Modelling of the interplay between hard and soft processes in pp

Peter Skands (CERN)

Main tools for high-p_T calculations

Factorization and IR safety

Corrections suppressed by powers of Λ_{QCD}/Q_{Hard}

Soft QCD / Min-Bias / Pileup

NO HARD SCALE

Typical Q scales ~ Λ_{QCD}

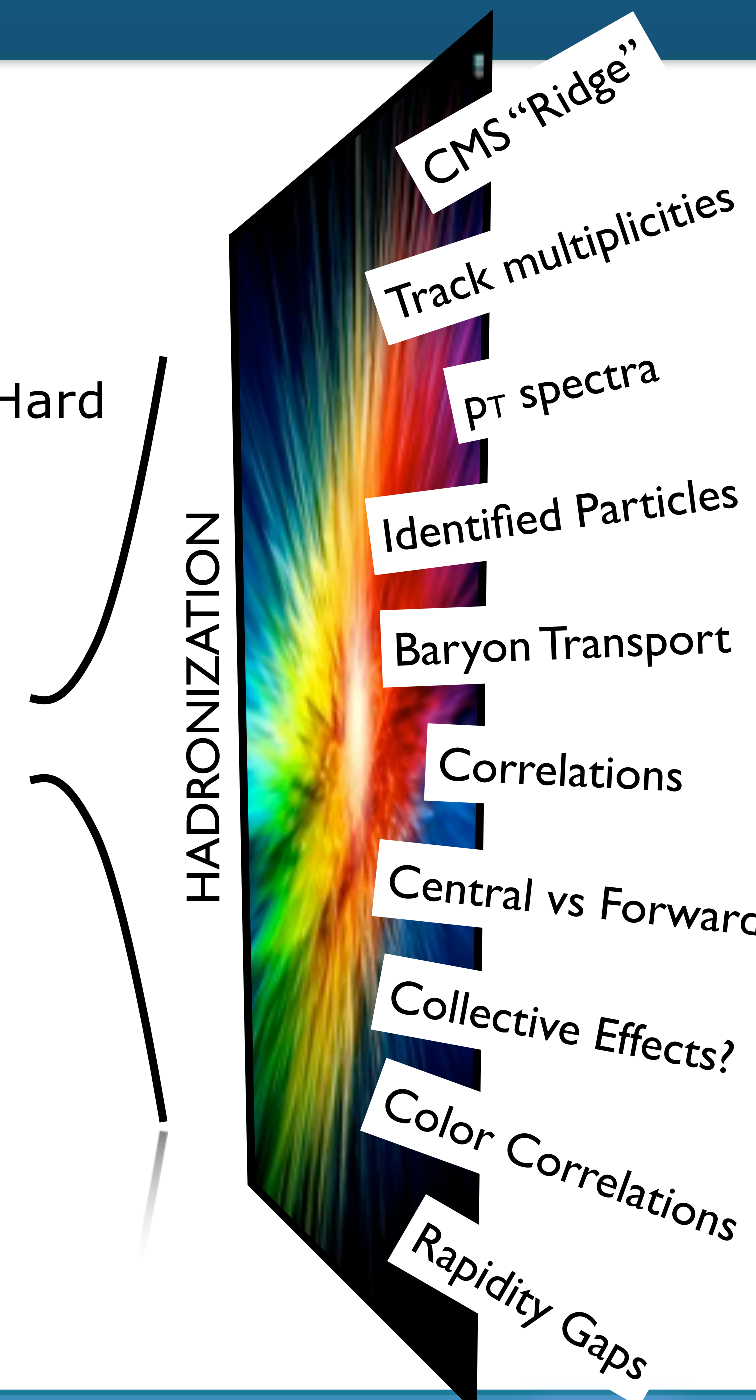
Extremely sensitive to IR effects

→ Excellent LAB for studying IR effects

~ ∞ statistics for min-bias

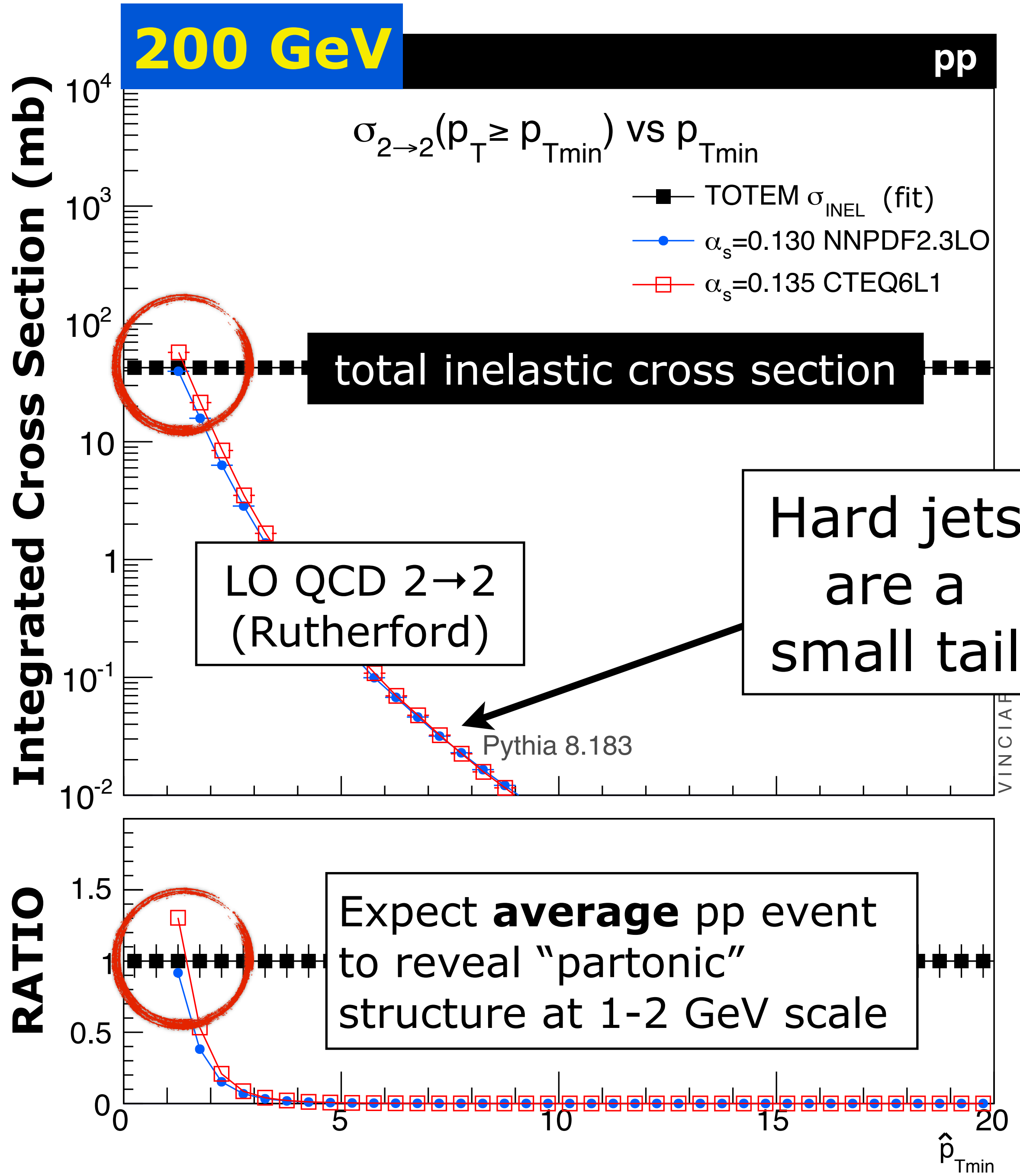
→ Access tails, limits

Universality: Recycling PU ↔ MB ↔ UE



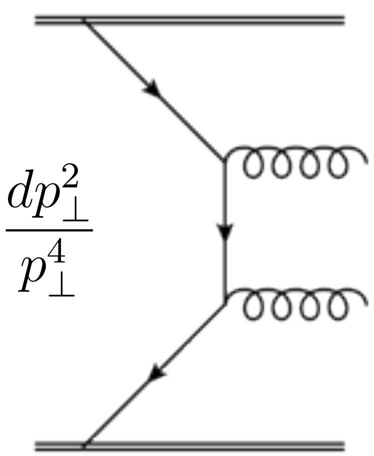
Is there no hard scale?

Compare total (inelastic) hadron-hadron cross section to calculated parton-parton (LO QCD 2→2) cross section



Leading-Order pQCD

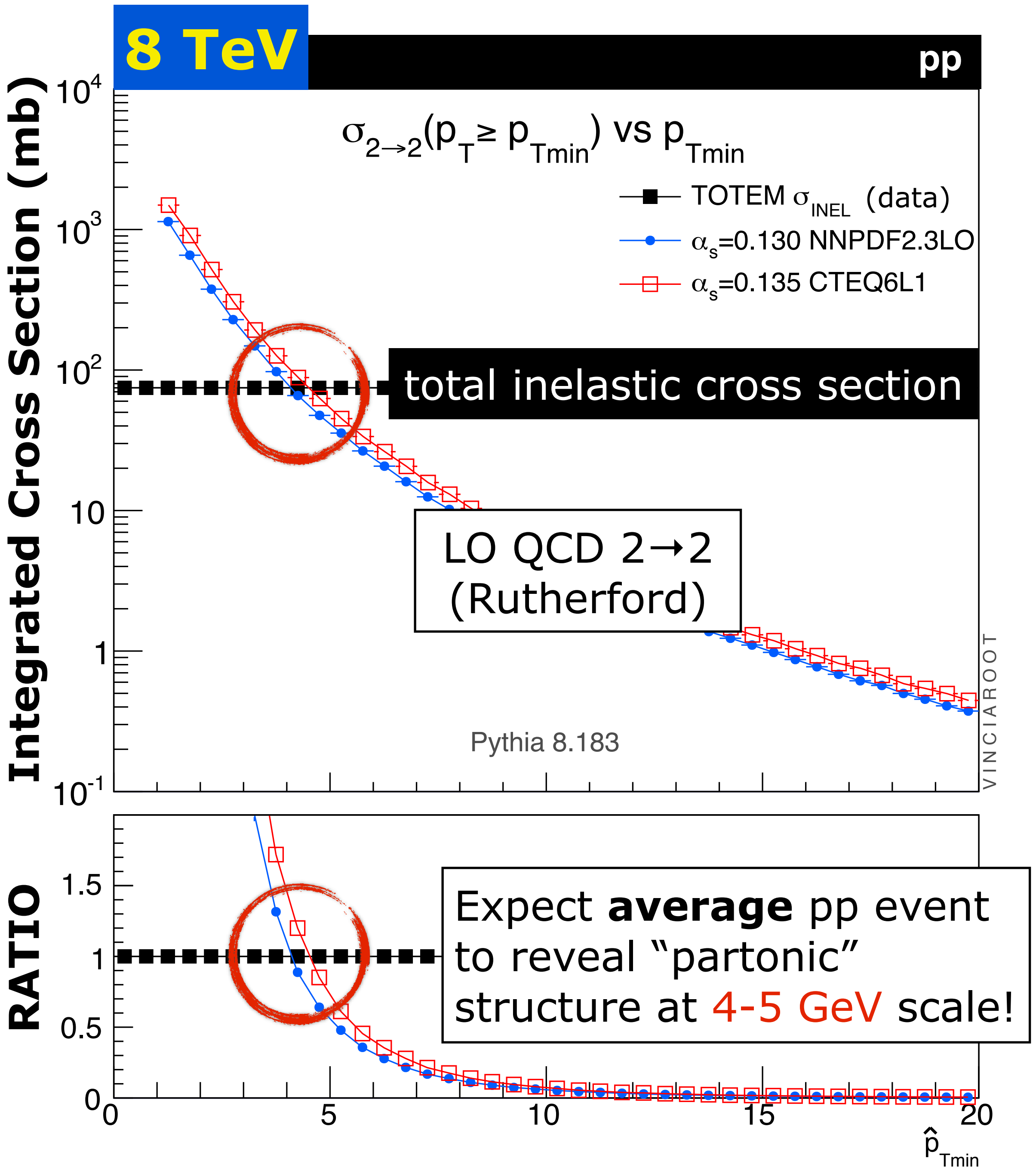
$$\int_{p^2_{\perp,\mathrm{min}}} dp^2_\perp \frac{d\sigma_{\mathrm{Dijet}}}{dp^2_\perp}$$

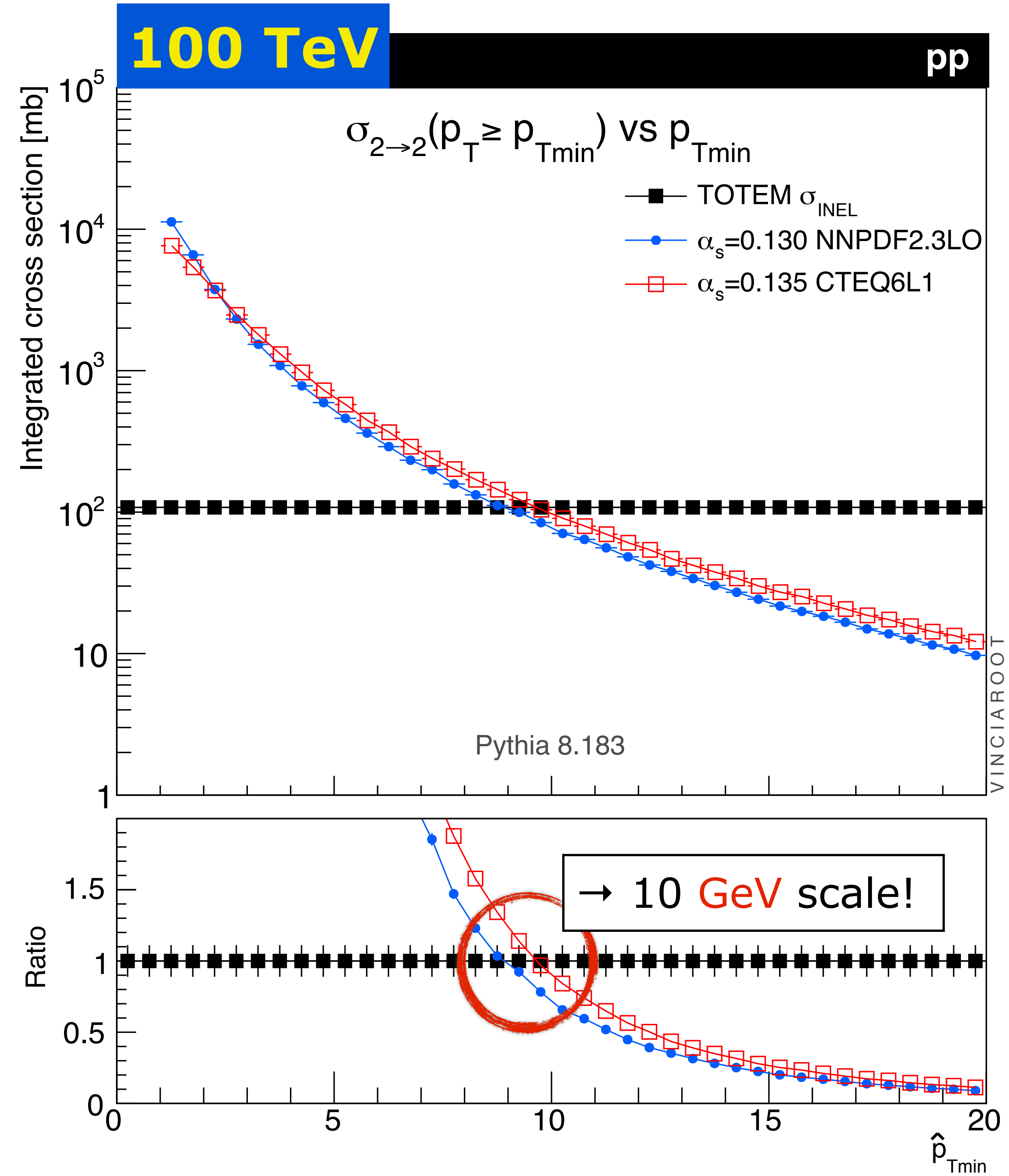


$$d\sigma_{2\to2} \propto \frac{dp^2_\perp}{p^4_\perp} \quad \otimes \text{ PDFs}$$

→ 8 TeV → 100 Tev

→ Trivial calculation indicates hard scales in min-bias





MPI

Multiple perturbative **parton**-parton **interactions**

Simple consequence of having lots of partons (in each hadron) and large interaction cross section

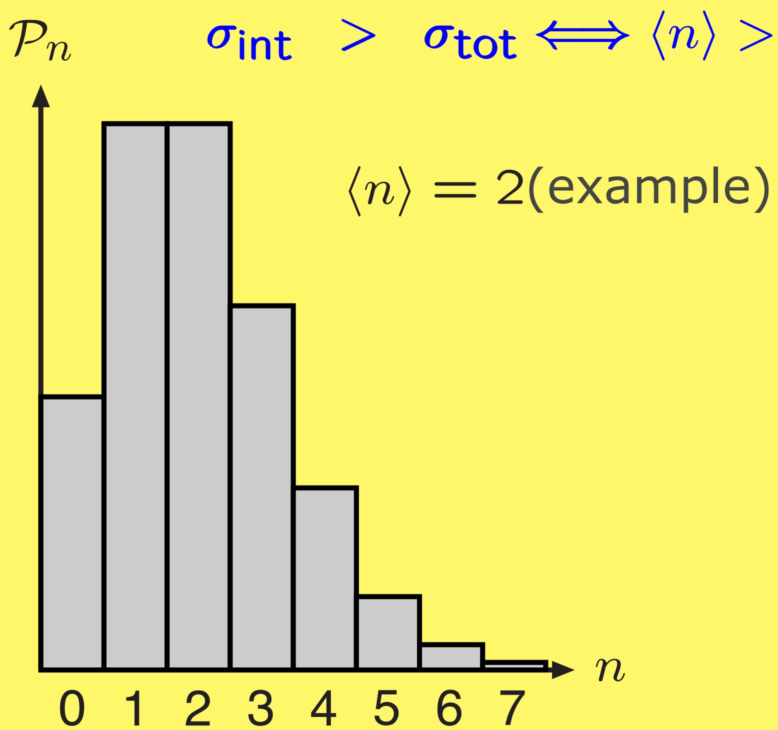
Naively $\langle n_{2\to 2}(p_{\perp\min})\rangle = \dfrac{\sigma_{2\to 2}(p_{\perp\min})}{\sigma_{\mathrm{tot}}}$

Interactions independent (naive factorization) → Poisson

$$\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\mathrm{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\mathrm{int}} > \sigma_{\mathrm{tot}} \iff \langle n\rangle > 1$$



$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!}\, e^{-\langle n\rangle}$$

Real Life

Color screening: $\sigma_{2\to 2} \to 0$ for $p_\perp \to 0$

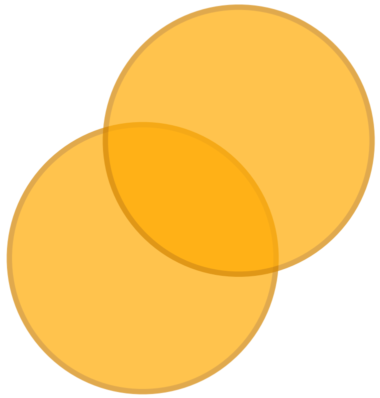
Momentum conservation suppresses high-n tail

Impact-parameter dependence

+ physical correlations

→ not simple product

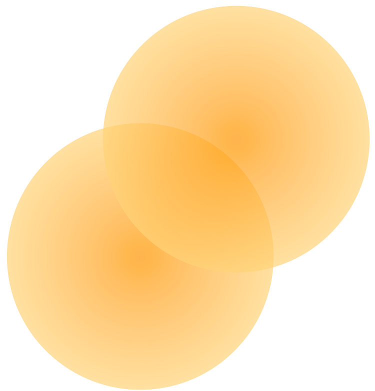
Impact Parameter



1. **Simple Geometry** (in impact-parameter plane)

Simplest idea: smear PDFs across a uniform disk of size πr_p^2
→ simple geometric overlap factor ≤ 1 in dijet cross section
Some collisions have the full overlap, others only partial
→ Poisson distribution with different mean <n> at each b

2. More realistic **Proton b-shape**



Smear PDFs across a non-uniform disk
MC models use Gaussians or **more**/less peaked
Overlap factor = convolution of two such distributions

→ Poisson distribution with different mean <n> at each b
"Lumpy Peaks" → large matter overlap enhancements, higher <n>

Note: this is an *effective* description. Not the actual proton mass density.
E.g., peak in overlap function (»1) can represent unlikely configurations with huge overlap enhancement. Typically use total σ_{inel} as normalization.

→ **see next talk by M. Strikman**

Charged Multiplicity

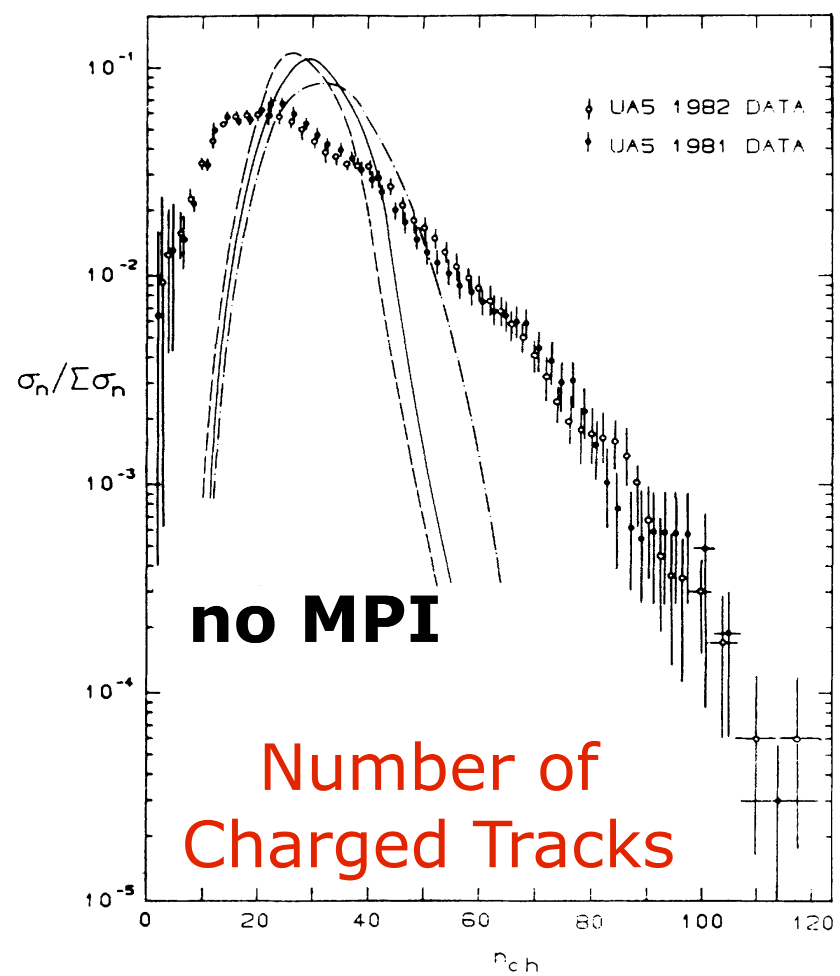


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

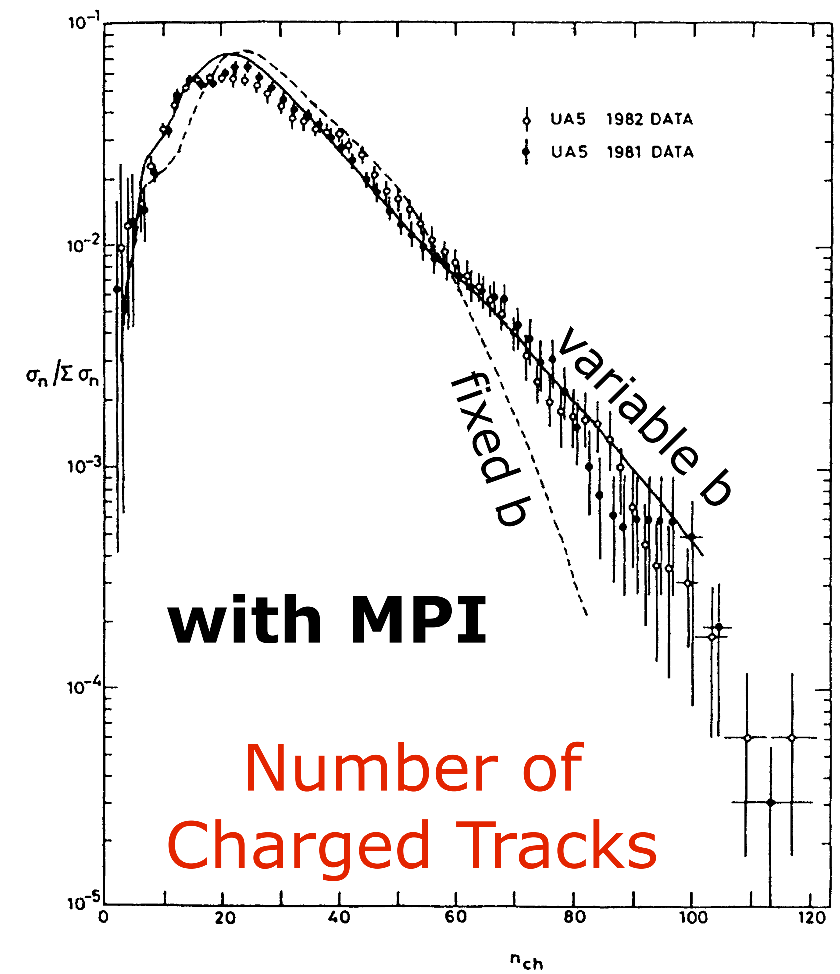
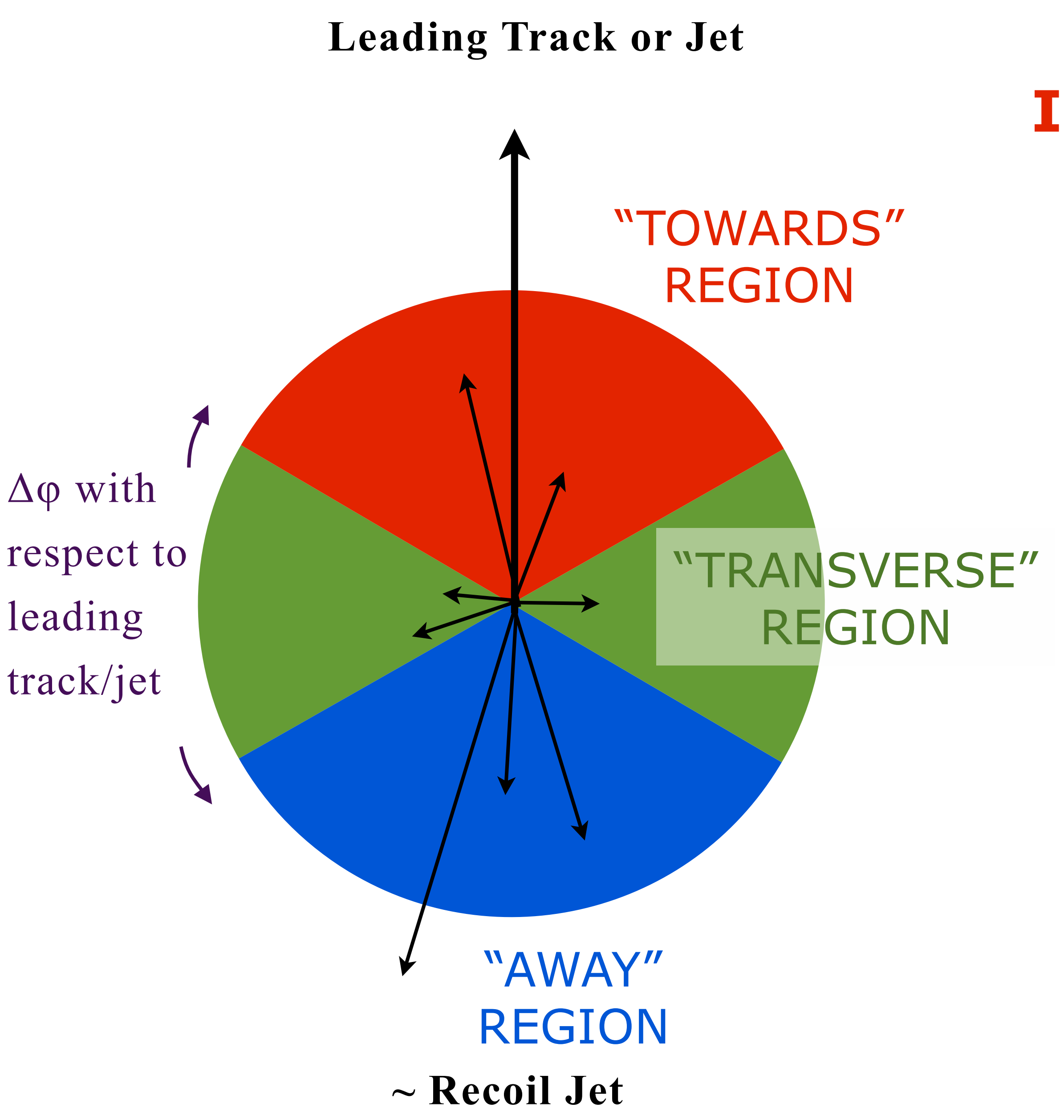


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

The Pedestal Effect
(now called the Underlying Event)

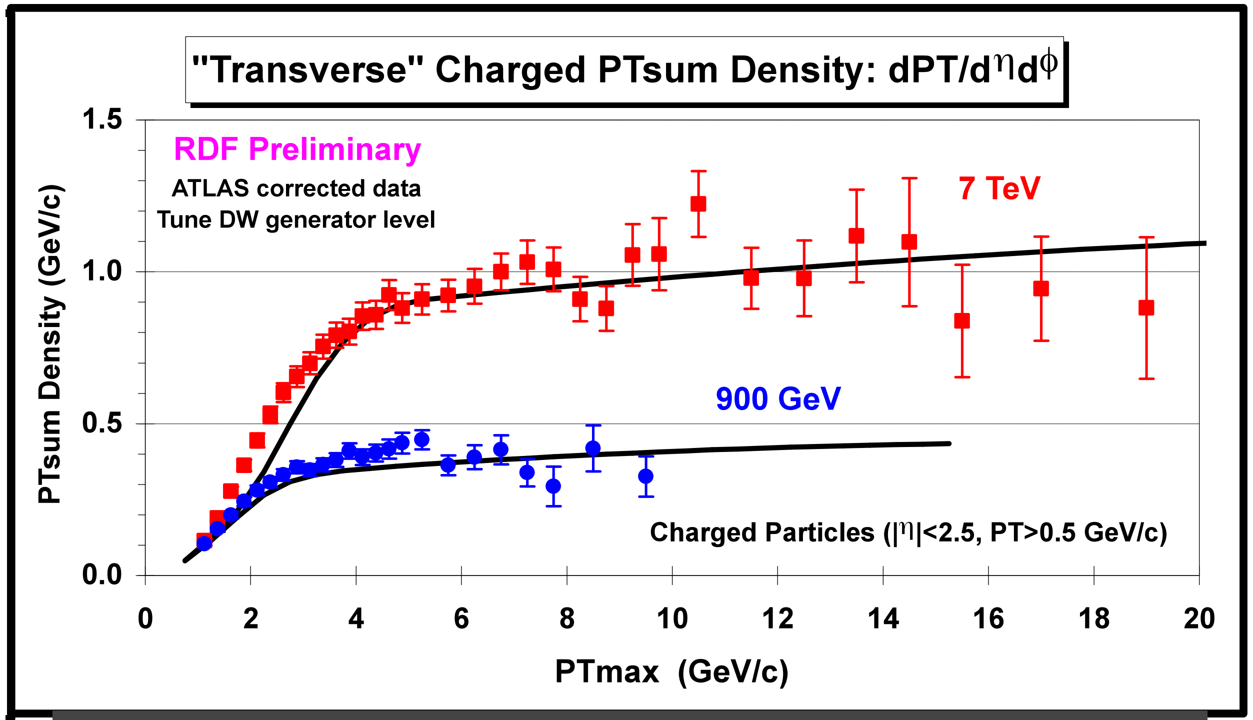
As you trigger on progressively higher p_T, the entire event increases …



… until you reach a plateau ("max-bias")

Interpreted as impact-parameter effect

Qualitatively reproduced by MPI models

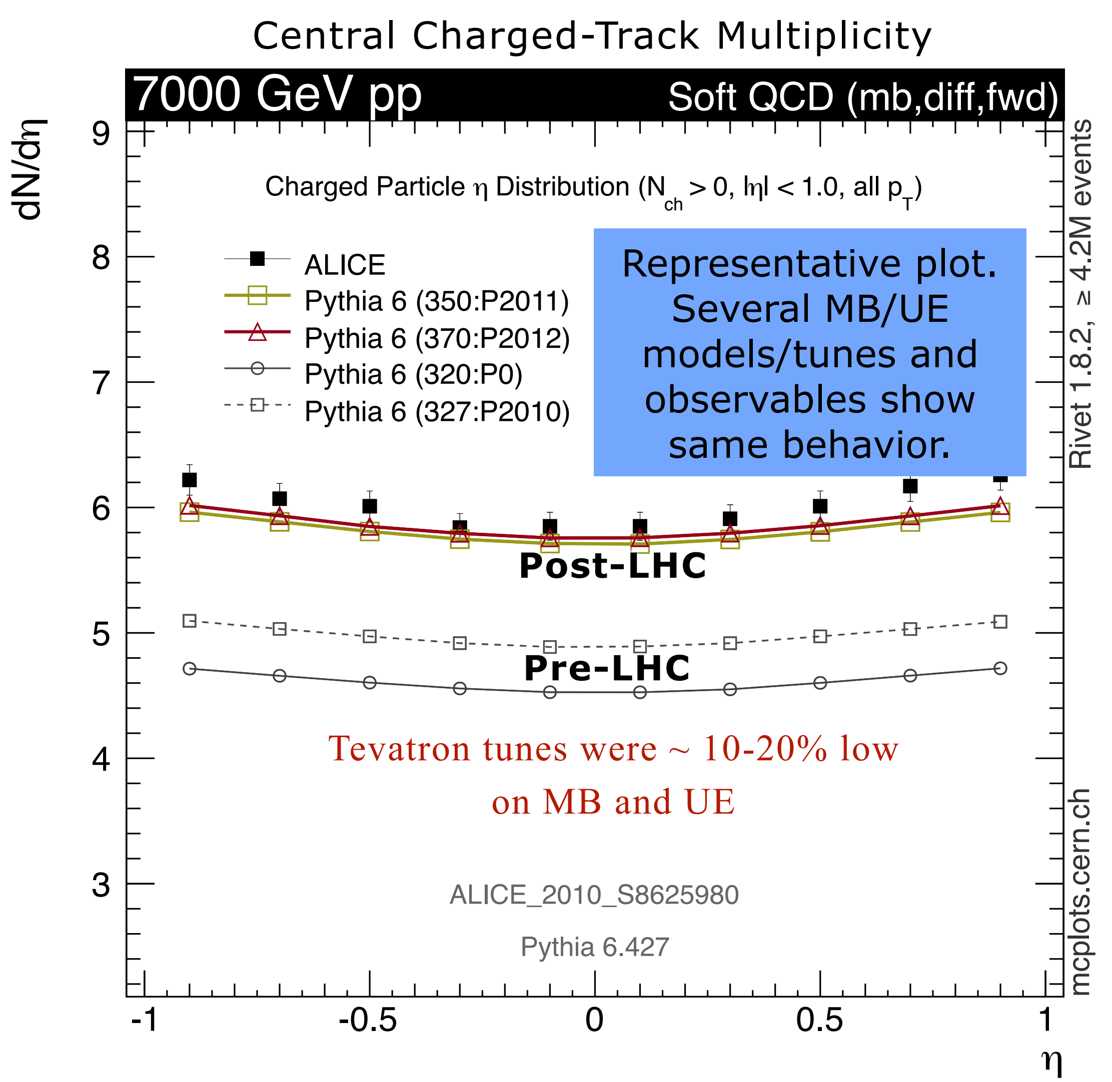


Sum(pT) Density (TRANS)

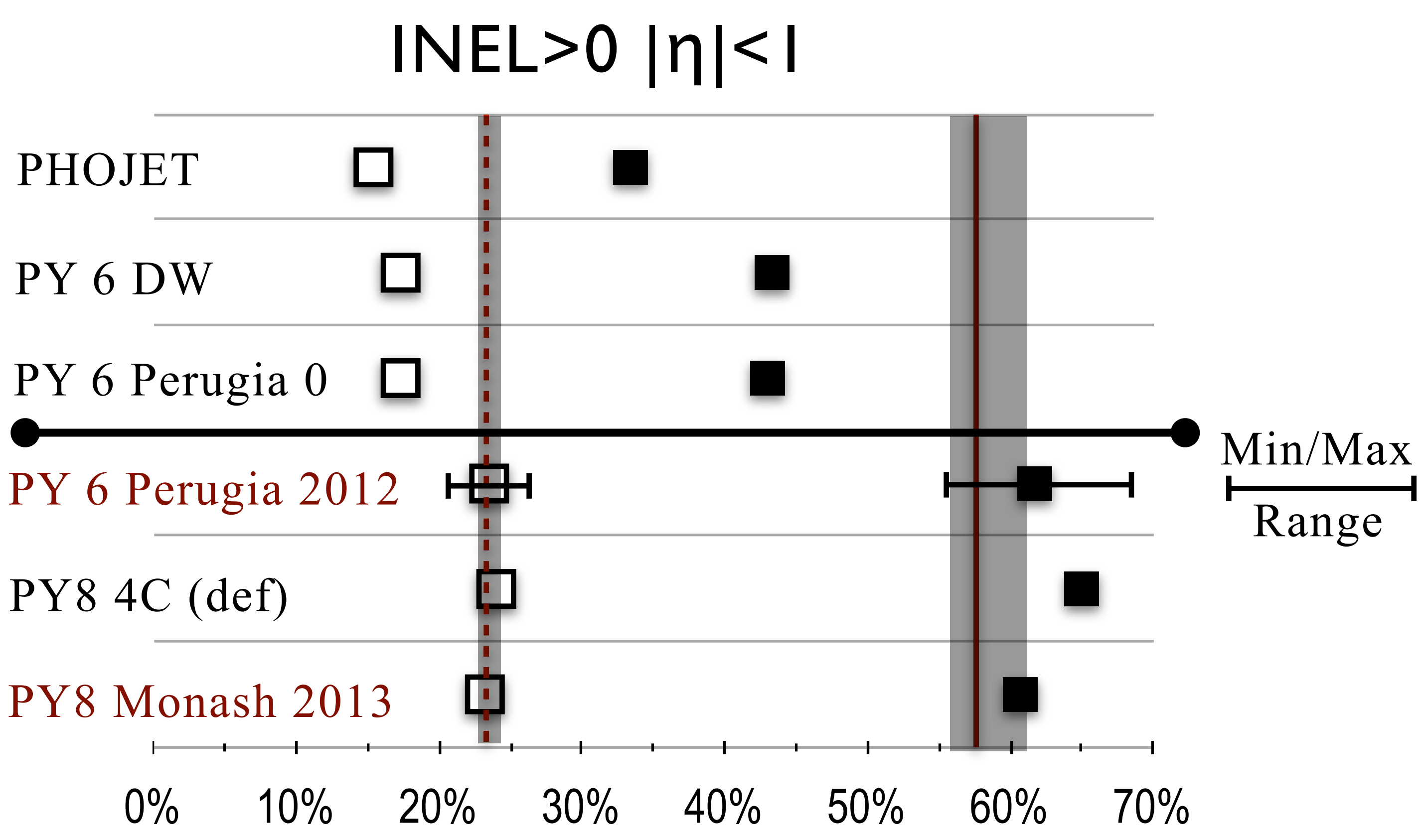
LHC from 900 to 7000 GeV - ATLAS

A note on Energy Scaling

Discovery at LHC
Min-Bias & UE are 10-20% larger than we thought
Scale a bit faster with energy
→ Be sure to use up-to-date (LHC) tunes



A 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, Plot from arXiv:1308.2813

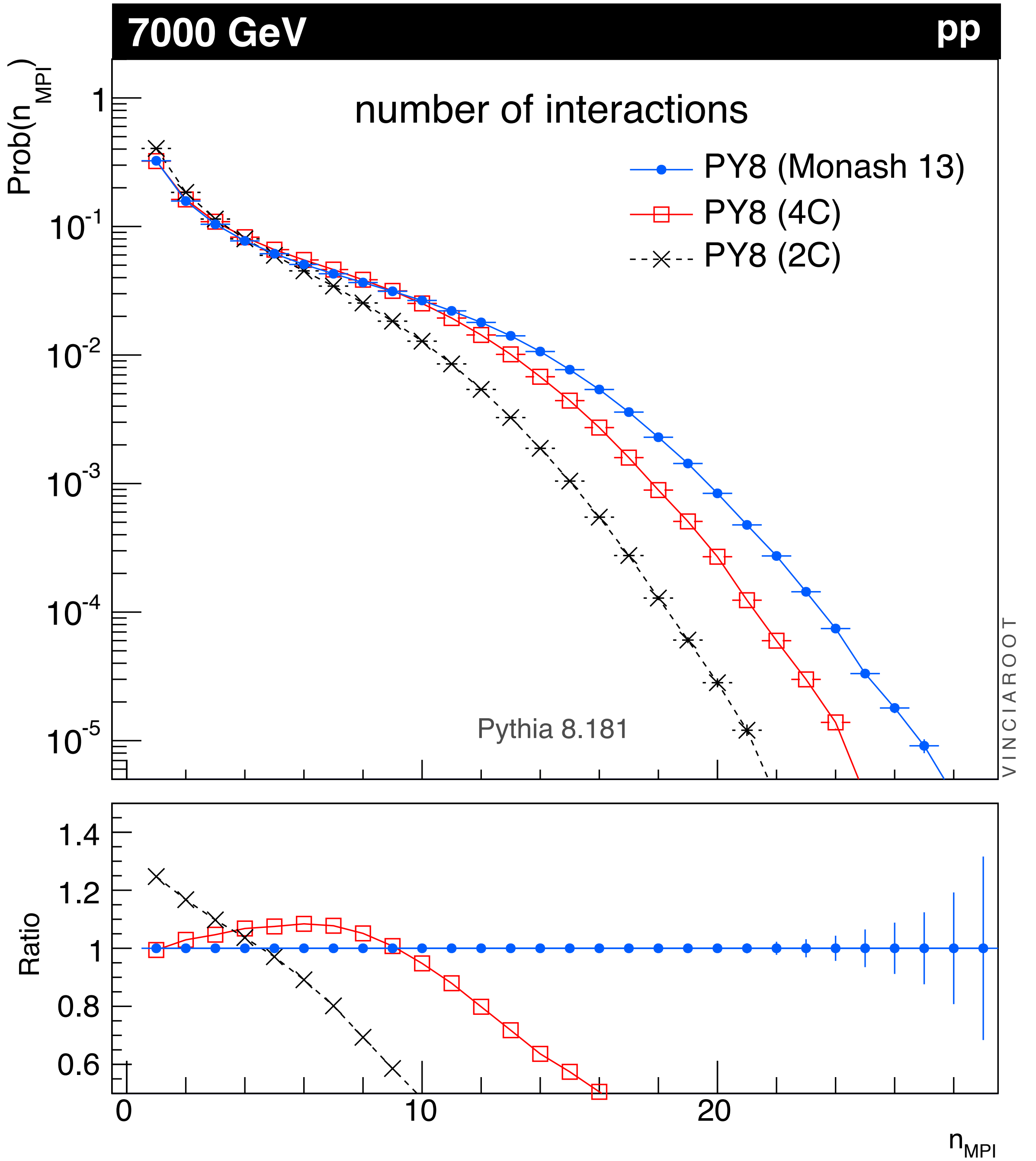
See also energy-scaling tuning study, Schulz & PS, EPJ C71 (2011) 1644

Number of MPI *

Minimum-Bias pp collisions at 7 TeV

Averaged over all pp impact parameters

(Really: averaged over all pp overlap enhancement factors)



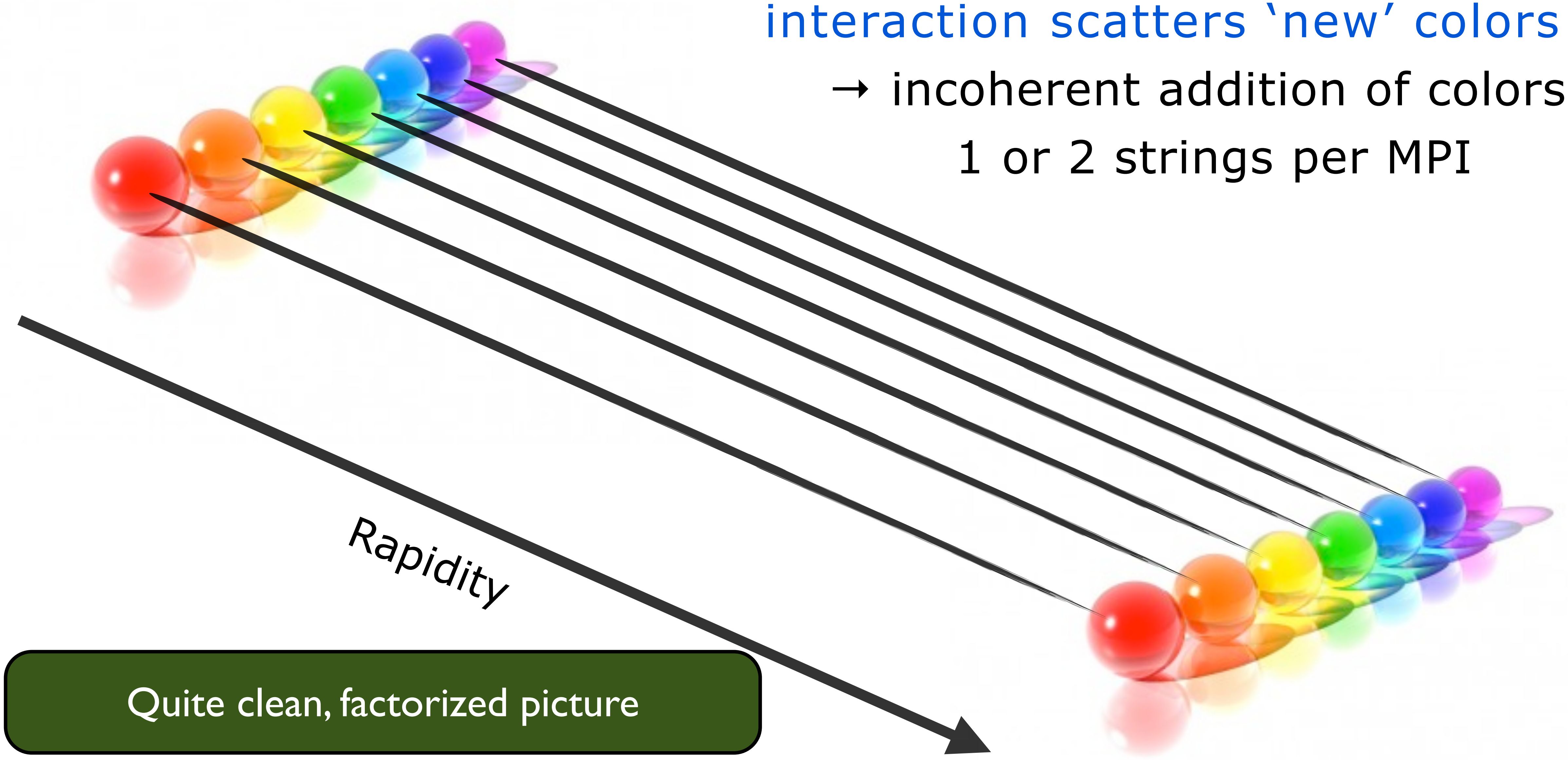
*note: can be arbitrarily soft

Color Connections: $n_{MPI} \leftrightarrow n_{Ch}$?

Leading N_C: each parton-parton interaction scatters 'new' colors

→ incoherent addition of colors

1 or 2 strings per MPI



Quite clean, factorized picture

WRONG!

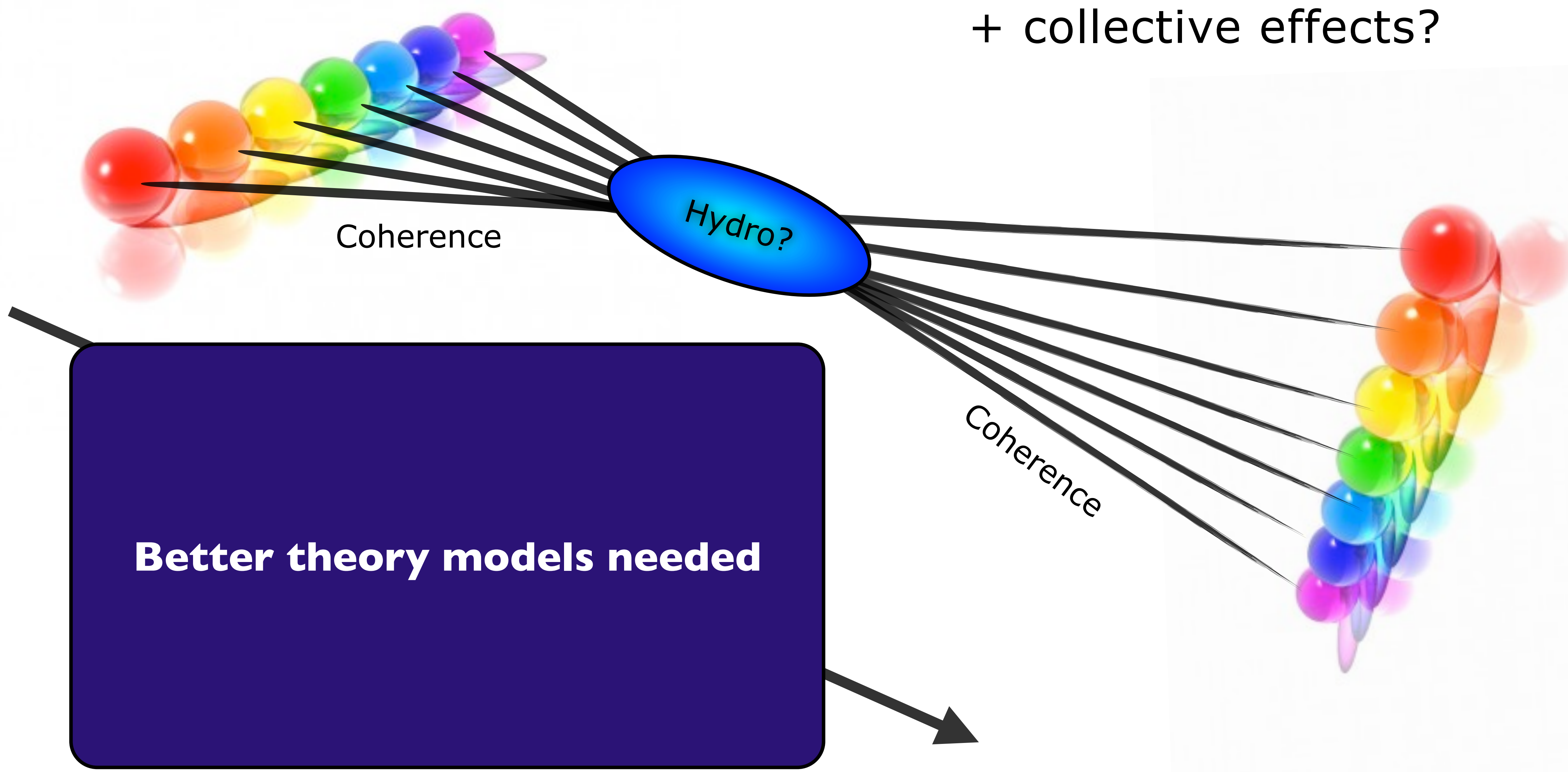
Multiplicity $\propto N_{MPI}$

Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (P.S., Wicke: Eur. Phys. J. C52 (2007) 133)
…

N_C=3: Colors add coherently

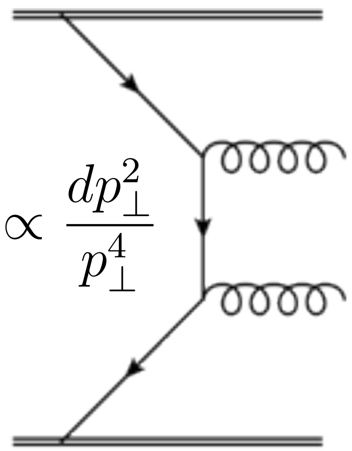
\+ collective effects?



Multiplicity $\overset{<}{\not\propto}$ N_{MPI}

MPI Models: Caveats

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

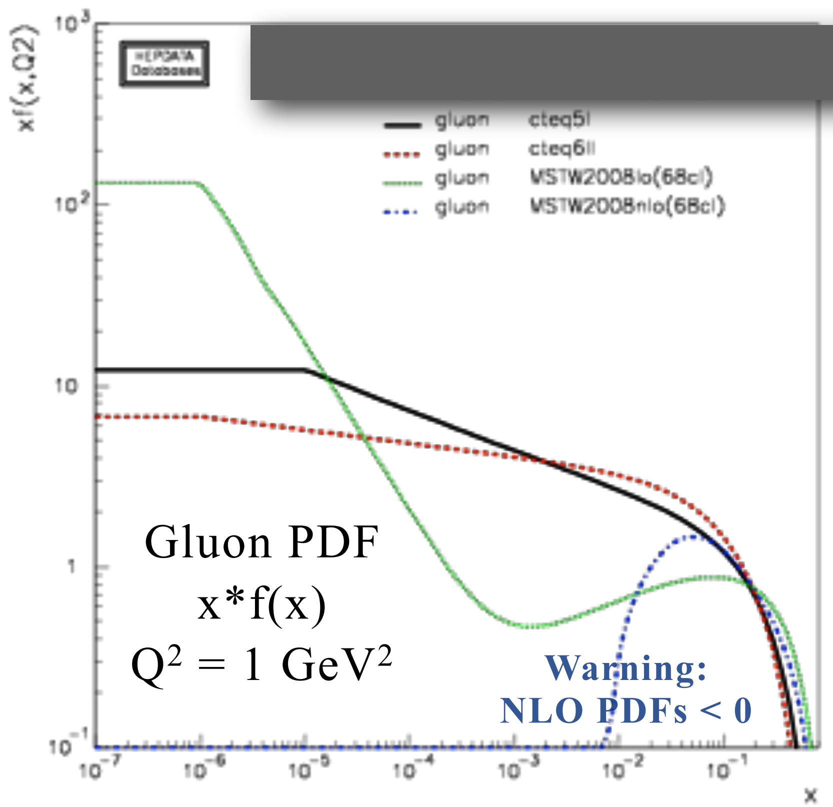
Extrapolation to soft scales delicate.

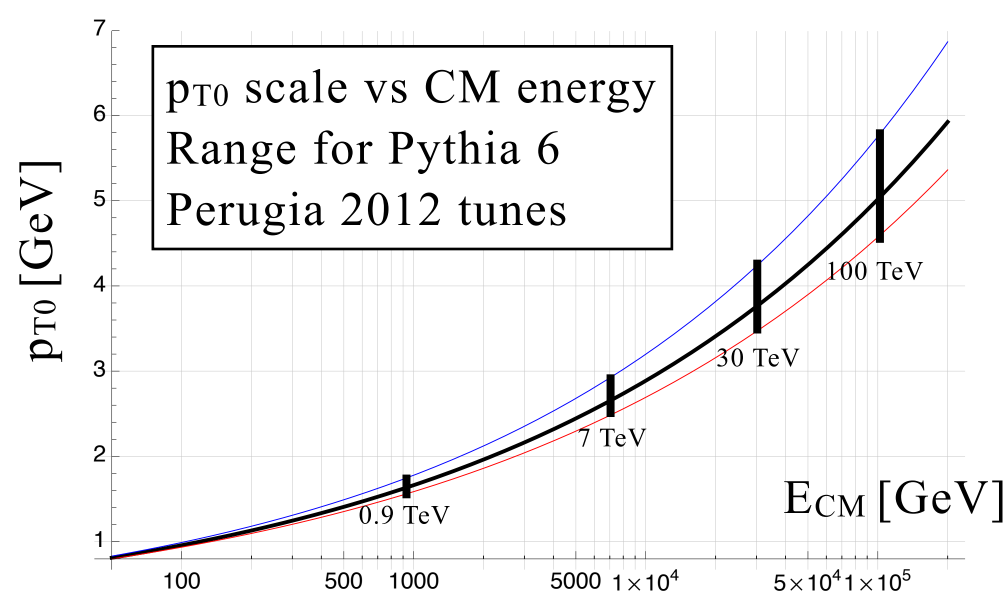
Impressive successes with MPI-based models but still far from a solved problem

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

Saturation

Poor Man's Saturation





See also Connecting hard to soft: KMR, EPJ C71 (2011) 1617 + PYTHIA "Perugia Tunes": PS, PRD82 (2010) 074018 + arXiv:1308.2813

Summary

Impact parameter plays important role in description of pp collisions

- Models incorporate variable b, with non-trivial overlap profiles
- Pedestal effect interpreted as min → max bias

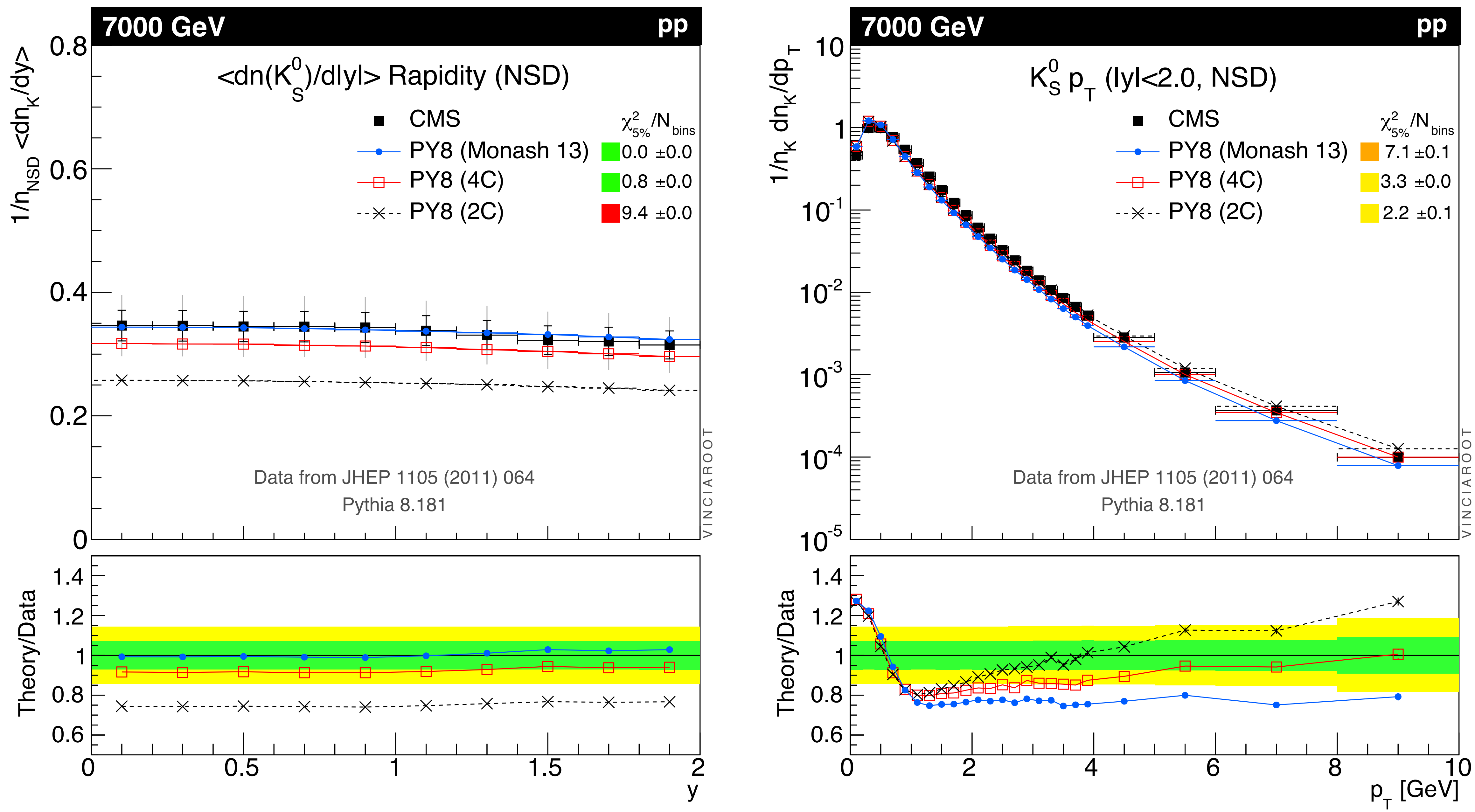
Large PDFs + Divergent partonic QCD $\sigma_{2\to2}$

- Average collisions at LHC and beyond may involve perturbatively hard scales
- "Central (or lumpy)" collisions → enhancements

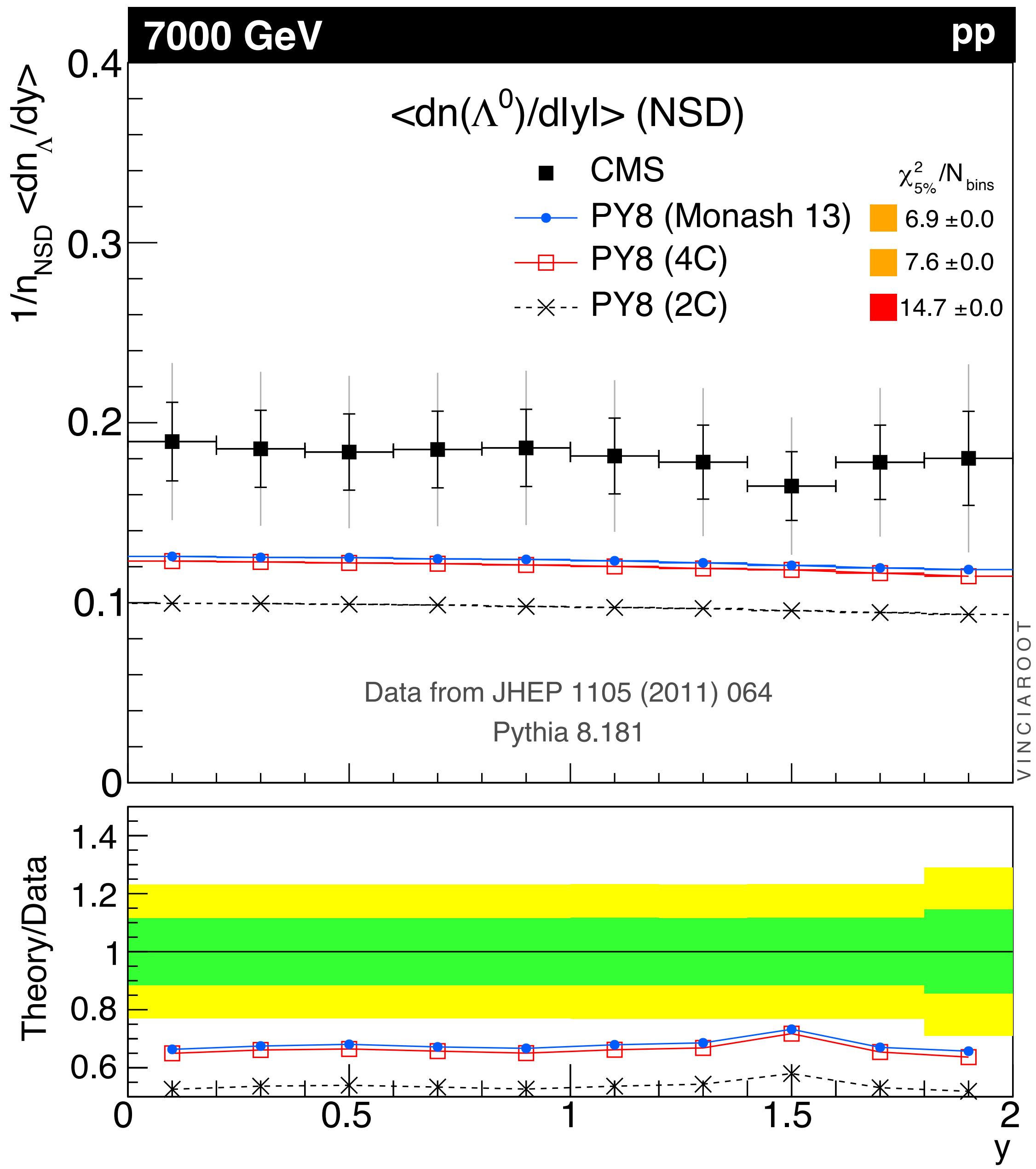
Connections between b, $\langle n_{MPI} \rangle$, and $\langle n_{Ch} \rangle$

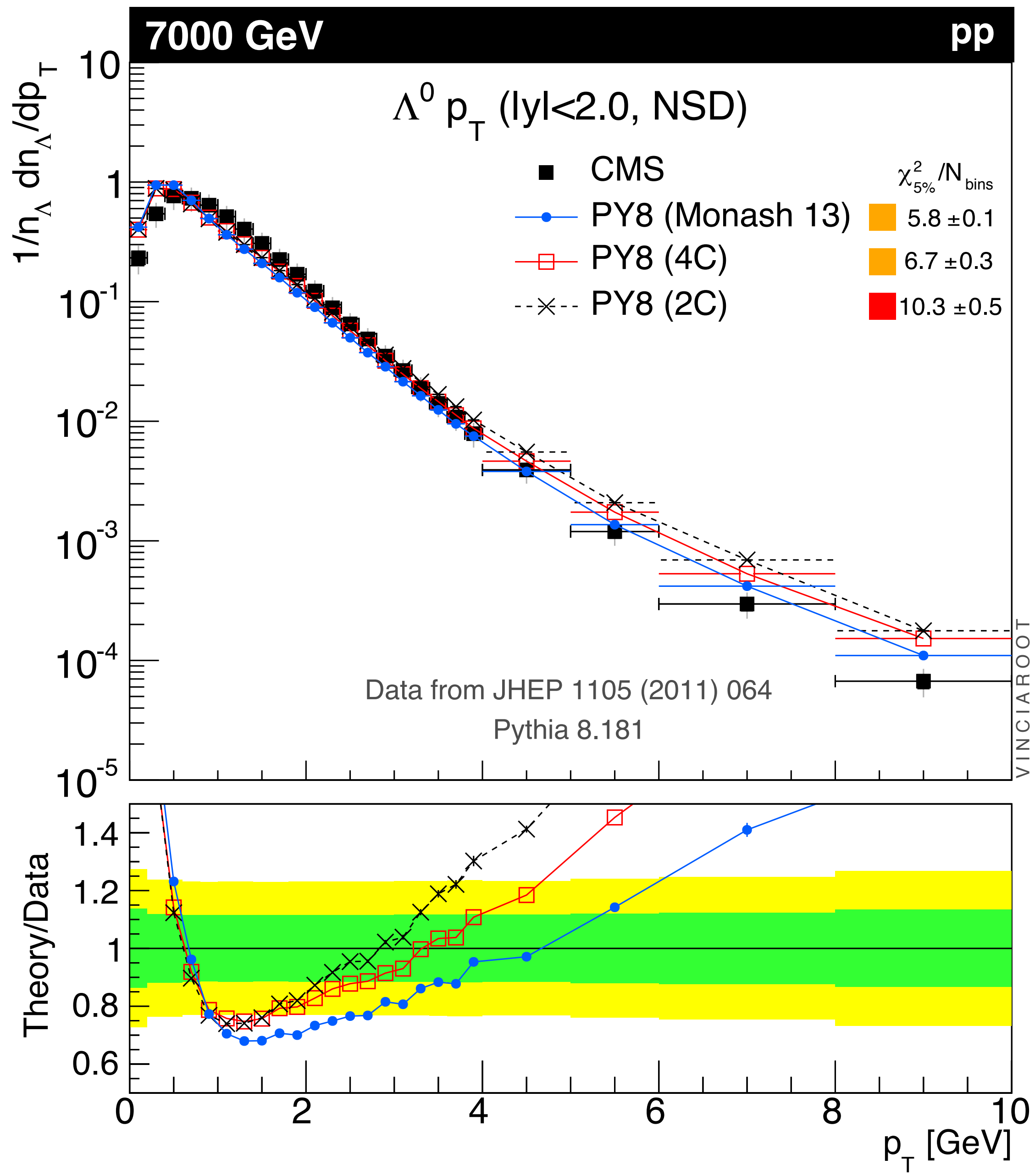
- Complicated by colour structure → hadronization
- Significant fluctuations (and uncertainties)

Strangeness: Kaons



Strangeness: Λ hyperons

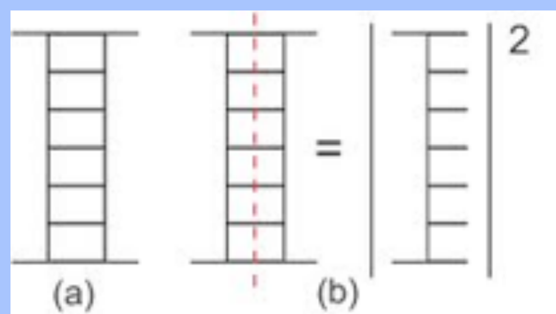




Dynamical Models of Soft QCD

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

A — Regge Theory



Optical Theorem

+ Eikonal multi-Pomeron exchanges

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

Froissart-Martin Bound

Cut Pomerons → Flux Tubes (strings)

Uncut Pomerons → Elastic (& eikonalization)

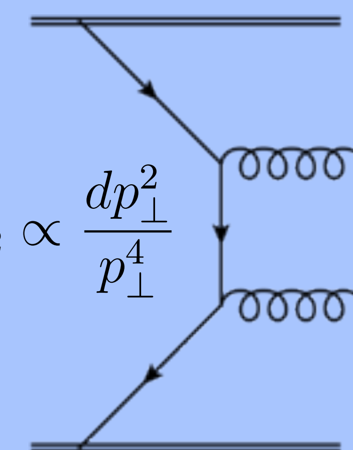
Cuts unify treatment of all soft processes

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 $d\sigma$ at low p_{T0} ~ few GeV

Screening/Saturation → energy-dependent p_{T0}

Total cross sections from Regge Theory

(e.g., Donnachie-Landshoff + Parametrizations)

+ "Mixed"

E.g., QGSJET, SIBYLL

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

E.g., **PYTHIA**, HERWIG, SHERPA

Diffraction (in PYTHIA 8)

Navin, arXiv: 1005.3894

Diffractive Cross Section Formulæ:

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

$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\, \beta_{A\mathbb{P}}\, \beta_{B\mathbb{P}}\, \frac{1}{M_1^2}\, \frac{1}{M_2^2}\, \exp(B_{dd}t)\, F_{dd}\,.$$

$M_X \leq 10$ GeV (and for all masses in PYTHIA 6)

Represent M_X as longitudinal string → Fragment

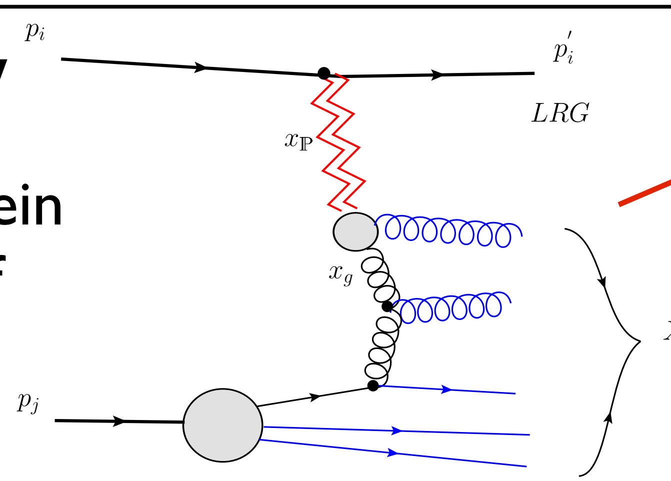
→ Typical string-fragmentation spectrum

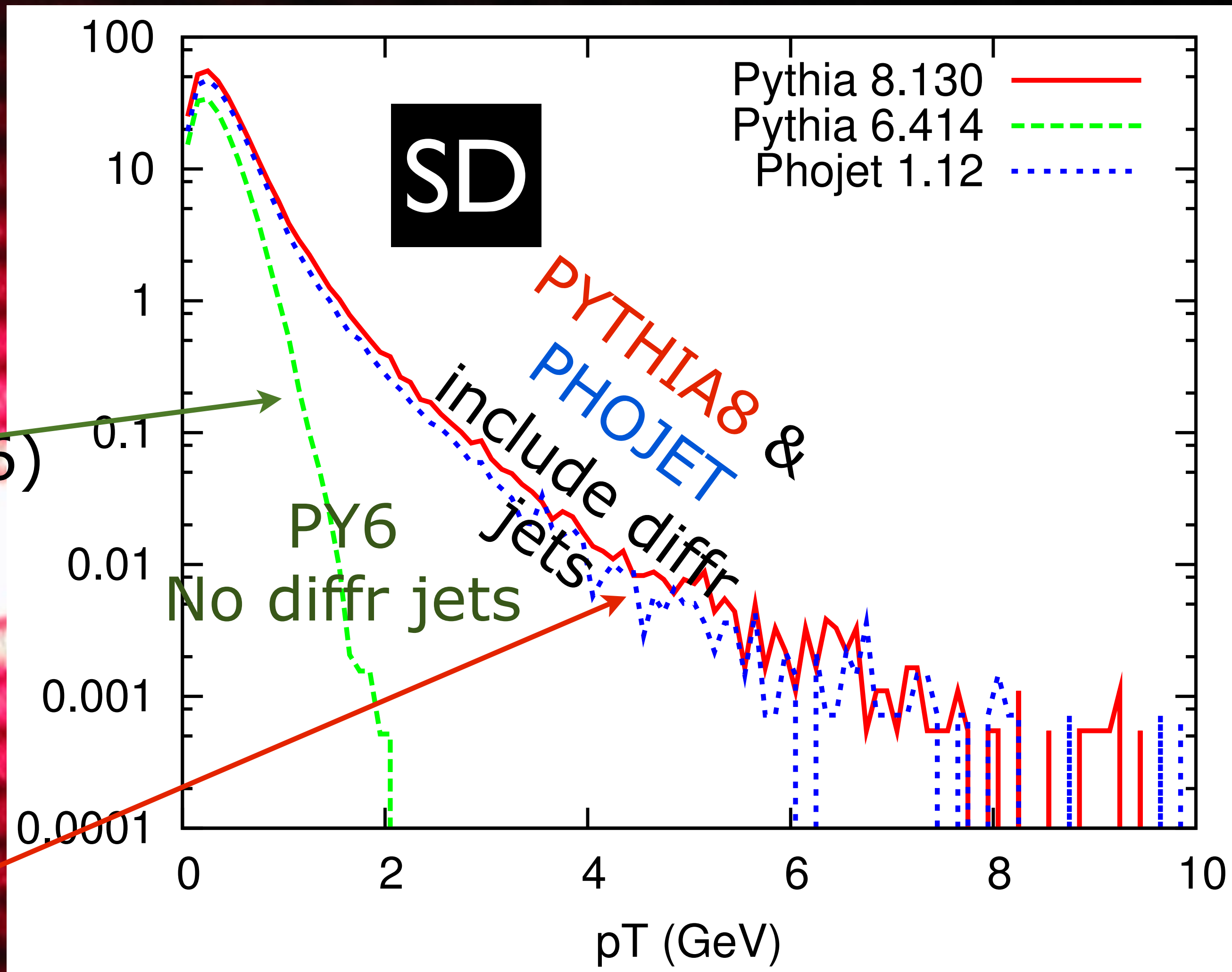
Partonic Substructure in Pomeron:

$M_X > 10$ GeV

Follows the Ingelman-Schlein approach of Pompyt

PYTHIA 8





system (→ UE in Diffraction)

+ NEW! Central Diffraction (→ fully contained gap-X-gap events)

+ NEW! Alternative Min-Bias Rockefeller (MBR)

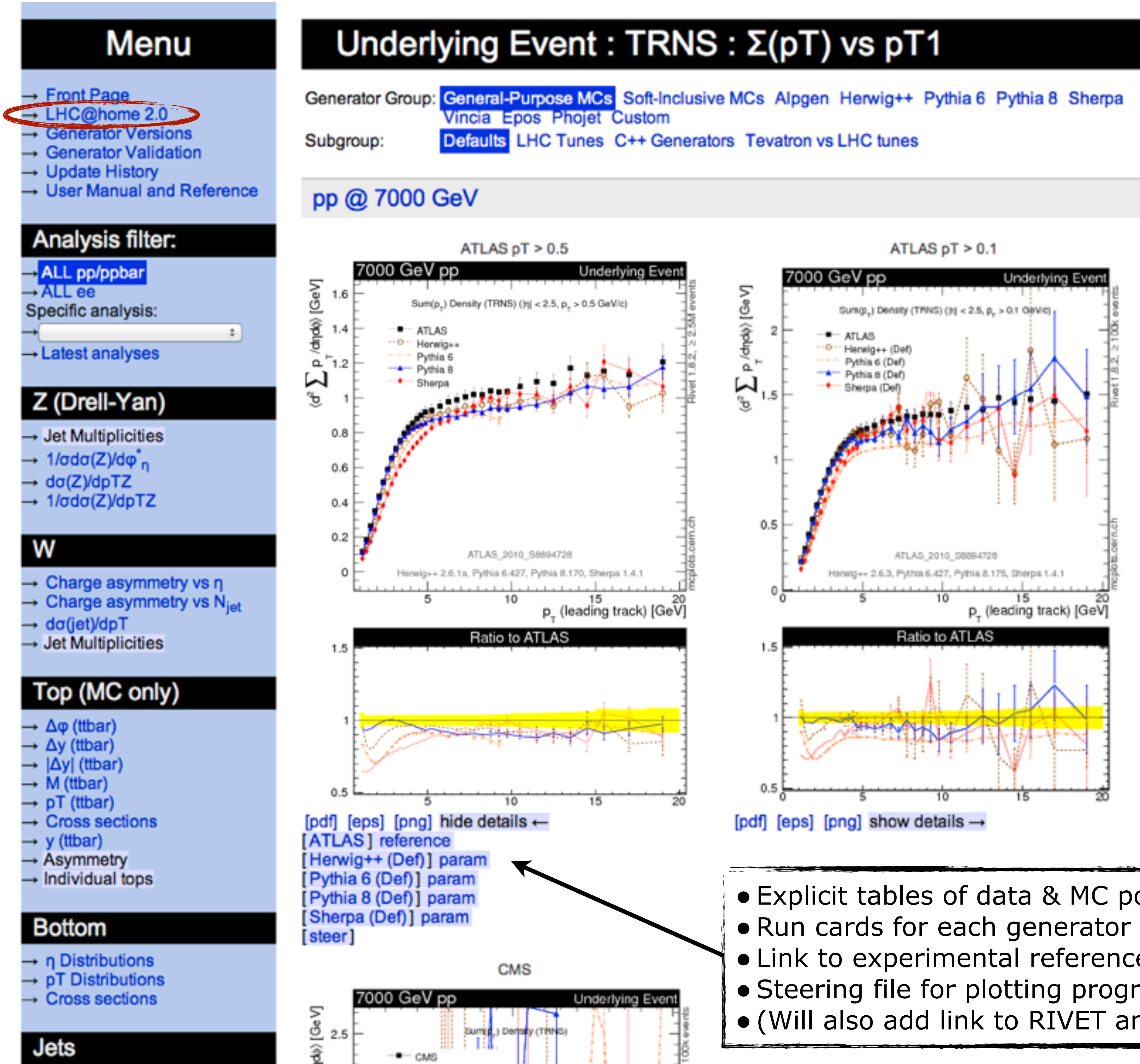
Choice between 5 Pomeron PDFs.

Free parameter $\sigma_{\mathbb{P}p}$ needed to fix $\langle n_{\text{interactions}}\rangle = \sigma_{\text{jet}}/\sigma_{\mathbb{P}p}$.

+ Recently Central Diffraction!

Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}p}$.

mcplots.cern.ch



- Explicit tables of data & MC points
- Run cards for each generator
- Link to experimental reference paper
- Steering file for plotting program
- (Will also add link to RIVET analysis)

1: A Simple Model

The minimal model incorporating single-parton factorization, perturbative unitarity, and energy-and-momentum conservation

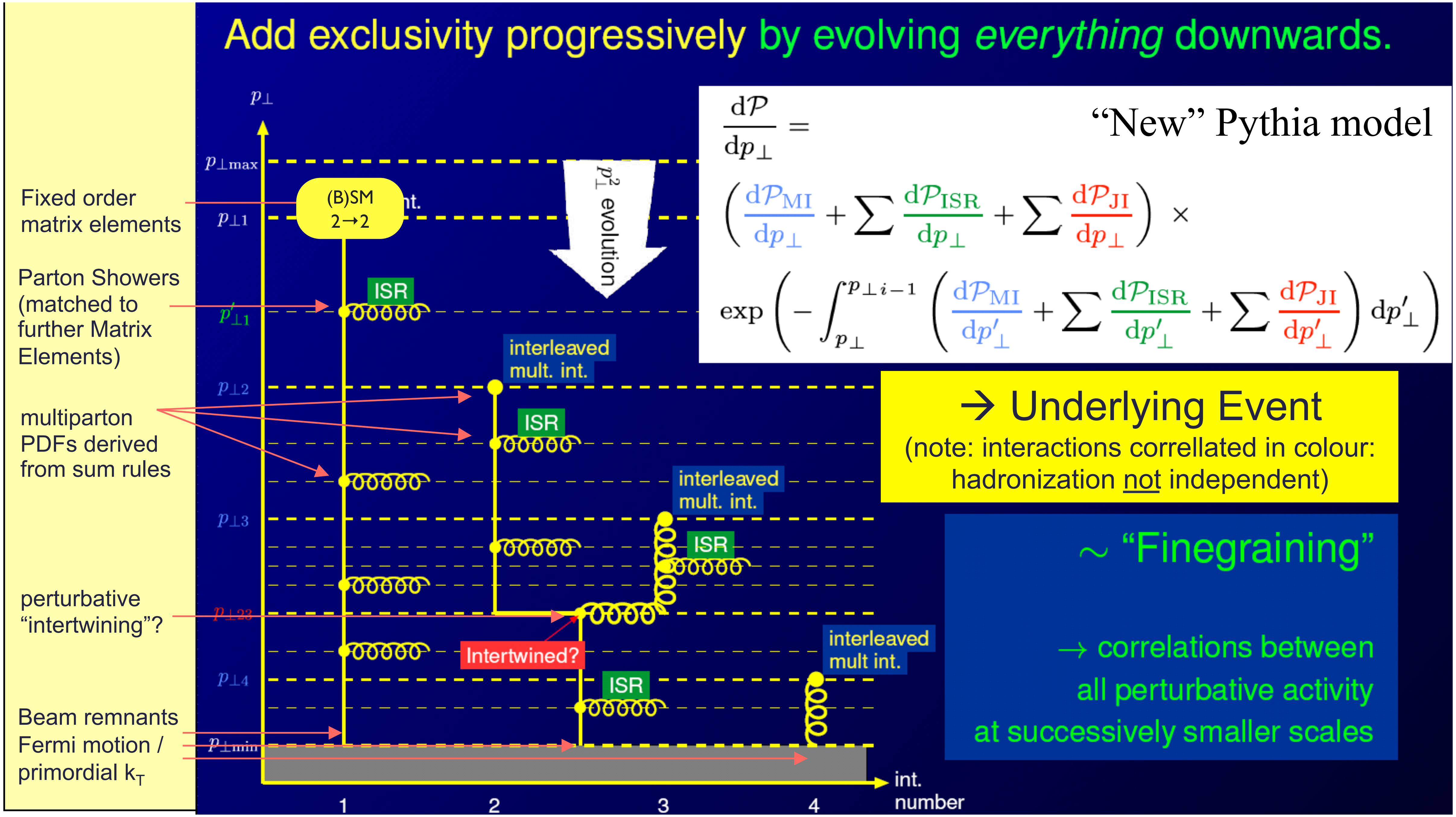
$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section — Hadron-Hadron Cross Section

1. Choose $p_{T\min}$ cutoff
   - = main tuning parameter
2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   - Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton
3. Generate n parton-parton interactions (pQCD 2→2)
   - Veto if total beam momentum exceeded → overall (E,p) cons
4. Add impact-parameter dependence → $<n> = <n>(b)$
   - Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$ (Ordinary CTEQ, MSTW, NNPDF, …)
   - b distribution ∝ EM form factor → **JIMMY model** Butterworth, Forshaw, Seymour Z.Phys. C72 (1996) 637
   - Constant of proportionality = second main tuning parameter
5. Add separate class of "soft" (zero-p_T) interactions representing interactions with $p_T < p_{T\min}$ and require $\sigma_{\rm soft} + \sigma_{\rm hard} = \sigma_{\rm tot}$
   - → **Herwig++ model** Bähr et al, arXiv:0905.4671

2: Interleaved Evolution

Sjöstrand & Skands, JHEP 0403 (2004) 053; EPJ C39 (2005) 129

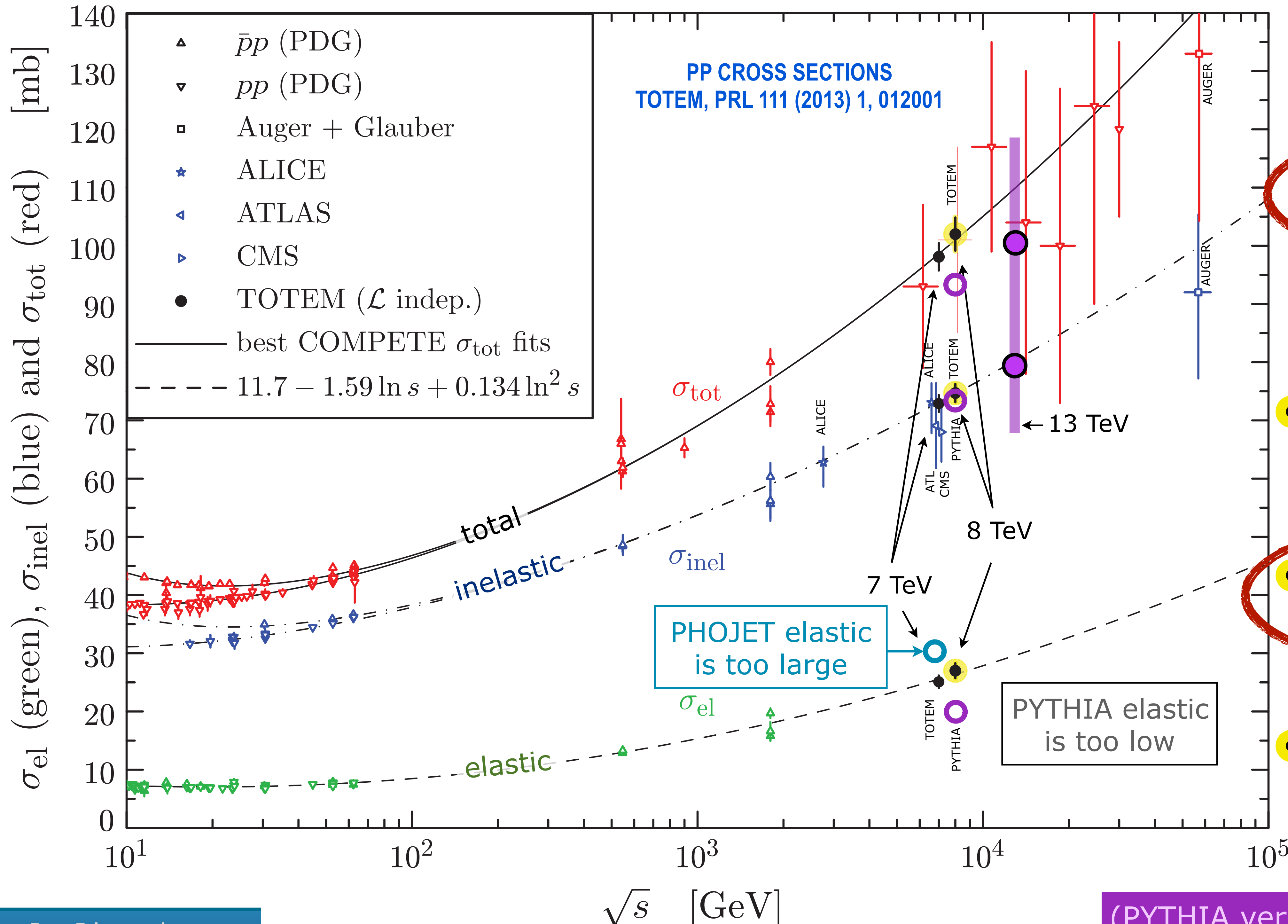


Also available for Pomeron-Proton collisions since Pythia 8.165

Cross sections

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

Donnachie-Landshoff Froissart-Martin Bound



$\sigma_{\rm tot}(13\text{ TeV}) \sim 110 \pm 6$ mb

PYTHIA: 100 mb

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

PYTHIA: 78 mb

(2.9%)

$\sigma_{\rm tot}(8\text{ TeV}) = 101 \pm 2.9$ mb

PYTHIA: 93 mb

(2.3%)

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

PYTHIA: 73 mb

(5.1%)

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

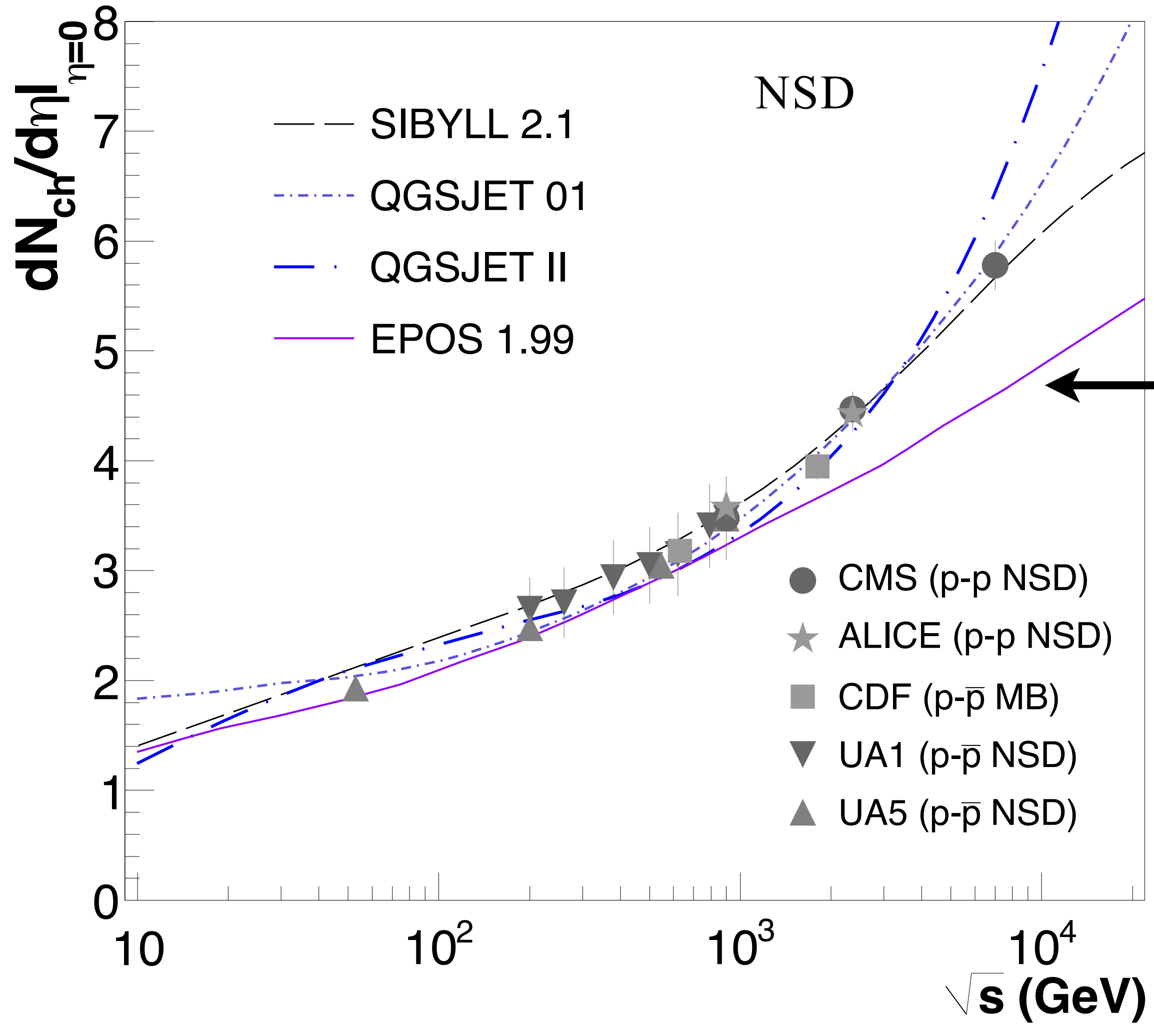
PYTHIA: 20 mb

(PYTHIA versions: 6.4.28 & 8.1.80)

Scaling of Multiplicities

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

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



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