Experimental Aspects of soft QCD

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Content

- An experimental overview of non-perturbative effects on selected variety of measurements
- Providing a link between soft to hard observables
    - Min Bias and pile-up
    - Inclusive jet cross section
    - Jet vetos
    - Jet shapes
    - (Event shapes)
    - (Double hard Parton Scatters)

Soft QCD

- No unambiguous definition
- Soft QCD = QCD at a low energy/momentum scale Q
- Low: where $\alpha_s(Q) \approx O(1)$
- BUT: depends on observables and precision needed
- Power corrections and leading logs can be substantial even in cases where $\alpha_s(Q) < 1$

My definition: SOFT QCD is hadronic physics that implies the need for techniques beyond inclusion of higher order perturbative (ME) calculations in α_s:

Power corrections
Resummations
Parton Showers
Multiple Parton Interactions
Hadronisation models

The need is driven by desires for precision

Partonic level

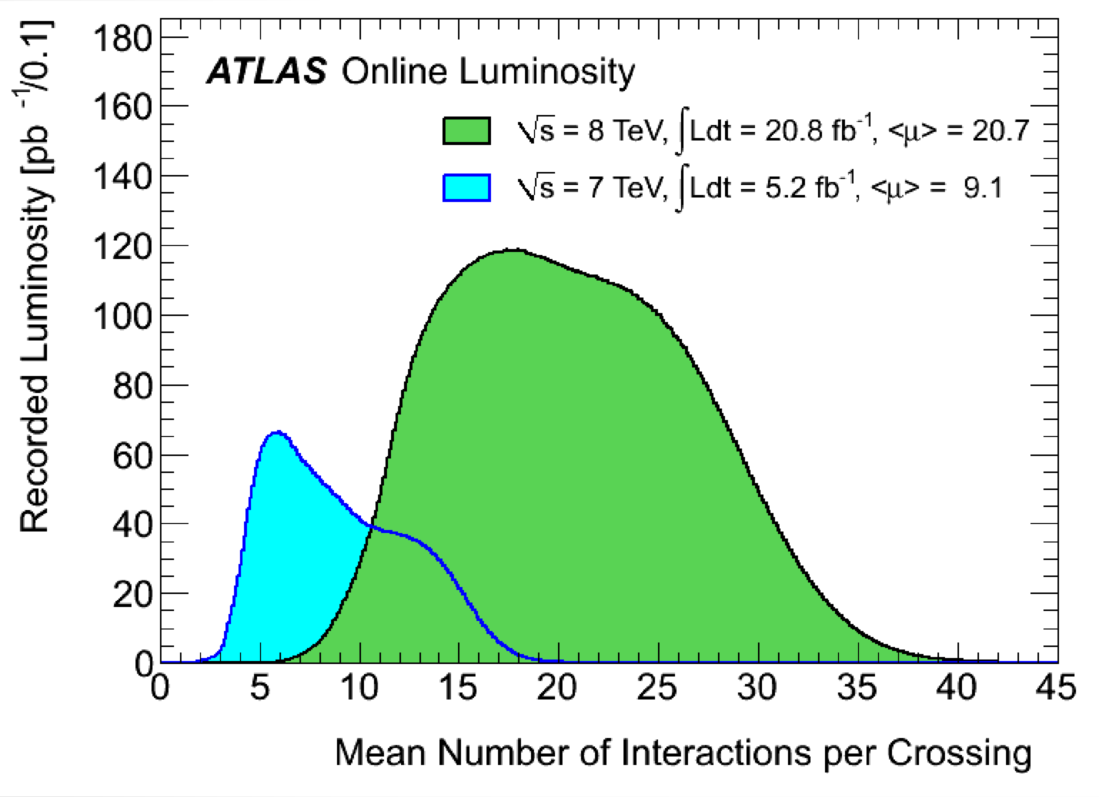
Hadronic level

Particle & Energy flow with and without presence of jets

…

Pile Up

- Most unbiased data at LHC
- Currently modeled by using biased min-bias data
- Most models only tuned to Underlying event observables
- At 8 TeV: average of 21 pile-up events (~4 PU per nb^{-1}/s)
- For nominal LHC lumi of $10 nb^{-1}/s$ and 25 ns bunch spacing: 27 PU

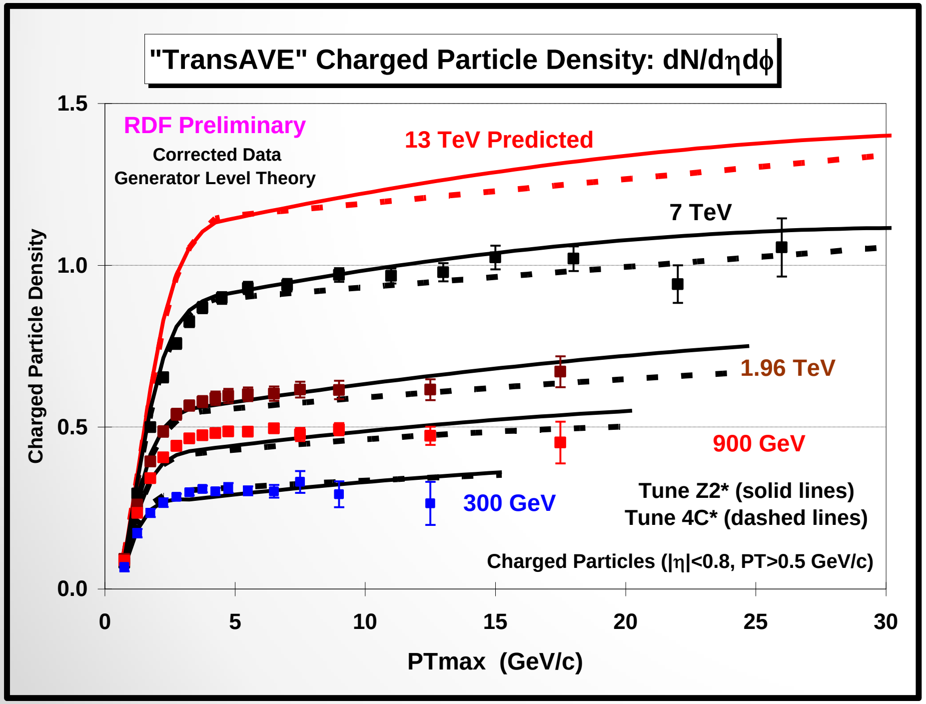


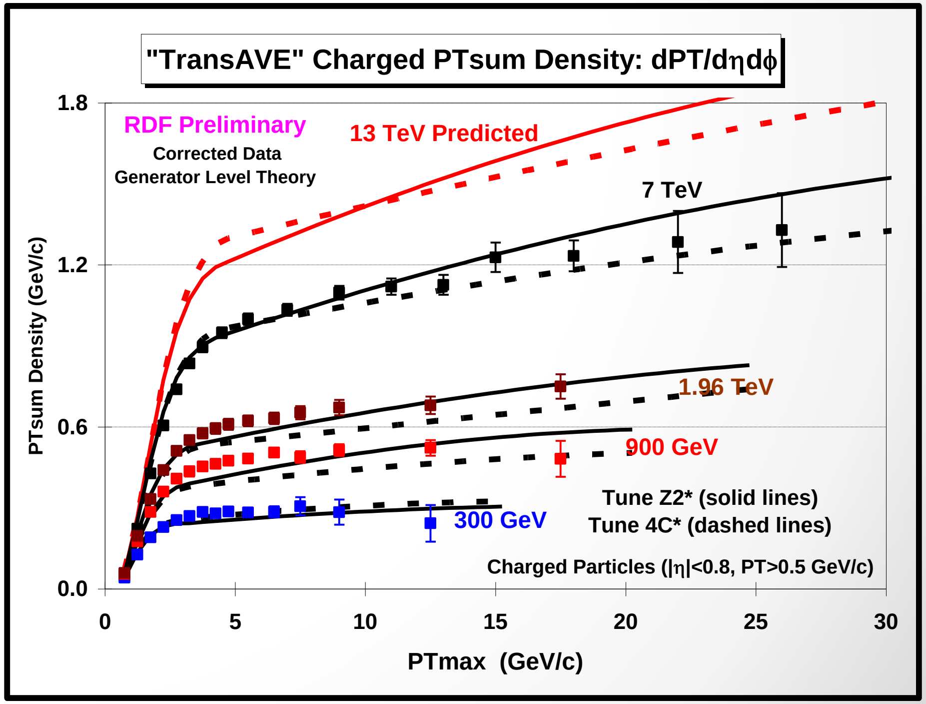
- Prospects:

HL LHC lumi = 5×10^{34} cm^{-2} /s with levelling and 25 ns bunch spacing : 140 Pile up!

Underlying event tunes

- We tune on UE because we want to tune the MPI part, jet fragmentation & hadronisation parameters were tuned on LEP data
- Underlying event contains on average 1±0.1 charged particle with p_t>500MeV per unit rapidity and unit azimuth in the presence of a jet with P_T>10 GeV in the transverse region at $\sqrt{s}$=7TeV
- Underlying event contains on average 1.2±0.2 GeV of transverse momentum in that same kinematic region

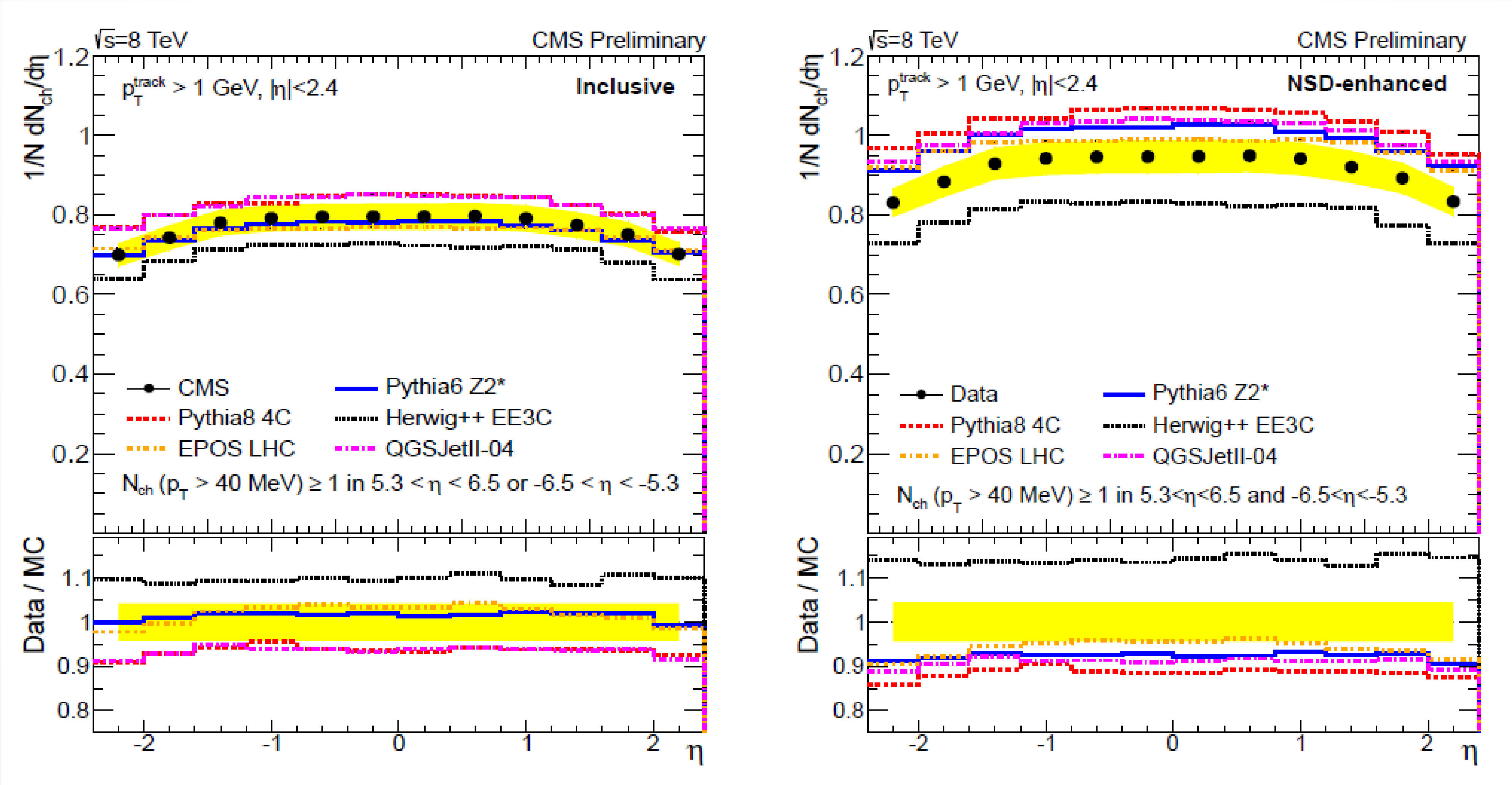

"TransAVE" Charged Particle Density: dN/dηdϕ


"TransAVE" Charged PTsum Density: dPT/dηdϕ

- From Rick Field at MPI@LHC workshop , Antwerpen december 2013

Min Bias modeling

- Dedicated CMS+TOTEM low pile-up run at $\sqrt{s}$=8 TeV: CMS PAS FSQ-12-026
- Inclusive charged particle rapidity density predicts ~ 1 charged particle with p_t>1GeV per unit rapidity ± 10-15% model uncertainty
- Inclusive sample better described than Non-single diffractive



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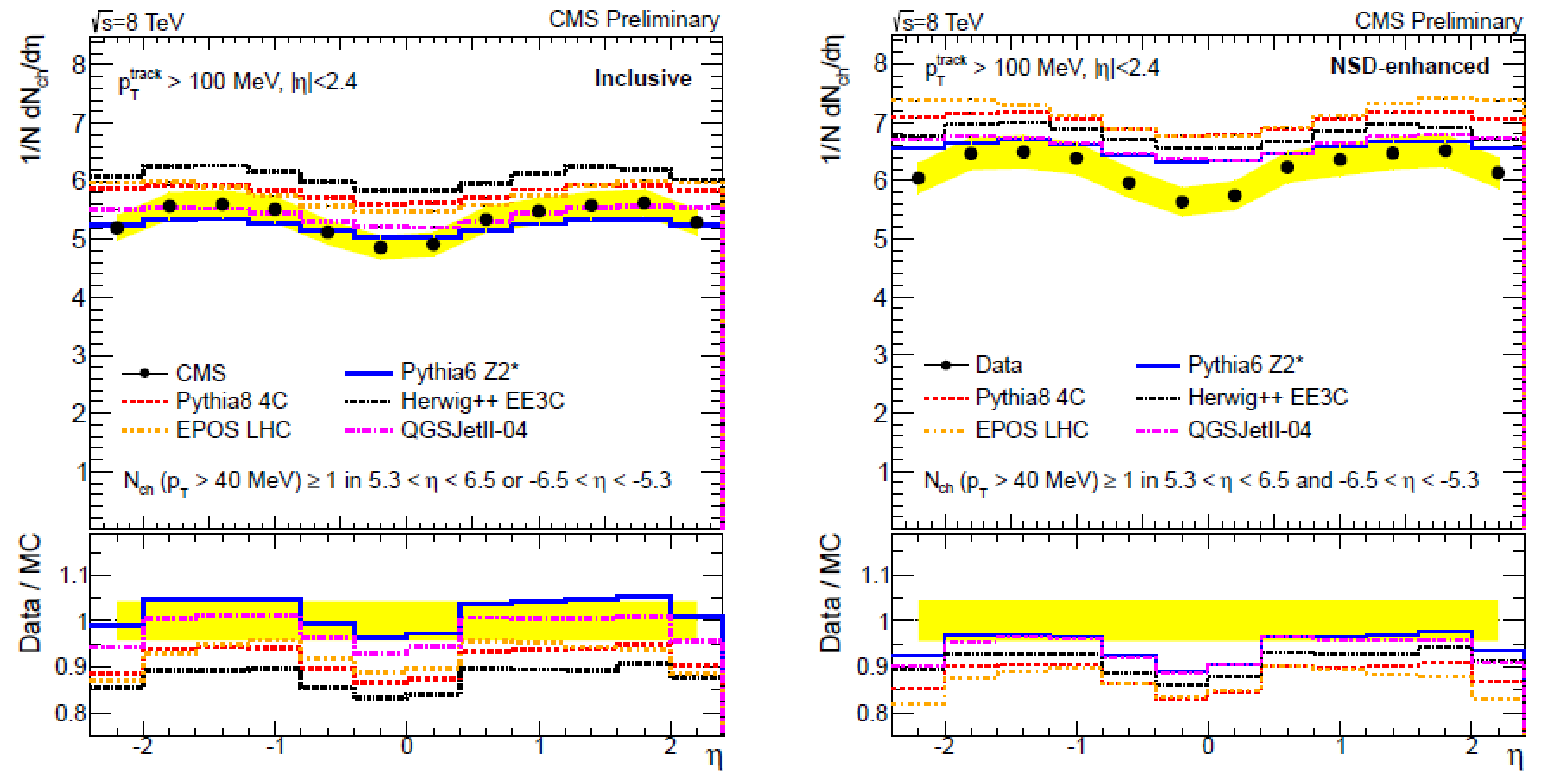
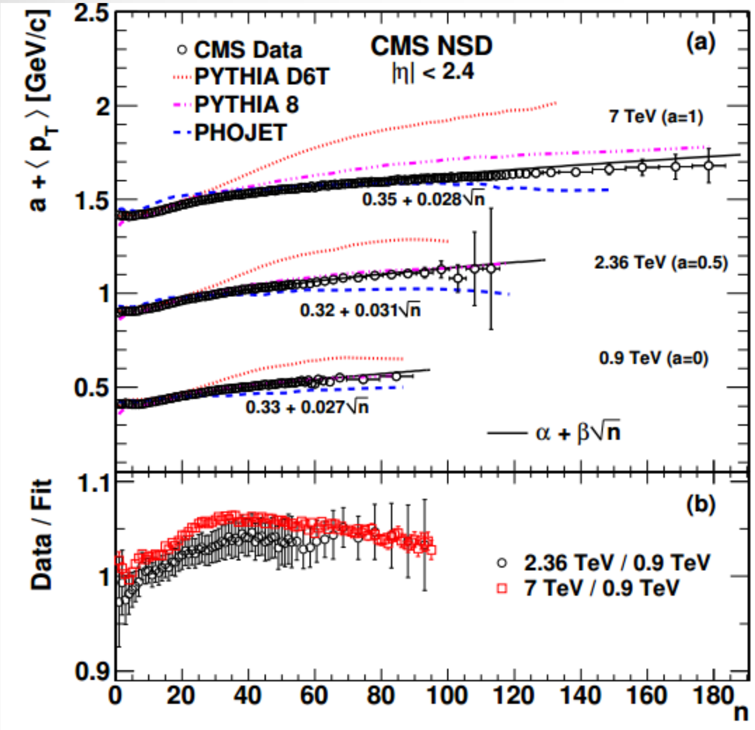
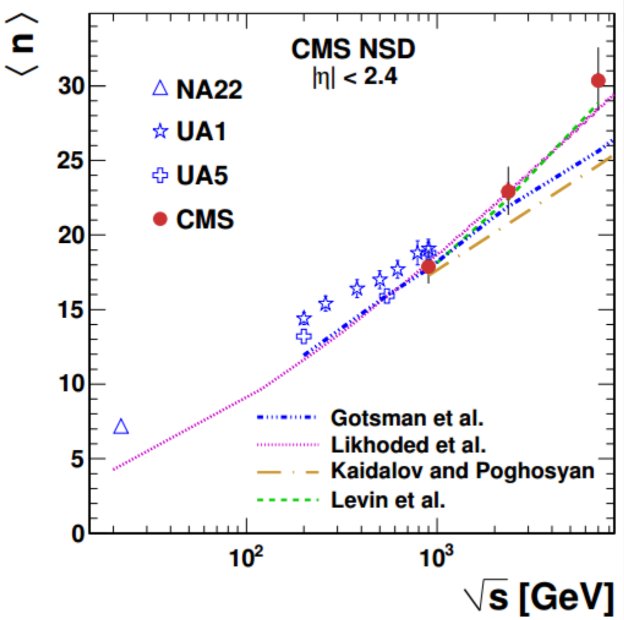
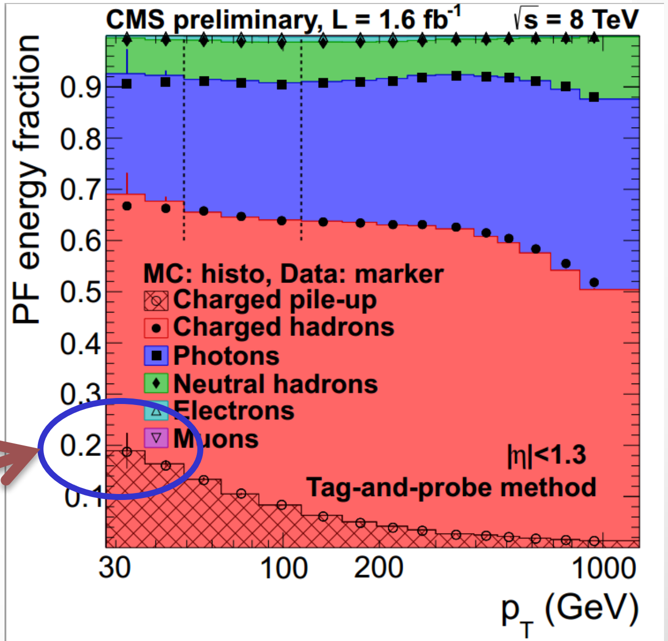
- Inclusive charged particle rapidity density predicts ~1 charged particle with p_t>1GeV per unit rapidity ± 10-15% model uncertainty
- Inclusive sample better described than Non-single diffractive
- 6 charged particles with p_t>100 MeV ± 20% model uncertainty



Consistent with pile-up



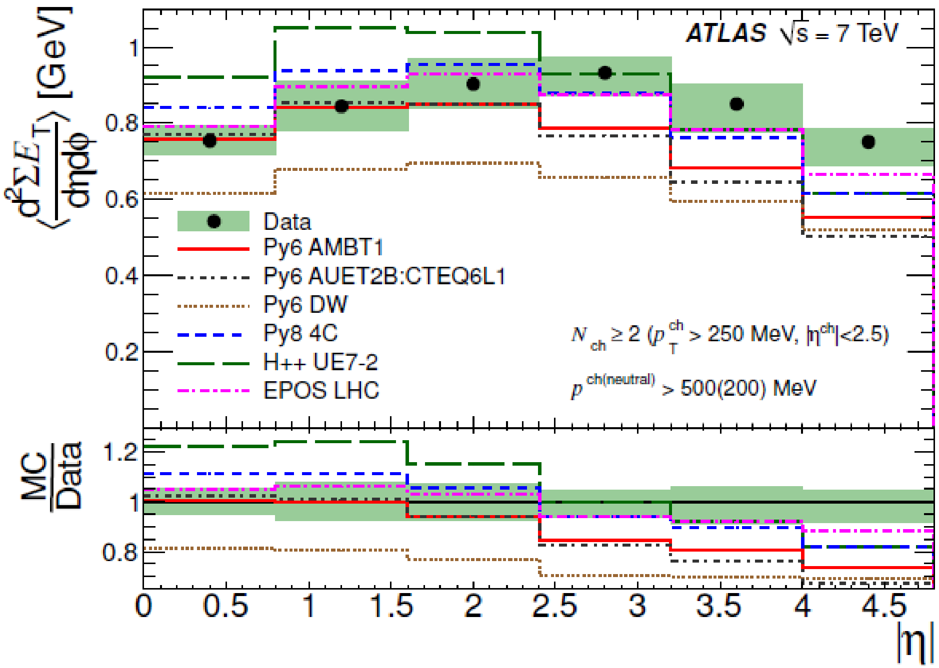




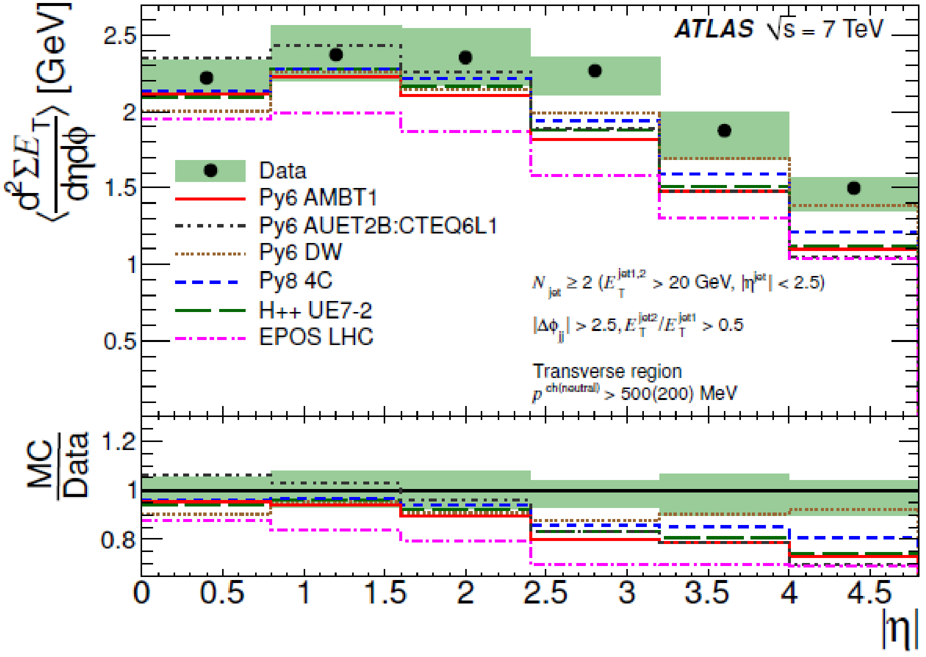
- $\langle n_{ch} \rangle = 30$ in 5 units of rapidity with $\langle p_t \rangle$ of 0.5GeV per particle adds on average 3 GeV of charged particle transverse momentum per unit rapidity
- → 0.3 GeV added to a cone of R=0.5 for each pile-up
- X 20pile up =6 GeV charged particle energy added!

Transverse energy flow

Minimum bias events



Underlying Event
transverse region measured in di-jet events



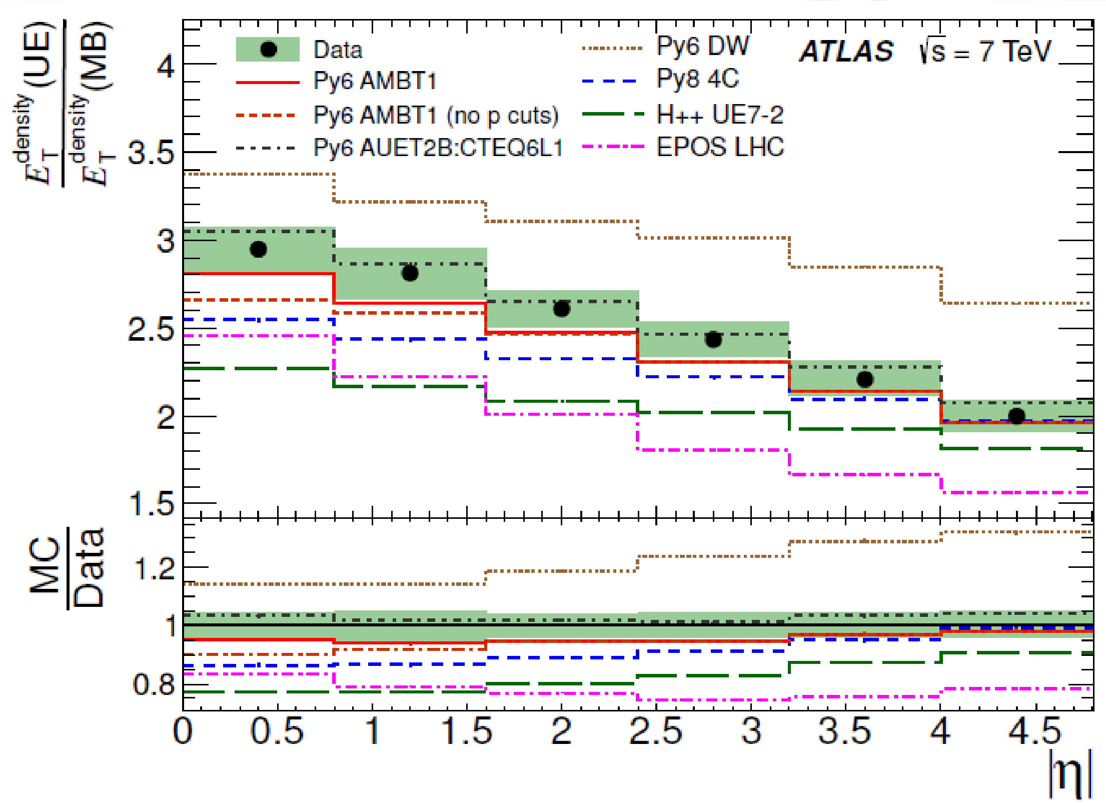
- Total transverse energy density ≈ 2 x the charged energy density
- Underlying Event:
  - First time measured as function of rapidity
  - UE activity decreases at higher rapidity and falls steeper than for min bias

  → Mostly due to high particle momentum cuts
  - Trend not well modeled by our tunes: 20-30% deviations!

ATLAS Coll., JHEP11(2012)033

Transverse energy flow

ATLAS Coll., JHEP11(2012)033



- Ratio energy density of Underlying Event/Min Bias
  - UE activity decreases at higher rapidity and falls steeper than for min bias

  → Mostly due to high particle momentum cuts
  - Di-jet events produce more high p_t particles, especially close to the jet
  - Trend pretty well modeled by our tunes, but ratio is off by 20%
- Also very interesting CMS measurement of energy dependence of UE at very forward rapidity : CMS Coll., JHEP04(2013)072

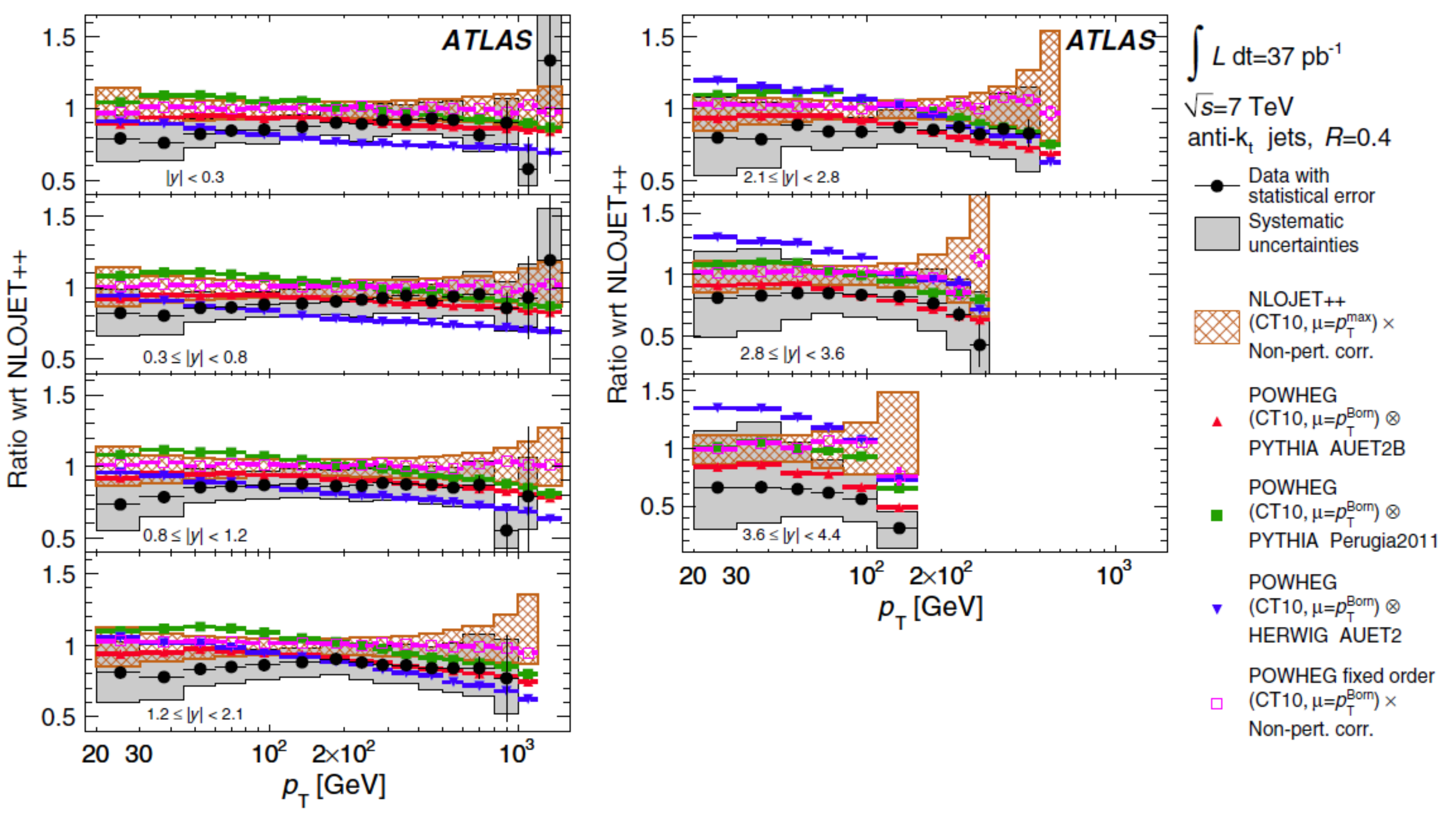
Summary 1

- Pile up effects on jets make sense from min bias data
- BUT:
  - Models always tuned at central rapidity!
  - Pile-up generates soft jets
  - Jet events have higher multiplicity
  - Measure it on jet-by-jet basis
  - Dedicated mitigation methods : see F. Pandolfi's talk
- Take home message:
  - Accuracy of our UE&MIN bias tunes as good as 10%
  - Degrades to 20% at high rapidity
  - Keep measuring and tune models to both min bias and UE data, it is the input to everything!
  - Tune more differentially if you can
- In all that follows we assume that pile-up is completely subtracted → only parton shower, MPI and hadronisation effects

Non-Pertuarbative effects on jets

…

Inclusive Jet cross sections



PHYSICAL REVIEW D 86, 014022 (2012)

Two approaches for inclusive jet cross section measurement:

- NLO theory predictions + posteriori corrections by means of matched parton showers and hadronisation MC wrt LO predictions
- Straight simulation of ‘NLO matched’ parton showers and hadronisation

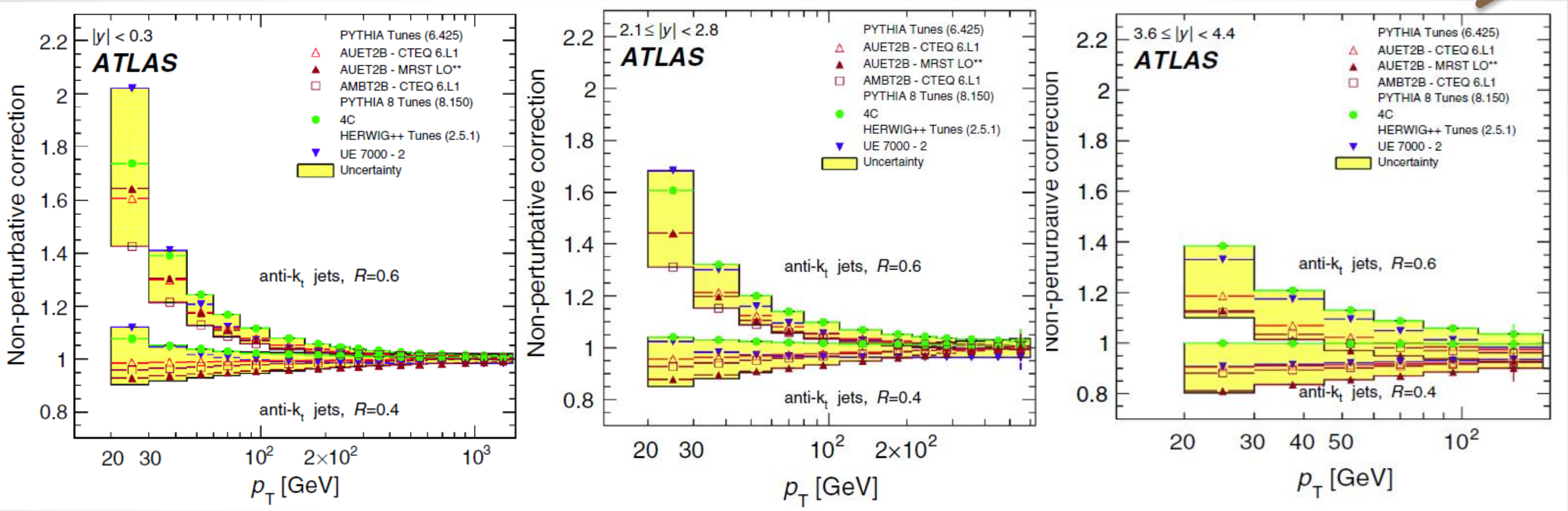
NLO+corrections start to fail at high rapidities and pt (small-x physics)
Parton showers+hadronisation including higher order radiative contributions can do better but large spread due to details of showering (underlying event)

Inclusive Jet cross sections

PHYSICAL REVIEW D 86, 014022 (2012)

Non-perturbative corrections applied to NLO calculations:
Ratio of NLO ME/ NLO ME parton shower + hadr.

Rapidity y



Nature of non-perturbative corrections

- **Corrections dominant for**
  - **Large Cone size**
  - **Small pt**
  - **Small dijet masses**
- **Relative uncertainties remain rather constant**
- **Taken into account by parton shower + MPI (+ hadronisation)**
- **Corrections diminish at high rapidity at high energies because UE activity diminishes at high rapidities (see previous slides)**

What dominates the effect?

- Parton shower ?
- MPI ?
- Hadronisation?

Generator study

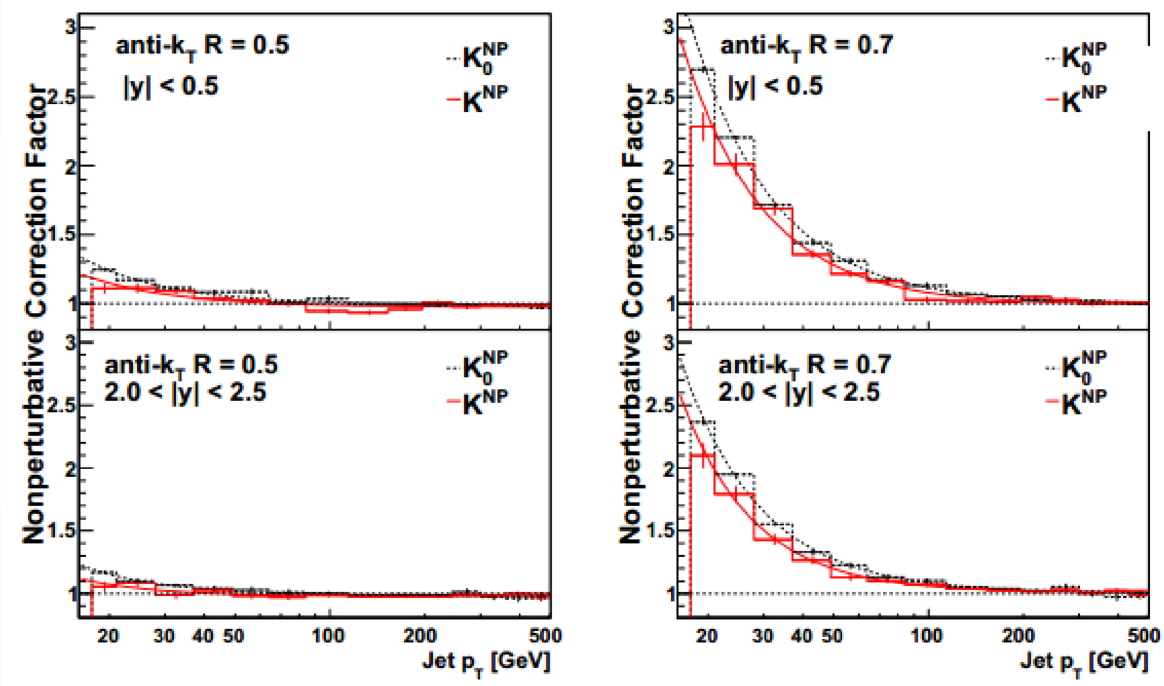
arXiv:1212.6164v2 [hep-ph], arXiv:1304.7180v1 [hep-ph],
Dooling, Gunnellini, Jung, Hautmann

Small cones

Large cones

Central

Forward



Corrections with LO MC:
PYTHIA, HERWIG

$$K_0^{NP} = N^{(ps+mpi+had)}_{LO-MC} / N^{(ps)}_{LO-MC} \quad ,$$

Corrections with NLO MC:
POWHEG+PYHIA,HERWIG

$$K^{NP} = N^{(ps+mpi+had)}_{NLO-MC} / N^{(ps)}_{NLO-MC} \quad ,$$

- NP correction factors obtained with LO generators are larger than factors obtained with matched NLO generators, in particular at low jet $p_T < 50$ GeV
- An increase of cone size from 0.5 to 0.7 increases these correction factors dramatically

Generator study

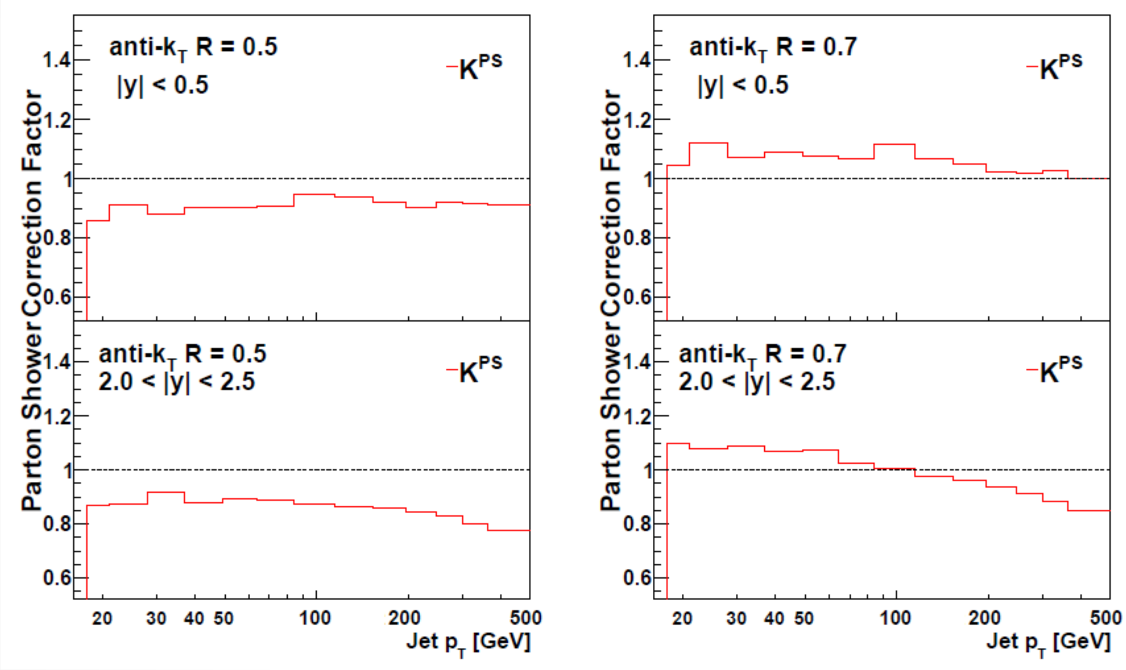
Corrections with NLO MC: POWHEG+PYHIA allow to separate Parton shower correction from MPI&hadronisation

Small cones

Large cones

Central

Forward



$$K^{NP} = N^{(ps+mpi+had)}_{NLO-MC} / N^{(ps)}_{NLO-MC} \;,$$

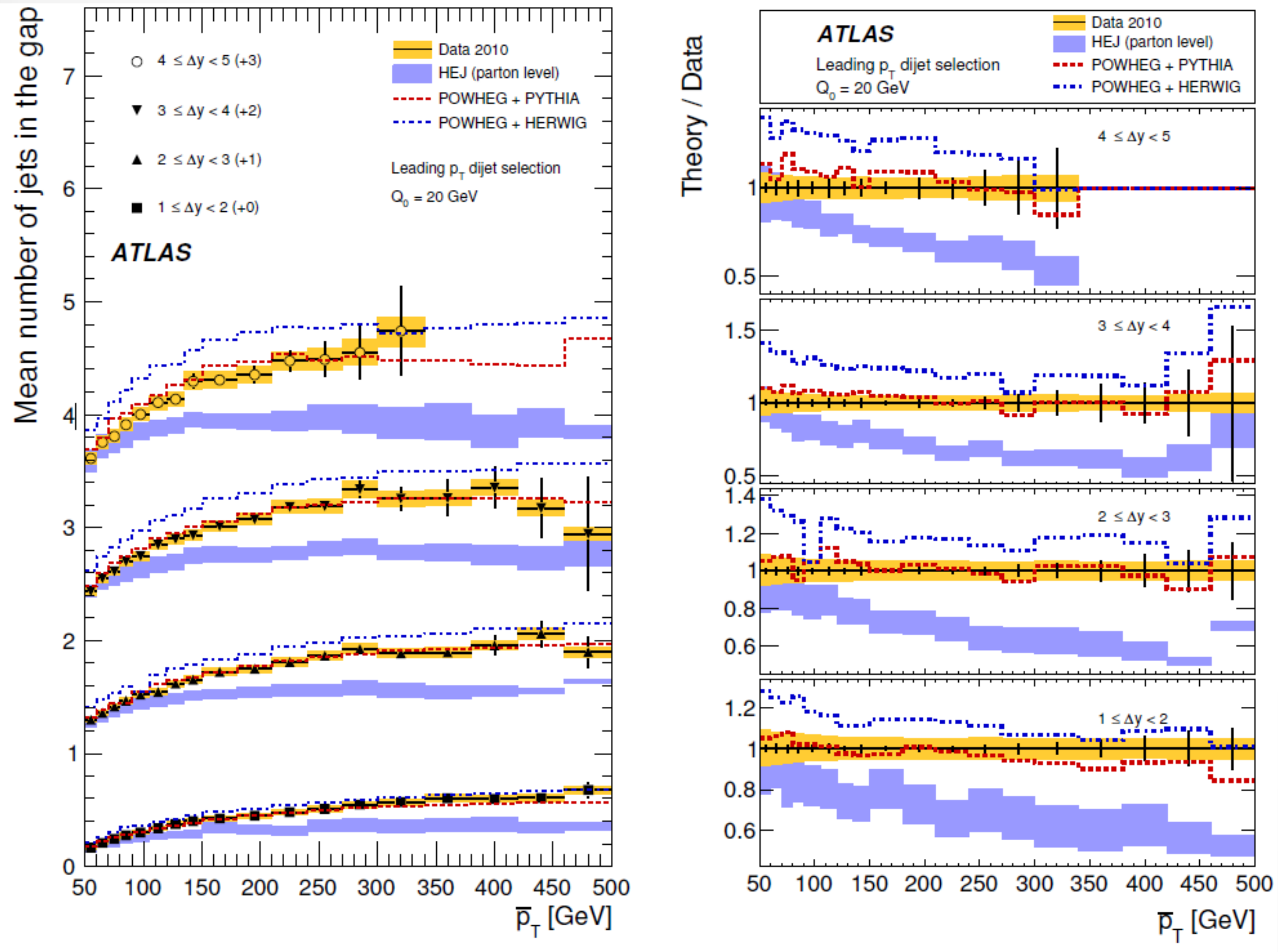
$$K^{PS} = N^{(ps)}_{NLO-MC} / N^{(0)}_{NLO-MC} \;,$$

- Parton shower effects are generally smaller than MPI effects for large cone sizes
- For small cone sizes they are equal and nearly cancel each other
- Parton shower effects become largest (20%) at high rapidity and large pT and and have non-trivial effects when treated consistently with other NP effects

➔ caution when extracting PDF's from these measurements

Jet Vetos

- Very interesting measurements on jet activity BETWEEN two high P_T forward-backward jet configurations
- Very important for any jet veto imposed in VBF event topology selections
- Modeling is stretching validity of DGLAP shower development, however agreements still outstanding for PYTHIA + NLO parton shower



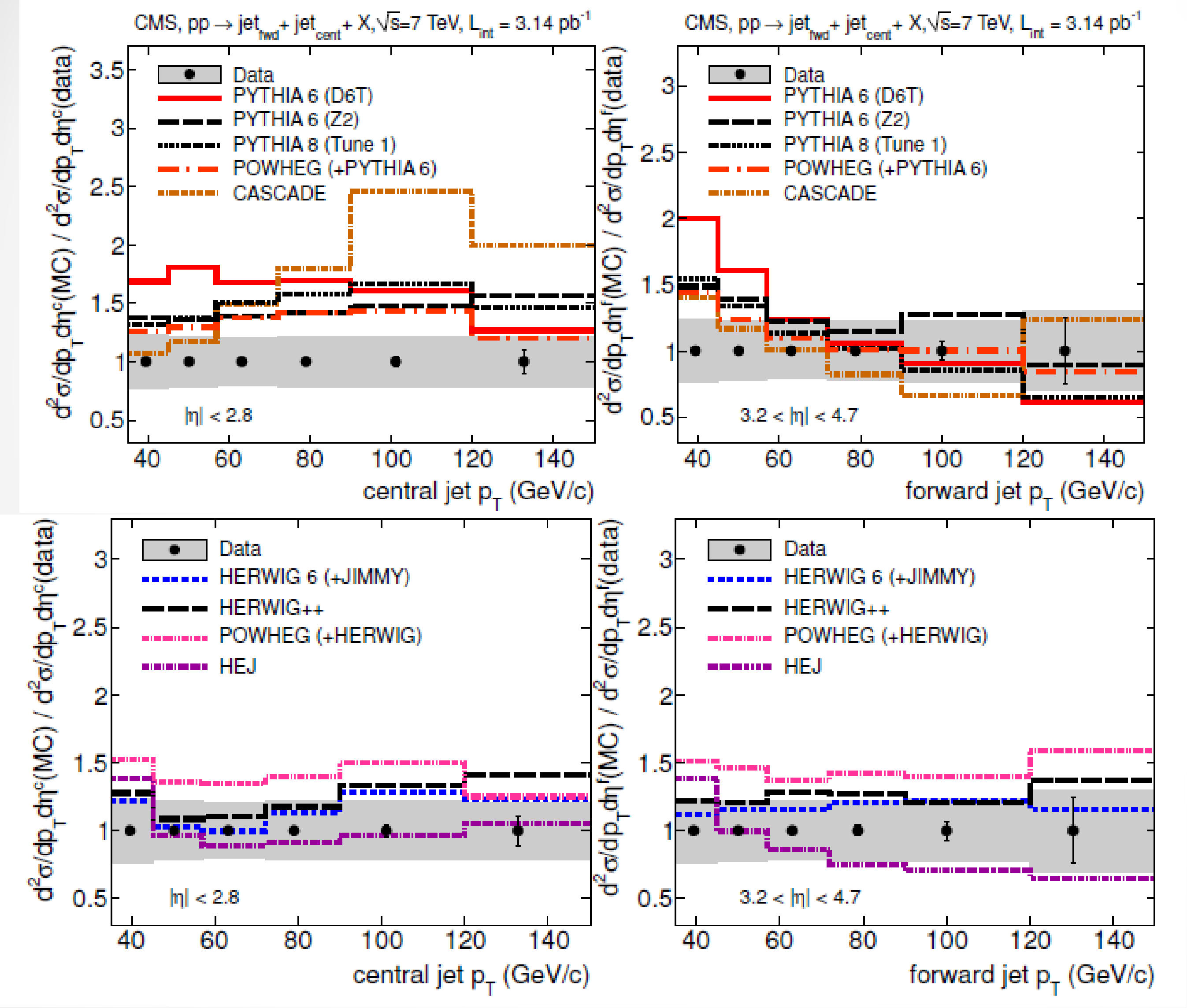
ATLAS Coll., JHEP09(2011)053

HEJ:
BFKL inspired parton shower
BUT: only suited if all jets have similar P_T

More on BFKL and Non-linear PS: see K. Kutak's talk

Jet Vetos

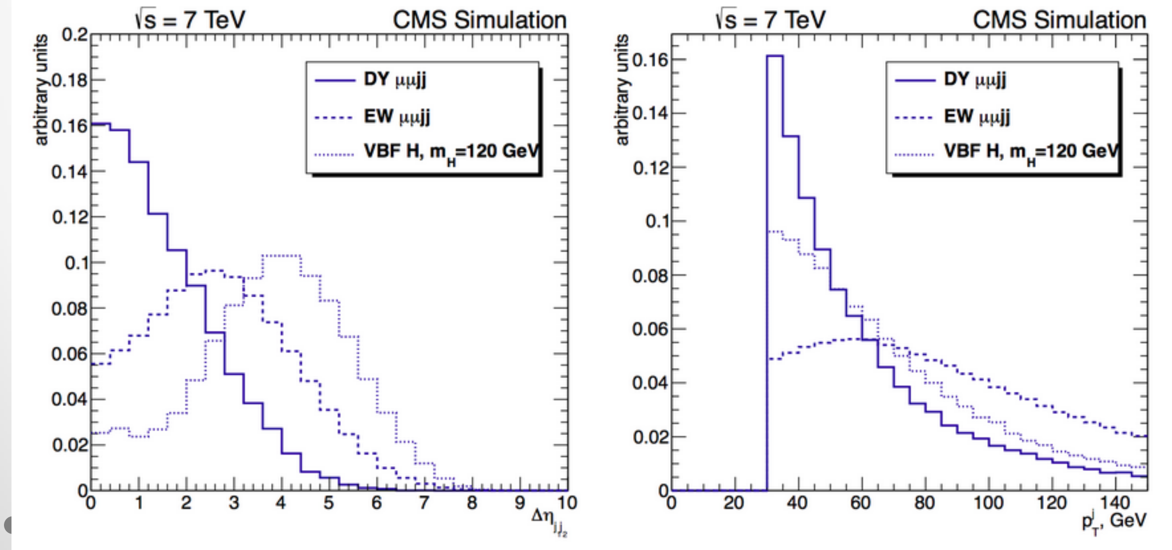
- Similar measurement of CMS: single jet cross section for di-jet events with one central and one forward jet



CMS Coll., JHEP06(2012)036

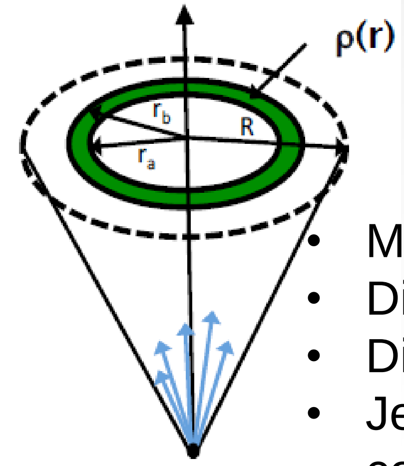
Summary 2

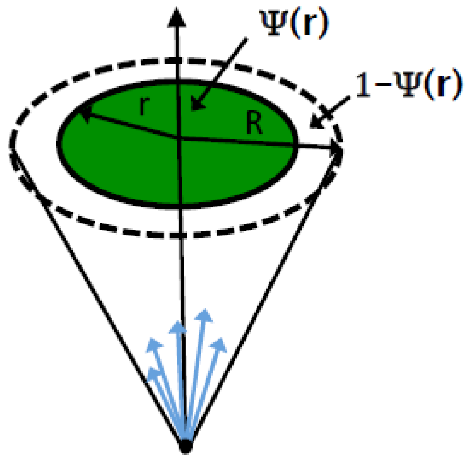
- Multi Parton Interactions dominate the non-perturbative corrections for large cone sizes for jets with P_T<100 GeV
- They decrease and cancel with parton shower corrections for small cone sizes
- Parton shower corrections dominate at high Pt and high rapidity, regardless of the cone size
- Relevant for VBF tag jets: typically forward and high Pt



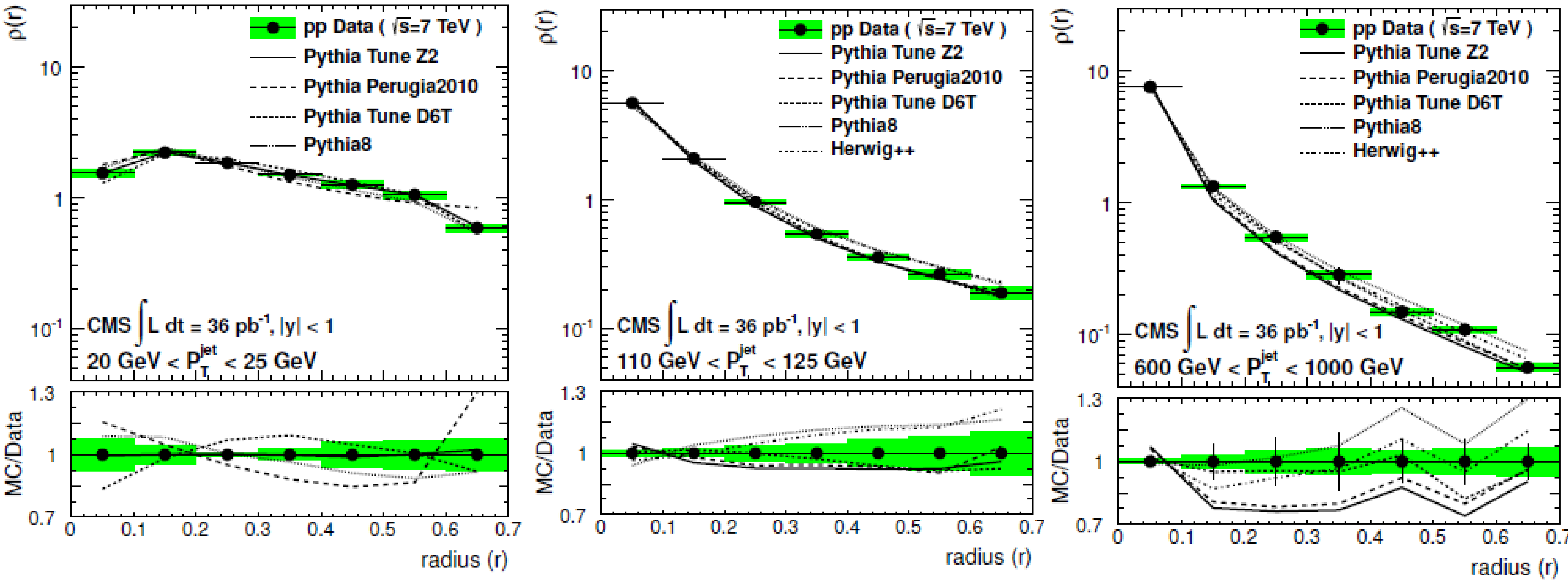
CMS Coll., JHEP10(2013)062

Jet shapes



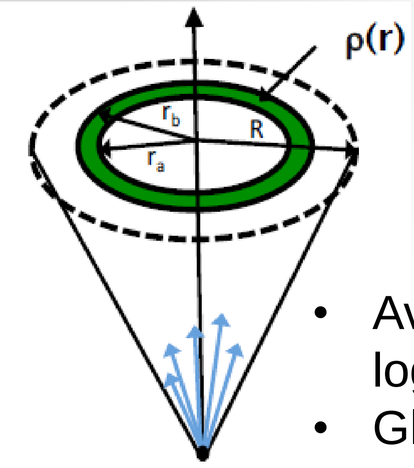


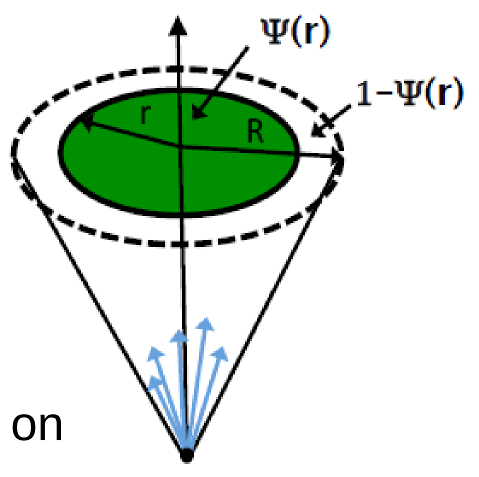
- Many quantities to describe jet (sub-) structure
- Differential jet shape is classic measure
- Different jet algorithms result in different shapes
- Jets get narrower as their P_T increases as a consequence of the Lorenz boost
- Multi jet topologies can be boosted into single jet !
- Model uncertainties contained within ~20%



CMS Coll., JHEP06(2012)160

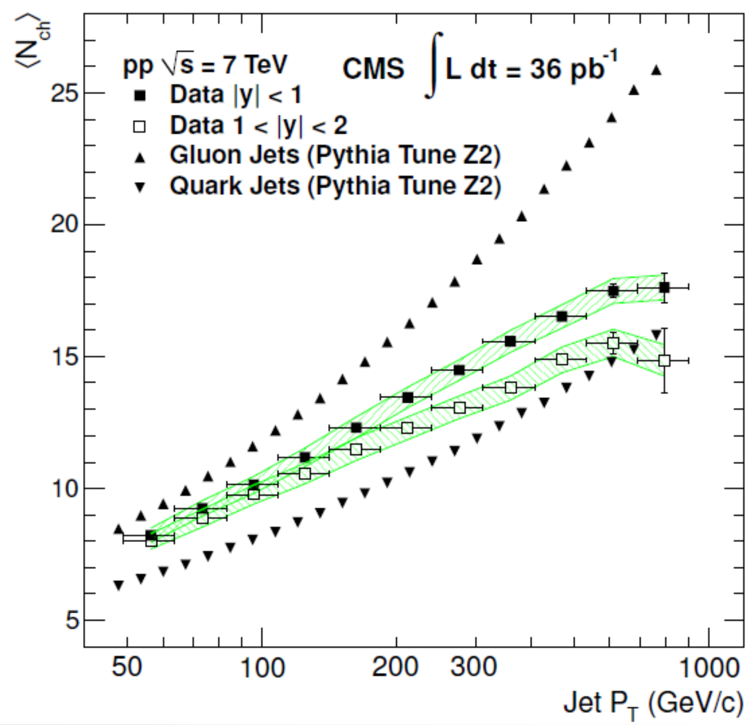
Jet shapes

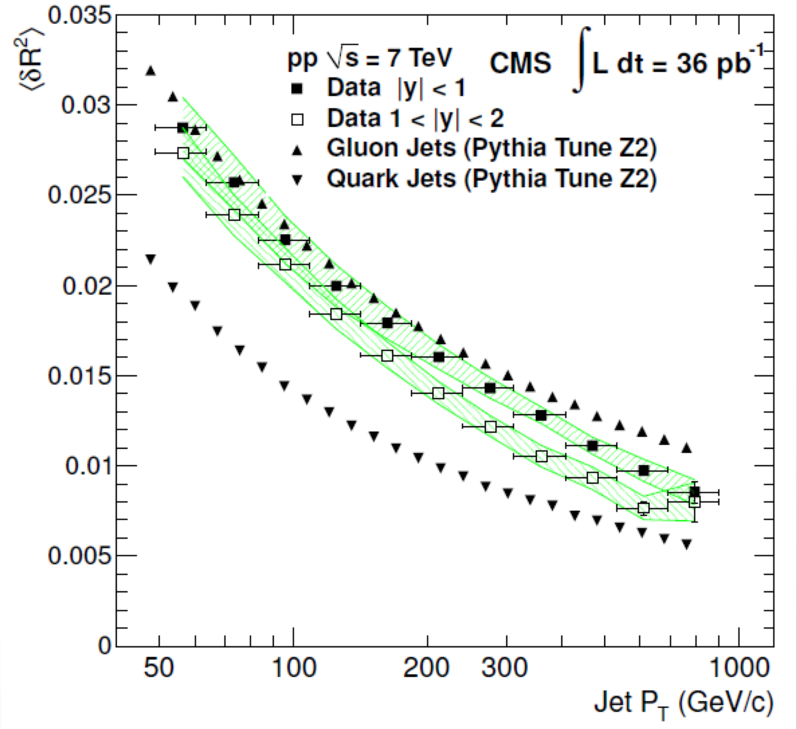




CMS Coll., JHEP06(2012)160

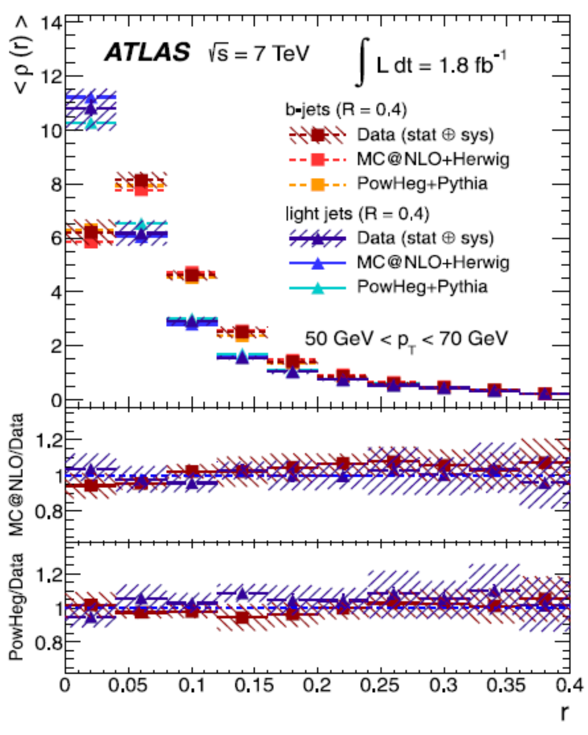
- Average charged particle multiplicity grows logarithmically with jet P_T
- Gluon jets are broader than quark jets and contain on average more charged particles
- Quark jets more ‘elliptical’ (planar flow)
- Properties can be exploited in dedicated quark taggers (see F. Pandolfi’s talk)

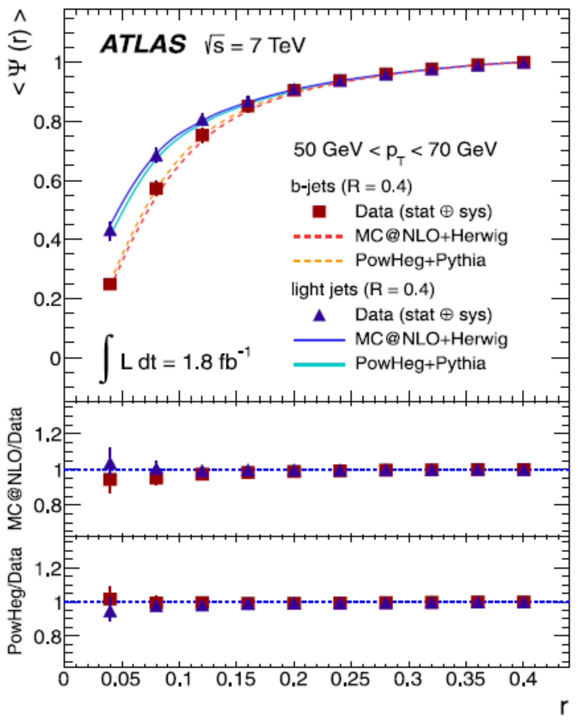


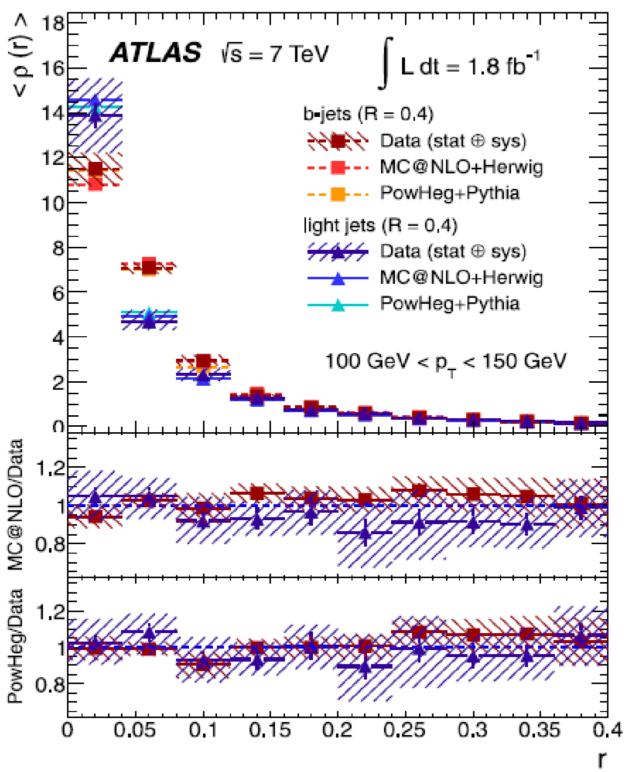


B-Jets

- Top decays as handle to very pure b-jet samples
- B-jets are broader than light quark jets
- Differences become negligible when jet P_T>100GeV
- Inclusive b jets are somewhat smaller than b jets in tt decays (color flow)







ATLAS Coll., Eur. Phys. J. C (2013) 73:2676

Conclusion and outlook

☞ **The modeling of non-perturbative effects is under control and has typical uncertainties of O(10-20%)**
☞**Effects of parton shower and MPI are most relevant**
☞**Largest discrepancies with data observed at large rapidities and in peculiar kinematic regimes involving large rapidity separation between jets (VBF like topologies) or highly boosted (massive) jets**

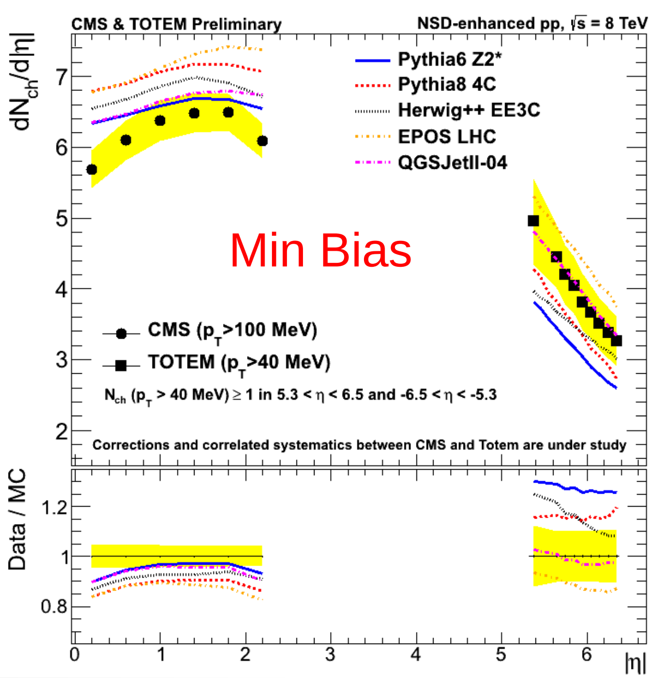
Backup

Definitions

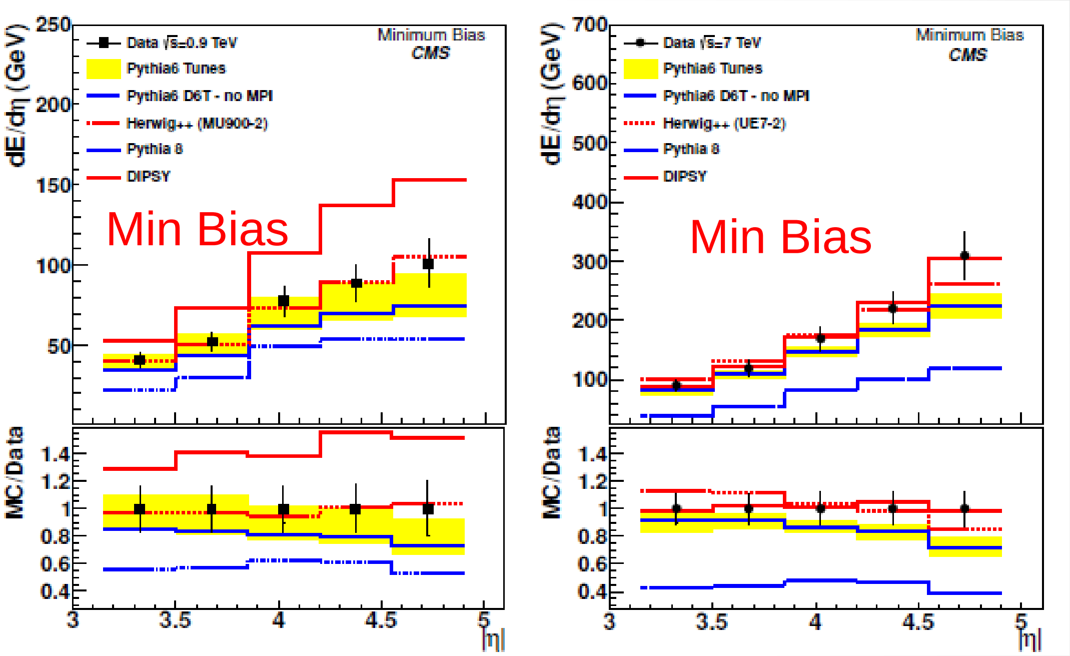
- Multi Parton Interactions (MPI): The occurrence of more than one 2->2 partonic interaction when hadrons collide at high energies
- Minimum Bias (MB) data: data accumulated with ‘unbiased’ triggers sampling the inelastic xsec in its natural proportions
  - Contains predominantly low energetic jets with Pt<10 GeV
  - Is not completely unbiased (wrt single diffractive processes)
  - Test of parton shower, MPI, hadronisation modeling
- Underlying event: all hadronic activity produced by a single hadron-hadron interaction that does not originate from primary hard parton scatter:
  - Initial and final state parton showers
  - Beam remnant
  - MPI

What happens at high eta

CMS PAS FSQ-12-026



CMS Coll., JHEP11(2011)148



- At |η| >3 the charged particle density starts to fall for min bias (MB) events
- BUT:
  - Energy flow increases at high rapidity, factor 2 for MB events in range 3<|η| <5
  - Energy flow increases with almost factor 3 between √s=0.9 and 7 TeV (larger than multiplicity increase over same energy domain)
  - Model uncertainties (tunes) amount to 20%
  - MPI's account for more than 50% of the energy flow, even in min bias
  - Parton shower alone accounts for ~20-25%

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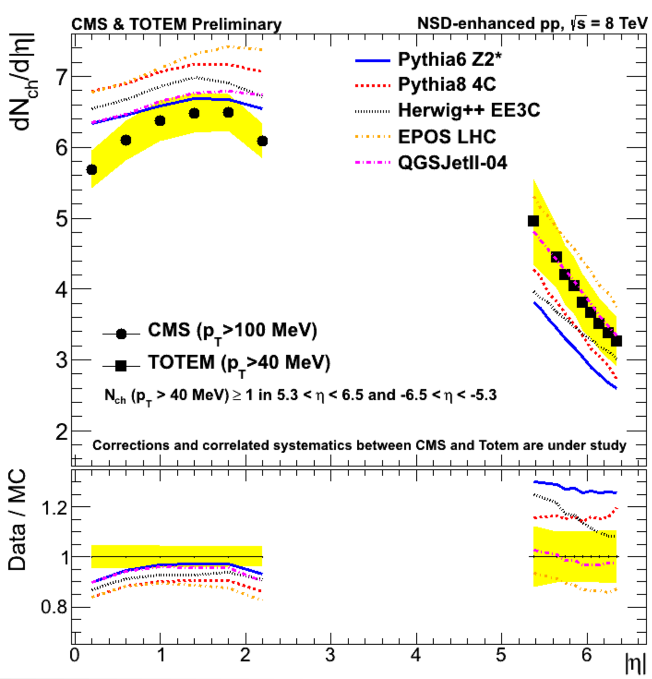
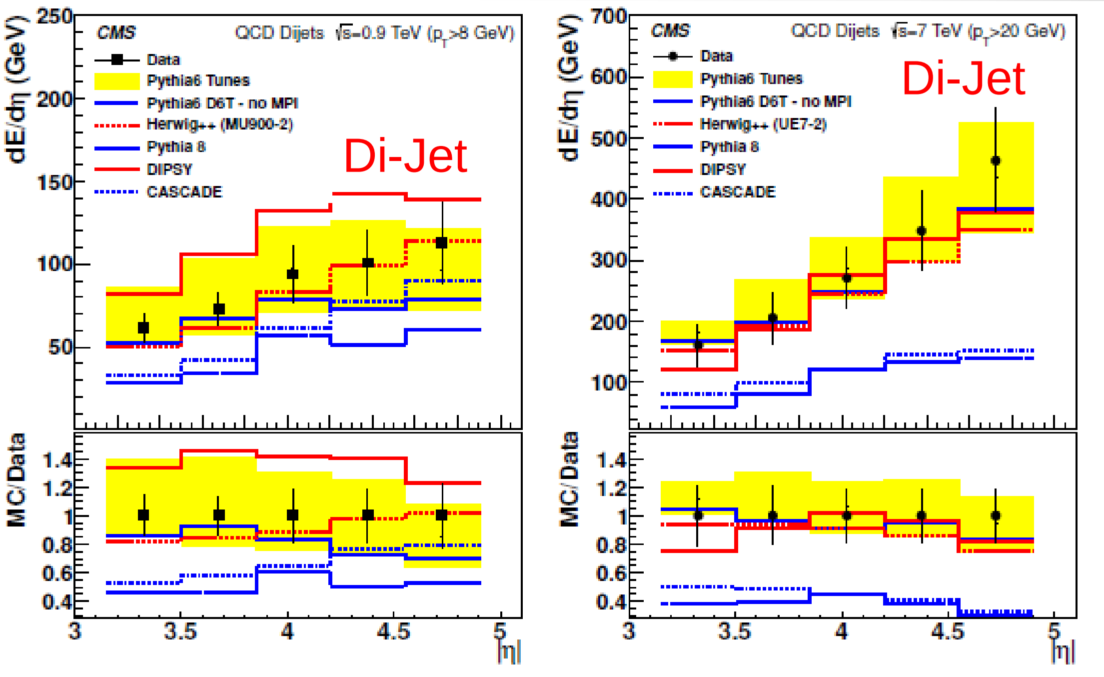


CMS Coll., JHEP11(2011)148



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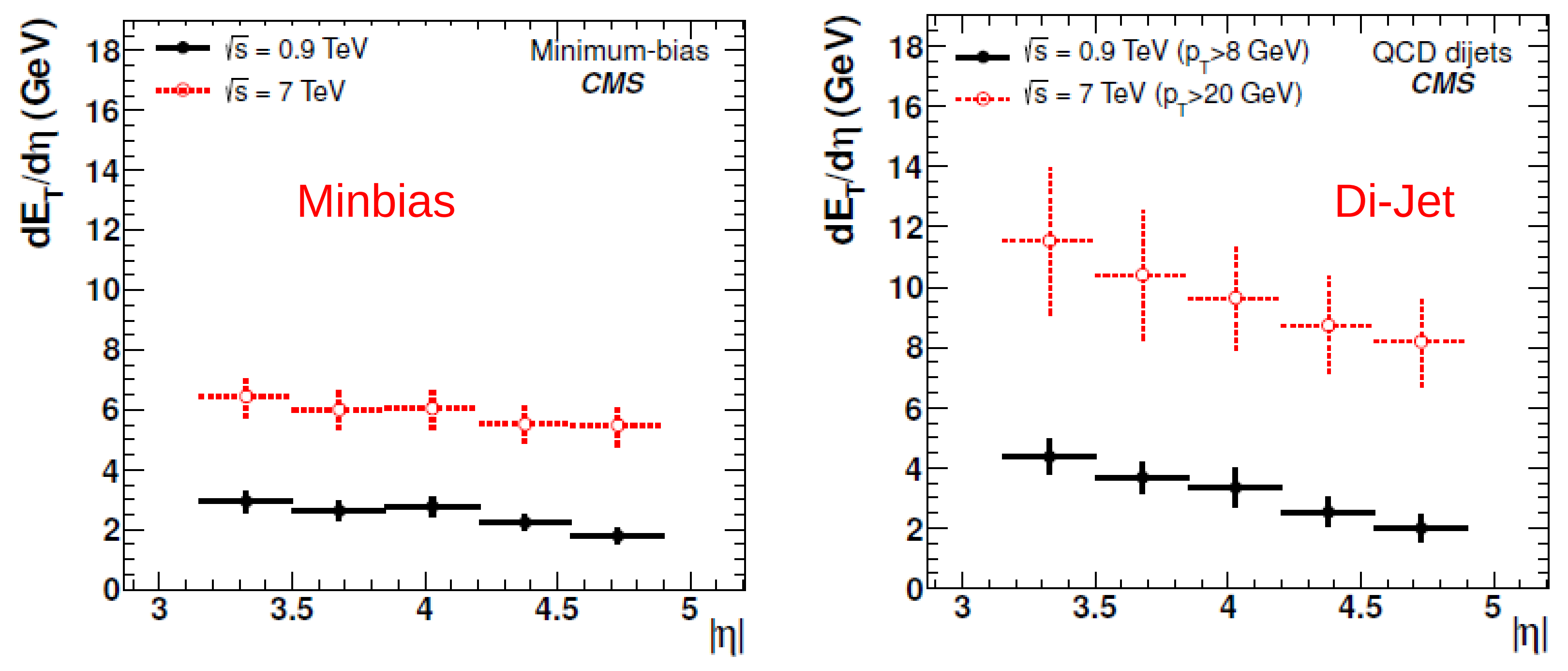
  - Model uncertainties (tunes) amount to 20%
  - MPI’s account for more than 50% of the energy flow, even in min bias
  - Parton shower alone accounts for ~20-25%
  - Magnitude of energy flow is much higher for di-jet compared to MB events
  - Relative increase smaller for di-jet than MB events
- → Need to measure UE in rapidity bins and as function of rapidity of di-jet system

What happens at high eta



CMS Coll., JHEP11(2011)148

- Transverse Energy flow is roughly constant for Min bias
- Decreases with rapidity for central di-jet events

➔ Consistent with p_T (or virtuality) ordered parton showers where the largest p_T parton is closest (in rapidity) to the hard scatter and the lowest p_T emission closest to the beam remnants

Multiple Parton interactions

- Realisation from experiment: ISR, Tevatron, ...
  - Some p-p collisions exhibit 2 or more (semi-) hard parton-parton scatters
- Realisation from theory: below pt scale of ~2GeV the parton-parton cross section exceeds the total p-p cross section

Amount of parton-parton interactions
Is Poisson process with mean

$$< N_{\text{int}} >= \frac{\sigma_{\text{int}}(p_{t_{\min}})}{\sigma_{nd}}$$

Modeling MPI

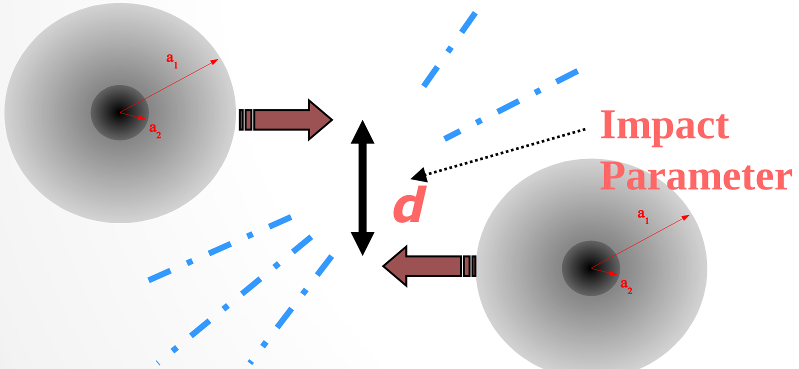
Basic idea T. Sjöstrand and M. Van Zijl, Phys. Rev. D 36 (1987) 2019

- Theoretical fact: differential 2→2 cross section diverges as $p_t \rightarrow 0$
- Solution: Introduce cut-off p_{t0} to ensure finite and calculable results

Screens color and evolves with center of mass energy as s^{α}

$$\frac{d\hat{\sigma}}{dp_t^2} \propto \frac{\alpha_s^2(p_t^2)}{p_t^4} \rightarrow \frac{\alpha_s^2(p_t^2+p_{t0}^2)}{\left(p_t^2+p_{t0}^2\right)^2}$$

Pythia MPI Model with Varying impact parameter between the colliding hadrons: hadronic matter is described by double Gaussians



Introduce IP correlations in Multiple Parton Interactions →

Describe Tails!

- Independent MPI: Poisson process, with minimal 1 interaction
- Make Poisson broader by impact parameter based average number of MPI
- All generators use this model, but differ in choice of p_{t0} and subsequent showers
- Currently only way to get N_{ch} and p_{tch} correct over wide energy range