On color reconnection effects in J/ψ hadroproduction

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Motivation: puzzles and questions in heavy vector quarkonia hadroproduction

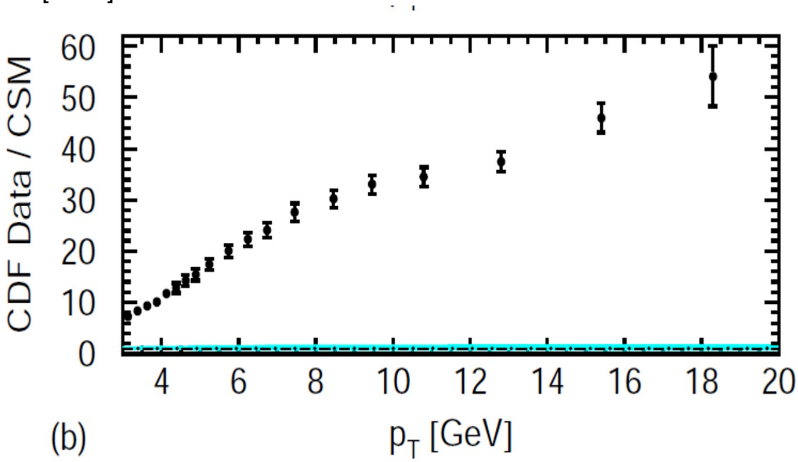
As motivation we consider classical processes $pp \to J/\psi + X$ and $p\bar{p} \to J/\psi + X$ and double J/ψ production $pp \to J/\psi J/\psi + X$

Challenge for theory: puzzles and questions

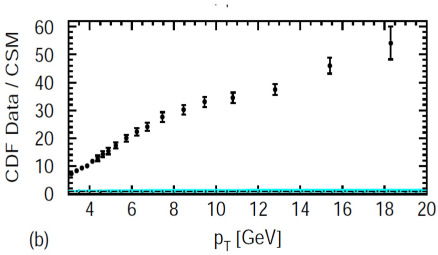
1. Spectacular failure of the most natural QCD description with Color Singlet Model
   $\longrightarrow$ widely accepted solution with Color Octet Model
2. Problems of Color Octet Model with double J/ψ hadroproduction — theory underestimates the DPS cross section by factor of about 3
3. Does hard factorization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

Puzzle 1: Why does the color singlet mechanism fail?

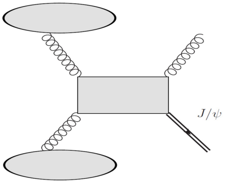
The old surprise: the QCD Color Singlet Model vs Tevatron (CDF) data [1992]



Puzzle 1: Why does the color singlet mechanism fail?



- 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

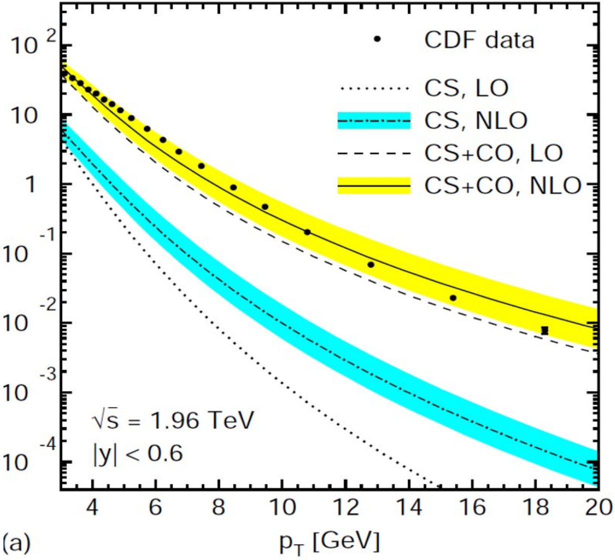


Puzzle 1: A way out – the Color Octet Model

- 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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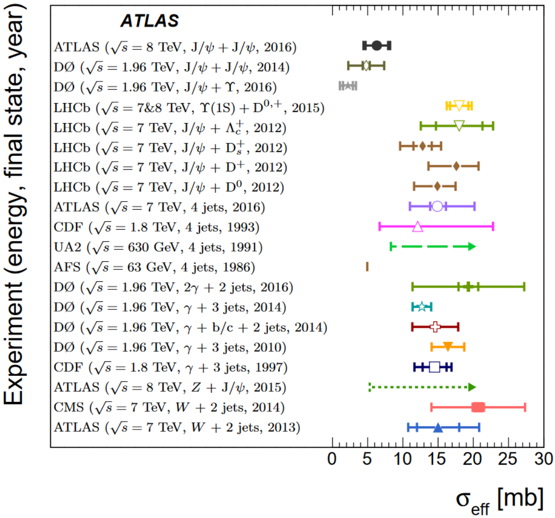
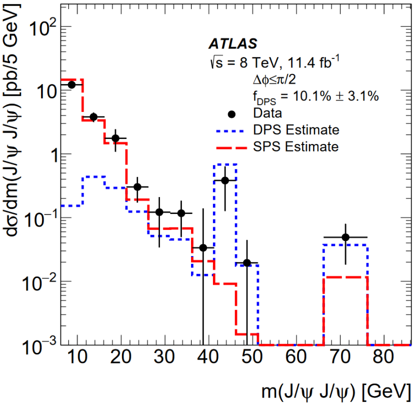


[ATLAS, 1612.02950]

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

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

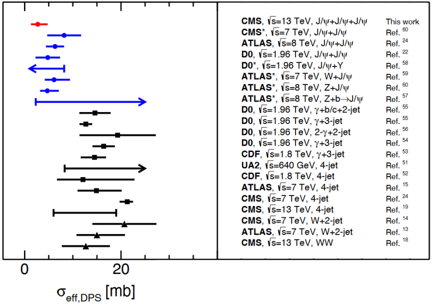
Double heavy vector quarkonium production requires about 3 times stronger DPS effects than other processes!

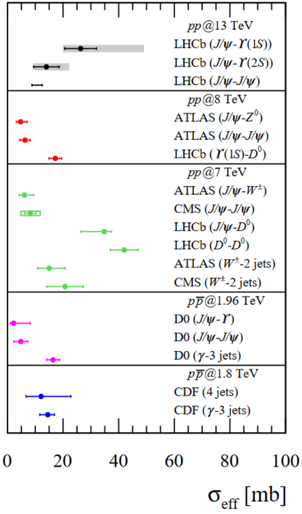
Puzzle 2: the news

Recent measurements:

Triple J/ψ at CMS [2111.05370]: $\sigma_{eff} = 2.7^{+1.4}_{1.0}(exp)^{+1.5}_{1.0}(th)$ mb

Associated J/ψ and Υ production at LHCb [2305.15580]: large σ_{eff}





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

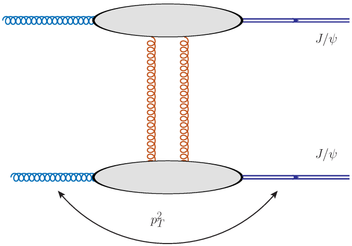
Can perturbative multiple scattering solve the problem?

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

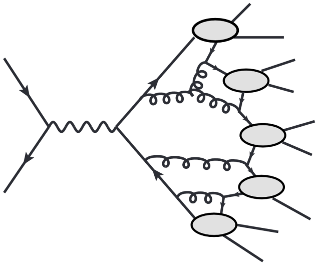


Explicit calculations: by A. Szczurek, A. Cisek and W. Schafer [1710.11450] and our in-house calculations show that this mechanism is by far too weak

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

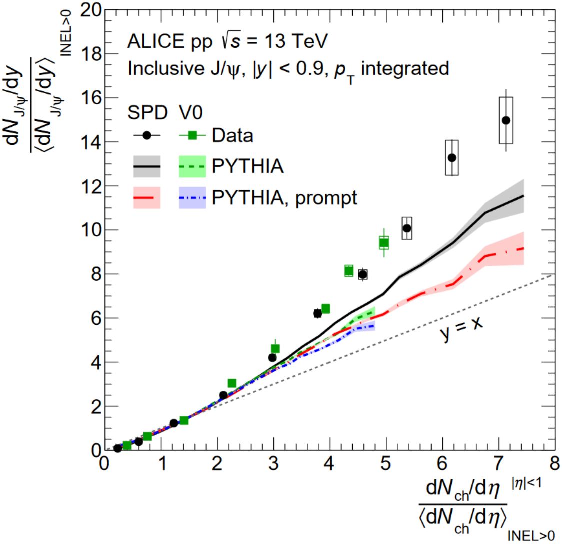
Answer by John Collins, 1610.09994: it is not guaranteed that hard factorization works in fragmentation.

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
- For these reasons multi-purpose event simulators like PYTHIA and HERWIG include possibility of changing 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 showed that Color Reconnection effects in certain realization may lead to a good description of quarkonia production and hard diffractive processes

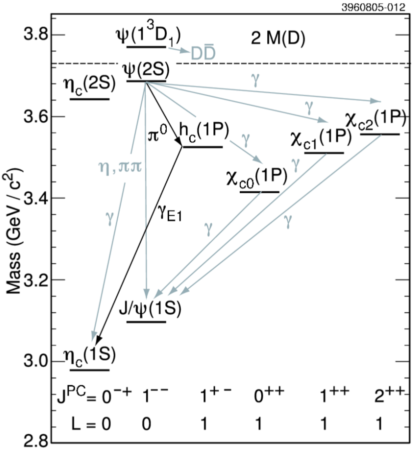
Color Reconnection in PYTHIS — "QCD inspired' model'

1. In PYTHIA the color flow is descibed in the large N_c limit
2. Each parton in the fundamental color representation (QCD triplet) has a definite color tag or antitag. Color singlets are made by pairs of partons with matching color tag and antitag
3. Gluons are in the adjoint representation — they are represented by a pair of a different tag and antitag
4. Before Color Reconnection the tags reproduce the leading color topologies. The pair of partons with tag and antitag goes into Lund string that hadronizes
5. Color Reconnection exchanges color tags in a given pair with certain probability
6. In the "QCD inspired" model of CR, probabilities for non-leading color topologies are calculated in QCD. The Color Reconnection occurs to a non-leading color topology if the resulting length of the Lund strings is smaller after the reconnection

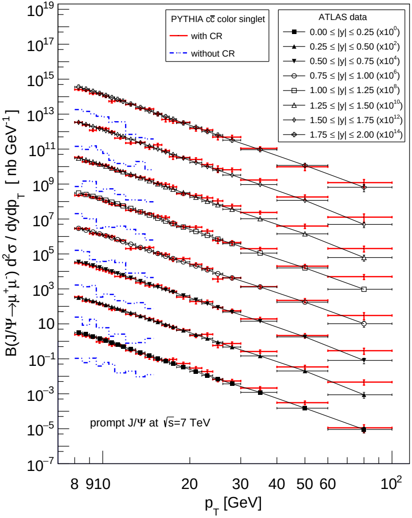
A model for J/ψ production proposed in this study

Model assumptions:

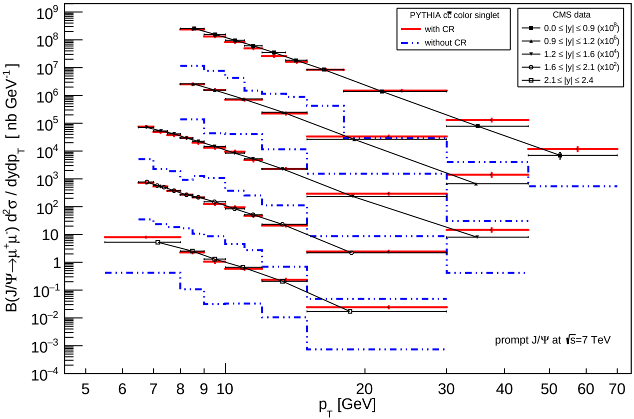
1. Generate with PYTHIA standard *pp* events with $c\bar{c}$ pair(s), at the parton level
2. Allow for Multiple Interactions and Color Reconnection effects within a standard PYTHIA setup
3. Classify as J/ψ-s the $c\bar{c}$ singlets with suitable invariant mass $2m_c < M_{c\bar{c}} < M_{\rm cut}$



Results — J/ψ cross sections at ATLAS

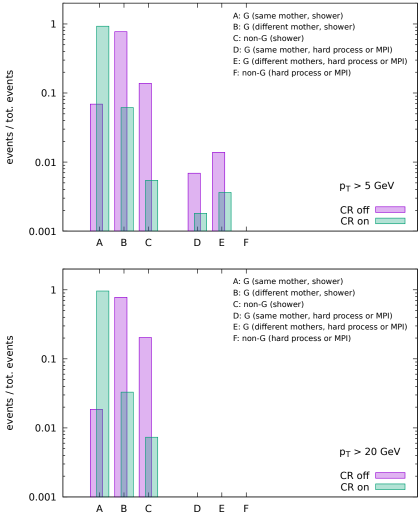


- Overall good description of p_T-dependence — generic
- Normalization — adjusted to fit the data by choosing one global parameter: $M_{c\bar{c}} < 3.3$ GeV
- Color reconnection is essential: when turned off the cross section is too low by factor of ~ 30



Features of the description as it was for the ATLAS data

Results — the origin of c and $\bar{c}$ that make J/ψ



Histograms normalized to 1 independently for CR on and CR off

- CR on: dominance of class A: $c\bar{c}$ pairs from the same gluon in the shower, stronger at large p_T
- CR on: next, much smaller class B: $c\bar{c}$ pairs from different gluons
- CR off: dominance of class B: $c\bar{c}$ pairs from different gluons
- Non-shower contributions small and dying out with p_T

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!