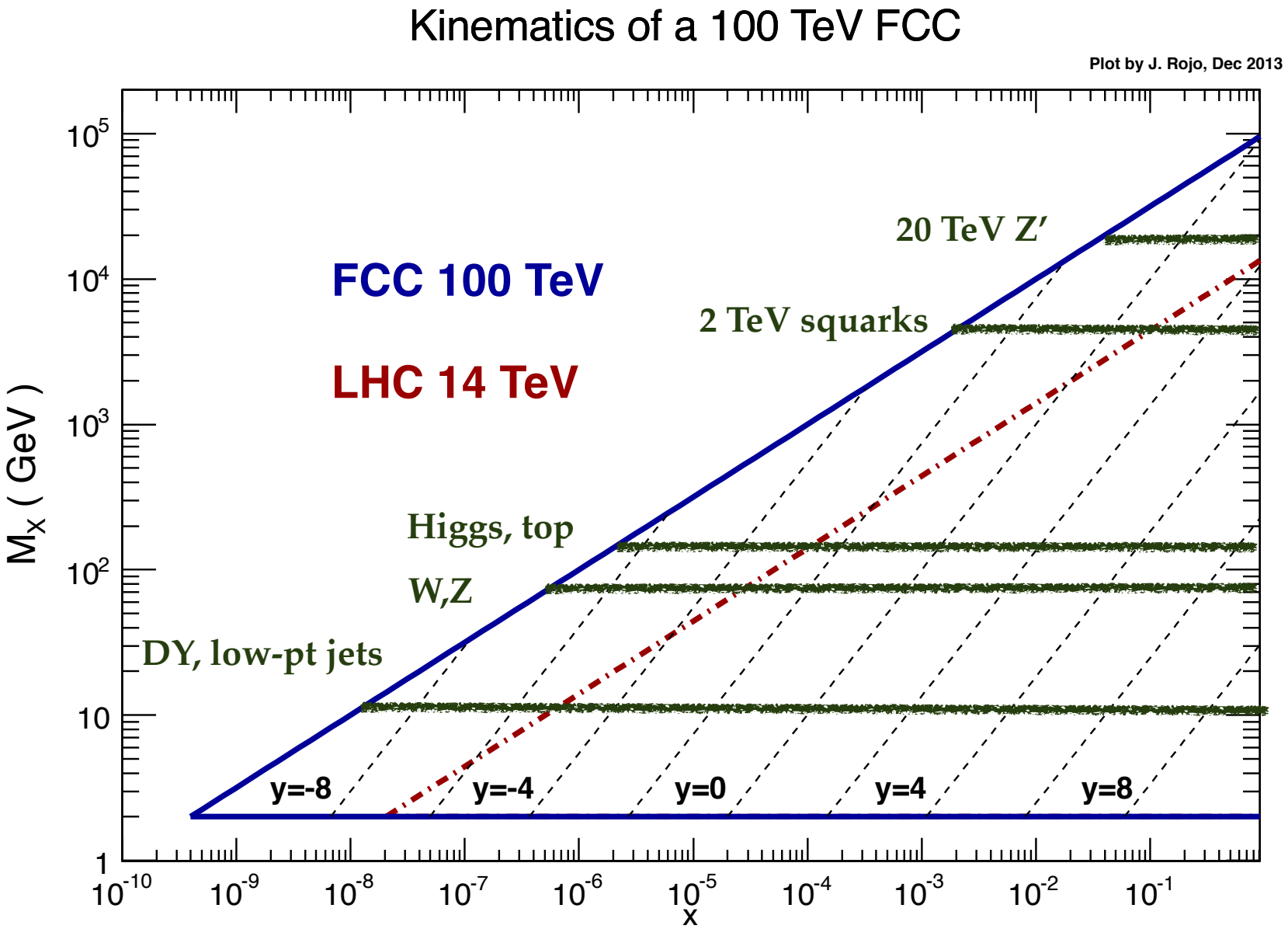
Soft (& some hard) Physics at 100 TeV

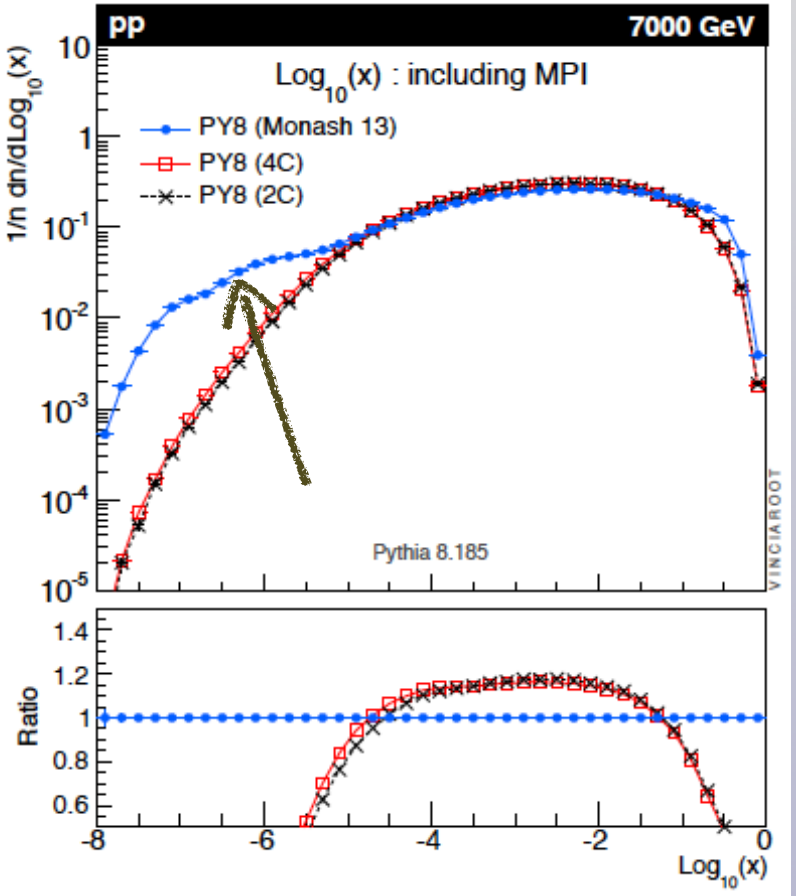
Torbjörn Sjöstrand

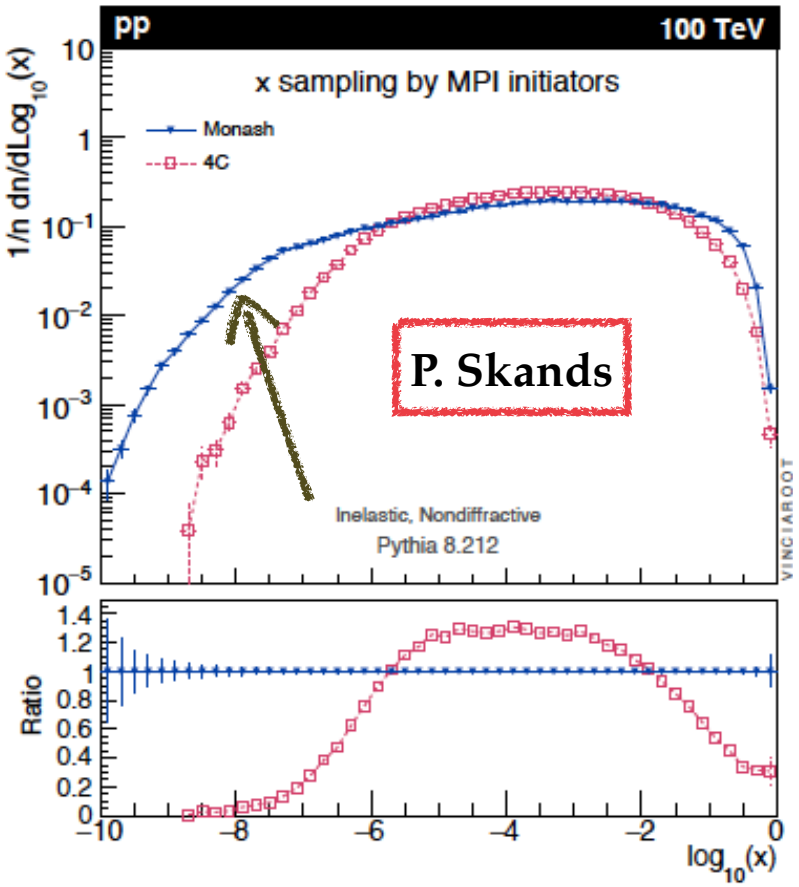
Mainly taken from presentations at
"QCD, EW and tools at 100 TeV",
CERN, 7–9 October 2015,
`https://indico.cern.ch/event/437912`
(report on arXiv within next few days)
+ some slides by Jesper Roy Christiansen

The kinematical range at 100 TeV (Juan Rojo)



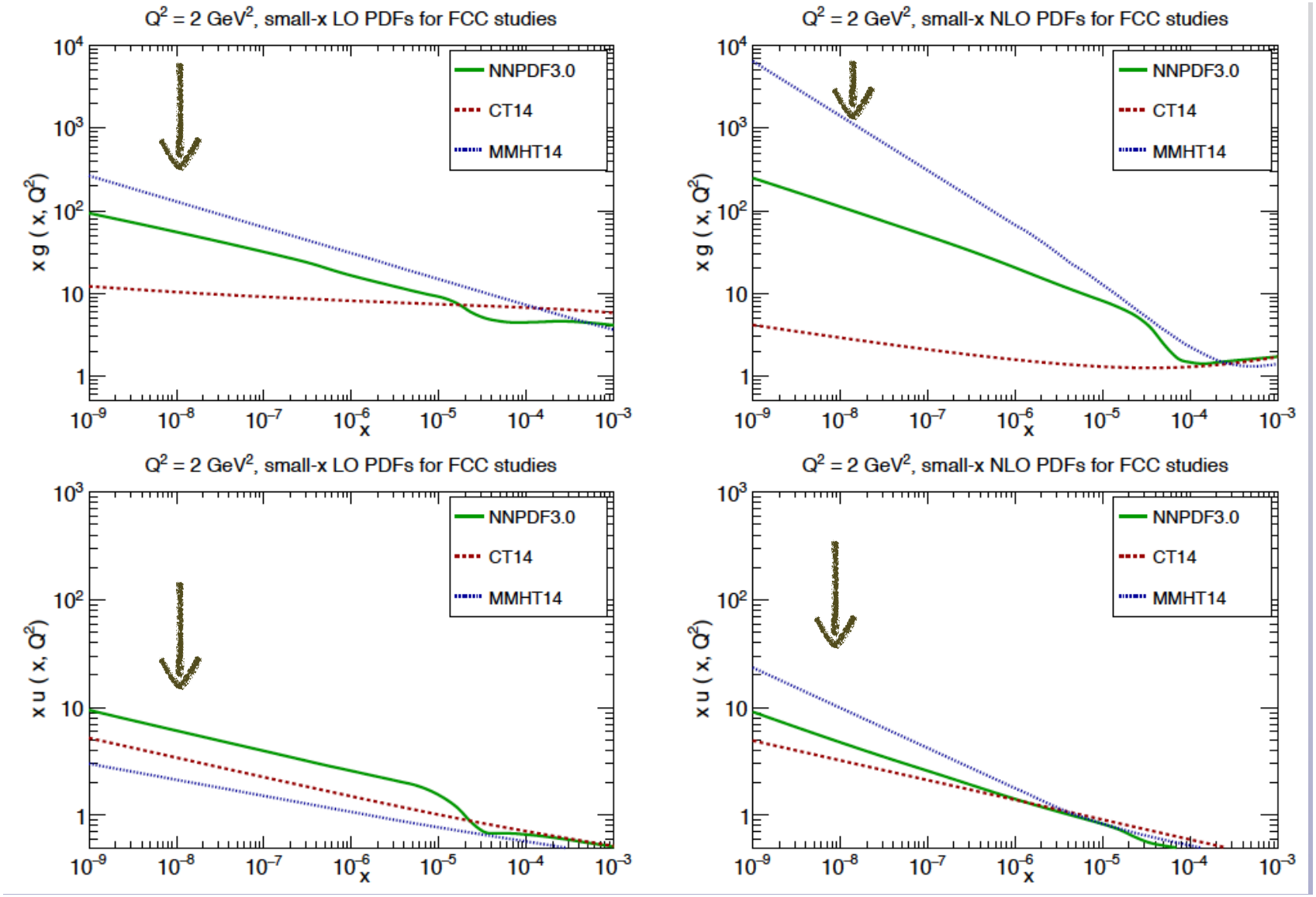
The role of small x (Juan Rojo)





- Small-x, small-Q PDFs are required for the description of **soft and semi-hard physics in MC generators**. Can be quantified by **sampling of Bjorken-x in Pythia8** at 7 and 100 TeV
- At the **LHC, small-x PDFs** are required down to $\mathbf{10^{-6}}$ while at the **FCC** we require $\mathbf{10^{-8}}$

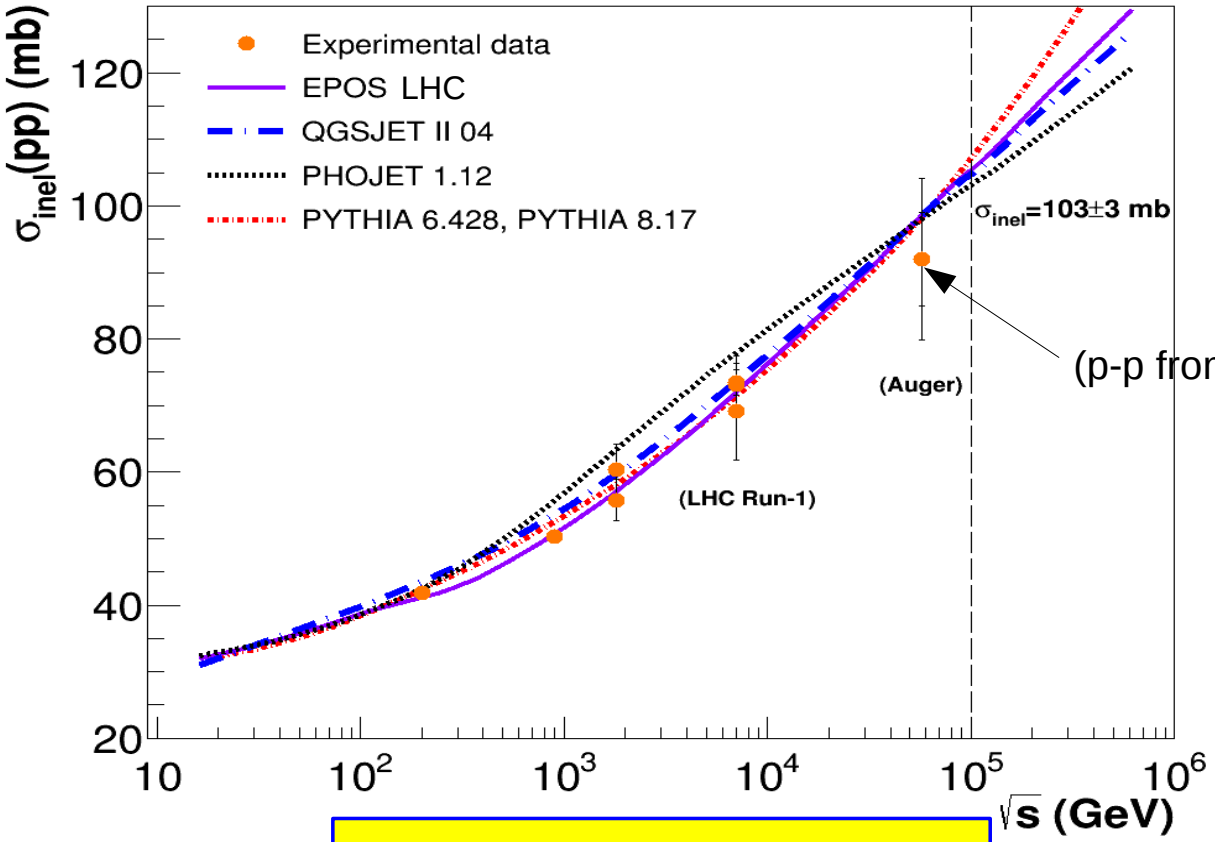
Small x at small Q^2 (Juan Rojo)



Inelastic cross section (David d'Enterria)

$\sigma_{\rm tot} = \sigma_{\rm elastic} + \sigma_{\rm inel}$

- Non-computable from QCD Lagrangian (lattice?), but constrained by fundamental QM relations: Froisart bound, optical th., dispersion relations
- Similar MC predictions of $\sigma_{\rm inel}$ evolution, in agreement with LHC data:
  (Interestingly, deviations seem to appear at energies *above* 100 TeV)



(p-p from p-Air at 57 TeV)

- Models indicate: **$\sigma_{\rm inel}$ (100 TeV) = 103 ± 3 mb**

Diffraction and non-diffraction (Peter Skands)

Inelastic Cross Section = ND + SD + DD (+CD)

$$\sigma_{\mathrm{ND}}^{\mathrm{pp}}(s) \;=\; \sigma_{\mathrm{INEL}}^{\mathrm{pp}}(s) - \int \left(\mathrm{d}\sigma_{\mathrm{SD}}^{\mathrm{pp}\to X\mathrm{p}}(s) + \mathrm{d}\sigma_{\mathrm{SD}}^{\mathrm{pp}\to \mathrm{p}X}(s) + \mathrm{d}\sigma_{\mathrm{DD}}^{\mathrm{pp}}(s) + \mathrm{d}\sigma_{\mathrm{CD}}^{\mathrm{pp}}(s) \right)$$

Can in principle interfere

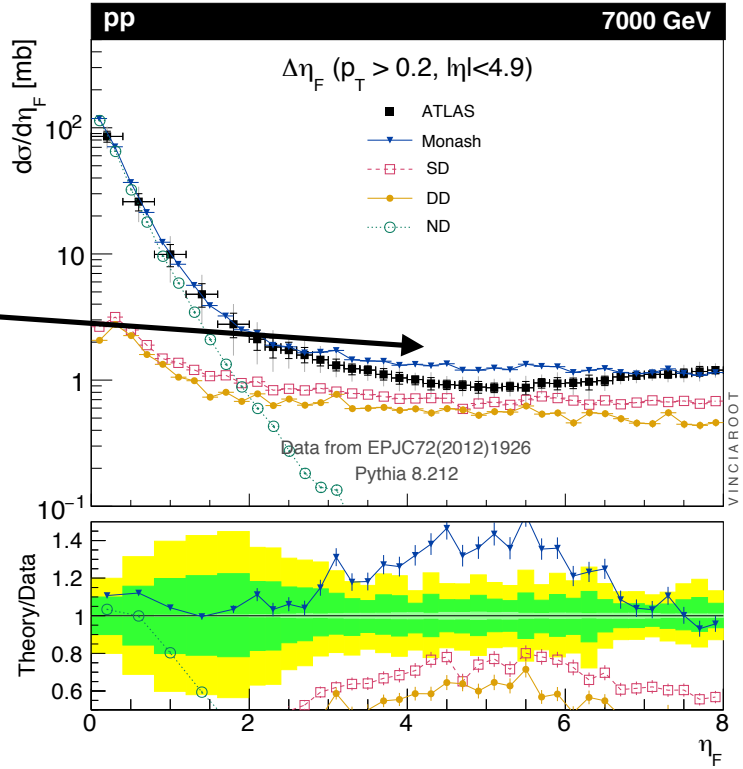
➜ model-dependent classification

Define physical observables

(large gaps, identified protons, …)

Too many large-gap events

Diffractive parameters in need of updating.

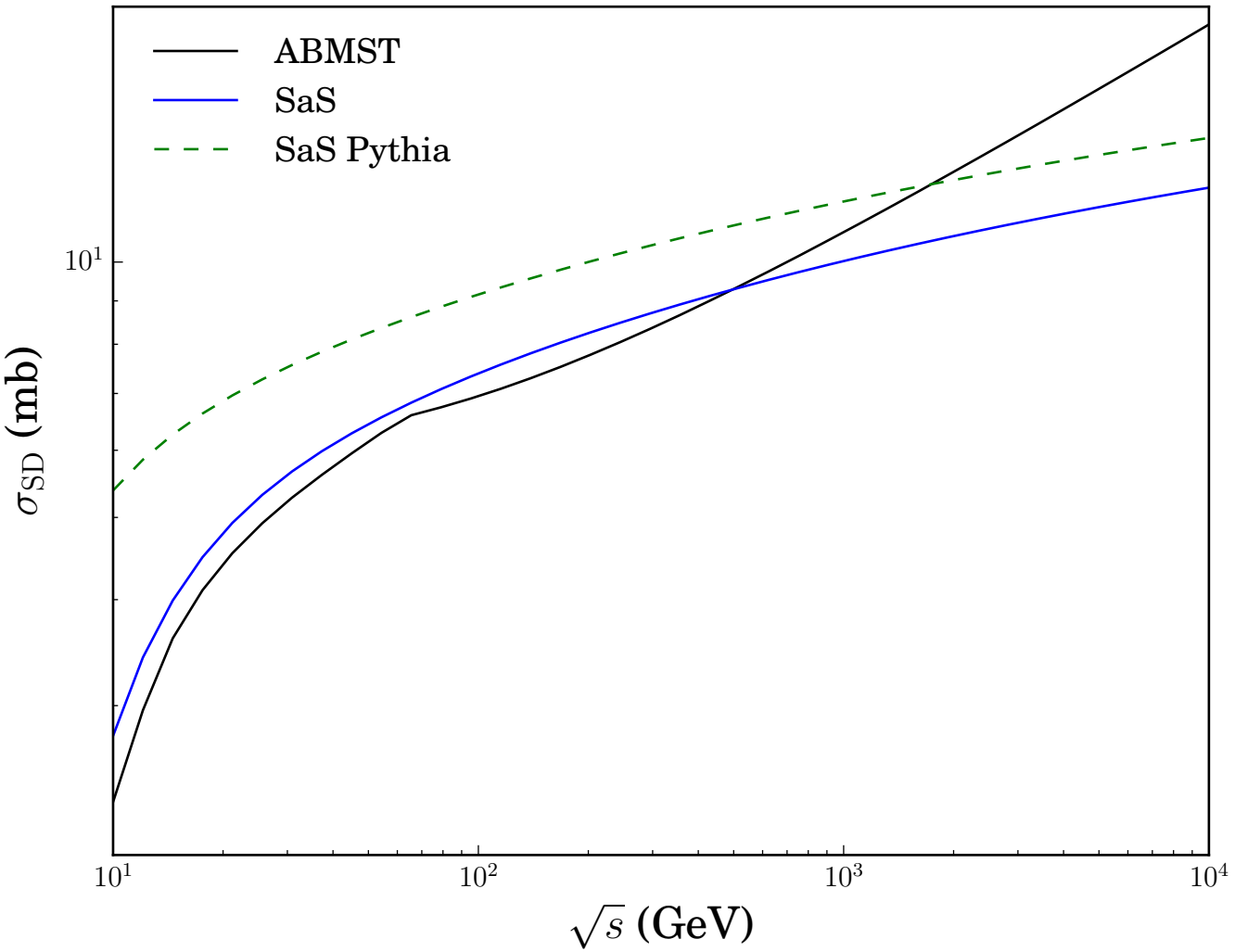


Spectra: 5 different possibilities. Default is Schuler-Sjöstrand:

$$\frac{\mathrm{d}\sigma_{\mathrm{SD}}^{\mathrm{pp}\to X\mathrm{p}}(s)}{\mathrm{d}t\,\mathrm{d}M_X^2} \;=\; \frac{g_{3\mathbb{P}}}{16\pi}\frac{\beta_{\mathrm{p}\mathbb{P}}^3}{M_X^2}\,F_{\mathrm{SD}}(M_X)\,\exp\left(B_{\mathrm{SD}}^{X\mathrm{p}}\,t\right)\;,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{DD}}^{\mathrm{pp}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} \;=\; \frac{g_{3\mathbb{P}}^2}{16\pi}\frac{\beta_{\mathrm{p}\mathbb{P}}^2}{M_1^2 M_2^2}\,F_{\mathrm{DD}}(M_1,M_2)\,\exp\left(B_{\mathrm{DD}}\,t\right)$$

Single diffractive cross section (Christine Rasmussen)



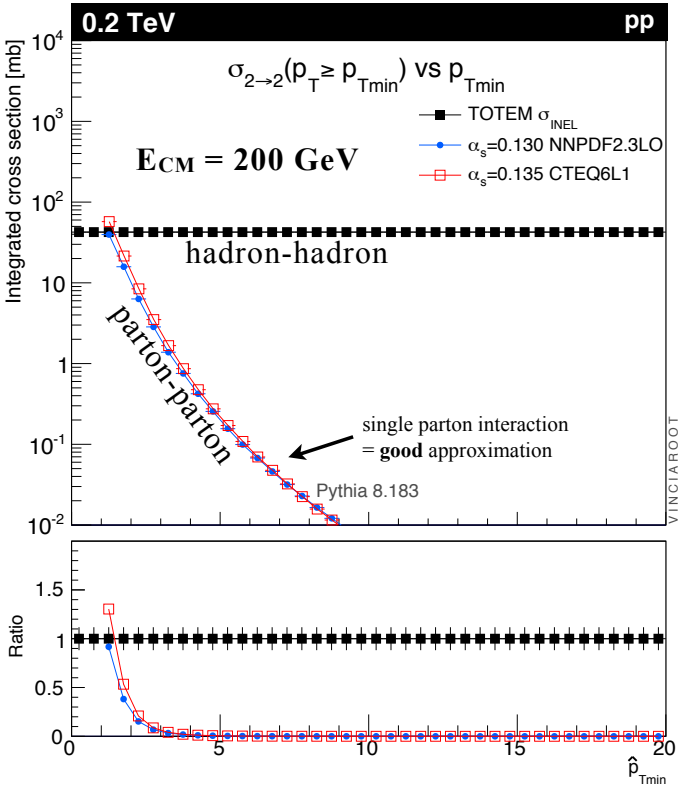
solid curves: $M_X^2/s < 0.05$, dashed all diffraction

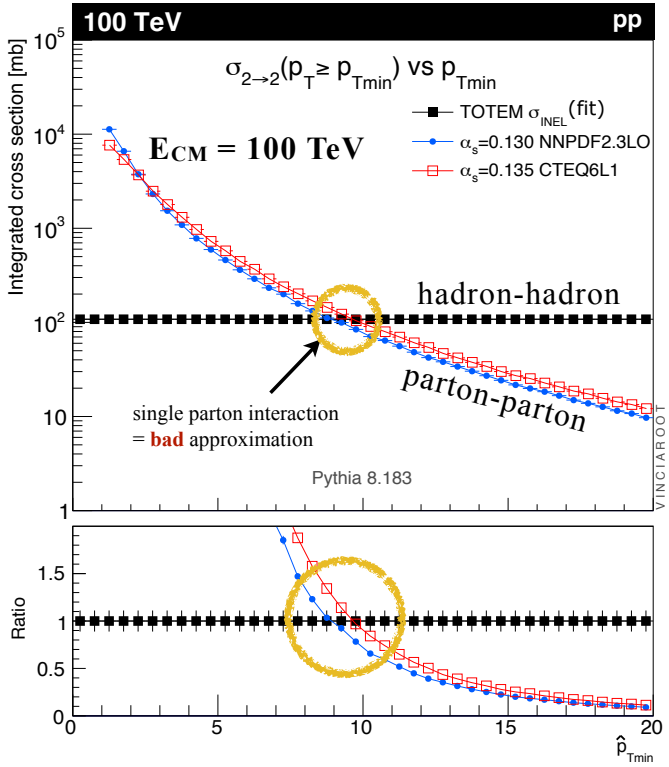
More on this tomorrow!

QCD jet cross section (Peter Skands)

Consider the inclusive-jet cross section in QCD

At LO = perturbative parton-parton (2→2) QCD cross section (tree-level)





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

Modelling of MPI in PYTHIA (Peter Skands)

Interleaved Evolution (FSR + ISR + MPI)

Perturbative MPI evolution regulated by colour-screening scale p_{T0}

$$\frac{d\sigma_{2\to 2}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{(p_\perp^2 + p_{\perp 0}^2)^2}$$

Main MB/UE tuning parameter

p_{T0} scales with CM energy: $p_{T0}^2(s) \propto s^\gamma$

Main energy-scaling parameter

```
Old Default (4C)   : γ = 0.19
Monash 2013        : γ = 0.215
New "Monash Slow"  : γ = 0.23
```

(➜ cutoff increases faster → N_{ch} grows slower)

Event structure (e.g., N_{ch} distributions) further significantly affected by:

Proton b profile; Low-x PDFs; Colour Reconnections; Other collective effects?

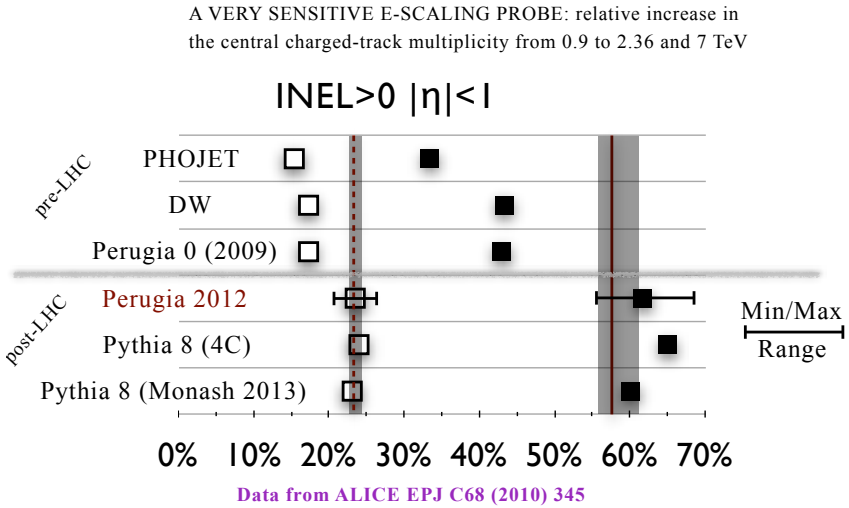
Hadronization: Lund String Model

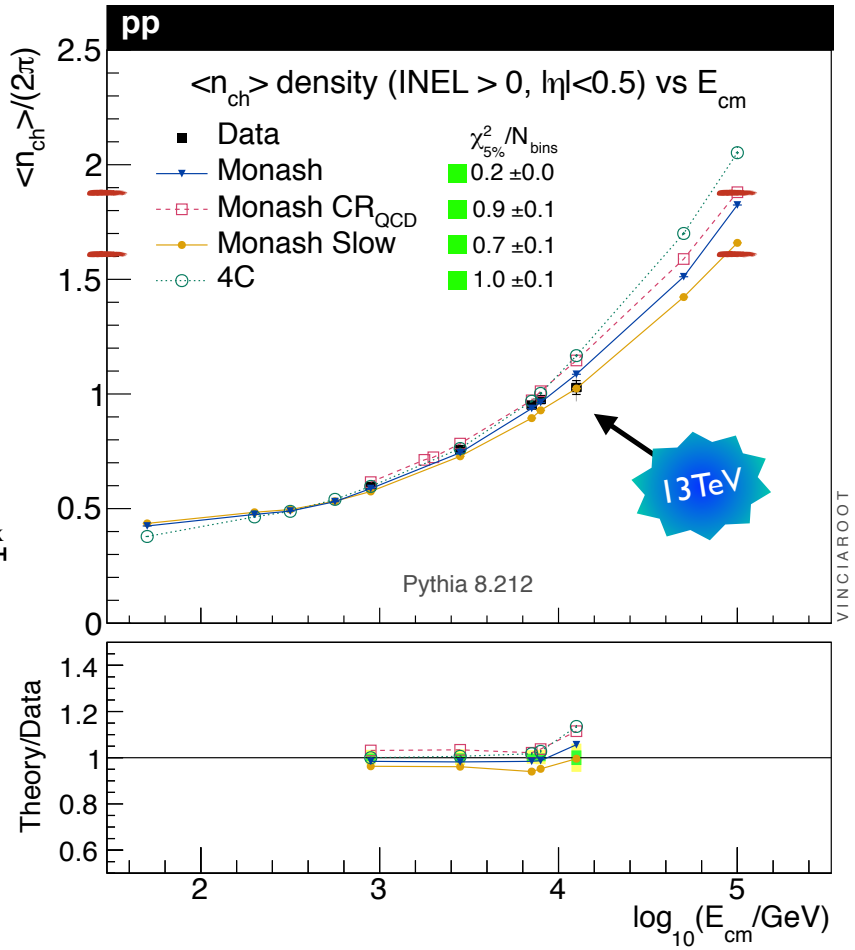
Jet Universality: fundamental parameters constrained by LEP data

No additional parameters for gluon jets, nor for pp collisions (modulo dynamics)

Central charged-track density (Peter Skands)

Best measured: INEL > 0
(at least one charged particle inside |eta| < 1)





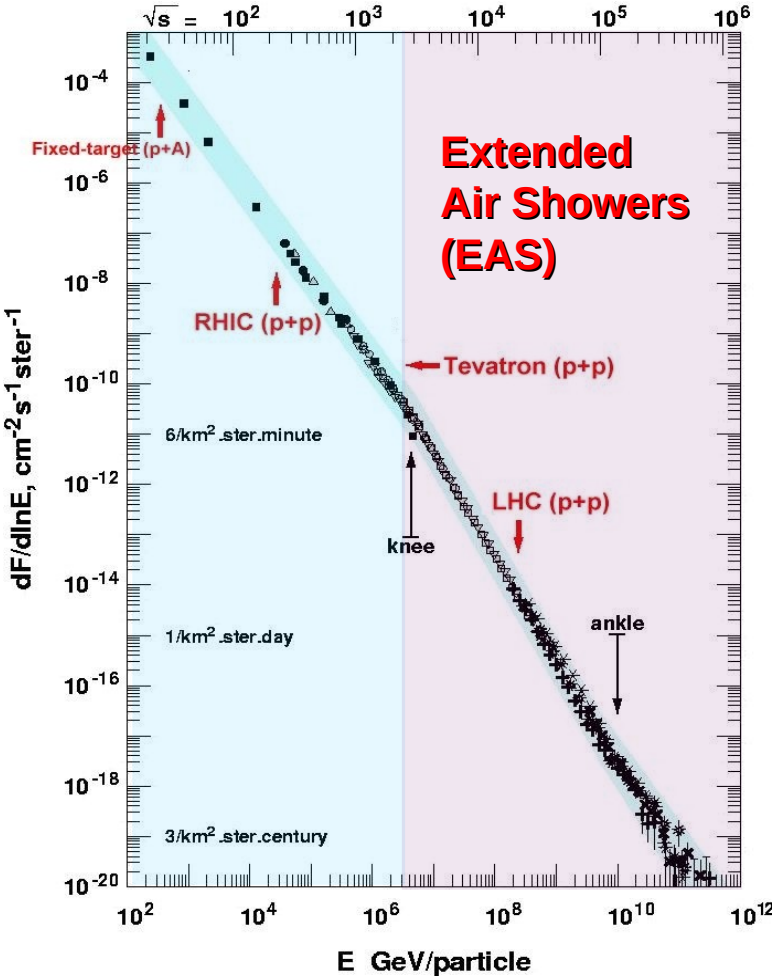
INEL > 0

100 TeV: $\langle N_{ch}\rangle/\Delta\eta\Delta\varphi = 1.75 \pm 0.15$

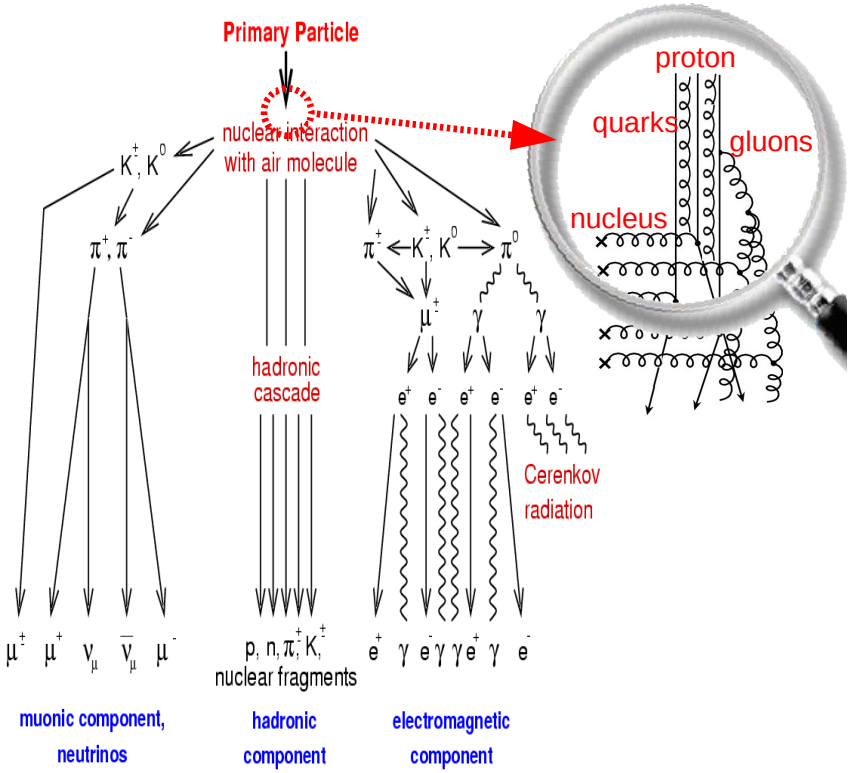
drops to 1.5 ± 0.15 including all inelastic

Cosmic Ray Scales (David d'Enterria)

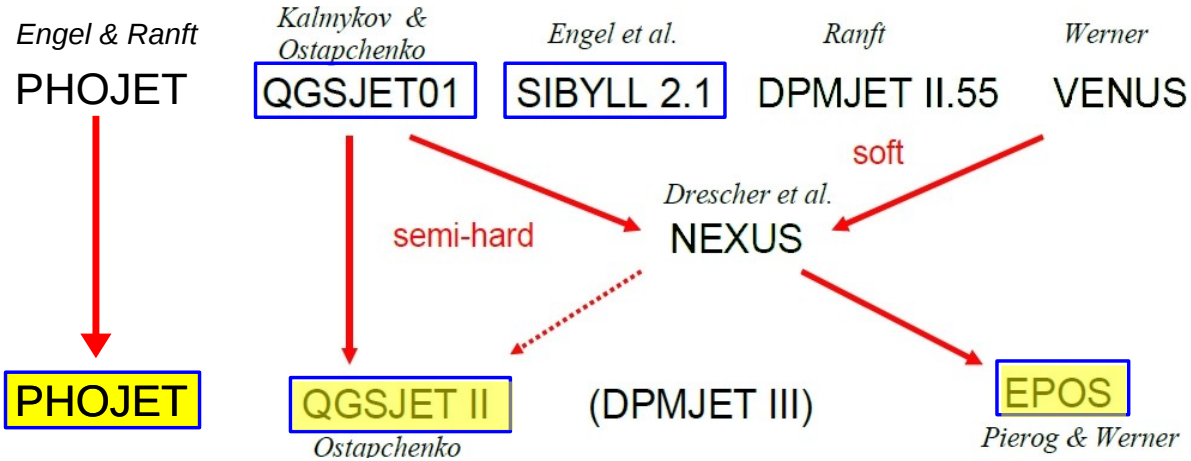
- CR energy & identity for $E_{CR}=10^{15}$–10^{21} eV determined using atmosphere as "calorimeter" and comparing shower to hadronic MCs:



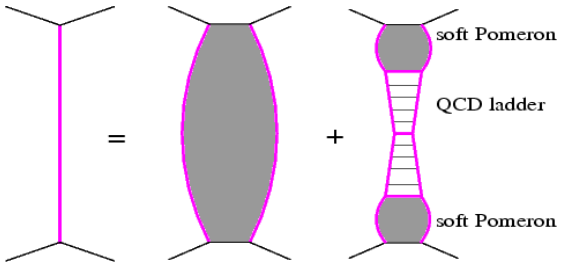
- CR+Air collisions: QCD interactions at c.m. energies up to $\sqrt{s}_{GZK}$~300 TeV



Reggeon-Field-Theory models (David d'Enterria)



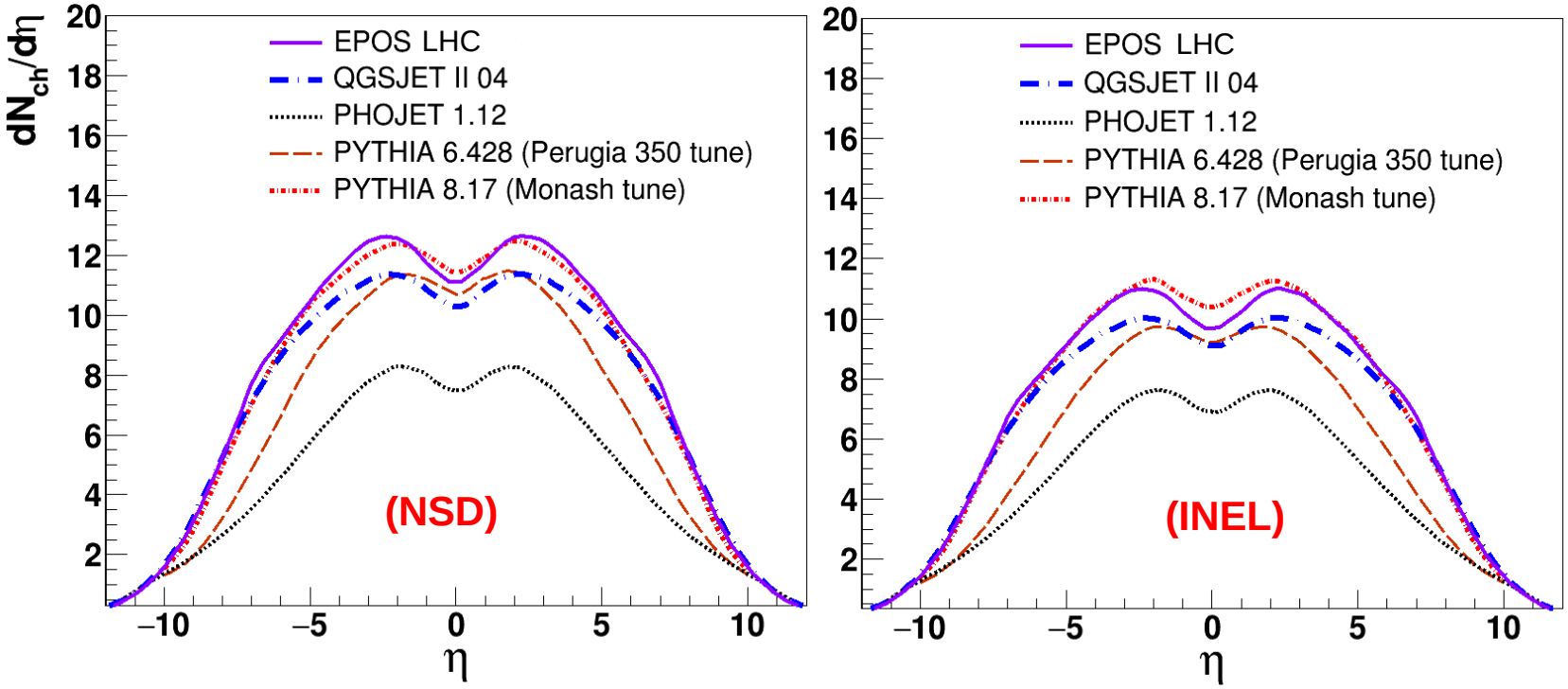
- Soft interactions via Reggeons & Pomerons:
  Elastic/Diffractive/Inelastic scatts. consistently treated through unitarity/analiticity/crossing
- Perturbative interactions via "cut (hard) Pomerons" (≅ LO pQCD)



- Semi-hard dynamics:
  - eikonal (multi)parton ladders (p-A, A-A possible)
  - parton saturation via enhanced |P diags, or running $p_{T,0}$~Q_{sat} (as PYTHIA/HERWIG)
- Non-perturbative ingredients:
  - string fagmentation (Lund model)
  - beam-remnants
- Model parameters:
  - Tuned with accelerator data.
  - $O(20)$, much less than in std collider MCs

Pseudorapidity distribution (David d'Enterria)

- ~50% of charged-hadron production due to semihard MPI activity:



- EPOS, QGSJET-II and PYTHIA 8 very similar results:

$dN_{ch}/d\eta$(NSD)=11±0.5, $dN_{ch}/d\eta$(inel)=9.5±1.0

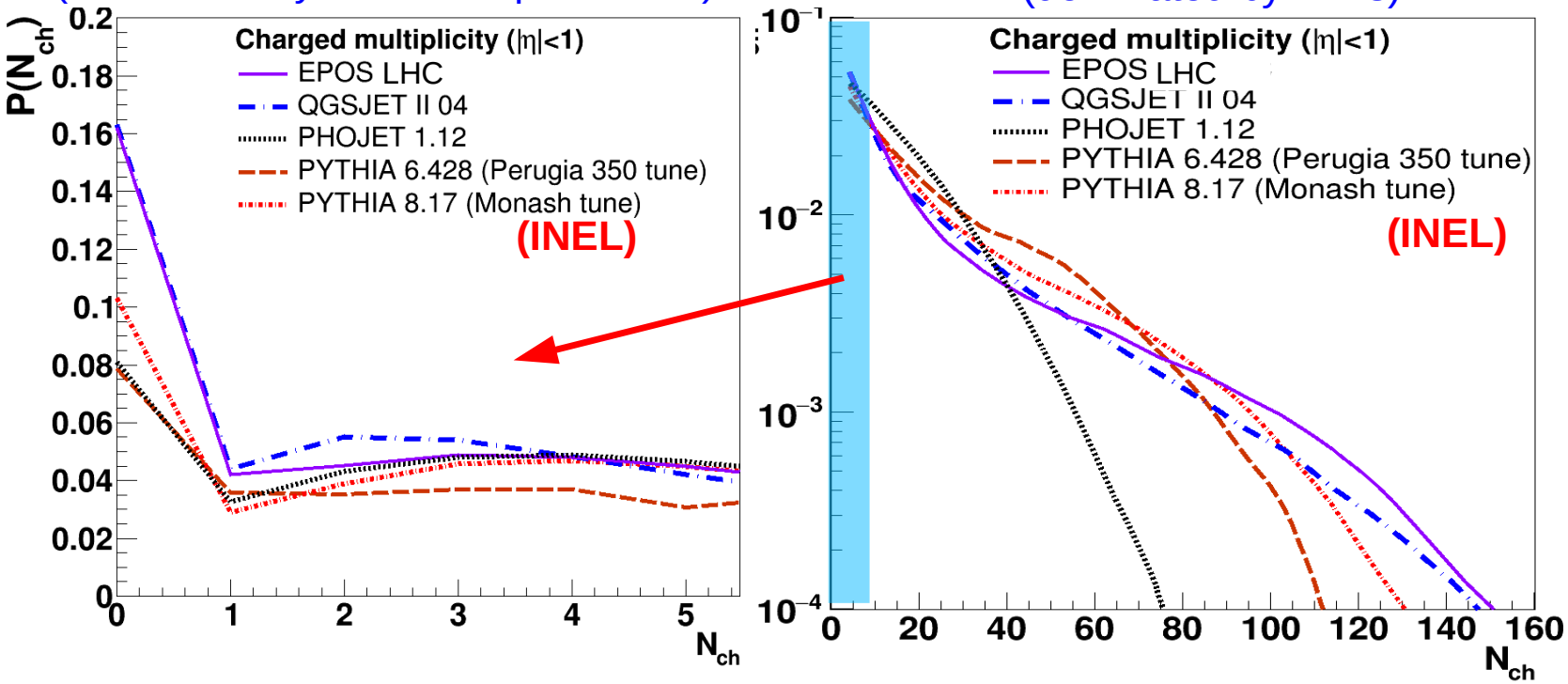
- PYTHIA 6 & PHOJET "thinner" distributions (impact of low-x PDFs). PHOJET lower by ~40% (wrong Q_s running? not enough MPIs?).

Charged multiplicity (David d'Enterria)

- Per-event charged multiplicity at $\eta=0$ for low & large N_{ch} :

Multiplicity peak
(dominated by diffractive processes)

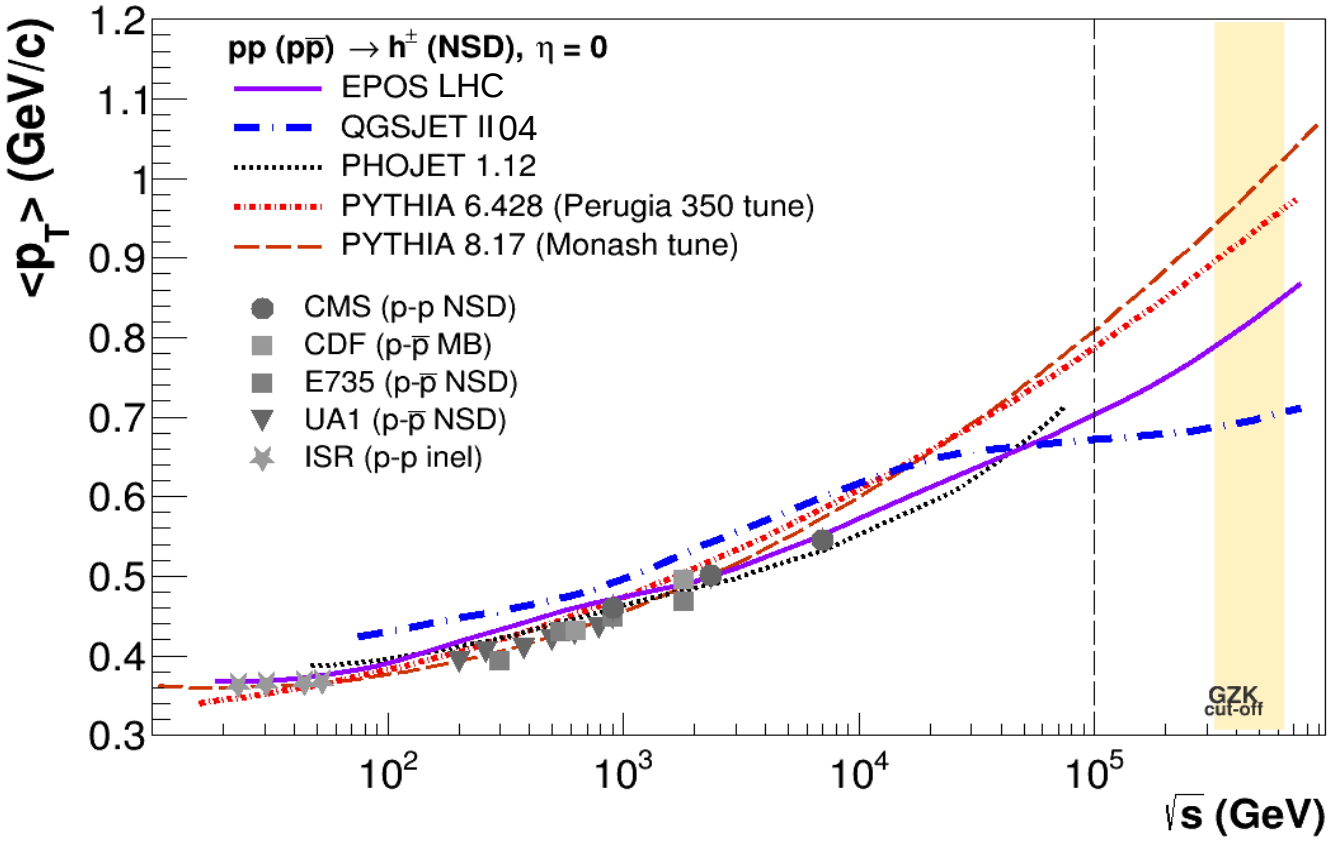
High-multiplicity tails
(dominated by MPIs)



- P(large N_{ch}): EPOS/QGSJET-II similar, PYTHIA ~smaller, PHOJET off
  >1% probability of N_{ch}>100 within $|\eta|<1$
- P(low N_{ch}): PYTHIA/PHOJET less soft/diffractive activity.

Average transverse momentum (David d'Enterria)

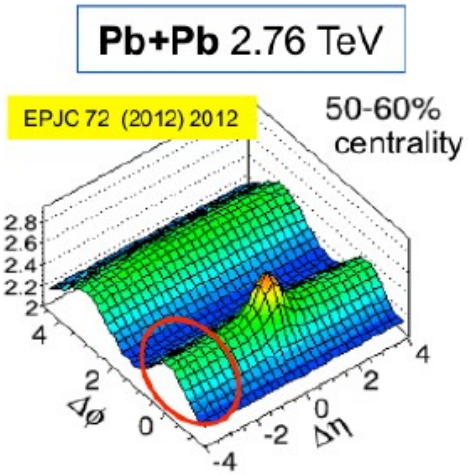
- $<p_T>$ is sensitive to pQCD x-sections, gluon saturation and possible final-state collective flow:

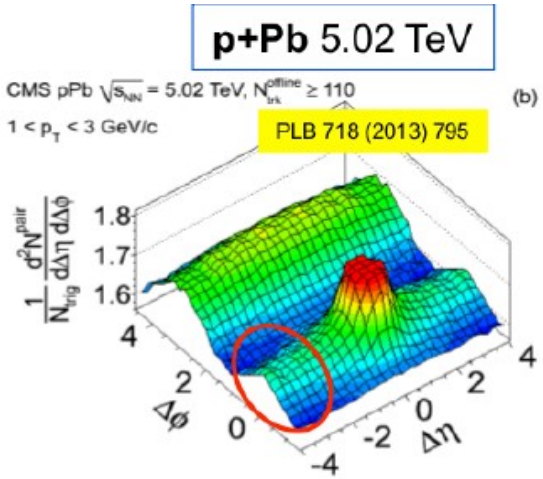


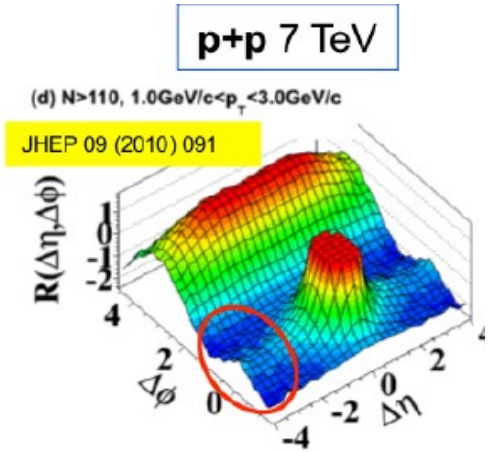
- CRs MCs predict slower $<p_T>$ evolution than PYTHIA (less minijets).
- At FCC-100 TeV: **$<p_T>$ = 0.65–0.75 GeV/c** (PYTHIA: $<p_T>$=0.8 GeV/c)

The ridge effect (David d'Enterria)

- Long-range (over $\Delta\eta$~8) near-side hadron correlations "ridge" in central (high multiplicity) pp, pPb and PbPb collisions at LHC:

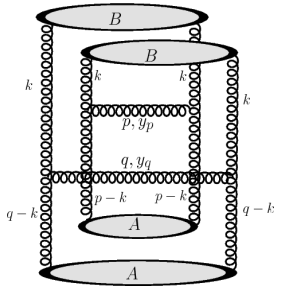






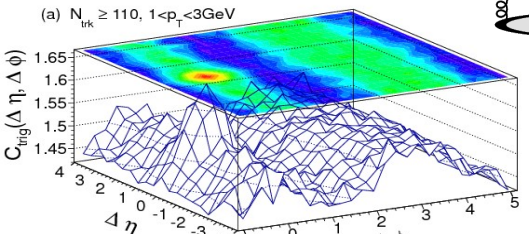
- Initial-state? Correlated gluons around saturation scale:

  Multiparton interactions enhance the near-side diagrams



- Final-state? Collective parton-flow:

  Hydro calculations (EPOS) reproduce well the details of such structure



Colour Reconnection (CR)

CR needed to explain e.g. $\langle p_\perp \rangle (n_{\rm ch})$, 1987 and now:

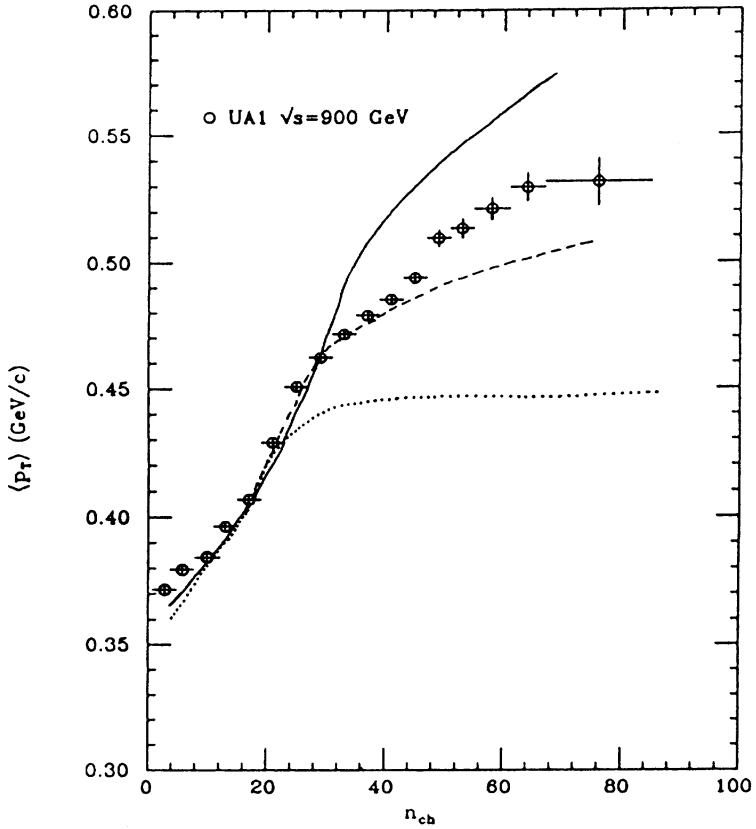
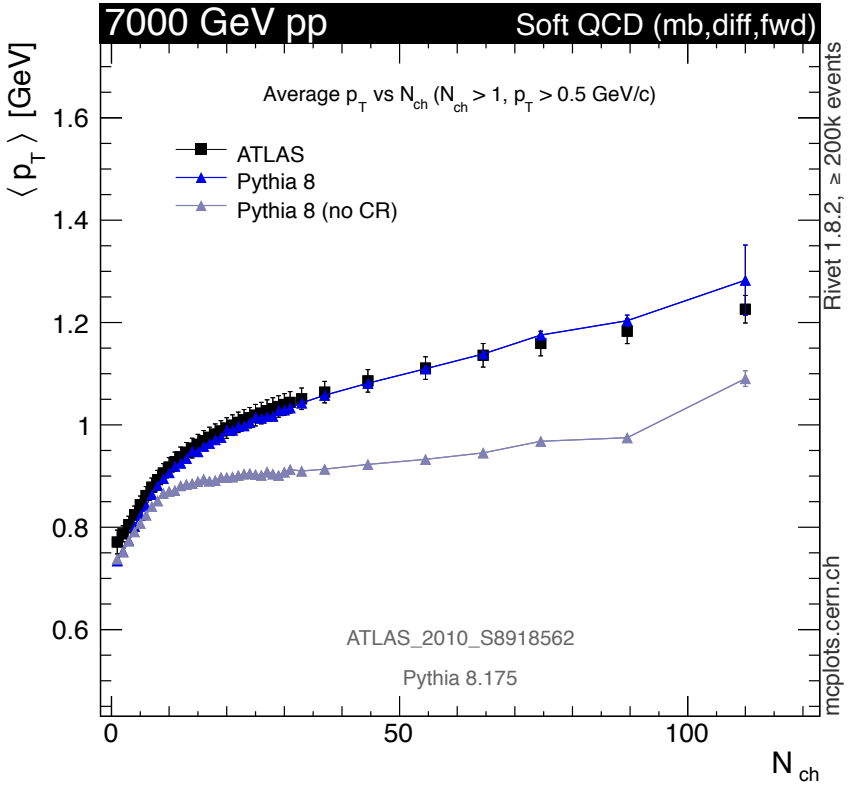


FIG. 27. Average transverse momentum of charged particles in $|\eta| < 2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.



CR reduces total string length

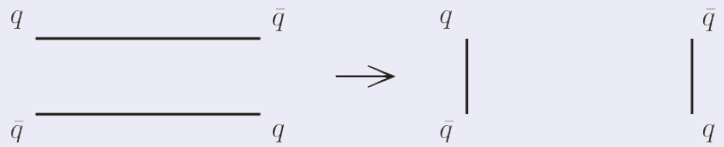
$\Rightarrow$ reduces hadronic multiplicity

The new QCD-based CR model (Christiansen + Skands)

New model relies on two main principles

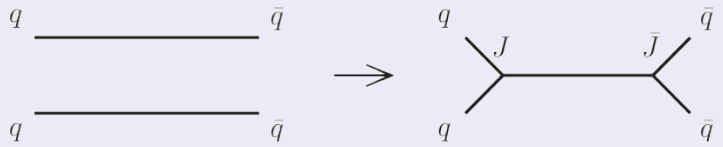
⋆ **SU(3)** colour rules give allowed reconnections

Ordinary string reconnection



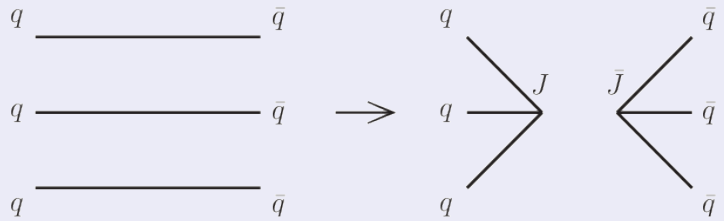
(q$\bar{q}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection



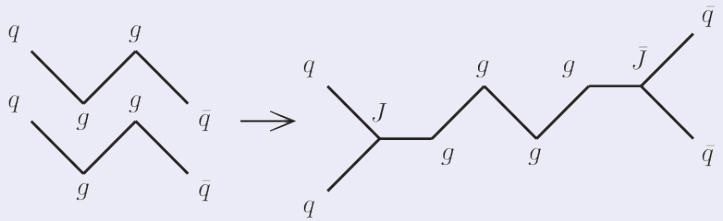
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection



(q$\bar{q}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection



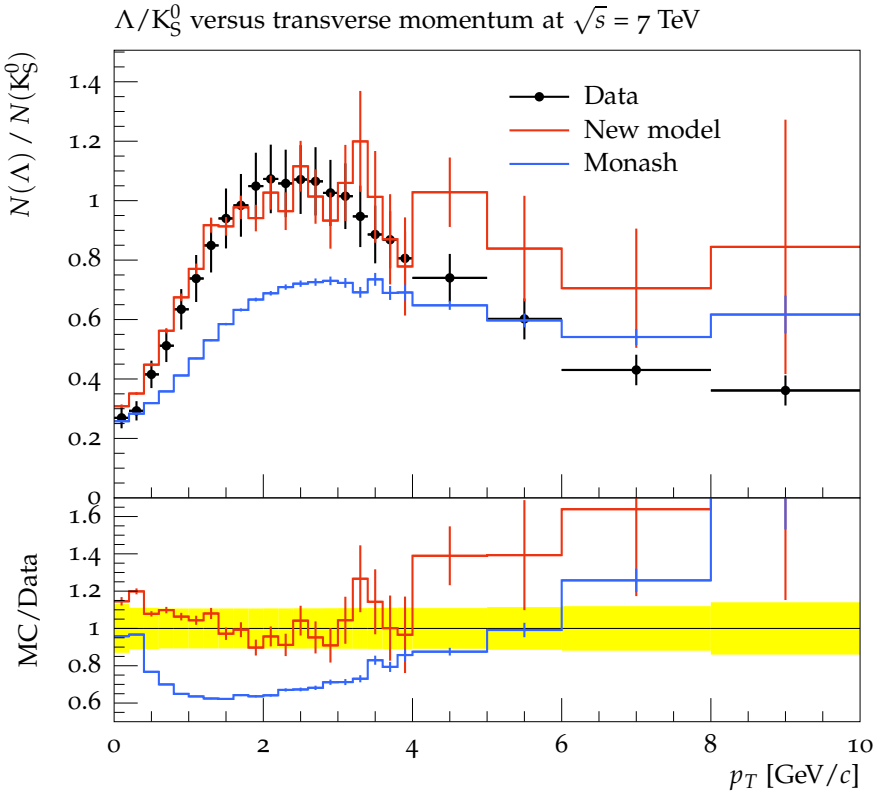
(Depends on number of gluons)

⋆ minimal λ measure gives preferred reconnections

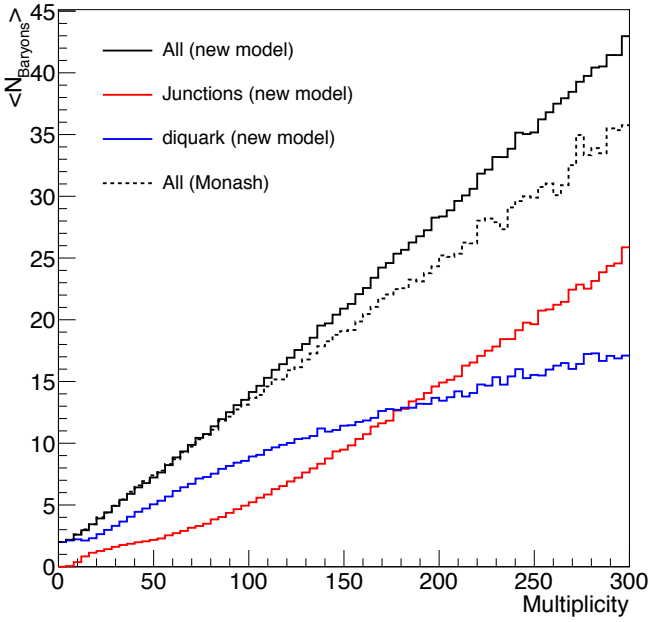
$\lambda \approx \sum_{\text{dipoles}} \ln(1 + m_{ij}^2/m_0^2)$ measure of string length, $\propto n_{\text{hadronic}}$

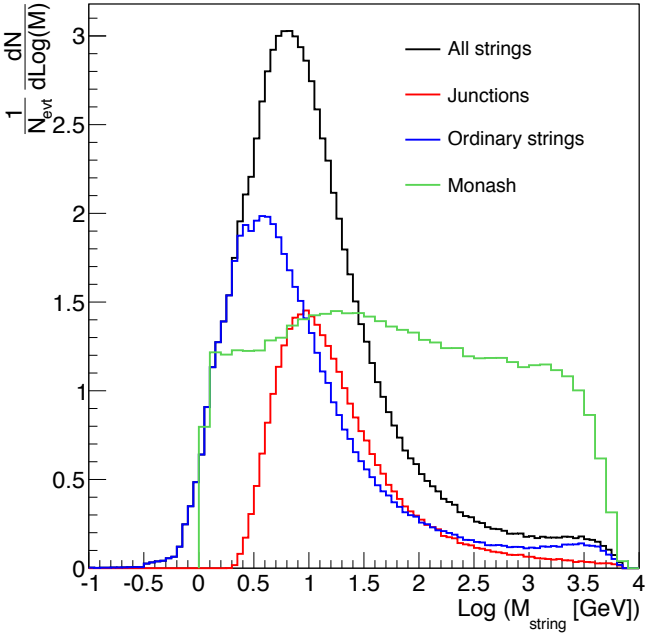
The new QCD-based CR model (Christiansen + Skands)

Comparison with LHC data:



(arXiv:1102.4282)



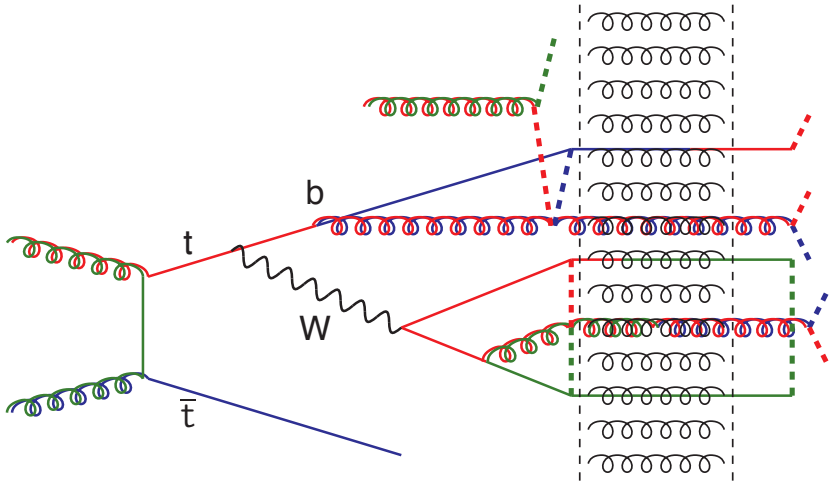


many baryons from junctions,
but few from regular strings
(big-mass string systems cut up!)

A top mass puzzle (Spyros Argyropoulos)

$$\left.\begin{array}{l}\Gamma_{\rm t} \approx 1.5\ {\rm GeV}\\ \Gamma_{\rm W} \approx 2\ {\rm GeV}\\ \Gamma_{\rm Z} \approx 2.5\ {\rm GeV}\end{array}\right\} \Rightarrow c\tau \approx 0.1\ {\rm fm}:$$

p "pancakes" have passed,
MPI/ISR/FSR for $p_\perp \geq 2$ GeV,
inside hadronization colour fields.



Experiment	m_{top} [GeV]	Error due to CR	Reference
World comb.	173.34±0.76	310 MeV (**40%**)	arXiv:1403.4427
CMS	172.22±0.73	150 MeV (**20%**)	CMS-PAS-TOP-14-001
D0	174.98±0.76	100 MeV (**13%**)	arXiv:1405.1756

1. Great job in reducing the errors.
2. CR is one of the dominant systematics.
3. Why is the CR uncertainty going down when there are
   - no advances in theoretical understanding, and
   - no measurements to constrain it?

Effects on top mass after tuning (Spyros Argyropoulos)

- Afterburner models tuned to ATLAS jet shapes in $t\bar{t}$ events
  $\Rightarrow$ high CR strengths disfavoured.
- Early-decay models tuned to ATLAS minimum bias data
  $\Rightarrow$ maximal CR strengths required to (almost) match $\langle p_\perp \rangle (n_{\rm ch})$.

model	$\Delta m_{\rm top}$ rescaled
default (late)	$+0.239$
forced random	-0.524
swap	$+0.273$

$\Delta m_{\rm top}$ relative to no CR

Excluding most extreme (unrealistic) models

$$\mathbf{m_{top}^{max} - m_{top}^{min} \approx 0.50} \text{ GeV}$$

(in line with Sandhoff, Skands & Wicke)

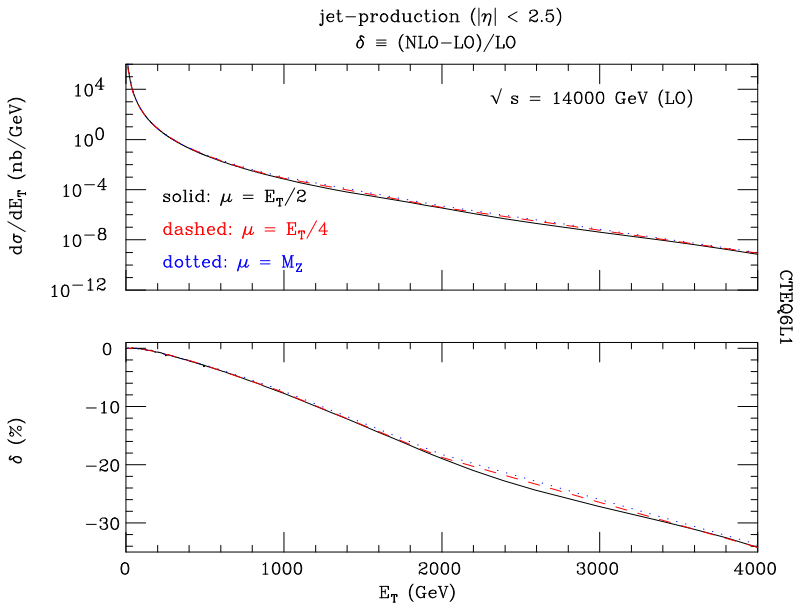
New: $\Delta m_{\rm top} \approx 0$ in QCD-based model

Studies of top events could help constrain models:

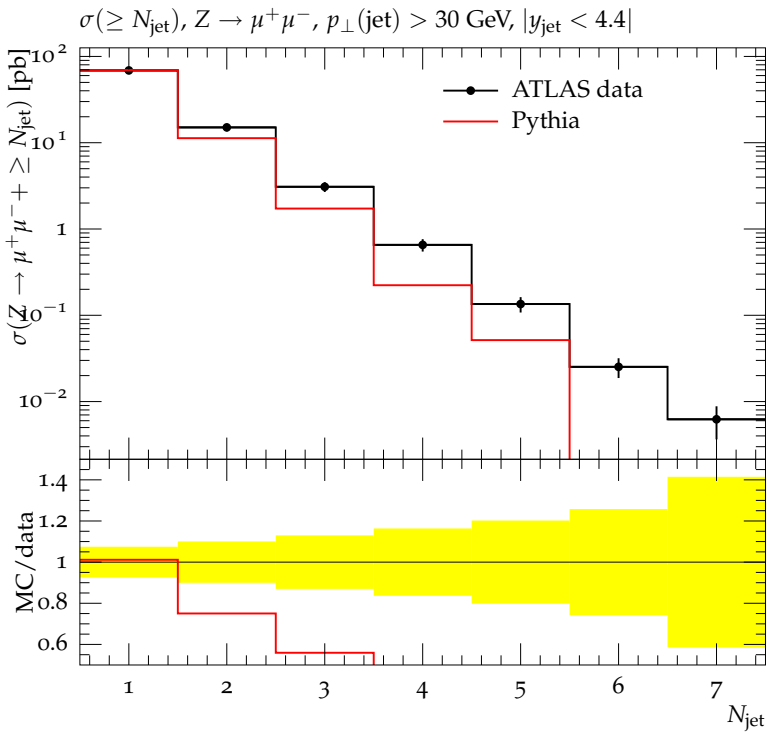
- jet profiles and jet pull (skewness)
- underlying event

Impacts any future precision measurement involving (partly) hadronic final state.

W/Z emission in showers (Jesper Christiansen)



S. Moretti, M.R. Nolten and D.A. Ross,
Nucl. Phys. B759 (2006) 50



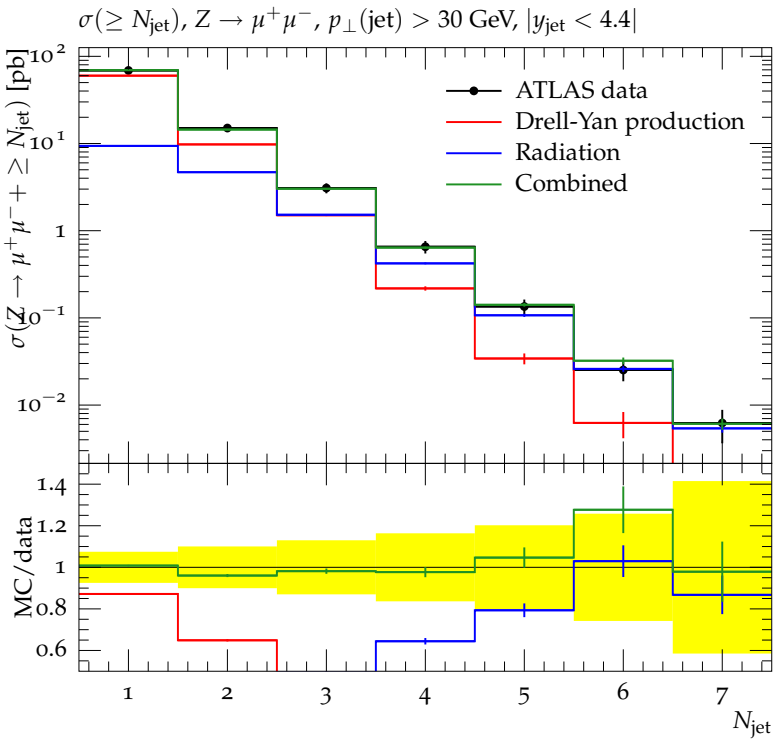
Weak correction to QCD 2 jets has log enhancement of form $\alpha_{\mathrm{weak}} \ln^2(p_\perp^2/m_{\mathrm{W}}^2)$.

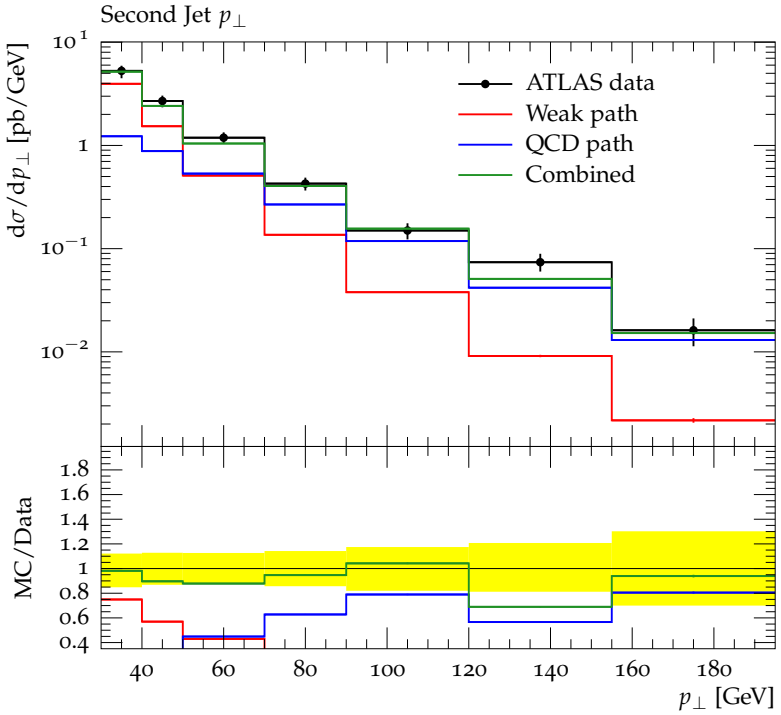
PYTHIA QCD shower starting from $\mathrm{q\overline{q}} \to \mathrm{Z}^0$ underestimates $\mathrm{Z} + n$ jet rate.

W/Z emission in showers (Jesper Christiansen)

Implement W/Z emission as part of standard shower.

Add contribution to W/Z production from QCD $2 \to 2$.





W/Z emission in showers (Jesper Christiansen)

Angular distributions still not great: φ selection too simple.

Input for merging, with broader range of shower histories.