

Introduction to the eA/pA/AA session

Kazuhiro Watanabe
(on behalf of the conveners)

Quarkonia As Tools 2022, Aussois, 01/13/2022

Diverse topics on physics in eA/pA/AA + pp

Thursday

Introduction to the sessions for eA/pA/AA	Audrey Francisco et al.
Centre Paul Langevin	08:30 - 09:00
Experimental status of not-so-conventional quarkonium production ($\chi_{c,c}, \eta_{c,b}, X(3872)$)	Valeriia Zhovkovska
Centre Paul Langevin	09:00 - 09:30
MPI/production in pp collisions at RHIC	Leszek Krzysztof Kosarzewski
Centre Paul Langevin	09:30 - 10:00
Coffee break	
Centre Paul Langevin	10:00 - 10:30
Experimental review of pA results	Theraa M A Tork
Centre Paul Langevin	10:30 - 11:00
EPOS event generator	Johannes Jahan
Centre Paul Langevin	11:00 - 11:30
Quarkonium physics at SPD NICA	Amaresh Datta
Centre Paul Langevin	11:30 - 12:00

Friday

Experimental status: AA collisions	Kazuhiro Watanabe et al.
Centre Paul Langevin	08:30 - 09:00
Recent developments in factorisation formalisms for heavy quarkonium production	Dr Hee Sok Chung
Centre Paul Langevin	09:00 - 09:30
pNRQCD EFT and application to phenomenology	Peter Vander Griend
Centre Paul Langevin	09:30 - 10:00
Coffee break	
Centre Paul Langevin	10:00 - 10:30
Open quantum systems	Stéphane Delorme
Centre Paul Langevin	10:30 - 11:00
Quarkonium's properties at finite temperature from Lattice QCD	Johannes Heinrich Weber
Centre Paul Langevin	11:00 - 11:30
Transport approach in pA and AA collisions	Xiaojian Du
Centre Paul Langevin	11:30 - 12:00

Monday

Constraining the nuclear gluon PDF with quarkonium production data	Pit Duwentaster
Centre Paul Langevin	11:00 - 11:30

Saturday

DPS as MPI in eA/pA collisions	Matteo Rinaldi
Centre Paul Langevin	09:30 - 10:00

Many other talks are also essential inputs to consider physics opportunities in eA/pA/AA!

Our goals

Quarkonium production in eA and pA collisions (**small systems**):

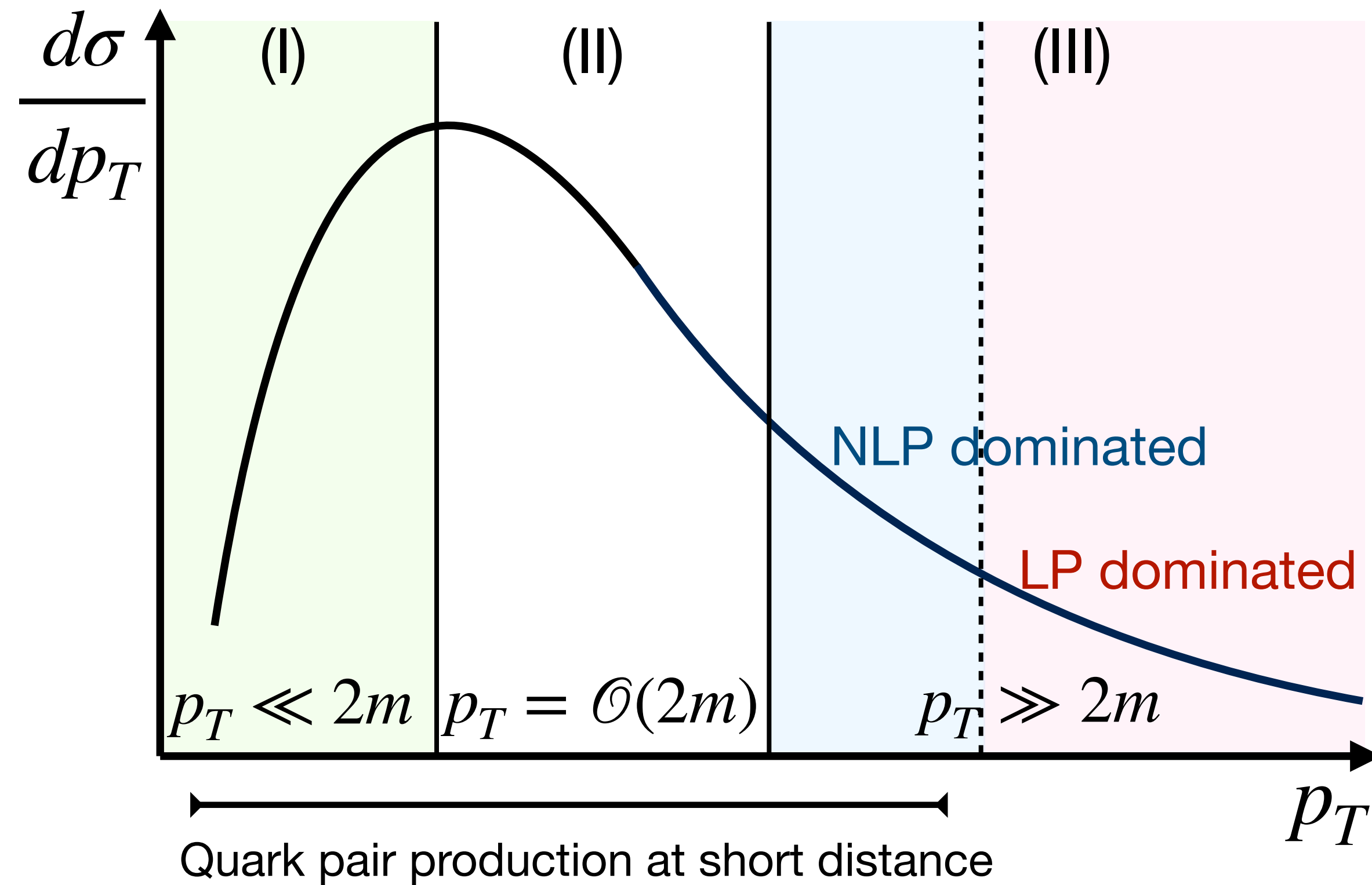
- To pursue quarkonium production mechanism with backgrounds.
- To map multi-dimensional quantum images of nuclei with quarkonia.
- To study nuclear enhanced multiple scattering effects (higher twists).
- To pin down the origin of collectivity (multi-particle correlations).
- To assess small systems as the baseline against large systems.
- ...

Quarkonium production in AA collisions (**large systems**):

- To explore novel features of Quark-Gluon Plasma.
- To pin down the origin of collectivity (together with small systems).
- To study new paradigms for QCD under extreme conditions.
- ...

- complementary theory inputs: mainly pA -

Hadronic quarkonium production at a glance



This part is modified by “cold” nuclear effects:
nPDFs-shadowing, twists, saturation, energy-loss,
and so forth.

(I) TMD factorization + CEM or NRQCD

Berger, Qiu and Wang, PRD 71, 034007 (2005)
Sun, Yuan and Yuan, PRD88, 054008 (2013)

CGC framework + CEM or NRQCD (forward)

Ma, Venugopalan, PRL113, 19, 192301 (2014)
KW, Xiao, PRD92, 11, 111502 (2015)
Ma, Venugopalan, KW, Zhang, PRC97, no.1, 014909 (2018)

(II) NRQCD factorization

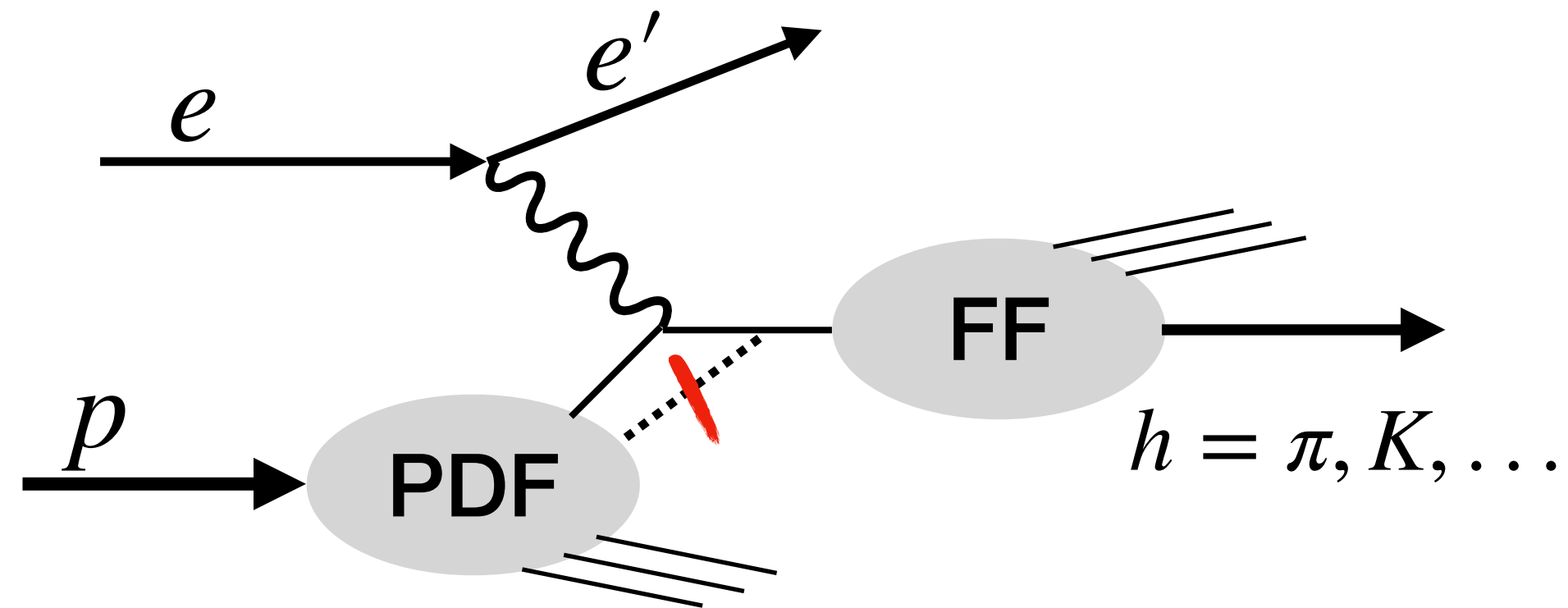
Butenschoen, Kniehl, PRD84, 051501 (2011)
Chao, Ma, Shao, Wang, Zhang, PRL108, 242004 (2012)
Gong, Wan, Wang, Zhang, PRL110, 042002 (2013)

(III) QCD factorization w/ Fragmentation Functions

Kang, Qiu and Sterman, PRL108, 102002 (2012)
Bodwin, Chung, Kim, Lee, PRL113, 022001 (2014)
Ma, Qiu, Sterman, Zhang, PRL113, 14, 142002 (2014)
Lee, Qiu, Sterman, KW, 22xx.xxxx

Lessons from ep/pp

Semi-inclusive DIS: $e + p \rightarrow e' + h + X$

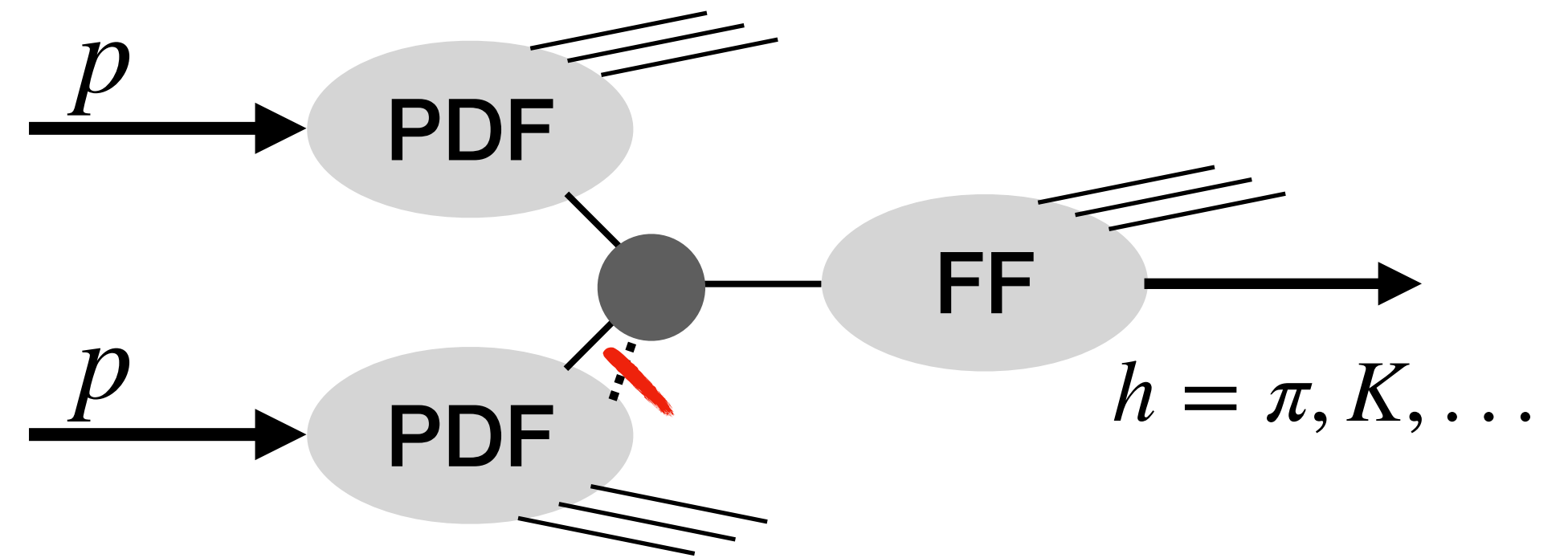


$$\sigma_{e+p \rightarrow e'+h+X} \approx f_{i/p} \otimes D_j^h \otimes C$$

Nonperturbative universal functions

Perturbatively calculable coefficients

Hadronic collision: $p + p \rightarrow h + X$

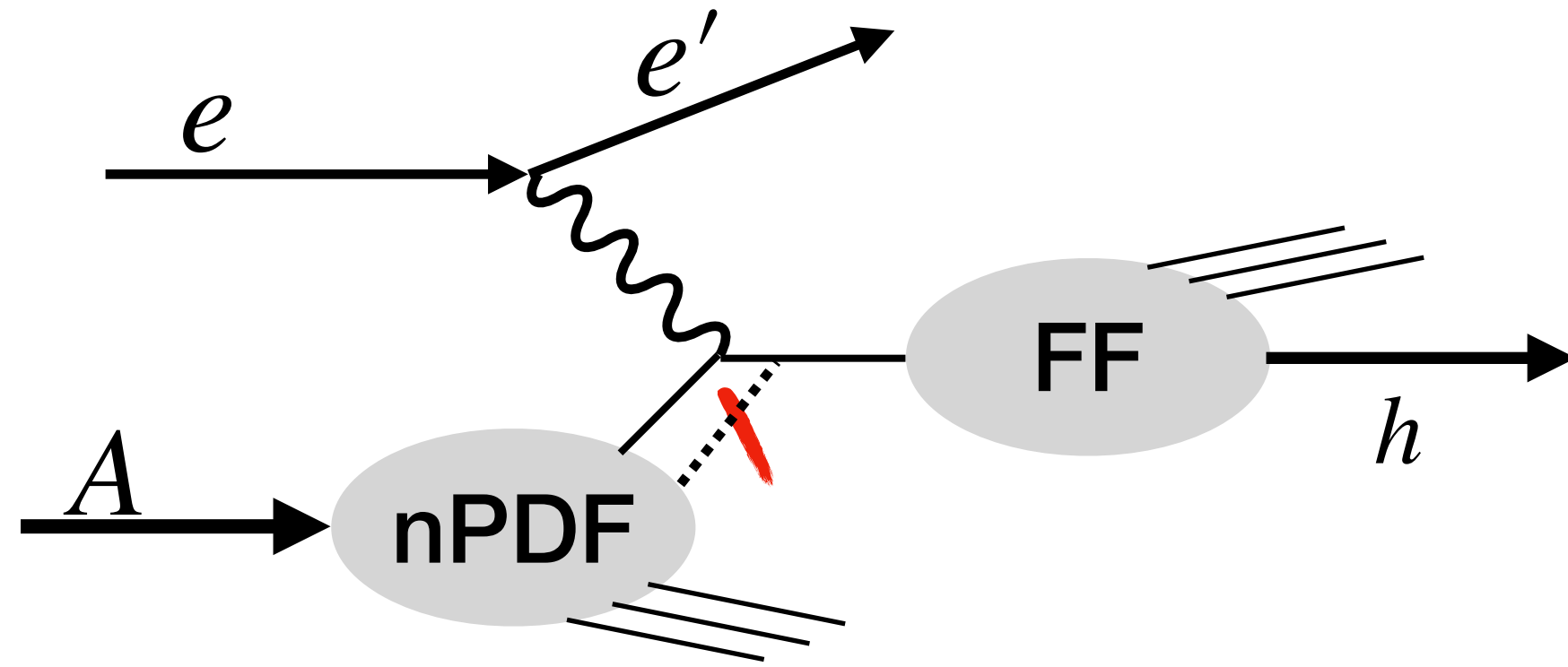


$$\sigma_{p+p \rightarrow h+X} \approx f_{i/p} \otimes f_{j/p} \otimes D_k^h \otimes C$$

- Power corrections ($1/Q$ -expansion) are neglected.
- $\ln^2(Q^2/p_T^2)$ -type enhanced corrections can be resummed and taken into the definition of TMD PDFs and/or FFs.

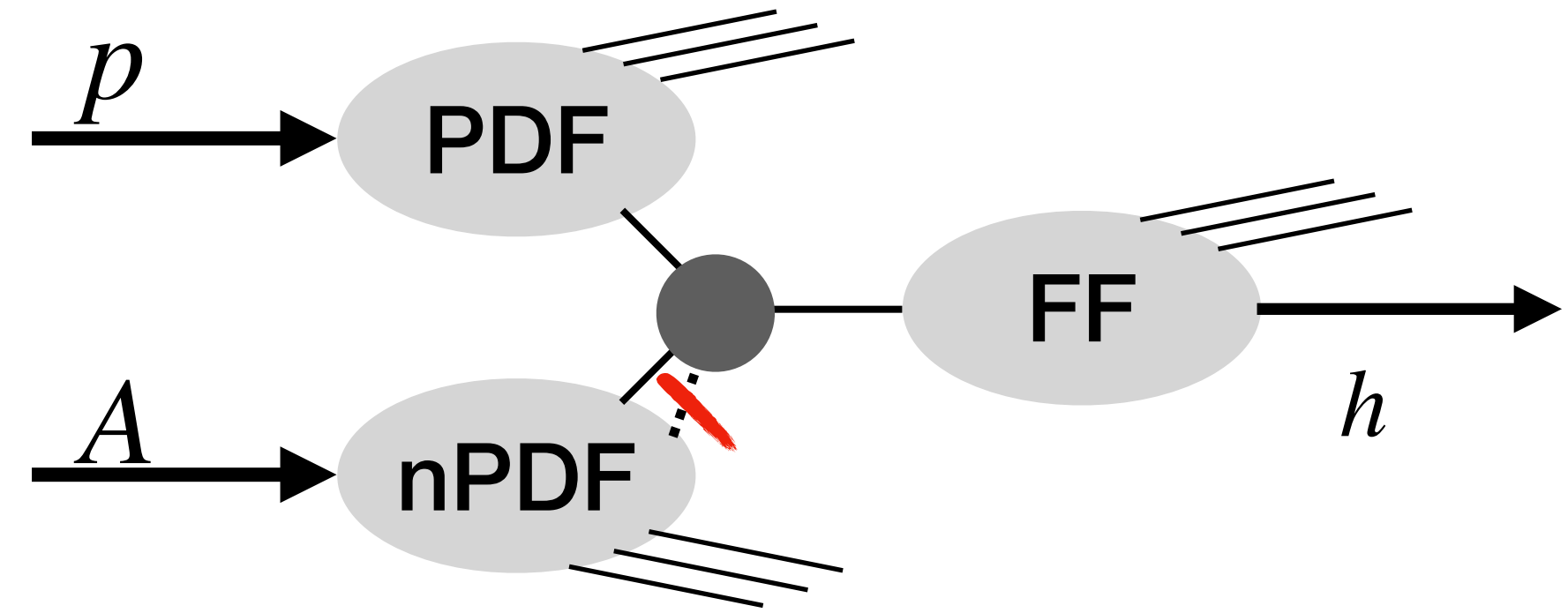
Going to eA/pA

Semi-inclusive nuclear DIS: $e + A \rightarrow e' + h + X$



$$\sigma_{e+A \rightarrow e'+h+X} \approx A f_{i/A} \otimes D_j^h \otimes C$$

hadron-ion collision: $p + A \rightarrow h + X$



$$\sigma_{p+A \rightarrow h+X} \approx f_{i/p} \otimes A f_{j/A} \otimes D_k^h \otimes C$$

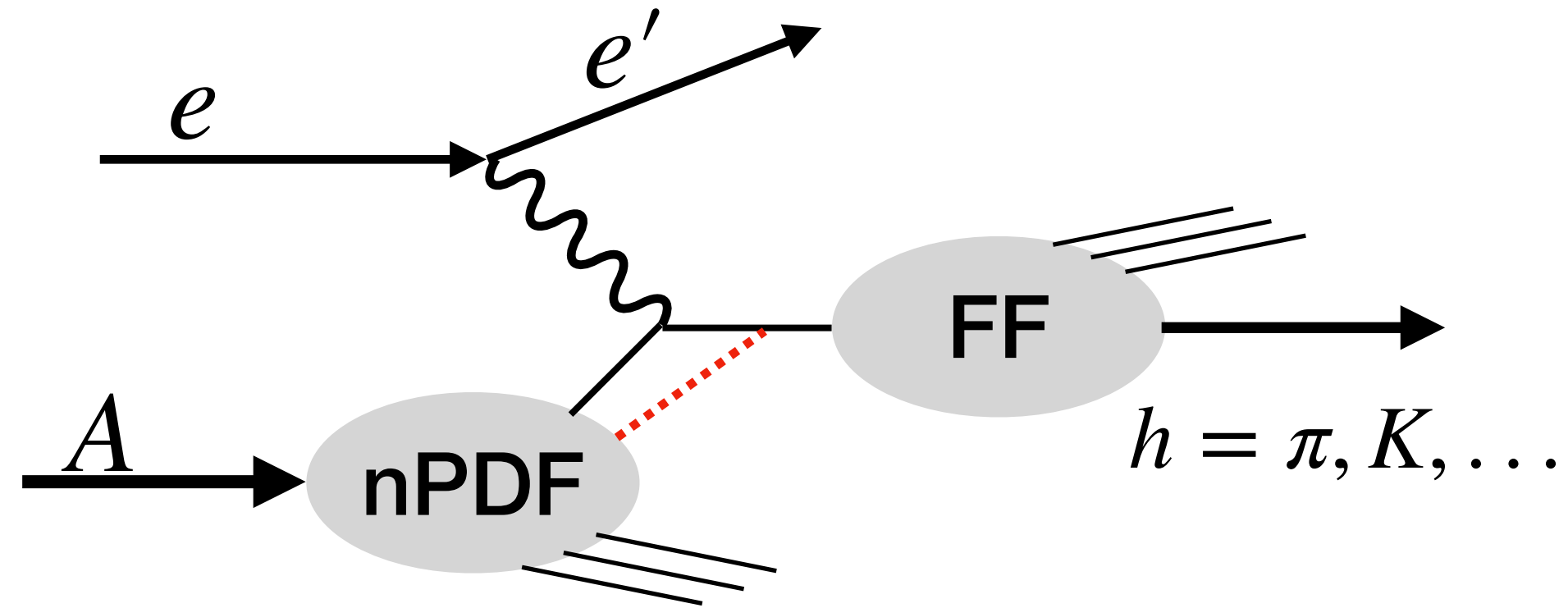
nPDFs: talk by Pit Duwentaester (Mon.)

- Provided power corrections are neglected, nuclear effects are included only in nPDFs.
- Nuclear dependence should also be inherited in the TMDs.
- How does nuclear dependence come into nonperturbative TMD distributions?

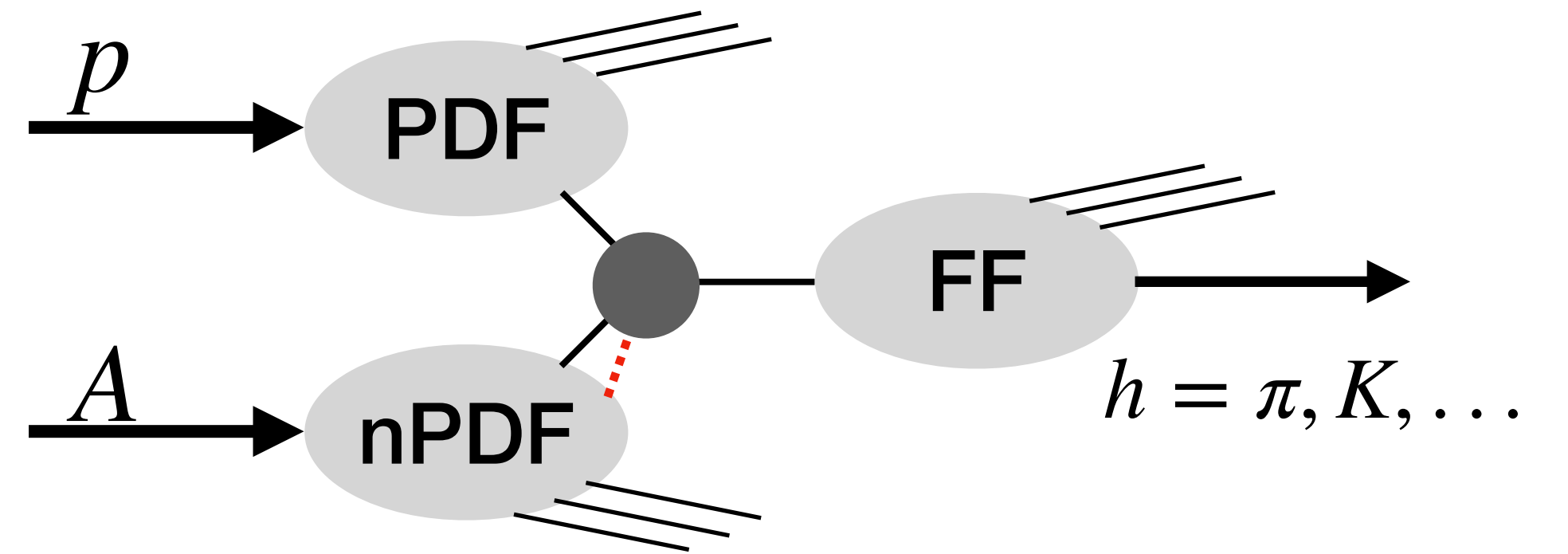
TMDs: talk by Francesco Giovanni Celiberto (Wed.)

Multiple scattering and power corrections (1/2)

Semi-inclusive nuclear DIS: $e + A \rightarrow e' + h + X$



hadron-ion collision: $p + A \rightarrow h + X$



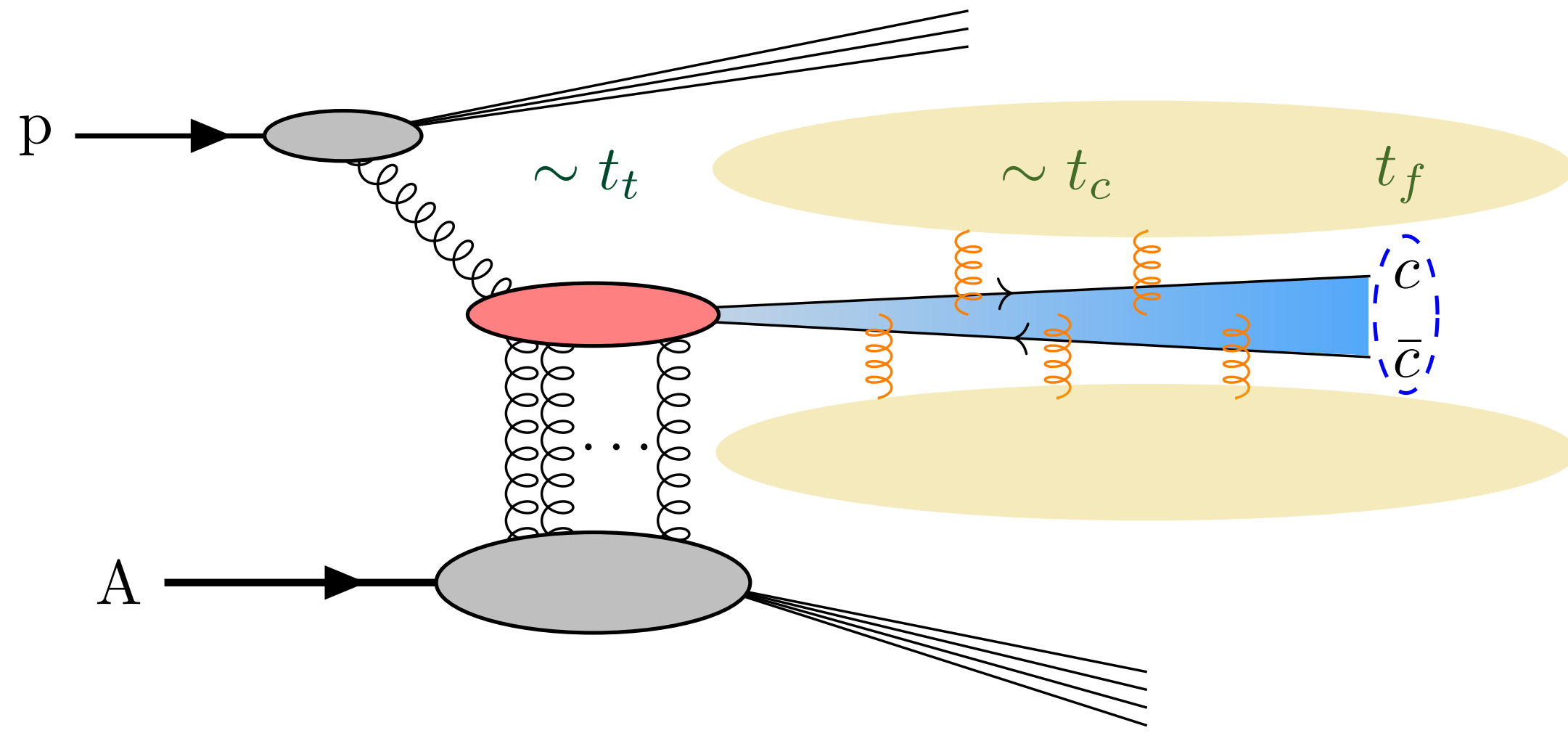
A nuclear target can enhance power corrections (twists):

$$d\sigma \sim \text{PDF} \otimes \text{nPDF} \otimes \text{FF} \otimes d\hat{\sigma} + \mathcal{O} \left(\dots, \frac{A^{1/3} \Lambda_{\text{QCD}}^2}{Q^2} \right) \xrightarrow{\text{Semi-hard saturation scale}} Q_s^2$$

At extreme small-x or low p_T and for heavier nuclear targets, power corrections are not negligible.

Need to calculate higher twist correlation functions, depending on theory: pQCD, CGC

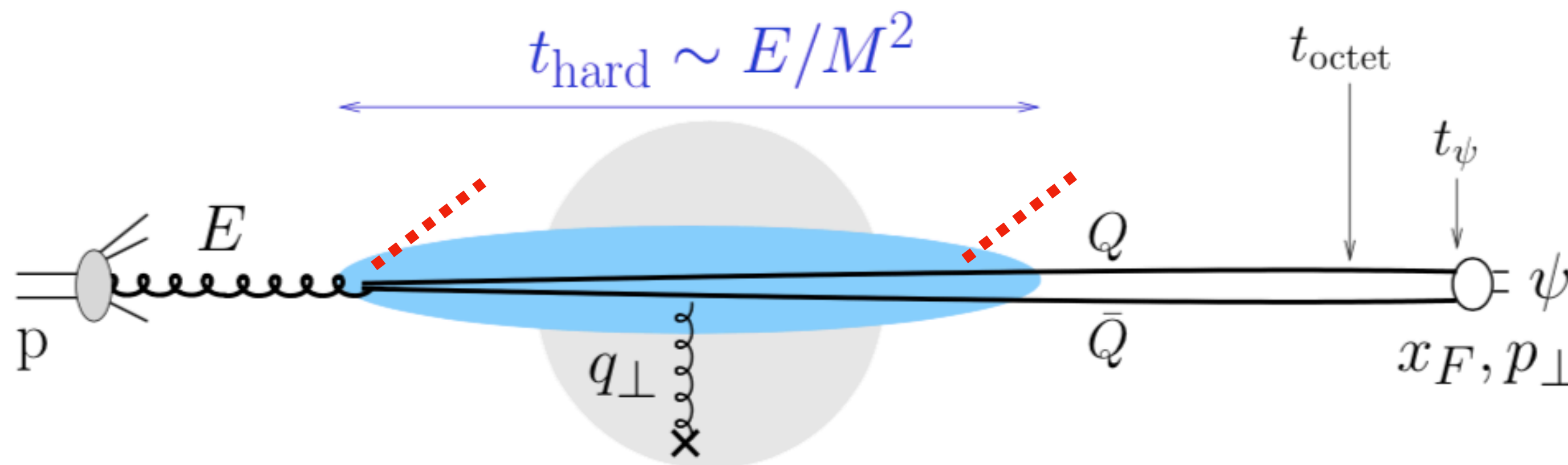
Multiple scattering and power corrections (2/2)



Power corrections to Onia production

1. Interactions between a produced pair and the target might be suppressed by the powers of $1/M$.
2. Bound state formation should occur later, so a produced pair could suffer from spectator interactions.
3. Even though spectator interactions can be suppressed by the powers of $1/p_{\perp}$ or $1/p_{\parallel}$, loosely bound states can break up easily!

Note: multiple scattering induces gluon radiation, leading to coherent energy loss:



Arleo and Peigne, PRL109, 122301 (2012),
JHEP03, 122 (2013)

Traversing in the cold QCD medium

Adam et al. [ALICE], JHEP11, 127 (2015)

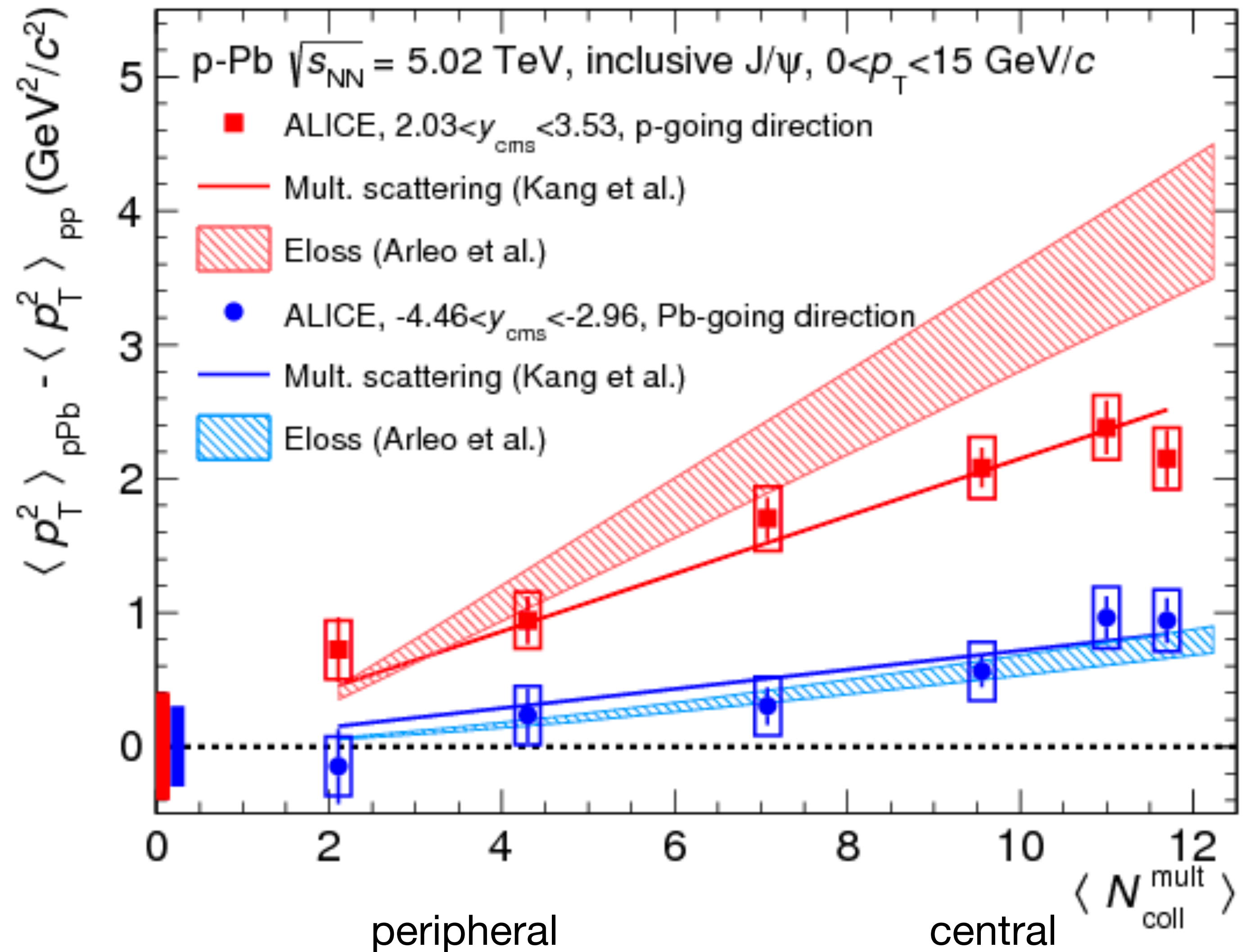
*In the target rest frame, we may define

Medium independent

$$\langle p_T^2 \rangle_{pA} = \langle p_T^2 \rangle_{vac} + \hat{q}_{cold} L_A$$

Multiple scattering effect
in cold nuclear medium

In the small- x limit, the transport coefficient could be read $\hat{q}_{cold} \propto Q_s^2$.

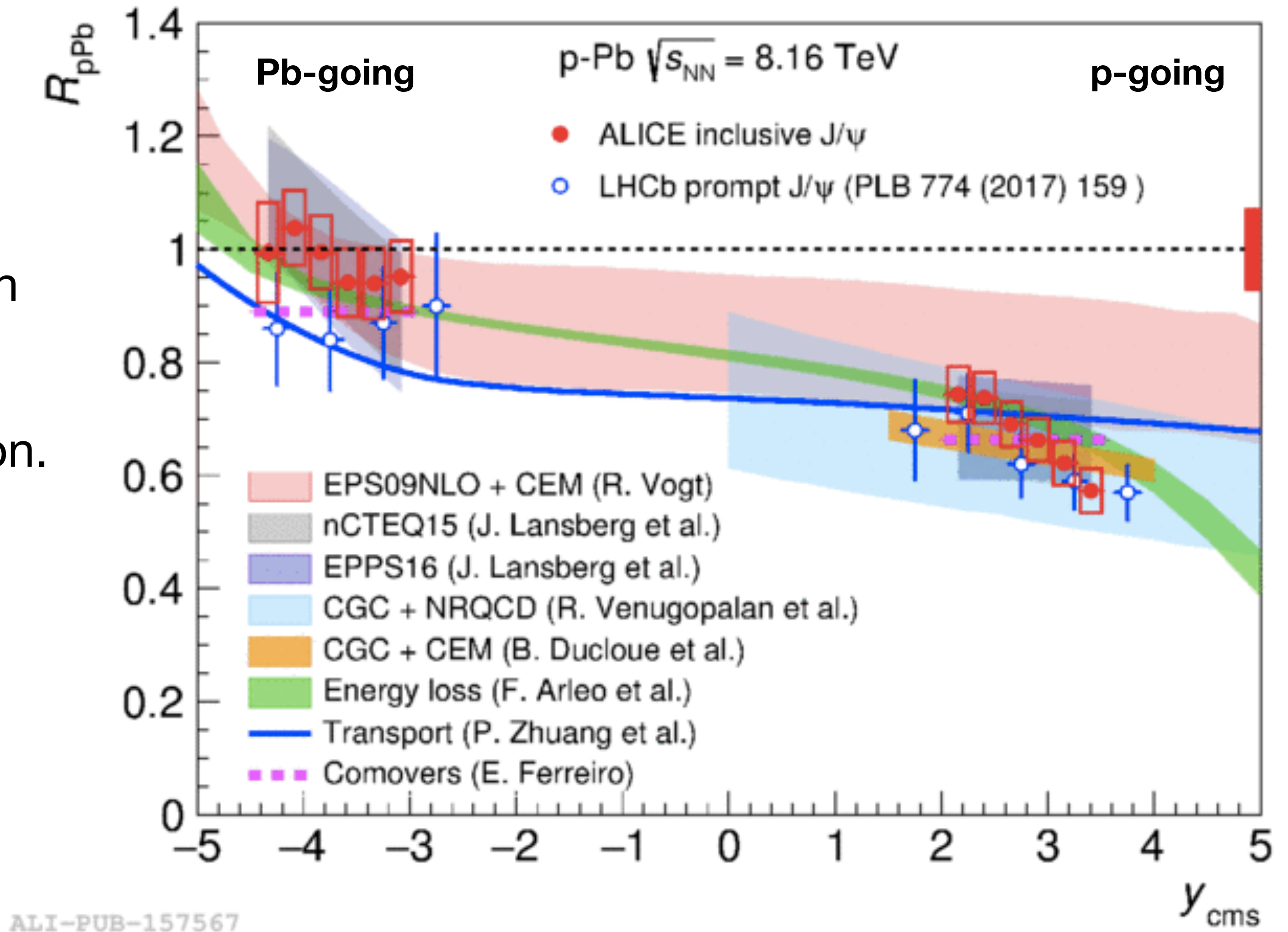


Centrality dep: refer to Afnan Shatat (Tue.)

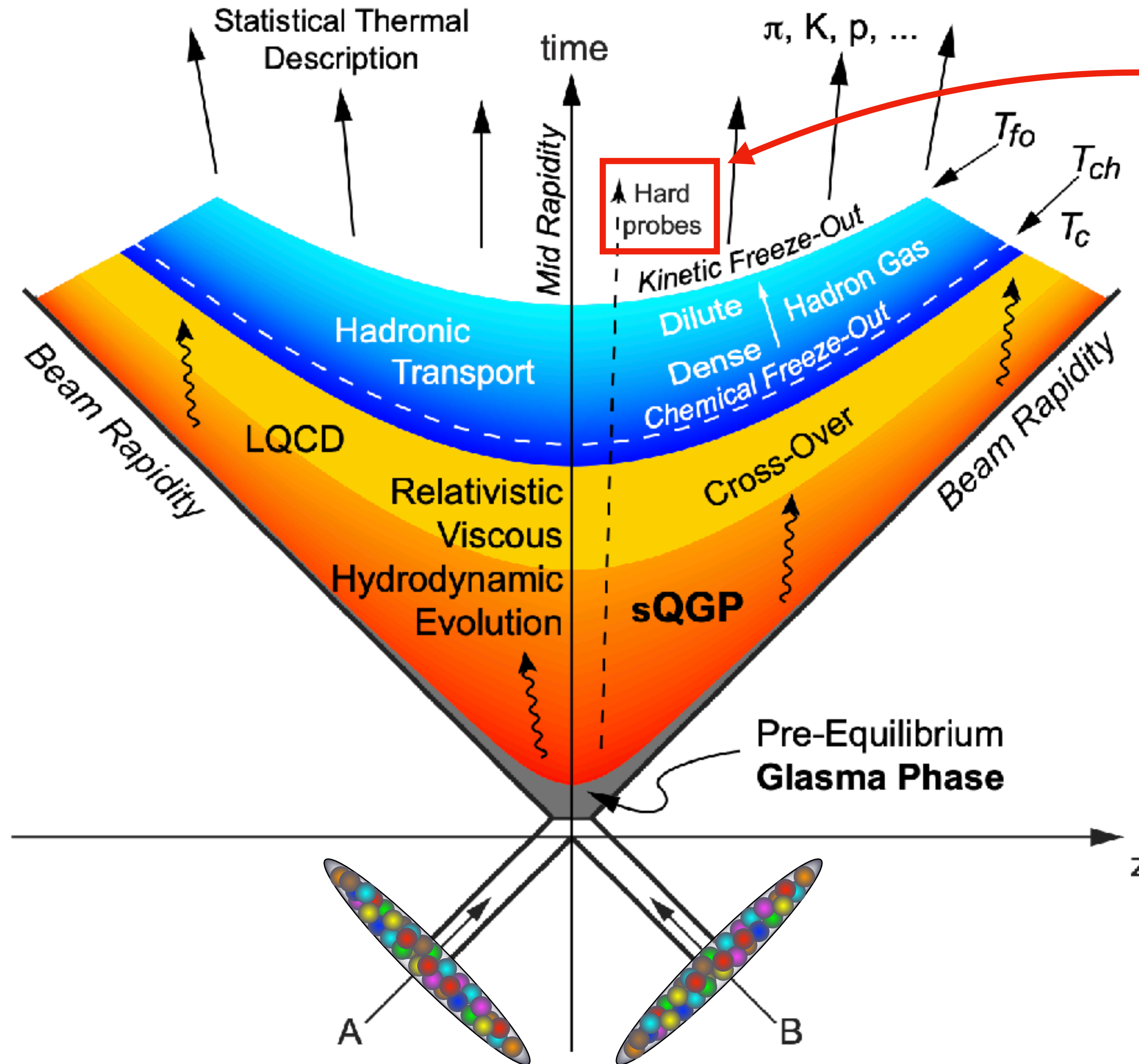
Nuclear modifications under control?

- Nuclear PDFs
 - Leading-twist
- CGC / Energy loss
 - Multiple scattering, induced radiation
- Comovers effect
 - Soft partonic and hadronic interaction.
- Transport approach
 - Cold + Hot medium effects.

*There is no clear consensus about the dominant Cold Nuclear Matter effect yet.



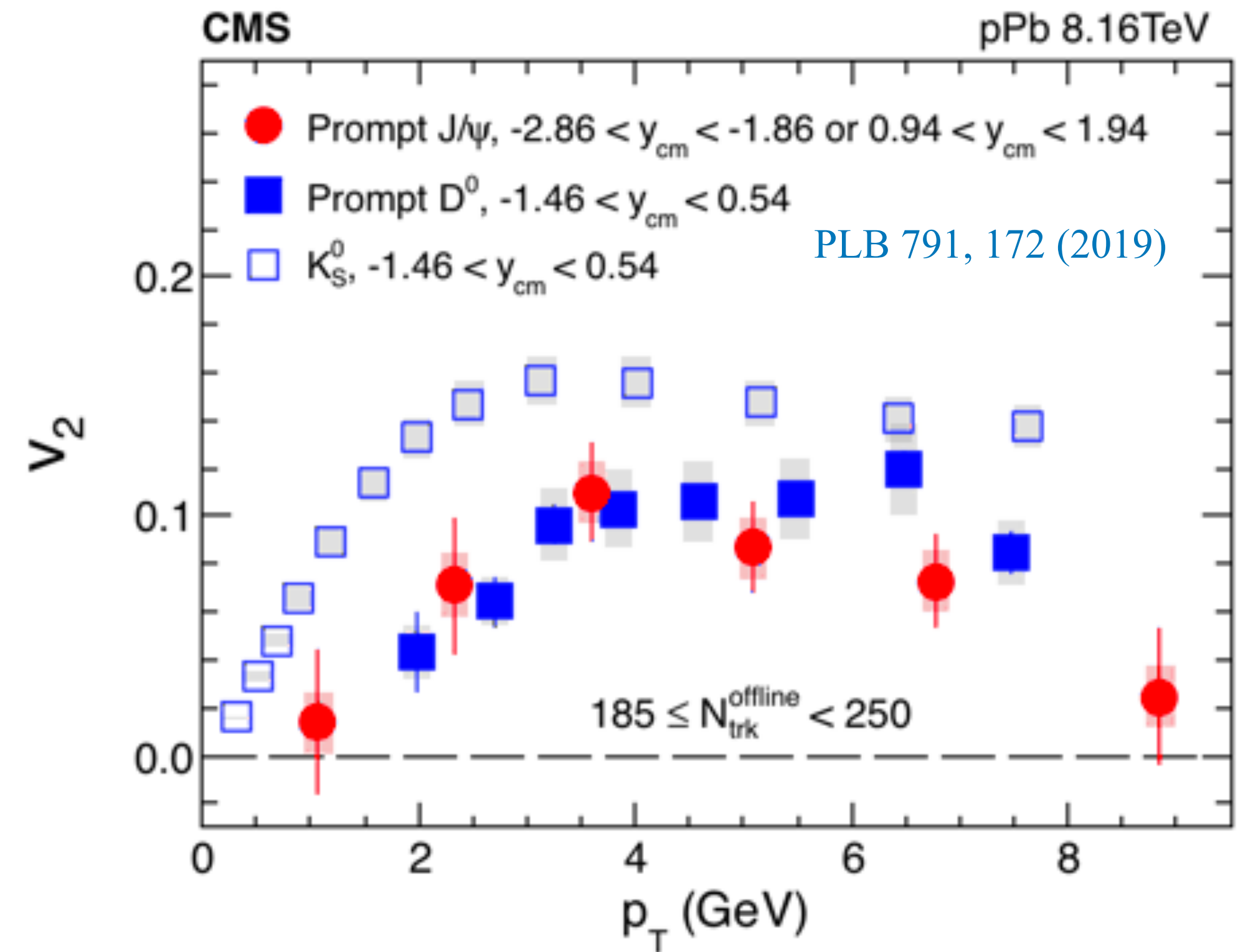
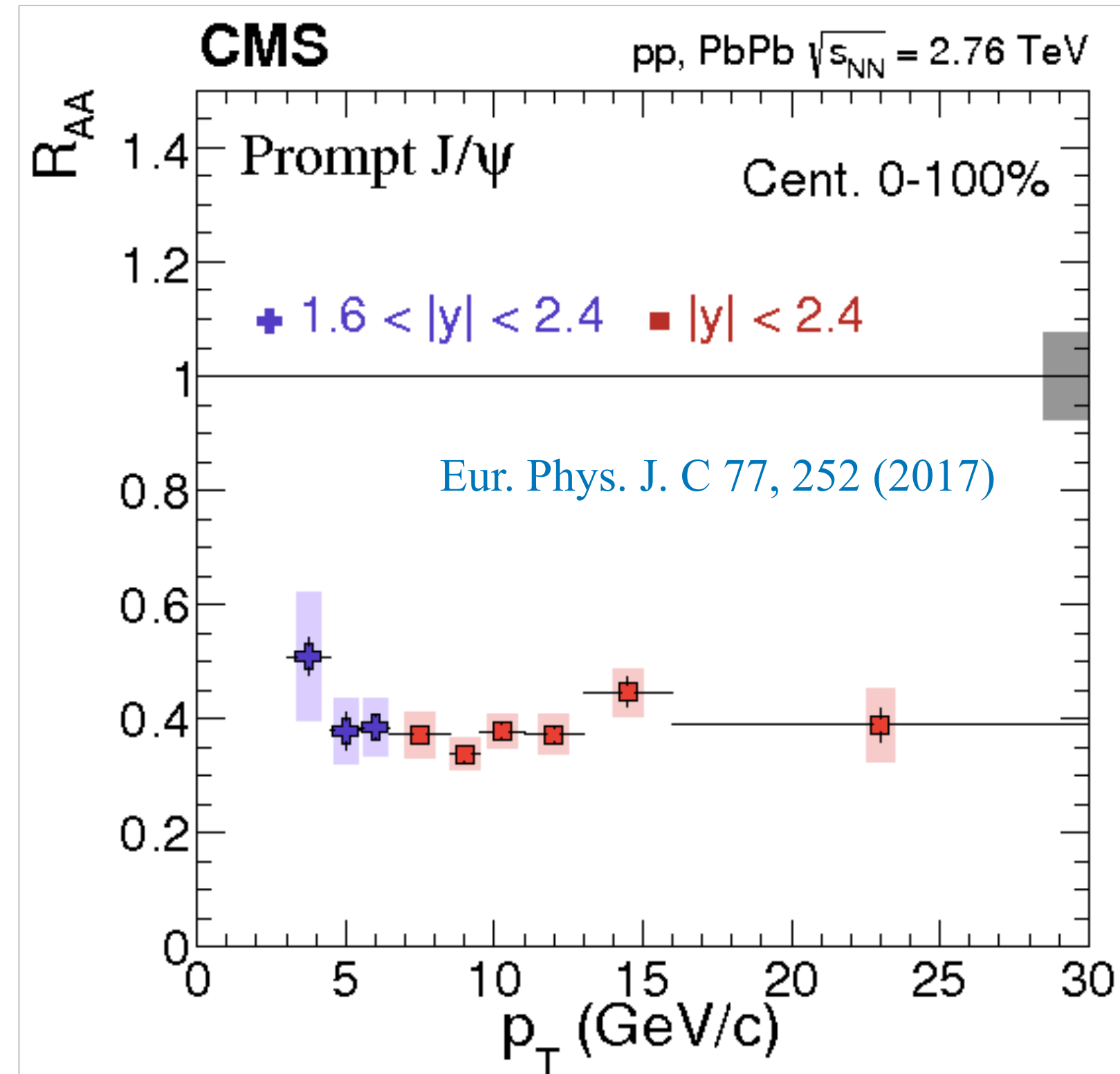
From “dilute-dense” to “dense-dense”



Main Topics on Friday

- Pre-collision initial state described by CGC EFT.
- Implementation of the impact parameter dependence needs to rely on models such as the Glauber model or some other parametrizations.
- Thermalization, as well as quarkonium production in Glasma, is beyond the scope of this meeting.

Traversing in the hot QCD medium

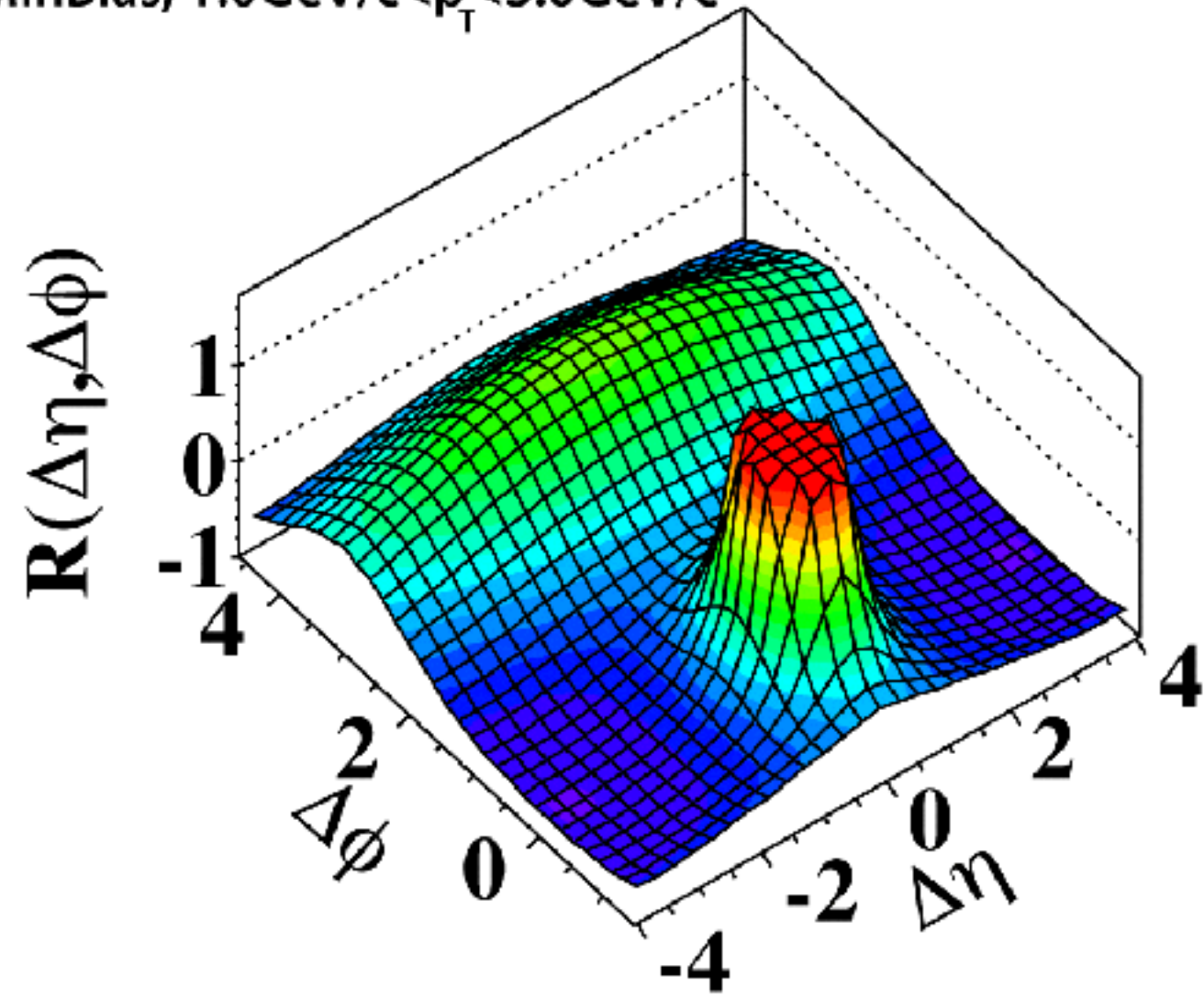


- J/ψ , Υ suppression due to the presence of QGP, strong flow effects.
- How to apply our knowledge of onium production in pp to AA?

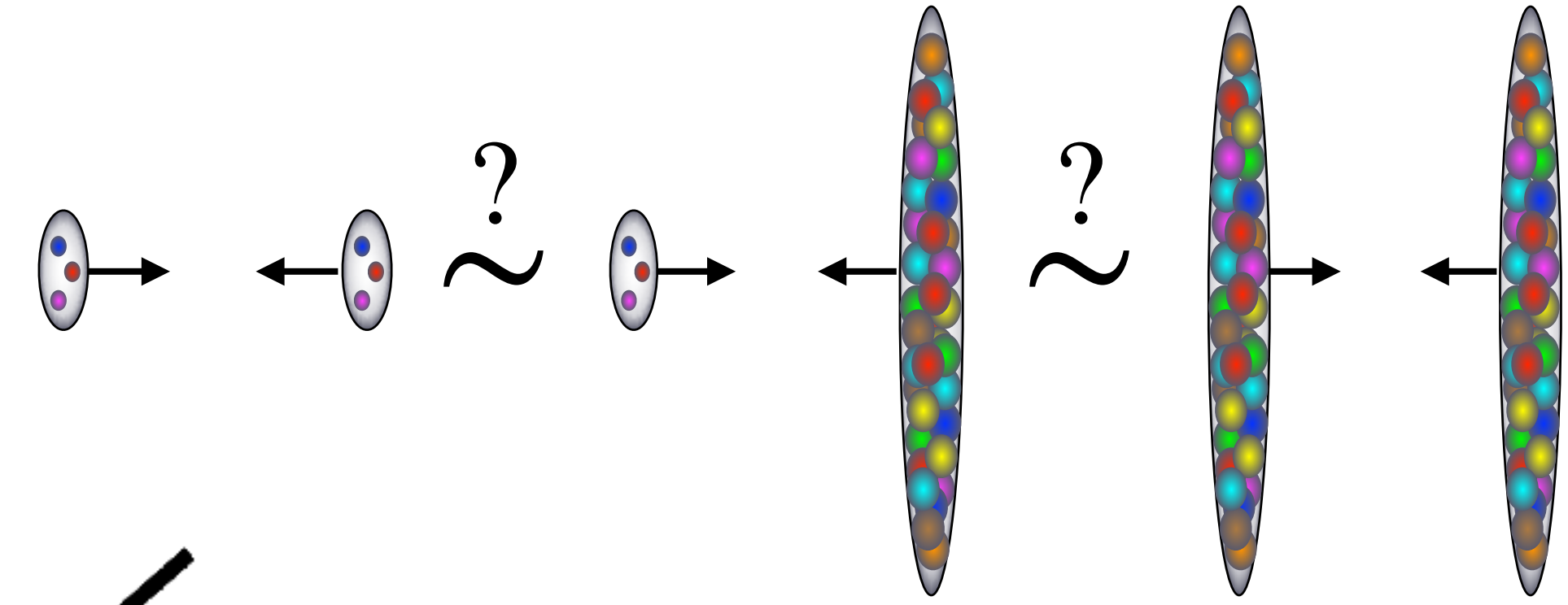
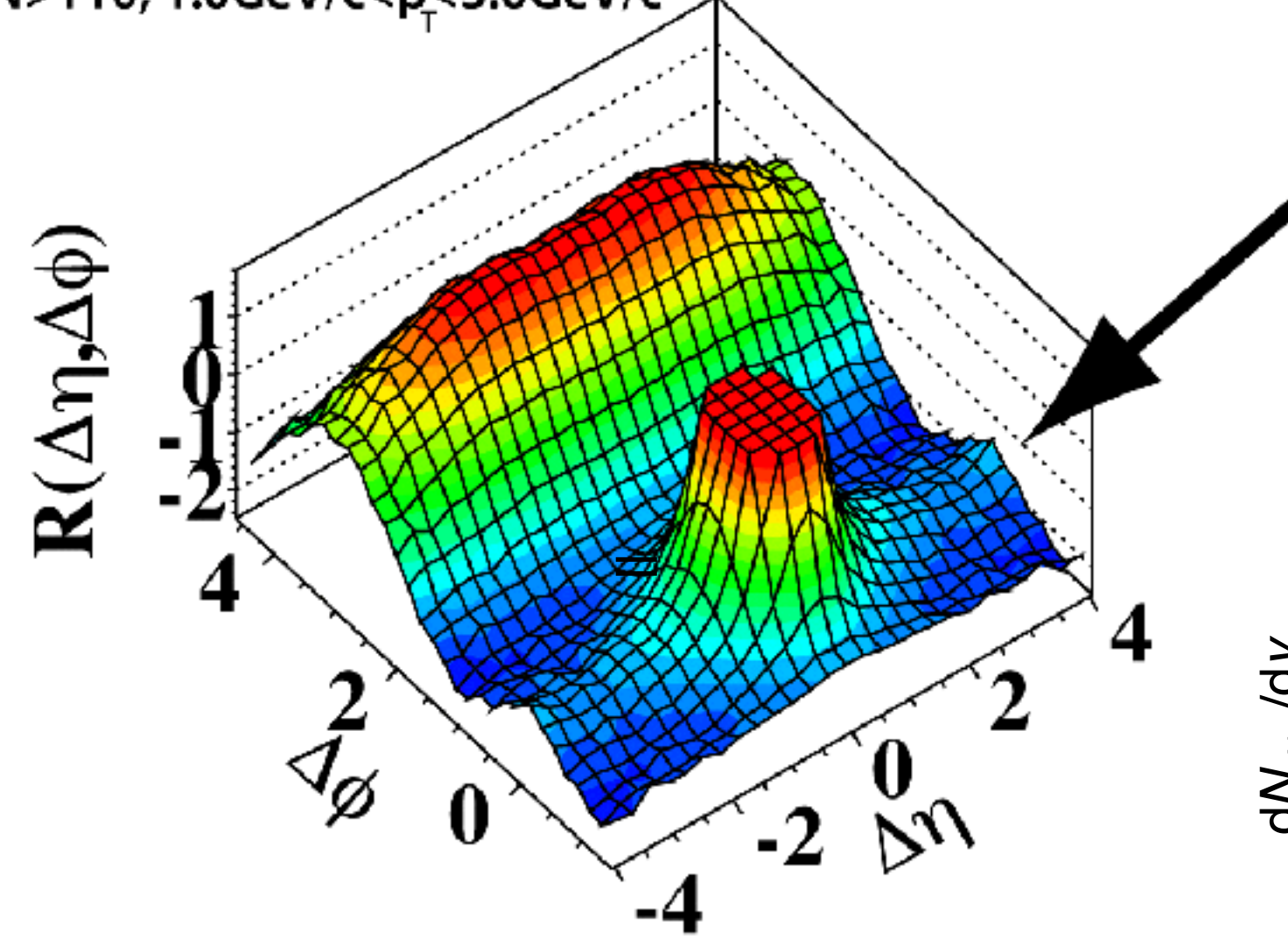
High multiplicity events in small systems

The ridge (long-range rapidity correlation)

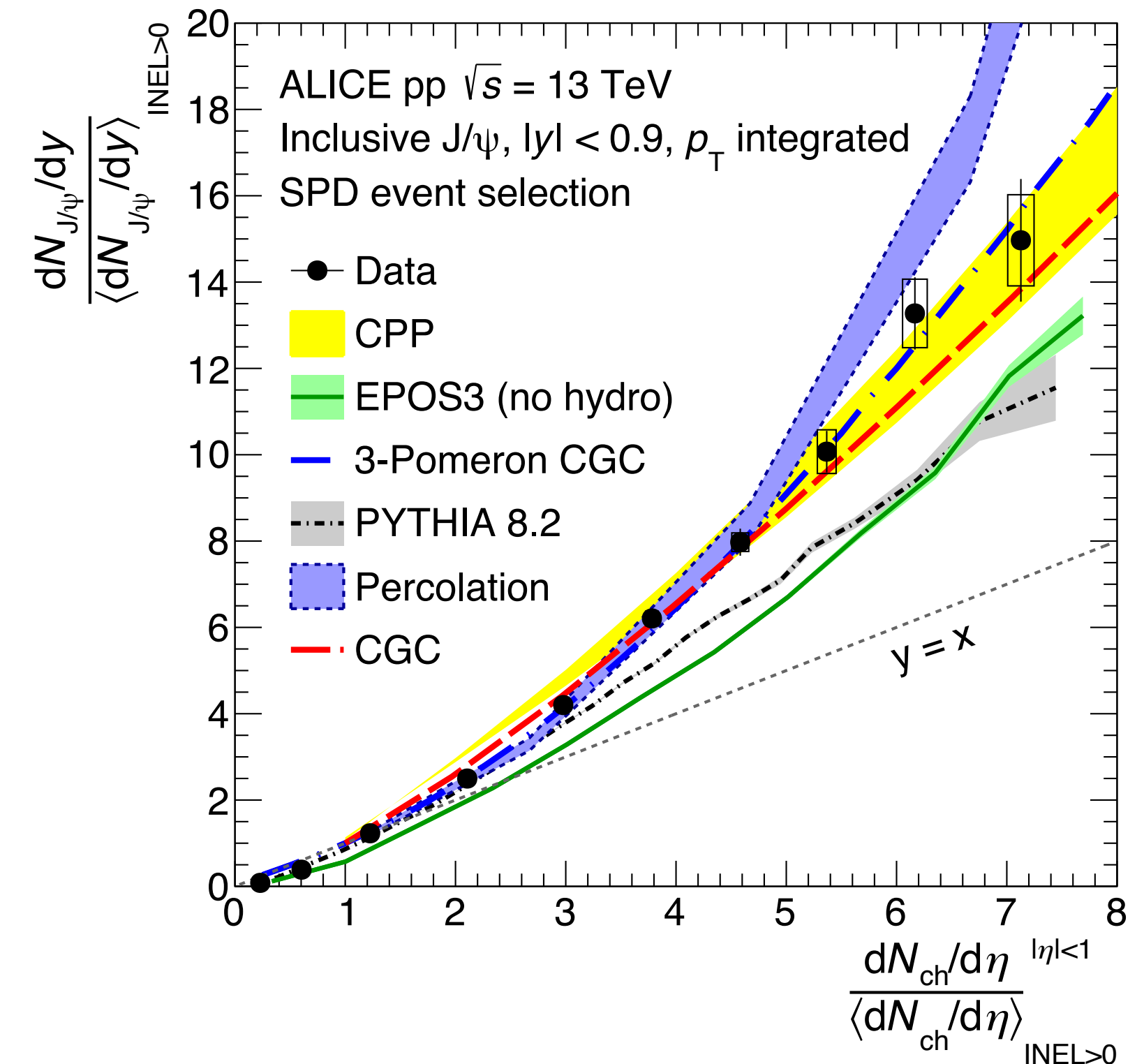
CMS 2010, $\sqrt{s}=7\text{TeV}$
MinBias, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



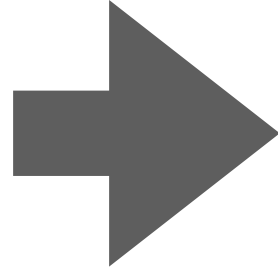
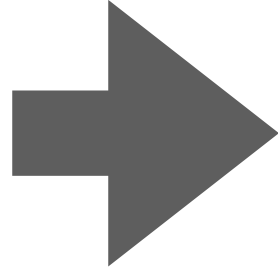
$N > 110$, $1.0\text{GeV}/c < p_T < 3.0\text{GeV}/c$



- Similar features in pp, pA, and AA collisions!
- QGP Fireball formed in pp and pA?
- Initial state (CGC) vs. Final state (Hydro), which is the origin?
- Need more insights into multi-parton interactions.



Enjoy exciting talks and discussion!



17:00 **Round table discussion II: MPI effects, what to expect from eA collisions** *Leszek Kosarzewski et al.*
 Centre Paul Langevin 17:00 - 18:00

18:00 **Round table discussion II: Exotic states (XYZ), excited states (Psi2S, Upsilon3S), and feed-down corrections** *Benjamin Audurier*
 Centre Paul Langevin 18:00 - 19:00

17:00 **Round table discussion I: Flow in all systems, initial vs final state effects**
 Centre Paul Langevin 17:00 - 18:00

18:00 **Round table discussion I: Quarkonia suppression and regeneration in medium** *Pol-Bernard GOSSIAUX*
 Centre Paul Langevin 18:00 - 19:00