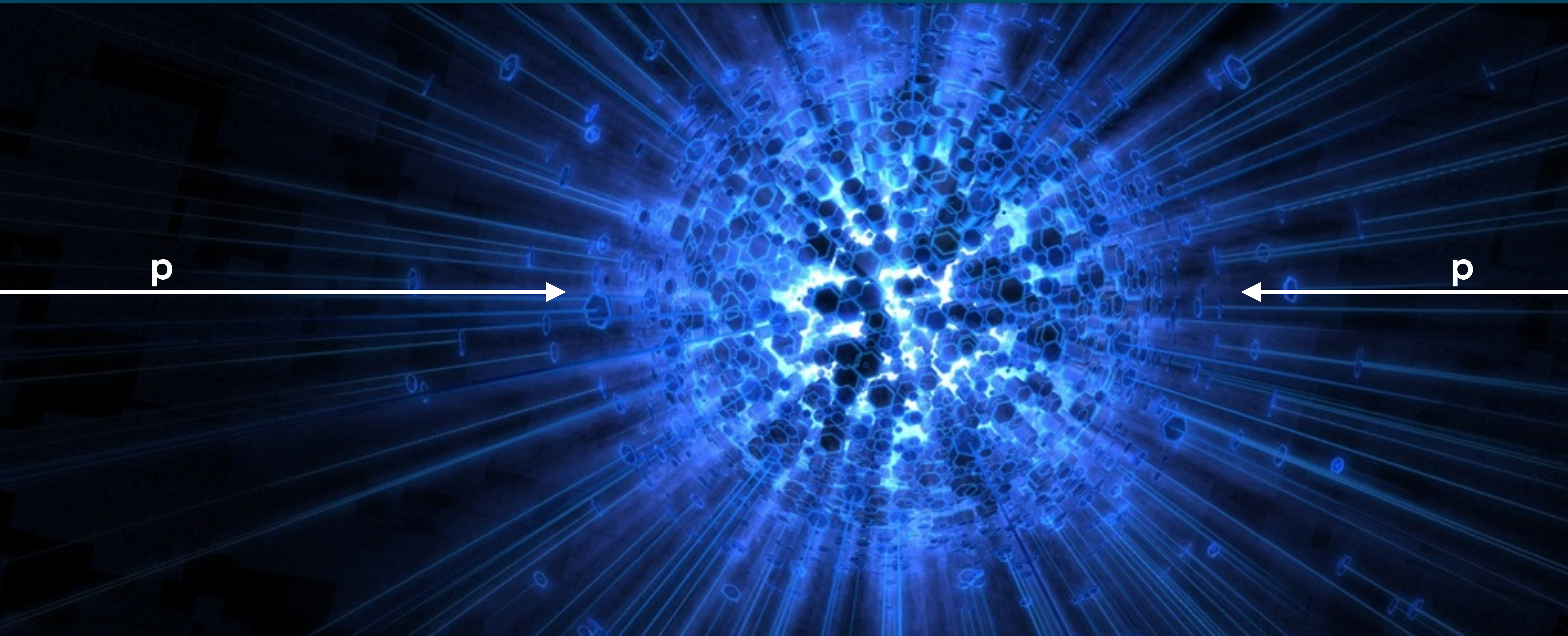
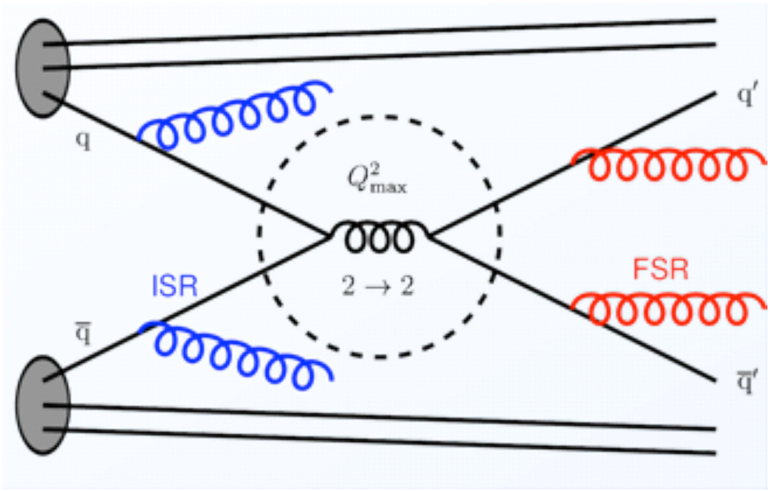
Modeling Hadronic Interactions in HEP MC Generators



Peter Skands (CERN Theory Dept)
(From October: Monash University, Melbourne)

18th International Symposium on Very High Energy Cosmic Ray Interactions. CERN, August 2014

Modeling Hadronic Final States



Calculate Everything ≈ solve QCD → requires compromise!

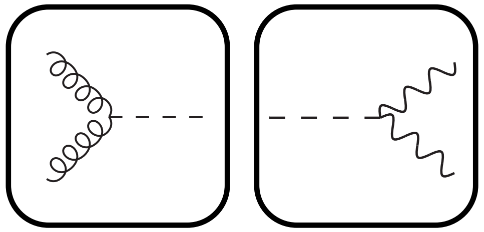
HEP Monte Carlo Event Generators:

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

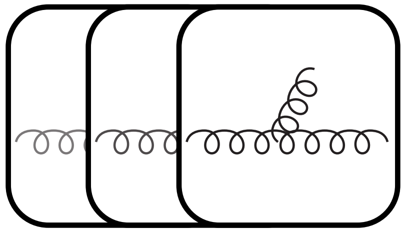
Factorization → Split the problem into many (nested) pieces

+ Quantum mechanics → Probabilities → Random Numbers (MC)

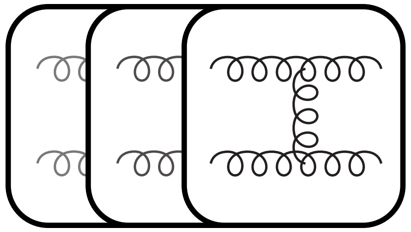
$$\mathcal{P}_{\rm event} = \mathcal{P}_{\rm hard} \otimes \mathcal{P}_{\rm dec} \otimes \mathcal{P}_{\rm ISR} \otimes \mathcal{P}_{\rm FSR} \otimes \mathcal{P}_{\rm MPI} \otimes \mathcal{P}_{\rm Had} \otimes \ldots$$



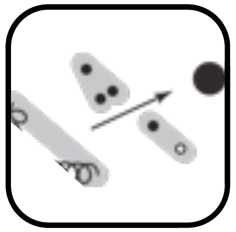
Matrix Elements (+ Sudakov Corrections)



Shower Kernels (+ ME corrections)



Multiple Parton Interactions Hard + Soft → INEL & UE

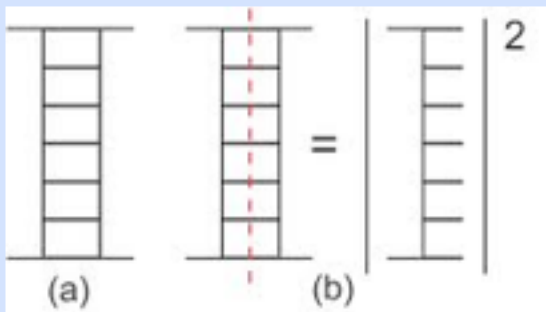


Hadronization, Decays, Soft Diffraction, Beam Remnants

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

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

Cut Pomerons → Flux Tubes (strings)

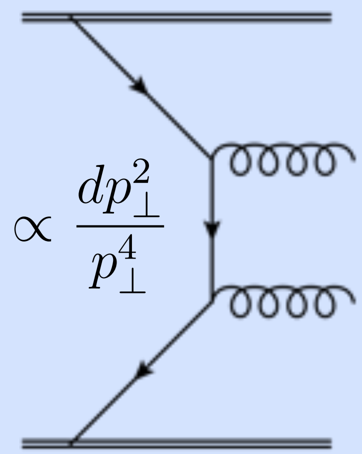
Uncut Pomerons → Elastic (& eikonalization)

Cuts unify treatment of all soft processes

EL, SD, DD, … , ND

Perturbative contributions added above Q_0

B Parton Based



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

+ Unitarity & Saturation

→ Multi-parton interactions (MPI)

+ Parton Showers & Hadronization

Regulate dσ at low $p_{T0} \sim$ few GeV

Screening/Saturation → energy-dependent p_{T0}

Total cross sections from Regge Theory

(Donnachie-Landshoff + Parametrizations)

E.g., QGSJET, SIBYLL

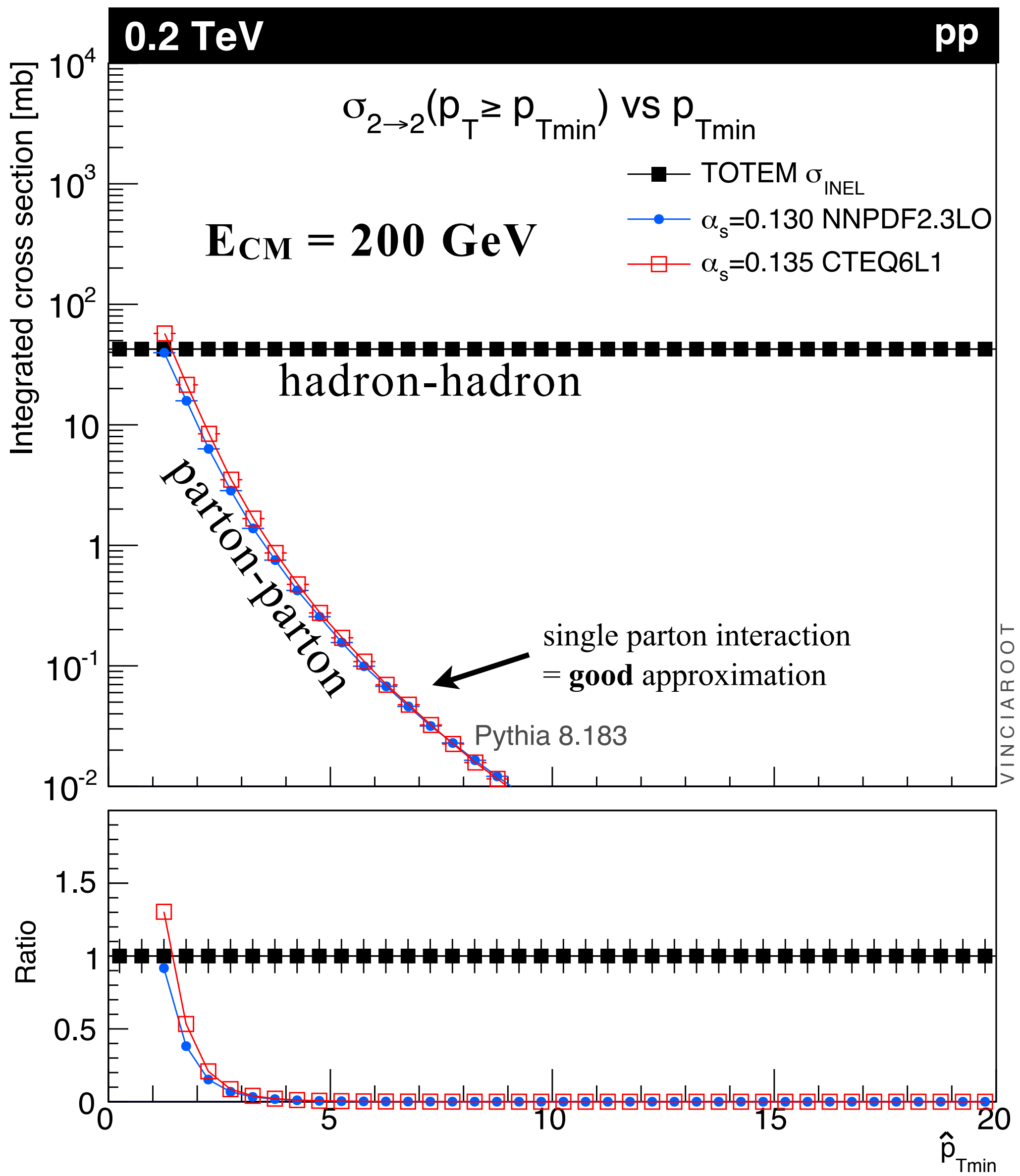
+ "Mixed"

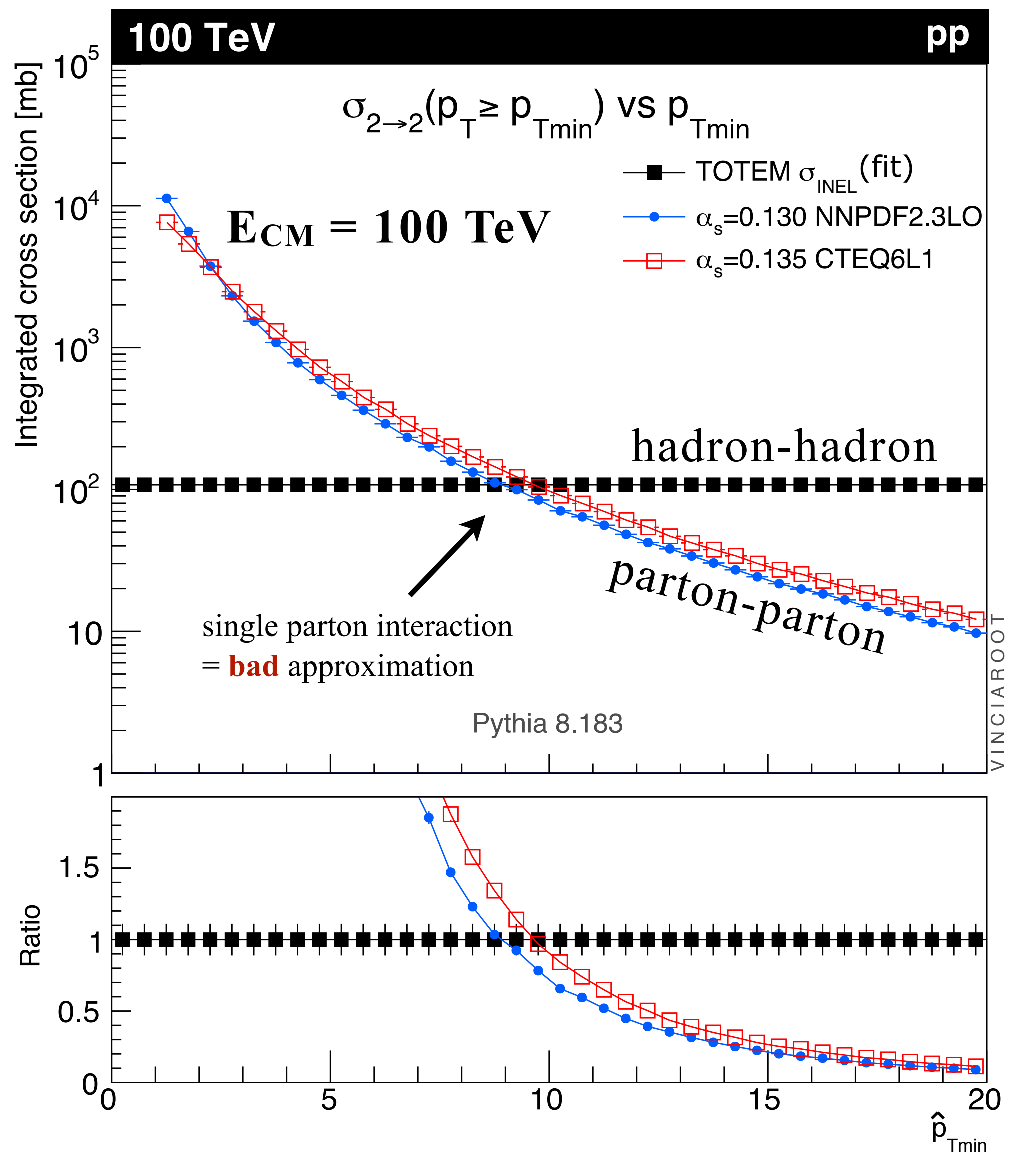
E.g., PHOJET, EPOS, SHERPA-KMR

E.g., PYTHIA, HERWIG, SHERPA

Parton-Based Models : MPI

Consider the inclusive di-jet cross section in QCD



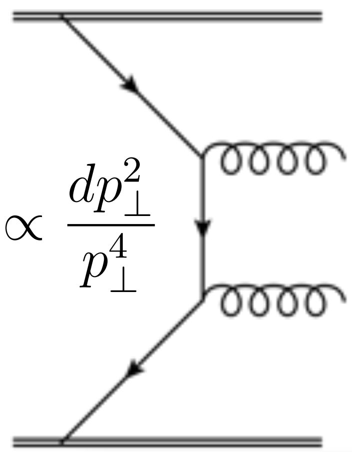


$\sigma_{2\to2} > \sigma_{pp}$ interpreted as consequence of each pp containing several 2→2 interactions: MPI

Soft MPI

Starting Point: Perturbative QCD 2 → 2

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



$\otimes$ PDFs

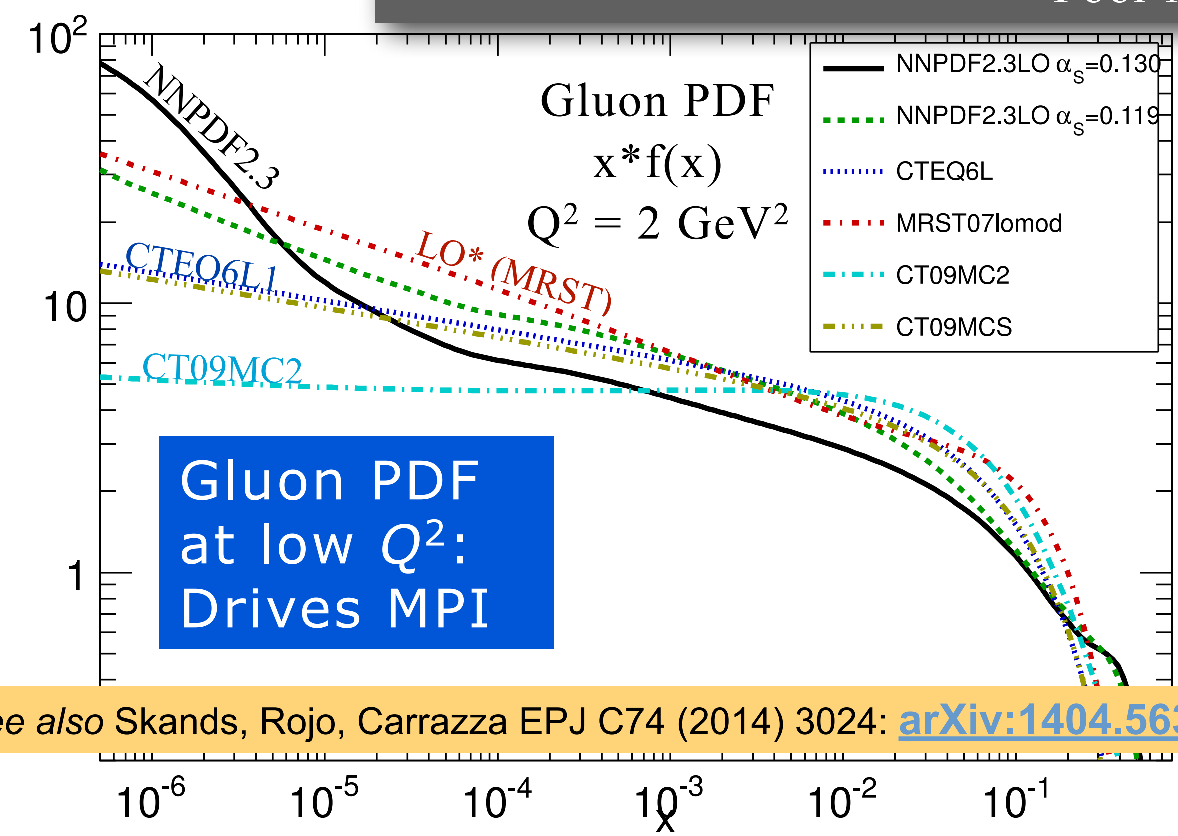
Good at High Q^2 and finite x

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} (and/or x) dependence of p_{T0} regulator
- Modeling of the diffractive component
- Proton transverse mass distribution
- Colour Reconnections, Collective Effects

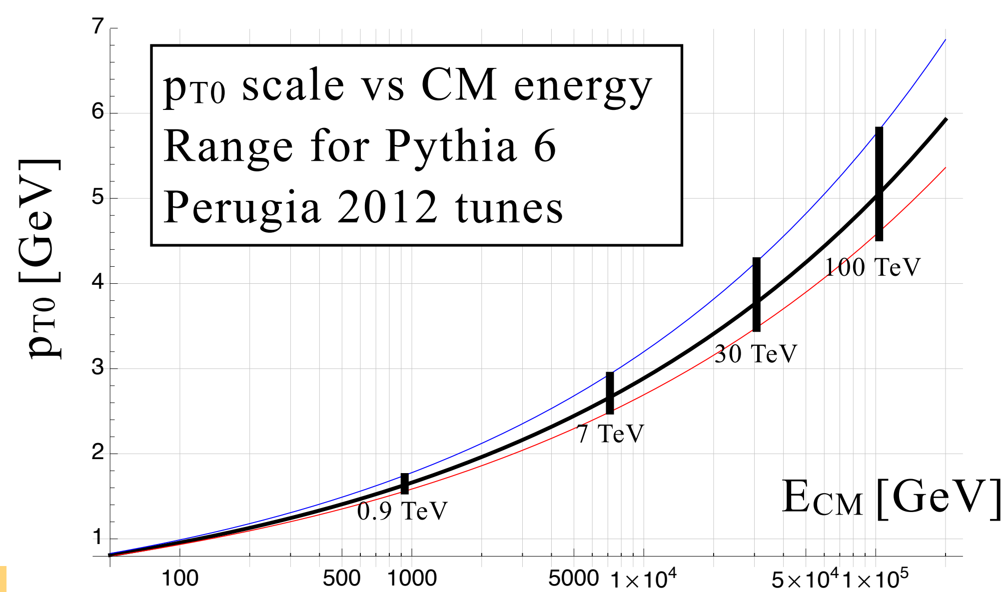
Saturation

Poor Man's Saturation



Gluon PDF at low Q^2: Drives MPI

See also Skands, Rojo, Carrazza EPJ C74 (2014) 3024: arXiv:1404.5630

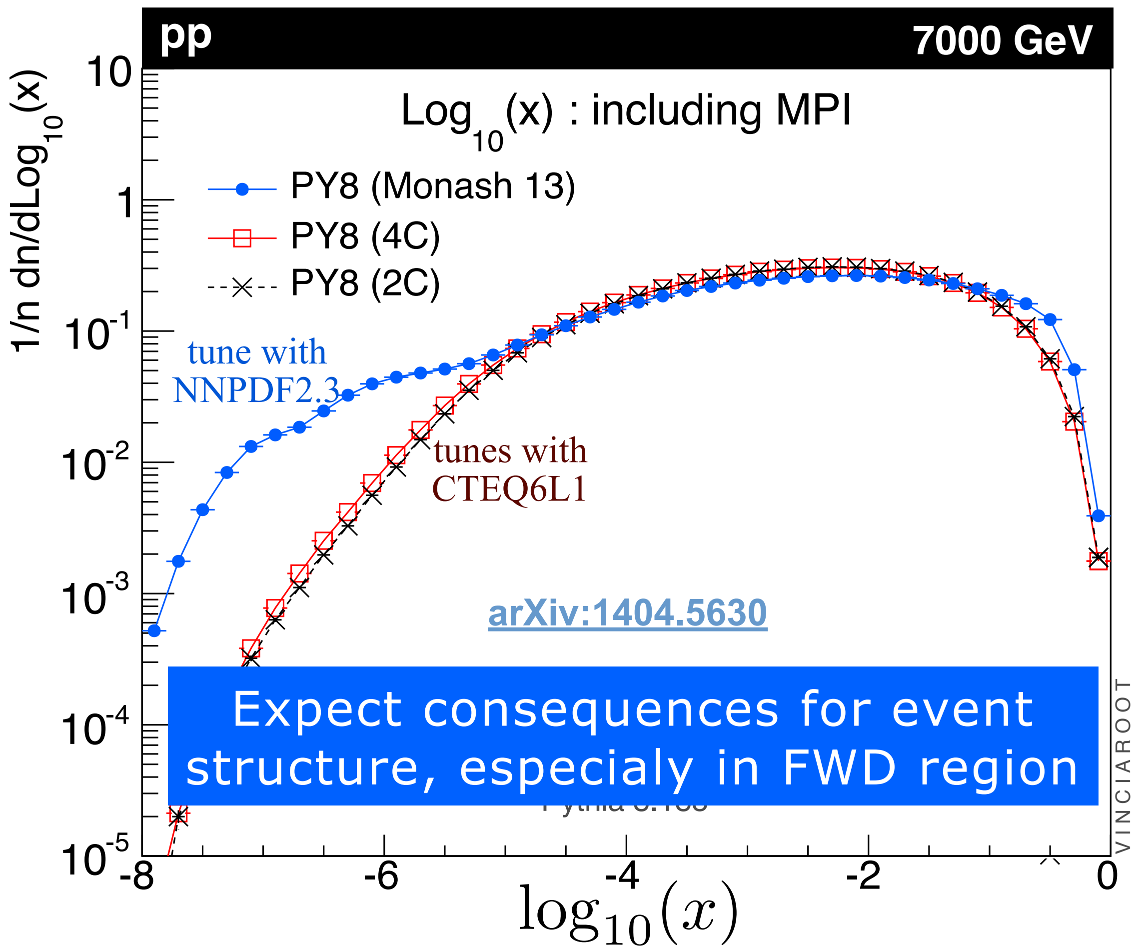


See also Connecting hard to soft: KMR, EPJ C71 (2011) 1617 + PYTHIA "Perugia Tunes": PS, PRD82 (2010) 074018

MPI models and Low x

What range of X values are actually probed?

EXAMPLE: PYTHIA 8
Range of x values probed by different MPI tunes



See also Skands, Rojo, Carrazza EPJ C74 (2014) 3024: [arXiv:1404.5630]

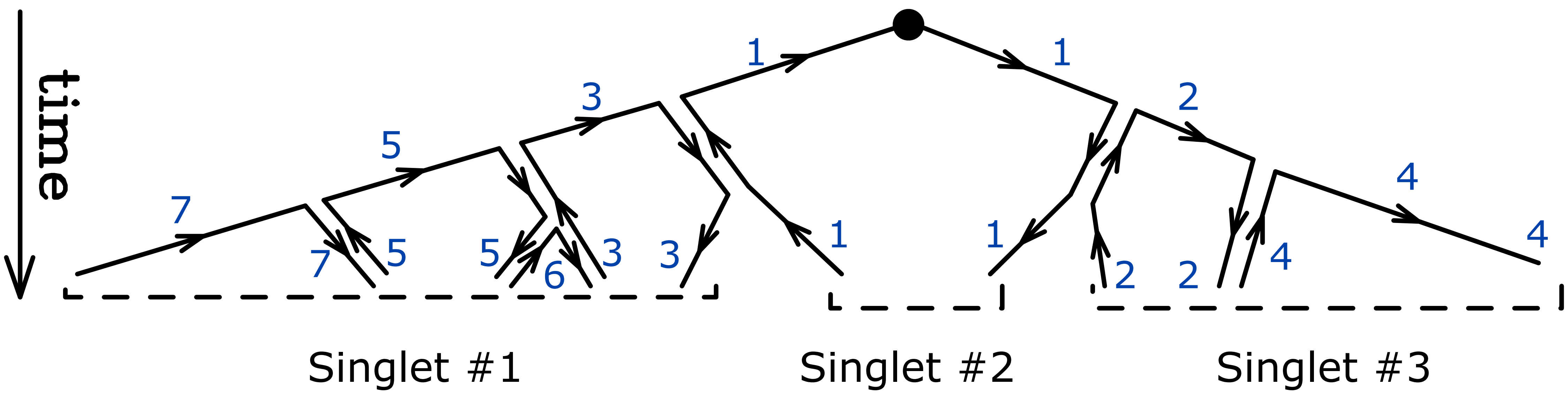
Controlling these issues will require an improved understanding of the interplay between low-x PDFs, saturation / screening, and MPI in MC context. (+ Clean model-independent experimental constraints!)

Warning: Not automatic: difficult cross-community communication (+ low visibility)

Hadronization and Colour

Example of Color Flow in a Parton Cascade

Example: $Z^0 \rightarrow q\bar{q}$



Coherence of pQCD cascades → not much "overlap" between singlet subsystems
→ Leading-colour approximation pretty good

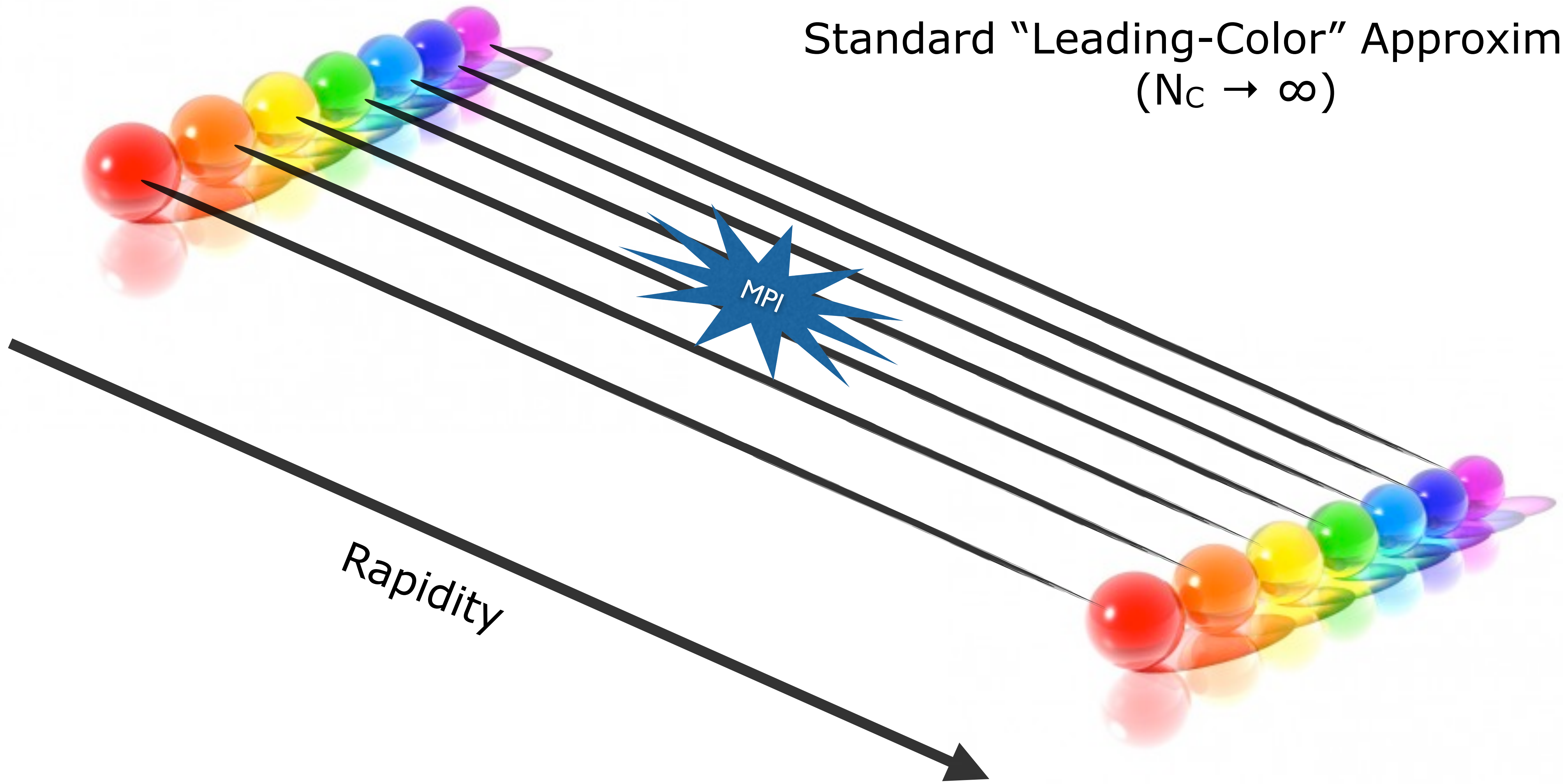
LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$)

Note: (much) more color getting kicked around in hadron collisions

MPI and Colour

Better theory models needed

Standard "Leading-Color" Approximation
($N_C \to \infty$)



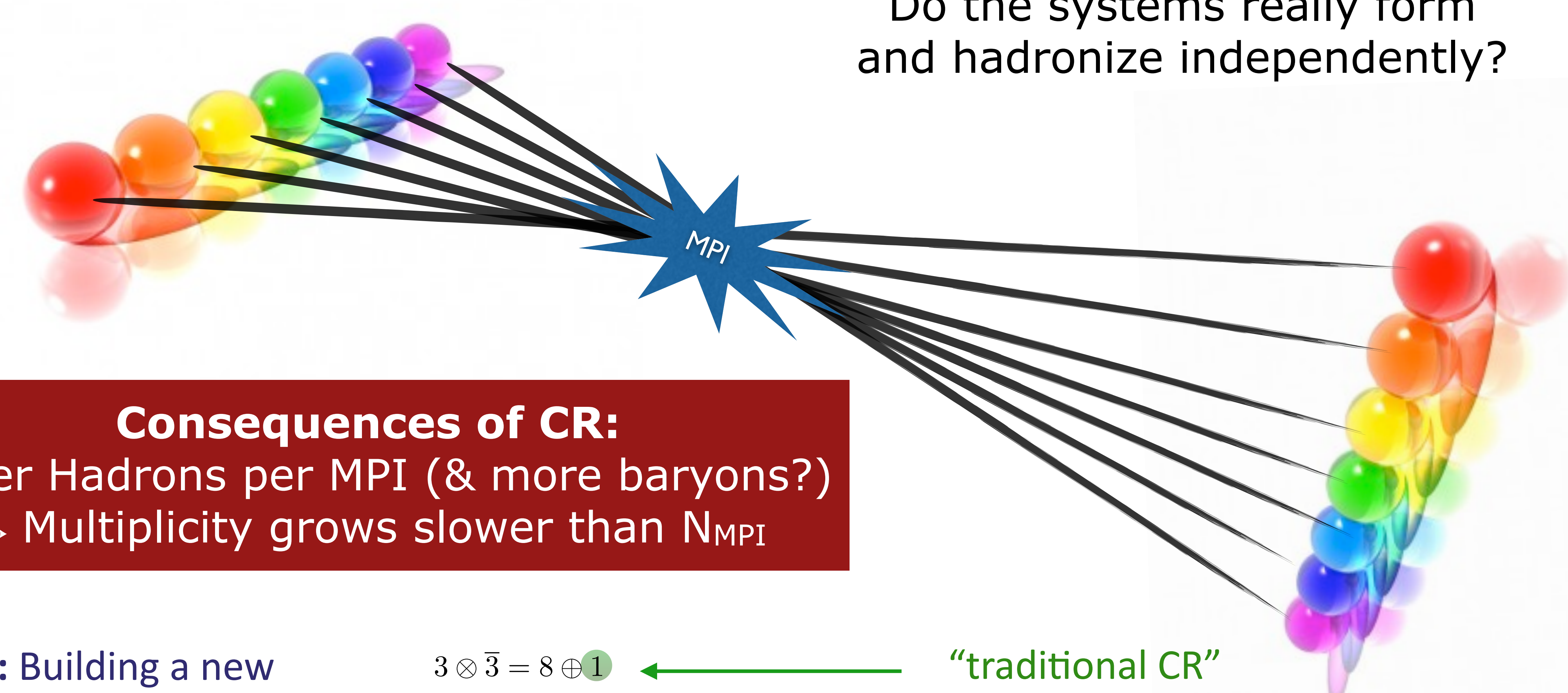
Multiplicity $\propto N_{MPI}$

Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (Skands, Wicke: Eur. Phys. J. C52 (2007) 133)
Herwig++ model (Gieseke, Rohr, Siodmok : Eur.Phys.J. C72 (2012) 2225)

Better theory models needed

Do the systems really form
and hadronize independently?



Consequences of CR:
Fewer Hadrons per MPI (& more baryons?)
↳ Multiplicity grows slower than N_{MPI}

New: Building a new model for PYTHIA 8, based on SU(3) weights
[with J. Christiansen (Lund U)]

$3 \otimes \overline{3} = 8 \oplus 1$ ← "traditional CR"

$3 \otimes 3 = 6 \oplus \overline{3}$ ← "new" sources of baryons (& antibaryons)

$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$,

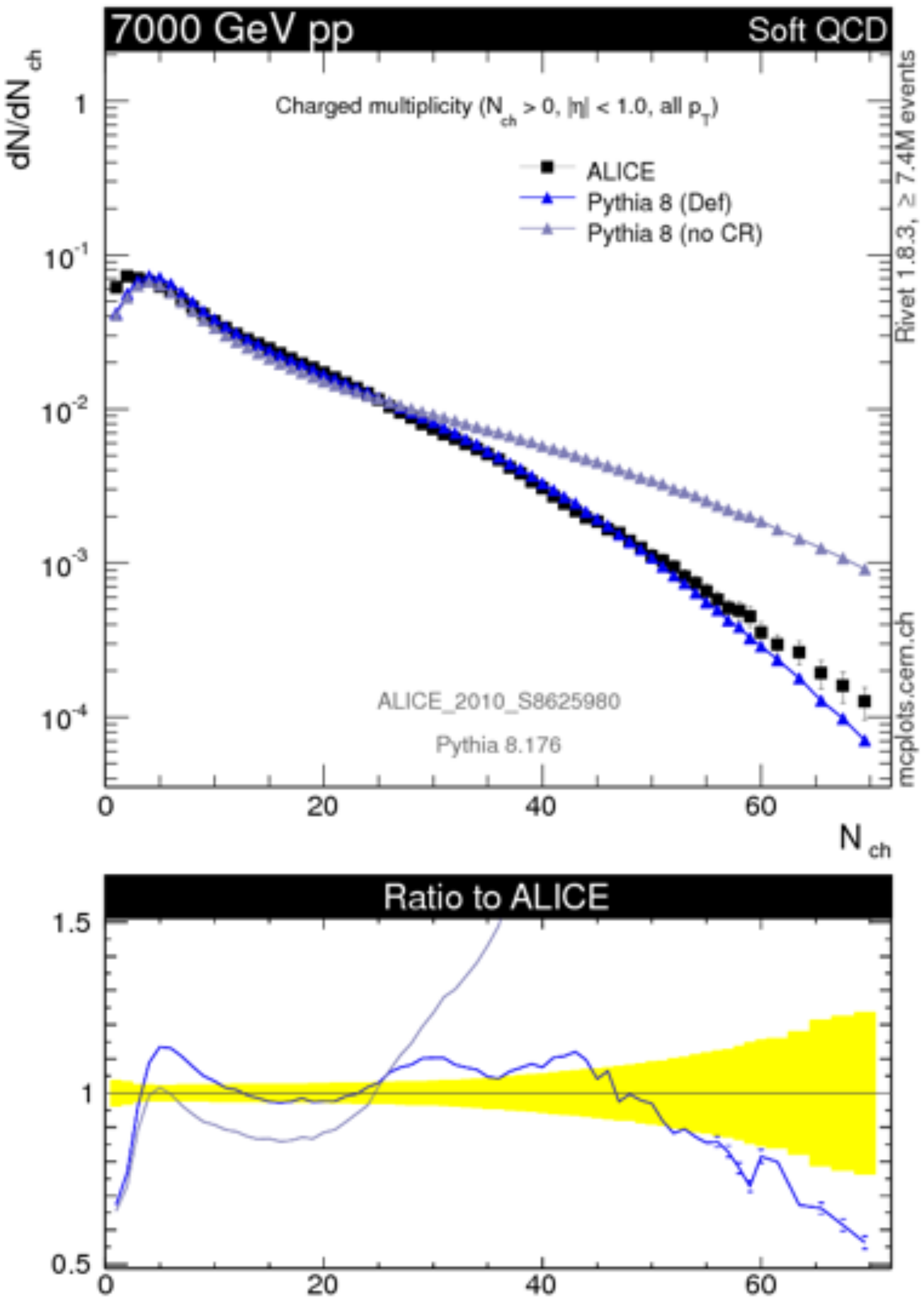
$3 \otimes 8 = 15 \oplus 6 \oplus 3$,

also indicated by LHC data!

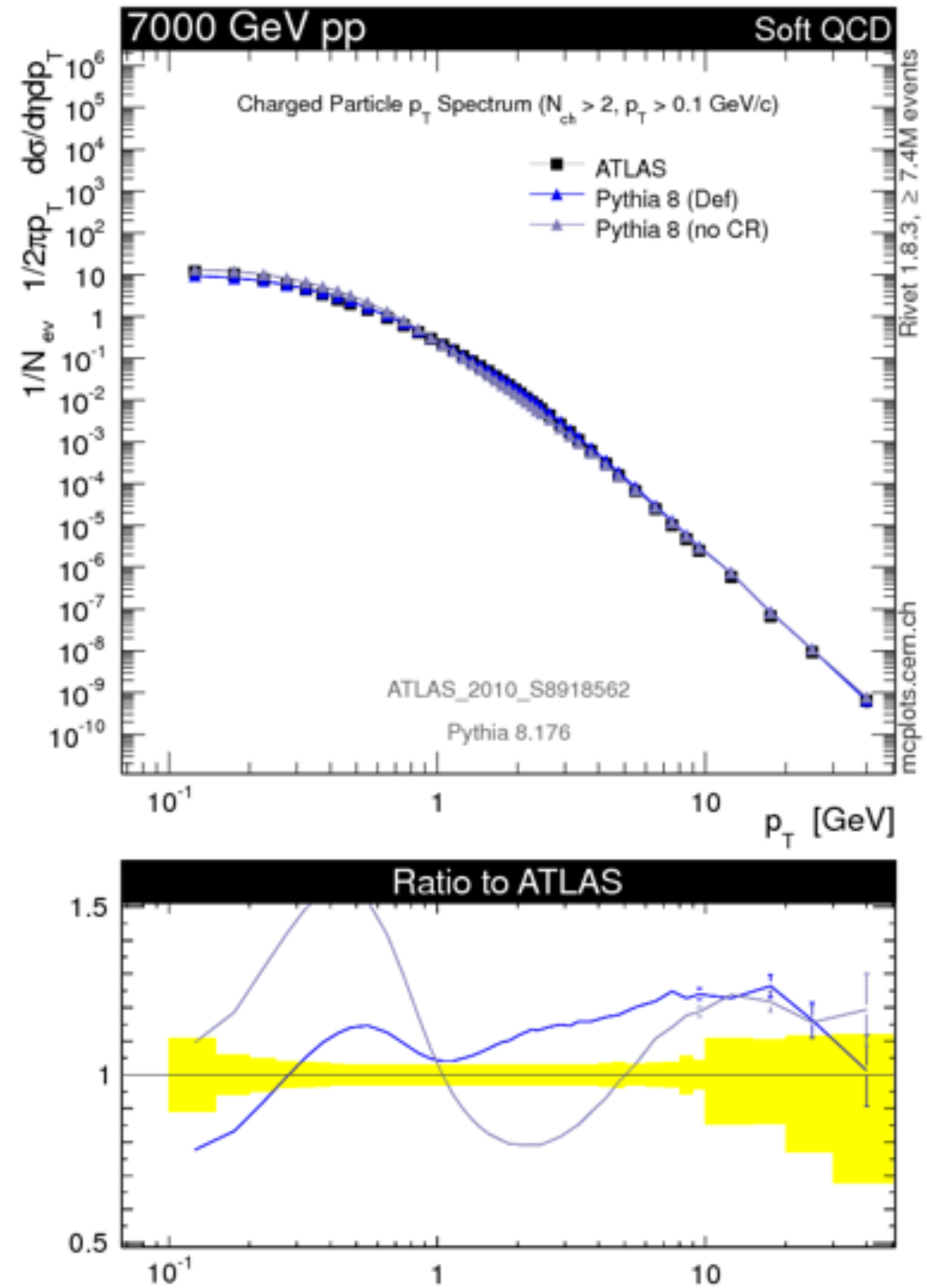
The Effects of CR

(Showing default (old) Pythia 8 CR model here; new one still in progress)

Fewer particles



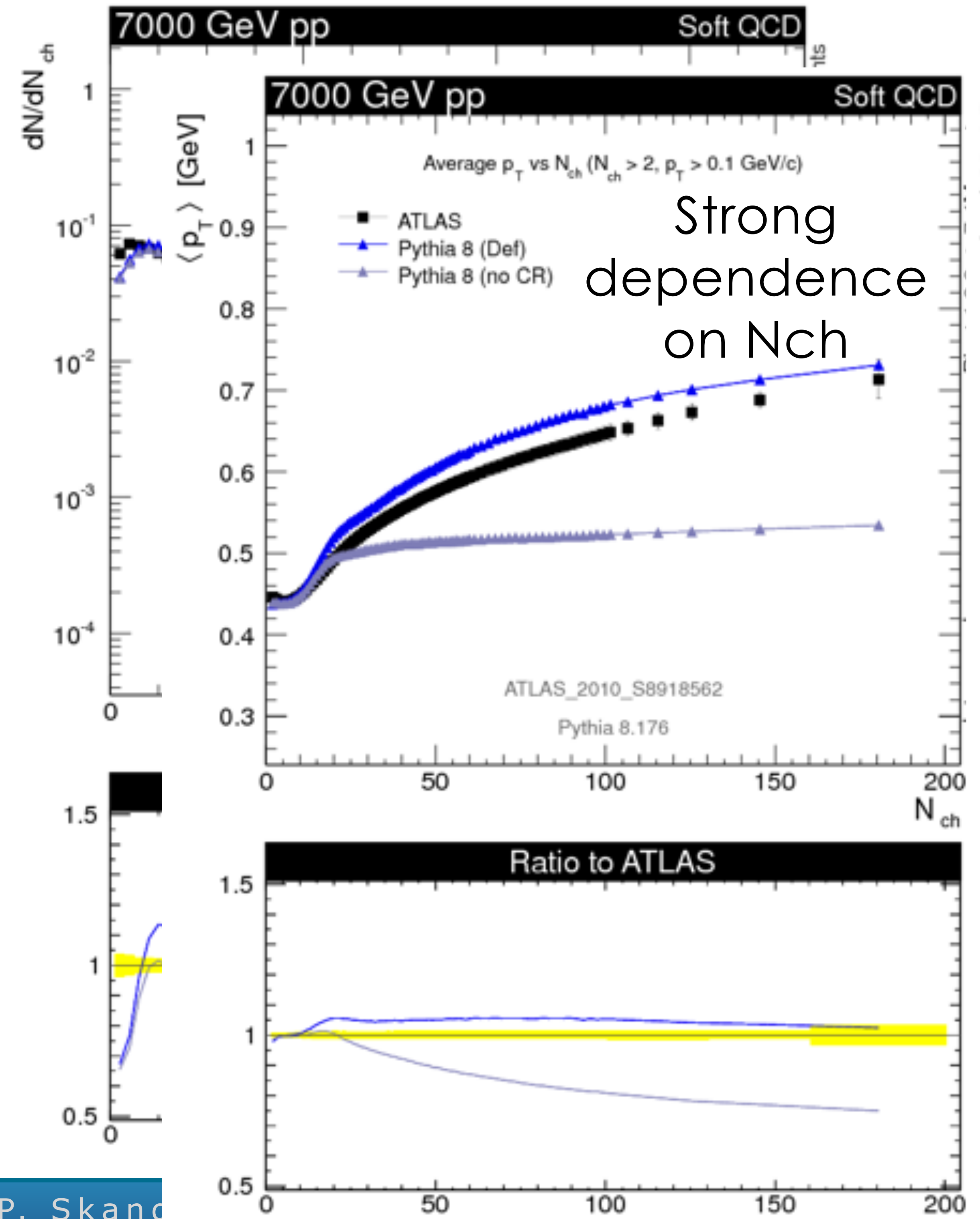
... with higher pT



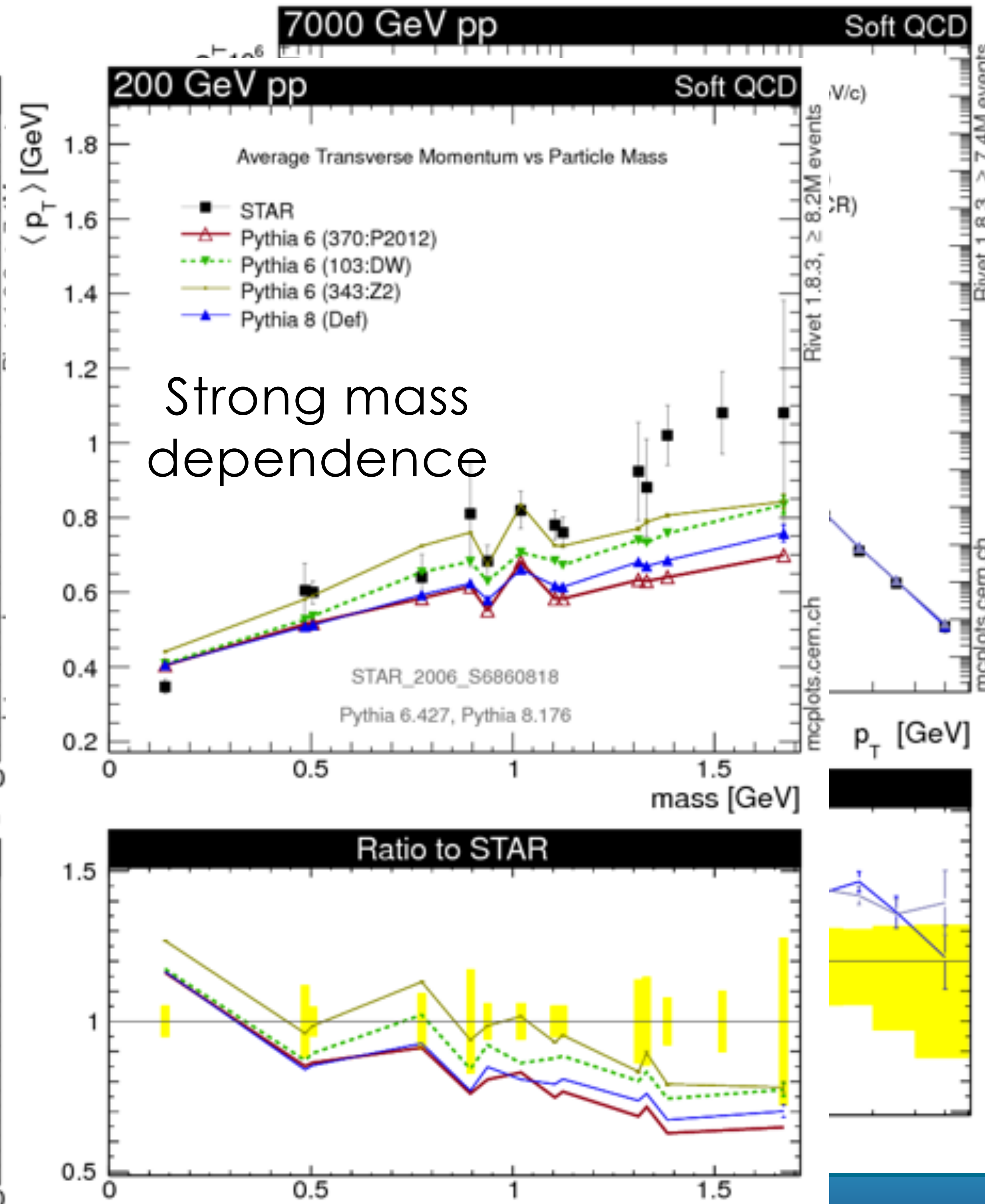
The Effects of CR

(Showing default (old) Pythia 8 CR model here; new one still in progress)

Fewer particles



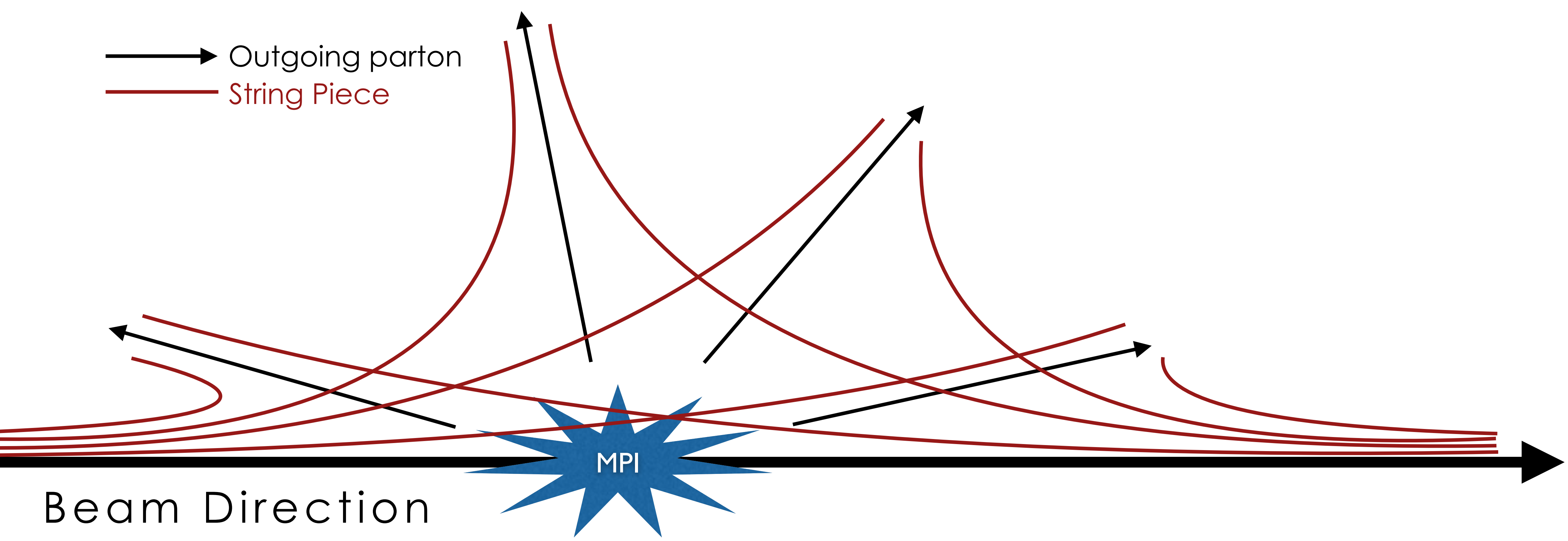
... with higher pT



Collective Flow?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

Without Colour Reconnections
Each MPI hadronizes **independently** of all others

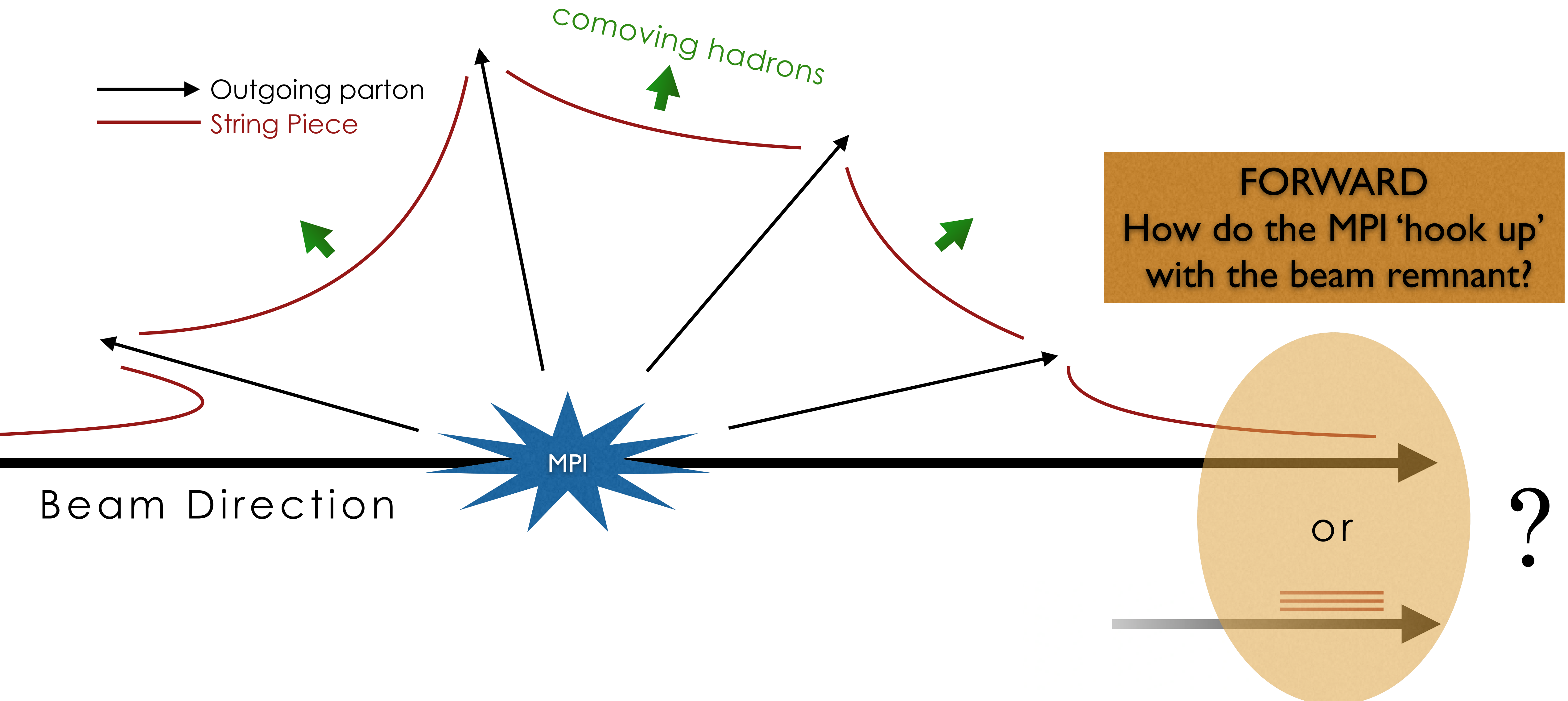


… from boosted strings?

See also Ortiz et al., Phys.Rev.Lett. 111 (2013) 4, 042001

With Colour Reconnections
MPI hadronize **collectively**

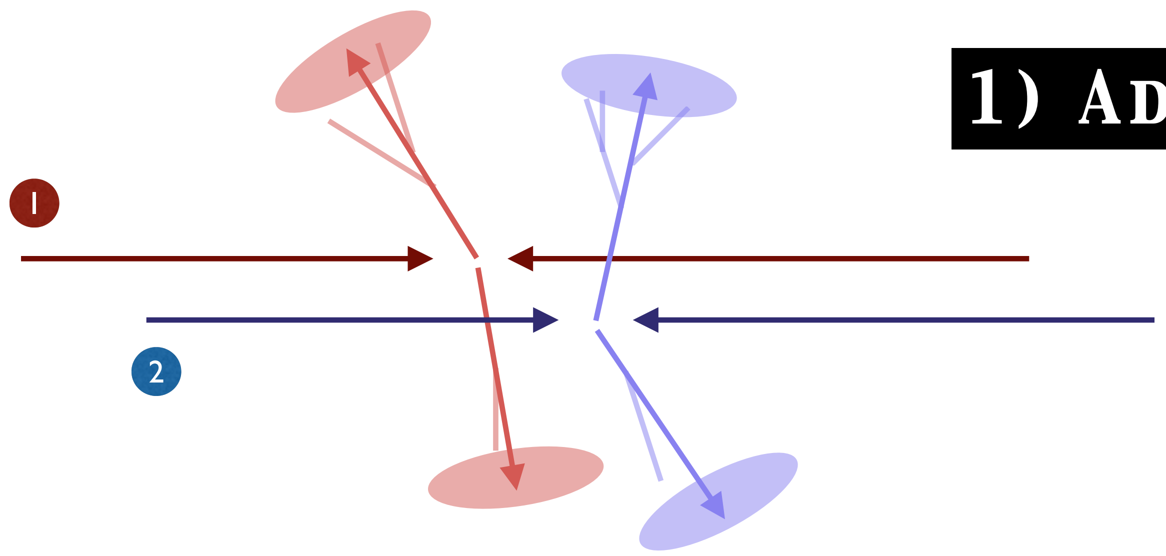
Highly important theory question now
Is there collective flow in pp? Or not?
Is it stringy, or hydrodynamic ? (or …?)



FORWARD
How do the MPI 'hook up' with the beam remnant?

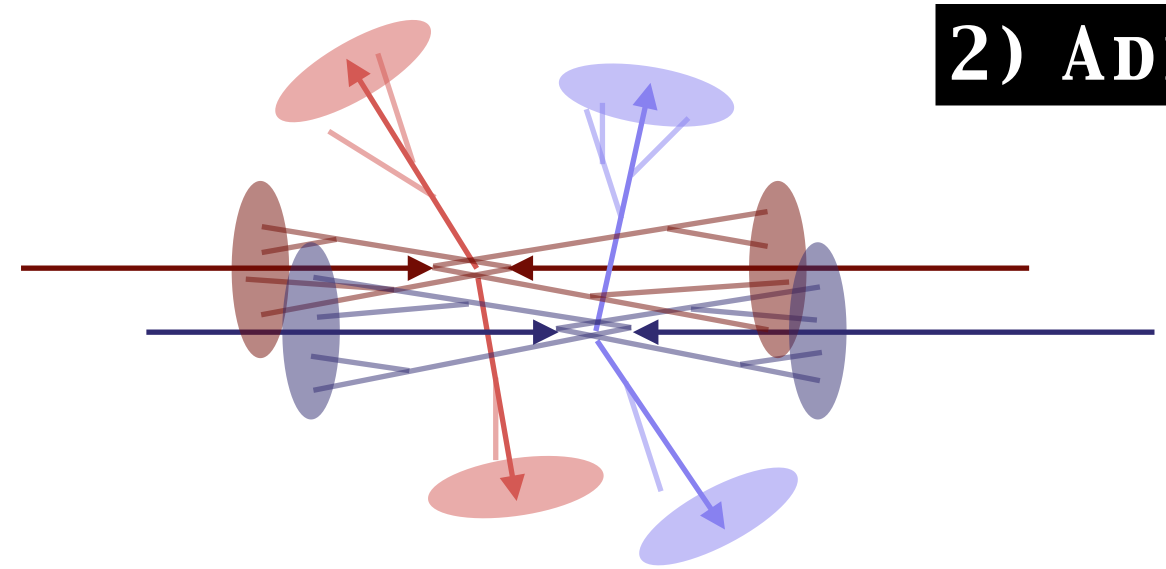
Central vs Forward

Take an extremely simple case of just 2 MPI



1) ADD FINAL-STATE RADIATION

Small overlaps between different jets
: main CR questions are
  inter-jet and jet-beam
: boosted strings etc.



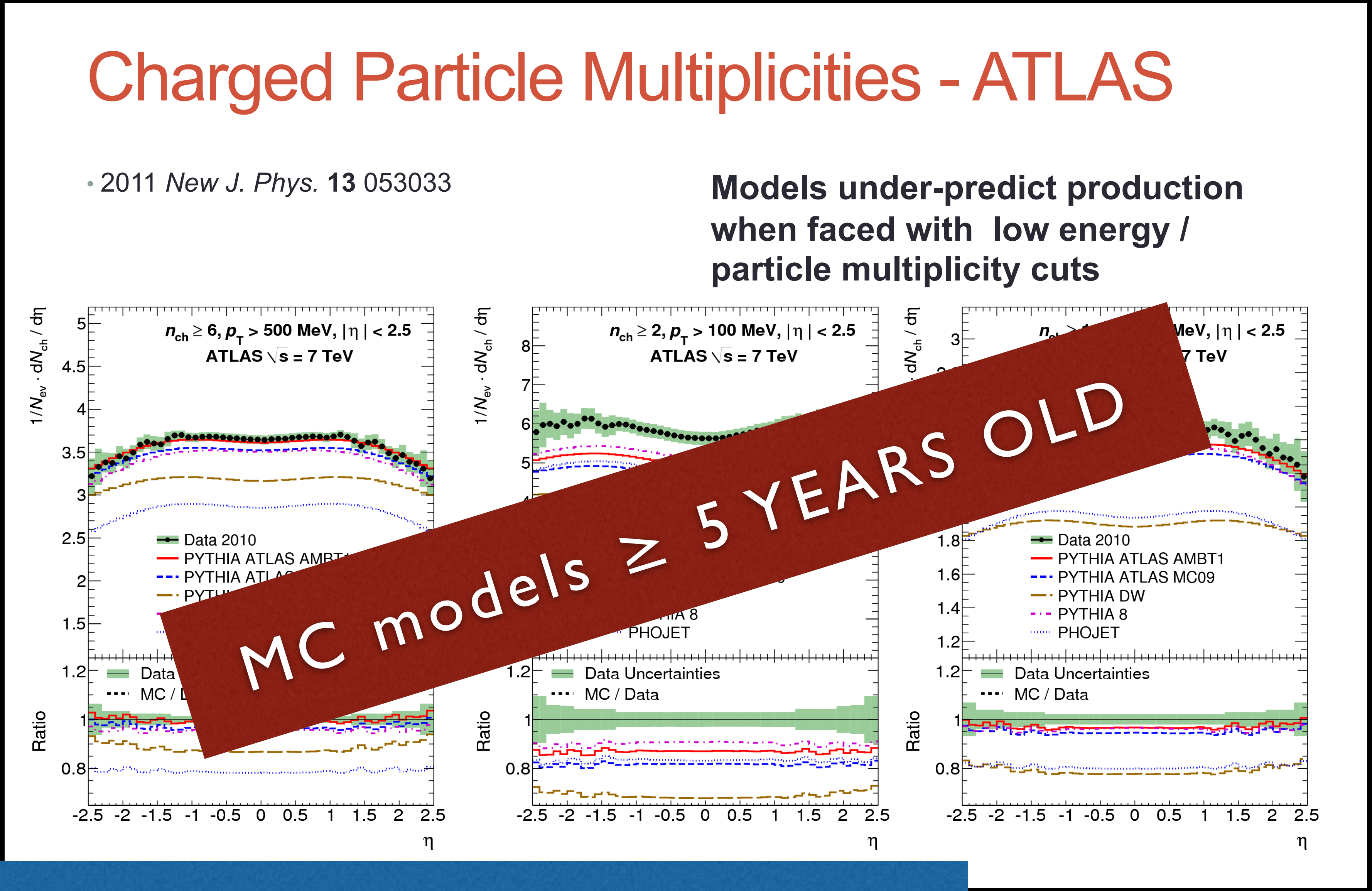
2) ADD INTIAL-STATE RADIATION

All the ISR radiation overlaps!
(each MPI scattering centre must reside within *one* proton radius of all others)
: expect significant 'colour confusion'
: intra-jet CR (unlike central and LEP)
: Strong effects in FWD region
(in addition to low-x gluon / saturation)

Recent Models/Tunes

CR community may not be as up-to-date as LHC community (not a criticism)

But be aware that LHC is ongoing, with very active interpretations & MC modeling efforts



This was indeed an interesting lesson 3-4 years ago.
But not very well representative of current state of the art.

Check e.g.:
mcplots.cern.ch

Recent PYTHIA Models/Tunes

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

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)

Monash 2013 Tune Highlights

Monash 2013 Tune: Skands, Rojo, Carrazza EPJ C74 (2014) 3024: arXiv:1404.5630

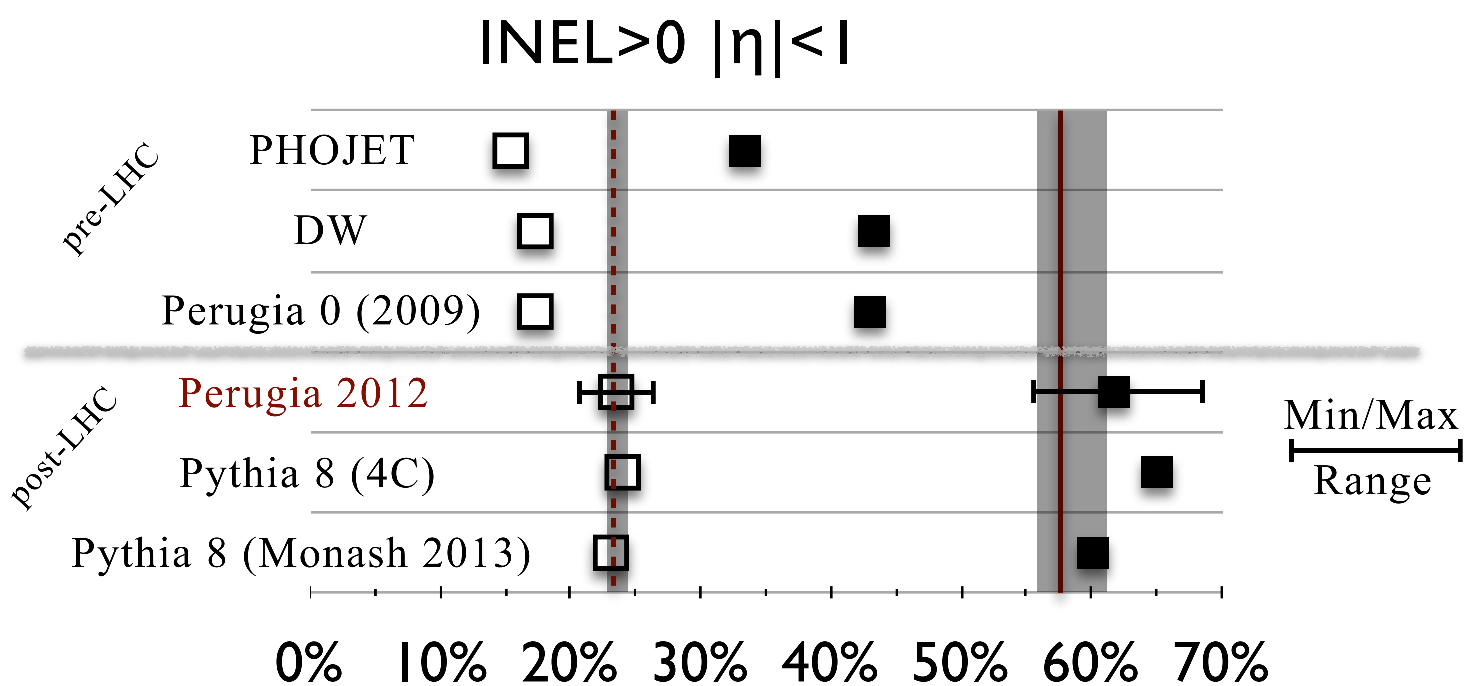
10% more strangeness

Better agreement with ee identified-strange measurements across all LEP energies, and with Kaons at LHC

Better CM-energy Scaling

LHC

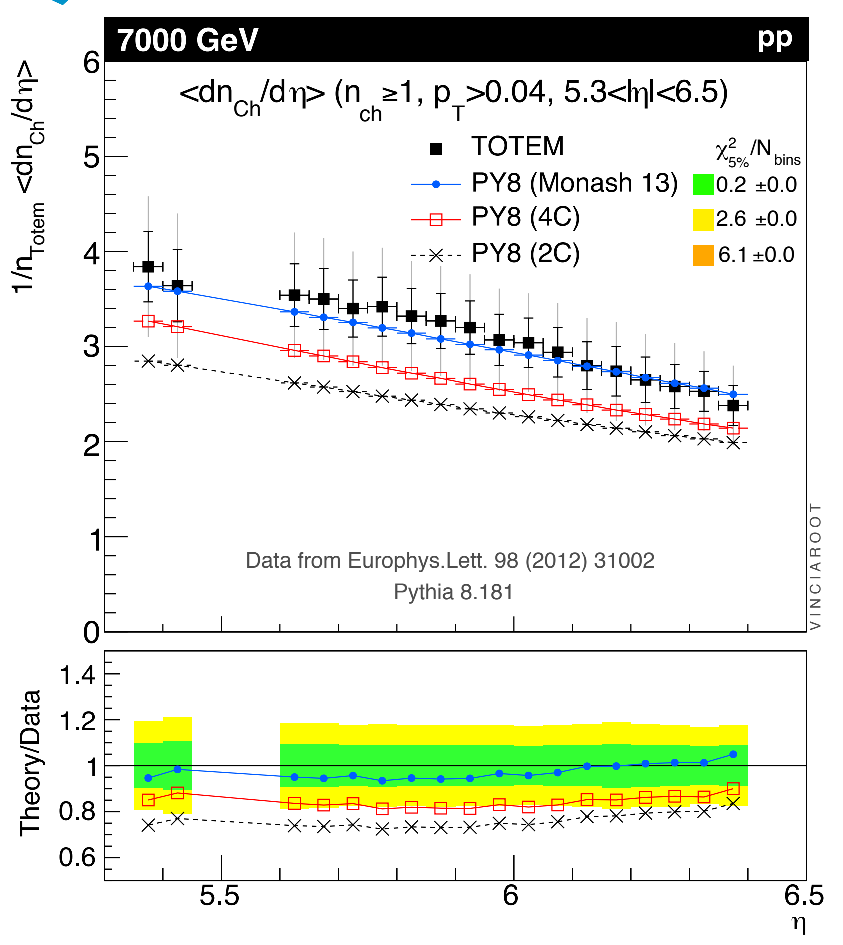
A VERY SENSITIVE E-SCALING PROBE: relative increase in the central charged-track multiplicity from 0.9 to 2.36 and 7 TeV



Data from ALICE EPJ C68 (2010) 345

More forward activity

LHC



Better agreement with TOTEM N_{ch} and with forward E and ET flows. (Note: diffraction still needs tuning, and saturation not explicit)

Set M13 Tune: → in PYTHIA 8	Tune:ee = 7 Tune:pp = 14

Summary & Puzzles

HEP MC Models mainly target (and rooted in) high-p_T perturbative scattering processes

- Jets and Jet Structure (ISR & FSR: parton showers) + hadronization (strings/clusters)

Lesson from Tevatron (Rick Field): Underlying Event mandates MPI

- Already hinted at from AFS, SPS. No doubt after LHC

PYTHIA, HERWIG, and SHERPA all include MPI models

- Under quite active development, mainly in response to LHC
- Also used as basis to model (nondiffractive) minimum-bias

Check e.g.:
mcplots.cern.ch

Lessons from LHC

- Energy scaling is somewhat faster than we thought (larger UE)
- More strangeness (?) and more baryons
- Flow-like spectra? Nch and Mass dependencies. Correlations? (cf RHIC, Tevatron)
- Forward measurements: baryon transport, low-x, forward E, ET, and jets
- The role and modeling of diffraction, from low to high masses? Gap fractions.

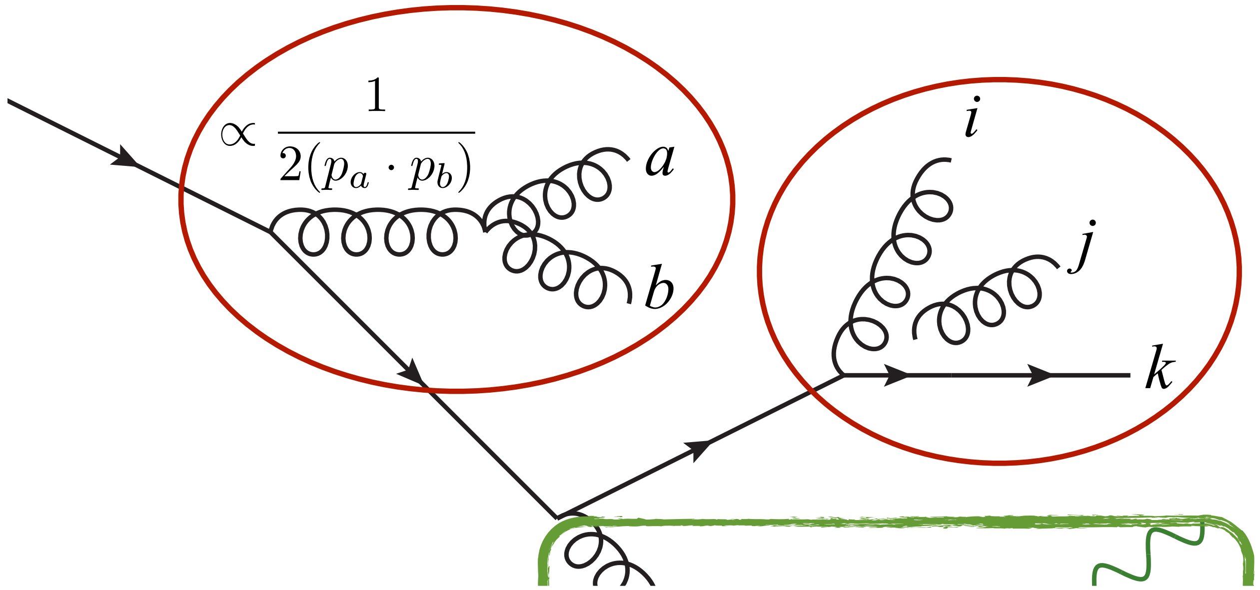
Quo Vadis?

- Understand process of color neutralization (CR) vs hydro flow?
- Spacetime picture of MPI
- Understand connection with initial state: saturation, color-glass condensates?

ISR & FSR: Jets ≈ Fractals

Most bremsstrahlung is driven by divergent propagators → simple structure

Amplitudes factorize in singular limits (→ universal "conformal" or "fractal" structure)



Partons ab → "collinear":

P(z) = DGLAP splitting kernels, with z = energy fraction = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \overset{a||b}{\rightarrow} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j → "soft":

Coherence → Parton j really emitted by (i,k) "colour antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \overset{j_g\to 0}{\rightarrow} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

+ scaling violation: $g_s^2 \rightarrow 4\pi\alpha_s(Q^2)$

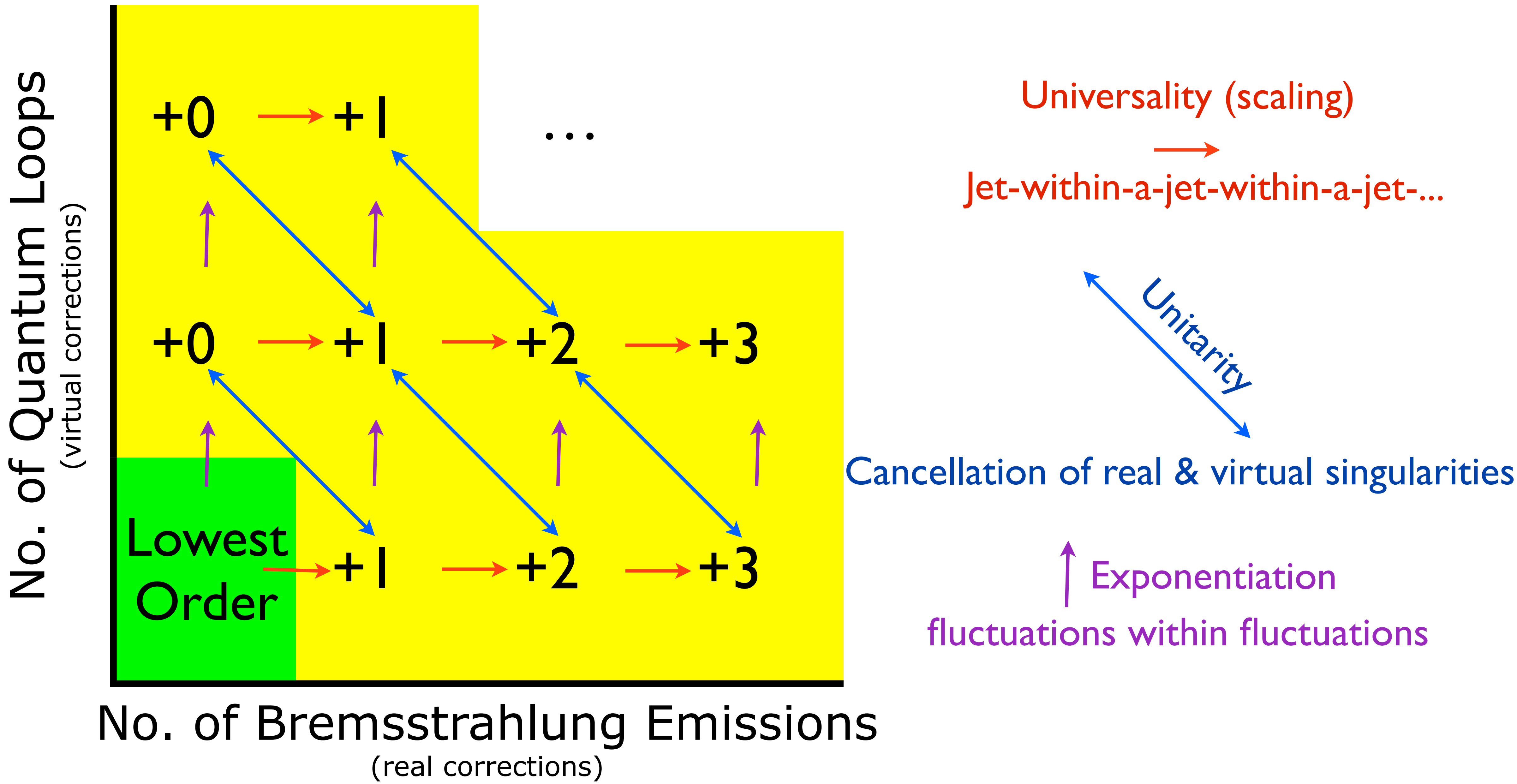
Can apply this many times
→ nested factorizations

See: PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Bootstrapped Perturbation Theory

Start from an **arbitrary lowest-order** process (green = QFT amplitude squared)

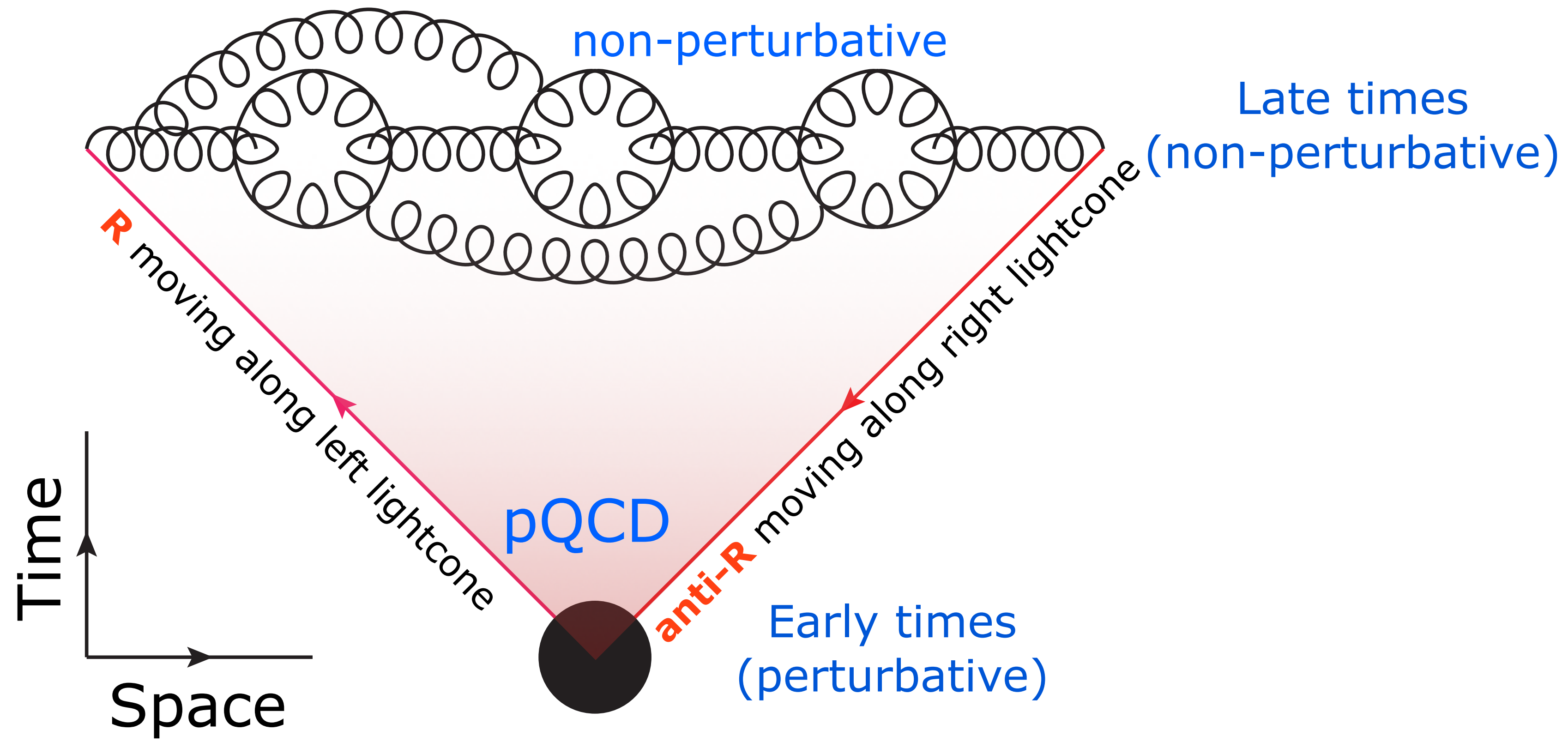
Parton showers generate the bremsstrahlung terms of the rest of the perturbative series (approximate infinite-order resummation)



Colour Neutralization

A physical hadronization model

Should involve at least **2** partons, with opposite color charges (e.g., **R** and **anti-R**)

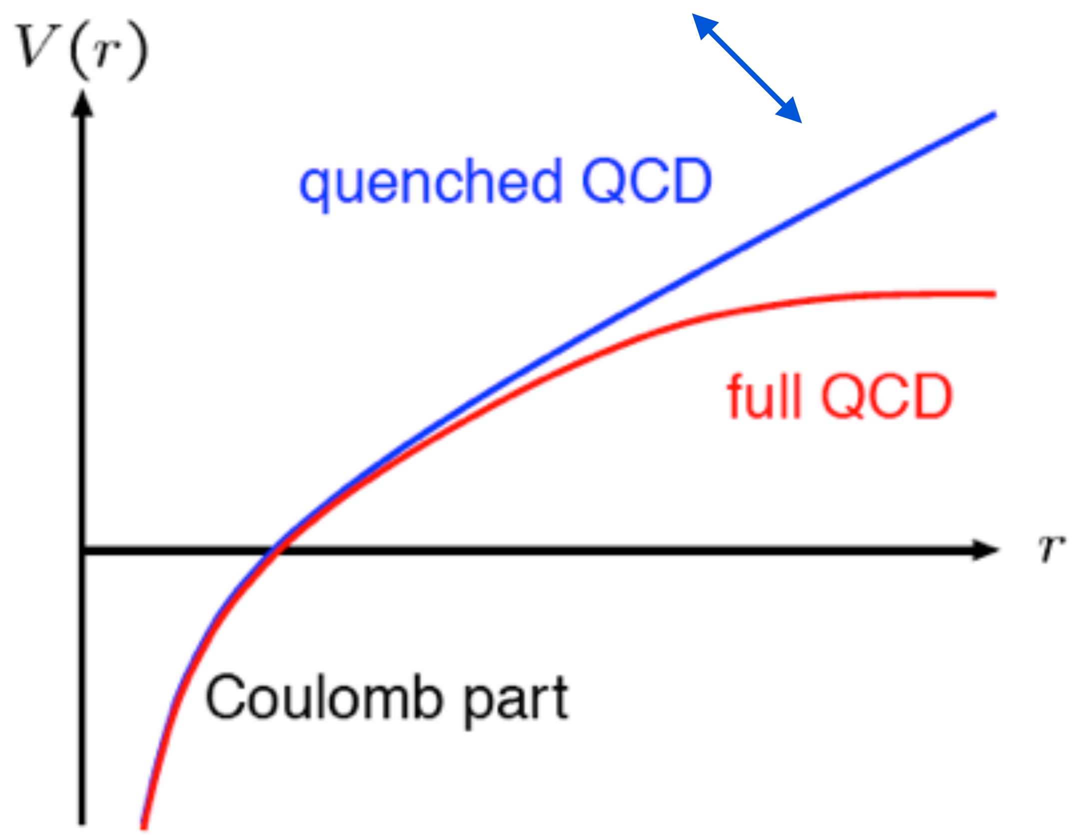


Strong "confining" field emerges between the two charges when their separation > ~ 1fm

Linear Confinement → Strings

Lattice QCD

Linear potential (without string breaks)

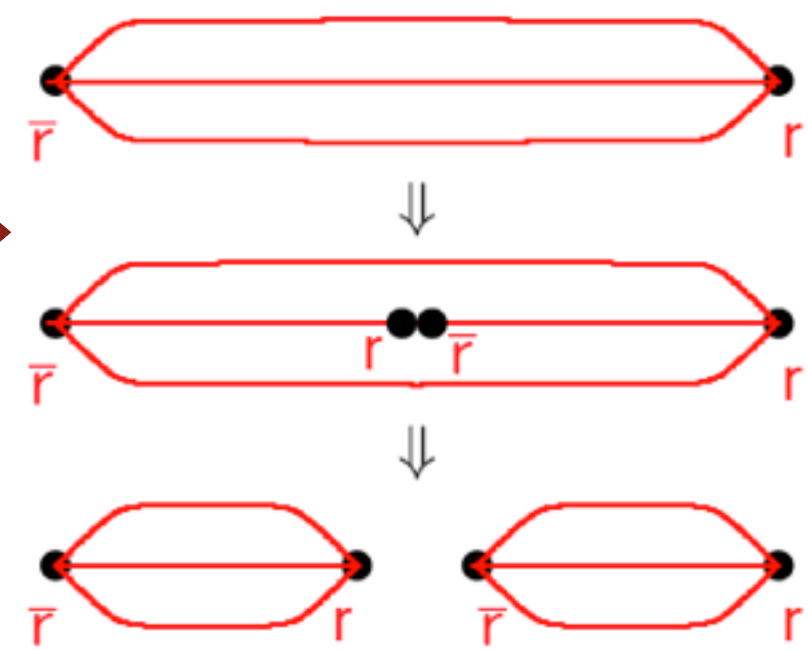


$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r$

~ Force required to lift a 16-ton truck

Lund Model

+ string breaks via Quantum Tunneling



(simplified colour representation)

$$\mathcal{P} \propto \exp\left(\frac{-m_q^2 - p_\perp^2}{\kappa/\pi}\right)$$

→ Gaussian p_T spectrum (string tension = tuning parameter)
→ Heavier quarks suppressed. Prob(q=d,u,s,c) ≈ 1 : 1 : 0.2 : 10^{-11}

Illustrations by T. Sjöstrand

Iterative String Breaks

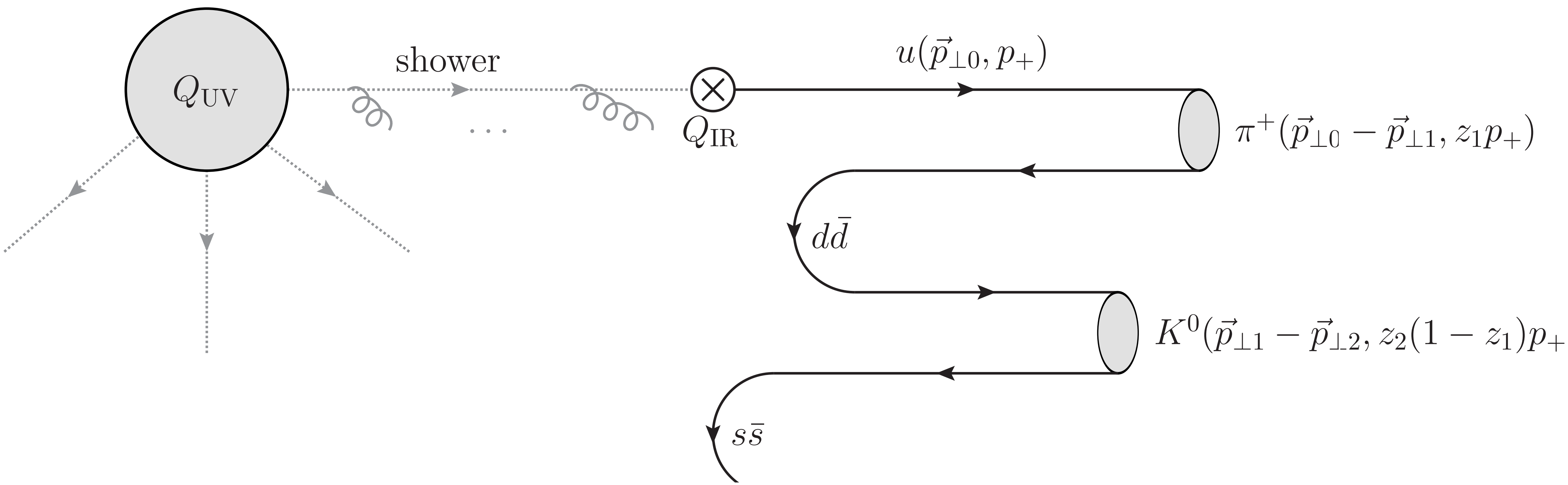
… the fragmentation of a fast parton into a jet …

Iterate String → Hadron + String'

Causality + Left-Right Symmmetry:

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Lund Symmetric String Fragmentation Function



The Lund

Low-x Issues (in MC/PDF context)

Low x : parton carries tiny fraction of beam energy.

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

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

Higher *x* : momenta > Λ_{QCD}

→ pQCD ~ OK

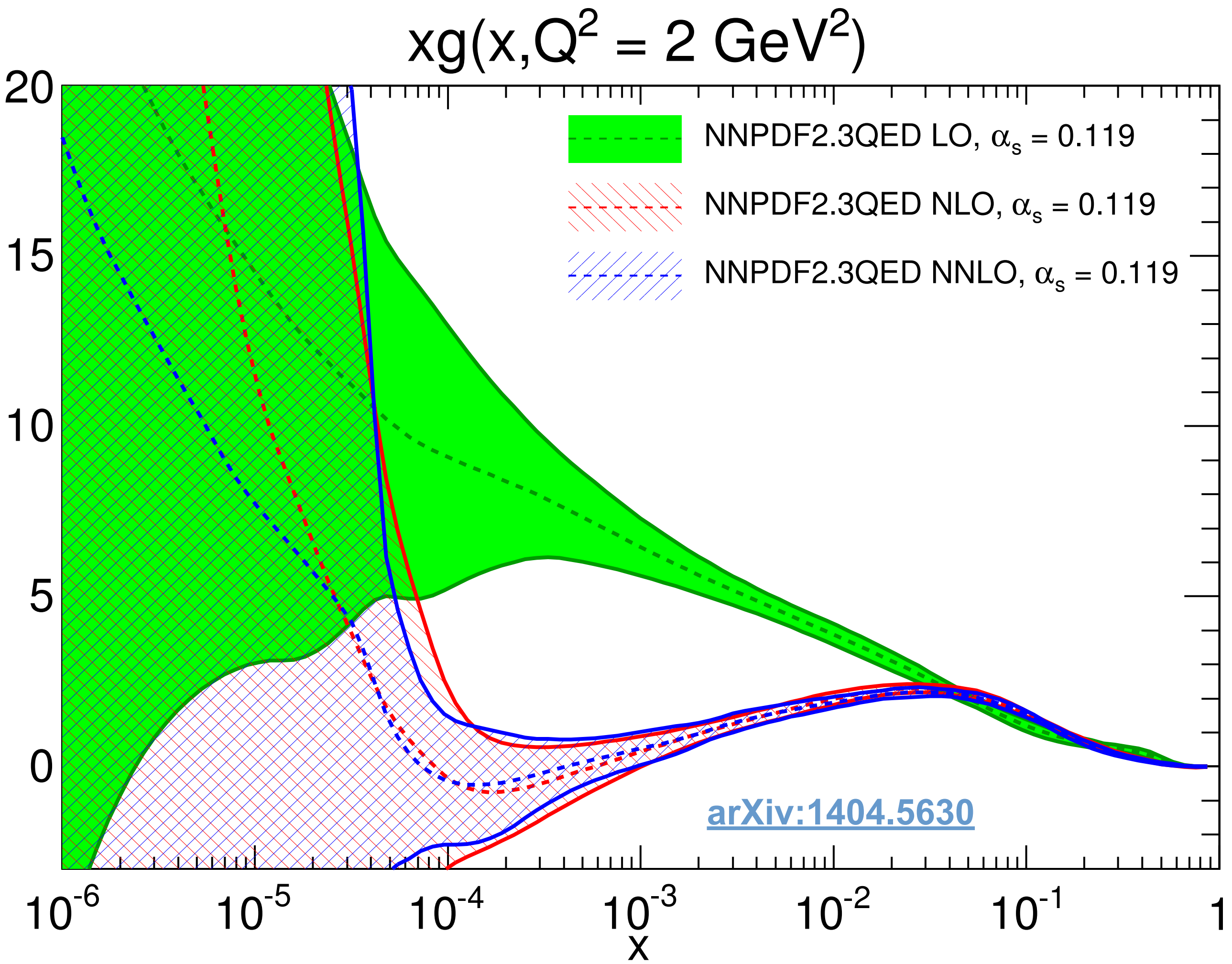
Smaller *x* : strong non-perturbative / colour-screening / saturation effects expected

What does a PDF even mean?

Highly relevant for MPI (& ISR)

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

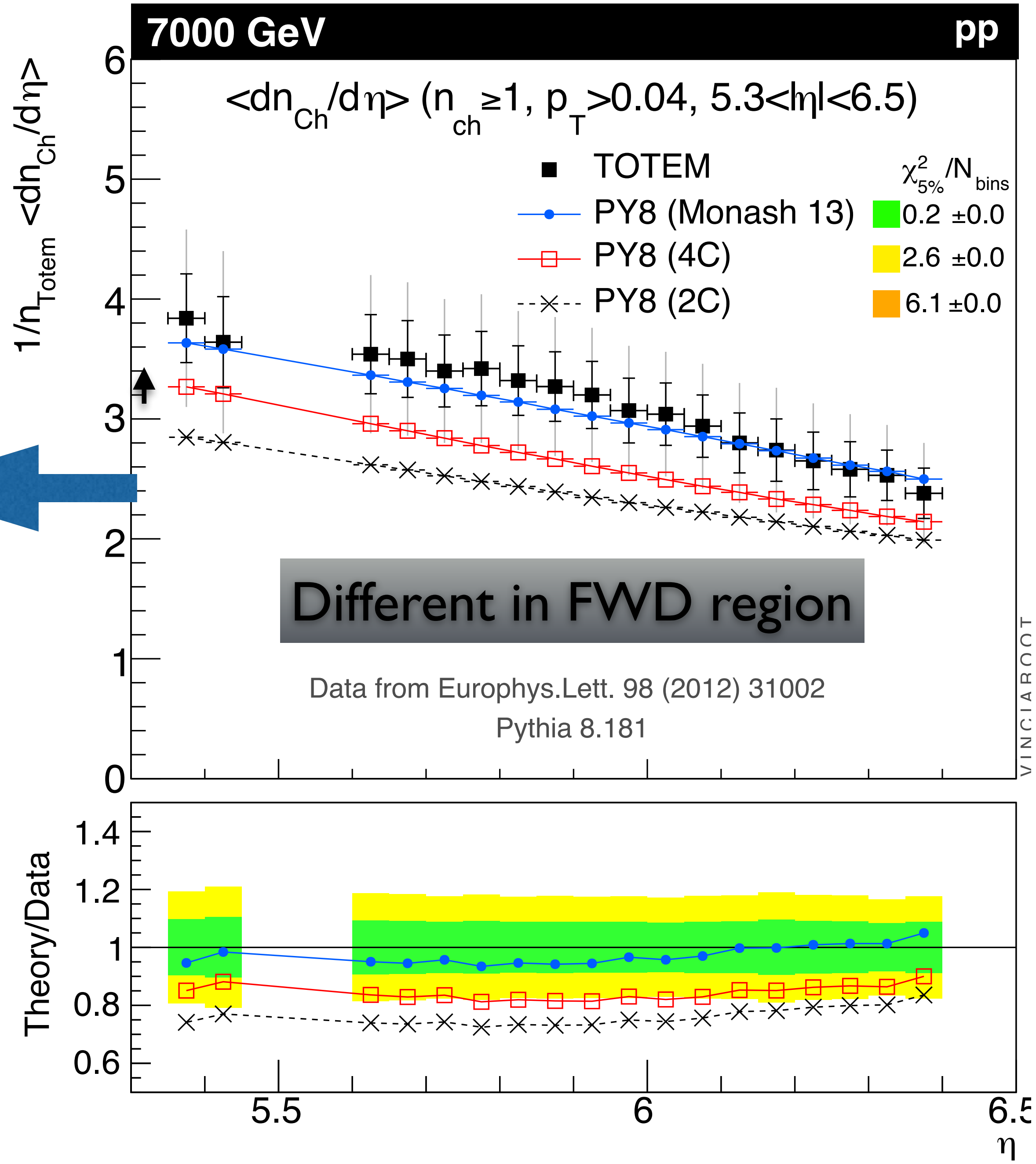
(+ Constraints below x ~ 10^{-4} essentially just momentum conservation + flavour sum rules)

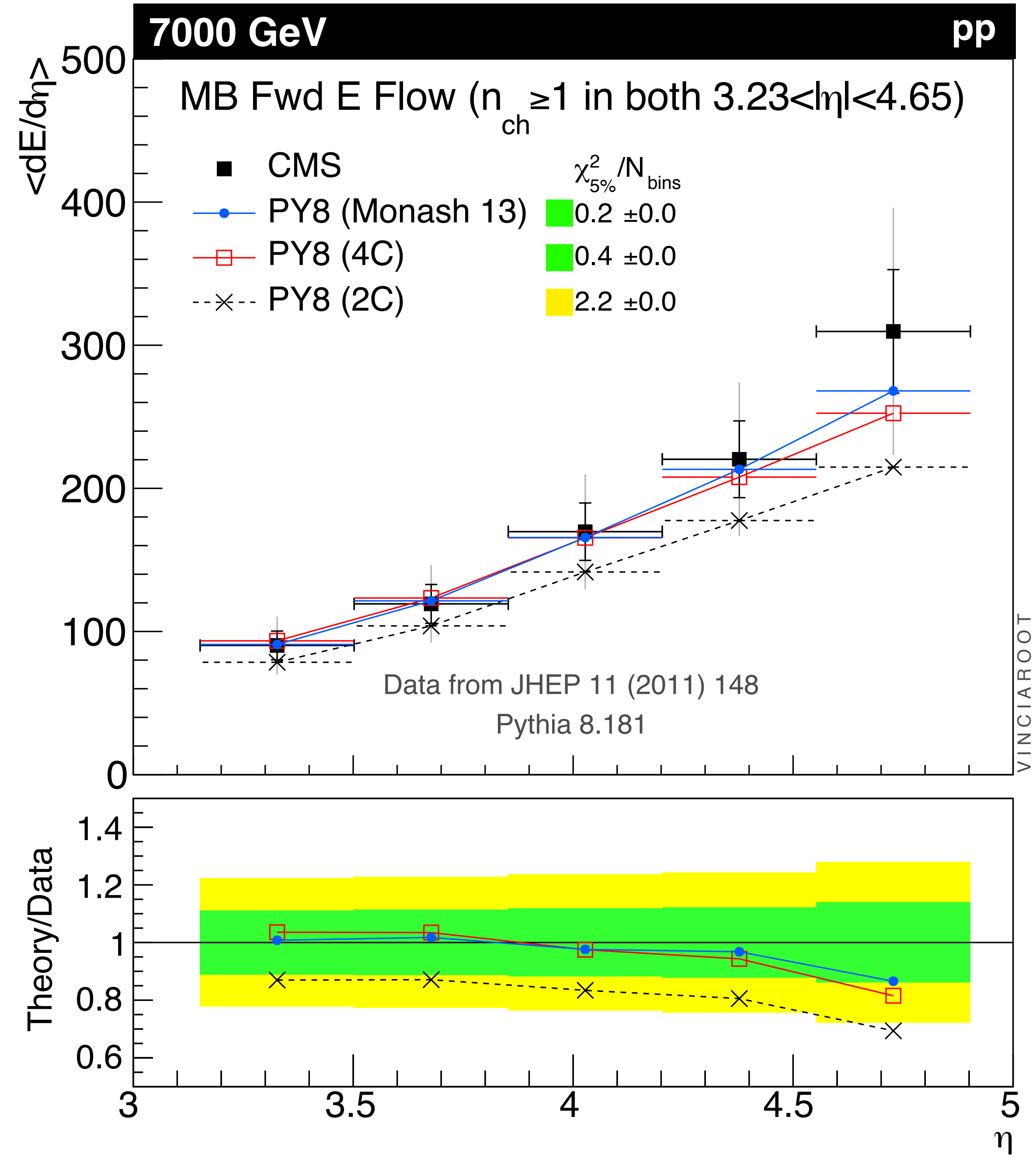


Examples: Nch and E Flow

4C and Monash 13 ~ same in central region

2<η<4.8 (LHCb): Eur. Phys. J. C: 74, 2014





Depends on low-x gluon PDF and on CR/remnant modeling → constraints!