J/ψ Production and Polarization within a Jet in pp Collisions

邢宏喜

Many thanks to my collaborators:
Yang-Ting Chien, **Zhong-Bo Kang**, Jian-Wei Qiu,
Felix Ringer, Ivan Vitev, Hong Zhang

量子物质研究院

Institute of Quantum Matter

华南师范大学
SOUTH CHINA NORMAL UNIVERSITY

Nuclear and Particle Physics

- Heavy Ion
  - 王恩科
  - 郭星雨
  - 茹 芃
  - 邢宏喜
- EIC / Spin
  - 邢宏喜
  - Shinsuke Yoshida
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❖ Call for applications!

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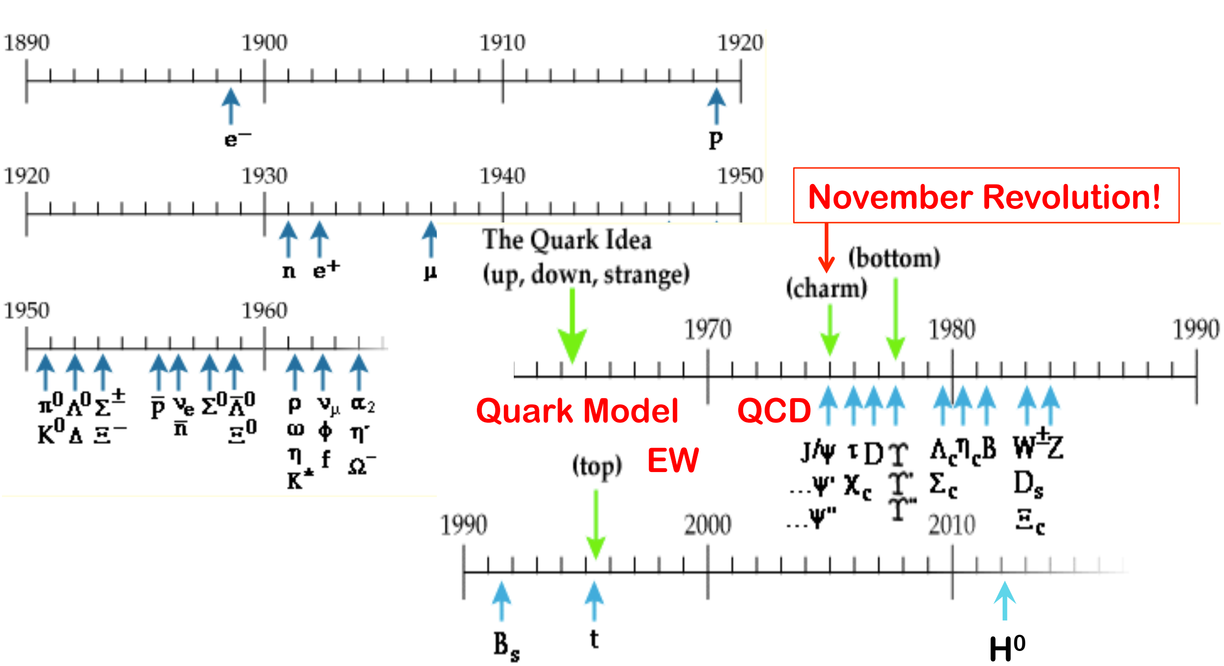
Outline

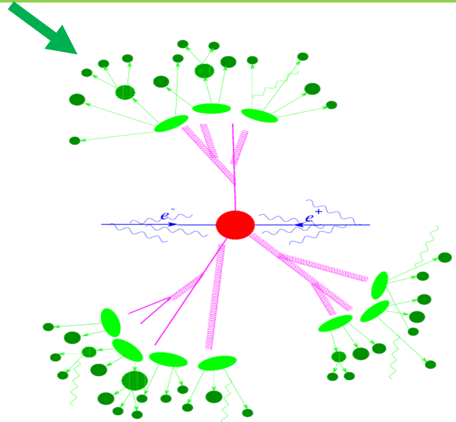
- Introduction
  - Why heavy quarkonium?
  - Theoretical frameworks and puzzle
- Jet fragmentation functions
  - J/Psi production within a jet
  - J/Psi polarization within a jet
- Summary

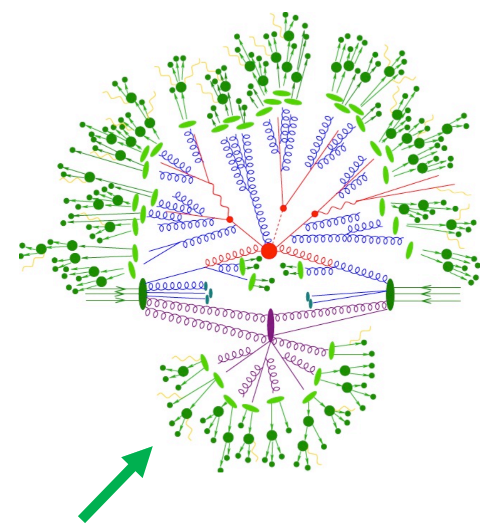
How hadrons are emerged from quarks and gluons?

❑ Time evolution of new particle discovery



Electron-positron collision





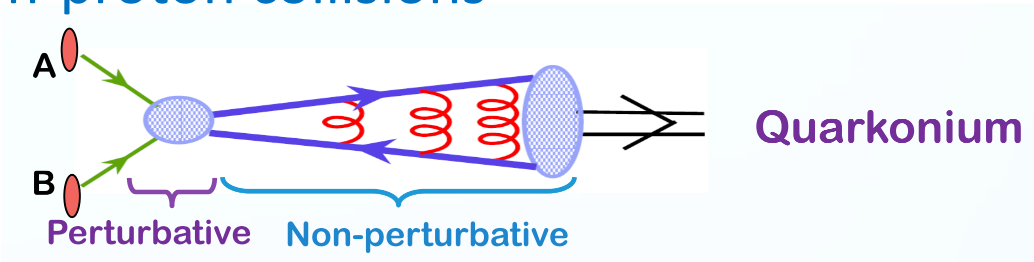
Proton-proton collision

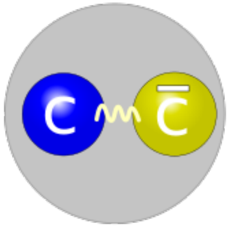
❑ Probe hadron fragmentation mechanism

- ❖ Clean in electron-positron collision (CEPC).
- ❖ Take advantages of current RHIC and LHC runs.
- ❖ More opportunities in future EicC & EIC.

Heavy quarkonium production

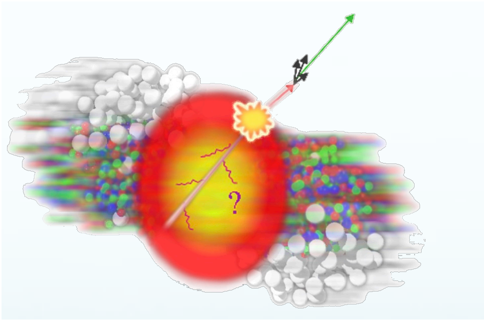
- Proton-proton collisions





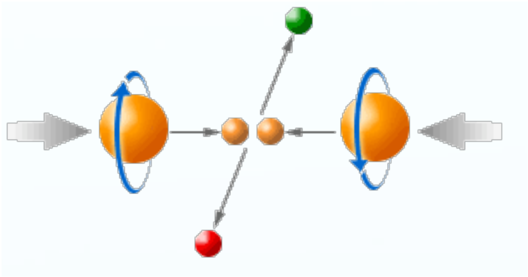
Precision test of our understanding on QCD and hadronization.

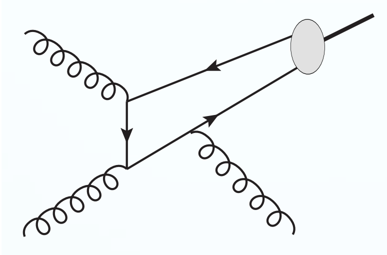
- Heavy ion collisions



Produced in the early stage of the collisions, provide information of quark-gluon plasma.

- Polarized proton-proton and electron-proton collisions





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Discover proton spin origin from gluon spin contribution.

QCD frameworks for J/Psi at collider energies

QCD frameworks

- Color Singlet Model, Einhorn, Ellis (1975) …
- Color Evaporation Model, Fritsch (1977), Halzen (1977) …
- Color Octet Model, Caswell, Lepage (1986), Bodwin, Braaten, Lepage (1995) …
- CGC + NRQCD, Kang, Ma, Venugopalan (2014) …
- SCET + NRQCD, Fleming, Leibovich, Mehen (2012) …

NRQCD factorization

Bodwin, Braaten, Lepage, PRD 51, 1125 (1995)

$$d\sigma_{A+B\to H+X} = \sum_n d\hat{\sigma}_{A+B\to[Q\bar{Q}(n)]+X} \langle \mathcal{O}_n^H \rangle$$

$$n: \ {}^{2S+1}L_J^{(1,8)}$$

pQCD factorization

- Leading power

Nayak, Qiu, Sterman, PRD 72, 114012 (2005)

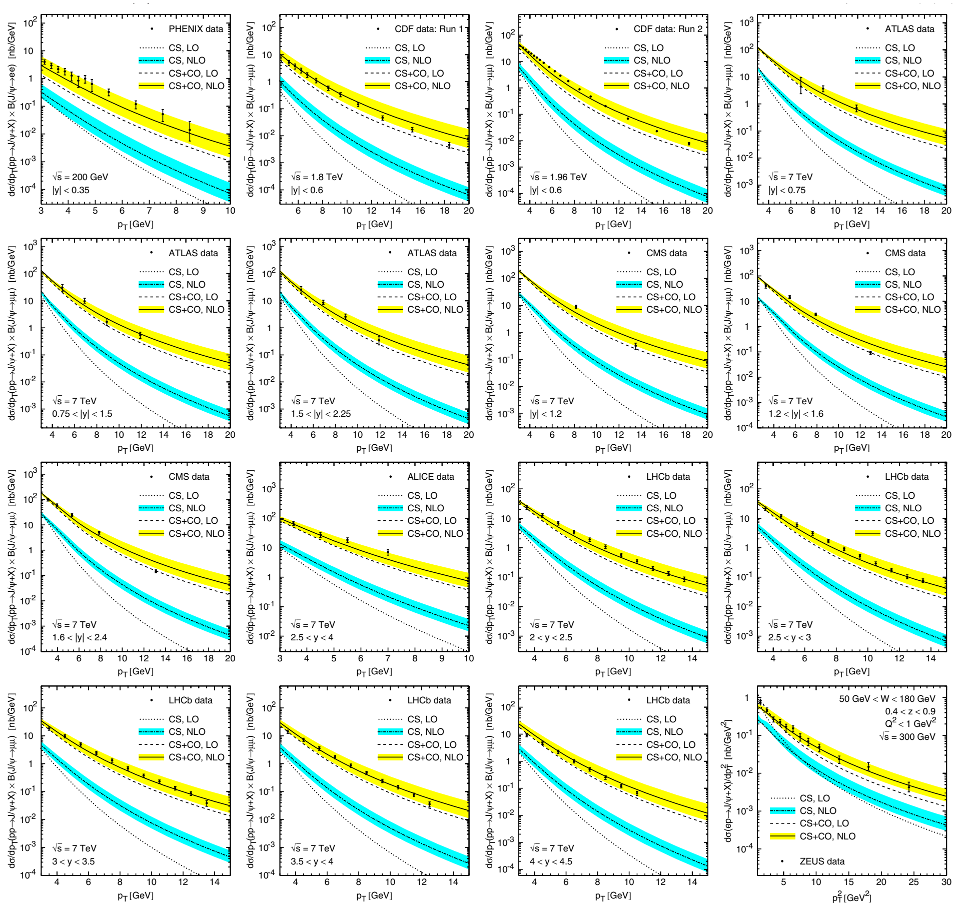
$$d\sigma_{A+B\to H+X} = \sum_i d\hat{\sigma}_{A+B\to i+X}(p_T/z,\mu) \otimes D_{H/i}(z,m_c,\mu) + \mathcal{O}(m_H^2/p_T^2)$$

- Next-to-leading power

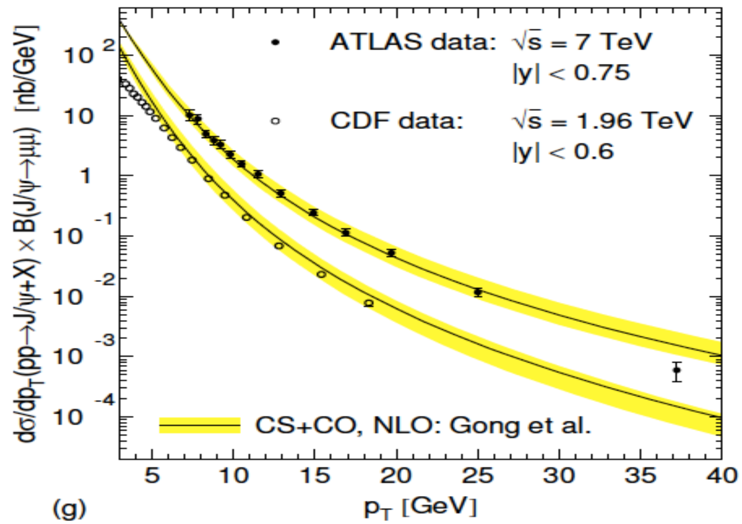
Kang, Ma, Qiu, Sterman, PRD 90, 034006 (2014)

NLO NRQCD fits

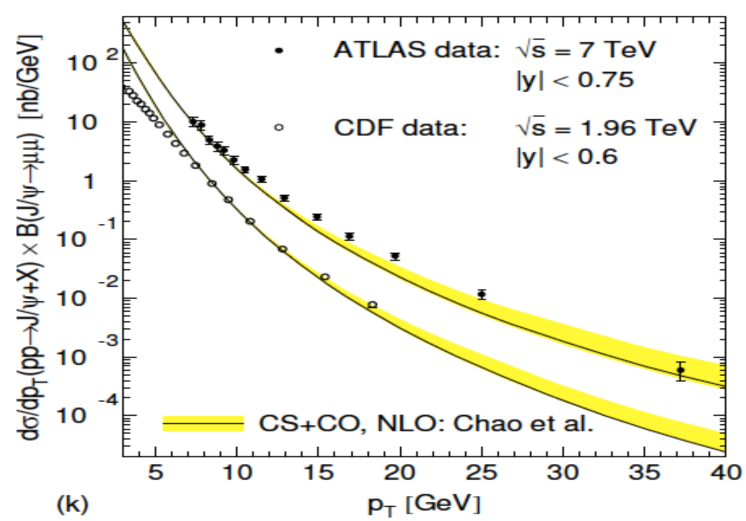
$$e^+e^-, \gamma\gamma, \gamma p, p\bar{p}, pp \rightarrow J/\psi + X$$



Butenschoen et al. PRL (2011)



Gong et al. PRL (2012)



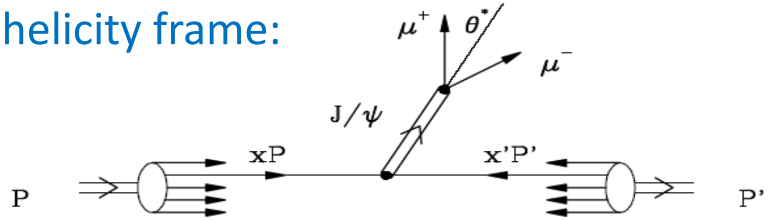
Chao et al. PRL (2012)

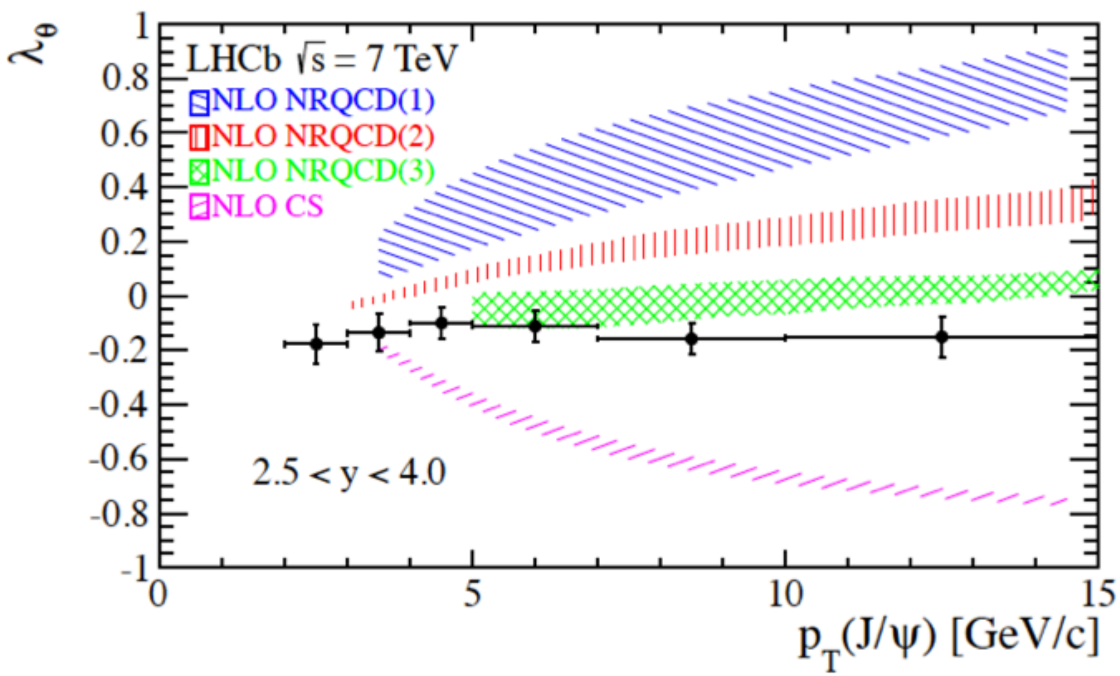
Quarkonium Polarization – ultimate test of NRQCD

- Clear mismatch between theory prediction and data

$$\frac{d\sigma^{J/\psi(\to\ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_\theta \cos^2\theta$$

helicity frame:





$\lambda_\theta = +1$ fully transverse polarized

$\lambda_\theta = 0$ unpolarized

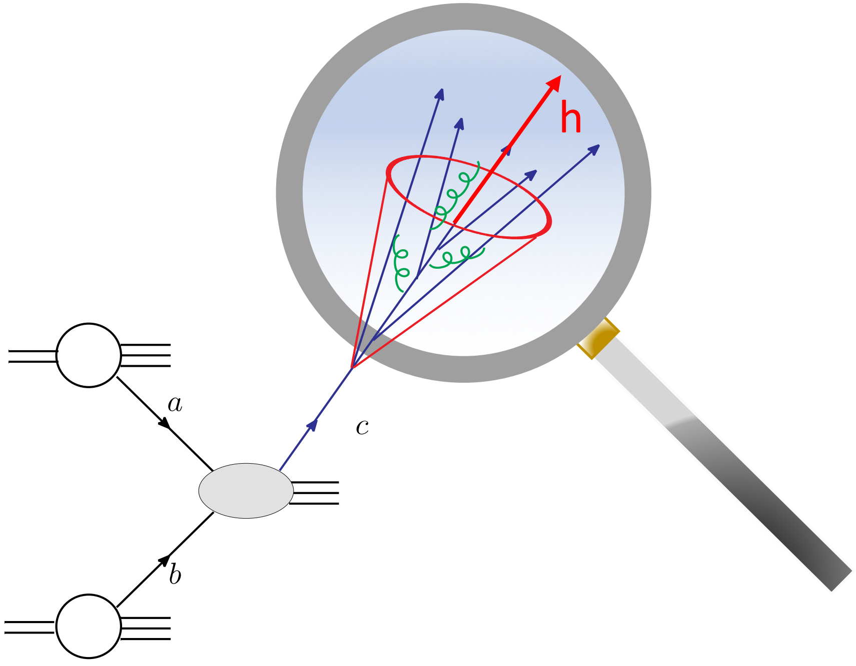
$\lambda_\theta = -1$ fully longitudinal polarized

[1] 1201.1872
[2] 1205.6682
[3] 1209.4610

Longstanding puzzle!

New observable to probe fragmentation process

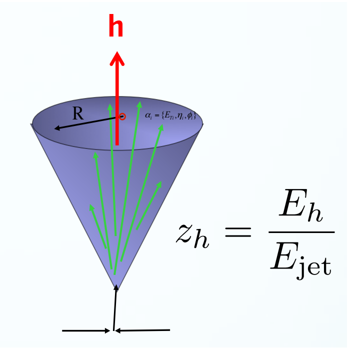
- Jet substructure



Jet fragmentation function – light hadron

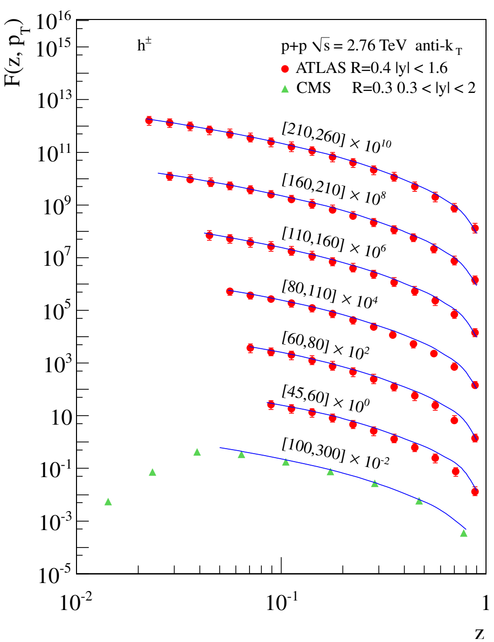
- Hadron distribution inside a jet in proton-proton collisions

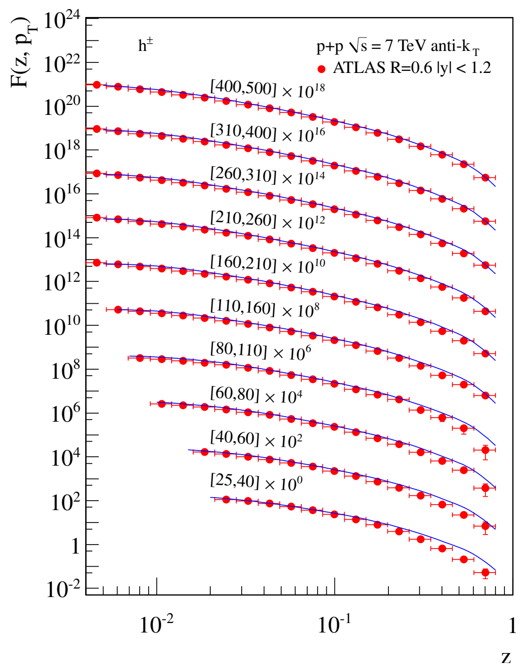
$$F(z_h, p_T) = \frac{d\sigma^h}{dp_T d\eta dz_h} \Big/ \frac{d\sigma^h}{dp_T d\eta}$$

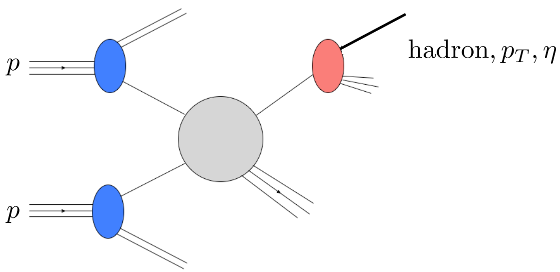


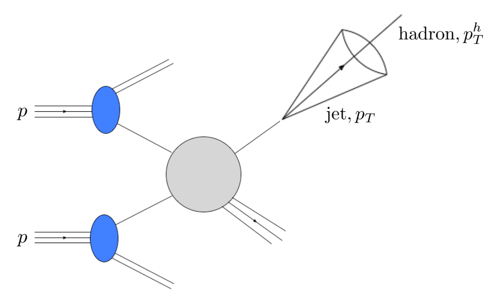
- Light hadrons work very well

Xing et.al., JHEP 1605, 125 (2016), Kang et.al., JHEP (2016)



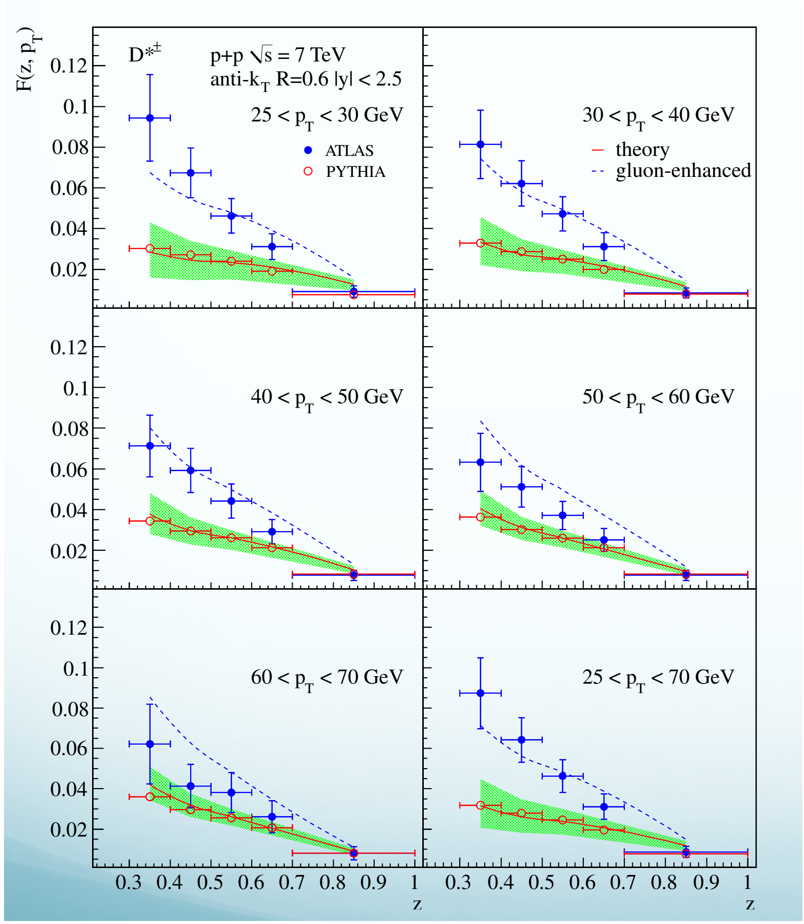






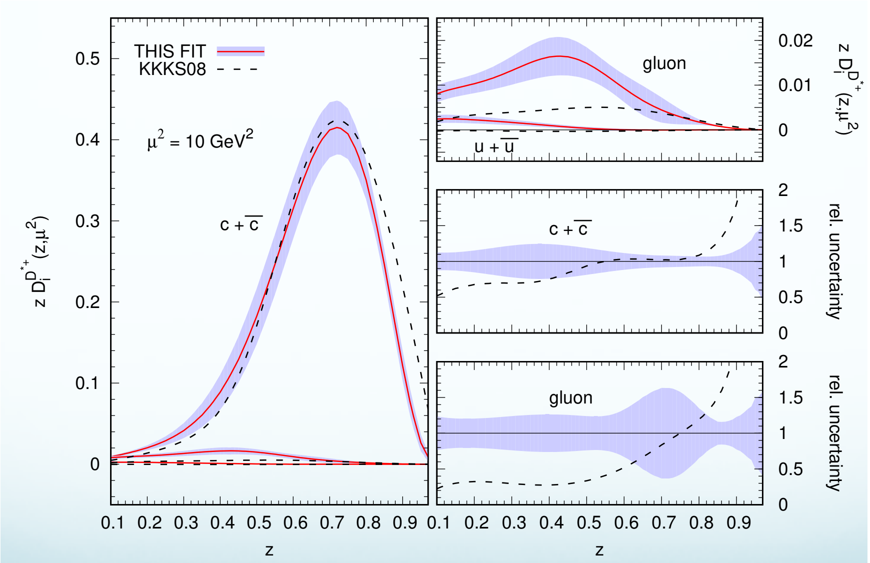
Jet fragmentation function – heavy meson

❑ Disagreement between theory and data for heavy meson in jet



Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing,
1512.06851, JHEP 16

$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

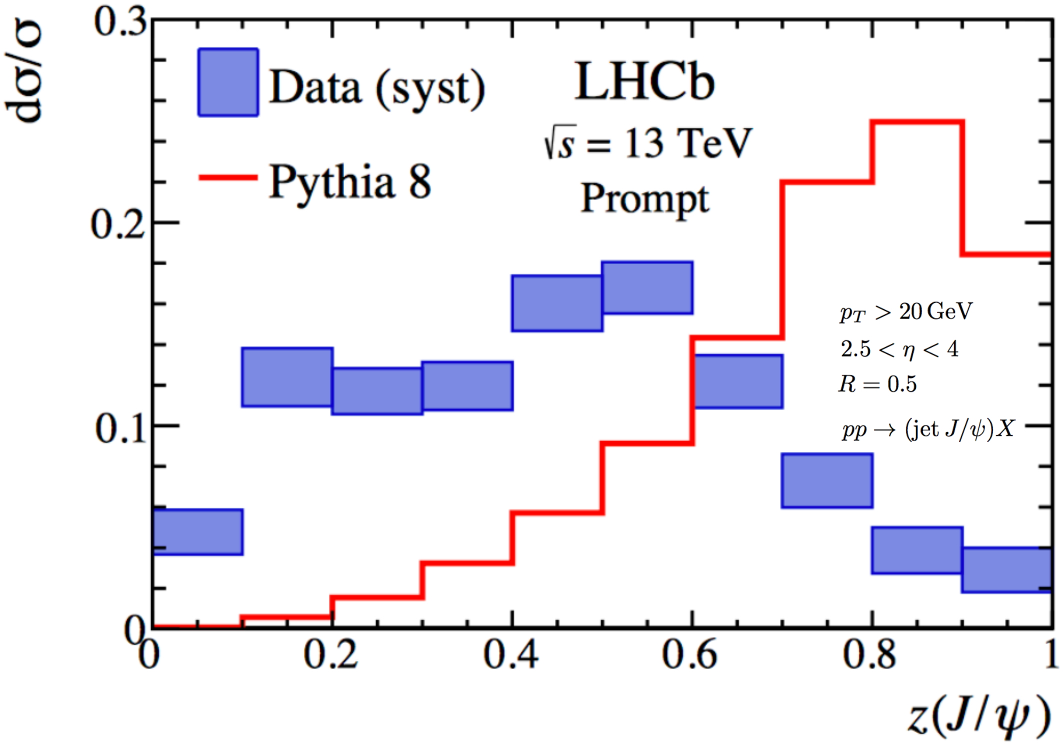


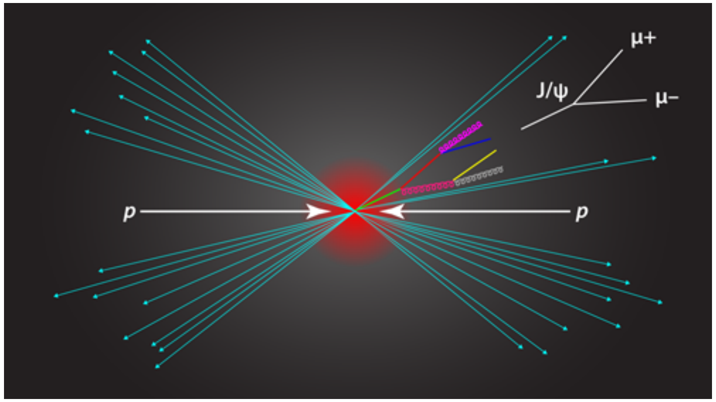
New fit by Stratmann, et.al., PRD 2017

puzzle = opportunity

New extraction of D-meson fragmentation from experimental data!

J/Psi in jet measurement from LHCb



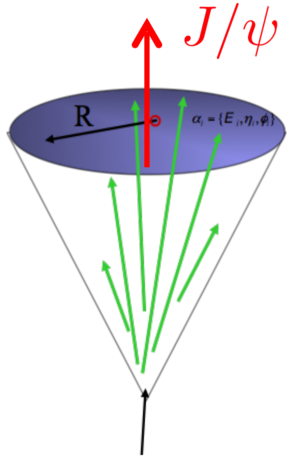


- Disagreement between Pythia and data.
- Different shapes represent for different J/Psi production mechanism.
  - Data prefers that the jet was initiated by a single parton fragmentation
  - Pythia prefers that the jet was initiated by a produced heavy quark pair

Jet fragmentation function

- Defined as the ratio of two physical observables

$$F^{J/\psi}(z_h, p_T) = \frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} \Big/ \frac{d\sigma}{dp_T d\eta}$$



$$z = \frac{\omega_J}{\omega}, \quad z_h = \frac{\omega_h}{\omega_J}.$$

- Factorization framework

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^{J/\psi}$$

resum large logs

expand in α_s

- Semi-inclusive fragmenting jet functions

$$\mathcal{G}_i^{J/\psi}(z, z_h, p_{\rm jet}^+ R, \mu) = \sum_j \int_{z_h}^1 \frac{dz_h'}{z_h'} \mathcal{J}_{ij}(z, z_h/z_h', p_{\rm jet}^+ R, \mu)$$
$$\times D_j^{J/\psi}(z_h', \mu) + \mathcal{O}(m_{J/\psi}^2/(p_{\rm jet}^+ R)^2)$$

- J/Psi fragmentation functions

$$D_{i\to J/\psi}(z_h', \mu_0) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}(z_h', \mu_0)\left\langle \mathcal{O}^{J/\psi}_{[Q\bar{Q}(n)]}\right\rangle$$

expand in α_s & v

hadronization

Semi-inclusive fragmenting jet function

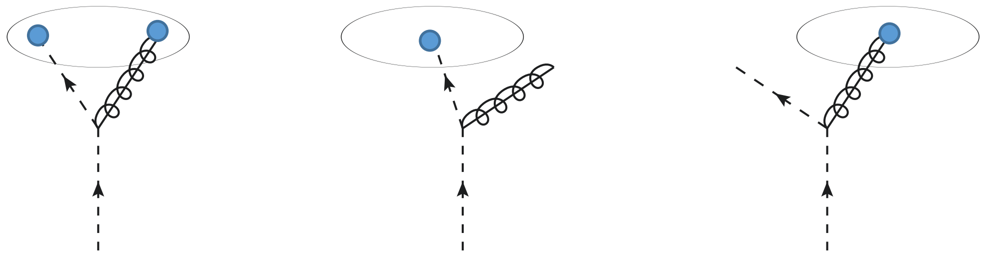
Kang, Ringer, Vitev (2016)

❑ Definition of semi-inclusive fragmenting jet function in SCET

$$\mathcal{G}_q^h(z, z_h, \omega_J, \mu) = \frac{z}{2N_c}\delta\left(z_h - \frac{\omega_h}{\omega_J}\right) \mathrm{Tr}\left[\frac{\bar{\not{n}}}{2}\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\chi_n(0)|(Jh)X\rangle\langle(Jh)X|\bar{\chi}_n(0)|0\rangle\right]$$

$$\mathcal{G}_g^h(z, z_h, \omega_J, \mu) = -\frac{z\,\omega}{(d-2)(N_c^2-1)}\delta\left(z_h - \frac{\omega_h}{\omega_J}\right)\langle 0|\delta\left(\omega - \bar{n}\cdot\mathcal{P}\right)\mathcal{B}_{n\perp\mu}(0)|(Jh)X\rangle \times \langle(Jh)X|\mathcal{B}_{n\perp}^{\mu}(0)|0\rangle$$

❑ NLO SCET Feynman diagrams



- RG evolution equation - resummation of single logarithm in R

$$\mu\frac{d}{d\mu}\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \frac{\alpha_s(\mu)}{\pi}\sum_k\int_z^1\frac{dz'}{z'}P_{ki}\left(\frac{z}{z'}\right)\mathcal{G}_k^h(z', z_h, \omega_J, \mu)$$

- Matching onto standard collinear fragmentation functions

$$\mathcal{G}_i^h(z, z_h, \omega_J, \mu) = \sum_j\int_{z_h}^1\frac{dz_h'}{z_h'}\mathcal{J}_{ij}\left(z, z_h', \omega_J, \mu\right)D_j^h\left(\frac{z_h}{z_h'}, \mu\right)$$

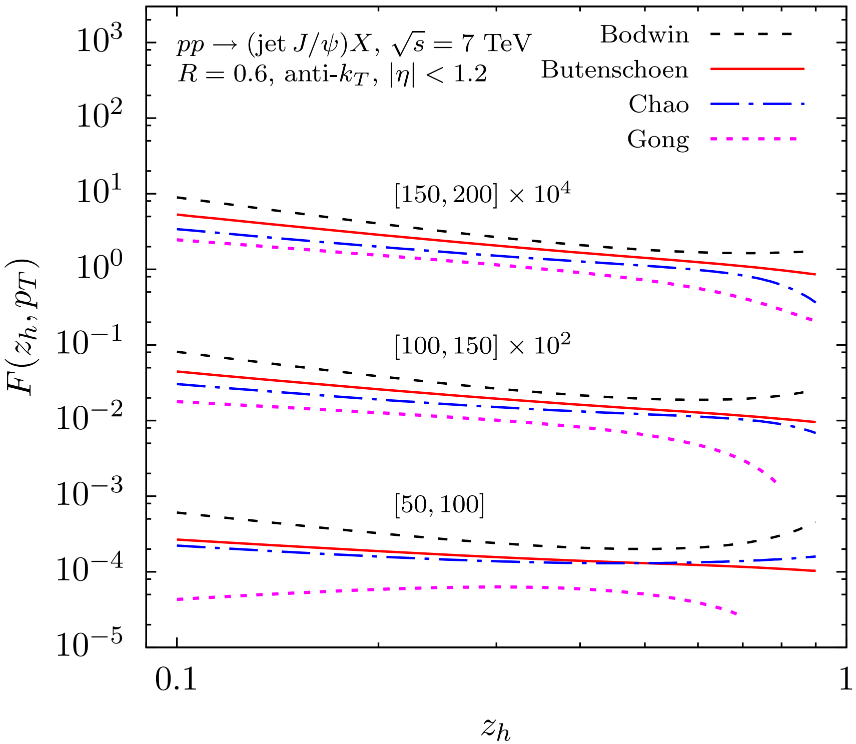
J/Psi production within a jet at the LHC

- Nonperturbative parameters from global fits on inclusive J/Psi data

TABLE I. 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	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Bodwin	0[a]	9.9	1.1	1.1
Butenschoen	1.32	3.04	0.16	−0.91
Chao	1.16	8.9	0.30	1.26
Gong	1.16	9.7	−0.46	−2.14

- Better discriminate different NRQCD parametrizations



precision: NLO + NLL

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^{J/\psi}$$

More differential than inclusive J/Psi pT spectrum.

Kang, Qiu, Ringer, **HX**, Zhang, PRL (2017)

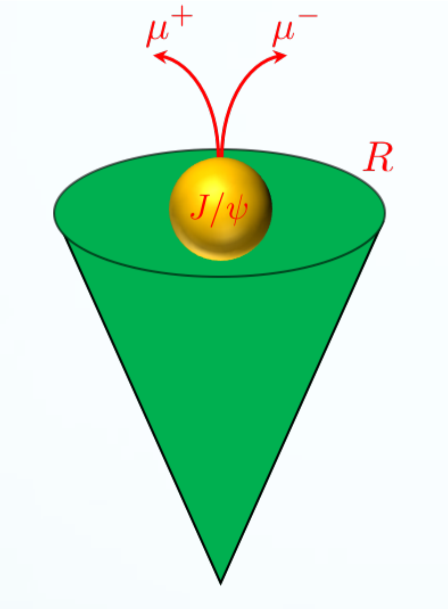
J/Psi polarization in the jet

❑ Angular distribution in helicity frame

$$\frac{d\sigma^{J/\psi(\to \ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta \qquad \lambda_F(z_h, p_T) = \frac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}}$$

$$\lambda_F(z_h, p_T) = \frac{F_T^{J/\psi} - F_L^{J/\psi}}{F_T^{J/\psi} + F_L^{J/\psi}} = \begin{cases} +1, & \textbf{Transverse} \\ -1, & \textbf{Longitudinal} \end{cases}$$

$$\frac{d\sigma^{J/\psi}}{dp_T d\eta dz_h} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \mathcal{G}_c^{J/\psi}$$



❑ Polarized fragmentation function

$$D_{i\to J/\psi}^{T,L}(z_h', \mu_0) = \sum_n \hat{d}_{i\to[Q\bar{Q}(n)]}^{T,L}(z_h', \mu_0)\left\langle \mathcal{O}_{[Q\bar{Q}(n)]}^{J/\psi}\right\rangle$$

Kang, Xing, in preparation.

J/Psi polarization within a jet at the LHC

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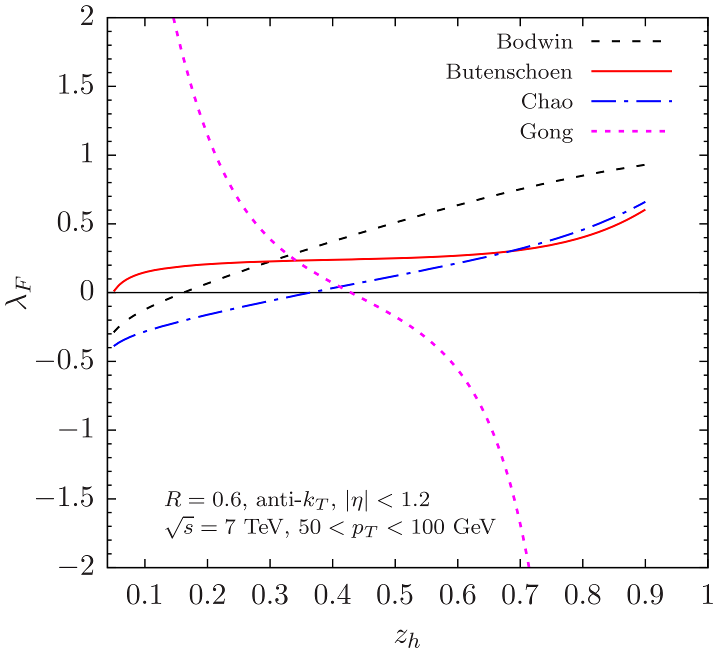
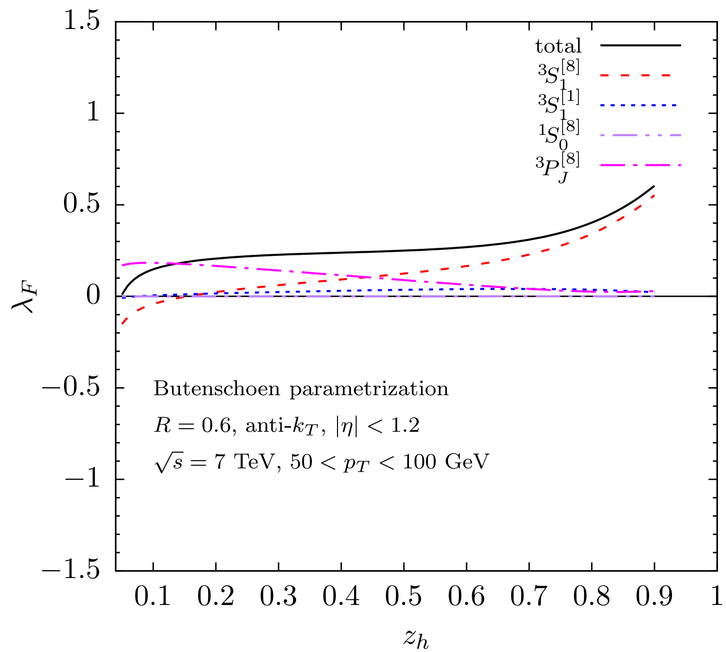
Xing et al, PRL (2017)





J/Psi polarization within a jet is a very sensitive observable to constrain NRQCD LDMEs!

Summary

- NRQCD has been successful in interpreting and predicting inclusive J/Psi pT spectrum, but failed to predict J/Psi polarization.

- J/Psi production and polarization within a jet could be a very good observable to pin down the production mechanism.