Event structure and small-x issues at 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)

Image Credits: blepfo (deviantart.com)

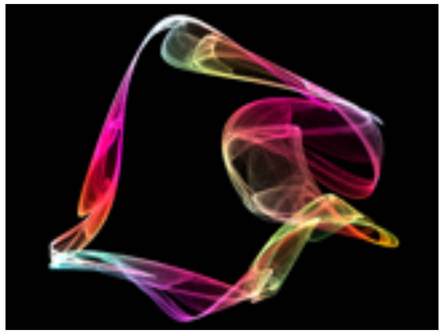
Event Structure at PP Colliders

Dominated by QCD

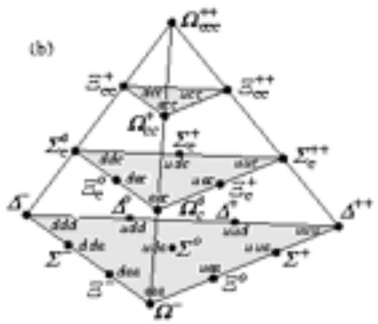
More than just a perturbative expansion in α_s

Emergent phenomena:

Jets (the QCD fractal) $\longleftrightarrow$ amplitude structures $\longleftrightarrow$ fundamental quantum field theory. Precision jet (structure) studies.



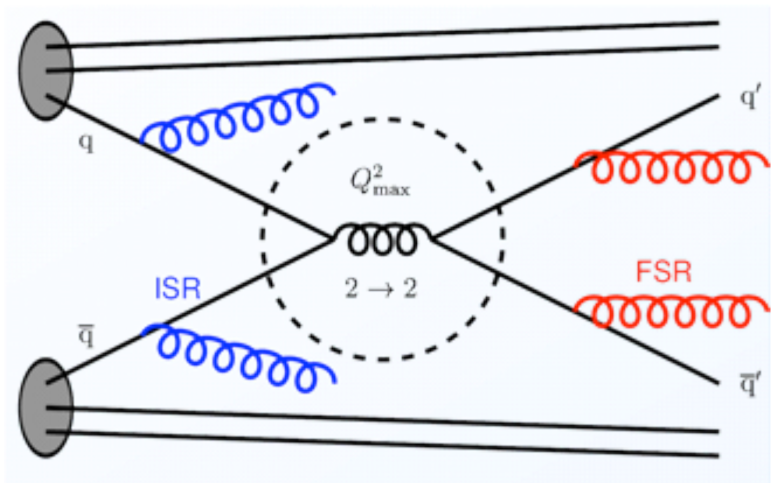
Strings (strong gluon fields) $\longleftrightarrow$ quantum-classical correspondence. String physics. Dynamics of hadronization phase transition.



Hadrons $\longleftrightarrow$ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Hadron beams → MPI, diffraction, …

See eg TASI lectures, e-Print: arXiv:1207.2389

Modeling Hadronic Final States



Calculate Everything ≈ solve QCD → requires compromise!

Monte Carlo Event Generators:

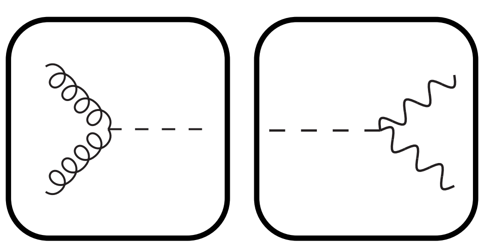
Explicit Dynamical Modeling → complete events (can evaluate any observable you want)

Factorization → Split the problem into many (nested) pieces

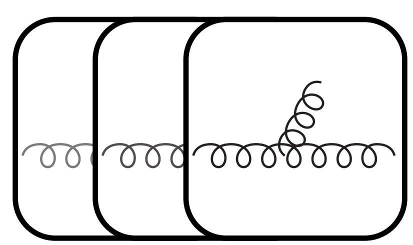
+ Quantum mechanics → Probabilities → Random Numbers (MC)

Soft Physics

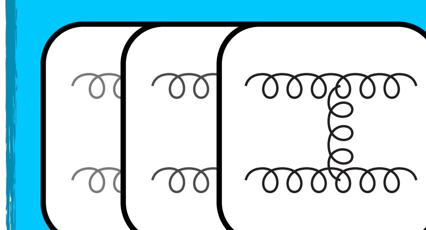
$$\mathcal{P}_{\rm event} = \mathcal{P}_{\rm hard} \otimes \mathcal{P}_{\rm dec} \otimes \mathcal{P}_{\rm ISR} \otimes \mathcal{P}_{\rm FSR} \otimes \mathcal{P}_{\rm MPI} \otimes \mathcal{P}_{\rm Had} \otimes \ldots$$



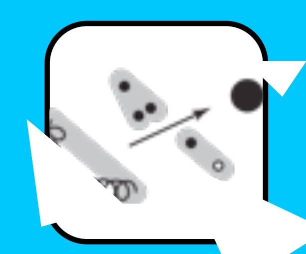
Matrix Elements
(+ Sudakov Corrections)



Shower Kernels
(+ ME corrections)



Multiple Parton Interactions
Hard + Soft → INEL & UE

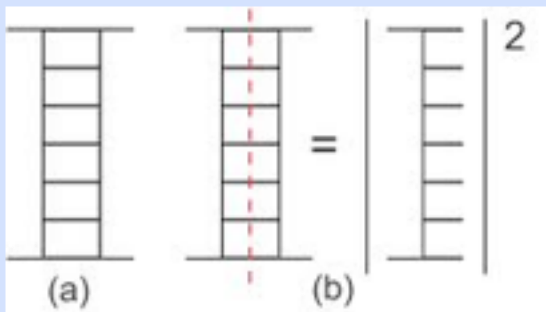


Hadronization, Decays, Soft
Diffraction, Beam Remnants

Soft Physics : 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

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

Cut Pomerons → Flux Tubes (strings)

Uncut Pomerons → Elastic (& eikonalization)

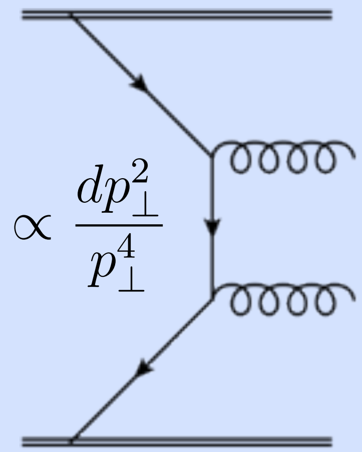
Cuts unify treatment of all soft processes

EL, SD, DD, … , ND

Perturbative contributions added above Q_0

B — Parton Based

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



+ 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)

E.g., QGSJET, SIBYLL

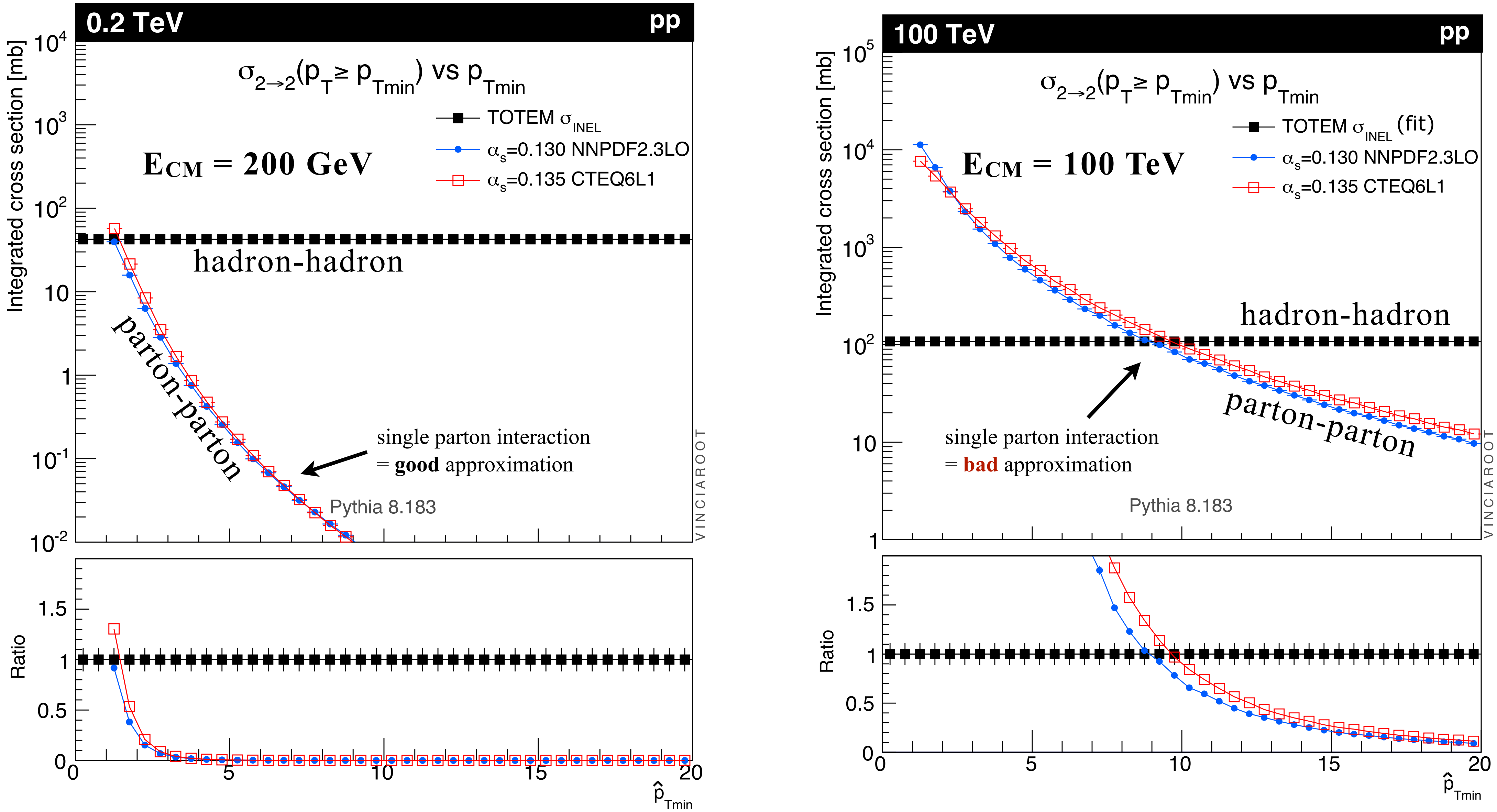
+ "Mixed"

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

E.g., PYTHIA, HERWIG, SHERPA

B Parton-Based Models : MPI

Consider the inclusive di-jet cross section in QCD

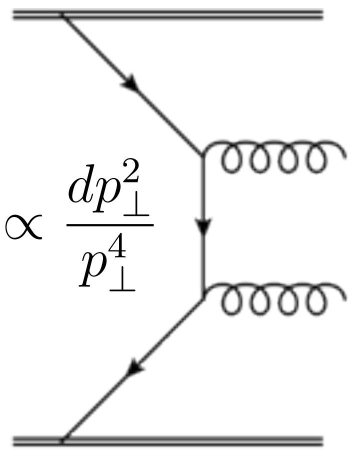


$\sigma_{2\to2} > \sigma_{pp}$ interpreted as consequence of each pp containing several 2→2 interactions: MPI

Soft MPI

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

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



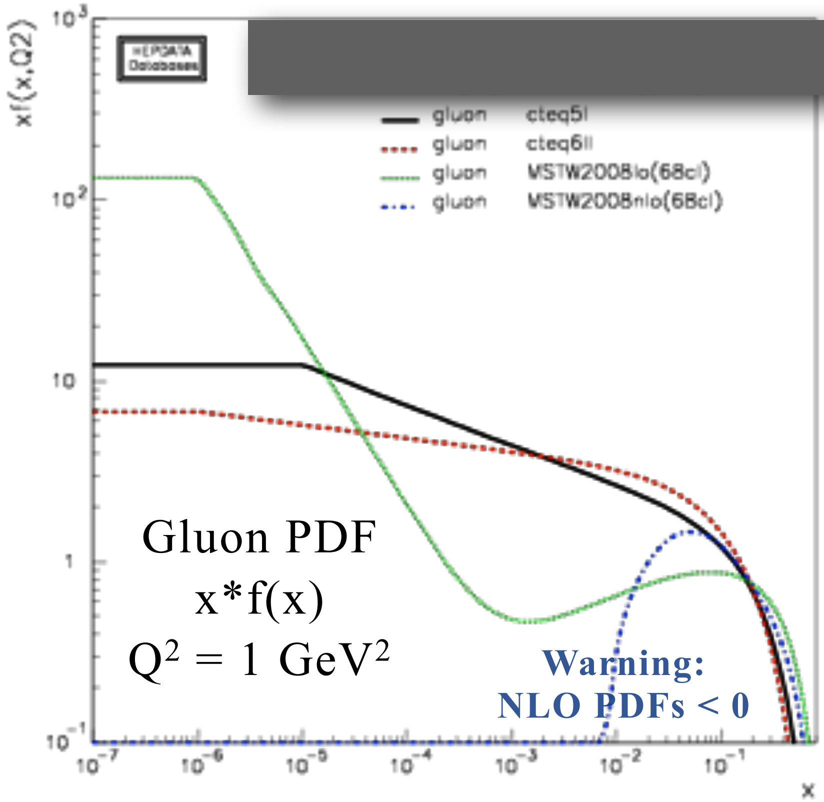
$\otimes$ PDFs

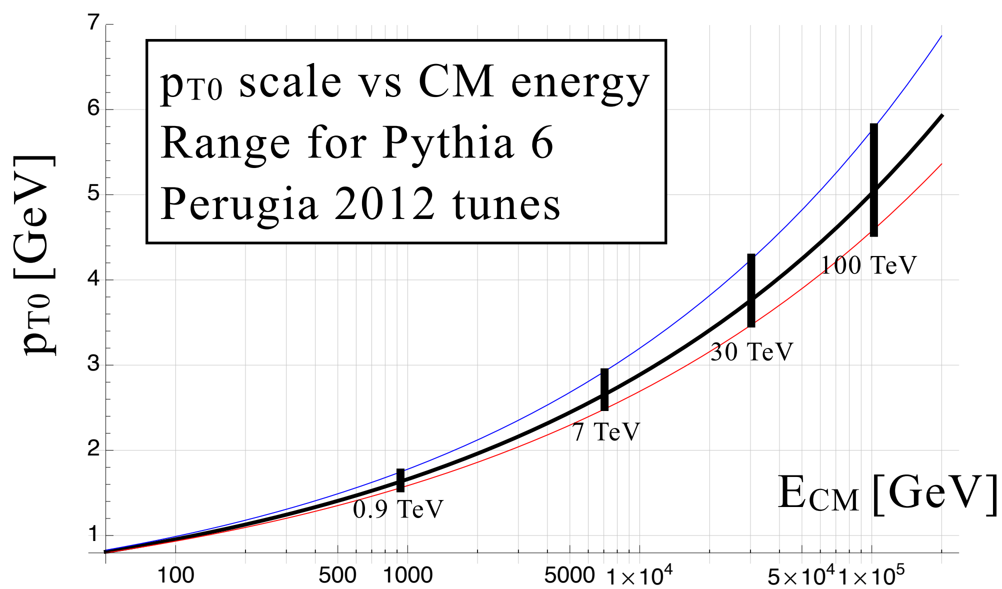
High Q^2 and finite x

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

- Form of PDFs at small x and Q^2 ↔ Saturation
- Form and E_{cm} (and/or x) 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

Low-x Issues (in MC/PDF context)

Low x : parton carries tiny fraction of beam energy.

E.g.: $x_\Lambda = \frac{2\Lambda_{\mathrm{QCD}}}{E_{\mathrm{CM}}}$ $\quad x_{\perp 0} = \frac{2p_{\perp 0}}{E_{\mathrm{CM}}}$

7 TeV: $x \sim 10^{-5}$ - 10^{-4}
100 TeV: $x \sim 10^{-6}$ - 10^{-4}

Higher x : momenta > Λ_{QCD}

→ pQCD ~ OK

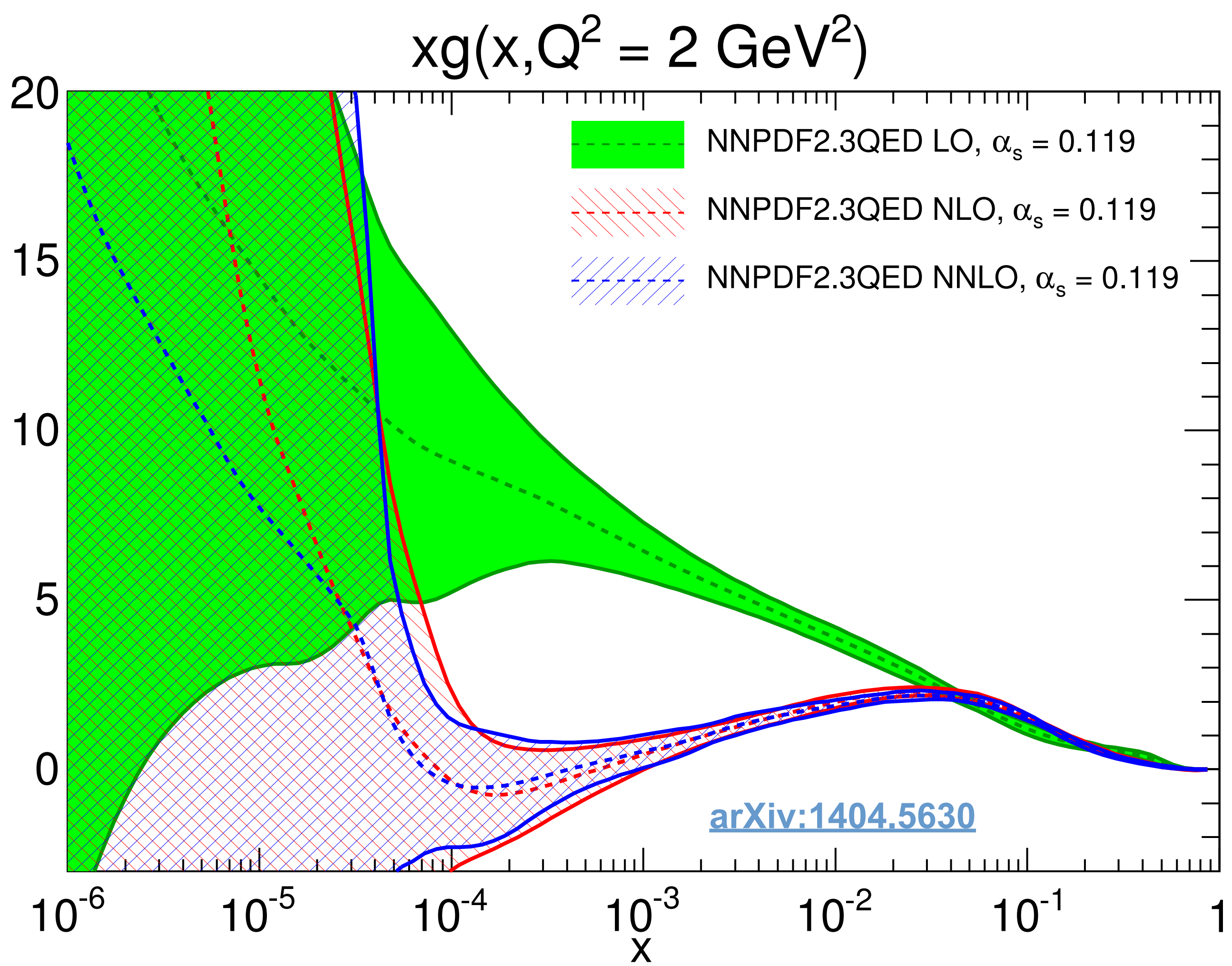
Smaller x : strong non-perturbative / colour-screening / saturation effects expected

What does a PDF even mean?

Highly relevant for MPI (& ISR)

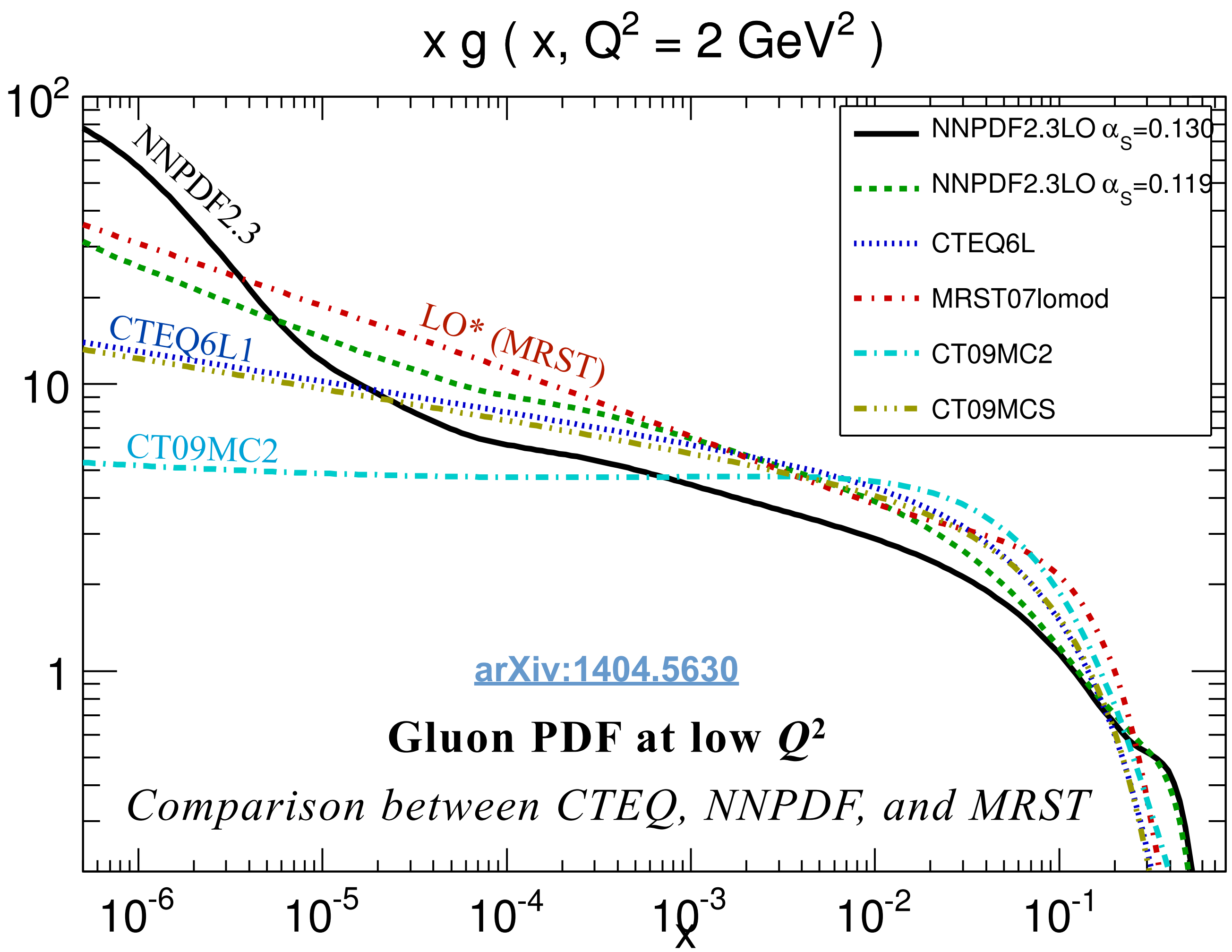
PDF ***must*** be a probability density → can ***only*** use LO PDFs

(+ Constraints below $x \sim 10^{-4}$ essentially just momentum conservation + flavour sum rules)



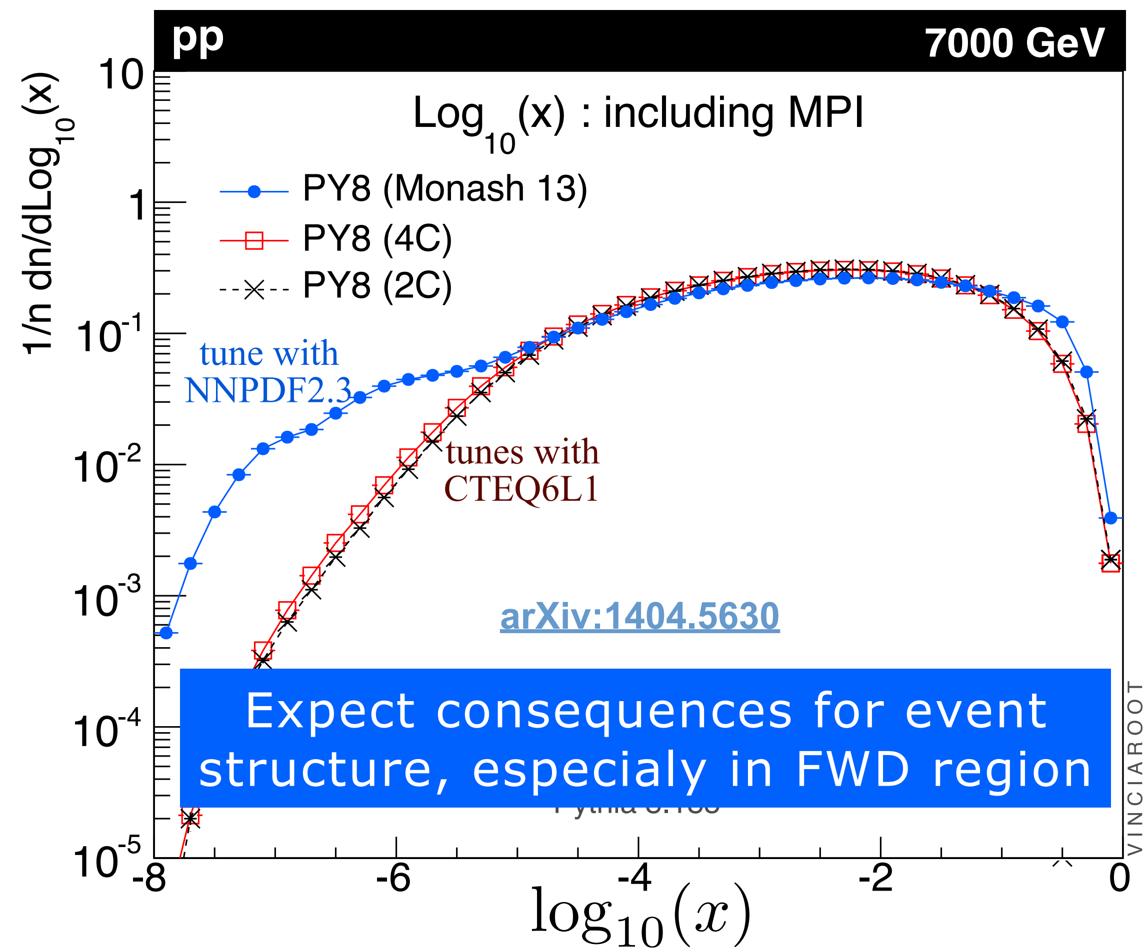
MPI models and Low x

Gluon PDF at low Q^2 drives MPI



EXAMPLE: PYTHIA 8

Range of x values probed by different MPI tunes



Expect consequences for event structure, especialy in FWD region

Controlling these issues will require an improved understanding of the interplay between low-x PDFs, saturation / screening, and MPI in MC context. (+ Clean model-independent experimental constraints!)

Not automatic: Communities don't speak same language (+ low visibility)

Recent PYTHIA Models/Tunes

& Extrapolations to Event Structure at 100 TeV

PYTHIA 8.1

Current Default = **4C** (from 2010)

Tunes 2C & 4C: e-Print: arXiv:1011.1759

LEP tuning undocumented (from 2009)
LHC tuning only used very early data
based on CTEQ6L1

Aims for the Monash 2013 Tune

Monash 2013 Tune: e-Print: arXiv:1404.5630

Set M13 Tune: → in PYTHIA 8

Tune:ee = 7
Tune:pp = 14

- Revise (and document) constraints from e^+e^- measurements
  - In particular in light of possible interplays with LHC measurements
- Test drive the new NNPDF 2.3 LO PDF set (with $\alpha_s(m_Z) = 0.13$) for pp & ppbar
  - Update min-bias and UE tuning + energy scaling → 2013
  - Follow “Perugia” tunes for PYTHIA 6: use same α_s for ISR and FSR
  - Use the PDF value of α_s for both hard processes and MPI

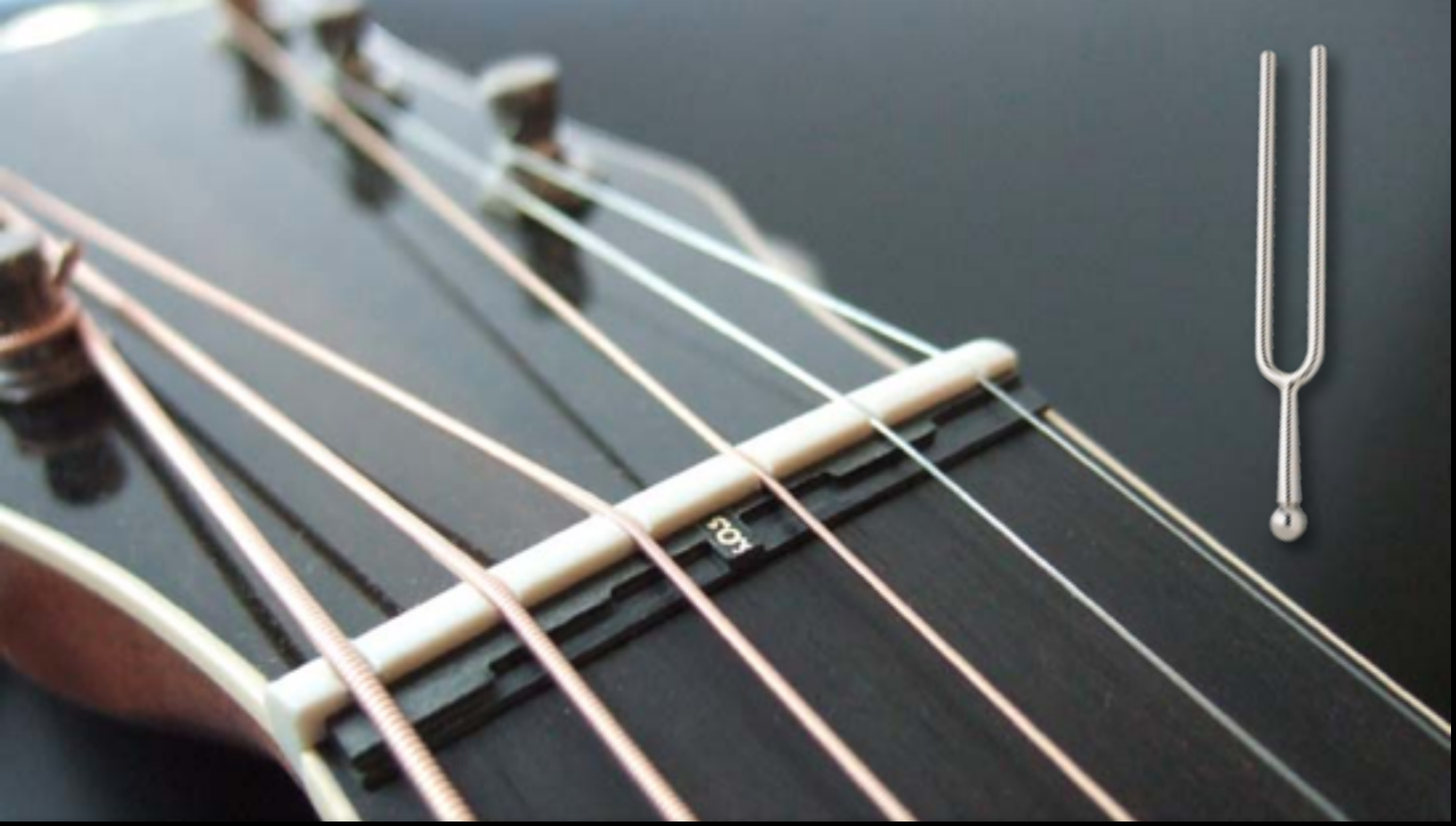
PYTHIA 6.4 (*warning:* no longer actively developed)

Perugia Tunes: e-Print: arXiv:1005.3457
(+ 2011 & 2012 updates added as appendices)

Default: still rather old Q^2-ordered tune ~ Tevatron Tune A

Most recent: Perugia 2012 set of p_T-ordered tunes (370 - 382) + Innsbruck (IBK) Tunes (G. Rudolph)

Note: I will focus on default / author tunes here
(Important complementary efforts undertaken by LHC experiments)



Tuning

means different things to different people

10% agreement is great for (N)LO + LL

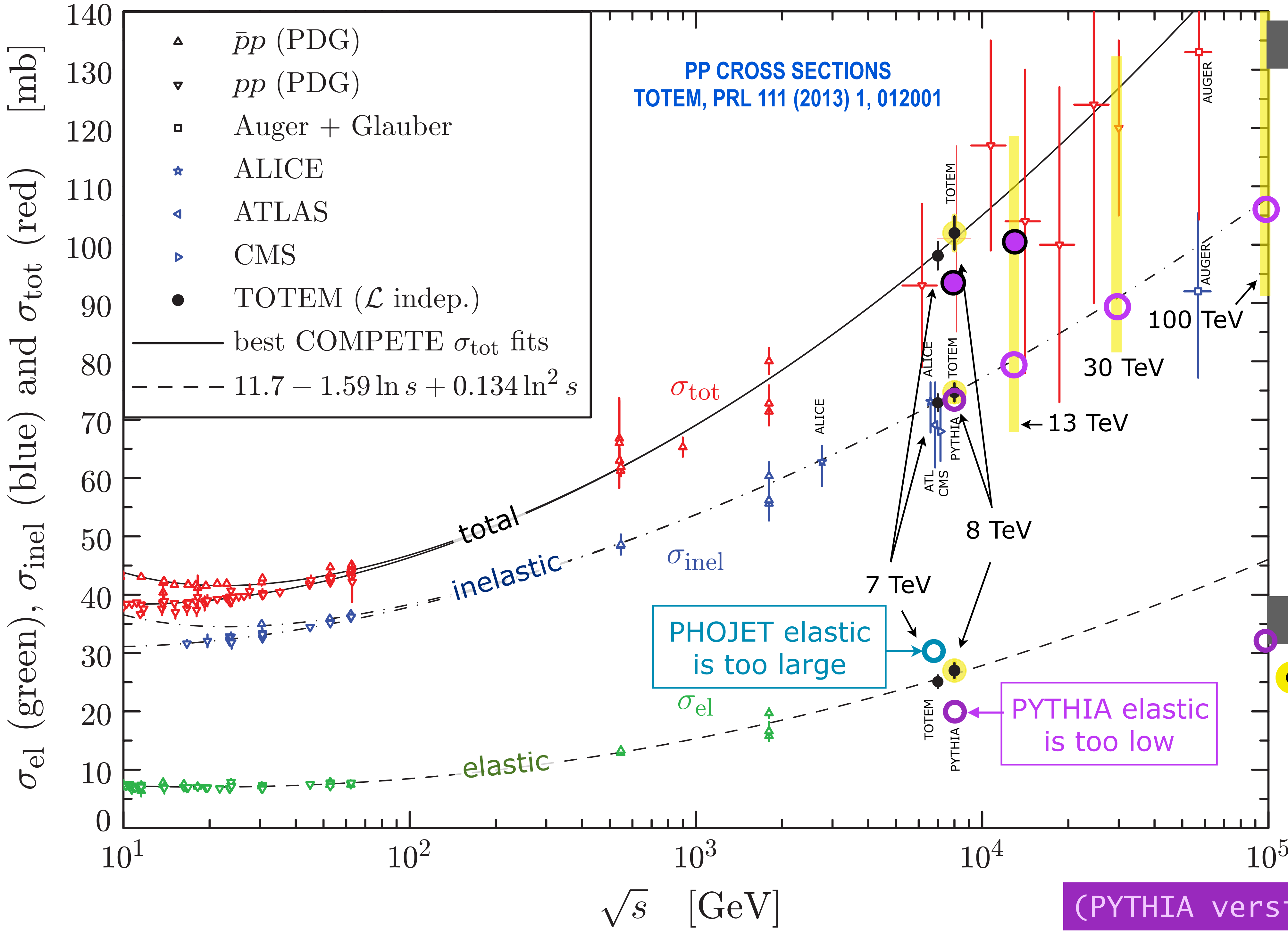
MB/UE/Soft: larger uncertainties since driven by non-factorizable and non-perturbative physics

Complicated dynamics: If a model is simple, it is wrong *(T. Sjöstrand)*

Cross Sections & Energy Scaling

$$\text{Pileup rate} \propto \ \sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s) \propto s^{0.08} \ \text{or} \ \ln^2(s) \ ?$$

Donnachie-Landshoff (or 0.096?) Froissart-Martin Bound



INELASTIC

(INEL = SD+DD+CD+ND)

TOTEM (+COMPETE)

$\sigma_{inel}(8\ \text{TeV}) = 74.7 \pm 1.7$ mb

$\sigma_{inel}(13\ \text{TeV}) \sim 80 \pm 3.5$ mb

PYTHIA ($DL_{0.08}$)

σ_{inel}(8 TeV): 73 mb
σ_{inel}(13 TeV): 78 mb
σ_{inel}(30 TeV): 89 mb
σ_{inel}(100 TeV): 107 mb

OK

ELASTIC

$\sigma_{el}(8\ \text{TeV}) = 27.1 \pm 1.4$ mb

PYTHIA: 20 mb

LOW

(PYTHIA versions: 6.4.28 & 8.1.80)

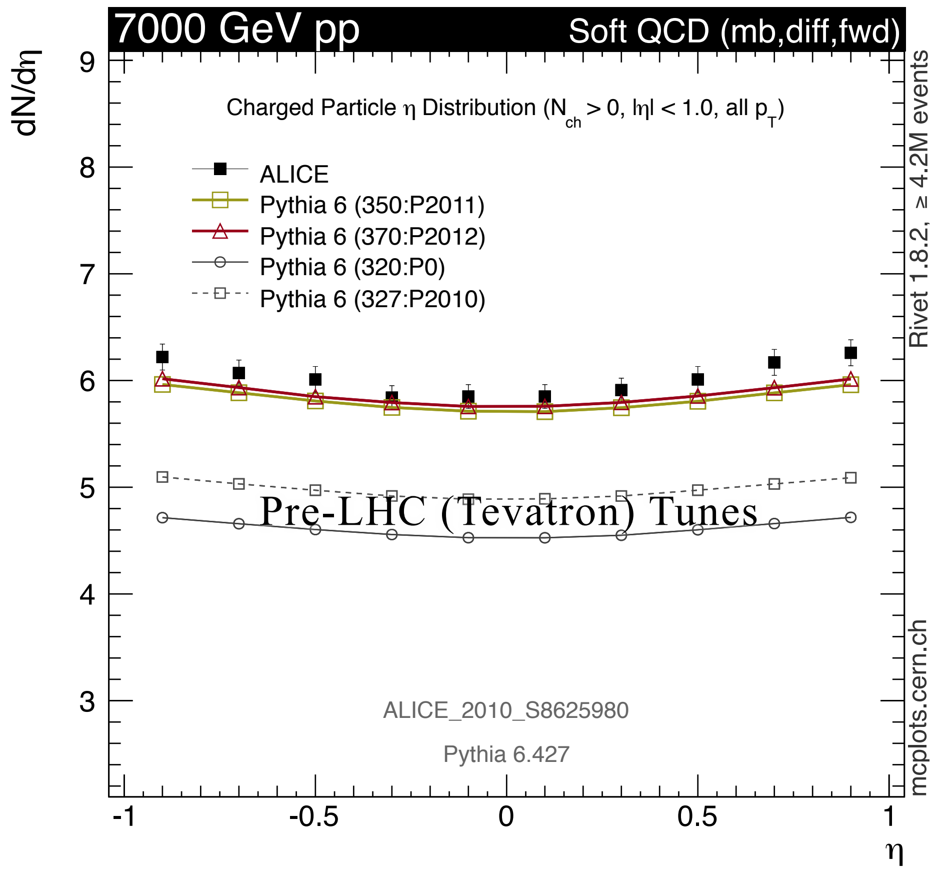
Event Properties: Minimum-Bias
How many charged tracks? (in central region)

The updated models (as represented here by the Perugia 2012 and Monash 2013 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

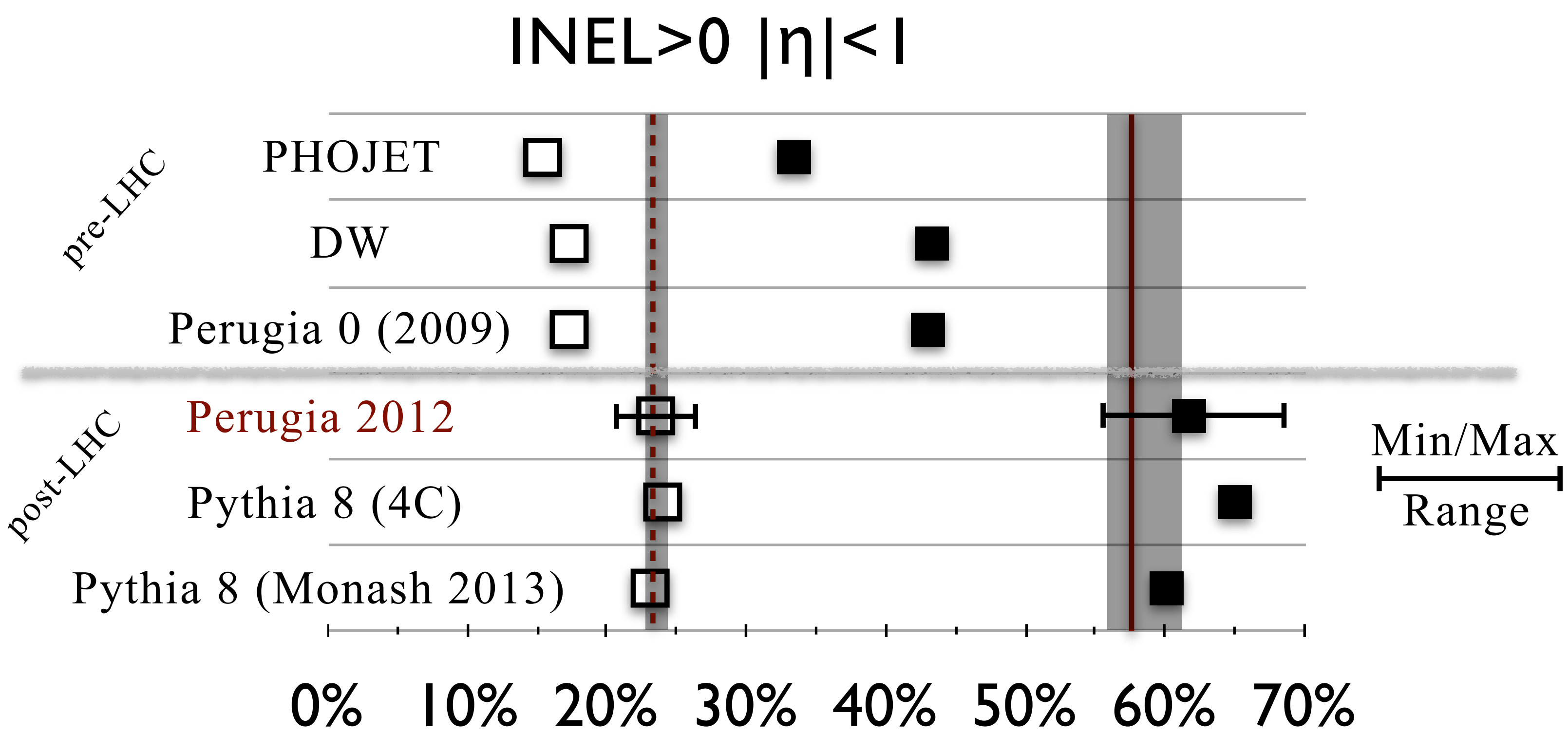
So we may have some hope that we can use these models to do extrapolations

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

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

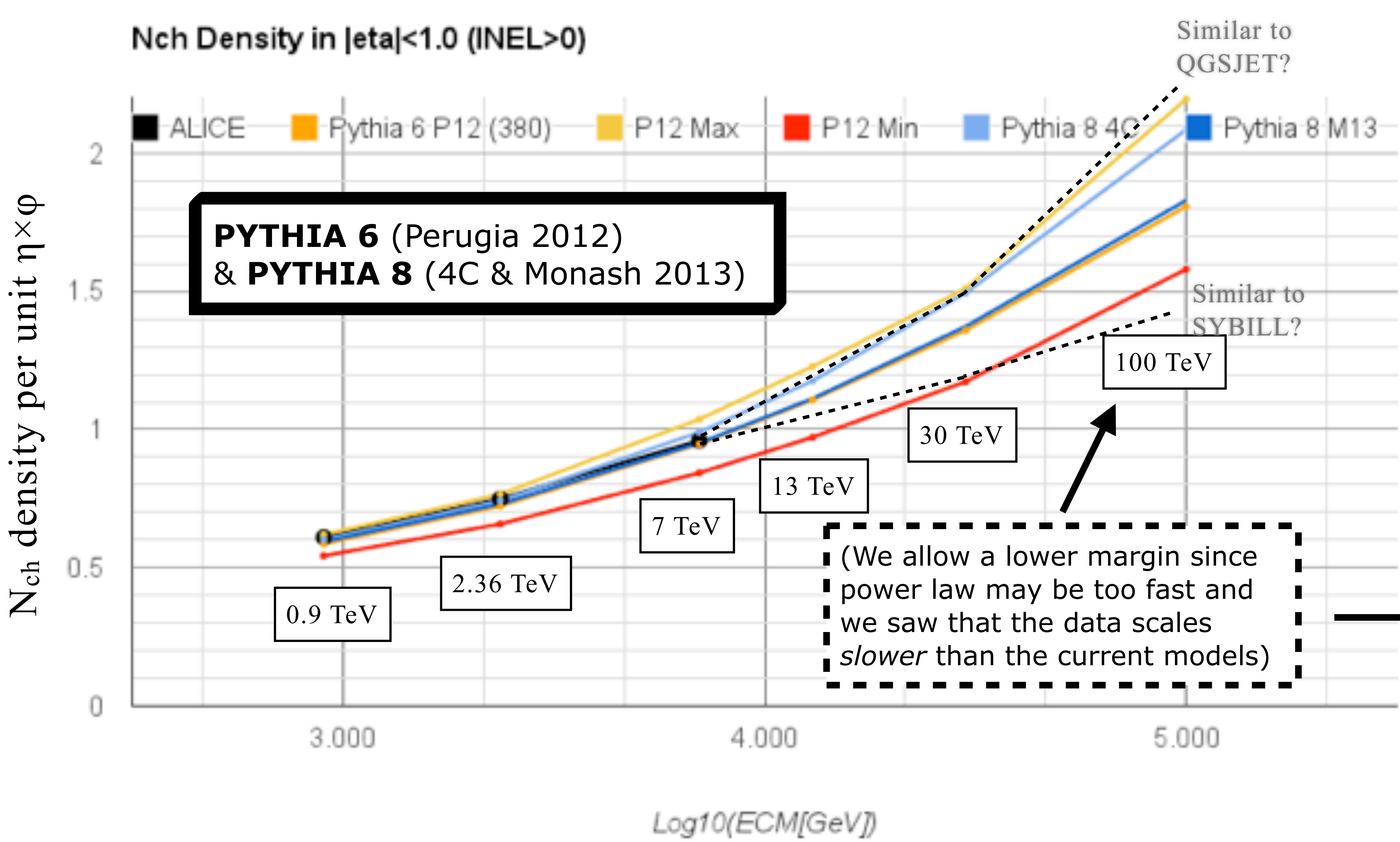
Caveat: still not fully understood why Tevatron tunes were low.

See also: Schulz & Skands, arXiv:1103.3649

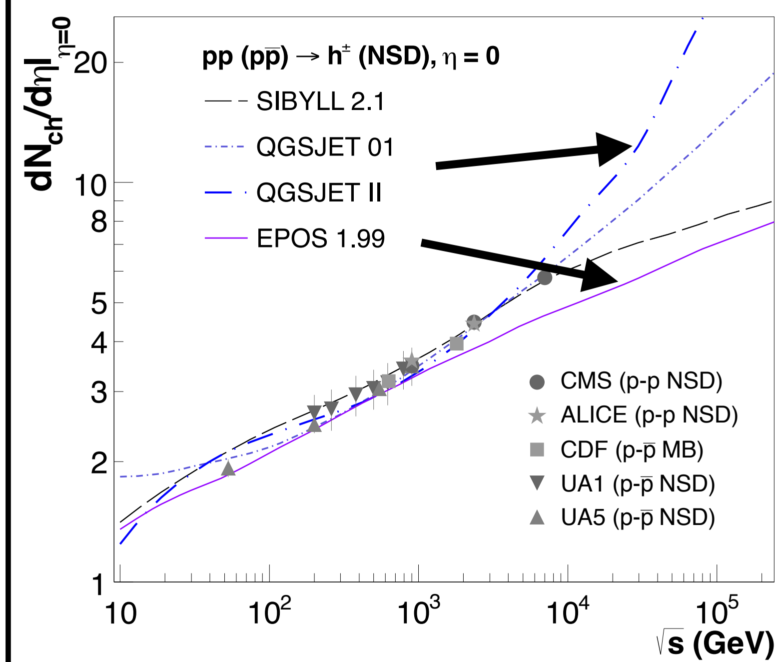
Central <N_{ch}> → 100 TeV

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 $|\eta|<1$
charged particle defined with $c\times\tau > 10$ mm



A *Comparison with Pomeron-based models.*
From D. d'Enterria et al, arXiv:1101.5596



QGSJET too agressive? Would predict very high densities at 100 TeV
EPOS too low (new version fits LHC better, worth trying out)

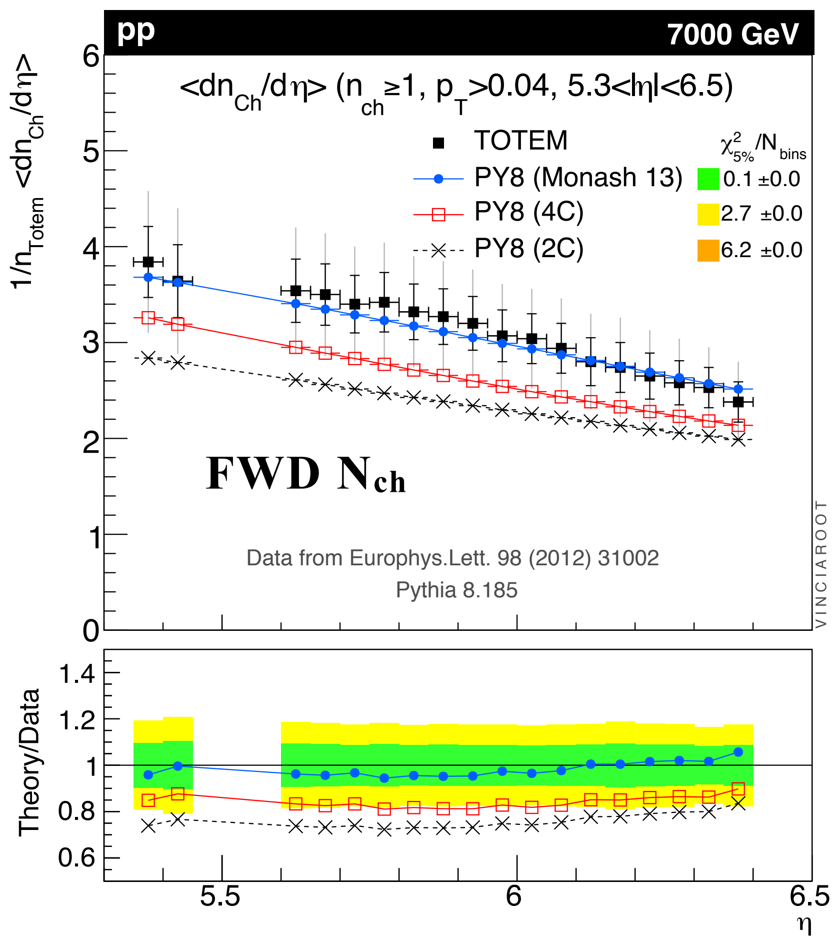
Extrapolations for INEL>0
Central <N_{ch}> density
(per unit $\Delta\eta\Delta\varphi$ in $|\eta|<1$; $c\tau>10$mm)

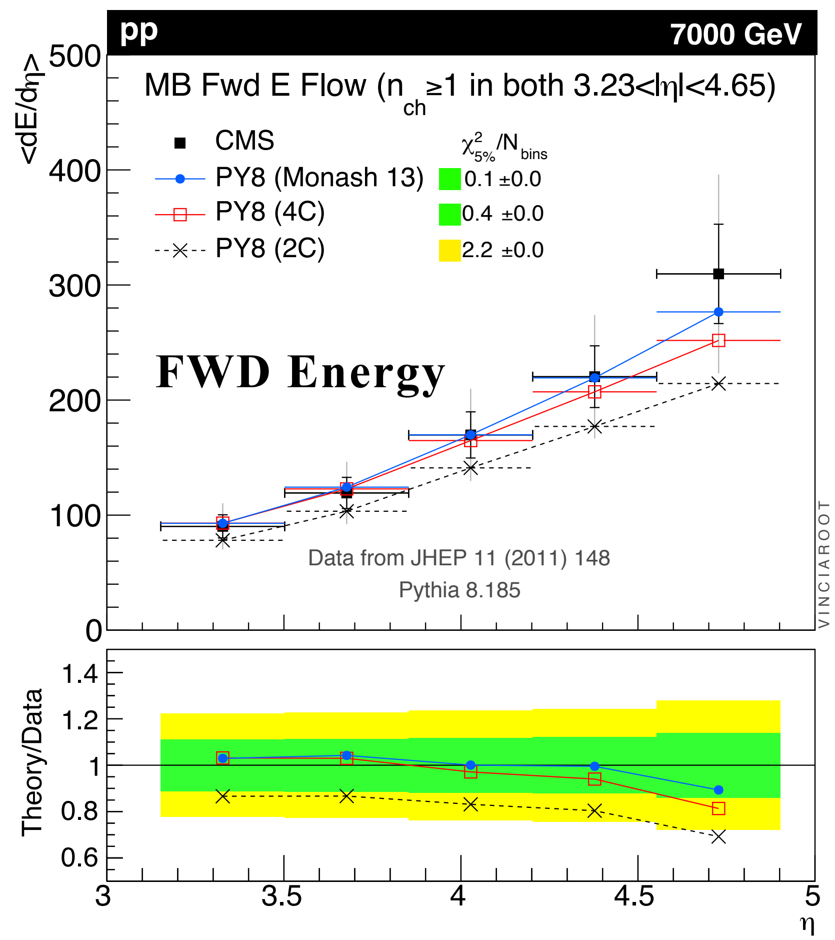
```
@13 TeV  : 1.1 ± 0.1
@30 TeV  : 1.33 ± 0.14
@100 TeV : 1.8 ± 0.4
```

Low x: Looking Forward

Higher NNPDF gluon at low x → more forward activity

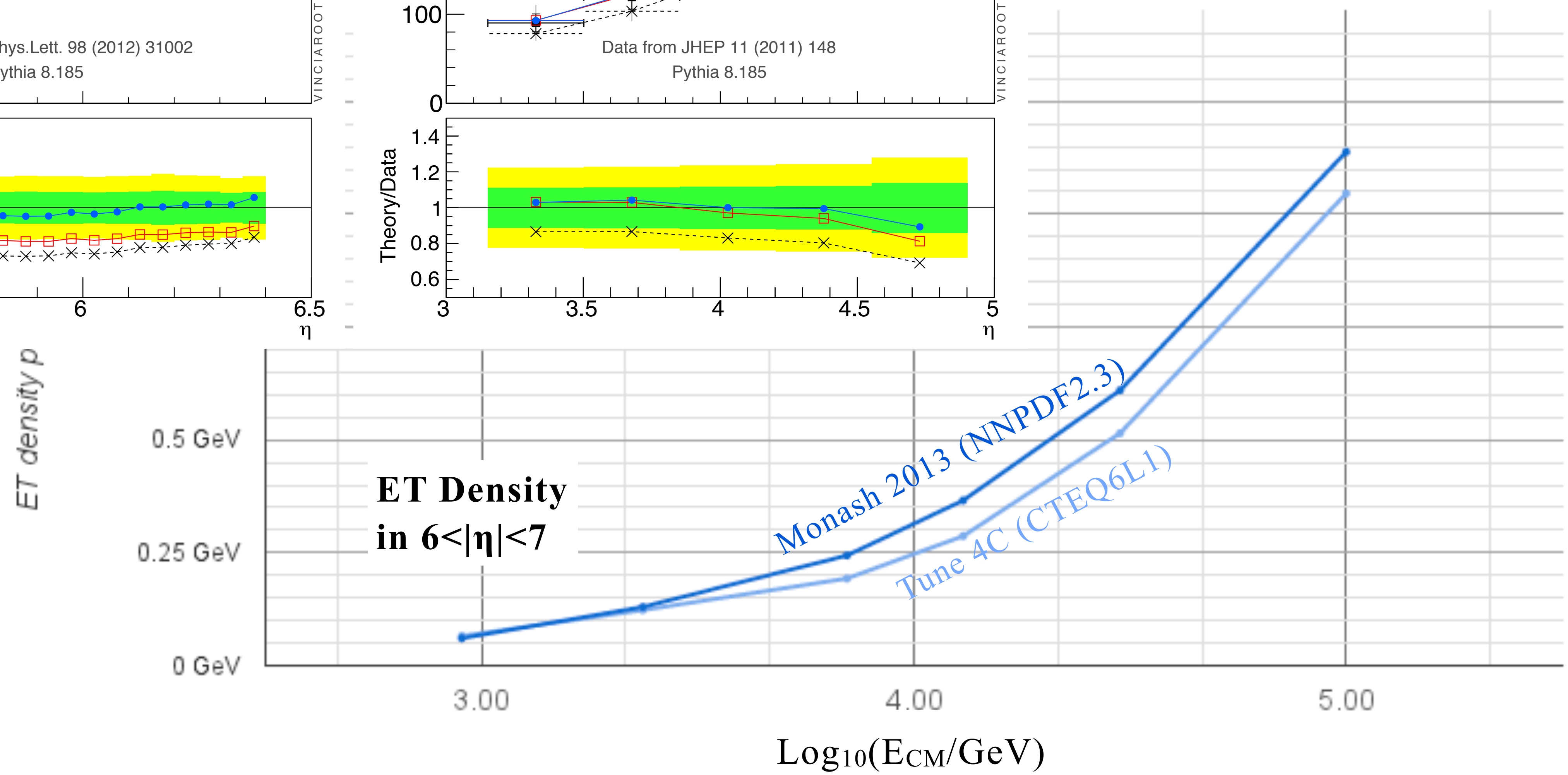
Monash 2013 Tune: e-Print: arXiv:1404.5630





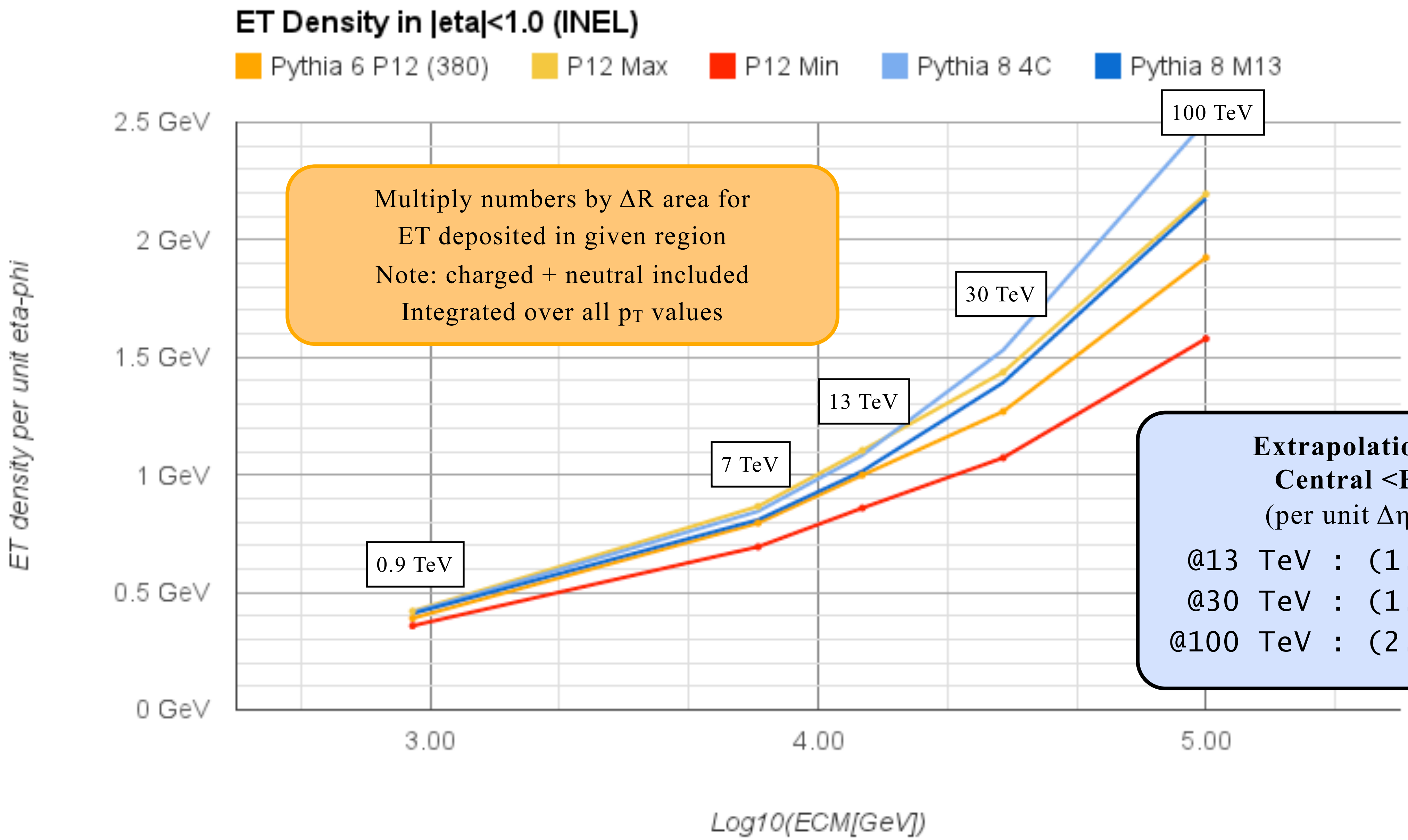
E.g., 4C (CTEQ6L1) has higher *central* density than Monash 2013 (NNPDF2.3)

But the *opposite* is true in the forward region



How Much E_T? (in central detectors)

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



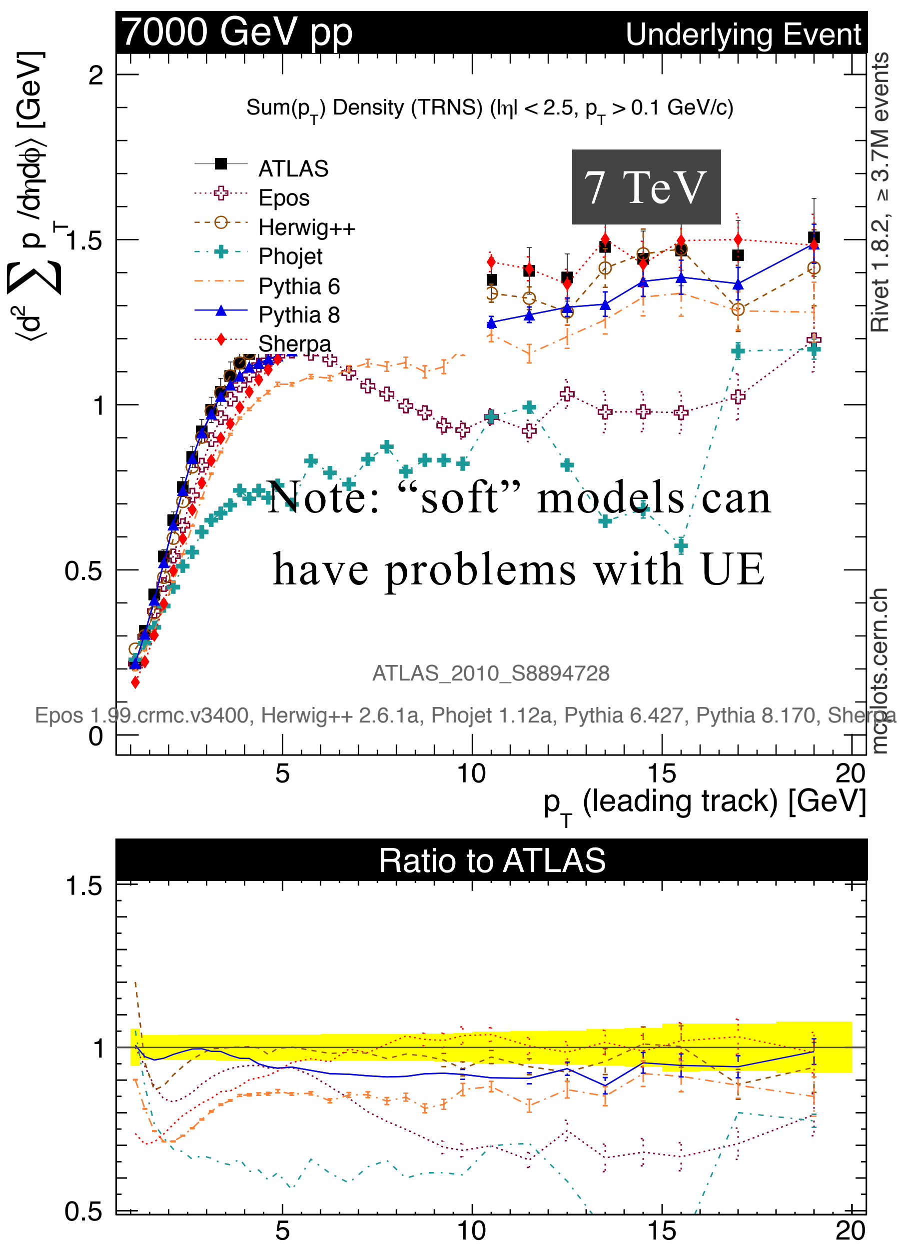
Extrapolations for INEL
Central <E_T> density
(per unit $\Delta\eta\Delta\varphi$ in $|\eta|<1$)

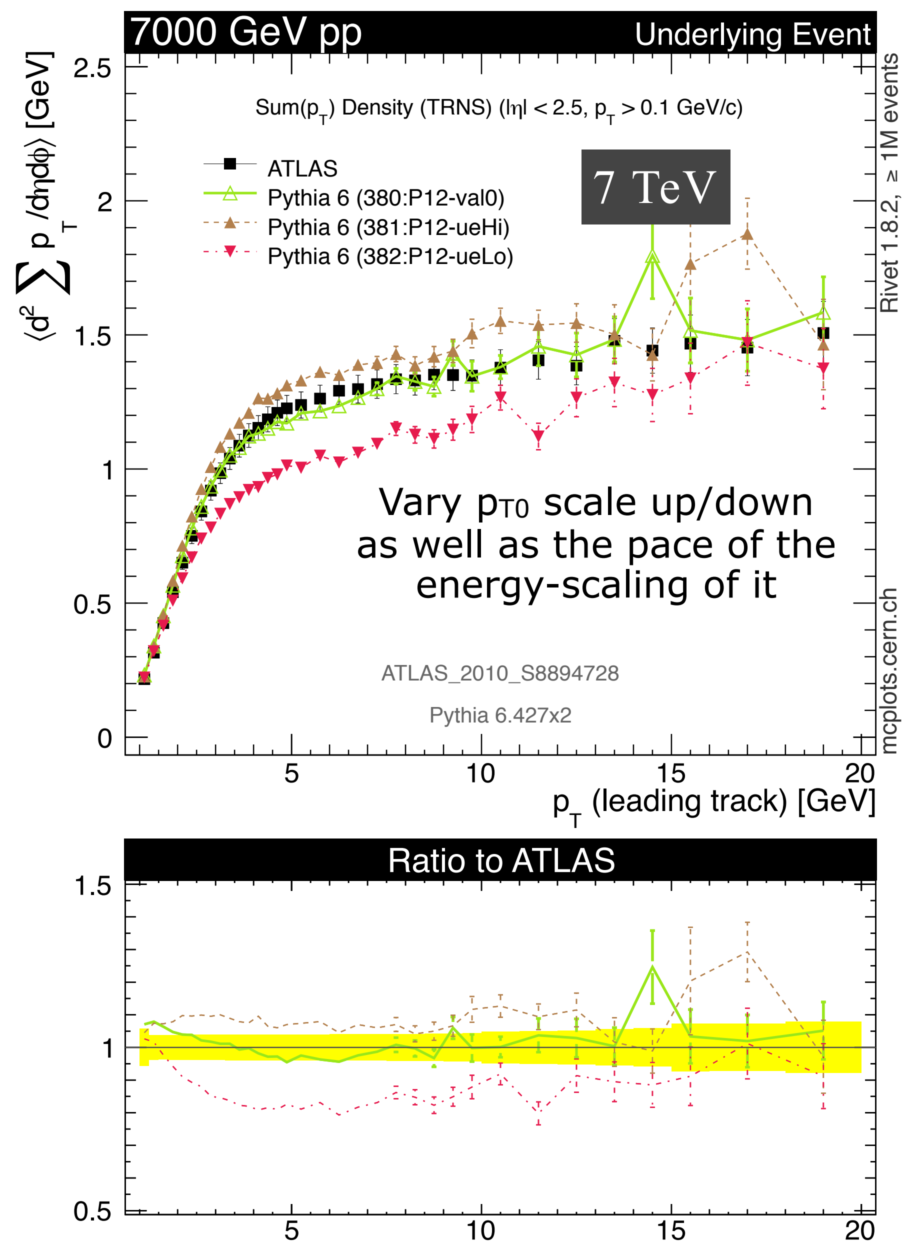
```
@13 TeV  : (1.0 ± 0.15) GeV
@30 TeV  : (1.3 ± 0.2) GeV
@100 TeV : (2.0 ± 0.4) GeV
```

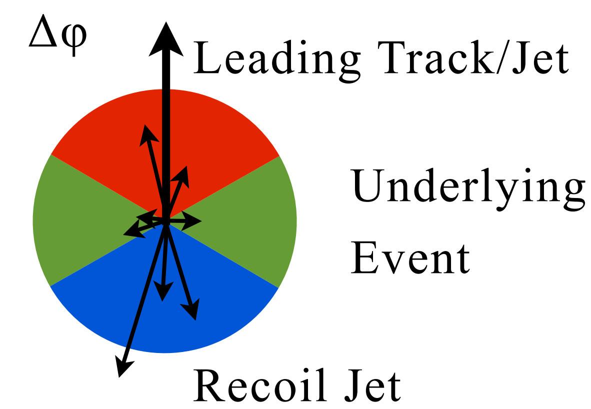
Underlying Event

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

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







Transverse Region (TRNS)

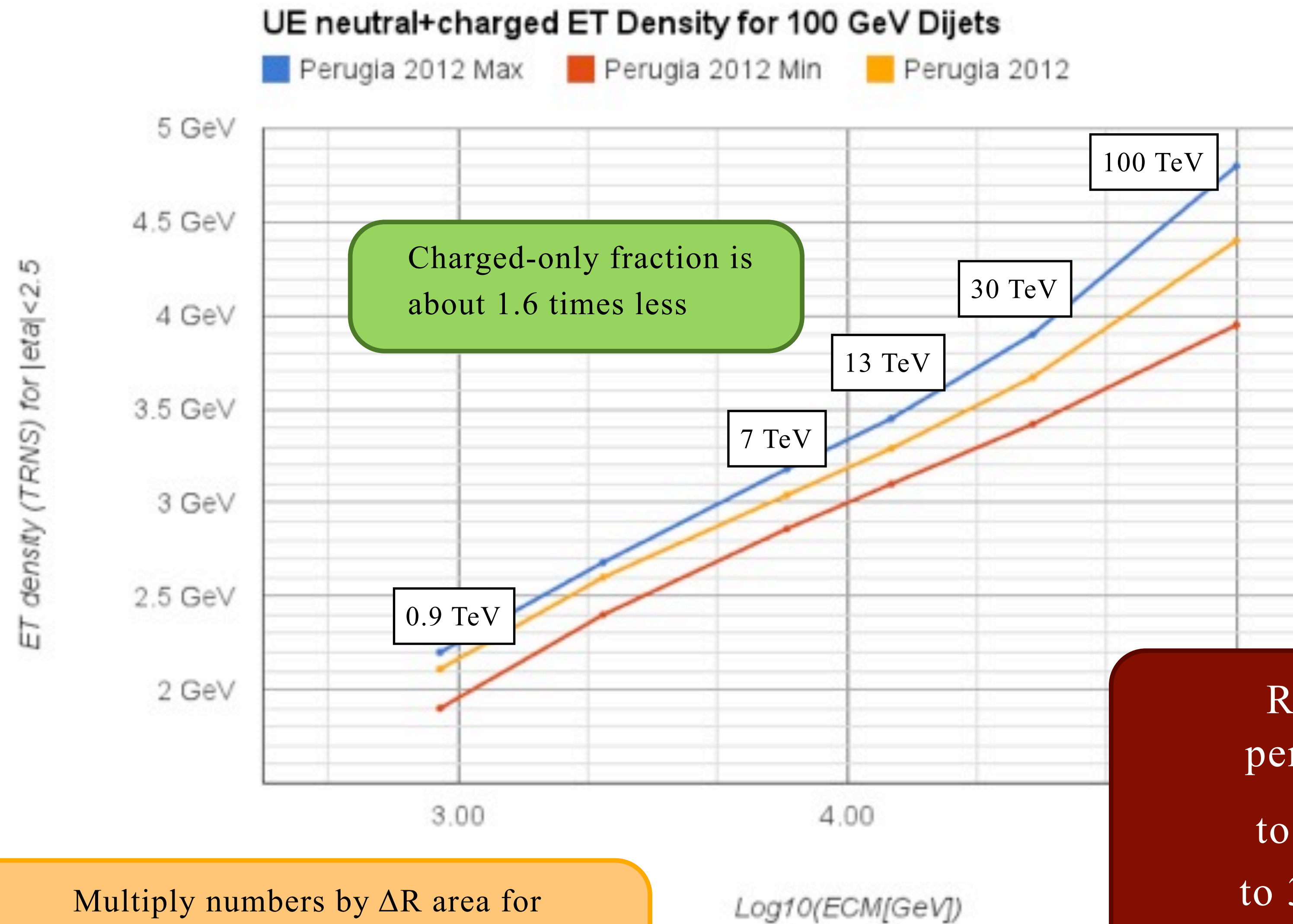
Sensitive to activity at right angles to the hardest jets

Useful definition of Underlying Event

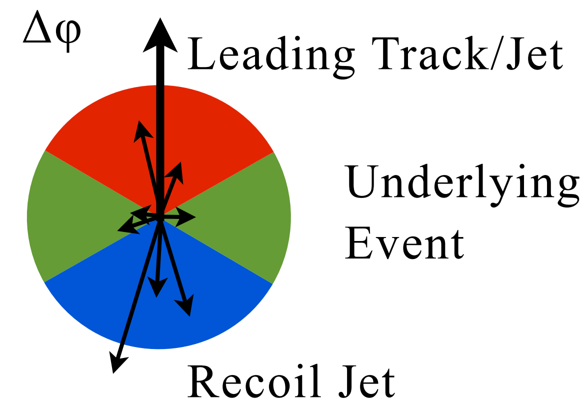
UE → 100 TeV

Test case: 100 GeV dijets

Measure ET in region transverse to the hardest track (in $|\eta|<2.5$)



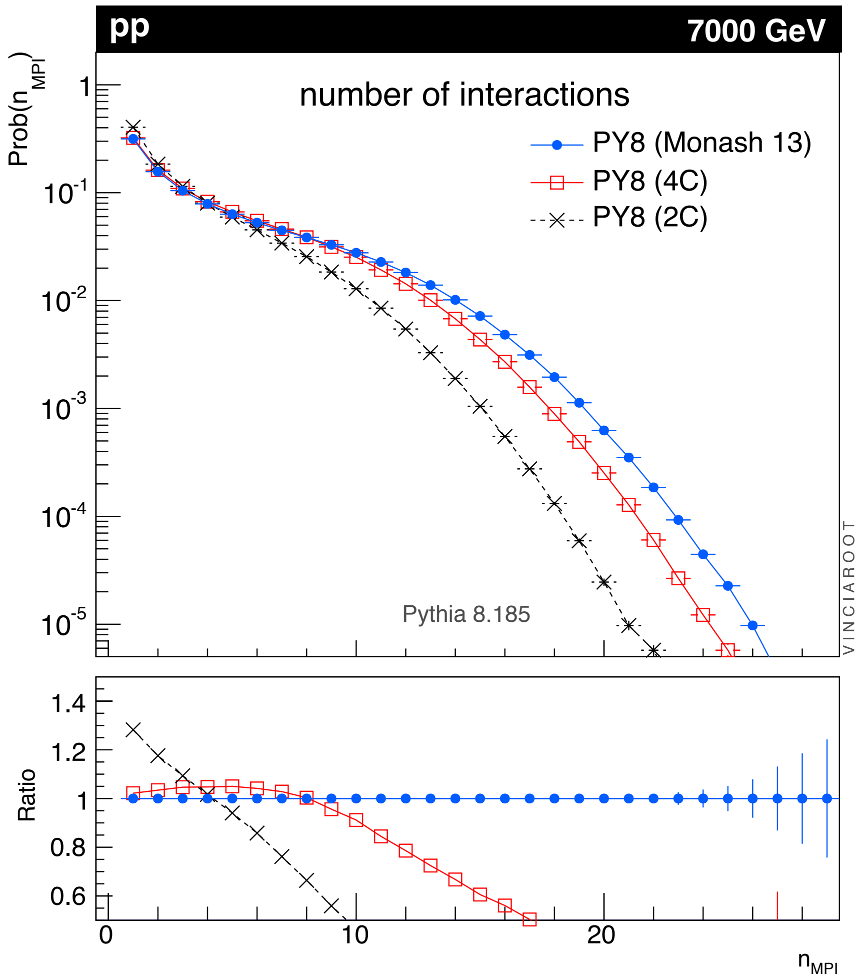
Charged-only fraction is about 1.6 times less

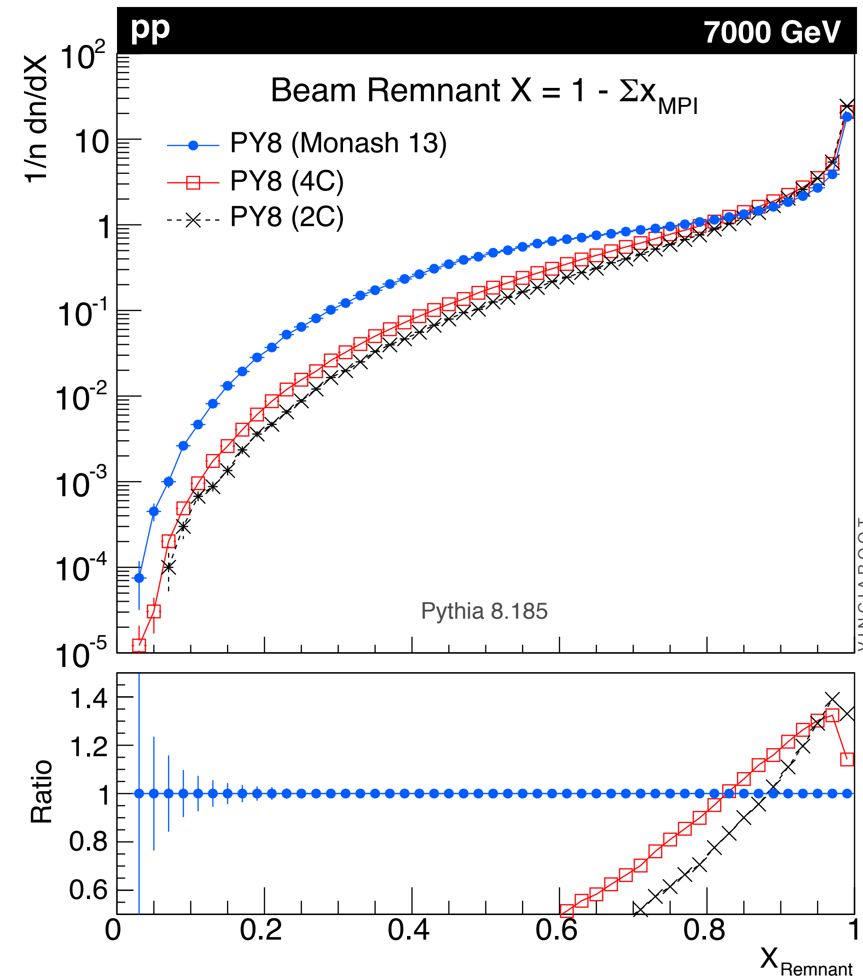


Multiply numbers by ΔR area for ET deposited in given region
Note: charged + neutral included
Integrated over all p_T values

Rises from about 2.1 GeV per unit ΔR area at 900 GeV
to 3.3 ± 0.2 GeV at 13 TeV
to 3.65 ± 0.25 GeV at 30 TeV
and 4.4 ± 0.45 GeV at 100 TeV

100 TeV: Total Inelastic Scattering?





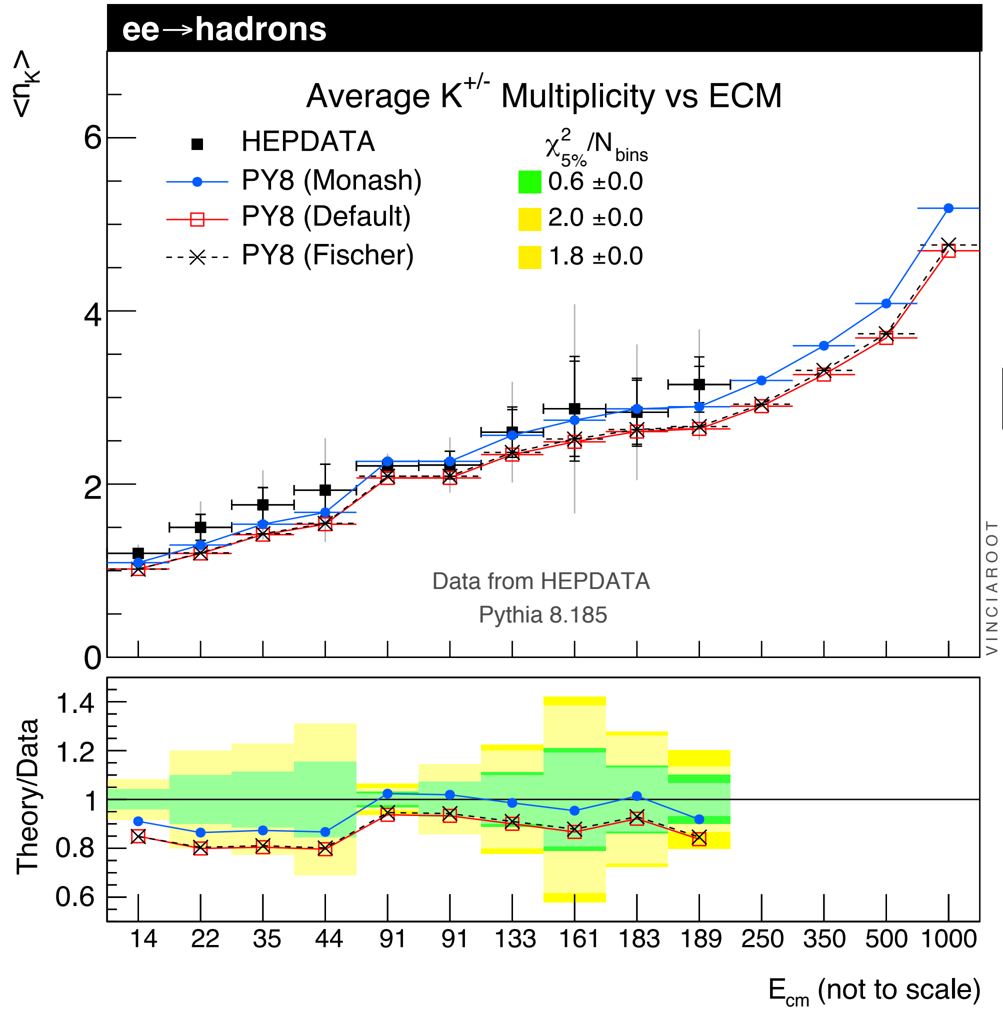
At O(10^{-4} - 10^{-5}) of total cross section, the beam remnant (BR) retains < 10% of beam energy. → **"Catastrophic Energy Loss"** events. Intrinsic consequence of MPI. (Typically not caused by a single hard partonic scattering process; vanishing PDFs in the region x > 0.5).

→ **"Total Inelastic Scattering"**?: more than 90% of the energy scattered out of both beams, may occur at a level of 10^{-10} – 10^{-8} of the cross section → 10 - 1000 pb. Extremely interesting part of hadron-hadron collision physics, far from single-interaction limit.
Triggers for this class of events are presumably non-trivial.

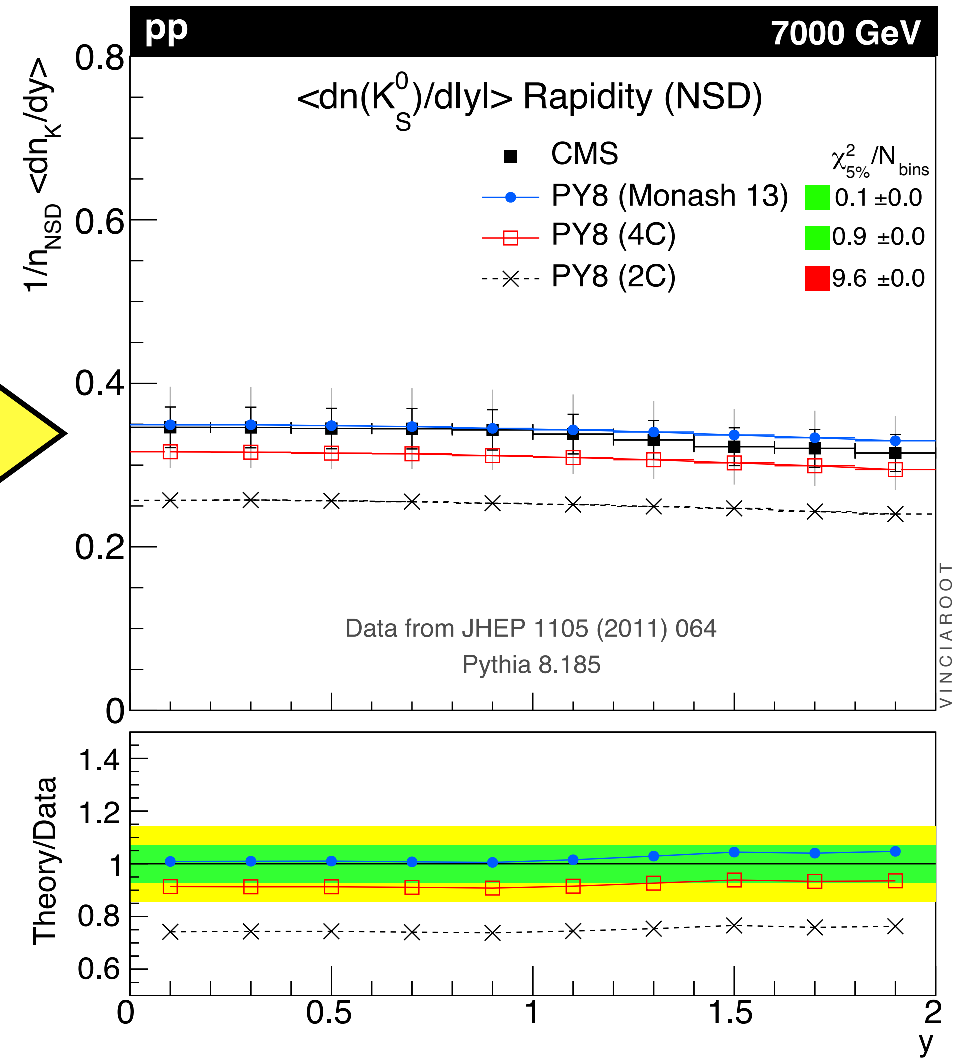
(Event Structure: Strangeness)

Strangeness (& baryons): much recent debate sparked by LHC measurements. Collectivity in pp? Especially at high multiplicity?

Kaons : ee at different CM energies



Kaons: dn/dy in pp at 7000 GeV



"Trivial part": 10% more strangeness in ee (nothing to do with collectiveness)

Non-trivial part (still not understood!): p_T spectra & baryon sources

Summary

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

If you don't require precision better than 10%

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
- ~ 1.3 ± 0.2 GeV / ΔηΔφ @ 30 TeV
- ~ 2.0 ± 0.4 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

For tuning, Perugia 2012 (PY6) → Monash 2013 (PY8)

Diffraction could still use more dedicated pheno / tuning studies

Baryon and strangeness spectra in pp still not well understood → color reconnections?

Forward region highly sensitive to PDF choice → what do low-x PDFs mean?

(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