The Infrared

Confinement

Hadronization

Underlying Event

& Soft QCD interactions

Disclaimer

Focus on ideas, make you think about the physics

P. Skands (CERN)

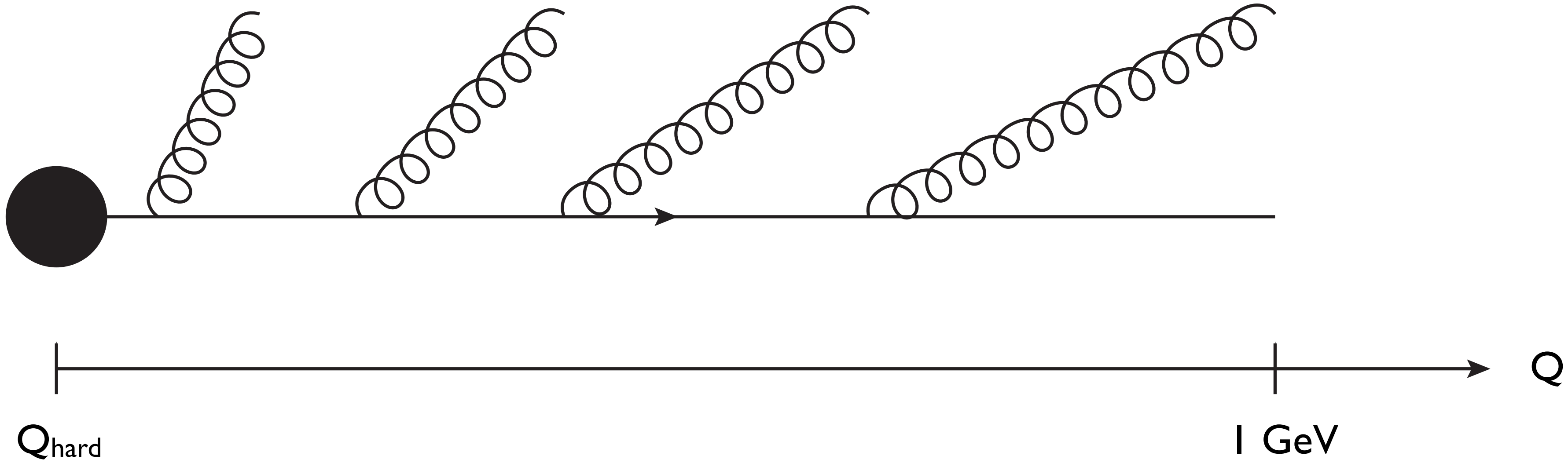
From Partons to Pions

Here's a fast parton

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

It showers (bremsstrahlung)

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



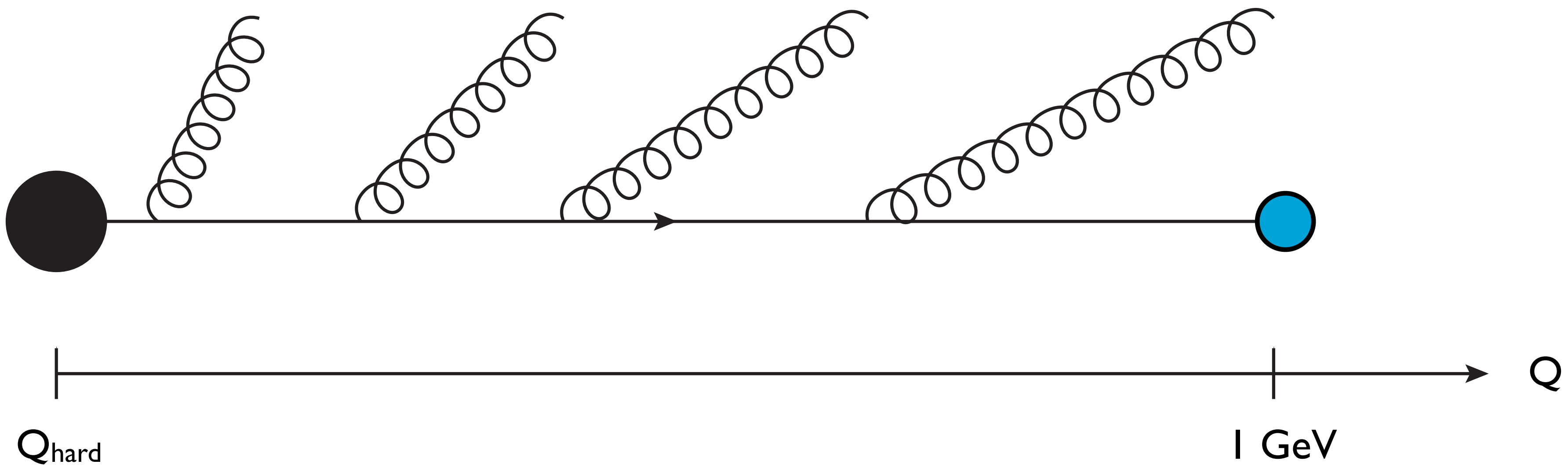
From Partons to Pions

Here's a fast parton

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

It showers (bremsstrahlung)

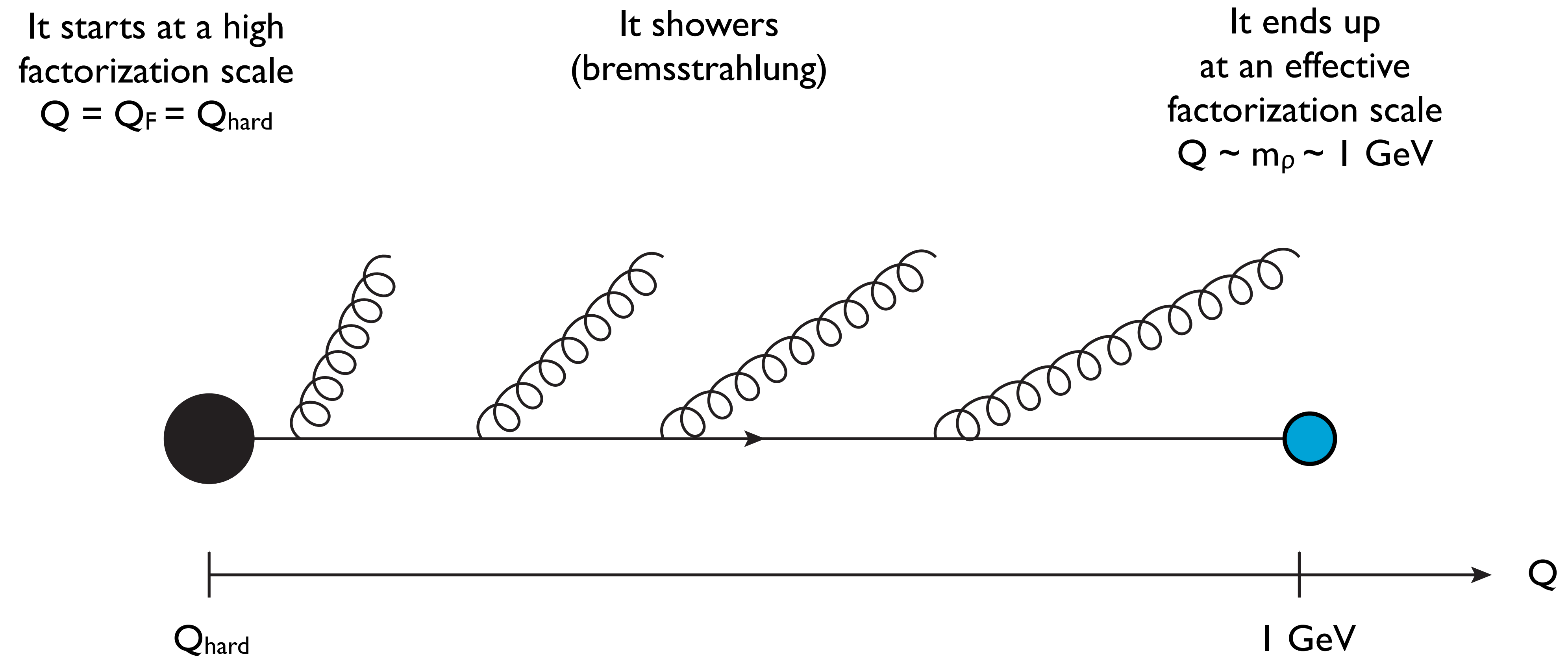
It ends up at an effective factorization scale $Q \sim m_\rho \sim 1$ GeV



How about I just call it a hadron?

From Partons to Pions

Here's a fast parton



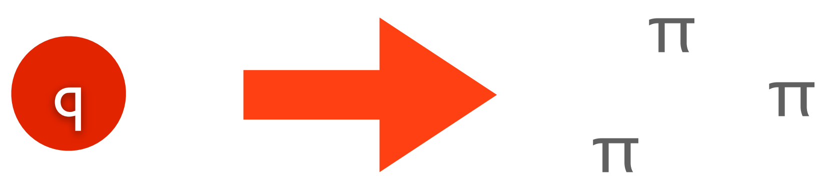
How about I just call it a hadron?

→ "Local Parton-Hadron Duality"

Parton → Hadrons?

Parton Hadron Duality

Universal fragmentation of a parton into hadrons

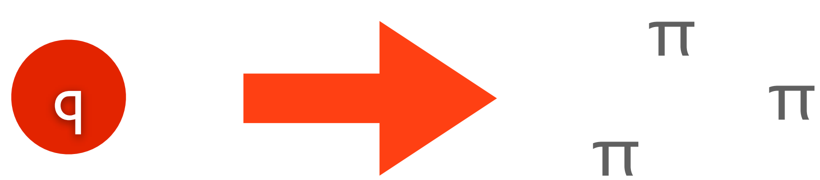


*LPHD = Local Parton Hadron Duality

Parton → Hadrons?

Parton Hadron Duality

Universal fragmentation of a parton into hadrons



But …

The point of confinement is that partons are <u>colored</u>

Hadronization = the process of color <u>neutralization</u>

I.e, the one question NOT addressed by LPHD or I.F.

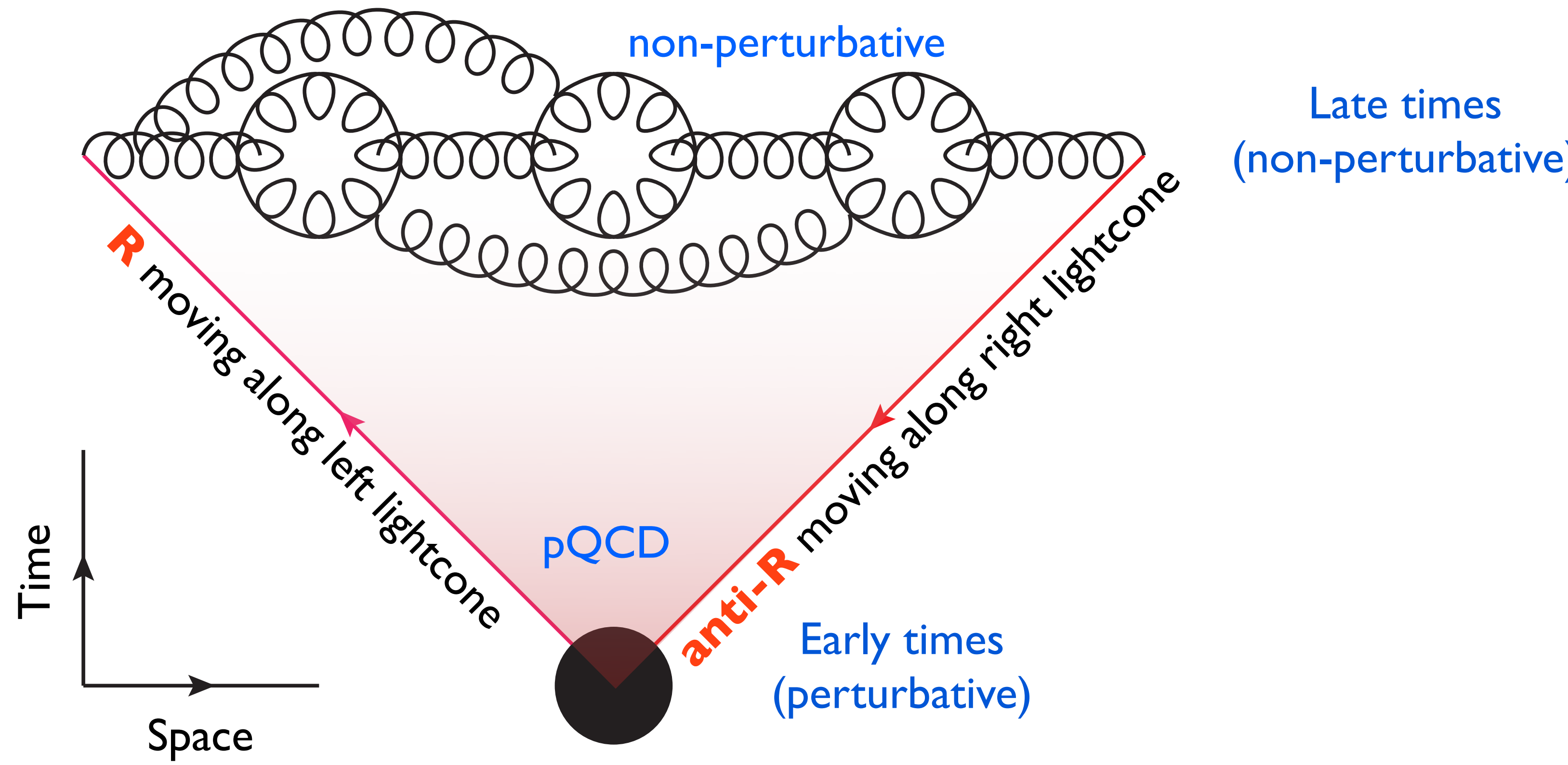
→ Unphysical to think about independent fragmentation of individual partons

*LPHD = Local Parton Hadron Duality

Color Neutralization

A physical hadronization model

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

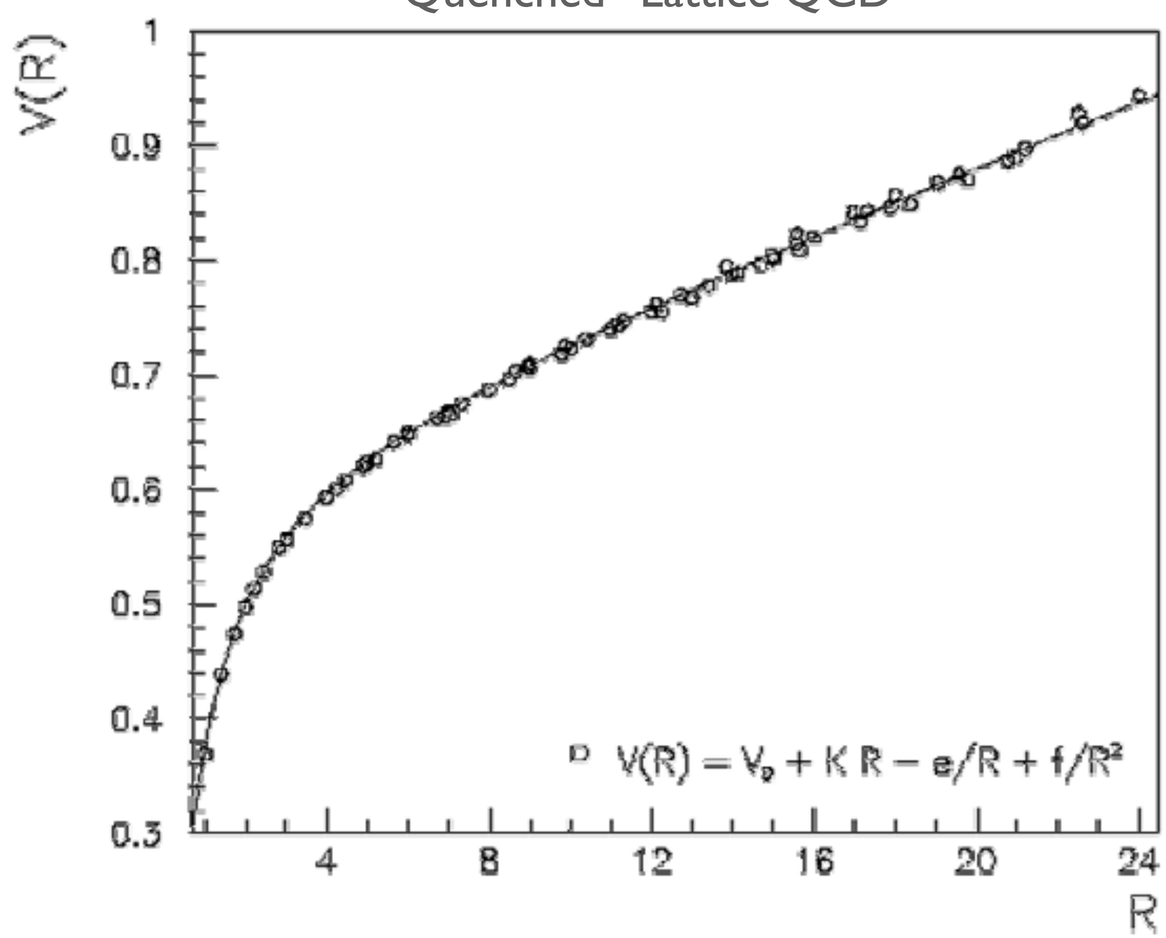


Strong "confining" field emerges between the two charges when their separation > ~ 1fm

Linear Confinement

Lattice QCD: Potential between a quark and an antiquark as function of distance, R

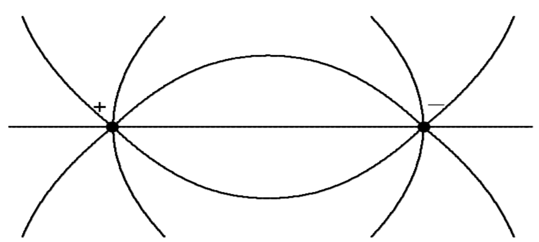
"Quenched" Lattice QCD



Linear Confinement

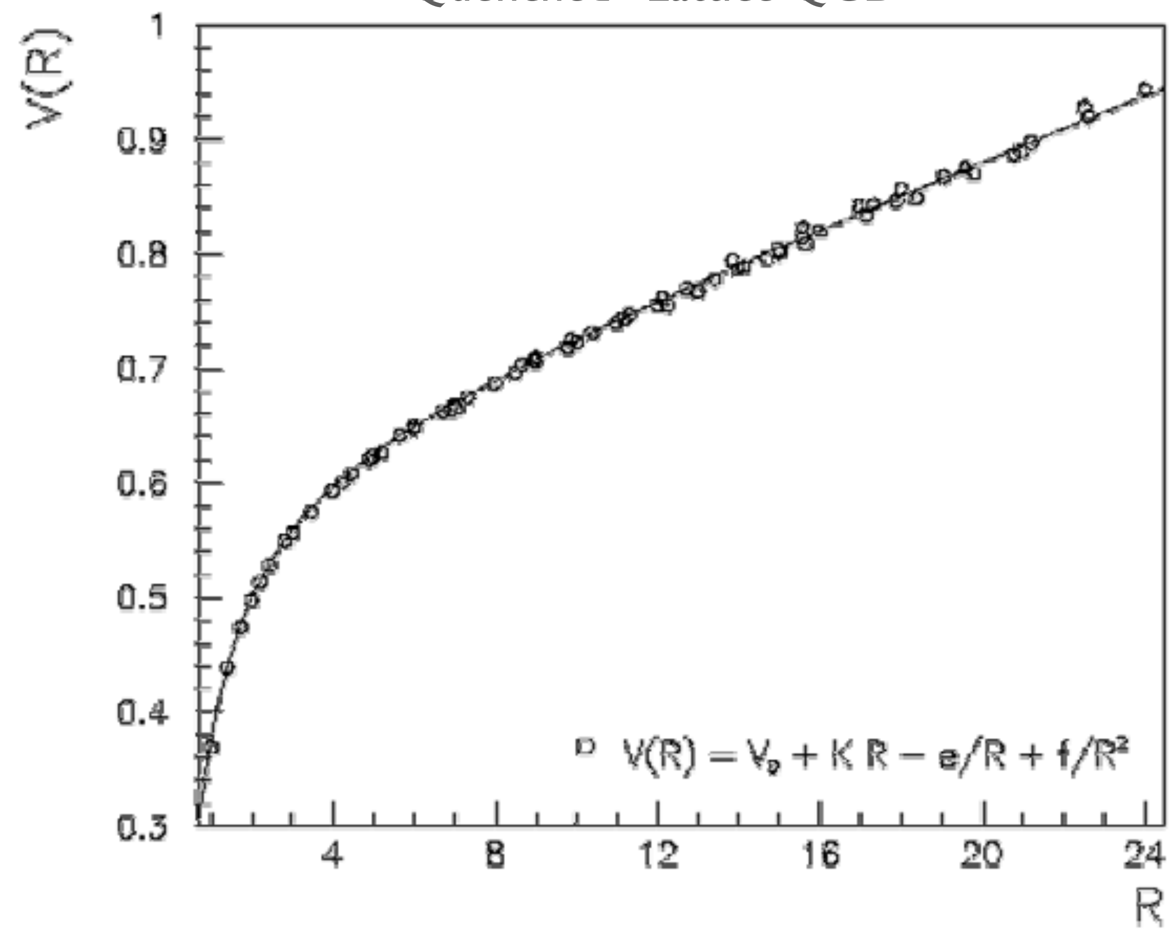
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Short Distances ~ pQCD



Partons

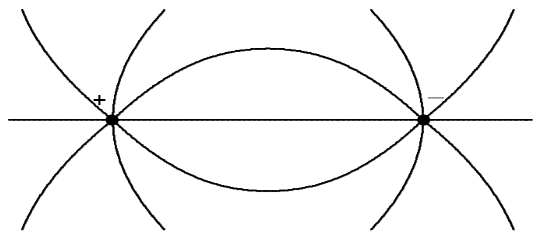
“Quenched” Lattice QCD



Linear Confinement

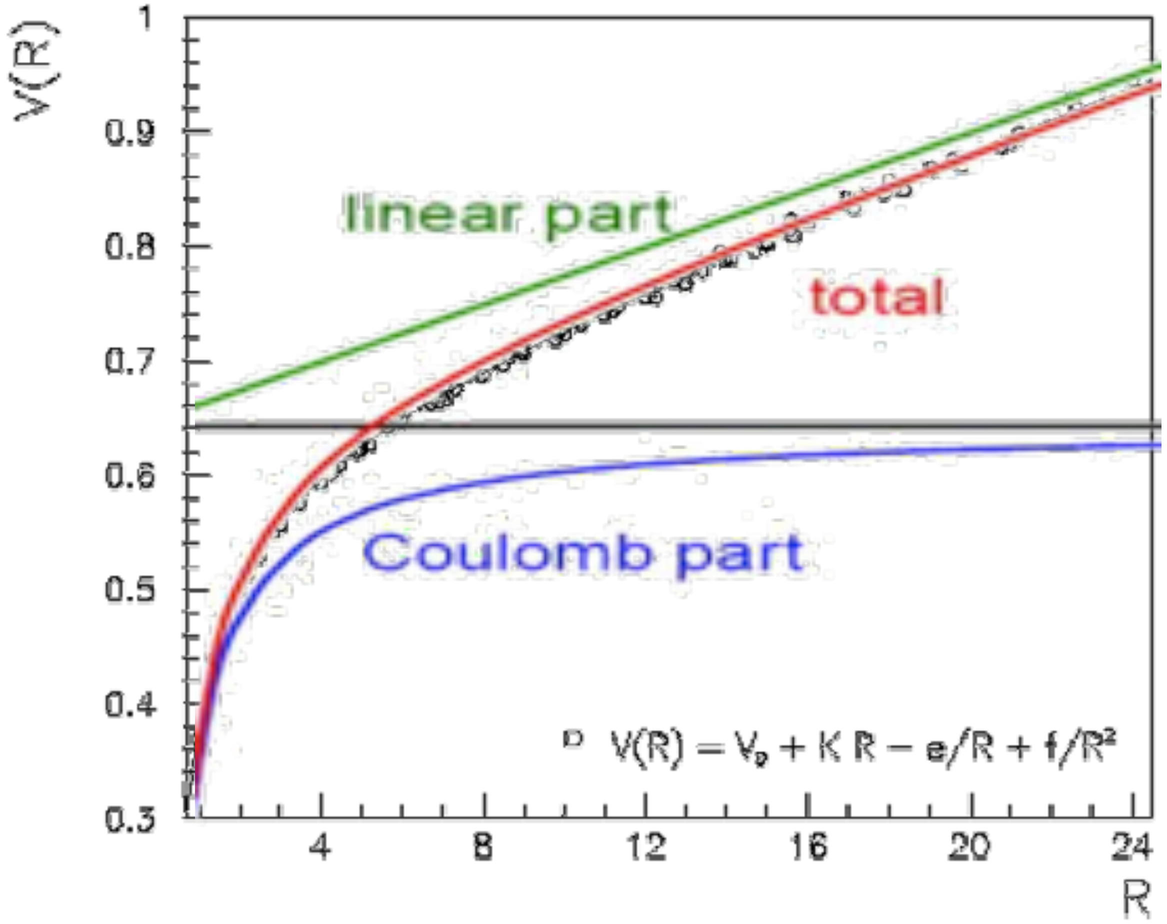
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Short Distances ~ pQCD



Partons

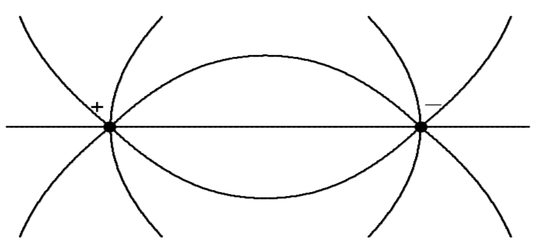
"Quenched" Lattice QCD



Linear Confinement

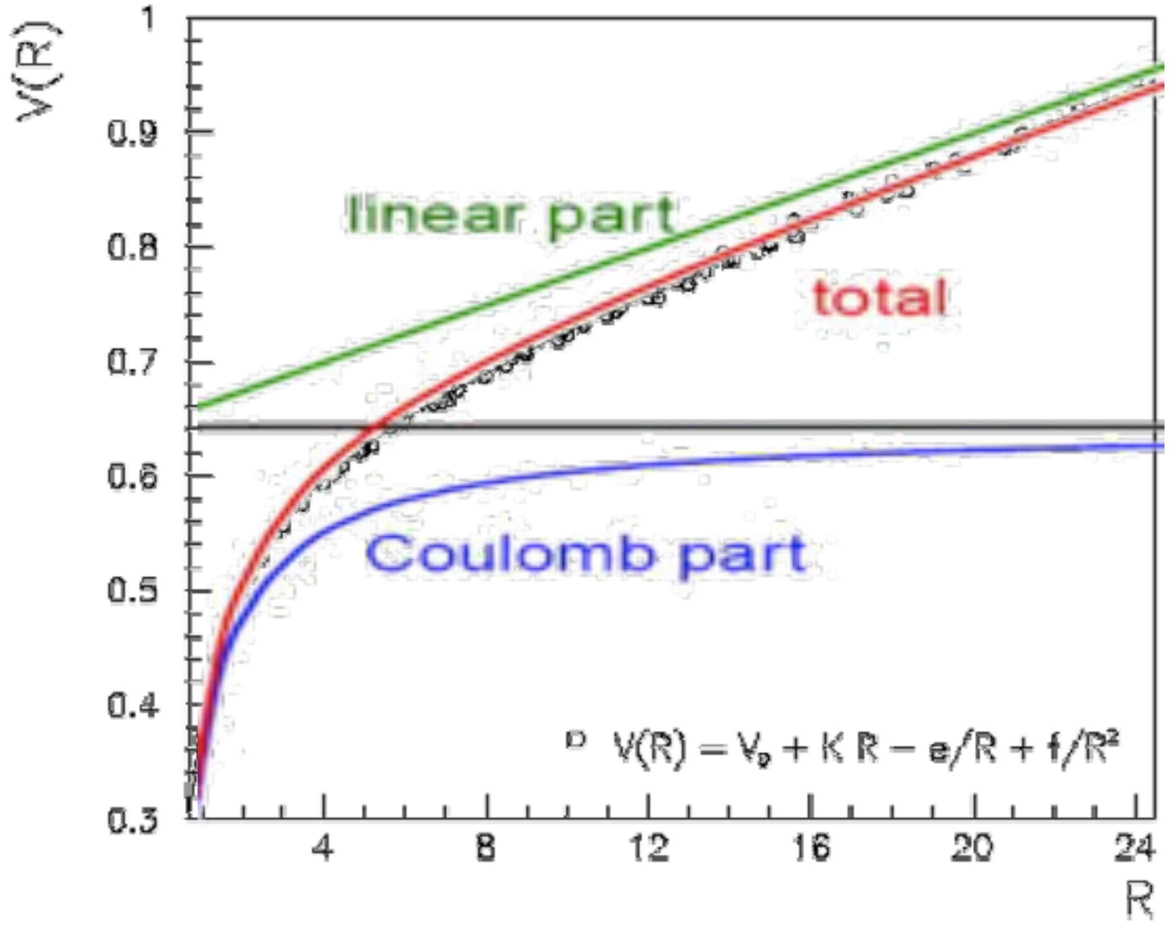
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Short Distances ~ pQCD

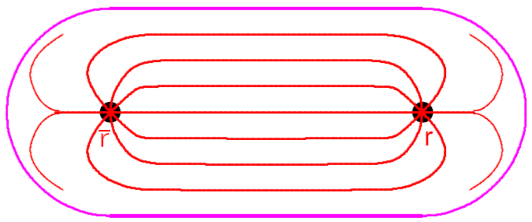


Partons

"Quenched" Lattice QCD



Long Distances ~ Linear Confinement

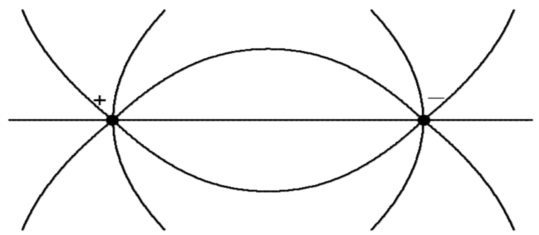


Hadrons

Linear Confinement

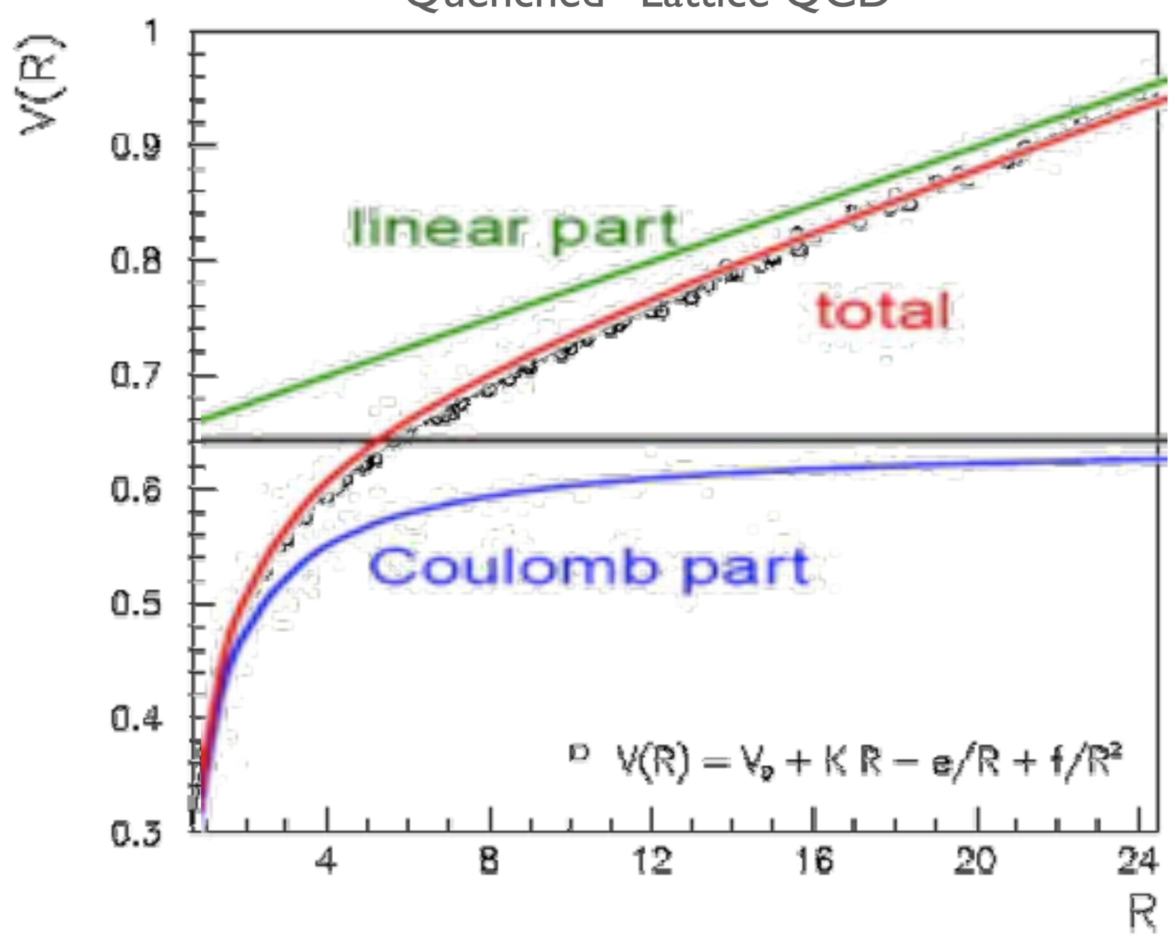
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Short Distances ~ pQCD

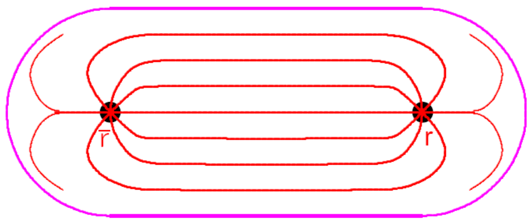


Partons

“Quenched” Lattice QCD



Long Distances ~ Linear Confinement



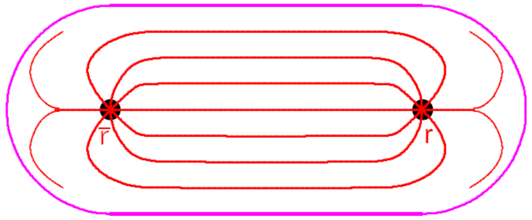
Hadrons

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

Linear Confinement

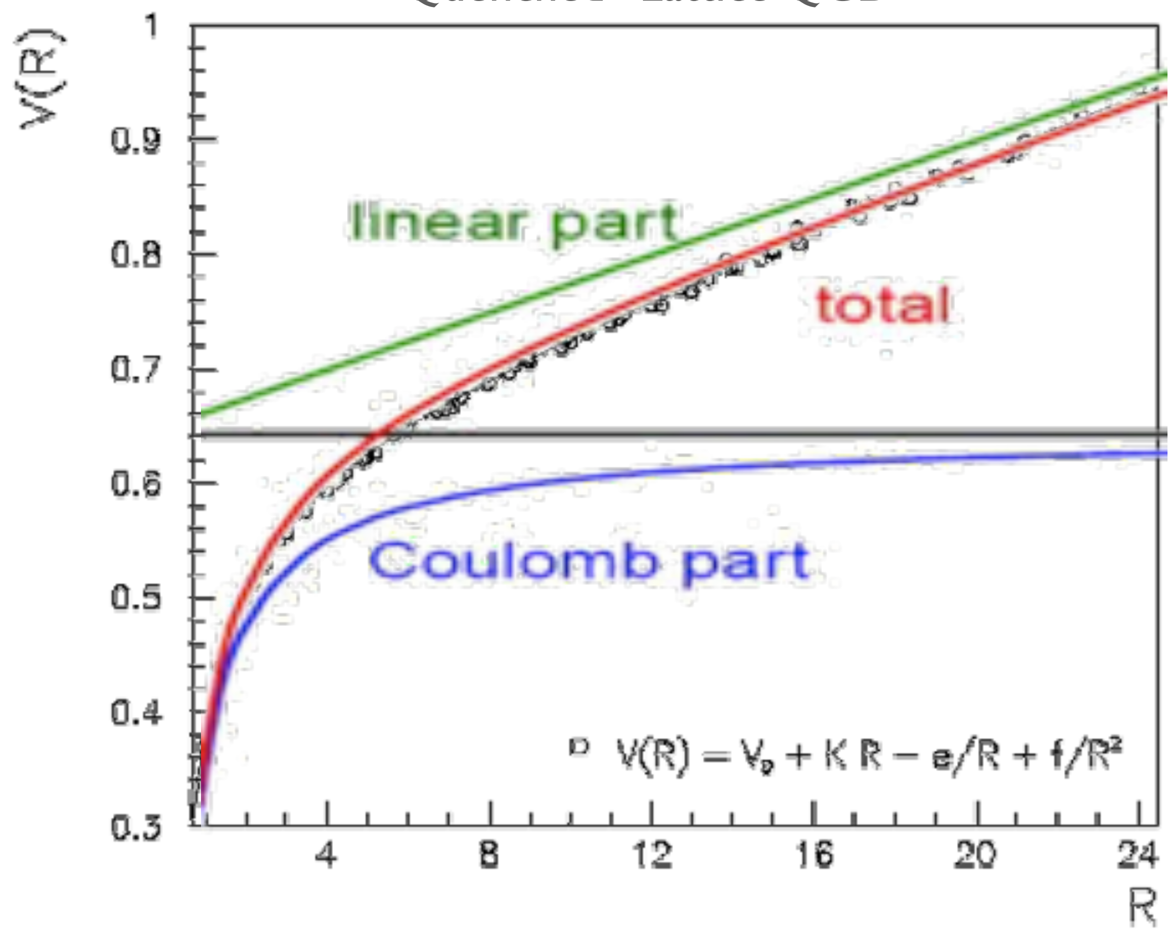
Lattice QCD: Potential between a quark and an antiquark as function of distance, R

Long Distances ~ Linear Confinement

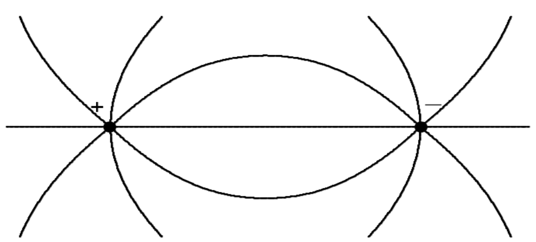


Hadrons

"Quenched" Lattice QCD



Short Distances ~ pQCD

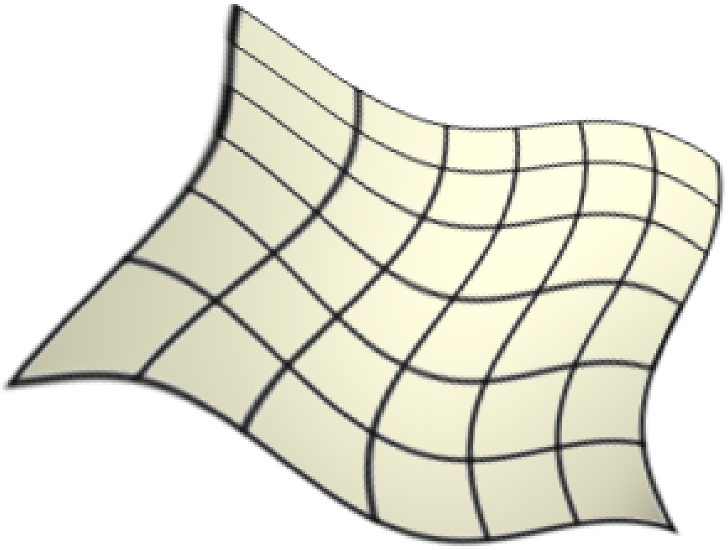


Partons

Question: What physical system has a linear potential?

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

From Partons to Strings



Motivates a model:

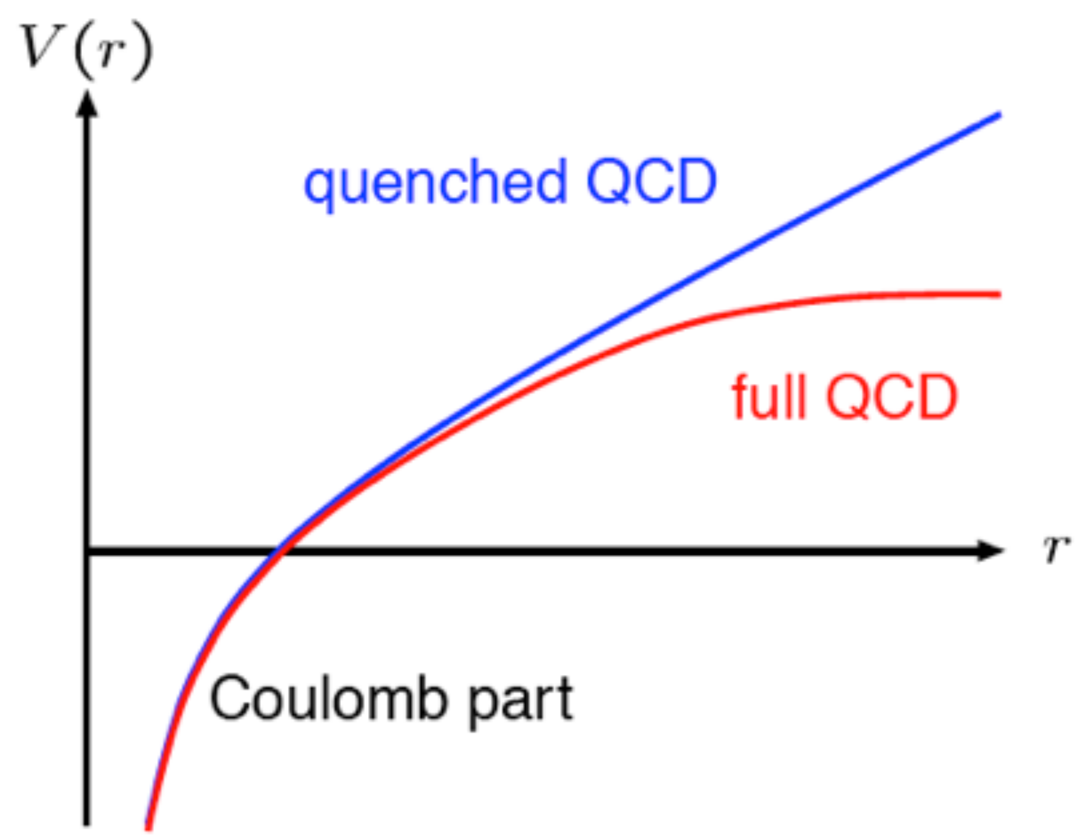
Let color field collapse into a (infinitely) narrow flux tube of uniform energy density $\kappa \sim 1$ GeV / fm

→ Relativistic 1+1 dimensional worldsheet – string

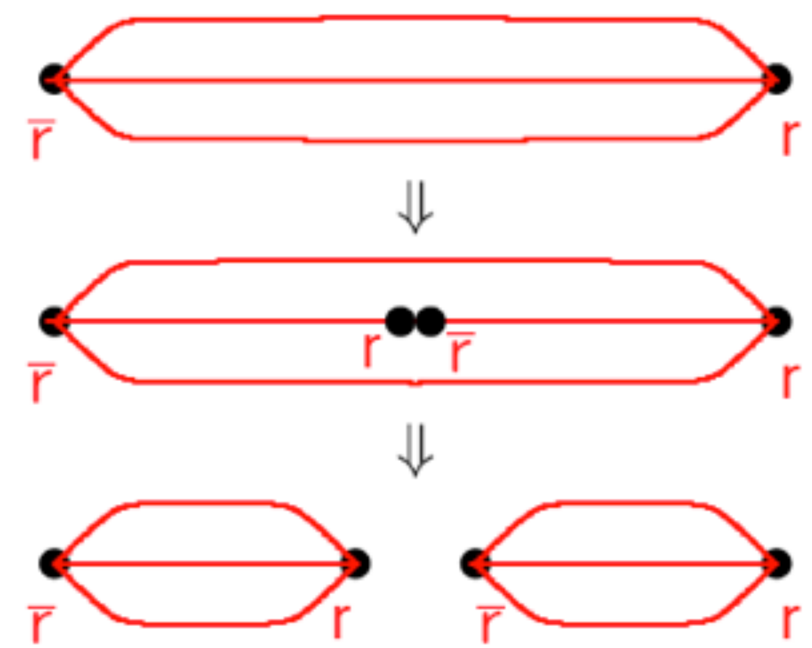
String Breaks

In “unquenched” QCD

g→qq → The strings would break



simplified colour representation:



Illustrations by T. Sjöstrand

Hadronization Models

The problem:

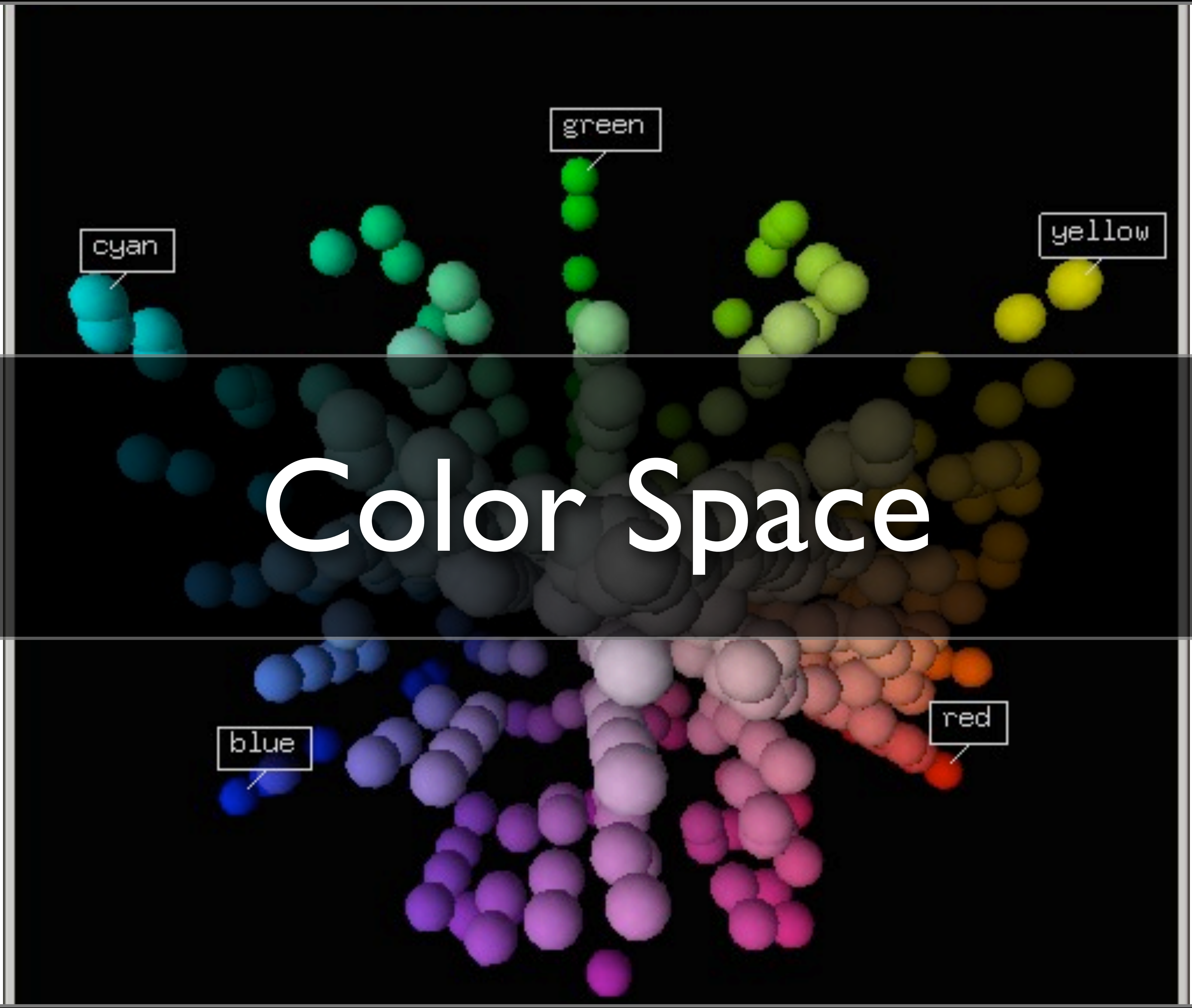
- Given a set of partons resolved at a scale of ~ 1 GeV (the perturbative cutoff), need a **"mapping"** from this set onto a set of on-shell colour-singlet (i.e., confined) hadronic states.

MC models do this in three steps

1. Map partons onto **continuum of excited hadronic states** *(called 'strings' or 'clusters')*
2. Iteratively map strings/clusters onto **discrete set of primary hadrons** *(string breaks / cluster splittings / cluster decays)*
3. Sequential decays into **secondary hadrons** (e.g., $\rho > \pi\ \pi$, $\Lambda^0 > n\ \pi^0$, $\pi^0 > \gamma\gamma$, ...)

Distance Scales ~ 10^{-15} m = 1 fermi

Color Space



Color Flow

Between which partons do confining potentials arise?

Set of simple rules for color flow, based on large-N limit

(Never Twice Same Color: true up to $O(1/N_C^2)$)

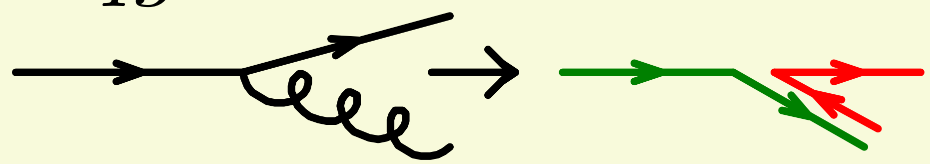
Illustrations from: P.Nason & P.S., PDG Review on *MC Event Generators*, 2012

Color Flow

Between which partons do confining potentials arise?

Set of simple rules for color flow, based on large-N limit

$q \to qg$



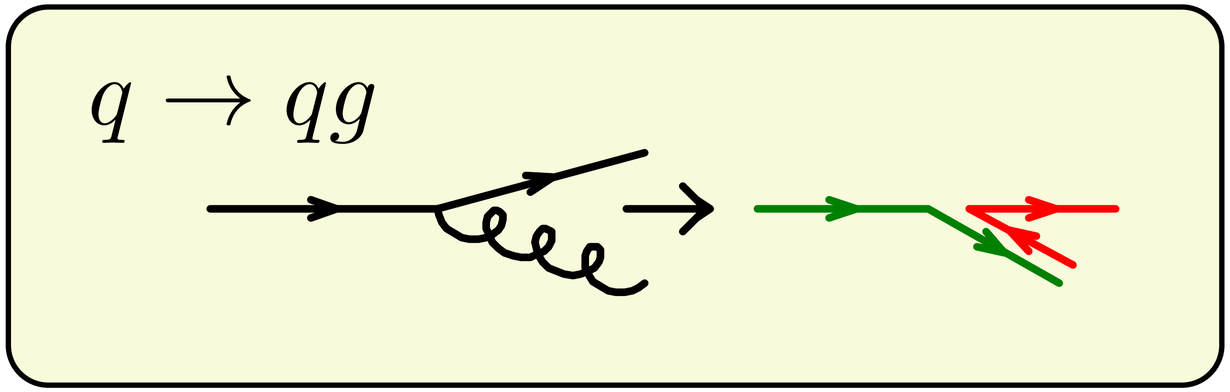
(Never Twice Same Color: true up to $O(1/N_C^2)$)

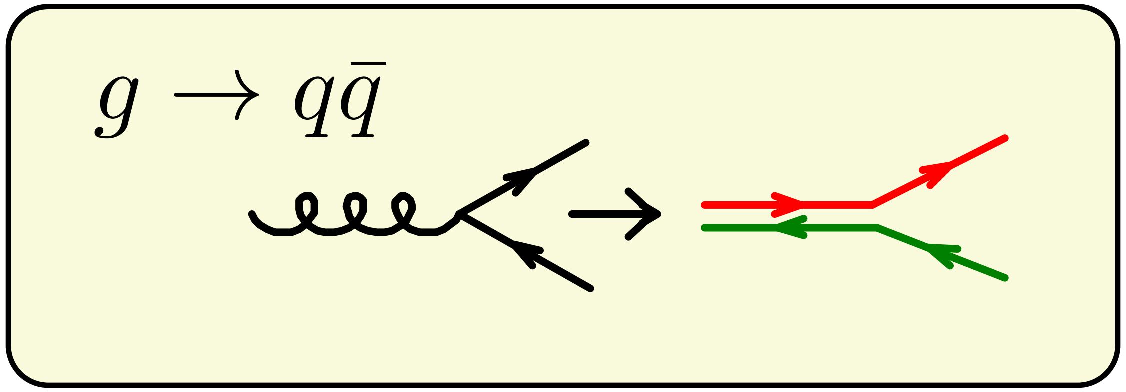
Illustrations from: P.Nason & P.S.,
PDG Review on *MC Event Generators*, 2012

Color Flow

Between which partons do confining potentials arise?

Set of simple rules for color flow, based on large-N limit





(Never Twice Same Color: true up to $O(1/N_C^2)$)

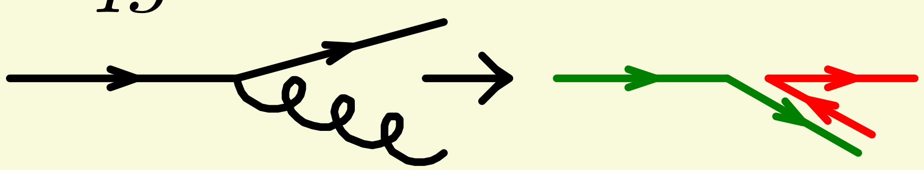
Illustrations from: P.Nason & P.S., PDG Review on *MC Event Generators*, 2012

Color Flow

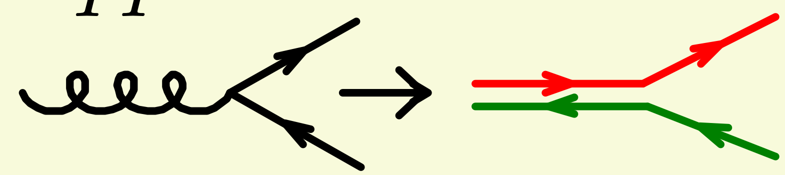
Between which partons do confining potentials arise?

Set of simple rules for color flow, based on large-N limit

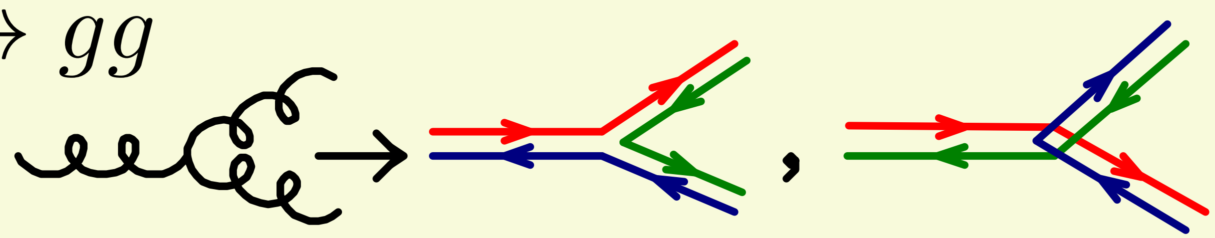
$q \to qg$



$g \to q\bar{q}$



$g \to gg$



(Never Twice Same Color: true up to $O(1/N_C^2)$)

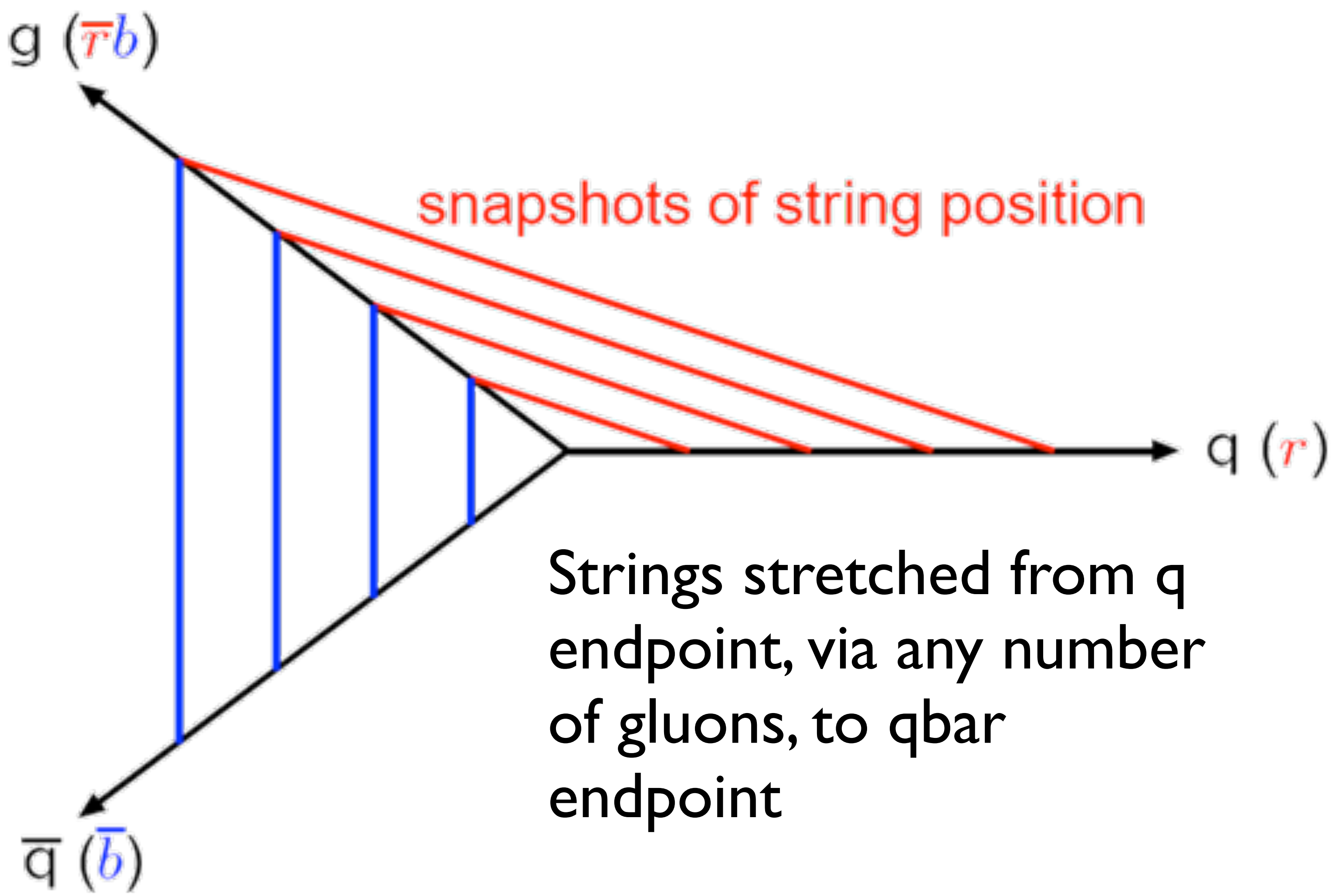
Illustrations from: P.Nason & P.S., PDG Review on *MC Event Generators*, 2012

From Partons to Strings

Illustrations by T. Sjöstrand

Map:

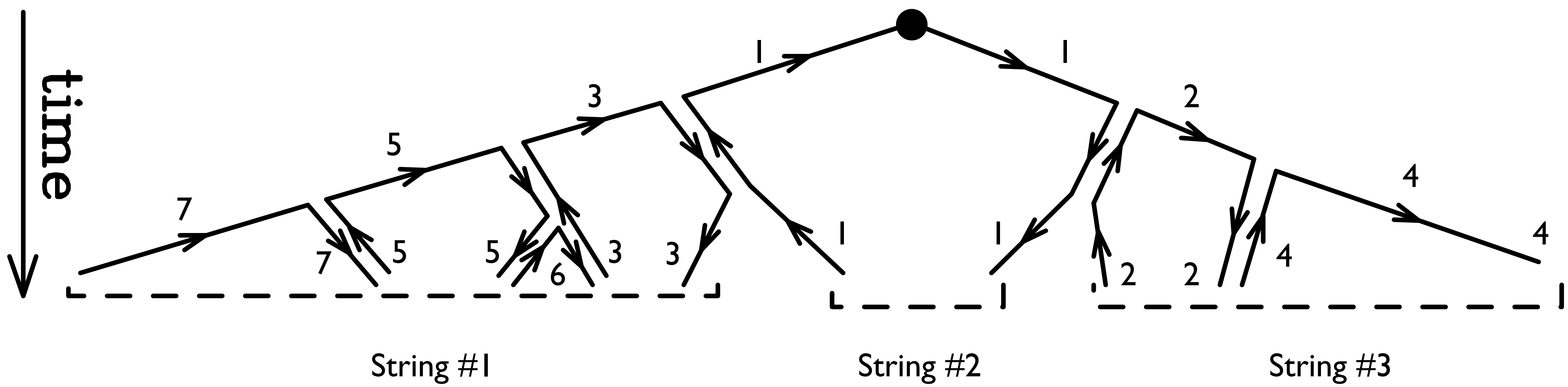
- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)



Strings stretched from q endpoint, via any number of gluons, to qbar endpoint

Color Flow

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



Coherence of pQCD cascades → not much "overlap" between strings
→ planar approx pretty good

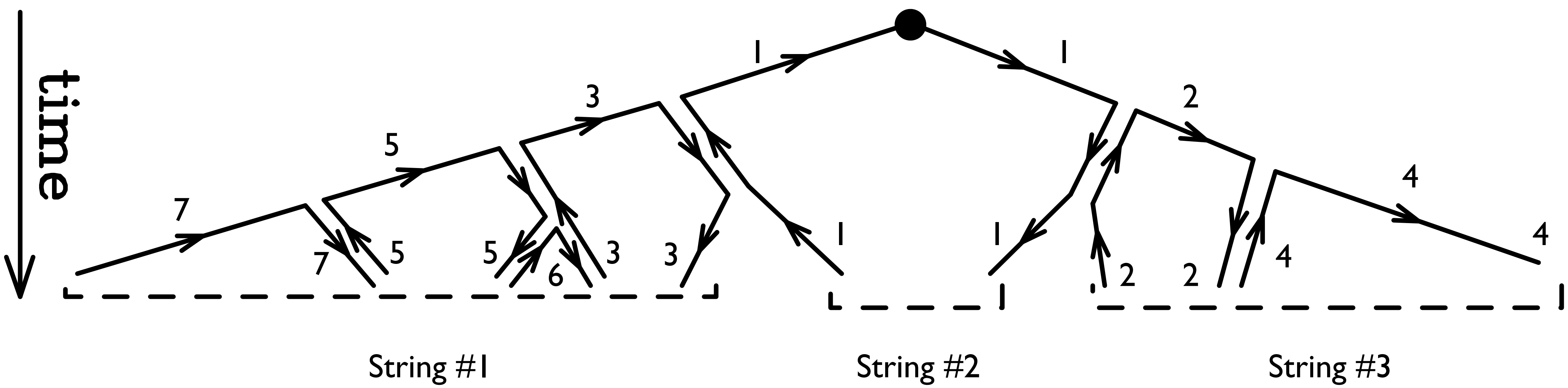
(LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$))

Note: (much) more color getting kicked around in hadron collisions → color reconnections important there? …

Color Flow

For an entire Cascade

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



Coherence of pQCD cascades → not much "overlap" between strings
→ planar approx pretty good

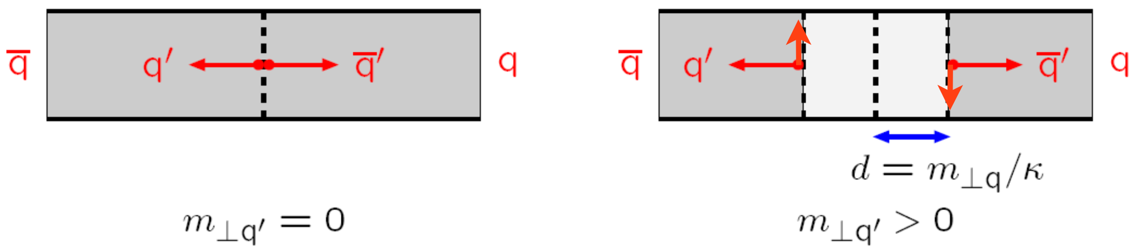
(LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$))

Note: (much) more color getting kicked around in hadron collisions → color reconnections important there? …

String Breaks

String Breaks

Modeled by tunneling



$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp\mathrm{q}}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp\mathrm{q}}^2}{\kappa}\right) \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right)$$

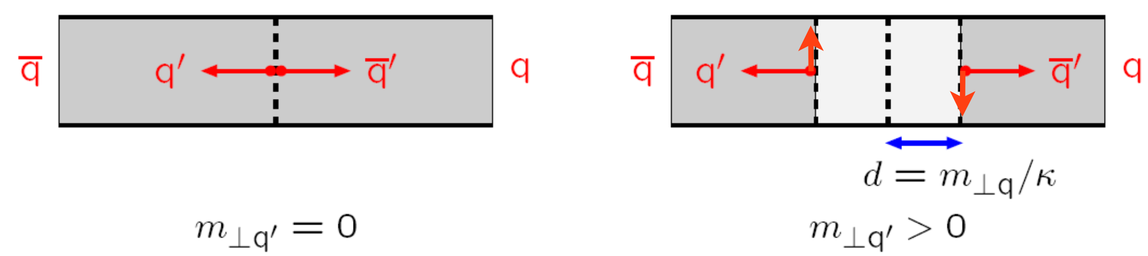
1) common Gaussian $p_\perp$ spectrum

2) suppression of heavy quarks $\mathrm{u\overline{u}} : \mathrm{d\overline{d}} : \mathrm{s\overline{s}} : \mathrm{c\overline{c}} \approx 1 : 1 : 0.3 : 10^{-11}$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

String Breaks

Modeled by tunneling



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

1) common Gaussian $p_\perp$ spectrum

2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

Also depends on:

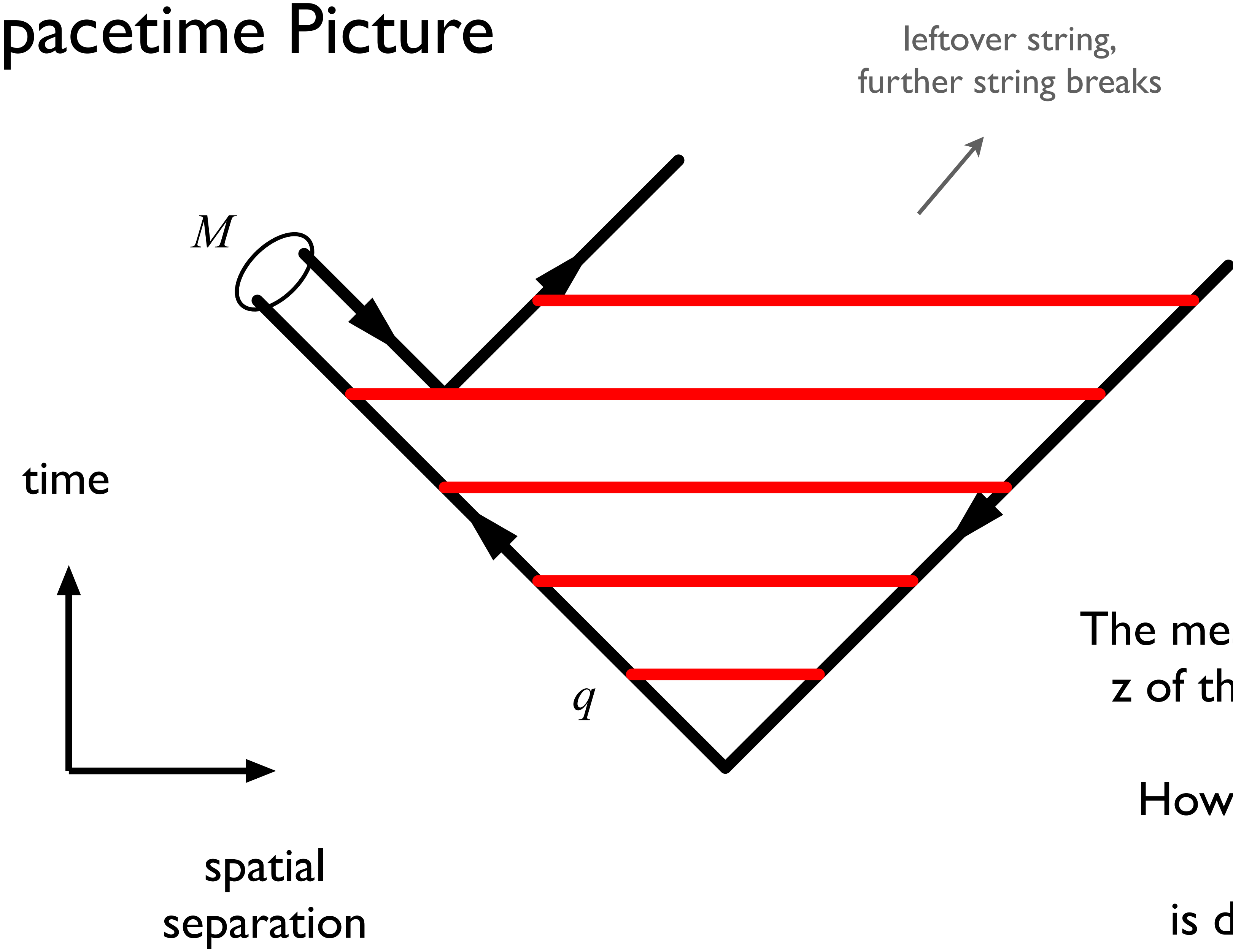
Spins, hadron multiplets, hadronic wave functions, phase space, …

→ (much) more complicated → many parameters

→ Not calulable, must be constrained by data → 'tuning'

Fragmentation Function

Spacetime Picture

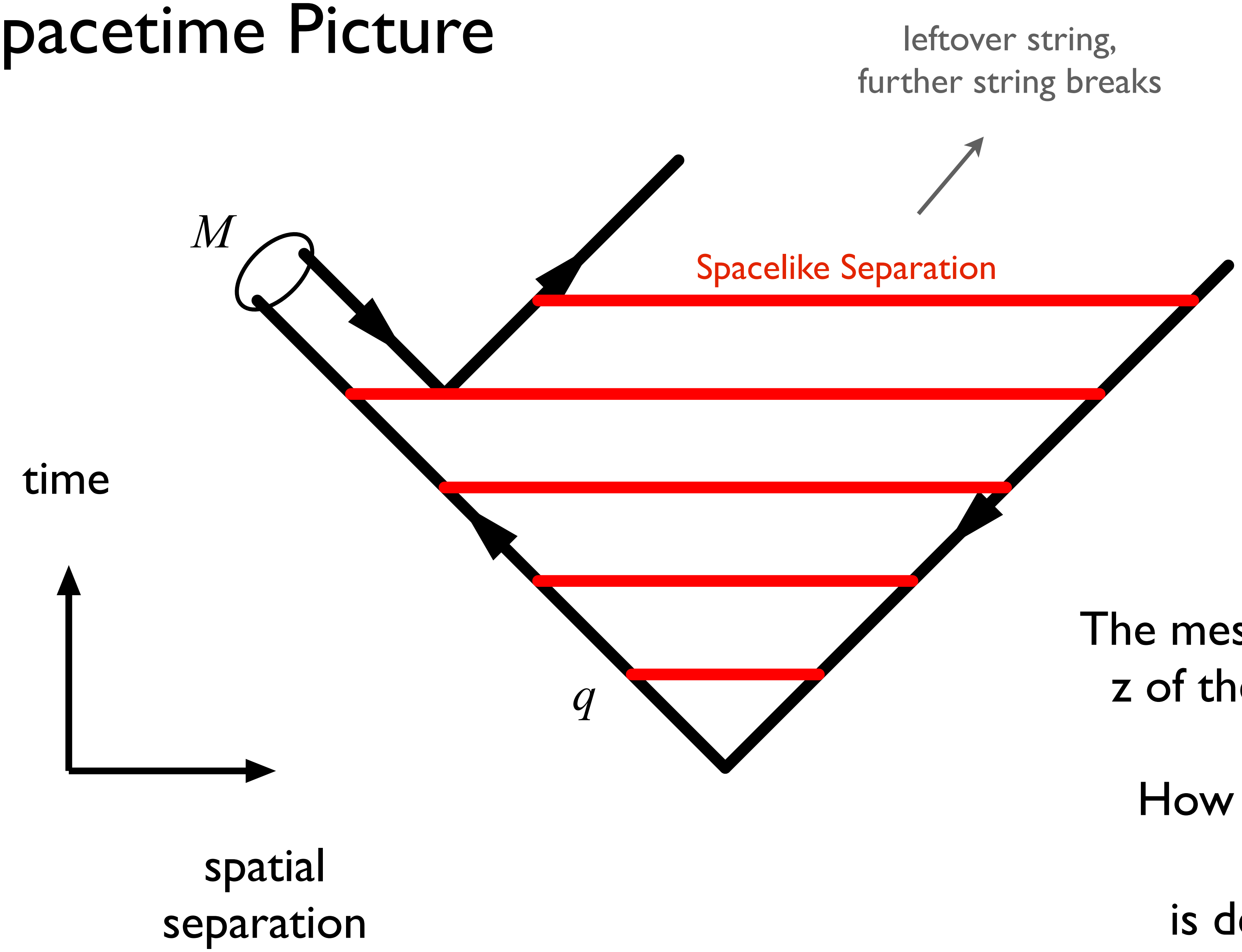


The meson M takes a fraction z of the quark momentum,

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

Fragmentation Function

Spacetime Picture



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

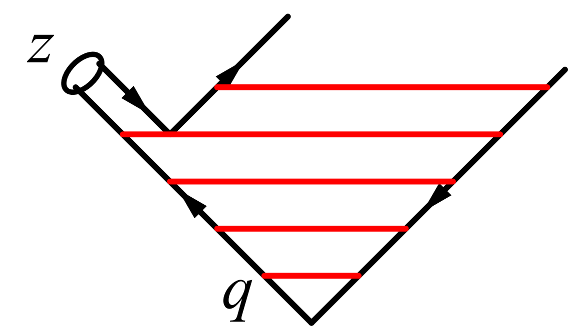
How big that fraction is,
$z \in [0,1]$,
is determined by the *fragmentation function*, $f(z,Q_0^2)$

Left-Right Symmetry

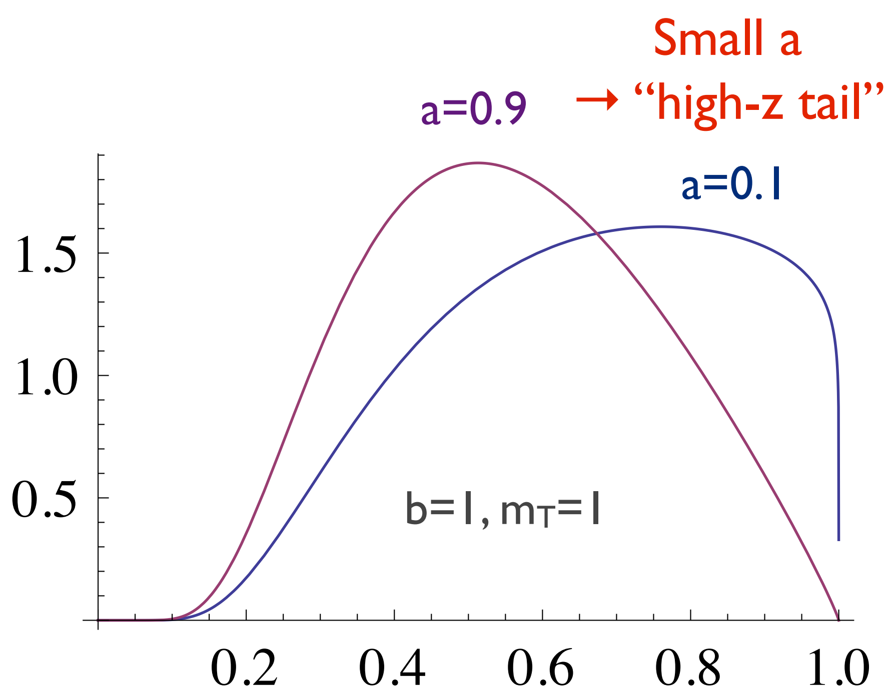
Causality → Left-Right Symmetry

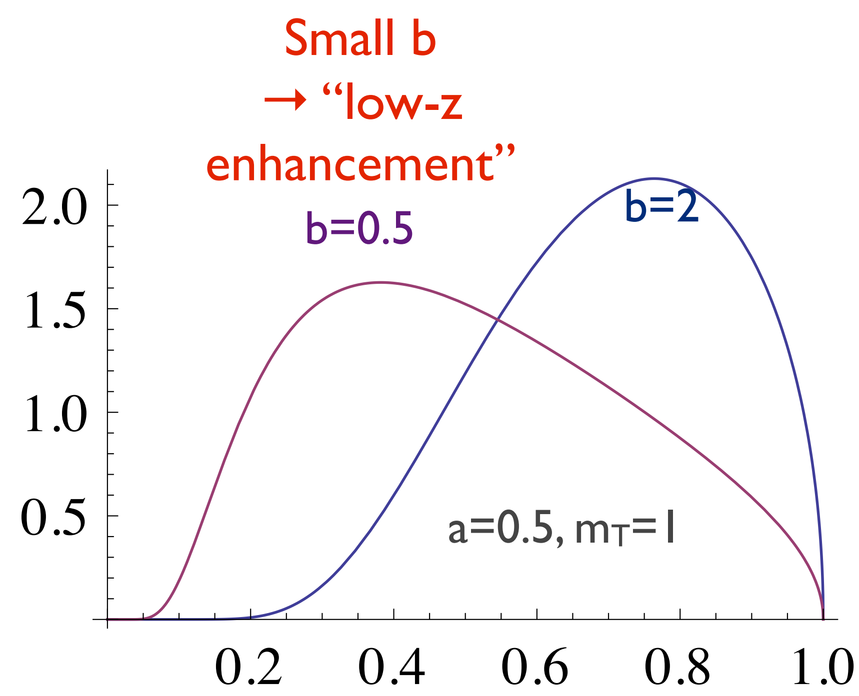
→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function



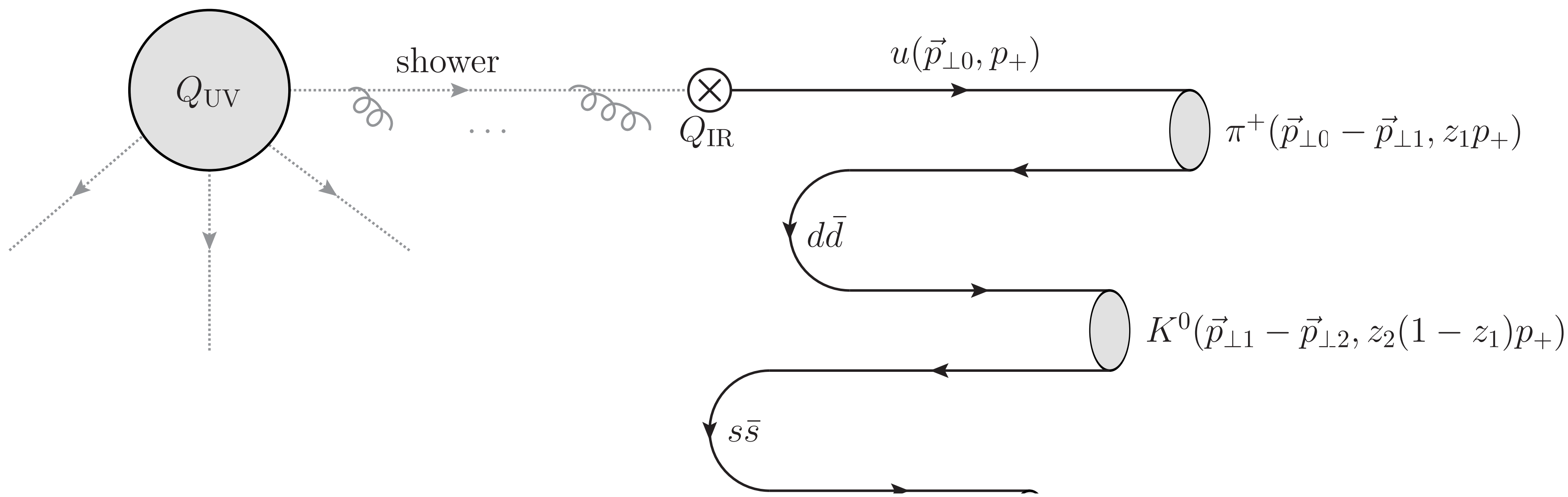
$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$



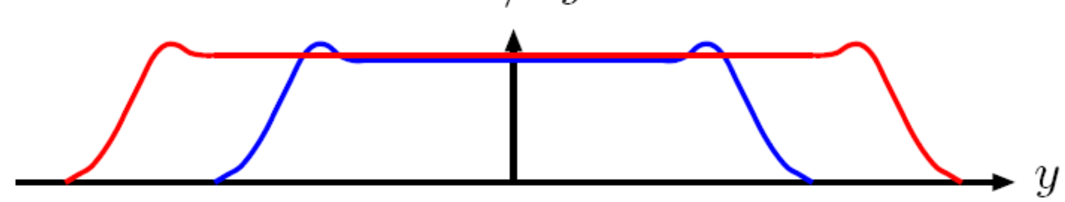


Iterative String Breaks

Causality → May iterate from outside-in



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



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

Illustration by T. Sjöstrand

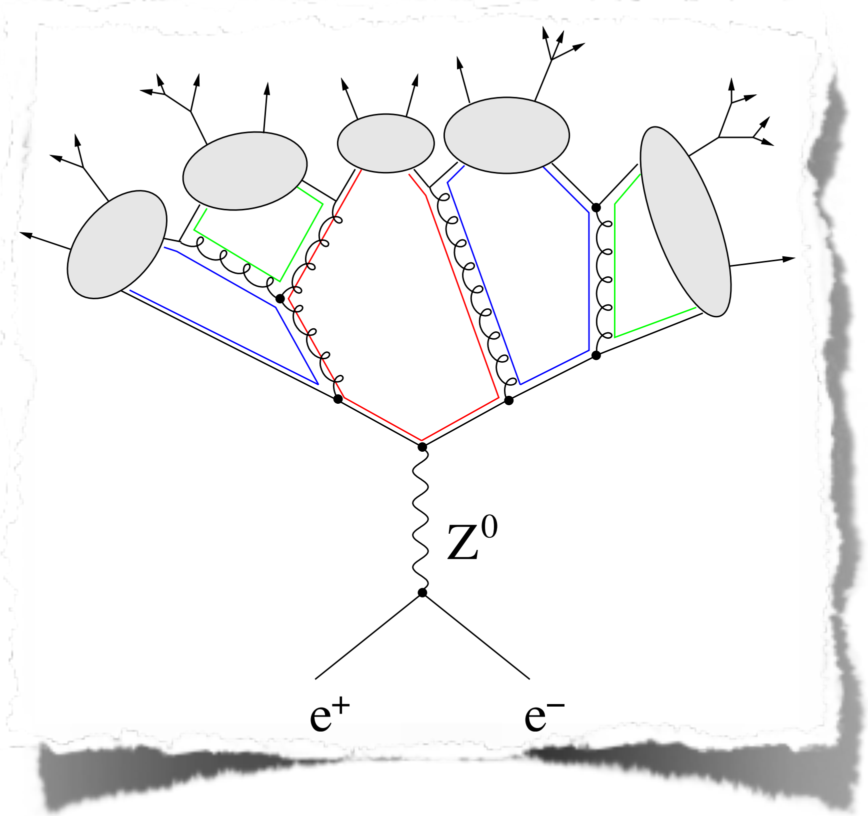
"Preconfinement"

Force $g \rightarrow qq$ splittings at Q_0

$\rightarrow$ high-mass qq "clusters"

Isotropic 2-body decays to hadrons

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



Alternative: The Cluster Model

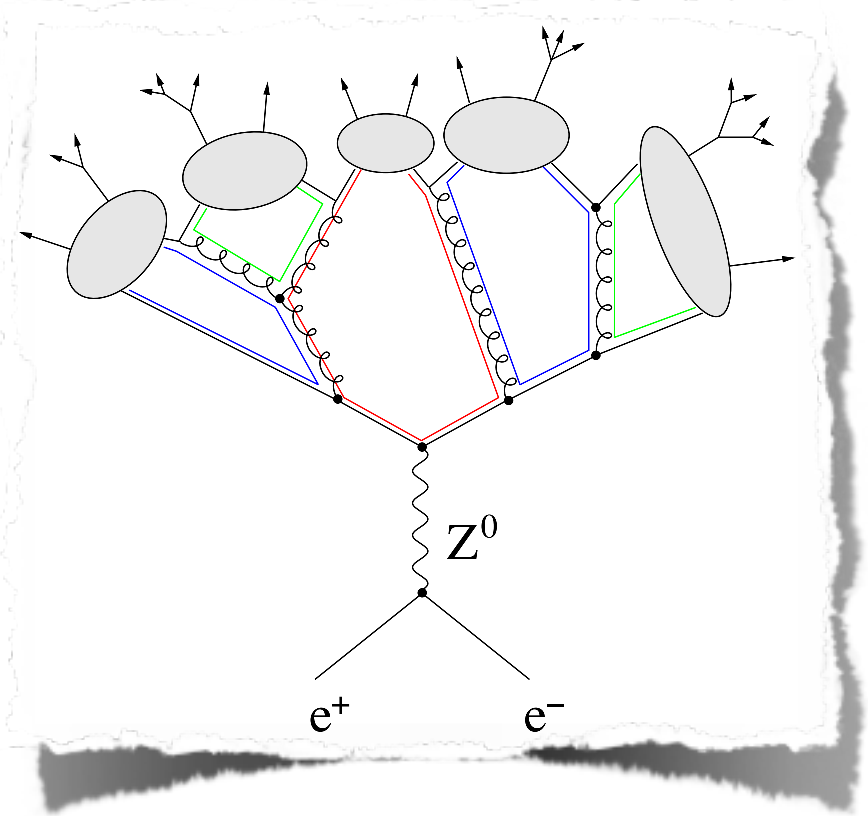
"Preconfinement"

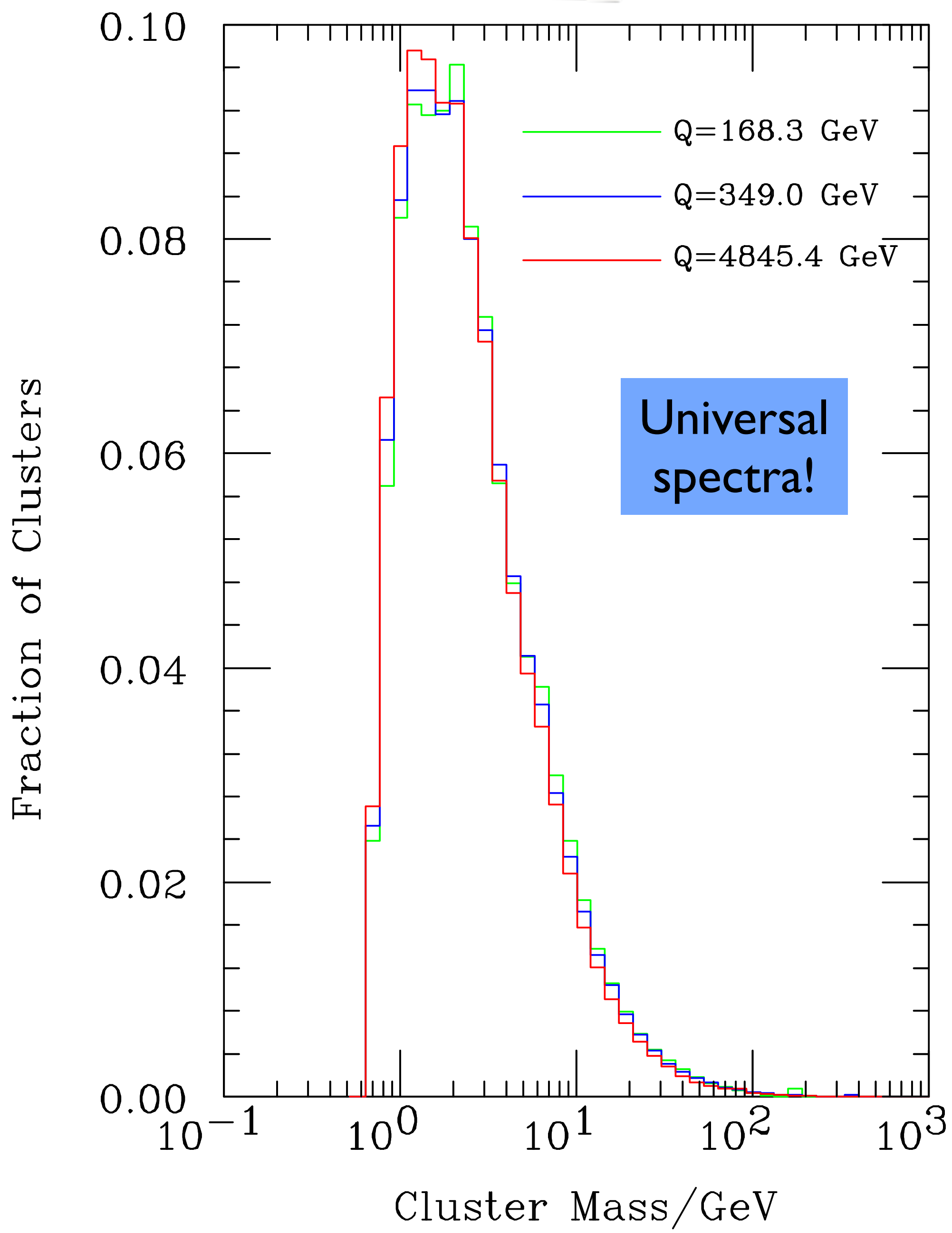
Force g→qq splittings at Q_0

→ high-mass qq "clusters"

Isotropic 2-body decays to hadrons

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





Alternative: The Cluster Model

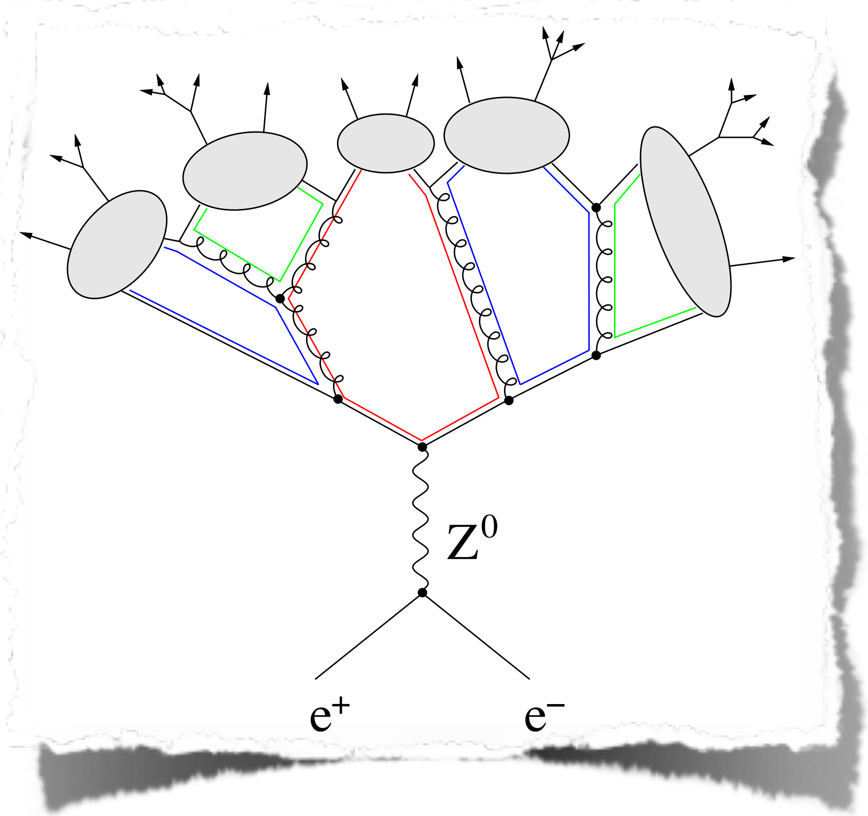
“Preconfinement”

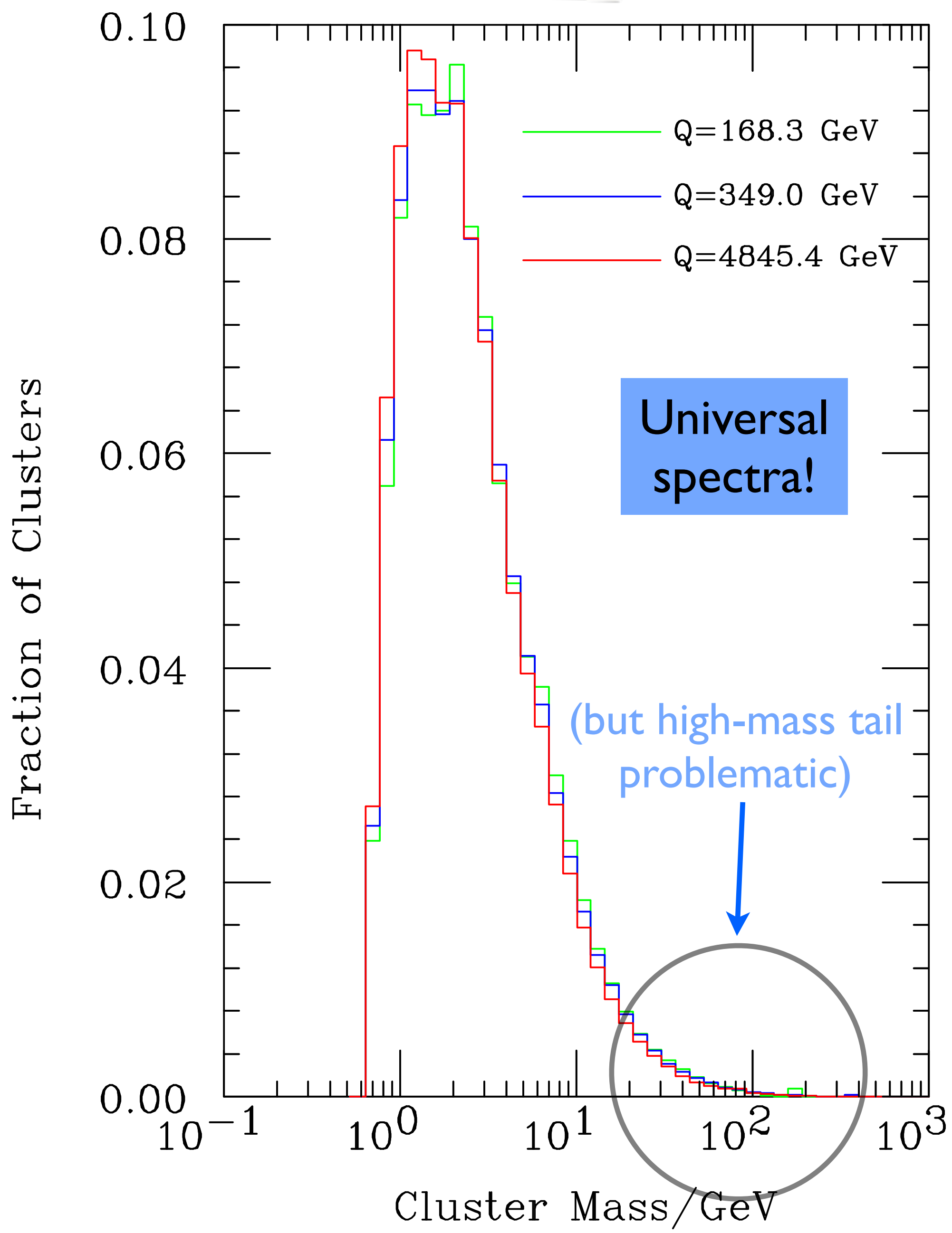
Force $g \to qq$ splittings at Q_0

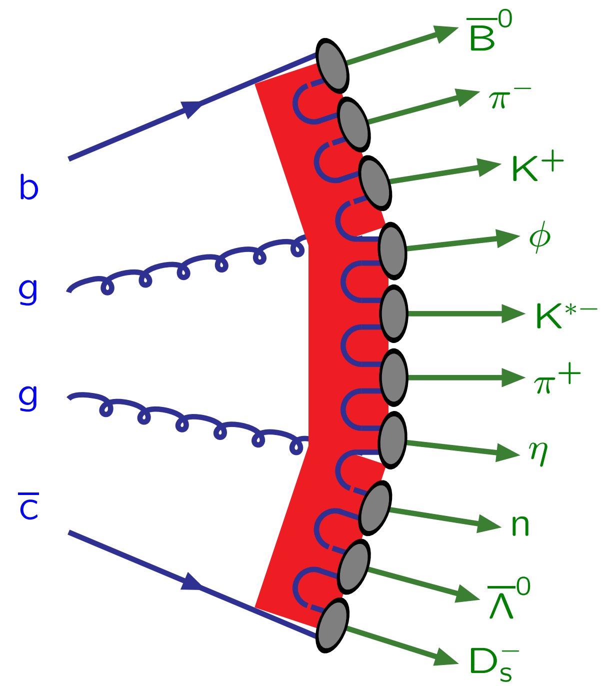
$\to$ high-mass qq “clusters”

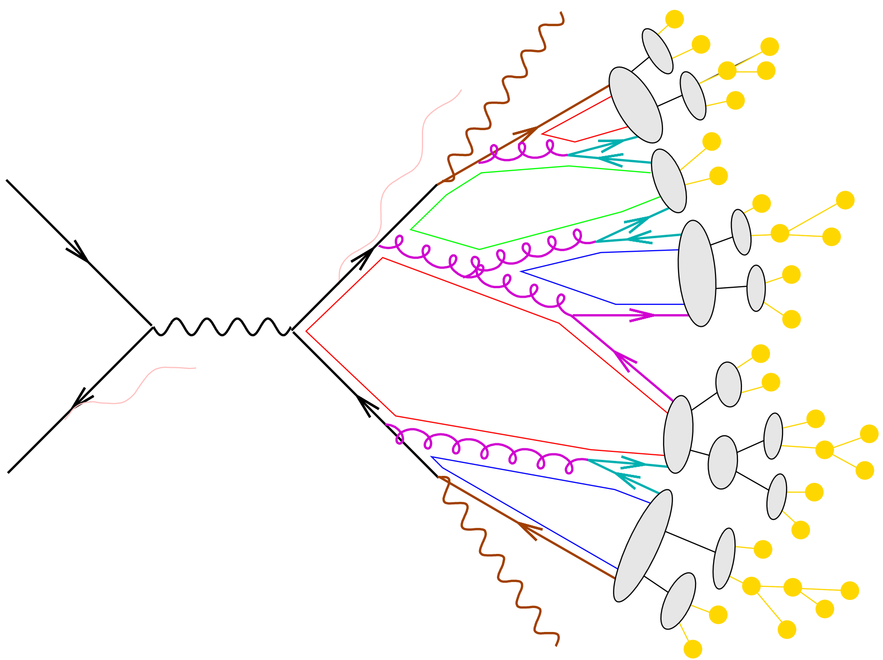
Isotropic 2-body decays to hadrons

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









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

Small strings → clusters. Large clusters → strings

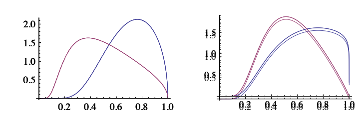
String Hadronization

Main IR Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function

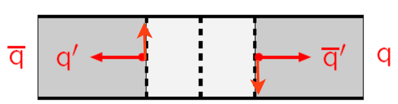
The a and b parameters



pT in string breaks

Scale of string breaking process

<p_T> in string breaks



Meson Multiplets

Mesons

Strangeness suppression, Vector/Pseudoscalar, η, η’, …

Baryon Multiplets

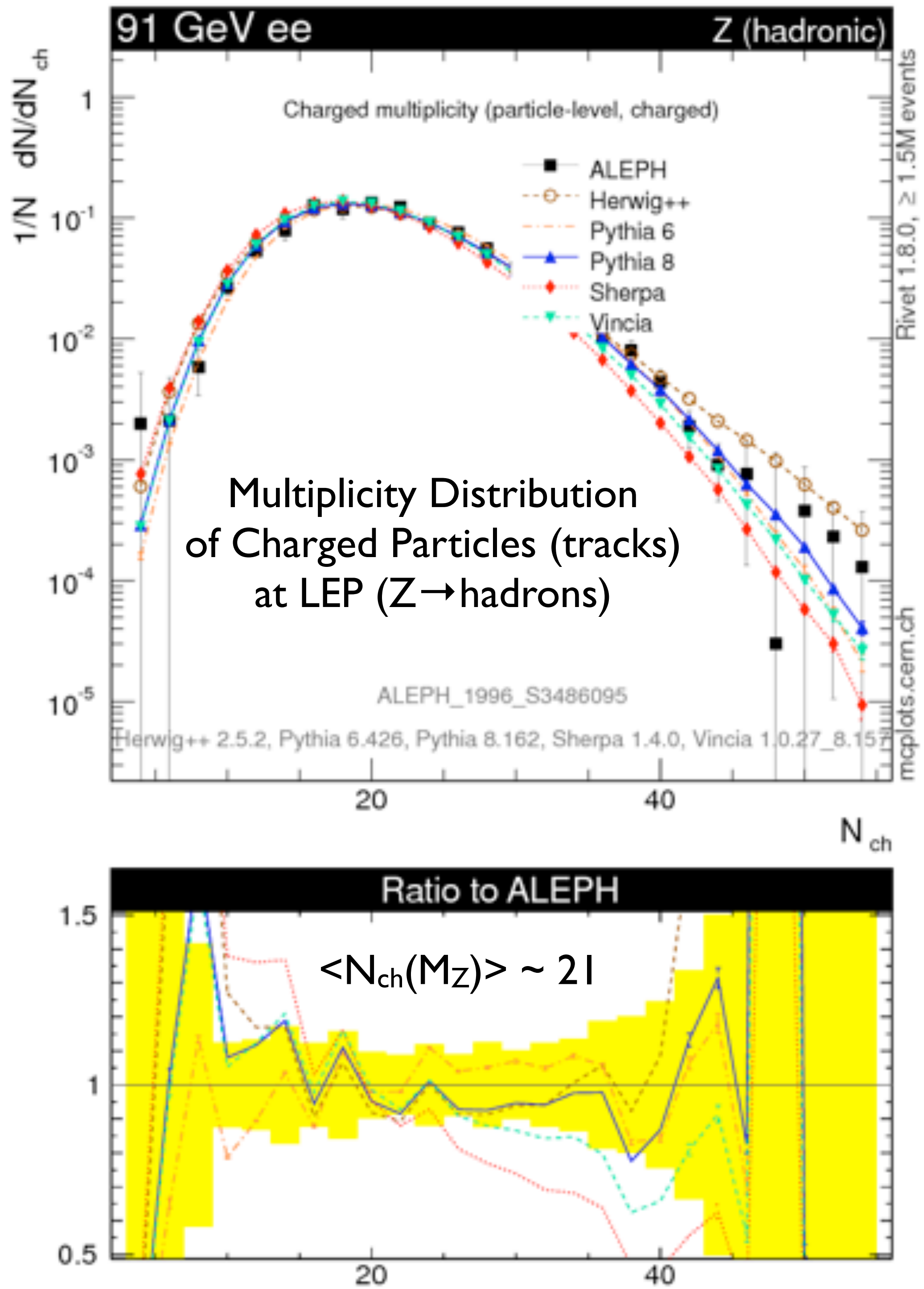
Baryons

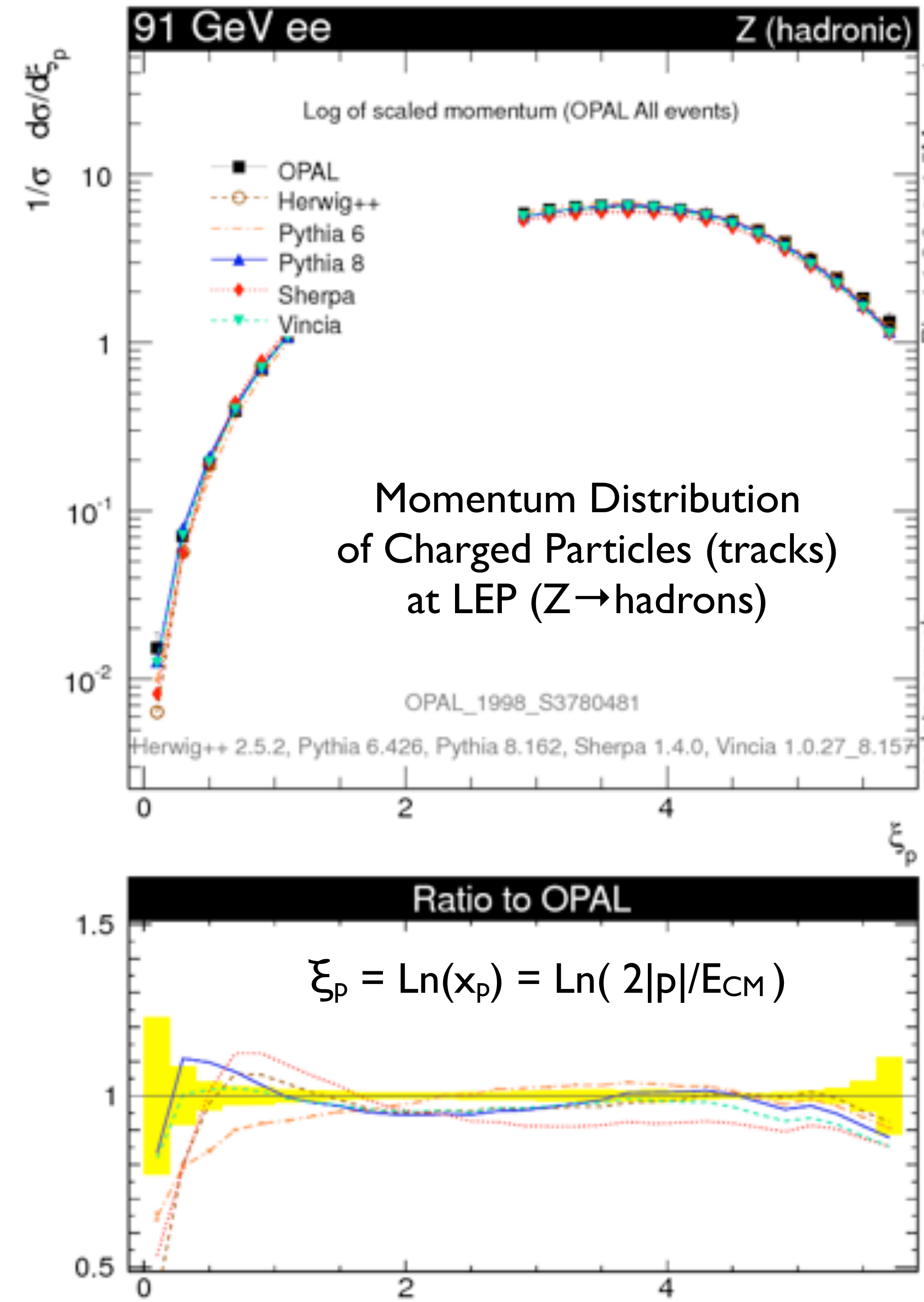
Diquarks, Decuplet vs Octet, popcorn, junctions, … ?

QCD
Lecture V

Fragmentation Tuning

(example)





Hadron Collisions

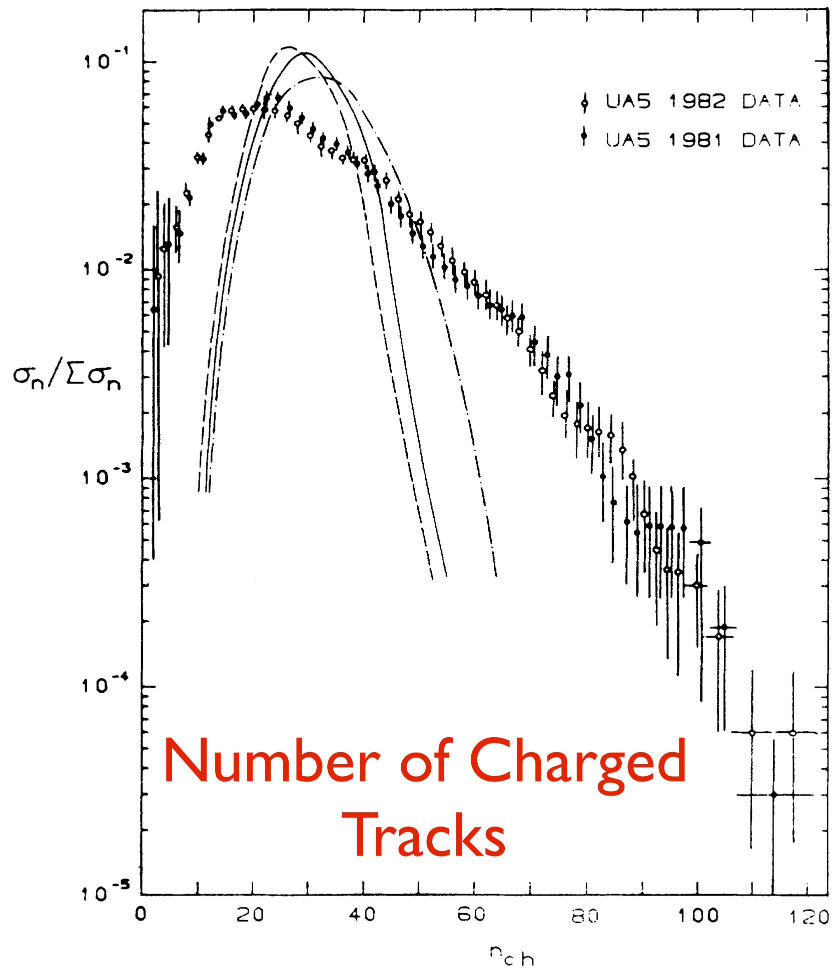


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

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

Hadron Collisions

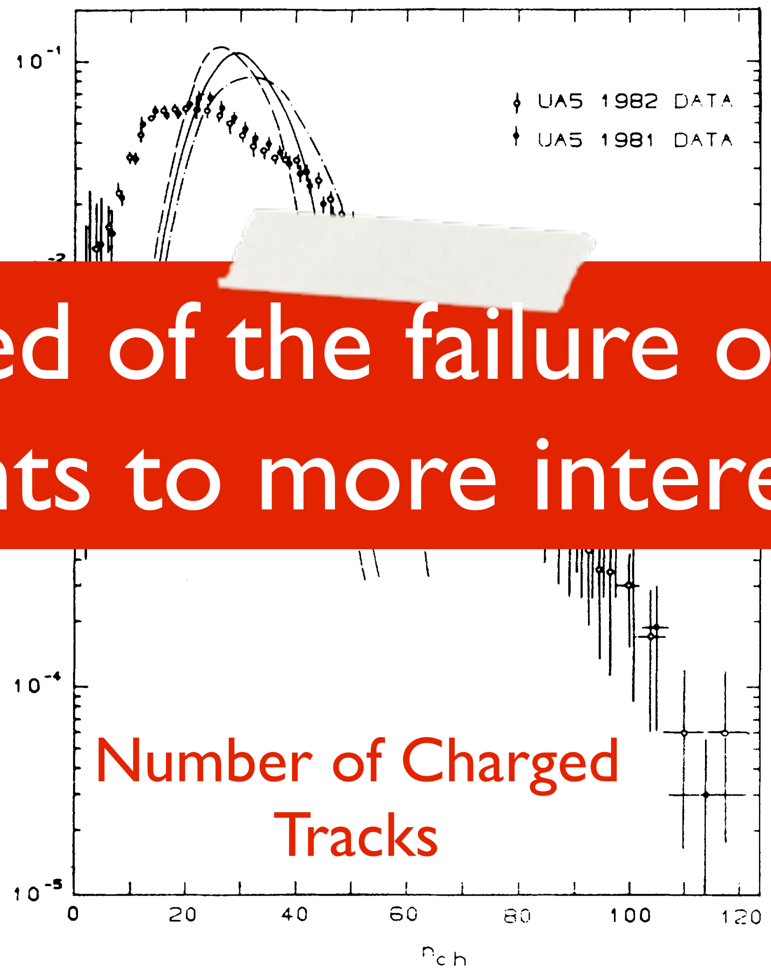


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

Do not be scared of the failure of physical models
Usually points to more interesting physics

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

Hadron Collisions

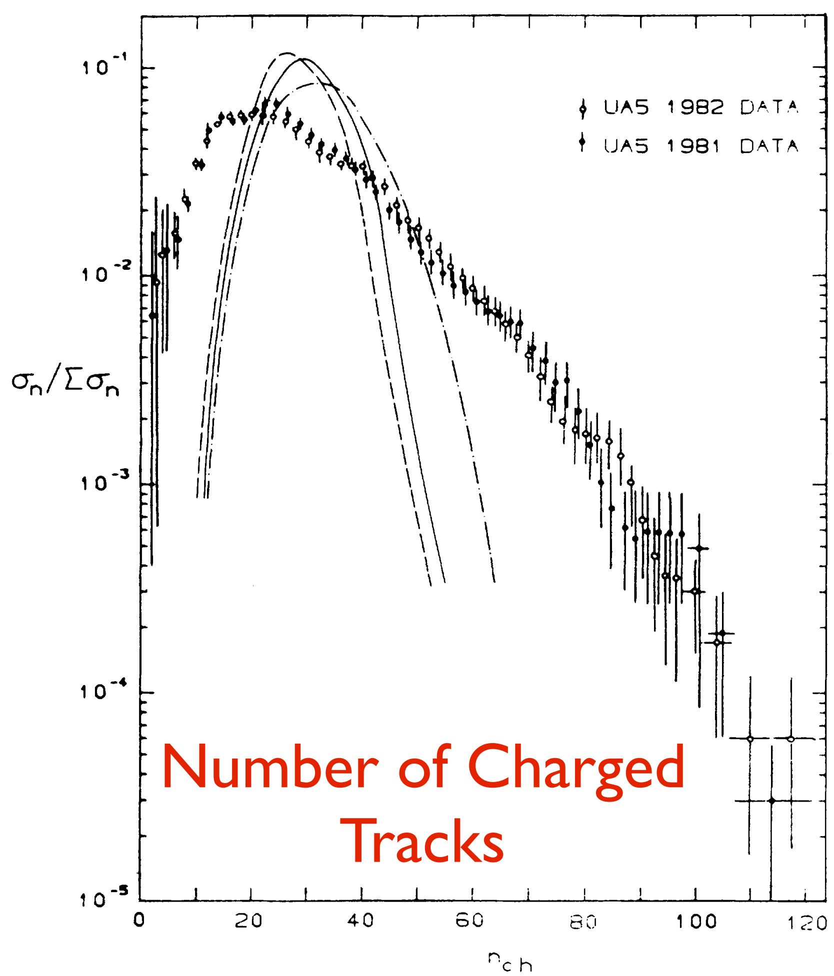


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

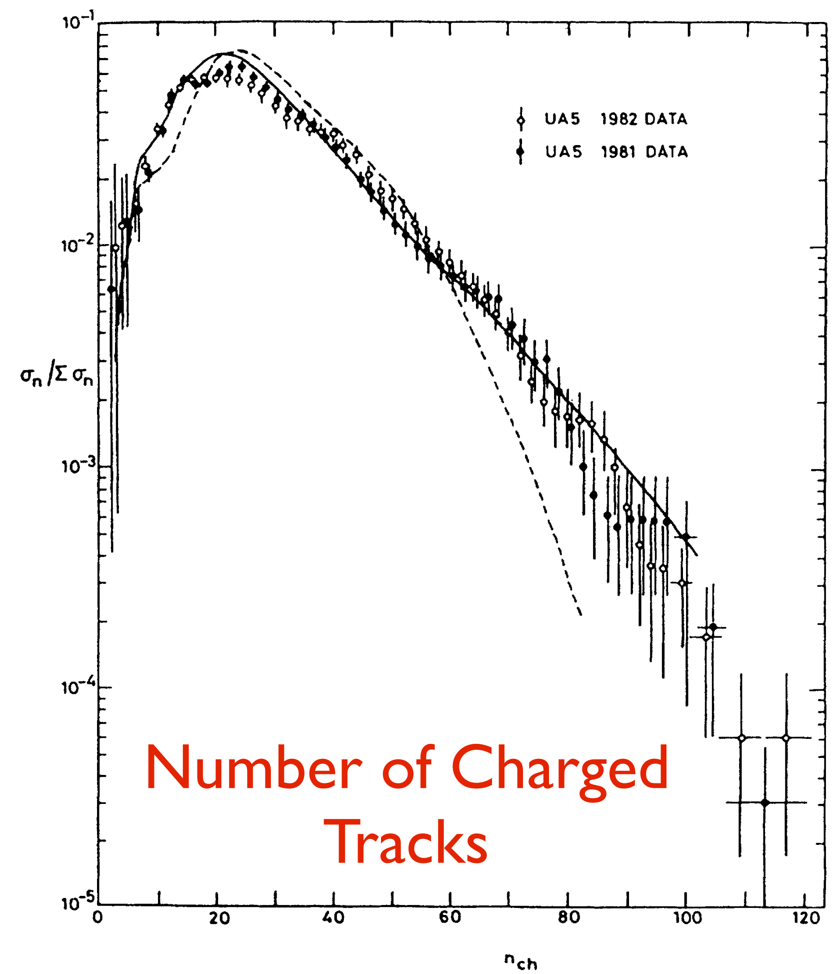


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

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

Soft-inclusive QCD

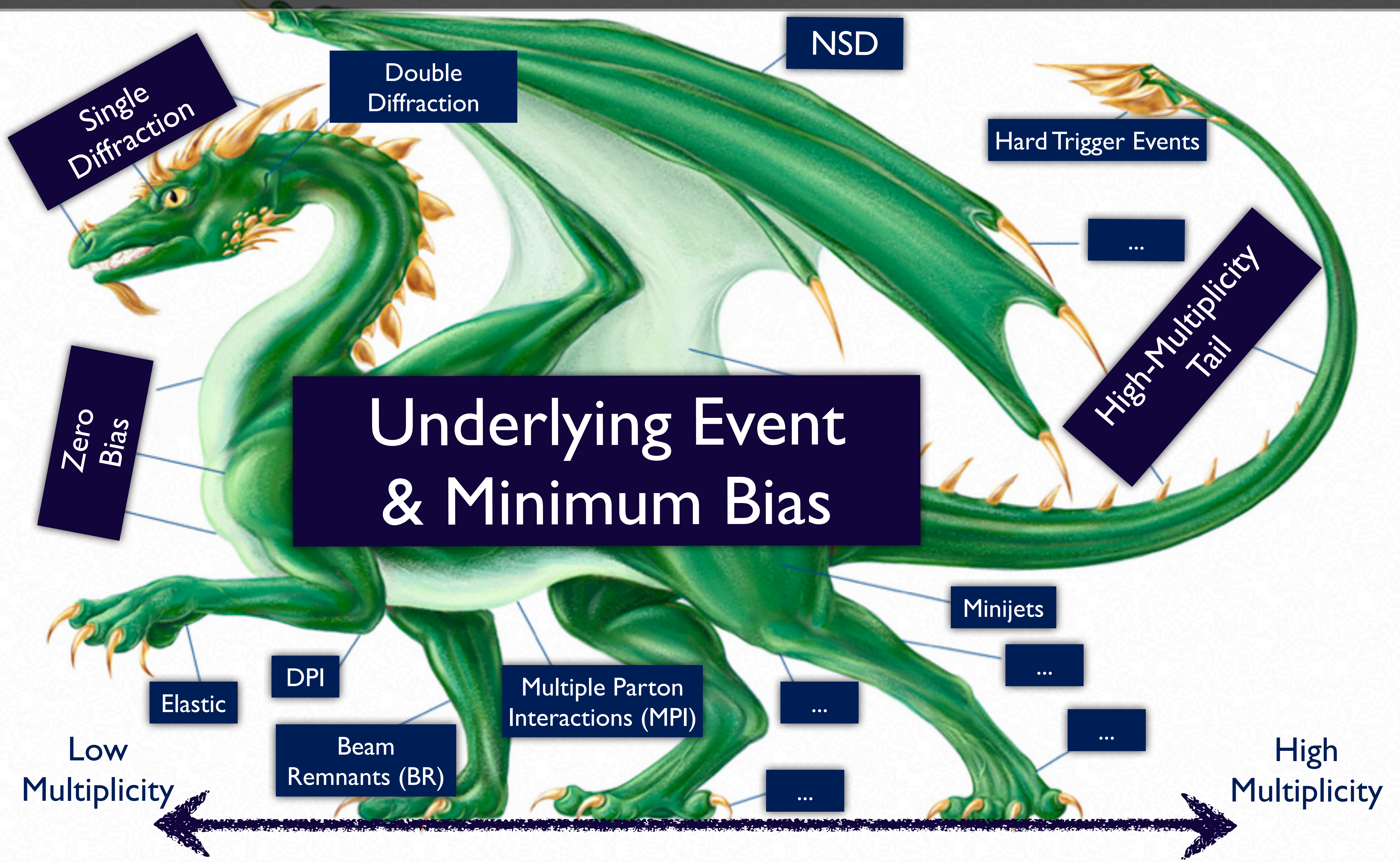
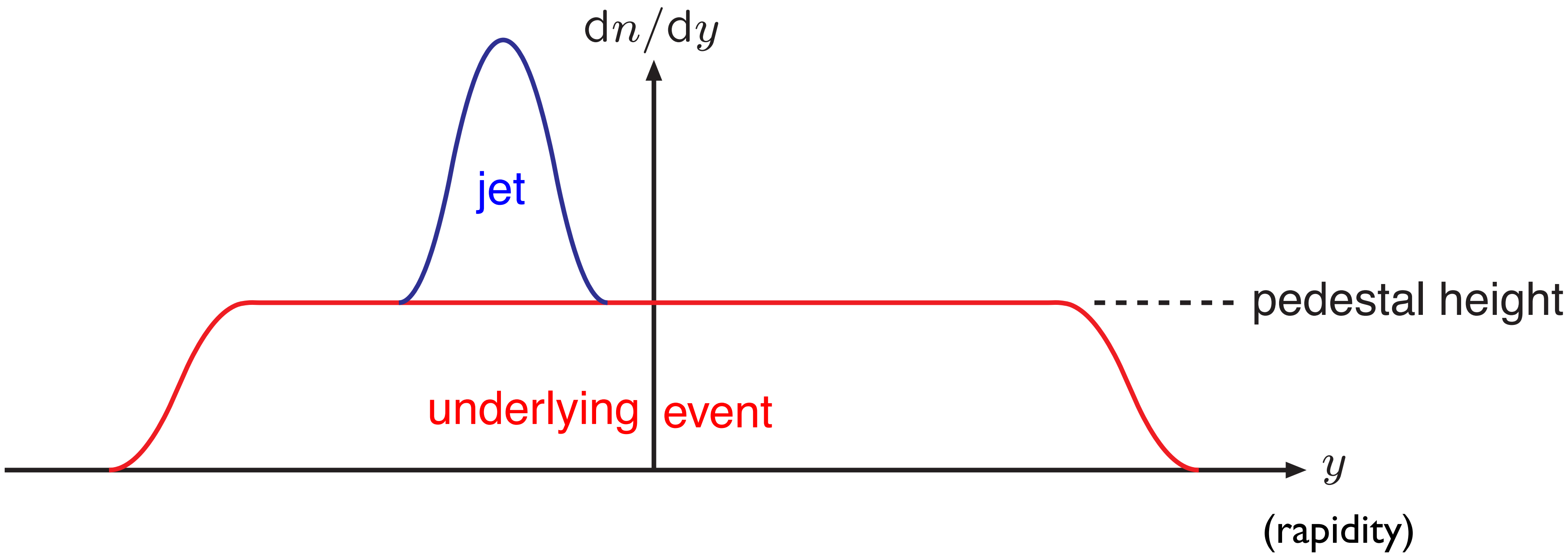


Image credits: E. Arenhaus & J. Walker

What is Underlying Event ?

"Pedestal Effect"



Useful variable in hadron collisions: **Rapidity**

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

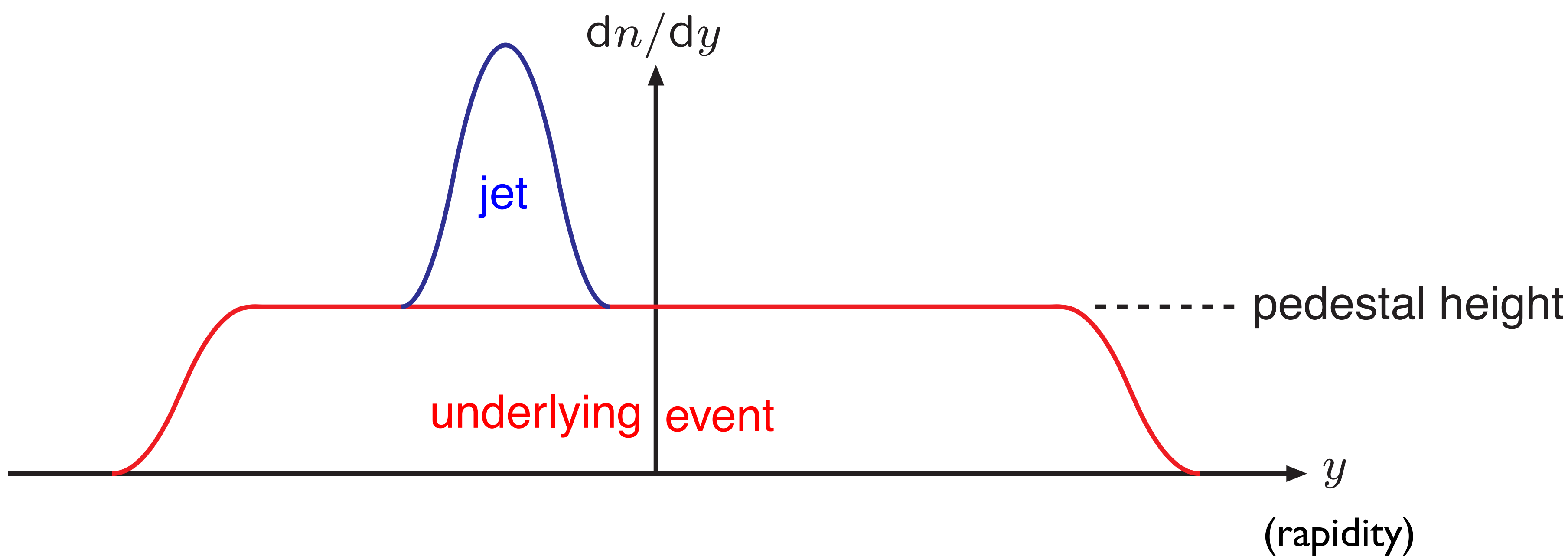
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$$y \to -\infty \quad \text{for} \quad p_z \to -E \qquad y \to 0 \quad \text{for} \quad p_z \to 0 \qquad y \to \infty \quad \text{for} \quad p_z \to E$$

Illustrations by T. Sjöstrand

What is Underlying Event ?

"Pedestal Effect"



Useful variable in hadron collisions: **Rapidity**

Homework:
Check how y transforms under Lorentz boost along z

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

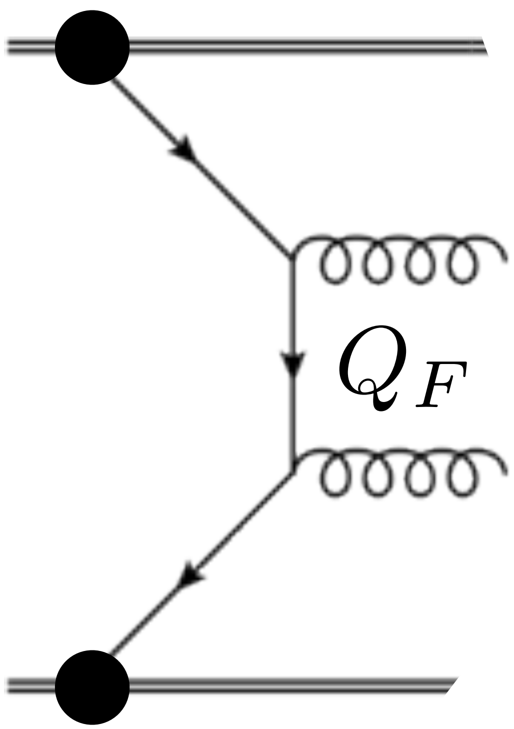
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

$$y \to -\infty \quad \text{for} \quad p_z \to -E \qquad y \to 0 \quad \text{for} \quad p_z \to 0 \qquad y \to \infty \quad \text{for} \quad p_z \to E$$

Illustrations by T. Sjöstrand

Twisted Stuff

Factorization: Subdivide Calculation



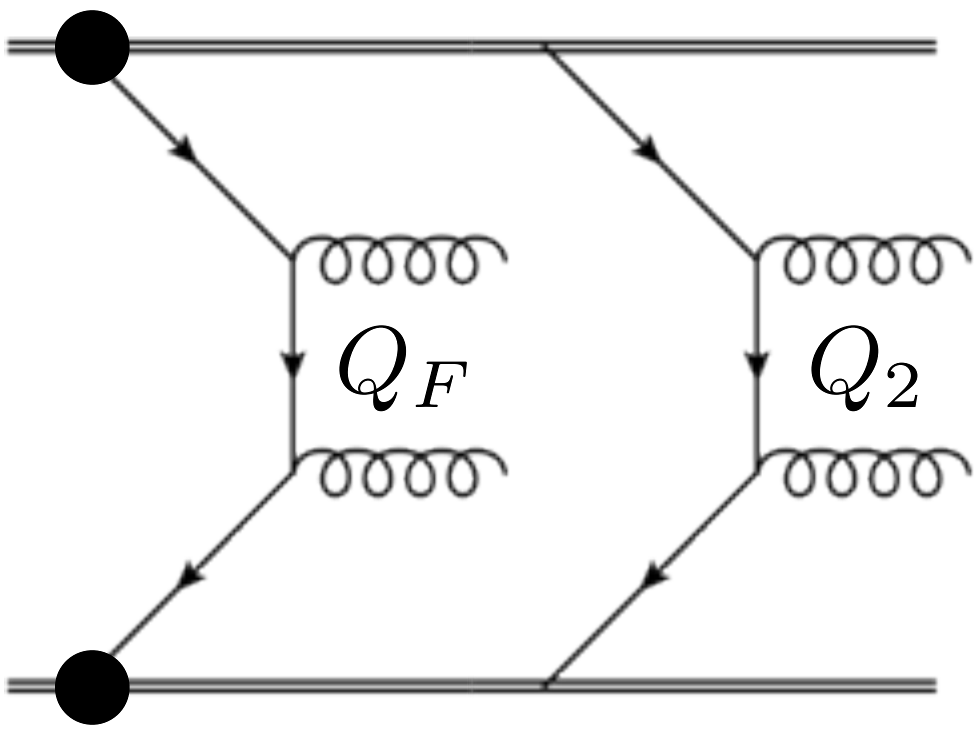
Multiple Parton Interactions go beyond existing theorems

→ perturbative short-distance physics in Underlying Event

→ Need to generalize factorization to MPI

Twisted Stuff

Factorization: Subdivide Calculation



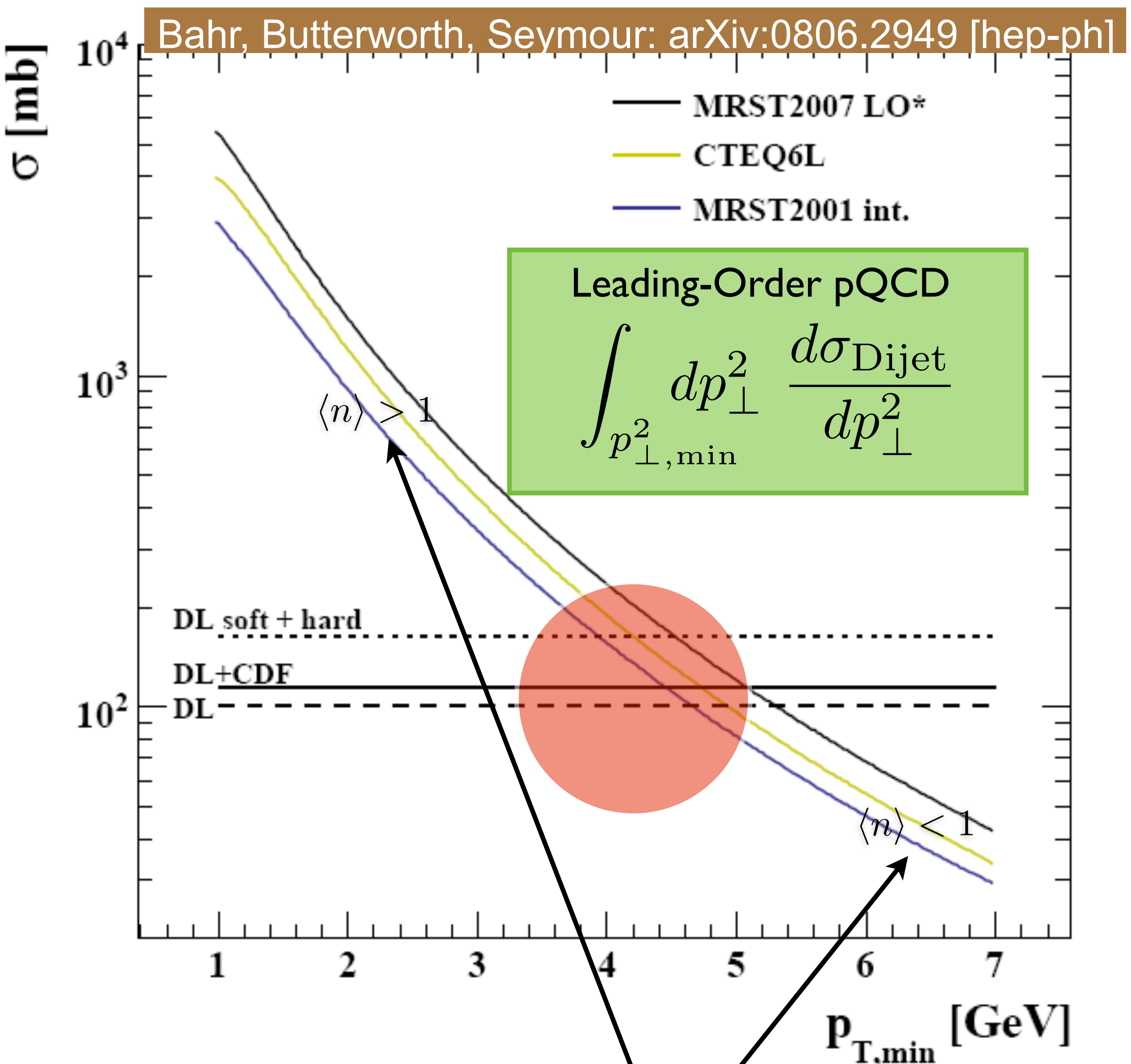
Multiple Parton Interactions go beyond existing theorems

→ perturbative short-distance physics in Underlying Event

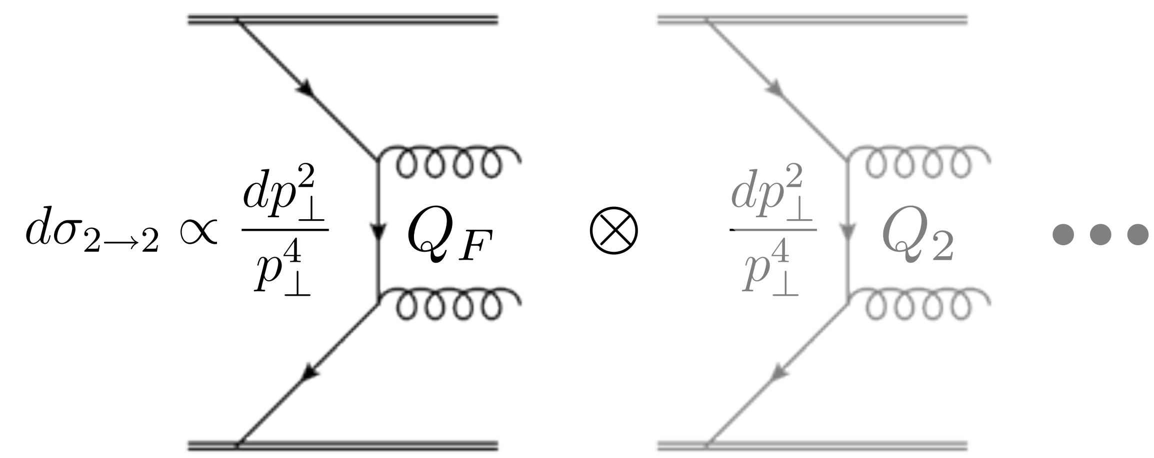
→ Need to generalize factorization to MPI

Multiple 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



Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down
Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

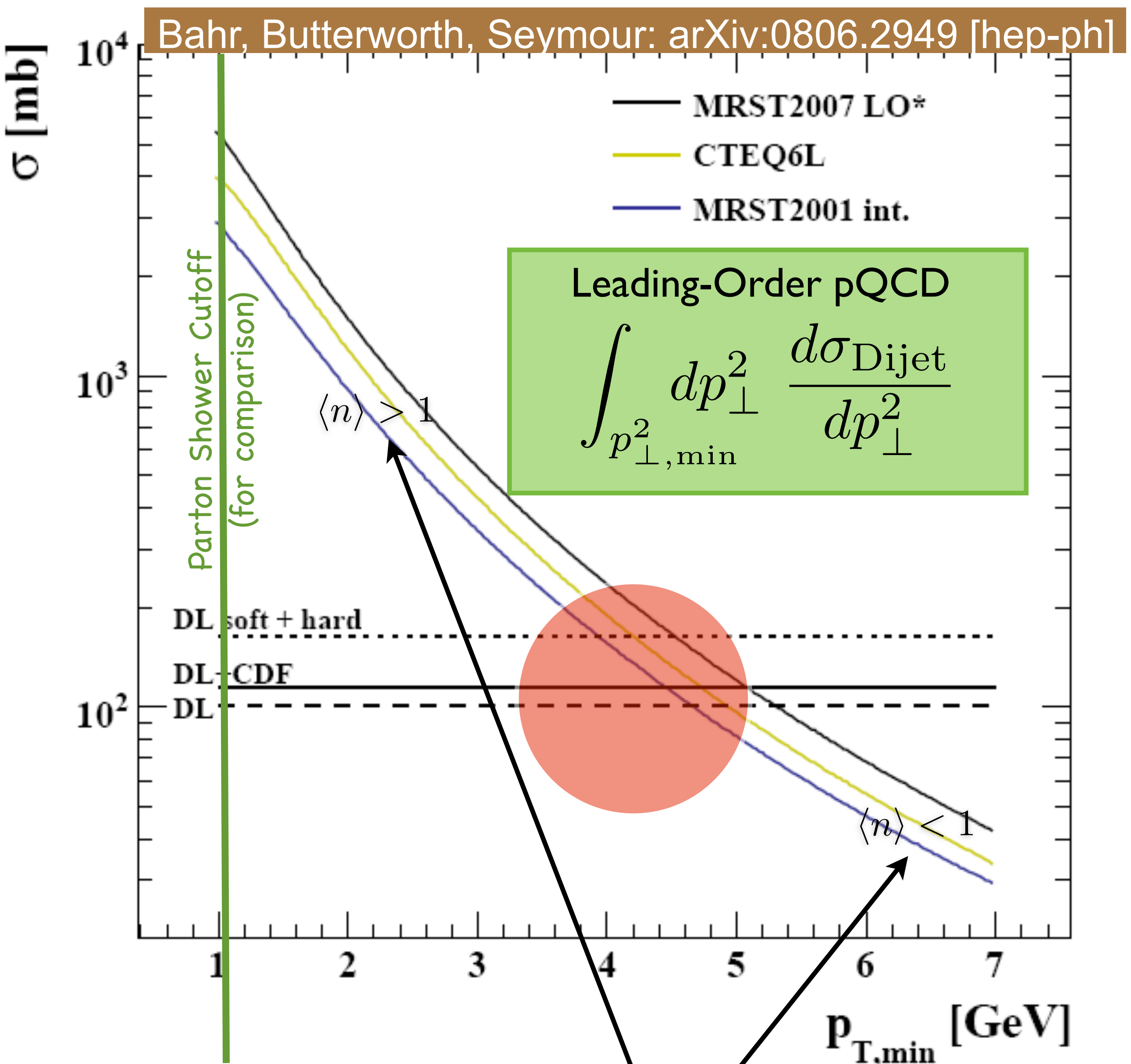
$$\sigma_{2\to2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section

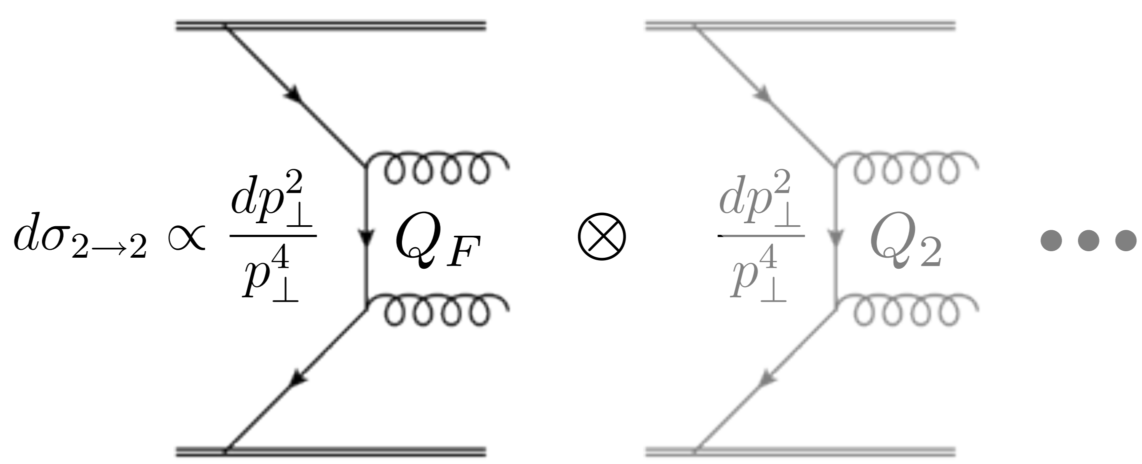
Hadron-Hadron Cross Section

Multiple 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



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?

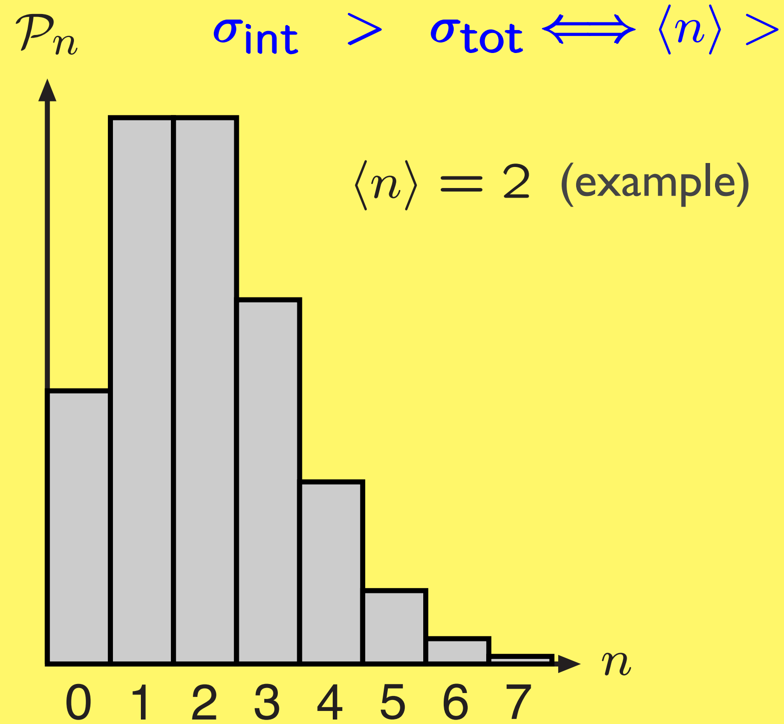
Naively $\langle n_{2\to 2}(p_{\perp\min})\rangle = \frac{\sigma_{2\to 2}(p_{\perp\min})}{\sigma_{\mathrm{tot}}}$

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

Momentum conservation suppresses high-n tail

+ physical correlations → not simple product

1: A Simple Model

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

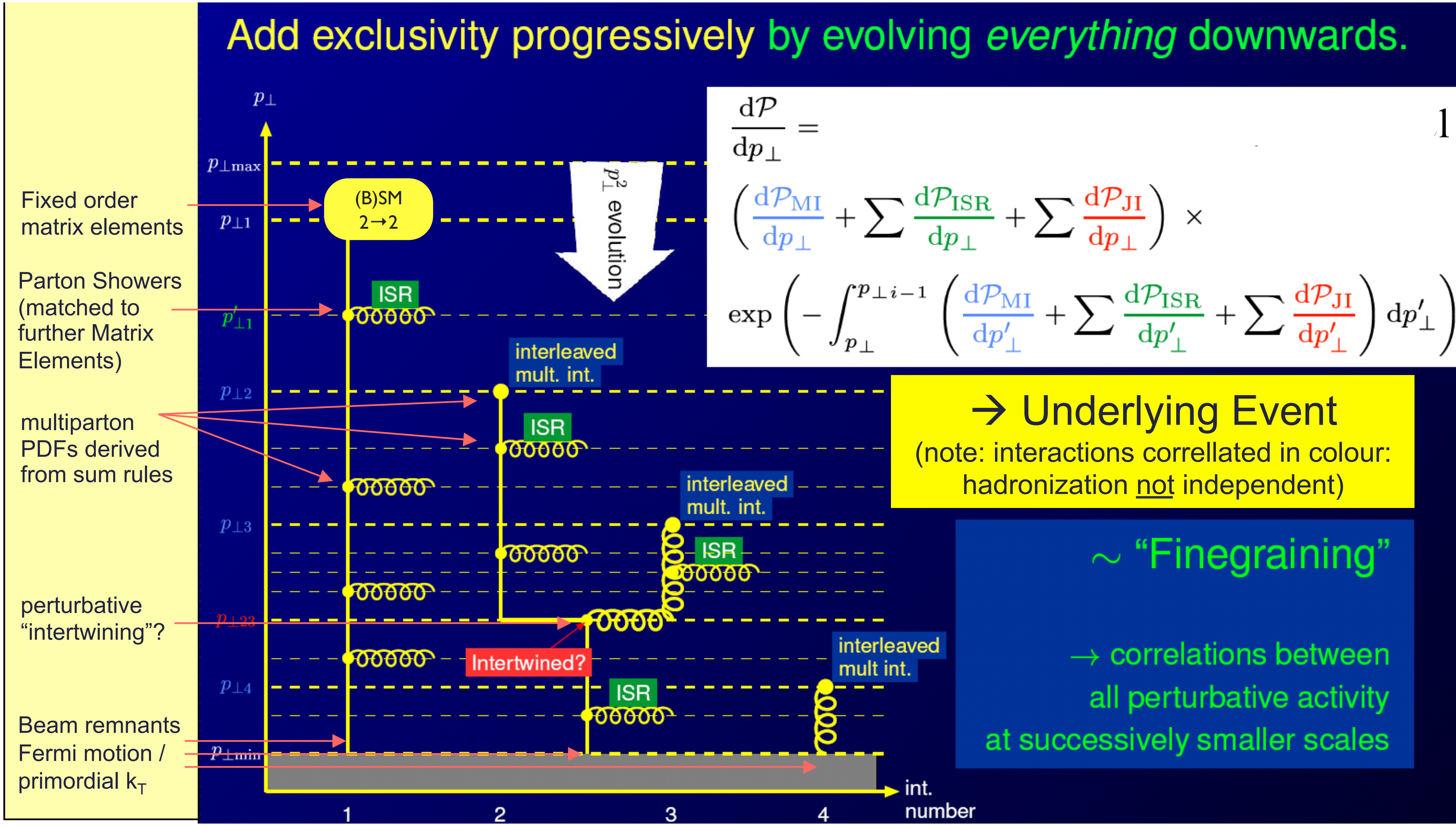
$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\mathrm{tot}}$$

Parton-Parton Cross Section | Hadron-Hadron Cross Section

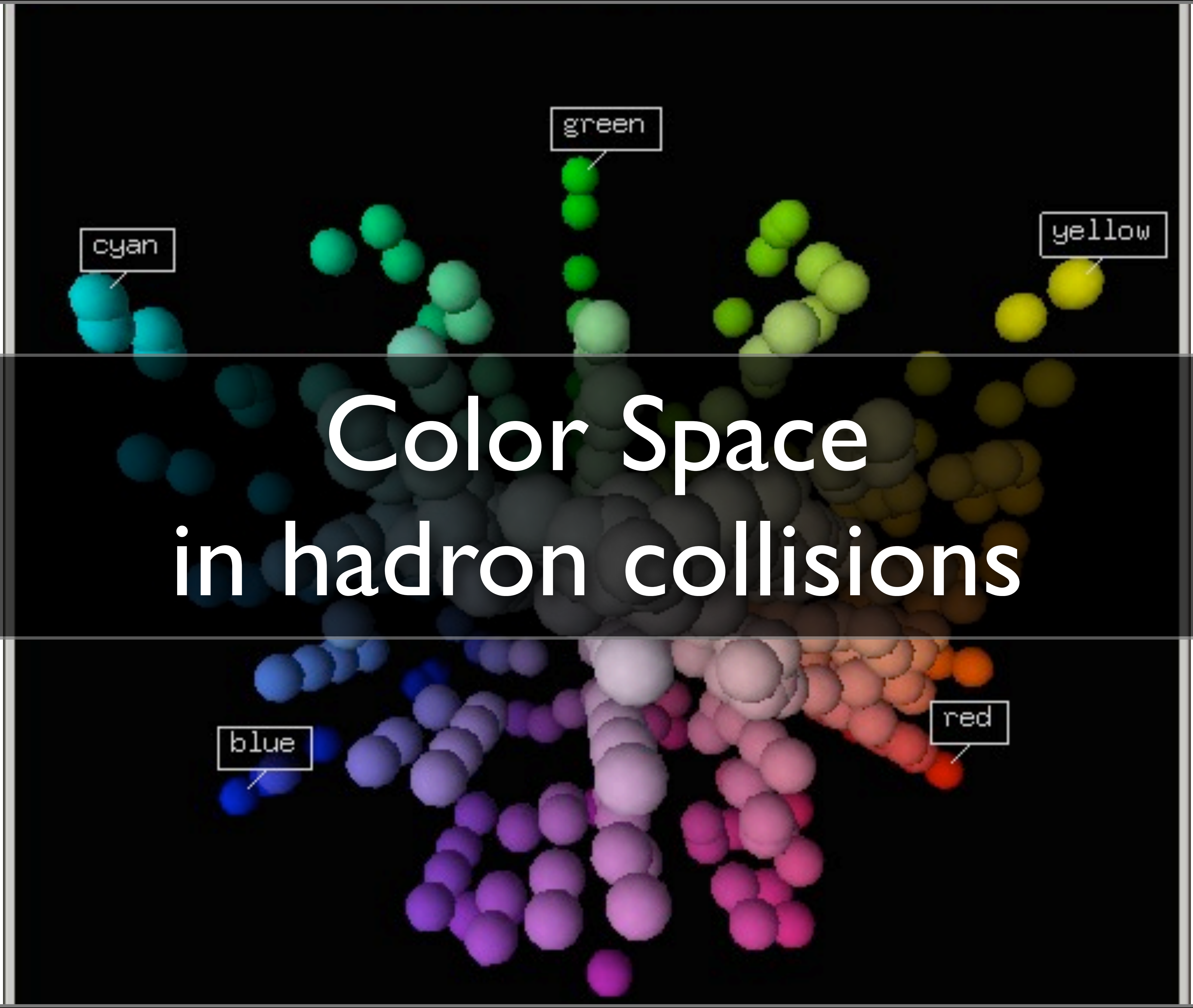
1. Choose $p_{T\min}$ cutoff
   = main tuning parameter
2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton
3. Generate n parton-parton interactions (pQCD 2→2)
   Veto if total beam momentum exceeded → overall (E,p) cons
4. Add impact-parameter dependence → $<n> = <n>(b)$
   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 $\sigma_{\mathrm{soft}} + \sigma_{\mathrm{hard}} = \sigma_{\mathrm{tot}}$
   → **Herwig++ model** Bähr et al, arXiv:0905.4671

(2: Interleaved Evolution)

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



Color Space
in hadron collisions

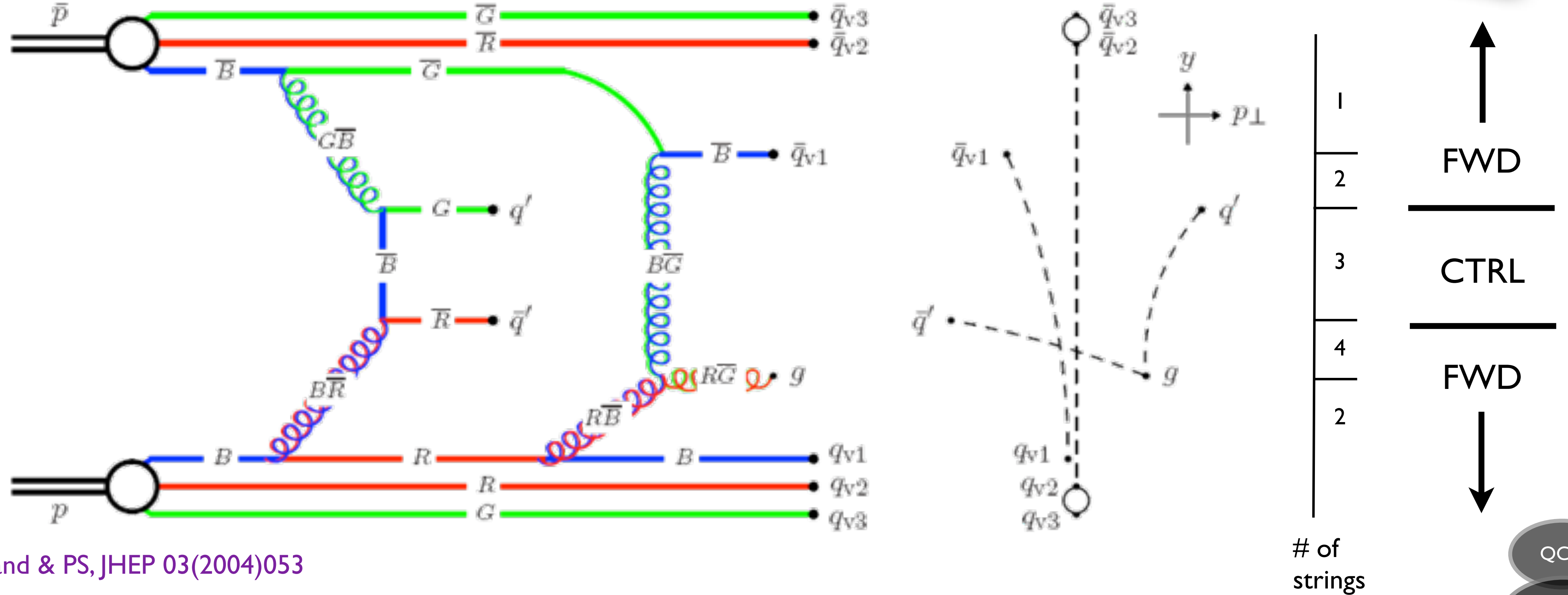


Color Connections

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



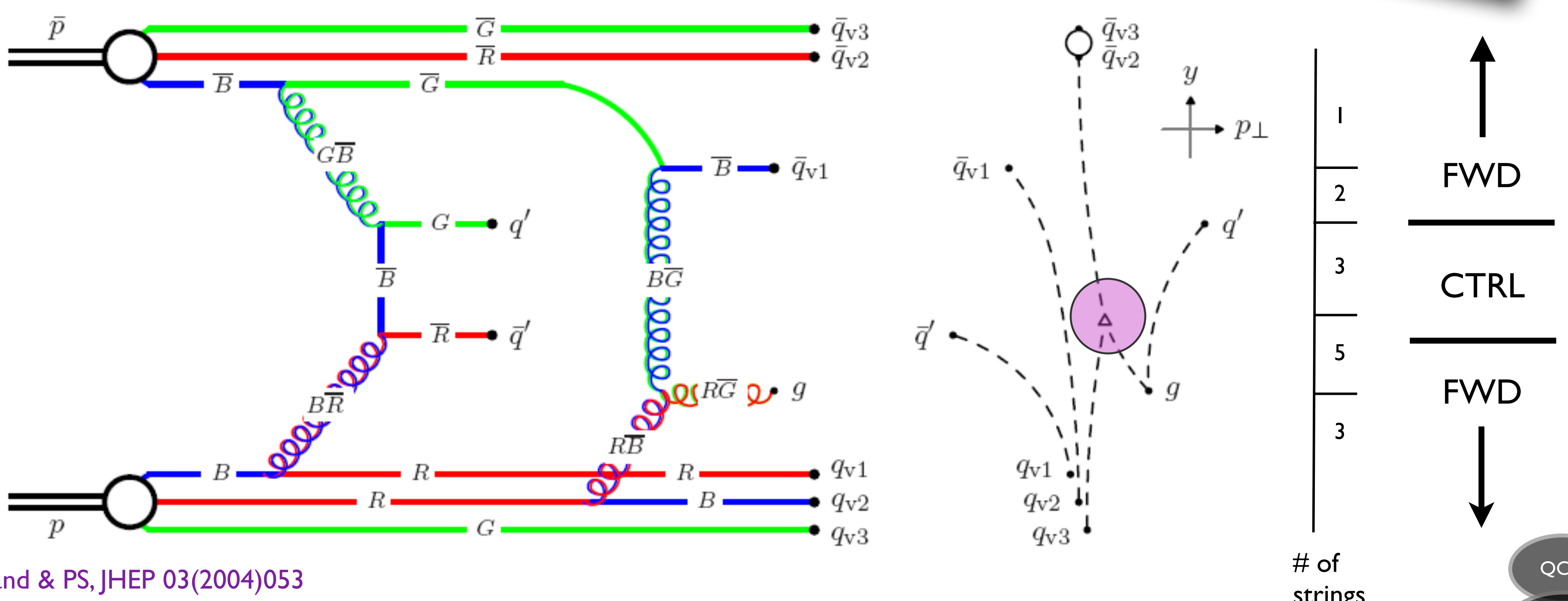
Sjöstrand & PS, JHEP 03(2004)053

Color Connections

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 crucially depend on color space

Different models make different ansätze

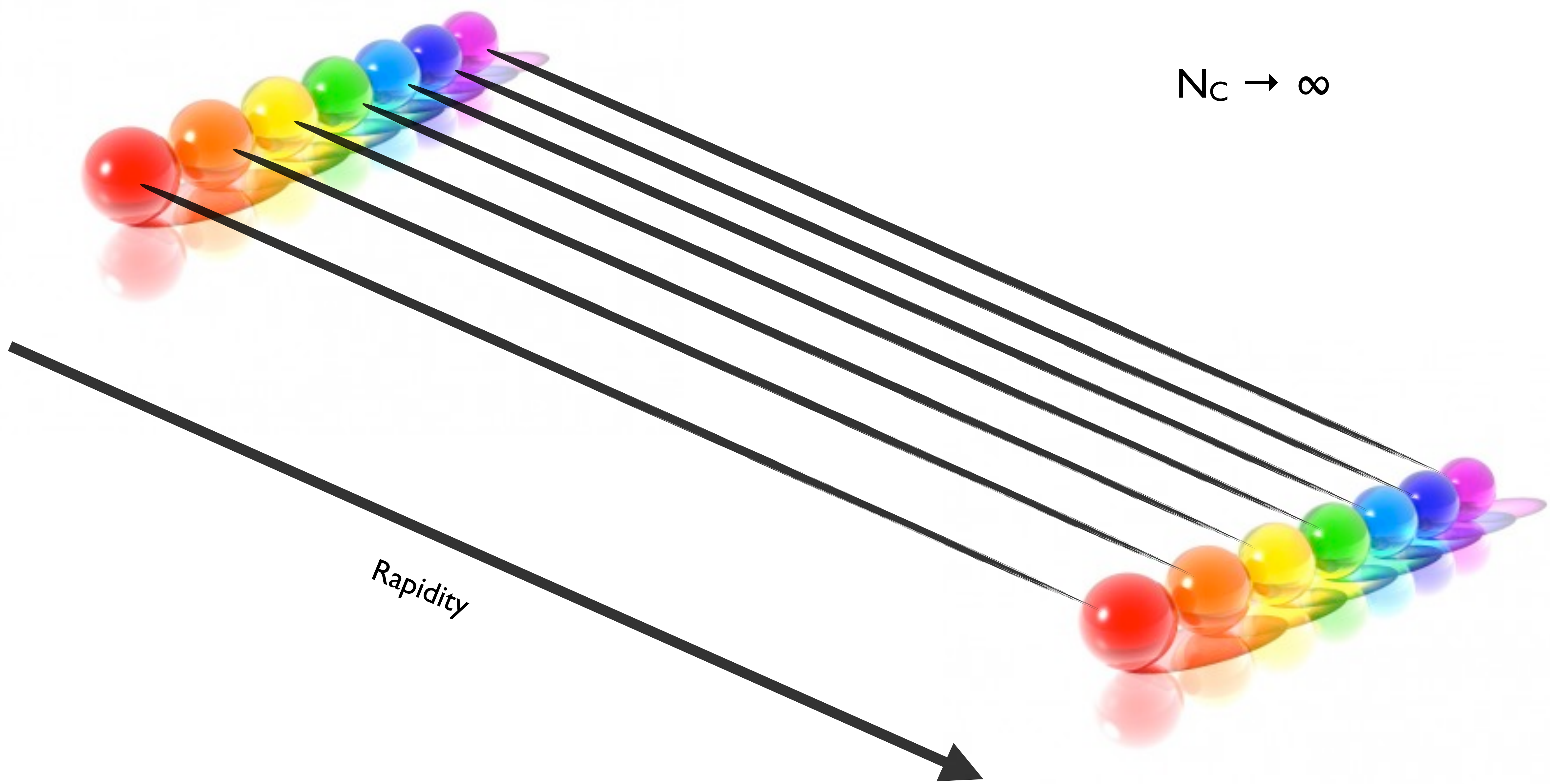


Sjöstrand & PS, JHEP 03(2004)053

Color Connections

Better theory models needed

$N_C \to \infty$



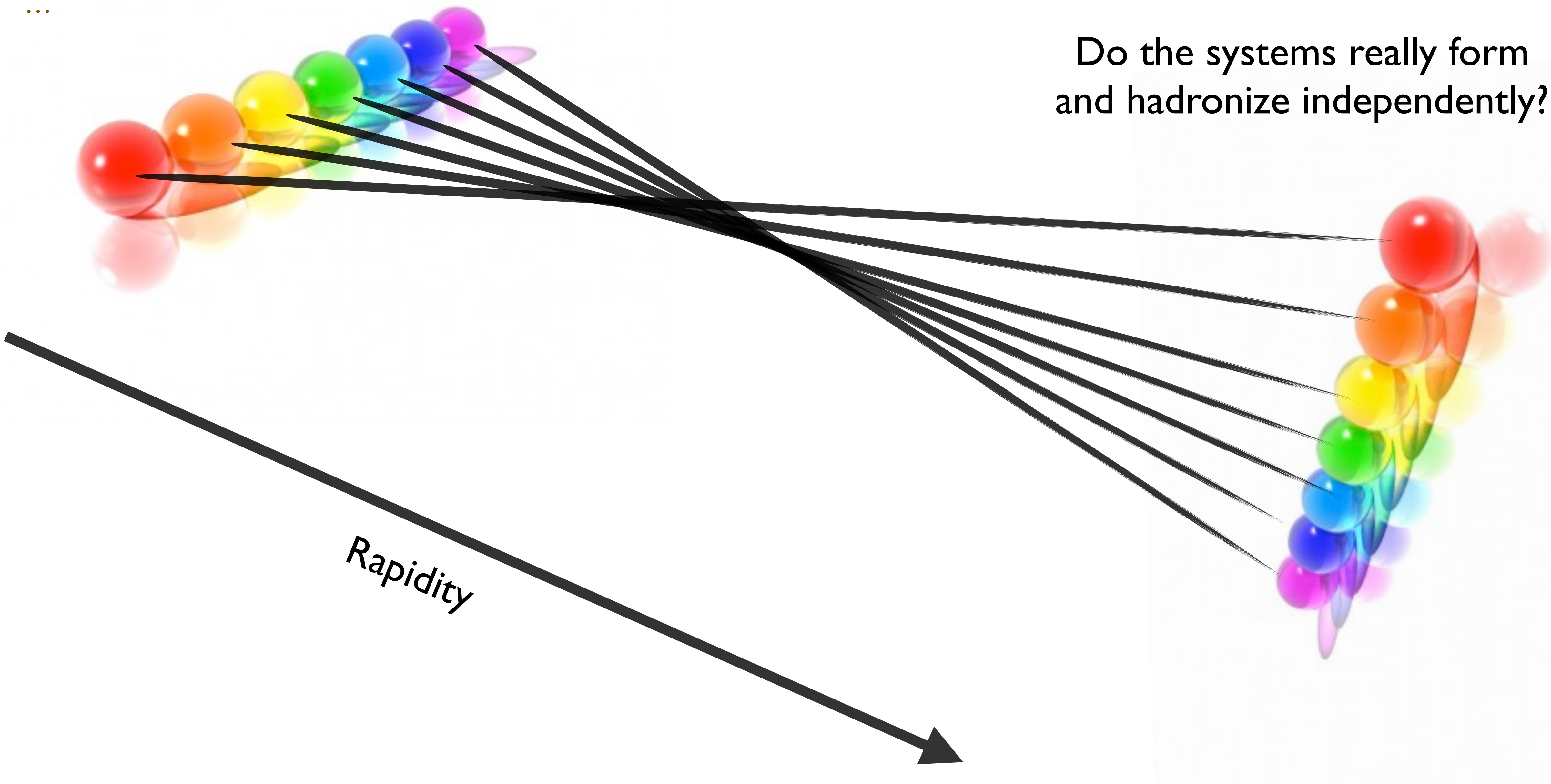
Multiplicity $\propto N_{MPI}$

Color Reconnections?

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

Better theory models needed

Do the systems really form
and hadronize independently?



Multiplicity $\overset{<}{\cancel{\propto}}$ N_{MPI}

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Pedestal Rise

Strings per Interaction

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) **→ size of overall activity**

Pedestal Rise

Strings per Interaction

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) → size of overall activity

Pedestal Rise

Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions

Strings per Interaction

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) → size of overall activity

Pedestal Rise

Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions

Strings per Interaction

Color correlations between multiple-parton-interaction systems → shorter or longer strings → less or more hadrons per interaction

Main IR Parameters

Number of MPI

Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) → size of overall activity

Pedestal Rise

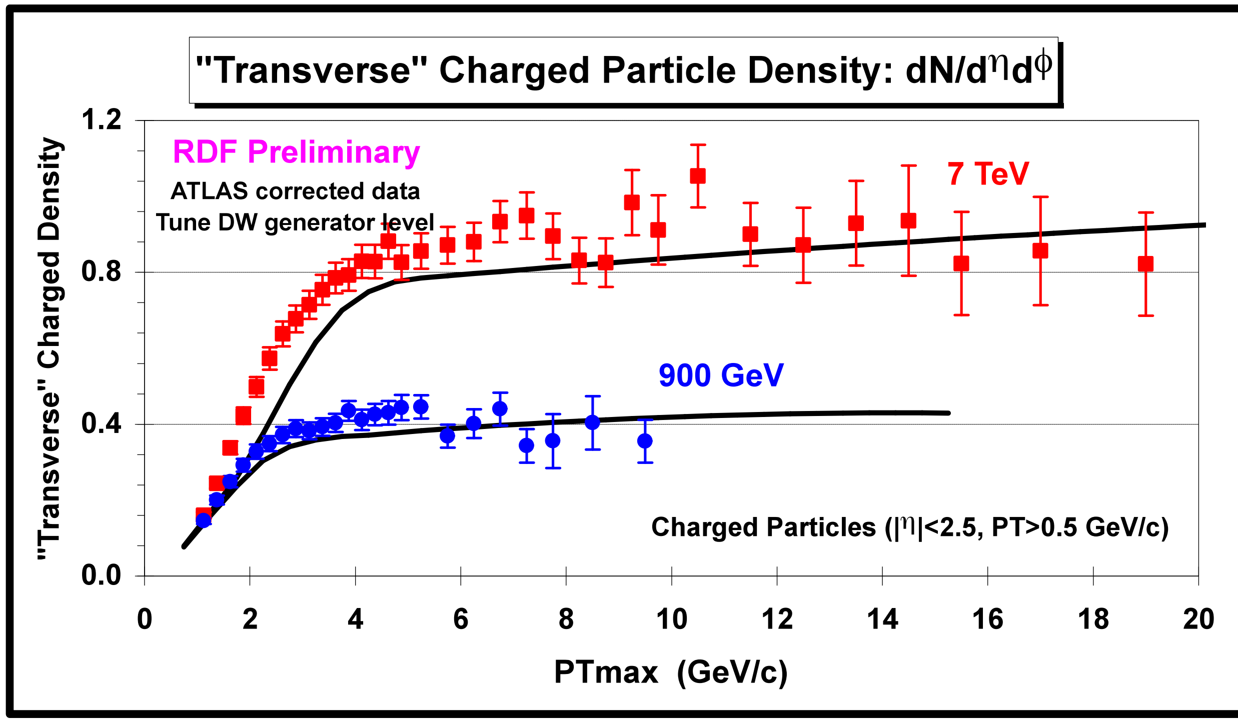
Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions

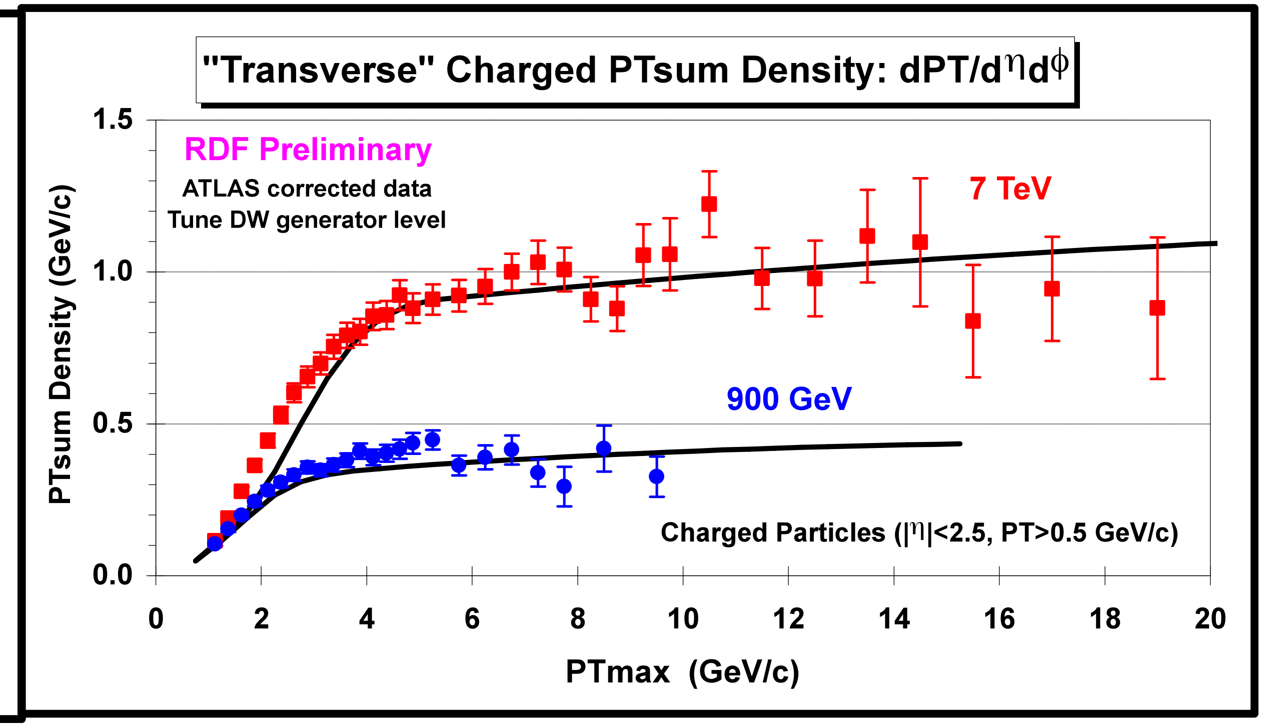
Strings per Interaction

Color correlations between multiple-parton-interaction systems → shorter or longer strings → less or more hadrons per interaction

(Underlying Event)

LHC from 900 to 7000 GeV - ATLAS



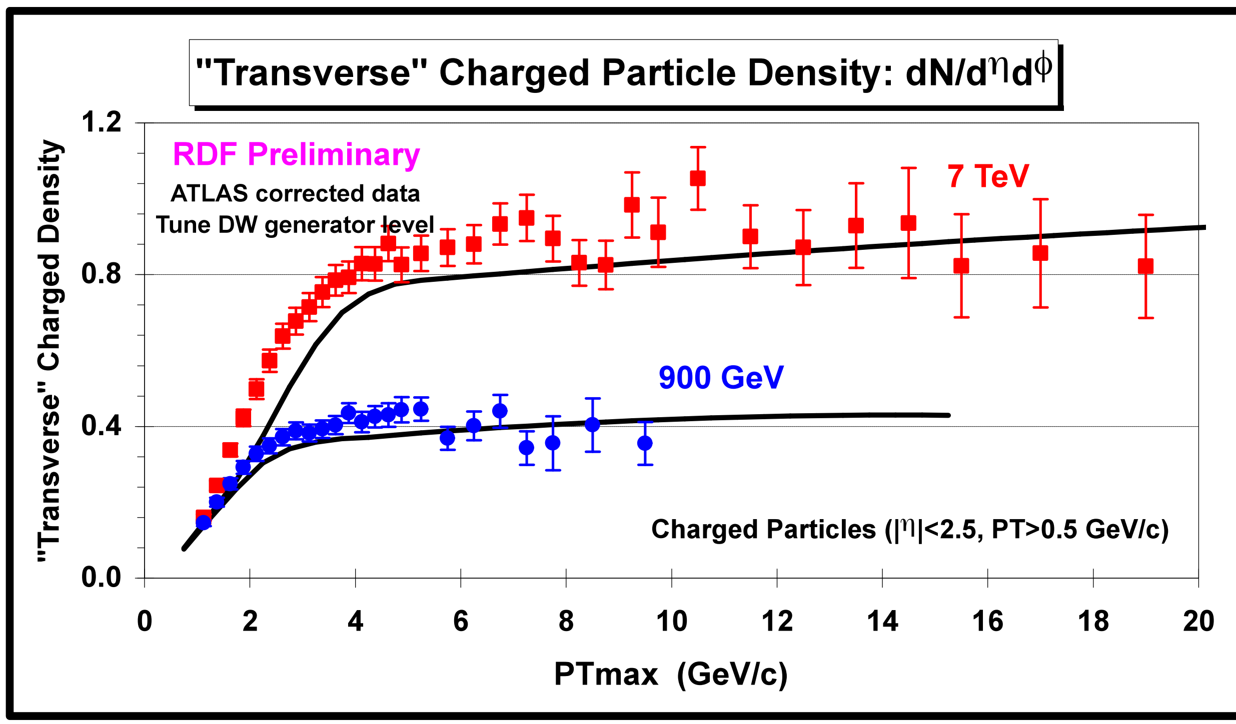


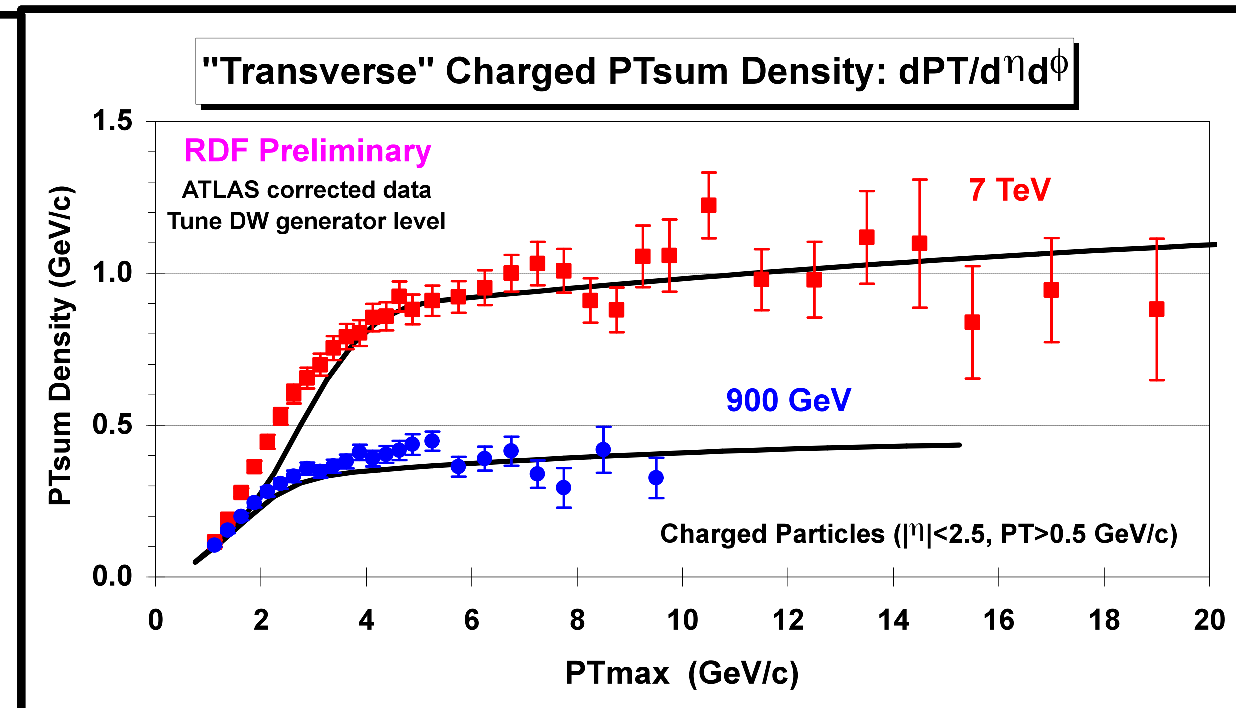
Track Density (TRANS)

Sum(pT) Density (TRANS)

(Underlying Event)

LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)

Sum(pT) Density (TRANS)

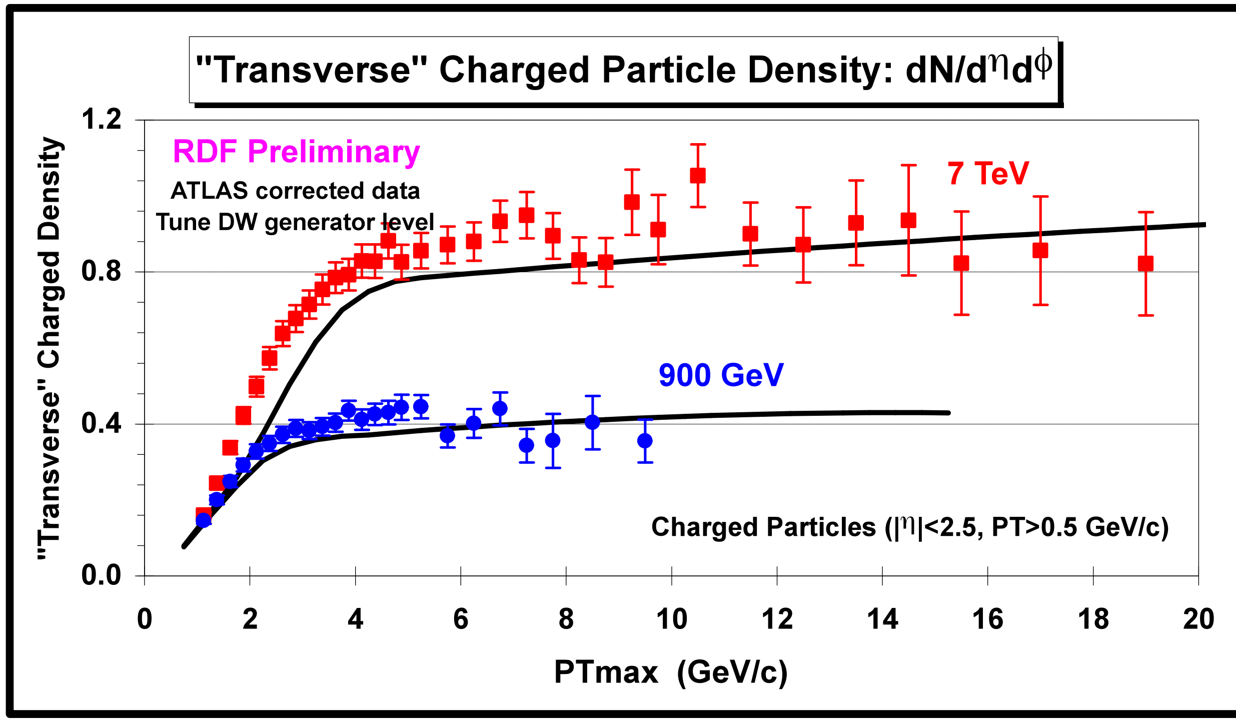
Not Infrared Safe

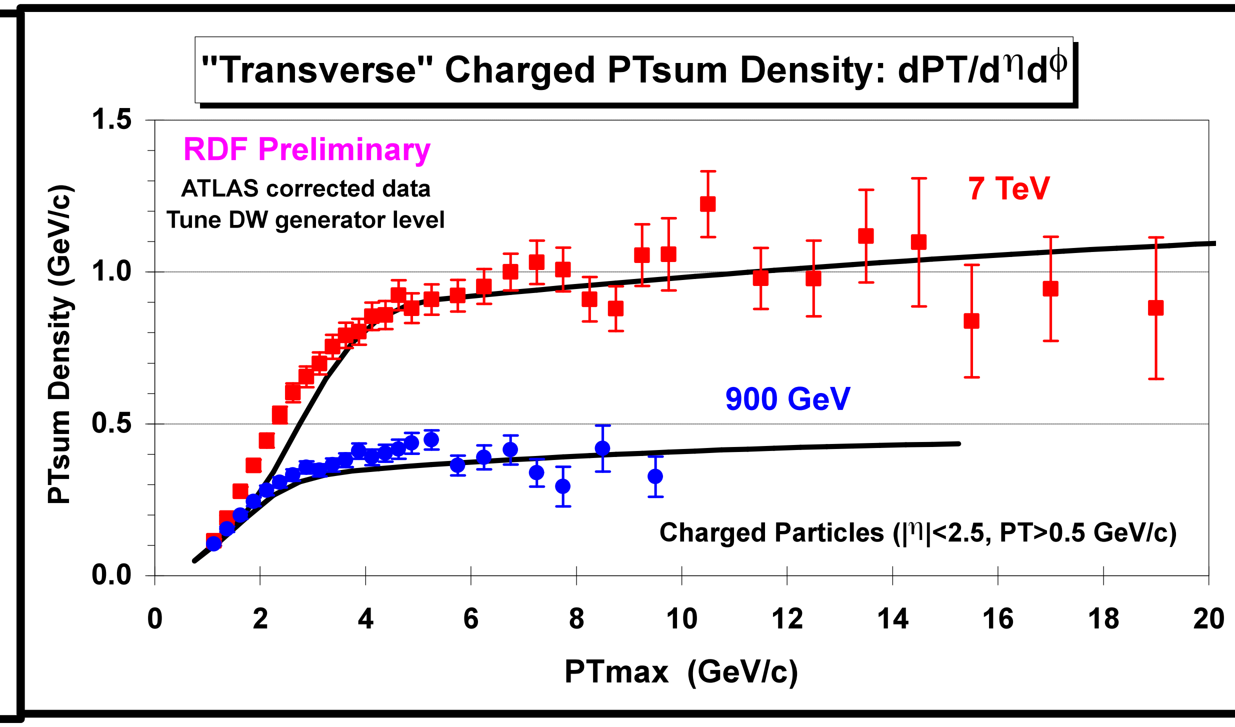
Large Non-factorizable Corrections

Prediction off by ≈ 10%

(Underlying Event)

LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)

Not Infrared Safe

Large Non-factorizable Corrections

Prediction off by ≈ 10%

Sum(pT) Density (TRANS)

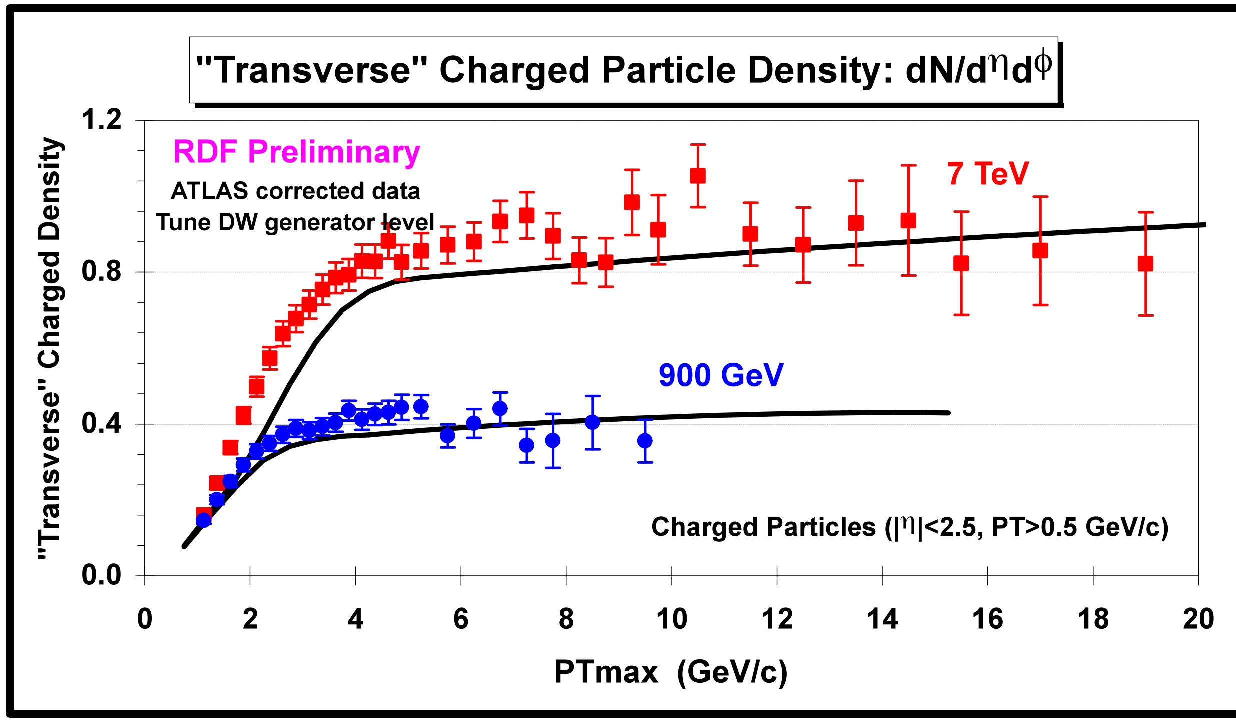
(more) Infrared Safe

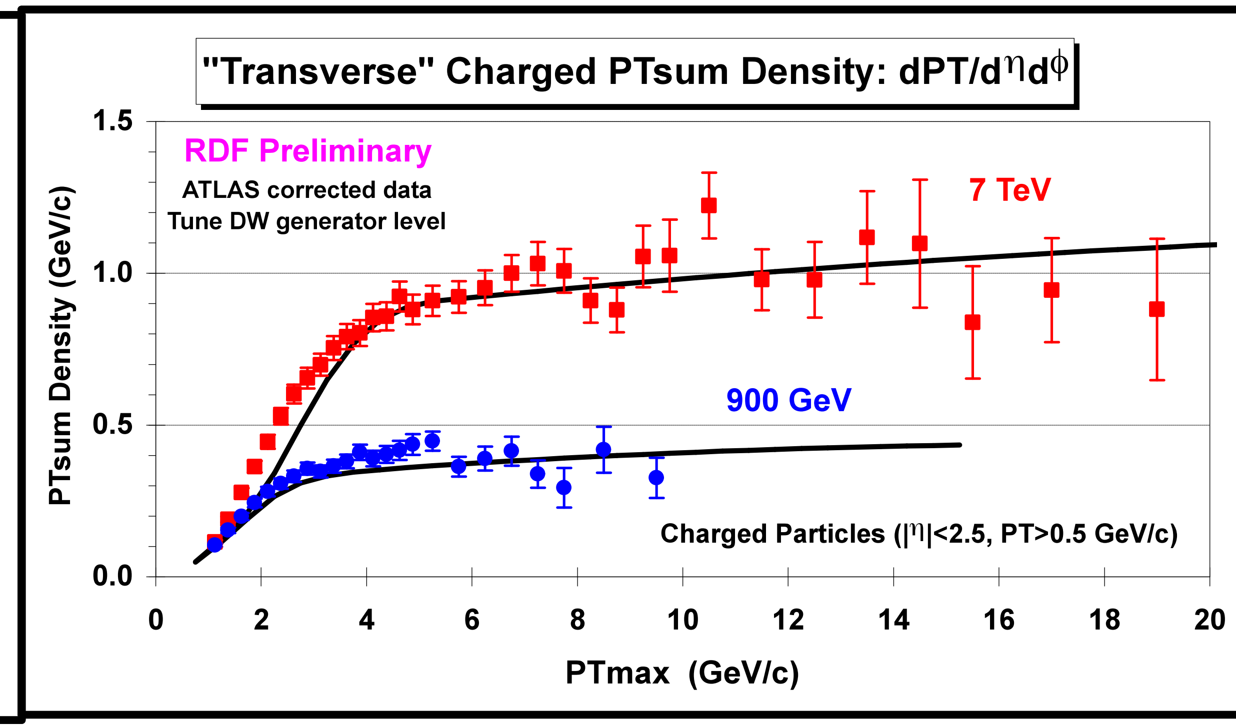
Large Non-factorizable Corrections

Prediction off by < 10%

(Underlying Event)

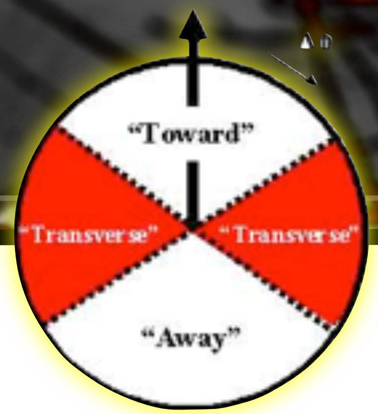
LHC from 900 to 7000 GeV - ATLAS





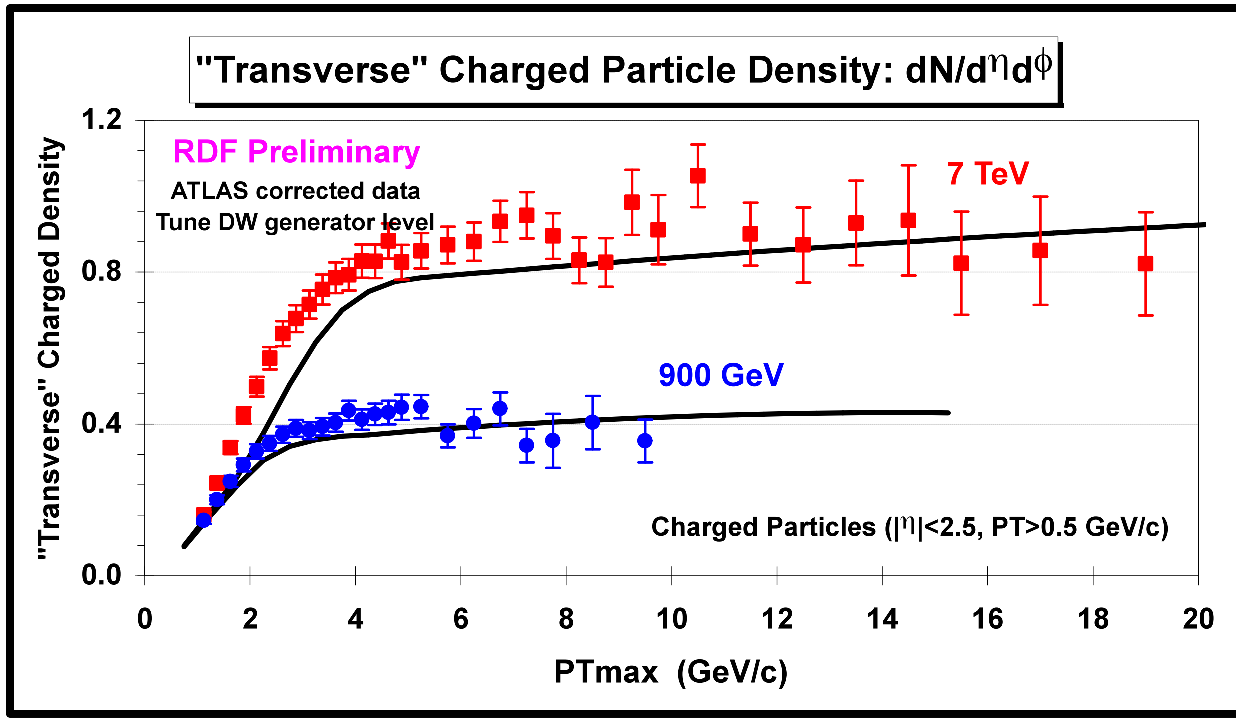
Track Density (TRANS)	Sum(pT) Density (TRANS)
Not Infrared Safe	(more) Infrared Safe
Large Non-factorizable Corrections	Large Non-factorizable Corrections
Prediction off by ≈ 10%	Prediction off by < 10%

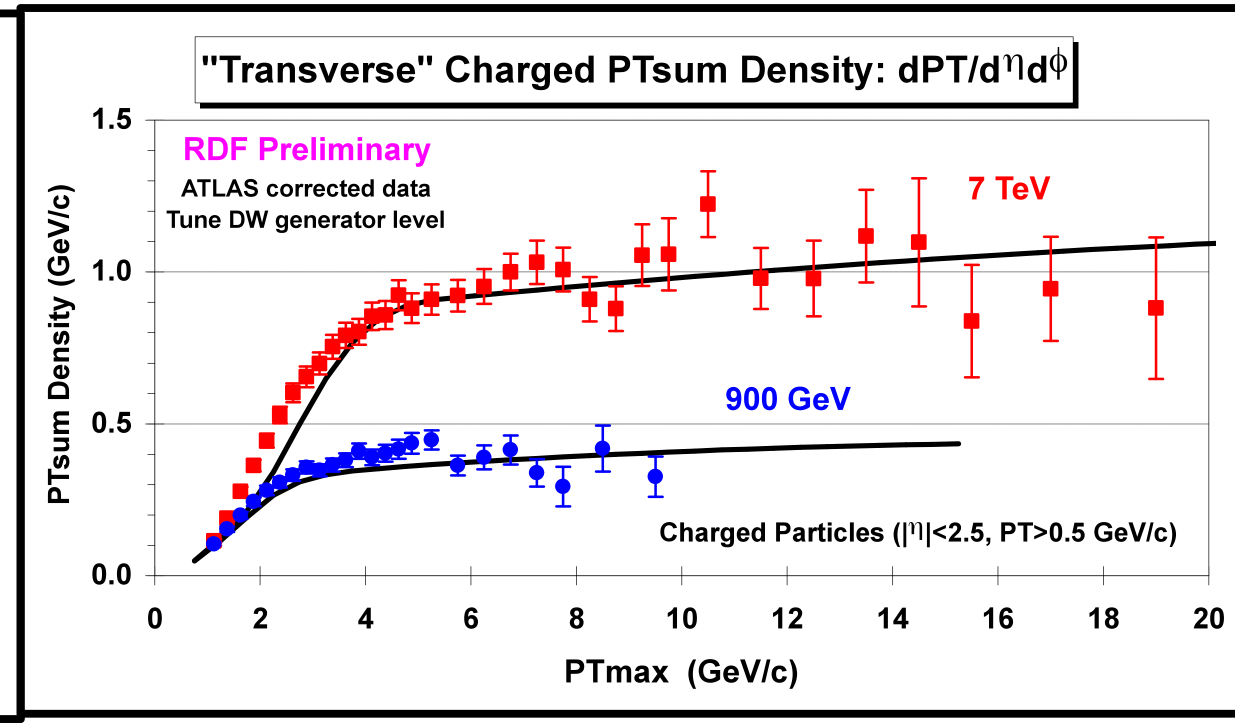
R. Field: "See, I told you!"



(Underlying Event)

LHC from 900 to 7000 GeV - ATLAS





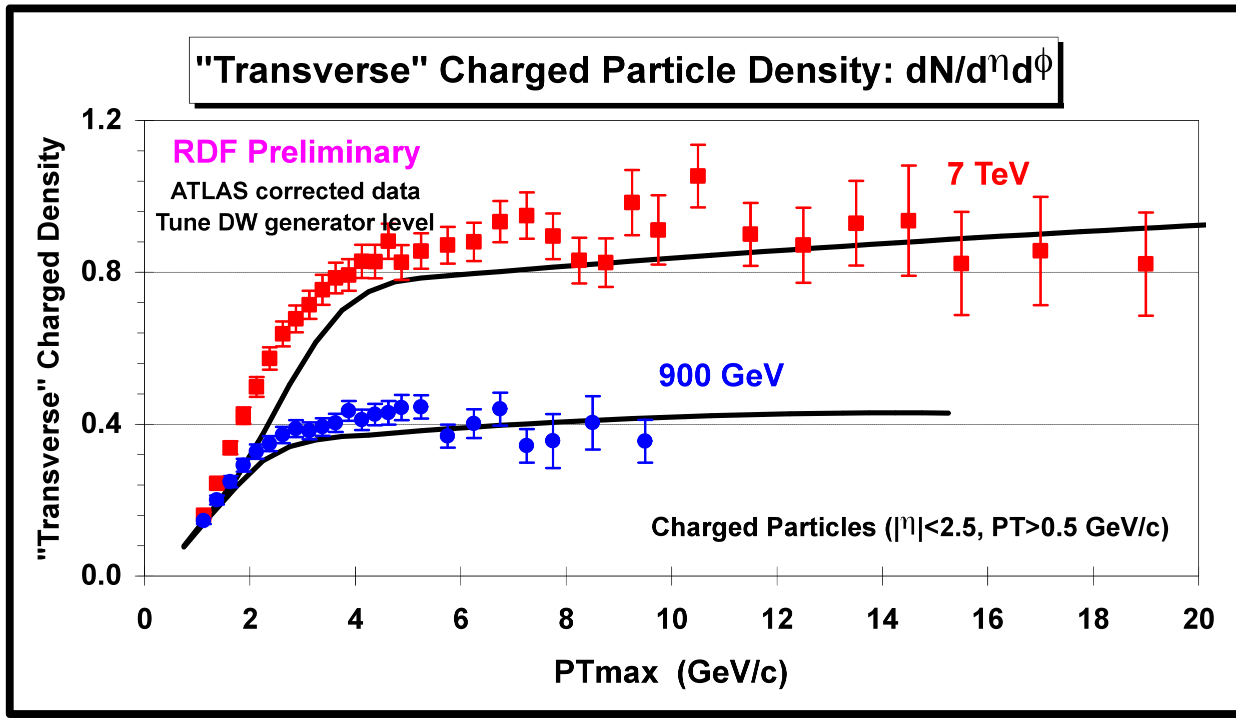
Track Density (TRANS)	Sum(pT) Density (TRANS)
Not Infrared Safe	(more) Infrared Safe
Large Non-factorizable Corrections	Large Non-factorizable Corrections
Prediction off by ≈ 10%	Prediction off by < 10%

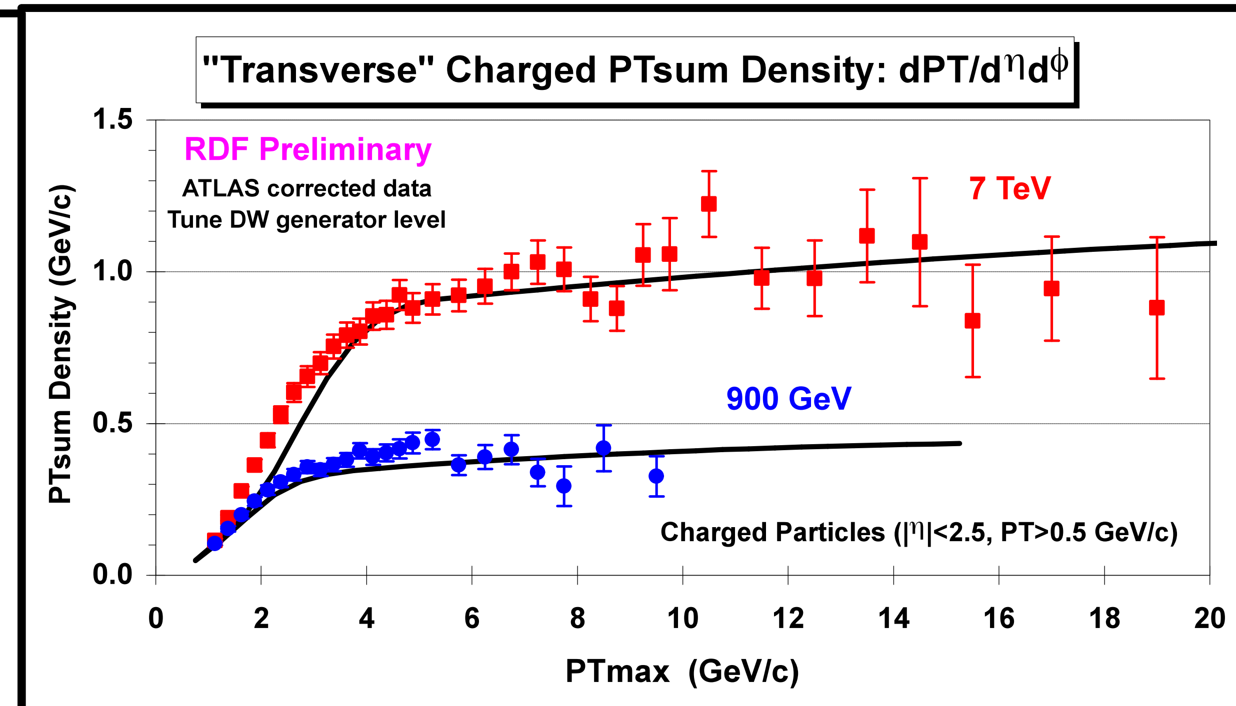
R. Field: "See, I told you!"

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

(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"

Summary 1/2

Fixed Order pQCD: Good for jets ~ hard scale

Beware: hierarchies / multi-scale problems

→ Scale choices become more important and more complicated

→ Enhancements from soft/collinear (conformal) singularities can invalidate fixed-order truncation

Parton Showers: Good for jets << hard scale

Bootstrapped approximation to infinite-order perturbation theory (resummation)

Exact in soft/collinear limits. Unpredictive for hard radiation

Coherence → Angular Ordering or Dipole-Antenna showers

Summary 2/2

Matching

At tree level (CKKW, MLM) → LO for multiple hard jets

At NLO (MC@NLO, POWHEG) → NLO precision for Born

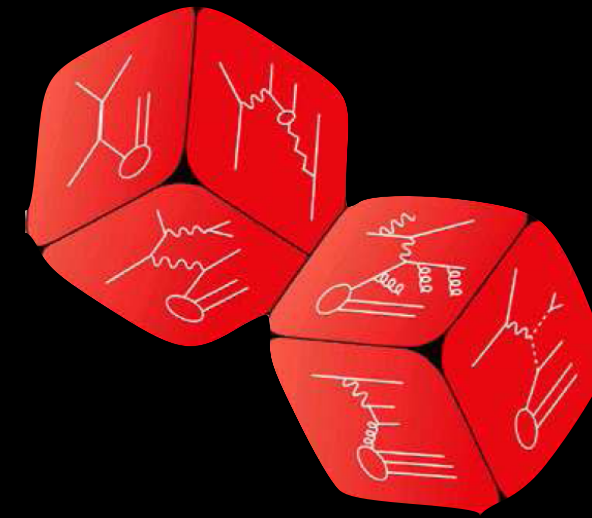
Substantial modeling uncertainties for soft physics. But fortunately … it's soft.

Hadronization: based on tracing color flow through event. String model based on linear confinement, causality, and tunneling. Cluster model based on preconfinement and phase space.

Underlying Event: based on multiple parton interactions and impact-parameter dependence.

TASI 2012

Ready to Roll



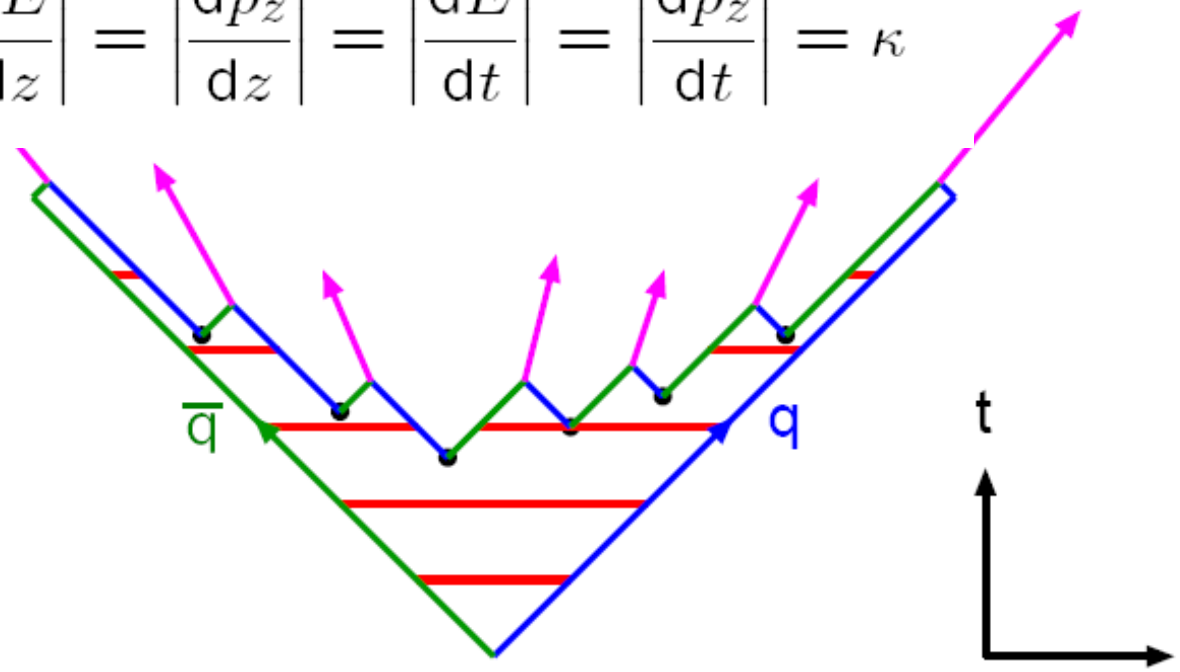
Thank you

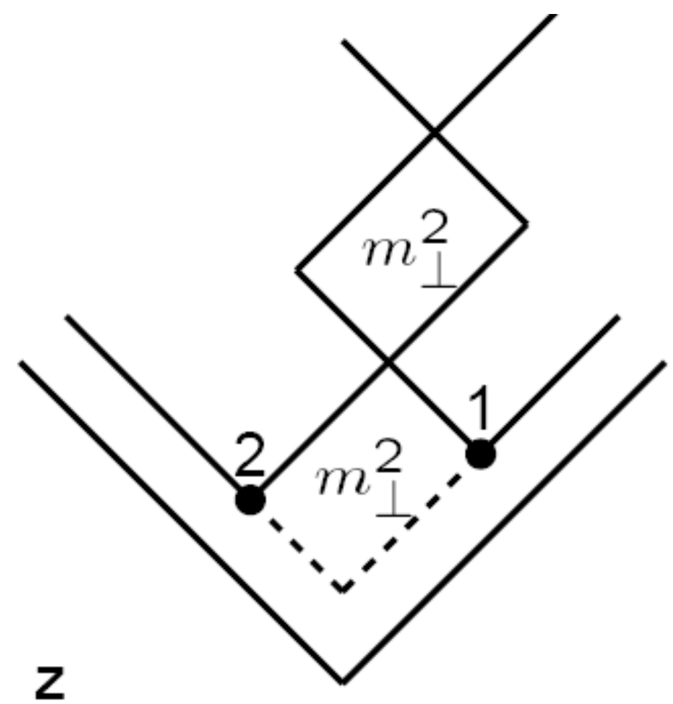
Additional Slides

Large System

Illustrations by T. Sjöstrand

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$

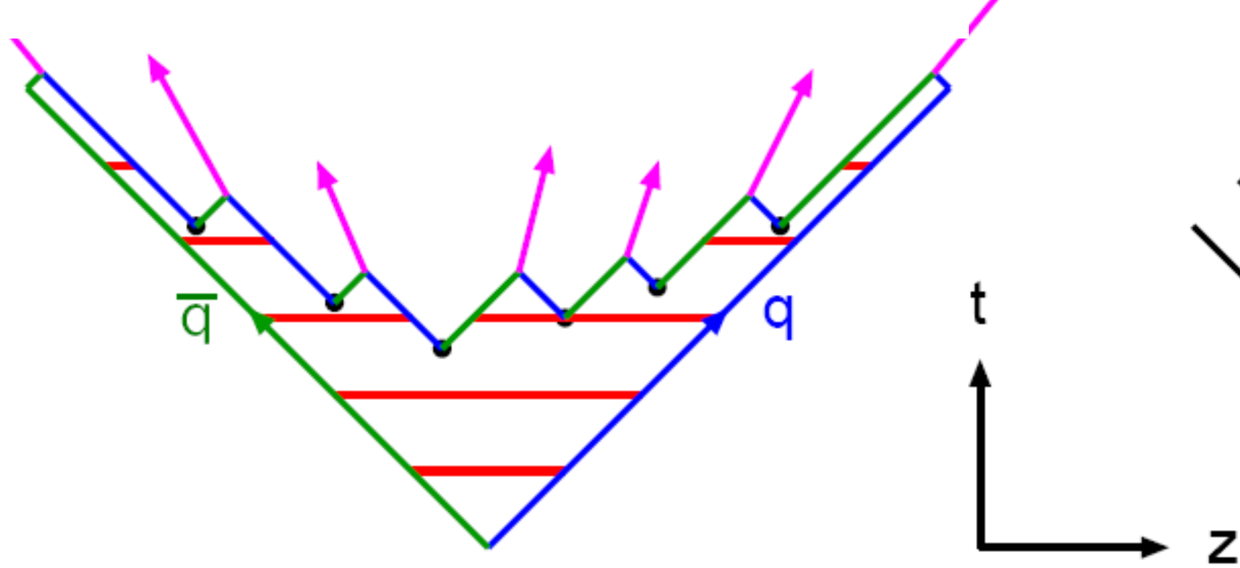


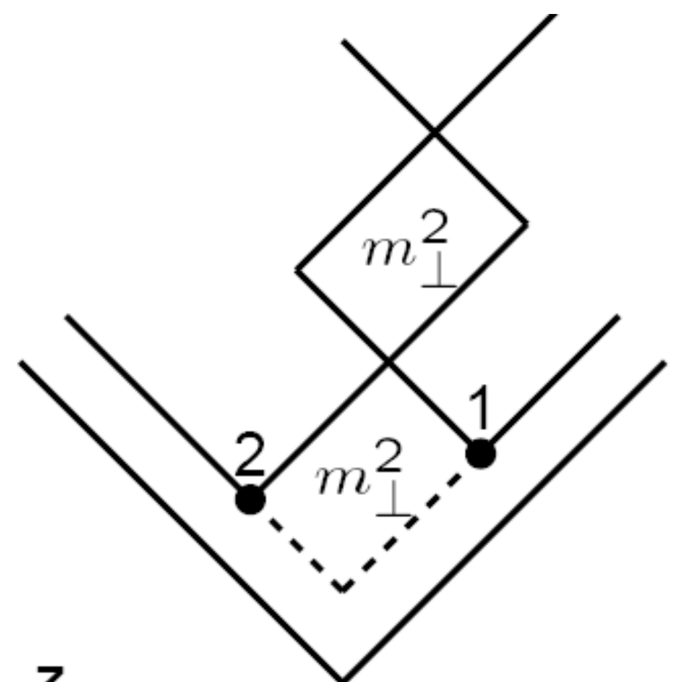


Large System

Illustrations by T. Sjöstrand

$$\left|\frac{\mathrm{d}E}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}z}\right| = \left|\frac{\mathrm{d}E}{\mathrm{d}t}\right| = \left|\frac{\mathrm{d}p_z}{\mathrm{d}t}\right| = \kappa$$





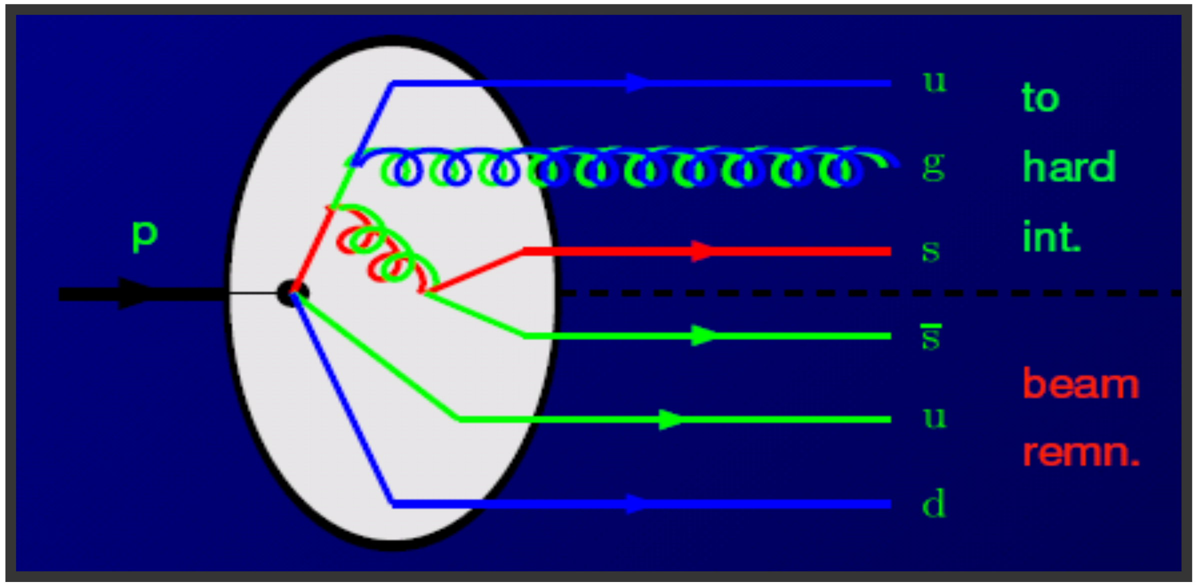
String breaks causally disconnected

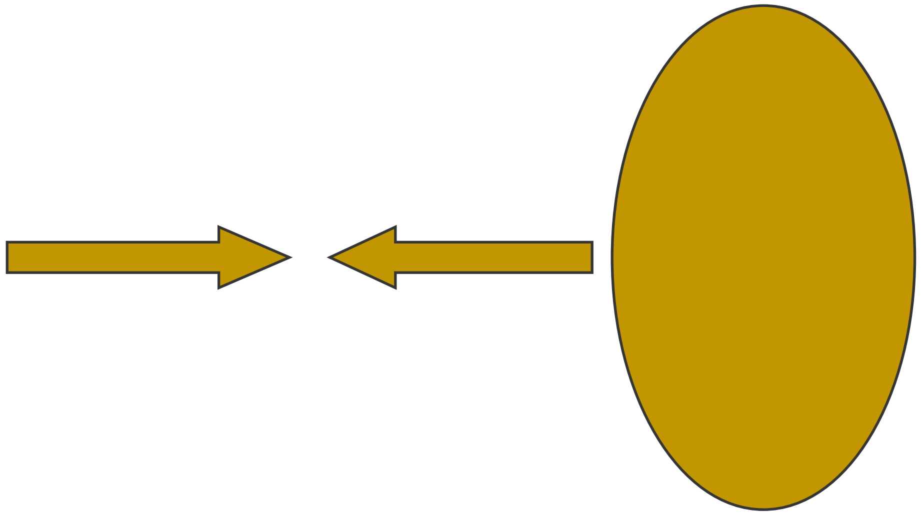
→ can proceed in arbitrary order (left-right, right-left, in-out, …)

→ constrains possible form of fragmentation function

→ Justifies iterative ansatz (useful for MC implementation)

Multi-Parton PDFs





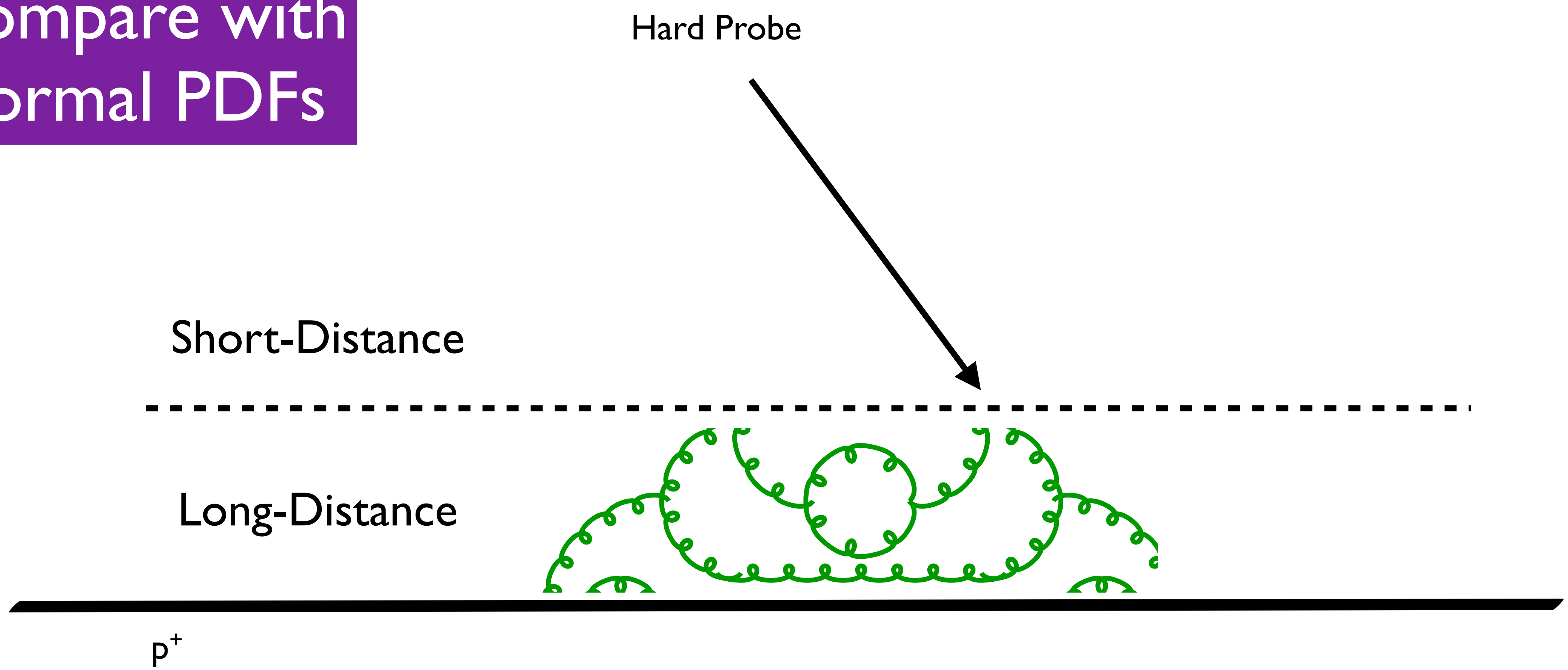
How are the initiators and remnant partons correllated?

- in impact parameter?
- in flavour?
- in x (longitudinal momentum)?
- in k_T (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

(+ Diffraction)

"Intuitive picture"

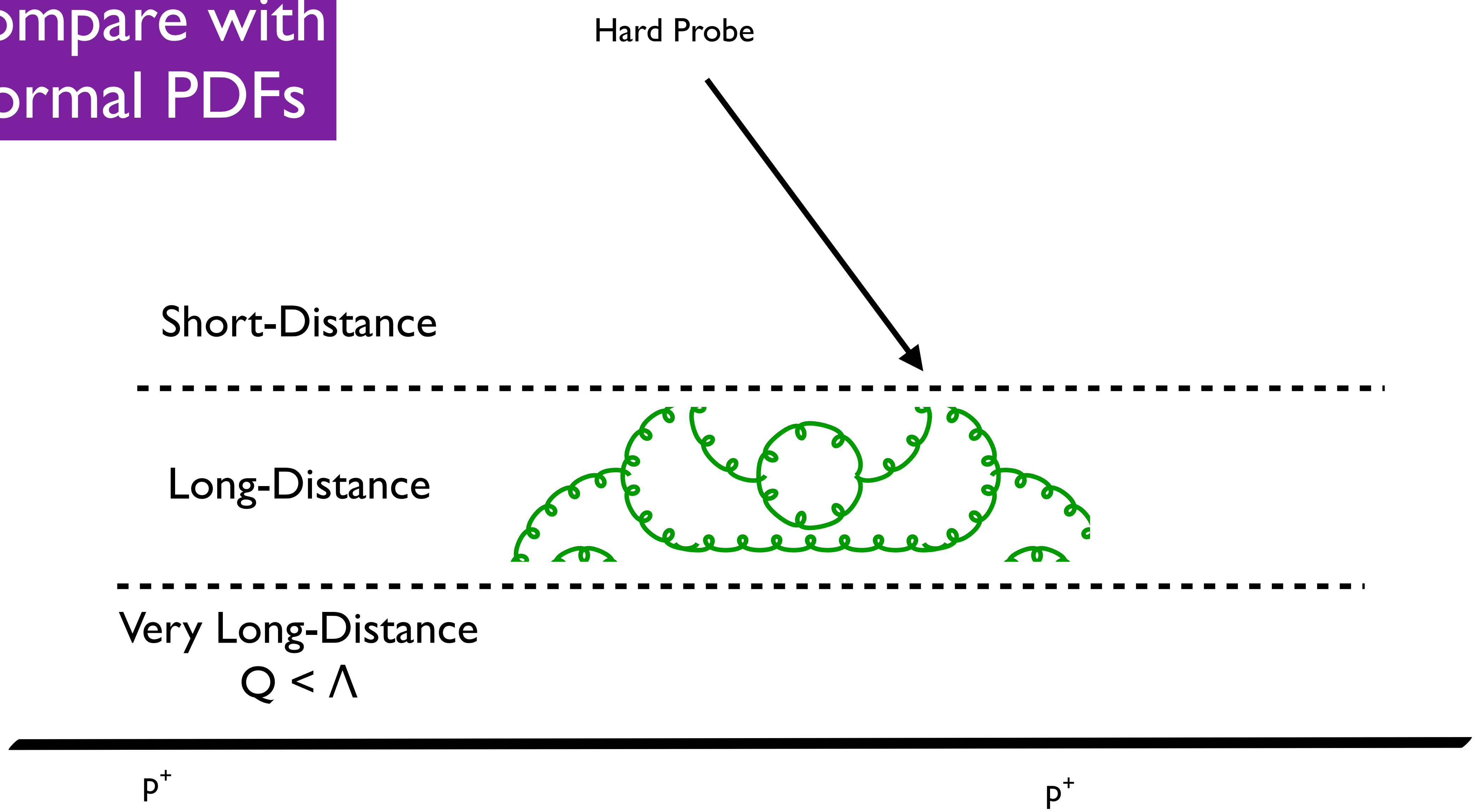
Compare with normal PDFs



(+ Diffraction)

“Intuitive picture”

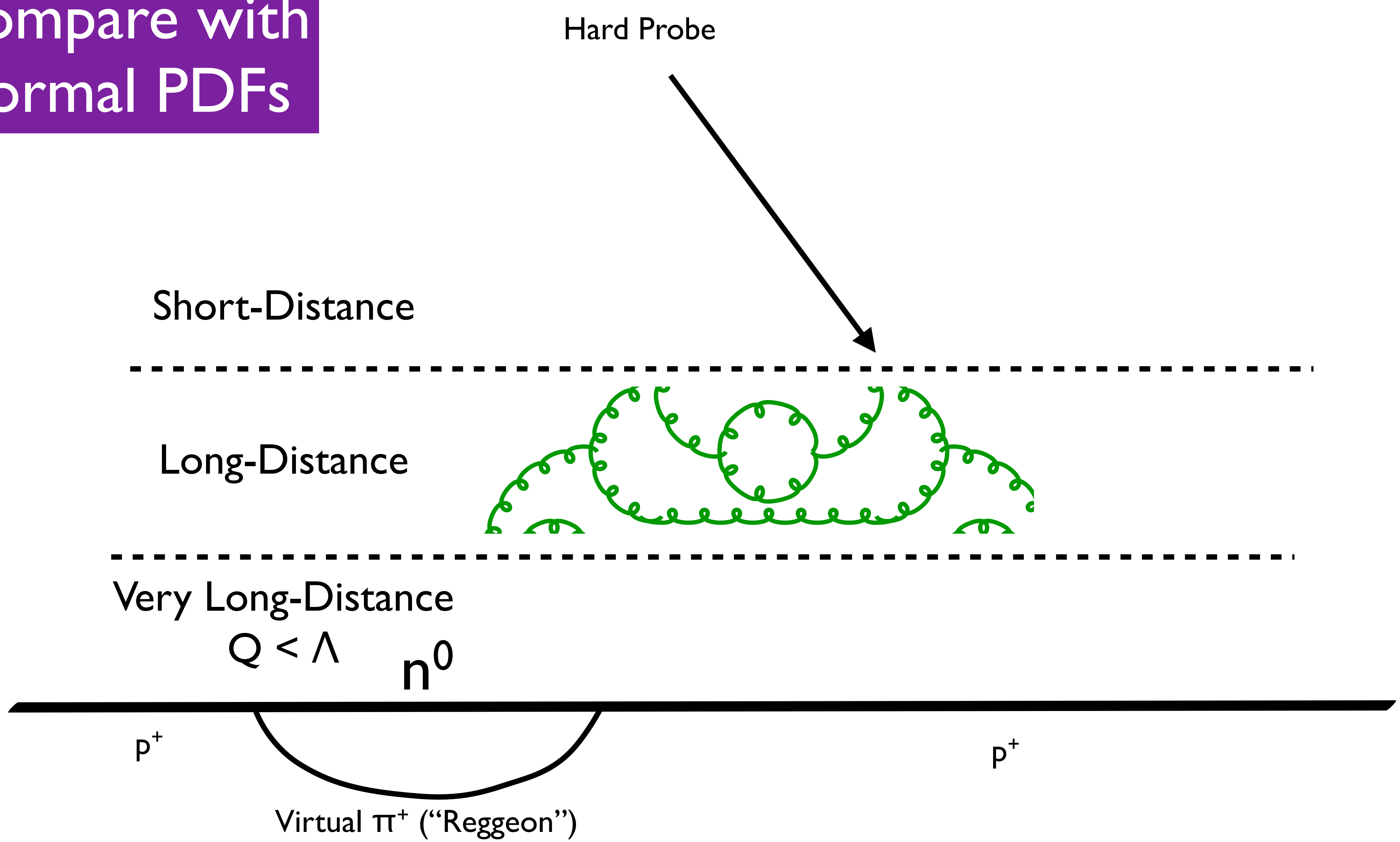
Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

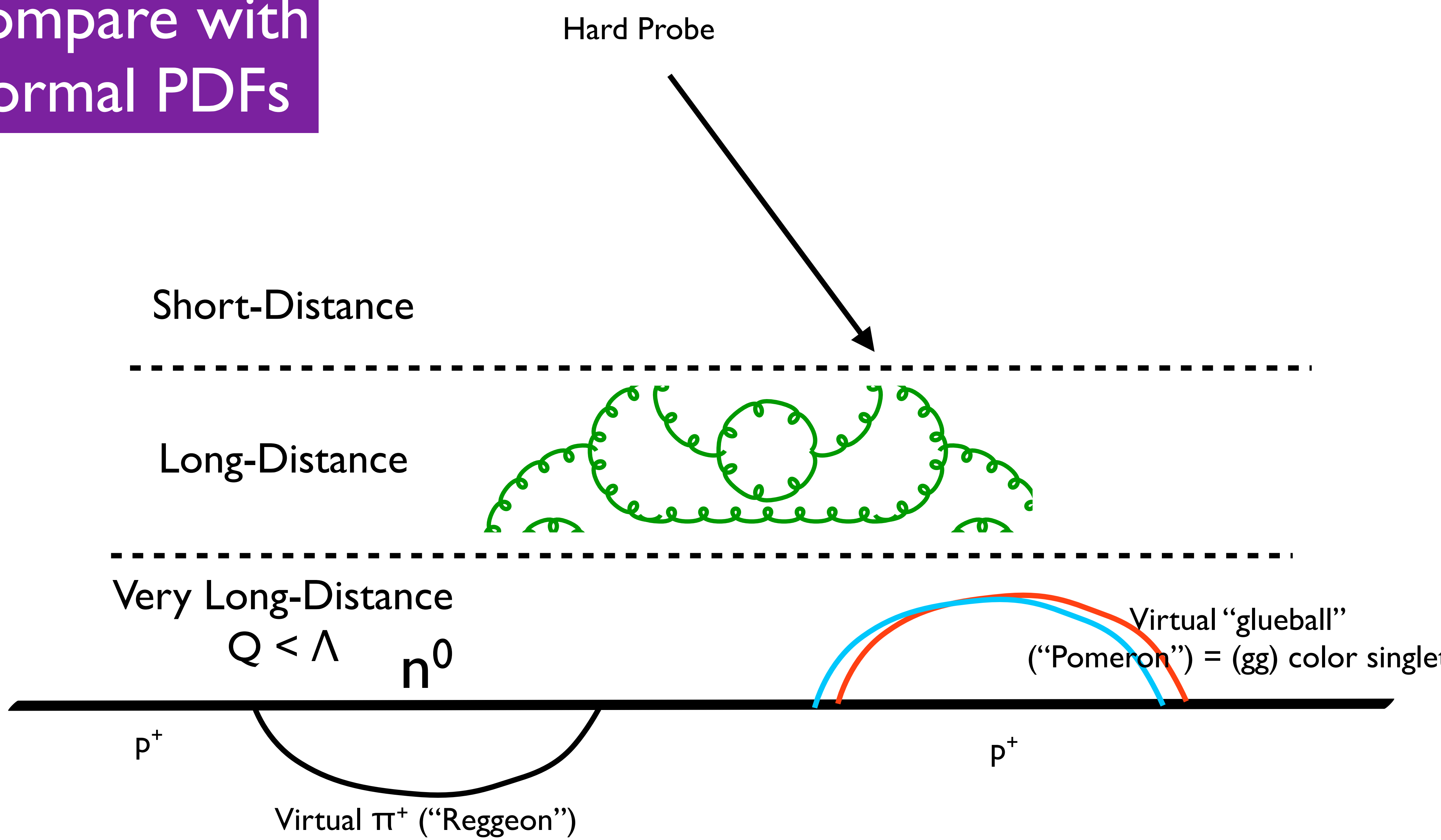
Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

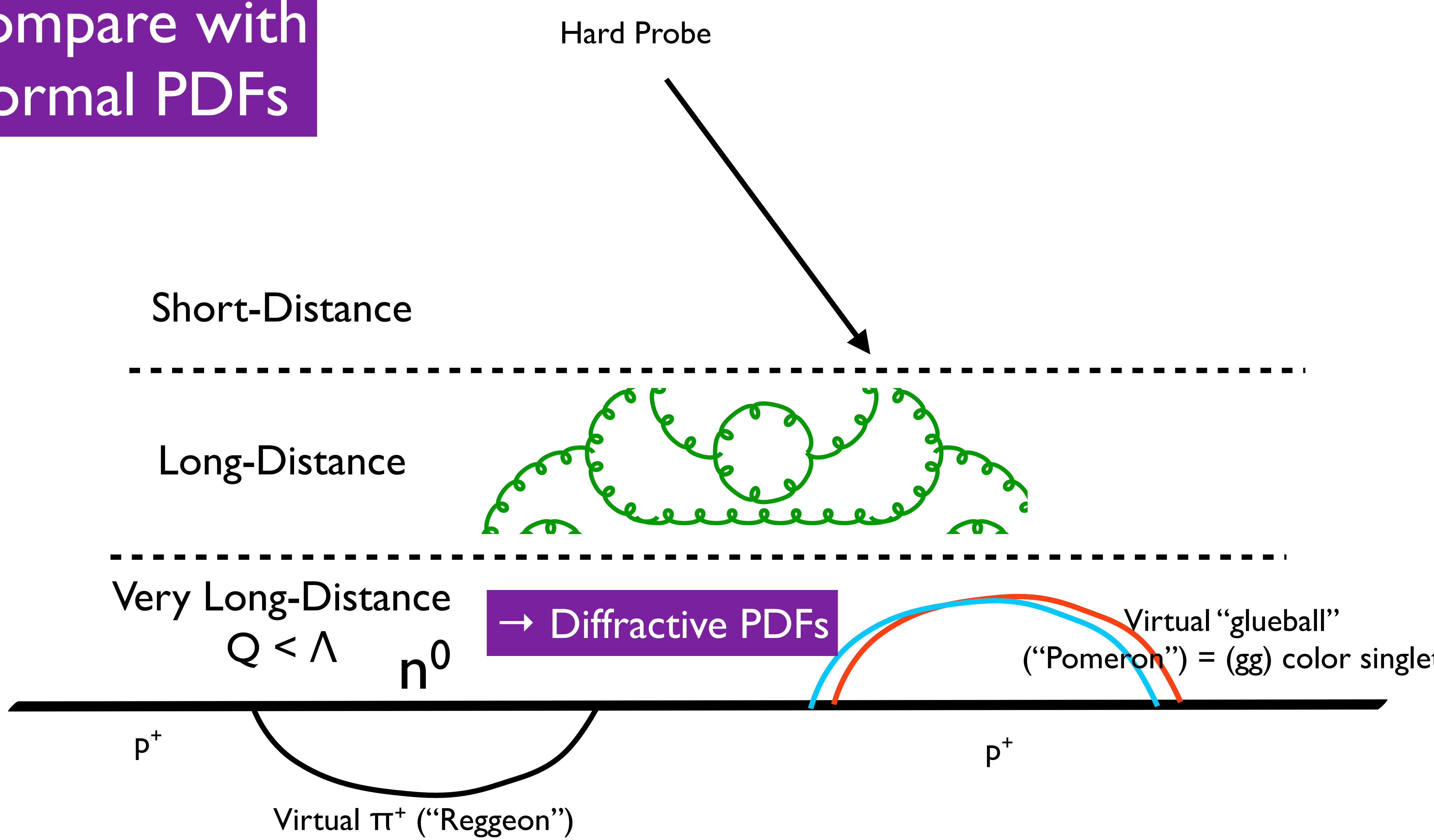
Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs



(+ Diffraction)

"Intuitive picture"

Compare with normal PDFs