Theoretical overview of cold nuclear matter effects in quarkonium production in p+A collisions

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1/15/2019, Quarkonia as Tools

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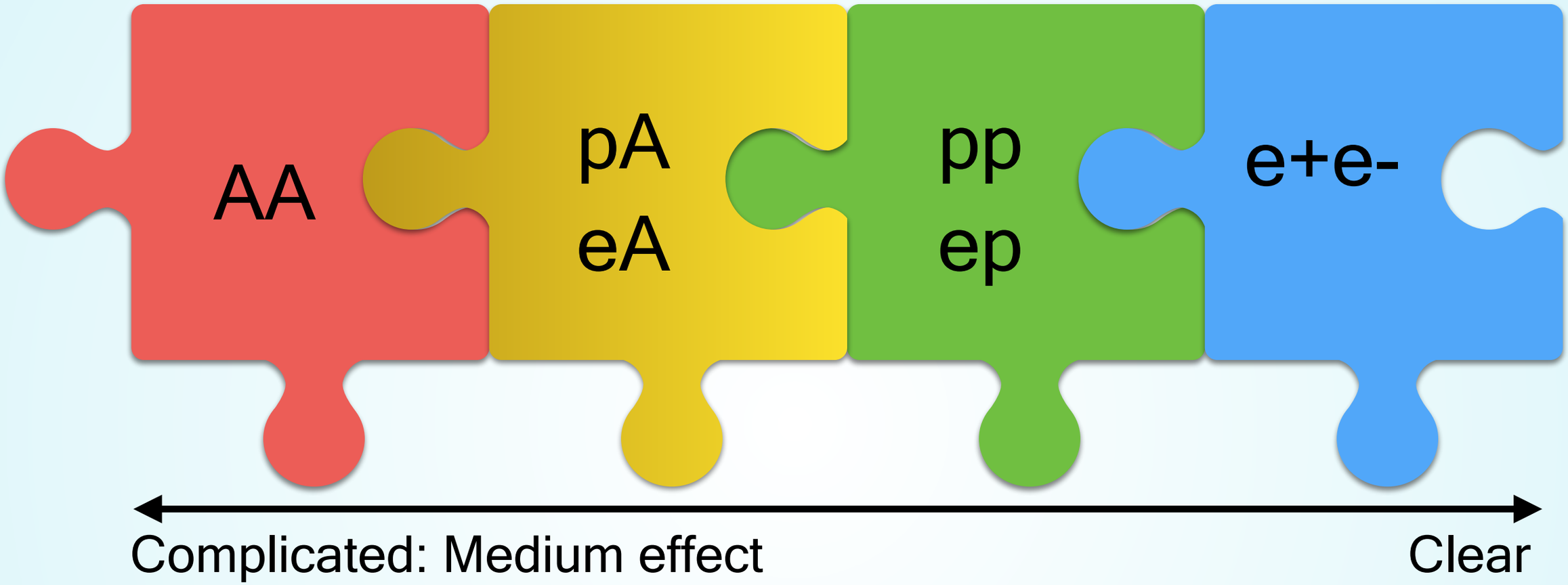
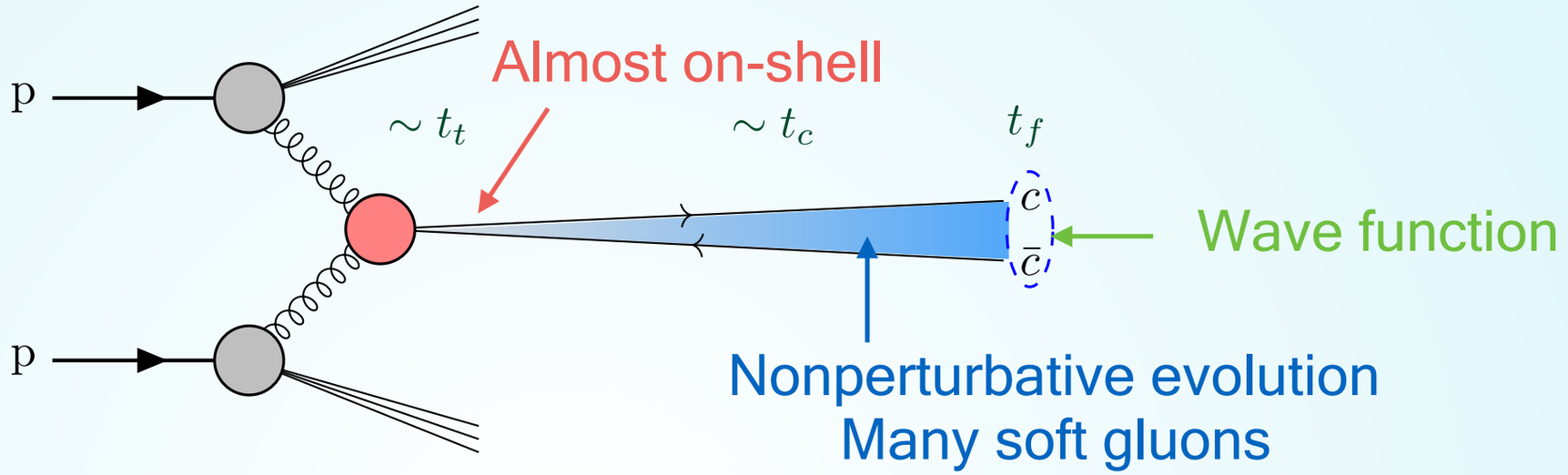
Thomas Jefferson National Accelerator Facility

Quarkonium production: Playgrounds



- pA (eA) collision gives a good test of Cold Nuclear Matter effects in quarkonium.
- pA collision gives a good lesson for going through eA collision (EIC) in the future.

Quarkonium production in p+p



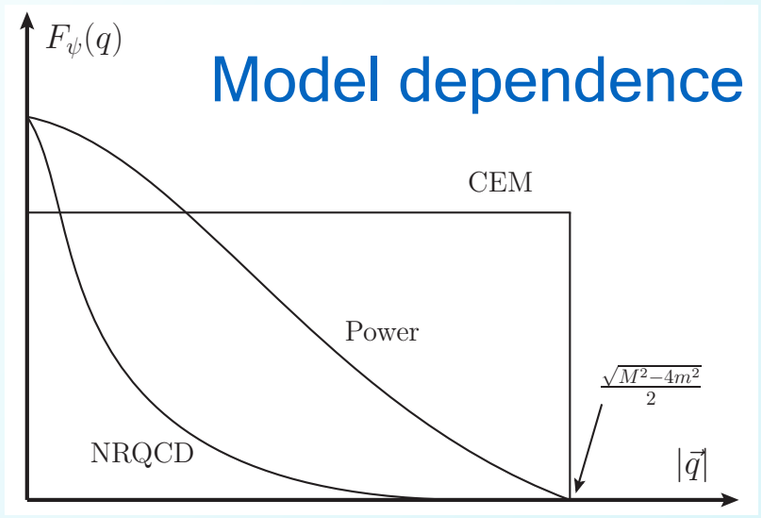
CoM for p+p collision

$$t_t \sim 2R_p \frac{m_n}{E_n} \quad < \quad t_c \sim \frac{1}{2m}\frac{E_{q\bar{q}}}{2m} \quad < \quad t_f \sim \frac{2}{M_{\psi'} - M_\psi}\frac{E_{q\bar{q}}}{2m} \sim \frac{t_c}{v^2}$$

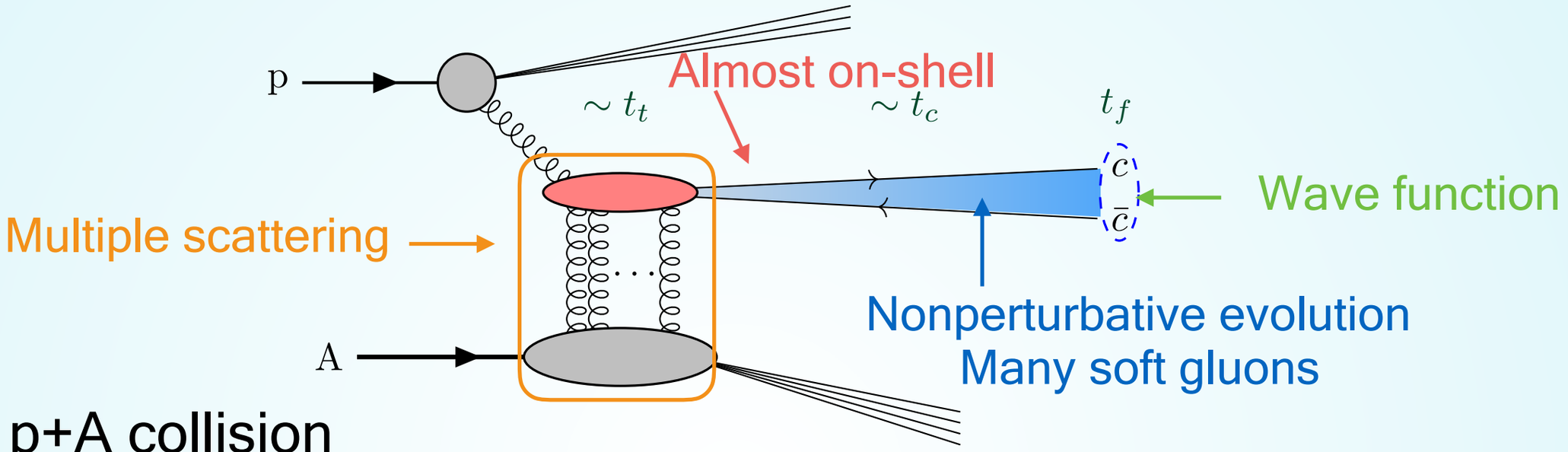
Factorization assumption:

$$\sigma_{pp\to\psi} = \int d\mathcal{P}.S. \hat{\sigma}_{pp\to Q\bar{Q}} F_{Q\bar{Q}\to\psi}$$

On-shell QQbar production



Quarkonium production in p+A



CoM for p+A collision

$$t_t \sim 2R_A \frac{m_n}{E_n} \quad < \quad t_c \sim \frac{1}{2m}\frac{E_{q\bar{q}}}{2m} \quad < \quad t_f \sim \frac{2}{M_{\psi'} - M_\psi}\frac{E_{q\bar{q}}}{2m} \sim \frac{t_c}{v^2}$$

Factorization assumption:

$$\sigma_{pp\to\psi} = \int d\mathcal{P}.S. \underbrace{\hat{\sigma}_{pp\to Q\bar{Q}}}_{\text{Modified}} \underbrace{F_{Q\bar{Q}\to\psi}}_{\text{The same as in pp}}$$

Production rates of quarkonium are modified due to multiple scattering effects with a target nucleus $\Longrightarrow$ CNM effects

At a glance: CNM effects

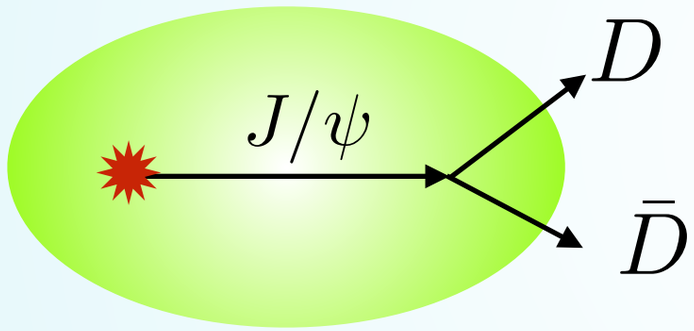
- Nuclear absorption
- Nuclear PDFs
- Multiple scattering and Energy loss
- Gluon saturation
- Comover effect

How can we test CNM effects in pA?

- Total x-section
- pt distribution
- Rapidity distribution

Nuclear absorption

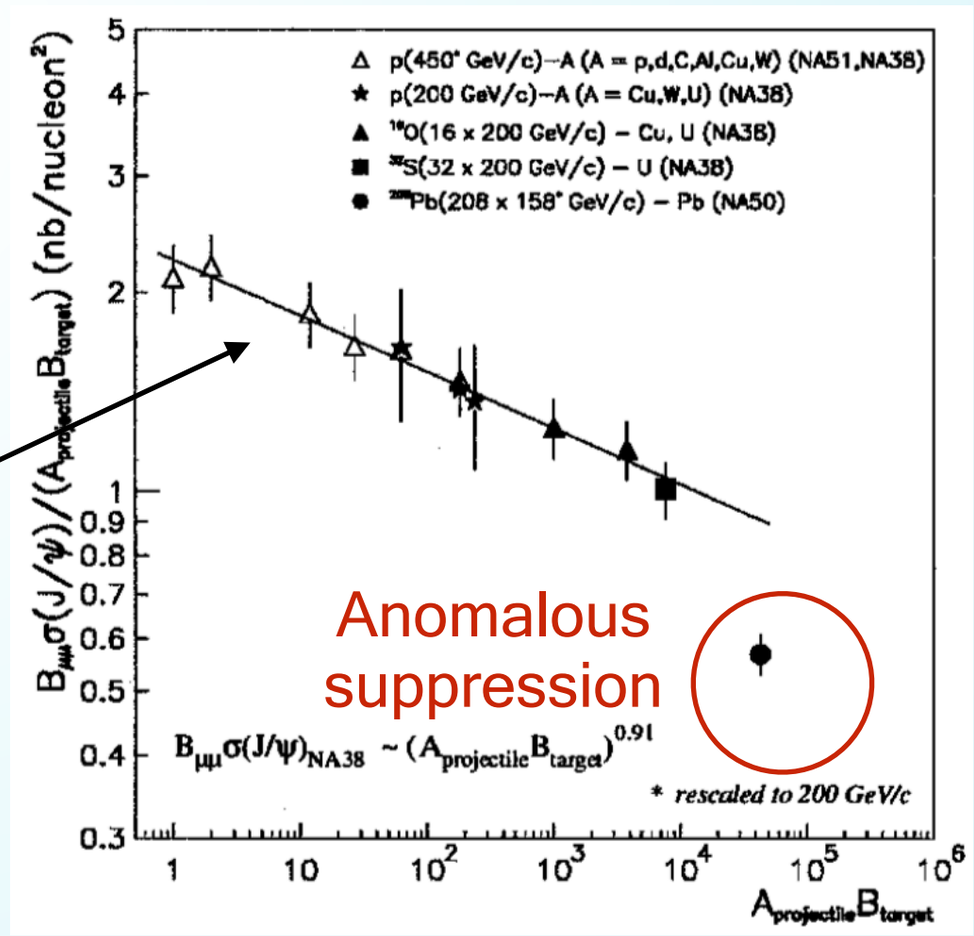
- Total x-section is calculated in collinear factorization.
- Heavy quark pair is produced inside the nucleus.
- The nuclear medium breaks up J/psi



Classical Glauber absorption model

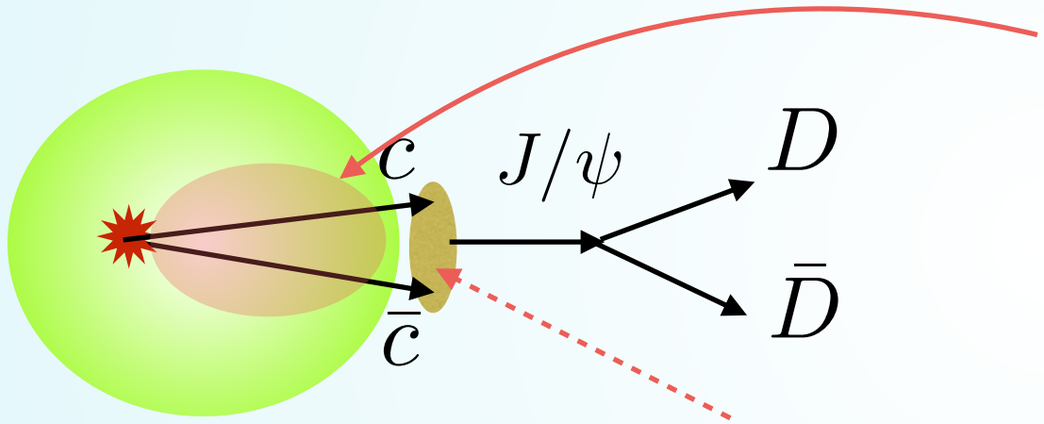
$$\frac{\sigma_{AB}}{\sigma_{NN}} = AB\, e^{-\rho_0 \cdot \sigma_{\mathrm{abs}}^{J/\psi} \cdot L_{AB}}$$

Parameter



Broadening in nuclear medium

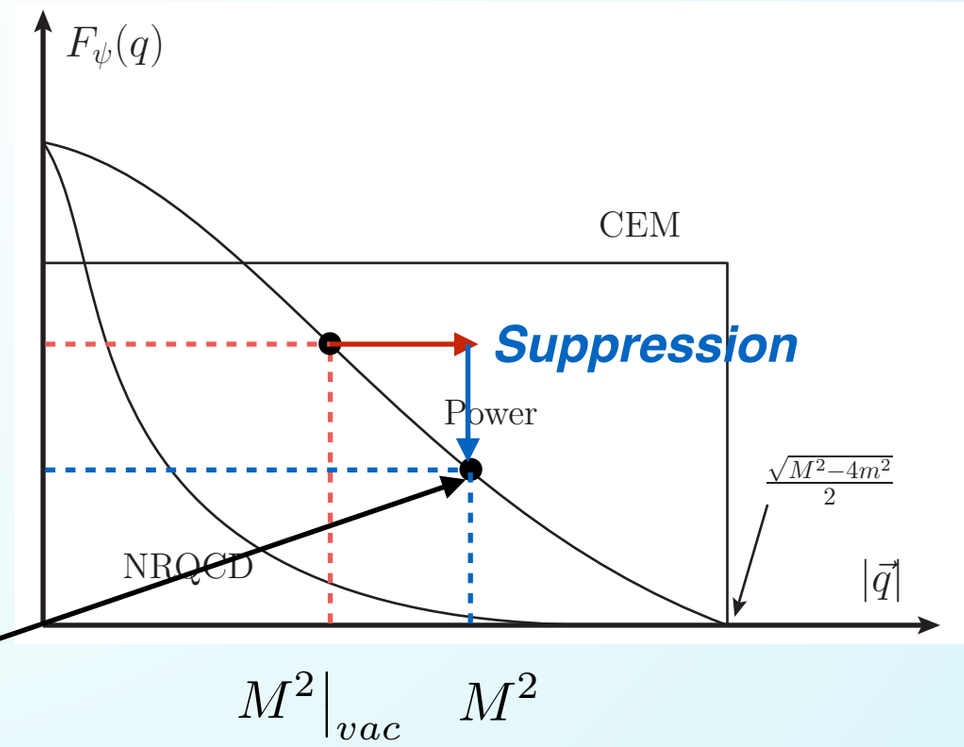
- Quark pair does not form a bound state immediately.
- Quark pair traverses nuclear matter and gains large invariant mass due to momentum kick from the nucleus.



$$M^2 = M^2\big|_{vac} + \xi^2 L_{AB}$$
$$\xi^2 \sim \hat{q} \sim \Delta\langle p_\perp^2 \rangle$$

ccbar has a finite spatial size

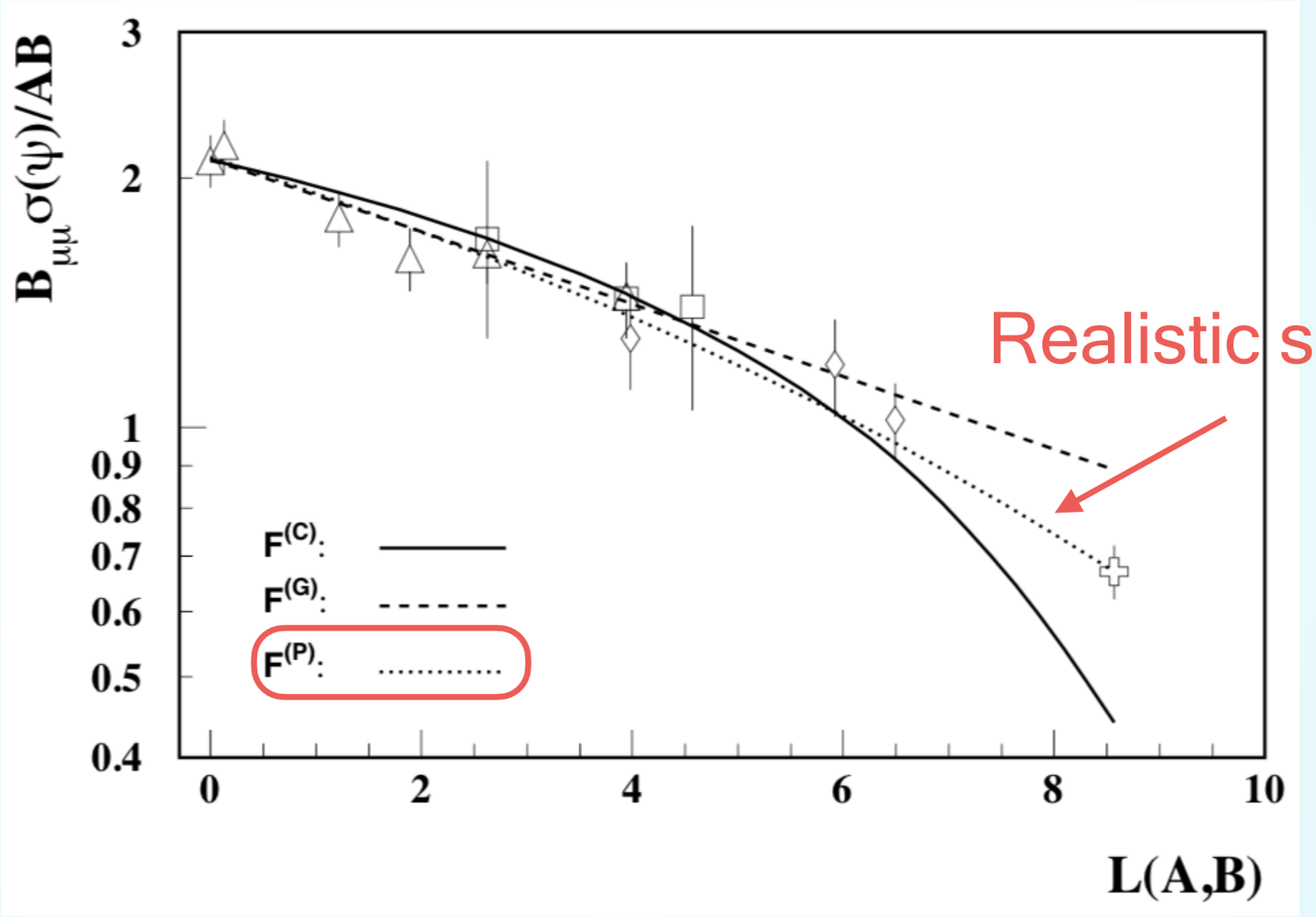
Decoherence of the pre-resonance ccbar: the pair with large invariant mass is likely to form a bound state.



We should match F on this point.

Broadening in nuclear medium

Qiu, Vary, Zhang (1998)



Nuclear suppression tells us an insight into quarkonium production mechanism in pA.

Factorization in p+p

Parton distribution functions (PDFs): Universal, leading twist

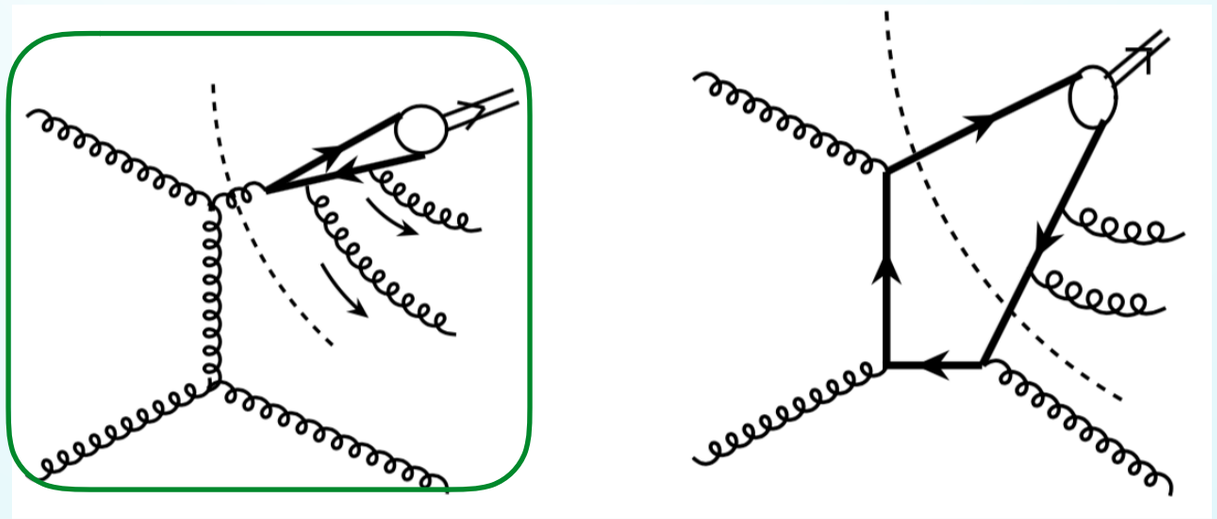
Kang, Ma, Qiu, Sterman (2014)

$$\frac{d\sigma_{p+p}}{dyd^2p_\perp} = \int dx_1 f_i^p(x_1,\mu) \int dx_2 f_j^p(x_2,\mu) \frac{d\hat{\sigma}|_{q,\bar{q},g\to\psi}}{dyd^2p_\perp}$$ Leading

$$+ \int dx_1 f_i^p(x_1,\mu) \int dx_2 f_j^p(x_2,\mu) \frac{d\hat{\sigma}|_{c\bar{c}\to\psi}}{dyd^2p_\perp}$$ First subleading

$$+ \mathcal{O}\left(\frac{1}{Q^4}\right)$$ Higher twist correction

Dominant at high pt



Probing nPDFs at large pt

$$\frac{d\sigma_{p+A}}{dyd^2p_\perp} = A\int dx_1 f_i^p(x_1,\mu)\int dx_2 f_j^A(x_2,\mu)\frac{d\hat{\sigma}}{dyd^2p_\perp} + \cdots$$

Nuclear PDFs (nPDFs): Universal, leading twist

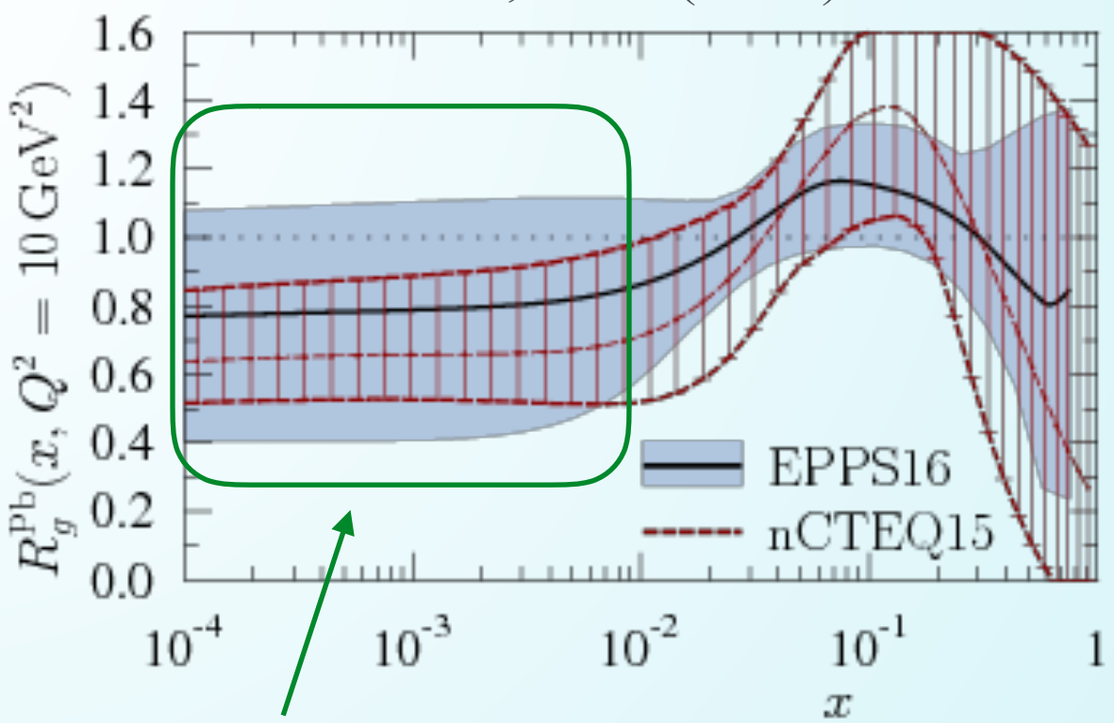
Note: nPDFs can include some higher twist effects.

Nuclear correction factors

$$f_i^A(x,Q_0) = R_i^A(x,Q_0)(Zf_i^p(x,Q_0) + (A-Z)f_i^n(x,Q_0))$$

$$R_i^{A=1}(x,Q_0) = 1$$

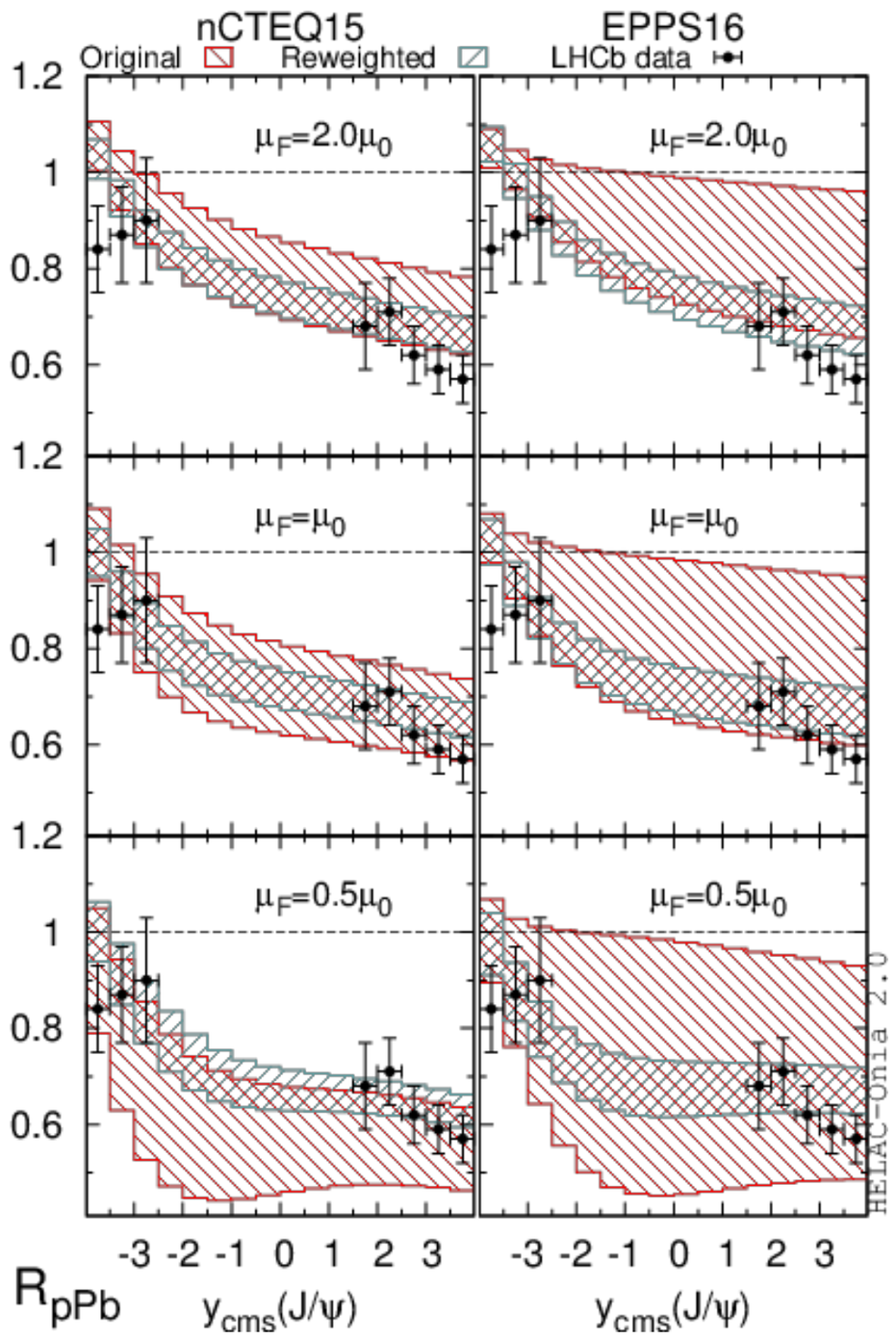
Eskola, et al. (2016)

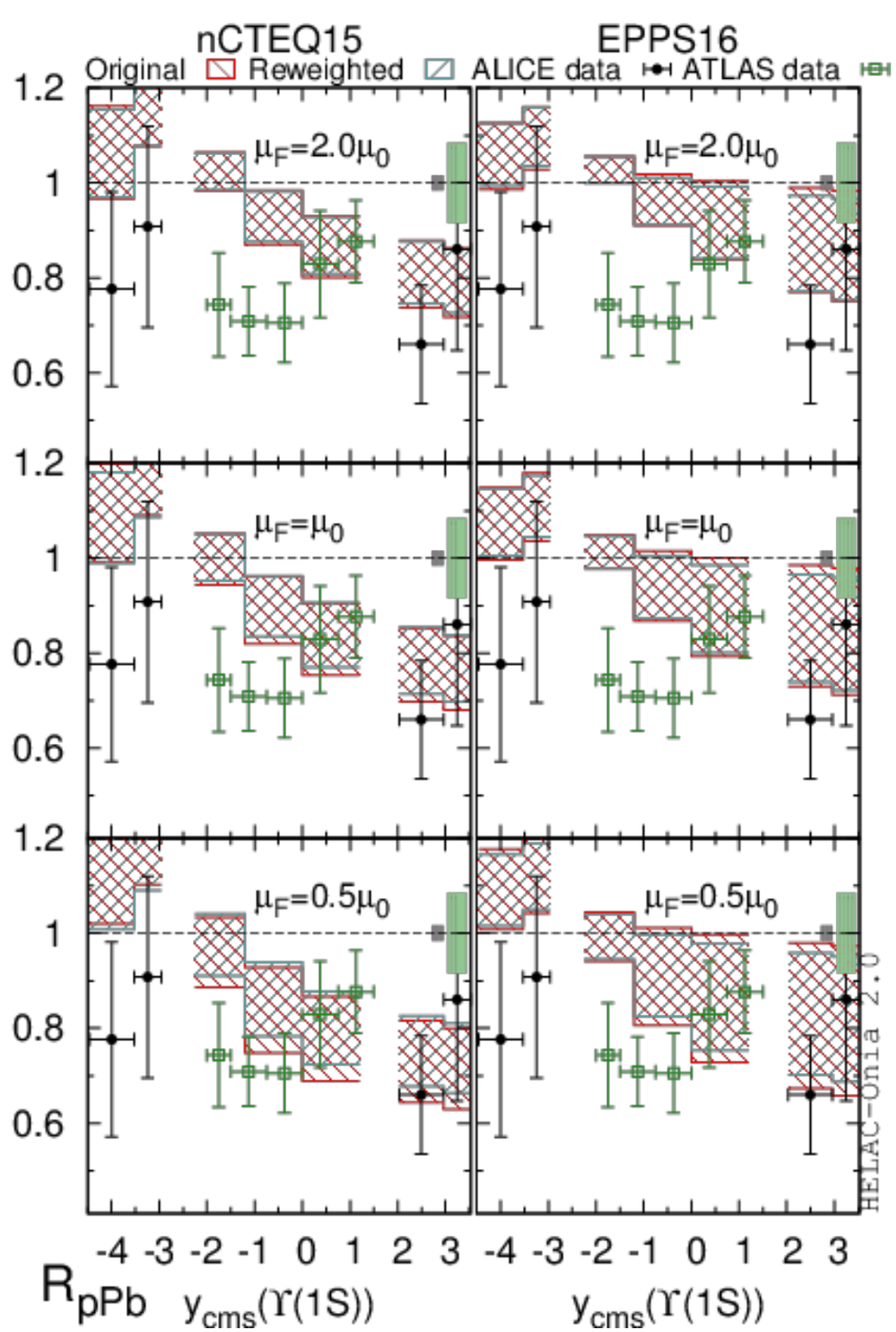


Large uncertainties at small-x

Sample

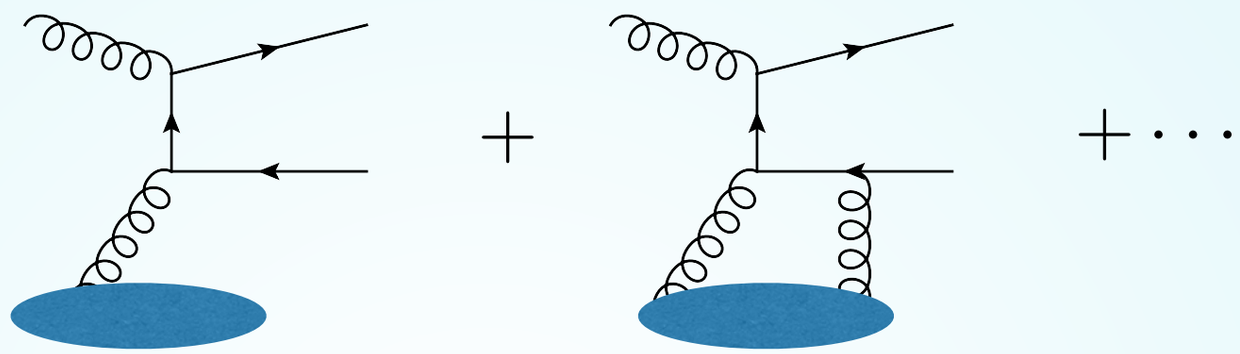
Kusina et al. (2017)





Multiple scattering at low pt

$$\hat{\sigma}_{pA\to Q\bar{Q}} \propto \frac{1}{2\hat{s}} \left| \quad + \quad + \cdots \right|^2$$



$$= \hat{\sigma}^S + \hat{\sigma}^D + \cdots$$

Multiple scattering modifies the pt-spectrum of quarkonium.

It is interesting to investigate pt-broadening in p+A compared to p+p.

$$\Delta\langle p_\perp^2 \rangle = \langle p_\perp^2 \rangle_{pA} - \langle p_\perp^2 \rangle_{pp} \qquad \langle p_\perp^2 \rangle = \frac{\int dp_\perp^2 \, p_\perp^2 \, \frac{d\sigma}{dp_\perp^2}}{\int dp_\perp^2 \, \frac{d\sigma}{dp_\perp^2}}$$

Quarkonium production at low-pt is well described in TMD factorization framework. But, here we do not need to worry about parton shower effect in initial state.

Pt-broadening

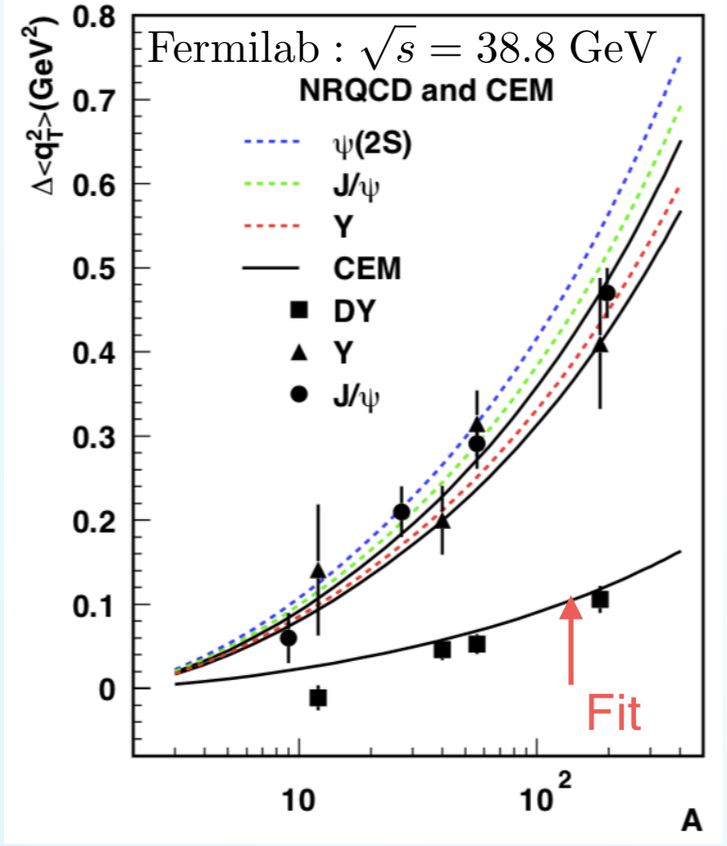
$$\Delta\langle p_\perp^2\rangle^{\rm CEM} = \frac{8\pi^2\alpha_s}{N_c^2-1}\boxed{\lambda^2}A^{1/3}\frac{(C_F+C_A)\sigma_{q\bar{q}}+2C_A\sigma_{gg}}{\sigma_{q\bar{q}}+\sigma_{gg}}$$

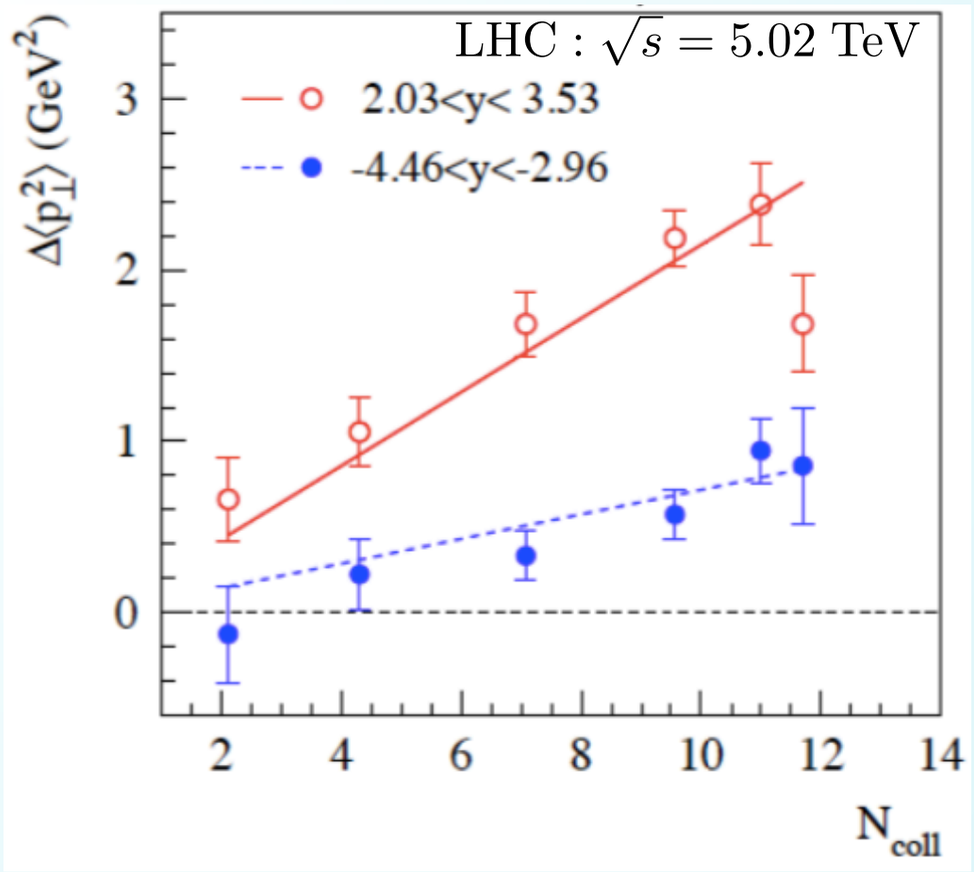
Kang, Qiu (2008)

$$\Delta\langle p_\perp^2\rangle^{\rm NRQCD} = \frac{8\pi^2\alpha_s}{N_c^2-1}\boxed{\lambda^2}A^{1/3}\frac{(C_F+C_A)\sigma_{q\bar{q}}^{(0)}+2C_A\sigma_{gg}^{(0)}+\sigma_{q\bar{q}}^{(1)}}{\sigma_{q\bar{q}}^{(0)}+\sigma_{gg}^{(0)}}$$

$$\Delta\langle p_\perp^2\rangle^{\rm Drell\text{-}Yan} = C_F\frac{8\pi^2\alpha_s}{N_c^2-1}\boxed{\lambda^2}A^{1/3}$$

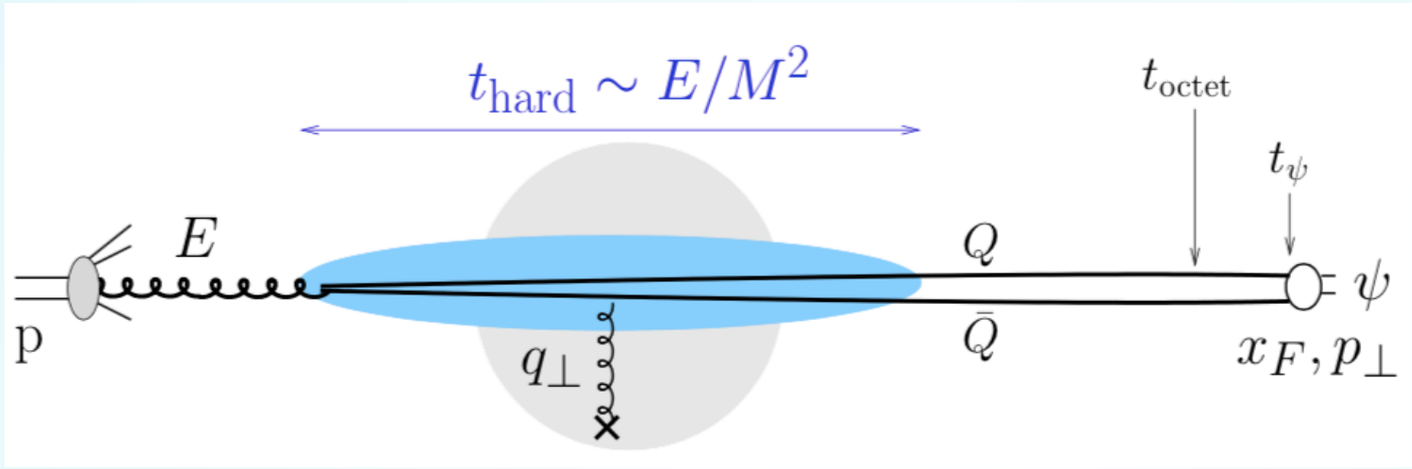
$\lambda^2 \propto \hat{q}$ parameter





Coherent Energy Loss

Multiple scattering induced gluon radiation $\Longrightarrow$ Energy loss



Arleo, Peigne (2012)
Arleo et al. (2013)
…

Interference between initial state radiation and final state radiation.

$$\frac{1}{A}\frac{d\sigma^{\psi}_{pA}}{dE} = \int_0^{\epsilon^{\max}} d\epsilon \, \mathcal{P}(\epsilon, E, l^2) \frac{d\sigma^{\psi}_{pp}}{dE}(E+\epsilon)$$

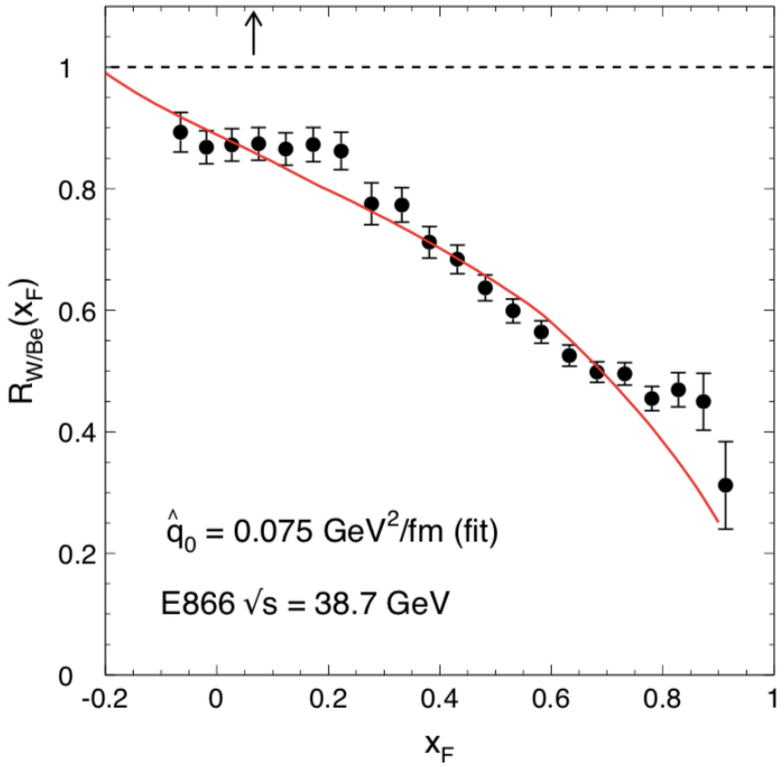
Energy loss probability distribution

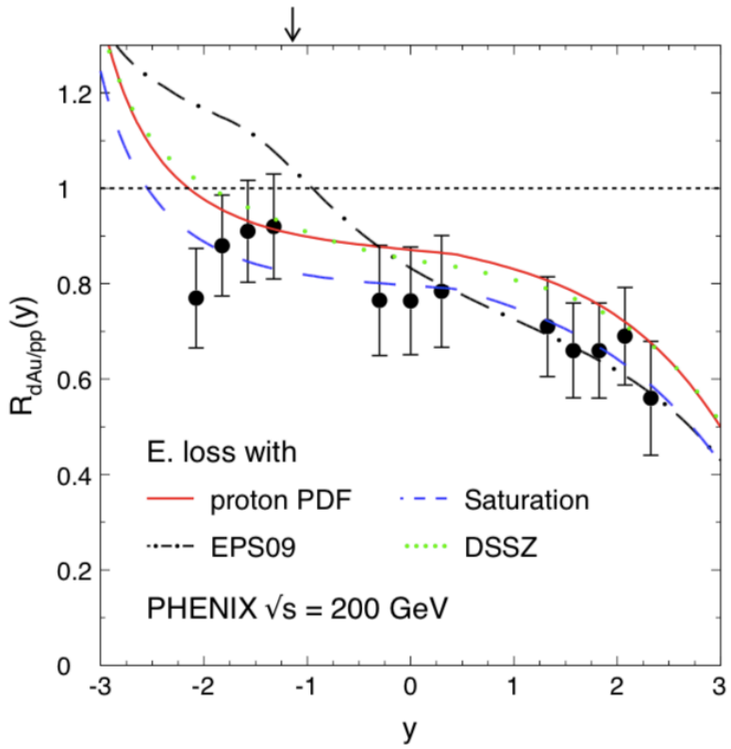
Data fitting

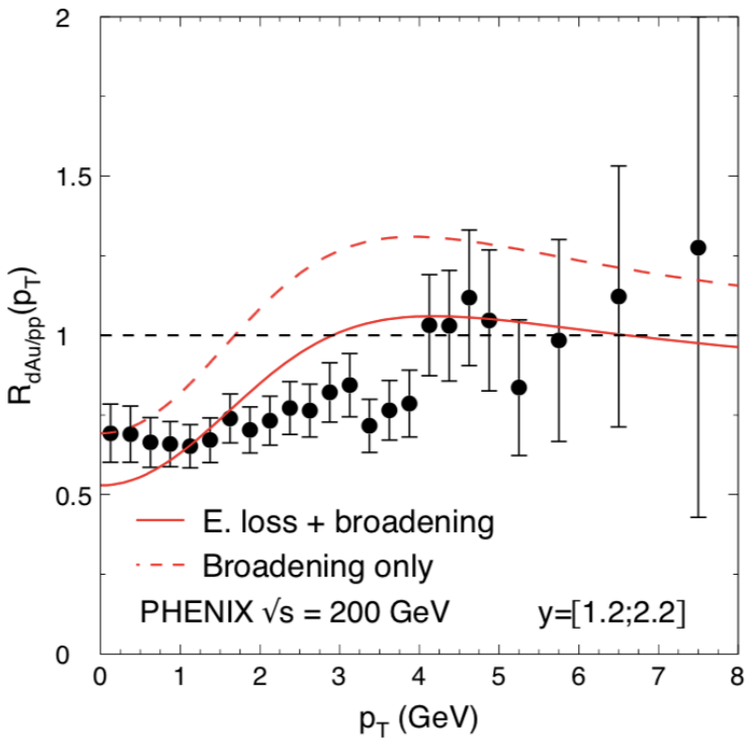
The nuclear broadening: $l^2 = \hat{q} L_{\rm eff}$

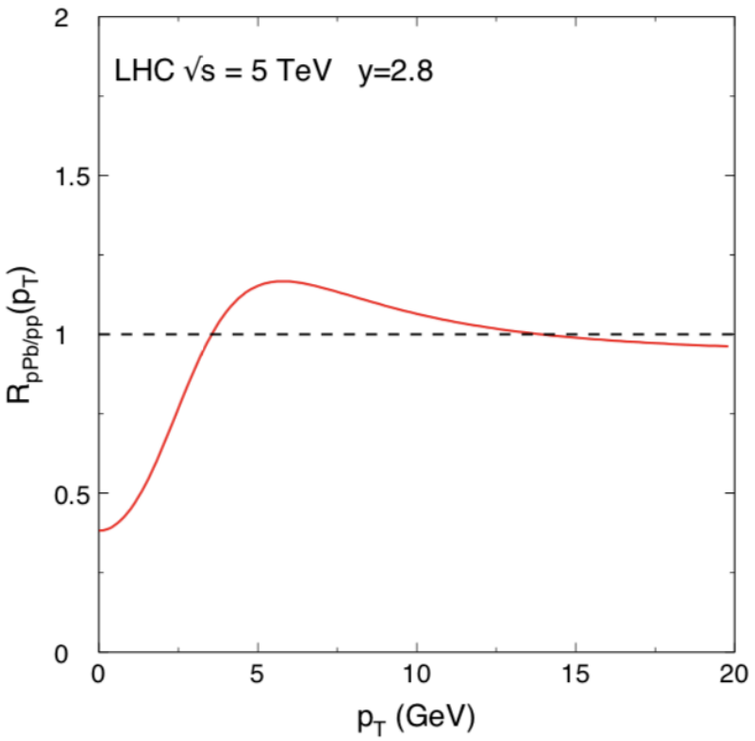
the transport coefficient in the nucleus (parameter)

Sample


$R_{W/Be}(x_F)$
$\hat{q}_0$ = 0.075 GeV^2/fm (fit)
E866 √s = 38.7 GeV
x_F


$R_{dAu/pp}(y)$
E. loss with
proton PDF
Saturation
EPS09
DSSZ
PHENIX √s = 200 GeV
y


$R_{dAu/pp}(p_T)$
E. loss + broadening
Broadening only
PHENIX √s = 200 GeV
y=[1.2;2.2]
p_T (GeV)


LHC √s = 5 TeV y=2.8
$R_{pPb/pp}(p_T)$
p_T (GeV)

Initial state Energy Loss

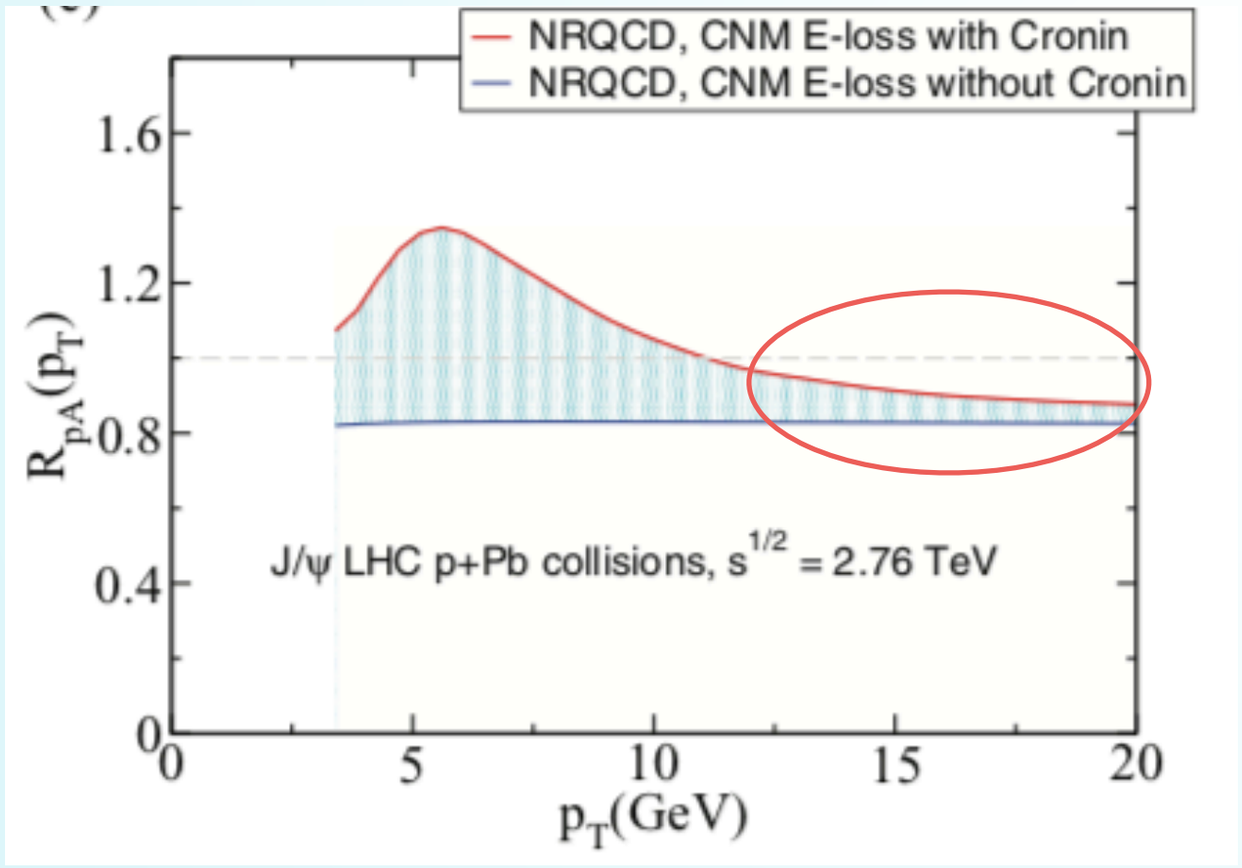
Modified PDFs

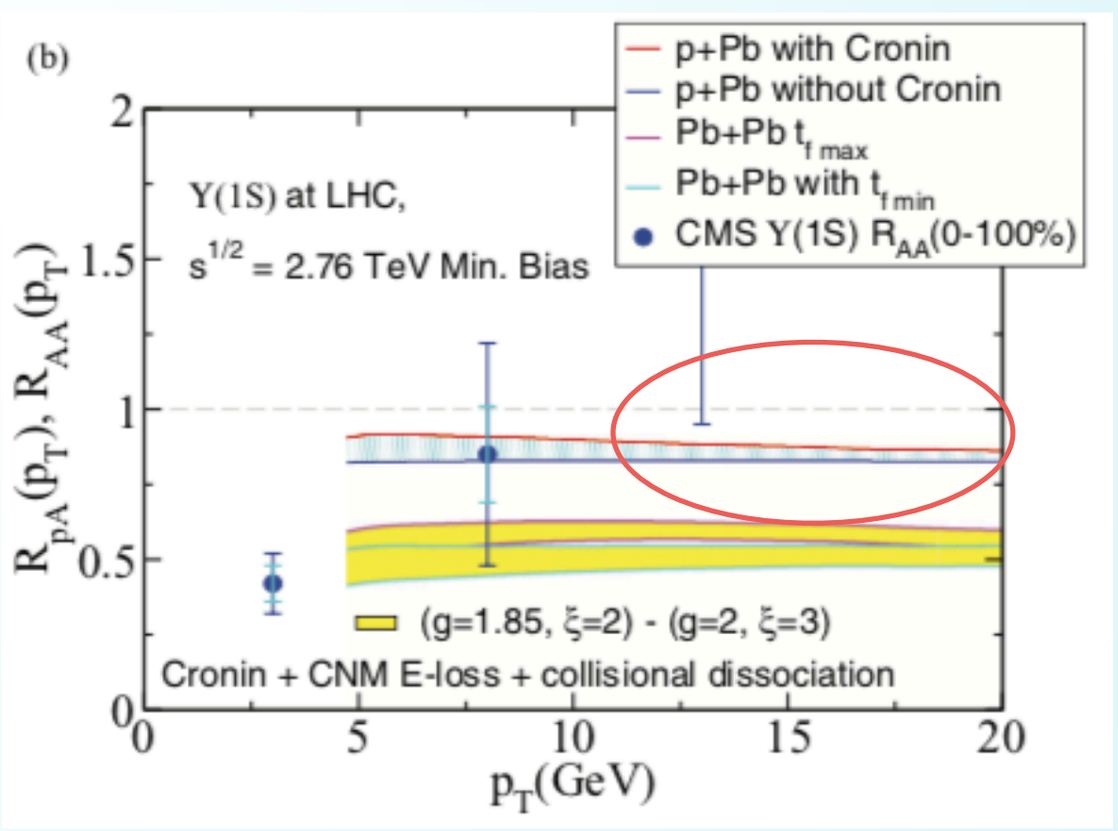
$$f_{q,\bar{q}}(x,\mu) \to \int_0^1 d\epsilon P_{q,\bar{q}}(\epsilon) f_{q,\bar{q}}\left(\frac{x}{1-\epsilon},\mu\right)$$

$$f_g(x,\mu) \to \int_0^1 d\epsilon P_g(\epsilon) f_g\left(\frac{x}{1-\epsilon},\mu\right)$$

The probability density for quarks and gluons to lose a fraction energy: ϵ

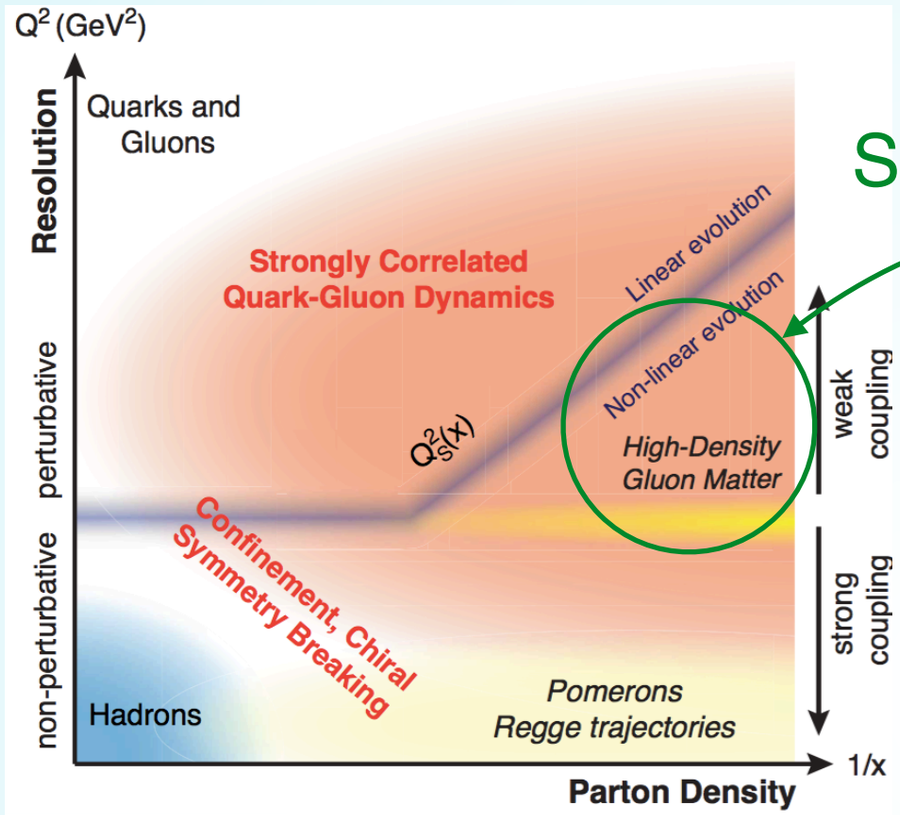
Sharma, Vitev (2013)



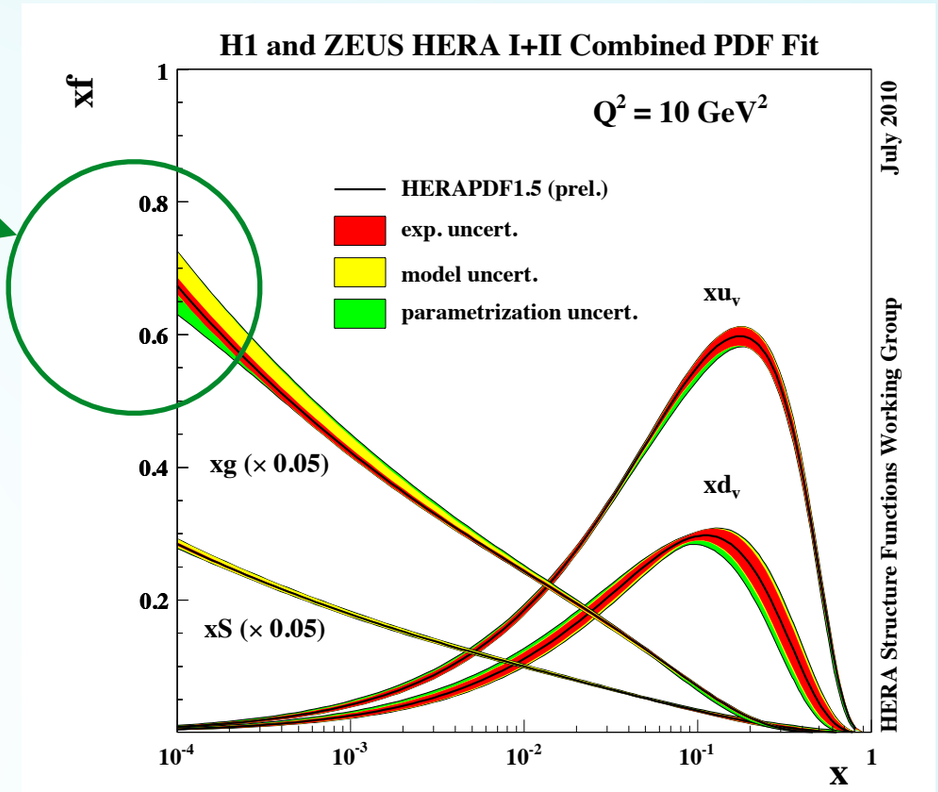


RpA∼0.8 even at high pt (15--20GeV)!

Gluon Saturation

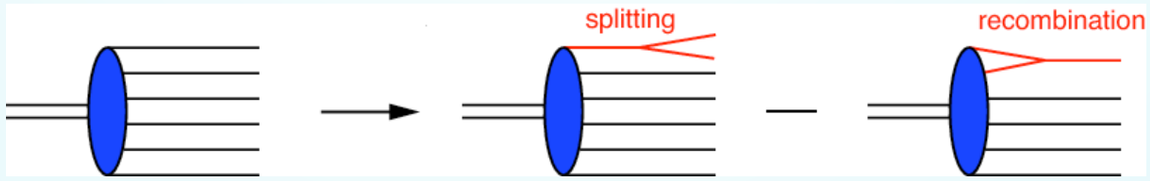


Saturation?



Balitsky-Kovchegov Equation

$$\frac{dN_{Y,r_\perp}}{dY} = \int d^2 r_{1\perp} \mathcal{K}(r_\perp, r_{1\perp}) \Big[N_{Y,r_{1\perp}} + N_{Y,r_{2\perp}} - N_{Y,r_\perp} - N_{Y,r_{1\perp}} N_{Y,r_{2\perp}} \Big]$$



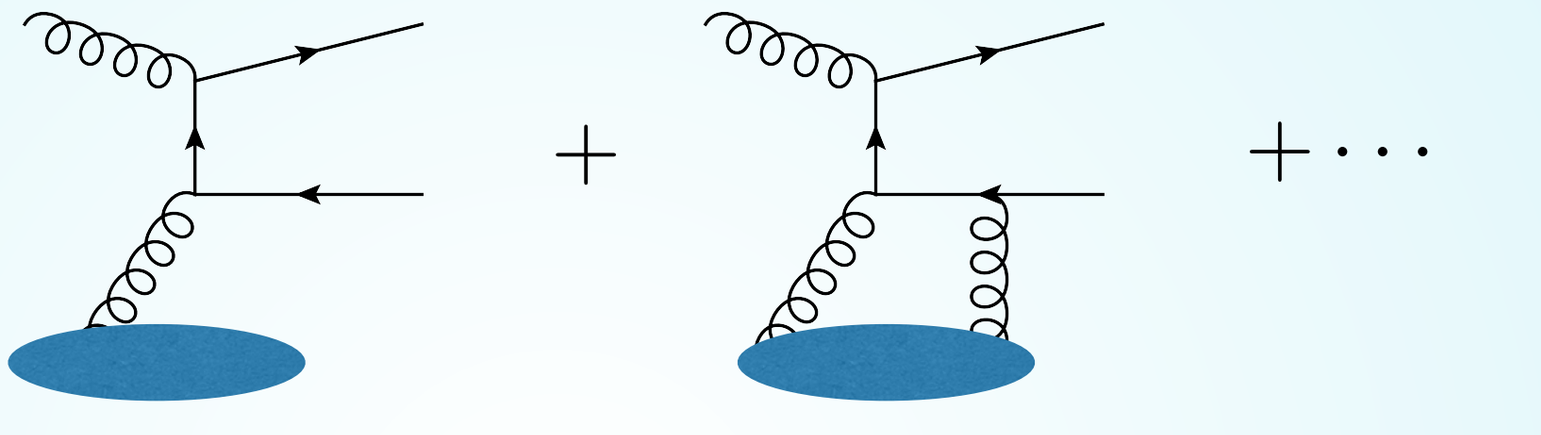
Saturation scale

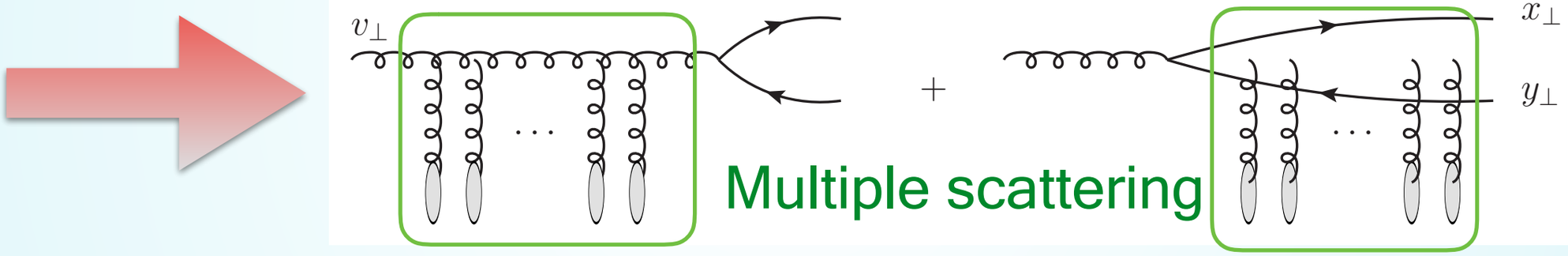
$$Q_{s,A}^2(x) = \frac{\alpha_s N_c}{S_{A\perp}} x G_A(x) \propto A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

Gribov, Levin, Ryskin (1983)
Mueller, Qiu (1986)

Color-Glass-Condensate (CGC): All twist

$$\hat{\sigma}_{pA\to Q\bar{Q}} \propto \frac{1}{2\hat{s}} \left| \quad + \quad + \cdots \right|^2$$





Wilson line in the Eikonal approximation

$$U(x_\perp) \equiv \mathcal{P}_+ \exp\left[ig \int dx^+ t^a A_a^-(x^+, x_\perp)\right] = 1 + ig \int dx^+ t^a A_a^-(x^+, x_\perp) + \cdots$$

$$S(x_\perp, y_\perp) = \frac{1}{N_c}\langle \mathrm{Tr}\left[U_{x_\perp} U^\dagger_{y_\perp}\right]\rangle$$

Dipole scattering amplitude
Fundamental d.o.f in the CGC

CEM vs ICEM vs NRQCD

CEM

Fujii, Gelis, Venugopalan, (2006)

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

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

Improved CEM

Ma, Vogt, PRD94 (2016)

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

Gluon radiation during hadronization

NRQCD

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

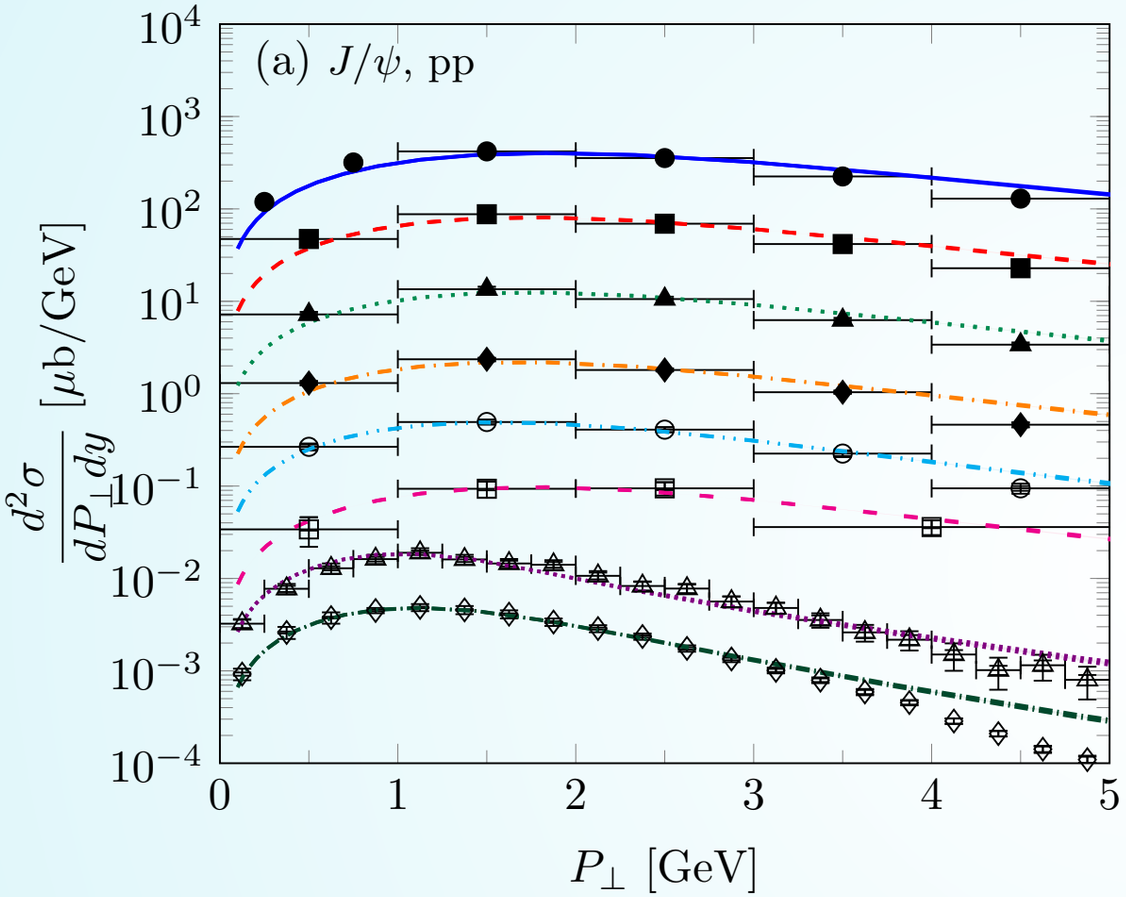
Kang, Ma, Venugopalan, (2013)

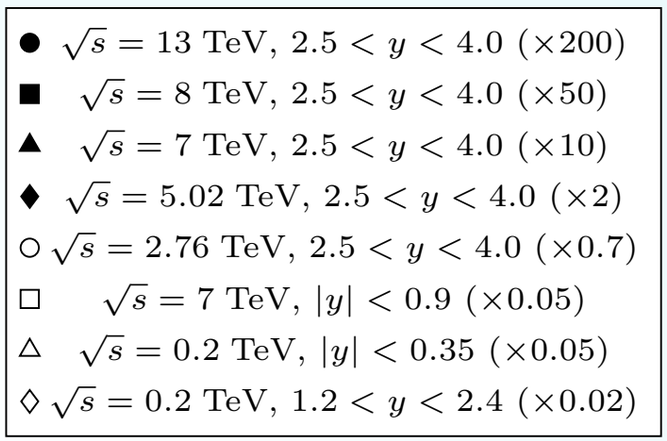
$$\frac{d\sigma^\kappa_{c\bar{c},\mathrm{CS}}}{d^2p_\perp dy} = \frac{\alpha_s\pi R_A^2}{(2\pi)^9 d_A}\int_{k_{2\perp},k_\perp,k'_\perp}\frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(k_\perp)\mathcal{N}_Y(k'_\perp)\mathcal{N}_Y(k_{2\perp}-k_\perp-k'_\perp)\,\mathcal{G}_1^\kappa$$

$$\frac{d\sigma^\kappa_{c\bar{c},\mathrm{CO}}}{d^2p_\perp dy} = \frac{\alpha_s\pi R_A^2}{(2\pi)^7 d_A}\int_{k_{2\perp},k_\perp}\frac{\varphi_{p,y_p}(k_{1\perp})}{k_{1\perp}^2}\mathcal{N}_Y(k_\perp)\mathcal{N}_Y(k_{2\perp}-k_\perp)\,\Gamma_8^\kappa$$

J/psi in the CGC+ICEM

Ma, Venugopalan, KW, Zhang (2018)



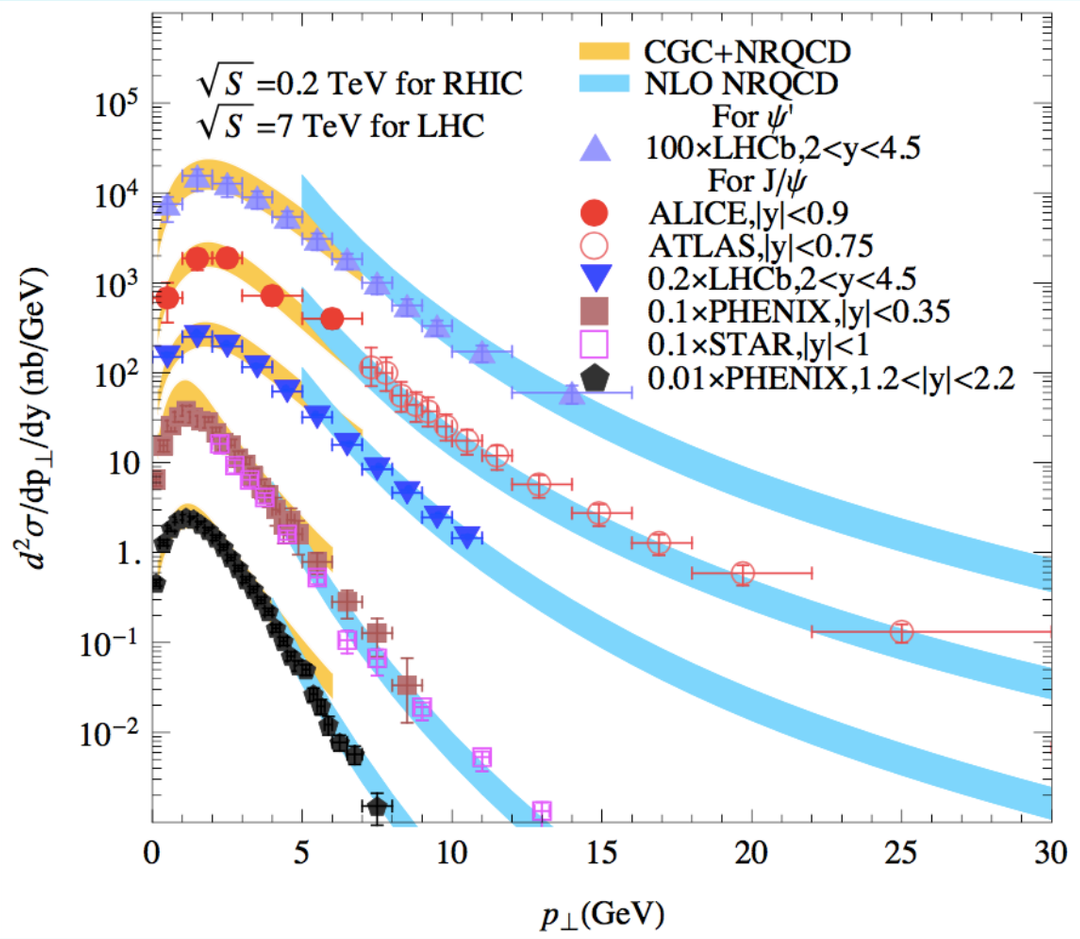


- MV IC + rcBK eq. gives a good parametrization of gluon TMD at small-x.

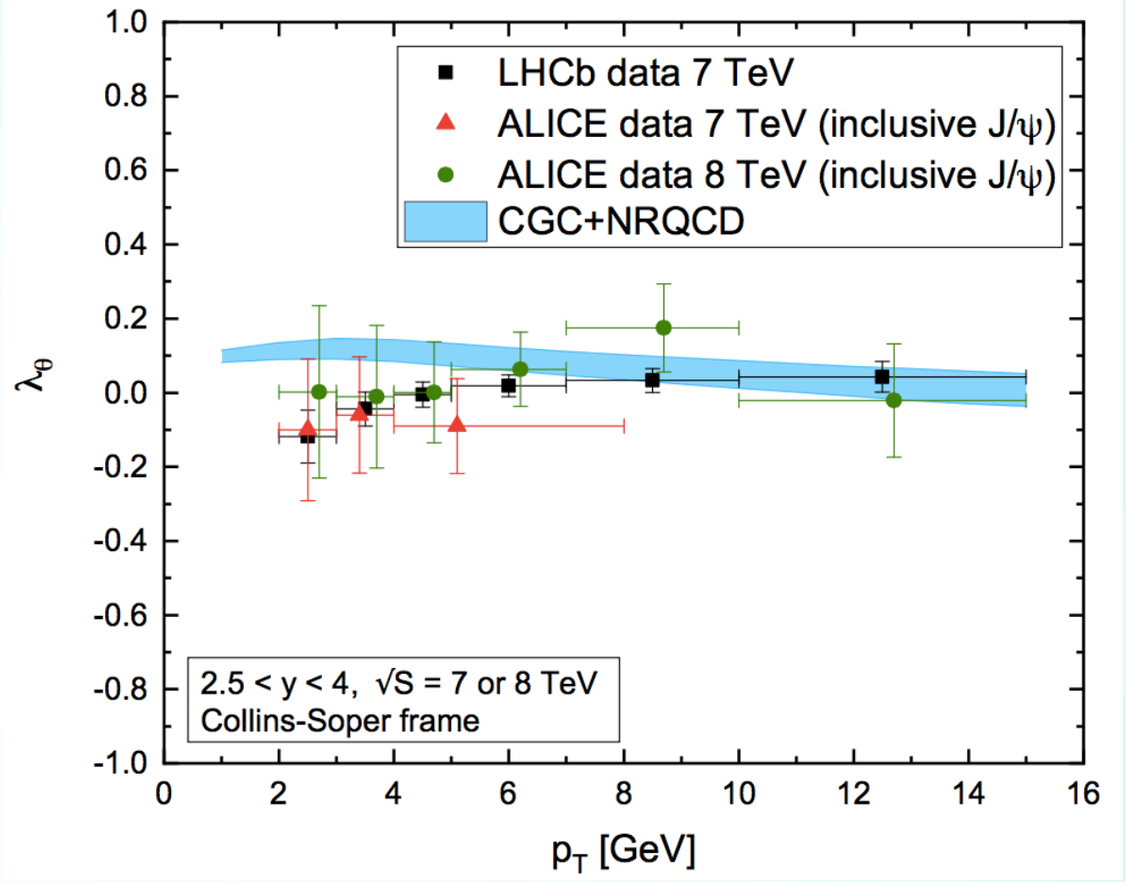
$\sqrt{s}$ [TeV]	y bin	Data points	$F_{J/\psi}$ (1.3)	$\chi^2/d.o.f.$
13	$2.5 < y < 4.0$	7	$5.63\times10^{-3} \pm 3.56\times10^{-4}$	8.7
8	$2.5 < y < 4.0$	6	$5.84\times10^{-3} \pm 3.79\times10^{-4}$	4.3
7	$\|y\| < 0.9$	5	$4.52\times10^{-3} \pm 2.33\times10^{-4}$	0.33
7	$2.5 < y < 4.0$	6	$4.86\times10^{-3} \pm 3.01\times10^{-4}$	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

J/psi in the CGC+NRQCD

Ma, Venugopalan (2014)



Ma, Stebel, Venugopalan (2018)



Prompt J/psi data at high pt at Tevatron;

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

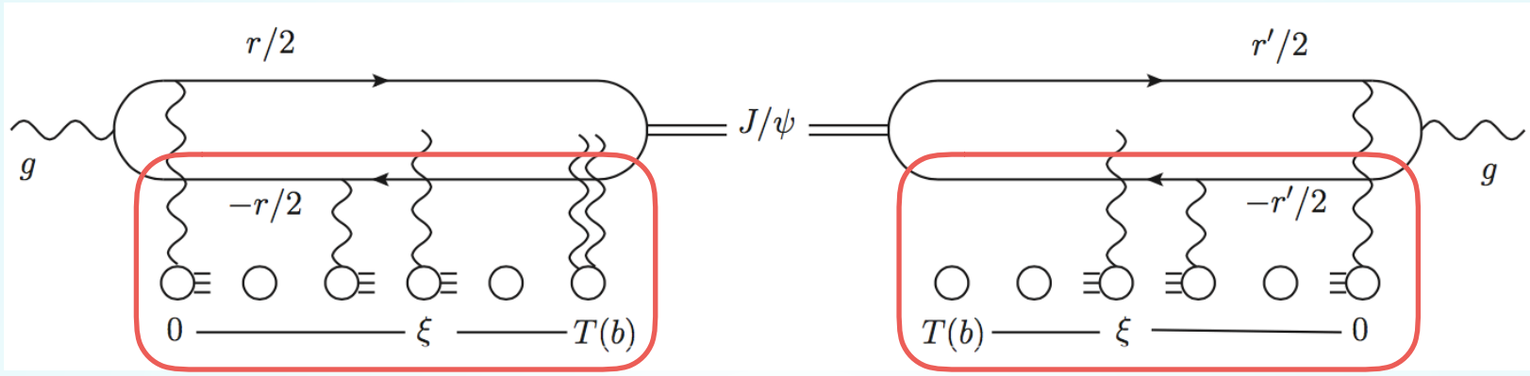
$$\langle \mathcal{O}^{J/\psi}[^1S_0^{[8]}] \rangle = 0.089 \pm 0.0098 \mathrm{GeV}^3$$

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

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

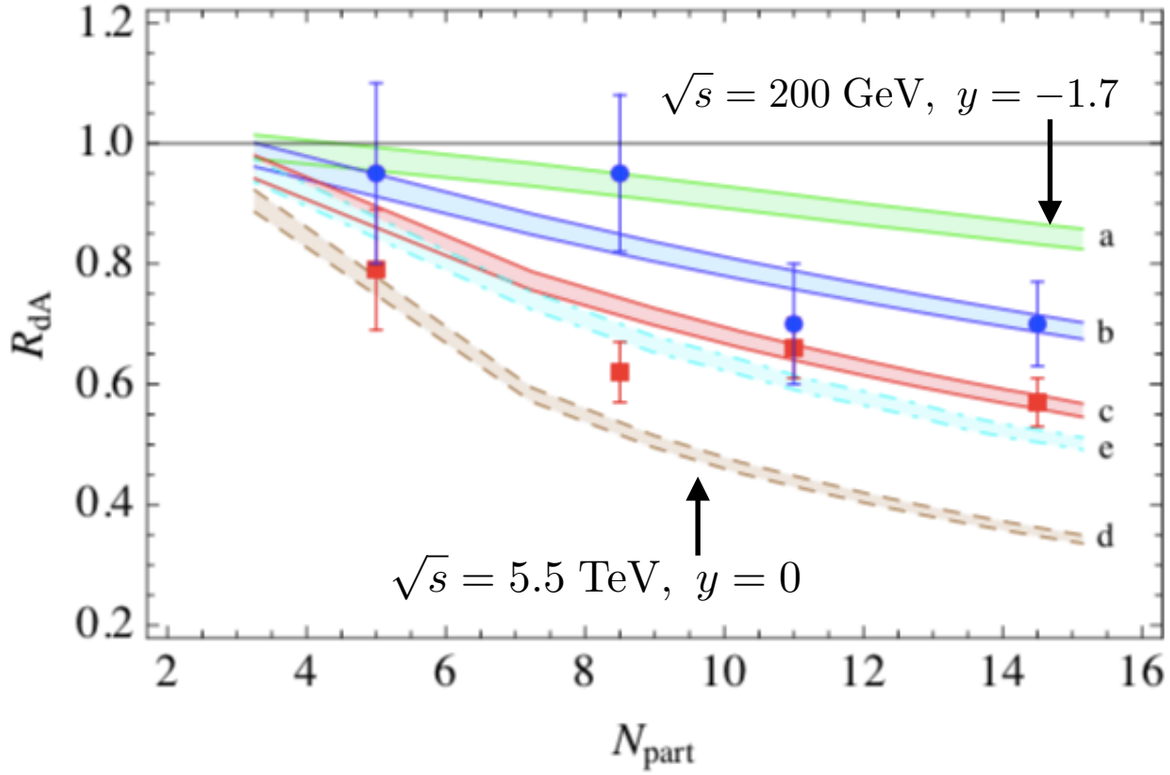
Multiple scattering in p+A and A+A

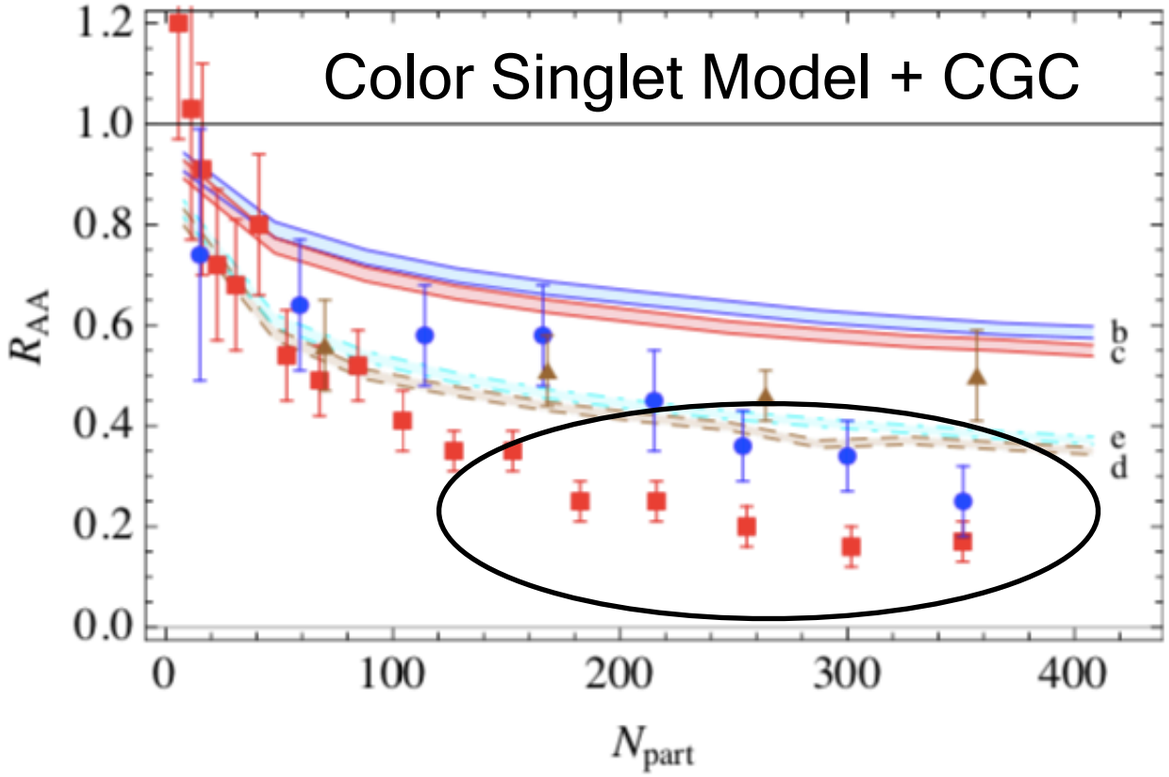
Dominguez et al. (2011)



$\langle k_\perp^2 \rangle \sim Q_s^2$

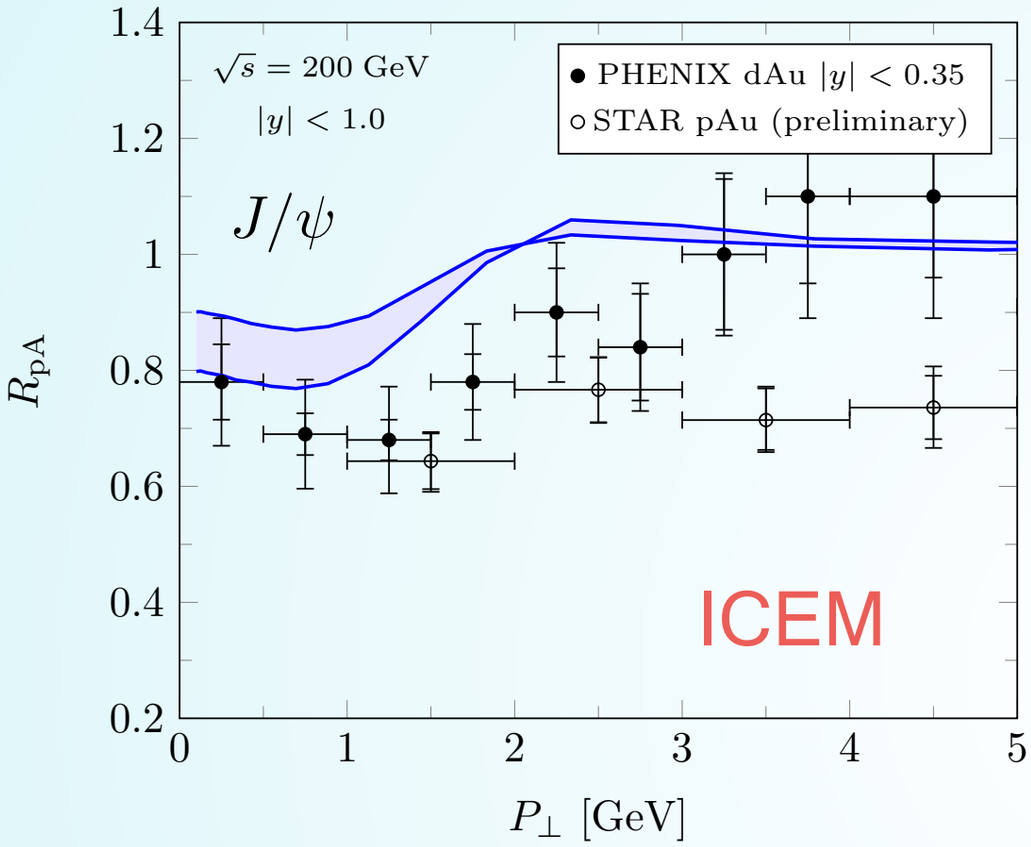
"Cronin effect": pt-broadening





Strong suppression in A+A $\Longrightarrow$ Final state effect

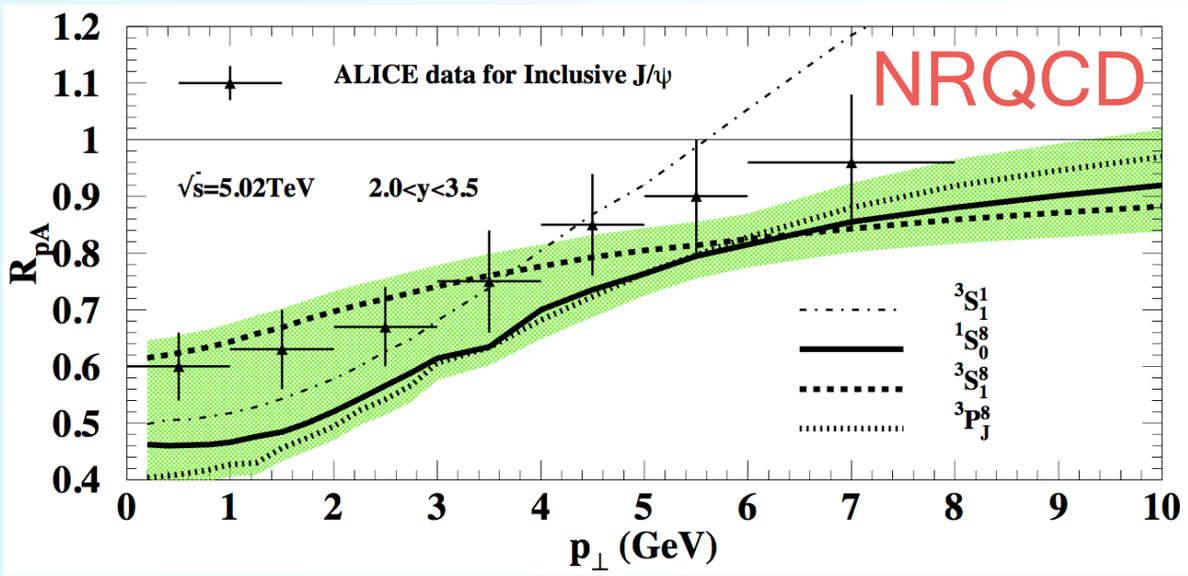
RpA in the NRQCD, ICEM

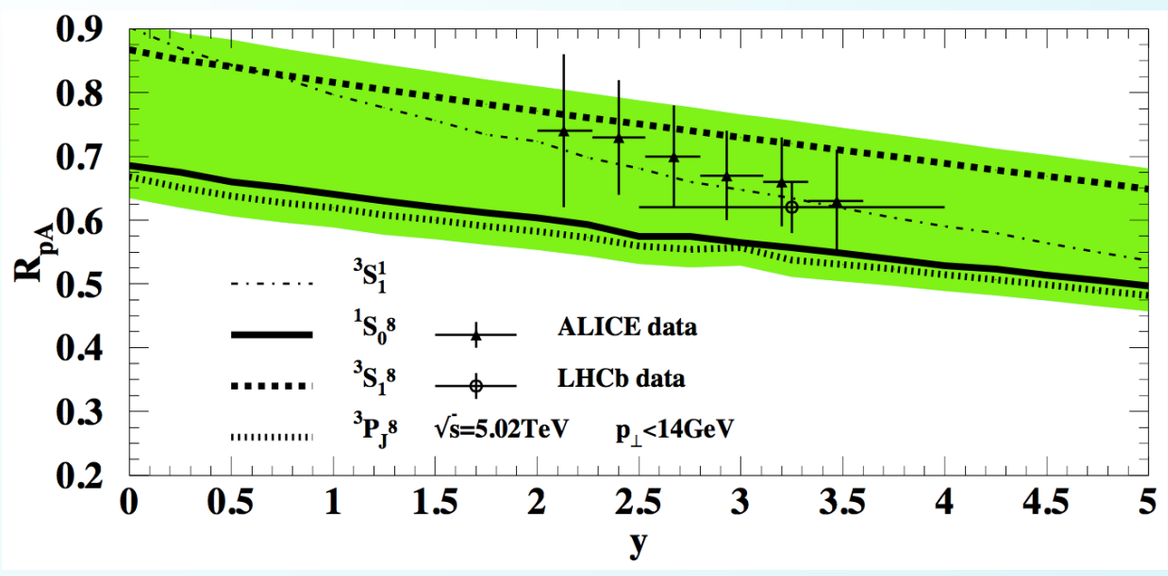


Fujii, KW (2013)
Ma, Venugopalan, KW, Zhang (2017)

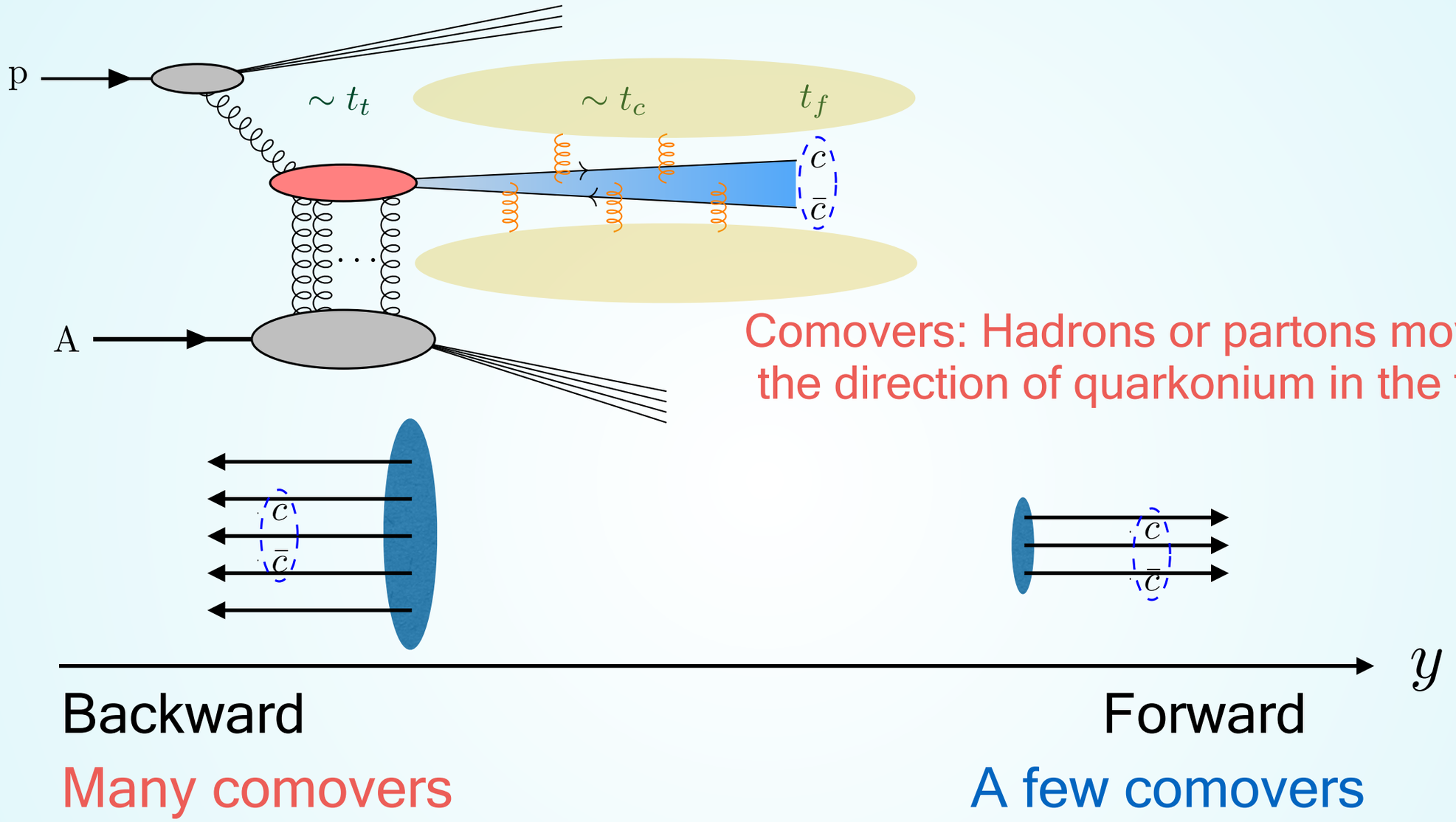
Cronin like peak disappears due to the running coupling BK evolution effect.

Ma, Venugopalan, Zhang (2015)





Comover effect in final state



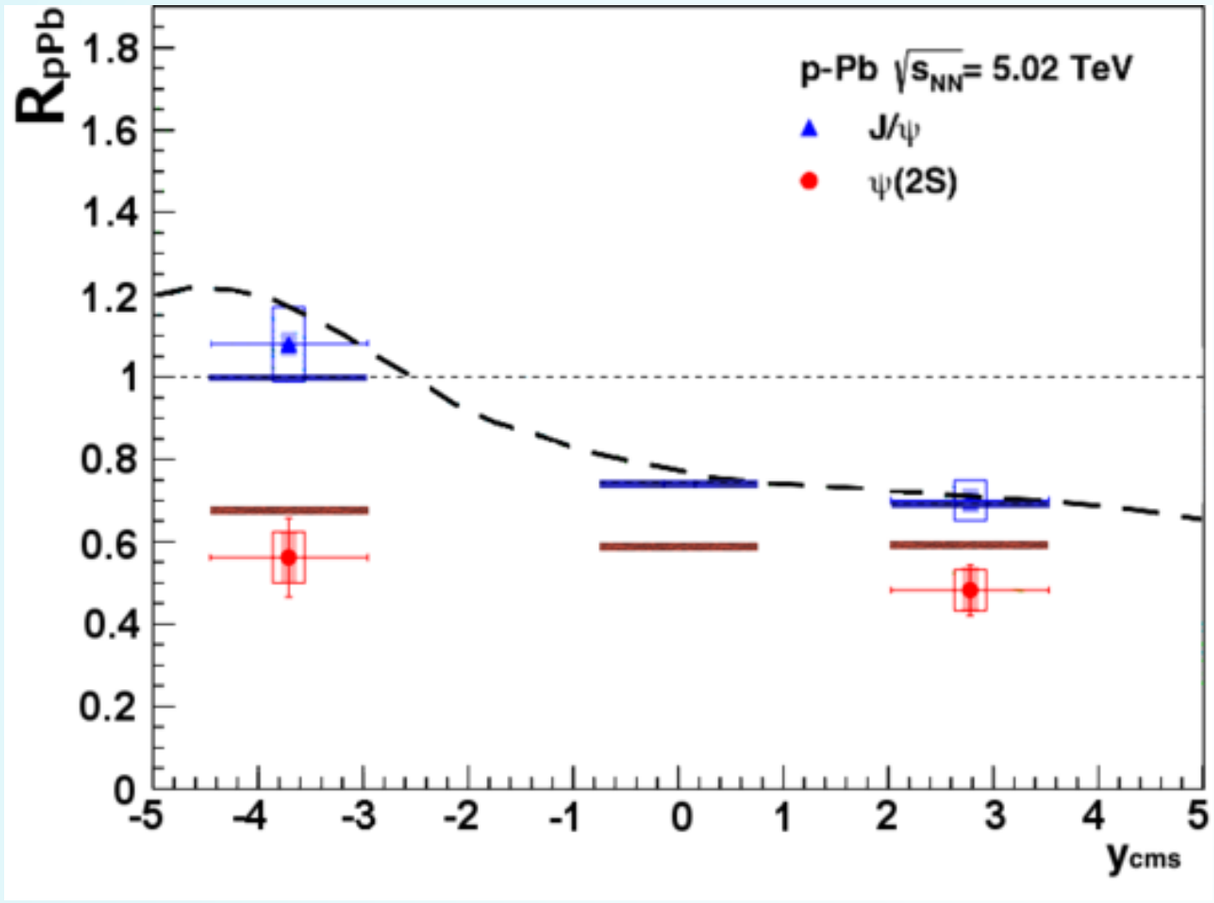
Comovers: Hadrons or partons moving along the direction of quarkonium in the final state

Many comovers

A few comovers

Comover effect breaks factorization of quarkonium production at long distance. However, quarkonium can be formed outside the medium when pt or rapidity is large. $\Longrightarrow$ Factorization breaking is weak at forward rapidity.

Hadron Comover model



Ferreiro (2014)

psi(2S) is a loosely binding system.

$$\sigma^{co-\psi(2S)} \gg \sigma^{co-J/\psi}$$

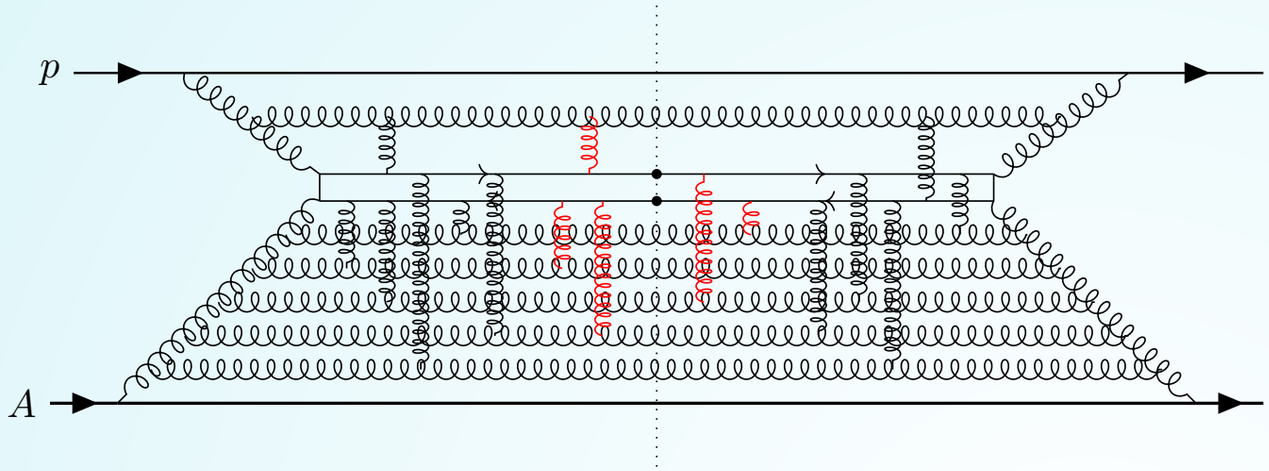
$$\left.\frac{dN_{ch}^{pA}}{dy}\right|_{\text{back}} > \left.\frac{dN_{ch}^{pA}}{dy}\right|_{\text{forw}}$$

$$\rho^{co}(b,s,y) = n(b,s) S_{co}^{sh}(b,s) \frac{3}{2} \frac{dN_{ch}^{pp}}{dy}$$

$$S_{\psi}^{co}(b,s,y) = \exp\left[-\sigma^{co-\psi} \rho^{co}(b,s,y) \ln \frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]$$

$$R_{pA}^{\psi}(b) = \frac{\int d^2s \sigma_{pA}(b) n(b,s) S_{\psi}^{sh}(b,s) S_{\psi}^{co}(b,s)}{\int d^2s \sigma_{pA}(b) n(b,s)}$$

Parton Comovers in the CGC



Ma, Venugopalan, KW, Zhang (2017)

Many gluons are produced in the direction of the pair at forward rapidity.

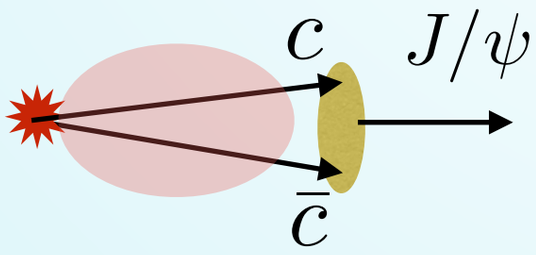
Fitted in p+p

$$\frac{d\sigma_\psi}{d^2p_\perp dy} = F_{Q\bar{Q}\to\psi}\int_{m_\psi}^{2m_Q-\Lambda} dM \left(\frac{M}{m_\psi}\right)^2 \frac{d\sigma_{Q\bar{Q}}}{dM d^2p'_\perp dy}\bigg|_{p'_\perp=\frac{M}{m_\psi}p_\perp}$$

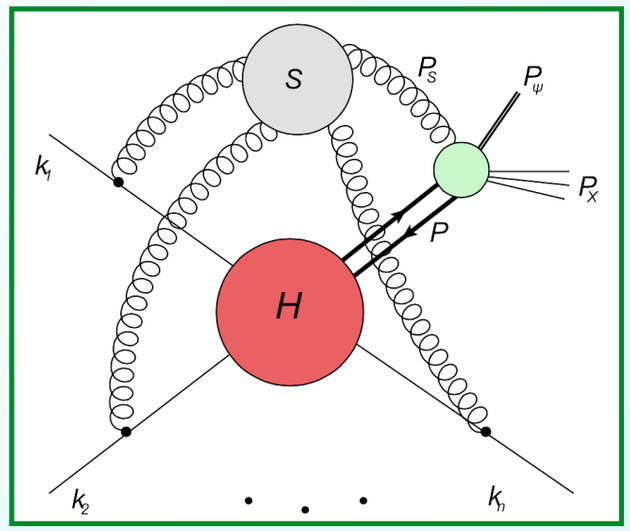
Λ: the average momentum kick given by additional nuclear parton comvers.

$$M^2 \to M^2 + \Lambda^2$$

Decoherence of the pair



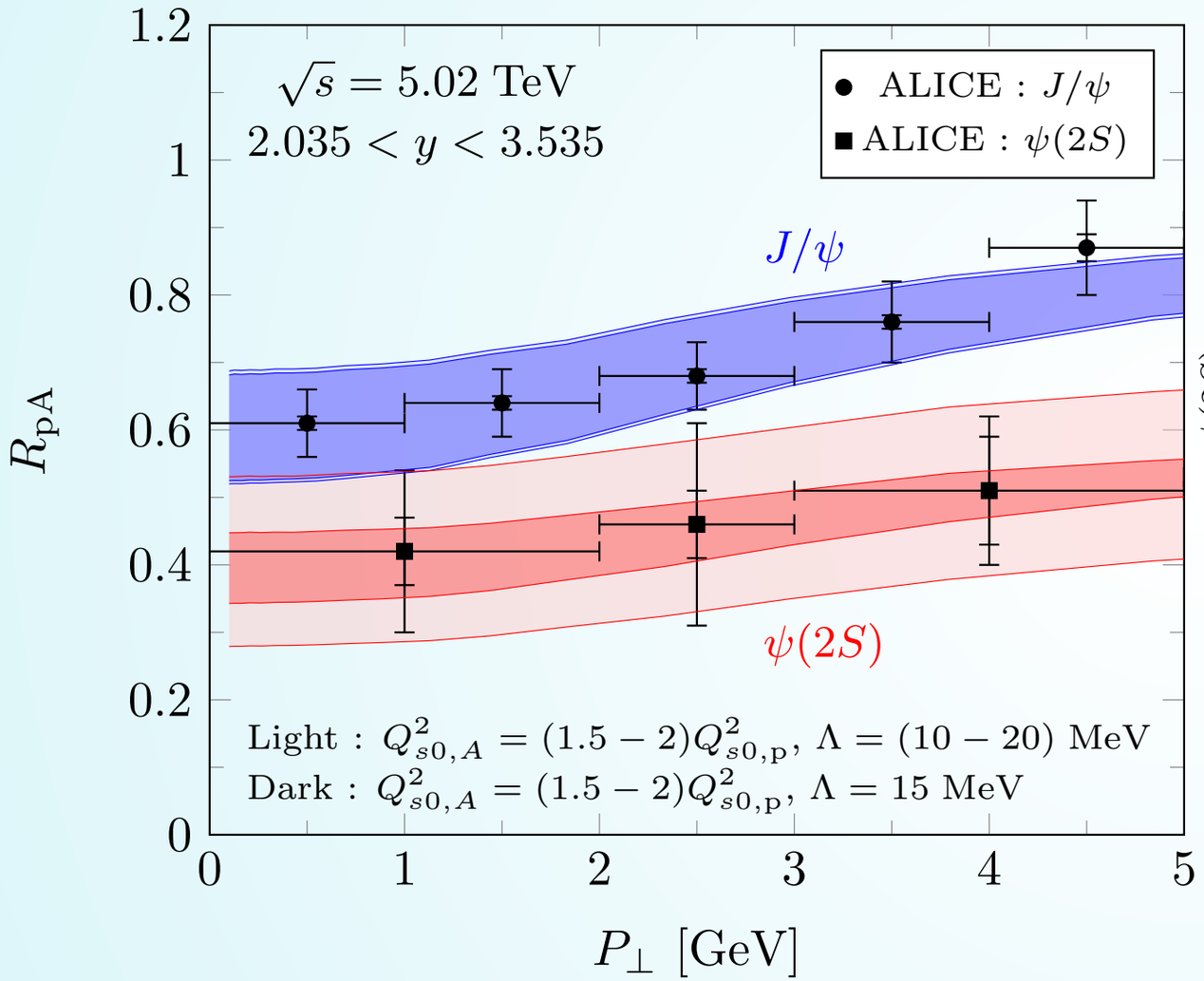
Improved CEM

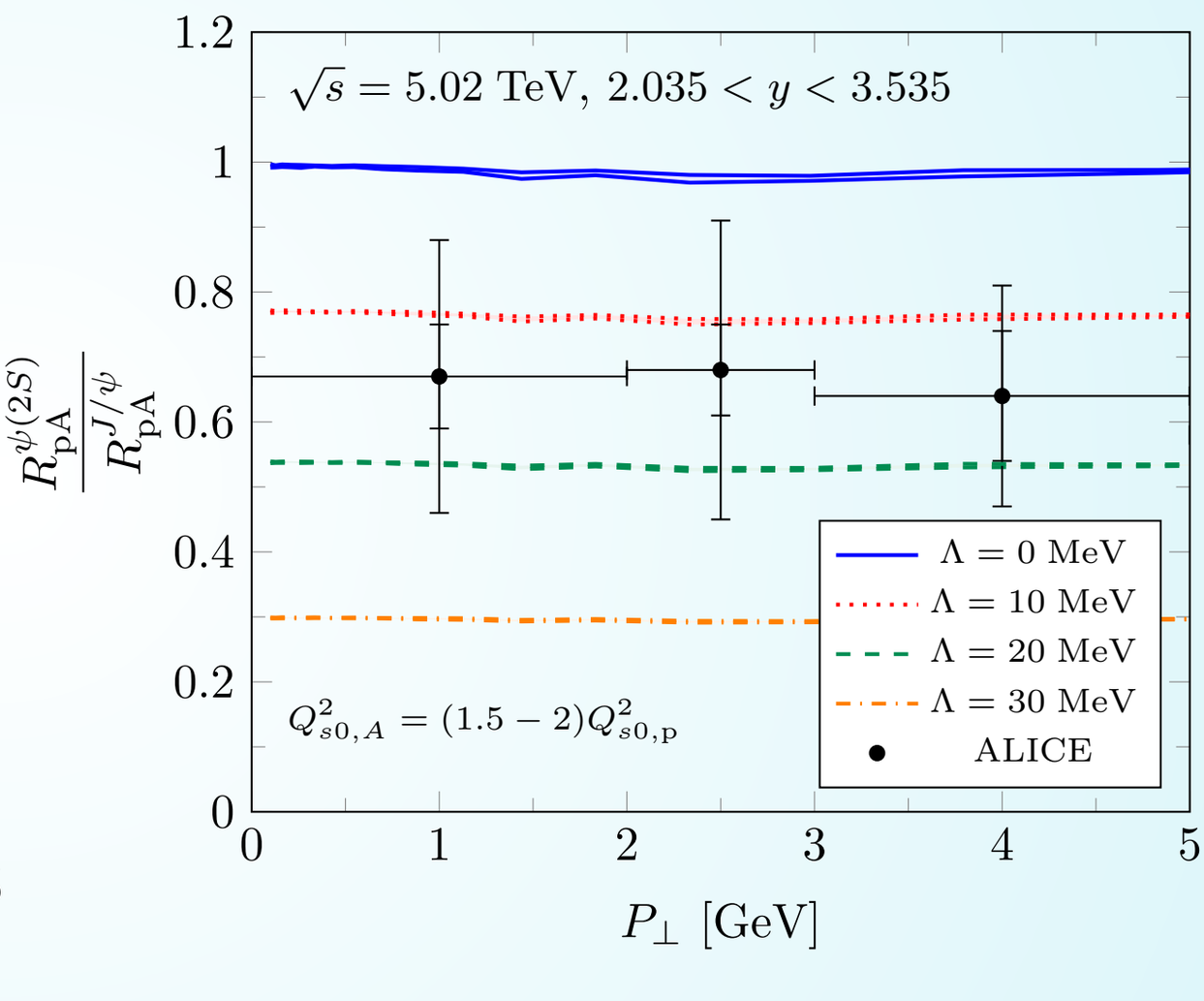


Parton shower effect during the quarkonium hadronization

Parton Comovers in the CGC

Ma, Venugopalan, KW, Zhang (2017)





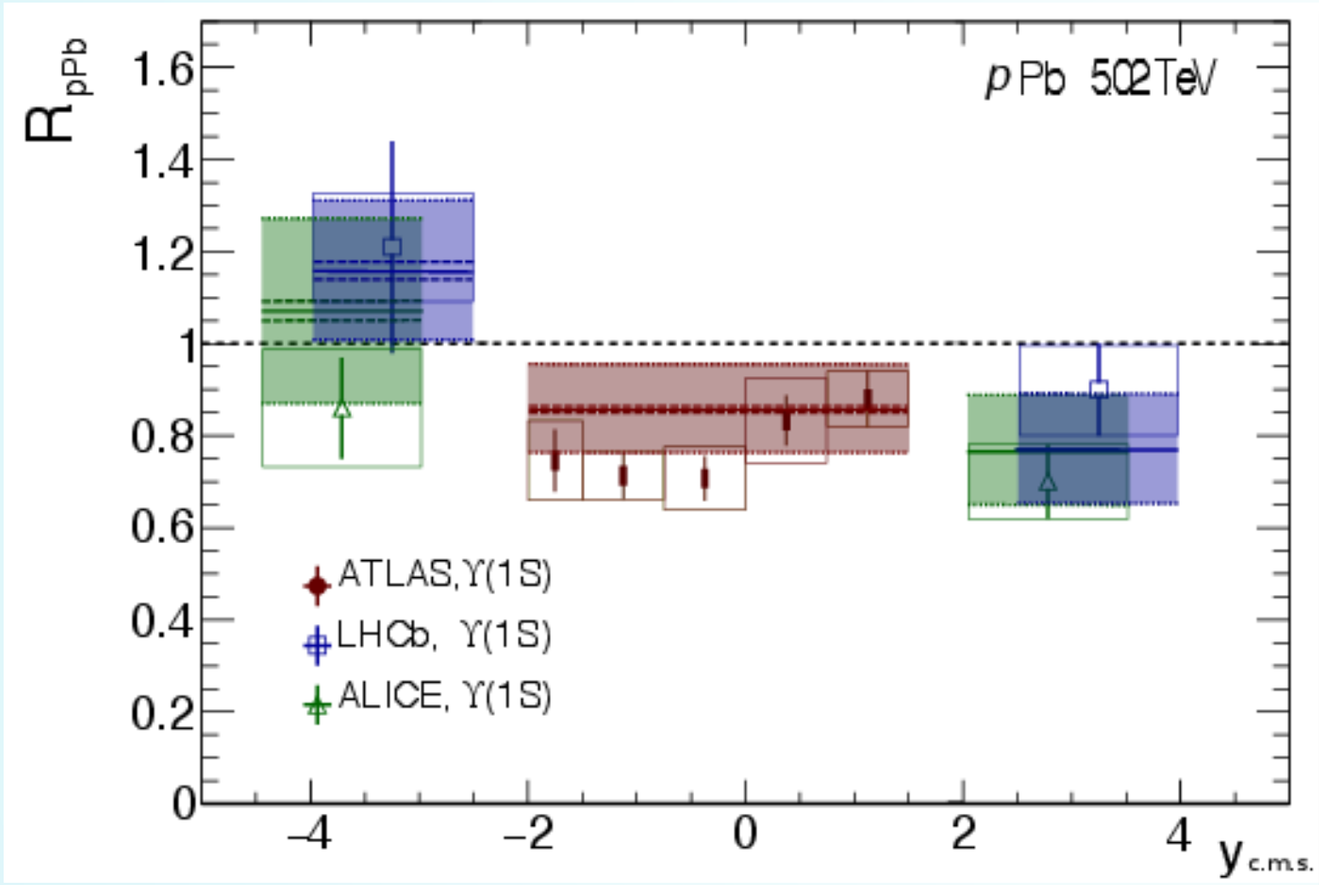
Important assumption: Λ does not depend on pt, y, s

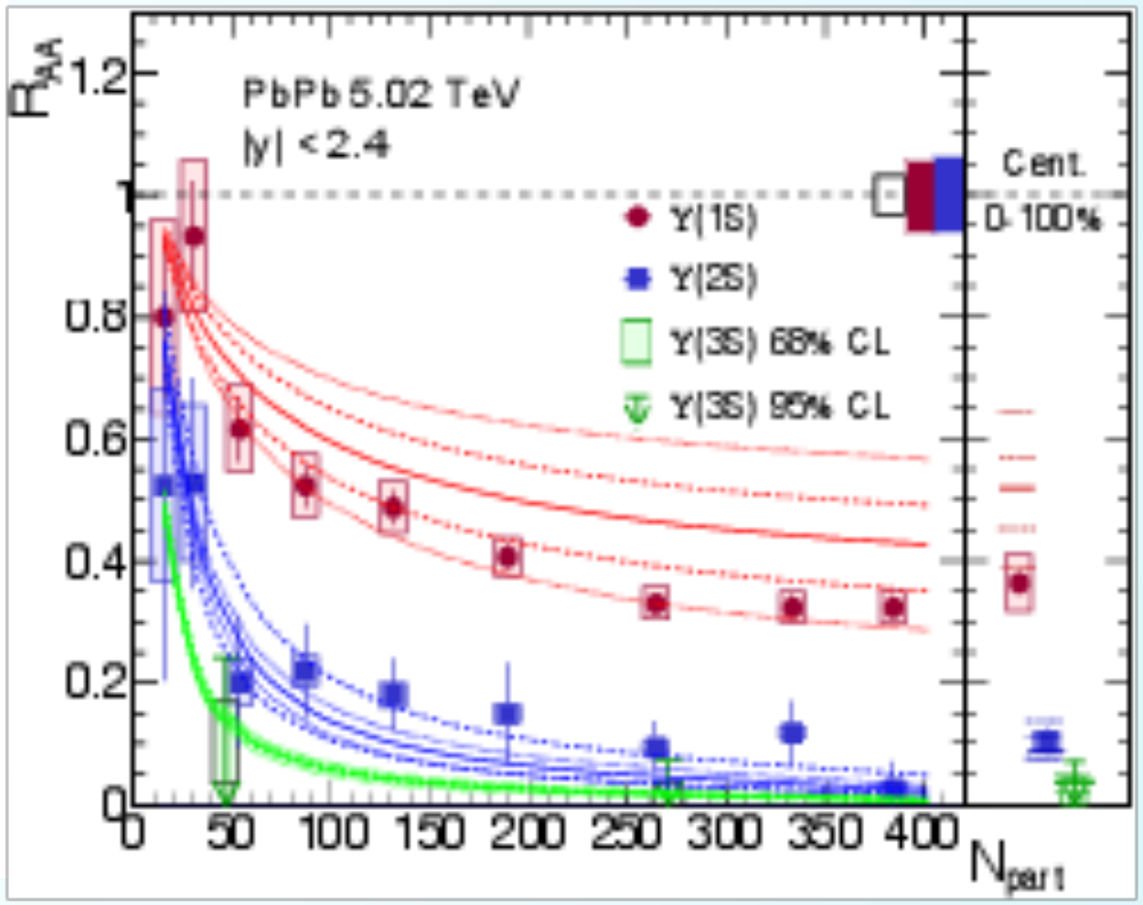
Caveat: The CGC works only at mid and forward rapidity.

Comover effect in A+A

nPDFs + Comover effect

Ferreiro, Lansberg (2018)

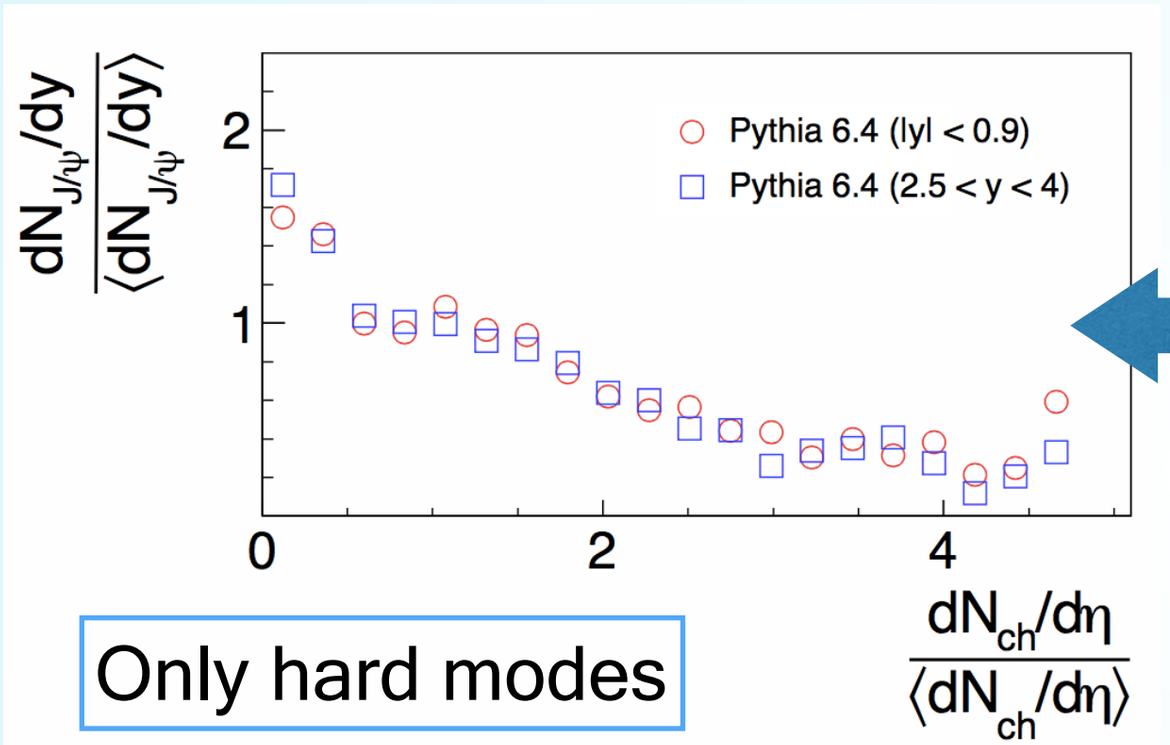




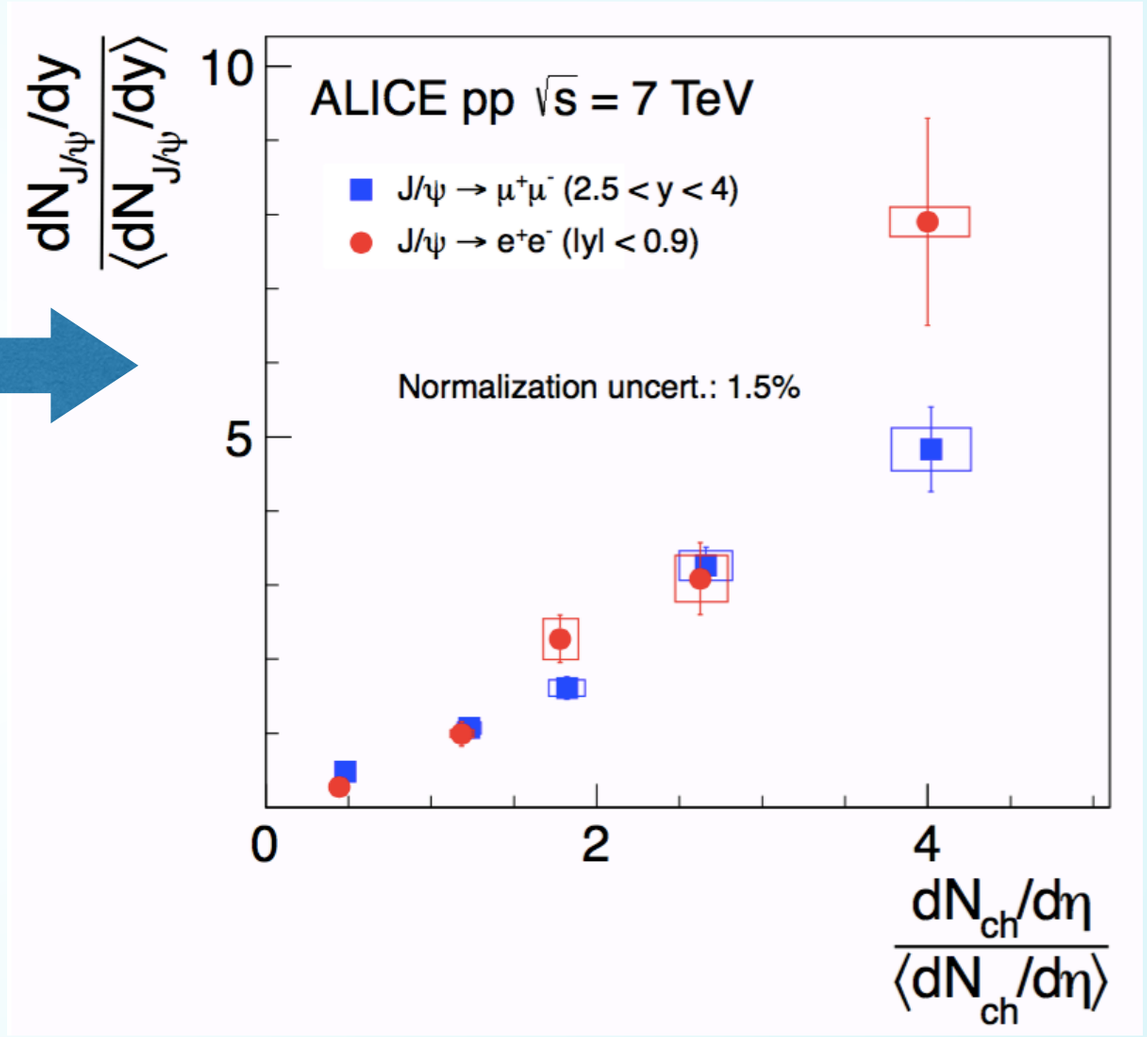
What should we learn from comover cross section?

Event activity dependence

ALICE Collaboration,
PLB712 (2012)



Only hard modes



Final state effect (Hydro) or Initial state effect (CGC)?

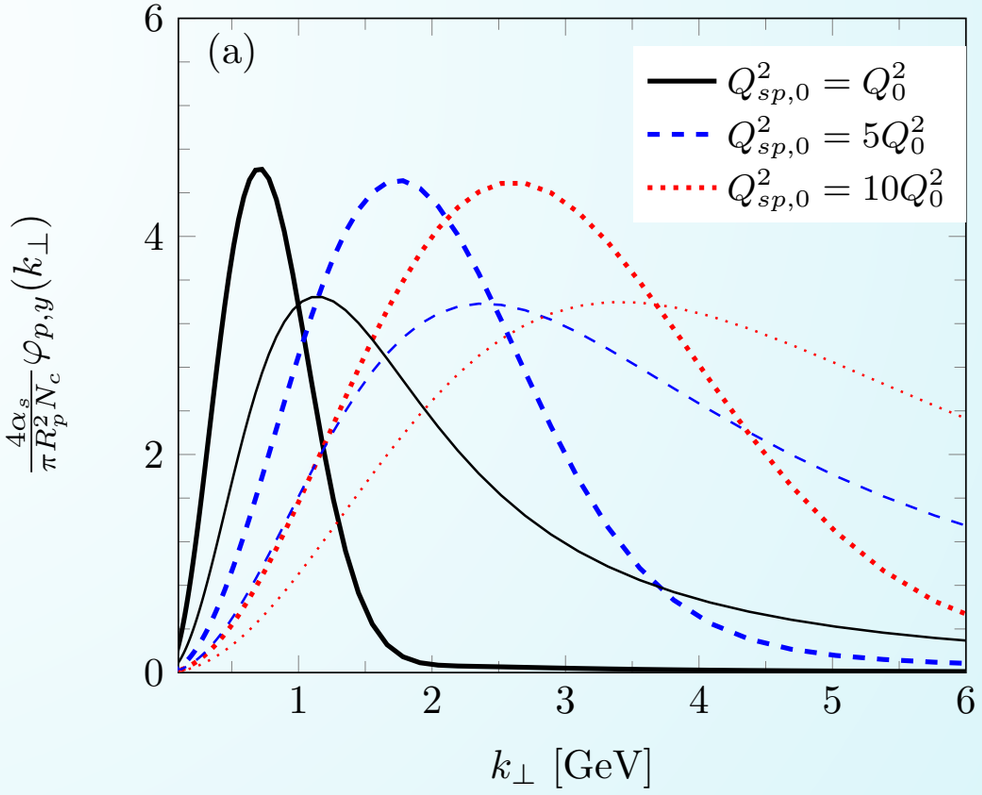
What is J/psi's production mechanism at large Nch?

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.
- High multiplicity events correspond to rare parton configurations with larger saturation scales.

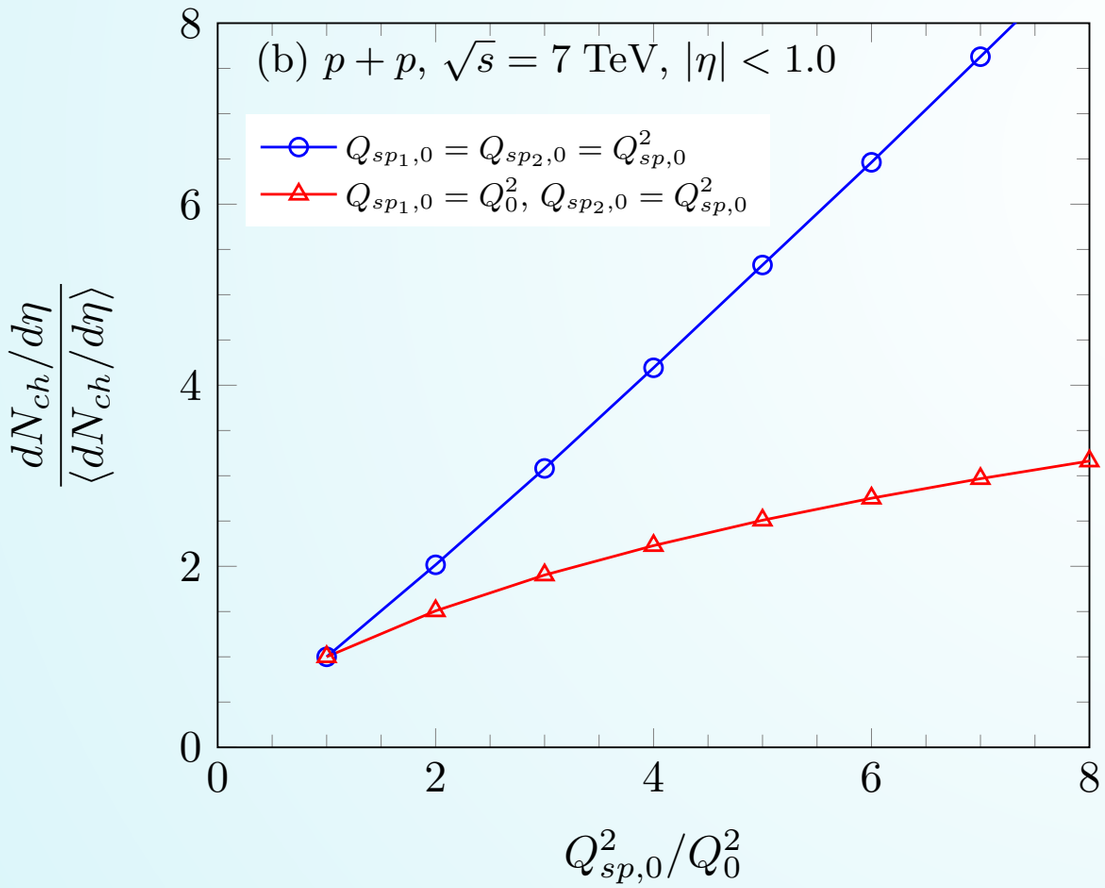


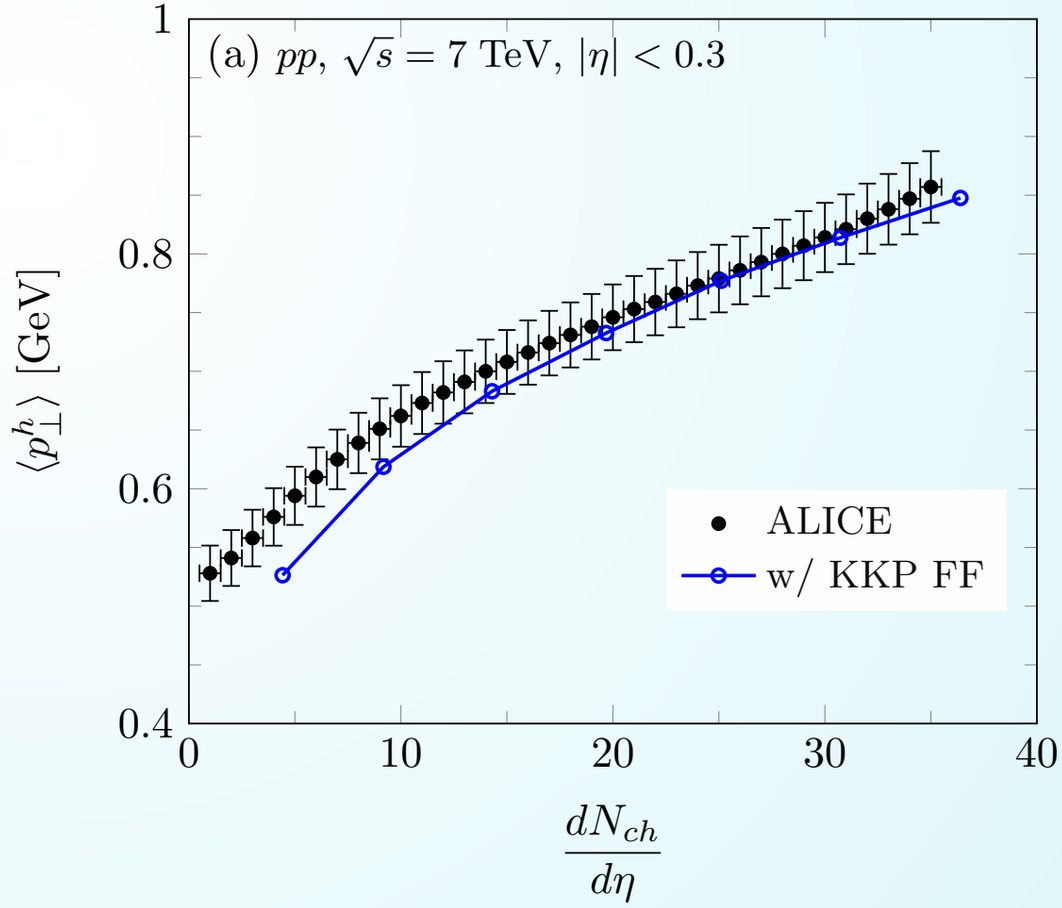
Nch vs Qs

Ma, Venugopalan, Tribedy, KW (2018)

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

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

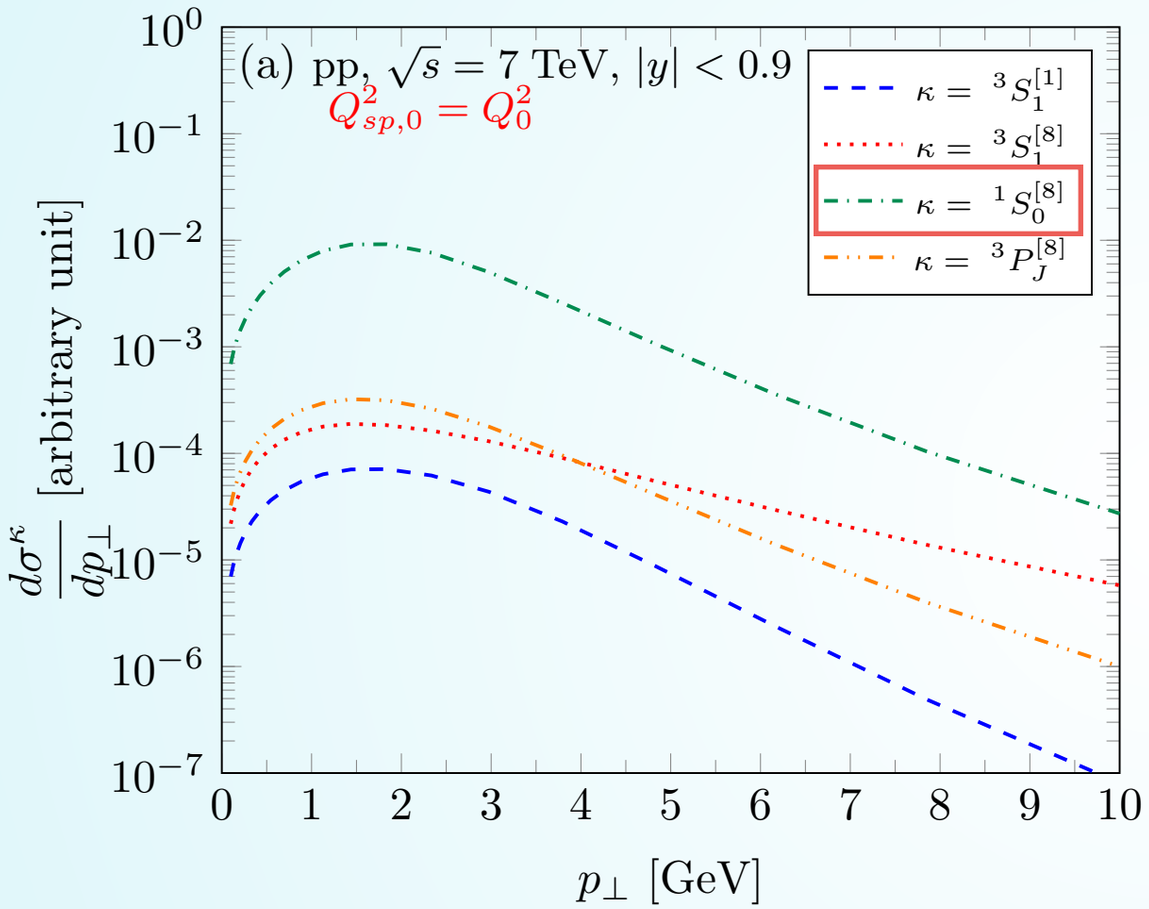




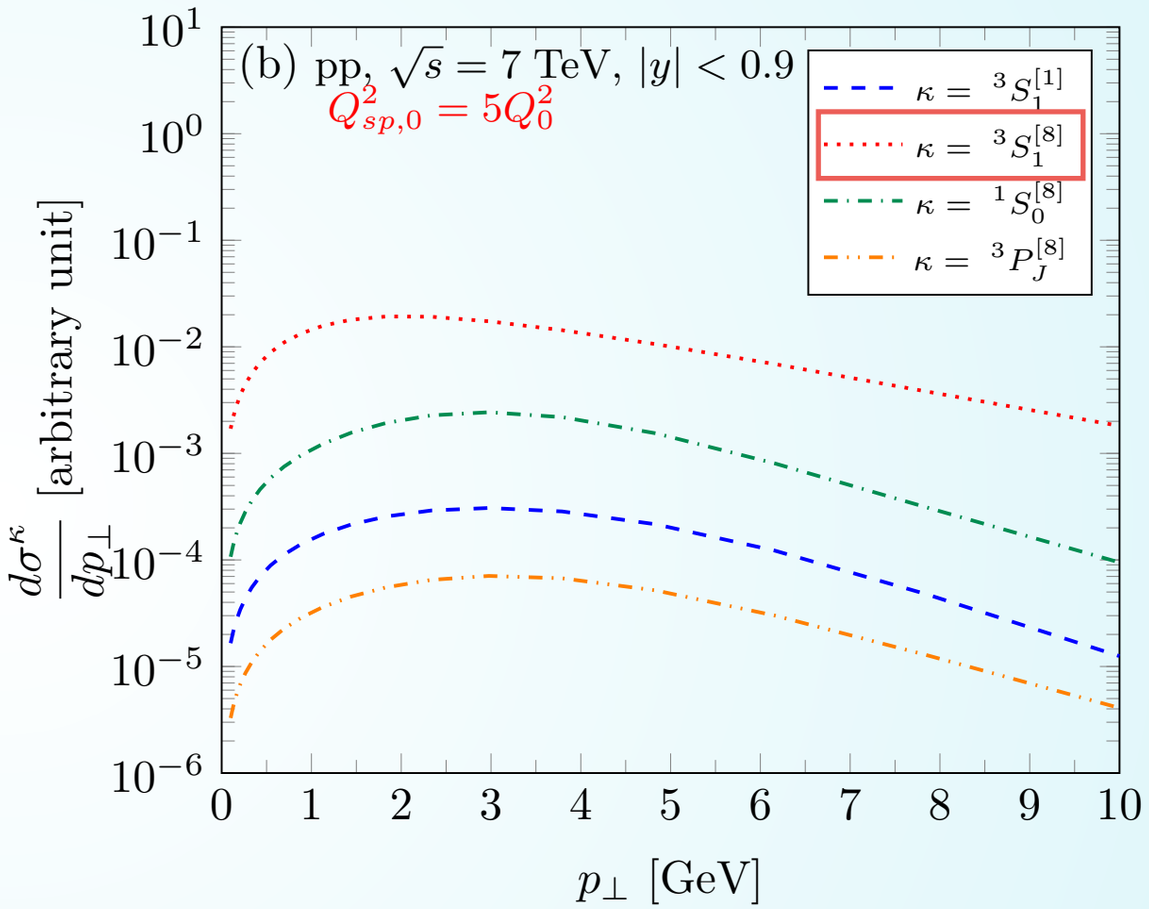
Similar pt-broadening is seen in high multiplicity p+A collisions.

MB vs High Multiplicity events

Ma, Venugopalan, Tribedy, KW (2018)

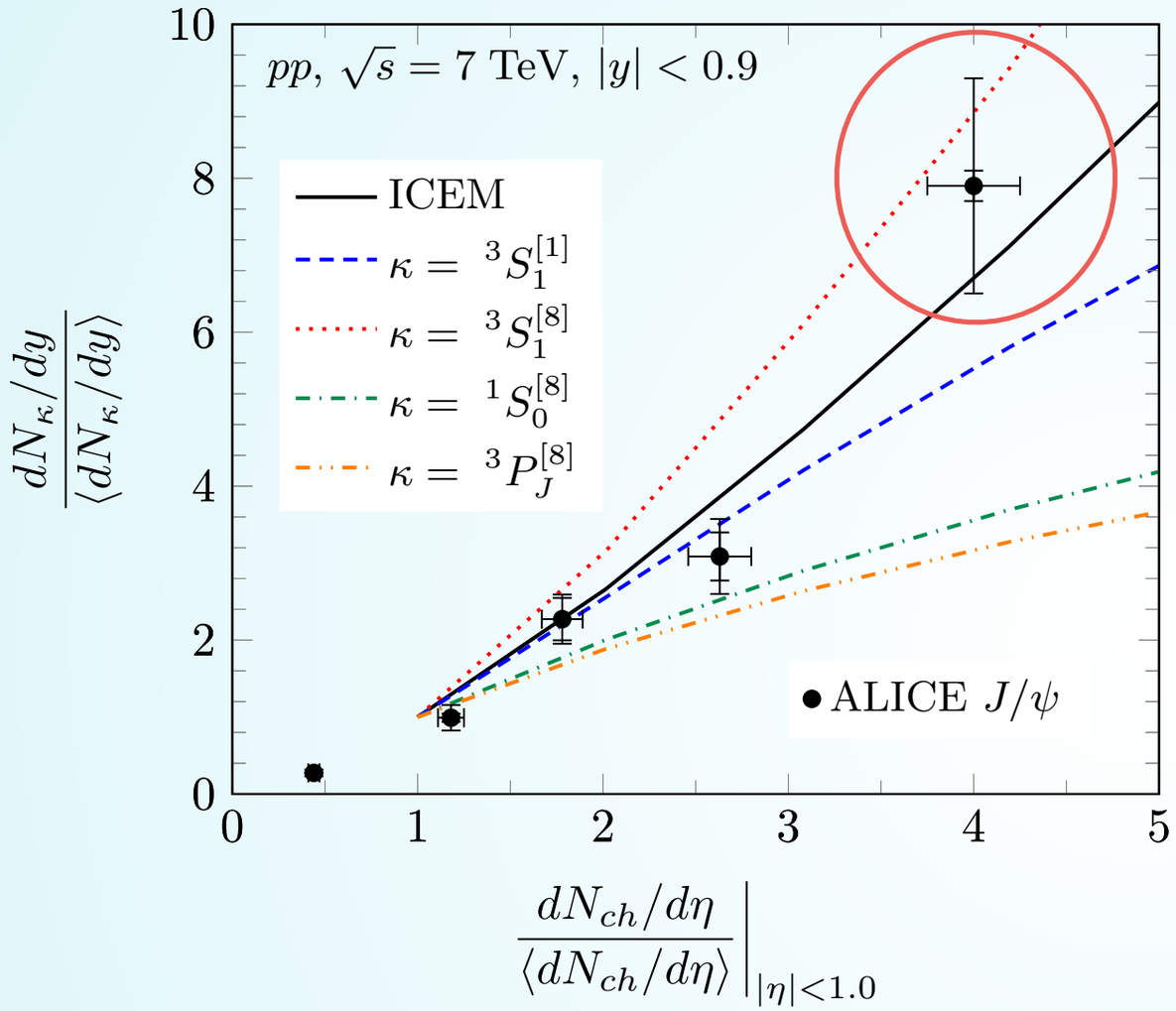


MB events



HM events

New insight into the LDMEs?



3S1 octet channel should have a larger weight compared to MB, if we require the CGC framework to reproduce the data.

Note: b-quark decay contribution is not included.

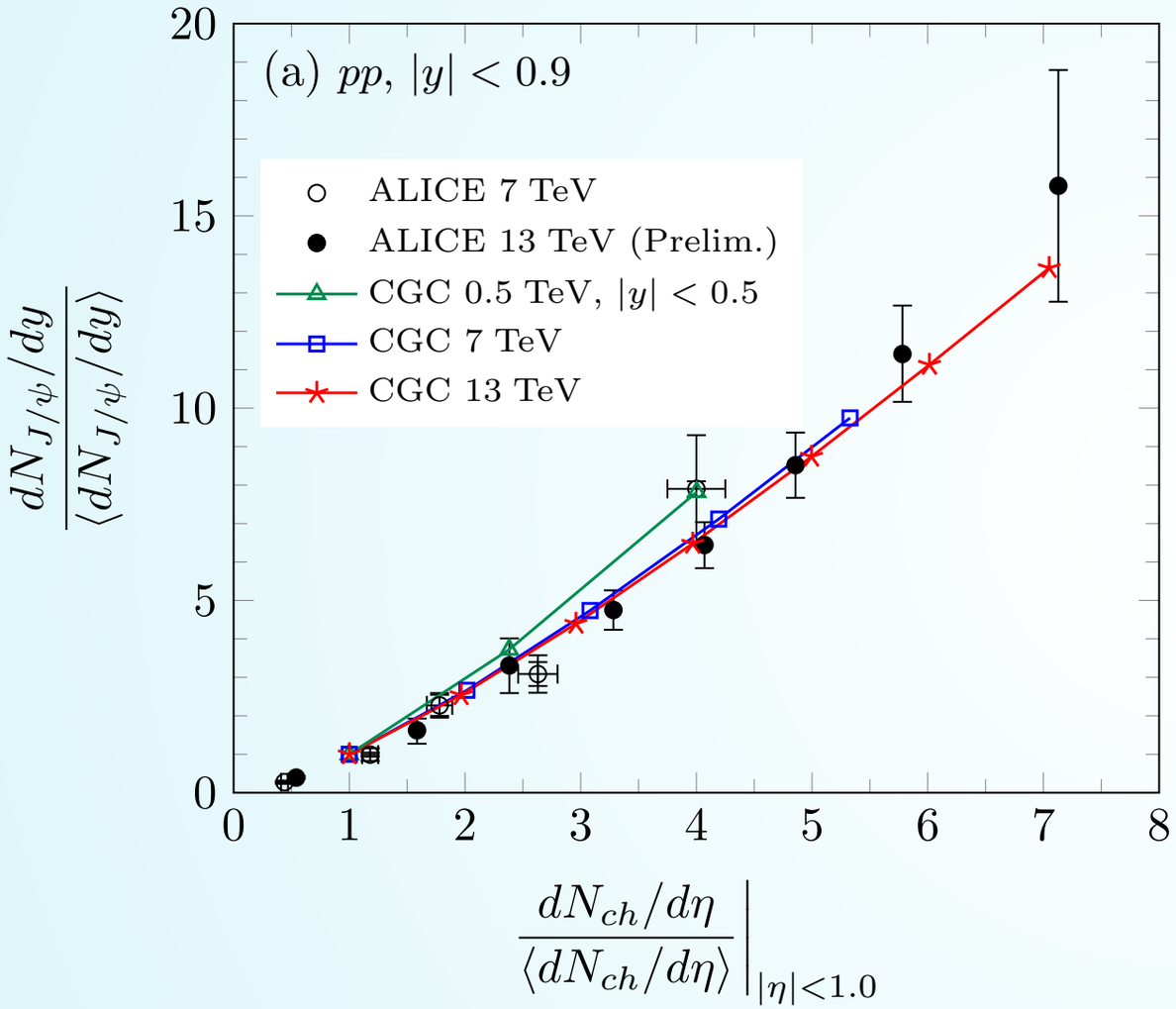
- Consistent with the universality requirement from BELLE e^+e^- data:

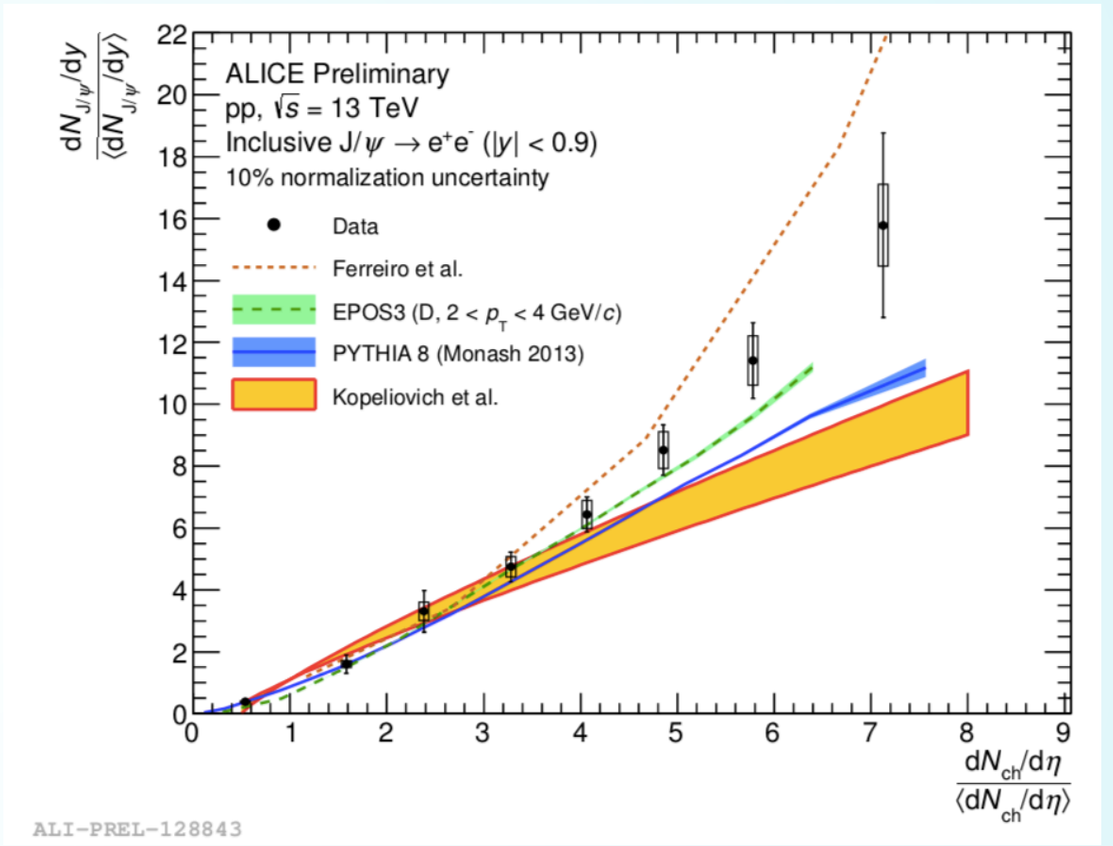
$$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle + 4.0\langle \mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m^2 < 2.0 \pm 0.6 \times 10^{-2}\mathrm{GeV}^3$$

Zhang, Ma, Wang, Chao, PRD**81** (2010)

Model comparisons

Ma, Tribedy, Venugopalan, KW (2018)





Similar results are obtained in p+A collisions in the CGC.

$\Longrightarrow$ The initial fluctuation effect is essential in the small system.

Wrap up

- nPDFs $\Longrightarrow$ Rapidity dependence, High pt
- Gluon saturation $\Longrightarrow$ Forward rapidity, Low pt
- Energy loss $\Longrightarrow$ Rapidity dependence, pt dependence
- Nuclear absorption and Comover effect $\Longrightarrow$ Target rest frame, Rapidity dependence

p+A collision gives a test of multiple scattering in the nucleus.

Thank you!

Backup