

Heavy-flavour production, energy loss, and flow in large and small collision systems

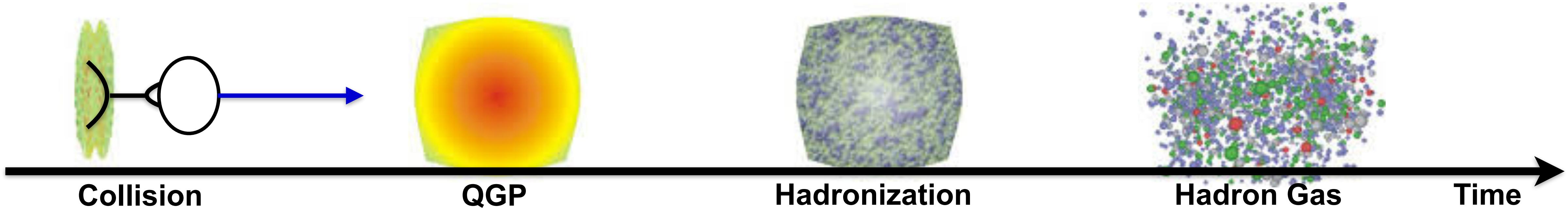
Andre Ståhl

European Organisation for Nuclear Research

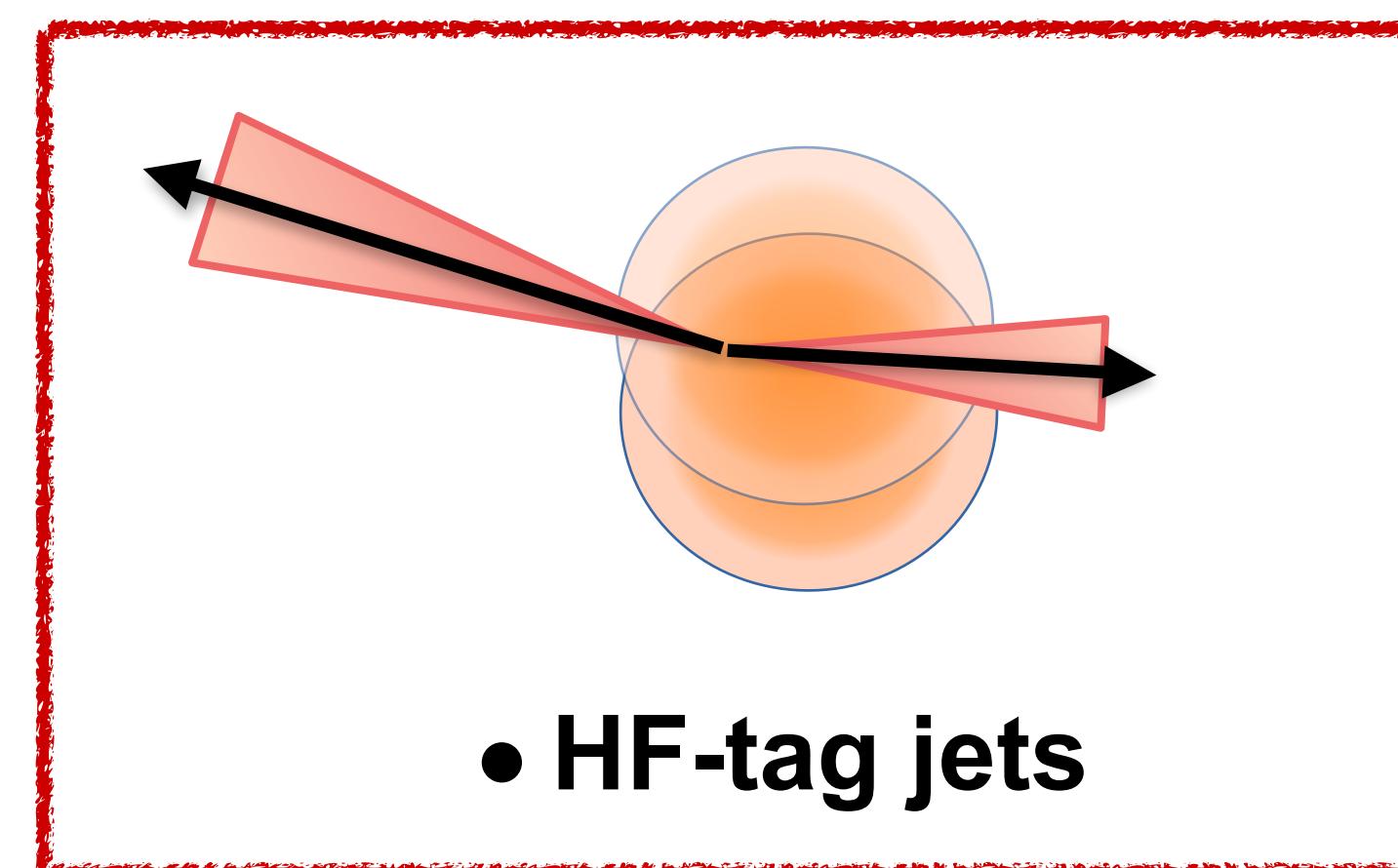
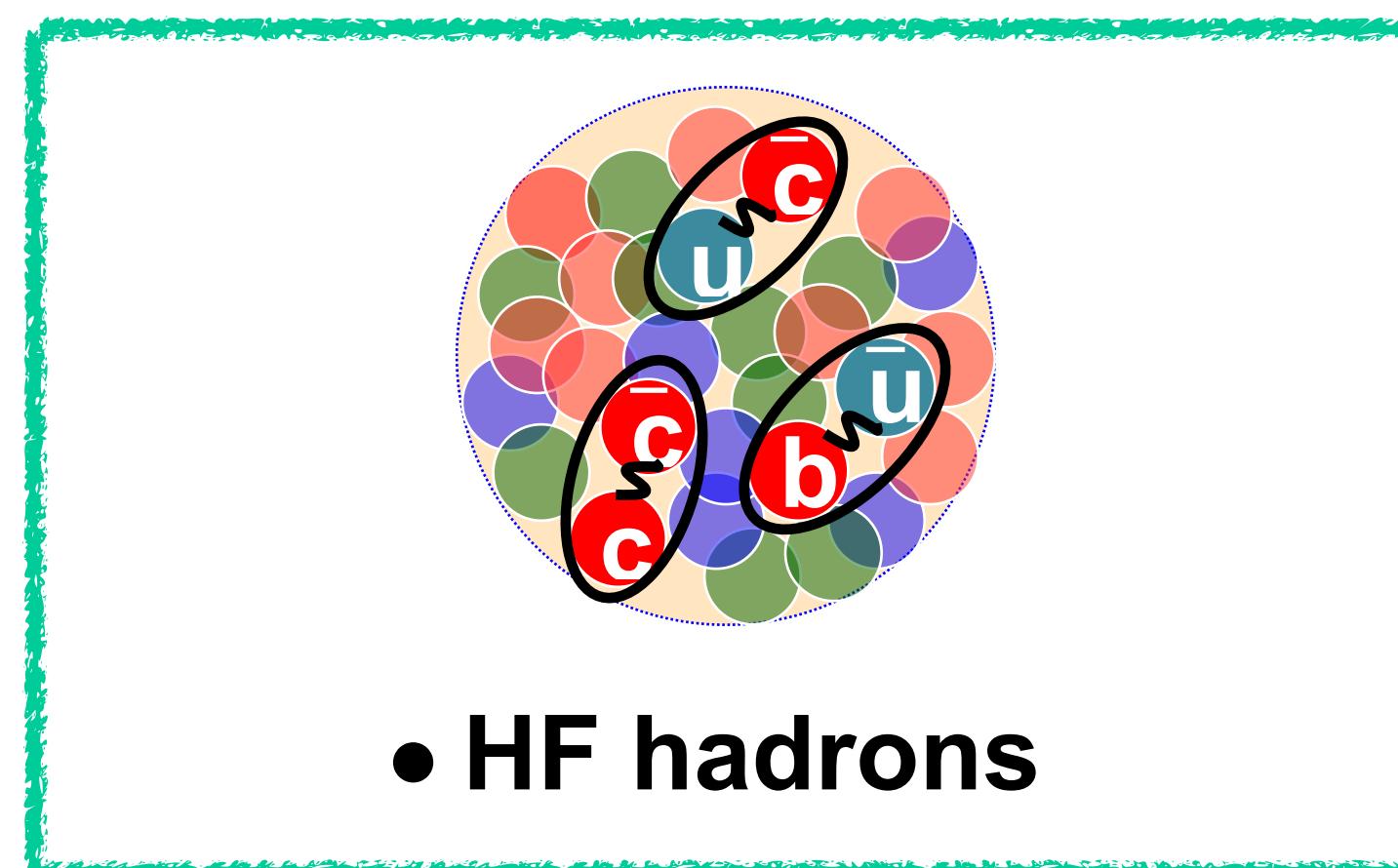
4th QCD challenges from pp to AA collisions workshop



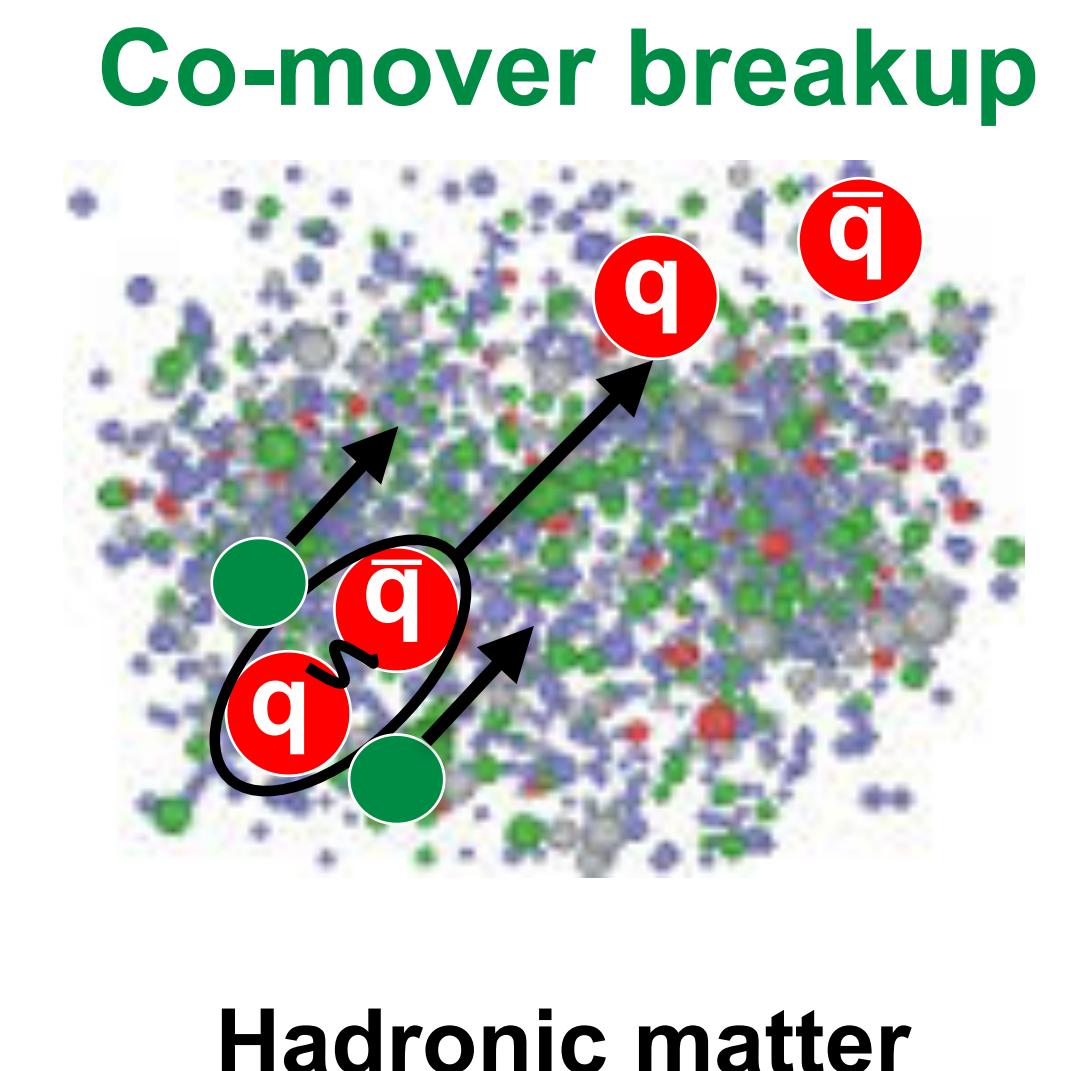
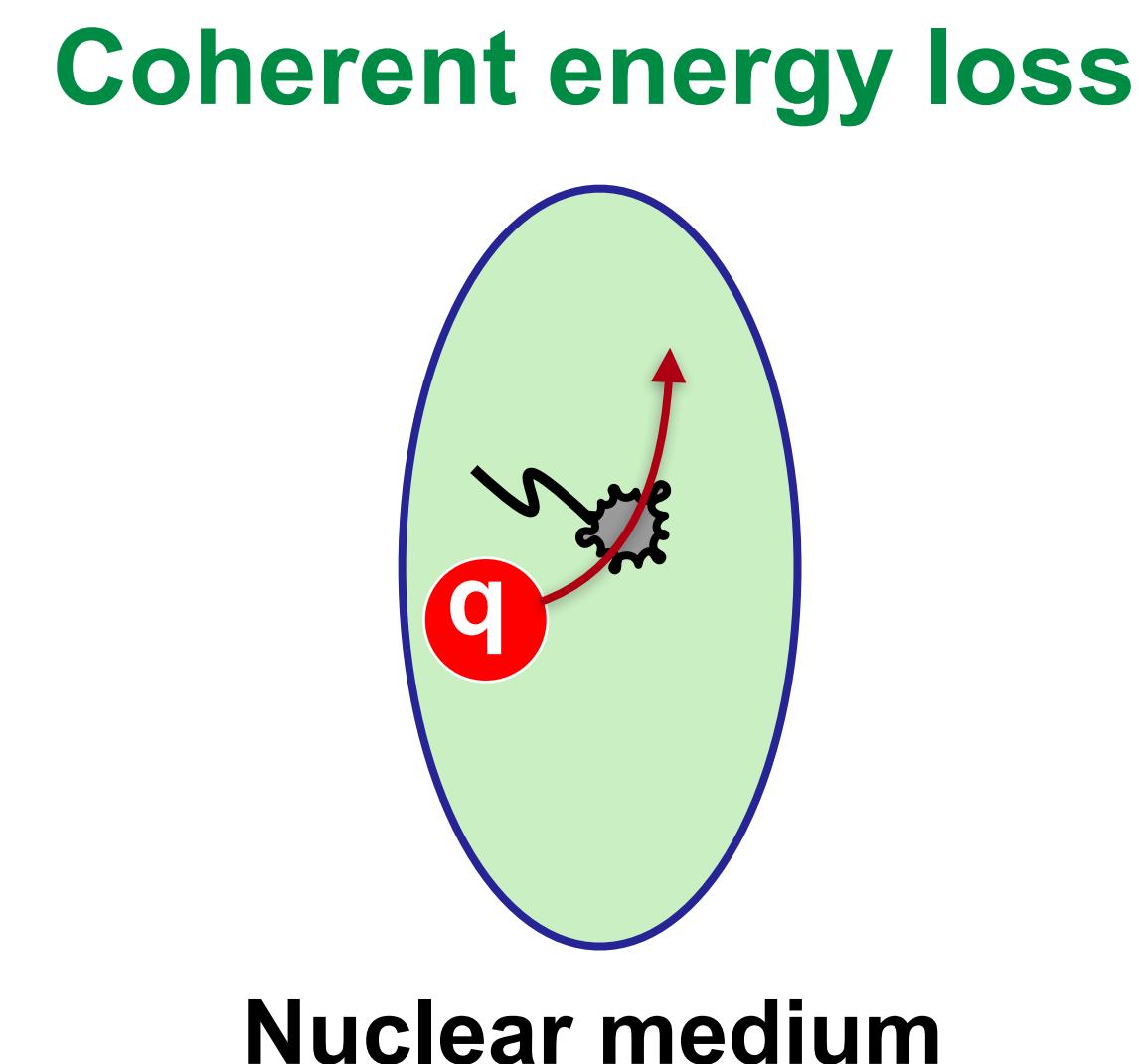
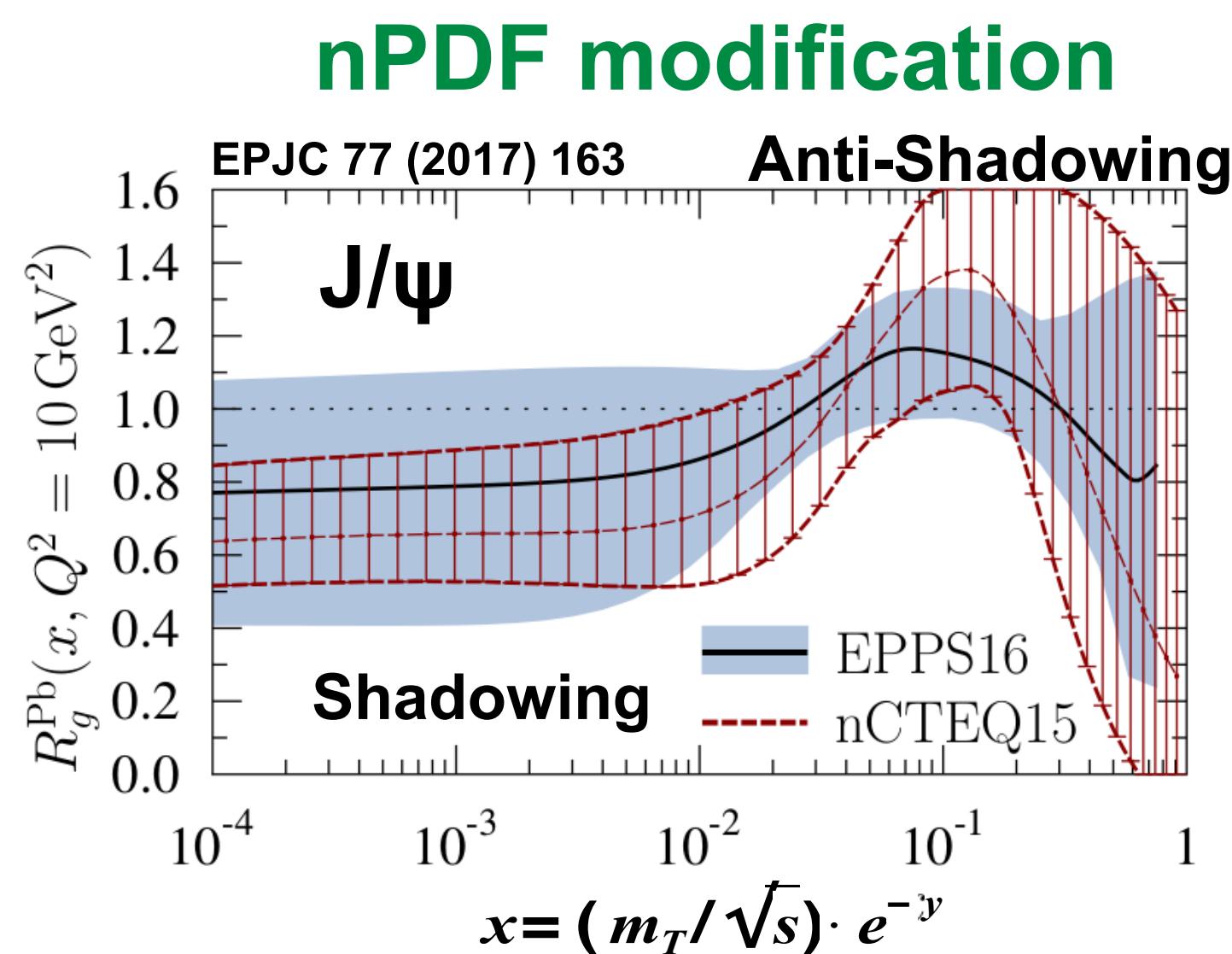
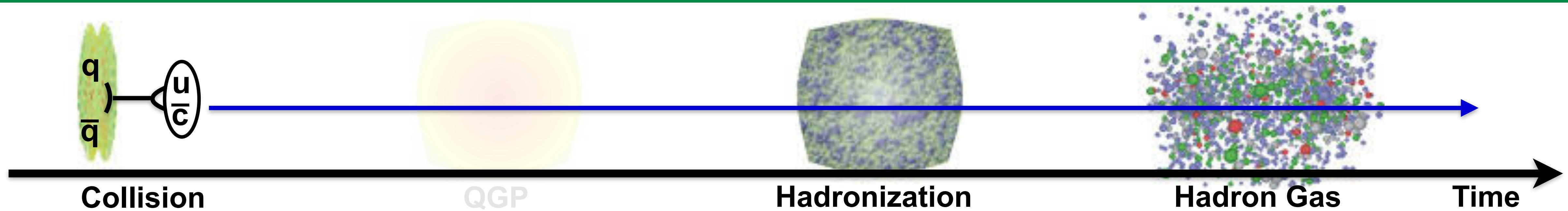
Heavy Quarks in HI collisions



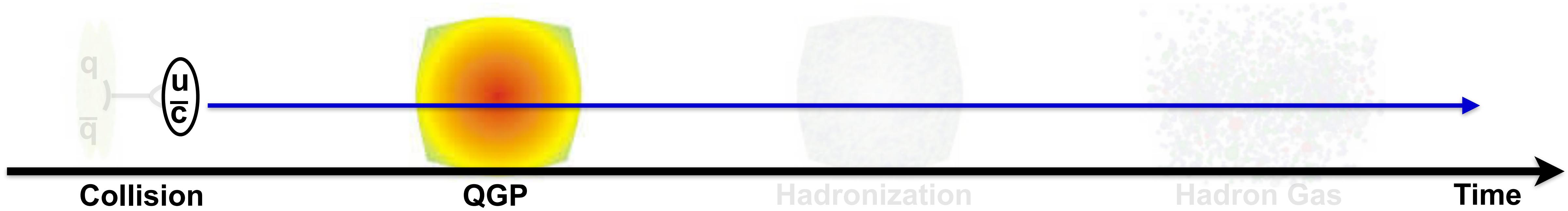
- Heavy quarks ($m_{c,b} \gg \Lambda_{\text{QCD}}$): high Q^2 processes → production well understood in pQCD.
- Produced in the initial hard scattering → experience the full space-time evolution of the QGP.
- QCD conserves quantum numbers: HF quarks retain the history of the collision.
- HF hadrons and jets can provide an experimental tag for an HF quark parent.



Cold nuclear matter effects



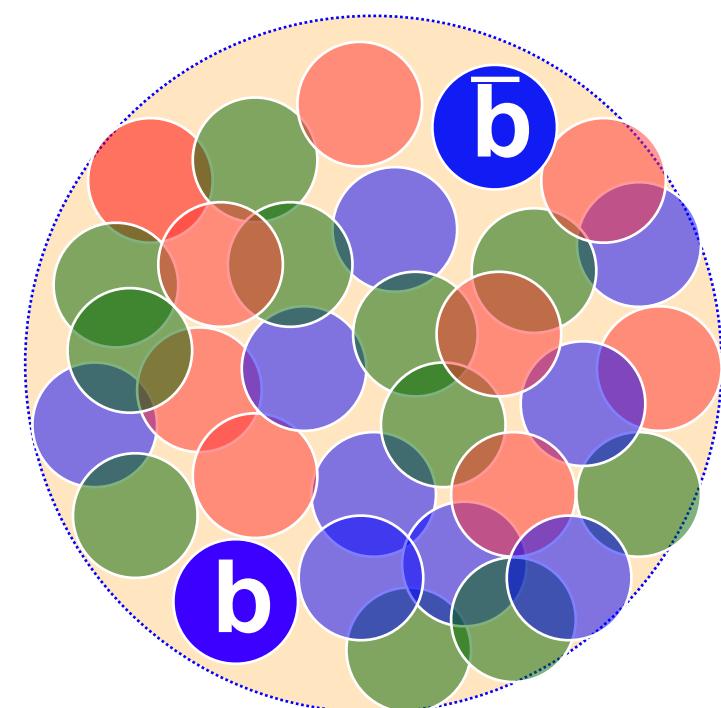
QGP medium effects



The QGP is expected to modify the HF hadron production

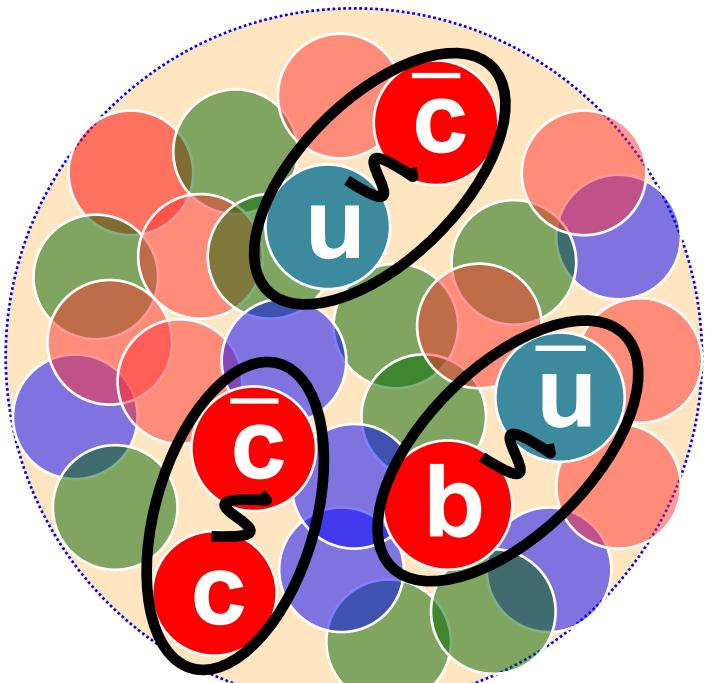
Session: Hadronization,
Feb 13, 15:15

Quarkonia



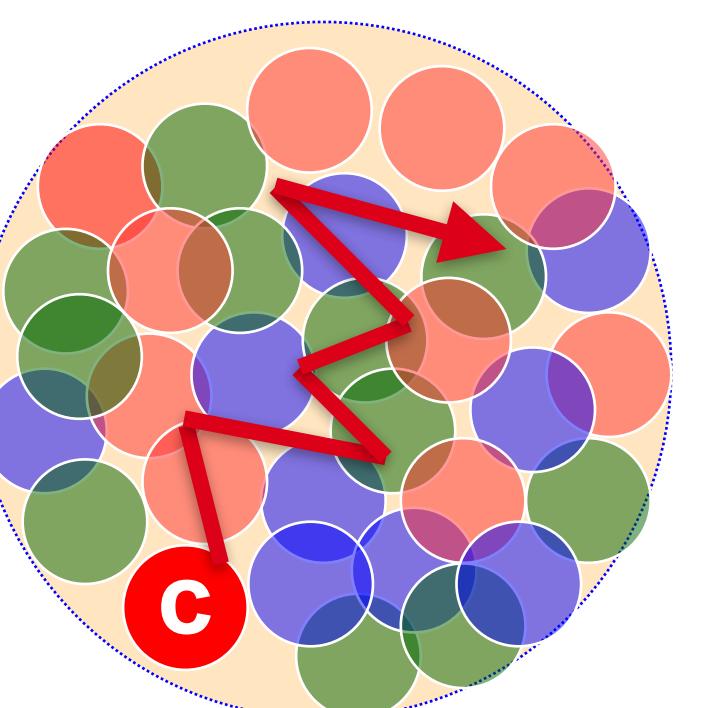
Suppression
Medium-induced
dissociation

HF hadrons



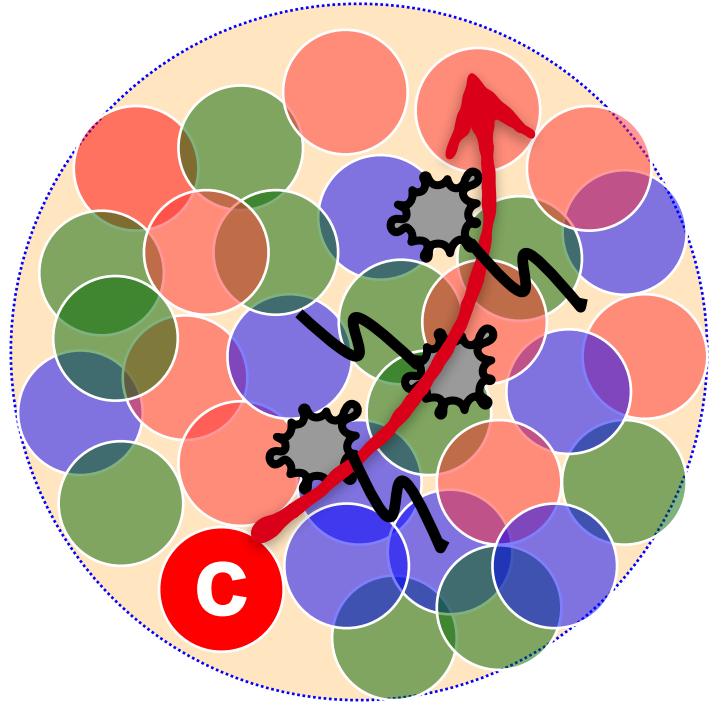
+Enhancement
Regeneration
Coalescence

HF quarks

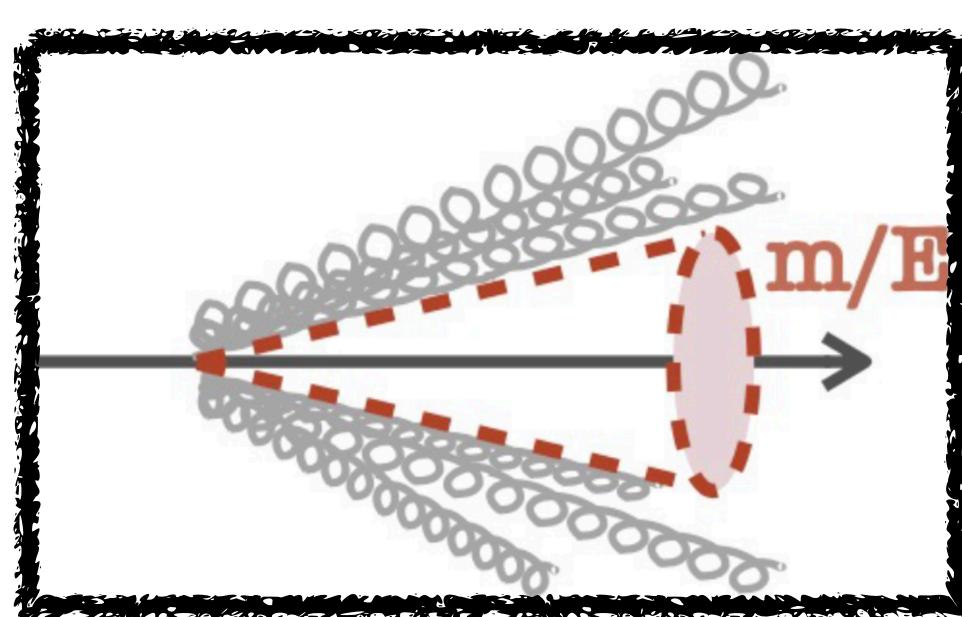


+Quark diffusion
Brownian motion
at low p_T

HF quarks

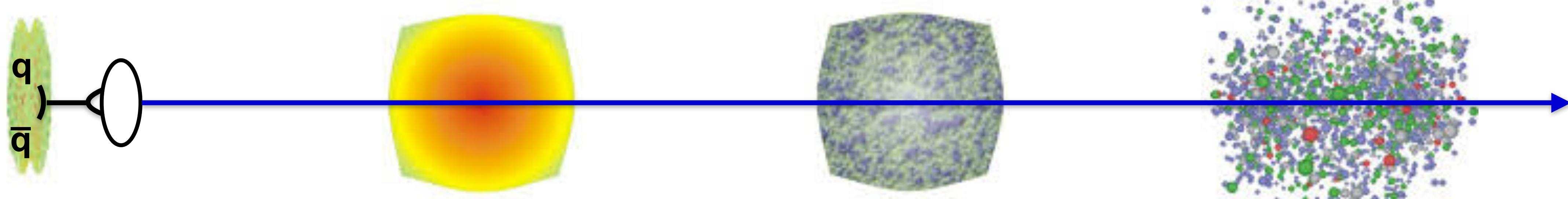


+Parton energy loss
via collisional and
radiative interactions



+Dead-cone effect
suppression of
radiative energy loss

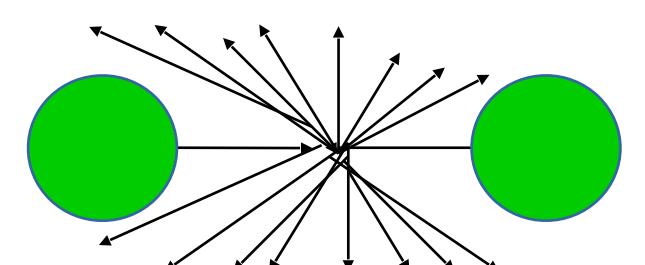
OUTLINE



HF production in pp

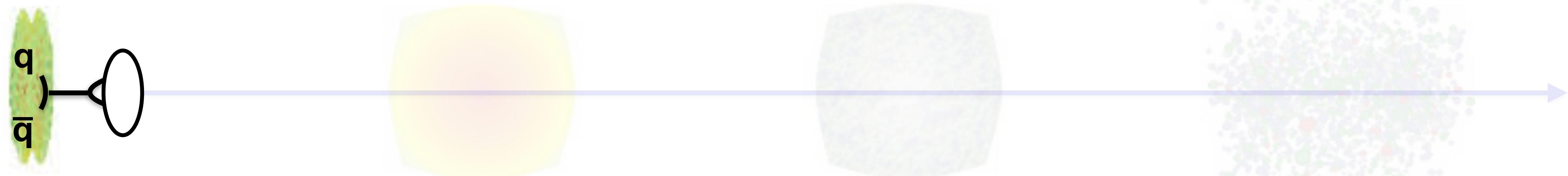
Probing cold nuclear effects

Probing QGP effects

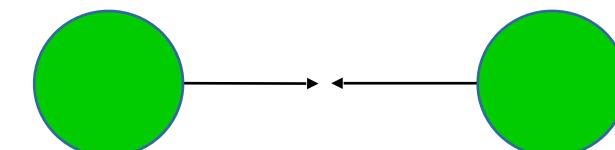


High multiplicity small systems

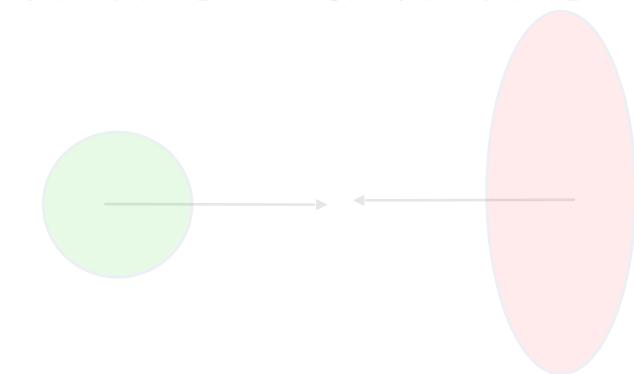
OUTLINE



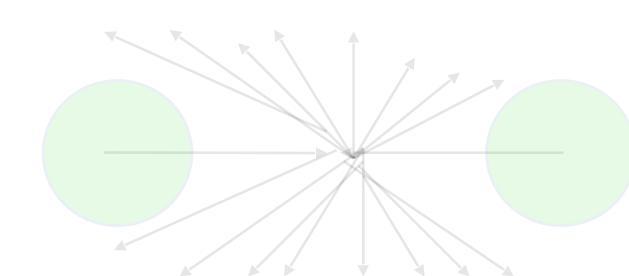
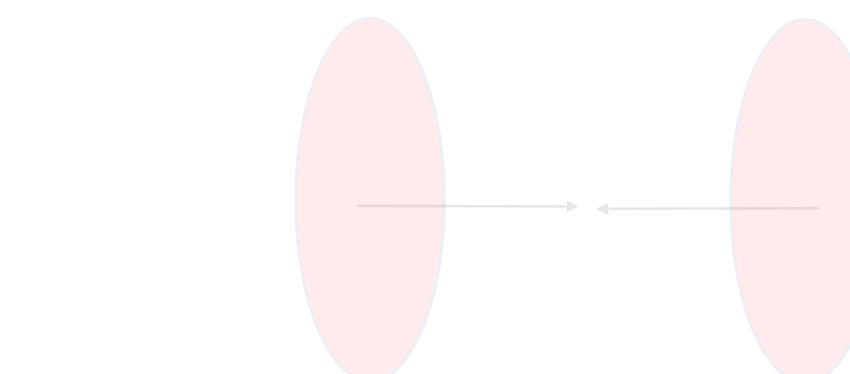
HF production in pp



Probing cold nuclear effects

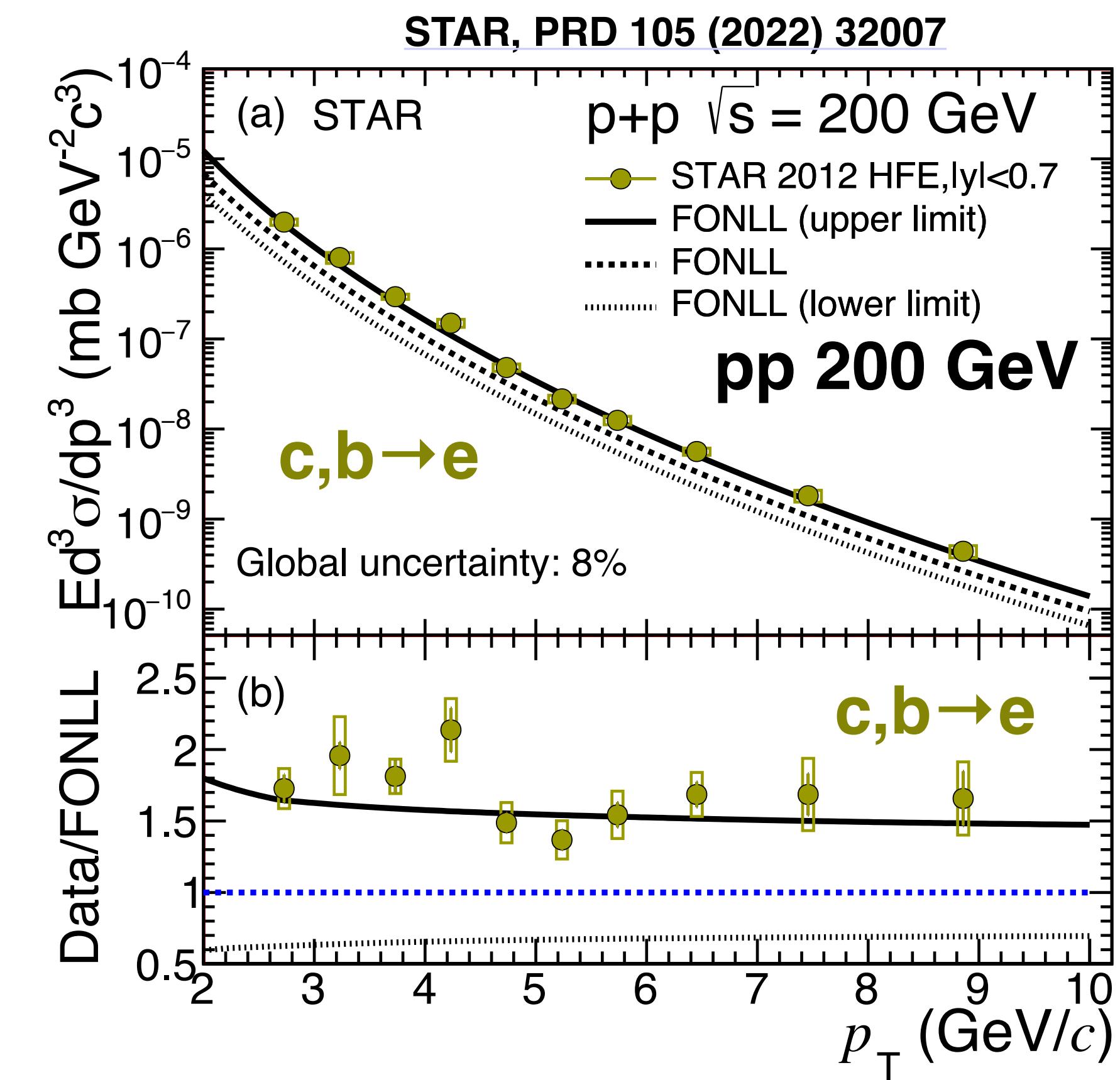
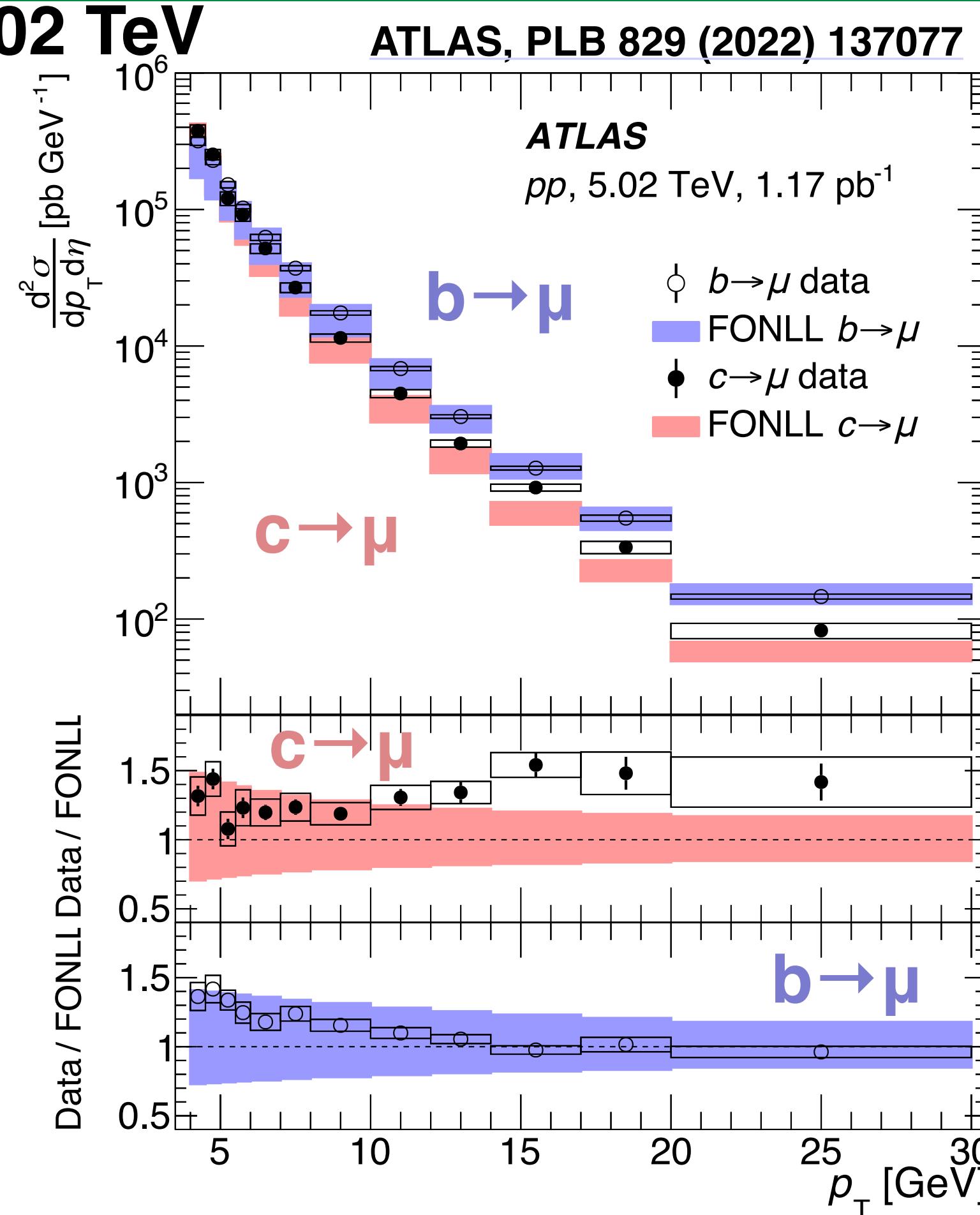
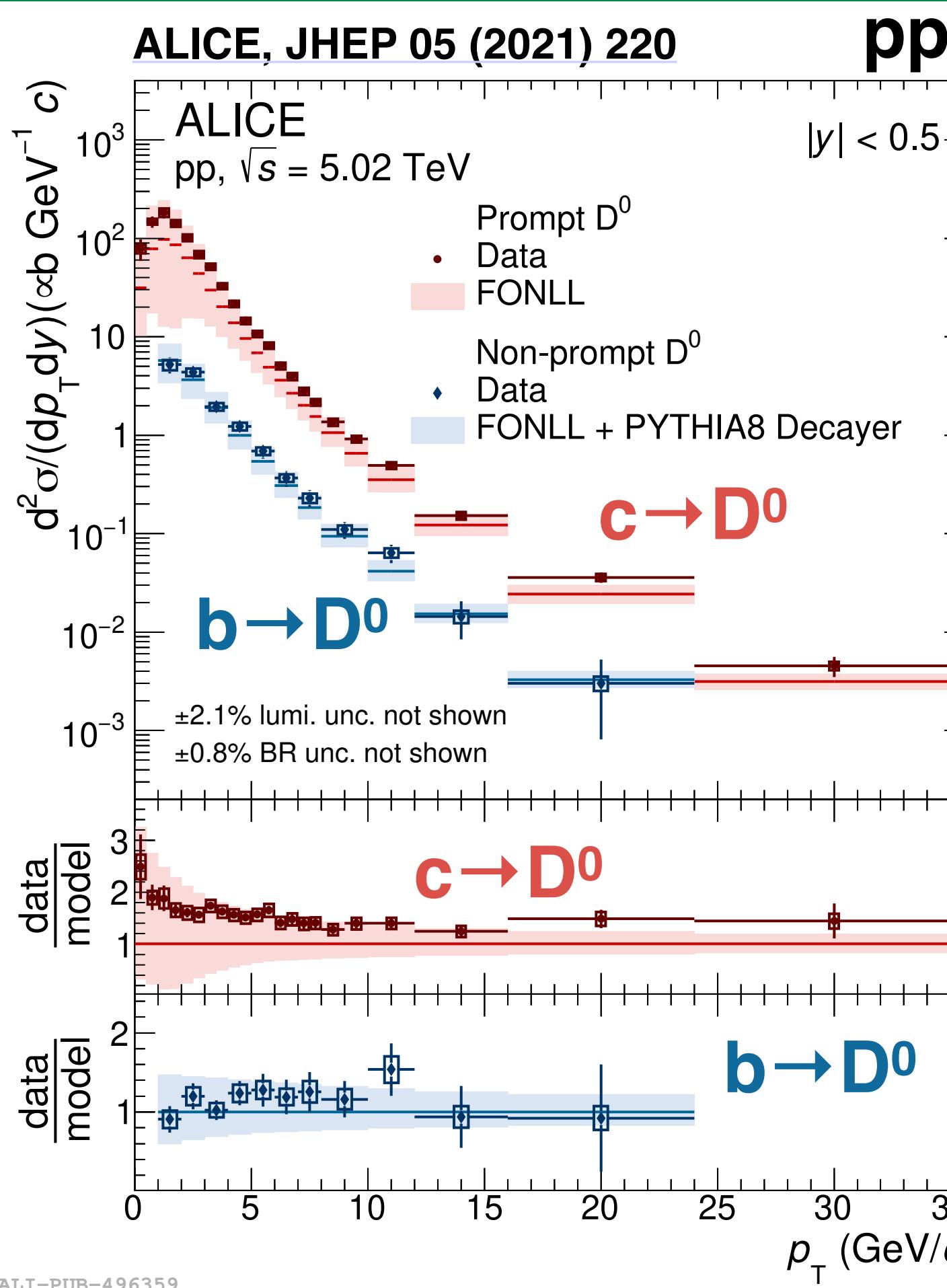


Probing QGP effects



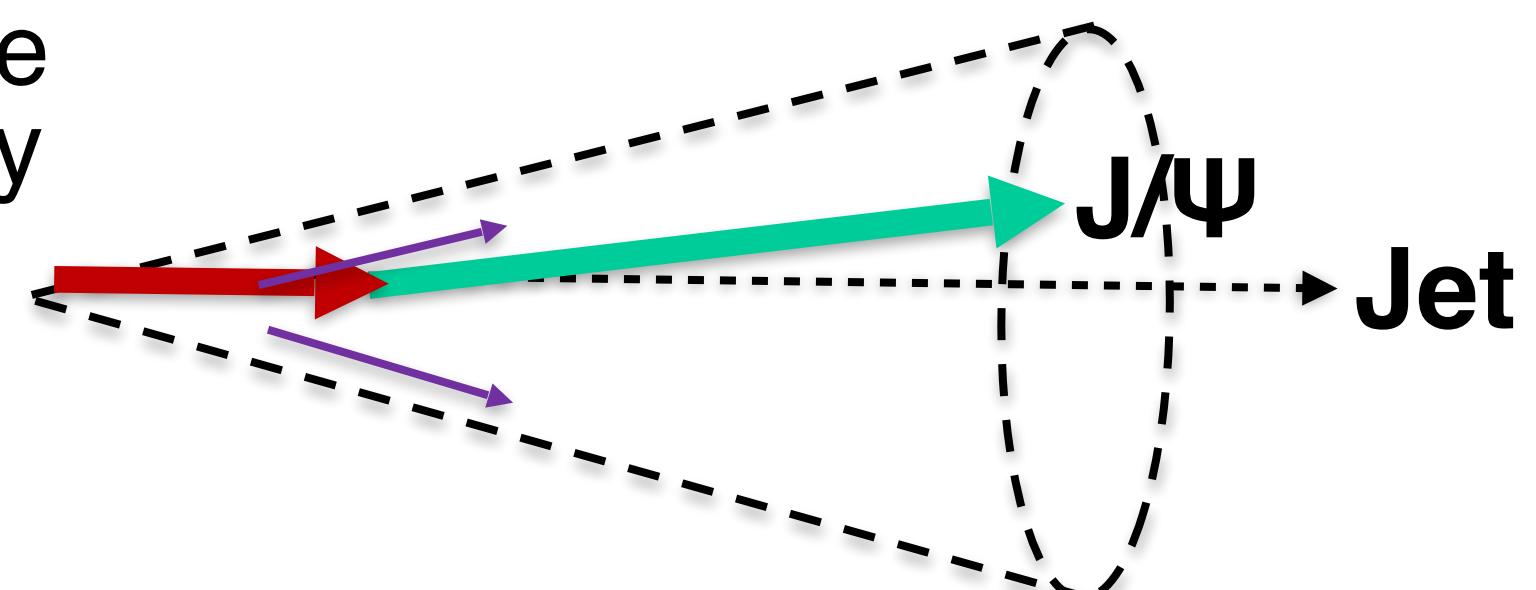
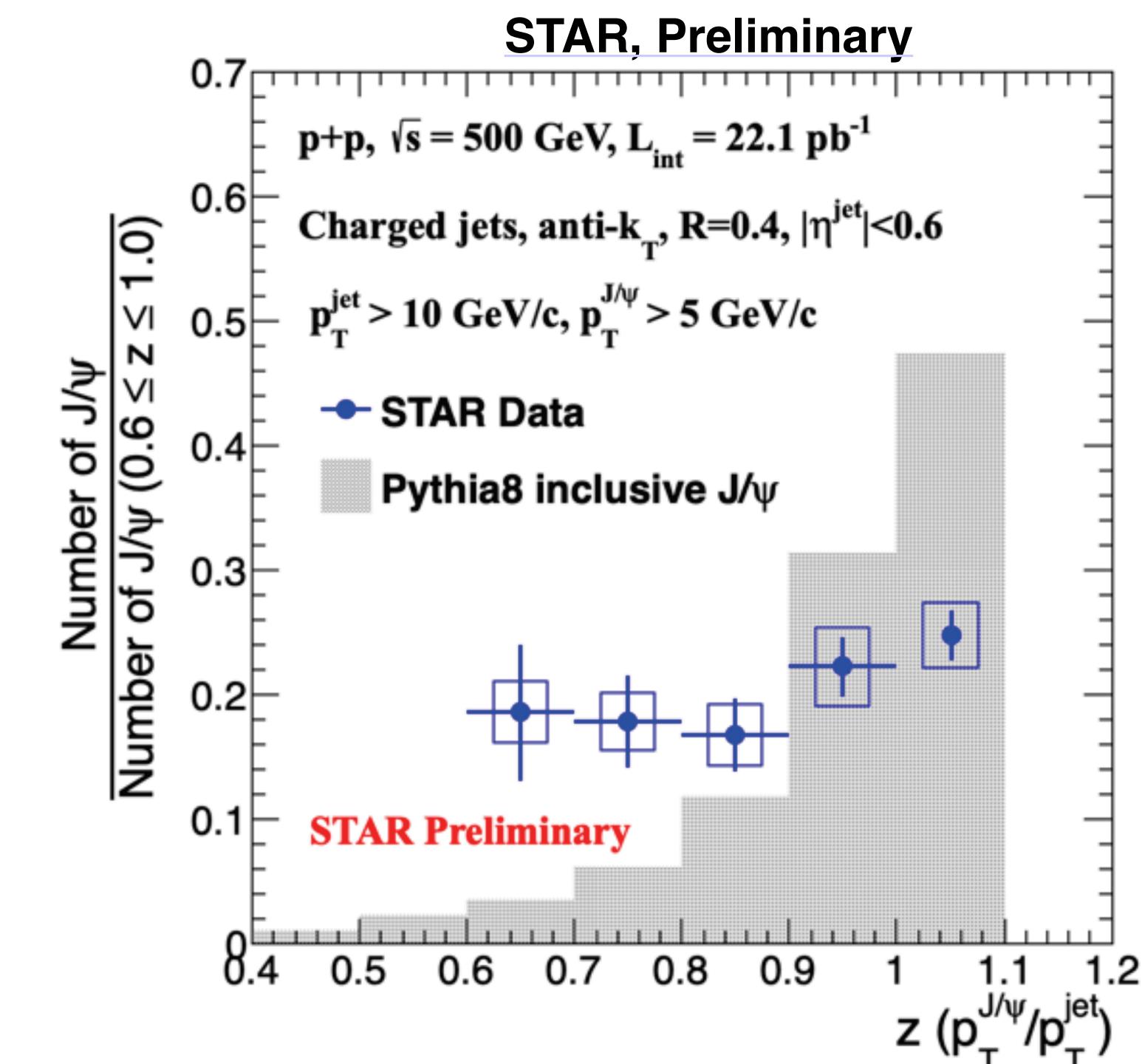
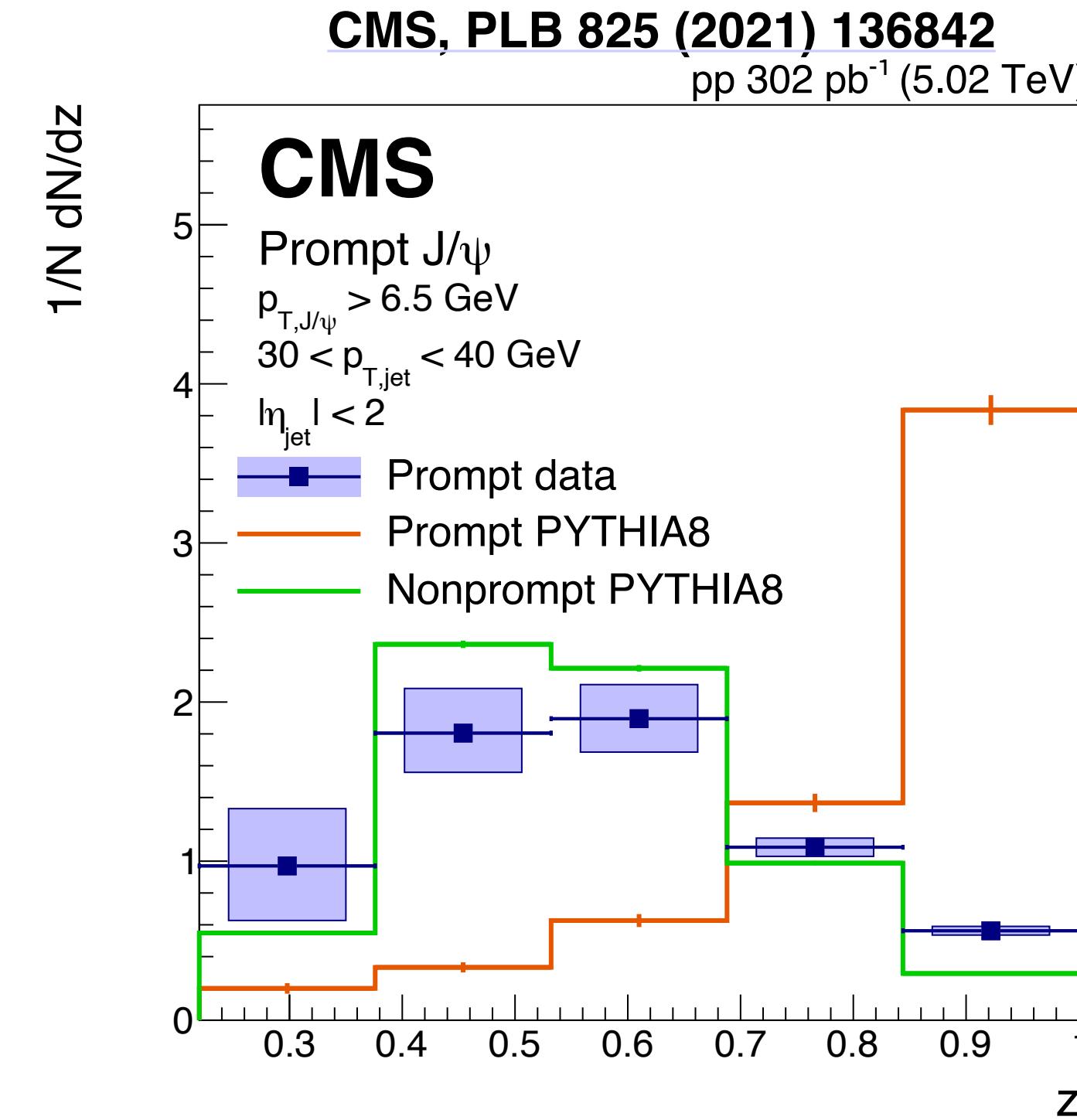
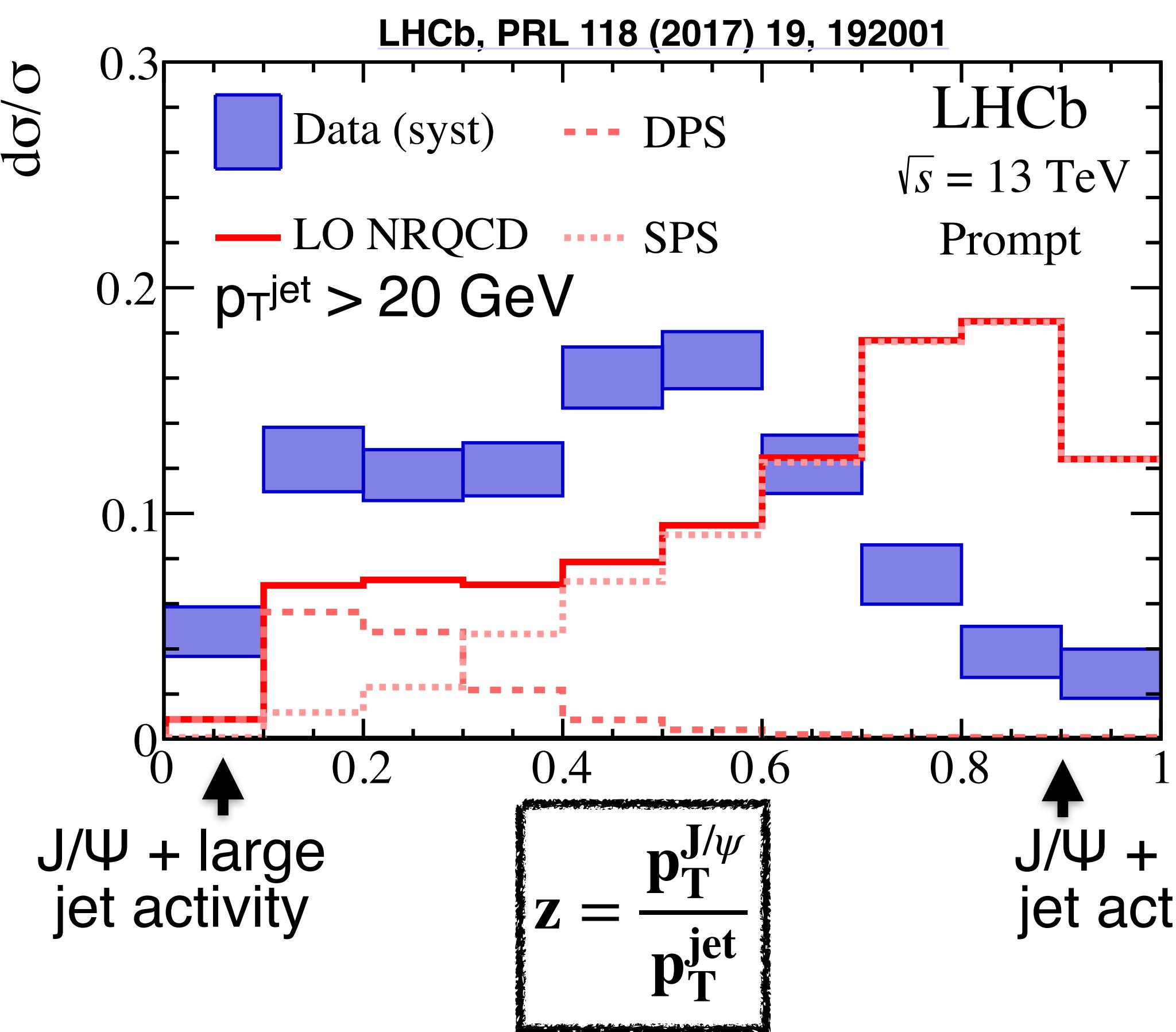
High multiplicity small systems

HF production in pp



- Precise pp data measured over a wide range of beam energies → reference for HF in HI collisions.
- FONLL (pQCD) describe bottom production in pp, while slightly underestimate charm at $p_T > 10 \text{ GeV}$.

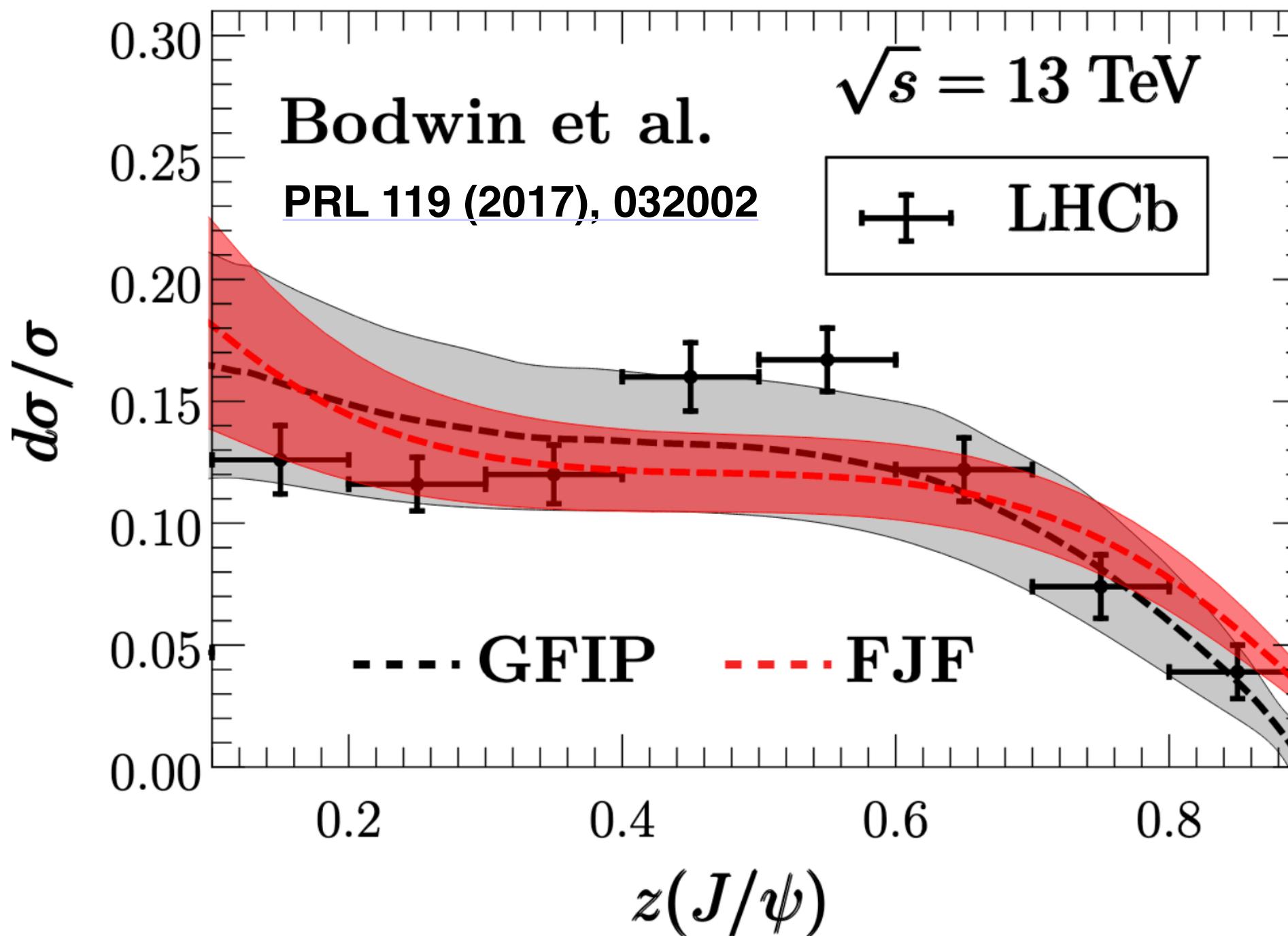
J/ ψ in jets in pp



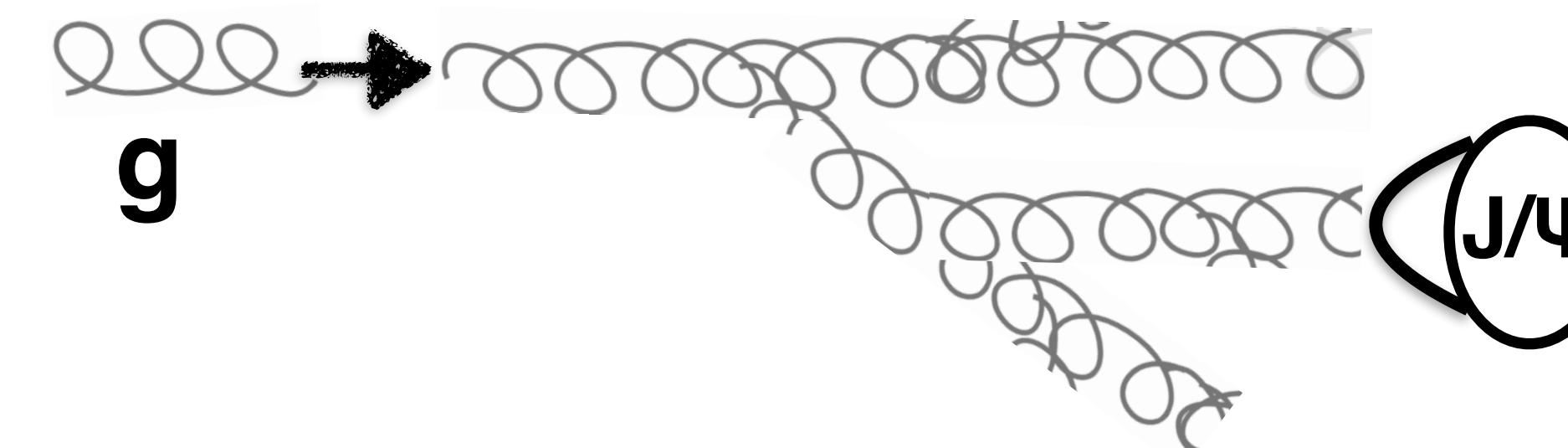
- Results at LHC show that prompt J/ψ is less isolated than expected by LO NRQCD in PYTHIA.
- Measurements from STAR also see more jet activity with no z-dependence.

J/ Ψ in jets in pp

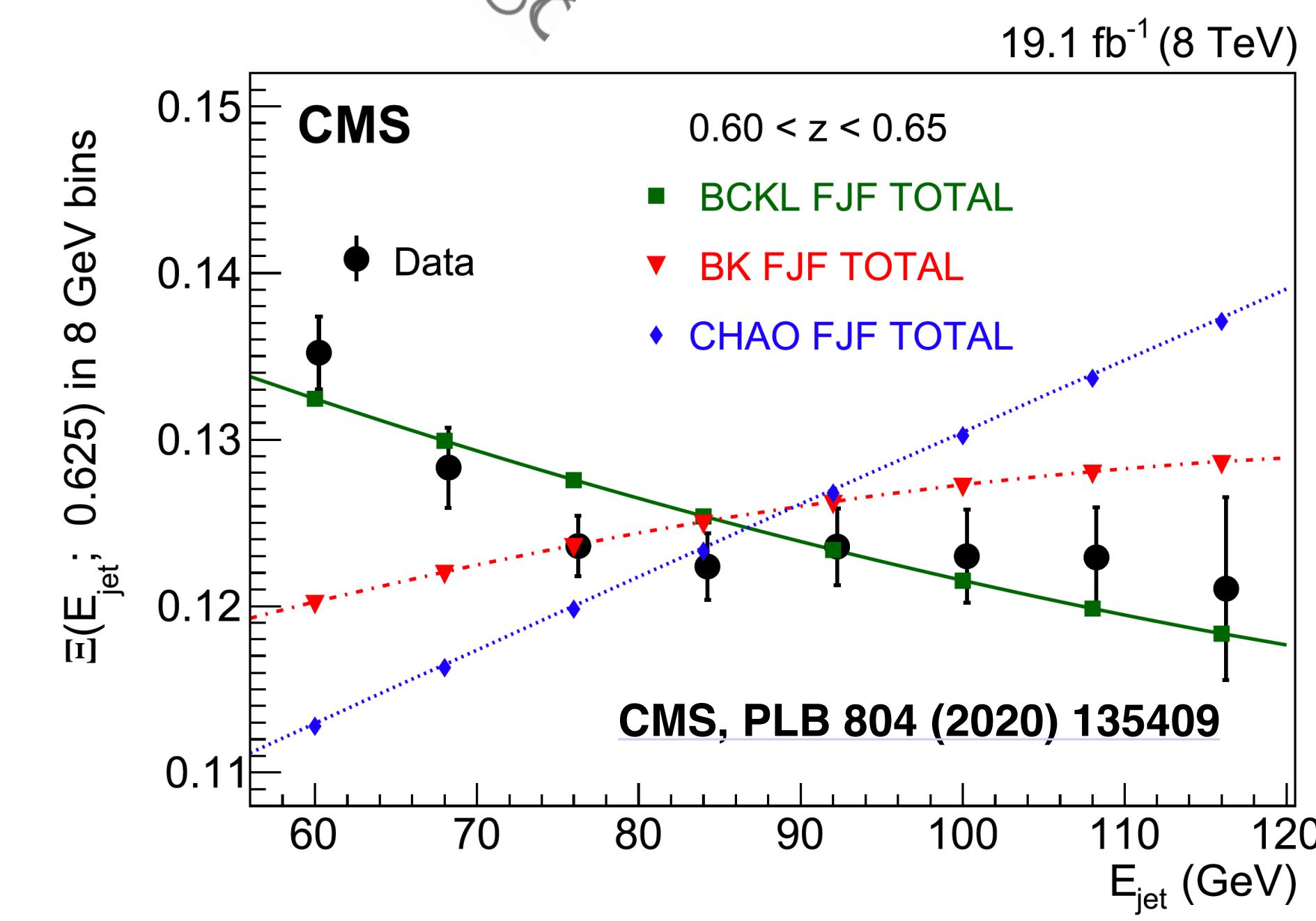
- Parton-parton scattering not enough to describe J/ Ψ production in pp.



- Model including J/ Ψ produced in parton showers successfully describe LHCb data.

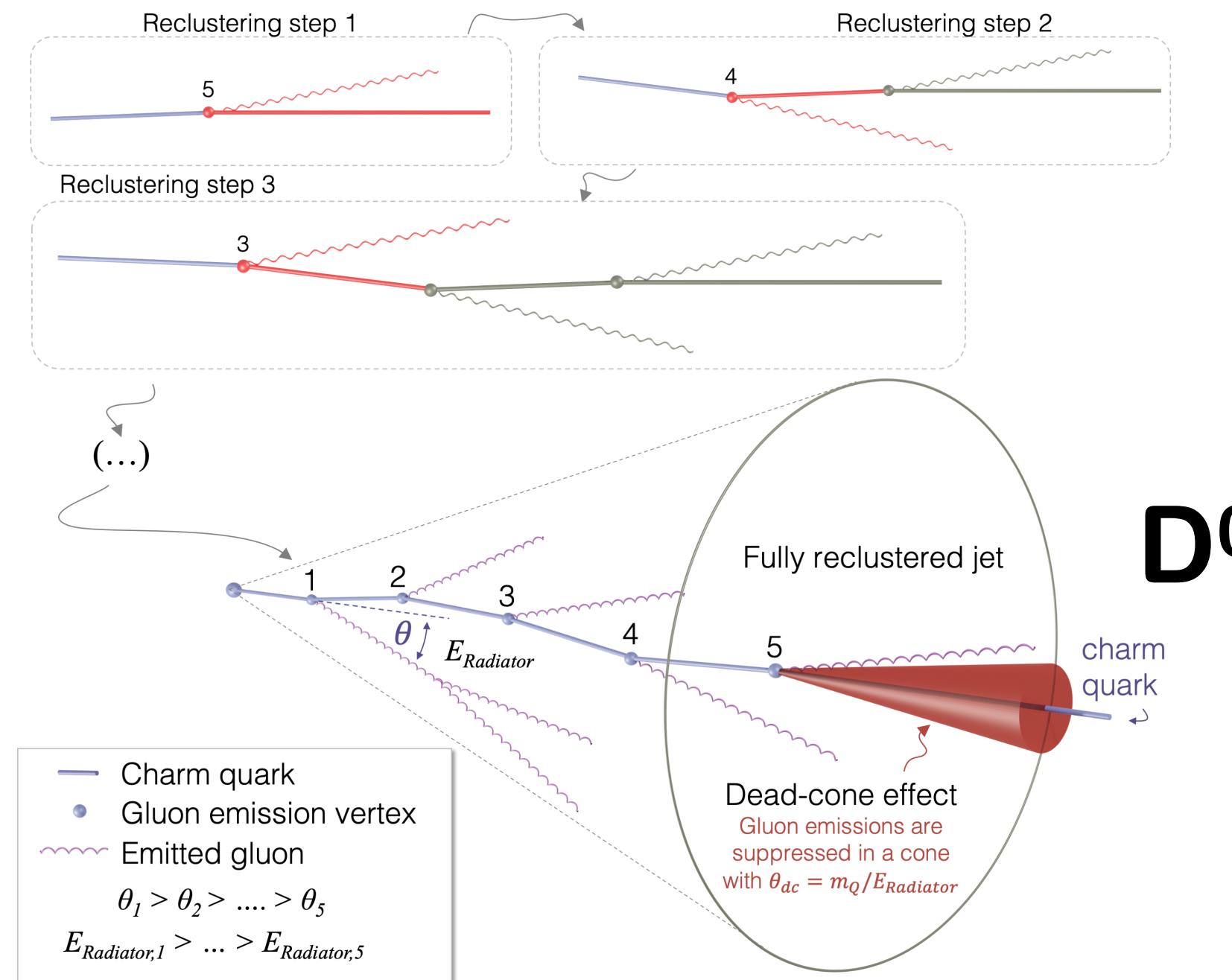


- CMS results of J/ Ψ in jets vs jet energy is also described by gluon jet fragmentation model.
- CMS data sensitive to LMDE parametrisation:
 - Favours LMDE set of Bodwin et al.



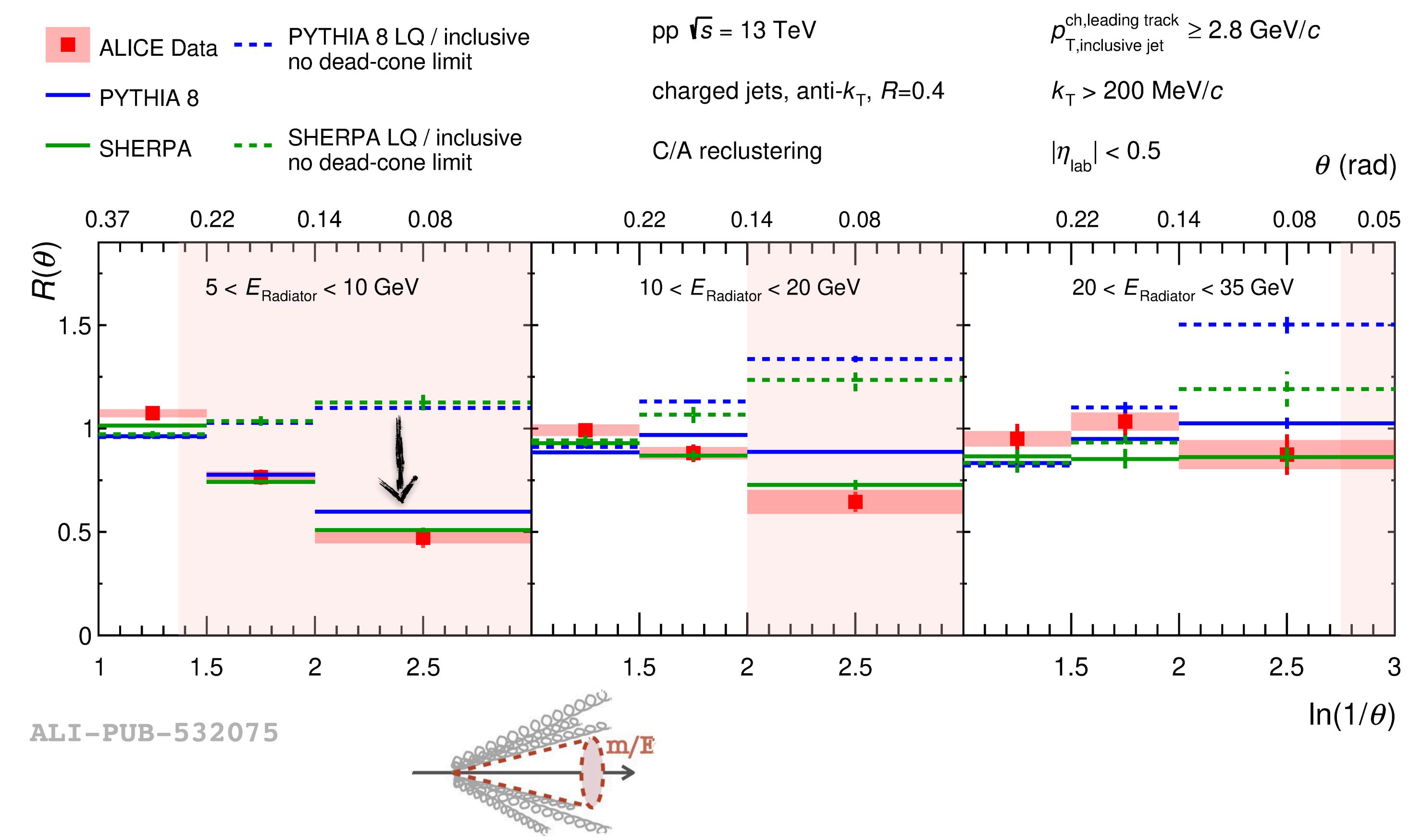
Observation of dead cone effect in pp

Cambridge-Aachen reclustering



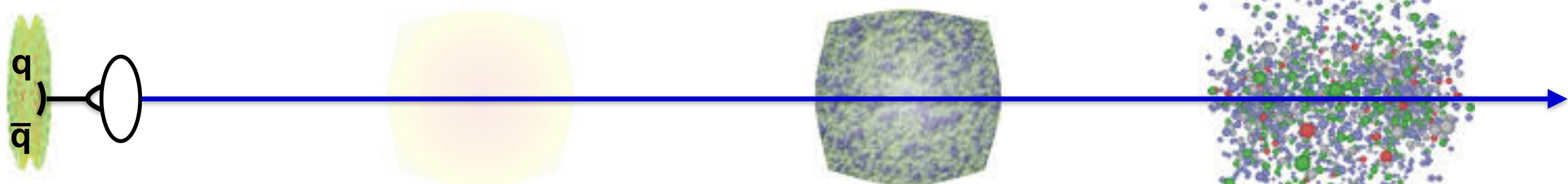
$$R(\theta) = \frac{1}{N^{D^0 \text{ jets}}} \frac{dn^{D^0 \text{ jets}}}{d\ln(1/\theta)} / \left. \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \right|_{k_T, E_{\text{Radiator}}}$$

ALICE, Nature 605 (2022) 440



- Declustered each splitting into two prongs, measuring the k_T , splitting angle (θ), and energy sum (E_{radiator}).
- Significant ($>5\sigma$) suppression ($R < 1$) at small-angle splittings is observed in D^0 -jets relative inclusive jets.
- Measurement sensitive to charm quark mass \rightarrow first direct observation of dead cone effect.
 - Paves the way to study dead cone effect in heavy ions and constrain quark mass.

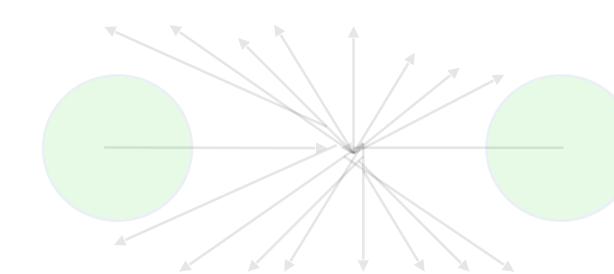
OUTLINE



HF production in pp

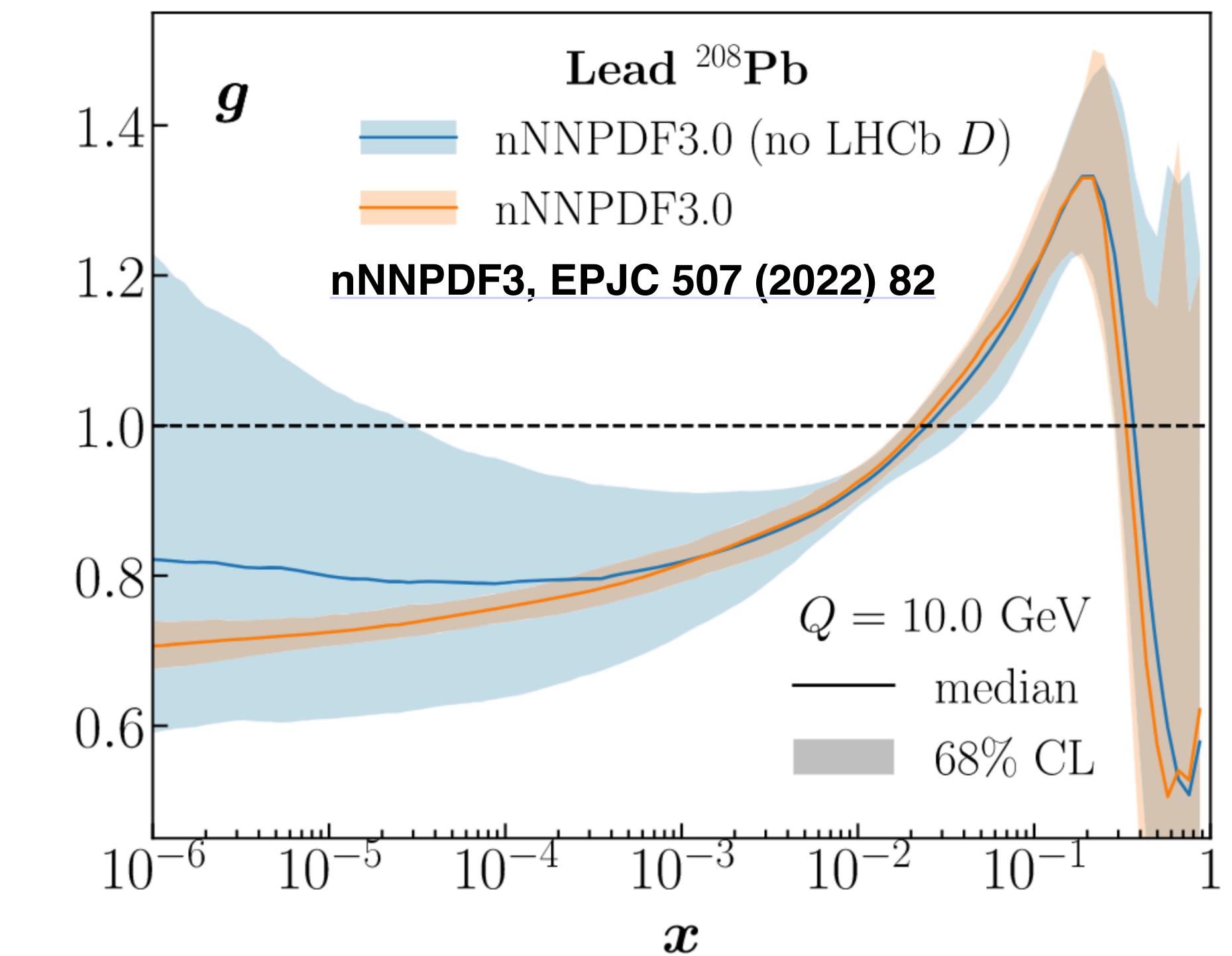
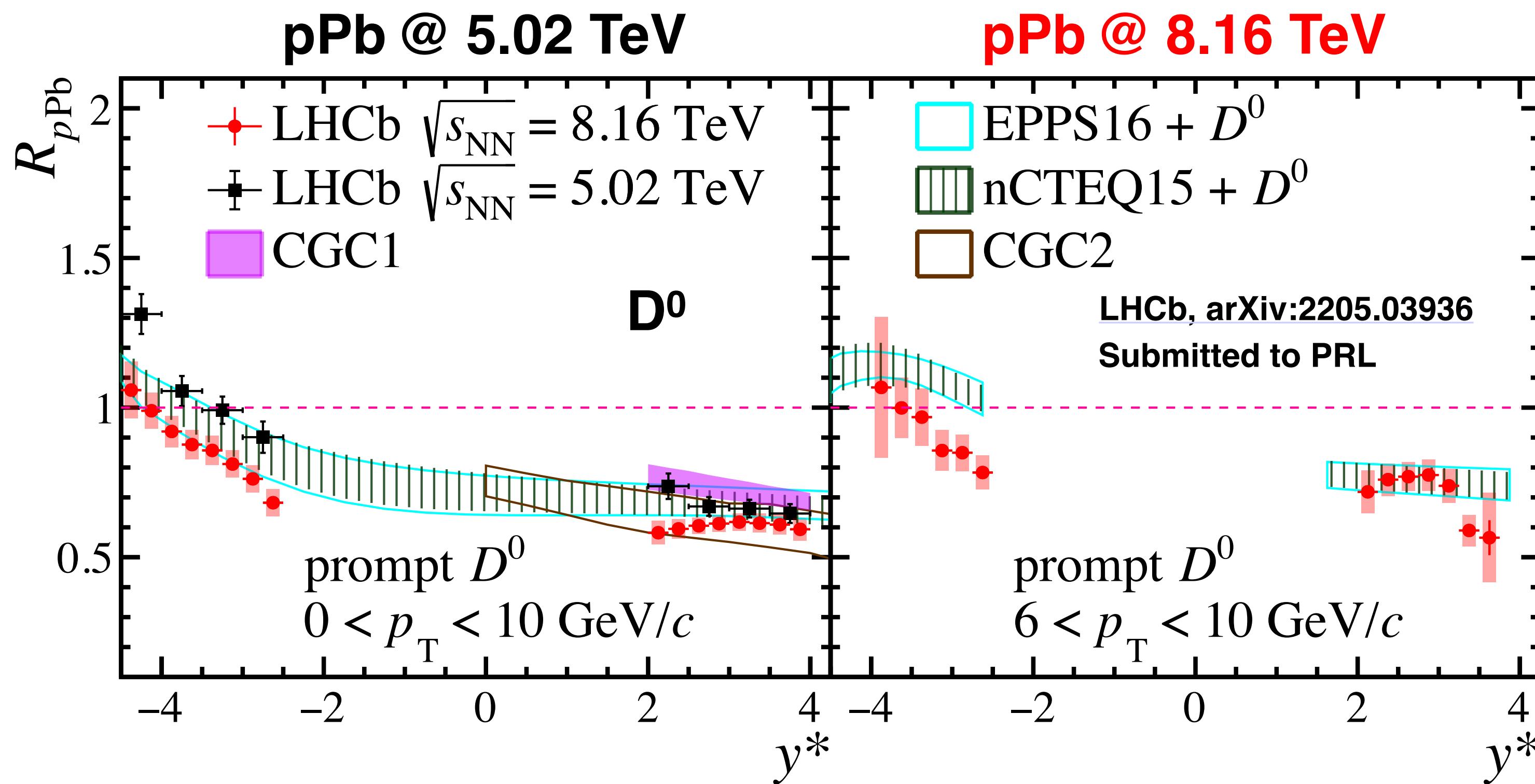
Probing cold nuclear effects

Probing QGP effects



High multiplicity small systems

D⁰ production in pPb

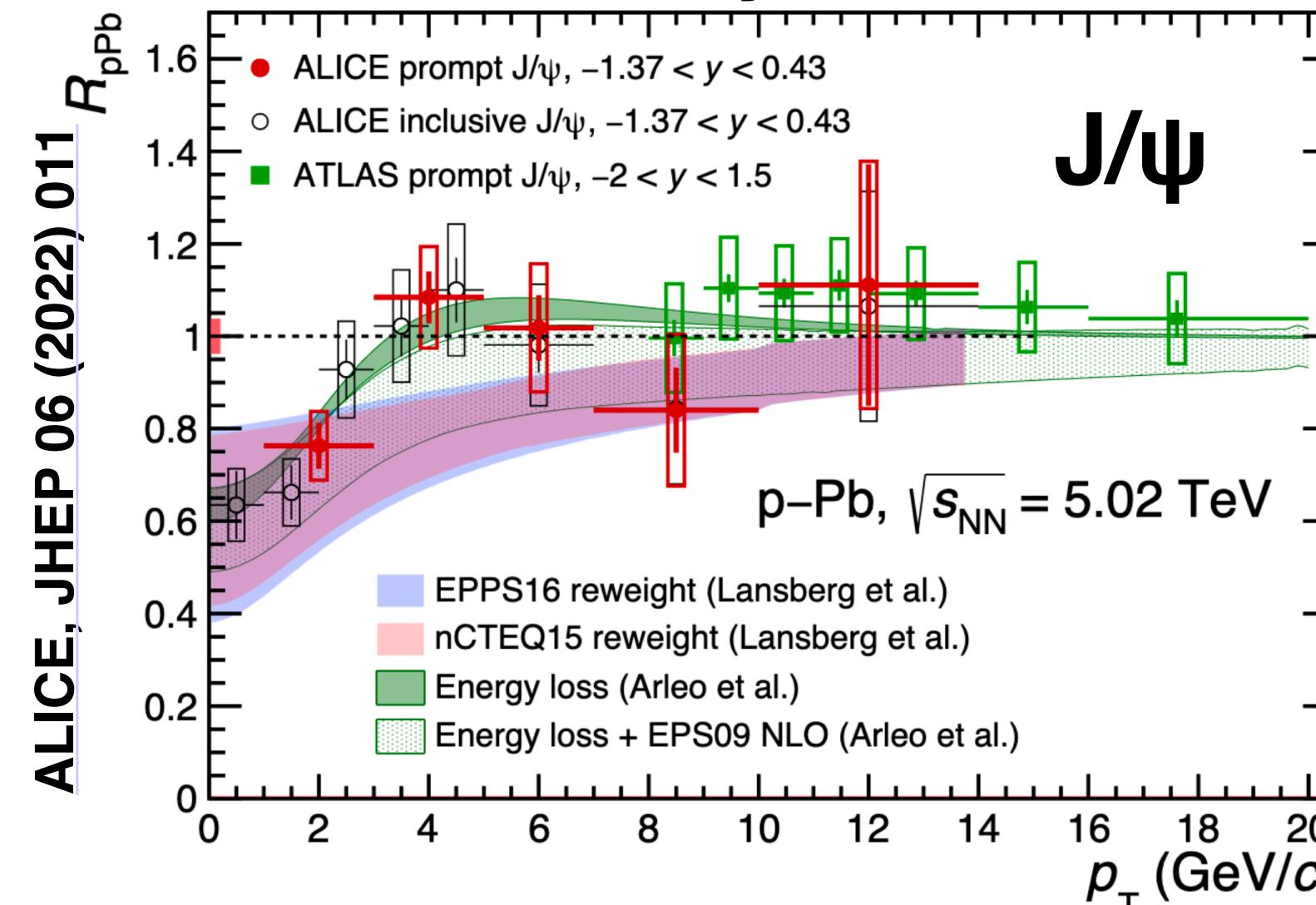


- nPDF slightly overestimates backward $D^0 R_{p\text{Pb}}$ at $p_T > 6 \text{ GeV} \rightarrow$ final state effects in backward region?
- D^0 in pPb provides strong nPDF constraints down to small x regions of $\sim 10^{-6}$.

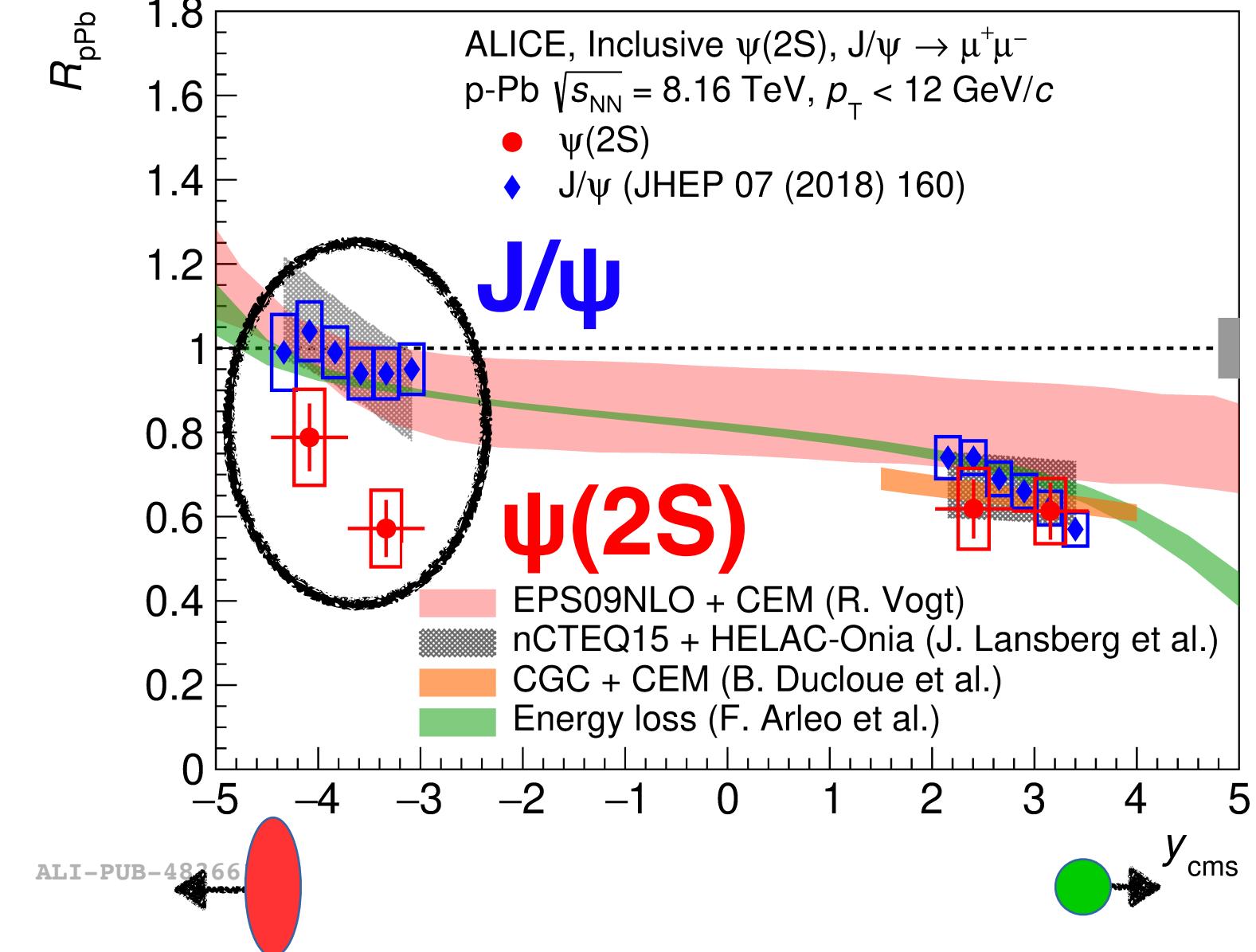
Cesar da Silva,
Feb 14, 14:00

$\Psi(nS)$ production in pPb

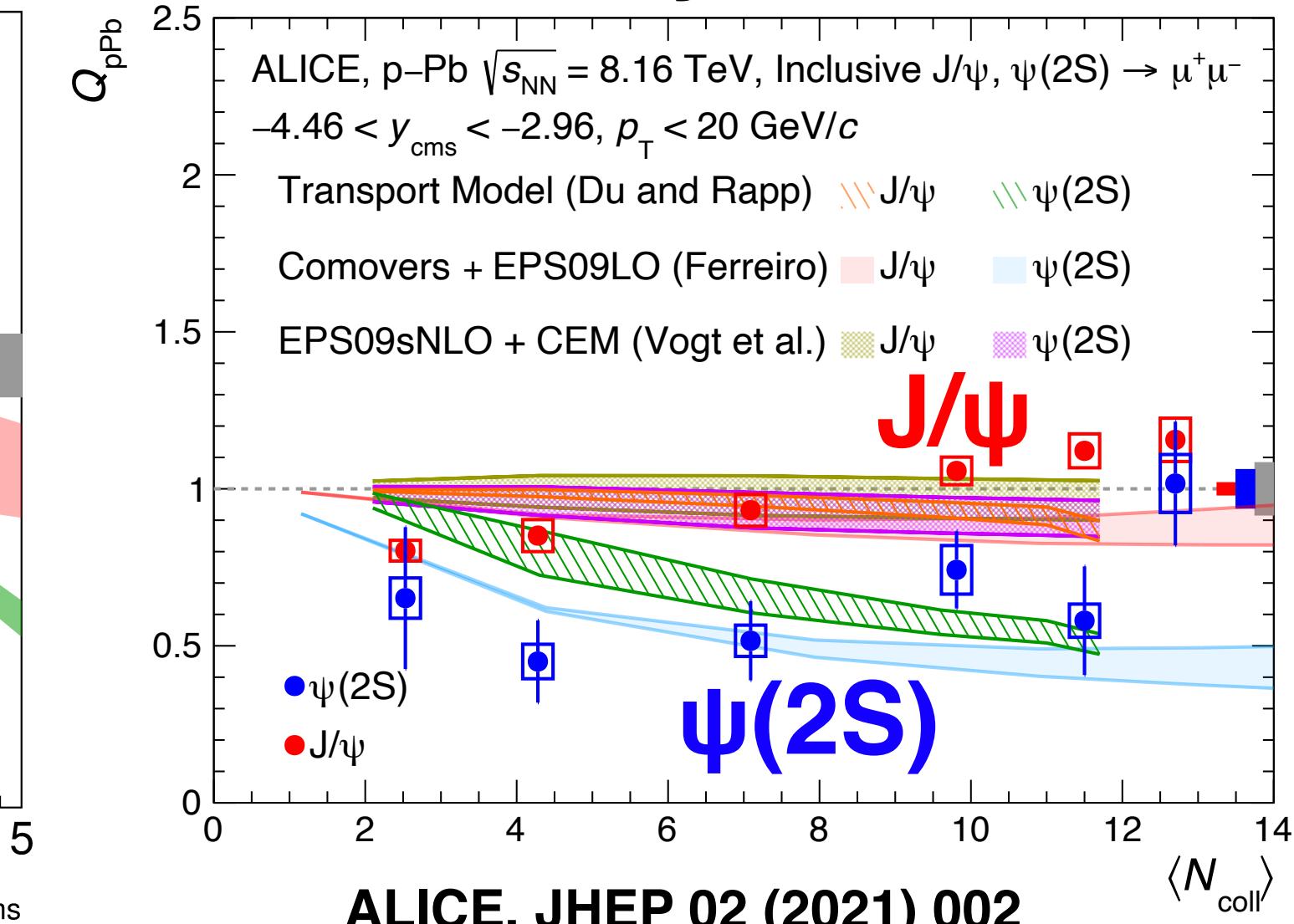
$-1.37 < y < 0.43$



ALICE, JHEP 07 (2020) 237

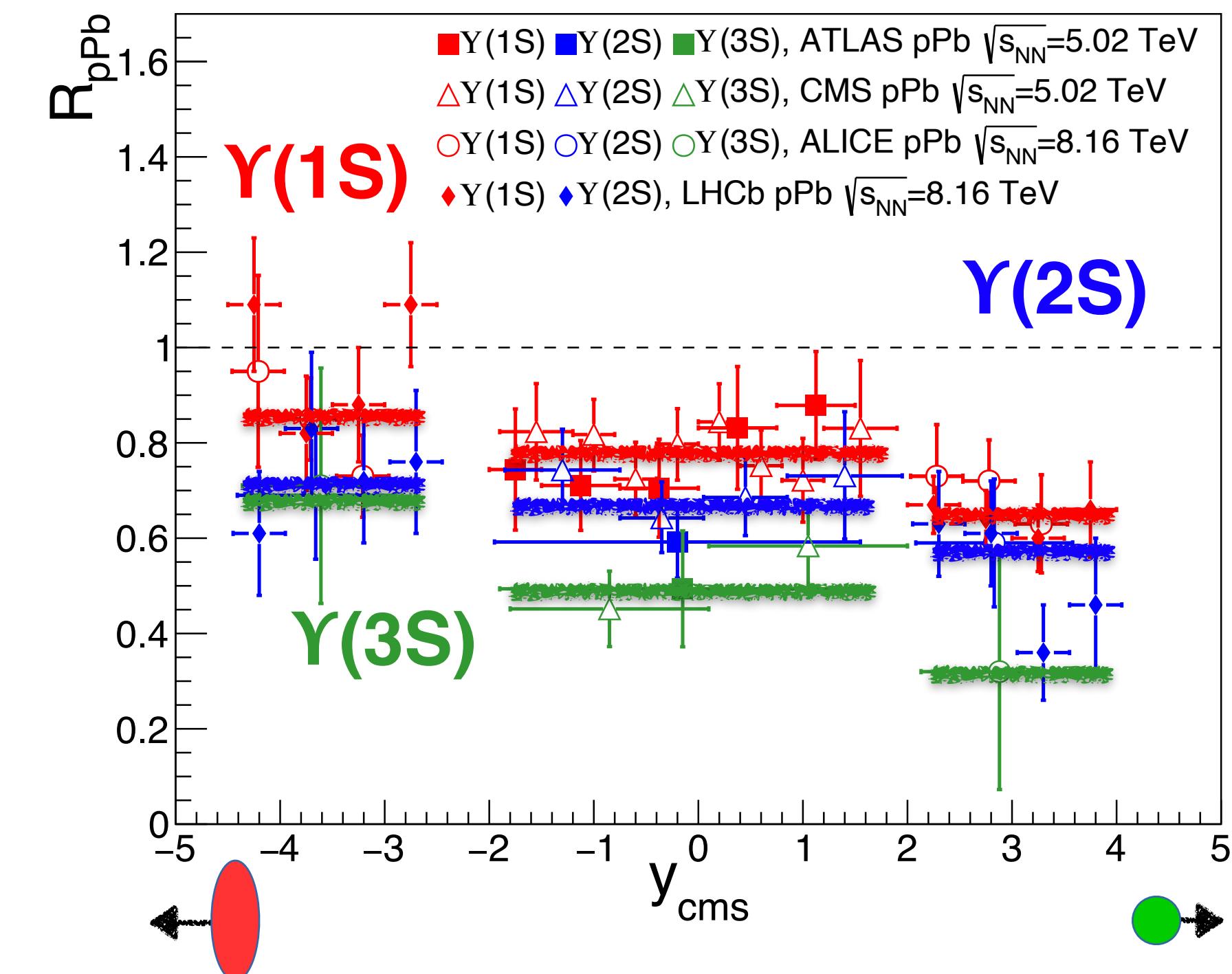
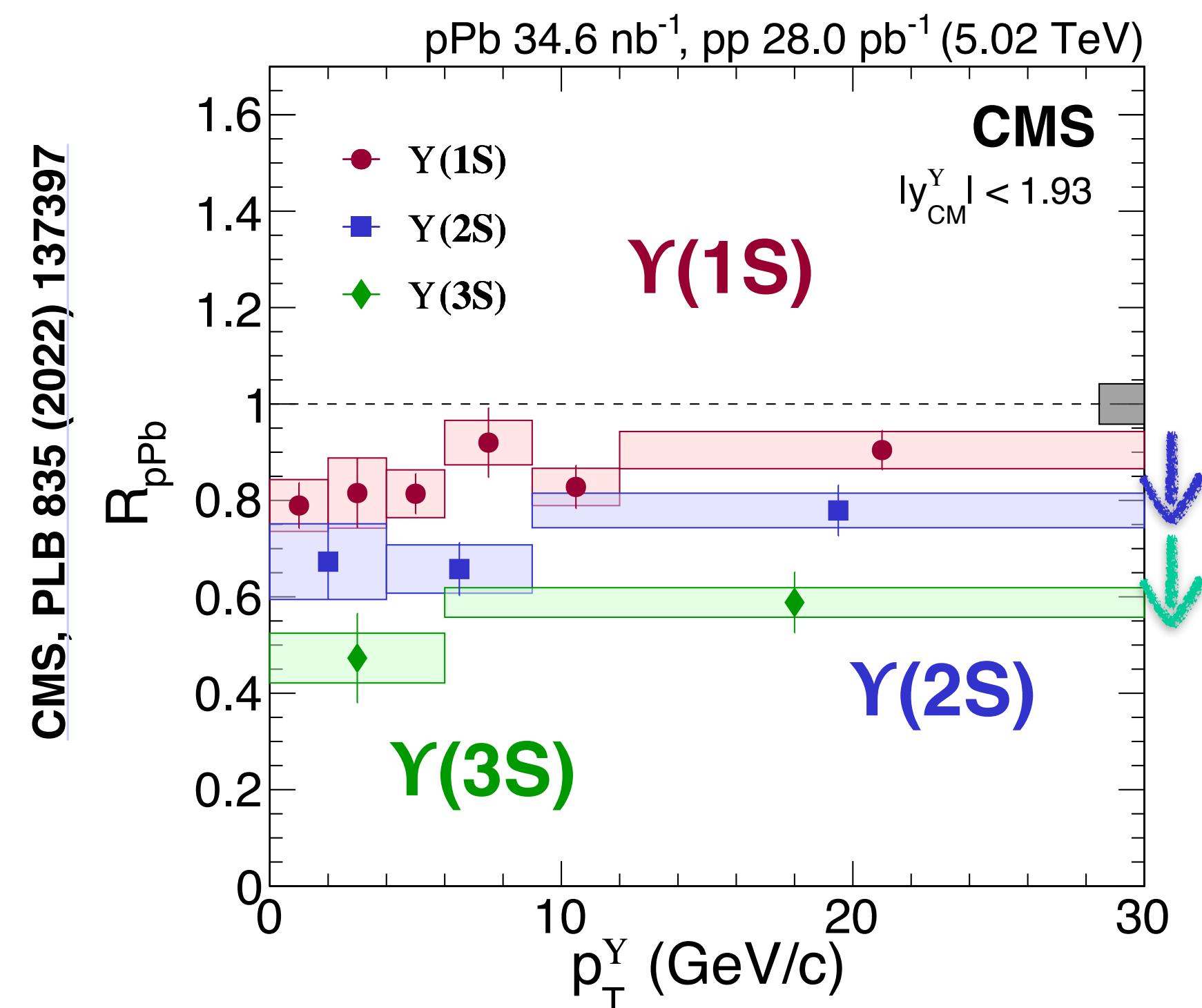


$-4.46 < y_{\text{cm}} < -2.96$



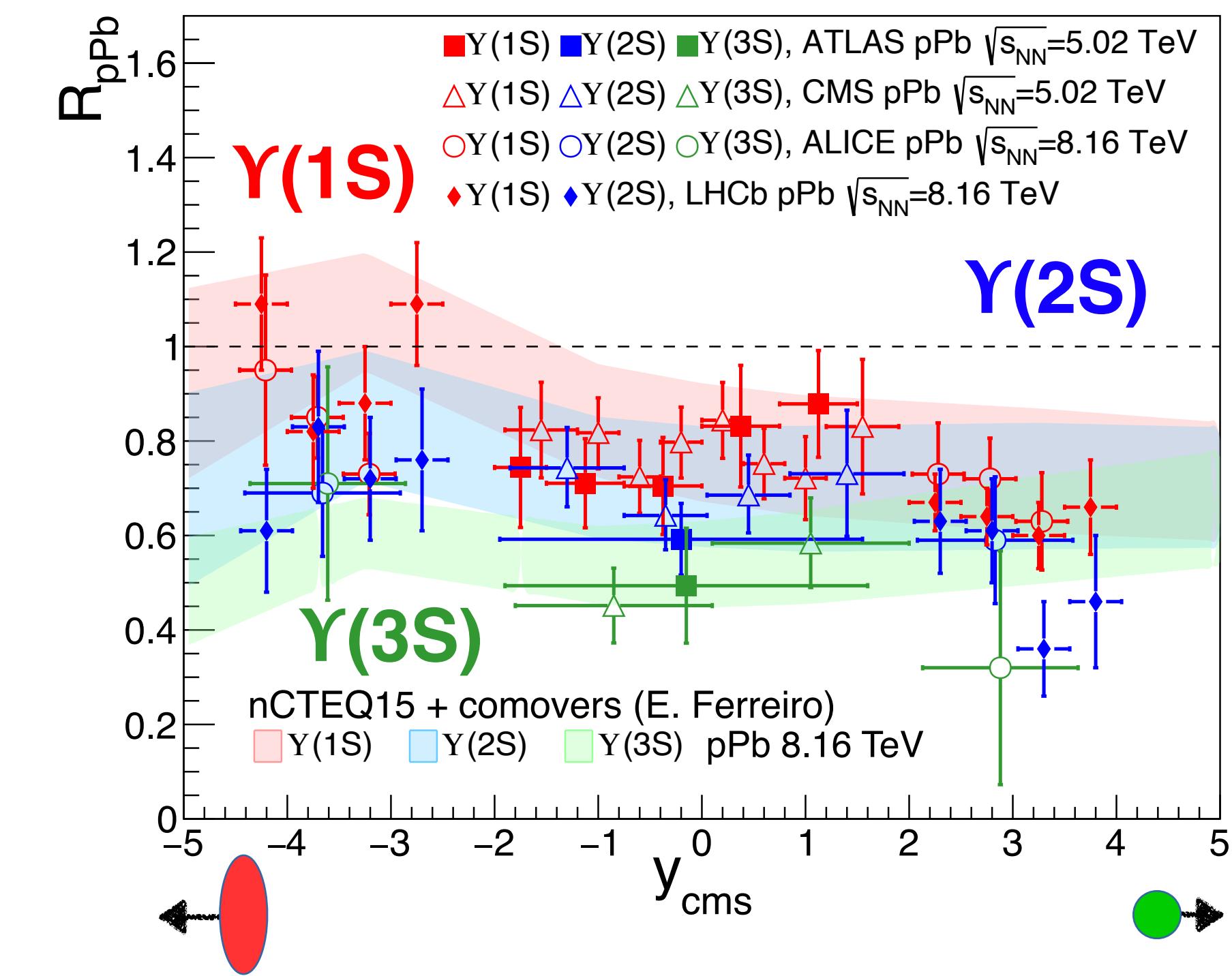
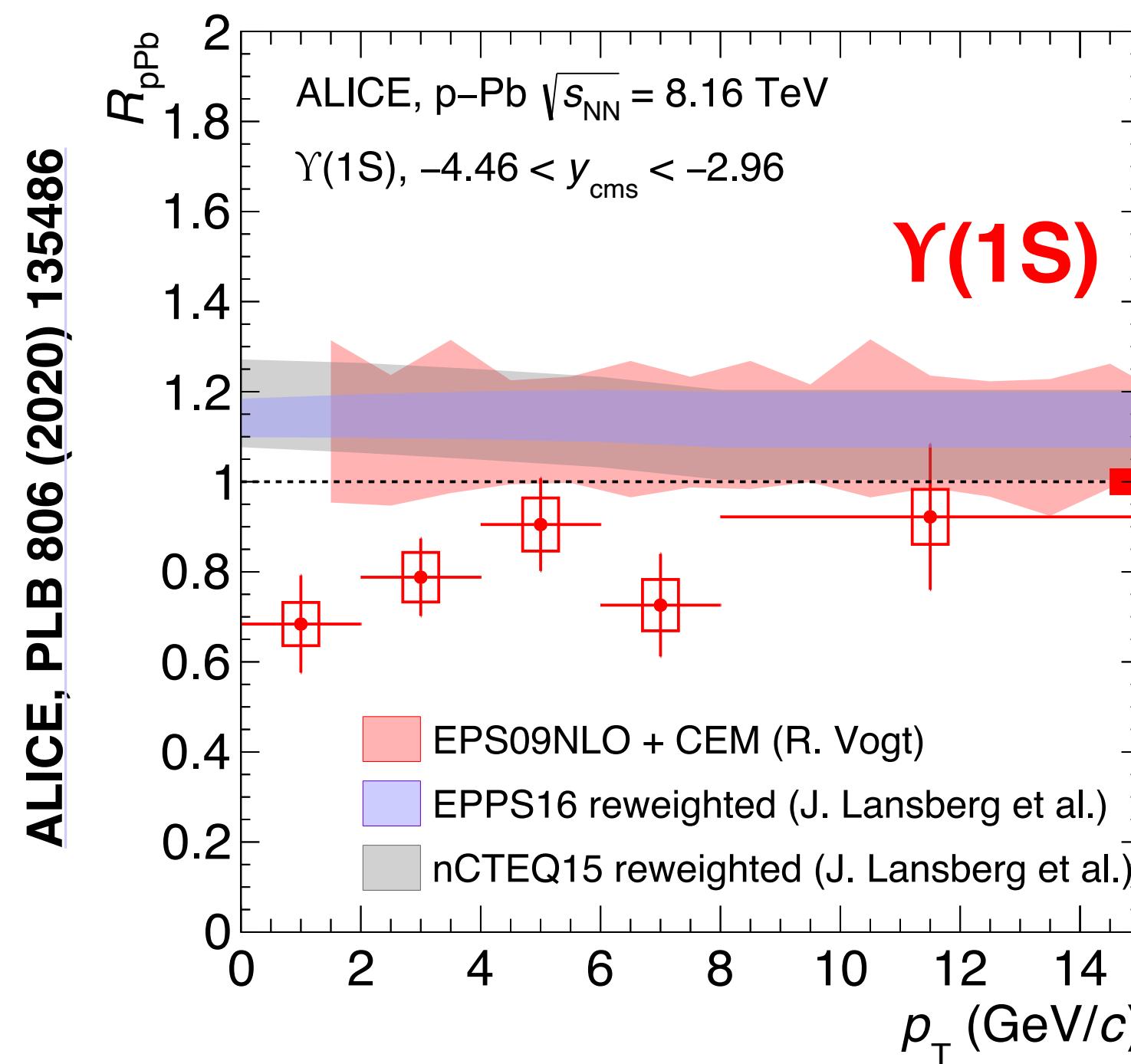
- J/ψ production suppressed at $p_T < 3 \text{ GeV}$ in mid rapidity.
 - Energy loss model captures p_T dependence of $J/\psi R_{pPb}$.
- $\Psi(2S) R_{pPb} < J/\psi R_{pPb}$ in Pb-going side (backward rapidity).
 - Final state comover model describe the trend of $\Psi(nS)$ production in pPb.

$\Upsilon(nS)$ production in pPb



- Hint of stronger $\Upsilon(nS)$ suppression towards low p_T .
- $\Upsilon(1S) R_{\text{pPb}} > \Upsilon(2S) R_{\text{pPb}} > \Upsilon(3S) R_{\text{pPb}} \rightarrow$ sequential suppression of bottomonium states

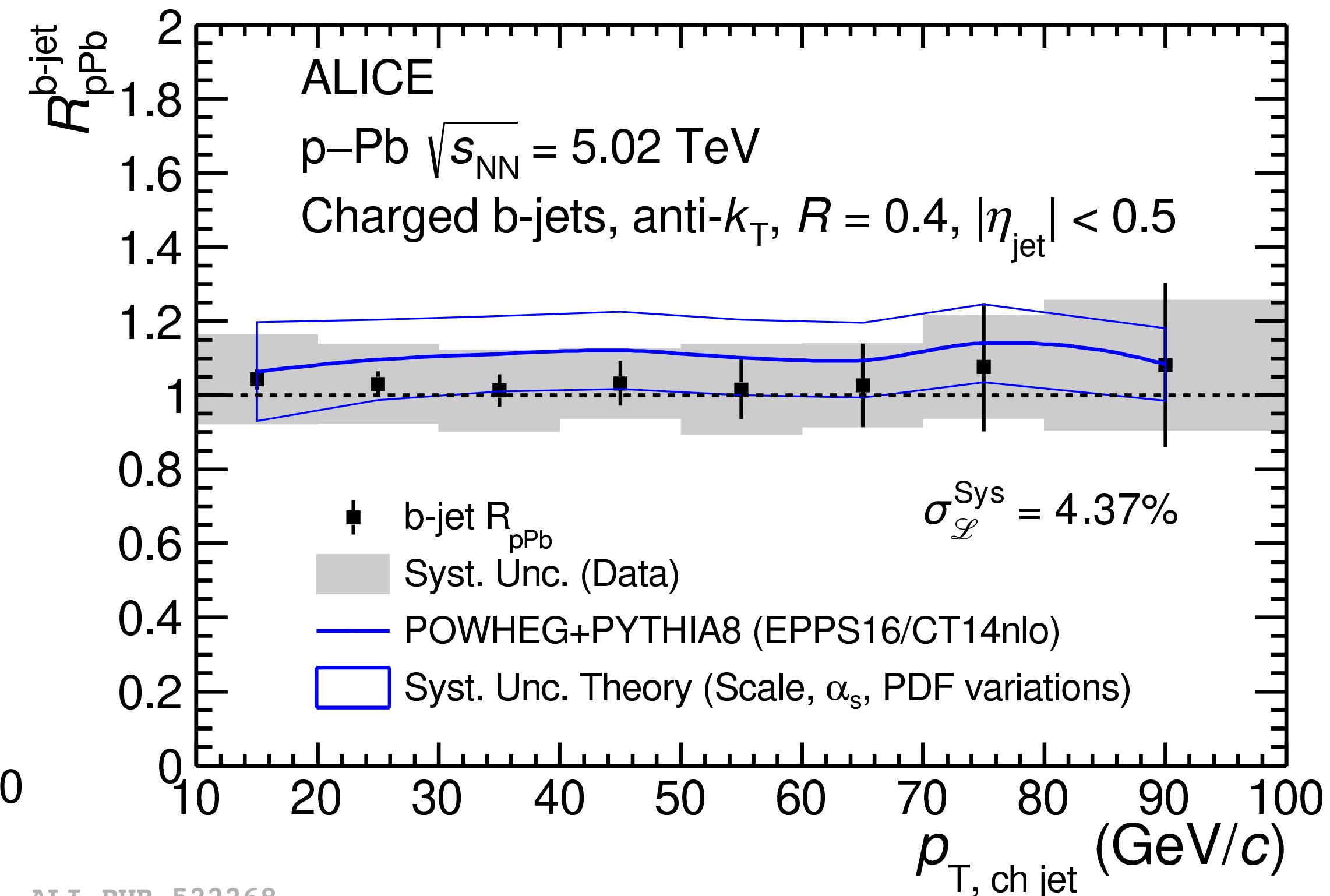
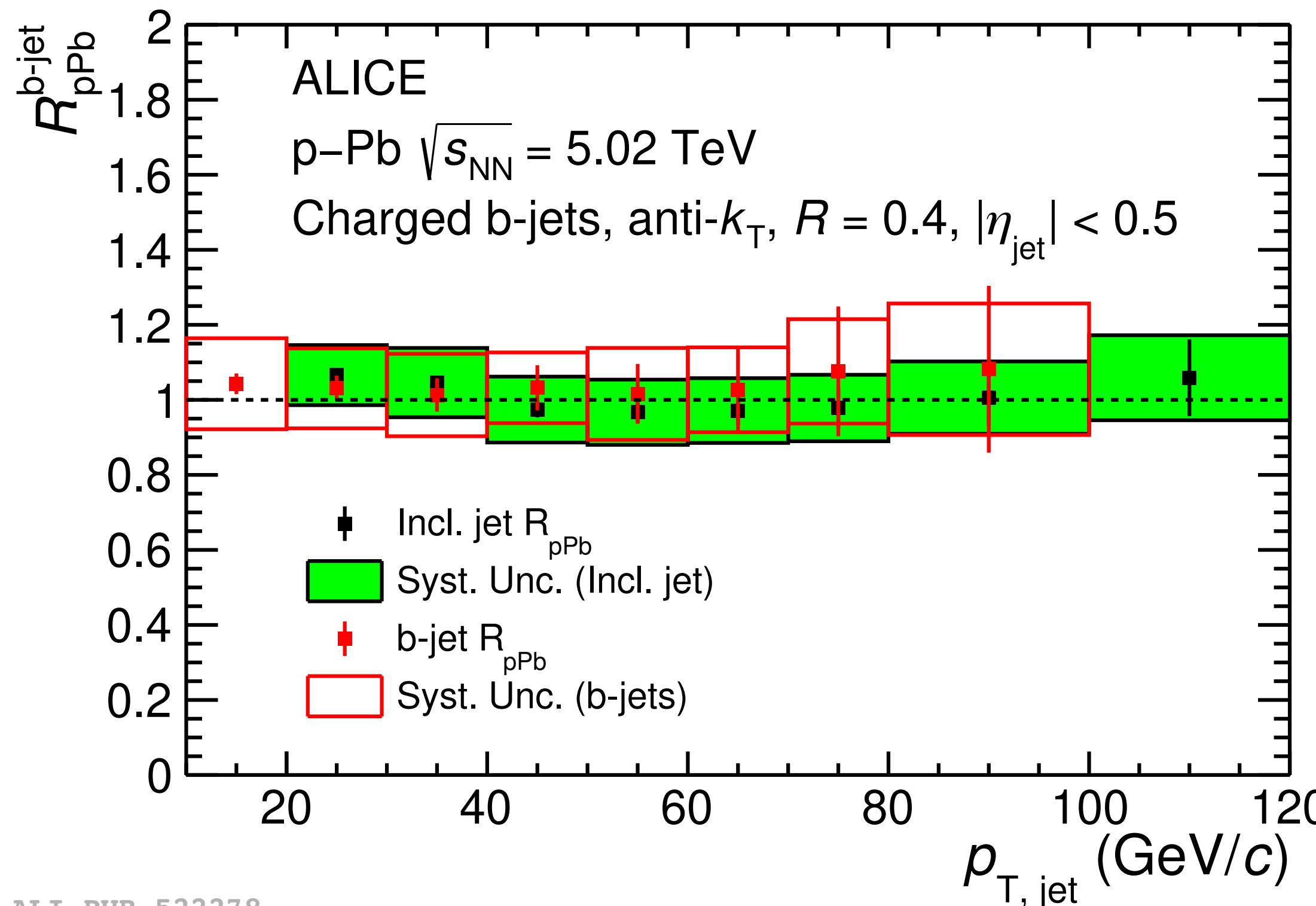
$\Upsilon(nS)$ production in pPb



- Hint of stronger $\Upsilon(nS)$ suppression towards low p_T .
- $\Upsilon(1S) R_{pPb} > \Upsilon(2S) R_{pPb} > \Upsilon(3S) R_{pPb} \rightarrow$ sequential suppression of bottomonium states
- nPDF models overestimate $\Upsilon(1S) R_{pPb}$ at backward rapidities.
- Comover + nPDF model predicts the suppression trend of $\Upsilon(nS)$ production in pPb.

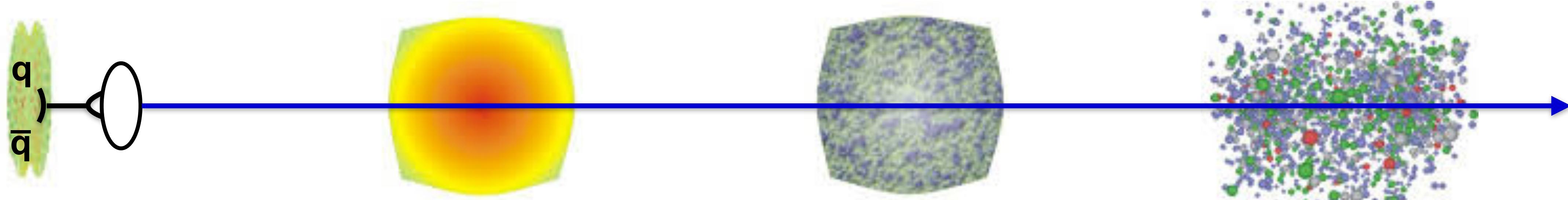
b-jet production in pPb

ALICE, JHEP 01 (2022) 178



- NLO pQCD calculations able to describe b-jet results in pPb collisions.
- R_{pPb} of b jets consistent with unity \rightarrow no significant CNM modifications at mid-rapidity in pPb.
- Similar nuclear modification for b and inclusive jets in pPb collisions.

OUTLINE



HF production in pp

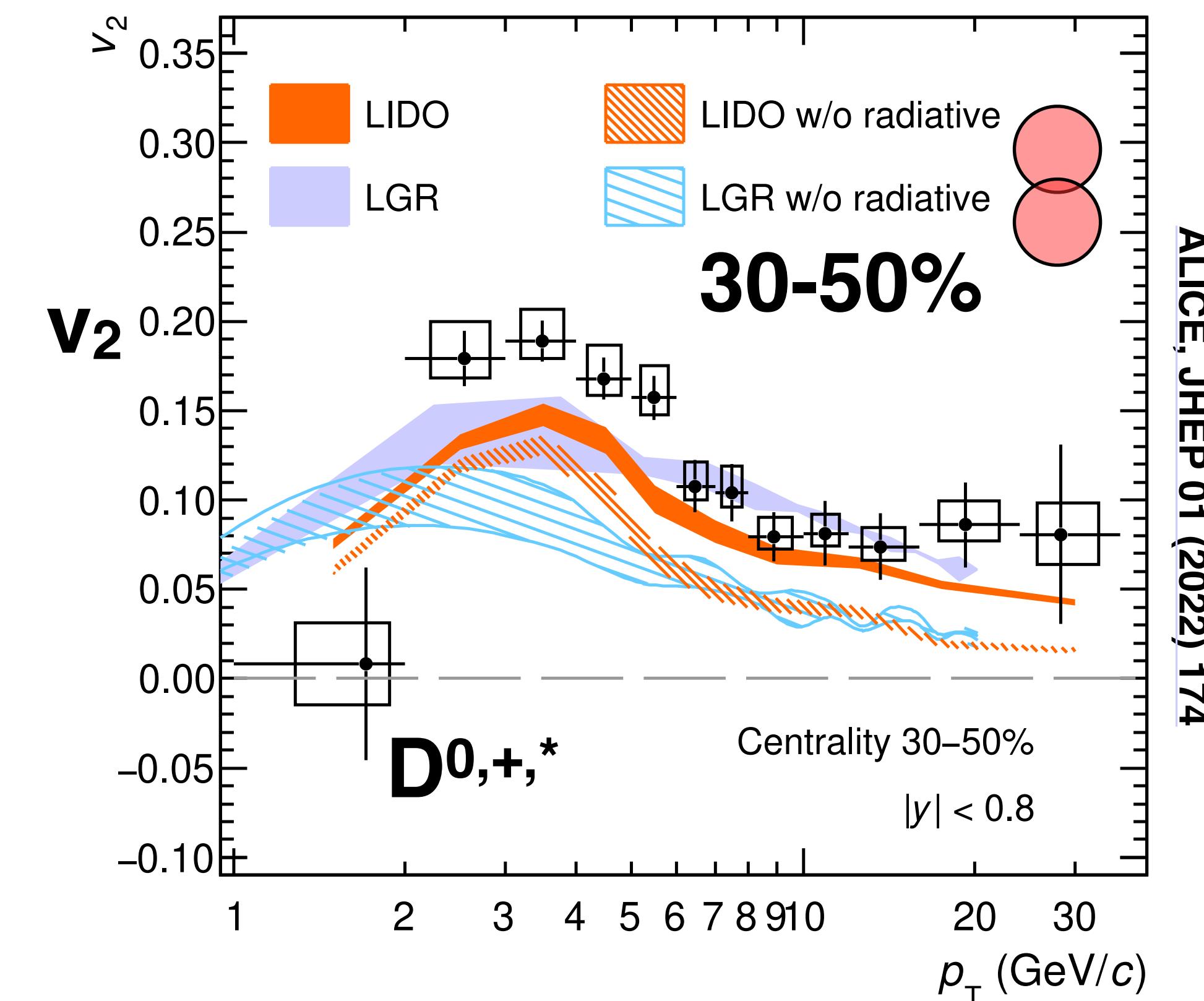
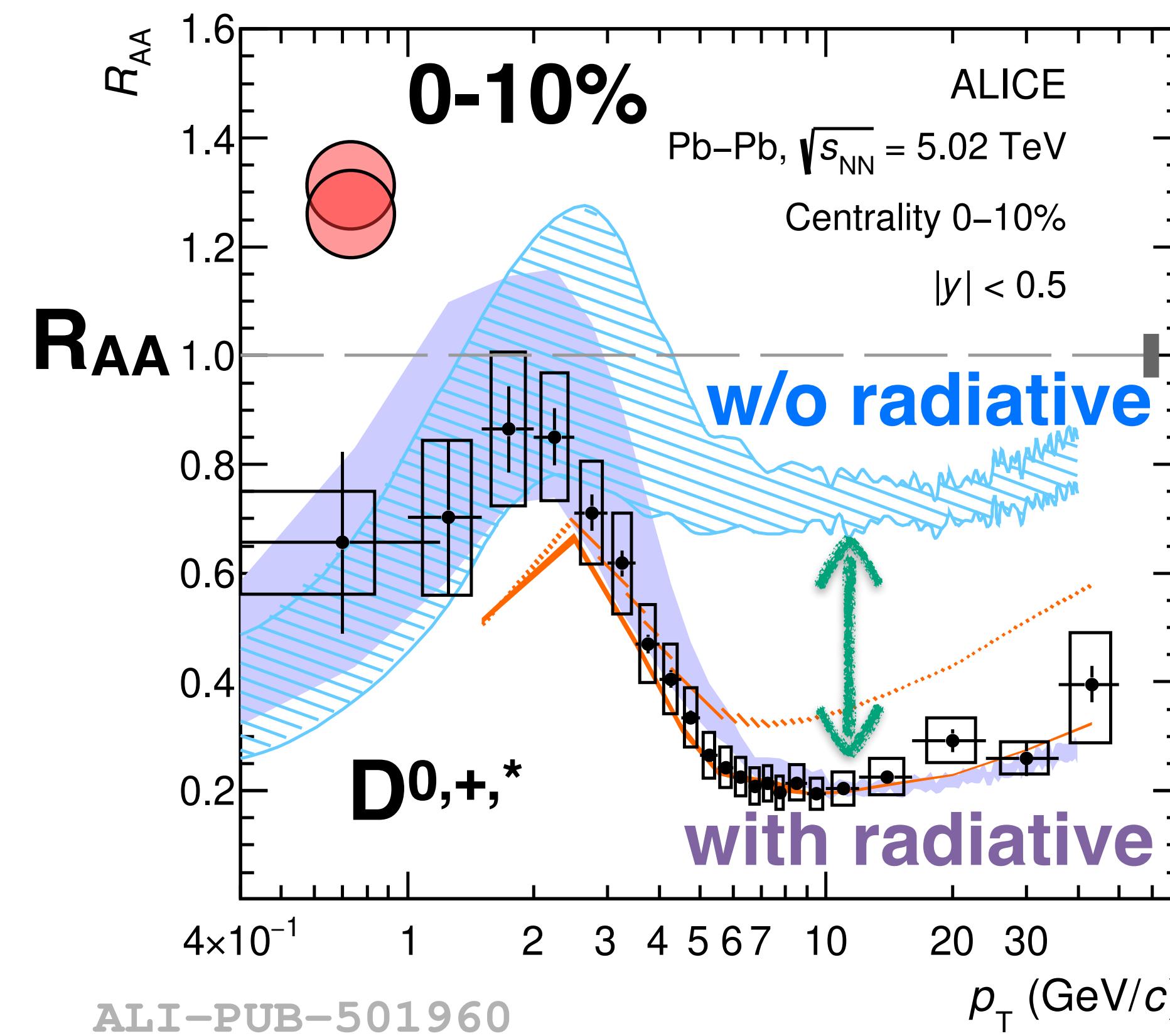
Probing cold nuclear effects

Probing QGP effects



High multiplicity small systems

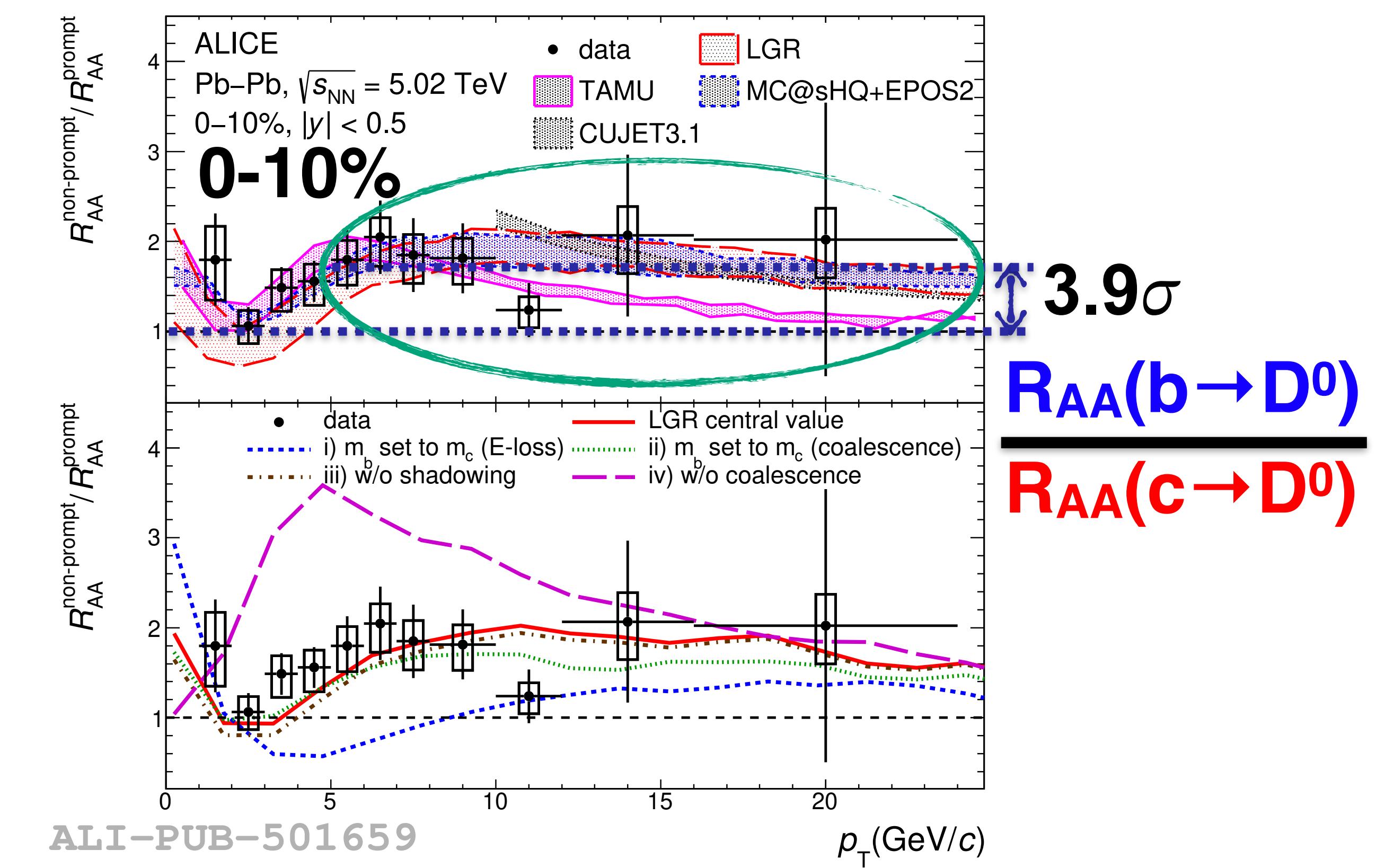
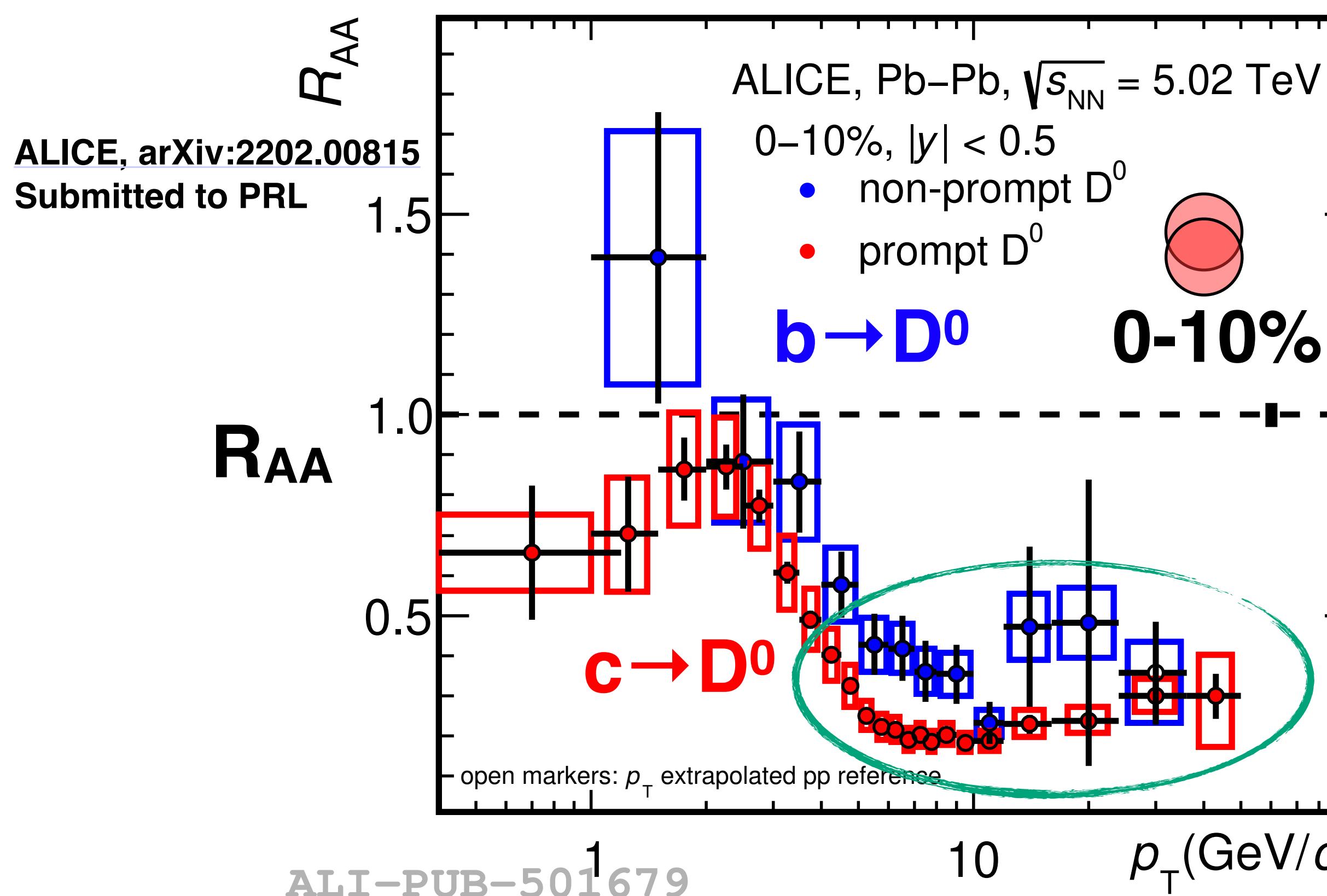
c-hadron production in PbPb



- LIDO: Boltzmann transport + energy loss
- LGR: Langevin transport + gluon radiation
- Model results include nPDF + recombination

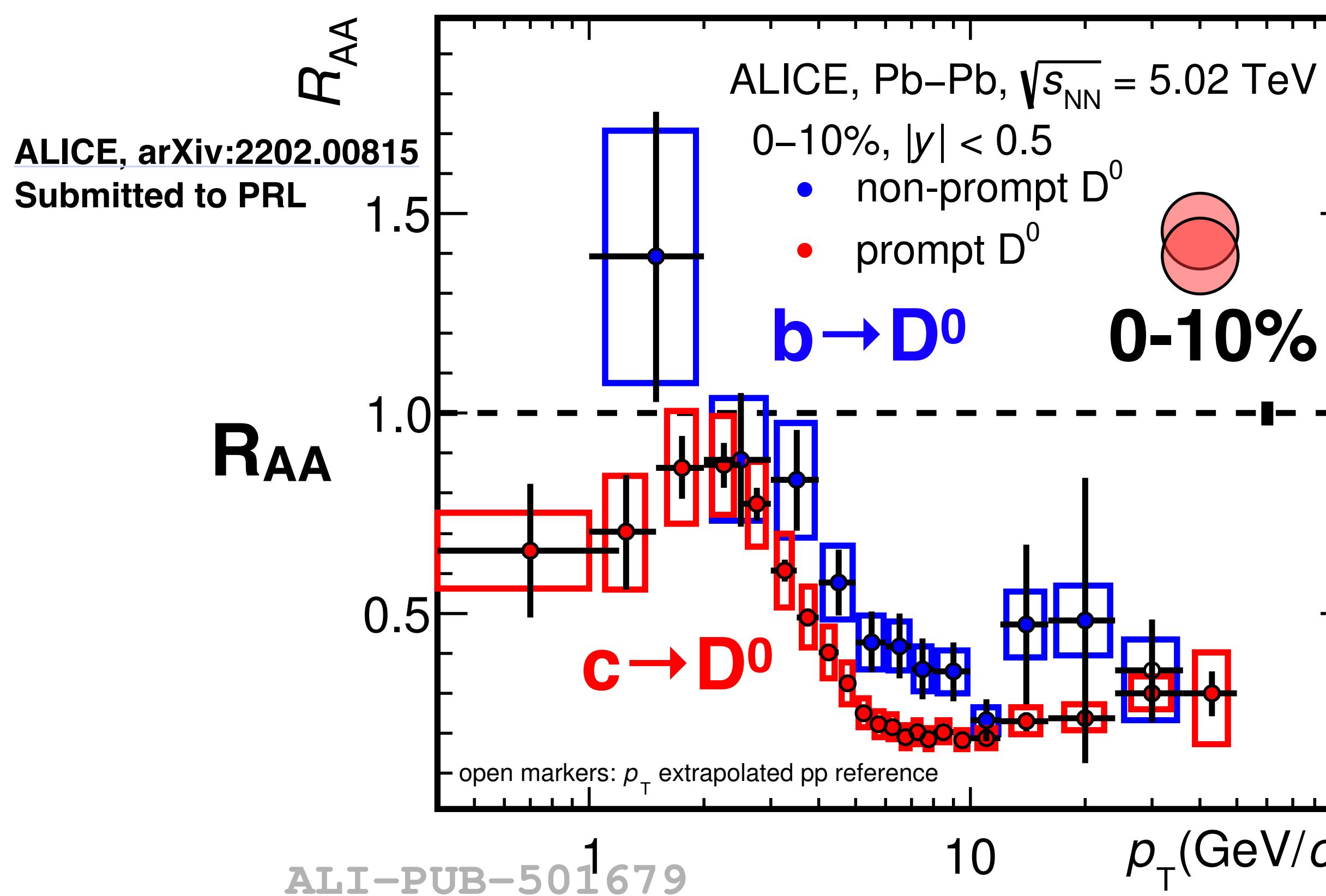
- Models including charm recombination and energy loss describe well D-meson R_{AA} .
- Radiative energy loss crucial to describe c-quark modification and flow at high p_T .

HF production in PbPb

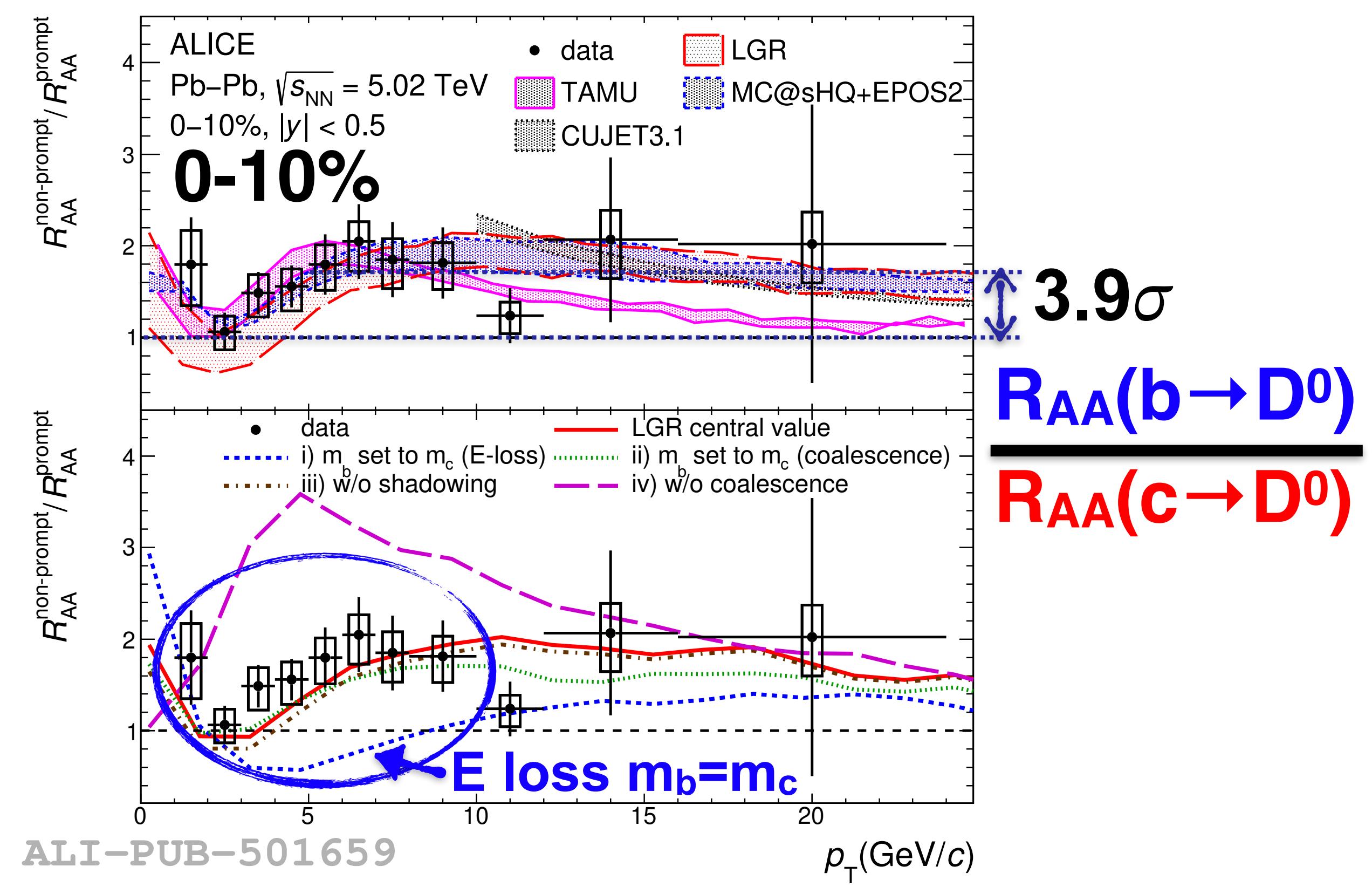


- $R_{AA}(b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$ at intermediate to high p_T → **b quarks** less suppressed than **c quarks**.

HF production in PbPb



- **TAMU**: Transport + recom. + elastic collisions only
- **LGR**: Transport + recom. + (coll+rad) energy loss



- **CUJET3.1**: pQCD + Hydro + (coll+rad) energy loss
- **MC@HQ+EPOS2**: EPOS + (coll+rad) energy loss

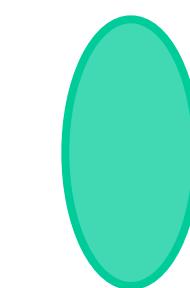
- $R_{AA}(b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$ at intermediate to high p_T → **b quarks** less suppressed than **c quarks**.
- Theory calculations including collisional and radiative energy loss describe data.
- $R_{AA}(b \rightarrow D^0) / R_{AA}(c \rightarrow D^0) > 1$ at p_T 3-10 GeV related to mass dependent medium energy loss.

HF flow in PbPb

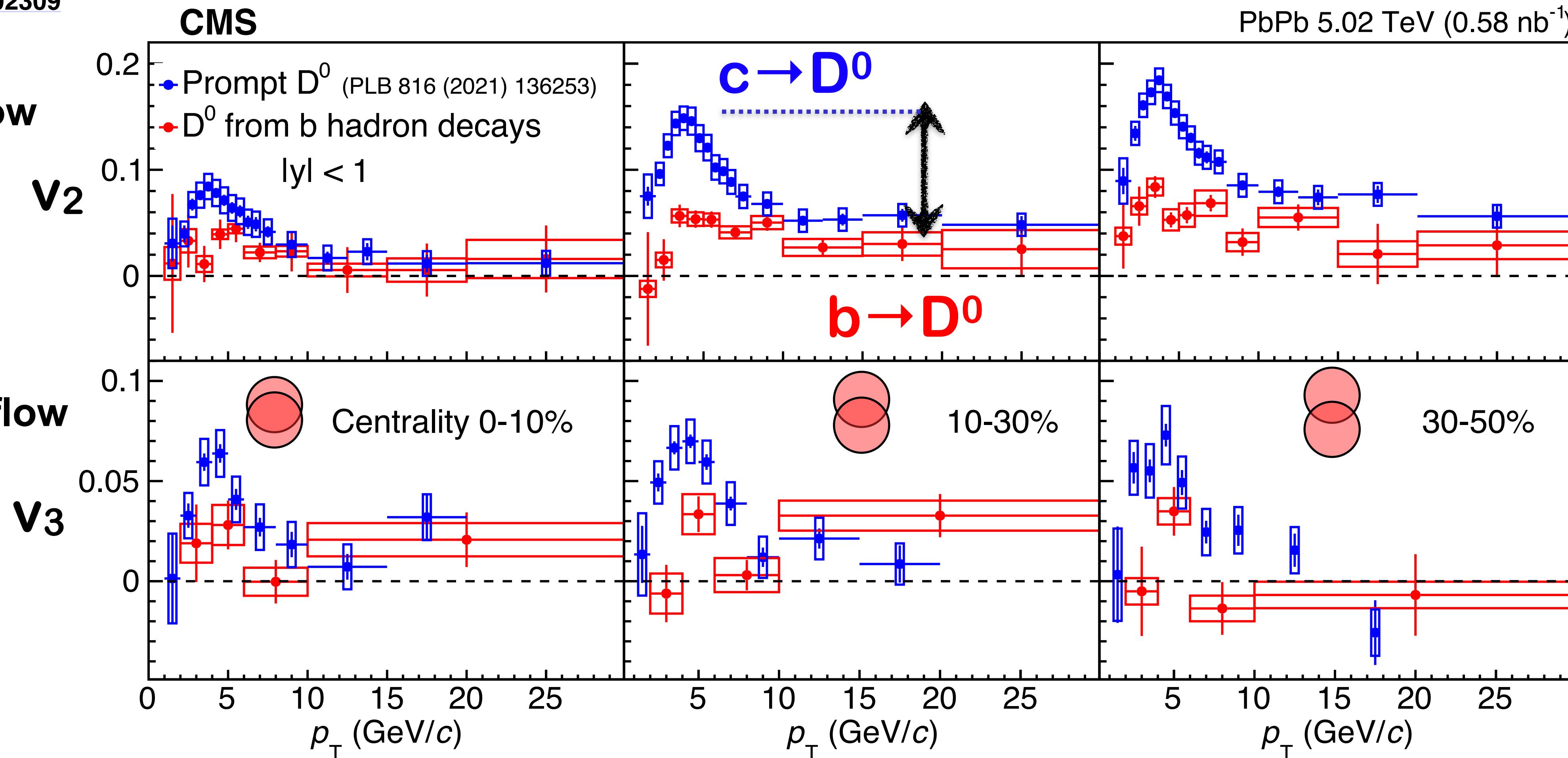
CMS, arXiv:2212.02309

Submitted to PRL

Elliptic flow



Triangular flow



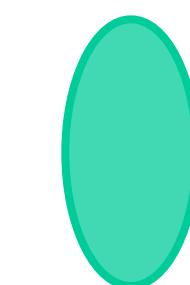
- $D^0 v_2 > b \rightarrow D^0 v_2 > 0 \rightarrow$ mass ordering of heavy flavour elliptic flow.
- $D^0 v_3 > 0 \rightarrow$ initial geometry fluctuations probed by charm quarks.

HF flow in PbPb

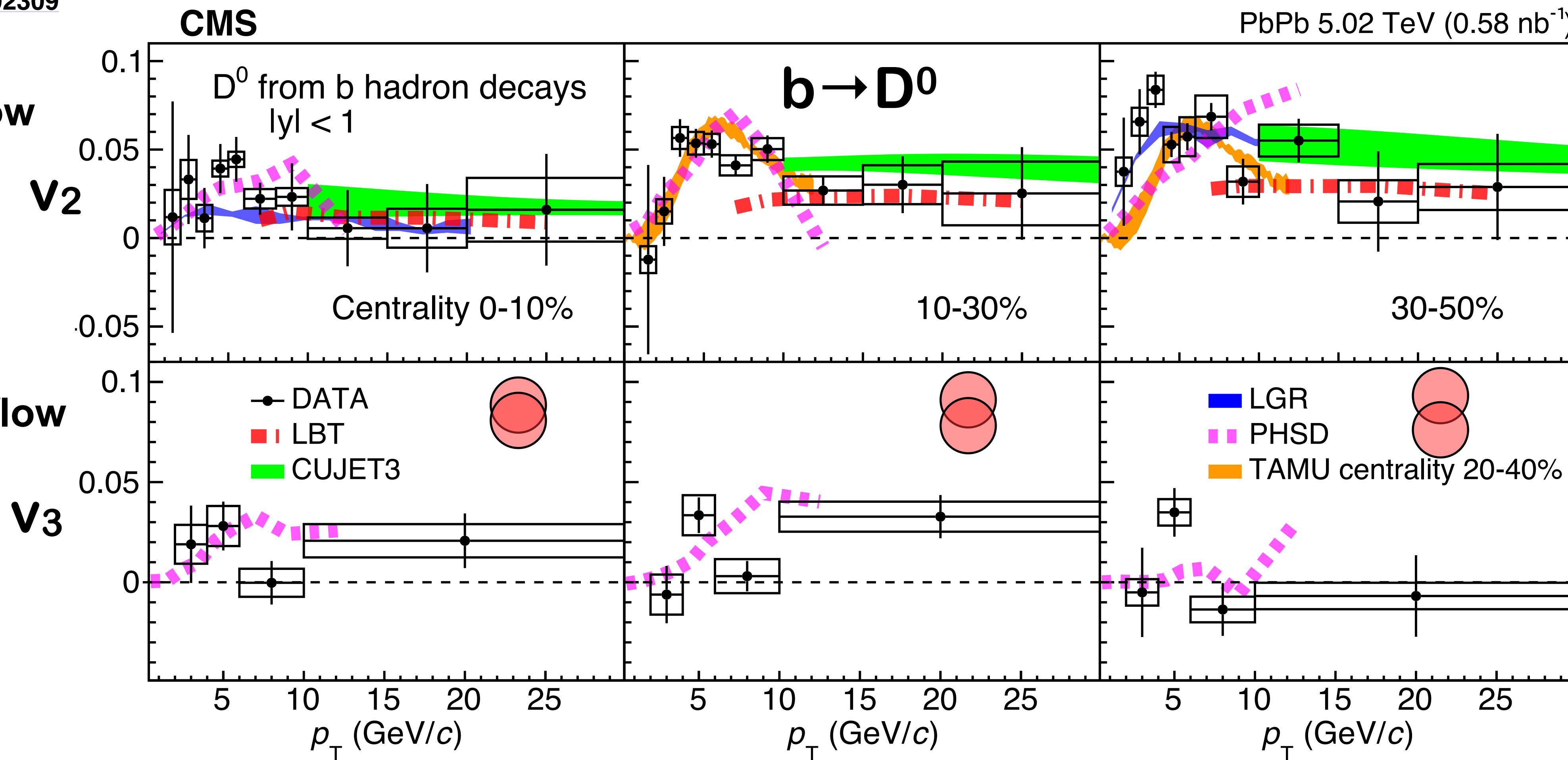
CMS, arXiv:2212.02309

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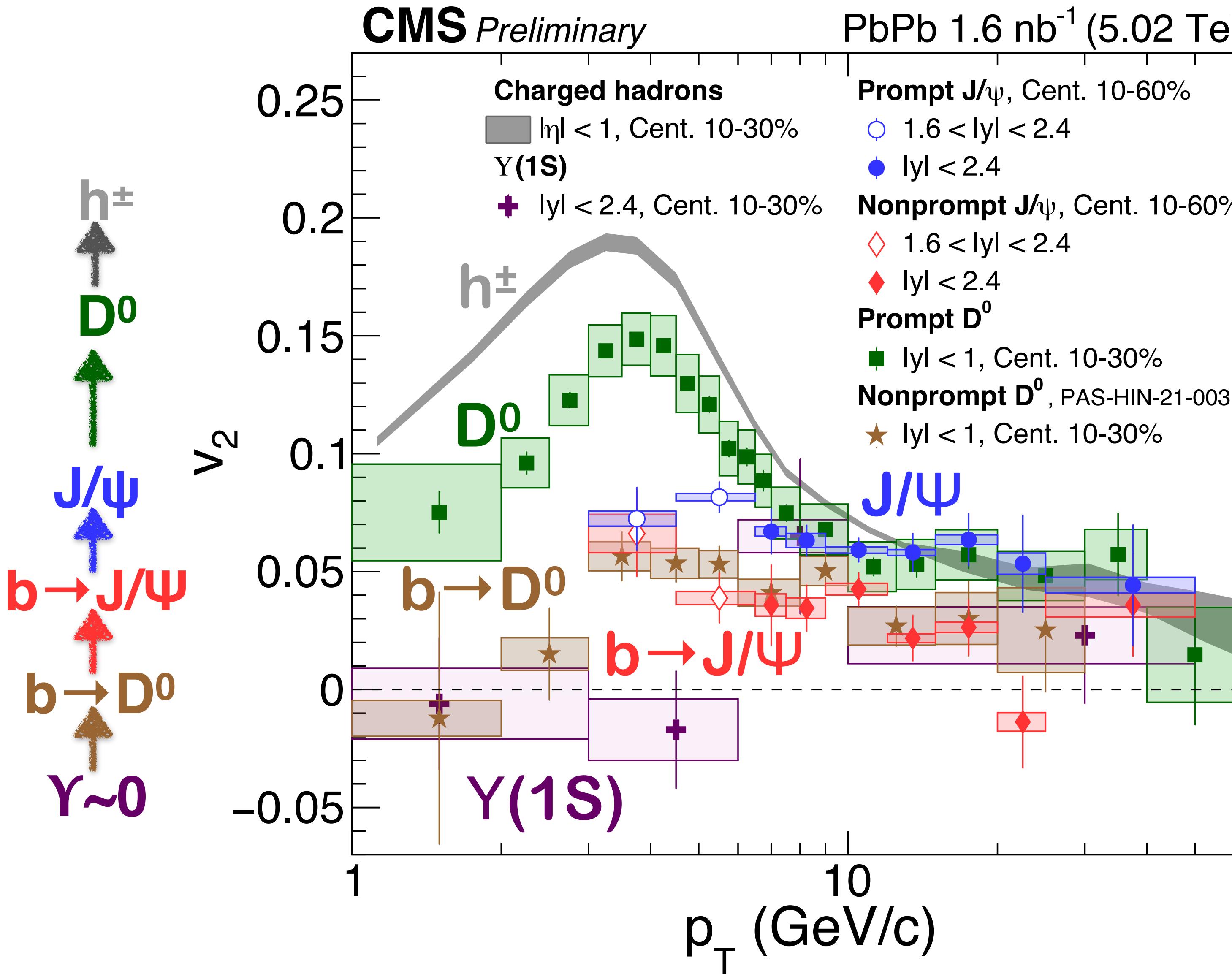
Triangular flow



- $D^0 v_2 > b \rightarrow D^0 v_2 > 0 \rightarrow$ mass ordering of heavy flavour elliptic flow.
- $D^0 v_3 > 0 \rightarrow$ initial geometry fluctuations probed by charm quarks.
- Weak centrality dependence of $b \rightarrow D^0$ flow \rightarrow qualitatively described by models.

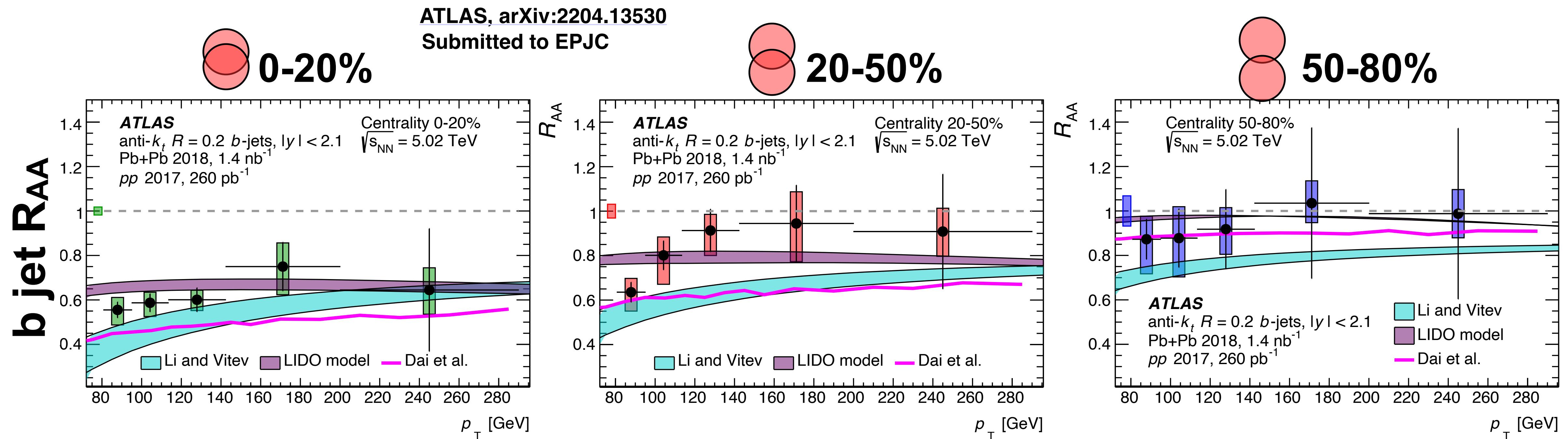
Summary of HF v_2 in PbPb

CMS, PAS-HIN-21-008



- **Low p_T :**
 - $v_2(h) > v_2(D) > v_2(J/\psi) > v_2(b) > v_2(\Upsilon) \sim 0$
 - Thermalization → mass ordering
- **High p_T :**
 - $v_2(h) \sim v_2(D) \sim v_2(J/\psi) \sim v_2(b)$
 - Energy loss

b-jet production in PbPb

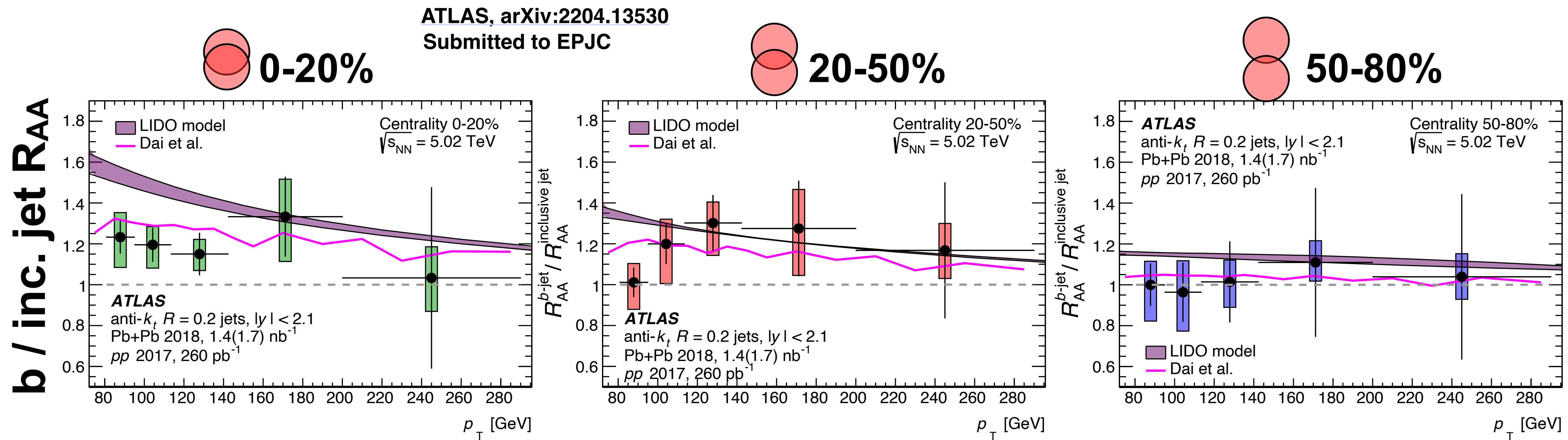


- $R_{\text{AA}}(\text{b jet}) < 1$ towards central PbPb collisions.

- **LIDO** model describe well b-jet R_{AA} , while **Li&Vitev** and **Dai** underpredict the data.

- **LIDO**: FONLL + HF diffusion+energy loss
- **Dai et al.**: Sherpa + Langevin transport+radiation
- **Li&Vitev**: (SCET) EFTs + medium modified splitting

b-jet production in PbPb



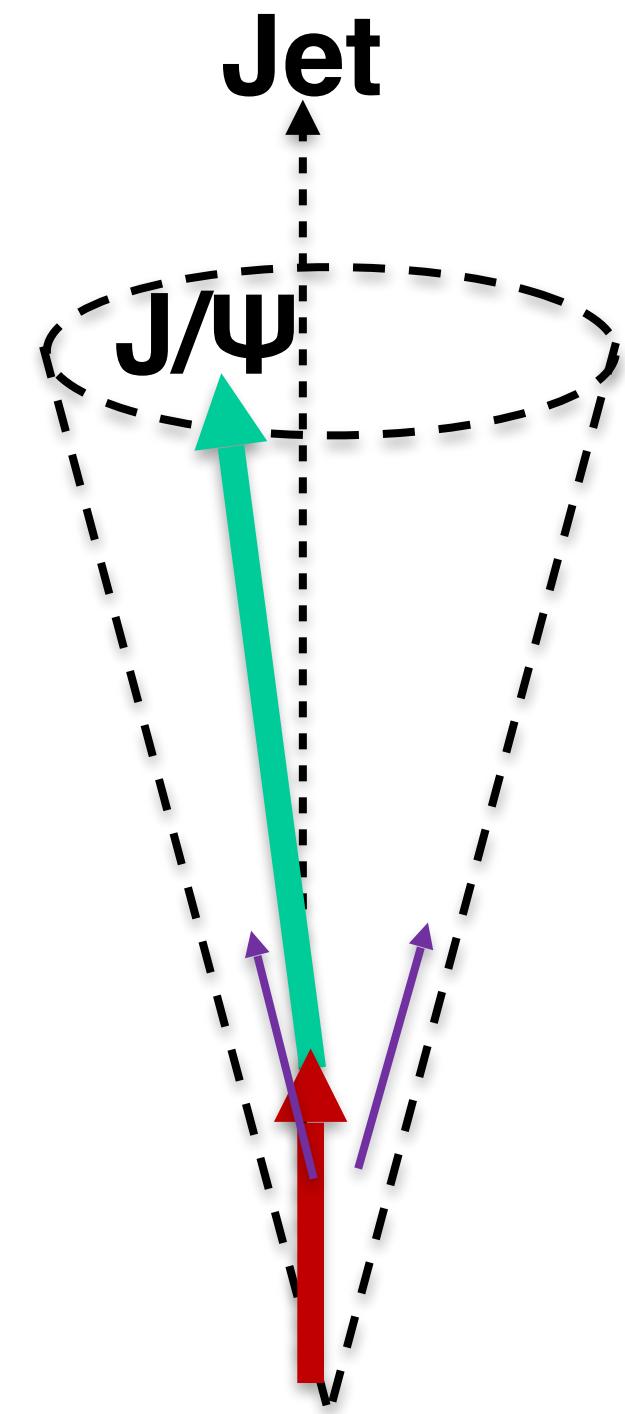
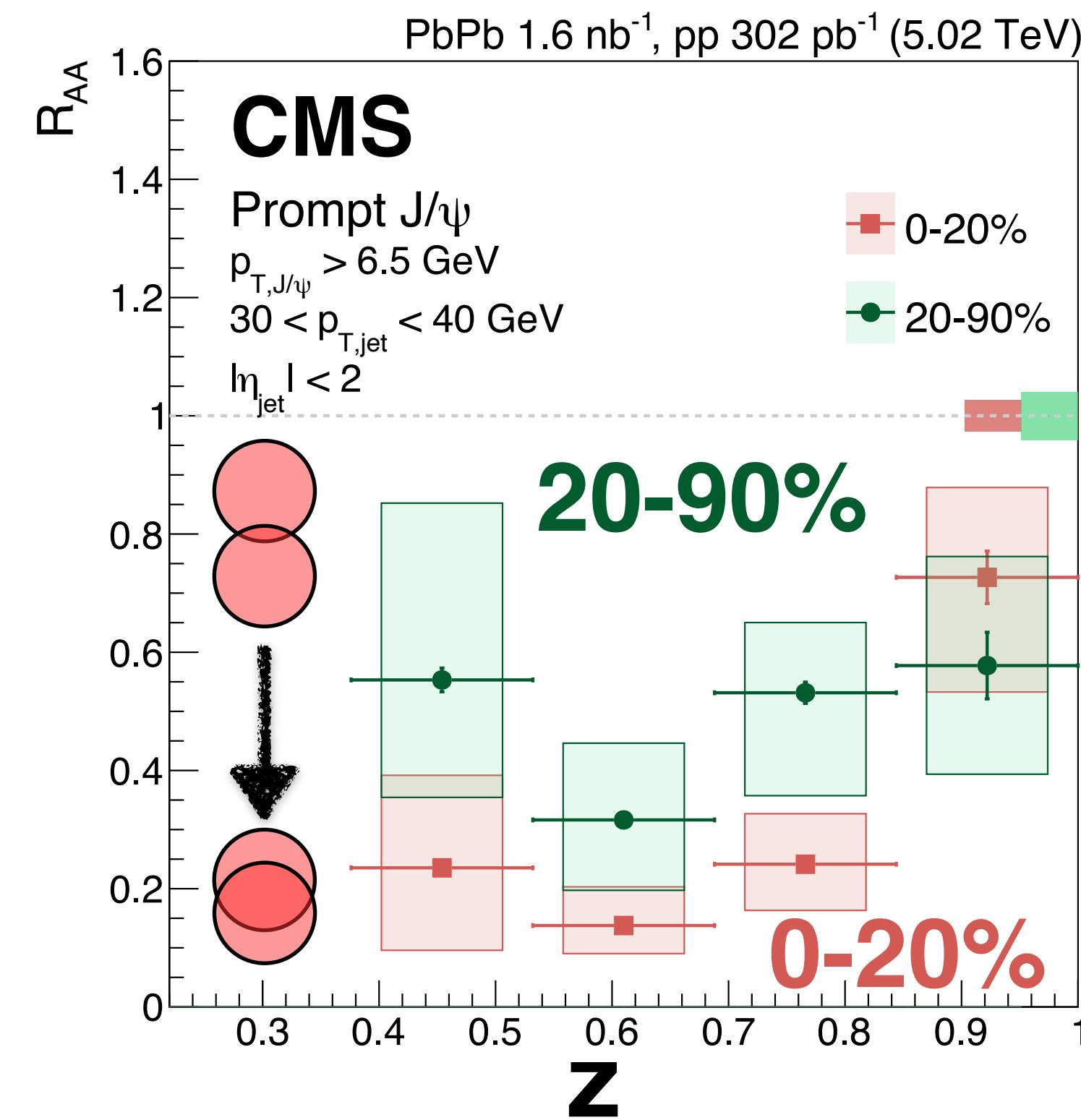
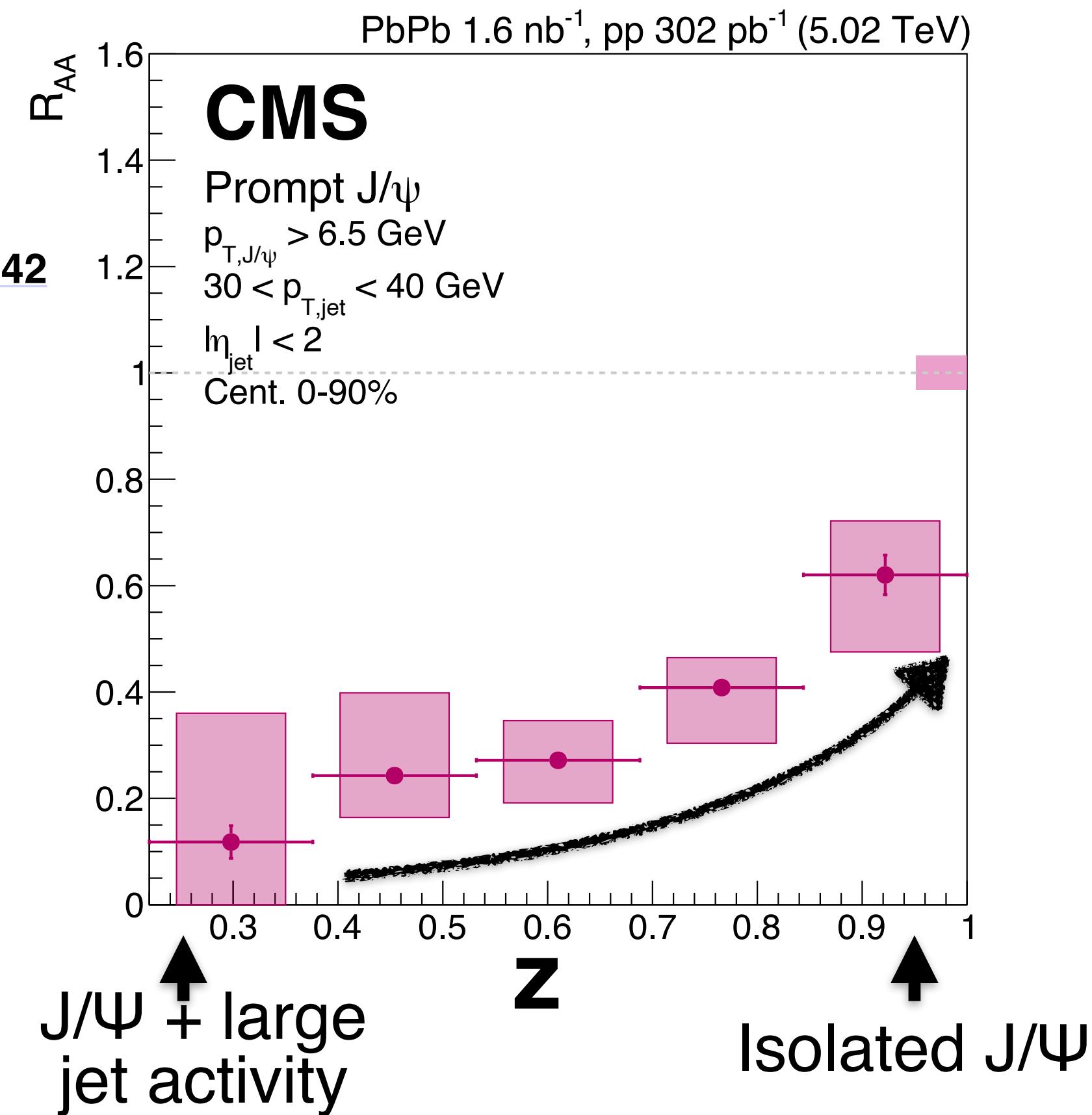
- **LIDO:** FONLL + HF diffusion+energy loss
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- $R_{AA}(\text{b jet}) < 1$ towards central PbPb collisions.
- **LIDO** model describe well b-jet R_{AA} , while **Li&Vitev** and **Dai** underpredict the data.
- $R_{AA}(\text{b jet}) \sim R_{AA}(\text{inc. jet})$ in peripheral while $R_{AA}(\text{b jet}) > R_{AA}(\text{inc. jet})$ in central collisions.
- **Dai** calculations describe better the b / inclusive jet R_{AA} ratio.
- Differences between b and inclusive jets dominated by **quark vs gluon** energy loss effects.

J/ Ψ in jets in PbPb

CMS, PLB 825 (2022) 136842

$$z = \frac{p_T^{J/\psi}}{p_T^{\text{jet}}}$$

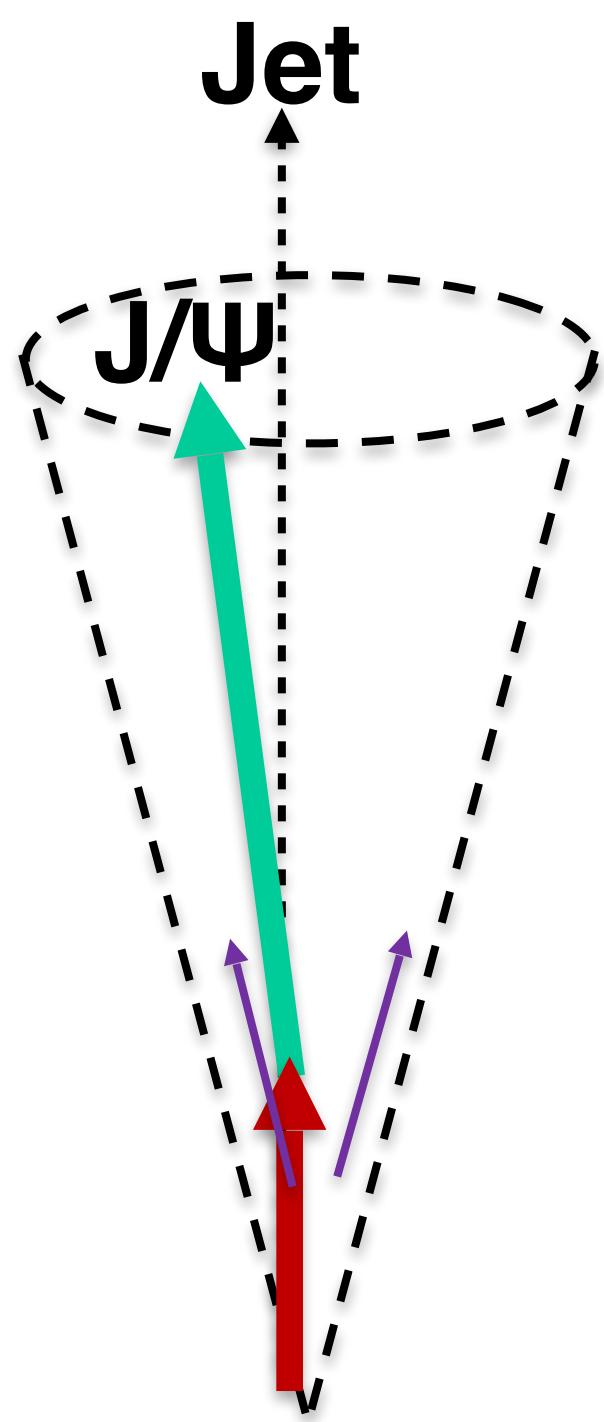
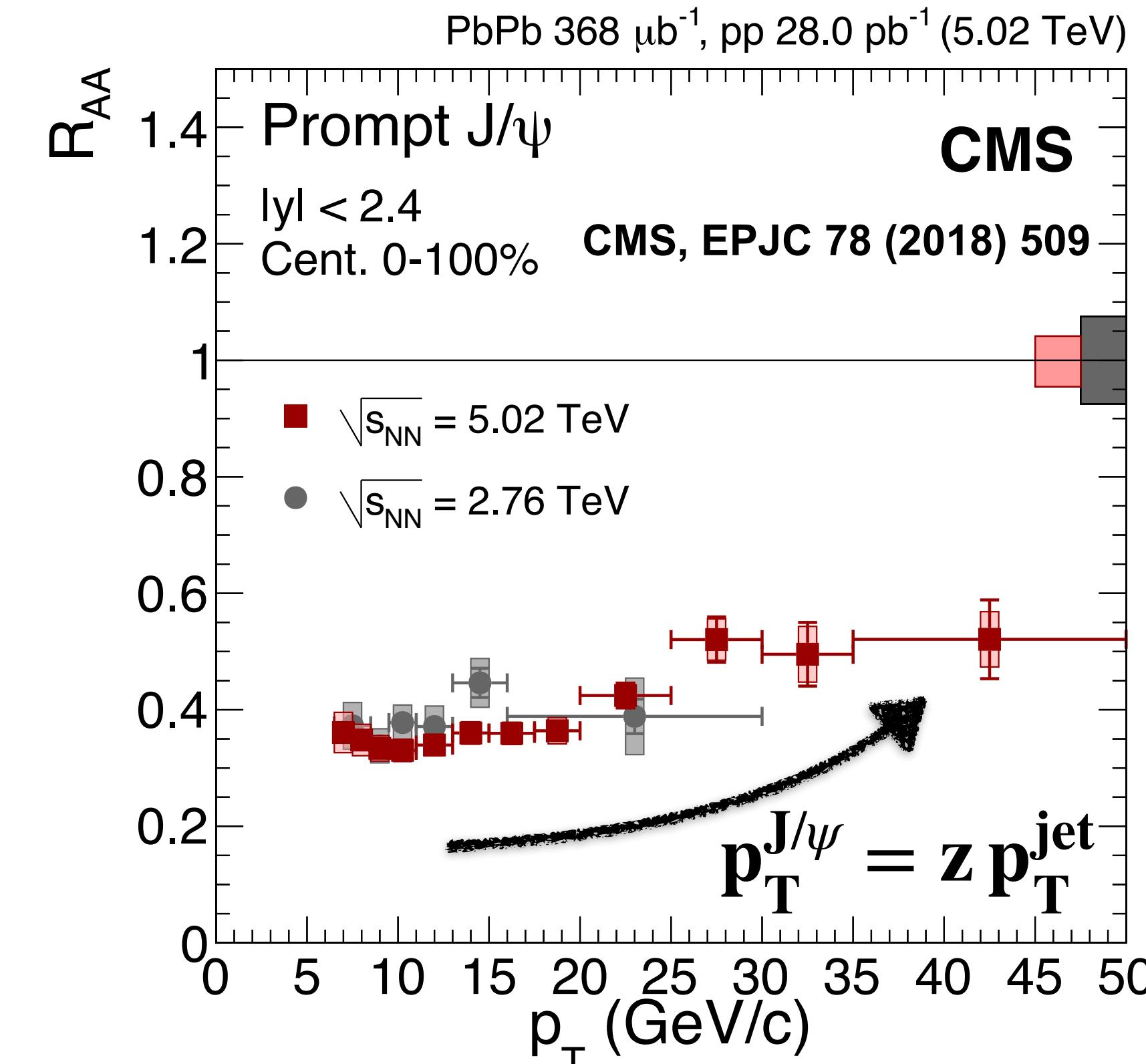
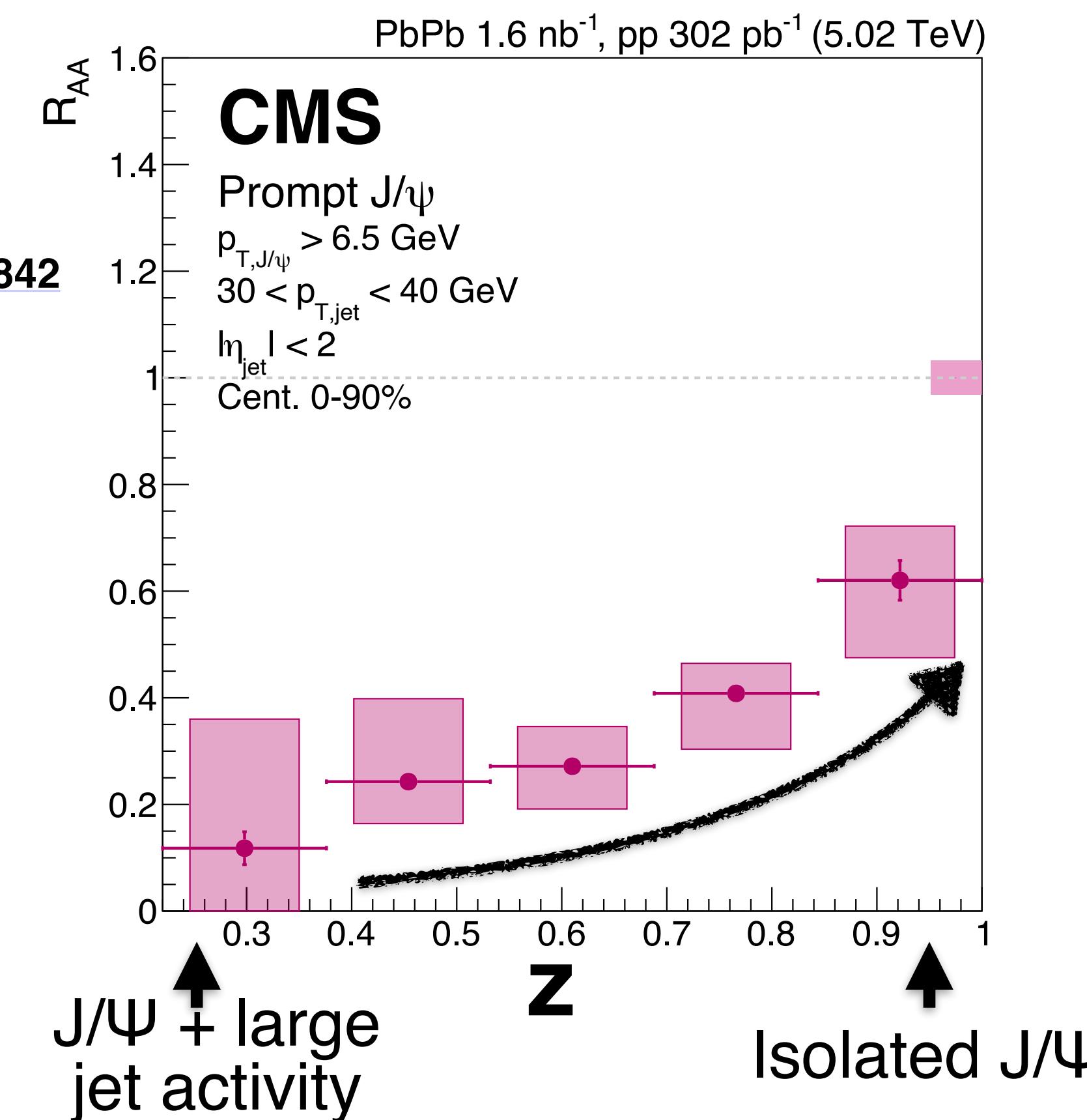


- CMS results show that isolated J/ Ψ less suppressed than J/ Ψ with larger jet activity in PbPb.
 - J/ Ψ with lower z are produced later in the parton shower → interacts more with QGP

J/ ψ in jets in PbPb

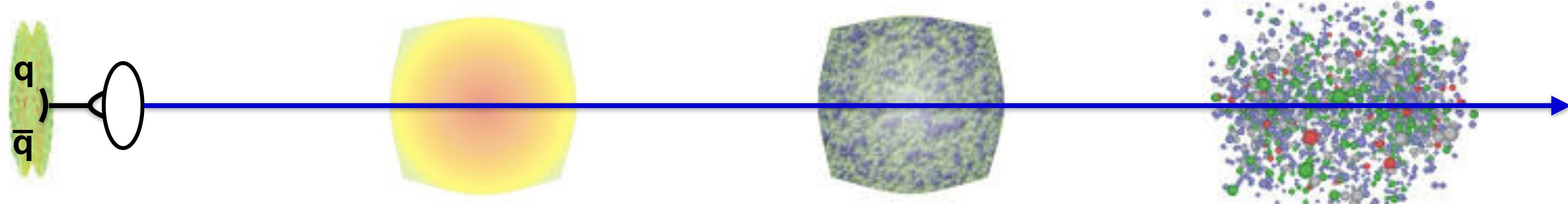
CMS, PLB 825 (2022) 136842

$$z = \frac{p_T^{J/\psi}}{p_T^{\text{jet}}}$$

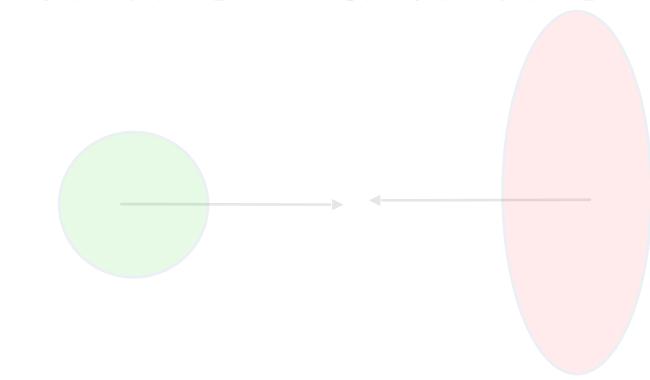


- CMS results show that isolated J/ ψ less suppressed than J/ ψ with larger jet activity in PbPb.
 - J/ ψ with lower z are produced later in the parton shower → interacts more with QGP
- Parton energy loss in QGP could explain rising trend of inclusive prompt J/ ψ R_{AA} at high p_T .

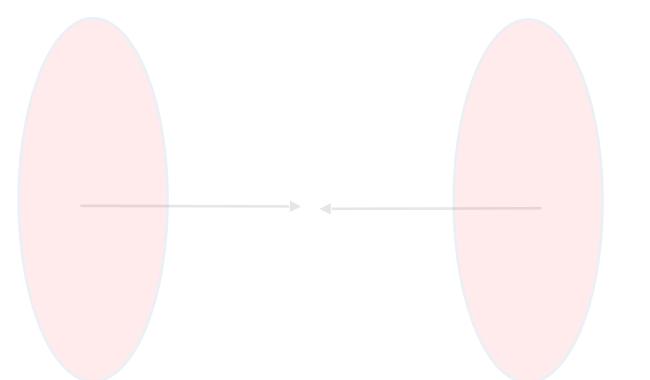
OUTLINE



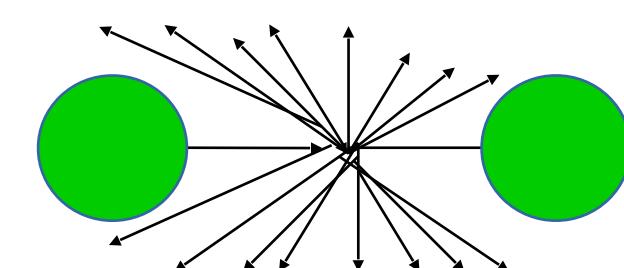
HF production in pp



Probing cold nuclear effects



Probing QGP effects

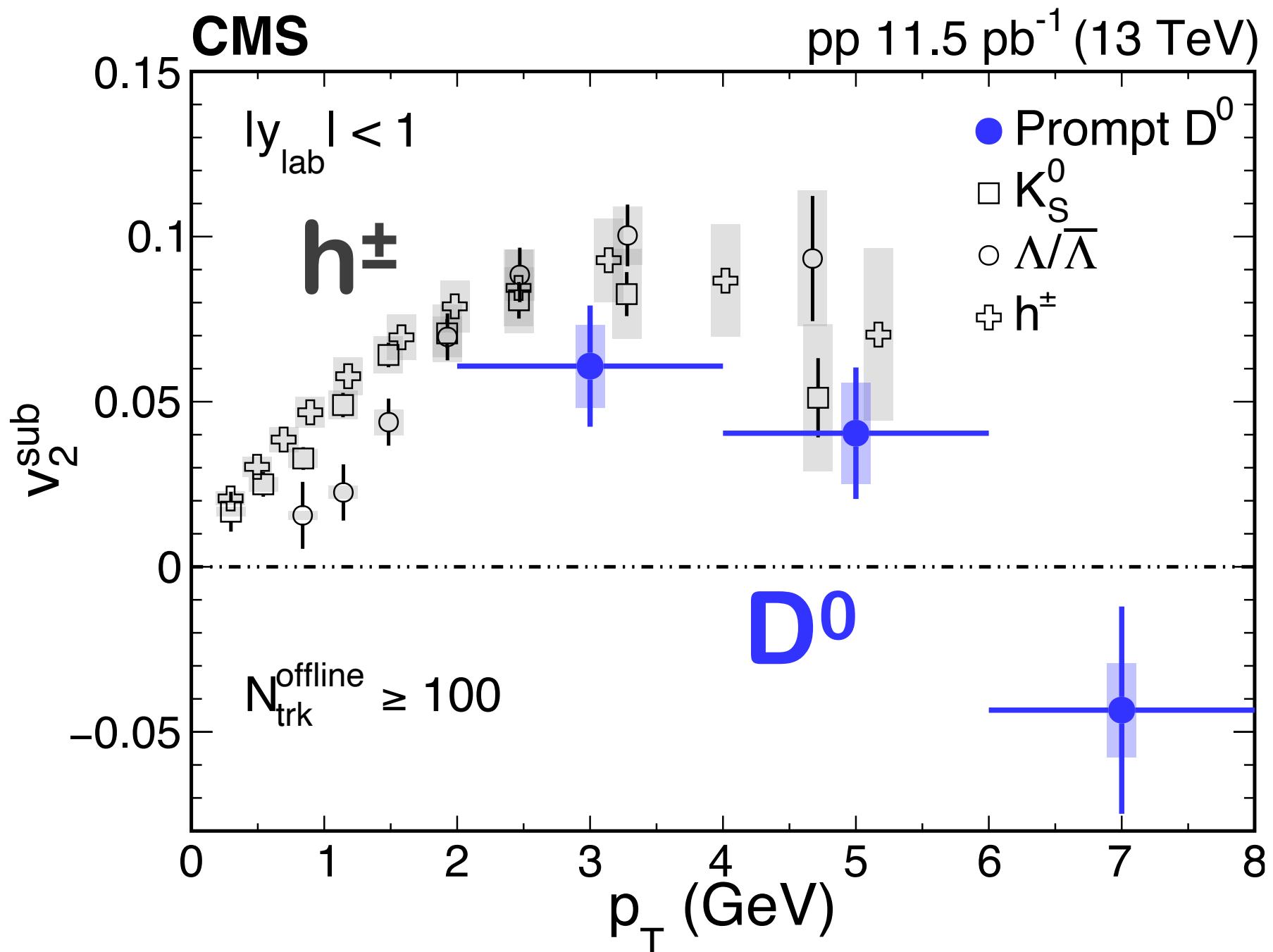


High multiplicity small systems

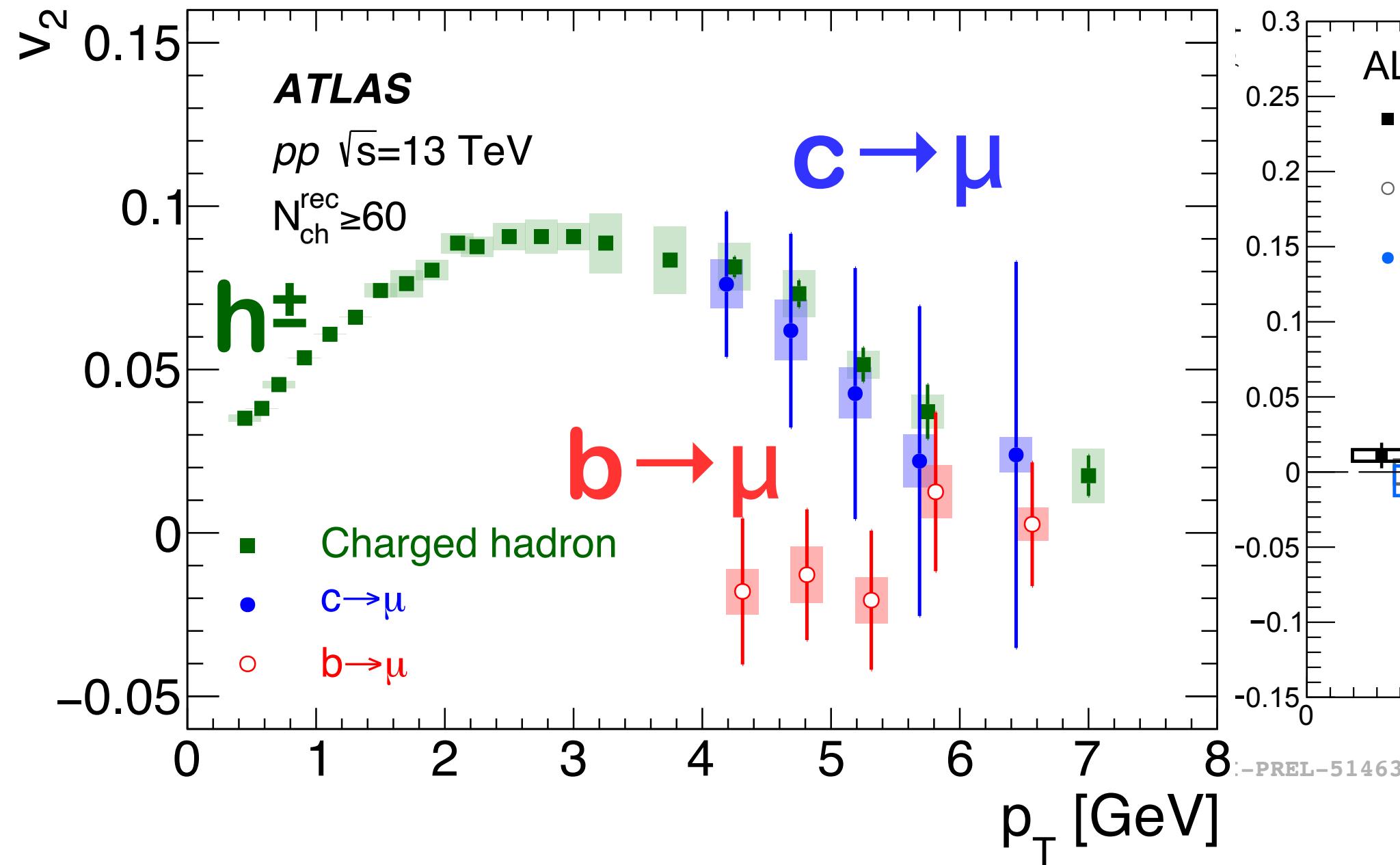
HF flow in high multiplicity pp

Jiayin Sun,
Feb 15, 09:00

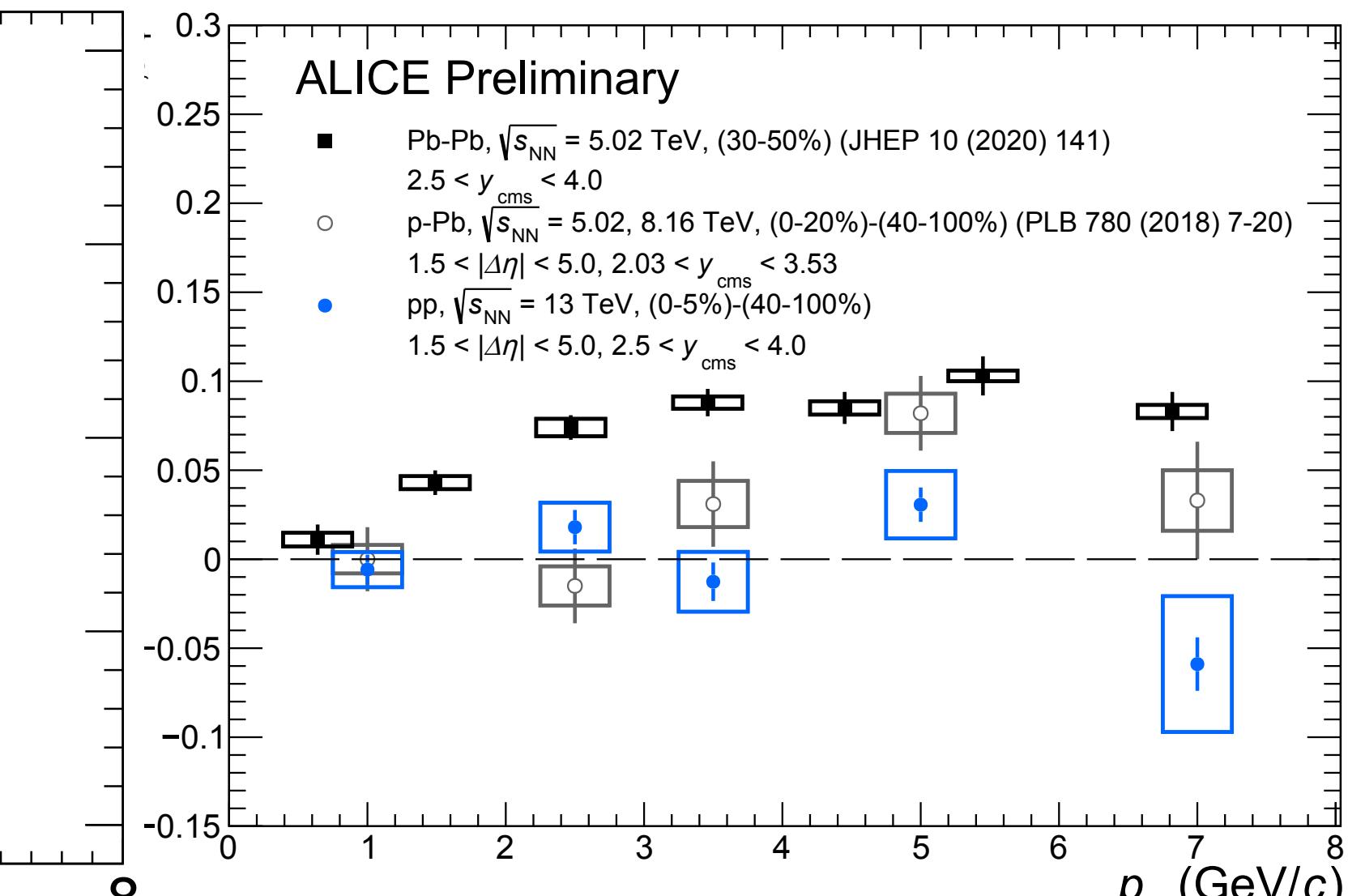
CMS, PLB 813 (2021) 136036



ATLAS, PRL 124 (2020) 082301

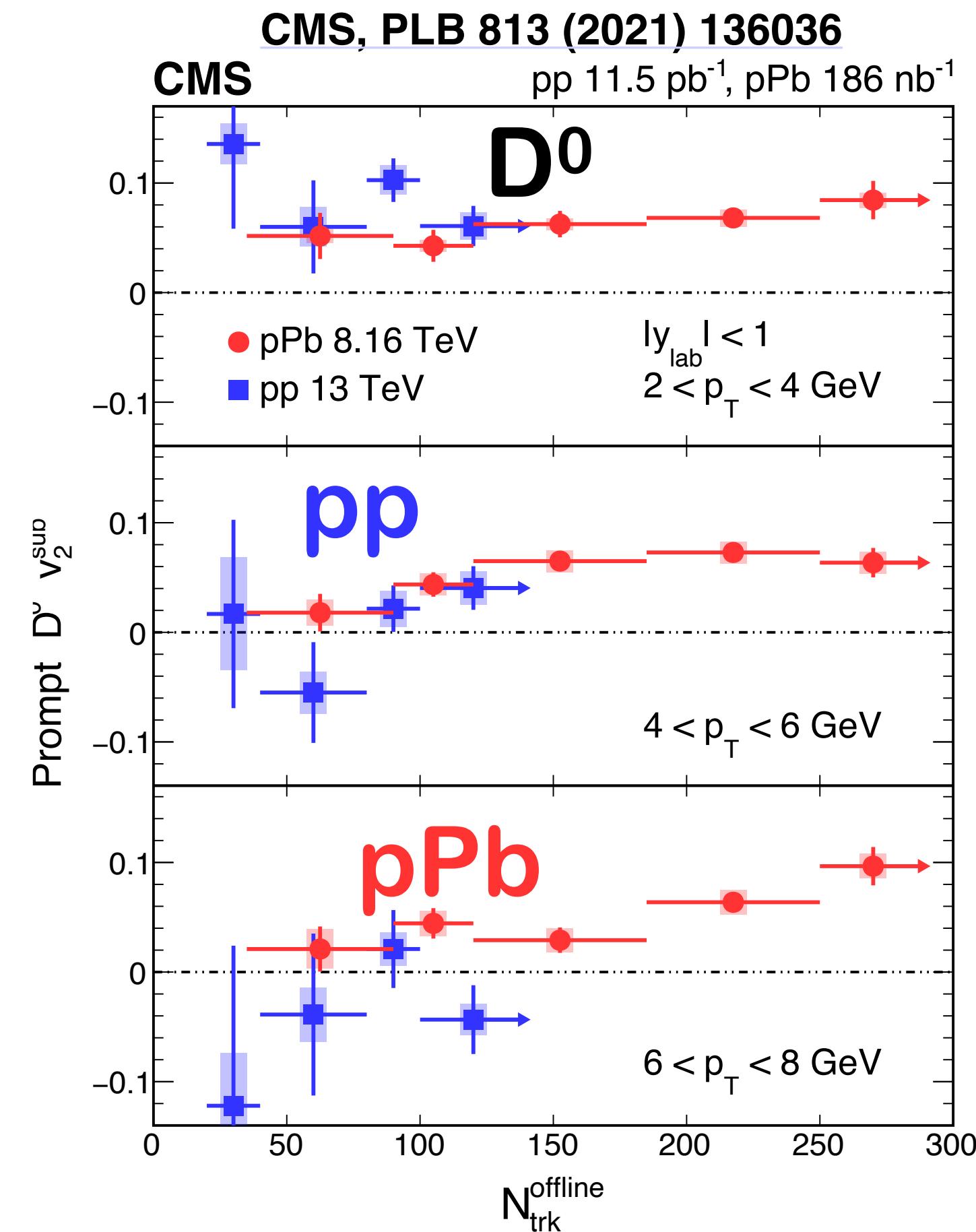
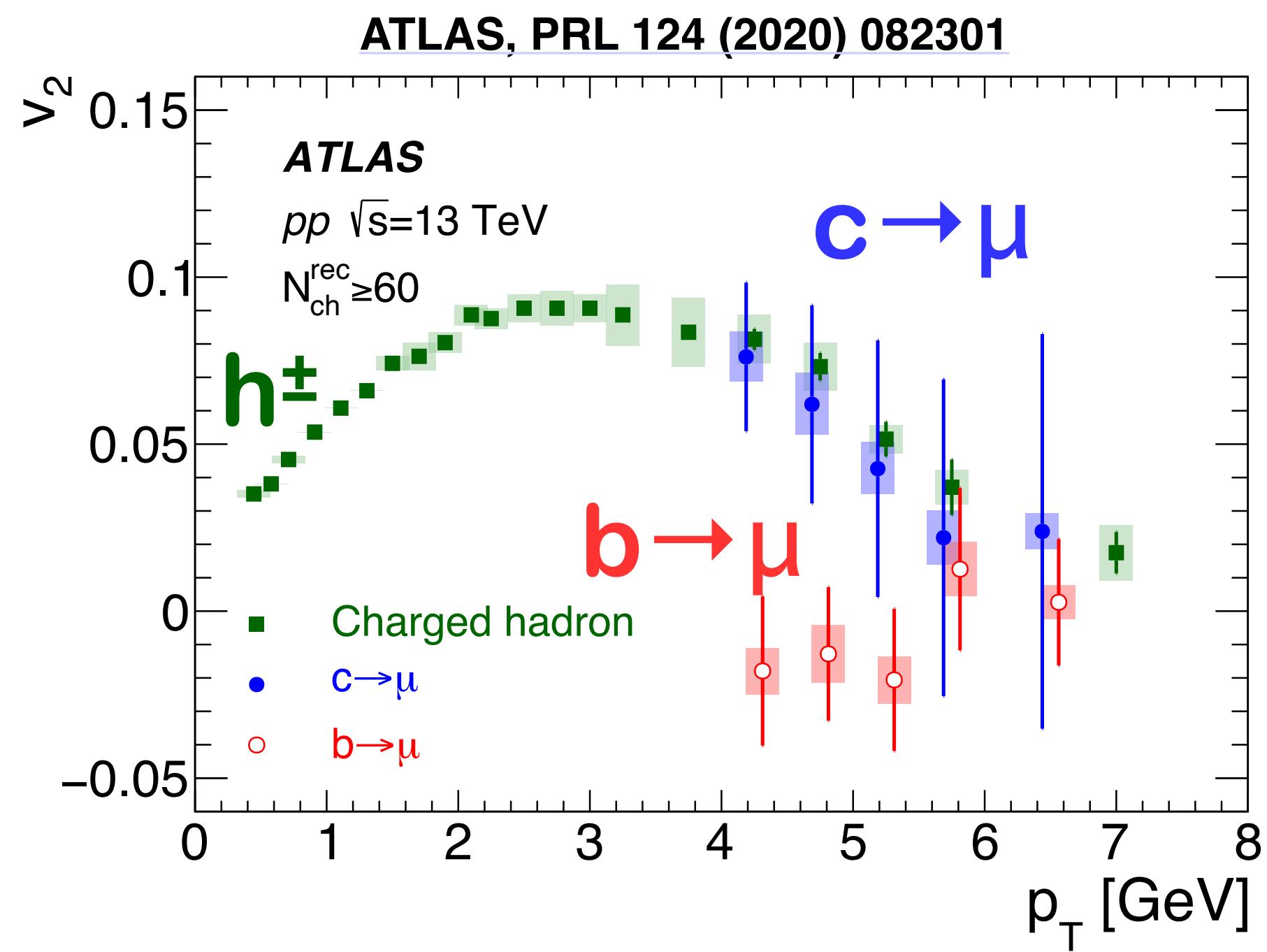
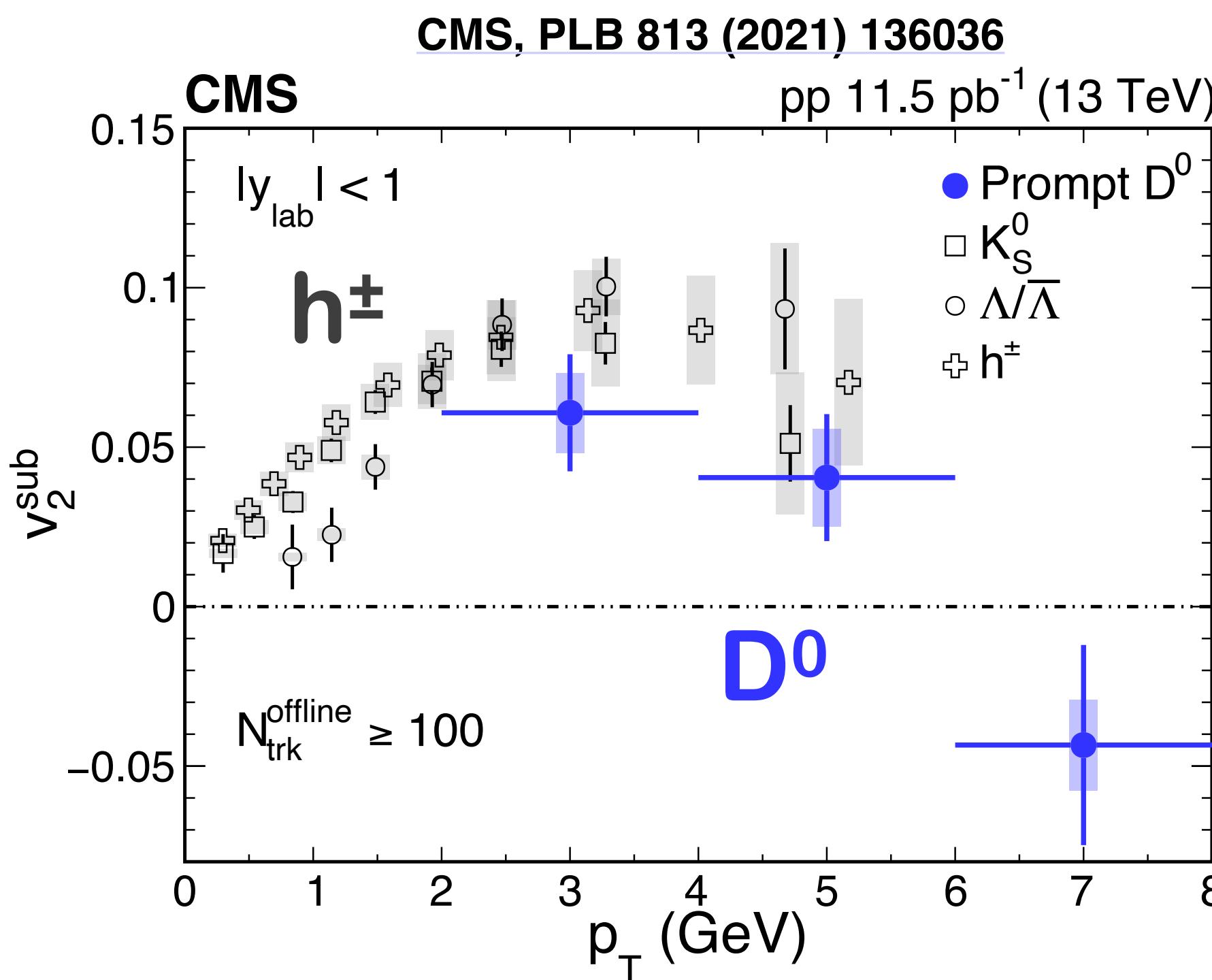


ALICE, Preliminary



- Indication of nonzero **charm** flow \rightarrow comparable with light hadrons.
- b** \rightarrow **μ** flow compatible with zero.

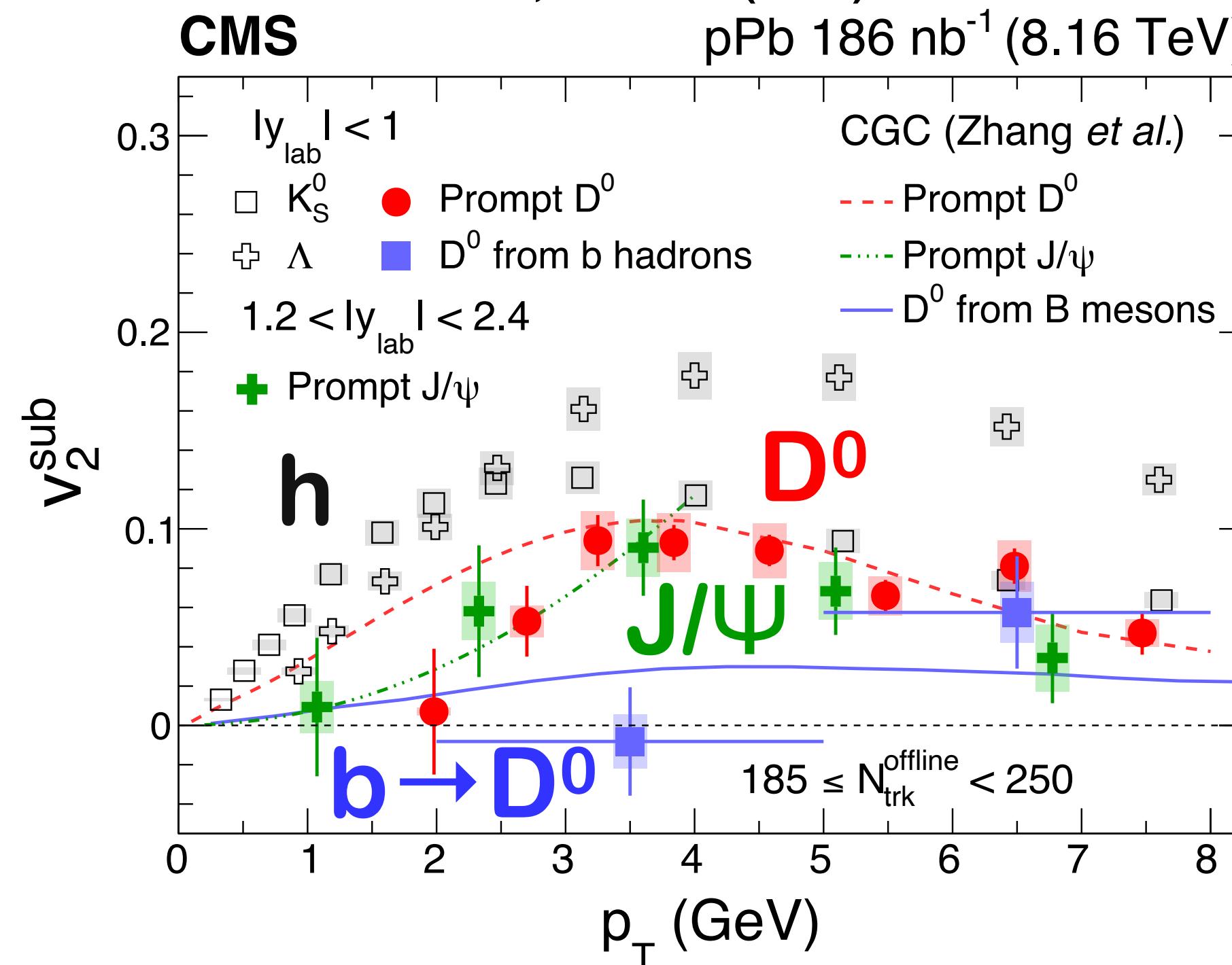
HF flow in high multiplicity pp



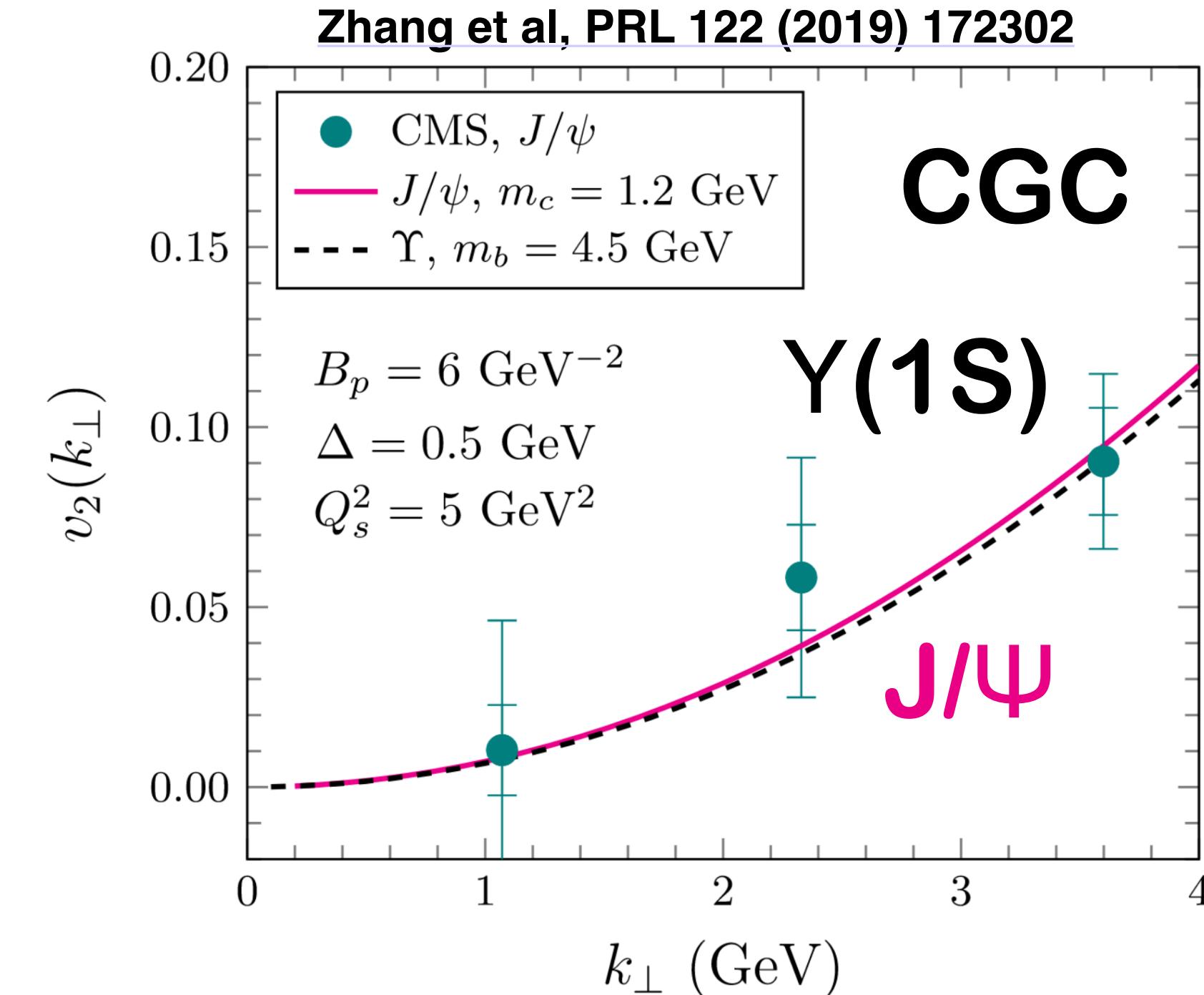
- Indication of nonzero **charm** flow → comparable with light hadrons.
- b** → **μ** flow compatible with zero.
- Positive **charm** v_2 of observed at high multiplicities → diminish towards lower multiplicities.

HF flow in high multiplicity pPb

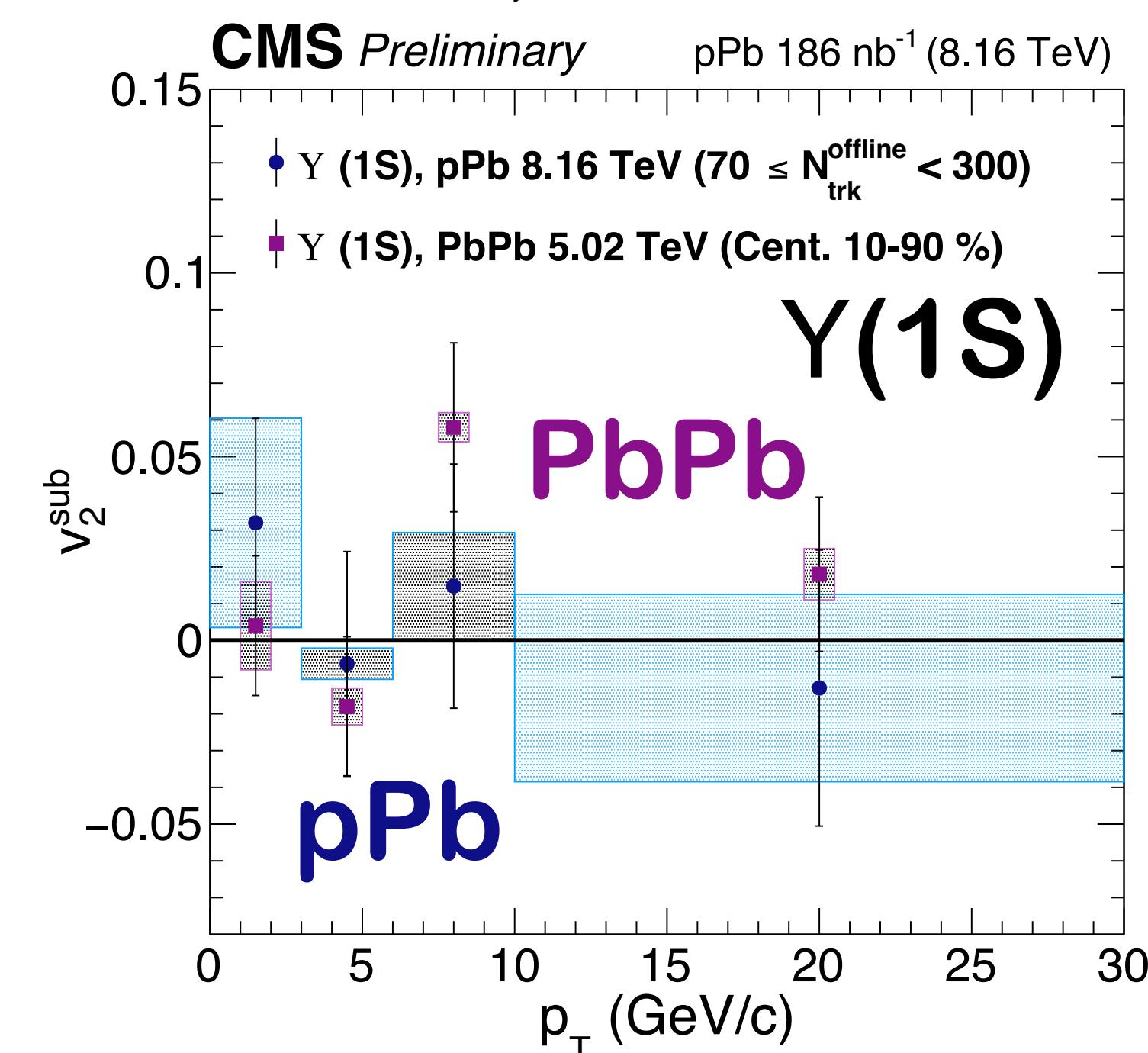
CMS, PLB 813 (2021) 136036



Zhang et al, PRL 122 (2019) 172302



CMS, PAS-HIN-21-001



- $v_2(D) \sim v_2(J/\psi) > 0$ also in high multiplicity pPb → What is the source of the charm flow?
- Charm flow described by CGC in pPb → could it be from initial state effect?
- But CGC expects $v_2(\Upsilon(1S)) \sim v_2(J/\psi) > 0$ while data shows $v_2(\Upsilon(1S)) \sim 0$.
- HF flow in small systems still a puzzle.

SUMMARY

Several exciting HF results published since last QCD workshop.

- Heavy Flavor hadrons:

- Final state effects needed to describe quarkonium production in pPb.
- Radiative energy loss crucial to describe HF production at high p_T .
- $R_{AA}(b \rightarrow D^0) > R_{AA}(c \rightarrow D^0) \rightarrow$ mass dependent medium energy loss.
- HF flow in high multiplicity small systems a puzzle.

- Heavy Flavor Jets:

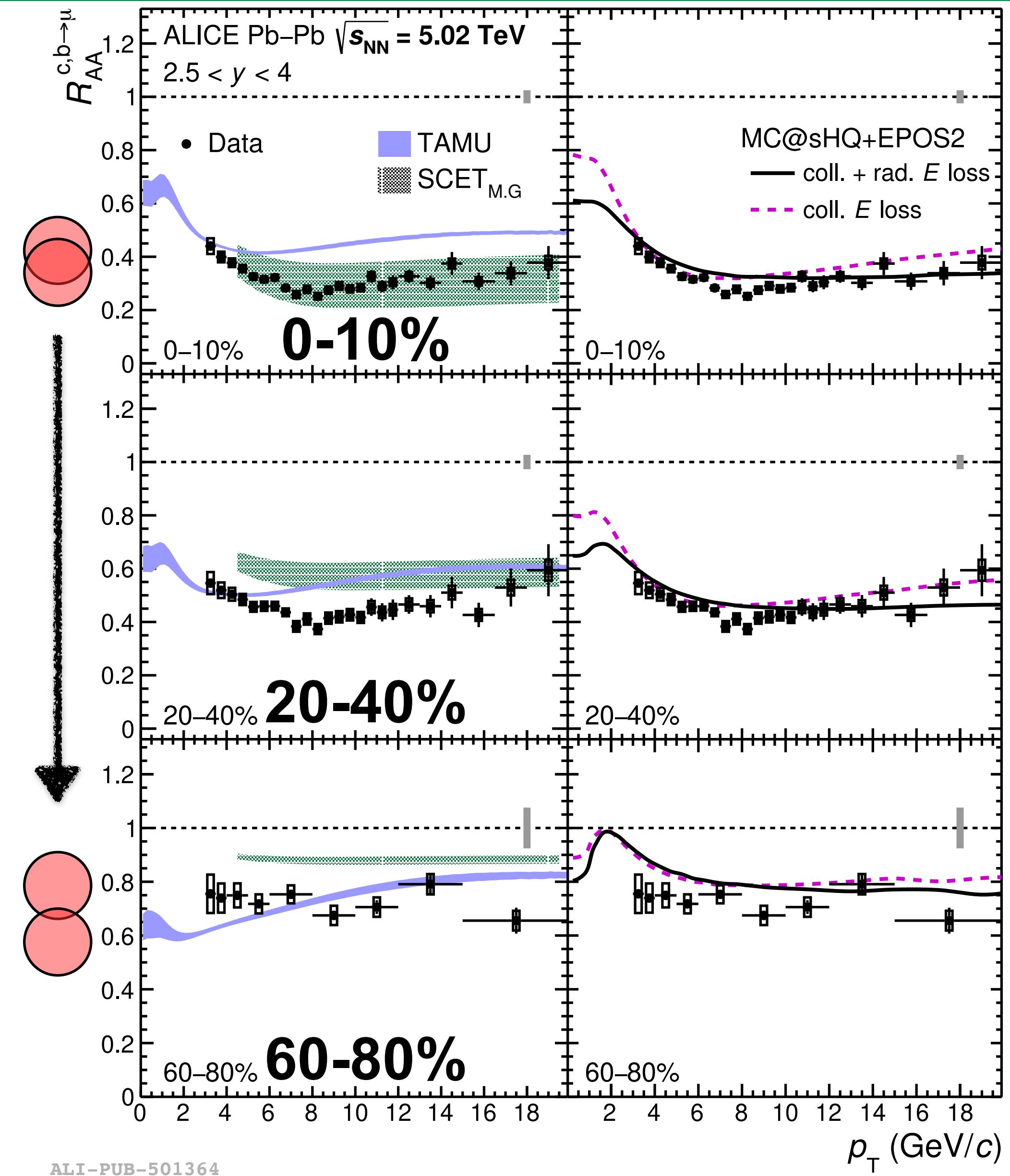
- Observation of dead cone effect in pp.
- No significant b-jet modifications in pPb collisions.
- b vs inc. jet PbPb modification dominated by color-dep. energy loss.
- J/ ψ in jets provides insights into production at high p_T .

Thank you for your attention!

BACKUP

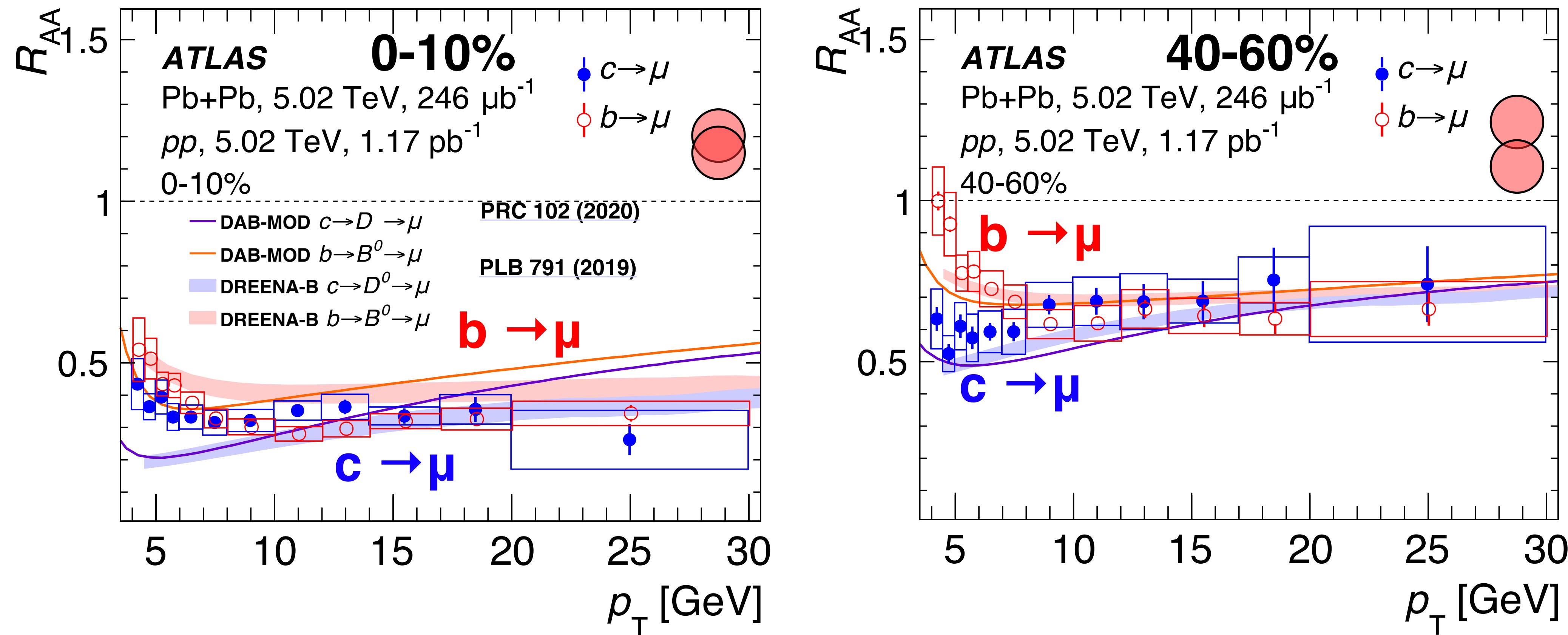
HF muons in PbPb

- HF muons more suppressed towards central PbPb.
Suppression largest at intermediate p_T .
- Results described by model with gluon radiation
(SCET) in central collisions.
- MC@sHQ calculations with collisional and/or
radiative energy loss reproduce high- p_T
measurements.
- Suppression pattern is compatible with a large
heavy-quark in-medium energy loss.



HF muons in PbPb

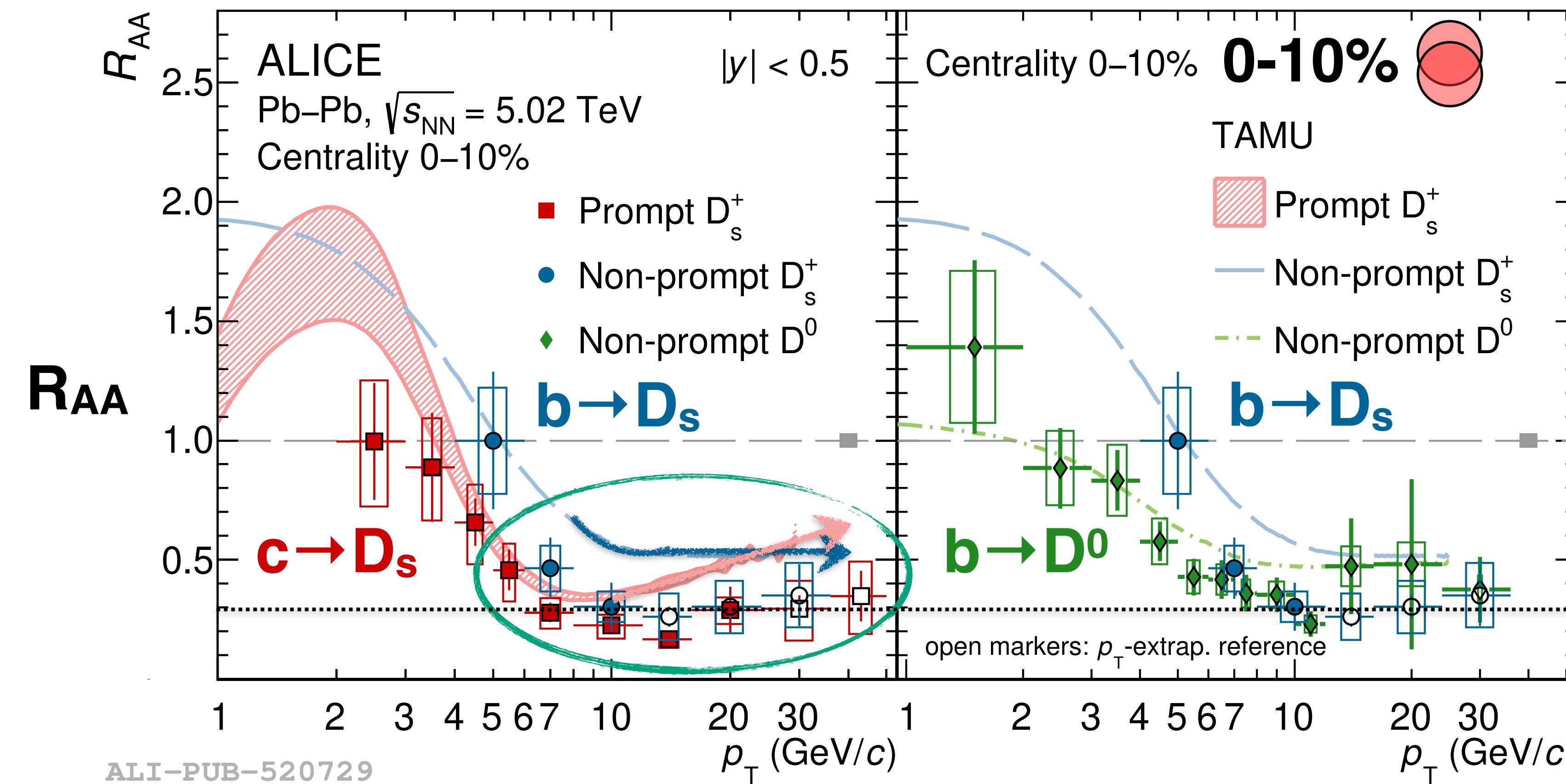
ATLAS, PLB 829 (2022) 137077



- Strong centrality dependence of $c \rightarrow \mu$ and $b \rightarrow \mu$ suppression in PbPb collisions.
- $R_{AA}(c \rightarrow \mu) < R_{AA}(b \rightarrow \mu)$ at $p_T < 8 \text{ GeV}$: $c \rightarrow \mu$ more suppressed than $b \rightarrow \mu$.
- Models including energy loss and heavy-quark diffusion in QGP fairly describe data.

b-hadron production in PbPb

arXiv:2204.10386
Submitted to PLB

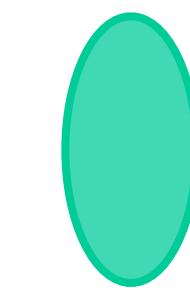


- $R_{AA}(c \rightarrow D_s) \sim R_{AA}(b \rightarrow D_s) \sim R_{AA}(b \rightarrow D^0) \sim 0.3$ at $p_T > 6$ GeV in central PbPb collisions.
- TAMU (Langevin+recombination) model describes well the $R_{AA}(b \rightarrow D^0)$ but overestimates the $R_{AA}(b \rightarrow D_s)$ and $R_{AA}(c \rightarrow D_s)$ at high p_T .

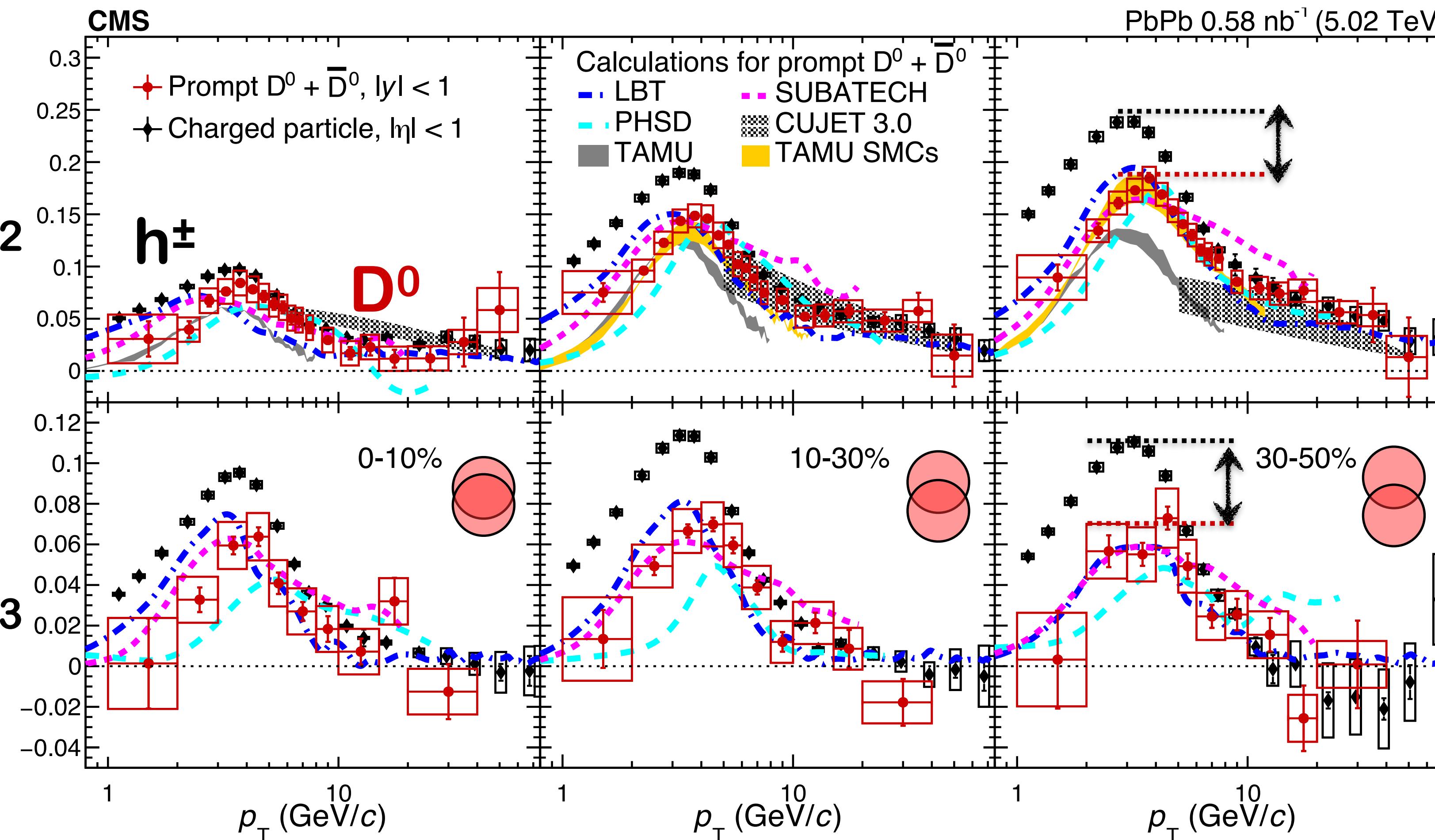
D⁰ flow in PbPb

CMS, PLB 816 (2021) 136253

Elliptic flow



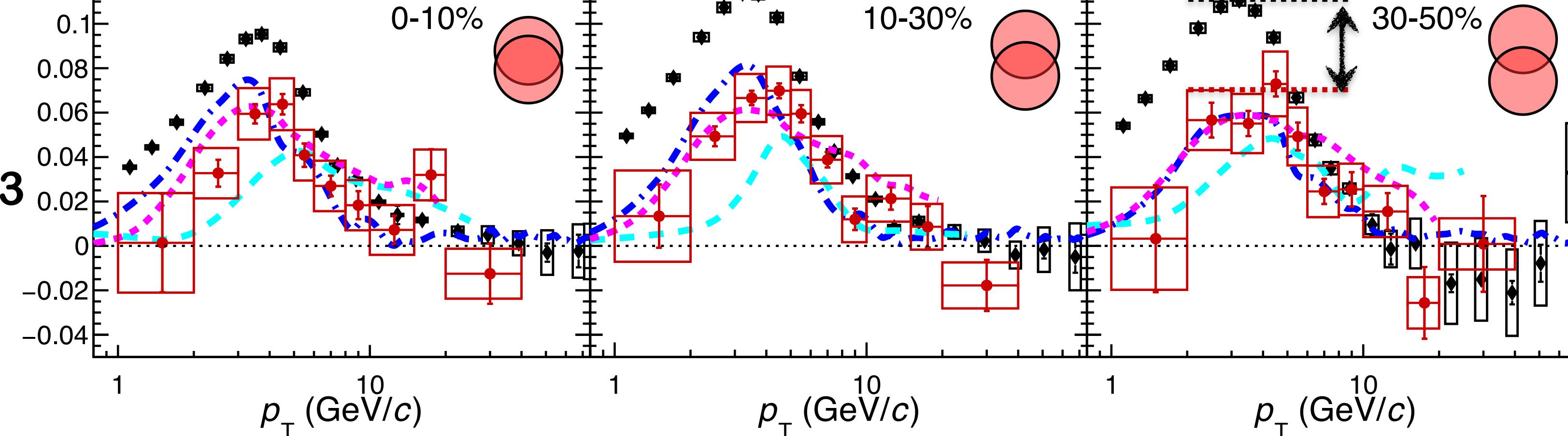
v₂



Triangular flow

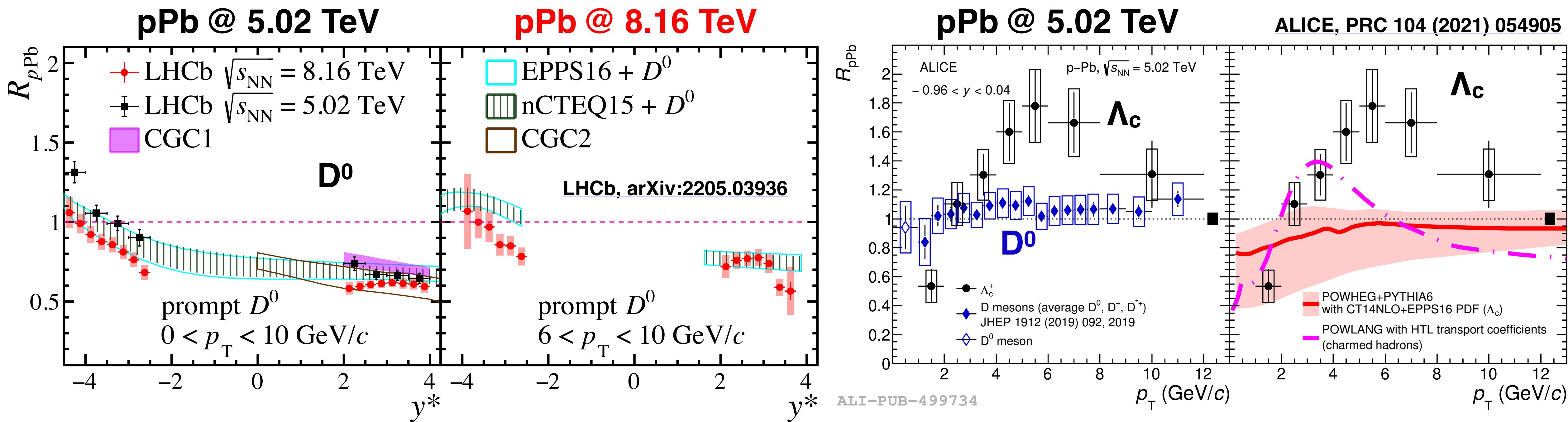


v₃



- $h^\pm v_n > D^0 v_n > 0$ at $p_T < 6 \text{ GeV}$ → collective motion of light quarks larger than charm quarks.
- D^0 and h^\pm flow converges at high p_T → path-dependent energy loss.
- No model is able to describe the data over the full centrality and p_T ranges.

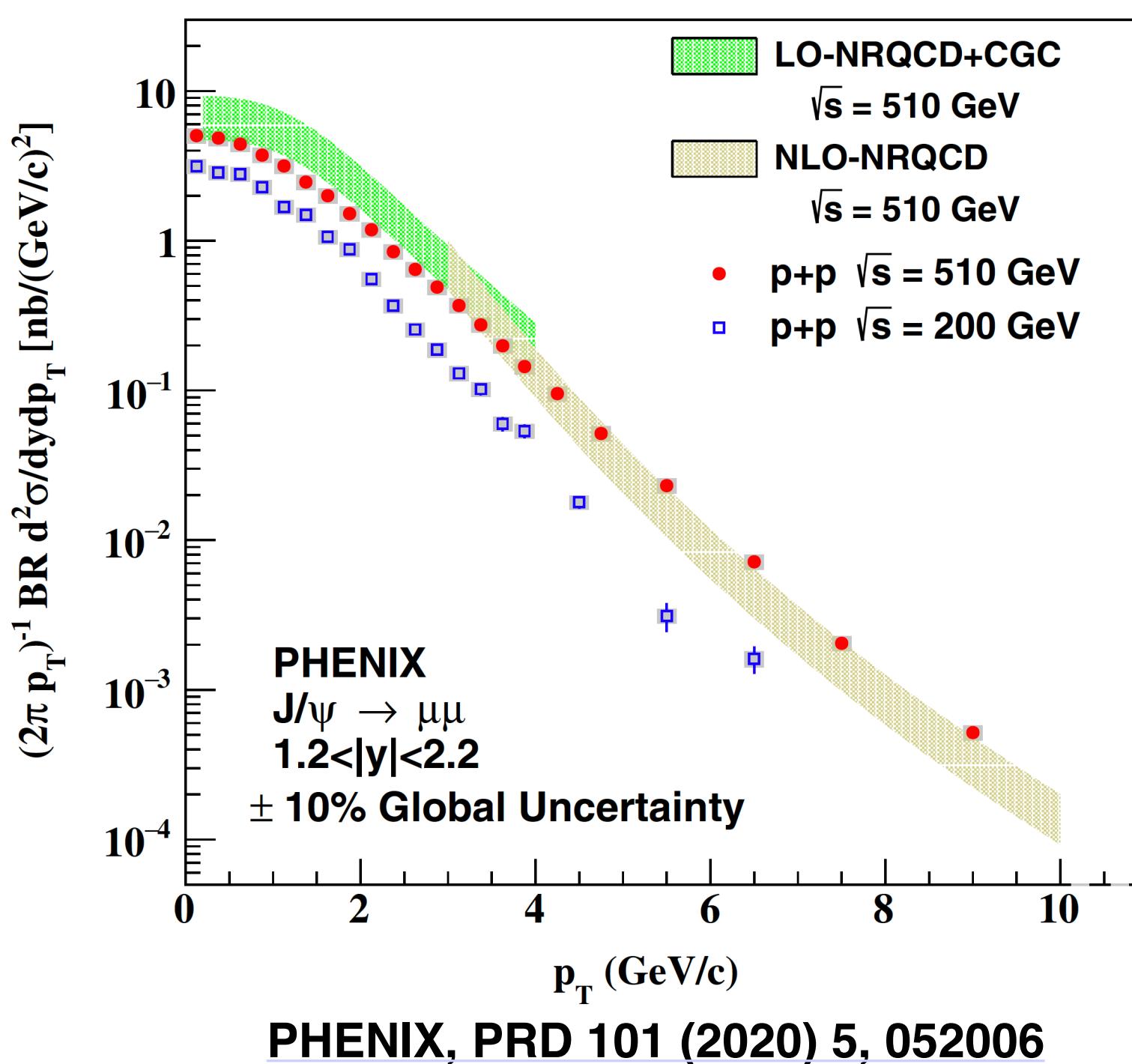
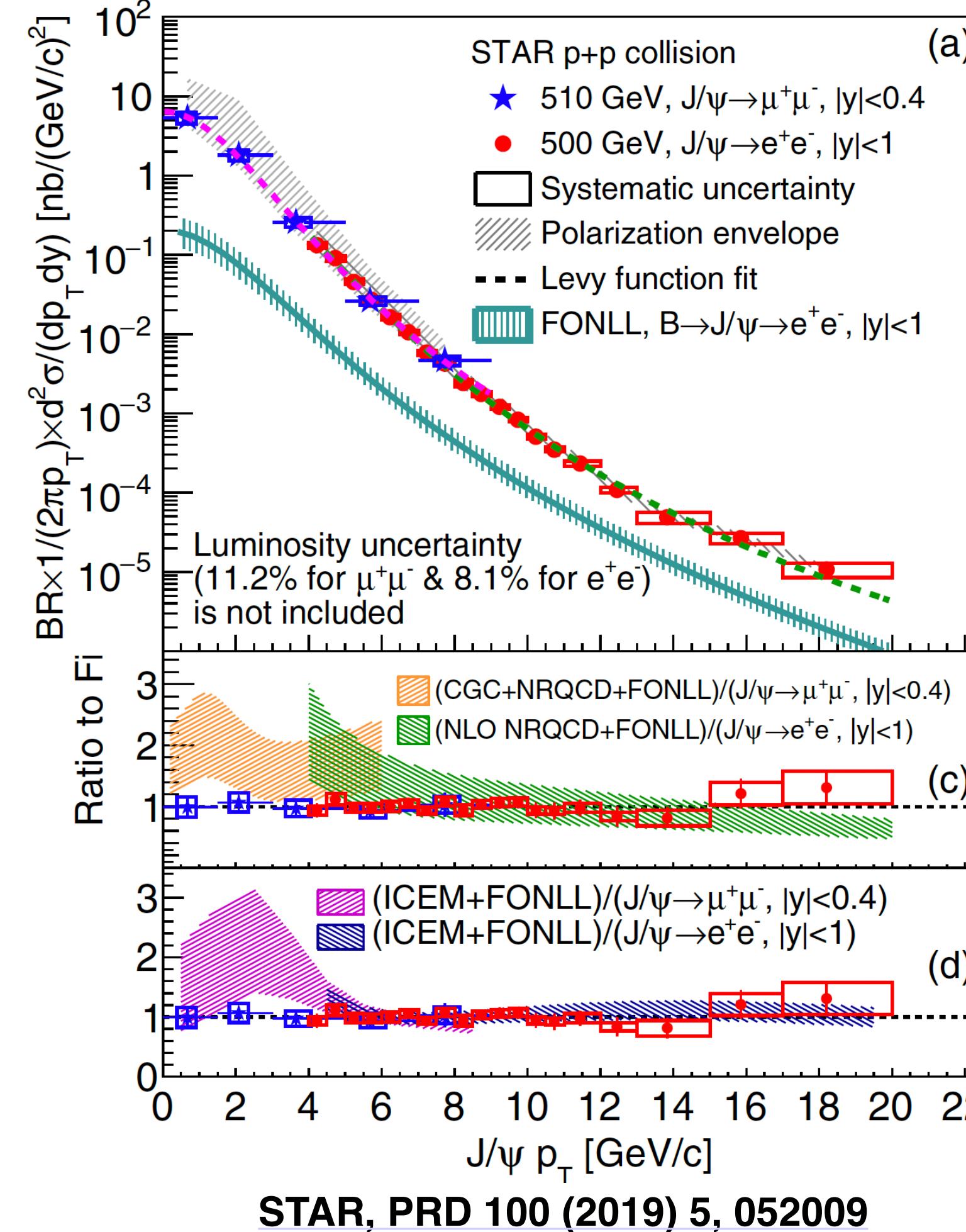
HF hadron production in pPb



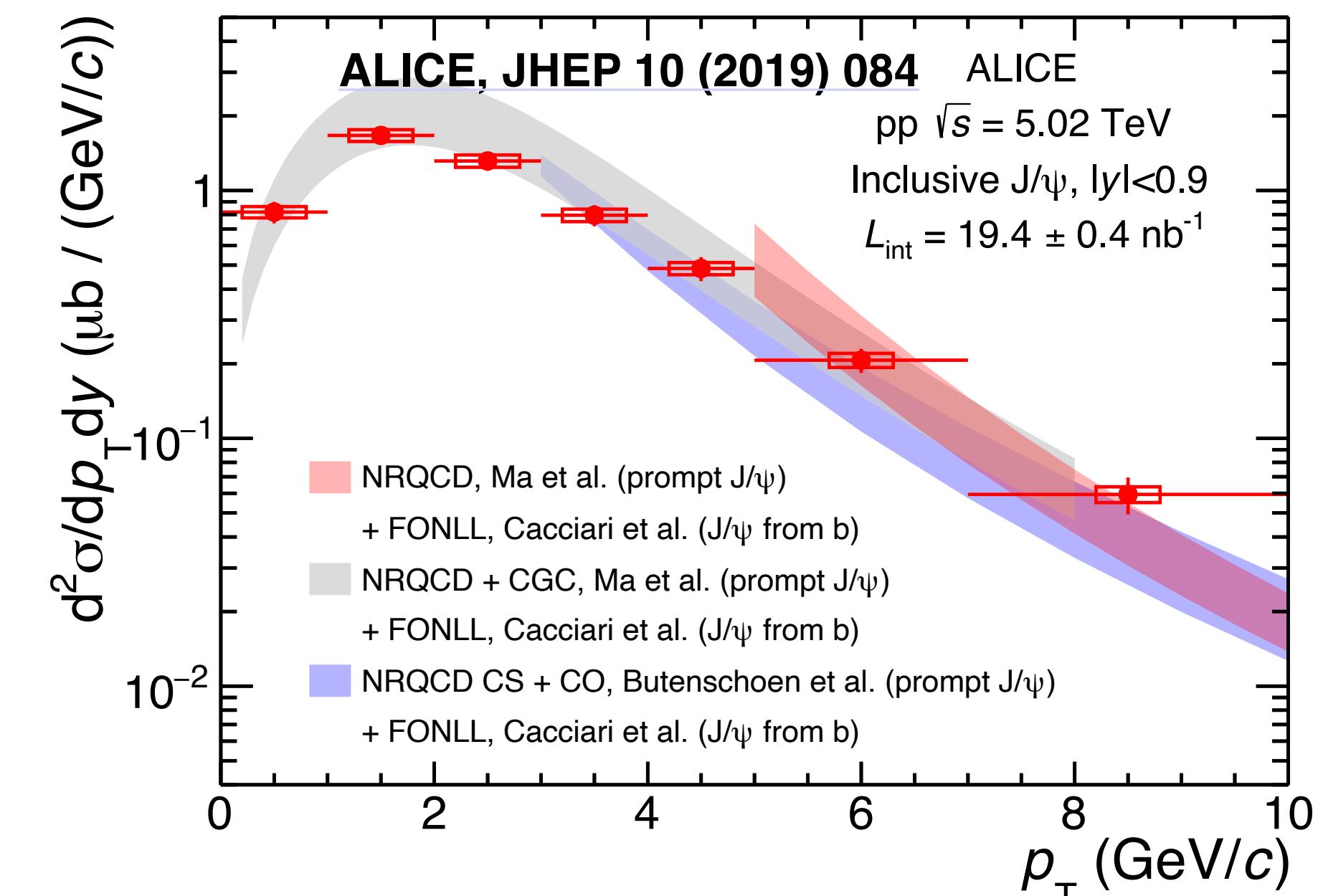
- D^0 in pPb provides strong nPDF constraints down to small x regions of $\sim 10^{-6}$.
- nPDF slightly overestimates backward $D^0 R_{p\text{Pb}}$ at $p_T > 6 \text{ GeV} \rightarrow$ final state effects in backward region.
- Hints of Λ_c suppression at $p_T < 2 \text{ GeV}$ and enhancement at $p_T > 4 \text{ GeV}$.
- Λ_c production in pPb not described neither by nPDF or QGP (POWLNG) models.

J/ Ψ production in pp

RHIC pp @ 510 GeV

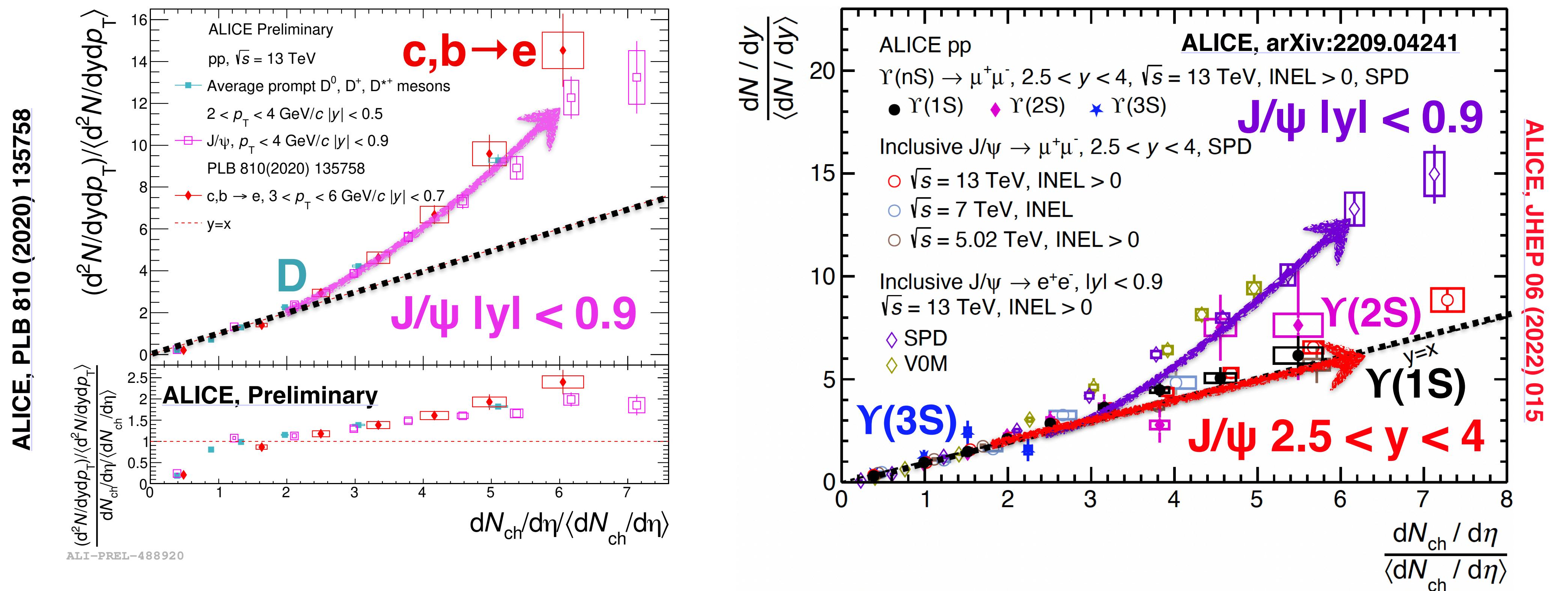


LHC pp @ 5 TeV



- Precise pp data measured over a wide range of beam energies.
- NRQCD + FONLL (b-hadron decays) describe pp measurements at both RHIC and LHC.

HF production in high multiplicity pp



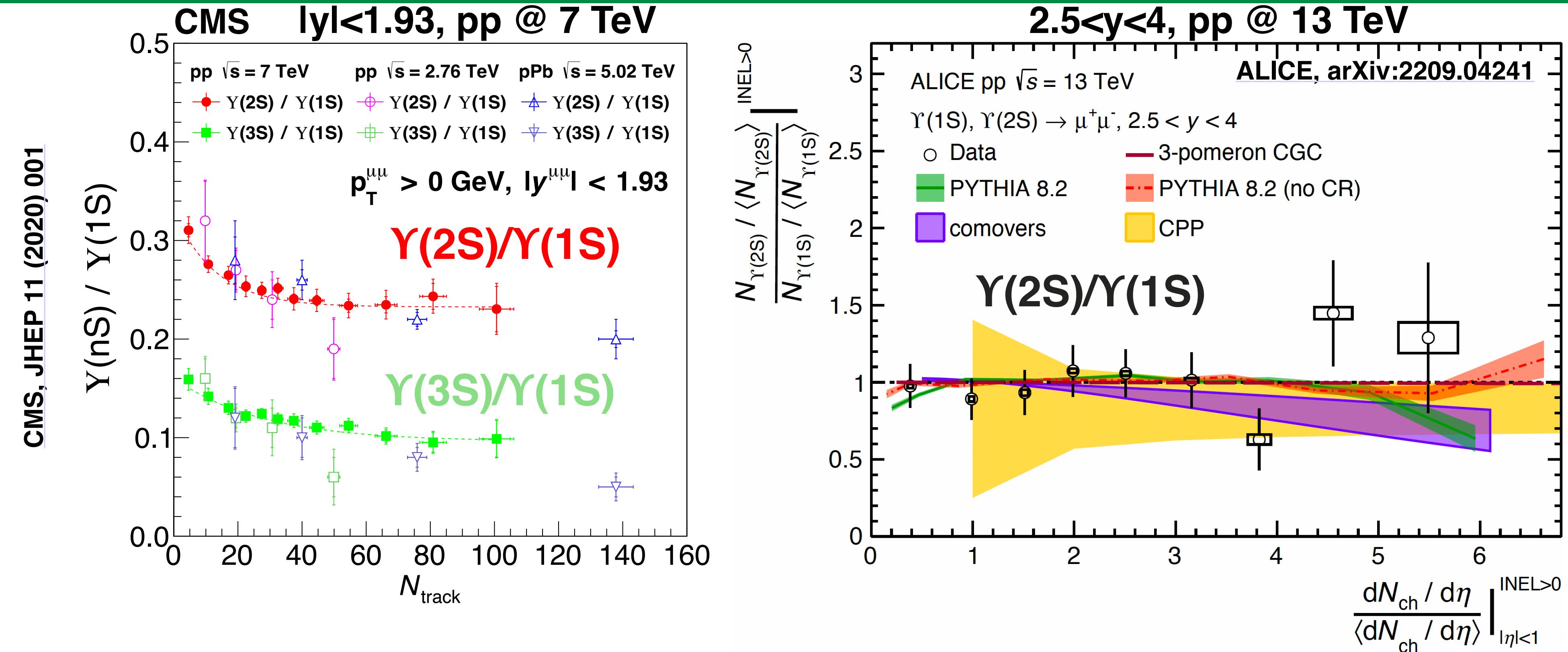
Mid rapidity

- c-hadron yield grows faster than linear.

Forward rapidity

- QQ yields consistent with linear growth.

HF production in high multiplicity pp



Mid rapidity

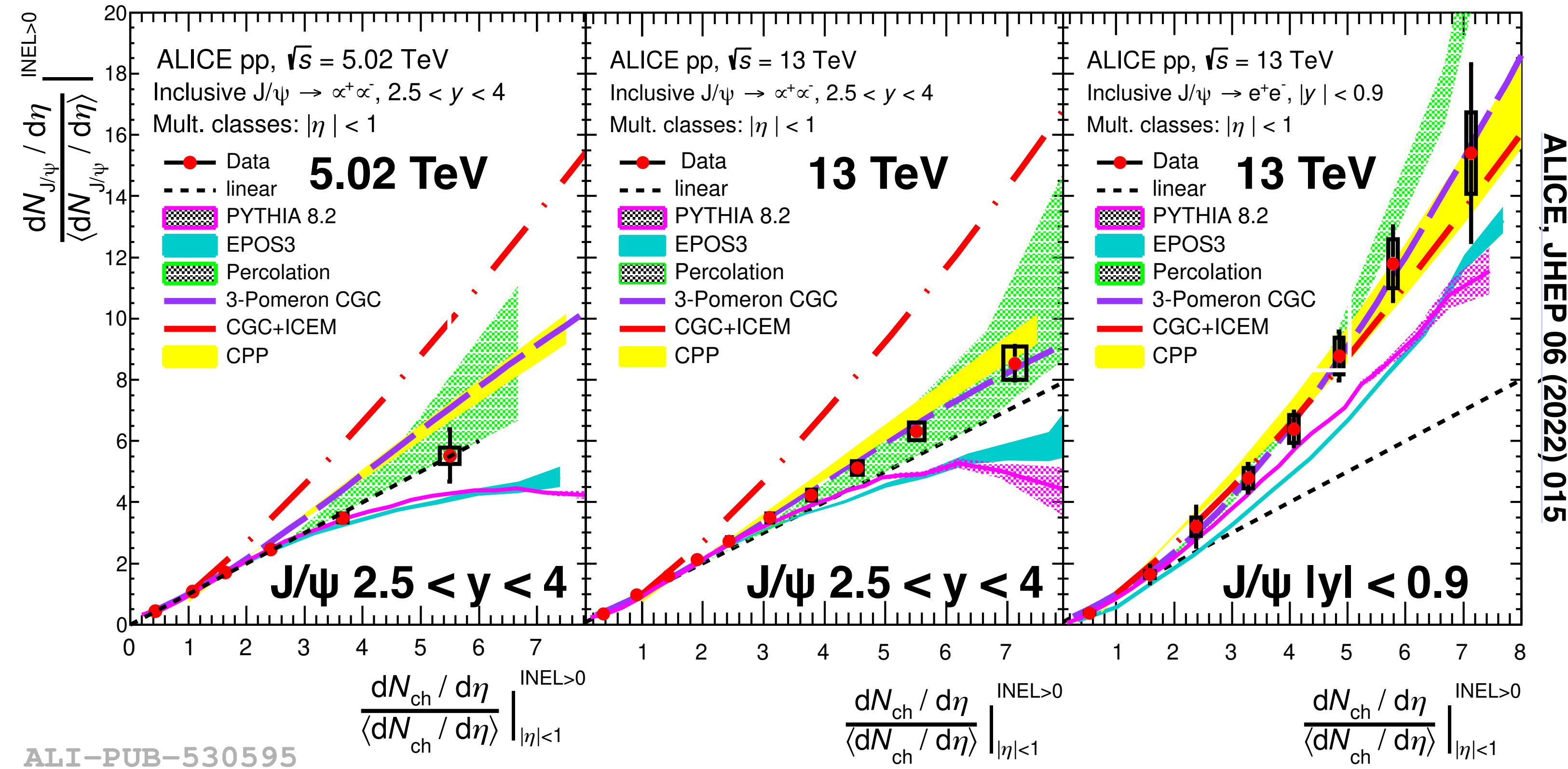
- c-hadron yield grows faster than linear.
- $\Psi(nS) / \Psi(1S)$ reduced at larger $dN/d\eta$.

Forward rapidity

- QQ yields consistent with linear growth.
- Flat 2S/1S ratios vs event activity.

$\Psi(2S)/J/\Psi$ ratios: [ALICE, arXiv:2204.10253](#)

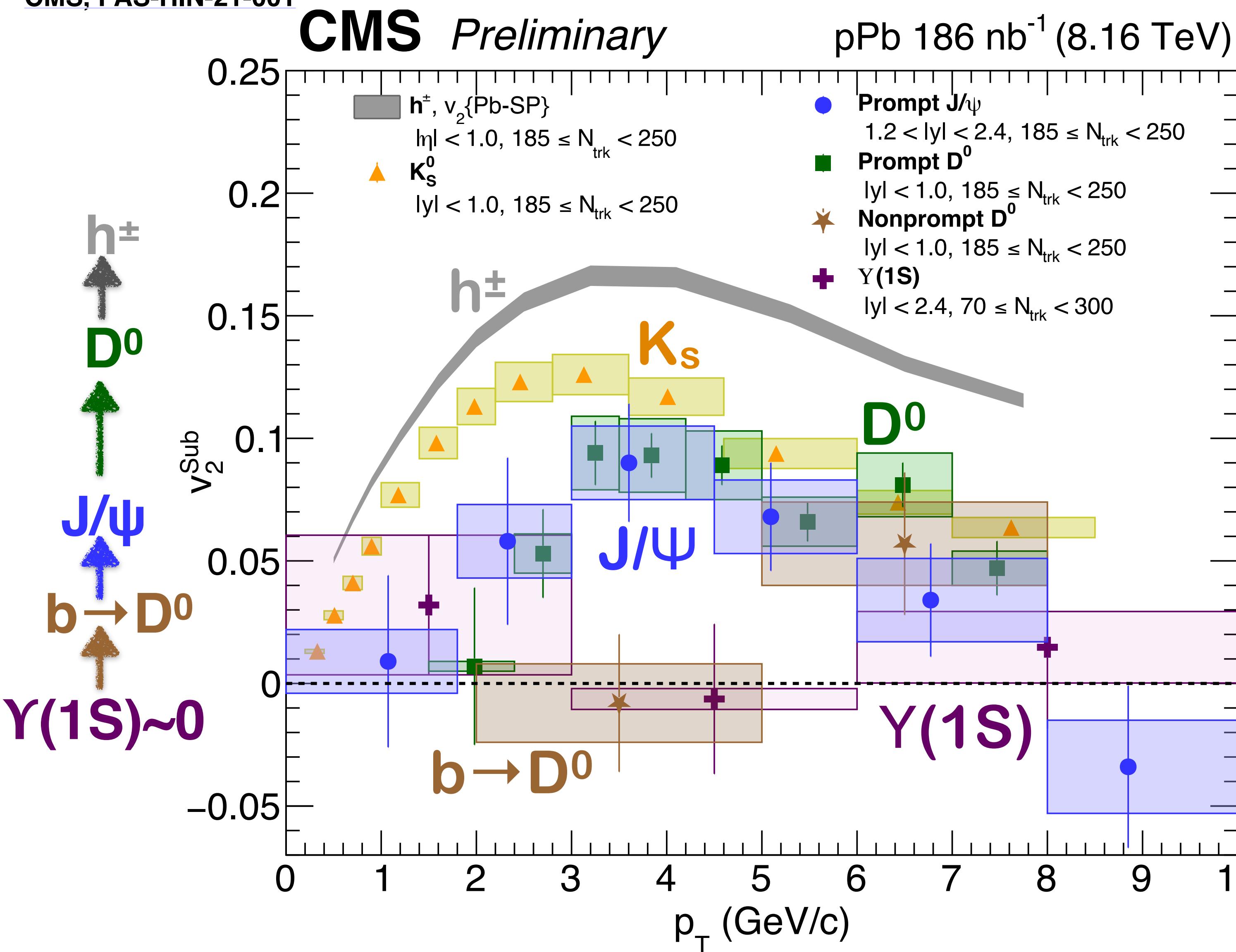
HF production in high multiplicity pp



- J/Ψ production in high multiplicity pp well described by models:
 - **Percolation**: collisions driven by exchange of color strings.
 - **3-pomeron CGC**: assumes gluon fusion dominates + HF quark \rightarrow QQ emits soft gluons.
 - **CPP**: parametrisation derived from p-Pb assuming N_{coll} linear dependence.

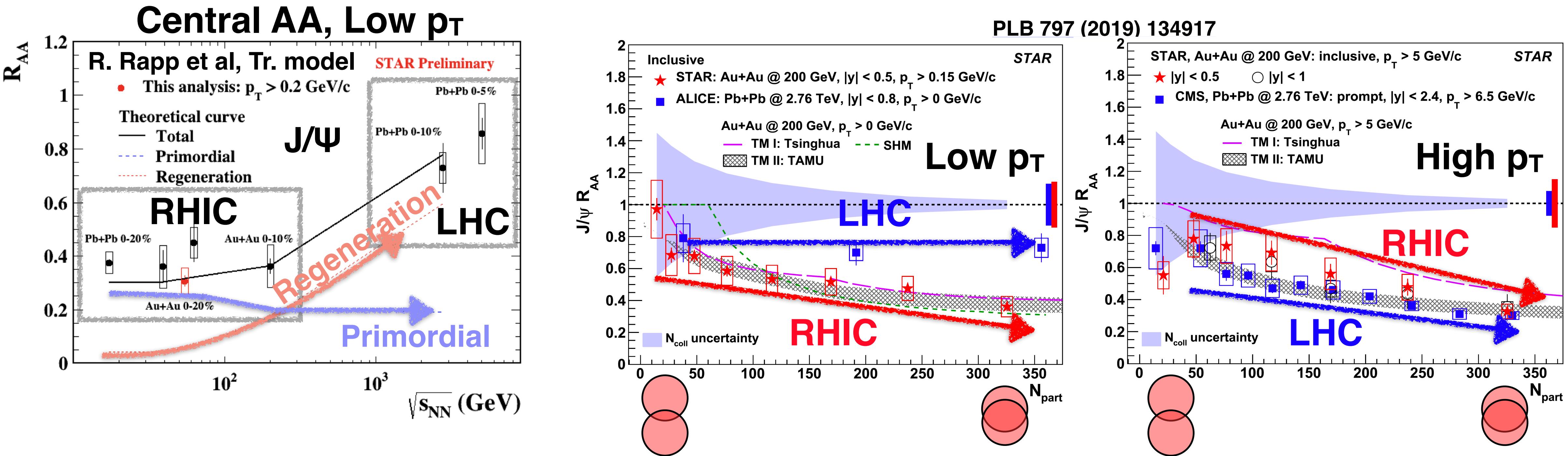
Summary of HF v_2 in pPb

CMS, PAS-HIN-21-001



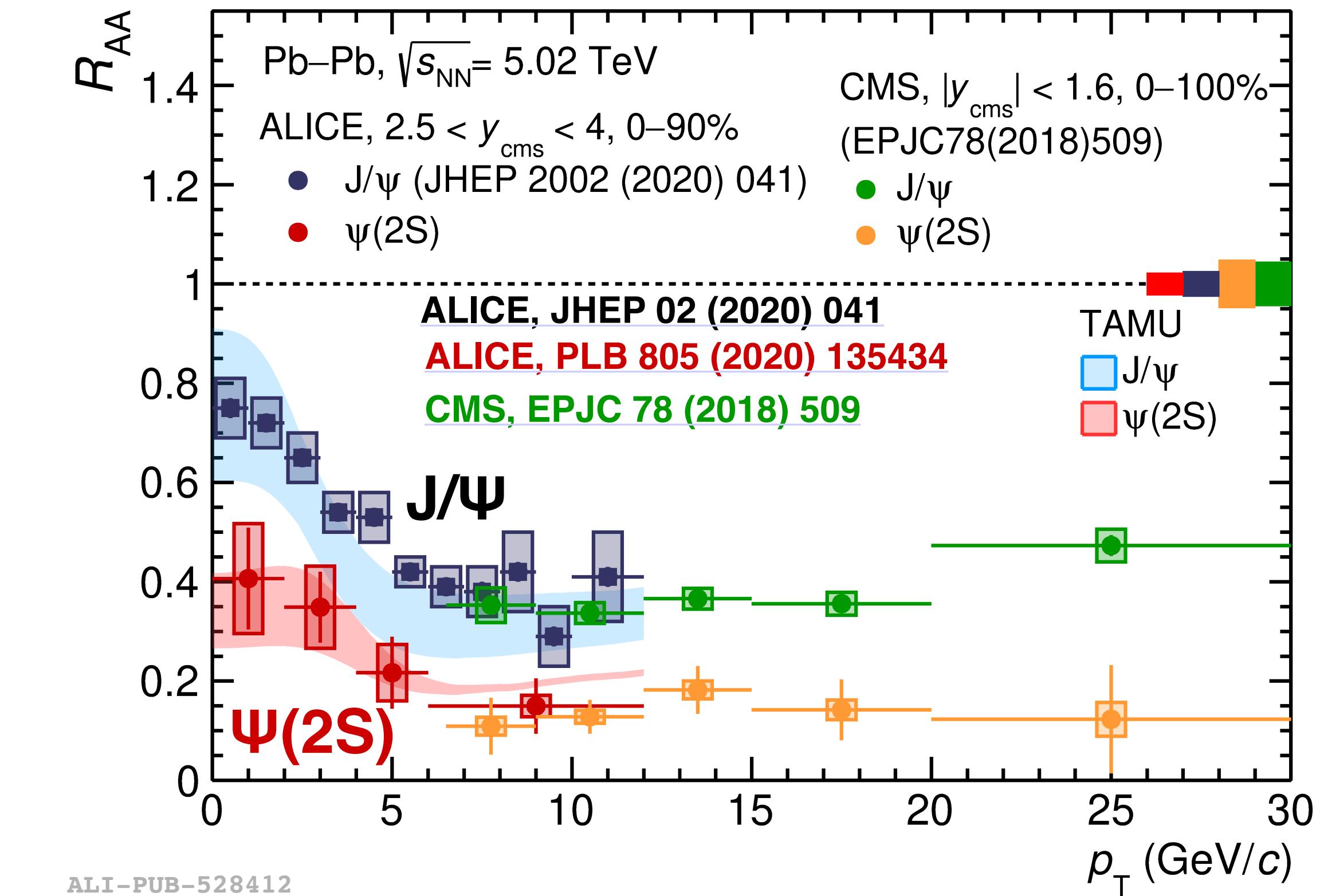
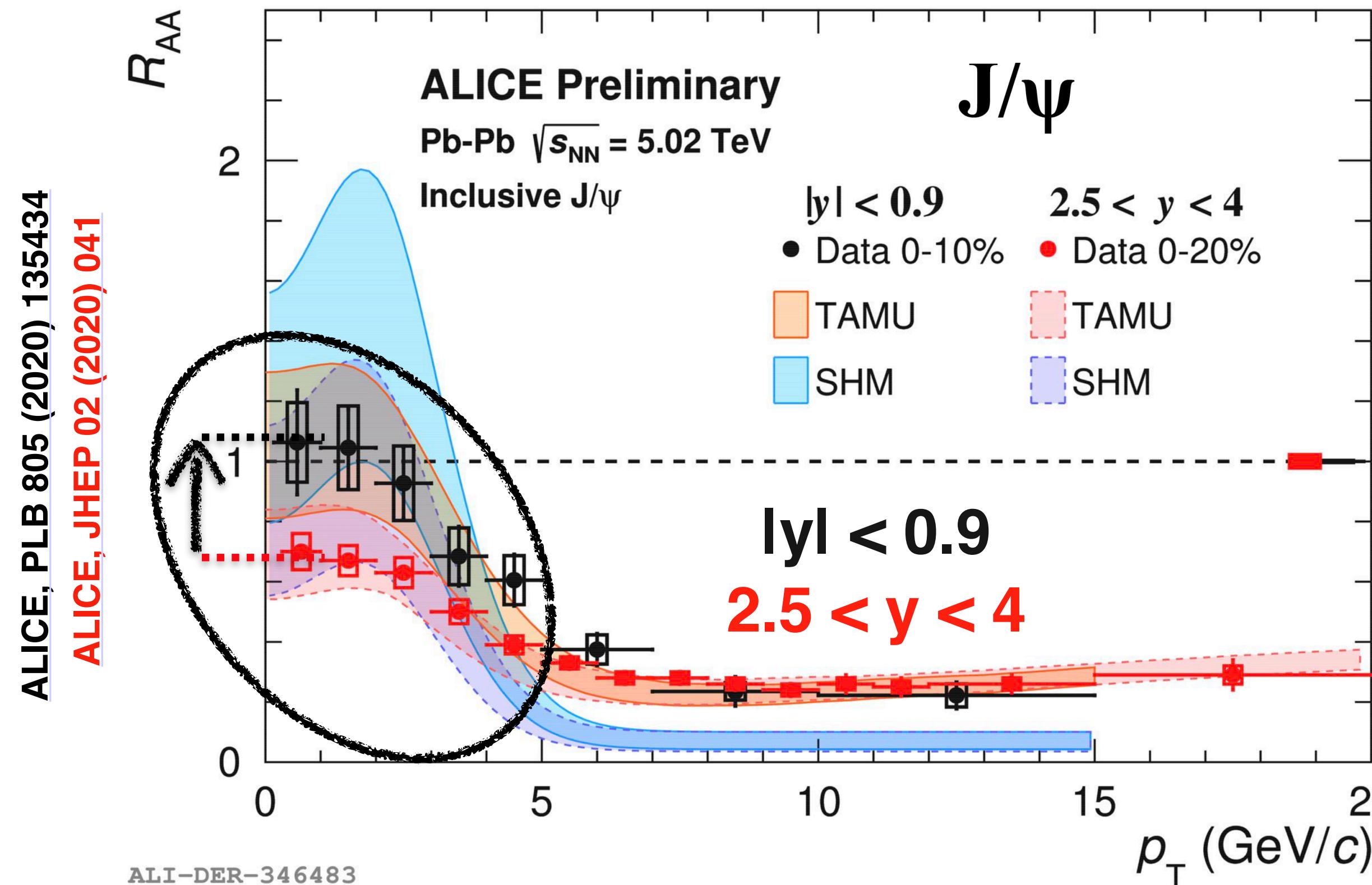
- **Low p_T :**
 - $v_2(h) > v_2(D) \sim v_2(J/\psi) > v_2(b \rightarrow D) \sim v_2(Y) \sim 0$
- **High p_T :**
 - $v_2(h) ? v_2(D) \sim v_2(J/\psi) \sim v_2(b \rightarrow D) \sim v_2(Y) \sim 0$

J/ Ψ production in AA



- J/ Ψ production suppressed in all centrality bins, decreasing from peripheral to central events.
 - Interplay of J/ Ψ primordial and regenerated production in central AA vs beam energy.
 - **LHC** > **RHIC** R_{AA} at low p_T : higher charm production at LHC \rightarrow larger regeneration.
 - **LHC** < **RHIC** R_{AA} at high p_T : primordial production \rightarrow larger suppression at LHC.

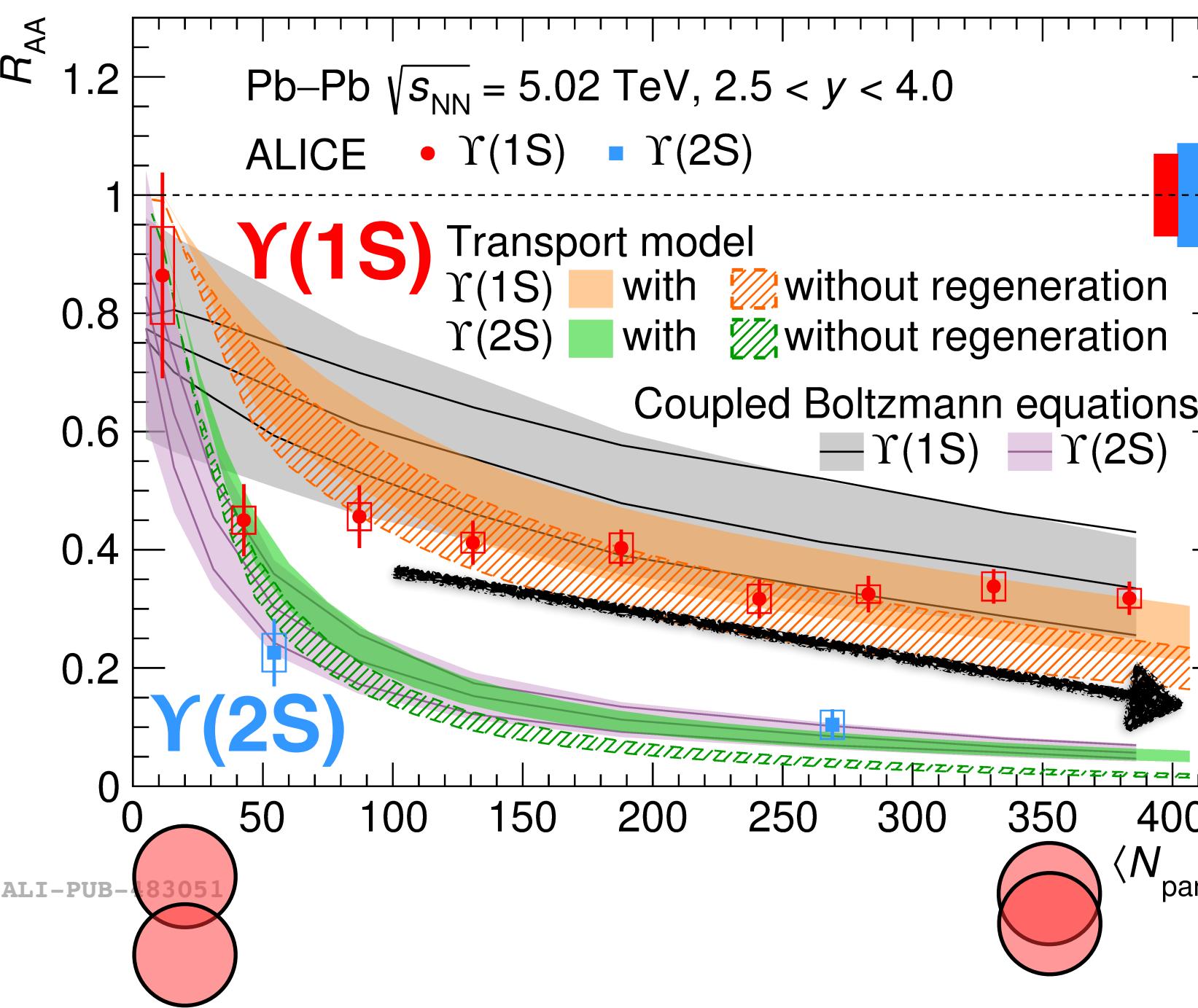
$\Psi(nS)$ production in PbPb



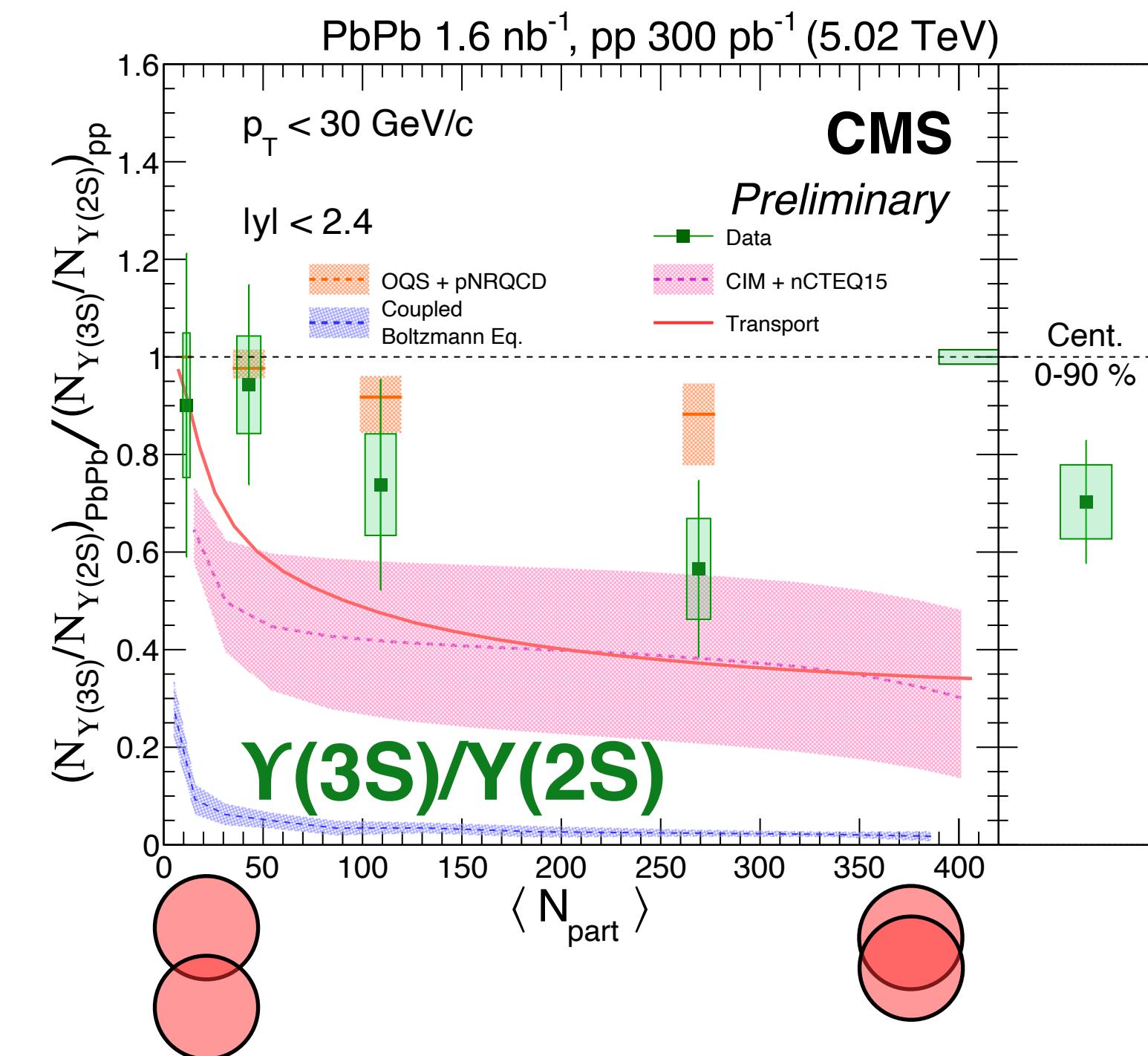
- $\Psi(2S) R_{AA} < J/\psi R_{AA} \rightarrow$ sequential suppression of charmonia.
- Hint of less **J/ ψ** suppression at mid-rapidity compared to forward rapidity.
- Models including $\Psi(nS)$ production via regeneration (TAMU) are able to describe data at low p_T .

$\Upsilon(nS)$ production in PbPb

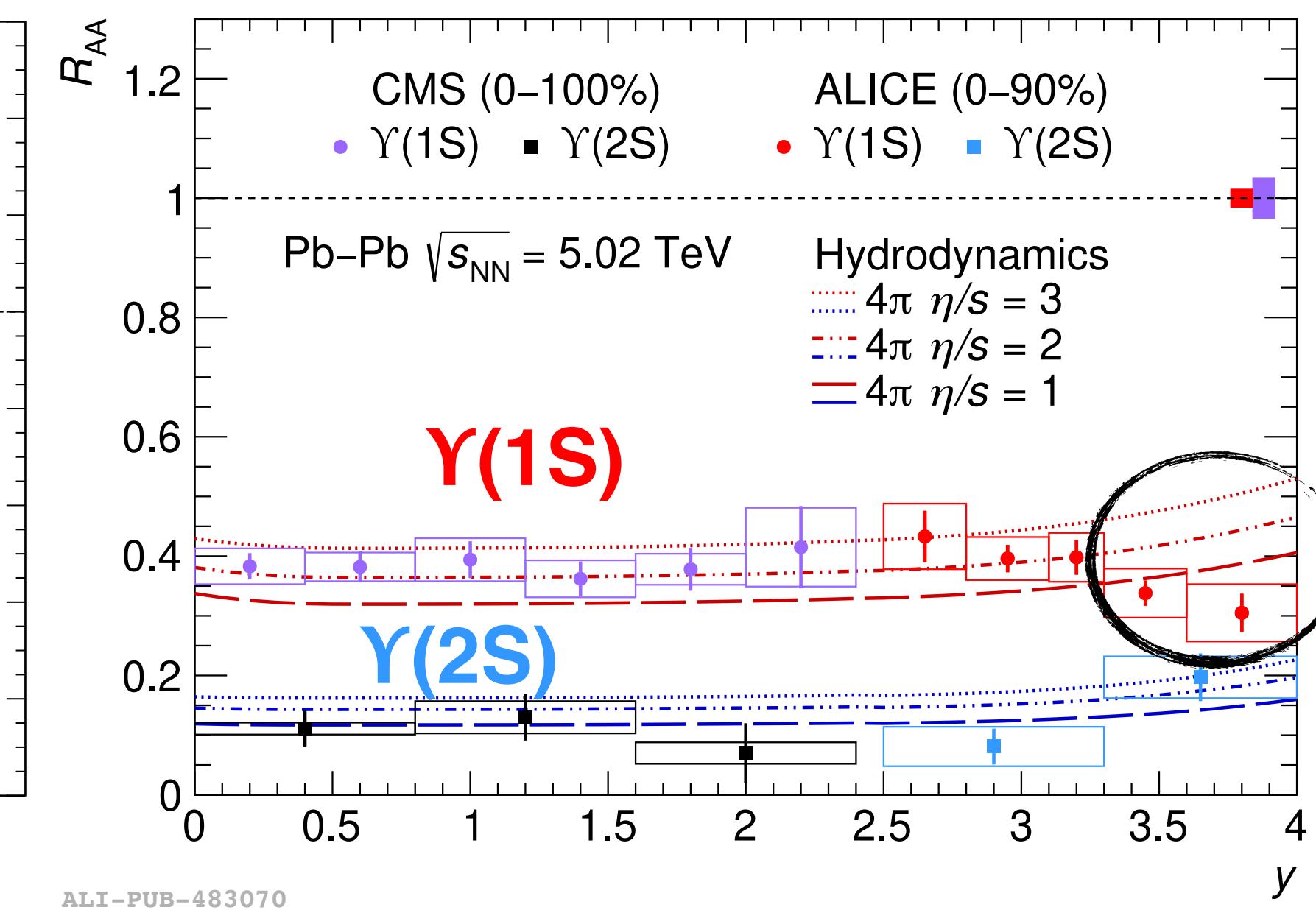
ALICE, PLB 822 (2021) 136579



CMS, PAS-HIN-21-007



ALICE, PLB 822 (2021) 136579

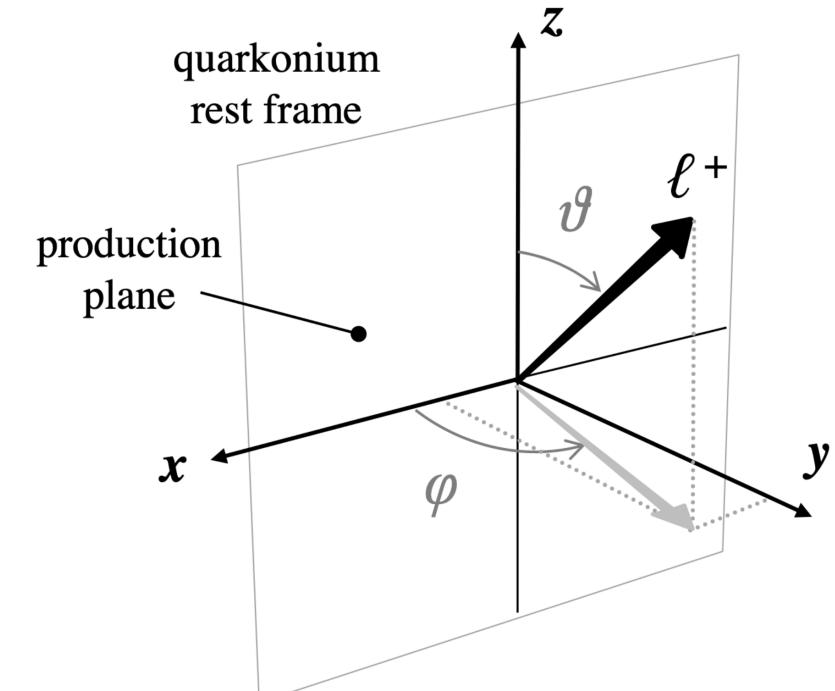


- $\Upsilon(3S) R_{\text{AA}} < \Upsilon(2S) R_{\text{AA}} < \Upsilon(1S) R_{\text{AA}} \rightarrow$ sequential suppression of bottomonia.
- $\Upsilon(2S)$ and $\Upsilon(1S)$ data favours model with regeneration and hydrodynamics.
- $\Upsilon(3S)/\Upsilon(2S)$ not fully resolved by models across centrality.
- Hydrodynamic model show tension in $\Upsilon(1S) R_{\text{AA}}$ at forward rapidity.

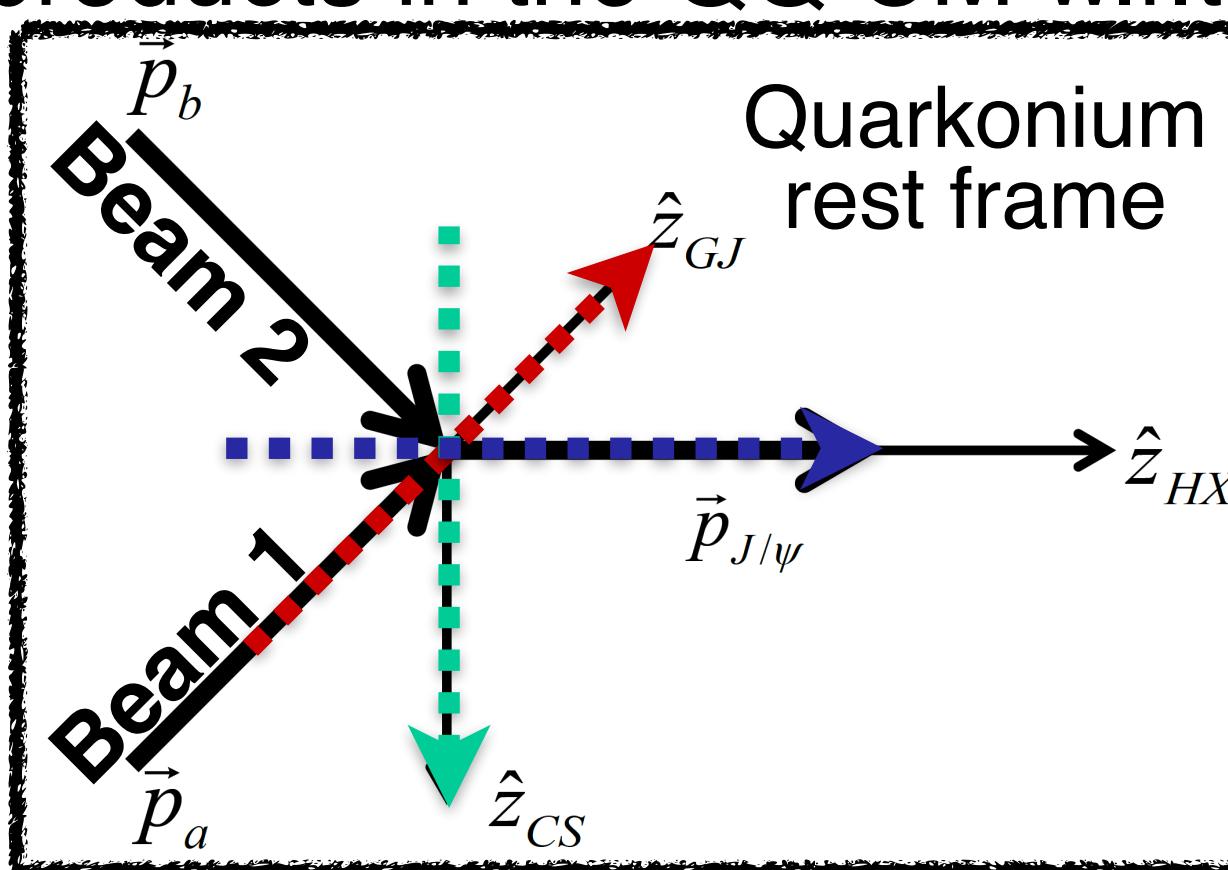
Quarkonium polarization

- Polarization is defined as the spin alignment with respect to a chosen direction.

$$W(\theta, \phi) \propto \frac{1}{3 + \lambda_\theta} \left(1 + \boxed{\lambda_\theta} \cos^2 \theta + \boxed{\lambda_\phi} \sin^2 \theta \cos 2\phi + \boxed{\lambda_{\theta\phi}} \sin 2\theta \cos \phi \right)$$

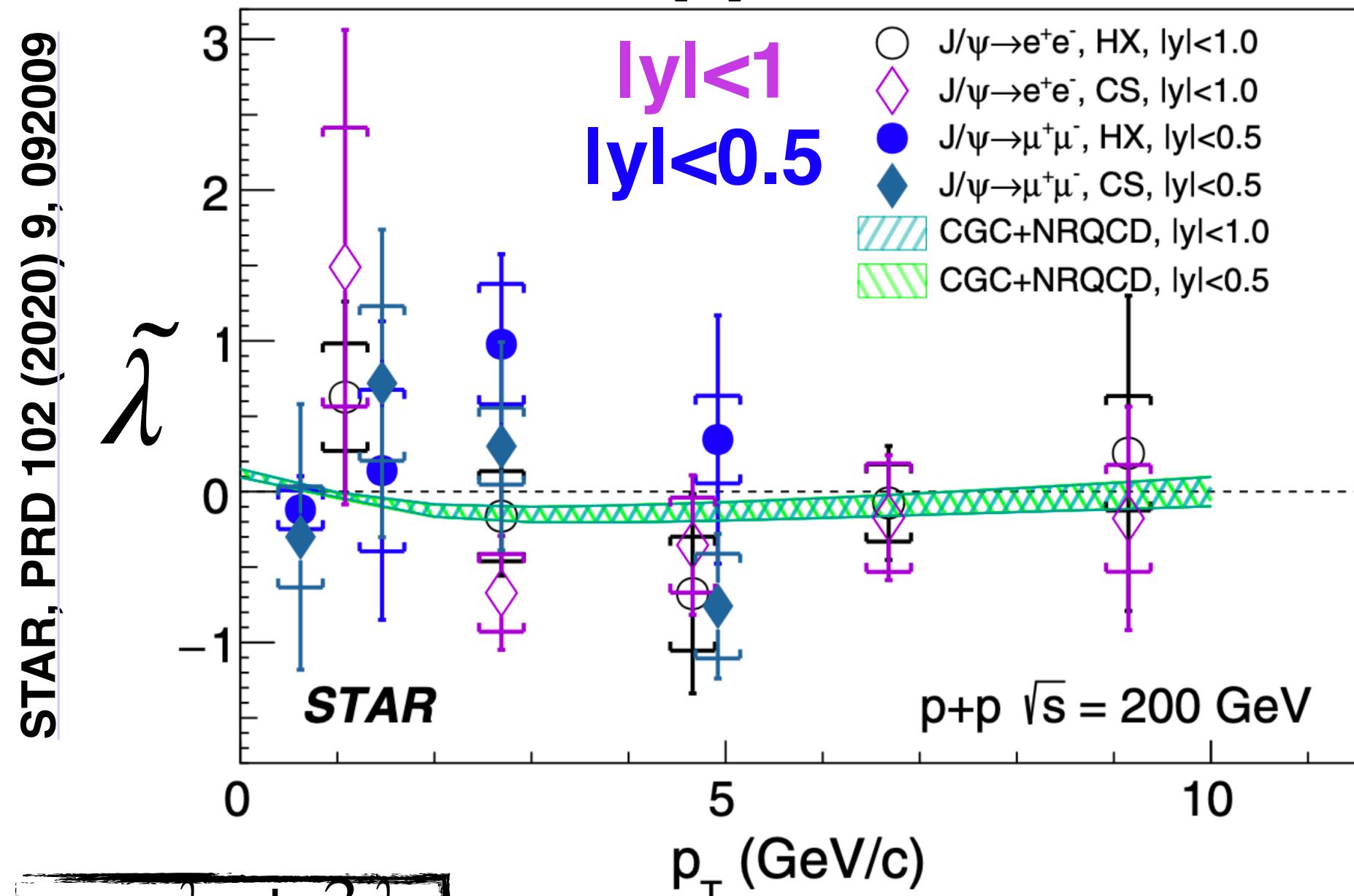


- Measured as anisotropies in the angular distributions of decay products in the QQ CM w.r.t:
 - Helicity (HX):** quarkonium p_T direction.
 - Collins-Soper (CS):** bisector of angle between beams.
 - Gottfried-Jackson (GJ):** direction of one beam.
- Constrains J/ Ψ production mechanism:
 - LO NRQCD: transverse polarization ($\lambda_\theta > 0$) at high p_T .
 - NLO CSM: longitudinal polarization ($\lambda_\theta < 0$).
 - Medium effects could possibly modify J/ Ψ polarization.



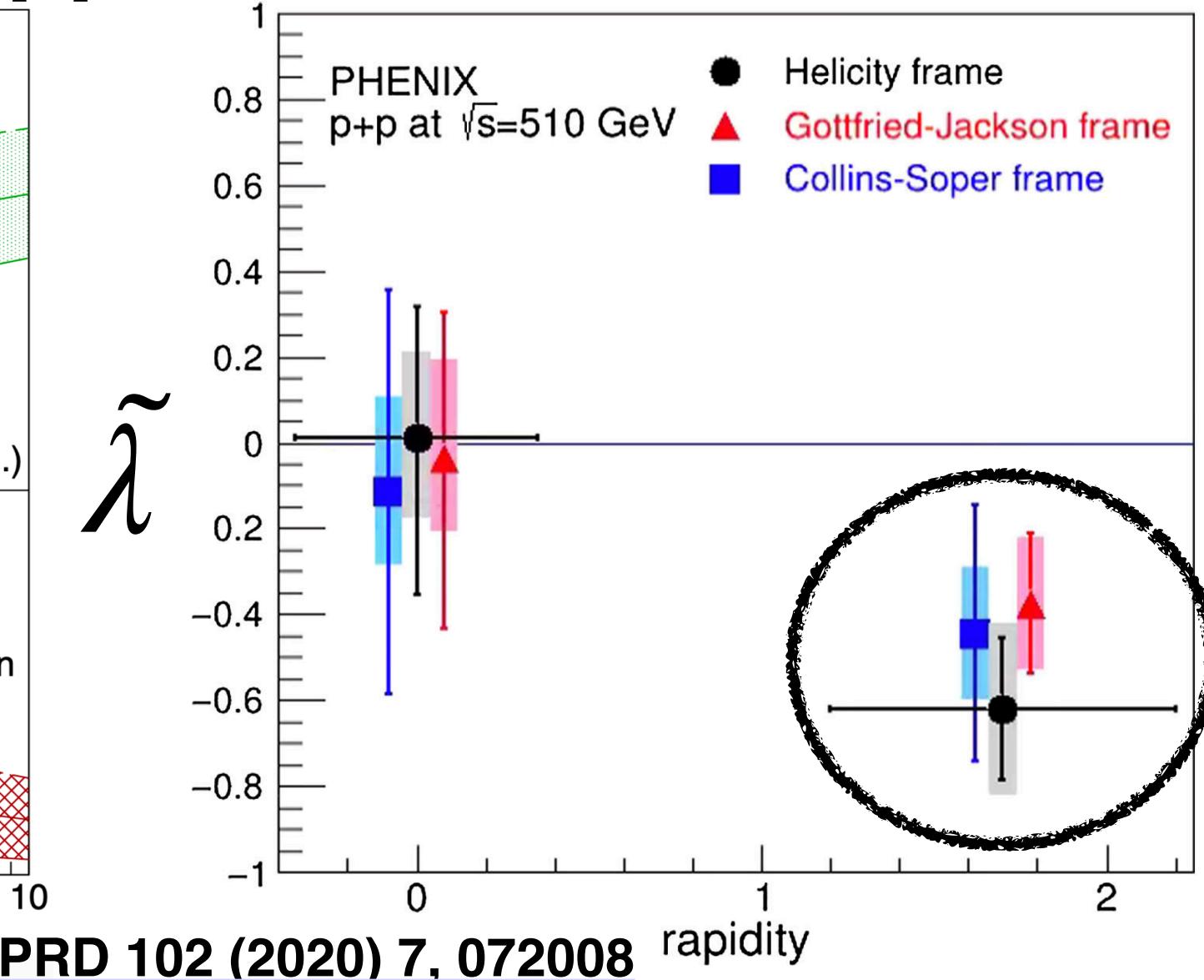
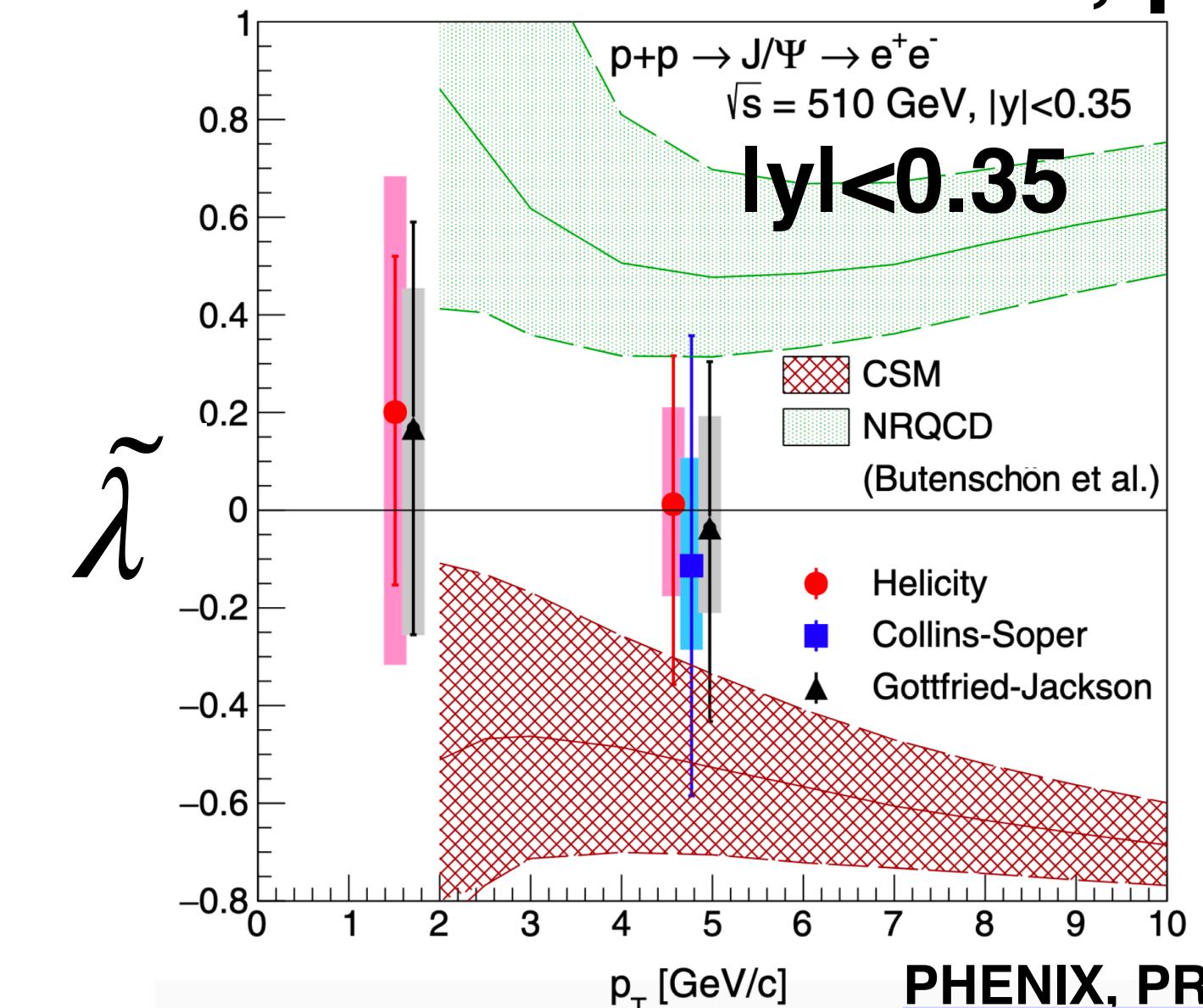
J/Ψ polarization in pp at RHIC

STAR, pp @ 200 GeV



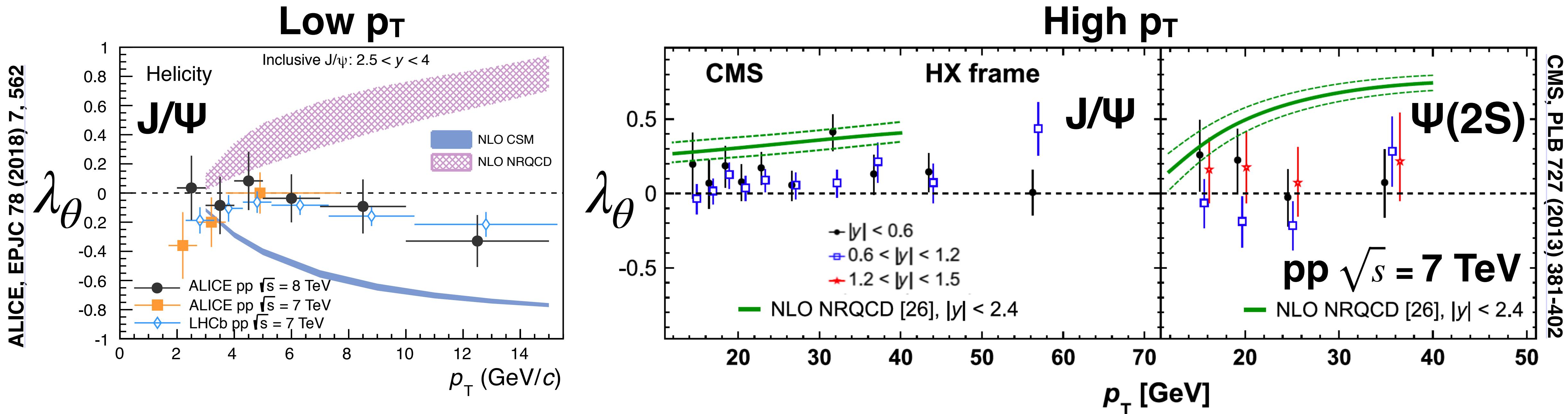
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

PHENIX, pp @ 510 GeV



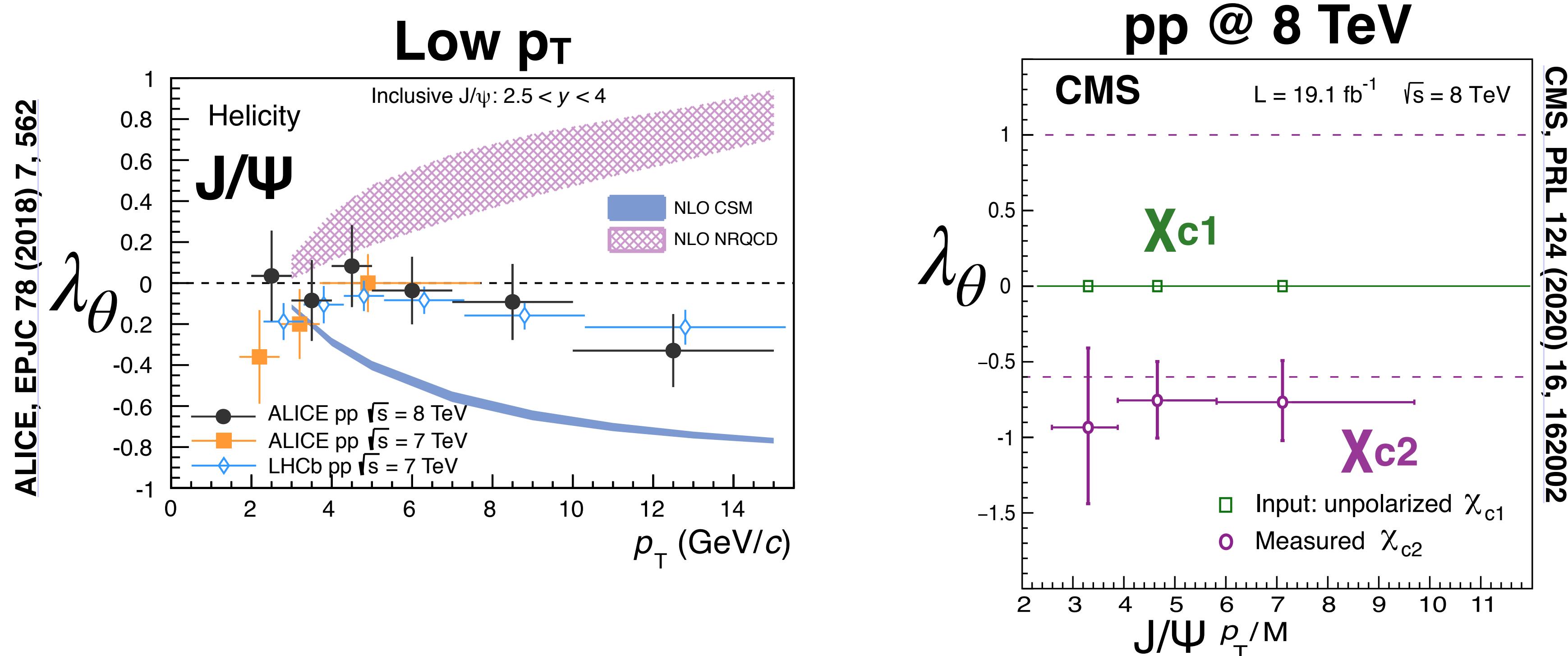
- J/ψ production at mid-rapidity do not exhibit significant polarization.
 - CGC+NRQCD expects no polarization in agreement with data.
 - CSM and NRQCD predicts non-zero polarization towards high p_T .
- J/ψ production at forward rapidity shows hint of longitudinal polarization ($\tilde{\lambda} < 0$).

Charmonium polarization in pp at LHC



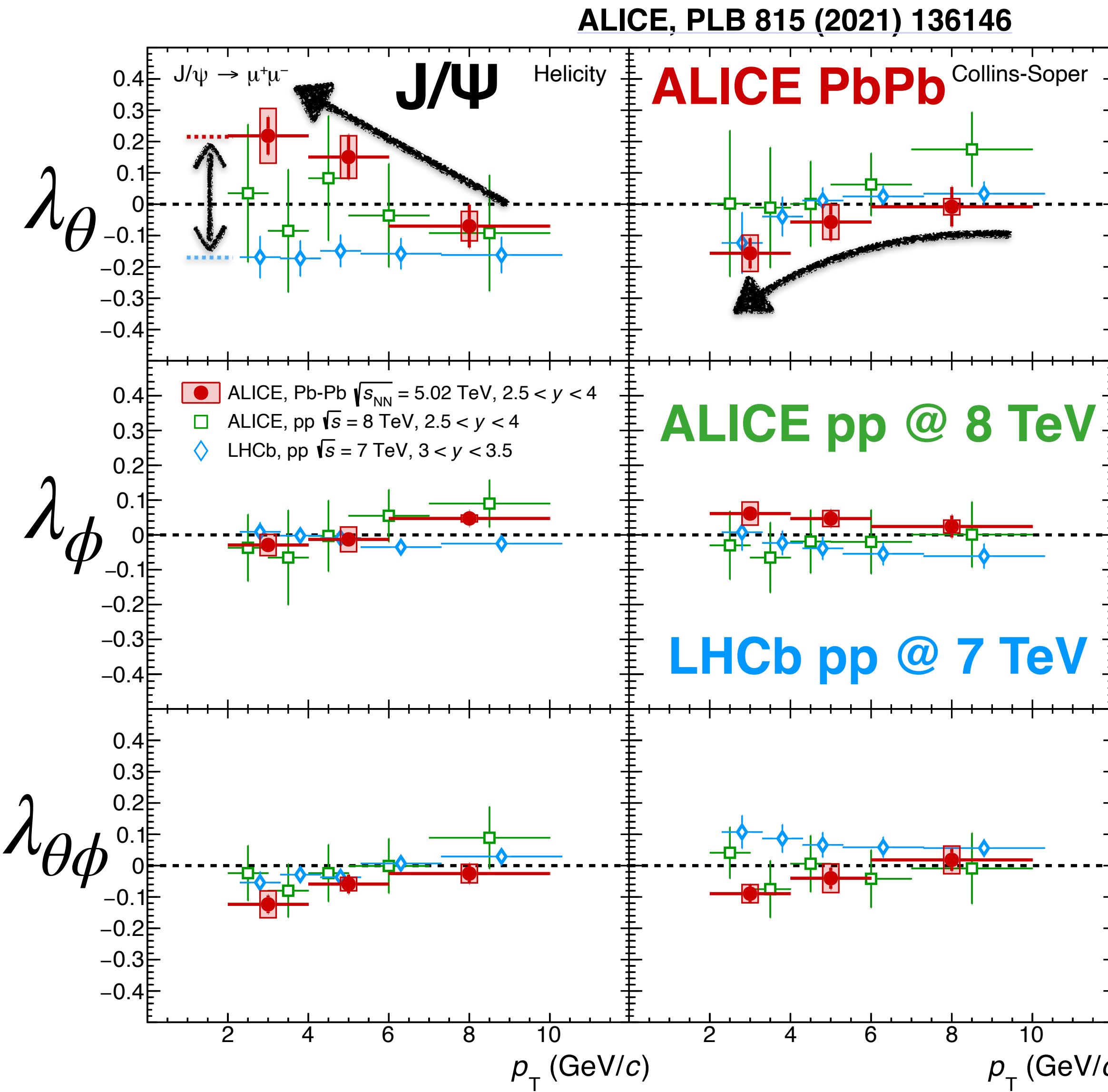
- $\Psi(nS)$ production in pp at LHC shows no significant polarization up to $p_T \sim 60$ GeV.
- NRQCD and CSM also fail to describe $\Psi(nS)$ polarization @ 8 TeV.

Charmonium polarization in pp at LHC



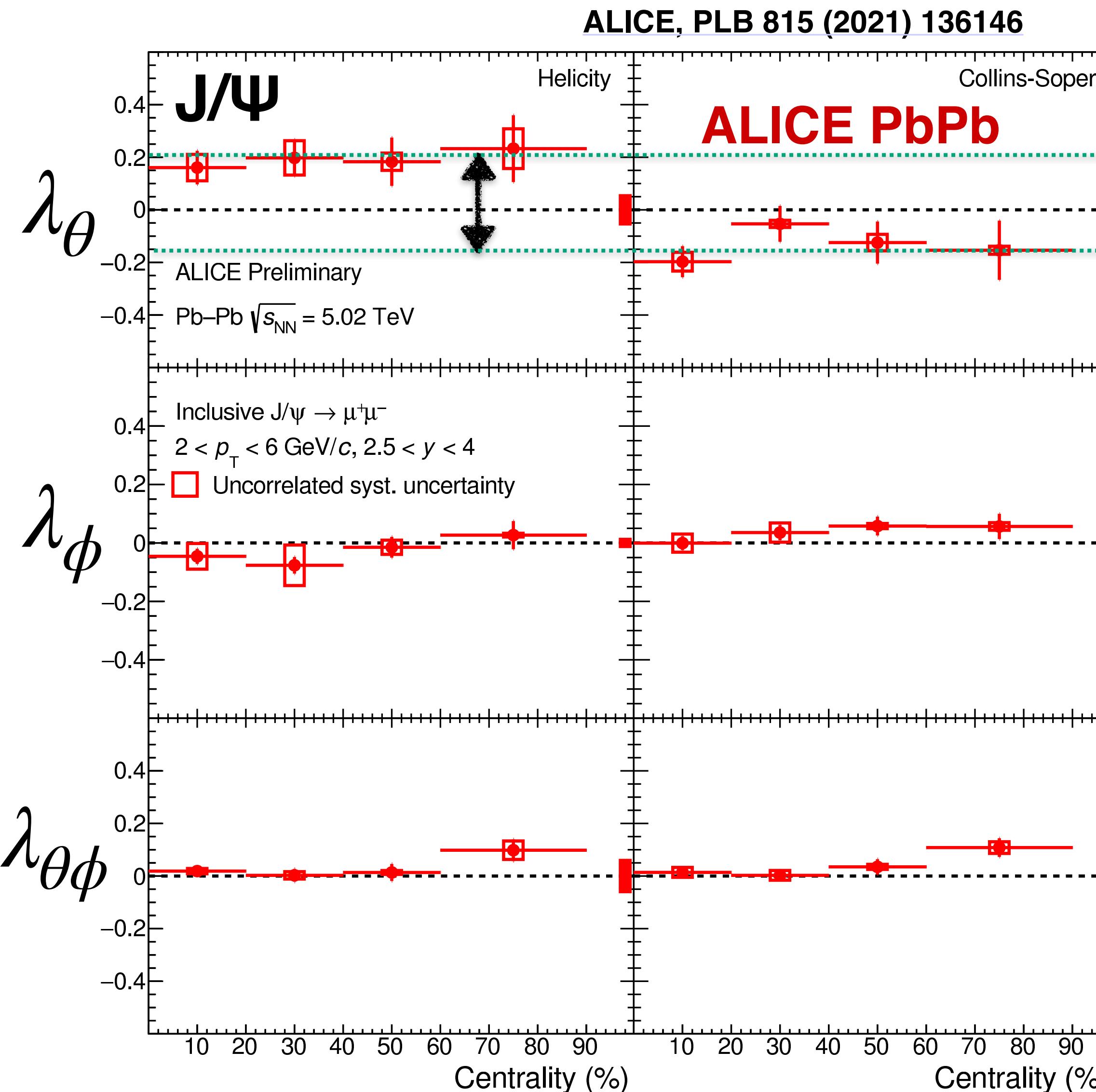
- $\Psi(nS)$ production in pp at LHC shows no polarization up to $p_T \sim 60$ GeV.
- NRQCD and CSM also fail to describe $\Psi(nS)$ polarization @ 8 TeV.
- Prompt $X_c \rightarrow J/\psi + \gamma$ production favours scenario where at least one X_c state is polarized.
 - Need to be careful with feed-down contribution when studying J/ψ polarization.

Quarkonium polarization in PbPb



- J/ψ polarization in PbPb:
 - Polarization parameters close to zero.
 - Hint of J/ψ polarization towards low p_T .
 - Tension with pp LHCb λ_θ at low p_T in HX frame.

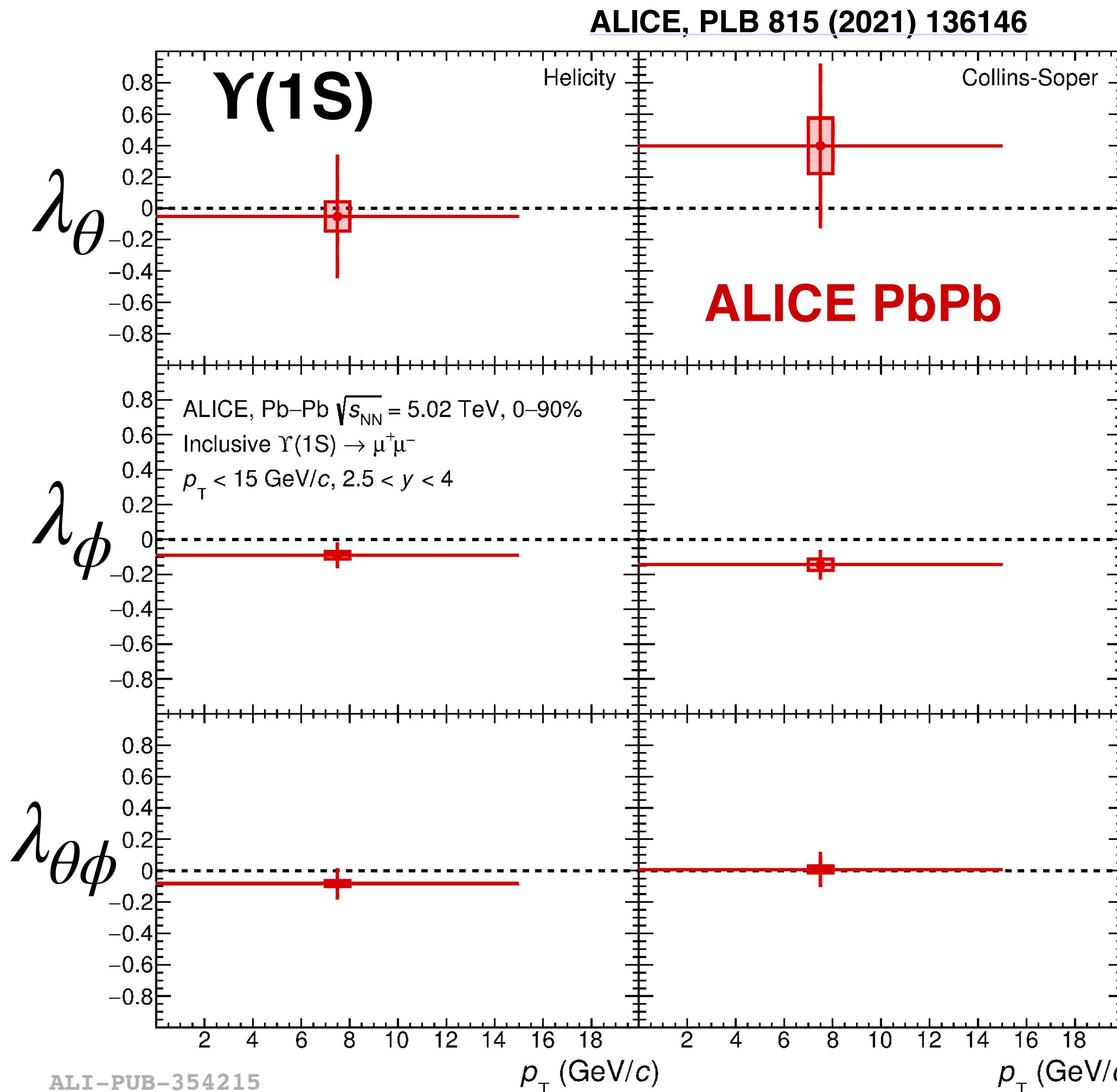
Quarkonium polarization in PbPb



ALI-PREL-347065

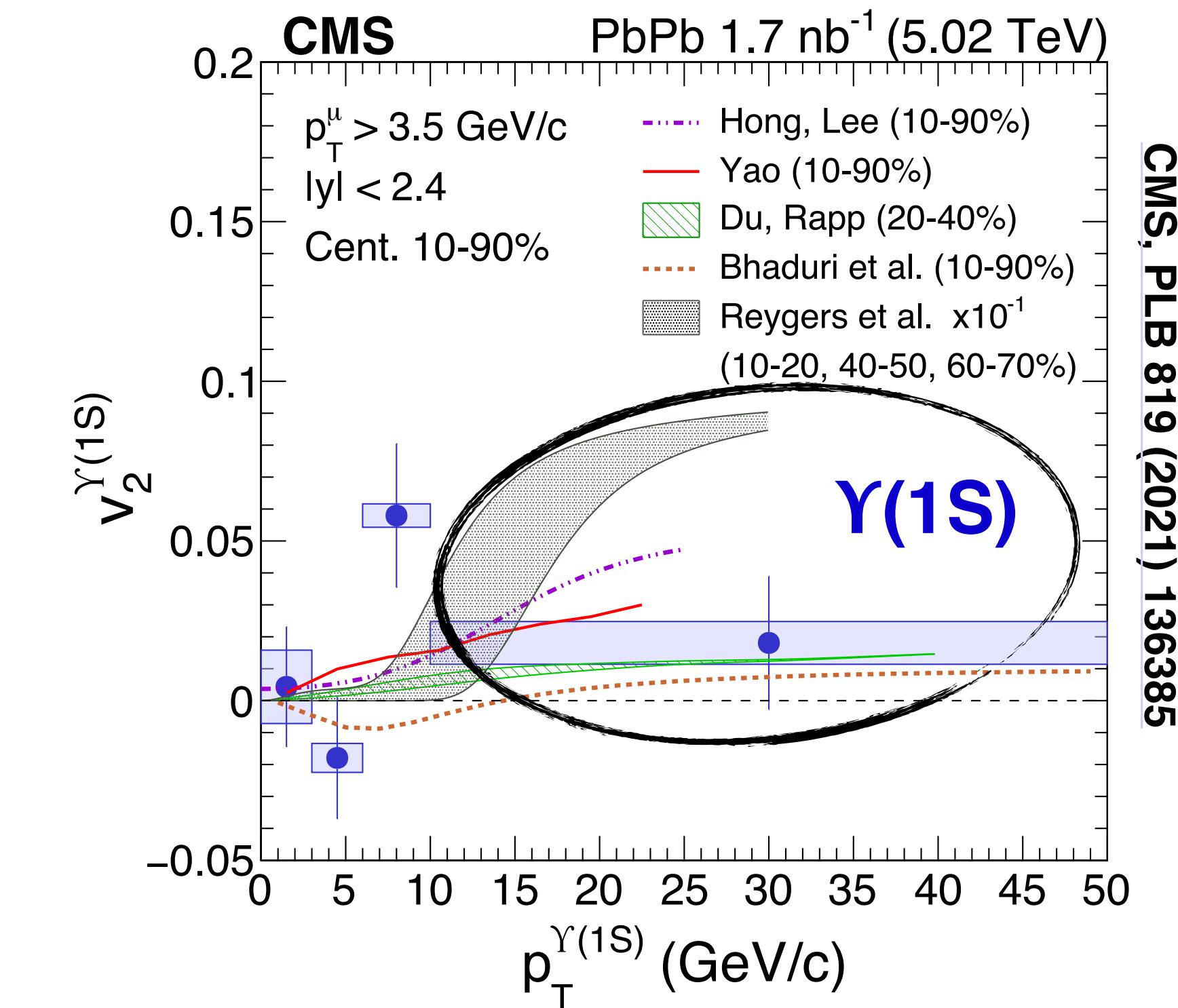
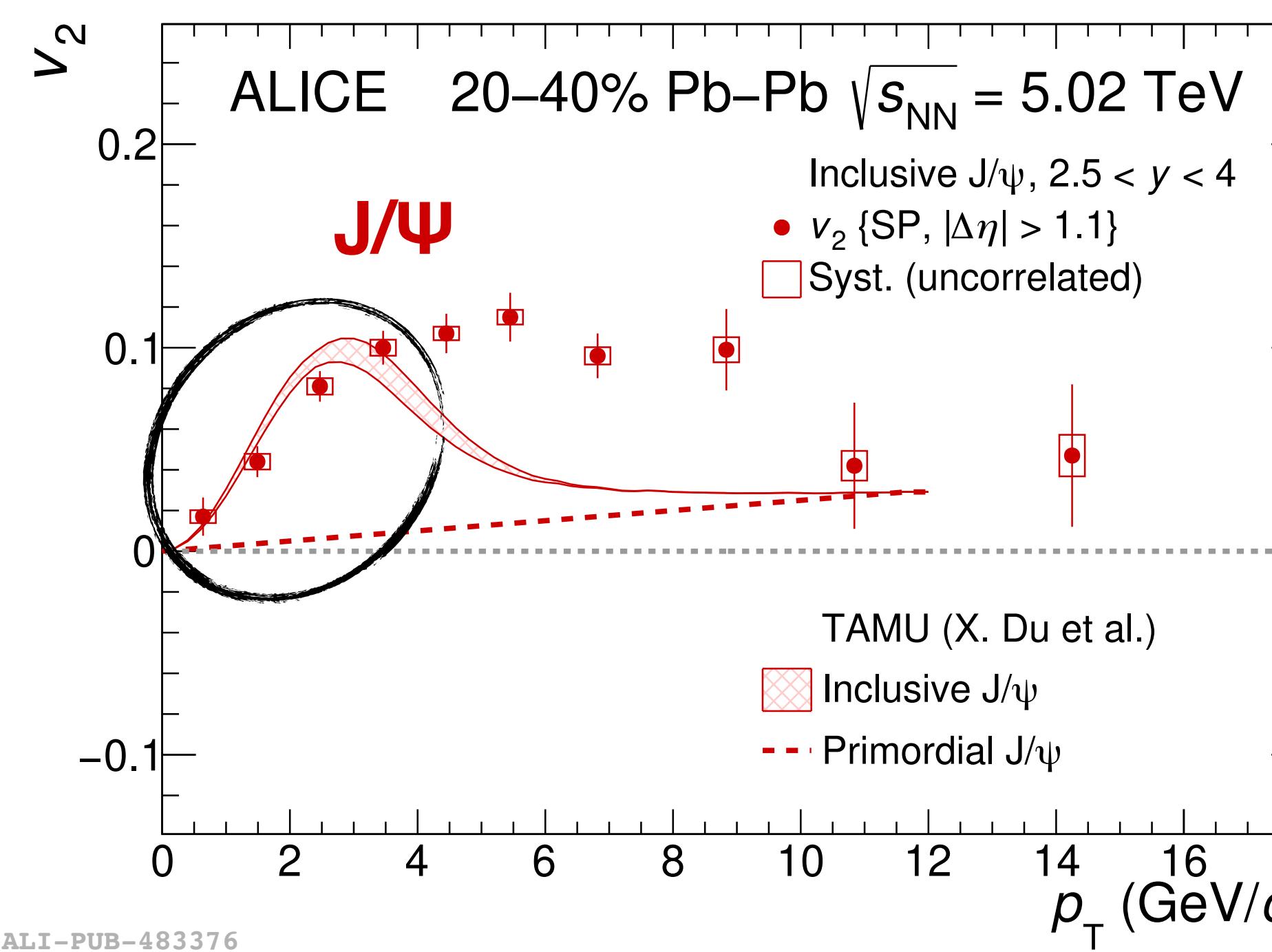
- J/ Ψ polarization in PbPb:
 - Polarization parameters close to zero.
 - Hint of J/ Ψ polarization towards low p_T .
 - Tension with pp LHCb λ_θ at low p_T in HX frame.
 - No significant centrality dependence.
 - Differences between reference frames.

Quarkonium polarization in PbPb



- J/Ψ polarization in PbPb:
 - Polarization parameters close to zero.
 - Hint of J/Ψ polarization towards low p_T .
 - Tension with pp LHCb λ_θ at low p_T in HX frame.
 - No significant centrality dependence.
 - Differences between reference frames.
- $\Upsilon(1S)$ polarization in PbPb:
 - Compatible with zero within uncertainties.

Quarkonium collectivity in PbPb

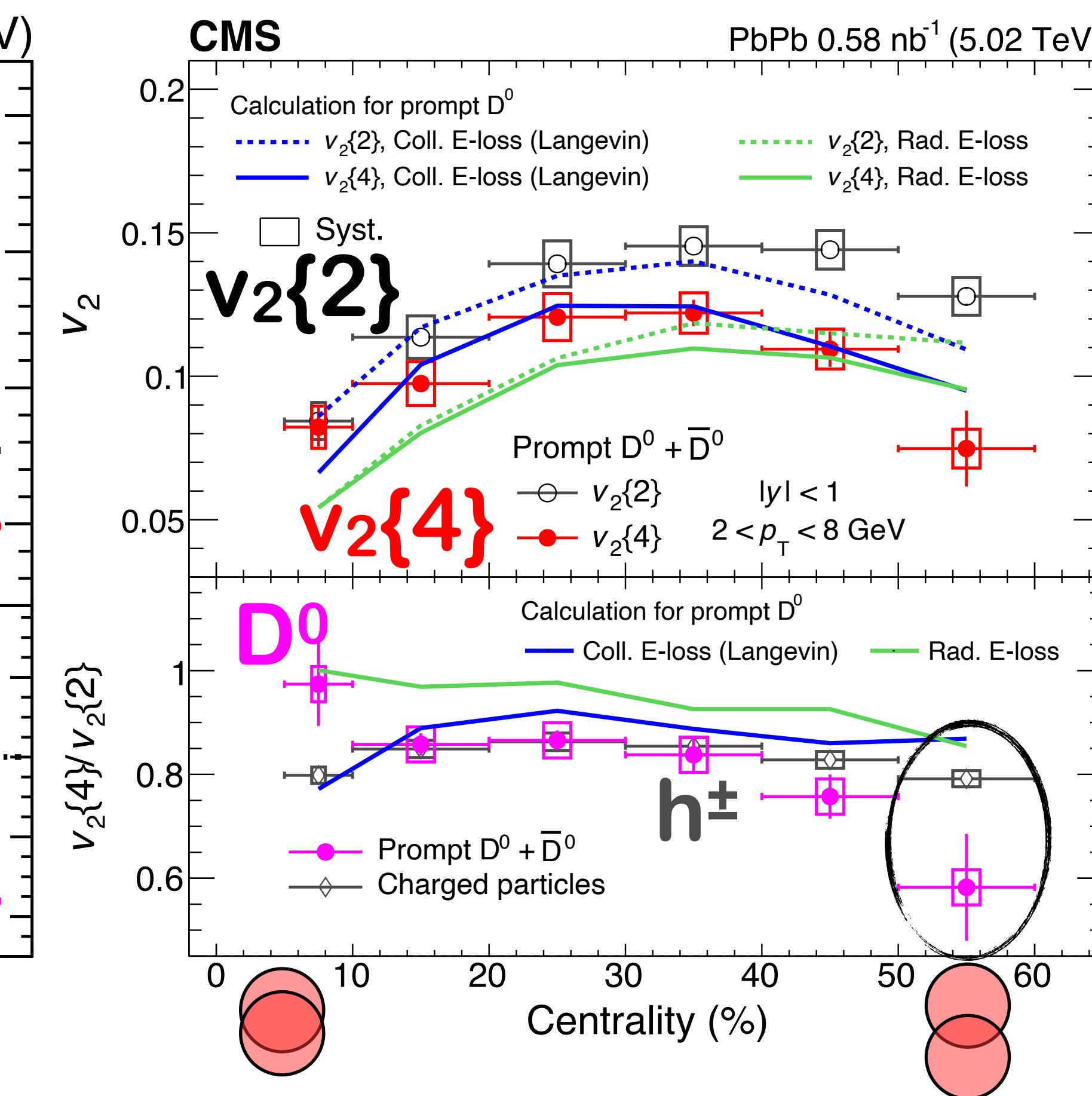
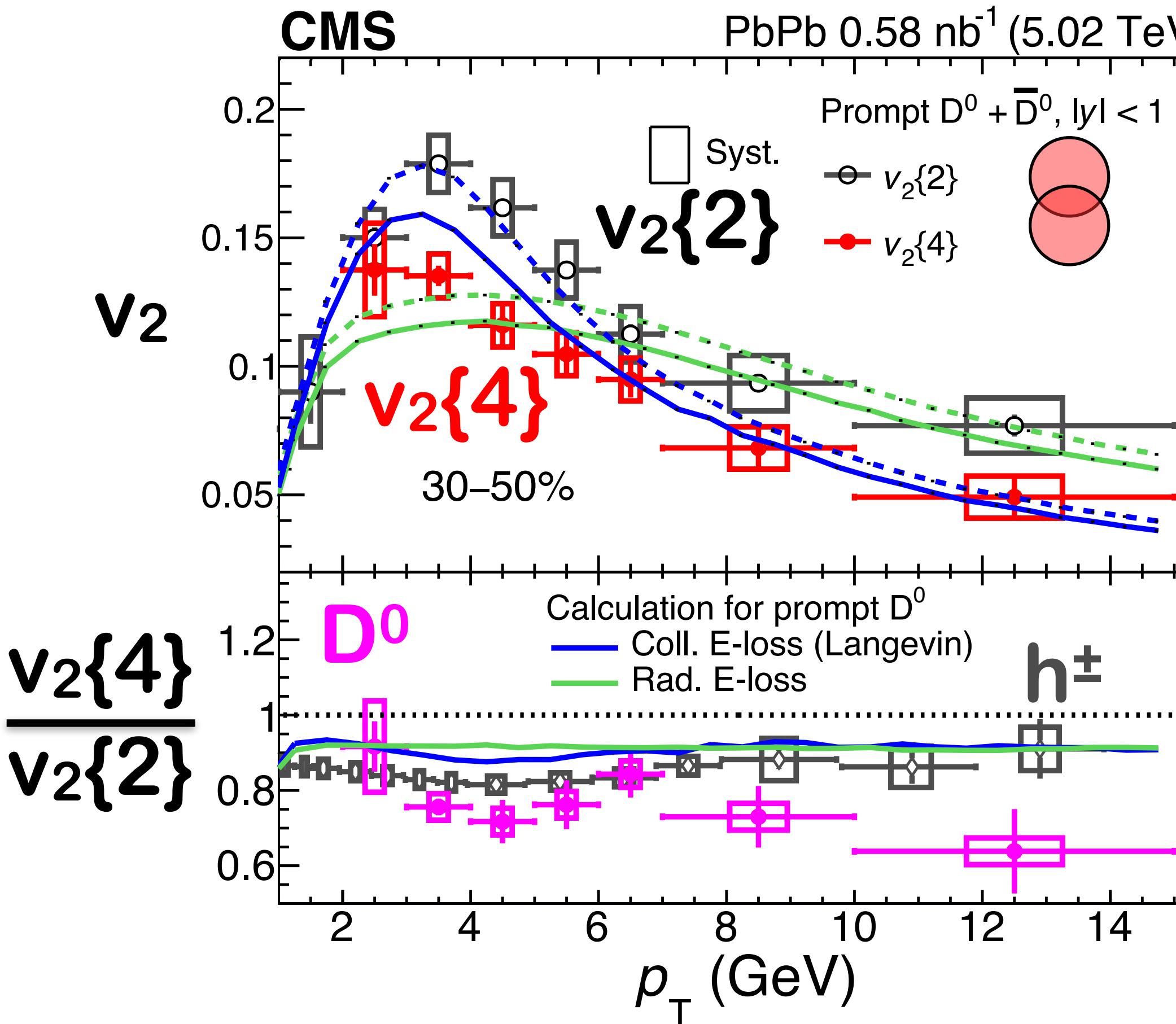


- Models with recombination describe low p_T .
- Large v_2 at high p_T not explained by TAMU.

- Models predict small v_2 at low p_T as in data.
- Clear differences start to appear at high p_T .

D⁰ flow fluctuations in PbPb

CMS, PRL 129 (2022) 022001



2-particle correlation mean

$$v_2\{2\}^2 \approx \langle v_2 \rangle^2 + \sigma^2$$

fluctuation

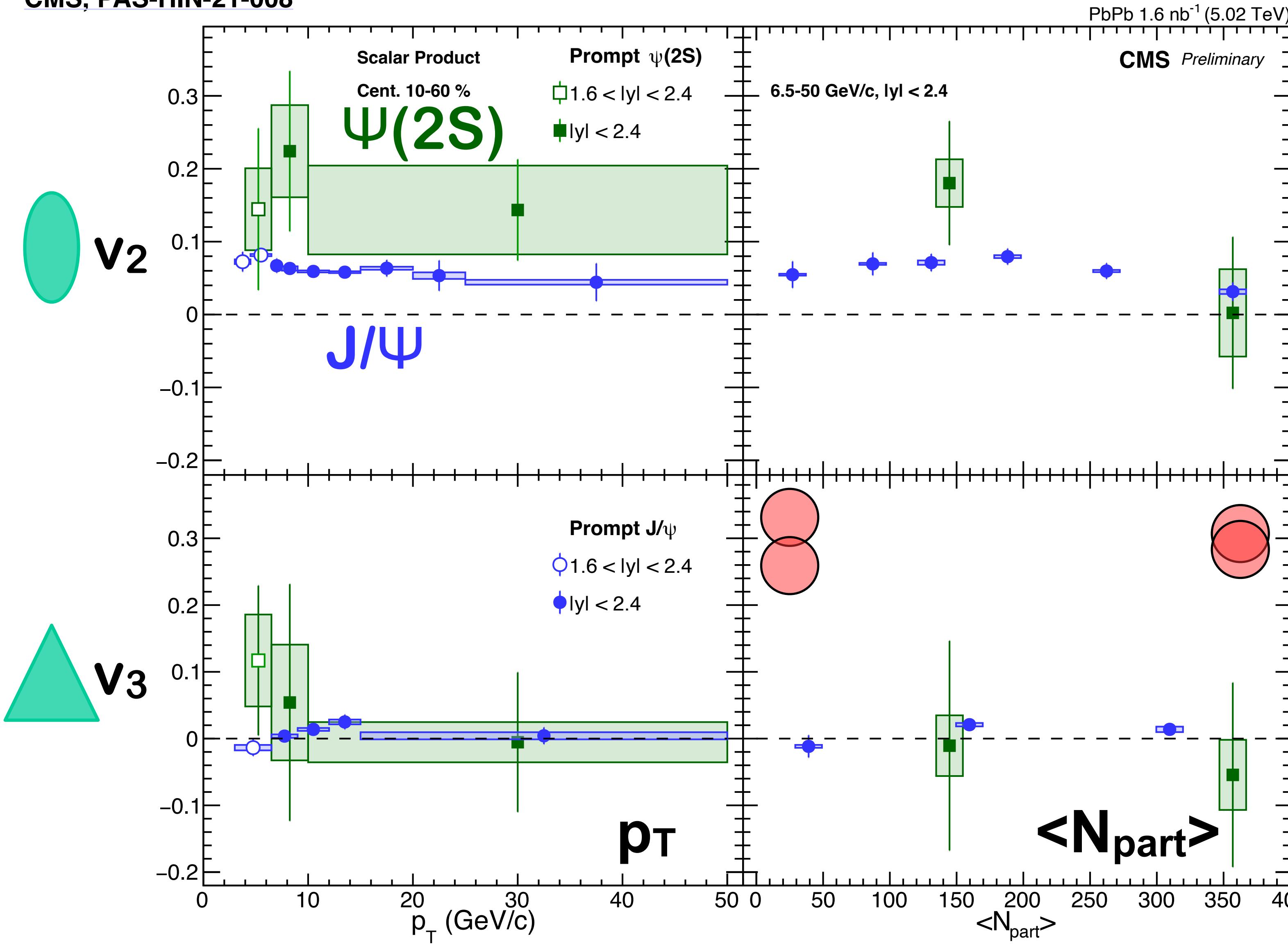
$$v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma^2$$

4-particle correlation

- $v_2\{n\}$ probe event-by-event fluctuations from initial geometry and final state effects.
- $h^\pm \sim D^0 v_2\{4\}/v_2\{2\}$ at cent < 40% → suggest initial state fluctuations are dominant.
- Hint of larger charm quark final state fluctuations at peripheral collisions.

Charmonium flow in PbPb

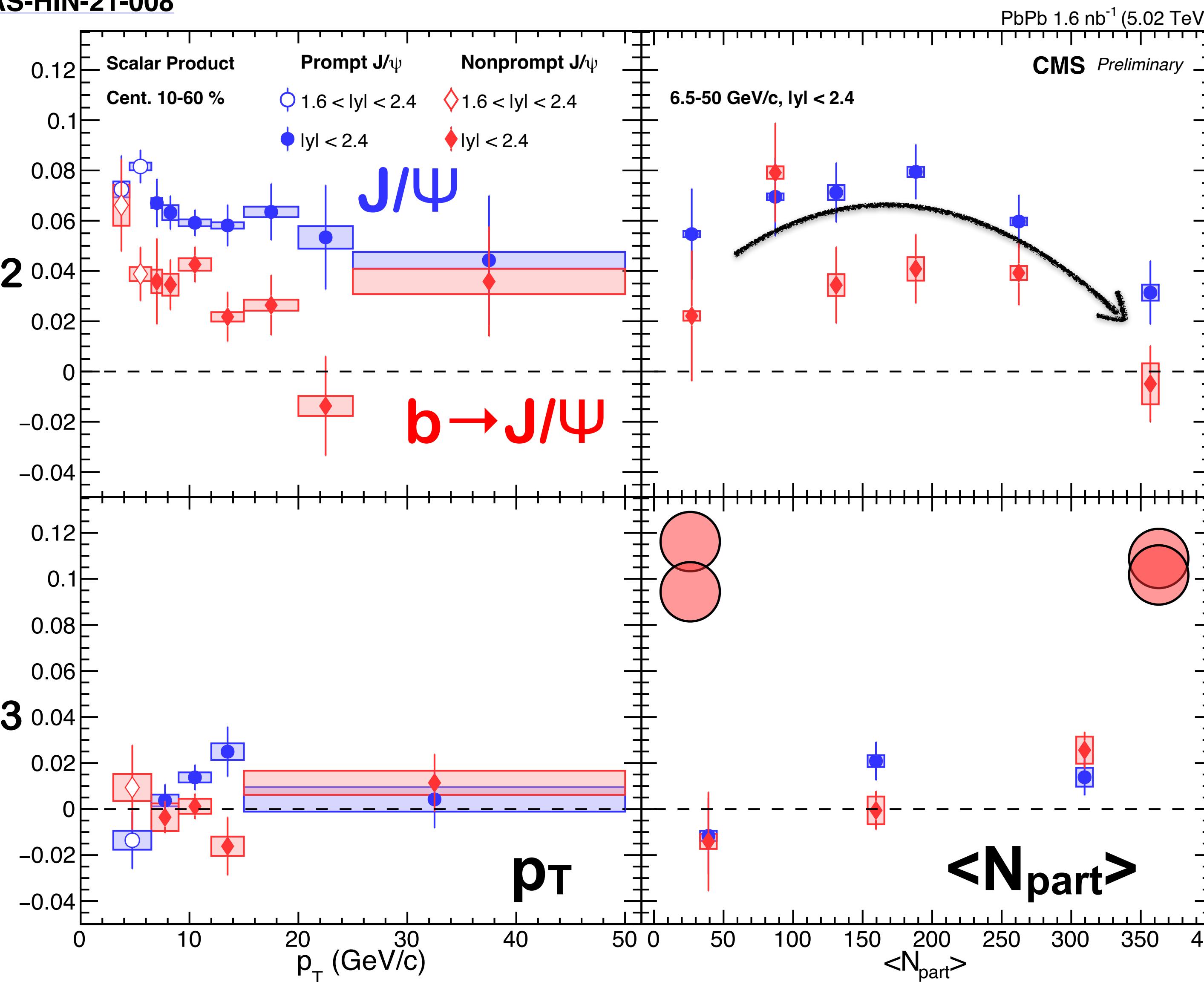
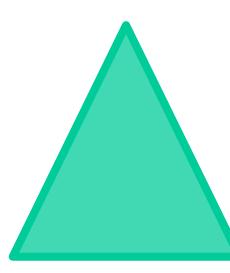
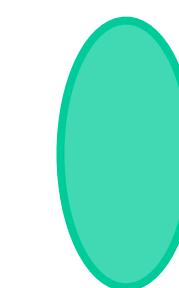
CMS, PAS-HIN-21-008



- First measurement of $\Psi(2S)$ flow.
- $\Psi(2S) v_2 \gtrsim J/\psi v_2 > 0 \rightarrow$ hint of larger v_2 for excited states.
- $\Psi(2S) v_3 \sim J/\psi v_3 \sim 0$.

Charmonium flow in PbPb

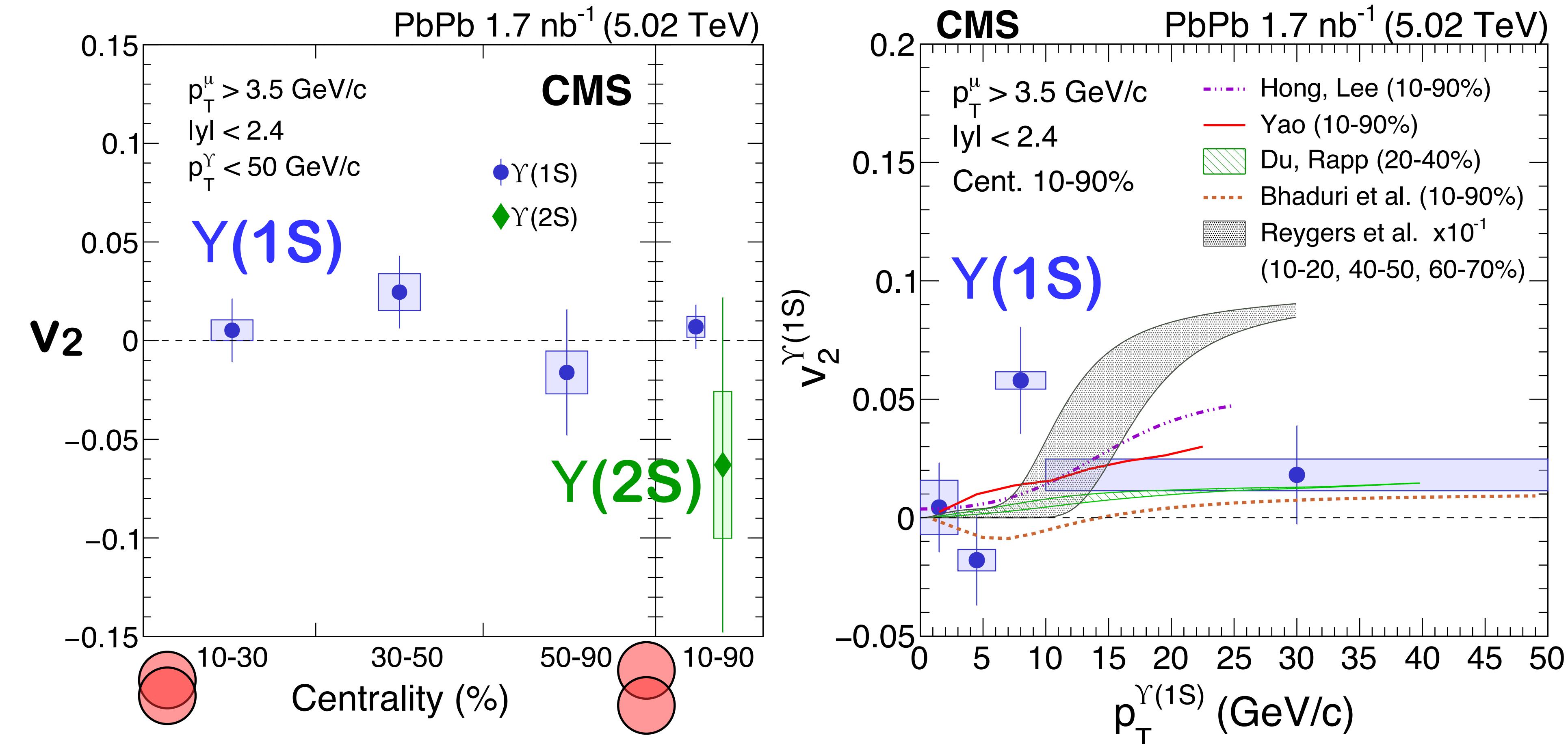
CMS, PAS-HIN-21-008



- First measurement of $\Psi(2S)$ flow.
- $\Psi(2S) v_2 \gtrsim J/\Psi v_2 > 0 \rightarrow$ hint of larger v_2 for excited states.
- $J/\Psi v_2 > b \rightarrow J/\Psi v_2 > 0 \rightarrow$ different flow for charm and beauty quarks.
- v_2 increase and then decrease from central to peripheral events \rightarrow as expected by hydrodynamics.
- $\Psi(2S) v_3 \sim J/\Psi v_3 \sim b \rightarrow J/\Psi v_3 \sim 0$.

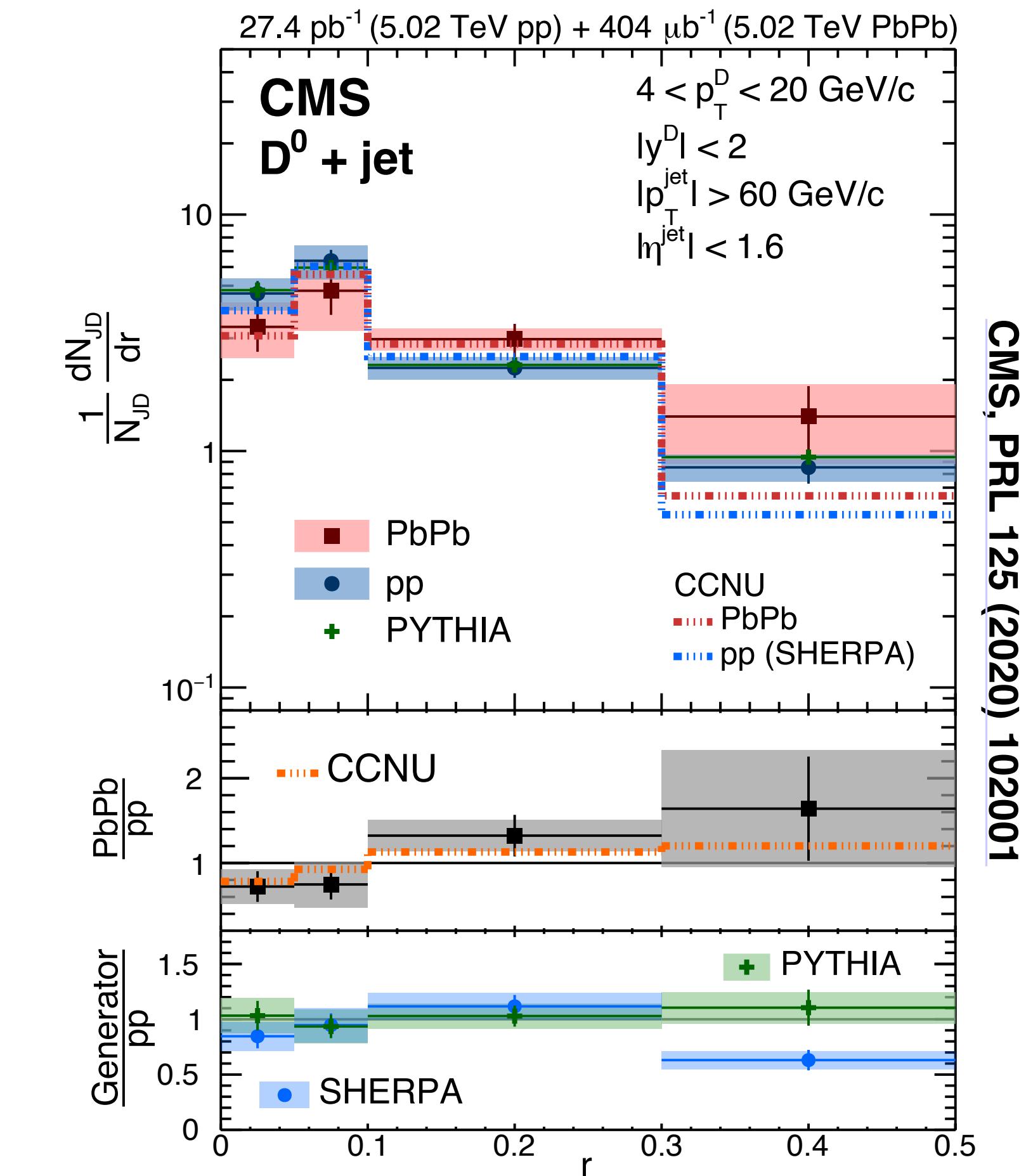
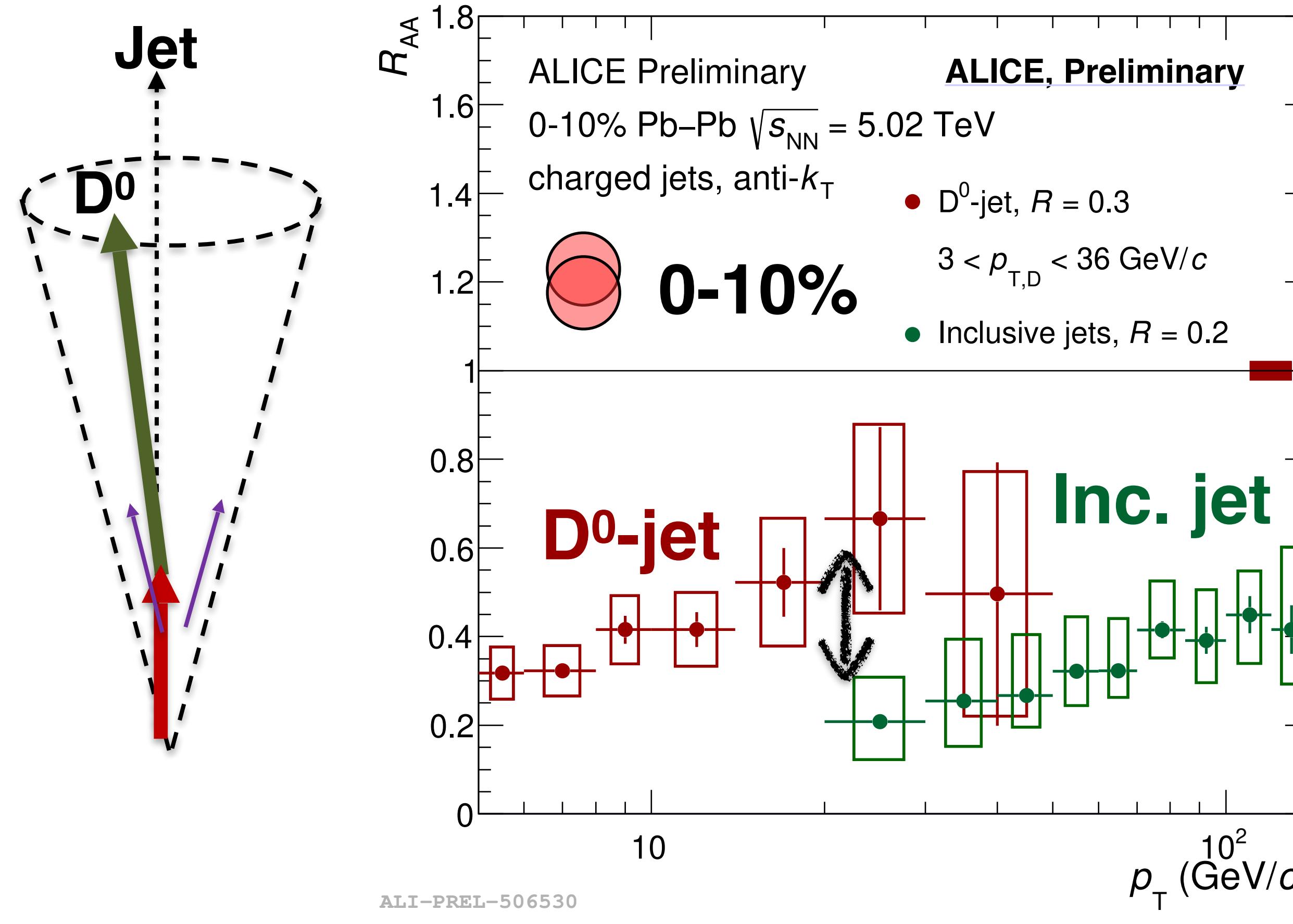
Bottomonium flow in PbPb

CMS, PLB 819 (2021) 136385



- $\gamma(1S) v_2$ consistent with 0 → no significant bottomonium collectivity.
- Current precision will be improved with future LHC Run 3/4 data → help constrain models.

D⁰-jet production in PbPb

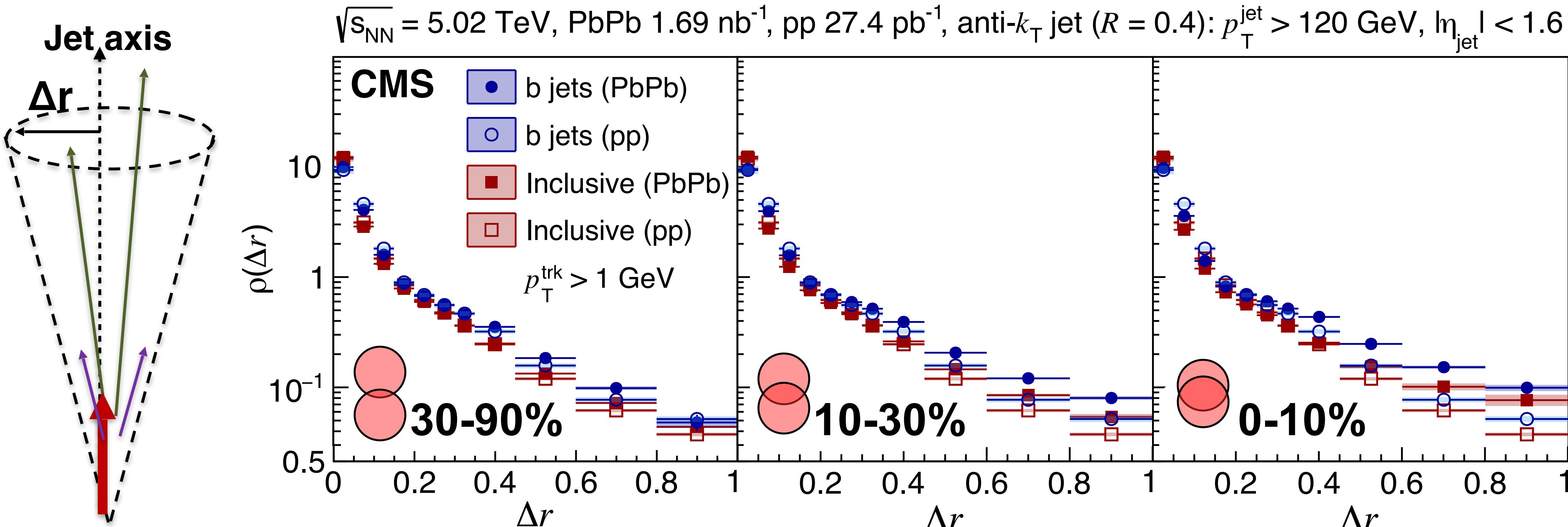


- Hint of less suppression of D⁰-jets compared to inclusive jets.
- Comparison sensitive to energy loss differences between quarks and gluons.
- R_{AA} values may also be affected by different dN/dp_T slopes and fragmentation.

b-jet radial shape in PbPb

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\sum_{\text{jet}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_{\text{T}}^{\text{trk}}}{\sum_{\text{jet}} \sum_{\text{trk}} p_{\text{T}}^{\text{trk}}}$$

CMS, arXiv:2210.08547
Submitted to PLB

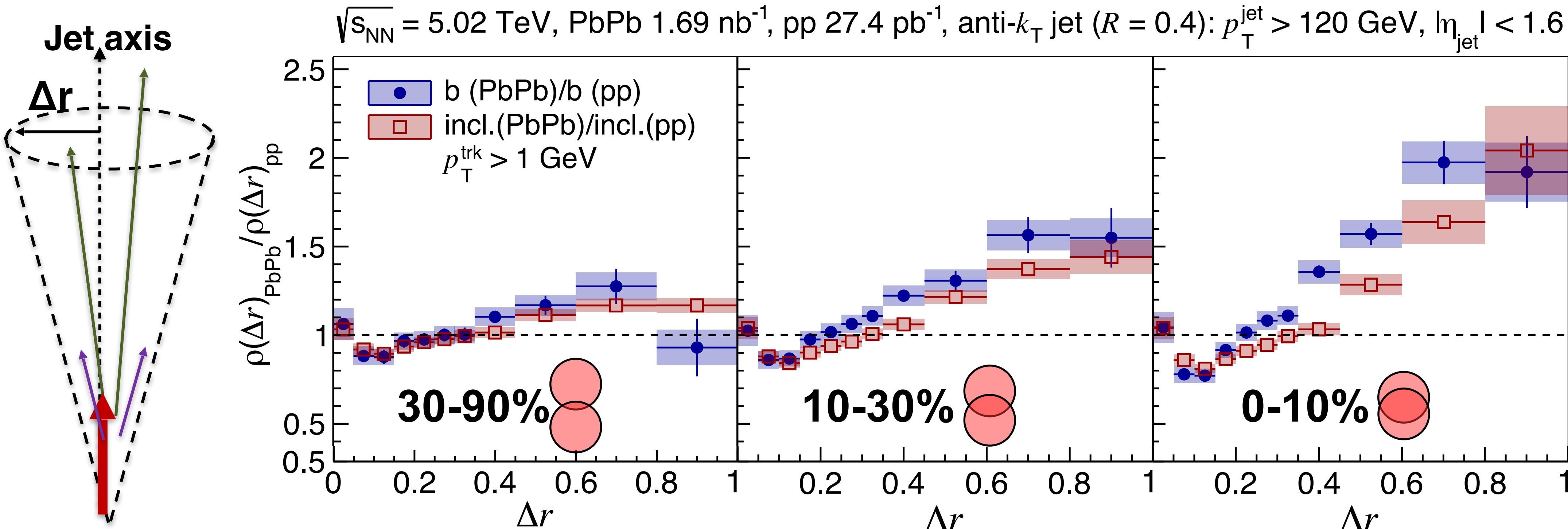


- b and inclusive jet shapes are broader in PbPb collisions.

b-jet radial shape in PbPb

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{\sum_{\text{jet}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_T^{\text{trk}}}{\sum_{\text{jet}} \sum_{\text{trk}} p_T^{\text{trk}}}$$

CMS, arXiv:2210.08547
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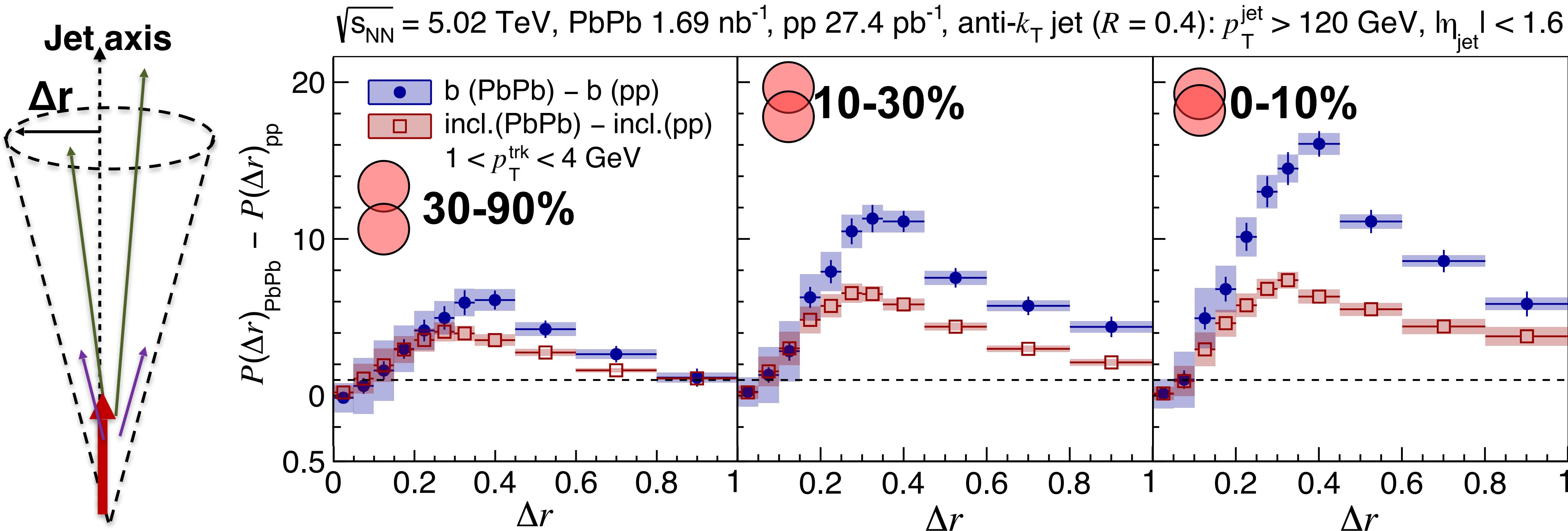


- b and inclusive jet shapes are broader in PbPb collisions.
- Relative modification of b jets slightly stronger than inclusive jets.

b-jet radial shape in PbPb

$$P(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_{\text{T}}^{\text{trk}}$$

CMS, arXiv:2210.08547
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- b and inclusive jet shapes are broader in PbPb collisions.
- Relative modification of b jets slightly stronger than inclusive jets.
- b jets accumulate more low p_{T} tracks at large radius than inclusive jets.