Basic jet clustering at the LHC

Grégory Soyez

IPhT, CEA Saclay

SMLHC — Copenhagen — April 10-13 2012

Plan

- Introduction:
  elementary concepts everyone knows

- Challenge #1: LHC v. pQCD
  - inclusive-jet and dijet cross-sections
  - cross-section ratios

- Challenge #2: pile-up (and UE in PbPb collisions)
  - Background effects on jet reconstruction
  - Latest prescription for pile-up subtraction

What are the jets at the LHC?

All LHC experiments use the anti-k_t algorithm

[M.Cacciari,G.Salam,GS, 0802.1189]

- Works by successively recombining the particles that minimise the distance

$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2})\,[\Delta y_{ij}^2 + \Delta\varphi_{ij}^2] \qquad d_{iB} = k_{ti}^{-2}\,R^2$$

  Min is d_{ij}: cluster $i, j \to k$; min is d_{iB}: call i a jet

- Fully defined only when R is specified!
- ATLAS and CMS do not use the same jets:
  ATLAS $R = 0.4, 0.6$, CMS $R = 0.5, 0.7$
- Main characteristic: resilient to soft radiation
  - Easier experimental calibration
  - Some easier pQCD computations (e.g. resum)

Challenge #1: LHC v. pQCD

Things to focus on:

- stability of the NLO QCD prediction (scale, PDF, ...)

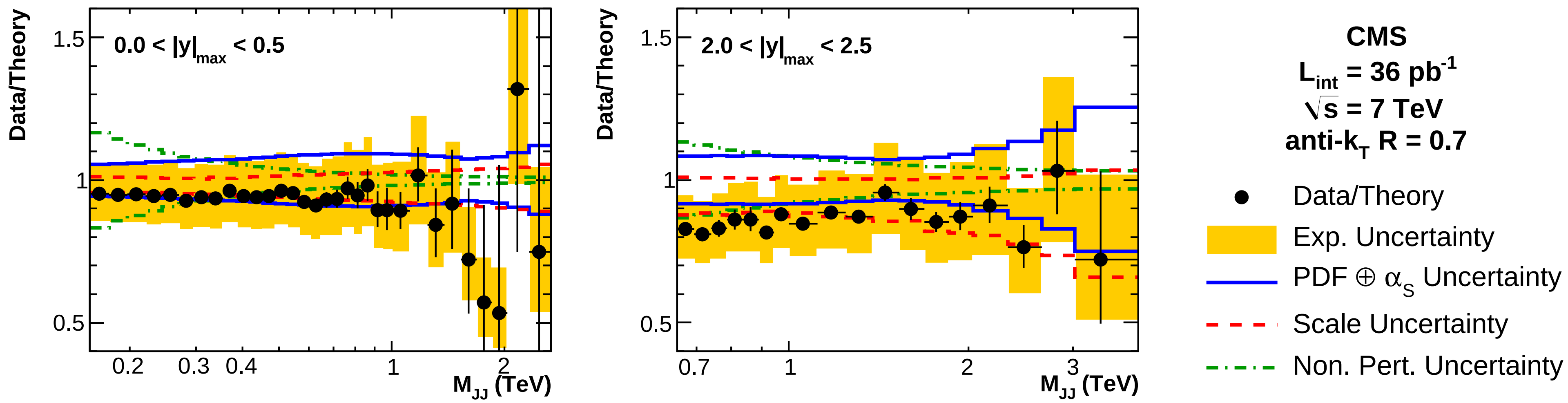
- importance of non-perturbative effects

Who does what? (roughly)

Both experiments have similar y and p_t coverage
They both measure inclusive and dijet cross-sections

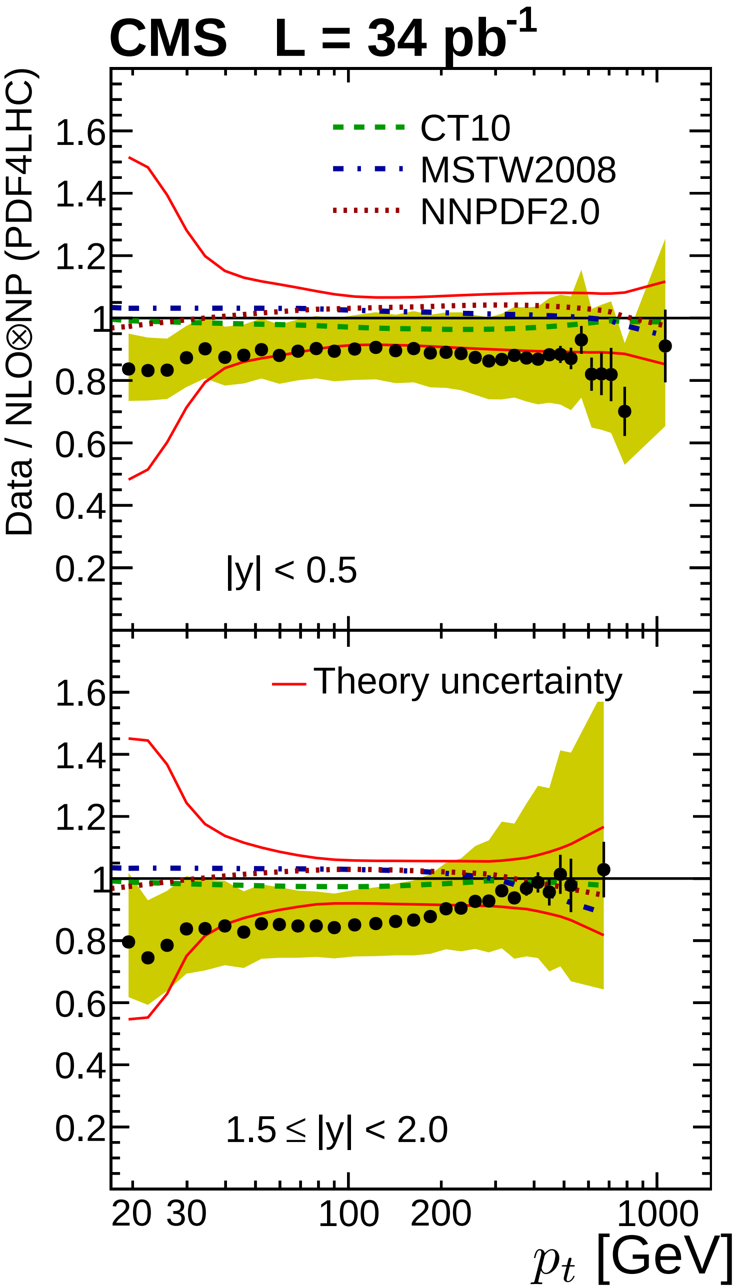
Theory	ATLAS	CMS
Jets	R=0.4, 0.6	R=0.5 or 0.7
PDFs	CT10 MSTW2008 NNPDF2.1 HERAPDF1.5	CT10 MSTW2008 NNPDF2.0 (PDH4LHC)
MCs	NLOJet++ POWHEG(NLO) POWHEG+PS	NLOJet++
scale	$\mu = p_{t,\mathrm{hardest}}$	$\mu = p_{t,\mathrm{jet}}$
N-pert.	Py6(AUET2B)	Py6(D6T,Z2)

Dijets at CMS



- forward: important scale uncertainty
- small scale (M_{JJ}): non-pert. corrections dominate
  Room for tune improvement
- large scale: PDF uncertainty dominate
  Room for PDF improvement
- Agreement but theory systematically above data

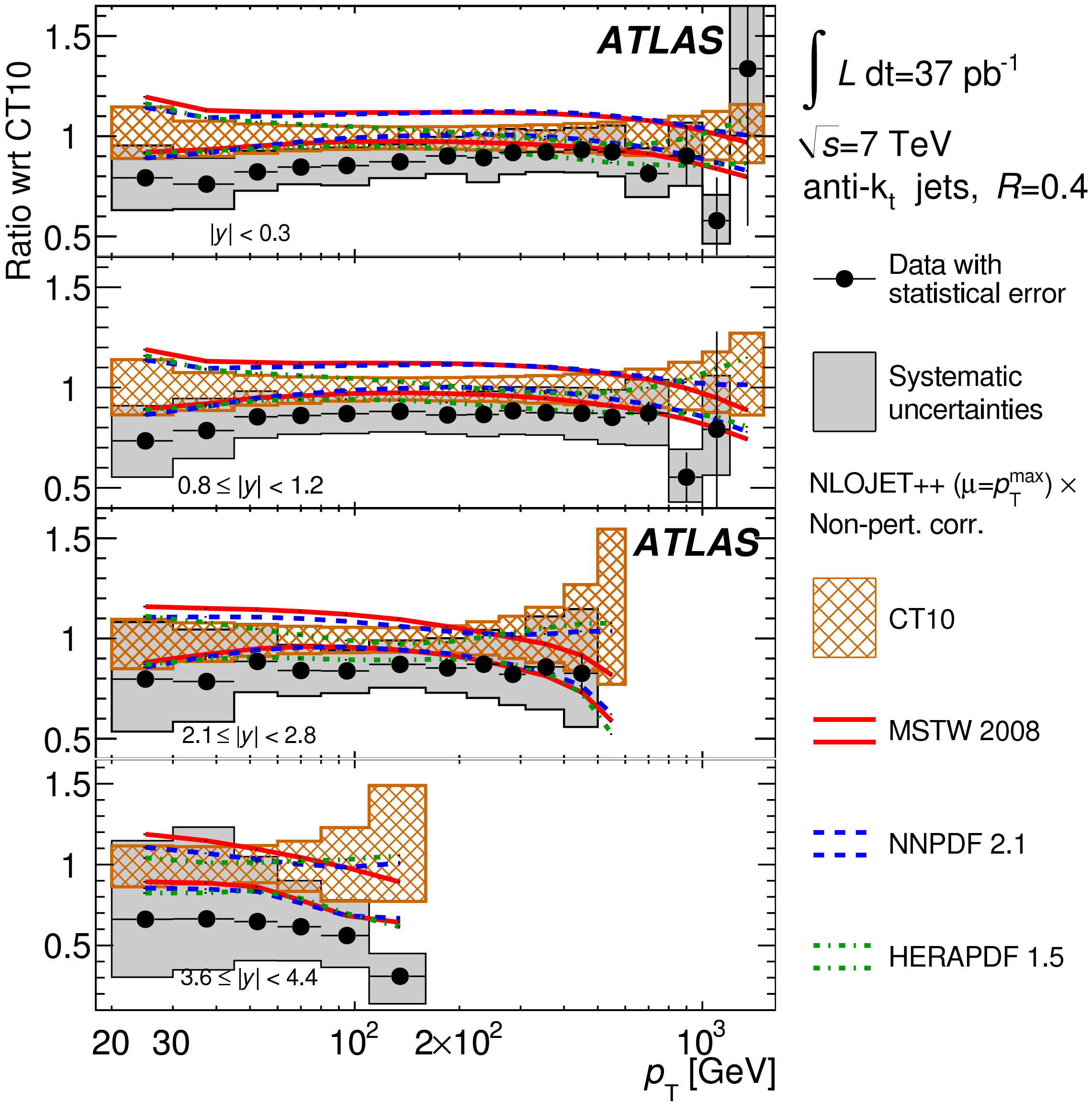
Inclusive jets at CMS



$\sqrt{s}$=7 TeV, anti-k_t(R=0.5)

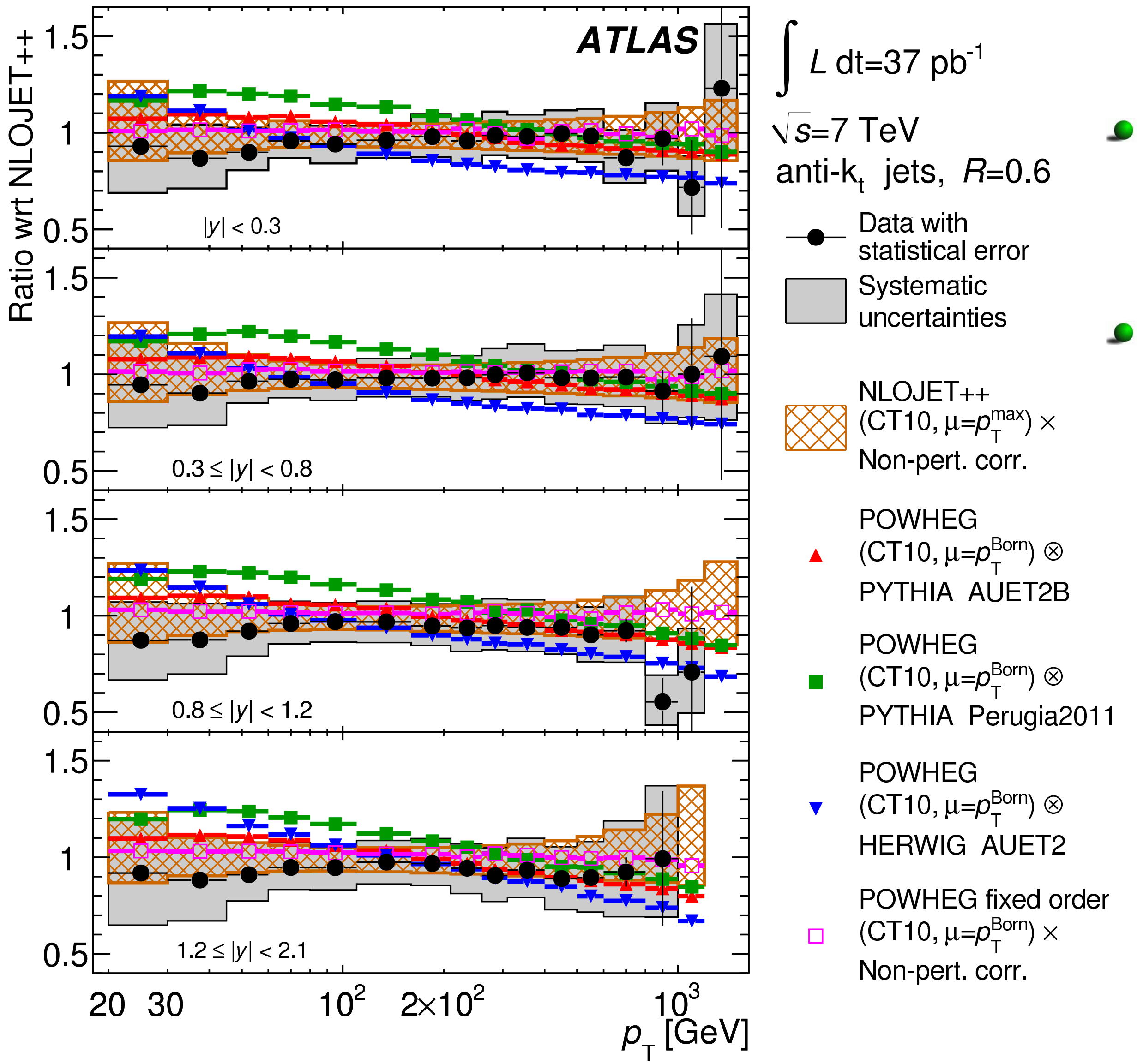
- again theory on the high side
- NP dominates at low p_t
- small PDF dependence

Inclusive jets at ATLAS



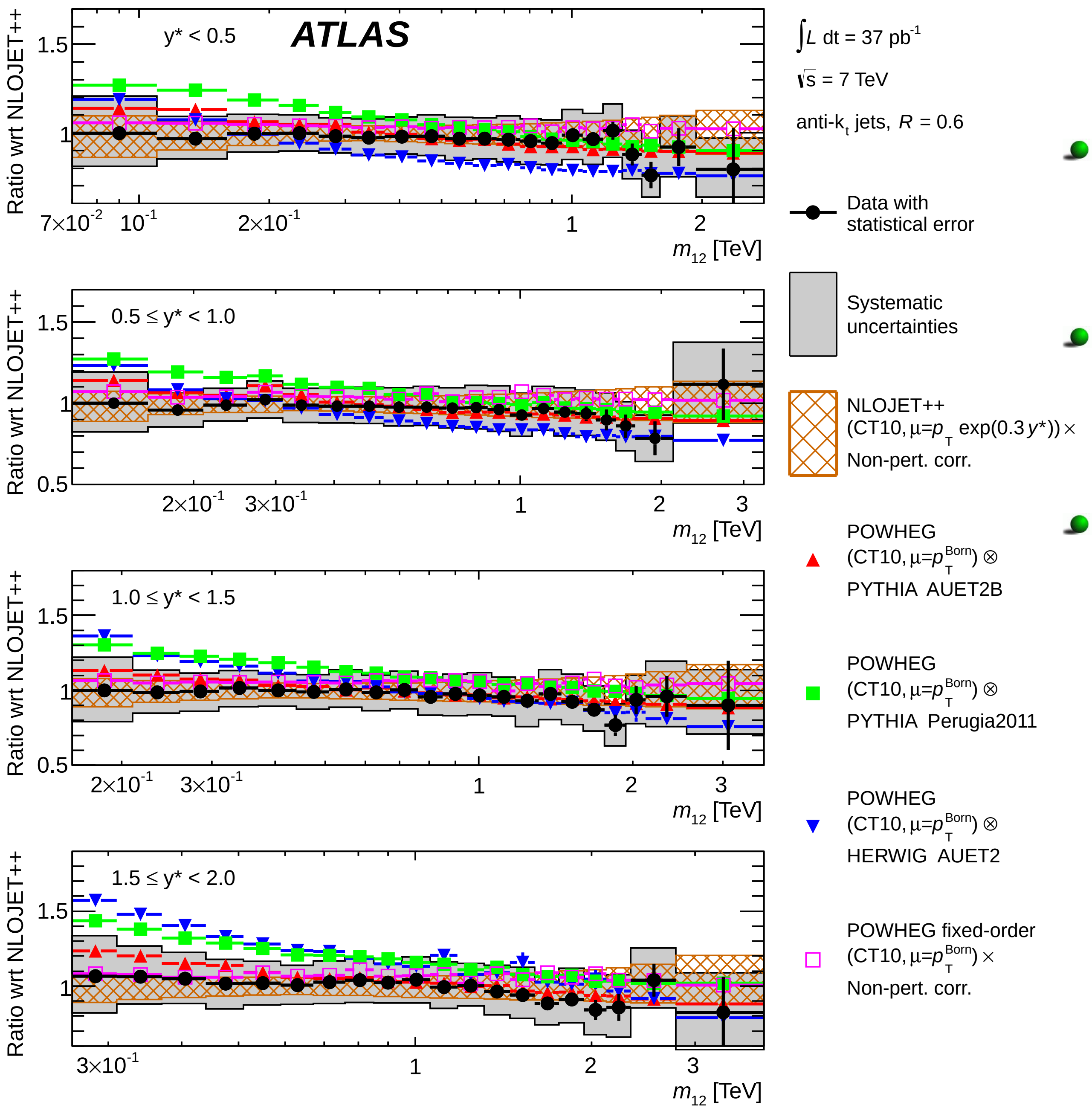
- same conclusion as for CMS
- CT10 slightly larger at large p_t

Inclusive jets at ATLAS



- NLOJet++ agrees with POWHEG(NLO)
- tune dependence
  - rather large
  - no p_t dep?
  - AUET2B (default) looks better

Dijets at ATLAS

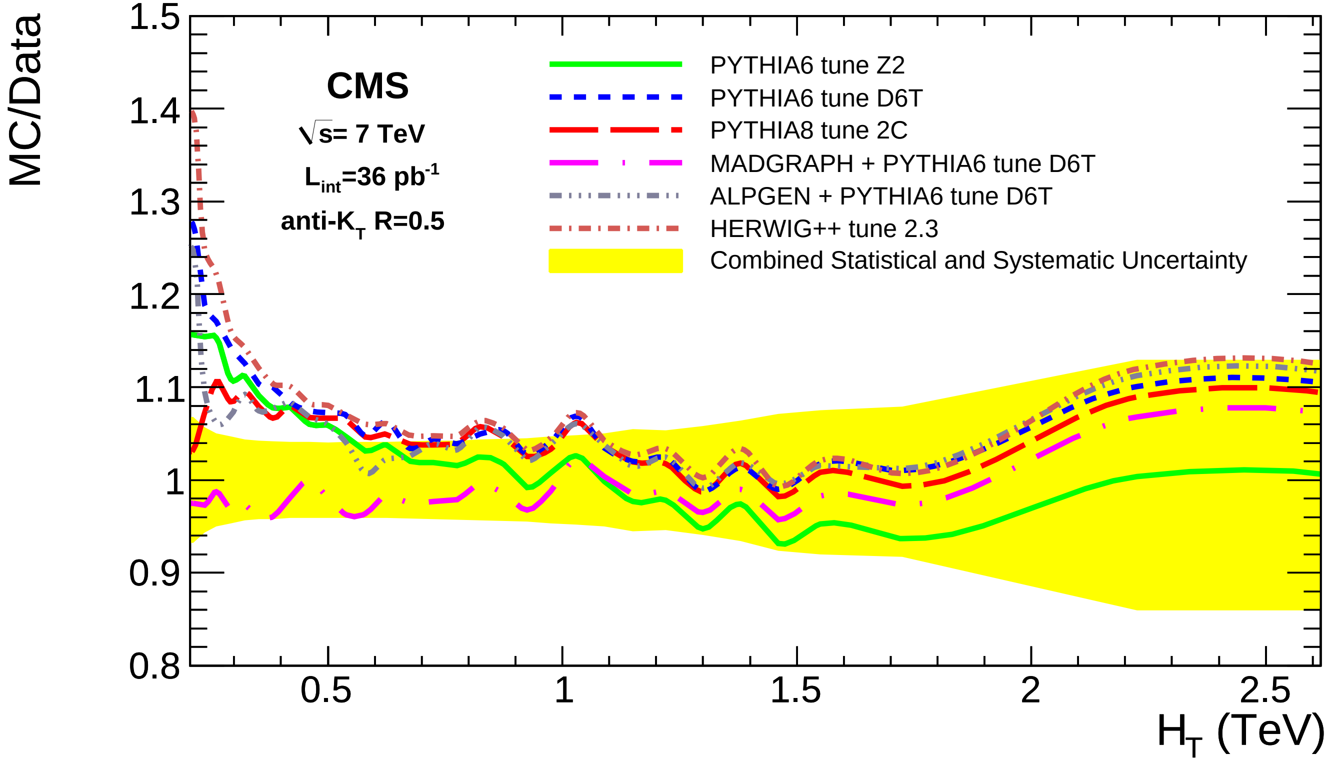


- Same message as before
- for PDFs too (not shown)
- strange scale for NLOJet++

$$\mu = p_{t,\mathrm{hardest}} e^{0.3y^*}$$

3-jet to 2-jet ratio (CMS)

$p_{t,\mathrm{jet,min}} = 50$ GeV, $H_T = \sum p_{t,\mathrm{jet}}$



Alpgen
v.
Madgraph?

Matching uncertainty?
Proper tune for ME+PS?

Cross-section ratio at different radii

Another potentially interesting ratio to look at is

$$\mathcal{R}(p_t; R_1, R_2) = \frac{d\sigma/dp_t(R = R_1)}{d\sigma/dp_t(R = R_2)}$$

Cross-section ratio at different radii

Another potentially interesting ratio to look at is

$$\mathcal{R}(p_t; R_1, R_2) = \frac{d\sigma/dp_t(R = R_1)}{d\sigma/dp_t(R = R_2)}$$

Naive perturbative computation:

$$\mathcal{R} = \frac{\alpha_s^2 \sigma_{\mathrm{LO}} + \alpha_s^3 \sigma_{\mathrm{NLO}}(R_1)}{\alpha_s^2 \sigma_{\mathrm{LO}} + \alpha_s^3 \sigma_{\mathrm{NLO}}(R_2)} = 1 + \frac{\Delta \sigma_{\mathrm{NLO}}(R_1, R_2)}{\sigma_{\mathrm{NLO}}(R_2)} \alpha_s$$

Cross-section ratio at different radii

Another potentially interesting ratio to look at is

$$\mathcal{R}(p_t; R_1, R_2) = \frac{d\sigma/dp_t(R = R_1)}{d\sigma/dp_t(R = R_2)}$$

Better perturbative computation:

$$\begin{aligned}\sigma(p_t; R) &= \alpha_s^2 \sigma_{\text{tree}}^{2\to 2} + \alpha_s^3 [\sigma_{\text{tree}}^{2\to 3}(R) + \sigma_{1-\text{loop}}^{2\to 2}] \\ &+ \alpha_s^4 [\sigma_{\text{tree}}^{2\to 4}(R) + \sigma_{1-\text{loop}}^{2\to 3}(R) + \sigma_{2-\text{loop}}^{2\to 2}] + \mathcal{O}\left(\alpha_s^5\right)\end{aligned}$$

The unknown 2-loop contribution cancels in the ratio:

$$\begin{aligned}\mathcal{R} &= 1 + \alpha_s \frac{\Delta\sigma_{\text{tree}}^{2\to 3}}{\sigma_{\text{tree}}^{2\to 2}} \\ &+ \alpha_s^2 \frac{\Delta\sigma_{\text{tree}}^{2\to 4} + \Delta\sigma_{1-\text{loop}}^{2\to 3}}{\sigma_{\text{tree}}^{2\to 2}} - \alpha_s^2 \frac{\sigma_{\text{NLO}}(R_2)\Delta\sigma_{\text{tree}}^{2\to 3}}{[\sigma_{\text{tree}}^{2\to 2}]^2}\end{aligned}$$

Cross-section ratio at different radii

Another potentially interesting ratio to look at is

$$\mathcal{R}(p_t; R_1, R_2) = \frac{d\sigma/dp_t(R = R_1)}{d\sigma/dp_t(R = R_2)}$$

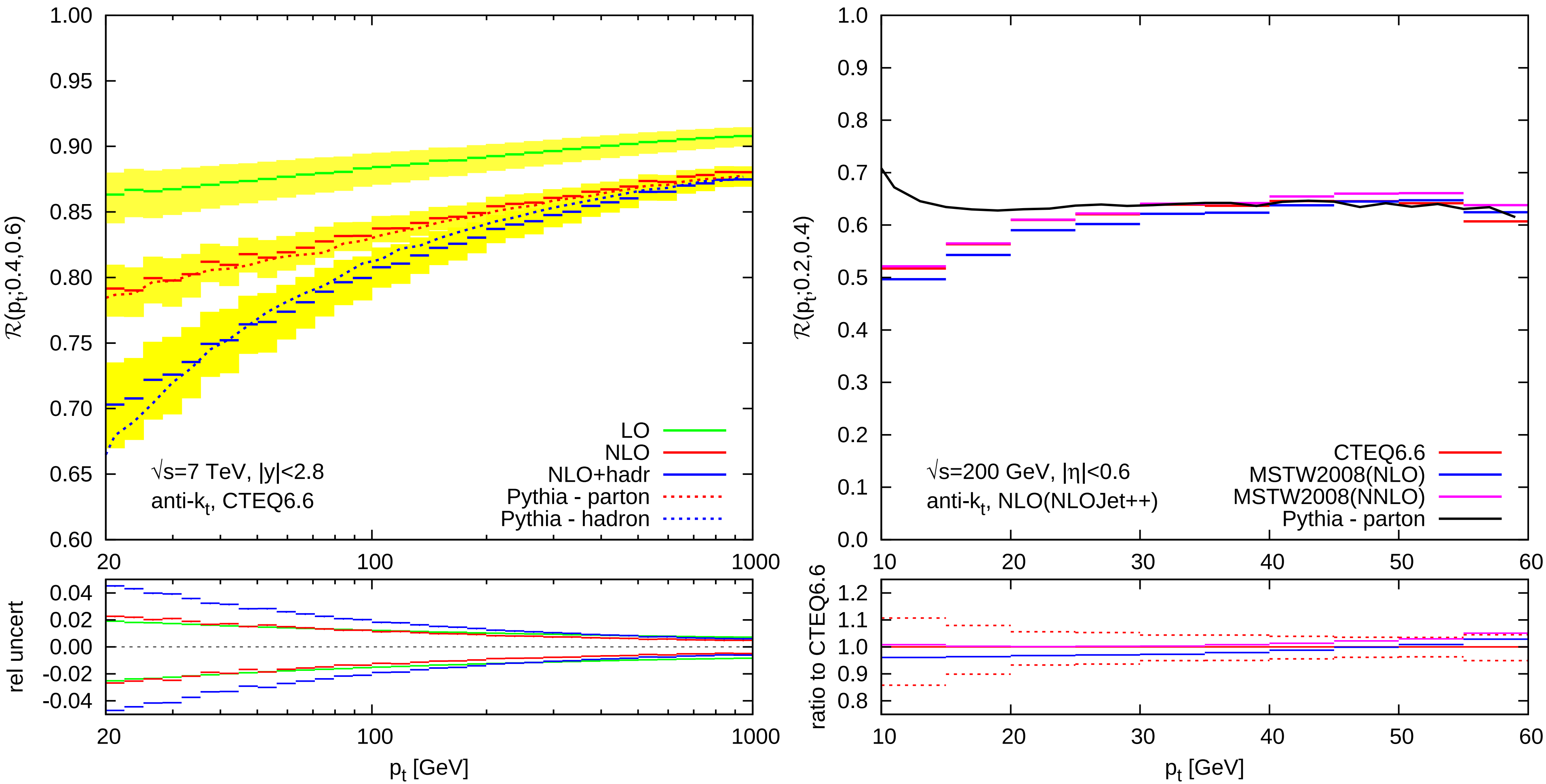
Hadronisation effects can be estimated analytically

[see Mrinal's talk]

Note: We use $\langle \delta p_t \rangle_{\mathrm{hadr}} = -\mu/R$.

This neglects the (unconstrained) smearing *i.e.* slightly overestimates the effect.

Predictions...



- Reduced experimental uncertainty?
- Constraints on non-pert. corrections? on PDFs?

Pileup and noisy backgrounds

- The LHC will operate routinely with ~ 30 PU events
what are the implications?
- valid also for UE in PbPb collisions

Basic considerations

Pileup mostly$^{(*)}$ characterised by 3 numbers:

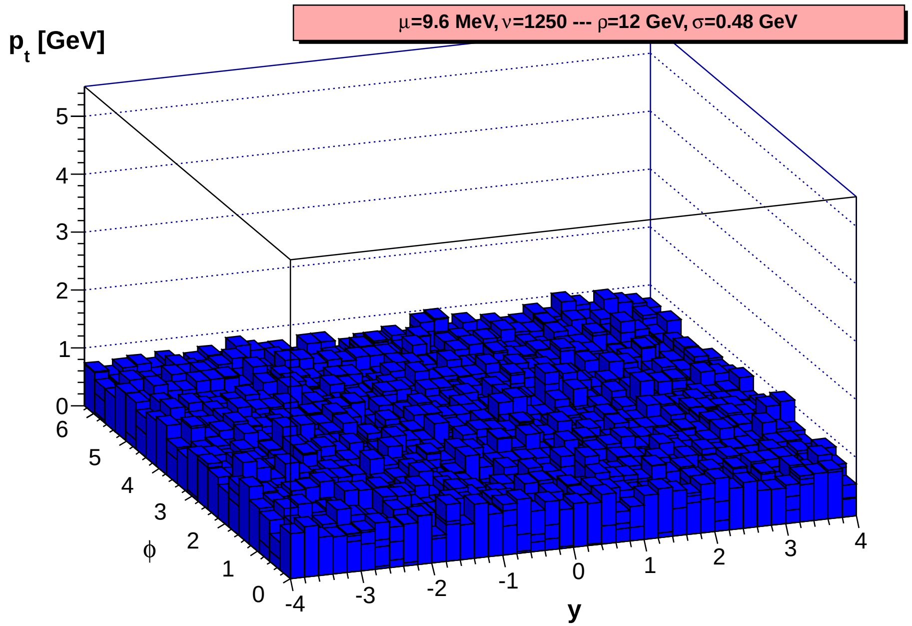
- ρ: the average activity (per unit area)
- σ: the intra-event fluctuations (per unit area)
- σ_ρ: the event-to-event fluctuations of ρ

$^{(*)}$ for qualitative discussions (e.g. full fluctuation spectrum needed for proper unfolding)

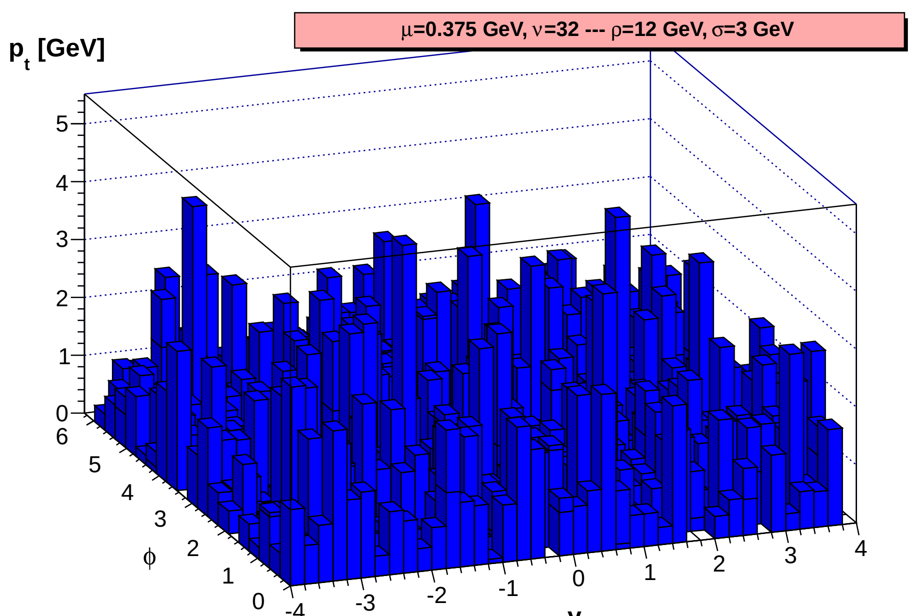
For a jet (of area A) that means:

$$p_t \to p_t + \rho A \pm \sigma_\rho A \pm \sigma\sqrt{A}$$

ρ and σ illustration

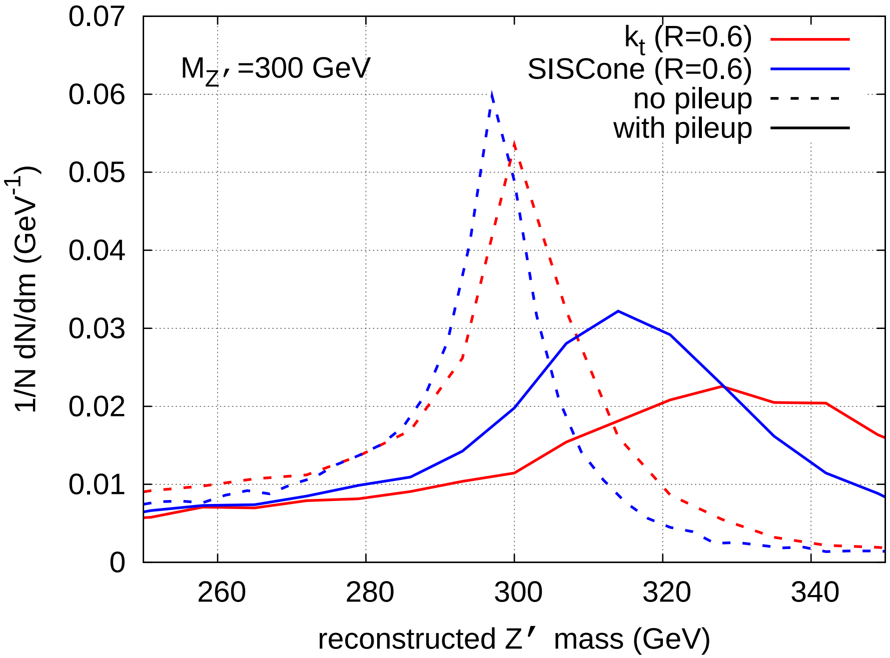


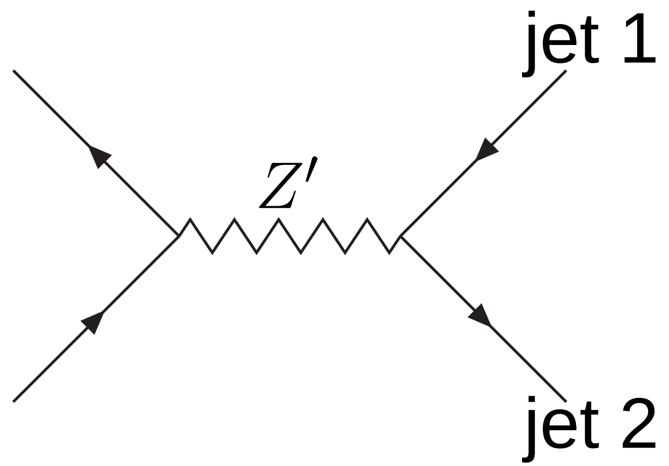
$\rho = 12$ GeV, $\sigma = 0.48$ GeV



$\rho = 12$ GeV, $\sigma = 3$ GeV

Illustration of the consequences

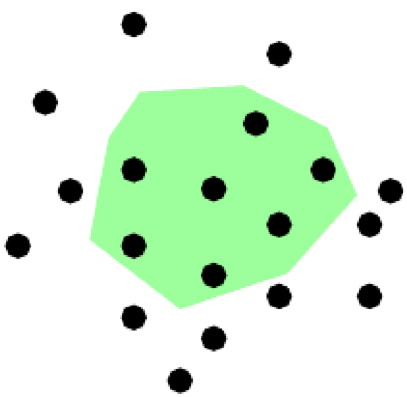




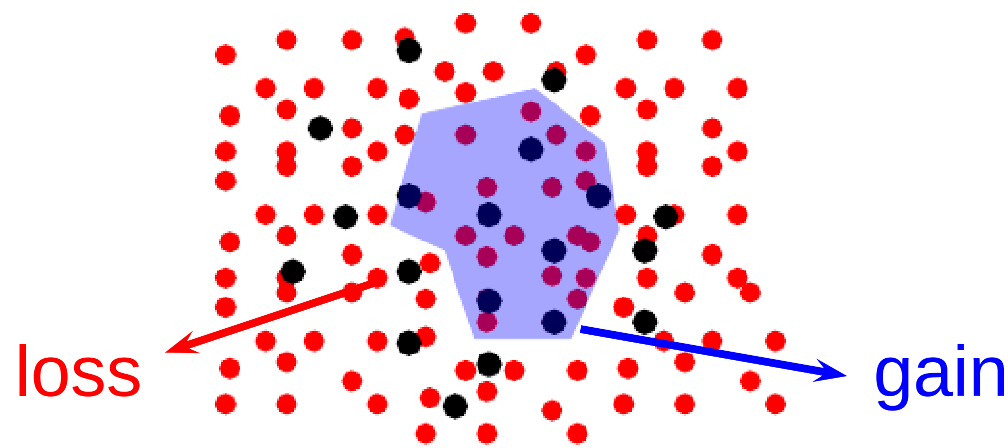
- Shift due to the "ρA" term
- Smearing due to the "$\sigma_\rho A$" and "$\sigma\sqrt{A}$" terms

Back reaction

No background



With background



Negligible for anti-k_t
(a nice consequence of its soft resilience)

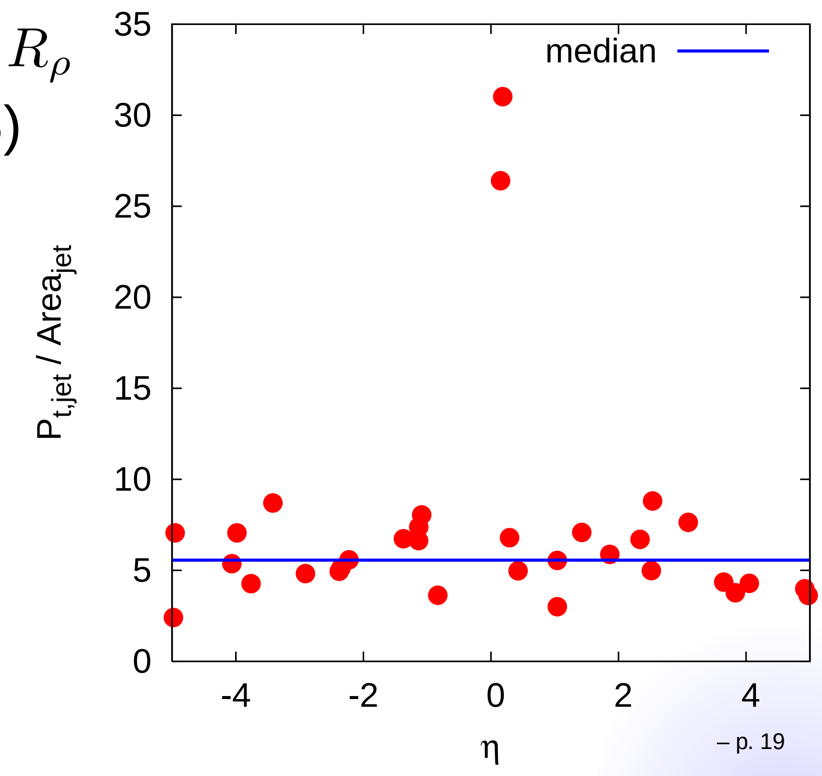
Jet-area-based subtraction

[M.Cacciari, G.P. Salam, GS]

$$p_{t,\mathrm{jet}}^{(\mathrm{sub})} = p_{t,\mathrm{jet}} - \rho_{\mathrm{est}} A_{\mathrm{jet}}$$

- jet area: throw *ghosts particles* (area quanta) in the event
- ρ_{bkg}, the background p_t density per unit area
  - Cluster with k_t of C/A with “radius” R_ρ OR split into grid cells ($R_{\mathrm{cell}} \sim 0.55$)
  - Estimate ρ_{bkg} using

$$\boxed{\rho_{\mathrm{bkg}} = \underset{j \in \mathrm{patches}}{\mathrm{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}}$$



Jet-area-based subtraction

[M.Cacciari, G.P. Salam, GS]

$$p_{t,\mathrm{jet}}^{(\mathrm{sub})} = p_{t,\mathrm{jet}} - \rho_{\mathrm{est}} A_{\mathrm{jet}}$$

- Jet area A_{jet}: per jet
- Bkg density ρ: (typically) per event

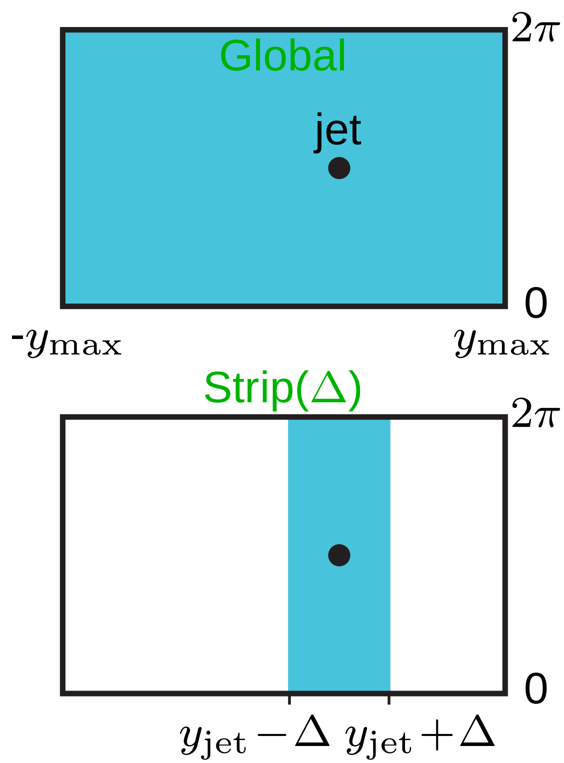
Consequences:

- corrects for the ρA shift
- gets rid of the $\sigma_\rho A$ smearing
- left with the fluctuations $\sigma\sqrt{A}$

Rapidity dependence

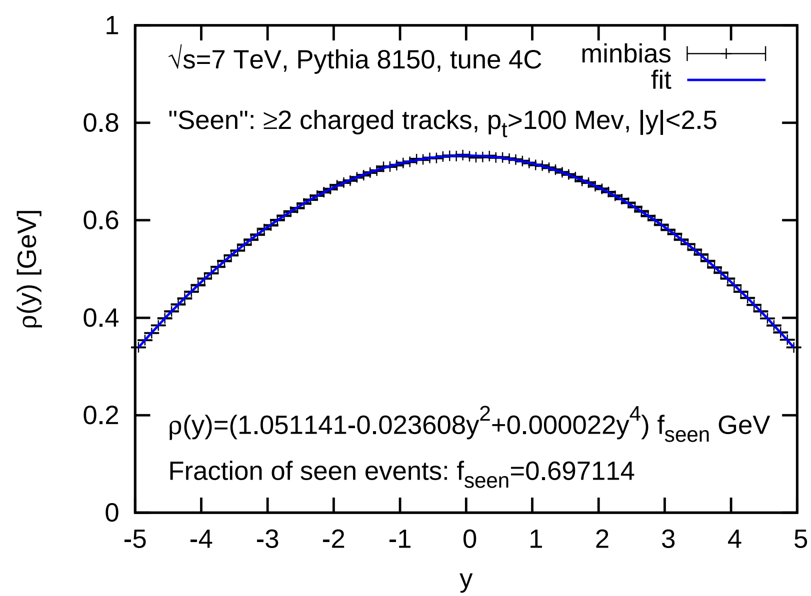
local range $\mathcal{R}$

$$\rho(j) = \operatorname*{median}_{j' \in \mathcal{R}(j)} \left\{ \frac{p_{t,j'}}{A_{j'}} \right\}$$



rapidity rescaling

$$\rho(j) = f(y_j) \operatorname*{median}_{\text{all } j'} \left\{ \frac{p_{t,j'}}{A_{j'}\, f(y_{j'})} \right\}$$



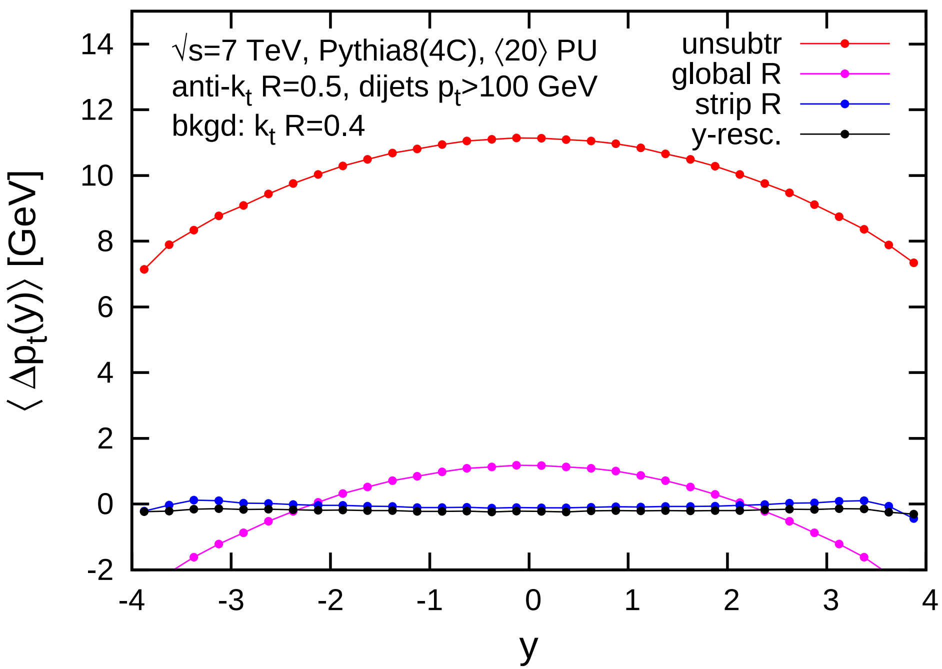
f from minbias

could use grid cells instead of jets

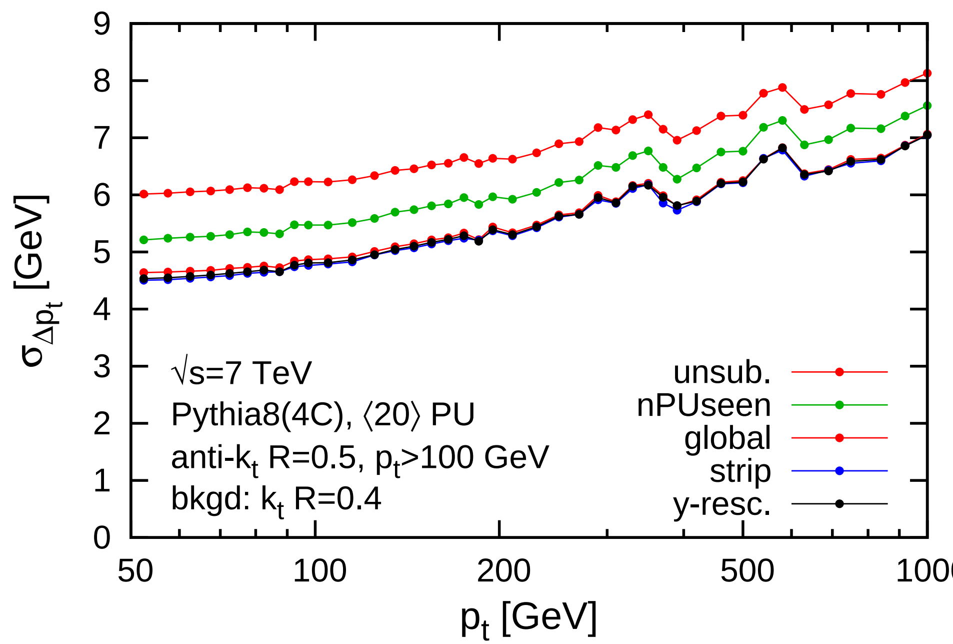
Subtraction benchmarks

LHC, anti-$k_t(R = 0.5)$ jets embedded into $\langle 20 \rangle$ PU events

average shift



dispersion



- local range & y-rescaling OK
- 100-200 MeV average precision
- y-resc. slightly better than local range for busy events

- resolution improved
- better than using $\rho \propto n_{\mathrm{PU}}$ + handles out-of-time PU
- residual $\sqrt{p_t}$ from back-reaction

Conclusions

- Jet data v. QCD predictions: good agreement but
  - theory systematically above the data
  - rather large tune dependence (small p_t)
  - NLOJet++ v. POWHEG(NLO) for dijets
  - Alpgen+PS v. Madgraph+PS: matching? tune?

  Better understanding these would certainly help!
  Other observables (*e.g.* ratios) for more constraints

- Pile-up subtraction: our recommended strategy
  - Jet-area based subtraction
  - ρ from y-rescaled median over grid cells
  - using a local range is a nice alternative

  Advantages: no shift, no event-to-event smearing

Ad: FastJet v3

[M.Cacciari,G.Salam,GS, 1111.6097, www.tastjet.fr]

FastJet v3 (Oct 2011) meets modern requirements:

- Addition of FastJet tools:
  - Jet substructure/post-processing common framework

    ```
    Transformer transformer;
    PseudoJet transformed_jet=transformer(jet);
    ```

    Ex: `Filter`, `Pruner`, `MassDropTagger`, `JHTopTagger`
  - New background estimation and subtraction interface:

    ```
    JetMedianBackgroundEstimator
    GridMedianBackgroundEstimator
    ```
- New functionalities:
  - PseudoJet aware of its structure *e.g.* `jet.constituents()`
  - associate arbitrary user information with a PseudoJet
  - Selectors for applying cuts: *e.g.*

    ```
    SelectorNHardest(2) * SelectorAbsRapMax(5)
    ```