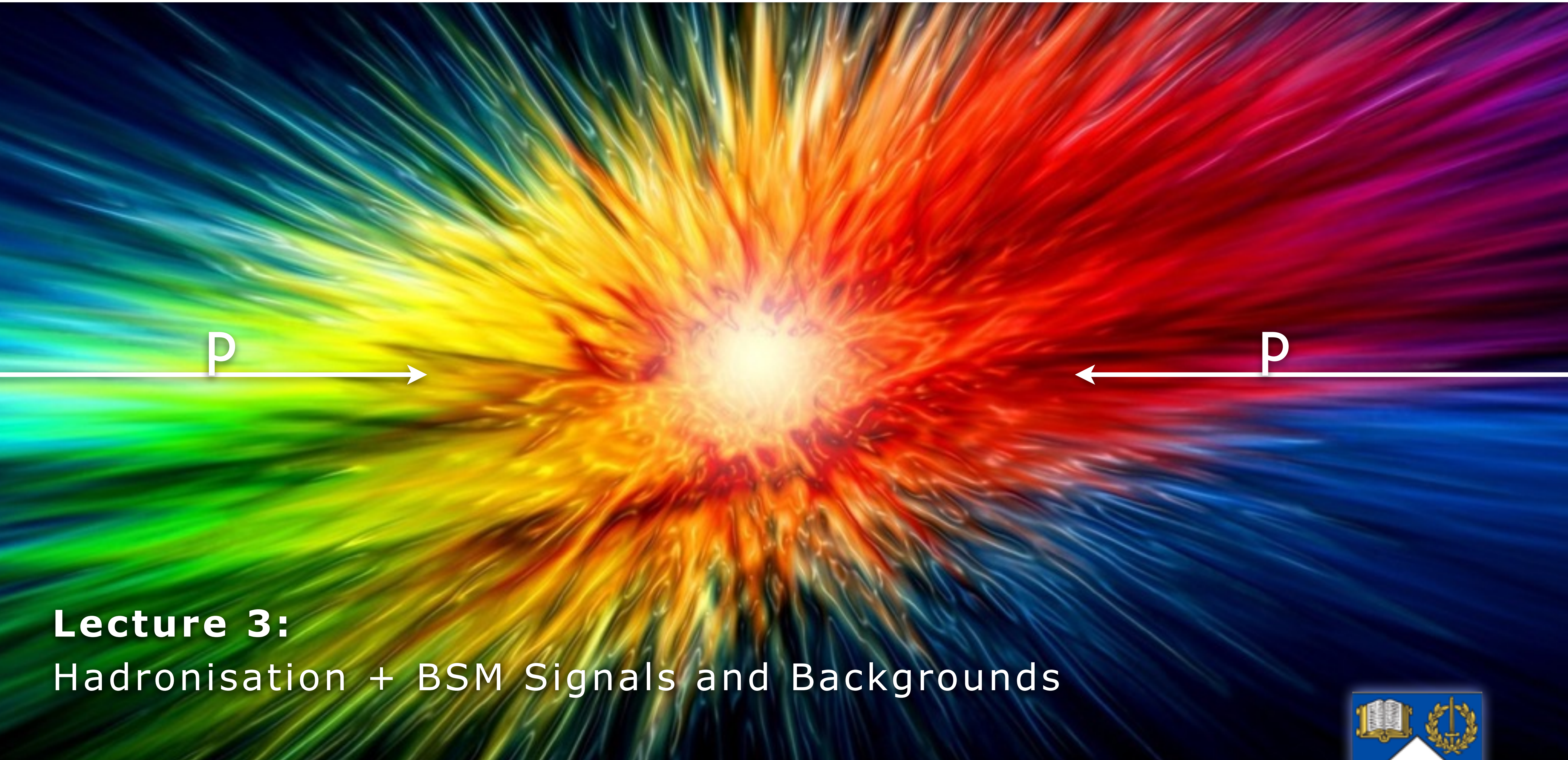
Monte Carlos and New Physics

Peter Skands (Monash University)



Lecture 3:

Hadronisation + BSM Signals and Backgrounds

Pre-SUSY - June 2016

Lecture Notes: P. Skands, arXiv:1207.2389

Monte Carlos & Fragmentation

PYTHIA anno 1978

(then called JETSET)

LU TP 78-18
November, 1978

A Monte Carlo Program for Quark Jet Generation

T. Sjöstrand, B. Söderberg

A Monte Carlo computer program is presented, that simulates the **fragmentation of a fast parton into a jet of mesons.** It uses an iterative scaling scheme and is compatible with the jet model of Field and Feynman.

```
      SUBROUTINE JETGEN(N)
      COMMON /JET/ K(100,2), P(100,5)
      COMMON /PAR/ PUD, PS1, SIGMA, CX2, EBEG, WFIN, IFLBEG
      COMMON /DATA1/ MESO(9,2), CMIX(6,2), PMAS(19)
      IFLSGN=(10-IFLBEG)/5
      W=2.*EBEG
      I=0
      IPD=0
C 1 FLAVOUR AND PT FOR FIRST QUARK
      IFL1=IABS(IFLBEG)
      PT1=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI1=6.2832*RANF(0)
      PX1=PT1*COS(PHI1)
      PY1=PT1*SIN(PHI1)
  100 I=I+1
C 2 FLAVOUR AND PT FOR NEXT ANTIQUARK
      IFL2=1+INT(RANF(0)/PUD)
      PT2=SIGMA*SQRT(-ALOG(RANF(0)))
      PHI2=6.2832*RANF(0)
      PX2=PT2*COS(PHI2)
      PY2=PT2*SIN(PHI2)
C 3 MESON FORMED, SPIN ADDED AND FLAVOUR MIXED
      K(I,1)=MESO(3*(IFL1-1)+IFL2,IFLSGN)
      ISPIN=INT(PS1+RANF(0))
      K(I,2)=1+9*ISPIN+K(I,1)
      IF(K(I,1).LE.6) GOTO 110
      TMIX=RANF(0)
      KM=K(I,1)-6+3*ISPIN
      K(I,2)=8+9*ISPIN+INT(TMIX+CMIX(KM,1))+INT(TMIX+CMIX(KM,2))
C 4 MESON MASS FROM TABLE, PT FROM CONSTITUENTS
  110 P(I,5)=PMAS(K(I,2))
      P(I,1)=PX1+PX2
      P(I,2)=PY1+PY2
      PMTS=P(I,1)**2+P(I,2)**2+P(I,5)**2
C 5 RANDOM CHOICE OF X=(E+PZ)MESON/(E+PZ)AVAILABLE GIVES E AND PZ
      X=RANF(0)
      IF(RANF(0).LT.CX2) X=1.-X**(1./3.)
      P(I,3)=(X*W-PMTS/(X*W))/2.
      P(I,4)=(X*W+PMTS/(X*W))/2.
C 6 IF UNSTABLE, DECAY CHAIN INTO STABLE PARTICLES
  120 IPD=IPD+1
      IF(K(IPD,2).GE.8) CALL DECAY(IPD,I)
      IF(IPD.LT.I.AND.I.LE.96) GOTO 120
C 7 FLAVOUR AND PT OF QUARK FORMED IN PAIR WITH ANTIQUARK ABOVE
      IFL1=IFL2
      PX1=-PX2
      PY1=-PY2
C 8 IF ENOUGH E+PZ LEFT, GO TO 2
      W=(1.-X)*W
      IF(W.GT.WFIN.AND.I.LE.95) GOTO 100
      N=I
      RETURN
      END
```

Note:
Field-Feynman was an early fragmentation model
Now superseded by the String (in PYTHIA) and Cluster (in HERWIG & SHERPA) models.

Fast-Forward ~ 40 Years

PYTHIA anno 2016

(now called PYTHIA 8)

CPC 191 (2015) p.159-177
October, 2014

An Introduction to PYTHIA 8.2

T. Sjöstrand et al. (10 authors)

The Pythia program is a standard tool for the generation of events in high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multiparticle final state. It contains a library of hard processes, models for initial- and final-state parton showers, matching and merging methods between hard processes and parton showers, multiparton interactions, beam remnants, string fragmentation and particle decays. It also has a set of utilities and several interfaces …

~ 100,000 lines of C++

What a modern MC generator has inside:

- Hard Processes (internal, interfaced, or via Les Houches events)
- BSM (internal or via interfaces)
- PDFs (internal or via interfaces)
- Showers (internal or inherited)
- Multiple parton interactions
- Beam Remnants
- String Fragmentation
- Decays (internal or via interfaces)
- Examples and Tutorial
- Online HTML / PHP Manual
- Utilities and interfaces to external programs

The Main Workhorses

PYTHIA (begun 1978)

Originated in hadronisation studies: Lund String model

Still special emphasis on soft physics

HERWIG (begun 1984)

Originated in coherence studies: angular-ordered showers

Cluster hadronisation as simple complement

SHERPA (begun ~2000)

Originated in "matching" of matrix elements to showers (CKKW-L), with own internal matrix-element generator(s)

+ Many more specialised:

Matrix-Element Generators, Matching/Merging Packages
Soft-QCD, Cosmic-Ray, and Heavy-Ion Generators
(BSM) Model Generators, Decay Packages, Alternative QCD showers, …

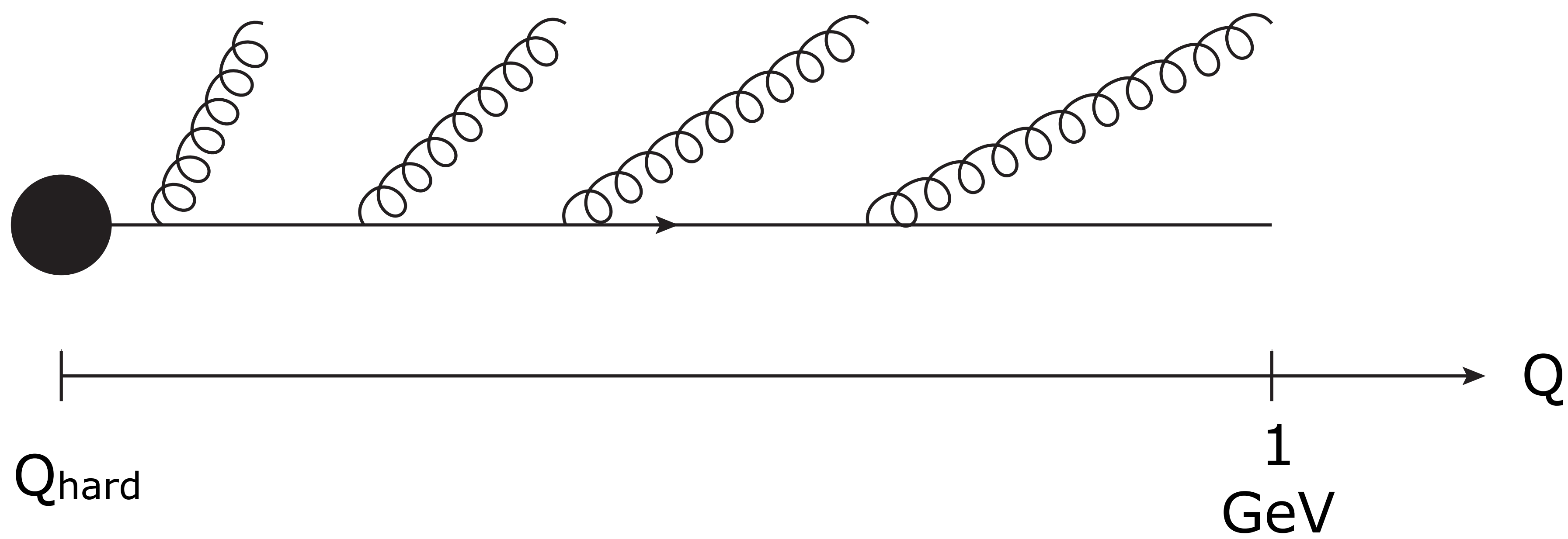
From Partons to Pions

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



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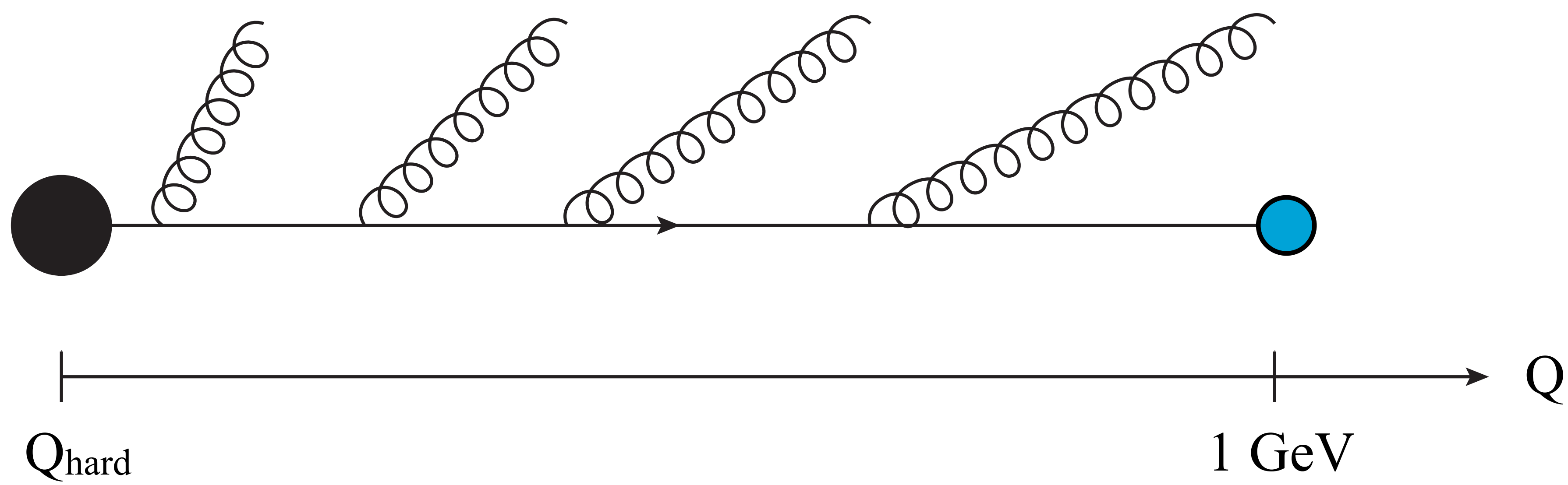


How about I just call it a hadron?

→ "Local Parton-Hadron Duality"

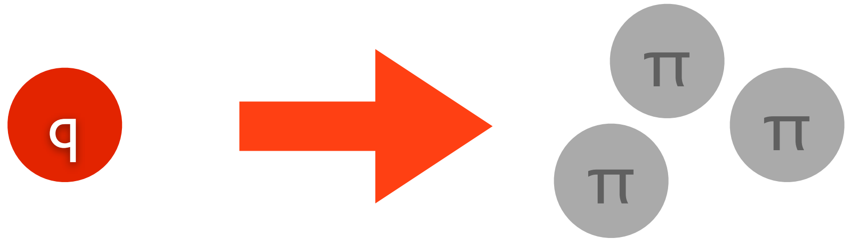
Parton → Hadrons?

Early models: "Independent Fragmentation"

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

Motivates a simple model:

"Independent Fragmentation"



But …

The point of confinement is that partons are coloured

Hadronisation = the process of **colour neutralisation**

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

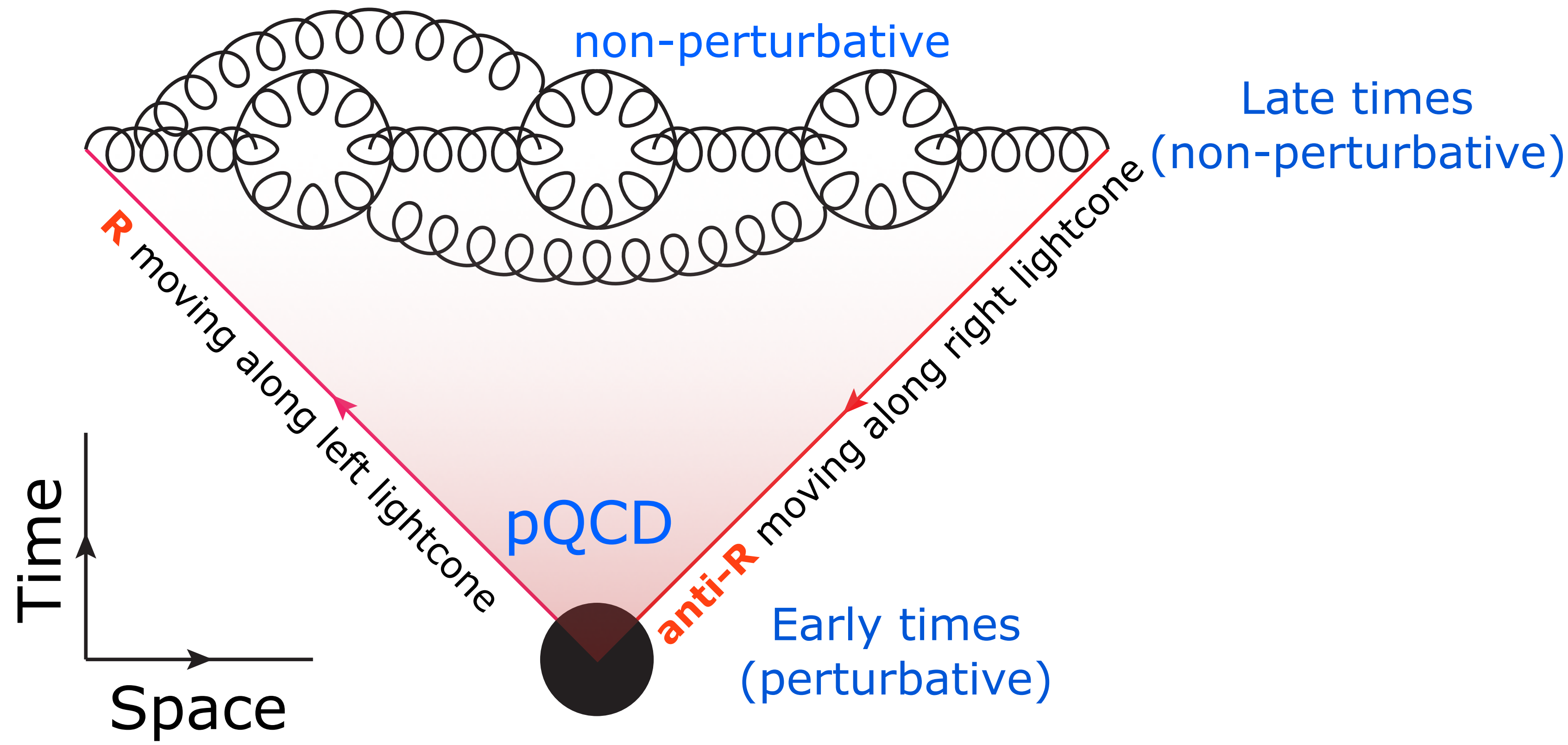
→ Too naive to see LPHD (inclusive) as a justification for Independent Fragmentation (exclusive)

→ More physics needed

Colour Neutralisation

A physical hadronization model

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



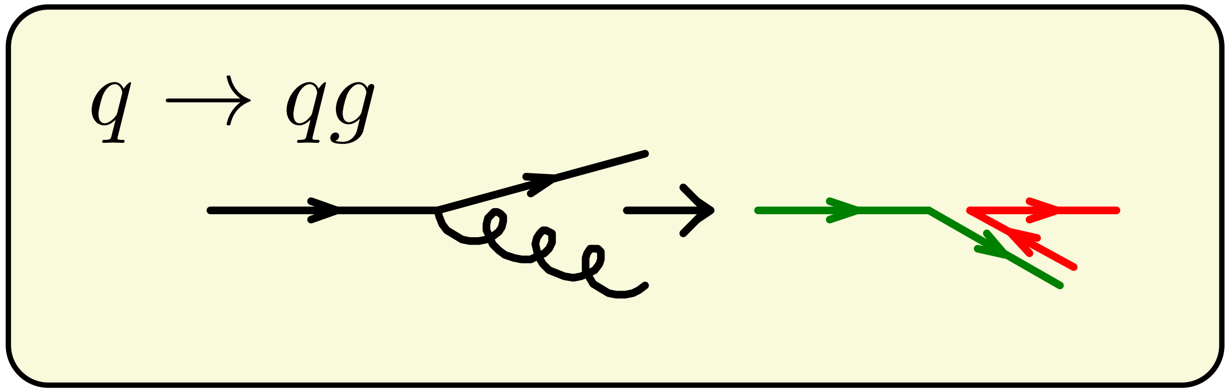
Strong "confining" field emerges between the two charges when their separation > ~ 1fm

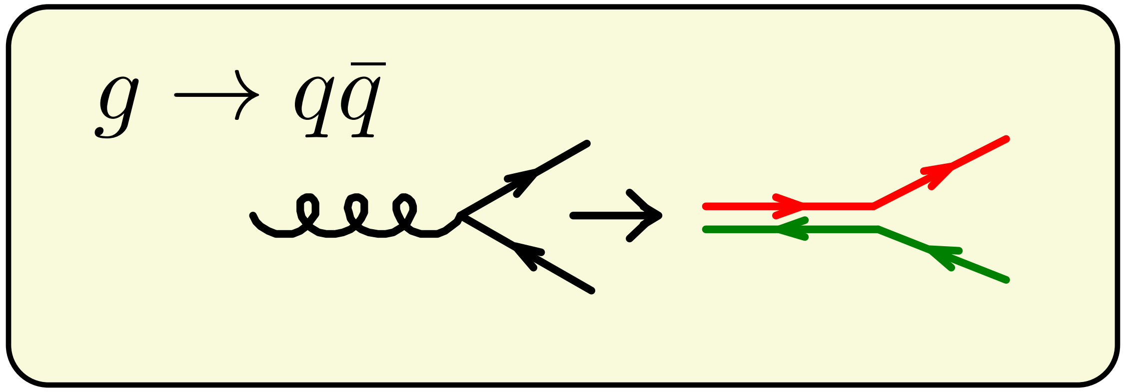
Which Charges? Colour Flow

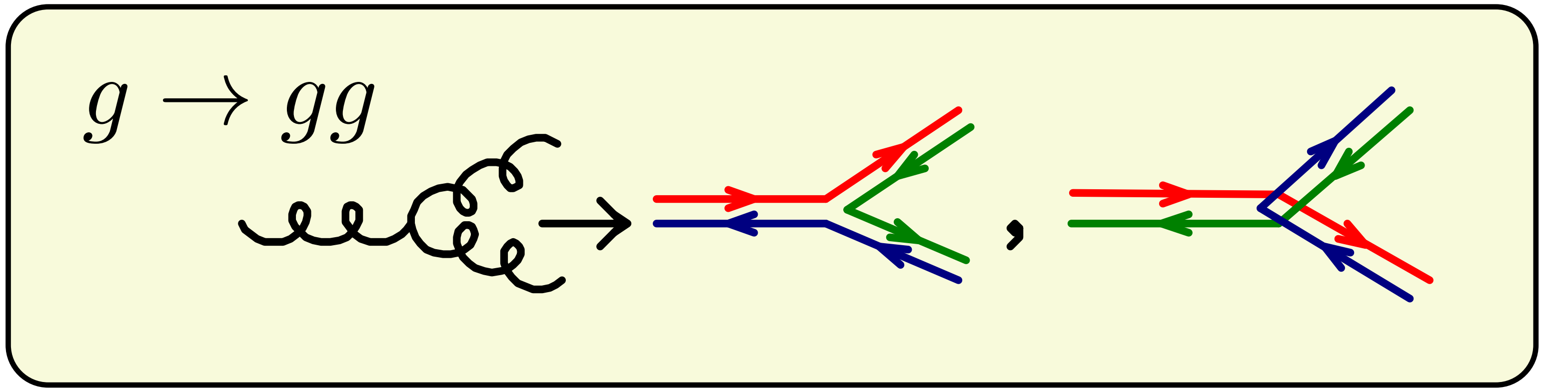
After the parton shower finishes, there can be lots of partons, $\mathcal{O}$(10-100). The main question is therefore:

Between which partons do confining potentials arise?

MC generators use a simple set of rules for color flow, based on large-N_C limit (valid to ~ $1/N_C^2$ ~ 10%)





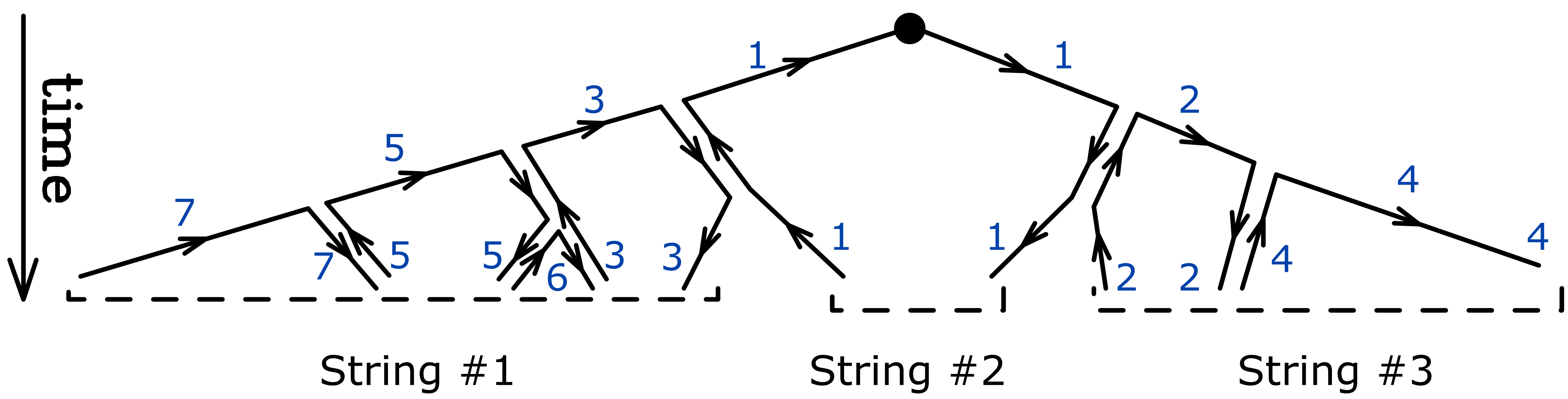


Illustrations from: Nason & Skands, PDG Review on *MC Event Generators*, 2014

Color Flow

For an entire Cascade

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



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

(LEP measurements in $e^+e^- \to W^+W^- \to$ hadrons confirm this (at least to order 10% ~ $1/N_c^2$))

Note: (much) more color getting kicked around in hadron collisions.
Signs that LC approximation is breaking down?
see, e.g., Christiansen, Skands JHEP 1508 (2015) 003

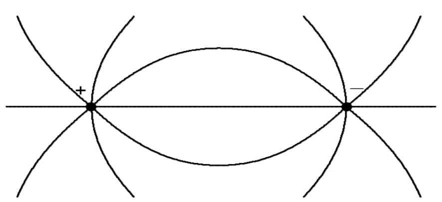
The Ultimate Limit: Wavelengths > 10^{-15} m

Quark-Antiquark Potential

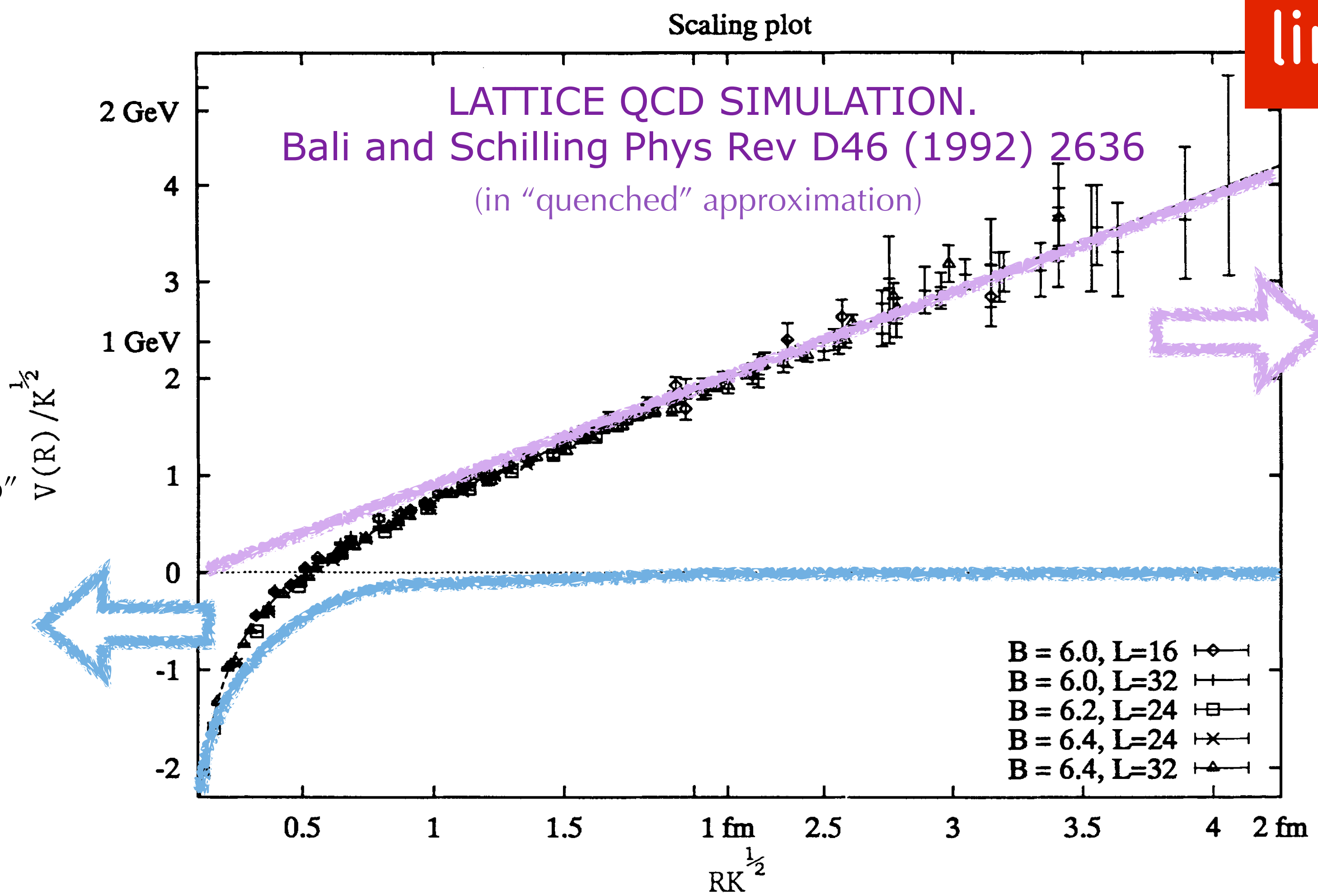
As function of separation distance

What physical system has a linear potential?

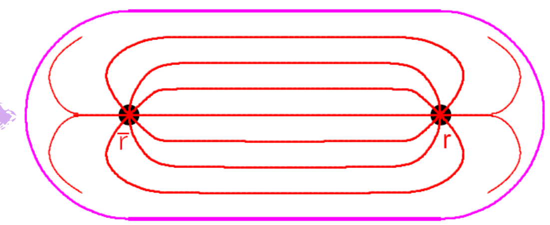
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



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

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

~ Force required to lift a 16-ton truck

From Partons to Strings

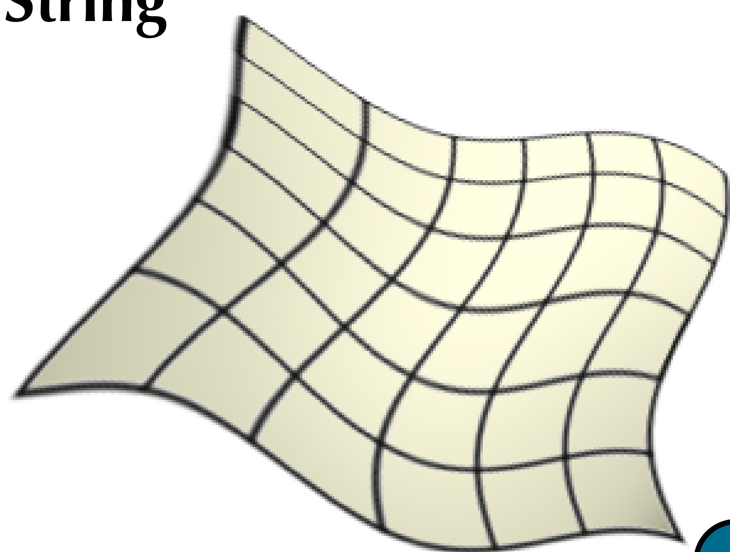
<u>Pedagogical Review:</u> B. Andersson, *The Lund model.* Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol., 1997.

Motivates a model:

Let color field collapse into a (infinitely) narrow flux tube of uniform energy density κ ~ 1 GeV / fm

→ Relativistic 1+1 dimensional worldsheet

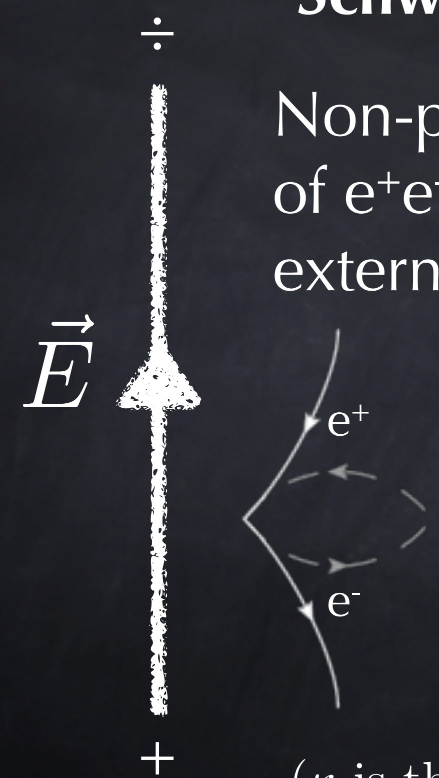
String



In “unquenched” QCD

g→qq → The strings will break

Schwinger Effect



Non-perturbative creation of e^+e^- pairs in a strong external Electric field

Probability from Tunneling Factor

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

(κ is the string tension equivalent)

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

(Note on 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 :

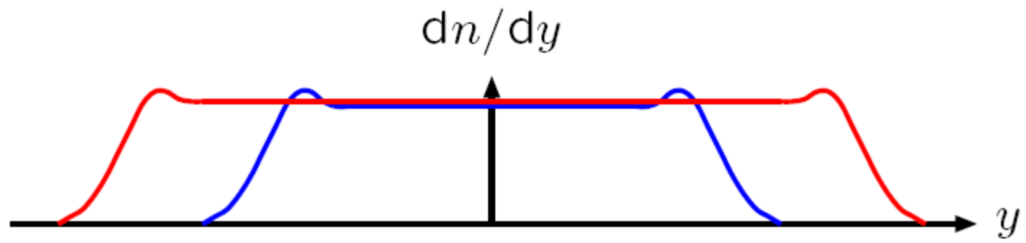
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right)$$

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 $q\bar{q}$ system along z axis) implies flat central rapidity plateau + some endpoint effects:

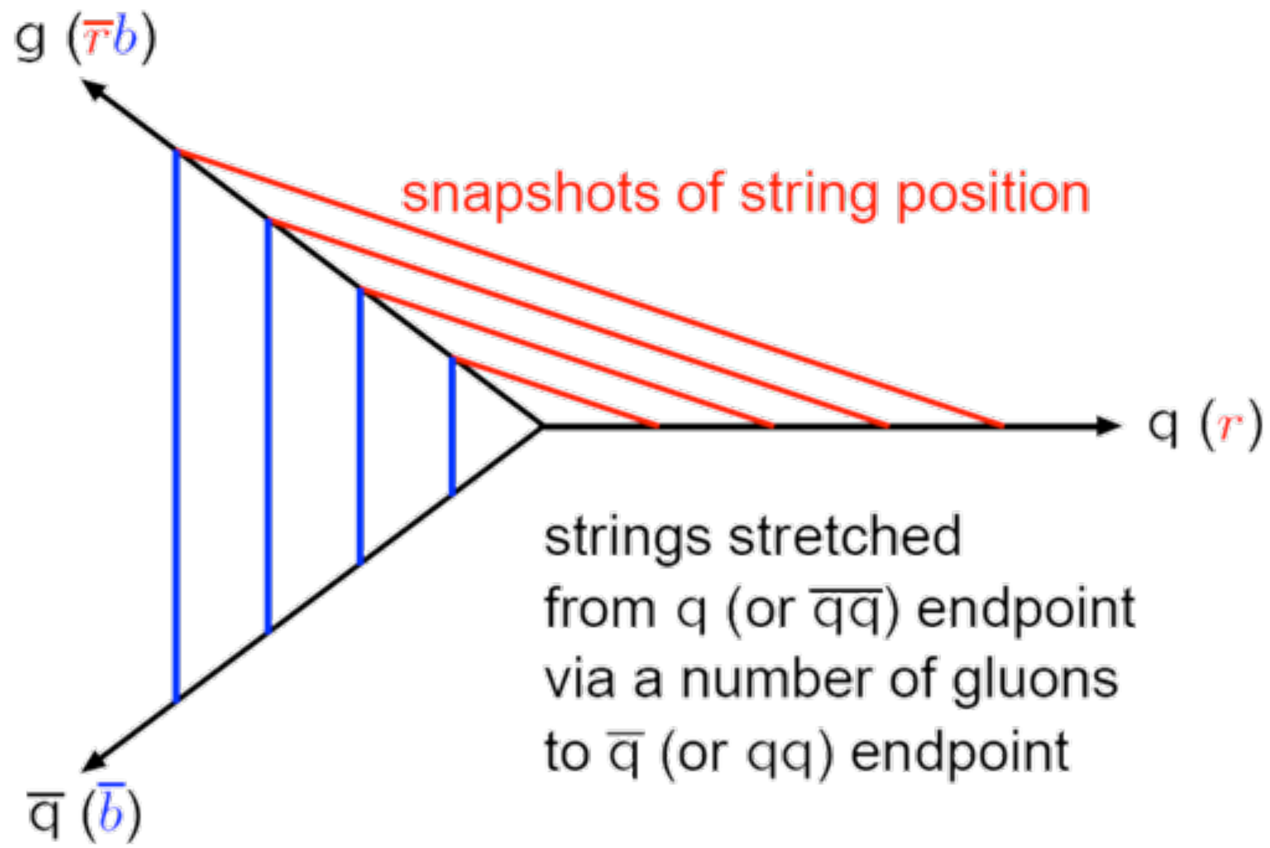


$\langle n_{\mathrm{ch}}\rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, ~ Poissonian multiplicity distribution

The (Lund) String Model

Map:

- **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**



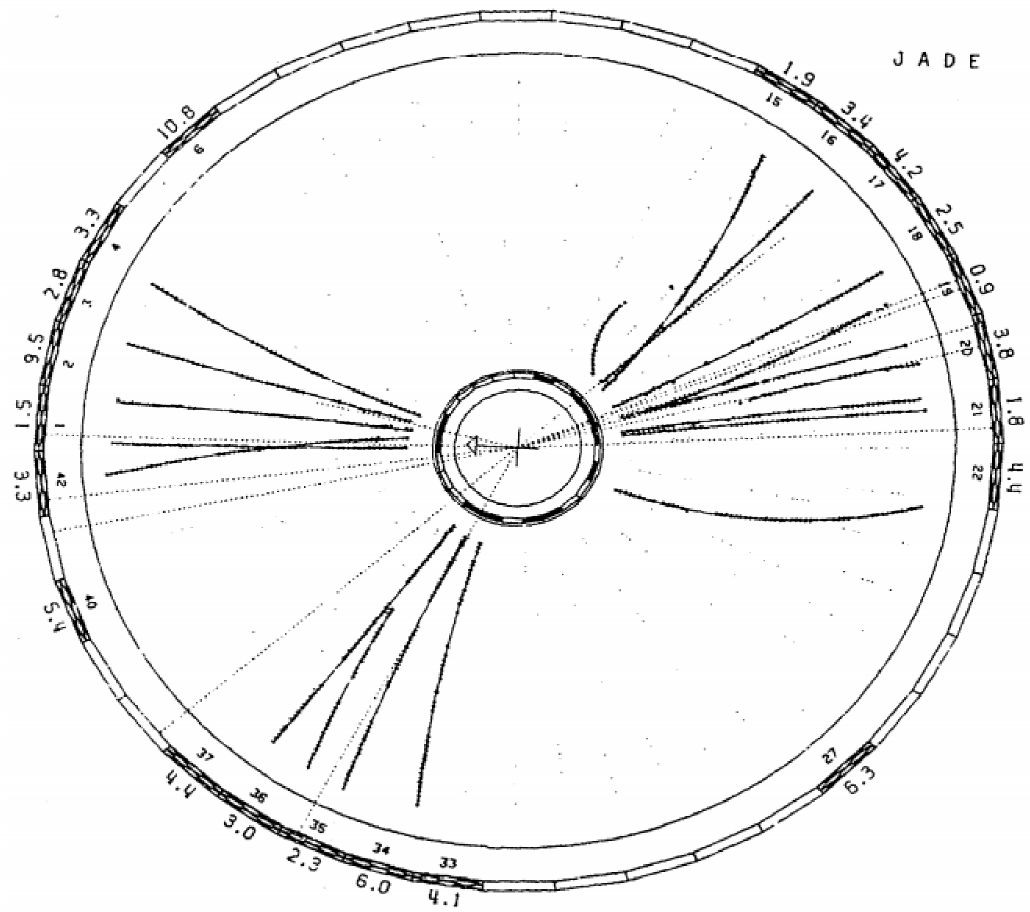
Gluon = kink on string, carrying energy and momentum

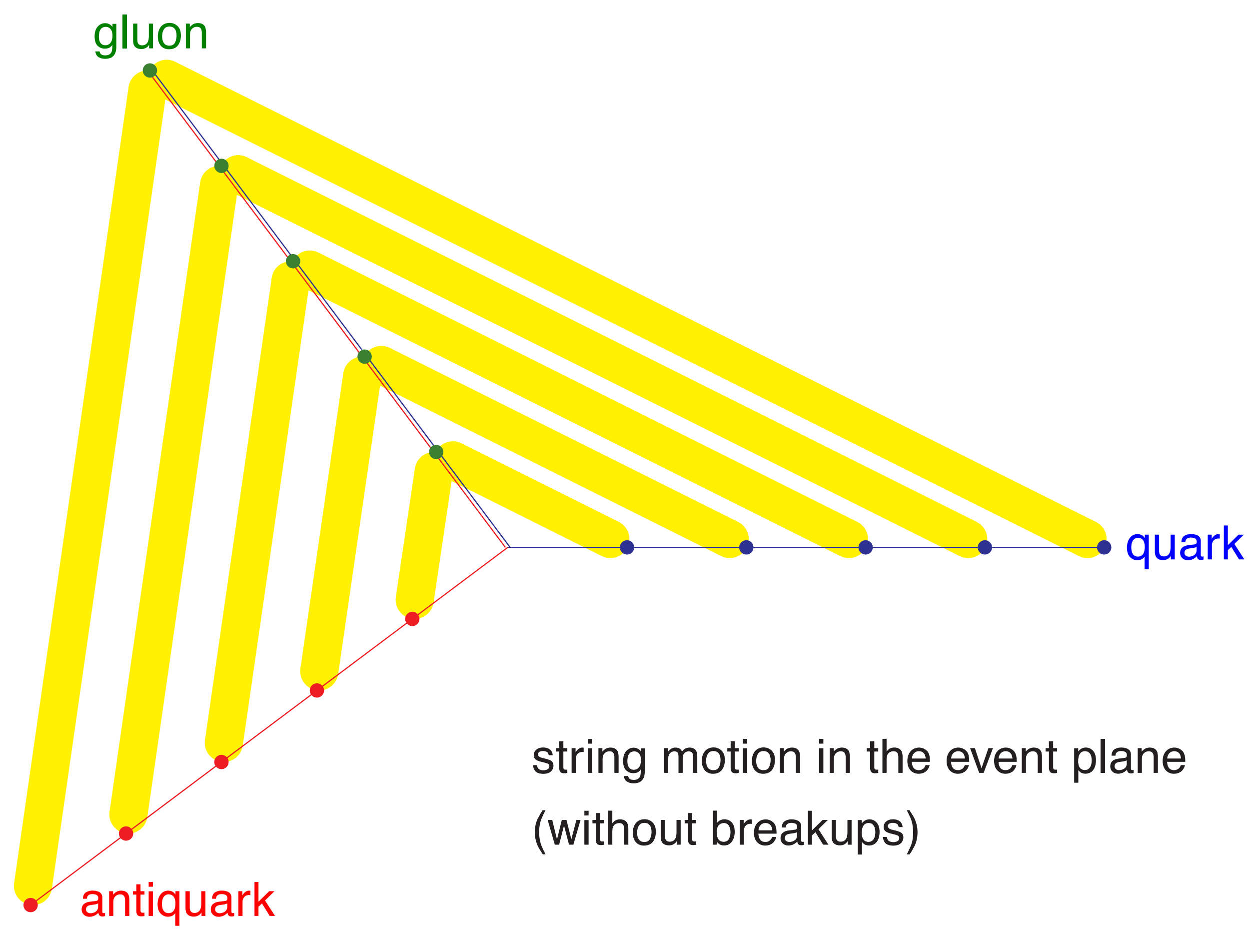
→ **STRING EFFECT**

Simple space-time picture

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

1980: string (colour coherence) effect





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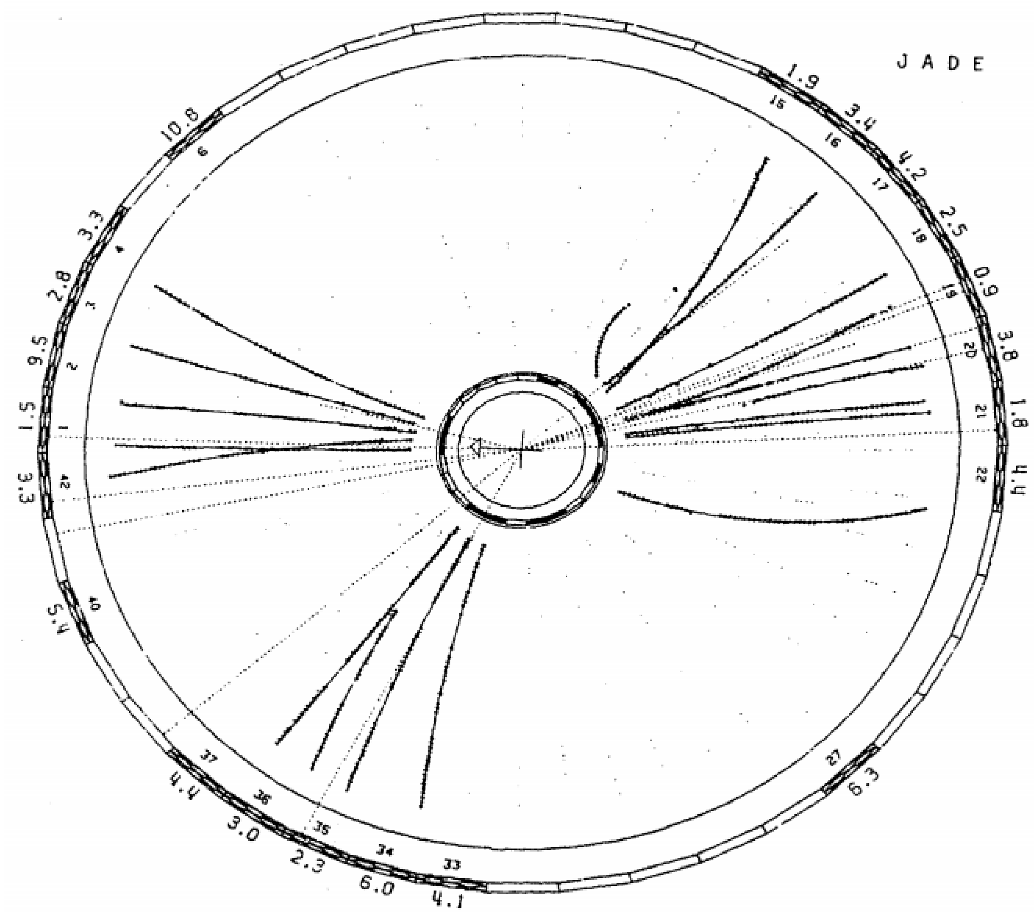
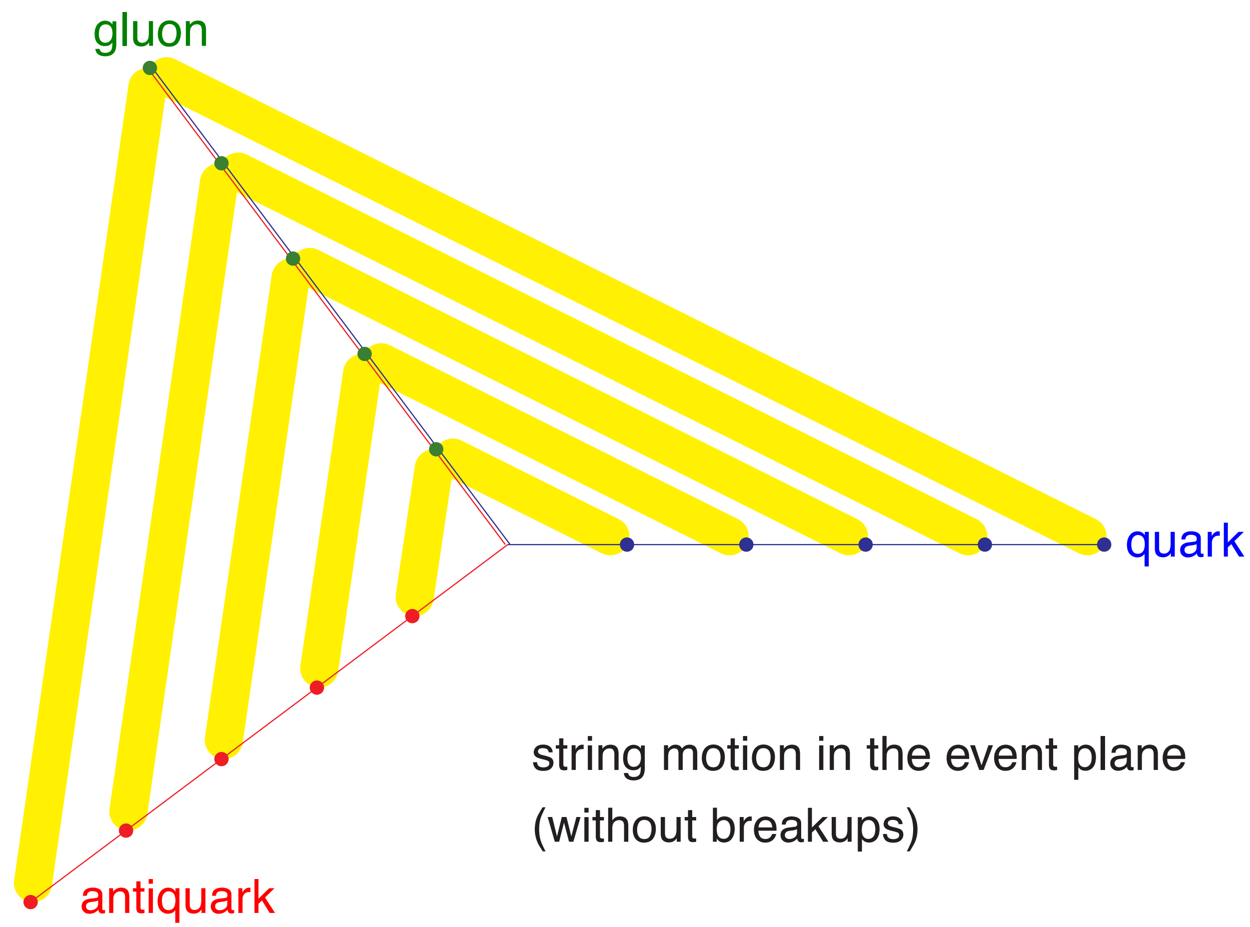
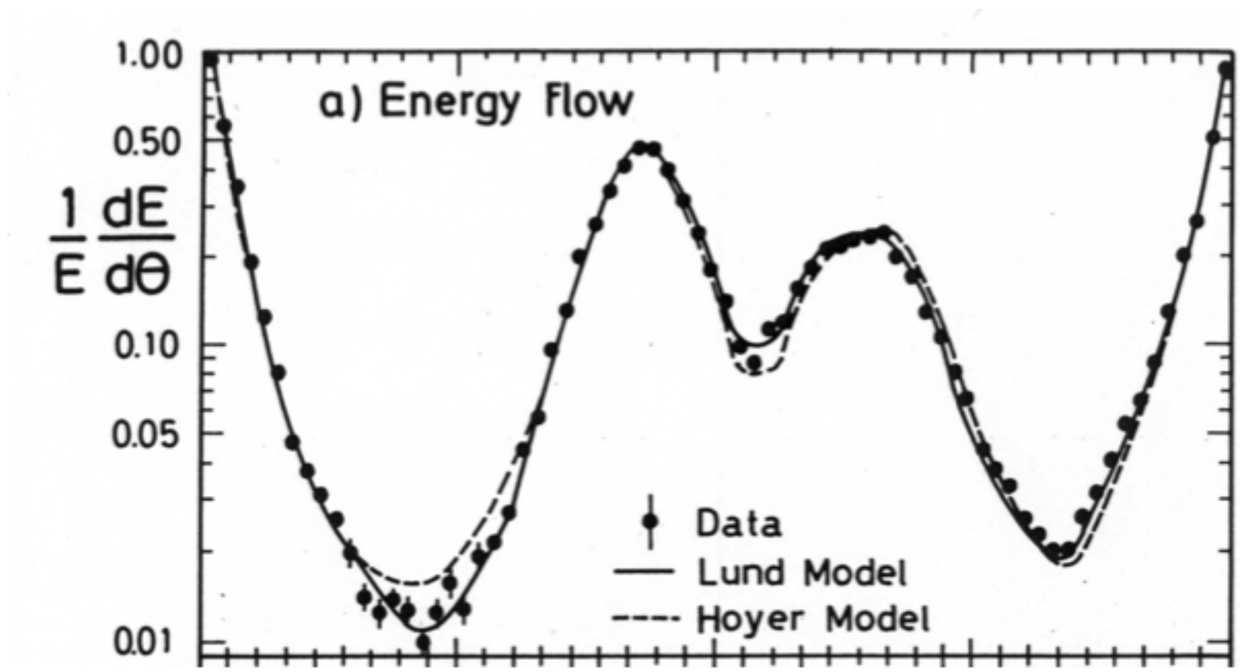






Predicted unique event structure; inside & between jets.

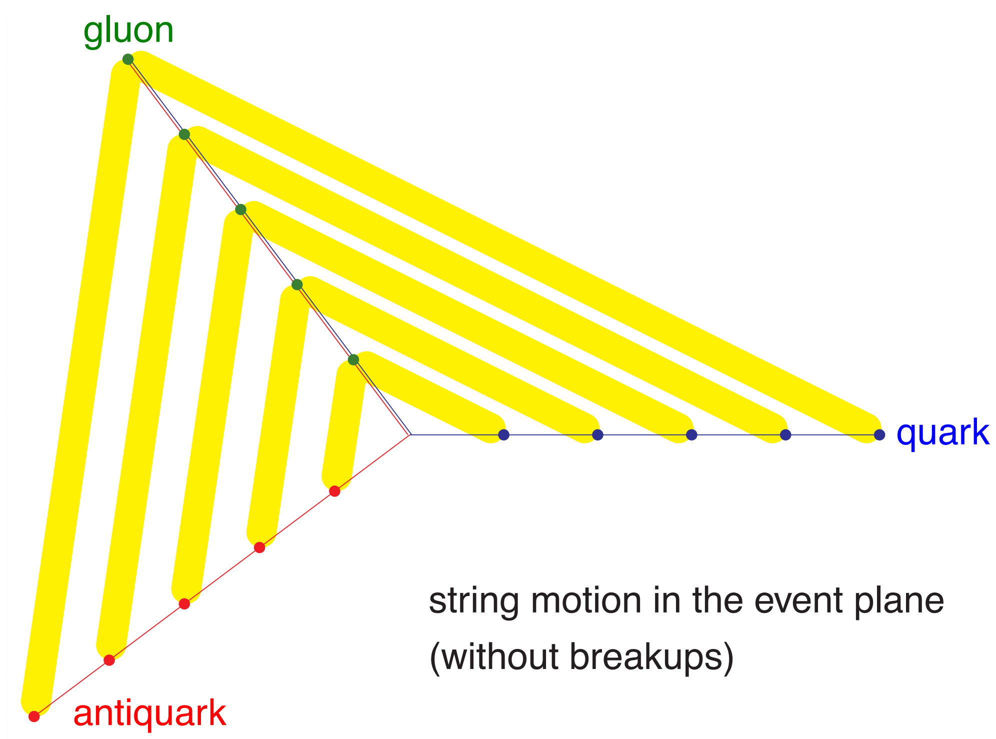
Confirmed first by JADE 1980.

Generator crucial to sell physics!

(today: PS, M&M, MPI, . . .)

More recent study (LHC)

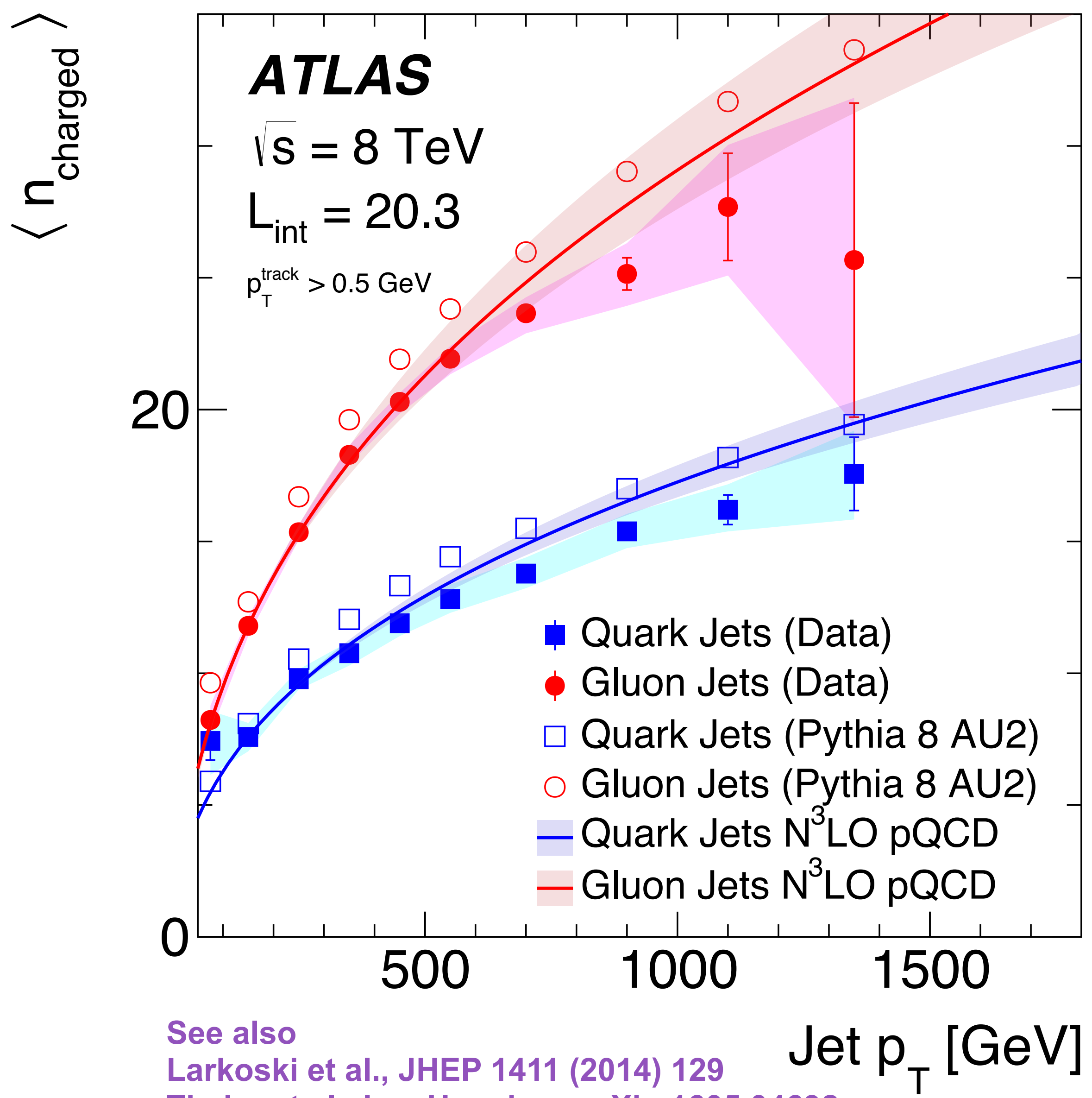
Gluon connected to two string pieces



Each quark connected to one string piece

→ expect factor 2 ~ C_A/C_F larger particle multiplicity in gluon jets vs quark jets

ATLAS, Eur.Phys.J. C76 (2016) no.6, 322



See also
Larkoski et al., JHEP 1411 (2014) 129
Thaler et al., Les Houches, arXiv:1605.04692

Can be hugely important for discriminating new-physics signals (decays to quarks vs decays to gluons, vs composition of background and bremsstrahlung combinatorics)

The Effects of Hadronisation

Generally, expect few-hundred MeV shifts by hadronisation

Corrections to IR safe observables are "power corrections"

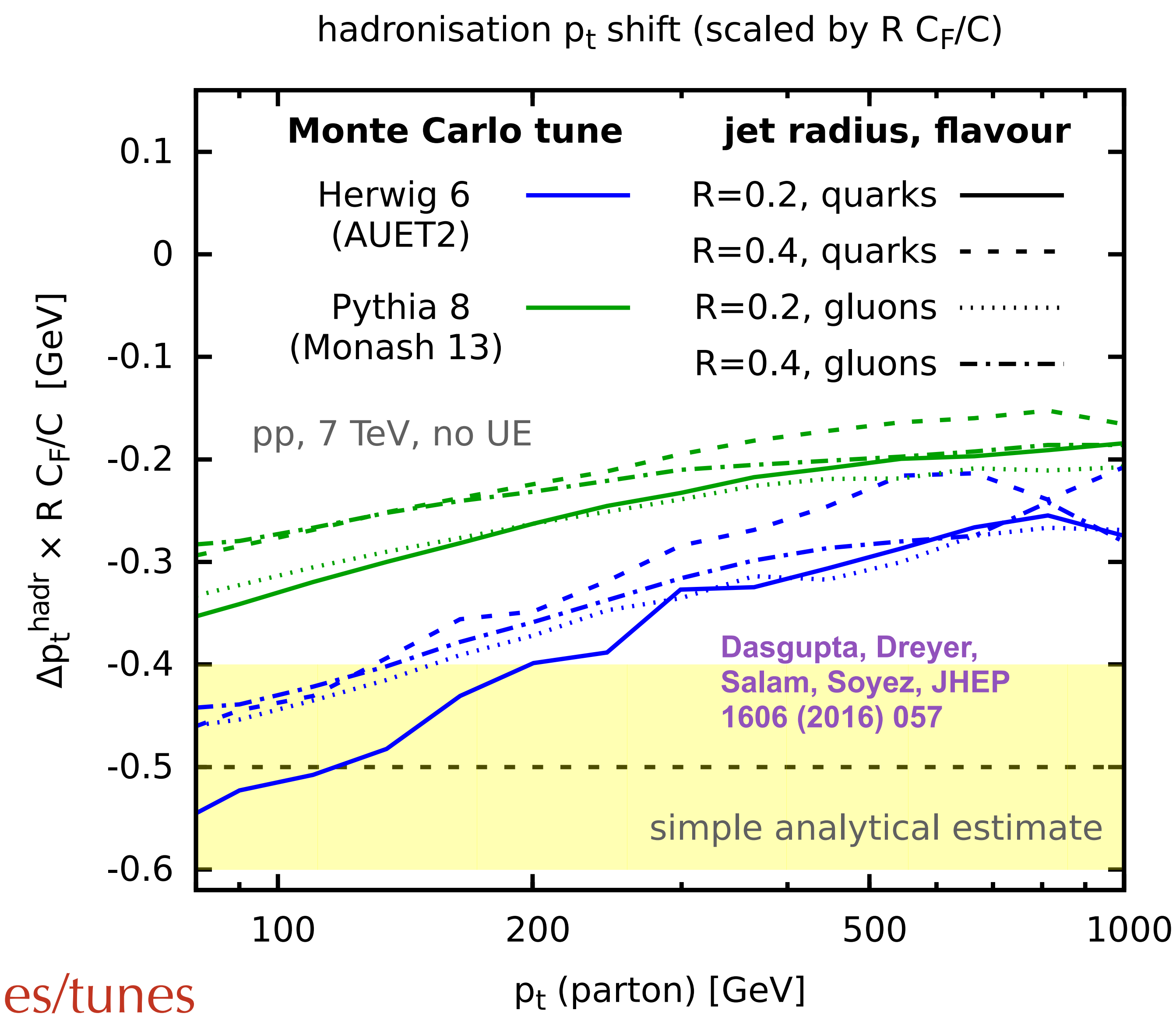
$$\propto \; \Lambda^2_{\mathrm{QCD}}/Q^2_{\mathrm{OBS}}$$

Corrections for jets of radius $R = \Delta\eta \times \Delta\phi$

$$\propto \; 1/R$$

See
Korchemsky, Sterman, NPB 437 (1995) 415
Seymour, NPB 513 (1998) 269
Dasgupta, Magnea, Salam, JHEP 0802 (2008) 055

Simple analytical estimate → ~ 0.5 GeV / R correction from hadronisation (scaled by colour factor)



Significant differences between codes/tunes

→ **important to pin down with precise QCD hadronisation measurements at LHC**

(Alternative: The Cluster Model)

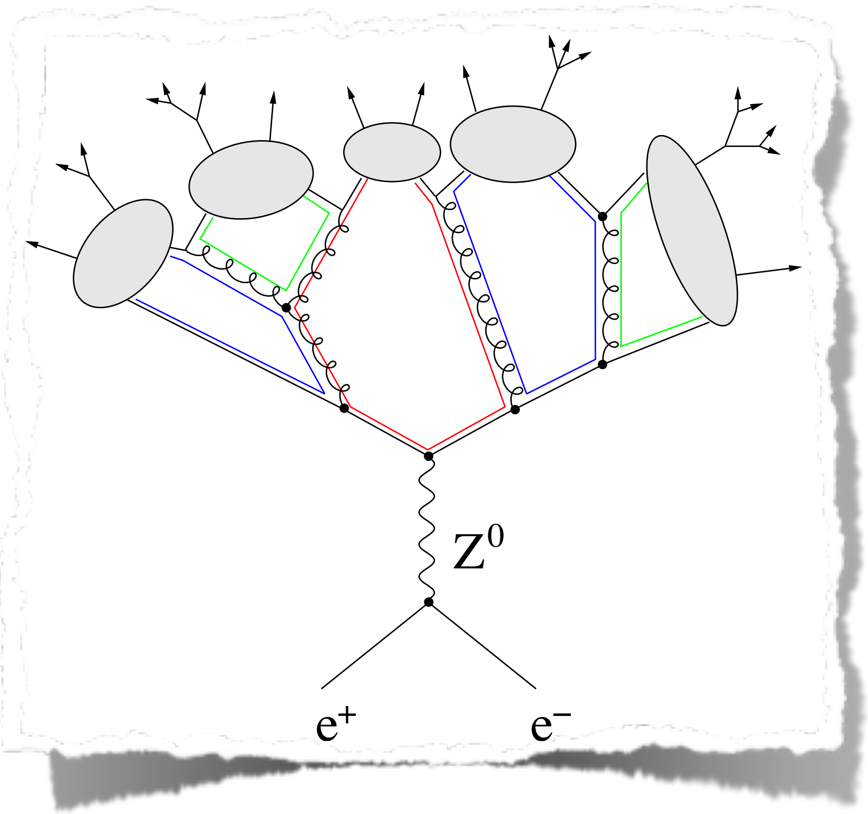
"Preconfinement"

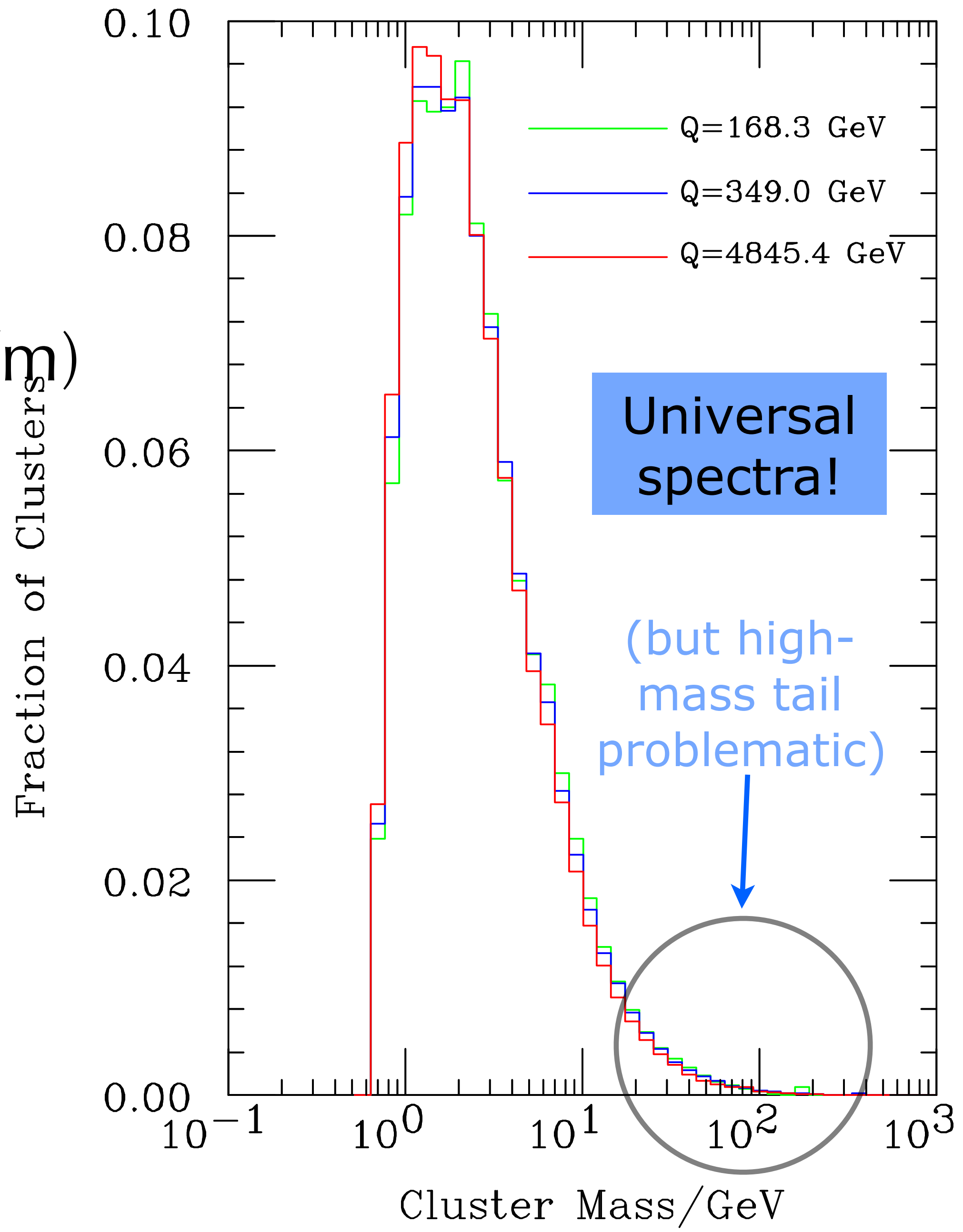
+ Force g→qq splittings at Q_0

→ high-mass q-qbar "clusters"

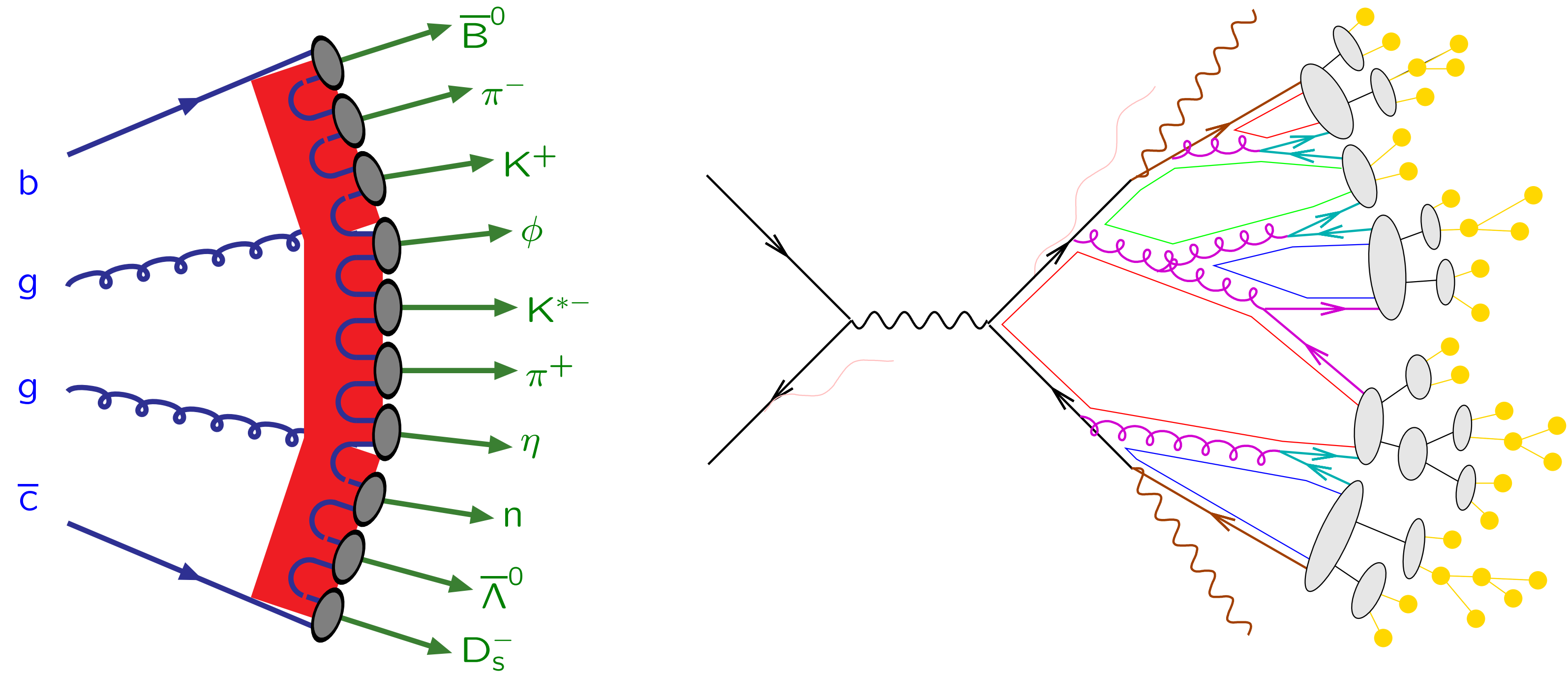
Isotropic 2-body decays to hadrons

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

Small strings → clusters. Large clusters → strings

Monte Carlos and New Physics

Aspects where MC is needed (apart from background modelling)

Signal properties

Decay distributions, extra jets, jet structure (→ jet calibrations),
QCD (& EW) corrections to kinematic distributions

Exclusions & "Recasting" of searches

Uncertainties / modelling deficiencies → worse exclusions

Dynamical modelling of BSM phenomena (some examples)

Long-Lived Coloured Particles → "R-hadrons"

Dark-Matter Annihilation to Coloured Particles

Hidden Valleys (showers/hadronisation in hidden sector)

Baryon Number Violation (RPV-SUSY) → colour-epsilon structures

Particles with "exotic" colour charges (e.g., colour sextets)

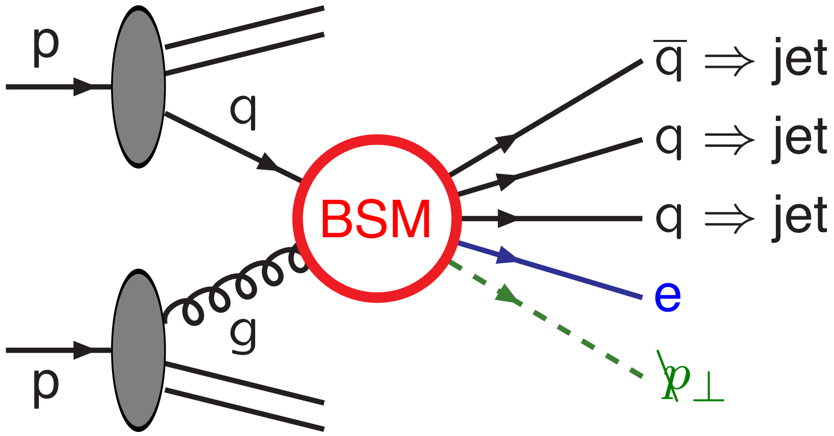
Black-Hole Evaporation, Sphaleron Decays, …

BSM at the LHC

(adapted from slides by T. Sjostrand)

BSM particles usually short-lived, or weakly interacting (like DM)

Then visible final state consists of hadrons, leptons and photons, just like ordinary processes.



As easy to model as SM processes.

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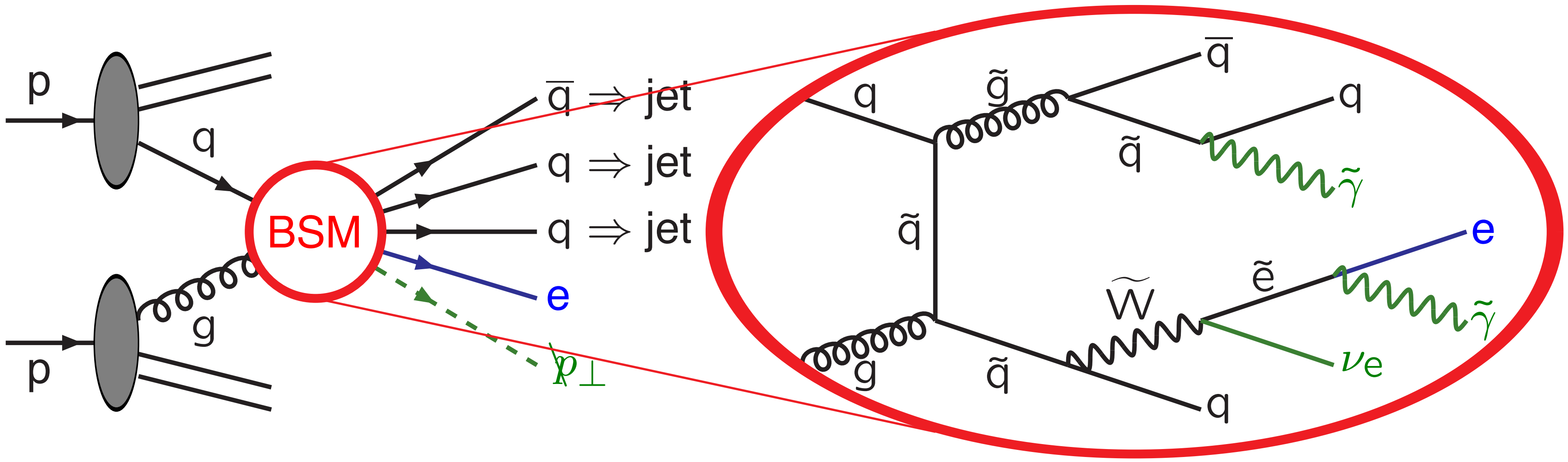


As easy to model as SM processes.

Original structure hidden, but traces of it may be left in terms of invariant masses and angular distributions

Discovery requires detailed understanding of rare signals and huge backgrounds

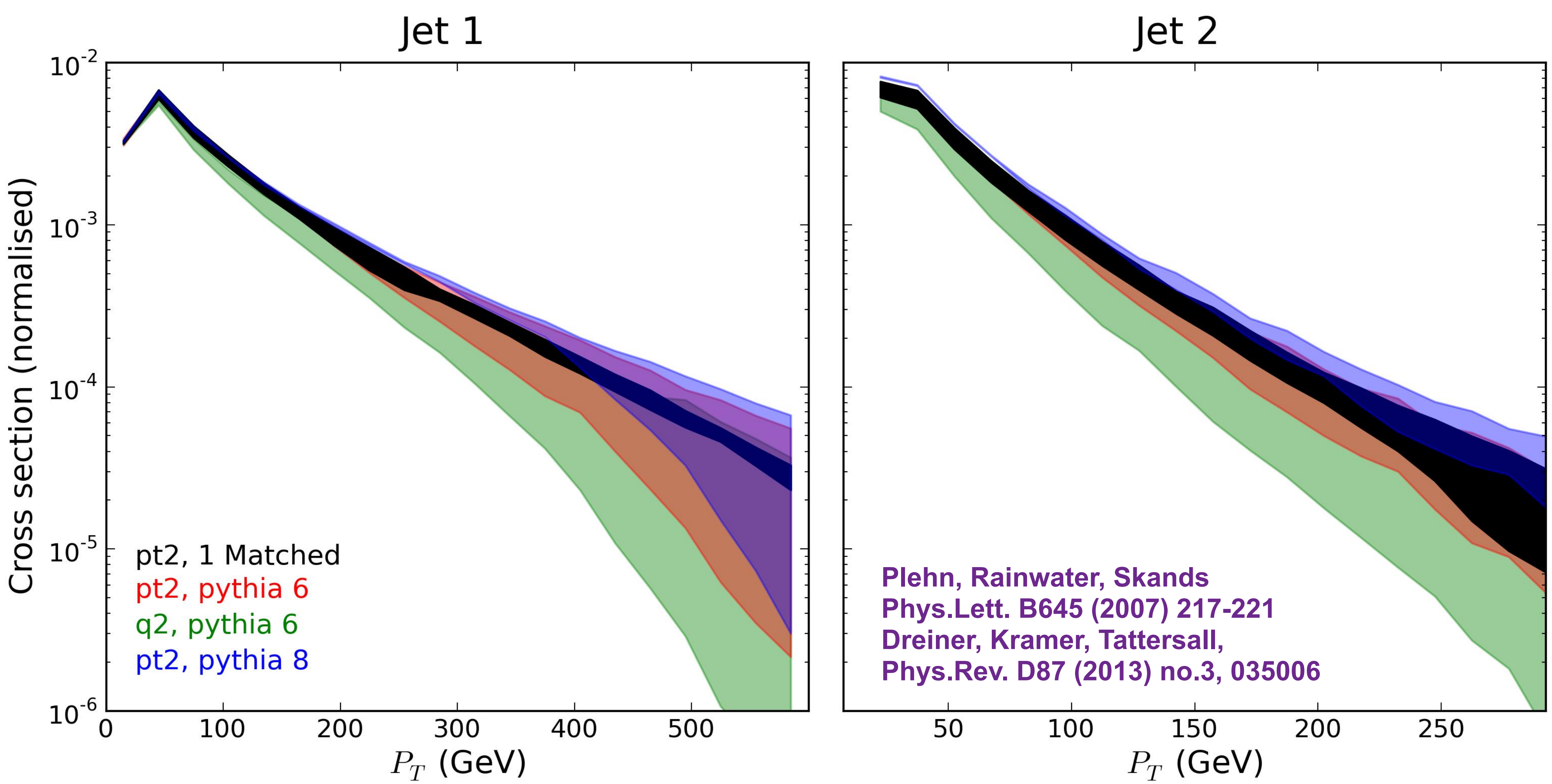
Signal Properties

(adapted from slides by S. Prestel, MC4BSM workshop)

Do you need ME + PS for BSM signals?

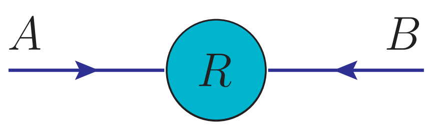
Example: pair production of 500-GeV squarks, plus QCD jets

Variation of shower profiles vs matrix-element-matched calc



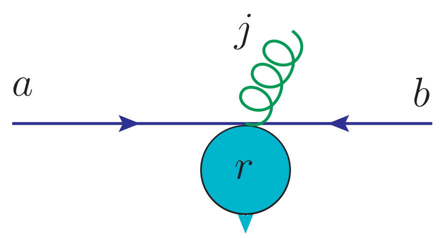
Improved QCD pins down the transverse momenta

Born-Level Kinematics



$p_{\text{Trecoil}} = 0$

+ Showers



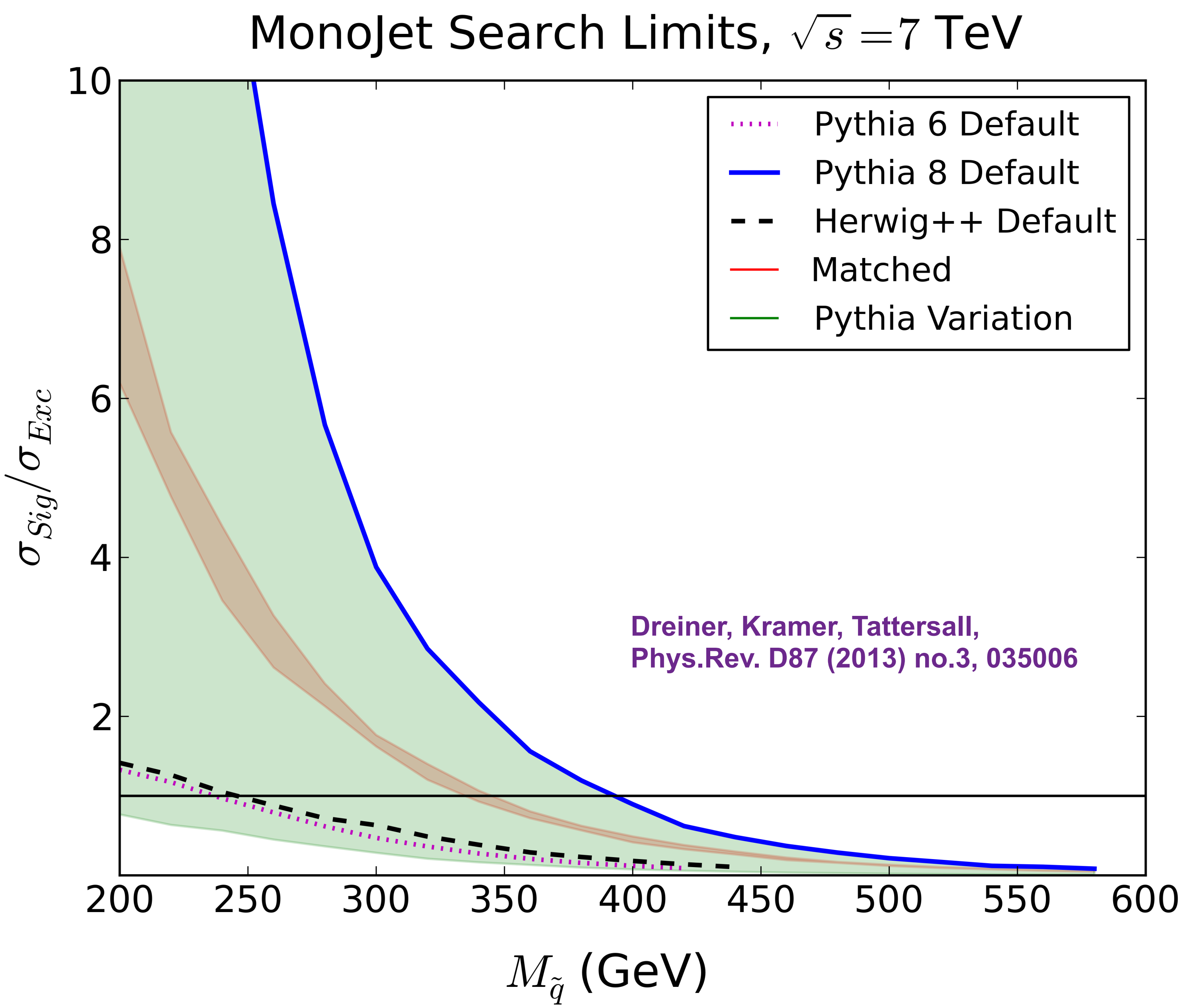
$p_{\text{Trecoil}} = \text{sum(QCD)}$

Exclusions (& Recasting)

(adapted from slides by S. Prestel, MC4BSM workshop)

How good is your exclusion?

Variation of shower profiles vs matrix-element-matched calc

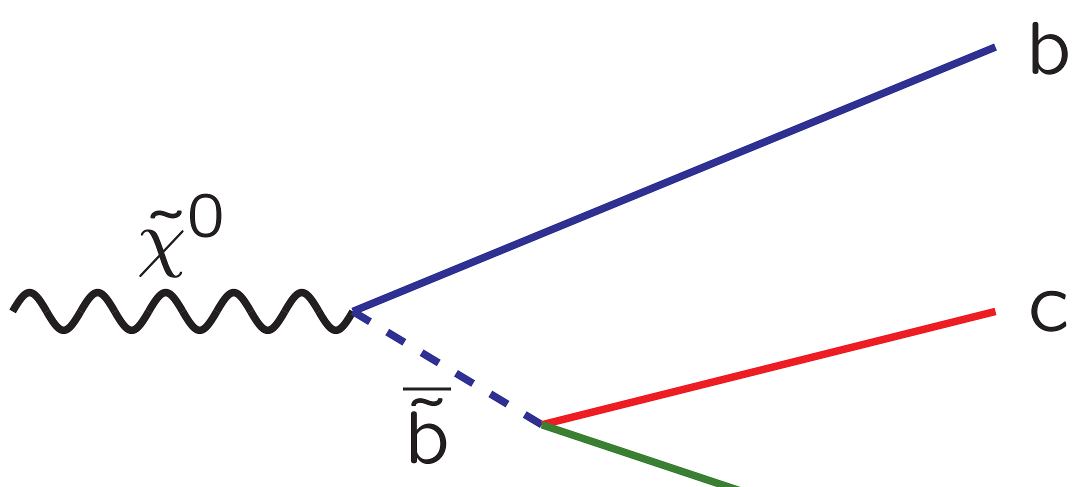


+ "Recasting" is getting to be a big activity; reinterpreting high-energy collider analyses.

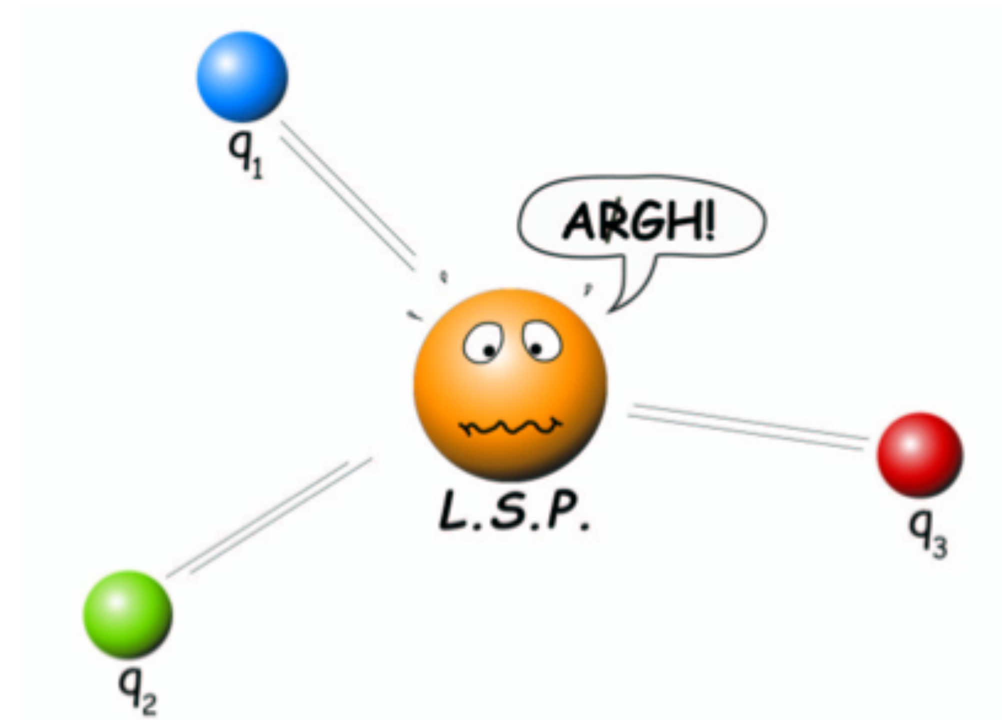
Cranmer, Yavin
JHEP 1104 (2011) 038

Basically use MC to reinterpret exclusion limits done for one model/topology in context of another model!

Baryon number violation (BNV) is allowed in SUSY superpotential.
Alternatively lepton number violation, but proton unstable if both.
BNV couplings should not be too big, or else large loop corrections
$\Rightarrow$ relevent for LSP (Lightest Supersymmetric Particle).



Note: $m(\bar{\tilde{b}}) > m(\tilde{\chi}^0)$



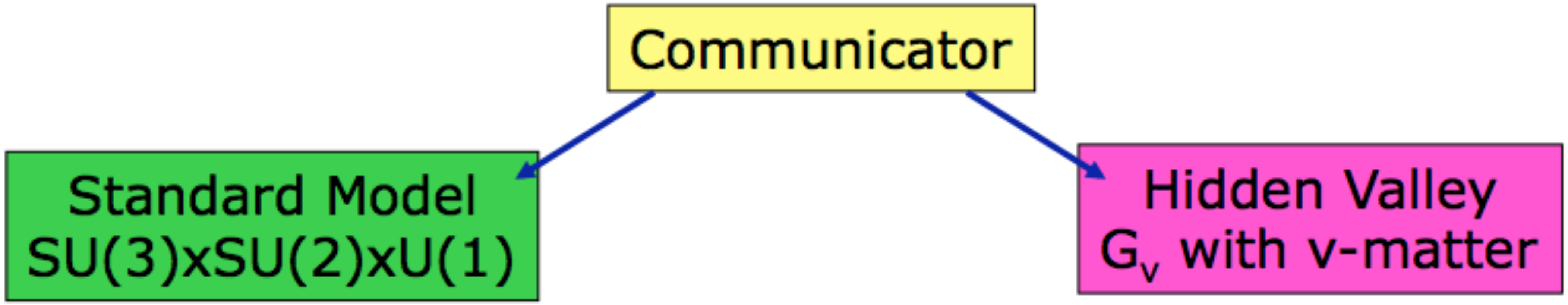
What about showers and hadronization in decays?

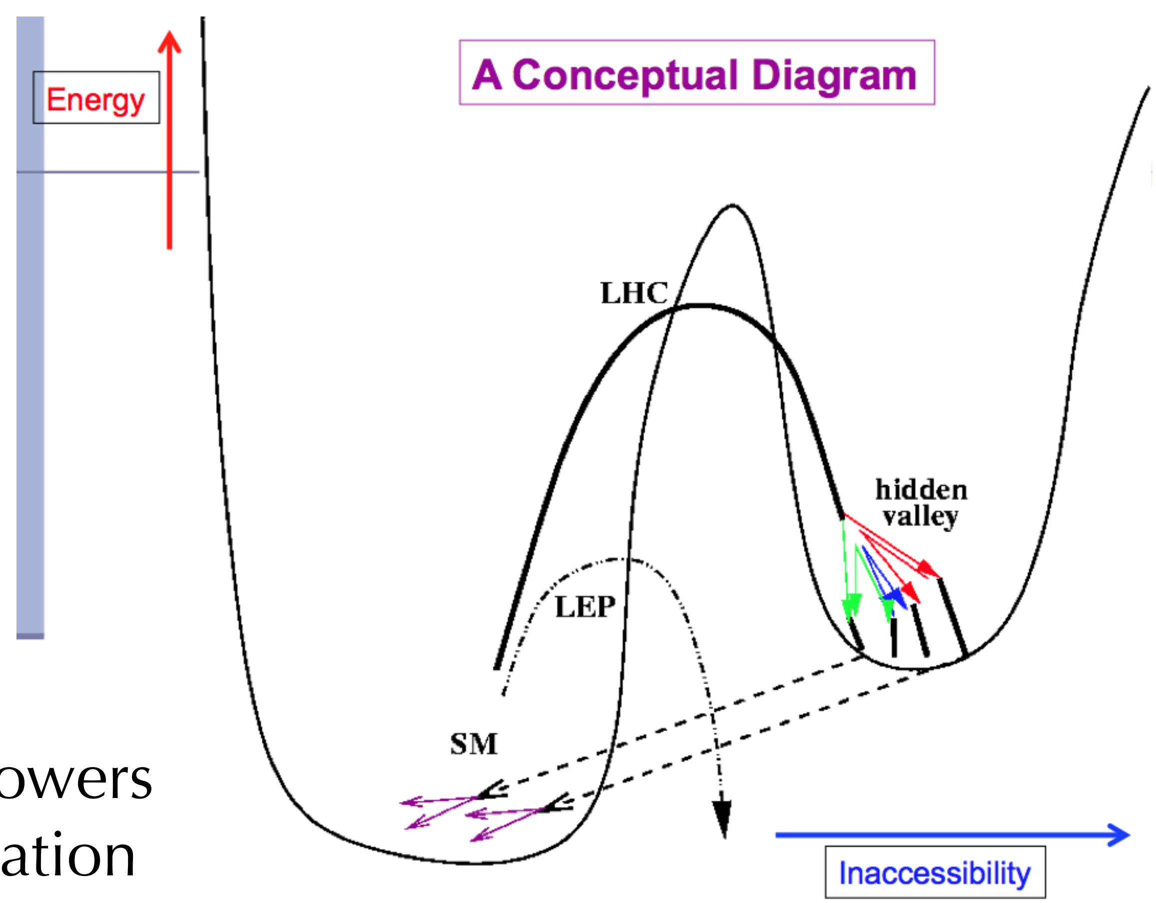
P. Skands & TS, Nucl. Phys. B659 (2003) 243;

N. Desai & P. Skands, arXiv:1109.5852 [hep-ph]

Hidden Valleys / Emerging Jets

M. Strassler, K. Zurek, Phys. Lett. B651 (2007) 374; . . .





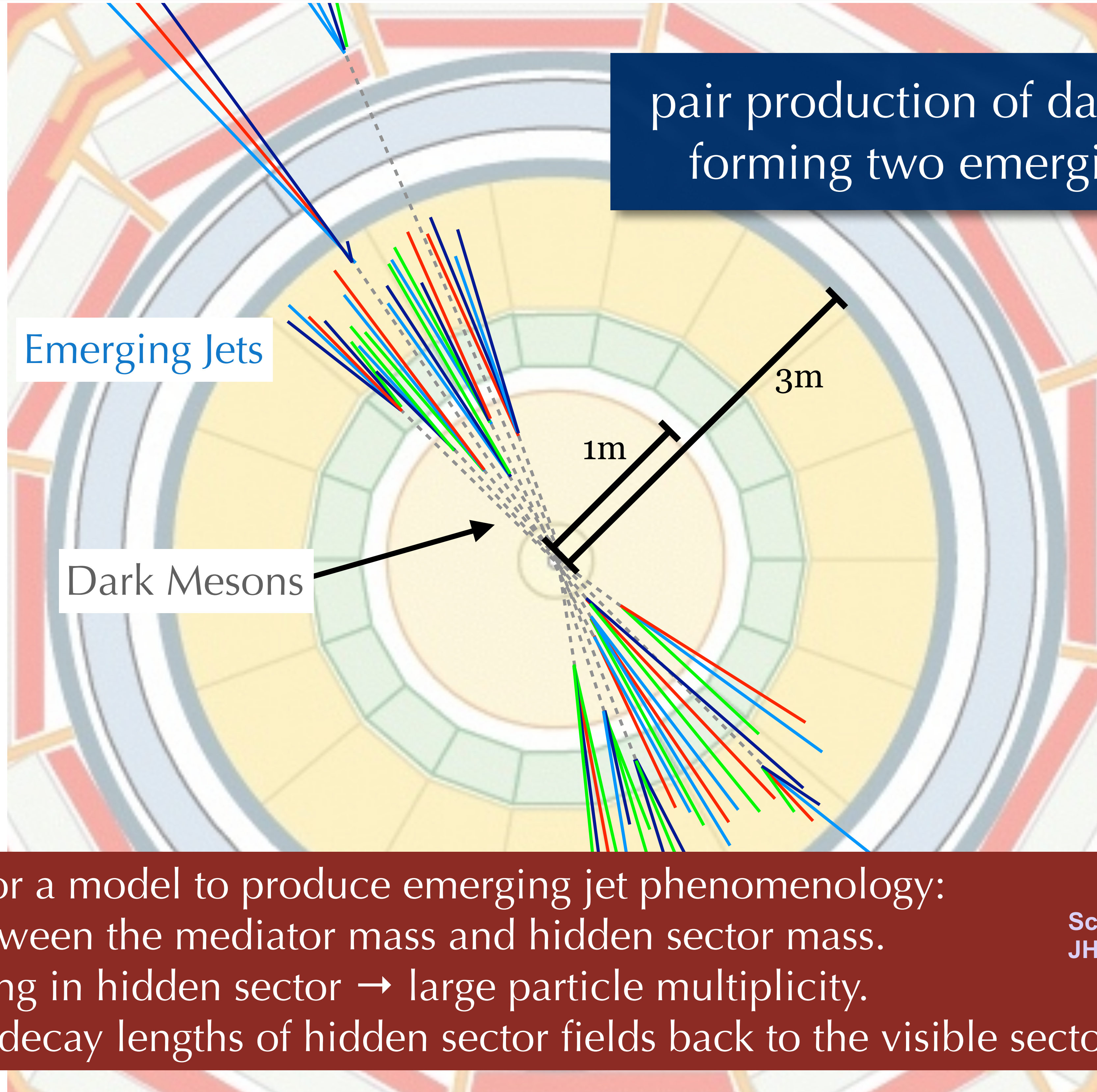
Hidden Valley
aka “Dark” Sector
aka “Hidden” Sector

Courtesy
M. Strassler

Hidden-Valley Showers
+ Valley Hadronisation

→ L. Carloni & TS, JHEP 1009, 105; L. Carloni, J. Rathsman & TS, JHEP 1104, 091

Hidden Valleys / Emerging Jets



pair production of dark quarks forming two emerging jets.

Requirements for a model to produce emerging jet phenomenology:

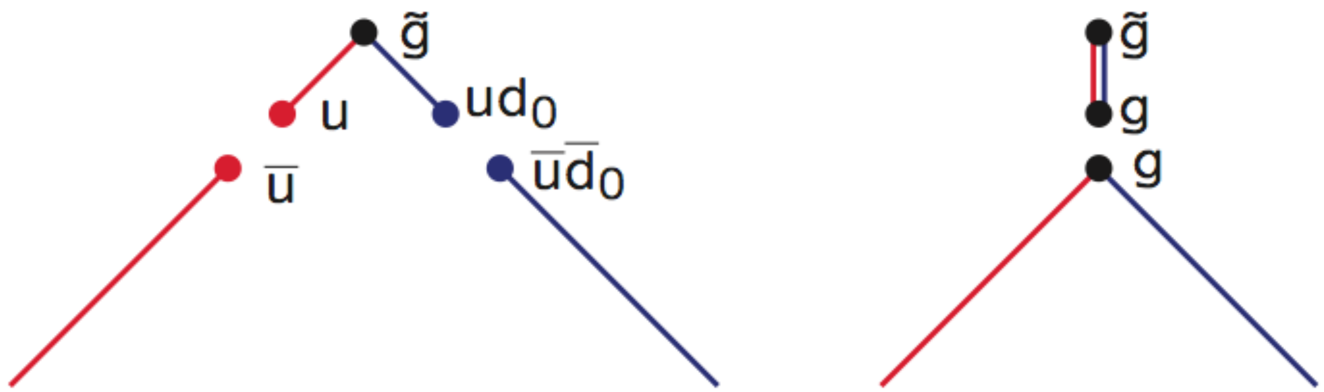
- Hierarchy between the mediator mass and hidden sector mass.
- Strong coupling in hidden sector → large particle multiplicity.
- Macroscopic decay lengths of hidden sector fields back to the visible sector

Schwaller, Stolarski, Weiler
JHEP 1505 (2015) 059

R-Hadrons

⇒ Pythia allows for hadronization of 3 generic states:

- colour octet uncharged, like $\tilde{g}$, giving $\tilde{g}u\bar{d}$, $\tilde{g}uud$, $\tilde{g}g$, ...,
- colour triplet charge $+2/3$, like $\tilde{t}$, giving $\tilde{t}\bar{u}$, $\tilde{t}ud_0$, ...,
- colour triplet charge $-1/3$, like $\tilde{b}$, giving $\tilde{b}\bar{c}$, $\tilde{b}su_1$, ...



Gluino fragmenting to baryon or glueball

Most hadronization properties by analogy with normal string fragmentation, but
glueball formation new aspect, assumed $\sim$ 10% of time (or less).

R-hadron interactions with matter: part of detector simulation, i.e. GEANT, not PYTHIA
Freight-train BSM particle surrounded by light pion/gluon cloud → little dE/dx
+ charge flipping ! A.C. Kraan, Eur. Phys. J. C37 (2004) 91; M. Fairbairn et al., Phys. Rep. 438 (2007) 1

Interfaces

Monte Carlo for BSM often involves **chains** of codes
→ **interfaces** play a central role

Model Building Tool (e.g., FeynRules, LanHEP, …)

→ Model File (e.g., UFO) arXiv:1108.2040

Matrix-Element Generator (e.g., MadGraph, CalcHEP, …)

→ Matrix Elements

→ Les Houches Event Files (LHEF) hep-ph/0609017

SLHA for SUSY spectra: hep-ph/0311123 arXiv:0801.0045

BSM-SLHA for new particles: arXiv:0712.3311

Matching/Merging Strategy + Parton Shower Generator

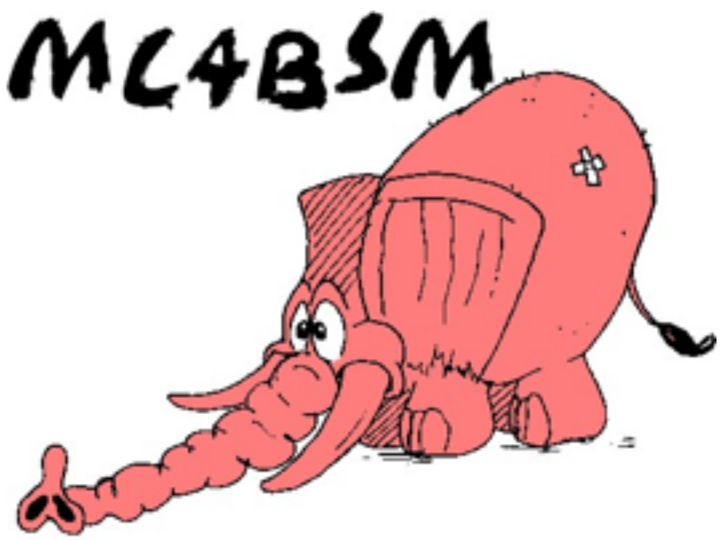
→ Interpretation of LHEF

→ Hadron-Level event files (HepMC) → Analysis Tools
(e.g., FASTJET, DELPHES, …)

MC for BSM

Yearly workshop series **MC4BSM** (running since 2006)

"Gather theorists and experimentalists interested in developing Monte Carlo tools to simulate signatures of BSM Physics, and to use such tools in searches and phenomenological studies"



http://theory.fnal.gov/mc4bsm/

This year, 20-24 July, UCAS-YuQuan (Beijing, China)

http://indico.ihep.ac.cn/event/5301/

Next year (2017): **SLAC** (Stanford, California)

The End

(Event recorded by CMS with 78 proton-proton collisions)

Extra Slides

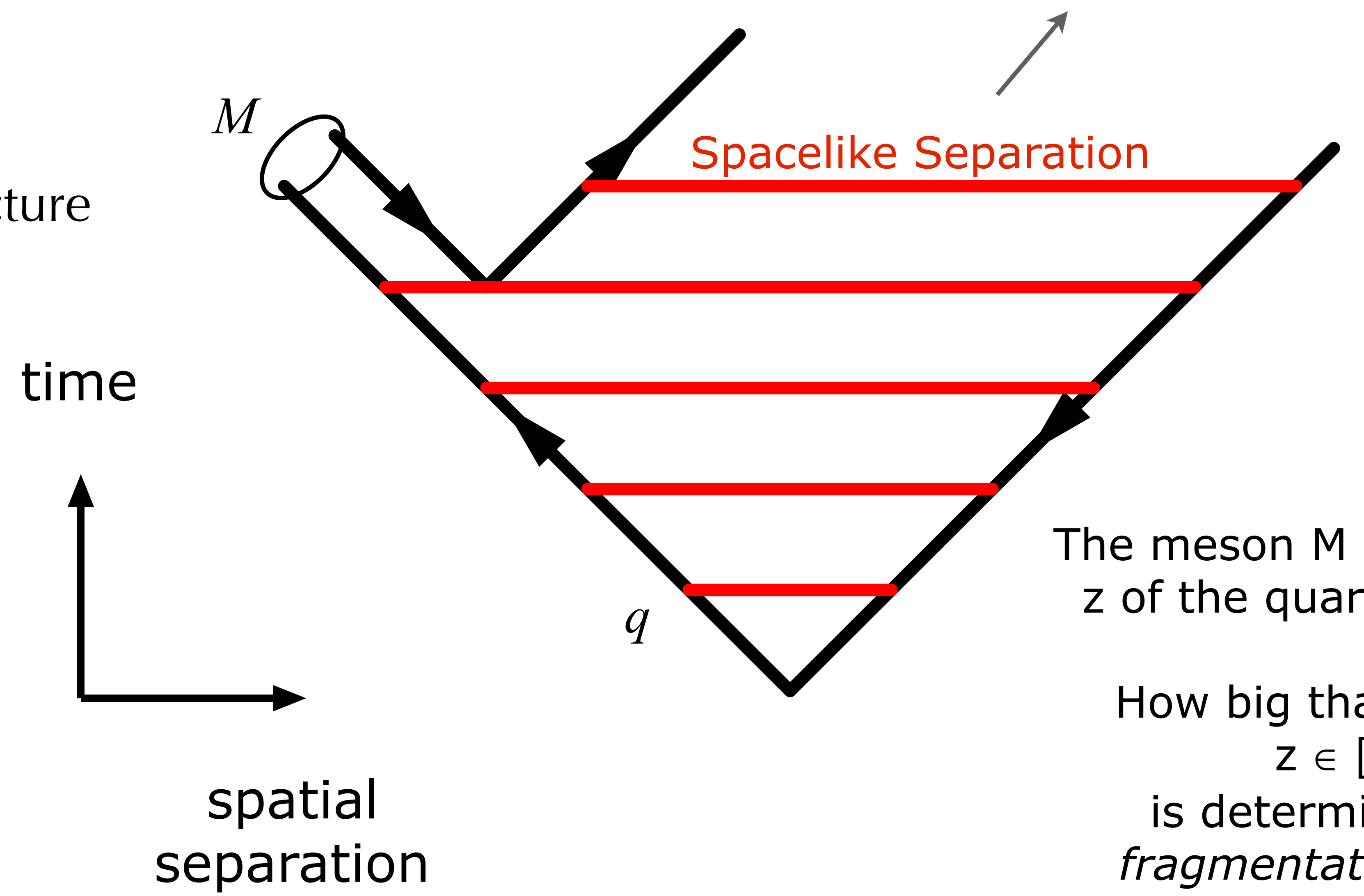
Fragmentation Function

Having selected a hadron flavor

How much momentum does it take?

Spacetime Picture

leftover string,
further string breaks



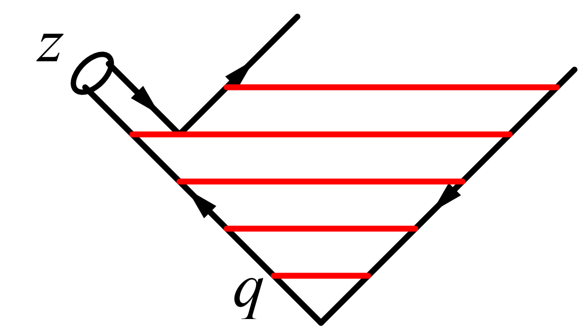
The meson M takes a fraction z of the quark momentum,

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

Left-Right Symmetry

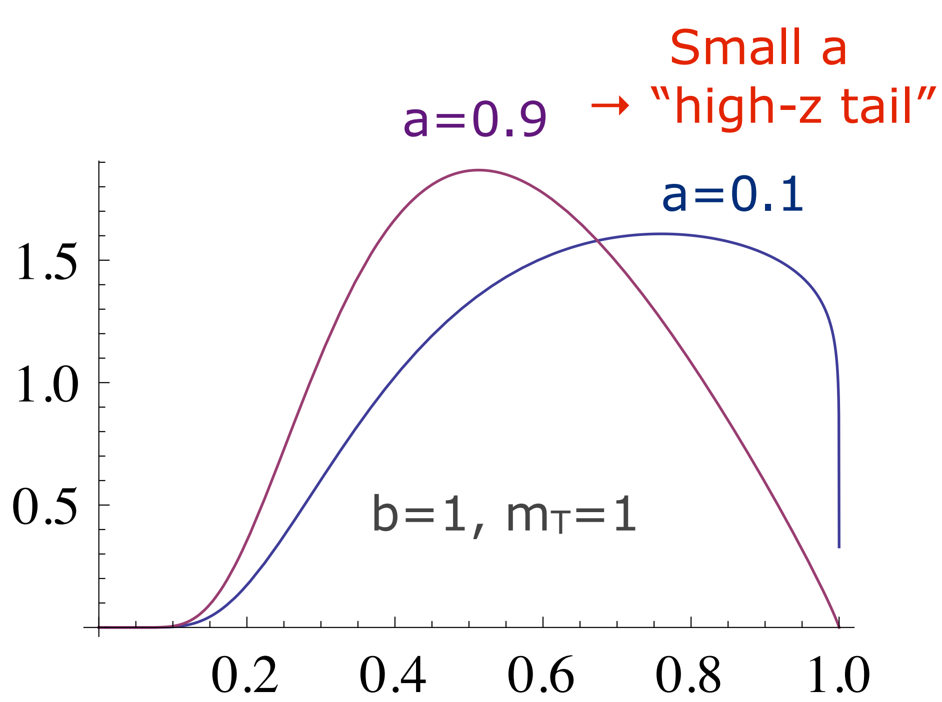
Causality → Left-Right Symmetry

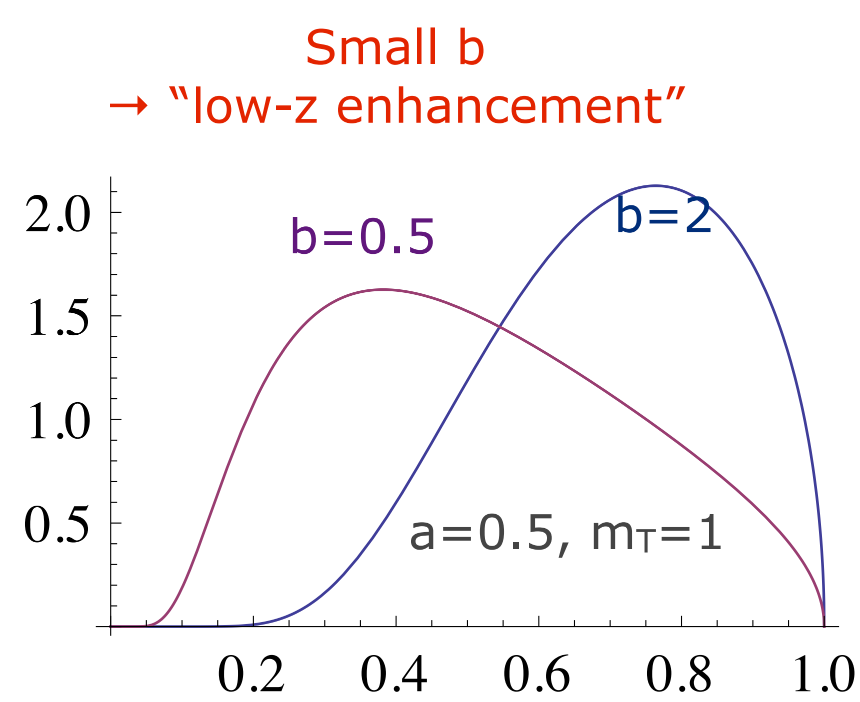
→ Constrains form of fragmentation function!



→ Lund Symmetric Fragmentation Function

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

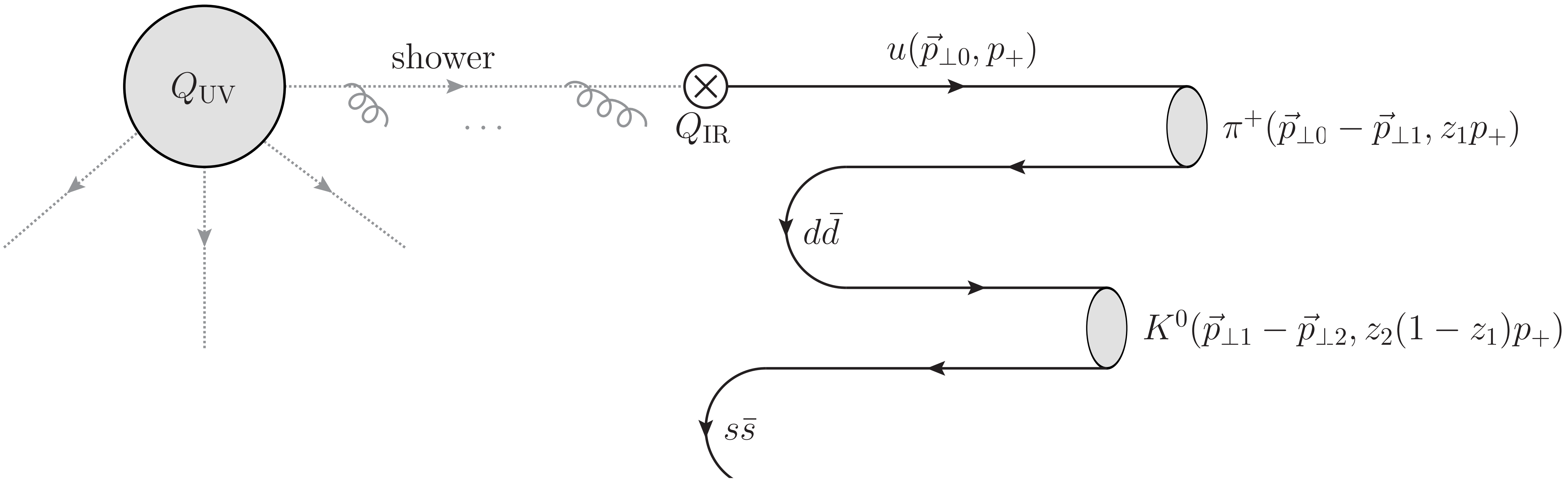




Note: In principle, a can be flavour-dependent. In practice, we only distinguish between baryons and mesons

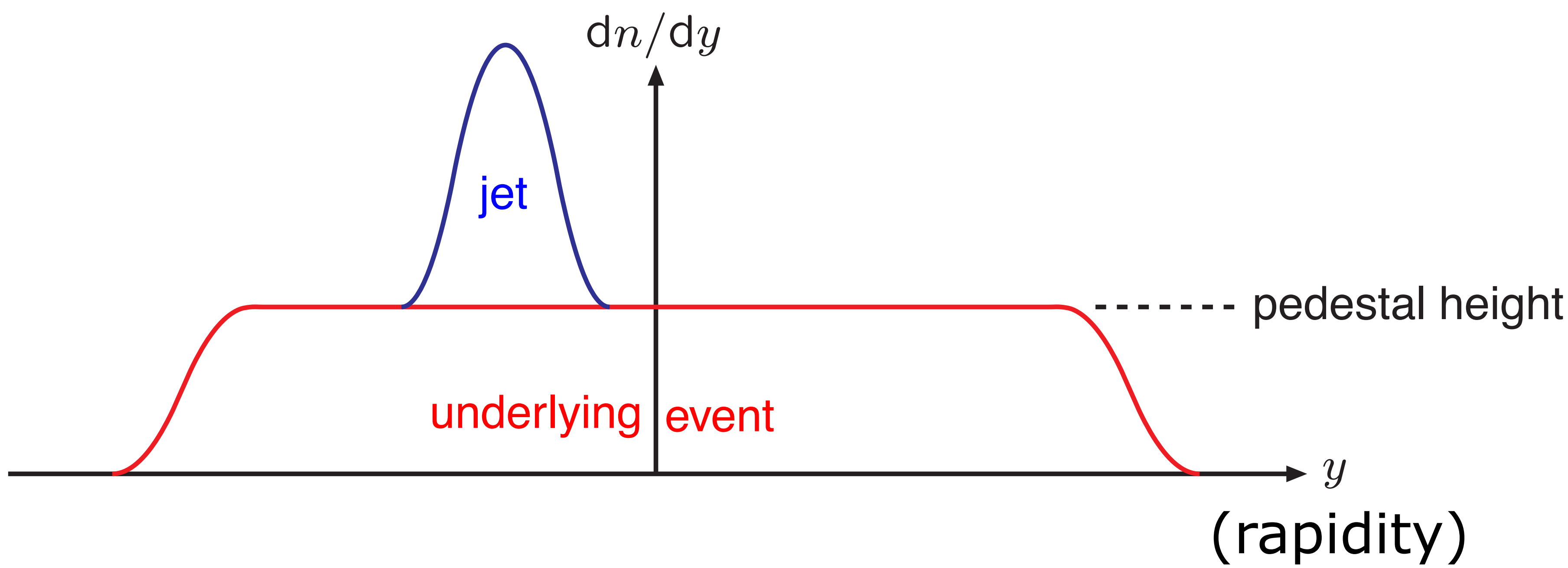
Iterative String Breaks

Causality → May iterate from outside-in



What is Underlying Event ?

"Pedestal Effect"



Useful variable in hadron collisions: **Rapidity**

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

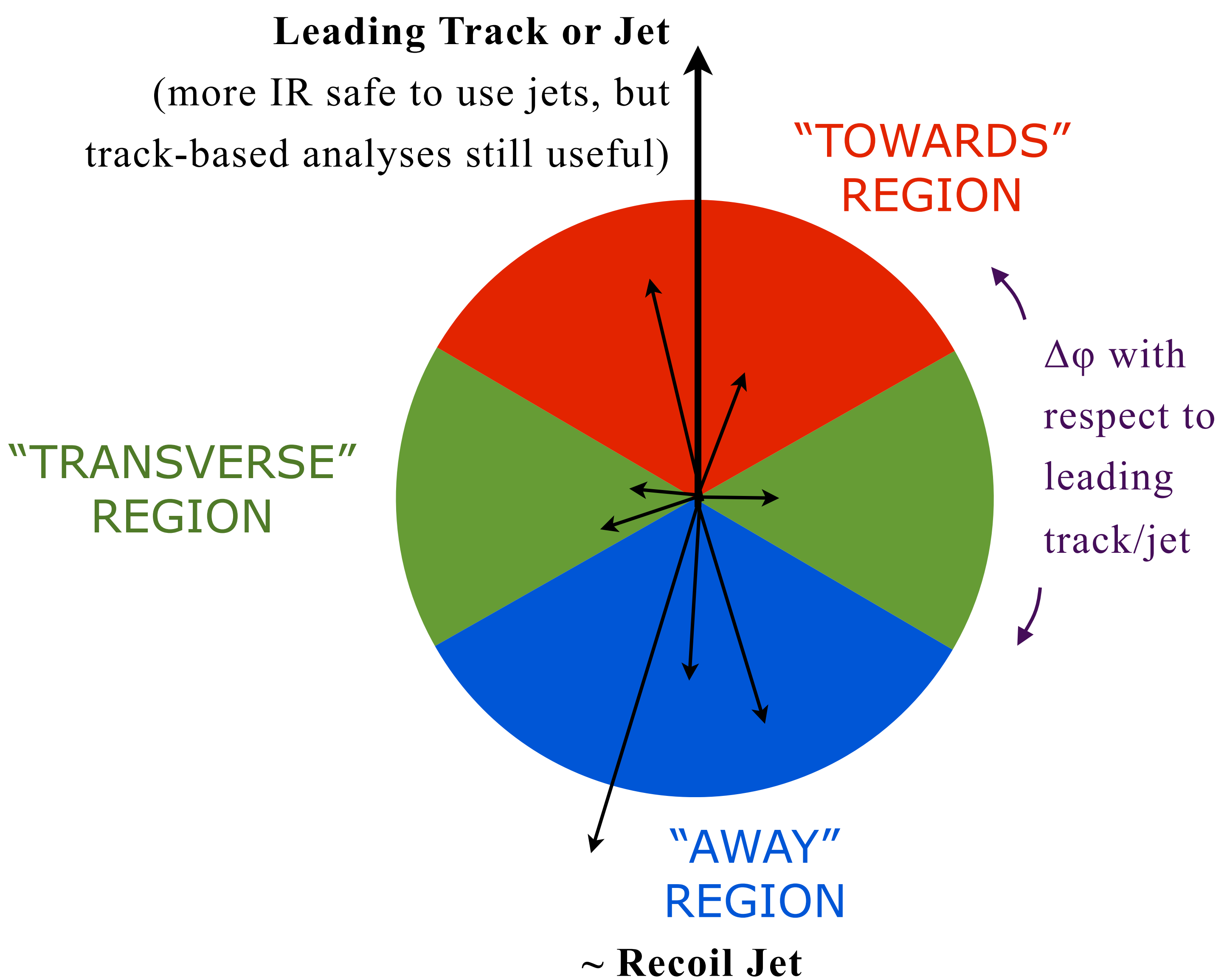
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

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

Illustrations by T. Sjöstrand

The "Rick Field" UE Plots

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



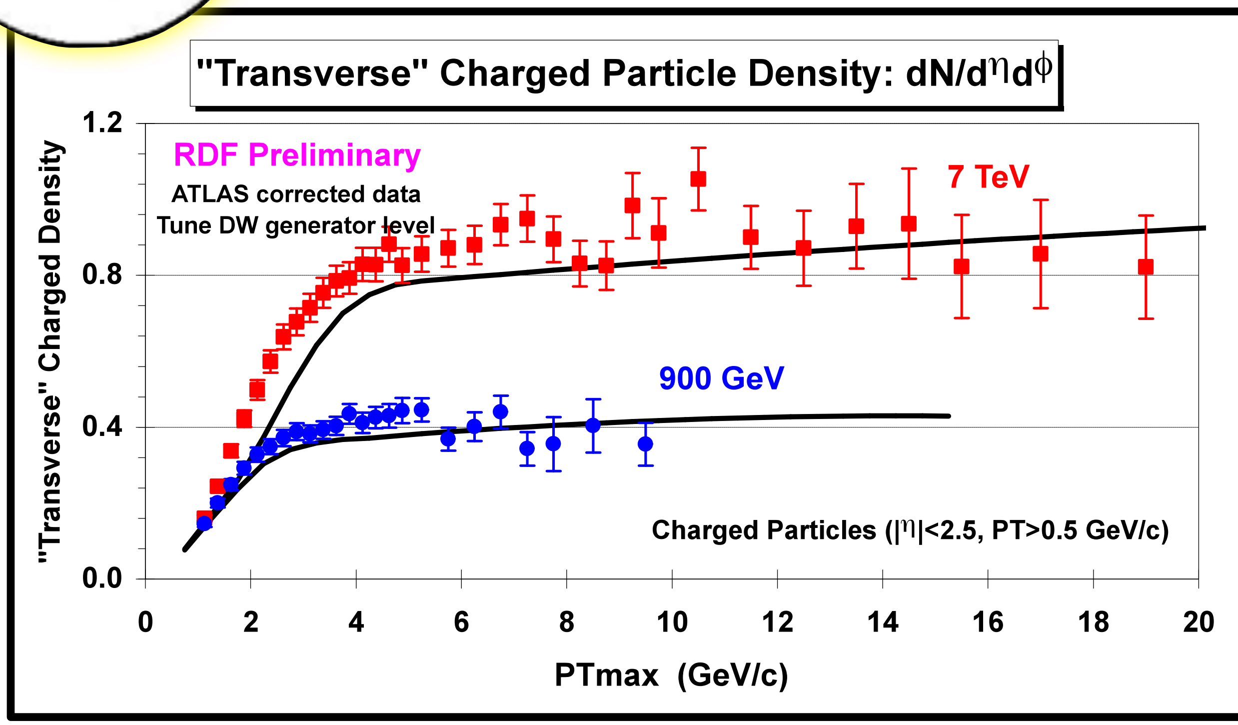
Transverse Region
(TRNS)

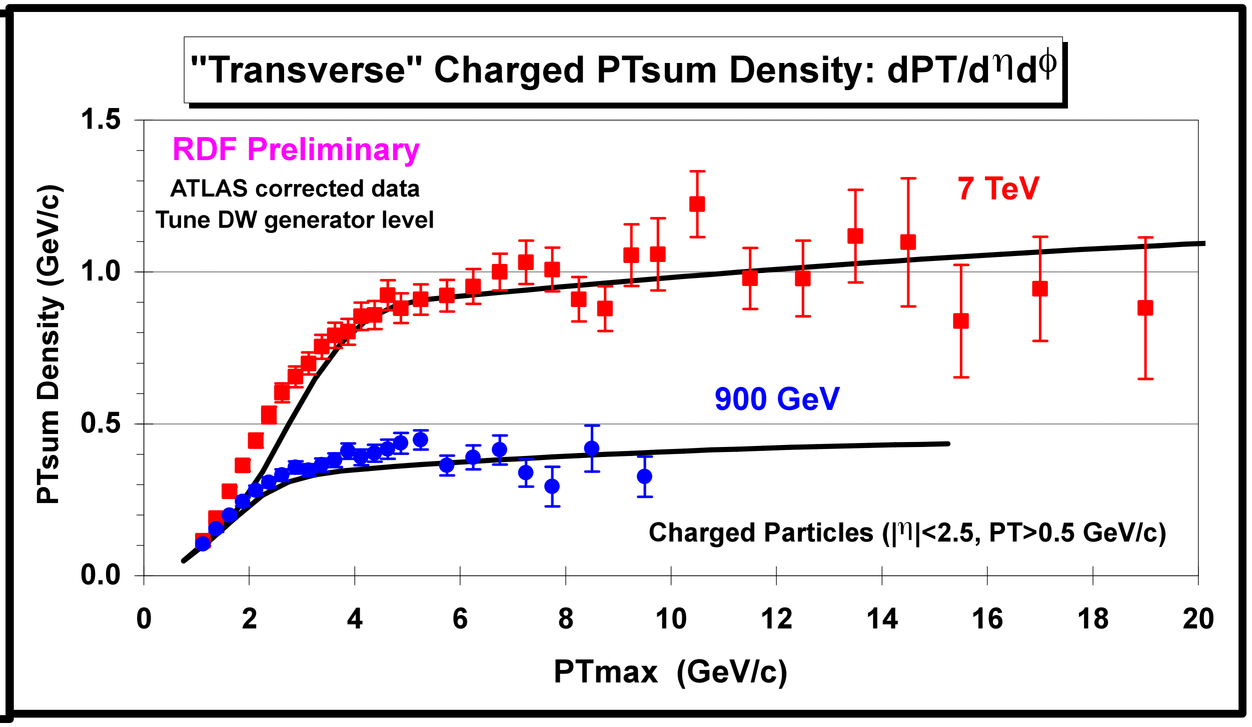
Sensitive to activity at right angles to the hardest jets

Useful definition of Underlying Event

The Pedestal

LHC from 900 to 7000 GeV - ATLAS





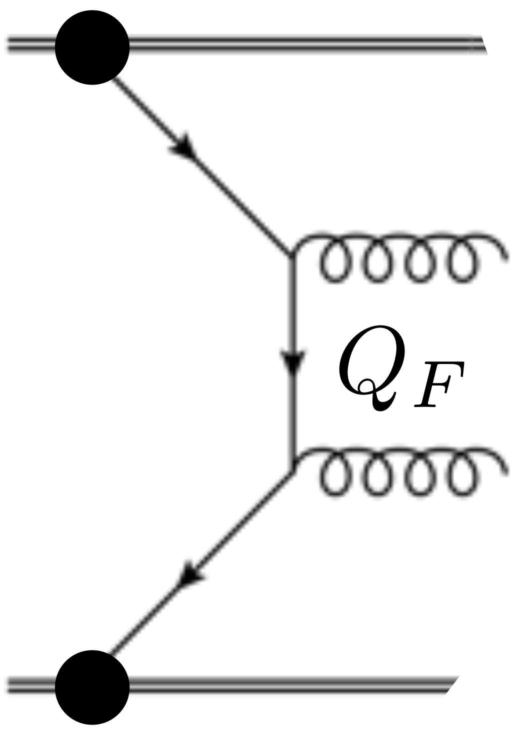
Track Density (TRANS)	Sum(pT) Density (TRANS)
Not Infrared Safe	(more) Infrared Safe
Large Non-factorizable Corrections	Large Non-factorizable Corrections
Prediction off by ≈ 10%	Prediction off by < 10%

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



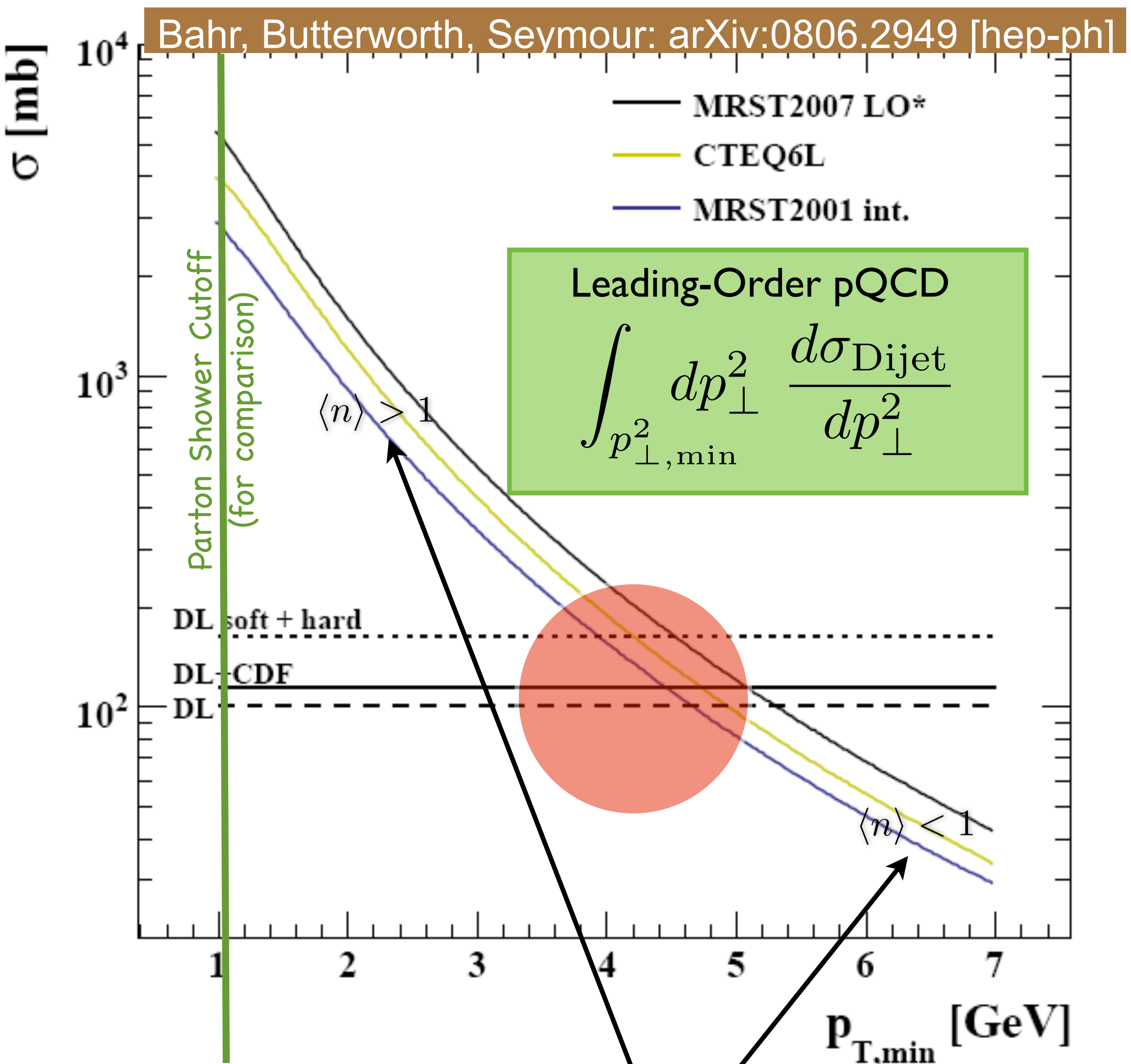
Multiple Parton Interactions go beyond existing theorems

→ perturbative short-distance physics in Underlying Event

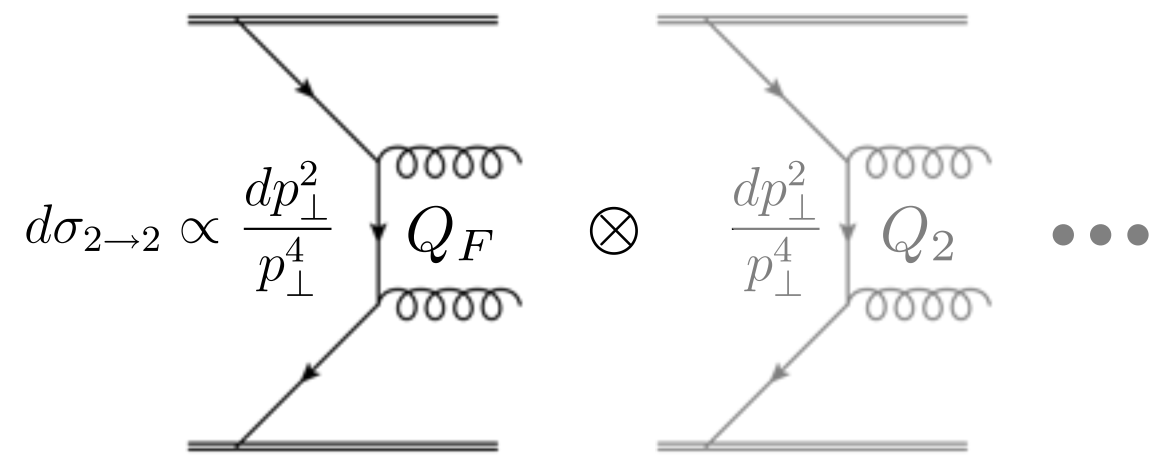
→ Need to generalize factorization to MPI

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!

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

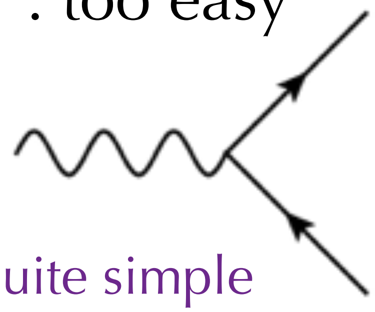
Parton-Parton Cross Section

Hadron-Hadron Cross Section

Colour Confusion

Between which partons do confining potentials arise?

e^+e^- : too easy



(still quite simple even after including bremsstrahlung etc.)

At e^+e^- colliders (eg LEP) : generally good agreement between **measured** particle spectra and **models** based on parton/antenna showers + strings

Basically a single **3-3bar** system, very close to the original lattice studies motivating the string model.

(+ extensions to WW reasonable to ~$O(1/N_c^2)$)

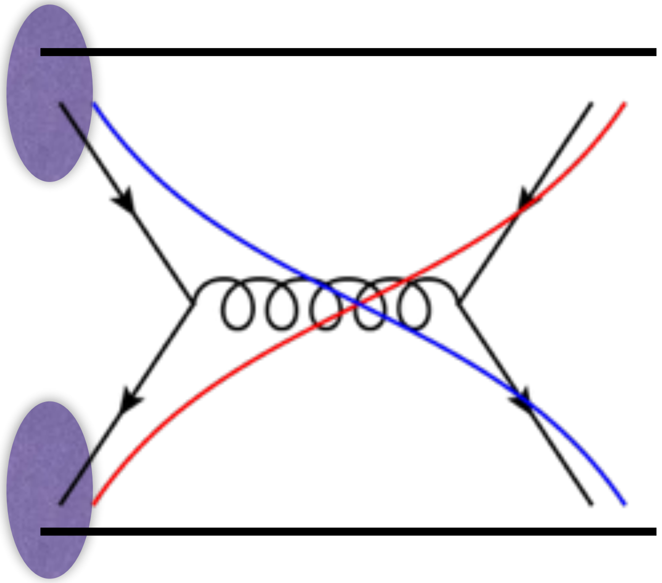
→ re-use same models as input for LHC (universality) ?

Proton-Proton (LHC)

A lot more colour kicked around (& also colour in initial state)

Include "Beam Remnants"

Still might look relatively simple, to begin with



(+baryon beam remnants → "string junctions")

String-fragmentation of junctions: Sjöstrand & Skands **Nucl.Phys. B659 (2003) 243**

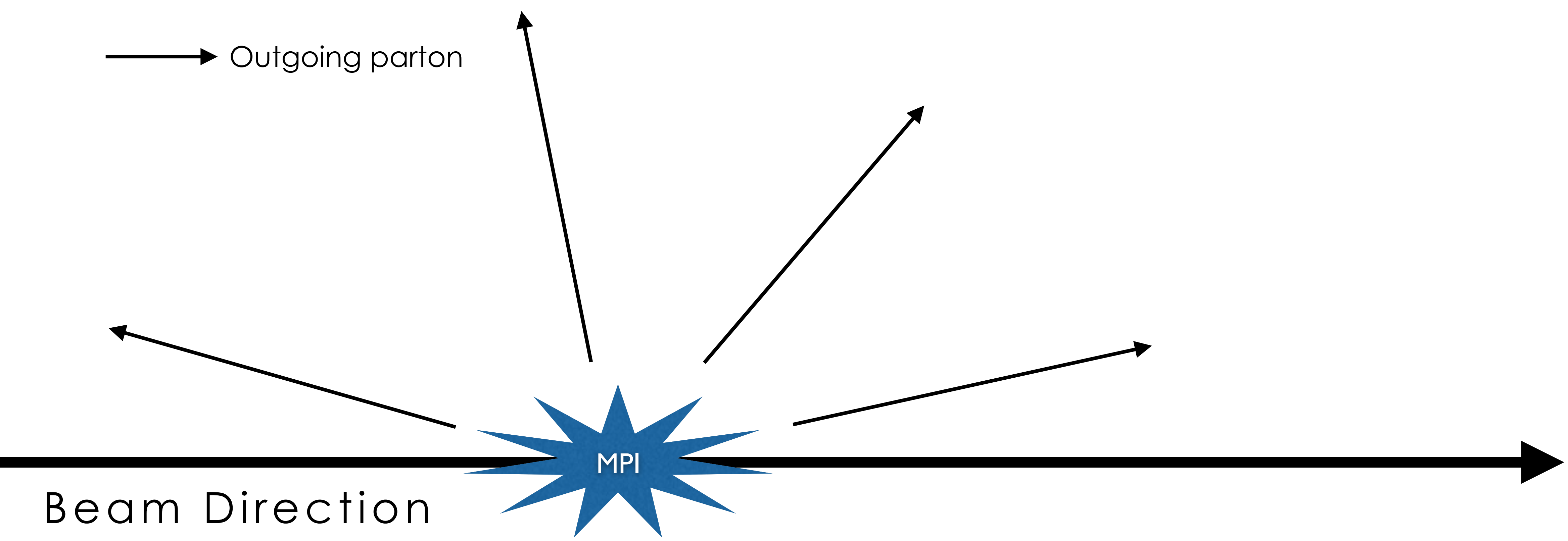
But no law against *several* parton-parton interactions

In fact, can easily be shown to happen frequently
Included in all (modern) Monte Carlo models
But how to make sense of the colour structure?

Colour: What's the Problem?

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

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

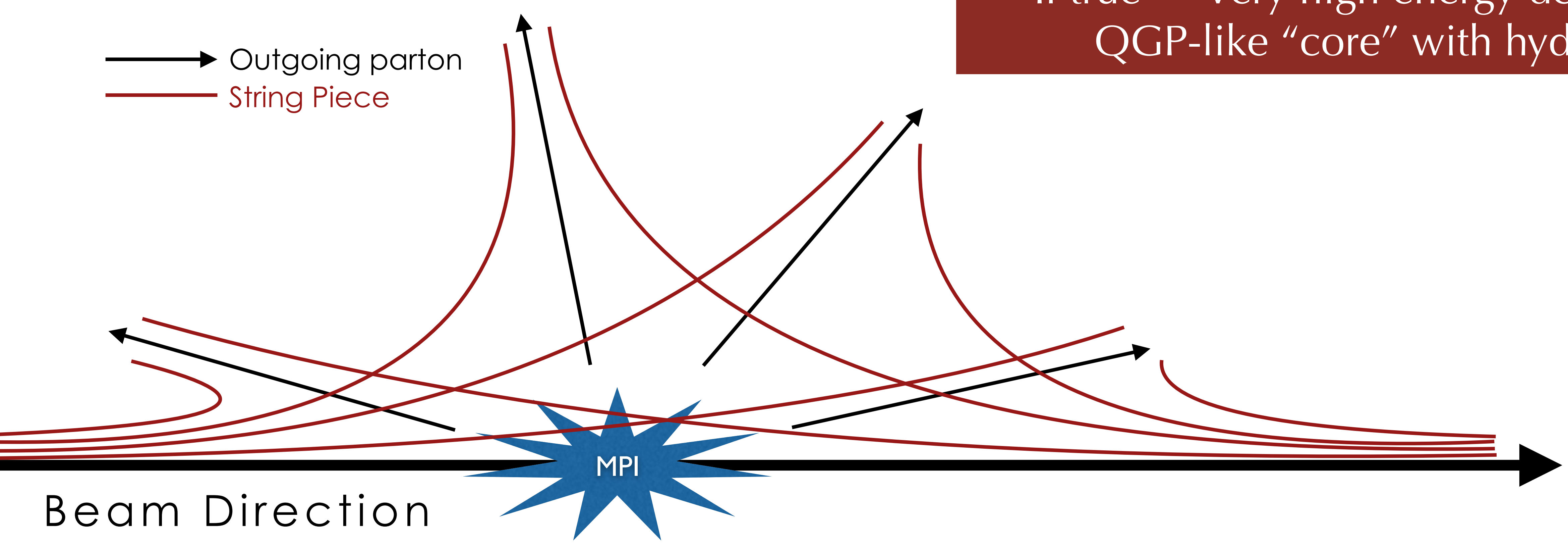


Colour: What's the Problem?

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

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

So many strings in so little space
If true → Very high energy densities
QGP-like "core" with hydro?



→ Thermal? E.g., EPOS

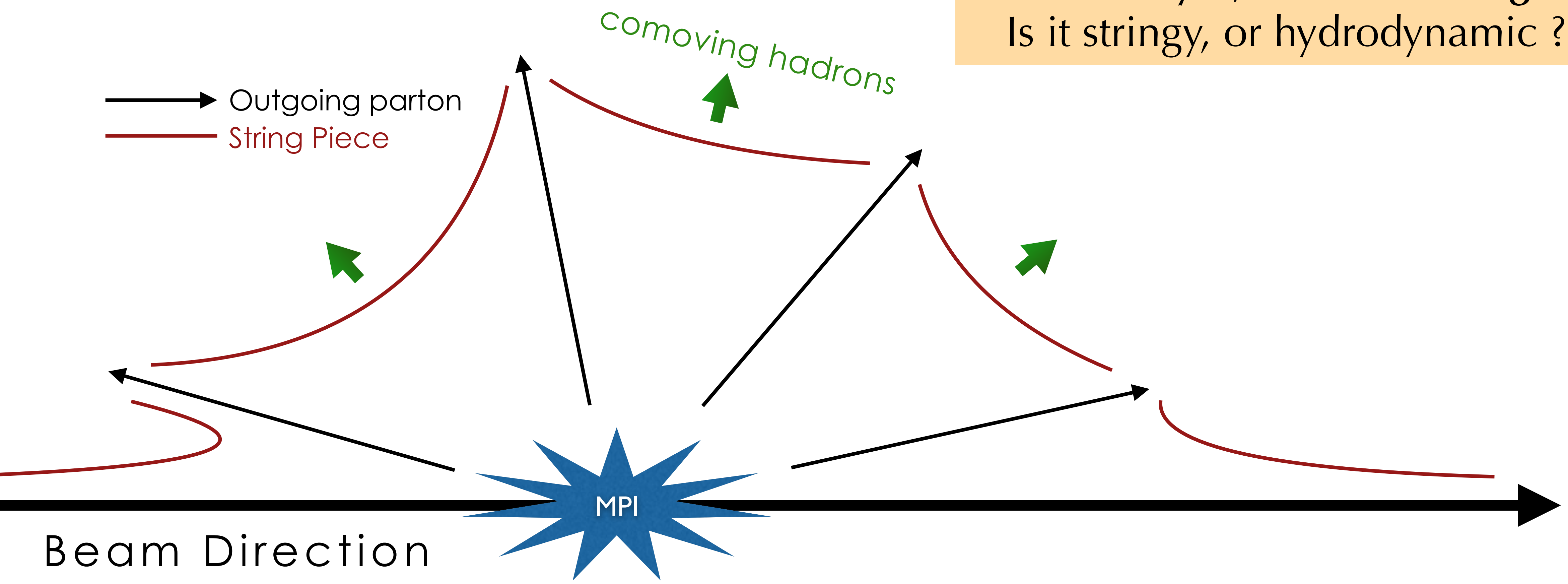
Colour Reconnections

(including **MPI:** Multiple Parton-Parton Interactions ~ the "underlying event")

With Colour Reconnections
MPI hadronize **collectively**

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

Highly interesting theory questions now.
Is there collective flow in pp? Or not?
If yes, what is its origin?
Is it stringy, or hydrodynamic ? (or …?)



String-Length Minimisation E.g., PYTHIA, HERWIG

Or Thermal? E.g., EPOS

Or Higher String Tension? E.g., DIPSY rope

What are "Colour Reconnections"?

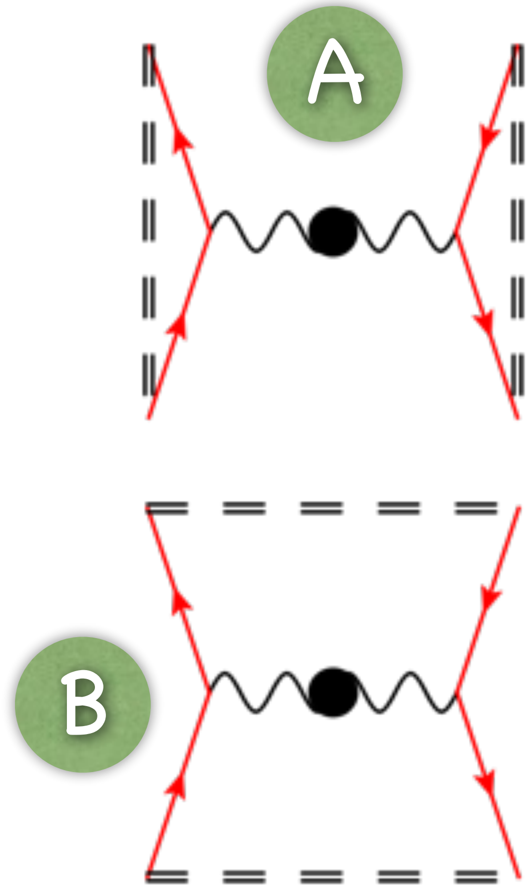
Simple example: $e^+e^- \to W^+W^- \to \text{hadrons}$

Intensely studied at LEP2.

CR implied a non-perturbative uncertainty on the W mass measurement, ΔMW ~ 40 MeV

CR constrained to ~ 10% ~ 1/NC2

Simple two-string system. What about pp?



Several modelling attempts

Based on "just" minimising the string action

String interactions (Khoze, Sjostrand)

Generalized Area Law (Rathsman et al.)

Colour Annealing (Skands et al.)

Gluon Move Model (Sjostrand et al.)

More recently: $SU(3)_C$ group multiplet weights

Dipole Swing (Lonnblad et al.)

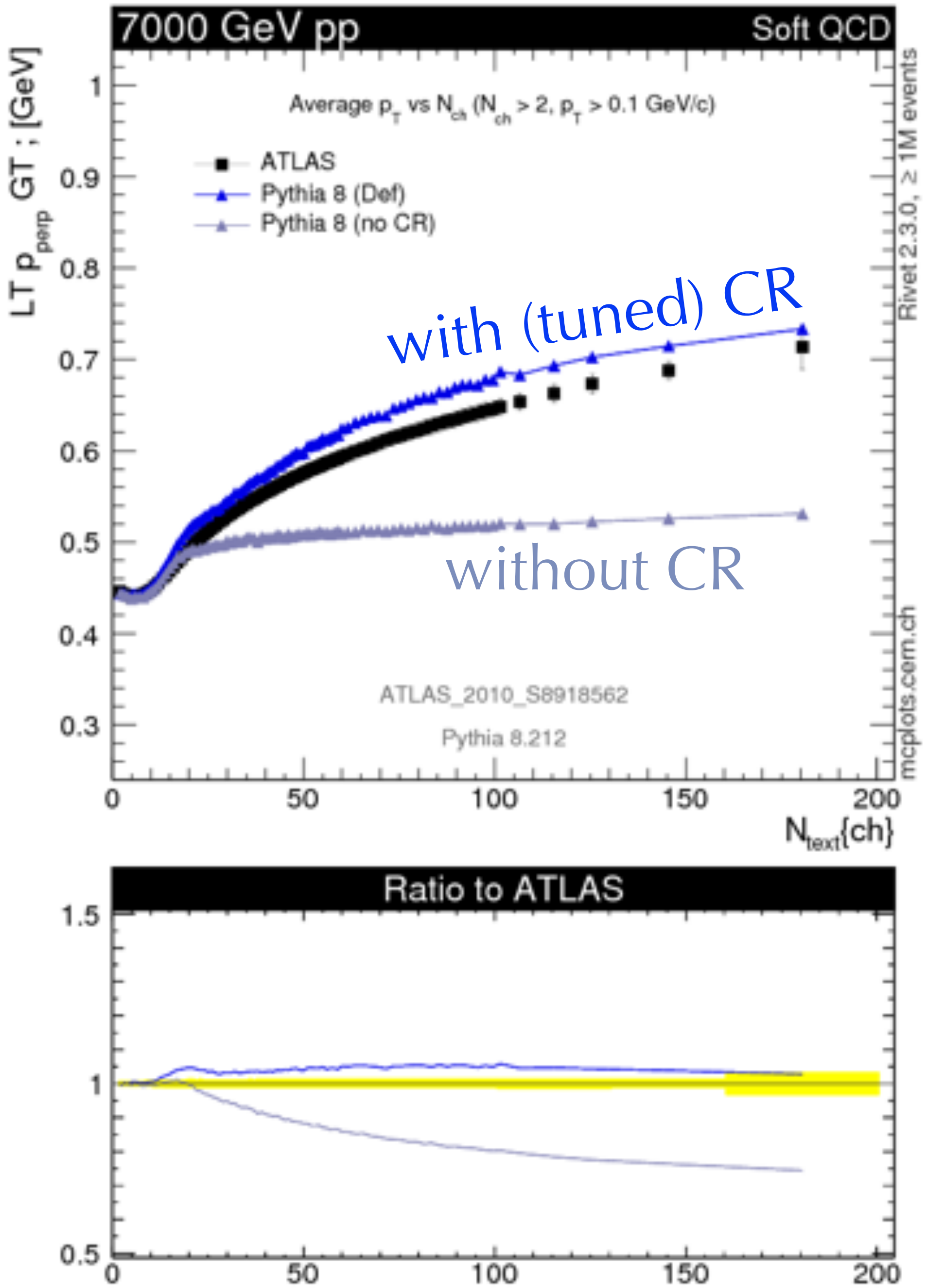
String Formation Beyond Leading Colour (Skands et al.)

$$\begin{aligned} 3 \otimes \bar{3} &= 8 \oplus 1 \\ 3 \otimes 3 &= 6 \oplus \bar{3} \\ 3 \otimes 8 &= 15 \oplus 6 \oplus 3 \\ 8 \otimes 8 &= 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1 \end{aligned}$$

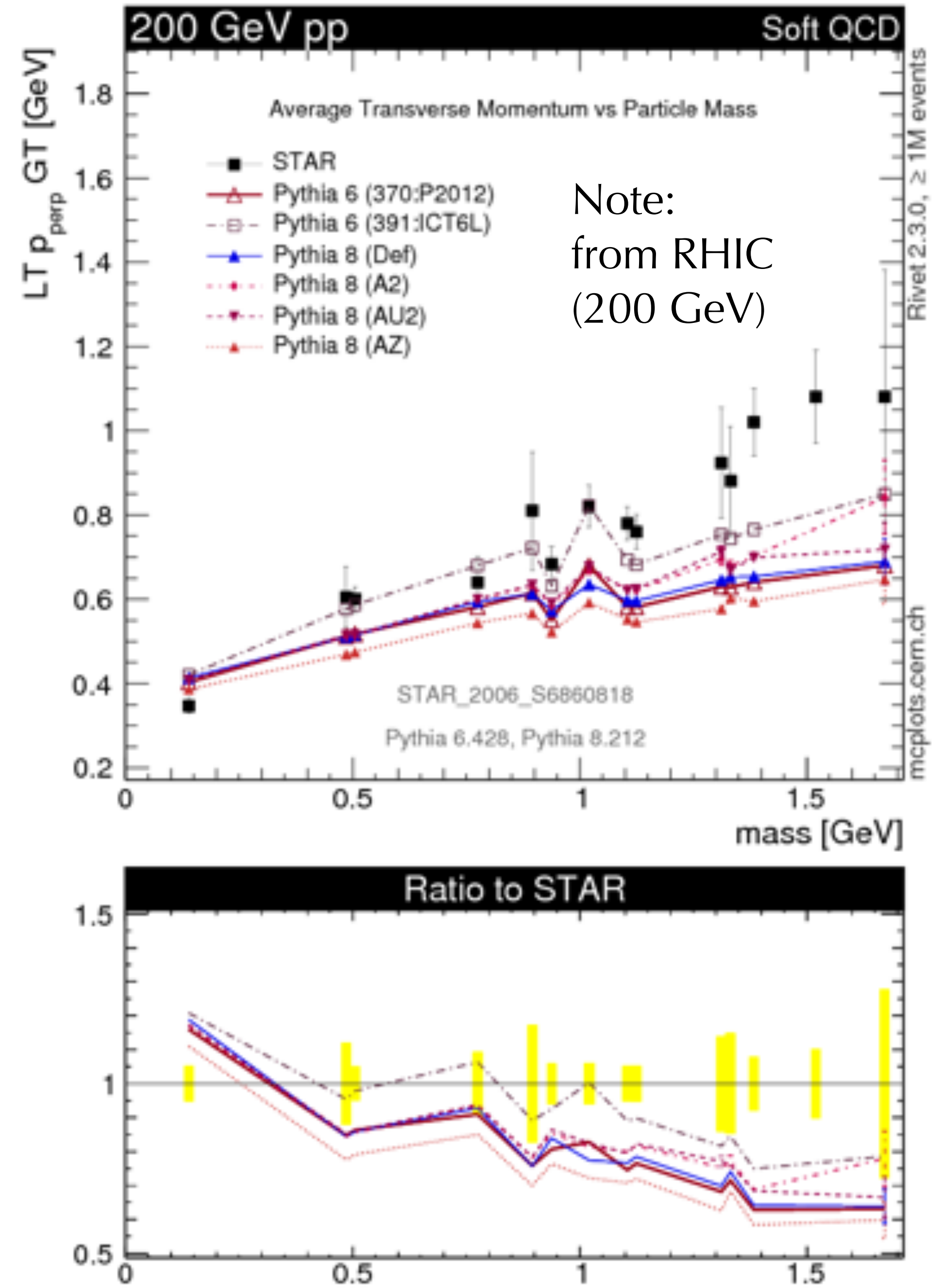
See Christiansen & Skands and references therein, **JHEP 1508 (2015) 003**

What do we see?

<pT> vs Number of Particles



<pT> vs Particle Mass



Average pT increases with particle multiplicity and (faster than predicted) with particle mass