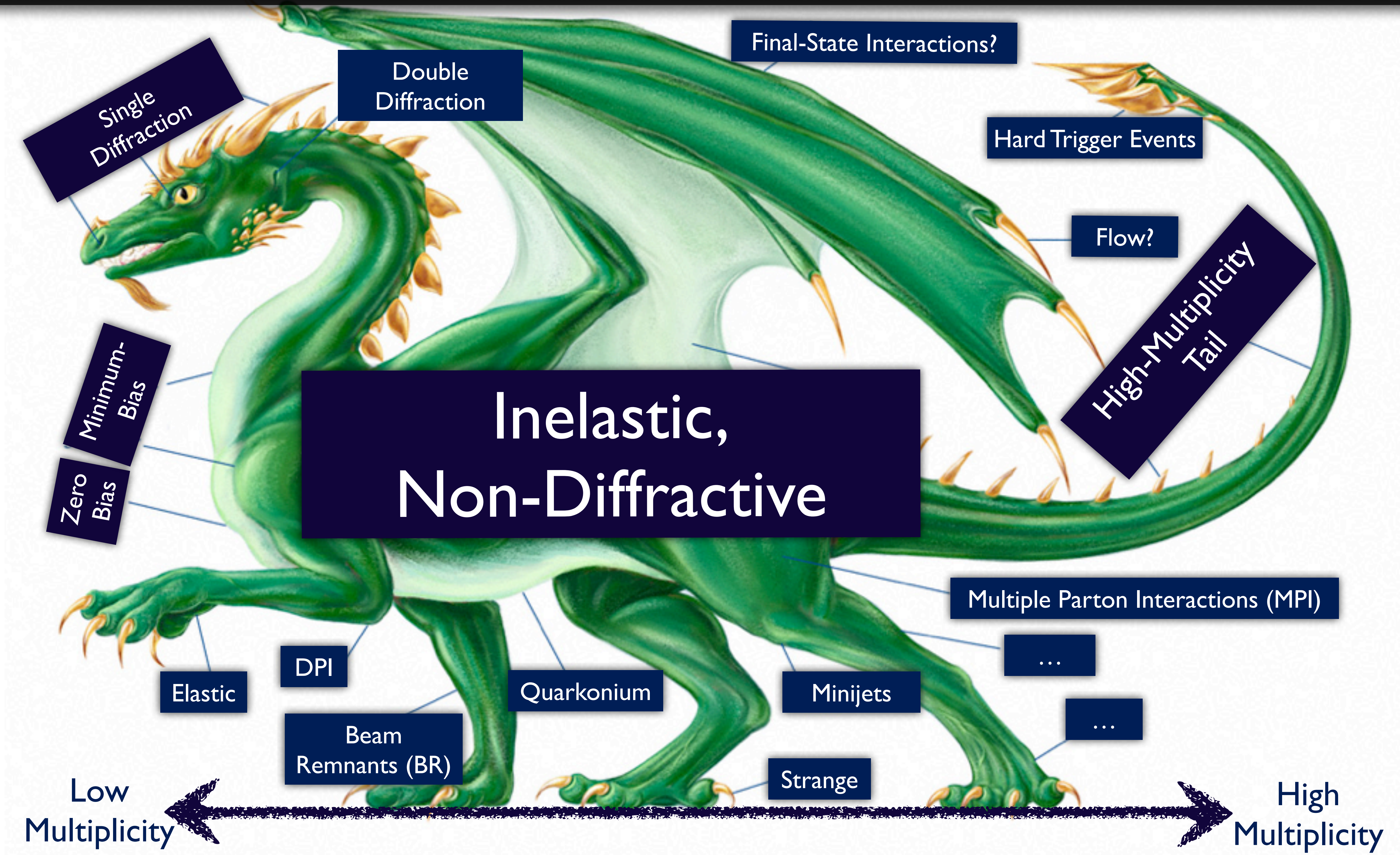
Soft Phenomenology

P. Skands (CERN)

Hadron Collider Physics Symposium, November 2012, Paris

Soft Physics



Terminology

$\sigma_{tot} \approx$		EXPERIMENT		THEORY MODELS
ELASTIC	pp→pp	QED+QCD	~	(*QED = ∞)
SINGLE DIFFRACTION	pp→p+gap+X	Gap = observable	≠	Small gaps suppressed but not zero
DOUBLE DIFFRACTION	pp→X+gap+X	Gap = observable	≠	Small gaps suppressed but not zero
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(+ multi-gap diffraction)

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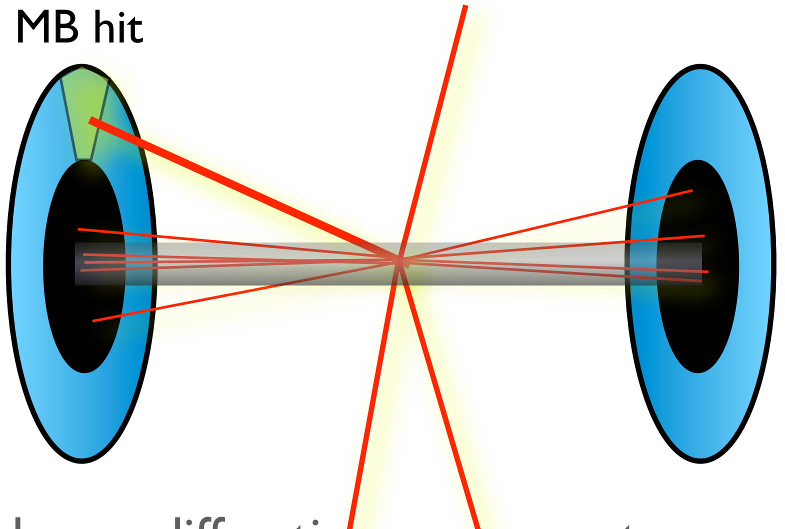


Min-Bias, Zero Bias, Single-Gap, etc.

= Experimental trigger conditions **(hardware-dependent)**

Corrected to hardware-independent reference conditions

"Theory" for Min-Bias?

Really = Model for ALL INELASTIC incl diffraction **(model-dependent)**

Impose model-independent reference conditions to suppress or enhance diffractive components

… in minimum-bias, we typically do not have a hard scale, wherefore *all* observables depend significantly on IR physics …

PS, "Tuning MC Generators: the Perugia tunes", PRD82(2010)074018

A Factorized View

1. Where is the energy going?

Note: only linearized Sphericity is IR safe

Sum(pT) densities, event shapes, mini-jet rates, ctrl&fwd energy flow, energy correlations… ≈ sensitive to pQCD + pMPI

2. How many tracks is it divided onto?

N_{tracks}, dN_{tracks}/dp_T, Associated track densities, track correlations… ≈ sensitive to hadronization + soft MPI

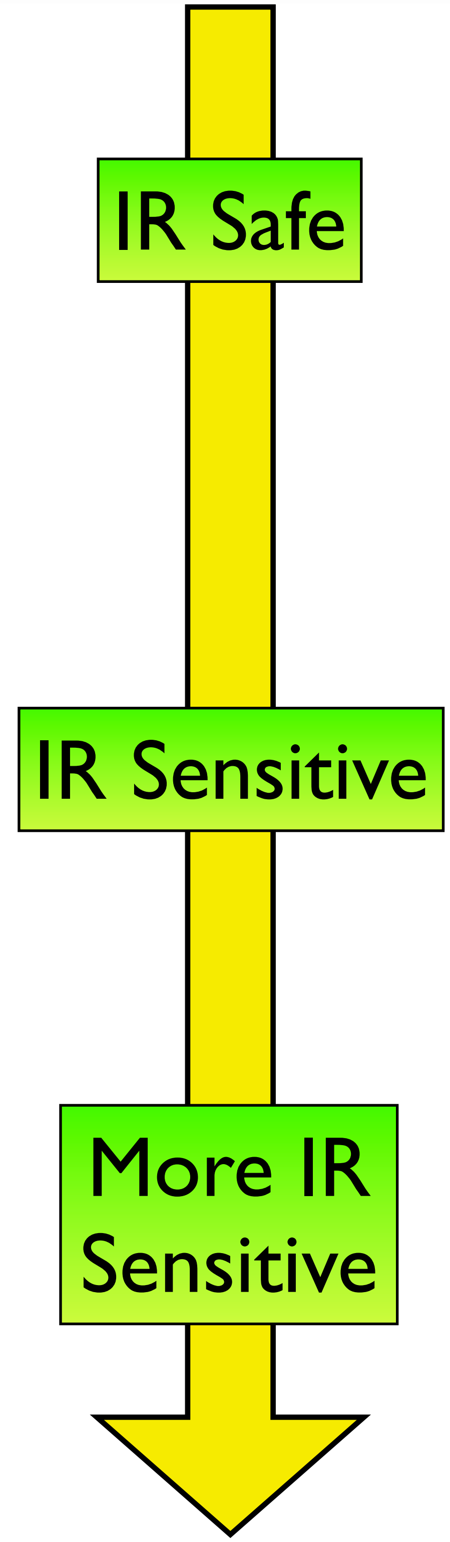
3. Are there gaps in it?

Created by diffraction (and color reconnections?). Destroyed by UE.

4. What kind of tracks?

Strangeness per track, baryons per track, baryon asymmetry, … hadron-hadron correlations ≈ sensitive to details of hadronization

+ collective effects (+Quarkonium sensitive to color reconnections?)



Organized Tuning

Can we be more general than this-tune-does-this, that-tune-does-that?

Yes Schulz & PS, **Eur.Phys.J. C71 (2011) 1644**

The new automated tuning tools can be used to generate unbiased optimizations for different observable regions

Same parameters → consistent model (not just "best tune")

Critical for this task (take home message):

Need "comparable" observable sets for each region

Example: use different collider energies as "regions" → test energy scaling
Other complementary data sets could be used to test other model aspects

QCD Models

A

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA

Elastic & Diffractive
Treated as separate class
No predictivity

Color Screening
Regularization of pQCD

Unitarity
Multiple 2→2
(MPI)

Quarks, Gluons
pQCD
2→2 (Rutherford)

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

Elastic — Min-Bias — Dijets

0 — Λ_{QCD} — 5 GeV — ∞

B

B) Start from Optical Theorem. Extend towards Ultraviolet.
PHOJET, DPMJET

Hadrons
Optical Theorem
pp→pp

Pomerons: Diffraction
Cut Pomerons: Non-diffractive (soft)

Hard Pomeron?

Note: PHOJET & DPMJET use **string fragmentation** (from PYTHIA) → some overlap

Multi-Parton Interactions

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA

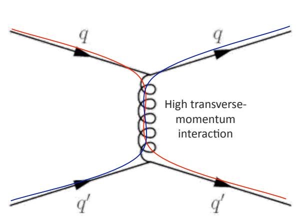
pQCD

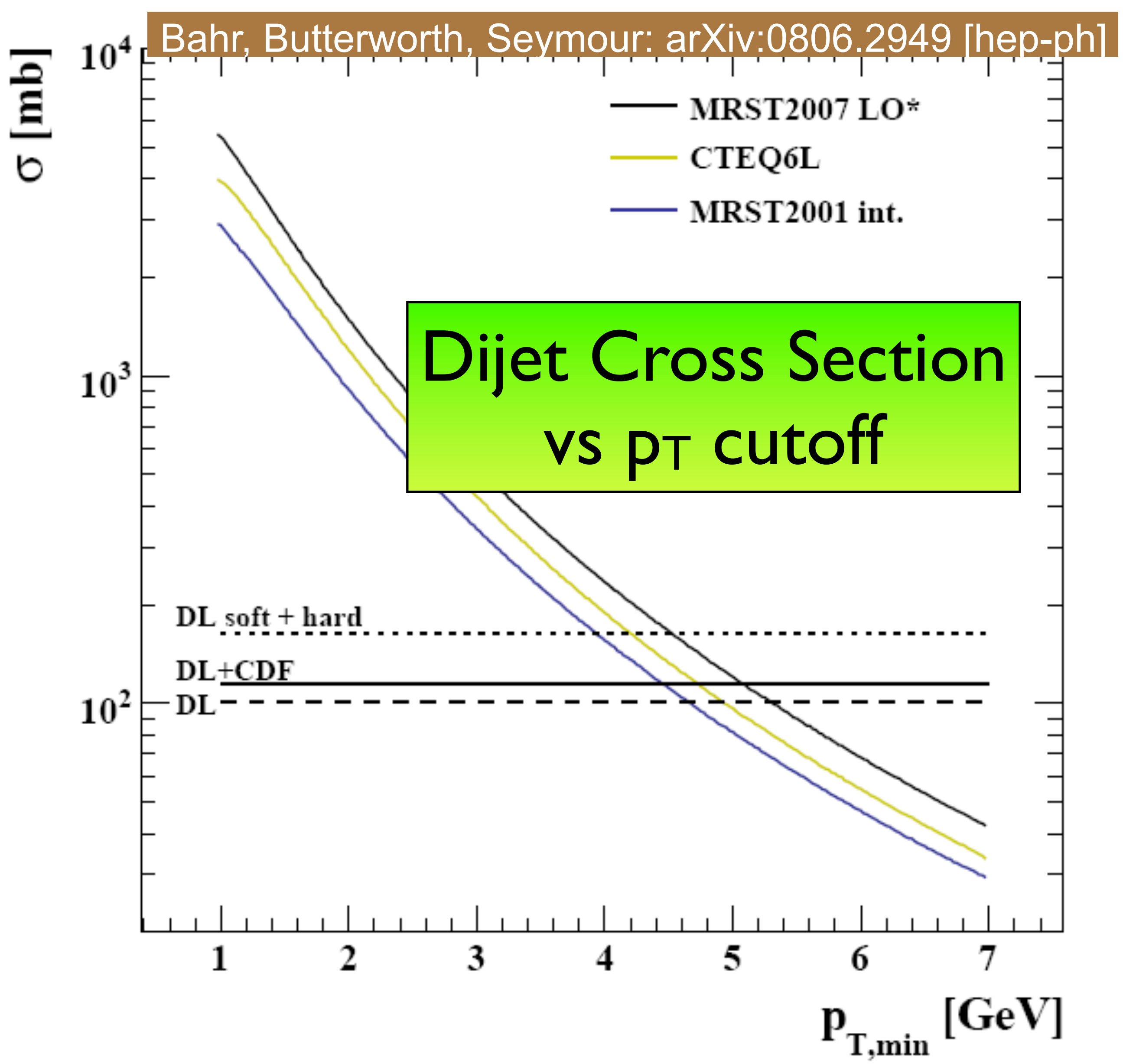
$2 \to 2$

= Sum of

$qq' \to qq'$
$q\bar{q} \to q'\bar{q}'$
$q\bar{q} \to gg$
$qg \to qg$
$gg \to gg$
$gg \to q\bar{q}$

≈ Rutherford
(t-channel gluon)





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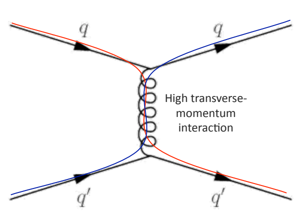

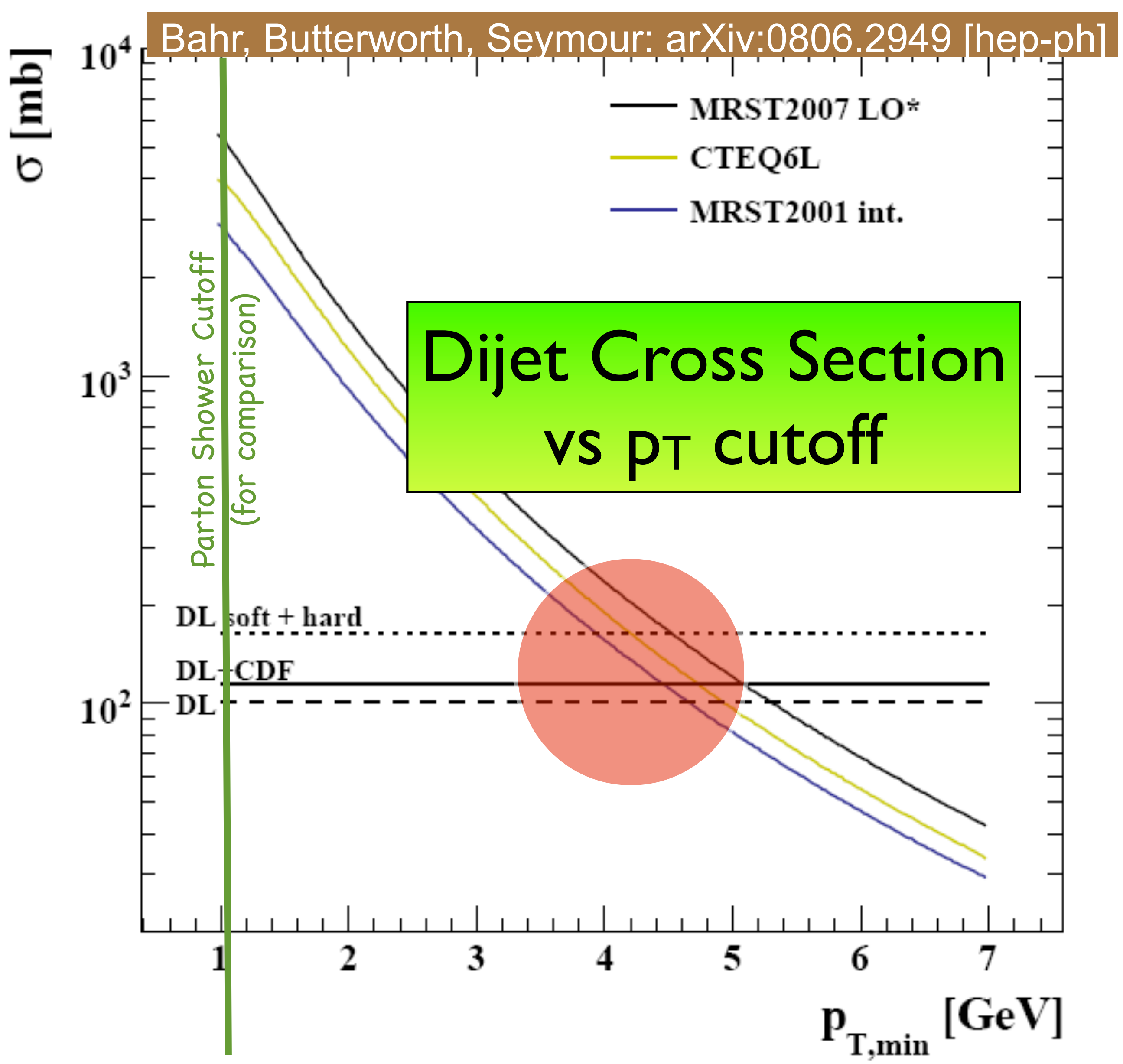

Becomes larger than total pp cross section?

At $p_\perp \approx 5$ GeV

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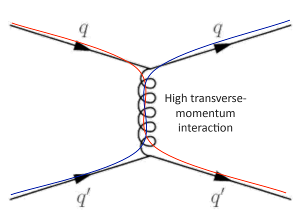

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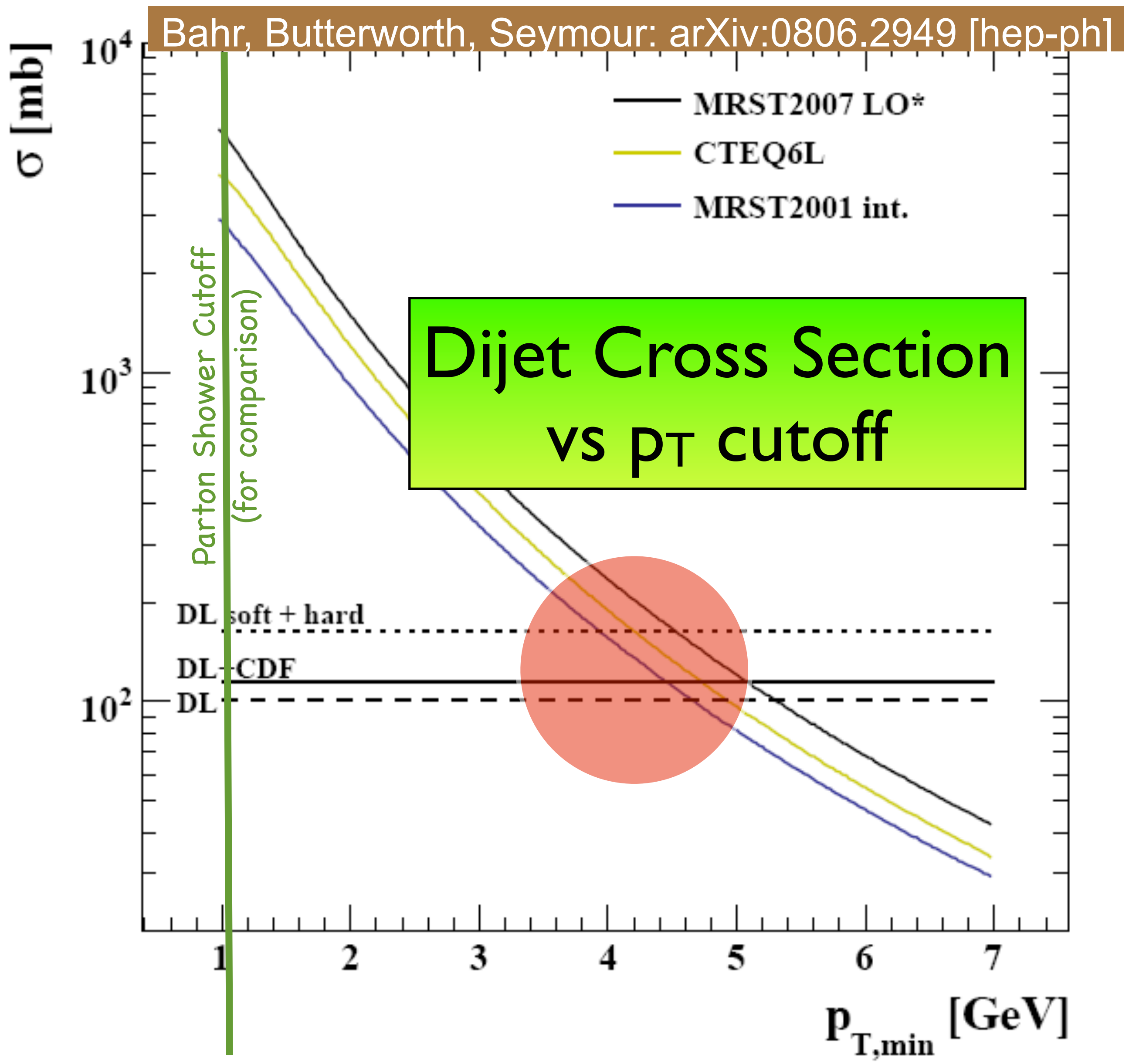

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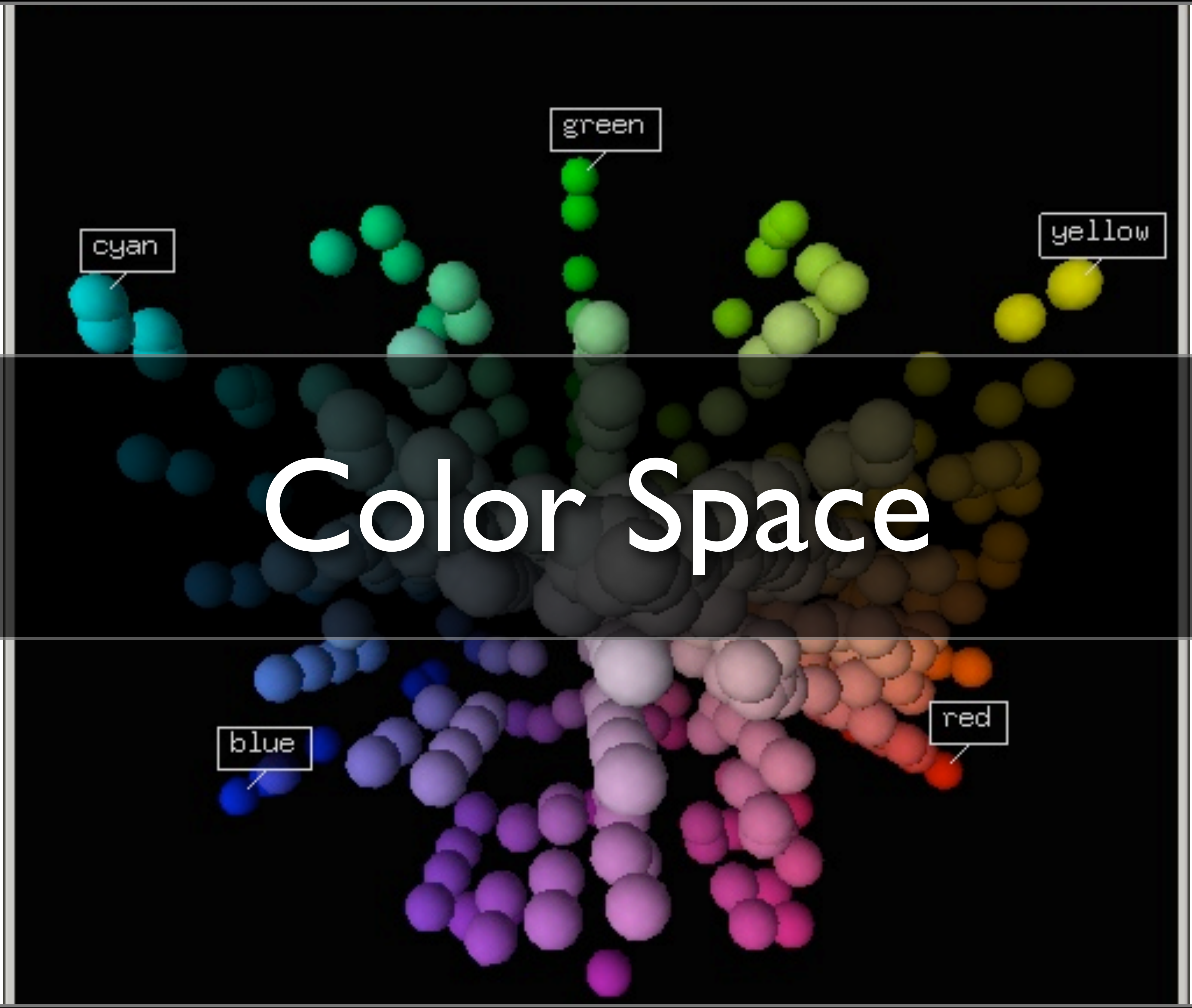
Lesson from bremsstrahlung in pQCD: divergences → fixed-order unreliable, but pQCD still ok <u>if resummed (unitarity)</u>

→ Resum dijets?
Yes → MPI!

Color Space



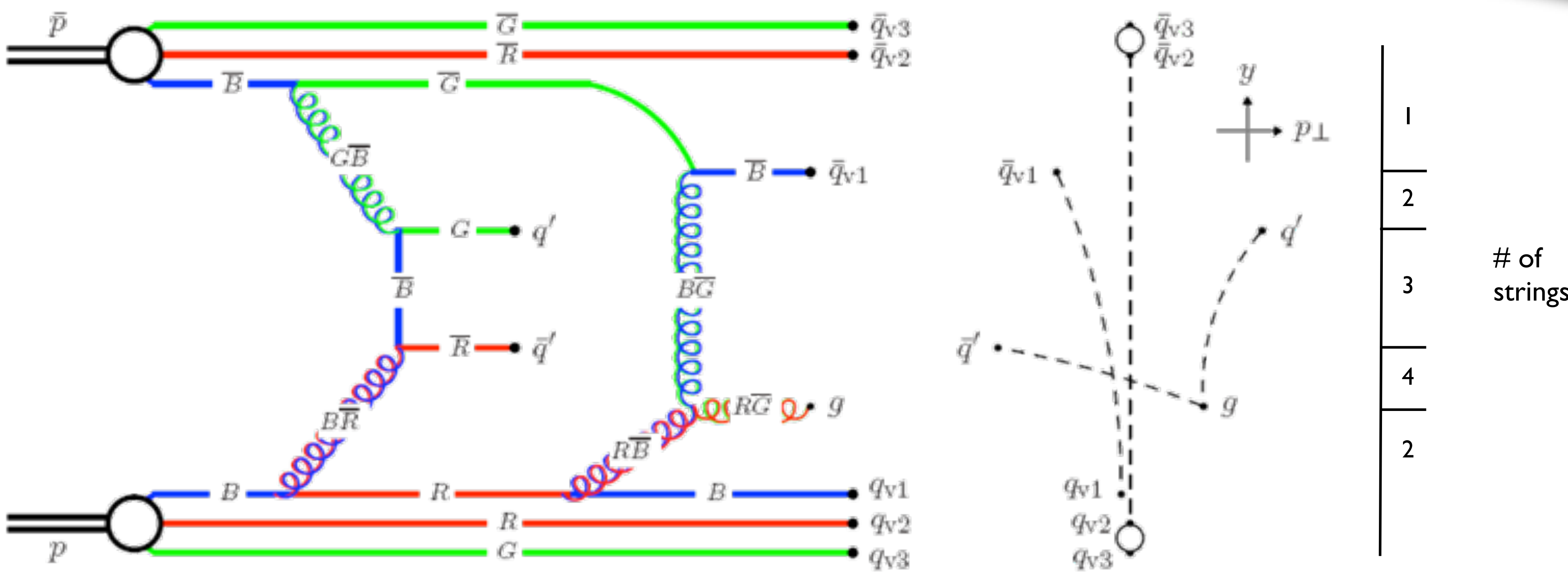
Questions

Colour 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



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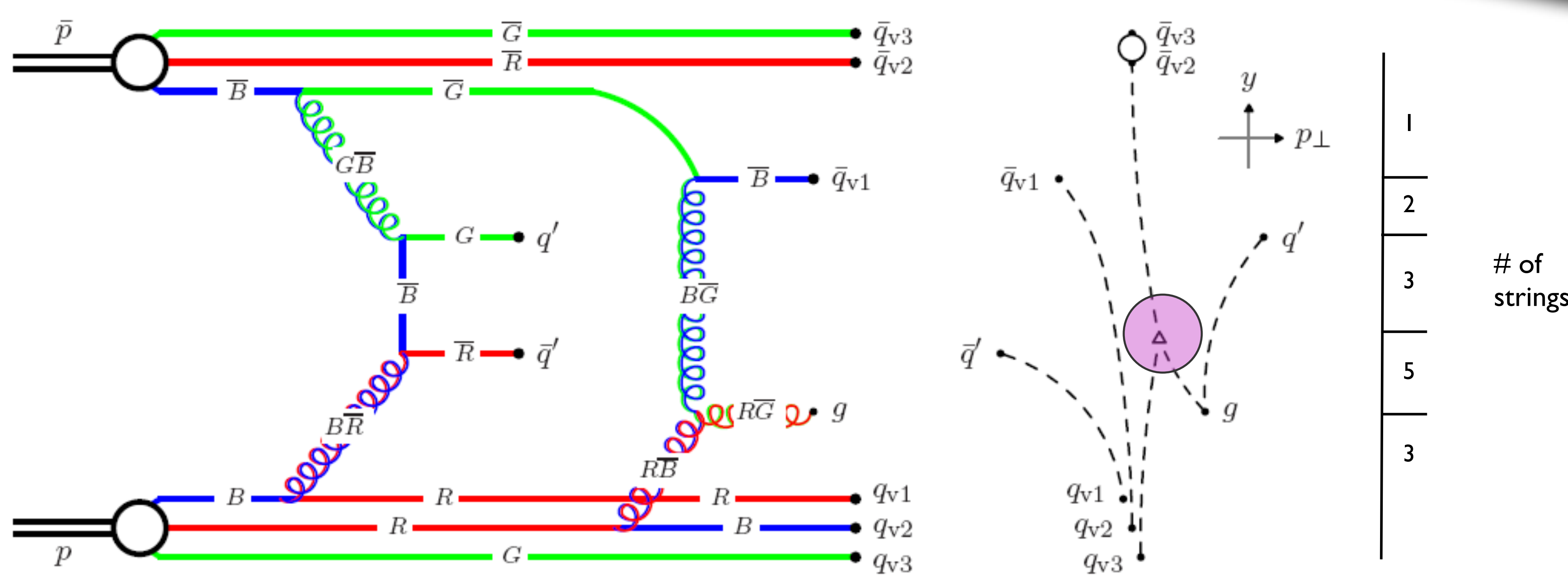

Models

1. Most naive

E.g., PYTHIA 6 with PARP(85)=0.0 & JIMMY/Herwig++

Each MPI ~ independent → separate singlets?

Physically inconsistent with exchanged objects being gluons

Corresponds to the exchange of singlets (uncut Pomerons) → All the MPI are diffractive!

This is just wrong.

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This is just wrong.

2. Valence quarks plus t-channel gluons?

Arrange original proton as (qq)-(q) system, arrange MPI gluons as (qq)-g-g-g-(q)

In which order? Some options:

A) Random (Perugia 2010 & 2011) **or B)** According to rapidity of hard 2→2 systems (Perugia 0)

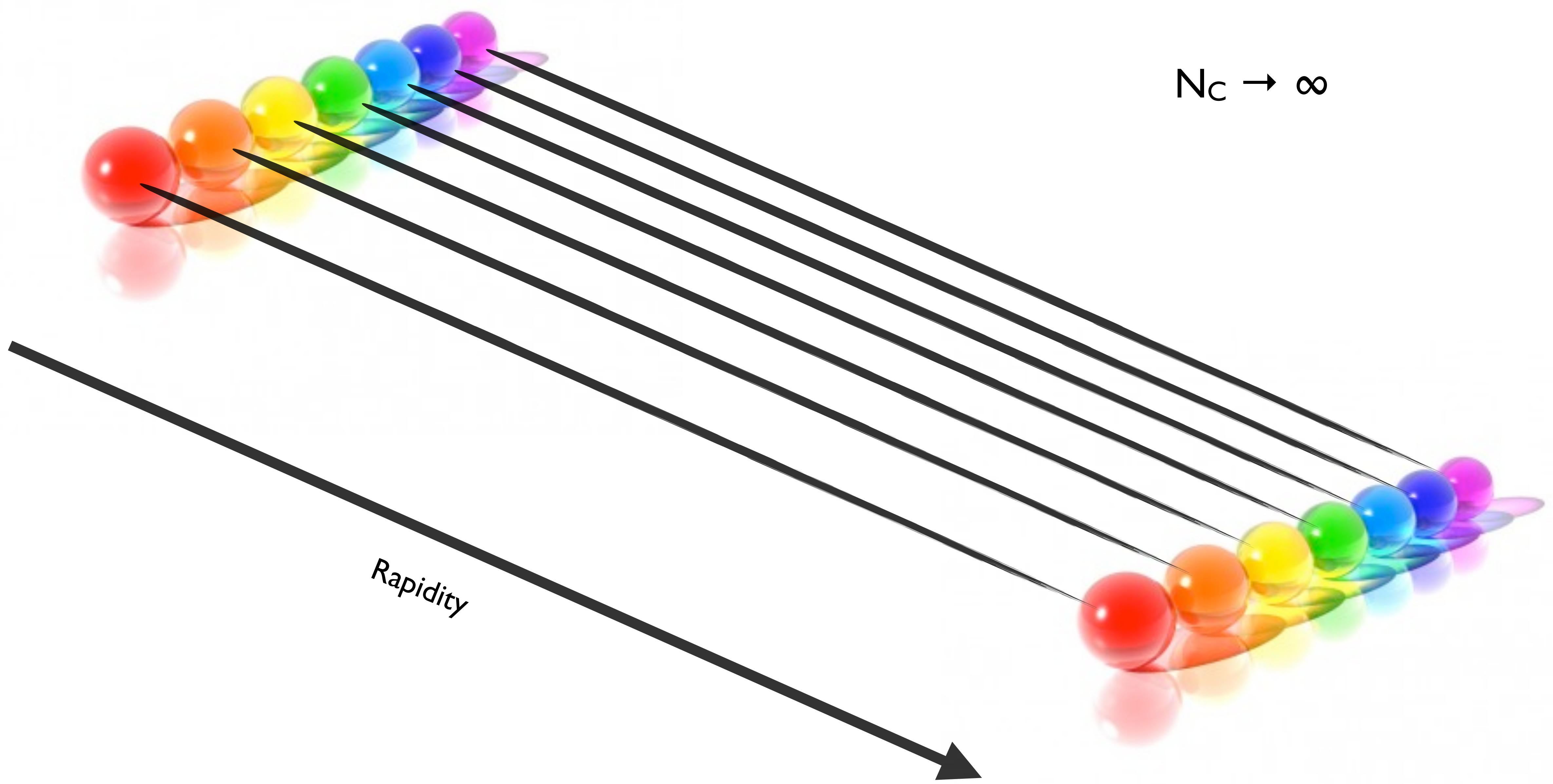
C) By hand, according to rapidity of each outgoing gluon (Tune A, DW, Q20, … + HIJING?)

May be more physical …

But both A & B fail on, e.g., the observed rise of <pT>(Nch) (and C "cheats" by looking at final-state gluons)

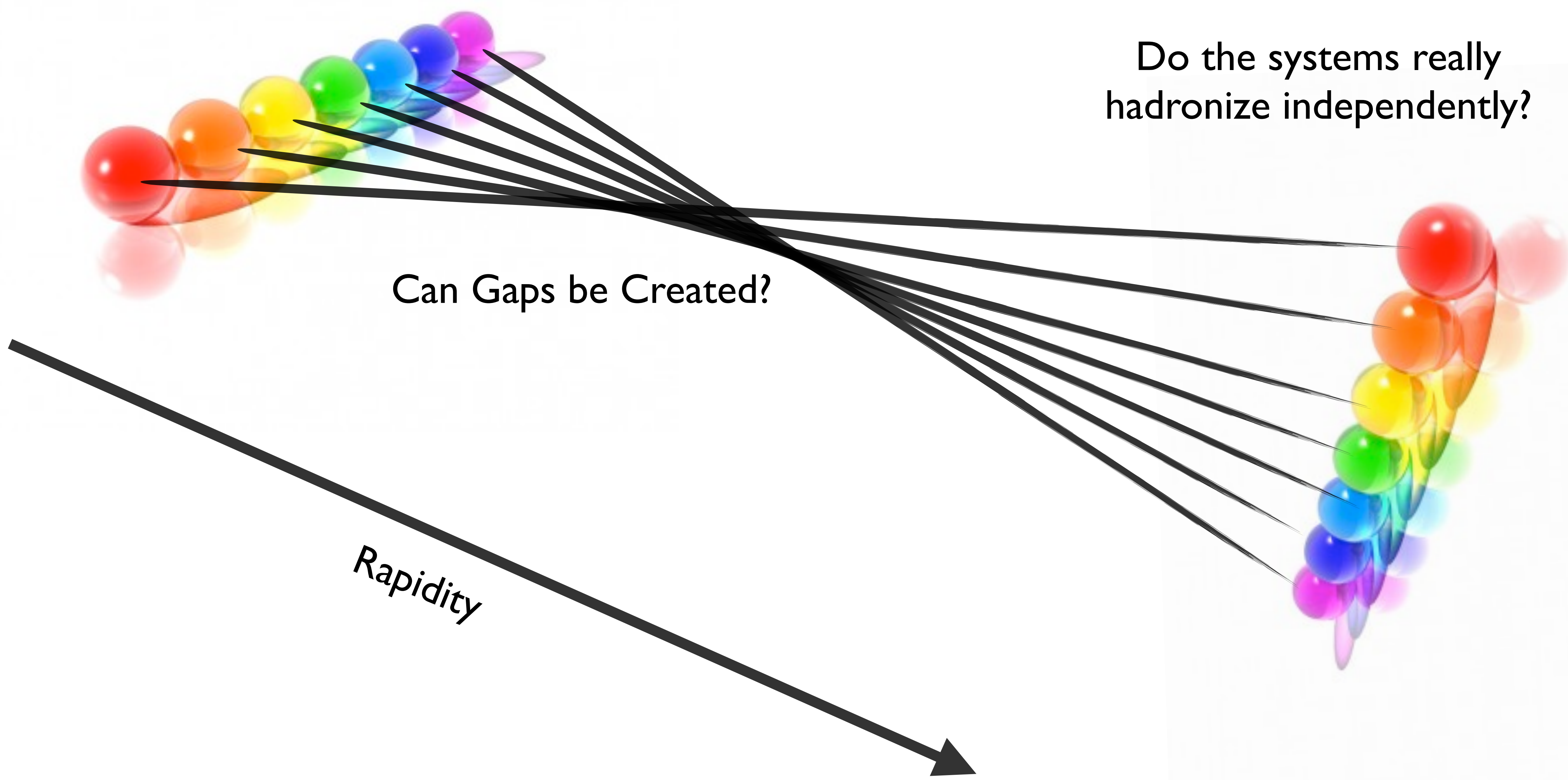
This must still be wrong (though less obvious)

Color Reconnections?



Multiplicity $\propto N_{MPI}$

Color Reconnections?



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

Color Reconnections?

In reality:

The color wavefunction is $N_C = 3$ when it collapses

One parton "far away" from others will only see the sum of their colours → coherence in string formation

On top of this, the systems may merge/fuse/interact with genuine dynamics (e.g., string area law)

And they may continue to do so even after hadronization

Elastically: hydrodynamics? Collective flow?

Inelastically: re-interactions?

New: basic hadron 2→2 re-interaction model in PYTHIA 8.157

This may not be wrong. But it sounds difficult!

→ Color Reconnections (in PYTHIA) , Color Disruption (in HERWIG)

Brief News from PYTHIA 8

PYTHIA 8.157 released Nov 11

Diffraction

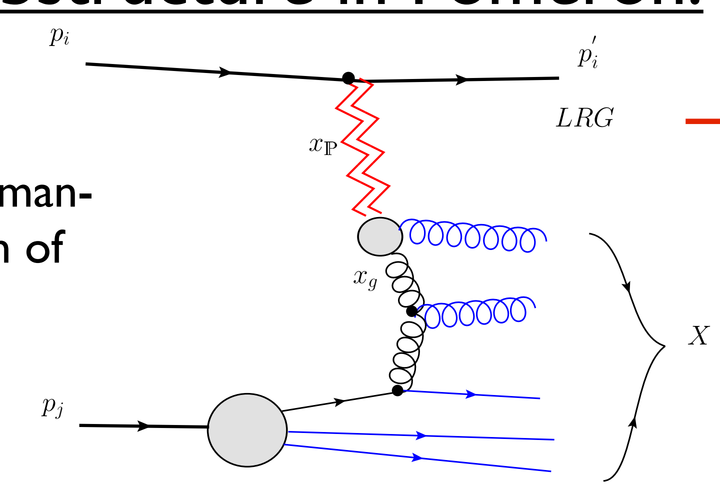
Diffractive Cross Section Formulæ:

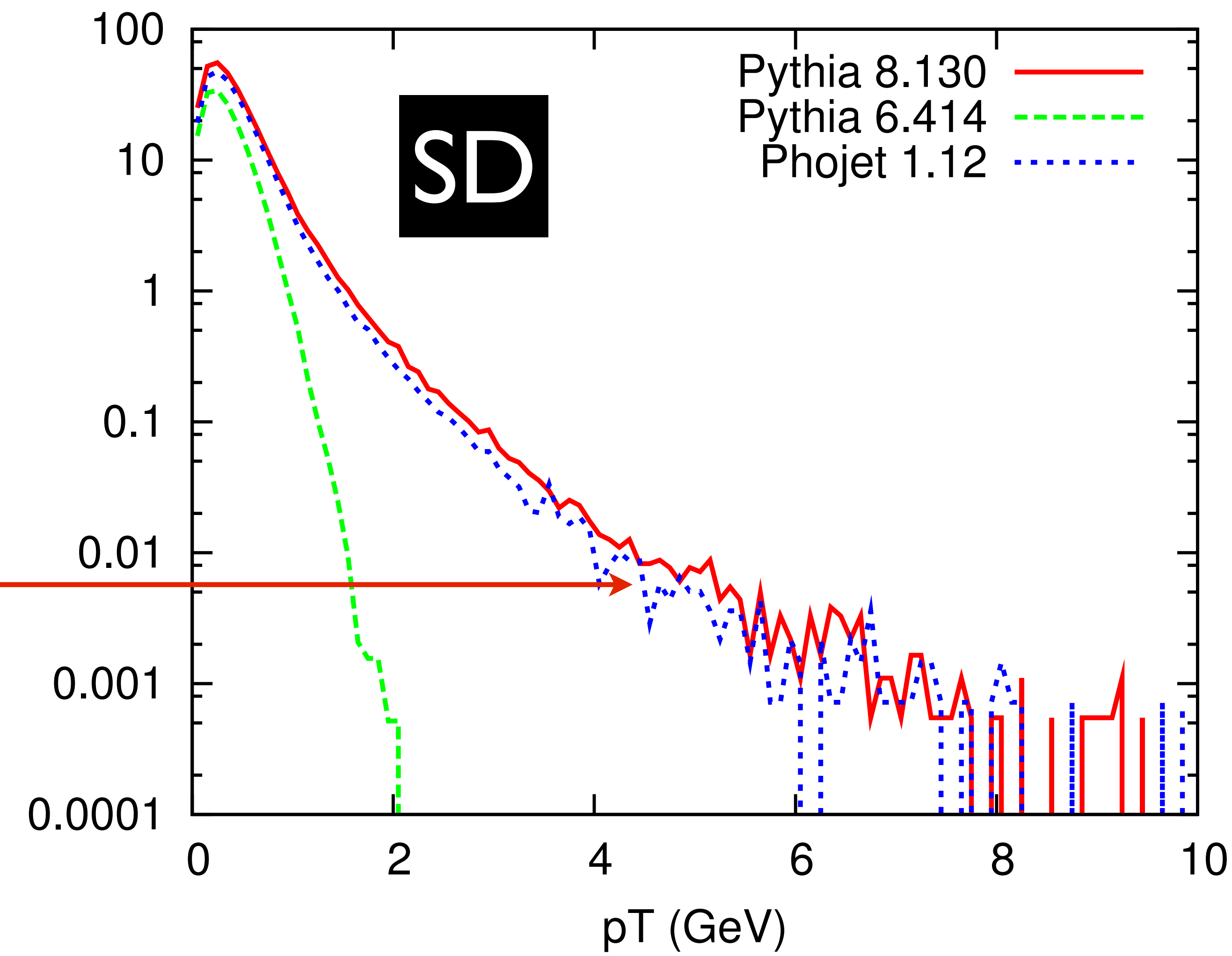
$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta^2_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\ ,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g^2_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\ .$$

Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt





- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used

PYTHIA 8

- $M_X > 10\,\mathrm{GeV}$: new perturbative description used (incl full MPI+showers for $\mathbb{P}$p system)

Choice between 5 Pomeron PDFs. Free parameter $\sigma_{\mathbb{P}p}$ needed to fix $\langle n_{\text{interactions}}\rangle = \sigma_{\text{jet}}/\sigma_{\mathbb{P}p}$.

Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}p}$.

Navin, arXiv:1005.3894

The Matter Distribution

Default in PYTHIA (and all other MC*)

*: except DIPSY

Factorization of longitudinal and transverse degrees of freedom

f(x,b) = f(x) × g(b)

Corke, Sjöstrand, arXiv:1101.5953

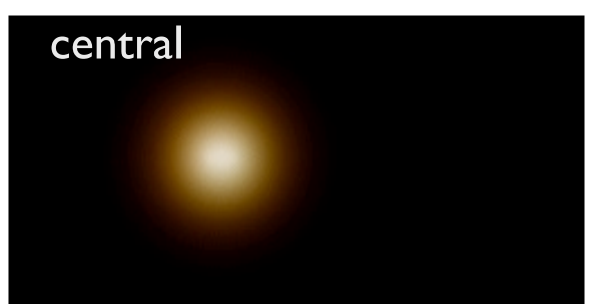
An x-dependent Model for Phenomenological Studies

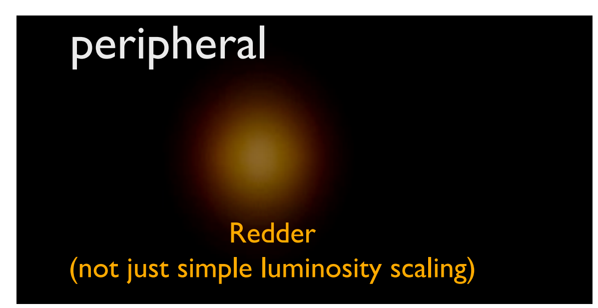
Mass distribution = Gaussian but with x-dependent width (wider at low x)

$$\rho(r,x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \qquad a(x) = a_0\left(1 + a_1 \ln\frac{1}{x}\right)$$

PYTHIA 8
E.g., Tune 4Cx

Constrain by requiring a_1 responsible for growth of cross section

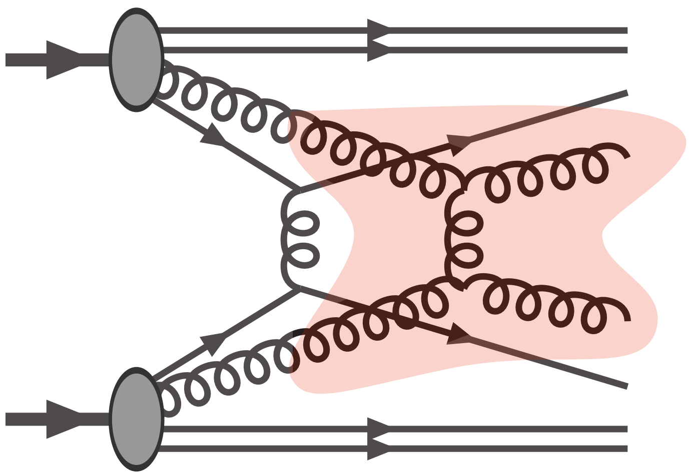




High x concentrated at low b → hard interactions stronger bias for central collisions → relatively larger pedestal effect (<UE>/<MB>)
Less variation at large x? (e.g., smaller ATLAS UE "RMS" distributions)

Other News in PYTHIA 8

Can choose 2nd MPI scattering

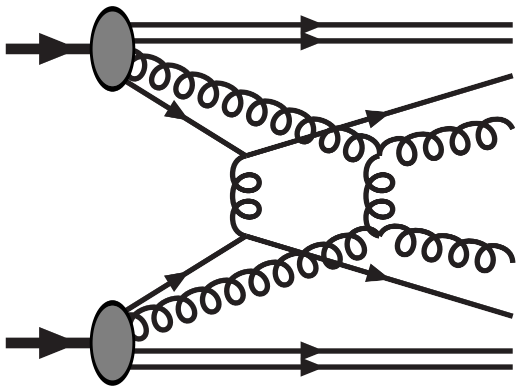


- TwoJets (with TwoBJets as subsample)
- PhotonAndJet, TwoPhotons
- Charmonium, Bottomonium (colour octet framework)
- SingleGmZ, SingleW, GmZAndJet, WAndJet
- TopPair, SingleTop

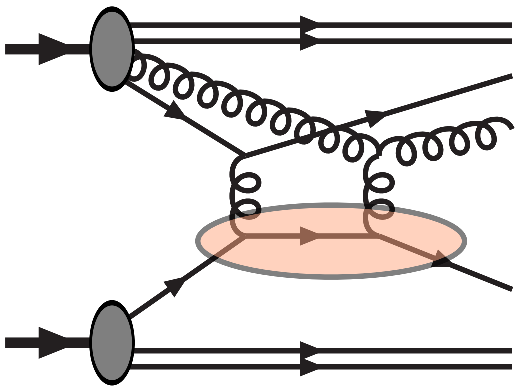
See the PYTHIA 8 online documentation, under "A Second Hard Process"

Rescattering

Often assume that MPI =



. . . but should also include



An explicit model available in PYTHIA 8

Same order in α_S, $\sim$ same propagators, but
• one PDF weight less $\Rightarrow$ smaller σ

Corke, Sjöstrand, JHEP 01(2010)035

Summary

How did the models fare?

Lots could be said…

Bottom line:

Not too bad on averages

E.g., UE level underpredicted by ~ 10% relative to Tevatron tunes (I won my bet!)

Significant discrepancies on more exclusive physics

Strangeness

p_T spectra

High-multiplicity tail (+ridge!) → needs more study!

Baryon production and baryon transport

No single model/tune does it all **… (game still open)**