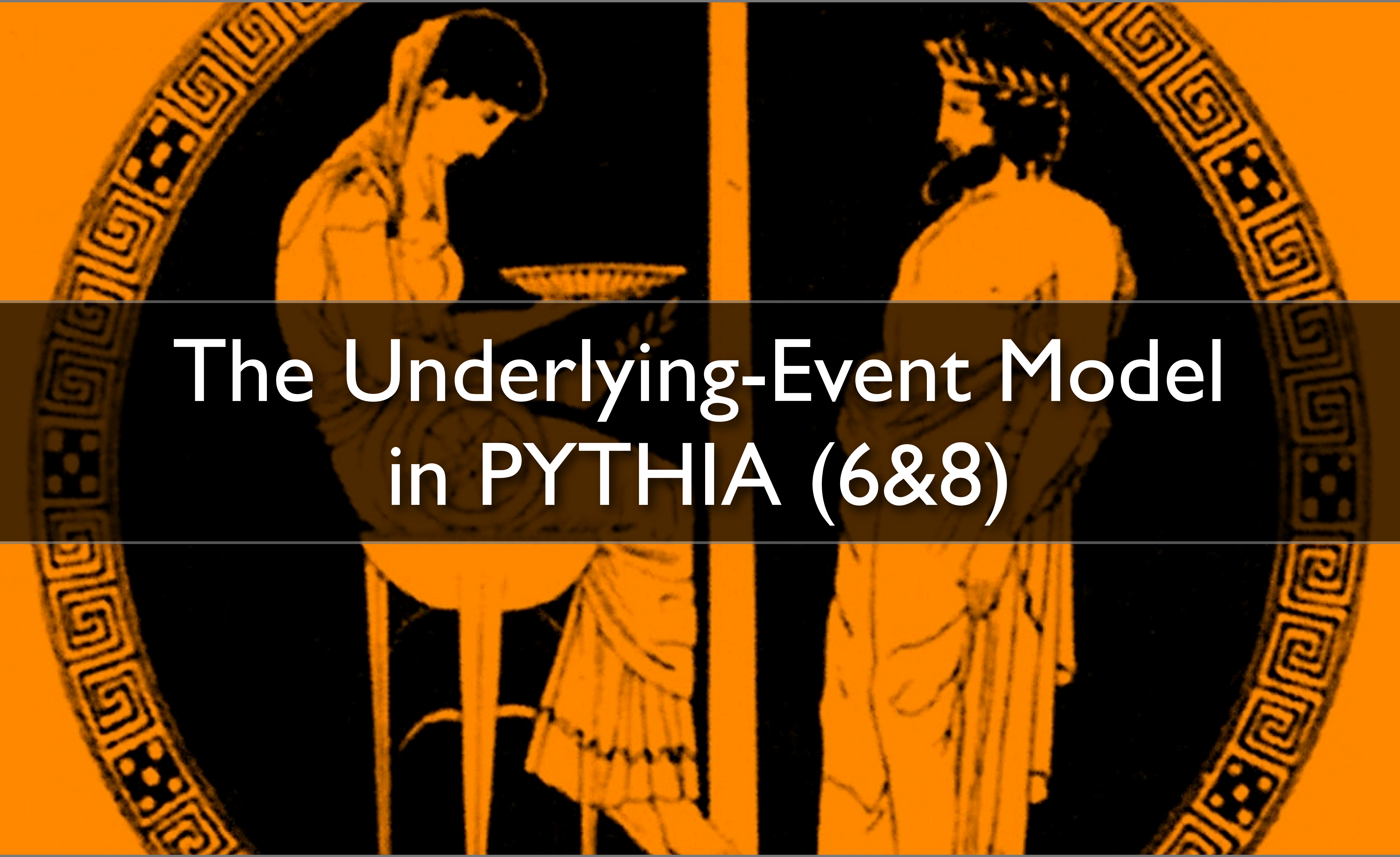


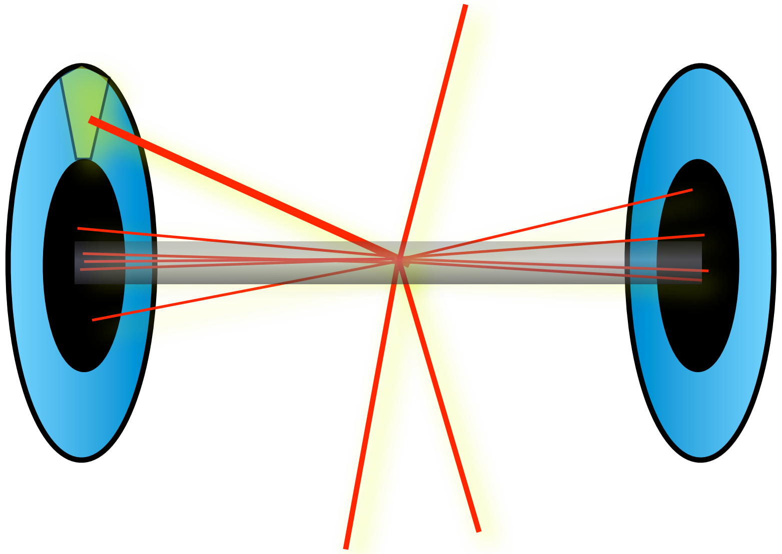
The Underlying-Event Model in PYTHIA (6&8)

Peter Skands (CERN)

Models of Soft-inclusive Physics

Min-Bias, Zero Bias, etc.

= Experimental trigger conditions



"Theory for Min-Bias"?

Really = Model for ALL INELASTIC

But … how can we do that?

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

A) Start from perturbative model (dijets) and extend to IR

B) Start from soft model (Pomerons) and extend to UV

MPI a la PYTHIA

Multiple Perturbative Parton-Parton Interactions

A) Start from perturbative model (dijets) and extend to IR

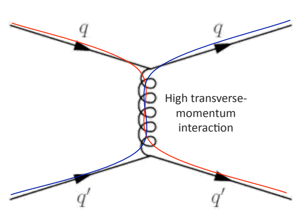
pQCD

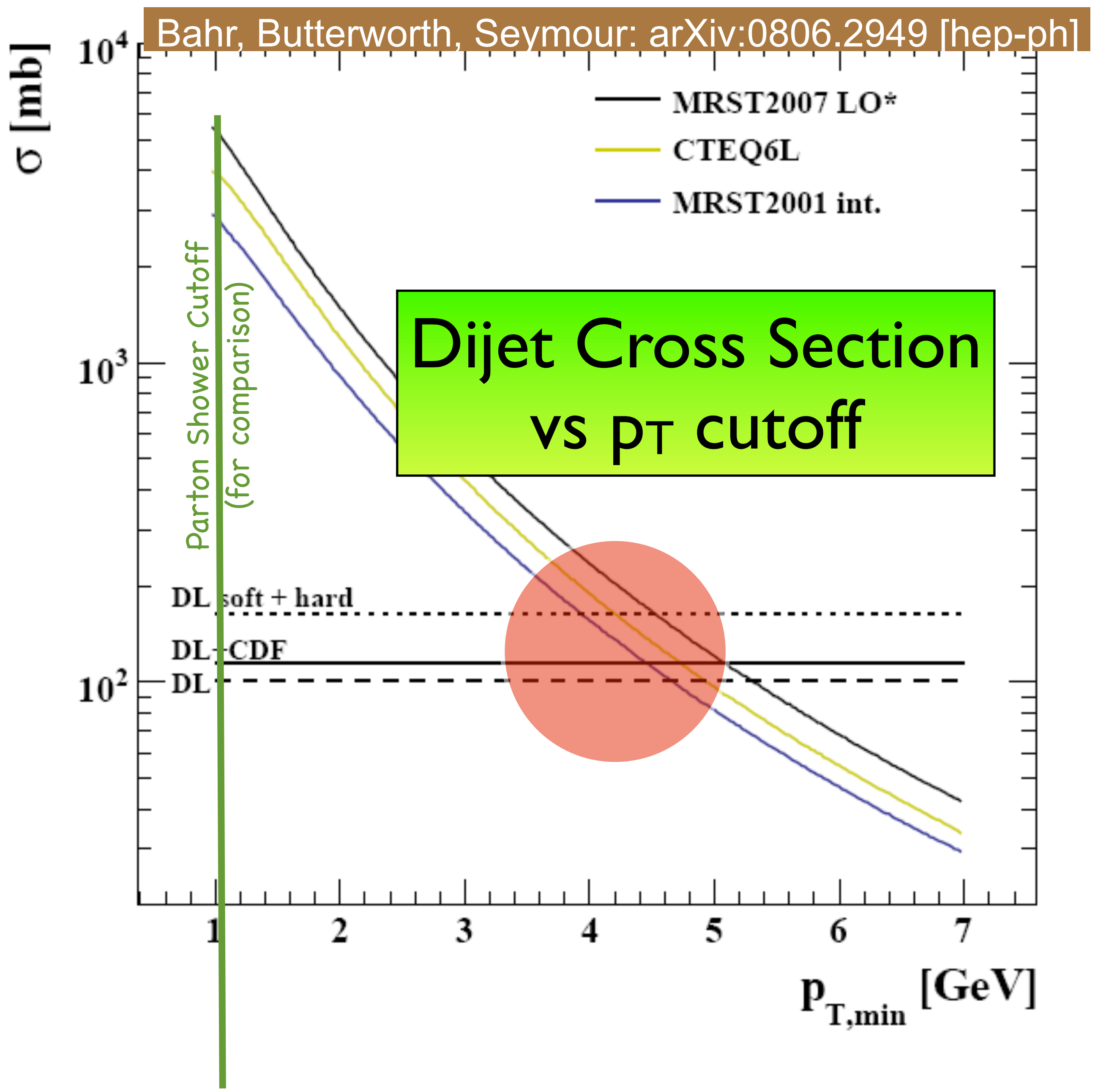
2→2

= 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)





Becomes larger than total pp cross section?

At $p_\perp \approx 5$ GeV

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

→ Resum dijets?
Yes → MPI!

MPI a la PYTHIA

Multiple Perturbative Parton-Parton Interactions

A) Start from perturbative model (dijets) and extend to IR

pQCD

2→2

= Sum of

$qq' \to qq'$
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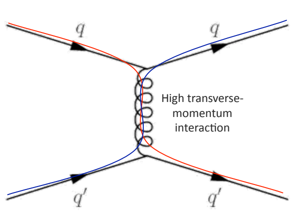


Regularise cross section with $p_{\perp 0}$ as free parameter

IR Regularization

$$\frac{d\hat{\sigma}}{dp_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with energy dependence

Energy Scaling

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}}\right)^{\epsilon}$$

See, e.g., new MCnet Review: *"General-purpose event generators for LHC physics"*, arXiv:1101.2599

Normalize to total cross section:

$$f(x_\perp) = \frac{1}{\sigma_{\mathrm{nd}}(s)} \frac{d\sigma}{dx_\perp} \qquad x_\perp = 2p_\perp / E_{\mathrm{cm}}$$

+ Resum/Unitarize → Probability for a 2→2 interaction at x_{T1} =

$$f(x_{\perp 1}) \exp\left\{ - \int_{x_{\perp 1}}^{1} f(x'_\perp)\, dx'_\perp \right\}$$

→ This is now our basic (UV & IR) 2→2 cross section

Naive Factorization: σ_{eff}

Interactions independent (naive factorization) → Poisson

Often used for simplicity

(i.e., assuming corrections are small / suppressed)

CDF Collaboration, Phys. Rev. Lett. 79 (1997) 584

Measurement of Double Parton Scattering in $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.8 Tev

The double parton scattering (DP) process [1], in which two parton-parton hard scatterings take place within one $\overline{p}p$ collision, can provide information on both the distribution of partons within the proton and on possible parton-parton correlations, topics difficult to address within the framework of perturbative QCD. The cross section for DP comprised of scatterings A and B is written

$$\sigma_{DP} \equiv \frac{\sigma_A \sigma_B}{\sigma_{eff}}, \quad (1)$$

with a process-independent parameter σ_{eff} [2–5]. This expression assumes that the number of parton-parton interactions per collision is distributed according to Poisson statistics [6], and that the two scatterings are distinguishable [7]. Previous DP measurements have come

$\sigma_{eff} \approx$ "first moment" of true MPI distributions

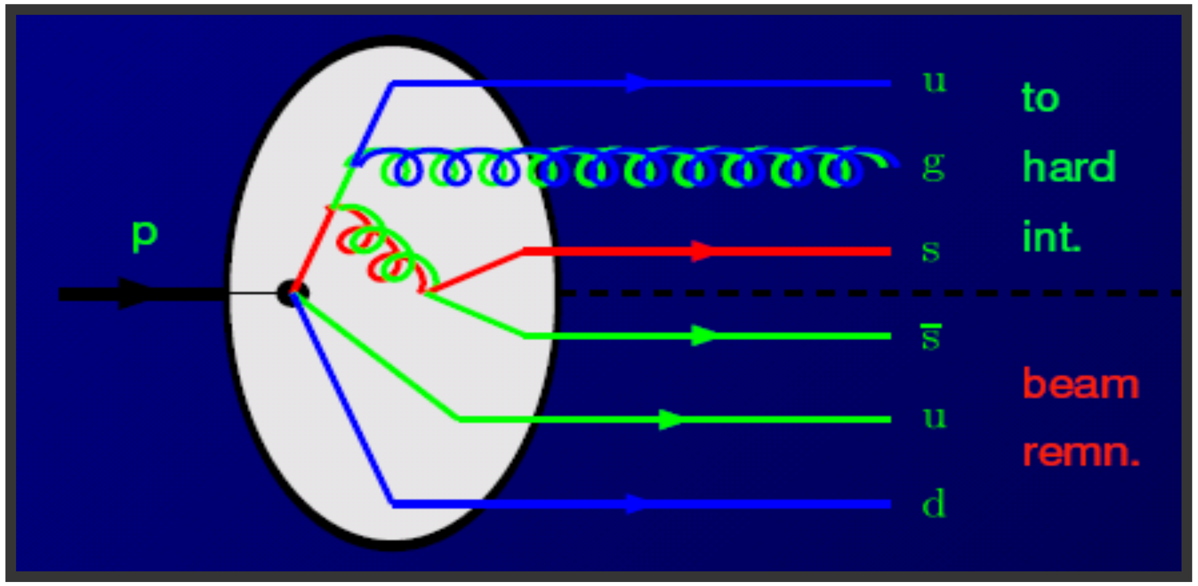
But only exists within very crude/naive approximation

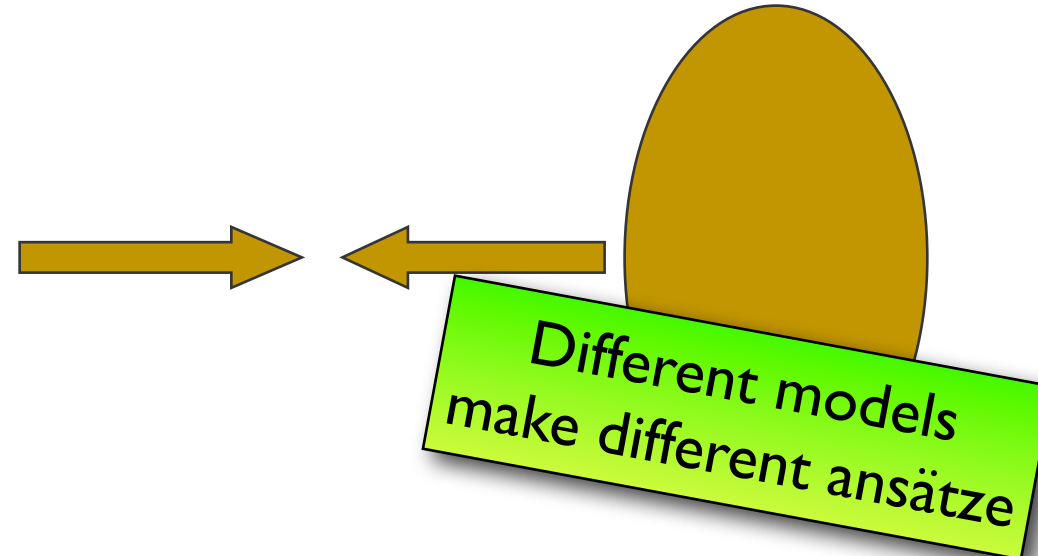
No MC model is that crude !

Extracting σ_{eff} is fine, but need model-independent physical observables to test MC models

Questions

Beyond naive factorization: Correlations & 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?

Key Ingredients in PYTHIA's Model

Interleaved Evolution

Initial-State Radiation ↓   Multiple Parton Interactions ↙

At each step: Competition for *x* among ISR and MPI

+ in pT-ordered model and (optionally) Q-ordered one: showers off the MPI

+ Modifications to subsequent PDFs caused by momentum and (in pT-ordered model) flavor conservation from preceding interactions

Impact-parameter dependence

Pedestal Effect …

Color Correlations

How does the system Hadronize?

Color connections vs color re-connections … ?

Re-interactions after hadronization?

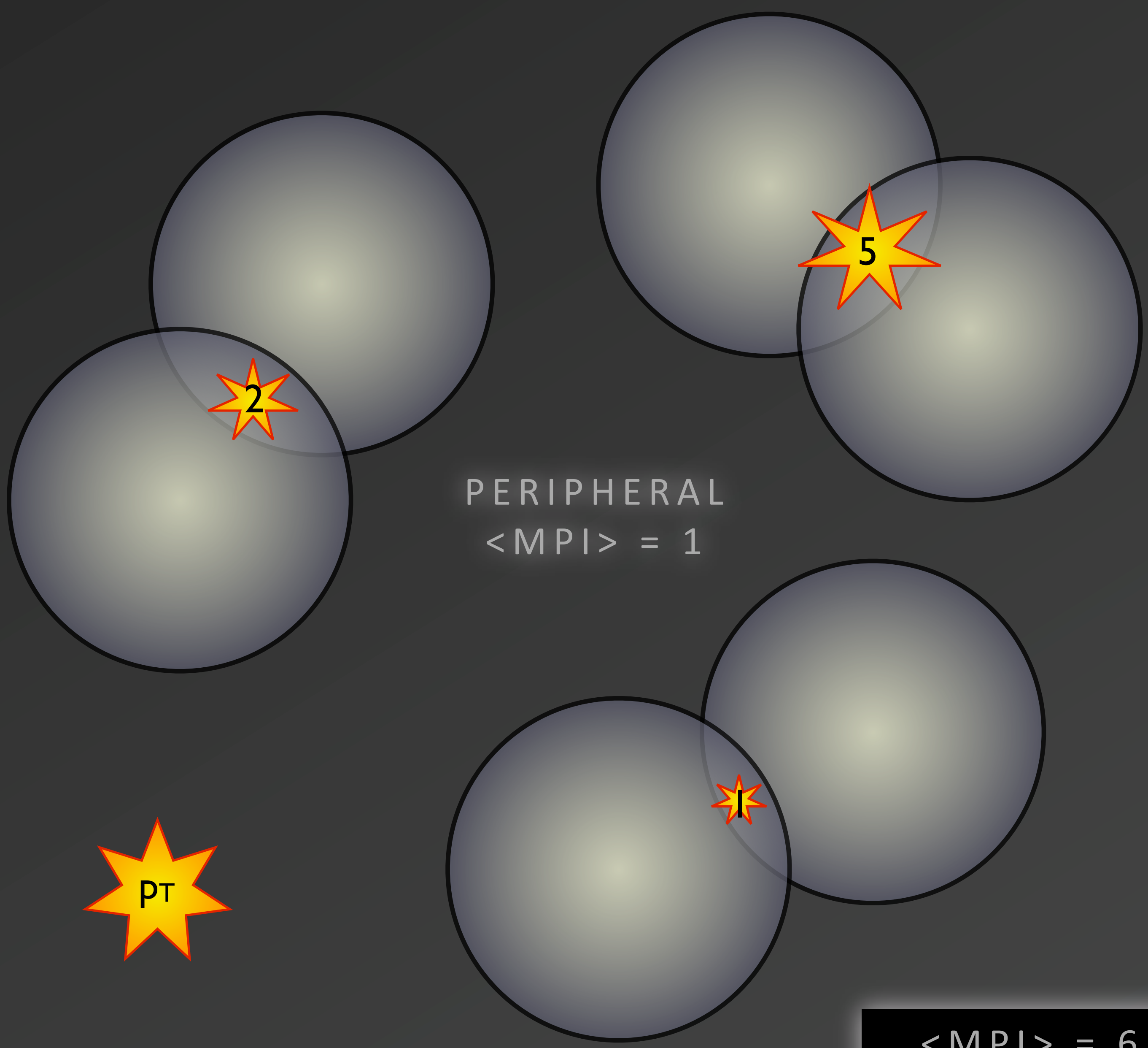
The Pedestal Effect

BIG JETS SIT ON BIG PEDESTALS

The Pedestal Effect

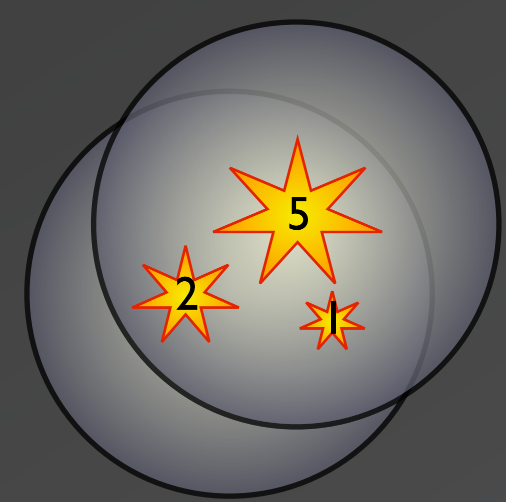
and Multiple Parton-Parton Interactions

MINIMUM BIAS



+

CENTRAL
<MPI> = 3



<MPI> = 6 / 4 = 1.5

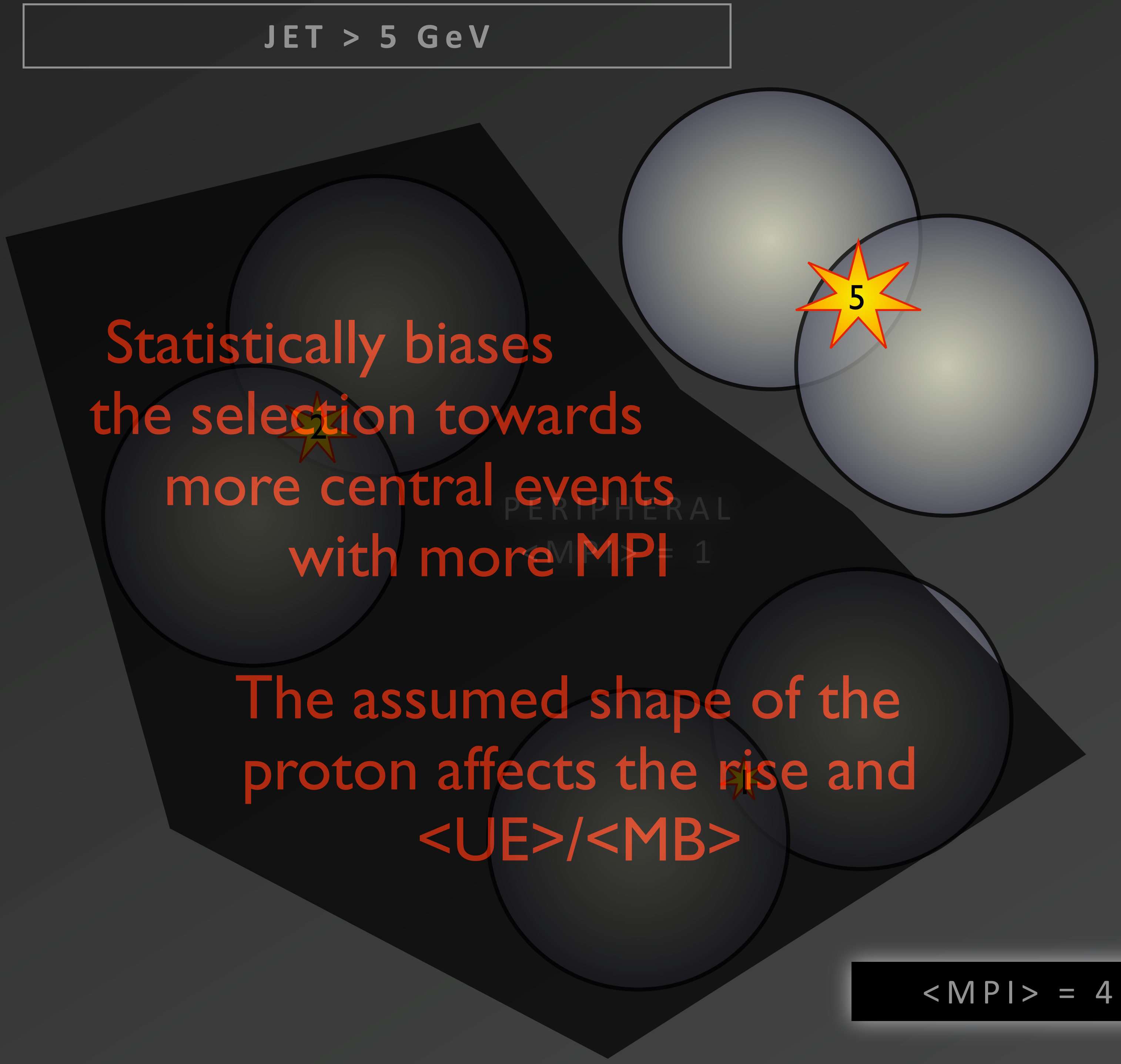
QCD ANALOGUE:

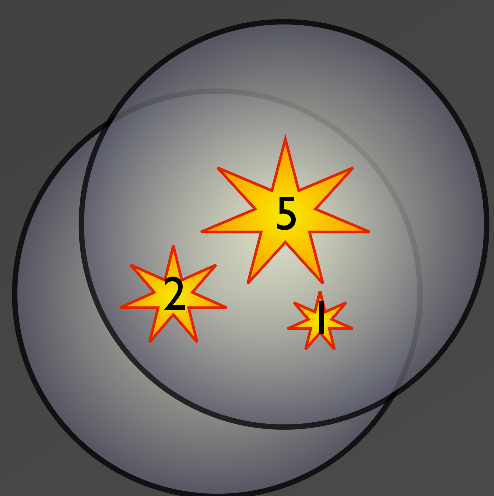
Parton Showers: resum divergent perturbative *emission* cross sections

MPI: resum divergent perturbative *interaction* cross sections

The Pedestal Effect

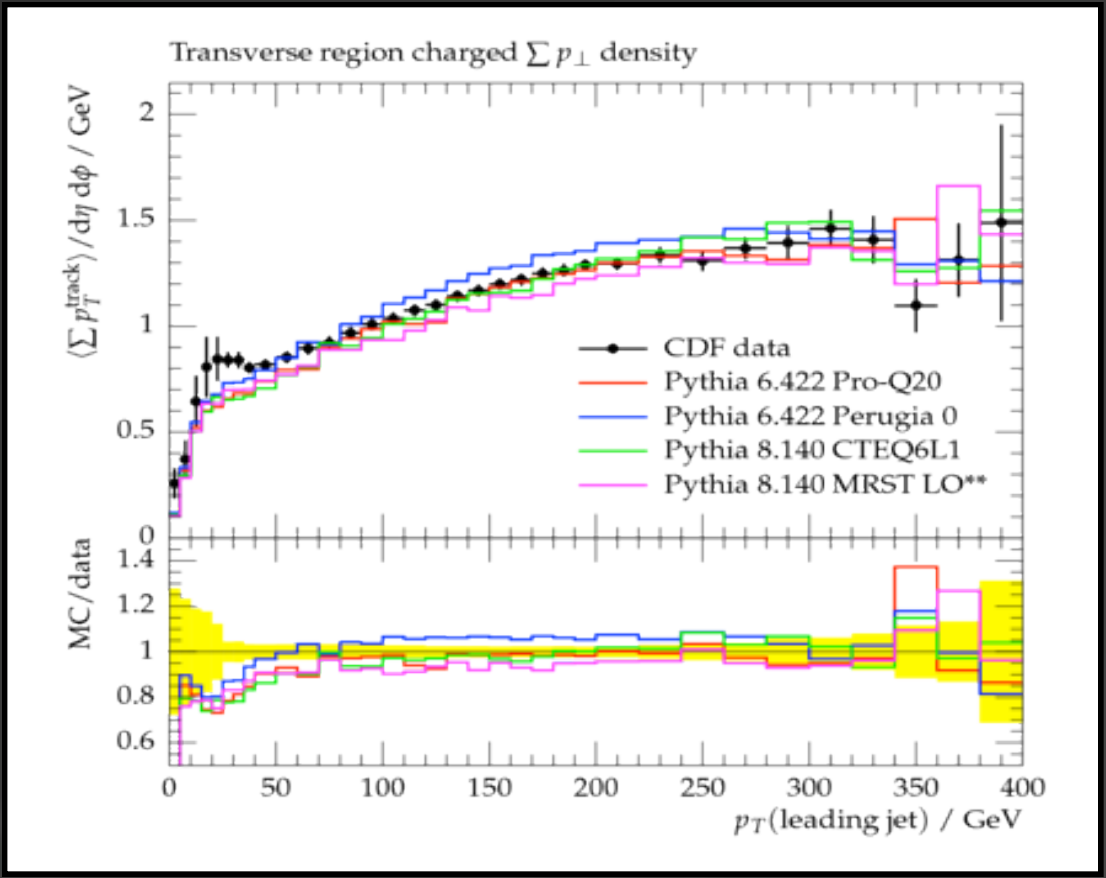
and Multiple Parton-Parton Interactions





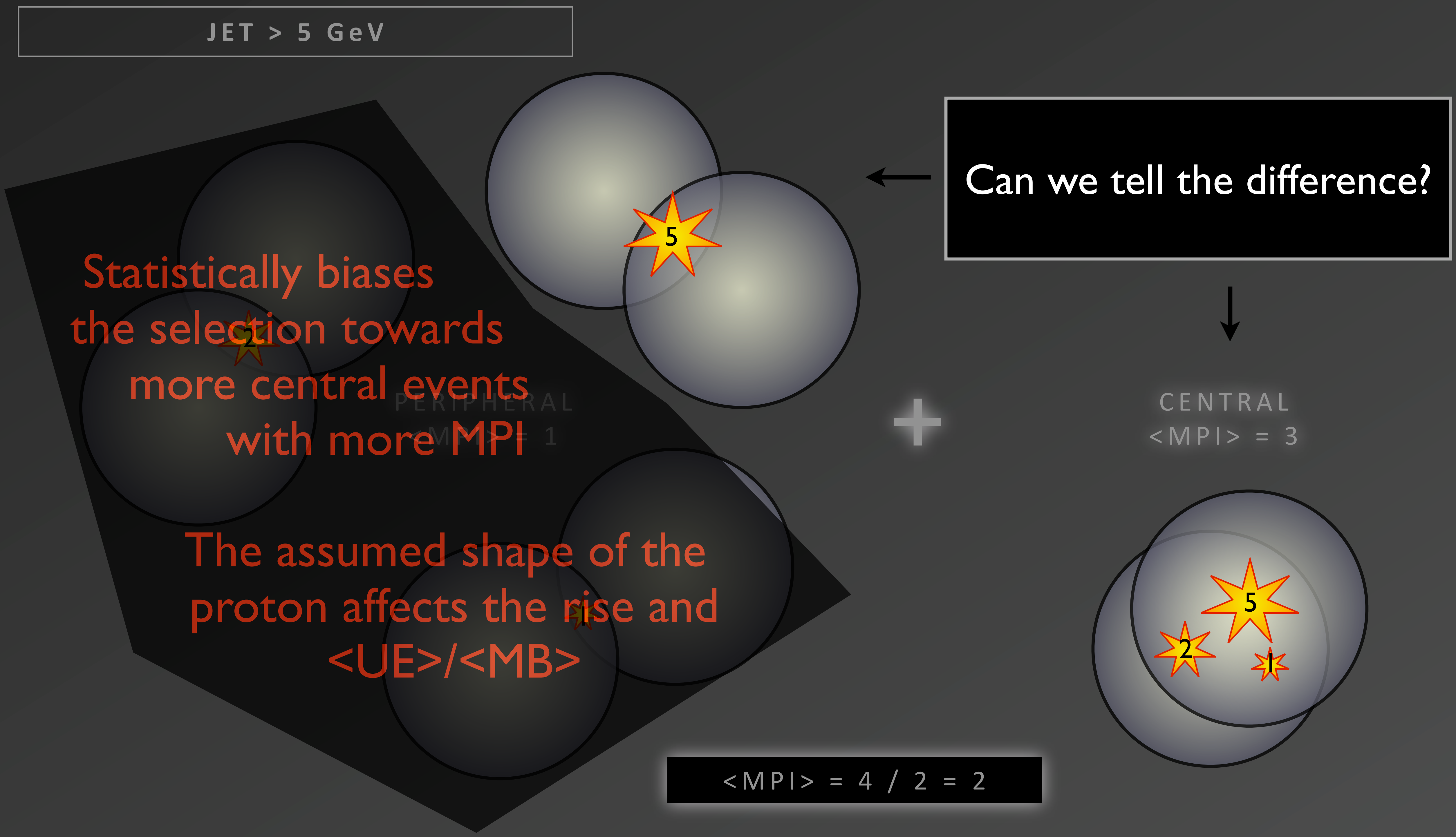
Statistically biases the selection towards more central events with more MPI

The assumed shape of the proton affects the rise and <UE>/<MB>



The Pedestal Effect

and Multiple Parton-Parton Interactions

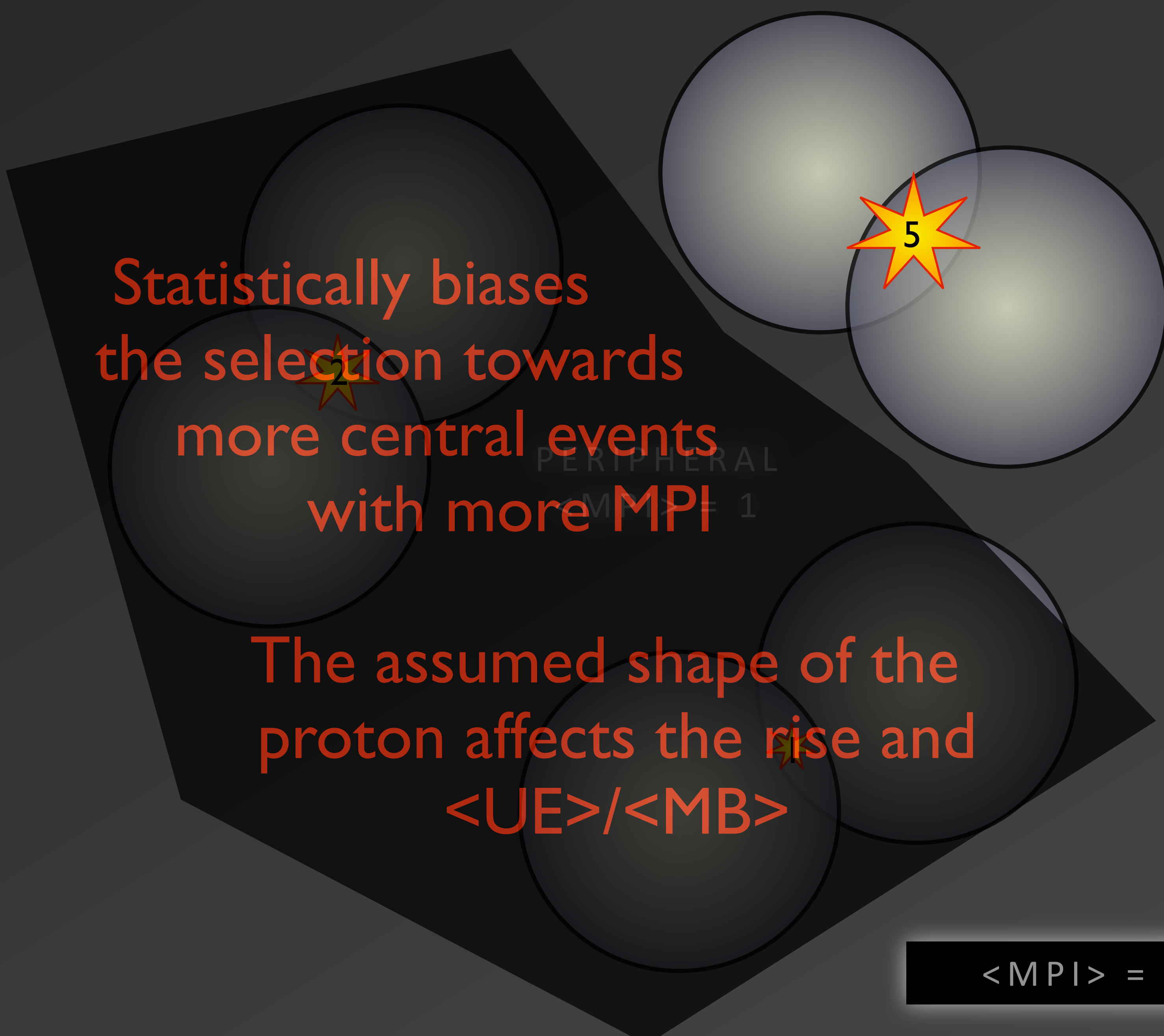


Statistically biases the selection towards more central events with more MPI

The assumed shape of the proton affects the rise and <UE>/<MB>

Dissecting the Pedestal

JET > 5 GeV



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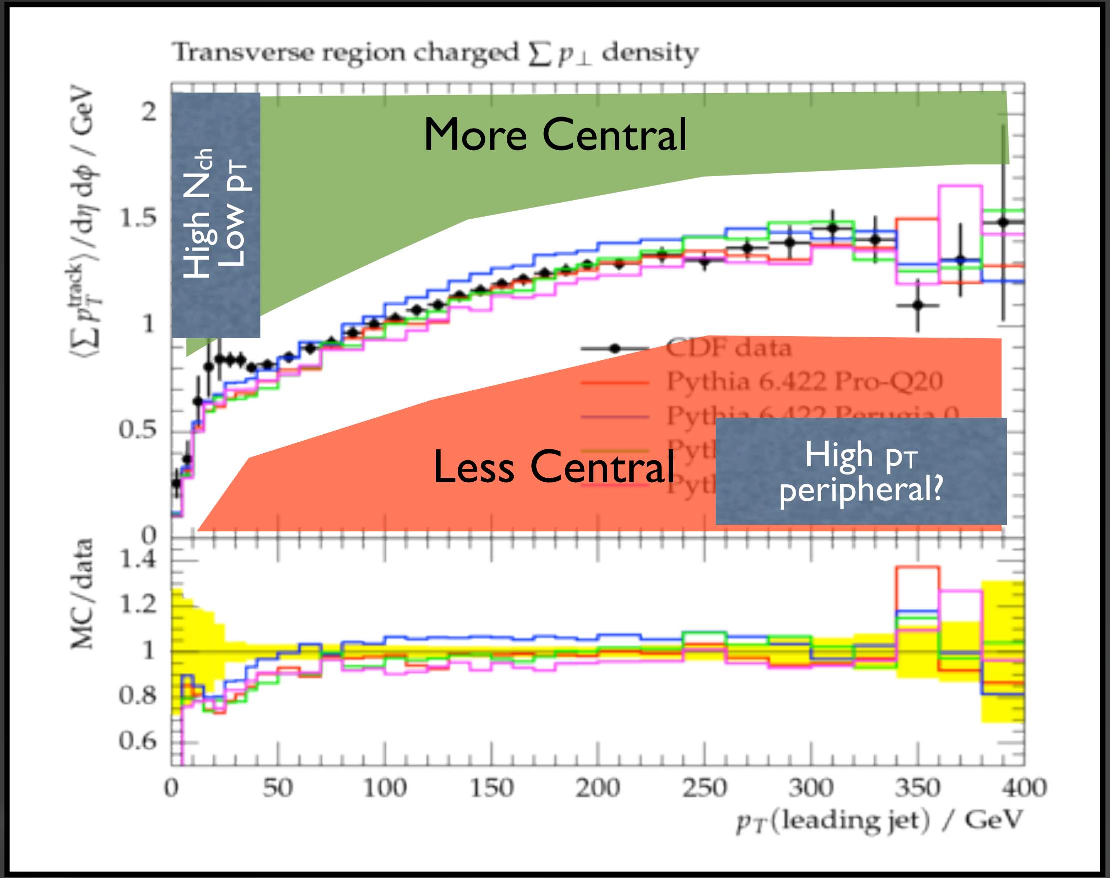
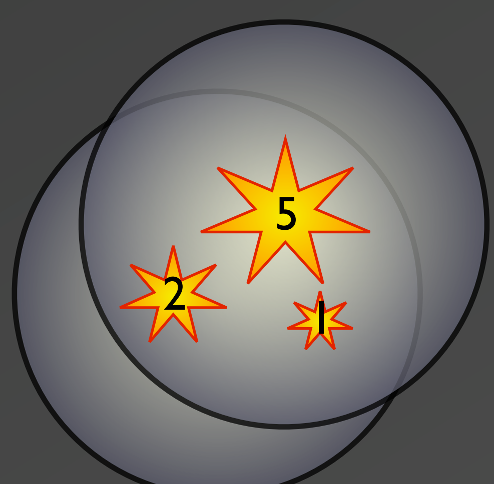
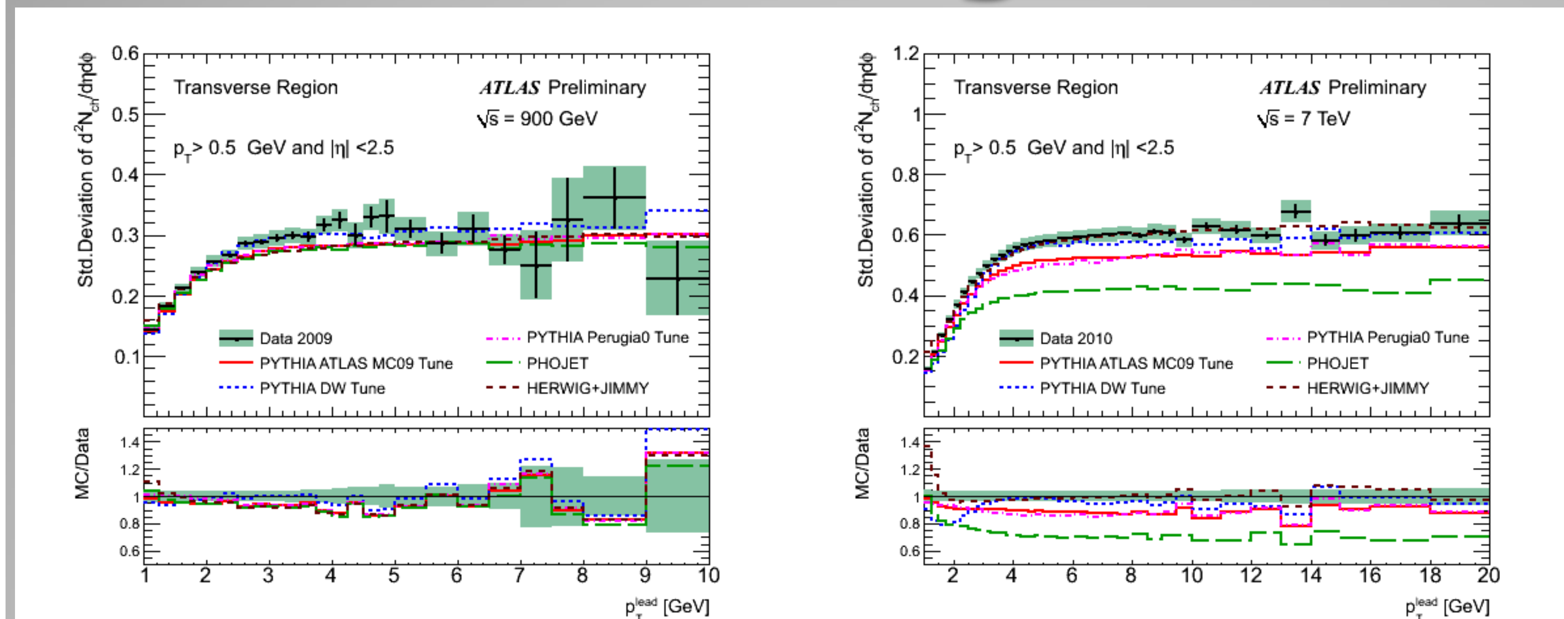




<MPI> = 4 / 2 = 2

Possible to do at Tevatron?

Transverse Region Variances



S.D. lower than mean, but more than square root of mean.

Suggests tracks not independently

Analyzing the Pedestal?

Initial rise & <UE>/<MB> → "average" proton shape

Focus on specific x range *(pick jet p_T and y, for given collider energy)*

Scan over transverse activity → b dependence for that x ?

And/or look for abundance of minijets in transverse region

Deepak Kar

Workshop on Multi-Parton Interactions at the LHC
13th September, DESY

TECHNISCHE UNIVERSITÄT DRESDEN

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)

OK for inclusive measurements, but:

Physics: *Shape = delta function at 0 for x → 1*

Can also be seen in lattice studies at high x

Gribov theory: *high s ↔ low x ⇒ Growth of total cross section ↔ size grows ∝ ln(1/x)*

BFKL "intuition": "random walk" in x from few high-x partons at small b diffuse to larger b at smaller x (More formal: Balitsky/JIMWLK and Color Glass Condensates)

A Model for Phenomenological Studies

Corke, Sjöstrand, arXiv:1101.5953

Basic assumption: Mass distribution = Gaussian. Make width x-dependent

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

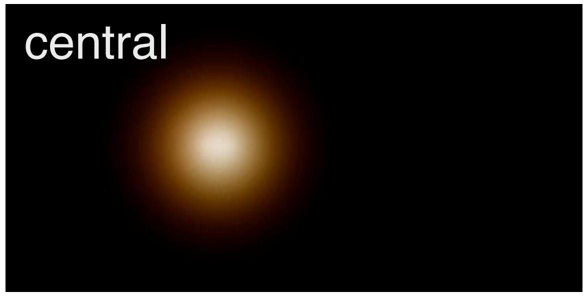
Constrain by requiring a_1 responsible for growth of cross section

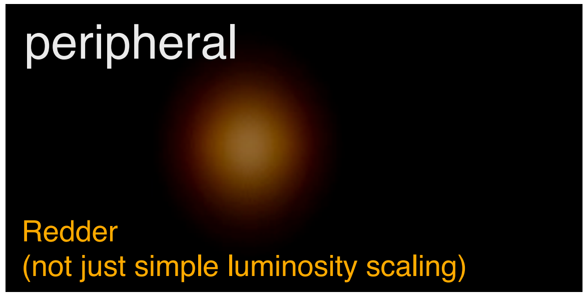
X-Dependent Proton Size

Initial study + tuning in arXiv:1101.5953

At least as good MB/UE fits as old model (based on "Tune 4C")

Details will be different!





E.g.,

"Homogenous" model: can have (rare) high-x scattering at large b:

$\Rightarrow$ *There should be a tail of dijets/DY/… with essentially "no" UE*

E.g., ATLAS "RMS" distributions, and/or take UE/MB density ratios

"X-Dependent" model: high-x scatterings only at small b:

$\Rightarrow$ *Enhanced pedestal effect? (increased selection bias)*

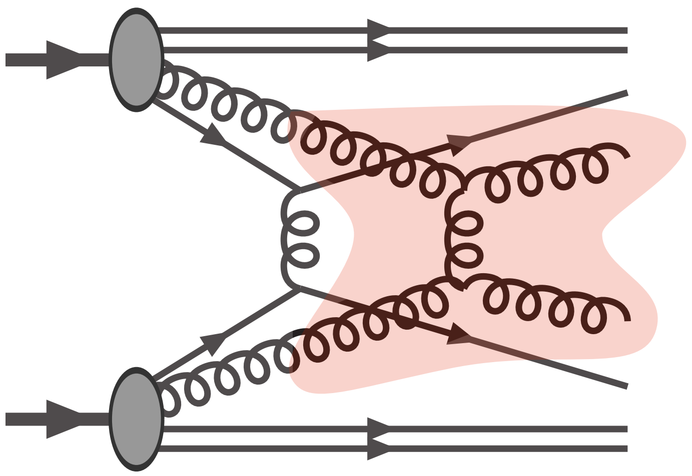
(needs to be interpreted with care, due to effects of (re)tuning …)

Model available from next PYTHIA 8 version, ready for playing with …

Other News in PYTHIA 8

Can choose 2nd MPI scattering

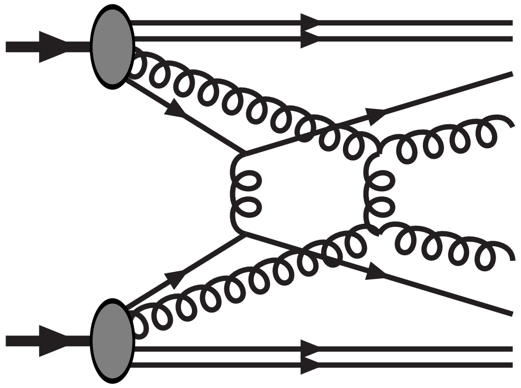
- TwoJets (with TwoBJets as subsample)
- PhotonAndJet, TwoPhotons
- Charmonium, Bottomonium (colour octet framework)
- SingleGmZ, SingleW, GmZAndJet, WAndJet
- TopPair, SingleTop



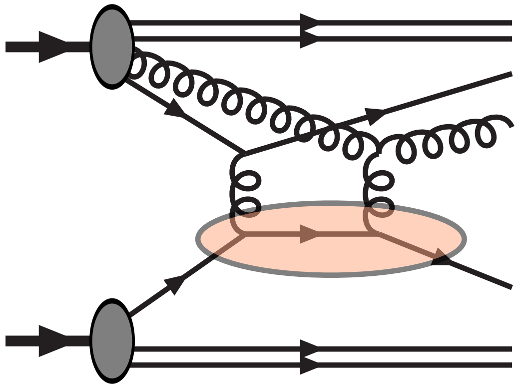
See the PYTHIA 8 online documentation, under "A Second Hard Process"

Rescattering

Often assume that MPI =



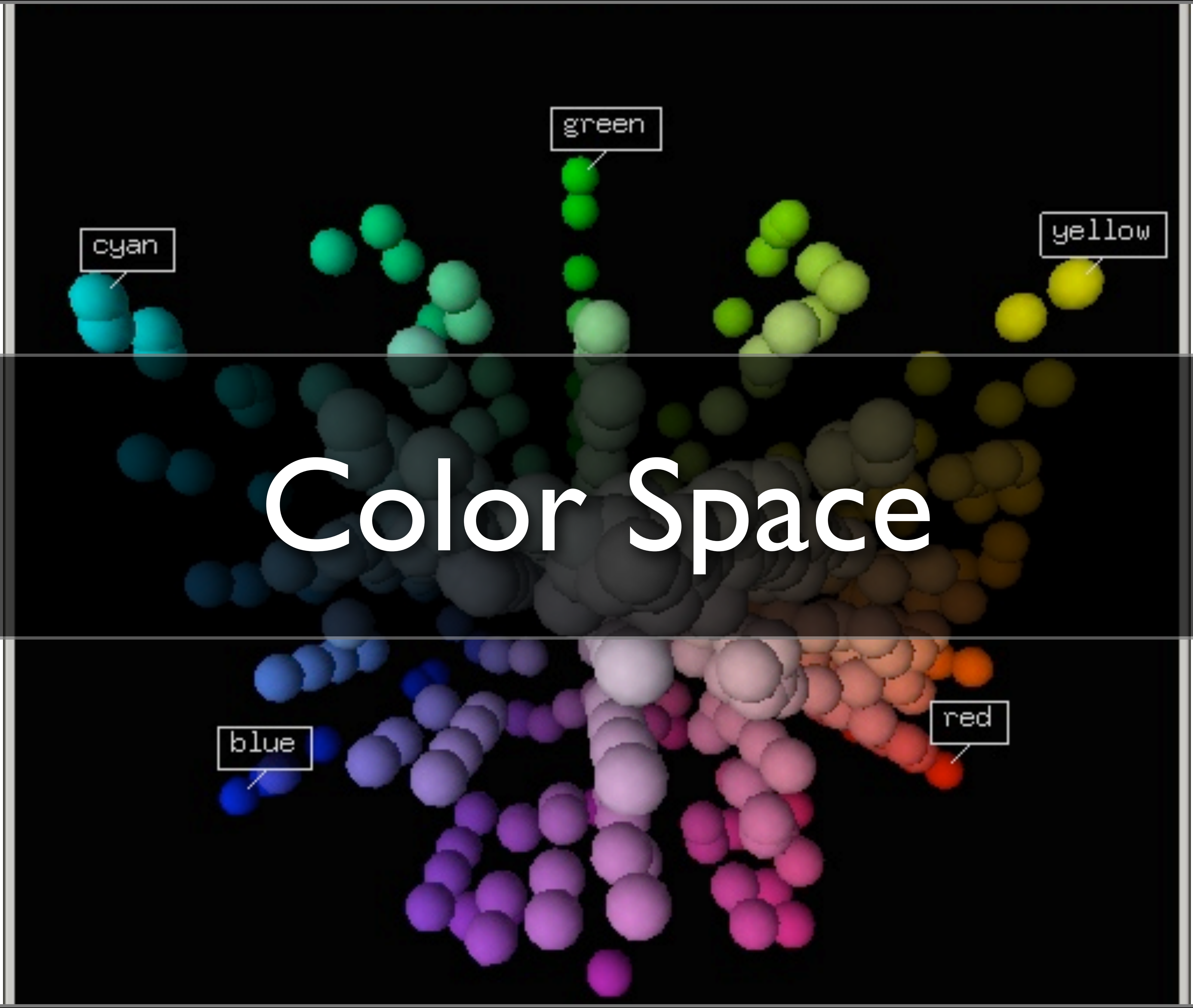
. . . but should also include



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



Color Space

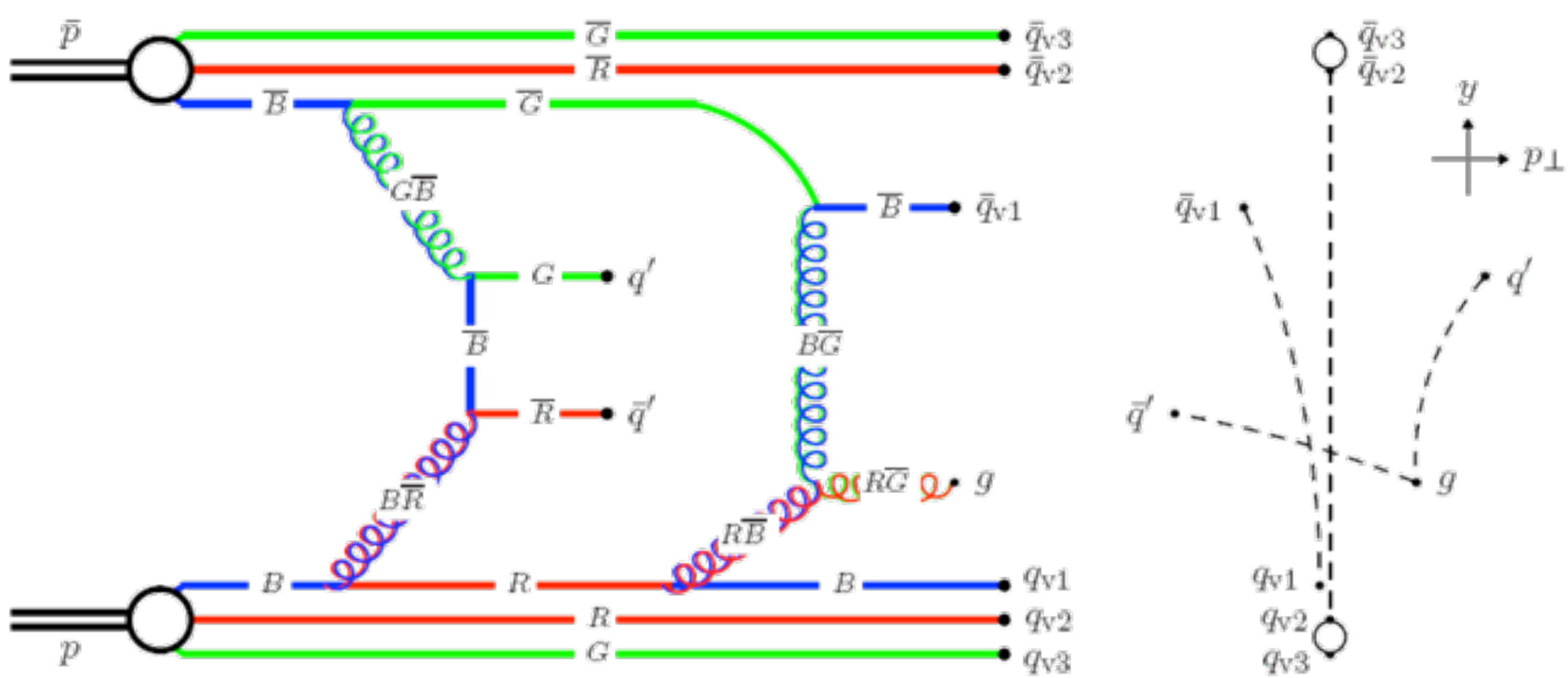
Questions

Colour Connections

Each MPI 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



Questions

Colour Connections

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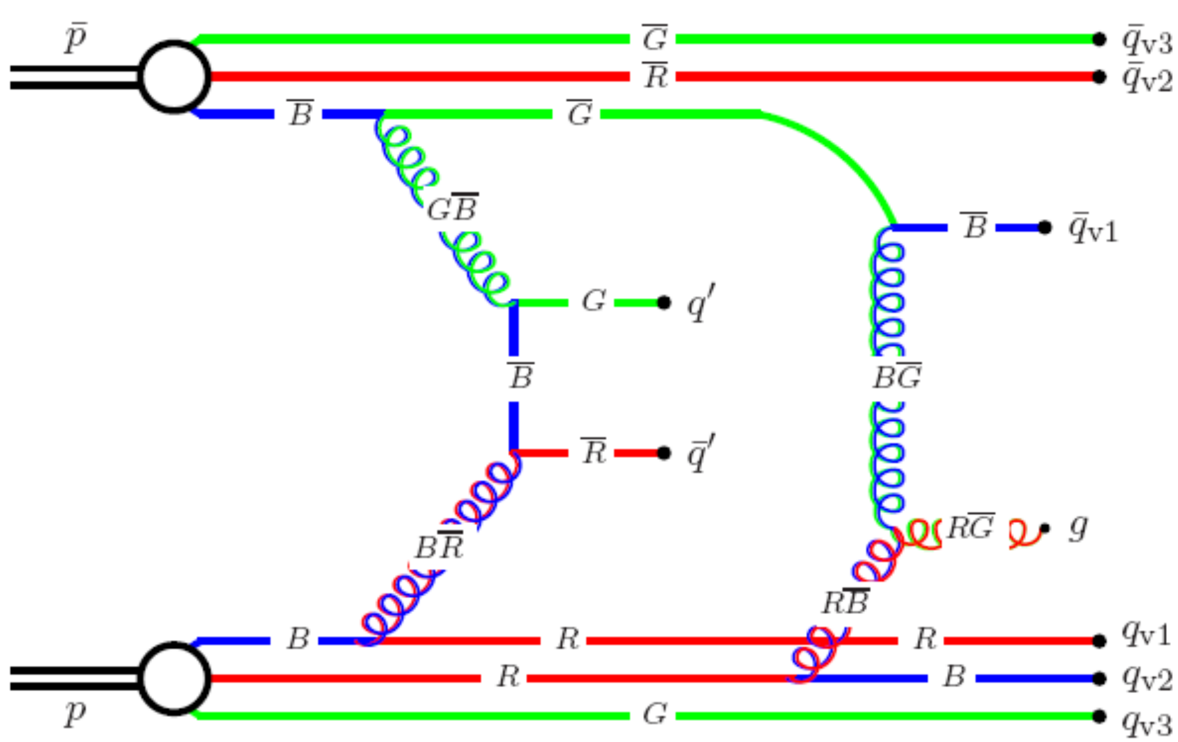
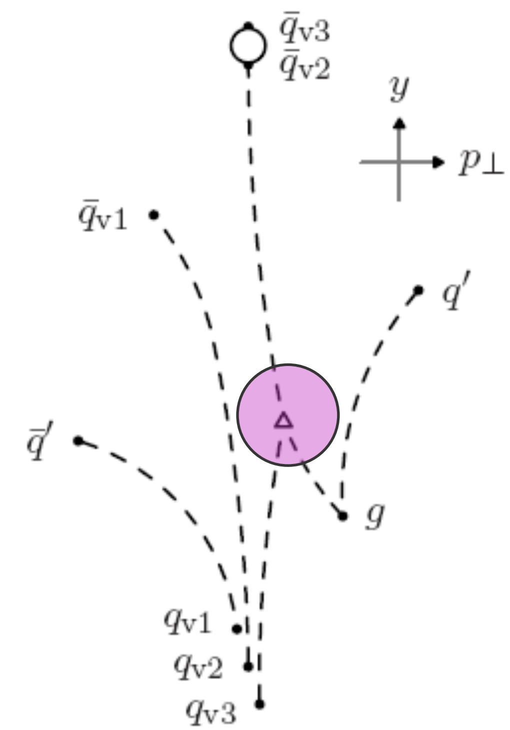




Models

Extremely difficult problem

Here I just remark on currently available models/options and what I think is good/bad about them

1. Most naive

Each MPI ~ independent → start from picture of each system as separate singlets?

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

This is *physically inconsistent* with the exchanged objects being gluons

Instead, it corresponds to the exchange of singlets, i.e., Pomerons (uncut ones)

→ *In this picture, all the MPI are diffractive!*

This is just wrong.

Models

2. Valence quarks plus t-channel gluons?

Arrange original beam baryon as (qq)-(q) system

Assume MPI all initiated by gluons → connect them as (qq)-g-g-g-(q)

In which order? Some options:

A) Random (Perugia 2010 & 2011)

B) According to rapidity of hard scattering systems (Perugia 0)

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

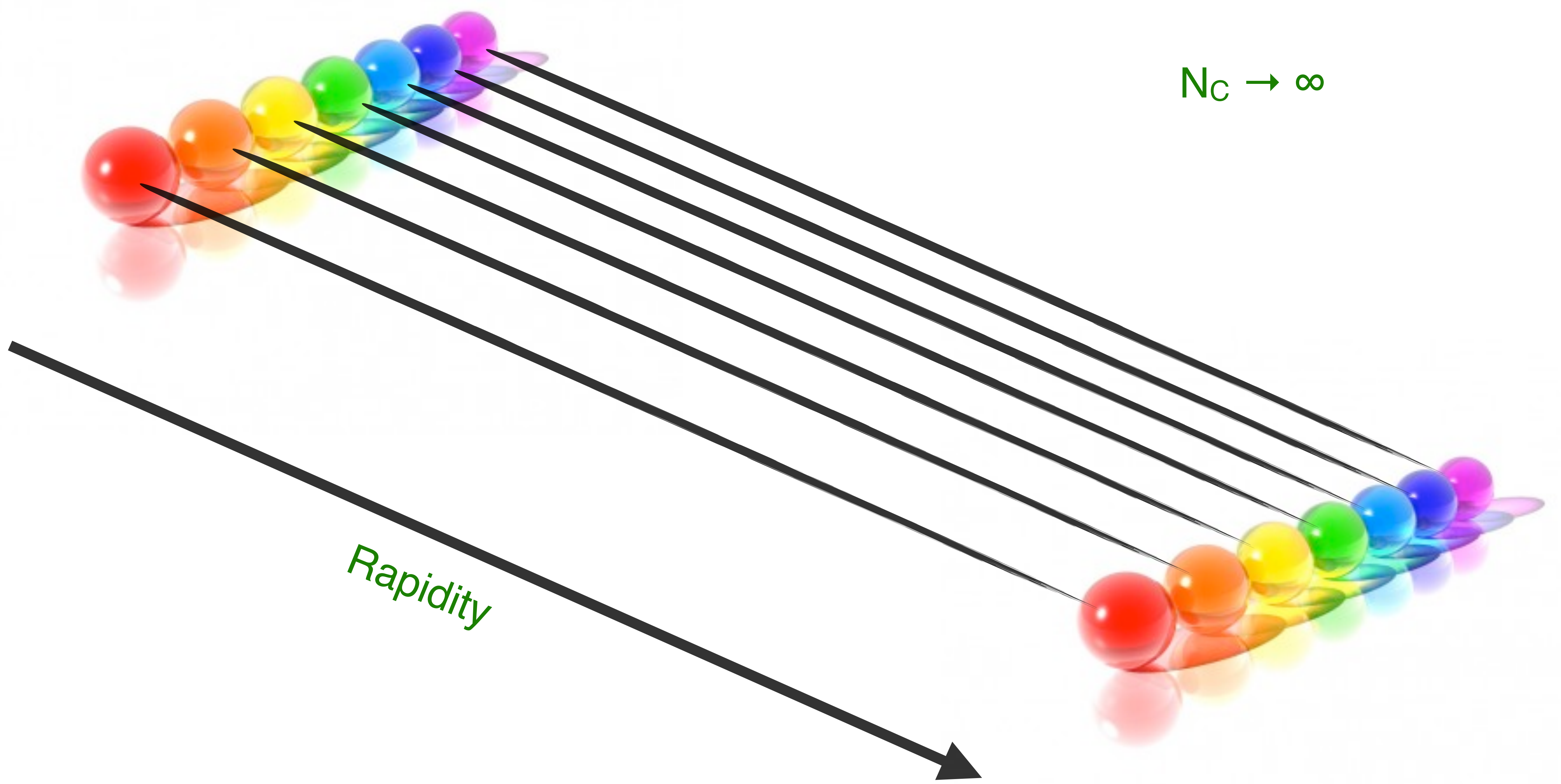
(pT-ordered PYTHIA also includes quark exhanges, but details not important)

OK, may be more physical …

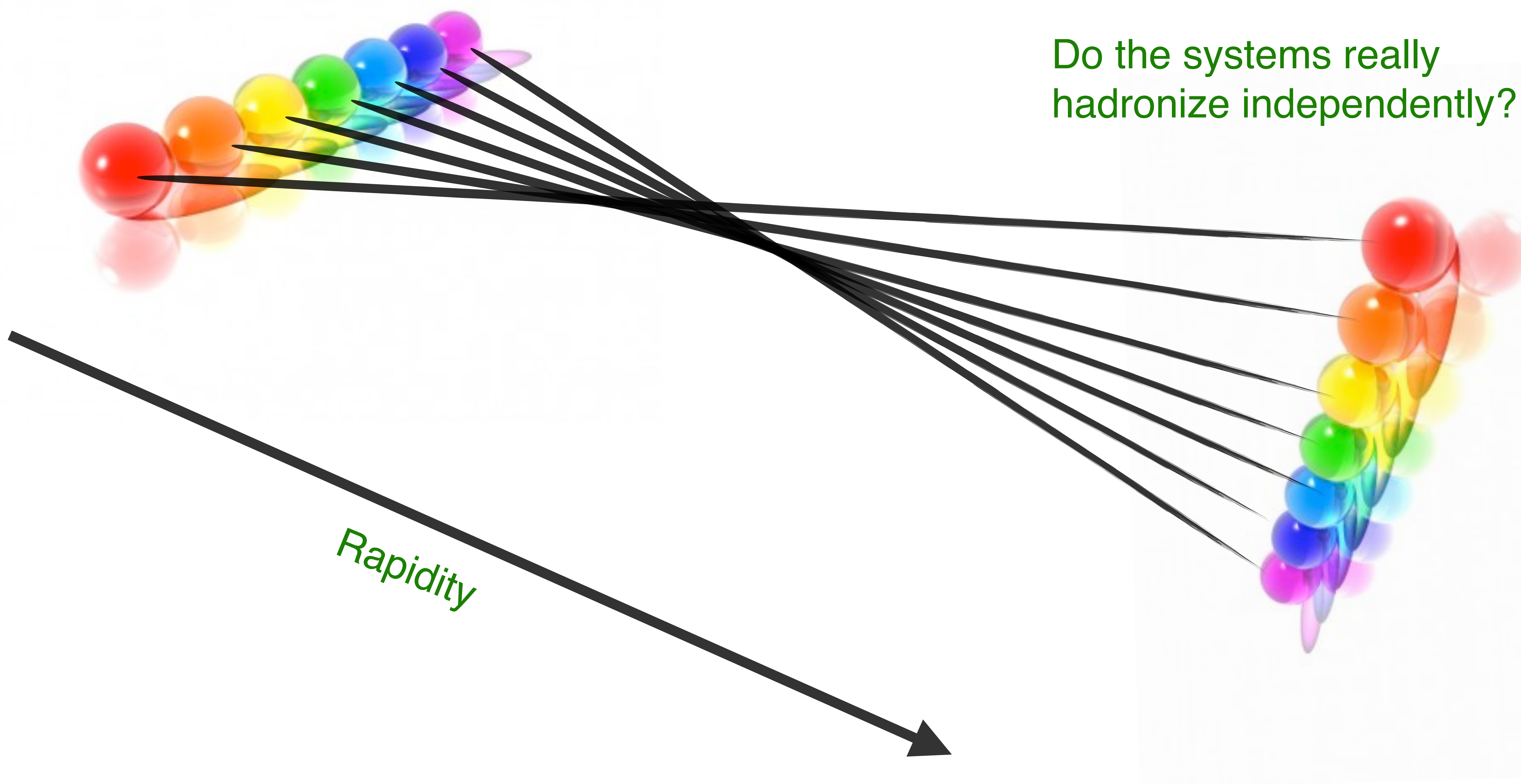
But both A and B drastically fail to predict, e.g., the observed rise of the <pT>(Nch) distribution (and C "cheats" by looking at the final-state gluons)

This must still be wrong (though less obvious)

Color Reconnections?

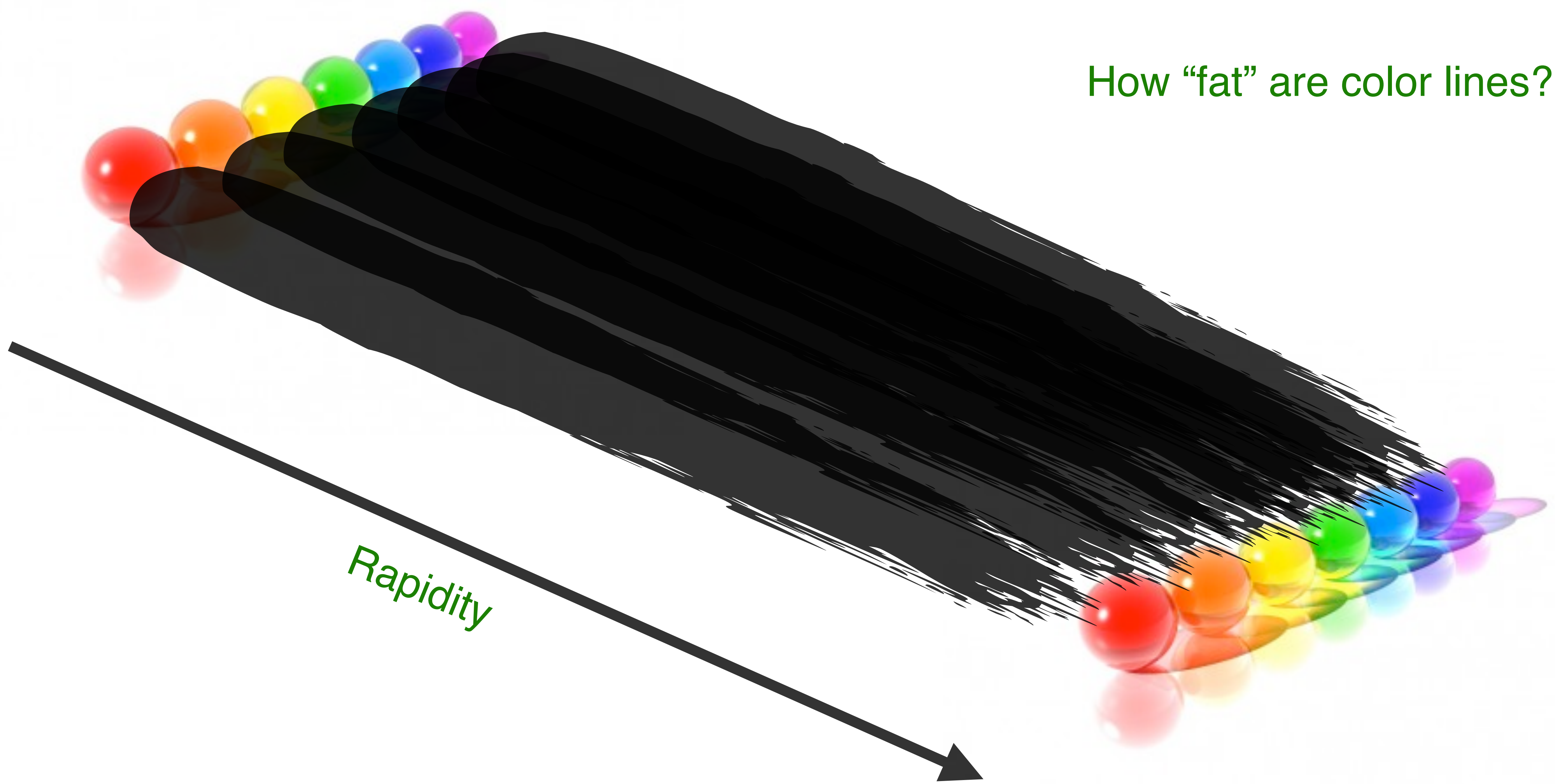


Color Reconnections?



Color Reconnections?

How “fat” are color lines?



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

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?

This may not be wrong. But it sure sounds difficult!

CR in PYTHIA

Old Model (PYTHIA 6, Tune A and friends)

Outgoing gluons from MPI systems have no independent color flow

Forced to just form "kinks" on already existing string systems

Inserted in the places where they increase the "string length" (the "Lambda" measure) the least

Looks like it does a good job on <pT>(Nch) at least

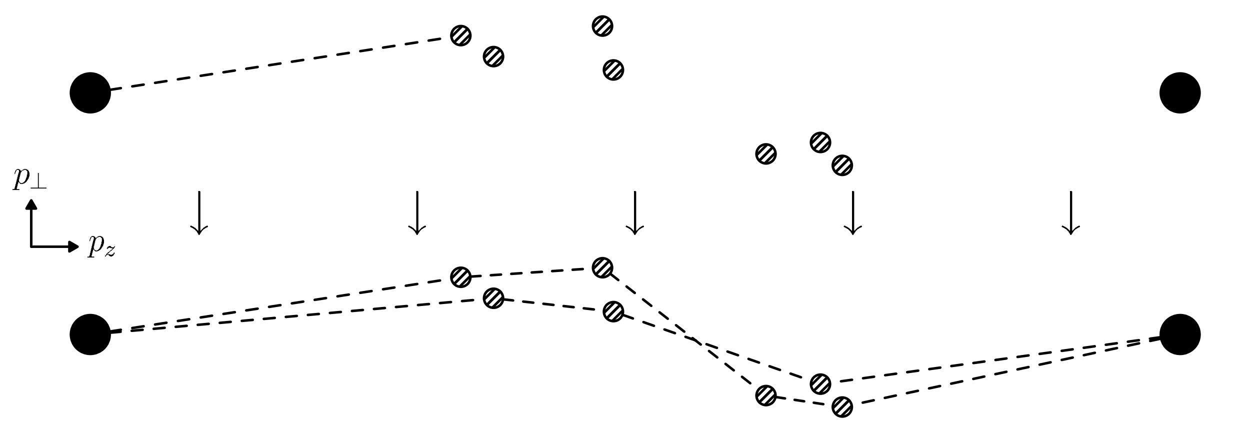
Brute force. No dynamical picture.

CR in PYTHIA

pT-Ordered Model (in PYTHIA 6.4): *Colour Annealing*

M. Sandhoff & PS, in hep-ph/0604120

- Consider each color-anticolor pair
  - *If (reconnect), sever the color connection*
  - *Different variants use different reconnect probabilities*
    - Fundamental string-string reconnect probability PARP(78)
    - Enhanced by either n_{MPI} (Seattle type) or local string density (Paquis type)



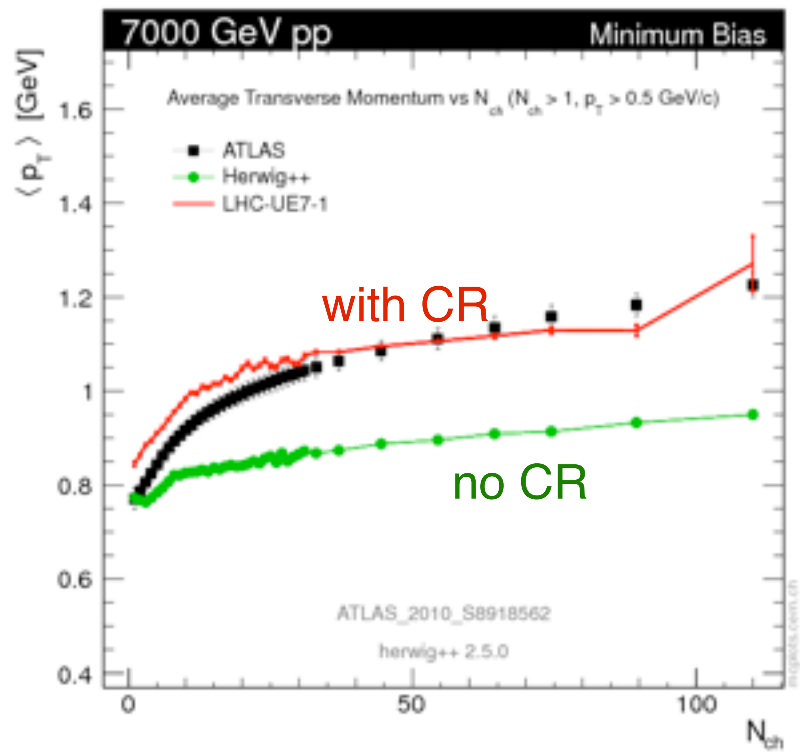
- For all severed connections, construct new color topology:
  - *Consider the parton which is currently "furthest away" (in λ) from all others*
  - *"Sees" the sum of the others → connect it to the closest severed parton to it.*
  - *Strike it off the list and consider the next-furthest parton, etc.*

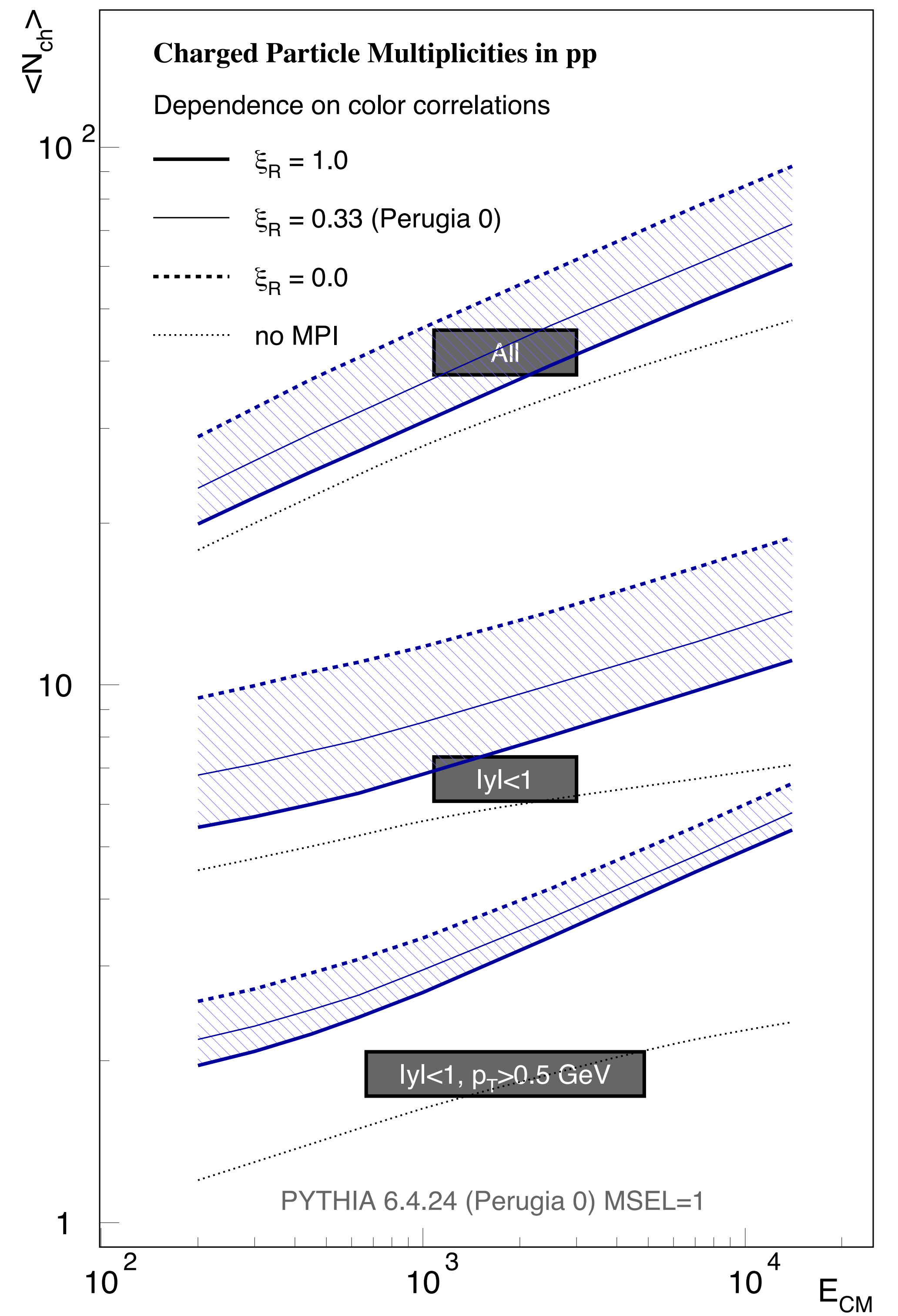
The Effect of CR

If driven by minimization of Area Law or similar:

Reduces multiplicity

Increases p_T





May or may not:

Create rapidity gaps → overcount diffraction?

Diffraction

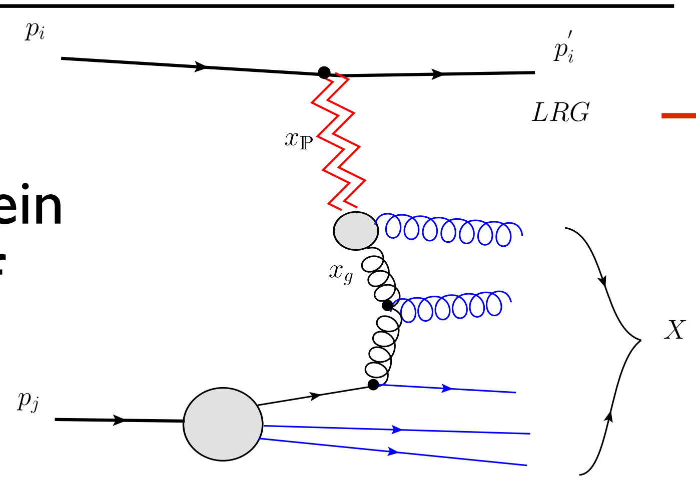
Diffractive Cross Section Formulæ:

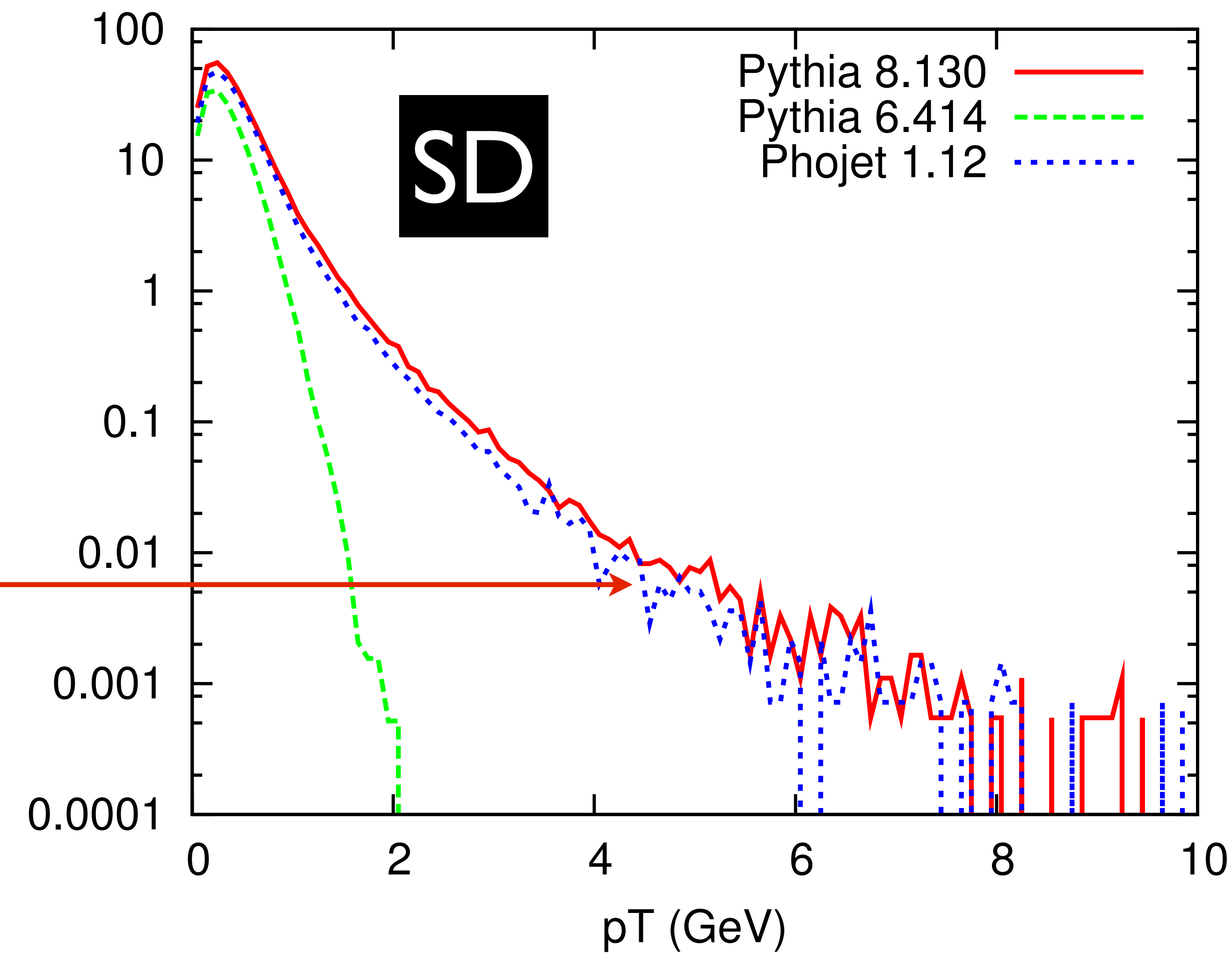
$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\, \beta^2_{A\mathbb{P}}\, \beta_{B\mathbb{P}}\, \frac{1}{M^2}\, \exp(B_{sd(AX)}t)\, F_{sd}\ ,$$

$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g^2_{3\mathbb{P}}}{16\pi}\, \beta_{A\mathbb{P}}\, \beta_{B\mathbb{P}}\, \frac{1}{M_1^2}\, \frac{1}{M_2^2}\, \exp(B_{dd}t)\, F_{dd}\ .$$

Partonic Substructure in Pomeron:

Follows the Ingelman-Schlein approach of Pompyt





PYTHIA 8

- $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- $M_X > 10\,\mathrm{GeV}$: 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 $\sigma_{\mathbb{P}p}$.

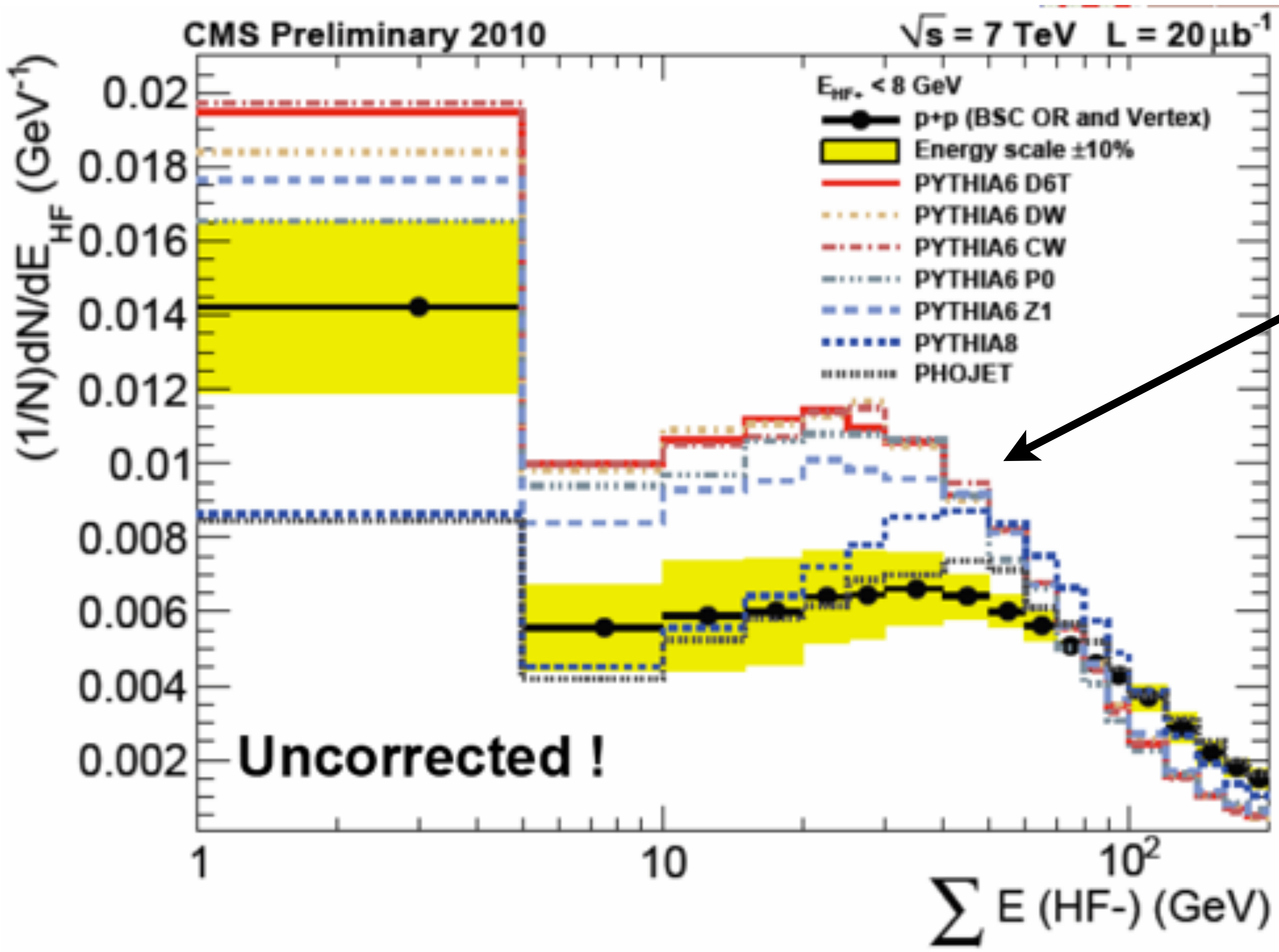
Navin, arXiv:1005.3894

Framework needs testing and tuning

E.g., interplay between non-diffractive and diffractive components

+ LEP tuning used directly for diffractive modeling

Hadronization preceded by shower at LEP, but not in diffraction → dedicated diffraction tuning of fragmentation pars?



Study this hump

+ Room for new models, e.g., KMR (SHERPA)
Others?

Energy Scaling

Energy Scaling

Multiple Parton Interactions (MPI)

Regularise cross section with $p_{\perp 0}$ as free parameter

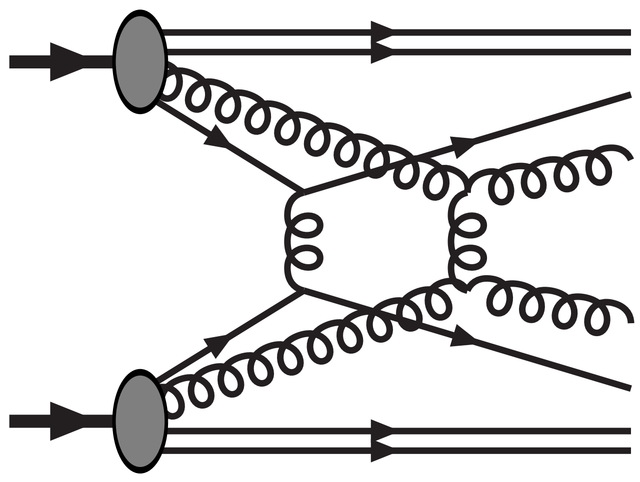
IR Regularization

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \to \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2}$$

with energy dependence

Energy Scaling

$$p_{\perp 0}(E_{\mathrm{CM}}) = p_{\perp 0}^{\mathrm{ref}} \times \left(\frac{E_{\mathrm{CM}}}{E_{\mathrm{CM}}^{\mathrm{ref}}}\right)^{\epsilon}$$



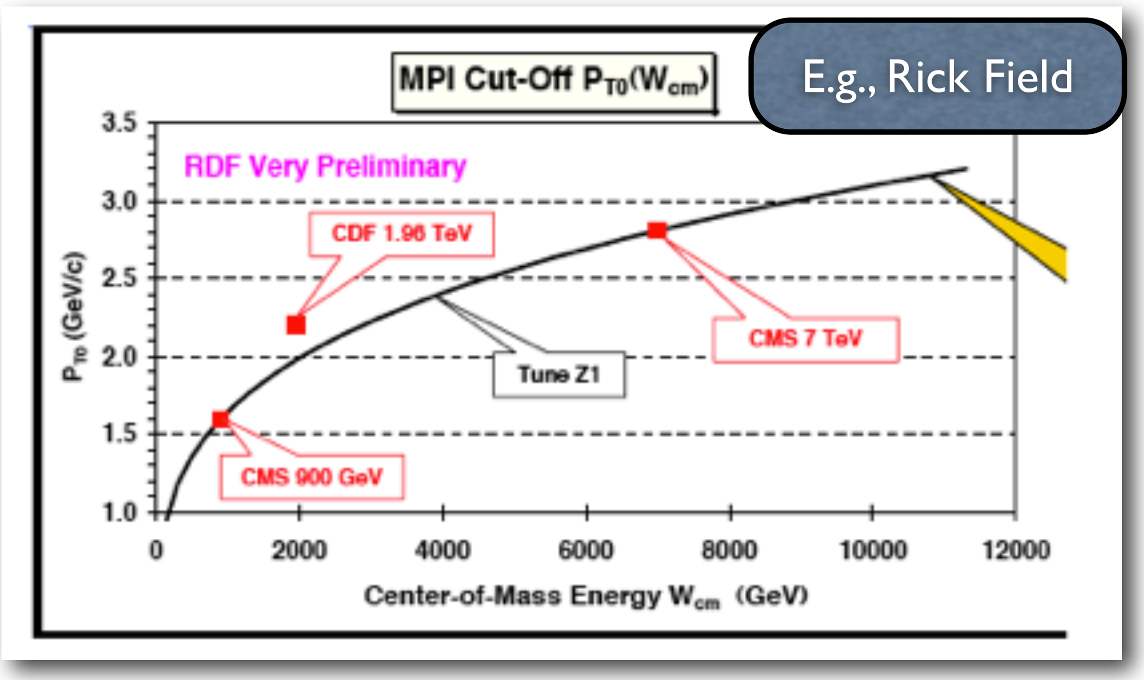
See, e.g., new MCnet Review: *"General-purpose event generators for LHC physics"*, arXiv:1101.2599

From Tevatron to LHC

Tevatron tunes appear to be "low" on LHC data

Problem for "global" tunes.

Poor man's short-term solution: dedicated LHC tunes



E.g., Rick Field

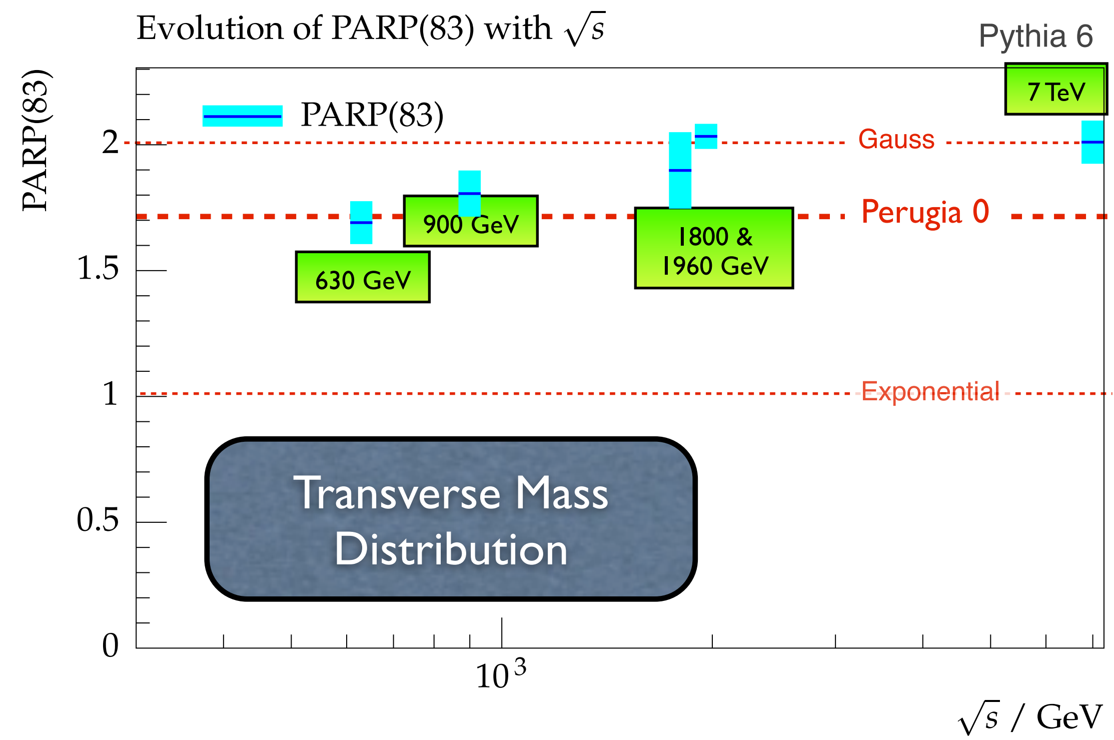
Tuning vs Testing Models

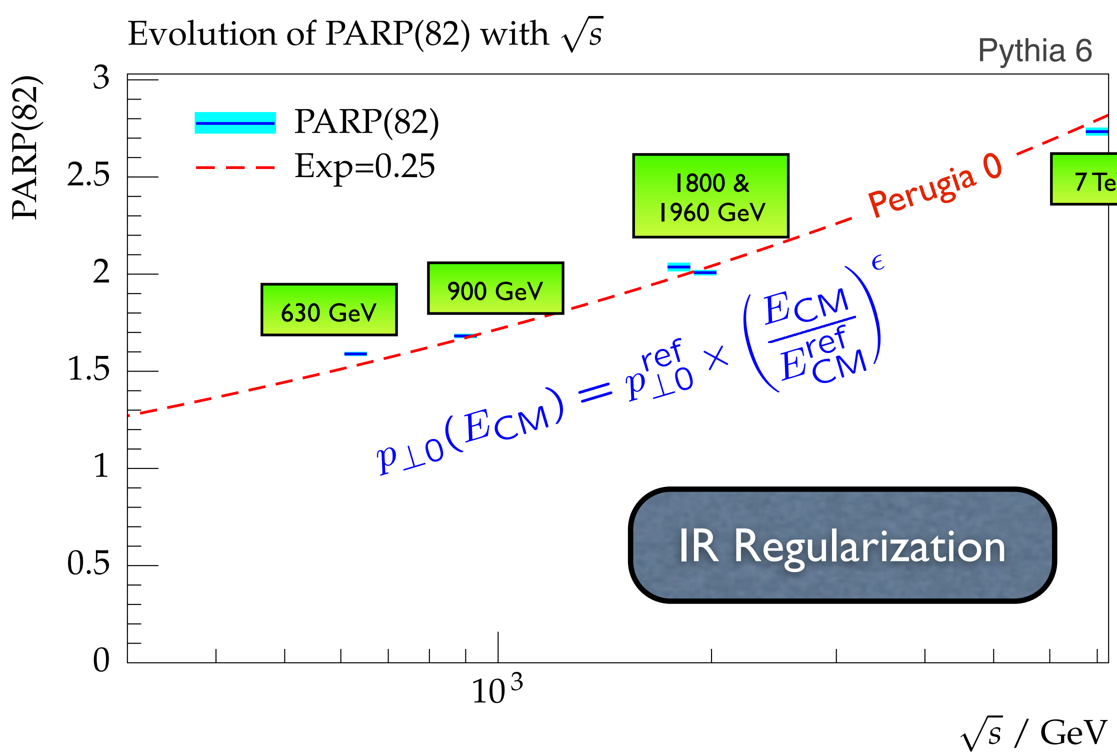
TEST models

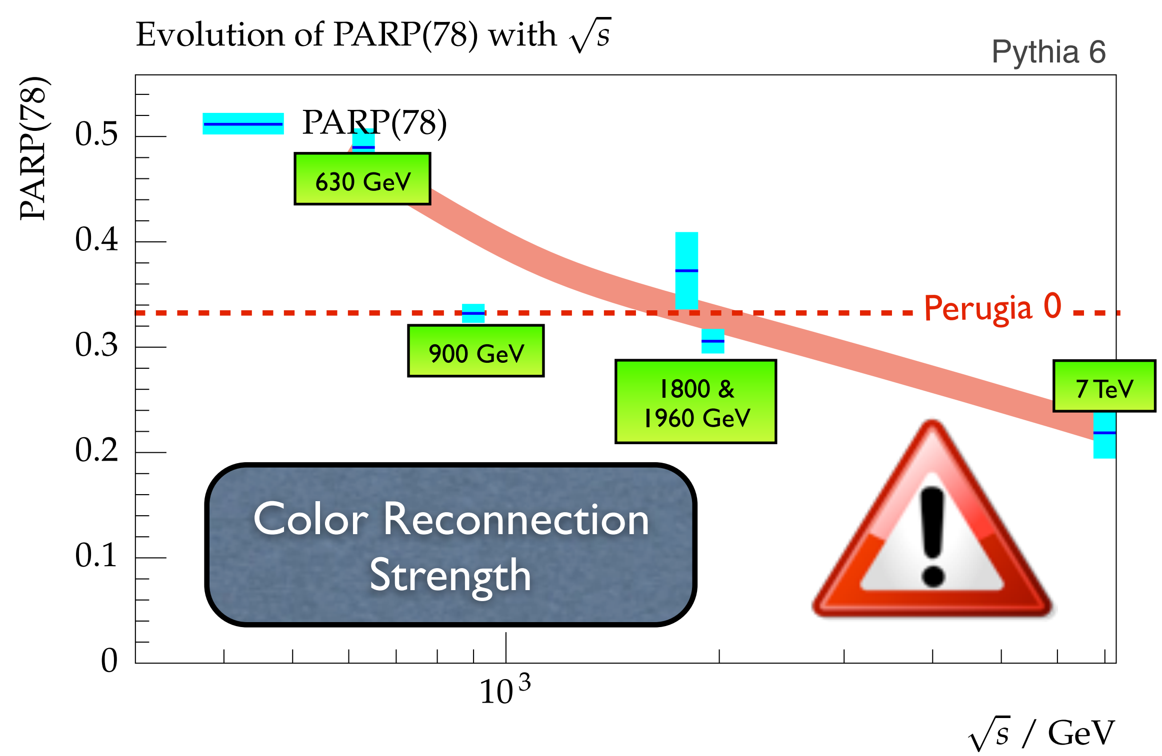
Tune parameters in several complementary regions

Consistent model → same parameters

Model breakdown → non-universal parameters







"Energy Scaling of MB Tunes", H. Schulz + PS, in preparation

Nota Bene

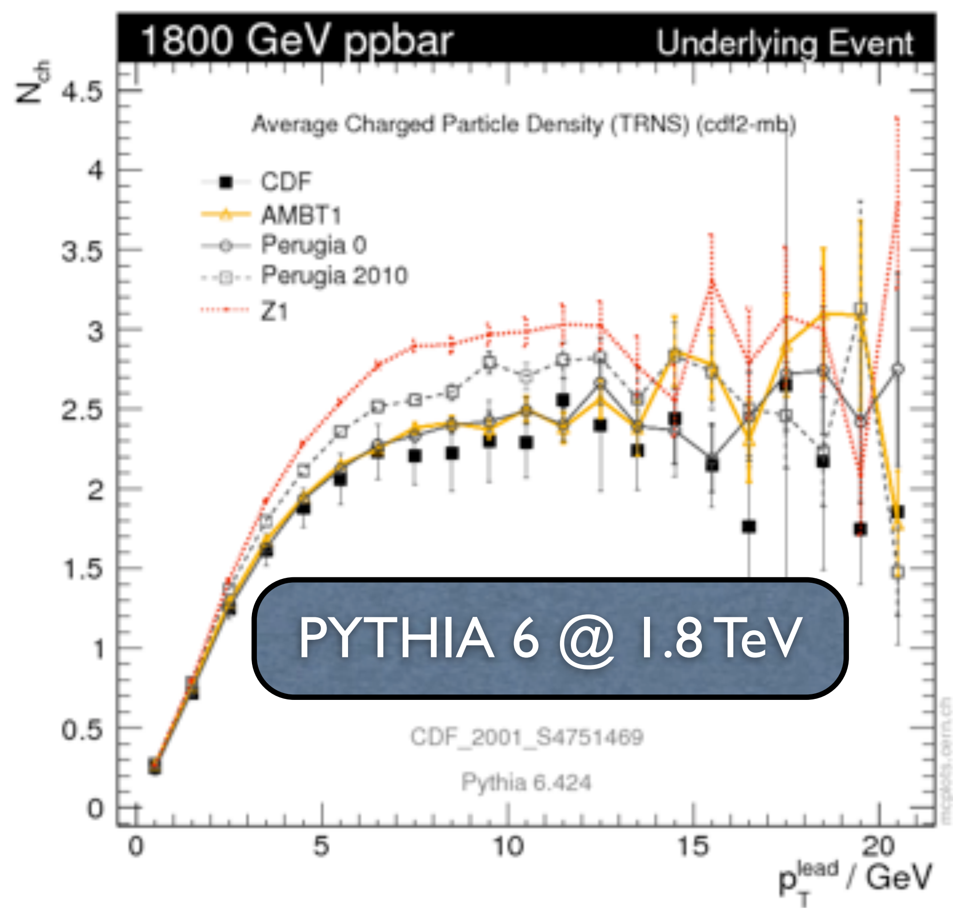
Crucial Task for run at 2.8 TeV

Make systematic studies to resolve possible Tevatron/LHC tension

Measure regions that interpolate between Tevatron and LHC
E.g., start from same phase-space region as CDF
$|\eta| < 1.0$ $p_T > 0.4$ GeV

Compromise between Tevatron and LHC?

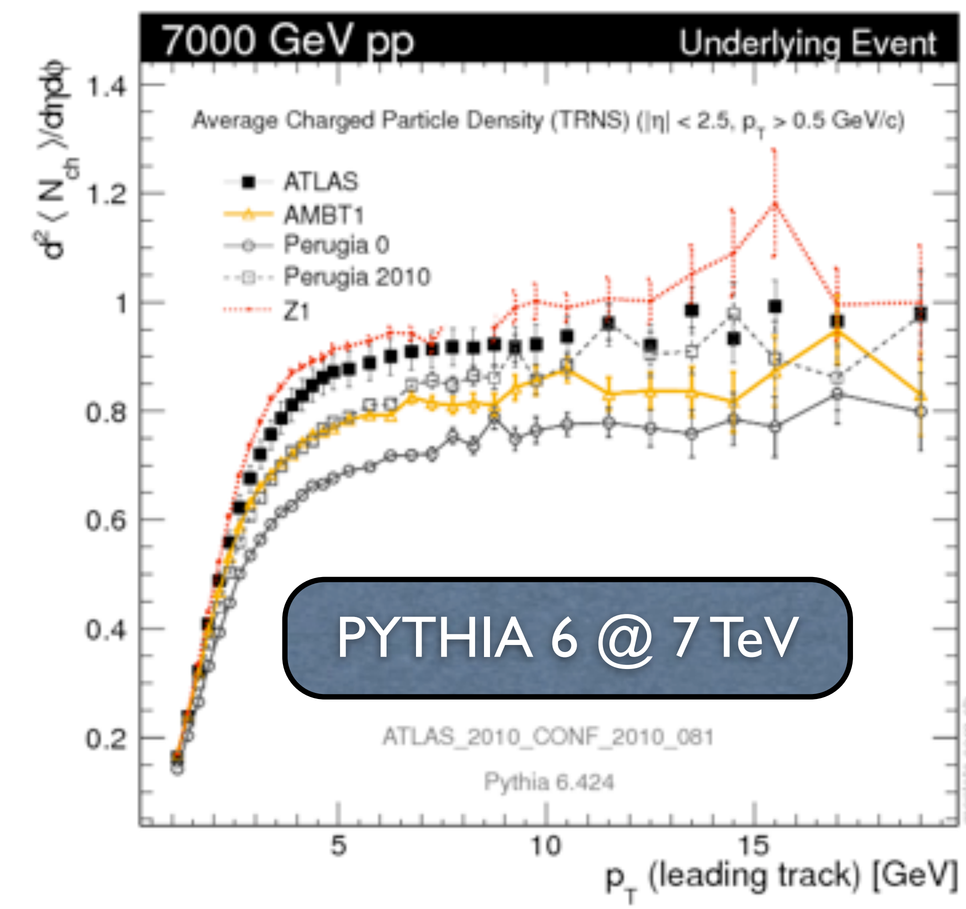
"Perugia 2010" : Larger UE at Tevatron → better at LHC



PYTHIA 6 Recommended: Perugia 2010

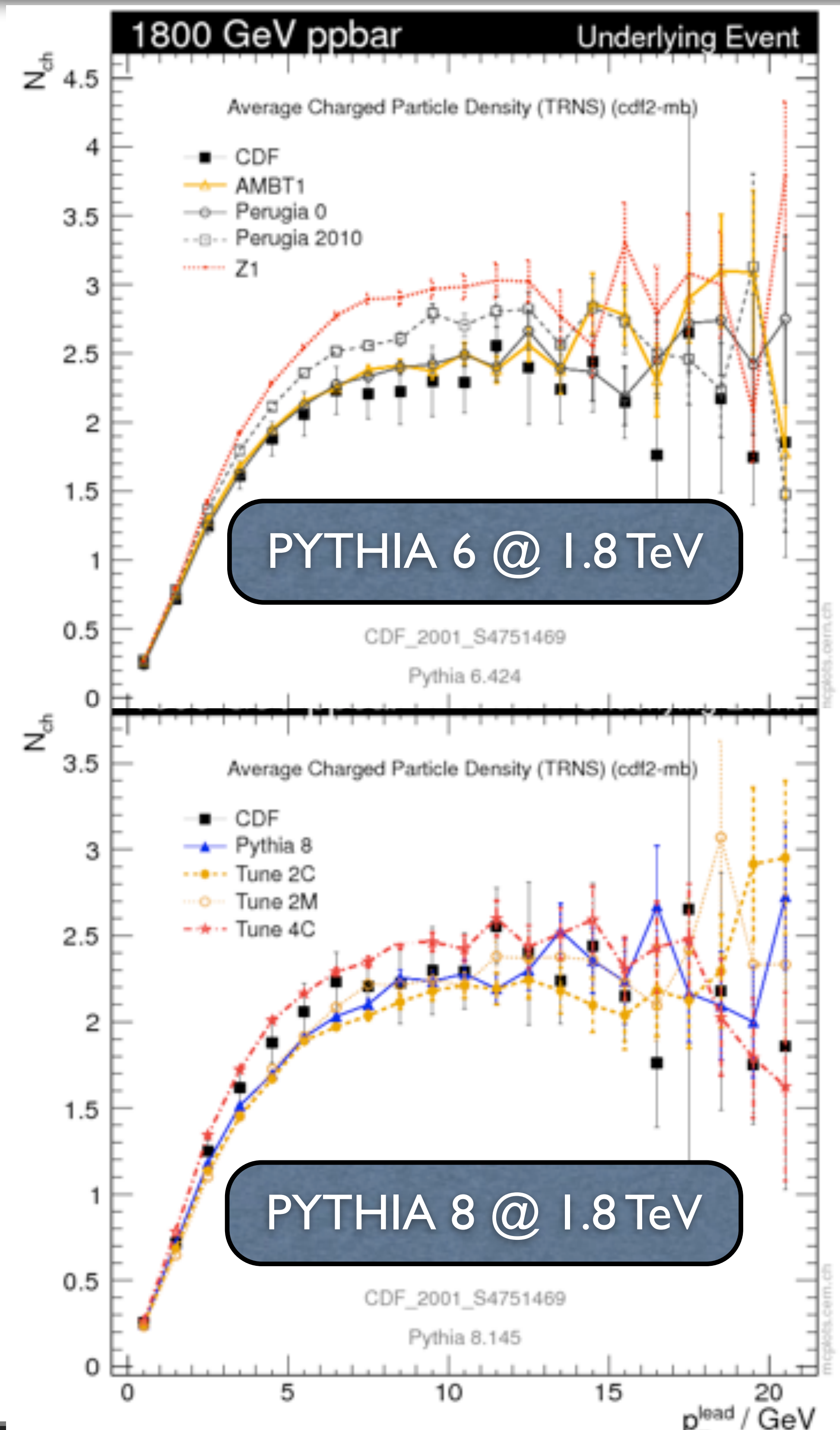
(or dedicated LHC tunes AMBT1, Z1)

For more on tuning PYTHIA 6, see PS, arXiv:1005.3457



(next iteration: fusion between Perugia 2010 and AMBT1, Z1?)

Underlying Event



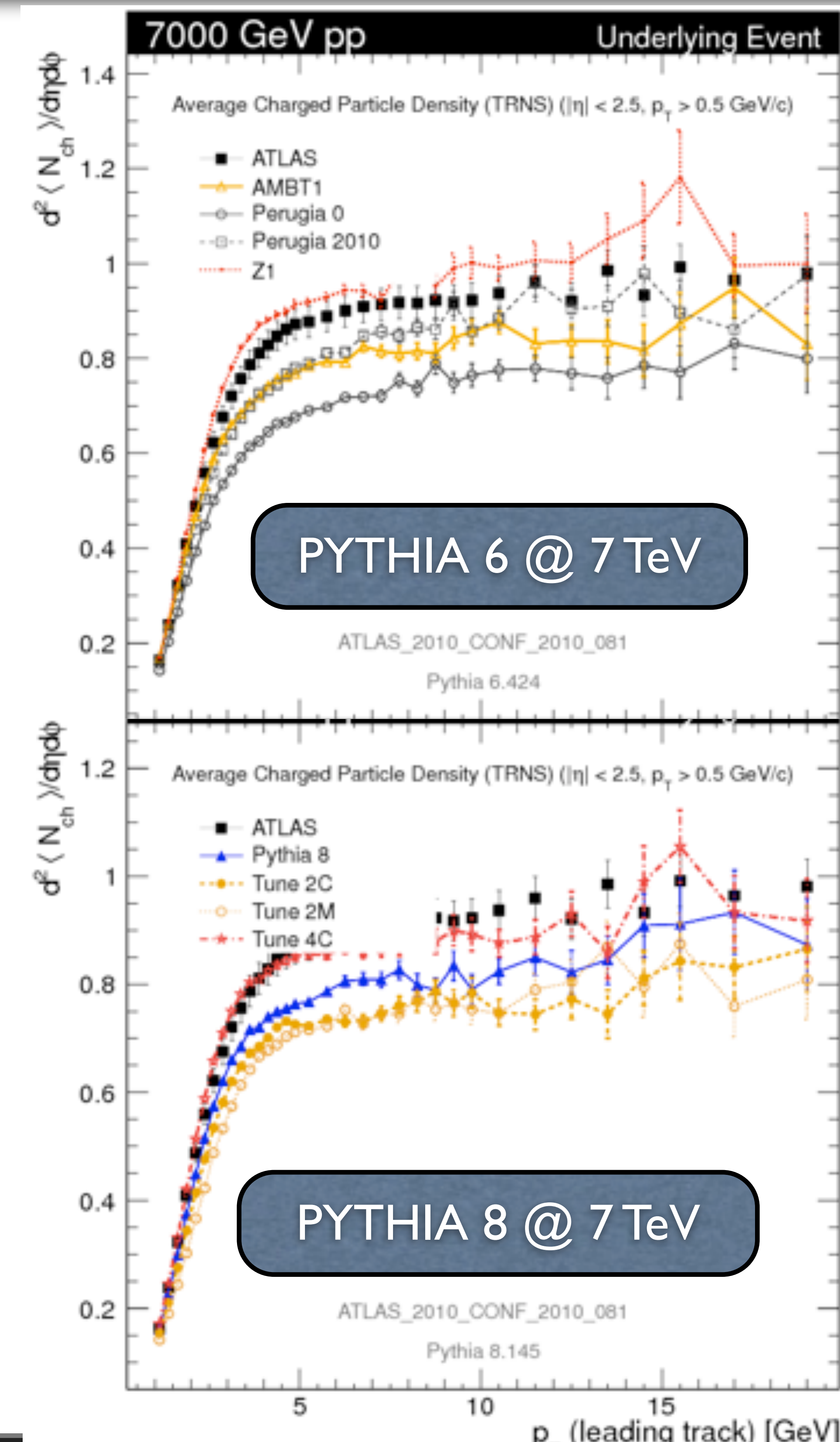
PYTHIA 6
Recommended:
Perugia 2010 (→ 2011)
(or dedicated LHC tunes AMBT1, Z1)

For more on tuning PYTHIA 6, see PS, arXiv:1005.3457

PYTHIA 8
Recommended:
Tune 4C
(probably default from next version)

(Also has damped diffraction following ATLAS-CONF-2010-048)

For more on tuning PYTHIA 8, see Corke, Sjostrand, arXiv:1011.1759



(Plots from mcplots.cern.ch)

Summary

PYTHIA6 is winding down

- Supported but not developed
- Still main option for current run (sigh)
- *But not after long shutdown 2013!*

Recommended for PYTHIA 6:
Global: "Perugia 2010" (MSTP(5)=327)
→ Perugia 2011 (MSTP(5)=350)
+ LHC MB: "AMBT1" (MSTP(5)=340)
+ LHC UE "Z1" (MSTP(5)=341)

PYTHIA8 is the natural successor

- Already several improvements over PYTHIA6 on soft physics
  - (including modern range of PDFs (CTEQ6, LO*, etc) in standalone version)
  - Though still a few things not yet carried over (such as *ep*, some SUSY, etc)
- If you want new features (e.g., x-dependent proton size, rescattering, ψ', MadGraph-5 and VINCIA interfaces, ...) then be prepared to use PYTHIA8
- Provide Feedback, both what works and what does not
  - Do your own tunes to data and tell outcome

Recommended for PYTHIA 8:
"Tune 4C" (Tune:pp = 5)

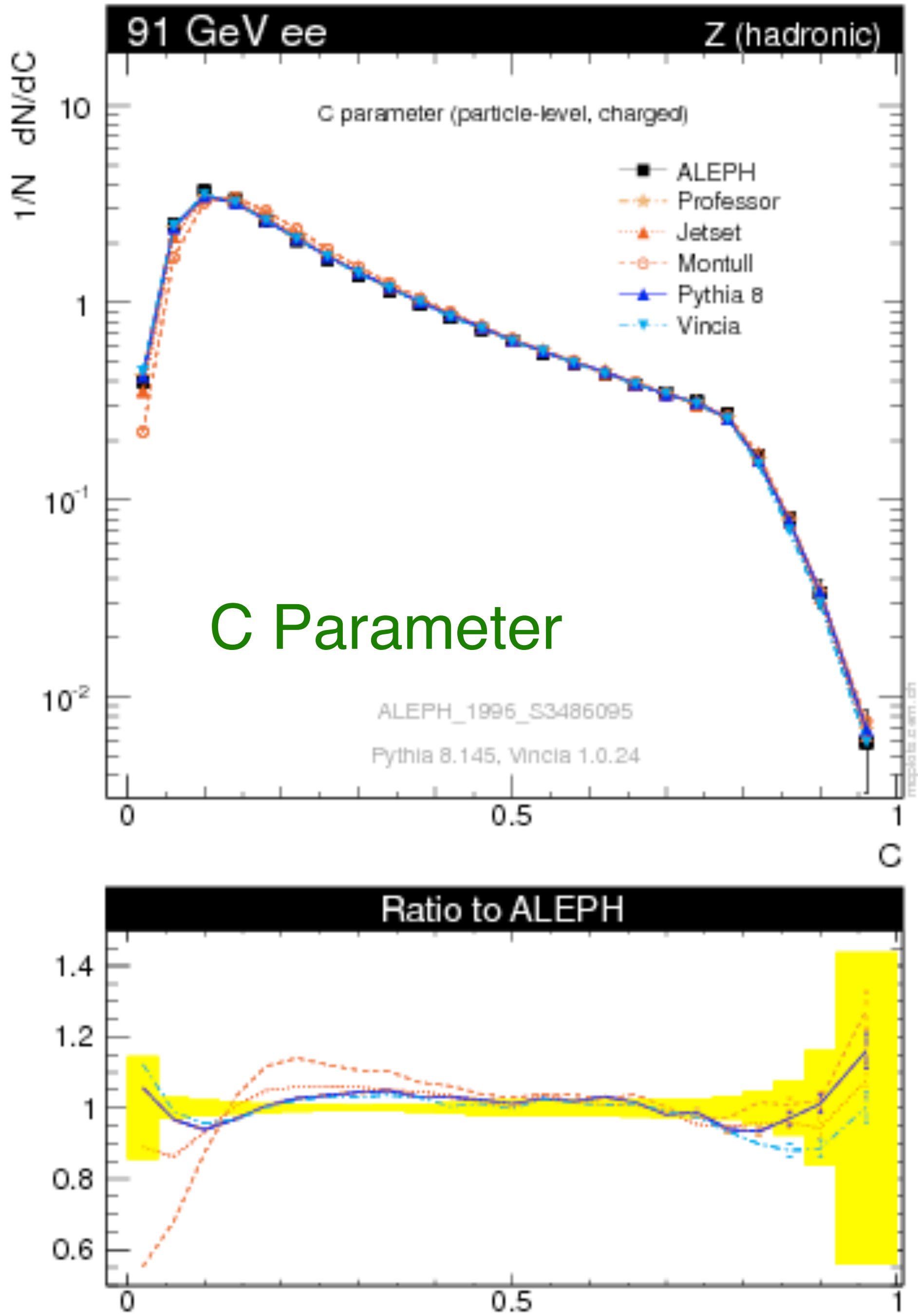
There is no way back!

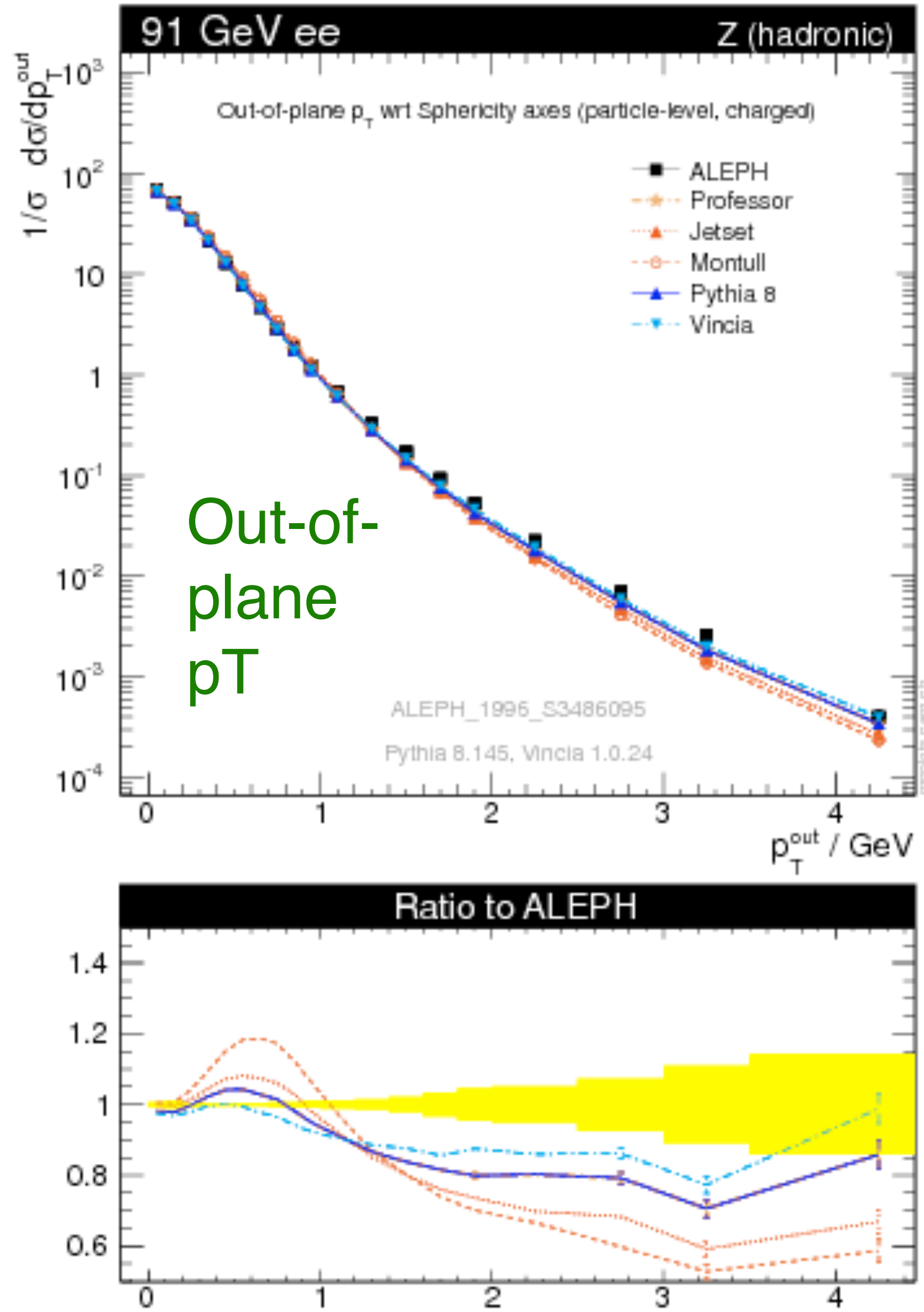
Additional Slides

Diffraction, Identified Particles, Baryon Transport, Tunes

Tuning of PYTHIA 8

Tuning to e+e- closely related to p⊥-ordered PYTHIA 6.4. A few iterations already. First tuning by Professor (Hoeth) → FSR ok?

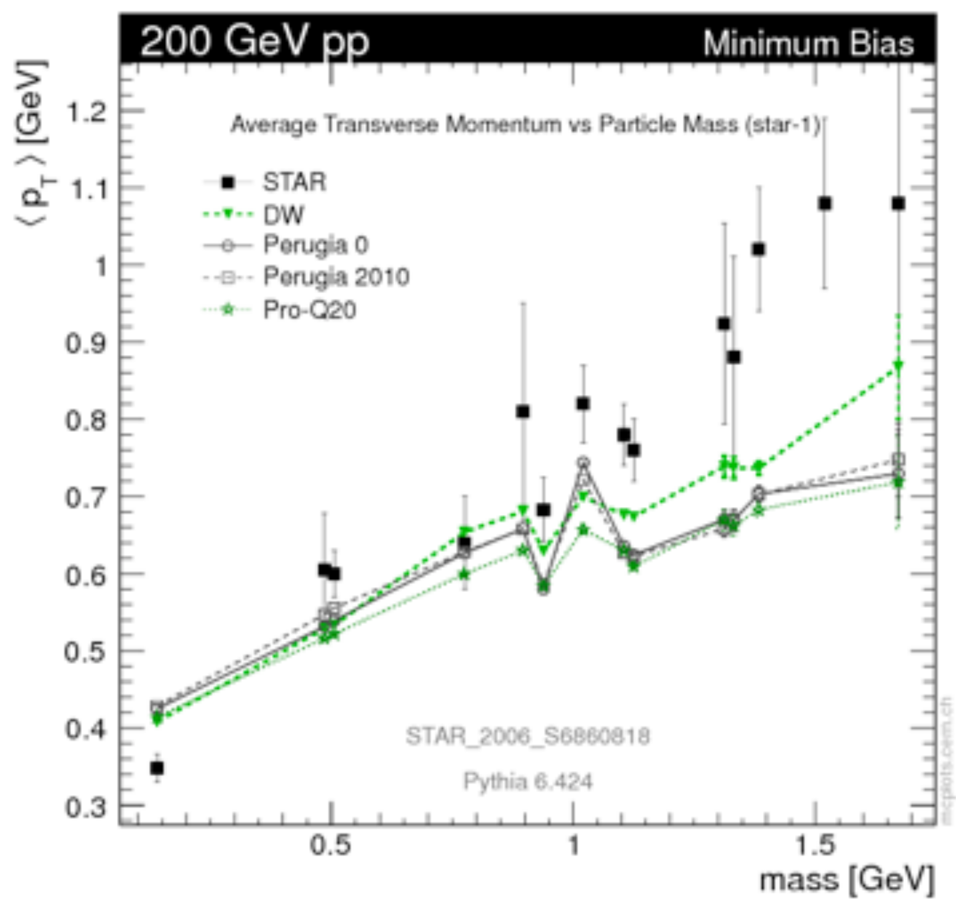




(Plots from mcplots.cern.ch)

(Identified Particles)

Interesting discrepancies in strange sector

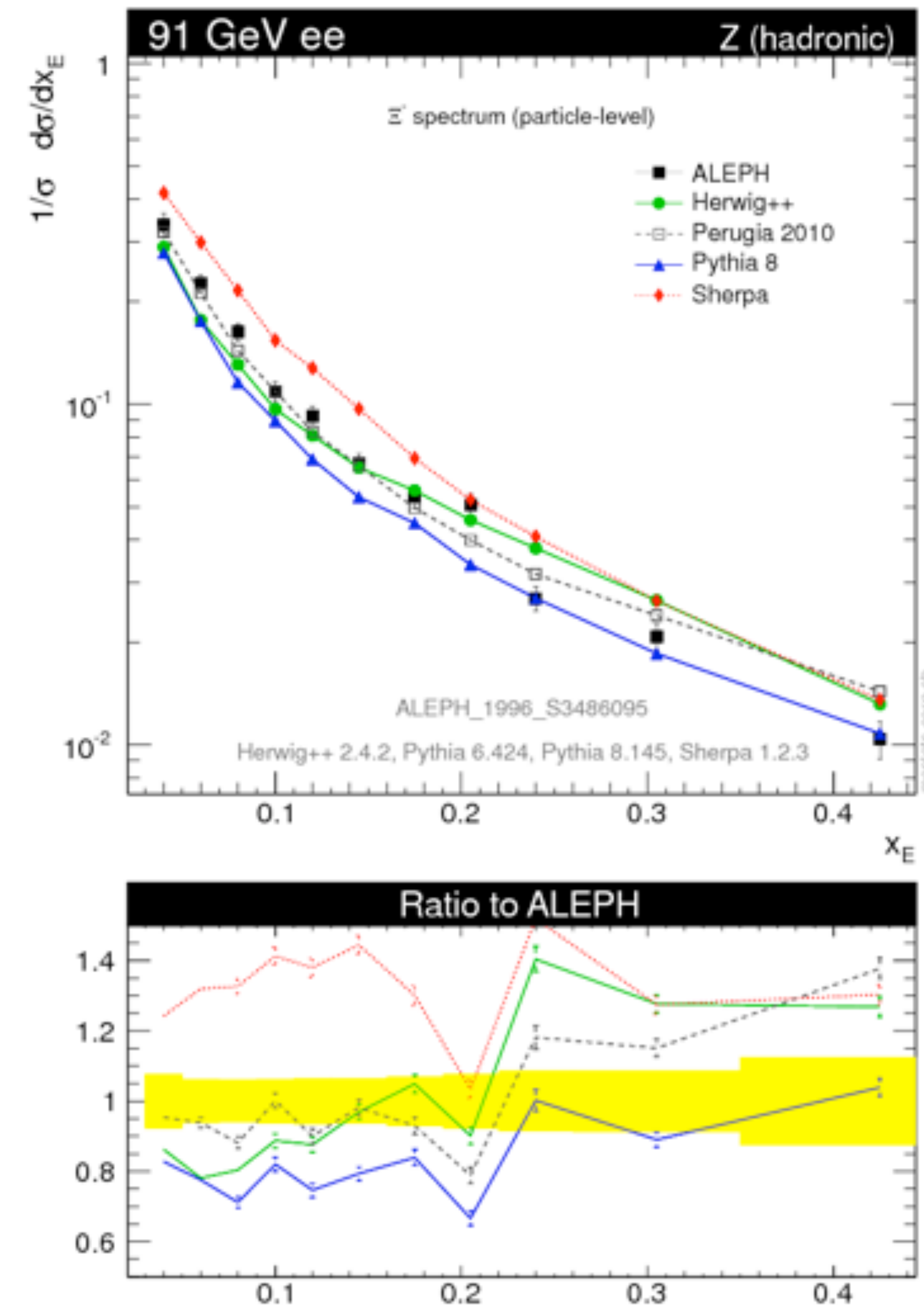


+ problems with Λ/K and s spectra also at LEP?

Grows worse (?) for multi-strange baryons

Flood of LHC data now coming in!

Interesting to do systematic LHC vs LEP studies



PYTHIA 8 Tune Parameters

Parameter	Tune 2C	Tune 2M	Tune 4C
SigmaProcess:alphaSvalue	0.135	0.1265	0.135
SpaceShower:rapidityOrder	on	on	on
SpaceShower:alphaSvalue	0.137	0.130	0.137
SpaceShower:pT0Ref	2.0	2.0	2.0
MultipleInteractions:alphaSvalue	0.135	0.127	0.135
MultipleInteractions:pT0Ref	2.320	2.455	2.085
MultipleInteractions:ecmPow	0.21	0.26	0.19
MultipleInteractions:bProfile	3	3	3
MultipleInteractions:expPow	1.60	1.15	2.00
BeamRemnants:reconnectRange	3.0	3.0	1.5
SigmaDiffractive:dampen	off	off	on
SigmaDiffractive:maxXB	N/A	N/A	65
SigmaDiffractive:maxAX	N/A	N/A	65
SigmaDiffractive:maxXX	N/A	N/A	65

R. Corke & TS, arXiv:1011.1759 [hep-ph]

Strangeness Tunable Paramters

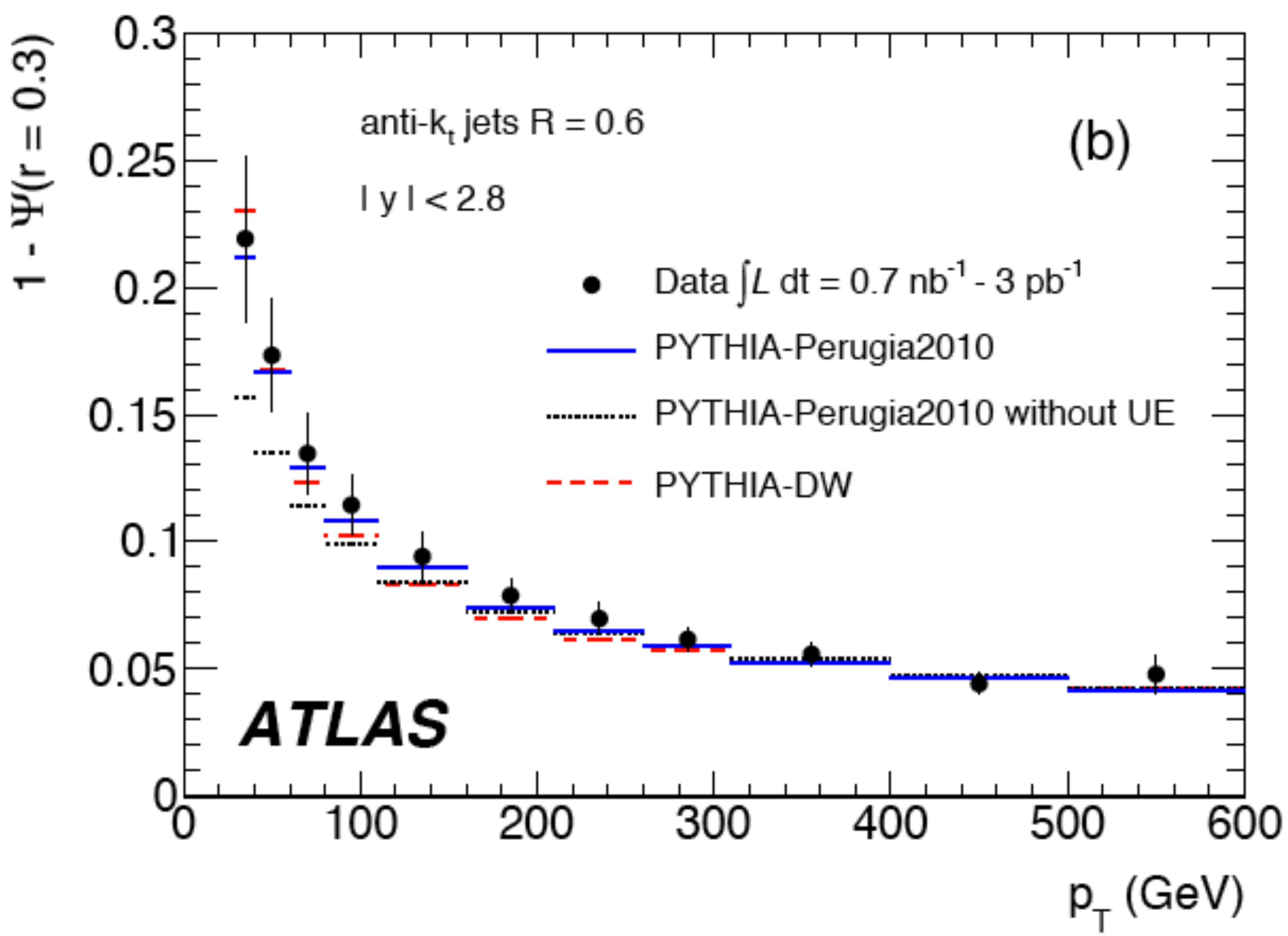
Flavor Sector
(These do not affect pT spectra, apart from via feed-down)

	Main Quantity	**PYTHIA 6**	**PYTHIA 8**
s/u	K/π	PARJ(2)	StringFlav:probStoUD
Baryon/Meson	p/π	PARJ(1)	StringFlav:probQQtoQ
Additional Strange Baryon Suppr.	Λ/p	PARJ(3)	StringFlav:probSQtoQQ
Baryon-3/2 / Baryon-1/2	Δ/p, …	PARJ(4) , PARJ(18)	StringFlav:probQQ1toQQ0 StringFlav:decupletSup
Vector/Scalar (non-strange)	\rho/π	PARJ(11)	StringFlav:mesonUDvector
Vector/Scalar (strange)	K^*/K	PARJ(12)	StringFlav:mesonSvector

Note: both programs have options for c and b, for special baryon production (leading and "popcorn") and for higher excited mesons. PYTHIA 8 more flexible than PYTHIA 6. Big uncertainties, see documentation.

For pT spectra, main parameters are **shower** folded with: **longitudinal and transverse fragmentation function** (Lund *a* and *b* parameters and p_T broadening (PARJ(41,42,21)), with possibility for larger *a* for Baryons in PYTHIA 8, see "Fragmentation" in online docs).

UE Contribution to Jet Shapes



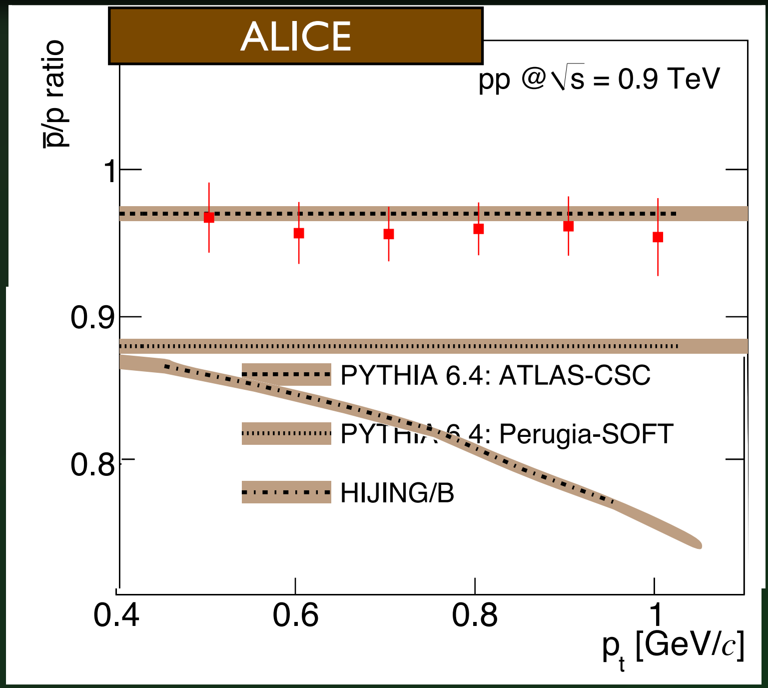
Baryon Transport

LESS than Perugia-SOFT

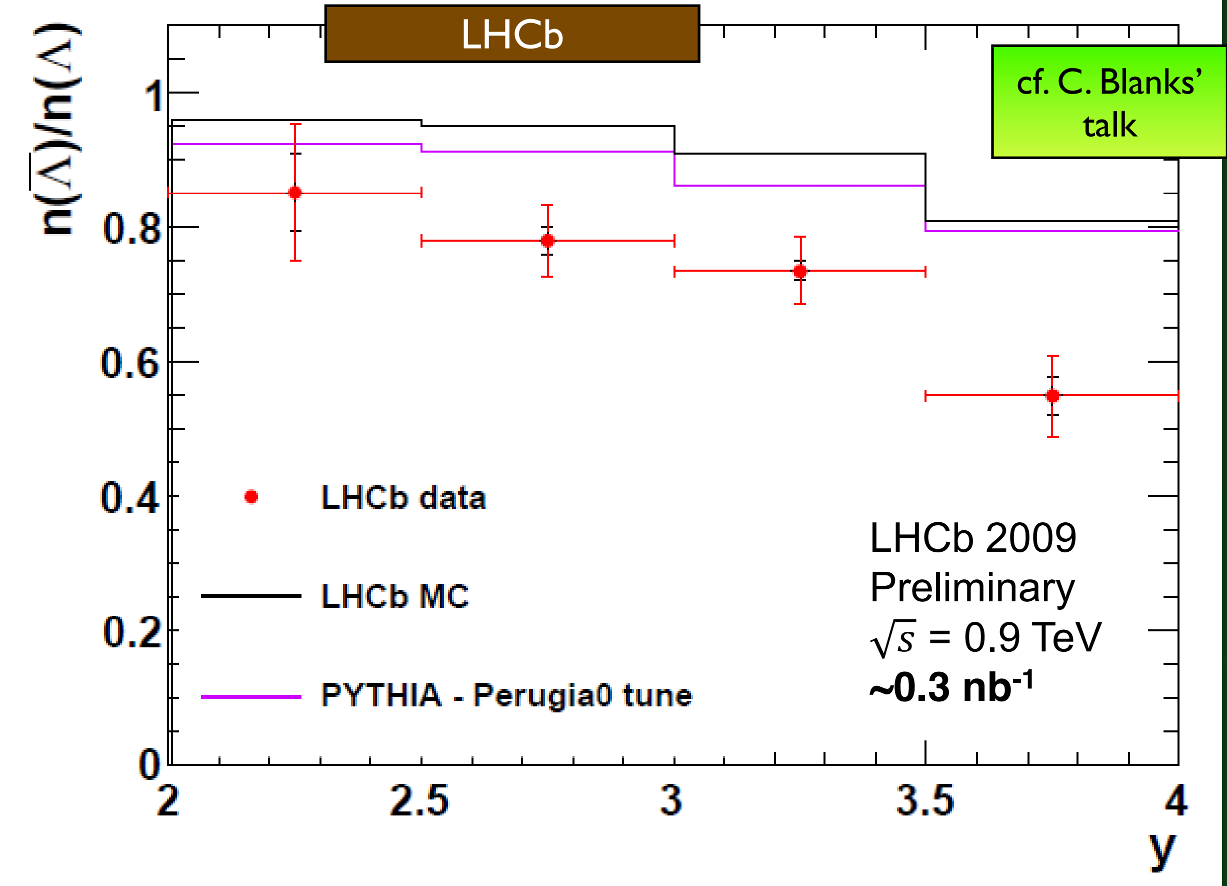
(at least for protons, in central region)

But MORE than Perugia-0

(at least for Lambdas, in forward region)



cf. J. Fiete's talk



cf. C. Blanks' talk

HIJING

From a brief look at the '94 HIJING paper (so apologies for misunderstandings and things not up to date), the HIJING pp model **appears** to be:

- Basic MPI formalism ~ Herwig++ (JIMMY+IVAN) model, with
  - Dijet cross section integrated above p_0 (with no unitarization?)
    - Poisson distribution of number of interactions
    - p_0 plays same main role as PYTHIA's p_{T0}, but is much more closely related to the Herwig++ cutoff parameter (which in turn is very highly correlated with the assumed proton shape, so hard to interpret independently of that)
    - The interactions appear to undergo ISR and FSR showers (using PYTHIA or something else???), with possibility to add medium modifications to evolution
  - "Soft" interactions below p_0
    - These are somehow also showered (below p_0), using ARIADNE it seems?
    - Soft + Hard constructed to add up to total inelastic (non-diffractive???)
- The multiple scatterings only involve gluons (?)
  - The outgoing gluons are color-ordered in rapidity (unlike Herwig++)
    - (Equivalent to **highly** correlated production mechanism ~ PYTHIA and/or CR models)
- Some unclear points:
  - Transverse mass distribution: Fourier transform of a dipole?
    - Related to EM form factor of Herwig++? To PYTHIA forms? Evolves with E? Does it get Smaller/Bigger?