J/ψ HADROPRODUCTION WITH COLOR RECONNECTIONS

PIOTR KOTKO

AGH University of Krakow

in collaboration with:

L. MOTYKA, A. STASTO,

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AGH

MOTIVATION

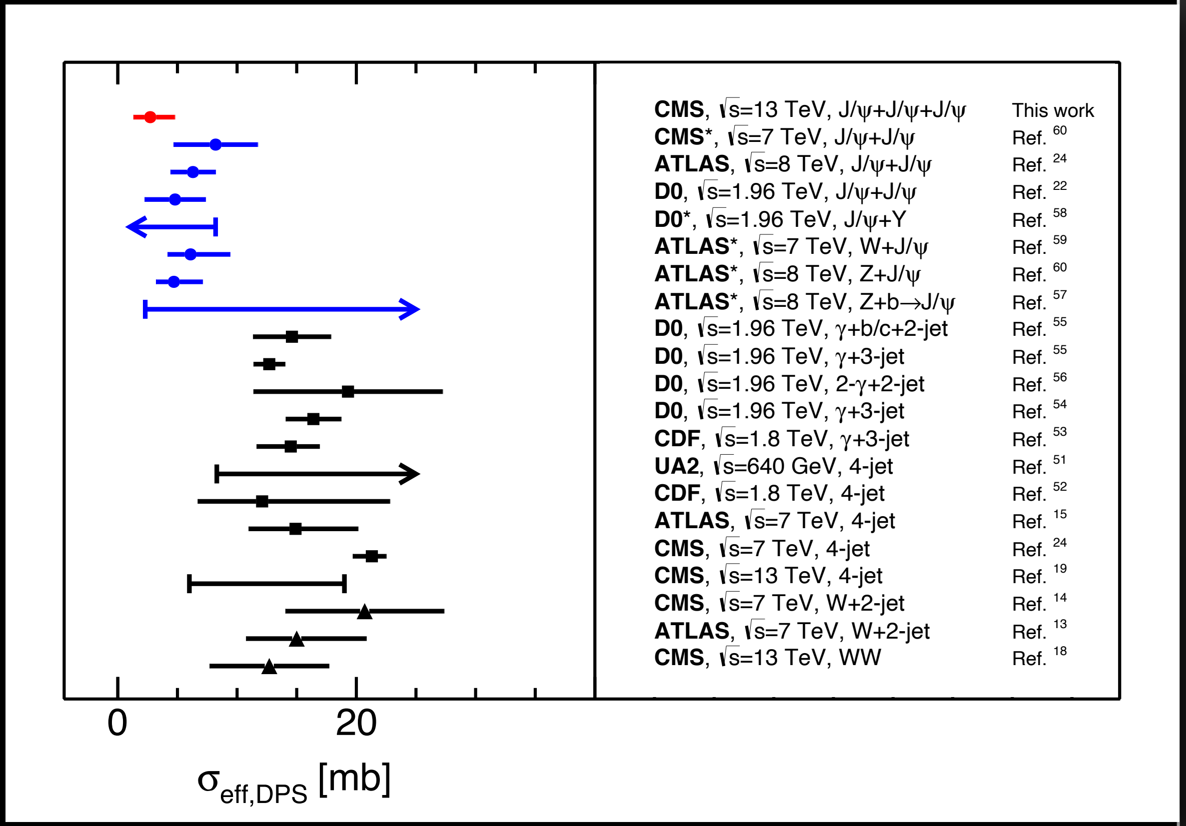
Puzzle of $pp \to 2\,J/\psi + X$ and $pp \to 3\,J/\psi + X$ processes

- standard approach for double parton scattering (DPS)

$$\sigma_{AB} = \frac{1}{2}\frac{\sigma_A\,\sigma_B}{\sigma_{eff}}$$

- σ_{eff} for DPS is about 3 times smaller than for other processes $\Longrightarrow$ **strong correlations**
- single charmonium production is well described by Color Singlet model (CSM) and Color Octet models (COM); both depend on universal fragmentation of partonic Fock states to charmonium
$\Longrightarrow$ **factorization breaking**?

[see eg. J. Collins, 2016]



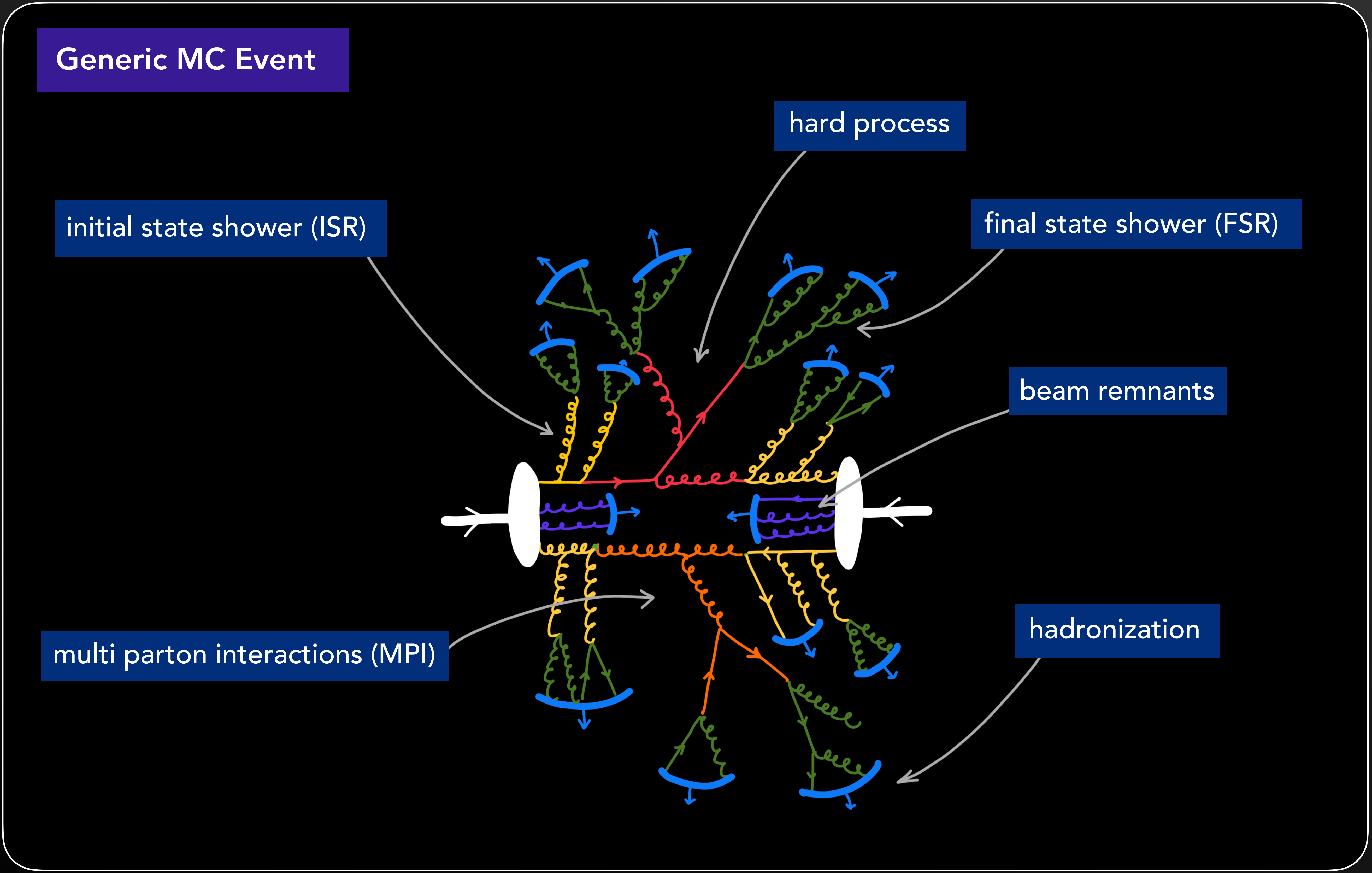
[CMS, Nature Phys. 19 (2023)]

General Idea

- study charmonium hadroproduction using controllable explicit mechanism, where particle production depends on the environment
- our choice: PYTHIA with Color Reconnection (CR) mechanism
- we study production of low invariant mass $c\bar{c}$ singlets, and how they are affected by the CR

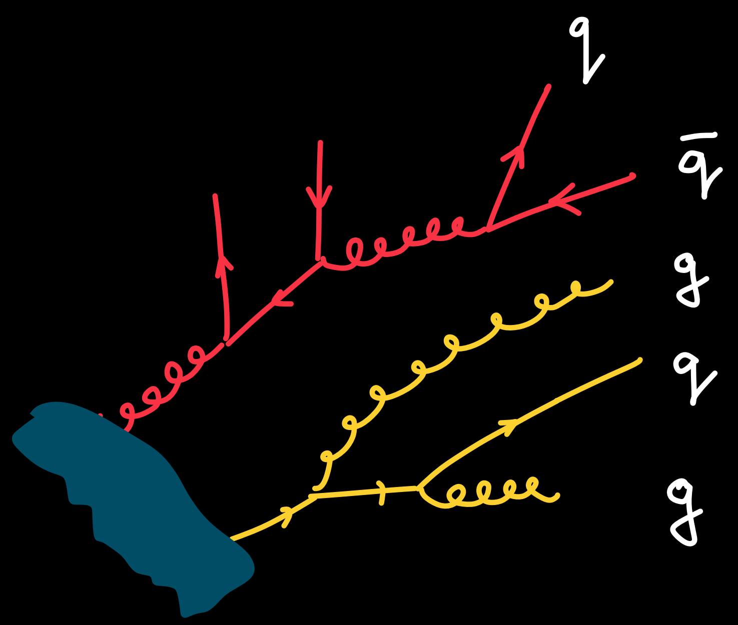
[motivated by Edin, Ingleman, Rathsman, 1997]

INTRODUCTION

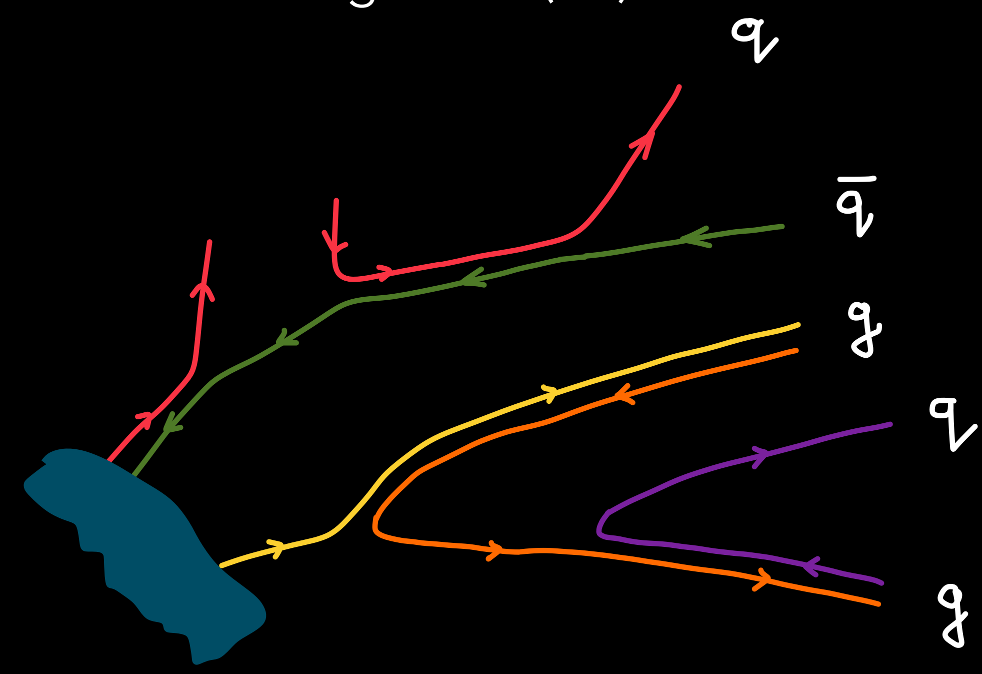


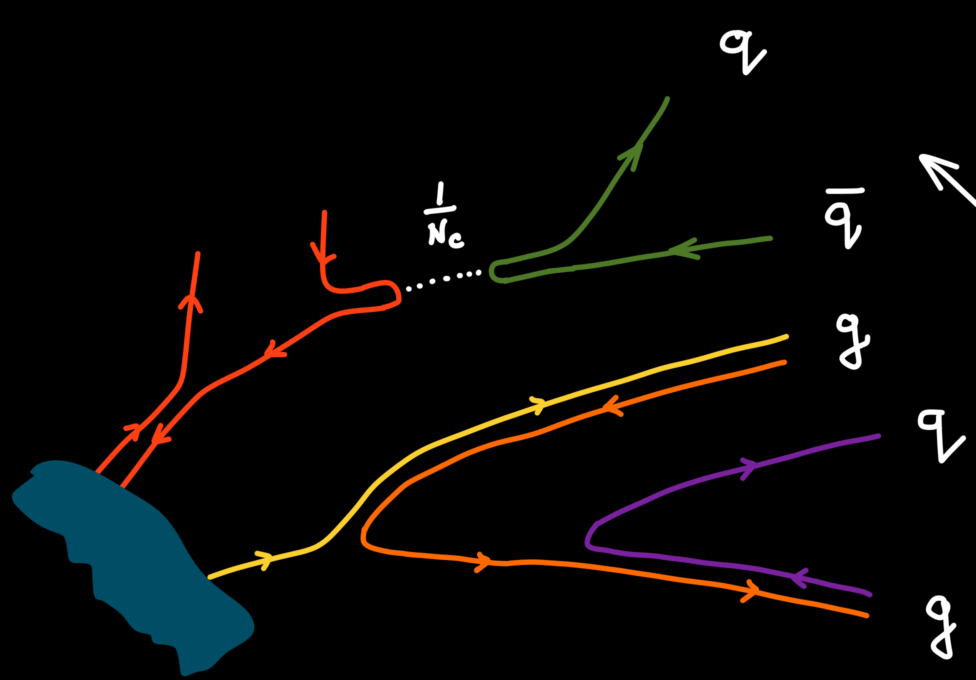
INTRODUCTION

Color management in a MC event

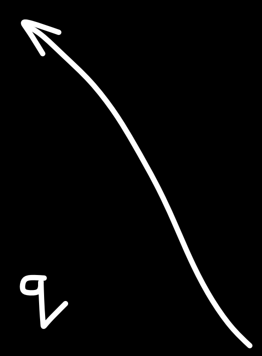


Leading Color (LC)





Non-Leading Color

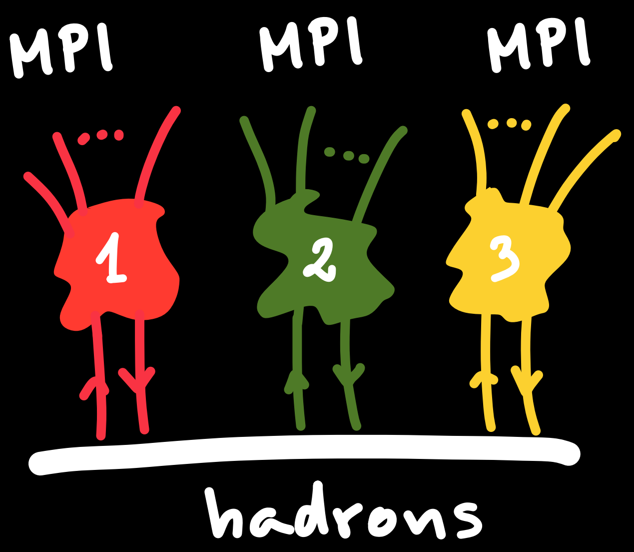


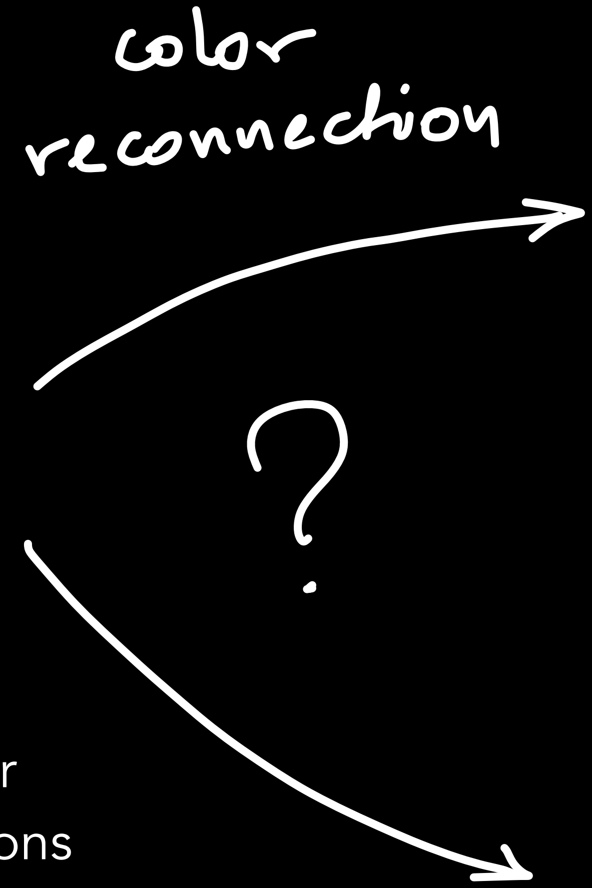
Each line has a "color tag" i or "anti-color tag" $\bar{i}$.
In Pythia $i, \bar{j} = 101{,}102{,}103{,}104{,}...$
Partons are characterized by a pair of tags $\{i, \bar{j}\}$.

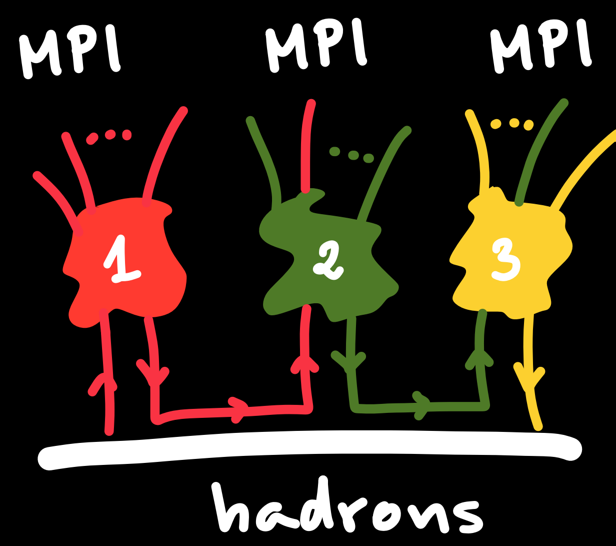
Requires switching the color tags for final state particles.

COLOR RECONNECTIONS

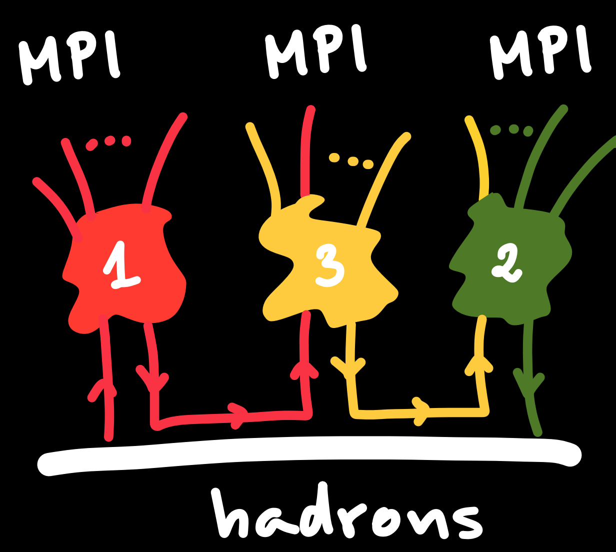
Color ambiguities







But why not to reconnect
1↔3↔2 ?



Uncorrelated MPIs give too much color charge extracted from the colliding hadrons

⇓

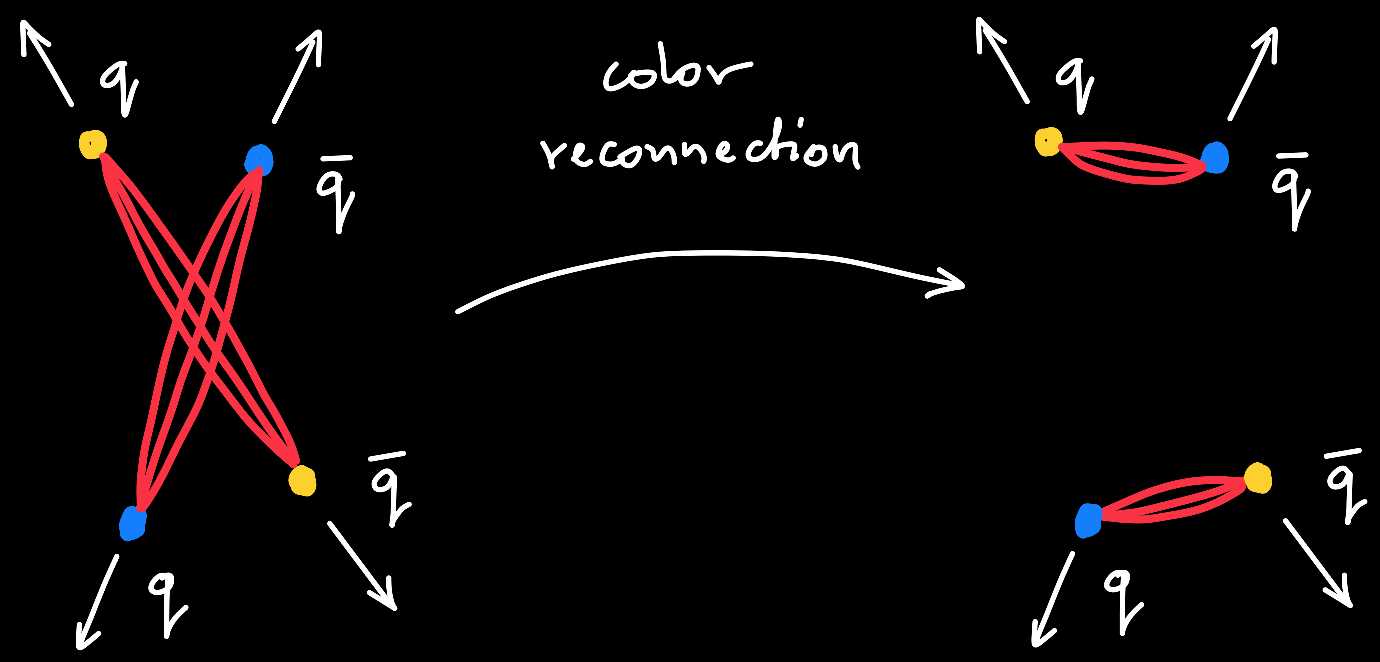
too large hadronic activities at forward rapidities...

[J. Christiansen, P. Skands, 2015]

COLOR RECONNECTIONS

QCD-based Pythia CR model

- possible color topologies are SU(3) QCD-driven
- detailed modeling of the beam remnants
- reconnections are such, that the color topology for which the “string length” is minimized, are passed on to hadronization



[based on J. Christiansen talk at MPI@LHC 2014]

J/ψ PRODUCTION IN PYTHIA

Algorithm

- we **do not** use COM or other models available in Pythia for charmonium production
- we take default Pythia 8.3, no tuning, with MPI and showers turned on
- the hadronization is turned off
- we scan through the event record to look for $c\bar{c}$ quarks
- if present, we look for $c\bar{c}$ pairs with matching color and anti-color tags
  - these are J/ψ candidates
- we apply the invariant mass cut: $3.0\,\mathrm{GeV} \leq M \leq M_{\mathrm{max}}$
  - the color singlets satisfying this cut are treated as J/ψ
- M_{max} is our free parameter; we fix $M_{\mathrm{max}} \approx 3.3\,\mathrm{GeV}$ to have best description of data
- we compute p_T spectra in central rapidity window $|y| \leq 2.4$
- we test color reconnection on/off

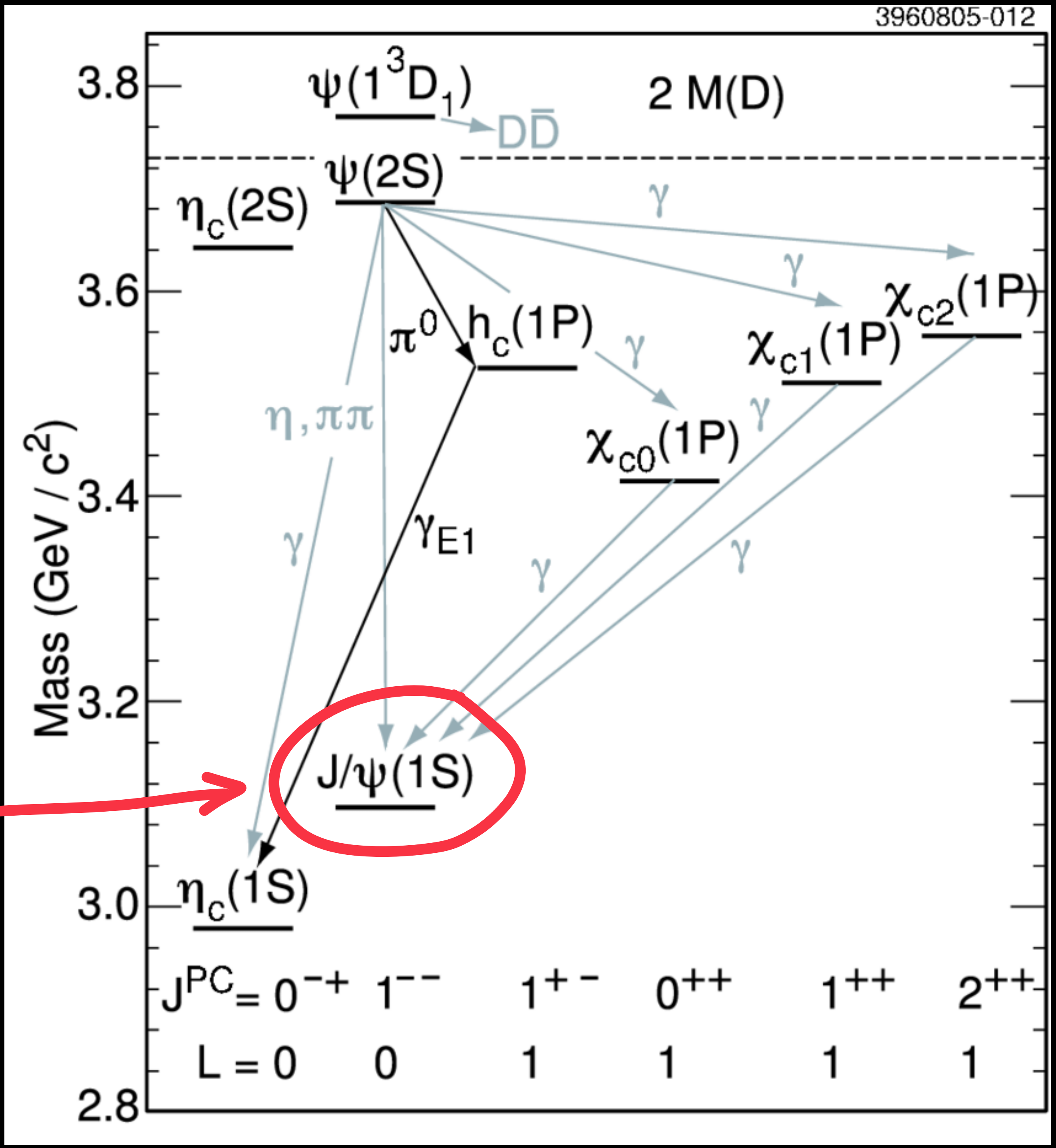
J/ψ PRODUCTION IN PYTHIA

Charmonium system

Our final invariant mass cut on the singlet system

$$3.0\,\text{GeV} \leq M \leq 3.3\,\text{GeV}$$

lies within reasonable range

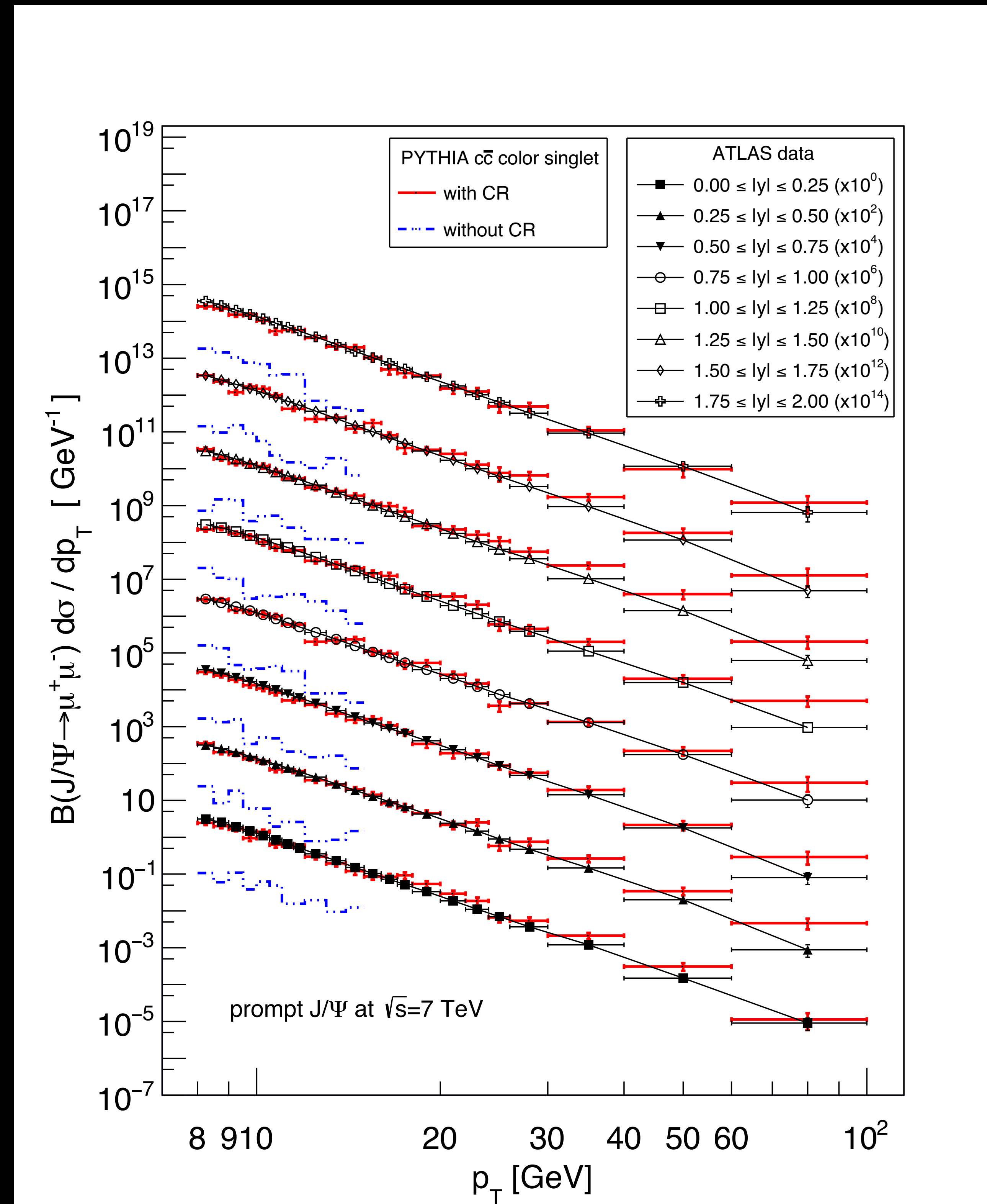


[taken from CLEO, Phys. Rev.D 72 (2005) 092004]

J/ψ PRODUCTION IN PYTHIA

Results for ATLAS kinematics

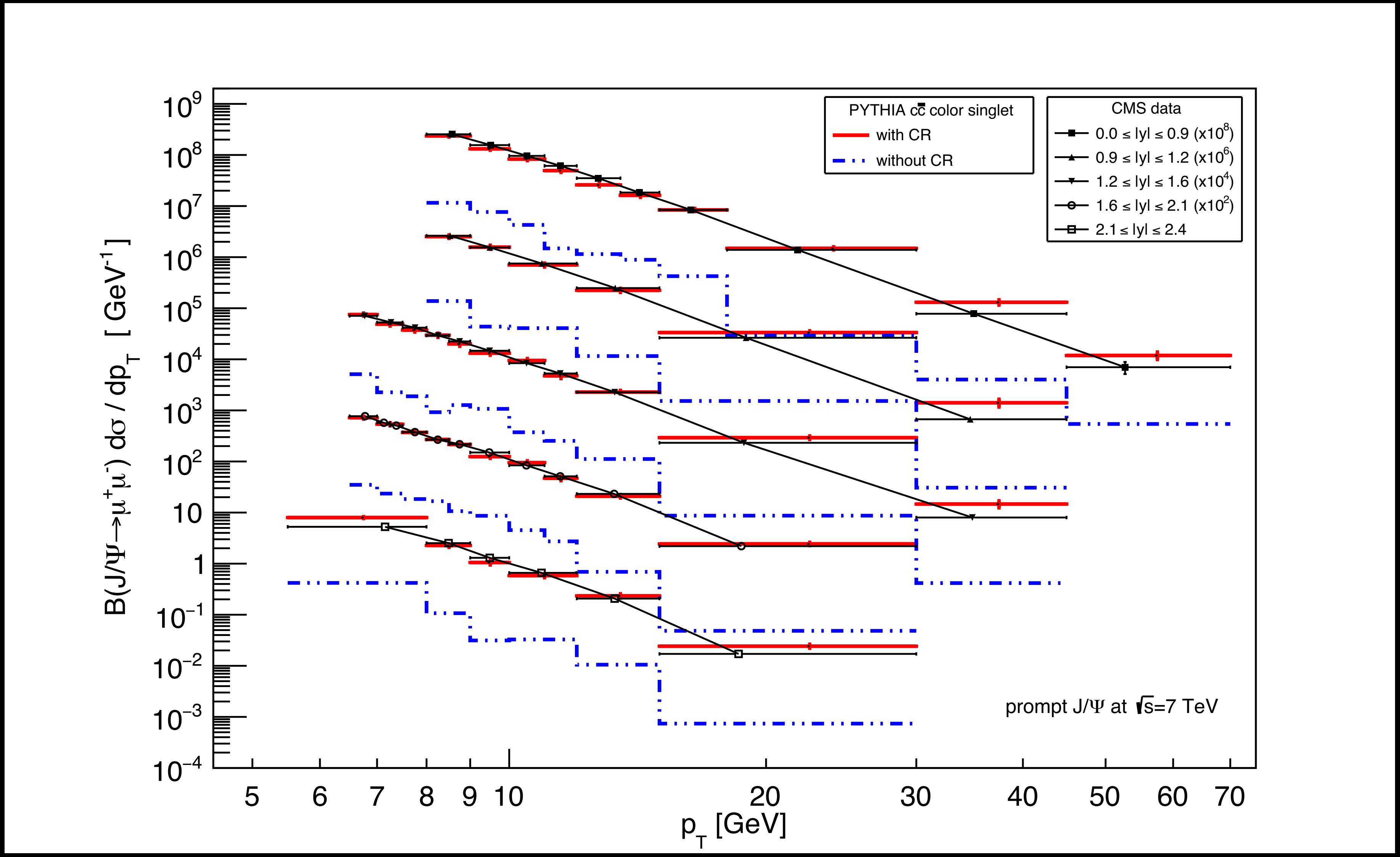
- comparison with ATLAS data [ATLAS, Eur.Phys.J C (2016) 283]
- **good description of data for most rapidity bins, provided the CR is on (red histograms)**
- without CR J/ψ production rate is dramatically insufficient to describe the data
- some deviations at large p_T, but also large statistical MC errors
- challenging computation; we used the PLGrid facility and Prometheus supercomputer to create sufficient statistics



J/ψ PRODUCTION IN PYTHIA

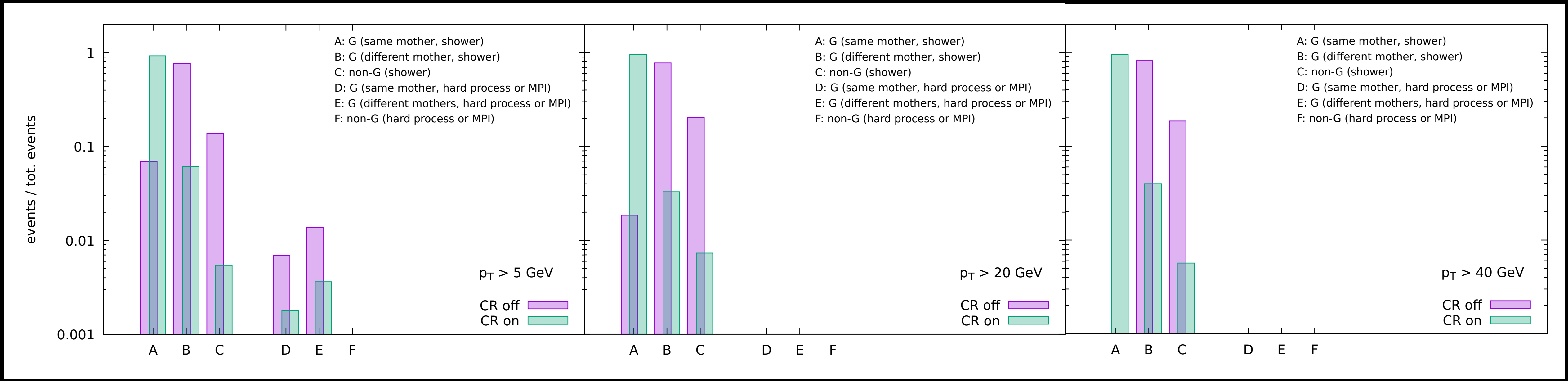
Results for CMS kinematics

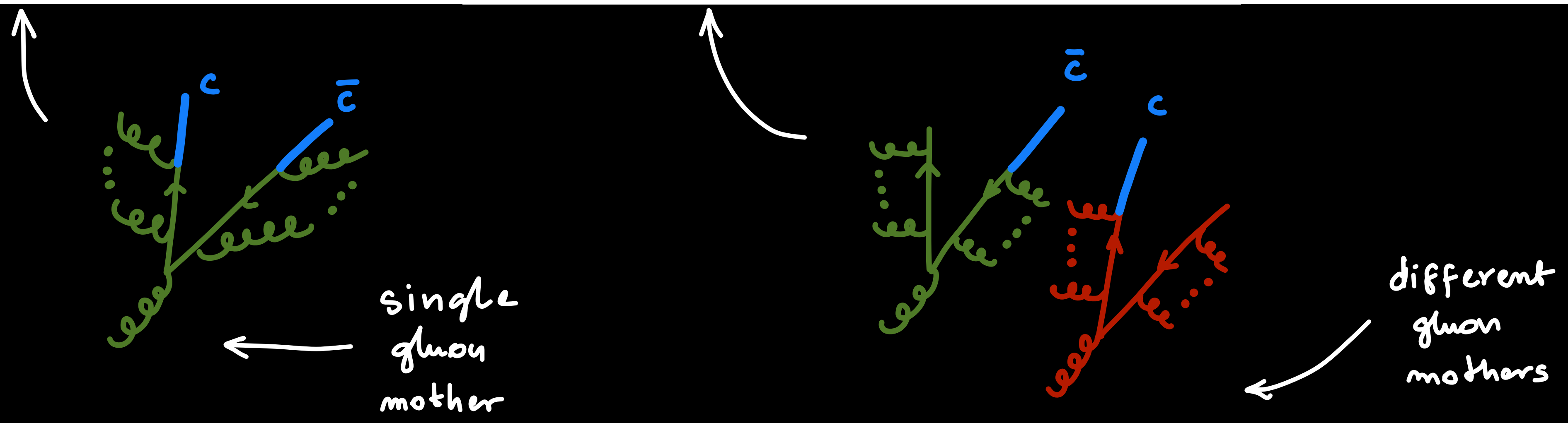
- comparison with CMS data [CMS, JHEP (2012) 011]
- similar conclusions



Origin of $c\bar{c}$ singlets in Pythia

- we analyze event records with low invariant mass $c\bar{c}$ singlets
- we extract information on mother partons and its production mechanism
- each plot is normalized by the total number of events, independently for CR on and CR off

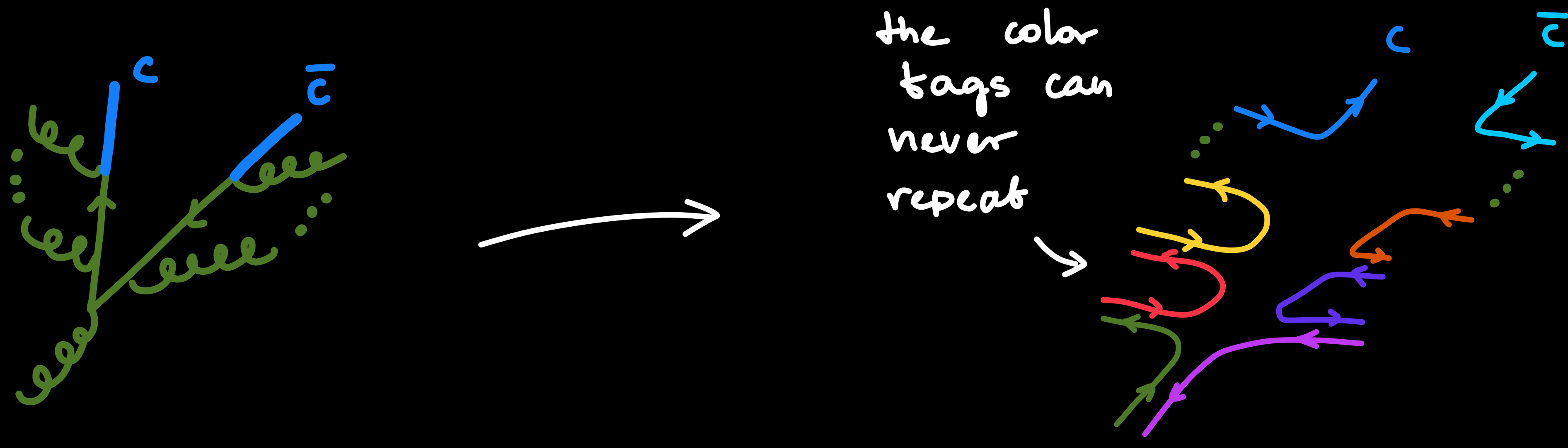




J/ψ PRODUCTION IN PYTHIA

Interpretation

- in the Leading Color (large N_c) no perturbative mechanism can contribute to class A ("single gluon mother")



- the very few events in class A with **CR off** are due to color reshuffling in the MPI and beam remnant; it dies out with p_T
- dominant mechanism when **CR is off** is via "different gluon mothers", but this has small probability due to less likely phase space overlap
- when **CR is on**, class A mechanism dominates; narrow angle quark pair is favored by the smallness of the string length and tend to be color-reconnected to become the singlet

SUMMARY

- The model of J/ψ hadroproduction using the Color Reconnection reproduces both the magnitude and p_T dependence.
- No tuning of PYTHIA parameters; just one extra parameter — cut on $c\bar{c}$ invariant mass, being in the expected range.
- Color Reconnection is essential to reproduce the data.
- Gluons from showers are the dominant source of J/ψ.

- What about double J/ψ hadroproduction in this model? Very challenging (statistics)…