Physics at the LHC

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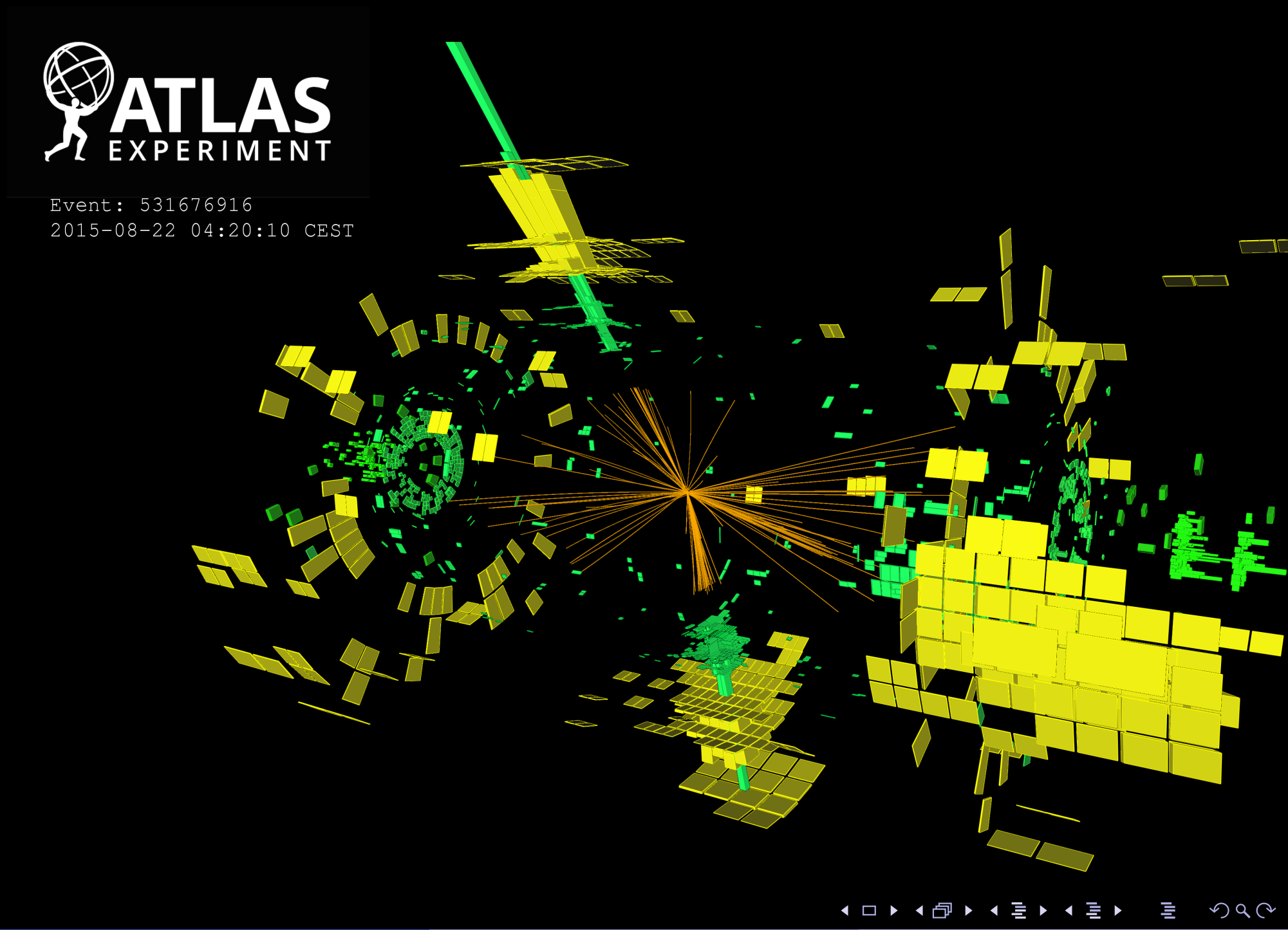
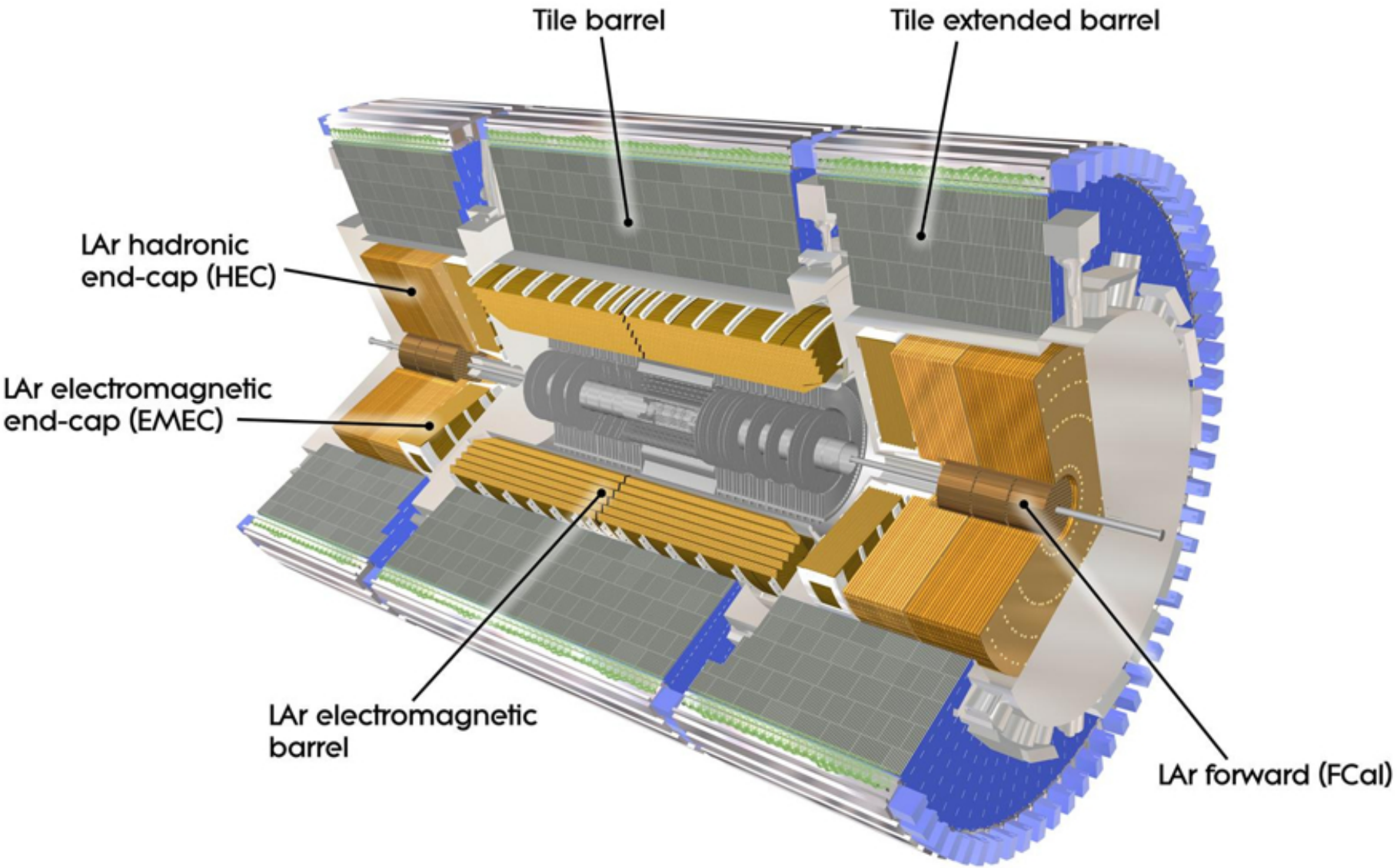
November 8, 2021


ATLAS
EXPERIMENT
Event: 531676916
2015-08-22 04:20:10 CEST

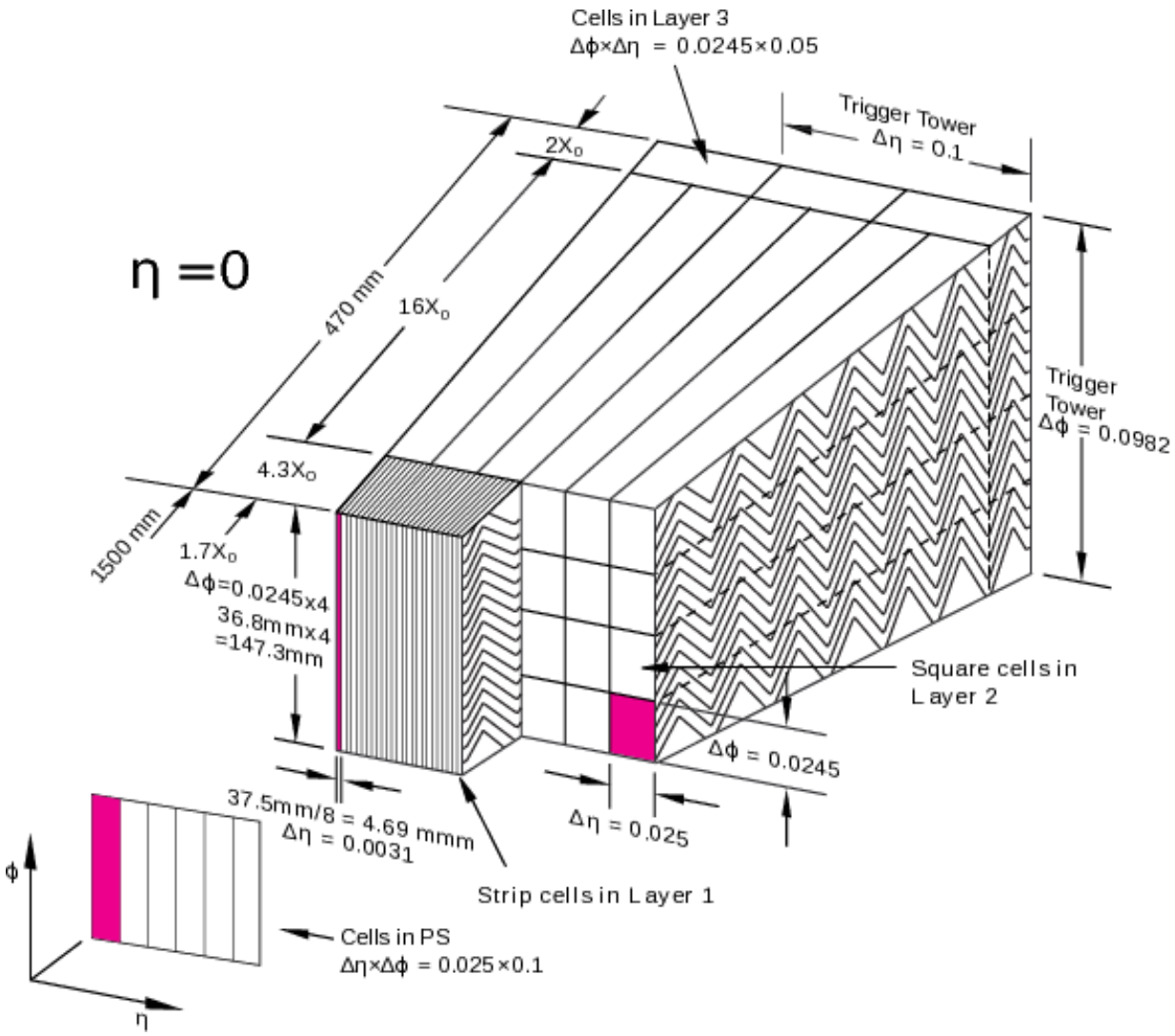
Outlook

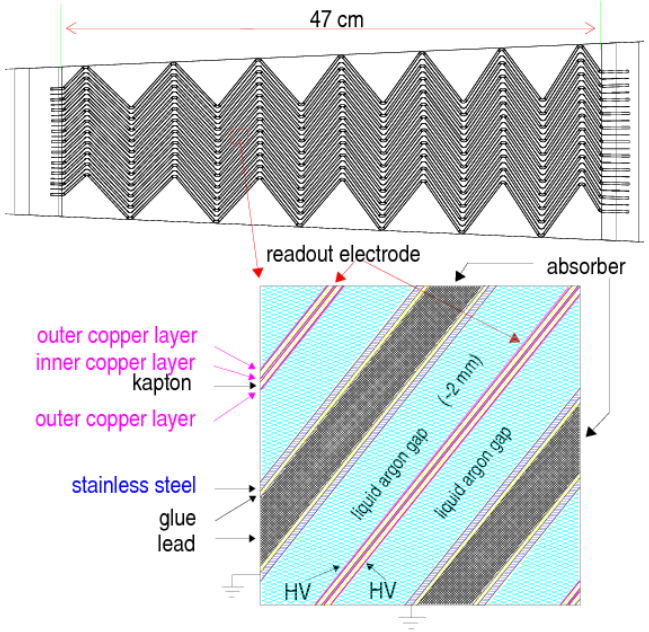
- Large Hadron Collider
  - proton-proton collisions, pileup, event size, bandwidth and triggering.
- ATLAS detector
  - Calorimeters : electromagnetic and hadronic
- Jet definition, reconstruction and calibration
  - jet algorithms, infra-red stability, pileup mitigation, topo-clusters, jet energy calibration
- 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

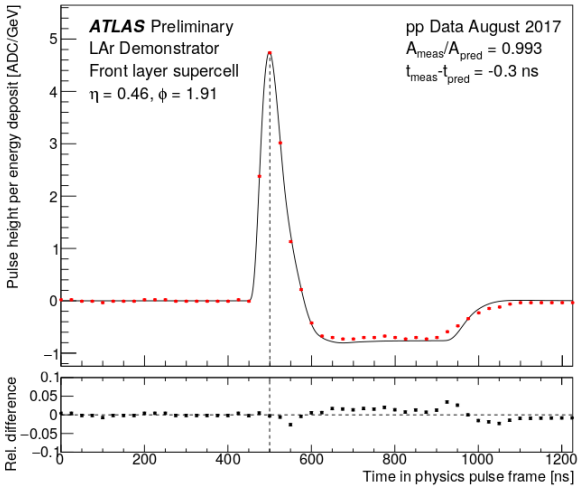
ATLAS Calorimeters



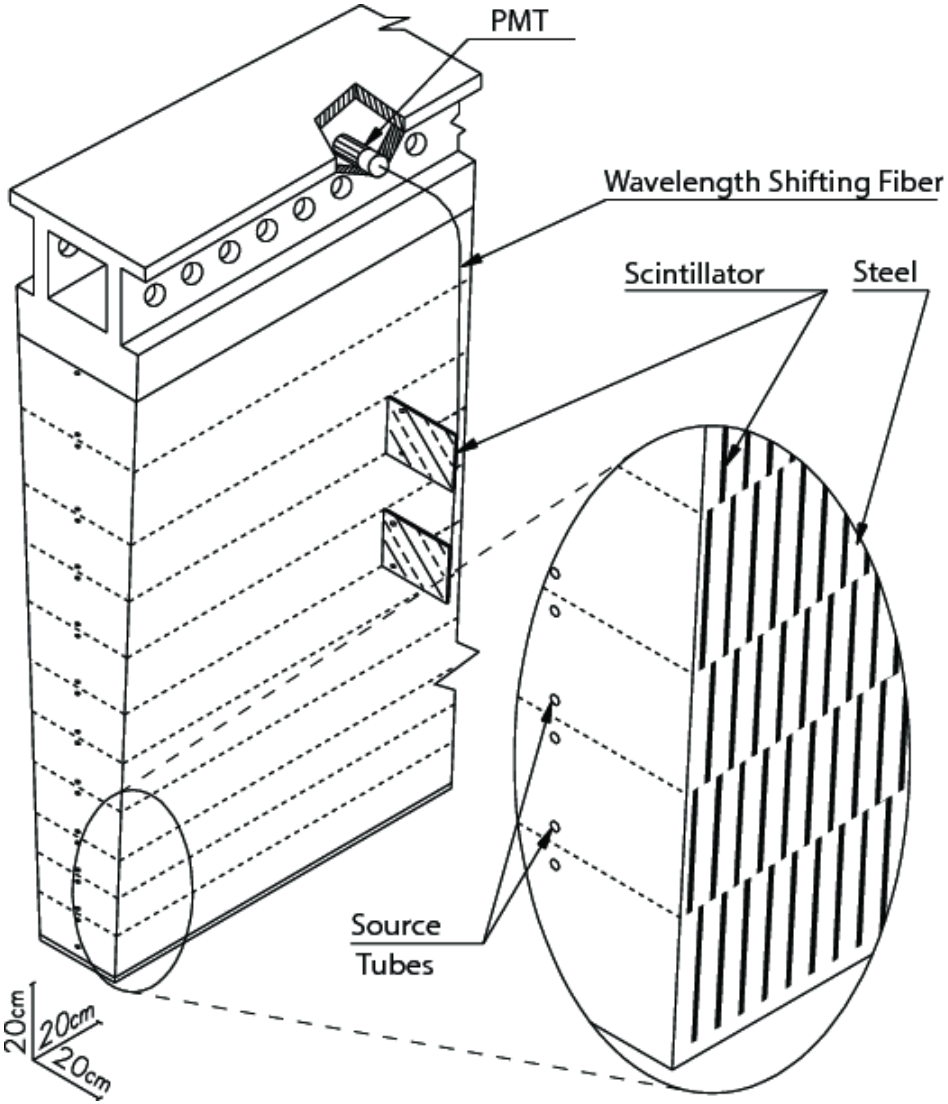
LAr Calorimeter

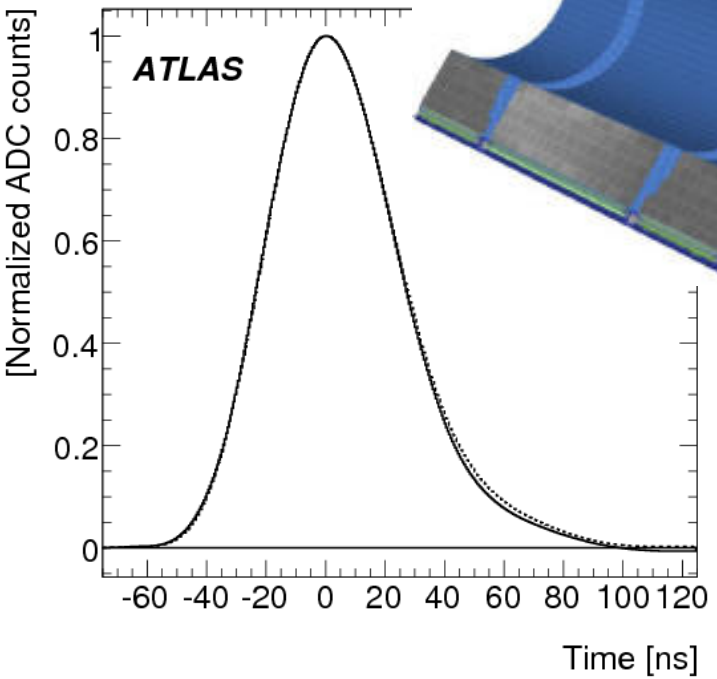


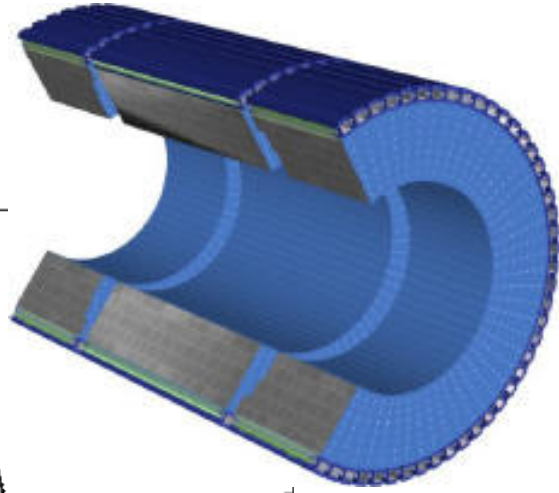


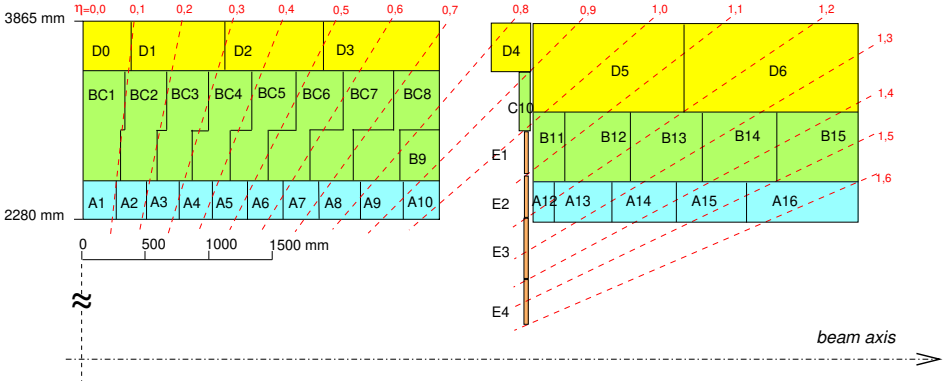


Tile Calorimeter

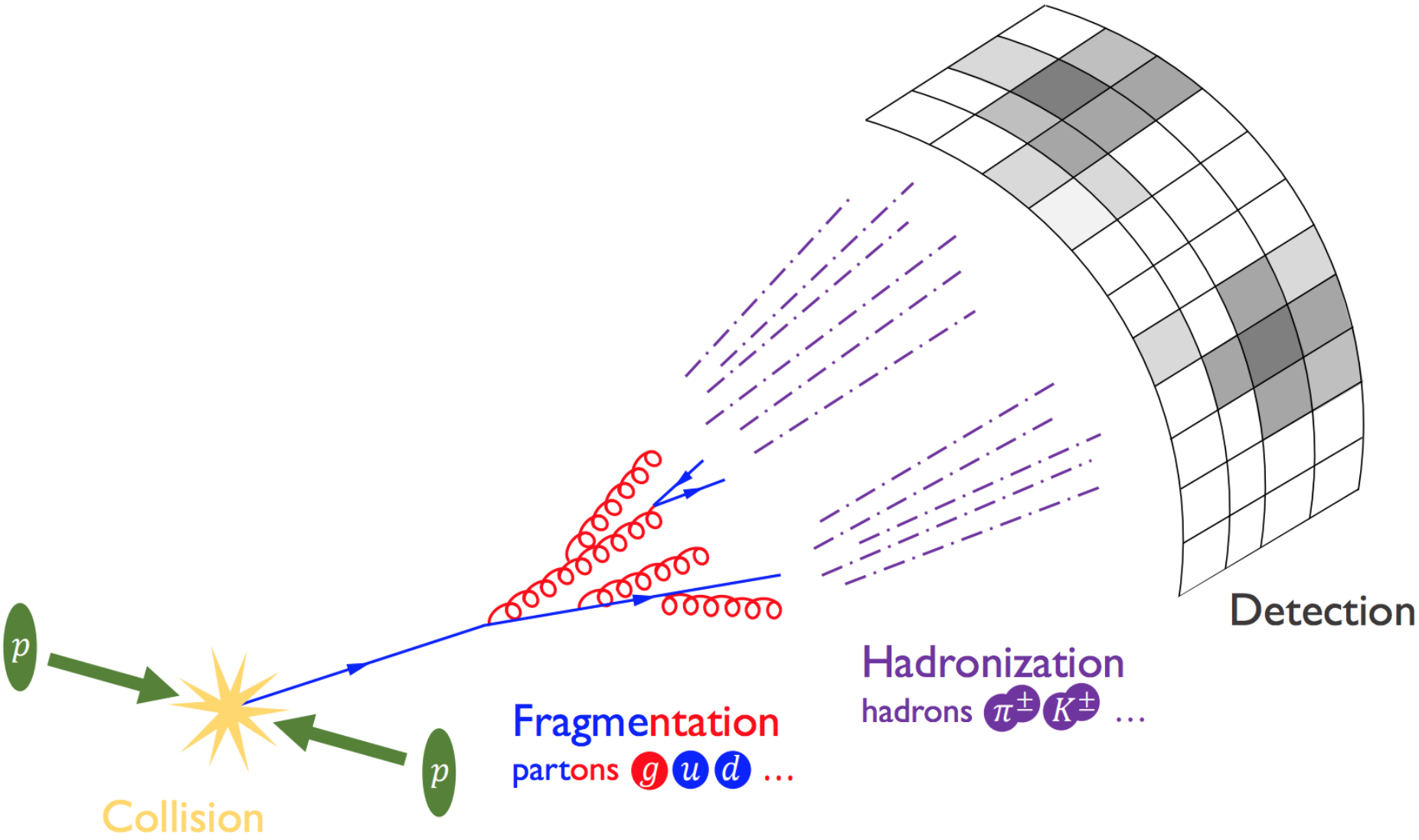




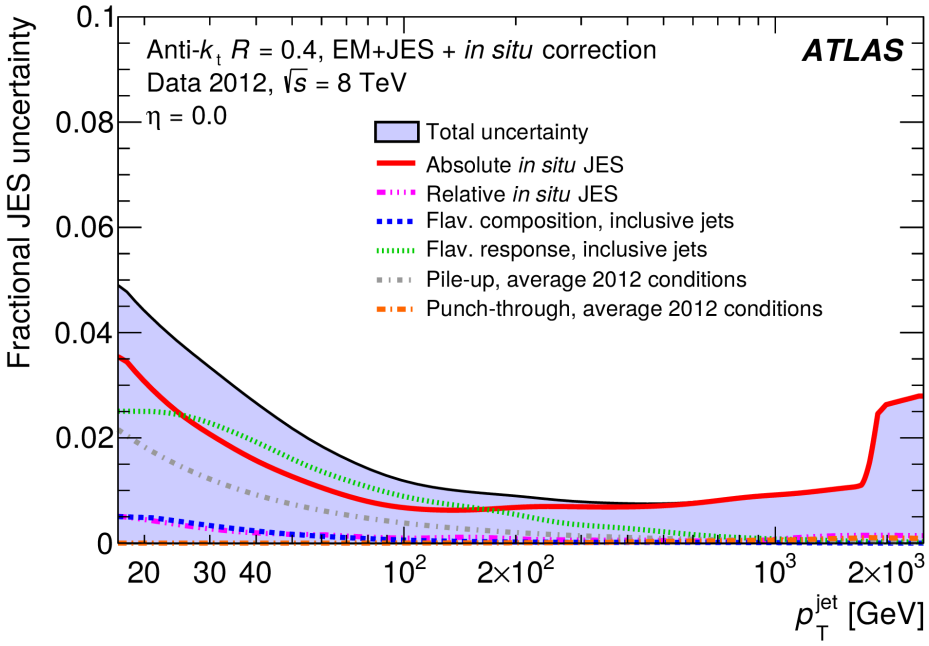


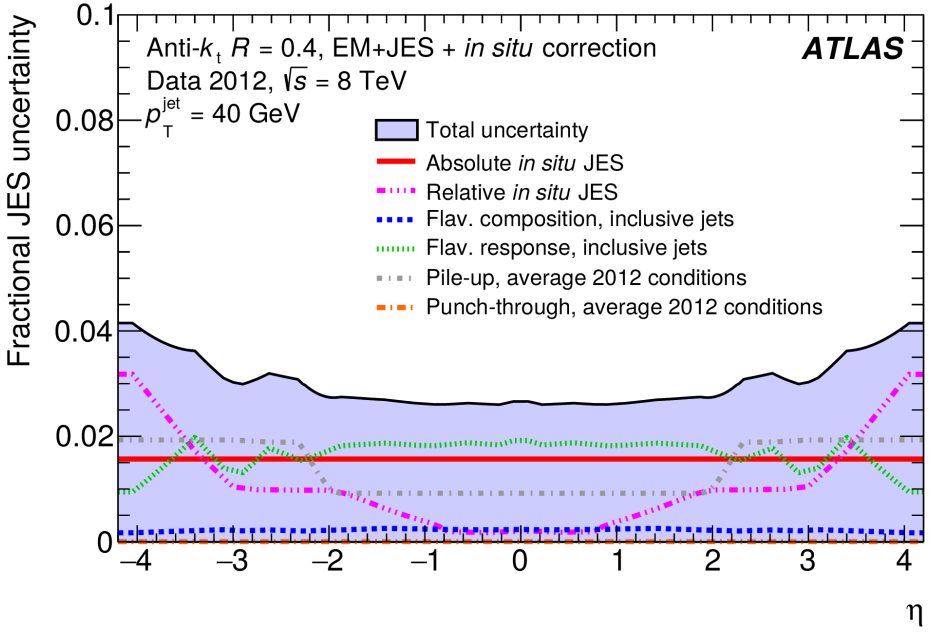


Jet life


p
p
Collision
Fragmentation
partons g u d ...
Hadronization
hadrons $\pi^{\pm}$ $K^{\pm}$ ...
Detection

Final JES precision

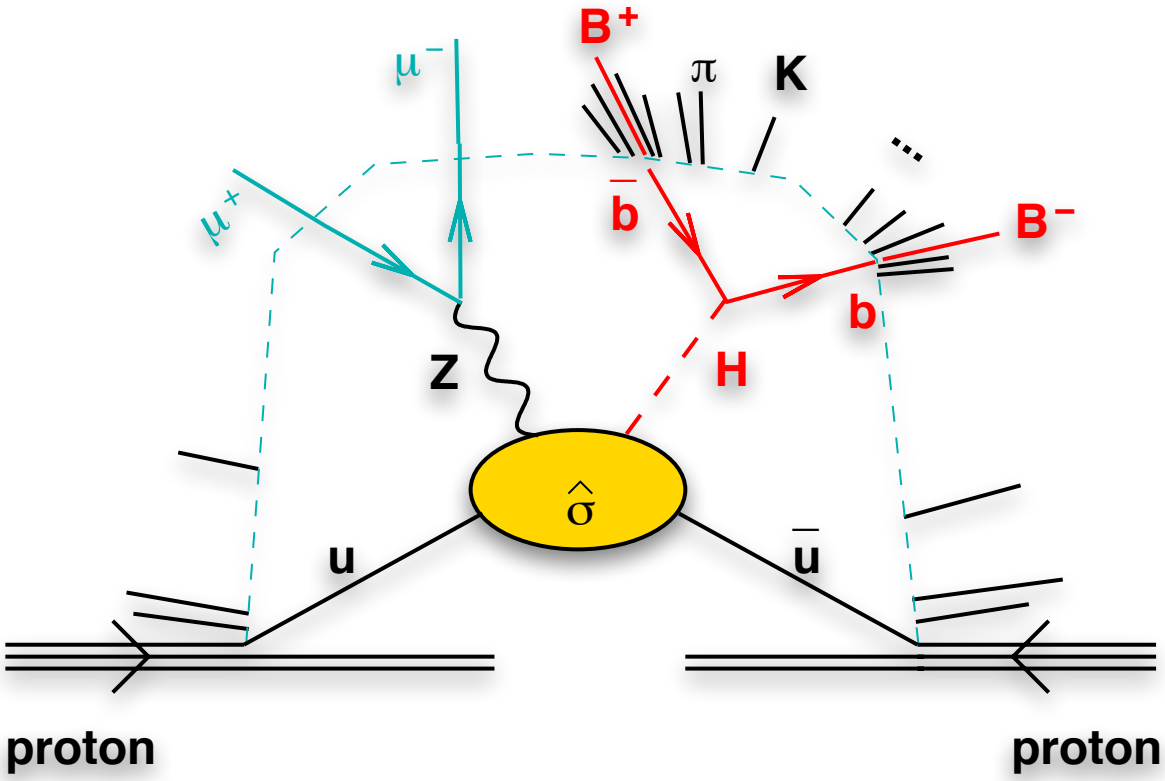




Final JES precision

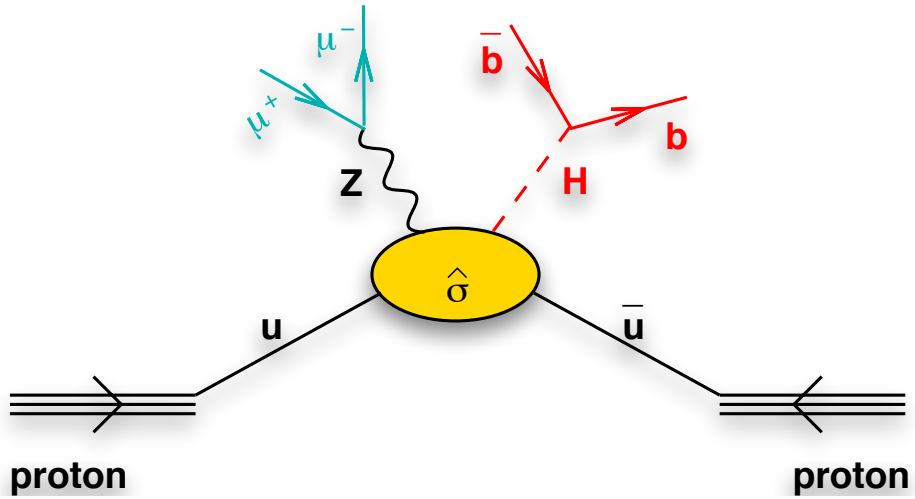
Name	Description	Category
Z+jet		
e E-scale material	Material uncertainty in electron energy scale	det.
e E-scale presampler	Presampler uncertainty in electron energy scale	det.
e E-scale baseline	Baseline uncertainty in electron energy scale	mixed
e E-scale smearing	Uncertainty in electron energy smearing	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

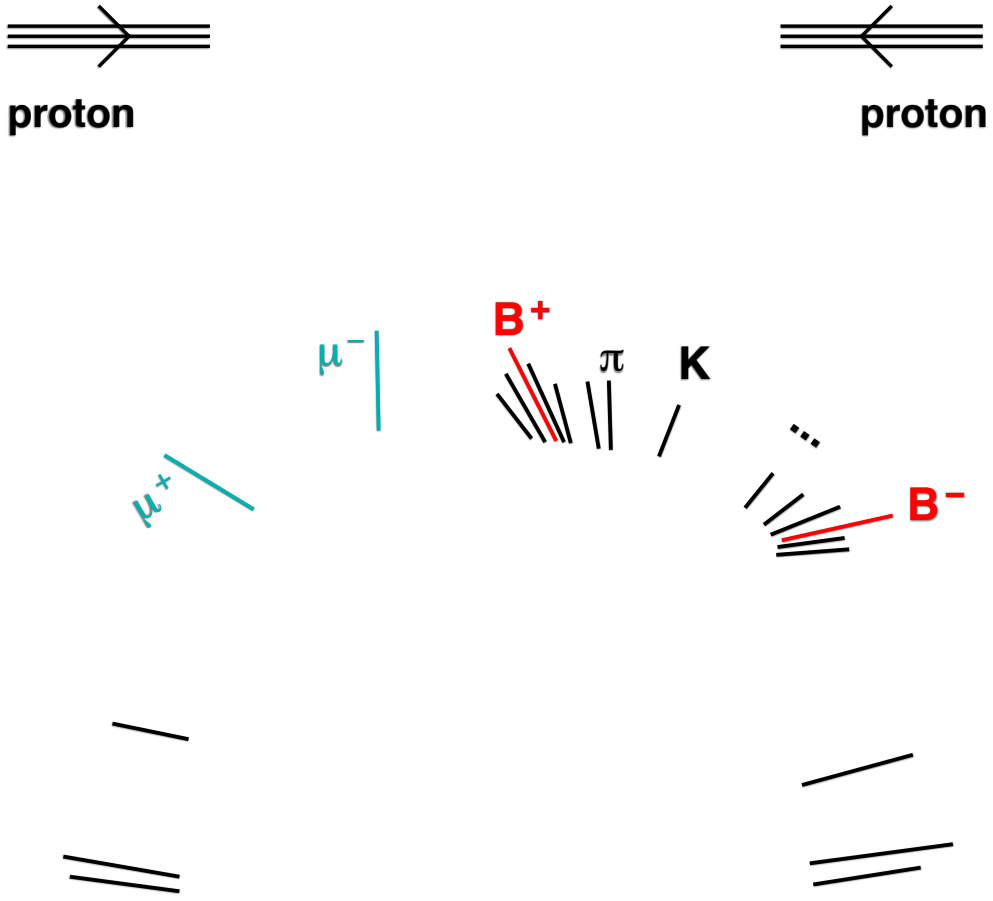


Proton-proton collisions : final state truth at the fixed order

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

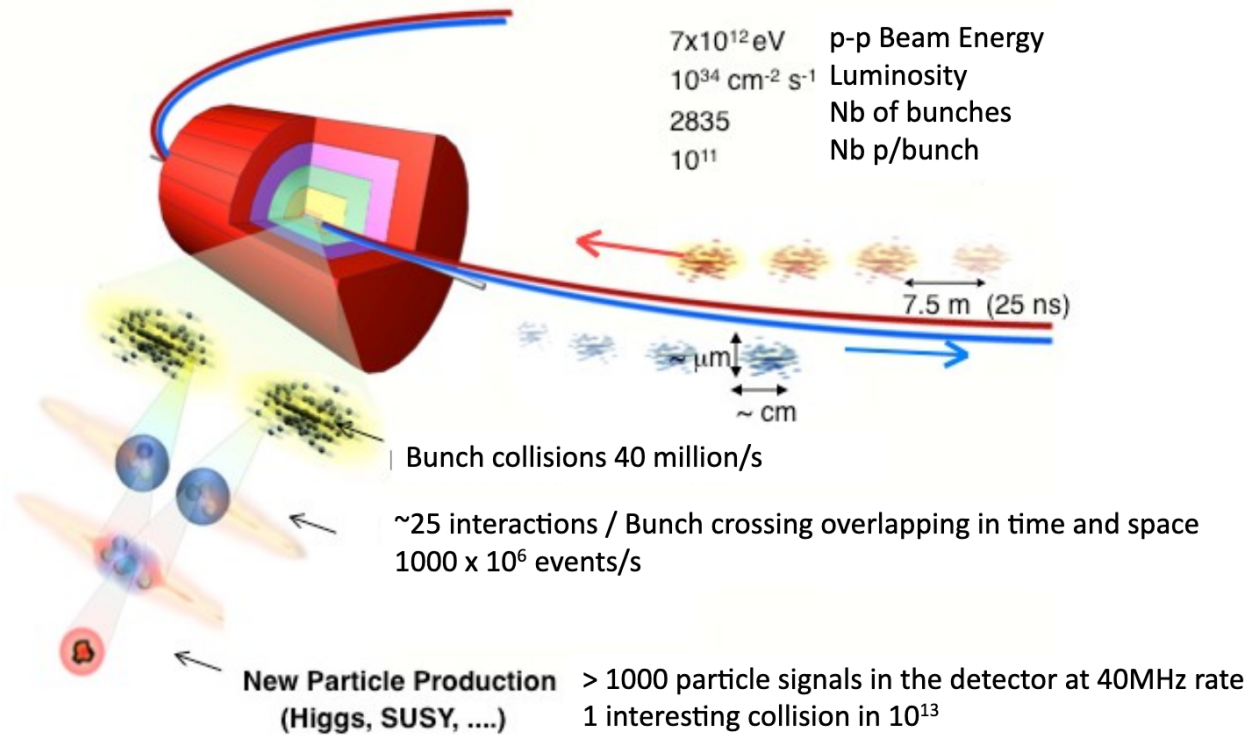


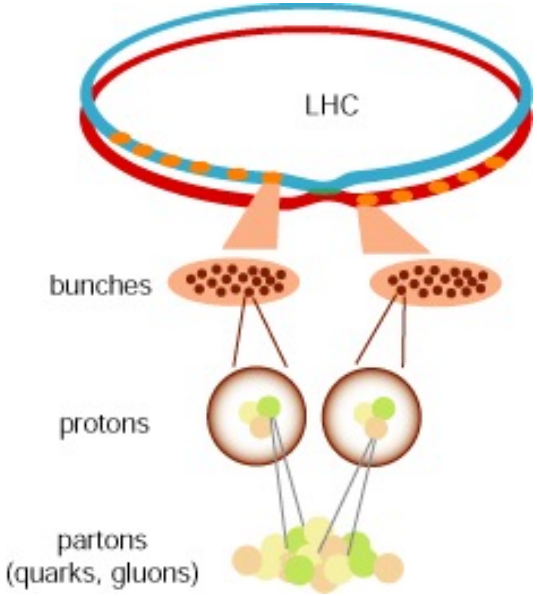
Proton-proton collisions : final state (visible by an ideal detector)



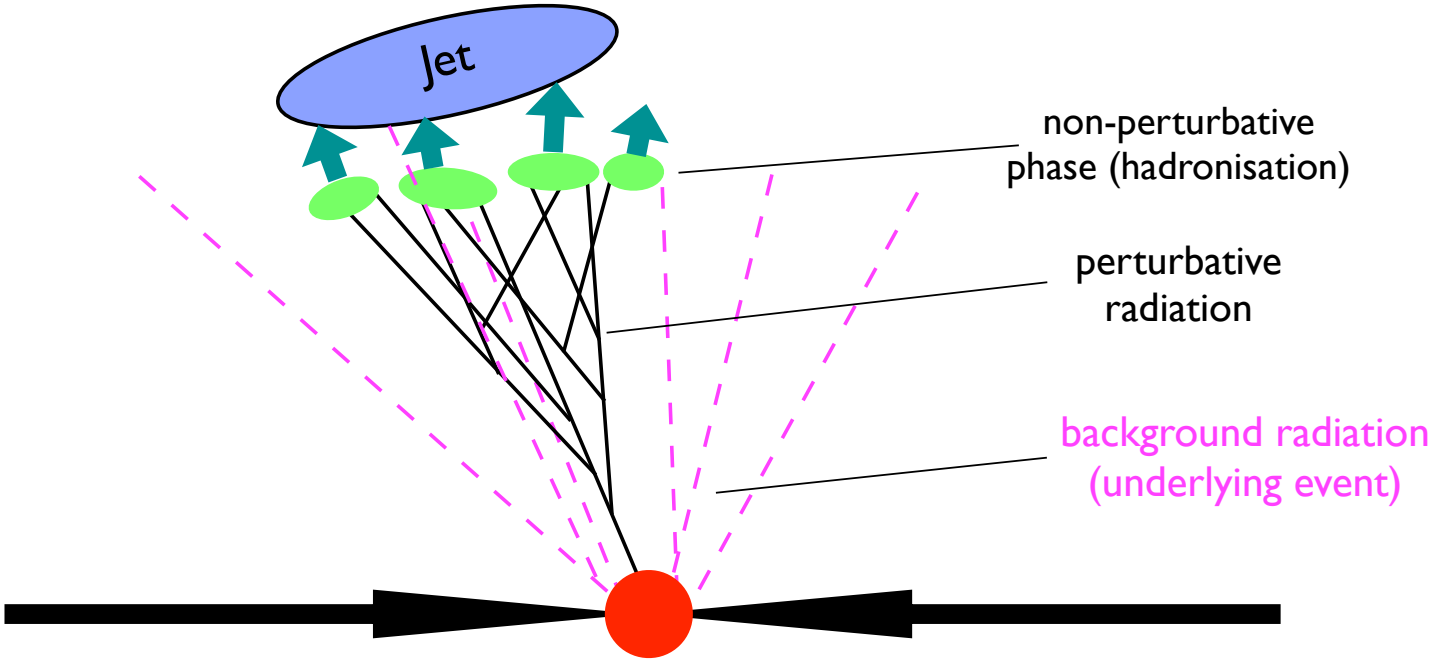
(actual final-state multiplicity ~ several hundred hadrons)

• LHC •

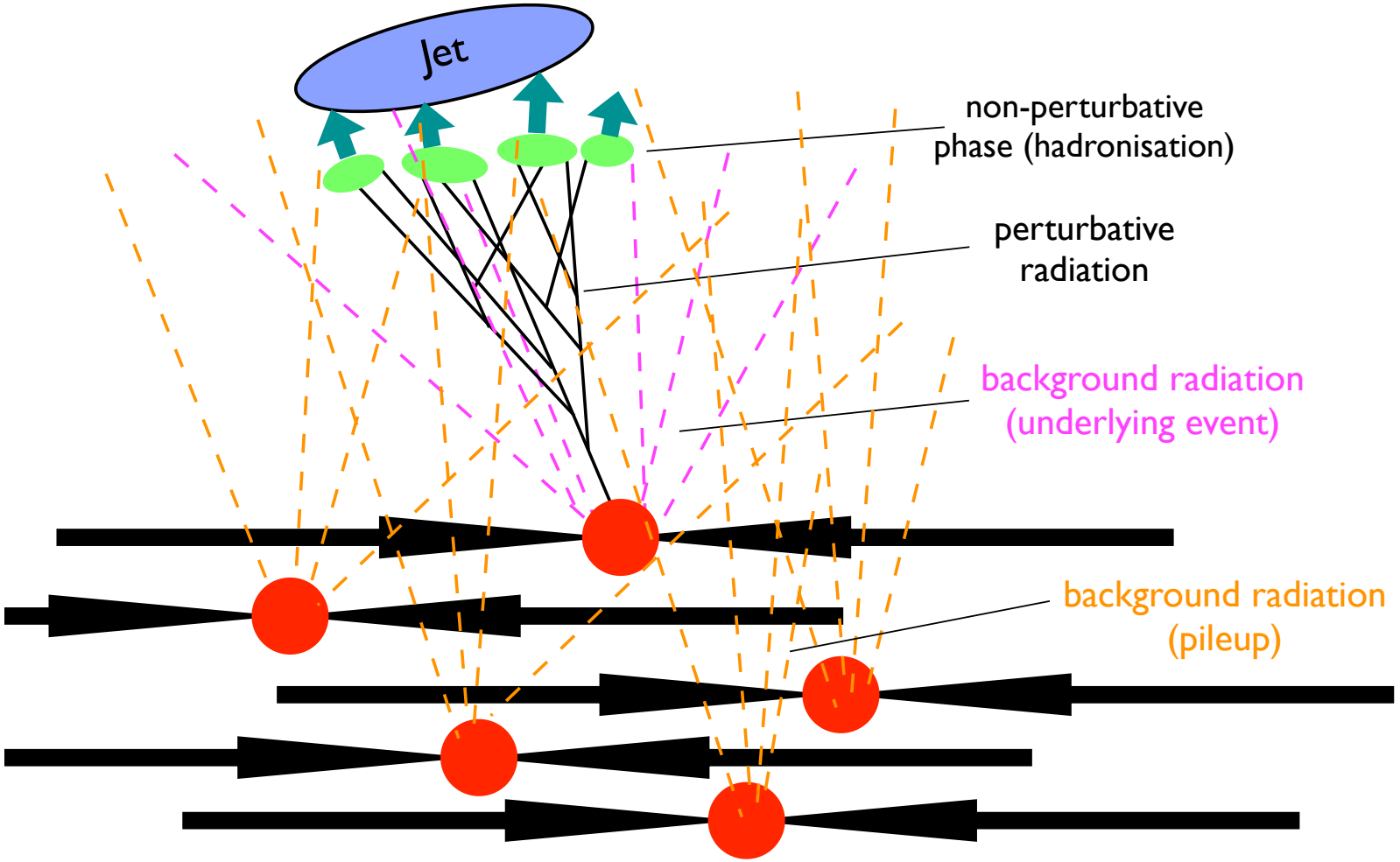

7x10¹² eV p-p Beam Energy
10³⁴ cm⁻² s⁻¹ Luminosity
2835 Nb of bunches
10¹¹ Nb p/bunch
7.5 m (25 ns)
~ μm
~ cm
Bunch collisions 40 million/s
~25 interactions / Bunch crossing overlapping in time and space
1000 x 10⁶ events/s
New Particle Production
(Higgs, SUSY, ...)
> 1000 particle signals in the detector at 40MHz rate
1 interesting collision in 10¹³


LHC
bunches
protons
partons
(quarks, gluons)

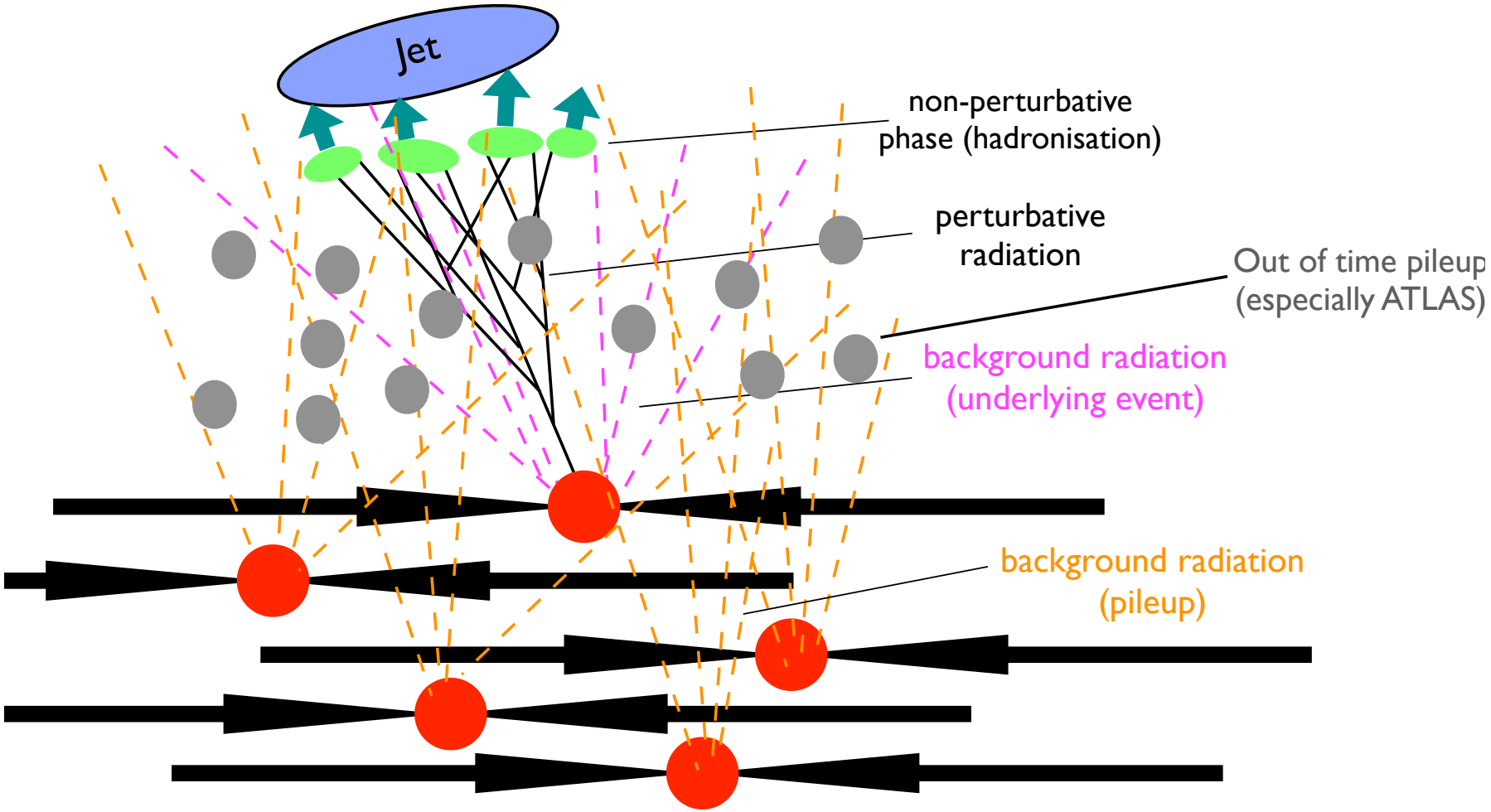
More realistic picture of proton-proton collisions



Even more realistic picture of proton-proton collisions

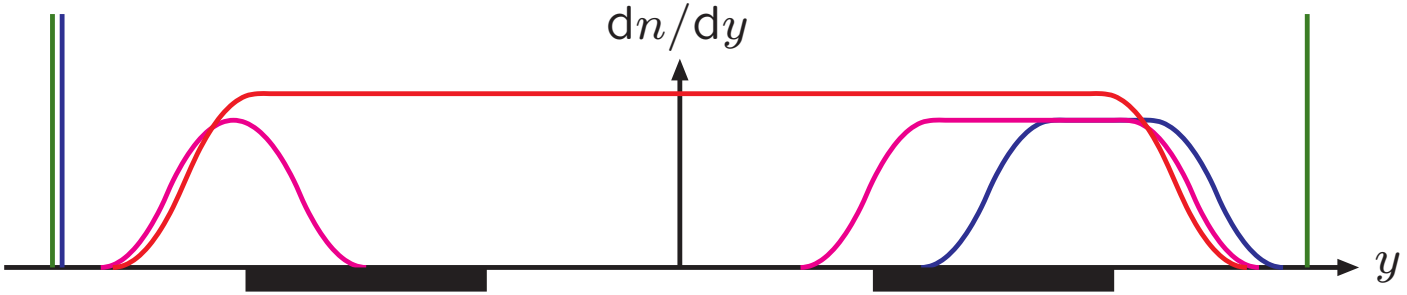


Very realistic picture of proton-proton collisions



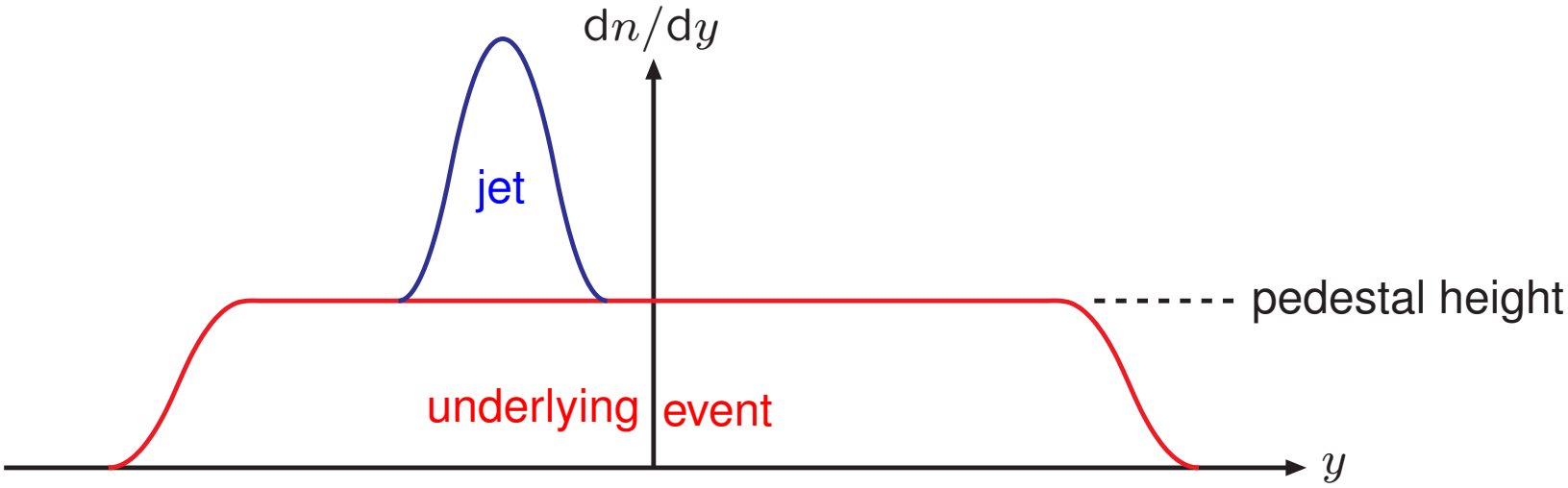
Total cross section

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



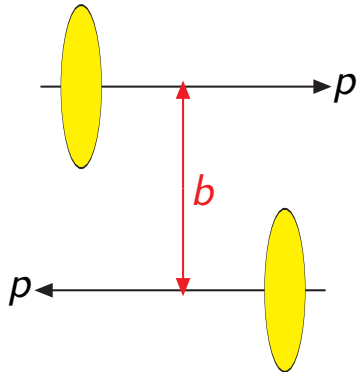
- Experimentally minimum bias $\approx$ all events with no bias from trigger conditions
- Theoretically $\sigma_{\text{min-bias}} \approx \sigma_{\textit{double-diffractive}} + \sigma_{\textit{non-diffractive}}$

Hard scattering + Underlying event



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

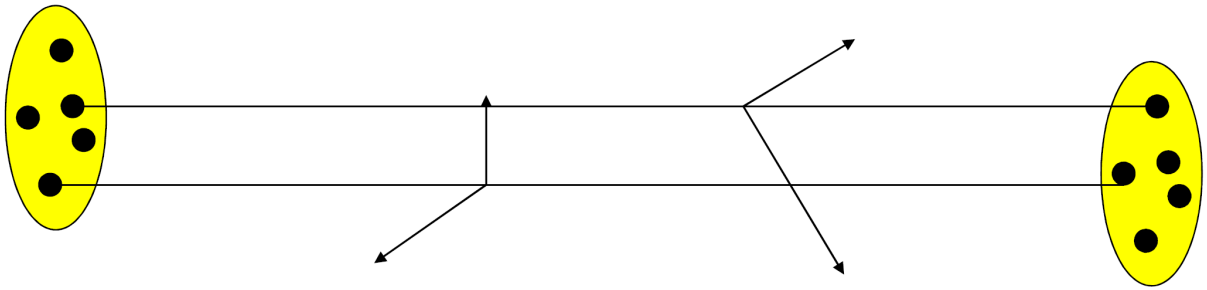
Underlying event



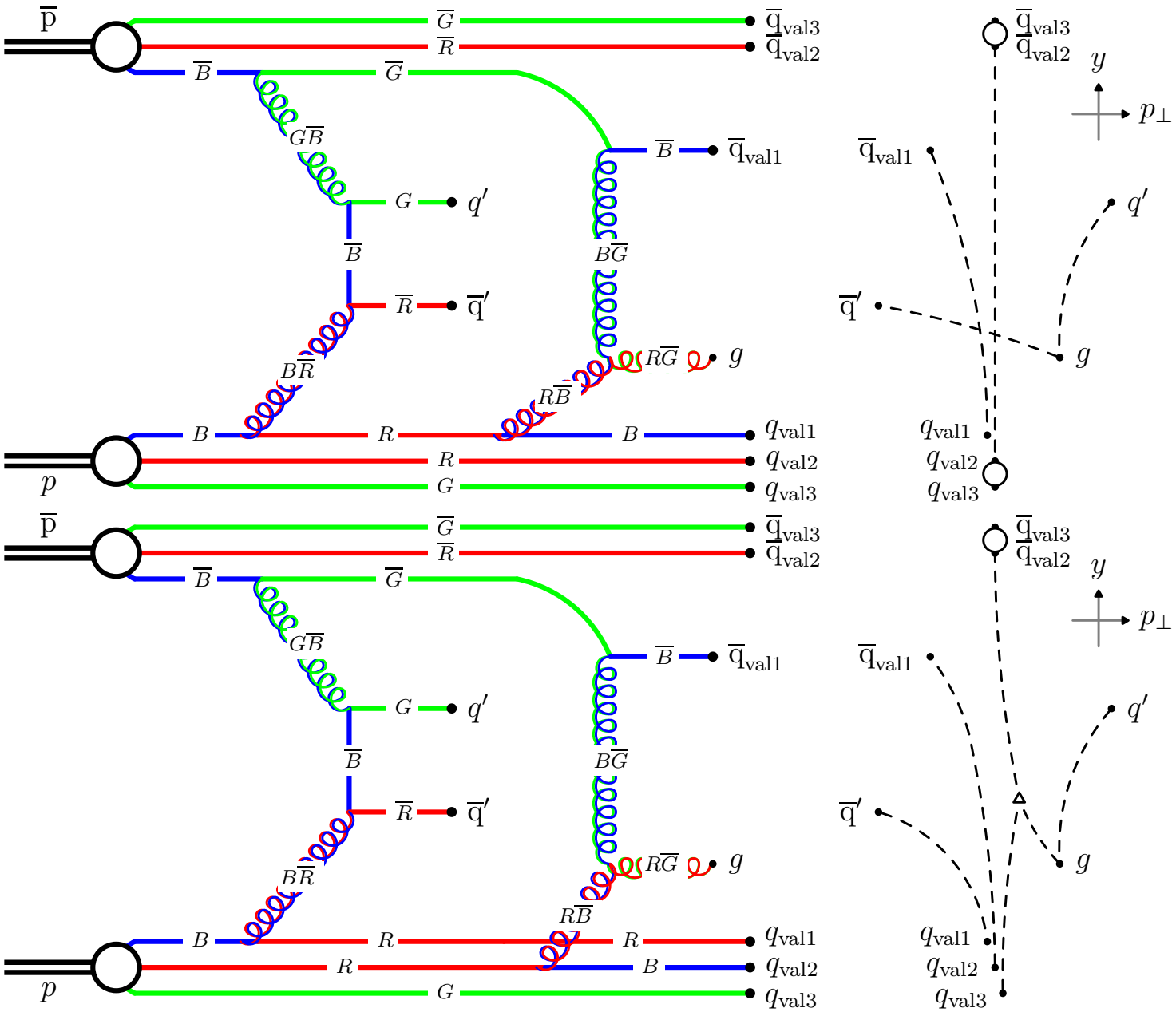
- If the interactions occur independently obeys Poissonian statistics

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

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

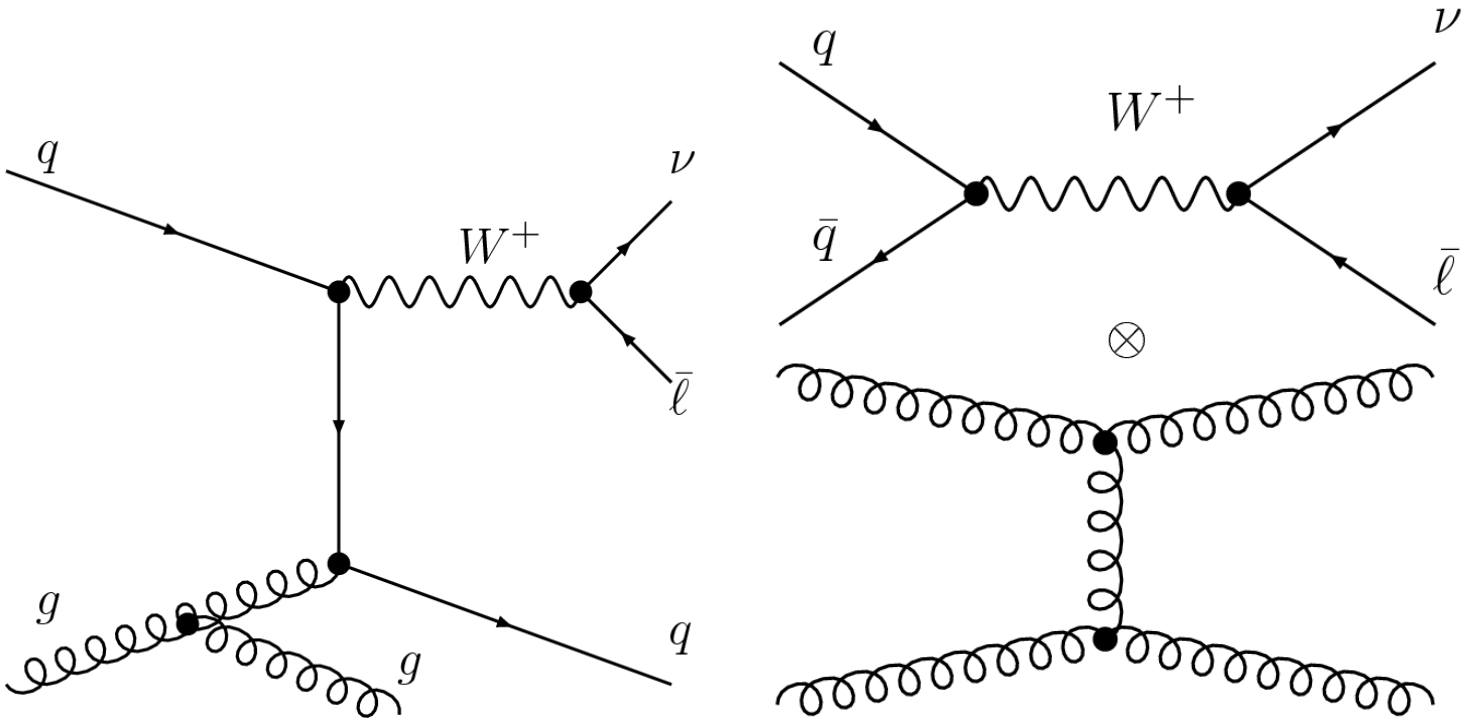


Underlying event (color correlation)



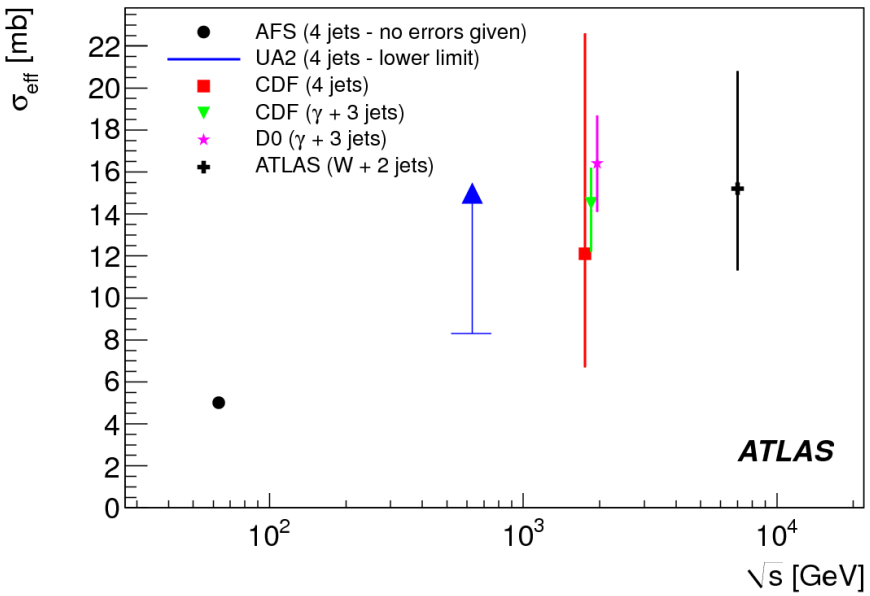
Multiple interactions : measurement

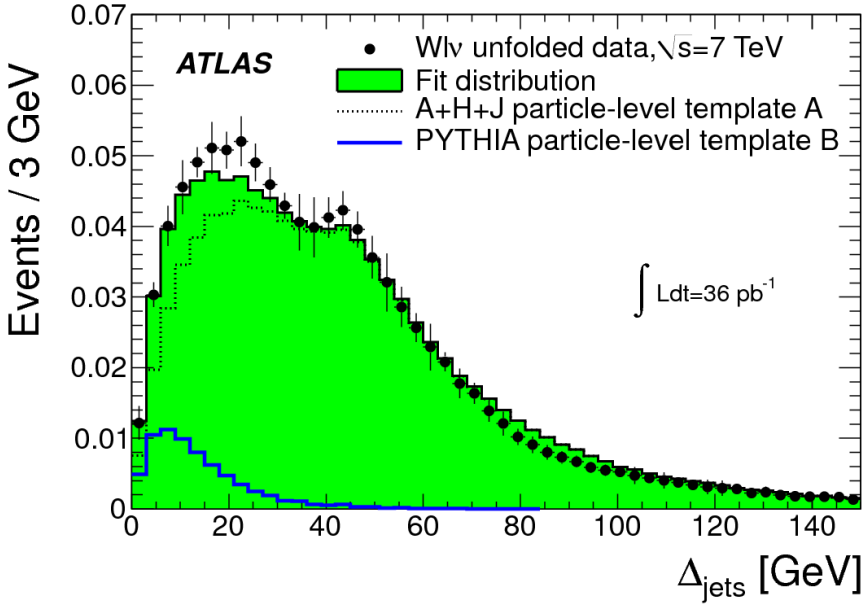
$$\mathrm{d}\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s) = \frac{m}{2\sigma_{\mathrm{eff}}(s)} \int \mathrm{d}x_{i_1}\, \mathrm{d}x_{j_1}\, \mathrm{d}x_{i_2}\, \mathrm{d}x_{j_2}\, [f_{i_1 j_1}(x_{i1}, x_{j_1}, \mu_F)$$
$$f_{i_2 j_2}(x_{i_2}, x_{j_2}, \mu_F)\, \mathrm{d}\hat{\sigma}_{i_1 i_2 \to Y}(x_{i_1},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



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

Multiple interactions : measurement



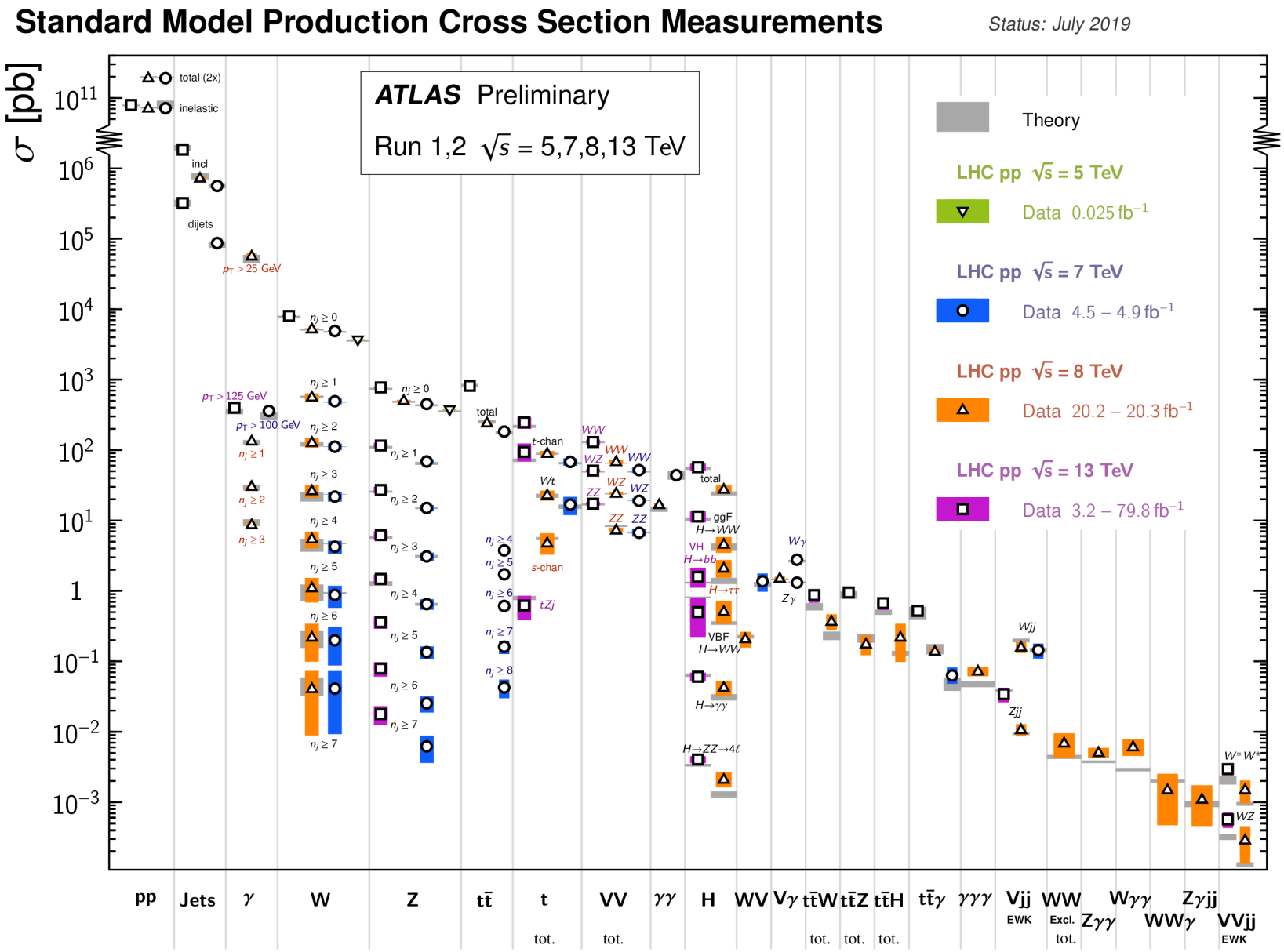


$$f_{DP}^{(P)} = \frac{N^P(W_{0j} + 2j_{DPI})}{N^P(W_{0j} + 2j_{DPI}) + N^P(W_{2j})},$$

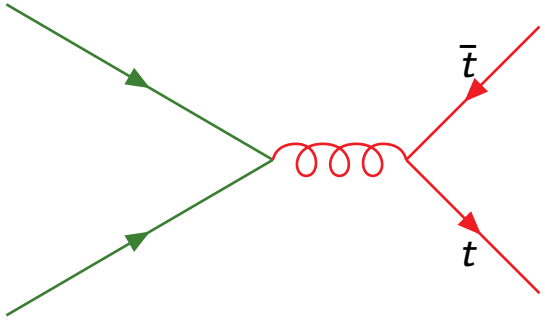
$$f_{DP}^{(D)} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{sys.})$$

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

Standard Model total cross sections

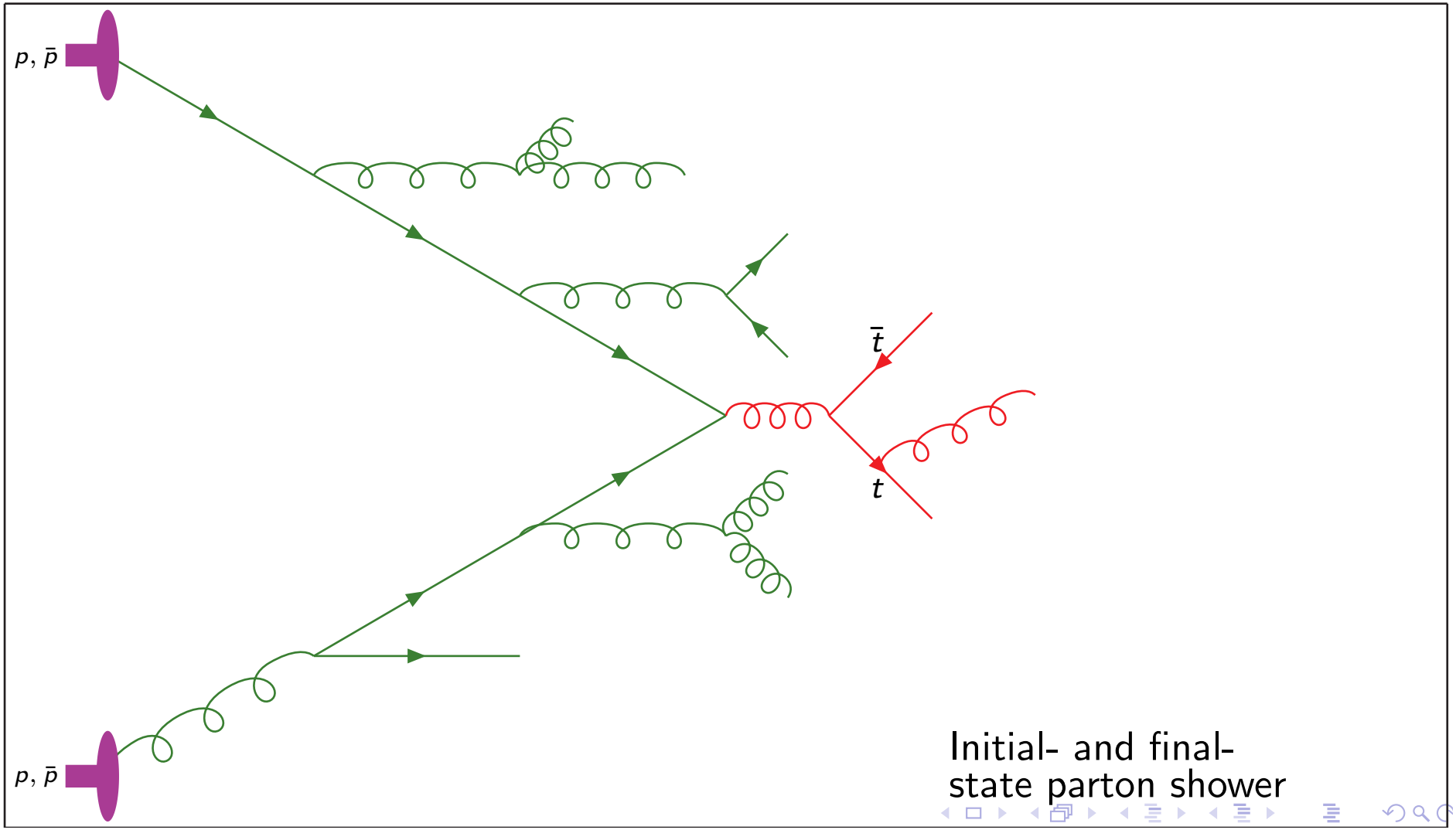


Proton-proton collision : Monte Carlo event

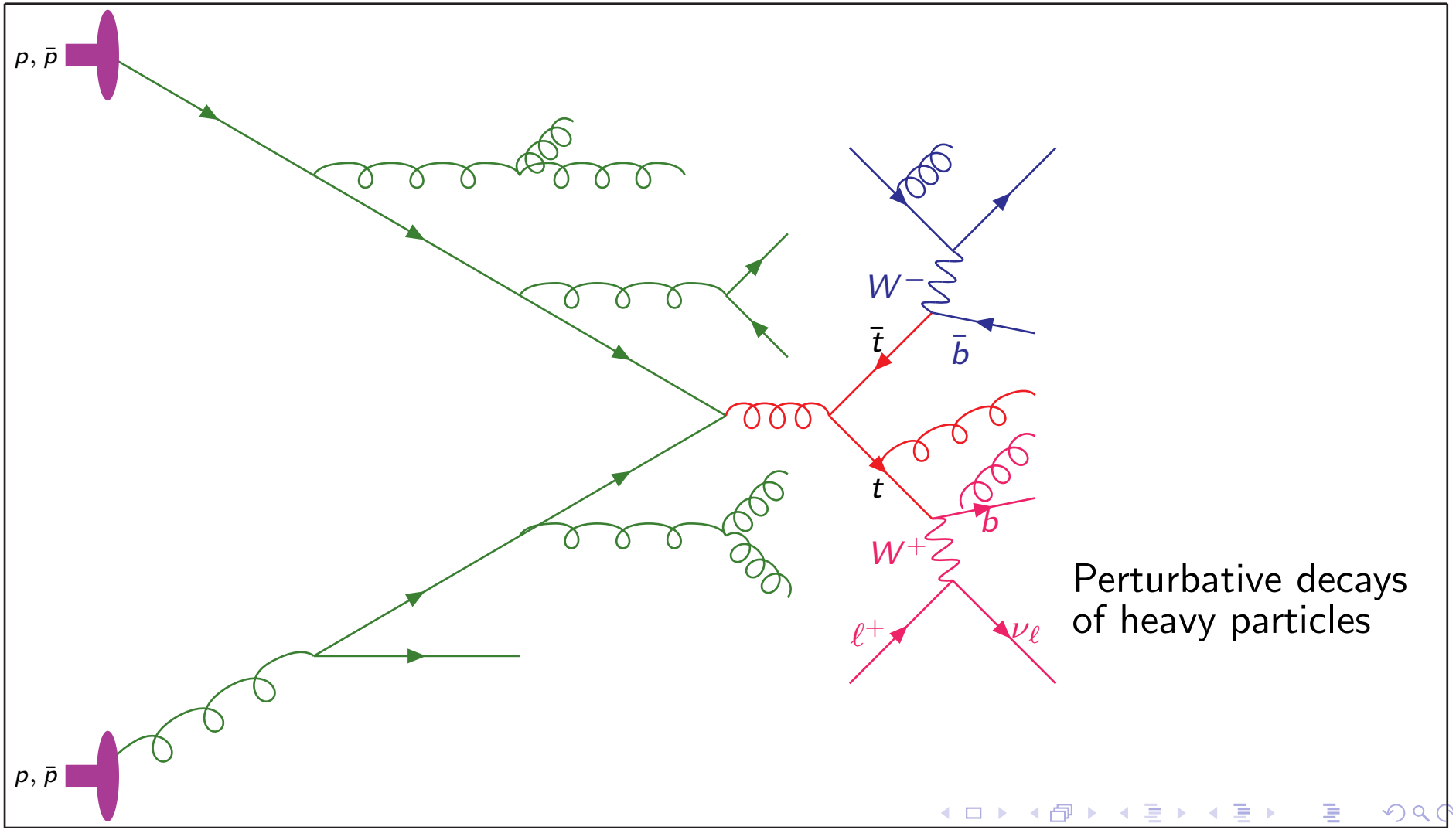


Hard Process, usually calculated at leading order

Proton-proton collision : Monte Carlo event

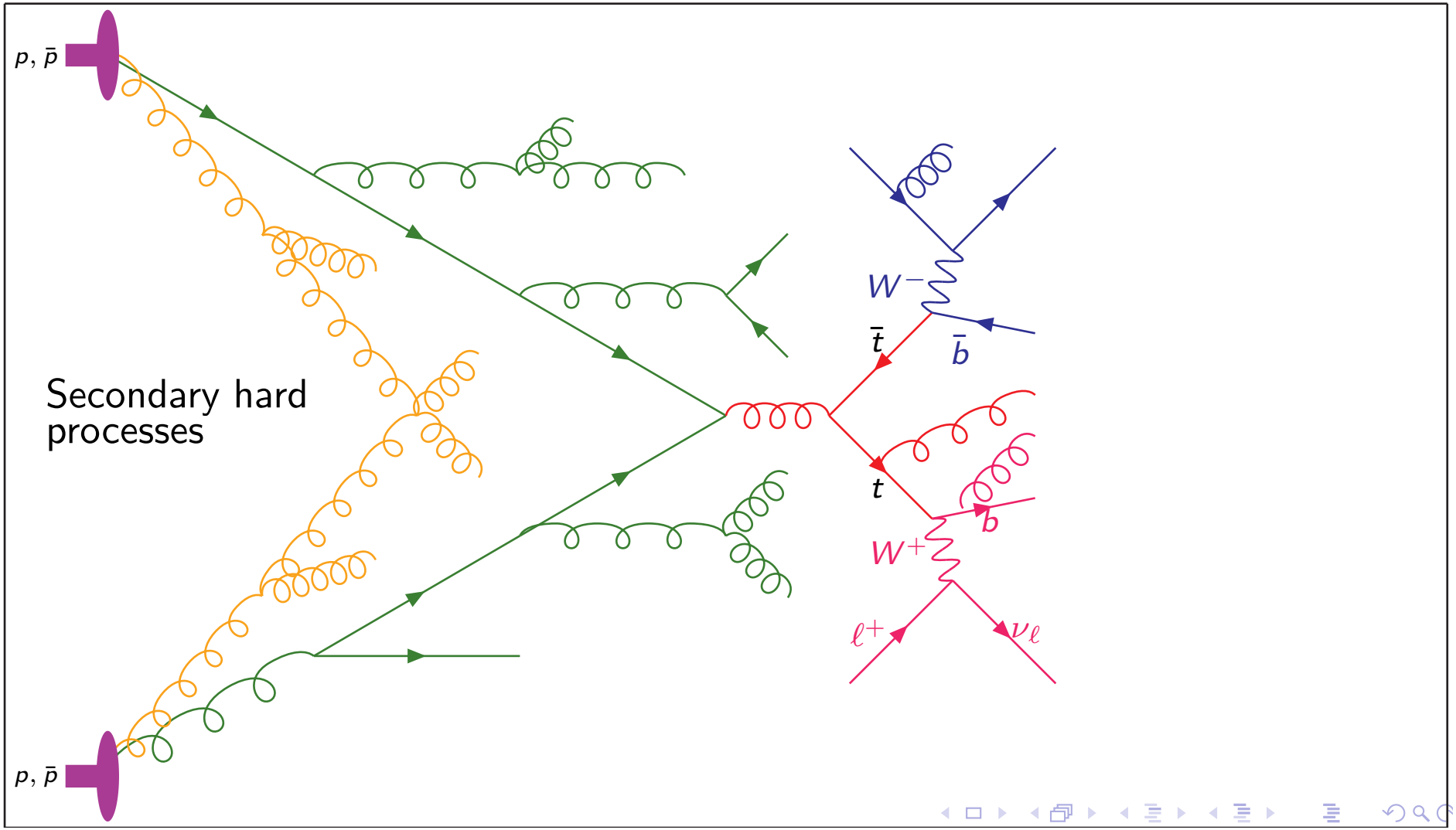


Proton-proton collision : Monte Carlo event

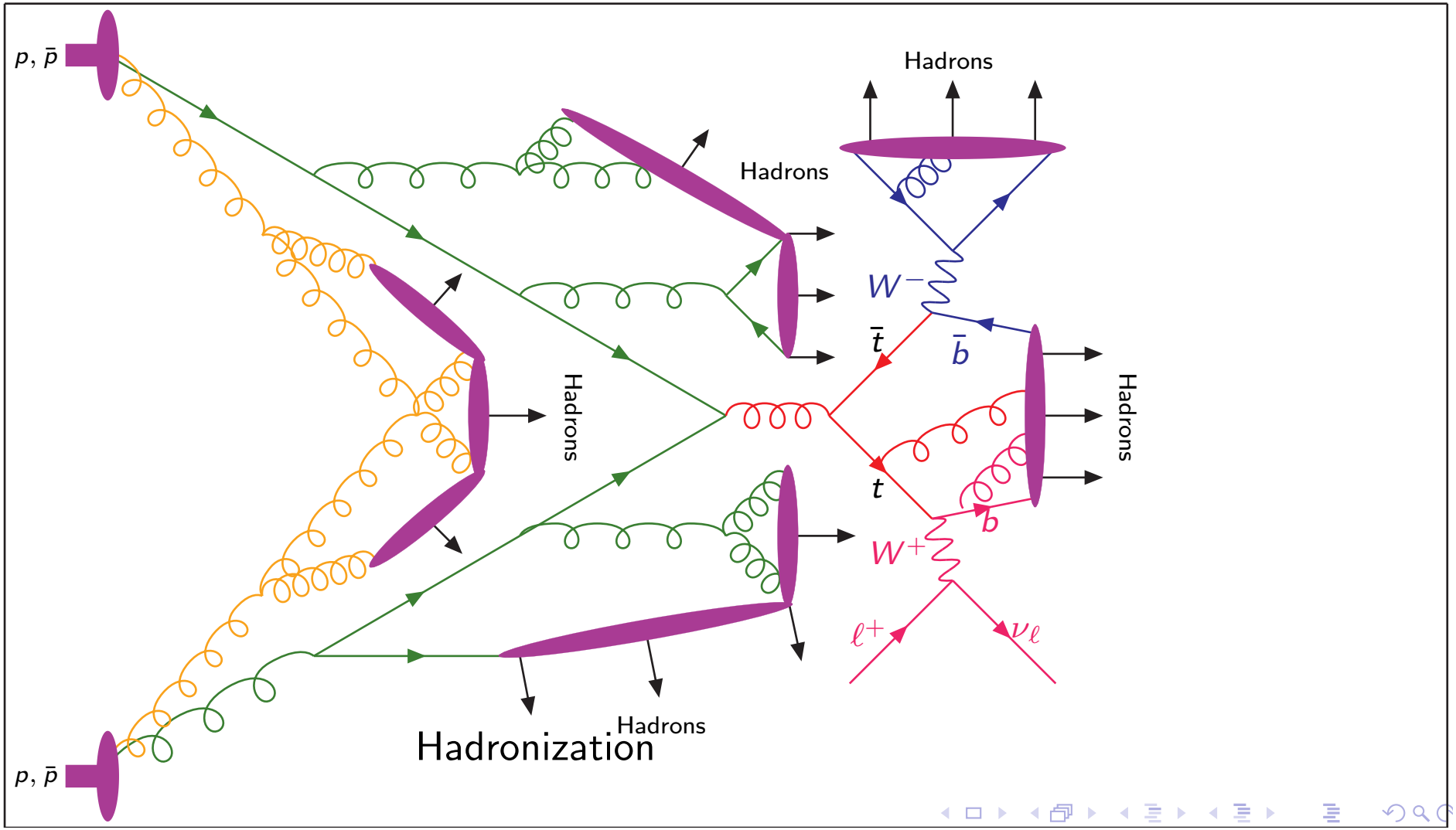


Perturbative decays of heavy particles

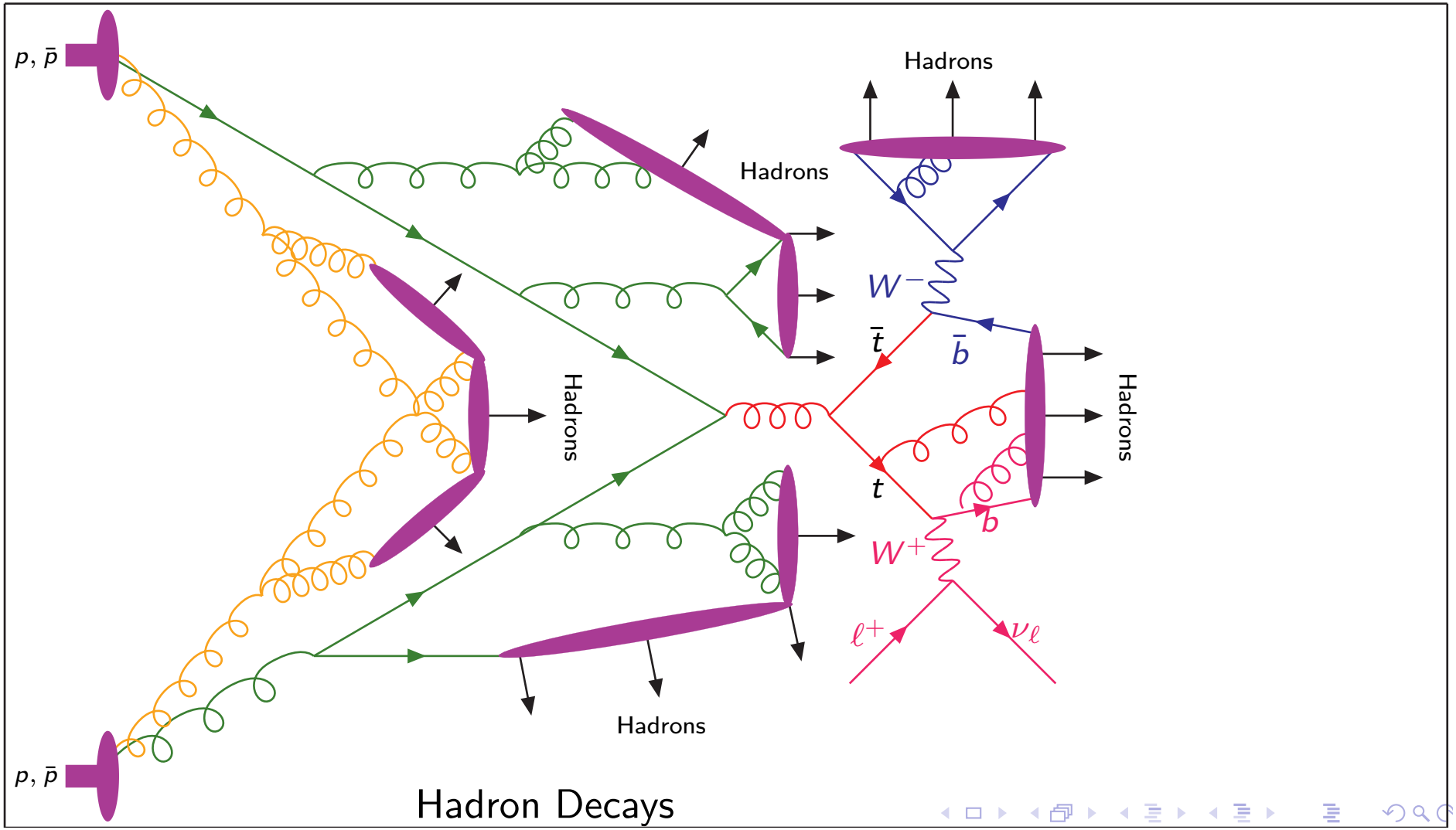
Proton-proton collision : Monte Carlo event



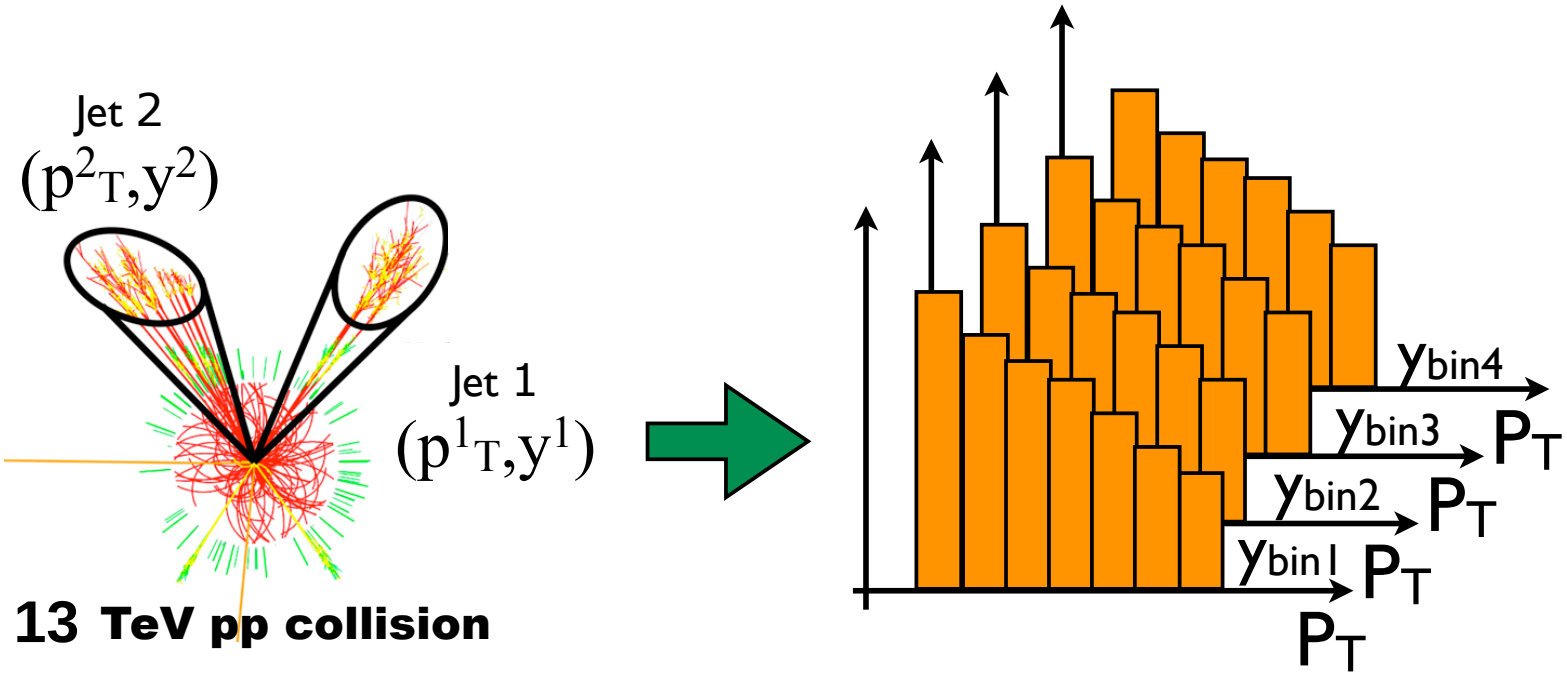
Proton-proton collision : Monte Carlo event



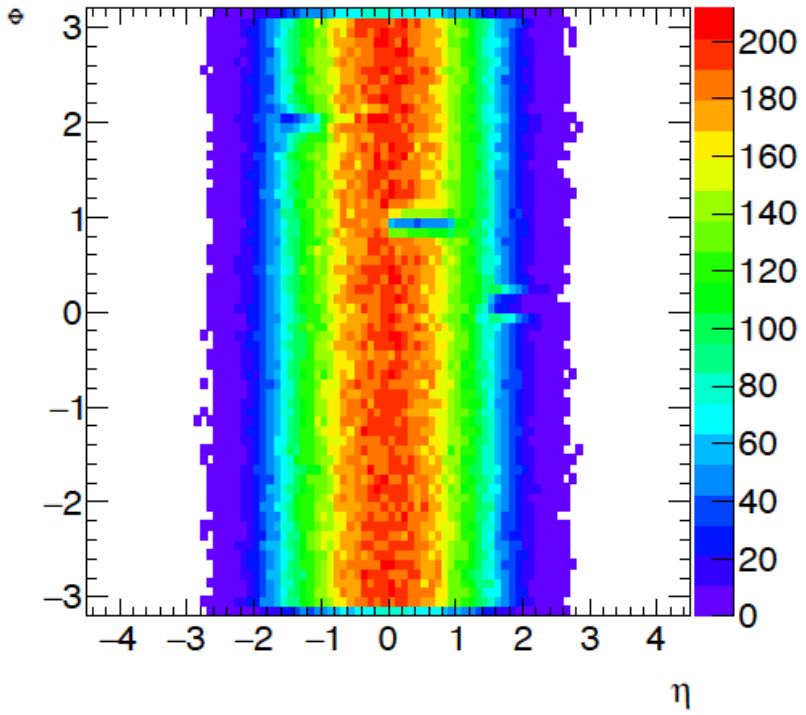
Proton-proton collision : Monte Carlo event

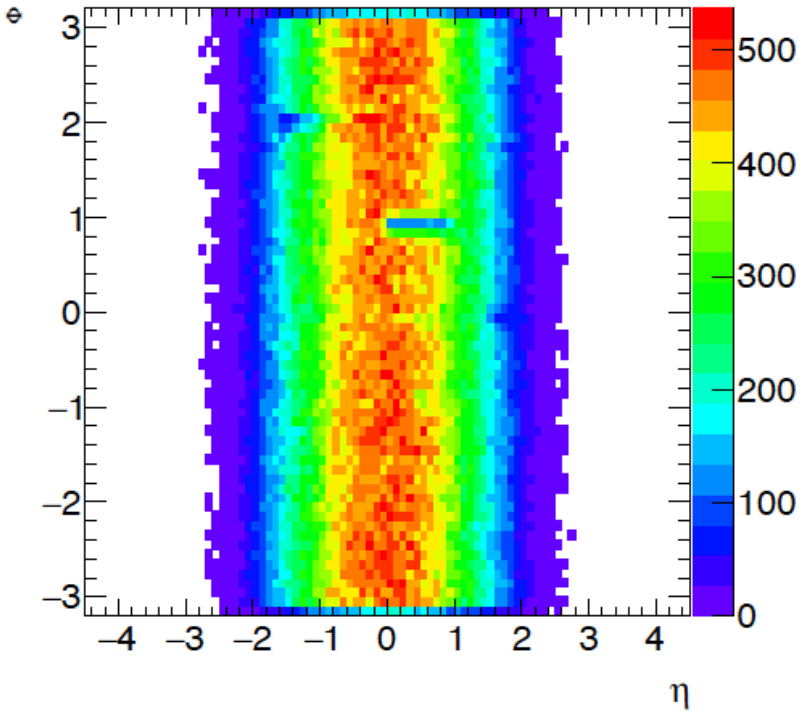


Jet cross section measurement

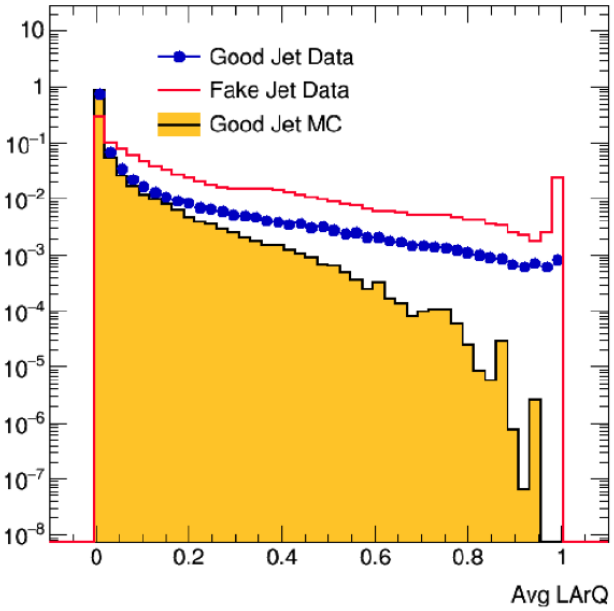


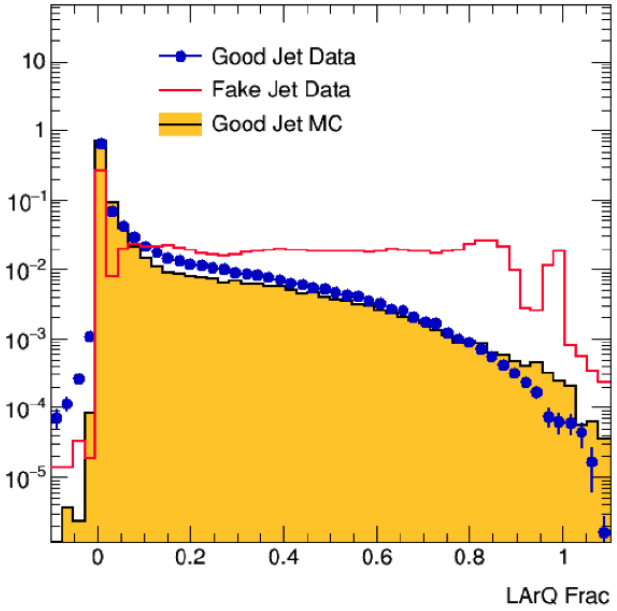
Instrumental effects : problematic modules

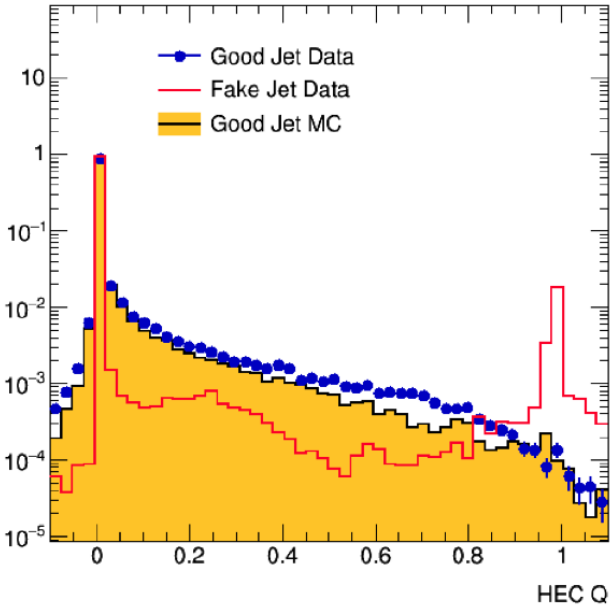




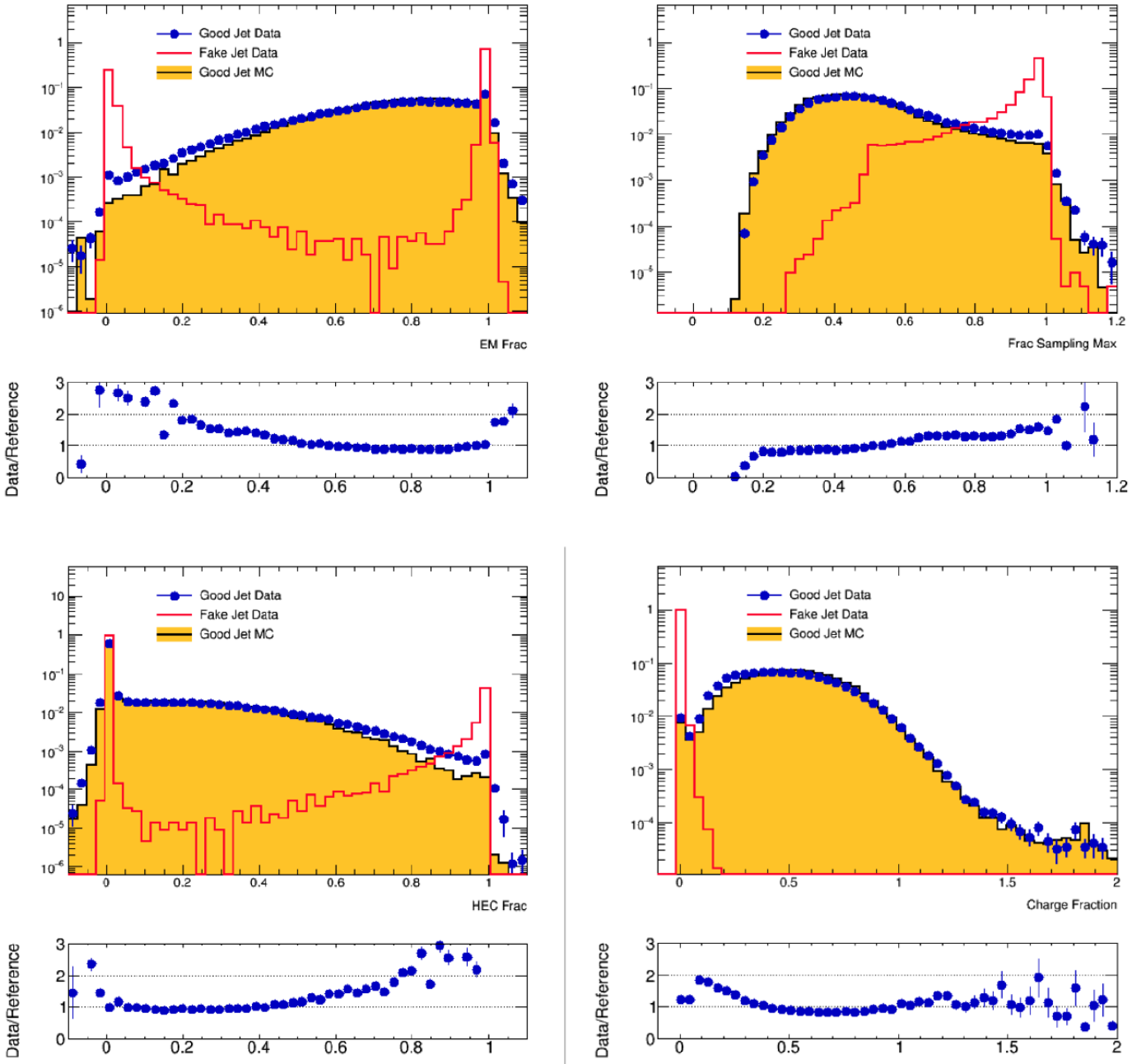
Instrumental effects : jet cleaning



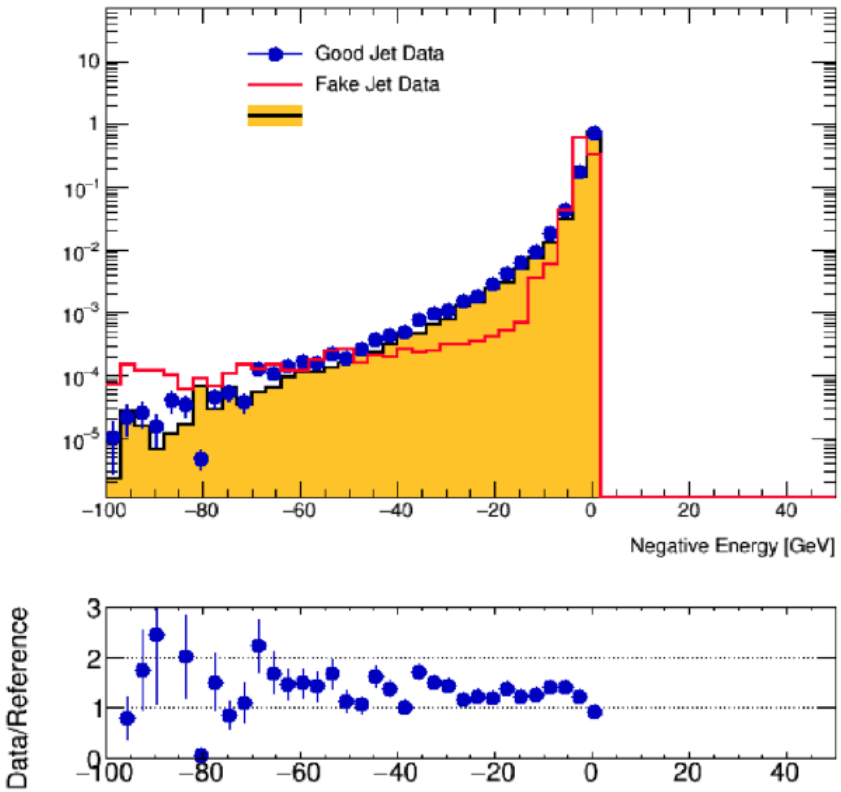


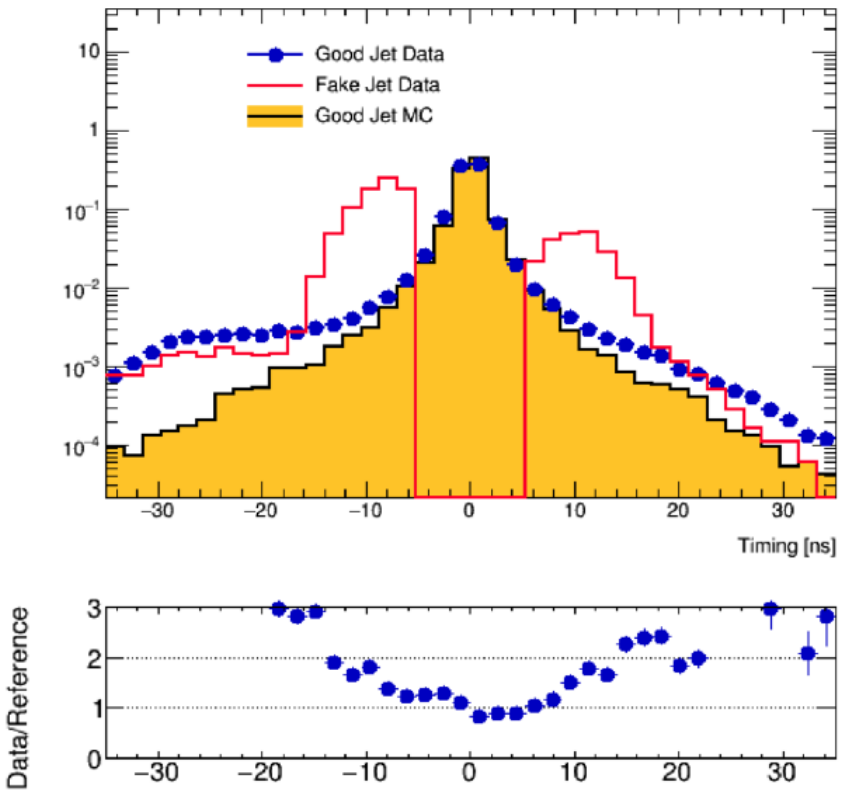


Instrumental effects : jet cleaning

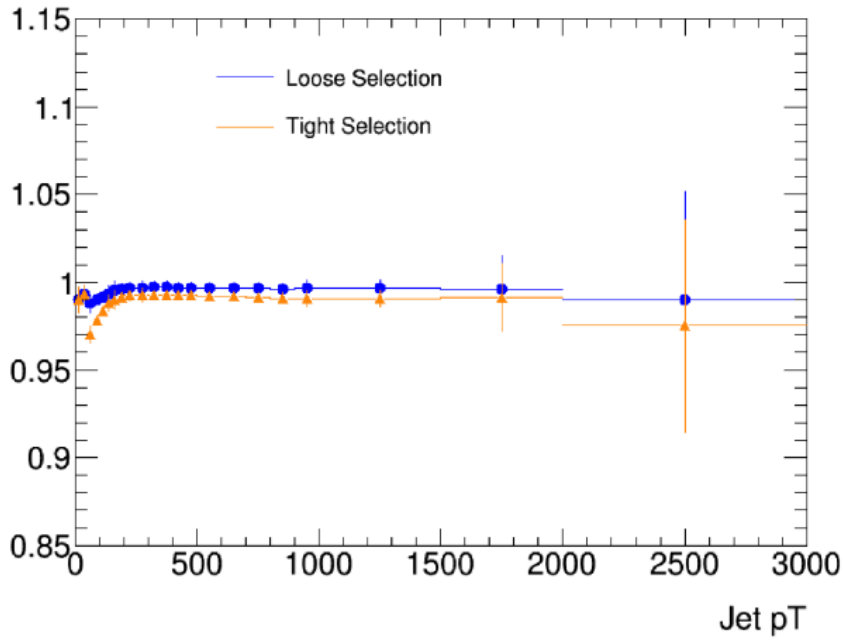


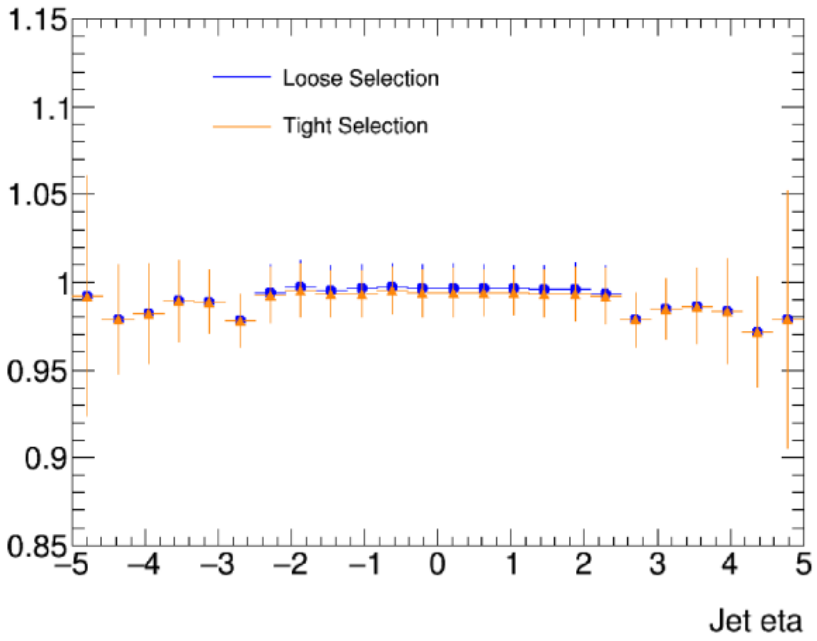
Instrumental effects : jet cleaning



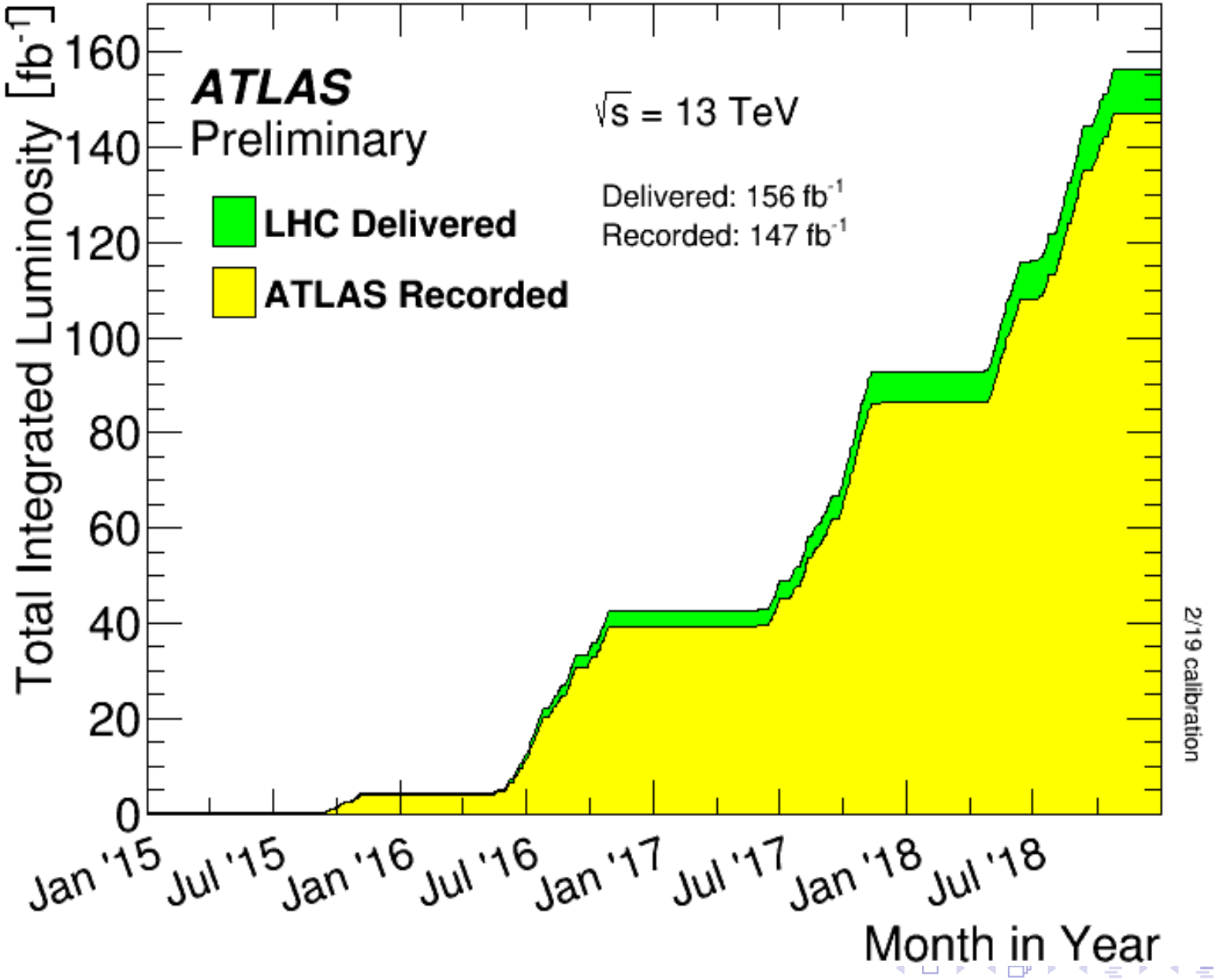


Instrumental effects : jet cleaning

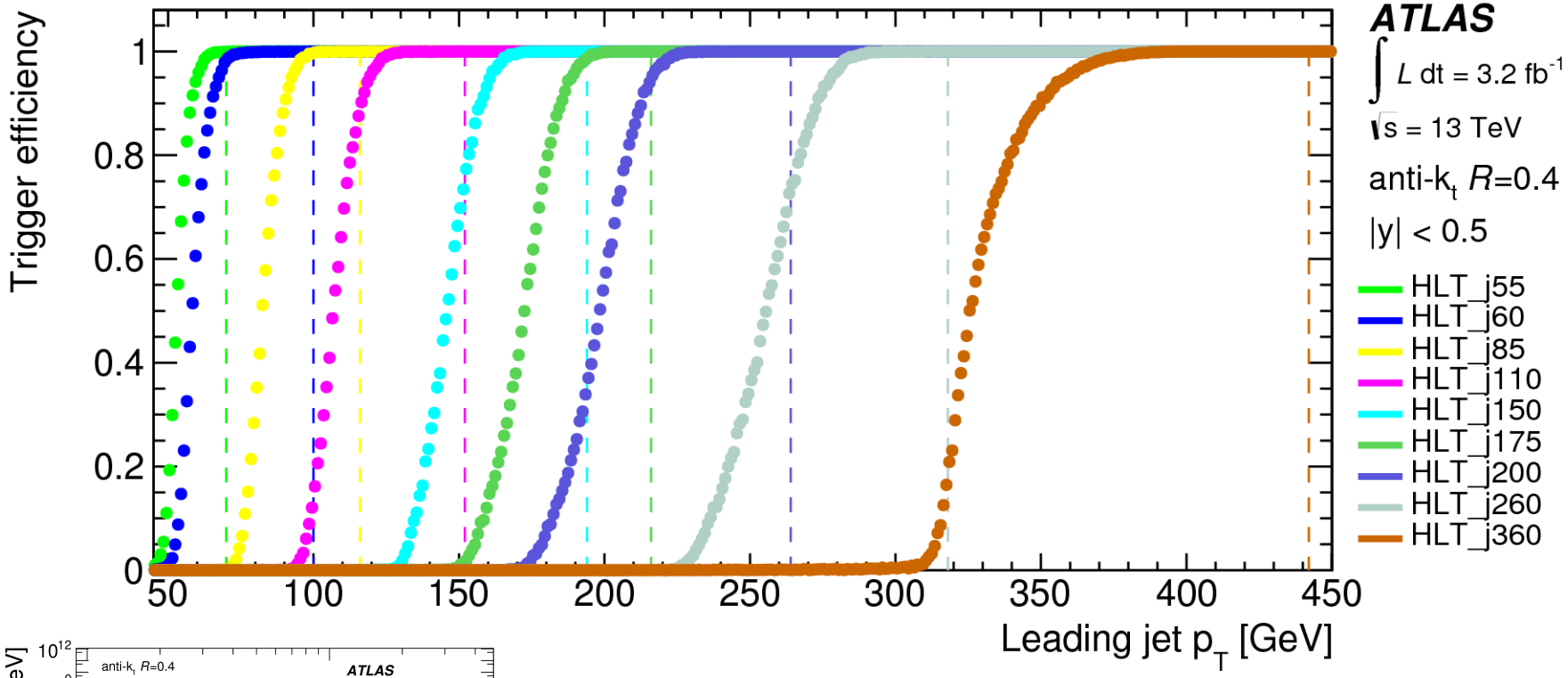


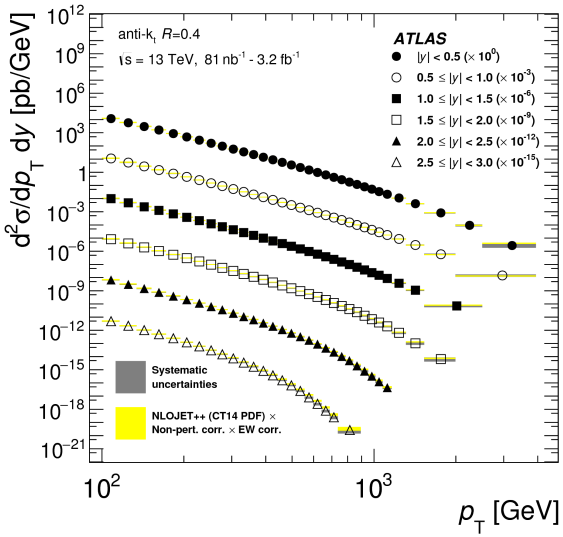


Luminosity

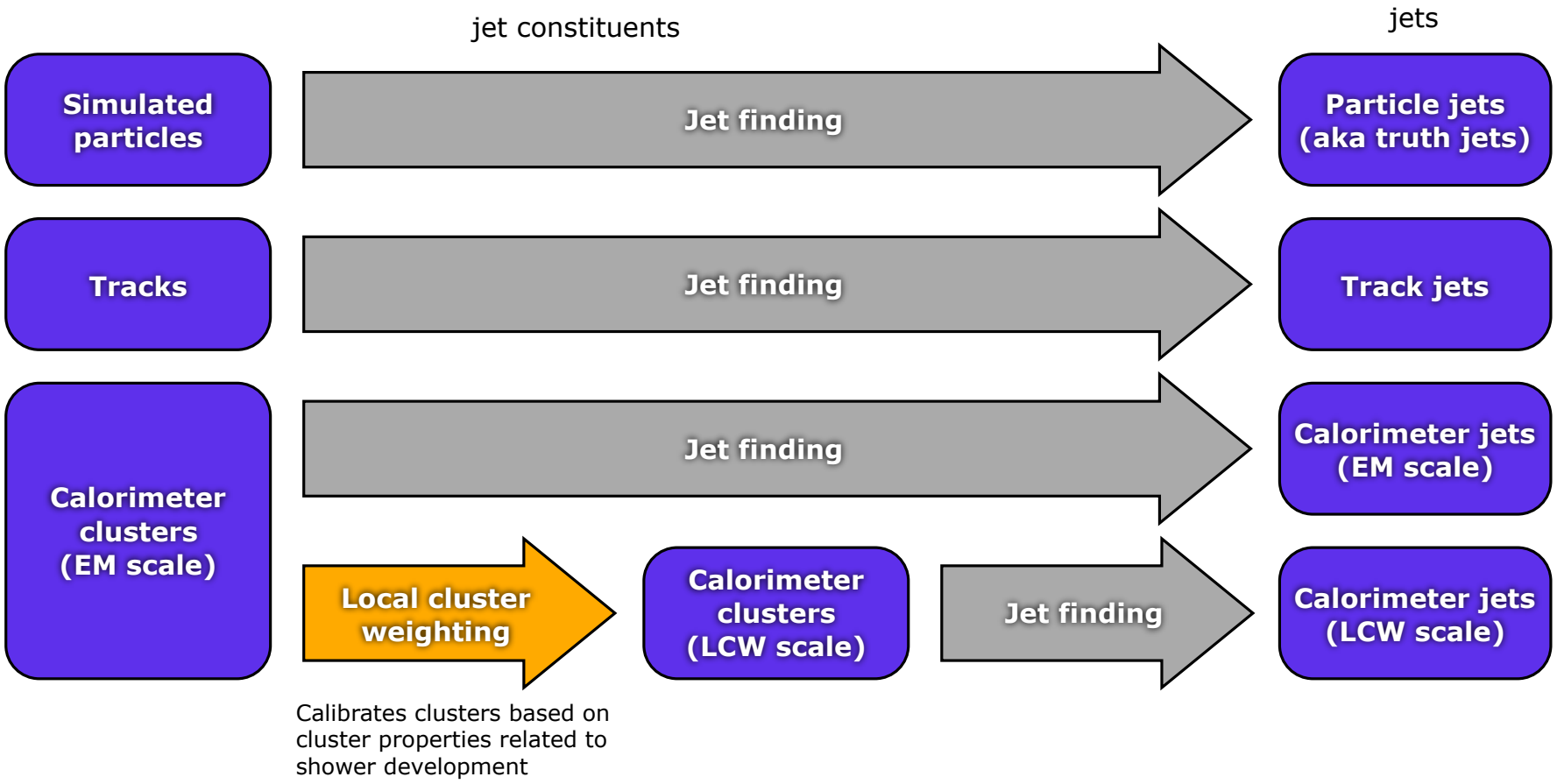

ATLAS
Preliminary
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Delivered: 156 fb-1
Recorded: 147 fb-1
Total Integrated Luminosity [fb-1]
0
20
40
60
80
100
120
140
160
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Month in Year
2/19 calibration

Triggering Inclusive jets

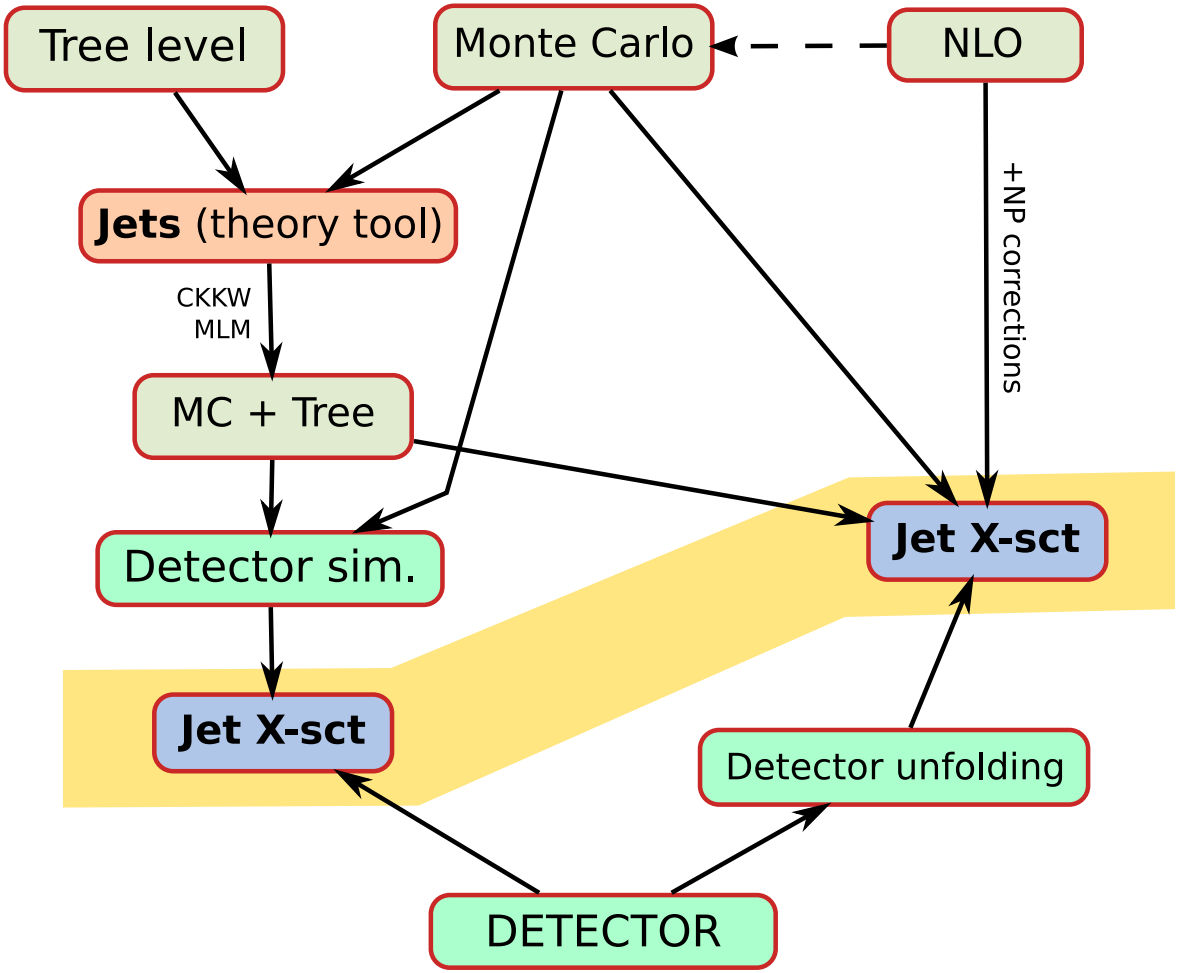




Levels of jet definition



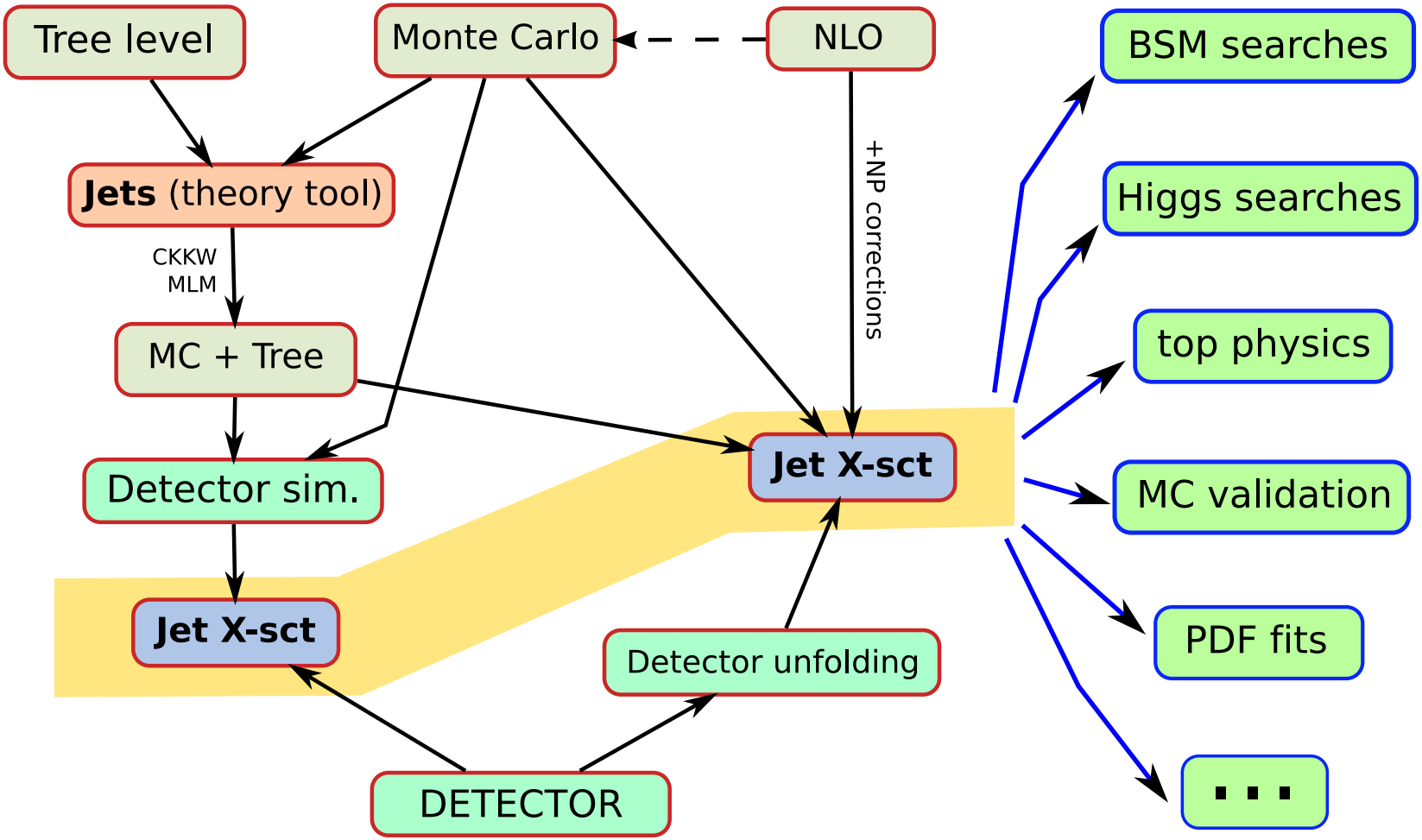
Unfolding



Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

Unfolding



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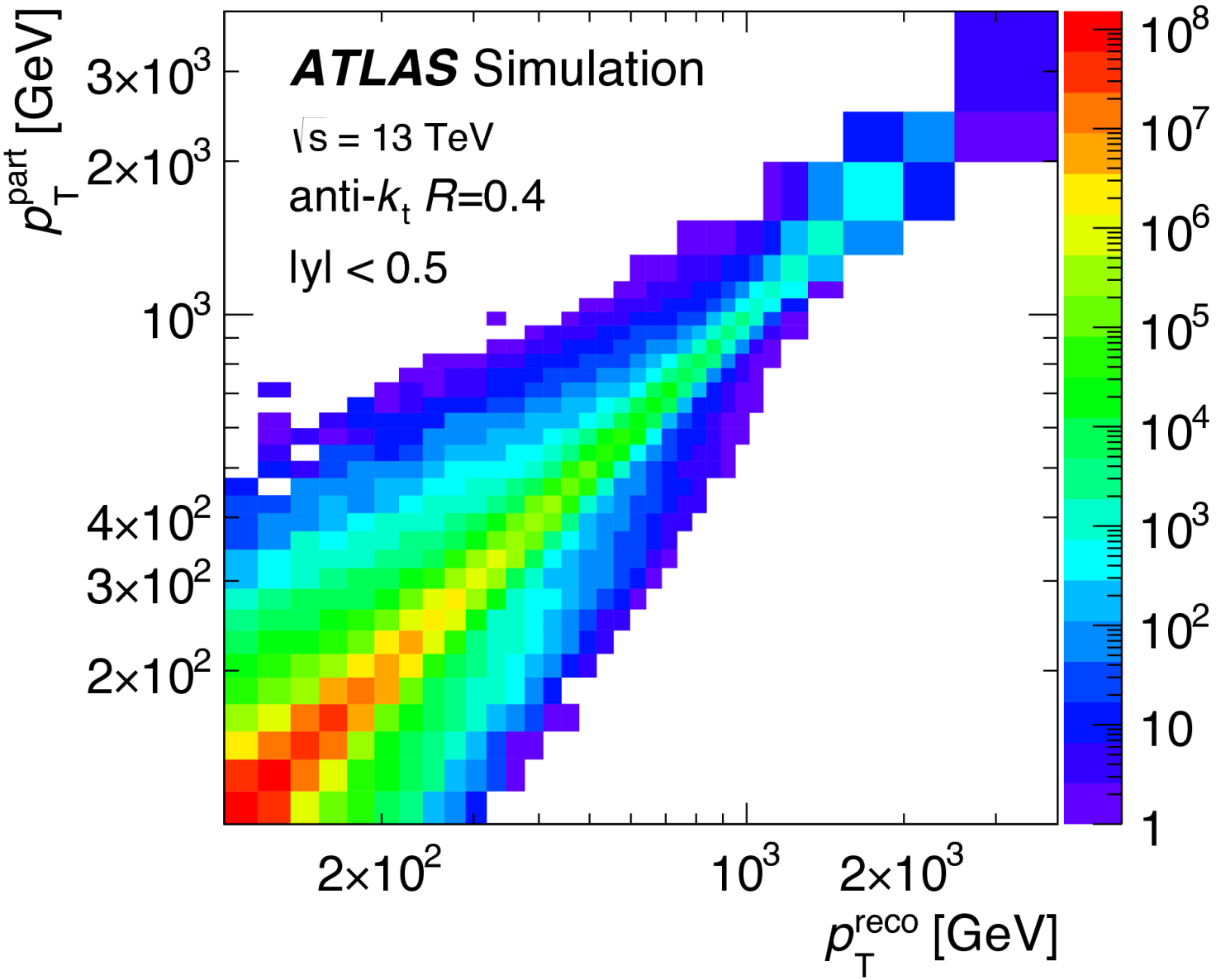
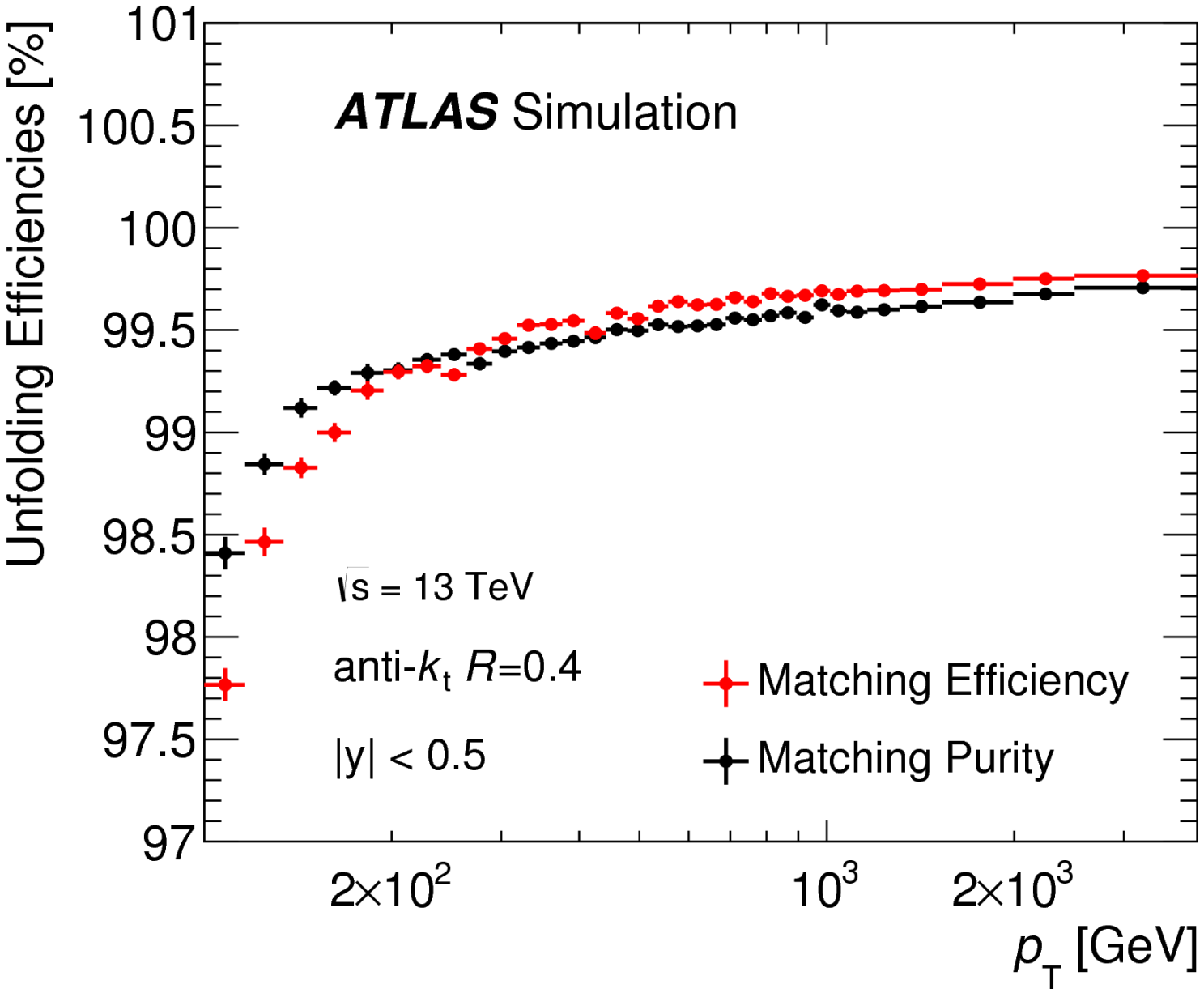
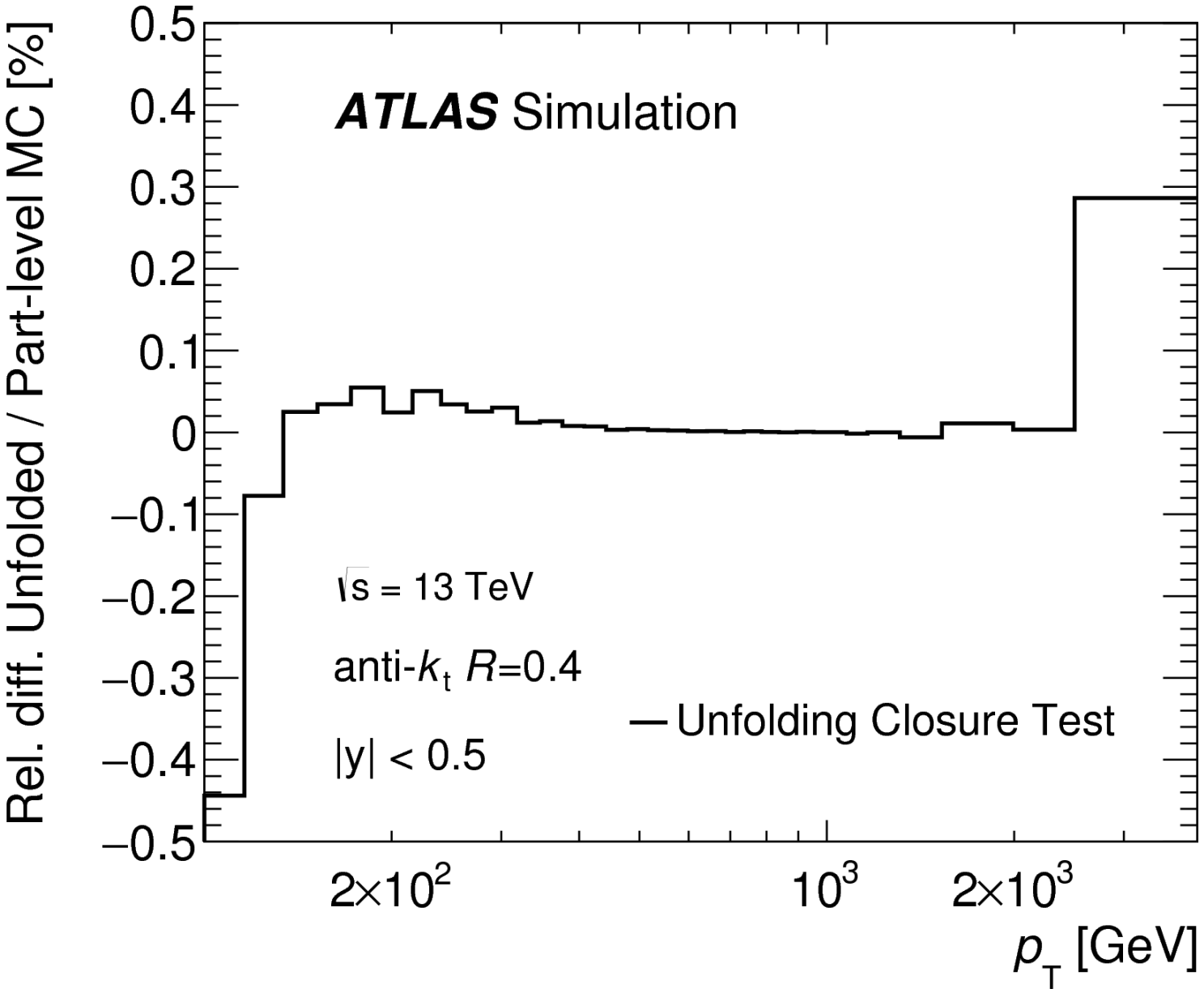
Unfolding matrix



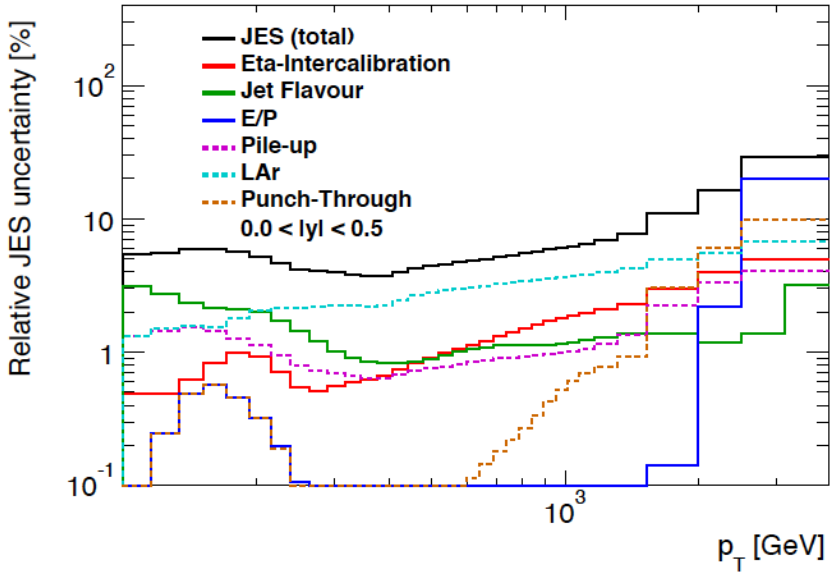
Unfolding efficiencies

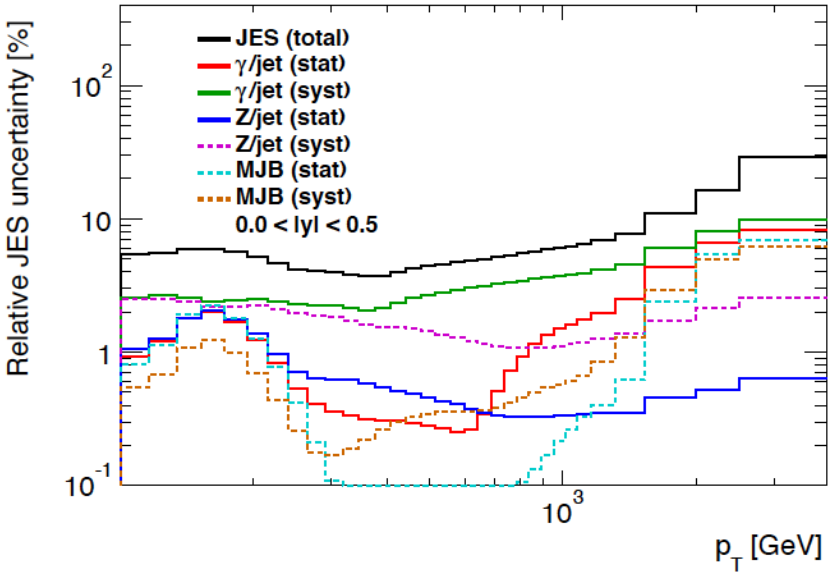


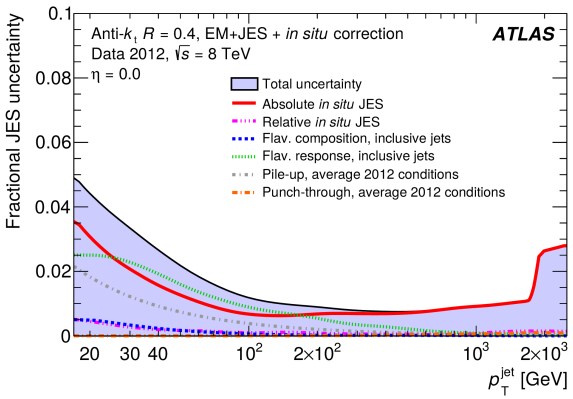
Unfolding bias



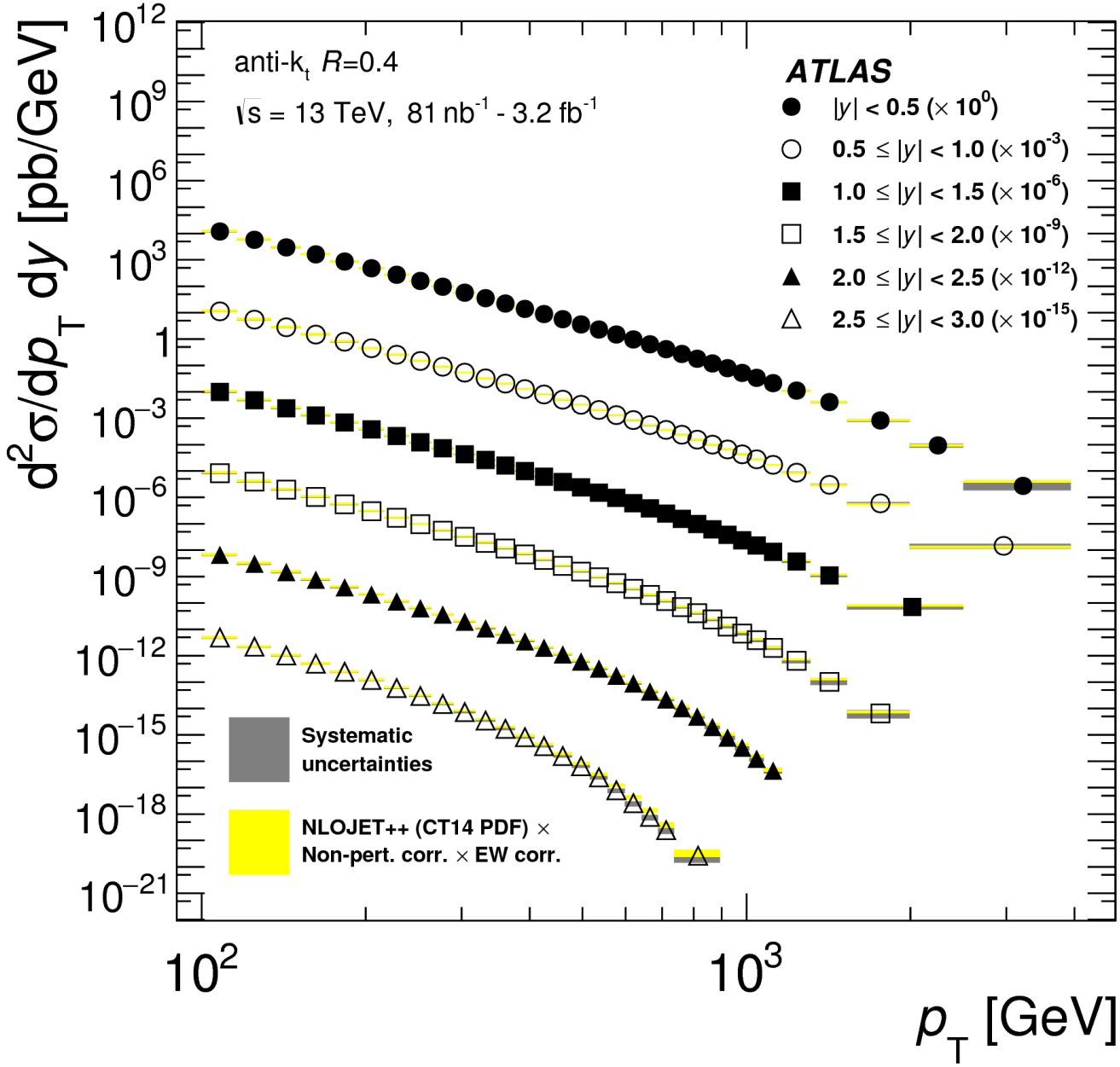
Systematic uncertainties propagation



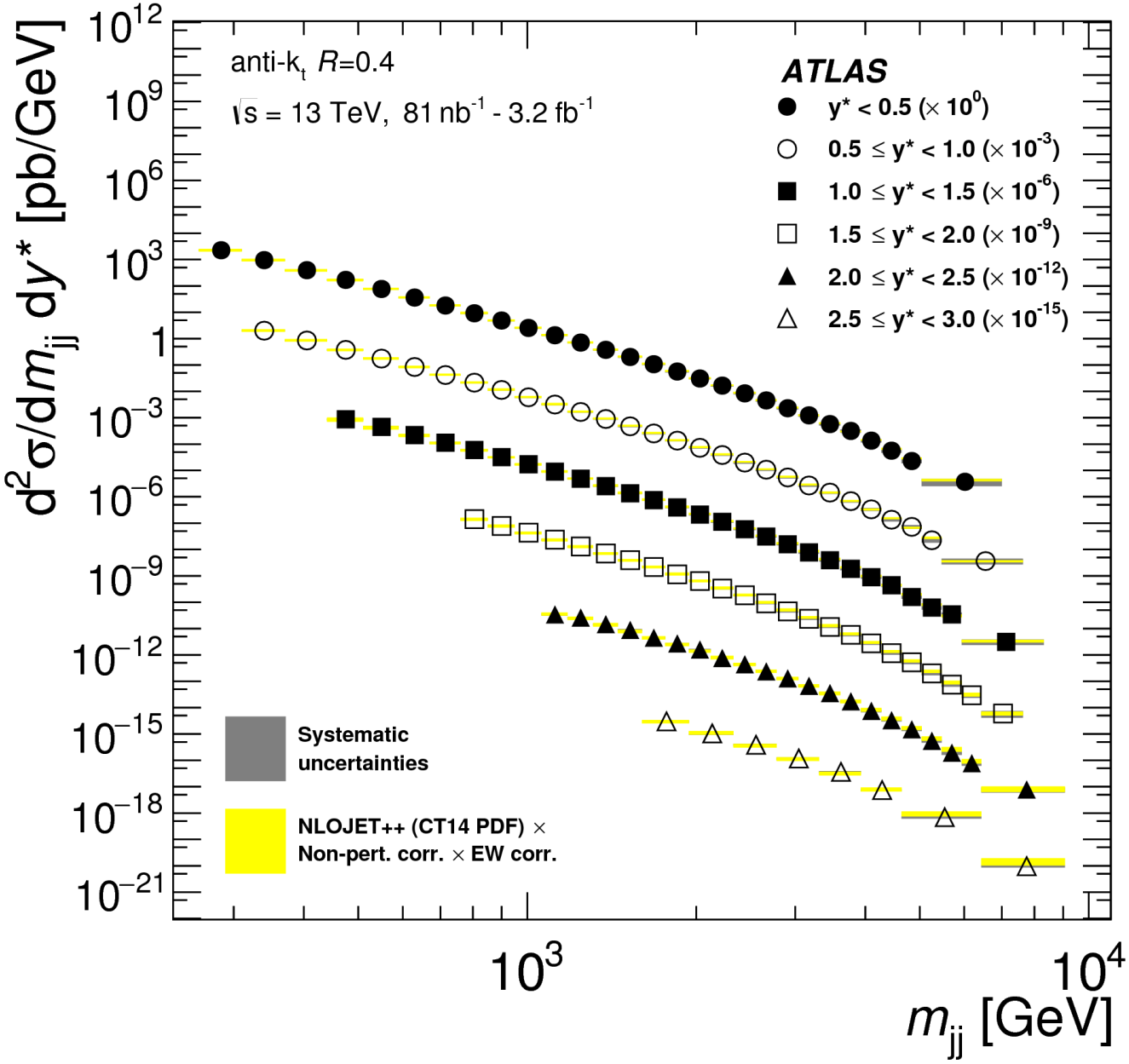




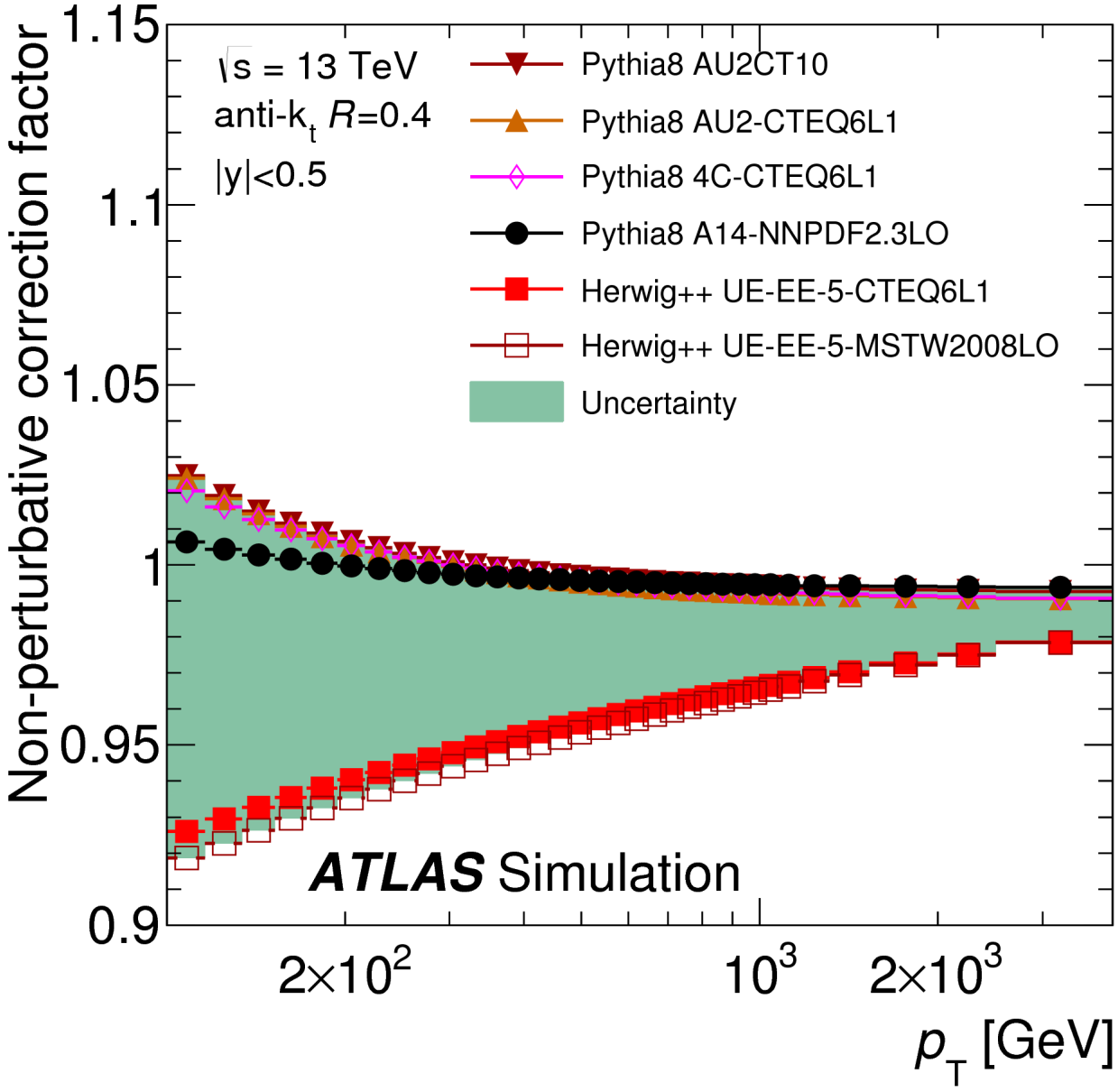
Inclusive jets



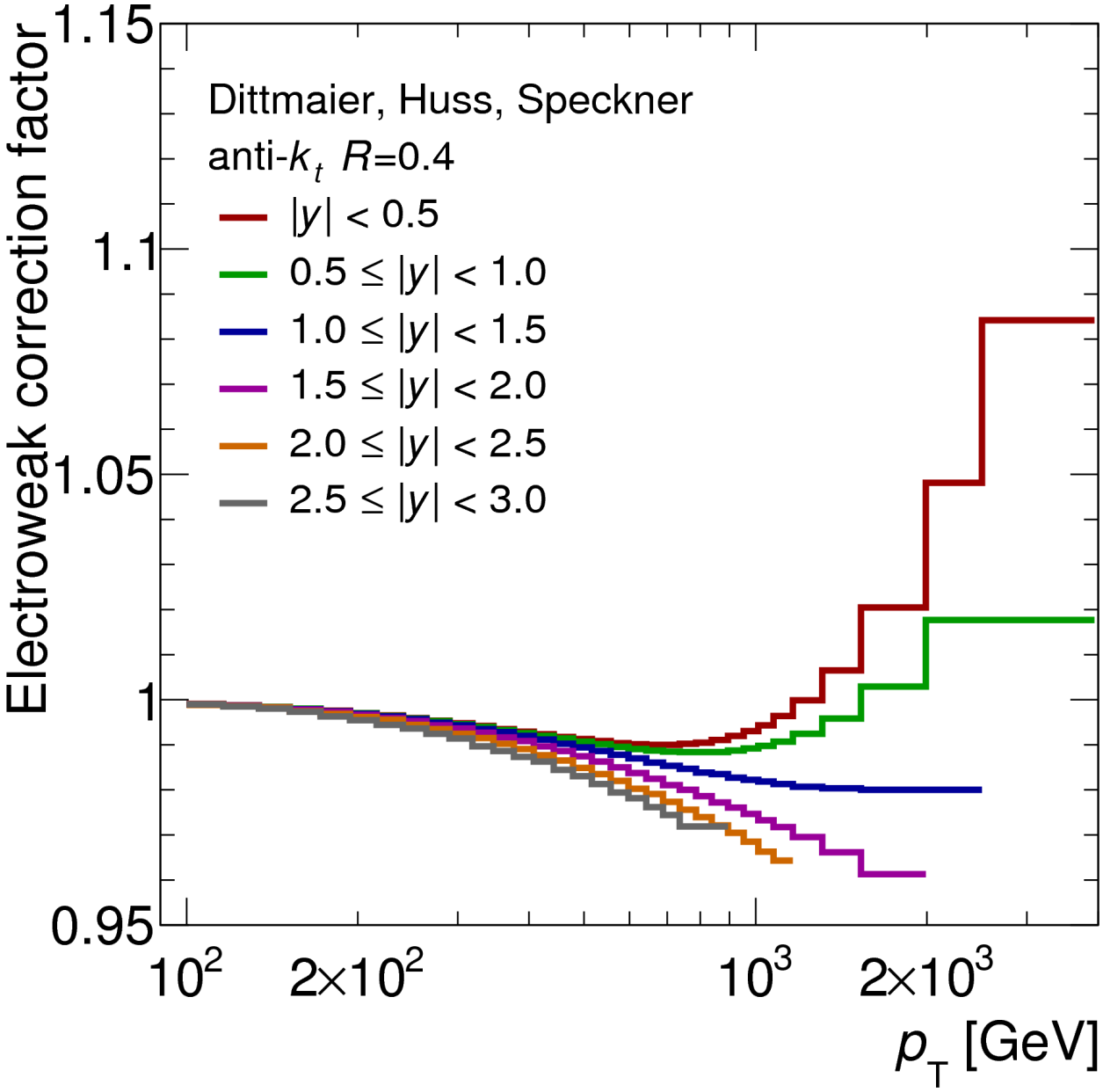
Dijets


anti-k_t R=0.4
$\sqrt{s}$ = 13 TeV, 81 nb^{-1} - 3.2 fb^{-1}
ATLAS
$y^* < 0.5$ ($\times 10^0$)
$0.5 \le y^* < 1.0$ ($\times 10^{-3}$)
$1.0 \le y^* < 1.5$ ($\times 10^{-6}$)
$1.5 \le y^* < 2.0$ ($\times 10^{-9}$)
$2.0 \le y^* < 2.5$ ($\times 10^{-12}$)
$2.5 \le y^* < 3.0$ ($\times 10^{-15}$)
Systematic uncertainties
NLOJET++ (CT14 PDF) $\times$ Non-pert. corr. $\times$ EW corr.
$d^2\sigma/dm_{jj}\,dy^*$ [pb/GeV]
m_{jj} [GeV]

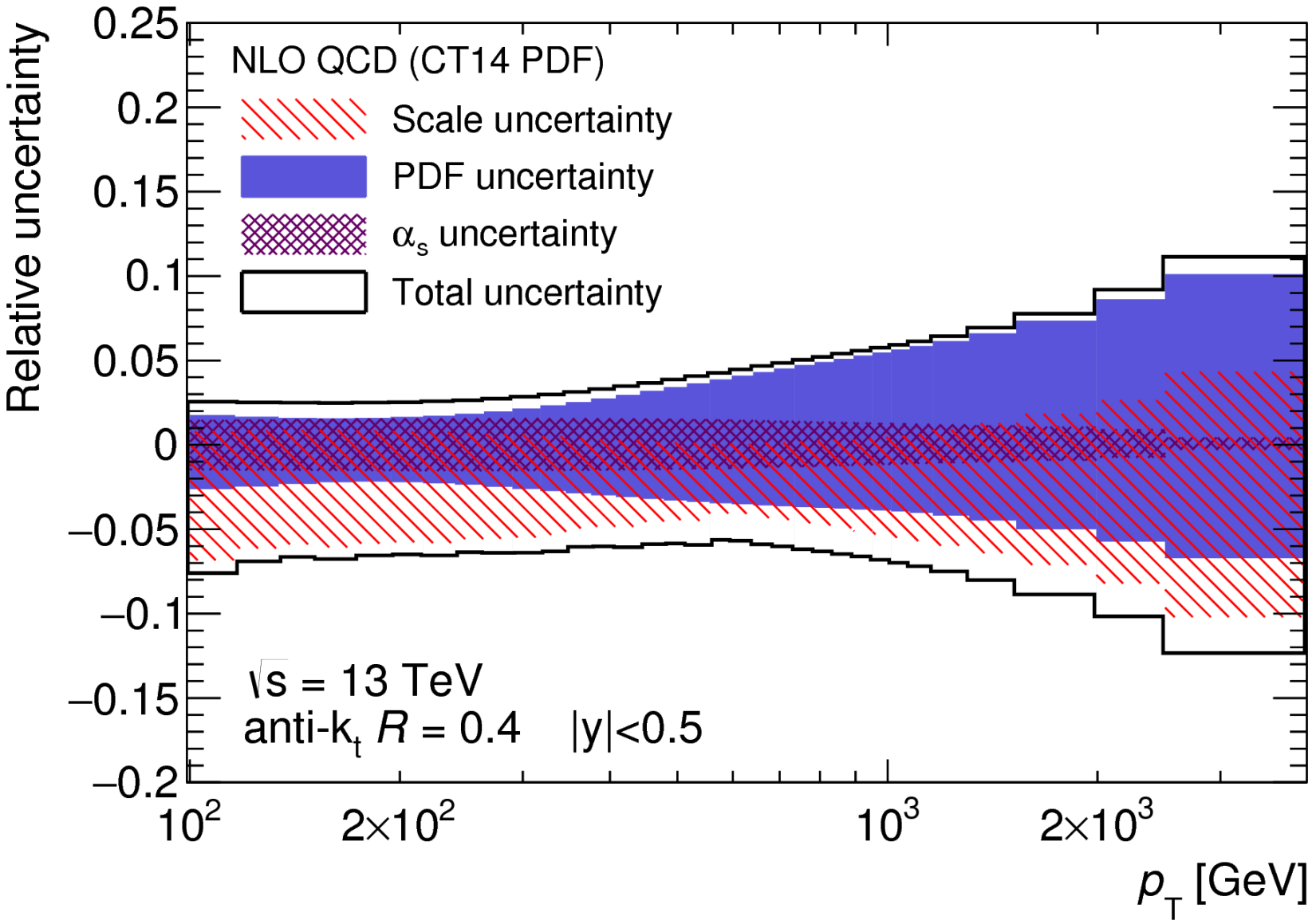
Non-perturbative



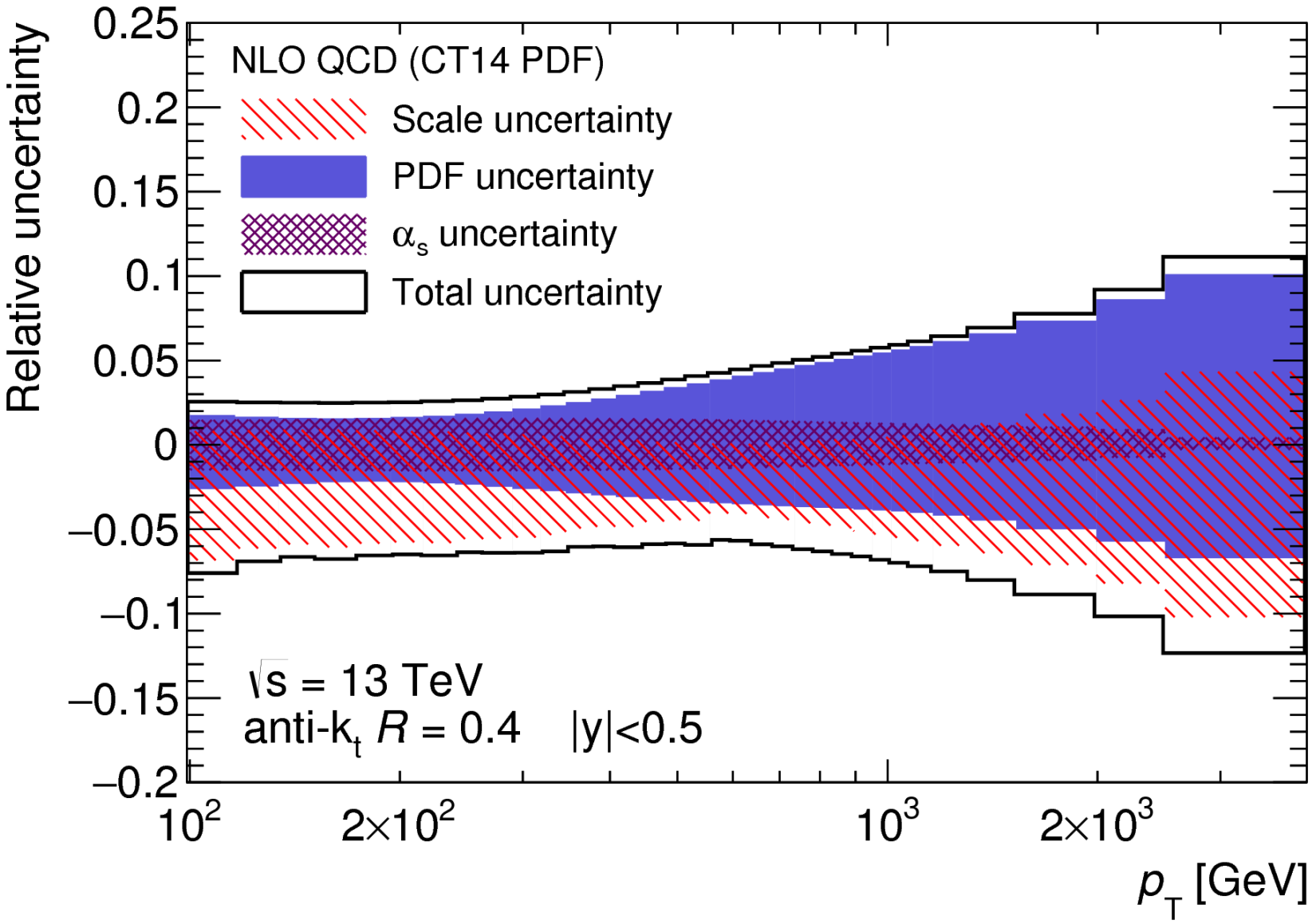
Electroweak



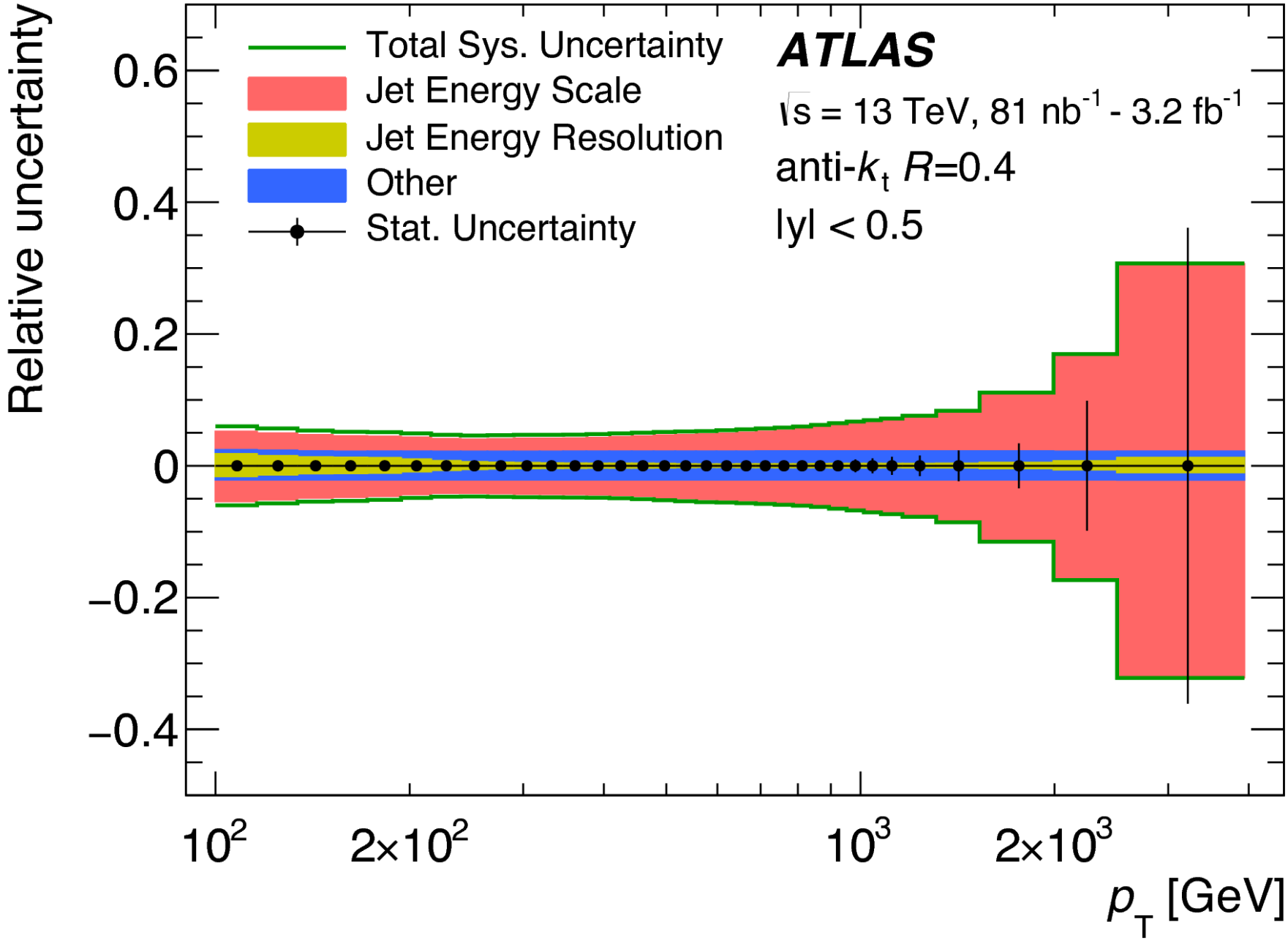
Cross section total uncertainty (fixed order theory)



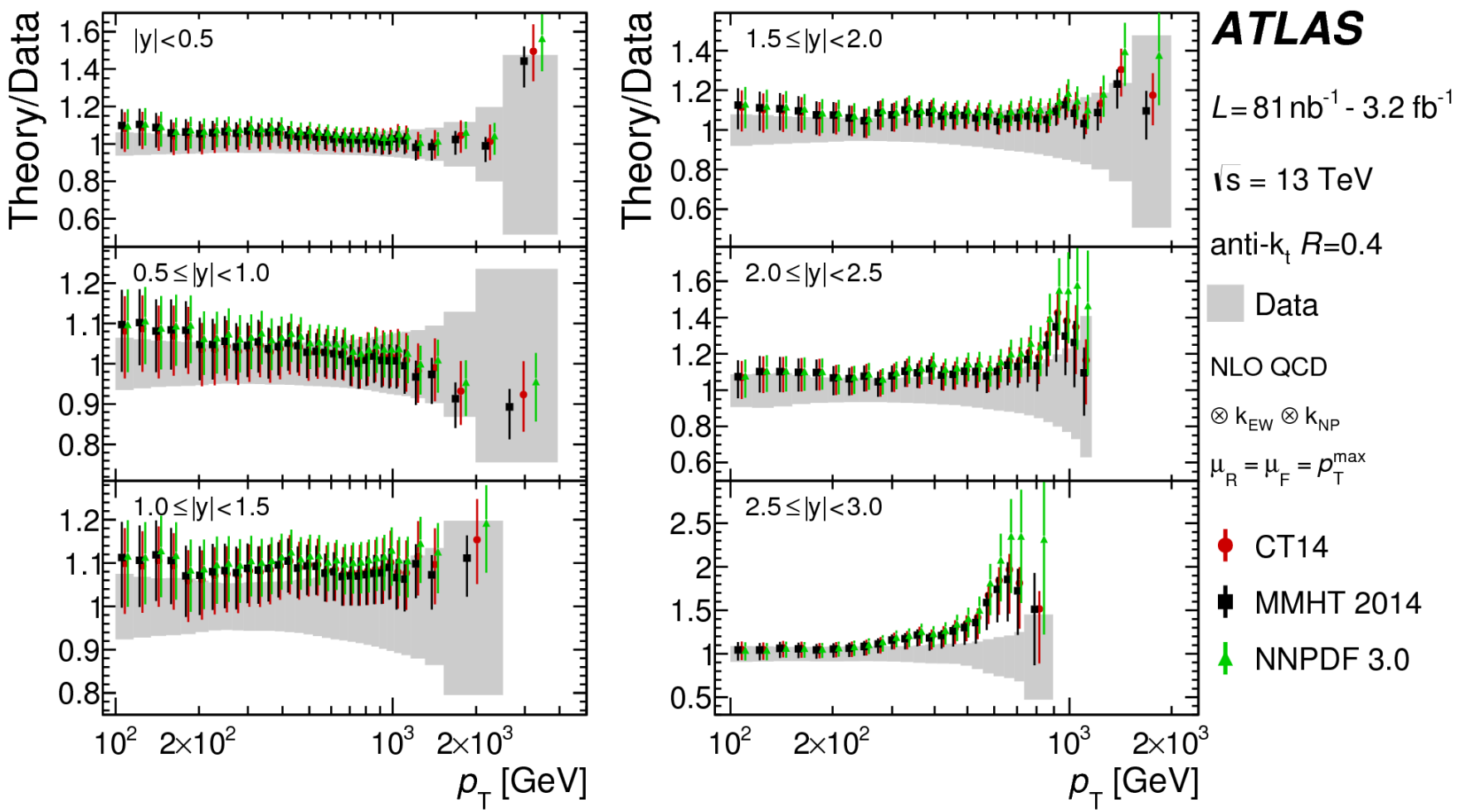
Cross section total uncertainty (fixed order theory)



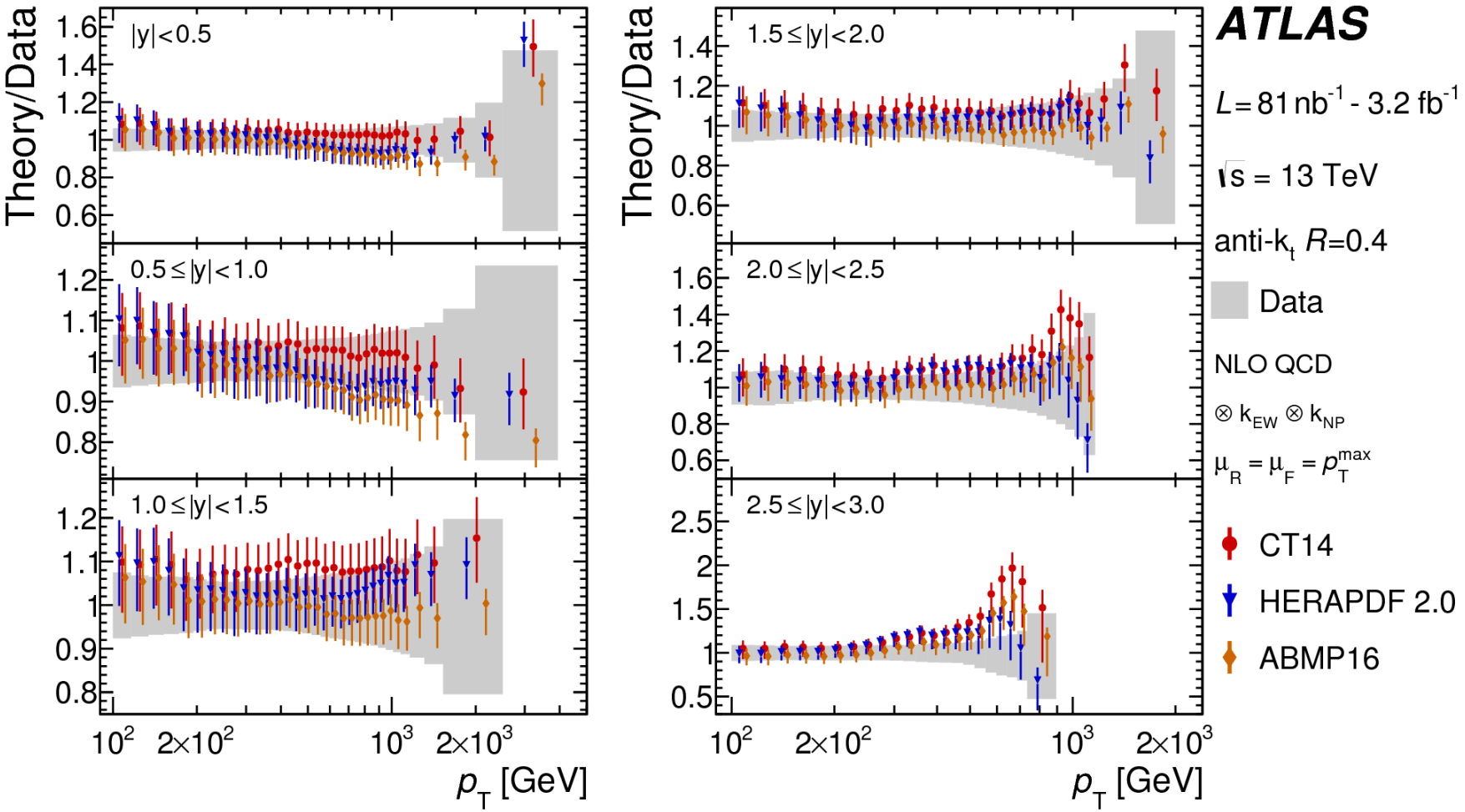
Cross section total uncertainty (exp)



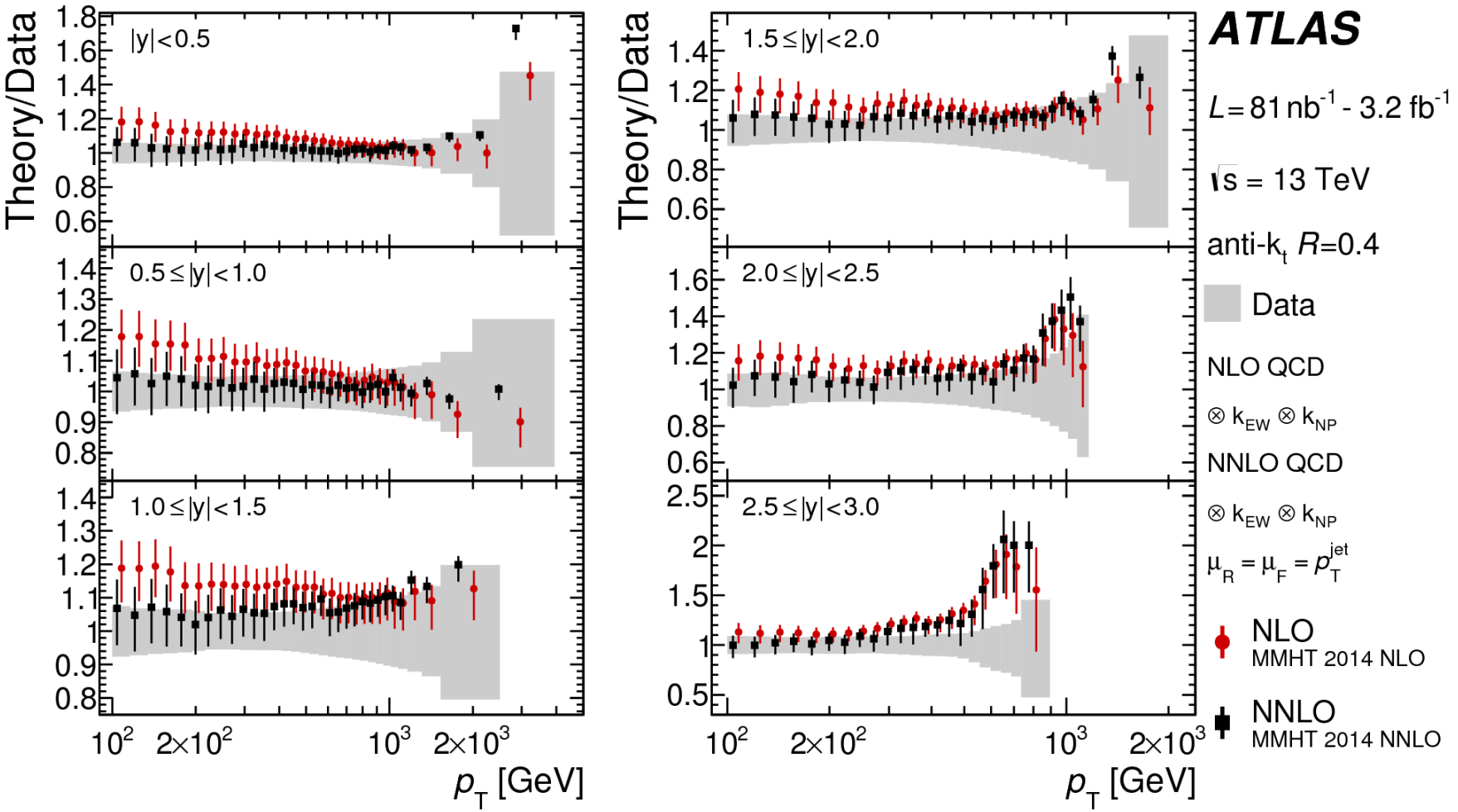
Inclusive jets: NLO PDF1



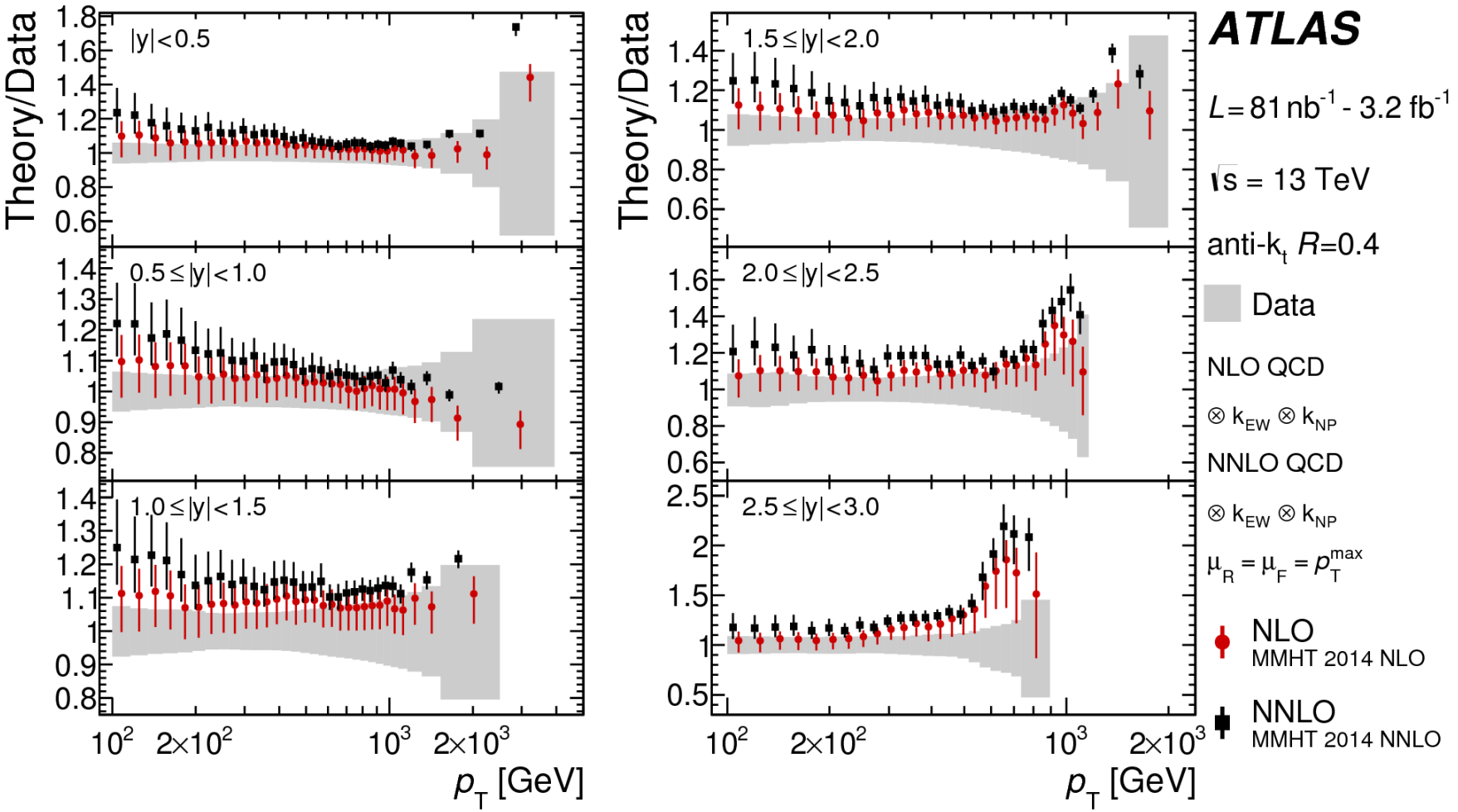
Inclusive jets: NLO PDF2



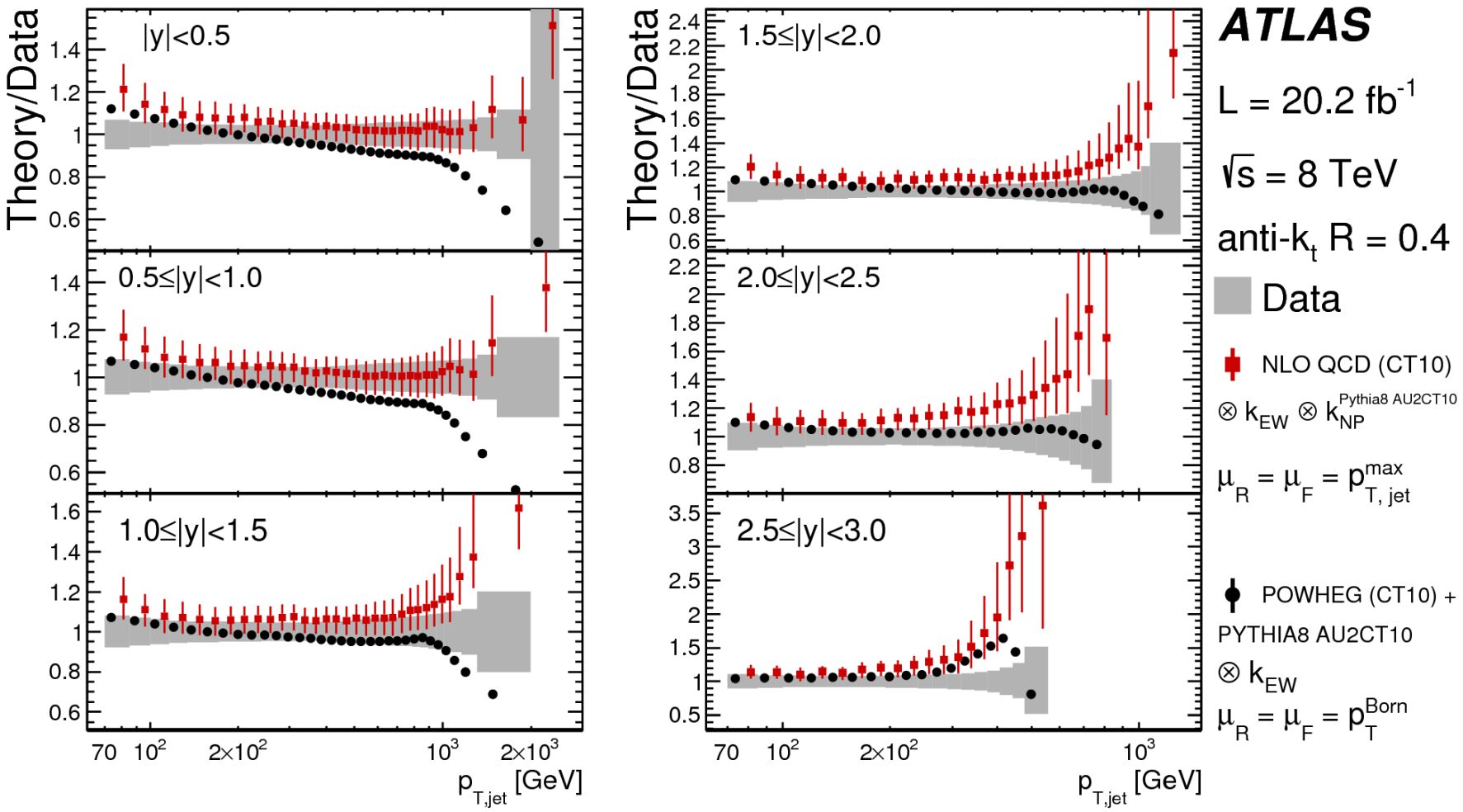
Inclusive jets: NLO vs NNLO ptjet



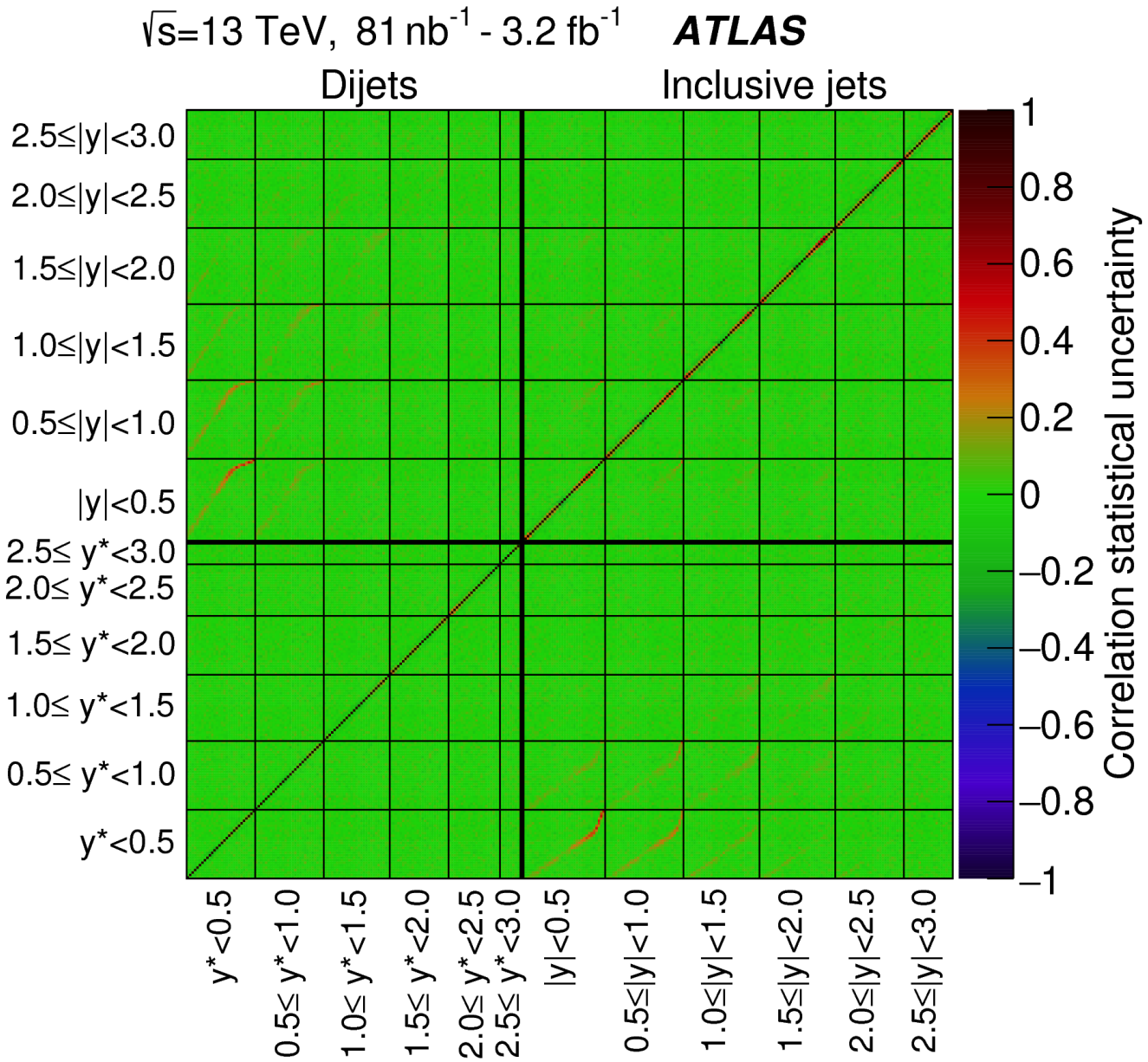
Inclusive jets: NLO vs NNLO ptmax



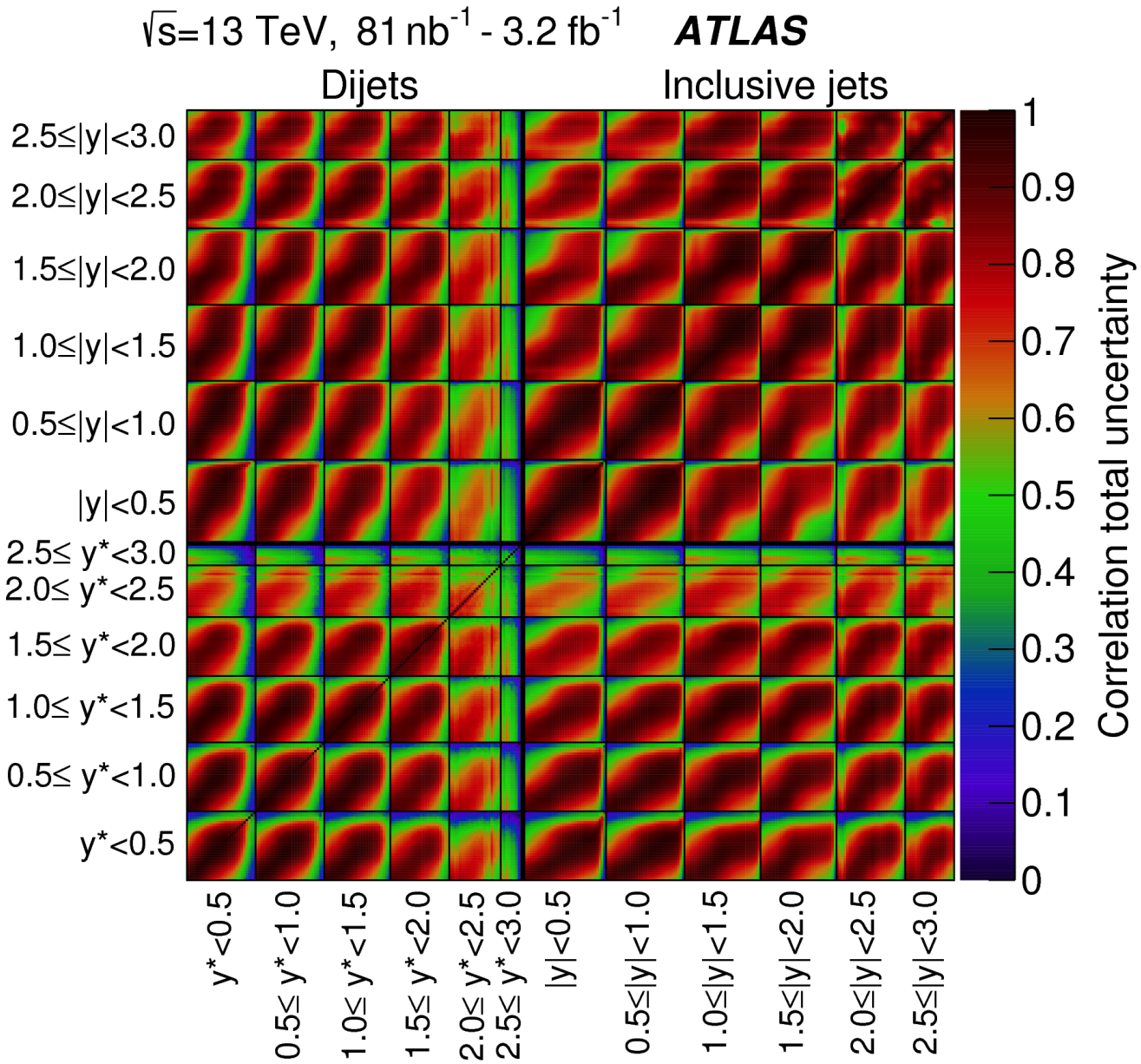
Inclusive jets: full NLO Monte Carlo sim



Correlation statistics



Correlation total



Quantitative comparison data to theory

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

Quantitative comparison data to theory

y^* ranges	P_{obs} CT14	MMHT 2014	NNPDF 3.0	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%