J/ψ hadroproduction from color reconnection

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Overview

We want to check whether inclusion of Color Reconnection effects may explain J/ψ hadroproduction data

Talk based on recent results [arxiv:2303.13128]

1. Part I (by LM):
   - WHAT?
   - WHY?
2. Part II: Piotr Kotko:
   - HOW?
   - THE RESULTS

"color reconnection effects in making mesons from charm quarks"

by AI: hotpot.ai/s/art-generator

Motivation: puzzles and questions in heavy vector quarkonia hadroproduction

As motivation we consider classical processes $pp \to J/\psi + X$ and $p\bar{p} \to J/\psi + X$ and double J/ψ production $pp \to J/\psi J/\psi + X$

Challenge for theory: puzzles and questions

1. Spectacular failure of the most natural QCD description with Color Singlet Model
   $\longrightarrow$ widely accepted solution with Color Octet Model
2. Problems of Color Octet Model with double J/ψ hadroproduction — theory underestimates the cross section by factor of about 3
3. Does hard factorization hold in fragmentation into J/ψ?
4. What is the origin of strong correlations of J/ψ rates with charged particle multiplicity?

What are we dealing with?

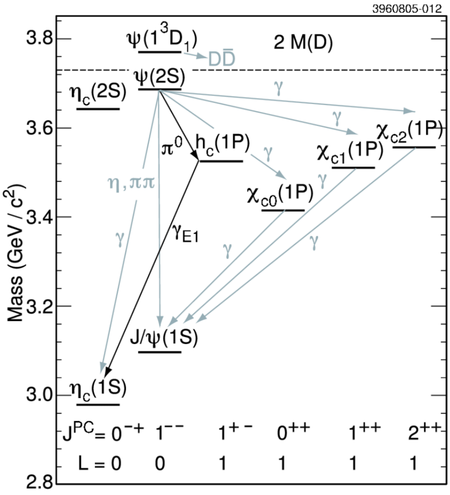
J / ψ: a $c\bar{c}$ state

Mass = 3.097 GeV

Charmonium system mass range:

$\sim$ 2.98 GeV — 3.74 GeV

Typical $\Delta M \sim 0.5$ GeV



[Fig.: CLEO. Phys.Rev.D 72 (2005) 092004]

Motivation of this study: puzzles and questions in J/ψ hadroproduction

As motivation we consider classical processes $pp \to J/\psi + X$ and $p\bar{p} \to J/\psi + X$ and double J/ψ production $pp \to J/\psi J/\psi + X$

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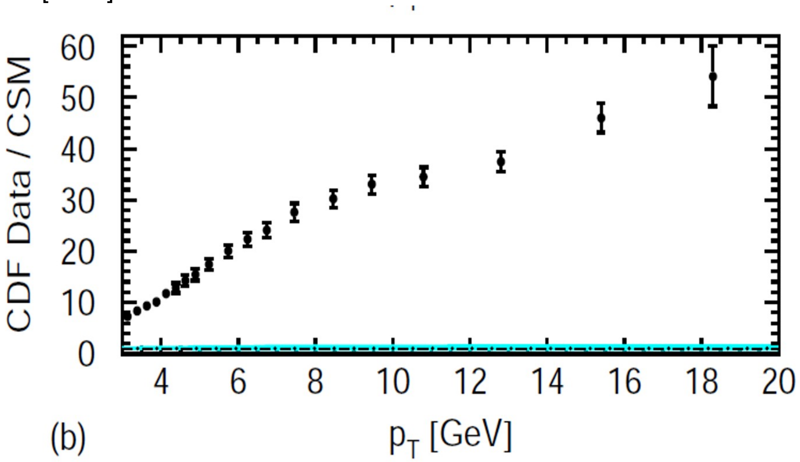
Puzzle 1: Why does the color singlet mechanism fail?

The old surprise: the QCD Color Singlet Model vs Tevatron (CDF) data [1992]



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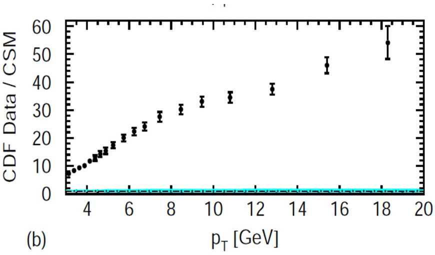
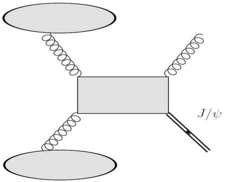


- Heavy vector quarkonia: the main issue is the **COLOR** treatment
- J/ψ a C-odd color singlet — in pQCD one needs at least three gluons to make it (for C-even, e.g. χ_c — two gluons)
- Color Singlet Model: gluon emission: $gg \to J/\psi + g$ — the leading twist partonic channel but too little p_T given

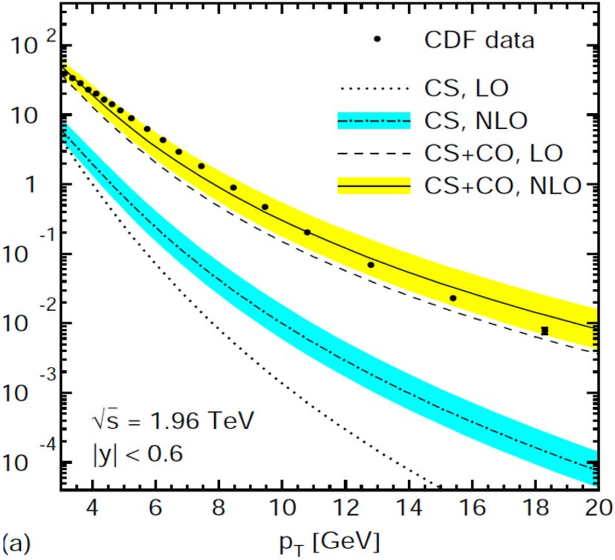


Puzzle 1: A way out – the Color Octet Model

- Observation: at the Tevatron the ratio of J/ψ and jet cross sections was found to be roughly constant as function of p_T. Implies: the hardest possible p_T dependence $d\sigma/dp_T \sim 1/p_T^5$
- Cho and Leibovitch [1995] (also Braaten, Yuan [1993]) gave the key idea of the COM:
  non-zero amplitudes of gluon fragmentation into J/ψ
- Formulation in terms of transition amplitudes of $c\bar{c}$ states in color **8** representation with various L and S into the meson, with the order of magnitude inspired by NRQCD
- The Color Octet Model assumes pQCD production mechanism of partonic $c\bar{c}$ states followed by **universal — i.e. environment independent**, fragmentation coefficients
- Currently calculated at the NLO. With several free parameters very good description of the data. High p_T part: driven by

$$gg \to \underbrace{g(-p_T) + g(p_T)}_{\sim dijets} \to g + (c\bar{c})(p_T) \to g + J/\psi(p_T)$$

Puzzle 1: A way out – the Color Octet Model



[M. Butenschoen, B.Kniehl, Phys.Rev.Lett. 106 (2011) 022003]

Puzzle 2: Double J/ψ hadroproduction

Double Parton Scattering

$$\sigma_{AB}^{(\mathrm{DPS})} = s_{AB}\,\frac{\sigma_A^{(1)}\sigma_B^{(1)}}{\sigma_{\mathrm{eff}}}$$

$s_{AB} = 1$ for $A \neq B$
$s_{AB} = 1/2$ for $A = B$

Typically measured:

$$\sigma_{\mathrm{eff}} \simeq 15 - 20\ \mathrm{mb}$$

Smaller σ_{eff}
$\longrightarrow$ **larger DPS**

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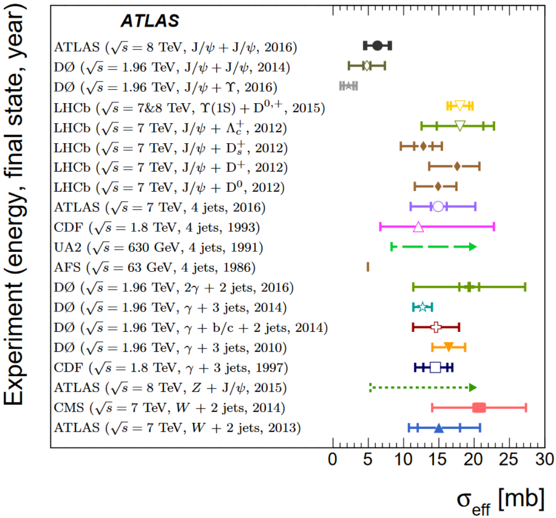
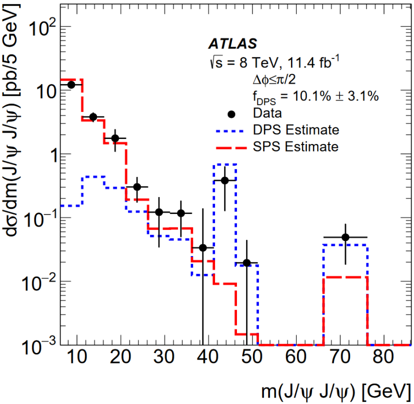


[ATLAS, 1612.02950]

Puzzle 2: Double J/ψ hadroproduction at ATLAS



- Two J/ψ-s can be created from in Single Parton (pair) Scattering (SPS) or in DPS
- At larger invariant masses of the pairs SPS dies out (COM included)
- Large DPS necessary there

$$\sigma_{\rm eff} \simeq 5 \text{ mb}$$

Double heavy vector quarkonium production requires about 3 times stronger DPS effects than other processes!

Puzzle 2: Implications

What does imply the strong enhancement of double J/ψ hadroproduction?

1. Possibility 1: initial state.

   The partonic mechanisms for individual parton-parton to J/ψ subprocesses factorize, but initial parton configurations are particularly strongly correlated in quarkonia pair production
   Problem: why should quarkonia pair production should have such a strong effect on parton correlations, while other hard processes do not show it?

2. Possibility 2: production mechanism.

   Partonic configurations are typical, but strong correlations in the production mechanisms of the two quarkonia. Such correlations could be introduced by multiple interactions in pQCD, but this would correspond to higher twist effects.

   Alternative: factorization breaking at the leading twist

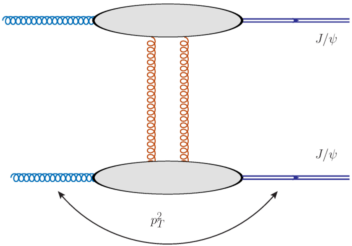
Can perturbative multiple scattering solve the problem?

We need a mechanism that generates large distance rapidity correlations

Natural candidate:

$gg \to J/\psi J/\psi$ via entangled $g + 2g \to J/\psi$ subprocesses

Problem: Large momentum flows through the mesons: additional power suppression

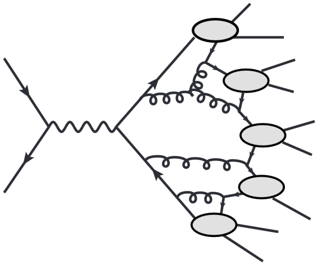


Explicit calculations: by A. Szczurek, A. Cisek and W. Schäfer [1710.11450] and our in-house calculations show that this mechanism is by far too weak

Question 3: Does hard factorization hold in $g \to J/\psi$ fragmentation?

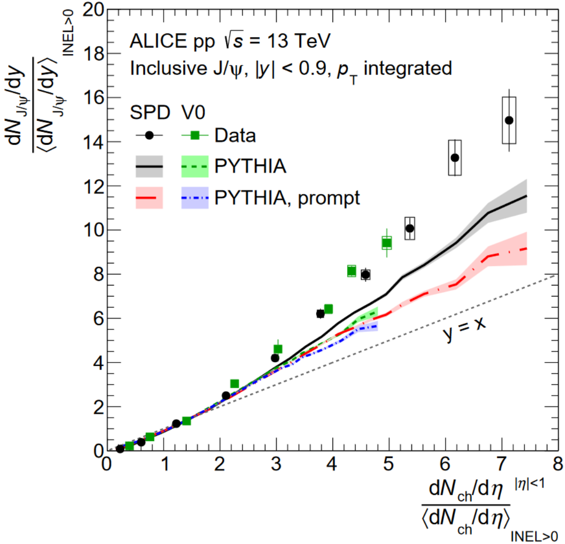
Answer by John Collins, 1610.09994: it is not guaranteed that hard factorization works in fragmentation.

The reason: hadronization effects that fill rapidity ranges between hard partons, and that are of non-perturbative origin (comment: e.g. the Schwinger pair creation effect)



Argument: *"Let Δy be total available rapidity range, about* $\ln(Q^2/m^2)$, *and let δy be typical cluster separation, i.e., $\Delta y/\#$clusters. Experimentally δy is typically small, a unit of rapidity or so. Now suppose we were able apply soft-to-collinear approximations. Errors would now be a power of* $\exp(-\delta y)$, *not m/Q, while the order of the relevant graphs increases with* $\ln Q$*."*

Puzzle 4: What is the reason of strong correlations of J/ψ production with multiplicity? [ALICE 2005.11123]



Possible solution: Color Reconnection

- Question: what happens between the partonic and hadronic phase?
- Color is not locally preserved in this transitions: colored partons get to white hadrons
- For quarks: they pick antiquarks from the vacuum to make color singlets — this is related to color string breaking in the Lund string picture
- Hadronization occurs at distances of ~ 1 fm. In the presence of color fields the short distance parton color ordering may not survive
- These reasons and data analysis $\longrightarrow$ multi-purpose event simulators like PYTHIA and HERWIG include possibility of changing large N_c color ordering between the partonic phase and hadronization: the Color Reconnection (CR) mechanism

Possible solution: Color Reconnection — why interesting?

Key features of Color Reconnection in the Lund approach:

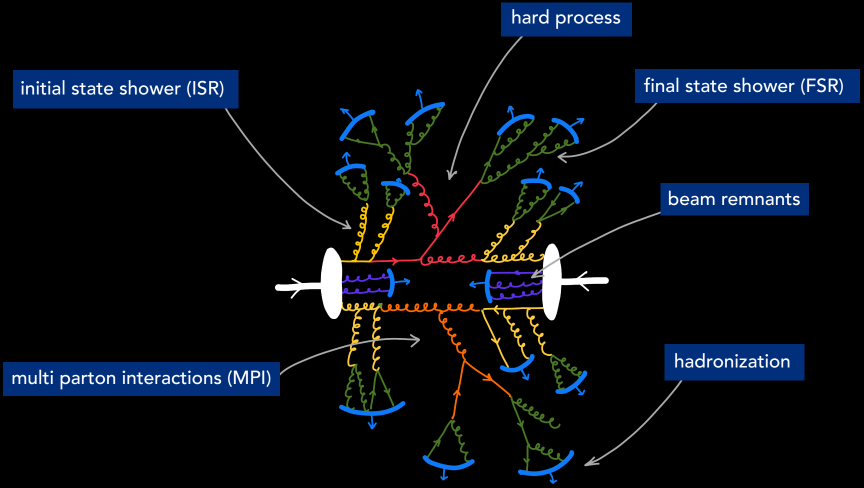
- Changes color configuration, while preserving the color strings connected to large N_c limit of QCD
- Allows to transform partonic color octets to singlets e.g. $(c\bar{c})^8 \longrightarrow (c\bar{c})^1$ *(like in Color Octet Model)*
- The effect of color reconnection depends on color flow in the whole event $\longrightarrow$ long range correlations in color flow *(unlike in Color Octet Model)*
- Simple combinatorics implies that probability of reconnection is higher for events with more partons *(unlike in COM)* higher multiplicity $\longrightarrow$ more reconnections $\longrightarrow$ more $(c\bar{c})^1$

Edin, Ingelman and Rathsman (1997) showed that Color Reconnection effects in certain realization may lead to a good description of quarkonia production and hard diffractive processes

Part II

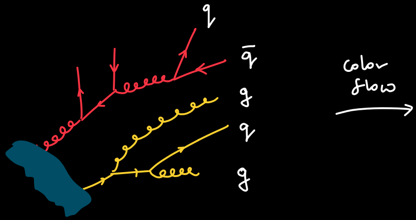
AGH

GENERIC MC EVENT

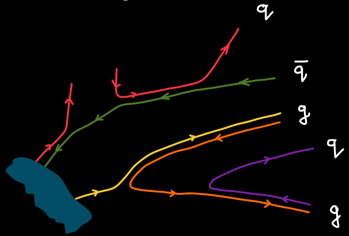


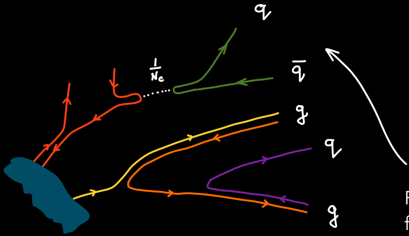
COLOR RECONNECTIONS

Color management in a MC event



Leading Color (LC)





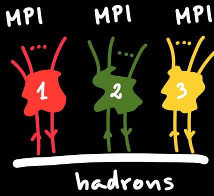
Non-Leading Color

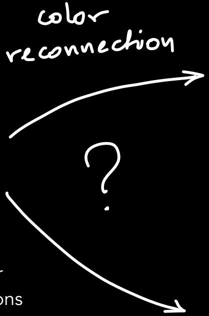
Each line has a “color tag” i or “anti-color tag” $\bar{i}$.
In Pythia $i, \bar{j} = 101,102,103,104,...$
Partons are characterized by a pair of tags $\{i, \bar{j}\}$.

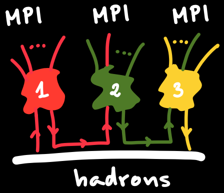
Requires switching the color tags for final state particles.

COLOR RECONNECTIONS

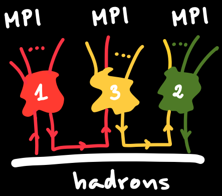
Color ambiguities







But why not to reconnect
1↔3↔2 ?



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

⇓

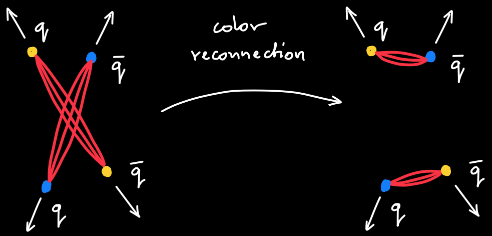
too large hadronic activities at forward rapidities...

[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: $3.0\,\mathrm{GeV} \leq M \leq M_{\max}$
  - the color singlets satisfying this cut are treated as J/ψ
- $M_{\max}$ is our free parameter; we fix $M_{\max} \approx 3.3\,\mathrm{GeV}$ 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

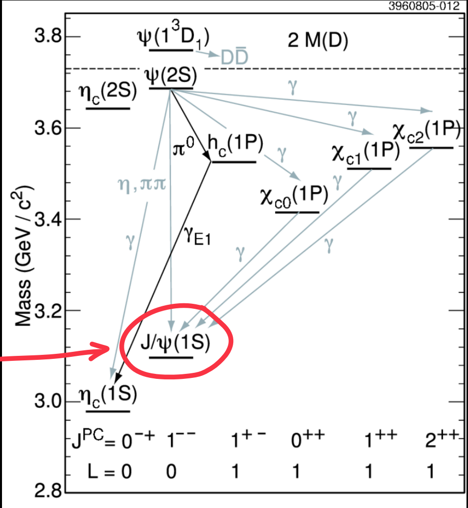
J/ψ PRODUCTION IN PYTHIA

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

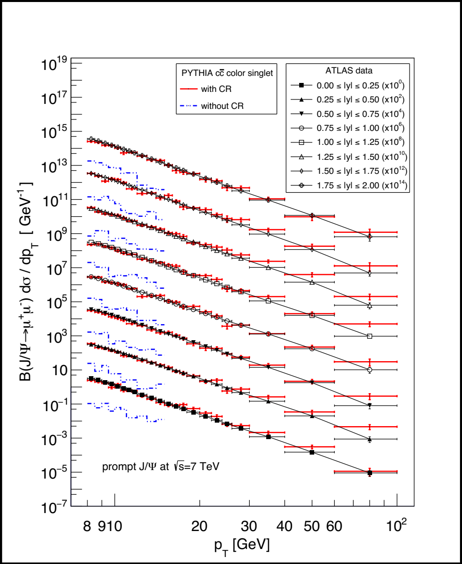


[taken from CLEO, Phys. Rev.D 72 (2005) 092004]

J/ψ PRODUCTION IN PYTHIA

Results for ATLAS kinematics

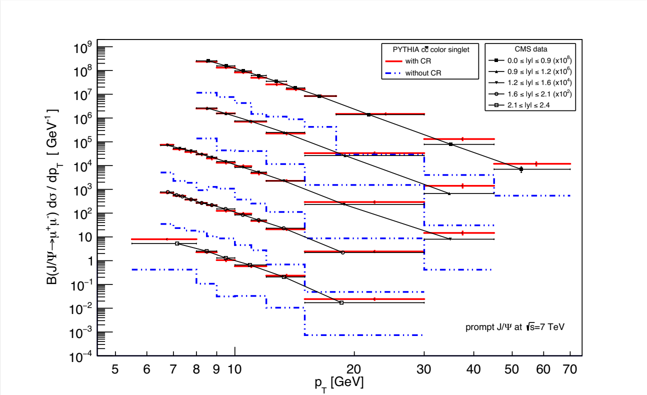
- comparison with ATLAS data [ATLAS, Eur.Phys.J C (2016) 283]
- **good description of data for most rapidity bins, provided the CR is on (red histograms)**
- without CR J/ψ production rate is dramatically insufficient to describe the data
- some deviations at large p_T, but also large statistical MC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



J/ψ PRODUCTION IN PYTHIA

Results for CMS kinematics

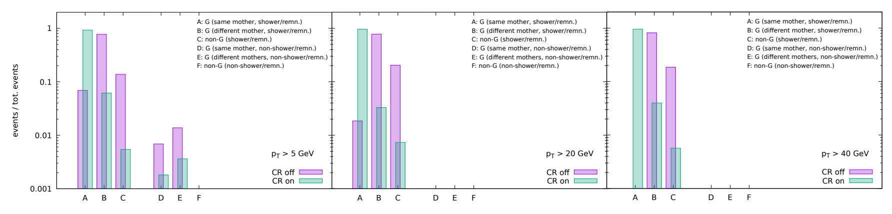
- comparison with CMS data [CMS, JHEP (2012) 011]
- similar conclusions

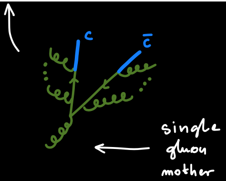


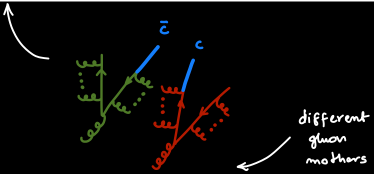
J/ψ PRODUCTION IN PYTHIA

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



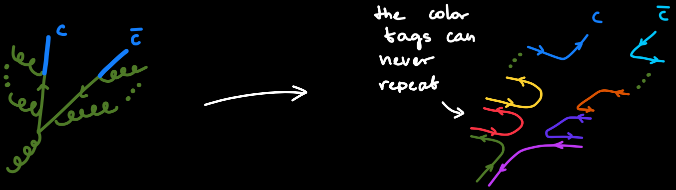




J/ψ PRODUCTION IN PYTHIA

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

Conclusions and outlook

1. The model of J/ψ hadroproduction by Color Reconnection works in a simple and natural way. Both the magintude of cross section and p_T dependence are well described
2. No need for any special tunning of PYTHIA, only one parameter added to describe J/ψ formation — the cut on $c\bar{c}$ invariant mass — found to be in the expected range
3. Without Color Reconnection the production rates are found to be by far too small
4. The key importance of gluon fragmentation, including the gluons from the shower
5. Color Reconnection correlates fragmentation in different regions of an event. Factorization breaking?
6. Outlook: interesting to test this model with data on J/ψ pair production and on J/ψ correlations with multiplicity. Also to constrain Color Reconnection.

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Thanks!