Latest measurements of open heavy flavour particles from LHC

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Heavy Flavour workshop

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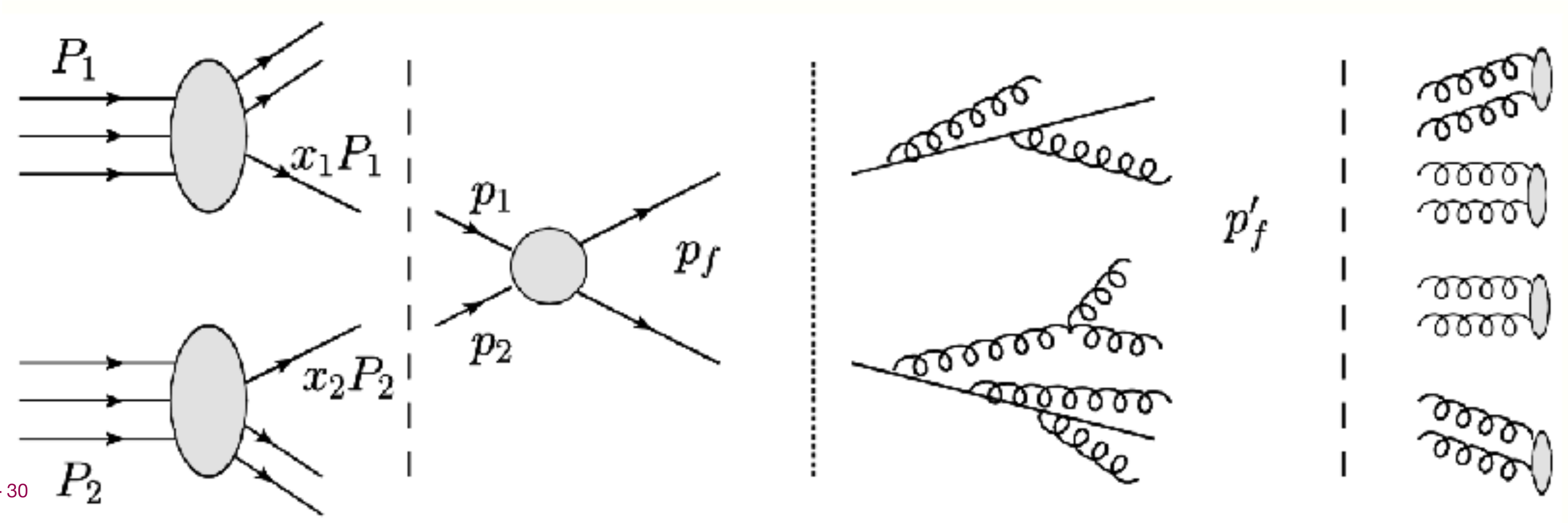
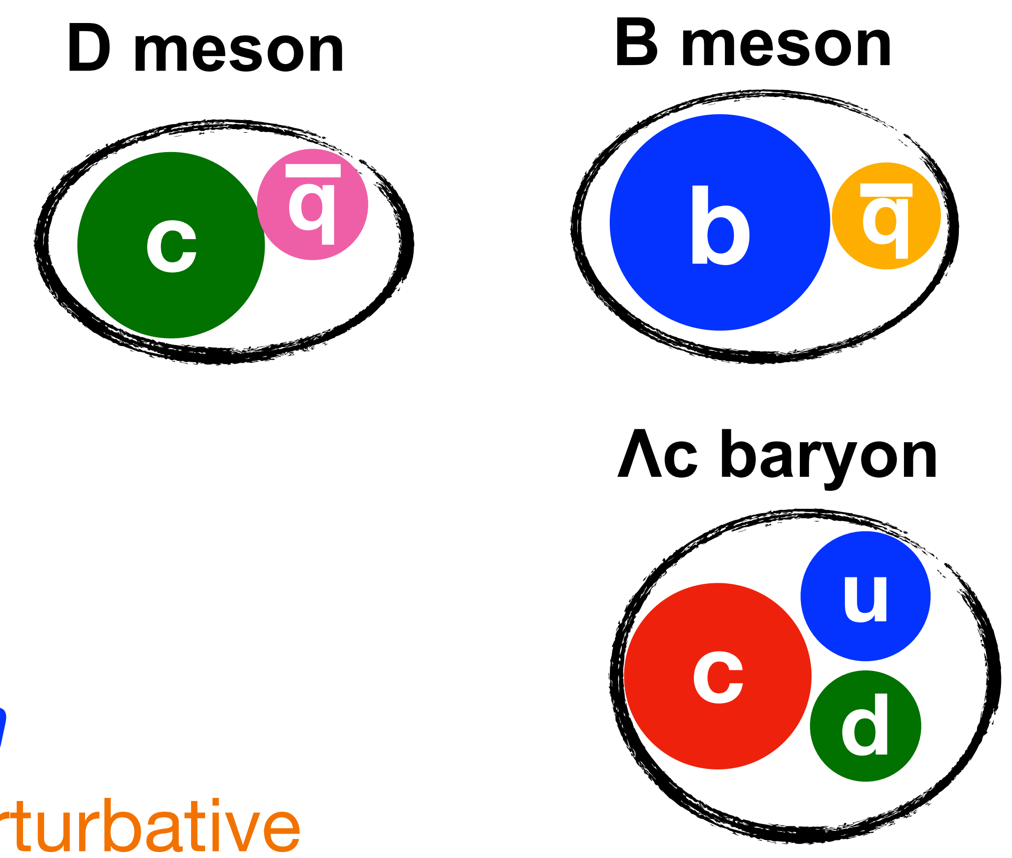
The University of Texas at Austin

Introduction

- Heavy quarks (charm and beauty) are primarily produced in hard scattering processes with large momentum transfer
- Production cross-sections is calculated in pQCD by the convolution of 3 ingredients utilizing a factorization approach.



Physics Procedia 51 (2014) 25 – 30



Fractorization theorem

$f_i(x_i, \mu_F)$ *pdf* — non-perturbative, Initial condition from data

$d\sigma$ *hard x-section* — perturbative

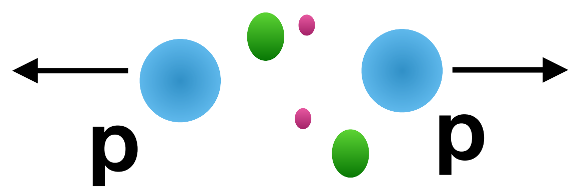
Parton shower — perturbative

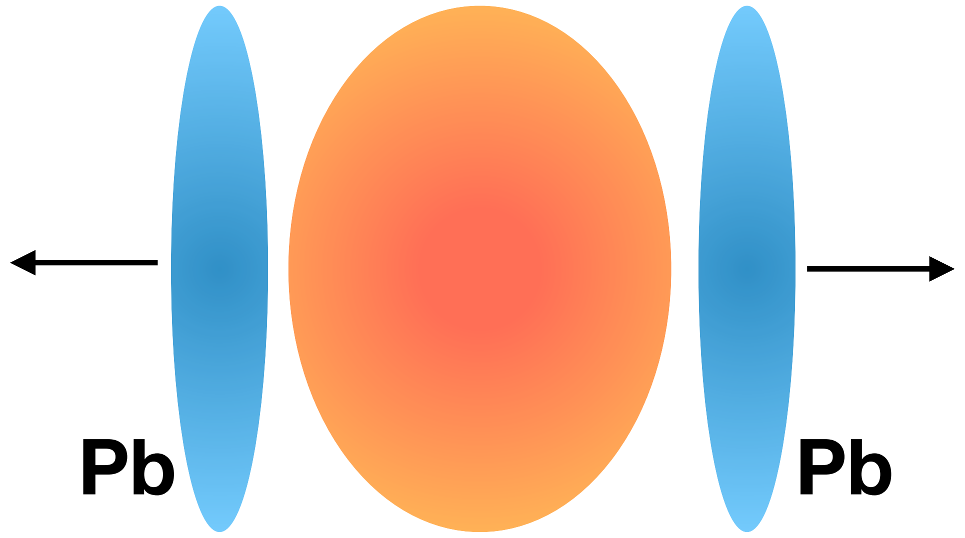
Hadronization — non-perturbative, phenomenology + fit to data (e+e-, e-p)

$$\frac{d\sigma^{\mathrm{D}}}{dp_T^{\mathrm{D}}}(\mu_F, \mu_R) = PDF(x_1)\ PDF(x_2) \times \frac{d\sigma^{\mathrm{c}}}{dp_T^{\mathrm{c}}} \times D_{\mathrm{c}\to\mathrm{D}}(z = p_{\mathrm{D}}/p_{\mathrm{c}})$$

Measurements of heavy flavor particles—> test the perturbative QCD (pQCD) calculations and provide input for the data driven non-perturbative QCD (npQCD) quantities.

System size dependence





pp and p-A

- Test and constraint pQCD calculations and phenomenological models.
- Jet fragmentation and hadronization
- Multiplicity dependent studies

Pb—Pb

- Study transport properties of QGP using heavy quark interactions with medium constituents.
- Hadronization in the presence of QGP.

This talk:

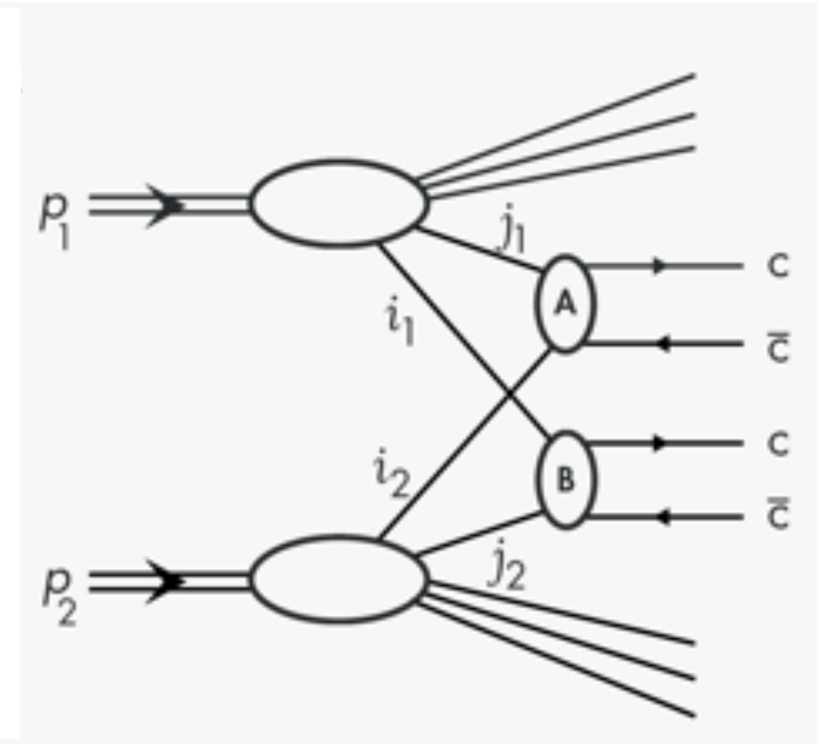
- **Latest charm and beauty hadron measurements from LHC experiments (most from QM 2025)**

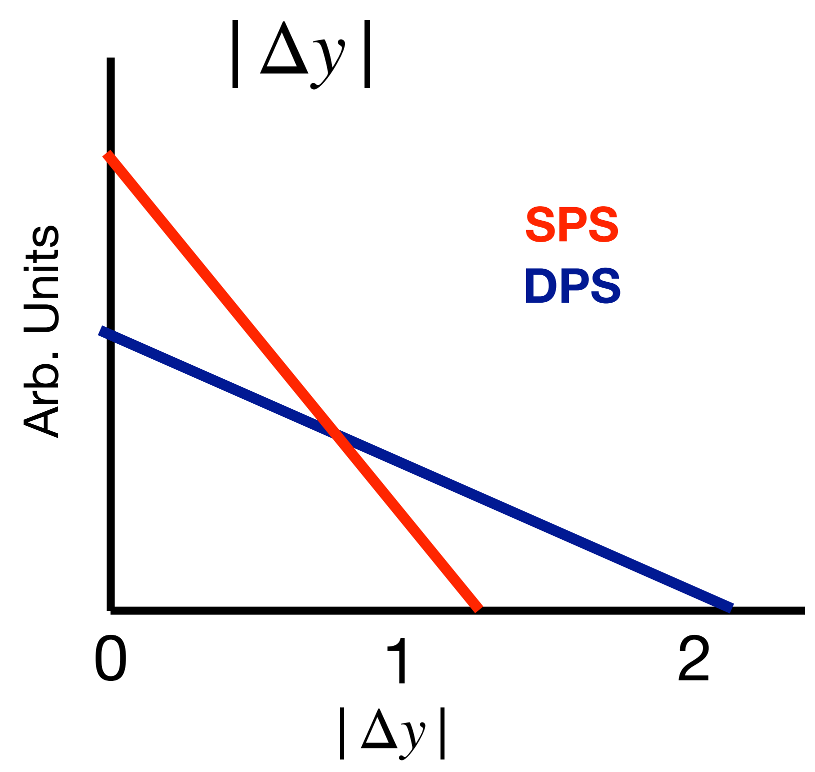
Double charm production

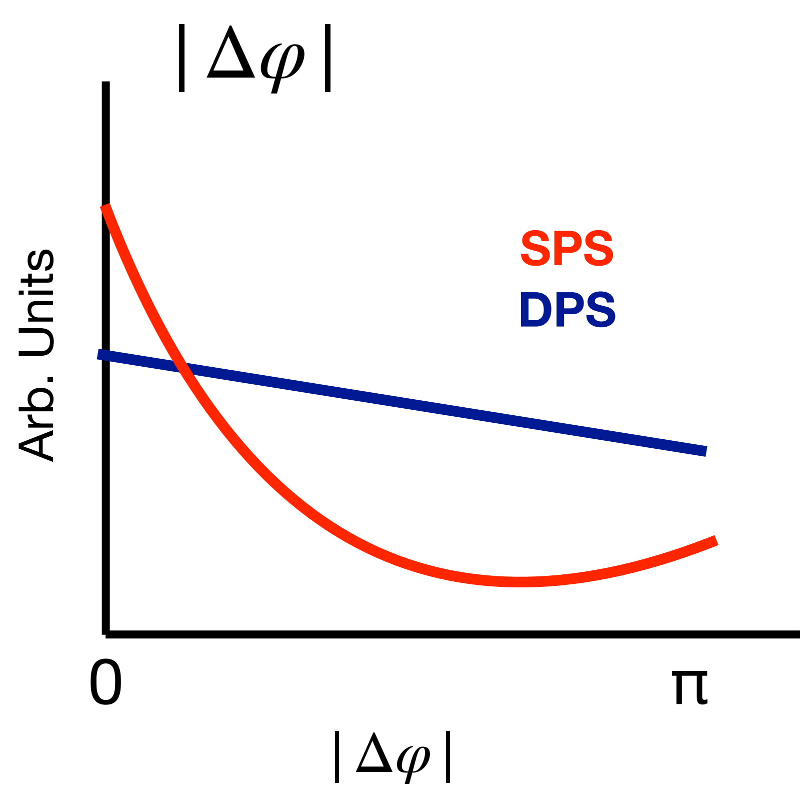
Measurement of double parton scattering (DPS) scattering

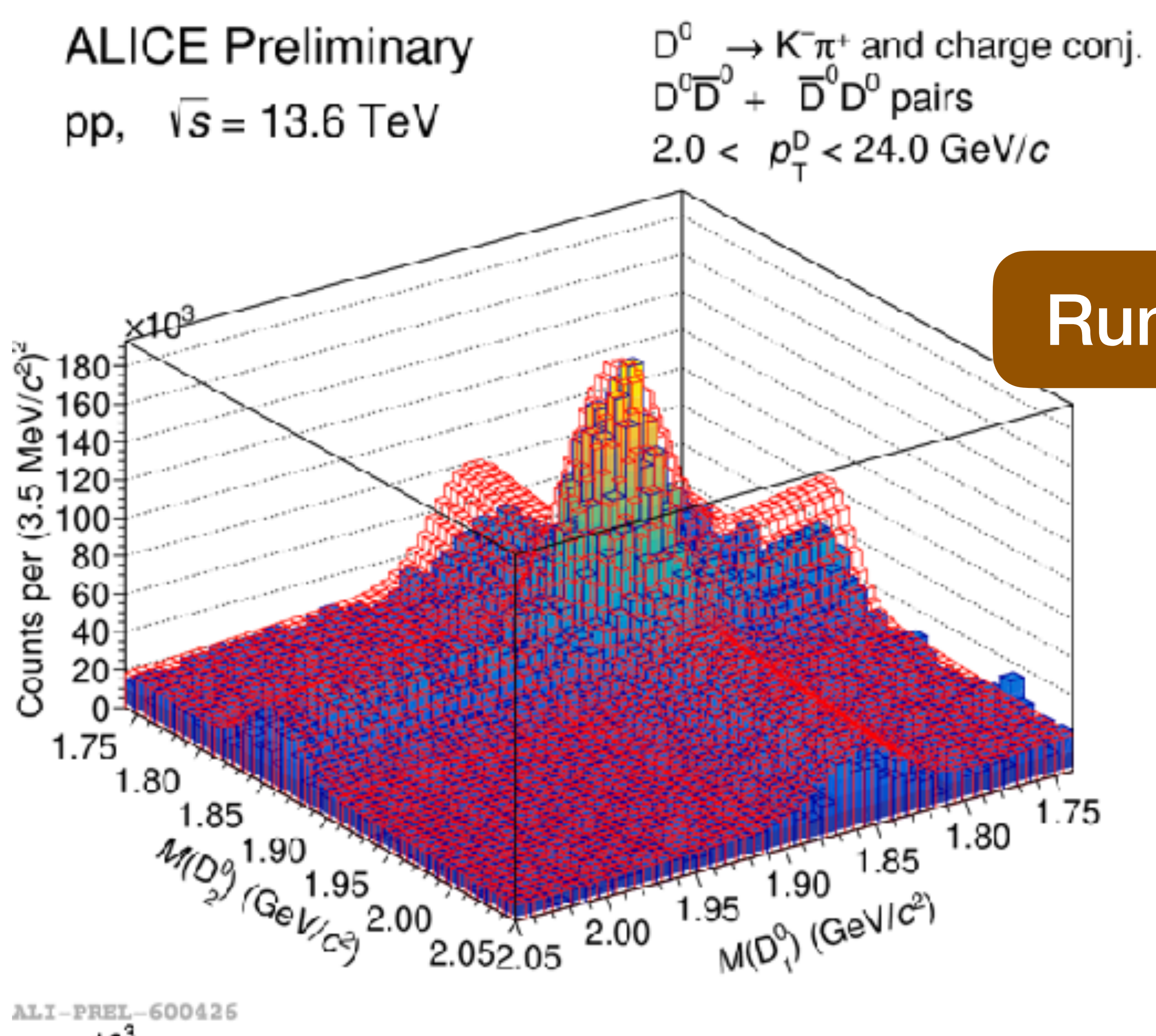
Two parton-parton collisions in a single hadron-hadron collisions —> measured via double-charm production
—> significant at LHC energies.

Different kinematic distributions of $c\bar{c}$ pairs for single parton scattering (SPS) and DPS









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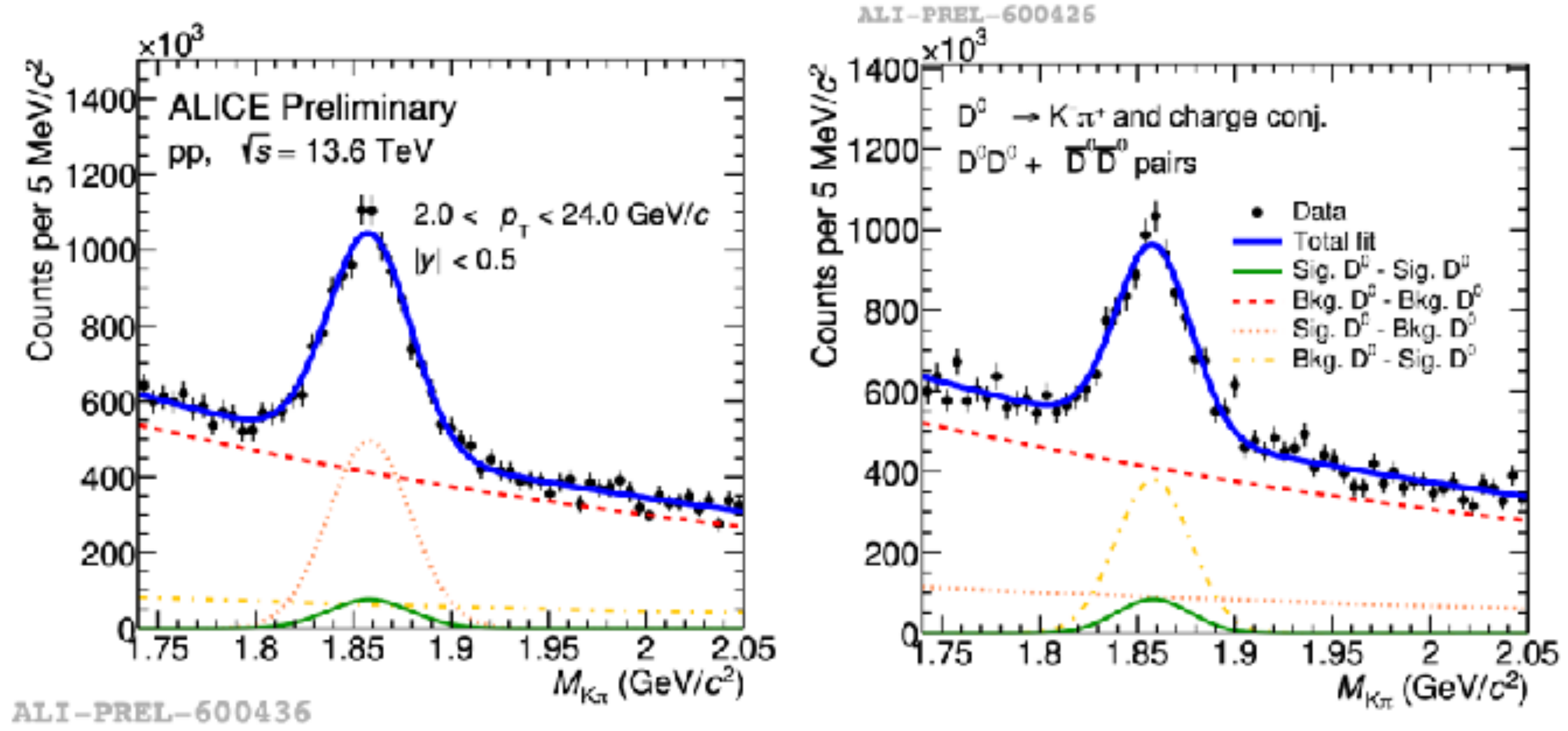
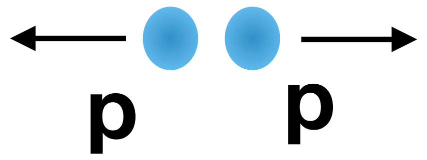
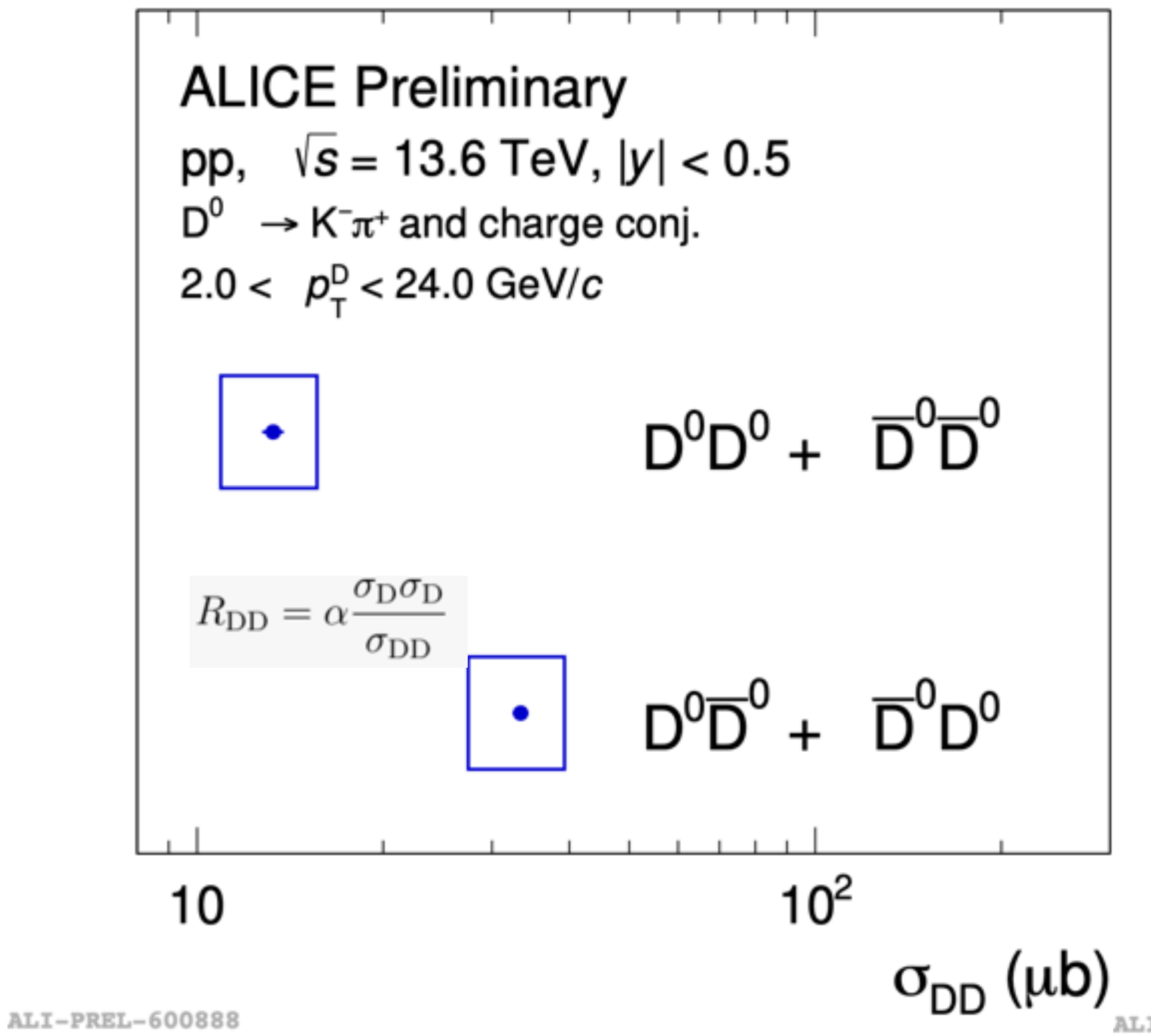


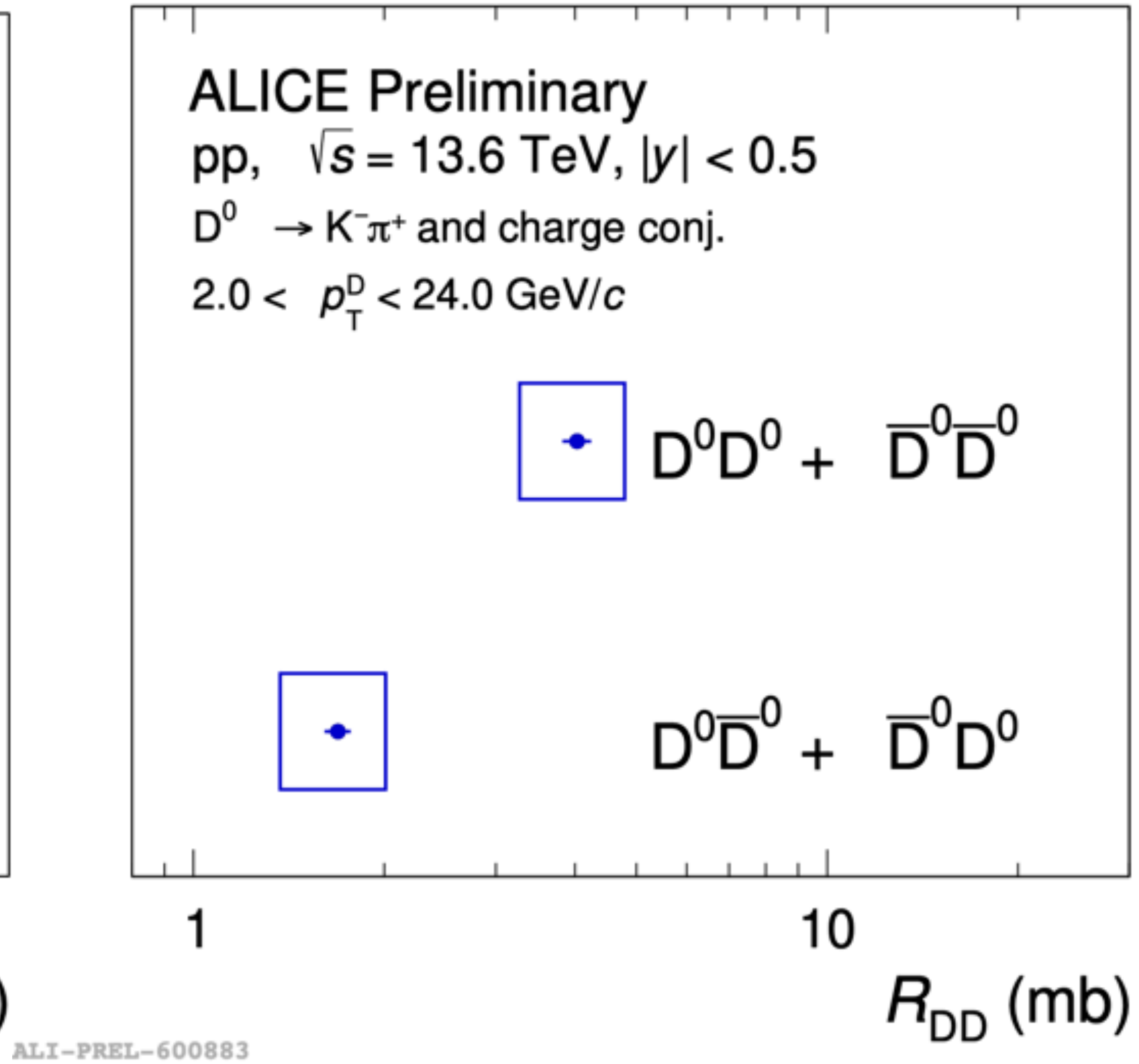
Unbinned-likelihood fit to the 2D invariant mass distribution to extract $D^0\bar{D}^0$ pair yields, and similarly D^0D^0 pair yields.

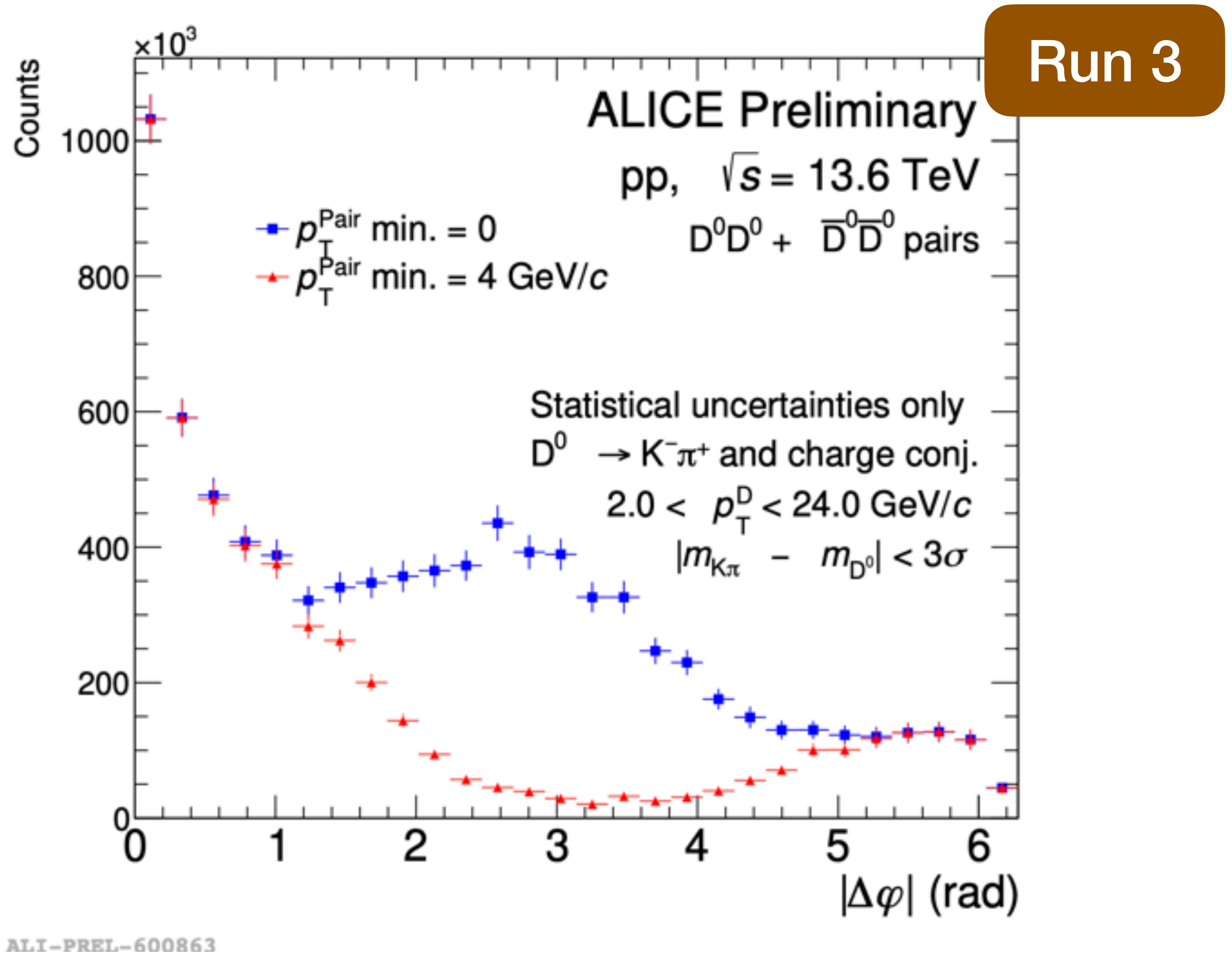
Double charm production



Measurement of double parton scattering (DPS) scattering







D^0D^0 and $D^0\bar{D}^0$ cross-sections measures as:

$$\sigma_{DD}^{prompt} = \frac{N_{raw} \cdot f_{prompt}^2}{(Acc \times \epsilon)^2 \cdot BR^2(D^0 \to K^+\pi^-) \cdot L_{int}}$$

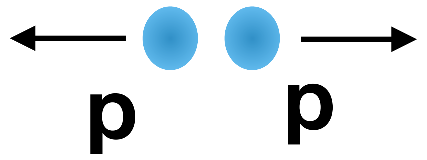
Ratio of single charm cross-section to double charm cross-section

$$R_{DD} = \alpha \frac{\sigma_D \sigma_D}{\sigma_{DD}}$$

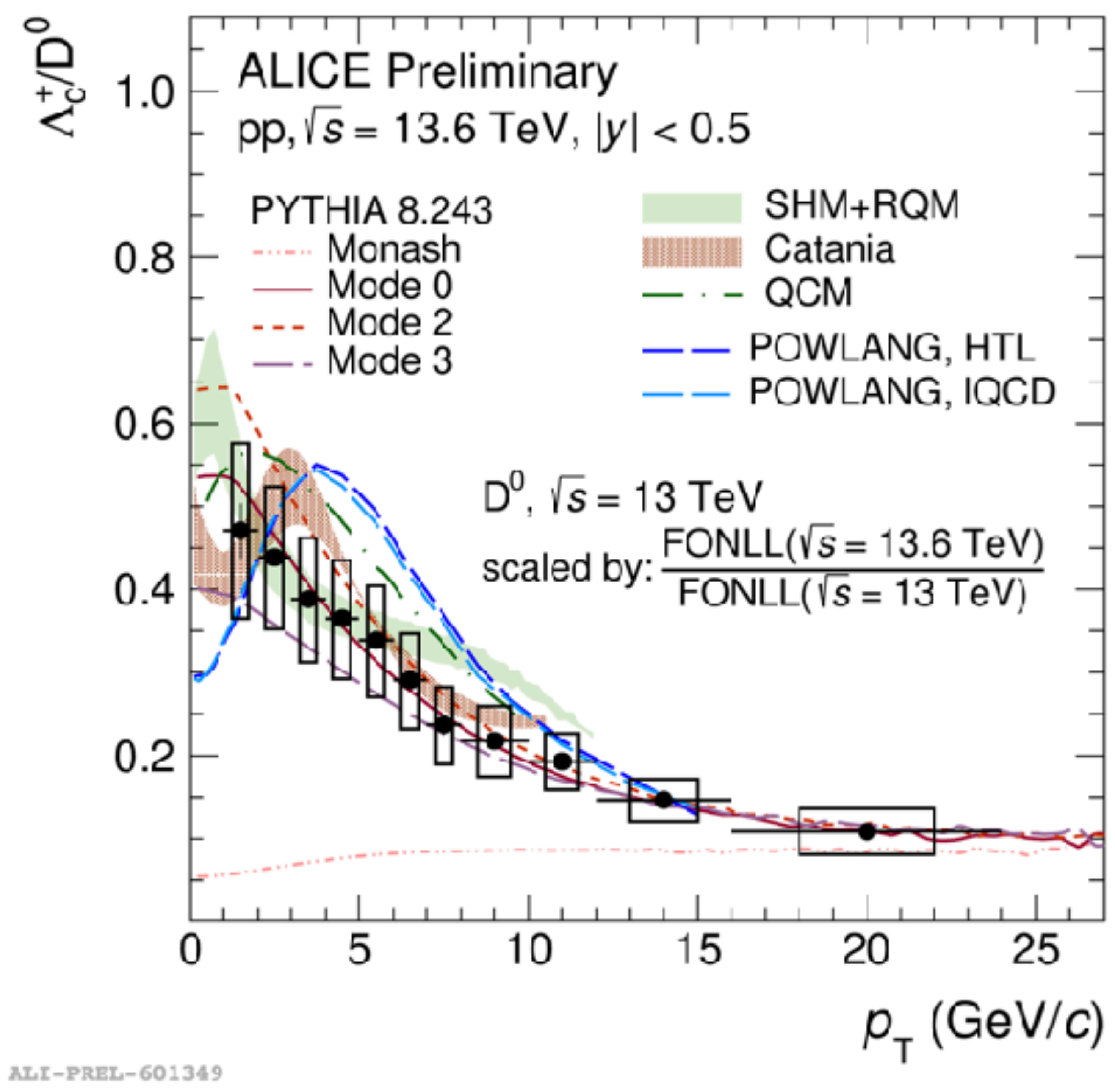
$\alpha = 1/4$, σ_D from previous measurement

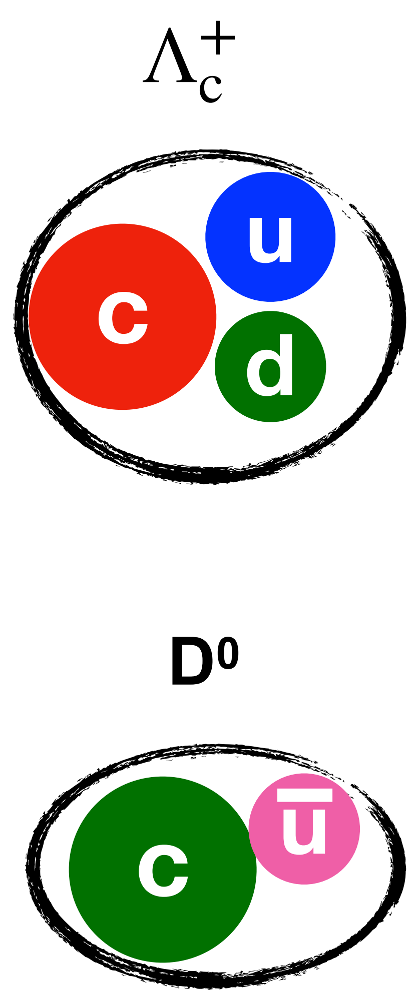
Next: separate SPS and DPS components in the D^0D^0 measurements to extract effect cross-section using $D^0D^0\Delta\varphi$ distribution

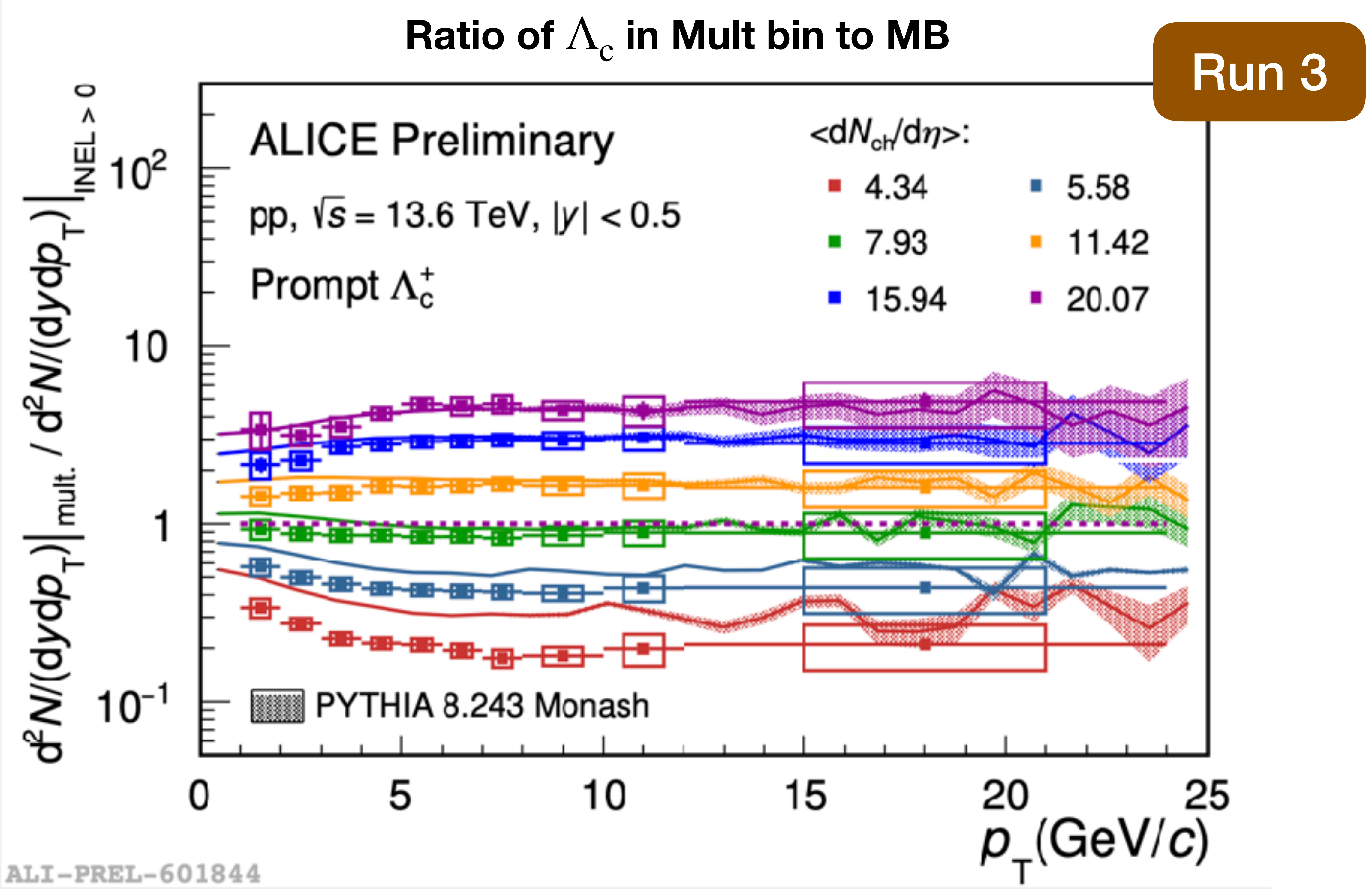
Charm hadronisation with Λ_c



Study charm quark hadronization using baryons





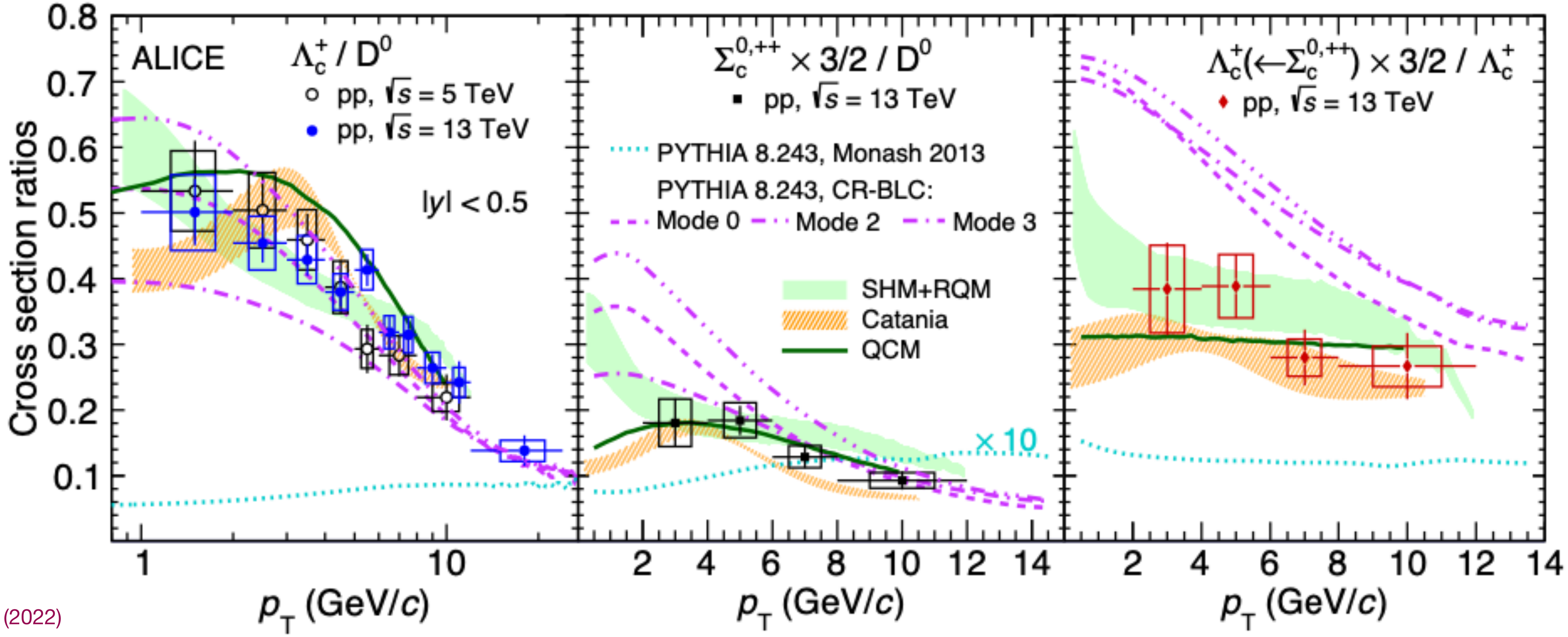


- Λ_c/D^0 ratio in pp higher than e^+e^- collisions; Strong p_T dependence
- Models based on fragmentation function parametrized on e^+e^- data (PYTHIA 8 Monash) cannot describe data.
- Different description of hadronization required.
  - PYTHIA 8 (CR-BLC), SHM+RQM, Catania, and QCM.

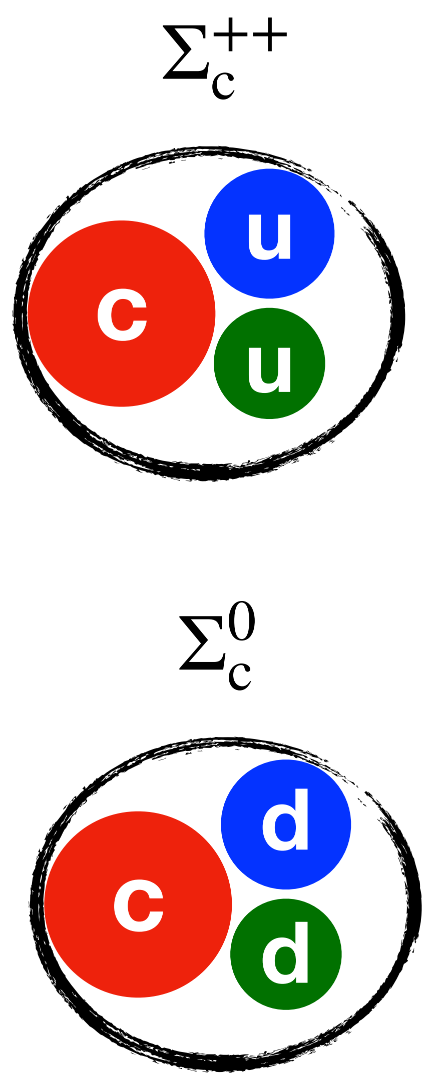
- p_T differential yield increases from lowest to the highest multiplicity class.
- Ratio to INEL > 0 increases (decreases) with increasing p_T for the highest (lowest) multiplicity class.
  - Hardening of the p_T spectra with increasing multiplicity.
- Data qualitatively described by PYTHIA Monash.

Charm Hadronization with $\Sigma_c^{++,0}$

Study charm quark hadronization using baryons



PRL 128,, 012001 (2022)



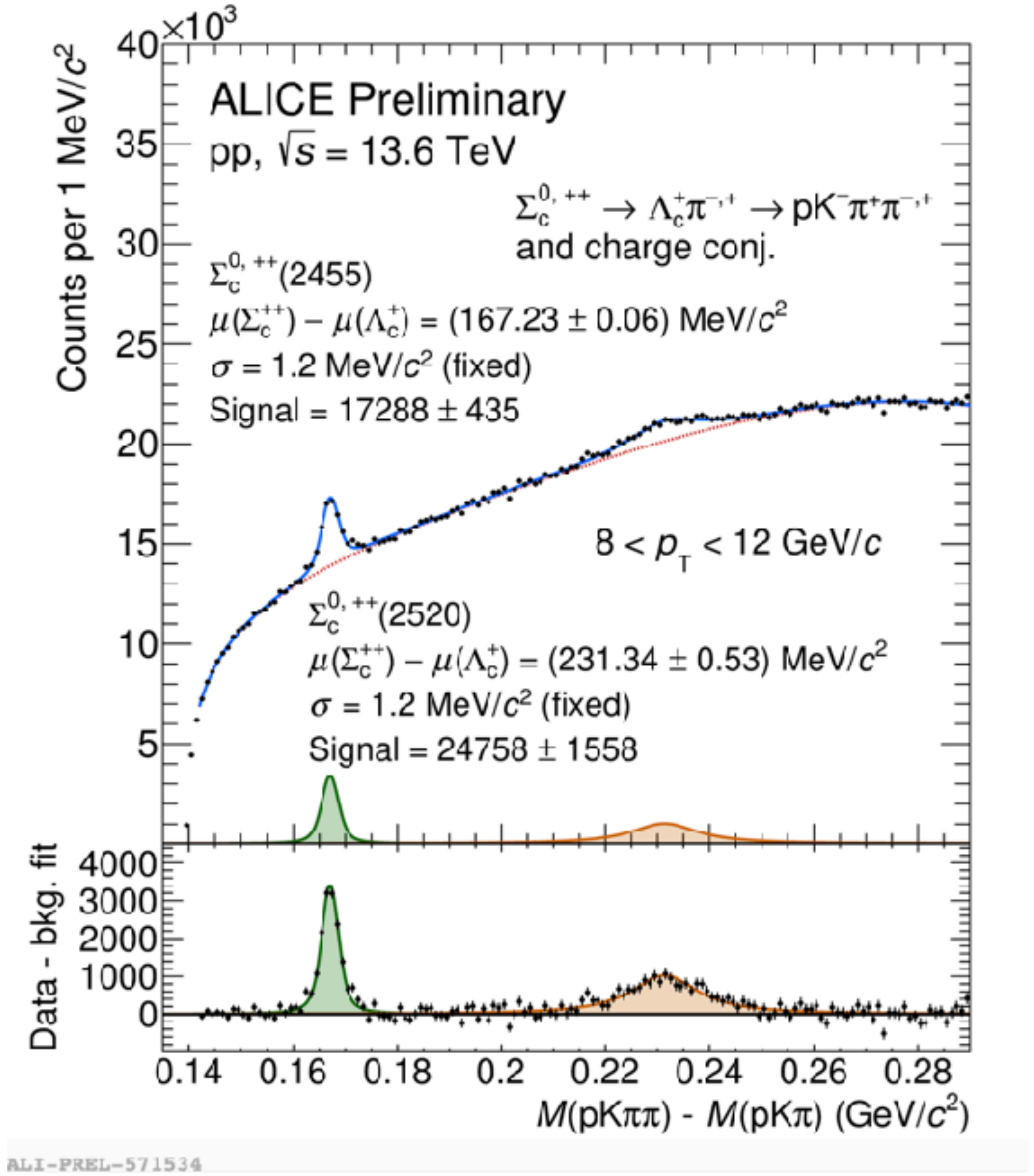
- $\Sigma_c^{++,0}/D^0$ and $\Lambda_c^+(\leftarrow \Sigma_c^{++,0})/\Lambda_c^+$ ratio in pp collisions higher than in e+e-
  - $\Sigma_c^{++,0}/D^0$ underestimated by PYTHIA 8 Monash tune; Described by other models
  - $\Lambda_c^+(\leftarrow \Sigma_c^{++,0})/\Lambda_c^+$ overestimated by PYTHIA 8 CR-BLC
- **Contribution from excited charm baryons?**

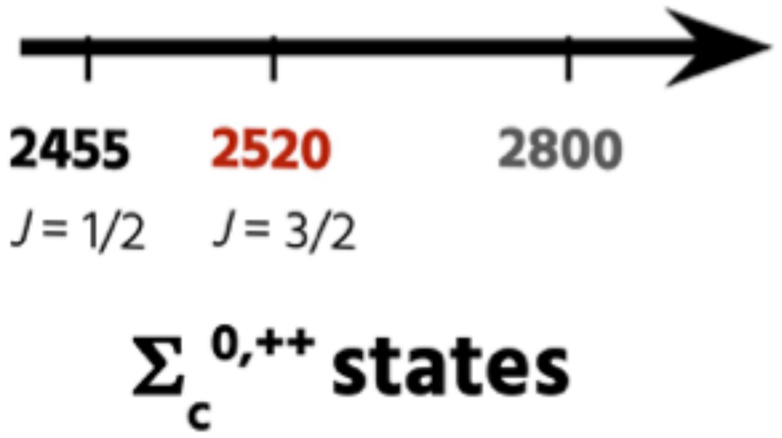
Himanshu Sharma
@ QM2025

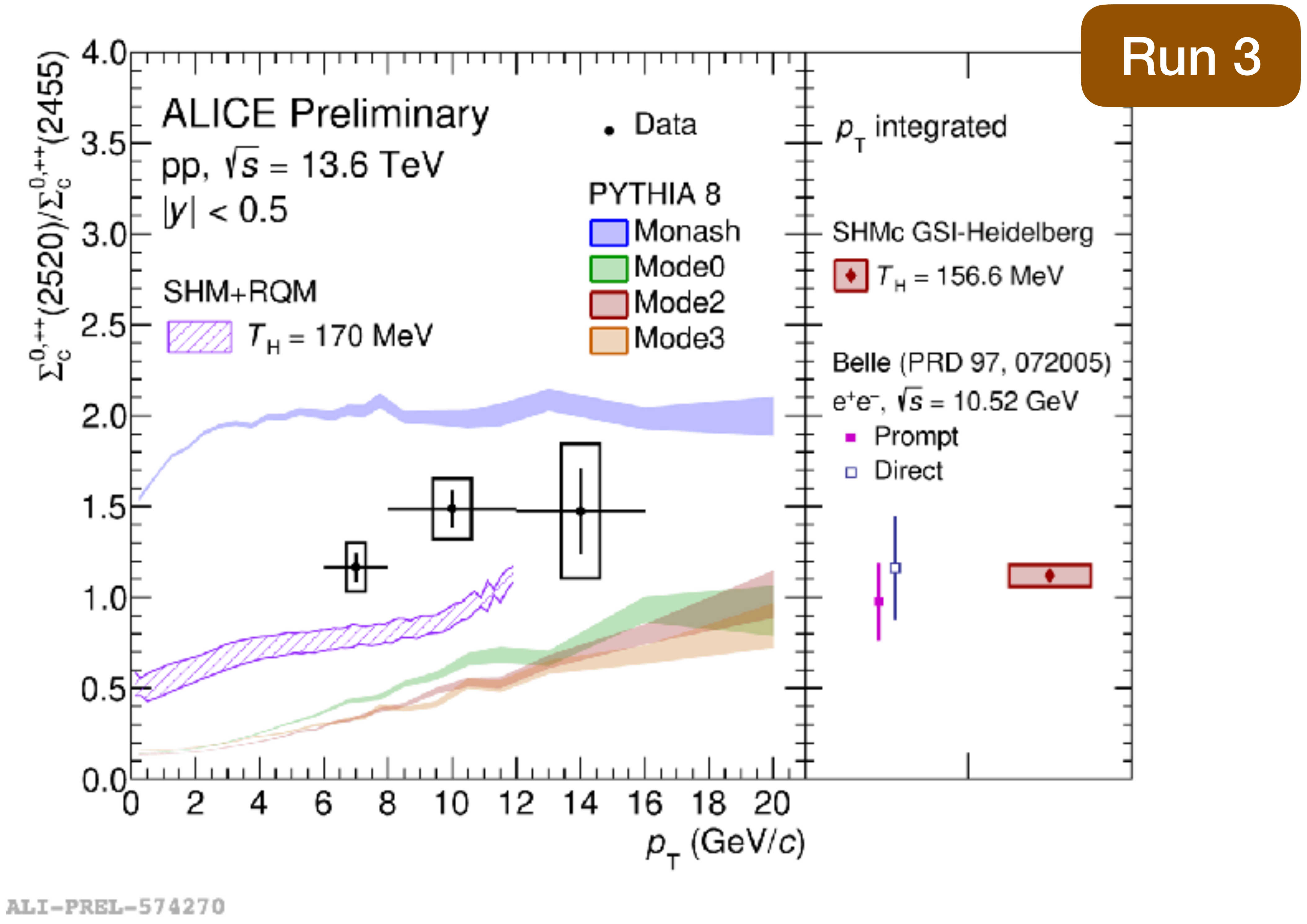
Excited $\Sigma_c^{++,0}$ production

p p

Excited $\Sigma_c^{++,0}$ baryons







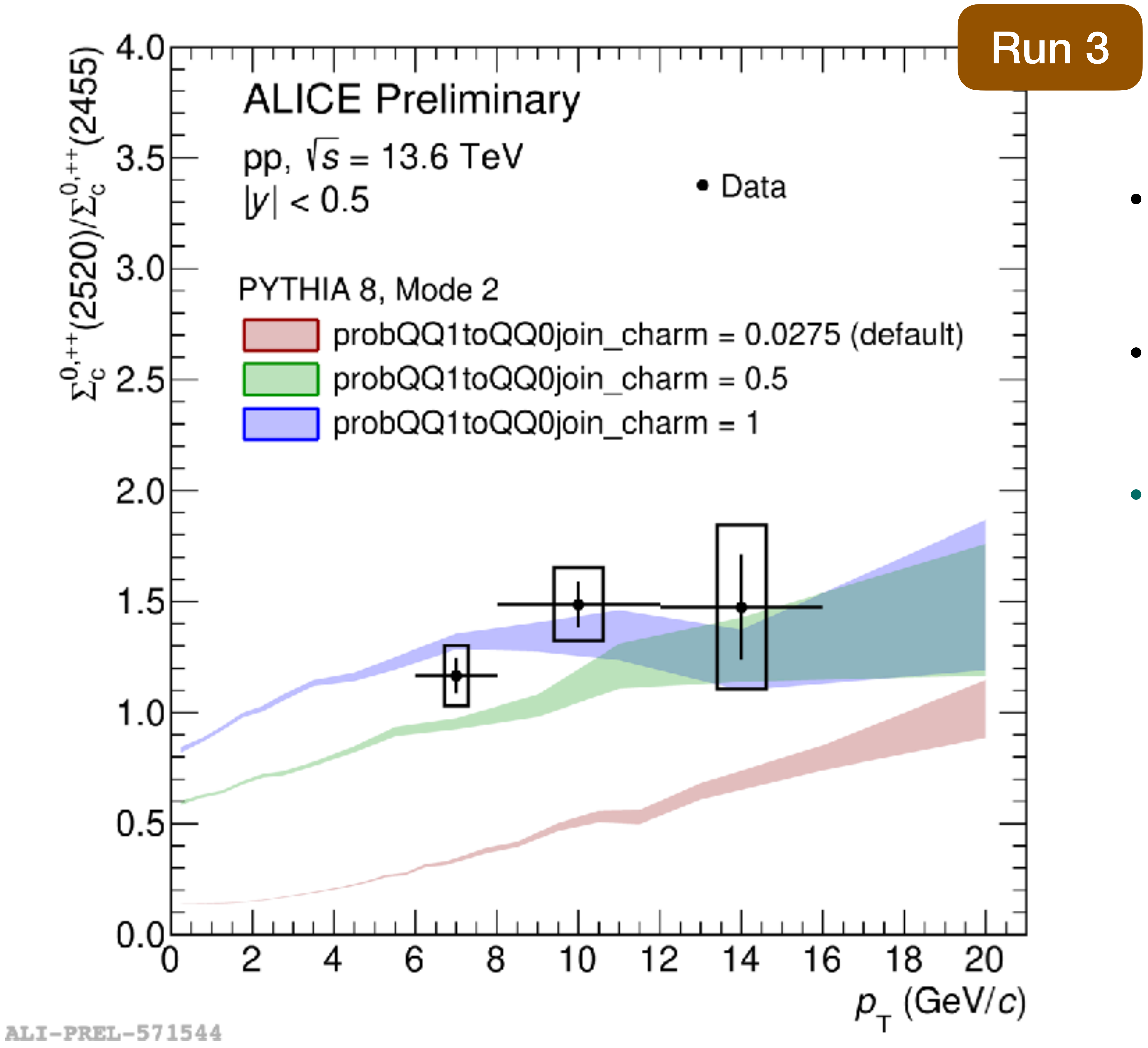
- $\Sigma_c^{++,0}$ (2520) measured at the LHC for the first time

- $\Sigma_c^{++,0}$ (2520) / $\Sigma_c^{++,0}$ (2455) ratio consistent with e+ e- measurement in the measured p_T range.
- Prediction from SHMc GSI+Heidelberg compatible with data in a different p_T range
- Other model predictions under or overestimate the measurement.
  - Measurements provide important constraints

Himanshu Sharma
@ QM2025

Excited $\Sigma_c^{++,0}$ production

p p



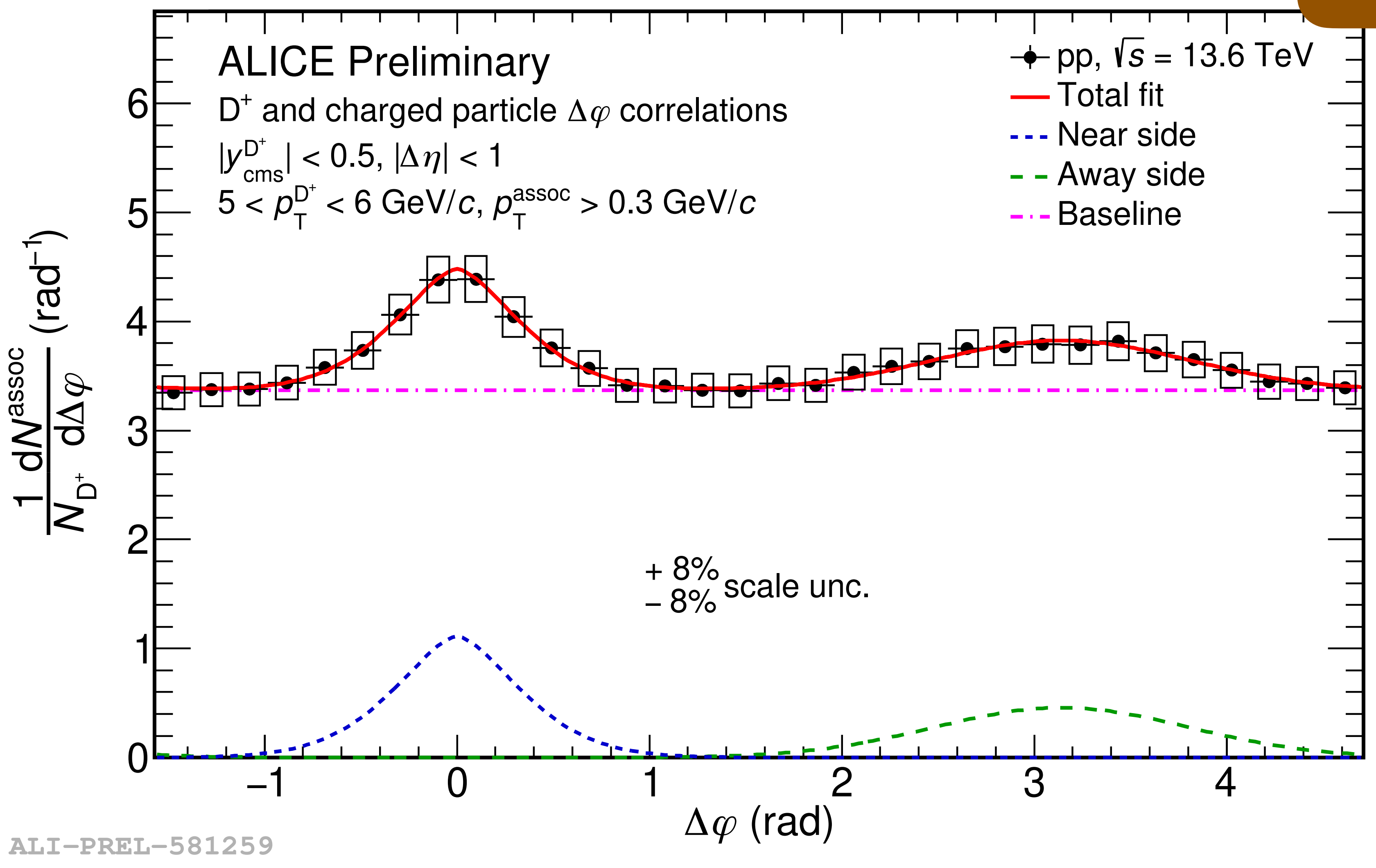
- In PYTHIA 8 Mode 2, tune of model parameter probQQ1toQQ0join_charm required for $\Sigma_c^{++,0}$ production
- Probability of forming junction diquark (cq) with spin 1 over spin 0
  - Changing the parameter changes the model prediction
- Measurements of excited states sets important constraints on the hadronization models

HF-h $\Delta\varphi$ correlations in pp

Study of heavy-flavor jet properties using $\Delta\varphi$ correlations

Two-particle angular correlations with a high p_T trigger —> complementary method to jet reconstruction to characterize jets and their properties, especially at low p_T.

Run 3



$$\Delta\varphi(\mathrm{HF}-\mathrm{h}) = \varphi^{\mathrm{HF}}_{\mathrm{trig}} - \varphi^{\mathrm{h}}_{\mathrm{asso}}$$

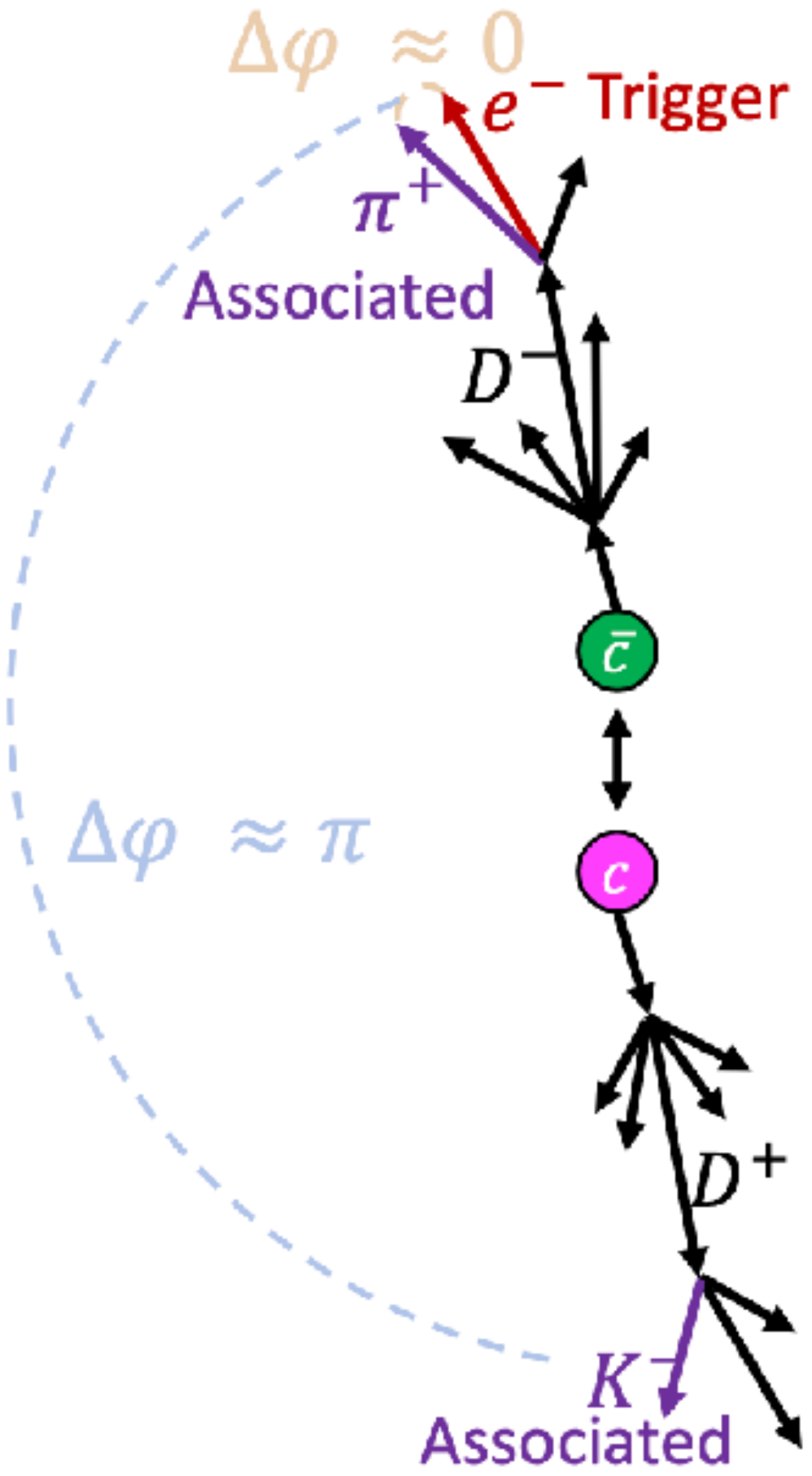
Typical structure at LO:

Near-side: $\Delta\varphi \approx 0$

- Associated particles from same jet as trigger

Away-side: $\Delta\varphi \approx \pi$

- Associated particles from the recoil jet



HF-h correlations characterizes:

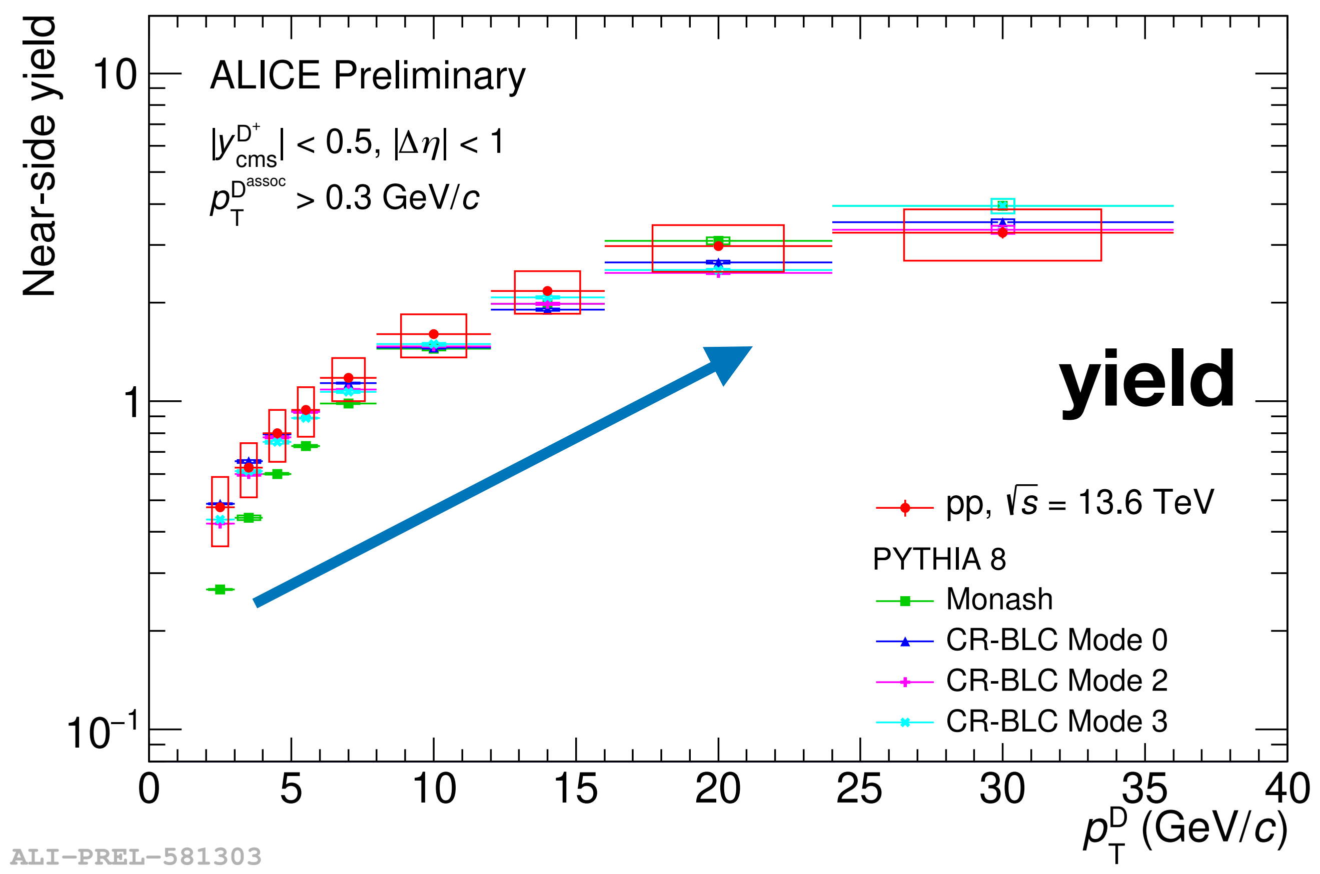
- Angular profile : fit with Generalized Gaussian or von Mises to describe the near-side and away-side peaks
- Associated particle multiplicity

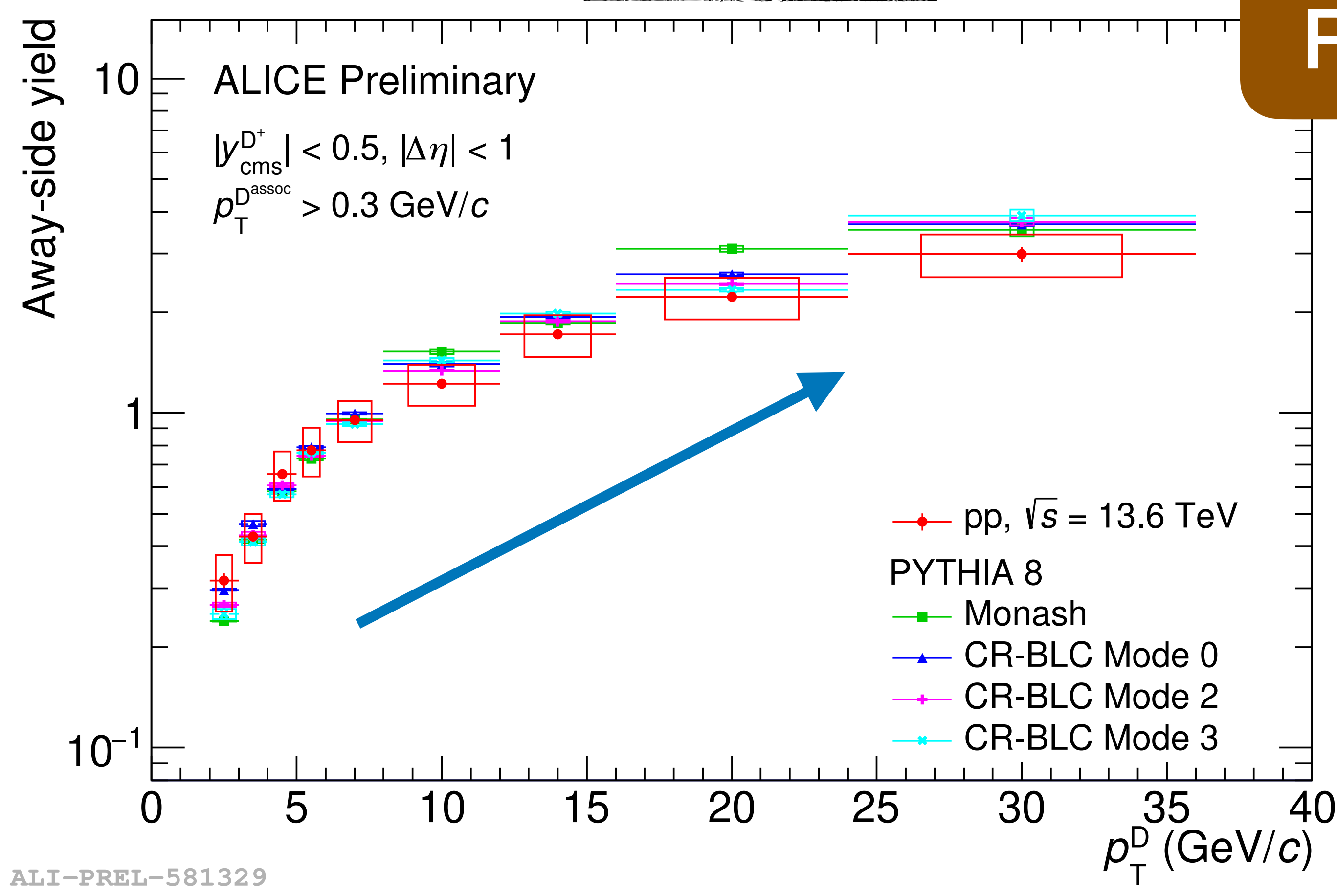
HF-h $\Delta\varphi$ correlations in pp

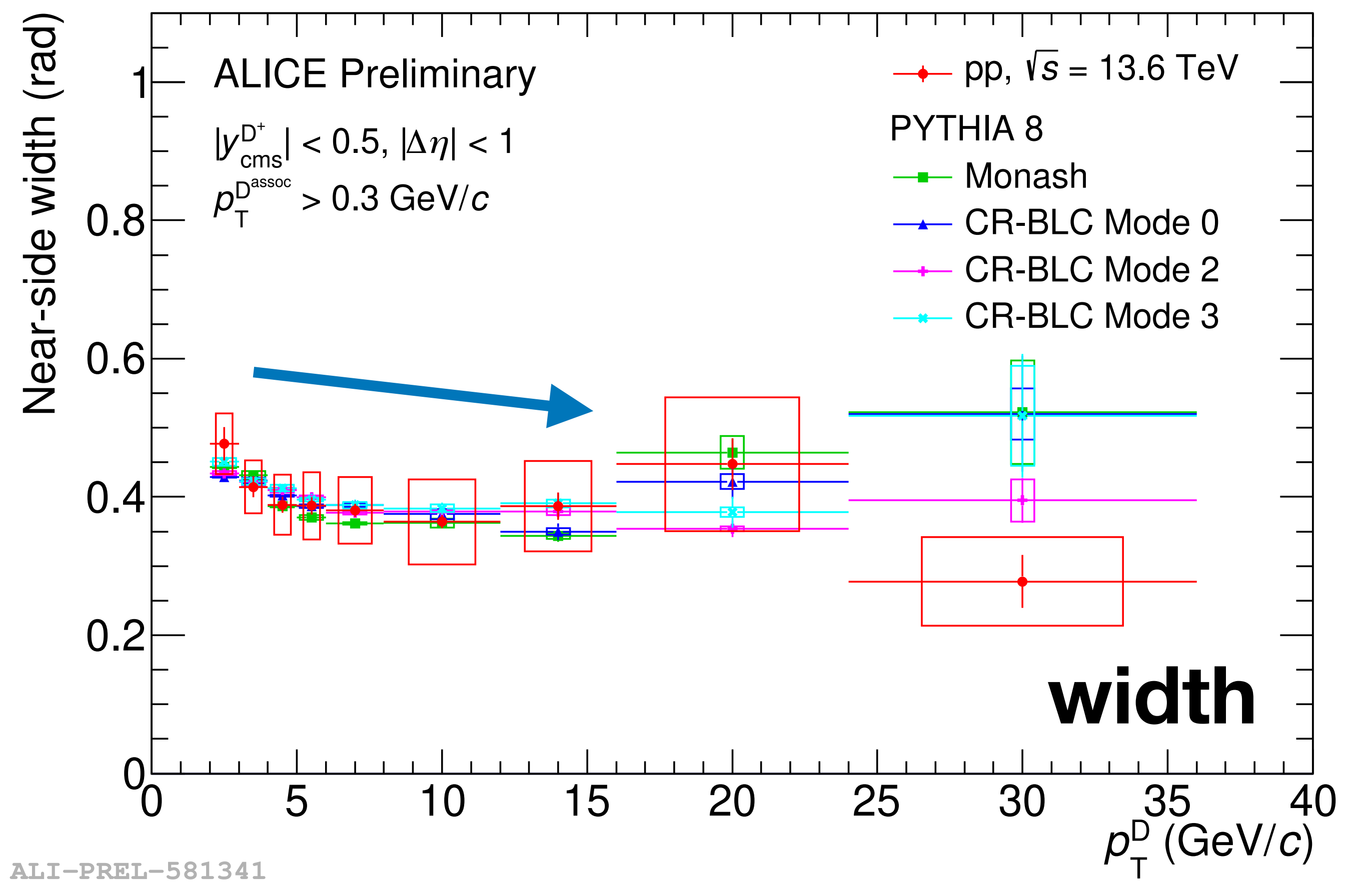
p p

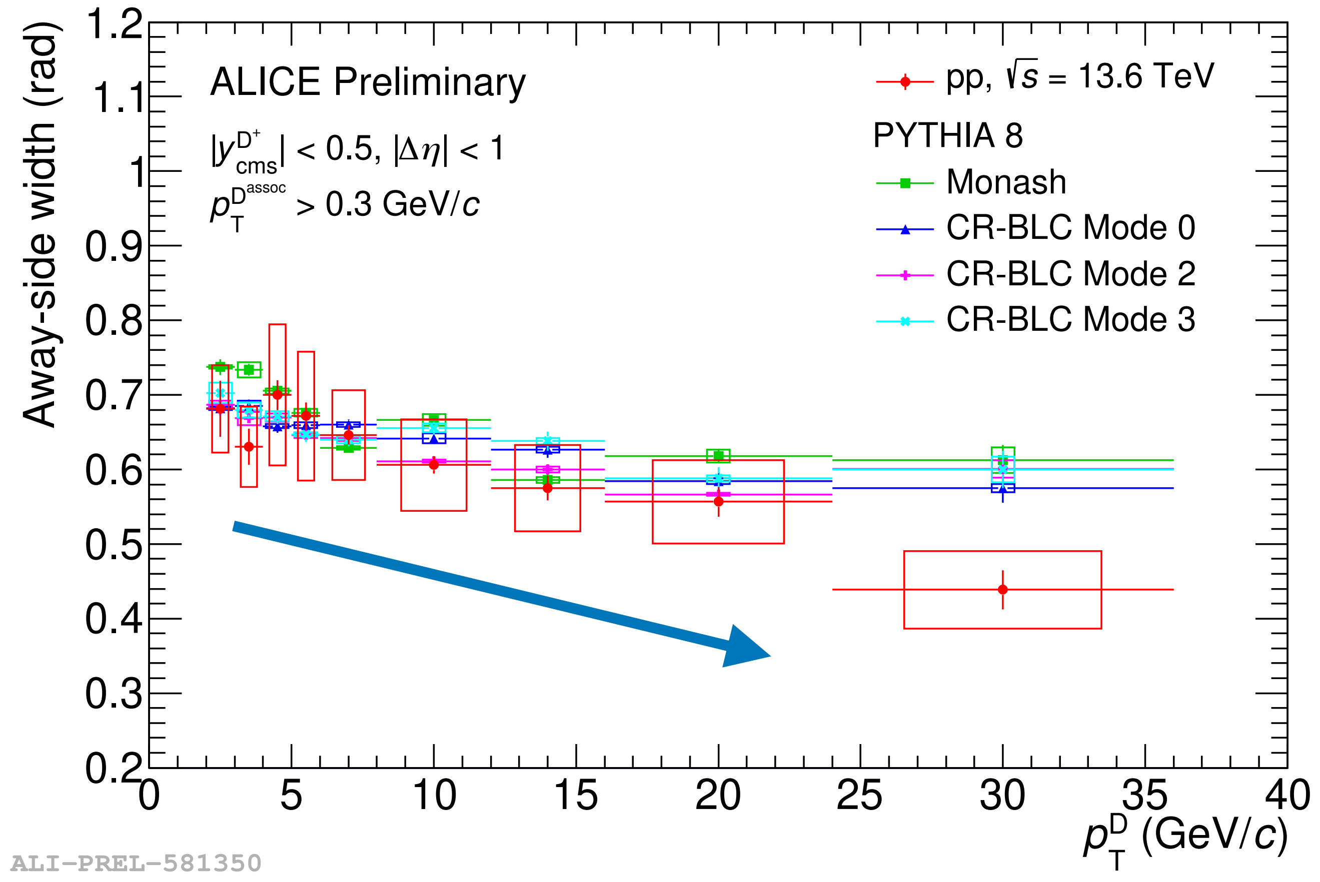
$\Delta\varphi(D^+ - h)$ correlations in pp collisions

Near-side **Away-side** Run 3









⟶ p_T^D

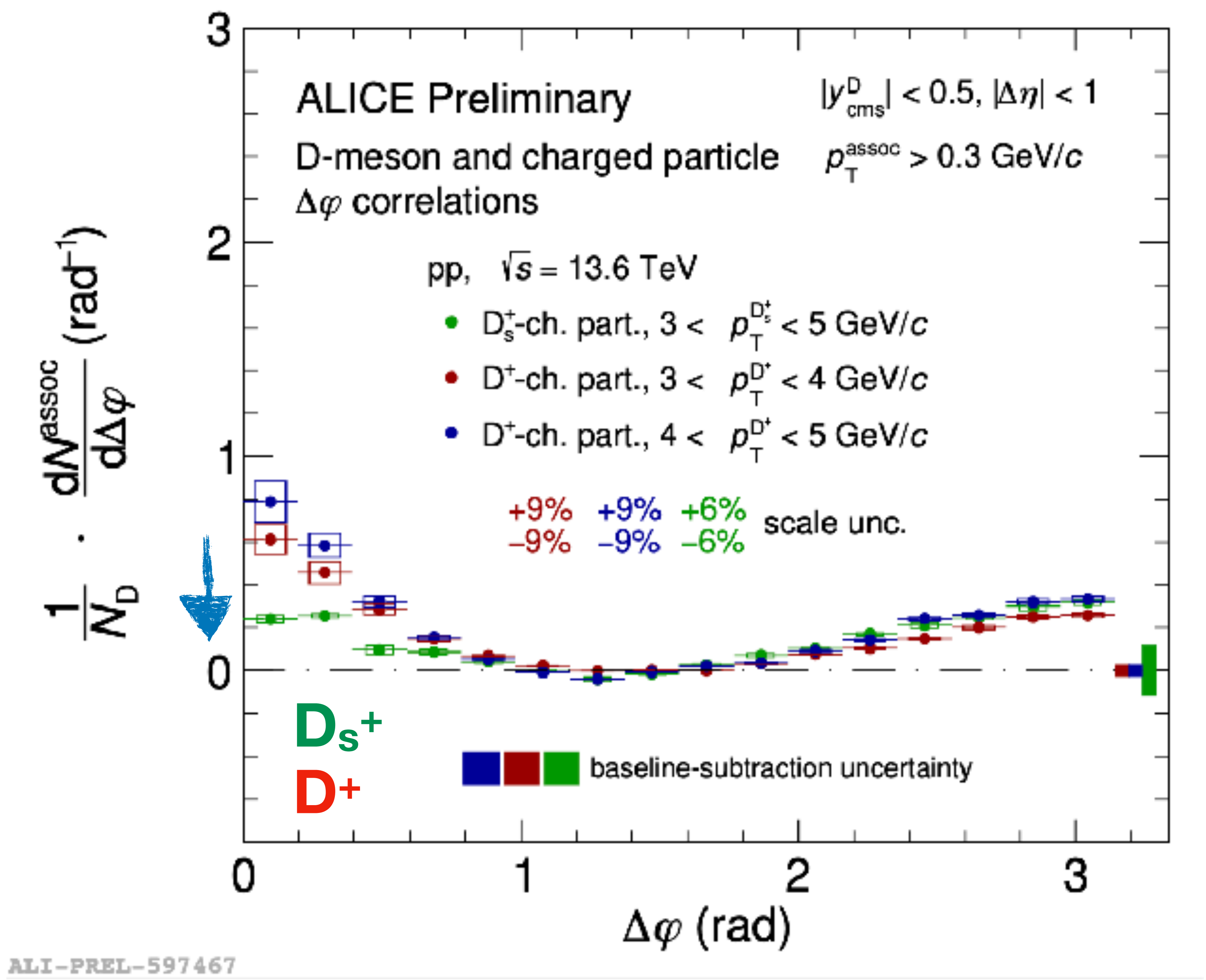
With increasing p_T^{trigger}

- higher associated yield from more energetic HF parton —> more phase phase for fragmentation
- larger heavy quark boost —> more collimated peaks

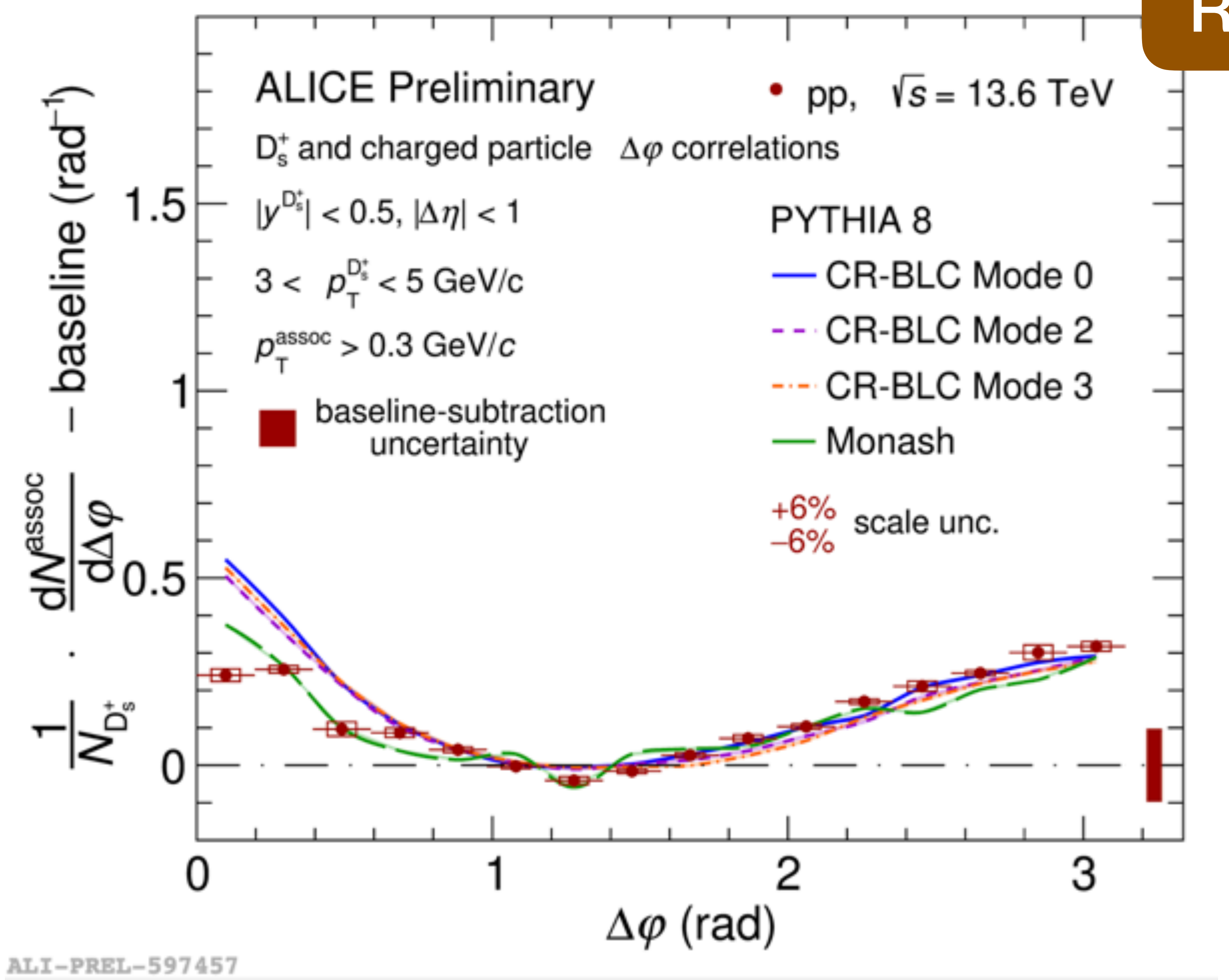
$\Delta\varphi(D_s^+ - h)$ correlations in pp

p p

$\Delta\varphi(D_s^+ - h)$ **correlations in pp collisions: study fragmentation mechanism**



Run 3



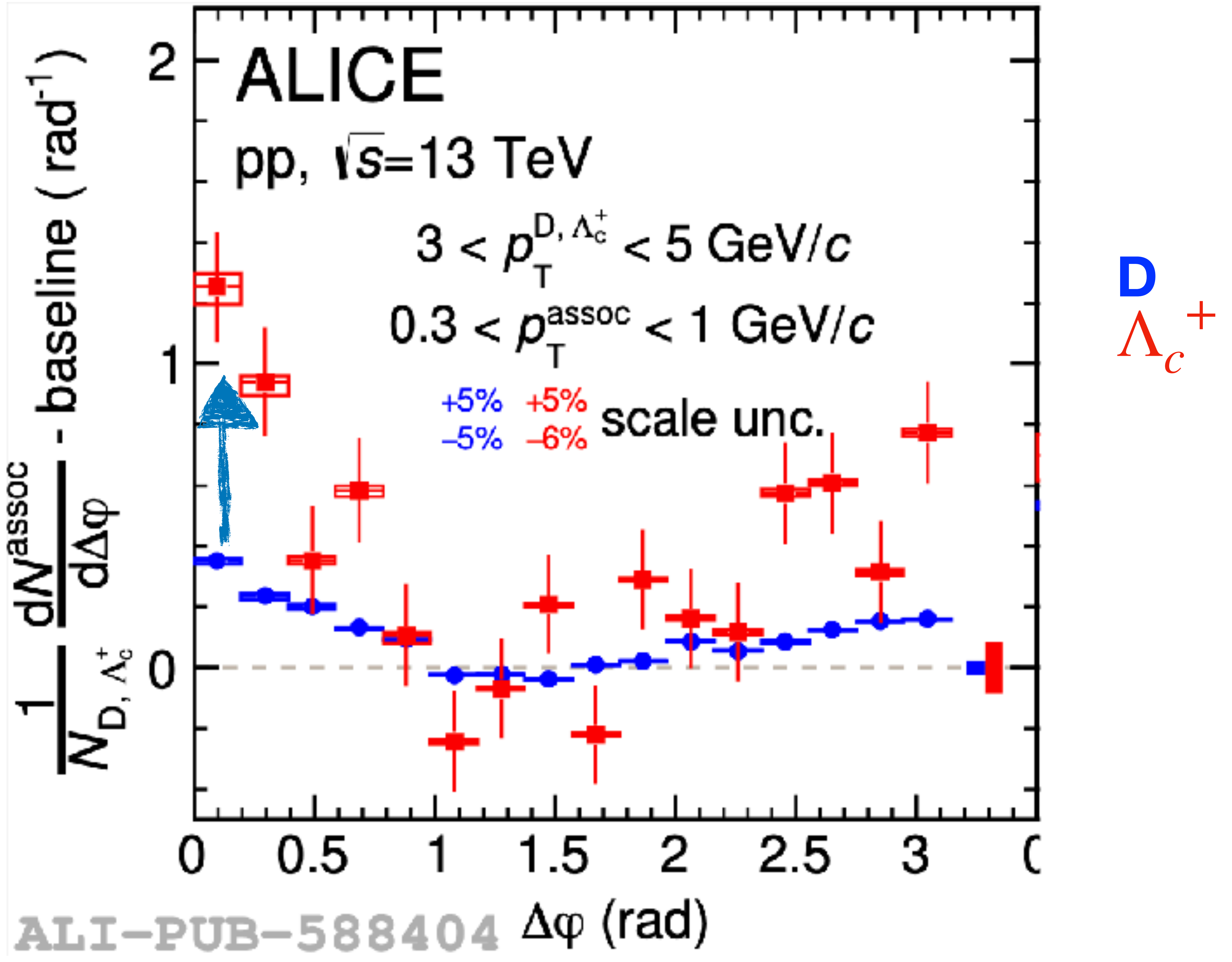
- D_s^+/D^+ ratio flat in p_T and multiplicity in pp collisions
- $\Delta\varphi(D_s^+ - h)$
  - Near-side: significantly lower associated yield for D_s^+ compared to D^+ at low $p_T^{trigger}$; Consistent at higher $p_T^{trigger}$
  - Away side: similar distributions for D_s^+ and D^+ triggered correlations in the full p_T range measured.

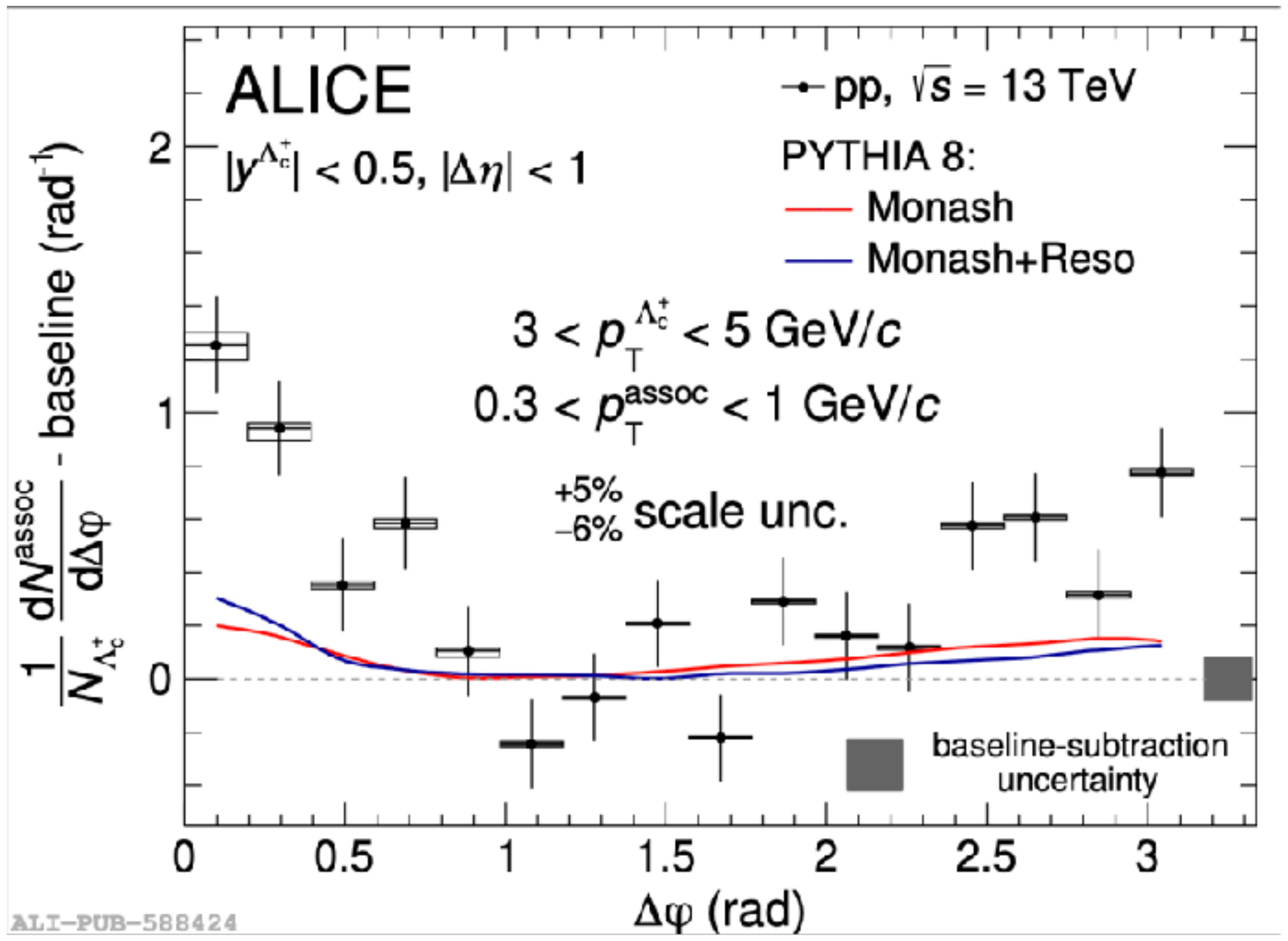
- Different tunes of PYTHIA overestimate the near-side peak at low D_s^+ p_T; describe the away-side peak, and the full distribution for $p_T > 5$ GeV/c
- Possible explanation for the difference: harder fragmentation of charm quark into D_s^+ than non-strange D mesons (consistent with $z_{||}$ measurement)

$\Delta\varphi(\Lambda_c^+ - \mathrm{h})$ correlations in pp

p p

$\Delta\varphi(\Lambda_c^+ - \mathrm{h})$ **correlations in pp collisions: study baryon hadronization mechanism**





arXiv:2411.10104

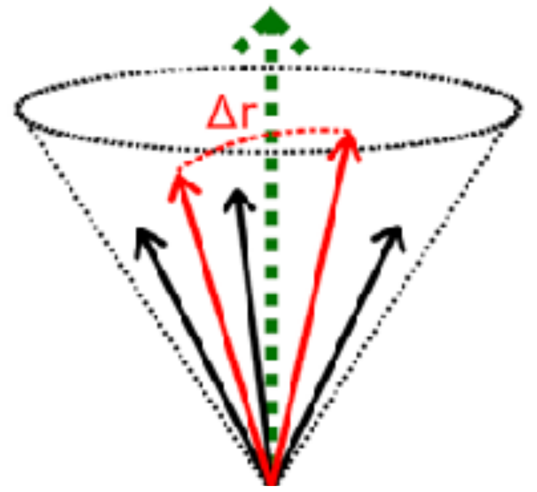
- Larger Λ_c^+/D^0 ratio measured in pp compared to e+e- at low and intermediate p_T.
- Λ_c^+ triggered correlations compared to D-meson.
- **Trend of enhanced correlation peaks at low Λ_c^+ and associated particle p_T.**

- PYTHIA underestimate the peaks at low Λ_c^+ p_T; describe the data at higher $p_T^{\Lambda_c^+}$

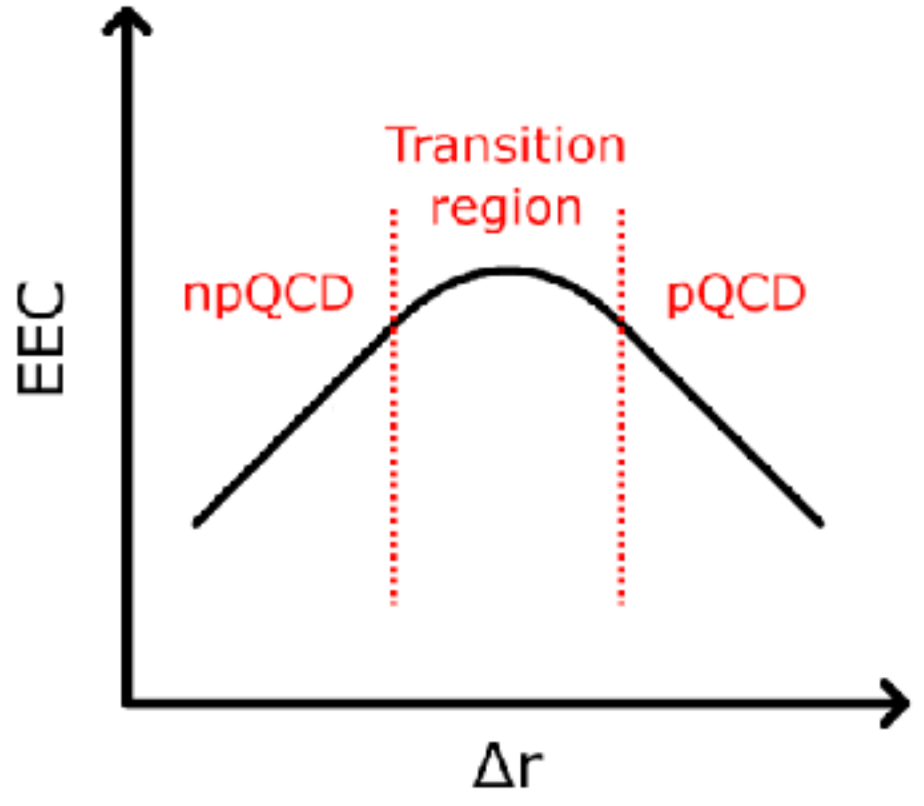
Energy-energy correlators of HF jets

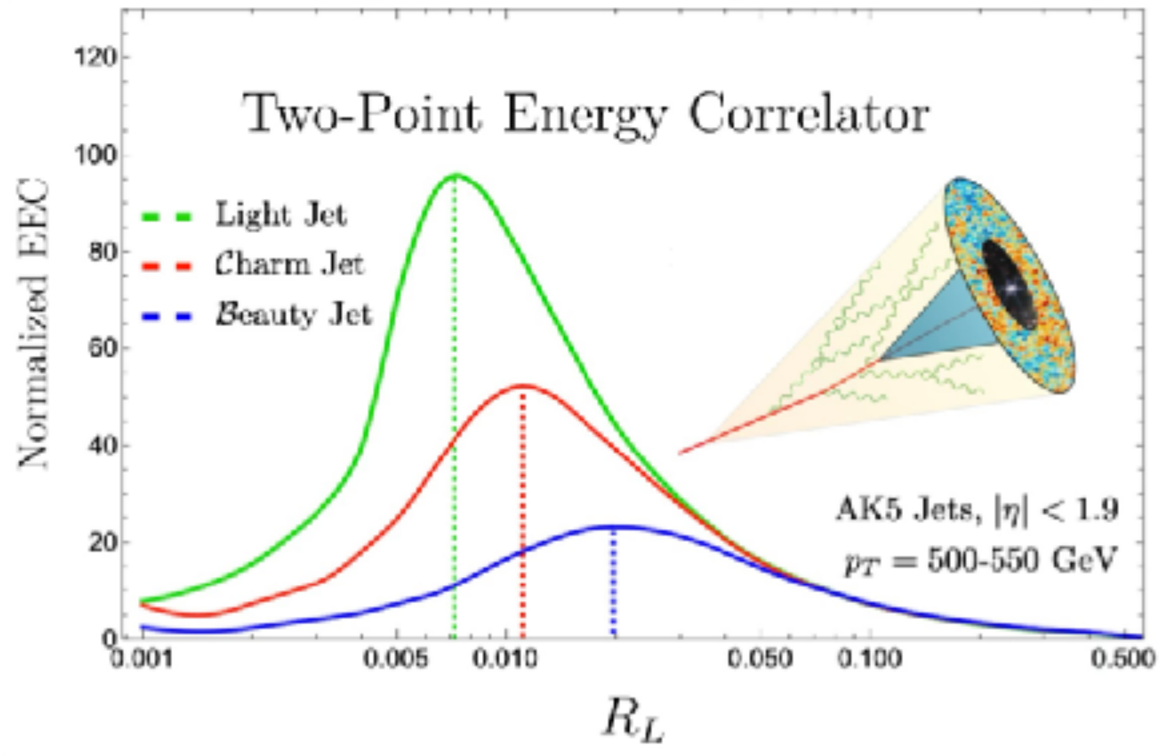
Probe different time scales of jet evolution using EEC

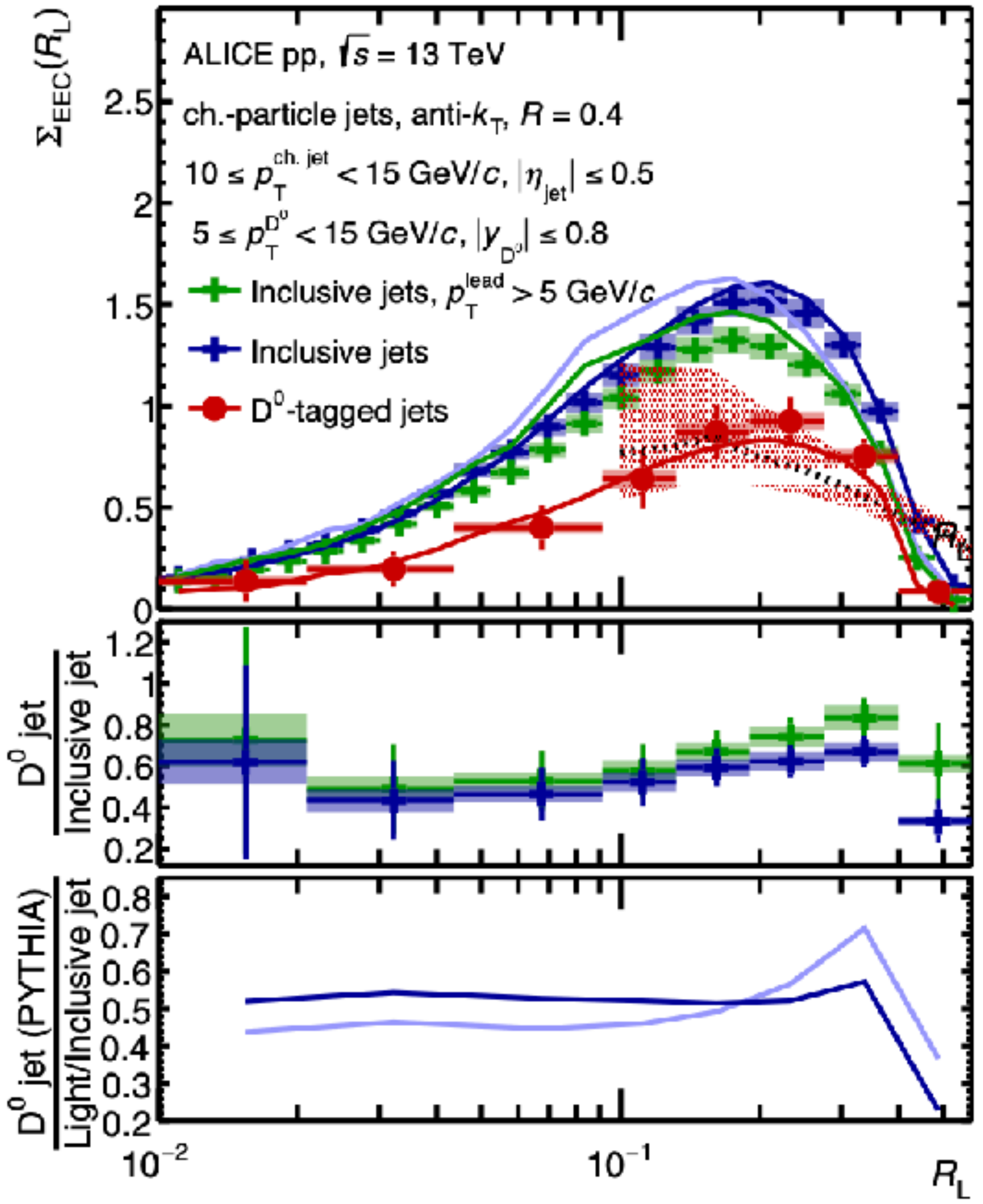
$$\mathrm{EEC}(\Delta r) = \frac{1}{\mathrm{W_{pairs}}} \frac{1}{\delta r} \sum_{\mathrm{jets}} \sum_{\mathrm{pairs} \in [\Delta r_a, \Delta r_b]} (p_{\mathrm{T,i}} p_{\mathrm{T,j}})^n$$



Varying Δr gives access to different time scales of jet evolution in vacuum







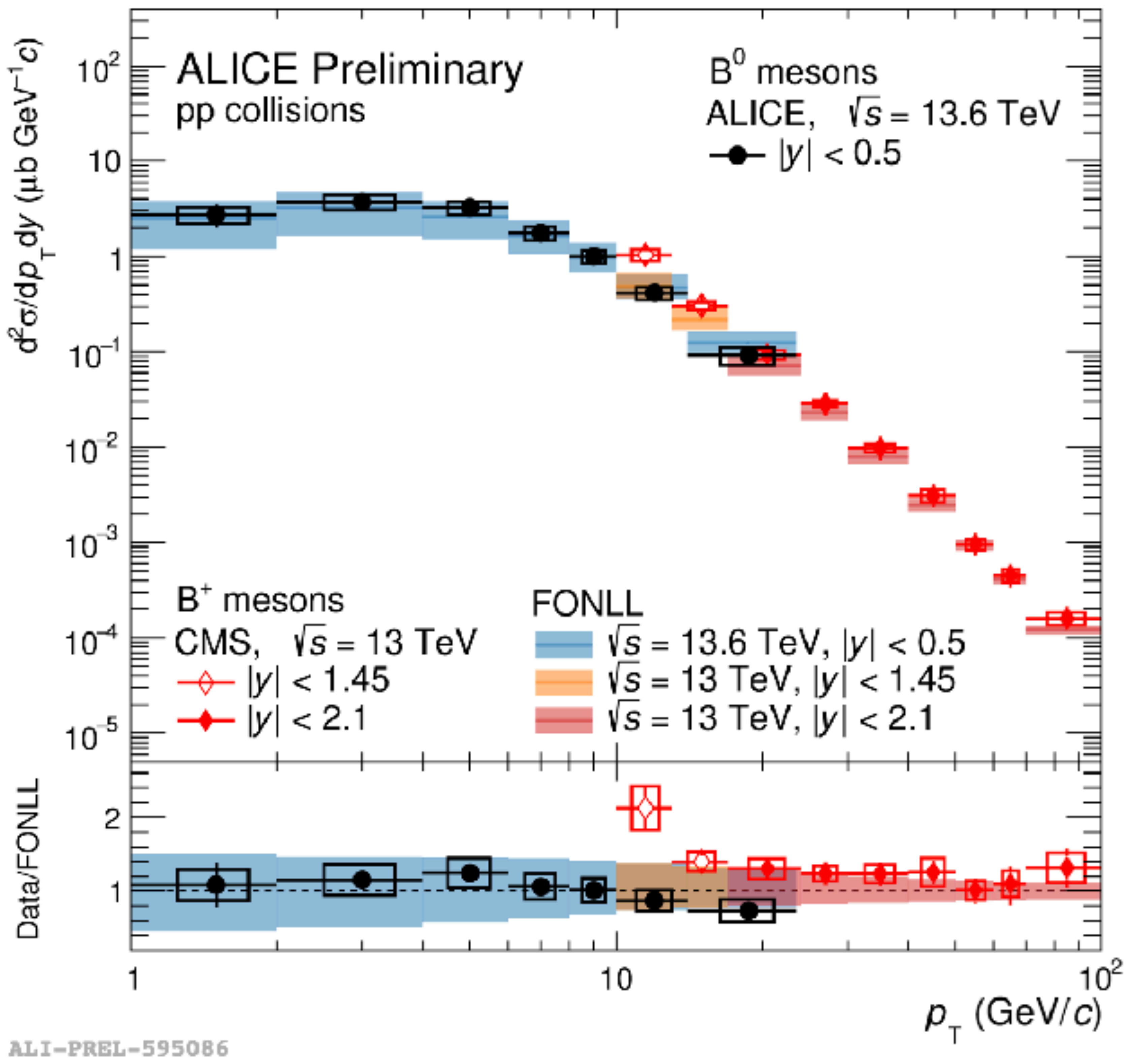
arXiv:2504.03431

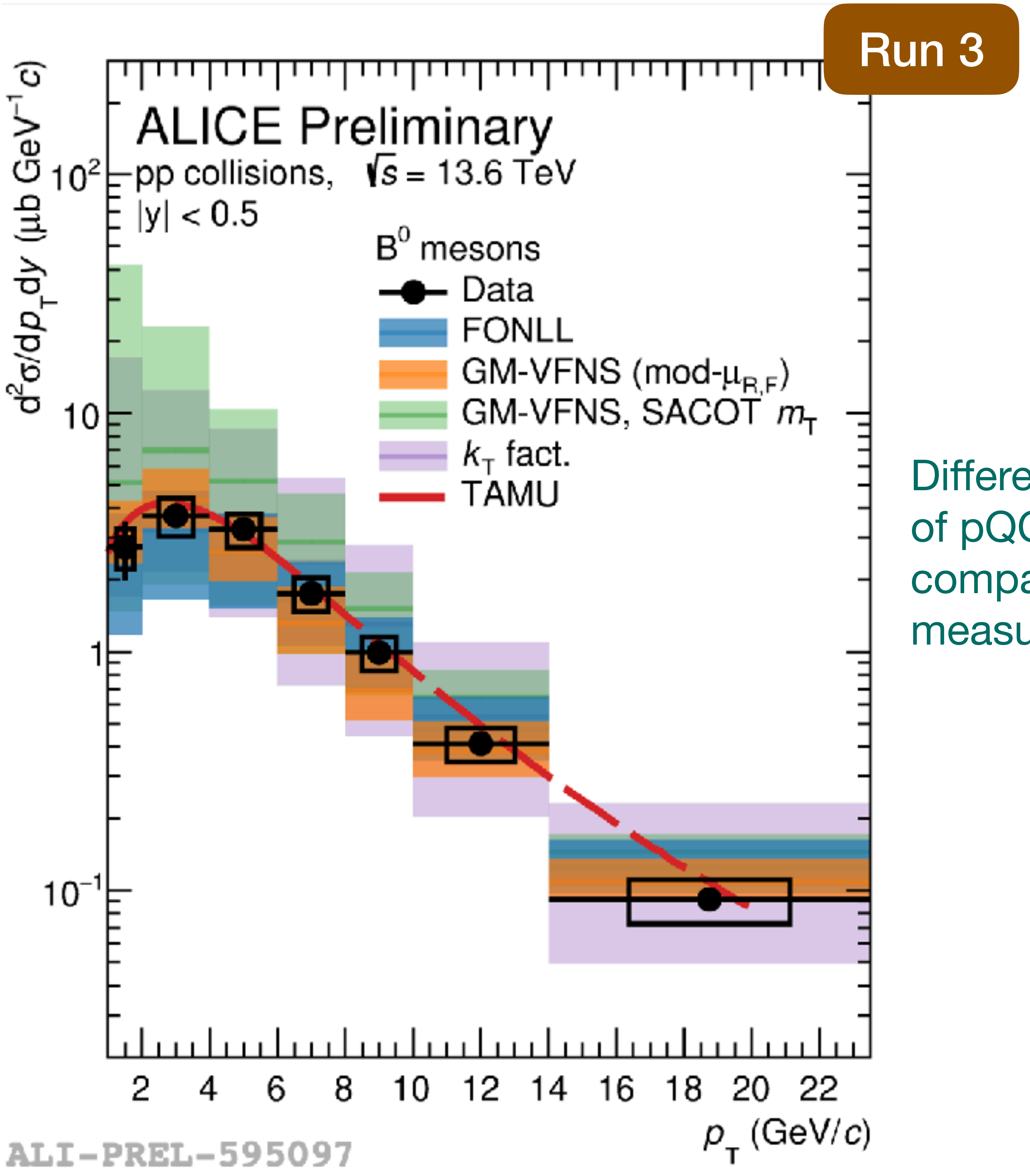
$$\Delta r \equiv R_L$$

- Charm-tagged EECs: lower amplitude —> EECs for massive quarks
- Similar peak position: inclusive (gluon dominated) <—> convolution of casimir and mass effects
- pQCD calculations indicate tension with data.

Beauty hadron production

Beauty hadron cross section in pp collisions





Different implementation of pQCD calculations compatible with the measurement.

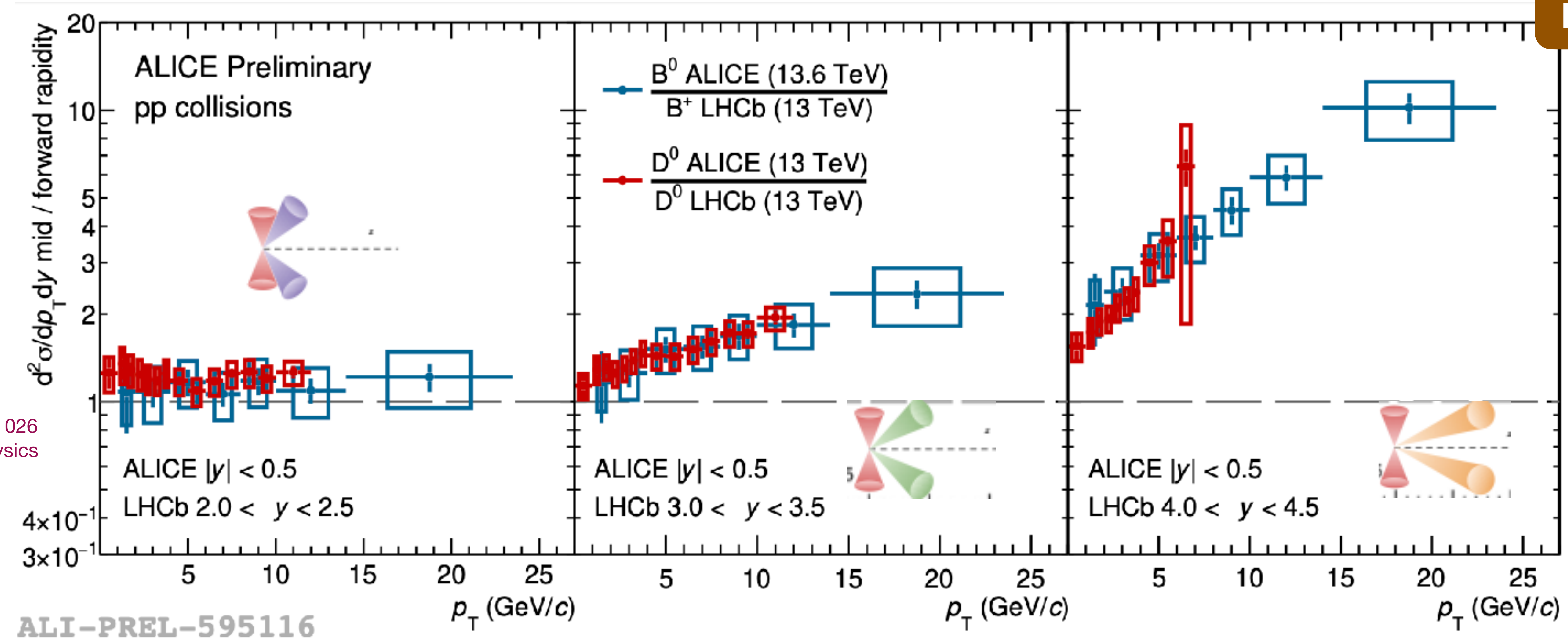
- New ALICE measurement of B^0 meson production cross-section down to very low p_T (1 GeV/c).
  - Extends the kinematic reach w.r.t previous measurements from other CMS and LHCb experiments

Rapidity dependence of beauty production

p p

Beauty production vs rapidity

Run 3

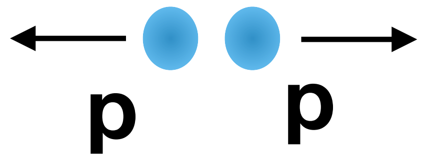


D mesons
B meson

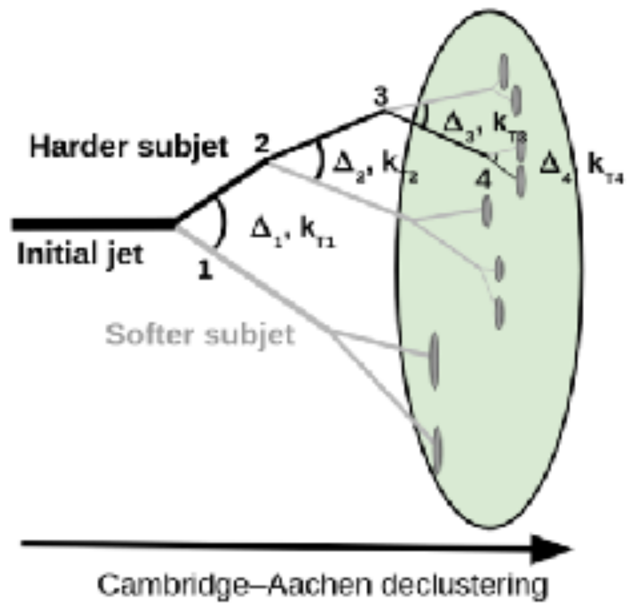
LHCb, JHEP 12 (2017) 026
ALICE, Preliminary Physics Summary

- B^0(mid) / B^+(fwd) ratio for 3 different rapidly ranges from ALICE and LHCb
- Increasing trend with p_T at higher rapidity
- FONLL prediction compatible within uncertainties
- **B meson** ratios compatible with that of **D mesons**

Parton shower of b-jets

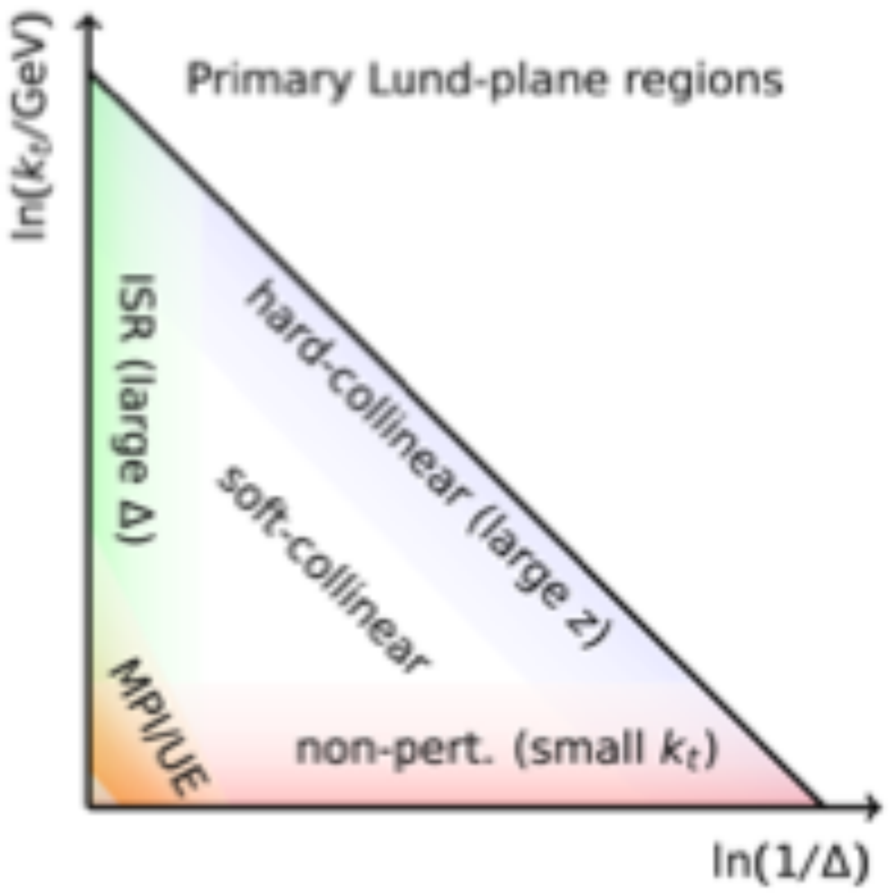


Substructure studies of beauty quark initiated jets

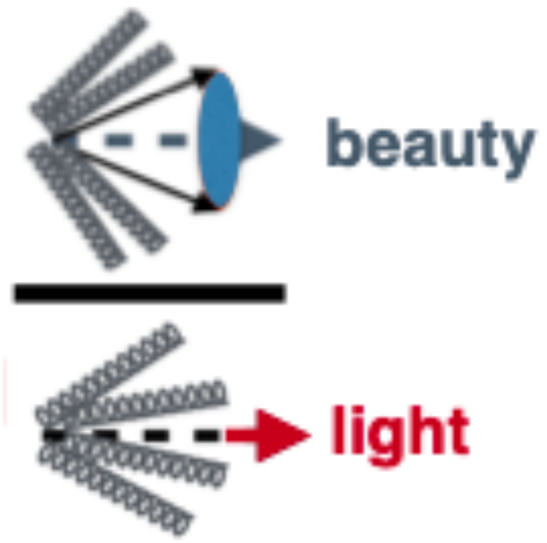


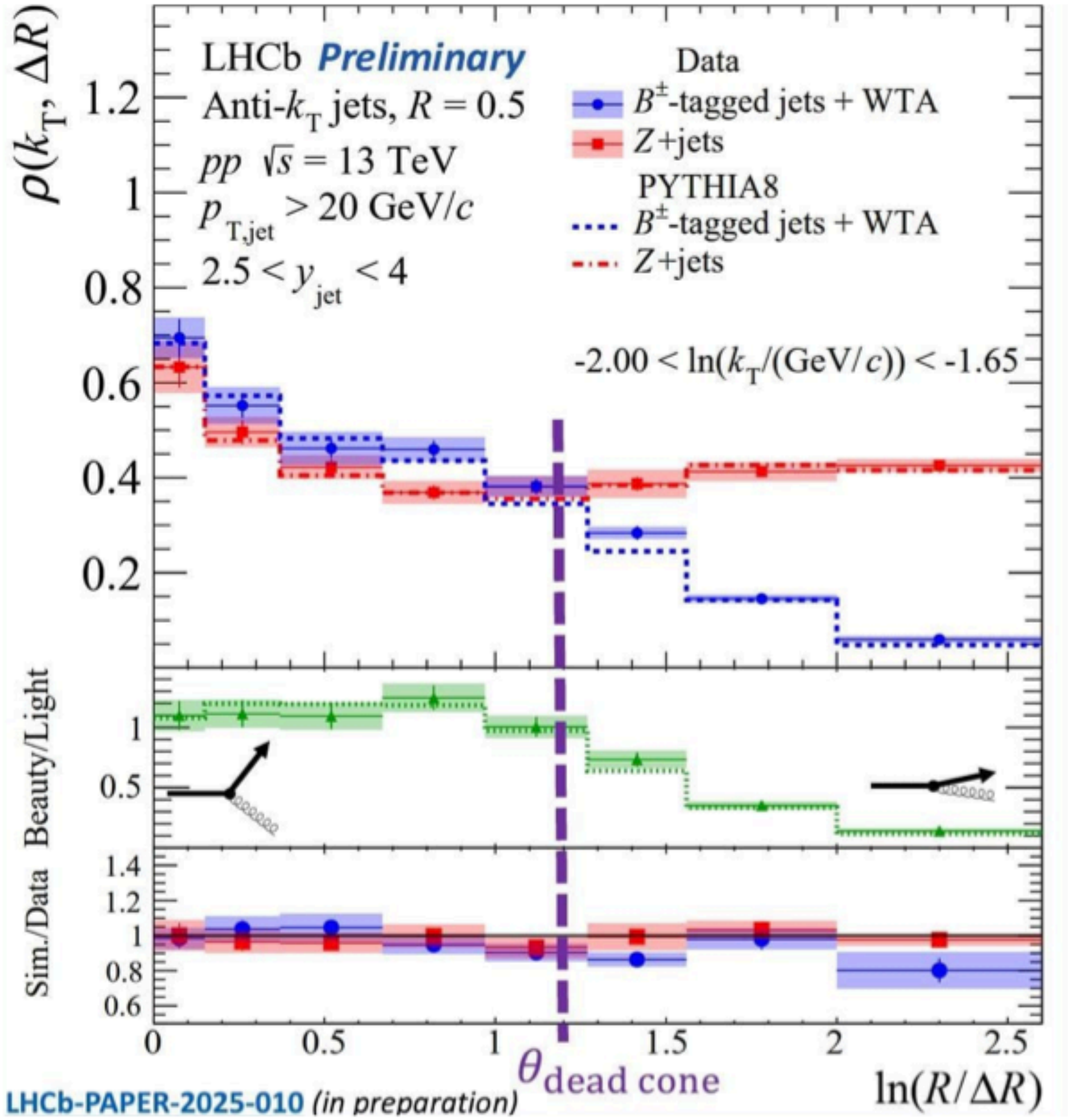
$$k_T = p_{T,soft} \cdot \Delta$$

- Lund plane visualizes branching kinematics (k_T vs emission angle)
  - High k_T -> early splitting
  - Small k_T -> later splitting



Dead-cone effect!



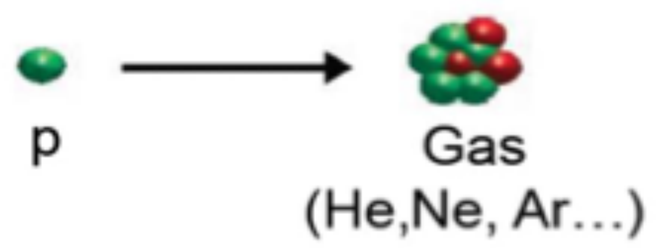


Evidence of dead-cone effect, b vs light quarks

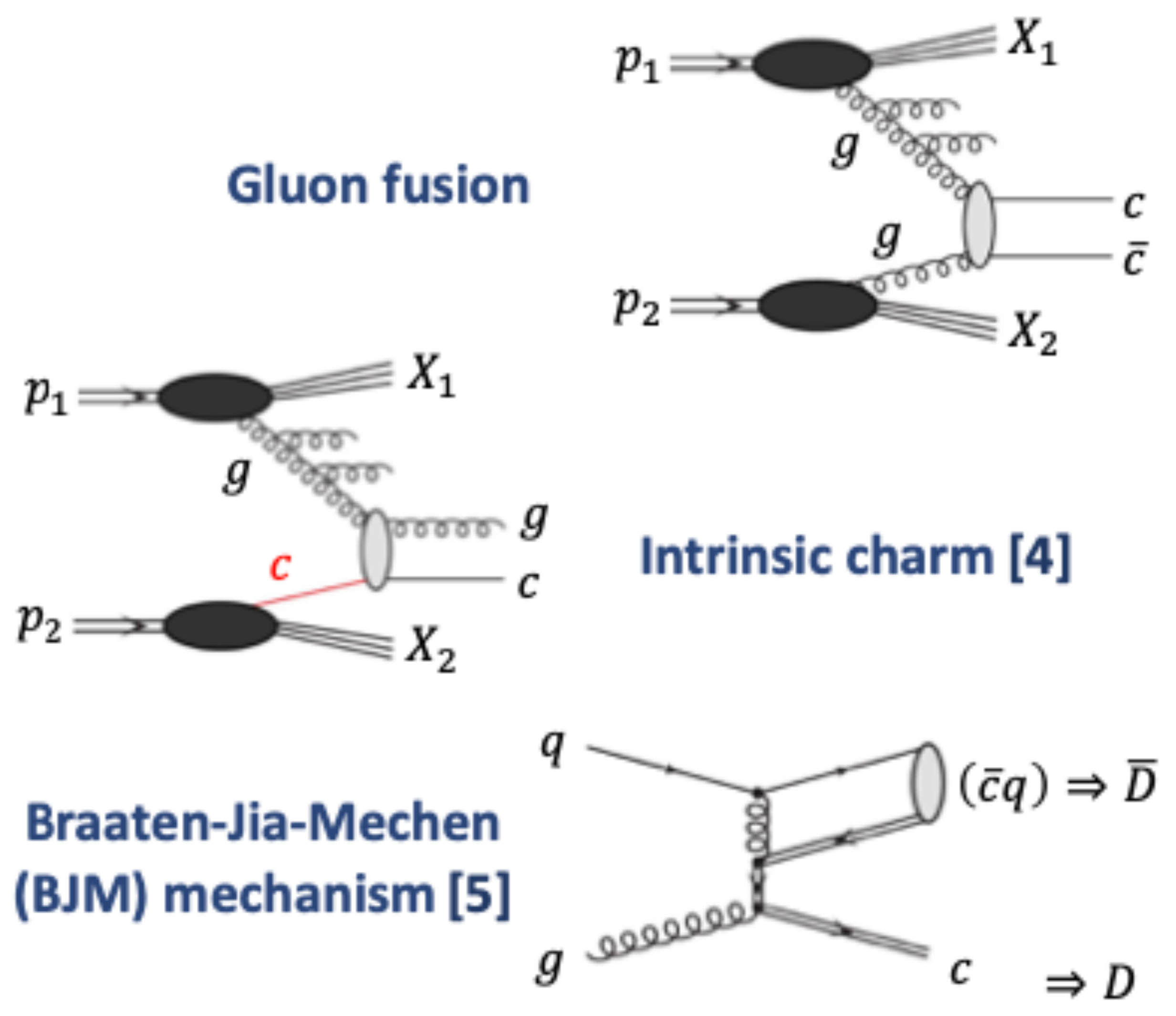
HF production in fixed target collisions (SMOG)

Fixed-target mode

$\sqrt{s_{NN}} = 70 - 113$ GeV



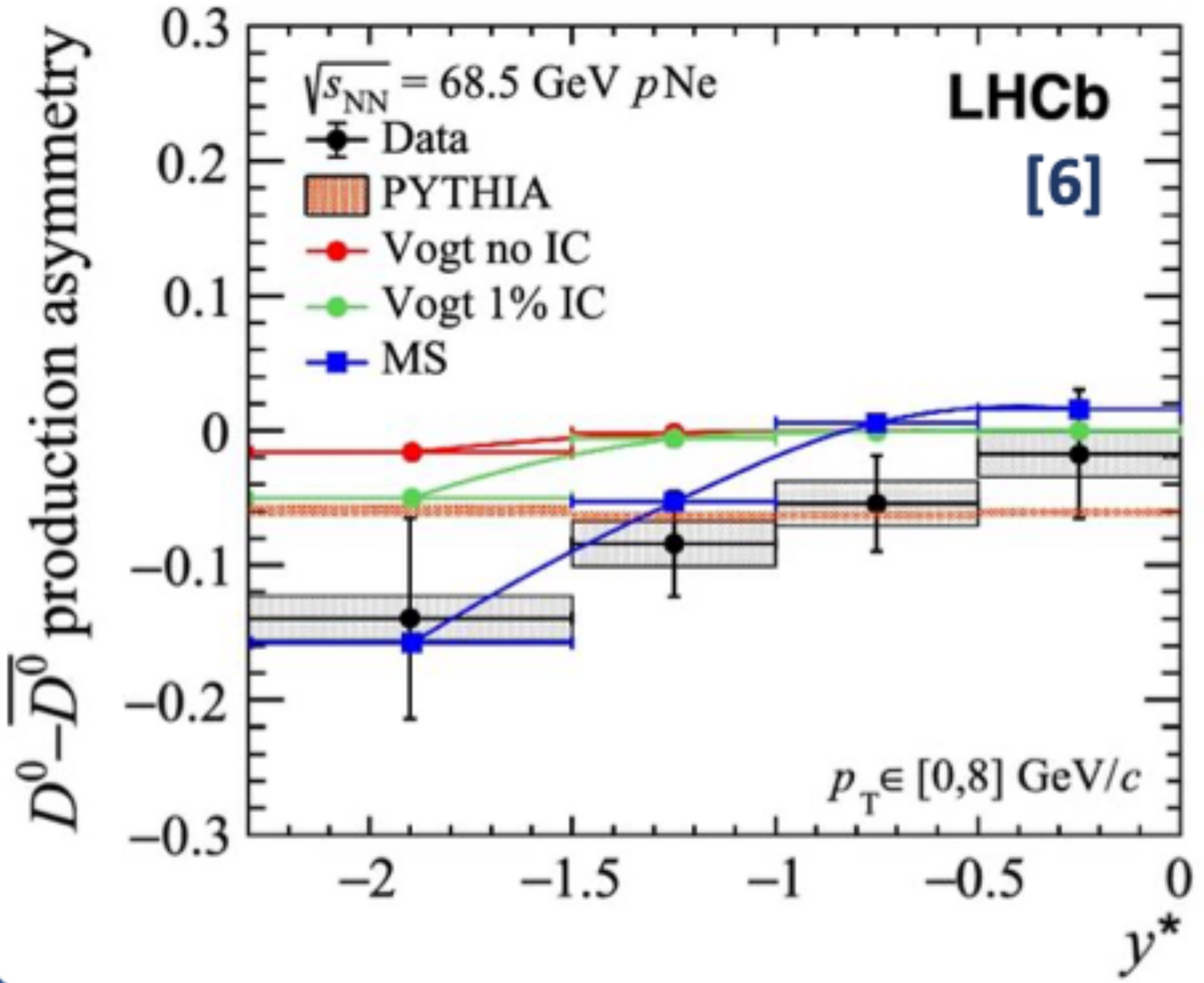
$-2.77 < y^* < 0.23$

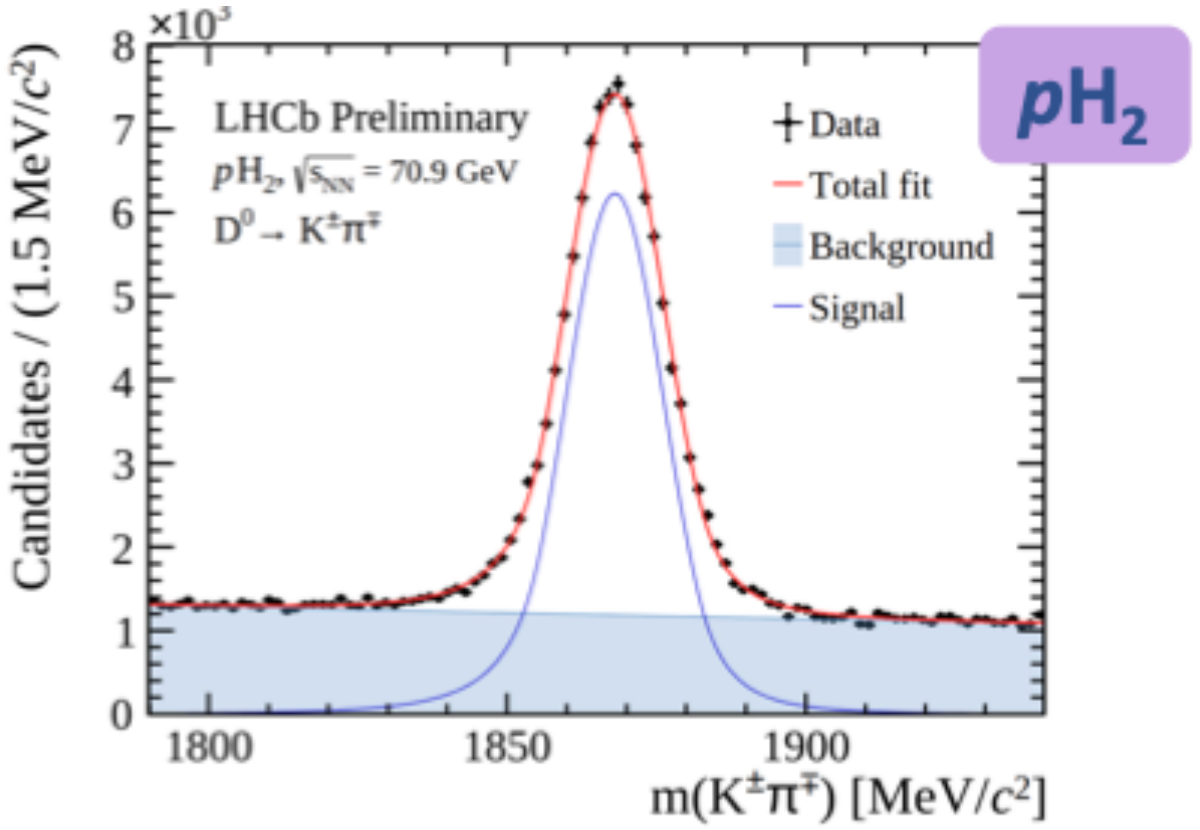


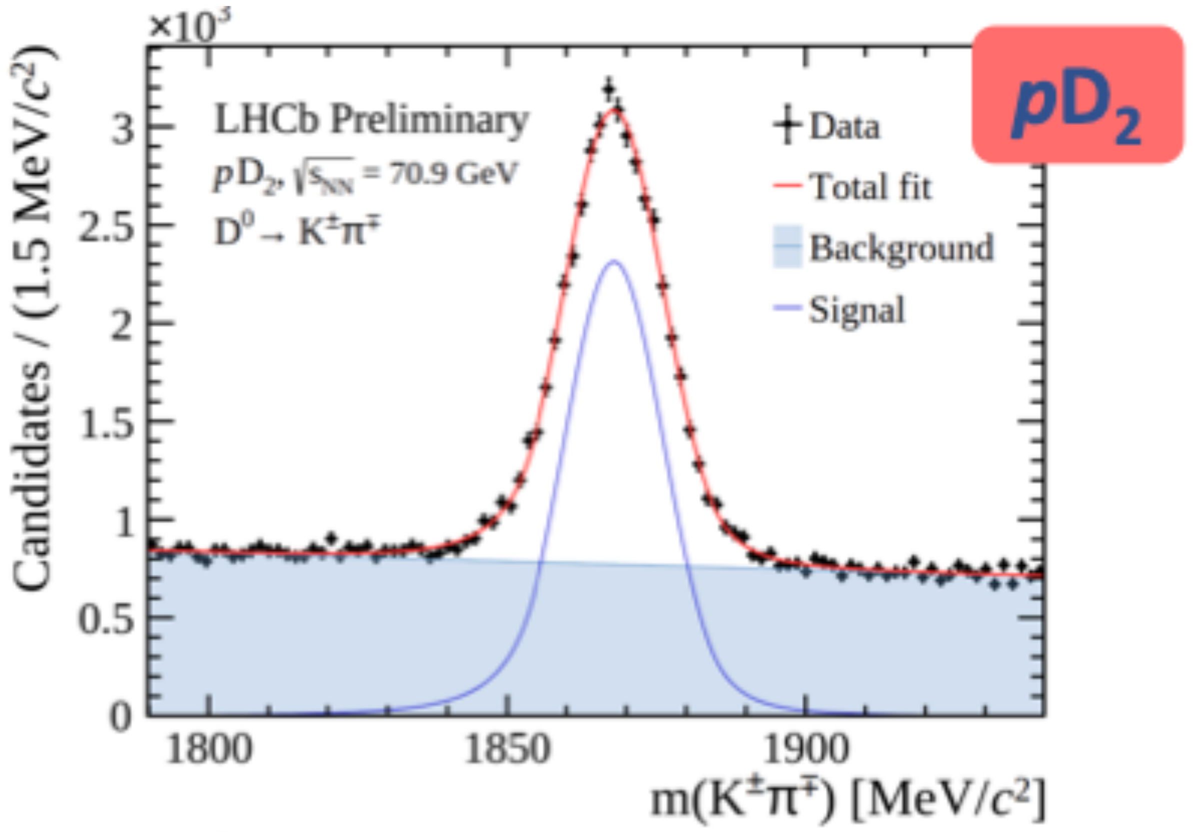
At y*<0, intrinsic charm and BJM mechanism contribute to charm hadron production —> experimentally observed through an asymmetry in D^0 production

$$A = \frac{N(D^0) - N(\overline{D^0})}{N(D^0) + N(\overline{D^0})}$$

- Different gases (H_2, D_2, He, Ar) injected in 2024 during pp run
- Effect of the systems's size on the asymmetry can be investigated.



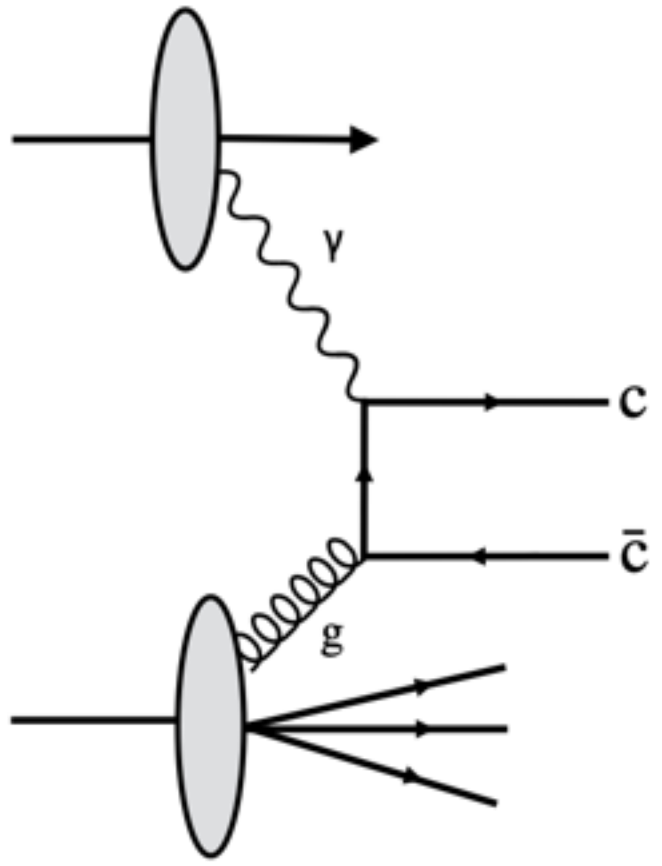




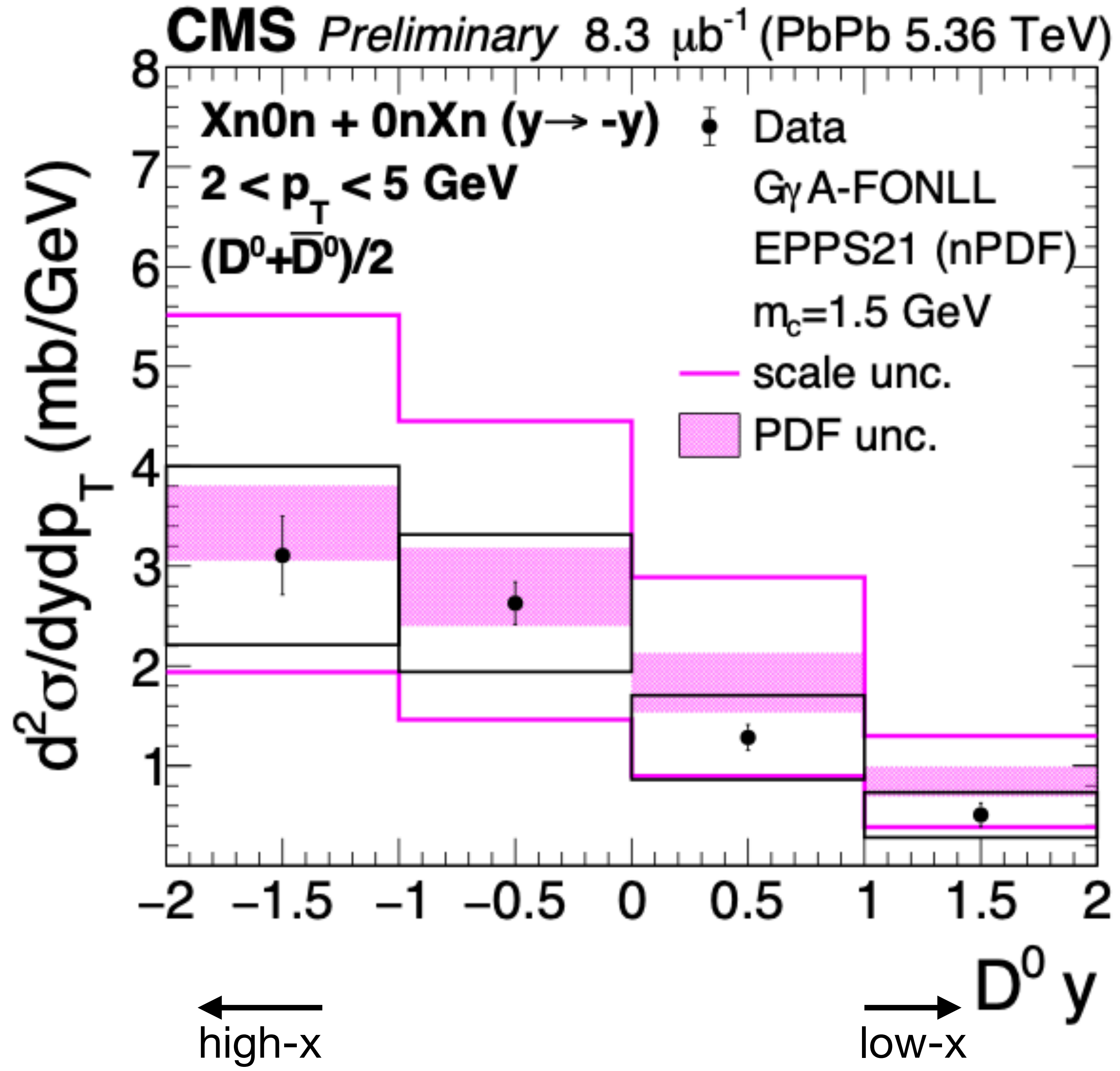
Yu (Janice) Chen
@ QM2025

Open charm photoproduction in UPC

Study gluon nPDFs over a wide (x, Q^2) down to low-x



- UPC: study cold nuclear matter effects, sensitive to gluon PDF, saturation and shadowing effects in a clear environment —> absence of final state effects.
- Open HF particles in UPC —> pQCD description even at low p_T



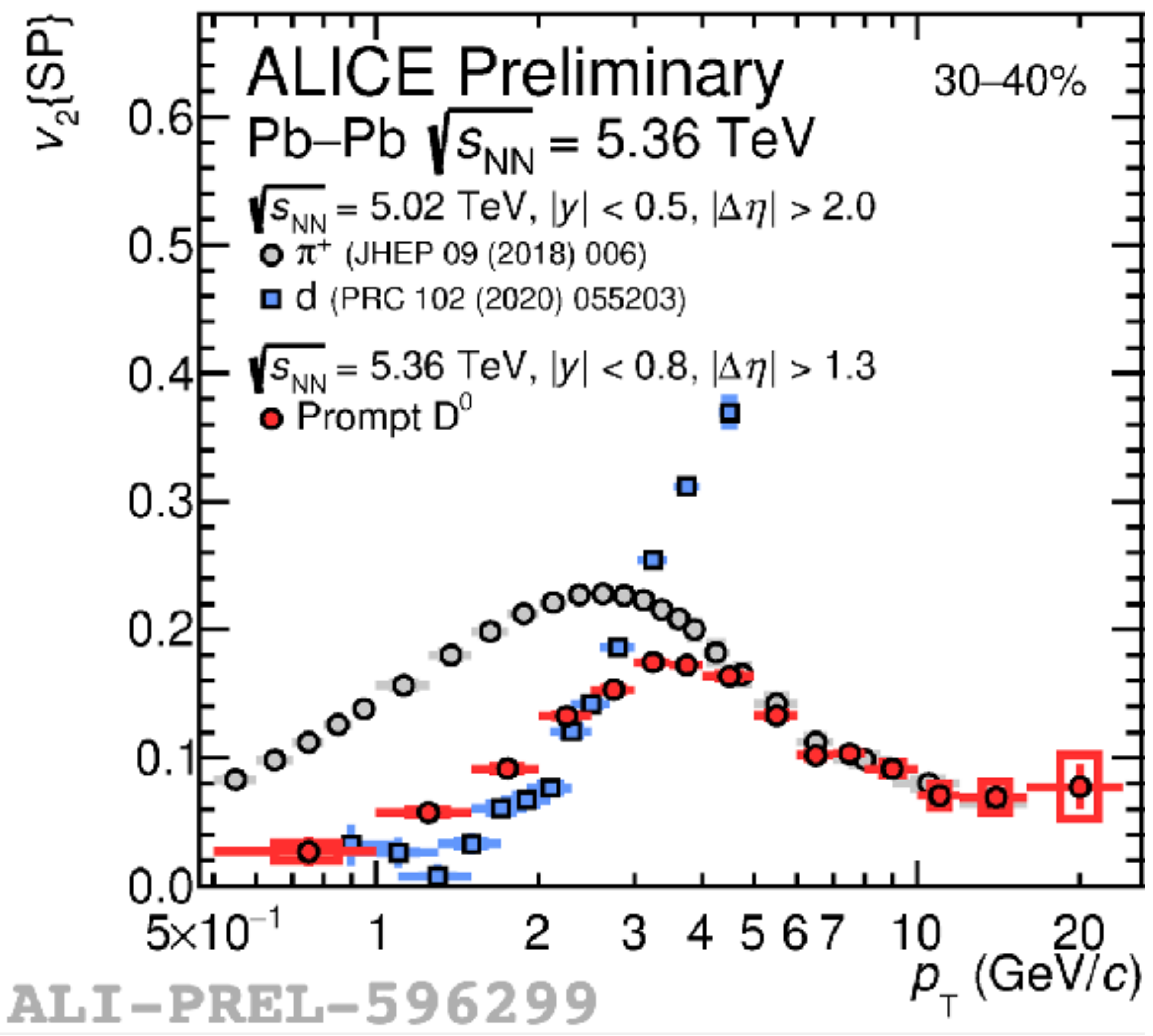
- First measurement of D^0 mesons in ultra peripheral Pb-Pb collisions.
- Data compared with FONLL pQCD calculations with nPDFs (EPPS21)
  - Good agreement with data within large uncertainties.
- Open HF measurements provide direct input to reduce nPDF uncertainties.

v_2 of charm quarks

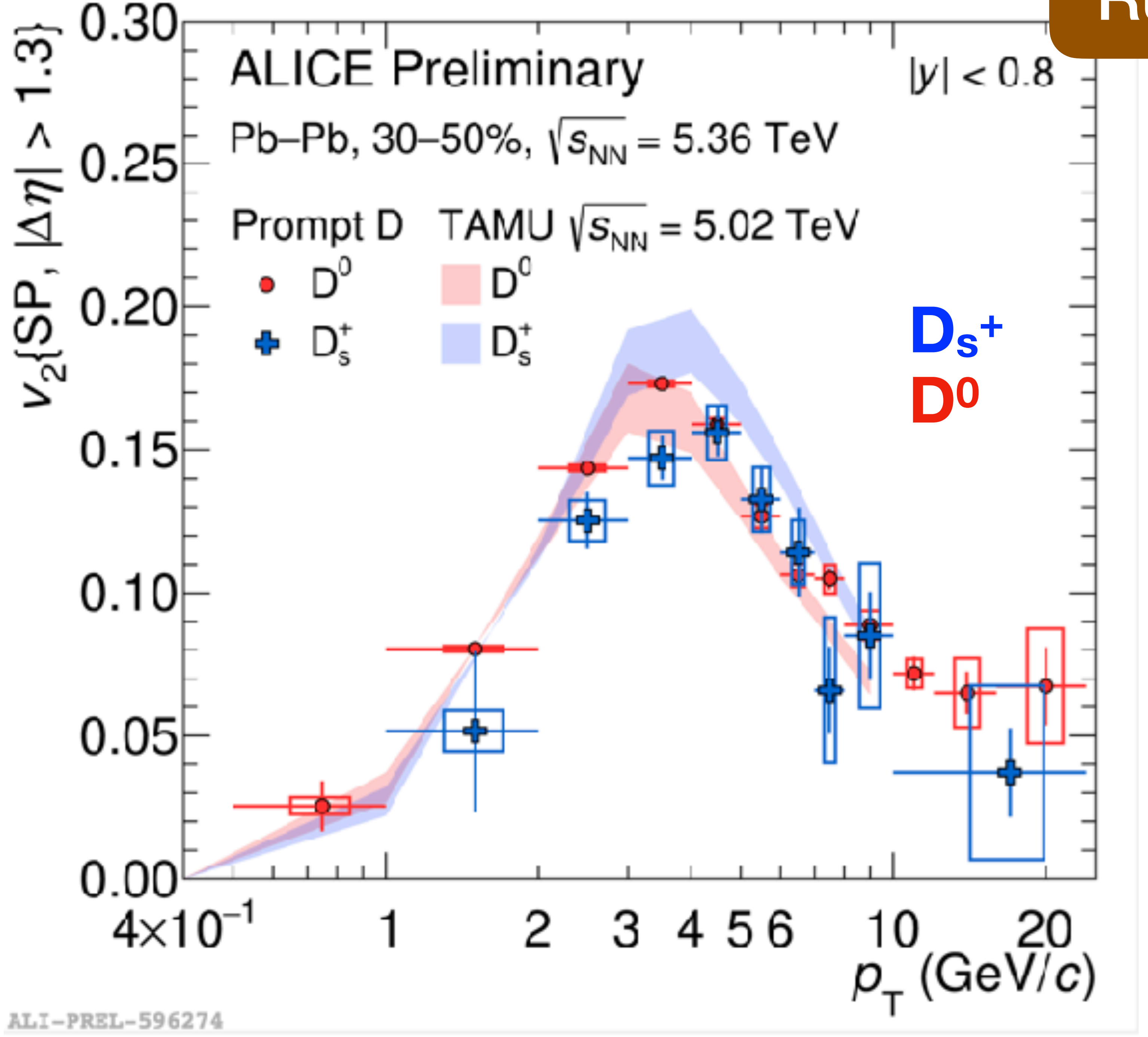
Heavy Flavor v_2: quantify HQ interaction strength at low p_T and constrains its path length dependent energy loss at high p_T

π^{+-}

D mesons



Run 3



- D^0 meson v_2 measured to very low $p_T < 1$ GeV/c
- Low p_T: $v_2(\pi^{+-}) > v_2$(D)
  - D-meson v_2 from charm quark flow + recombination with the light-flavor quark
- High p_T: $v_2(\pi^{+-}) \sim v_2$(D)
  - Path length dependent E.loss

D_s^+ v_2 close to non-strange D v_2
—> tendency to be smaller up to p_T = 4 GeV/c (different contribution of hadronic phase?)

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v_2 of charm quarks

Pb Pb

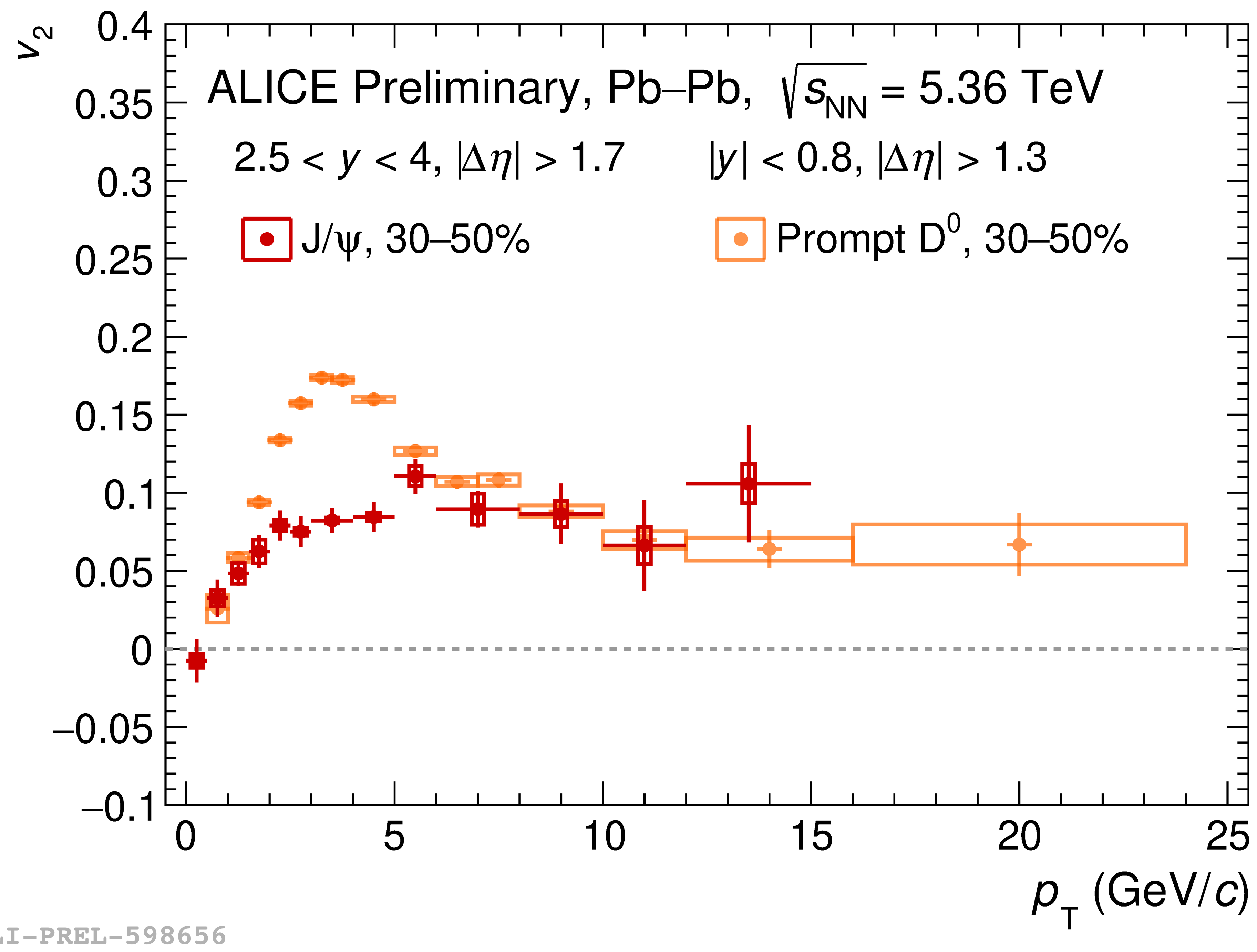
Open charm meson and charmonium v_2

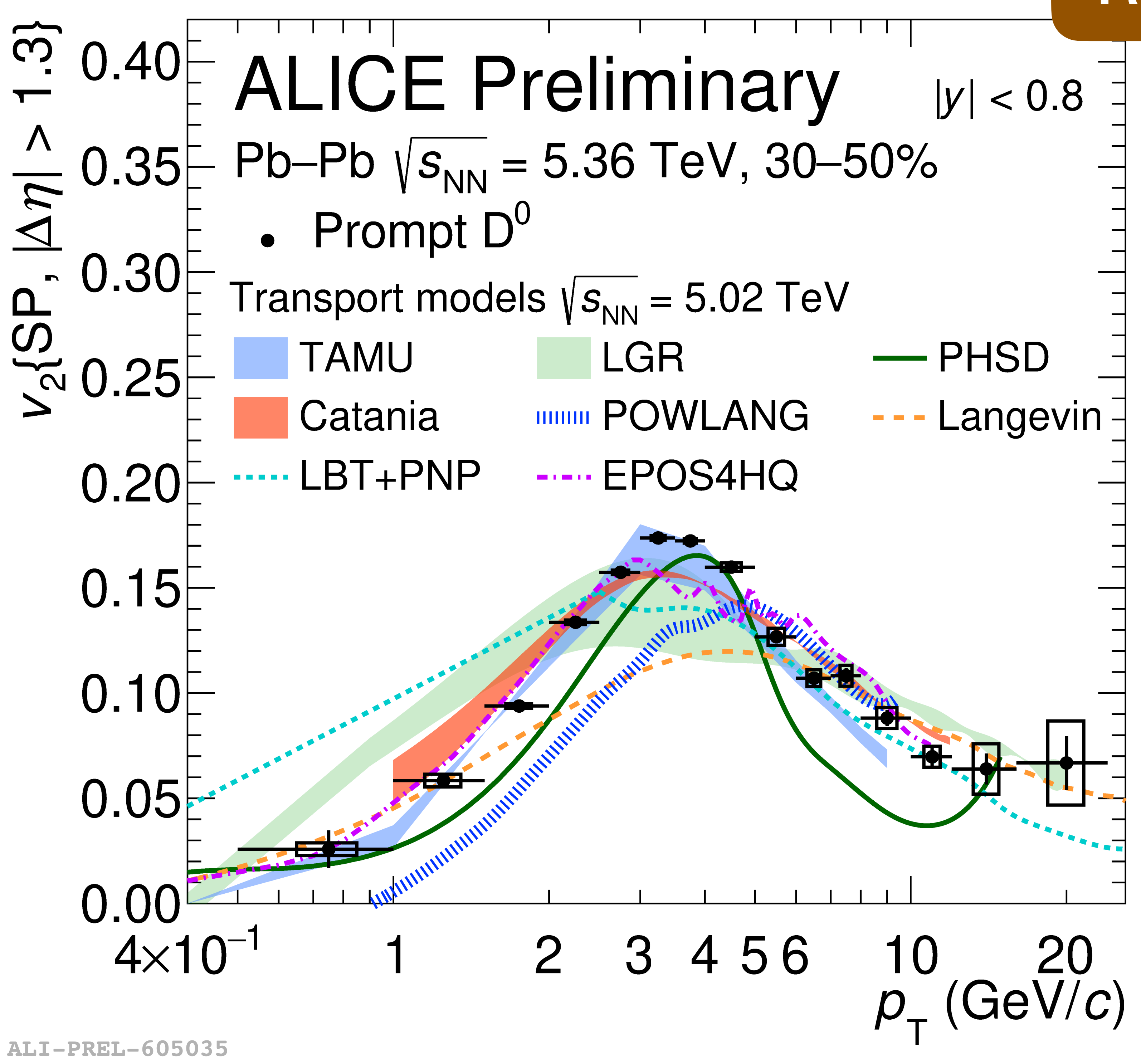
Run 3

TAMU PRL 124 (2020) 042301
Catania PRC 96 (2017) 04490
LBT PRC 94 (2016) 014909
LGR EPJC 80 (2020) 671
POWLANG EPJC 75 (2015) 121
EPOS4HQ arXiv:2401.17096
PHSD PRC 92 (2015) 014910
Langevin NPA 830 (2009) 865

D mesons

J/Ψ

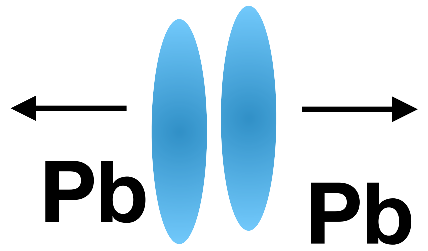




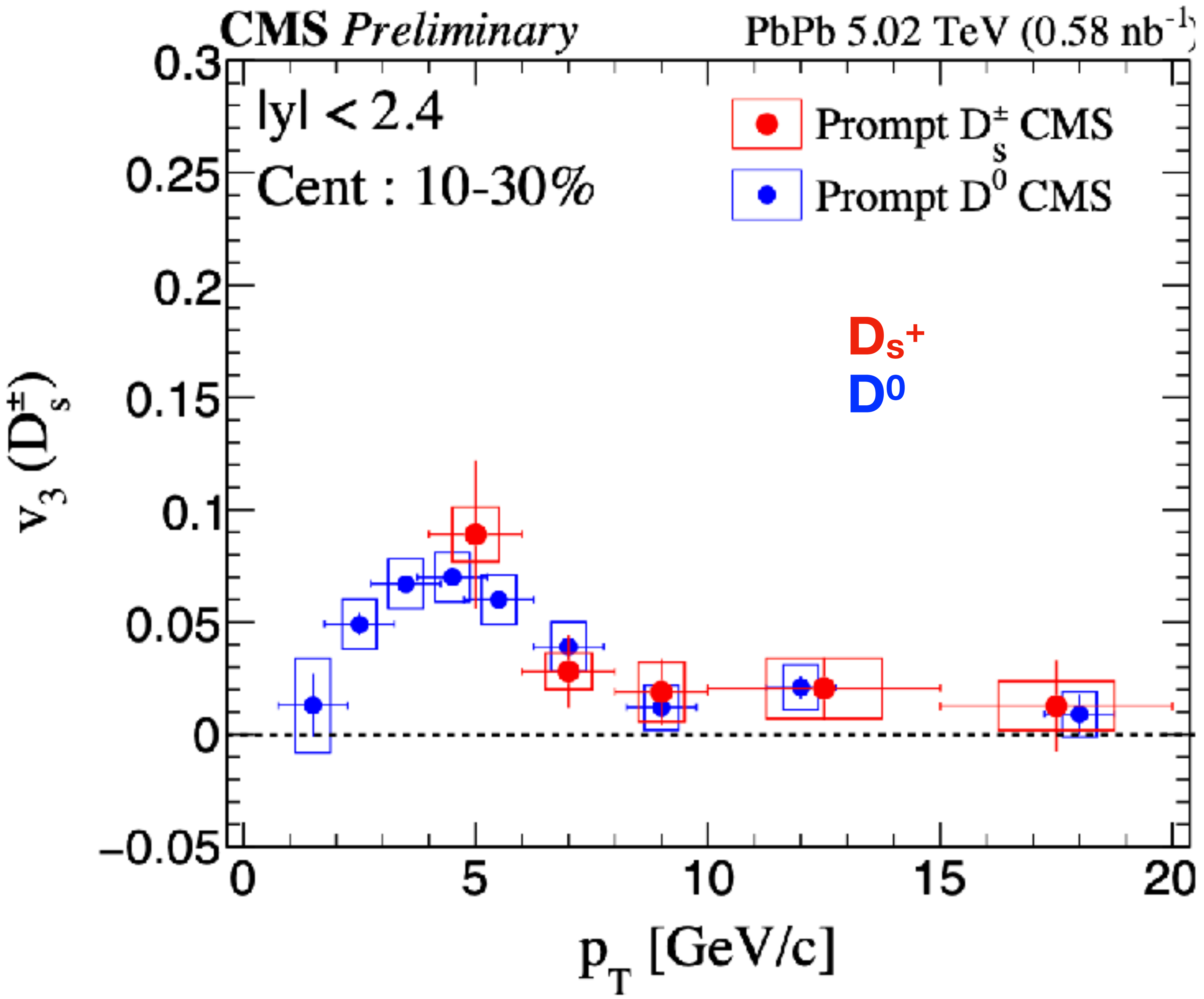
- Low p_T (< 3 GeV/c): v_2(D) ~ v_2(J/Ψ) : similar effects from charm quark flow
- Intermediate p_T (3-7 GeV/c): v_2(D) > v_2(J/Ψ) : hadronisation via recombination with light quarks
- High p_T: v_2(J/Ψ) ~ v_2(D): similar path length dependent E.loss

Model comparisons: **charm quarks strongly interacting with medium + critical role of hadronization via coalescence/recombination**

v_3 of charm quarks



Sensitive to the fluctuations in the initial energy-density within the overlap region

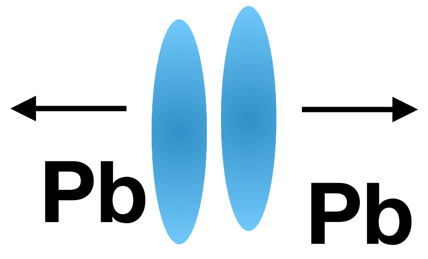


Non-zero v_3 measured for D^0 and D_s^+

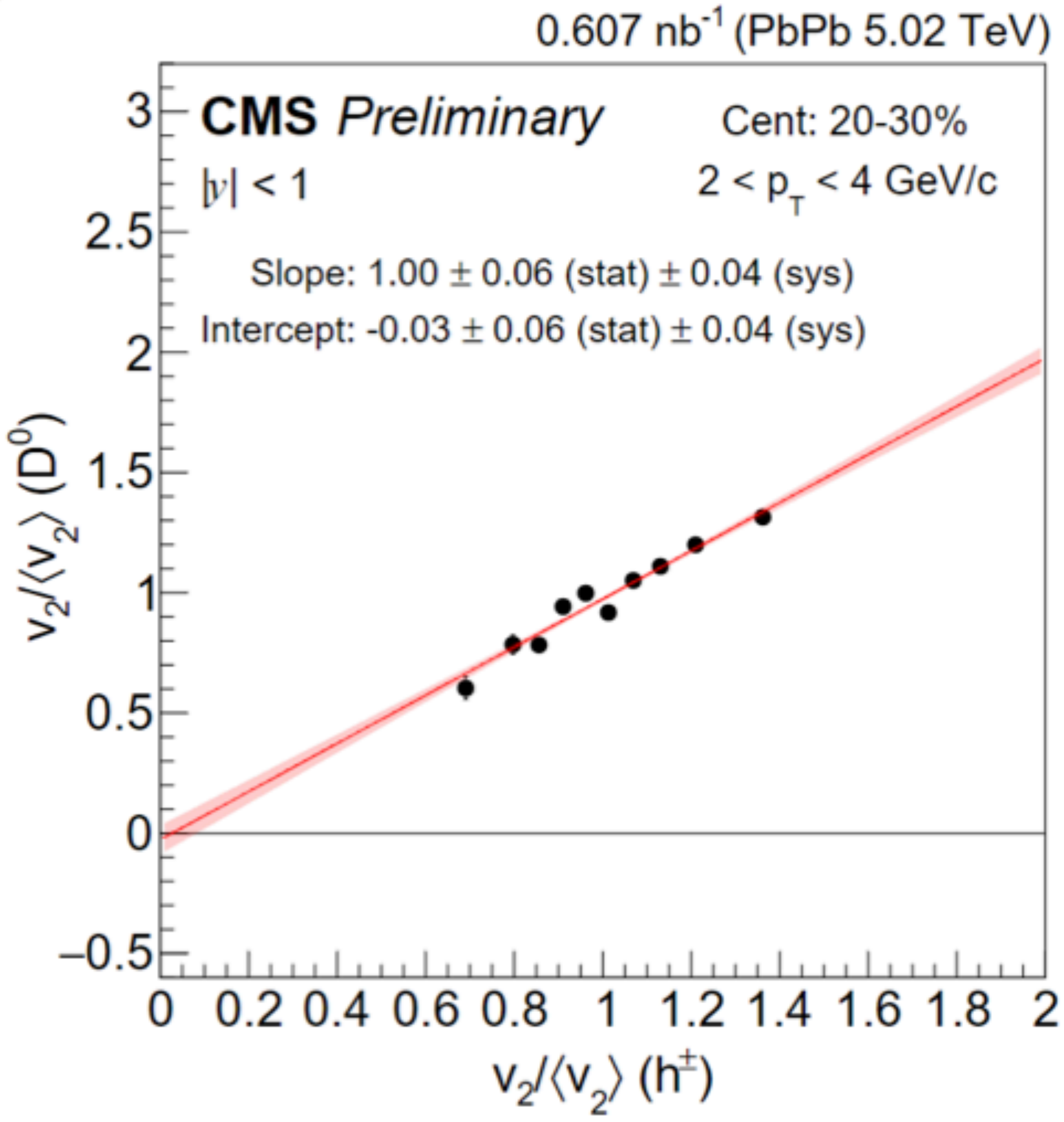
Similar v_3 values for D^0 and D_s^+ in the measured p_T range.

Confirms charm quark thermalized in the QGP medium.

HF vs LF v_2



Study of the correlation between v_2 of D^0 and the charged hadrons



Vary initial eccentricity by Event Shape Engineering q_2 while keeping same centrality

D^0 v_2 exhibits an approximate linear proportionality to the bulk flow

D^0 v_2 is entirely driven by initial shape as light flavors

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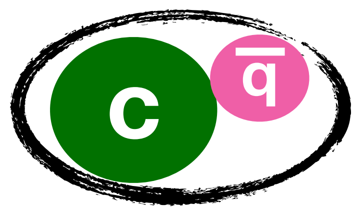
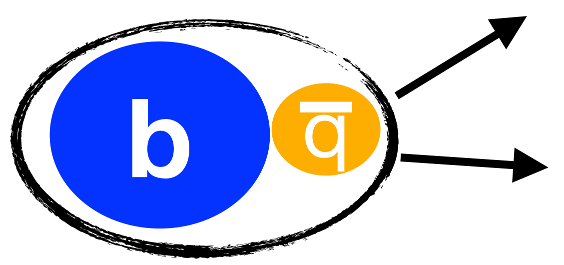
v_2 of beauty quarks

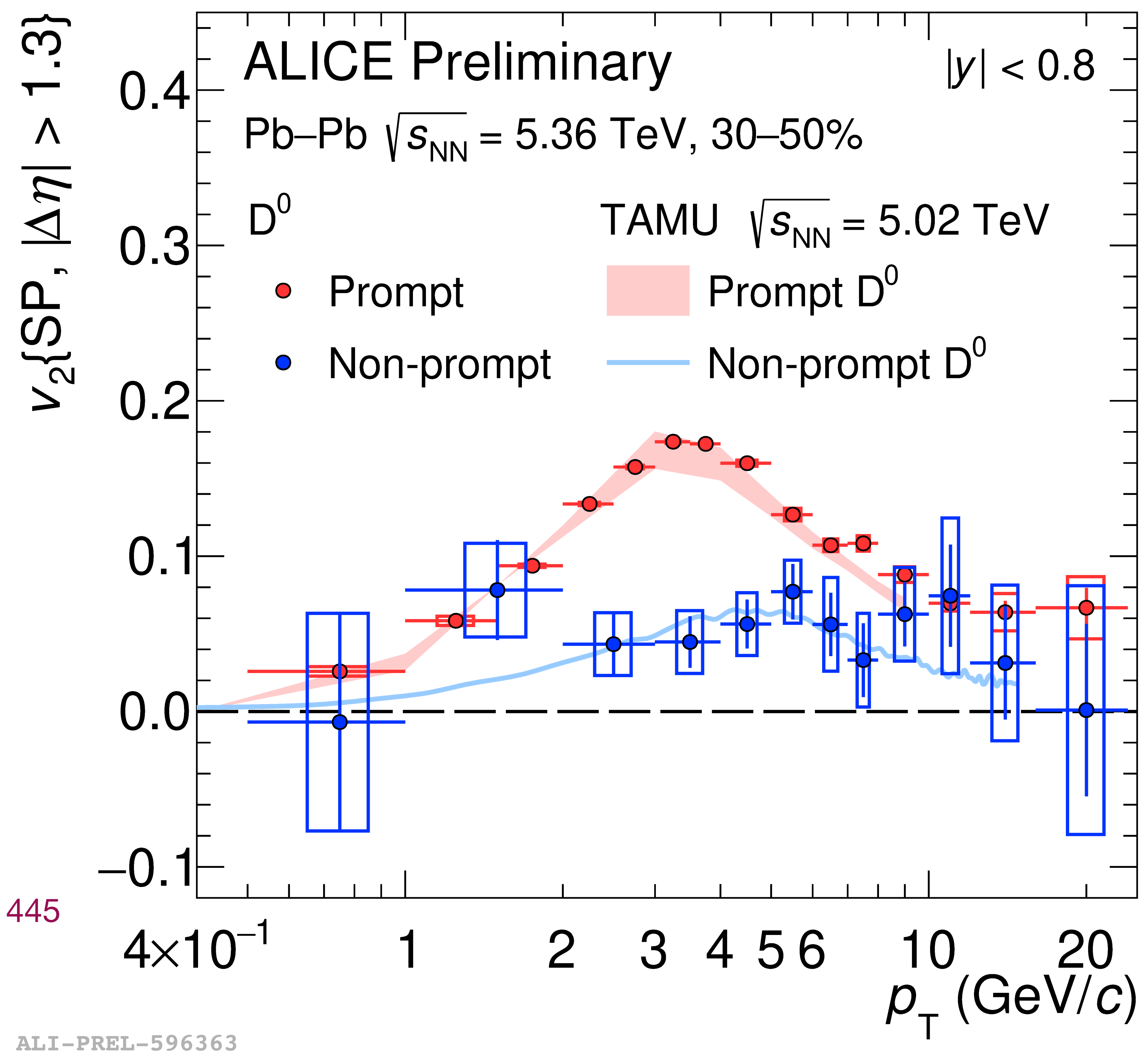
Mass dependence of v_2

D meson

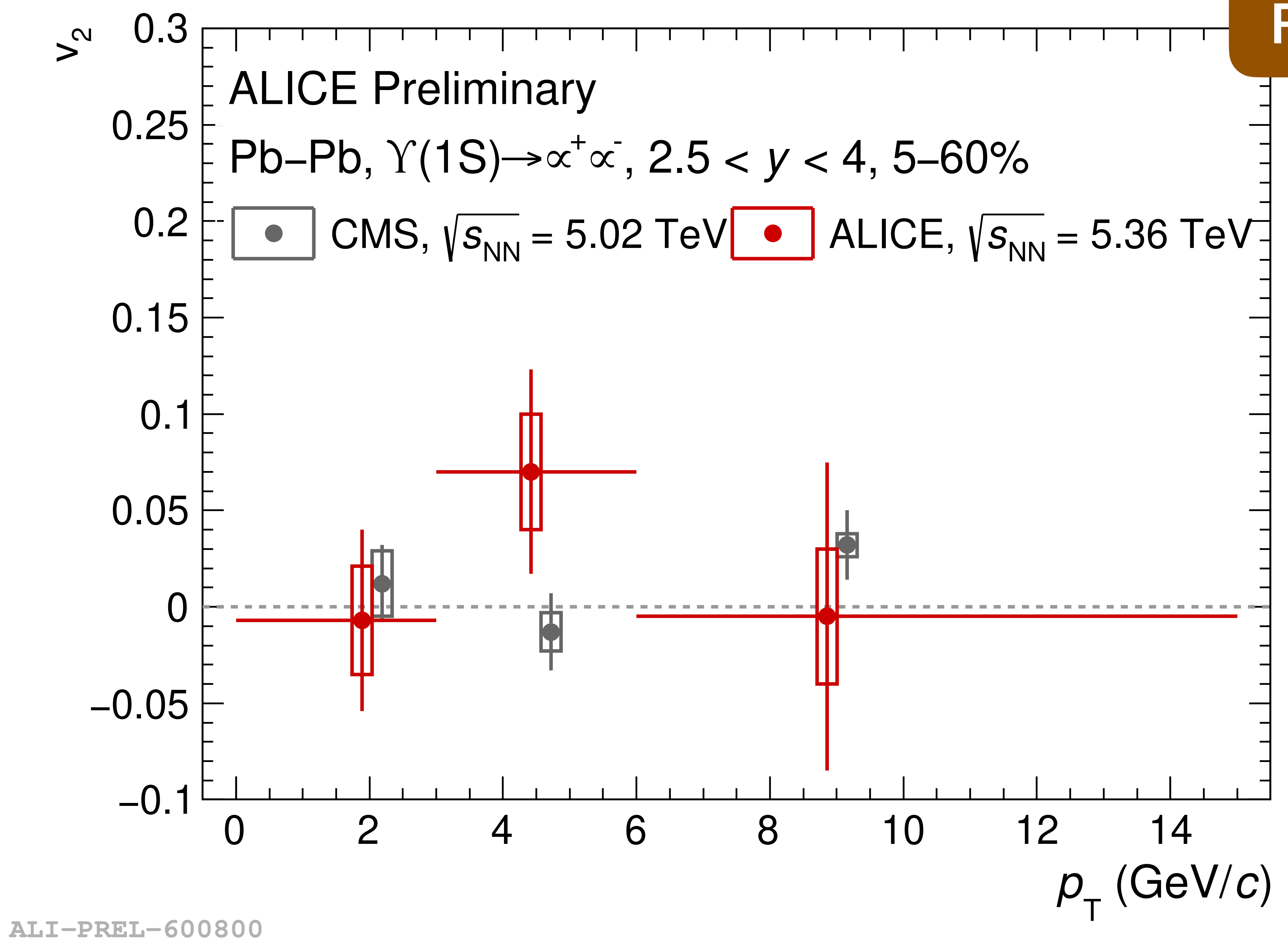


B meson **D**





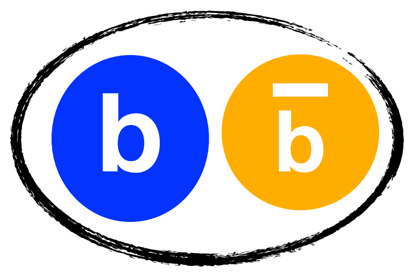
TAMU PLB 735 (2014) 445



Run 3

CMS PLB 819 (2021) 136385

Y(1S)



- Low and intermediate p_T (< 8 GeV/c): v_2(b->D^0) < v_2(D^0)
- High p_T v_2(b->D^0) ~ v_2(D^0)
- Model description: longer thermalization time for beauty quarks + recombination effects play significant role.

- Open-beauty $v_2 > 0$, while bottomonia v_2 ~ 0
  - Recombination and path-length dependent energy loss affecting open beauty?

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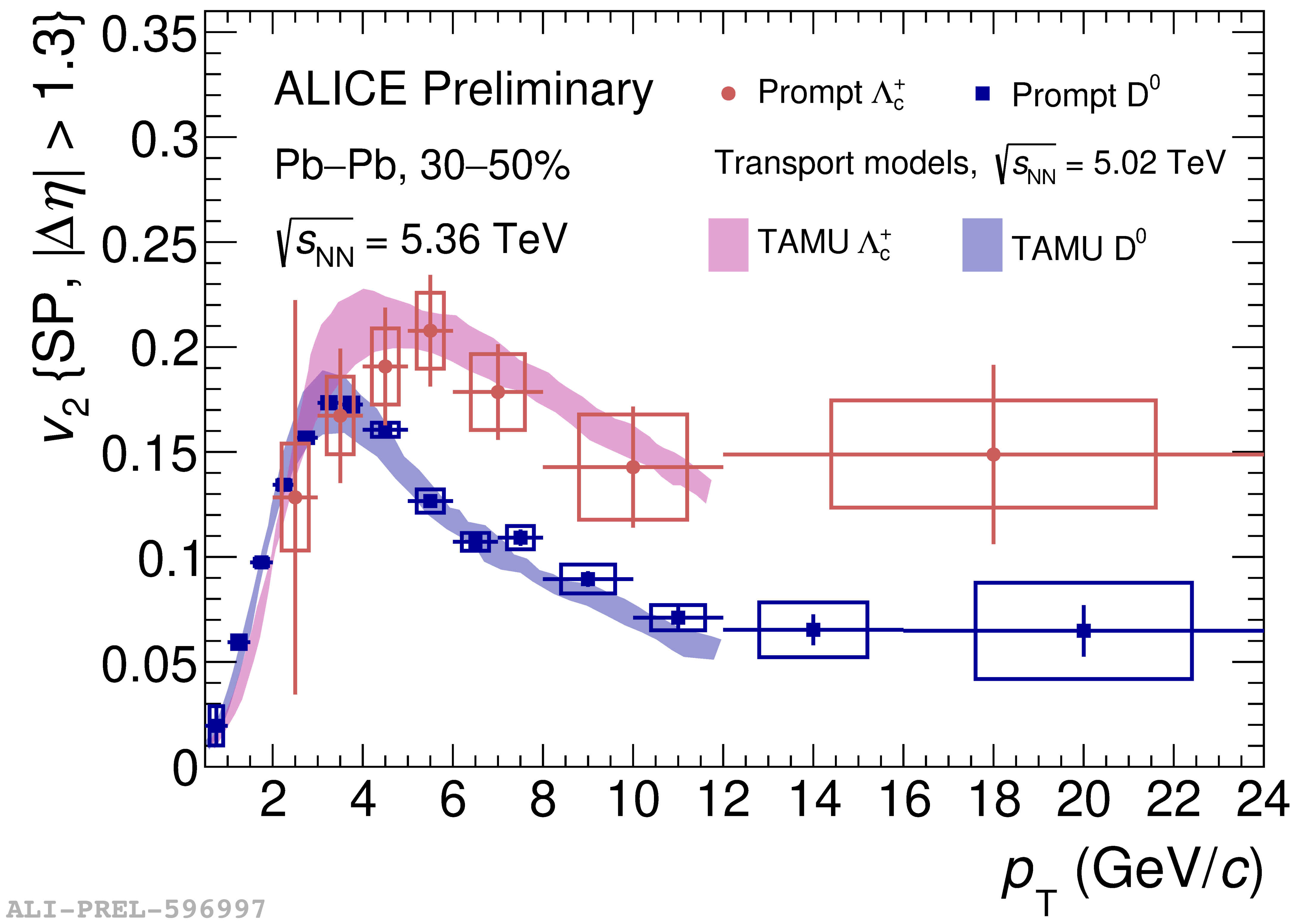
Meson vs baryon v_2

Pb Pb

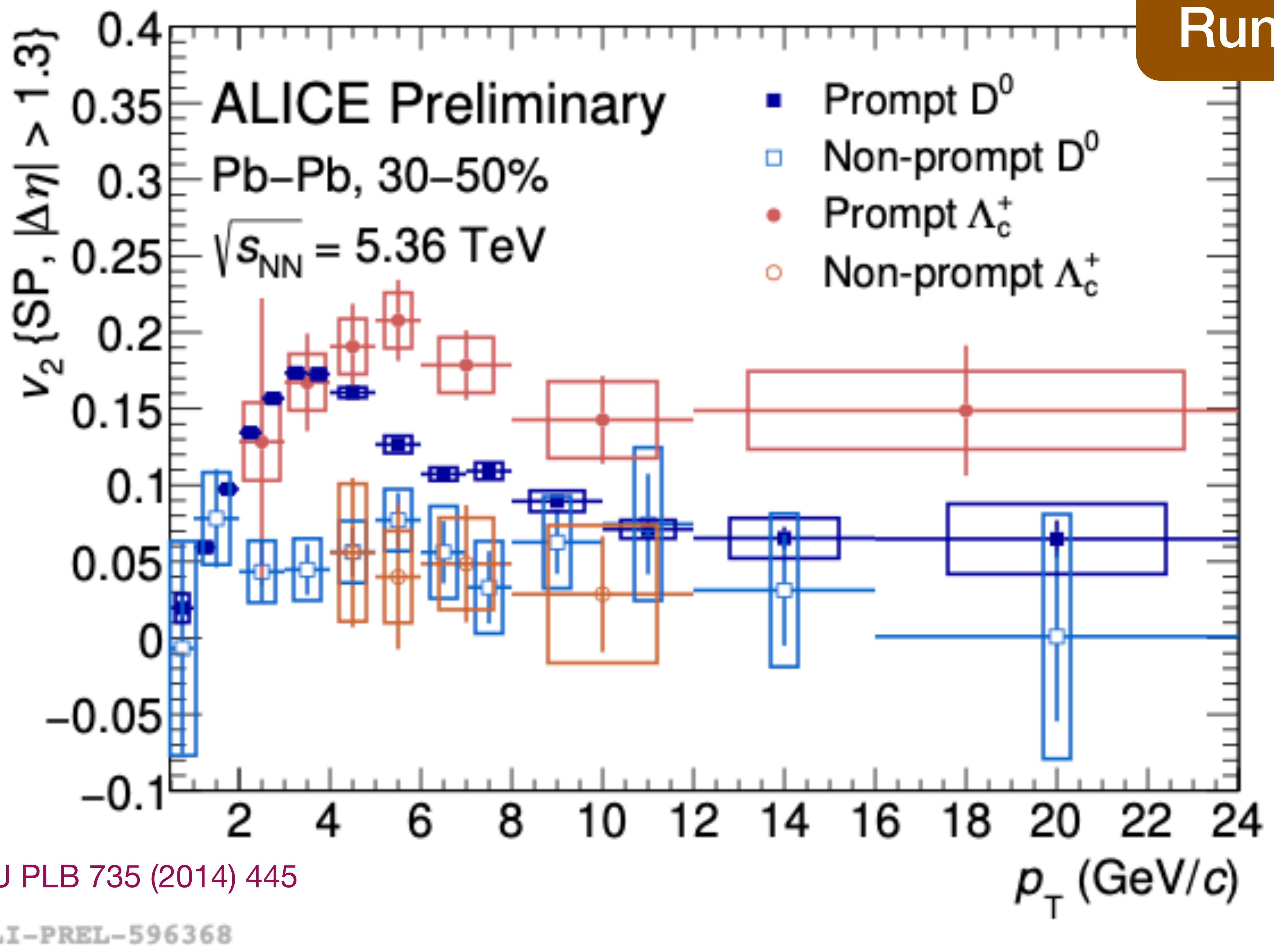
Charm meson vs baryon v_2

Λ_c baryon
D meson



Λ_c
D
b -> Λ_c
b -> D

Run 3



TAMU PLB 735 (2014) 445

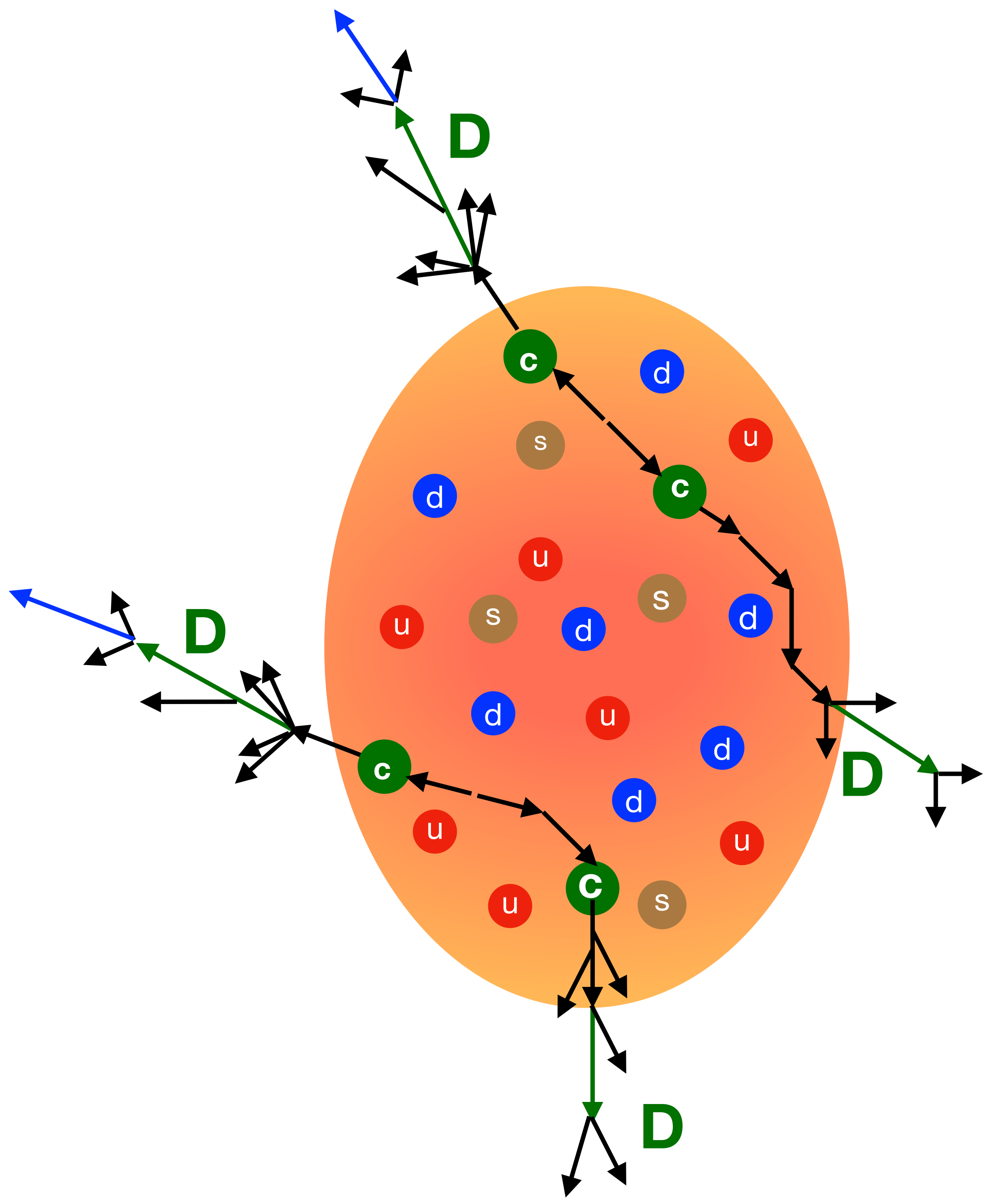
- Low p_T: similar v_2 of Λ_c and D^0 -> thermalized quarks
- p_T > 4 GeV/c: $v_2(\Lambda_c) > v_2(D^0)$
  - **Meson vs baryon behavior —> from hadronisation via recombination**

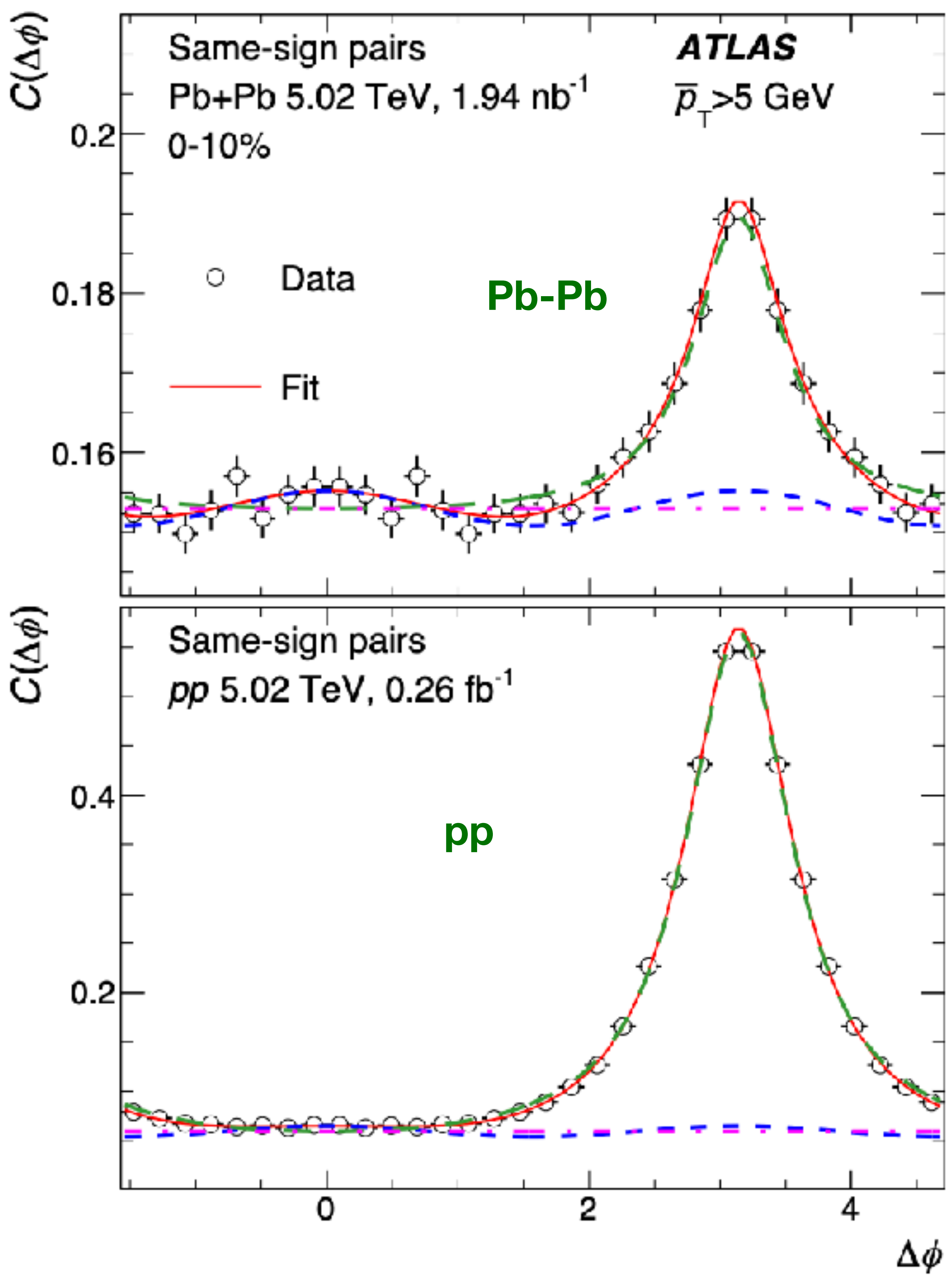
- Non-prompt D mostly from B mesons
- Non-prompt Λ_c mostly originate from Λ_b^0-baryons
- v_2(b -> D^0) ~ v_2(b -> Λ_c) < v_2 (prompt Λ_c)

Heavy quark pair dynamics

Further constraint heavy quark dynamics by tracking quark pairs

- Using $c\bar{c}$ and $b\bar{b}$ angular correlations —> sensitive to relative importance of collisional and radiative scattering





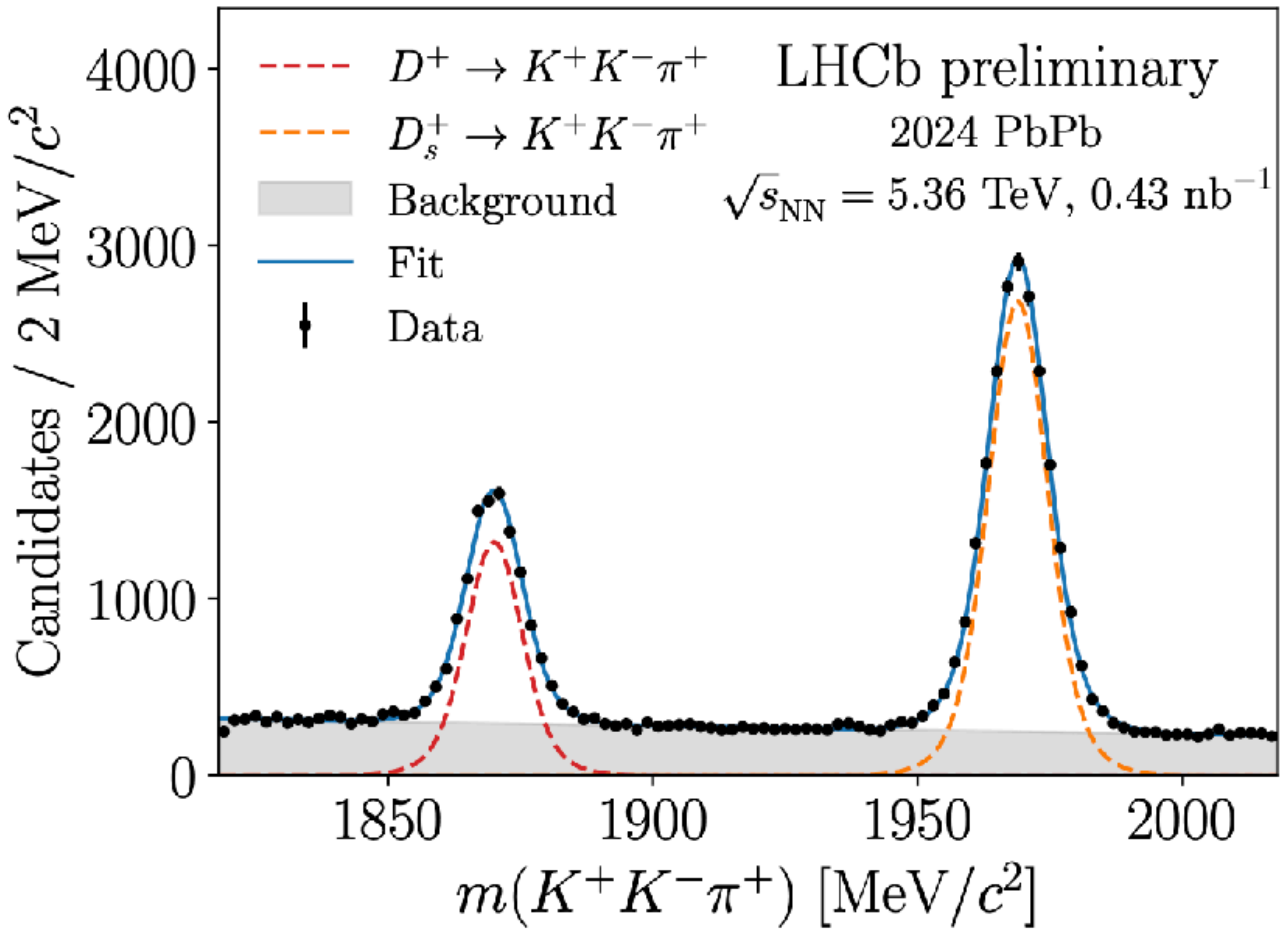
ATLAS PRL 132 (2024) 202301

Measurement of μ-μ angular correlations (largely from heavy flavor decays):

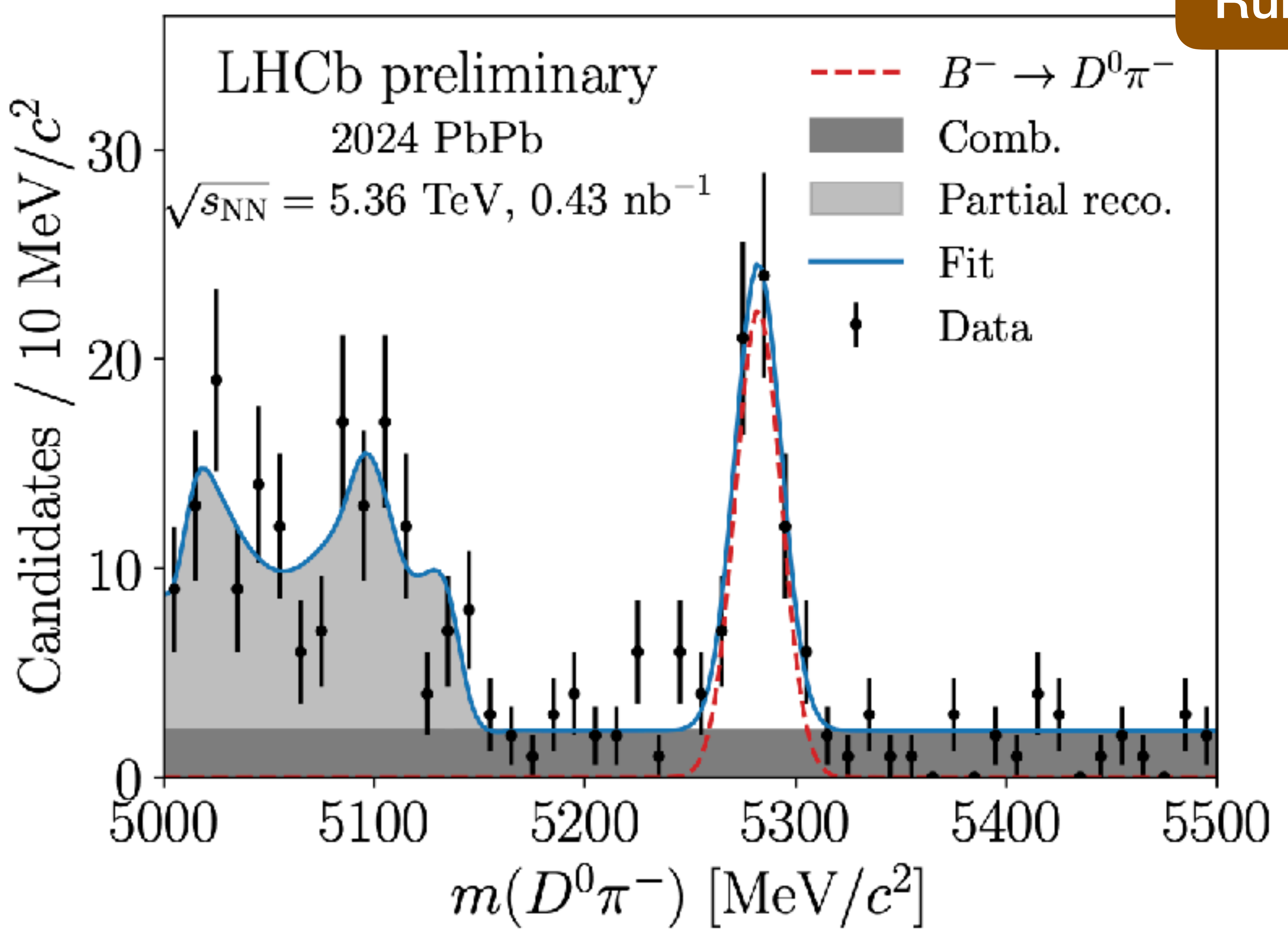
- No broadening effects observed in Pb-Pb compared to pp
- But width slightly narrow in most central collisions
  - High p_T range used?
  - Bias towards less quenched jets?

HF reconstruction at forward rapidity

Pb Pb



Run 3



LHCb-FIGURE-2025-004

Further extend study of heavy-flavour interactions using beauty quarks and at forward rapidity

Summary

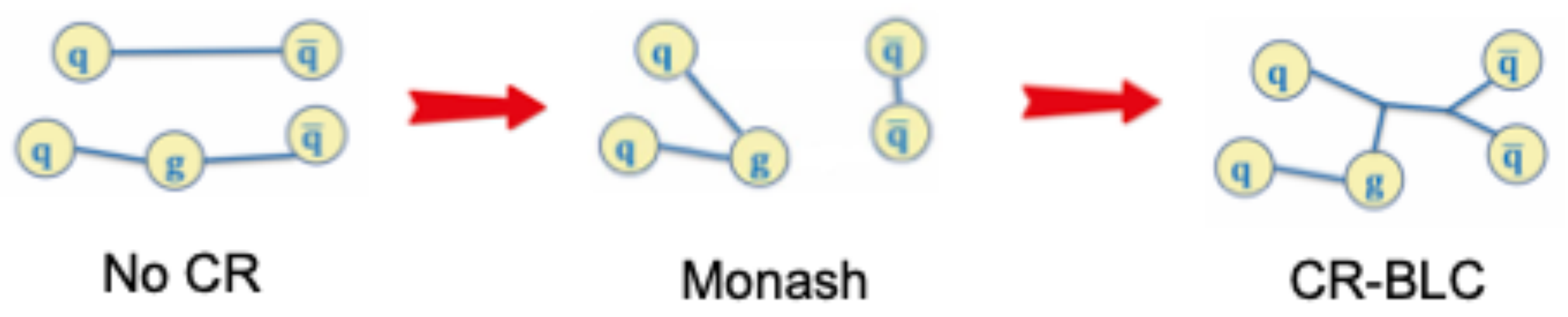
- Several new and exciting heavy flavor results from LHC —> more to come.
- **Moving forward**
  - Further constraint QGP transport properties using beauty quarks and differential measurements.
  - Heavy quark initiated jets and jet substructure measurements.
  - Possible with **LHC Run 3 & 4 and beyond.**

BACK UP

Model Description

PYTHIA 8 (CR Mode 2) (Christiansen & Skands, JHEP 1508 (2015) 003)

- **Colour reconnection mechanisms beyond leading colour** (BLC) approximation with new **junction topologies** that favour baryon formation.

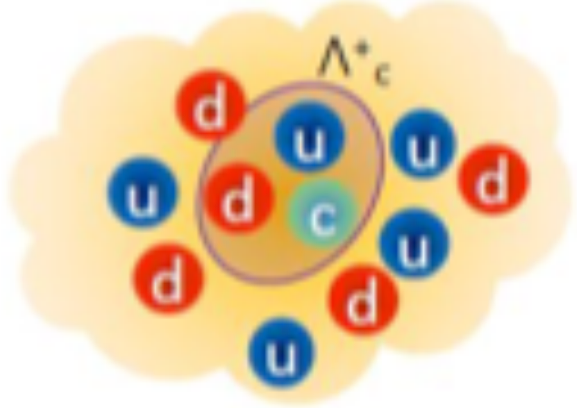


SH model + RQM (Hee & Rapp, PLB 795 (2019) 117-121)

- Quark hadronisation driven by statistical weights governed by hadron masses.
- Feed-down from excited baryon states predicted by the Relativistic Quark Model (RQM).

Catania (V. Minissale et al., PLB 821 (2021) 136622)

- Thermalised system of u,d,s quarks and gluons.
- Hadronisation via interplay of fragmentation and coalescence.



QCM (Song, Li & Shao, EPJC 78 (2018) 344)

- Pure coalescence model.
- Charm quark is combined with a co-moving light antiquark or two quarks.

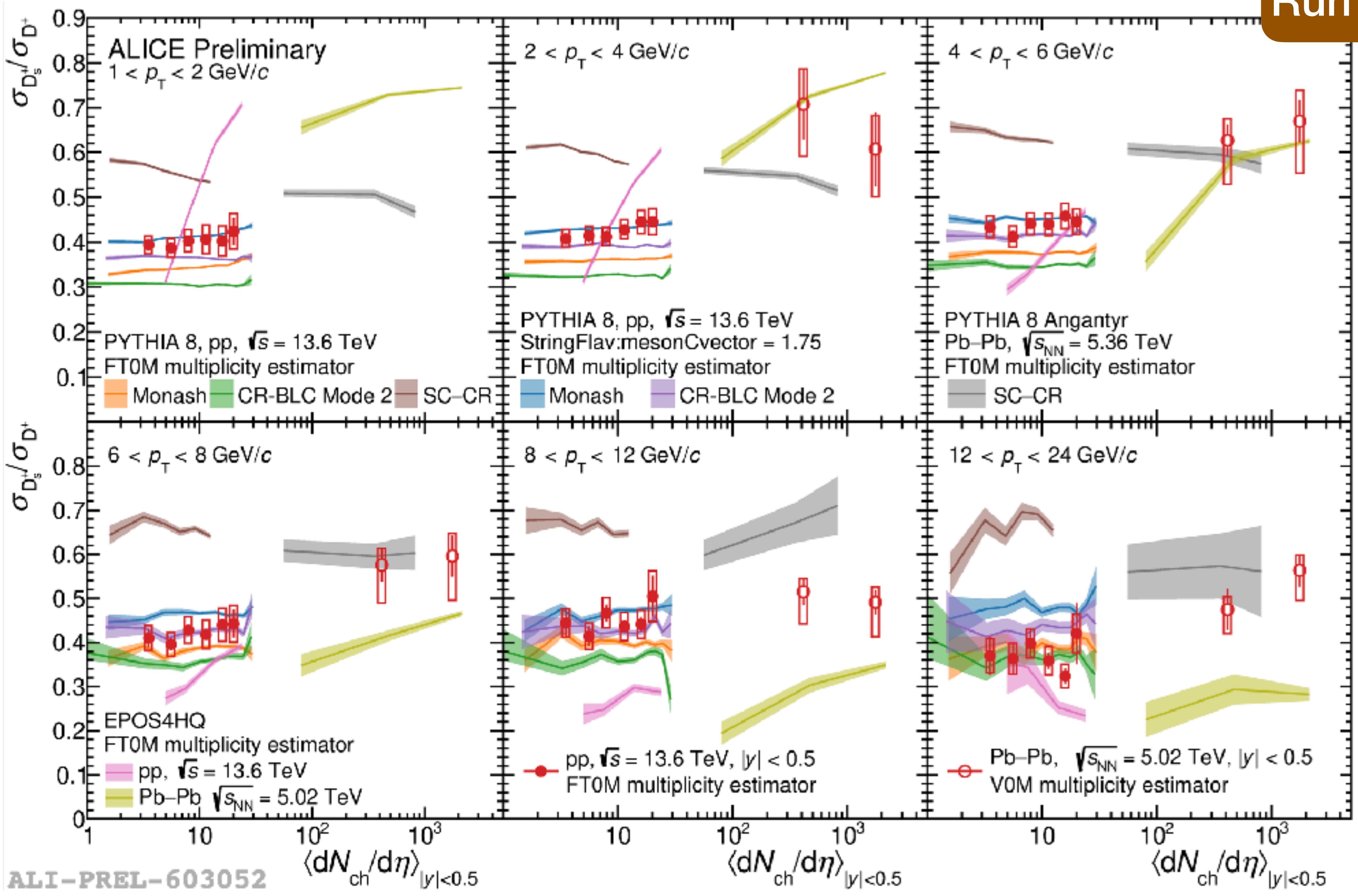
POWLANG (Beraudo et Al, arXiv:2306.02152)

- Expanding fireball assumed in pp collisions.
- Hadronisation via recombination with light quarks.
- Charm-baryon formation enhanced thanks to diquark excitations.

D_s^+/D^+ production

Strange D meson production

New Run 3

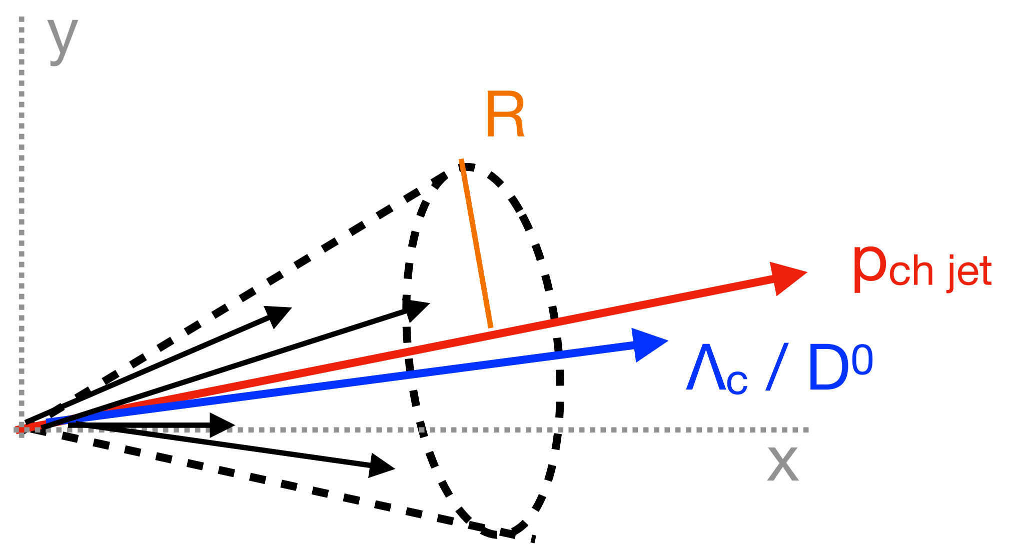


- D_s^+/D^+ ratio independent of p_T and multiplicity in pp collisions in the measured p_T range.
- Value in pp collisions consistent with e^+e^-
- Ratio compatible with **PYTHIA Monash** and **CR-BLC**.

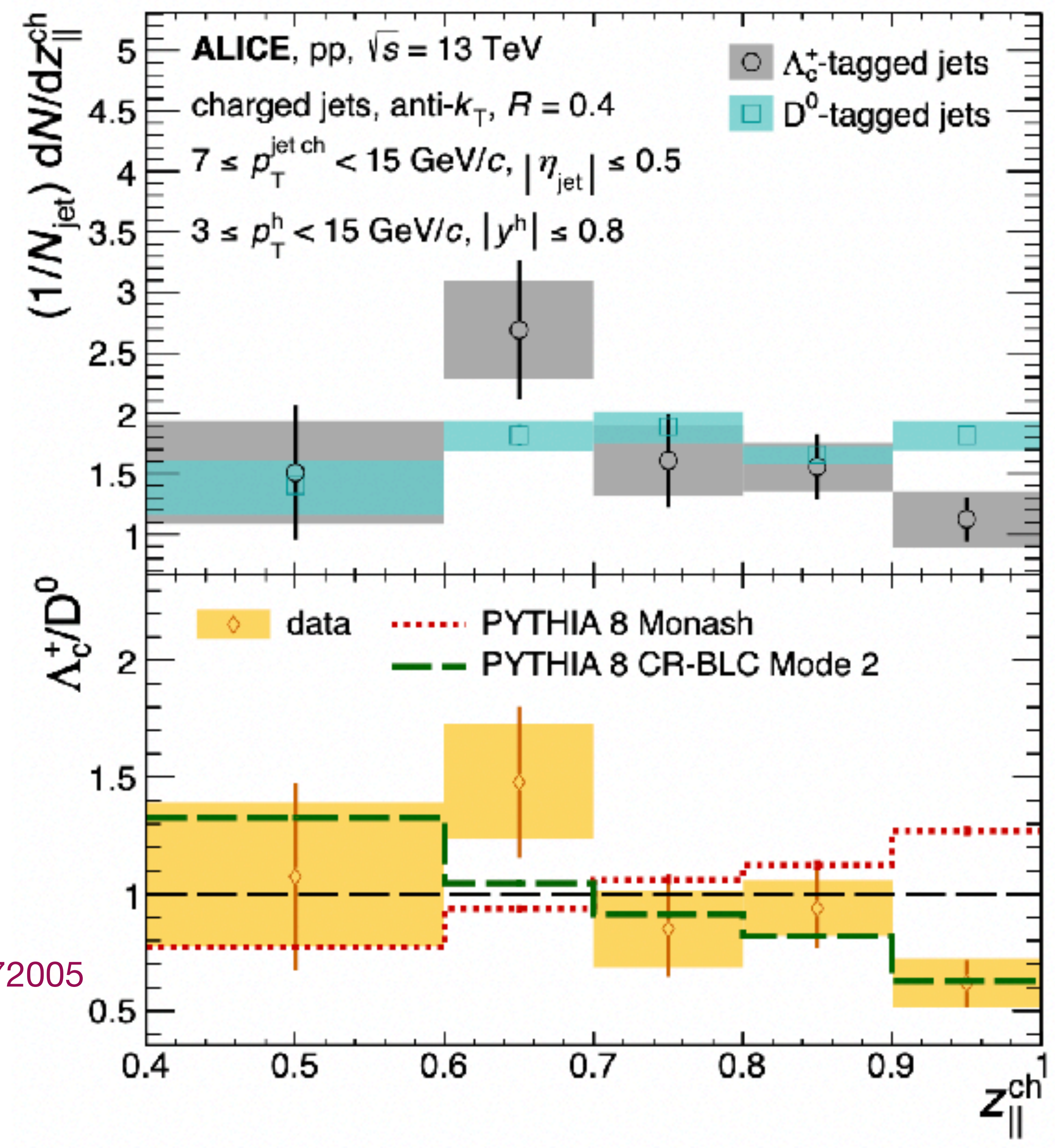
- Pb-Pb collisions:
  - Ratio higher at low and intermediate p_T compared to pp collisions.
  - Recombination of charm quarks with enhanced strange quarks in the QGP medium.

Fragmentation Function

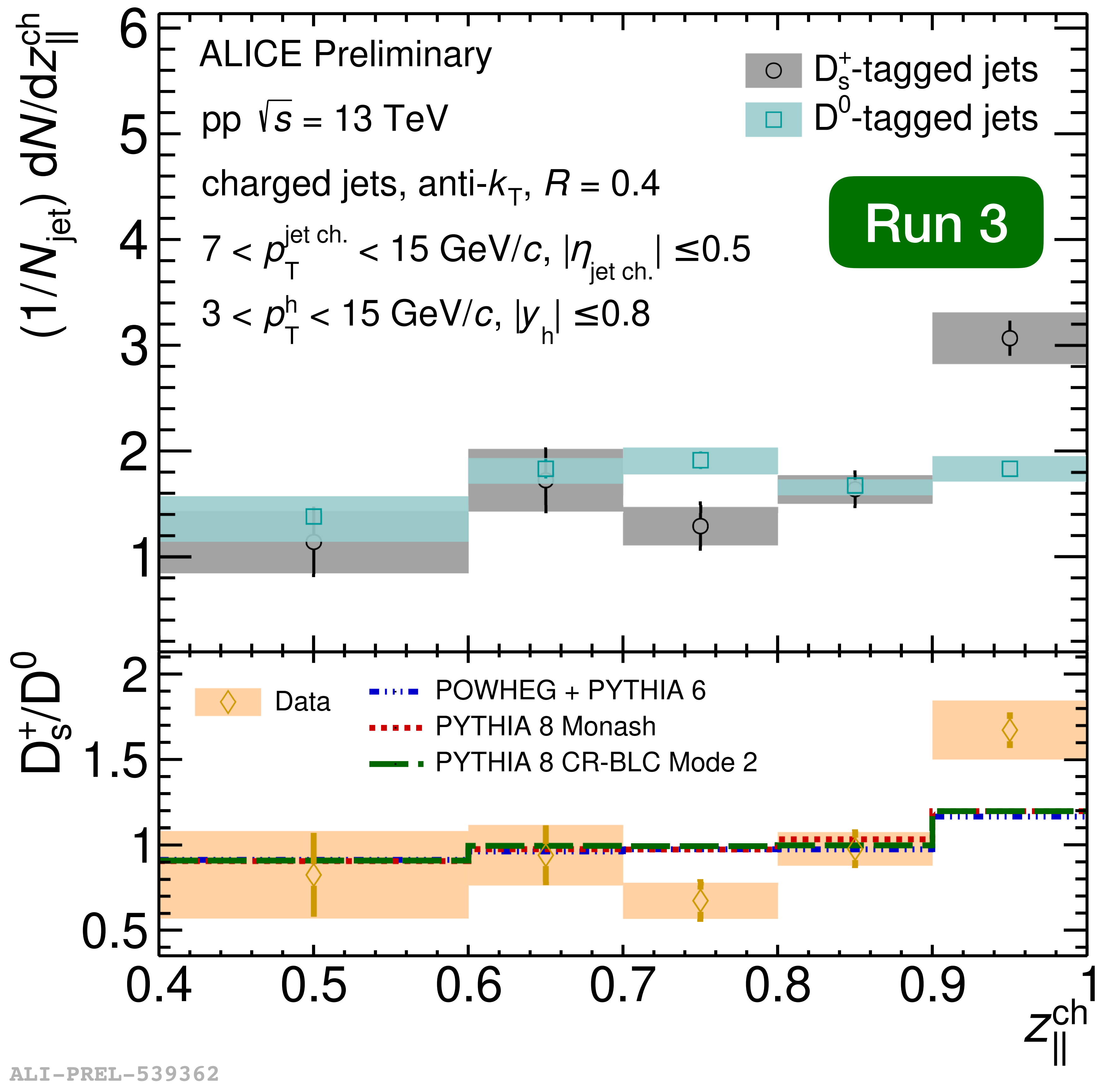
Study charm jet fragmentation functions



$$z_{||}^{ch} = \frac{p_{jet} \cdot p_{HF}}{p_{jet} \cdot p_{jet}}$$

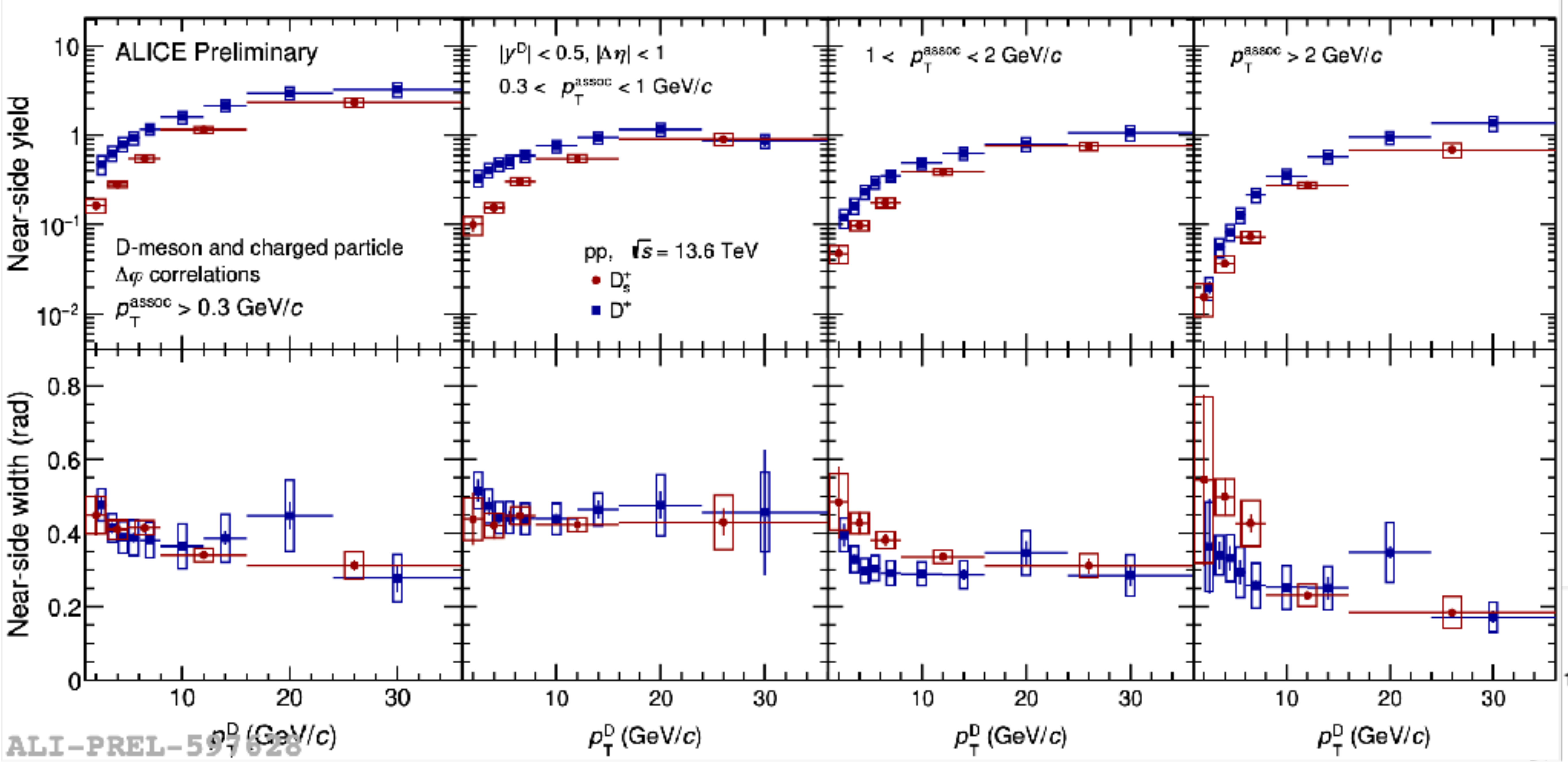


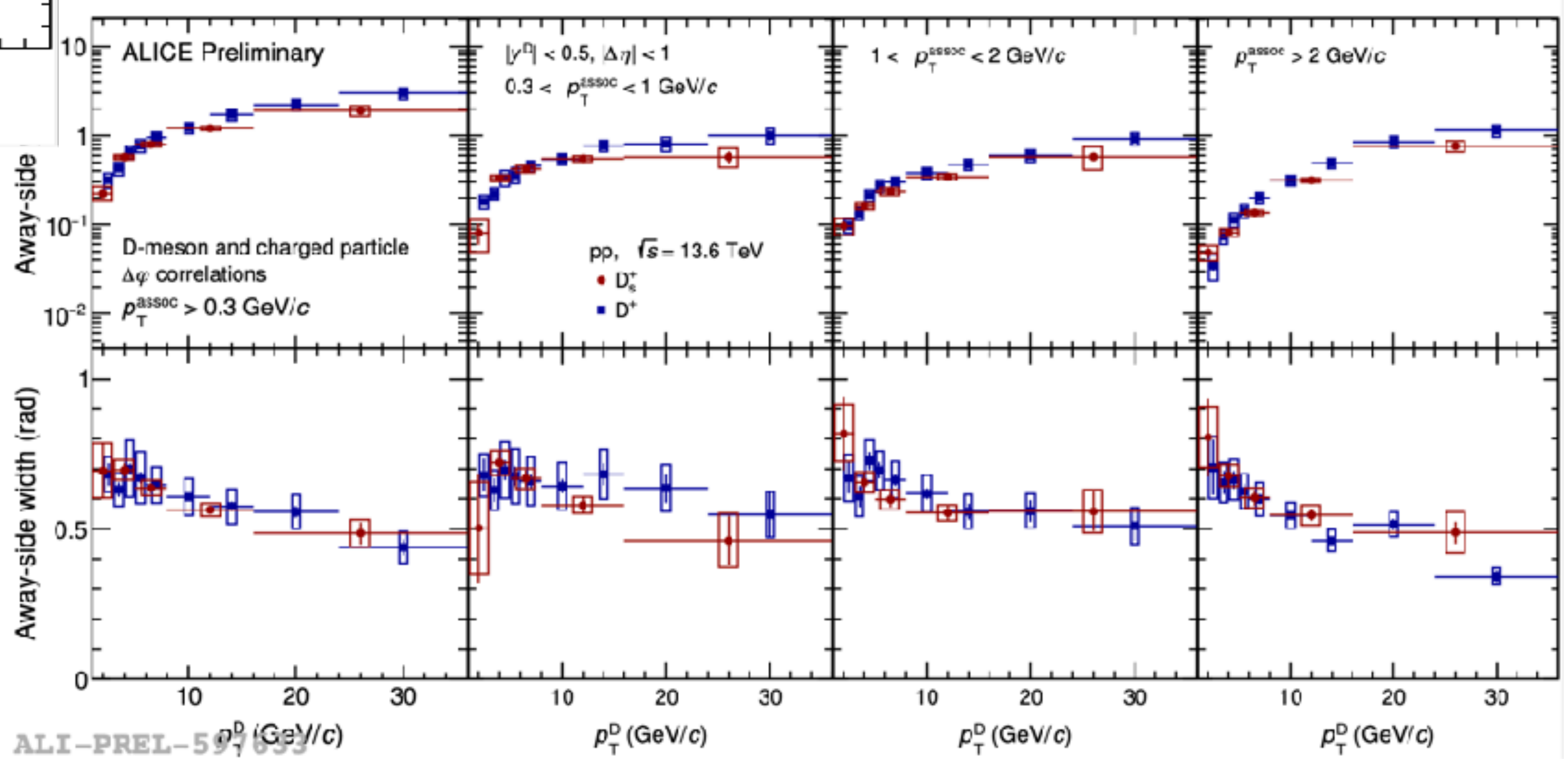
PRD 109 (2024) 072005

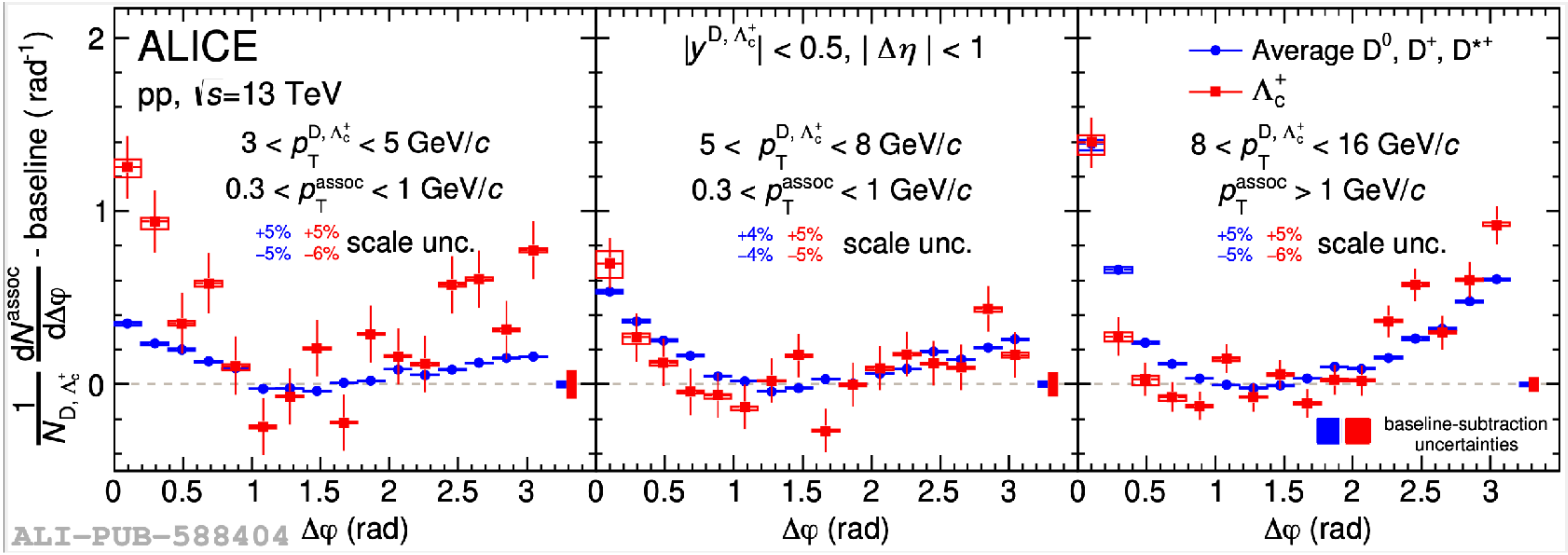


- Hint of softer fragmentation of charm quarks to Λ_c compared to D^0 mesons.
- PYTHIA 8 with CR describes the data

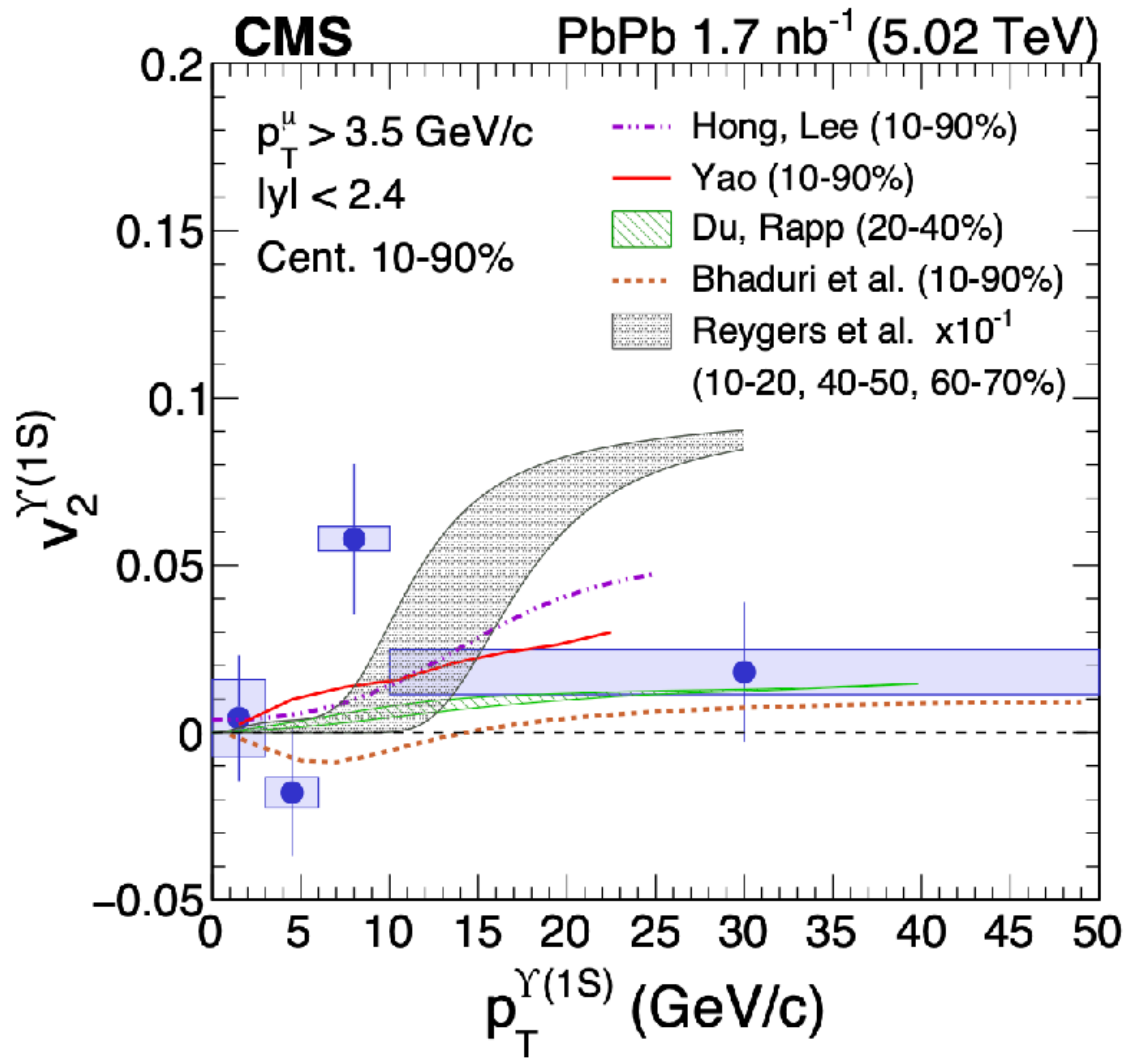
- Hint of harder fragmentation of charm quarks to D_s^+ compared to D^0 mesons.
- MC does not describe large $Z_{||}^{ch}$


ALICE Preliminary
$|y^D| < 0.5$, $|\Delta\eta| < 1$
$0.3 < p_T^{assoc} < 1$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c
$p_T^{assoc} > 2$ GeV/c
D-meson and charged particle
$\Delta\varphi$ correlations
$p_T^{assoc} > 0.3$ GeV/c
pp, $\sqrt{s}$ = 13.6 TeV
D_s^+
D^+
Near-side yield
Near-side width (rad)
p_T^D (GeV/c)
ALI-PREL-597628

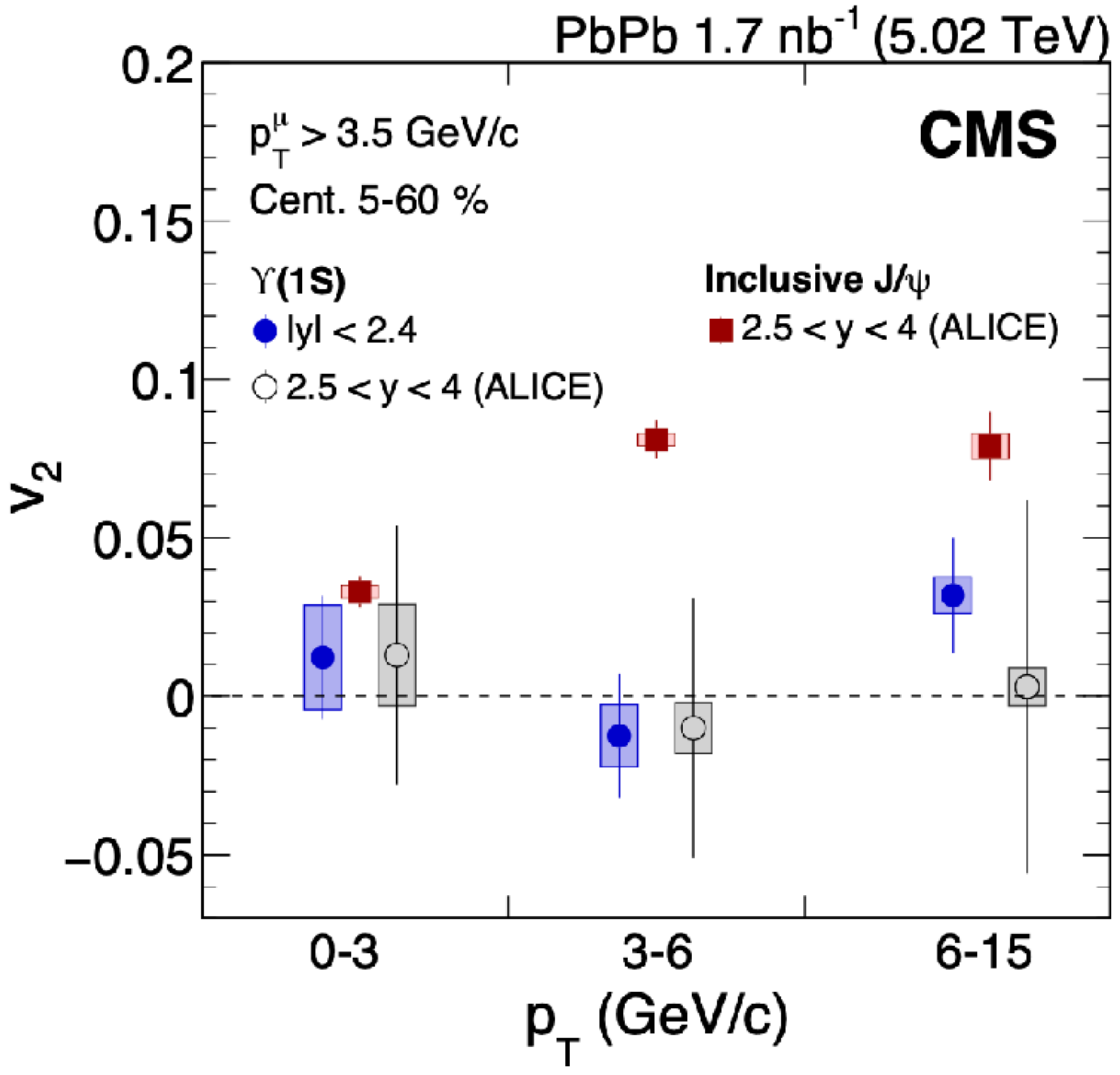

ALICE Preliminary
$|y^D| < 0.5$, $|\Delta\eta| < 1$
$0.3 < p_T^{assoc} < 1$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c
$p_T^{assoc} > 2$ GeV/c
D-meson and charged particle
$\Delta\varphi$ correlations
$p_T^{assoc} > 0.3$ GeV/c
pp, $\sqrt{s}$ = 13.6 TeV
D_s^+
D^+
Away-side
Away-side width (rad)
p_T^D (GeV/c)


ALICE
pp, √s=13 TeV
3 < p_T^{D, Λc+} < 5 GeV/c
0.3 < p_T^{assoc} < 1 GeV/c
+5% +5%
−5% −6% scale unc.
|y^{D, Λc+}| < 0.5, | Δη | < 1
5 < p_T^{D, Λc+} < 8 GeV/c
0.3 < p_T^{assoc} < 1 GeV/c
+4% +5%
−4% −5% scale unc.
Average D0, D+, D*+
Λc+
8 < p_T^{D, Λc+} < 16 GeV/c
p_T^{assoc} > 1 GeV/c
+5% +5%
−5% −6% scale unc.
baseline-subtraction
uncertainties
1/N_{D, Λc+} dN^{assoc}/dΔφ - baseline (rad^-1)
Δφ (rad)
ALI-PUB-588404

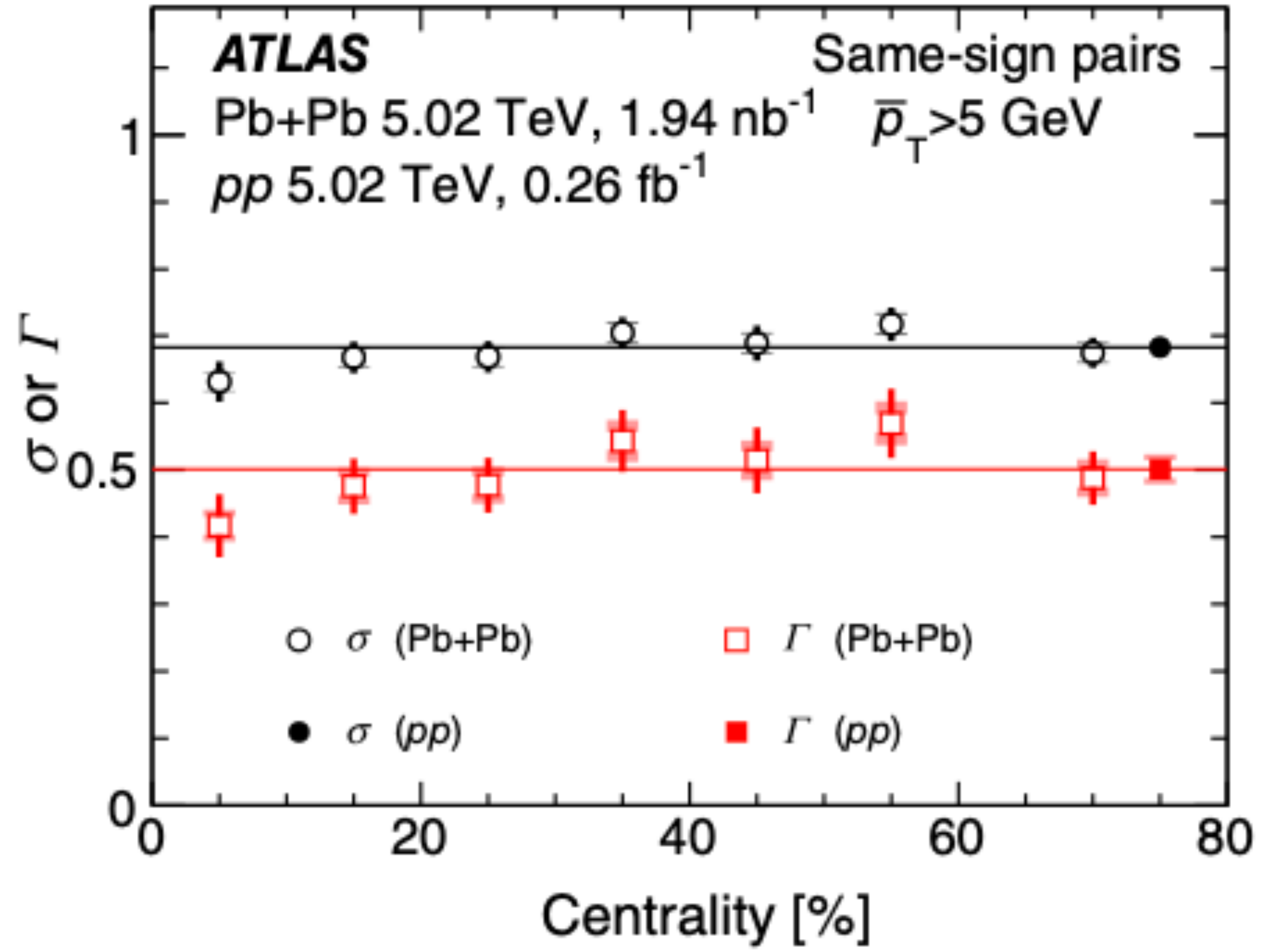
Model comparison of Υ(1S) v_2

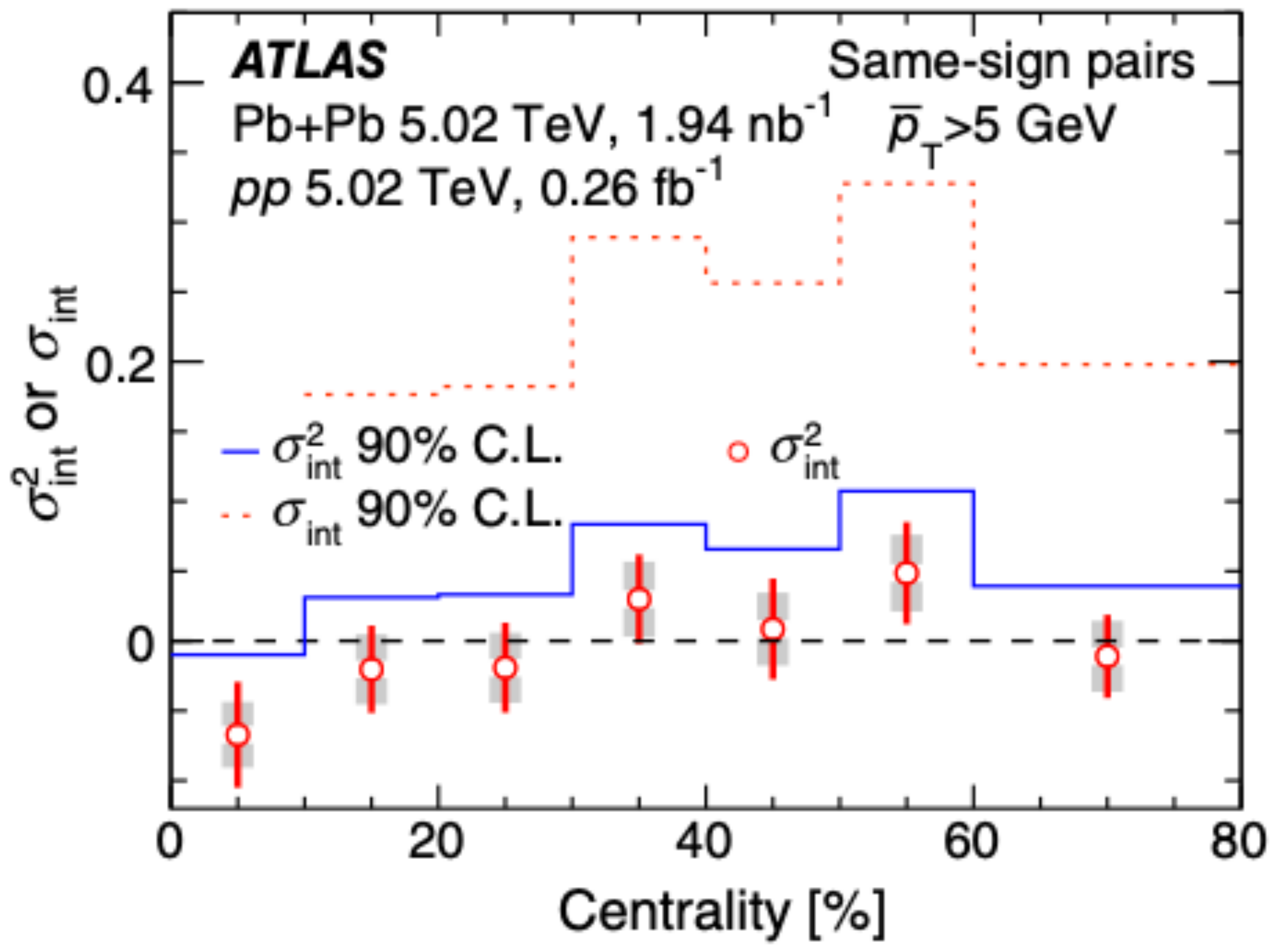


PLB 819 (2021) 136385



Azimuthal correlations of μ-μ pairs





PRL 132 (2024) 202301