Initial state fluctuations and heavy flavor production in small systems

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collaboration with Y.-Q. Ma, J.-W. Qiu, T. Stebel, P. Tribedy, R. Venugopalan, …

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CNRS IN2P3 Subatech SEIKEI

Introduction

➢ The underlying mechanism of open and hidden heavy flavor production in high multiplicity events in small systems is yet puzzling.

➢ The cut and thrust: initial state fluctuations or final state effects or both.

➢ Weak coupling approach, the CGC EFT, is useful to pin down initial state effects (i.e., non-hydro) on heavy quark production and hadronization.

- High multiplicity —> # of net gluons (xf_g) is large —> $\alpha_s(Q_s) \ll 1$
- Geometrical fluctuation and saturation scale fluctuation lead to high $N_{\rm ch}$.
  See Salazar's talk on Mon Oct 10.

➢ **This talk** will revisit heavy flavor and quarkonium production in high multiplicity p+p and p+A collisions, using a CGC based model.

Major saturation models

b-CGC model

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

- 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.

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

IP-Sat model

Kowalski, Teaney (2003)

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

BK model

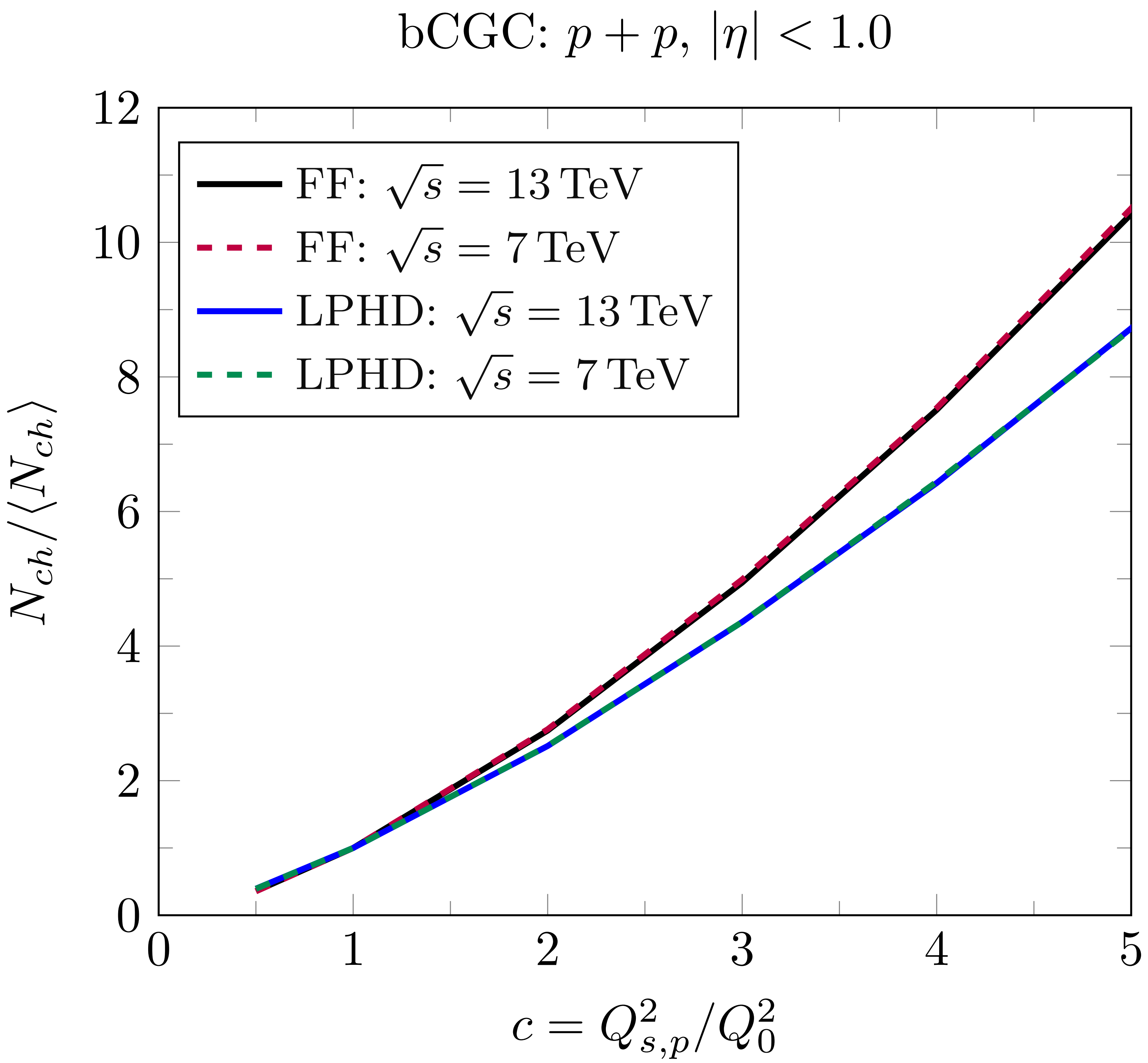
Balitsky (2006)

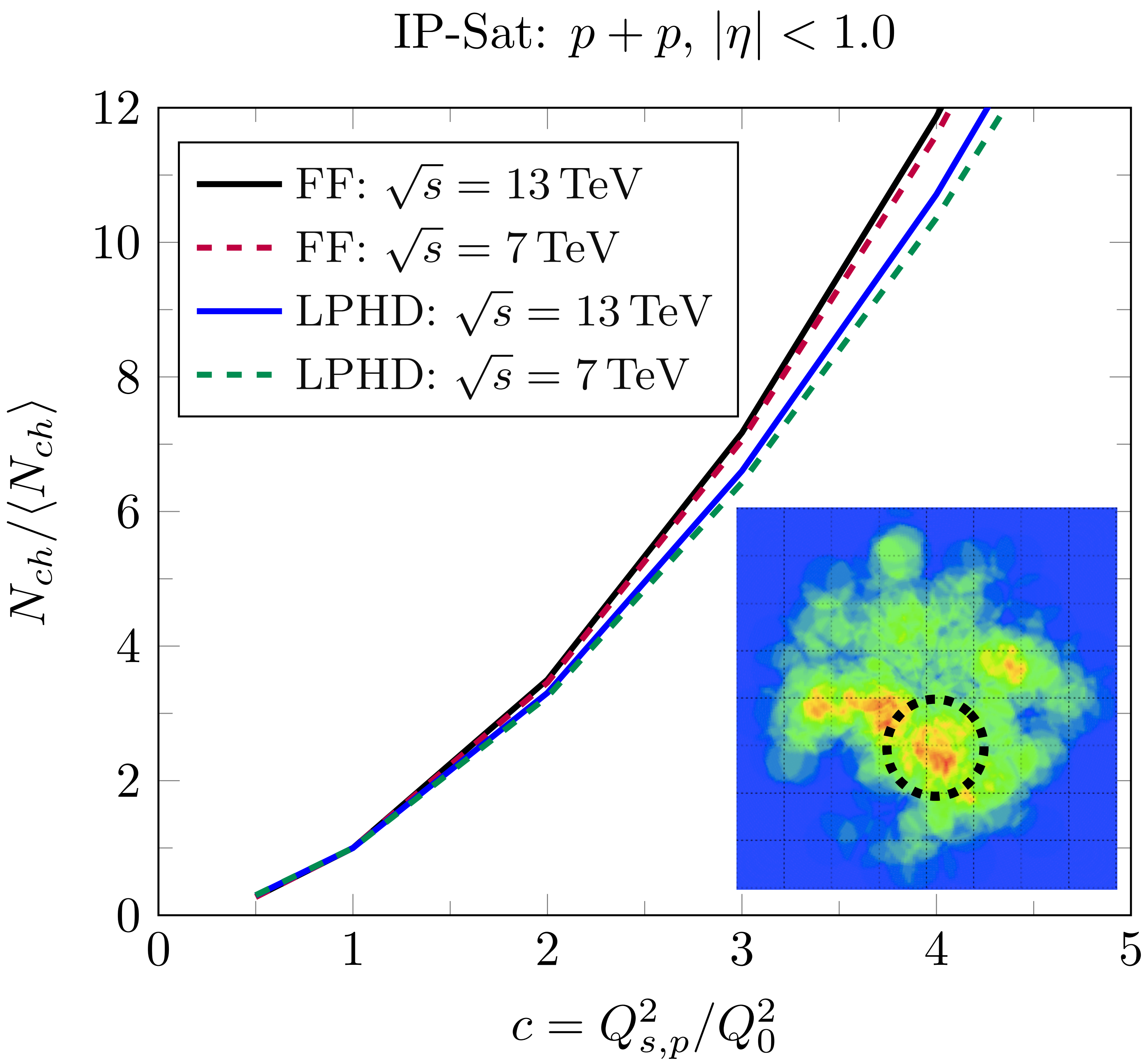
Ma, Tribedy, Venugopalan, KW (2018)

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

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

Initial state fluctuations: a simple model setup





- The difference between FF and LPHD is about <15% (<20%) at $c = 4$ in bCGC (IP-Sat).
- About 30% difference between bCGC and IPSat comes from the energy dependence of Q_s.
- Geometrical fluctuation off.

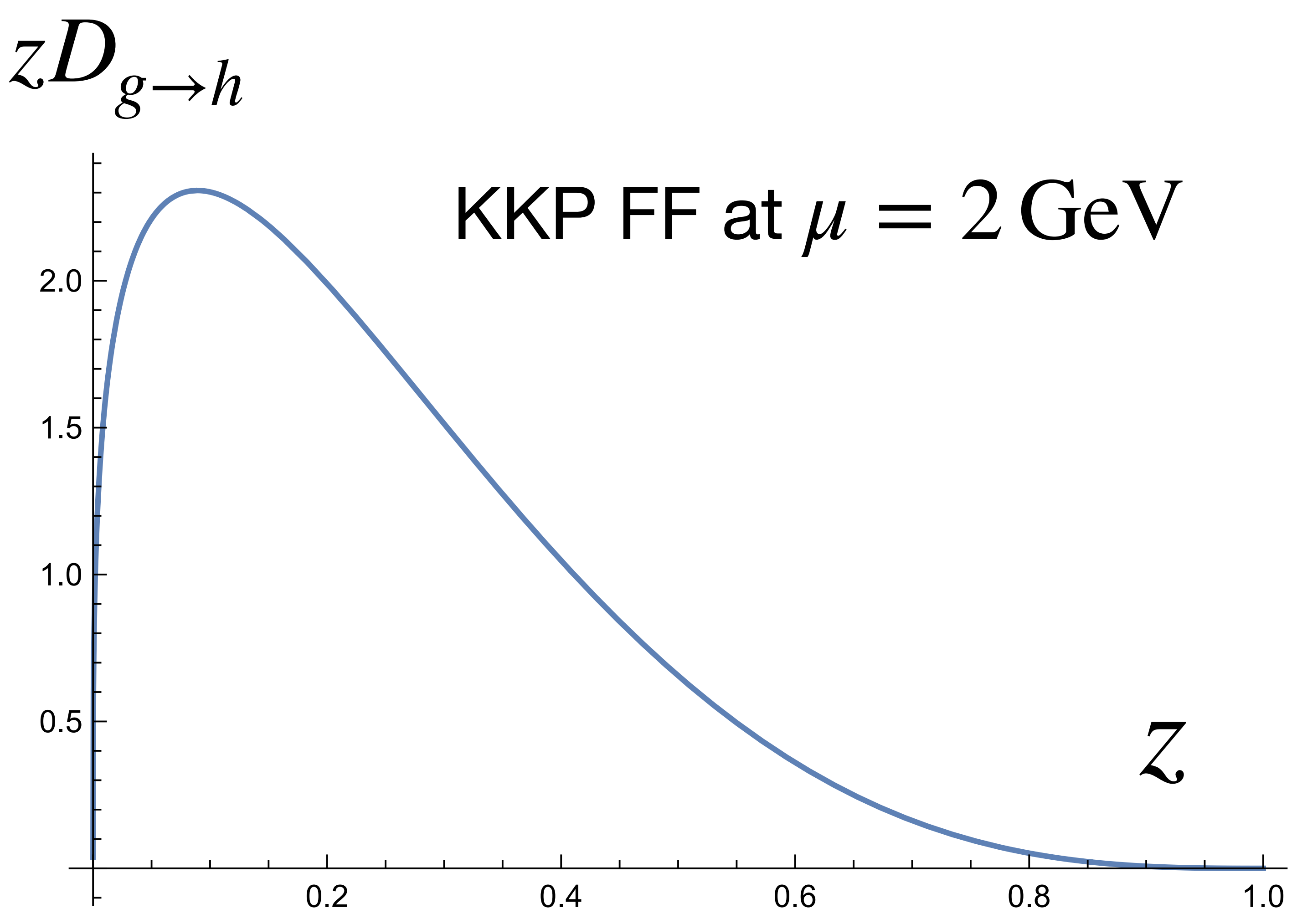
➢ High multiplicity events $N_{ch} \gg \langle N_{ch}\rangle$: In pp collisions, $Q_{s,p} = cQ_0^2$, $c \geq 1$. In pA collisions, implementation gets more complicated due to the fluctuation from $N_{\rm coll}$. Nevertheless, we shall set $Q_{s,A} = c\xi Q_0^2$, $c \geq 1$ and $\xi \sim 2\,\text{or}\,3$ for heavy targets.

Levin and Rezaeian, PRD82, 014022 (2010)
Dusling and Venugopalan, PRD87, no.9, 094034 (2013)

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

Hadronization approach

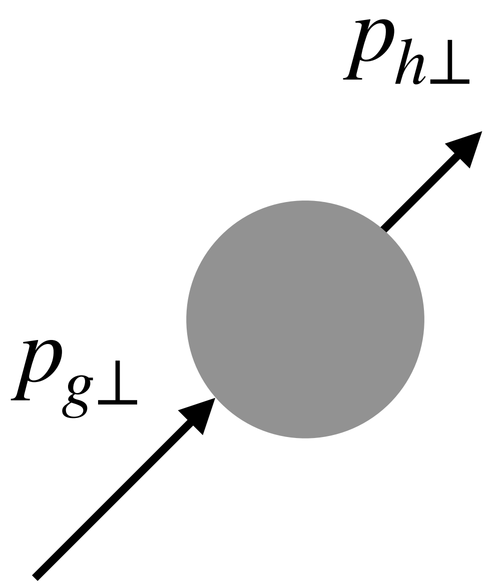
Charged hadron production of very low $p_\perp$ is governed by soft physics, and it is not straightforward to calculate hadron production from the first principle.



Fragmentation function approach

- DGLAP evolution changes the z-distribution of FF.
- Small-x ↔ Large-z: $0.1 < z < 1$ is relevant.
- Caveat: Should not apply when $\mu < 1\,\mathrm{GeV}$ or $p_\perp < 1\,\mathrm{GeV}$.

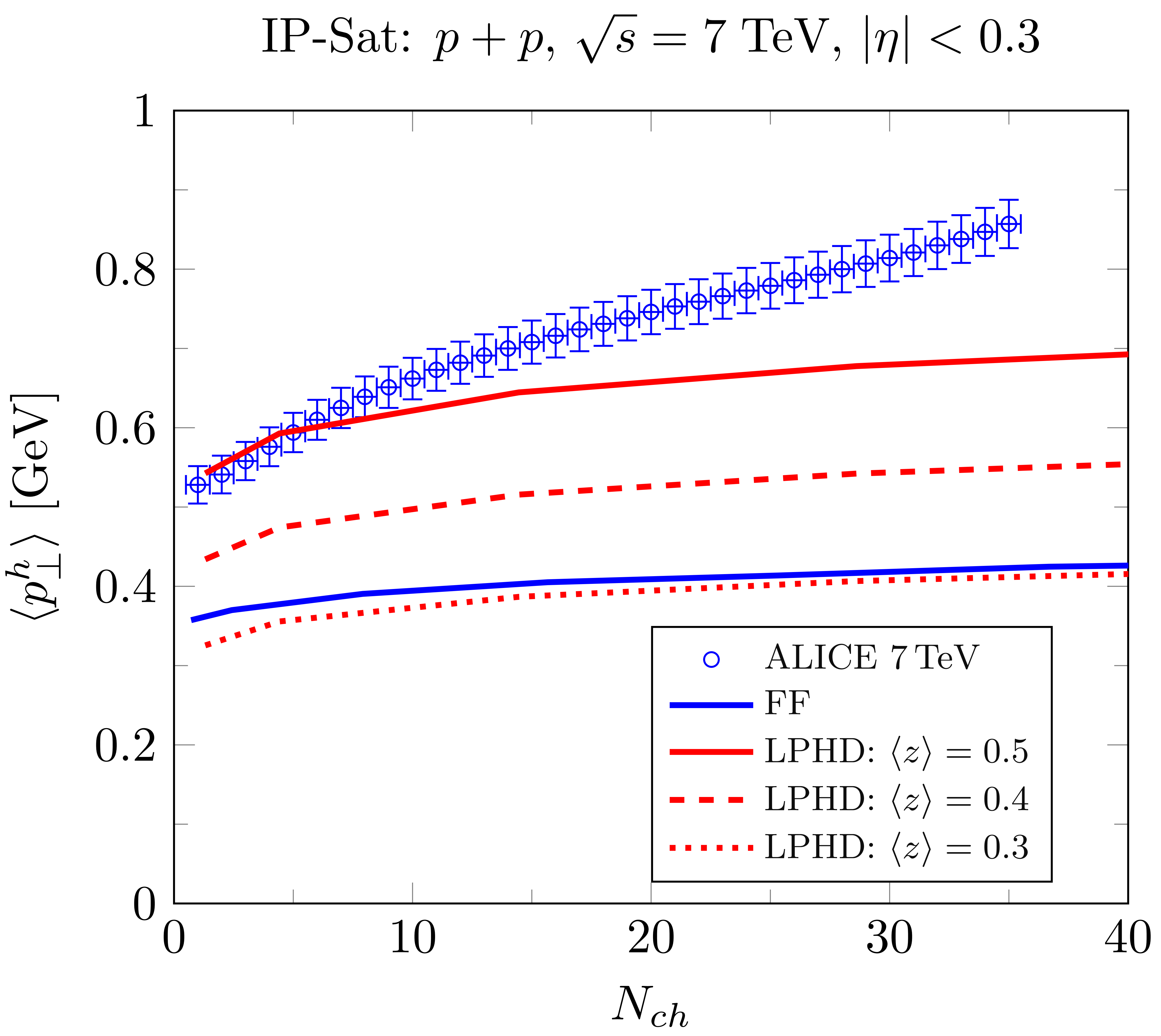
Local Parton Hadron Duality (LPHD) Hypothesis



- Hadronization happens at a later stage in vacuum (pre-confinement of QCD cascades).
- Parton's momentum direction does not change during hadronization: $p_\perp^g \langle z \rangle = p_\perp^h$.
- 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^-.

See Dokshitzer, Khoze, Troian (1991), Dokshitzer, Khoze, Mueller, Troian (1991), Khoze, Ochs (1997)

Charged hadron's mean $p_\perp$



- FF approach:

$$\langle p_\perp^h \rangle = \frac{\int d\eta d^2p_\perp^h J_{y\to\eta} |p_\perp^h| d\sigma/d^2p_\perp^h dy}{\int d\eta d^2p_\perp^h J_{y\to\eta} d\sigma/d^2p_\perp^h dy}$$

IP-Sat + FF approach cannot describe data.

- LHPD approach:

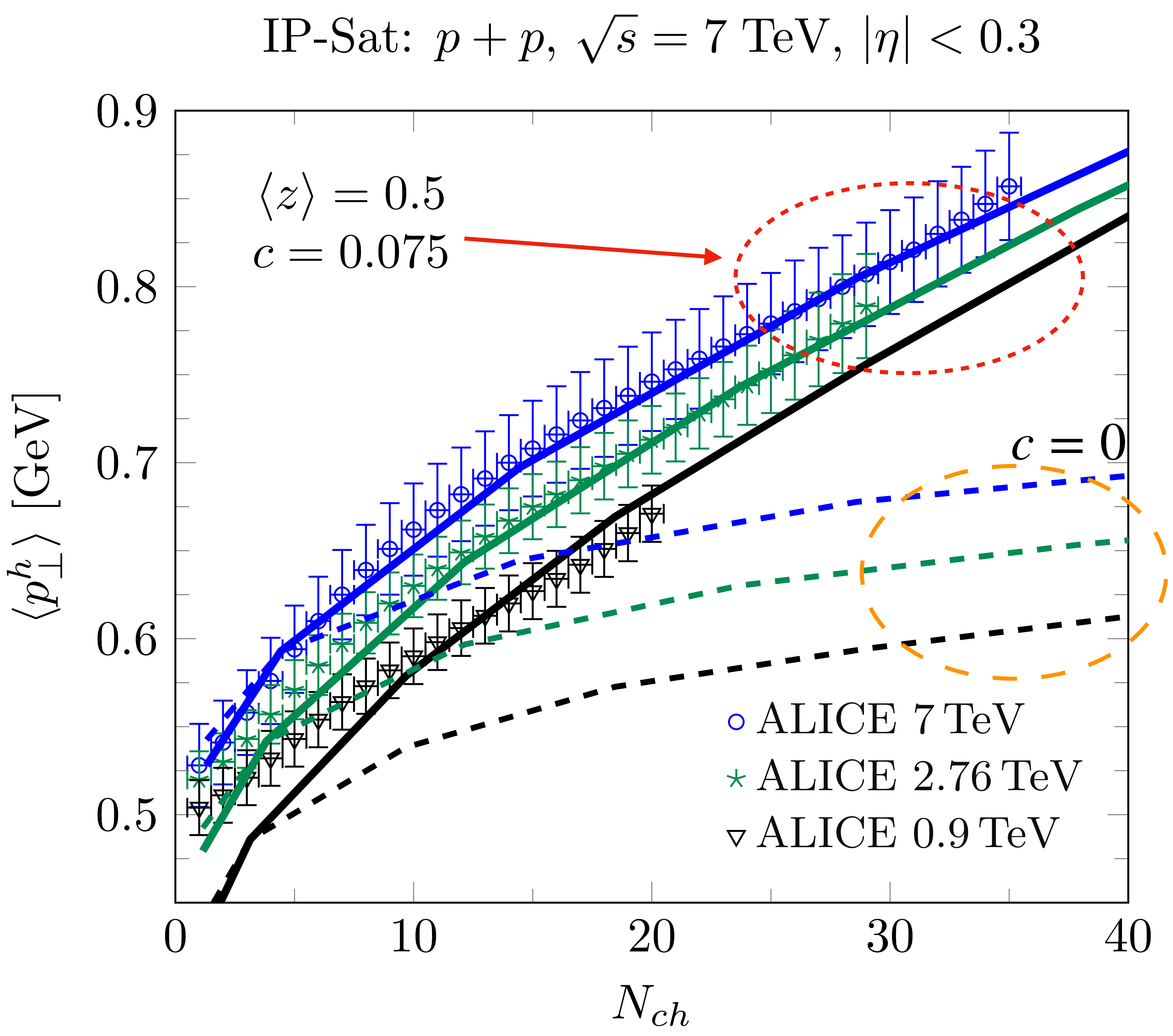
$$\langle p_\perp^h \rangle = \langle \langle z \rangle p_\perp^g \rangle = \frac{\int d\eta d^2p_\perp^g J_{y\to\eta} \langle z \rangle |p_\perp^g| d\sigma/d^2p_\perp^g dy}{\int d\eta d^2p_\perp^g J_{y\to\eta} d\sigma/d^2p_\perp^g dy}$$

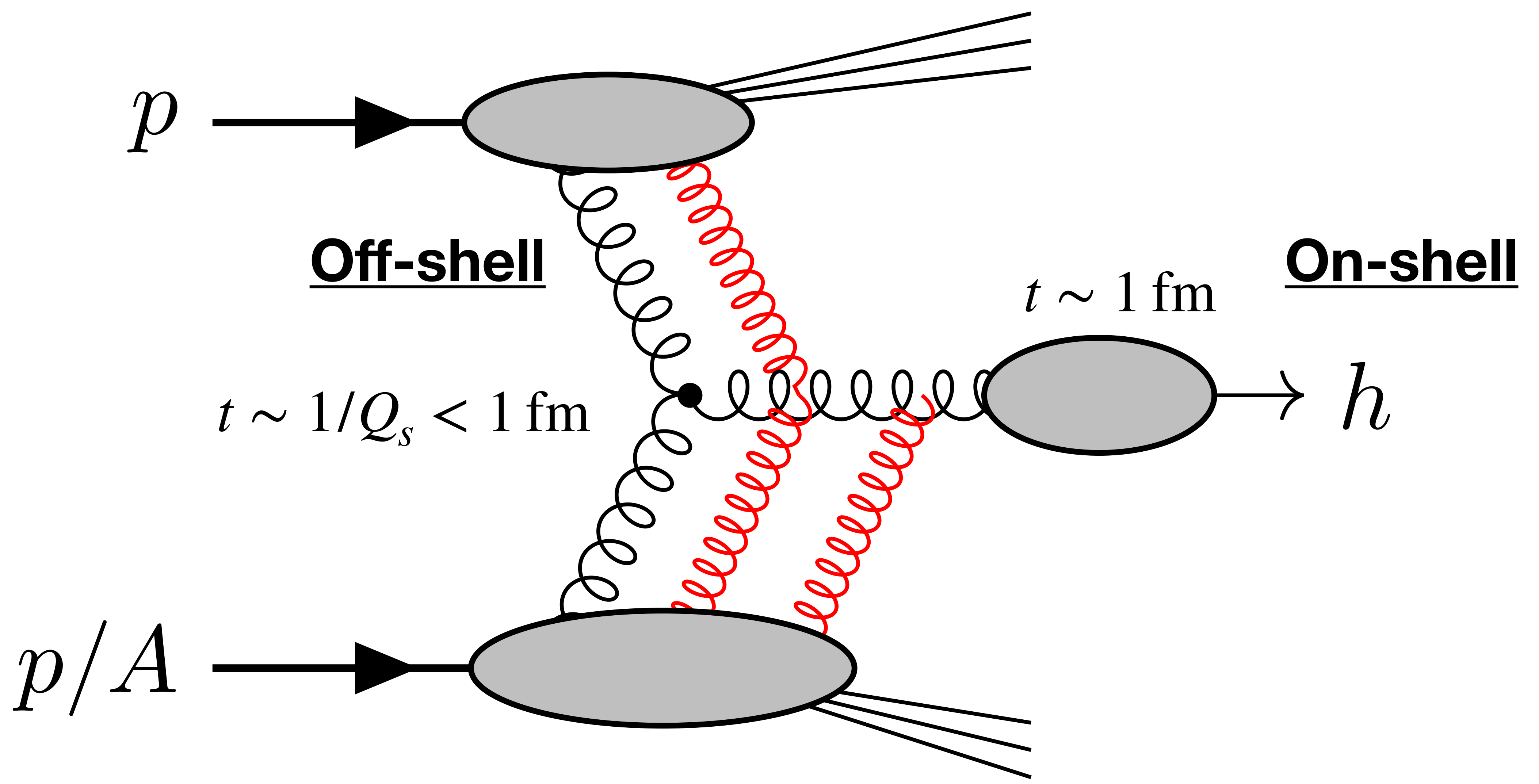
IP-Sat + LPHD with $\langle z \rangle = 0.5$ is still off data points at high $N_{\rm ch}$.

Note: MV model + rcBK + FF approach reproduces data, but ignores b-dep.

Coherent rescattering effect

Ma, Stebel, Venugopalan, **KW**, PoSHardProbes2020, 066 (2021)





Multiple rescattering can happen before the hadronization:
Coherent kicks before the gluons go on-shell.

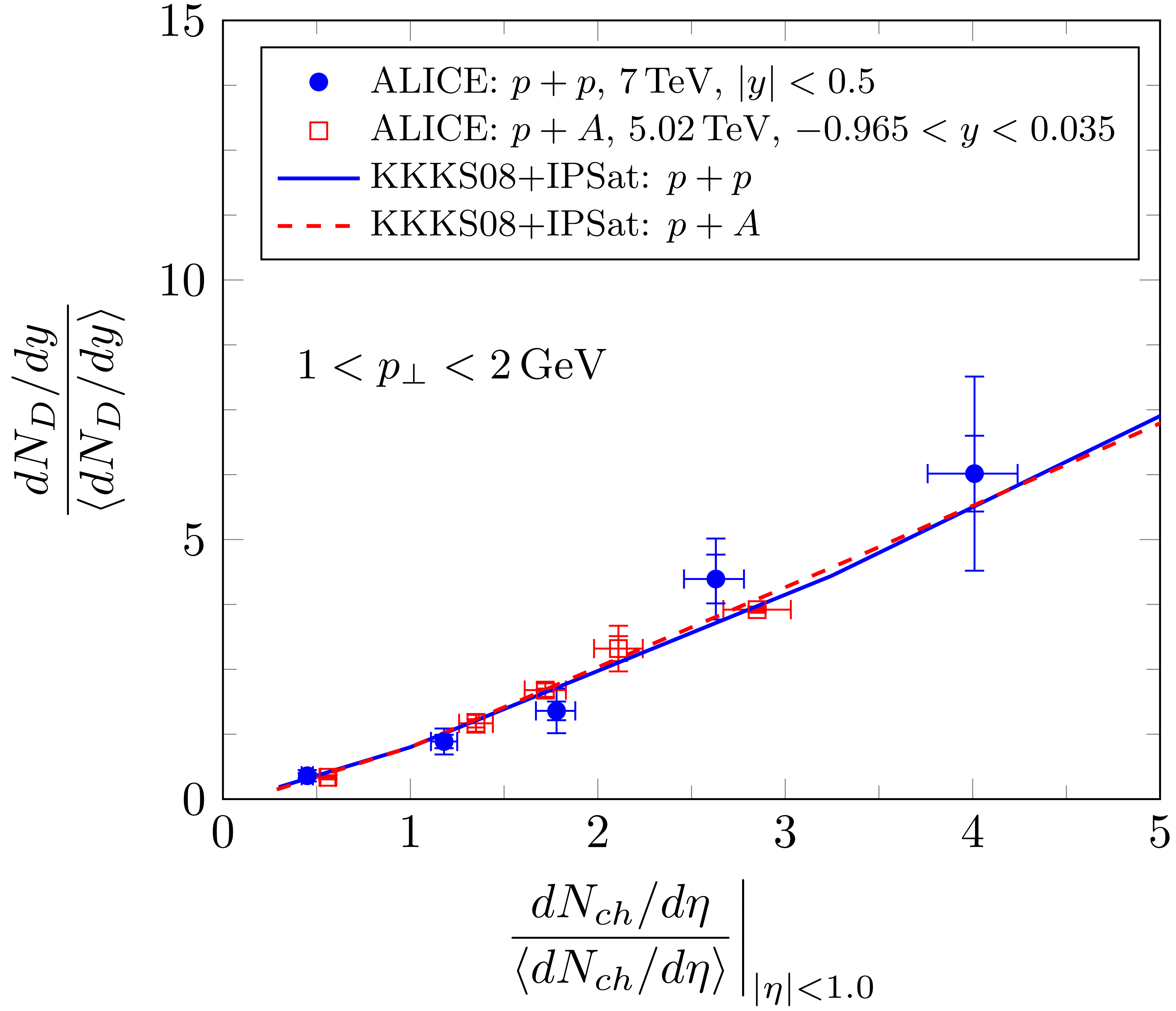
$$\boxed{\langle p_\perp^h \rangle = \sqrt{\langle \langle z \rangle p_\perp^g \rangle^2 [1 + c(n-1)]}}$$

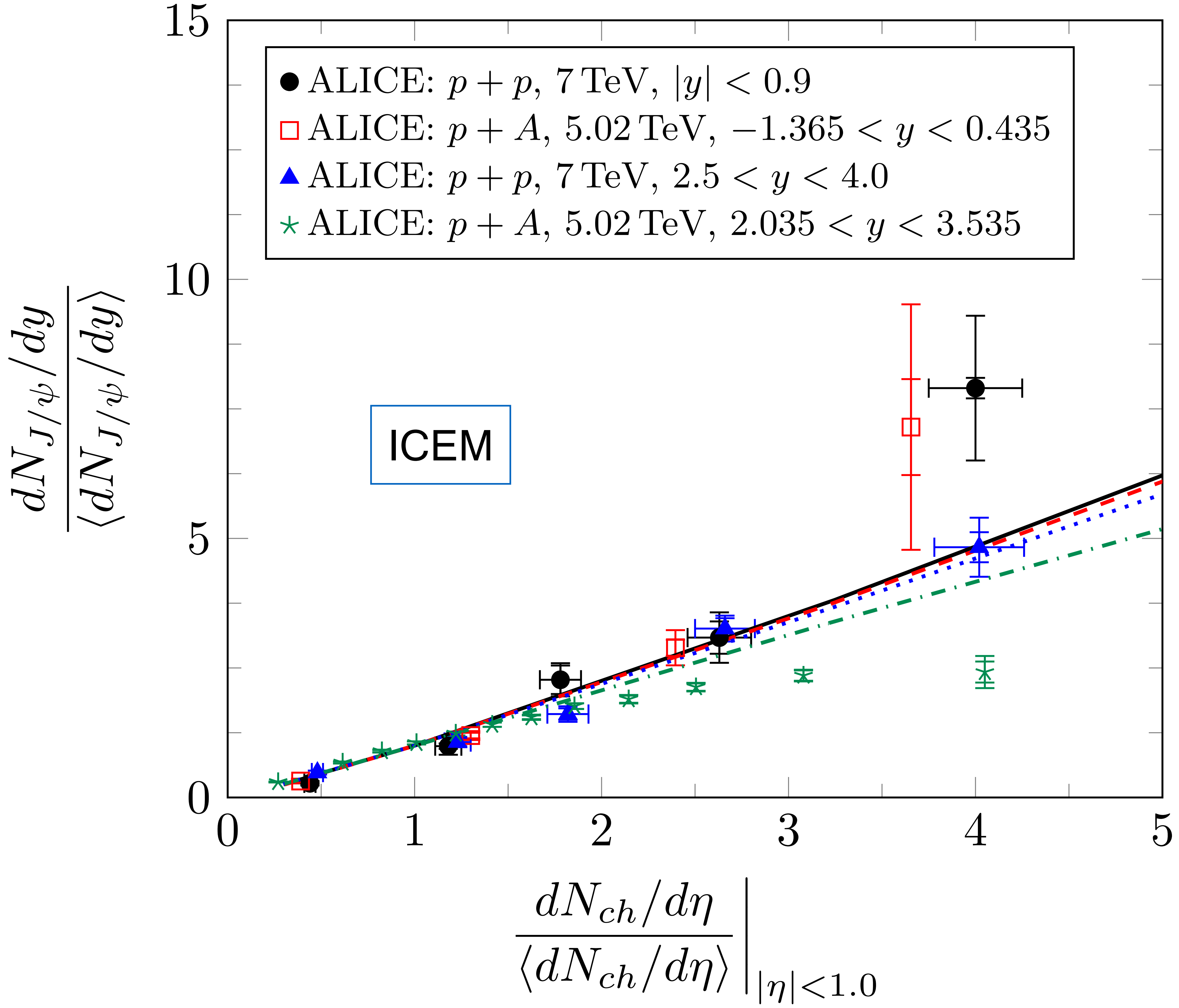
A simple random walk picture: $n = N_{\rm ch}/\langle N_{\rm ch} \rangle$

- ➢ More work is needed to pin down hadronization dynamics!
- ➢ The uncertainty concerning bulk hadron production affects other observables.

D-mesons and J/ψ production

Ma, Tribedy, Venugopalan, **KW**, PRD98, 7, 074025 (2018)
Ma, Tribedy, Venugopalan, **KW**, NPA982, 747-750 (2019)
Ma, Stebel, Venugopalan, **KW**, PoSHardProbes2020, 066 (2021)

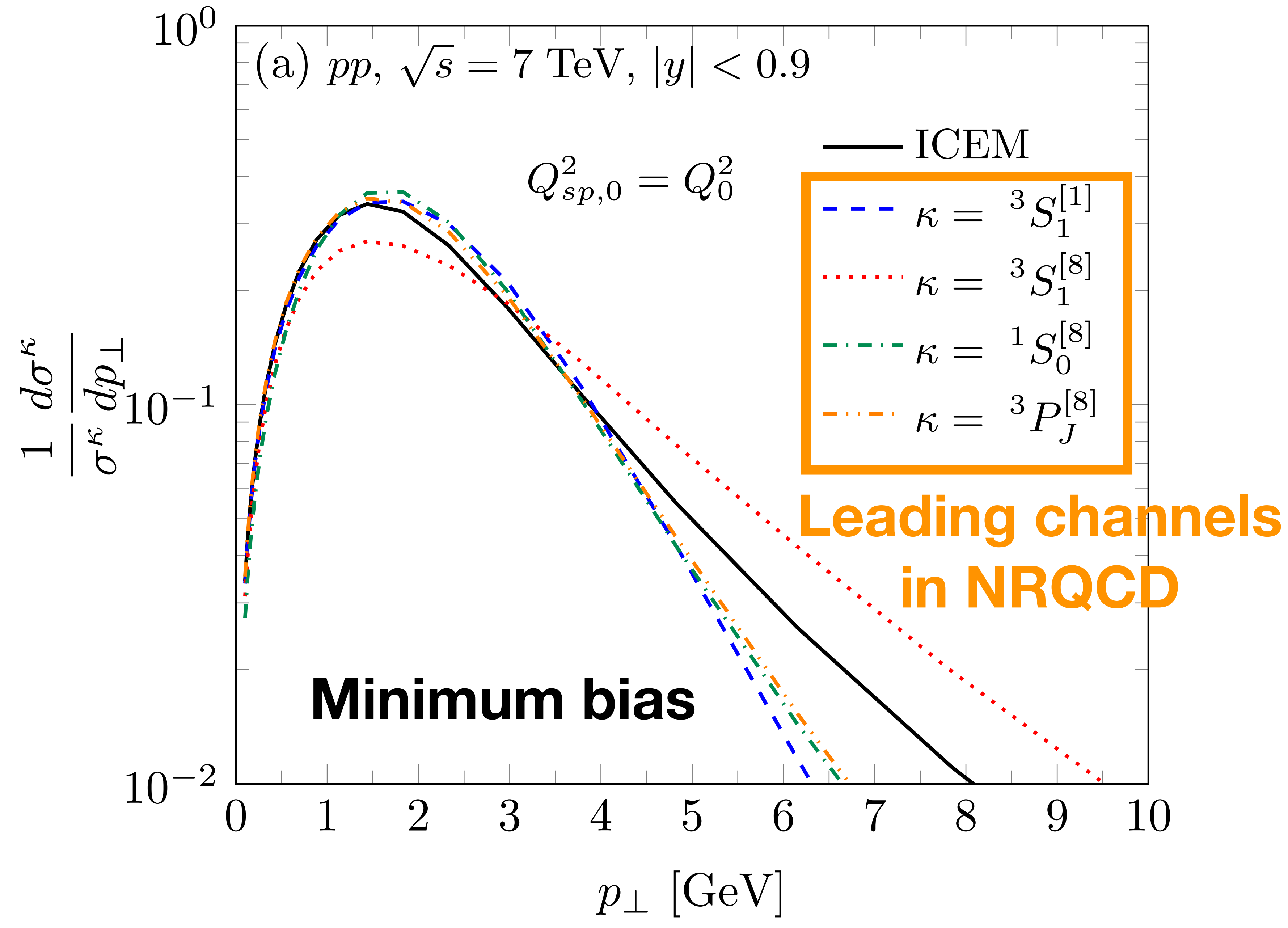


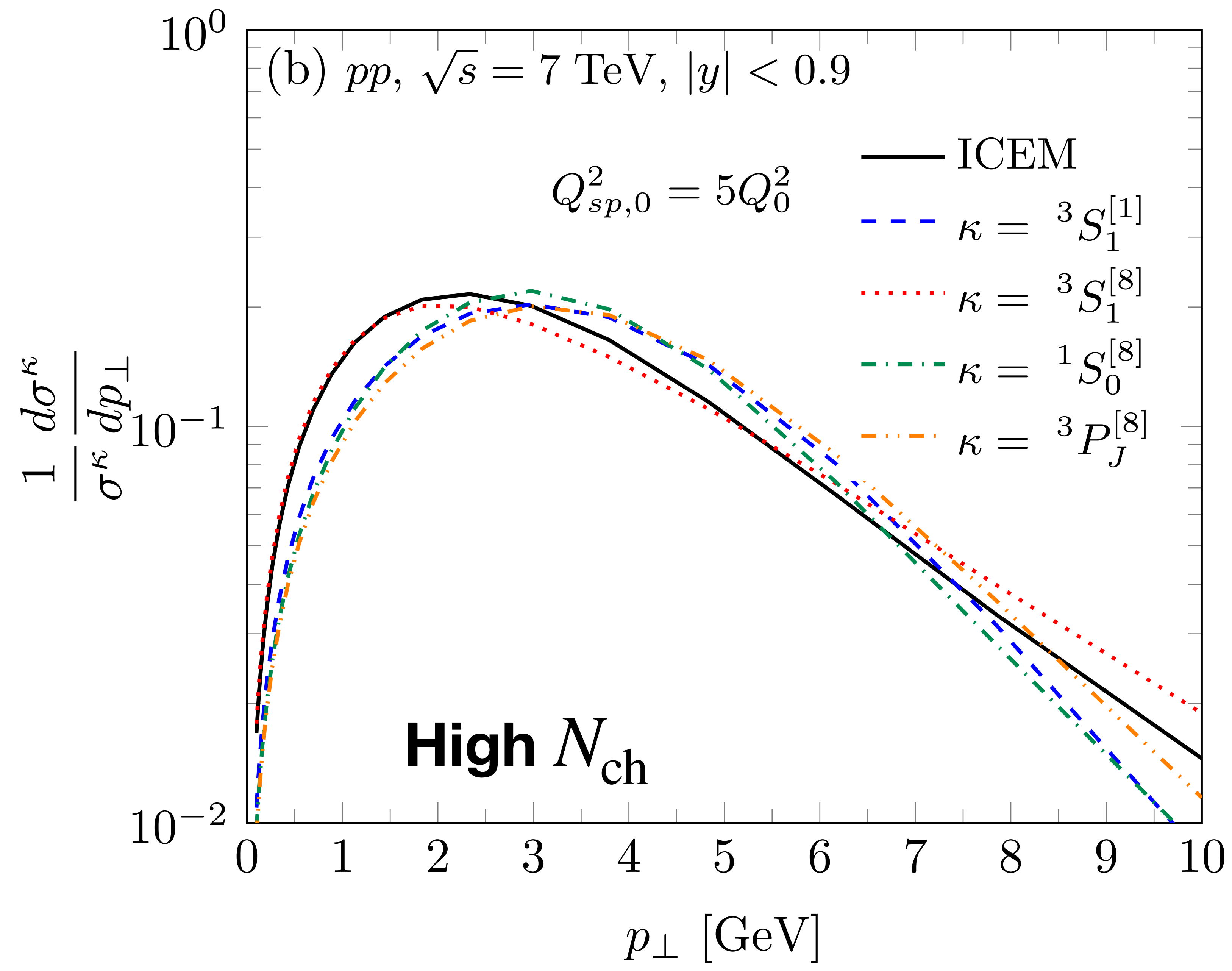


➢ IP-Sat + LPHD for N_{ch} , IP-Sat + KKKS08 set FF for D_0, D^{*+}, D^+, IP-Sat + ICEM for J/ψ.

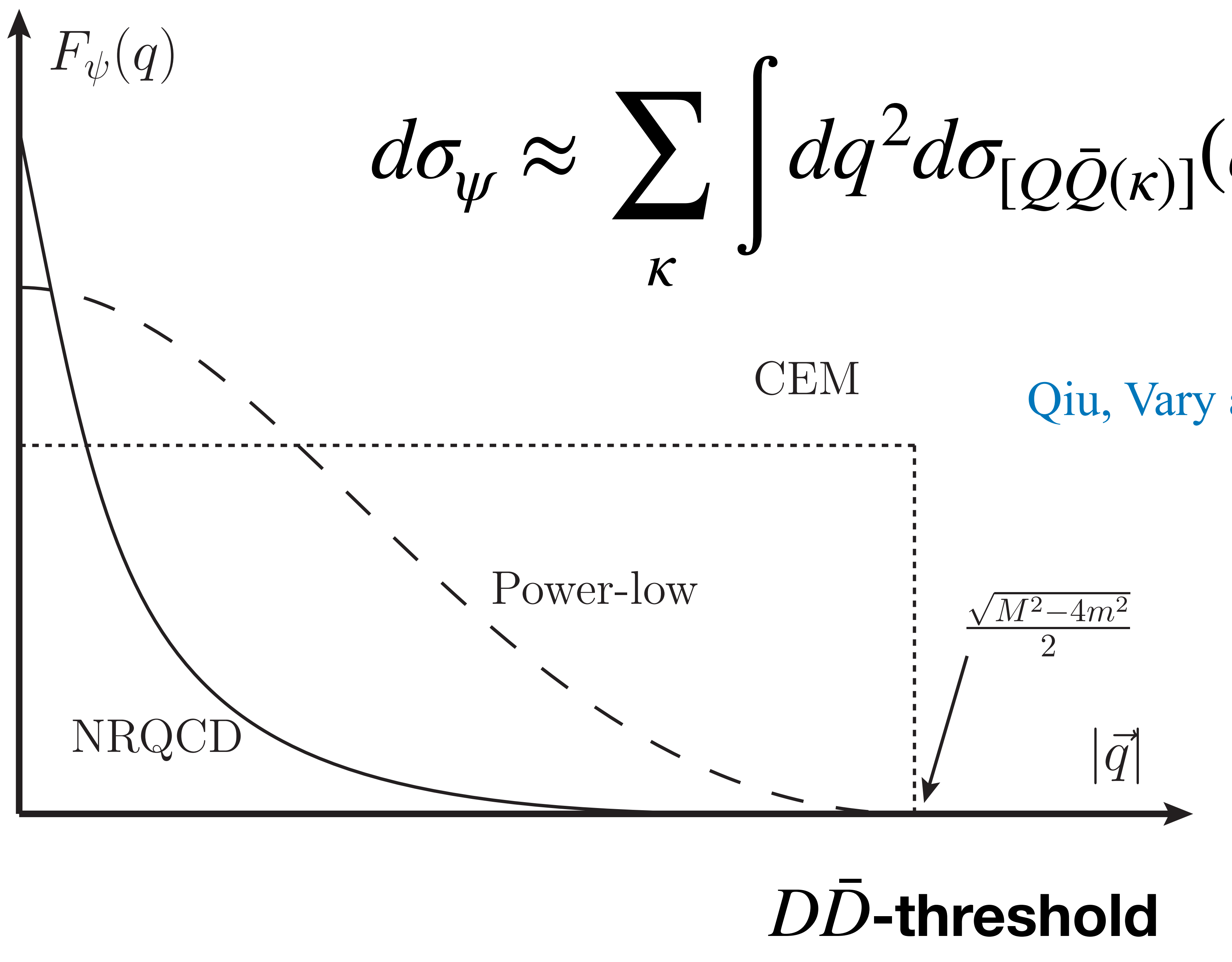
➢ Indeed, even when using light hadron FF instead LPHD, and rcBK model instead IP-Sat, the CGC prediction agree with data.

Onium production model: transition distribution





$$d\sigma_\psi \approx \sum_\kappa \int dq^2 d\sigma_{[Q\bar{Q}(\kappa)]}(q^2) F_{[Q\bar{Q}(\kappa)]\to\psi}(q^2)$$



Qiu, Vary and Zhang, PRL88, 232301 (2002)

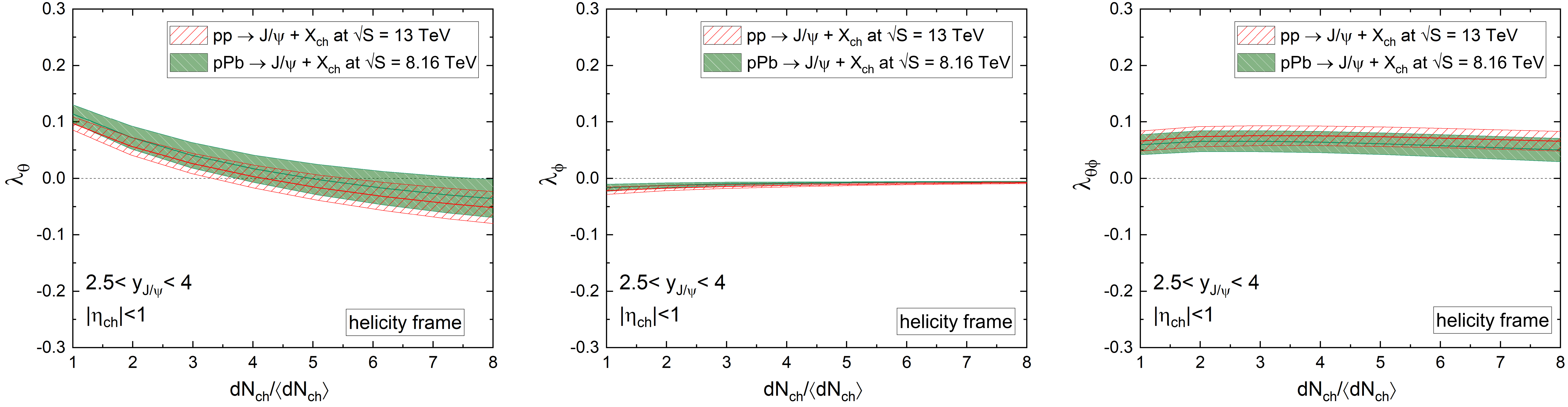
- ➢ Both ICEM and NRQCD give similar $p_\perp$ spectrums at low $p_\perp$, even at high $N_{\rm ch}$.
- ➢ Inclusive onium production is not very sensitive to the onium production model; to be addressed further.
- ➢ Other observables can explore the transition distribution F.

J/ψ polarization vs. N_{ch}

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

BK + NRQCD model

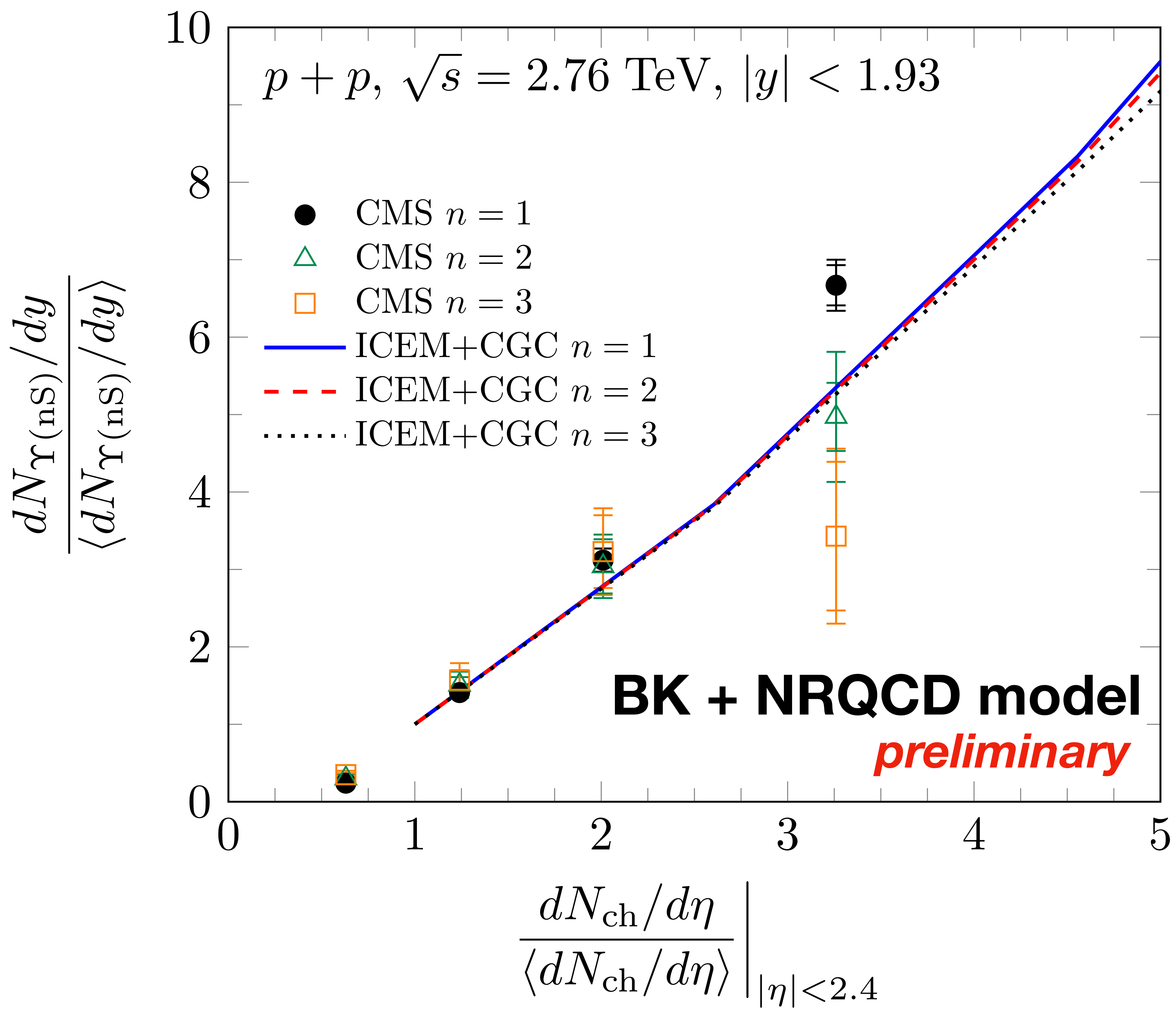
Stebel and **KW**, PRD104, no.3, 034004 (2021)

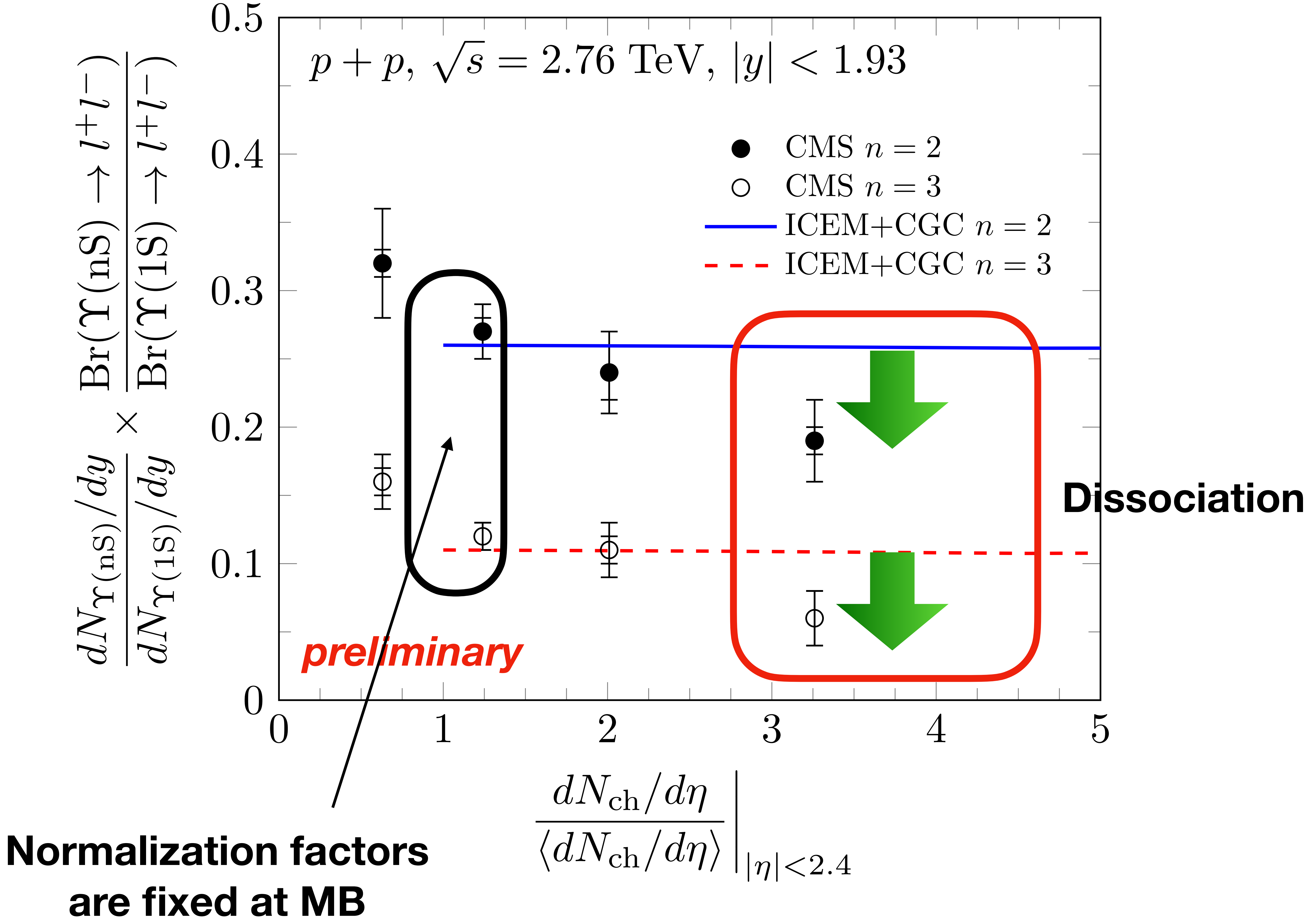


- J/ψ gets more unpolarized with N_{ch} due to the multiple-rescattering at a short distance; weak energy and system size dep.
- Predictable with ICEM as well. Cheung and Vogt, PRD104, no.9, 094026 (2021), PRC105, no.5, 055202 (2022)
- If other final state effects get into the game, the prediction can be changed.

Υ production and dissociation

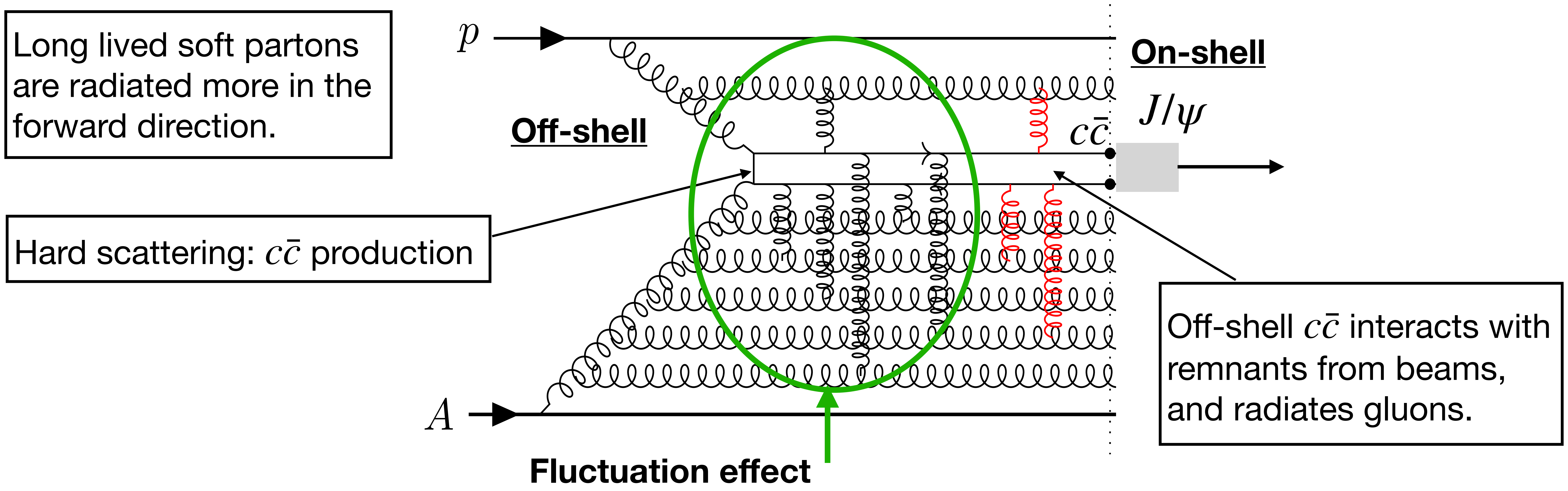
KW in progress



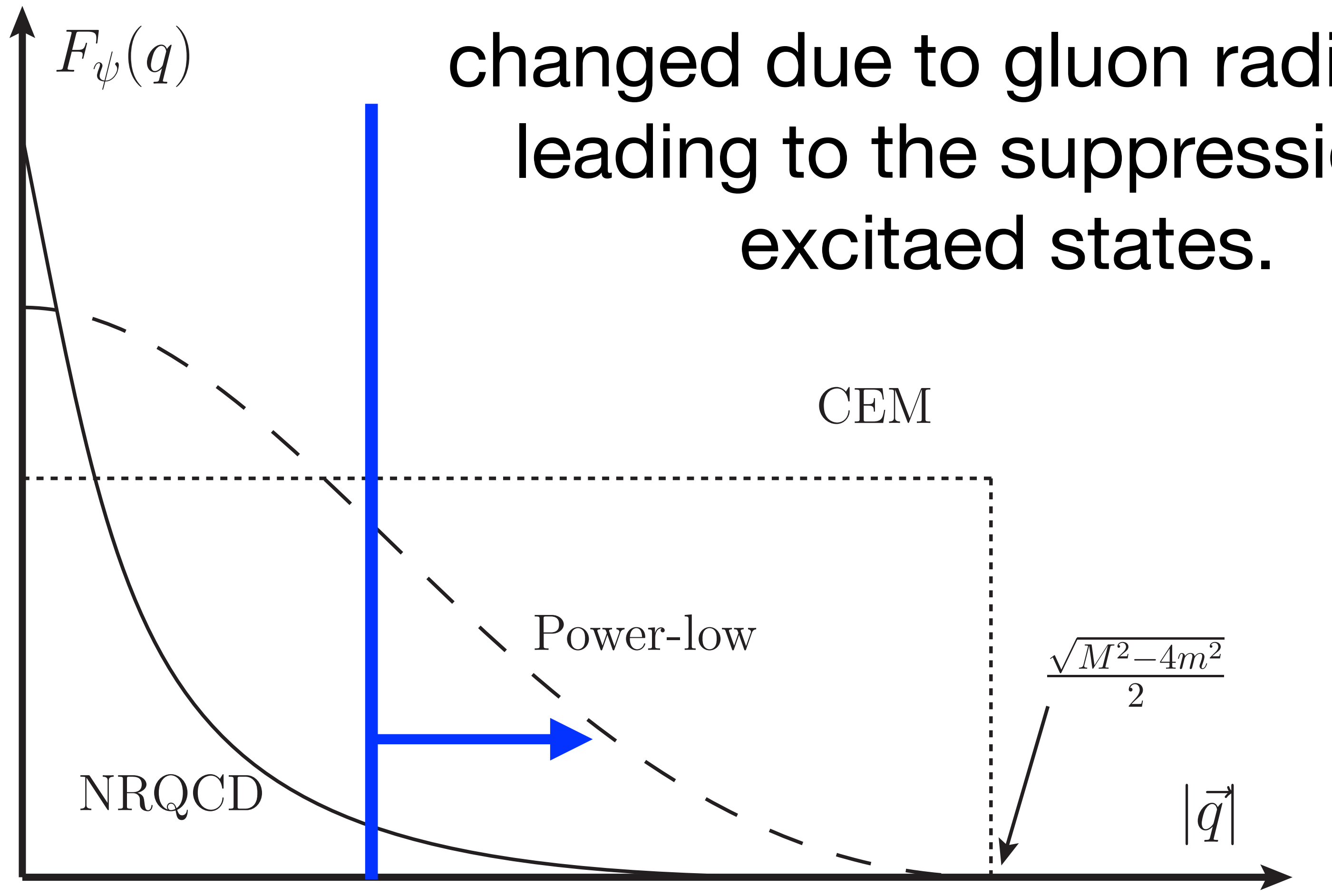


- No significant difference between 1S, 2S, and 3S.
- Additional final state effect may be needed to describe $\Upsilon(2S)$, $\Upsilon(3S)$ suppression at high N_{ch}.

Threshold effect



1. Semi-hard multiple rescattering of high occupied gluons: $k \sim \mathcal{O}(Q_s)$
   - $Q\bar{Q}$ production yield is enhanced at high multiplicity.
2. Nuclear enhanced soft colors transfer from spectators: $k \sim \mathcal{O}(\Lambda_{QCD}) \sim \Delta E_{J/\psi}$
   - The soft color exchange effect is clearly seen in ψ' stronger suppression in MB p+A collisions.
3. Gluon radiation from a produced pair
   - Over $6\,\mathrm{GeV}^2$ phase space for gluon radiation; $4M_D^2 - 4m_c^2$.



The transition distribution can be changed due to gluon radiations, leading to the suppression of excitaed states.

Qiu, **KW** in progress

Summary

➢ The strong enhancement of HF production yield at high multiplicity is a natural consequence of initial state fluctuation effect.

➢ Other theoretical approaches have took a similar setup; e.g., string percolation model [Ferreiro and Pajares, PRC86, 034903 (2012)], Pomeron fusion model [Levin, Schmidt and Siddikov, Eur. Phys. J. C80, no.6, 560 (2020)]

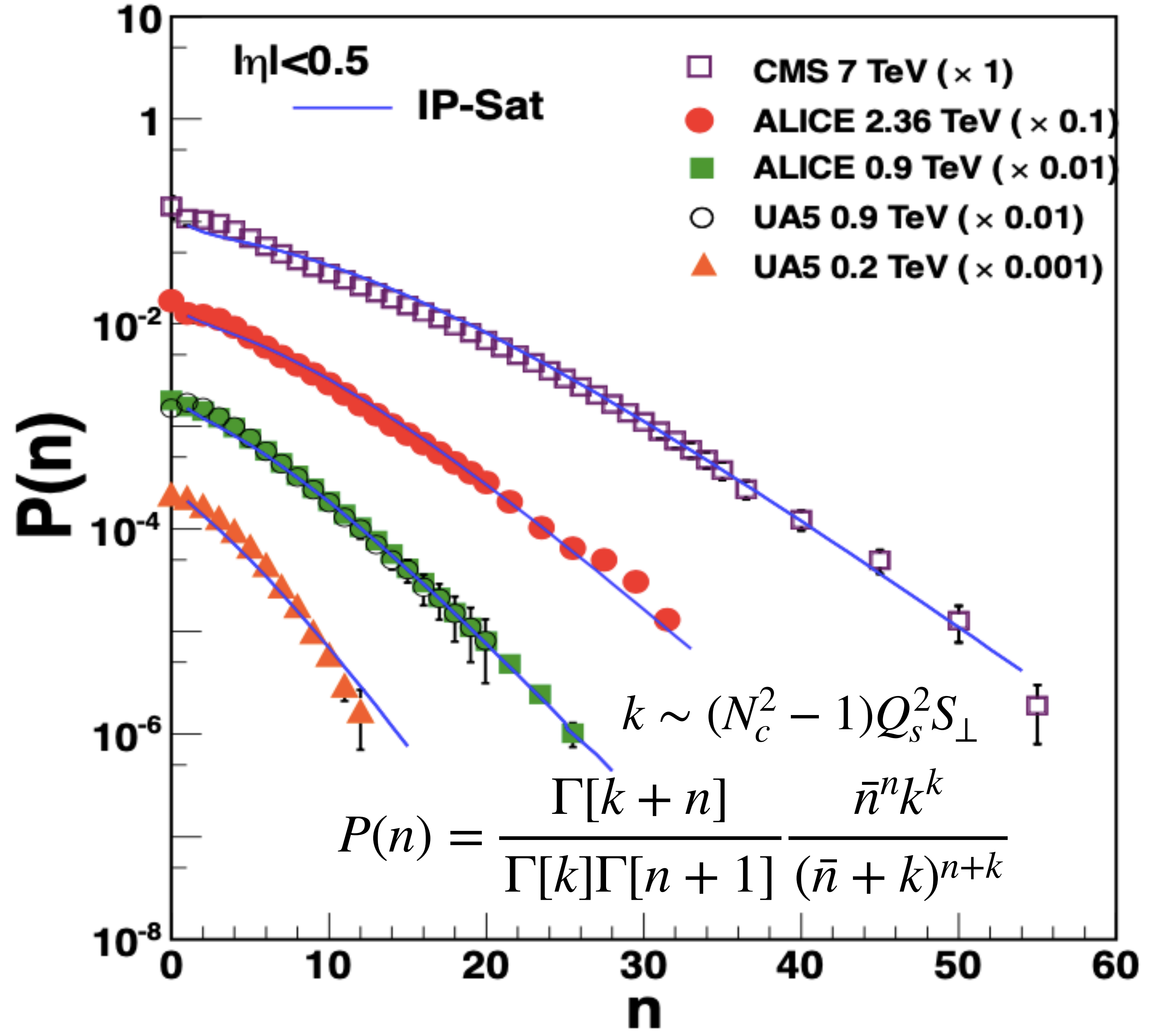
➢ High multiplicity events provide an opportunity to study hadronization dynamics of light hadron and heavy quarkonium.

Thank you!

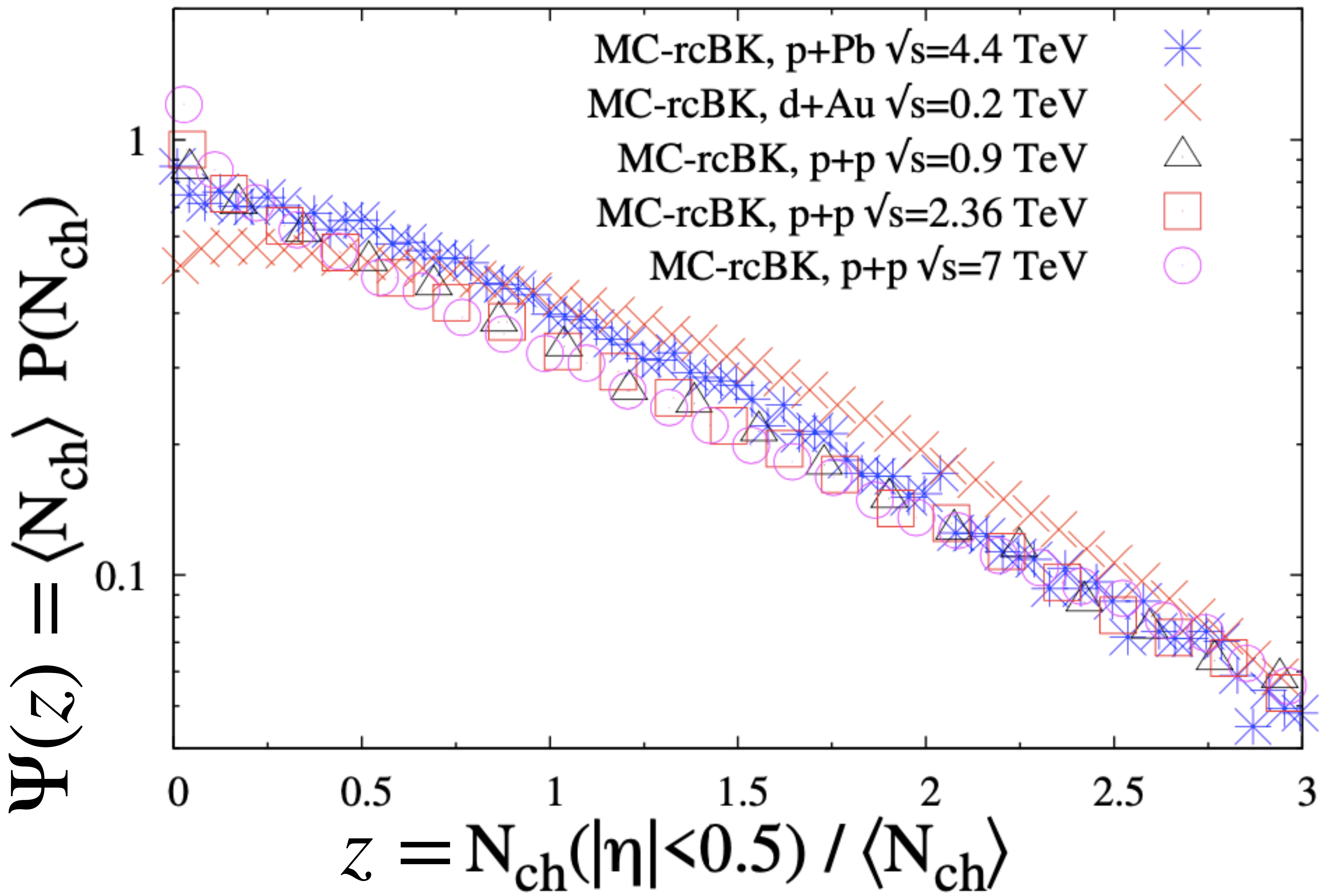
backup

Bulk particle production and KNO scaling

Tribedy and Venugopalan, PLB710, 125-133 (2012)



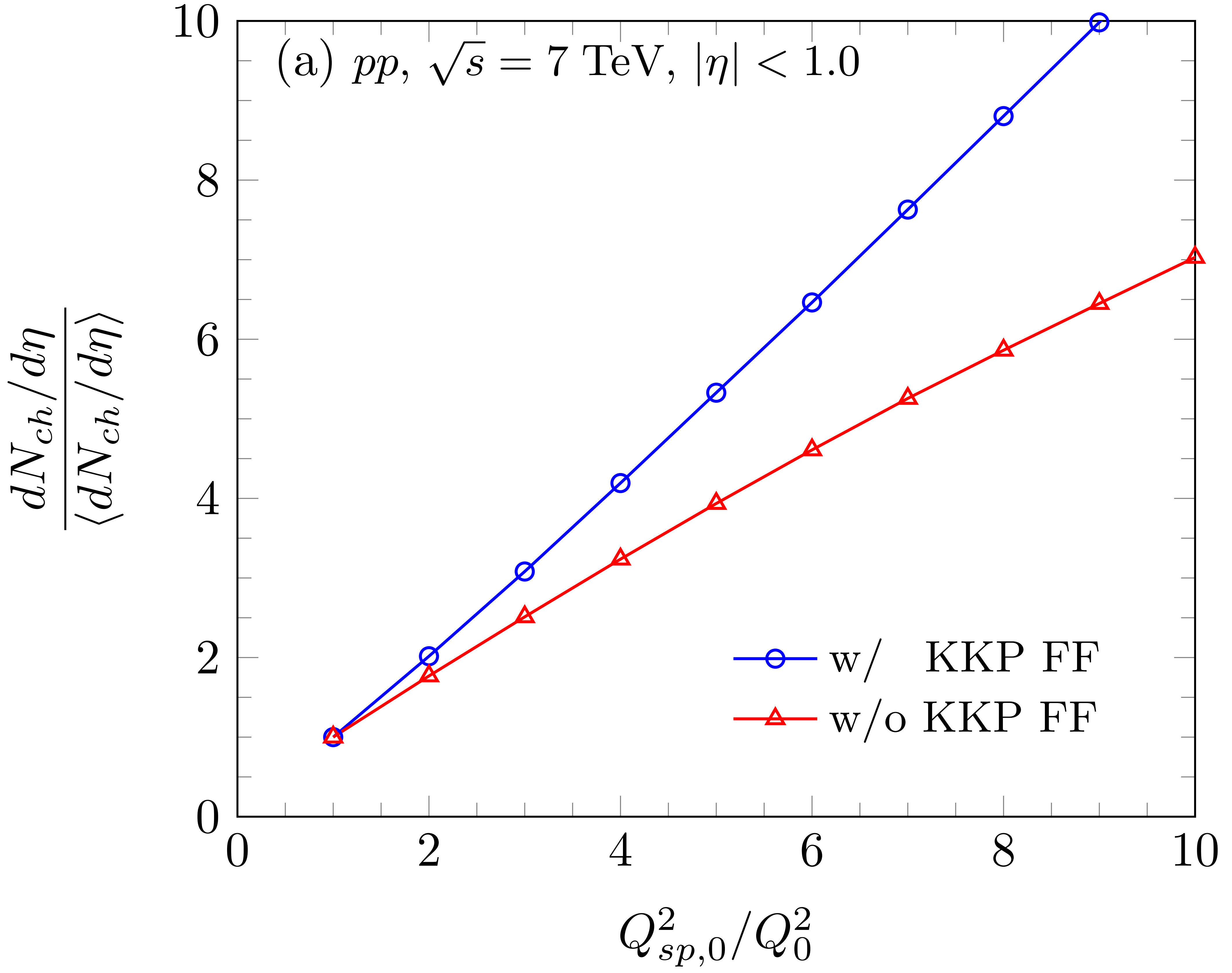
Dumitru and Nara, Phys. Rev. C85, 034907 (2012)

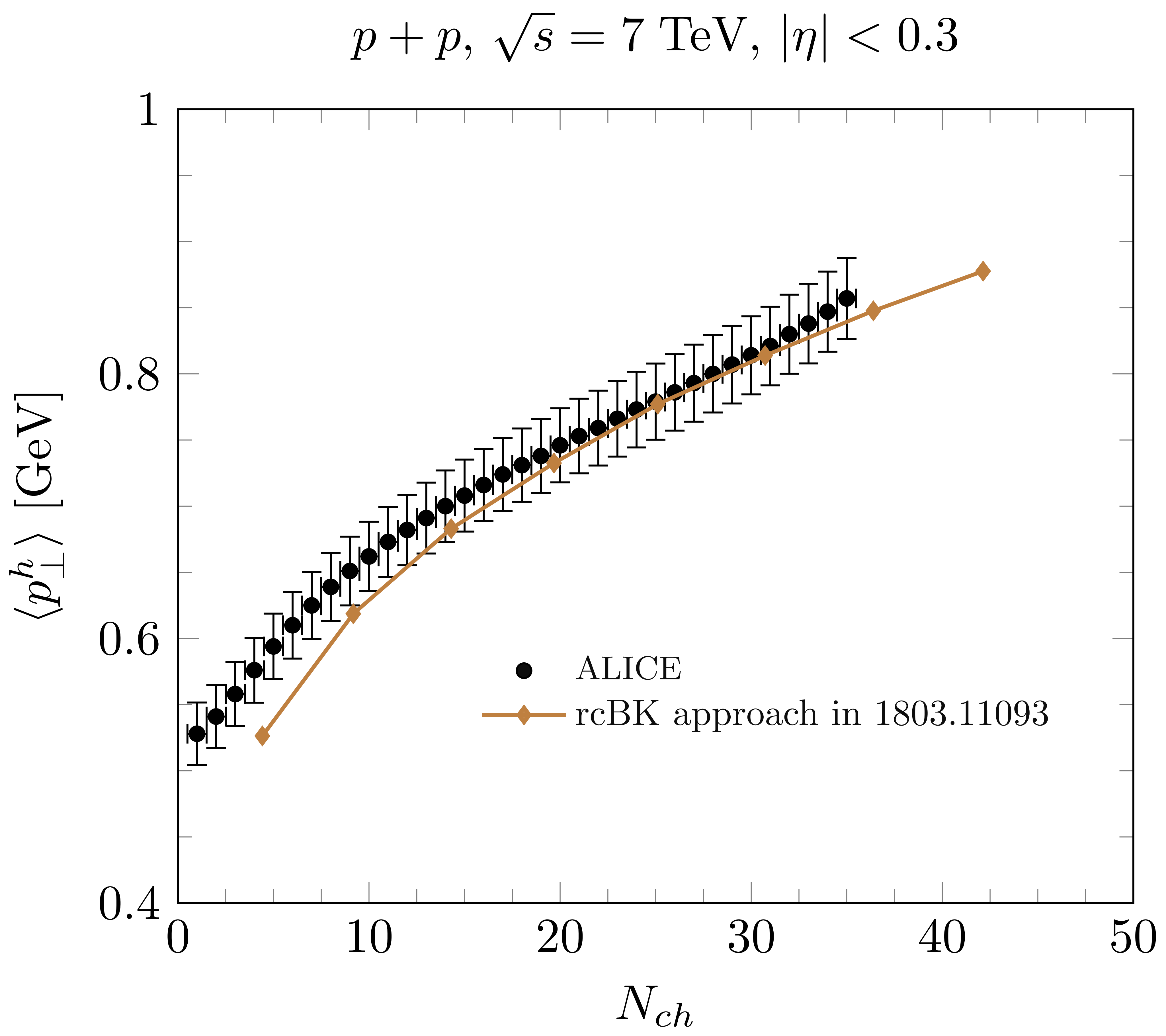


➢ If KNO scaling breaks down, soft multiple-particle interactions could play an essential role.

➢ In the CGC framework, KNO scaling is held in pp collisions at the LHC up to $n/\bar{n} \leq 3$, but weakly violated in pA collisions → soft modes are crucial at high N_{ch}!

Hadron production





Polarization: frame-dep

Stebel and **KW**, PRD104, no.3, 034004 (2021)