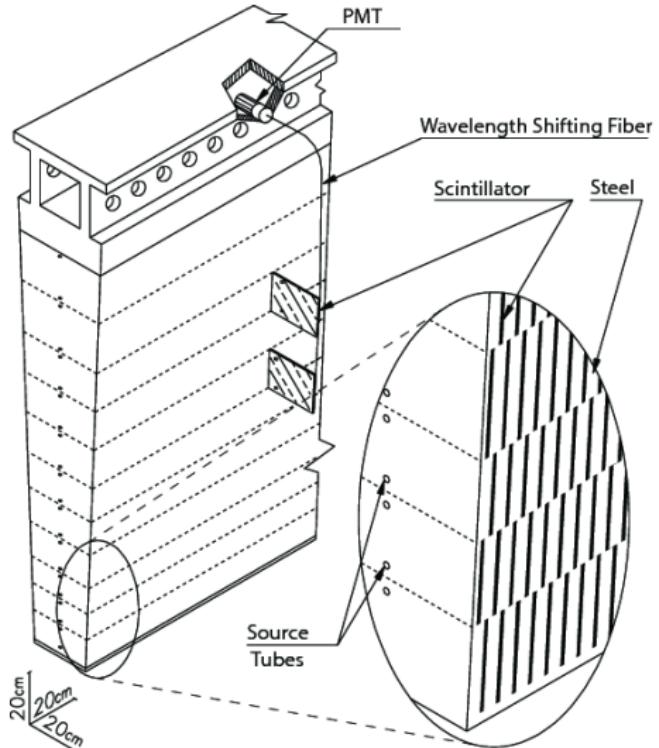
Outlook

- ATLAS detector
 - ▶ Calorimeters : electromagnetic and hadronic
- Jet definition, reconstruction and calibration
 - ▶ jet algorithms, infra-red stability, pileup, topo-clusters, jet energy calibration
- Jet cross-section measurements at 13 TeV
 - ▶ trigger strategy, event selection, detector effects, theory model, quantitative data to theory comparison
- Searches for a low-mass dijet resonance at 13 TeV
 - ▶ trigger strategy, data analysis, fit model, interpretation

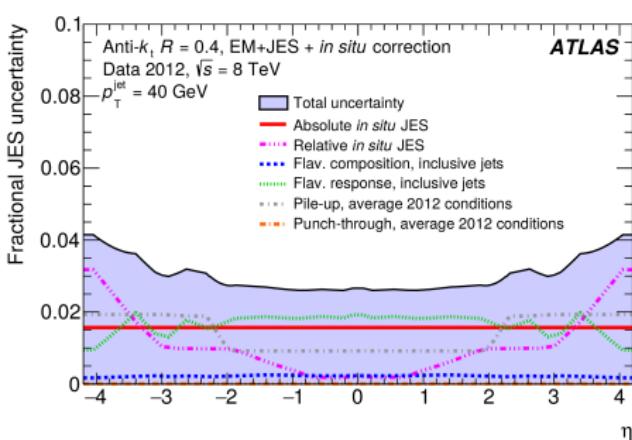
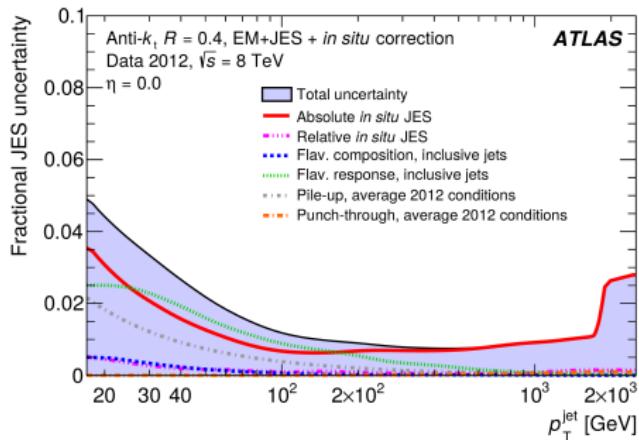
LAr Calorimeter



Tile Calorimeter



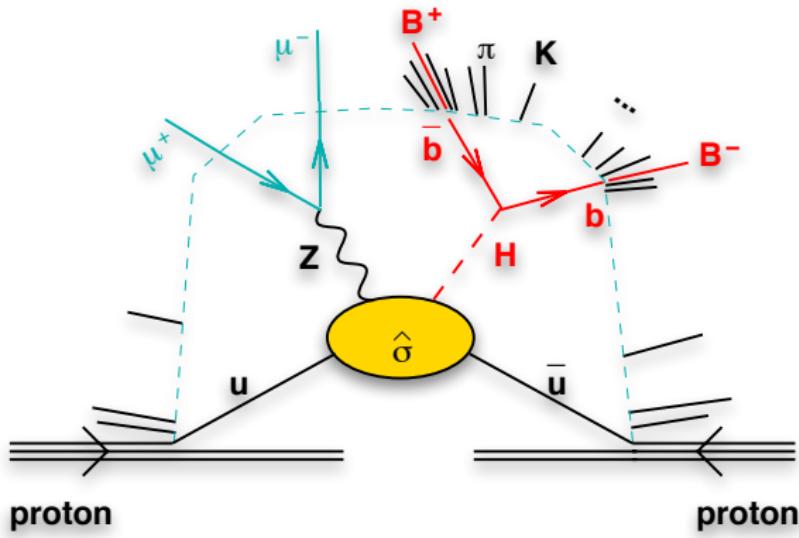
Final JES precision



Final JES precision

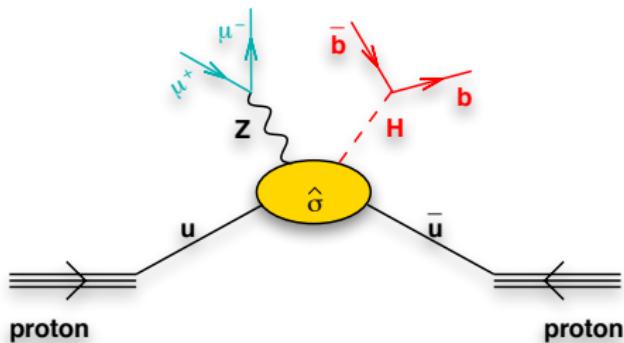
Name	Description	Category
Z+jet		
e E -scale material	Material uncertainty in electron energy scale	det.
e E -scale presampler	Presampler uncertainty in electron energy scale	det.
e E -scale baseline	Baseline uncertainty in electron energy scale	mixed
e E -scale smearing	Uncertainty in electron energy smearing	mixed
μ E -scale baseline	Baseline uncertainty in muon energy scale	det.
μ E -scale smearing ID	Uncertainty in muon ID momentum smearing	det.
μ E -scale smearing MS	Uncertainty in muon MS momentum smearing	det.
MC generator	Difference between MC generators	model
JVF	JVF choice	mixed
$\Delta\phi$	Extrapolation in $\Delta\phi$	model
Out-of-cone	Contribution of particles outside the jet cone	model
Subleading jet veto	Variation in subleading jet veto	model
Statistical components	Statistical uncertainty	stat./meth.
γ +jet		
γ E -scale material	Material uncertainty in photon energy scale	det.
γ E -scale presampler	Presampler uncertainty in photon energy scale	det.
γ E -scale baseline	Baseline uncertainty in photon energy scale	det.
γ E -scale smearing	Uncertainty in photon energy smearing	det.
MC generator	Difference between MC generators	model
$\Delta\phi$	Extrapolation in $\Delta\phi$	model
Out-of-cone	Contribution of particles outside the jet cone	model
Subleading jet veto	Variation in subleading jet veto	model
Photon purity	Purity of sample in γ +jets	det.
Statistical components	Statistical uncertainty	stat./meth.
Multijet balance		
α selection	Angle between leading jet and recoil system	model
β selection	Angle between leading et and closest subleading jet	model
MC generator	Difference between MC generators (fragmentation)	mixed
p_T asymmetry selection	Asymmetry selection between leading and subleading jet	model
Jet p_T threshold	Jet p_T threshold	mixed
Statistical components	Statistical uncertainty	stat./meth.

Proton-proton collisions : final state truth at the particle-level

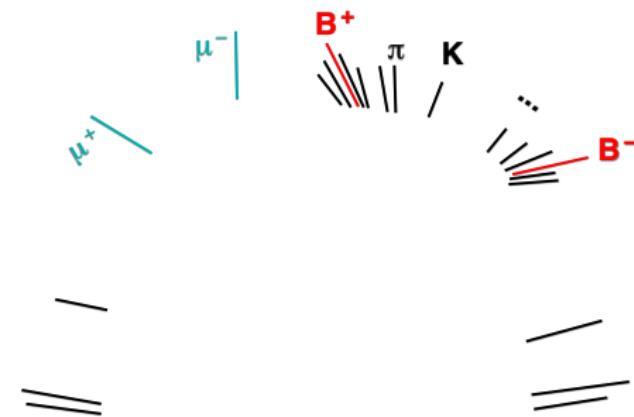
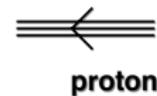


Proton-proton collisions : final state truth at the fixed order

$$\begin{aligned}\sigma(h_1 h_2 \rightarrow ZH + X) = & \sum_{n=0}^{\infty} \alpha_s^n (\mu_R^2) \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \\ & \times \hat{\sigma}_{ij \rightarrow ZH+X}^{(n)}(x_1 x_2 s, \mu_R^2, \mu_F^2) + \mathcal{O}\left(\frac{A^2}{M_W^4}\right),\end{aligned}$$

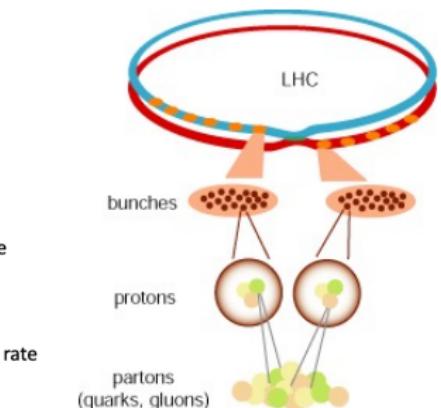
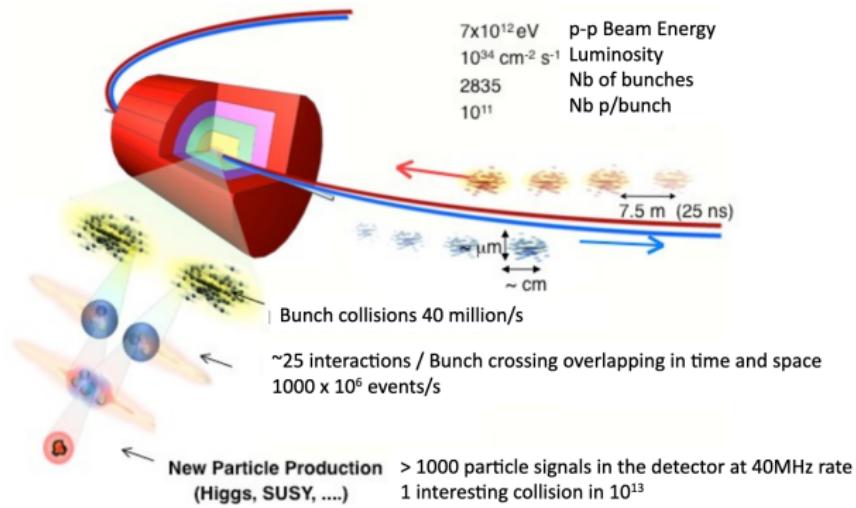


Proton-proton collisions : final state (visible by an ideal detector)

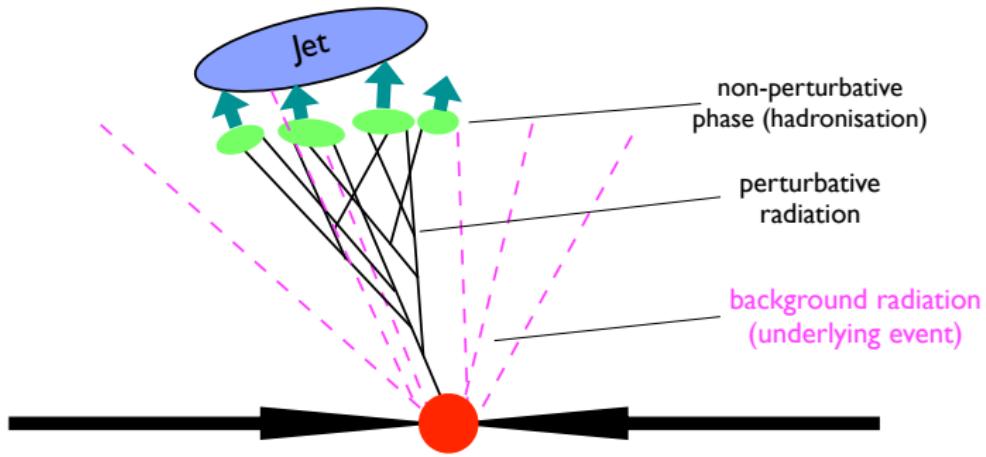


(actual final-state multiplicity \sim several hundred hadrons)

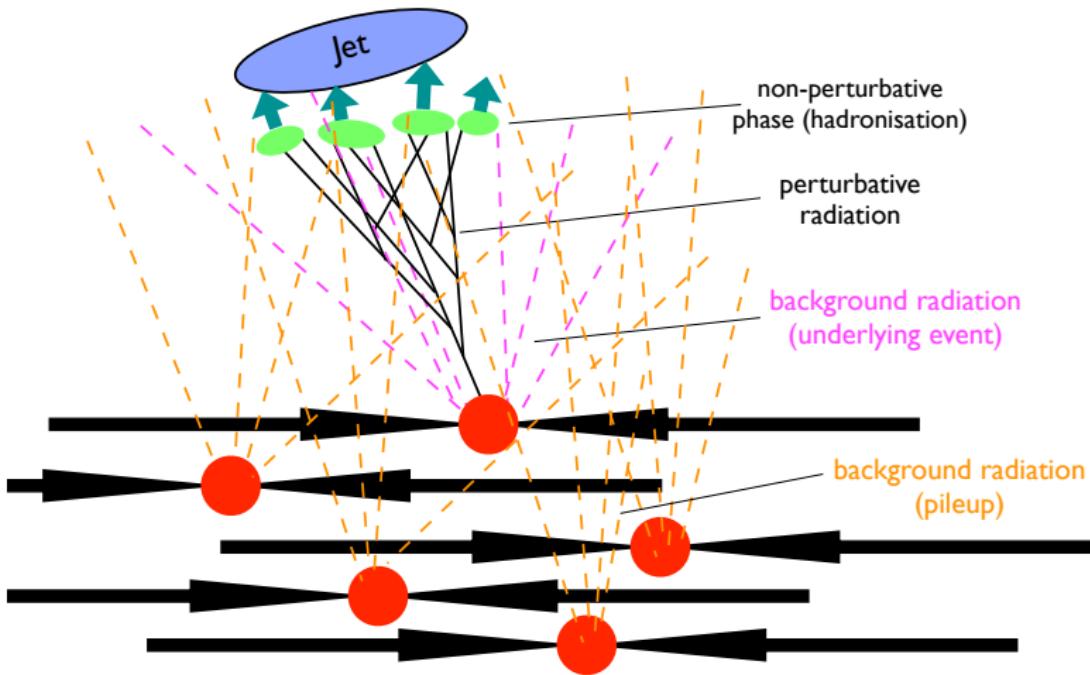
• LHC •



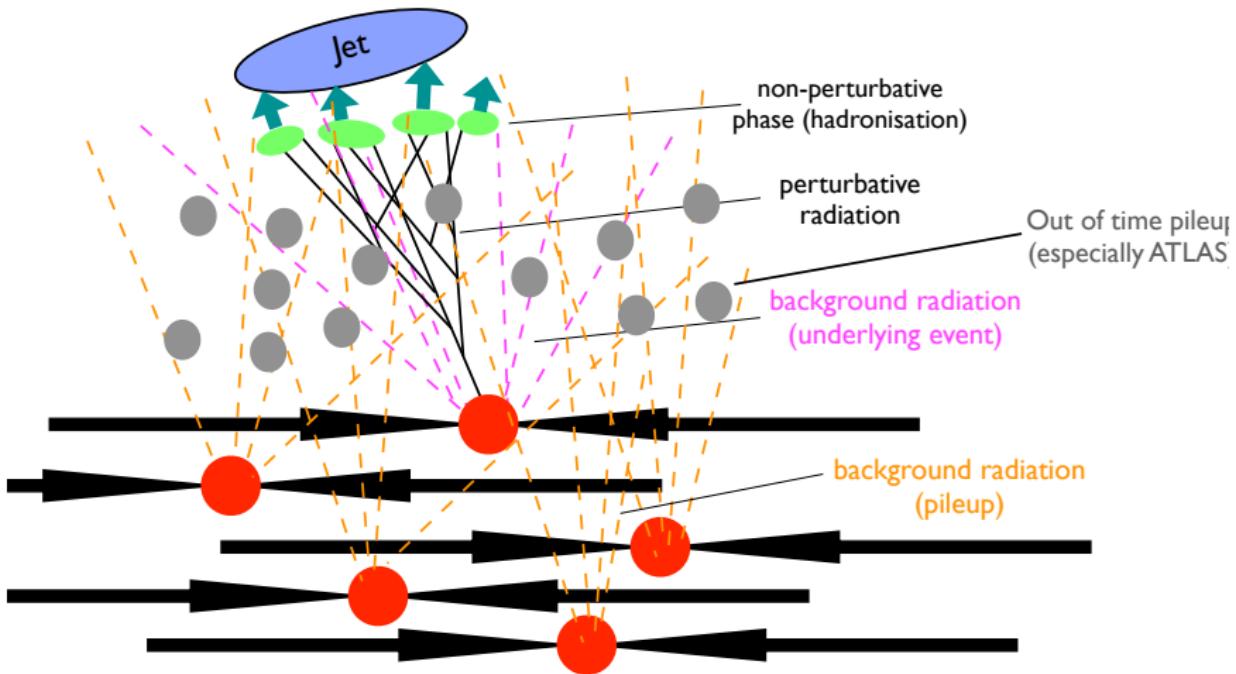
More realistic picture of proton-proton collisions



Even more realistic picture of proton-proton collisions

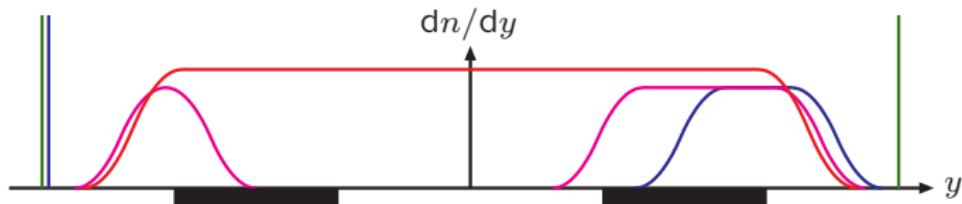


Very realistic picture of proton-proton collisions



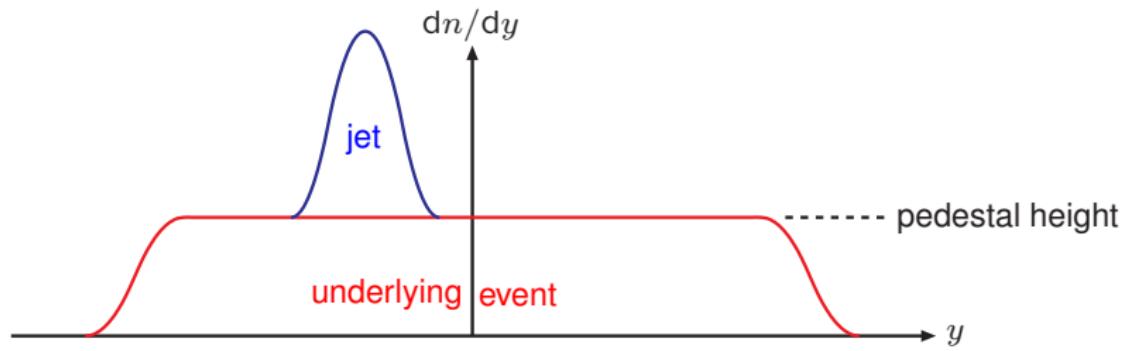
Total cross section

$$\sigma_{\text{total}} = \sigma_{\text{elastic}} + \sigma_{\text{single-diffractive}} + \sigma_{\text{double-diffractive}} + \dots + \sigma_{\text{non-diffractive}}$$



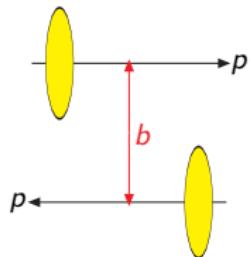
- Experimentally **minimum bias** \approx all events with no bias from trigger conditions
- Theoretically $\sigma_{\text{min-bias}} \approx \sigma_{\text{double-diffractive}} + \sigma_{\text{non-diffractive}}$

Hard scattering + Underlying event



- The underlying is the additional activity from soft interactions in addition to the primary hard partonic process.

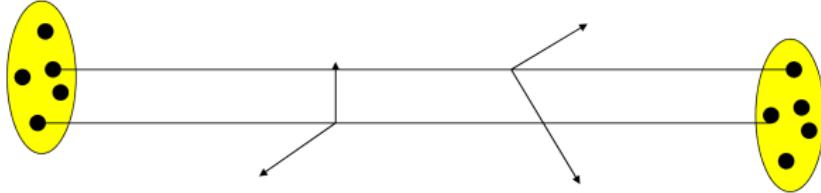
Underlying event



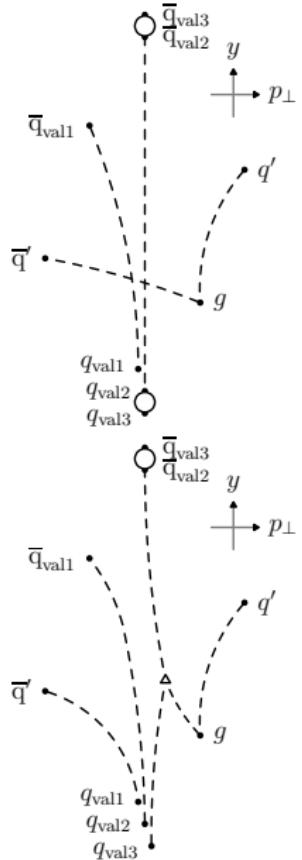
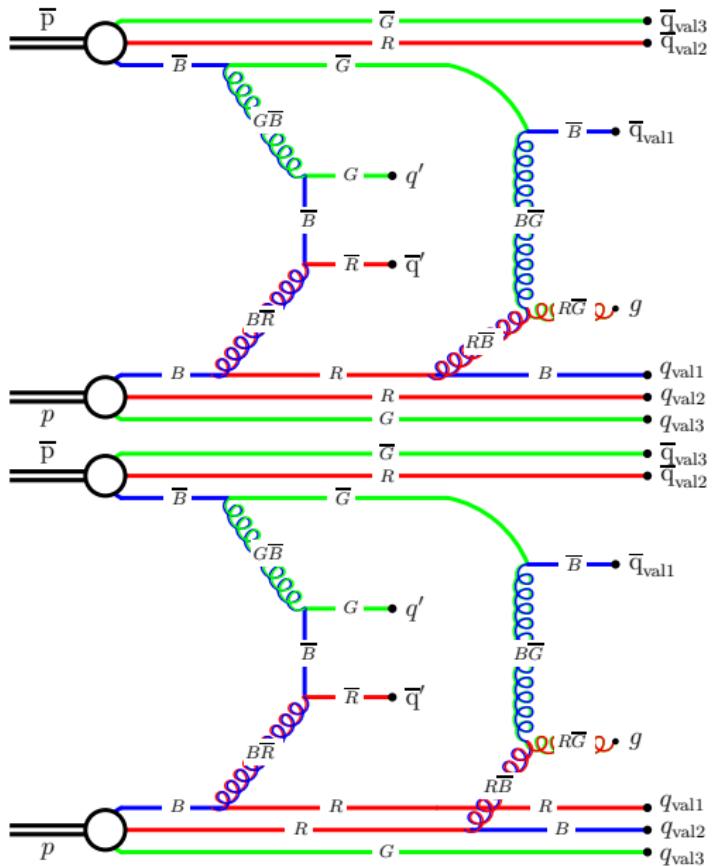
- If the interactions occur independently obeys Poissonian statistics

$$P_n = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle}$$

- However energy-momentum conservation tends to suppress large numbers of parton scatterings.

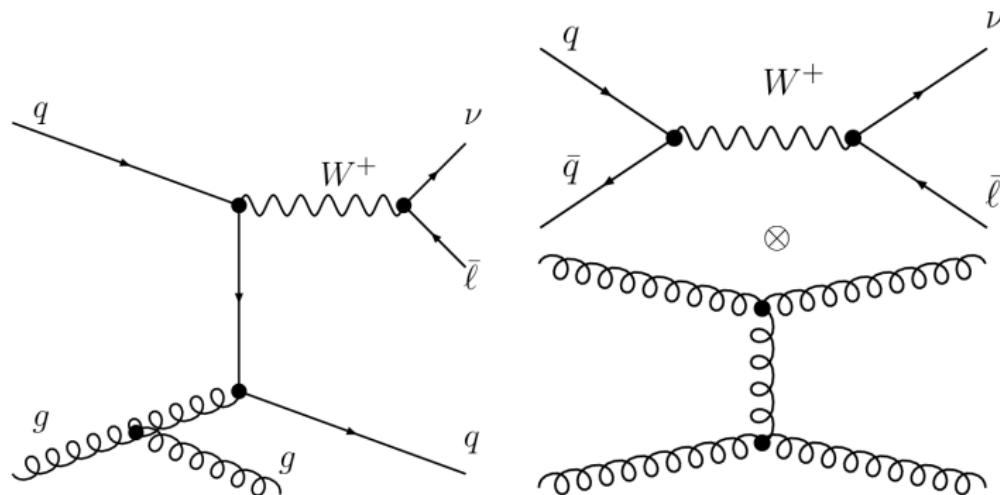


Underlying event (color correlation)



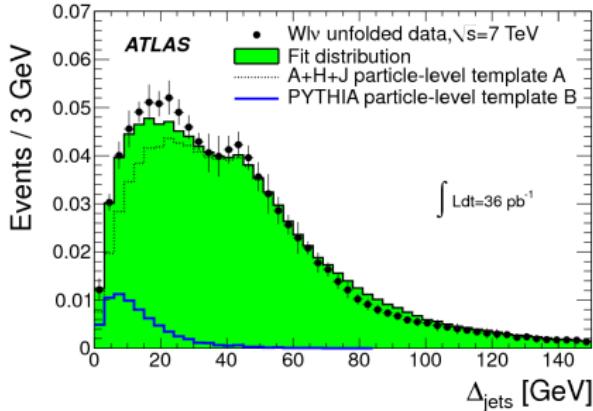
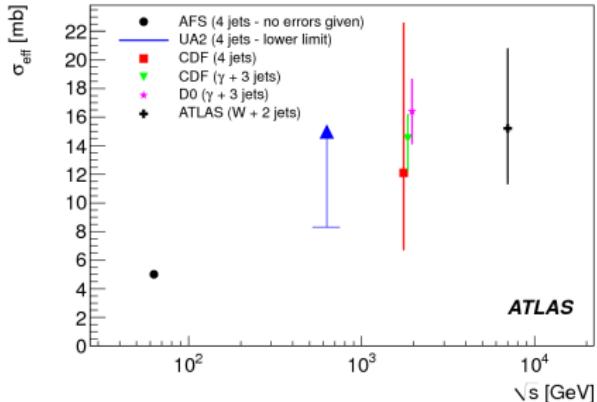
Multiple interactions : measurement

$$d\hat{\sigma}_{Y+Z}^{(\text{DPI})}(s) = \frac{m}{2\sigma_{\text{eff}}(s)} \int dx_{i_1} dx_{j_1} dx_{i_2} dx_{j_2} [f_{i_1 j_1}(x_{i1}, x_{j1}, \mu_F) f_{i_2 j_2}(x_{i2}, x_{j2}, \mu_F) d\hat{\sigma}_{i_1 i_2 \rightarrow Y}(x_{i1}, x_{i2}, s) d\hat{\sigma}_{j_1 j_2 \rightarrow Z}(x_{j1}, x_{j2}, s)],$$



$$d\hat{\sigma}_{Y+Z}^{(\text{tot})}(s) = d\hat{\sigma}_{Y+Z}^{(\text{SPI})}(s) + d\hat{\sigma}_{Y+Z}^{(\text{DPI})}(s) = d\hat{\sigma}_{Y+Z}^{(\text{SPI})}(s) + \frac{d\hat{\sigma}_Y(s) \cdot d\hat{\sigma}_Z(s)}{\sigma_{\text{eff}}(s)},$$

Multiple interactions : measurement



$$f_{\text{DP}}^{(\text{P})} = \frac{N^{\text{P}}(W_{0j} + 2j_{\text{DPI}})}{N^{\text{P}}(W_{0j} + 2j_{\text{DPI}}) + N^{\text{P}}(W_{2j})},$$

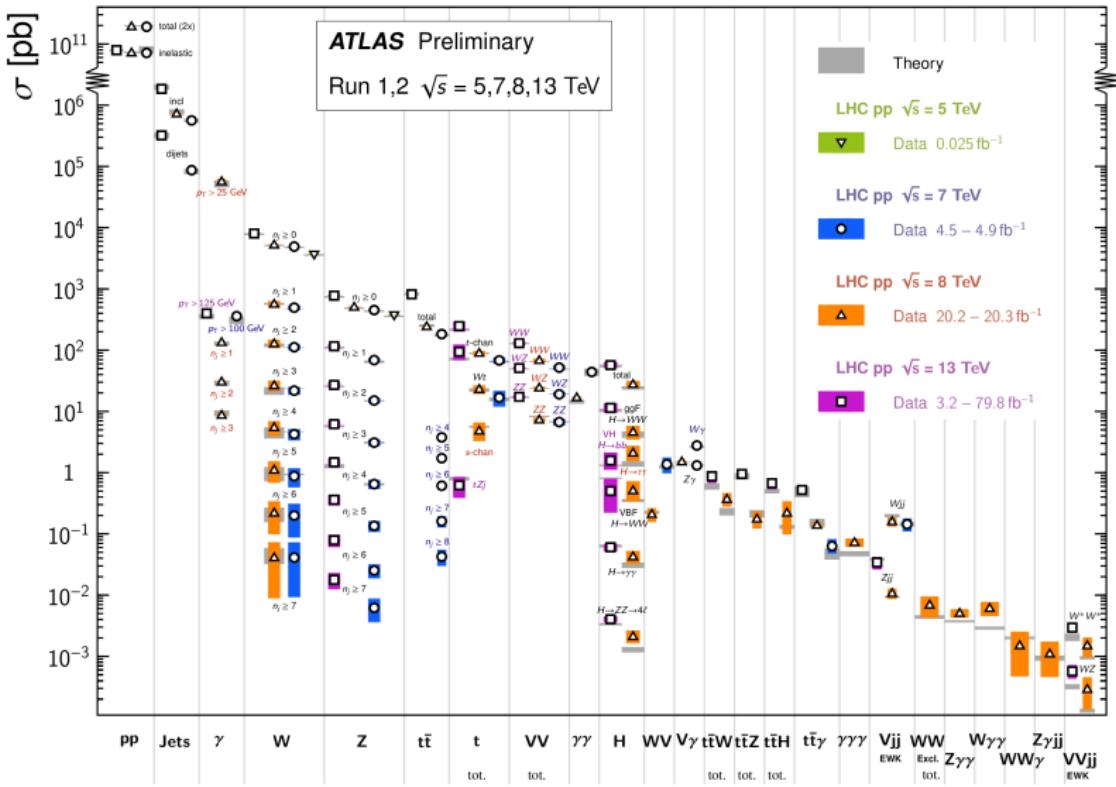
$$f_{\text{DP}}^{(\text{D})} = 0.08 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (sys.)}$$

$$\sigma_{\text{eff}}(7 \text{ TeV}) = 15 \pm 3 \text{ (stat.)} {}^{+5}_{-3} \text{ (sys.) mb.}$$

Standard Model total cross sections

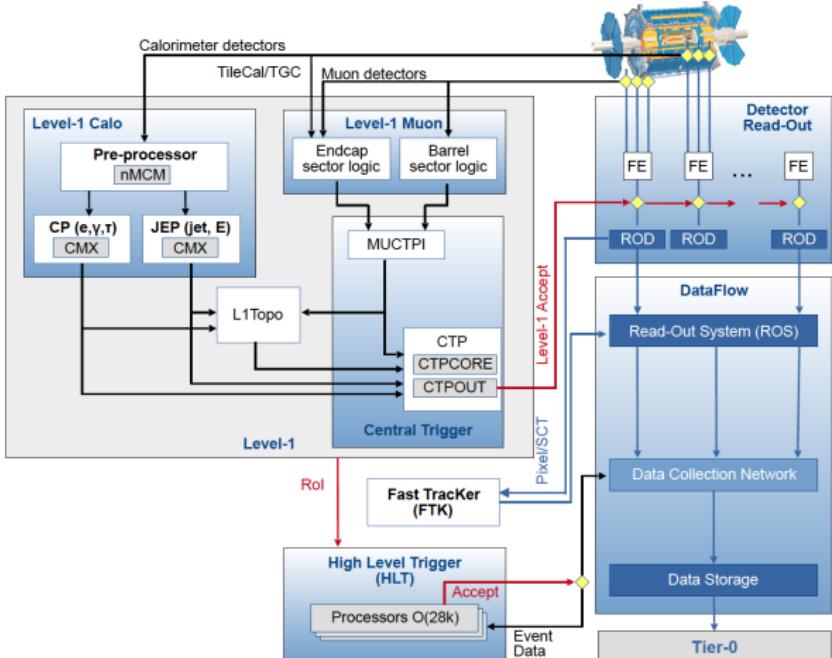
Standard Model Production Cross Section Measurements

Status: July 2019

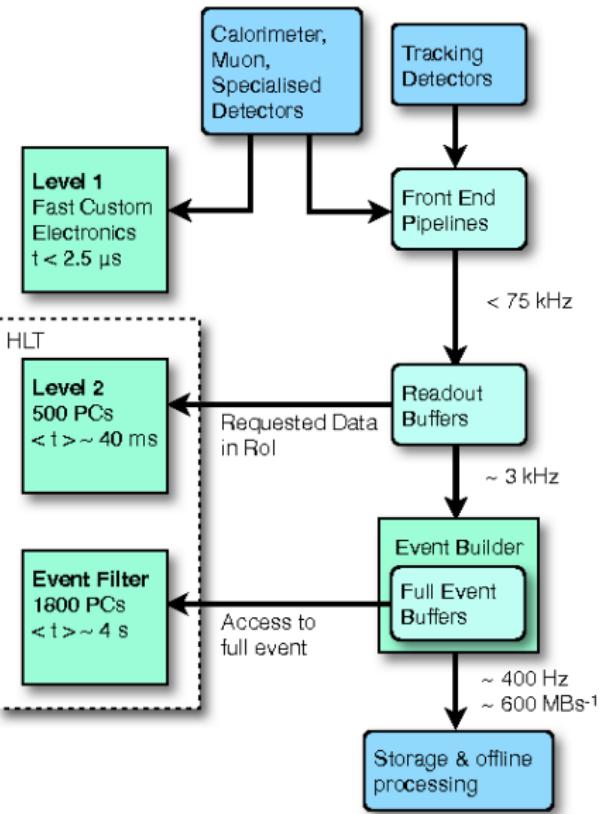
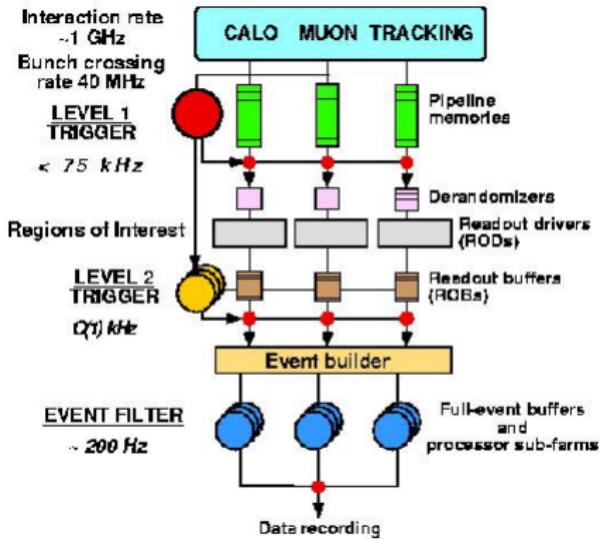


Data acquisition system

- L1Calo : any EM/HAD objects
- L1Muon : thresholds and multiplicities
- L1Topo : Combines information from L1Calo/L1Muon
- CTP : final decision

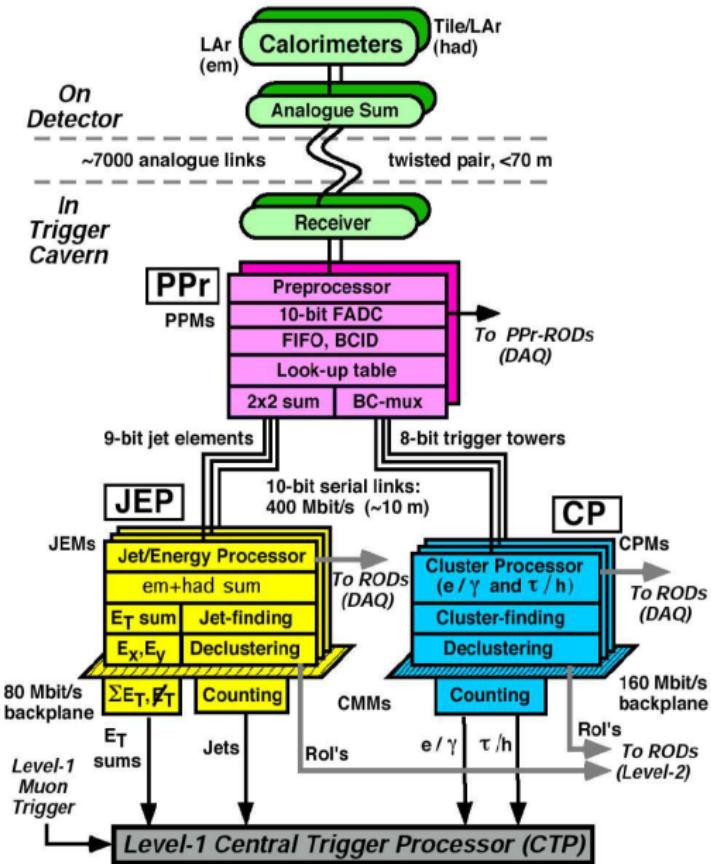


Trigger system



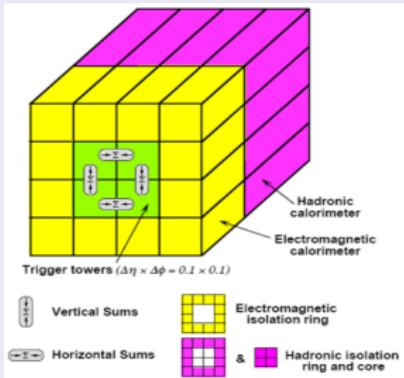
L1Calo trigger system

- L1Calo : Fixed latency $2\mu\text{s}$, HW based on custom electronics
- ~ 300 VME modules of 10 different types housed in 17 crates
- Off detector
 - ▶ PPr : digitisation and BCID
 - ▶ CP : electrons/photons/single hadrons
 - ▶ JEP: Jet findings and energy sums



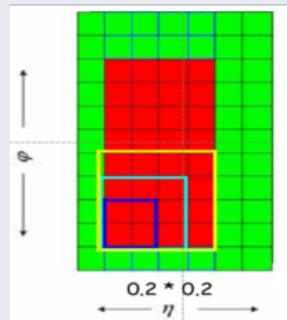
CP vs JEP

Cluster Processor



- e/γ or τ /single hadron
- Granularity 0.1×0.1

Jet/Energy-sum Processor



- Jets, Missing & total E_T
- Granularity 0.2×0.2
- Summation of EM + Had

L1Calo



Receivers& PPr



Processors



Readout drives

Preprocessor

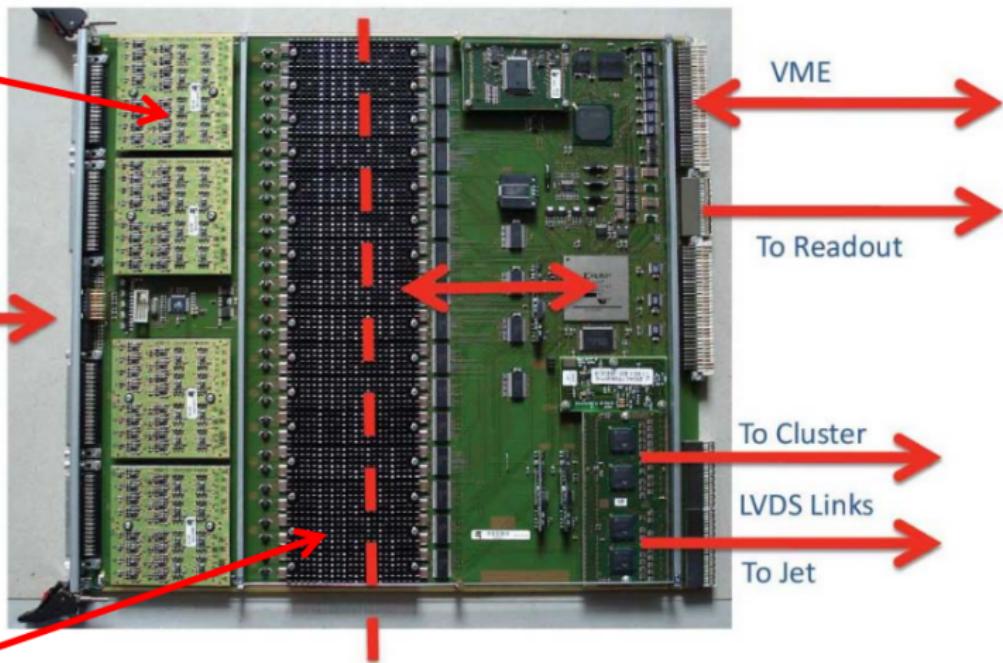
4 AnIn boards
16 signals each
Analogue signal
Conditioning

64 analogue
Inputs

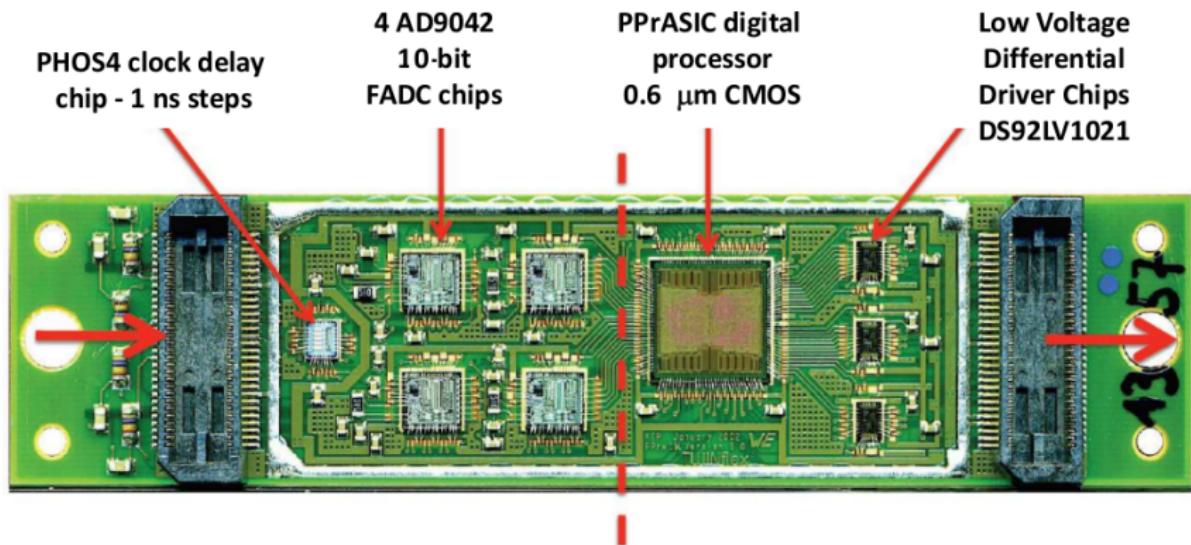
16 MCMs
Digitisation
& Digital
processing

Analogue

Digital



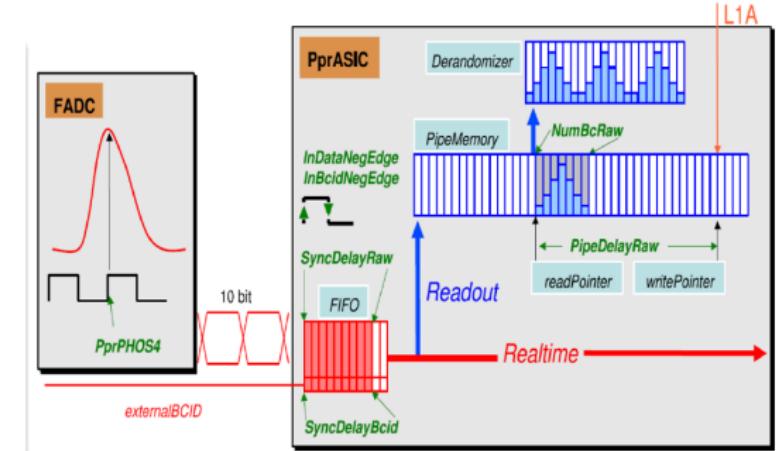
MCM



- Each FADC chip represents a L1Calo trigger tower

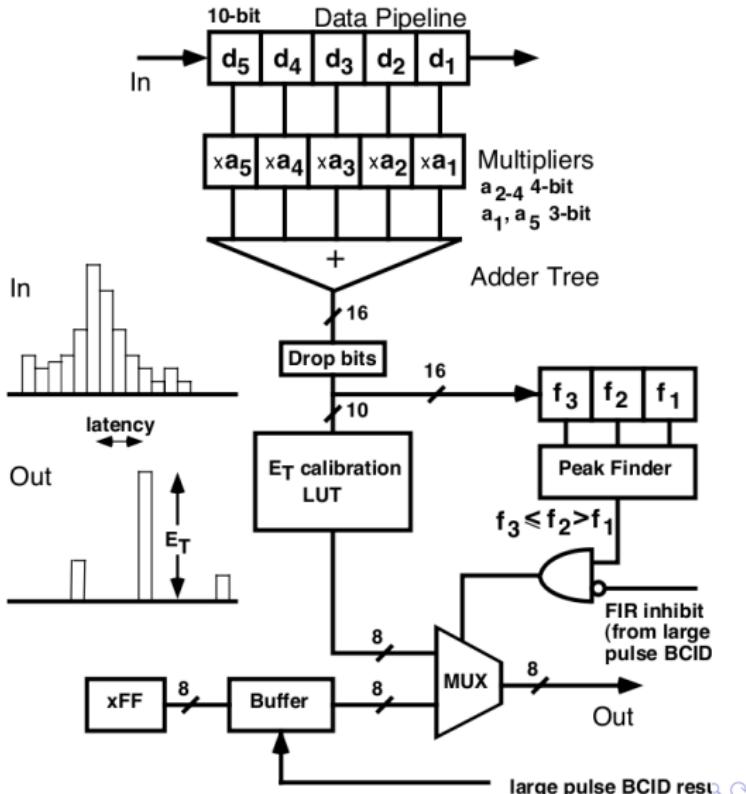
Timing calibration

- The pp collisions take place at the interaction point
- Time of flight to calorimeters is η -dependent
- Large variation in cable lengths from calorimeters to L1Calo
- Need to buffer early signals and process everything in time
- If we get the timing wrong we record the wrong event
- Timing calibration
 - For high physics acceptance everything must be in time
 - Coarse timing set in FIFO : Steps of 25 ns
 - Fine timing set by Phos4 : Steps of 1 ns

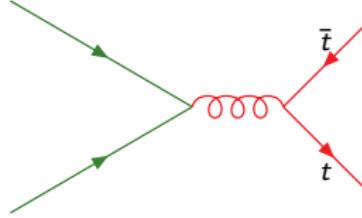


Finite Impulse response (FIR) filters

- Calorimeter signal pulses span many bunch-crossings
- The FIR filter coefficients improve:
 - BCID
 - Noise rejection
 - Energy measurement

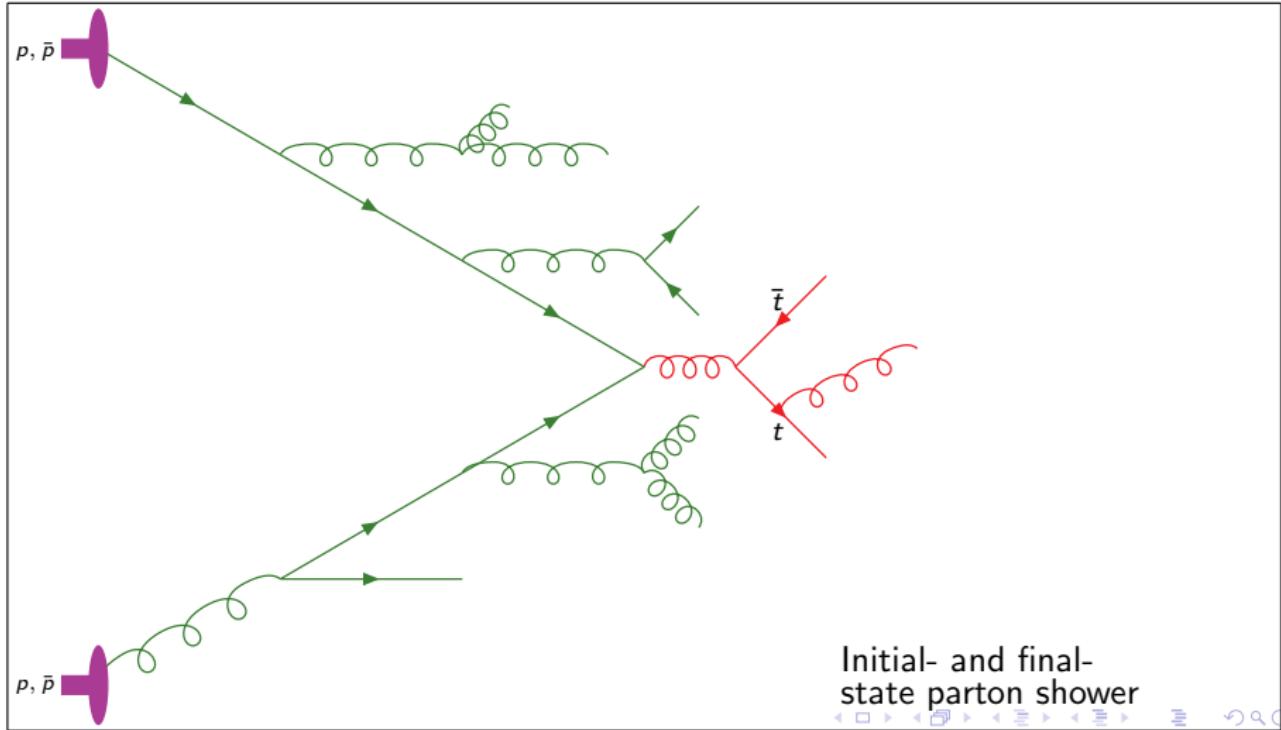


Proton-proton collision : Monte Carlo event

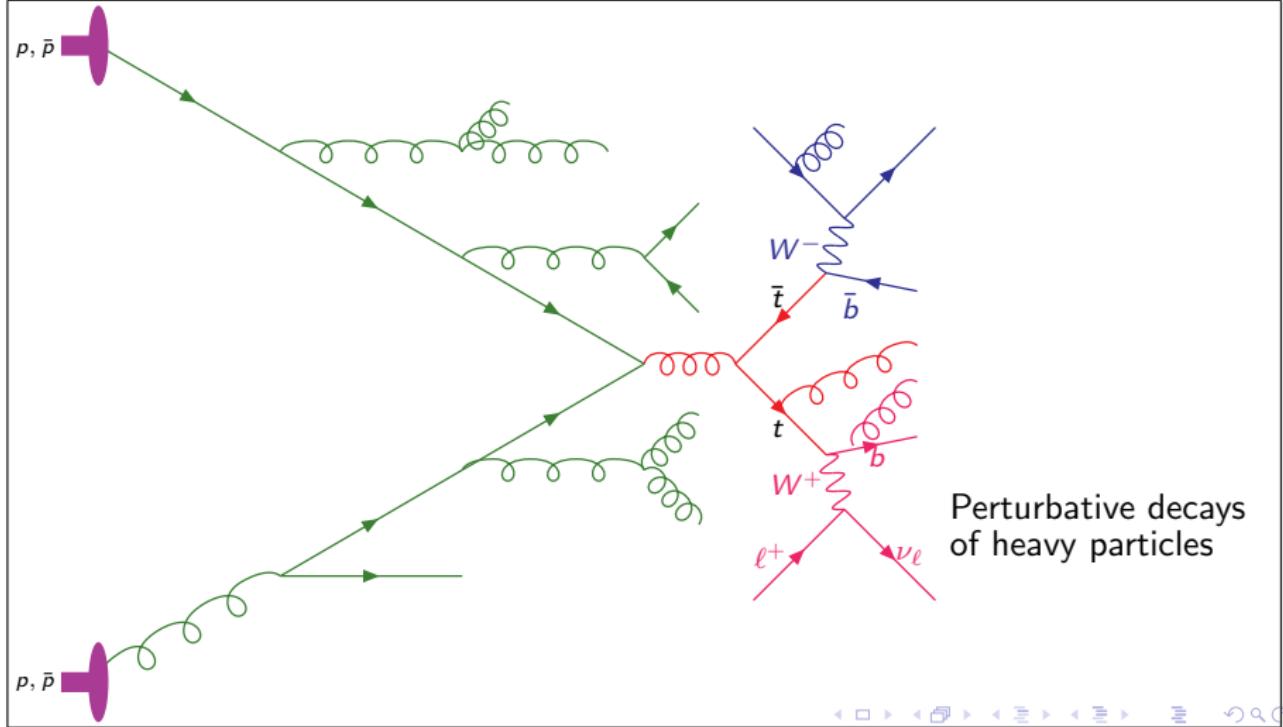


Hard Process, usually calculated at leading order

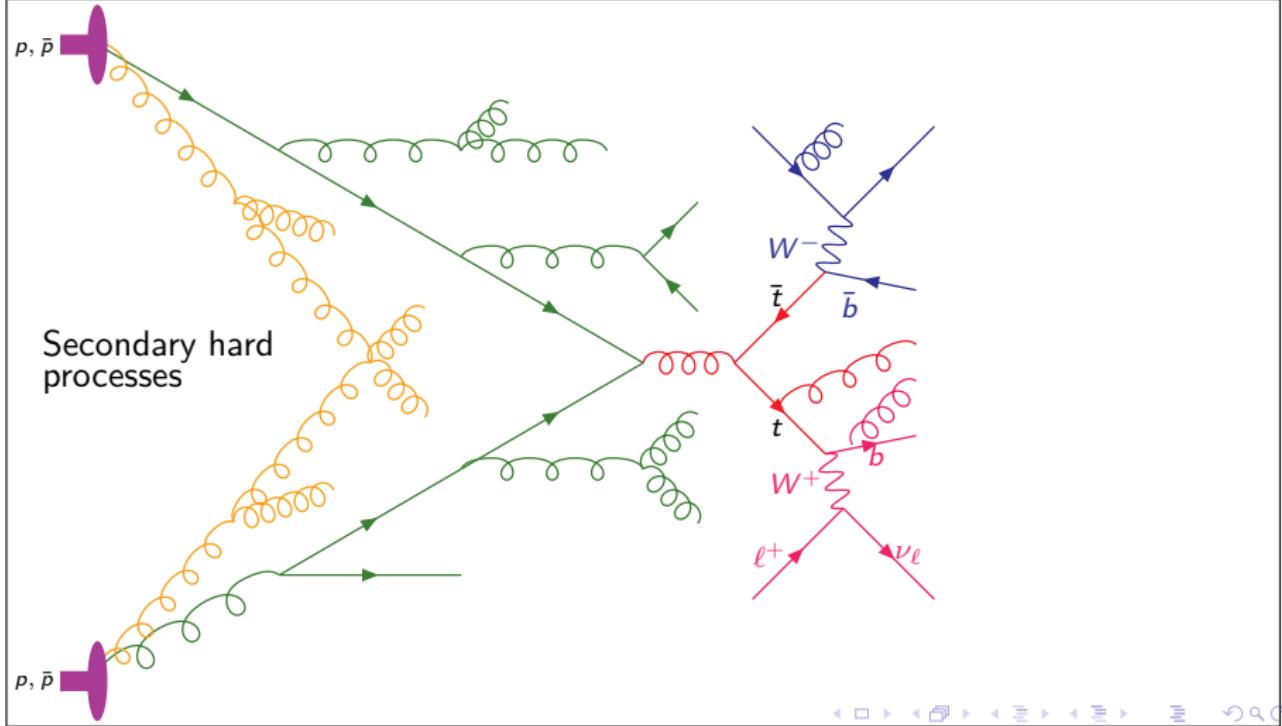
Proton-proton collision : Monte Carlo event



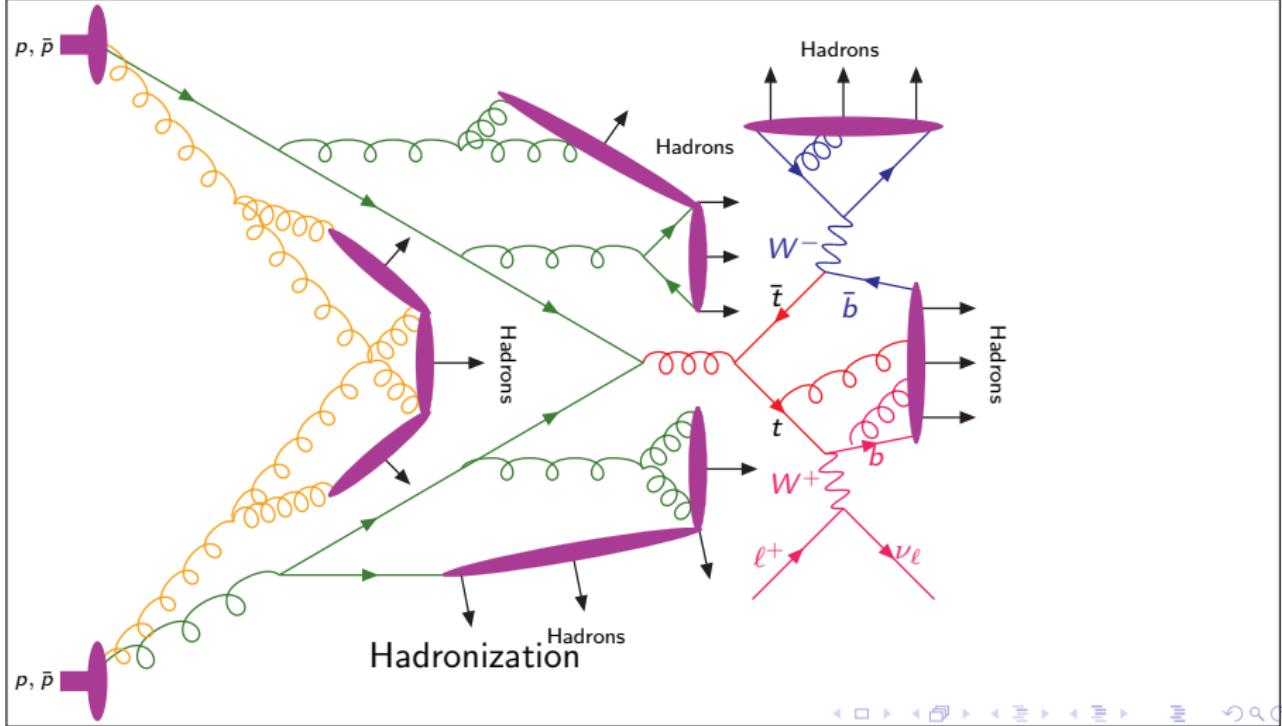
Proton-proton collision : Monte Carlo event



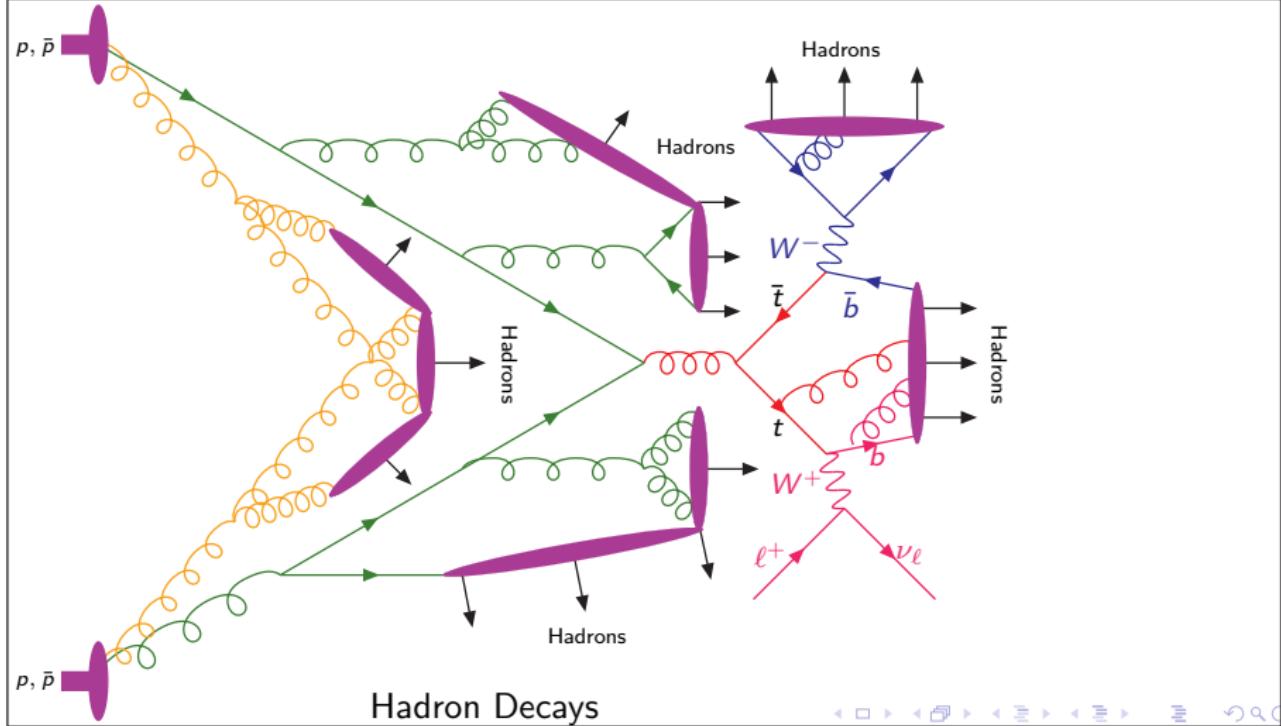
Proton-proton collision : Monte Carlo event



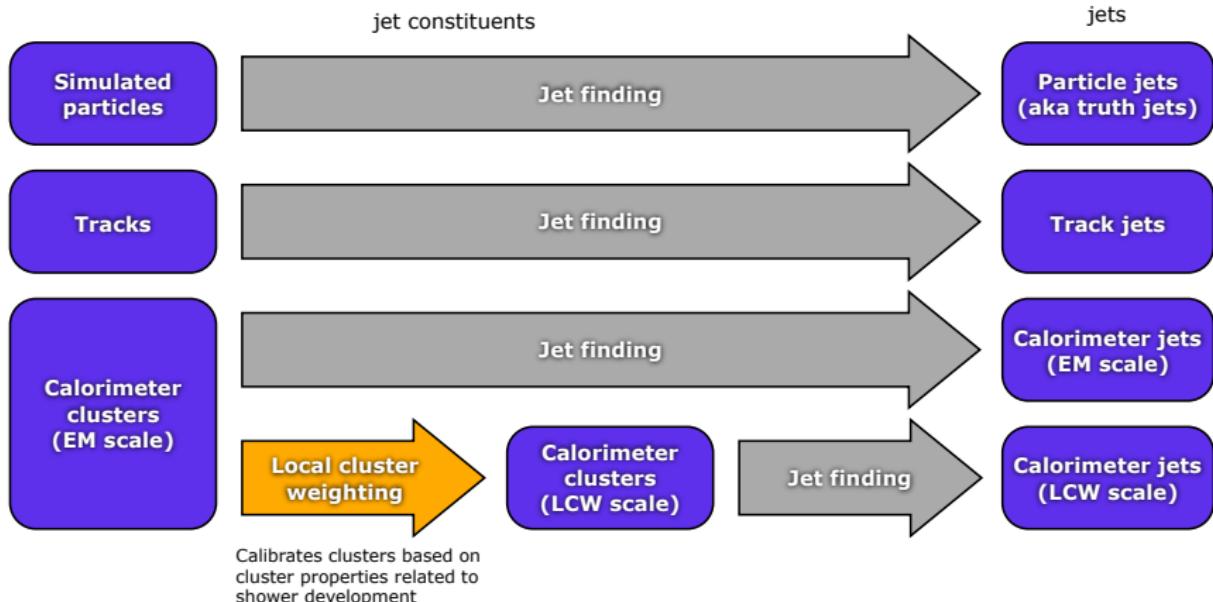
Proton-proton collision : Monte Carlo event



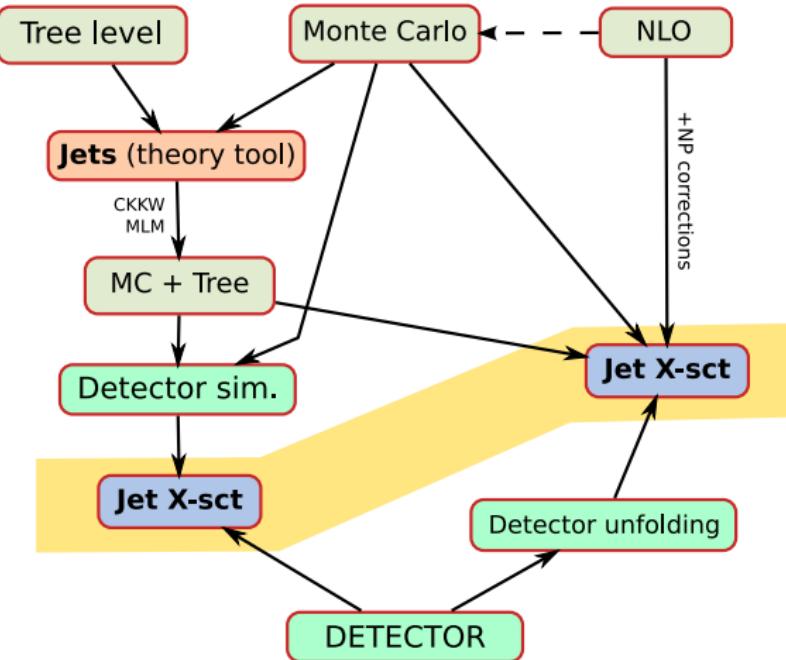
Proton-proton collision : Monte Carlo event



Levels of jet definition

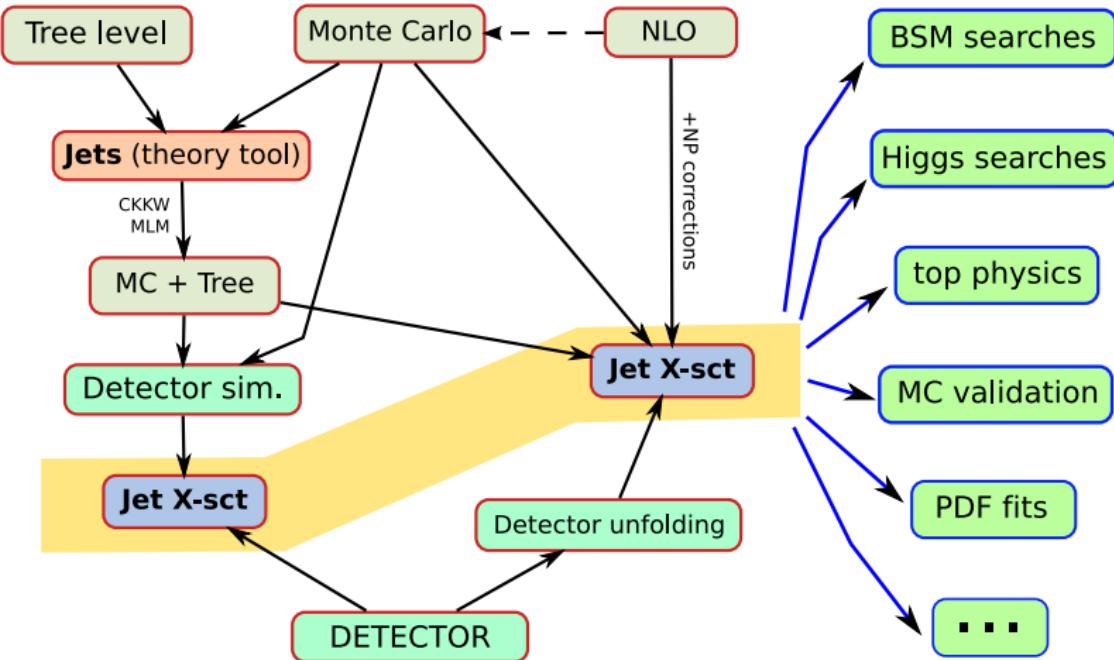


Unfolding



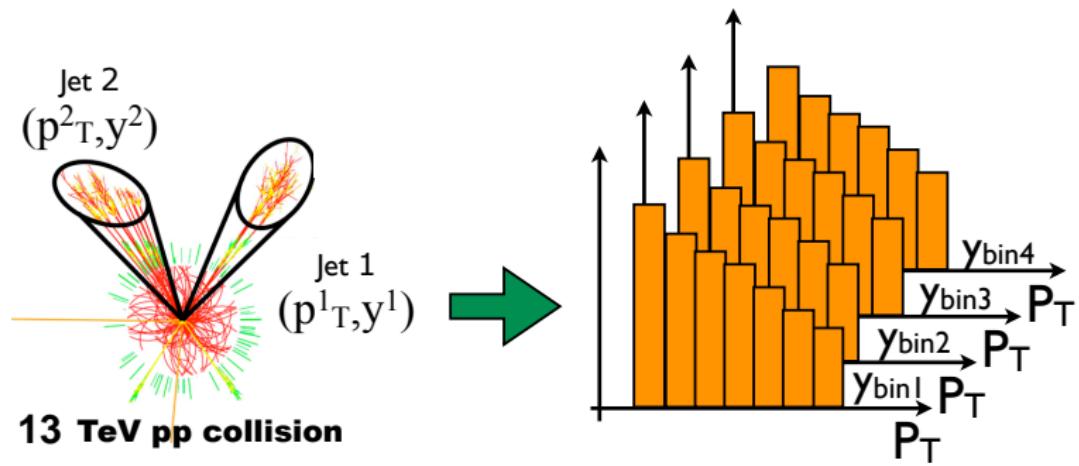
Jet (definitions) provide central link between expt., “theory” and theory
And jets are an input to almost all analyses

Unfolding

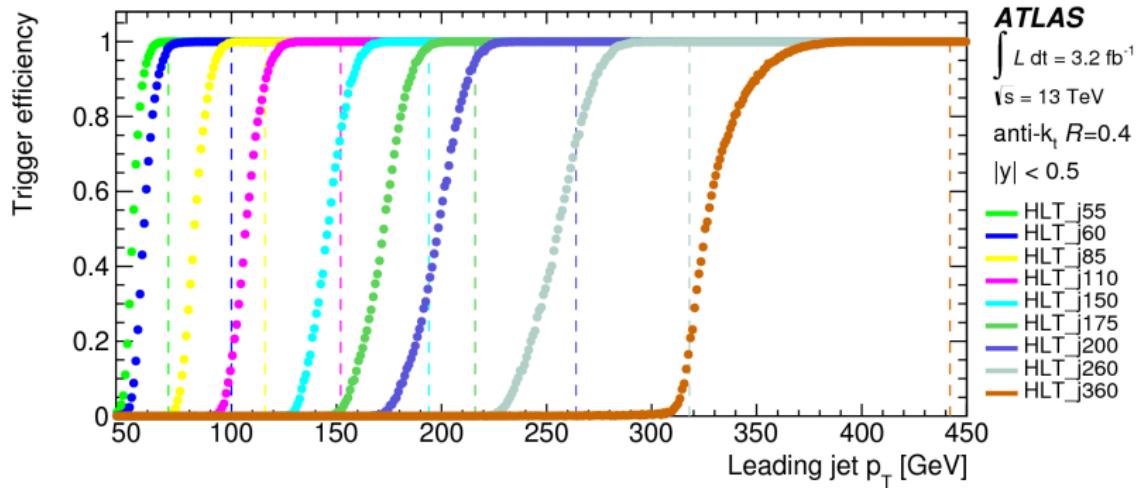


Jet (definitions) provide central link between expt., “theory” and theory
And jets are an input to almost all analyses

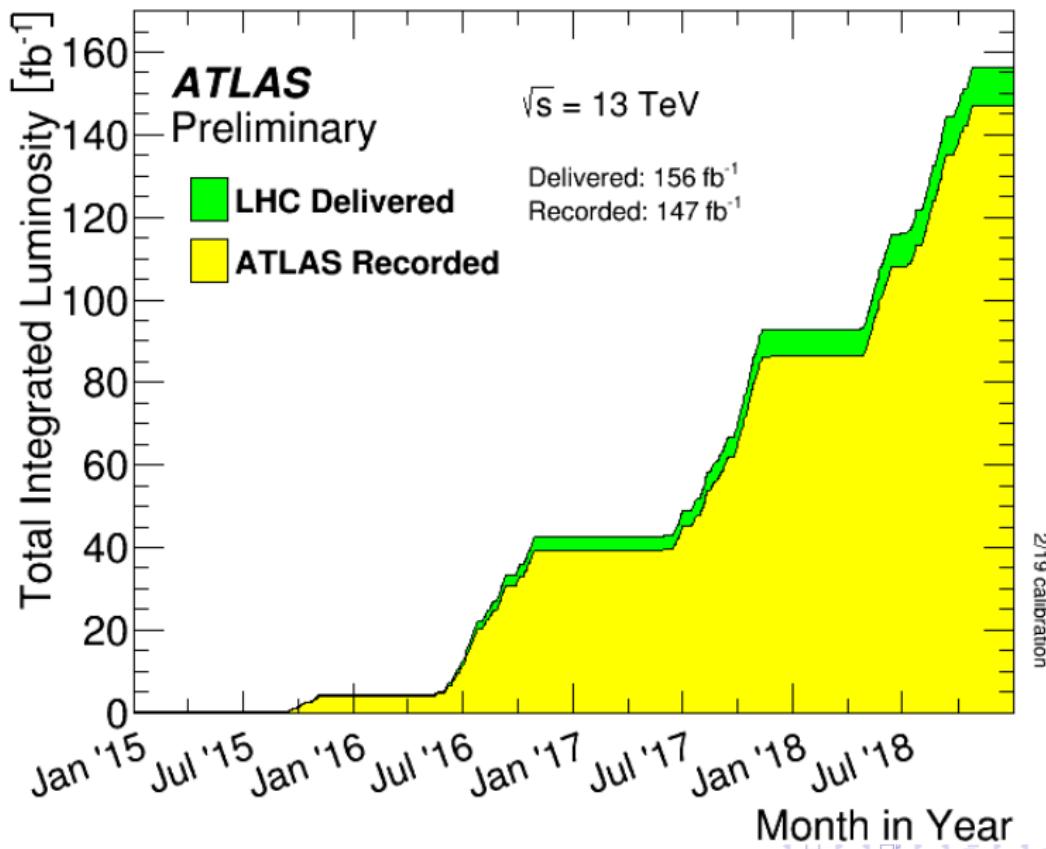
Jet cross section measurement



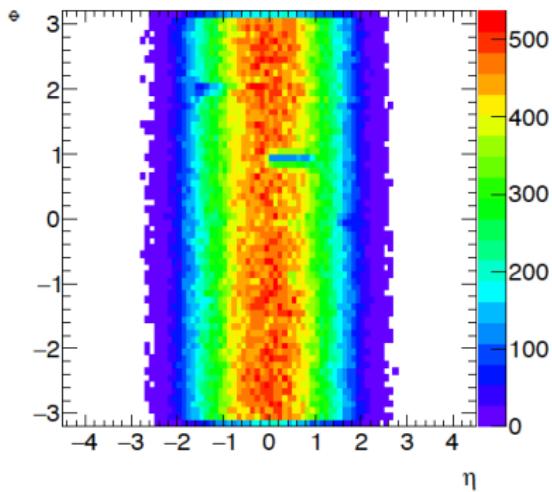
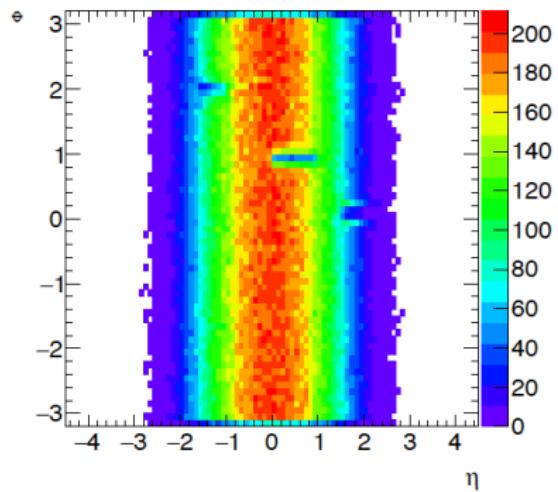
Triggering Inclusive jets



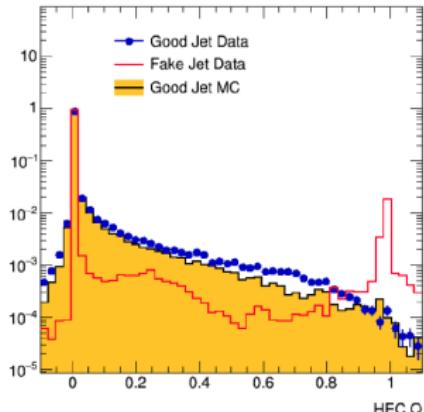
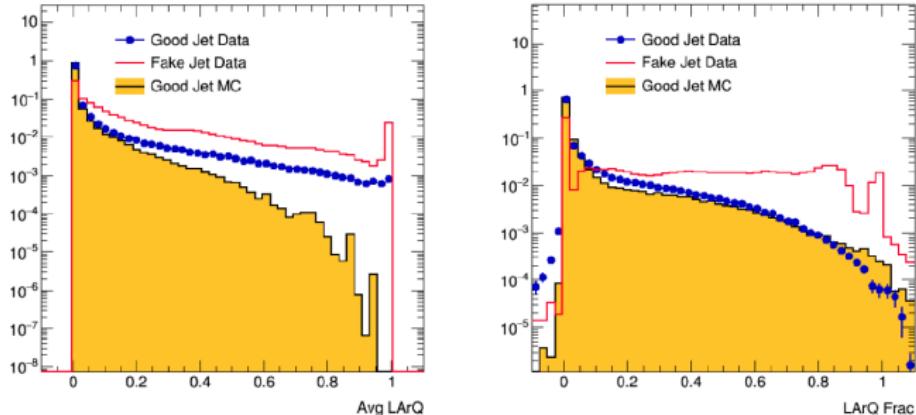
Event selection



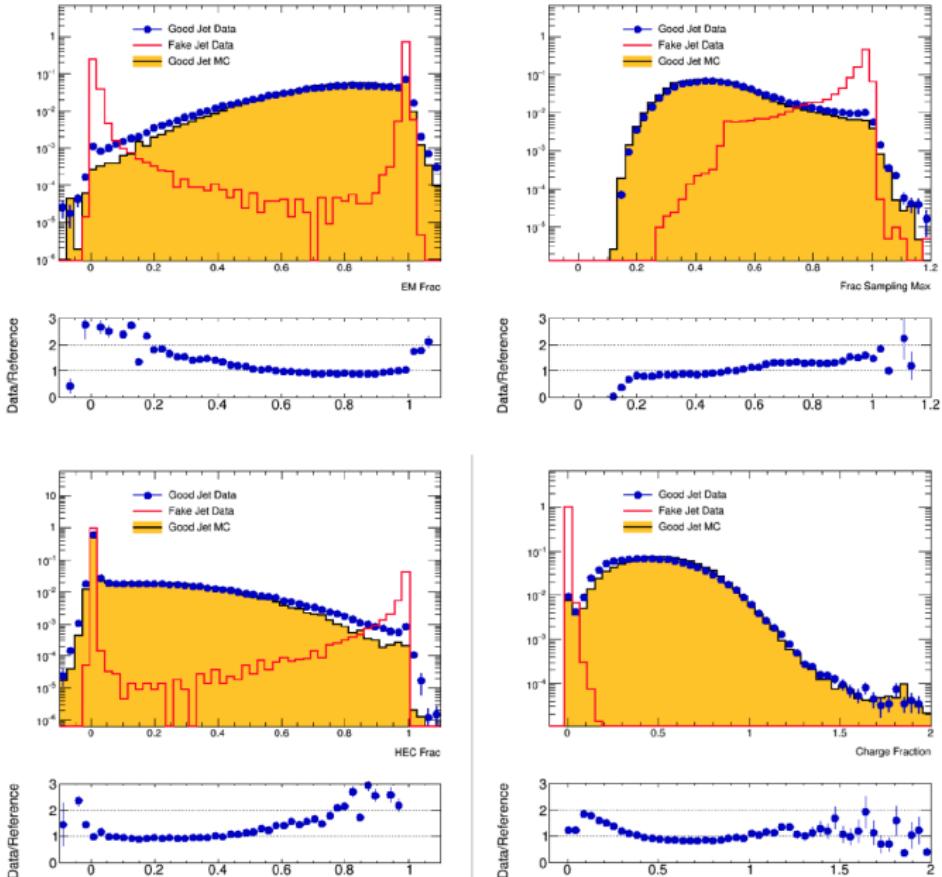
Instrumental effects : problematic modules



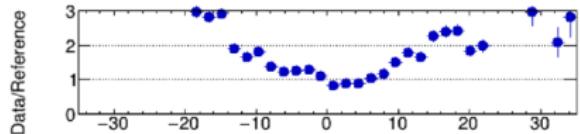
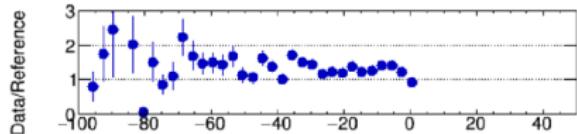
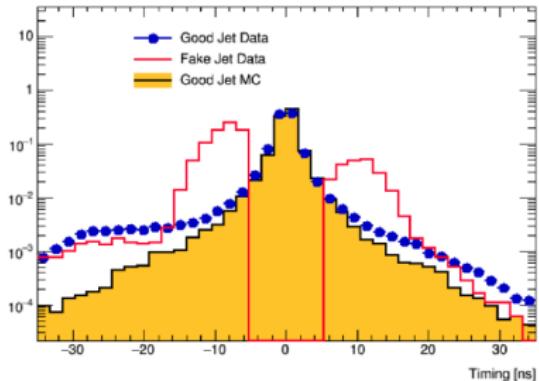
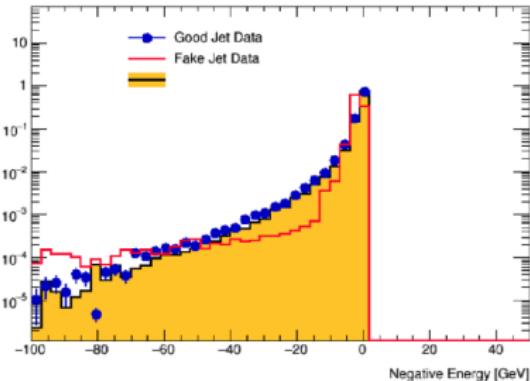
Instrumental effects : jet cleaning



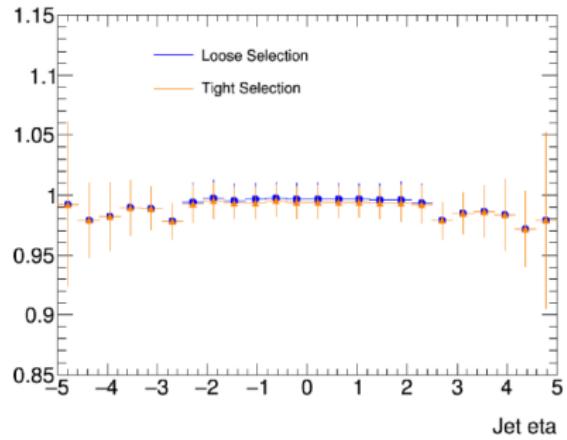
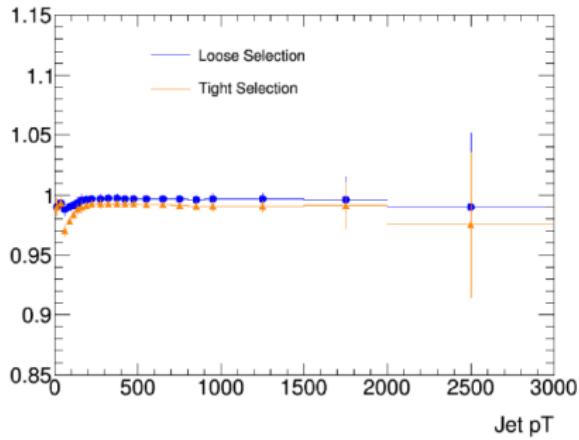
Instrumental effects : jet cleaning



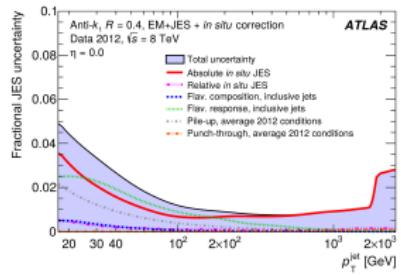
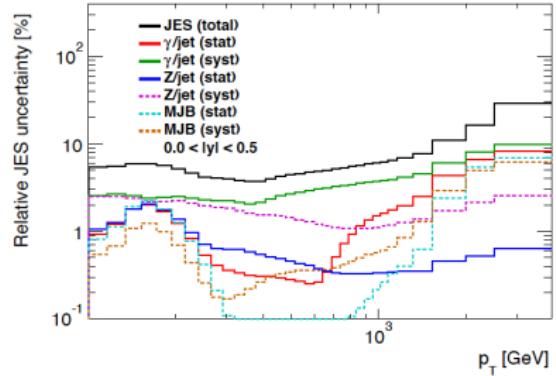
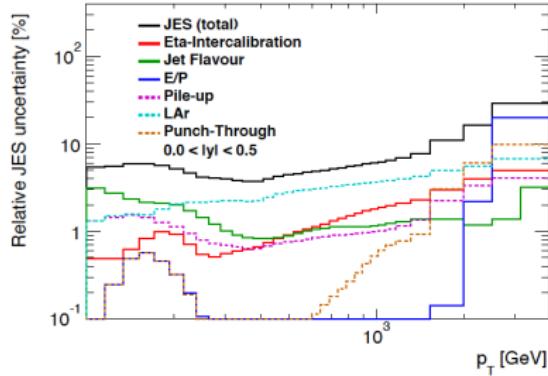
Instrumental effects : jet cleaning



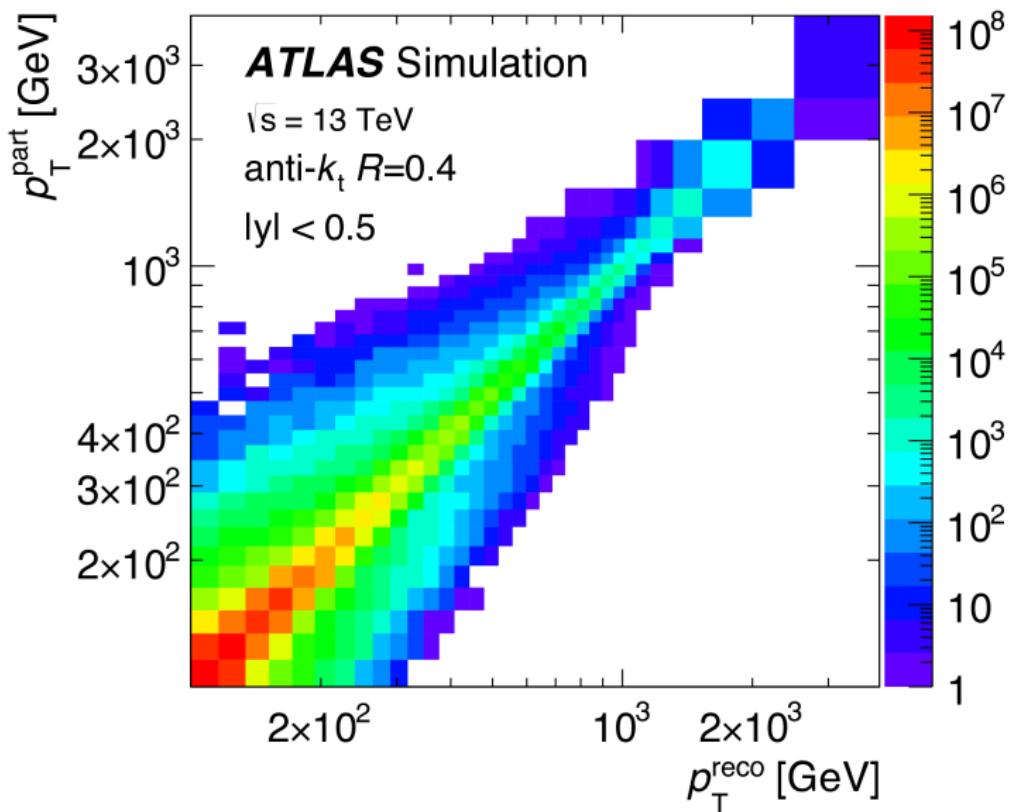
Instrumental effects : jet cleaning



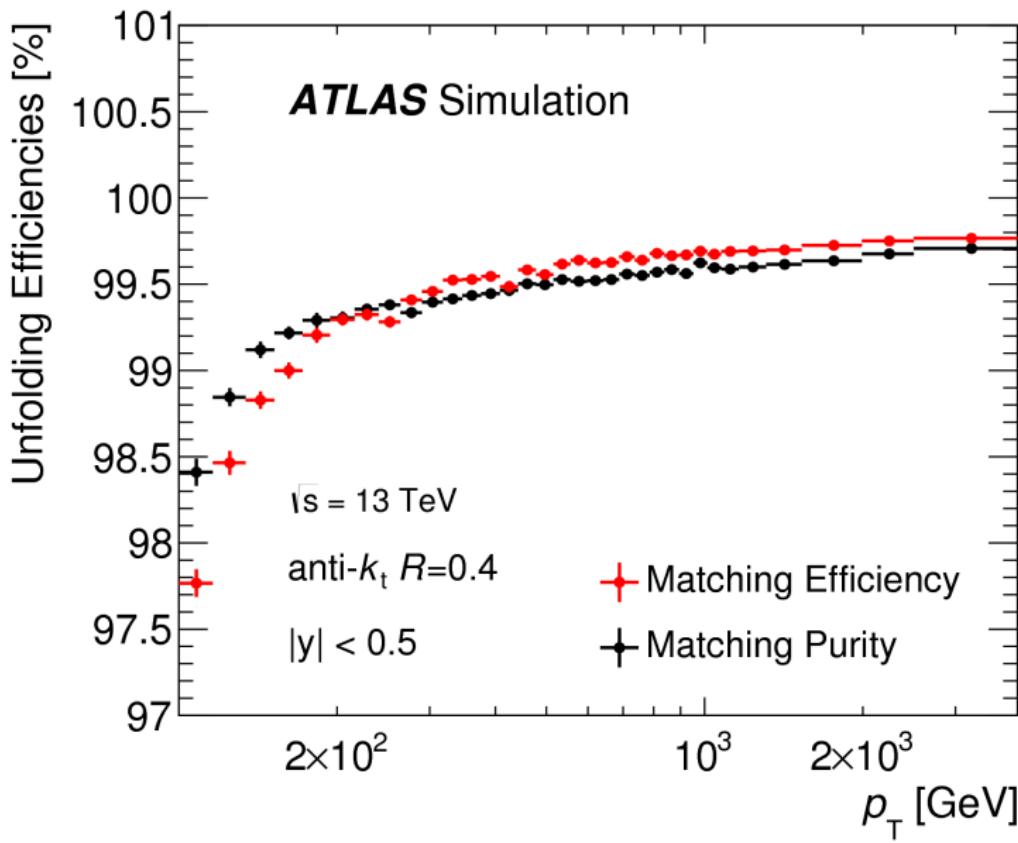
Systematic uncertainties propagation



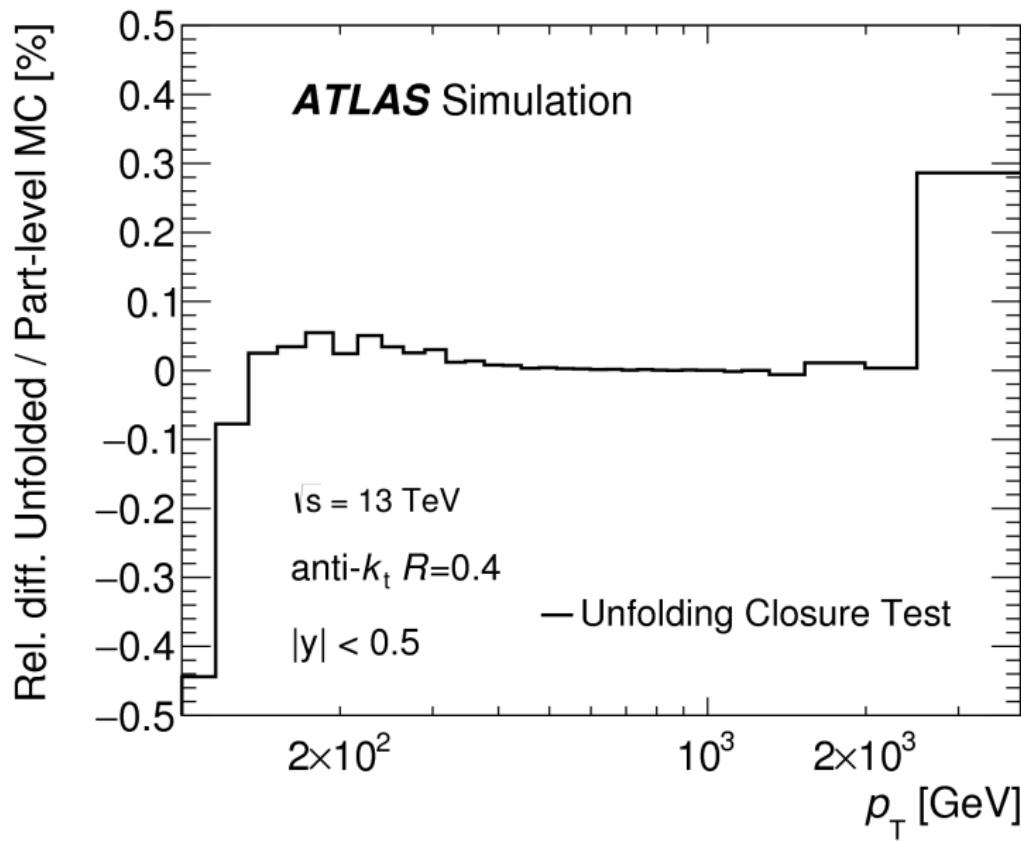
Unfolding matrix



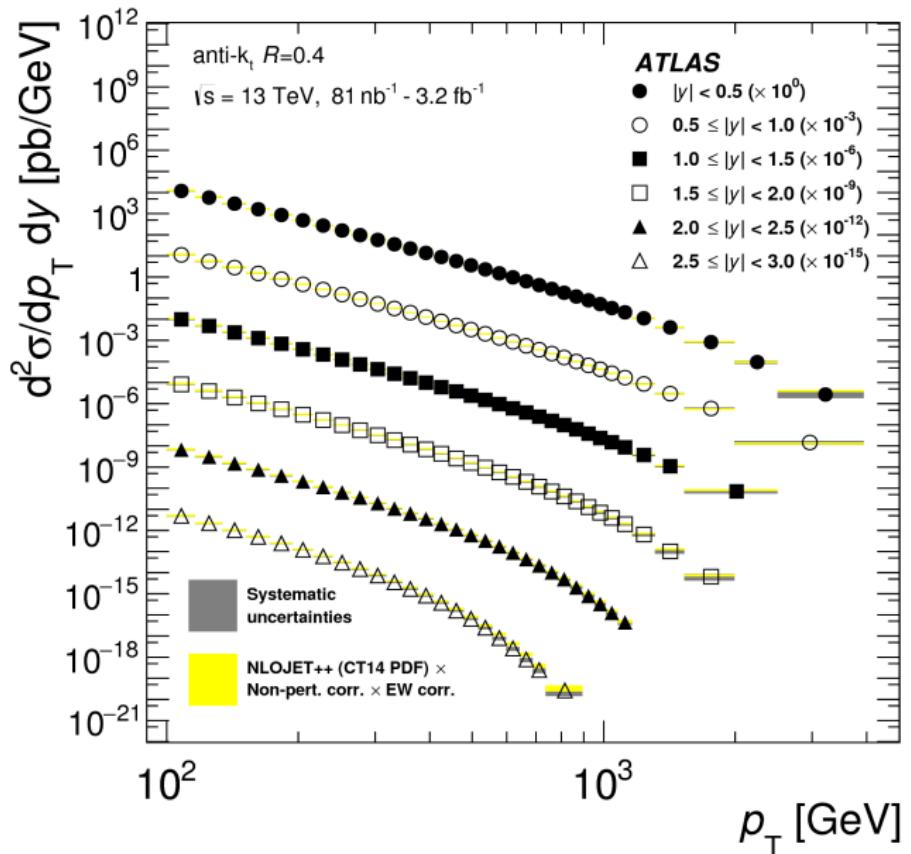
Unfolding efficiencies



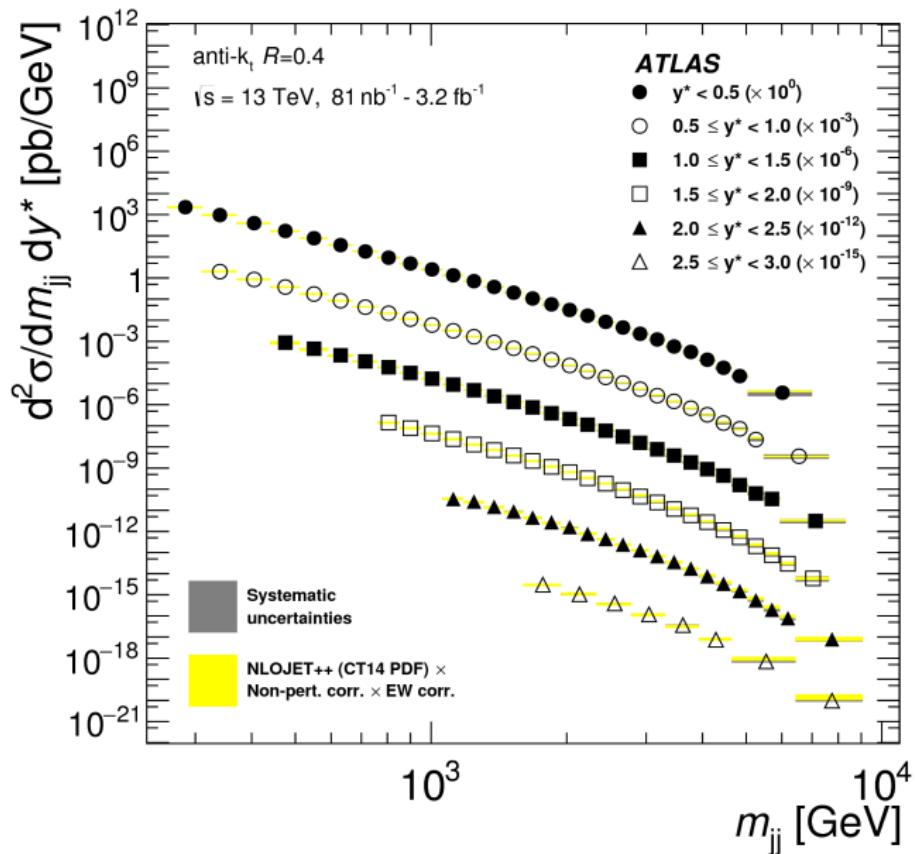
Unfolding bias



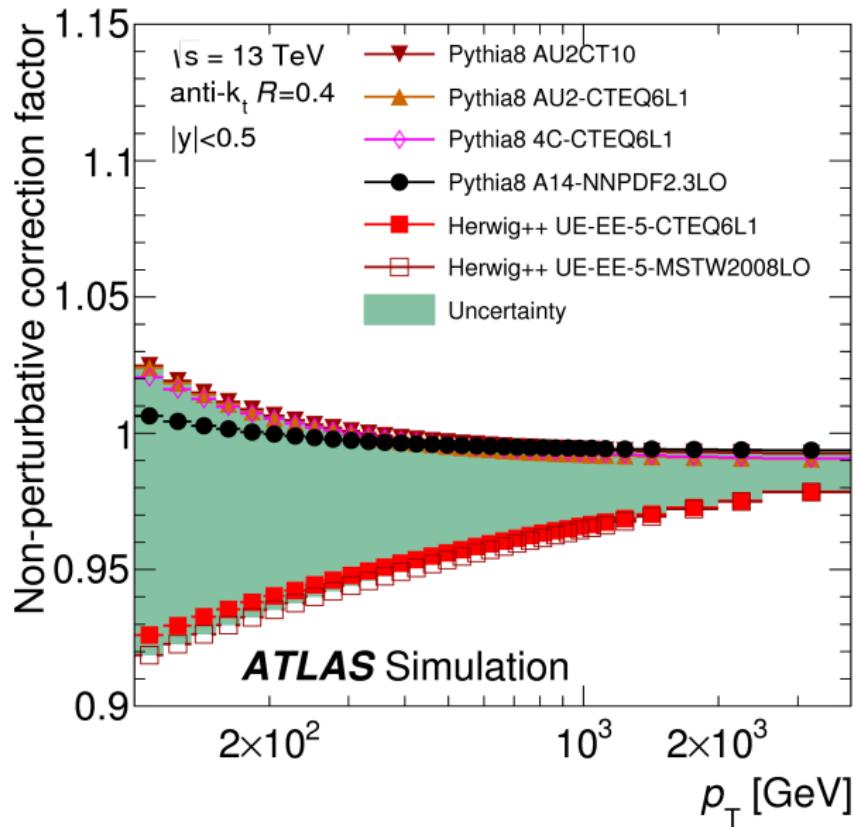
Inclusive jets



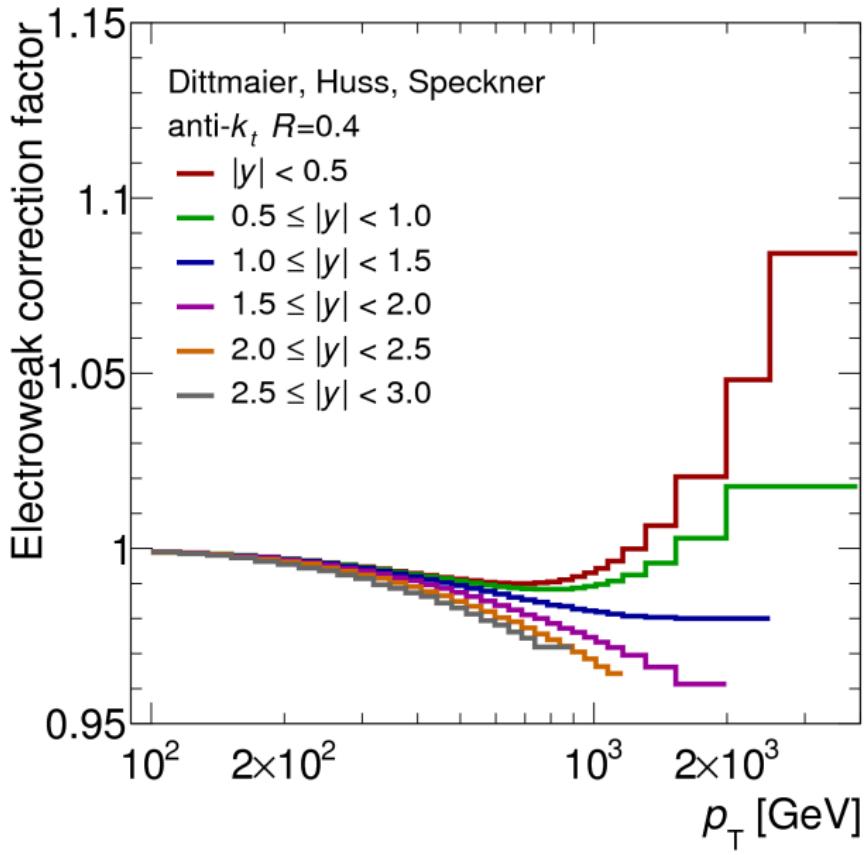
Dijets



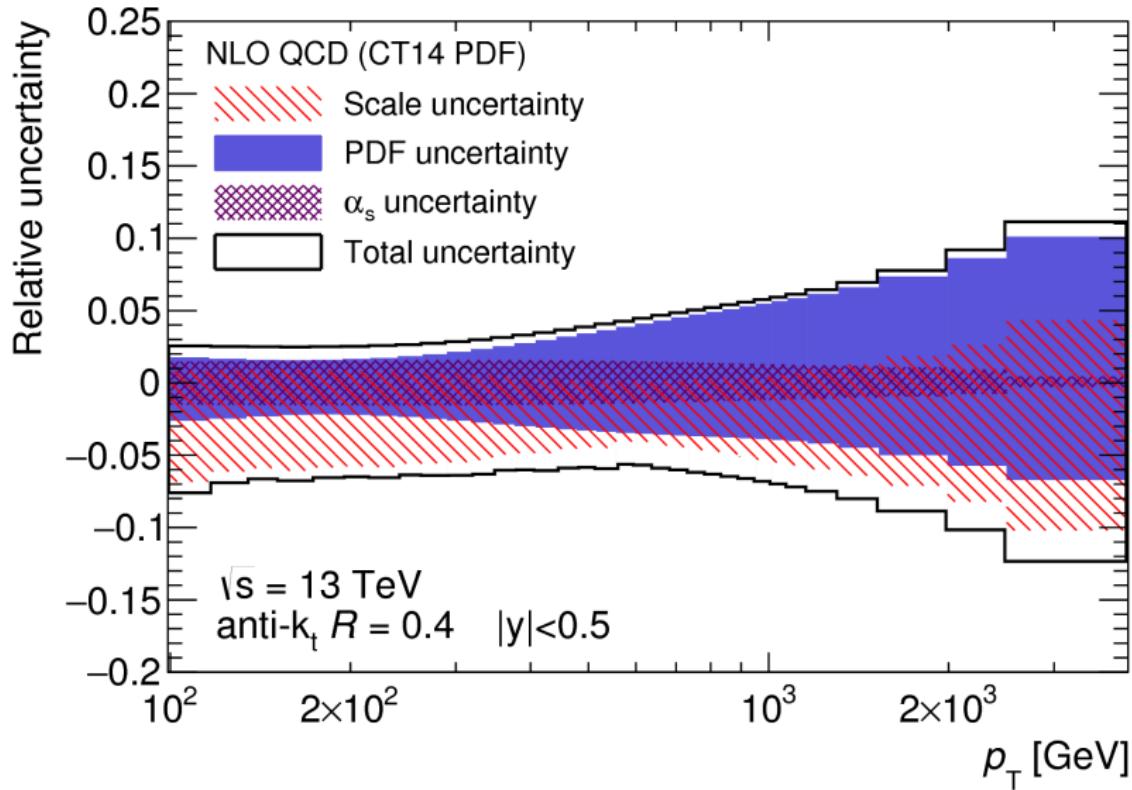
Non-perturbative



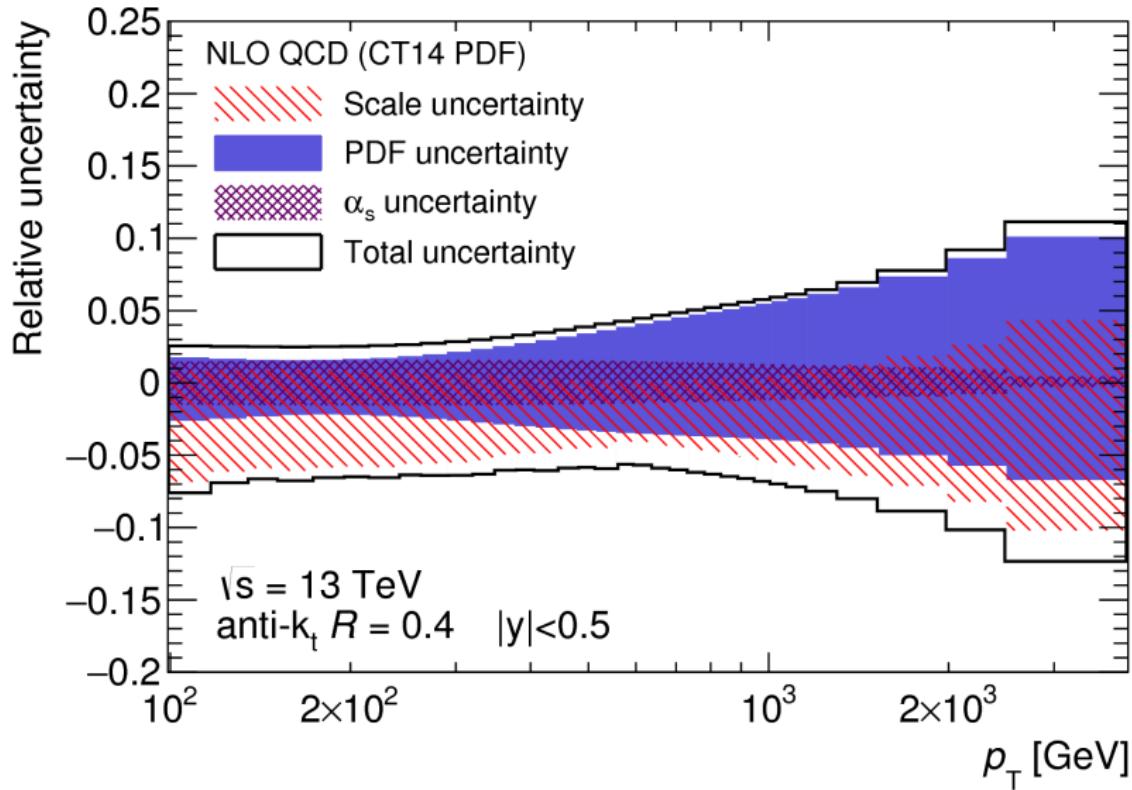
Electroweak



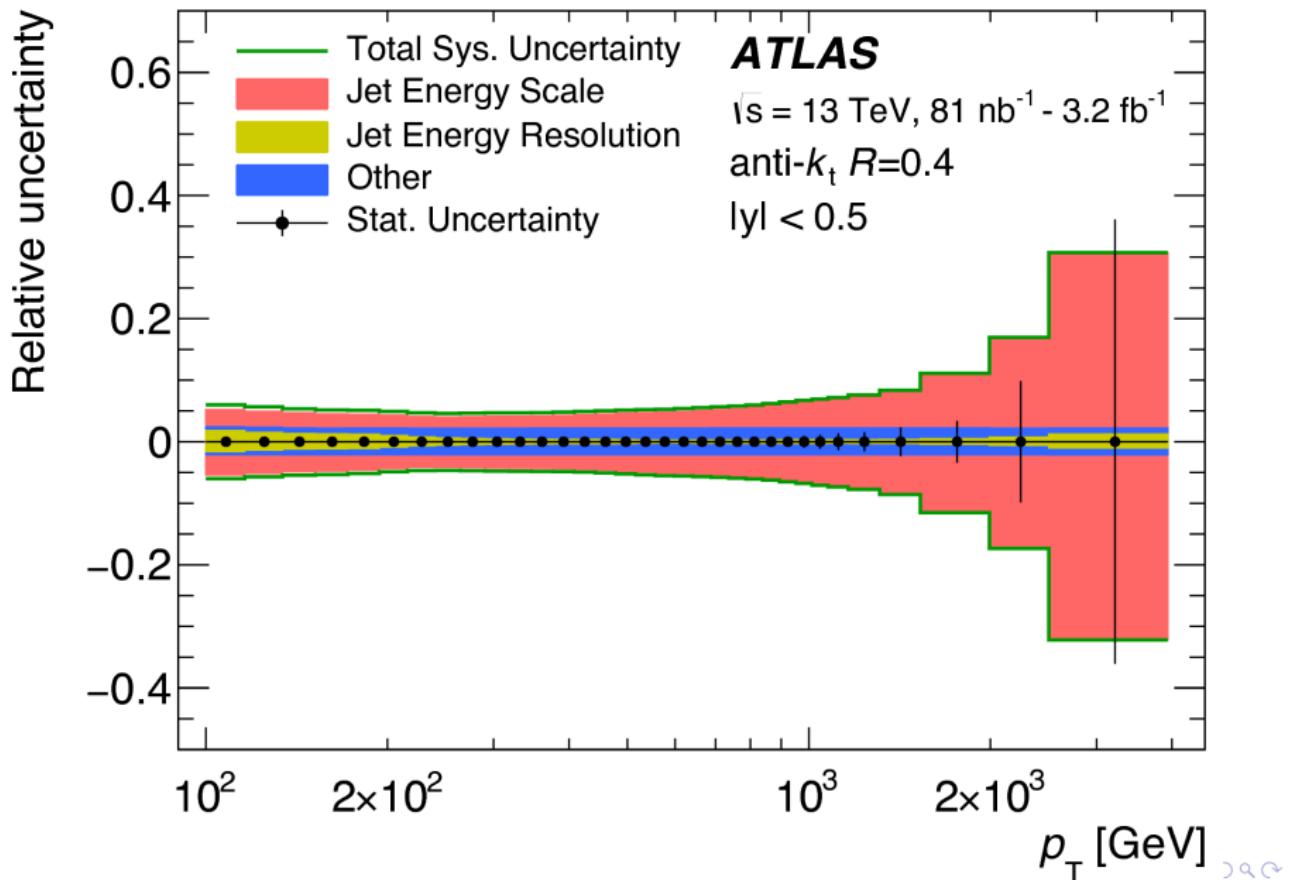
Cross section total uncertainty (fixed order theory)



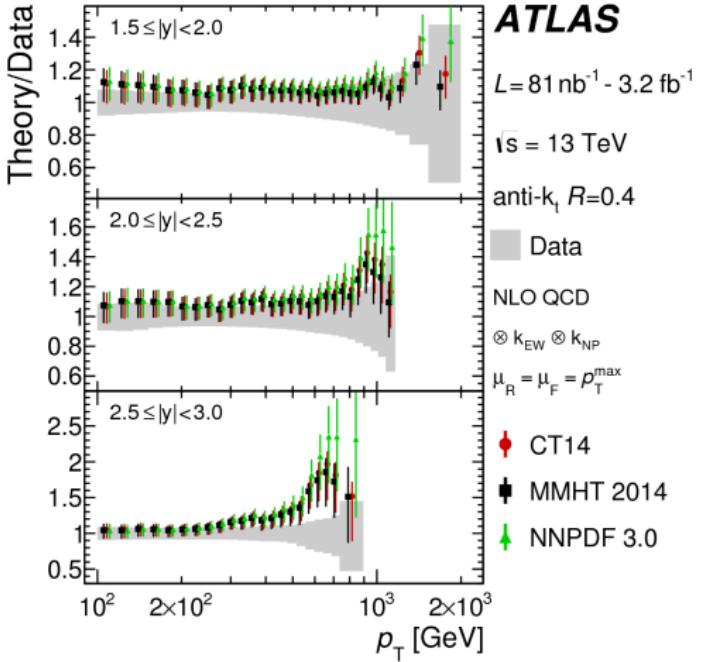
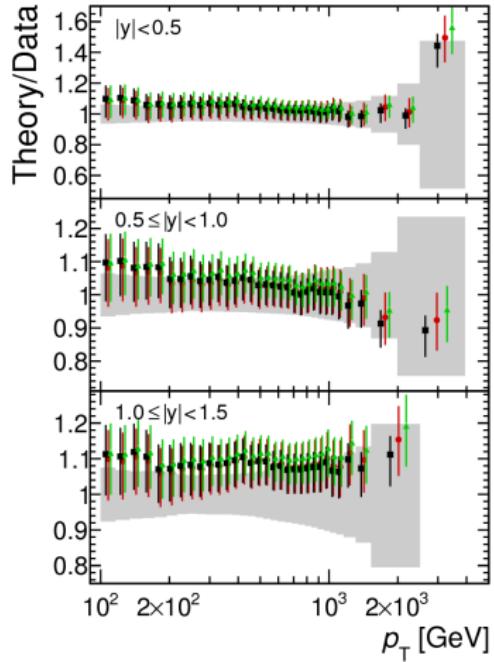
Cross section total uncertainty (fixed order theory)



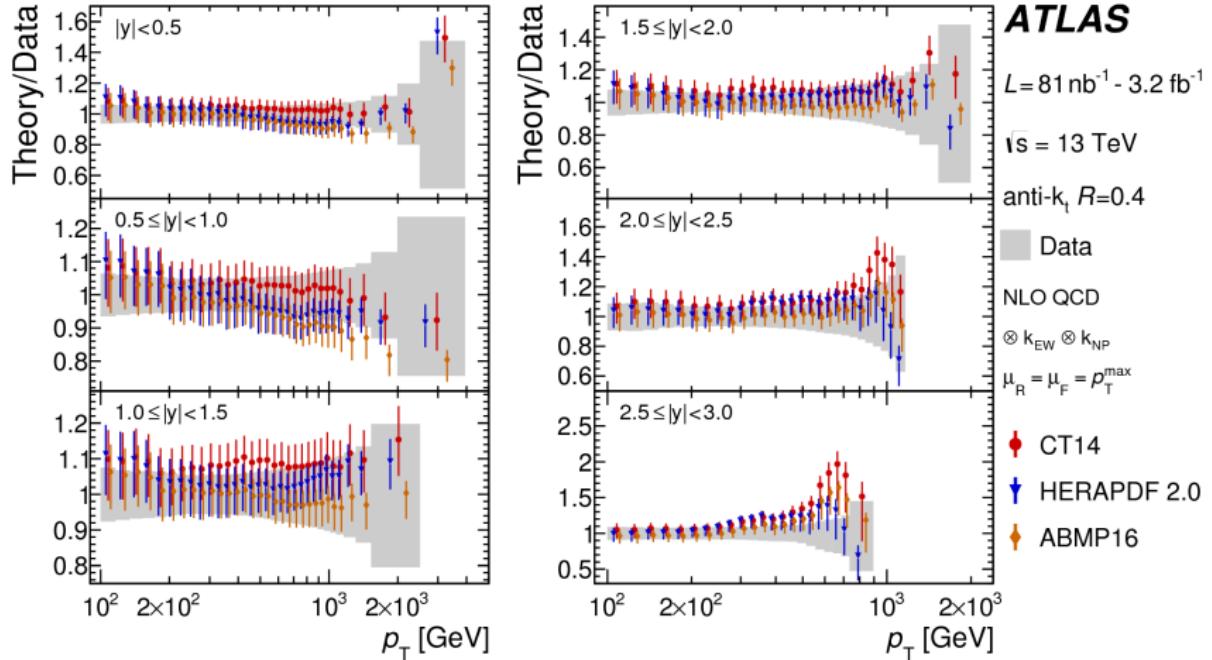
Cross section total uncertainty (exp)



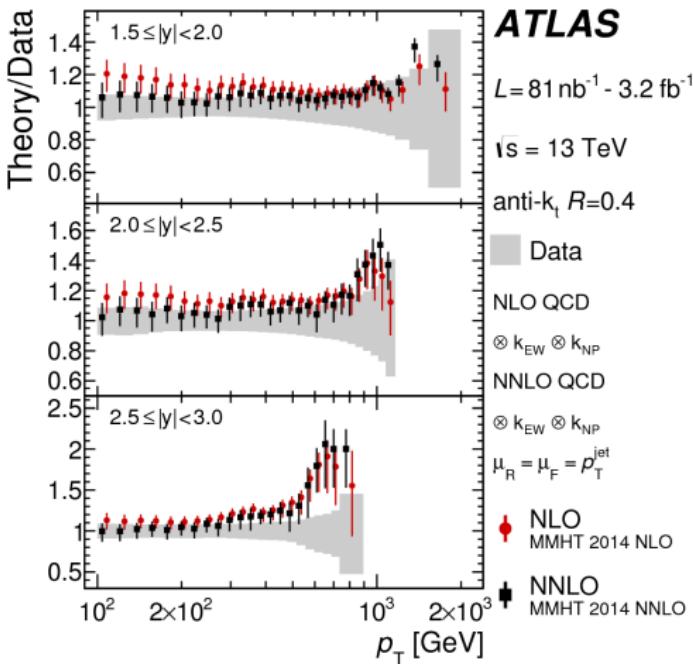
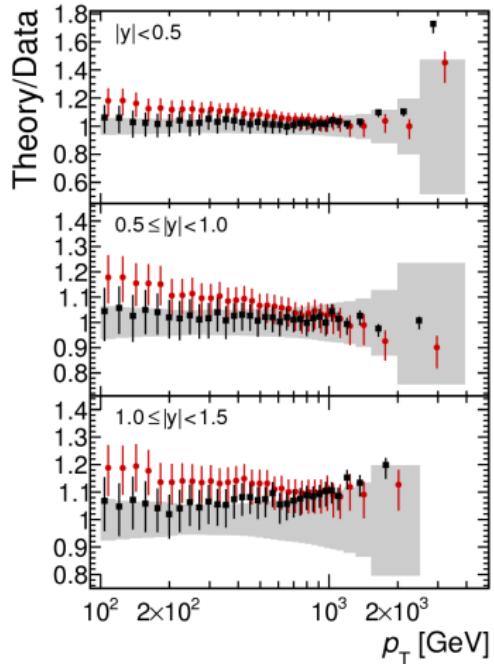
Inclusive jets



Inclusive jets

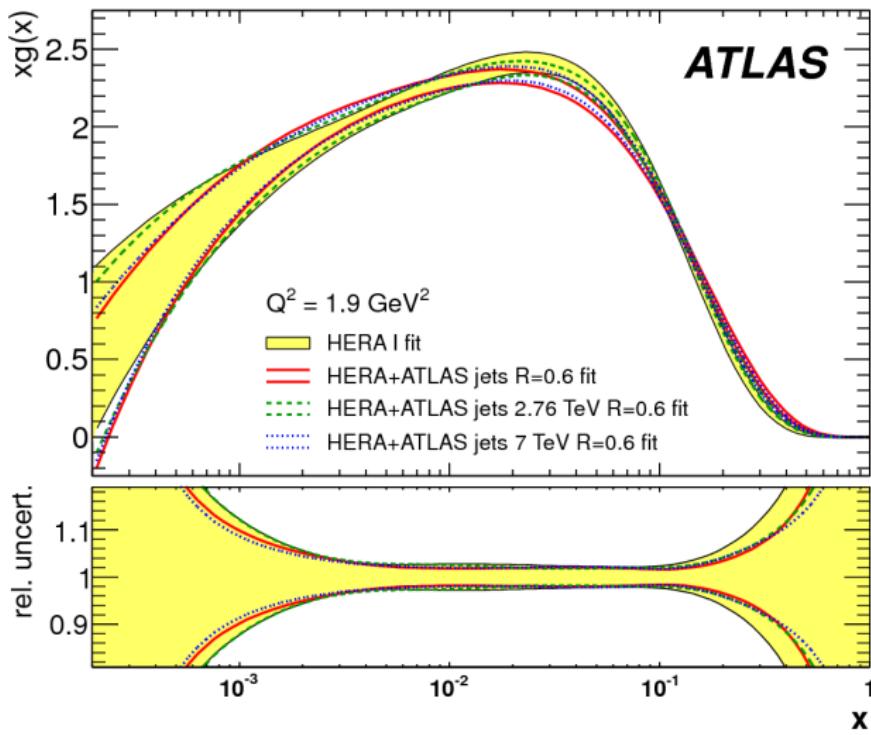


Inclusive jets



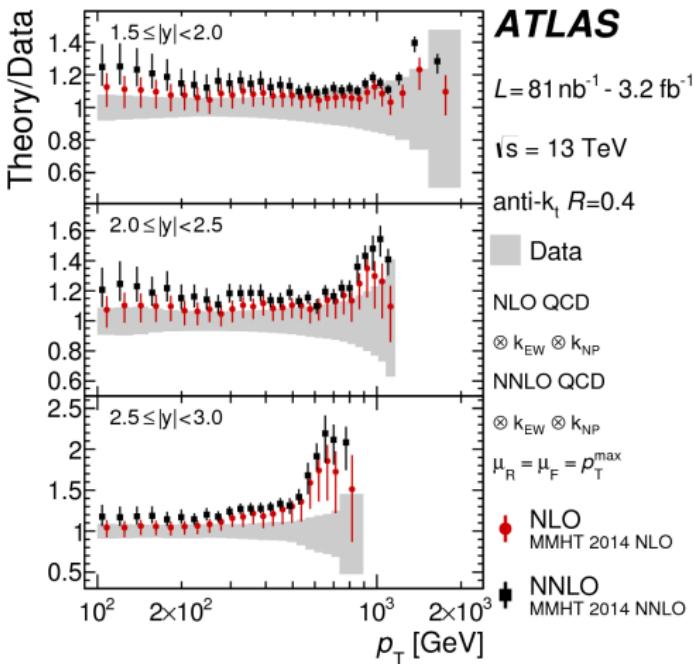
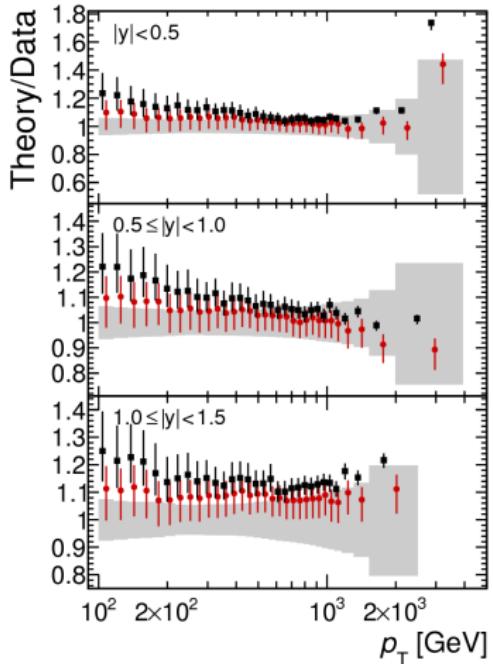
!8 TeV data !

Inclusive jets

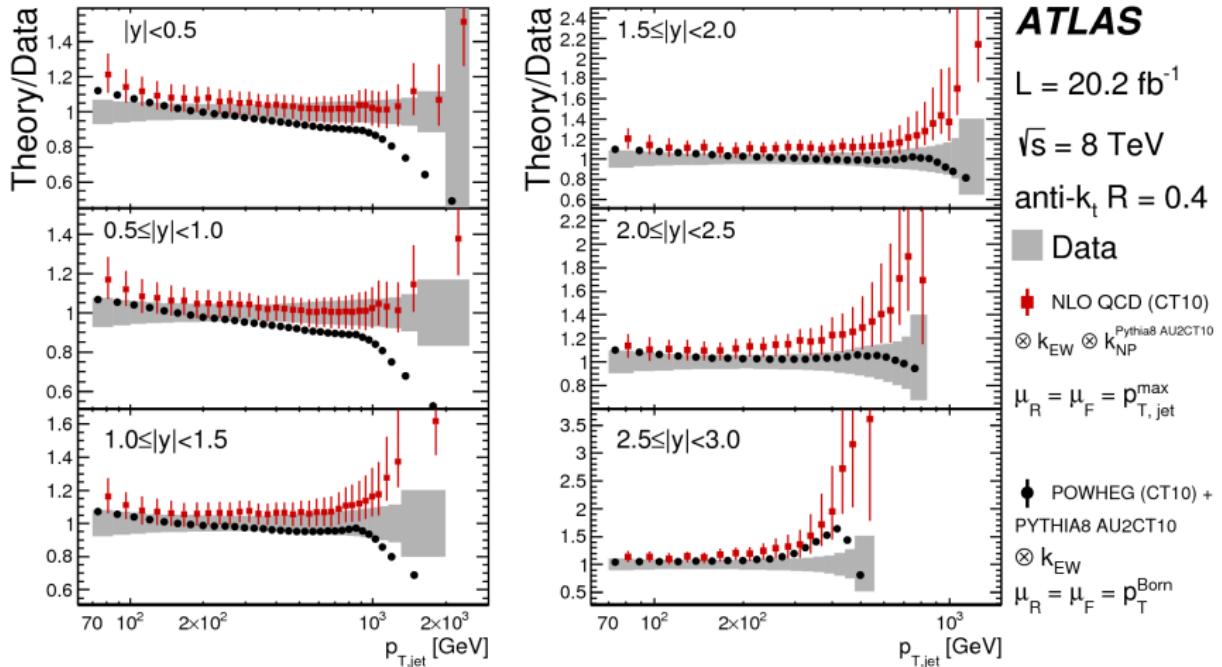


!2.76 + 7 TeV data !

Inclusive jets



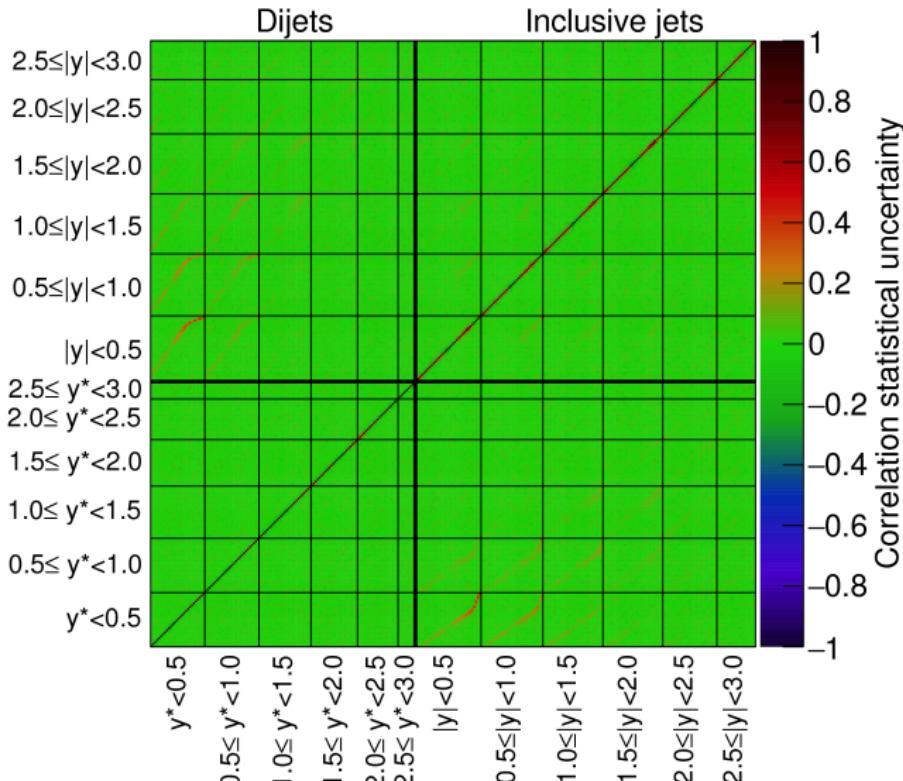
Inclusive jets



Correlation statistics

$\sqrt{s}=13 \text{ TeV}, 81 \text{ nb}^{-1} - 3.2 \text{ fb}^{-1}$

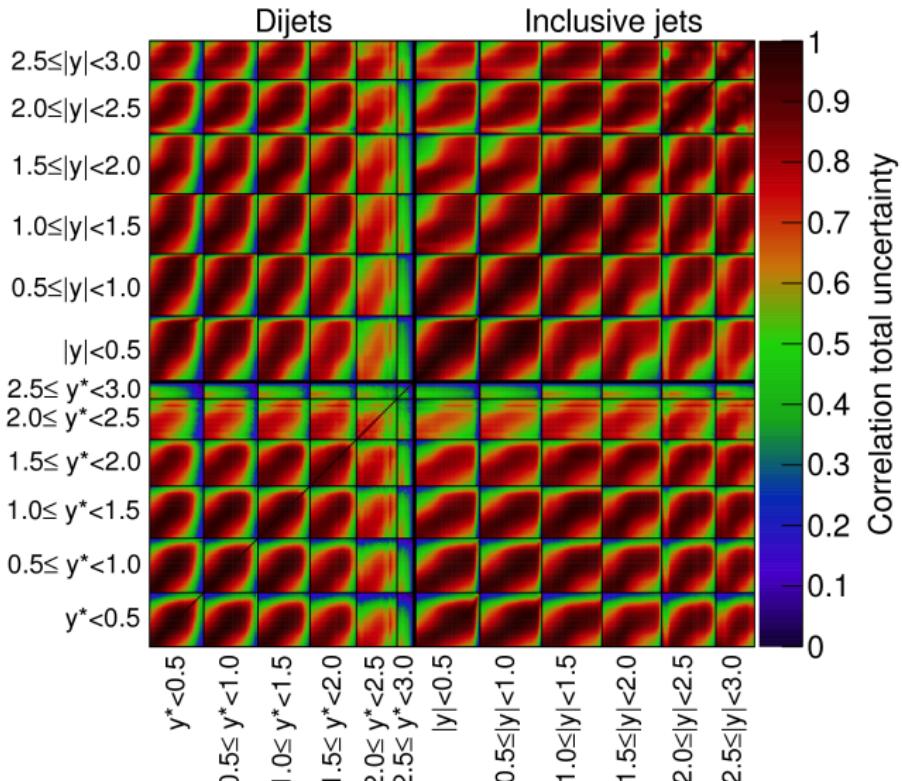
ATLAS



Correlation total

$\sqrt{s}=13 \text{ TeV}, 81 \text{ nb}^{-1} - 3.2 \text{ fb}^{-1}$

ATLAS



Quantitative comparison data to theory

Rapidity ranges	CT14	MMHT 2014	P_{obs}	HERAPDF 2.0	ABMP16
p_T^{\max}					
$ y < 0.5$	67%	65%	62%	31%	50%
$0.5 \leq y < 1.0$	5.8%	6.3%	6.0%	3.0%	2.0%
$1.0 \leq y < 1.5$	65%	61%	67%	50%	55%
$1.5 \leq y < 2.0$	0.7%	0.8%	0.8%	0.1%	0.4%
$2.0 \leq y < 2.5$	2.3%	2.3%	2.8%	0.7%	1.5%
$2.5 \leq y < 3.0$	62%	71%	69%	25%	55%
p_T^{jet}					
$ y < 0.5$	69%	67%	66%	30%	46%
$0.5 \leq y < 1.0$	7.4%	8.9%	8.6%	3.4%	2.0%
$1.0 \leq y < 1.5$	69%	62%	68%	45%	54%
$1.5 \leq y < 2.0$	1.3%	1.6%	1.4%	0.1%	0.5%
$2.0 \leq y < 2.5$	8.7%	6.6%	7.4%	1.0%	3.6%
$2.5 \leq y < 3.0$	65%	72%	72%	28%	59%

Quantitative comparison data to theory

y^* ranges	CT14	MMHT 2014	NNPDF 3.0	P_{obs}	HERAPDF 2.0	ABMP16
$y^* < 0.5$	79%	59%	50%	71%	71%	
$0.5 \leq y^* < 1.0$	27%	23%	19%	32%	31%	
$1.0 \leq y^* < 1.5$	66%	55%	48%	66%	69%	
$1.5 \leq y^* < 2.0$	26%	26%	28%	9.9%	25%	
$2.0 \leq y^* < 2.5$	41%	34%	29%	3.6%	20%	
$2.5 \leq y^* < 3.0$	45%	46%	40%	25%	38%	
all y^* bins	9.4%	6.5%	11%	0.1%	5.1%	