Min-Bias Cross Sections & Characteristics at 30 - 100 TeV

Peter Skands (CERN TH)

What does the average collision look like?

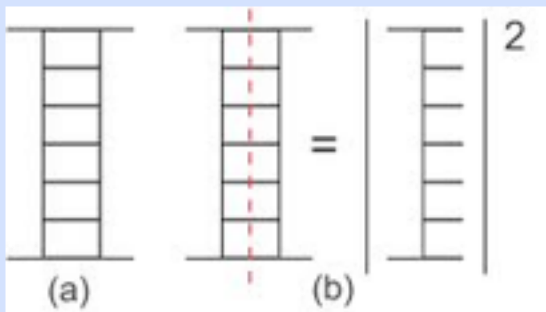
How many of them are there? (σ_{pileup})

How much energy in the Underlying Event? (UE)

Theory Models

See e.g. Reviews by MCnet [arXiv:1101.2599] and KMR [arXiv:1102.2844]

A Regge Theory



Optical Theorem

+ Eikonal multi-Pomeron exchanges

$\sigma_{\mathrm{tot,inel}} \propto \log^2(s)$

Cut Pomerons → Flux Tubes (strings)

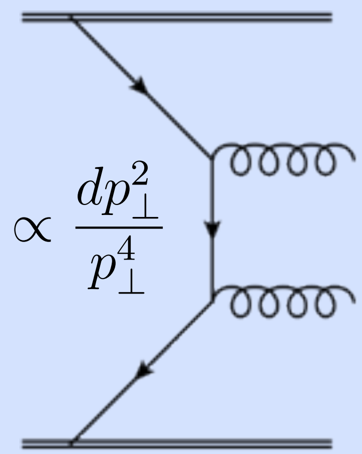
Uncut Pomerons → Elastic (& eikonalization)

Cuts unify treatment of all soft processes

EL, SD, DD, … , ND

Perturbative contributions added above Q_0

B Parton Based



$$d\sigma_{2\to2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \mathrm{PDFs}$$

+ Unitarity & Saturation

→ Multi-parton interactions (MPI)

+ Parton Showers & Hadronization

Regulate dσ at low p_{T0} ~ few GeV

Screening/Saturation → energy-dependent p_{T0}

Total cross sections from Regge Theory

(Donnachie-Landshoff + Parametrizations)

+ "Mixed"

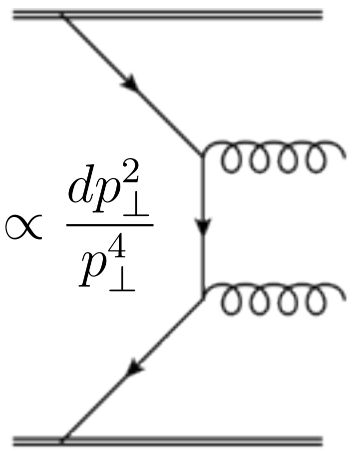
E.g., QGSJET, SIBYLL

E.g., PHOJET, EPOS, SHERPA-KMR

E.g., PYTHIA, HERWIG, SHERPA

A) Parton-Based Models

Main applications: Central Jets/EWK/top/ Higgs/New Physics



$$d\sigma_{2\to 2} \propto \frac{dp_\perp^2}{p_\perp^4} \otimes \text{PDFs}$$

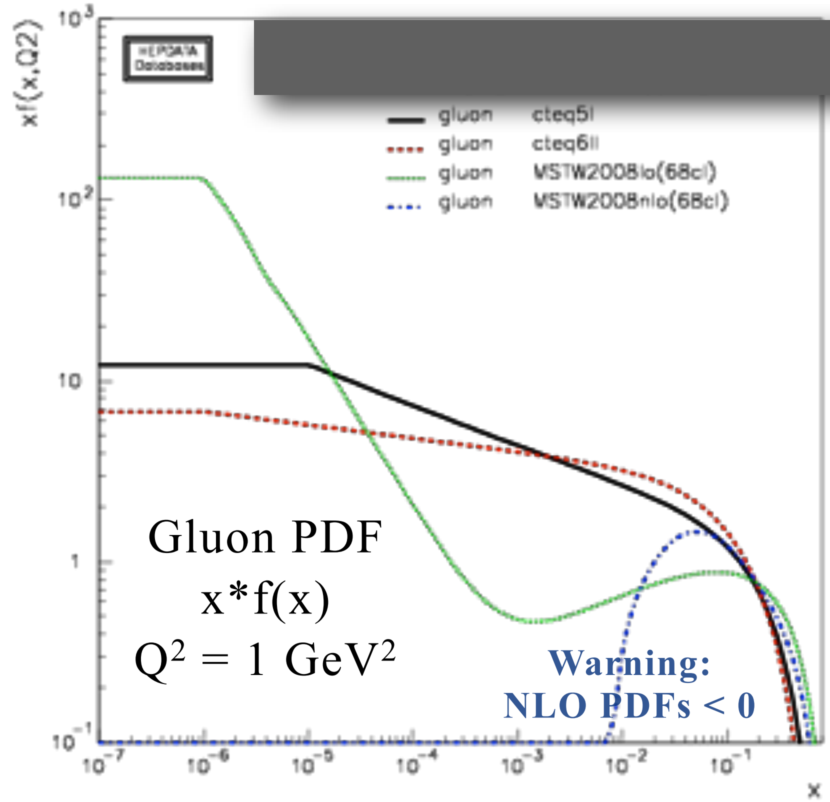
High Q^2 and finite x

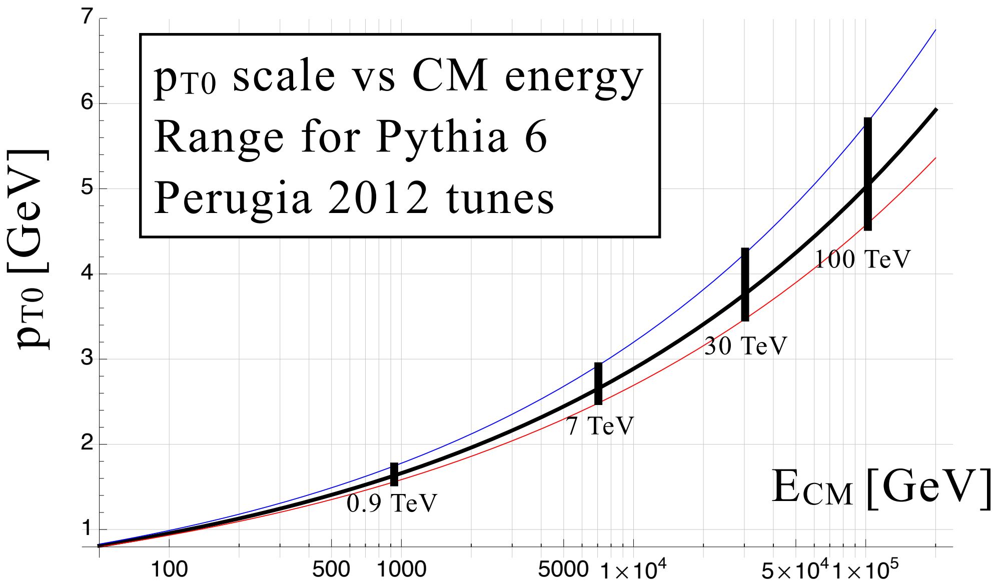
Extrapolation to soft scales delicate.
Impressive successes with MPI-based models but still far from a solved problem

Saturation

- Form of PDFs at small x and Q^2
- Form and E_{cm} dependence of p_{T0} regulator
- Modeling of the diffractive component
- Proton transverse mass distribution
- Colour Reconnections, Collective Effects

Poor Man's Saturation





See also Connecting hard to soft: KMR, EPJ C71 (2011) 1617 + PYTHIA "Perugia Tunes": PS, PRD82 (2010) 074018

Inelastic Cross Sections & Scaling

(elastic is included on summary slide)

Disclaimer: for this talk, I do not aim for a precision better than, say, 10%
I will be basing extrapolations mainly on Pythia 6 with LHC tunes
If you find that too crude, I am willing to bet a bottle of good champagne on the numbers

Total Inelastic: Donnachie-Landshof (ε~0.08)

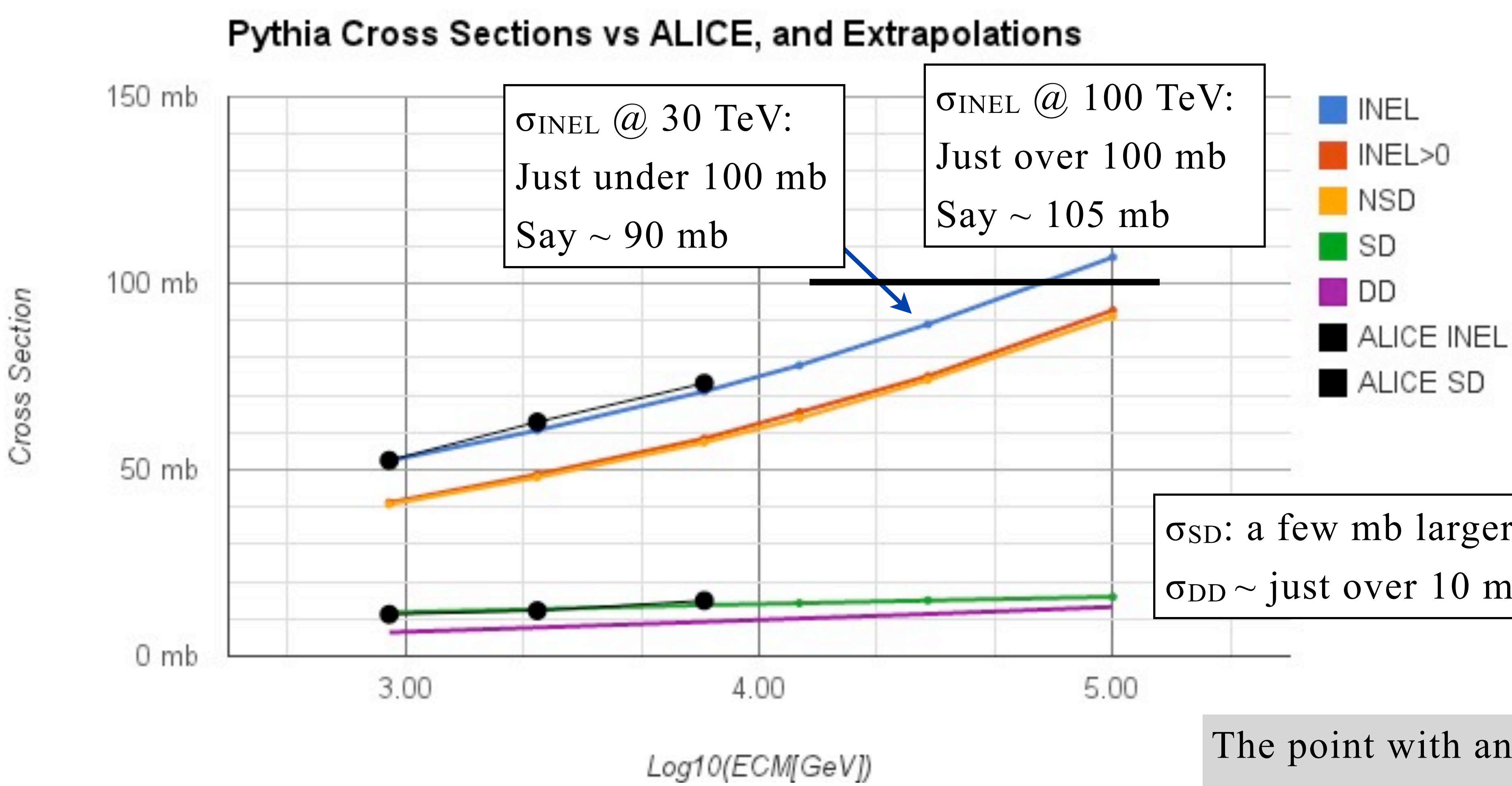
$\sigma_{\mathrm{INEL}} = \sigma_{\mathrm{TOT}} - \sigma_{\mathrm{EL}}$

$\sigma_{\mathrm{ND}} = \sigma_{\mathrm{INEL}} - \sigma_{\mathrm{SD}} - \sigma_{\mathrm{DD}}$

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\,,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\,.$$

$g_{3\mathbb{P}} \approx 0.318\ \mathrm{mb}^{1/2}$



What Cross Section?

INEL	Total Inelastic
INEL>0	Fraction with one charged particle in $|\eta|<1$
NSD	Ambiguous Theory Definition
SD	Ambiguous Theory Definition
DD	Ambiguous Theory Definition
ALICE INEL	Observed fraction corrected to total
ALICE SD	ALICE def : SD has MX<200

σ_{SD}: a few mb larger than at 7 TeV
$\sigma_{\mathrm{DD}} \sim$ just over 10 mb

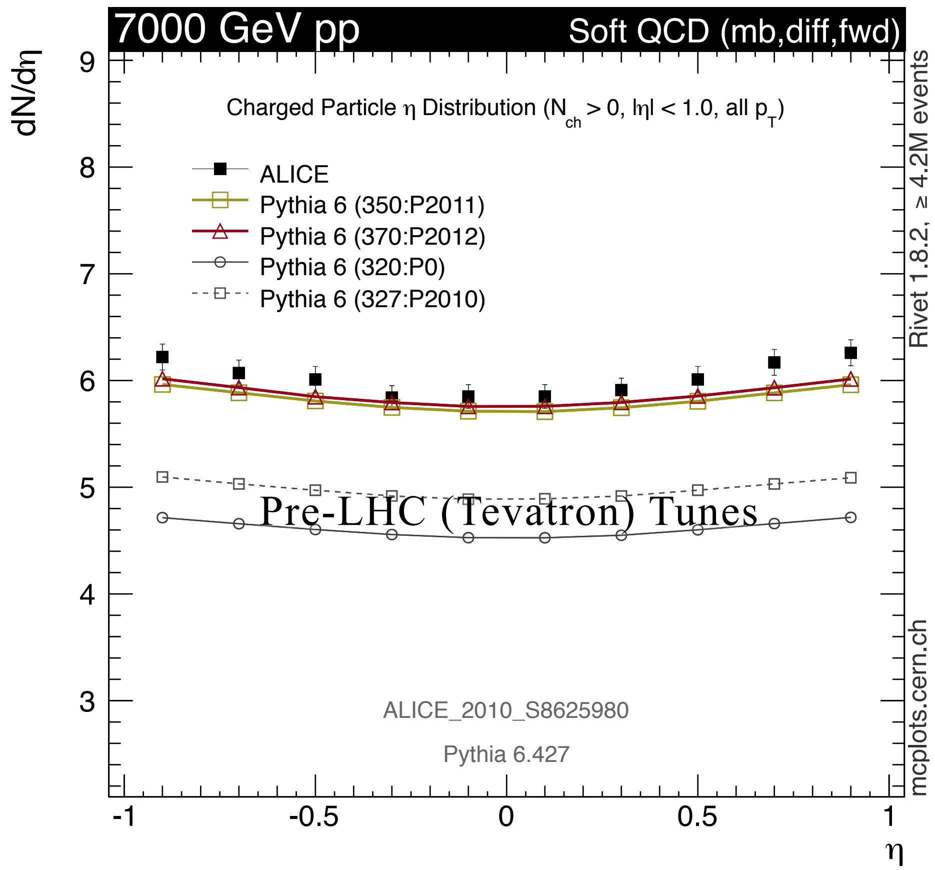
The point with an event generator is that we can now ask: *What do these events look like?*

Minimum-Bias Properties

LHC has produced a huge repository of min-bias constraints.
See e.g., mcplots.cern.ch
Only a few significant comparisons can be included here

Question: Why is it crucial to use updated (LHC) models/tunes?

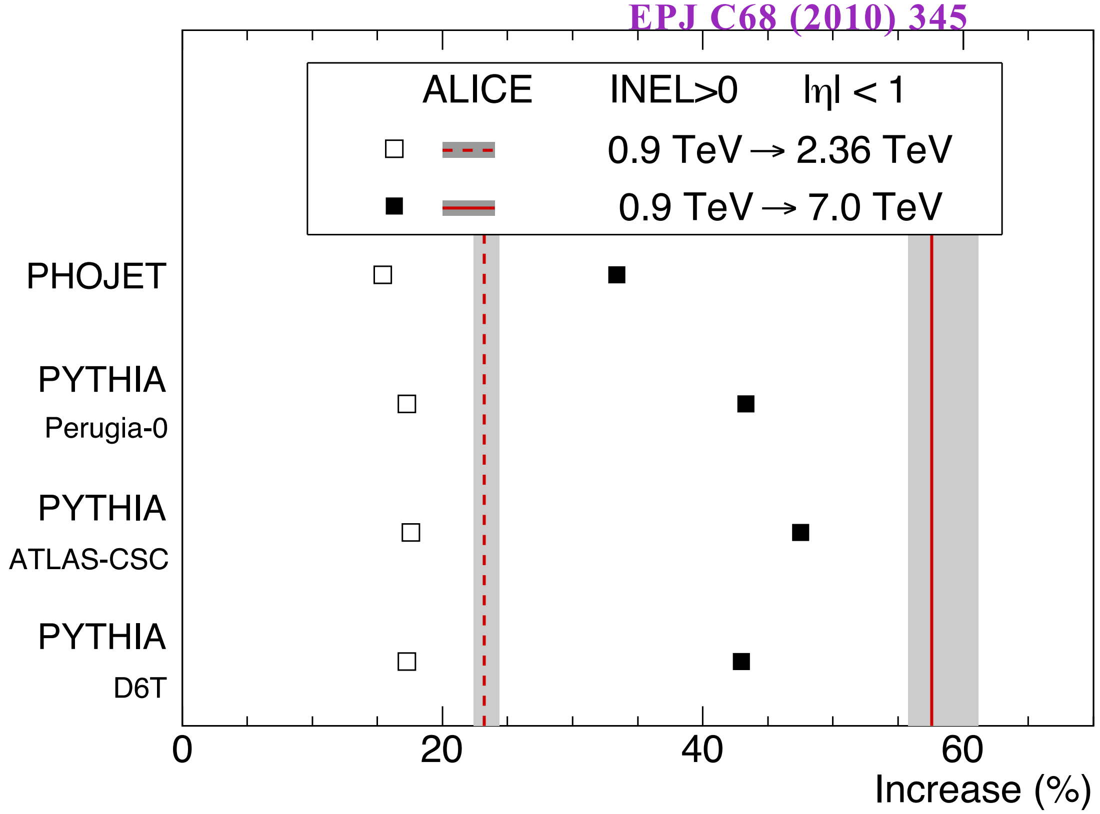
Central Charged-Track Multiplicity



Tevatron tunes were ~ 10-20% low on MB and UE

Relative increase in the central charged-track multiplicity from 0.9 to 2.36 and 7 TeV

EPJ C68 (2010) 345



… and scaled too slowly

Discovery at LHC: things are larger and scale faster than we thought they did

See also energy-scaling tuning study, Schulz & PS, EPJ C71 (2011) 1644

Minimum-Bias Properties

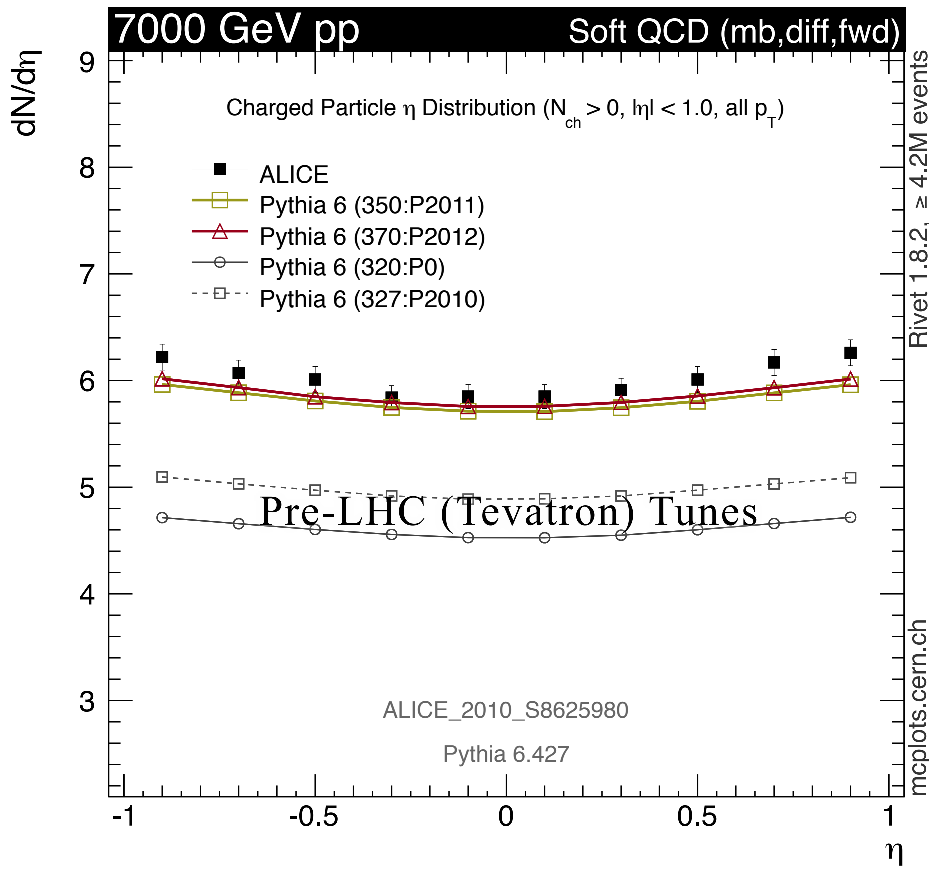
The updated models (as represented here by the Perugia 2012 tunes):

Agree with the LHC min-bias and UE data at each energy

And, non-trivially, they exhibit a more consistent energy scaling between energies

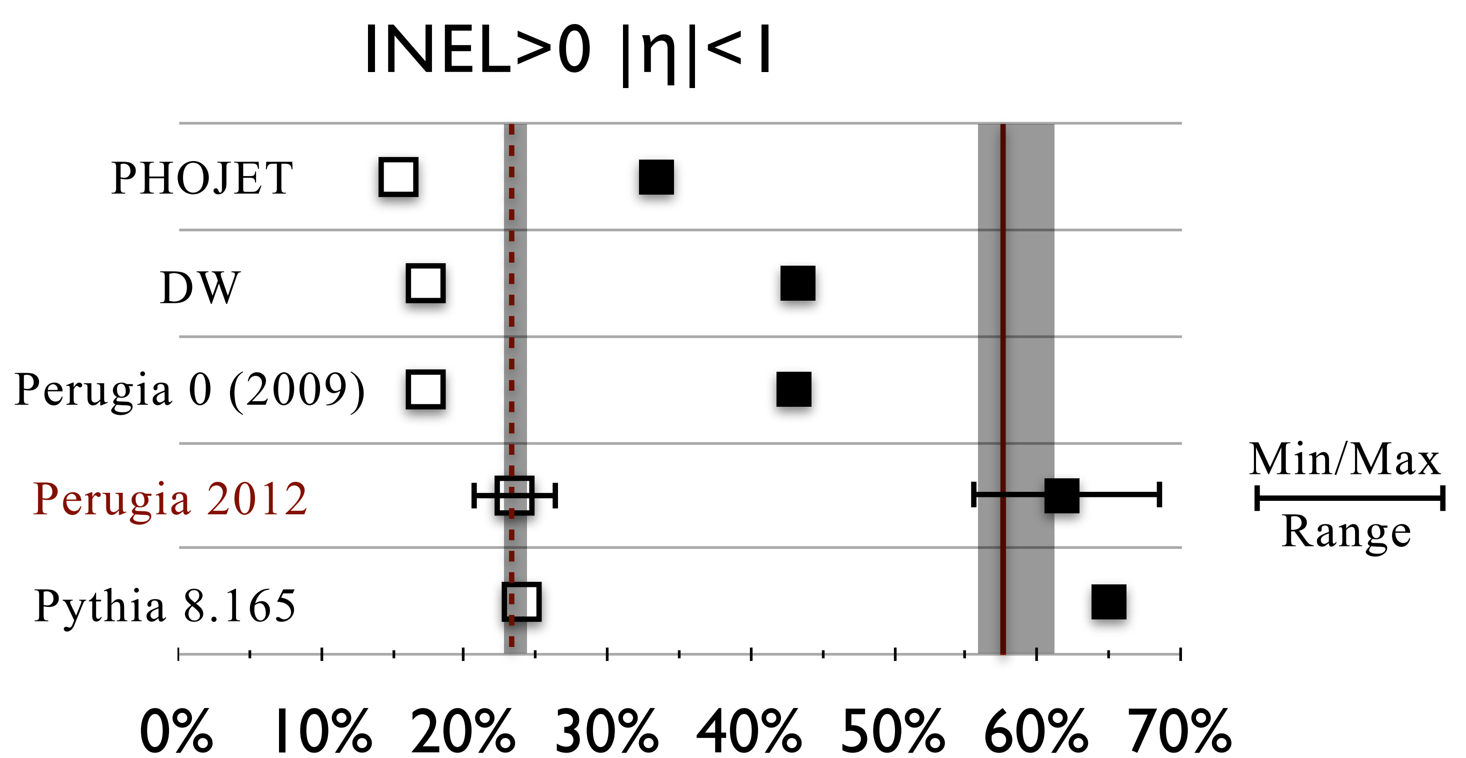
So we may have some hope that we can use these models to do extrapolations

Central Charged-Track Multiplicity



Tevatron tunes were ~ 10-20% low on MB and UE

A VERY SENSITIVE E-SCALING PROBE: relative increase in the central charged-track multiplicity from 0.9 to 2.36 and 7 TeV



Data from ALICE EPJ C68 (2010) 345

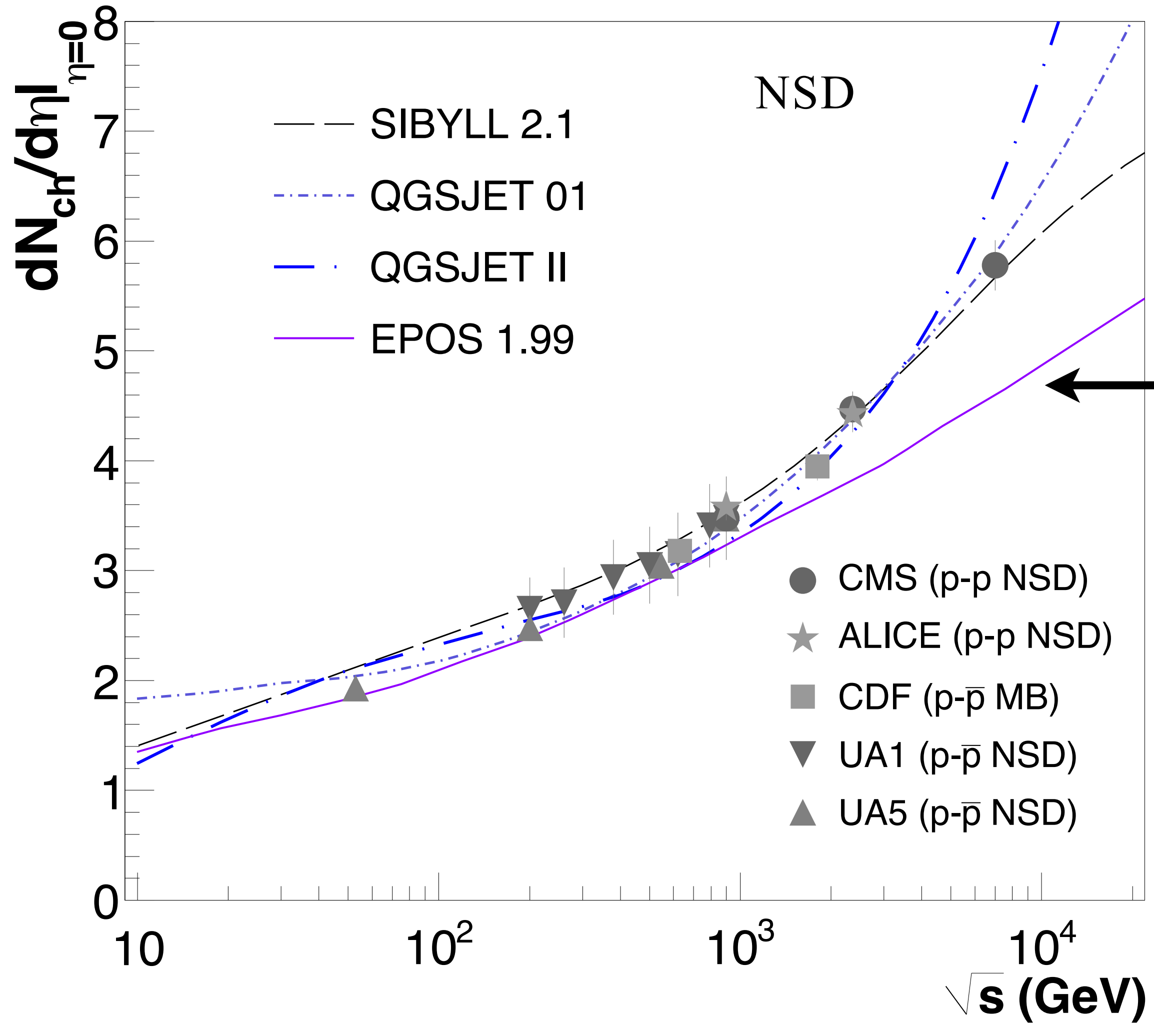
Caveat: still not fully understood why Tevatron tunes were low. May point to a more subtle energy scaling?

See also energy-scaling tuning study, Schulz & PS, EPJ C71 (2011) 1644

Scaling of Multiplicities

A From soft models based on Regge Theory, expect: D. d'Enterria et al. [arXiv:1101.5596],

$$\left.\frac{dN_{\rm ch}(s,\eta)}{d\eta}\right|_{\eta=0} \propto \frac{{\rm Im}\, f^{\mathbb{P}}(s,0)}{s\,\sigma_{pp}^{\rm inel}(s)} \sim \frac{s^{\Delta_{\mathbb{P}}}}{\log^2 s},$$



QGSJET too agressive? Would predict very high densities

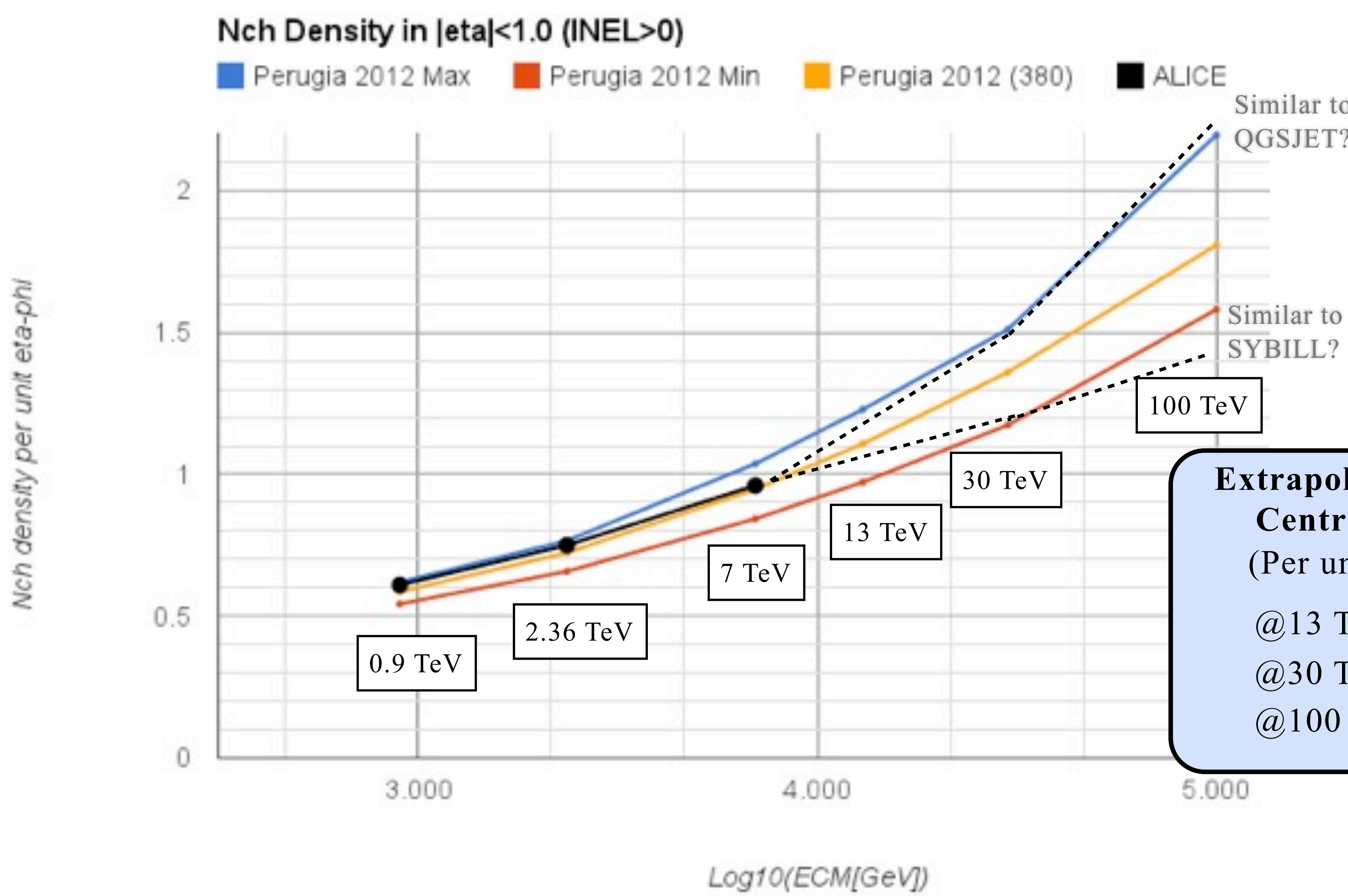
EPOS too low (but there is coming a new version which fits LHC better, worth trying out)

Will keep these models in mind but will base main extrapolations on PYTHIA Perugia tunes

Extrapolations: Central <N_{ch}>

B From parton-based models, expect ~ power law

Note: I use INEL>0
(rather than NSD, INEL, …)
Recap: this means events with at least one charged particle in $|\eta|<1$



(We allow a lower margin since power law may be too fast and we saw that the data scales *slower* than the current models)

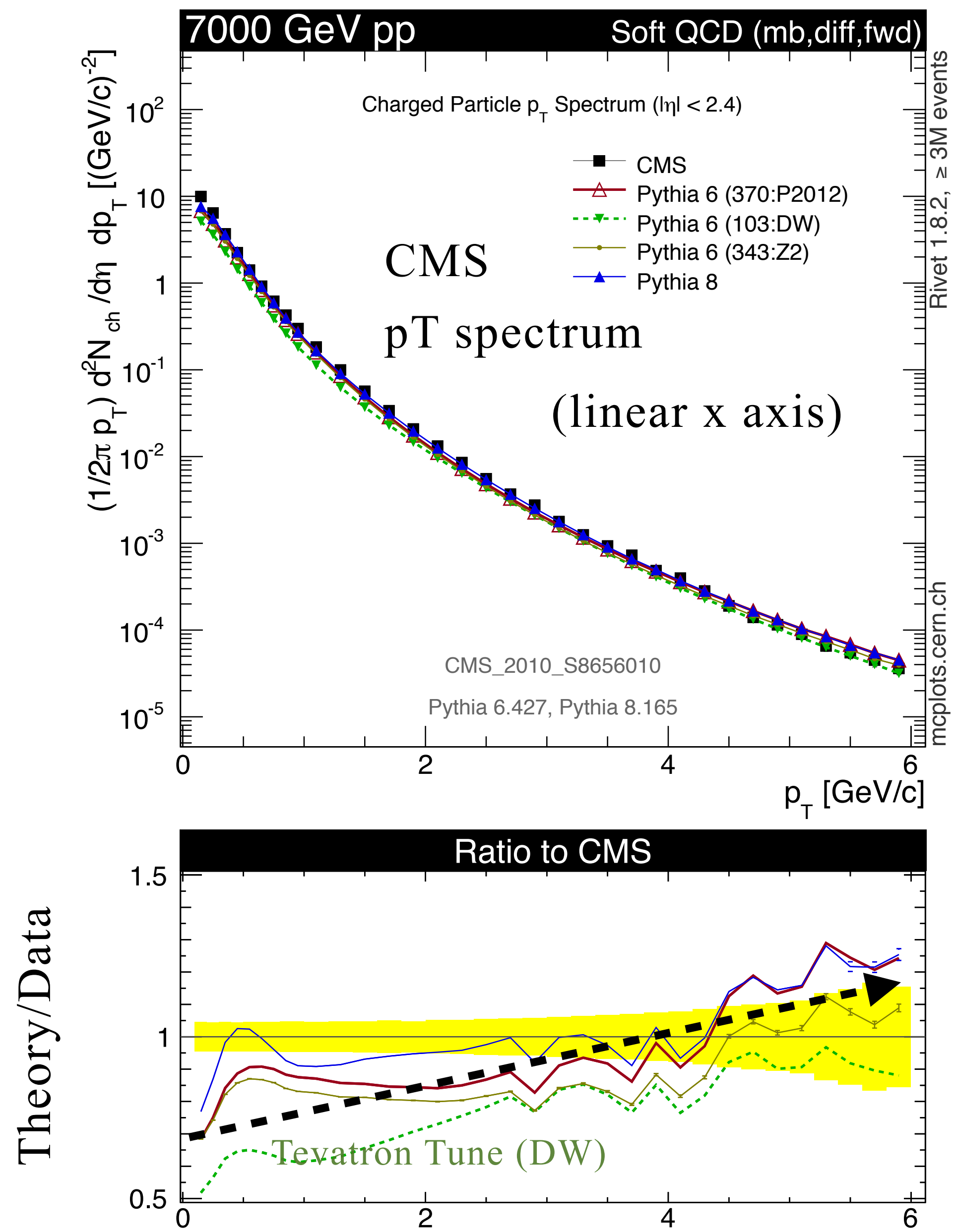
Extrapolations for INEL>0
Central <N_{ch}> density
(Per unit $\Delta\eta\Delta\varphi$ in $|\eta|<1$)

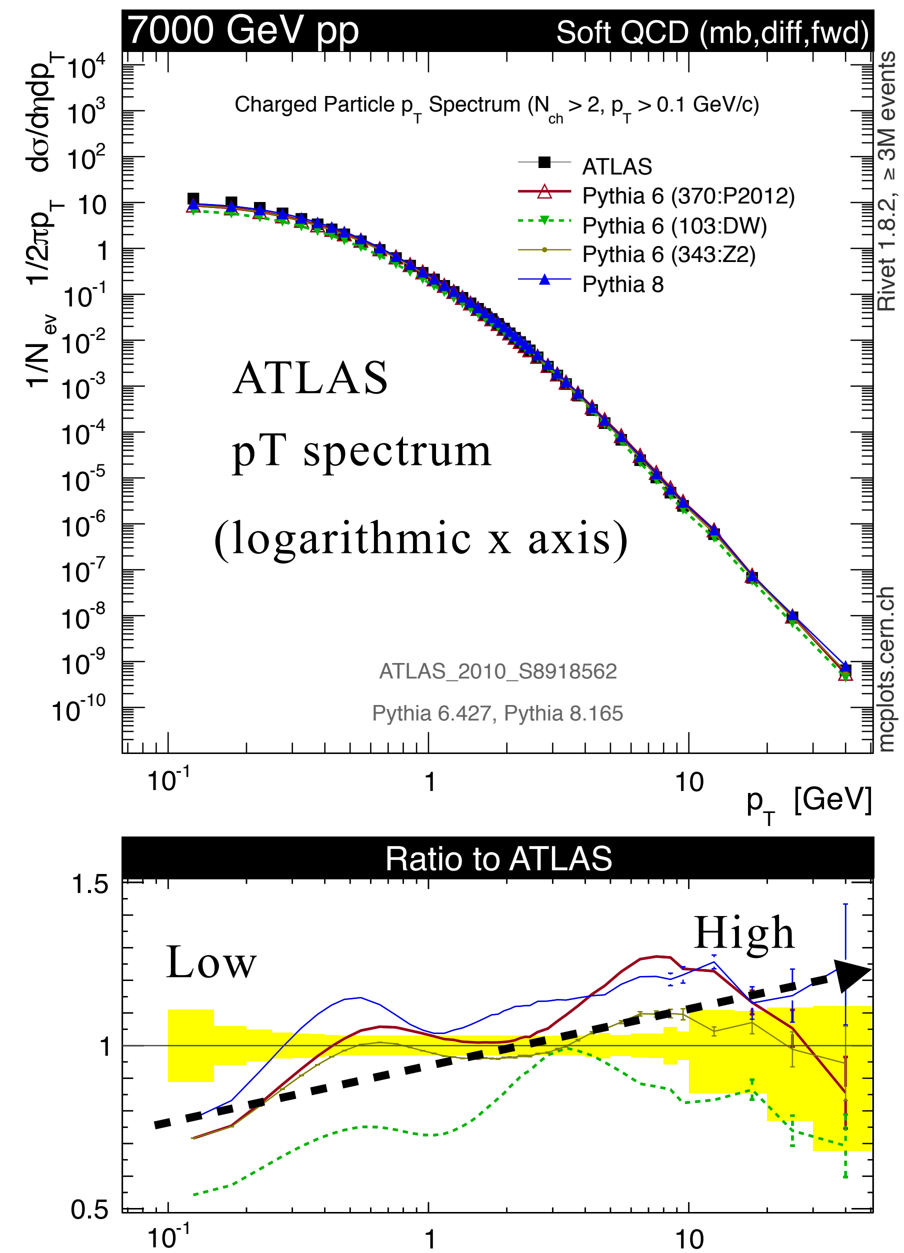
@13 TeV : 1.1 ± 0.1
@30 TeV : 1.33 ± 0.14
@100 TeV : 1.8 ± 0.4

(Multiplicities with p_T cuts)

Indication from LHC is that current PYTHIA models exhibit a slightly too hard pT spectrum.

Rates of very soft particles may be underpredicted. Very hard particles may be overpredicted





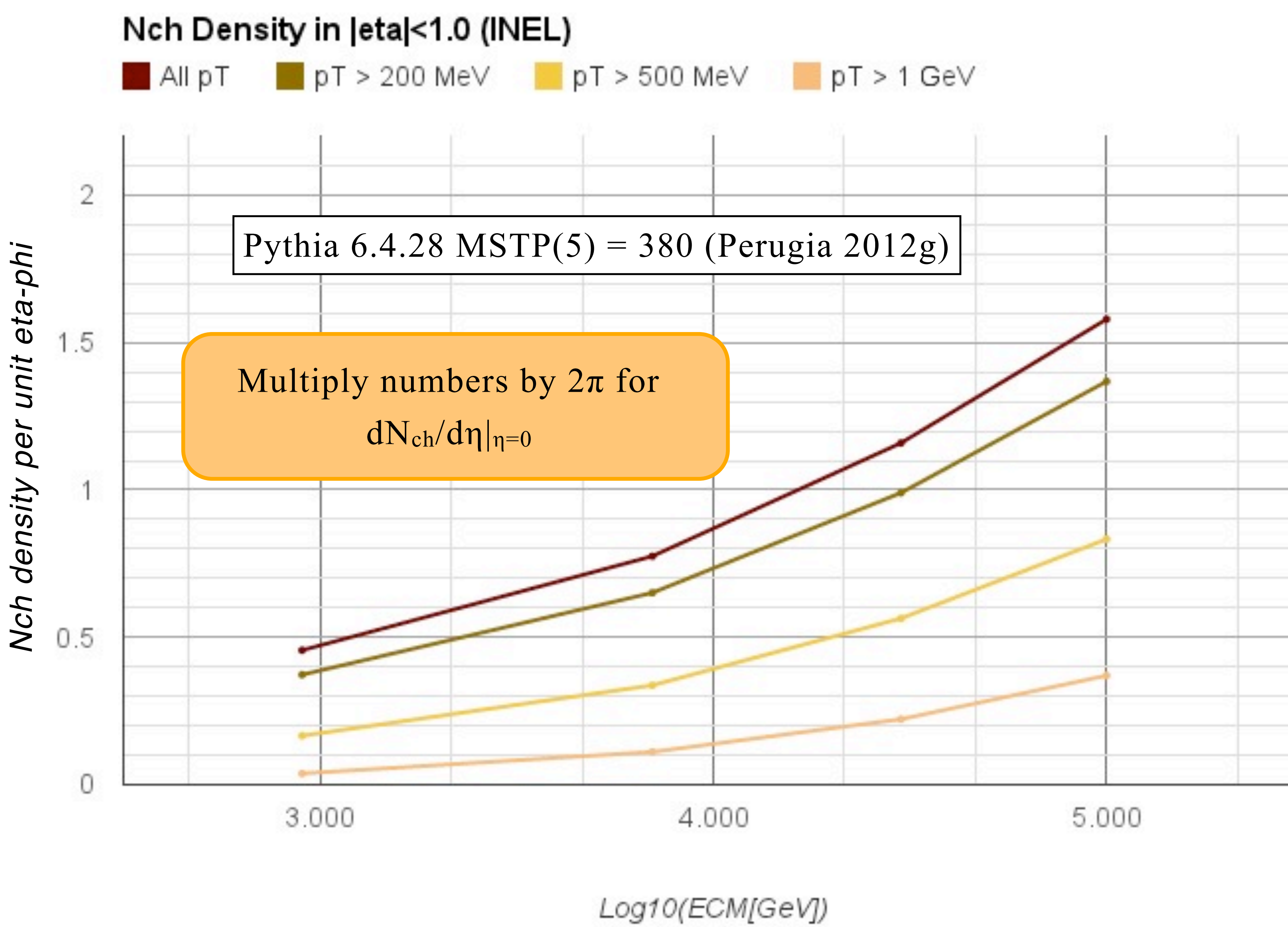
(Multiplicities with p_T cuts: Extrapolations)

Note: here using INEL (rather than INEL>0)

Thus, when we cut on p_T to only include hard particles, PYTHIA's numbers may be slightly high

We also saw that the total N_{ch} density in the central Perugia 2012 model scaled bit faster than the ALICE measurement indicated.

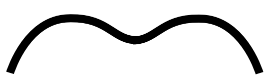
OK, so I would naively assume these numbers are conservative (high)



(Additional η regions)

Rapidity spectrum is flat (apart from high-y tails)

→ Pseudorapidity distribution has well-known 'seagull' shape



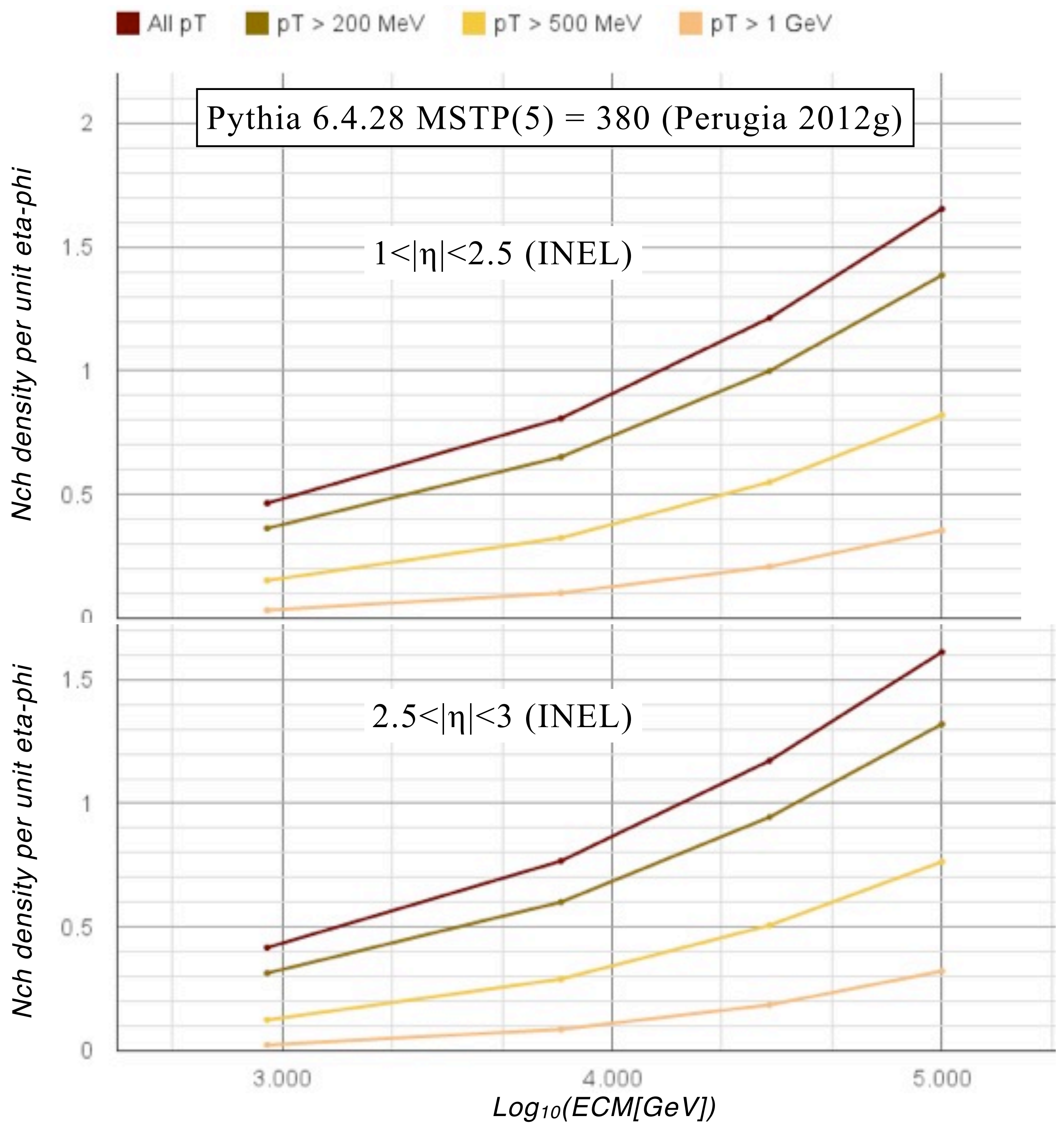
→ small (O(10%)) dependence on region (apart from high-y tails)

Here including two additional regions that may be relevant:

$1 < |\eta| < 2.5$

$2.5 < |\eta|\ 3.0$

Very small differences



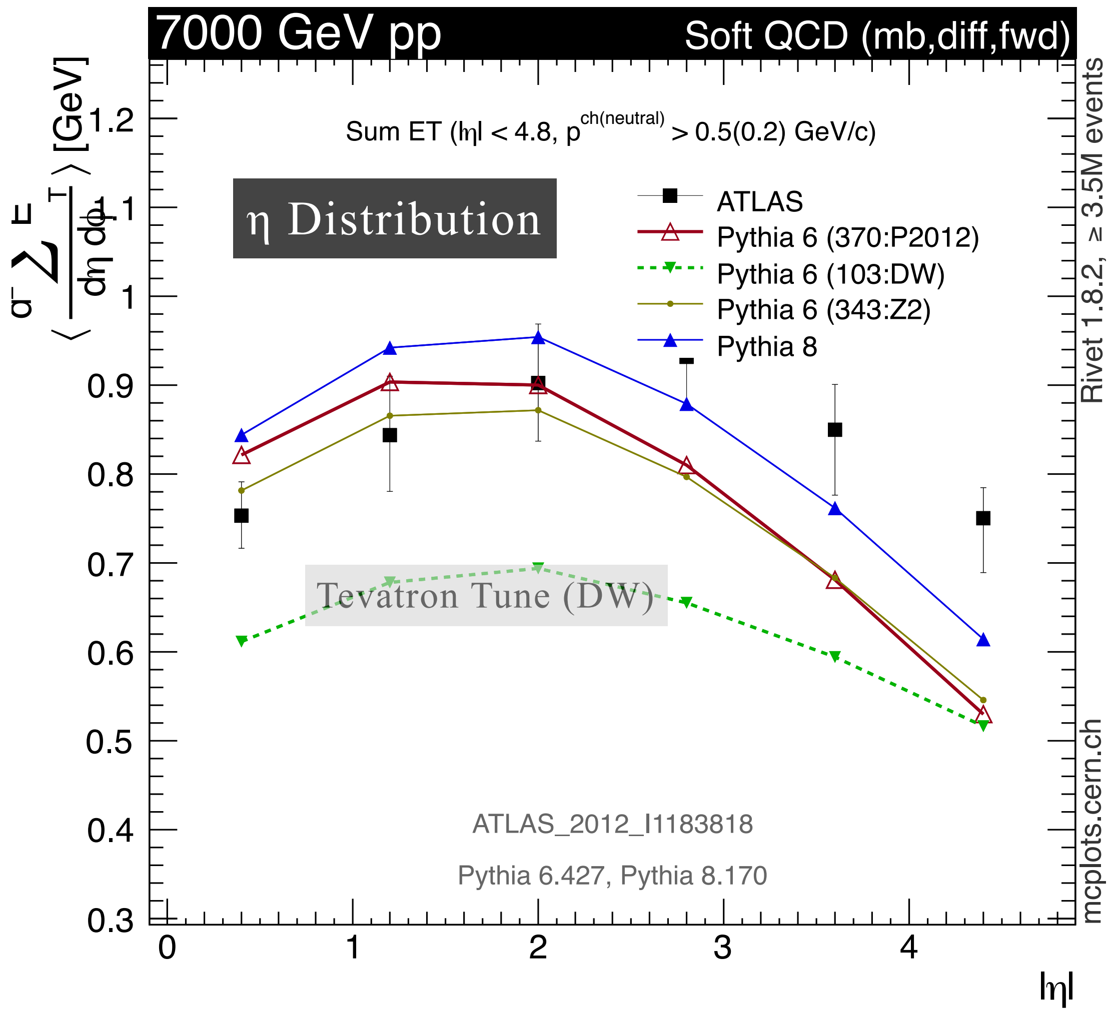
Central Transverse Energy

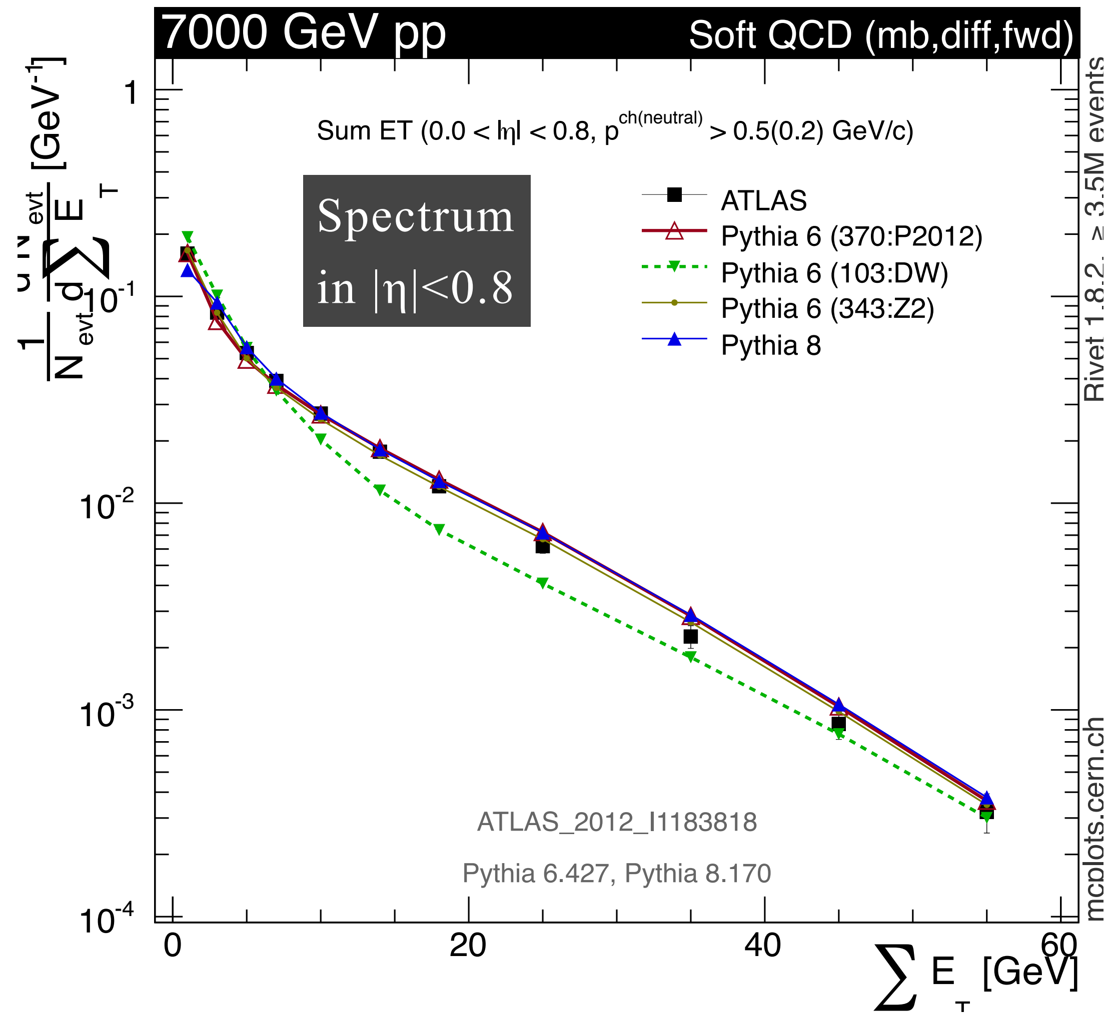
How much energy is deposited in the detector?

ATLAS measurements only available with cuts on pT of particles, but still useful

From other measurements, we know that there are more very soft particles in the data than in MC

This will partially compensate the difference for |η|<2 below, but will exacerbate it for |η|>2.0





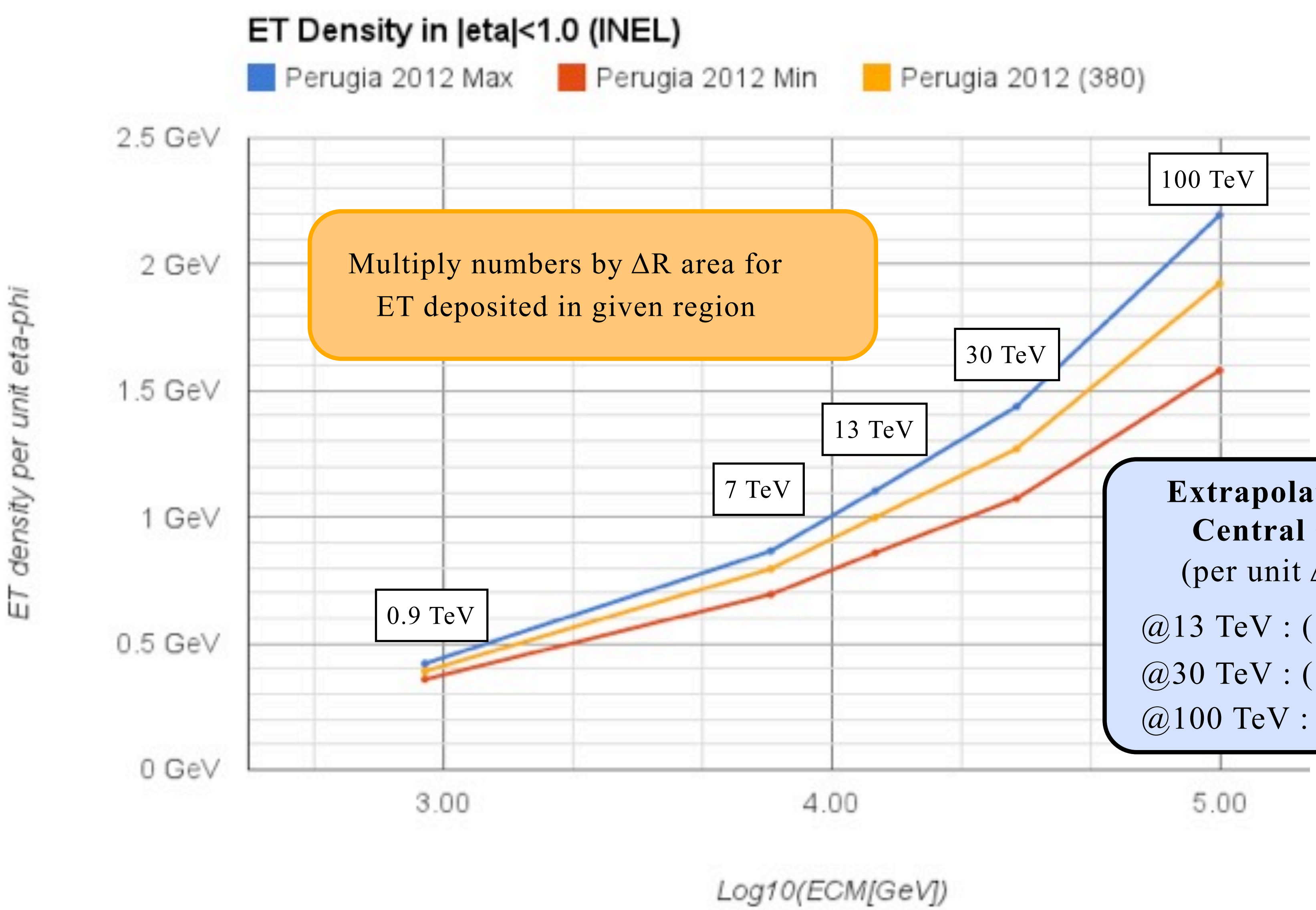
So it looks like the MC predictions should be fairly good at least in the central region …

Plots from http://mcplots.cern.ch

Central Transverse Energy

Note: I use INEL and include all charged+neutral

This can be combined with σ_{INEL} to find the central E_T deposited e.g. by pileup



Extrapolations for INEL Central <E_T> density

(per unit $\Delta\eta\Delta\varphi$ in $|\eta|<1$)

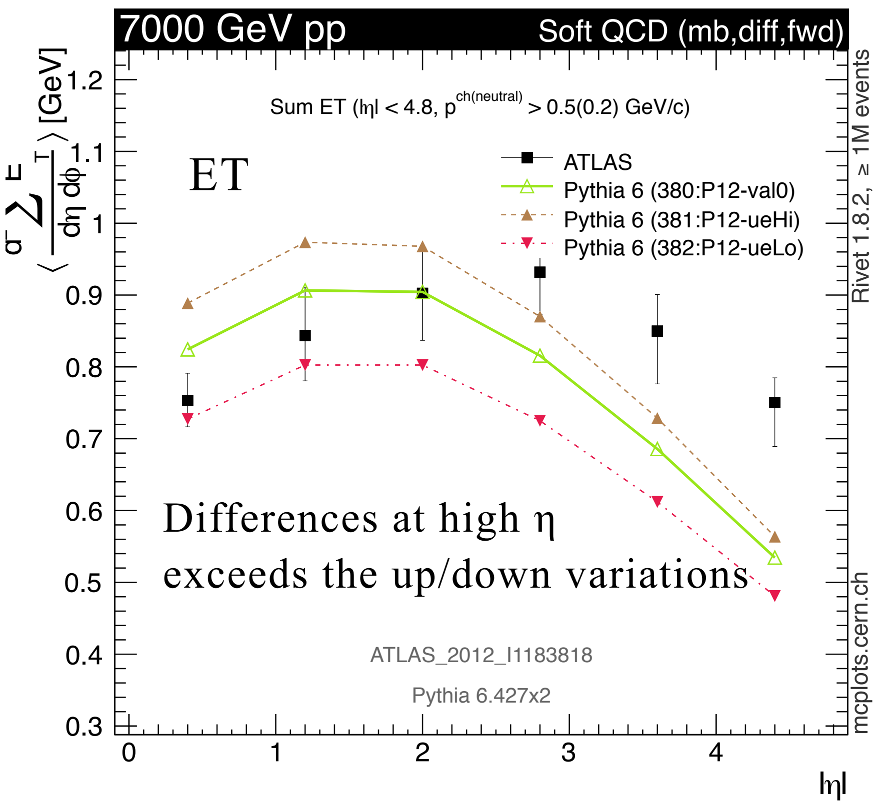
@13 TeV : (1.0 ± 0.15) GeV

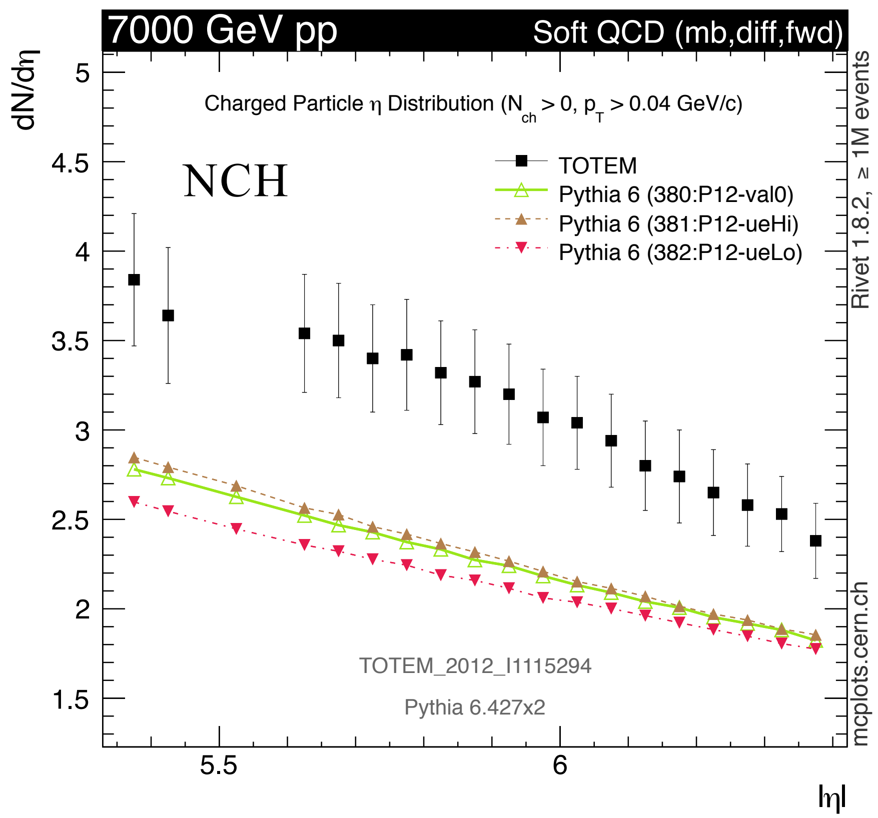
@30 TeV : (1.25 ± 0.2) GeV

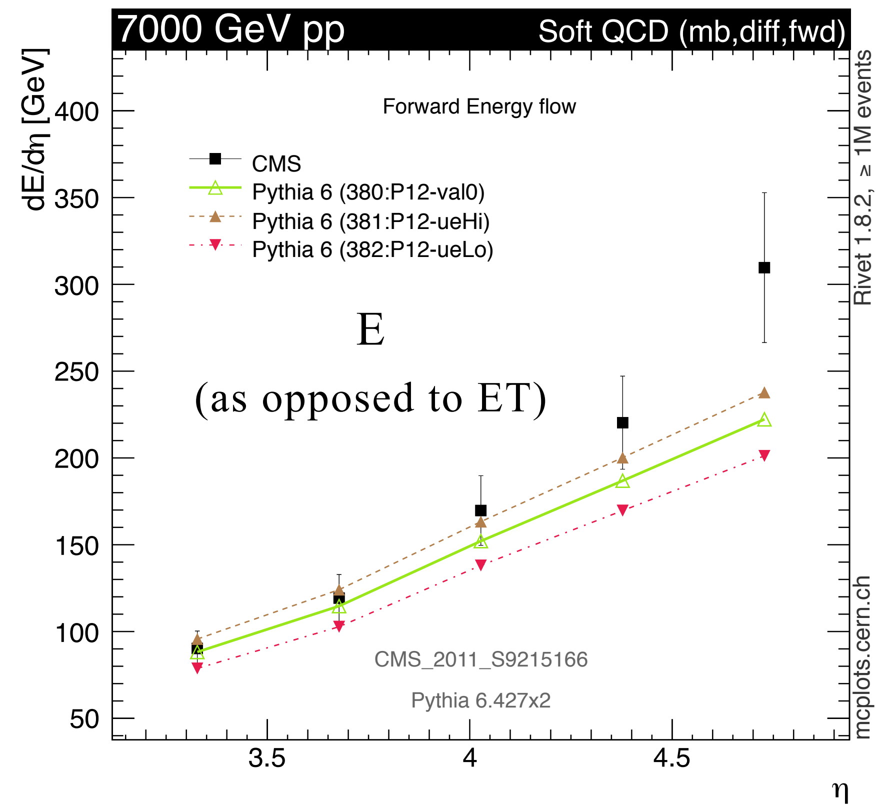
@100 TeV : (1.9 ± 0.35) GeV

Forward Caveat

Similar extrapolations (of <N_{ch}> and <E_T>) in the forward region would likely give underestimates, at least if done with current PYTHIA models







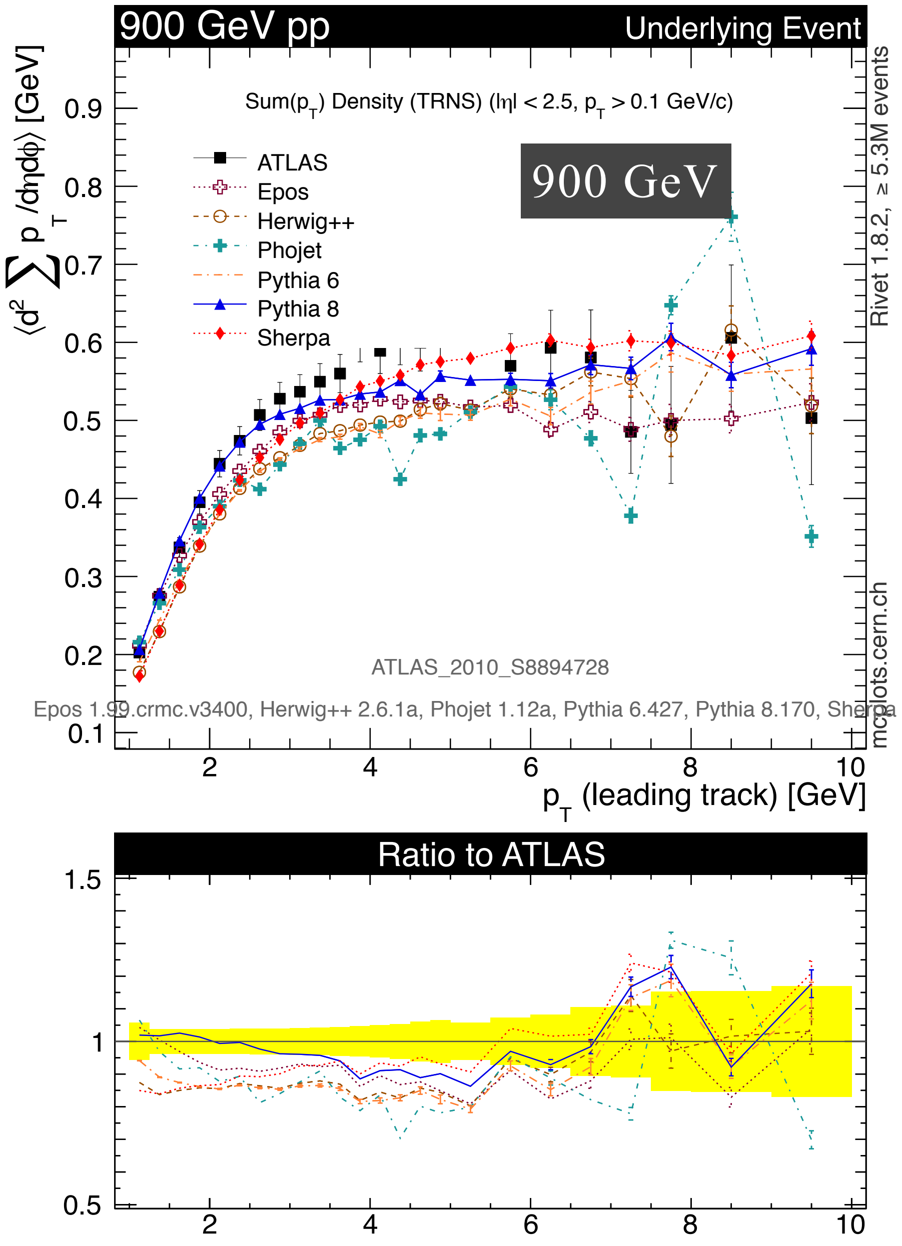
Would need at least some dedicated diffraction variations (more possibilities in PYTHIA 8)
Plus possibly improved (or at least systematically different) modeling → EPOS 2 or some of the dedicated cosmic-ray MC models? LHC-updated PHOJET? New Sherpa and/or Herwig models?

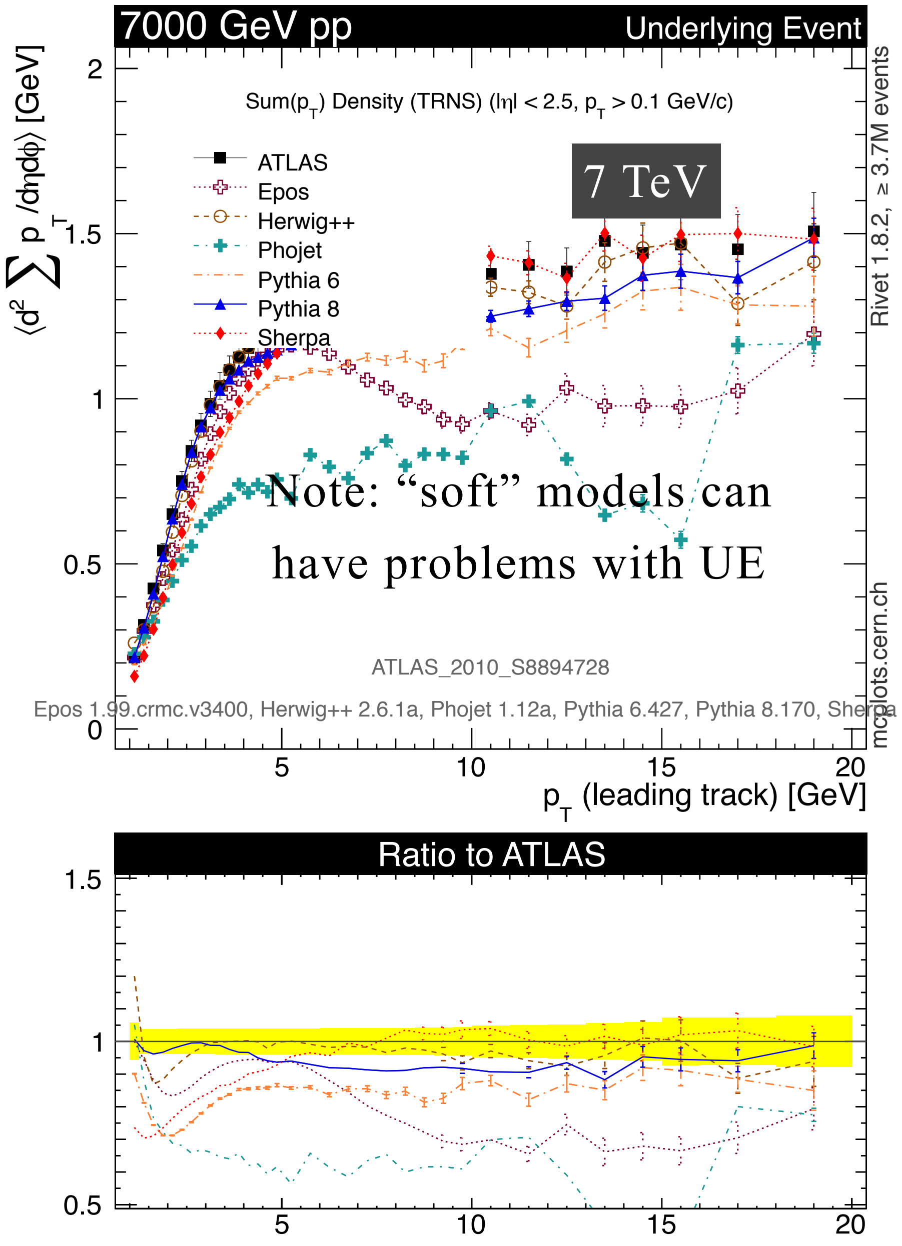
Plots from http://mcplots.cern.ch

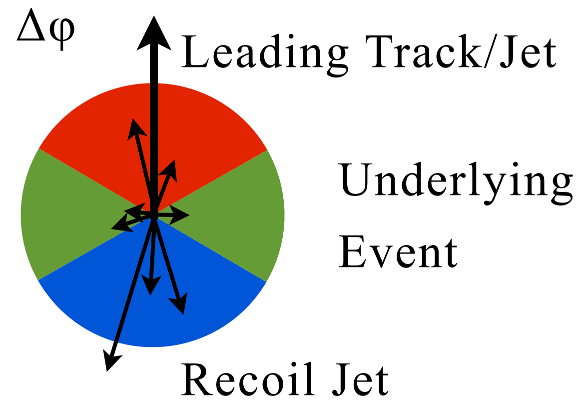
Underlying Event

There are many UE variables. The most important is <Σp_T> in the Transverse Region

That tells you how much (transverse) energy the UE deposits under a jet. It is also more IR safe than <N_{ch}>.







Transverse Region (TRNS)

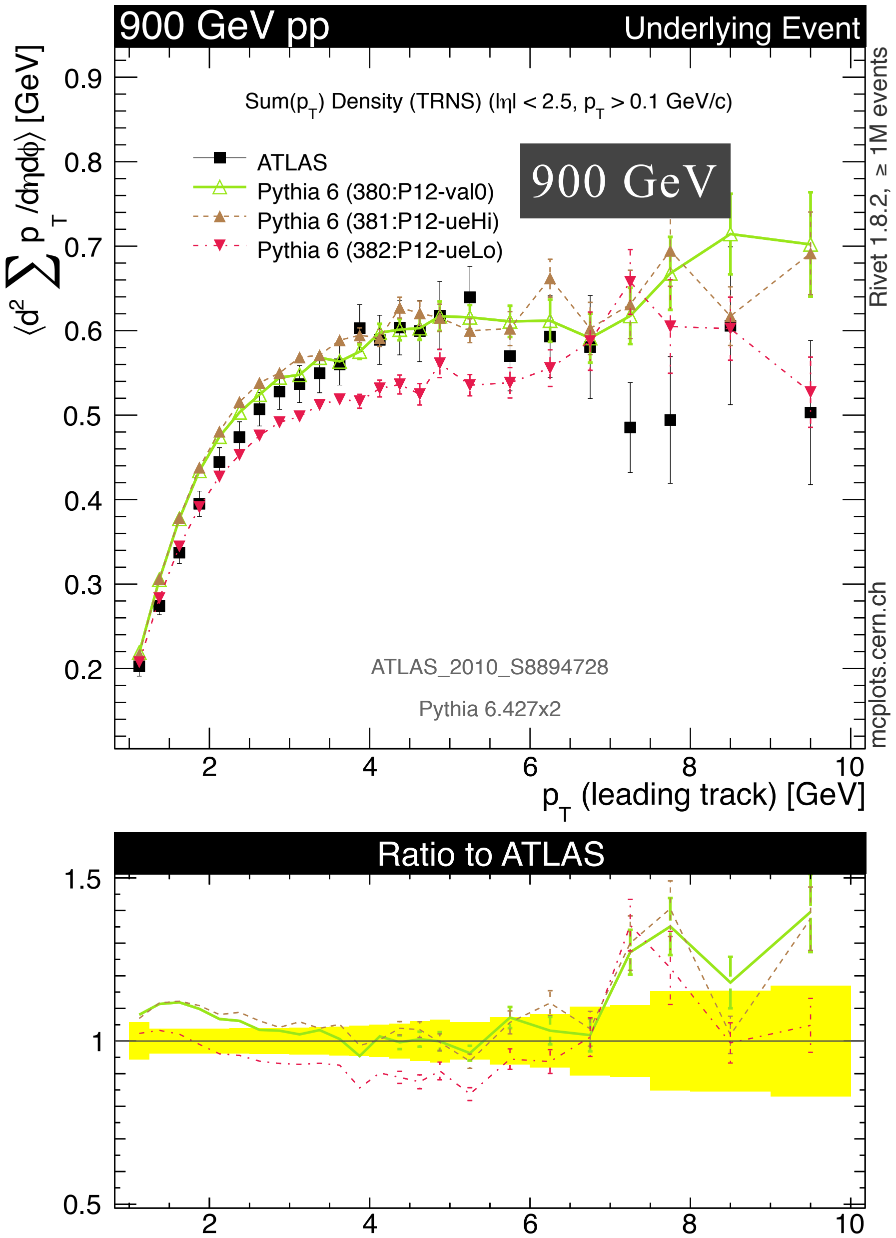
Sensitive to activity at right angles to the hardest jets

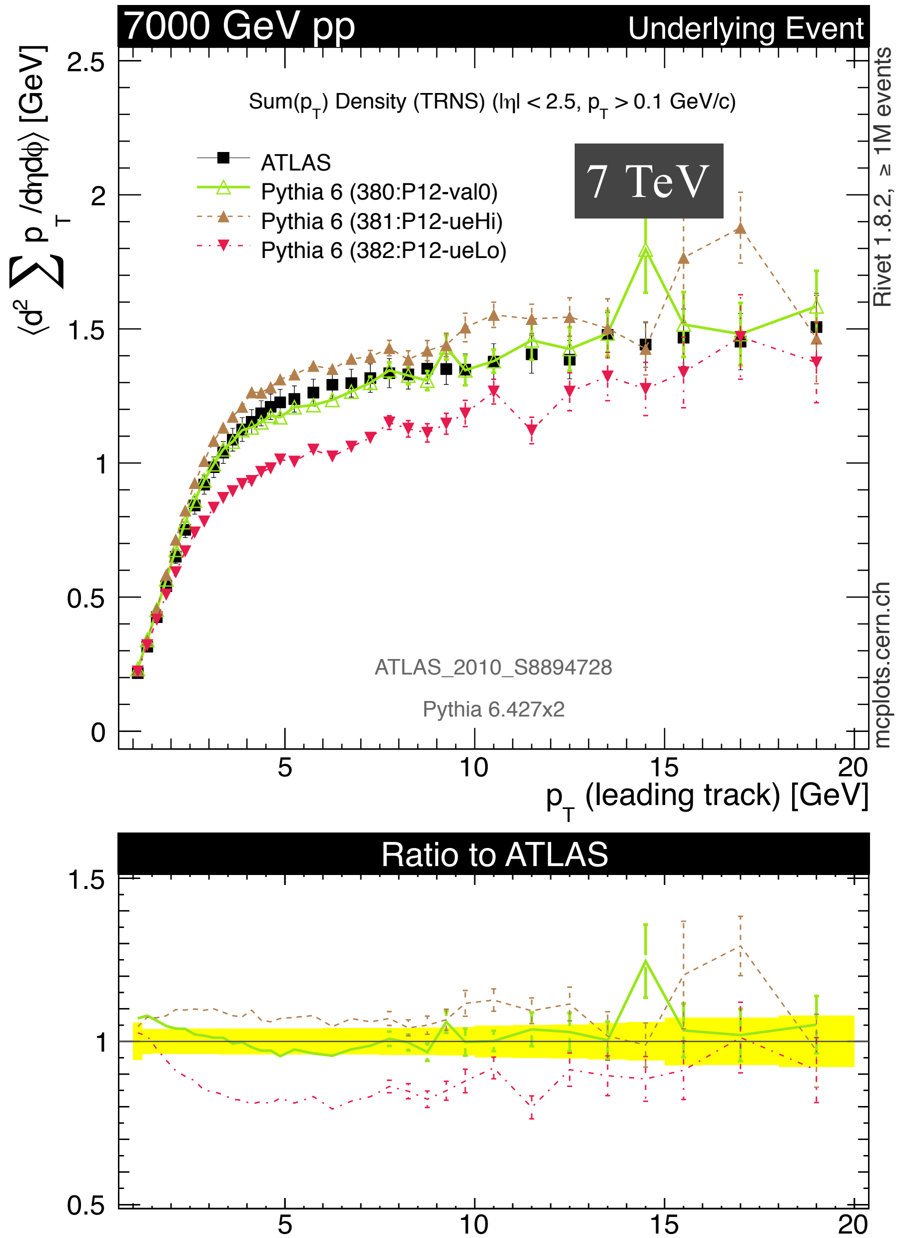
Useful definition of Underlying Event

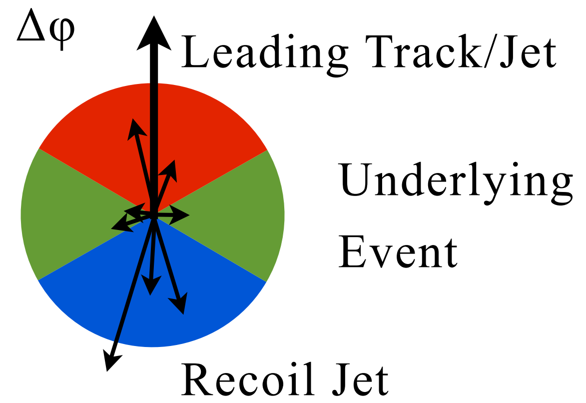
Underlying Event

These are the main variations I used (Perugia 2012 ueHi and ueLo)

They vary the p_{T0} regularization scale up/down as well as the pace of the energy-scaling of it.







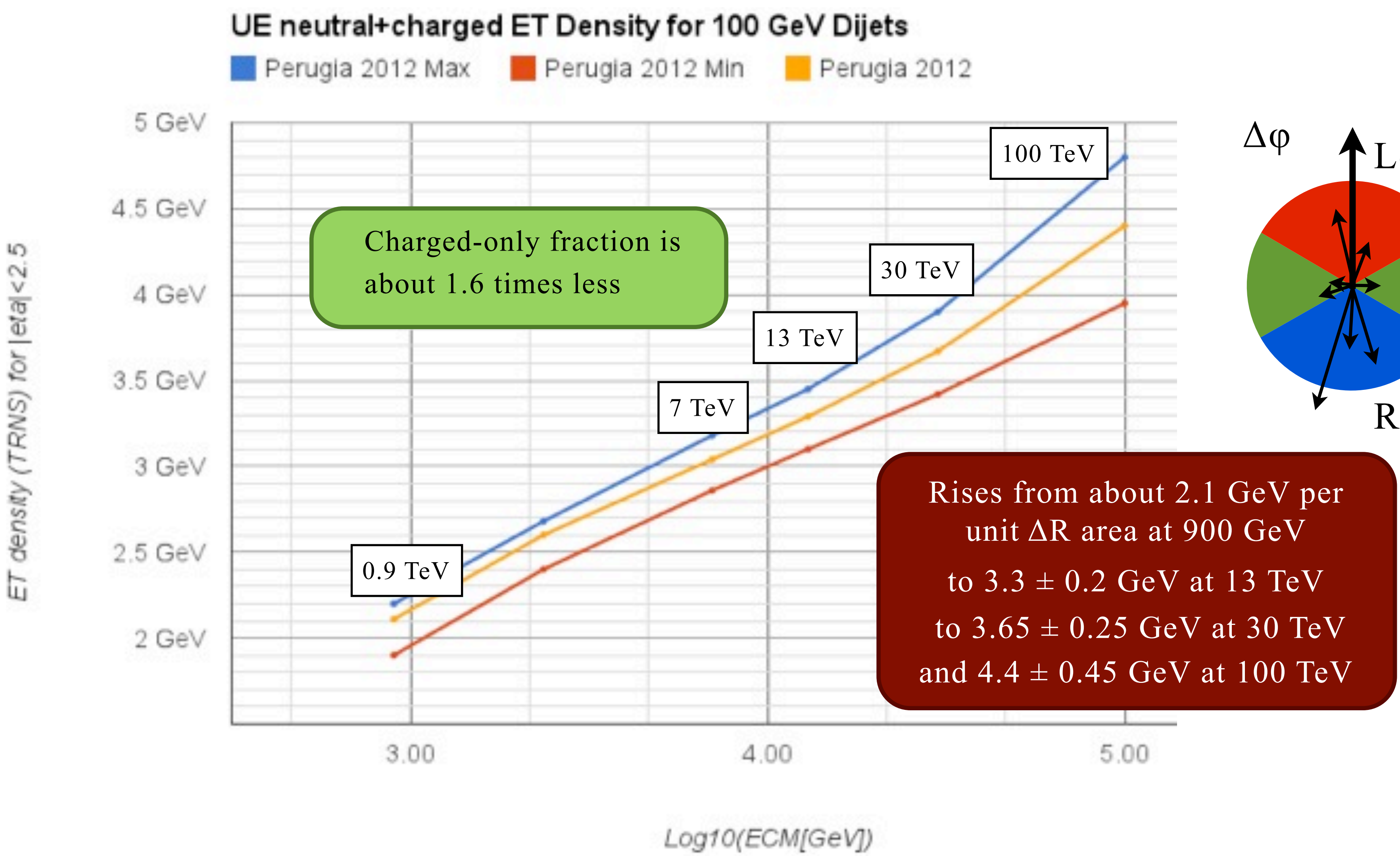
Transverse Region (TRNS)

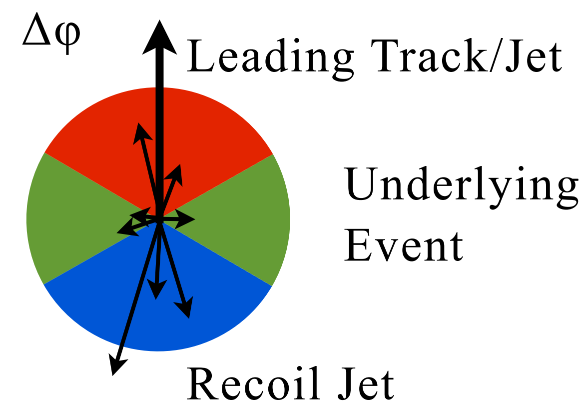
Sensitive to activity at right angles to the hardest jets

Useful definition of Underlying Event

Test case: 100 GeV dijets

Measure ET in region transverse to the hardest track (in |η|<2.5)





Summary

If you don't require precision better than 10%

And if you don't look too far forward

And if you don't look at very exclusive event details (such as isolating specific regions of phase space or looking at specific identified particles)

Then I believe these guesses are reasonable

σ_{INEL}	σ_{EL}	
~ 80 mb	~ 22 mb	@ 13 TeV
~ 90 mb	~ 25 mb	@ 30 TeV
~ 105 mb	~ 32 mb	@ 100 TeV

Central $\langle N_{ch} \rangle$ density (INEL>0)

- ~ 1.1 ± 0.1 / ΔηΔφ @ 13 TeV
- ~ 1.33 ± 0.14 / ΔηΔφ @ 30 TeV
- ~ 1.8 ± 0.4 / ΔηΔφ @ 100 TeV

Central $\langle E_T \rangle$ density (INEL)

- ~ 1.0 ± 0.15 GeV / ΔηΔφ @ 13 TeV
- ~ 1.25 ± 0.2 GeV / ΔηΔφ @ 30 TeV
- ~ 1.9 ± 0.35 GeV / ΔηΔφ @ 100 TeV

UE TRNS $\langle \Sigma p_T \rangle$ density (j100)

- ~ 3.3 ± 0.2 / ΔηΔφ @ 13 TeV
- ~ 3.65 ± 0.25 / ΔηΔφ @ 30 TeV
- ~ 4.4 ± 0.45 / ΔηΔφ @ 100 TeV

Note: I only got a few days to put this together. It could obviously benefit by a dedicated study.

See more control plots at http://mcplots.cern.ch