J/ψ production within a jet in high-energy proton-proton and nucleus-nucleus collisions

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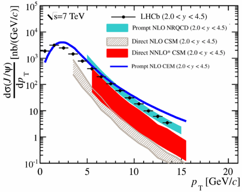
Outline

1. Introduction
    - Motivation
2. J/ψ Production in pp Collisions
    - LP NRQCD for J/ψ Production
    - Phenomenology at RHIC and the LHC energies
3. J/ψ in AA Collisions
    - The Linear Boltzmann transport model (LBT)
    - Numerical results
    - Extract gluon energy loss distributions via Bayesian analysis
4. Summary

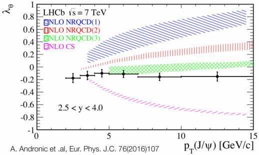
J/ψ in pp Collisions

- J/ψ: bound states of charm quark pairs.
- Production mechanism: the production of quark-antiquark pairs and their hadronization.
- Different models differ in the treatment of the hadronisation.
- NRQCD: perturbative (SDCs) and non-perturbative (LDMEs) processes.
- No consistent descriptions of cross section and polarization.

Cross-section

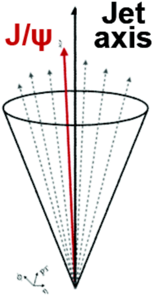


Polarization

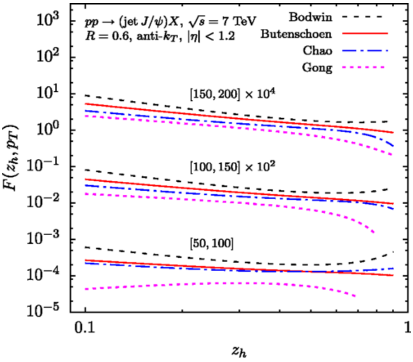


A. Andronic et .al, Eur. Phys. J.C. 76(2016)107
LHCb, Eur. Phys. J. C 73(2013)2631
LHCb, Eur. Phys. J. C 71(2011)1654

J/ψ within Jet



$$z_{J/\psi} = \frac{p_T^{J/\psi}}{p_T^{\text{Jet}}}$$

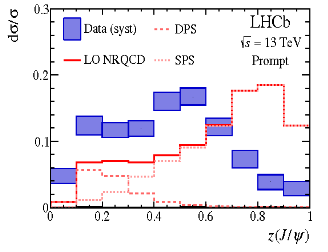


Phys.Rev. Lett. 119 (2017) 032001

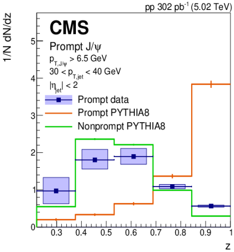
Fragmentation pattern is sensitive to production mechanism.

Measurements of J/ψ Production in Jets

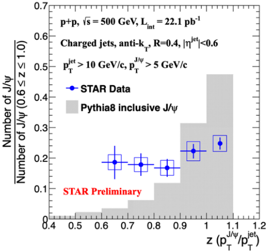
PRL.118.192001



PLB 825 (2022) 136842

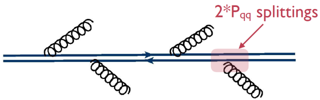


STAR@Qian Yang



- J/ψ is less isolated than expected by LO NRQCD in PYTHIA.
- Color-singlet $c\bar{c}(n)$: turns into the quarkonium directly.
- Color-octet $c\bar{c}(n)$: showers with the splitting function P_{qq} (peaked at $z = 1$)

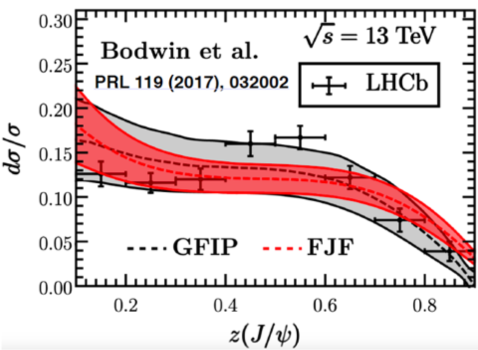
PYTHIA



Gluon Fragmentation Improved PYTHIA (GFIP)

- Parton-parton scattering not enough to describe J/ψ.
- Produced in parton shower?

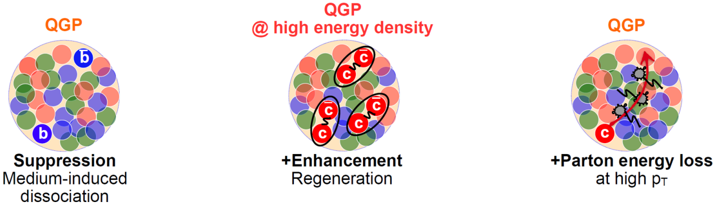
Gluon: ${}^3S_1^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_J^{[8]}$
Charm: ${}^3S_1^{[1]}$



- Model including J/ψ produced in parton showers successfully describe LHCb data. [PRL 119, 032002 (2017)]
- We utilize a theoretical framework analogous to GFIP.

J/ψ in AA Collisions

- Quark-gluon plasma (deconfined color medium) created in heavy-ion collisions.
- Regarded as a signature of color deconfinement and a thermometer of QGP. T. Matsui and H. Satz, PLB 178, 416 (1986).



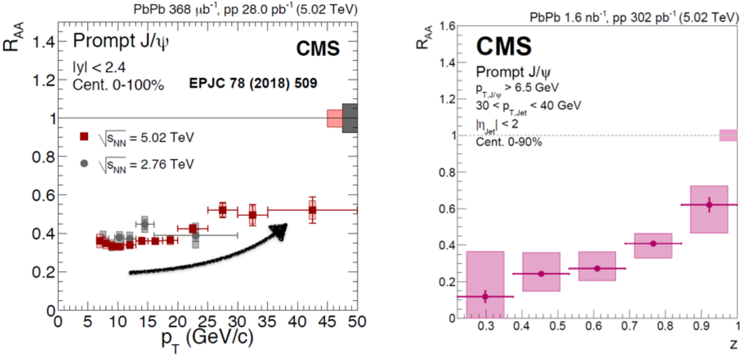
Suppression
Medium-induced dissociation

+Enhancement
Regeneration

+Parton energy loss
at high p_T

- Dissociation and regeneration well explain low-p_{T} J/ψ suppression in Pb+Pb and Au+Au PhysRevC.89.054911,PhysRevLett.128.162301
- In the region $p_{\mathrm{T}}^{J/\psi} \gg m_{J/\psi}$, jet quenching plays a dominant role for the J/ψ R_{AA}. Phys.Lett.B 767 (2017) 10-15,Sci.Bull. 68 (2023) 2003-2009

Measurements of J/ψ Production in Jets



- Rising R_{AA} trend for p_T and $z_{J/\psi}$ [PLB 825 (2022) 136842] ◦
- Parton energy could explain $R_{AA}(z_{J/\psi})$ rising trend at high p_T.
  - Large z, larger p_T, less suppressed.

LP NRQCD and GFIP for J/ψ Production

Leading Power of p_T^2/m_c^2

J. C. Collins and D. E. Soper, Nucl.Phys.B 194, 445 (1982).

$$d\sigma[AB \to J/\psi + X] = \sum_i d\hat{\sigma}_{AB\to i+X} \otimes D_{i\to J/\psi}$$

$d\hat{\sigma}_{AB\to i+X}$ Parton production cross section

$D_{i\to J/\psi}$ FF for i to produce a J/ψ

G. T. Bodwin et al. Phys. Rev. D 51, 1125 (1995)

$$D_{i\to J/\psi}(z,\mu) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z,\mu)\langle\mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

$\hat{d}_{i\to[Q\bar{Q}(n)]}$ FF for i to fragment into $Q\bar{Q}(n)$

Y.Q.Ma et al. Phys. Rev.D 89, 094029 (2014)

G. T. Bodwin et al. JHEP 11, 020 (2012)

$\langle\mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$ LDME: non-perturbative

M. Butenschoen et al. Phys.Rev.D84, 051501 (2011)
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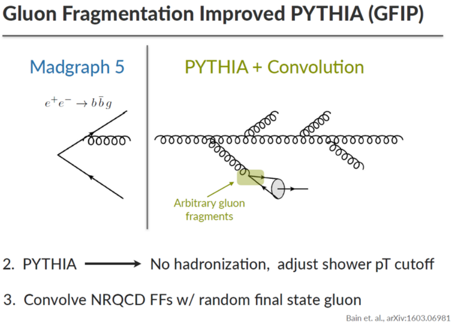

Gluon Fragmentation Improved PYTHIA (GFIP)

Madgraph 5

PYTHIA + Convolution

2. PYTHIA ⟶ No hadronization, adjust shower pT cutoff
3. Convolve NRQCD FFs w/ random final state gluon

Bain et. al., arXiv:1603.06981

$$\frac{d\sigma^{J/\Psi}}{dp_T^{J/\Psi}} = \sum_i \int dz \frac{d\sigma^i}{dp_T^i} \otimes D_{i\to c\bar{c}(n)}(z)\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\rangle$$

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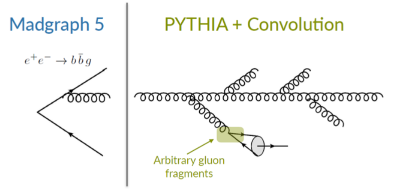

2. PYTHIA ⟶ No hadronization, adjust shower pT cutoff
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Bain et. al., arXiv:1603.06981

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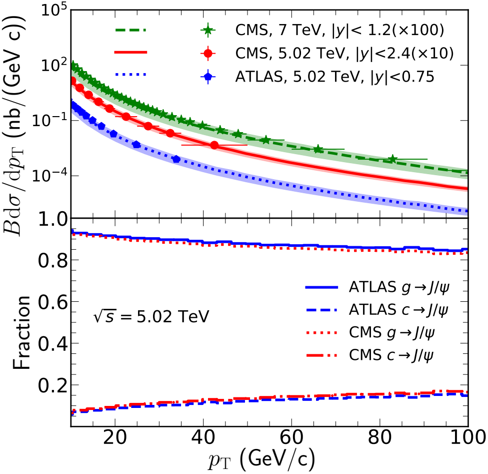
- LDMEs taken from Bodwin PRL.113,no.2,022001(2014).
- We restrict our discussion in the high p_T region ($p_T > 10 GeV/c$)

Results of J/ψ Production in pp

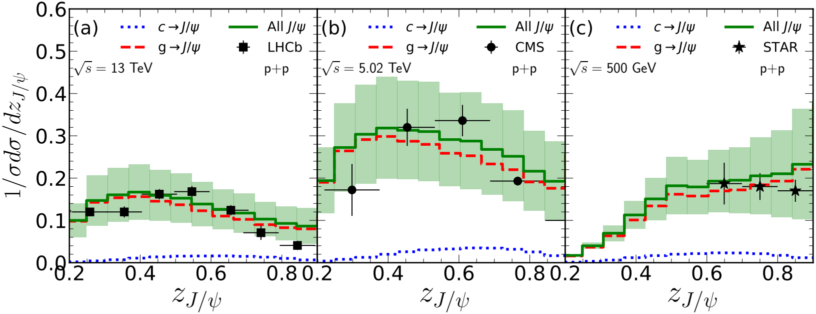


[arXiv:2208.08323]

GFIP well describe the experimental data.

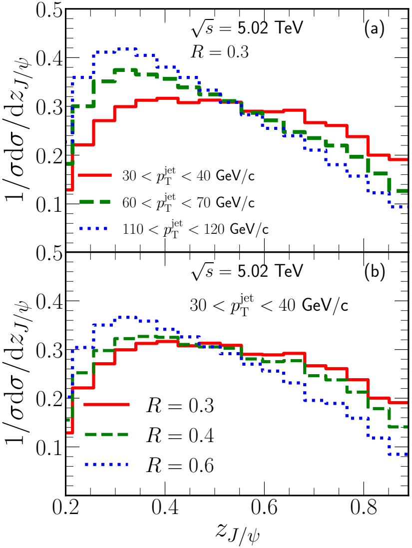
Gluon fragmentation dominates ($> 85\%$) the high-p_T J/ψ production.

J/ψ Production within Jet in pp



- GFIP well describe the experimental data. [arXiv:2403.12704]
- **Gluon fragmentation dominates ($> 85\%$) the high-p_T J/ψ production.**
- Large band, further constrain LDMEs.
- The peak of $z_{J/\psi}$ shifts to smaller values from RHIC to LHC.

$z_{J/\psi}$ vs p_T^{jet} and Jet Cone R



[arXiv:2403.12704]

$z_{J/\psi}$ is shifted to softer regions with larger $p_{\mathrm{T}}^{\mathrm{jet}}$: larger $p_{\mathrm{T}}^{\mathrm{jet}}$, more showered gluons.

$z_{J/\psi}$ distribution shifts to smaller value with larger jet cone R. : larger R, larger p_T^{jet}, smaller z.

J/ψ in AA Collisions

Energy loss model-LBT

Linear Boltzmann equation

$$p_a \cdot \partial f_a(x, p) = E_a(\mathcal{C}_{\rm el} + \mathcal{C}_{\rm inel}),$$

$\mathcal{C}_{\rm el}$ and $\mathcal{C}_{\rm inel}$ are the collision integrals for elastic and inelastic scatterings.

Elastic scattering PRC.91.054908, PRC.94.014909

$$\begin{aligned}\Gamma^a_{el}(E_a, T) = \frac{\gamma_2}{2E_a} \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \\ \times \frac{1}{2} \sum\nolimits_{b(c,d)} [f_a(p_1) f_b(p_2) - f_c(p_3) f_d(p_4)] |M_{ab\to cd}|^2 \\ \times S_2(s, t, u)(2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4)\end{aligned}$$

Inelastic scattering PhysRevLett.85.3591;PhysRevLett.93.072301;PhysRevD.85.014023.

$$\Gamma^a_{\rm inel}(E_a, T, t) = \int dx dk_\perp^2 \frac{dN^a_g}{dx dk_\perp^2\, dt}, \quad \frac{dN_g}{dx dk_\perp^2\, dt} = \frac{2\alpha_s C_A P(x) k_\perp^4}{\pi(k_\perp^2 + x^2 M^2)^4} \hat{q} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

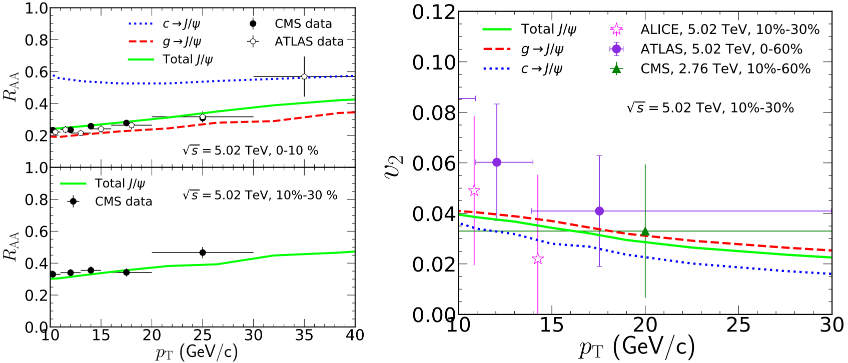
The total scattering probability

$$P^a_{\rm tot} = 1 - e^{-\Gamma_{\rm tot}\Delta t} = P^a_{\rm el} + P^a_{\rm inel} - P^a_{\rm el} P^a_{\rm inel}, \begin{cases} P^a_{\rm el} = 1 - e^{-\Gamma^a_{\rm el}\Delta t} \\ P^a_{\rm inel} = 1 - e^{-\Gamma^a_{\rm inel}\Delta t} \end{cases}$$

CLVisc3+1D Ideal hydrodynamatics Phys.Rev.C 86,024911 (2012).

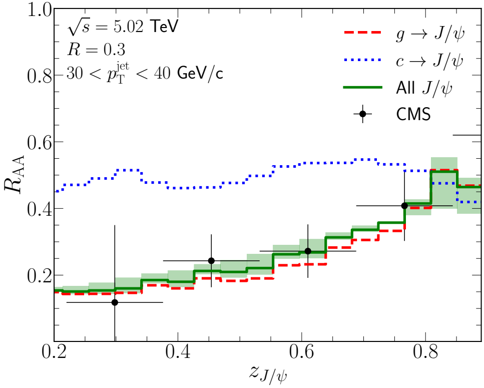
LBT: light/heavy flavor hadron, inclusive jet, Z/γ-hadron/jet.
Phys.Lett.B **782**, 707-716 (2018), Phys.Lett.B 777, 86(2018);Phys.Rev.C 94, no.1, 014909 (2016). .

Inclusive J/ψ production in AA



- Reasonable agreement with data.
- Gluon energy loss dominate large p_T J/ψ R_{AA} and elliptic flow v_2.

Results of J/ψ Production within Jet in AA

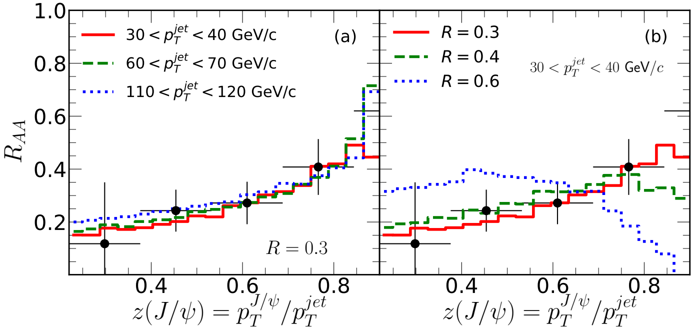


[arXiv:2403.12704]

GFIP well describe the experimental data.

Gluon jet quenching is the driving force for the suppression of J/ψ production in jet.

$R_{AA}(z_{J/\psi})$ vs $p_T^{\rm jet}$ and Jet Cone R



- Mild dependence of $R_{\rm AA}(z_{J/\psi})$ on $p_T^{\rm jet}$. [arXiv:2403.12704]
  - Both J/ψ and jet loss energy, and have similar tendency.
- $R_{\rm AA}(z_{J/\psi})$ is significantly modified with increasing jet radius.
  - Larger R, larger radiated gluons restored, less jet energy loss.

An Independent Bayesian Validation

Bayesian extraction of parton energy loss distributions.

$$\frac{d\sigma_{AA}}{dp_T} = \sum_i \int \frac{d\Delta p_T^i}{\langle \Delta p_T^i \rangle} \frac{d\sigma_{pp}^i(p_T + \Delta p_T^i)}{dp_T} W^i(x) \otimes D_{i\to J/\psi},$$

Energy loss distributions PhysRevLett.122.252302

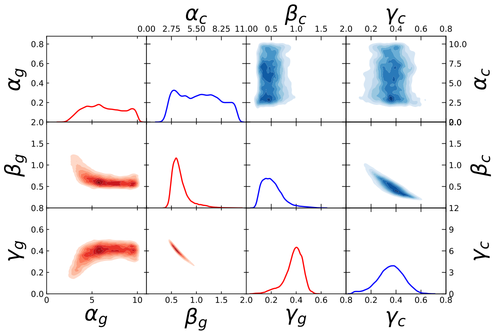
$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}, \begin{cases} x = \Delta p_T^i / \langle \Delta p_T^i \rangle \\ \langle \Delta p_T^i \rangle = \beta_i p_T^{\gamma_i} \log(p_T) \end{cases}$$

Three parameters in the above for each parton type: $[\alpha_i, \beta_i, \gamma_i]$

Uniform prior distribution for $[\alpha_i, \beta_i, \gamma_i] \in [(0, 10), (0, 8), (0, 0.8)]$

1M MCMC steps for equilibration, then 1M steps for scanning around the parameter space

Gluon and Charm Quark Energy Loss in Pb+Pb



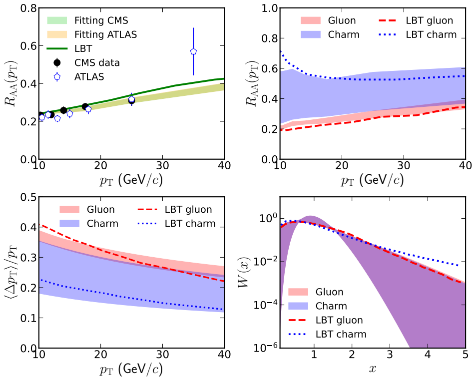
[arXiv:2208.08323]

One can see clearly a stronger sensitivity and constraint for gluon energy energy lose.

Extracted parameters for parton energy loss distributions

$(0-10\%)$5.02 TeV			
	α	β	γ
Gluon	5.25±1.09	0.7±0.07	0.37±0.03
Charm	6.33±2.06	0.53±0.19	0.36±0.09

Gluon and Charm Quark Energy Loss in Pb+Pb



[arXiv:2208.08323]

The optimized results agree perfectly with data, and confirms the dominance of gluon energy loss for high p_T J/ψ suppression.

In turn, this offers the unique opportunity for an accurate extraction of gluon energy loss distributions!

ALICE, JHEP 10, 141 (2020),
ATLAS, Eur. Phys. J. C 78, 784 (2018),
CMS, Eur. Phys. J. C 77, 252 (2017).

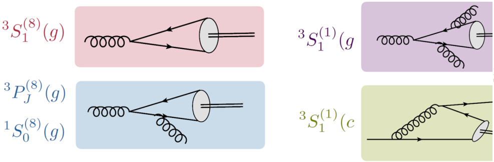
Summary

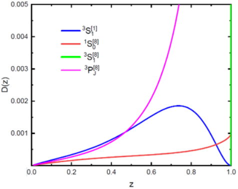
- High p_T J/ψ production in pp collisions can be well described and is demonstrated to be dominated by gluon contributions.
- $z_{J/\psi}$ is shifted to softer regions with larger $p_{\mathrm{T}}^{\mathrm{jet}}$ and R
- High p_T J/ψ suppression in AA collisions can also be well described and is shown to be mainly driven by the gluon in-medium energy loss.
- We expect mild $p_{\mathrm{T}}^{\mathrm{jet}}$ dependence and strong jet radius R dependence of $R_{\mathrm{AA}}(z_{J/\psi})$.
- An independent Bayesian analysis confirms the sensitivity of J/ψ R_{AA} to gluons and allows a quantitative extraction of gluon energy loss distributions

Thanks!

J/ψ production within jet in pp

$$\frac{d\sigma^{J/\psi}}{dz^{J/\psi}\,dp_T^{\text{jet}}} = \sum_i \int \frac{dz}{z}\,\frac{d\sigma^i}{dz_i\,dp_T^{\text{jet}}} \otimes D_{i\to c\bar{c}(n)}(z)\langle O(n)\rangle \qquad (1)$$



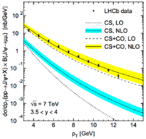


	$\langle\mathcal{O}({}^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}({}^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}({}^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}({}^3P_J^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	1.32± 0.2	9.9±2.2	1.1±1.0	1.1±1.0

Comparisons with LHCb Data

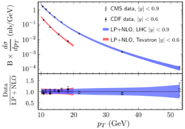
Relative contributions from mechanisms in different extractions

Global Fits + fixed order



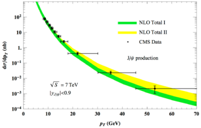
Buttenschon, Kniehl (2011), arXiv:1105.0820

High p_T + leading power



Bodwin, et. al. (2014) arXiv:1403.3612

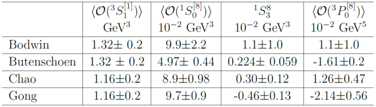
Simultaneous fit to high p_T & λ_θ



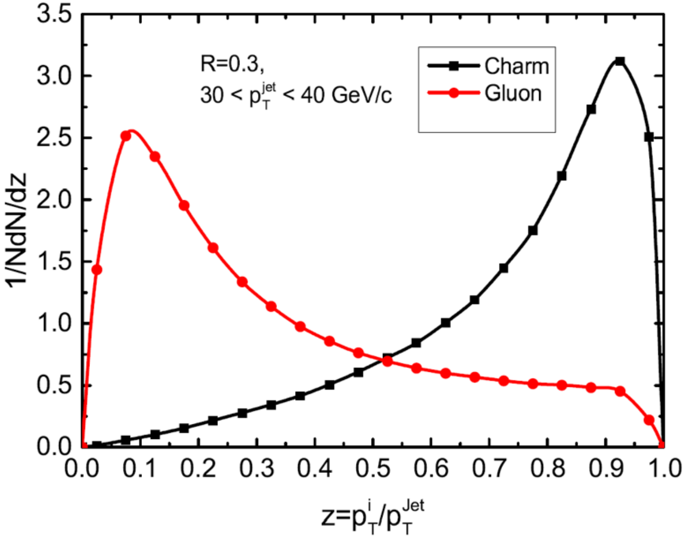
Chao, et al. (2012) arXiv:1201.2675

$$\underbrace{d\sigma_{A+B\to H+X} = \sum_n \boxed{d\sigma_{A+B\to Q\bar{Q}(n)+X}}}_{\text{calculate perturbatively}} \underbrace{\boxed{\langle\mathcal{O}^H(n)\rangle}}_{\text{LDME — non-perturbative}} \quad \text{with} \quad n - {}^{2S+1}L_J^{(1,8)}$$

Table 1. J/Ψ NRQCD LDMEs from four different groups.



	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$^1S_3^8$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	1.32± 0.2	9.9±2.2	1.1±1.0	1.1±1.0
Butenschoen	1.32 ± 0.2	4.97± 0.44	0.224± 0.059	-1.61±0.2
Chao	1.16±0.2	8.9±0.98	0.30±0.12	1.26±0.47
Gong	1.16±0.2	9.7±0.9	-0.46±0.13	-2.14±0.56


R=0.3,
$30 < p_T^{jet} < 40$ GeV/c
Charm
Gluon
1/NdN/dz
$z=p_T^i/p_T^{Jet}$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0