

Event activity dependence of heavy flavor and quarkonium production in small collision systems

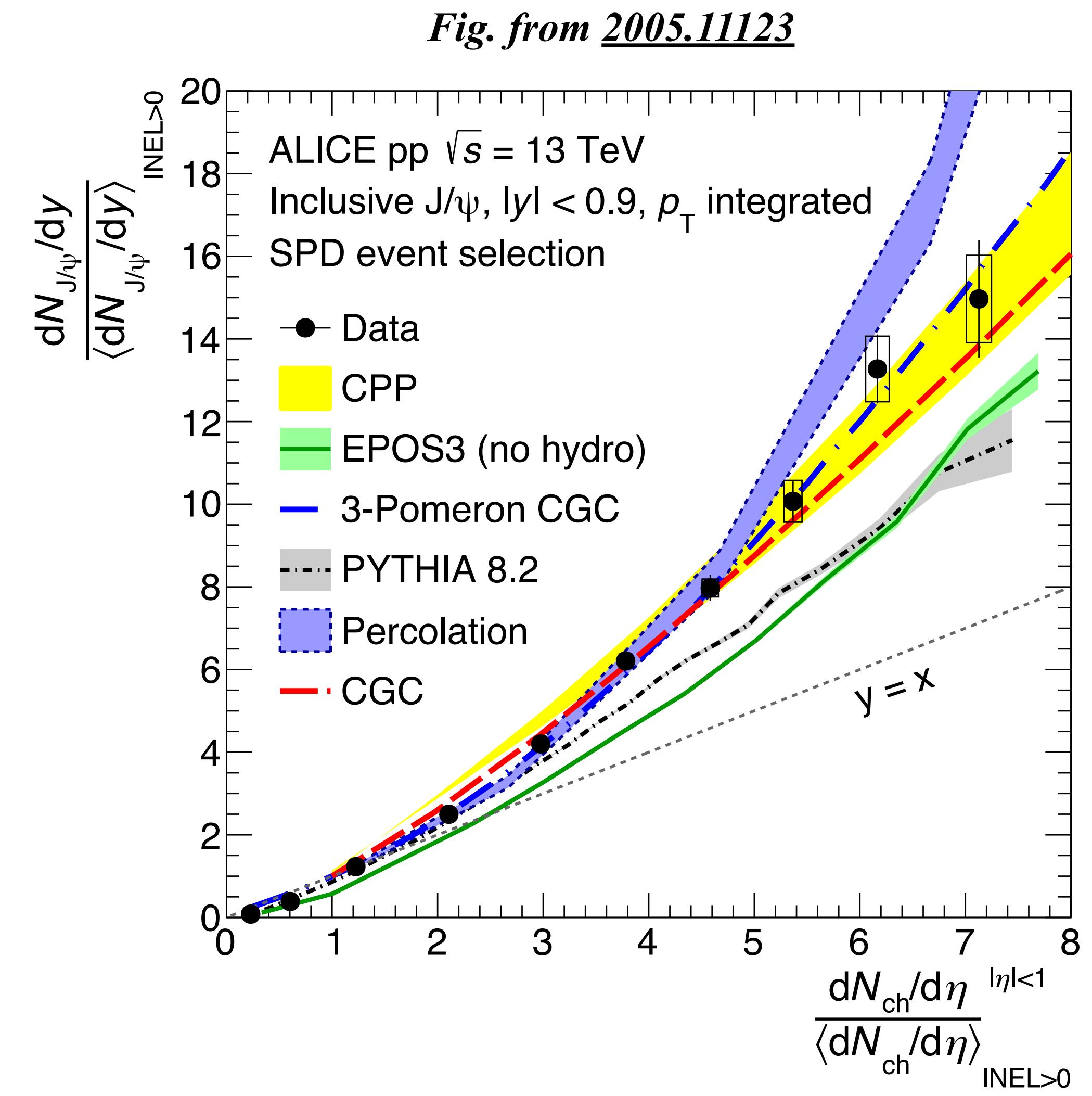
Kazuhiko Watanabe



March 25th, 2021
virtual Quarkonia As Tools 2021

Aims

- Multiplicity dependence of quarkonium production in small collision systems is a puzzle. We want to understand the QCD dynamics behind such rare events.
- Need to clarify how we can interpret data using theoretical models.
- We will look into some theoretical approaches, in particular, CGC/Saturation approach a little more closely.
- See [Guittiere's talk](#) (Monday 11am) about an experimental overview.



Bulk particle production

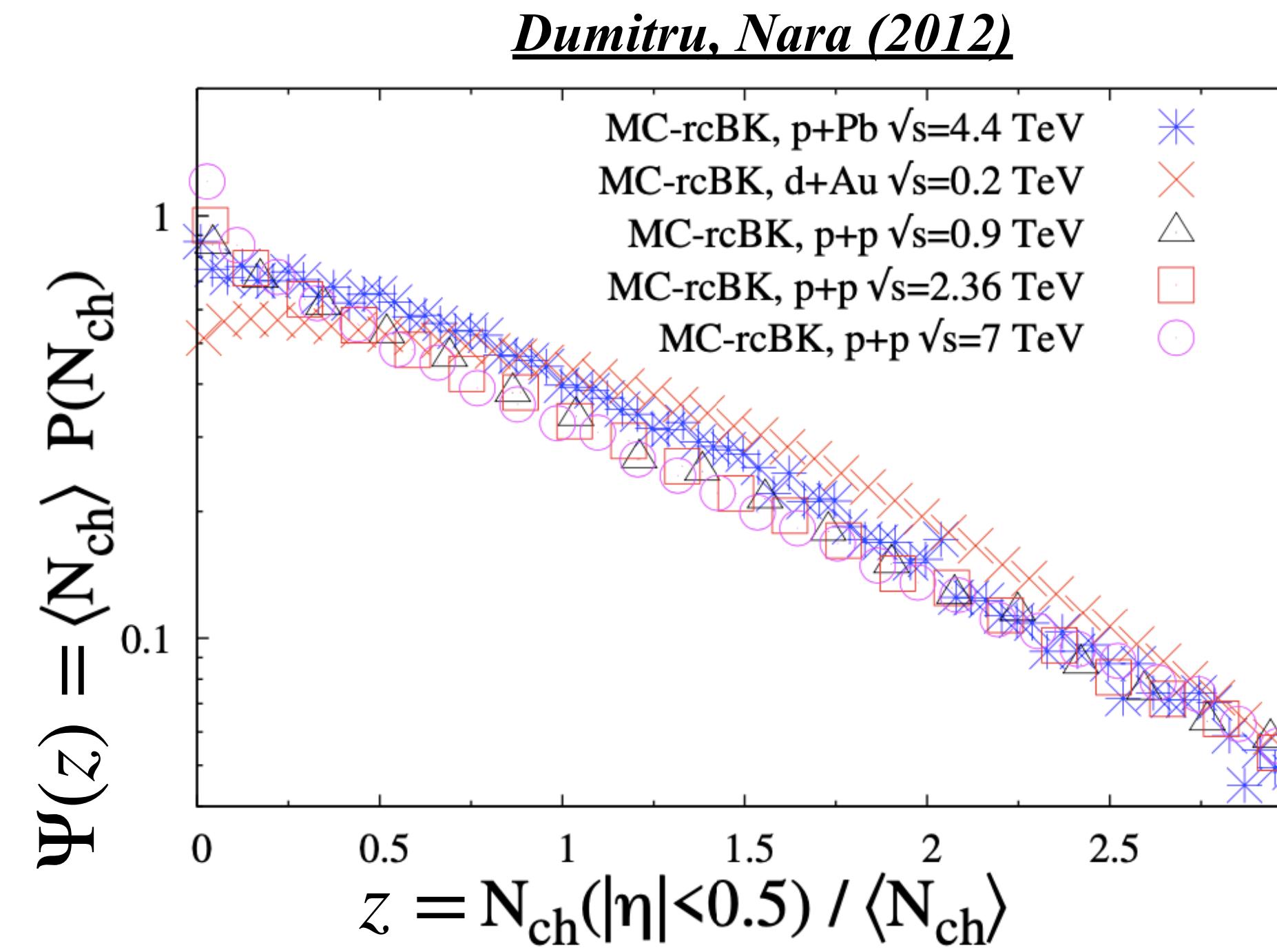
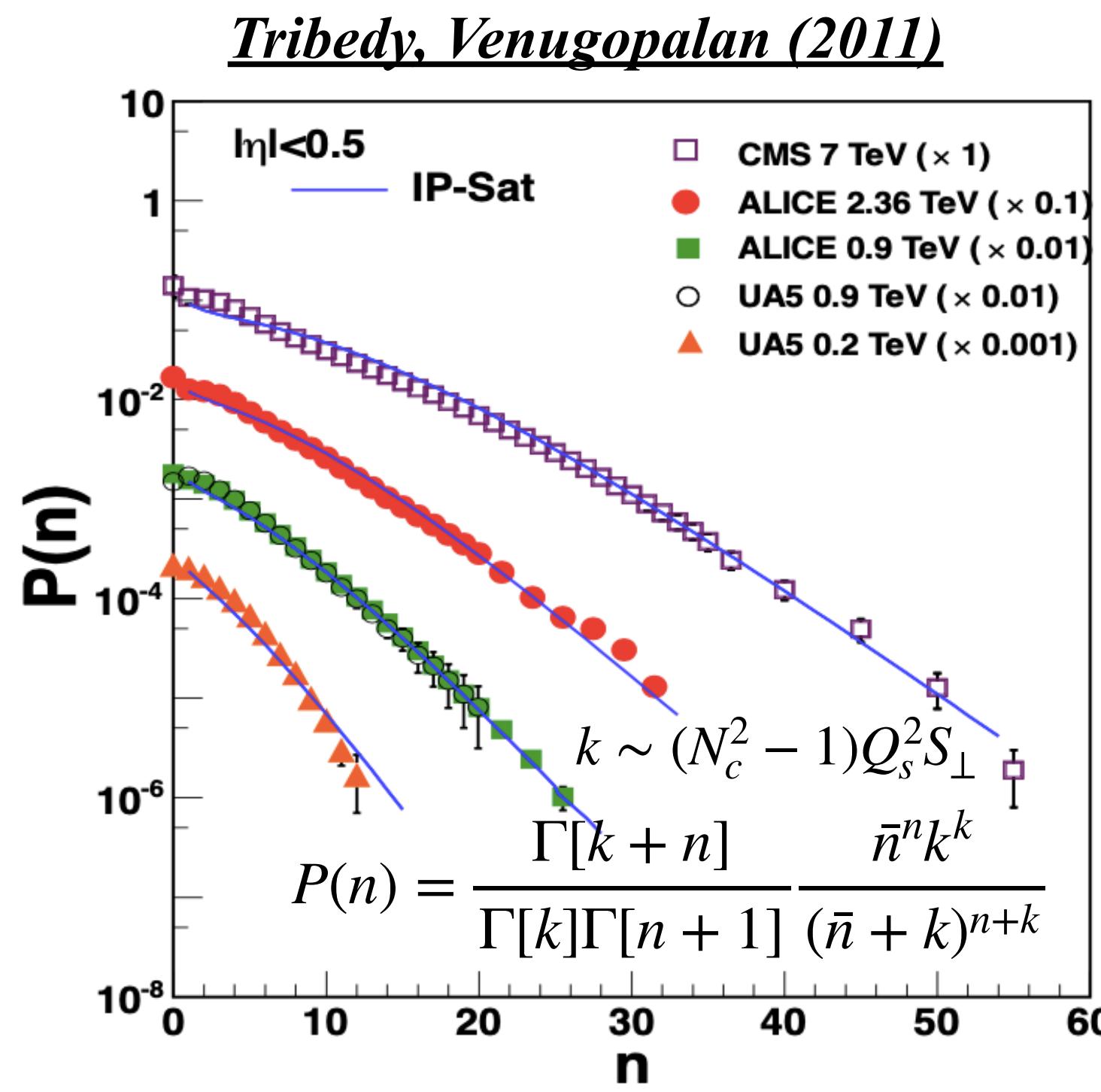
Color Glass Condensate EFT (weak coupling theory) is a robust tool to study bulk properties in heavy-ion collisions: $\alpha_s(Q_s) < 1$ when $Q_s \gg \Lambda_{\text{QCD}}$. Qualitative estimate in a dilute-dense system A+B (p+A) or dense system (p+p or A+A) at forward rapidity:

$$\frac{dN_{ch}}{d\eta} \propto S_\perp Q_{min}^2 \sim N_{\text{part}}$$

$$Q_{min} = \min . \{ Q_{s,A}, Q_{s,B} \} \quad \text{and} \quad Q_{max} = \max . \{ Q_{s,A}, Q_{s,B} \}$$

Dumitru, McLerran (2001)

Kharzeev, Nardi (2000)



- KNO scaling was found in pp/ppbar collisions at $\sqrt{s_{\text{NN}}} \lesssim 200 \text{ GeV}$ UA5 (1986)
- If KNO scaling breaks down, soft multiple particle interactions could play an essential role.
- In the CGC framework, we can see KNO scaling in pp collisions even at the LHC up to $n/\bar{n} \leq 3$, but not in pA collisions: KNO scaling is weakly violated.
- The CGC gives semihard multiple interactions.

Particle production from Glasma flux tubes gives negative binomial distribution.

Gelis, Lappi, McLerran (2009)

Inclusive particle production in the CGC framework

Multiple gluons are also produced from the Glasma flux tube decay that accounts for the negative binomial distribution of multiplicity. Even though multiple gluons are produced in a dense-dense Glasma system, we will start with k_t -factorization for inclusive multiplicity distributions in a dilute-dense system (CGC).

Inclusive gluon production at LO in a dilute-dense system:

Blaizot, Gelis, Venugopalan (2004)

$$\frac{dN_g(b_\perp)}{d^2p_{g\perp}dy_g} = \frac{\alpha_s}{(2\pi)^3 \pi^3 C_F} \frac{1}{p_{g\perp}^2} \int d^2k_\perp \int d^2s_\perp \frac{d\phi_{x_1}^{g,g}(k_\perp | s_\perp)}{d^2s_\perp} \frac{d\phi_{x_2}^{g,g}(p_{g\perp} - k_\perp | s_\perp - b_\perp)}{d^2s_\perp}$$

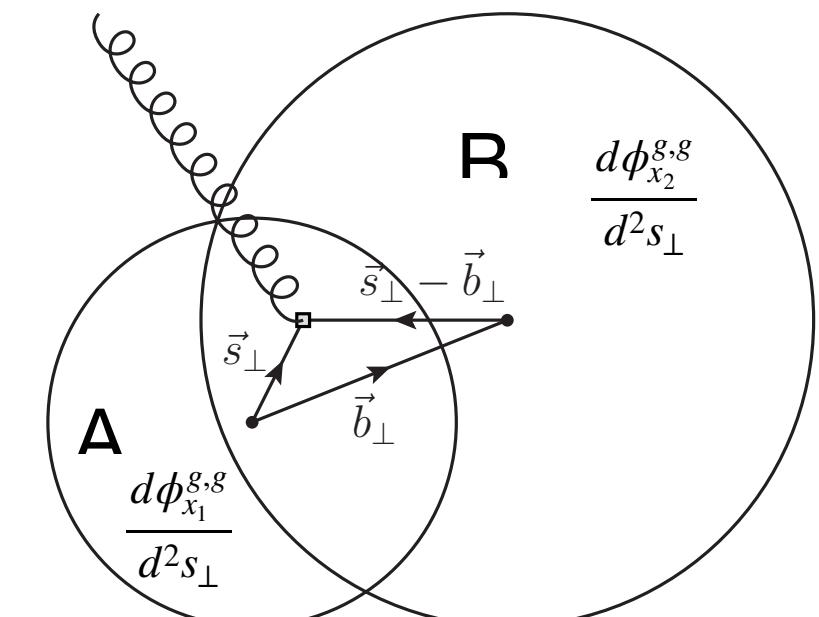
- Charged hadrons: FF or LPHD (next slide)

Inclusive heavy quark pair production at LO in a dilute-dense system:

$$\frac{dN_{c\bar{c}}(b_\perp)}{d^2p_{c\perp}d^2p_{\bar{c}\perp}dy_c dy_{\bar{c}}} = \frac{\alpha_s^2}{16\pi^4 C_F} \int \frac{d^2k_{2\perp} d^2k_\perp}{(2\pi)^6} \frac{\Xi(k_{1\perp}, k_{2\perp}, k_\perp)}{k_{1\perp}^2 k_{2\perp}^2} \int d^2s_\perp \frac{\phi_{x_1}^{g,g}(k_{1\perp} | s_\perp)}{d^2s_\perp} \frac{\phi_{x_2}^{q\bar{q},g}(k_{2\perp}, k_\perp | s_\perp - b_\perp)}{d^2s_\perp}$$

- D mesons: FF (KKKS, Peterson, BCFY,...)
For $1 < p_\perp < 4$ GeV, the dependence of FF models is small.
- Quarkonia: CEM, NRQCD, LC wave function,...

Large uncertainty associated with long-distance matrix elements (LDMEs).



Charged hadron production

Charged hadrons production of very low p_{\perp} is governed by soft physics, and it is not straightforward to calculate hadron production from the first principle: QCD.

- **Fragmentation function approach**

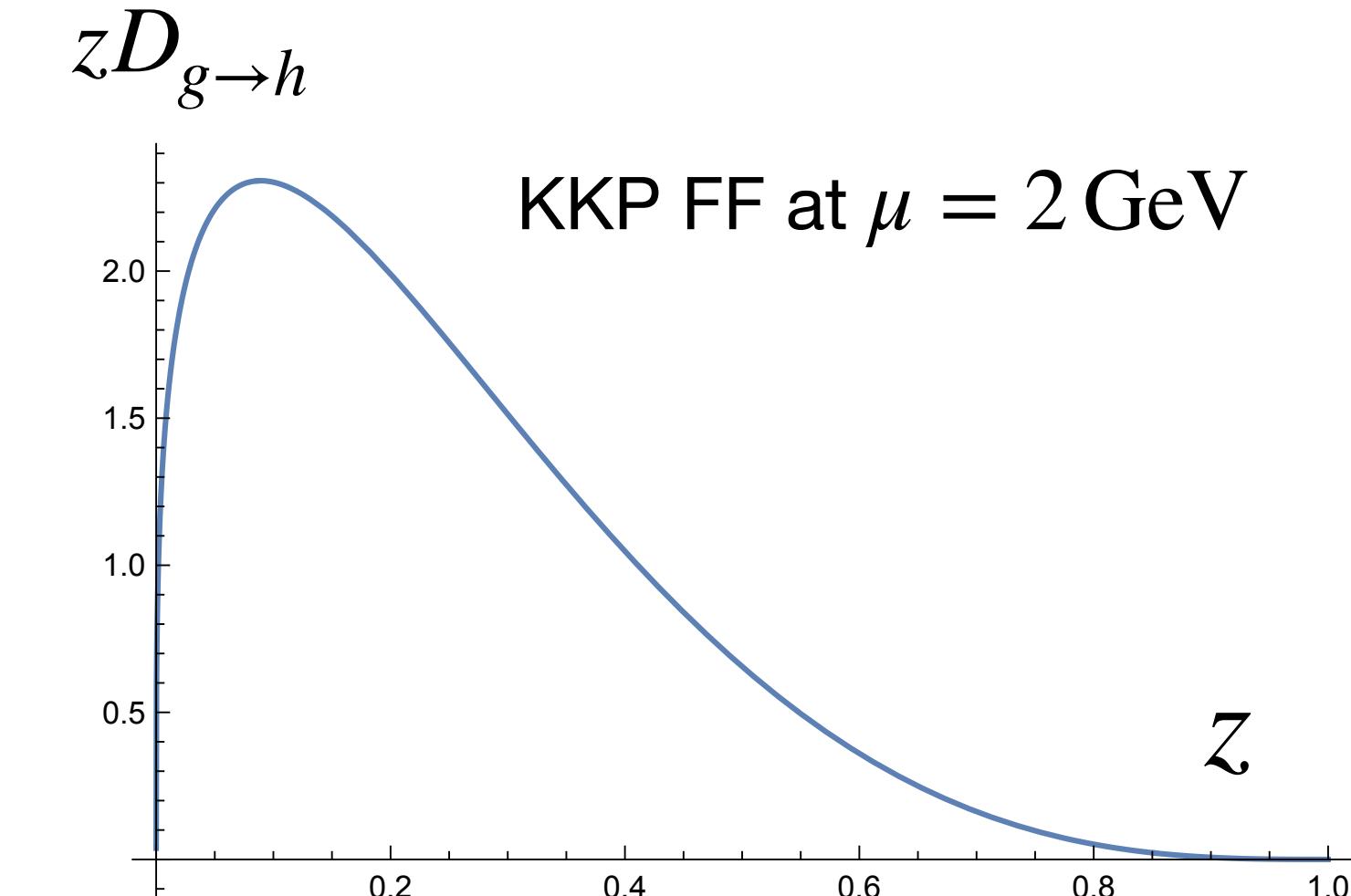
Hadronization happens at a later stage in vacuum.

DGLAP evolution changes the z-distribution of FF.

Small-x \longleftrightarrow Large-z: $0.1 < z < 1$ is relevant.

Caveat: Should not apply when $\mu < 1$ GeV or $p_{\perp} < 1$ GeV.

Need information on nonperturbative distribution.



- **Local Parton Hadron Duality (LPHD) Hypothesis**

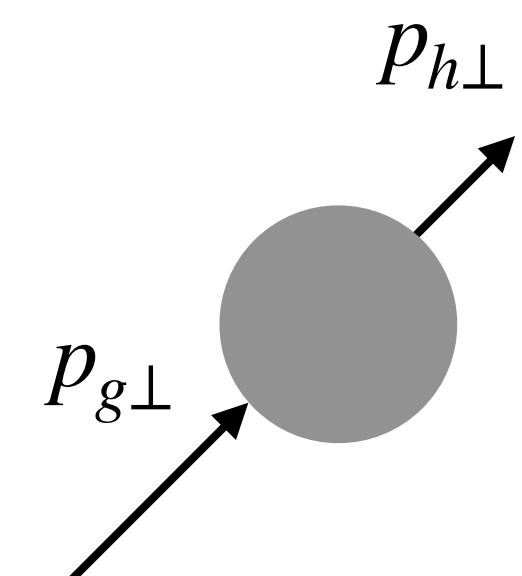
Hadronization happens at a later stage in vacuum (pre-confinement of QCD cascades).

Parton's momentum direction does not change during hadronization.

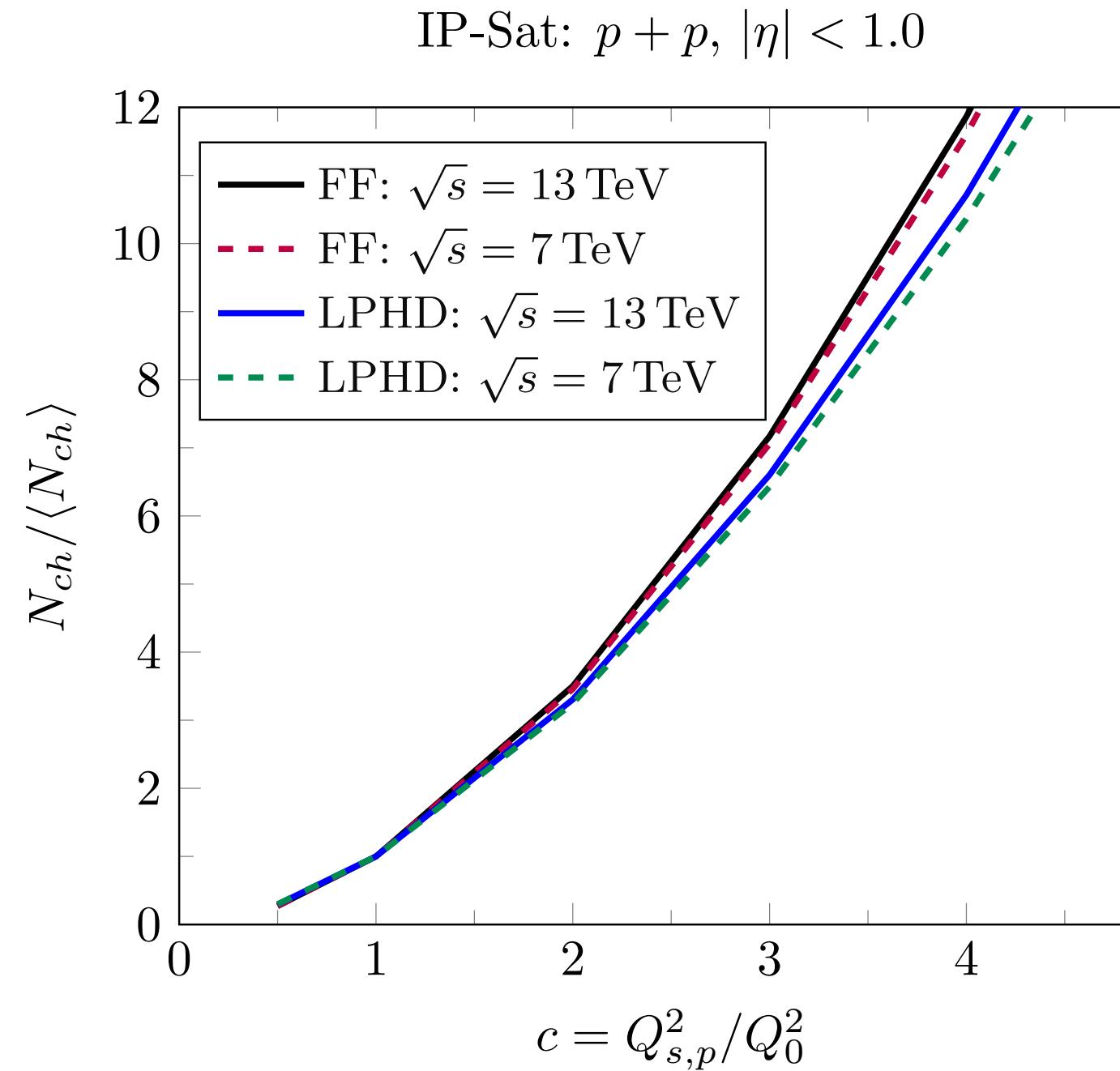
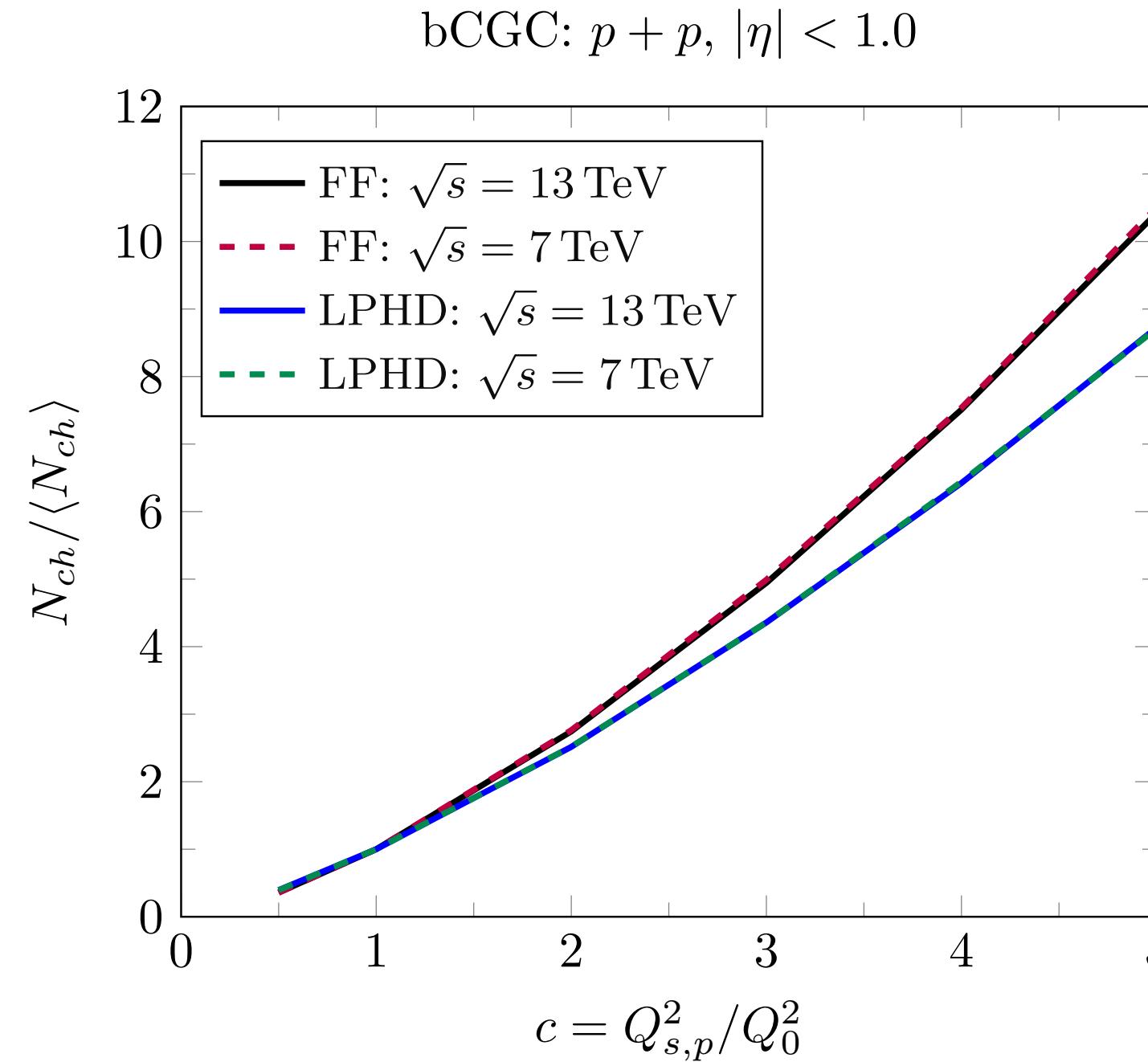
Pt spectrum is obtained by replacing $p_{\perp}^g \langle z \rangle = p_{\perp}^h$.

But, bulk multiplicity does not depend on $\langle z \rangle$: $dN_{ch}/d\eta \sim dN_g/d\eta$.

Good description of multiplicity in e^+e^- .



Initial fluctuations



- The difference between FF and LPHD is about $<15\% (<20\%)$ at $c = 4$ in bCGC (IP-Sat).
- About 30% difference between bCGC and IP-Sat comes from the energy dependence of Q_s .
- The dilute-dense calculations with IP-Sat model can be extended toward the dense-dense calculations with IP-Glasma model. We will focus on IP-Sat.

- High multiplicity events $N_{ch} \gg \langle N_{ch} \rangle$ reflect rare parton configurations inside hadrons and nuclei.
- Phenomenological implementation: In pp collisions, $Q_{s,p} = c Q_0^2$, $c \geq 1$. In pA collisions, implementation gets more complicated due to the fluctuation from N_{coll} . Nevertheless, we shall set $Q_{s,A} = c \xi Q_0^2$, $c \geq 1$ and $\xi \sim 2$ or 3 for heavy targets.

Levin, Rezaeian (2010)

Dusling, Venugopalan (2013)

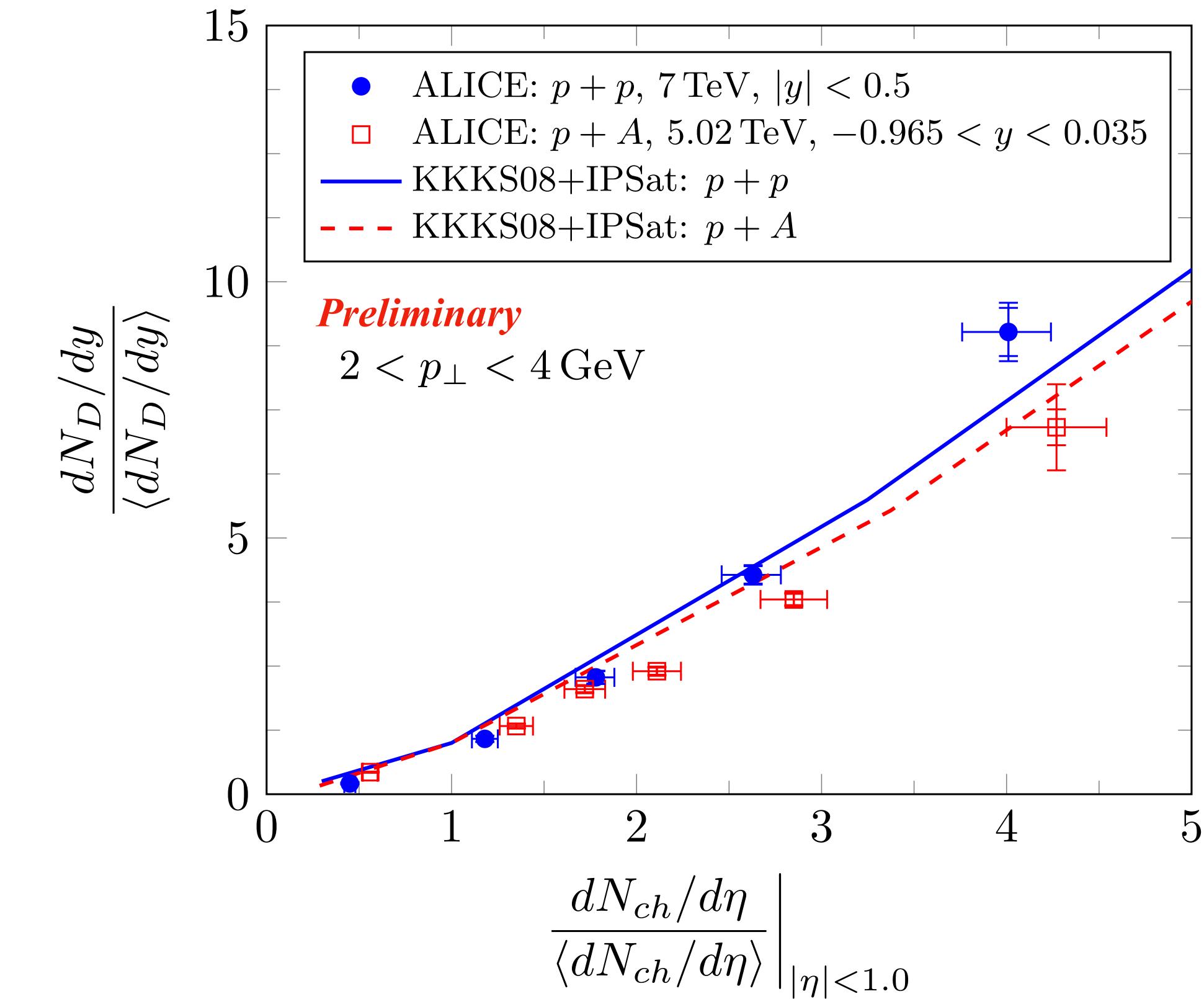
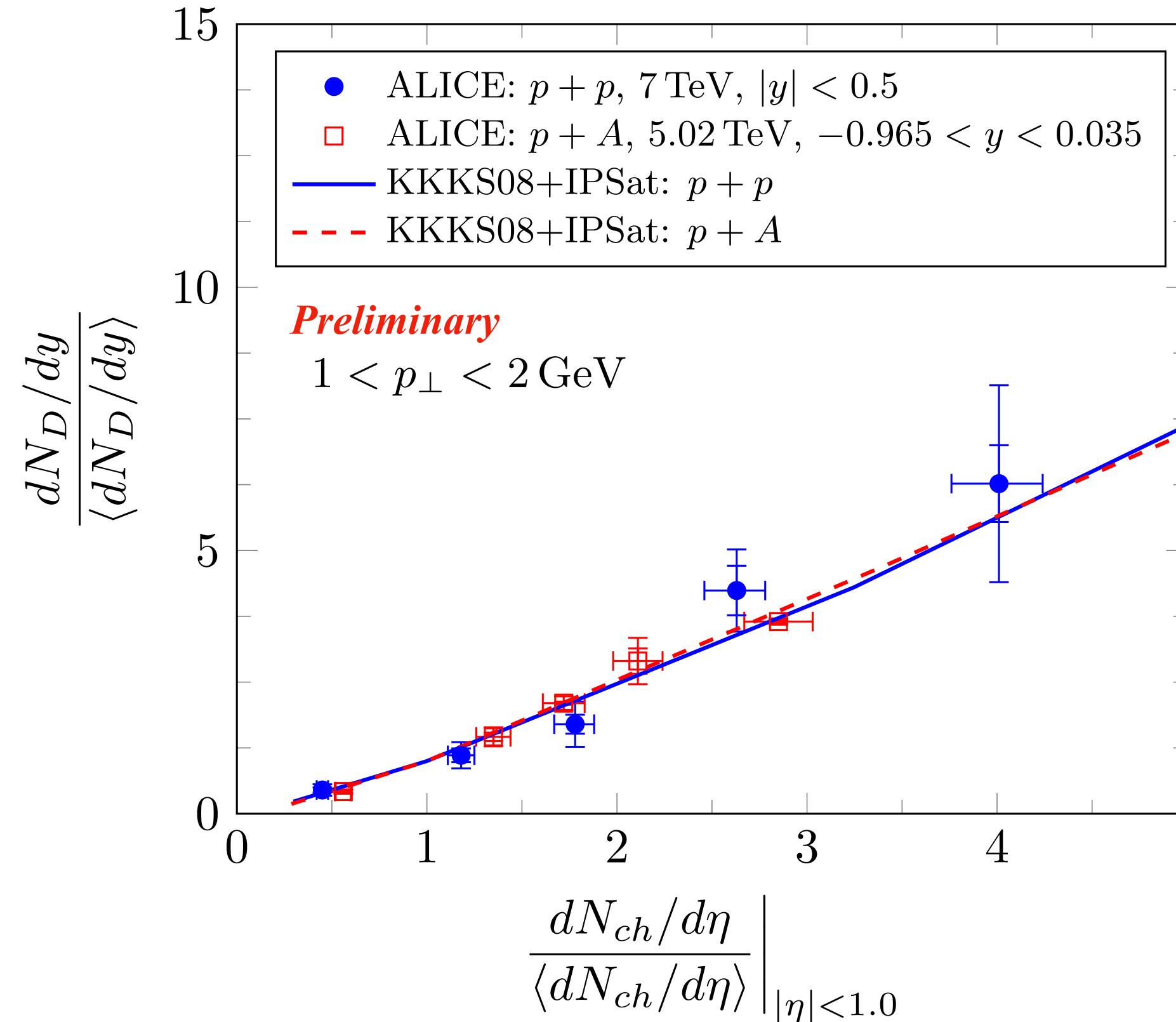
Note: These dense gluon configurations could have eccentric shapes whose final state interactions can in principle generate flow.

D-mesons production in small systems

Numerical results in IP-Sat + LPHD for N_{ch} + KKKS08 set FF for D_0 , D^{*+} , D^+ .

Stebel, Venugopalan, KW, in preparation

See also, Ma, Tribedy, Venugopalan, KW, [1803.11093](#), [1807.05655](#)

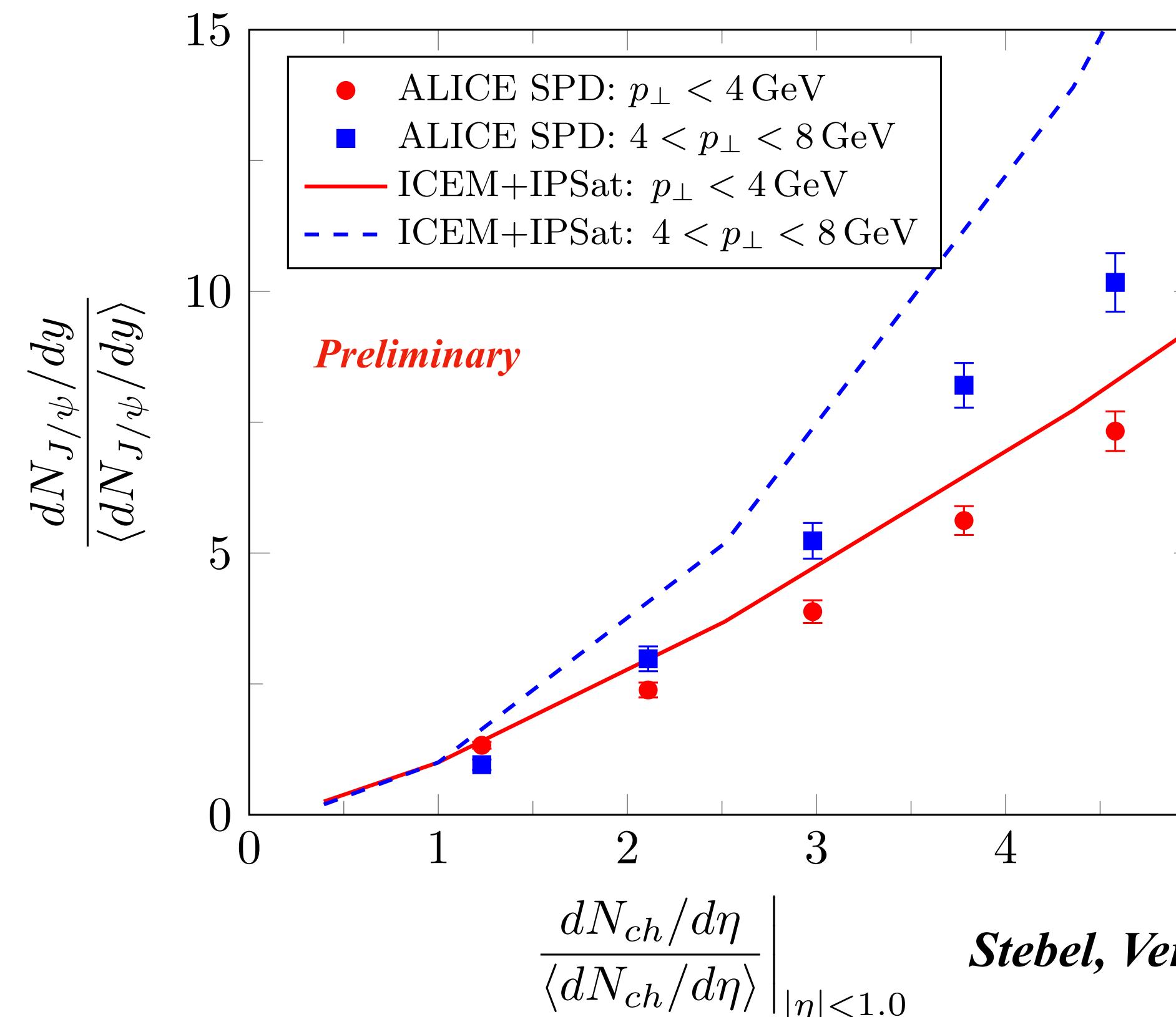


- The rapidity bin of D s coincides with the rapidity bin of charged hadron: $y_D \sim \eta_h$.
- Combinations of the saturation scales from the projectile and target explain data.
- Indeed, when using light hadron FF instead LPHD, and rcBK model instead IP-Sat, the CGC prediction agree with data.

J/ψ production in high multiplicity events

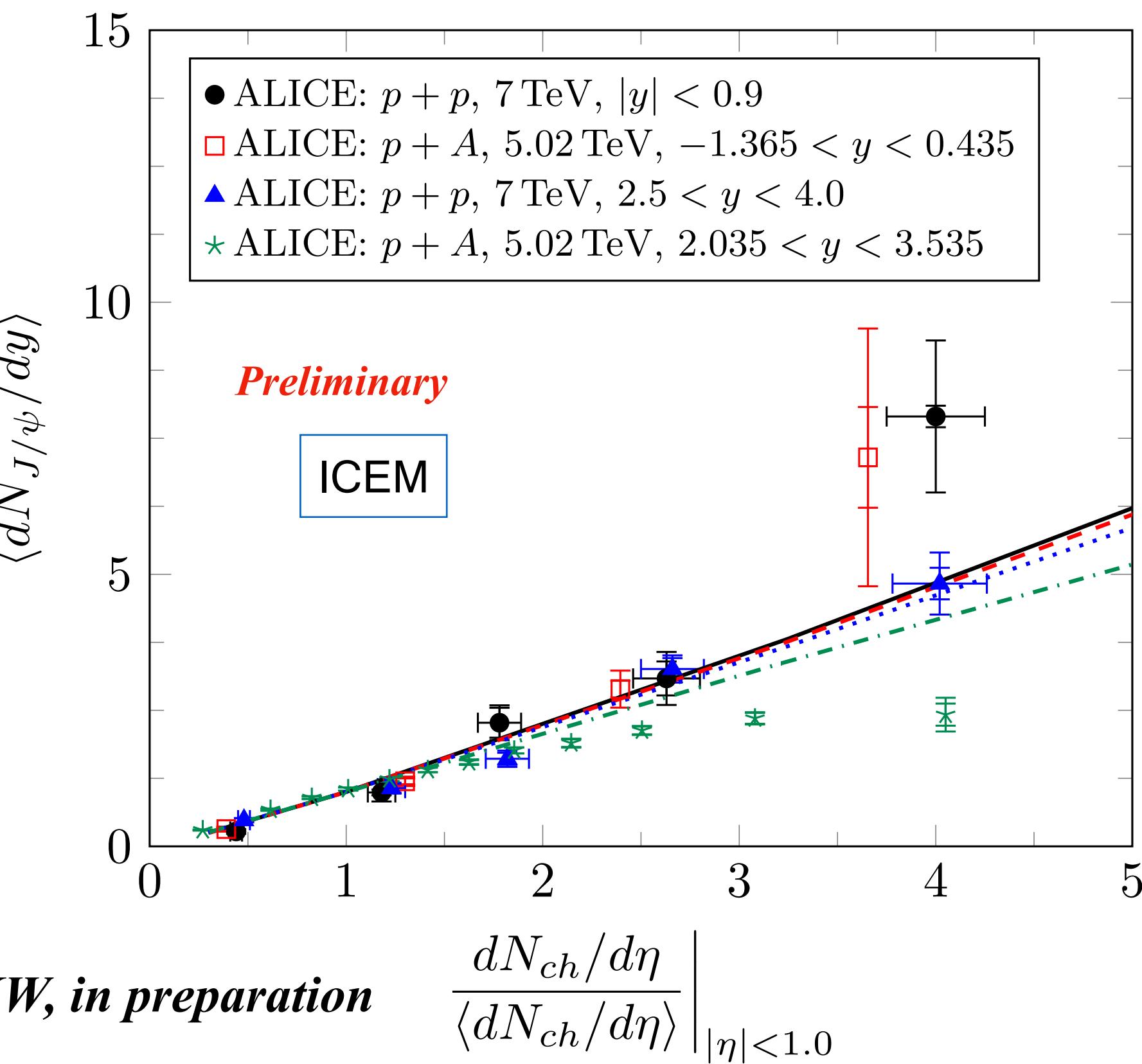
See Ma, Tribedy, Venugopalan, KW, [1803.11093](#), [1807.05655](#)

$p + p, \sqrt{s} = 13 \text{ TeV}, |y| < 0.9$



Ma, Stebel, Venugopalan, KW, HP2020 proceedings

See also <https://indico.cern.ch/event/751767/contributions/3770908/>



- The CGC framework can describe D -mesons vs. N_{ch} in $p+p$ at mid rapidity – analogous to J/ψ .
- Self-normalized J/ψ yield has a system size dependence: important constraint to the CGC.
- Need to consider carefully the rapidity dependence of J/ψ yield.

String interaction model (Percolation)

Ferreiro, Pajares (2012)

J/ψ is produced by hard parton scatterings. # of parton collisions = # of strings, N_s .

$$\frac{dN_{ch}}{d\eta} = F(\rho)N_s\mu$$

$$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} = \frac{N_s}{\langle N_s \rangle}$$

N_s : # of produced strings

μ_1 : the multiplicity of a single string in a rapidity bin

$F(\rho)$: the damping factor as a function of string density ρ

$$F(\rho) = \sqrt{\frac{1 - e^{-\rho}}{\rho}}$$

High string density $\rho \leftrightarrow$ Screening of multiplicities (**Saturation**)

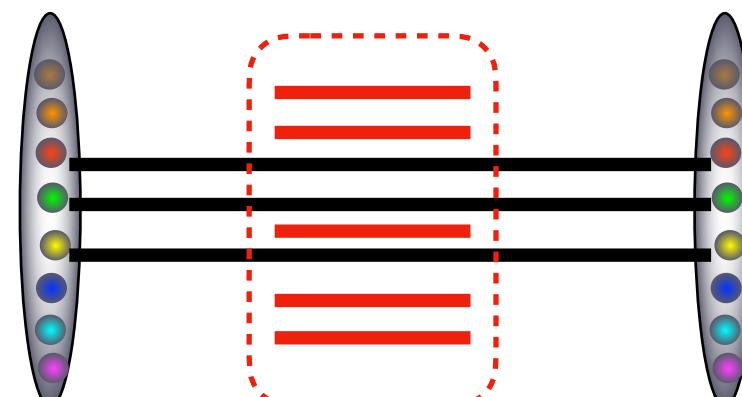
Low multiplicities (N_s , $\langle \rho \rangle$ small)

$$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} = \frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$$

$$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} = \langle \rho \rangle \left[\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle} \right]^2$$

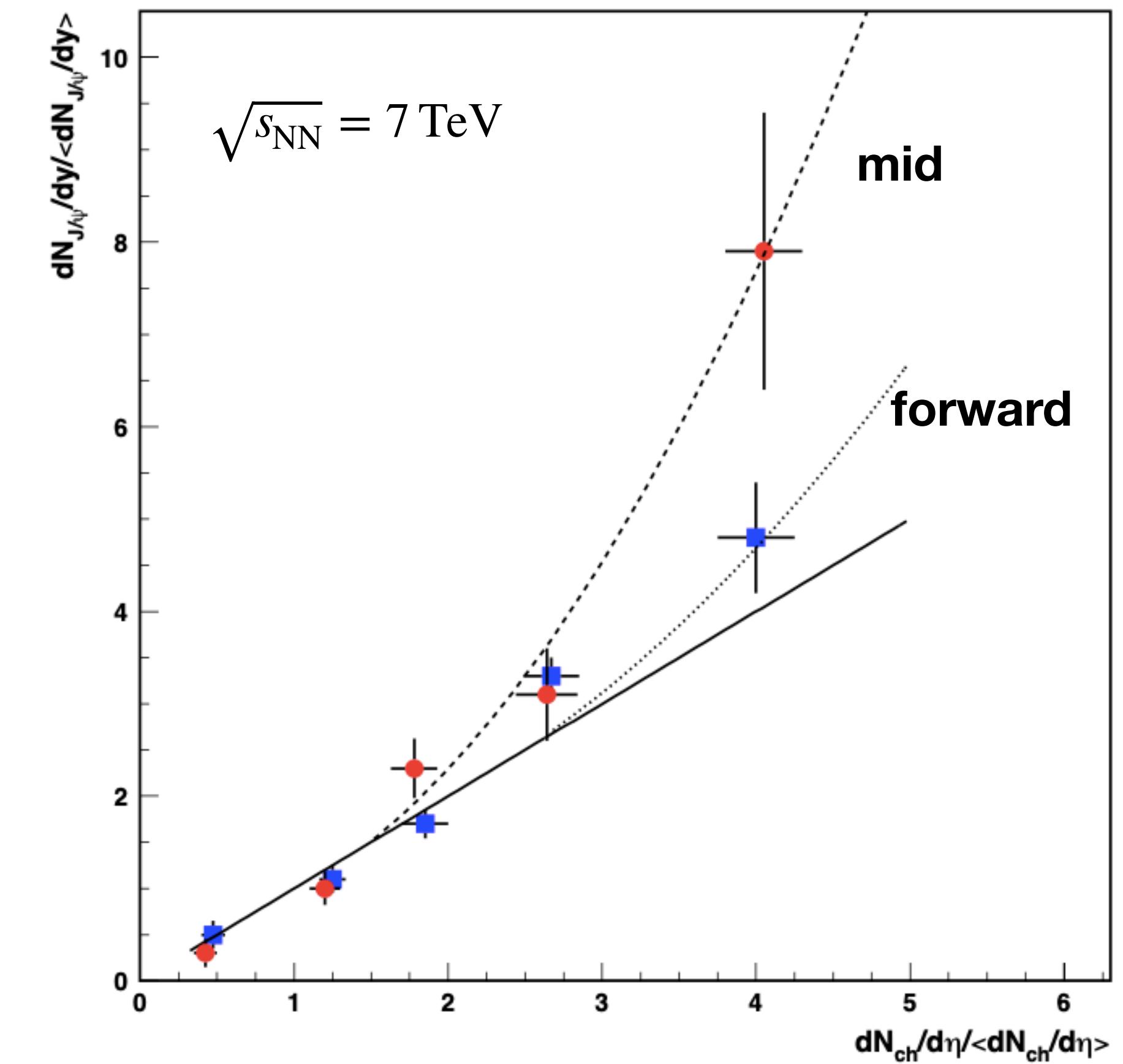
High multiplicities (N_s , $\langle \rho \rangle$ large)

Short strings at mid rapidities: sea quarks and gluon



$$\langle N_s \rangle_{\text{mid}} > \langle N_s \rangle_{\text{forward}}$$

Long strings at mid and forward rapidities: valence quarks



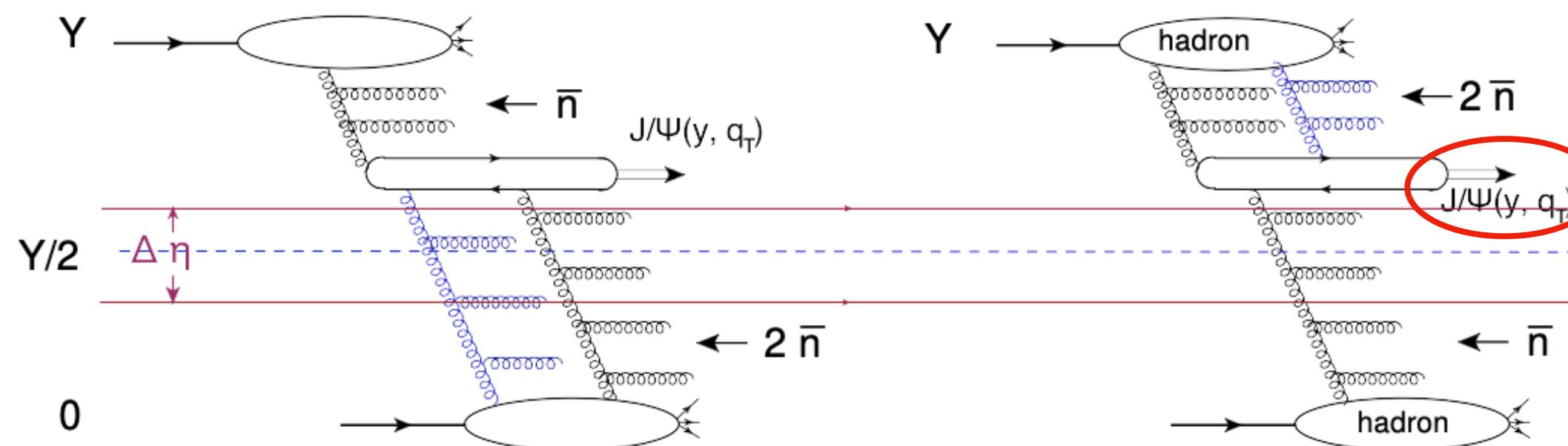
3-pomeron fusion model

Siddikov, Levin, Schmidt (2019)

In high energies, 3-pomerons fusion processes can be dominant for S-wave quarkonium production (e.g. J/ψ) in pA collisions, and even in pp collisions.

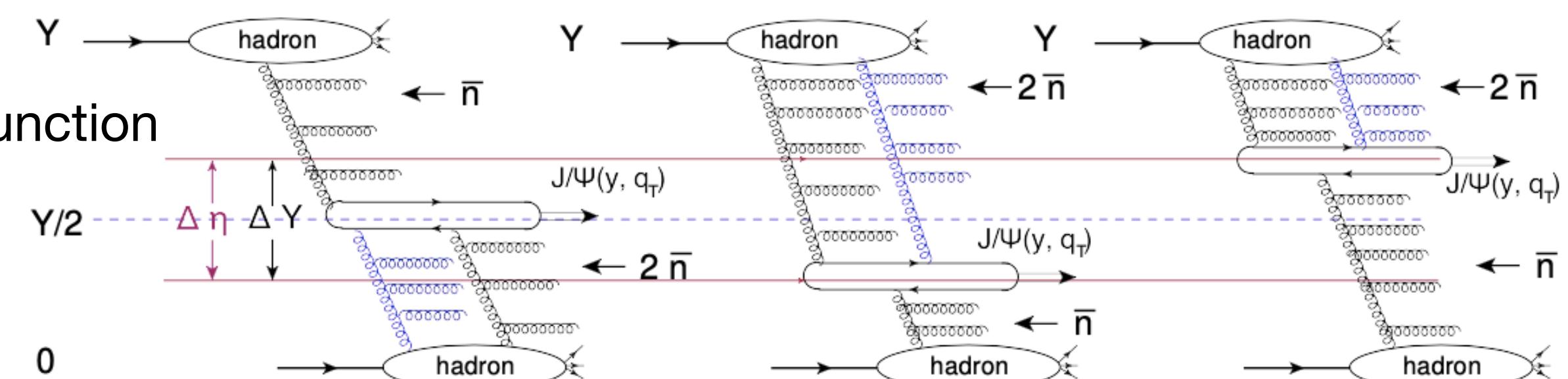
See Kharzeev, Tuchin (2005), Levin, Siddikov (2018),...

(i) J/ψ and hadrons are produced with a rapidity gap



LC-wave function

(ii) J/ψ and hadrons are produced in almost the same bin



Partons are produced from pomeron cascades

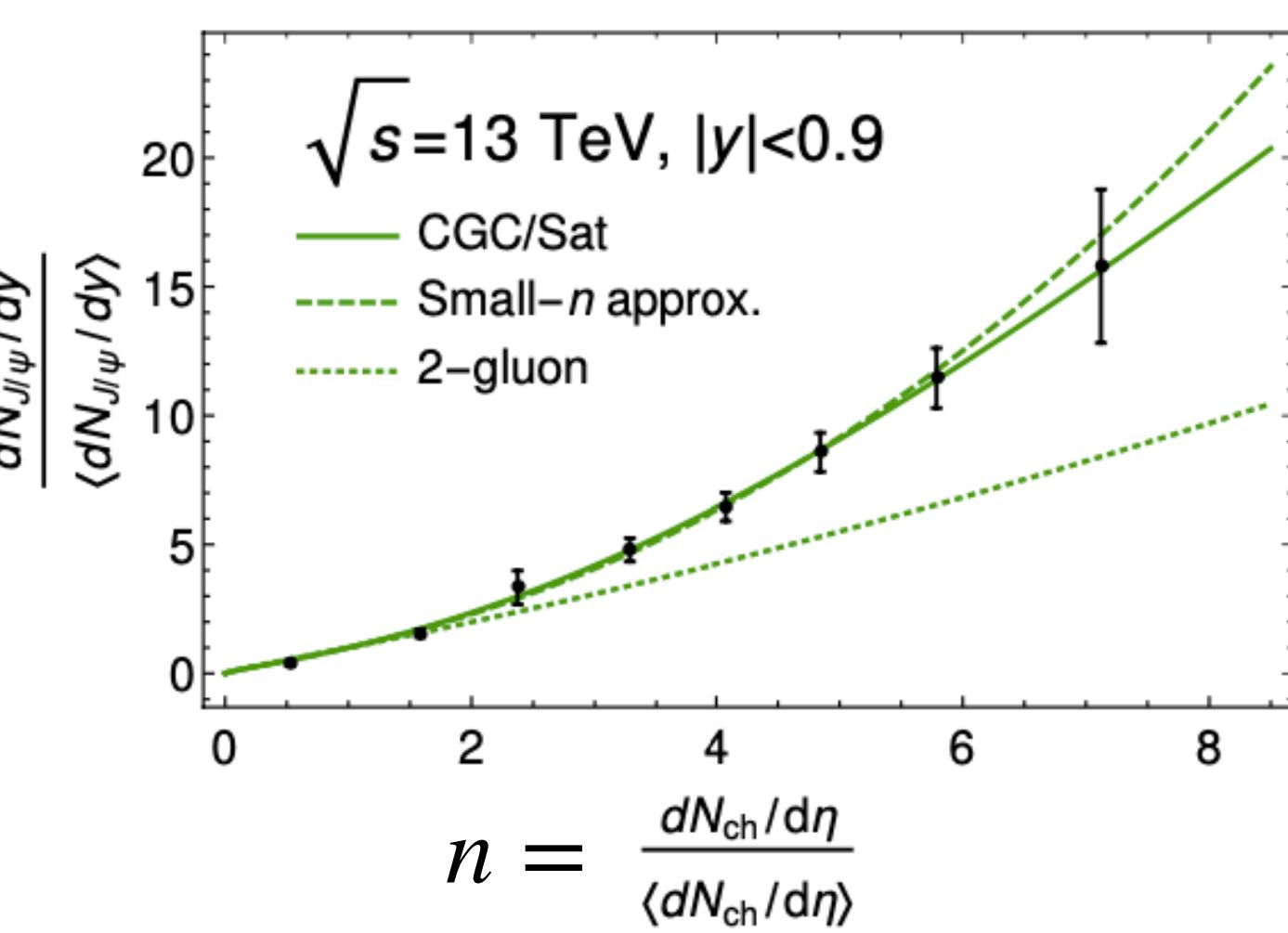
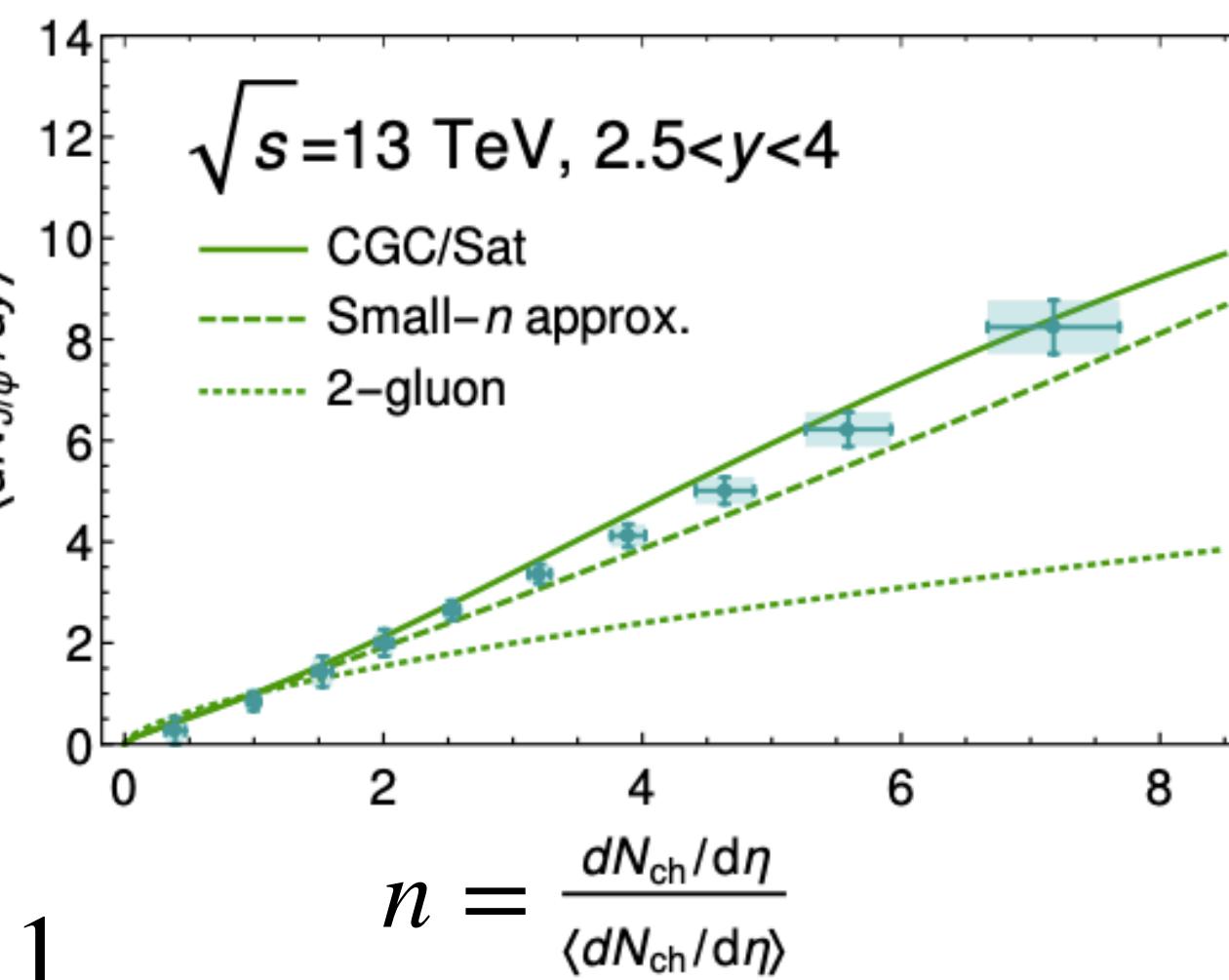
→ charged hadron production due to LPHD hypothesis.

$$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} \approx \frac{1}{\kappa + \left(\frac{1}{2}\right)^{2\bar{\gamma}} + \Delta y \left(\frac{1}{4}\right)^{\bar{\gamma}}} \left[\kappa n^{\bar{\gamma}} + \left(\frac{n}{2}\right)^{2\bar{\gamma}} + \Delta \eta \left(\frac{n^3}{4}\right)^{\bar{\gamma}} \right] \frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle}$$

$$\kappa = \left(\frac{Q_s^2(x_2)}{Q_s^2(x_1)} \right)^{\bar{\gamma}} \quad \bar{\gamma} = 0.63$$

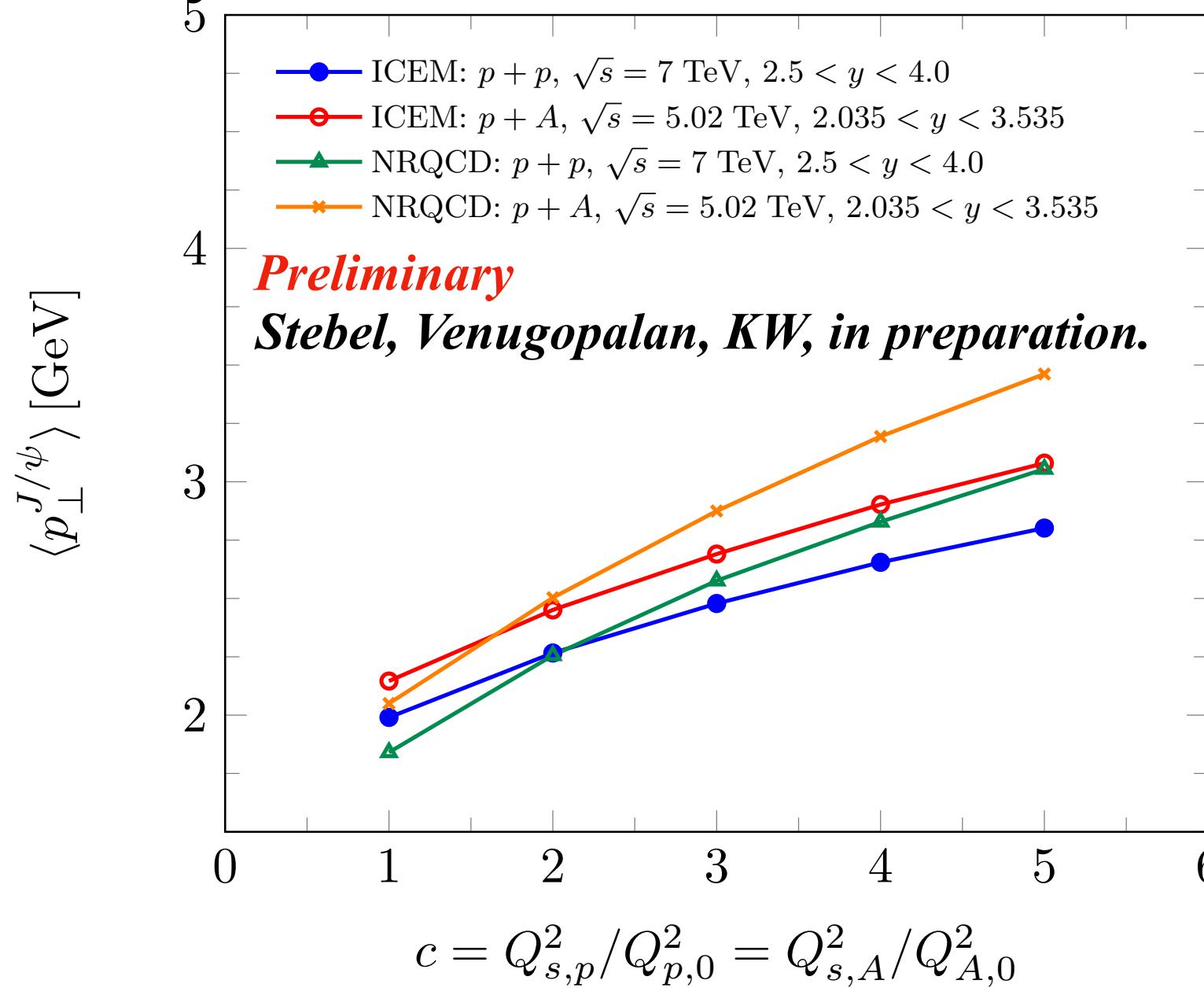
GBW model

Mid rapidity: $\kappa \sim 1$
Forward rapidity: $\kappa > 1$



Issues

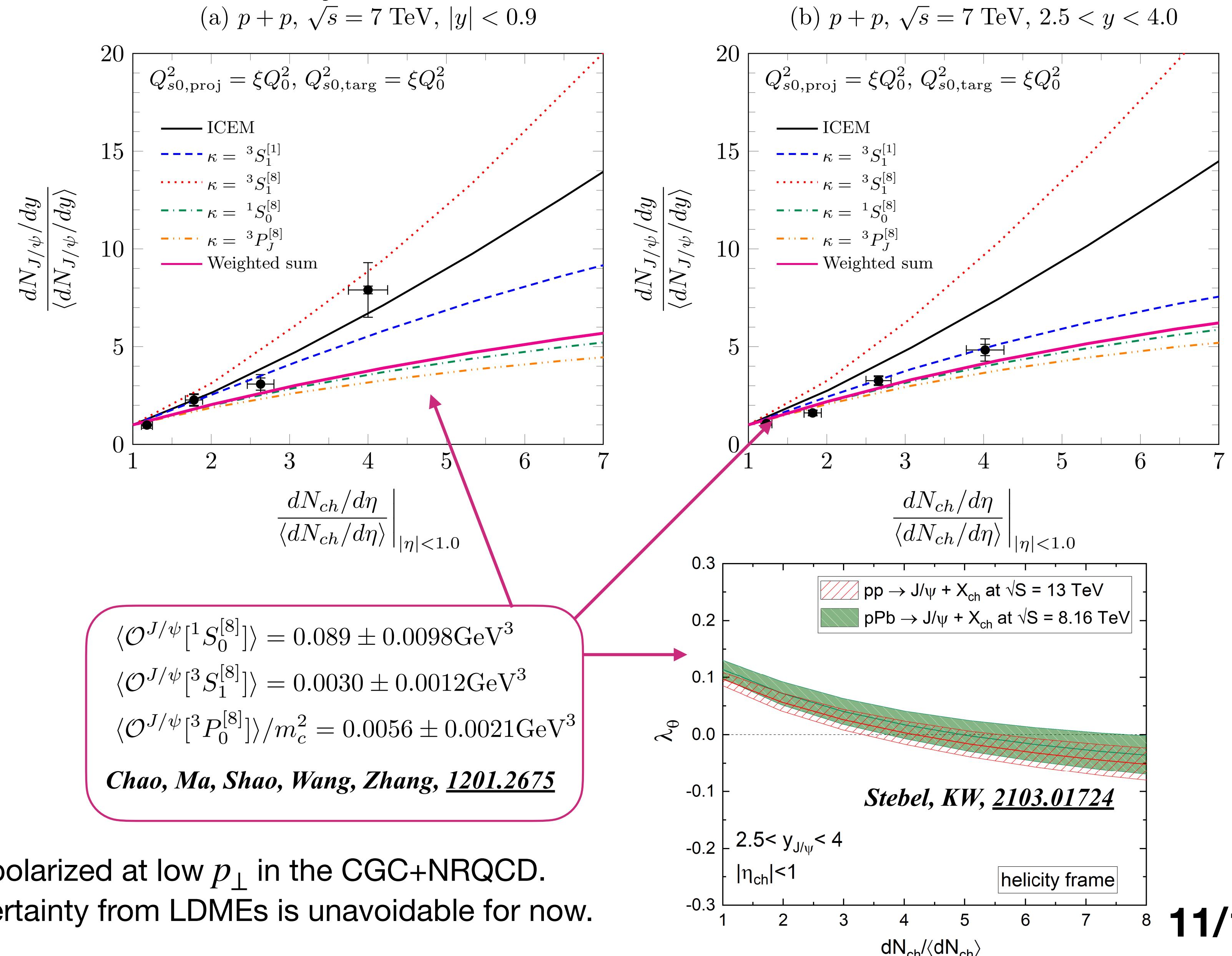
p_\perp -broadening



Mean $\langle p_\perp \rangle$ of J/ψ increases with N_{ch} in small systems in the CGC, however, LHC data tell not. J/ψ 's $\langle p_\perp \rangle$ does not depend on N_{ch} when $N_{ch} \gg 1$ in real.

J/ψ can be unpolarized at low p_\perp in the CGC+NRQCD.
Additional uncertainty from LDMEs is unavoidable for now.

Uncertainty about LDMEs in the NRQCD factorization



Wrap up

- Several theoretical approaches have took a similar setup for N_{ch} distribution of J/ψ yield at mid rapidity.
- Rapidity dependence of J/ψ , D -mesons, and decay leptons ($c \rightarrow e, \mu$) production would help us understand some aspects of quarkonium production in high multiplicity events:
 $y_{J/\psi, D, c \rightarrow l} \sim \eta_h$, $y_{J/\psi, D, c \rightarrow l} > \eta_h$
- LHC data on p_\perp broadening of J/ψ in high multiplicity events give a constraint to theory.
- Uncertainties from fluctuation effects in pA collisions and LDMEs in the CGC+NRQCD framework.
- In addition, NLO corrections could be important when looking at p_\perp cut dependence.

Thank you!

Backup

BFKL approach with Parton cascades

Gotsman, Levin, 2008.10911

The CGC and BFKL pompon approaches coincide when

$$Y \leq \frac{2}{\Delta_{\text{BFKL}}} \ln \left(\frac{1}{\Delta_{\text{BFKL}}^2} \right) \sim 1.2 \quad \text{where } \Delta_{\text{BFKL}} \sim 0.79.$$

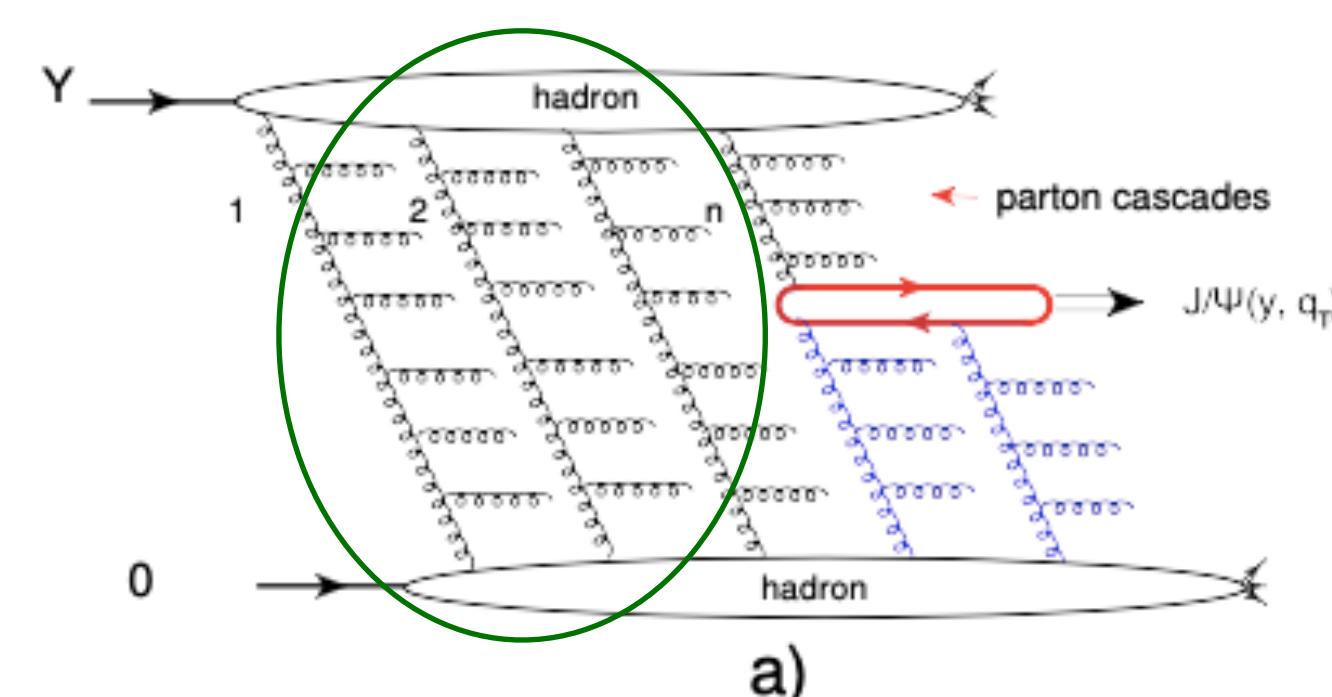
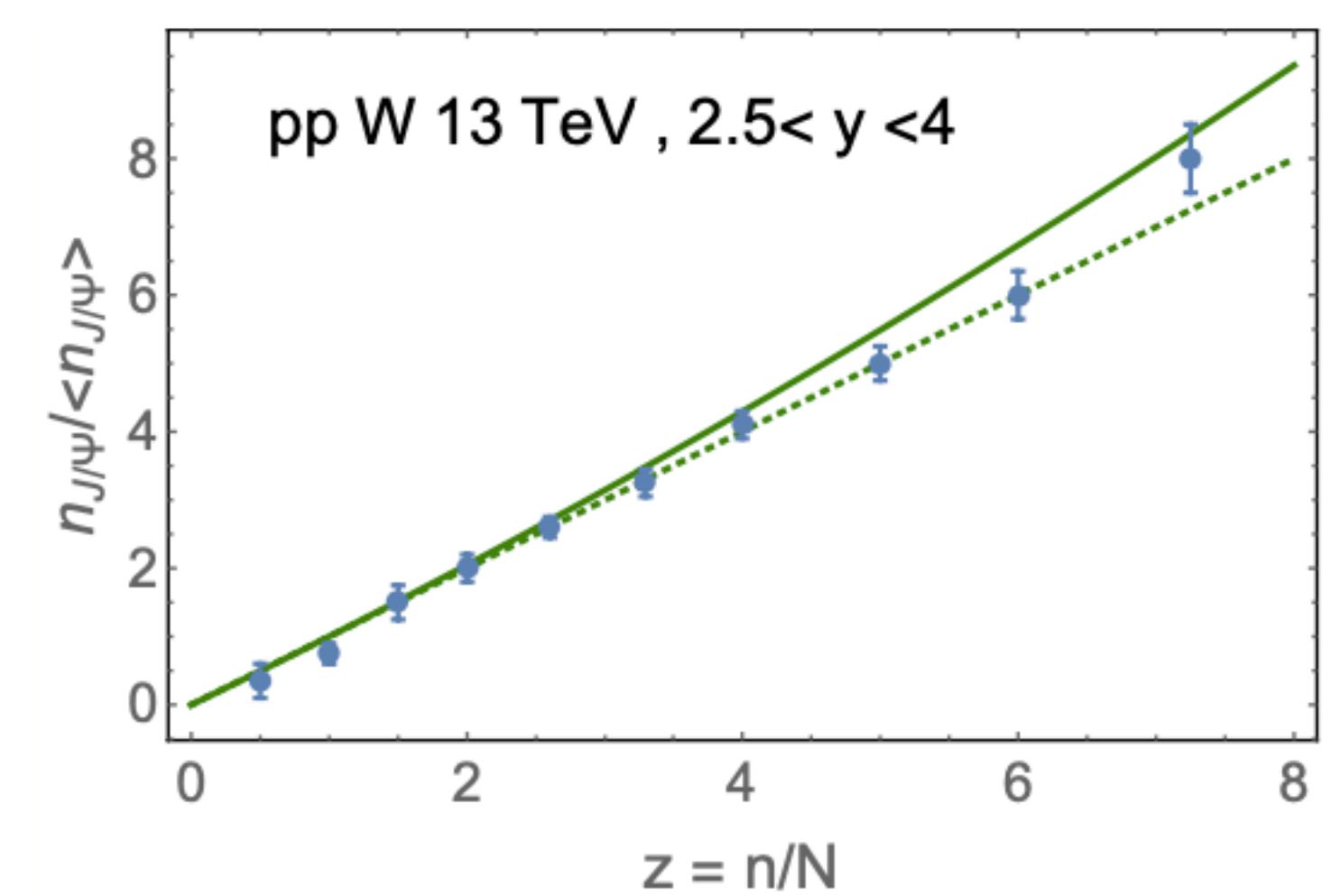
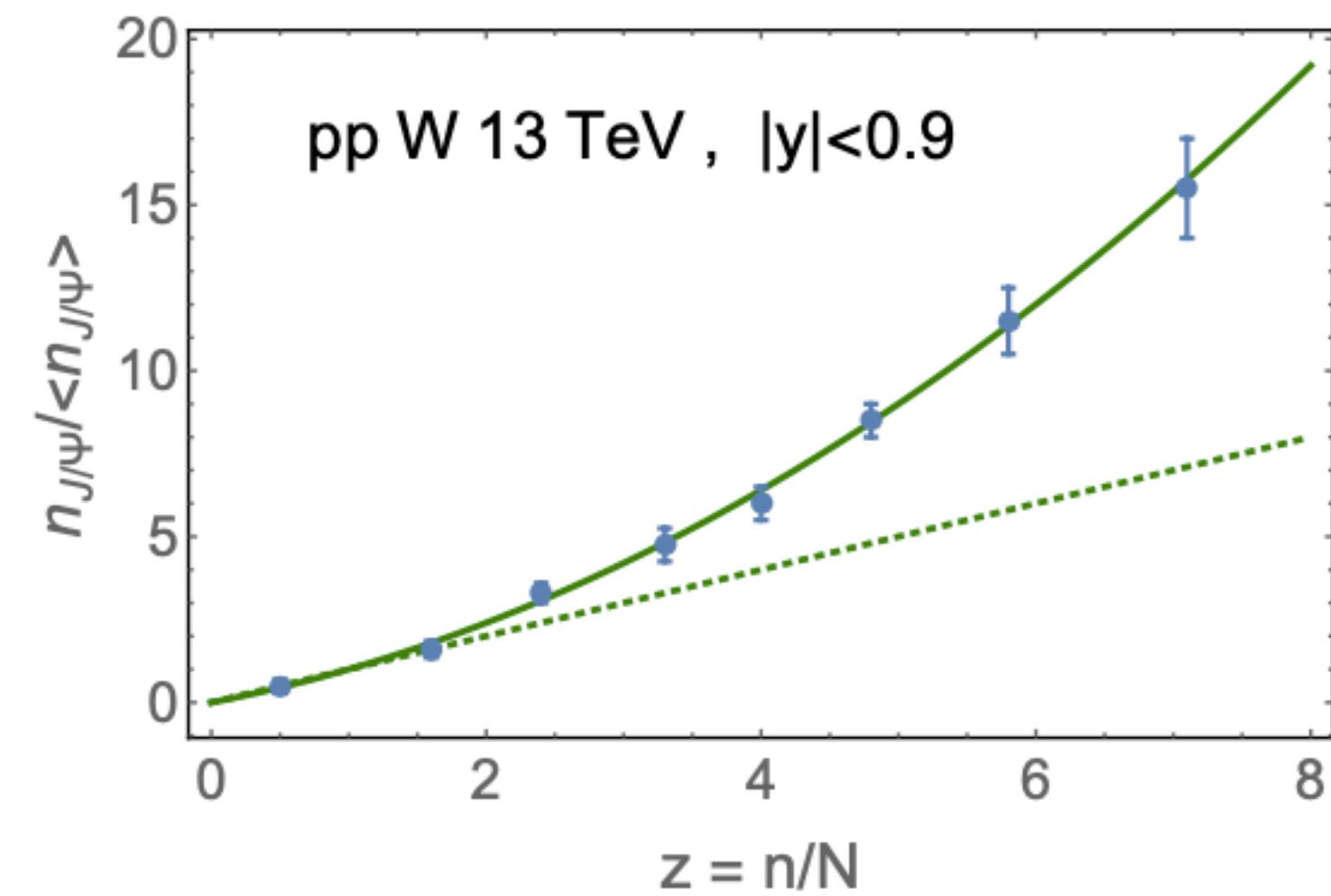
Altinoluk, Kovner, Levin, Lublinsky (2014)

$$\frac{dN_{J/\psi}/dy}{\langle dN_{J/\psi}/dy \rangle} \xrightarrow{z=n/N \gg 1} \frac{z + \frac{\kappa}{4} z^2}{1 + \frac{\kappa}{4}} = e^{-2\bar{\gamma}\lambda y}$$

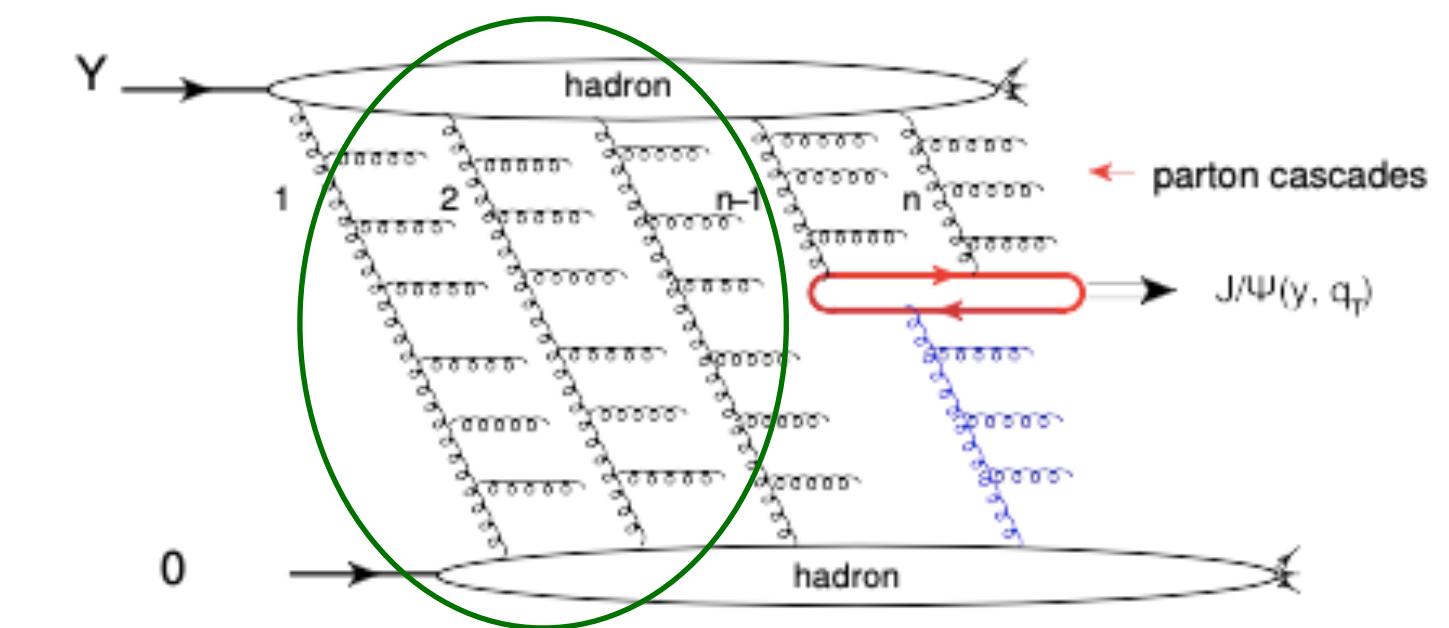
$\kappa =$

$\bar{\gamma} = 0.63, \lambda \approx 4.8\bar{\alpha}_s$

$y \sim 0 : \kappa = 1$
 $y \gg 0 : \kappa \rightarrow 0$



Parton cascades that are not included explicitly in the CGC framework



• b-CGC model

- Linear gluon bremsstrahlung at small-x: BFKL solution.
- Nonlinear recombination in the dense regime: BK solution.
- b-dependence introduced in the saturation scale Q_s .

Iancu, Itakura, Munier (2003)
Watt, Motyka, Kowalski(2006)
Watt, Kowalski (2008)

Since the b-dependence models also confinement, it cannot be constrained by saturation physics alone.

• IP-Sat model

- Glauber-Mueller dipole picture: Multiple scattering.
- Each dipole scattering xsection follows DGLAP evolution.
- b-dependence in a gluon profile function in hadrons/nuclei.

Kowalski, Teaney (2003)

• BK model

- NLO running coupling evolution kernel available. (stable numerically)
- MV model is an input distribution.
- b-dependence is not taken into account.

Balitsky (2006)

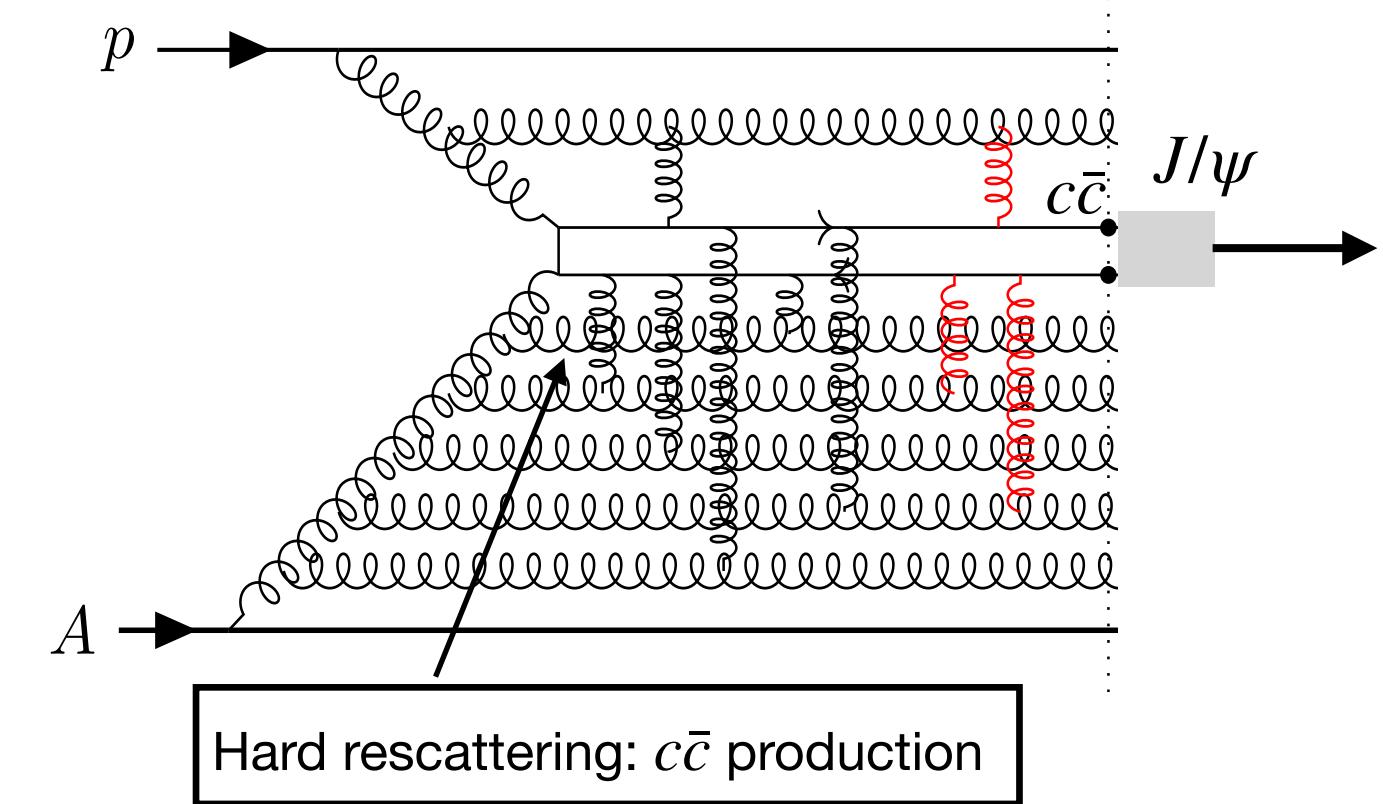
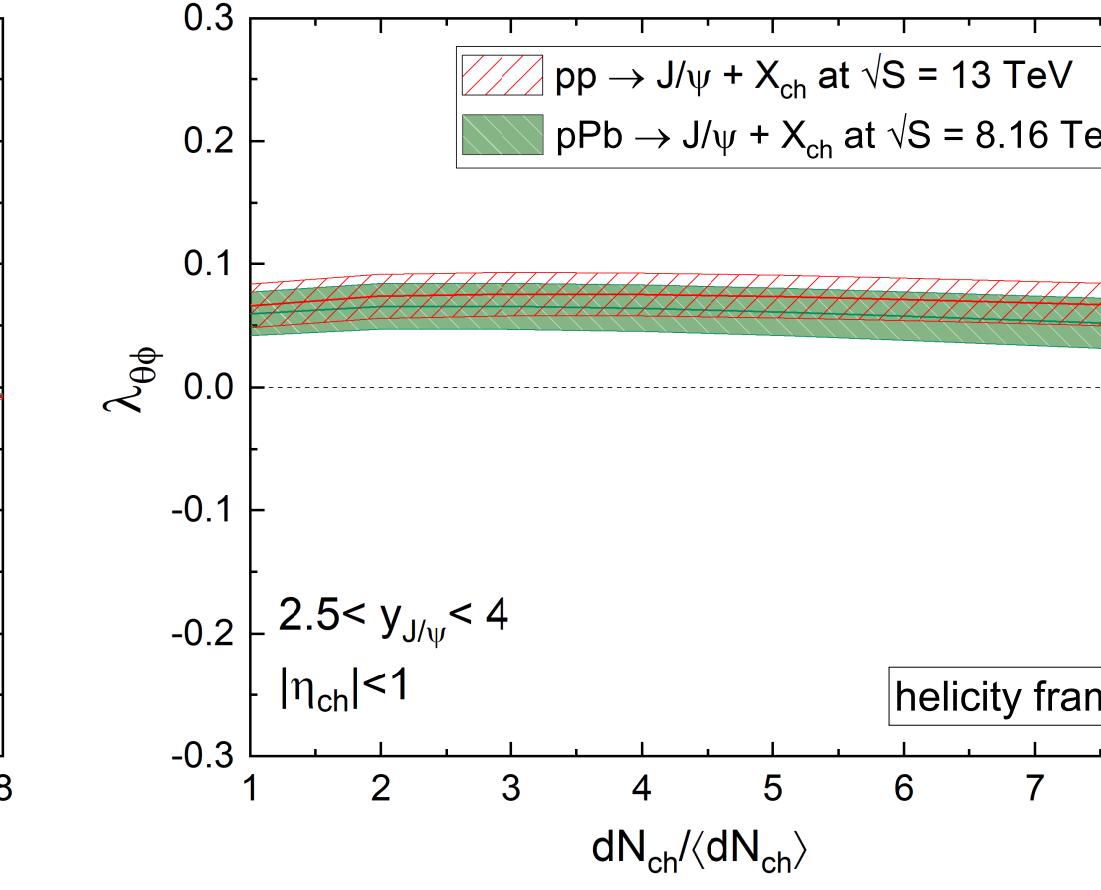
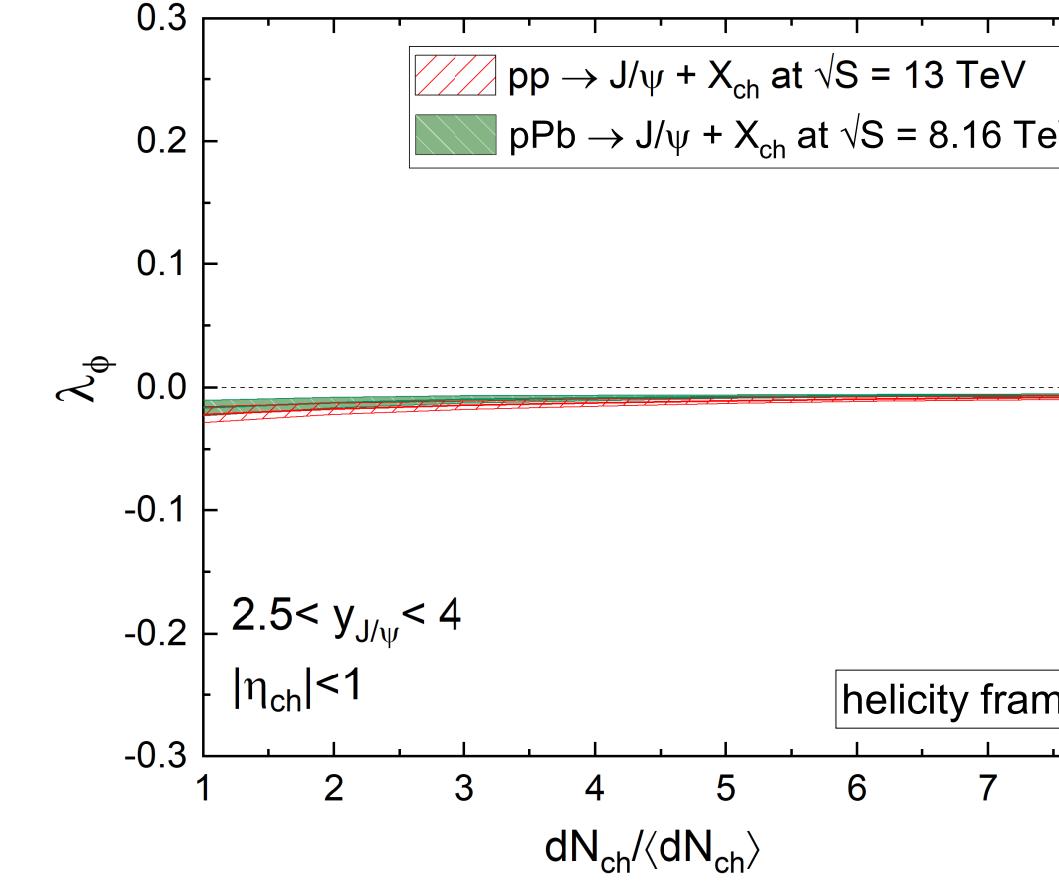
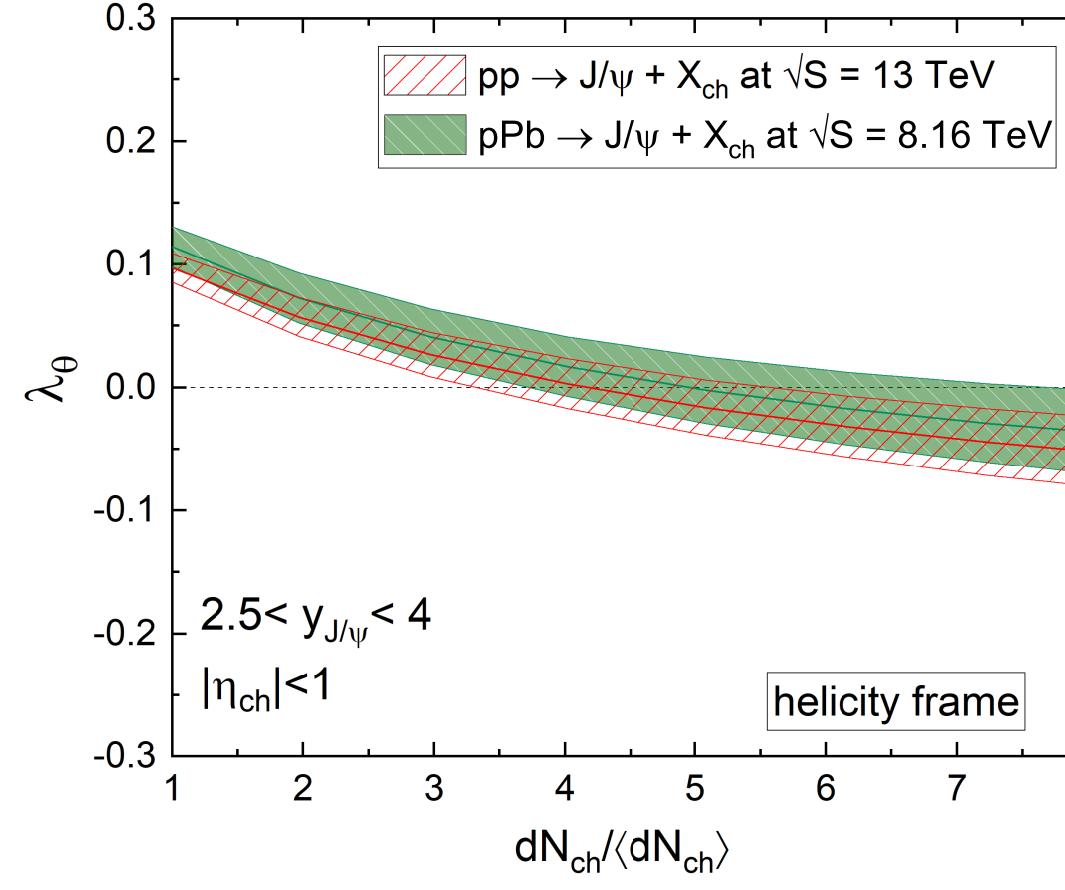
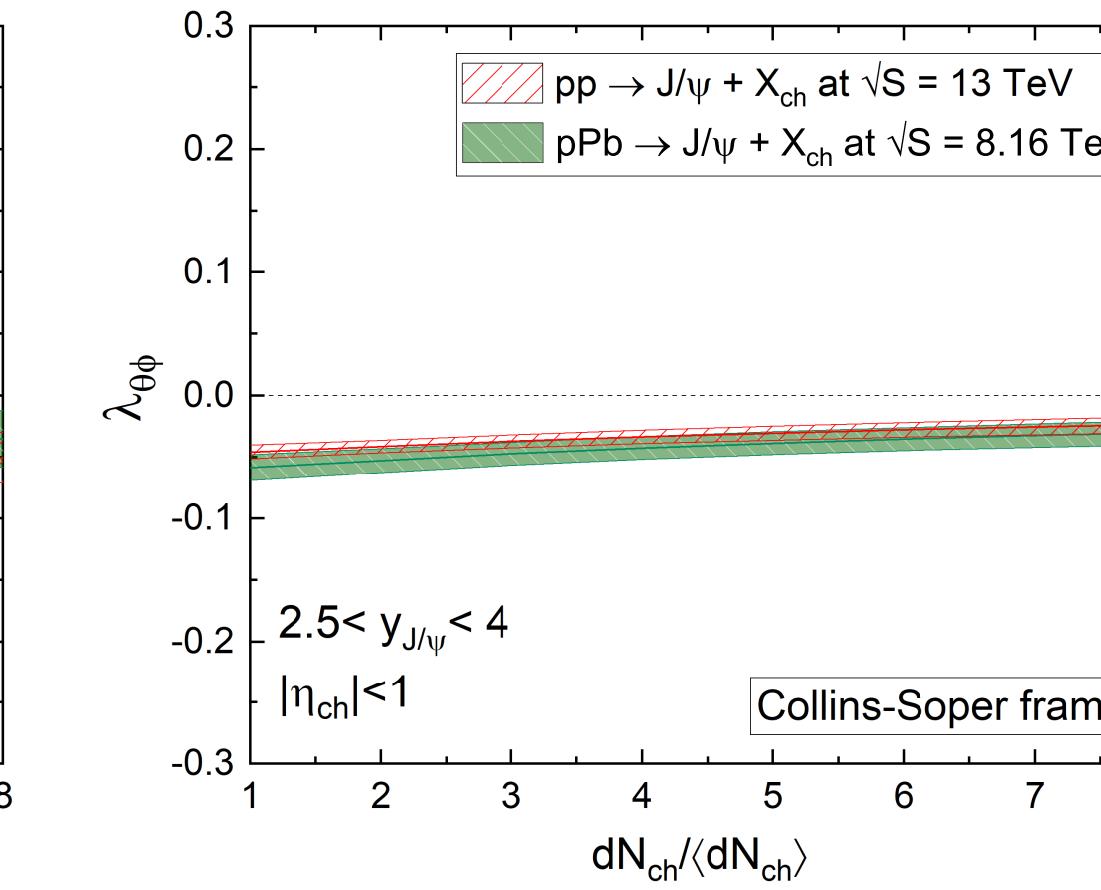
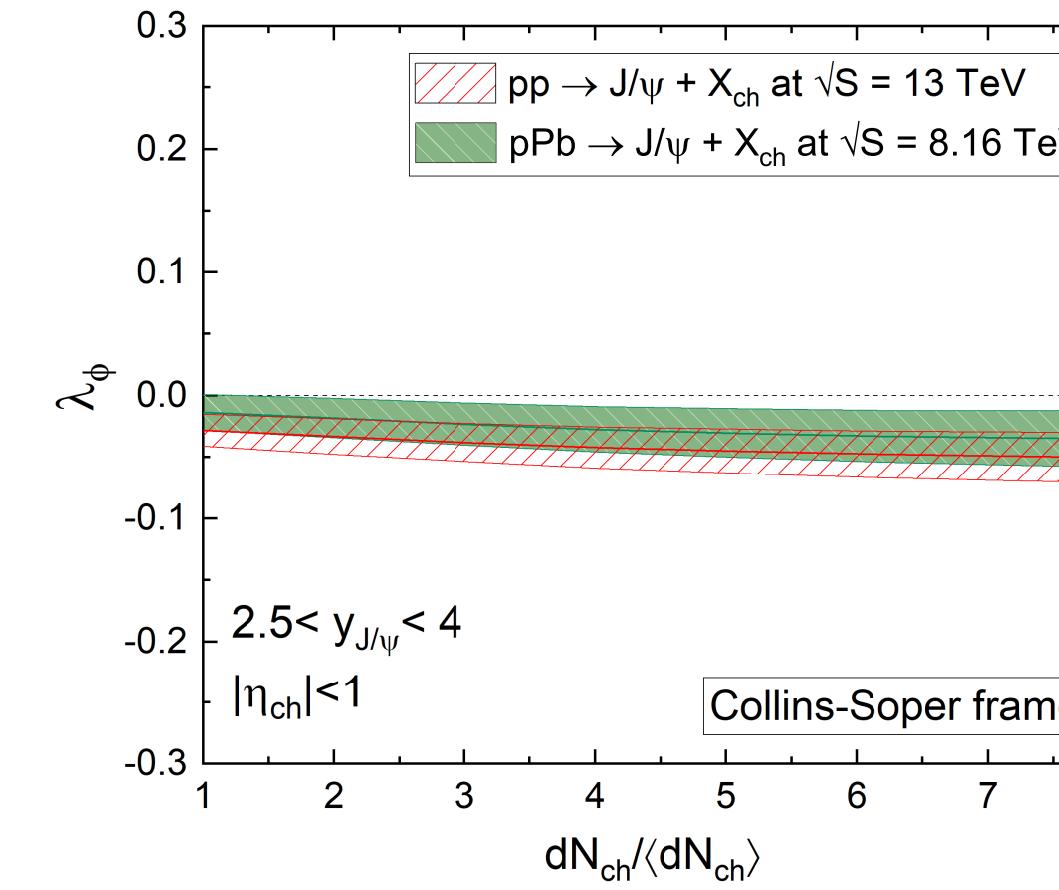
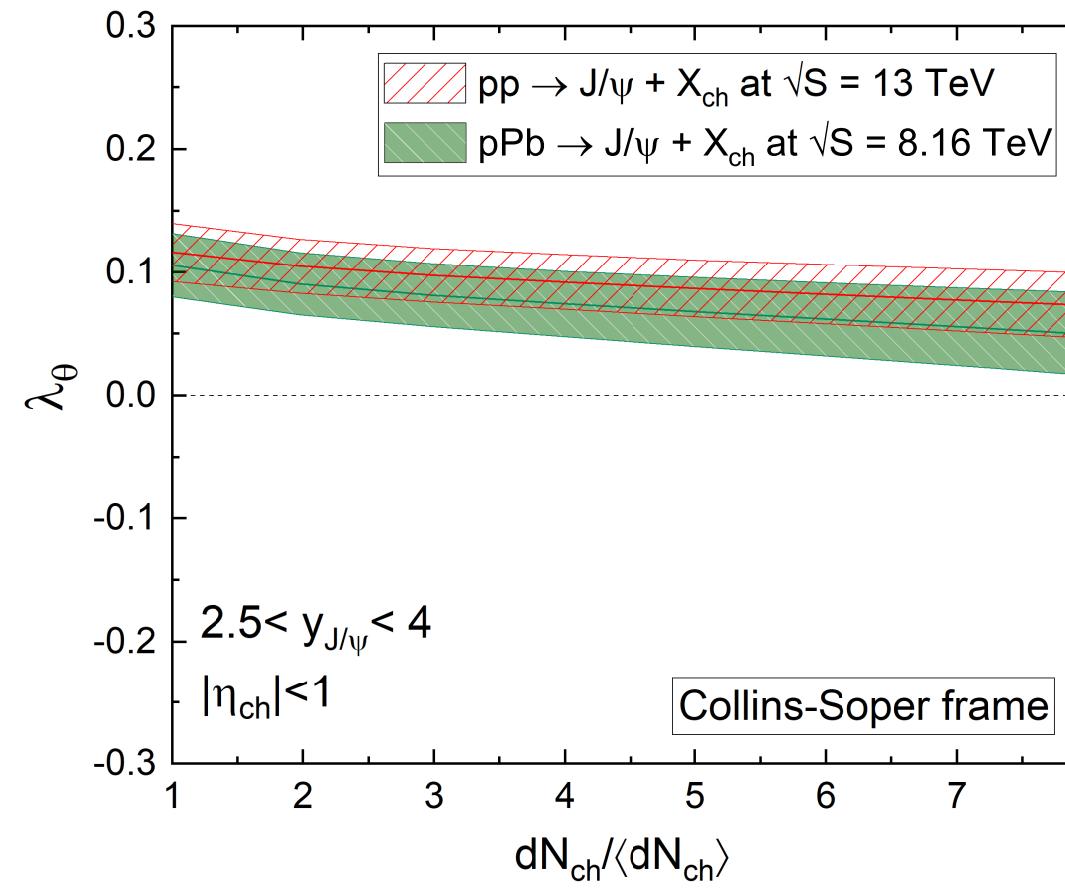
Ma, Tribedy, Venugopalan, KW (2018)

* Input parameters in each model are well constrained by precise HERA data.

Predictions for J/ψ polarization vs. N_{ch}

$$\frac{d\sigma^{J/\psi \rightarrow l^+l^-}}{d\Omega} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi$$

Stebel, KW, [2103.01724](#)



Hard rescattering: $c\bar{c}$ production

As N_{ch} increases, J/ψ gets more unpolarized due to the strong multiple-rescattering at a short distance.
This is a benchmark work for further study.