Heavy-ions* in the thirties with ALICE 3

Quark-Gluon Plasma Characterisation with Heavy Flavour Probes

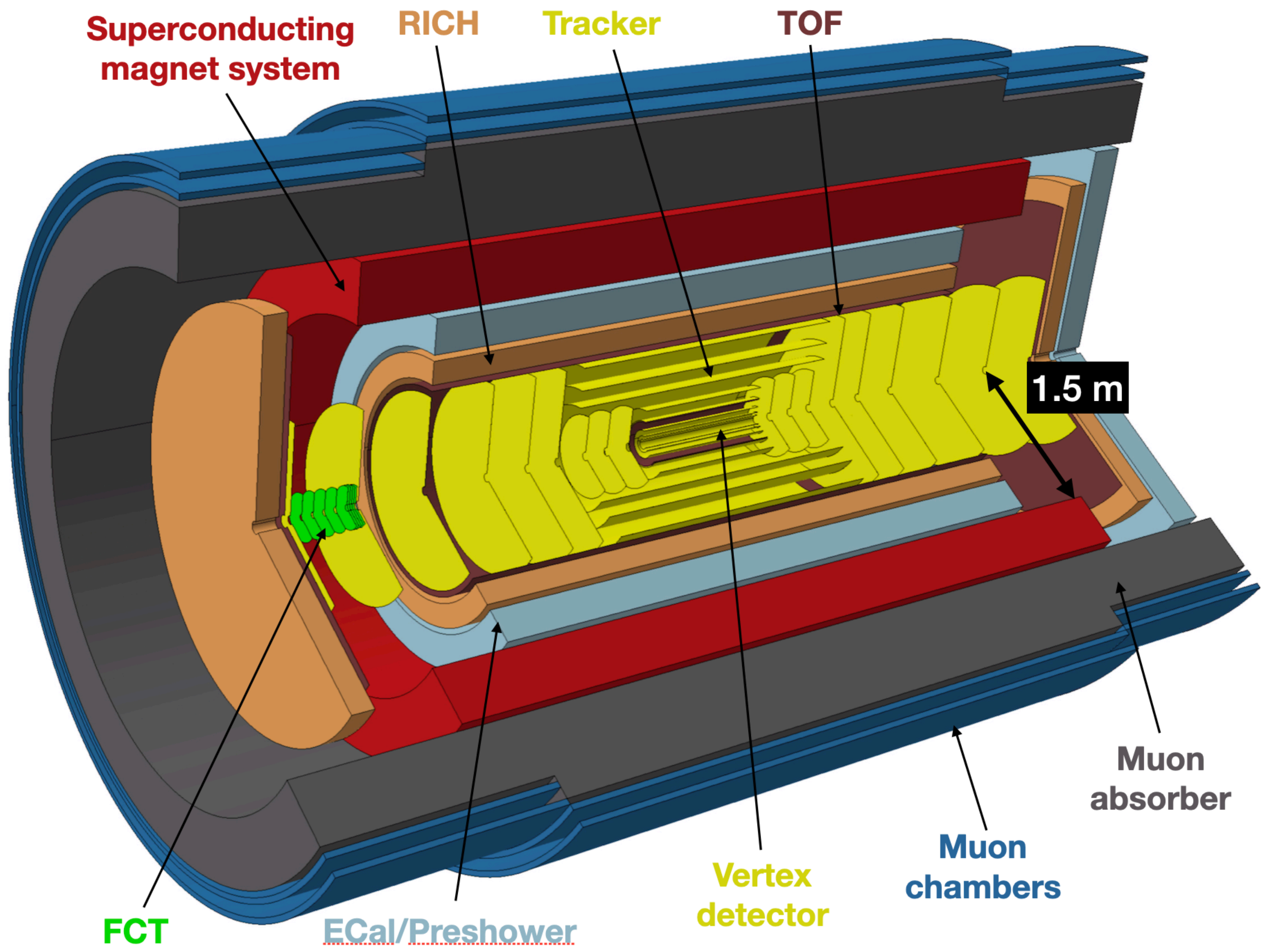
15-18 November 2021, ECT Trento

Gian Michele Innocenti (CERN)

* HF biased

Plans for ALICE 3: arXiv1902.01211

Outline of the presentation

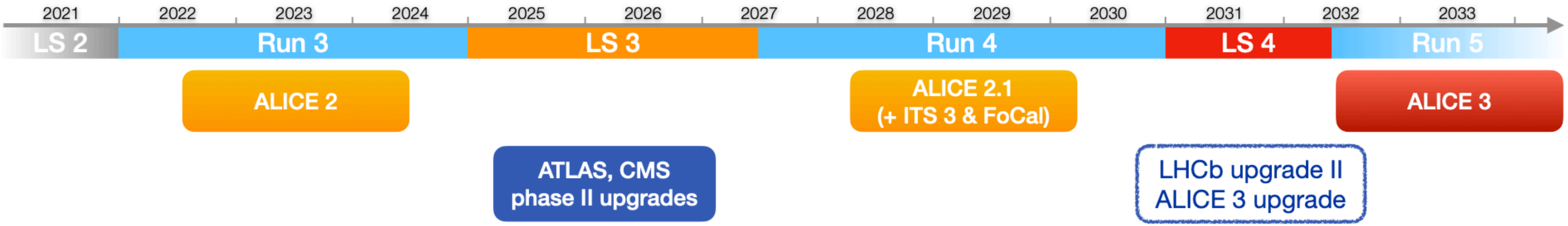


General physics goal of the ALICE 3 experiment

ALICE 3 design concept

Physics observables:
- impact on the detector design
- performance studies in pp and heavy-ion collisions

LoI being finalized, expected by end of the year

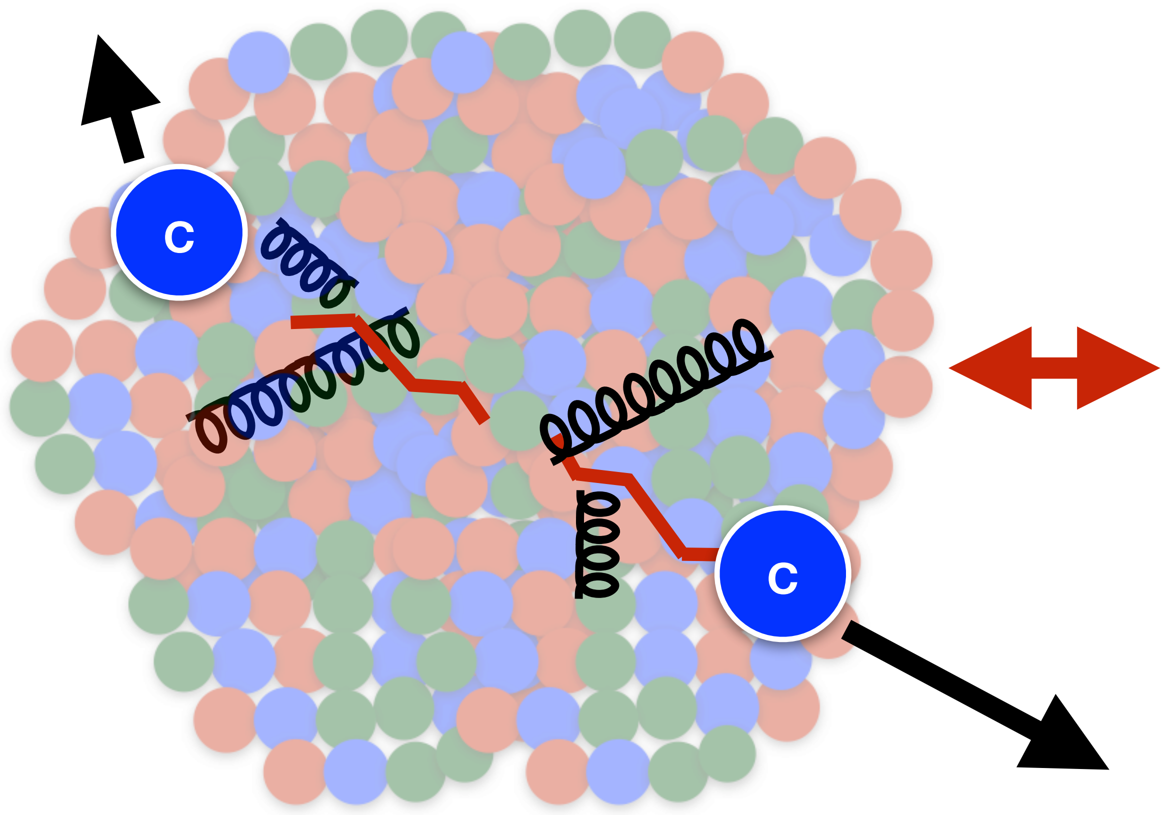


First ALICE 3 workshop (18-19 October 2021): link

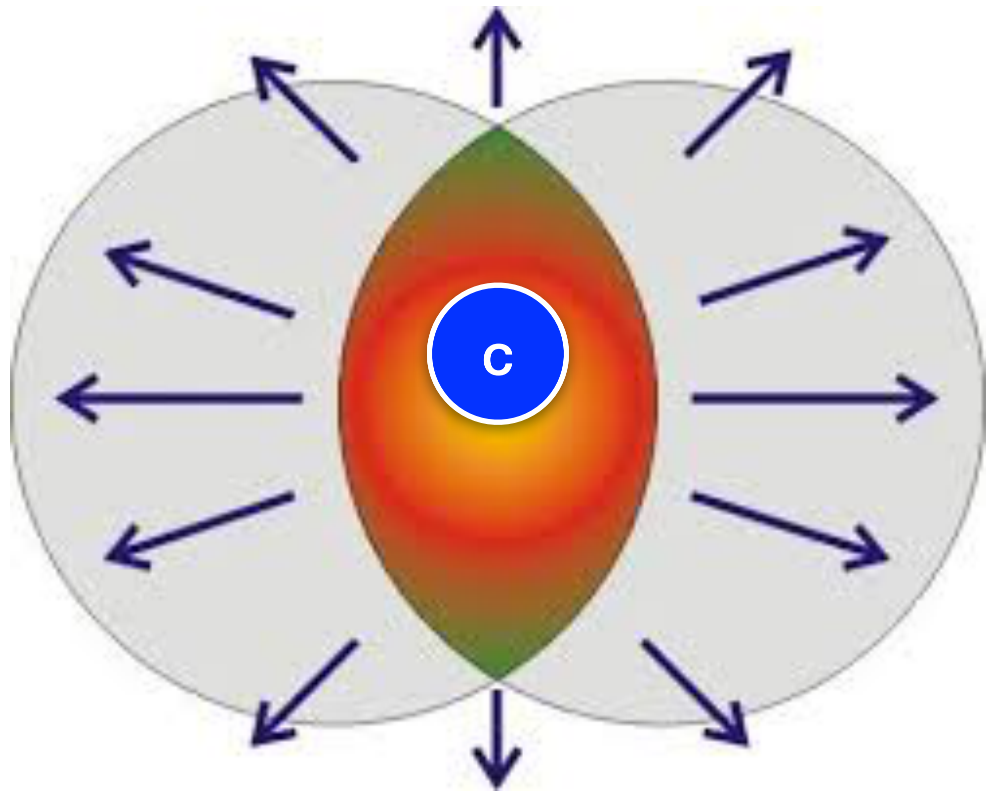
Plans for ALICE 3: arXiv1902.01211

(some) ALICE 3 physics goals

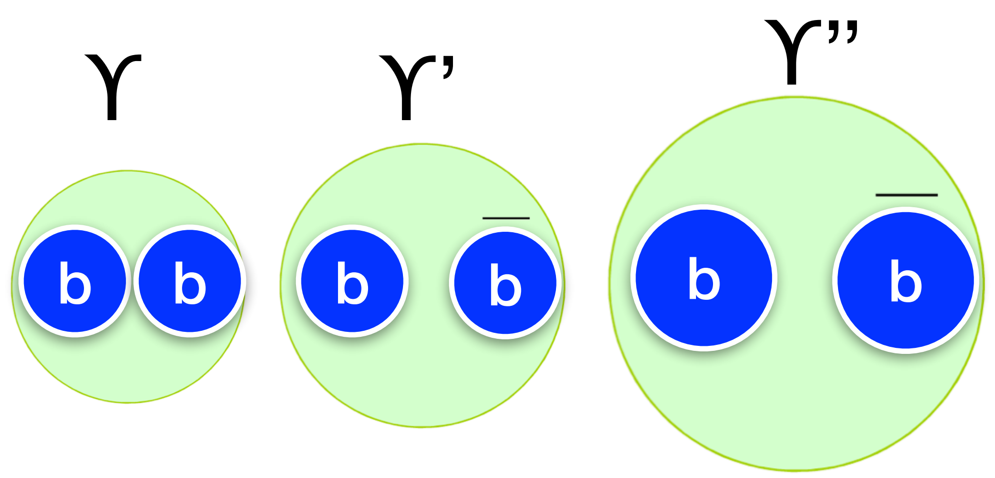
Heavy quarks interact and lose energy



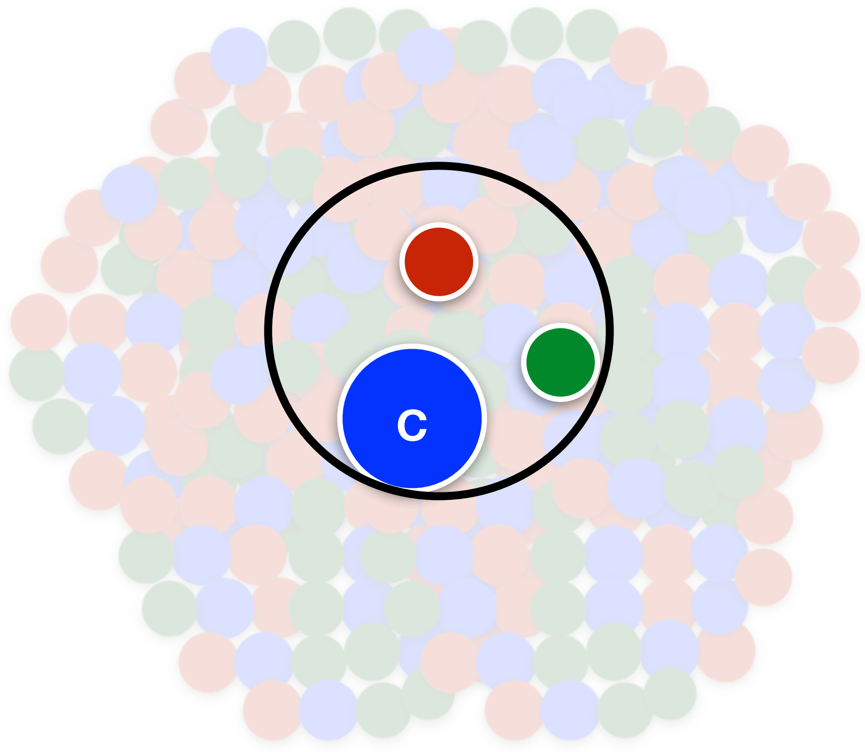
Heavy quarks “flow” with the medium



Bound states are affected by deconfined medium



HF-hadron production modified at high densities



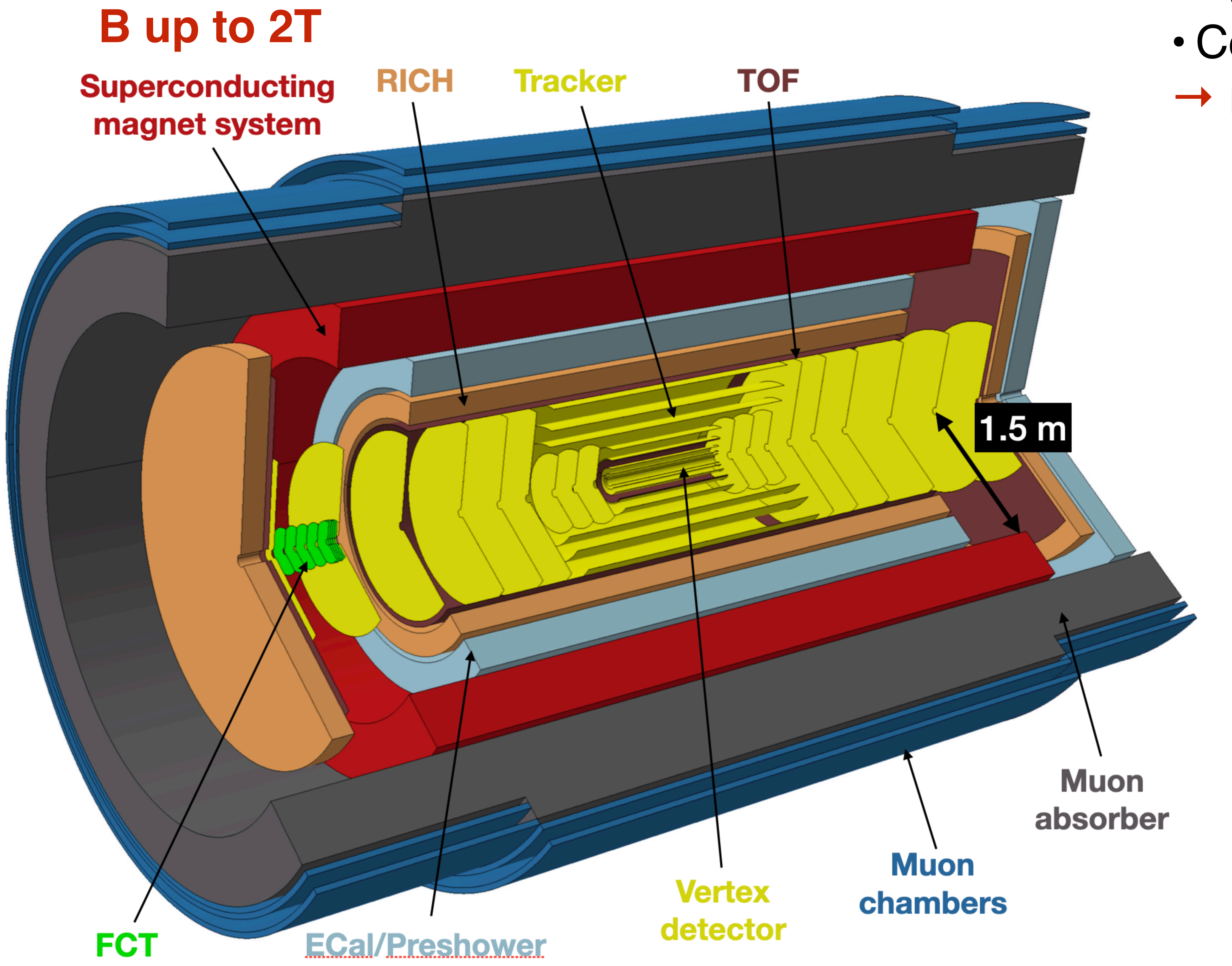
Identify and characterize the common microscopic dynamics underlying all of these phenomena

- **Microscopic description of heavy-quark interaction and medium structure at different scales**
- **High-precision determination of QGP coefficients**
  → with high accuracy charm/beauty hadron measurements and HF correlations and jets

New constraints of hadronization mechanisms in the QGP
→ multi-charmed hadrons and HF-jets
→ (charmed?) nuclei/hypernuclei

Complete/dynamic description of bound states in the QGP
→ with unexplored quarkonia states and exotic hadrons

The ALICE 3 design in a nutshell



- **|η|<4 of "massless" high-resolution tracker**
- Up to $\mathscr{L}_{NN} \sim 3 \times 10^{33}\ cm^{-2}s^{-1}$ events in pp and AA
- Complete suite of PID detectors (TOF, RICH, MuonID) and EMCAL

→ rare HF probes and correlations in the at ~ fb^{-1} NN-luminosities

First ALICE 3 workshop (18-19 October 2021): link

S. Cao et al. Phys. Rev C. 99.054907
Yellow Report, CERN-LPCC-2018-07
S. Bass et al, Phys. Rev. C 103, 054904 (2021)

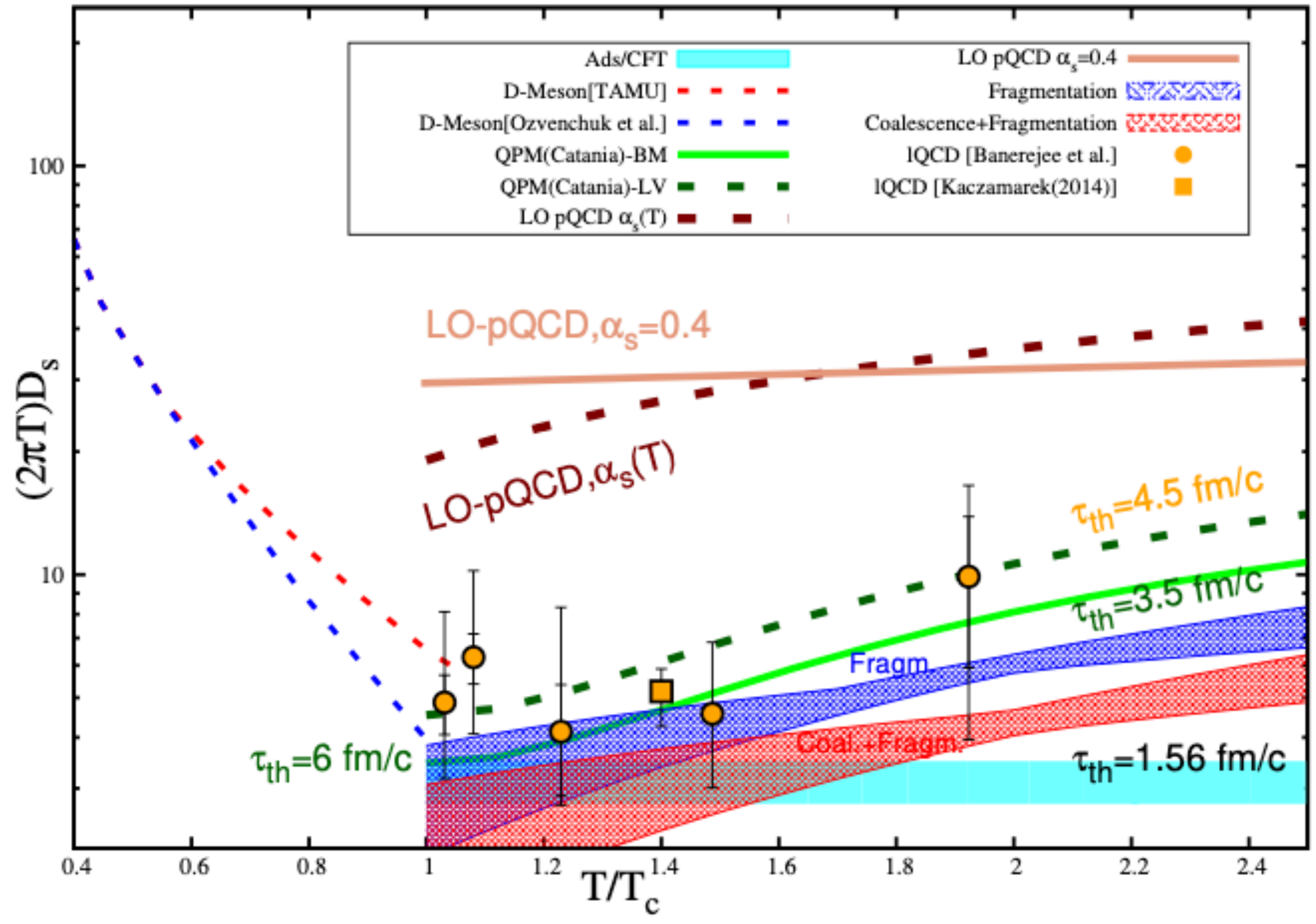
Extraction of diffusion parameters

- **$m_{c,b} \gg m_{u,d,s}$: "Brownian regime" in the QGP**
- incomplete thermalization for charm and beauty quarks

→ **Diffusion properties, characterized by D_s, inform of the coupling strength of the QGP and therefore its inner structure (e.g. strongly vs weakly coupled)**

$$\langle x^2 \rangle = 6 D_s t$$
$$\tau_c = (m_{HQ}/T) D_s$$

Projection for D_s extraction with charm with Run3+4 data using R_{AA} measurements only



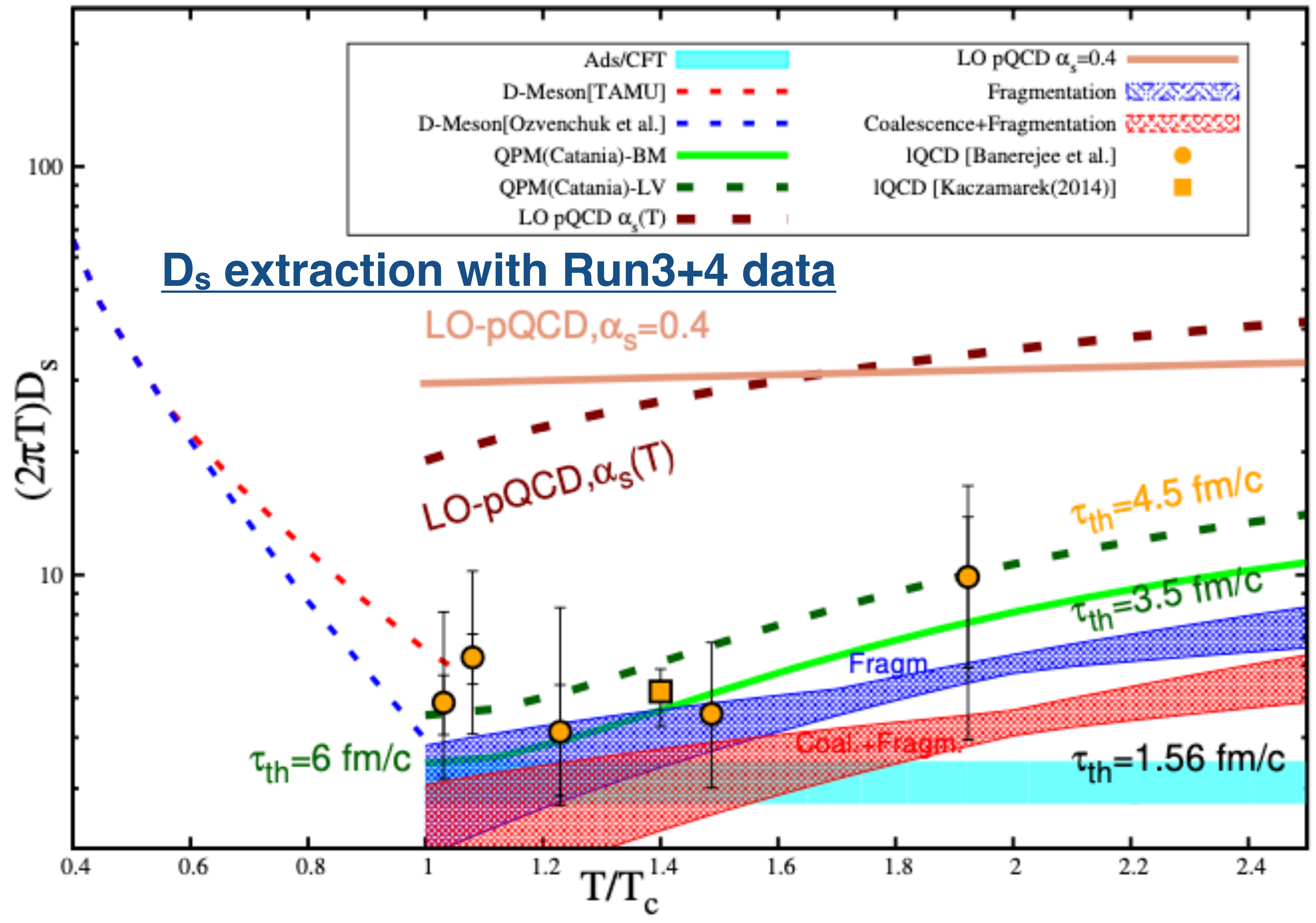
"Over-constraining" D_s with charm and beauty measurements of single-hadron production (R_{AA} and v_2) and correlations/jets (e.g. $D^0 D^{0,bar}$):

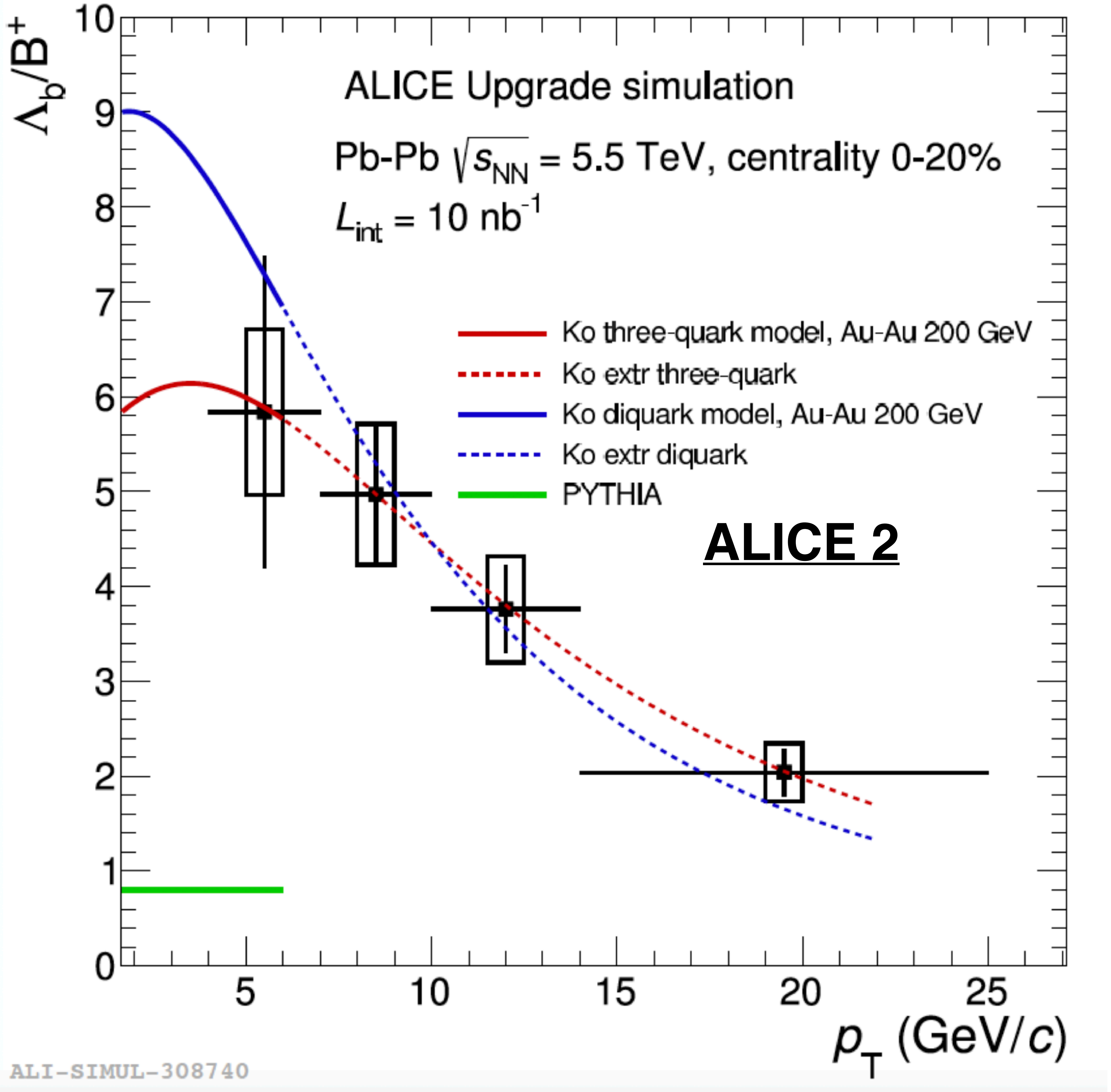
Relevance of beauty:

- beauty less "equilibrated"
- better theoretical control on in-medium transport calculations
- different sensitivity (?) from recombination

Single-hadron measurements with **ALICE 2**

S. Cao et al. Phys. Rev C. 99.054907
Yellow Report, CERN-LPCC-2018-07





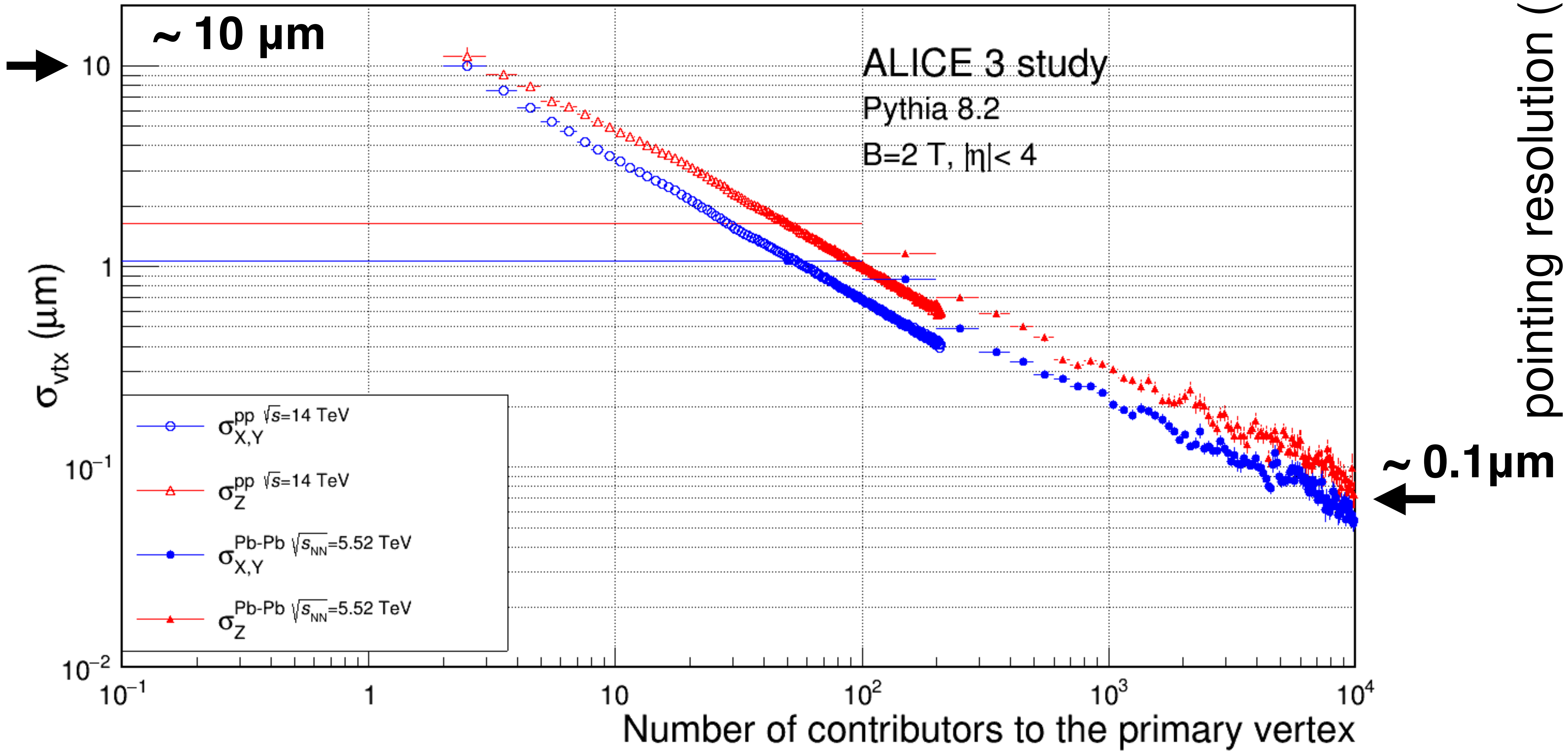
- high precision R_{AA} measurements for charmed mesons and baryons

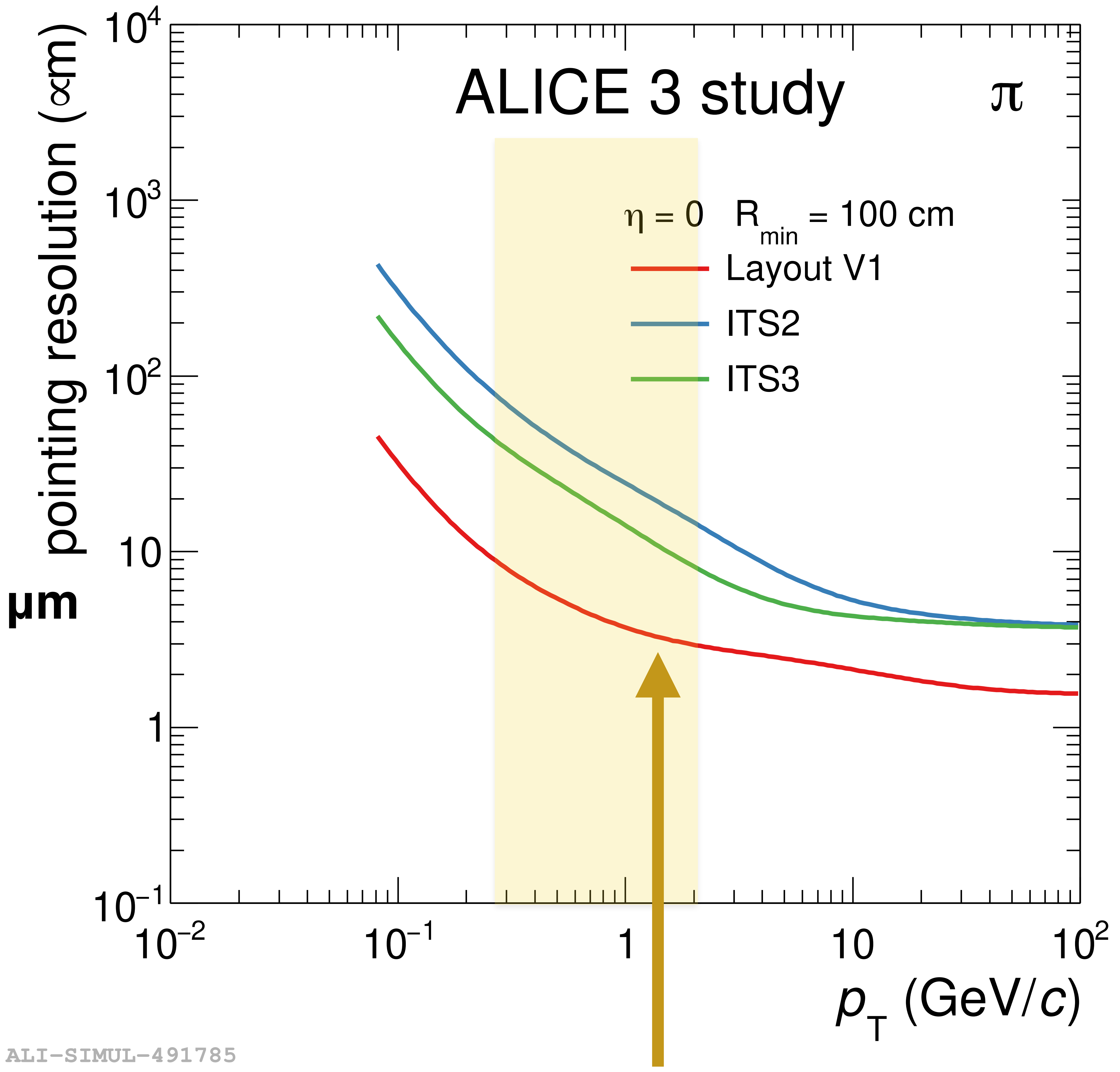
→ **Good accuracy for D_s coefficient with charm quarks**

- limited accuracy on the measurements of Λ_c collective properties
- **Poor accuracy at low p_T for beauty hadrons, in particular Λ_b baryons** (critical for D_s extraction with b-hadrons)

Single-hadron measurements with ALICE 3

Primary vertex resolution in pp and KrKr





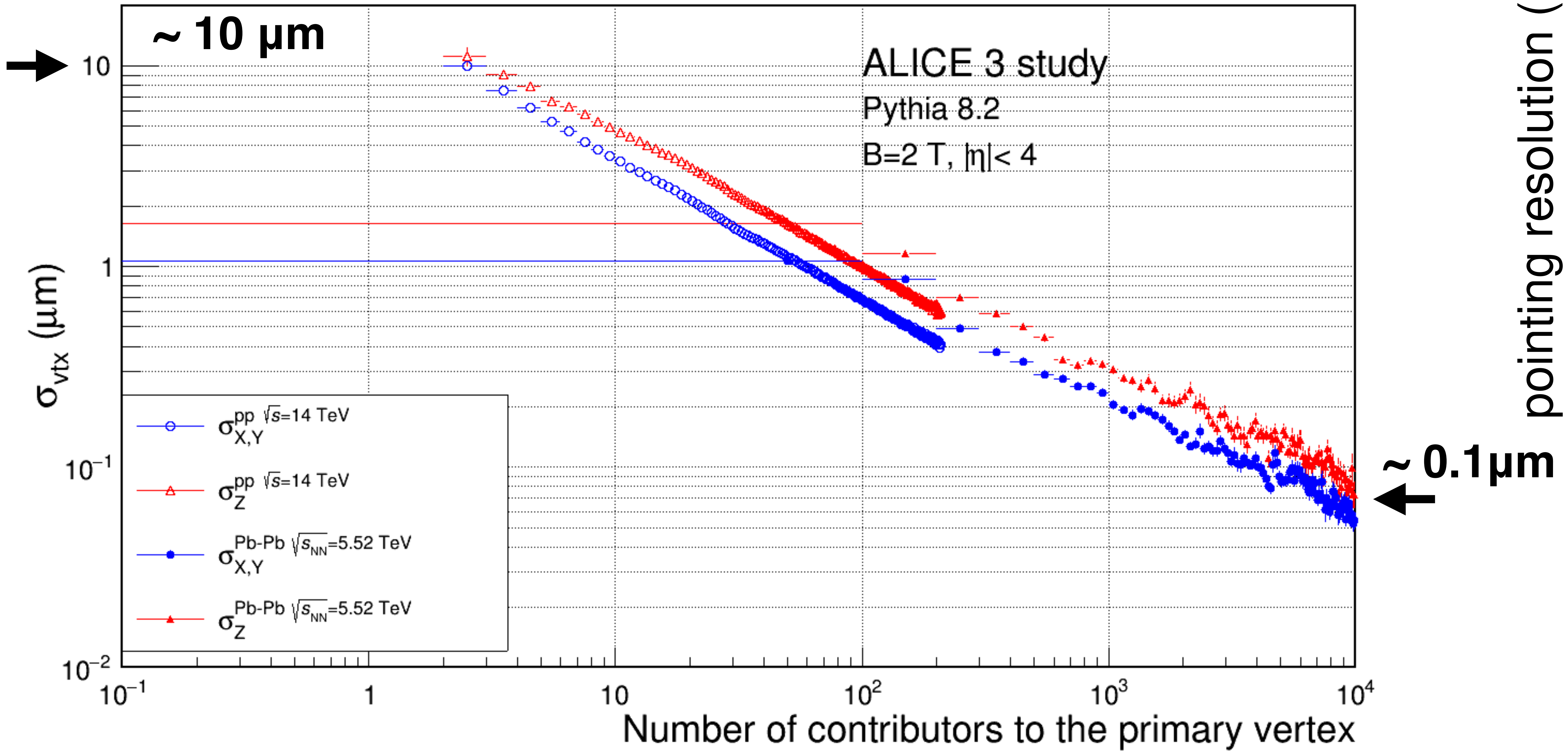
- Primary vertex resolution < 1 μm for collisions with > 40 tracks
- Secondary vertex resolution (e.g. 3 prongs) ~ 3-4 μm at 2-4 GeV

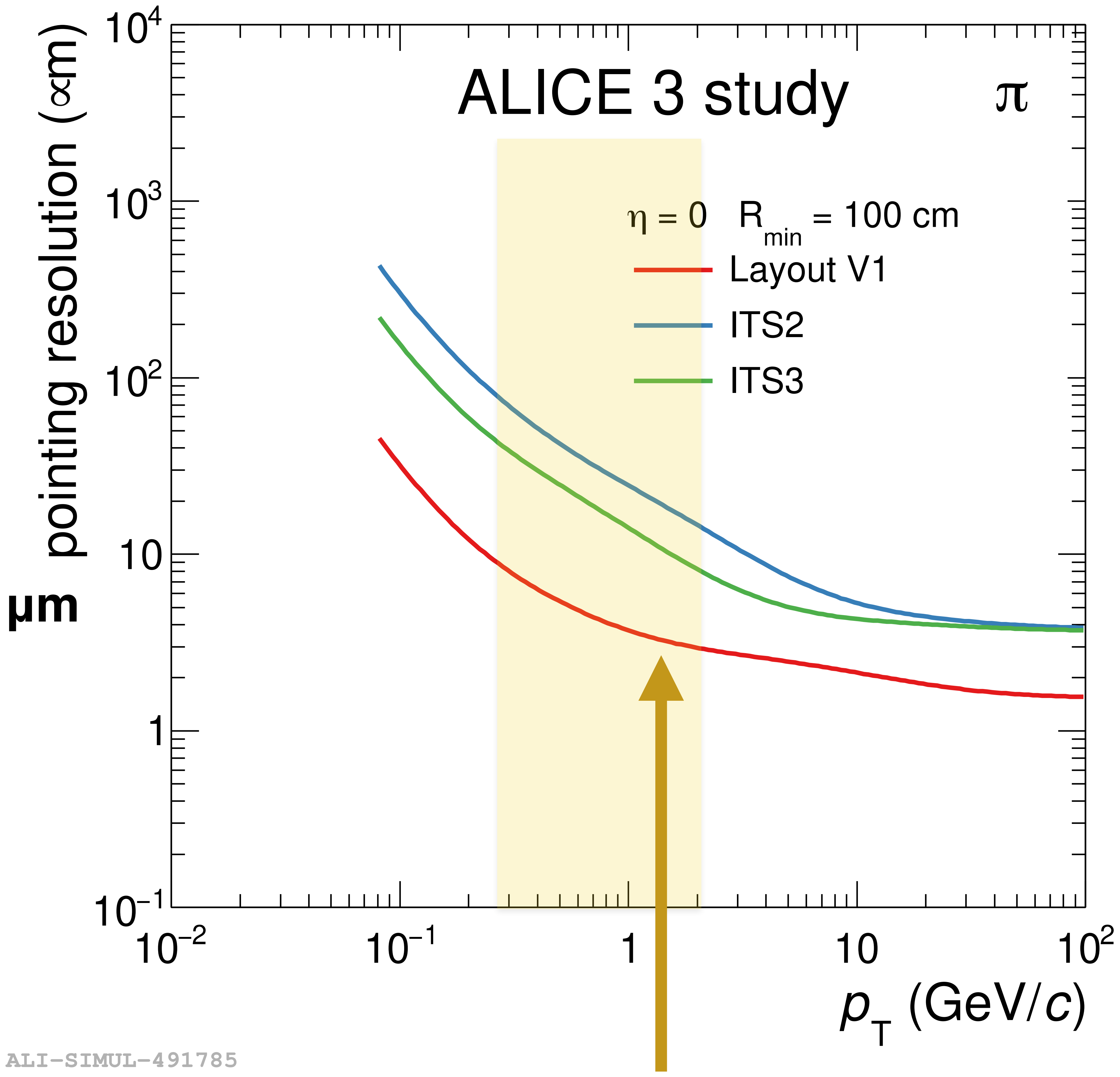
Substantial improvement w.r.t. ITS3 in a very critical p_T region:

- E.g. at p_T=0.5, from 20-30 μm **(ITS3)** to 5 μm **(ALICE 3)**

Single-hadron measurements with **ALICE 3**

Primary vertex resolution in pp and KrKr

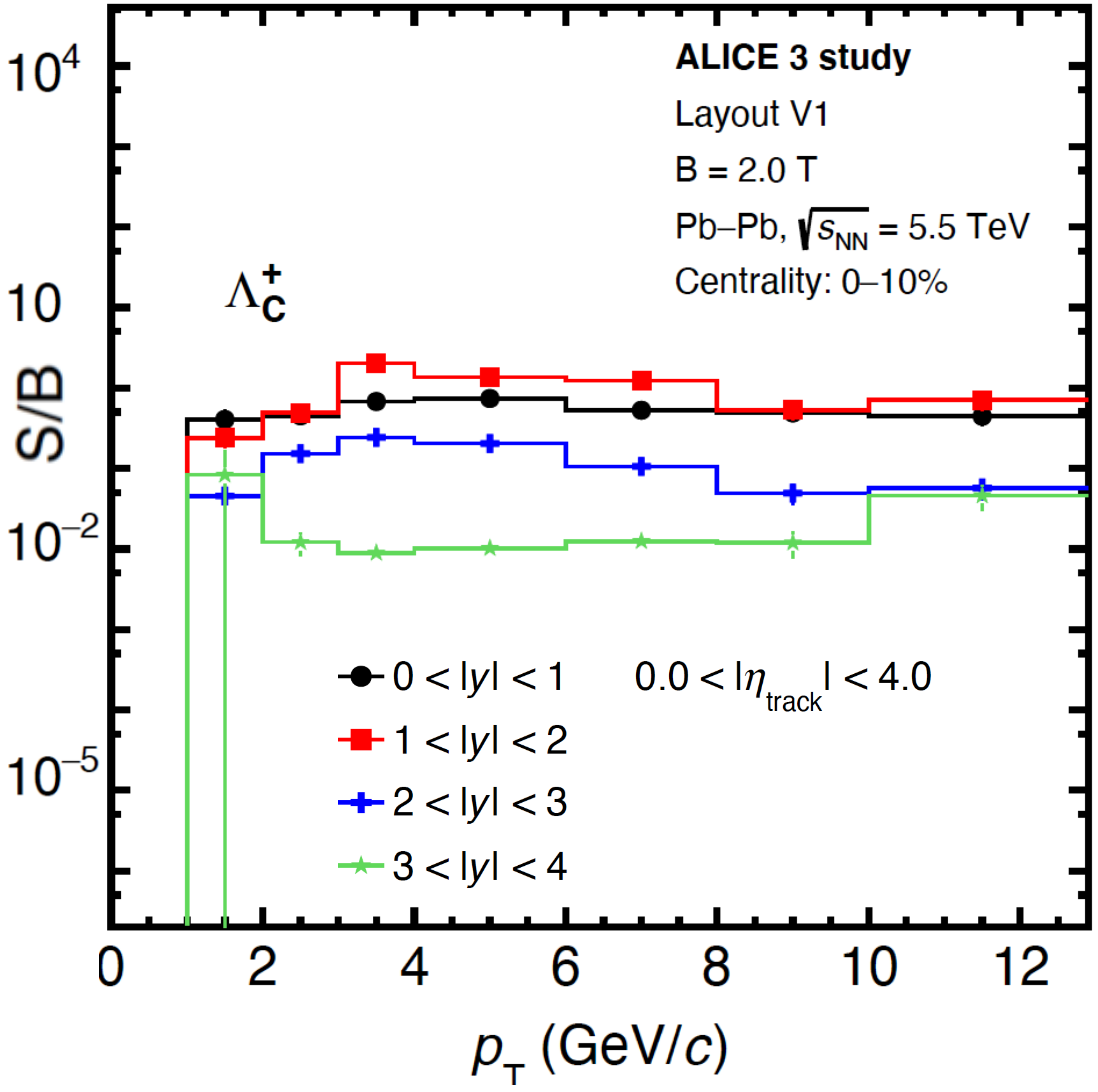




→ **"textbook" accuracy in extraction of medium coefficients**:
(better theoretical control of beauty quark diffusion in the QGP)

→ **stronger constraints on HF hadron collective properties and their relation with hadronization mechanisms**

Benchmark: Impact on flow analyses of Λ_c baryons

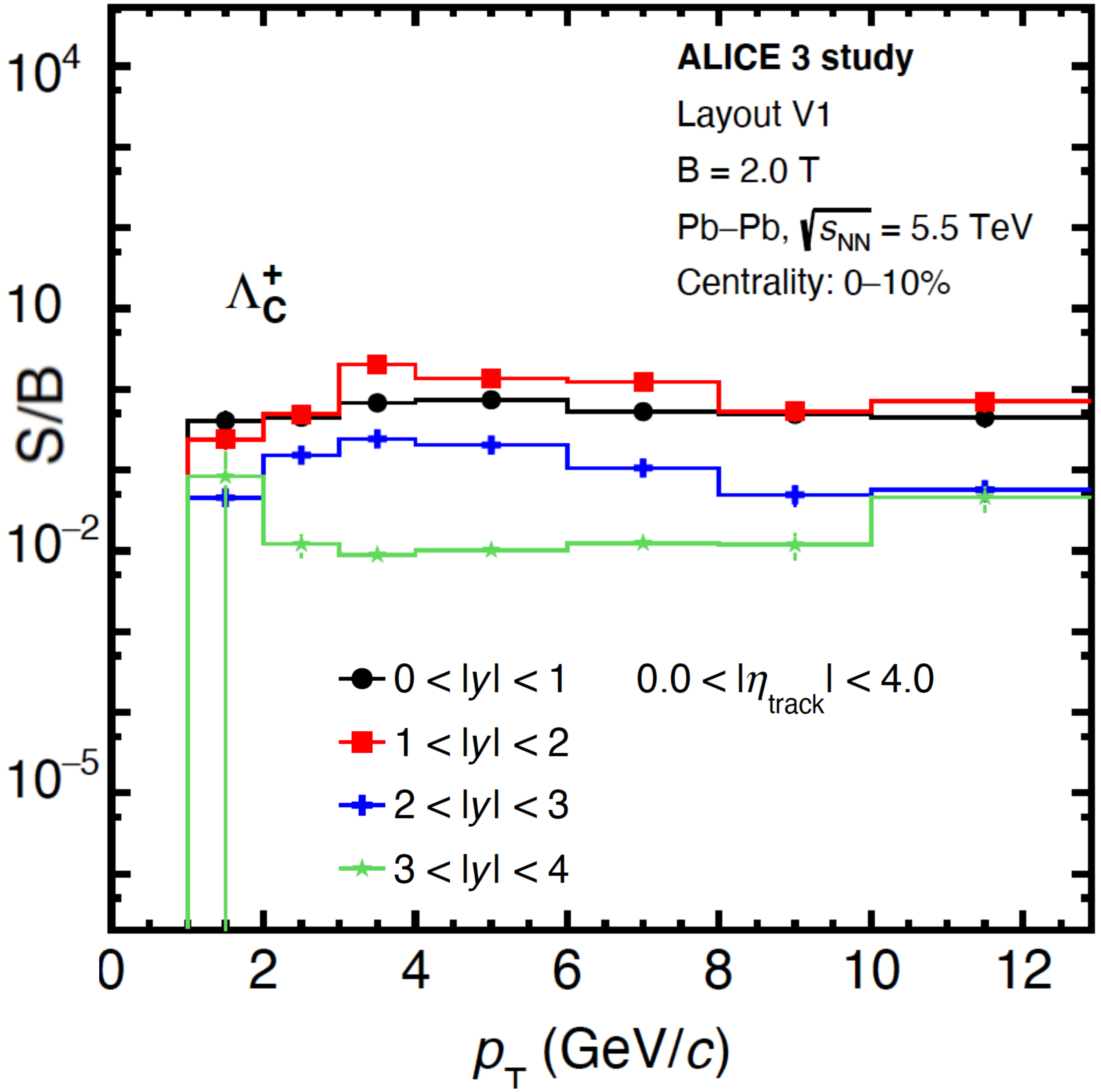


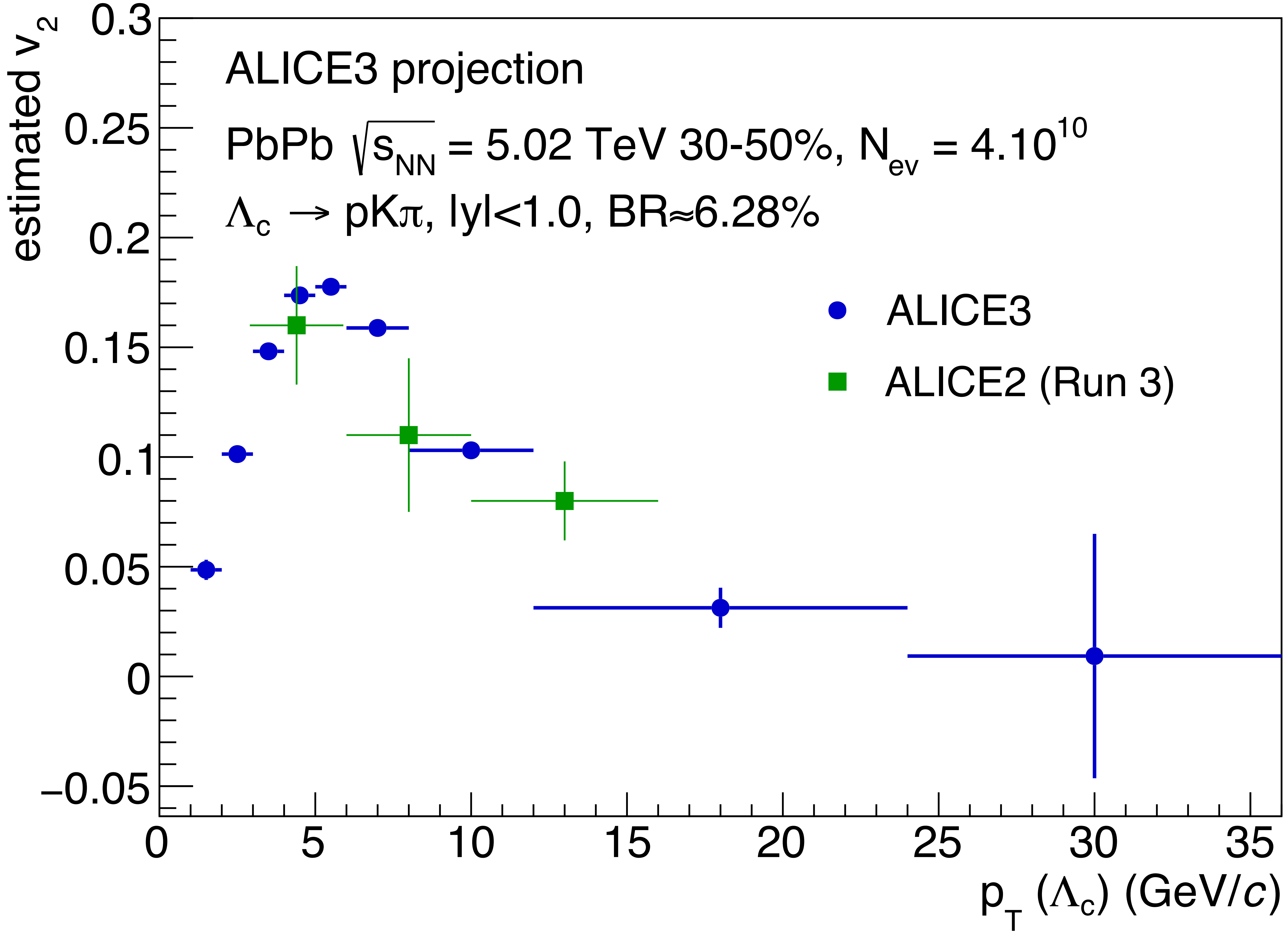
Unique combination over 8 units of η :

- high tracking resolution
- ~ flat p_T resolution as a function of η
- PID capabilities both at central and forward rapidities

→ **unprecedented signal purity for HF probes in the widest acceptance region at hadronic colliders**

Benchmark: Impact on flow analyses of Λ_c baryons





→ **High accuracy for flow measurements of charmed baryons**

→ **Constraints on the microscopic description of recombination and interplay with collective espansion**

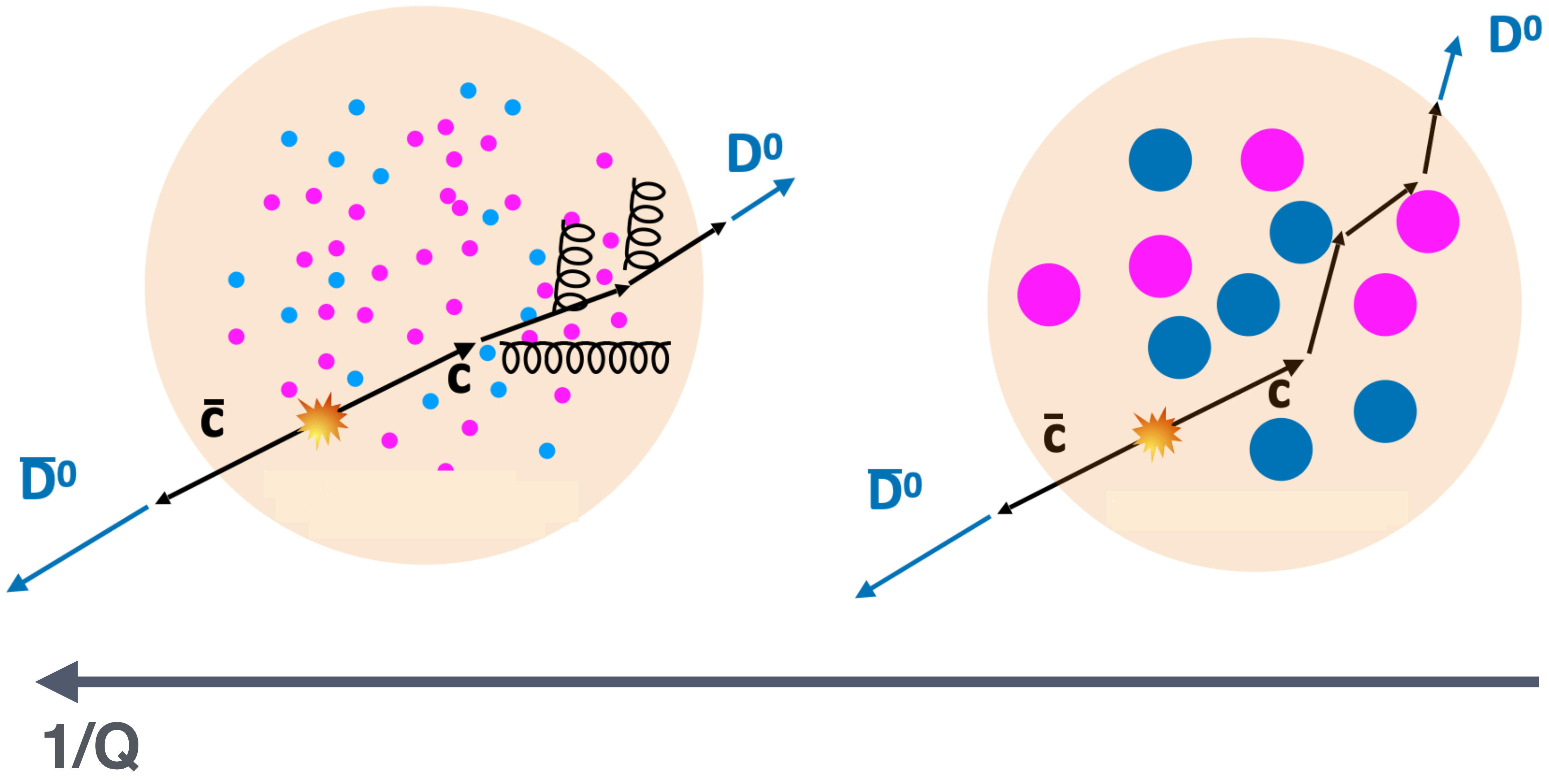
→ **Impact on Λ_b under study**

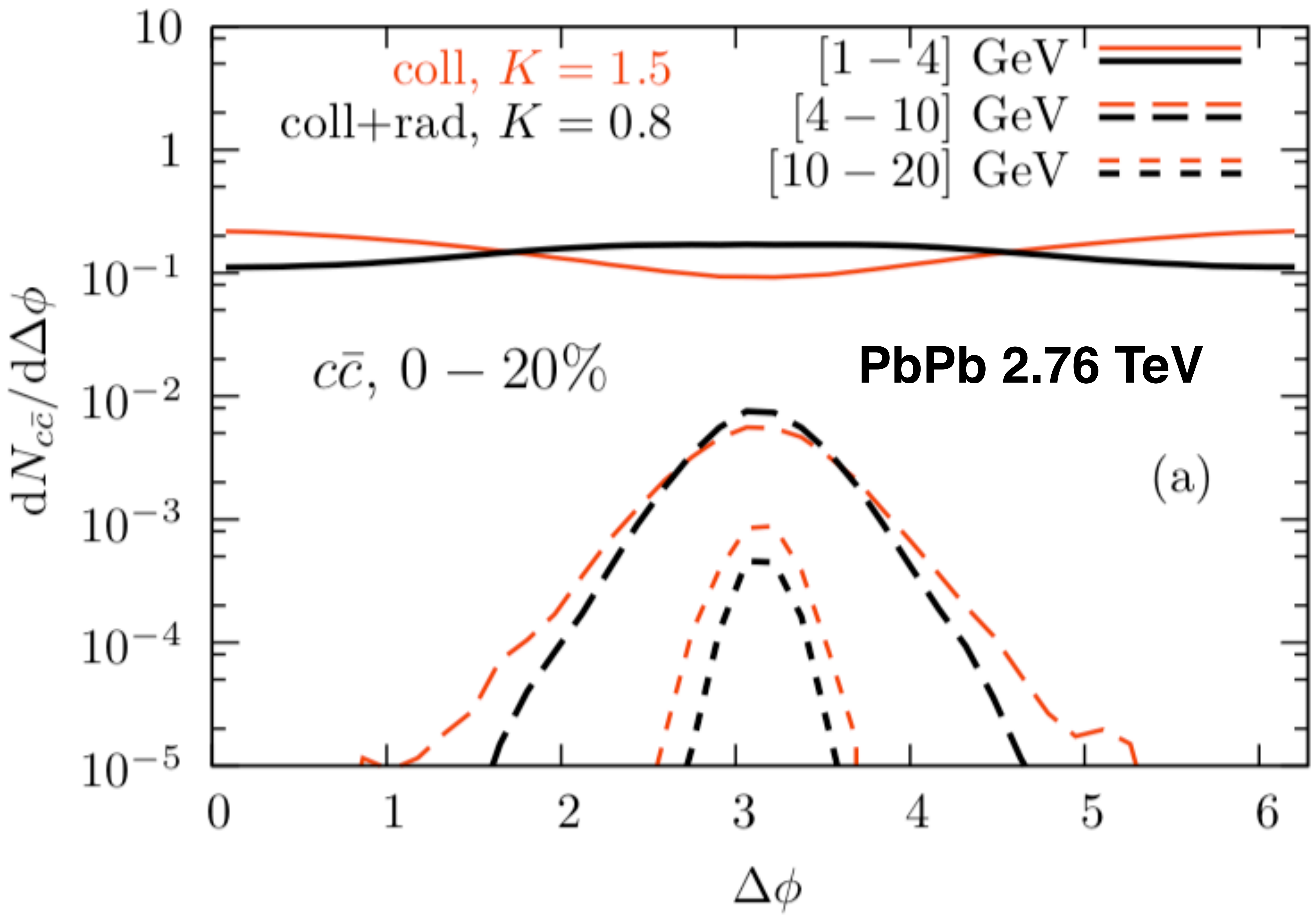
Heavy-flavor correlations

Study different "regimes" of quenching with sensitivity to "geometric" and microscopic properties of interactions and medium descriptions:

→ beyond "averaged" quenching observables

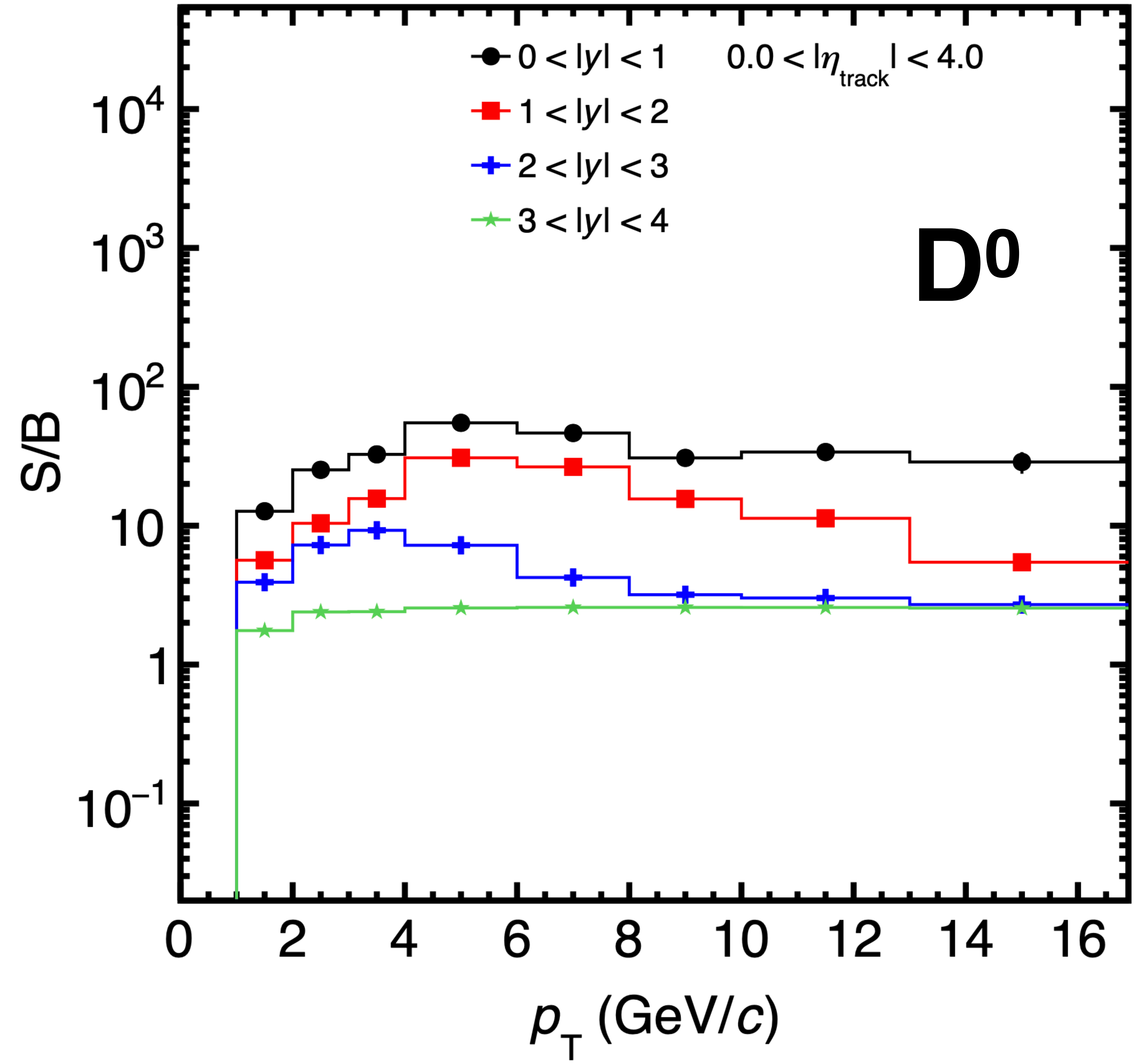
→ "controlled" access to low p_T region



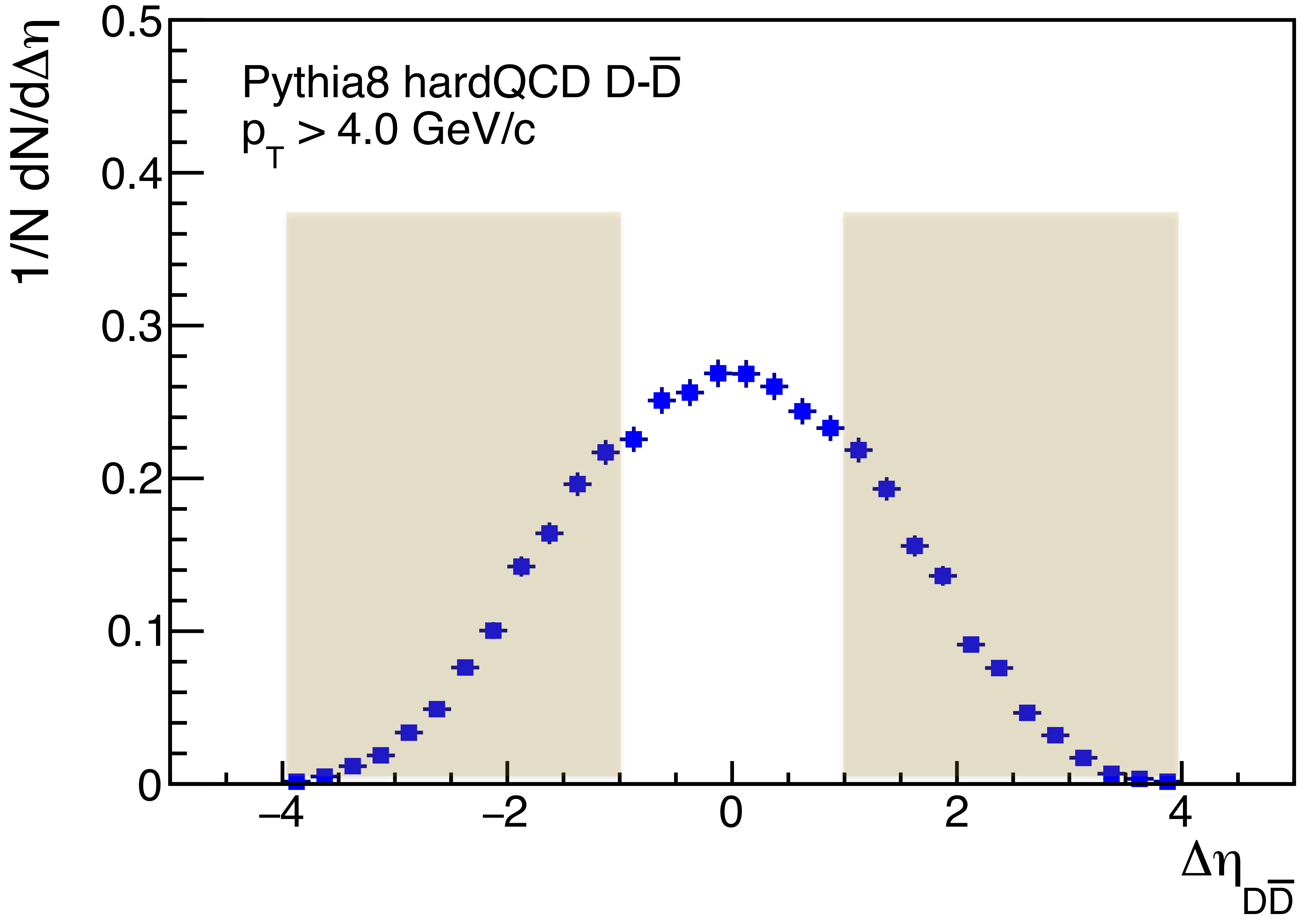


- At intermediate p_T
  → **properties of quenching mechanisms**
- At low p_T:
  → decorrelation measures momentum diffusion
  → **degree of thermalization in the QGP**

ALICE 3 uniqueness for HF correlation studies



Signal purity critical for correlation analyses

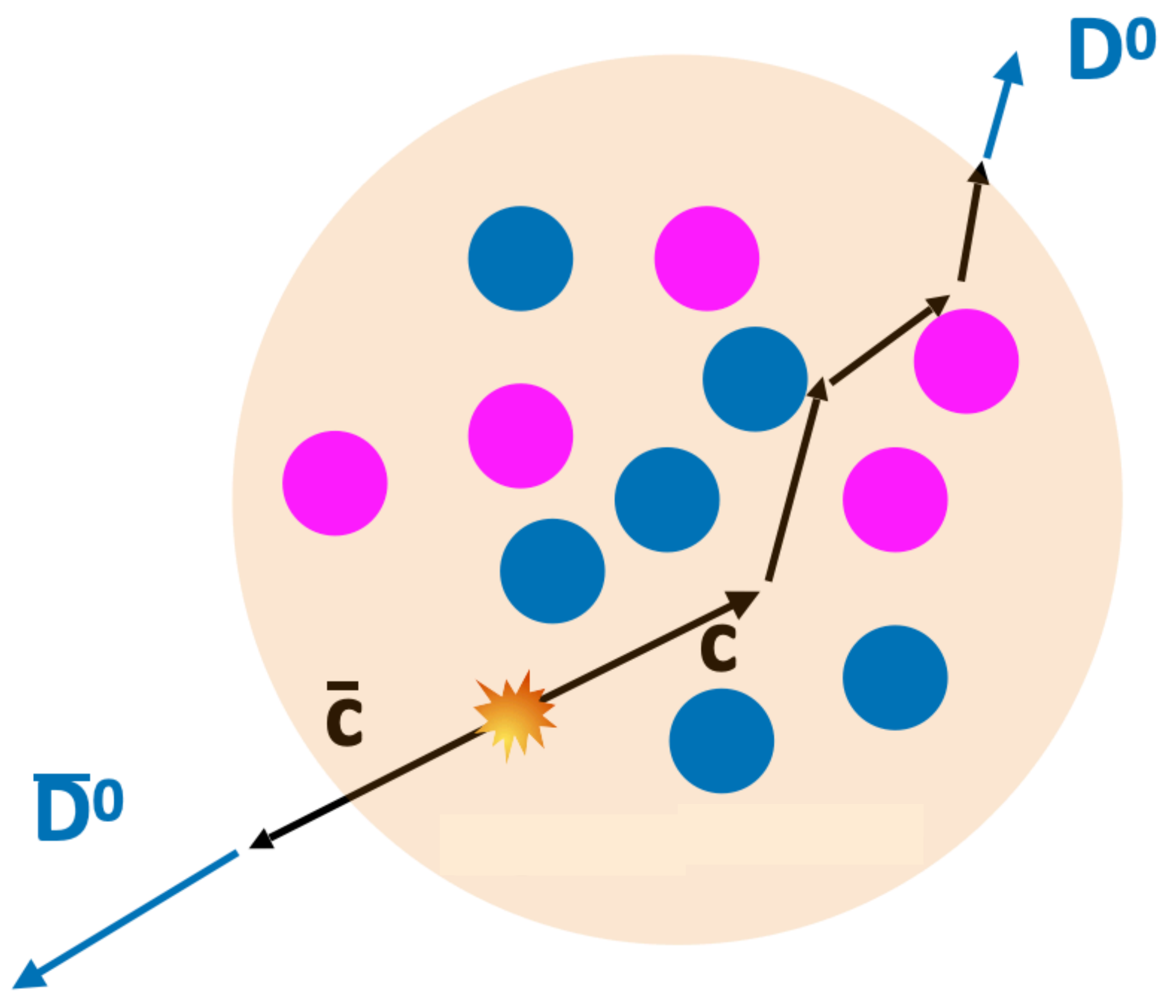


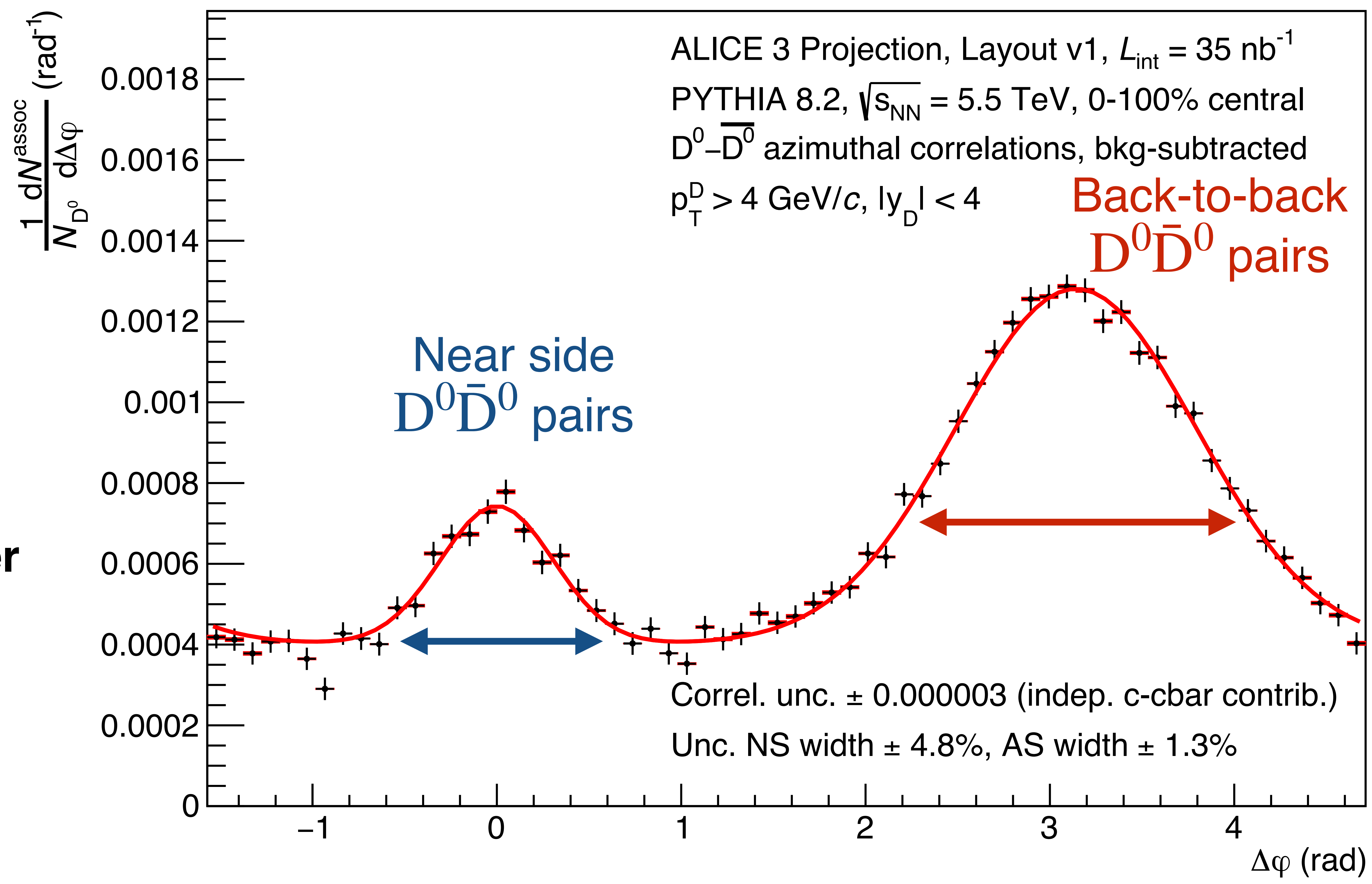
Larger acceptance implies:

- Significant increase of signal yield
- Access to **unexplored region of large Δη (> 2)**

→ longitudinal properties of medium evolution

$D^0\bar{D}^0$ correlations in PbPb collisions





- $D^0\bar{D}^0$ correlations are measurable down to low p_T **over about 8 units of rapidity**

→ High accuracy in measurement of the correlation pattern down to low p_T

Wide program of quenching/“flow” observables (and beyond) to be exploited:

- $\Lambda^+_c \Lambda^-_c$ $B^+ B^-$ correlations, HF-γ correlations
- Single and double-tagged HF jet studies

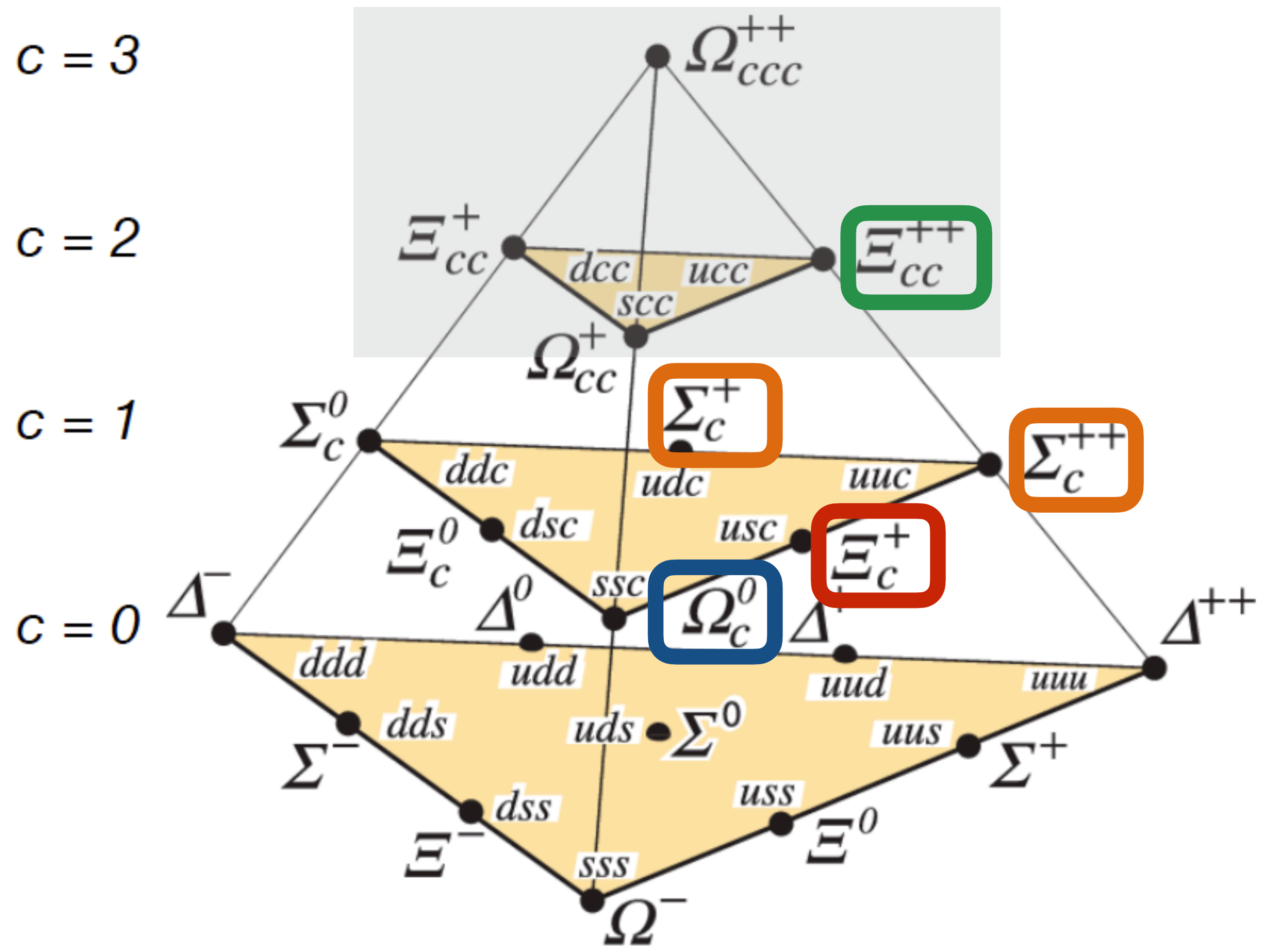
→ new simulation studies show we can access lower p_T, down to at least 2 GeV (~ thermalization regime)

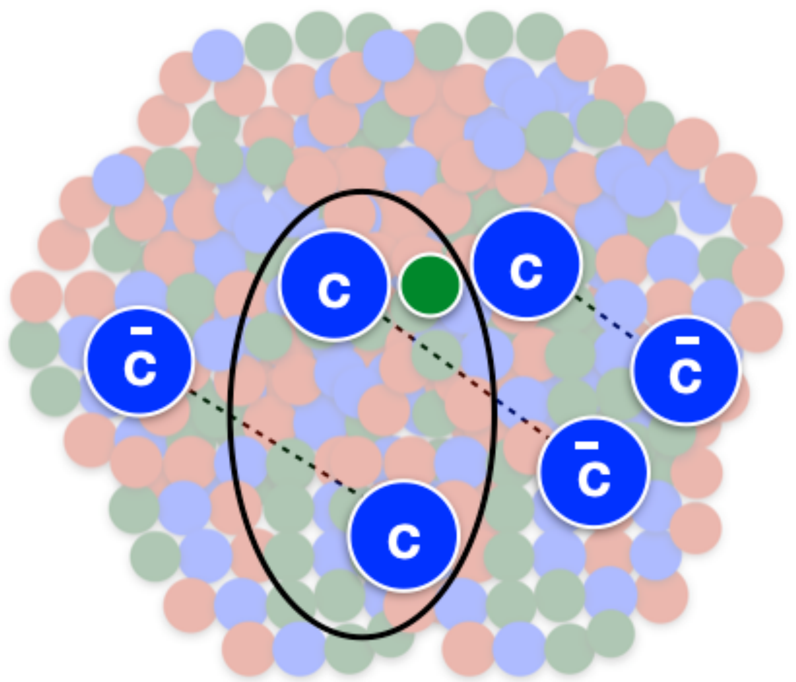
Multi-charm flavor hadrons

ALICE: arXiv.2011.06078
Beccatini: Phys. Rev. Lett. 95 (2005) 022301
SHMC: arXiv.2104.12754
G. Chen et al., Phys. Rev. D 89, 074020 (2014)

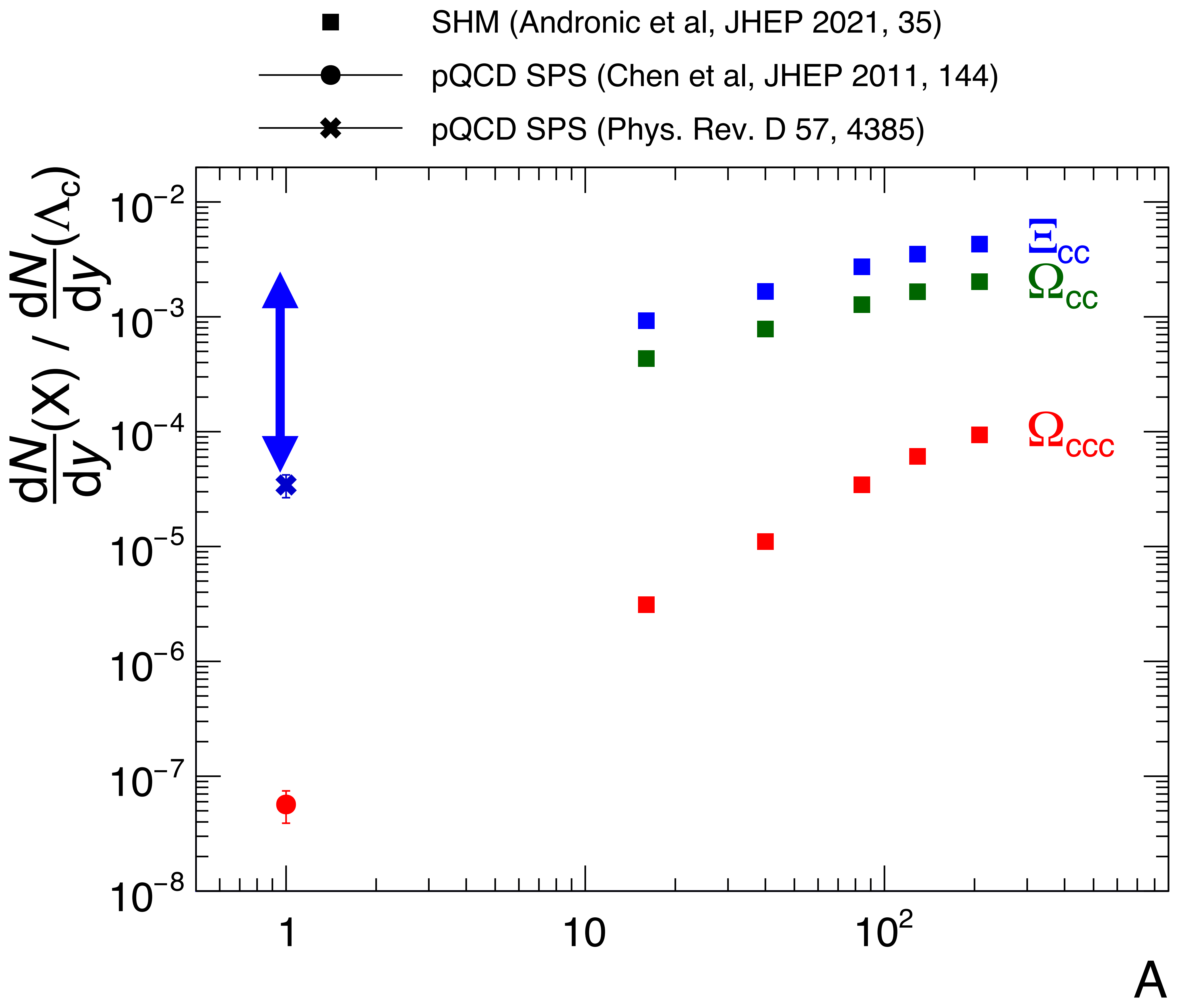
- Negligible same-scattering production
- Large **enhancement (up to x100 for Ξ_{cc}, Ω_{cc}) w.r.t. pp predicted** in presence of hadron production from uncorrelated charm quarks

double-c (~fb^{-1} region)





Ξ_{cc}, Ω_{cc}



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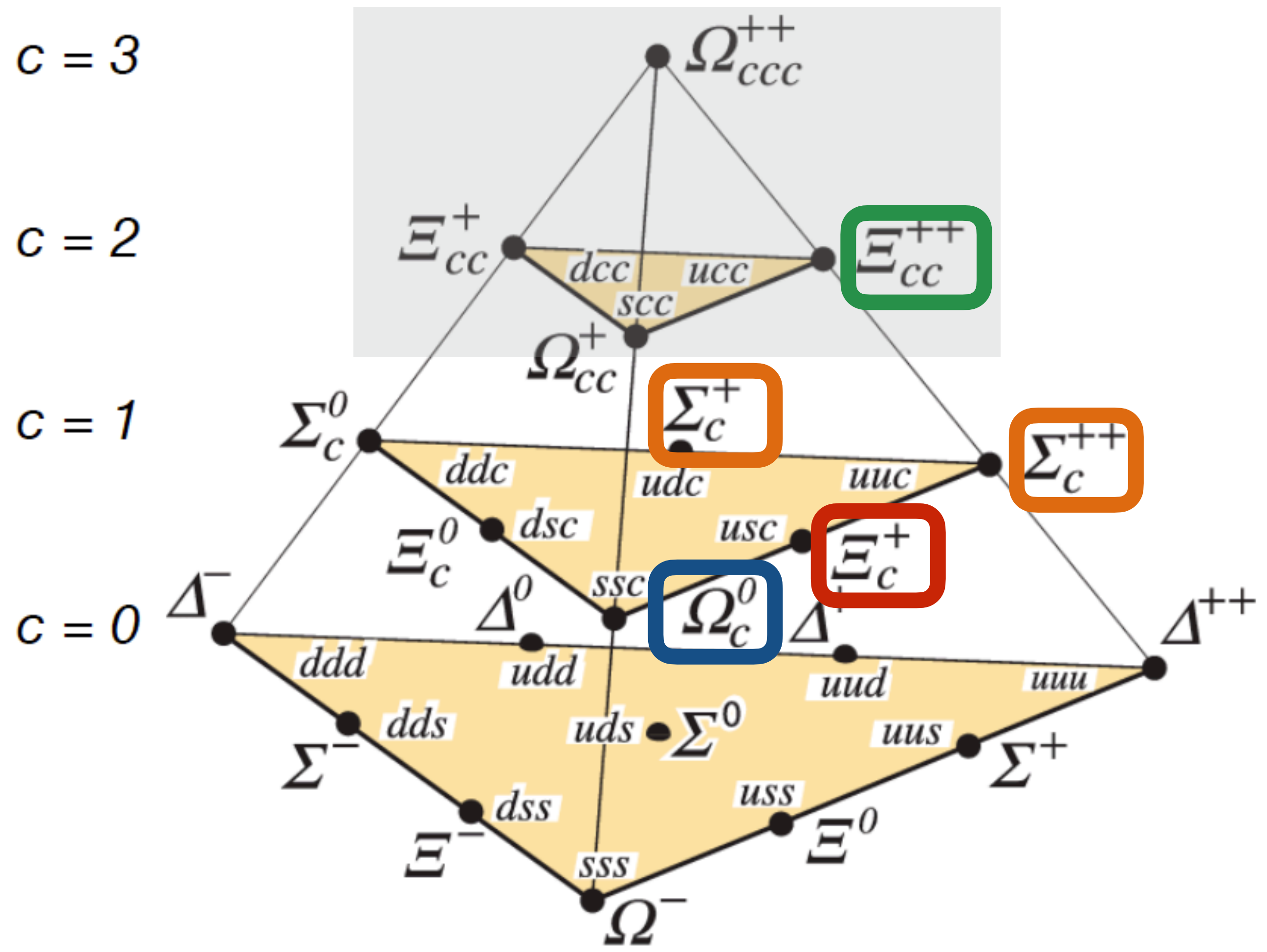
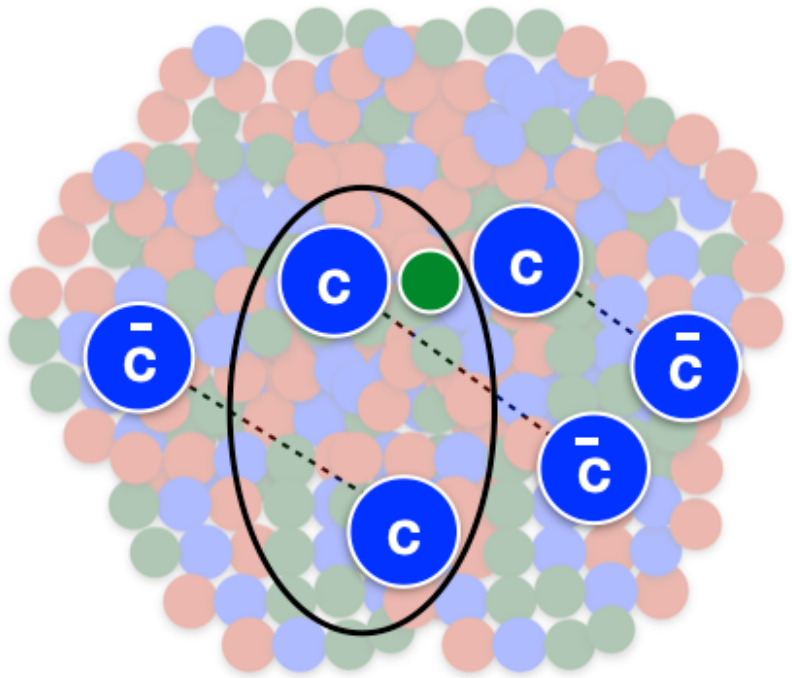




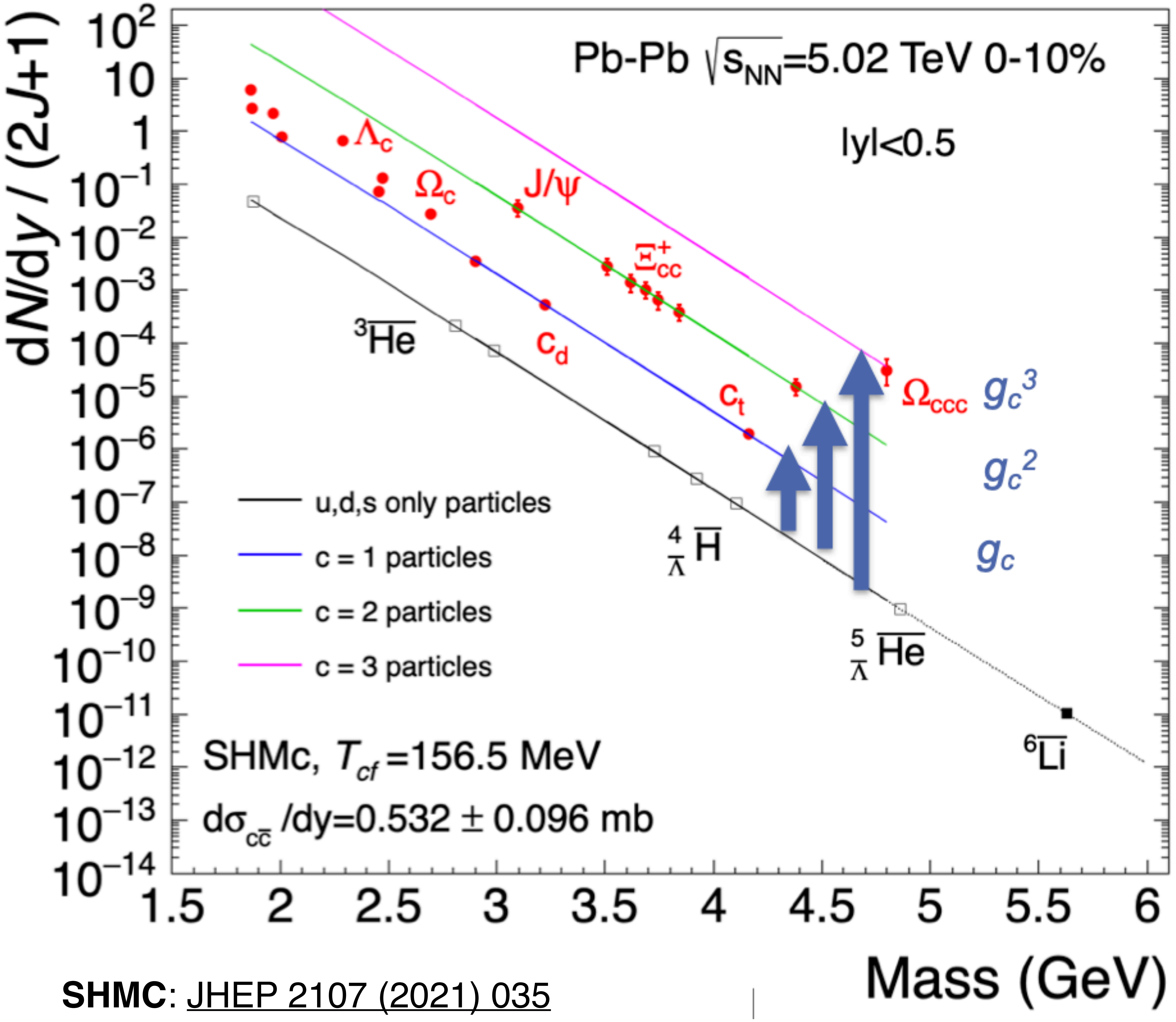
"Pure" (re)combination probes

- ~ entire AA expected production from hadronisation mechanisms beyond independent string fragmentation
- in general, not true for J/ψ

→ **Connection between degree of equilibration of charm quarks and hadronization modifications**

Linking multi-charm and nuclei within the SHMC

In the thermal limit (SHMC), specific pattern expected as a function of hadron mass and quark content



SHMC: JHEP 2107 (2021) 035

To test the "g_c-scaling" of charm production:

- access to hadrons with n_c>1
- have access to a "light" reference with similar mass

→(anti-)(hyper-)nuclei provide the baseline

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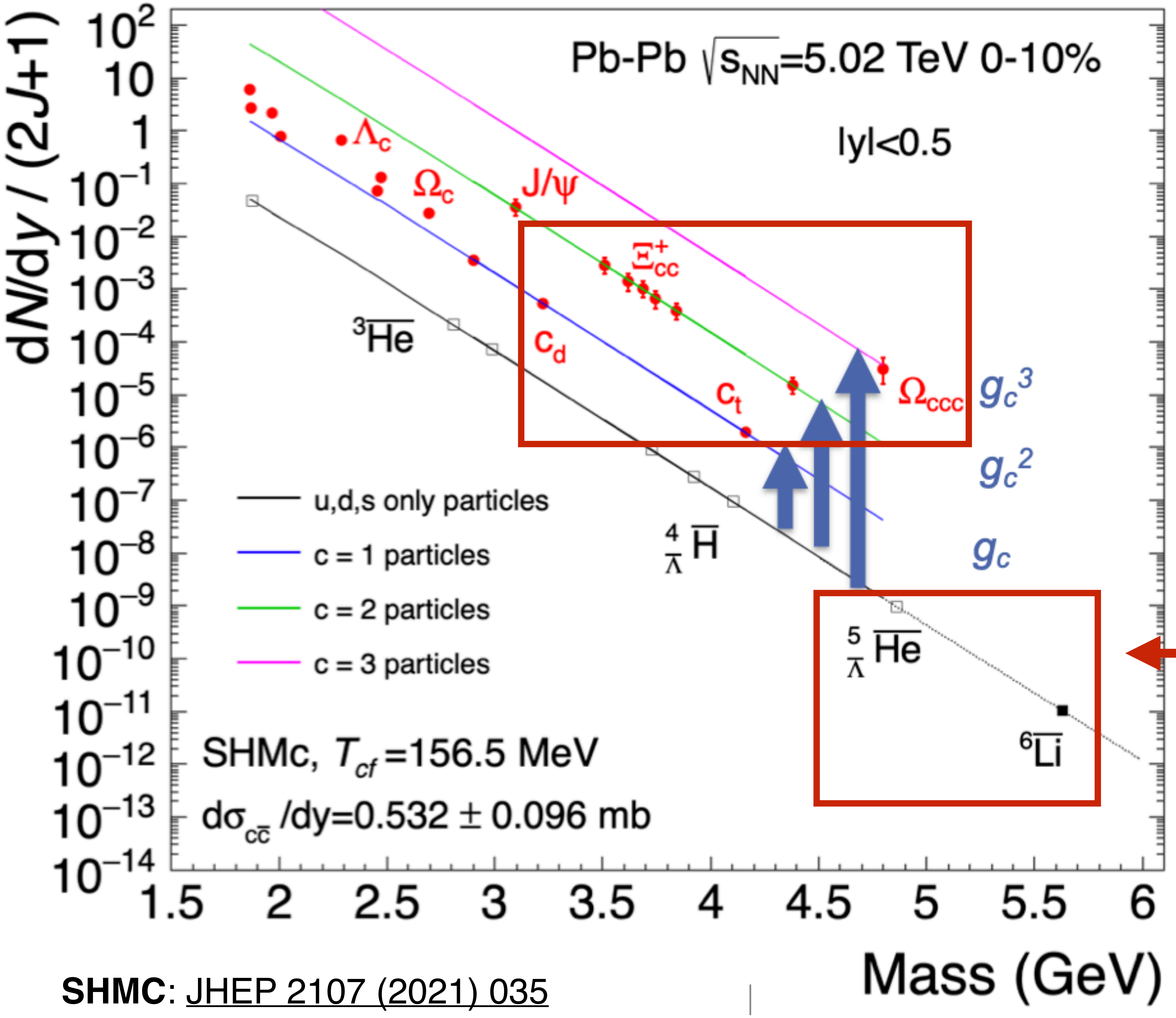

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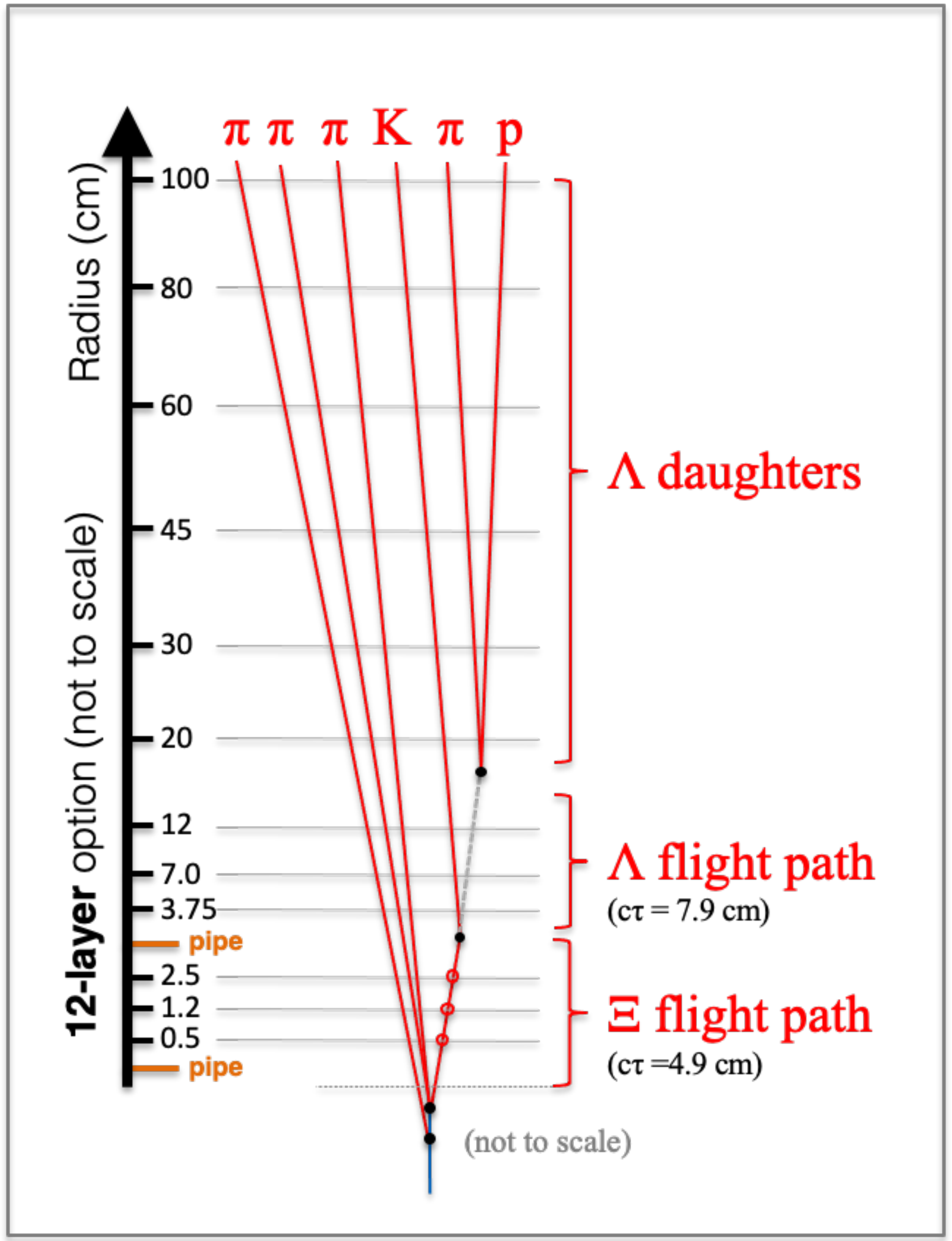
Multicharm and A=5 states:

→ ALICE 3 in Run5/6

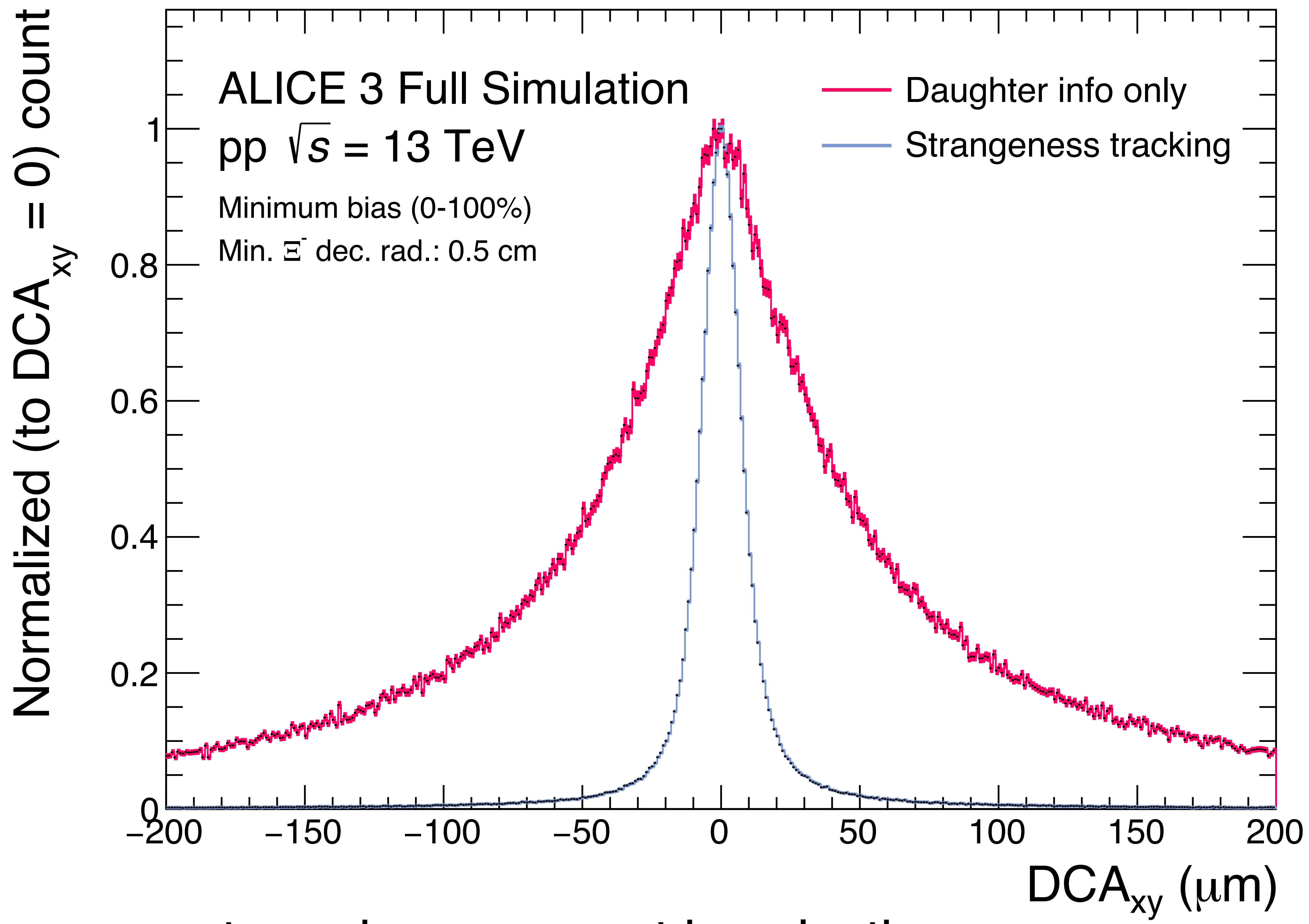
Ξ^{++}_{cc} with strangeness tracking



$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} + \pi^{+}$ ($c\tau \approx$ 76 μm)

$\Xi^{+}_{c} \rightarrow \Xi^{-} + 2\pi^{+}$ ($c\tau \approx$ 132 μm)

$\Xi^{-} \rightarrow \Lambda + K^{-}$

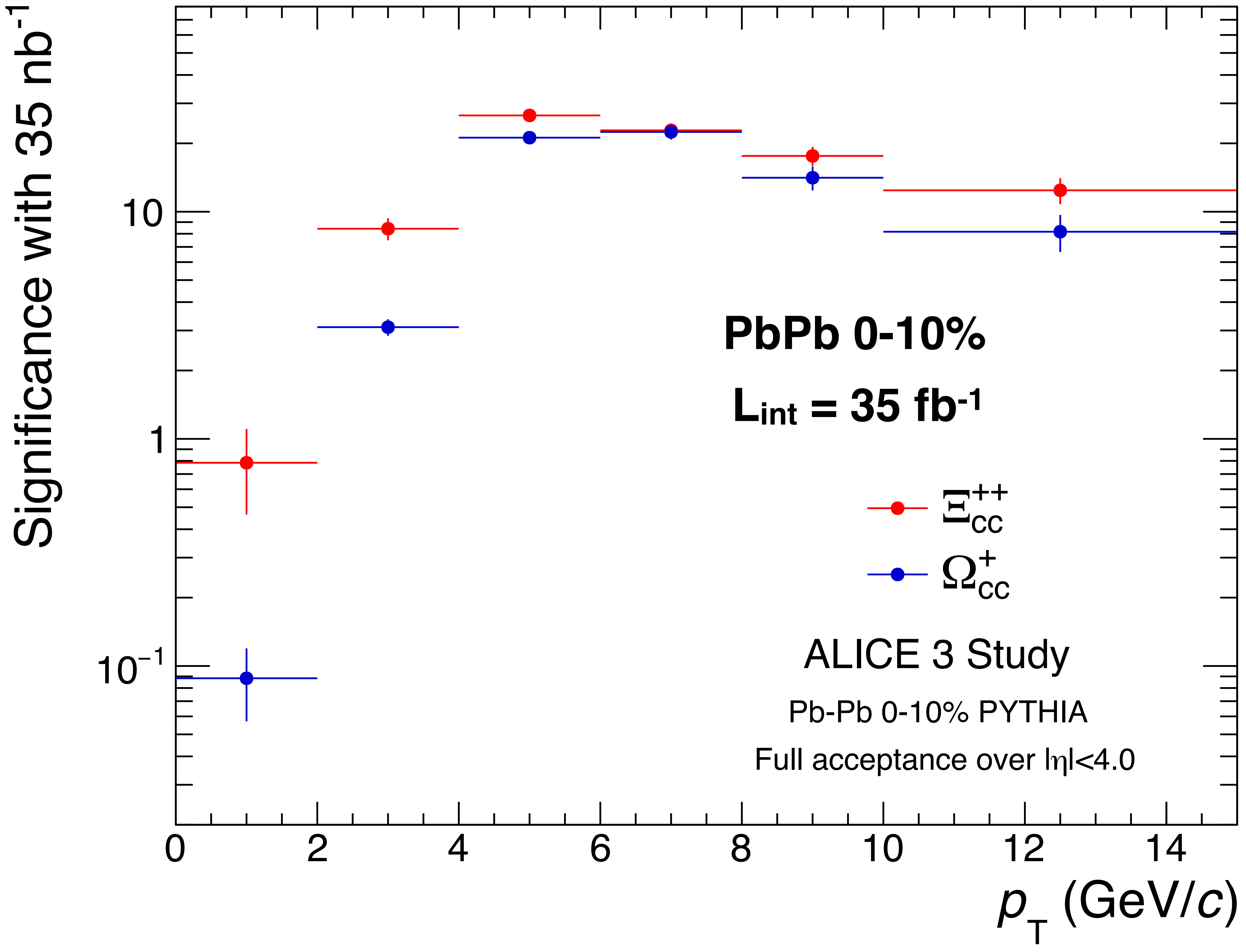


- strong improvement in selection accuracy
- large reduction of combinatorial background

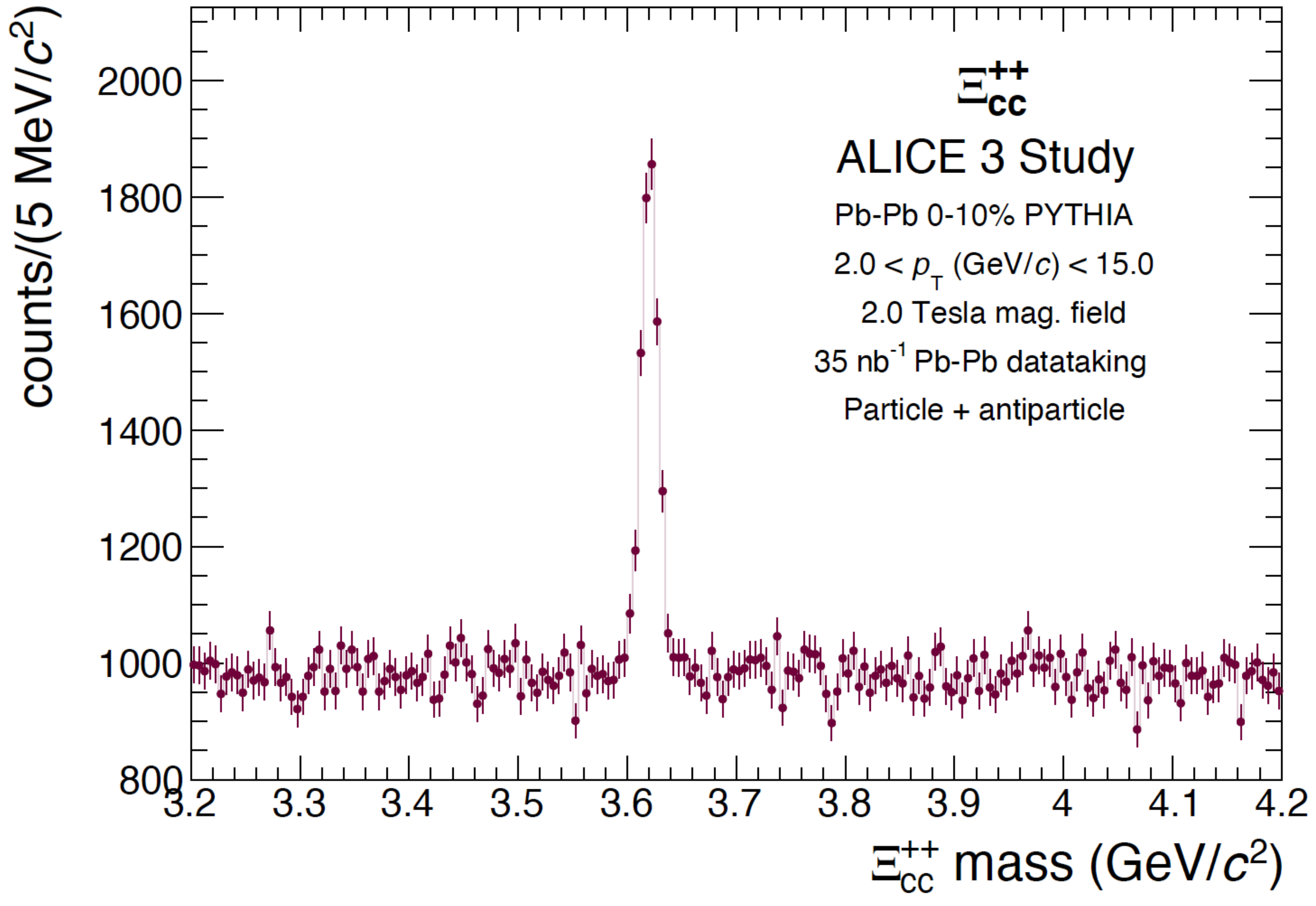
→ With ALICE 3, significant observation of Ξ^{++}_{cc} and Ω_{cc} signals expected in PbPb collisions down to low p_T

Multi-charm with strangeness tracking in PbPb

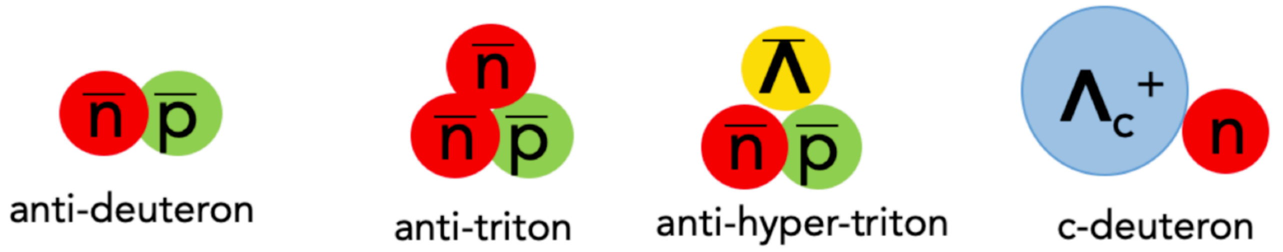
Multi-charm in AA as one of the most challenging experimental challenges:
→ extremely challenging also for estimating performance (large MC needed, CPU resources, cut optimization…)

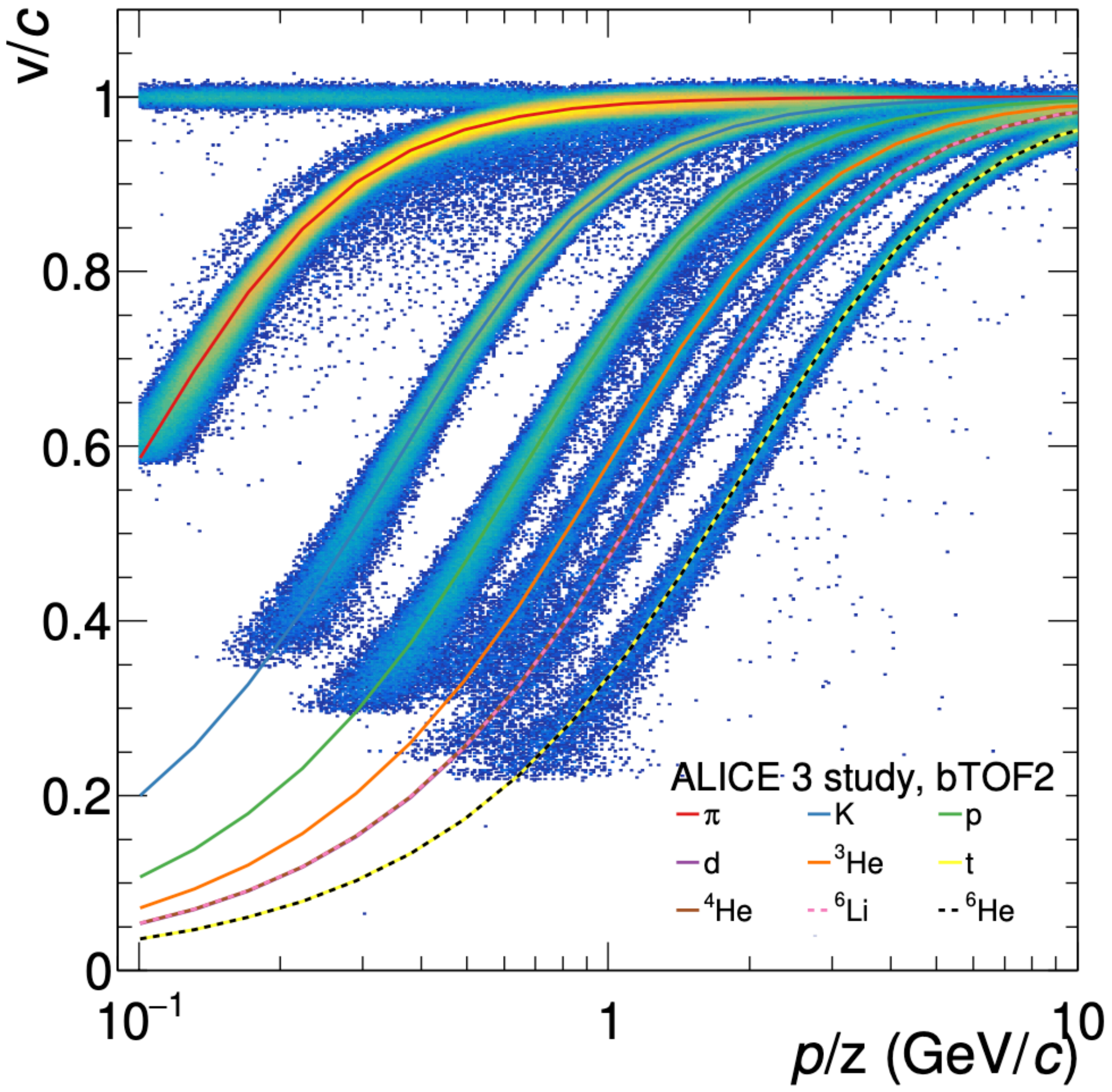


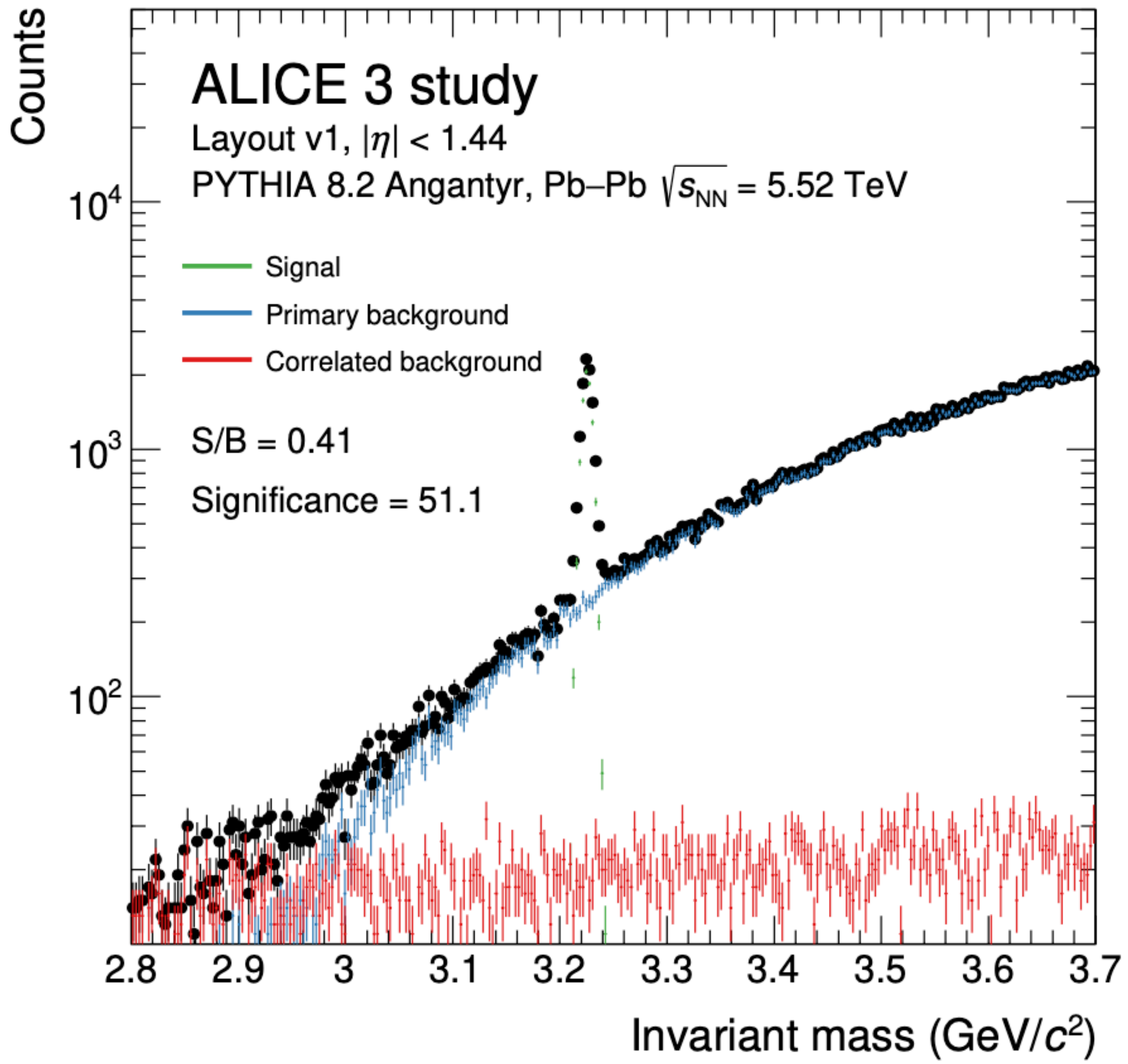
- Theoretical input: GSI/Heidelberg yields, PYTHIA mode 2 p_T distributions
- Very precise measurement possible in central Pb-Pb: maximum significance of ~33
  - Equivalent to statistical error of 3%



Nuclei and hypernuclei





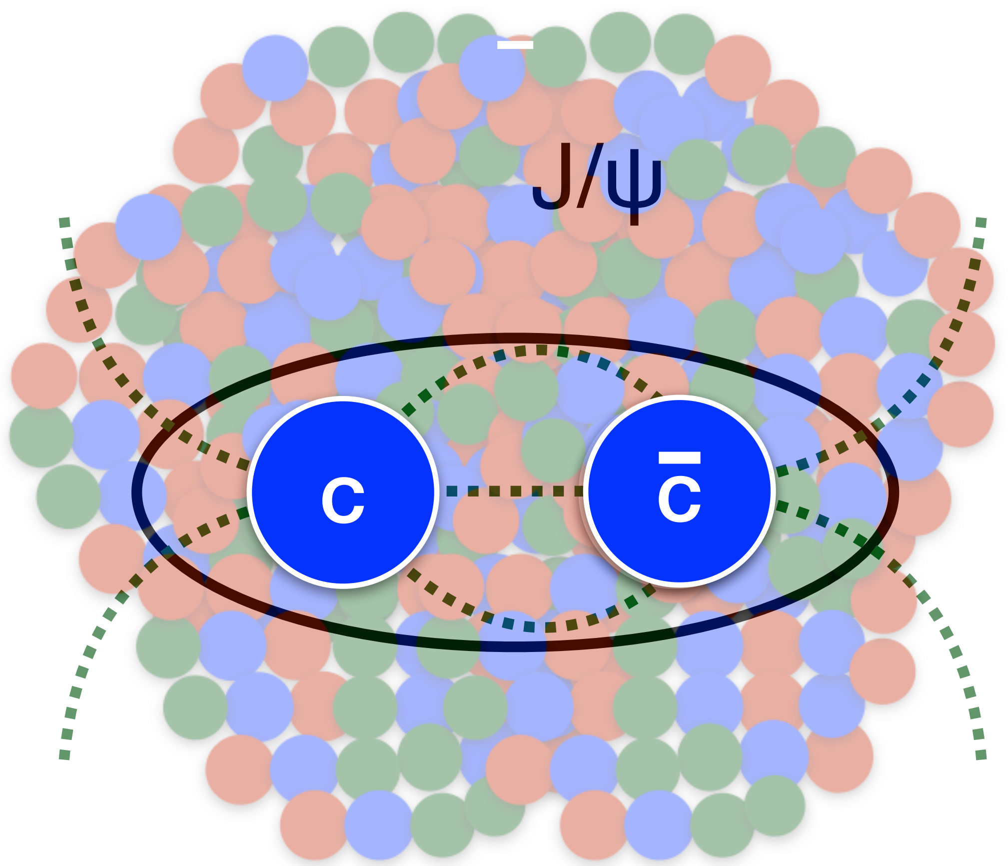


- Excellent performances for the identification of light nuclei thanks to the high resolution TOF

- Sensitivity to new states as c-deuteron

η_c and $\chi_{c,b}$ states in heavy-ions

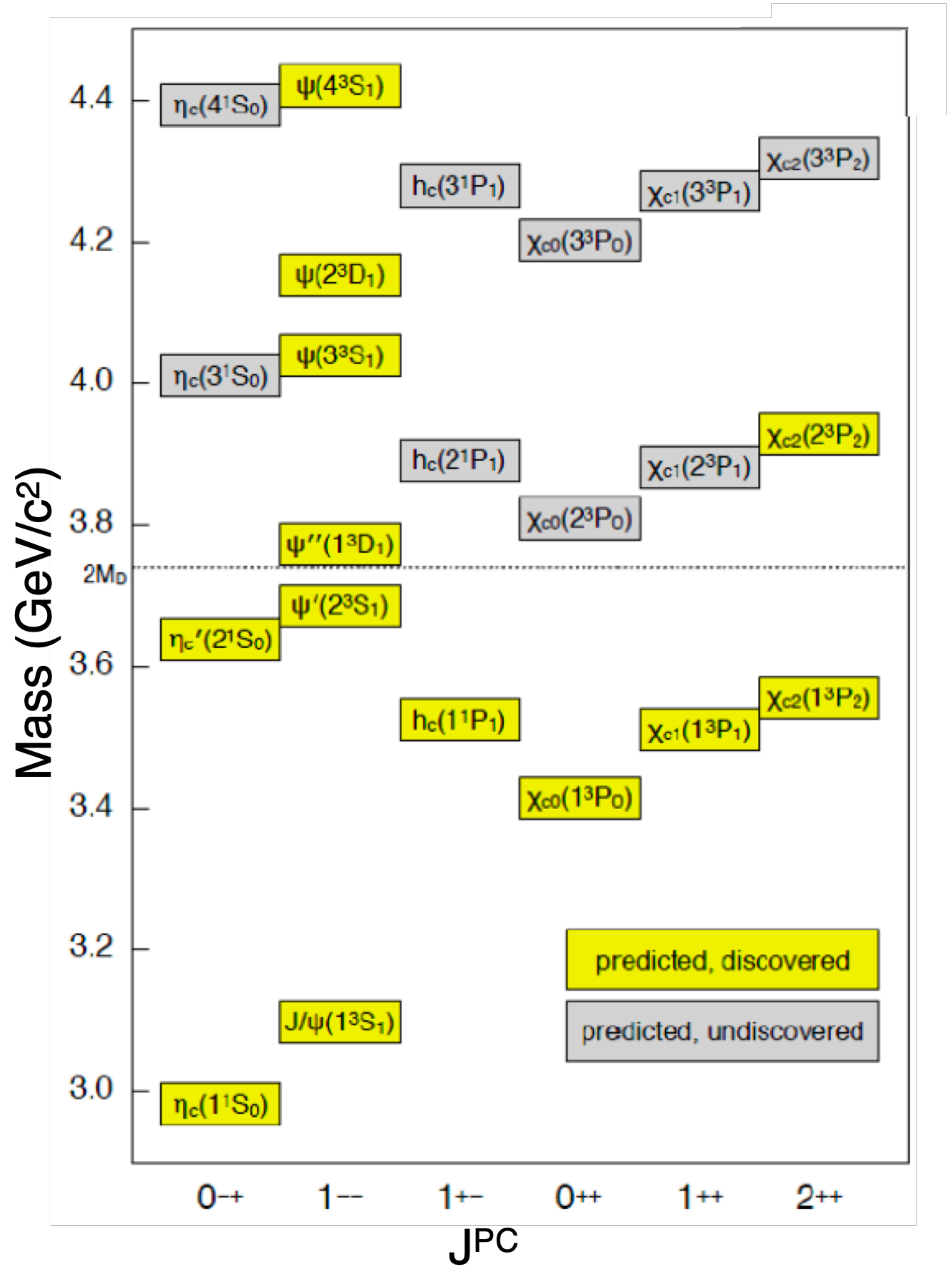
Strong push from the theoretical community to measure more states with different quantum number properties



Pseudo-scalars (η_c)
- never measured in HI collisions

χ_c and χ_b → J/ψ+γ (L=1):
- different bound-state stability and sensitivity to thermal fluctuations
  → **significant discrepancies among different theoretical predictions**

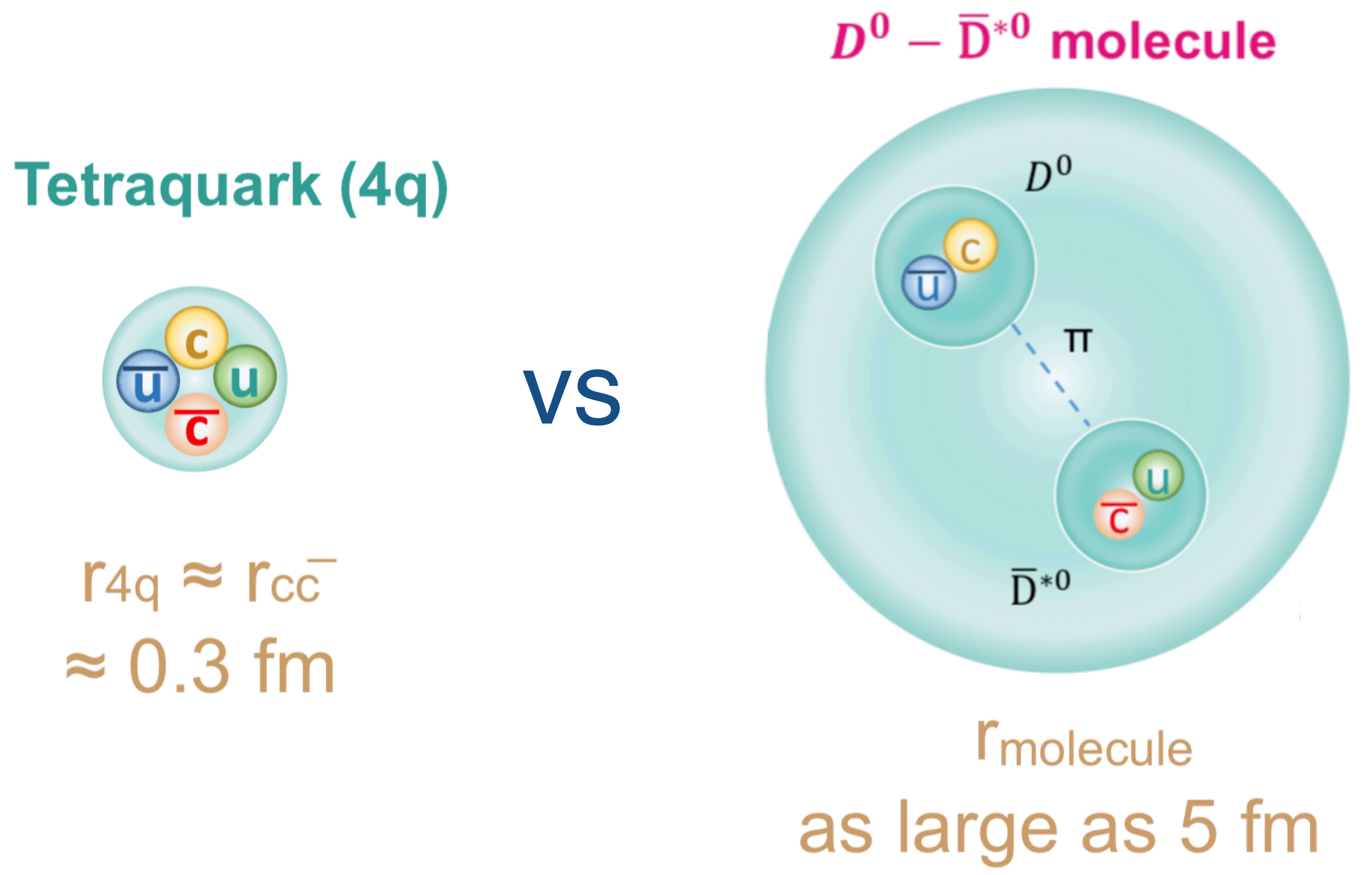
Challenging analyses in the high-density AA environment:
- Photon reconstruction down to ~ 0.5 GeV with good resolution:
- J/ψ and Υ reconstruction **down to low p_T**

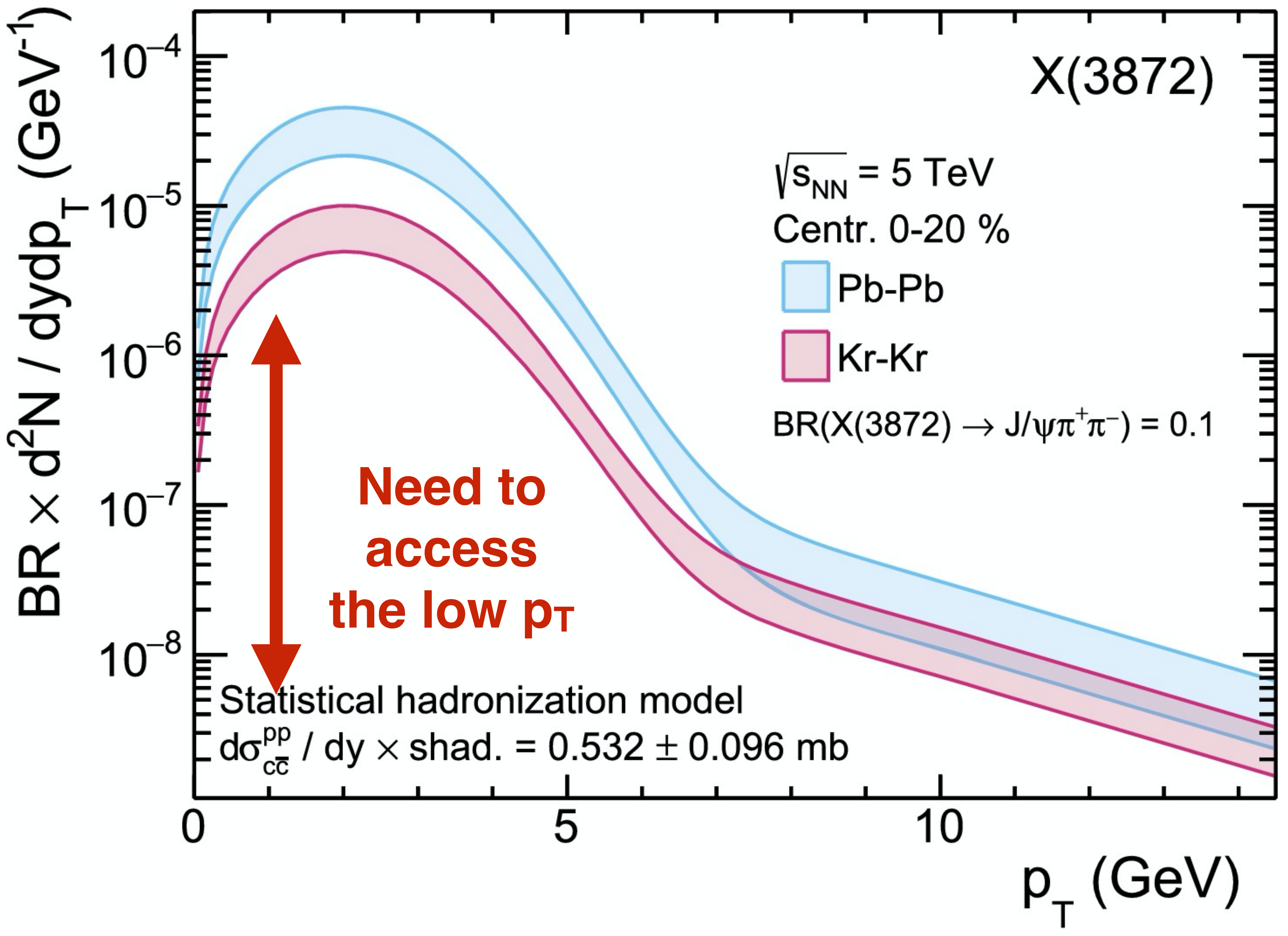


P. Artoisenet et al. Phys. Rev. D 81, 114018
A. Andronic et al.: PLB 797, 2019, 134836 + priv. communication
Belle: PRL 91, 262001 (2003)

CMS: arXiv.2102.13048

Exotic hadrons in HI collisions





- **Constrain their nature** by studying their interaction with the hadronic environment
- New insights into properties of complex bound states in the QGP

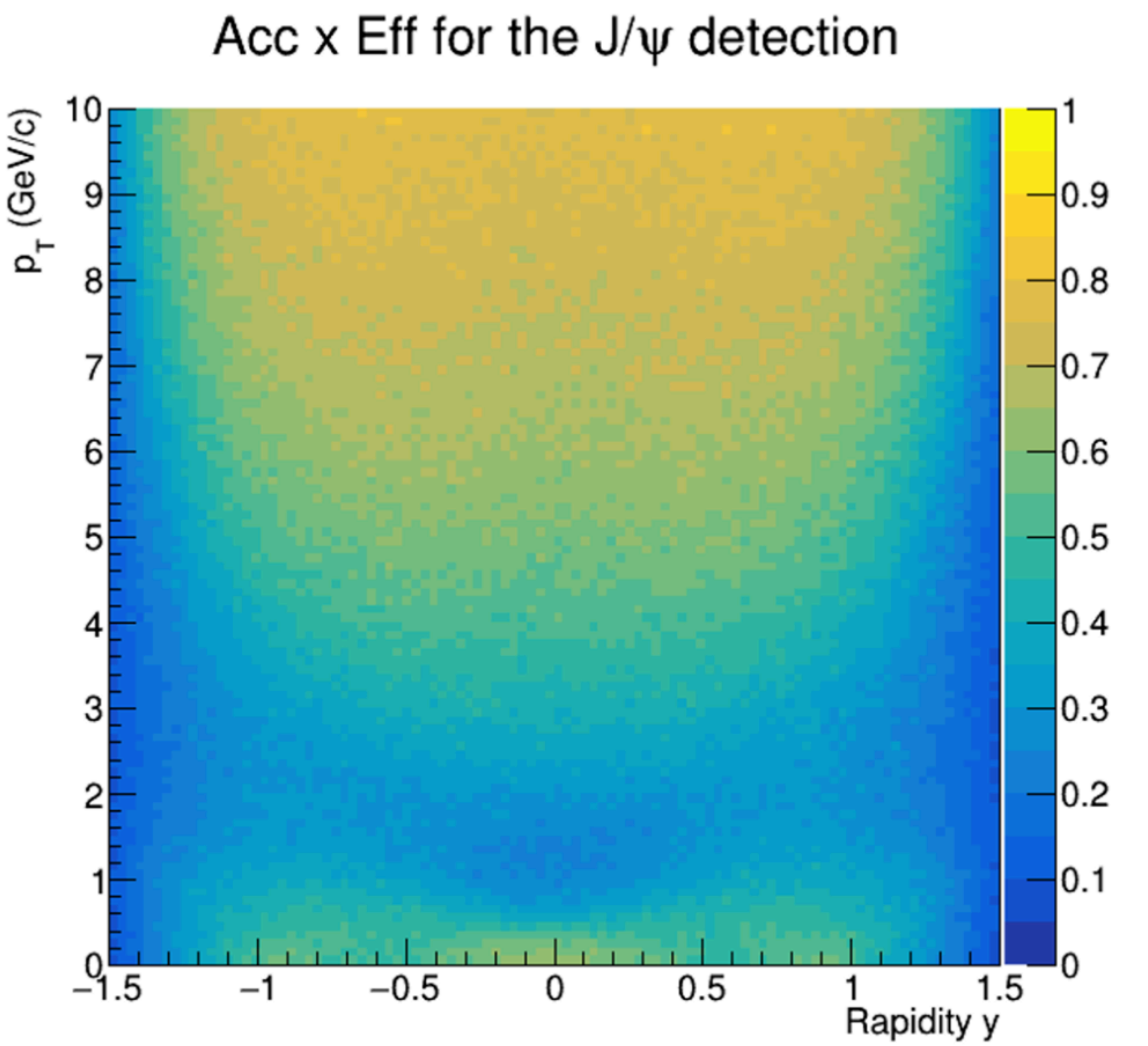
- J/ψ and Y reconstruction **down to 0 at mid- and forward rapidities**
- **low p_T reach for measuring soft pions**

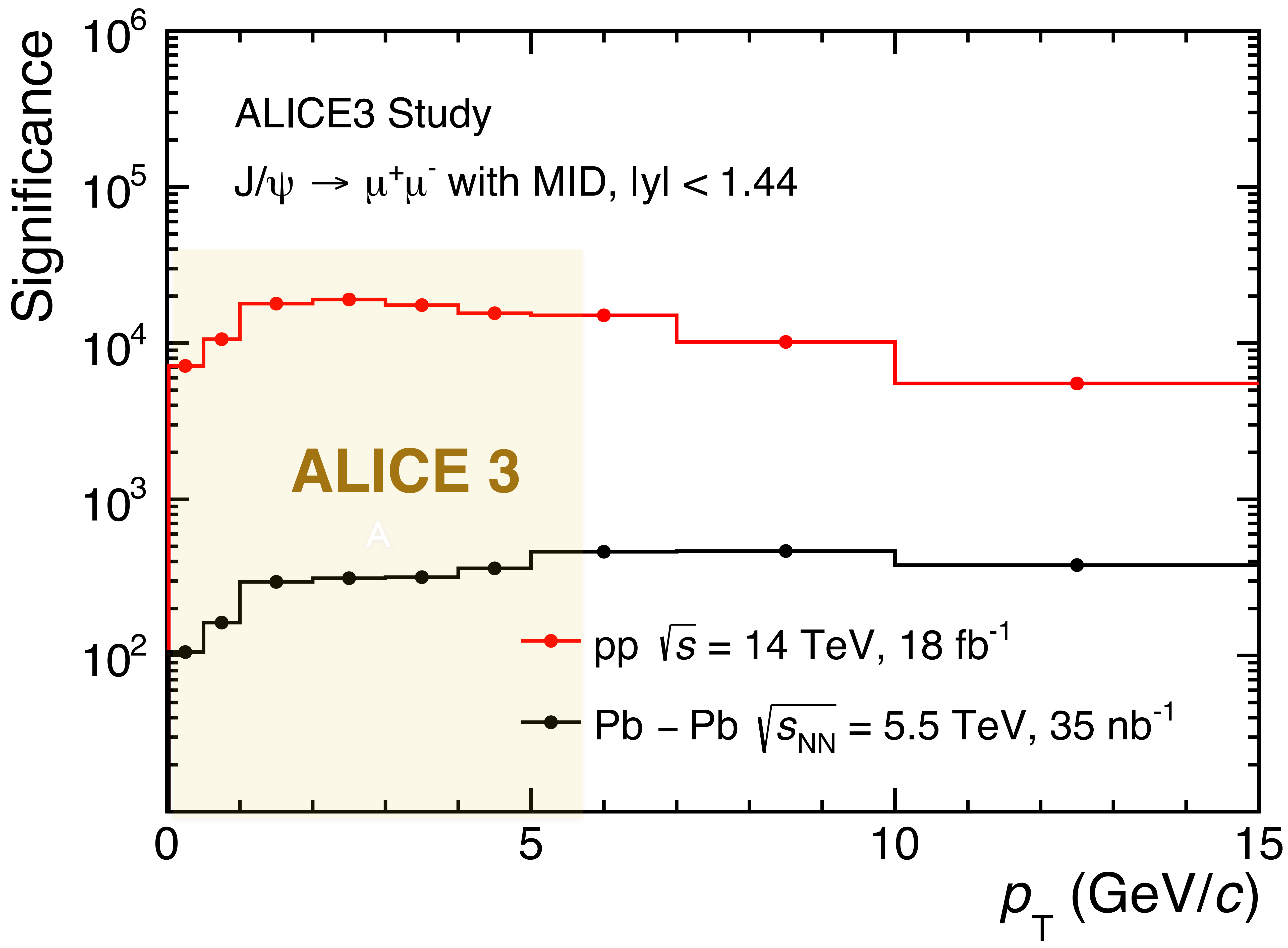
Wu, B., et al.: Eur. Phys. J. A 57, 122 (2021)

J/ψ performance as a benchmark

- J/ψ reconstruction as a building block of the quarkonia/exotic program of ALICE 3

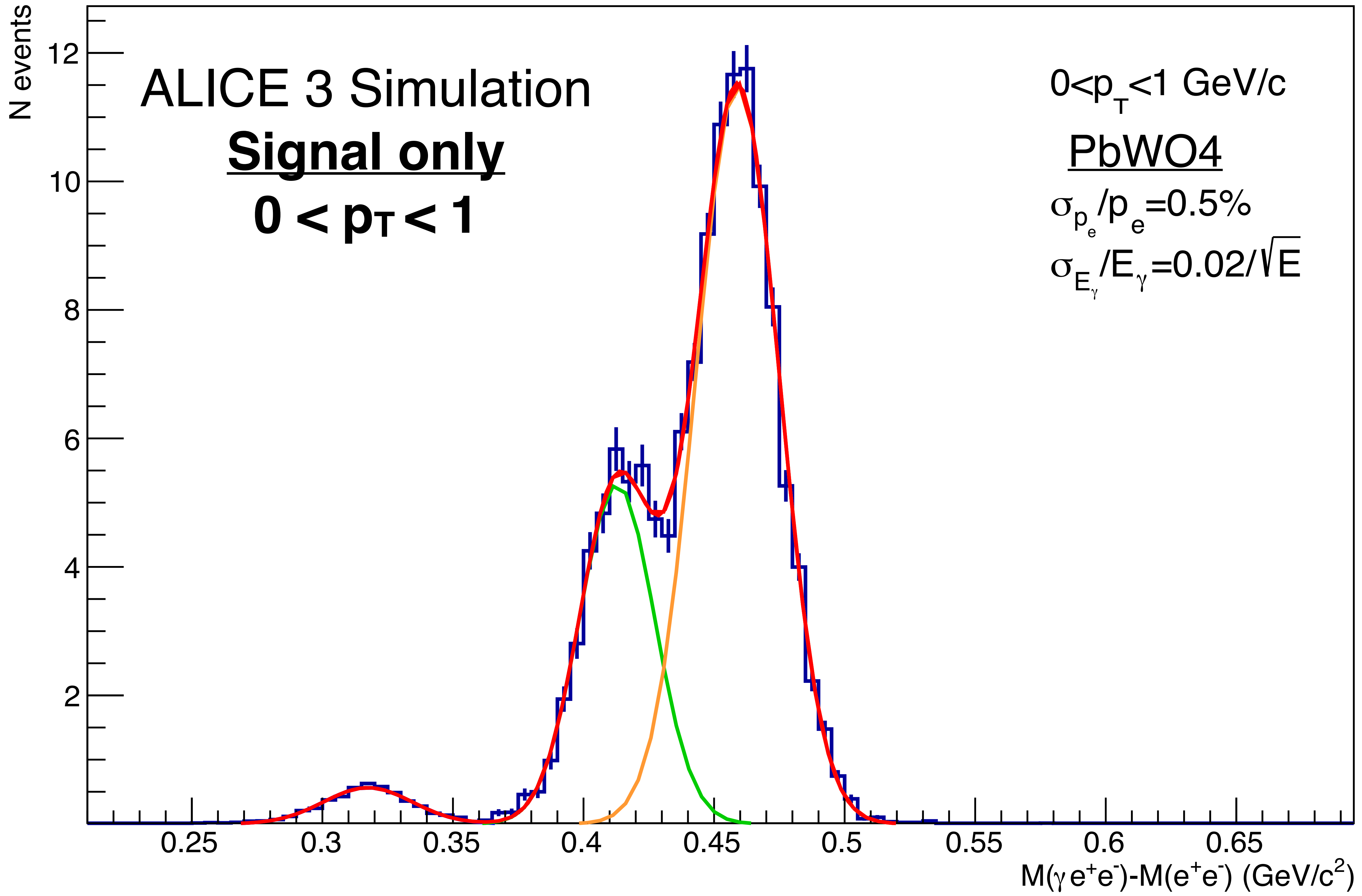
*Geant4 study for **Muon Identification detector***





- **J/ψ reconstruction at y=0 down to p_T = 0 GeV/c as a unique feature of the ALICE 3 detector**

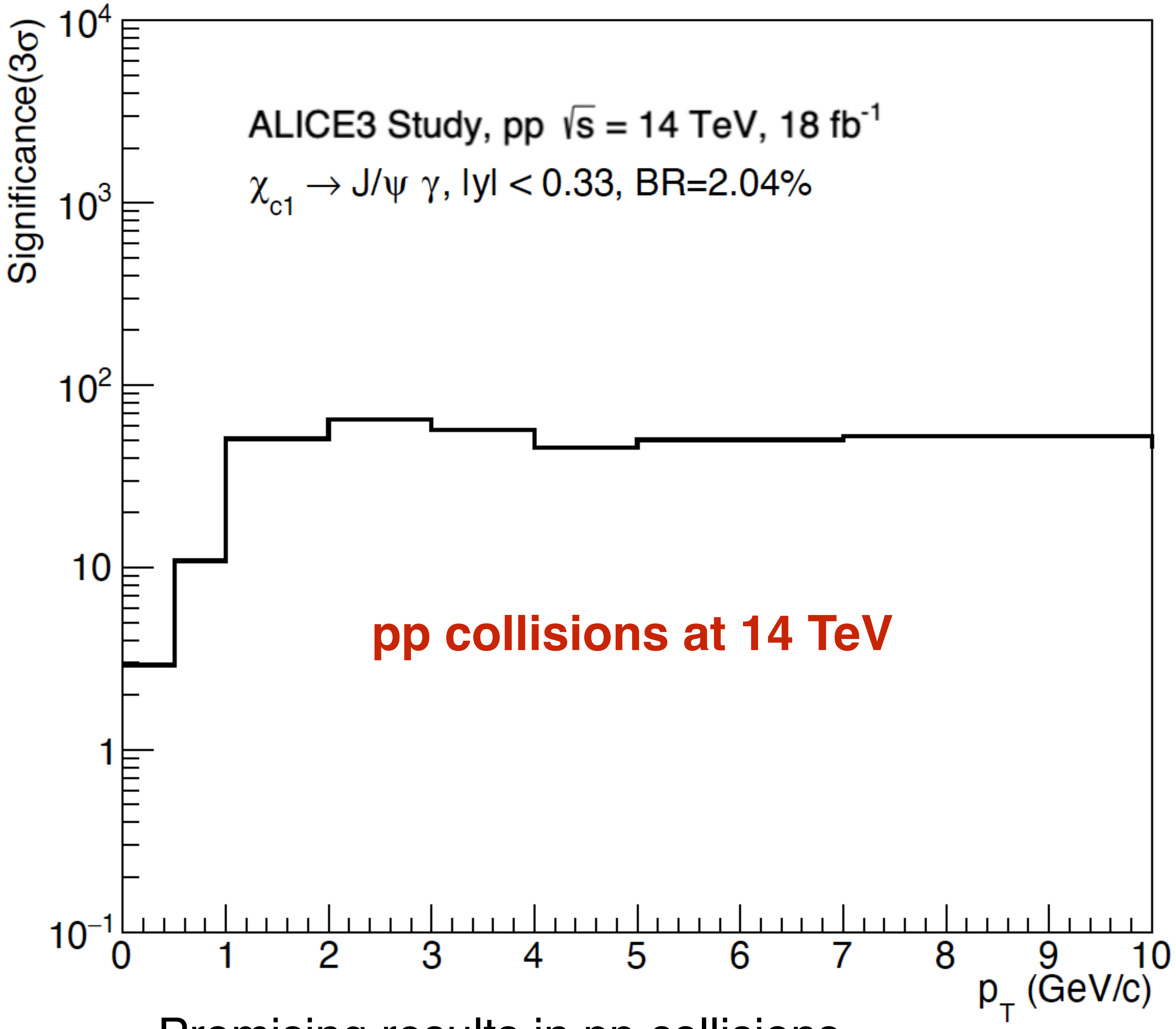
P-wave measurements with ALICE3



Photon identification performed with ECAL:

- high-resolution crystals at mid rapidity (no boost)
- sampling calorimeter at more forward rapidities

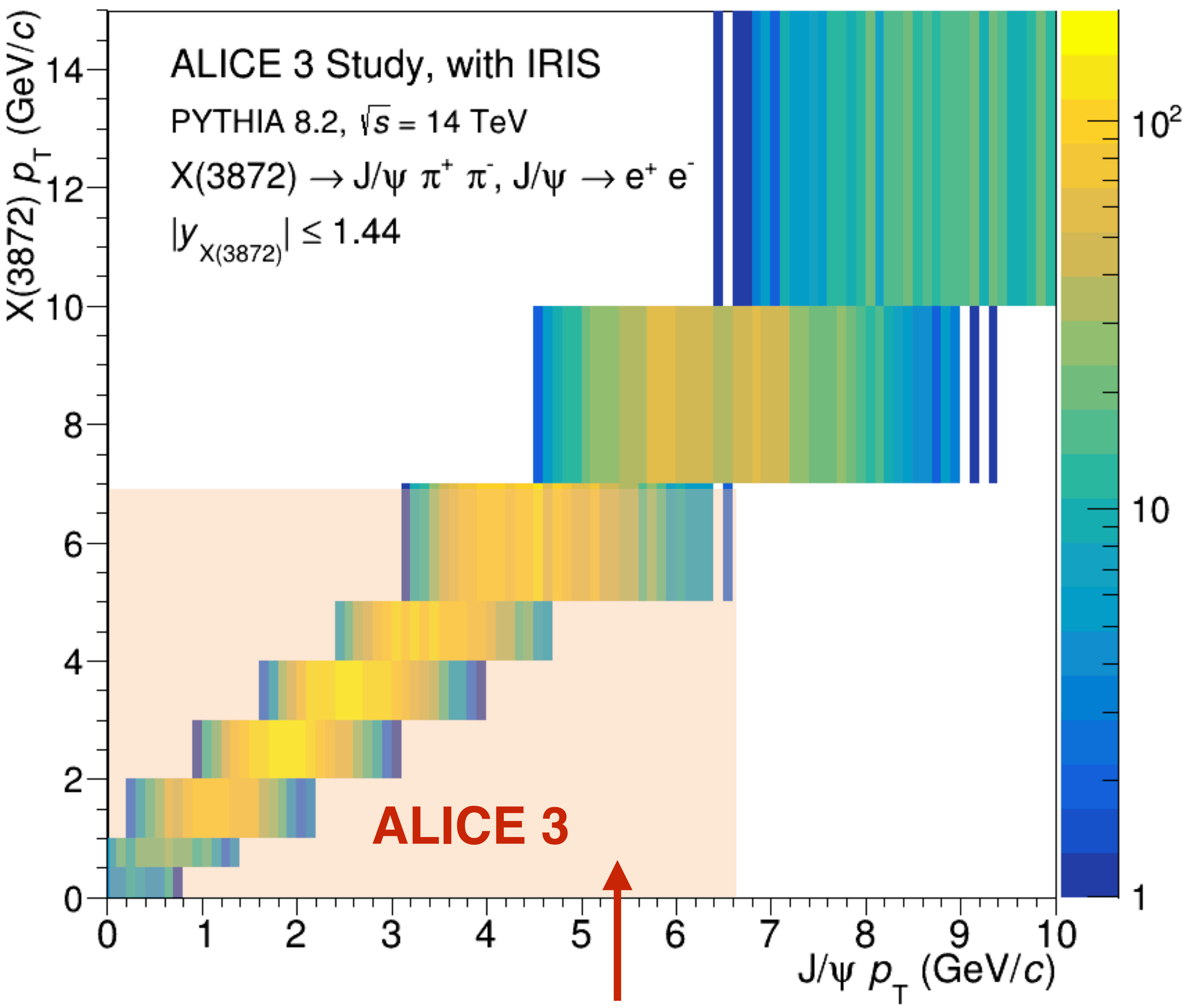
→ maximize photon reconstruction efficiency

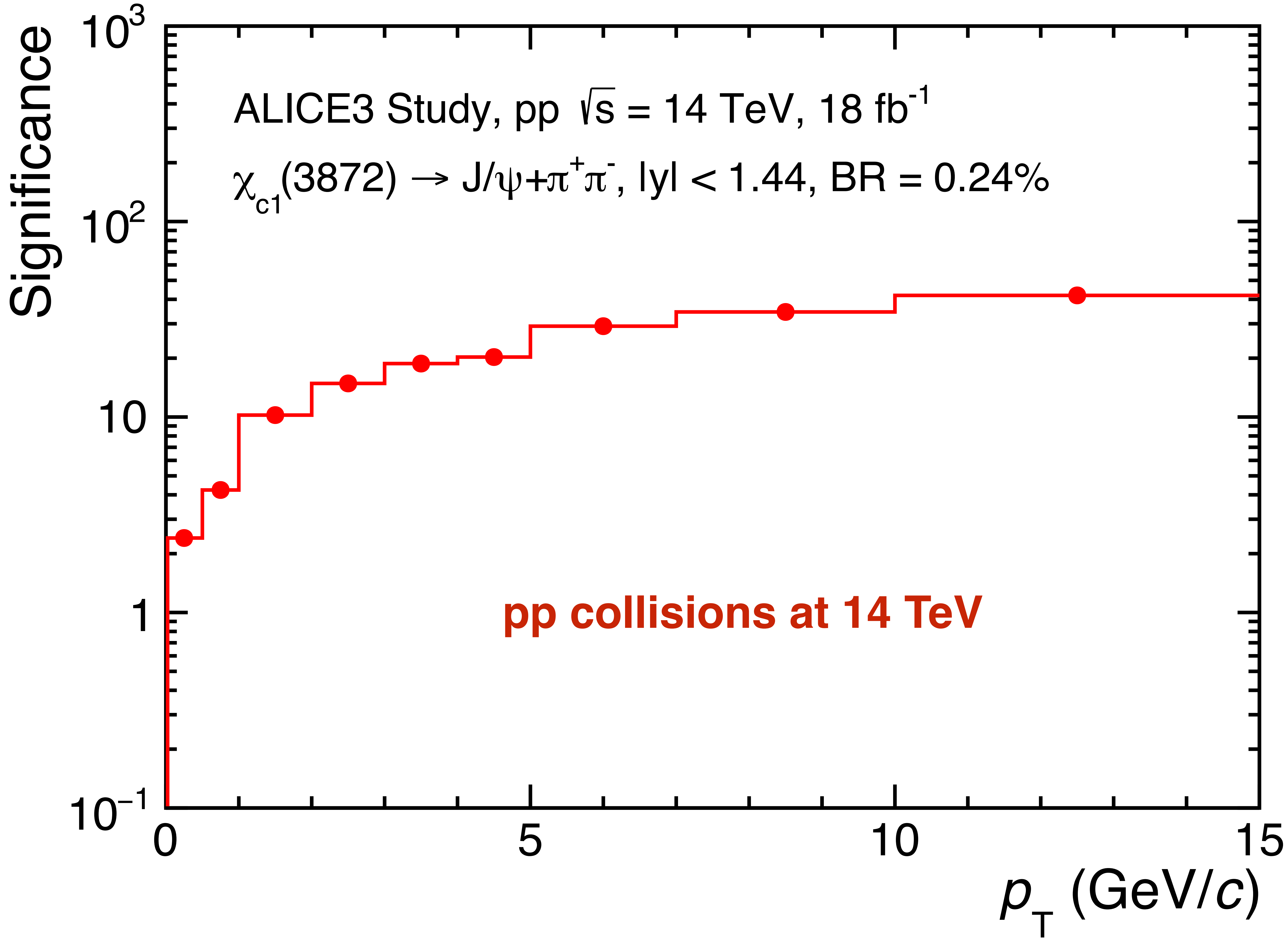


- Promising results in pp collisions

→ access to low p_T at mid rapidity

χ_{c1}(3872) measurements with ALICE 3





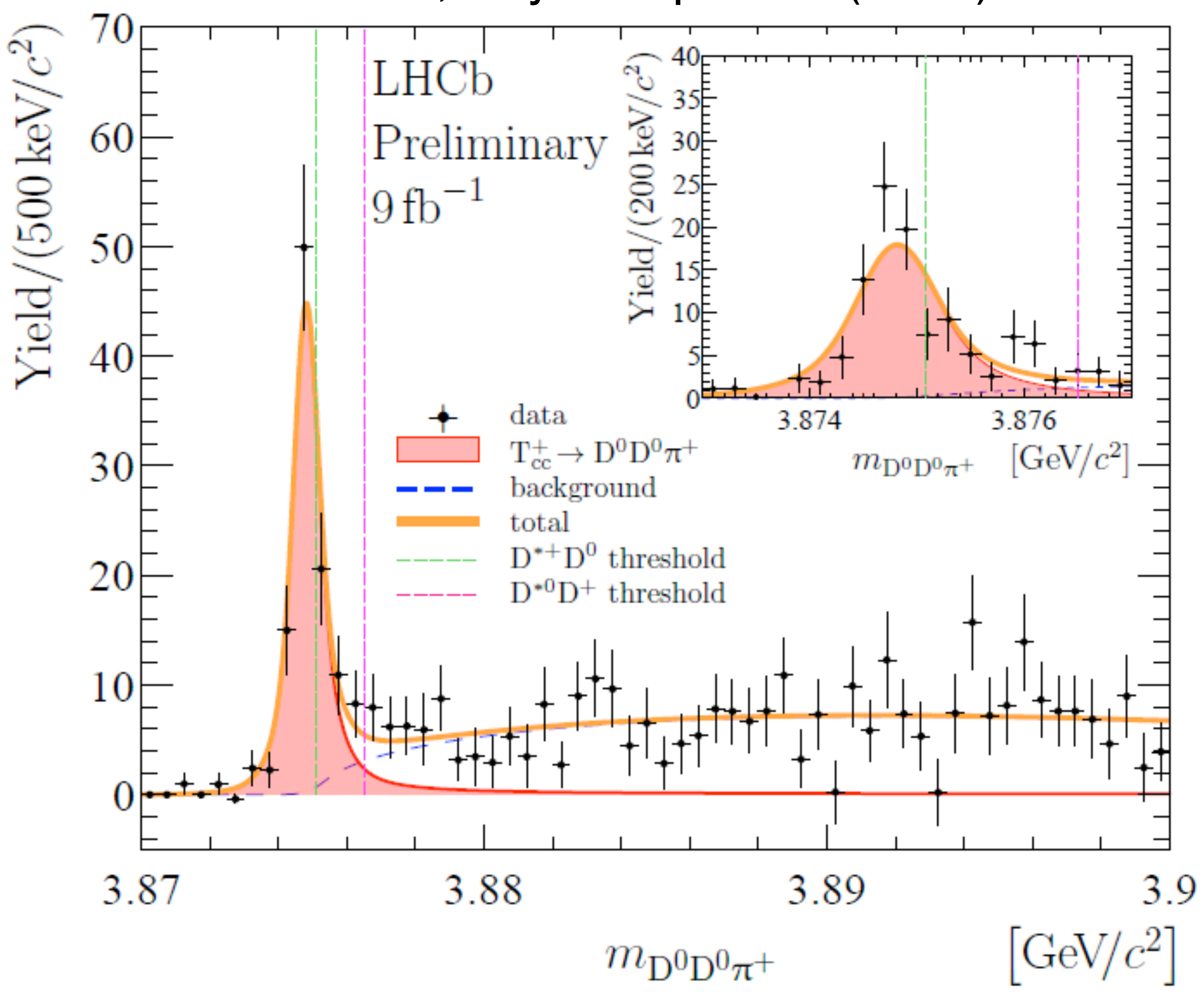
→ **Low p_T reach for J/ψ and charged tracks could allow for a unique kinematic reach at the LHC**

→ **For both $\chi_{c,b}$ and χ_{c1}(3872) work is ongoing to assess the low p_T reach for heavy-ion analyses**

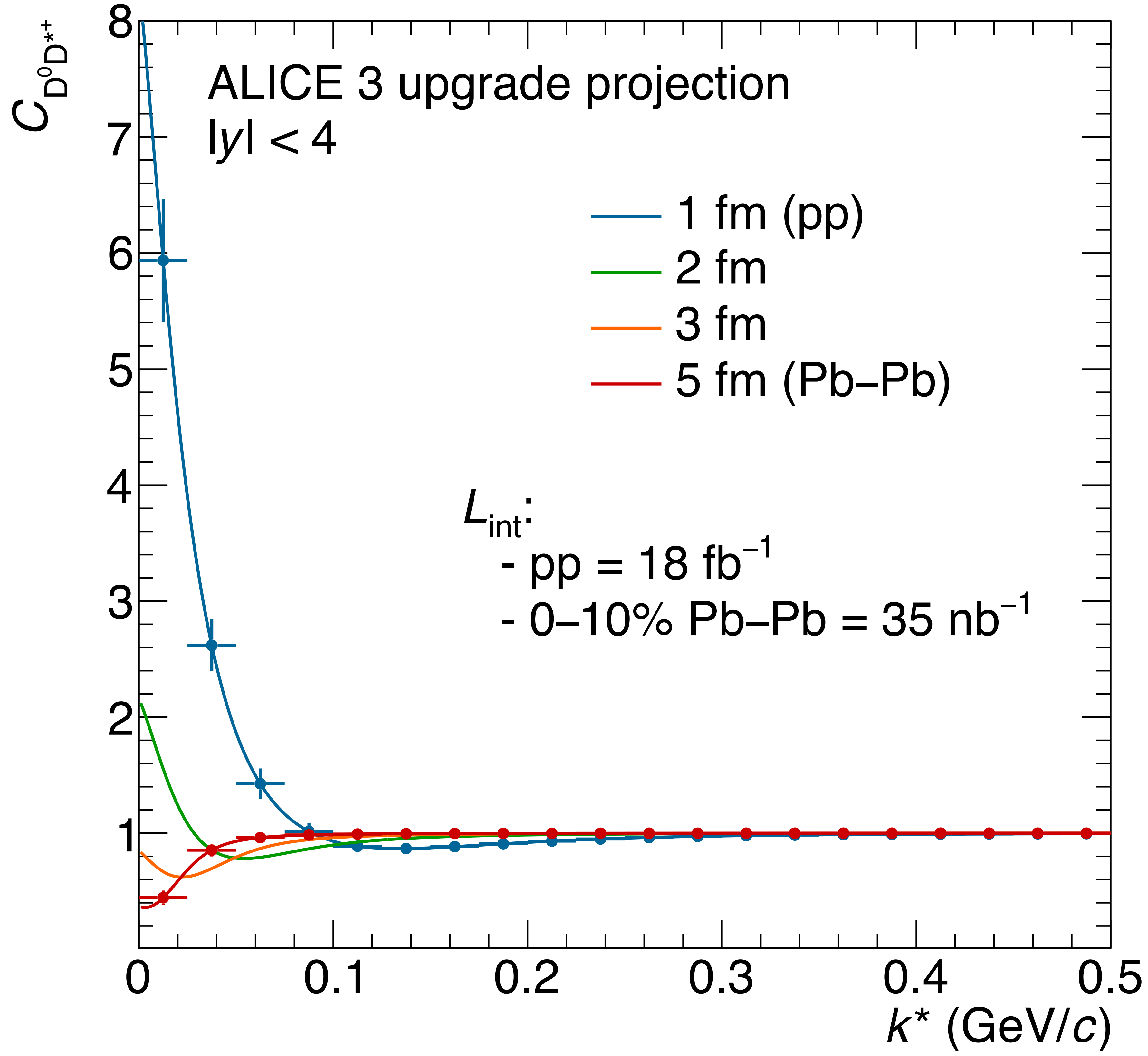
Femtoscopy techniques for “exotic” studies

- Recent measurement of tetraquark-like state by LHC
- Just below D^0D^{*+} and D^+D^{*0} thresholds → candidate to be a molecular state

E. S. Swanson, Phys. Rept. 429 (2006) 243-305



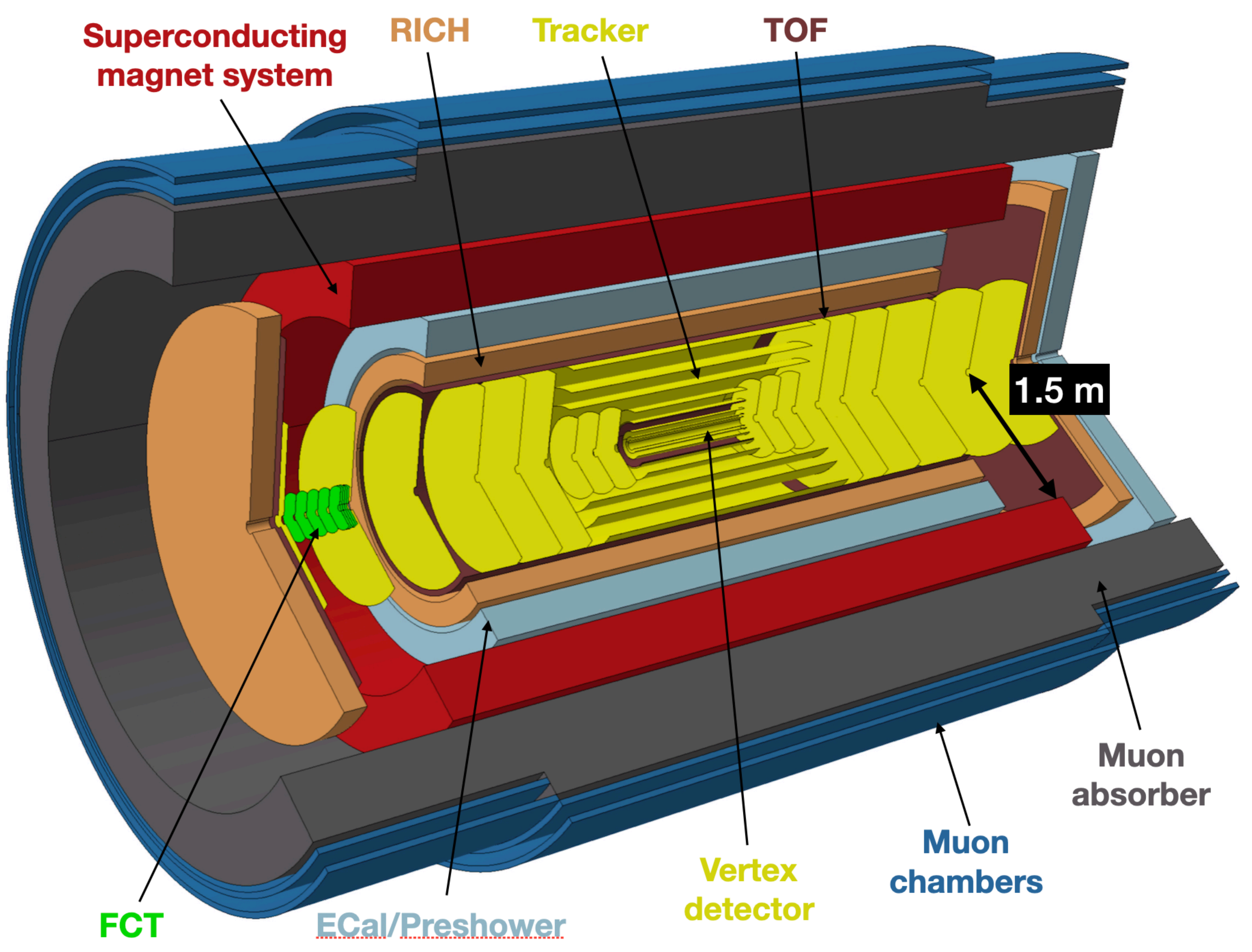
- Its nature can be assessed via the measurement of DD* correlations
  → In case of a bound state (T_{cc}^+) the correlation function is expected to change from smaller to larger than unity for different source sizes



- Scan from pp to AA collisions needed
- ALICE3 is the ideal detector for acceptance

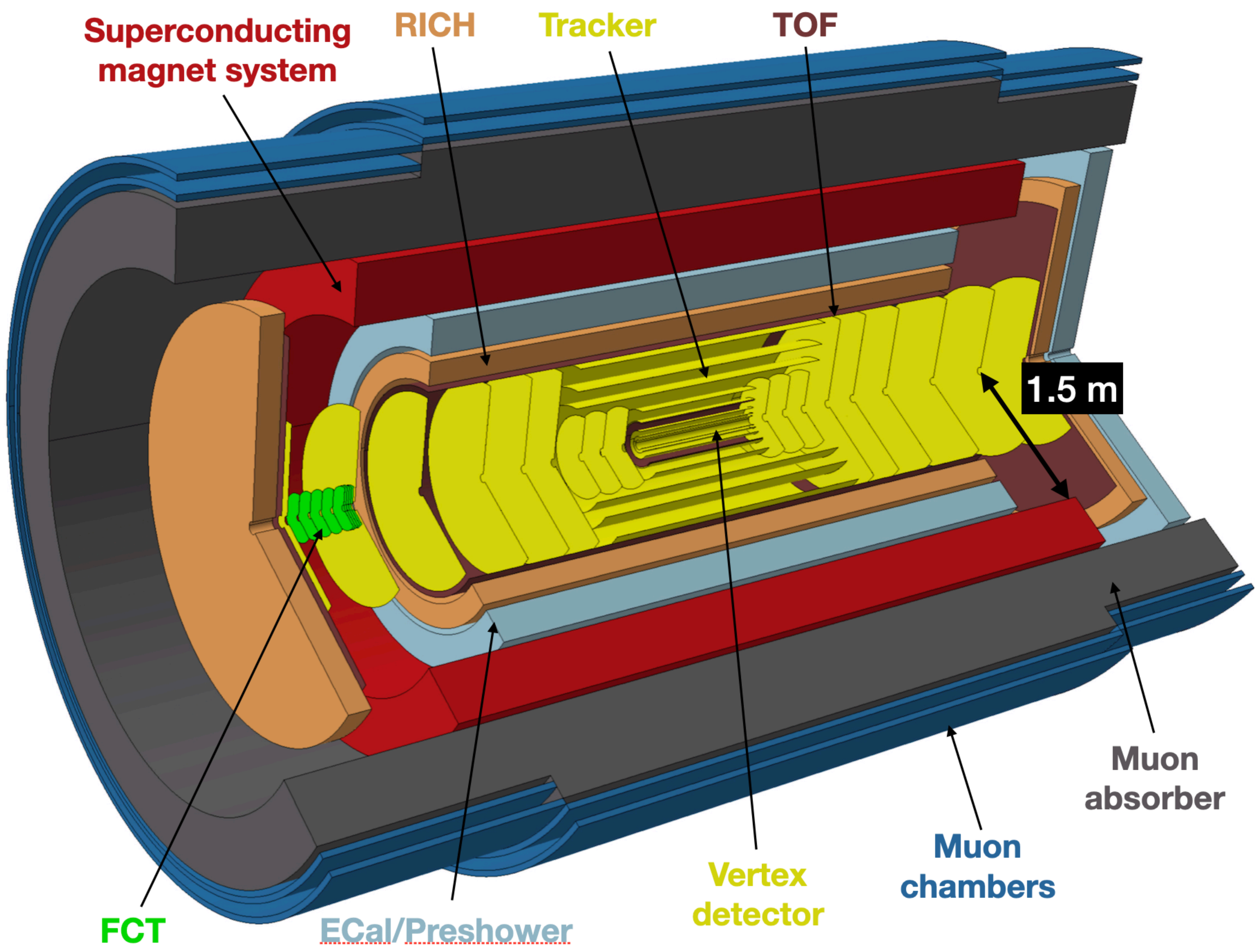
Predictions: courtesy of T. Hyodo and Y. Kamya

Conclusions and outlook



→ understanding heavy quark diffusion in the QGP
→ thermalisation and hadronisation
→ bound states' interactions and nature of the states
→ And much more, also beyond QGP physics

Conclusions and outlook



→ understanding heavy quark diffusion in the QGP
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→ And much more, also beyond QGP physics

Critical moment to shape the future of HI physics at the LHC beyond Run 4:

- In this talk, the "ALICE(3)" prospective much activities are ramping up also in the other LHC collaborations
- thank all the theorists that are helping out and strongly encourage new inputs/ideas

Thanks for your attention!

BACKUP