Production and Hadronization of Event engineering Quarkonium and Open Heavy Flavor in High Multiplicity p+p and p+A collisions

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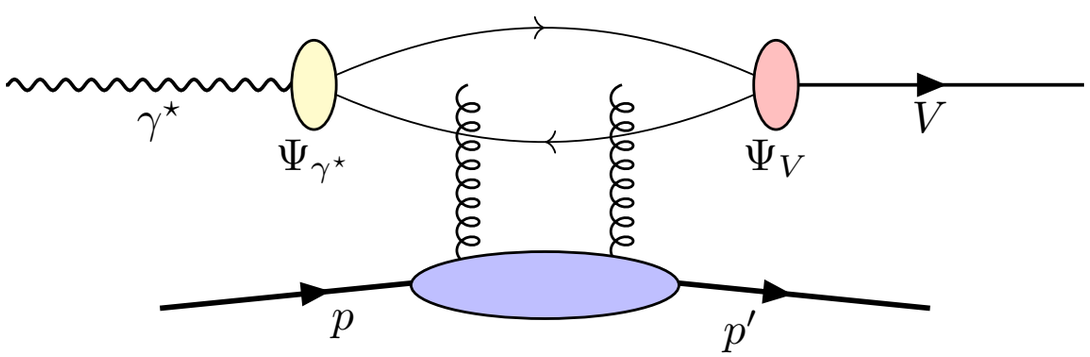
1803.11093 [hep-ph]

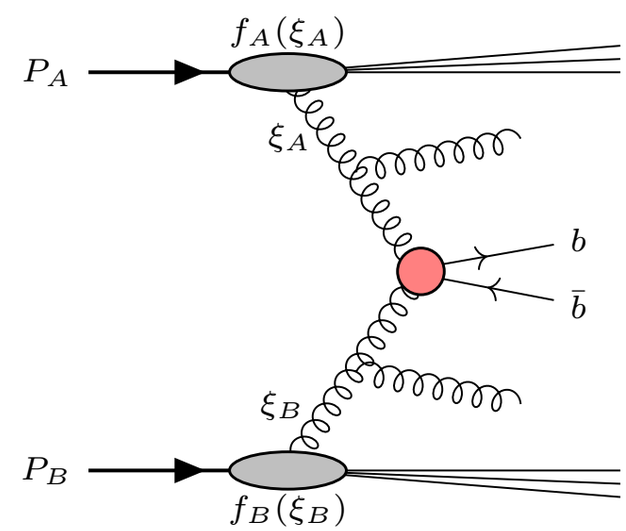
Why Heavy Quarks?

- Produced at short distance since $m \gg \Lambda_{\rm QCD}$
  →pQCD may work even at low $p_\perp$.

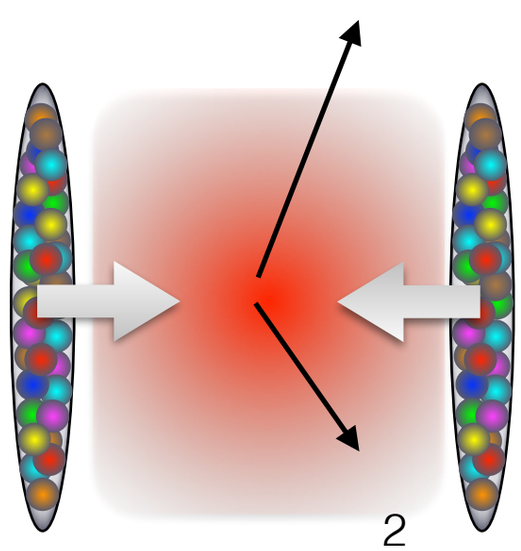
- Rare but Beneficial probe to investigate (i) hadron structure and (ii) parton/hadronic medium.



GPD



TMD

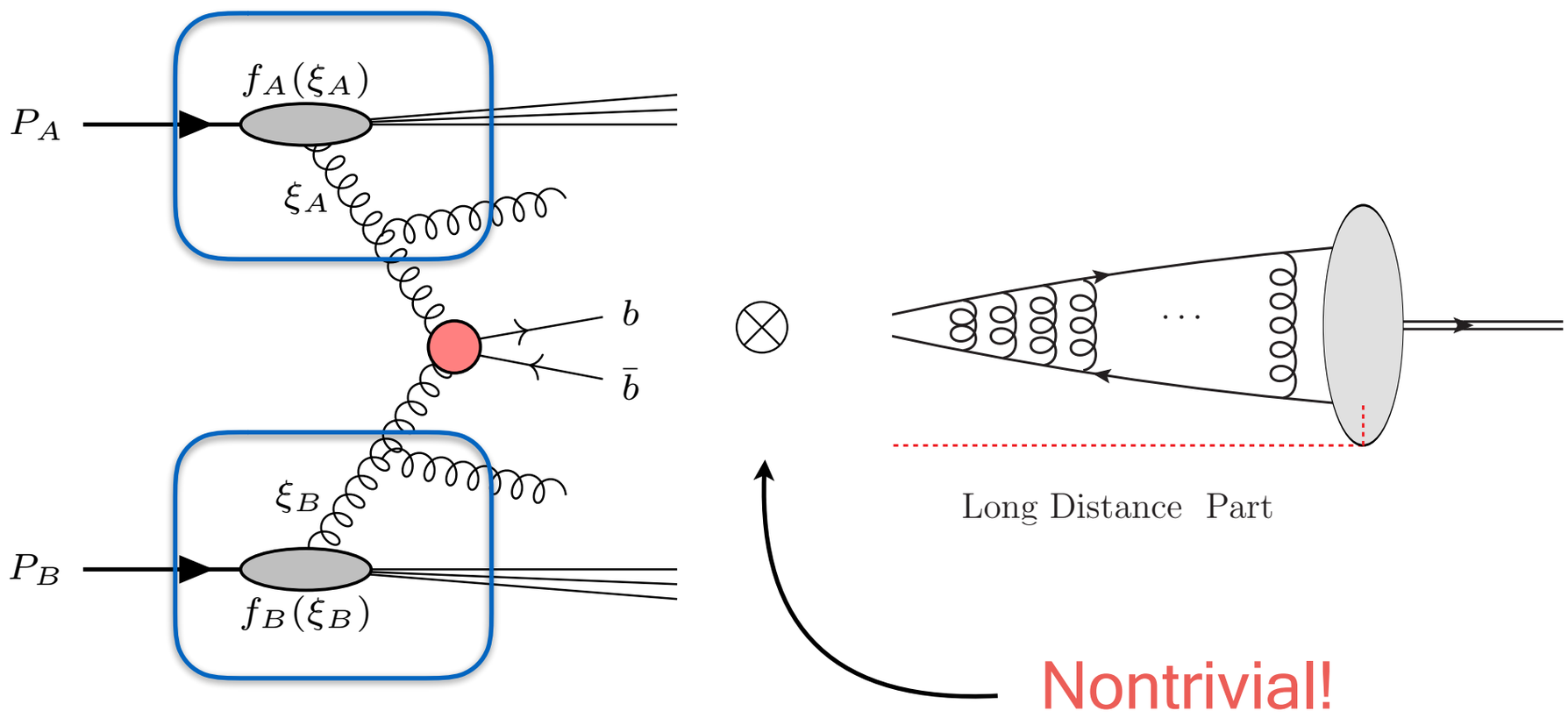


QGP

A challenge to QCD

- Quarkonium is an interesting probe, but, its production mechanism is poorly understood yet since the November Revolution.

- Difficulty: QQbar is a colored object and bound state.



Modern approaches

- Color Singlet Model (CSM) (v=0)

- Color Evaporation Model (CEM)

Transition Prob.

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = \boxed{F_{c\bar{c}\to\psi}} \int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM d^2p_\perp dy}$$

- Improved CEM

Ma, Vogt, PRD94 (2016)

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = \boxed{F_{c\bar{c}\to\psi}} \int_{m_\psi}^{2m_D} dM \left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{c\bar{c}}}{dM d^2p'_\perp dy}\Bigg|_{\boxed{p'_\perp = \frac{M}{m_\psi} p_\perp}}$$

Gluon radiation during hadronization

- Non-Relativistic QCD (NRQCD)

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = \sum_\kappa \frac{d\hat{\sigma}^\kappa_{c\bar{c}}}{d^2p_\perp dy} \boxed{\langle \mathcal{O}^\psi_\kappa \rangle}$$

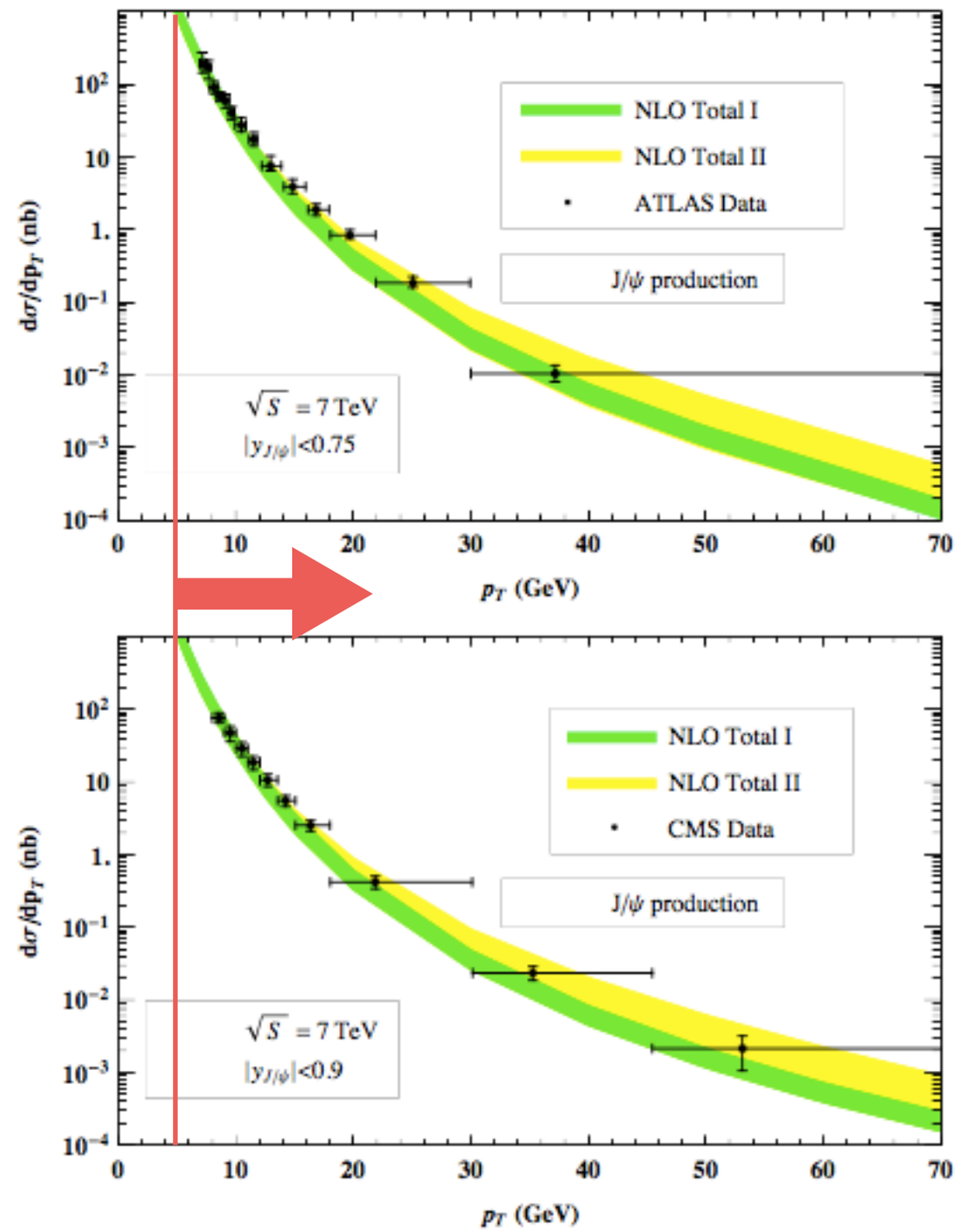
LDMEs

α_s, v expansion

Note: pQCD Fragmentation is beyond this talk.

Success in NRQCD at NLO

- Long Distance Matrix Elements are obtained by fitting Tevatron data at large $p_\perp$.
- Fixed order calculation works down to $p_\perp \sim 5\mathrm{GeV}$ (pt $\sim$ M).
- Understanding of low pt onium production is essential for many researches around JLab!



Chao, Ma, Shao, Wang and Zhang, PRL108 (2012)

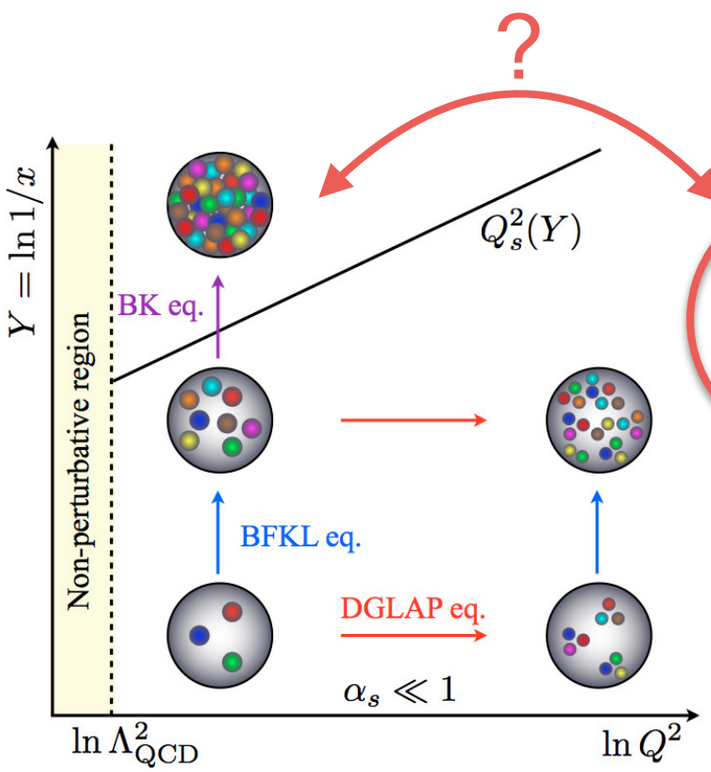
TMD (kt-factorization) approach

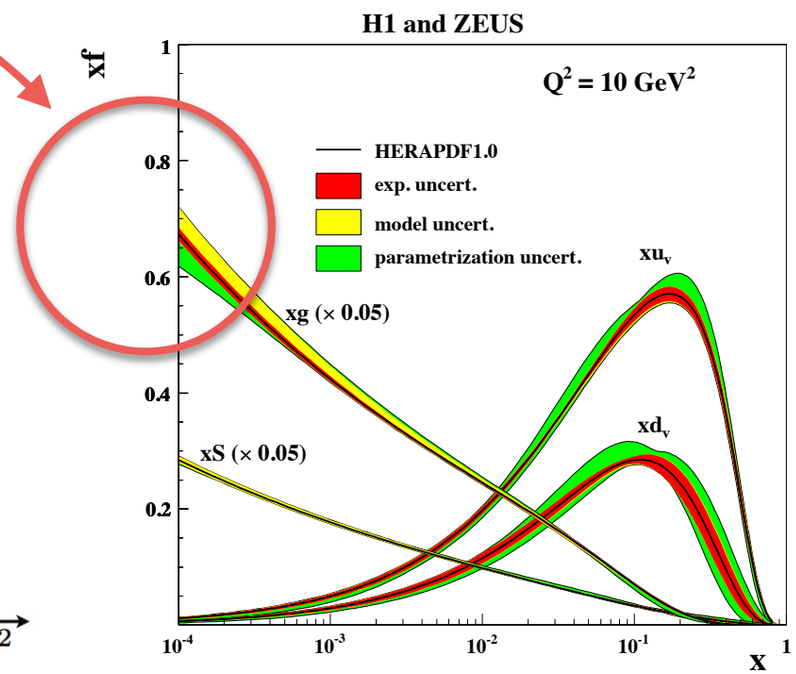
- Collins-Soper-Sterman formalism
- Transverse Momentum Dependent PDFs
- Single logs + Double logs
- DGLAP and Collins-Soper LINEAR evolution eqs.

- Color-Glass-Condensate (CGC) Effective Theory
- Transverse Momentum Dependent Gluon PDF
- Single logs (ln1/x)
- JIMWLK or BK NONLINEAR evolution eq.
- Hybrid formula includes DGLAP evolution.

The CGC ET describes Onium and Open heavy flavor production at low pt ?

Gluon Saturation

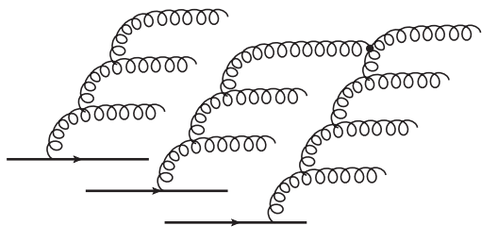




Gribov, Levin, Ryskin (1983)

Mueller, Qiu (1986)

Non-Linear gluon interaction can give rise to a saturation of gluon density at small-x.



Nonlinear Balitsky-Kovchegov eq.

$$-\frac{dD_{Y,r_\perp}}{dY} = \int d^2 r_{1\perp} \mathcal{K}(r_\perp, r_{1\perp}) \left[D_{Y,r_\perp} - D_{Y,r_{1\perp}} D_{Y,r_{2\perp}} \right]$$

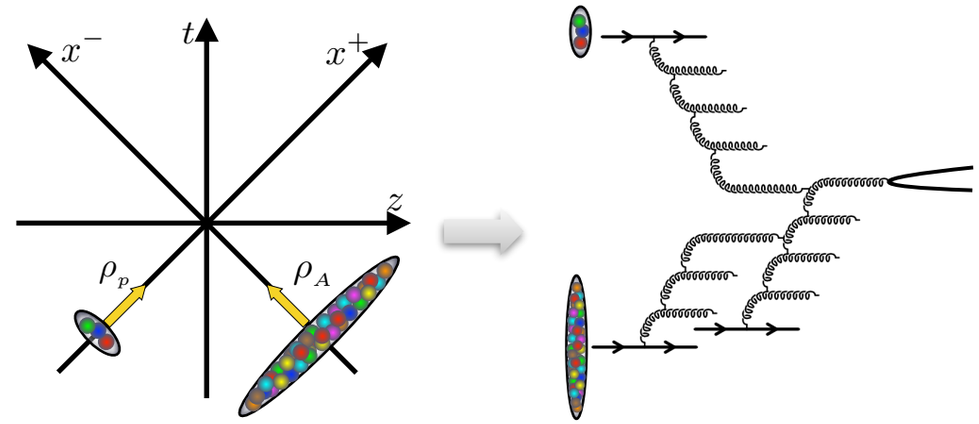
Semi-hard scale $Q_s^2 \propto A^{1/3} x^{-\lambda}$

High energy hadron/nucleus contains many gluons, that behave like classical.

The CGC framework

$$J^\nu = g\delta^{\nu+}\delta(x^-)\rho_p(x_\perp) + g\delta^{\nu-}\delta(x^+)\rho_A(x_\perp)$$

CYM eq. $[D_\mu, F^{\mu\nu}] = J^\nu$

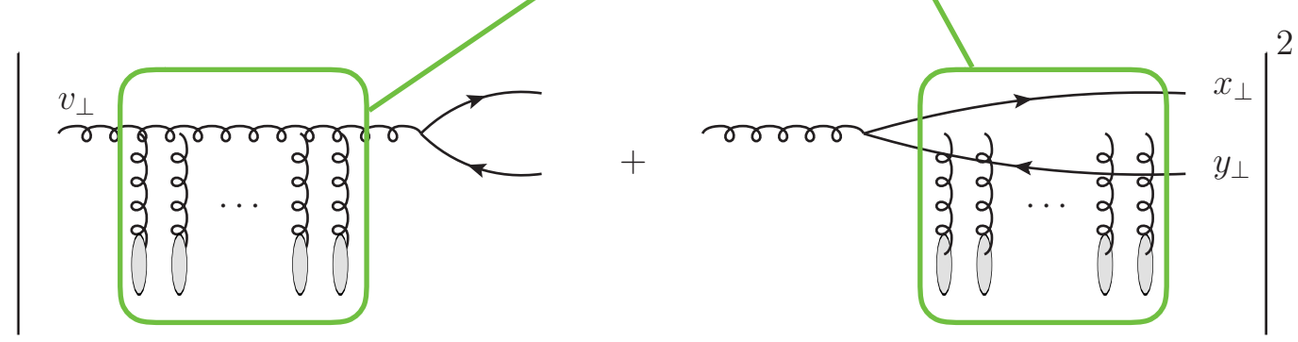


Background Gauge Field at Large-x
+ Small-x modes via BK eq.

$$\frac{d\sigma_{Q\bar{Q}}}{d^2p_{Q\perp}d^2q_{\bar{Q}\perp}dy_Q dy_{\bar{Q}}} = \frac{\alpha_s N_c^2 S_\perp}{2(2\pi)^{10}d_A}\int_{k_{2\perp},k_\perp}\frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(k_\perp)\mathcal{N}_Y(k_{2\perp}-k_\perp)\,\Xi$$

UGDF

Blaizot, Gelis and Venugopalan, NPA743 (2004)



Wilson lines in the Eikonal approximation

Note on CGC+NRQCD

$$\frac{d\sigma^{\psi}}{dydp_{\perp}^{2}} = \sum_{\kappa} \frac{d\hat{\sigma}_{c\bar{c}}^{\kappa}}{dydp_{\perp}^{2}} \times \left\langle \mathcal{O}_{\kappa}^{\psi} \right\rangle$$

$$\frac{d\sigma_{c\bar{c},\mathrm{CS}}^{\kappa}}{d^{2}p_{\perp}dy} = \frac{\alpha_{s}\pi R_{A}^{2}}{(2\pi)^{9}d_{A}} \int_{k_{2\perp},k_{\perp},k'_{\perp}} \frac{\varphi_{p,y_{p}}(k_{1\perp})}{k_{1\perp}^{2}} \mathcal{N}_{Y}(k_{\perp})\mathcal{N}_{Y}(k'_{\perp})\mathcal{N}_{Y}(k_{2\perp}-k_{\perp}-k'_{\perp})\, \mathcal{G}_{1}^{\kappa}$$

$$\frac{d\sigma_{c\bar{c},\mathrm{CO}}^{\kappa}}{d^{2}p_{\perp}dy} = \frac{\alpha_{s}\pi R_{A}^{2}}{(2\pi)^{7}d_{A}} \int_{k_{2\perp},k_{\perp}} \frac{\varphi_{p,y_{p}}(k_{1\perp})}{k_{1\perp}^{2}} \mathcal{N}_{Y}(k_{\perp})\mathcal{N}_{Y}(k_{2\perp}-k_{\perp})\, \Gamma_{8}^{\kappa}$$

CS channel probes the quadrupole amplitude. However, thanks to large-Nc approximation and quasi-classical approximation, the quadrupole amplitude is simply cubic in N_Y.

[Dominguez, Kharzeev, Levin, Mueller, Tuchin, PLB710,(2012)]

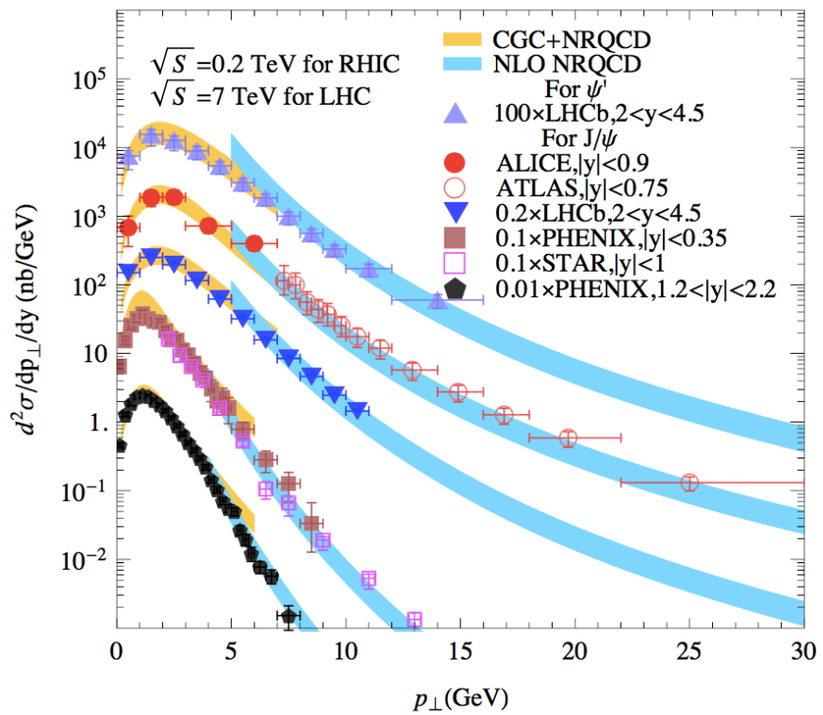
Event Engineering

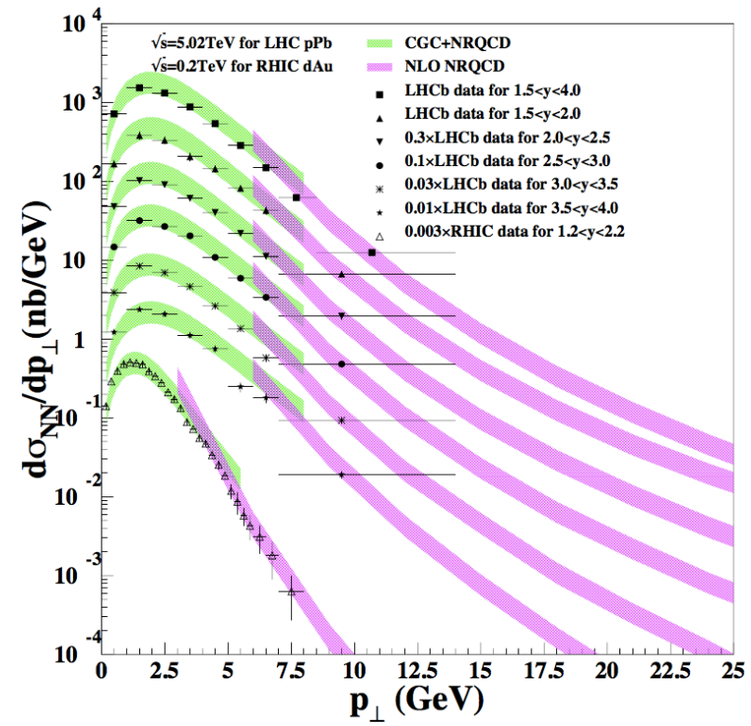
Varying $\sqrt{s},\ p_\perp,\ m,\ A$

Ma, Venugopalan (2014), and Zhang (2015)

Fujii, KW (2015), …

J/psi





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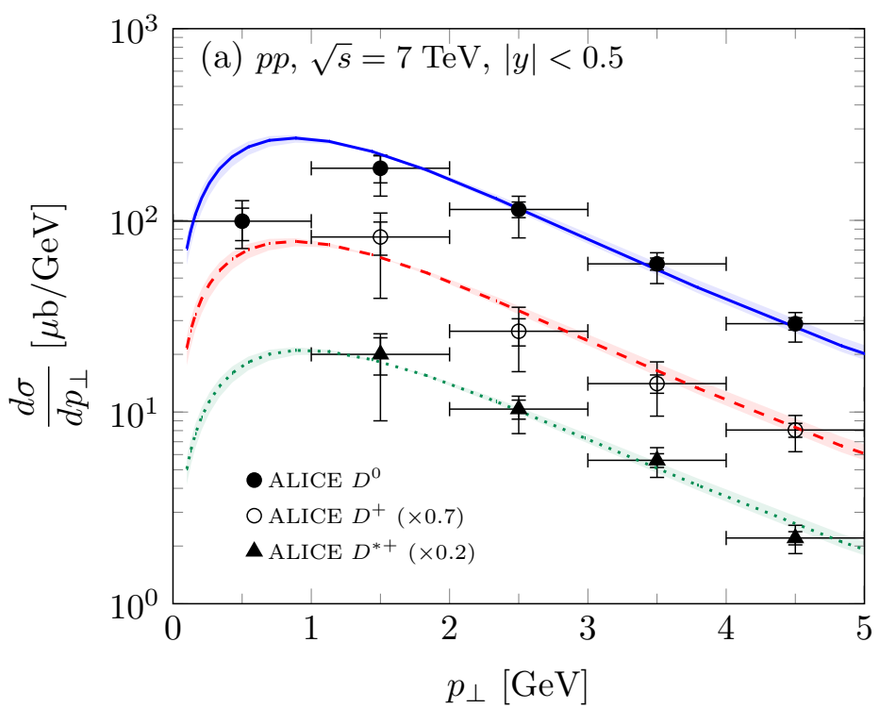
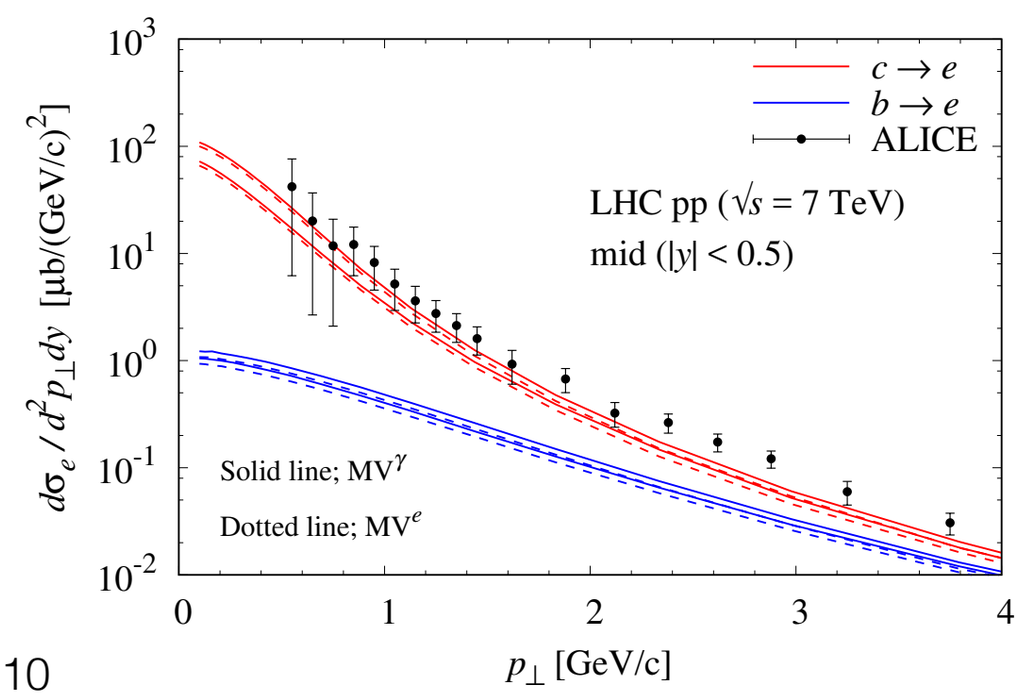
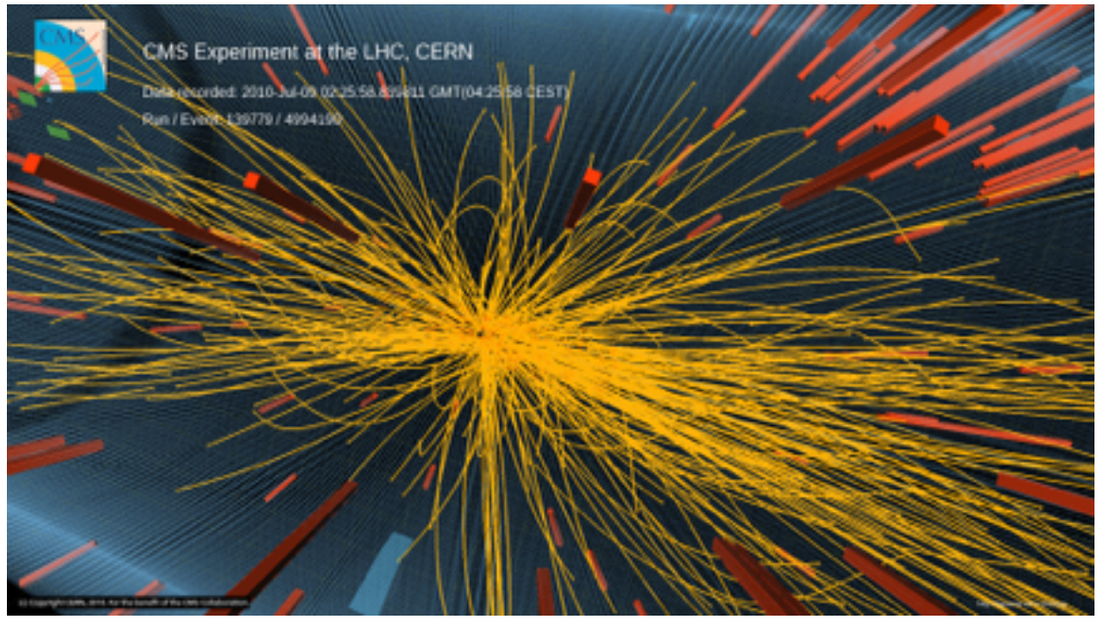
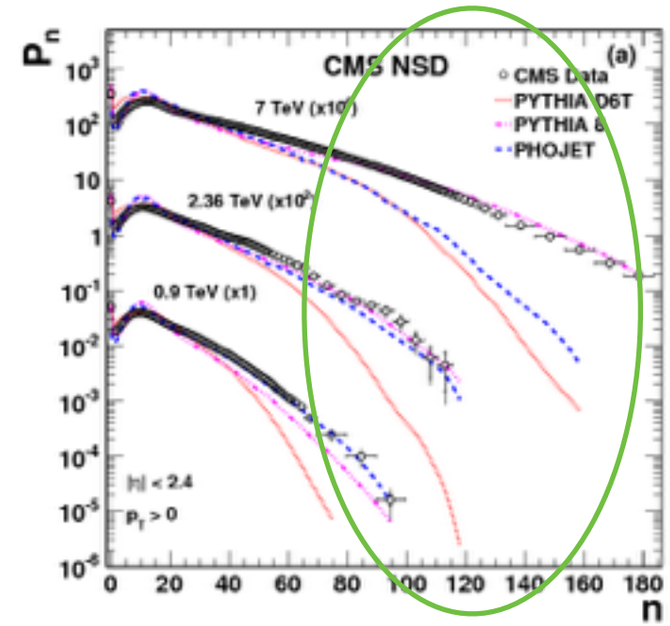




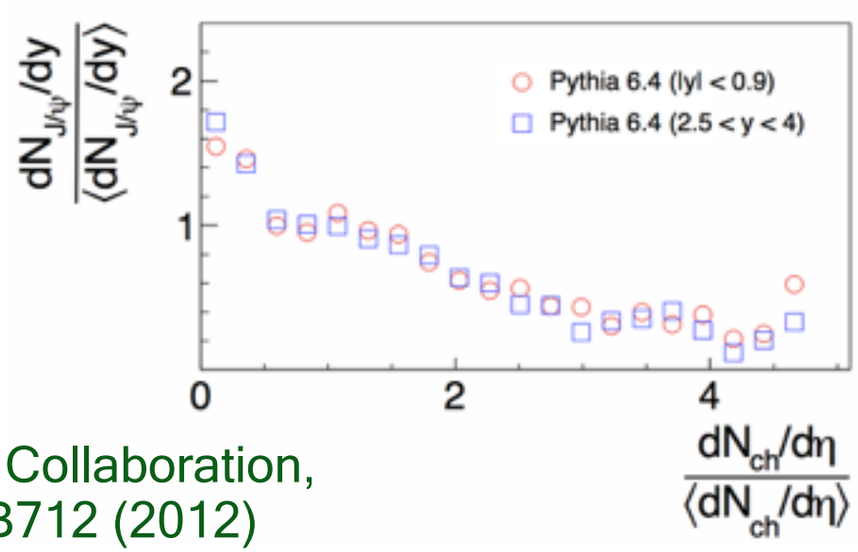
High Multiplicity Events



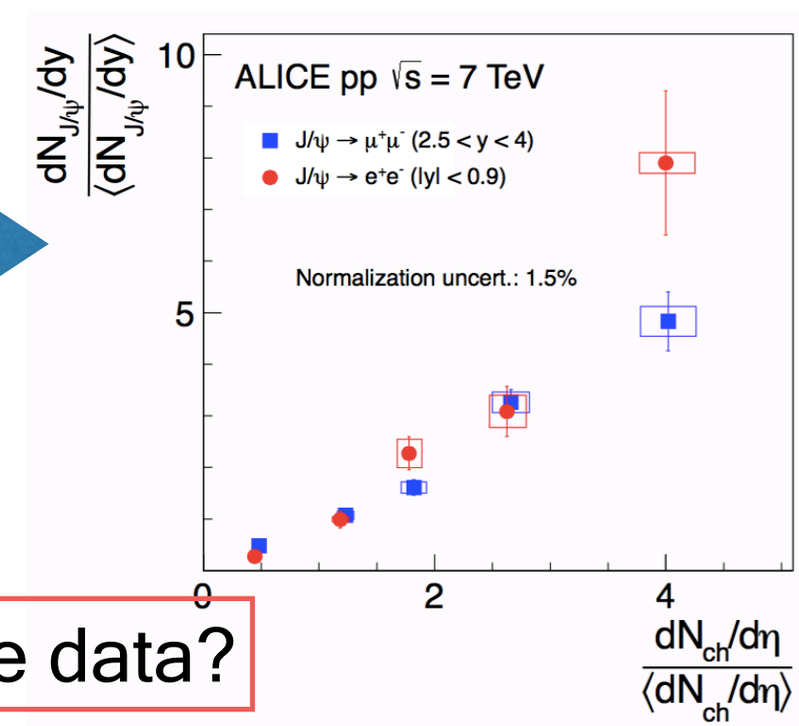


$$P_{\mathrm{MB}} \gg P_{\mathrm{HM}}$$

Extreme Rare!



ALICE Collaboration, PLB712 (2012)

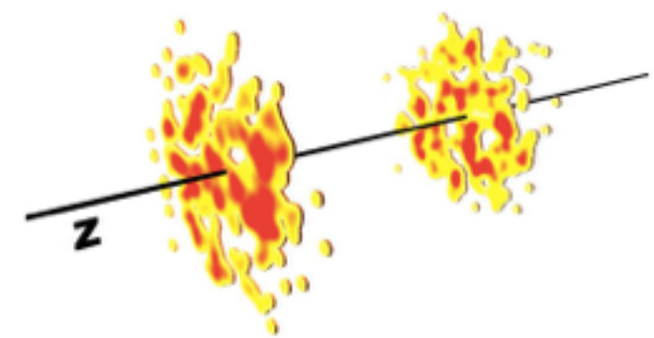


What do we need to describe data?

Quantum Fluctuation

At extreme high energy, gluon field behaves like classical: Small coupling constant and gluon nonlinear interaction. ↔ $A \sim 1/g$

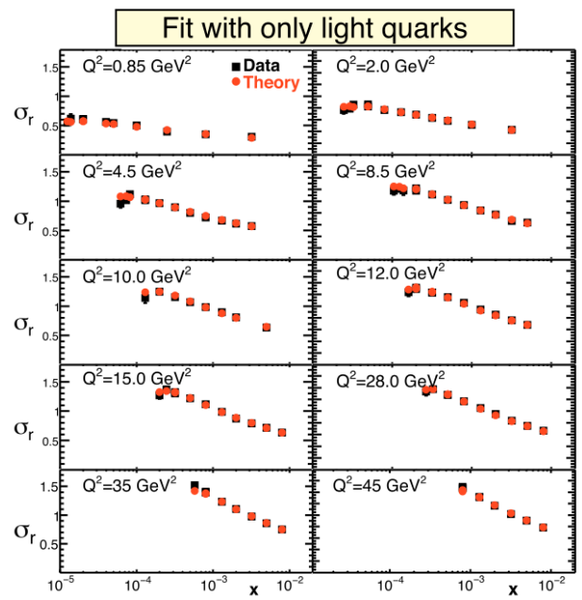
$$\frac{dN_{ch}}{d^2b_\perp d^2k_\perp dy} \sim \langle AA \rangle \sim \frac{f(k_\perp/Q_s)}{\alpha_s} \Rightarrow \frac{dN_{ch}}{dy} \sim \frac{S_\perp Q_s^2}{\alpha_s}$$



- If S_perp is fixed, Qs can controls Nch.
- Qs depends on impact parameter (b).
- Spacial configurations of color charge density of parton inside hadron are nonperturbative and complicated.
- IP-Sat Model deals with b-dependent Qs and can model NBD of Nch.

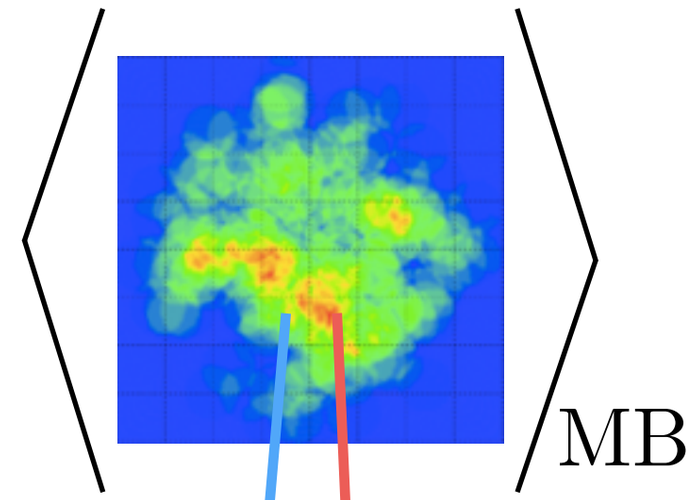
Tribedy, Venugopalan (2011)
Schenke, Tribedy, Venugopalan (2012)

Lumpy Configurations

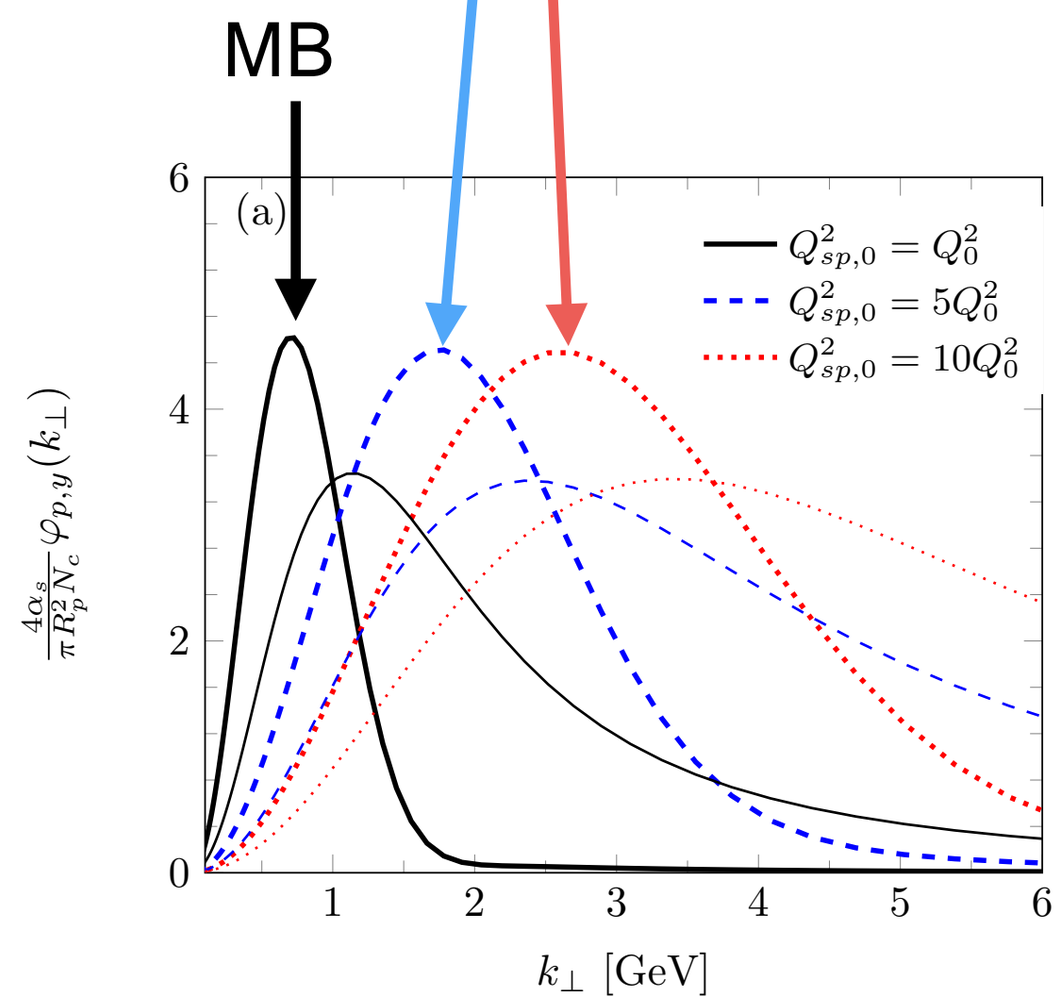


DIS data fitting

at x<0.01



Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, EPJC71 (2011)

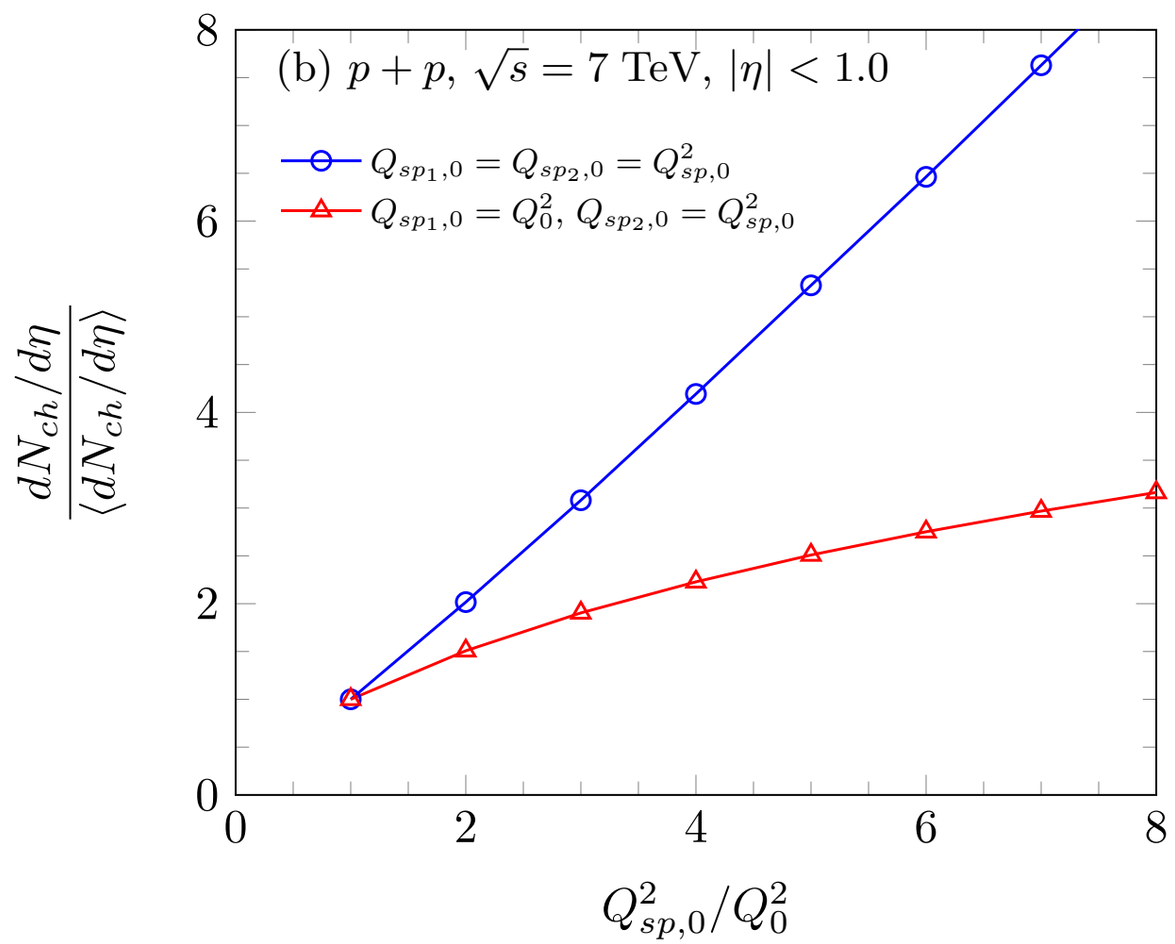


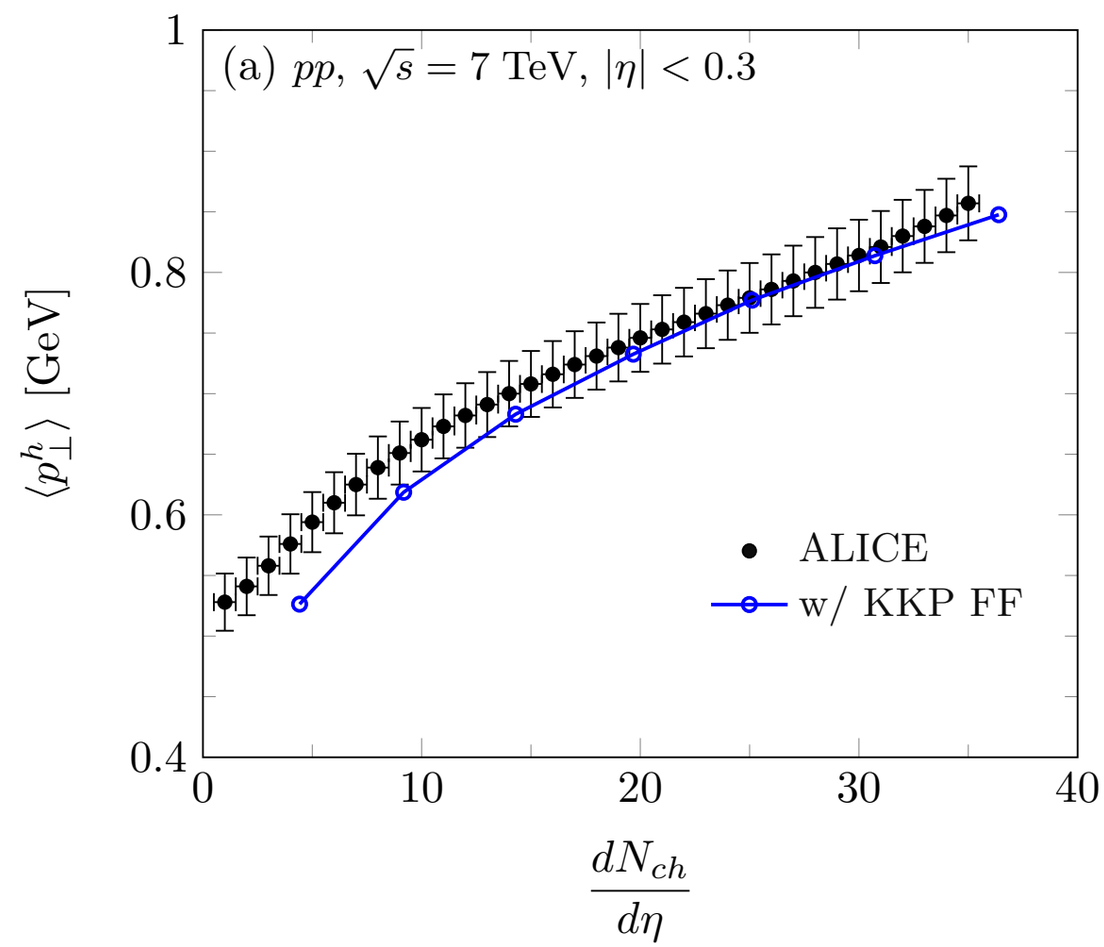
- rcBK evolution should hold Lumpy partons configuration.
  Balitsky, PRD75 (2007)
- Rare Partons Configuration corresponds to large Qs.
- Partons inside nucleus have the same fluctuation effect.

Nch in kt-factorization

$$\frac{d\sigma_g}{d^2p_{g\perp}dy} = \frac{\alpha_s \hat{K}_b}{(2\pi)^3\pi^3 C_F}\int \frac{d^2k_\perp}{p_{g\perp}^2}\varphi_{p,y_p}(k_\perp)\varphi_{A,Y}(p_{g\perp}-k_\perp)$$

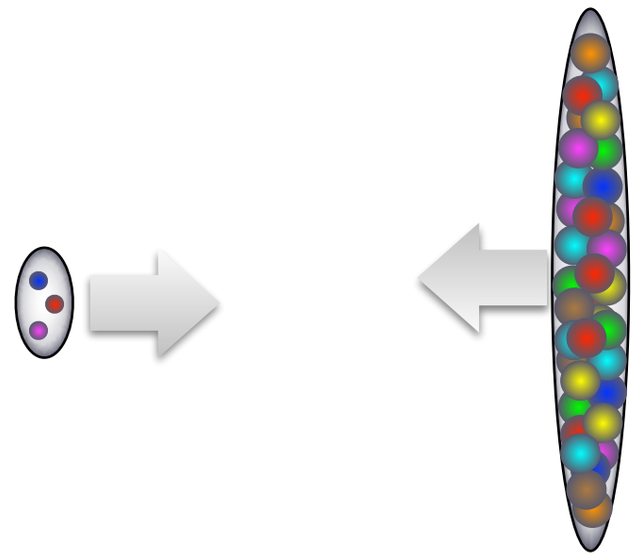
$$\frac{dN_{ch}}{d\eta} = \frac{\hat{K}_{ch}}{\sigma_{\rm inel}}\int d^2p_\perp \int_{z_{\rm min}}^{1} dz \frac{D_h(z)}{z^2} J_{y\to\eta}\frac{d\sigma_g}{d^2p_{g\perp}dy}$$



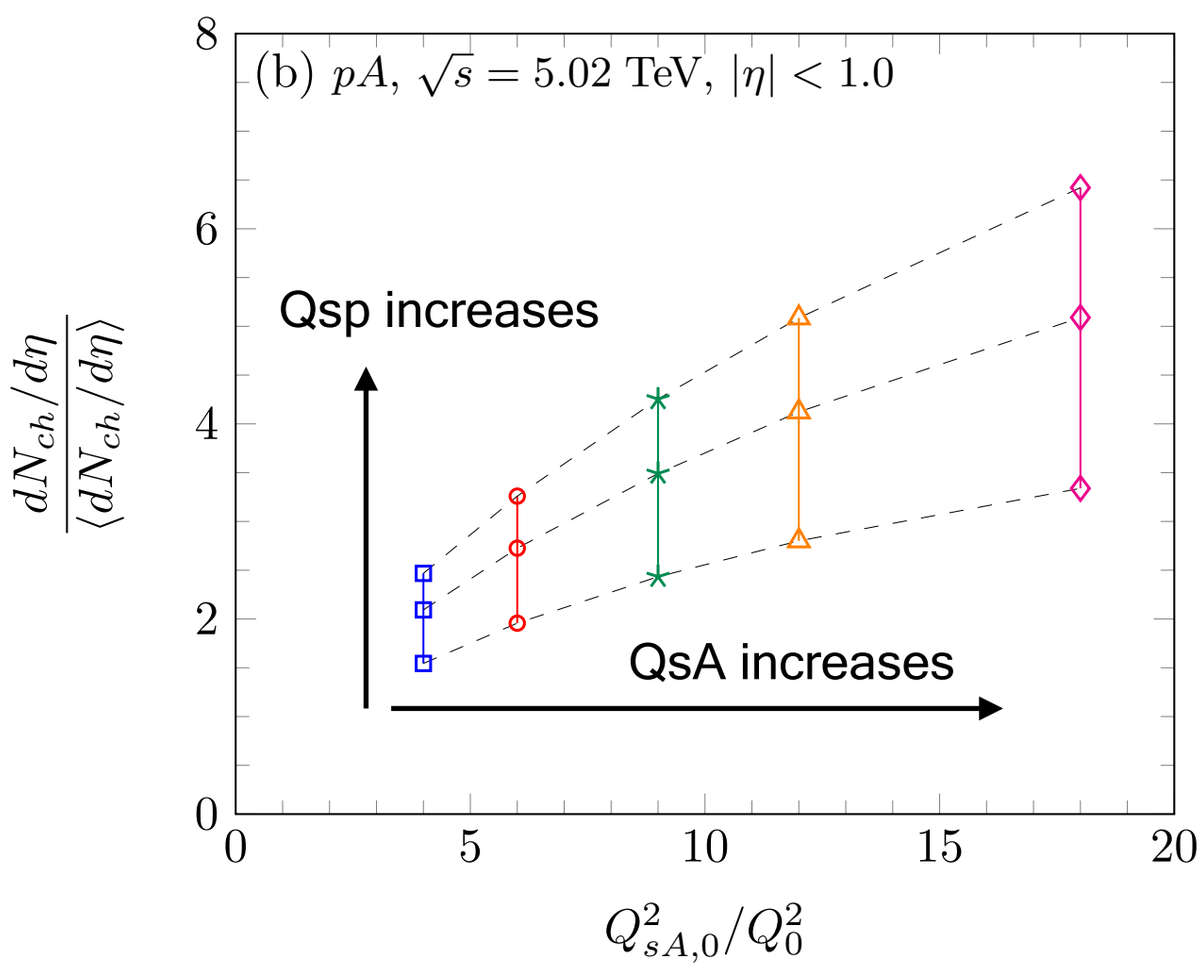


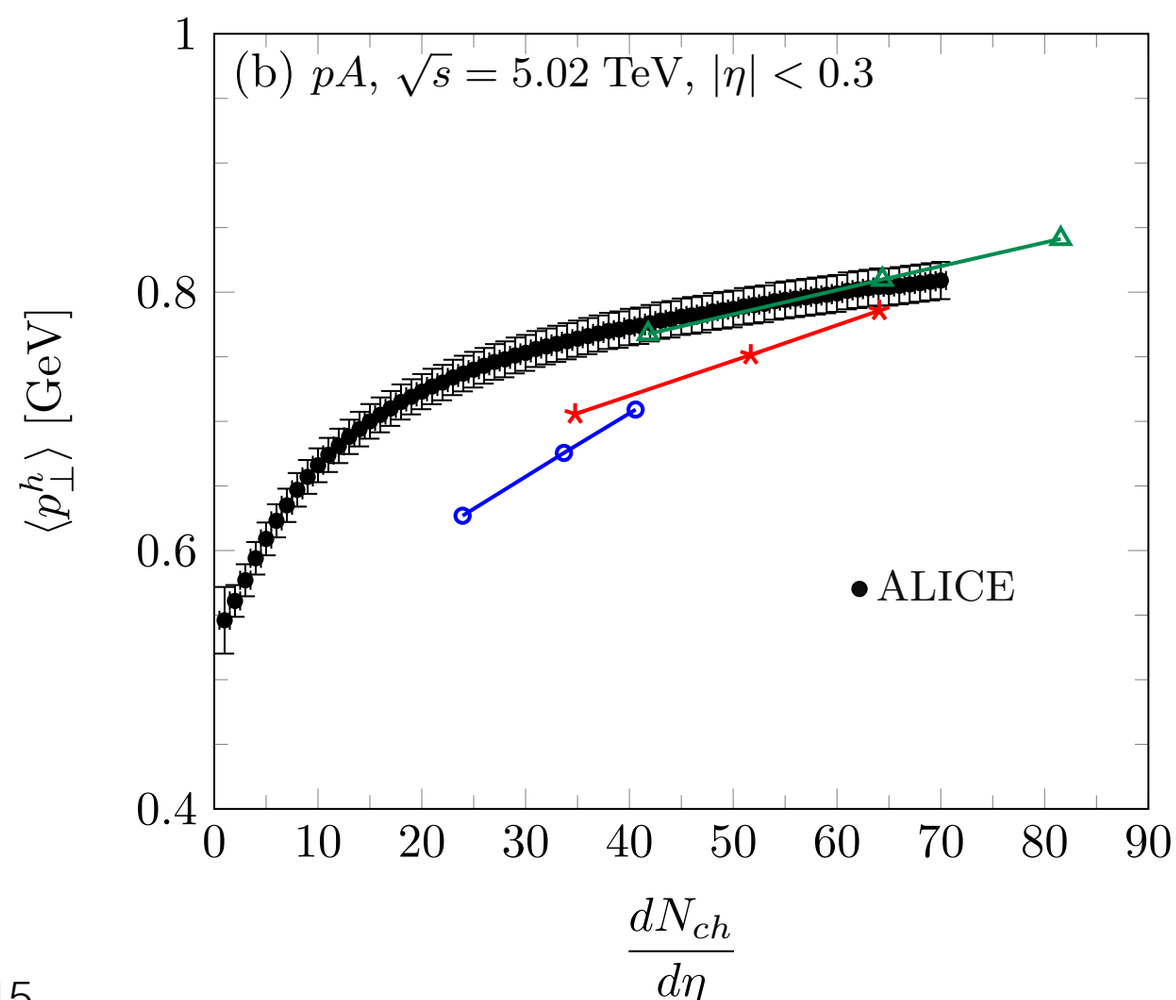
p+A system

Q^2_{sp}



$Q^2_{sA} \gtrsim Q^2_{sp}$



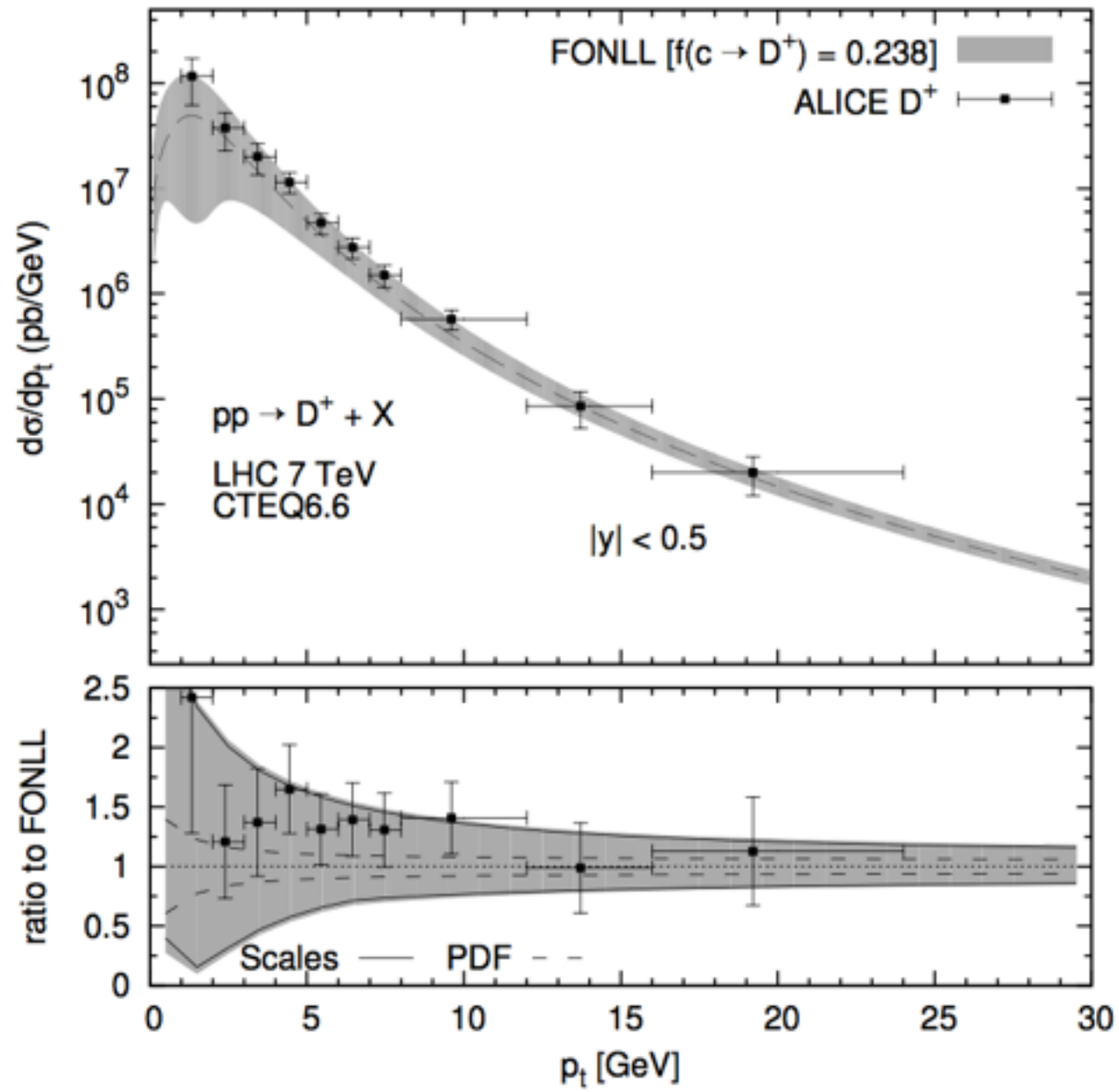


D-meson at collider energies

- FONLL (Fixed Order + Next-to-Leading Log) is the state of the arts framework.

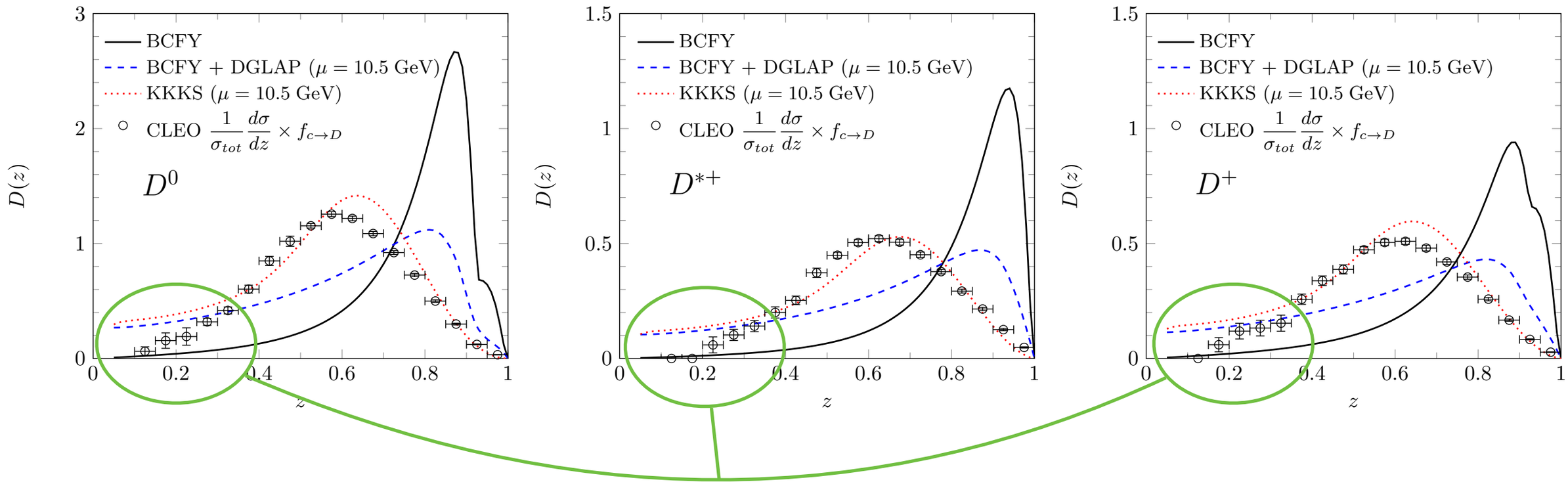
- BCFY FF is employed. NO QCD evolution and single parameter controls the FF.

  Braaten, Cheung, Fleming, Yuan, PRD51 (1995)



Cacciari, Frixione, Houdeau, Mangano, Nason, Ridolfi, JHEP1210 (2012)

FFs at B-factory

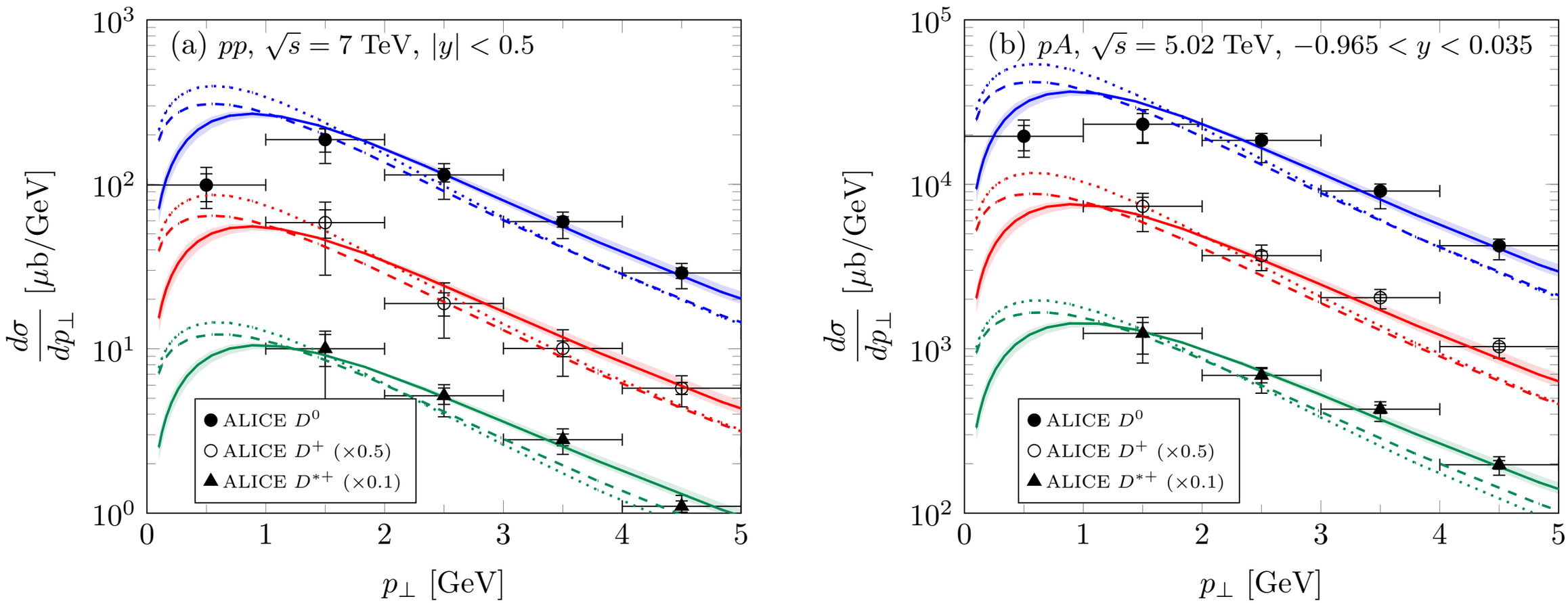


Note the hard part is not involved.

- KKKS set is favored at low energy scale. KKKS = initial functional form+ DGLAP. Kneesch, Kniehl, Kramer, Schienbein, NPB799 (2008)

- DGLAP evolution start at $\mu_0 = m_c \sim 1.5\ \mathrm{GeV}$.

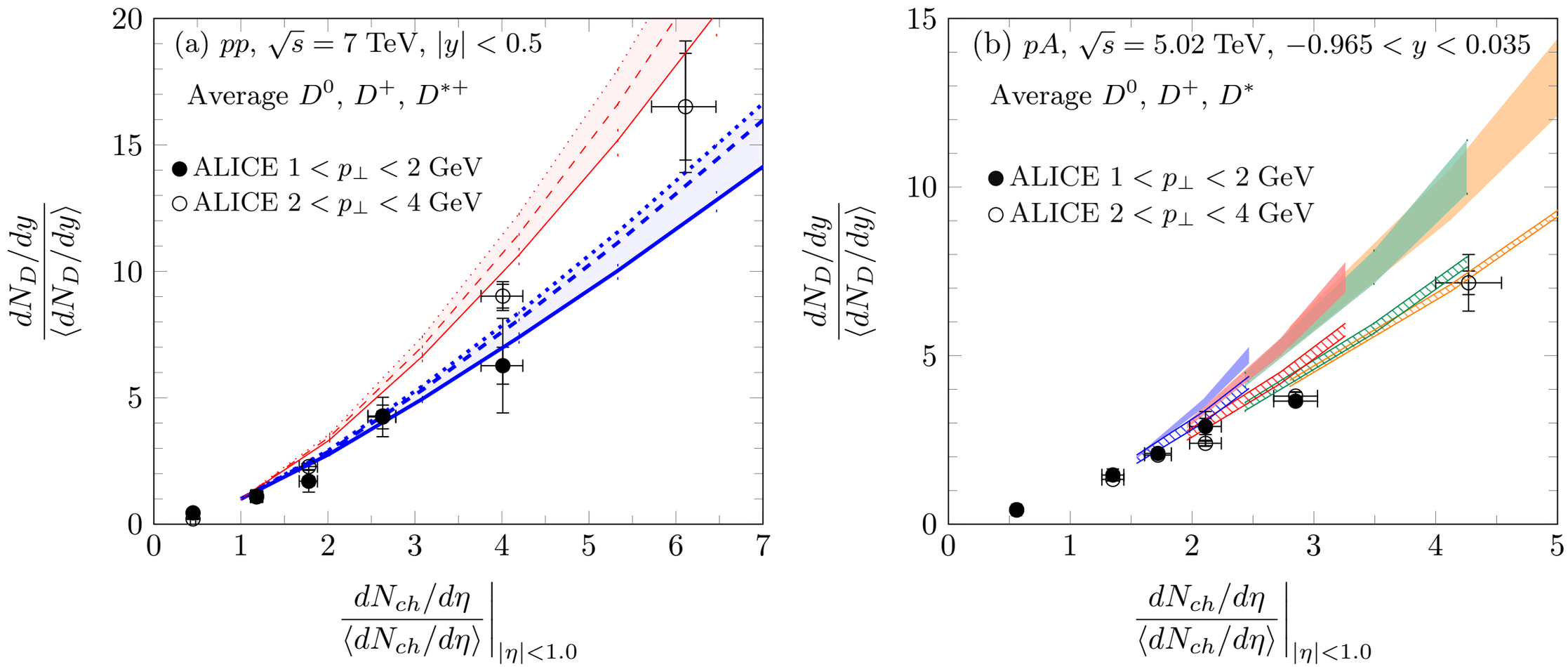
D mesons in MB events



- Solid: BCFY, Dashed: BCFY+DGLAP, Dotted: KKKS
- FF dependence is indistinguishable at $1 < p_\perp < 4$ GeV .

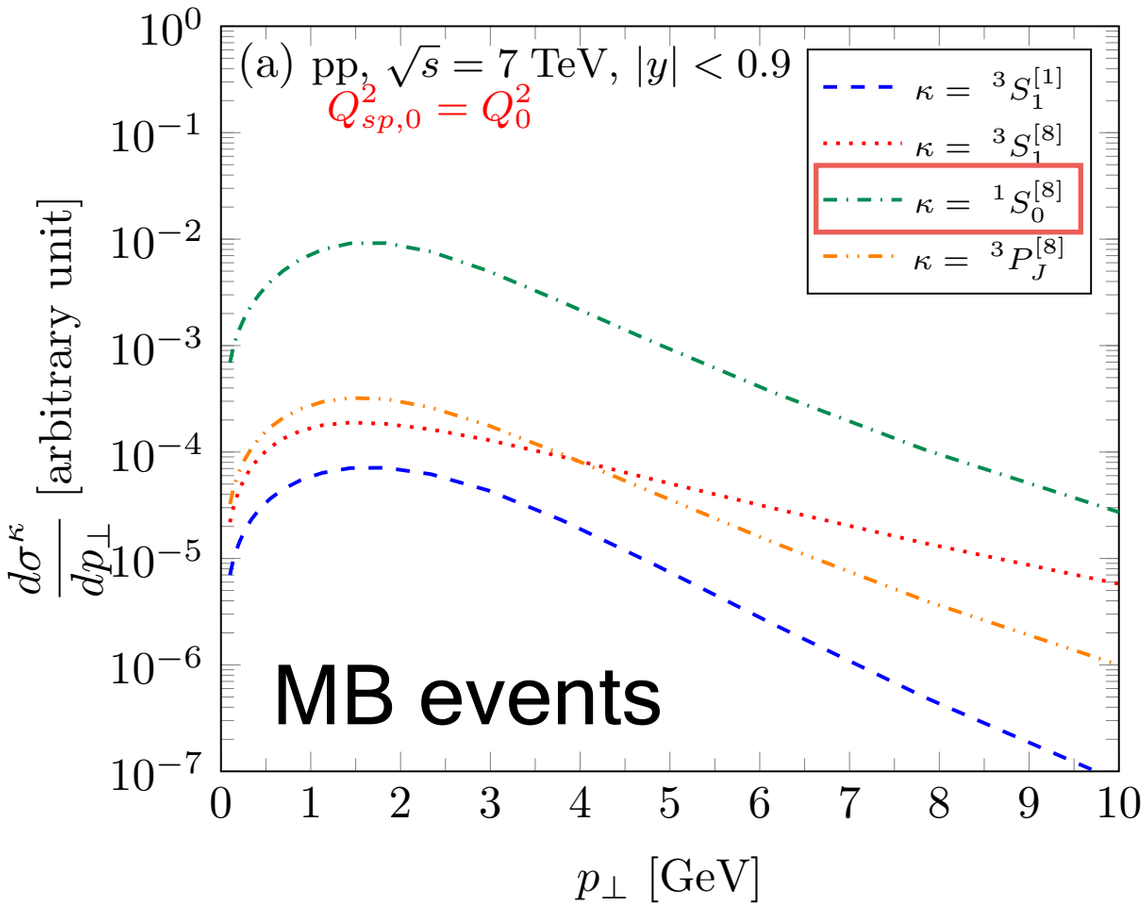
D mesons vs Nch

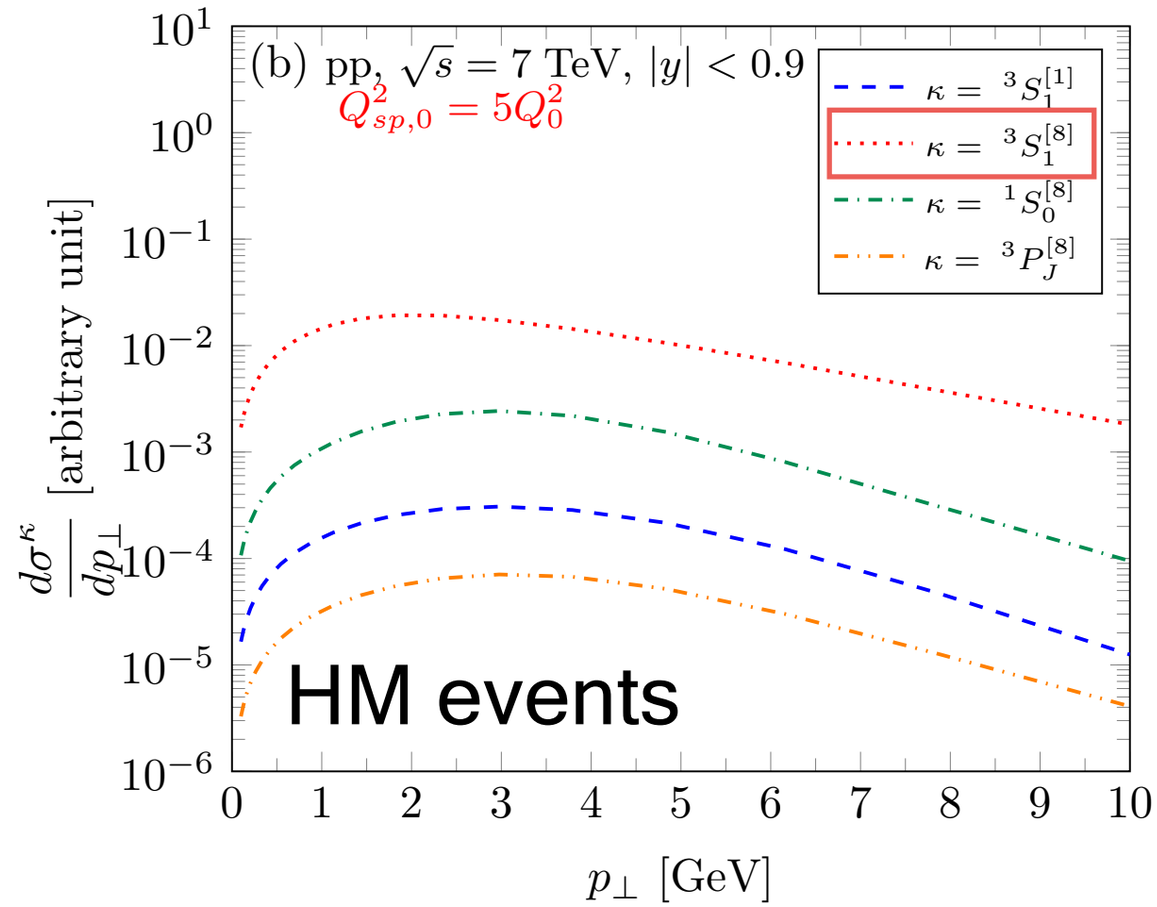
Ma, Venugopalan, Tribedy, KW (2018)



- Systematic uncertainty w.r.t. HF FF increases at large event activity but very nice agreements are found.
- The results in p+p and p+A collisions show the similar trend.

QQbar production in NRQCD





Tevatron data fitting at high pt

$$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}] \rangle = 0.089 \pm 0.0098 \mathrm{GeV}^3$$

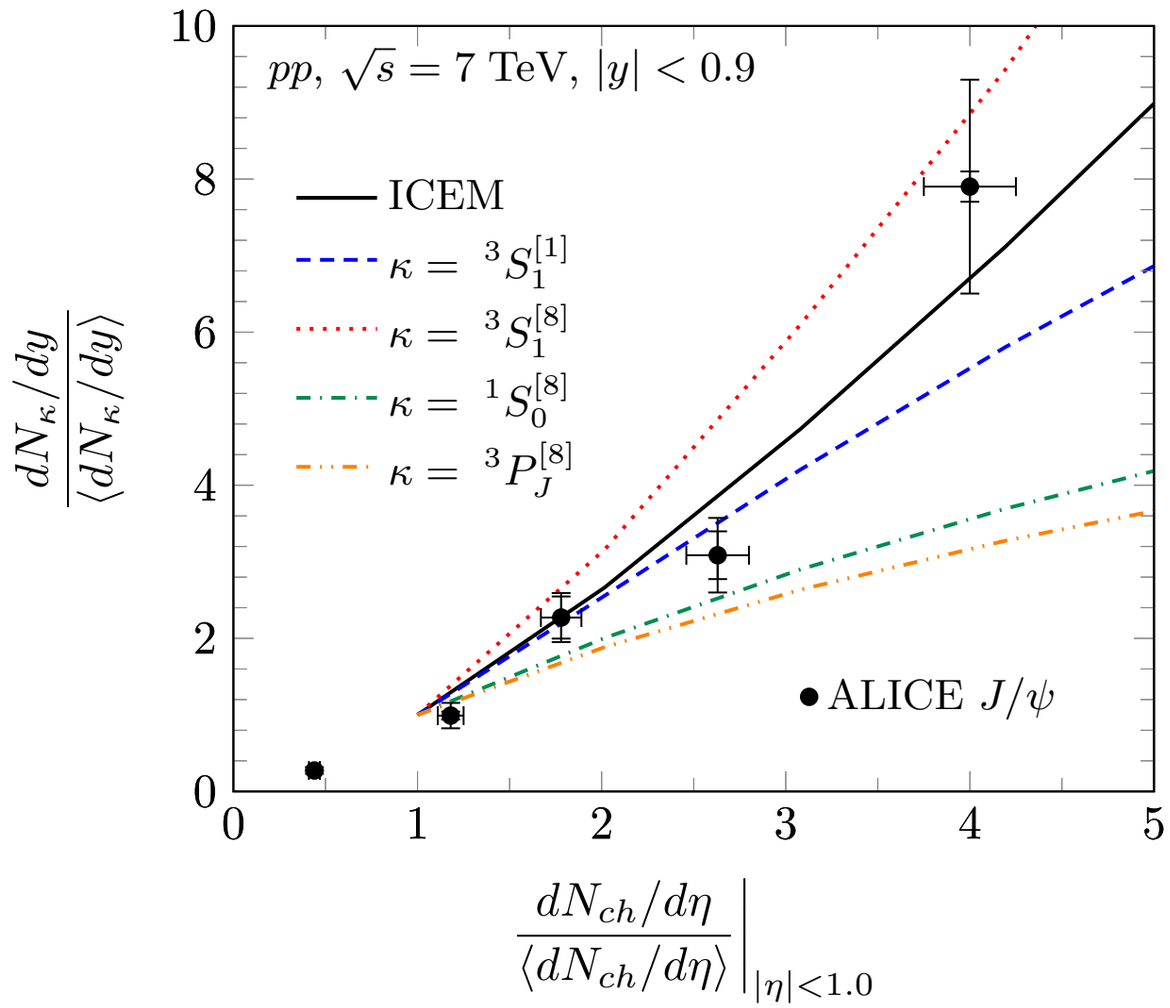
$$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[8]}] \rangle = 0.0030 \pm 0.0012 \mathrm{GeV}^3$$

$$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}] \rangle / m_c^2 = 0.0056 \pm 0.0021 \mathrm{GeV}^3$$

Universal ?

Chao, Ma, Shao, Wang and Zhang, PRL108 (2012)

New constraints on the LDMEs



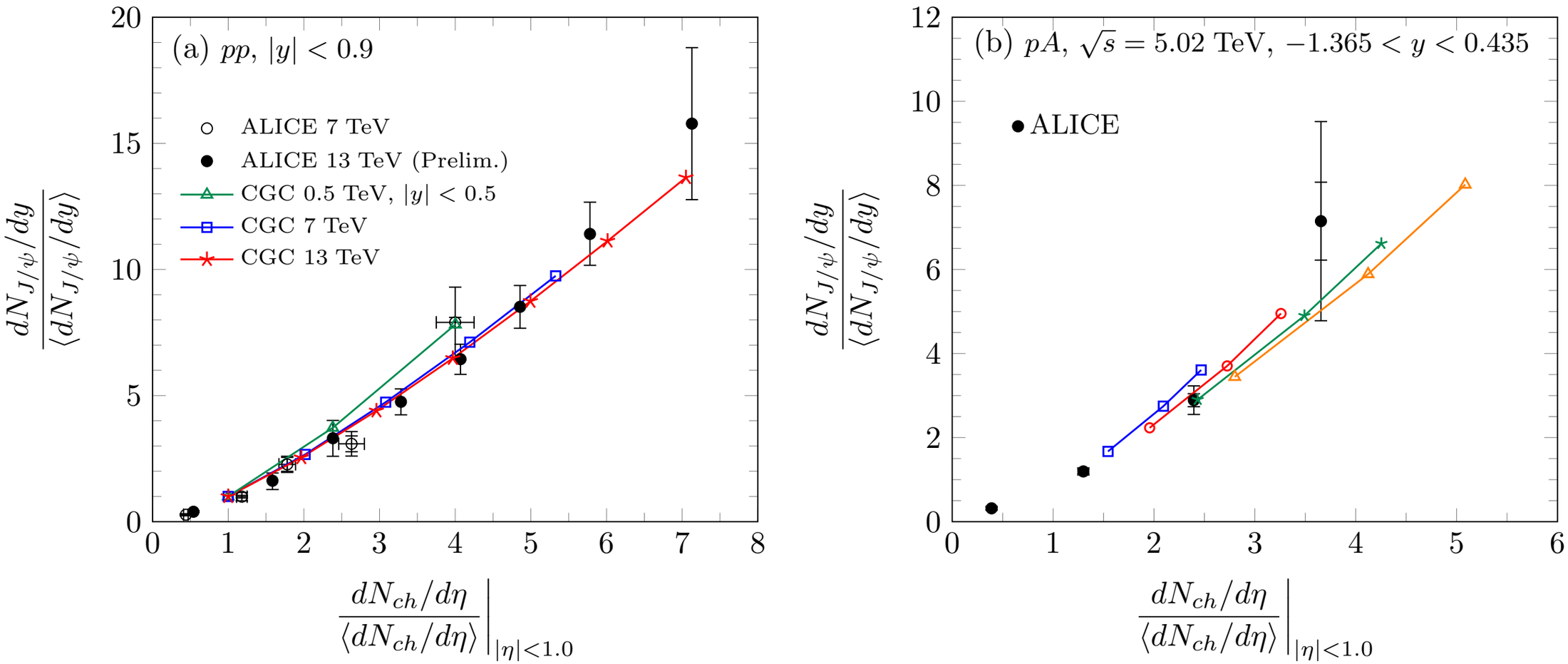
- Consistent with the universality requirement from BELLE e^+e^- data:

$$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle + 4.0\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m^2 < 2.0 \pm 0.6 \times 10^{-2}\mathrm{GeV}^3$$

Zhang, Ma, Wang, Chao, PRD81 (2010)

- Caveat: Tevatron data tell that ${}^1S_0^{[8]}$ has a large weight at high pt.

J/psi vs Nch



- The similar trends are seen for D and J/psi production.
- The saturation effect at short distance plays a key role in describing data.

Summary

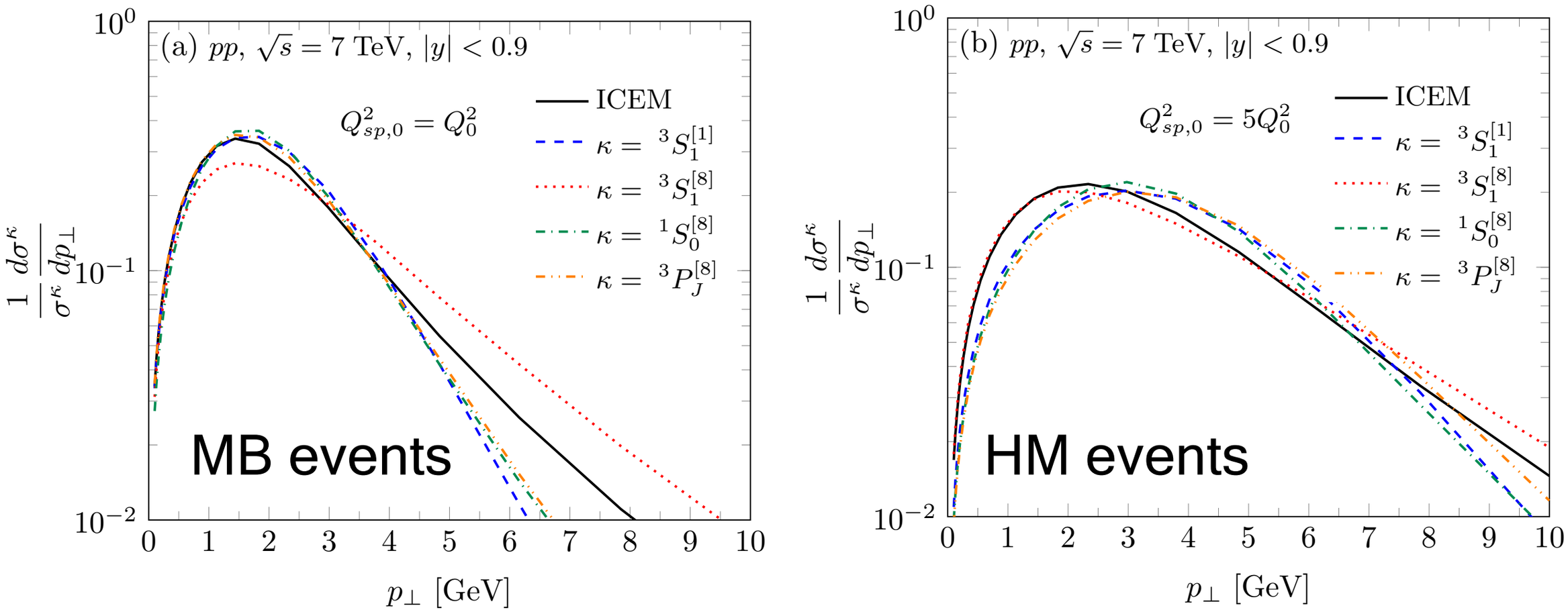
- Rare phenomena in High multiplicity events in p+p and p+A systems require Qs.
- Many nonperturbative uncertainties for D and J/psi cancel and short distance xsection is essential.
- New constraints on the NRQCD LDMEs for J/psi production : $\boxed{{}^1S_0^{[8]}}$ vs $\boxed{{}^3S_1^{[8]}}$

High pt spectrum in pp

1. Total xsection in e+e-
2. HM Events at low pt

Thank you.

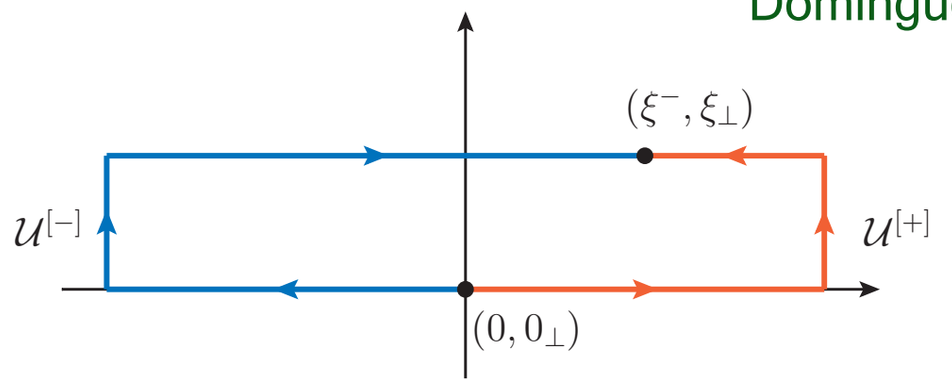
NRQCD vs ICEM



- ICEM captures pt spectrum of the dominant QQbar state in MB and HM events. → Useful reference against NRQCD.

TMDs at small-x

Dominguez, Marquet, Xiao, Yuan (2011)



Weizsacker-Williams gluon PDF (# density of gluon)

$$xG^{(1)}(x, k_\perp) = \int \frac{2d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \left\langle P \left| \mathrm{Tr}\left[F^{+i}(\xi^-, \xi_\perp)\mathcal{U}^{[+]\dagger} F^{+i}(0)\mathcal{U}^{[+]}\right] \right| P \right\rangle$$

Unintegrated dipole gluon PDF (Not clear partonic picture)

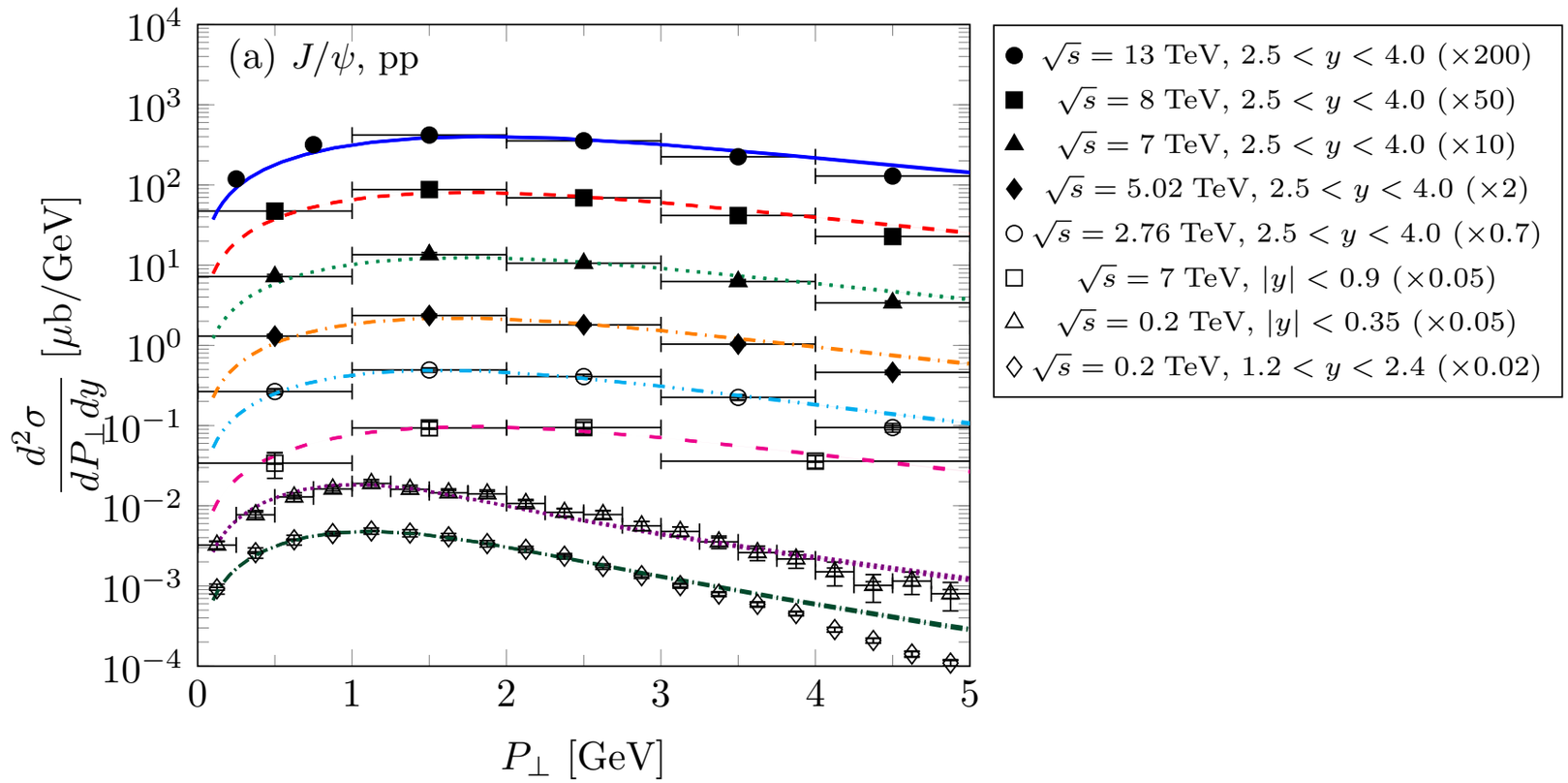
$$xG^{(2)}(x, k_\perp) = \int \frac{2d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \left\langle P \left| \mathrm{Tr}\left[F^{+i}(\xi^-, \xi_\perp)\mathcal{U}^{[-]\dagger} F^{+i}(0)\mathcal{U}^{[+]}\right] \right| P \right\rangle$$

$$\simeq \frac{k_\perp^2 N_c S_\perp}{2\pi^2 \alpha_s} \int \frac{d^2 r_\perp}{(2\pi)^2} e^{-ik_\perp\cdot r_\perp} \boxed{S_{x_g}(r_\perp)}$$

Dipole amplitude

J/psi in ICEM

Ma, Venugopalan, KW, Zhang (2018)



$\sqrt{s}$ [TeV]	y bin	Data points	$F_{J/\psi}$ (1.3)	$\chi^2/d.o.f.$
13	$2.5 < y < 4.0$	7	$5.63\times10^{-3} \pm 3.56\times10^{-4}$	8.7
8	$2.5 < y < 4.0$	6	$5.84\times10^{-3} \pm 3.79\times10^{-4}$	4.3
7	$\|y\| < 0.9$	5	$4.52\times10^{-3} \pm 2.33\times10^{-4}$	0.33
7	$2.5 < y < 4.0$	6	$4.86\times10^{-3} \pm 3.01\times10^{-4}$	5.3
5.02	$2.5 < y < 4.0$	6	$5.26\times10^{-3} \pm 3.35\times10^{-4}$	7.0
2.76	$2.5 < y < 4.0$	6	$5.27\times10^{-3} \pm 1.84\times10^{-4}$	0.88
0.2	$\|y\| < 0.35$	21	$6.36\times10^{-3} \pm 1.94\times10^{-4}$	0.93
0.2	$1.2 < y < 2.4$	24	$1.06\times10^{-2} \pm 1.30\times10^{-4}$	0.35