Hadronization & Underlying Event

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Lecture 2 / 2

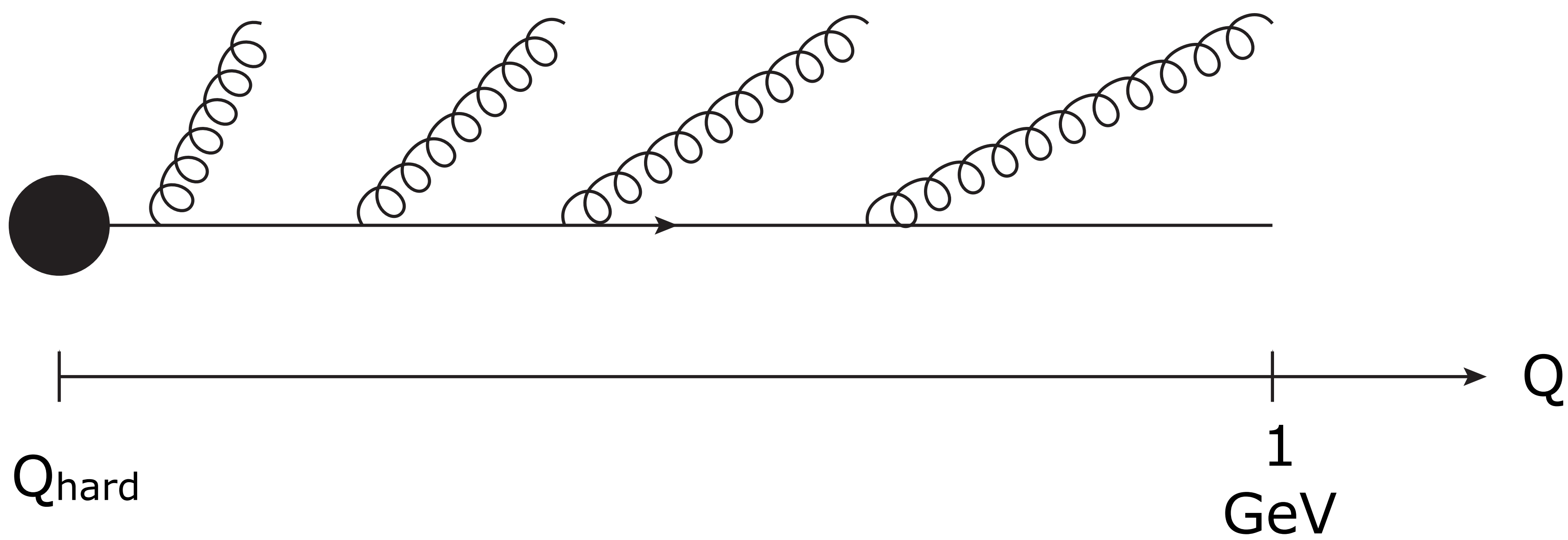
From Partons to Pions

Here's a fast parton

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

It showers (bremsstrahlung)

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



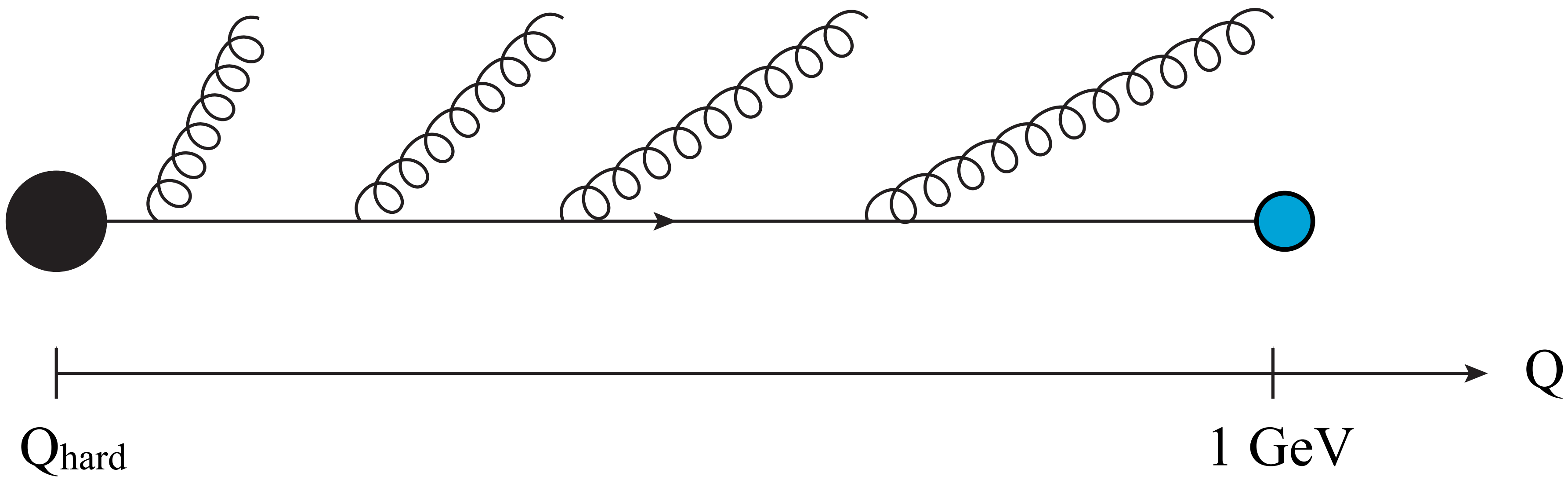
From Partons to Pions

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



How about I just call it a hadron?

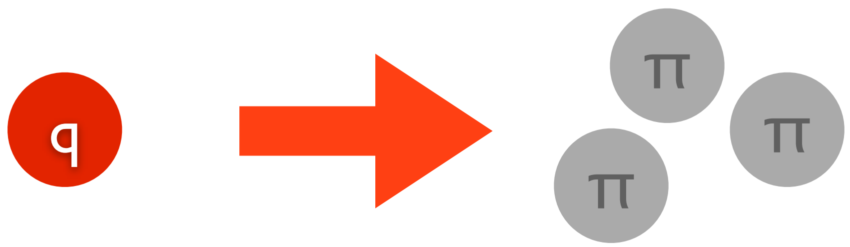
→ "Local Parton-Hadron Duality"

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

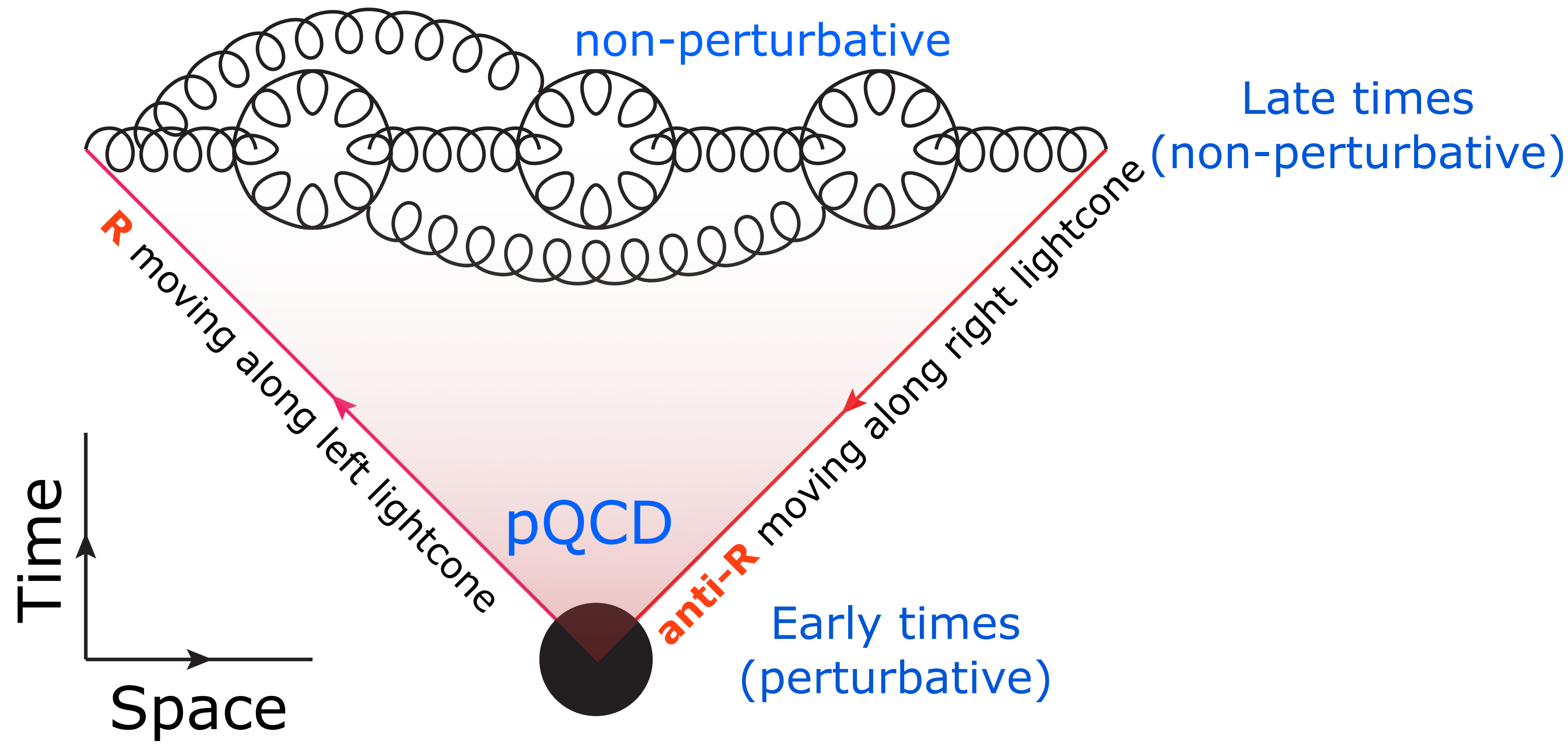
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ 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**)



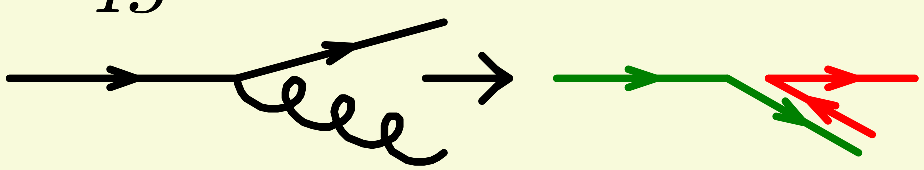
Strong "confining" field emerges between the two charges when their separation > ~ 1fm

Color Flow

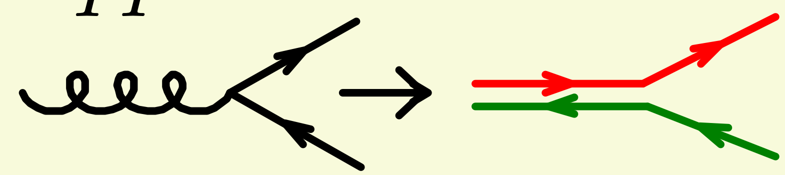
Between which partons do confining potentials arise?

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

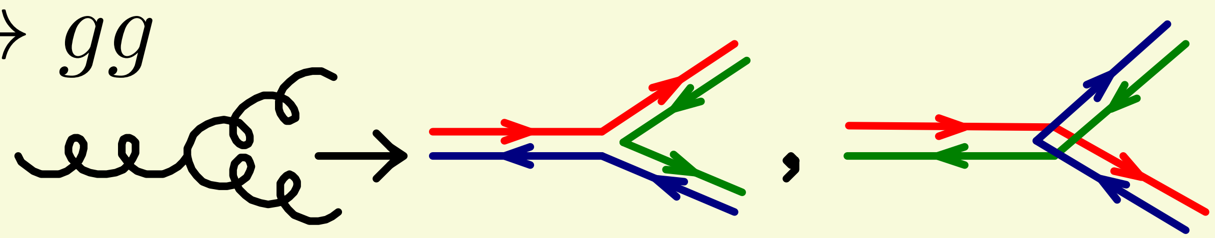
$q \to qg$



$g \to q\bar{q}$



$g \to gg$



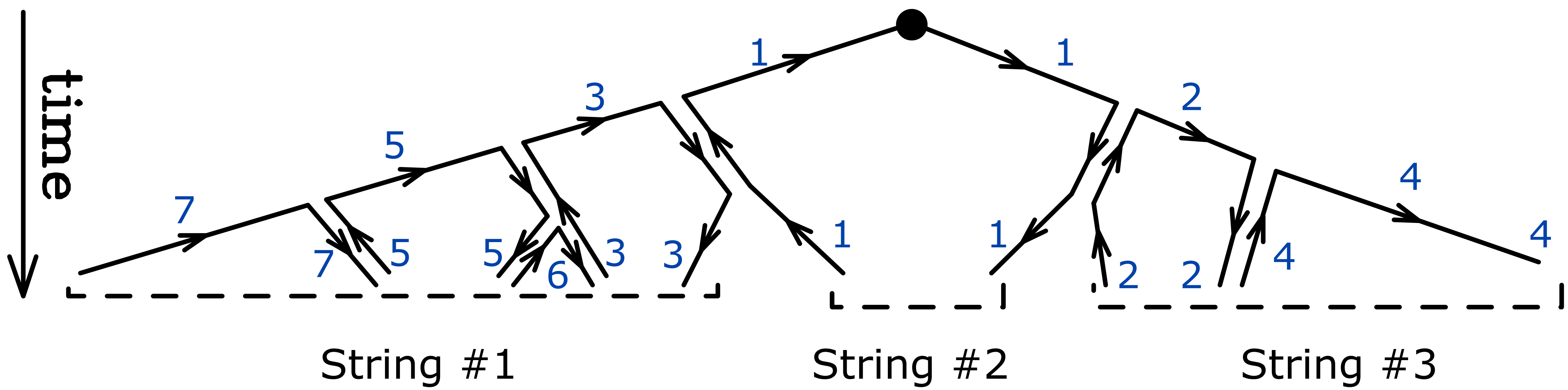
(Never Twice Same Color: true up to $O(1/N_C^2)$)

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

Color Flow

For an entire Cascade

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



Coherence of pQCD cascades → not much “overlap” between strings
→ Leading-colour approximation pretty good

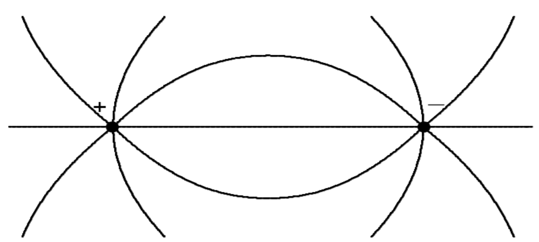
(LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$))

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

Confinement

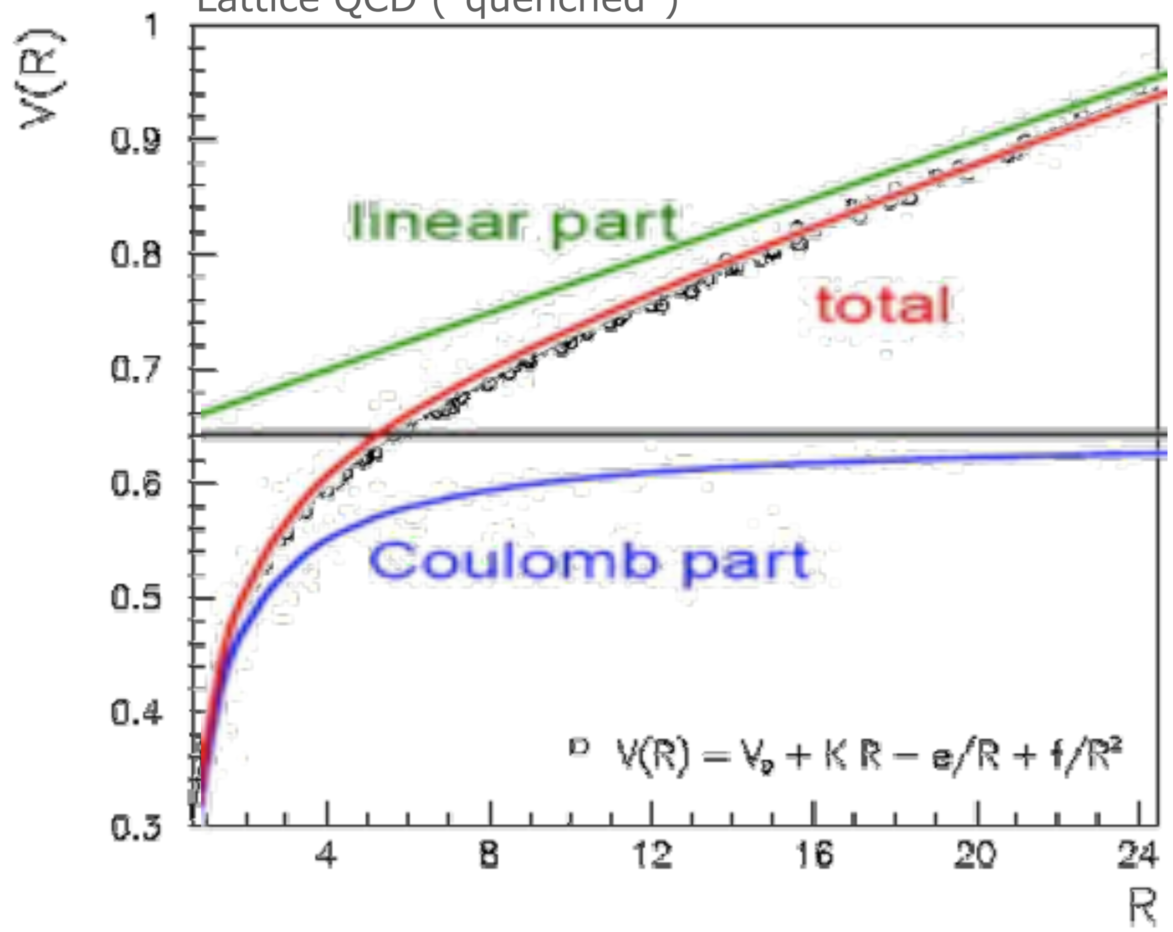
Potential between a quark and an antiquark as function of distance, R

Short Distances ~ "Coulomb"

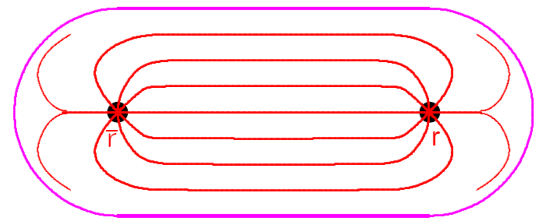


Partons

Lattice QCD ("quenched")



Long Distances ~ Linear Potential



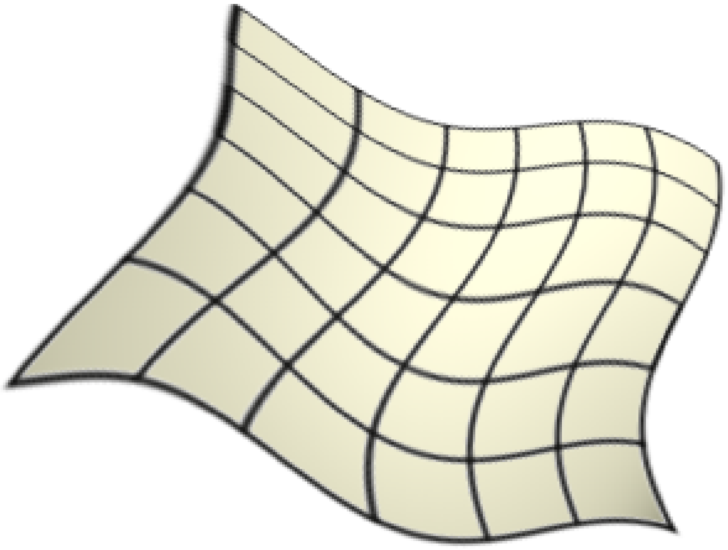
Quarks (and gluons) confined inside hadrons

What physical system has a linear potential?

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

~ 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

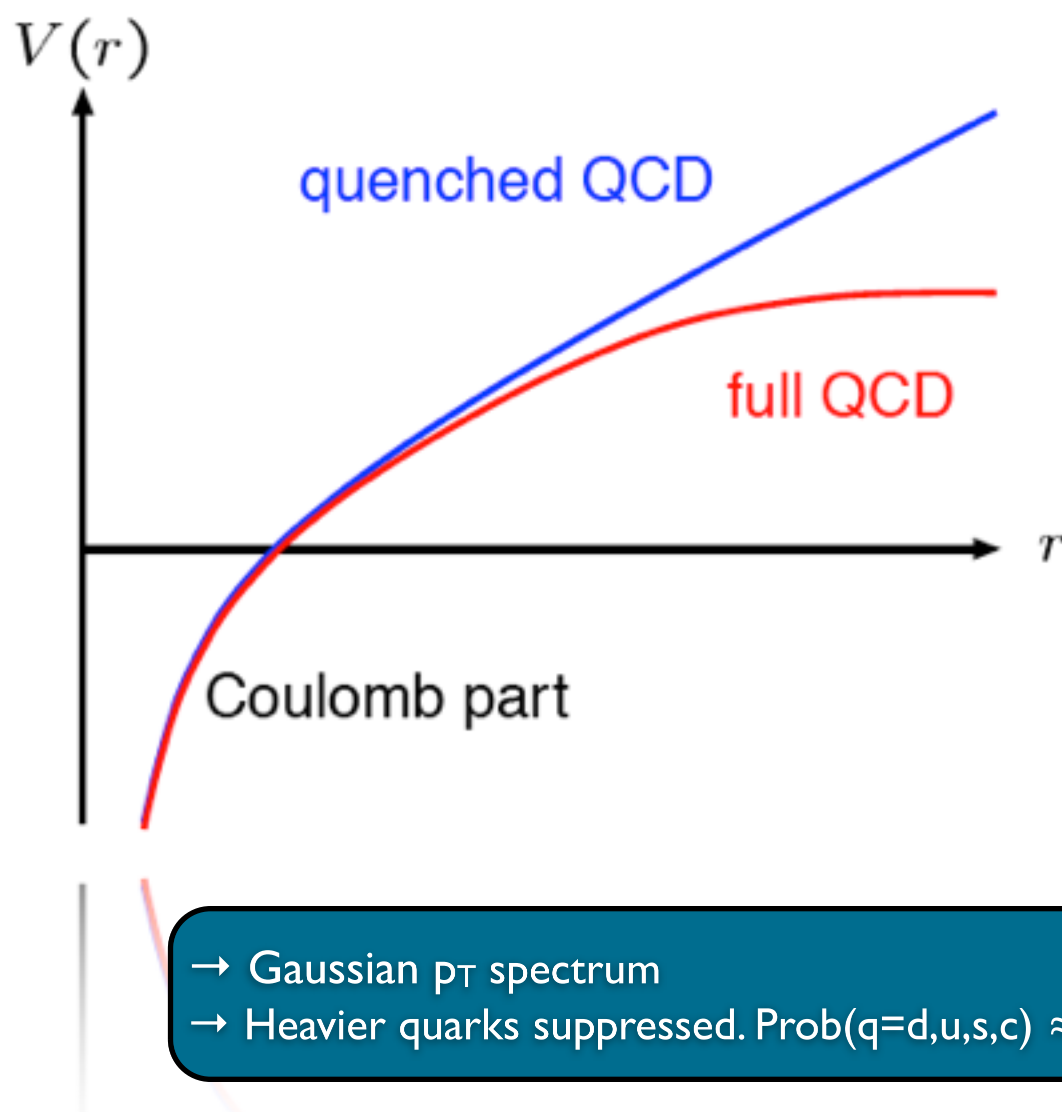
→ Relativistic 1+1 dimensional worldsheet – string

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

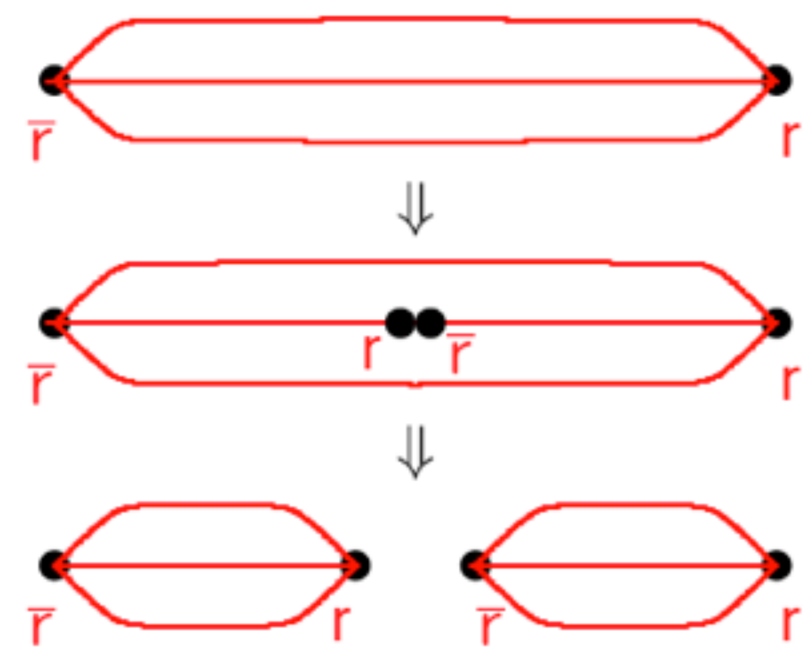
String Breaks

In "unquenched" QCD

g→qq → The strings would break



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
→ Heavier quarks suppressed. Prob(q=d,u,s,c) ≈ 1 : 1 : 0.2 : 10^{-11}

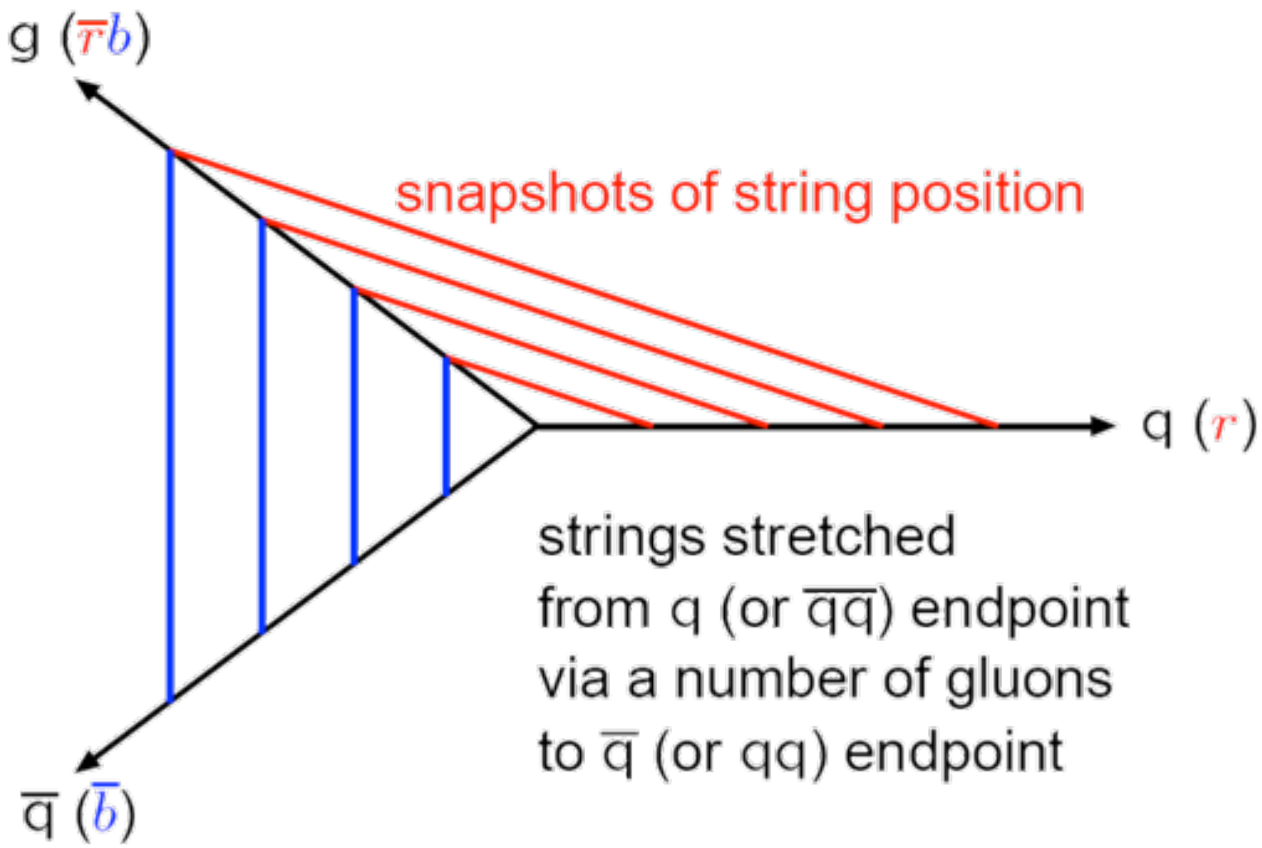
Illustrations by T. Sjöstrand

The (Lund) String Model

Map:

See also Yuri's 2nd lecture

- **Quarks** → String Endpoints
- **Gluons** → Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break (by quantum tunneling) constant per unit area → **AREA LAW**



Gluon = kink on string, carrying energy and momentum

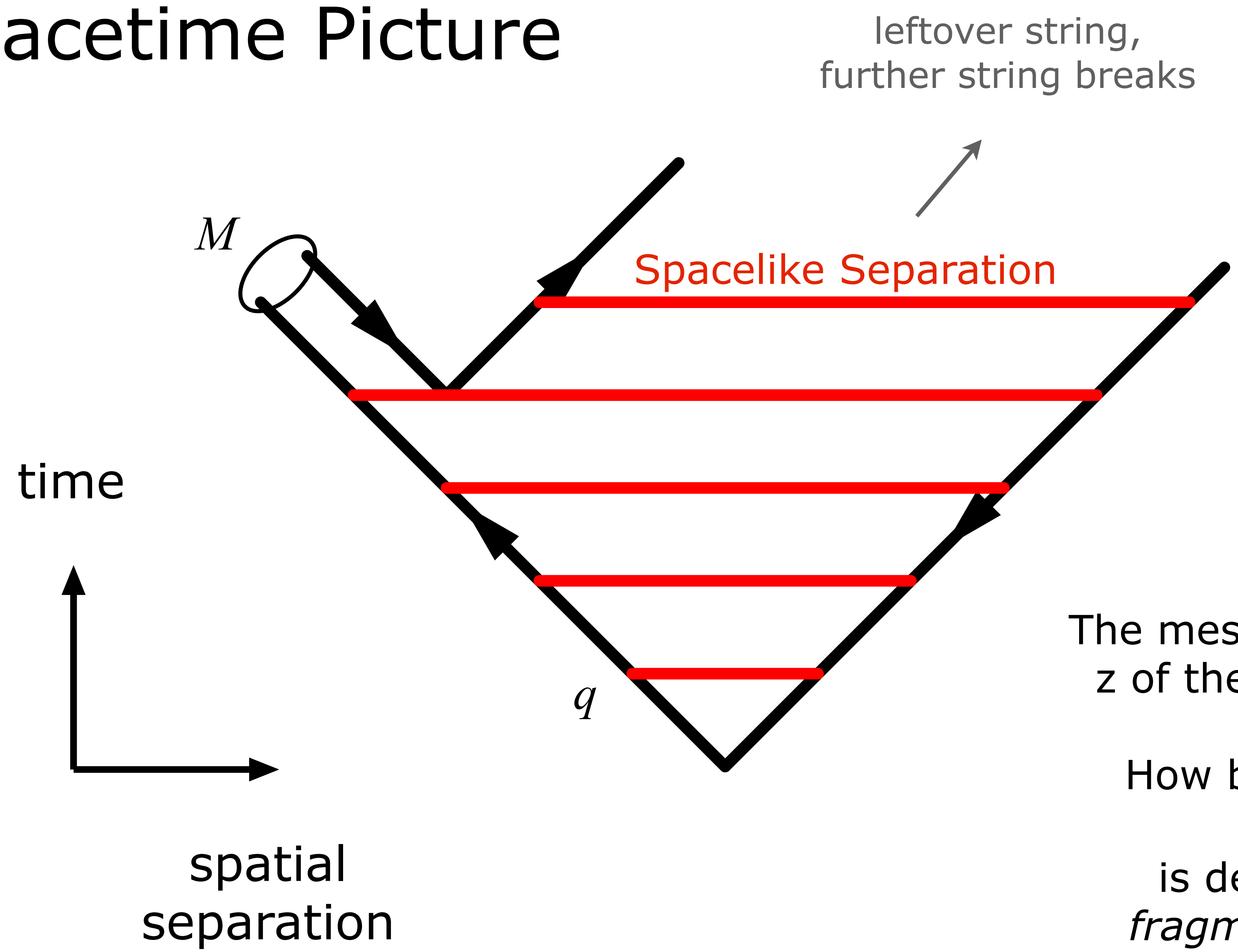
→ **STRING EFFECT**

Simple space-time picture

Details of string breaks more complicated (e.g., baryons, spin multiplets)

Fragmentation Function

Spacetime Picture



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

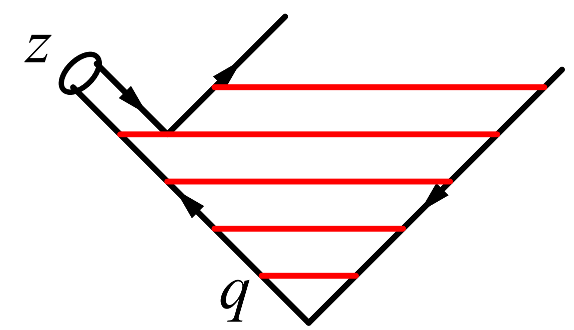
How big that fraction is, $z \in [0,1]$, is determined by the *fragmentation function*, $f(z,Q_0^2)$

Left-Right Symmetry

Causality → Left-Right Symmetry

→ Constrains form of fragmentation function!

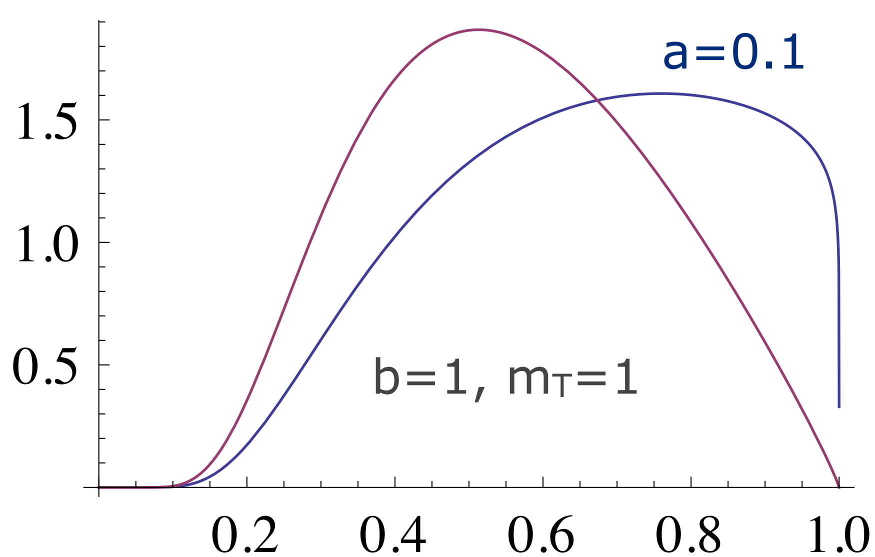
→ Lund Symmetric Fragmentation Function

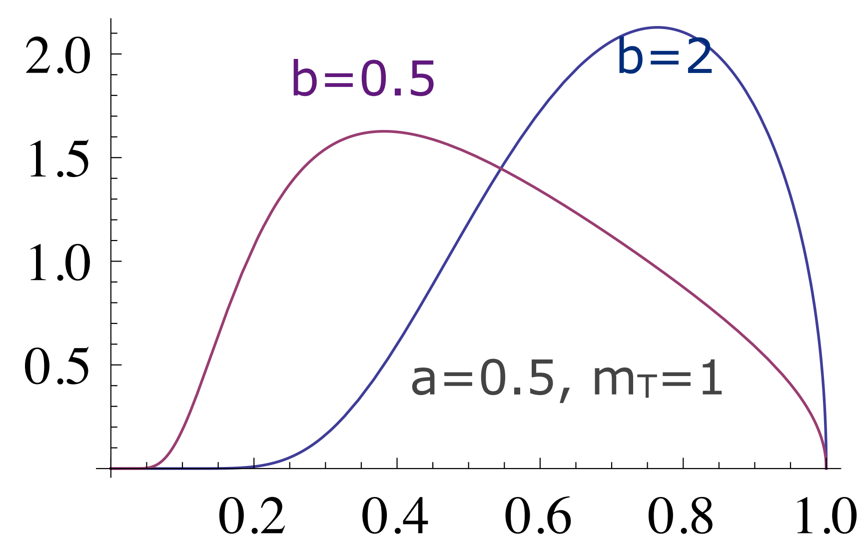


$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Small a
→ "high-z tail"

Small b
→ "low-z enhancement"

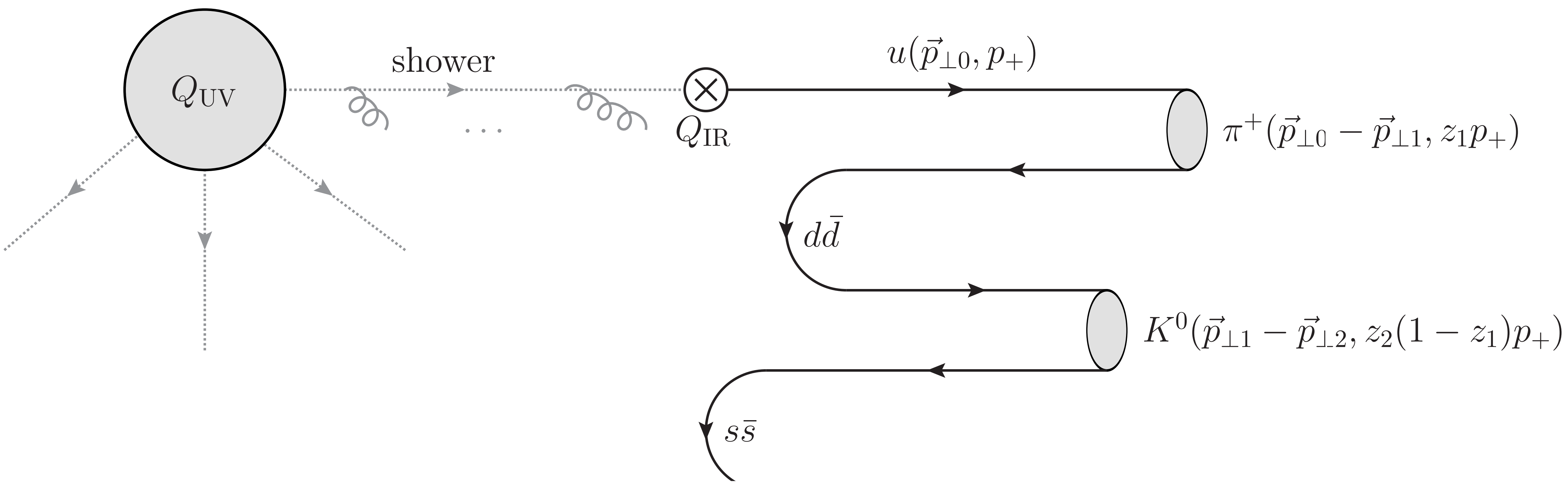




Note: In principle, a can be flavour-dependent. In practice, we only distinguish between baryons and mesons

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

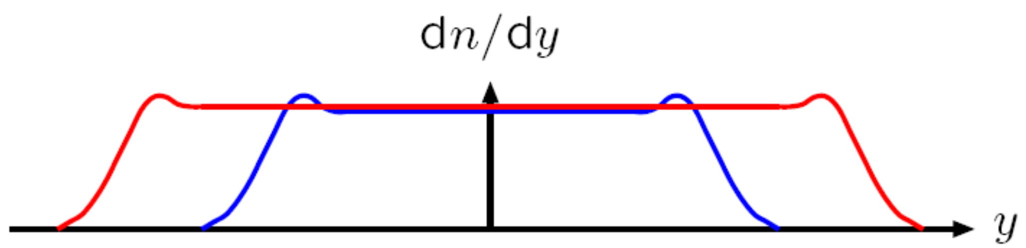
In Rapidity : $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$

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

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

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

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



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

Alternative: The Cluster Model

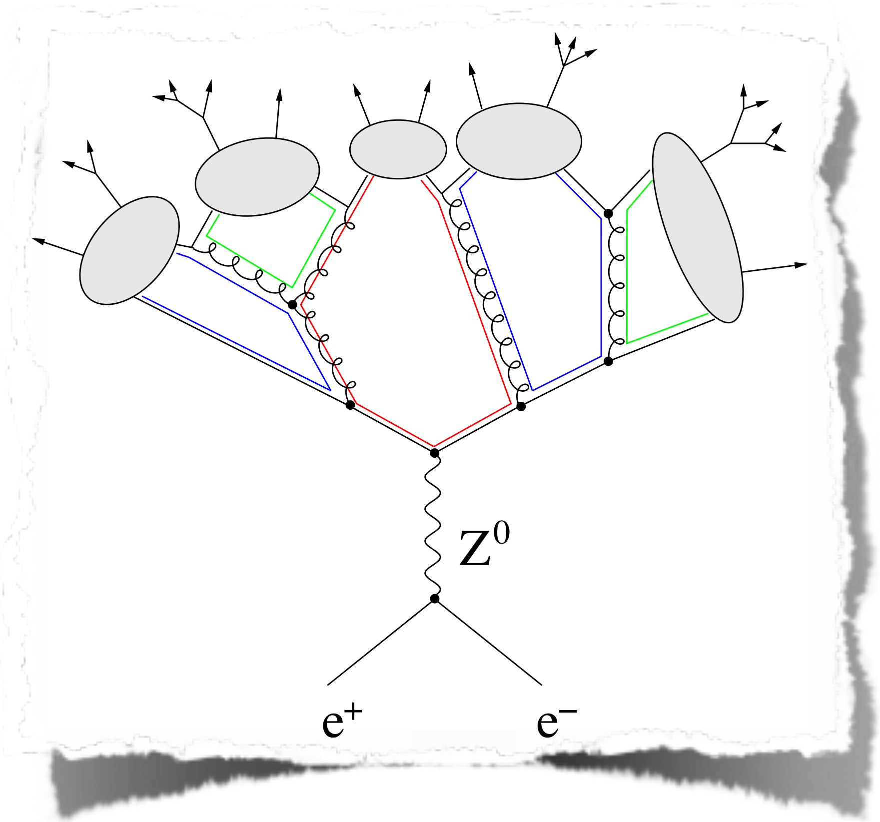
"Preconfinement"

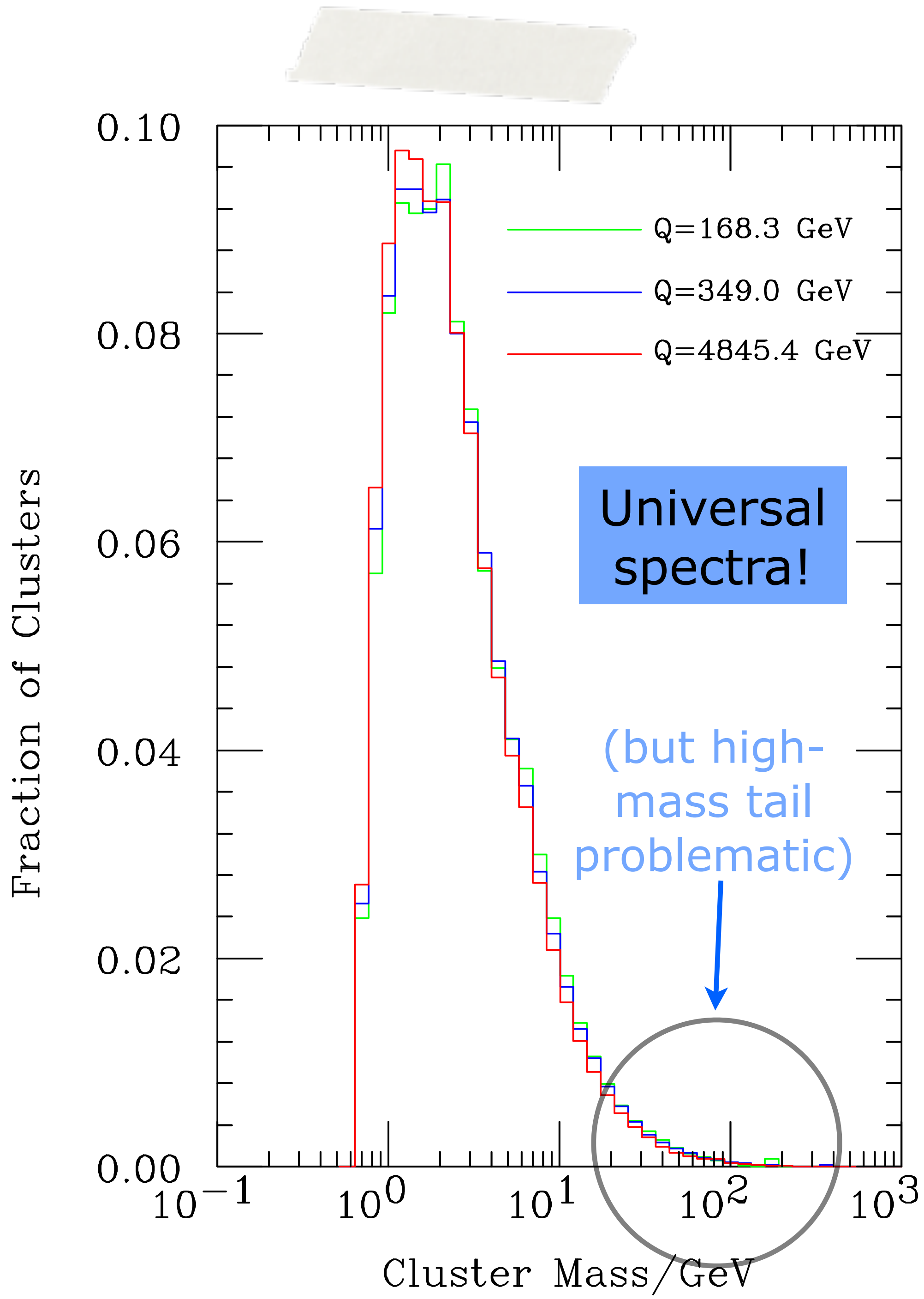
+ Force g→qq splittings at Q_0

→ high-mass q-qbar "clusters"

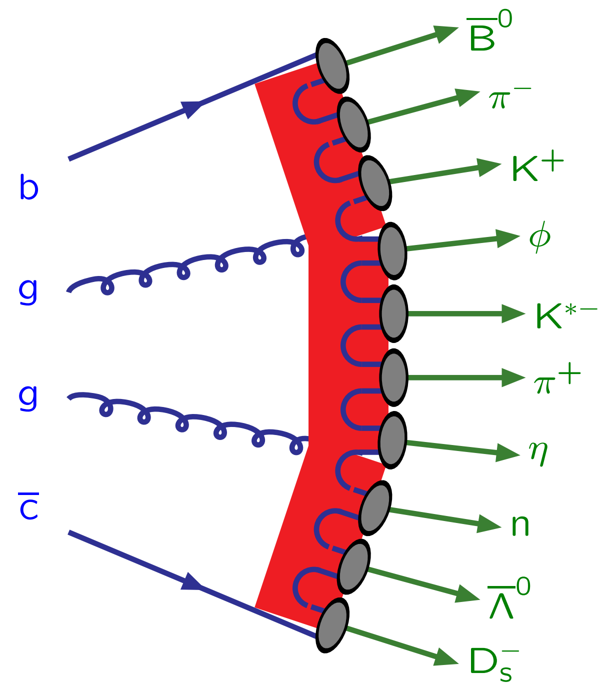
Isotropic 2-body decays to hadrons

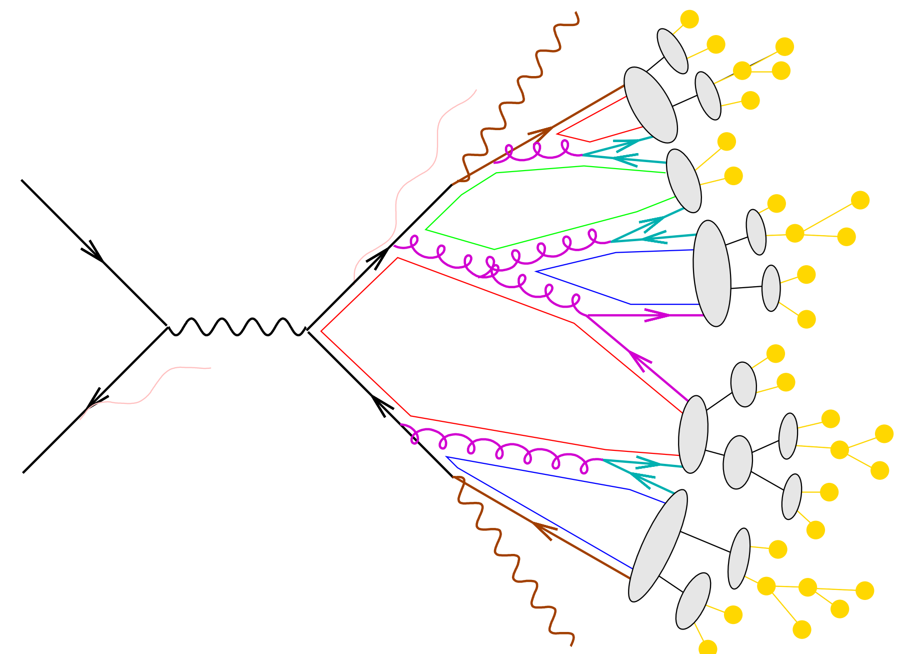
according to PS ≈ $(2s_1+1)(2s_2+1)(p^*/m)$





Strings and Clusters





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

Small strings → clusters. Large clusters → strings

Hadron Collisions

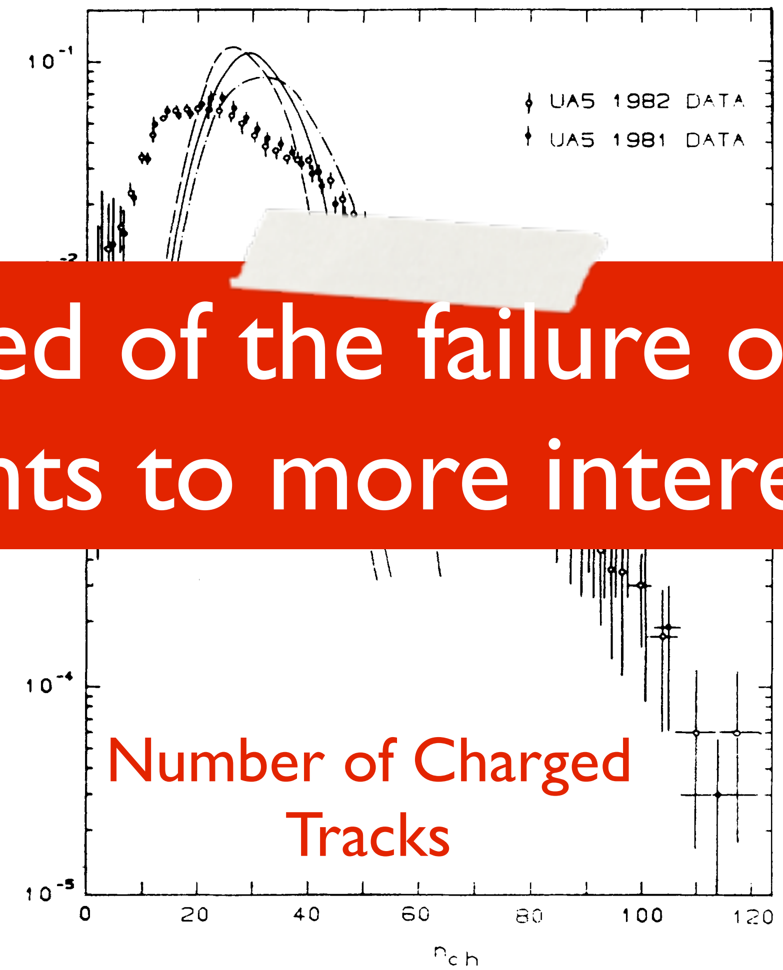


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

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

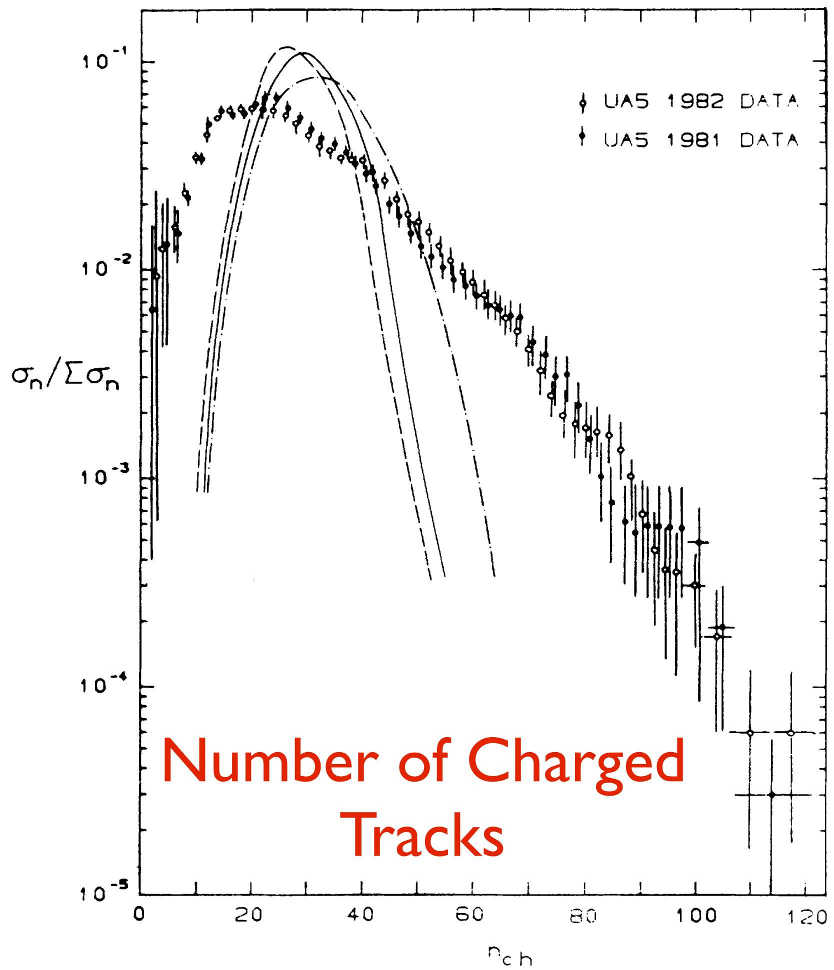


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

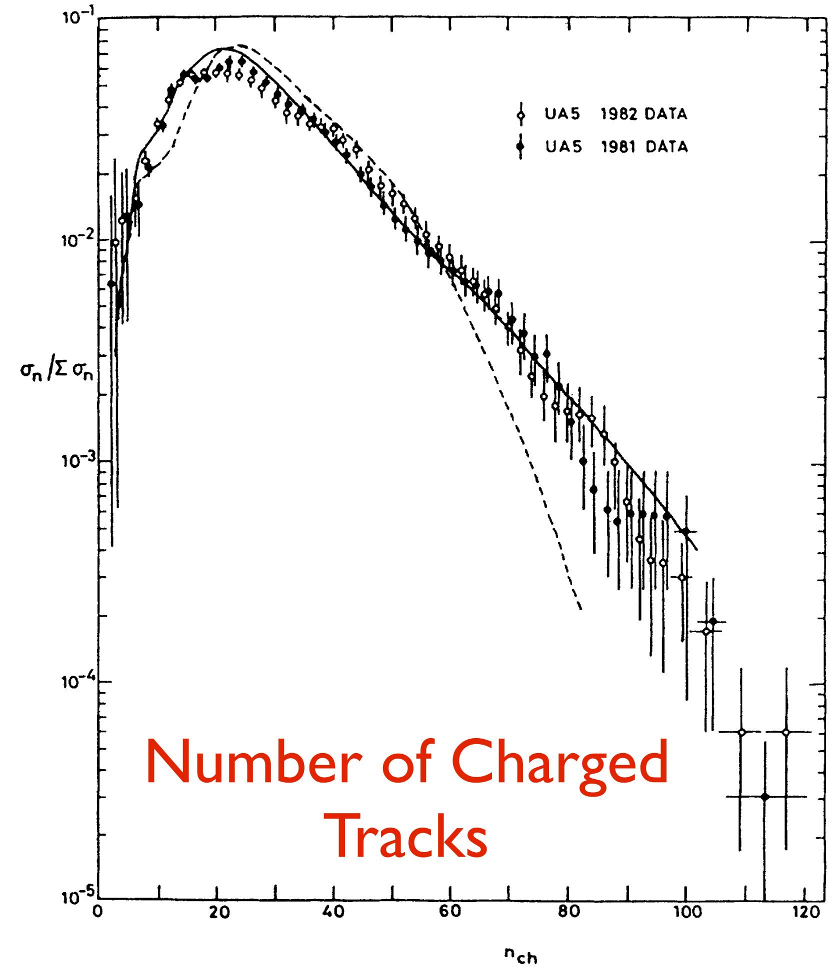


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

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

Soft-inclusive QCD

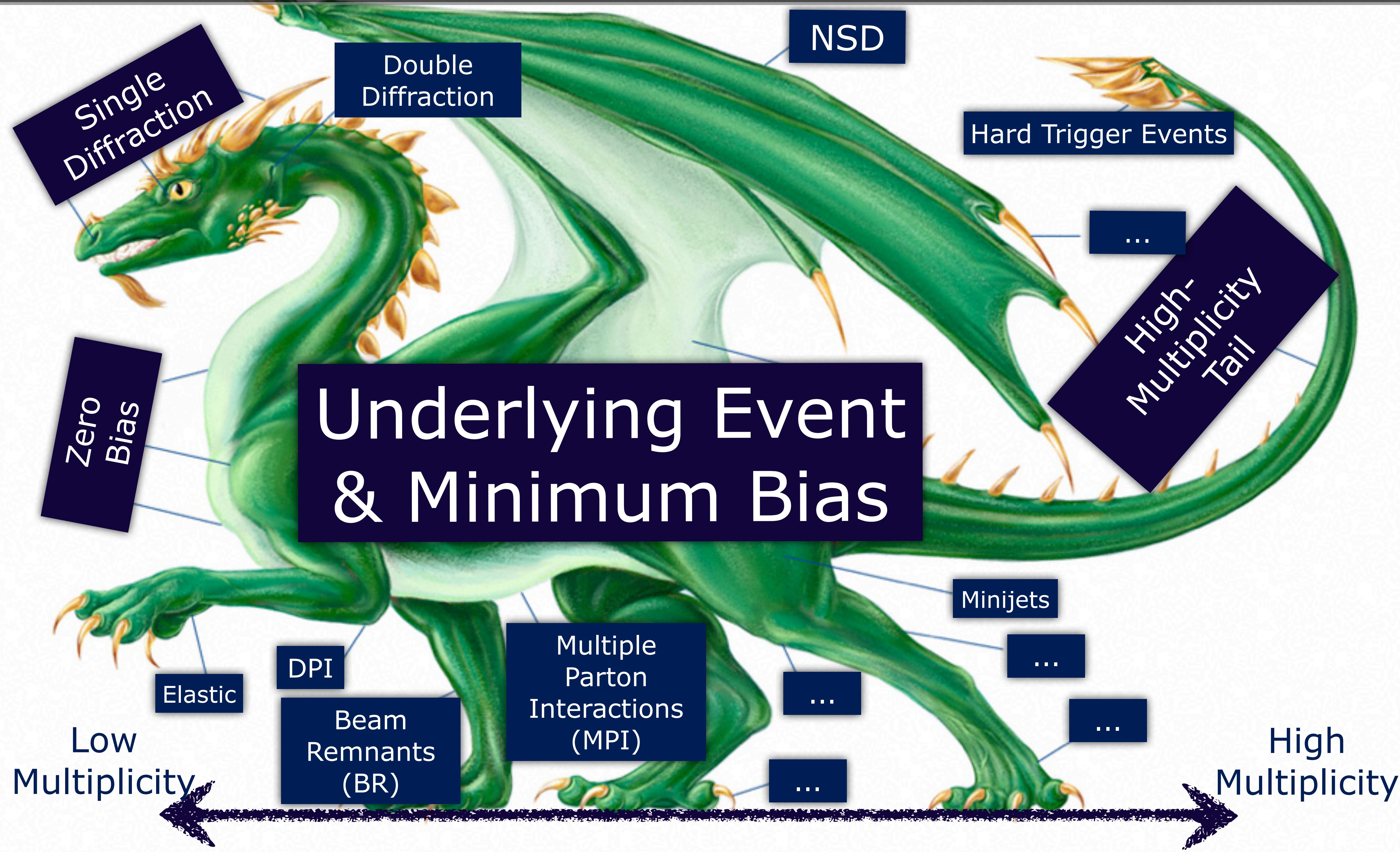
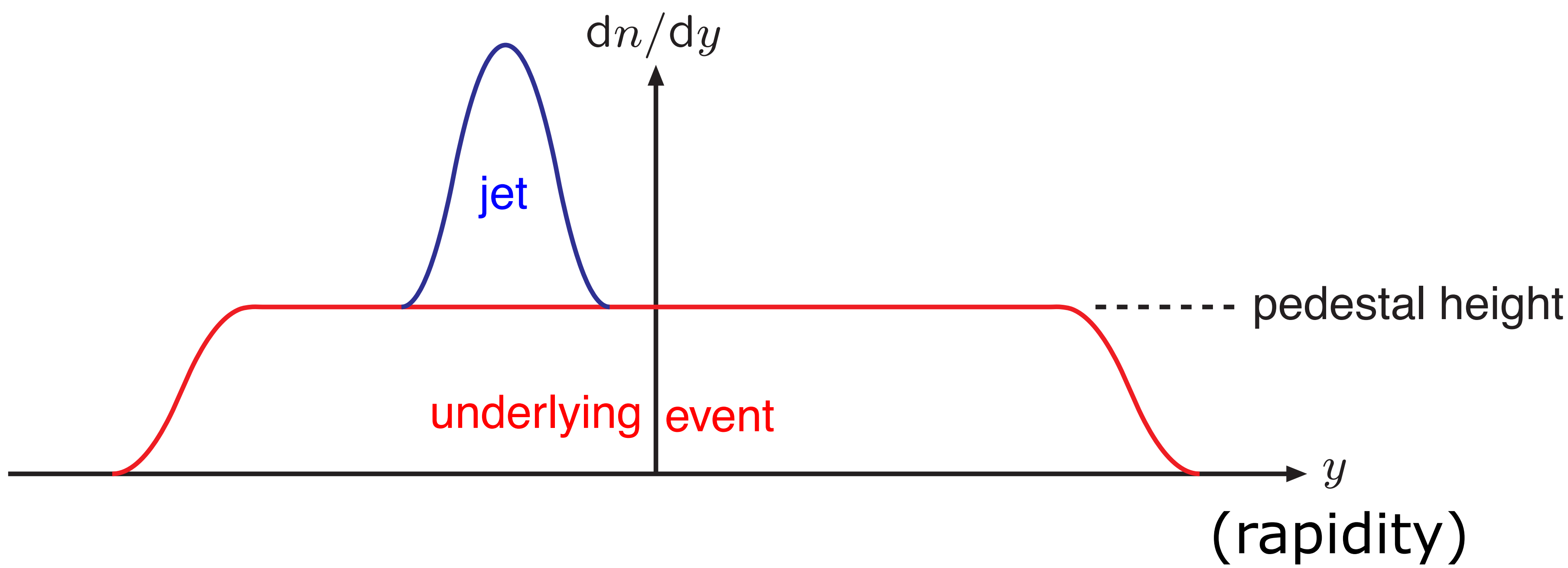


Image credits: E. Arenhaus & J. Walker

What is Underlying Event ?

"Pedestal Effect"



Useful variable in hadron collisions: **Rapidity**

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

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

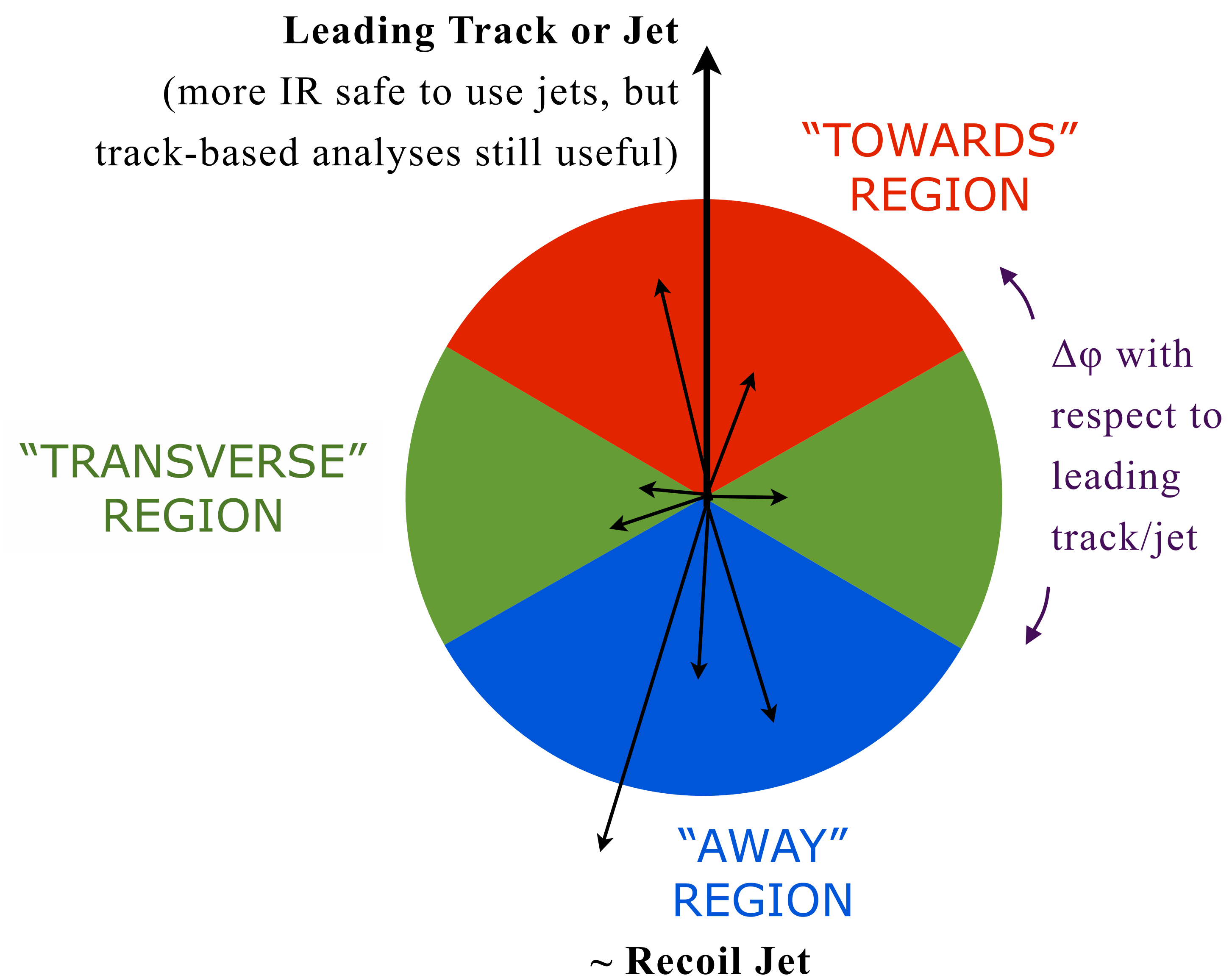
$$y \to -\infty \quad \text{for} \quad p_z \to -E \qquad y \to 0 \quad \text{for} \quad p_z \to 0 \qquad y \to \infty \quad \text{for} \quad p_z \to E$$

Illustrations by T. Sjöstrand

The "Rick Field" UE Plots

(the same Field as in Field-Feynman)

There are many UE variables.
The most important is <Σp_T> in the "Transverse Region"

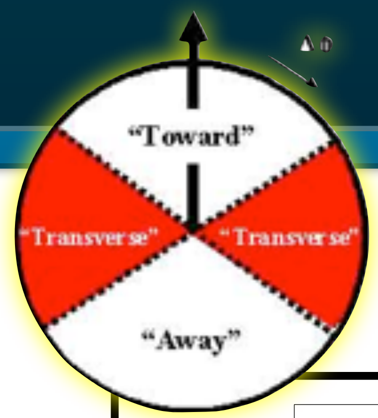


Transverse Region (TRNS)

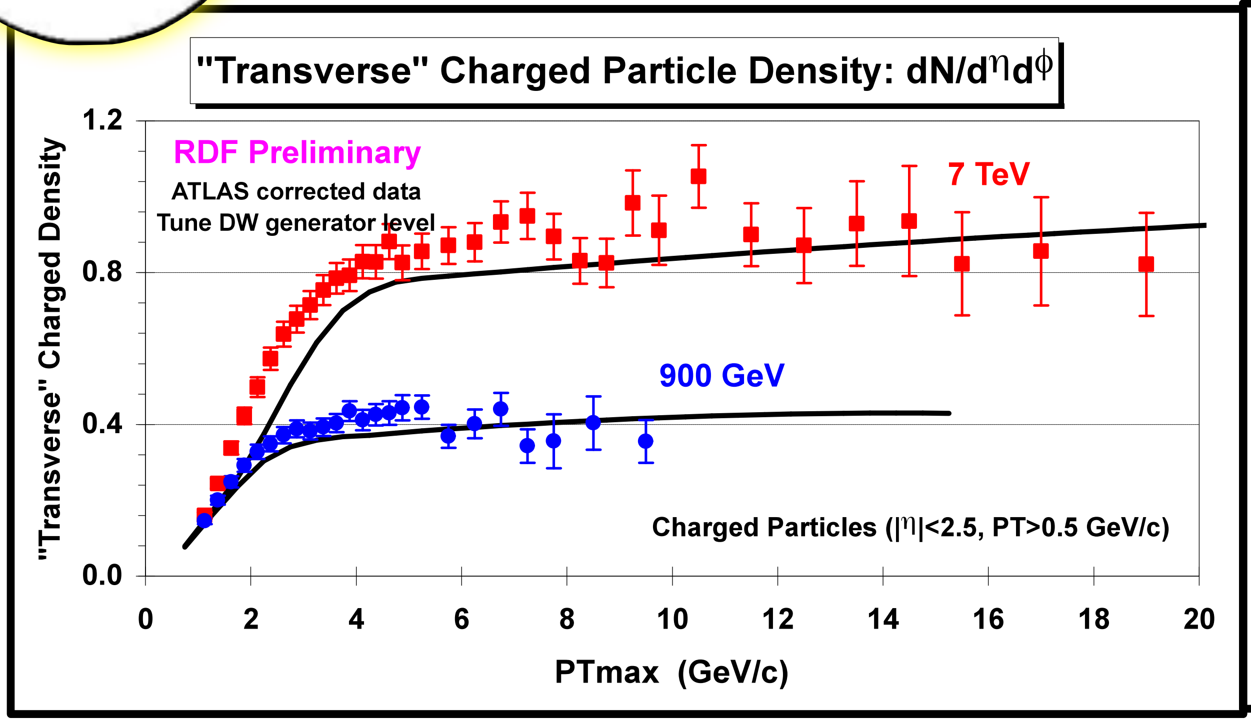
Sensitive to activity at right angles to the hardest jets

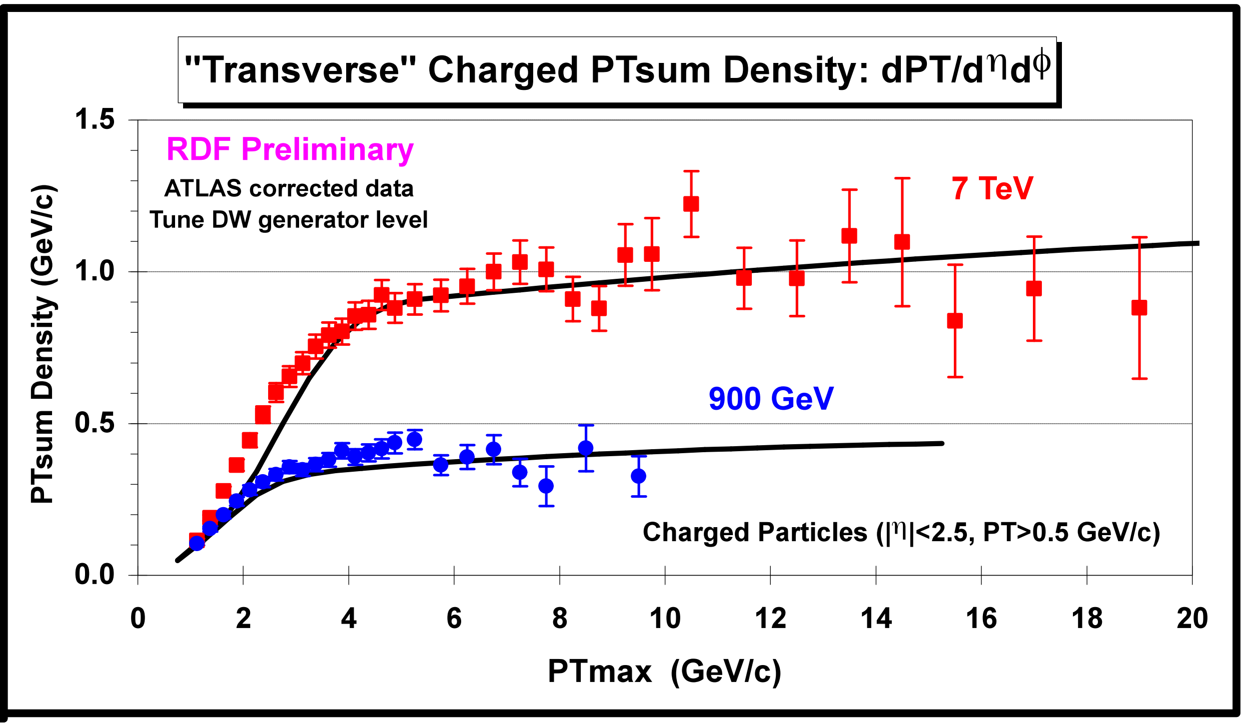
Useful definition of Underlying Event

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%

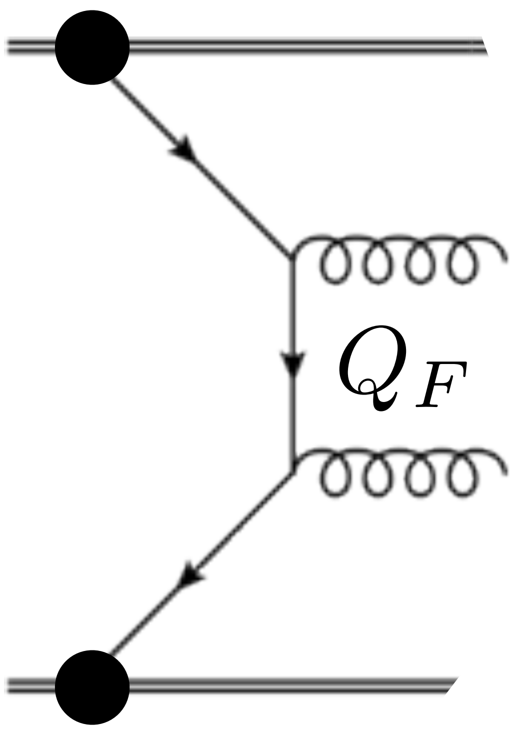
Truth is in the eye of the beholder:

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

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

Physics of the Pedestal

Factorization: Subdivide Calculation



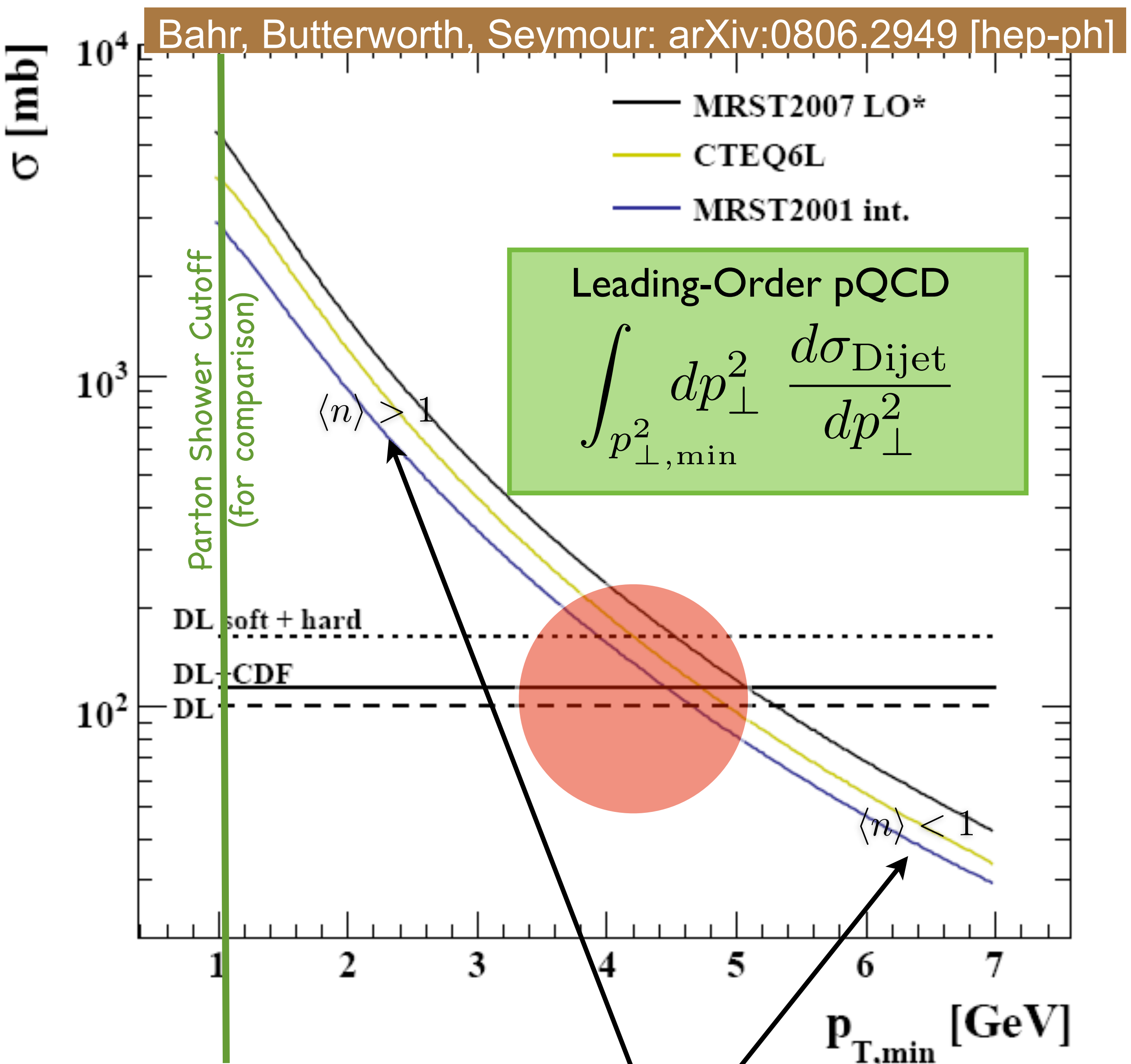
Multiple Parton Interactions go beyond existing theorems

→ perturbative short-distance physics in Underlying Event

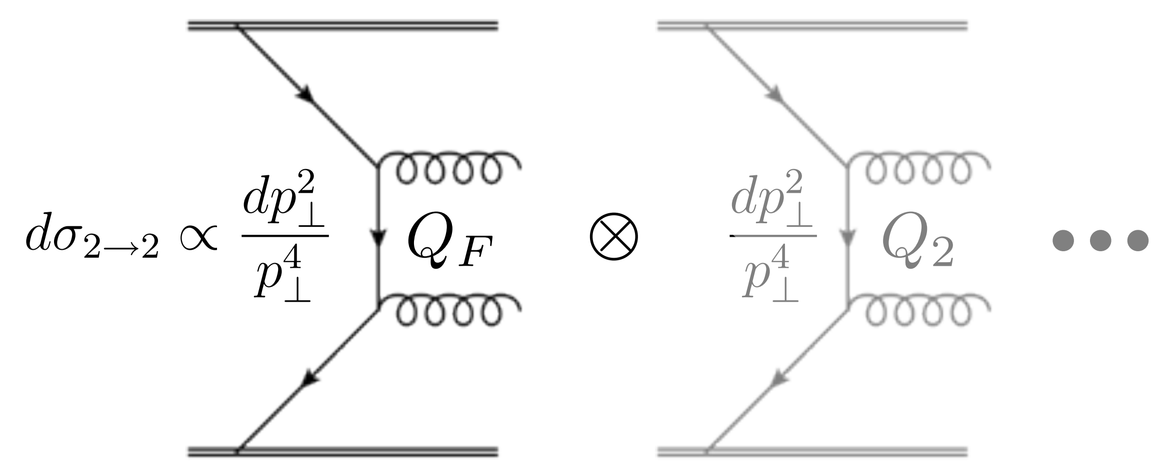
→ Need to generalize factorization to MPI

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



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

Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

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

Parton-Parton Cross Section — Hadron-Hadron Cross Section

How many?

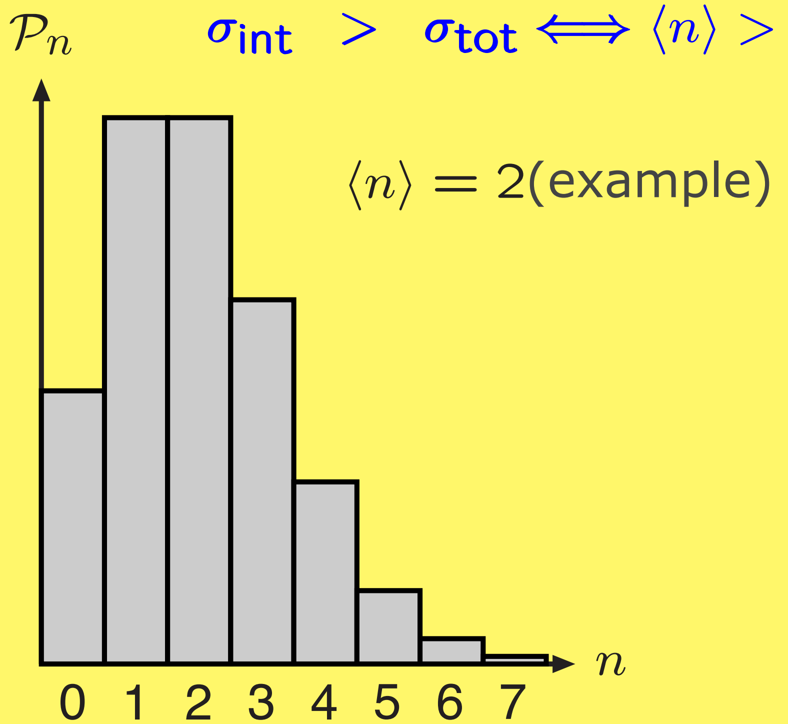
Naively $\langle n_{2\to 2}(p_{\perp\min})\rangle = \frac{\sigma_{2\to 2}(p_{\perp\min})}{\sigma_{\text{tot}}}$

Interactions independent (naive factorization) → Poisson

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

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

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



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

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

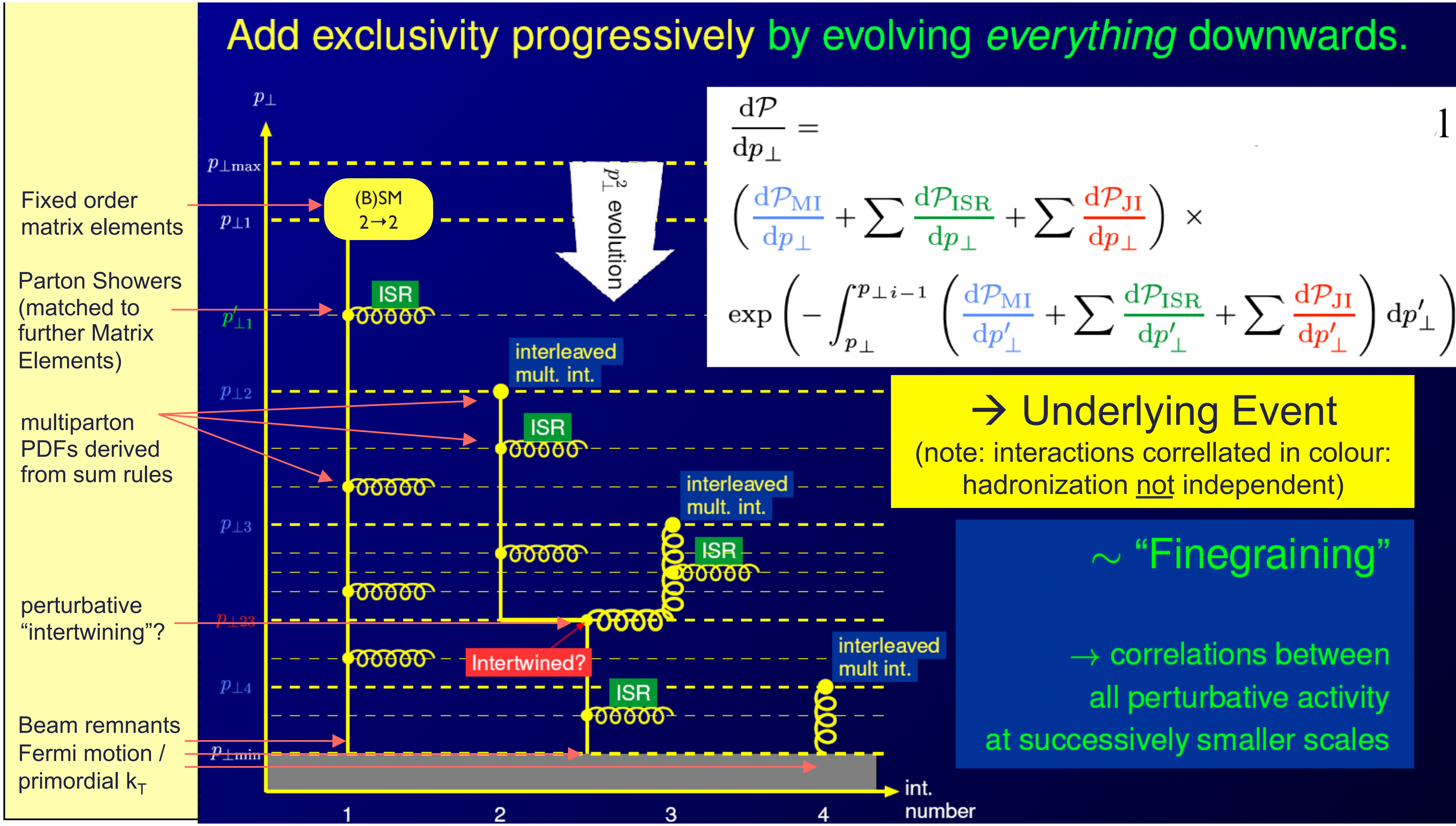
$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{tot}$$

Parton-Parton Cross Section — Hadron-Hadron Cross Section

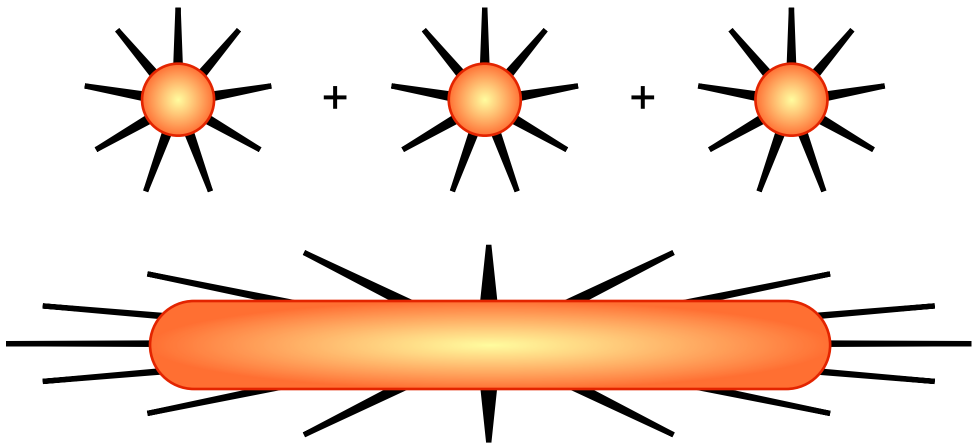
1. Choose $p_{T\min}$ cutoff
   = main tuning parameter
2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton
3. Generate n parton-parton interactions (pQCD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

2: Interleaved Evolution

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

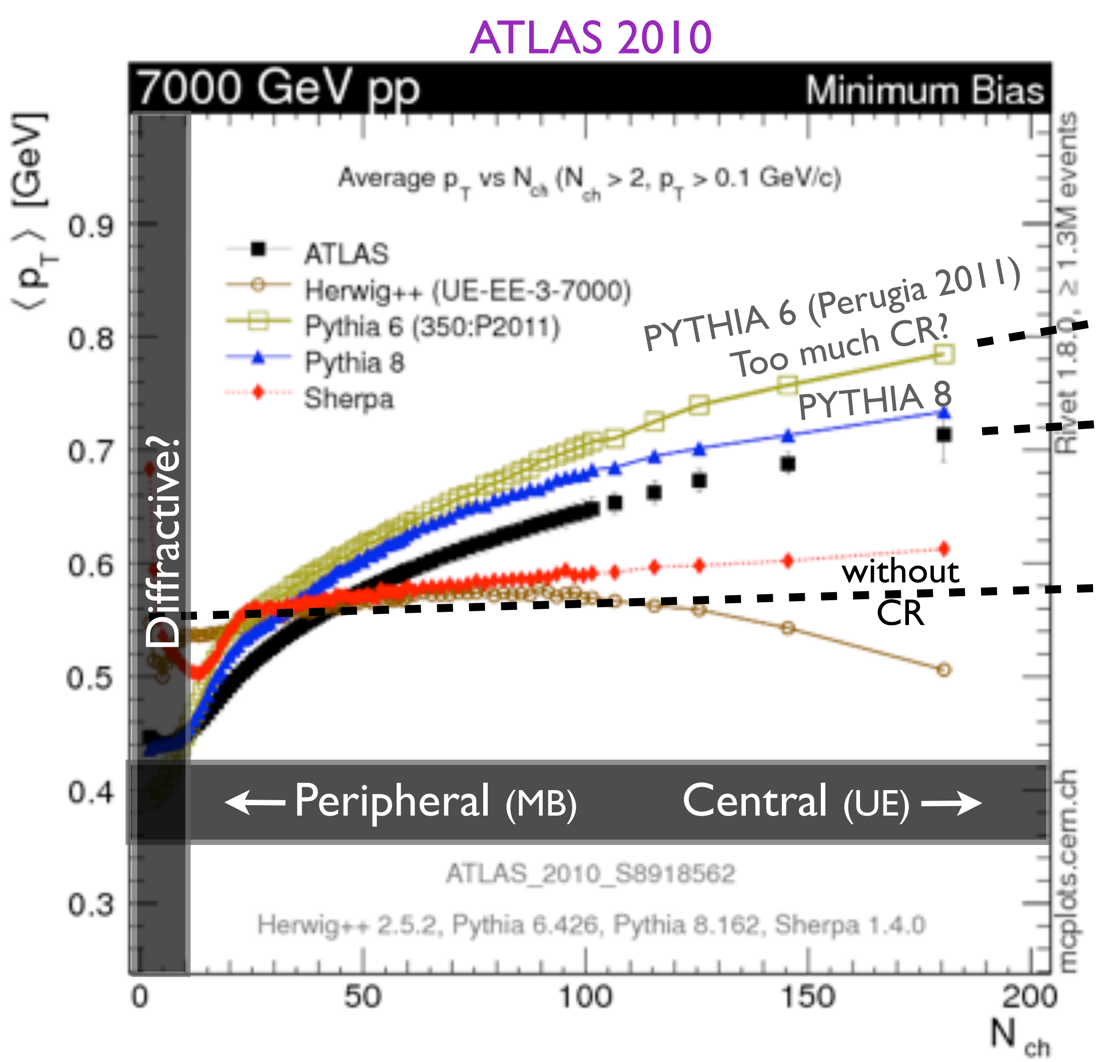


<p_T> vs N_{ch}



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

Correlations / Collective effects:
→ **average rises**



Extrapolation to high multiplicity ~ UE

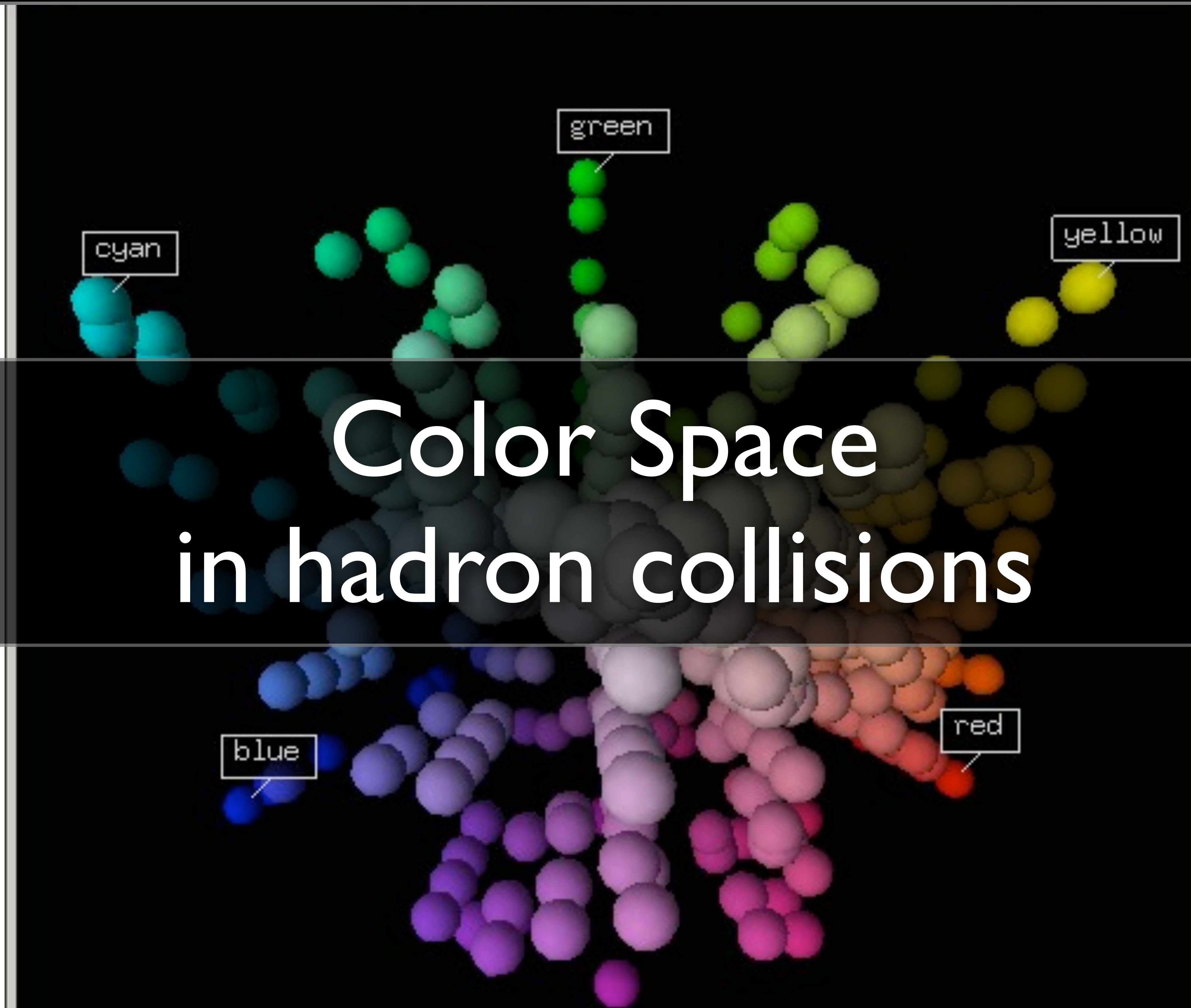
Average particles slightly too hard
→ Too much energy, or energy distributed on too few particles

~ OK?

Average particles slightly too soft
→ Too little energy, or energy distributed on too many particles

Evolution of other distributions with N_{ch} also interesting: e.g., <p_T>(N_{ch}) for identified particles, strangeness & baryon ratios, 2P correlations, …

Color Space
in hadron collisions

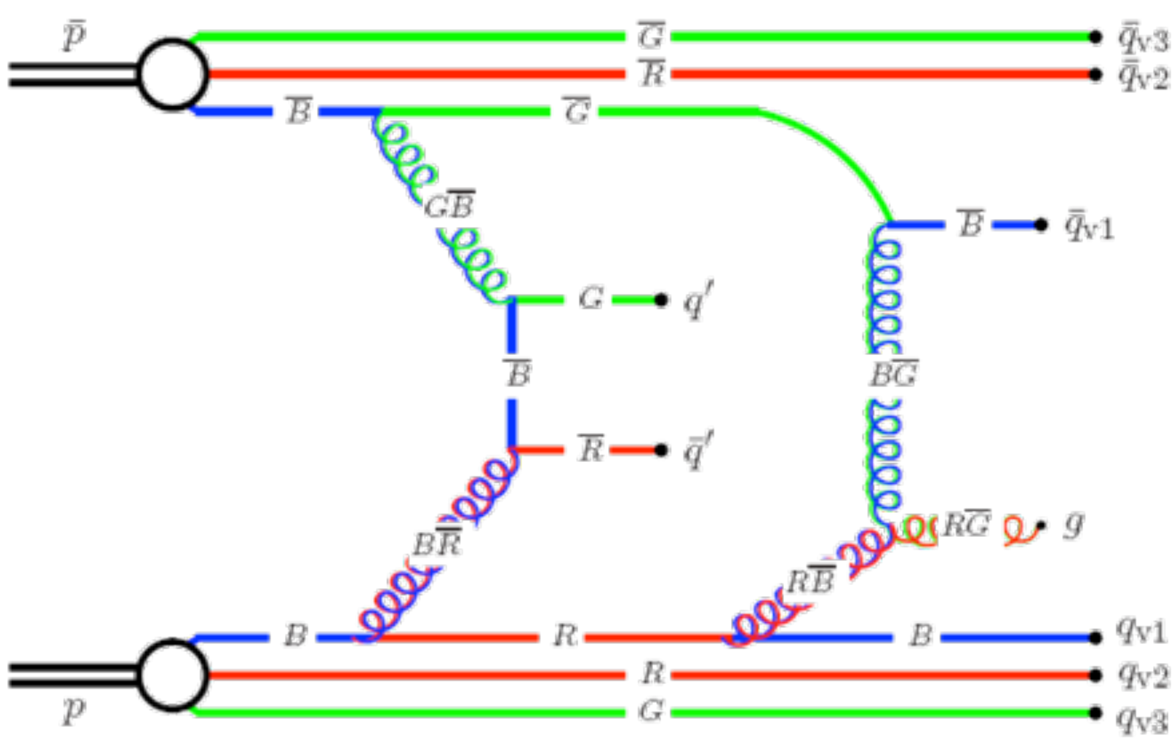


Color Correlations

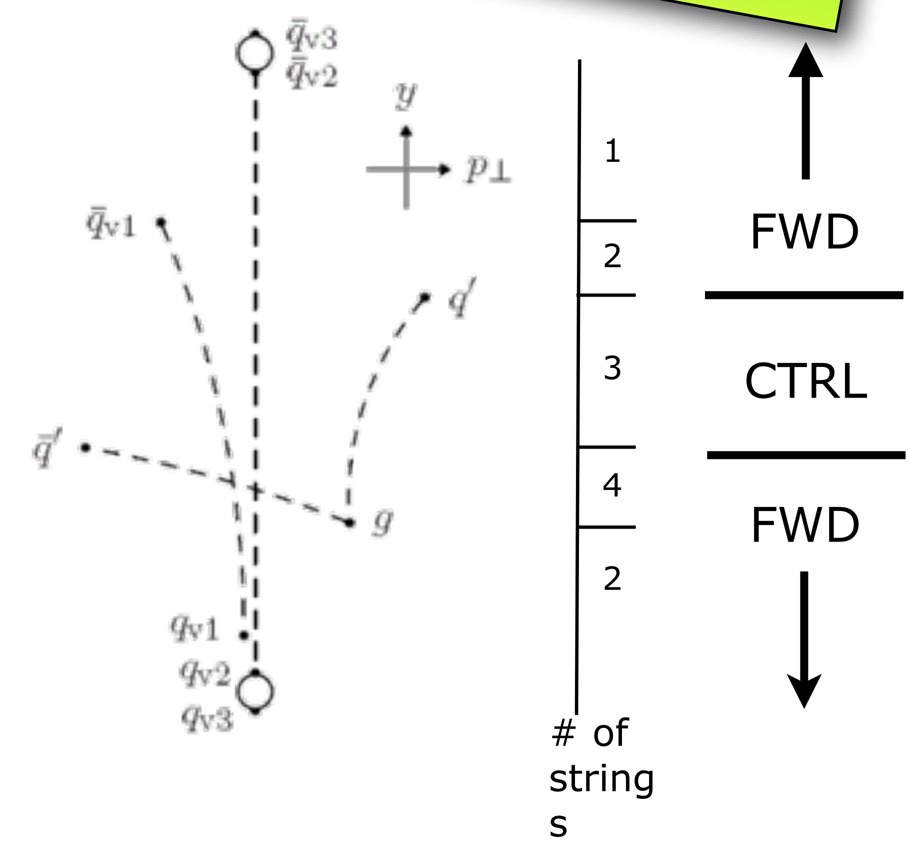
Each MPI (or cut Pomeron) exchanges color between the beams

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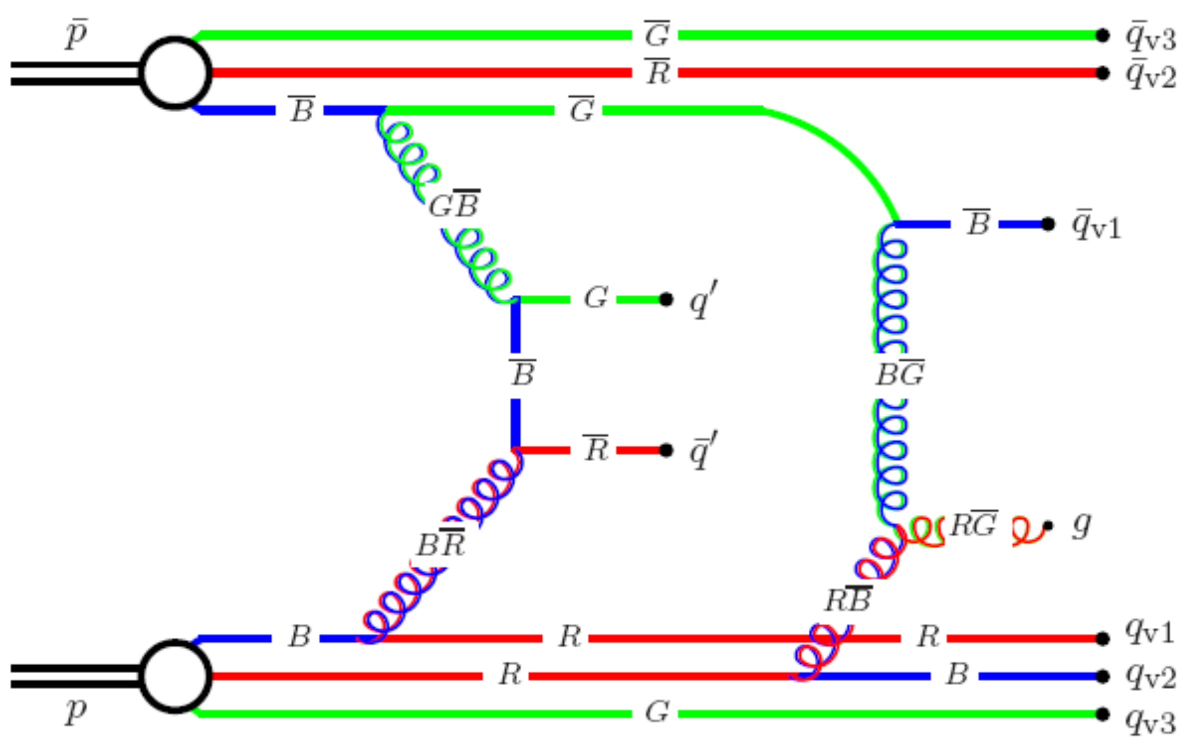
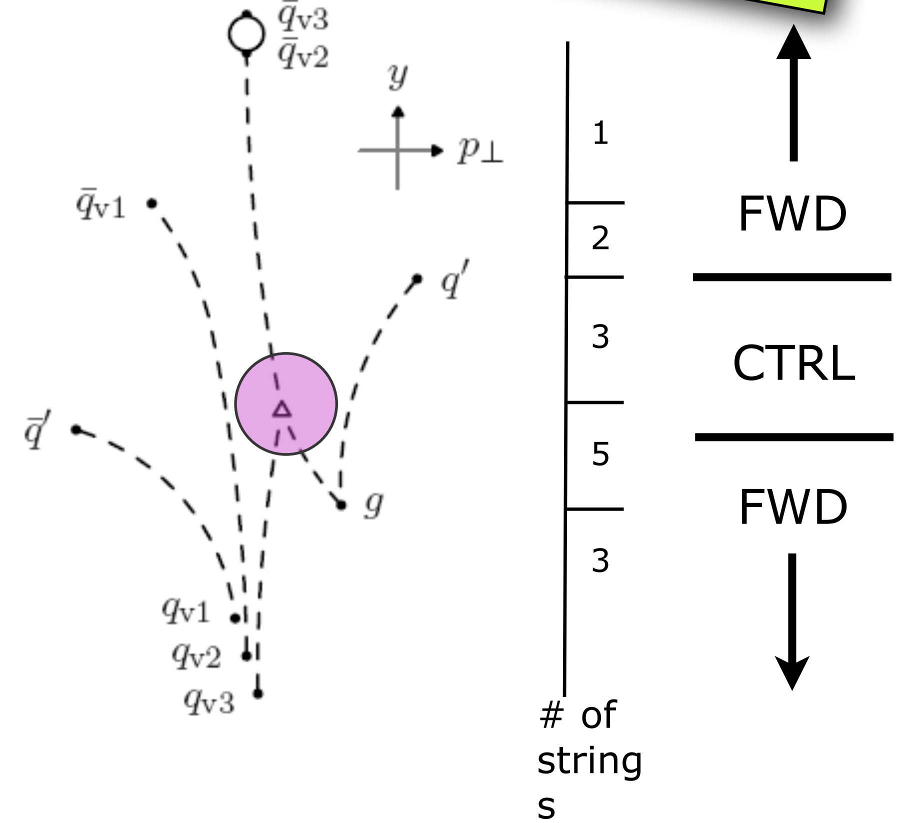
- The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions <u>crucially</u> depend on color space

Different models make different ansätze



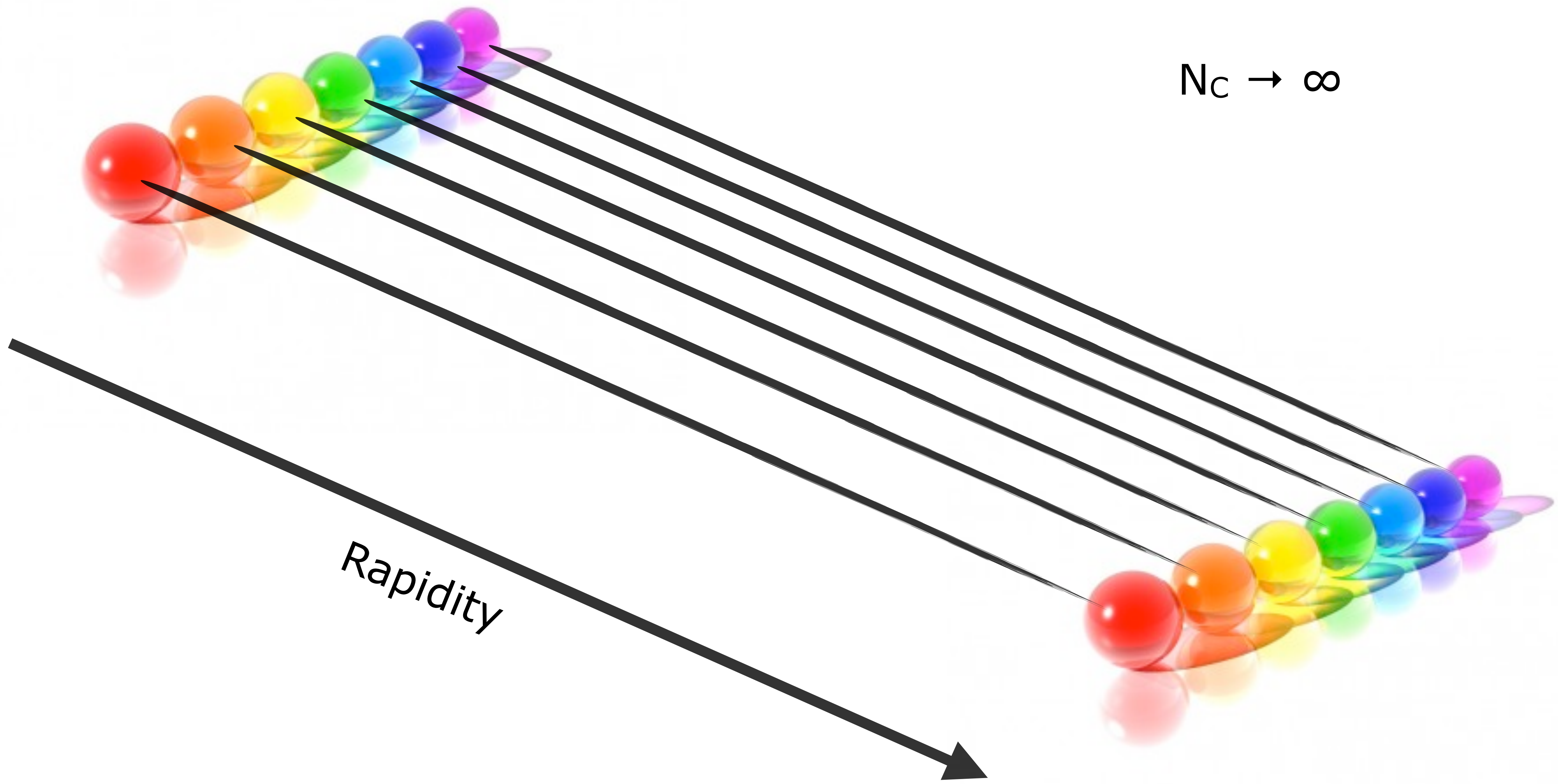
Sjöstrand & PS, JHEP 03(2004)053



Color Connections

Better theory models needed

$N_C \to \infty$



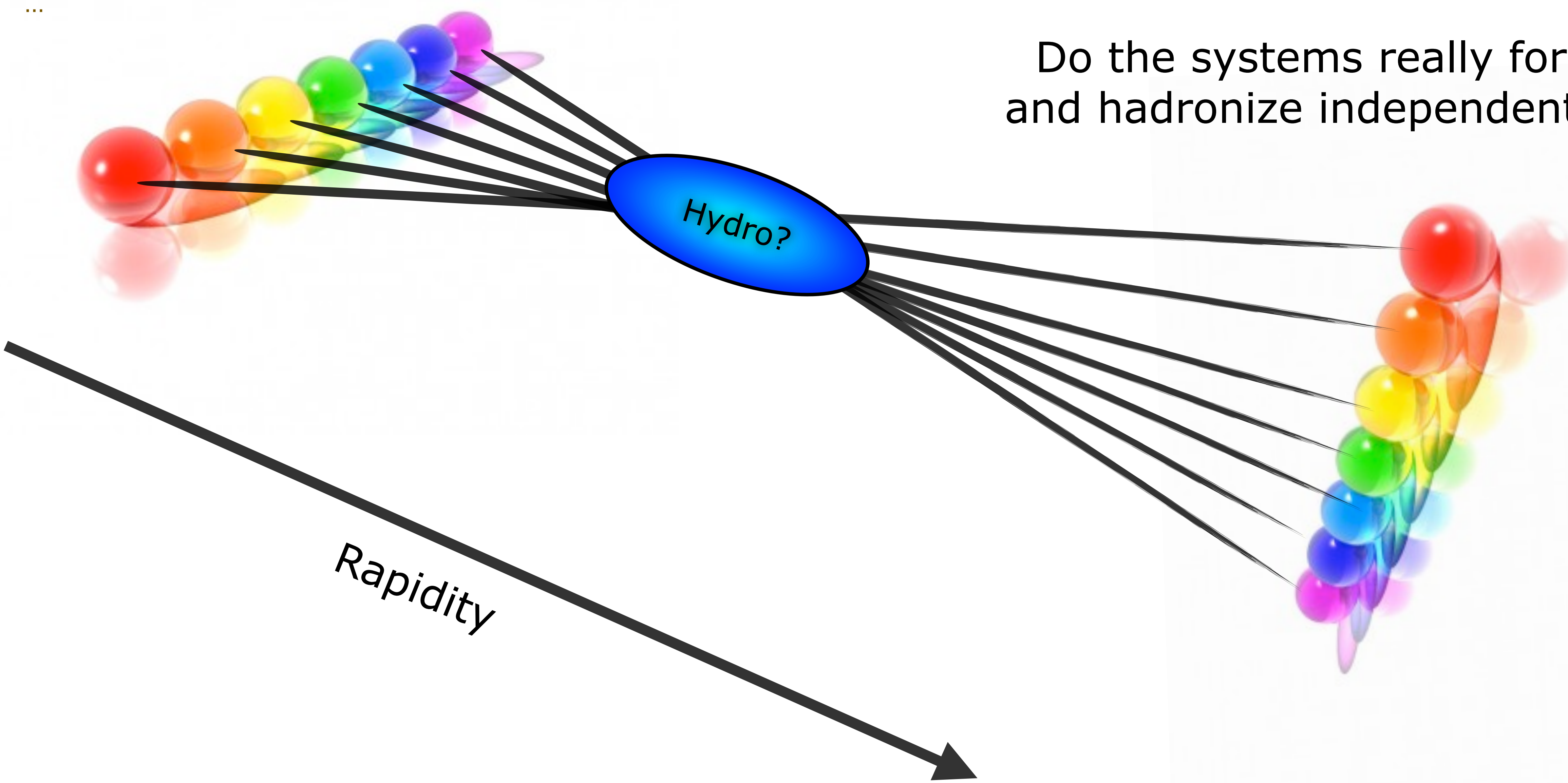
Multiplicity $\propto N_{MPI}$

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

Final Topic: Tuning

Theory

Experiment

Adjust this to agree with this

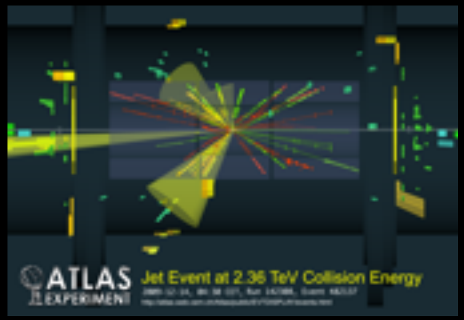
→ Science

In Practice


VINCIA


PYTHIA

...



"Virtual Colliders"
= Simulation Codes

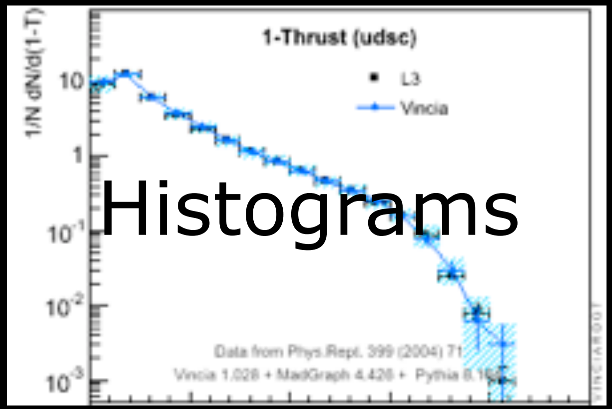
Particle Physics Models, Algorithms, …

→ Simulated Particle Collisions

Real Universe
→ Experiments & Data

Particle Accelerators, Detectors, and Statistical Analyses

→ Published Measurements



What is Tuning?

FSR pQCD Parameters

$\alpha_s(m_Z)$

The value of the strong coupling at the Z pole

Governs overall amount of radiation

α_s Running

Renormalization Scheme and Scale for α_s

1- vs 2-loop running, MSbar / CMW scheme, $\mu_R \sim p_T^2$

Matching

Additional Matrix Elements included?

At tree level / one-loop level? Using what matching scheme?

Subleading Logs

Ordering variable, coherence treatment, effective $1\to3$ (or $2\to4$), recoil strategy, …

Branching Kinematics (z definitions, local vs global momentum conservation), hard parton starting scales / phase-space cutoffs, masses, non-singular terms, …

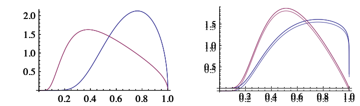
String Tuning

Main String Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function

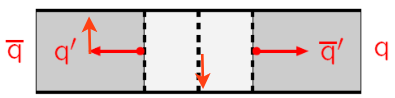
The a and b parameters



pT in string breaks

Scale of string breaking process

IR cutoff and $\langle p_T \rangle$ in string breaks



Meson Multiplets

Mesons

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

Baryon Multiplets

Baryons

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

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

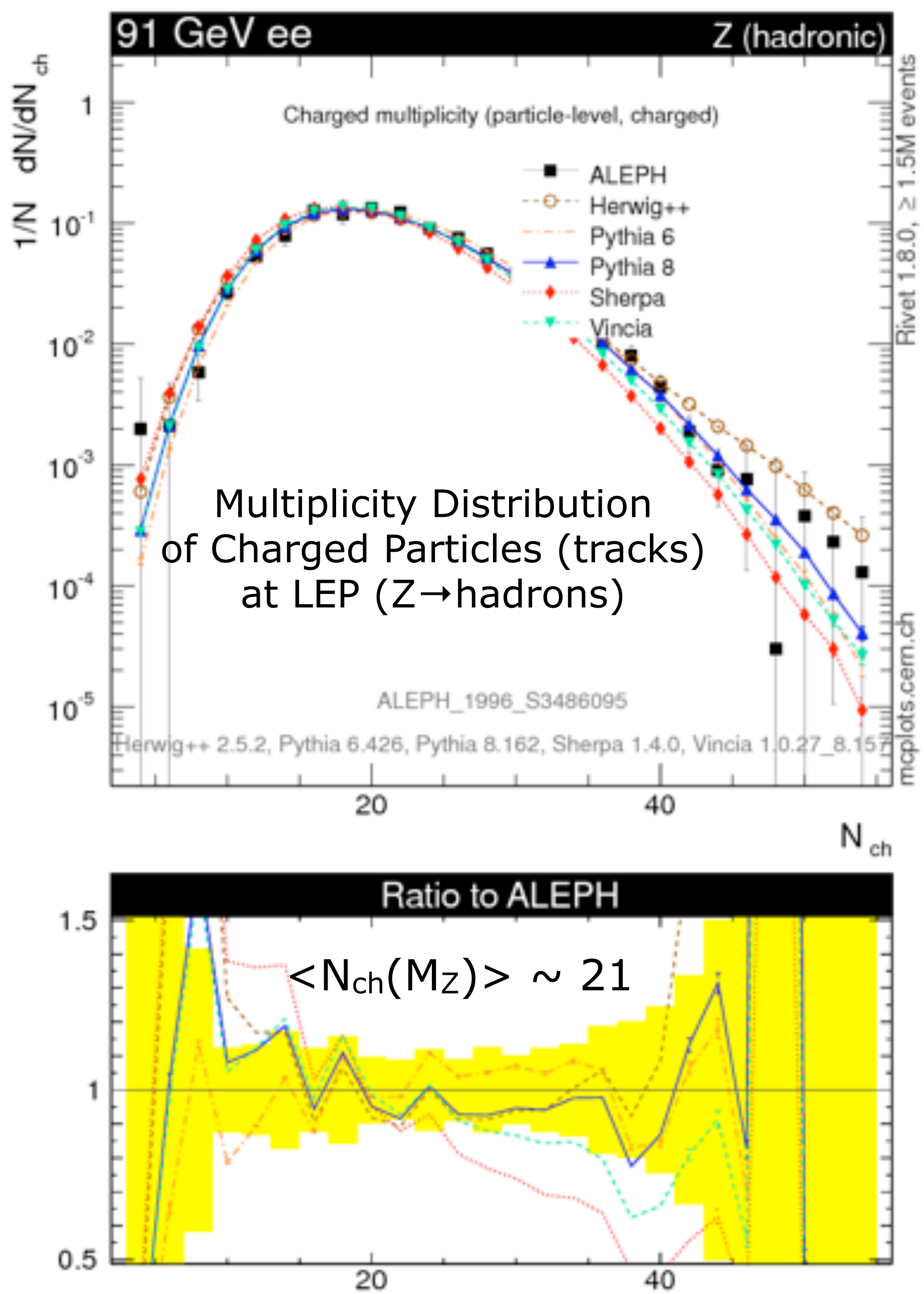
Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions

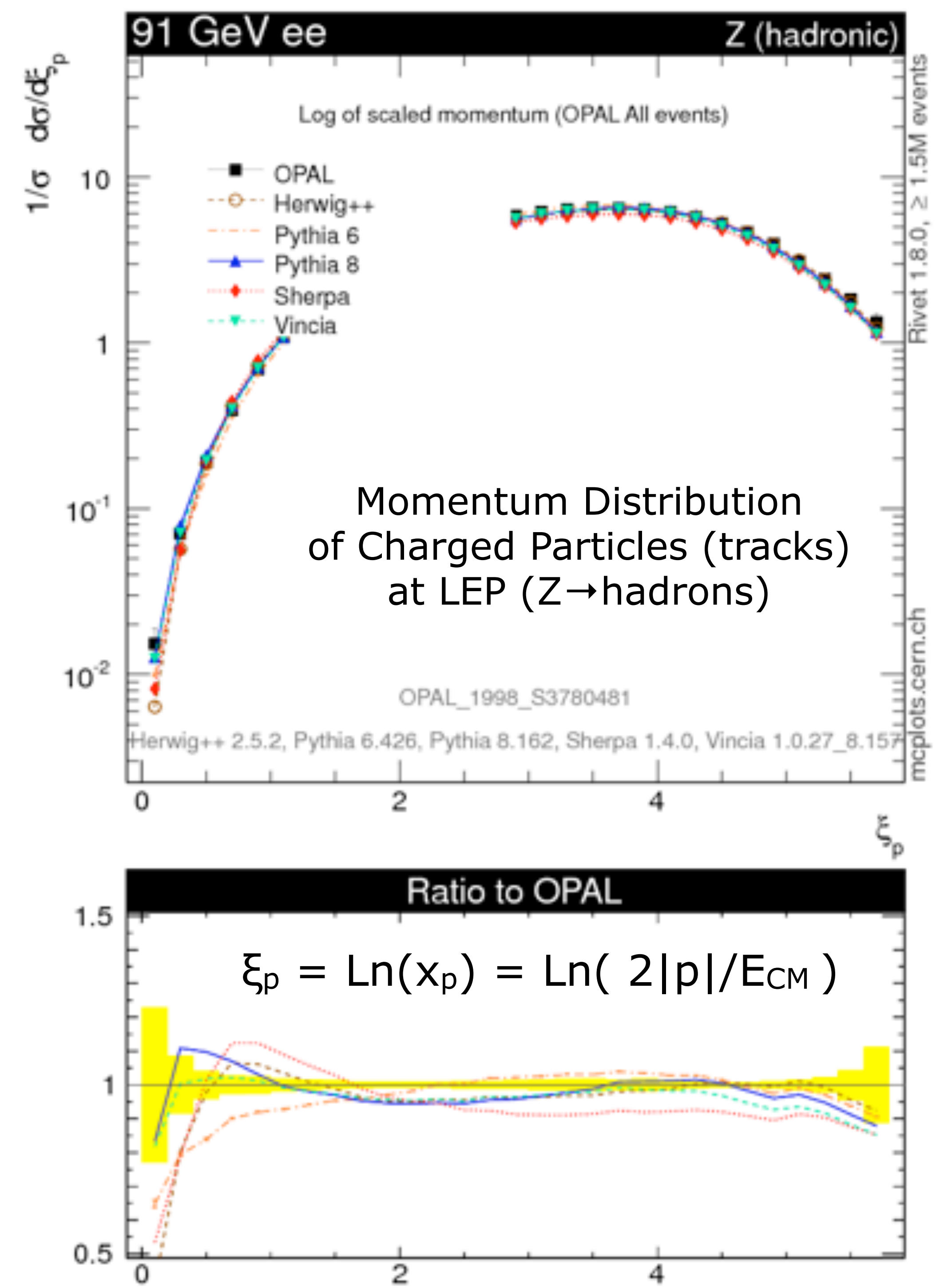
Strings per Interaction

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

Fragmentation Tuning

Note: use infrared-**unsafe** observables - sensitive to hadronization (example)



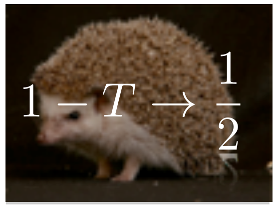


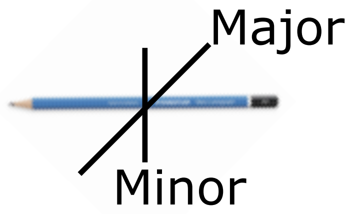
Need IR Corrections?

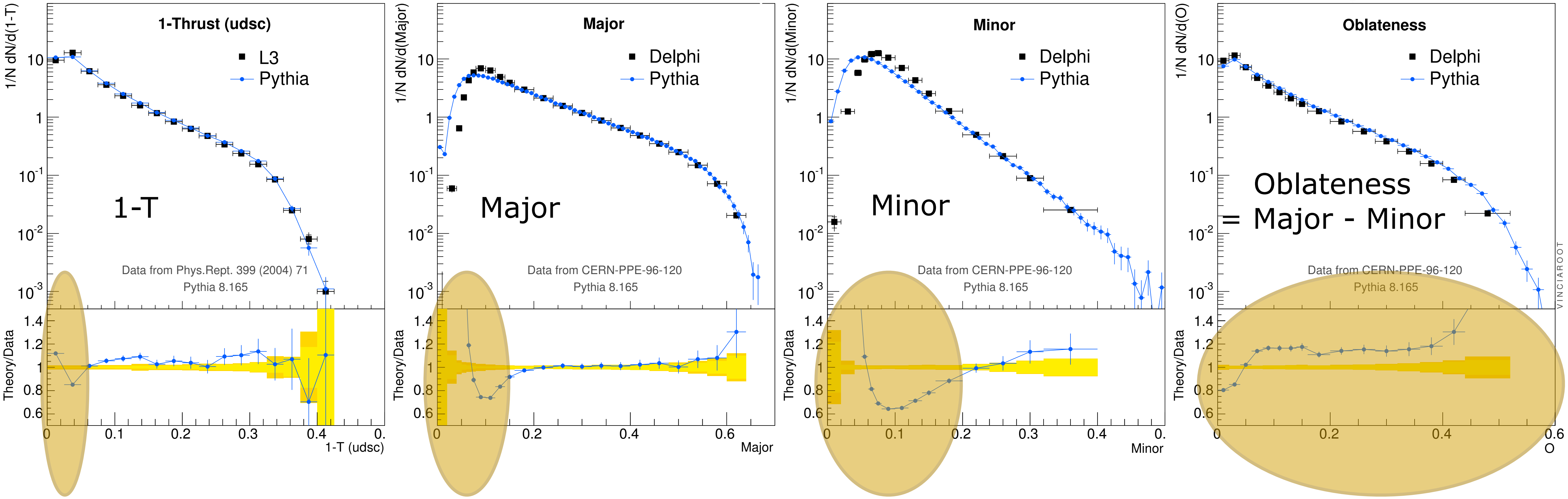
PYTHIA 8 (hadronization off) vs LEP: Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$1 - T \to 0$







Significant Discrepancies (>10%)

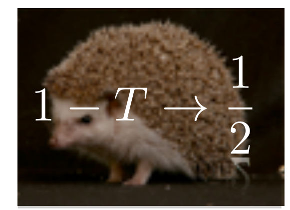
for T < 0.05, Major < 0.15, Minor < 0.2, and for all values of Oblateness

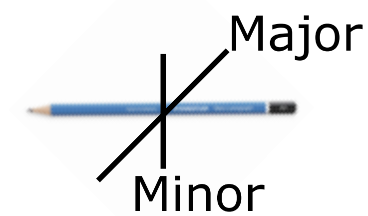
Need IR Corrections?

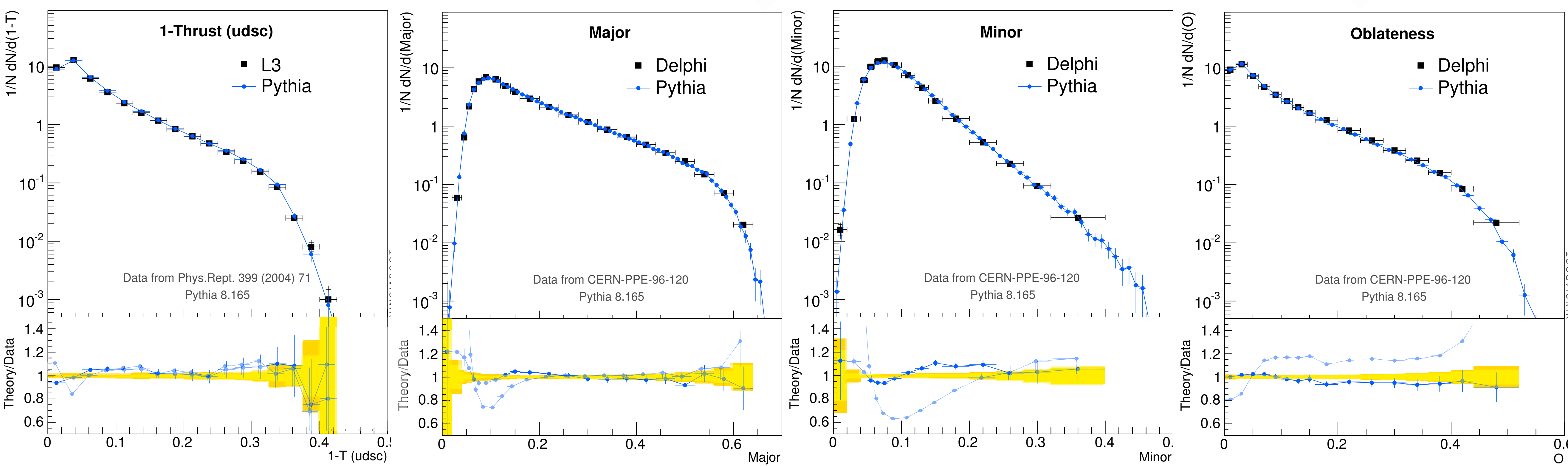
PYTHIA 8 (hadronization on) vs LEP: Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$1 - T \to 0$







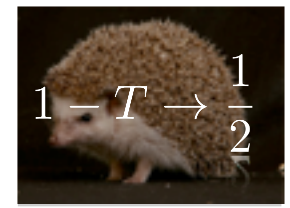
Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.14$

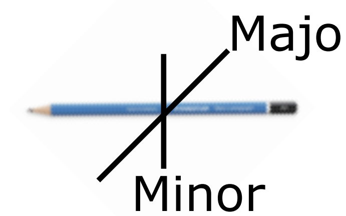
Value of Strong Coupling

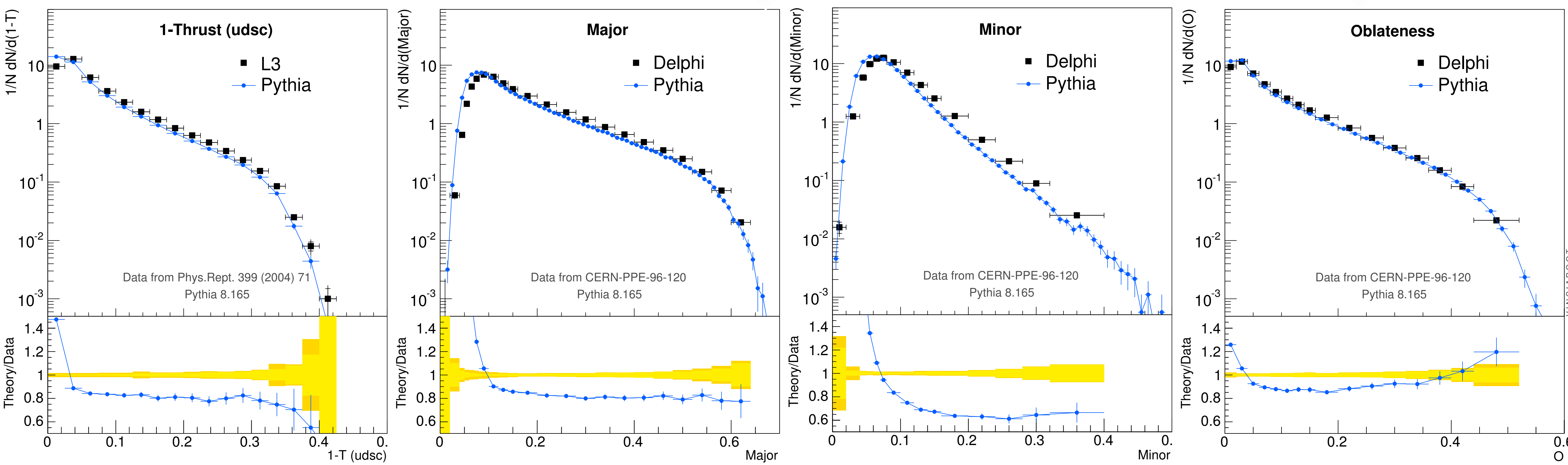
PYTHIA 8 (hadronization on) **vs LEP: Thrust**

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

$$1 - T \to 0$$







Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.12$

Wait … is this Crazy?

Best result

Obtained with $\alpha_s(M_Z) \approx 0.14$

$\neq$ World Average = 0.1176 ± 0.0020

Value of α_s depends on the order and scheme

MC ≈ Leading Order + LL resummation

Other leading-Order extractions of $\alpha_s \approx 0.13$ - 0.14

Effective scheme interpreted as "CMW" → 0.13;

2-loop running → 0.127; NLO → 0.12 ?

Not so crazy

Tune/measure even pQCD parameters with the actual generator.

Sanity check = consistency with other determinations at a similar formal order, within the uncertainty at that order (including a CMW-like scheme redefinition to go to 'MC scheme')

Improve → Matching at LO and NLO

Sneak Preview:

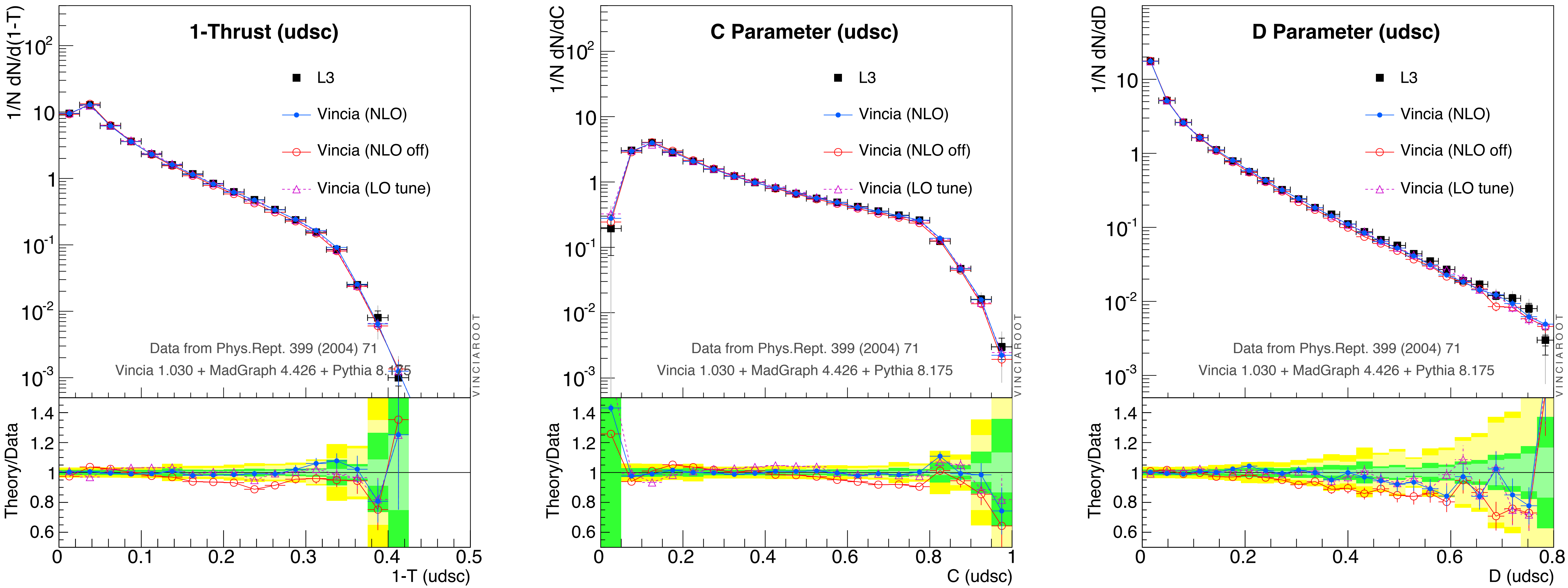
Multijet NLO Corrections with VINCIA

Hartgring, Laenen, Skands, arXiv:1303.4974

First LEP tune with NLO 3-jet corrections

LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)



Summary

(Matching: Hard Wide-Angle Radiation)

Slicing : MLM, CKKW, CKKW-L (but depends on Q_{cut})

Subtraction : MC@NLO (but generates w<0)

ME Corrections : PYTHIA, POWHEG, VINCIA

Next big steps:

Combining multileg NLO corrections with parton showers
It's perturbation theory = we should be able to solve it. Expect this for next run of LHC.
Improving the intrinsic accuracy of showers? NLL, NLC, … ?

Non-perturbative and soft physics

Is still hard. String model remains best bet, but ~ 30 years old by now. Ripe for a revolution?

Multi-parton interactions an extremely active field, with highly interesting connections to collectivity and related physics → stay tuned!

Many things omitted:

Random-number theory, BSM, B Physics, Beam Remnants, Elastic and Diffractive Scattering, Heavy Ions, ...

See also: **1)** MCnet Review (long): Phys.Rept. 504 (2011) 145-233 and/or **2)** PDG Review on Monte Carlo Event Generators, and/or PS, **4)** ESHEP Lectures (short): arXiv:1104.2863

MCnet Studentships

MCnet projects:

- PYTHIA (+ VINCIA)
- HERWIG
- SHERPA
- MadGraph
- Ariadne (+ DIPSY)
- Cedar (Rivet/Professor)

Activities include

- summer schools (2014: Manchester?)
- short-term studentships
- graduate students
- postdocs
- meetings (open/closed)

Monte Carlo

training studentships

3-6 month fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand and improve the Monte Carlos you use!

Application rounds every 3 months.

MCnet

funded by: MARIE CURIE ACTIONS

for details go to: **www.montecarlonet.org**

Come to Australia

Establishing a new group in **Melbourne**

Working on **PYTHIA** & **VINCIA**

NLO Event Generators

Precision LHC **phenomenology & soft physics**

Support LHC **experiments**, **astro-particle** community, and **future** accelerators

Outreach and Citizen Science

Oct 2014
→ Monash University
Melbourne, Australia