Opportunities: heavy flavor production in p+p and EIC

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2017 Heavy Flavor Workshop in High Energy Collisions
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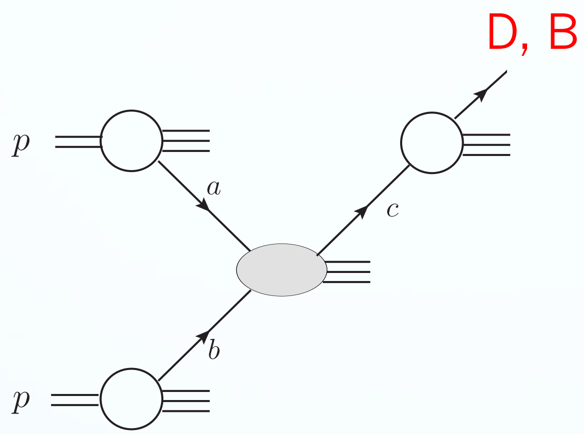
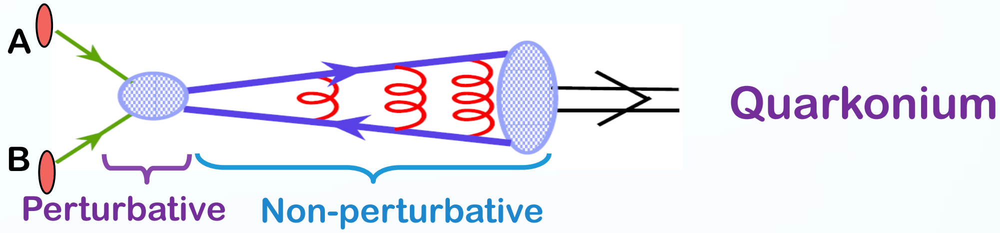
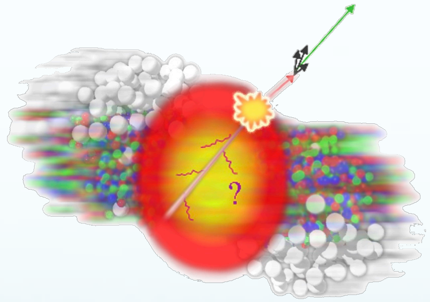
Why heavy flavor

- pp: precision tests of our understanding of QCD, e.g., quark mass effects (D, B), and hadronization (J/ψ, ...)

$$m_{c,b} \gg \Lambda_{\mathrm{QCD}}$$







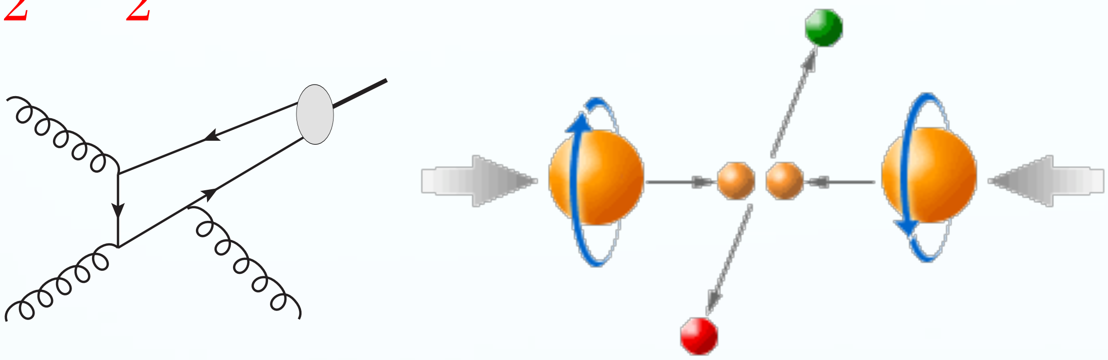
- AA: produced in the early stage of the collisions, provide information of the hot and dense medium (quark-gluon plasma)
  - Jet quenching: radiative E-loss in heavy quark < E-loss for light quark

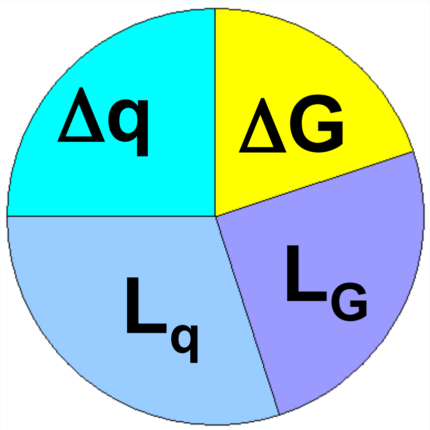
$$R_{AA}^{B} < R_{AA}^{h}$$

Why heavy flavor

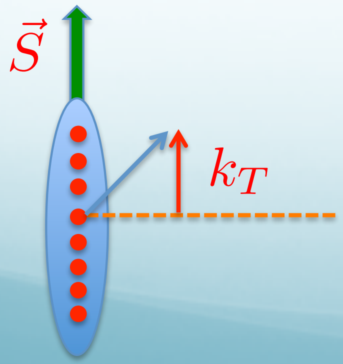
- Gluon spin contribution
  - J/ ψ is sensitive to gluon helicity distribution

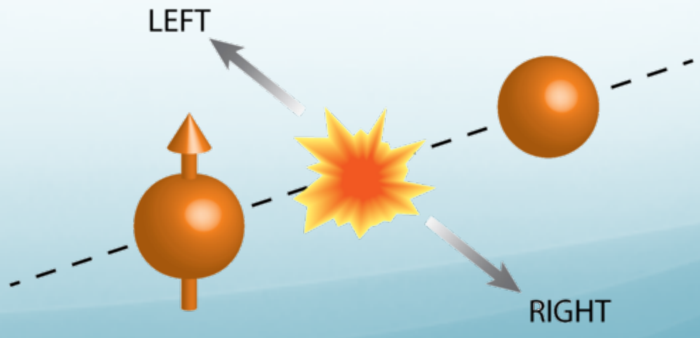
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$





- TMD physics: gluon Sivers function
  - Either heavy quarkonium or open heavy flavor production





Heavy quarkonium production

- Non-relativistic QCD

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

  - Double expansion in coupling and velocity

$$\sigma(gg \to J/\psi + X) = \sum_n \sigma(gg \to c\bar{c}(n) + X)\langle \mathcal{O}^{J/\psi}(n)\rangle$$

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

  - NRQCD long-distance matrix elements (LDMEs)

$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle \sim v^3$$

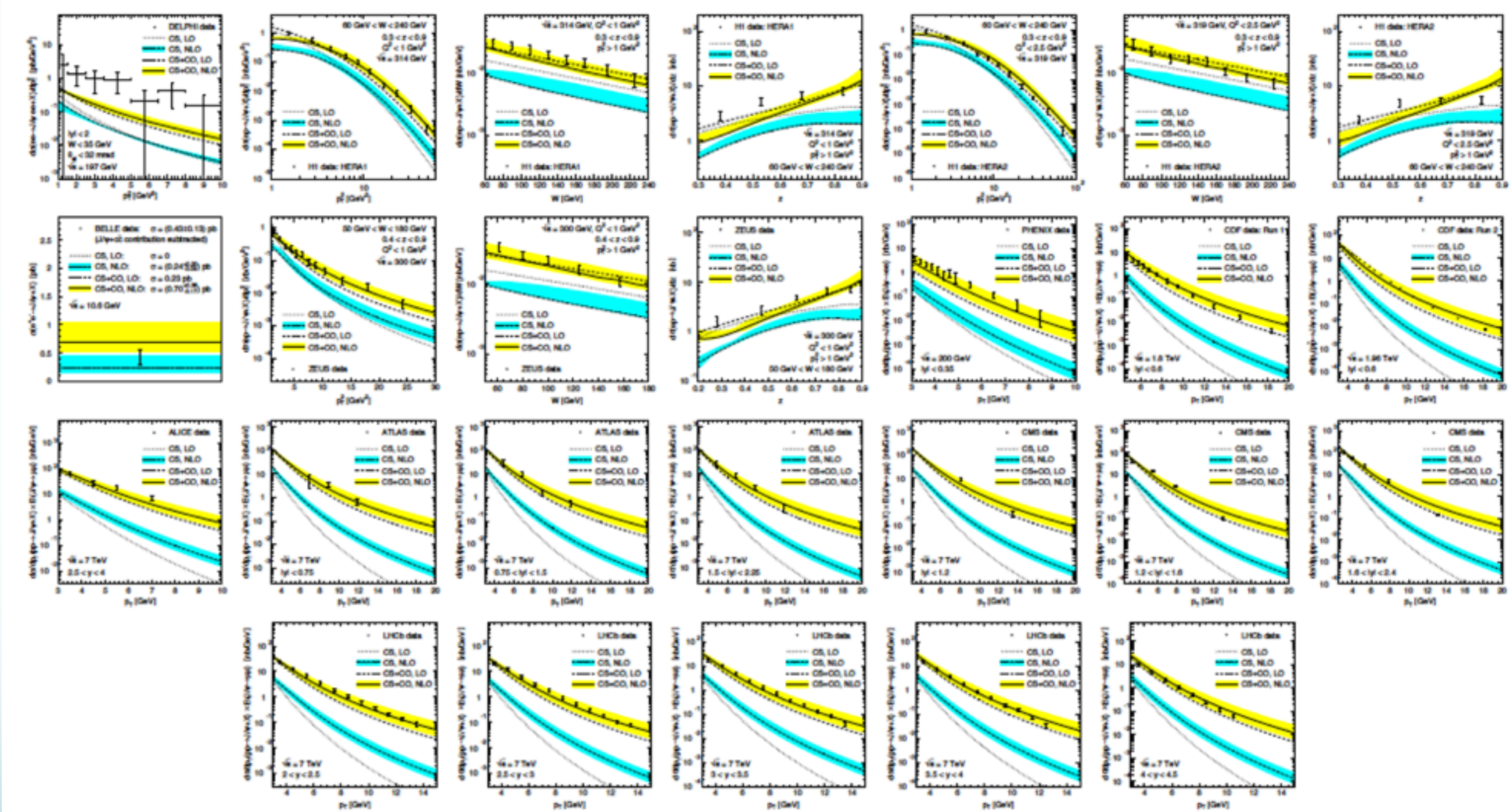
$$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle, \langle \mathcal{O}^{J/\psi}({}^3P_J^{[8]})\rangle \sim v^7$$

- Color Evaporation Model

$$\sigma = F_Q \sum_{i,j} \int_{M_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) \times \hat{\sigma}_{ij}(\hat{s})\delta(\hat{s} - x_1 x_2 s) \, , \quad (1)$$

NRQCD: Global analysis

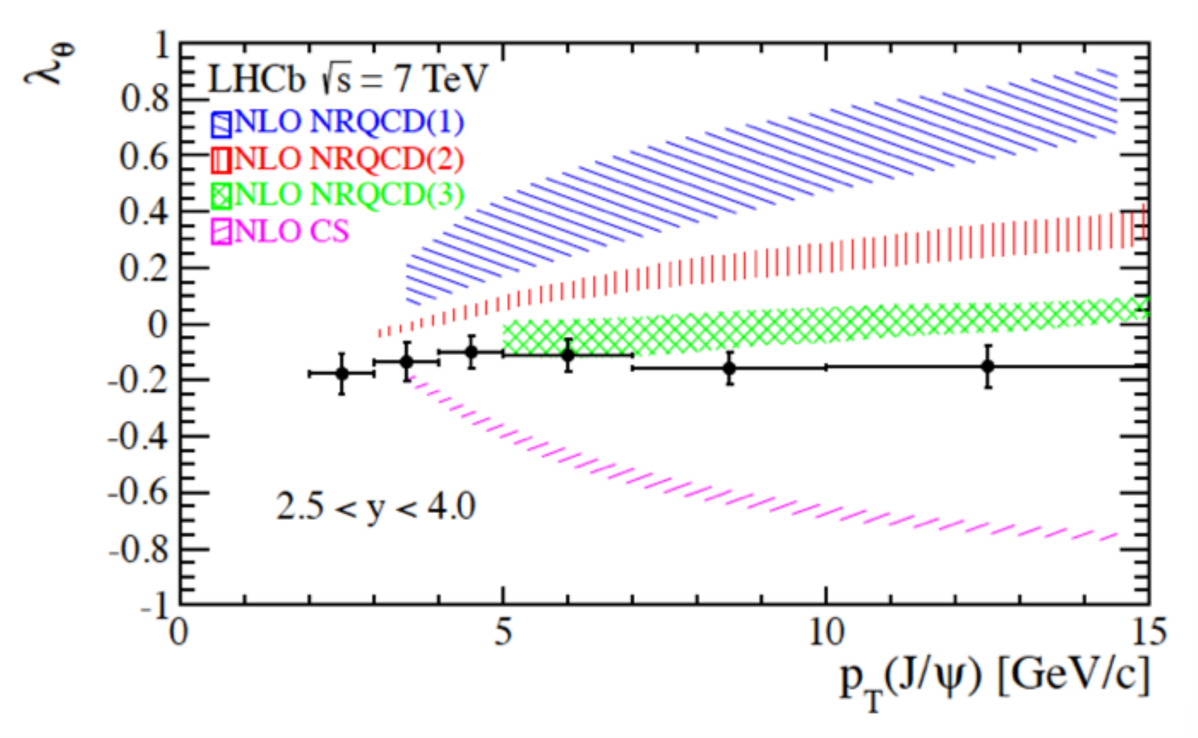
Butenschoen and Kniehl, PRD 84 (2011) 051501



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

Polarization of J/ψ

- Generally NRQCD do not describe the polarization data



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

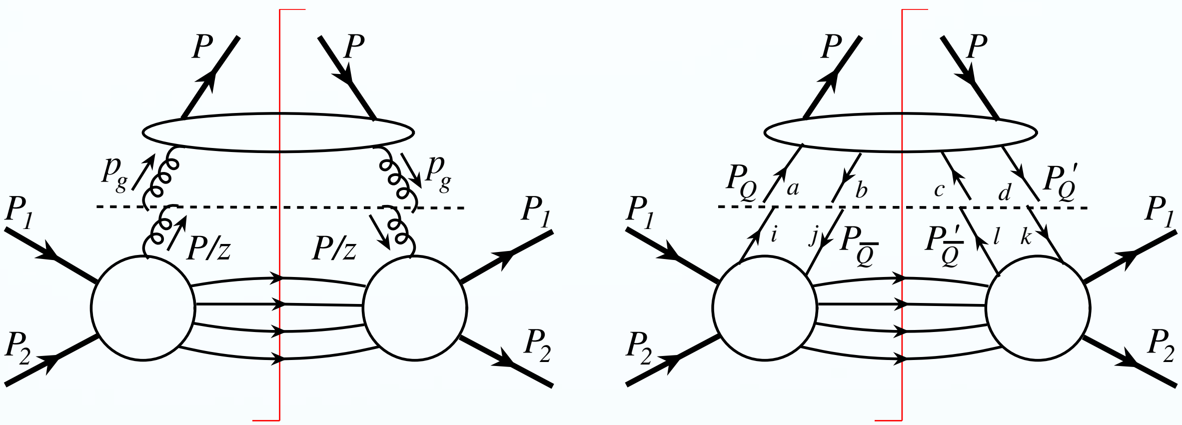
LHCb, 1307.6379, PRL
See more @talk by Kniehl on Tuesday

- See latest development on polarization of CEM model
  - Generalize to p_T dependence

Cheung, Vogt, 17

J/ψ production: fragmentation approach

- A new factorization approach based on fragmentation functions has been proposed: single parton vs double parton FFs
  - FFs follow coupled DGLAP type evolution equations

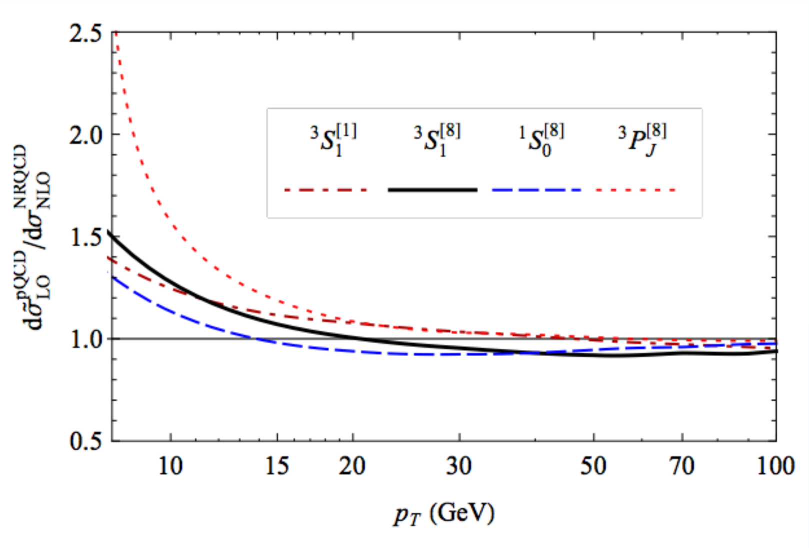


pQCD: Kang, Qiu, Ma, Sterman, 11, 14, 15, 16
SCET: Fleming, Leibovich, Mehen, Rothstein, 12, 13

$$
\begin{aligned}
& d\sigma_{A+B\to H+X}(p) \\
& \approx \sum_f \int_0^1 \frac{dz}{z^2} D_{f\to H}(z)\, d\hat{\sigma}_{A+B\to f(p_c)+X}(p/z) + \sum_\kappa \int_0^1 \frac{dz}{z^2} \int_{-1}^1 \frac{d\zeta_1 d\zeta_2}{4} \mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,\zeta_1,\zeta_2) \qquad (1) \\
& \times d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)](p_c)+X}(p(1\pm\zeta_1)/2z, p(1\pm\zeta_2)/2z),
\end{aligned}
$$

More efficient computation

- A better/more efficient reorganization
  - LO QCD calculations in the new framework can almost reproduce the NLO NRQCD calculations (channel by channel) for $p_T > 10 - 15$ GeV



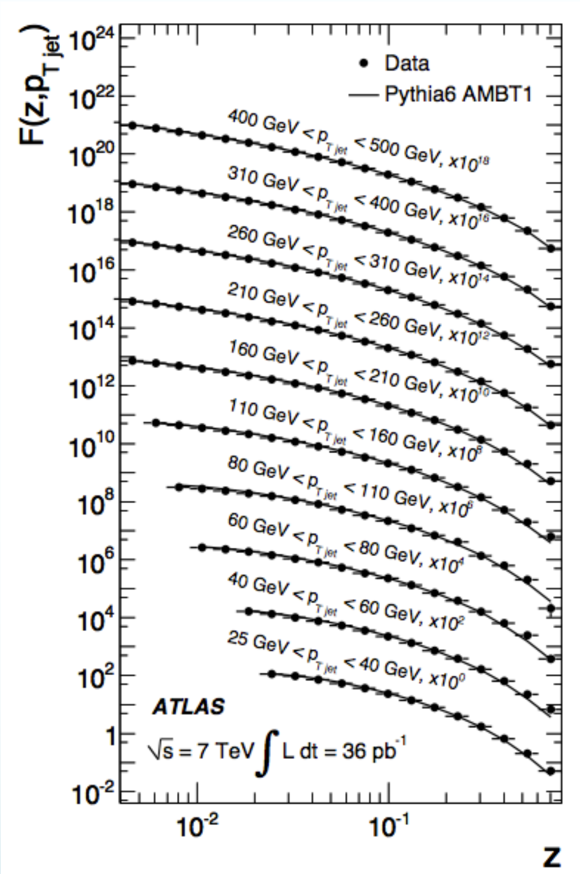
Kang, Qiu, Ma, Sterman, PRL 12, 14

- Single (double) parton FFs favor transverse (longitudinal) polarization: competition might lead to small polarization (with evolution and resummation)
  - Need short-distance partonic cross sections for other processes
  - Need global analysis within new framework

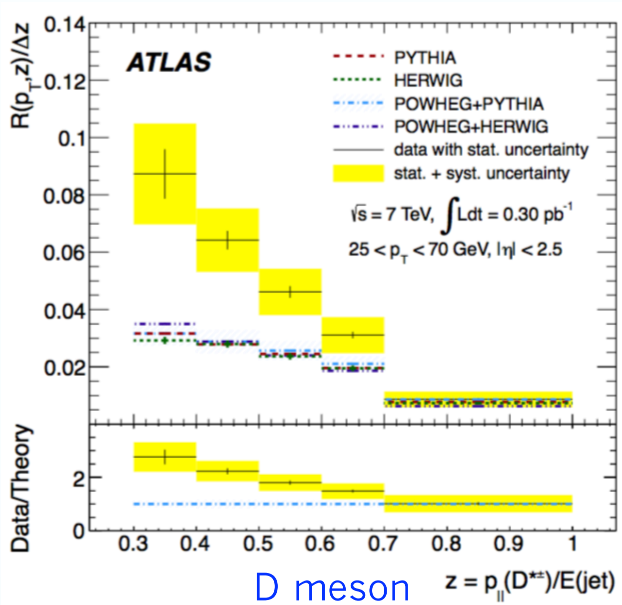
Kang, Lee, Qiu, Sterman, in preparation, 17

Better observables to probe fragmentation process

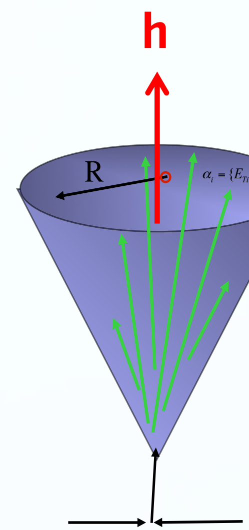
- Hadron distribution inside a jet $p + p \to \text{jet}\,(h) + X$



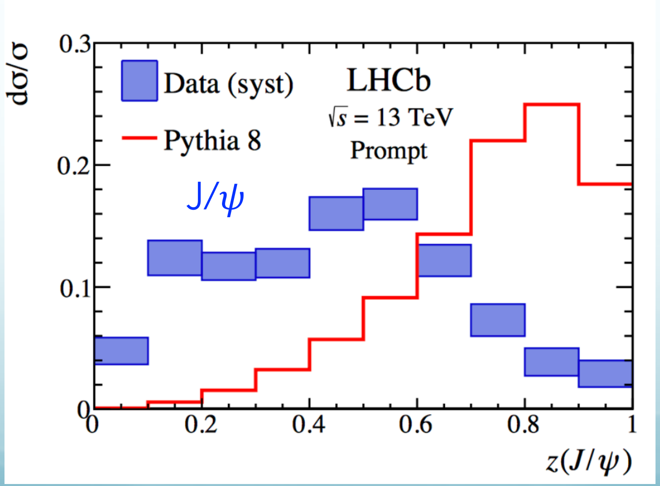
Light charged hadrons

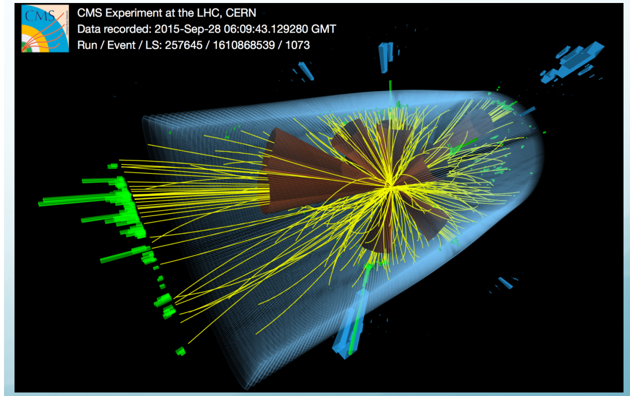


D meson



$$z_h = \frac{E_h}{E_{\text{jet}}}$$

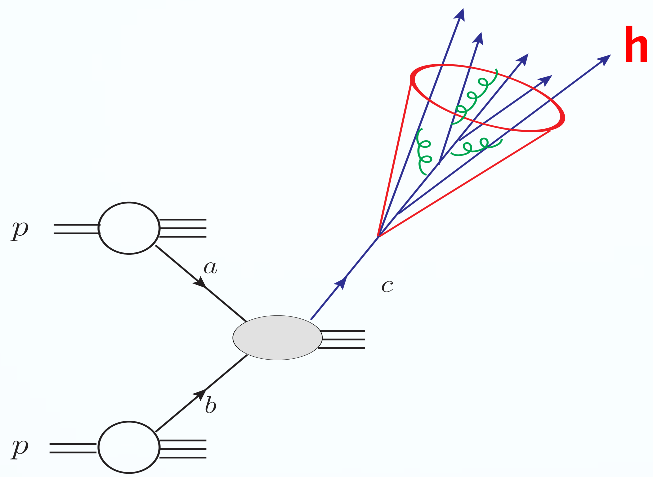




A two-step factorization formalism

- 1st produce the jet, 2nd hadron distribution inside the jet

Kang, Ringer, Vitev, JHEP 16, 16



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

$$z = p_T / p_T^c \qquad z_h = p_T^h / p_T$$

$$\frac{d\sigma}{dy dp_T dz_h} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, R, \mu)$$

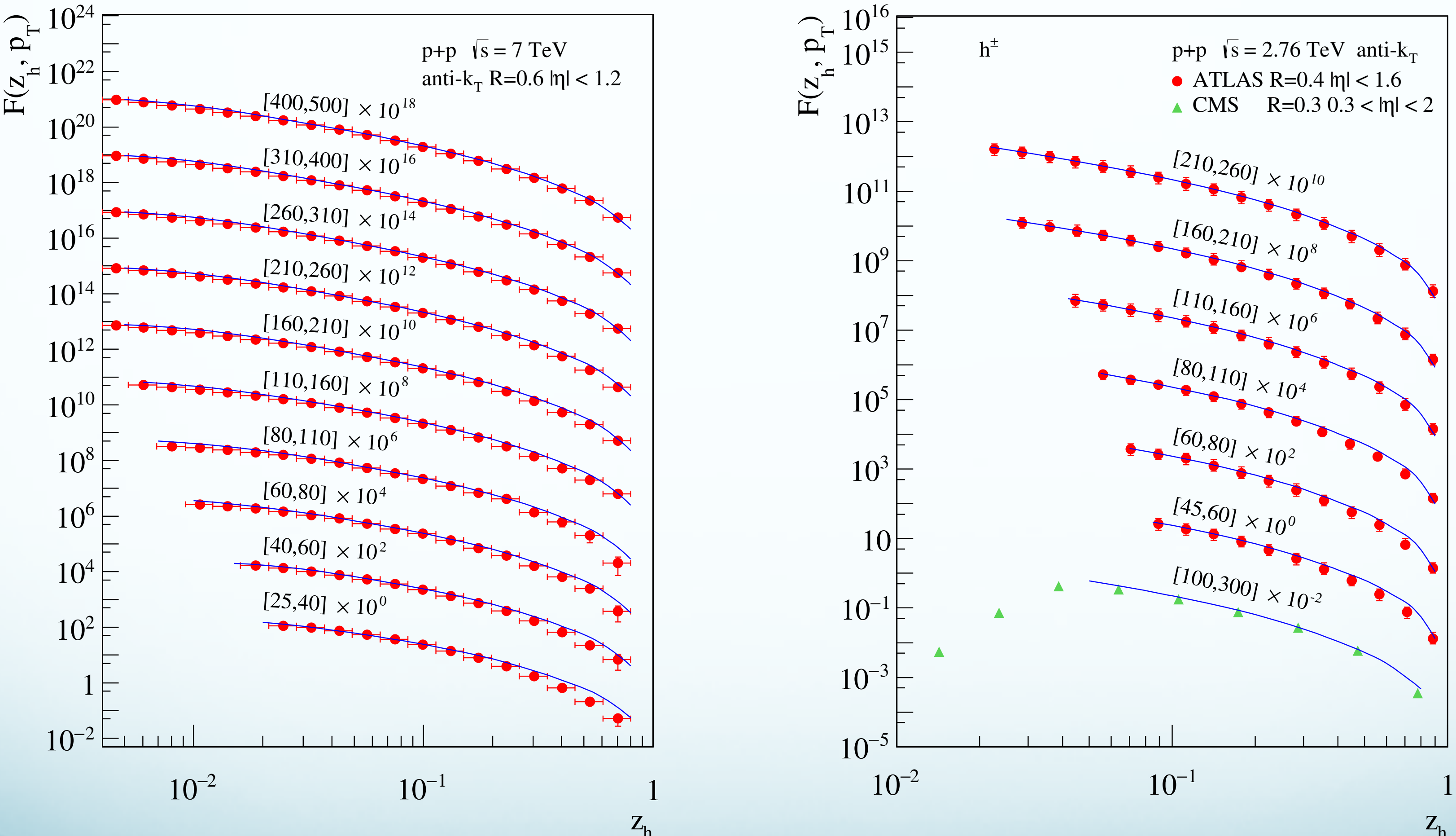
- Connection to standard FFs

$$\mu \frac{d}{d\mu} \mathcal{G}_i^h(z, z_h, \mu) = \frac{\alpha_s(\mu)}{\pi} \sum_j \int_z^1 \frac{dz'}{z'} P_{ji}\left(\frac{z}{z'}\right) \mathcal{G}_j^h(z', z_h, \mu)$$

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

Light hadrons: work well

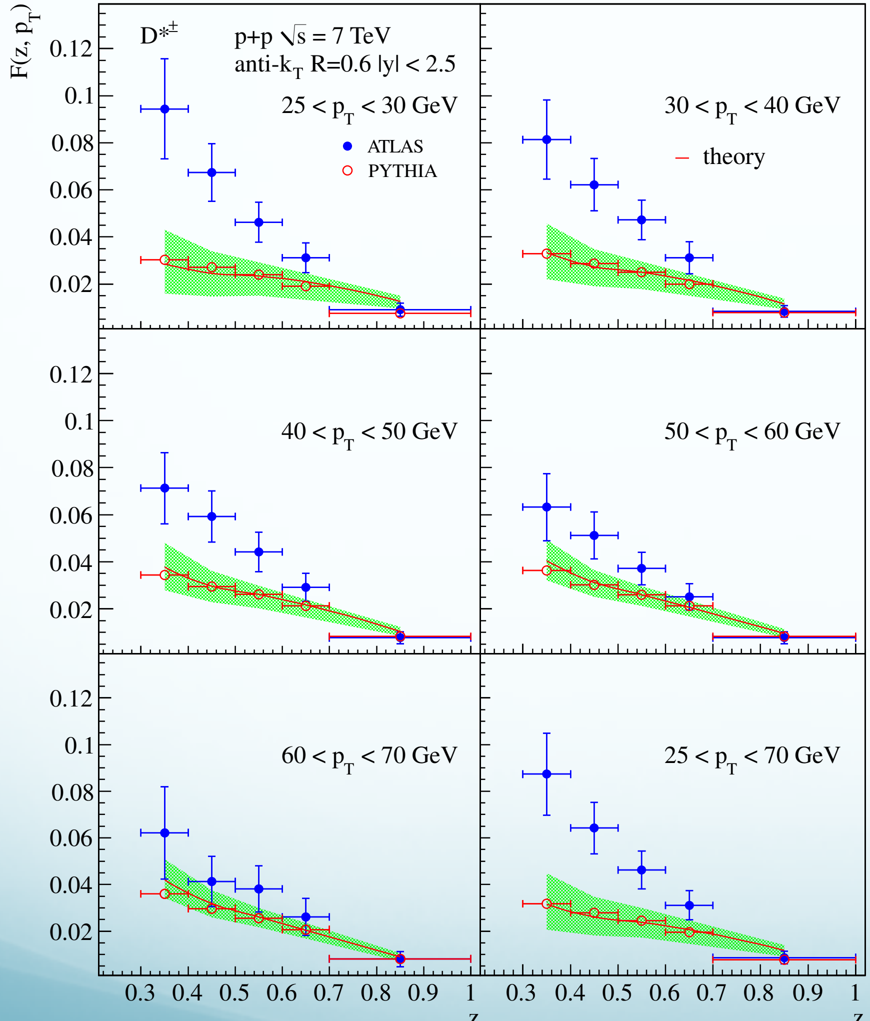
- Light charged hadrons



Kang, Ringer, Vitev, JHEP, 16

Jet fragmentation function for heavy meson

- Using D meson FFs fitted from e+e- data Kneesch, Kniehl, Kramer, Schienbein, 08



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

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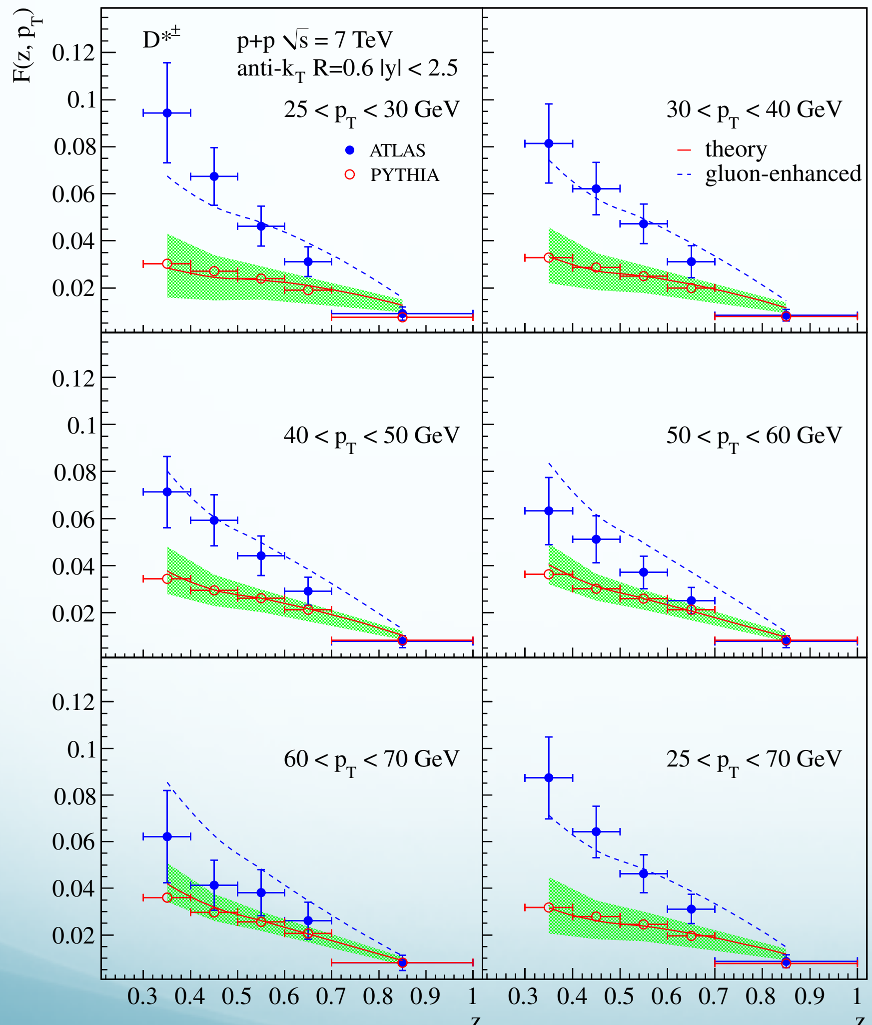


Using ZM-VFNS scheme:
Chien, Kang, Ringer, Vitev, Xing, 1512.06851, JHEP 16

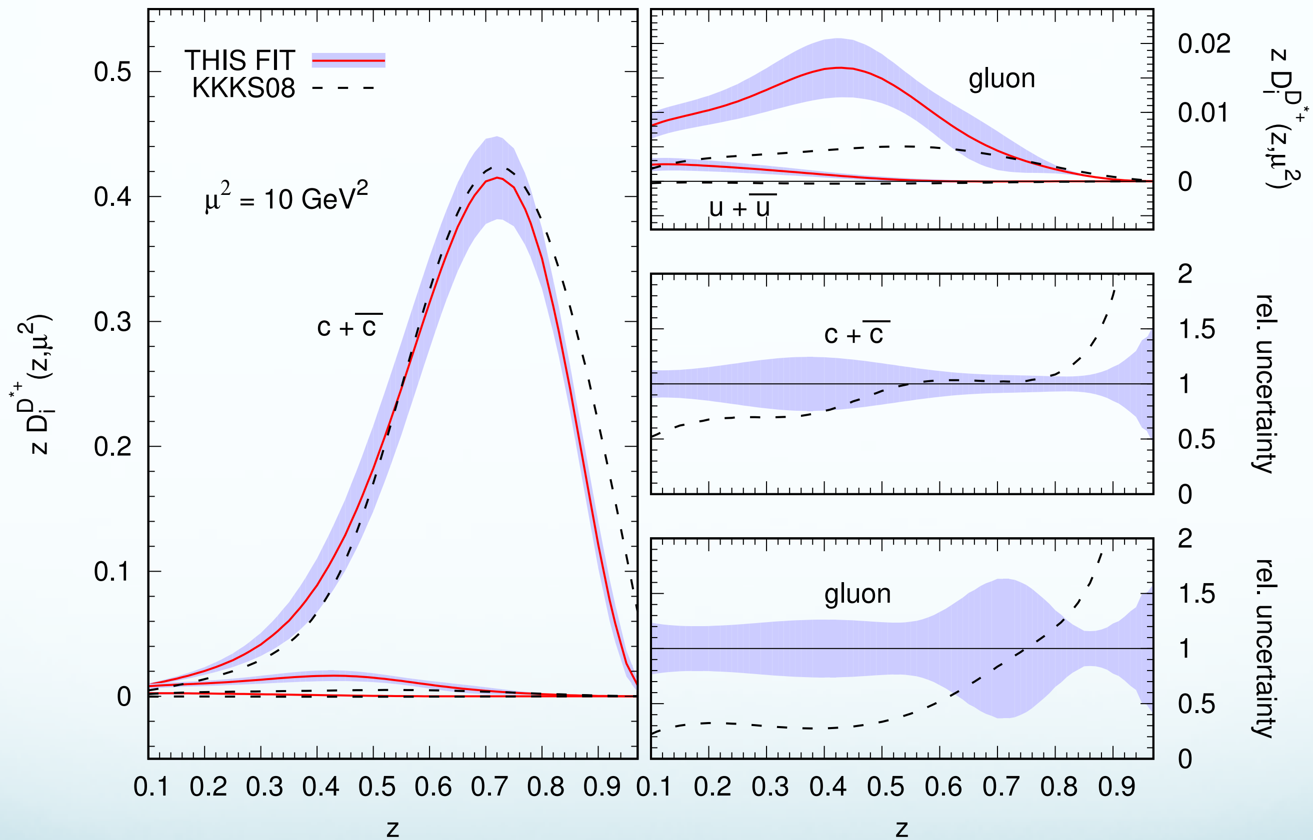
$$D_g^D(z,\mu) \to 2D_g^D(z,\mu)$$

New fit of D-meson FFs needed

A new global analysis of FFs

- New fit of D-meson FFs

New fit of D-meson FFs:
Stratmann, et.al., PRD 2017

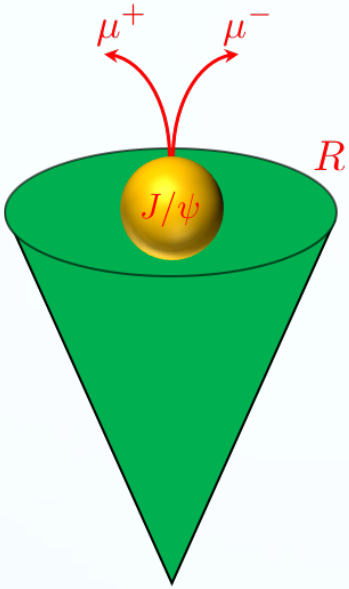


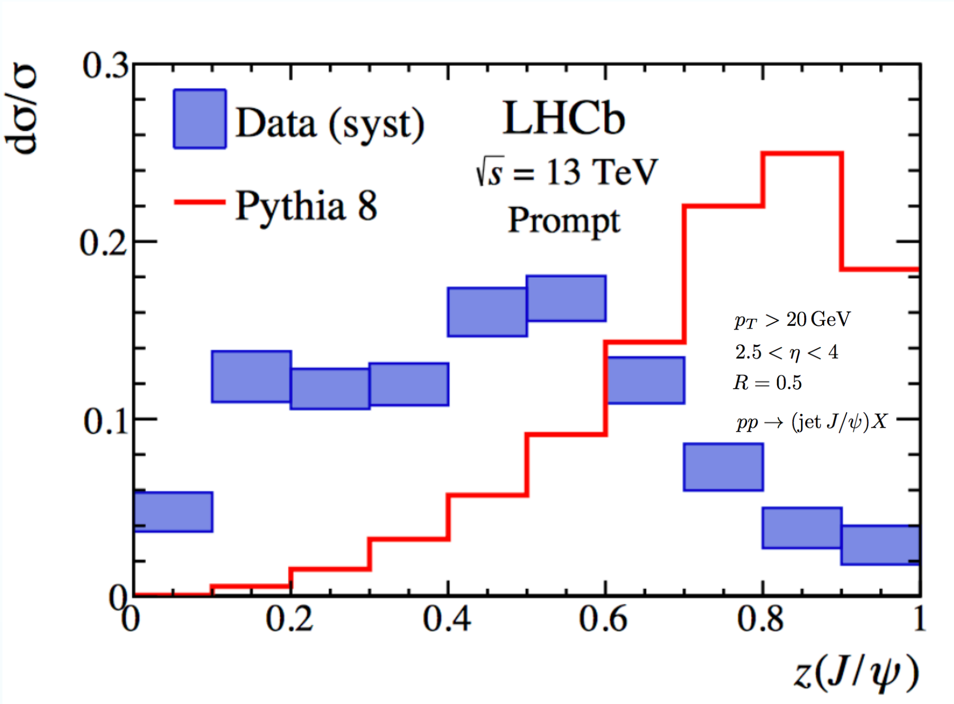
See talk by Vitev on Monday

Confirms our earlier guess

Quarkonium production in the jet

- J/ψ-in-jet measurement from LHCb





Production: Baumgart, Leibovich, Mehen, Rothstein, JHEP 14
Polarization: Kang, Ringer, Xing, et.al., PRL17

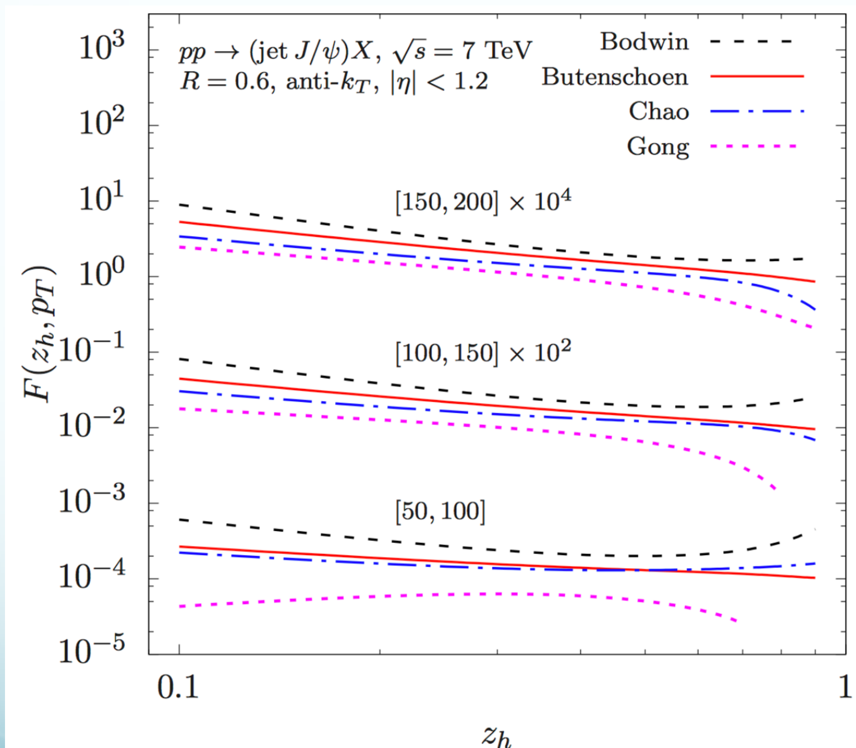
PRL 17

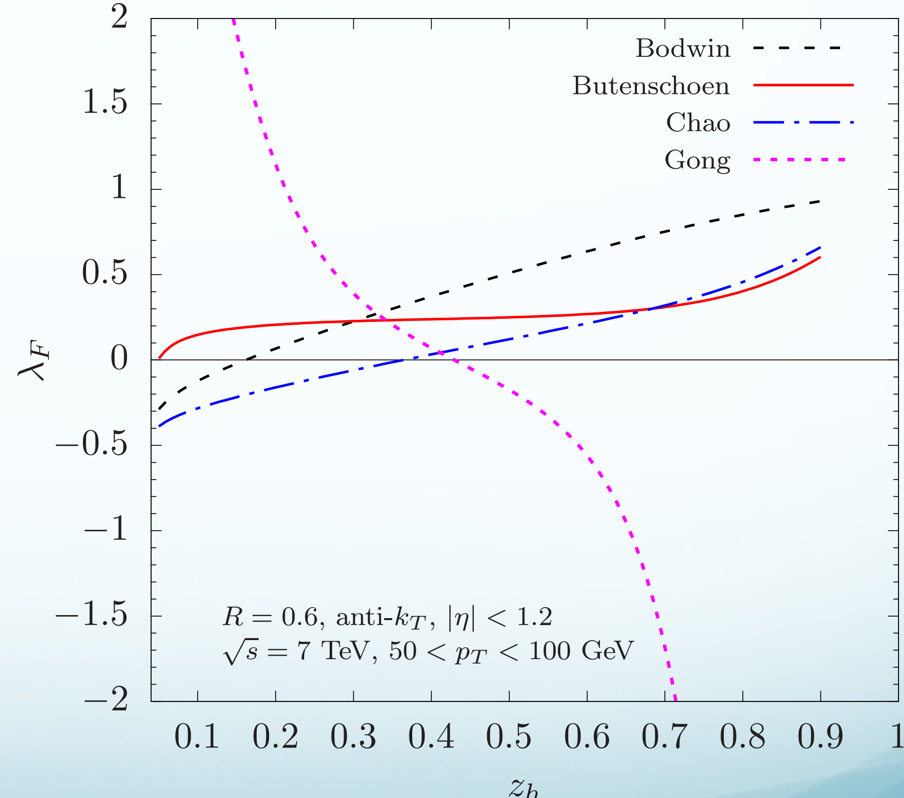
$$\frac{d\sigma^{J/\psi(\to\ell^+\ell^-)}}{d\cos\theta} \propto 1 + \lambda_F \cos^2\theta$$

$$\lambda_F = \begin{cases} +1, & \text{transversely polarized} \\ -1, & \text{longitudinally polarized} \end{cases}$$

J/ψ production and polarization in jets

- More differential than inclusive J/ψ p_T spectrum, and can discriminate different NRQCD parameterizations
  - Hadroproduction data alone cannot reliably fix all 3 CO LDMEs (Kniehl's talk)



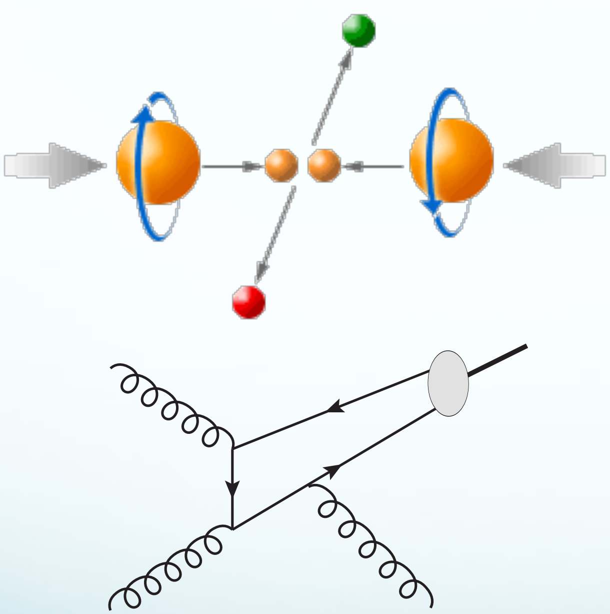


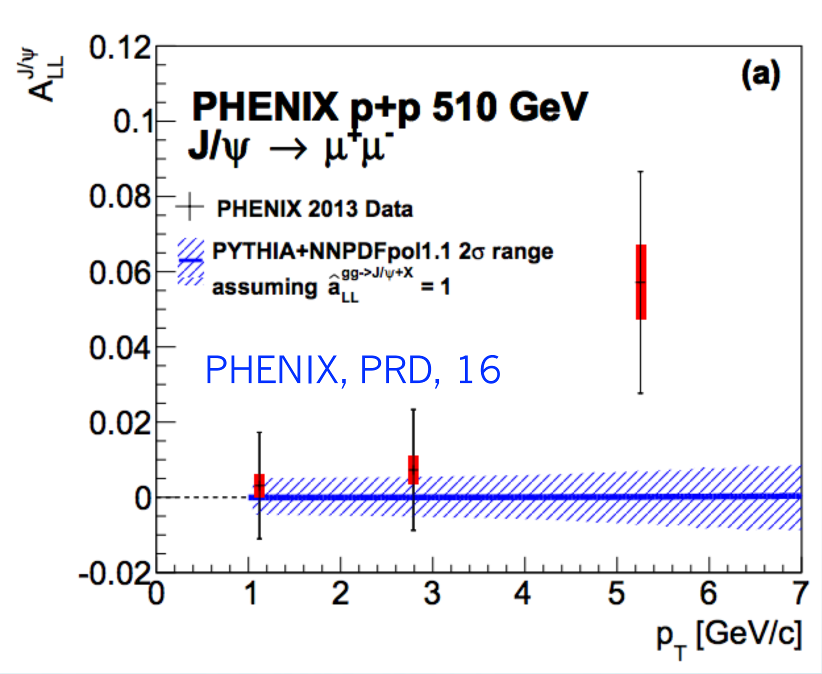
Kang, Qiu, Ringer, Xing, Zhang, PRL 2017,
See also the study by Bain, Dai, Leibovich, Makris, Mehen, PRL 2017

Gluon spin contribution: heavy quarkonium production

- Heavy quarkonium production in double longitudinal p+p collisions is a sensitive probe of gluon helicity distribution function

$$\Delta g(x, Q^2) \qquad \Delta G = \int_0^1 dx \Delta g(x, Q^2)$$



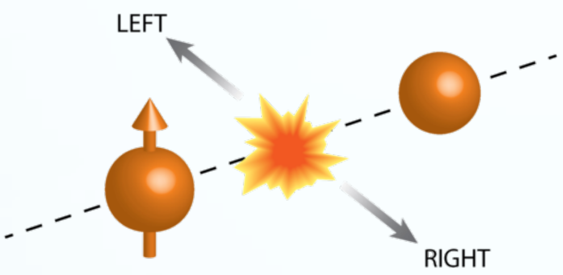


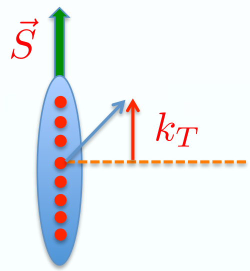
- It will be great to improve this measurement, hopefully can make better constrain on gluon helicity distribution

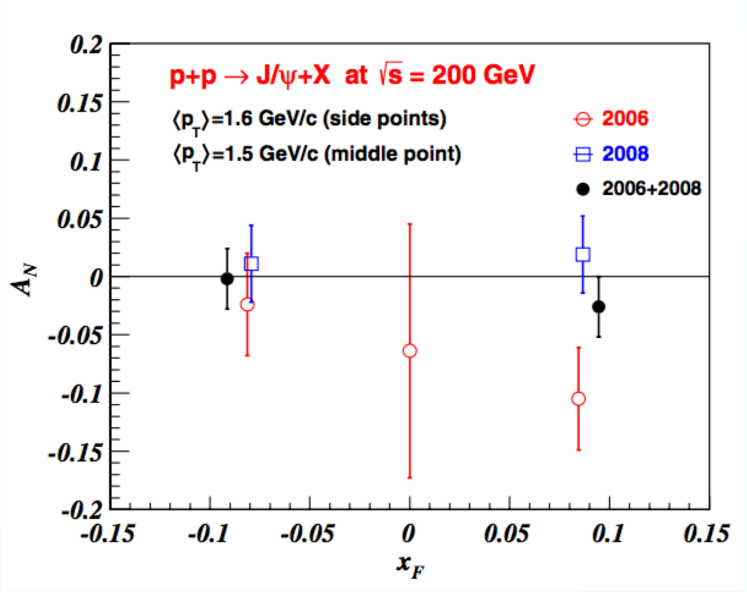
Kang, Xing, in preparation, 2017

Gluon Sivers functions

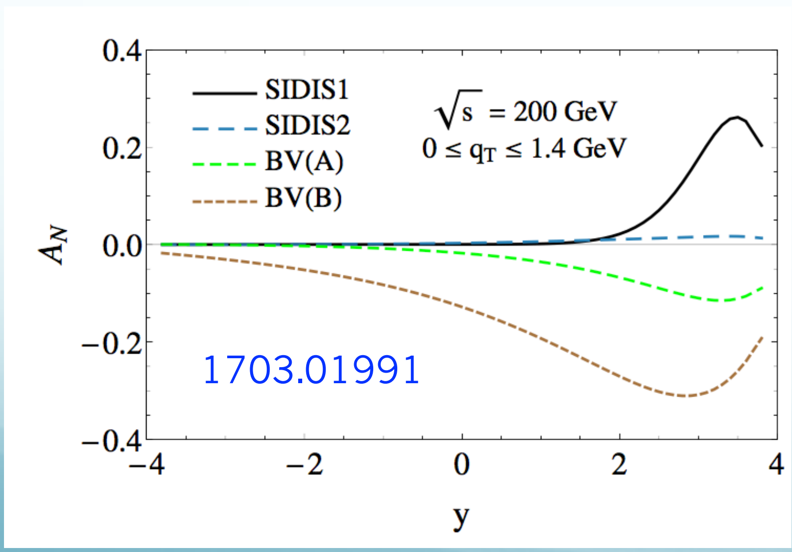
- Gluon Sivers function (or gluon spin-momentum correlation) can be studied through heavy flavor production in transversely polarized p+p or e+p collisions







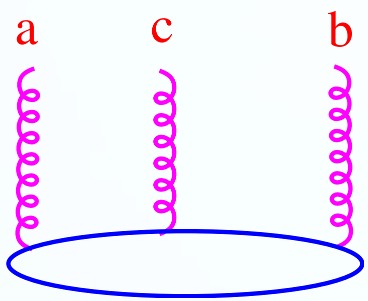
PHENIX, PRD, 12

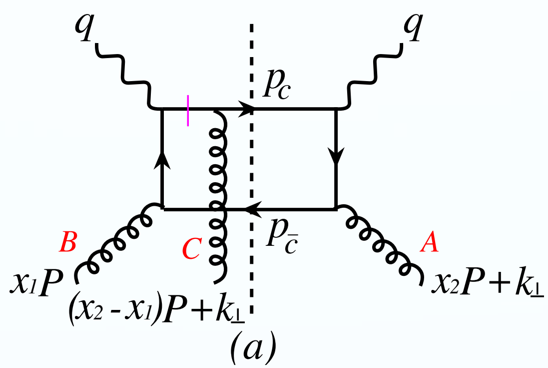


Open heavy flavor meson

- Open heavy flavor meson production
  - Two different correlation functions in gluon spin-momentum correlations lead to different asymmetries in D and $\bar{D}$

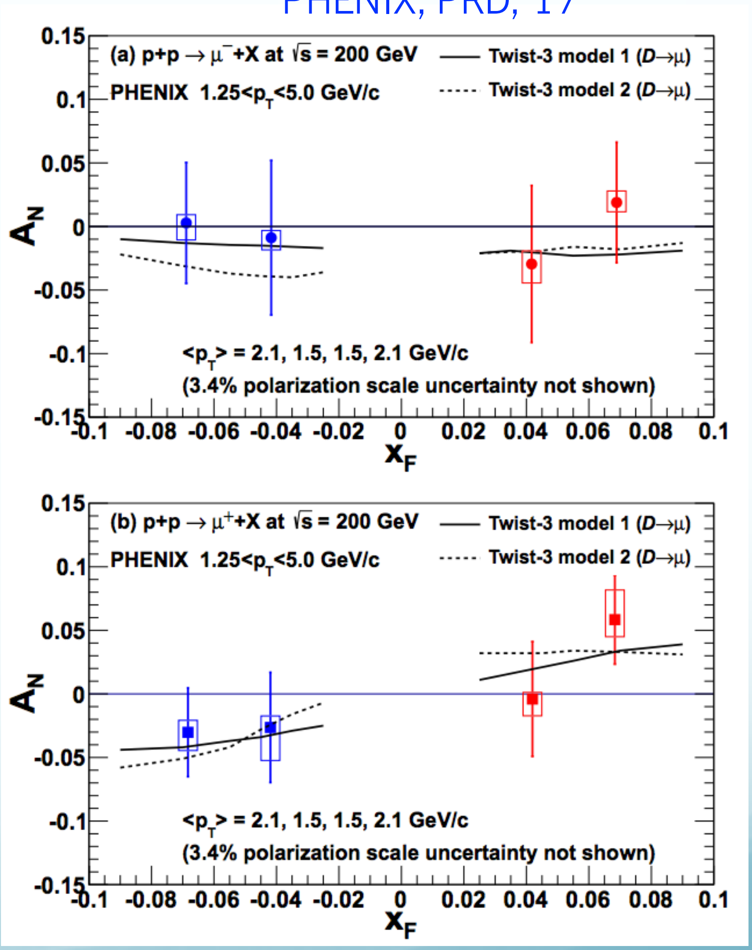
PHENIX, PRD, 17





$$i f^{abc} F^a F^c F^b$$

$$d^{abc} F^a F^c F^b$$

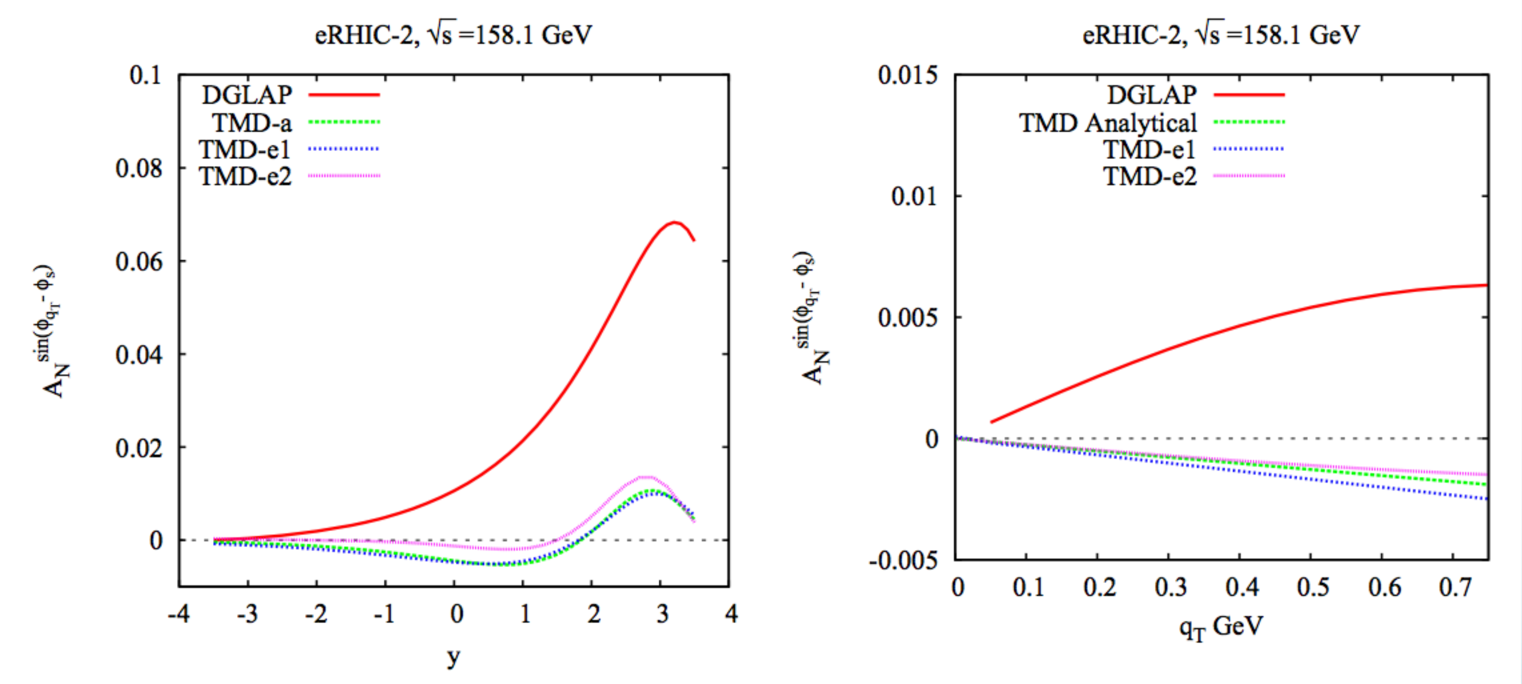


Kang, Qiu, Vogelsang, Yuan 08,
Koike, Yoshida 11
See also D'Alesio, Murgia, Pisano, Taels, 17

Some studies at EIC

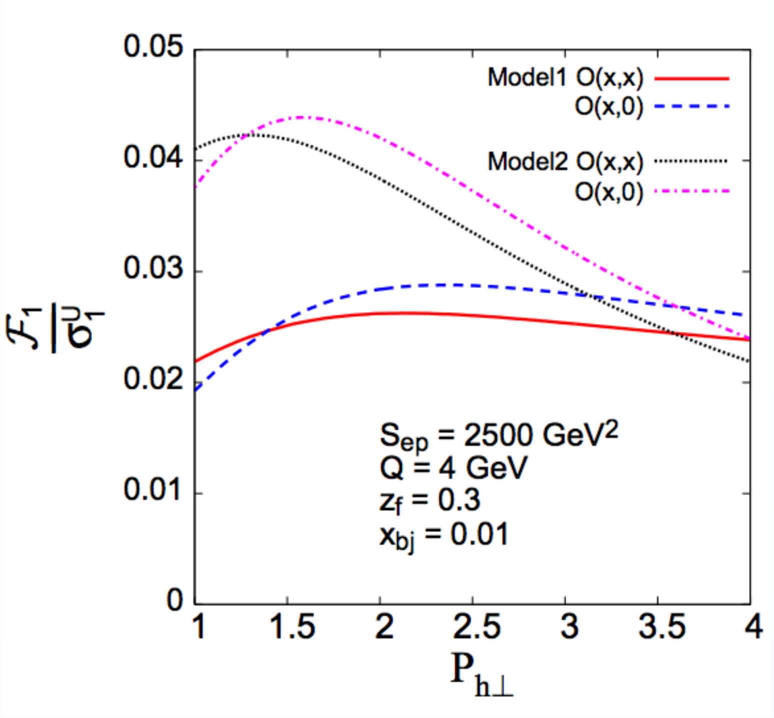
- Similar studies of course can be performed at EIC
  - A recent study J/ψ production at transversely polarized e+p collisions

Godbole, Kaushik, Misra, Rawoot, PRD, 14



Open heavy flavor at EIC

- Similar study for open heavy flavor production at EIC: Sivers asymmetry



Beppu, Koike, Tanaka, Yoshida, PRD, 12
See also Kang, Qiu, PRD, 08

- Key: we have almost no information about gluon Sivers function due to limited data, these measurements could provide for the first time such distribution, and thus enable a 3D gluon tomography of nucleon

Summary

- Heavy flavor production (both open heavy flavor and quarkonium) remains to be one of the most exciting topics in QCD

- While making great/steady progress, new opportunities arrive from the LHC
  - Particle distribution and polarization inside jets
  - Probing hadronization at a more differential level, thus more powerful in constraining theory/model

- Heavy flavor production is sensitive to polarized gluon distribution (both longitudinal and transverse), and provide unique information about gluon spin contribution and correlations
  - Both are key ingredients for an EIC

- Looking forward to the exciting experimental data in the future

Summary

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Thank you!