Hadronization & Underlying Event

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Lecture Notes:
P. Skands, arXiv:1207.2389

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Lecture 3

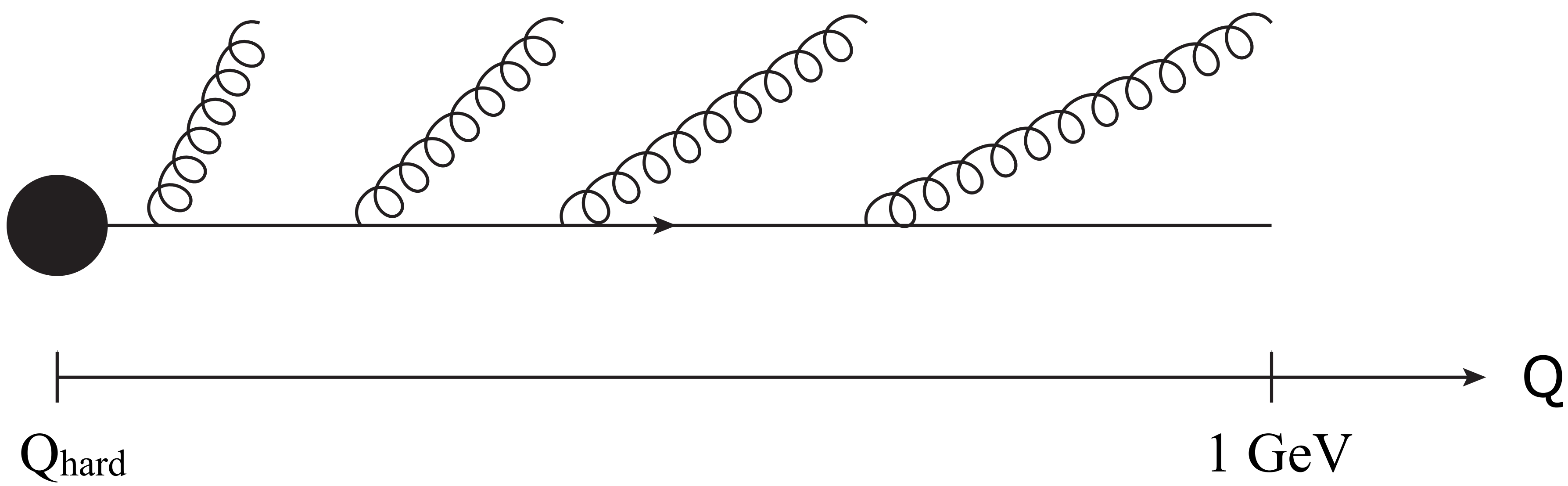
From Partons to Pions

Here's a fast parton

Fast: It starts at a high factorization scale
$Q = Q_F = Q_{hard}$

It showers (perturbative bremsstrahlung)

It ends up at a low effective factorization scale
$Q \sim m_\rho \sim 1$ GeV



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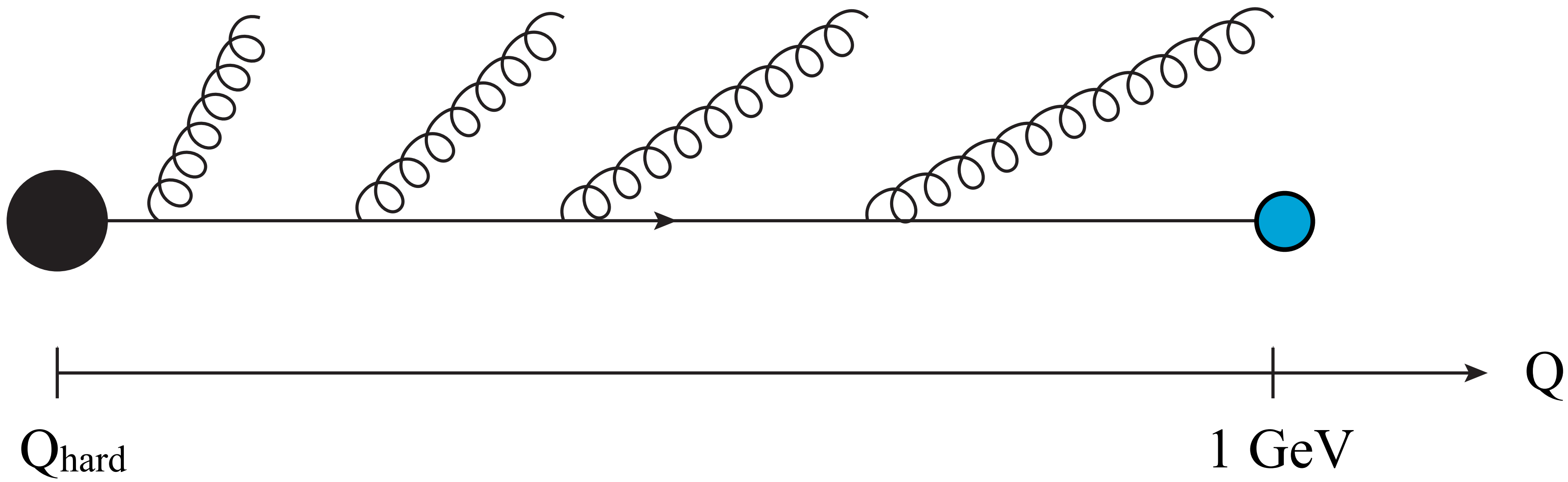


How about I just call it a hadron?

→ "Local Parton-Hadron Duality"

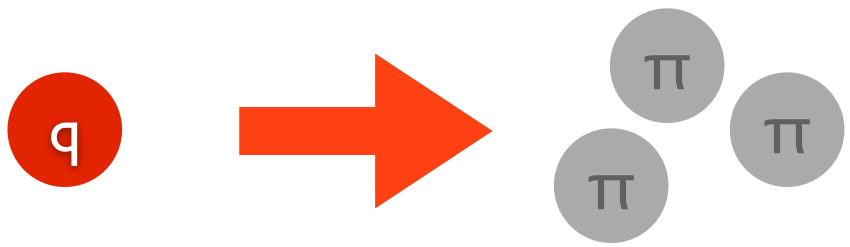
(captures the notion that a certain - perturbatively determined - amount of momentum goes in a certain direction and then just needs to be converted to hadrons, which involves kicks of at most order Λ_{QCD})

Parton → Hadrons?

Early models: "Independent Fragmentation"

Local Parton Hadron Duality (LPHD) can give useful results for **inclusive** quantities in collinear fragmentation

Motivates a simple model:



But ...

The point of confinement is that partons are coloured

Hadronization = the process of colour neutralization

→ Unphysical to think about independent fragmentation of a single parton into hadrons

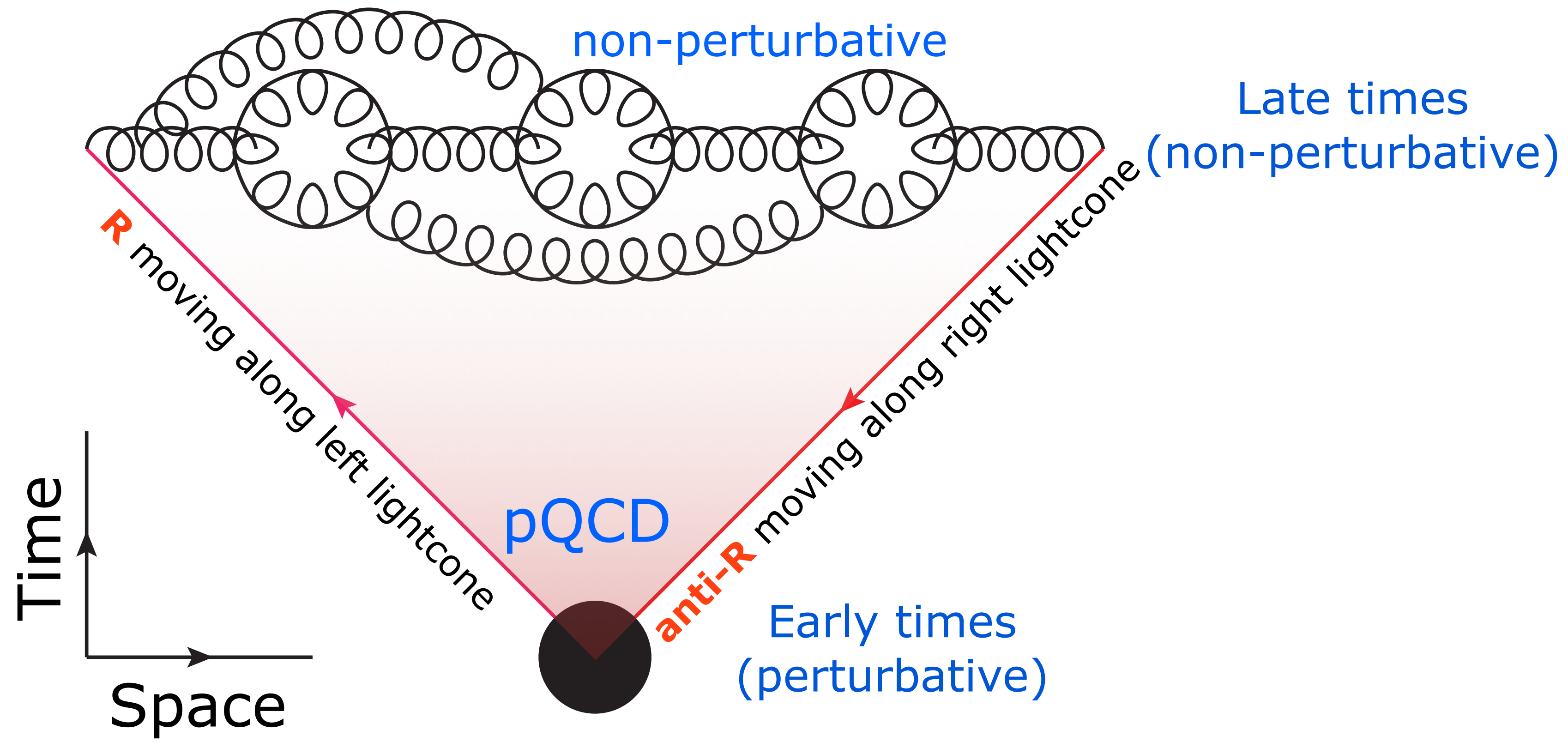
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

Colour Neutralization

A physical hadronization model

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



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

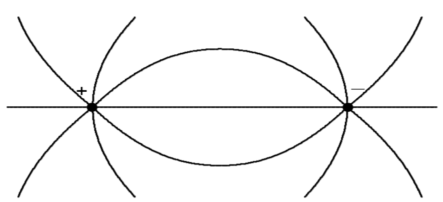
Confinement

Quark-Antiquark Potential

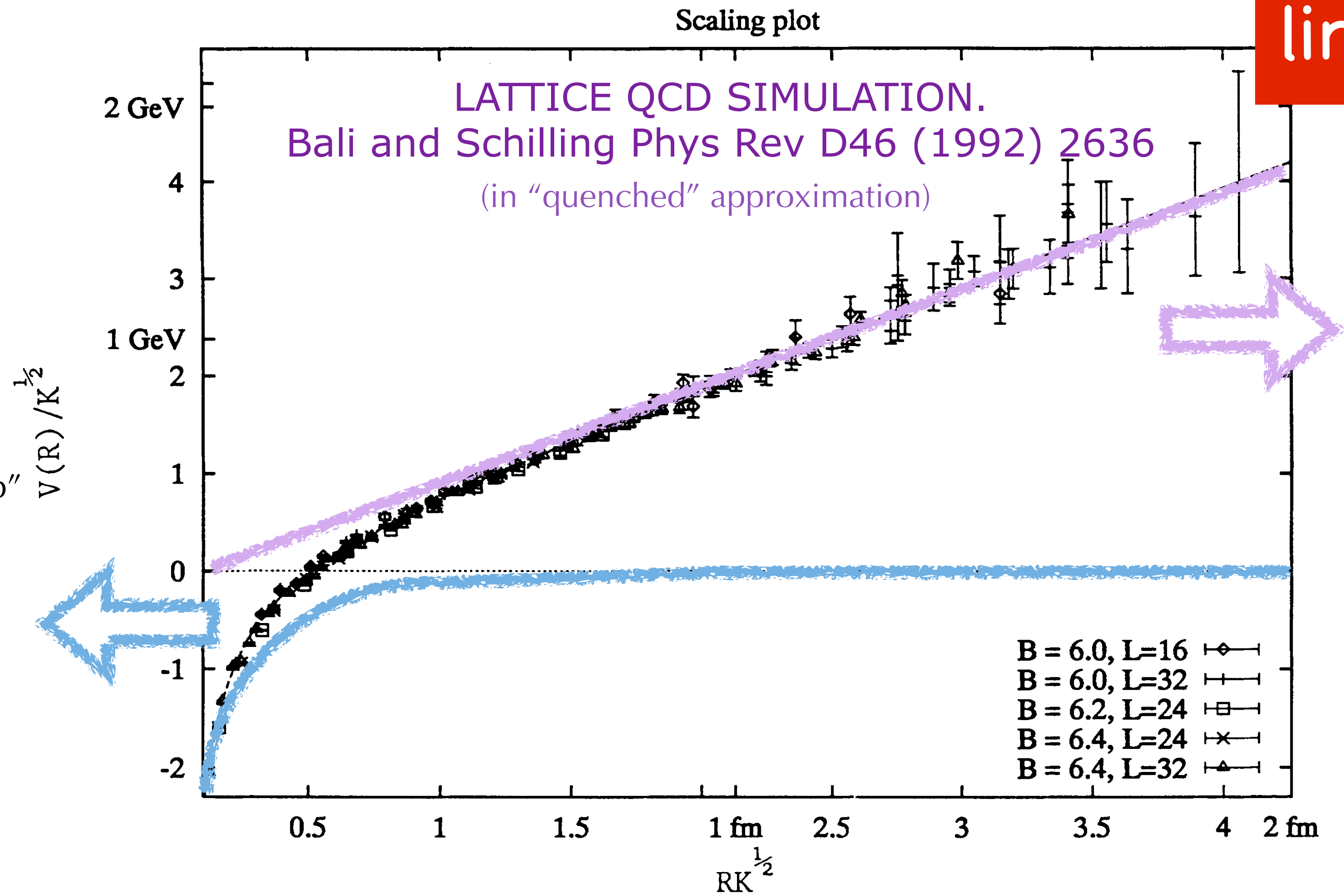
As function of separation distance

What physical system has a linear potential?

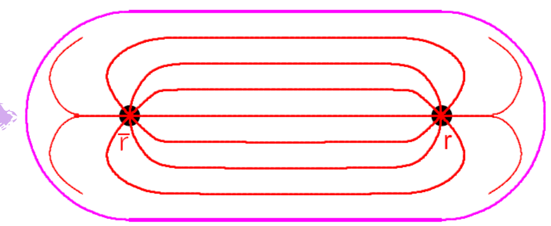
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential

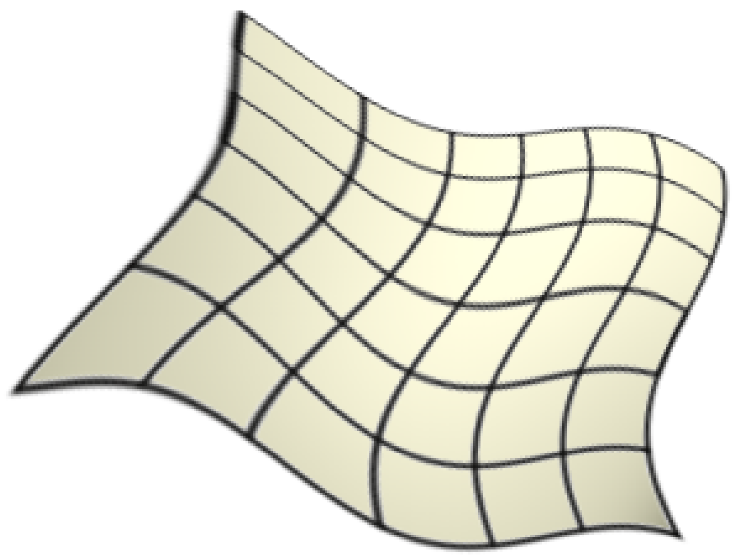


"Confined" Partons
(a.k.a. Hadrons)

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

~ Force required to lift a 16-ton truck

From Partons to Strings



Motivates a model:

Let color field collapse into a (infinitely) narrow flux tube of uniform energy density $\kappa \sim 1$ GeV / fm

→ Relativistic 1+1 dimensional worldsheet – string

Pedagogical Review: B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

String Breaks

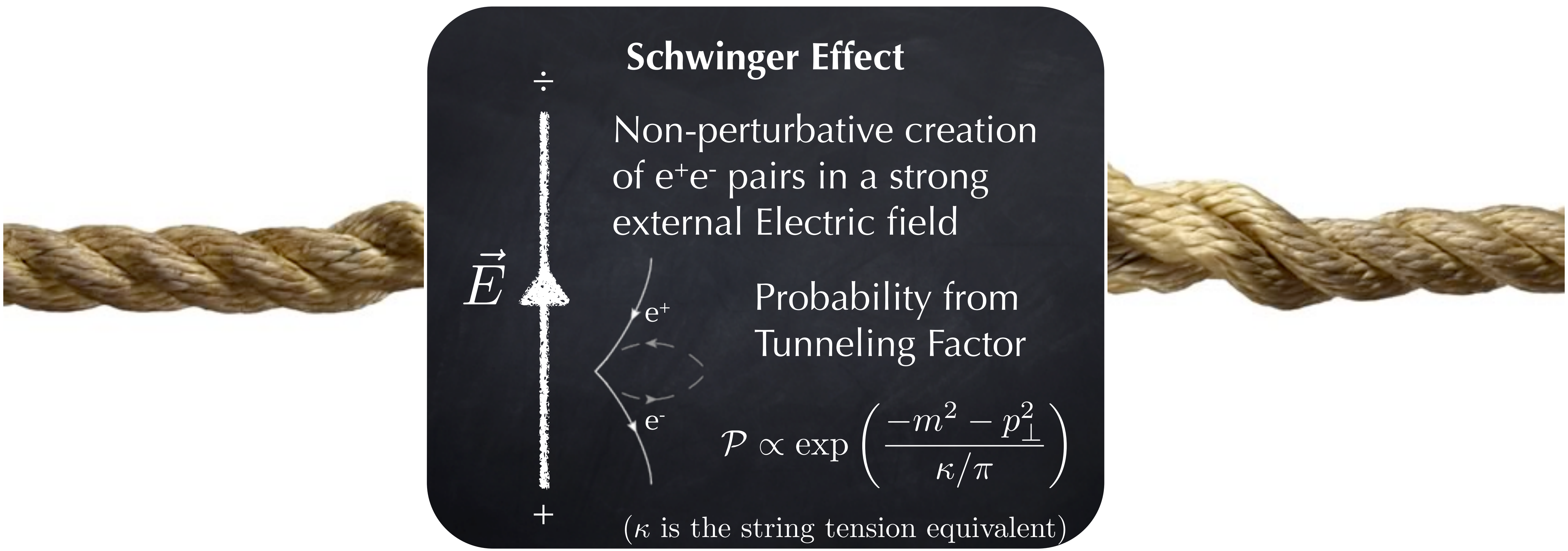
In real QCD, strings can (and do) break!

(In superconductors, would require magnetic monopoles)

In QCD, the roles of electric and magnetic are reversed

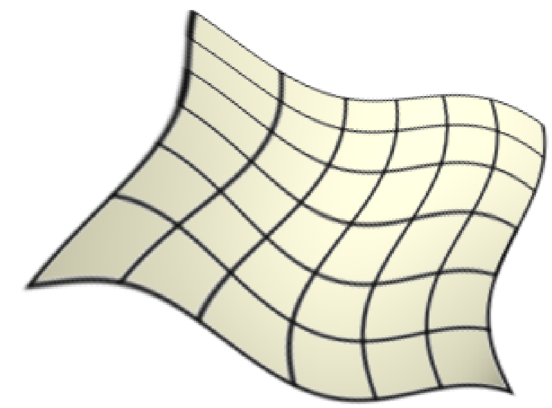
Quarks (and antiquarks) are "chromoelectric monopoles"

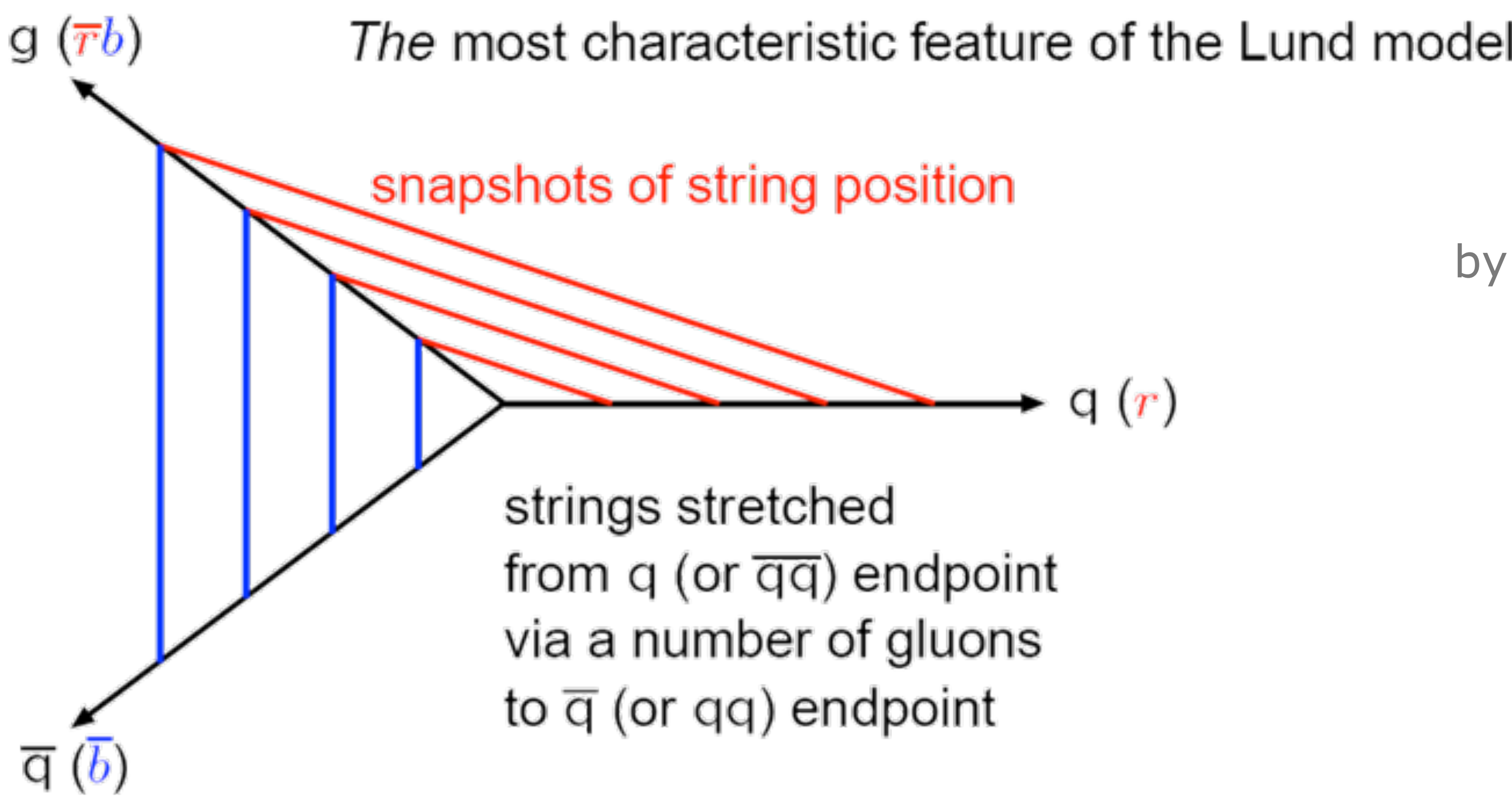
Physical analogy for string breaks: quantum tunnelling



The "Lund" String

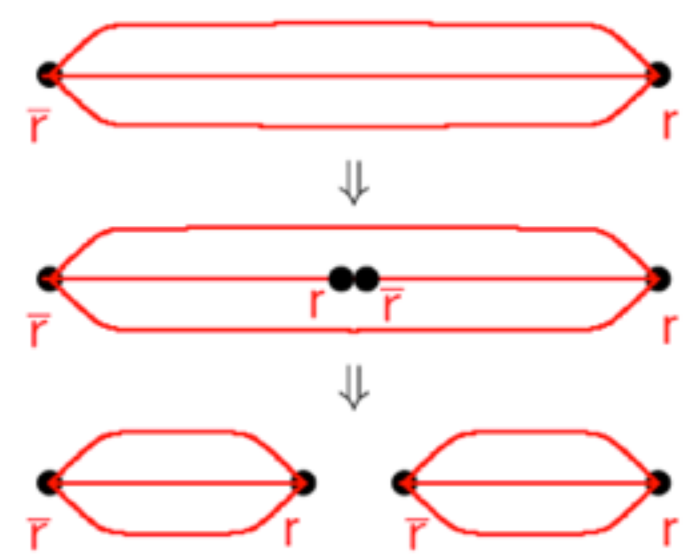
- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)





Gluon = kink on string, carrying energy and momentum

String Breaks
by Tunneling (a la Schwinger)



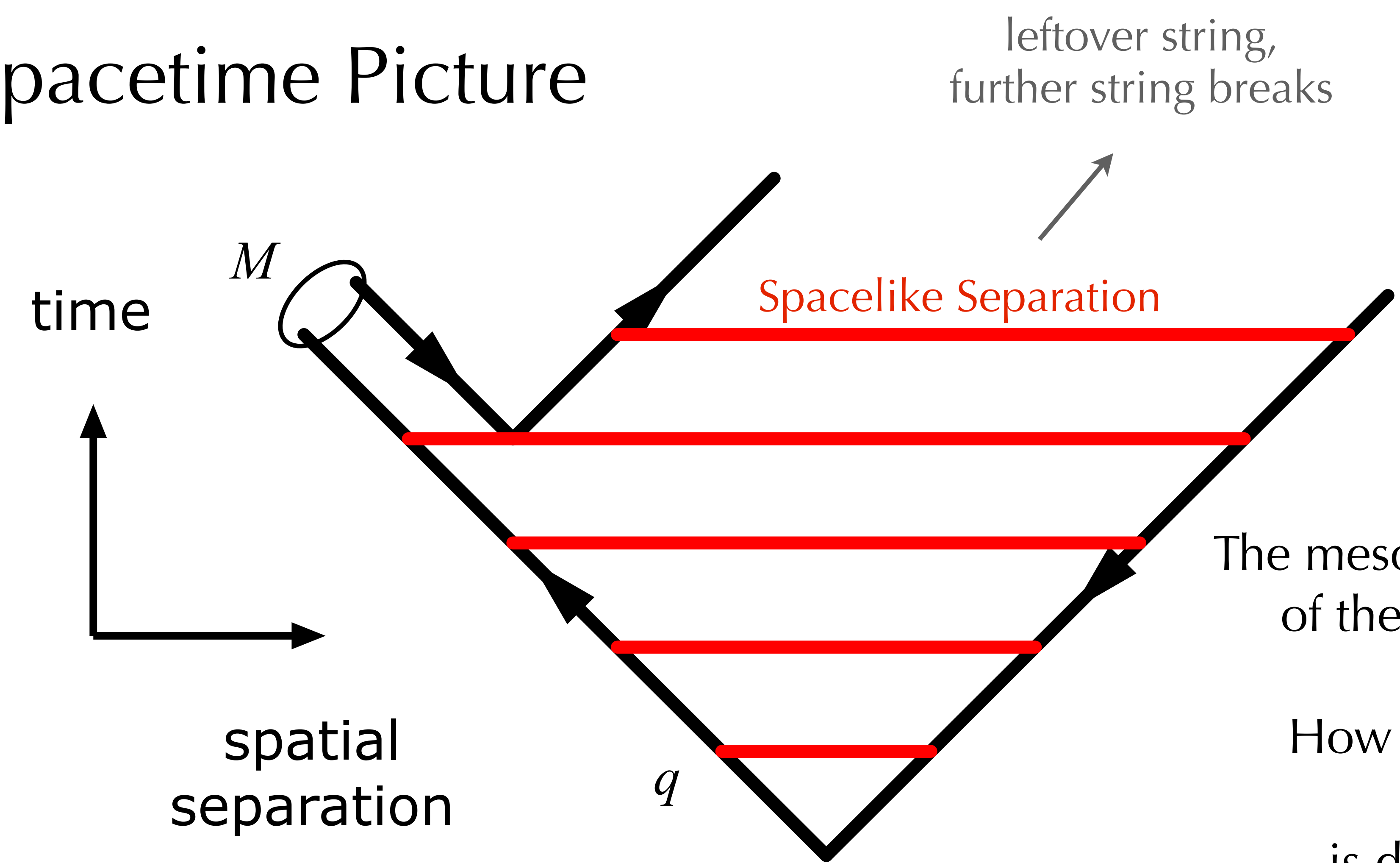
- Probability of string break constant per unit area → **AREA LAW**
- Breakup vertices causally disconnected → order is irrelevant → iterative algorithm

Fragmentation Function

Having selected a hadron flavor

How much momentum does it take?

Spacetime Picture



The meson M takes a fraction z of the quark momentum,

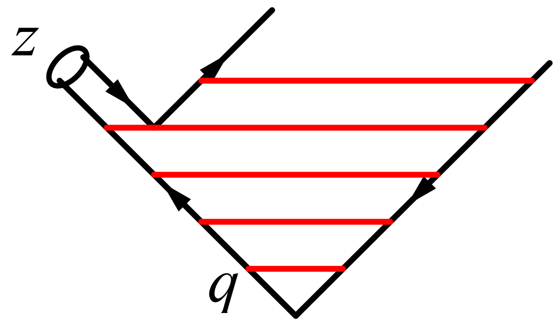
How big that fraction is,
$z \in [0,1]$,
is determined by the
fragmentation function, $f(z,Q_0^2)$

The Lund Fragmentation Function

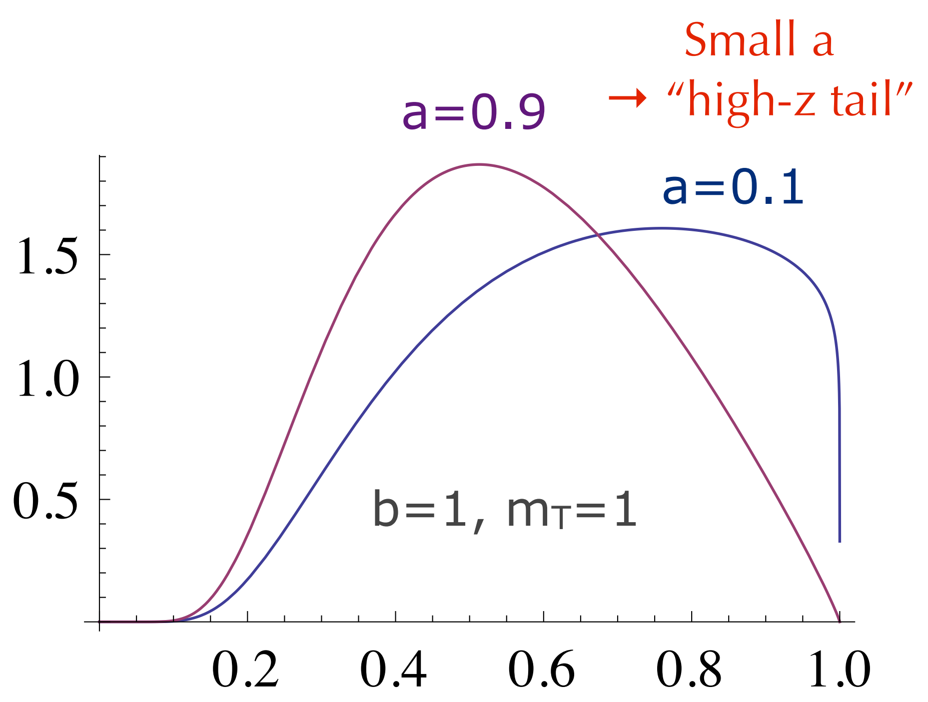
Causality → Left-Right Symmetry

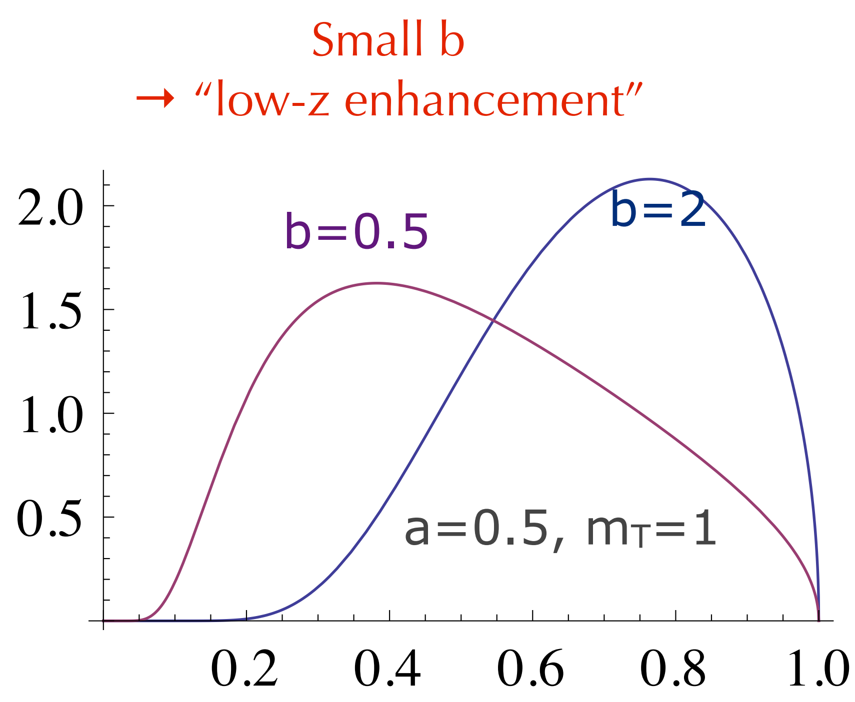
→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function



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

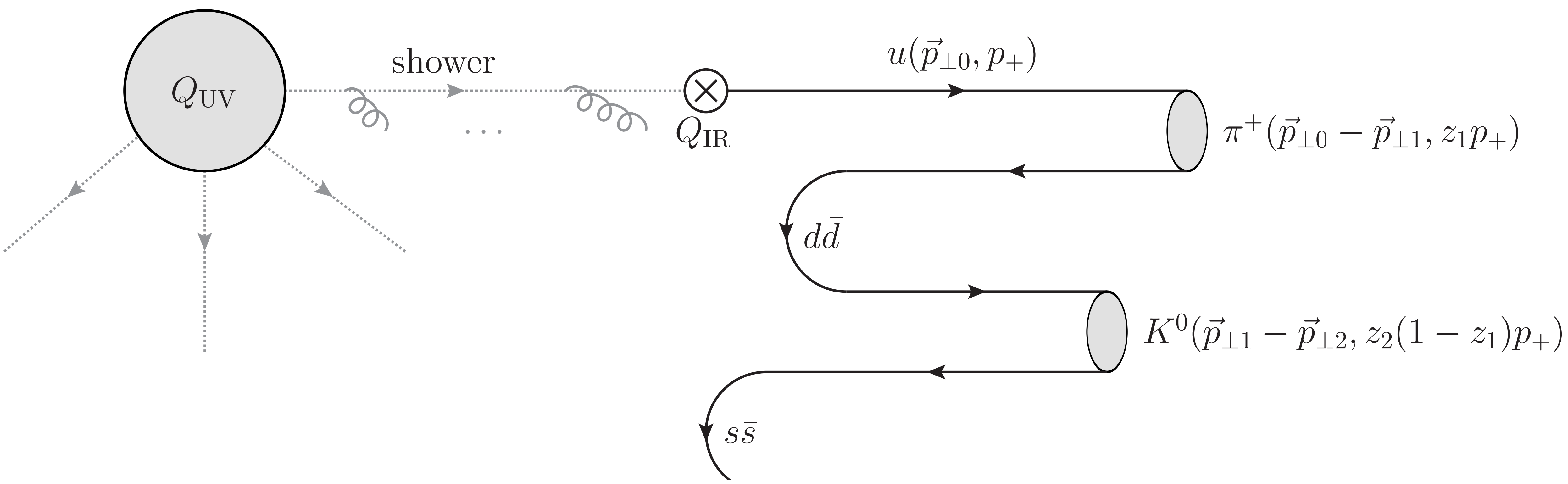




Note: In principle, a can be flavour-dependent. In practice, we only distinguish between baryons and mesons

Iterative String Breaks

Causality → May iterate from outside-in



The Length of Strings

In Space:

String tension ≈ 1 GeV/fm → a 5-GeV quark can travel 5 fm before all its kinetic energy is transformed to potential energy in the string.

Then it must start moving the other way. String breaks will have happened behind it → yo-yo model of mesons

In Rapidity :

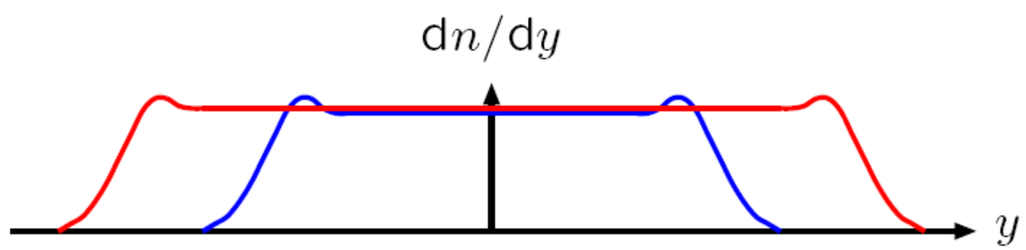
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$$

For a pion with z=1 along string direction (For beam remnants, use a proton mass):

$$y_{\mathrm{max}} \sim \ln\left(\frac{2E_q}{m_\pi}\right)$$

Note: Constant average hadron multiplicity per unit y → logarithmic growth of total multiplicity

Scaling in lightcone $p_\pm = E \pm p_z$ (for q$\overline{\mathrm{q}}$ system along z axis) implies flat central rapidity plateau + some endpoint effects:



$\langle n_{\mathrm{ch}}\rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, ~ Poissonian multiplicity distribution

Alternative: The Cluster Model

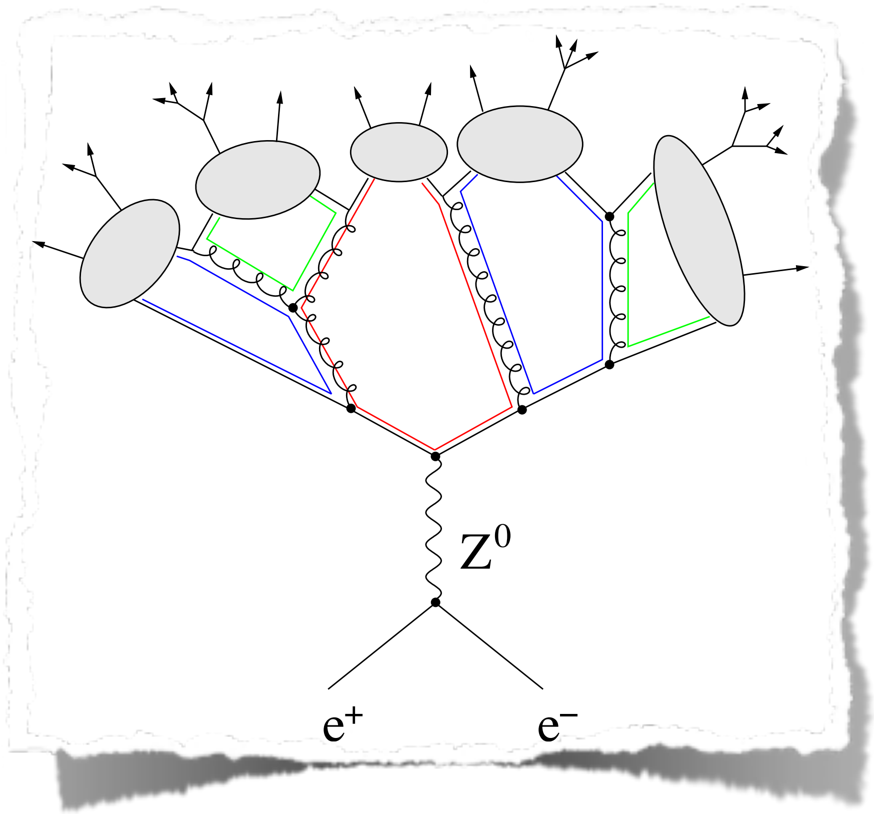
"Preconfinement"

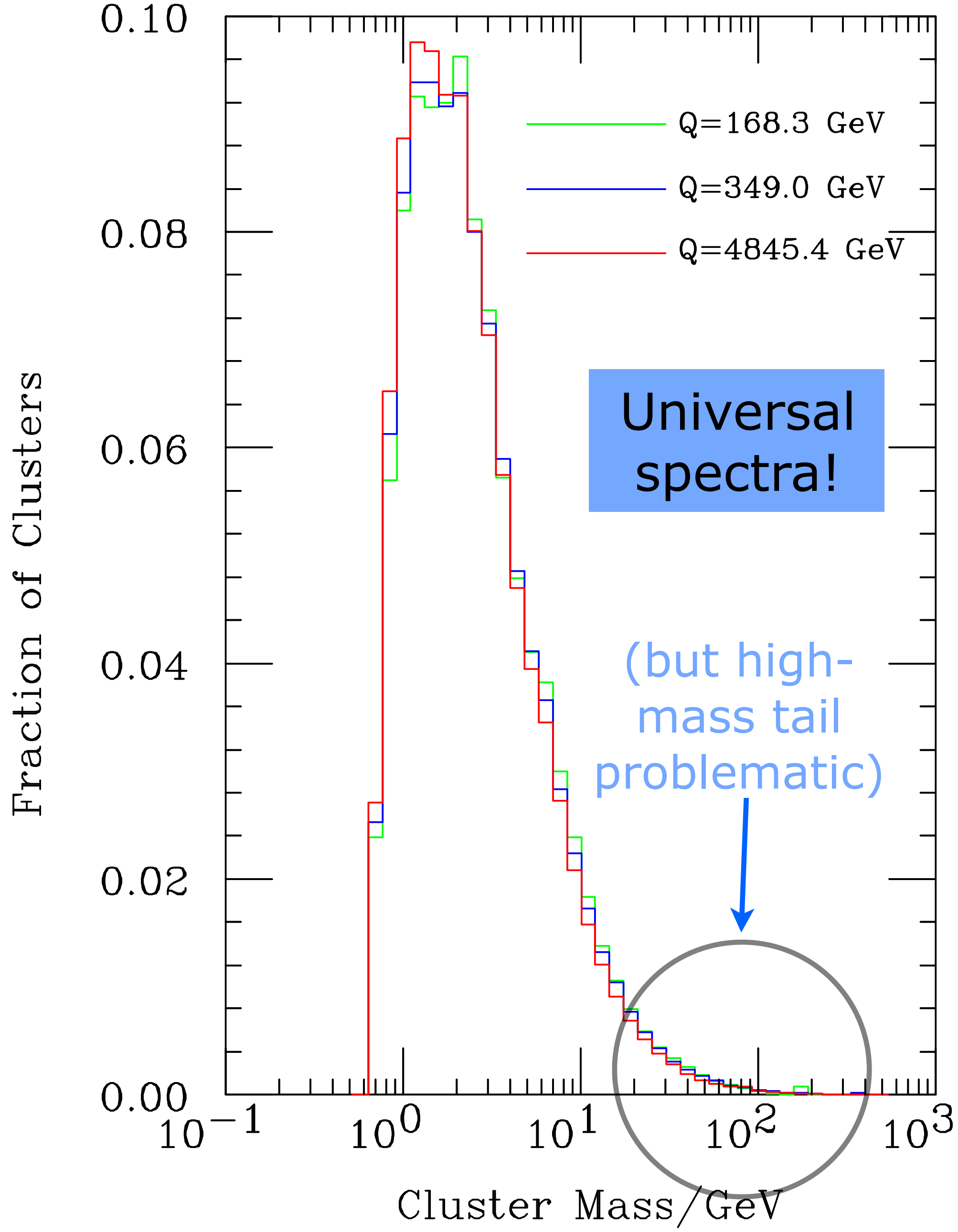
+ Force g→qq splittings at Q_0

→ high-mass q-qbar "clusters"

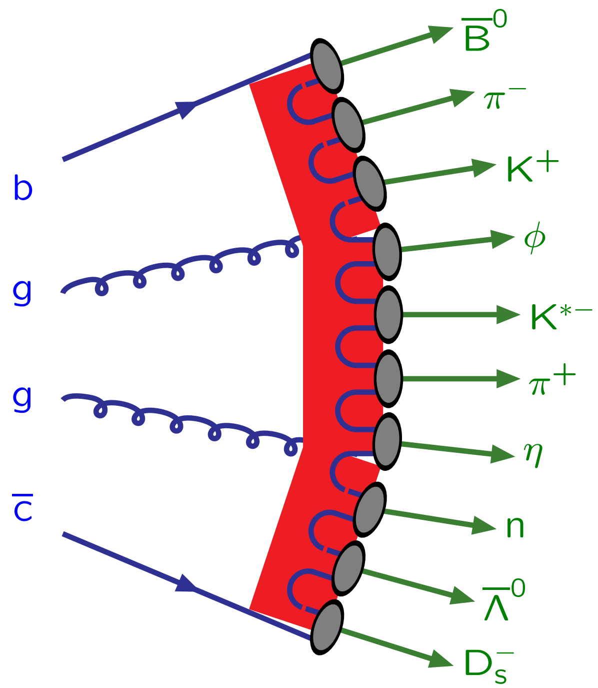
Isotropic 2-body decays to hadrons

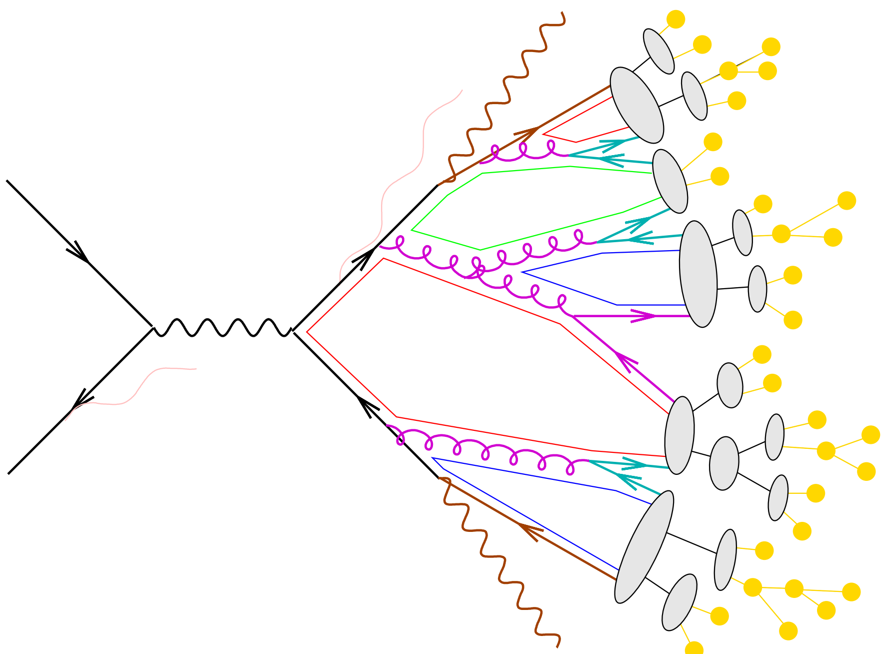
according to PS ≈ $(2s_1+1)(2s_2+1)(p^*/m)$





Strings and Clusters





program	PYTHIA	HERWIG (&SHERPA)
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Hadron Collisions

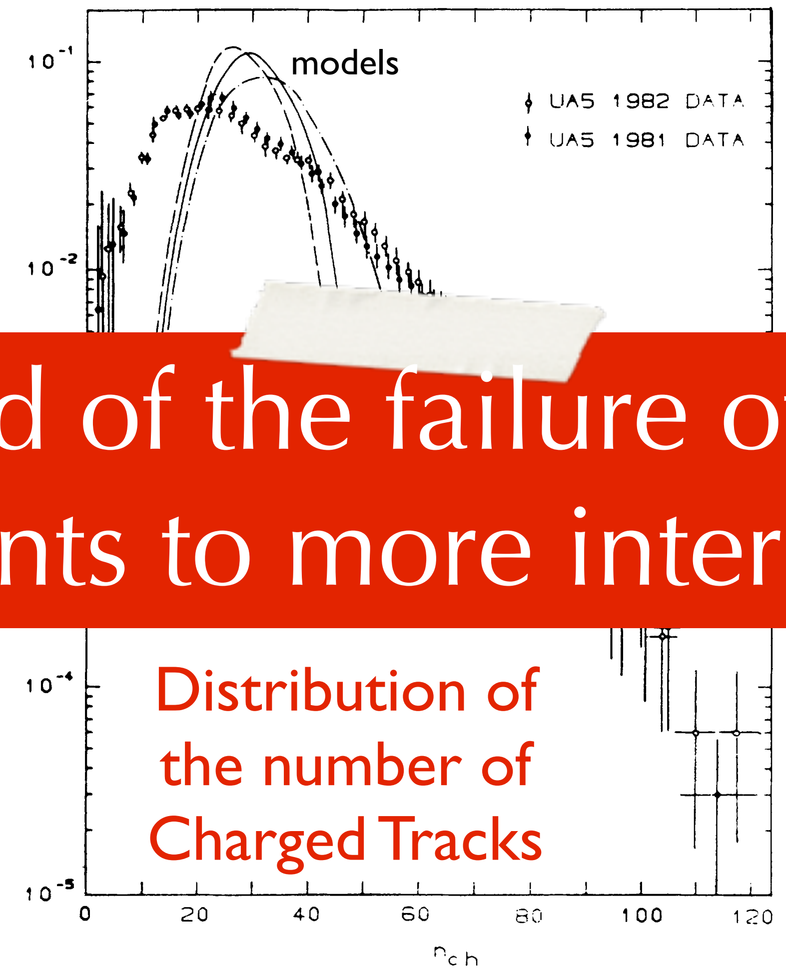
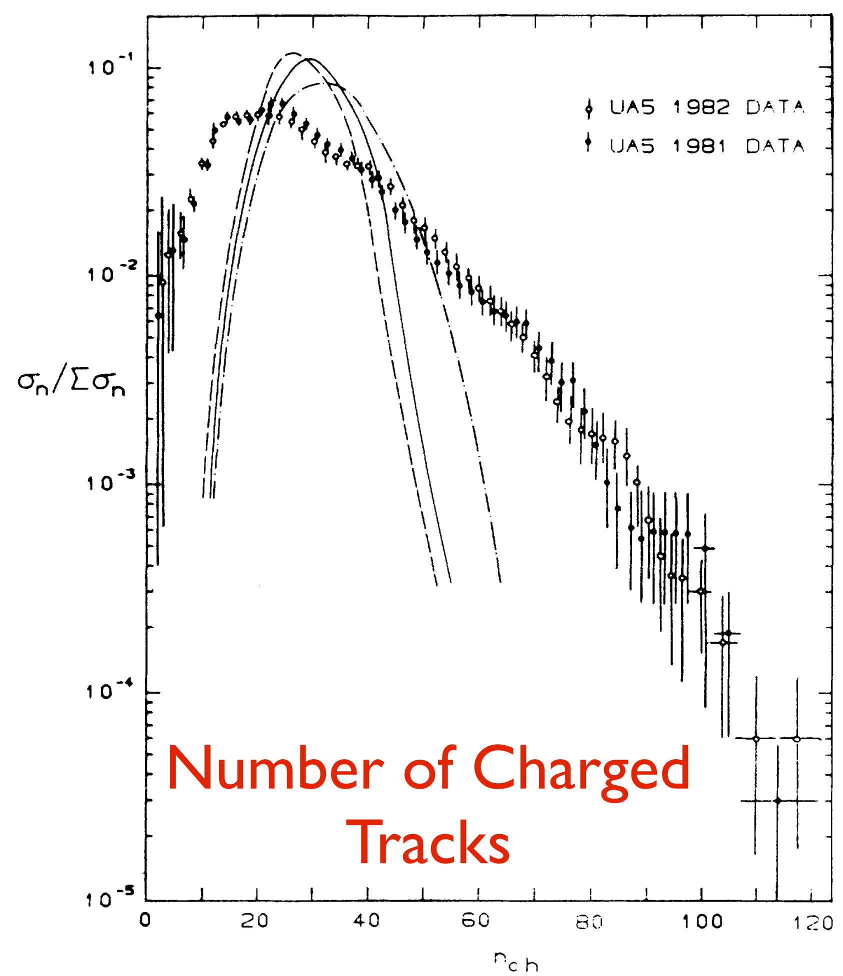


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

Do not be scared of the failure of physical models (typically points to more interesting physics)

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

Hadron Collisions



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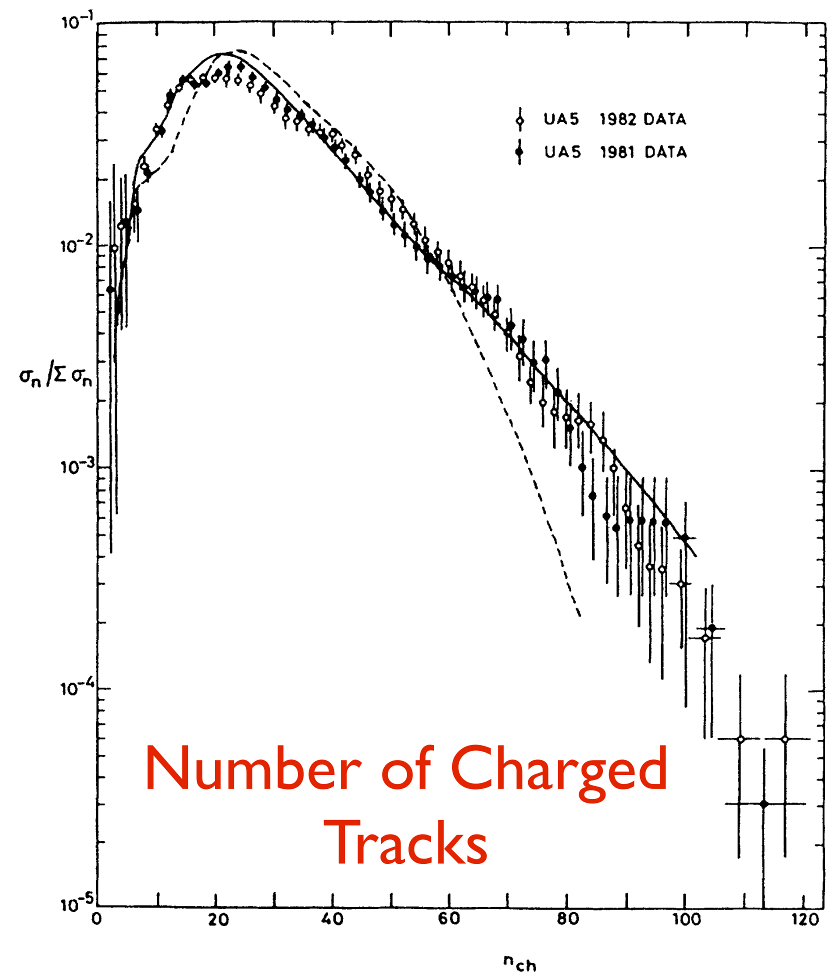


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

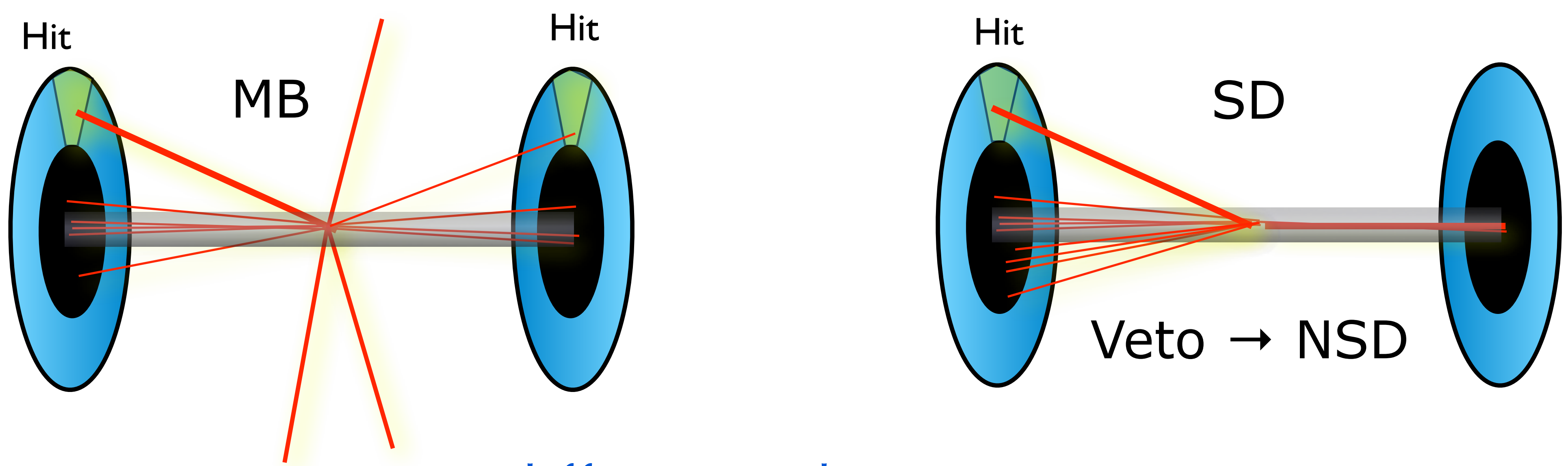
Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

What is Pileup / Min-Bias?

We use Minimum-Bias (MB) data to test QCD models

Pileup = "Zero-bias"

"Minimum-Bias" typically suppresses diffraction by requiring two-armed coincidence, and/or ≥ n particle(s) in central region



→ Pileup contains more diffraction than Min-Bias

Total diffractive cross section ~ 1/3 σ_{inel}

Most diffraction is low-mass → no contribution in central regions

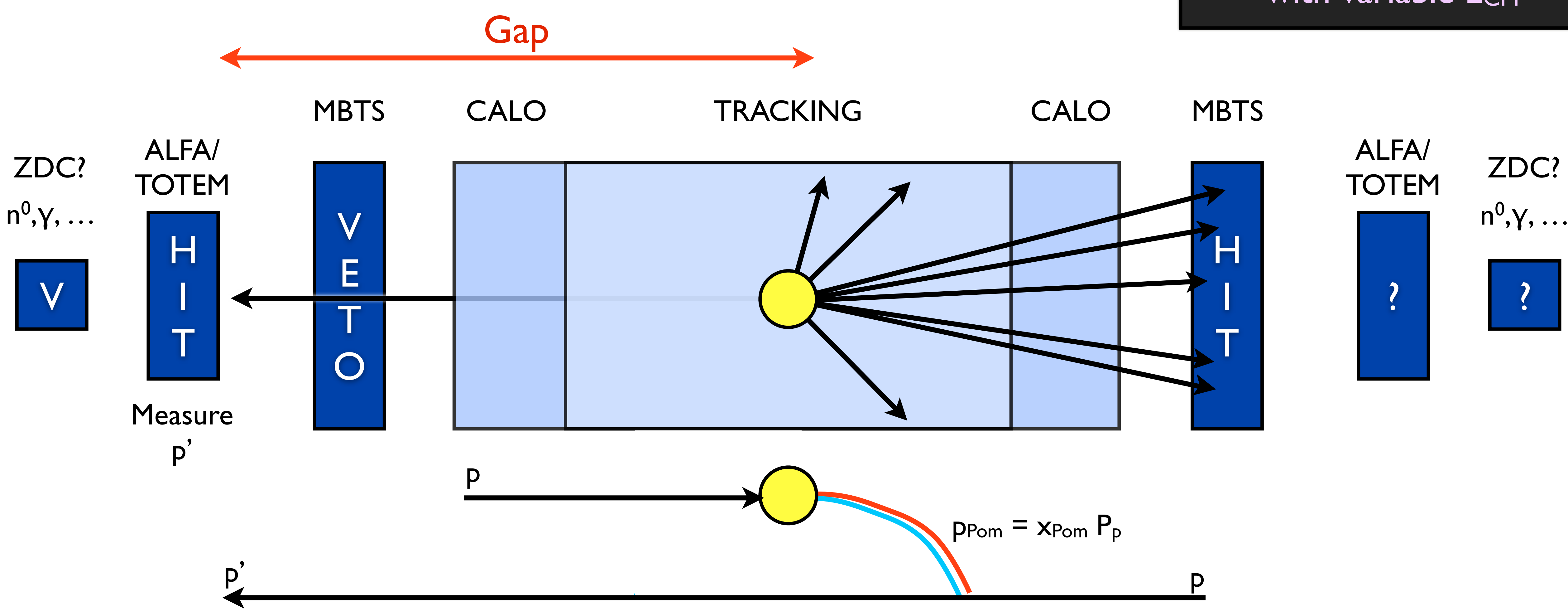
High-mass tails could be relevant in FWD region

→ direct constraints on diffractive components (→ later)

What is diffraction?

Single Diffraction

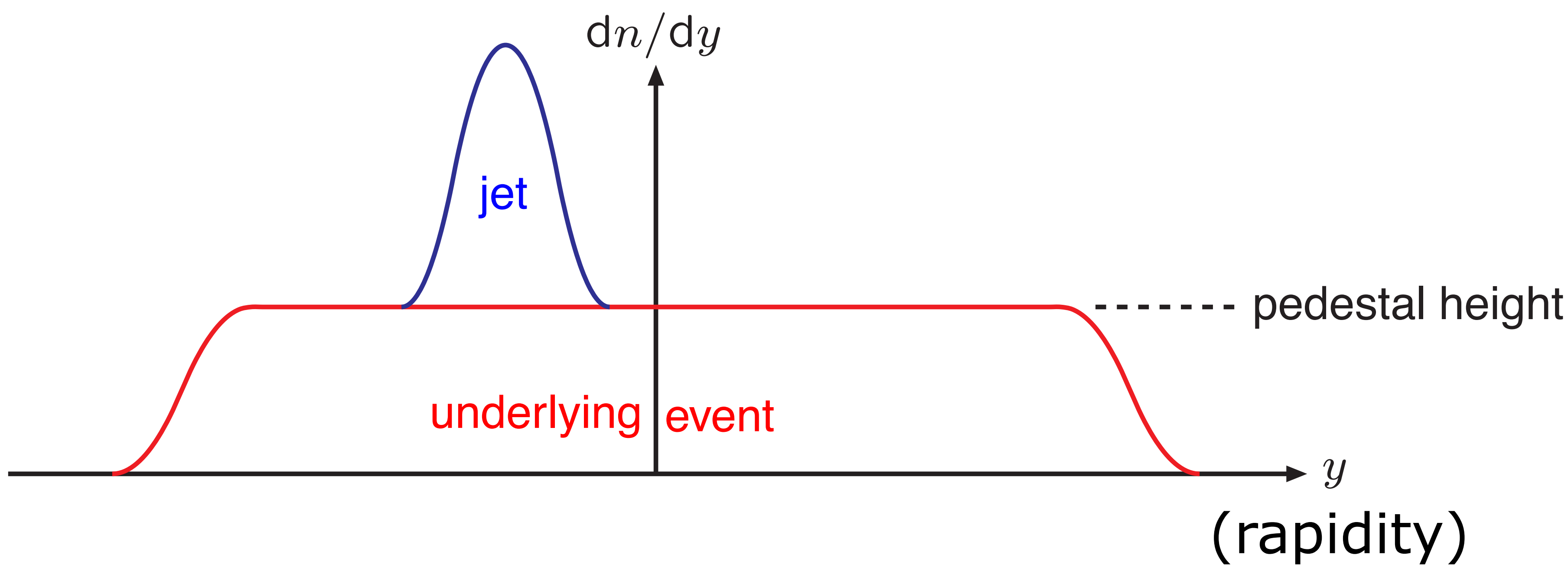
Glueball-Proton Collider
with variable E_{CM}



Double Diffraction: both protons explode; gap inbetween
Central Diffraction: two protons + a central (exclusive) system

What is Underlying Event ?

"Pedestal Effect"



Useful variable in hadron collisions: **Rapidity** (now along beam axis)

Designed to be additive under Lorentz Boosts along beam (z) direction

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

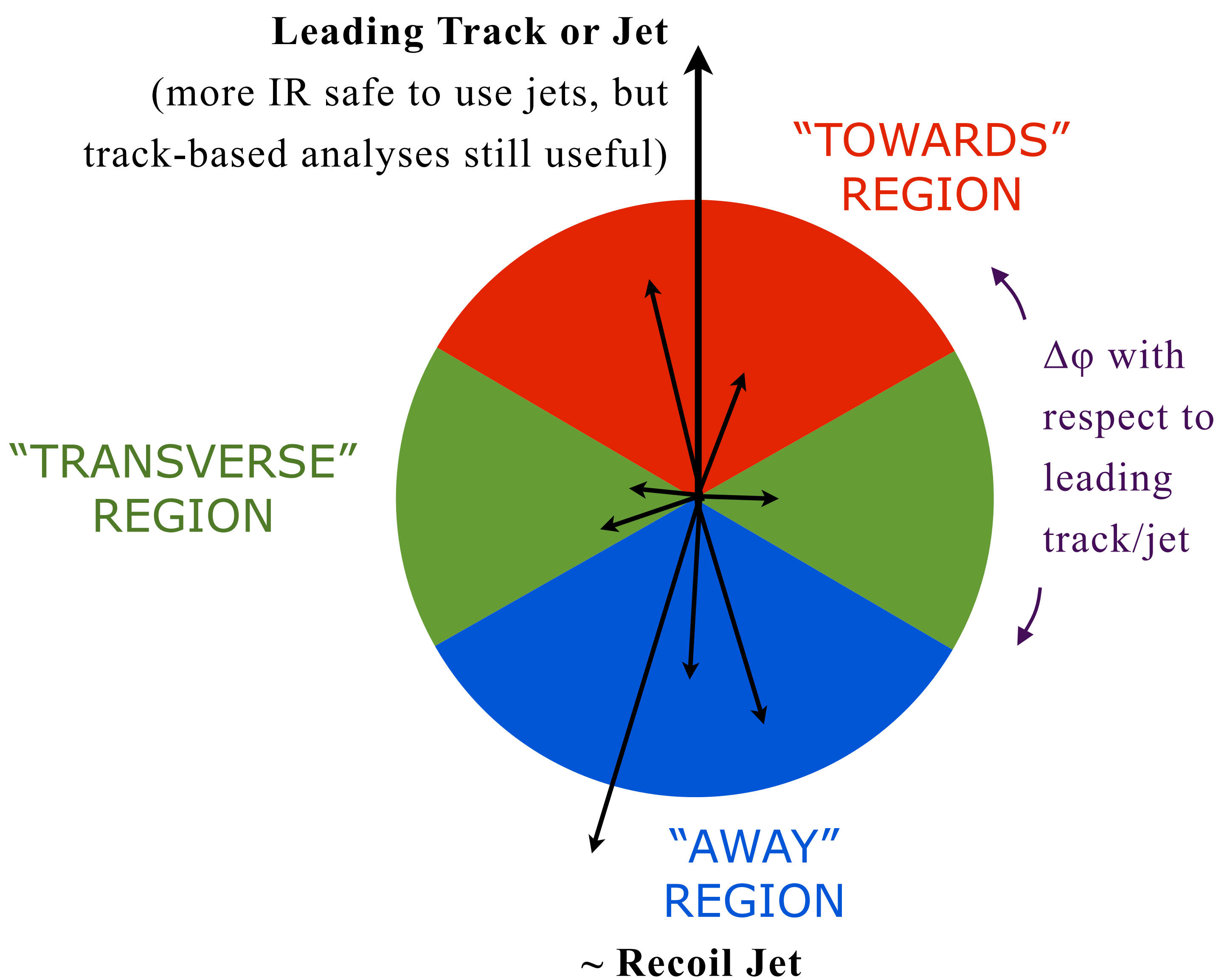
$y \to -\infty$ for $p_z \to -E$ $\quad$ $y \to 0$ for $p_z \to 0$ $\quad$ $y \to \infty$ for $p_z \to E$

Illustrations by T. Sjöstrand

The Underlying Event

(The "Rick Field" UE Plots - the same Field as in Field-Feynman)

There are many UE variables.
The most important is $\langle \Sigma p_T \rangle$ in the "Transverse Region"



Transverse Region (TRNS)

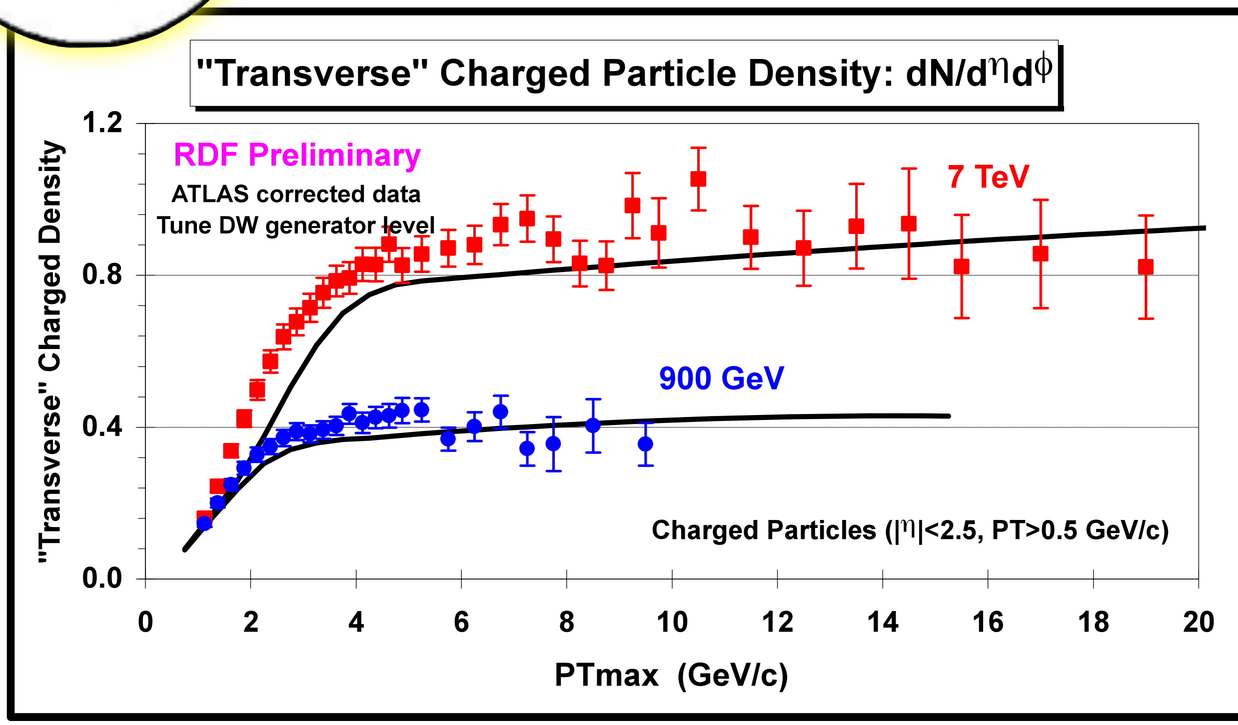
Sensitive to activity at right angles to the hardest jets

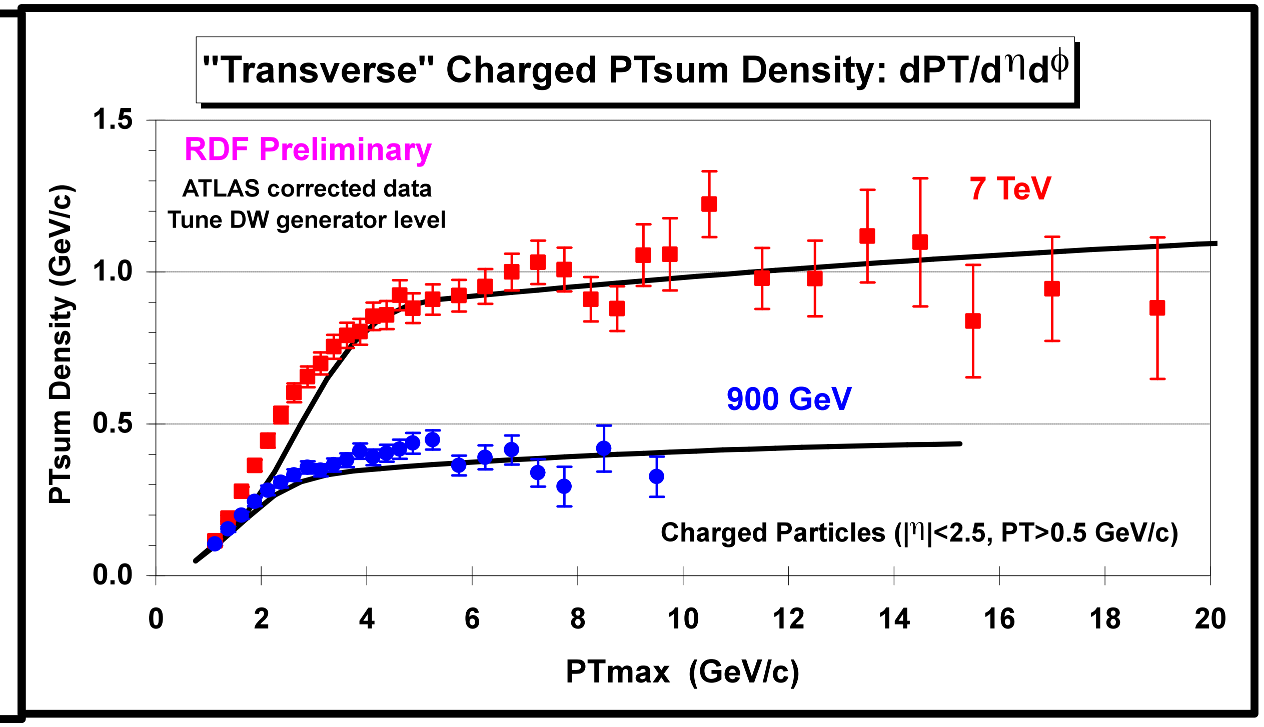
Useful definition of Underlying Event

The Pedestal

(now called the Underlying Event)

LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)	Sum(pT) Density (TRANS)
Not Infrared Safe	(more) Infrared Safe
Large Non-factorizable Corrections	Large Non-factorizable Corrections
Prediction off by ≈ 10%	Prediction off by < 10%

Truth is in the eye of the beholder:

R. Field: "See, I told you!"

Y. Gehrstein: "they have to fudge it again"

From Hard to Soft

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}

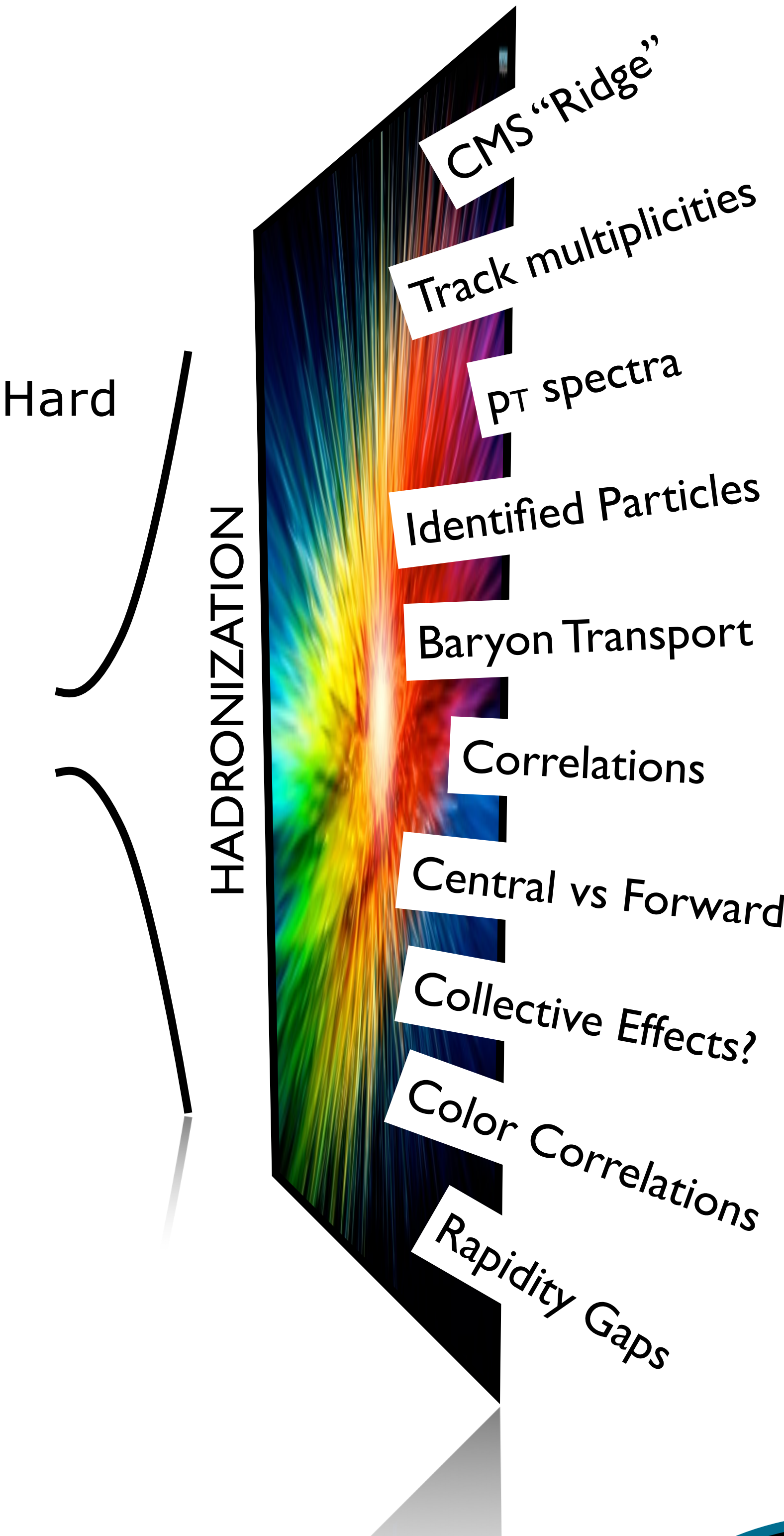
Extremely sensitive to IR effects

→ Excellent LAB for studying IR effects

~ ∞ statistics for min-bias

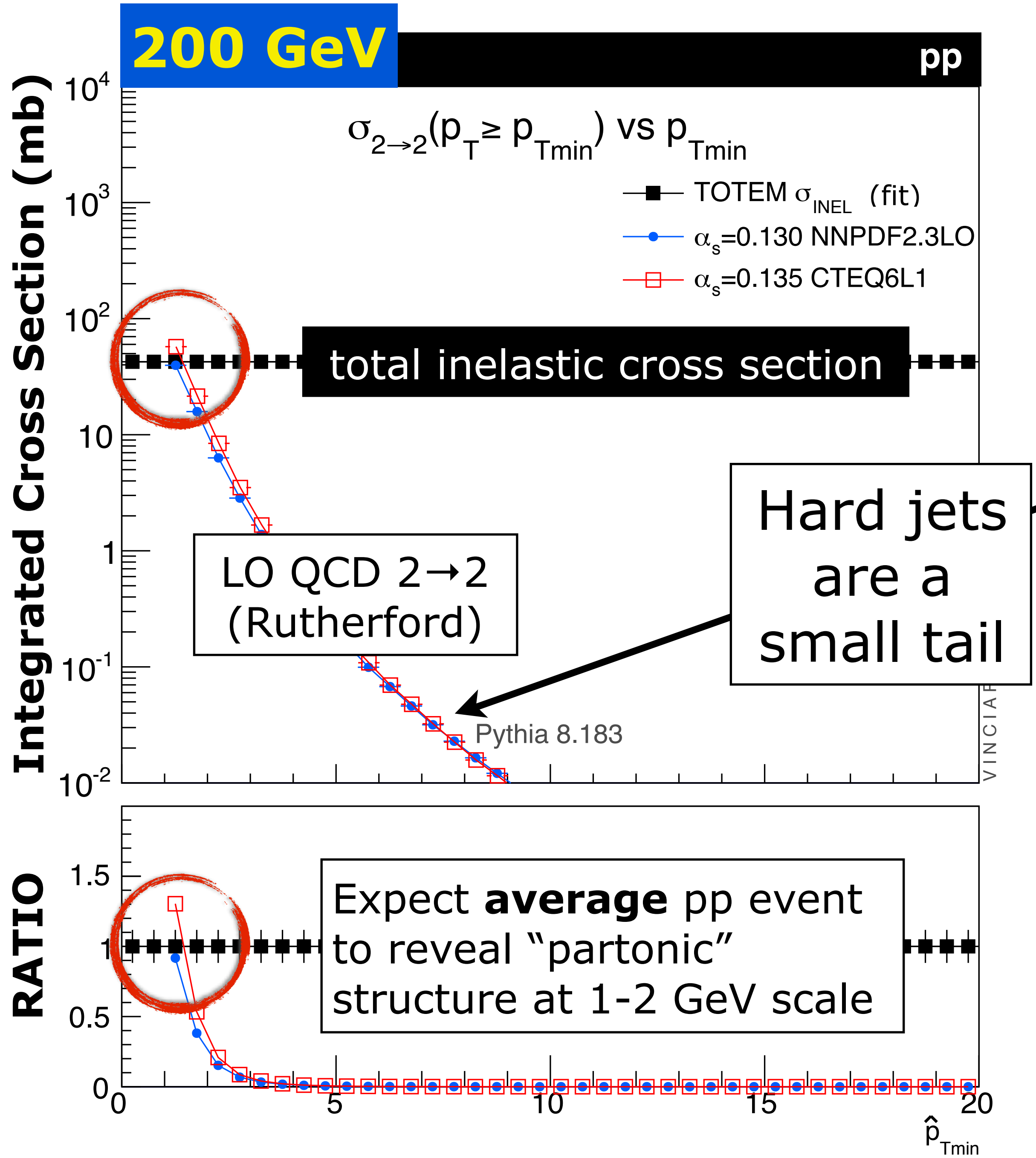
→ Access tails, limits

Universality: Recycling PU ↔ MB ↔ UE



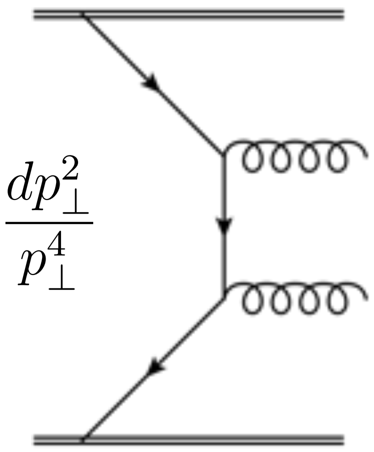
Is there no hard scale?

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



Leading-Order pQCD

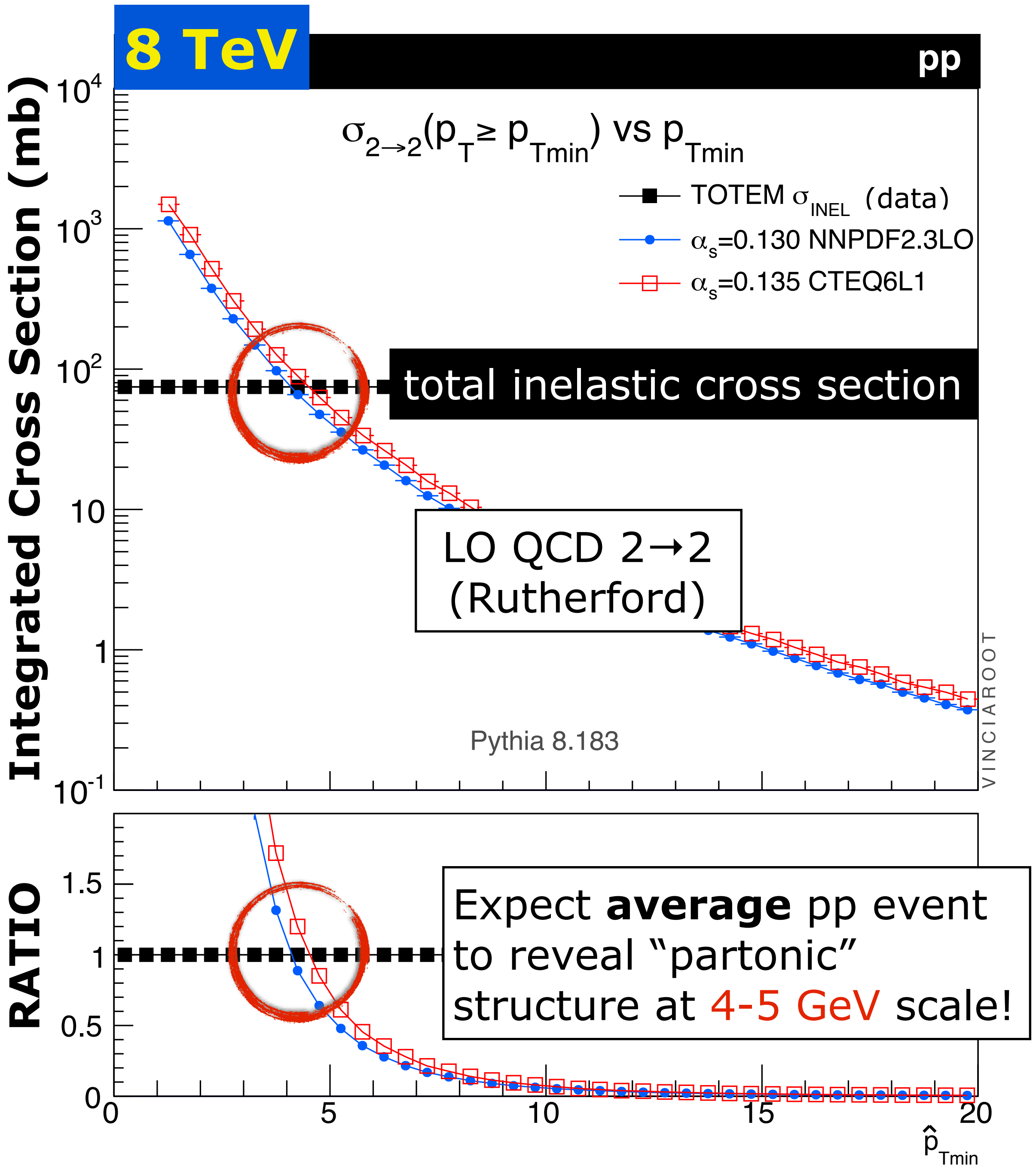
$$\int_{p^2_{\perp,\min}} dp^2_\perp \frac{d\sigma_{\rm Dijet}}{dp^2_\perp}$$

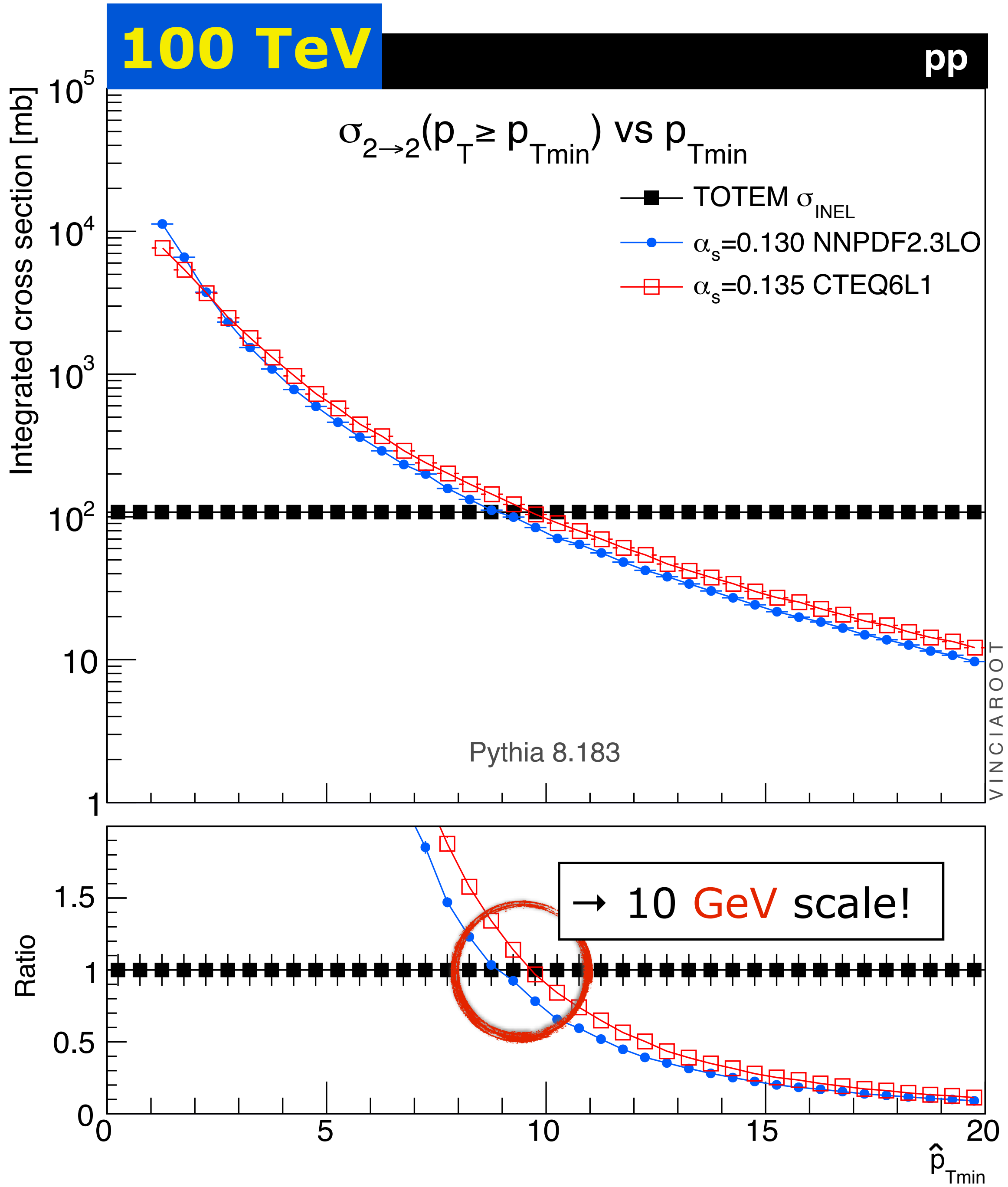


$$d\sigma_{2\to2} \propto \frac{dp^2_\perp}{p^4_\perp} \quad \otimes \text{ PDFs}$$

→ 8 TeV → 100 Tev

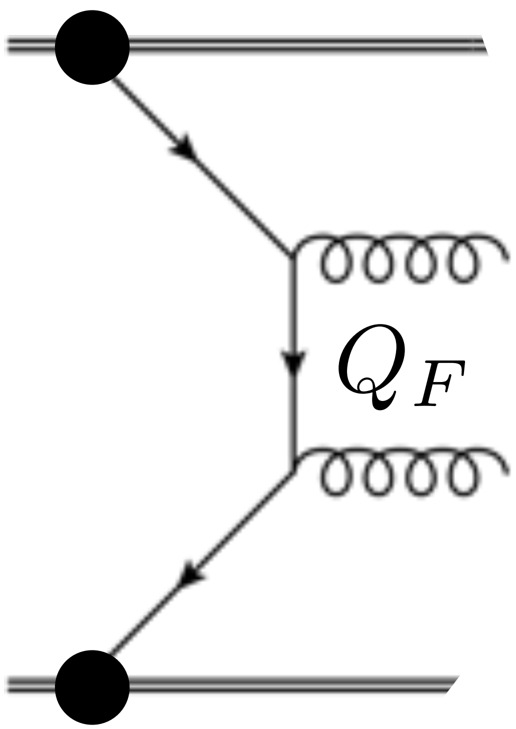
→ Trivial calculation indicates hard scales in min-bias





Physics of the Pedestal

Factorization: Subdivide Calculation



Multiple Parton Interactions go beyond existing theorems

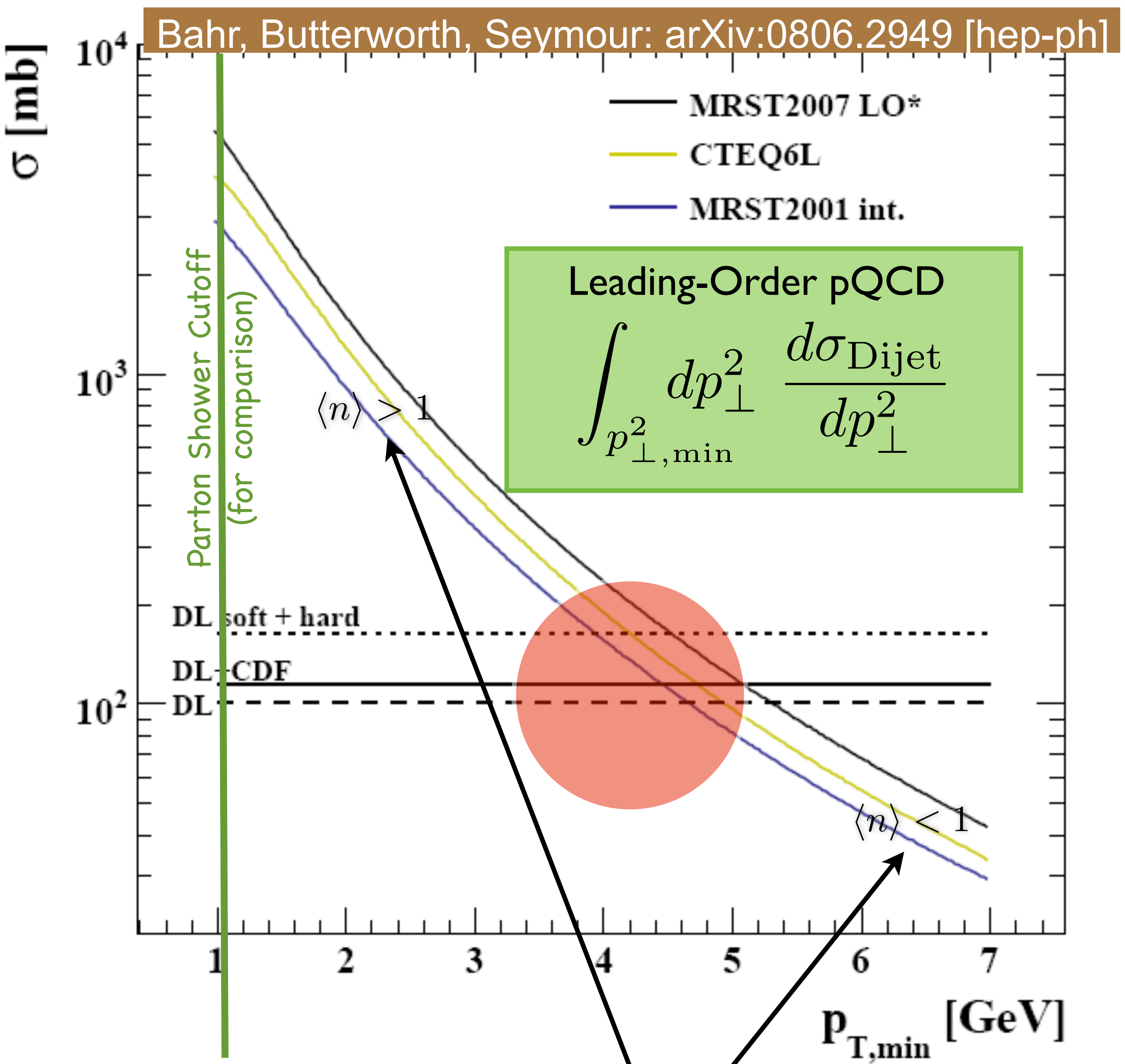
→ perturbative short-distance physics in Underlying Event

→ Need to generalize factorization to MPI

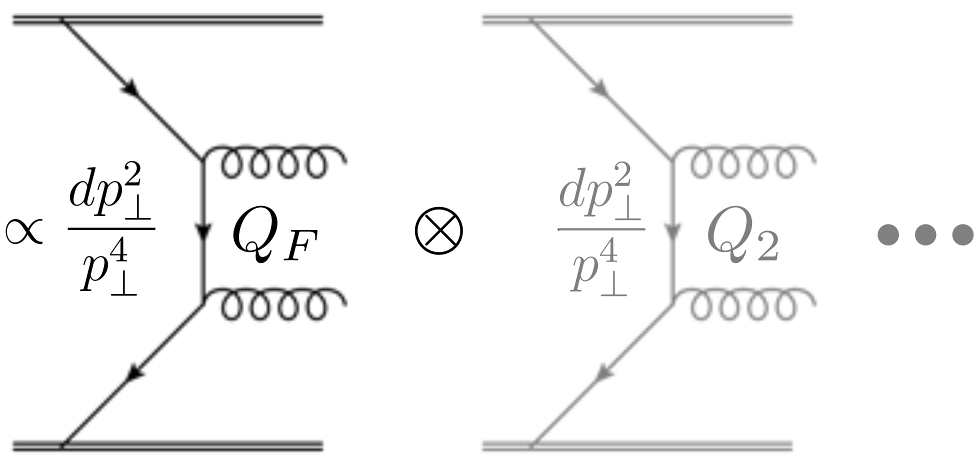
Multiple Parton Interactions

= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.

Earliest MC model ("old" PYTHIA 6 model)
Sjöstrand, van Zijl PRD36 (1987) 2019



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



Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down

Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

$$\sigma_{2\to2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section

Hadron-Hadron Cross Section

How many?

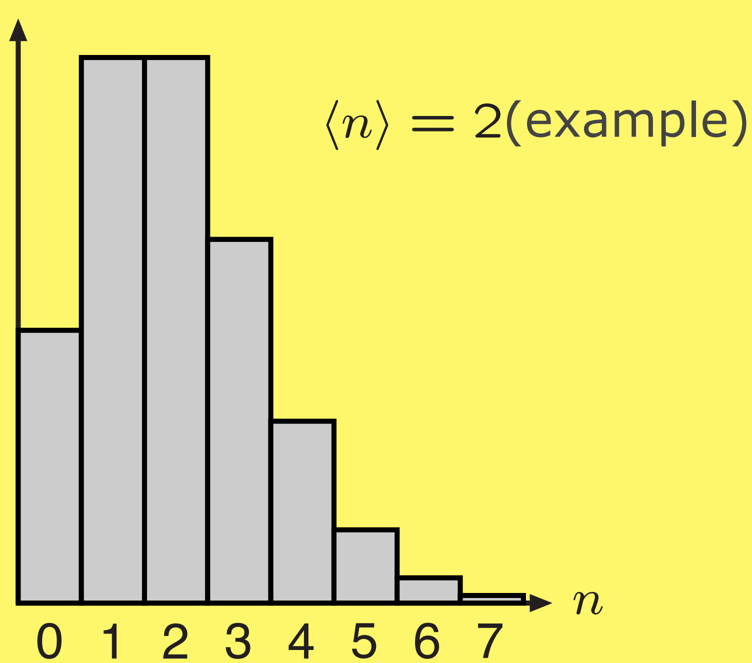
Naively $\langle n_{2\to 2}(p_{\perp\min}) \rangle = \dfrac{\sigma_{2\to 2}(p_{\perp\min})}{\sigma_{\mathrm{tot}}}$

Interactions independent (naive factorization) → Poisson

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

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

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



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

Real Life

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

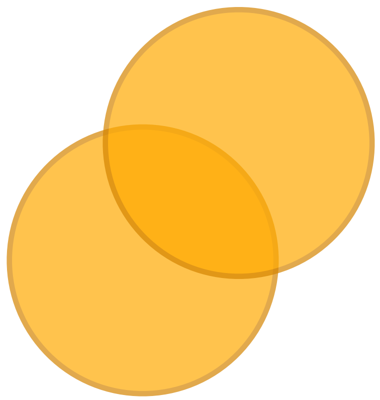
Momentum conservation suppresses high-n tail

Impact-parameter dependence

+ physical correlations

→ not simple product

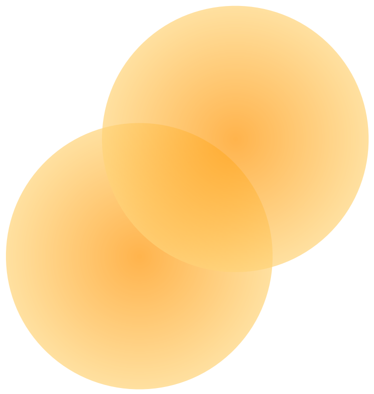
Impact Parameter



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>

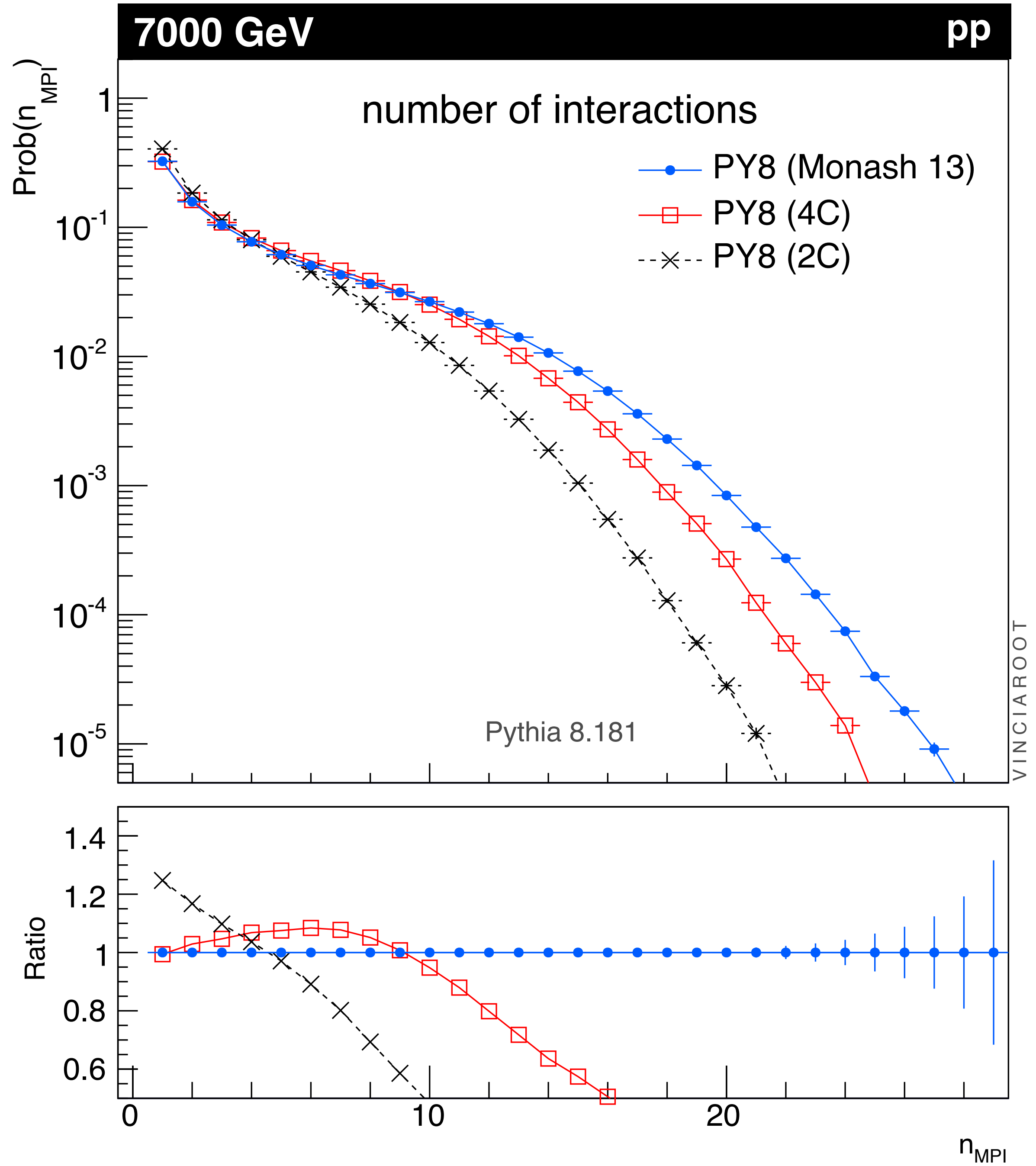
Note: this is an *effective* description. Not the actual proton mass density.
E.g., peak in overlap function (≫1) can represent unlikely configurations with huge overlap enhancement. Typically use total σ_{inel} as normalization.

Number of MPI *

Minimum-Bias pp collisions at 7 TeV

Averaged over all pp impact parameters

(Really: averaged over all pp overlap enhancement factors)

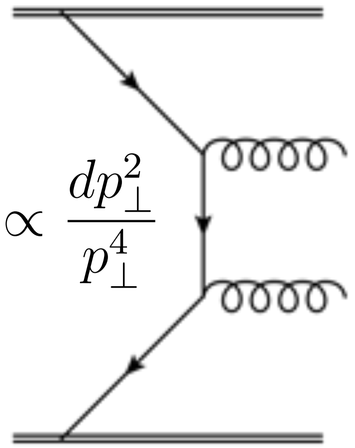


*note: can be arbitrarily soft

Caveats of MPI-Based Models

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

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



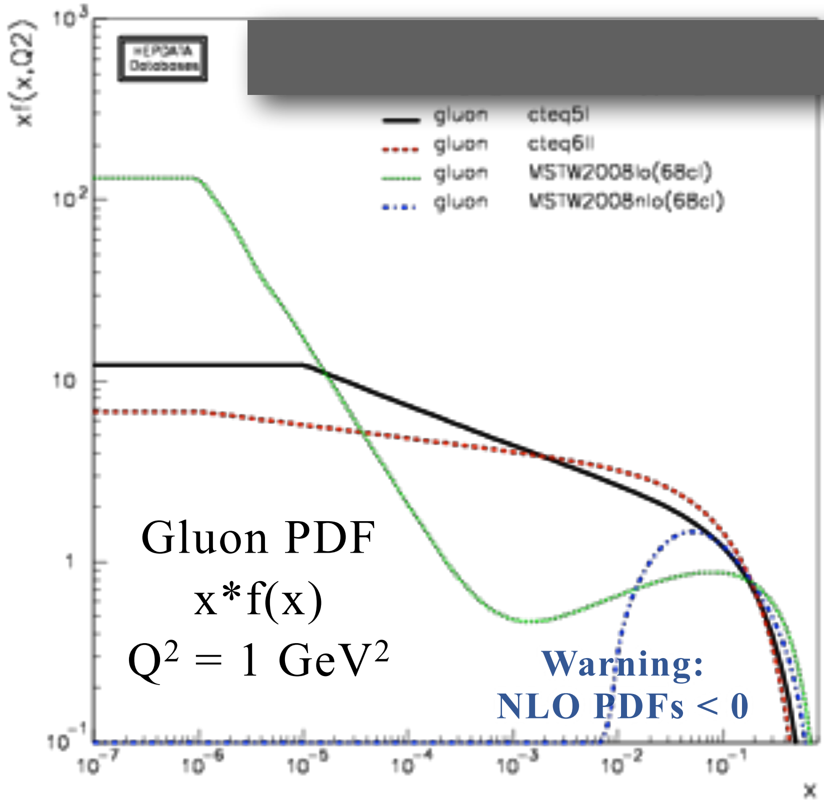
High Q^2 and finite x

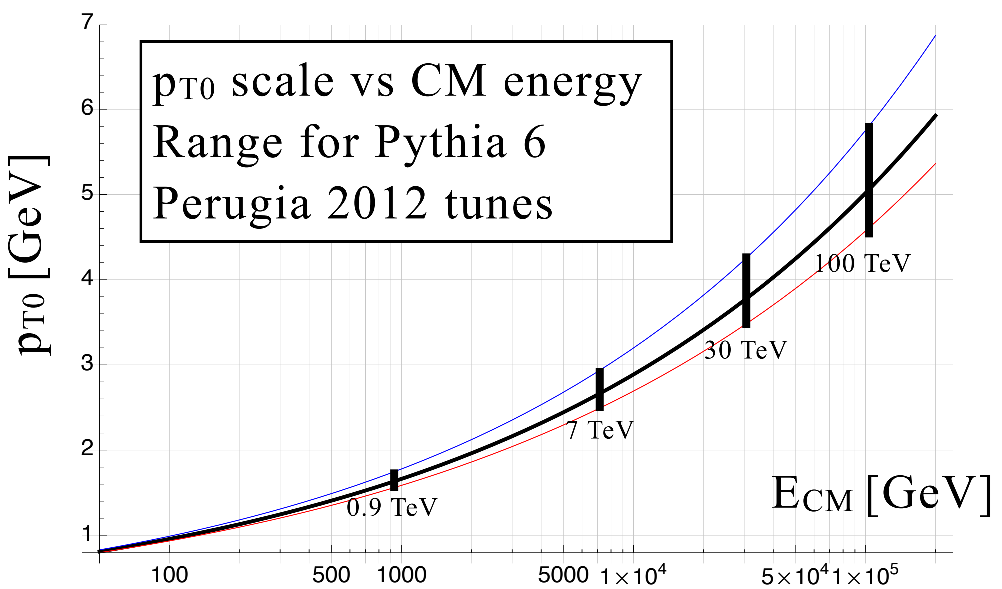
Extrapolation to soft scales delicate.
Impressive successes with MPI-based models but still far from a solved problem

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

See talk on UE by W. Waalewijn

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

1: A Simple Model

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

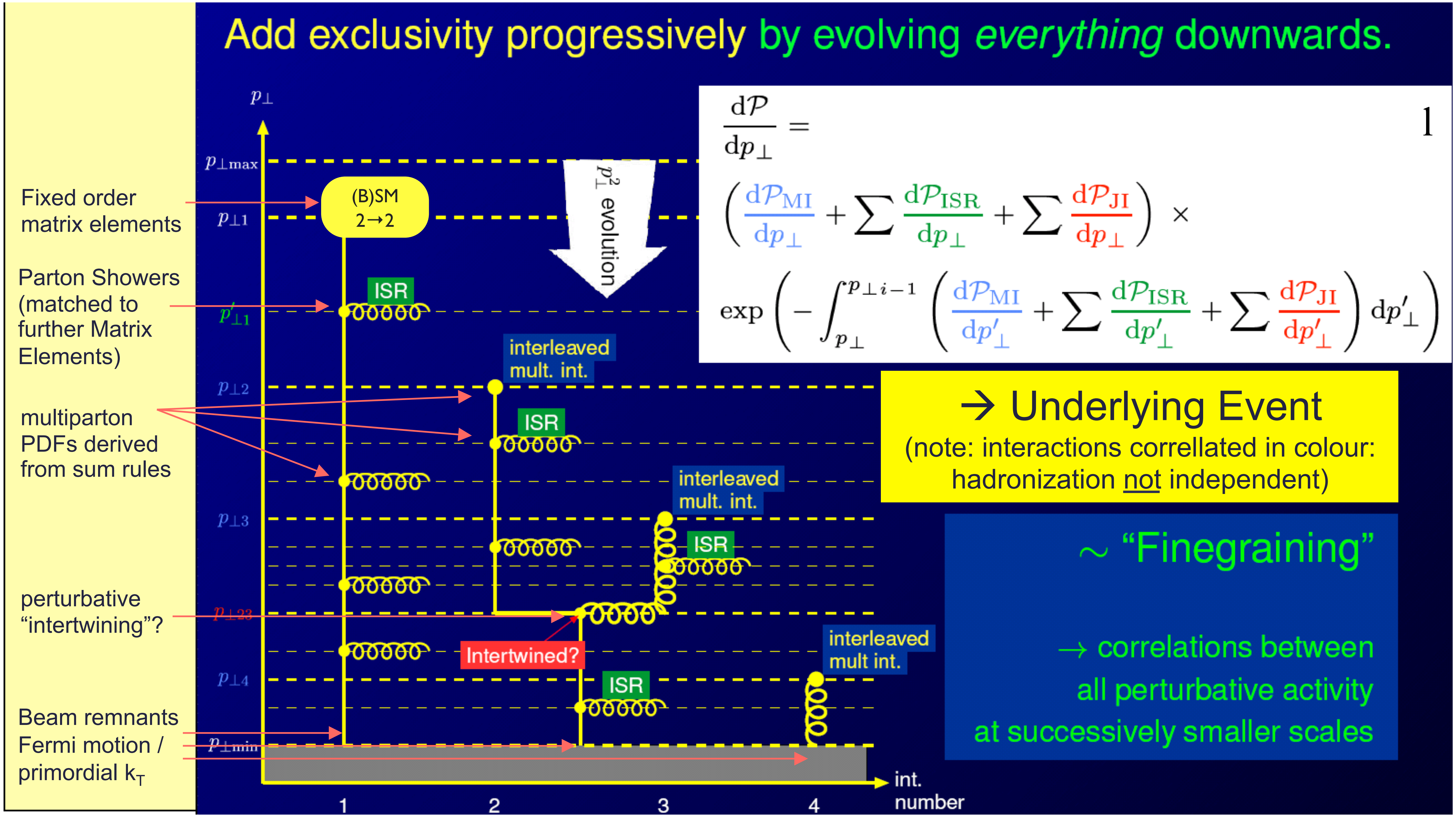
$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n\rangle(p_{\perp\min})\ \sigma_{\mathrm{tot}}$$

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 → $<n> = <n>(b)$
   - Ordinary CTEQ, MSTW, NNPDF, …
   - Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$
   - 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 $\sigma_{\mathrm{soft}} + \sigma_{\mathrm{hard}} = \sigma_{\mathrm{tot}}$
   - → **Herwig++ model** Bähr et al, arXiv:0905.4671

2: Interleaved Evolution

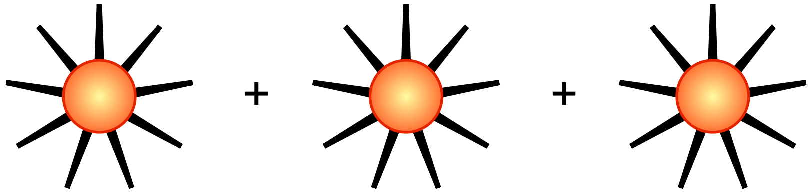
Sjöstrand, Skands., JHEP 0403 (2004) 053; EPJ C39 (2005) 129



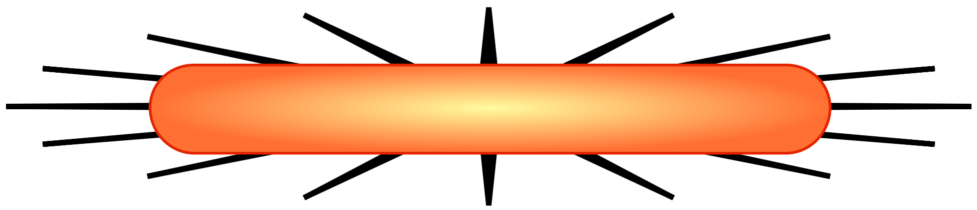
Collective Effects?

A rough indicator of how much colour gets kicked around, should be the number of particles produced

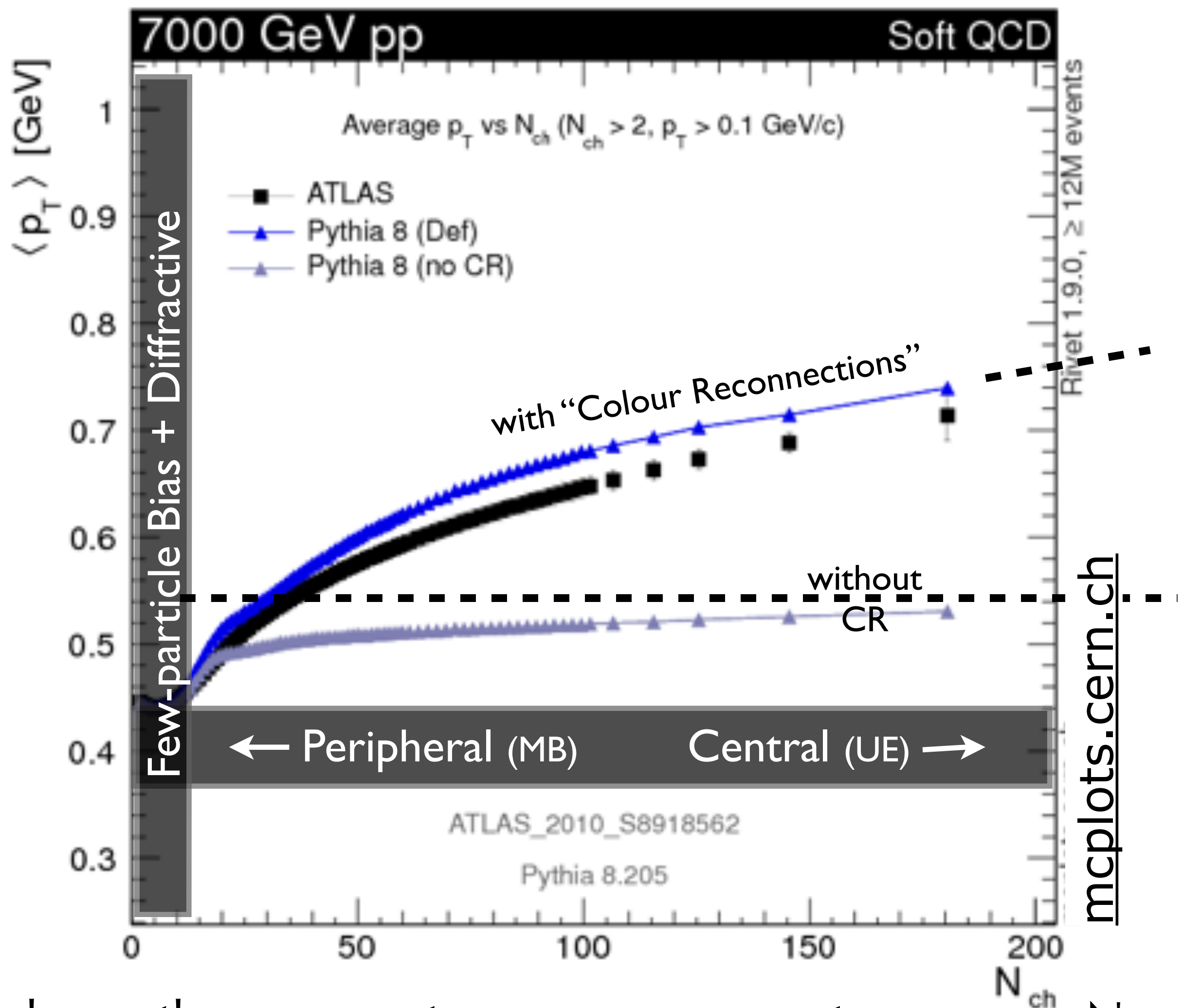
So we study event properties as a function of "N_{ch}" = N_{tracks}



Independent Particle Production:
→ **averages stay the same**

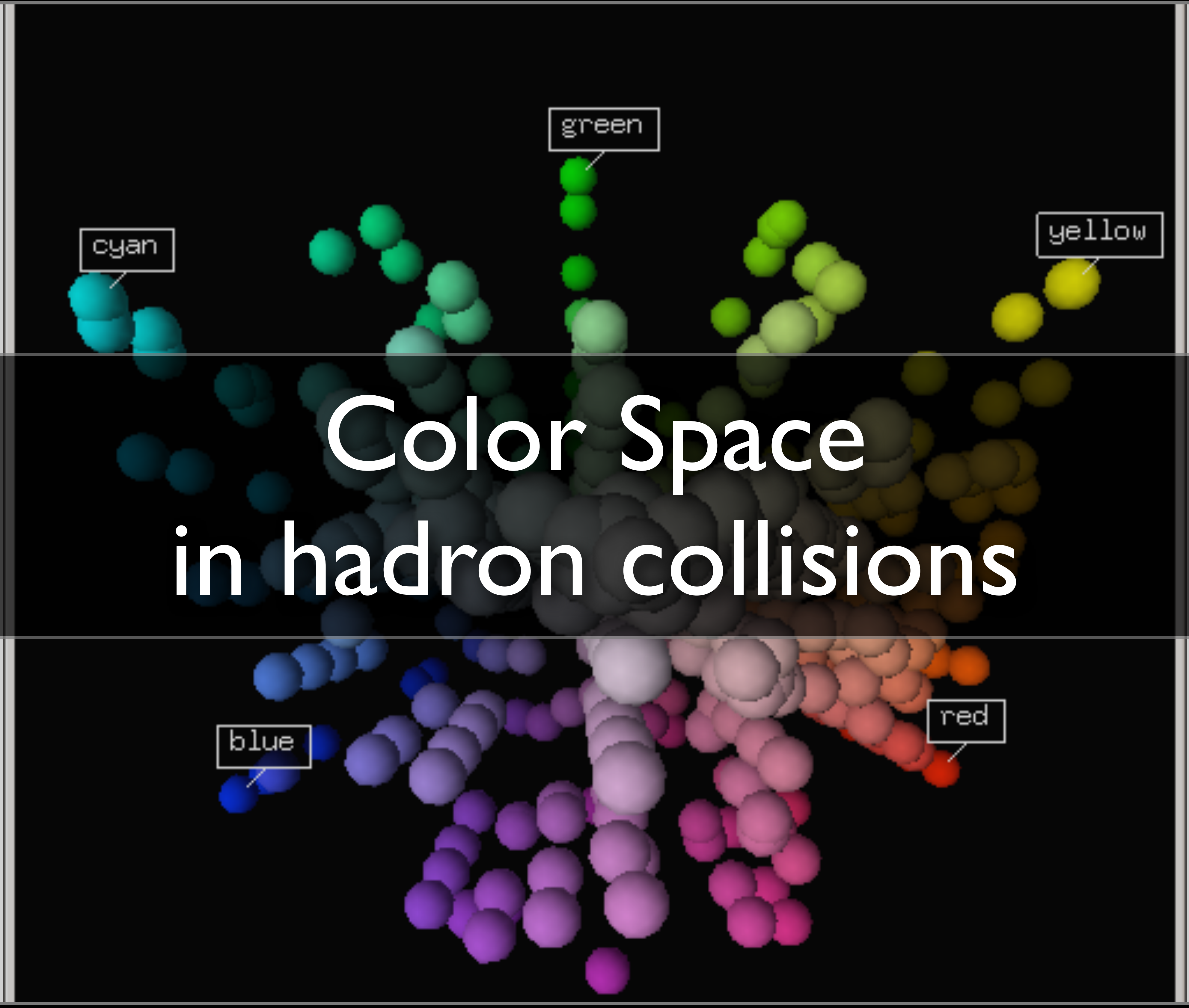


Correlations / Collective effects:
→ **averages depend on N_{ch}**



Plot shows the average transverse momentum versus N_{ch}

Color Space
in hadron collisions

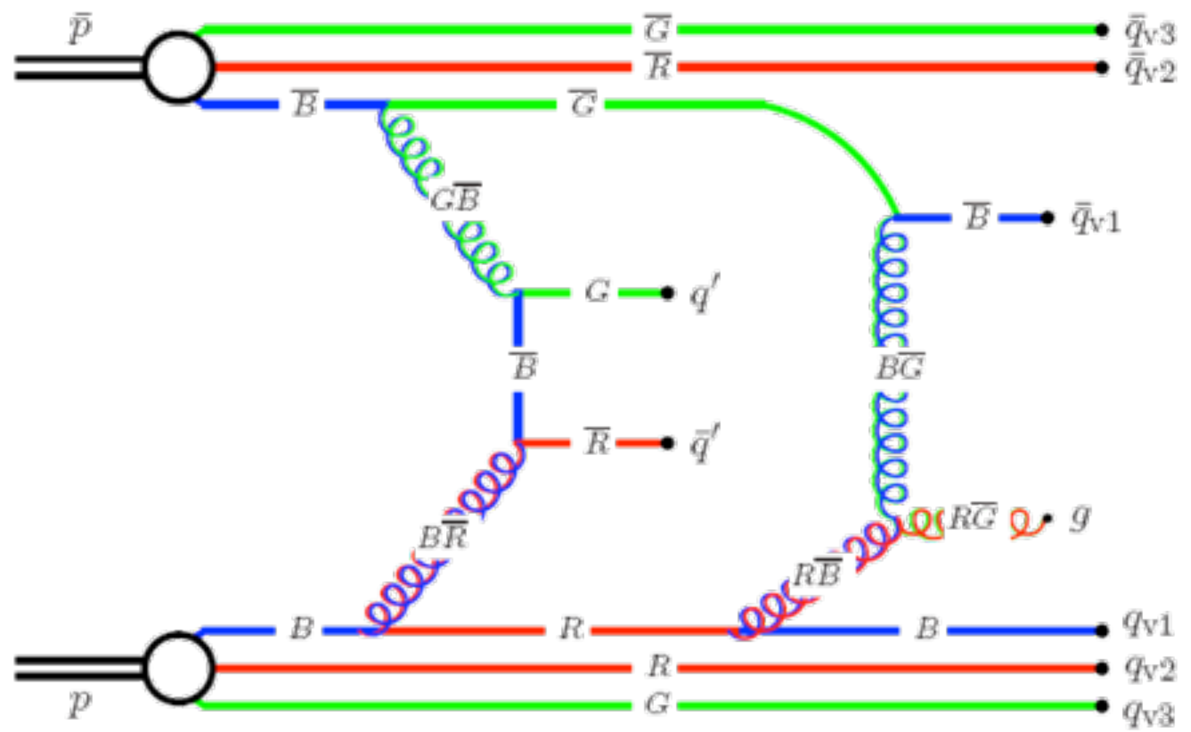


Color Correlations

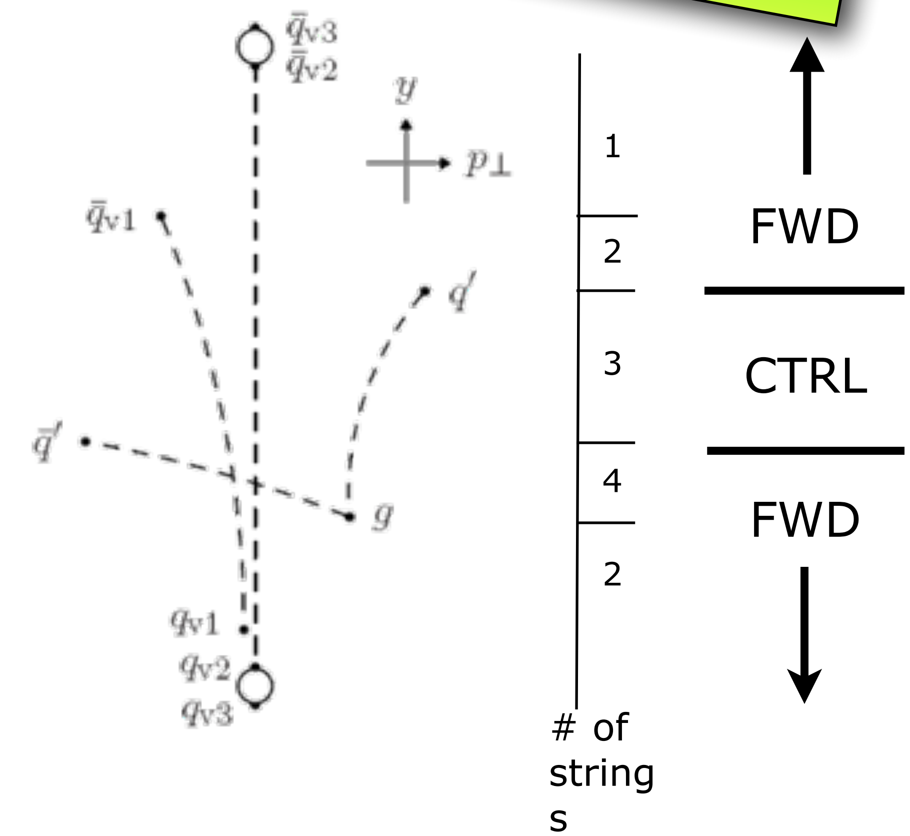
Each MPI (or cut Pomeron) exchanges color between the beams

- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions <u>crucially</u> depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053



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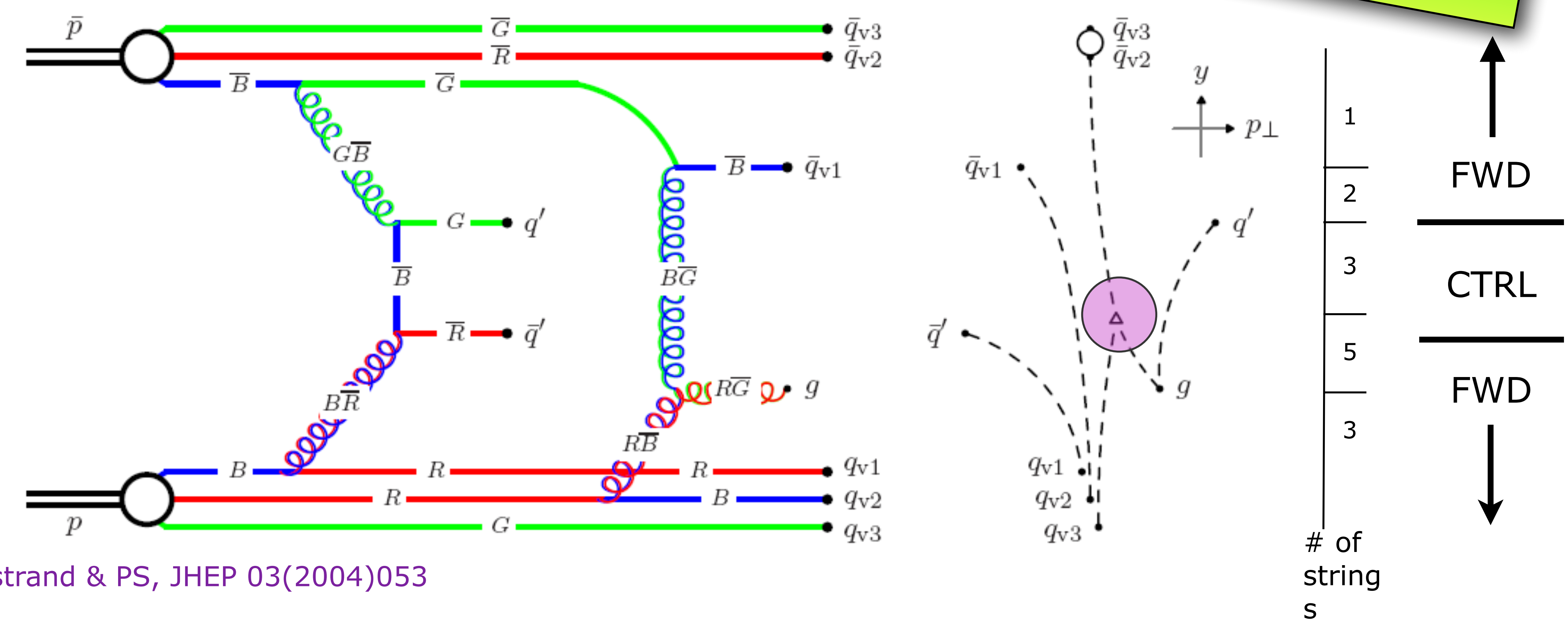

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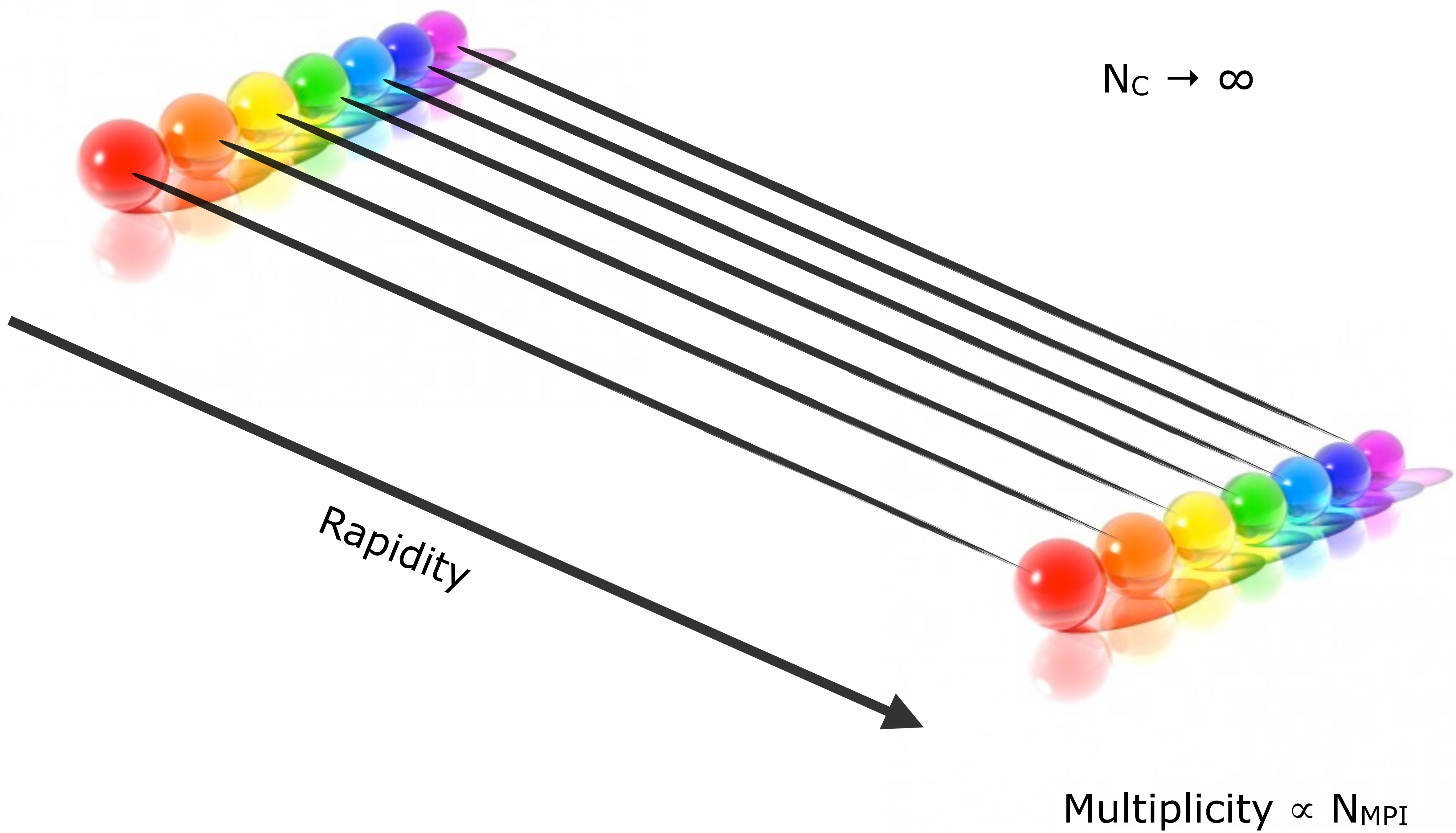
Color Connections

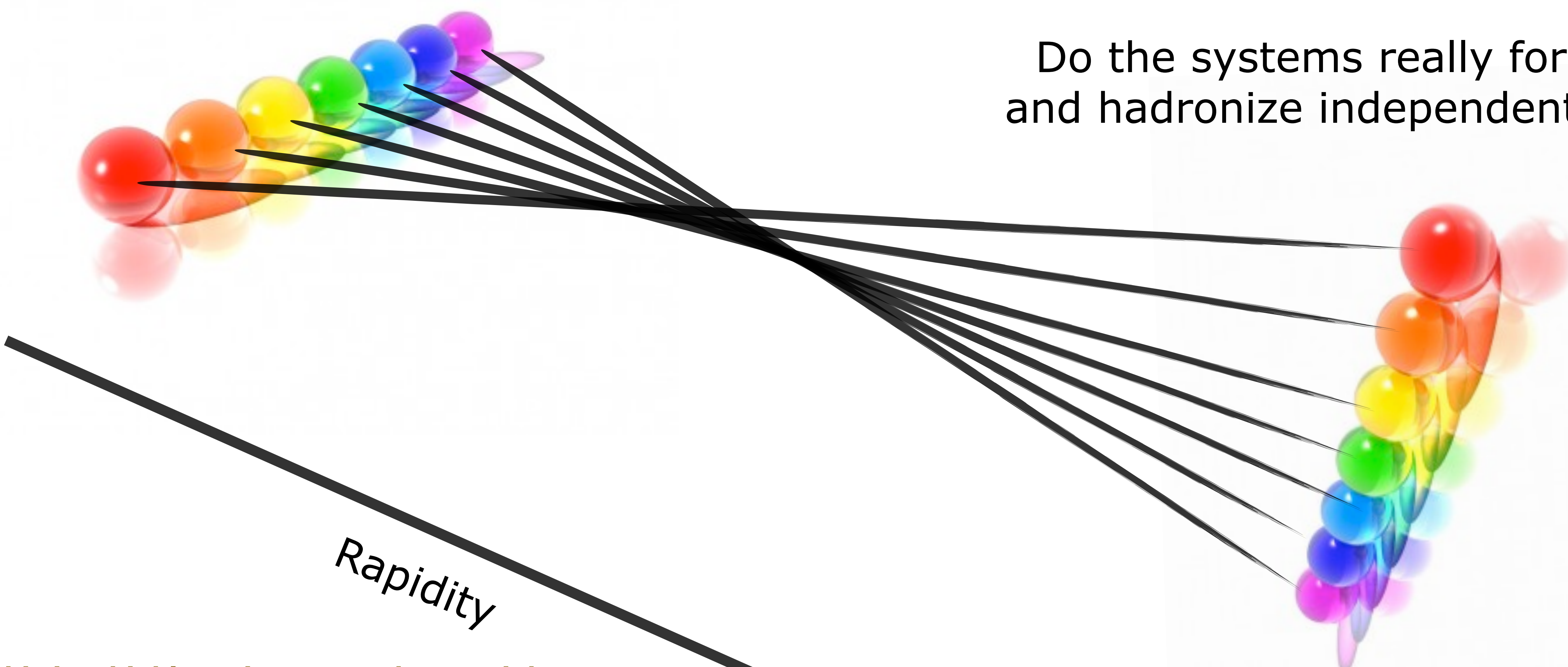
Better theory models needed



Color Reconnections?

Better theory models needed

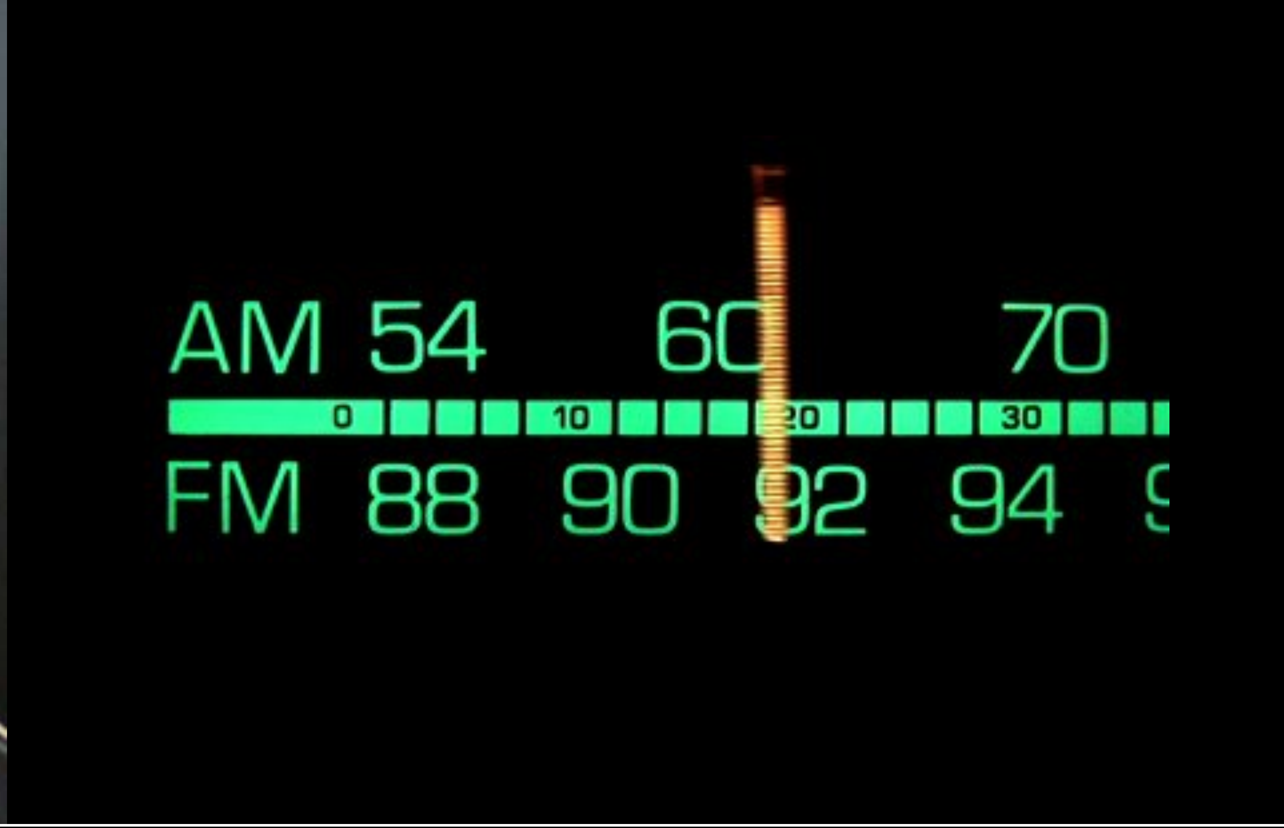
Do the systems really form and hadronize independently?



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

This is a highly active research area right now

Analogies with Strings in Superconductors: Khoze & Sjostrand Z.Phys. C62 (1994) 281
Generalized Area Law: Rathsman: Phys. Lett. B452 (1999) 364
Colour Annealing: Skands & Wicke: Eur. Phys. J. C52 (2007) 133
Cluster-based models: e.g. Gieseke et al., Eur.Phys.J. C72 (2012) 2225
Colour Ropes: Bierlich et al, JHEP 1503 (2015) 148
String Formation Beyond Leading Colour: Christensen & Skands: arXiv:1505.01681
String interactions? Hydrodynamics (EPOS)? Collective flow? Pressure? Rescatterings?



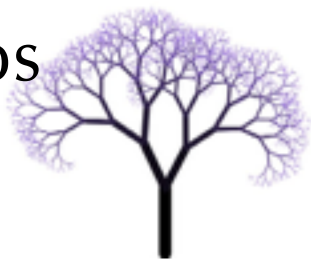
Tuning

means different things to different people

Summary

Jets

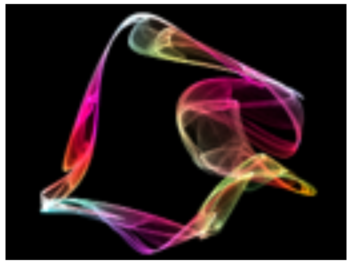
- Discovered at SPEAR (SLAC '72) and DORIS (DESY '73): E_{CM} ~ 5 GeV
  - Collimated sprays of nuclear matter (hadrons).
  - Interpreted as the "fragmentation of fast partons" -> MC generators
- Quasi-fractal structure of jets-within-jets & loops-within-loops



  - Simulated by parton-, dipole-, or **antenna** showers
  - Complementary to usual perturbative (LO, NLO, …) matrix elements
    - **Much focus on how to *combine* the two consistently and efficiently: "matching"**
  - Unitarity is a key aspect of both approaches; sums & detailed balance.

Strings enforce confinement; break up into hadrons

- ~ well understood in "dilute" environments ~ vacuum
- Many indications that confinement is more complicated in pp
  - LHC Run 1 provided a treasure trove of data on jet fragmentation, minimum-bias, underlying event, …
  - *'Ancora Imparo';* there will be new questions to ask in **Run 2** !

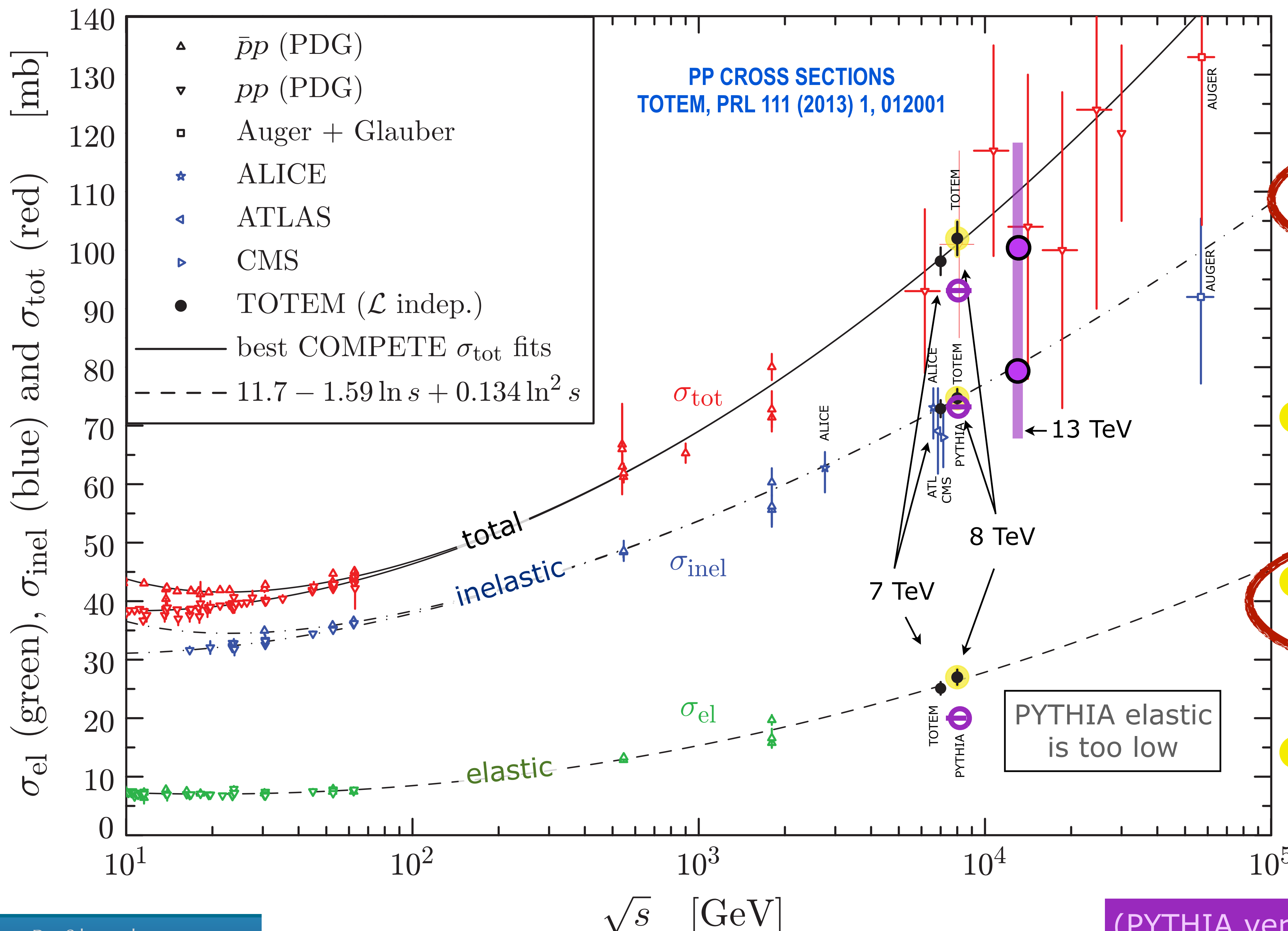


Extras

The Total Cross Section

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

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

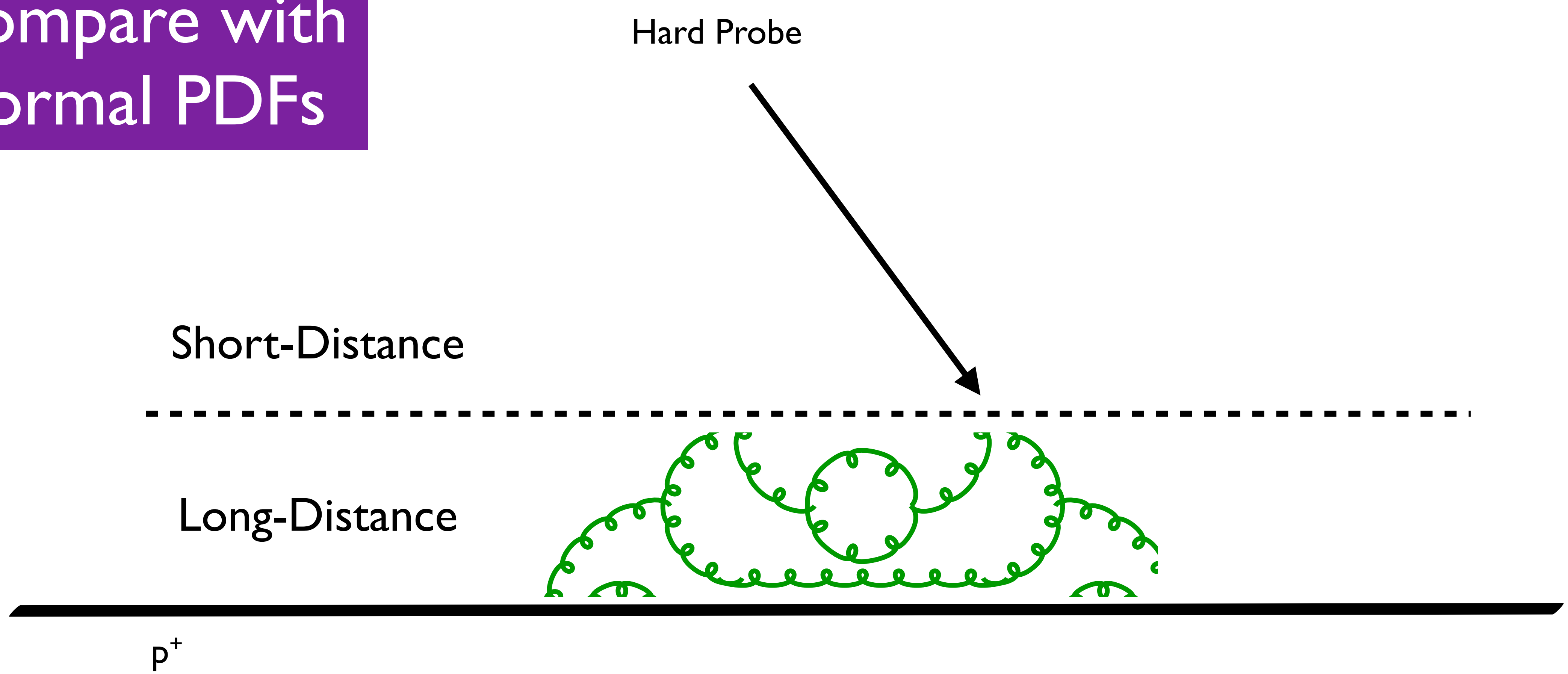
PYTHIA: 20 mb

(PYTHIA versions: 6.4.28 & 8.1.80)

(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs



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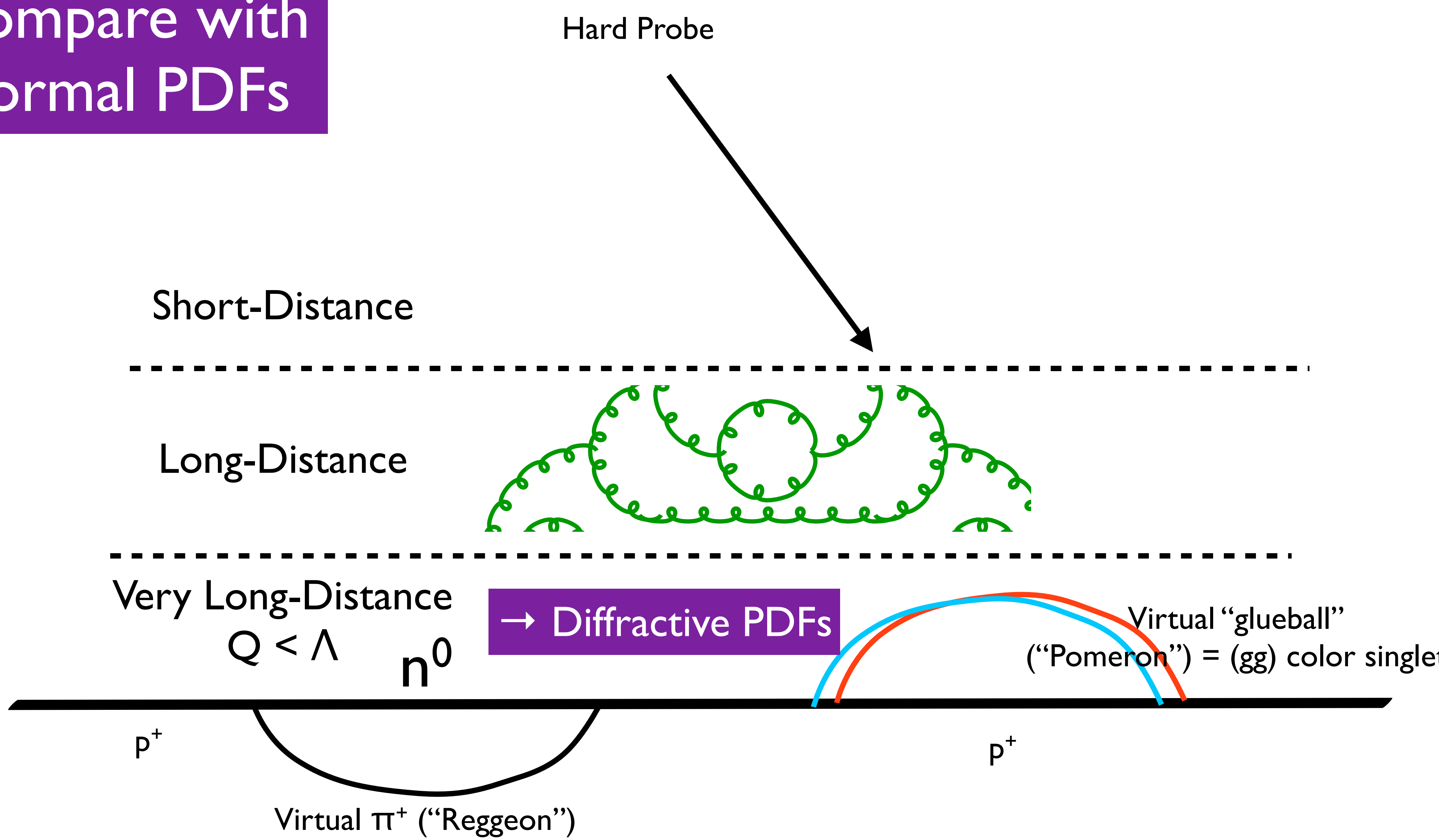

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