Color reconnection effects in J/ψ hadroproduction

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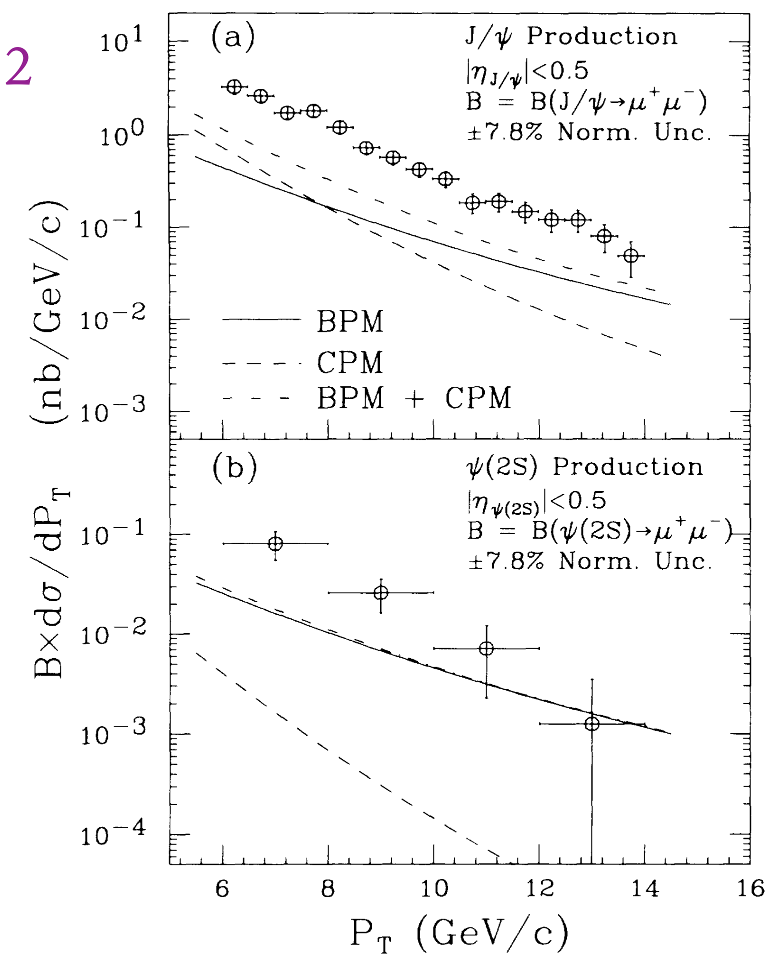
Outline

- Introduction: quarkonium production in hadronic collisions
- Motivation: puzzles with double(triple) production of J/ψ
- Study of charmonium production using Pythia with color reconnection
- Comparison with experimental data from LHC

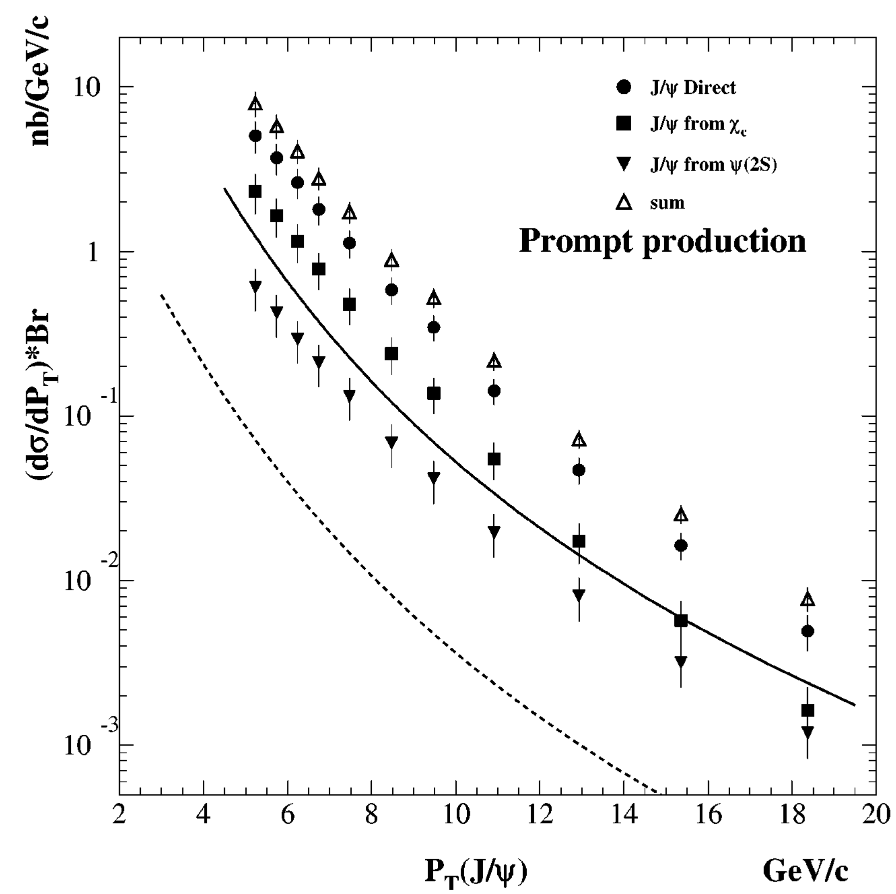
Piotr Kotko, Leszek Motyka, AS: 2303.12128 [PLB 844 (2023) 138104]

Introduction: Tevatron data vs early theory

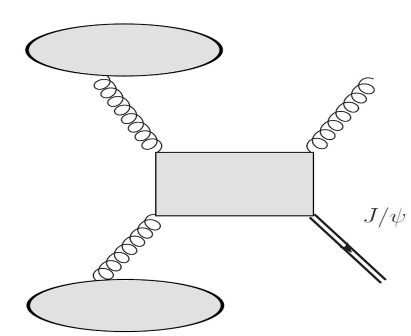
CDF 1992



CDF 1997



- Color Singlet Model (CSM) did not describe the data from Tevatron
- The main problem: color treatment
- To produce J/ψ C-odd colorless state need three gluons
- $gg \to J/\psi + g$ process, too small and too little p_T



Improvements in theory: Color Octet

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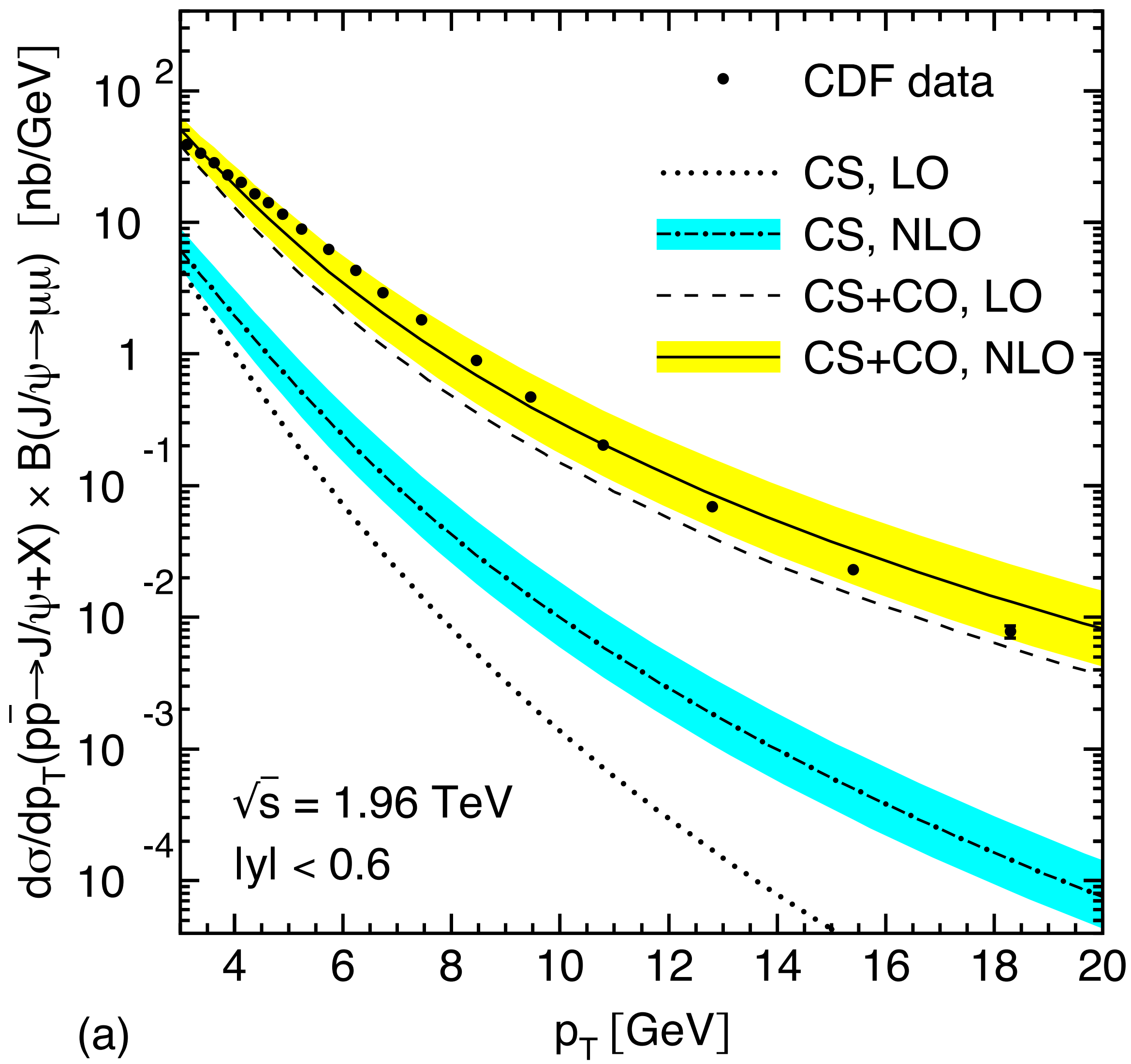
Color Octet approach [Braaten, Yuan; Cho, Leibovich]

Importance of gluon fragmentation

Transition amplitudes of $c\bar{c}$ states in octet representation into mesons

Perturbative production of $c\bar{c}$ states followed by a universal - environment independent - fragmentation process into mesons



Butenschoen, Kniehl PRL 106 (2011) 022003

Puzzle remains: double and triple production

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Double Parton Scattering

$$\sigma_{AB}^{(DPS)} = s_{AB}\frac{\sigma_A^{(1)}\sigma_B^{(2)}}{\sigma_{\text{eff}}}$$

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

$$s_{AB} = \frac{1}{2} \text{ for } A = B$$

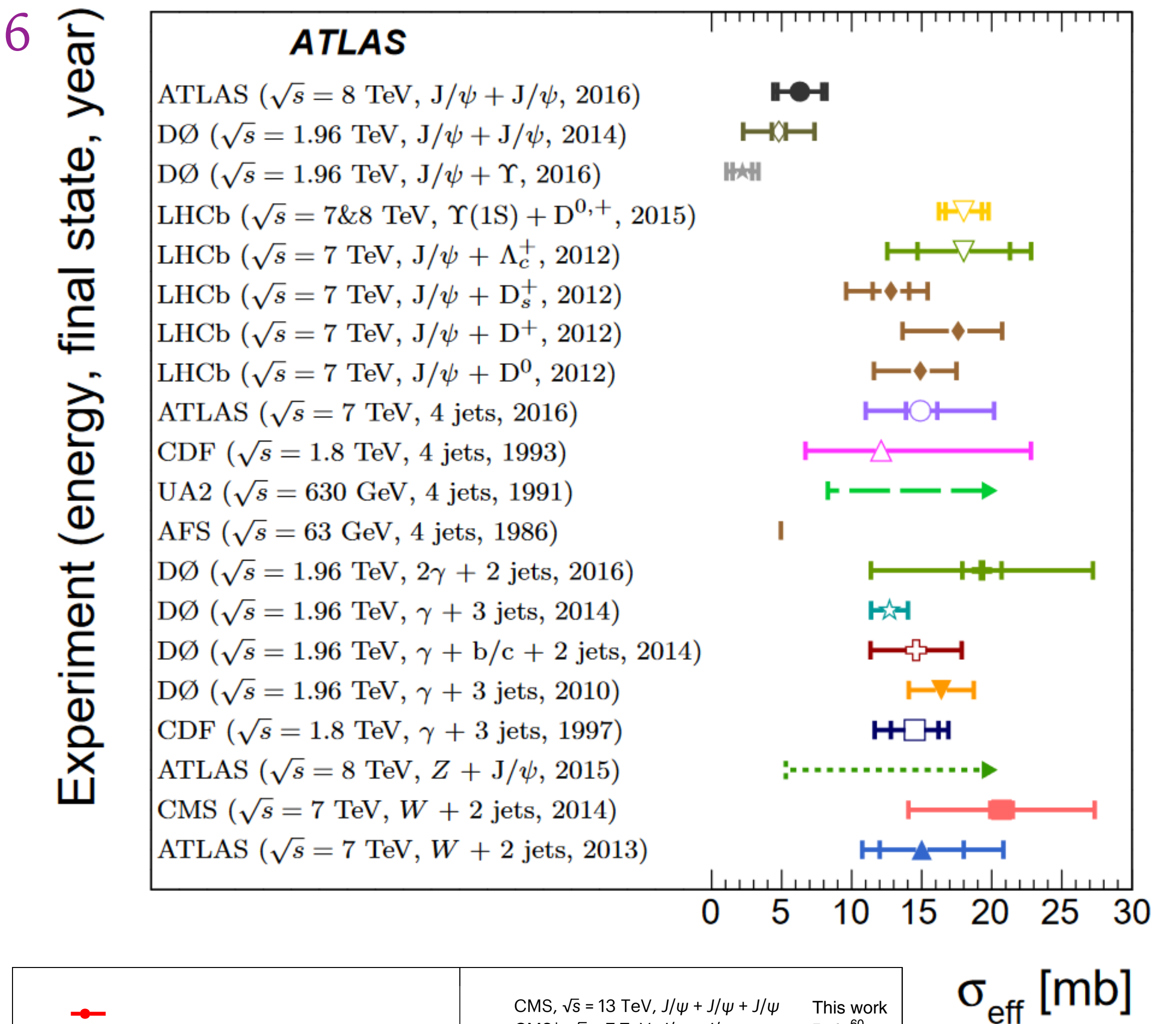
Typical values: $\sigma_{\text{eff}} \simeq 15 - 20\,\text{mb}$

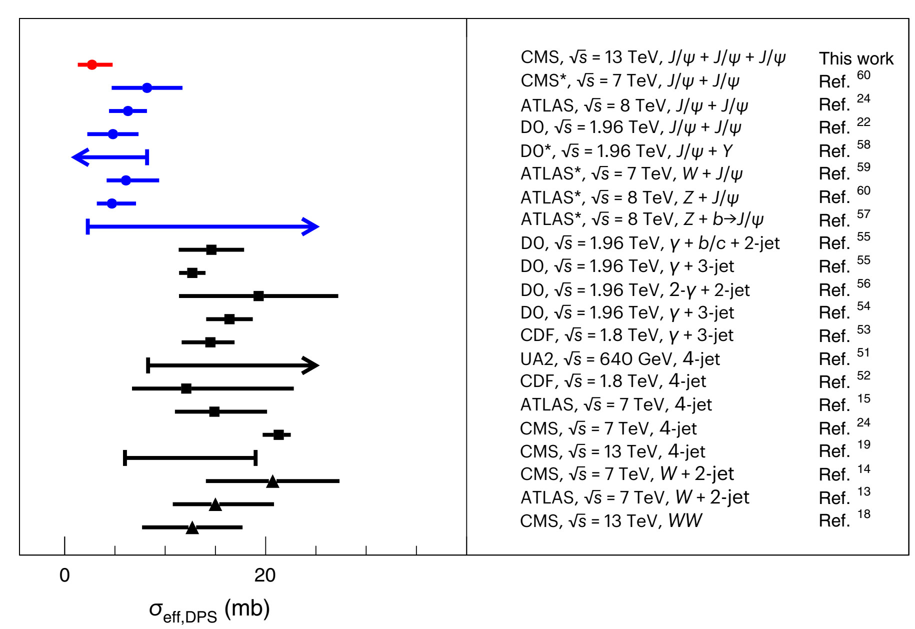
For double quarkonia smaller values measured

Smaller σ_{eff} leads to larger DPS

Triple J/ψ production $\sigma_{\text{eff}} \simeq 2.7\,\text{mb}$

ATLAS 2016





CMS 2023

Color reconnection

- Fundamental problem in QCD: transition of colored partons to colorless hadrons
- For quarks: they can pick up the antiquarks from vacuum, related to the Lund string breaking
- Hadronization occurs at large distances. In the presence of color fields, the color ordering of partons produced in short distance interaction may be changed

Basic idea put forward some time ago by Edin, Ingelman, Rathsman. Proposed Soft Color Interaction model (SCI) was shown to describe quarkonium production in hadronic collisions and rapidity gap processes in DIS

- Allows to transform the **color octets $c\bar{c}$ to color singlets** (similar to COM)
- The effect **of color reconnection** depends on the **color flow in the whole event**: dependence on the environment (unlike in COM)

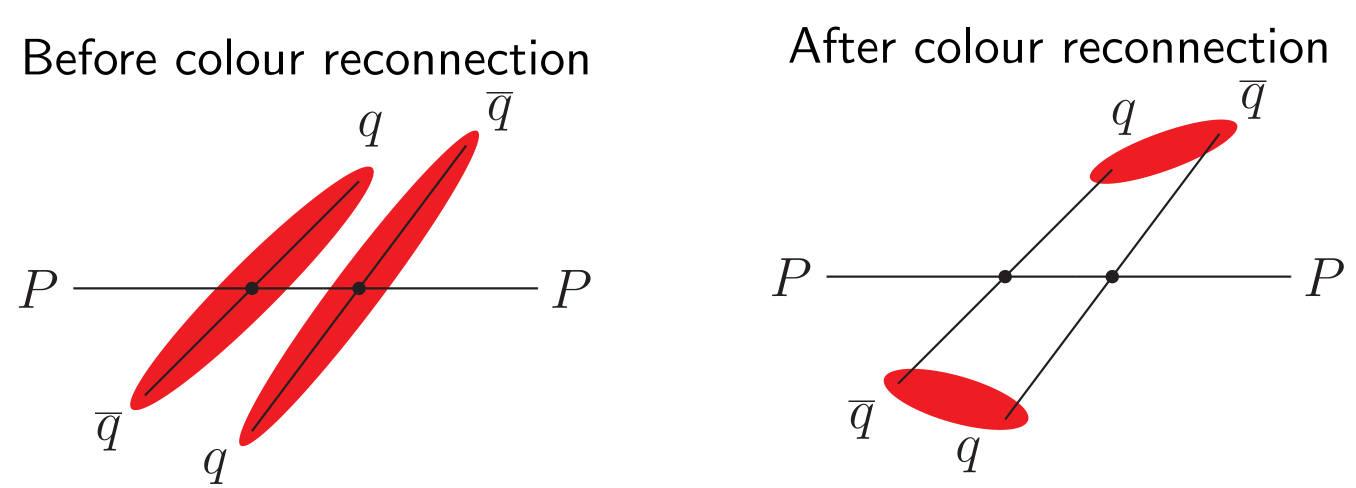
Color reconnection modeling in Pythia

Christiansen, Skands

- Partons in fundamental representation have color tags and anti-color tag. Color singlets made by partons with matching tags.
- Gluons in the adjoint representation, pair of different tag and anti-tag
- Before CR tags represent the leading color topology
- Probabilities for non-leading color topologies are calculated. QCD tells which reconnections are allowed.
- Color reconnection reshuffles the colors before the hadronization
- Reshuffling to non-leading color topology occurs if it minimizes the Lund string length, and then this configuration is passed to hadronization

From talk by Christiansen

at MPI@LHC 2014



Setup for selection of $c\bar{c}$ pairs in PYTHIA

- Default Pythia 8.3, no tuning, with MPI and showers turned on
- Hadronization turned off
- We do not use COM or other models for charmonium production
- Scan the even record to look for charm and anticharm quarks
- Select on those pairs which have matching color and anti-color tags: these are J/ψ candidates
- Apply the invariant mass cut window: $3.0 \leq M \leq M_{\max}$
- $M_{\max}$ is treated as a free parameter, fixed to $M = 3.3\,\mathrm{GeV}$ to obtain best description of data
- Perform two tests: color reconnection on/off

Mass window for selection of $c\bar{c}$ pairs in PYTHIA

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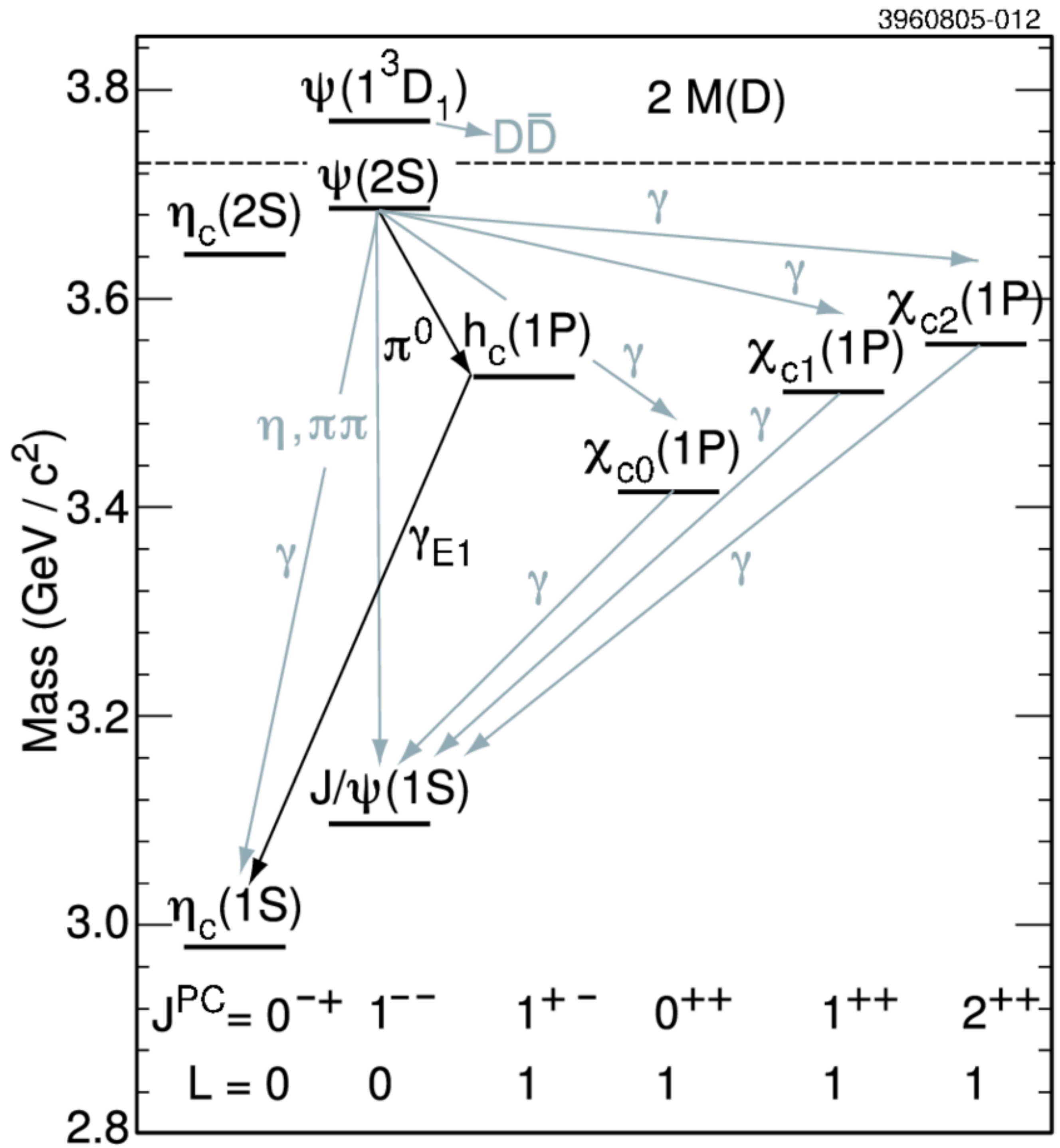
Final invariant mass cut window: $3.0 \leq M \leq 3.3\,\text{GeV}$

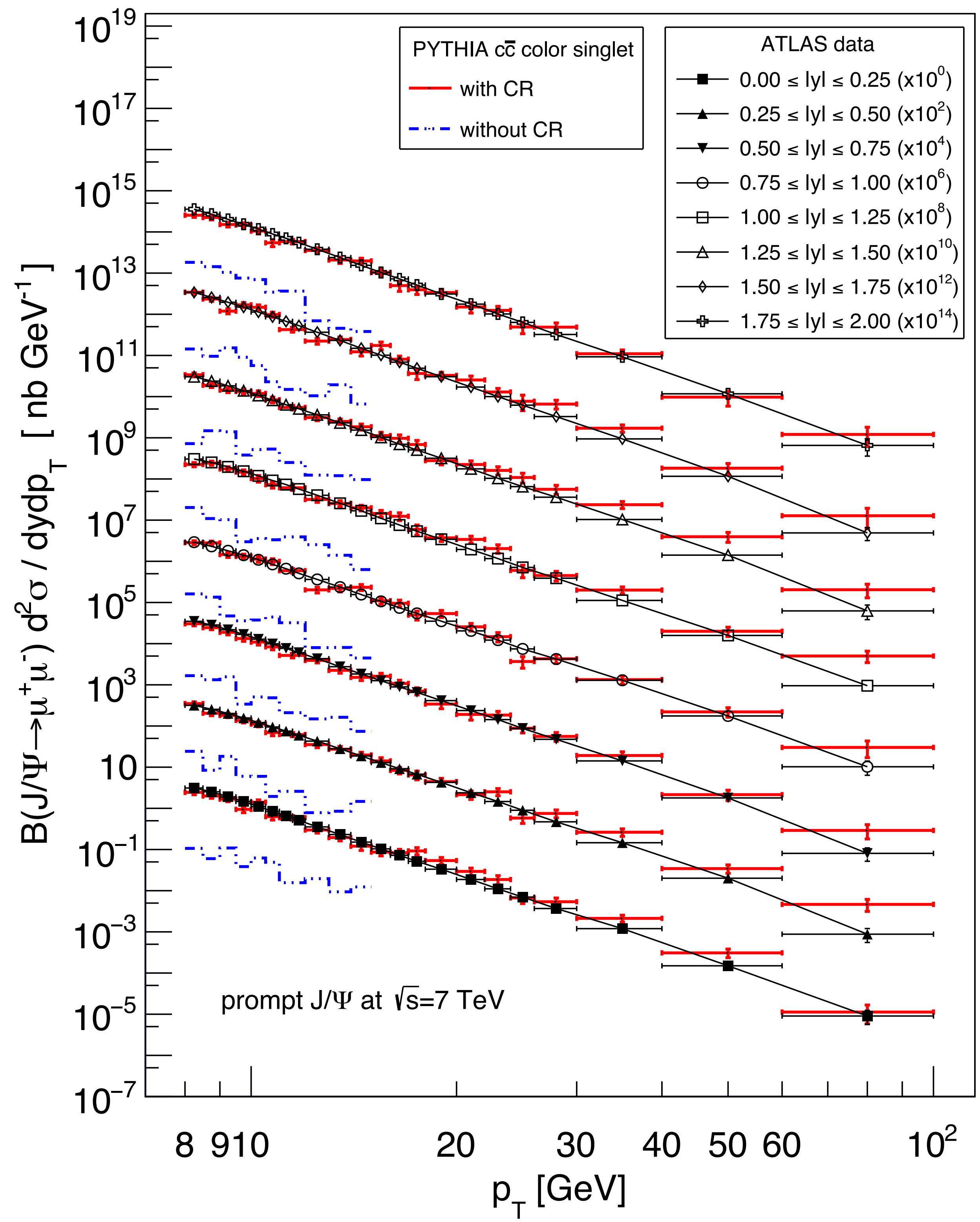
Lies in reasonable range and fully consistent with the spectrum of charmonium system



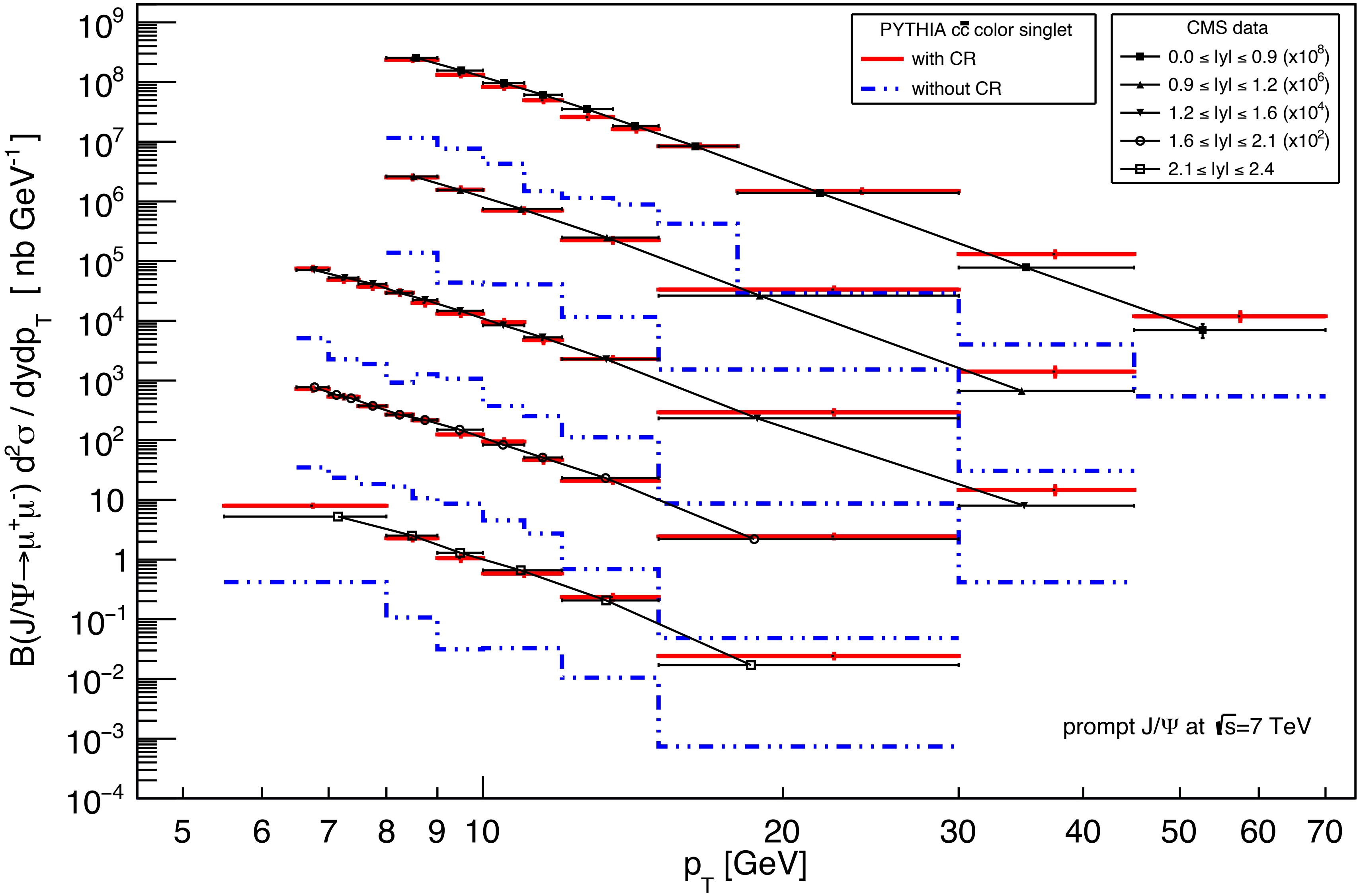
[taken from CLEO, Phys. Rev.D 72 (2005) 092004]

J/ψ production comparison with ATLAS data

- Comparison with ATLAS data [EPJC 76 (2016) 283]
- Overall, very good description when **color reconnection is on: red histograms**
- Only one parameter tuned: M_{max}
- **Transverse momentum dependence** is well reproduced (some deviations at largest momenta, though large stat errors)
- When **color reconnection is off**, the cross section drops by factor 30 (due to lack of statistics only low p_T range is shown)
- Computation requires large statistics, used high performance supercomputer PLGrid



J/ψ production comparison with CMS data



- Comparison with CMS data [JHEP 02 (2012) 011]
- Similar conclusions as for ATLAS data
- We emphasize that the only parameter is M_{max}.
- Tuning more parameters could likely improve description

Origin of $c\bar{c}$ pairs in PYTHIA

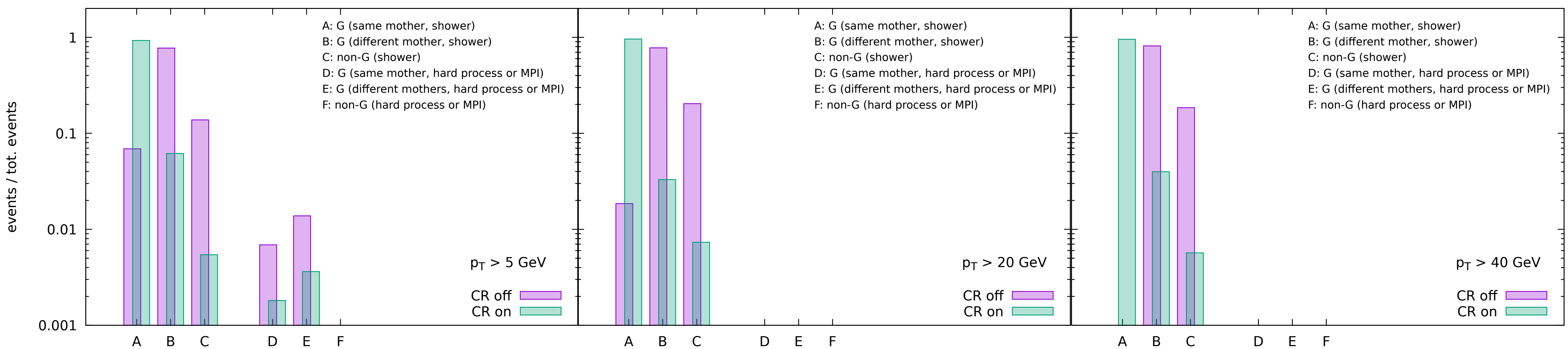
Analyze the records with the low invariant singlet $c\bar{c}$ pairs

Extract information on mother partons and production mechanism

Look at the different p_T ranges

Each plot is normalized by the total number of events, i.e. normalized independently for CR on/off

Note the logarithmic scale



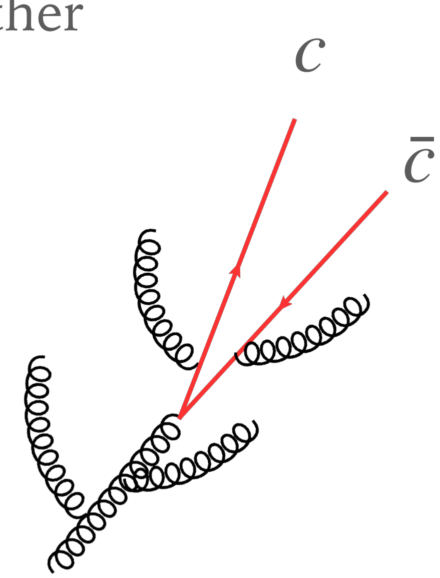
Dominant mechanisms:

CR on: A single gluon 'mother'

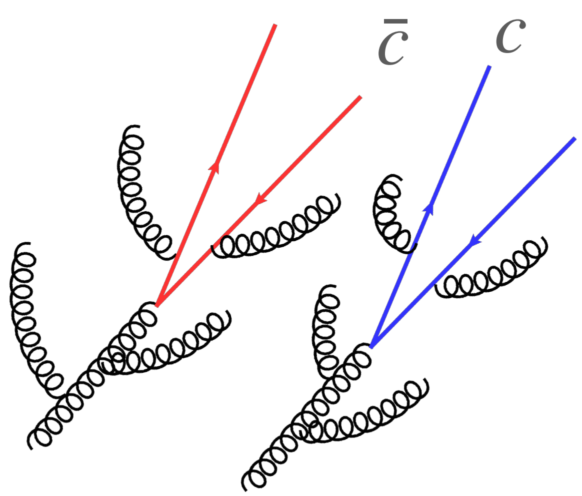
CR off: B different gluon 'mothers'

Origin of $c\bar{c}$ pairs in PYTHIA

A: single gluon mother



B: different gluon mothers



- In the leading color, no perturbative mechanism can give contribution to class A (single gluon mother)
- The very few events in A with CR off are (most likely) due to the color reshuffling in MPI and beam remnants, it dies out at large transverse momenta
- Dominant contribution when CR is off, is with B '**different gluon mothers**' in showers. It is very small probability due to the small phase space overlap.
- With color reconnection on, the class A dominates from showers, small angle quark pair is favored to produce the J/ψ

Summary and outlook

- The model for J/ψ hadroproduction with **Color Reconnection in Pythia** reproduces the experimental data well in **normalization and p_T dependence.**
- No special tuning of Pythia. Just one parameter: cut on the invariant mass of the $c\bar{c}$ being in the expected range.
- Color Reconnection is essential, without it the predictions are more than order of magnitude lower than the data.
- The dominant source for J/ψ production are **gluons from the showers**
- Color Reconnection correlates fragmentation in different regions. Question on the **validity or limitation of universality of fragmentation**. Environment dependent effects.

  Outlook:

  - Double, triple J/ψ production, would allow to test in detail environment effects. Need much more statistics, computationally intense.
  - Polarization ? Study with other MC generators, Herwig ?