ALICE 3:

a next-generation heavy-ion experiment for LHC Run 5 and beyond

G.M. Innocenti (CERN)

***NorCC workshop**, 14-15 September 2022*

special thanks to J. Klein for his help

NORCC

Overview of the talk

- **Heavy-ion physics in the ’30s**
- **Physics motivation for ALICE 3**
  (focus on heavy-flavour observables)
- **Detector design and (selected) performance studies**

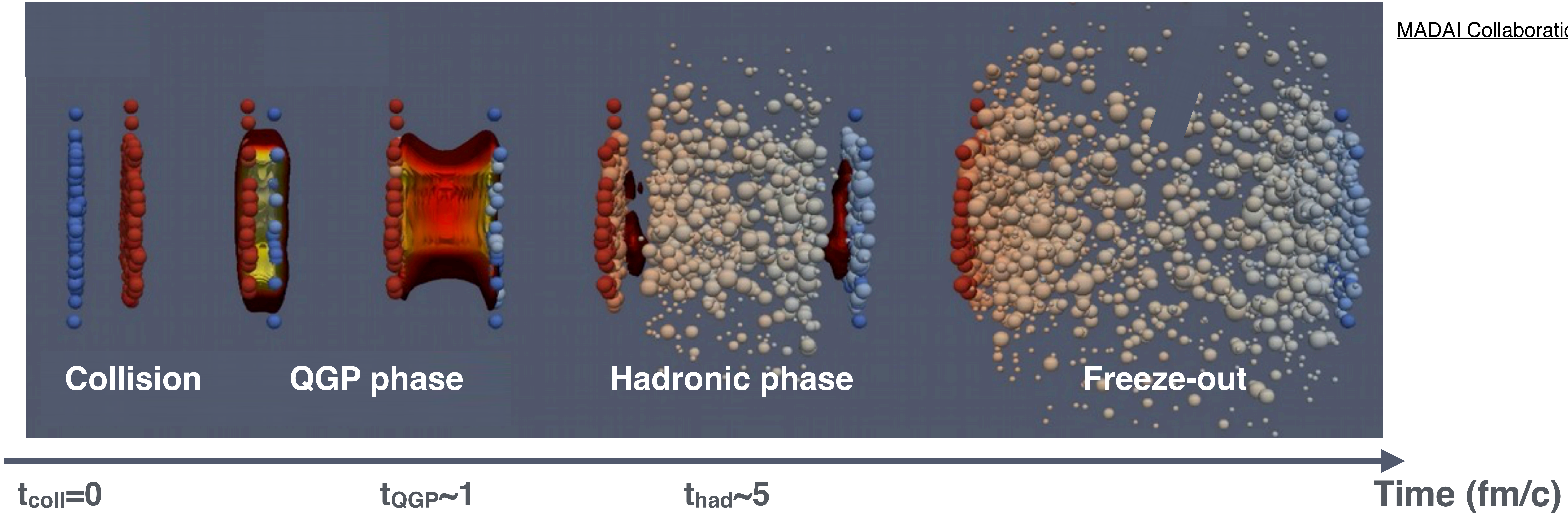
- **R&D and technological challenges**

ALICE 3 Letter of Intent (CERN-LHCC-2022-009)
LHCC review completed in March 2022
→ ALICE encouraged to continue with R&D!

Schematic evolution of heavy-ion collisions

Many years of experimental and theoretical works have shown the limit of a over-simplified description!

MADAI Collaboration



QGP deconfined phase

weakly-interacting QGP

strongly-interacting (**"liquid"**) QGP

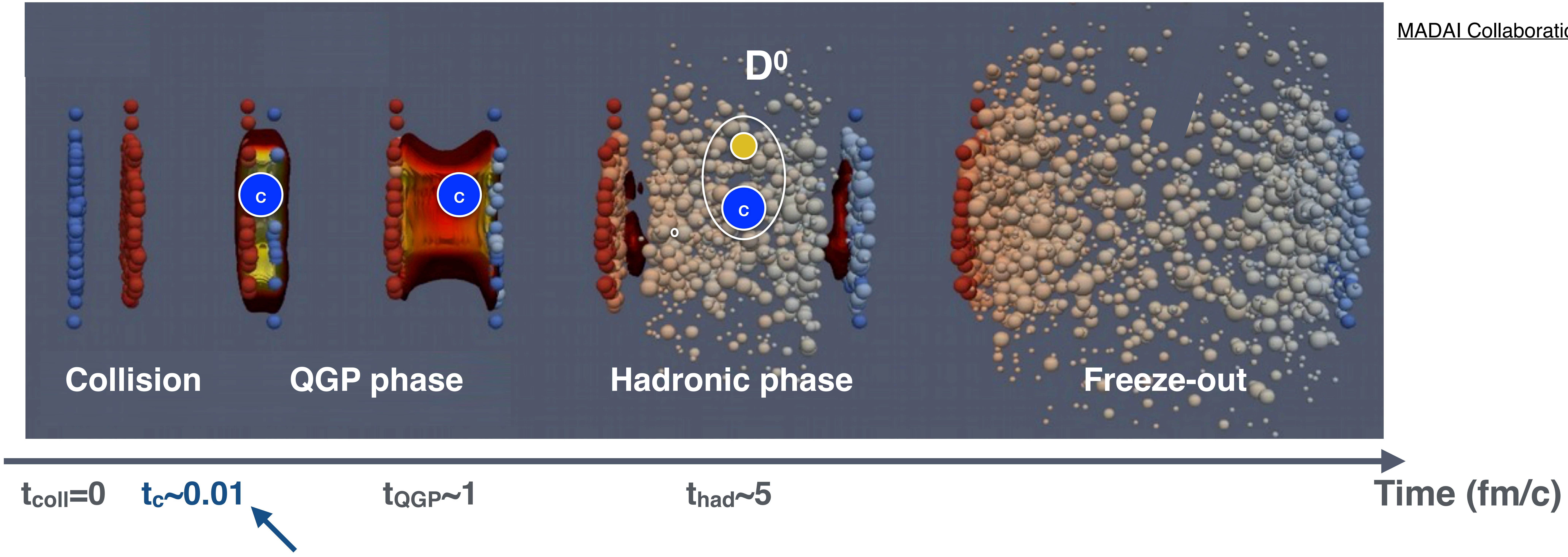
- Nature of the high-temperature deconfined phase?

- Microscopic characterization of hadronization?
- What is the smallest system where QGP can be formed?

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018

Heavy quarks in heavy ions: a recent revolution

Over the last decade, we witnessed a "revolution" in heavy-ion physics: heavy-quark studies became available!



$m_c \sim 1.5$ GeV
$\Lambda_{QCD} \sim 200$ MeV
$T_{QGP} \sim 300$ MeV
$m_{u,d,s} \lesssim T_{QGP}$

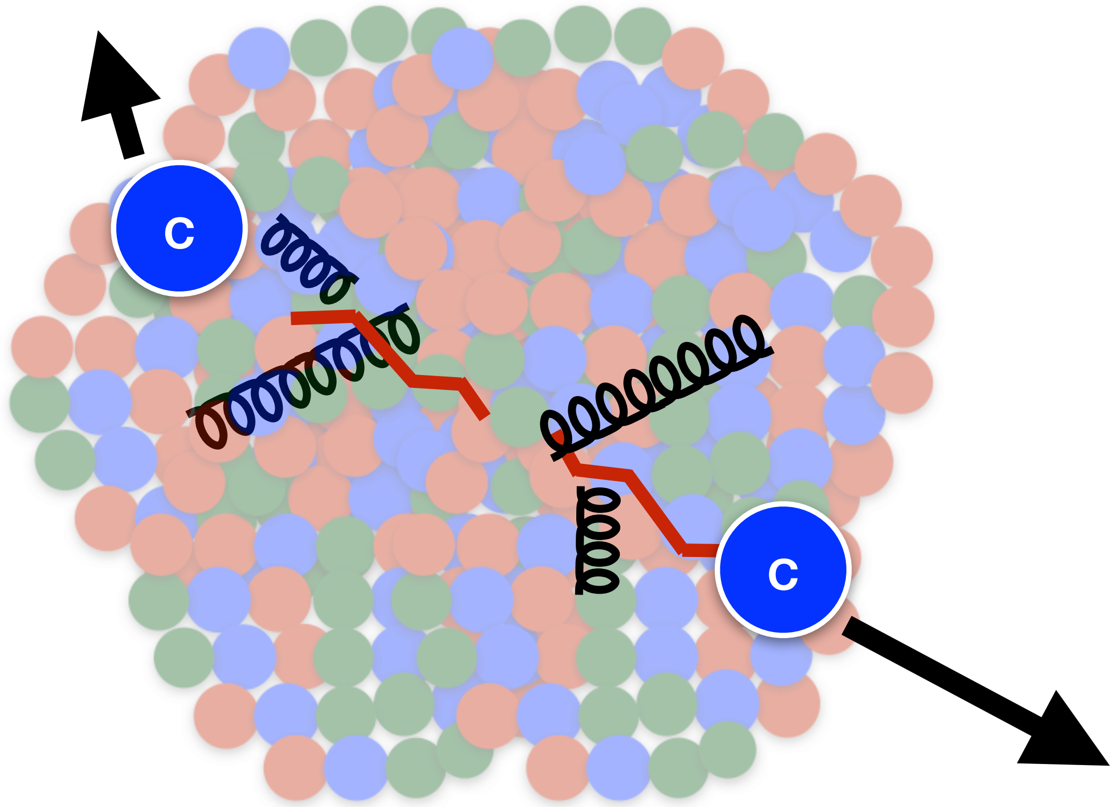
- **high-Q^2 scatterings (→pQCD) and early production**
- **no "thermal" production** (abundant for light quarks)

→ Conserved and traceable witness of the QGP evolution

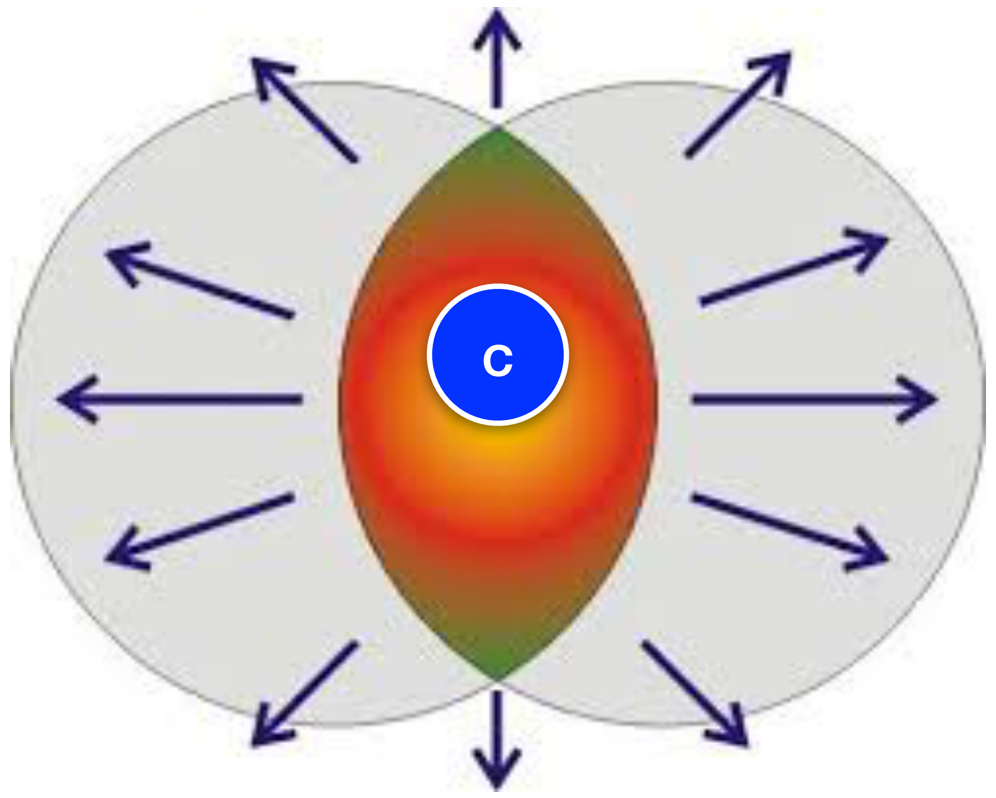
A. Andronic et al. EPJC 76 107 (2016)

Experimental evidence with heavy quarks

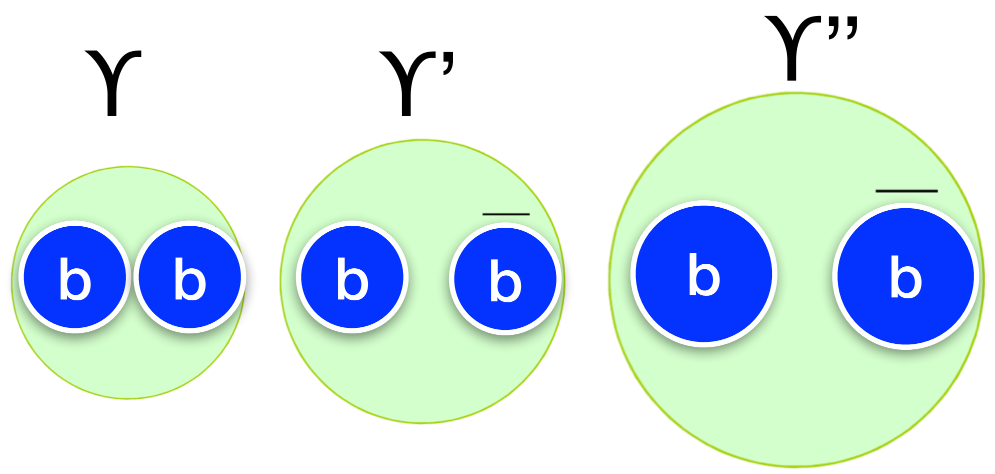
Heavy quarks interact and lose energy



Heavy quarks "flow" with the medium

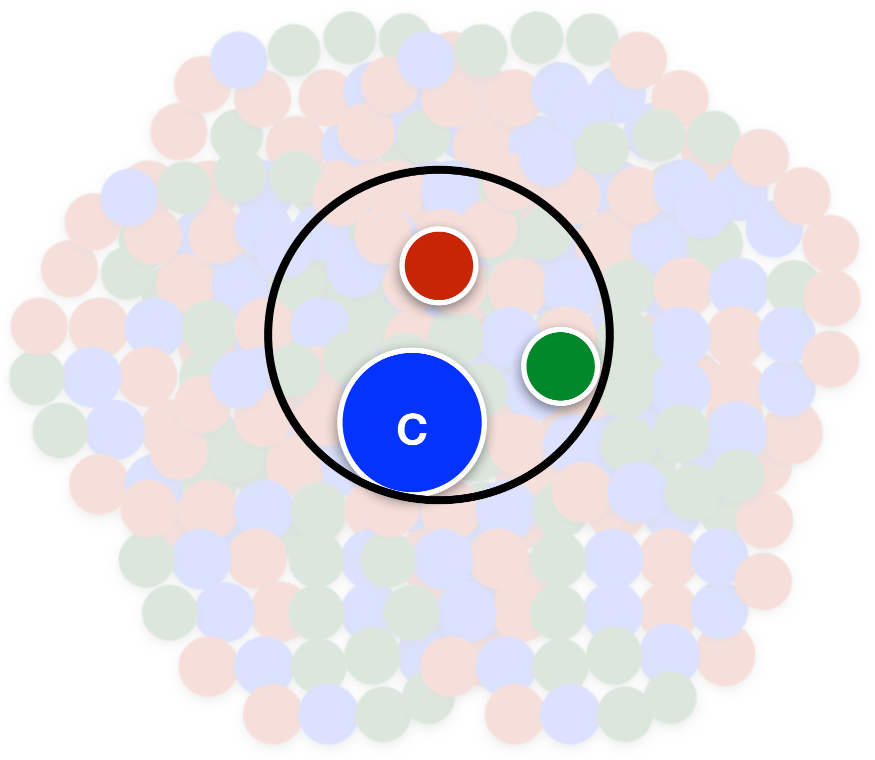


Bound states are affected by deconfined medium



→ different suppression for different binding energies

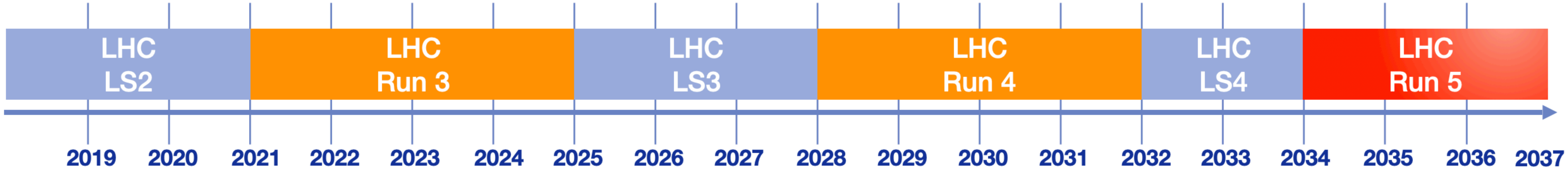
HF-hadron production modified at high densities



→ E.g. increased Λ_c/D^0 ratio

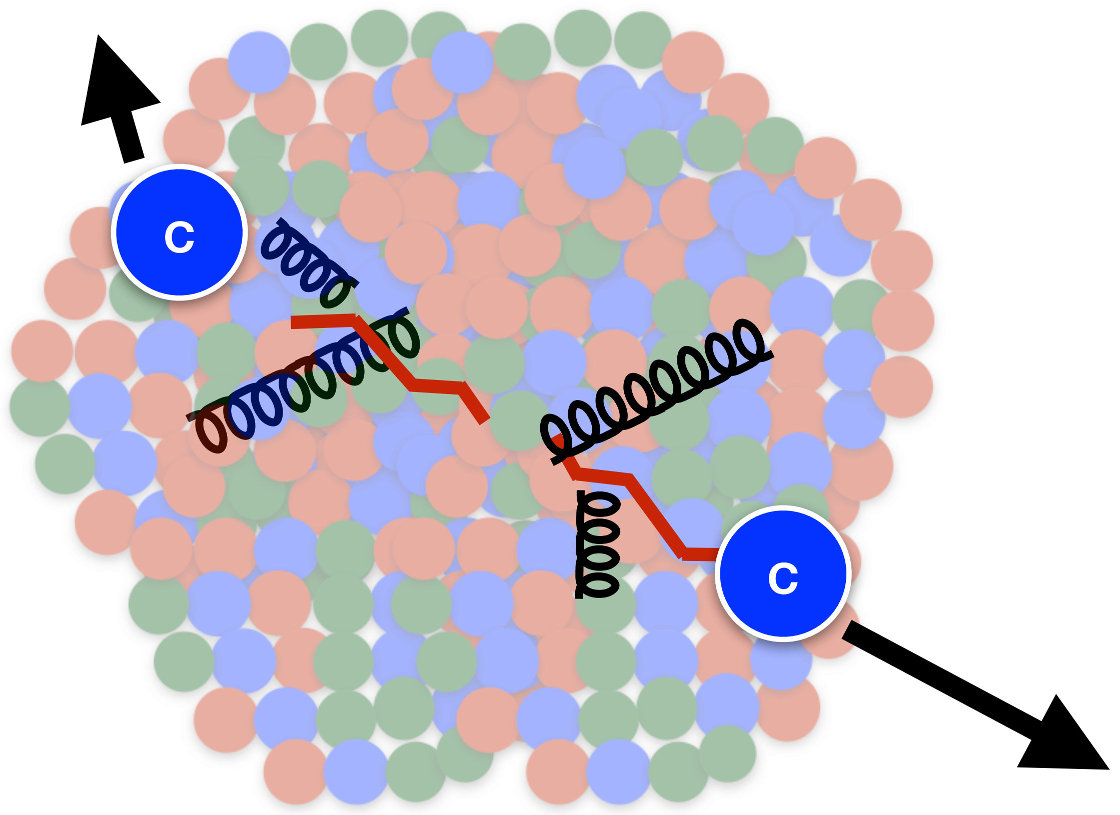
With Run 3 and 4 experimental campaigns:

- medium effects and hadrochemistry of single-charm observables
- characterization of collective effects from small to large system



Heavy-flavour physics with ALICE 3

Heavy quarks interact and lose energy



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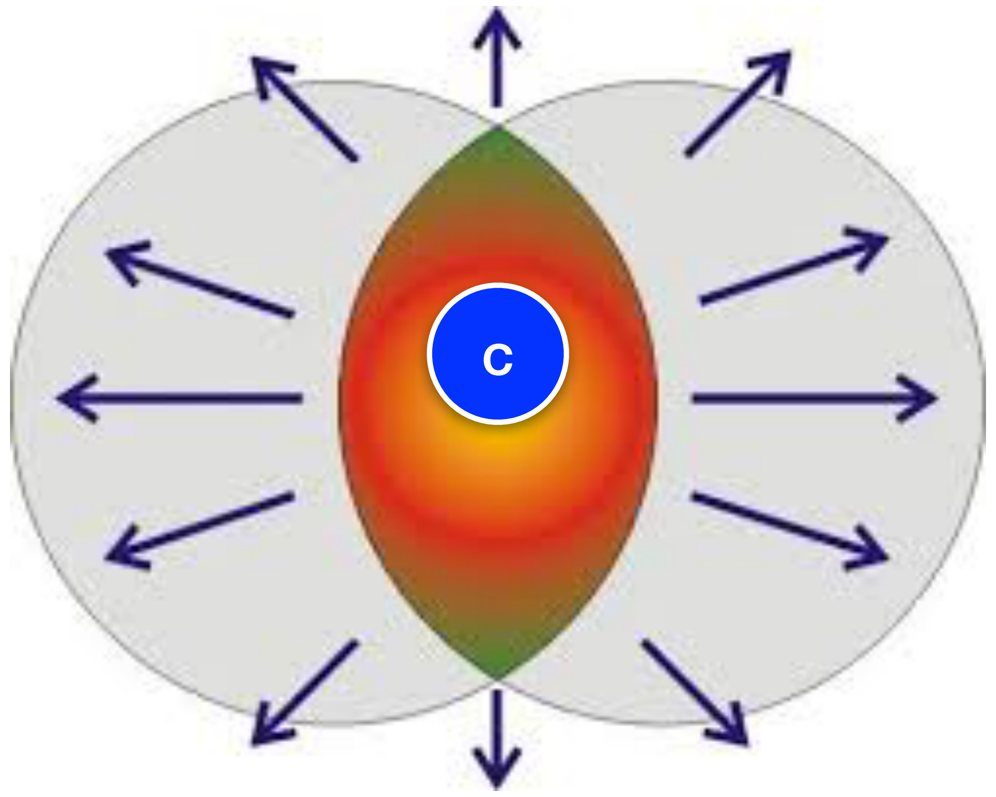

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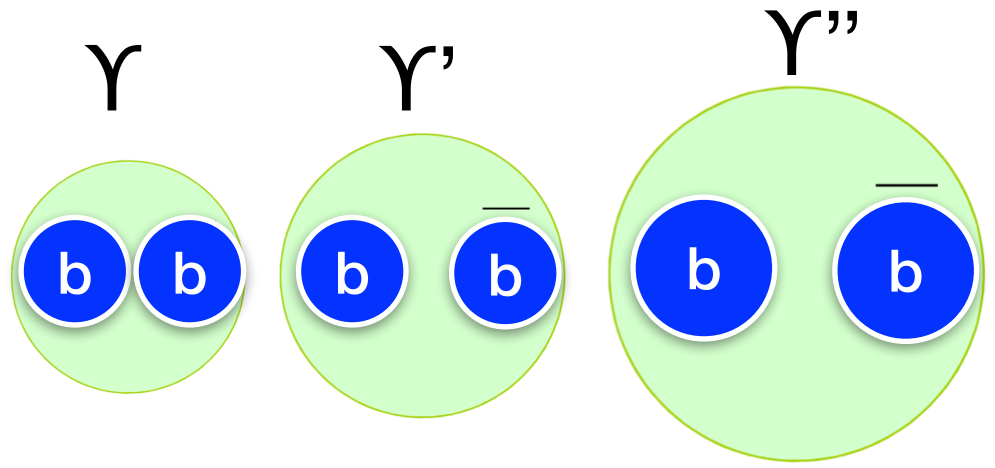
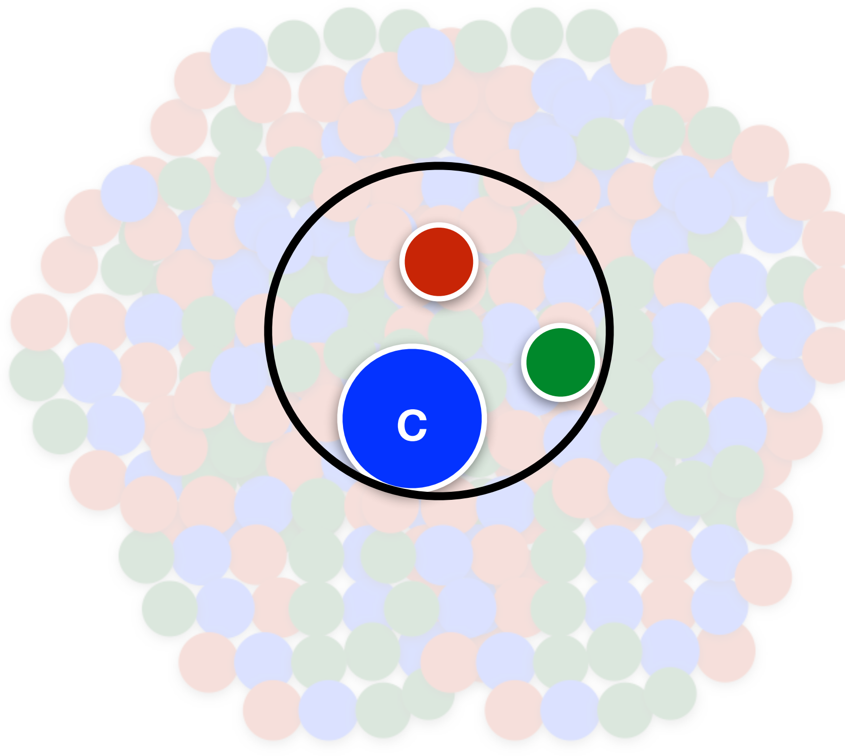


→ different suppression for different binding energies

HF-hadron production modified at high densities



→ E.g. increased Λ_c/D^0 ratio

Physics goal of ALICE 3: identify and characterize the common microscopic dynamics underlying all of these phenomena

New constraints of hadronization mechanisms in the QGP with multi-charmed hadrons and HF-jets

Microscopic description of heavy-quark interaction and medium structure with high accuracy charm/beauty hadron measurements and HF correlations

Complete description of bound states in the QGP with additional quarkonia states and exotic hadrons

Time-evolution and chiral-symmetry restoration

Understand time evolution and mechanisms of chiral symmetry restoration

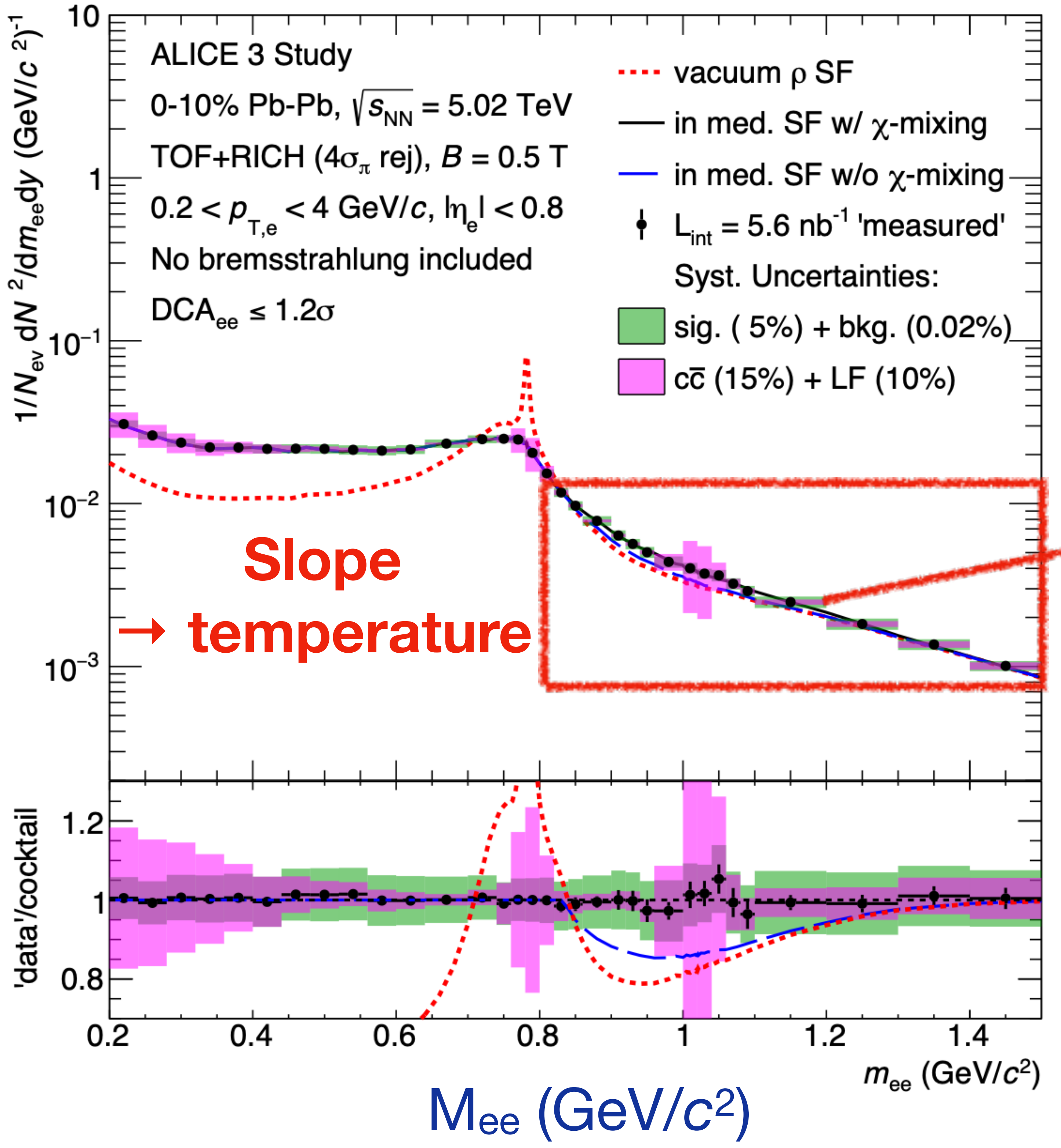
→ high-precision measurements of dileptons, also multi-differentially

→ further reduced material; excellent heavy-flavour rejection

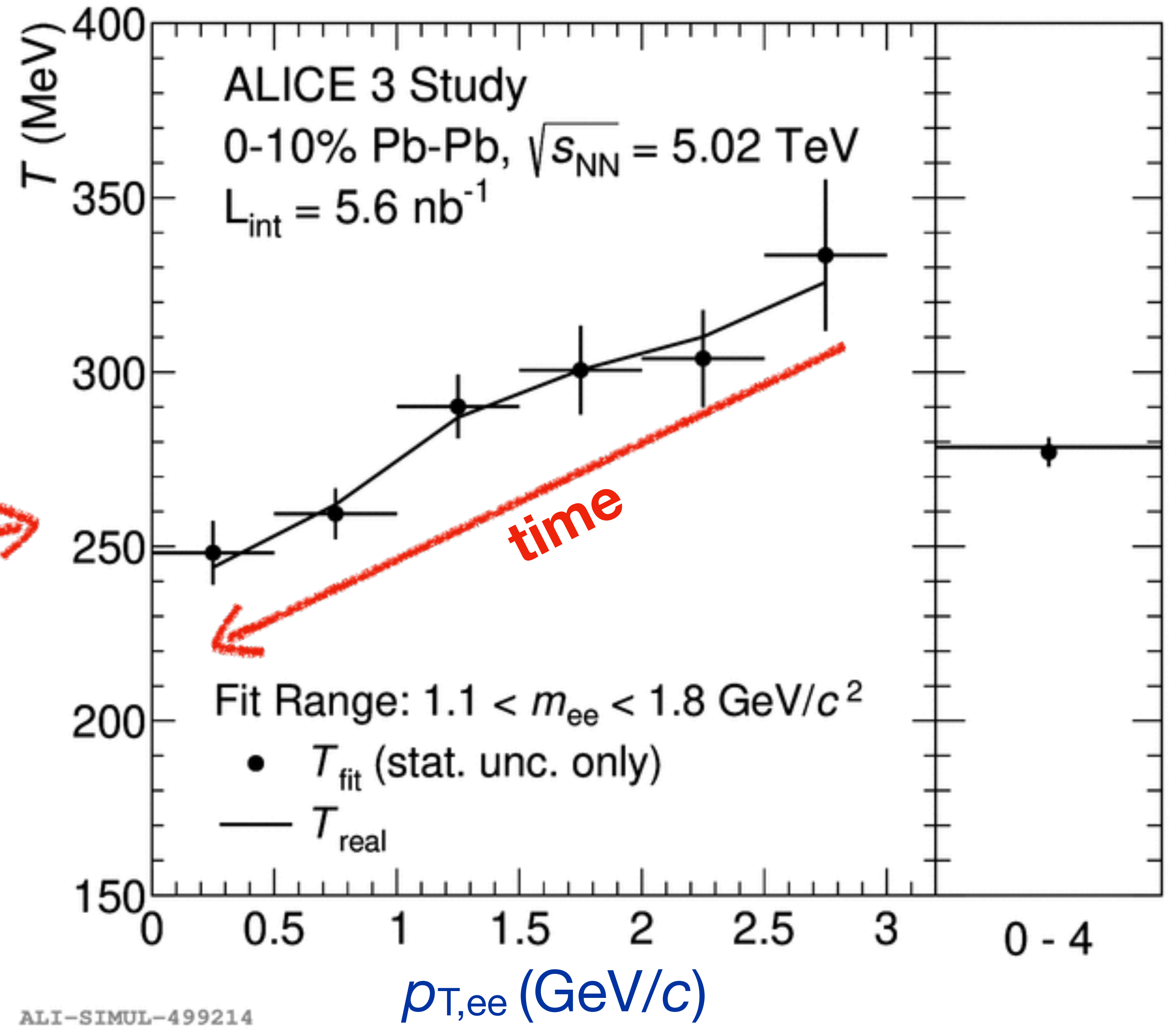
[CERN-LPCC-2018-07]

Run 5 & 6

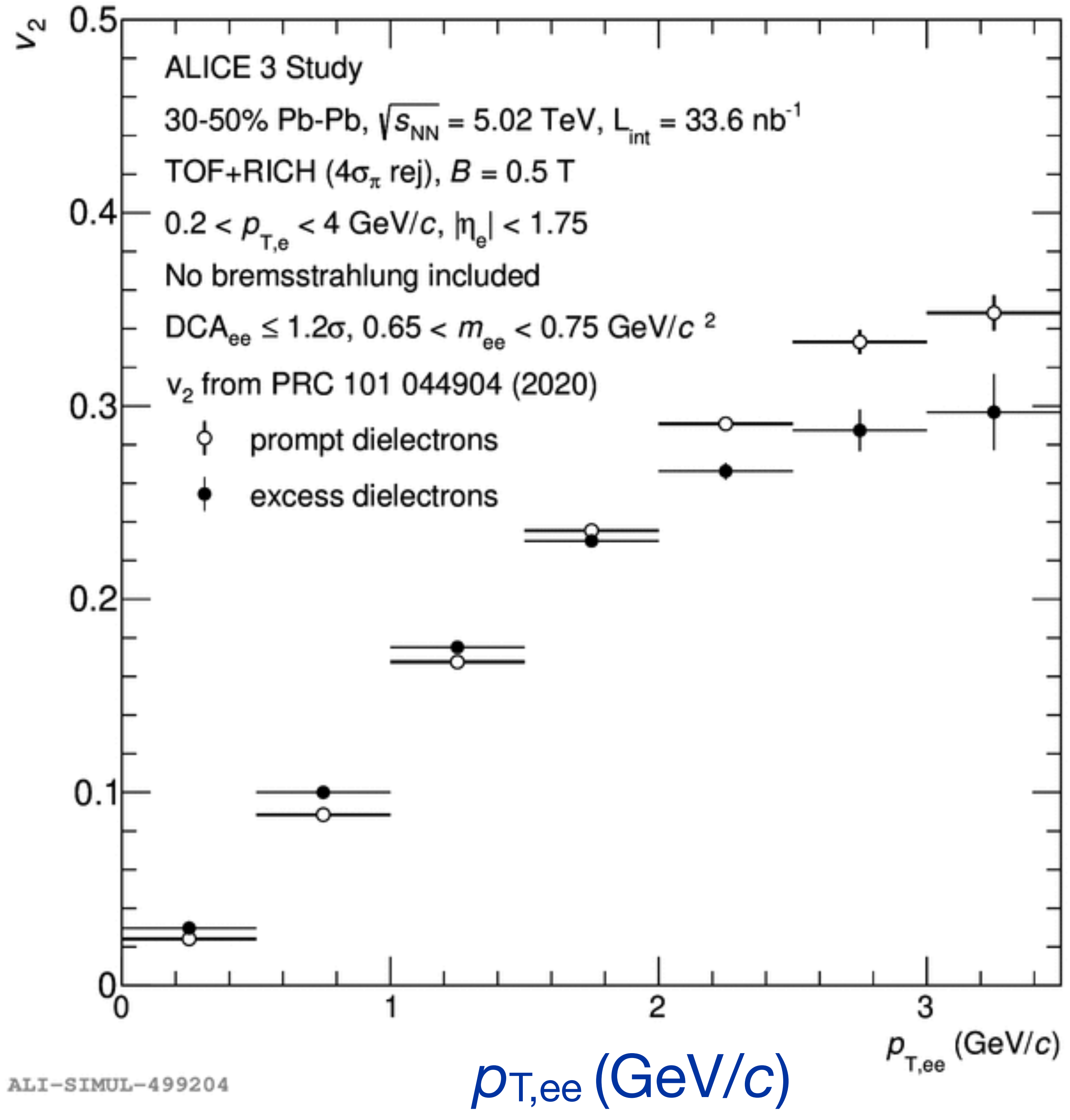
Invariant mass spectrum of dielectrons



***T*($p_{T,ee}$)**
→ control on emission time

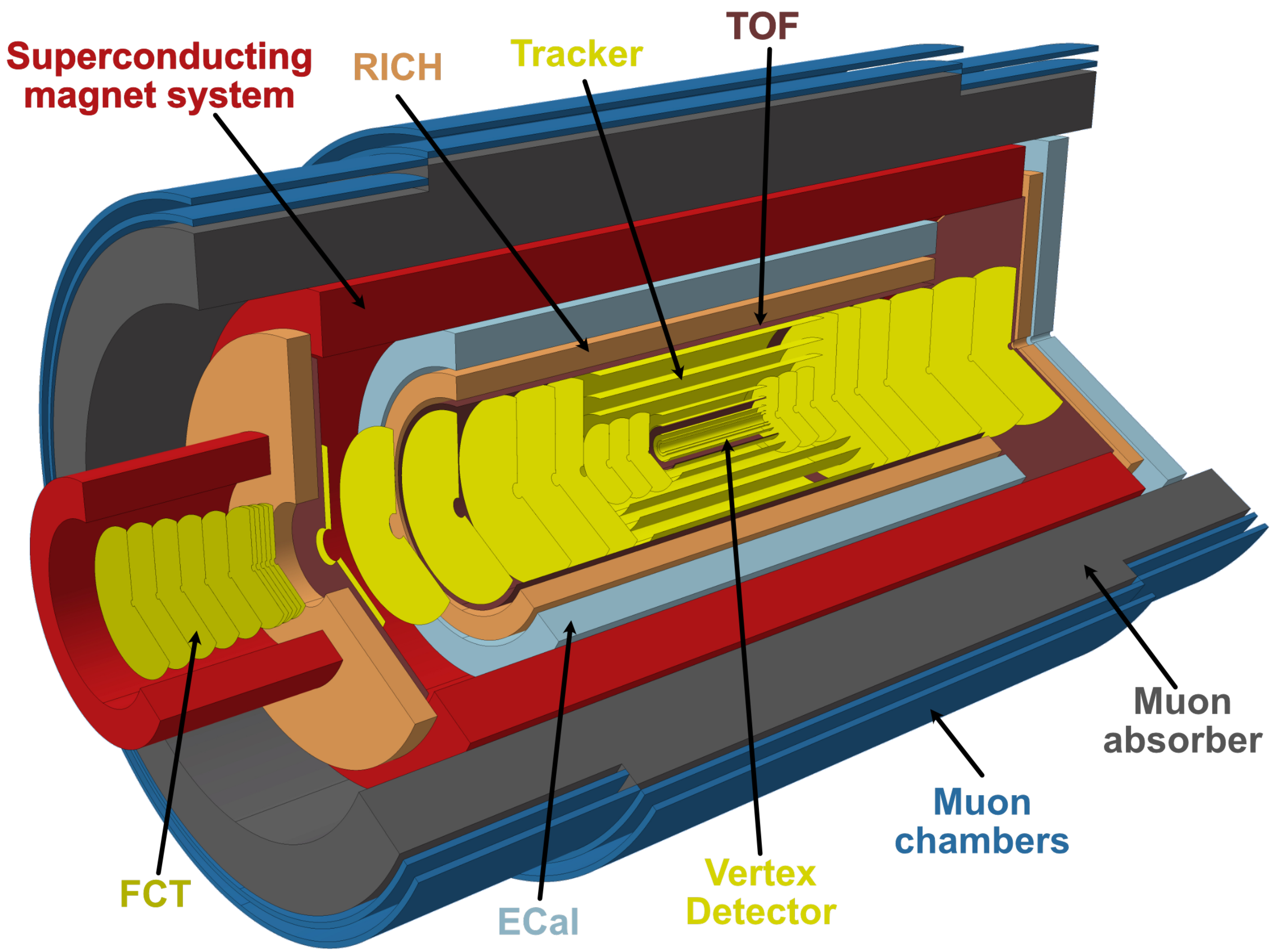


Dilepton v₂
→ temporal emission profile



ALICE 3 for heavy-ions in the '30

ALICE 3: A high-rate, high-resolution, large coverage **(|η|<4)** heavy-ion experiment for **Run 5 and 6**



Superconductive 2T solenoid:
→ flat p_T resolution over the entire acceptance

Run 5 and 6 with ALICE 3:
- 35 nb^{-1} of PbPb (or ArAr/KrKr) minimum bias
- 18 fb^{-1} of pp minimum bias

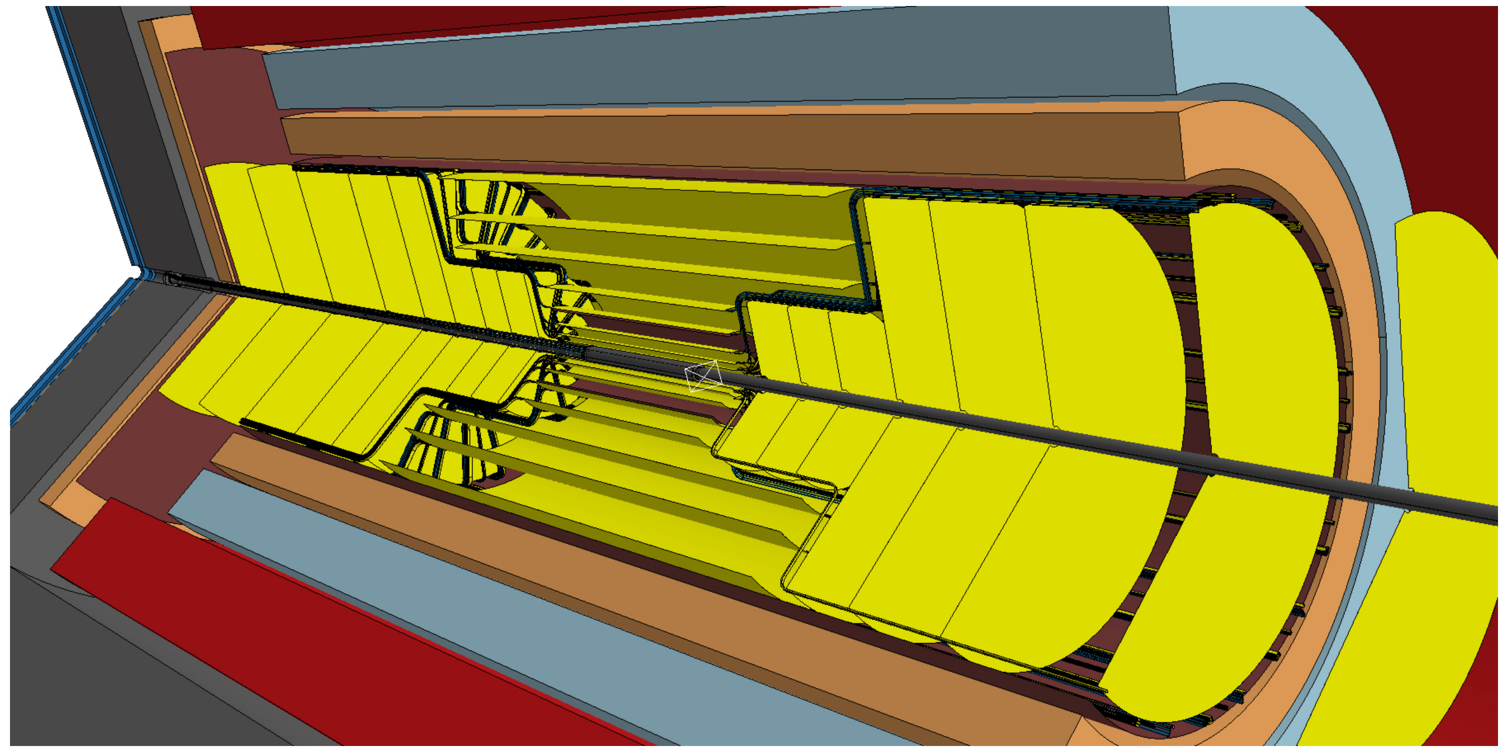
High resolution tracker + Time-of-Flight and RICH over 8 η units

"Low-p_T" muon detector:
→ accessing J/ψ down to pT=0

Calorimetry:
- Electromagnetic calorimeter (1.5 < η < 4)
- Design of HCAL calorimetry under development (sPHENIX)

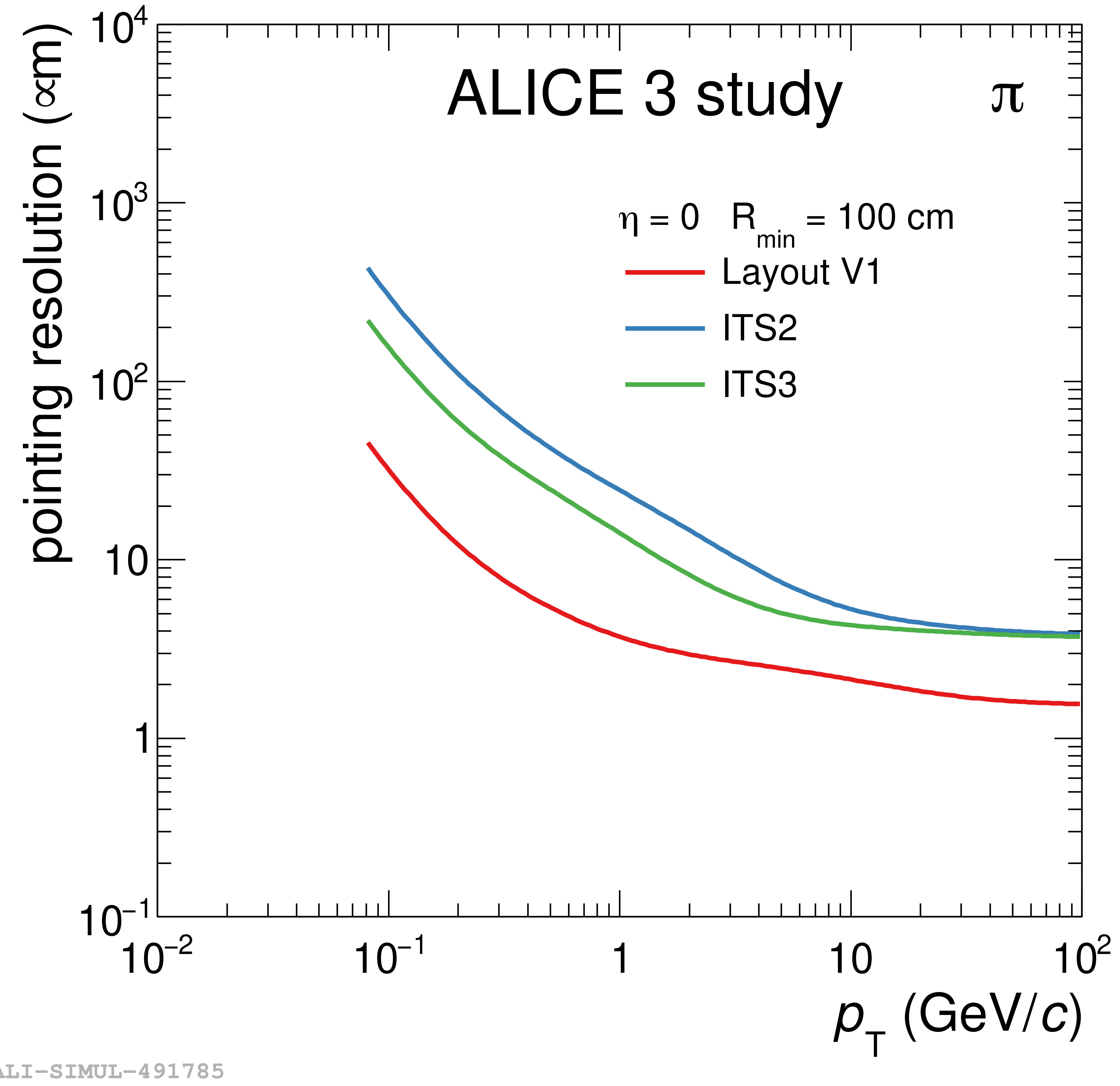
ALICE 3 tracker

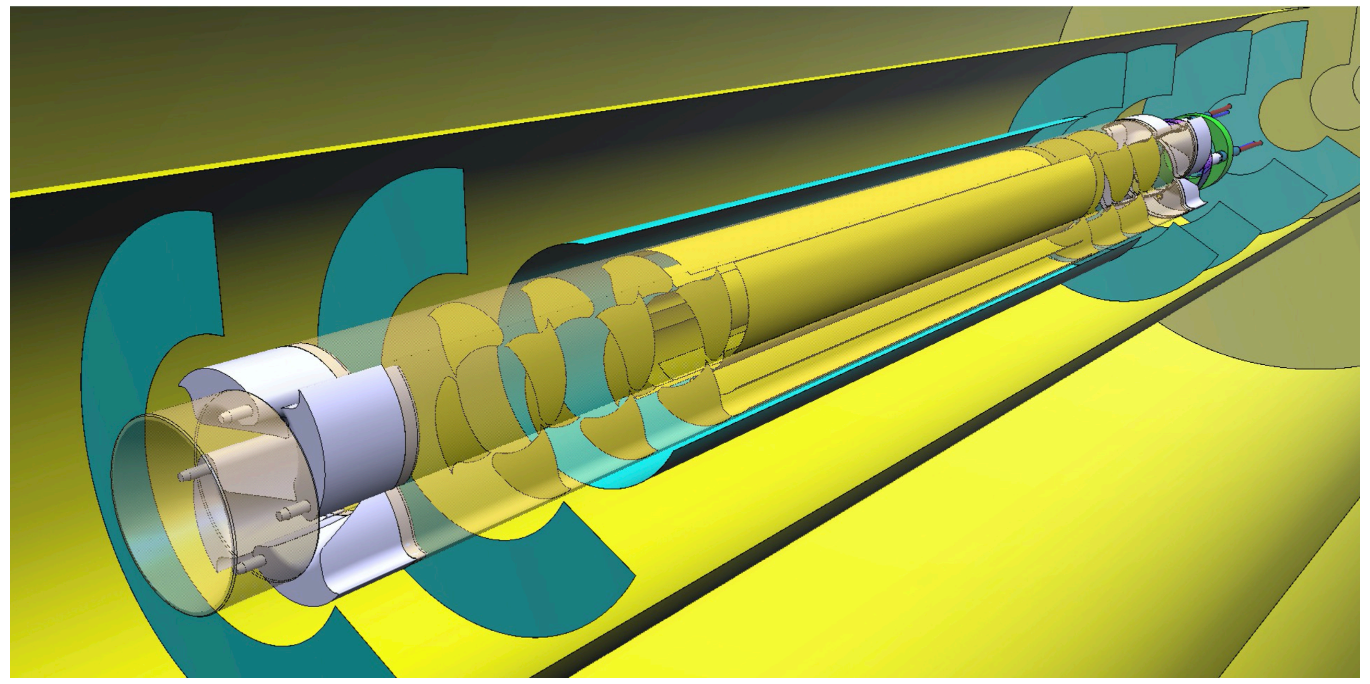
MAPS: ALICE-PUBLIC-2018-013
ITS3 LoI. CERN-LHCC-2019-018



Outer tracker layers |η| < 4.0:

- MAPS sensors
- $X/X_0 \sim 1\%$ per layer





Inner layers (E.g. IRIS):

- based on large, bent MAPS sensors, $X/X_0 \sim 0.1\%$ per layer
- in-secondary vacuum
- first layer at R=0.5 cm

- **DCA resolution** ~ few µm at ~1 GeV
- Secondary vertex resolution ~ 3-4 µm at low p_T

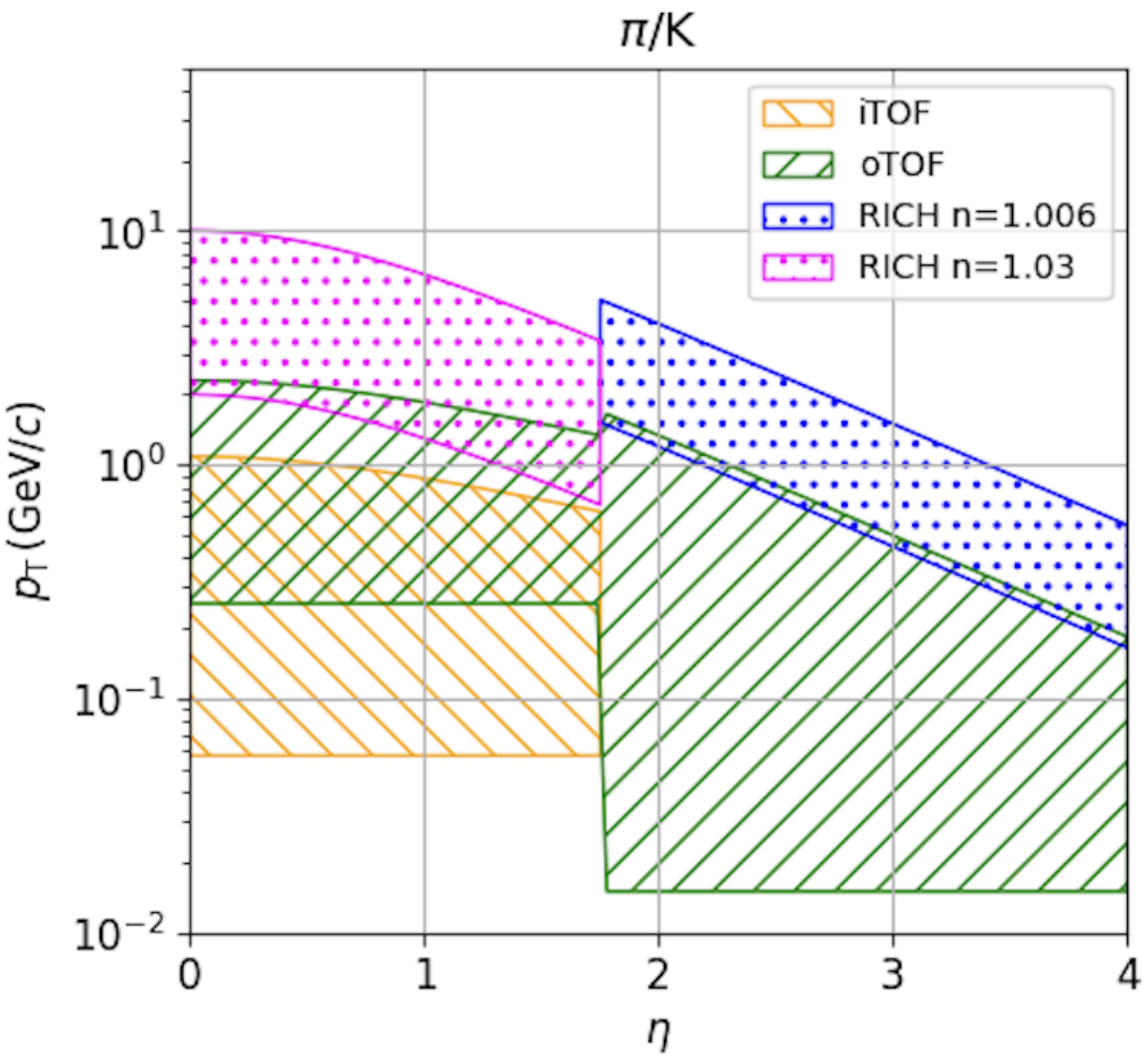
→ **critical for multiple-HF measurements**

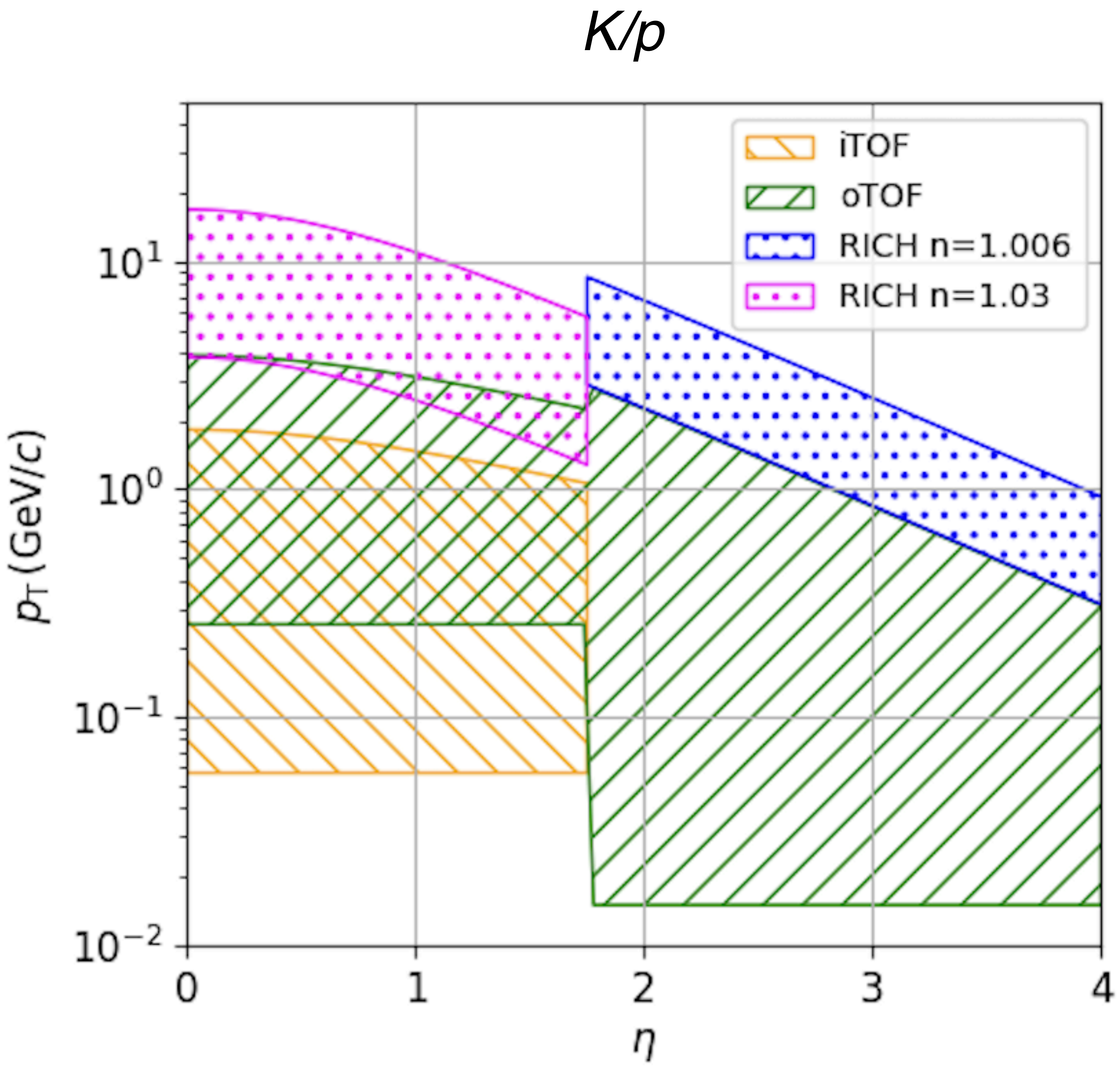
Retractable tracker concept (IRIS)

Hadron PID capabilities

PID performed with TOF and RICH detectors both in at central and forward rapidities:

→ continuous PID coverage from p_T<100 MeV until ~ 10 GeV for y=0



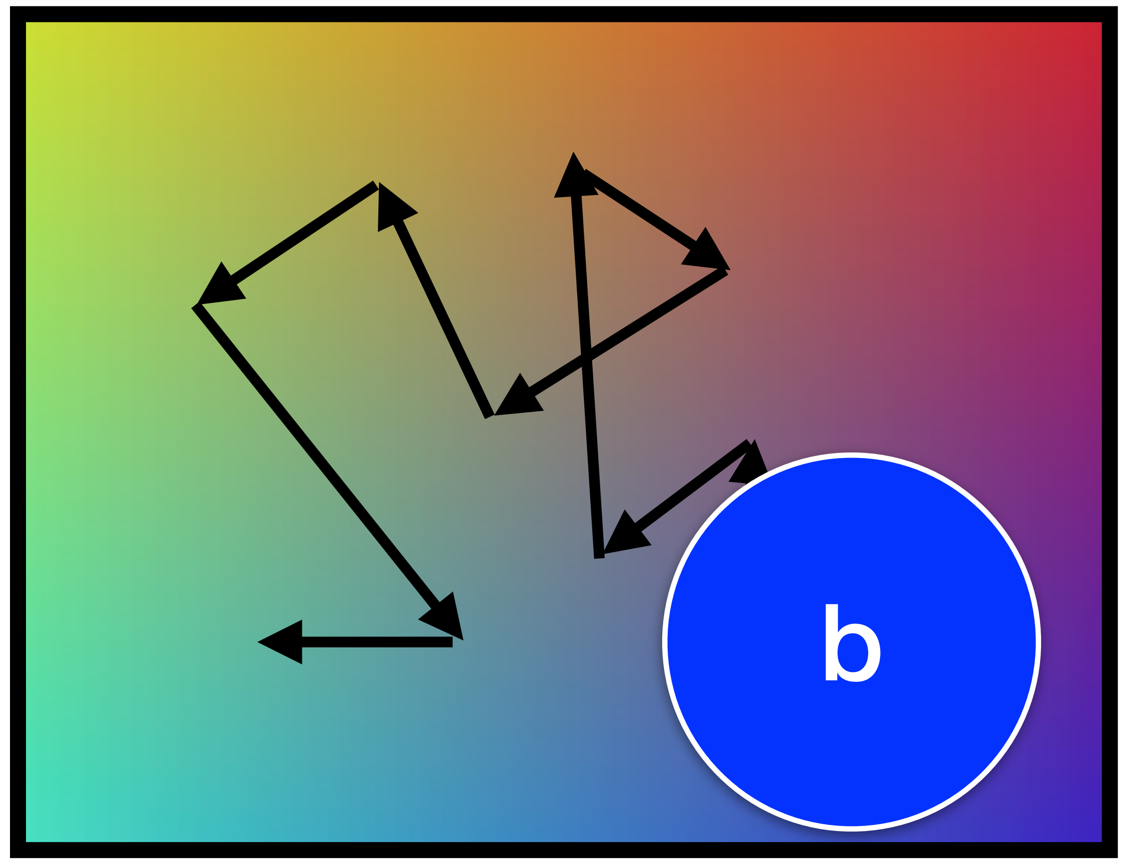


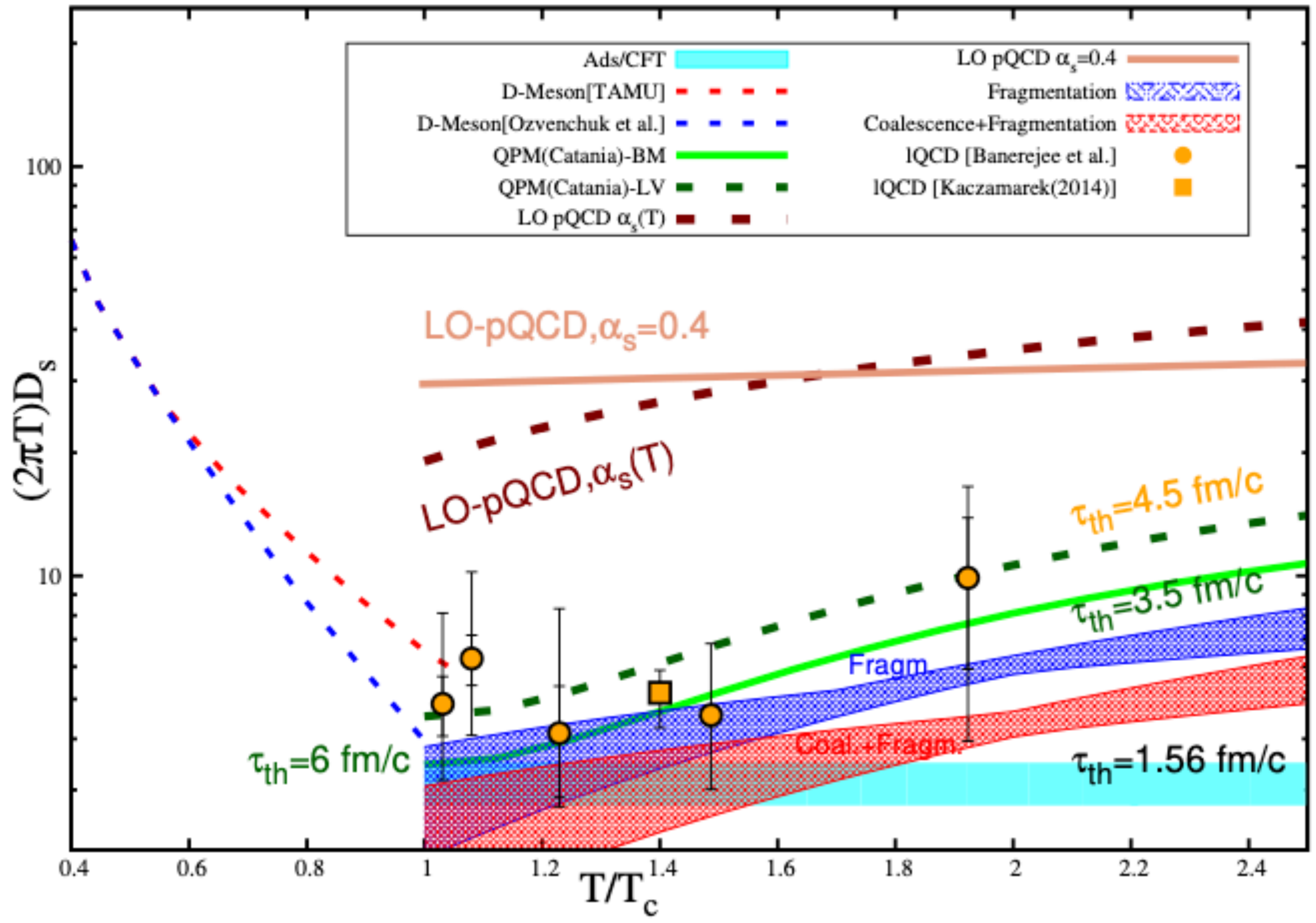
Heavy-quark
parton propagation

QCD structure of strongly-coupled QGP

charmed and beauty mesons down to $p_T = 0$ → strongly-interacting QGP

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)
R. Rapp et EMMI. NPA Vol. 97, 2018 21-86





- **$m_{c,b} > m_{u,d,s}$: "Brownian regime" in the QGP**

→ sensitive to the QGP diffusion and drag properties

→ constrain e.g. QGP spacial diffusion coefficient $D_s = D_s(T)$ in e.g. Bayesian fits

→ calculable from Lattice QCD, characterizes the structure of a strongly coupled QGP

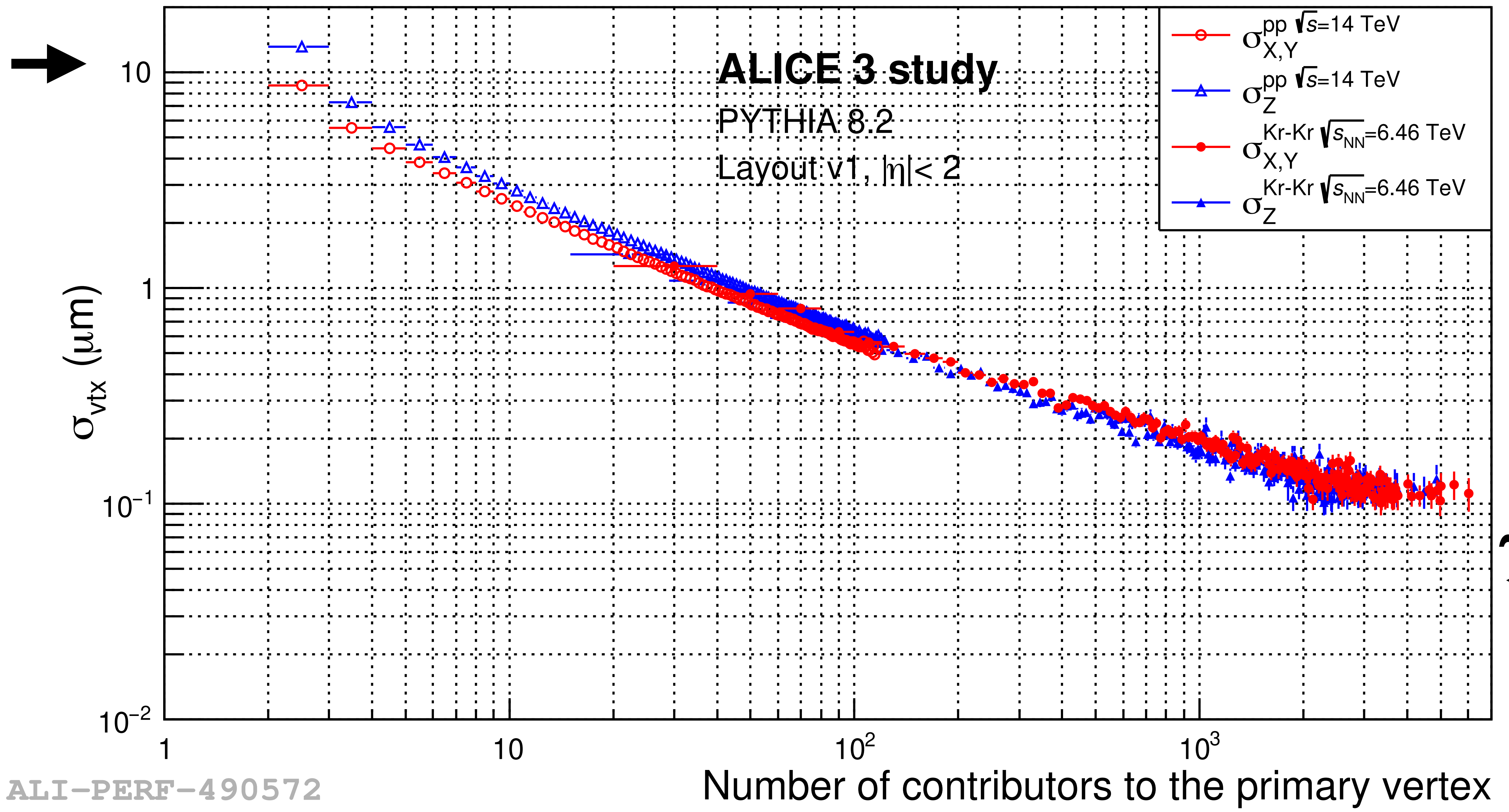
Beauty quarks have different interaction with the medium and different sensitivity to hadronization mechanisms:

- beauty less likely to thermalize, $\tau_{beauty} \sim 12$ fm/c ~ QGP lifetime ~ 3 τ_{charm}

Single-hadron measurements with **ALICE 3**

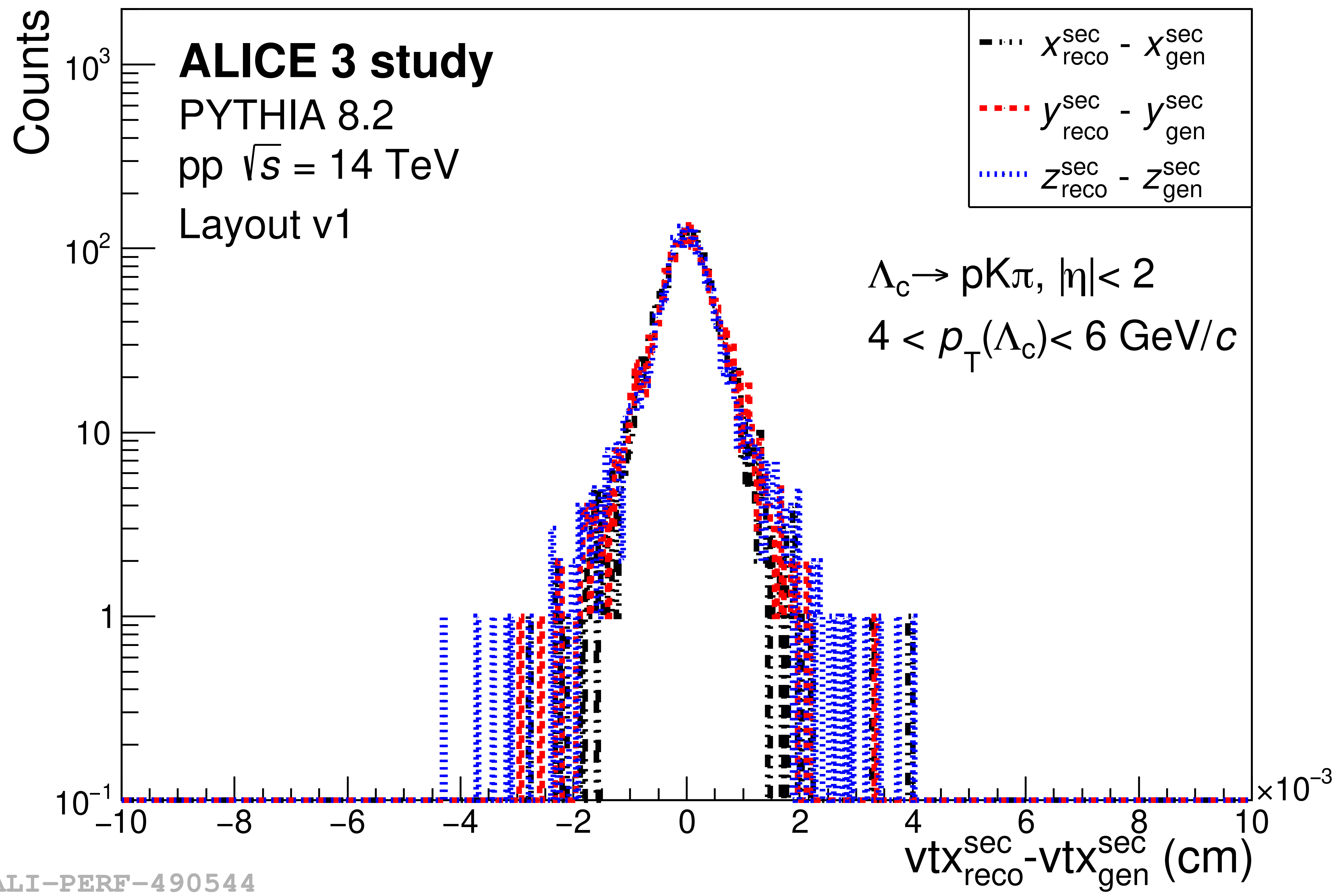
~ 10 μm

Primary vertex resolution in pp and KrKr



~ 0.1μm

Λc secondary vertex resolution



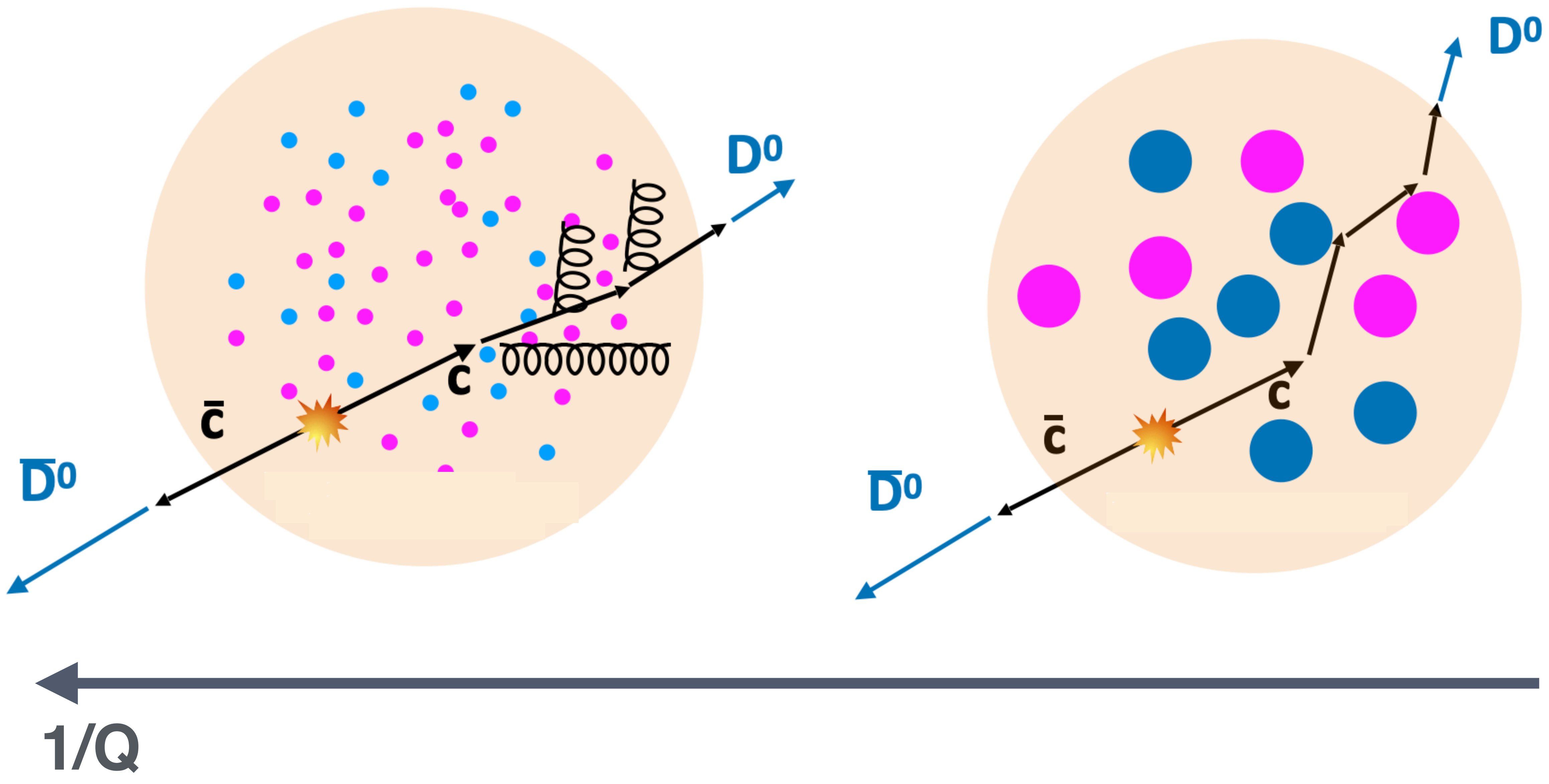
With ALICE3, high accuracy measurements of both charm and beauty mesons and baryons:

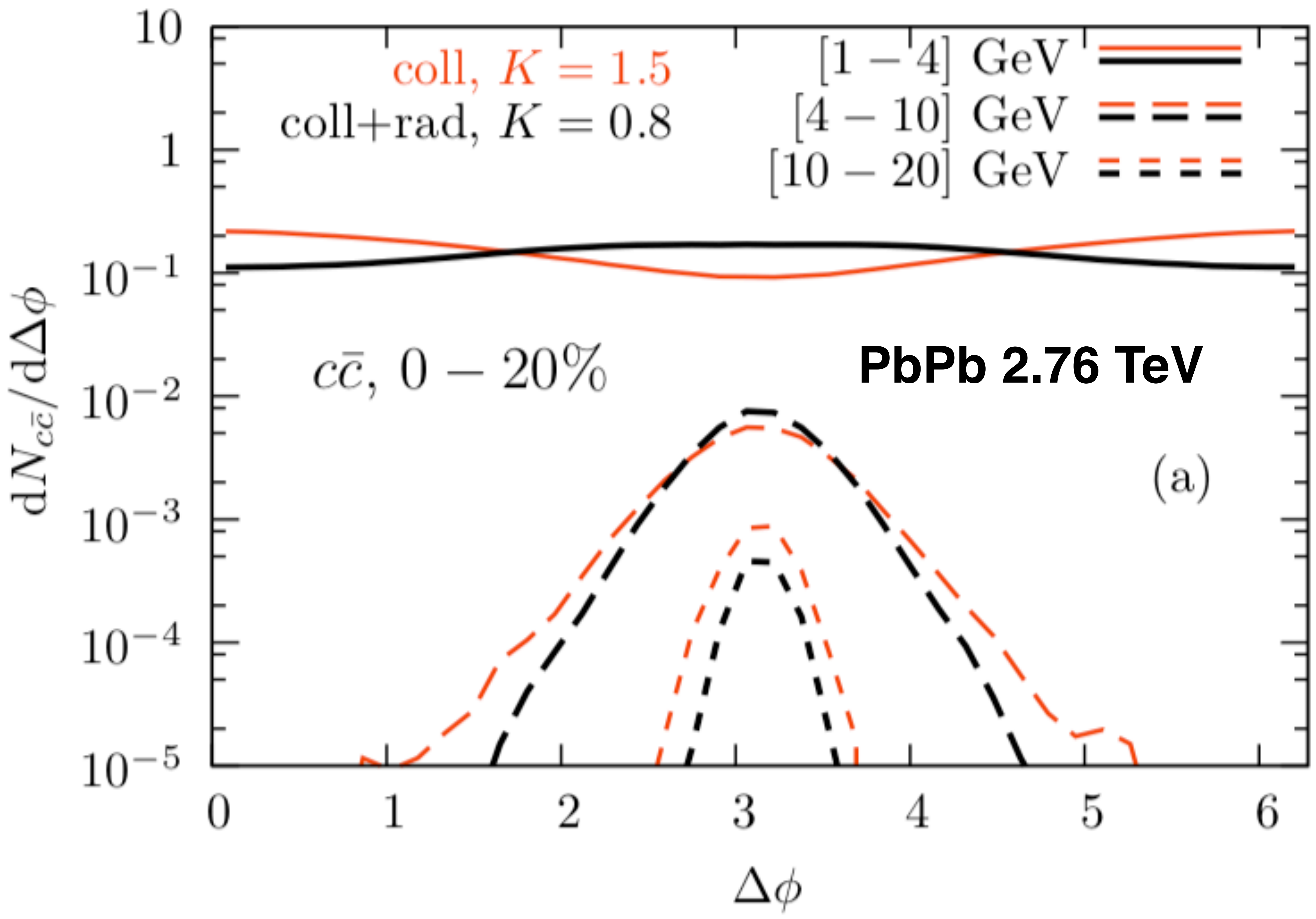
→ **"textbook" accuracy in extraction of medium coefficients**:
(better theoretical control of beauty quark diffusion in the QGP)

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

Heavy-flavor correlations

M. Nahrgang, et al. arXiv:1305.3823
S. Cao et al., Phys. Rev. C 92, 054909 (2015)
T. Stavreva et al., JHEP vol. 2013, 72 (2013)



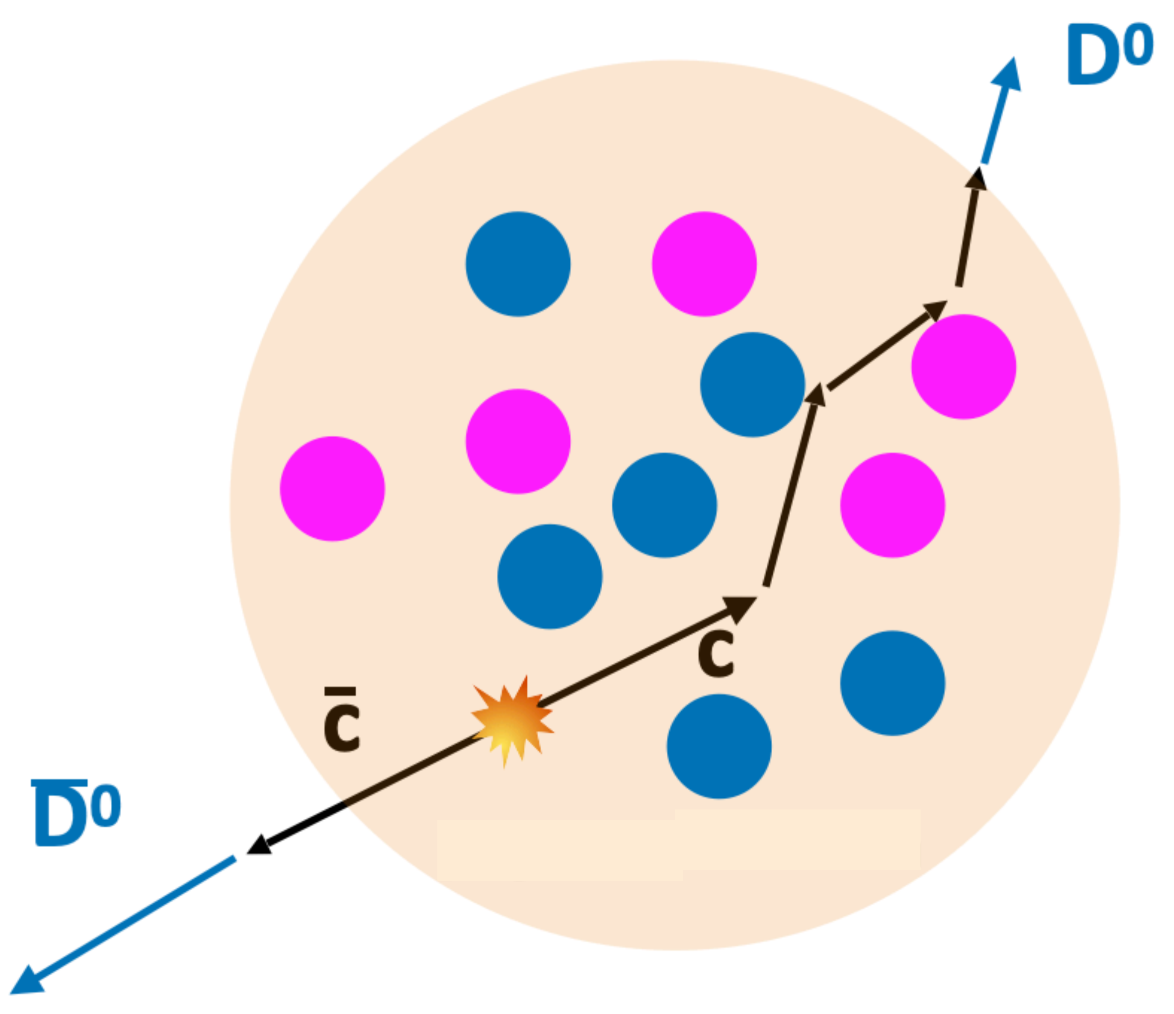


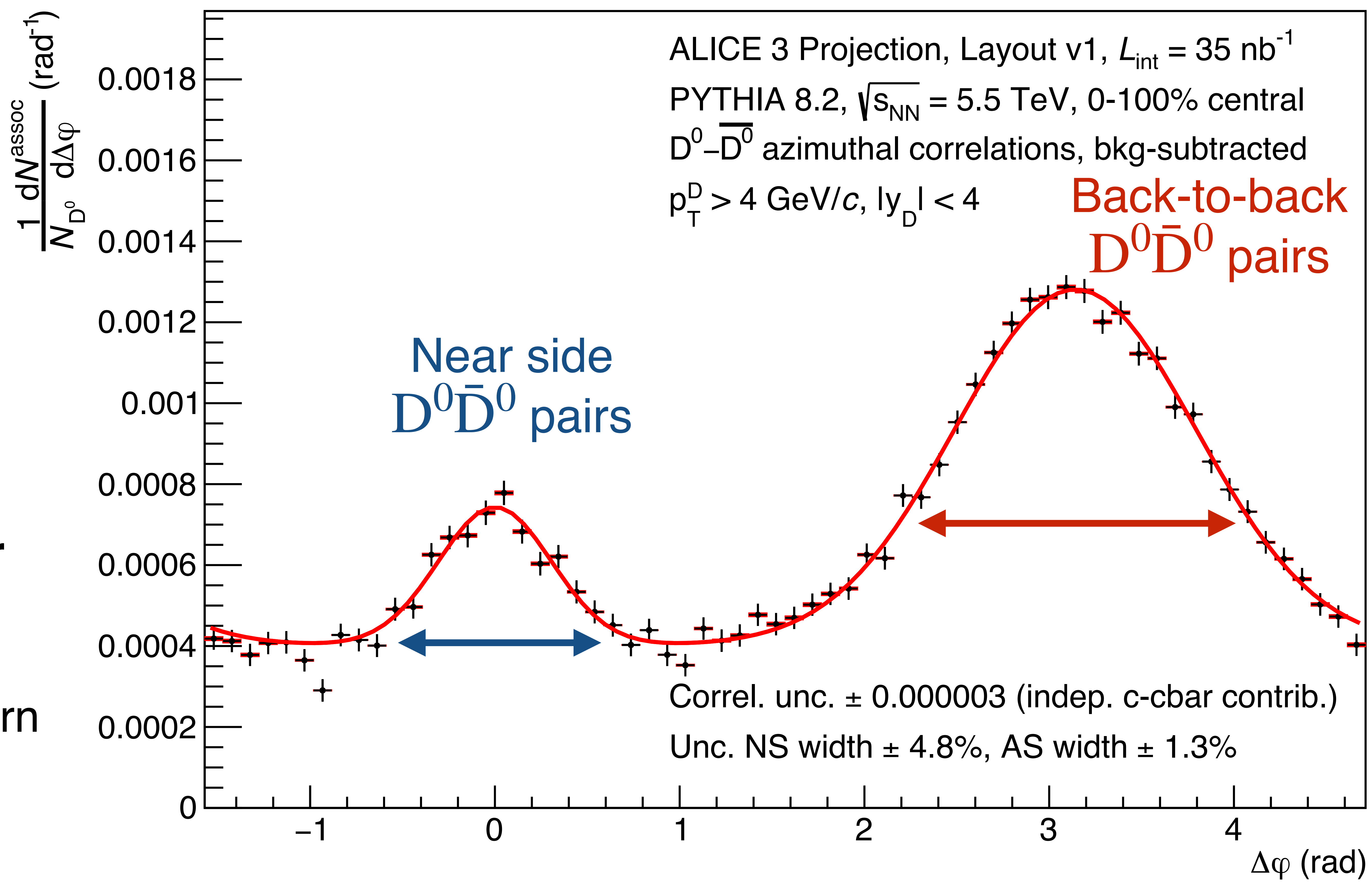
Δη-Δϕ deflection and p_T asymmetry of heavy-quark pairs:

- microscopic structure of QGP in different E_{loss} regimes
- **Decorrelation measures momentum diffusion**
  → degree of thermalization in the QGP

- Accurate secondary vertex reconstruction + hadron PID (~0.1 to few GeV)
  → need for very high signal purities
- **η-coverage and statistics**

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





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

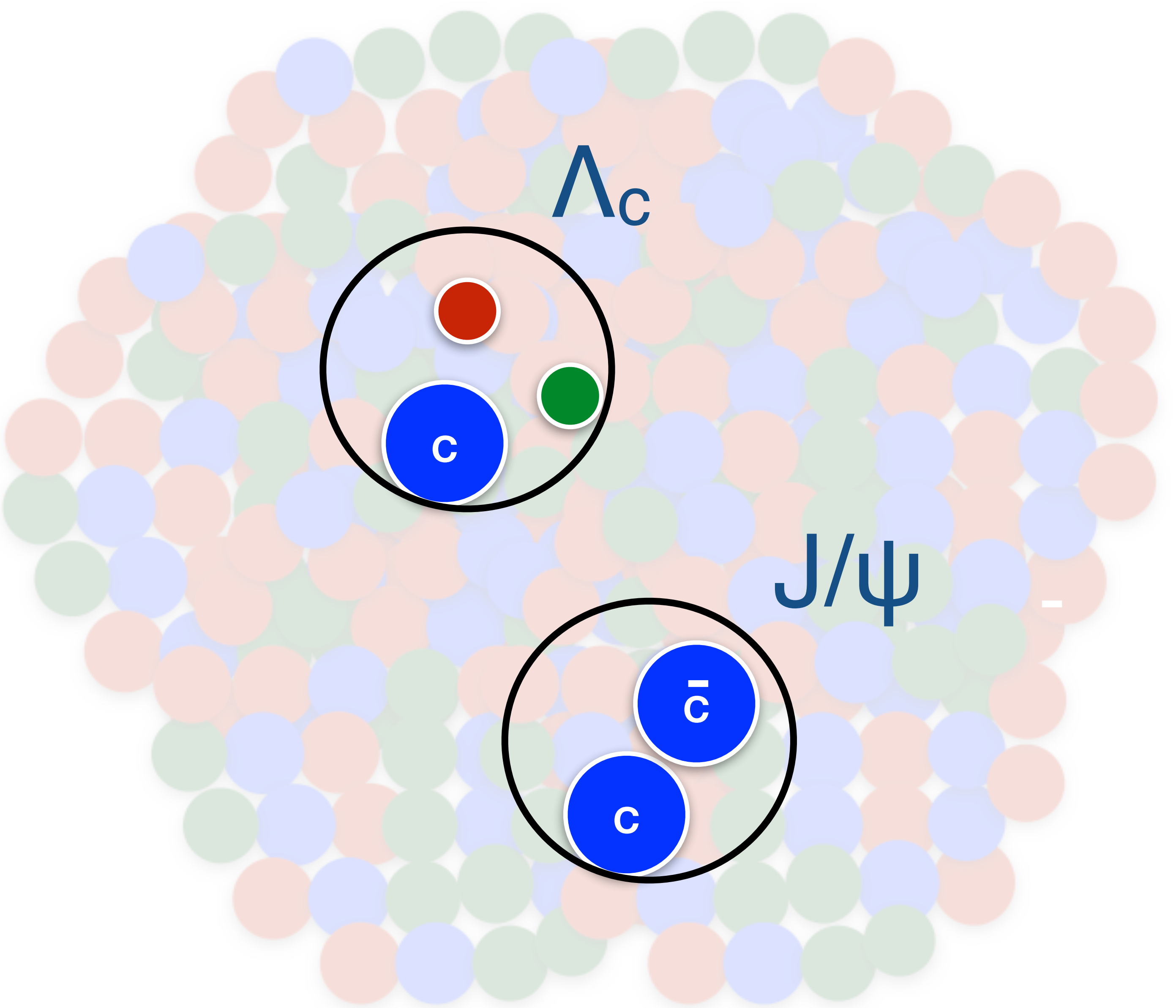
- High accuracy in measurement of the correlation pattern
→ unique sensitivity to broadening of $c\bar{c}$ pairs

ALICE 3 as the ideal experiment with multiple HF hadrons and correlations

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

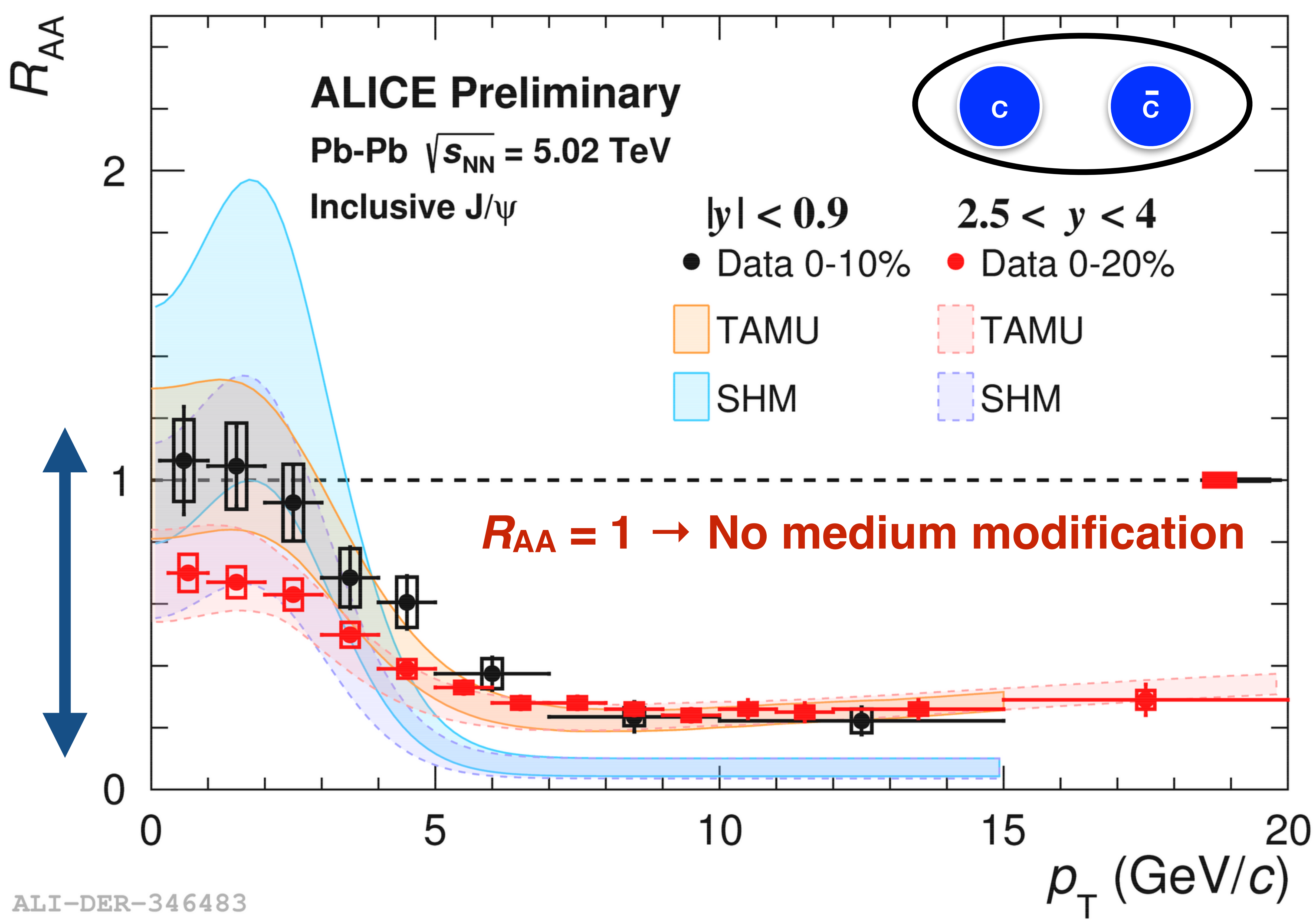
New probes for hadronization at high partonic densities

Heavy-flavor hadronization in heavy-ion collisions



Hadronization mechanisms beyond in-vacuum independent fragmentation:

→ charmed hadrons formed by combination of quarks from independent hard scatterings (described with statistical weights)



In Run 3 and 4:

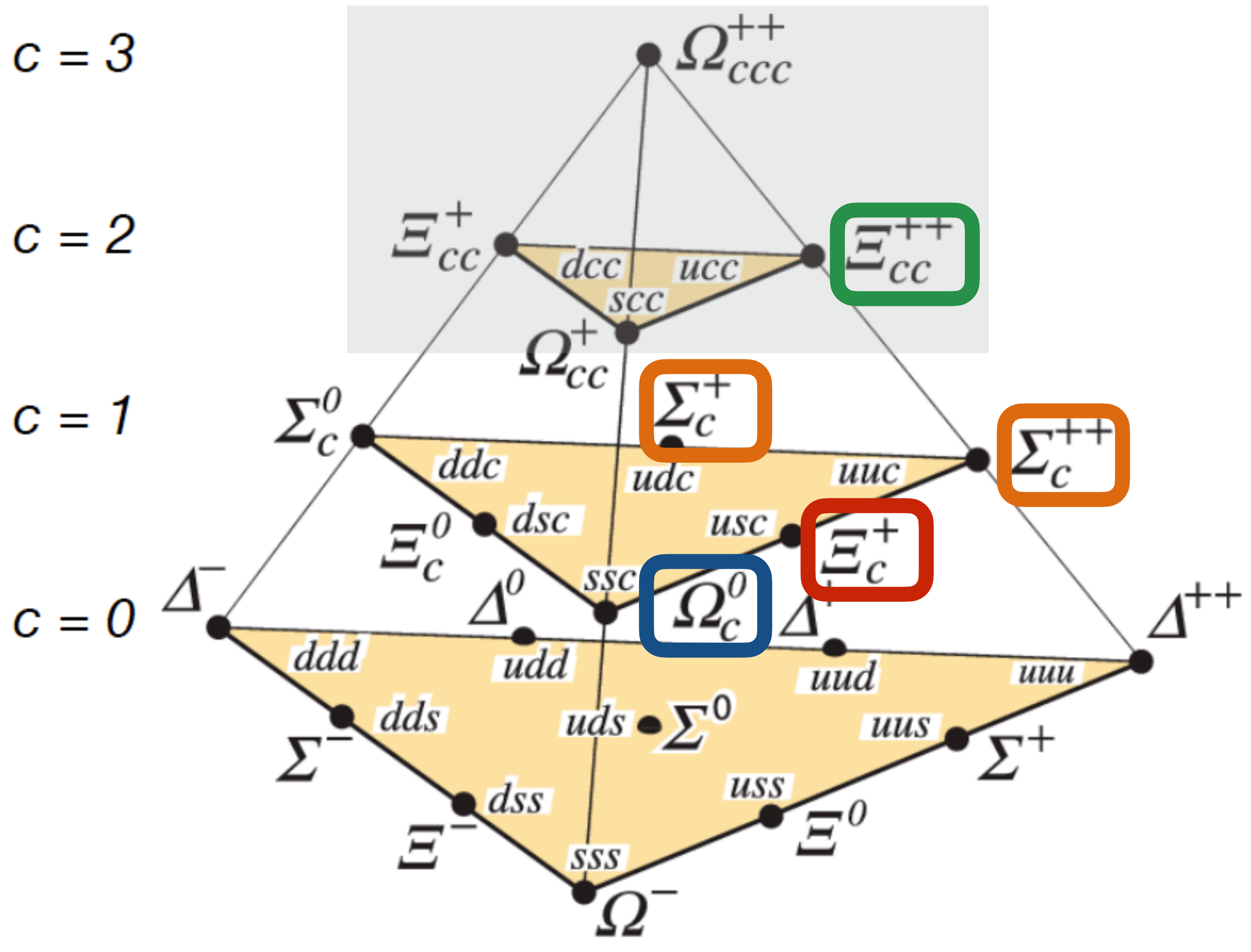
- extensive campaign to measure Λc, Ξc, Ωc in heavy-ion collisions

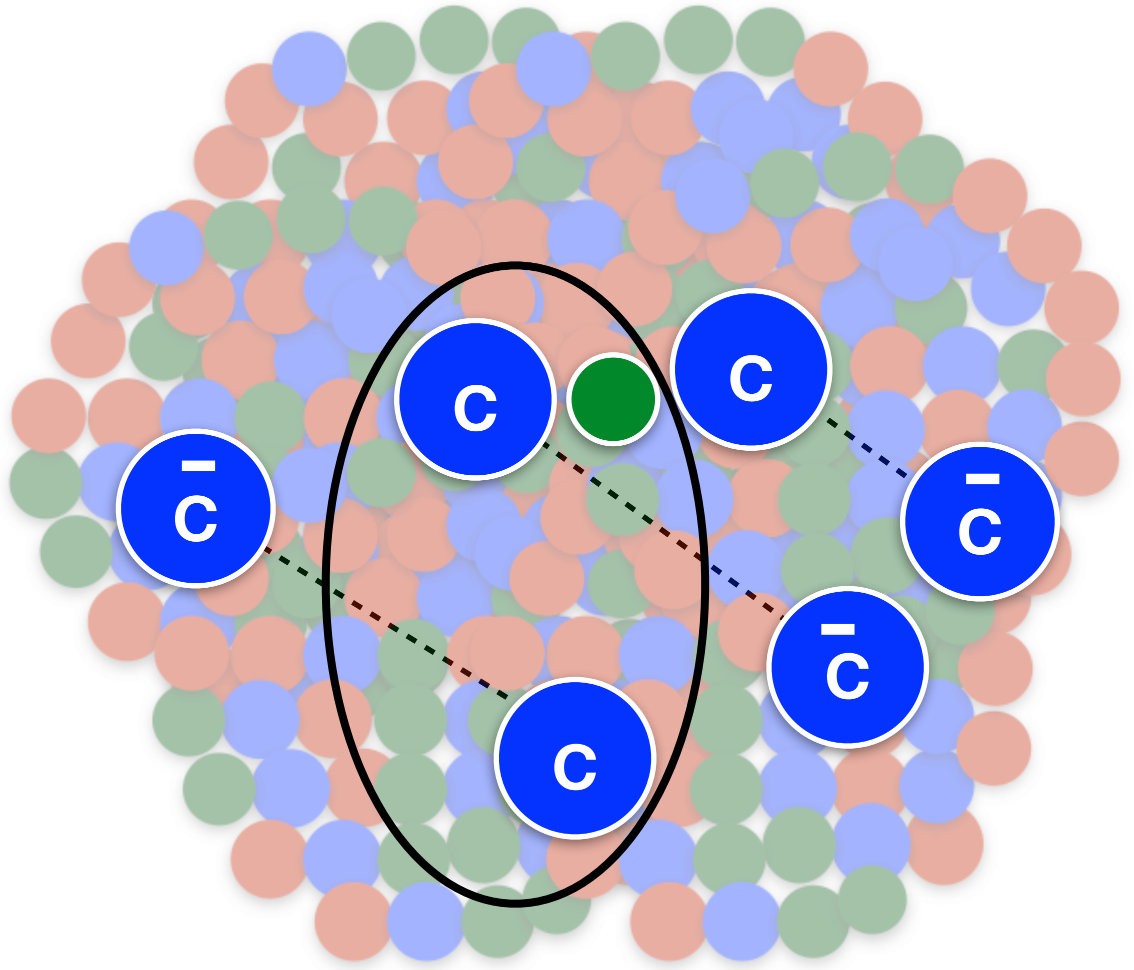
Multi-heavy flavor hadrons

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)

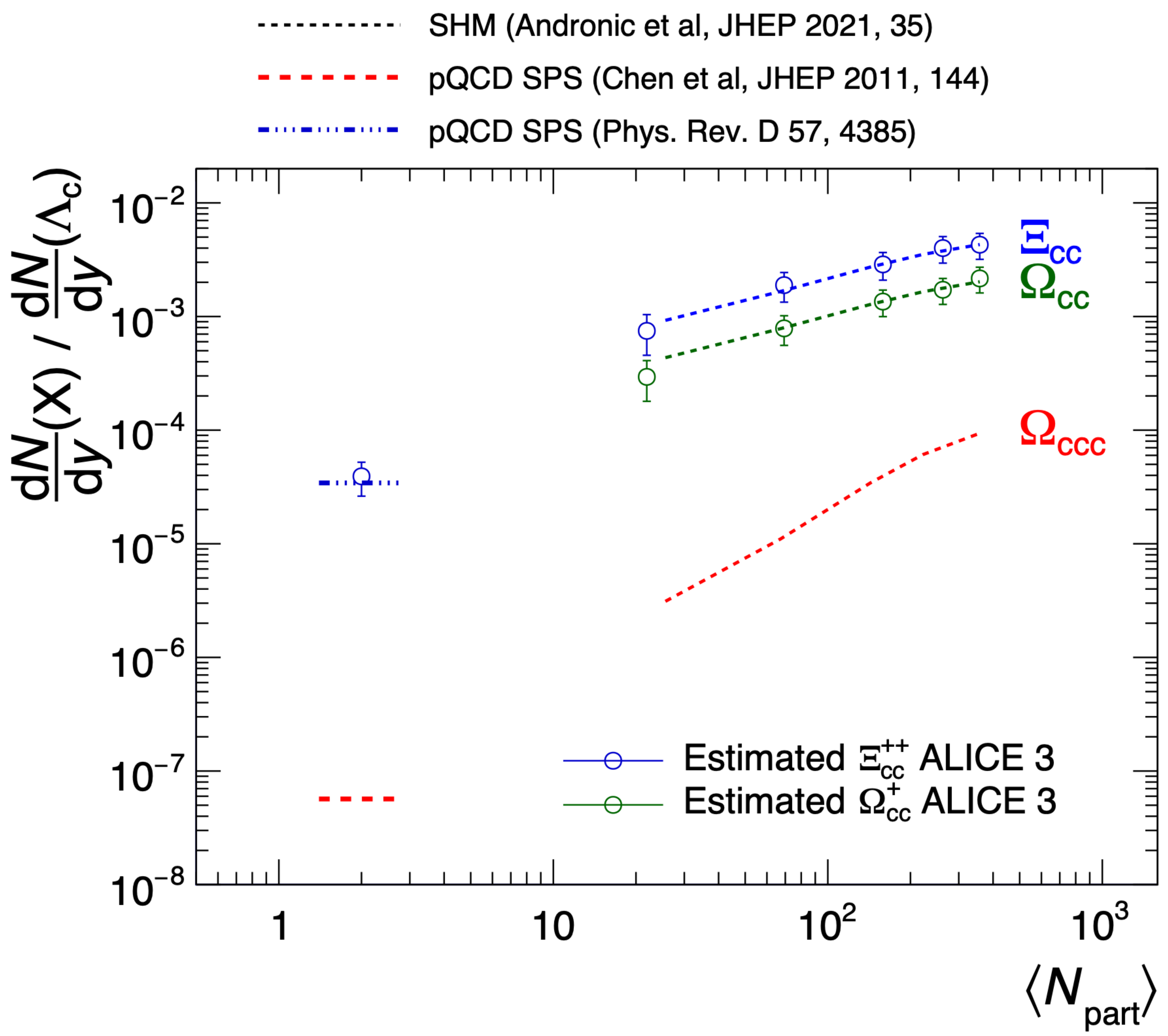
- Negligible same-scattering production
- **In presence of hadron production from uncorrelated charm quarks**
  → Large **enhancement (up to x100) w.r.t. pp predicted**

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





Ξ_{cc}, Ω_{cc}, B_c



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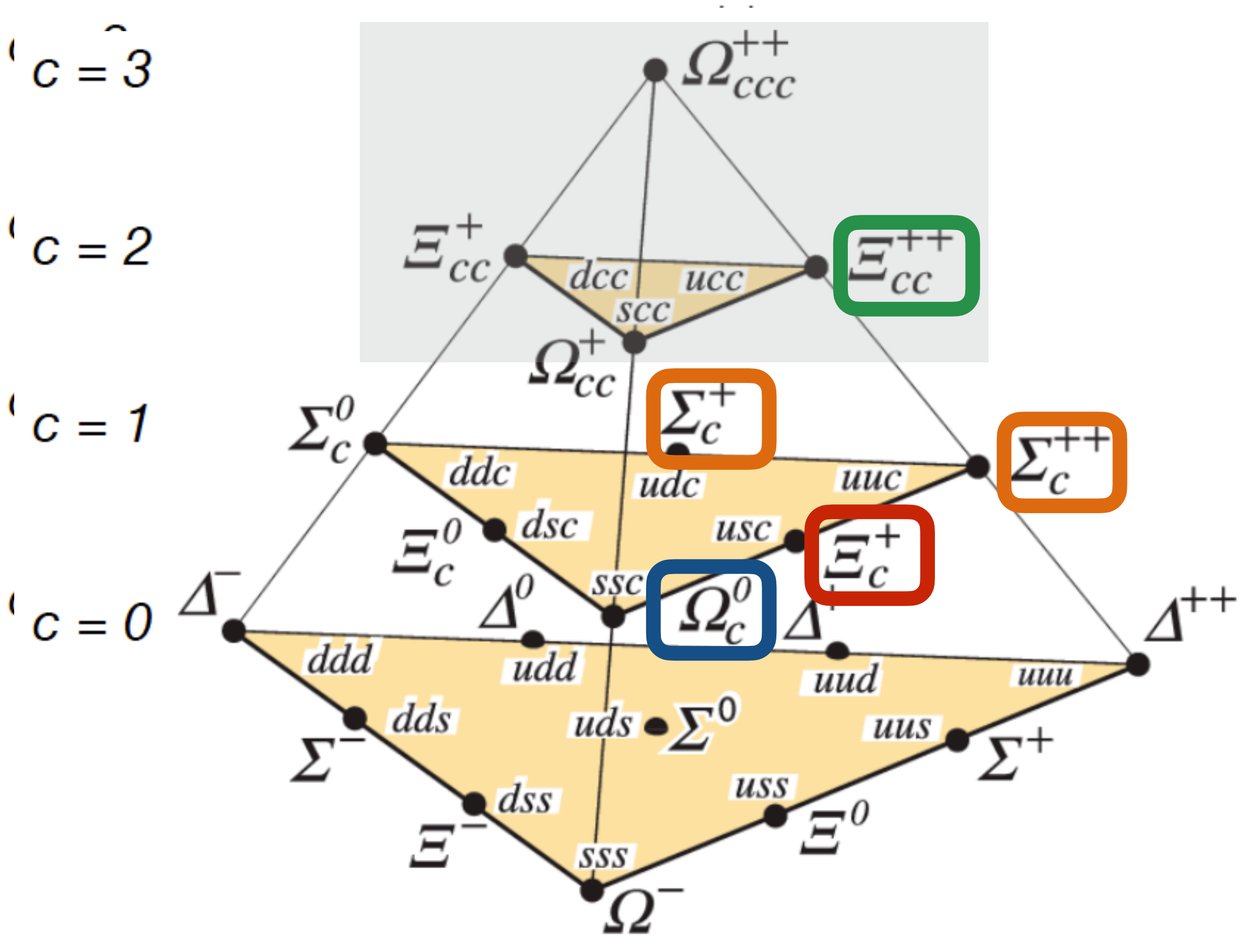
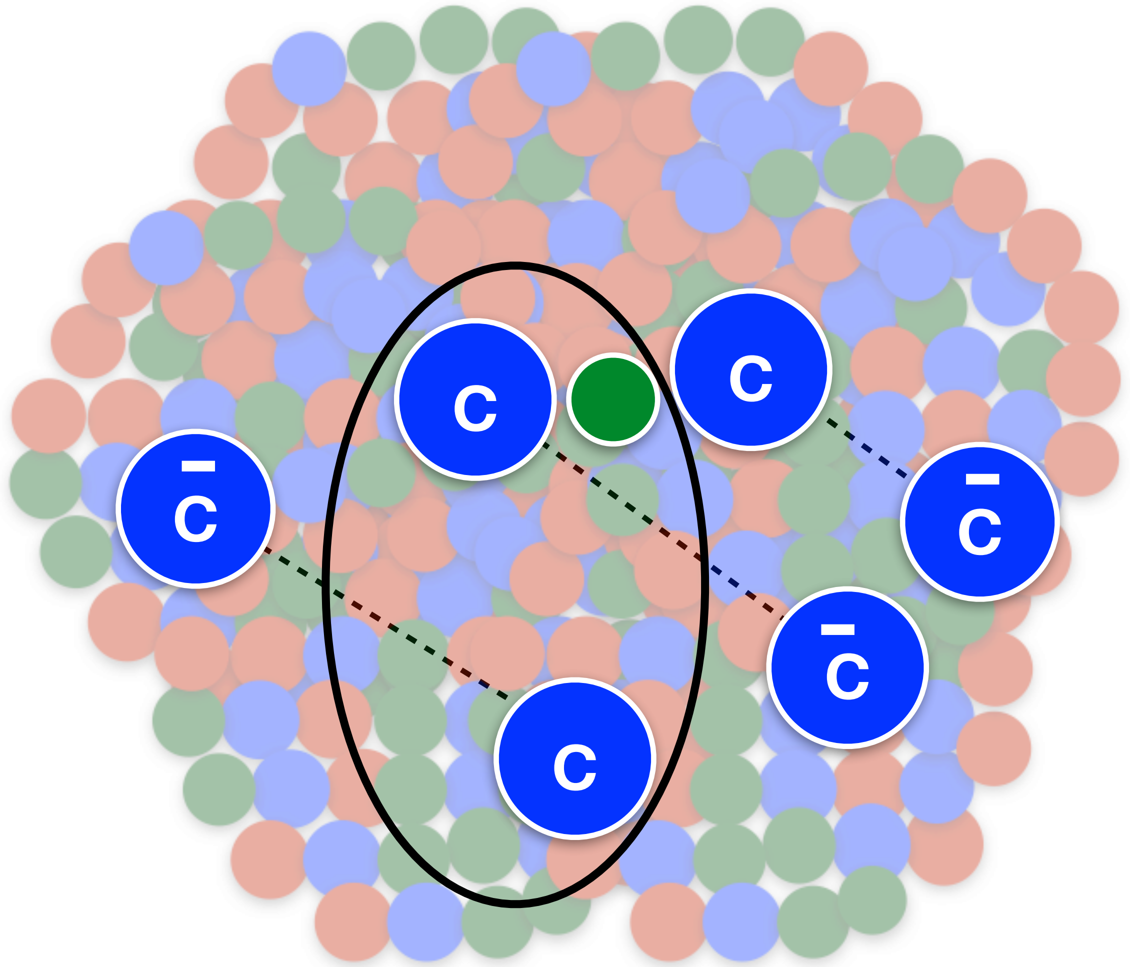
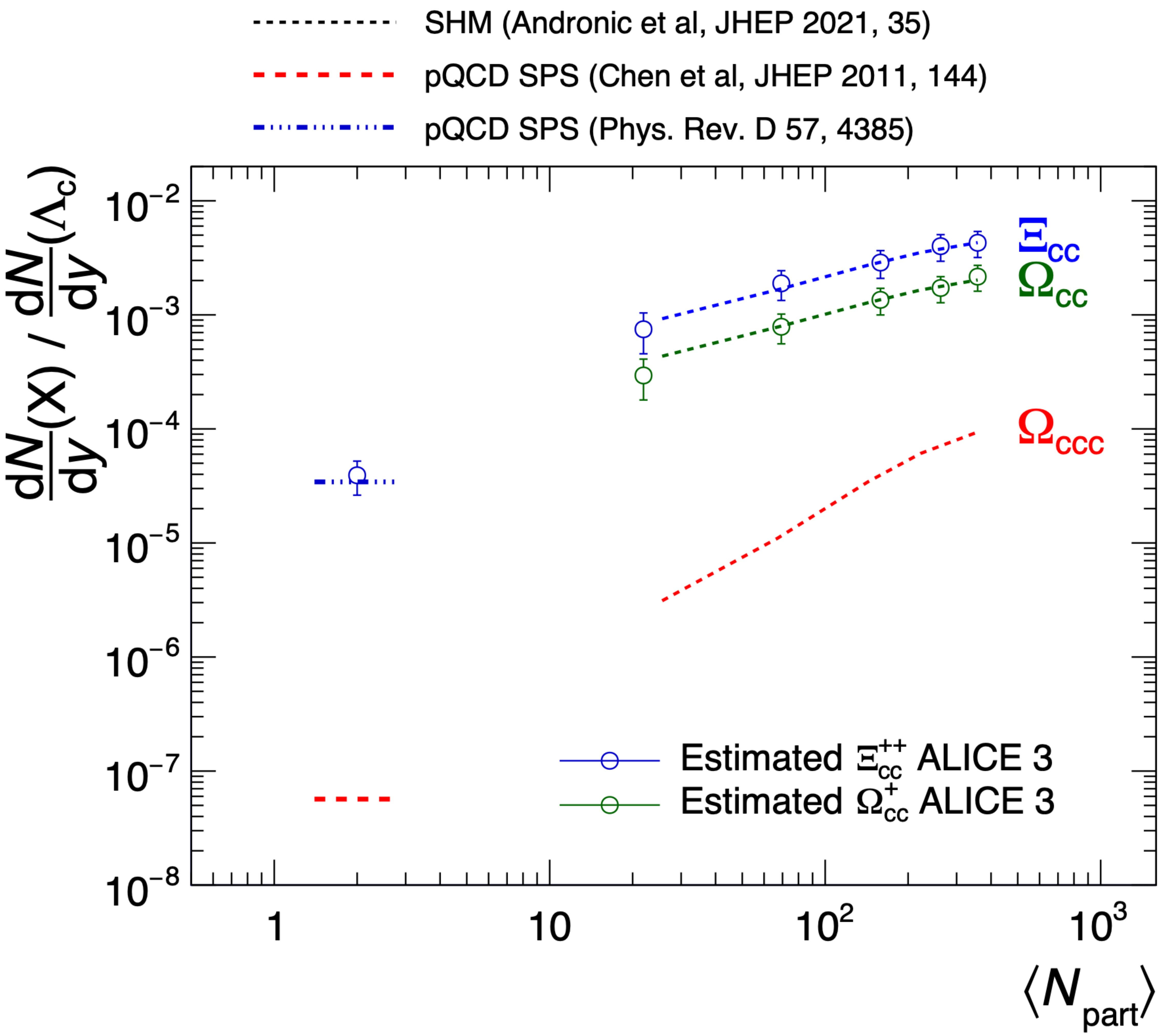




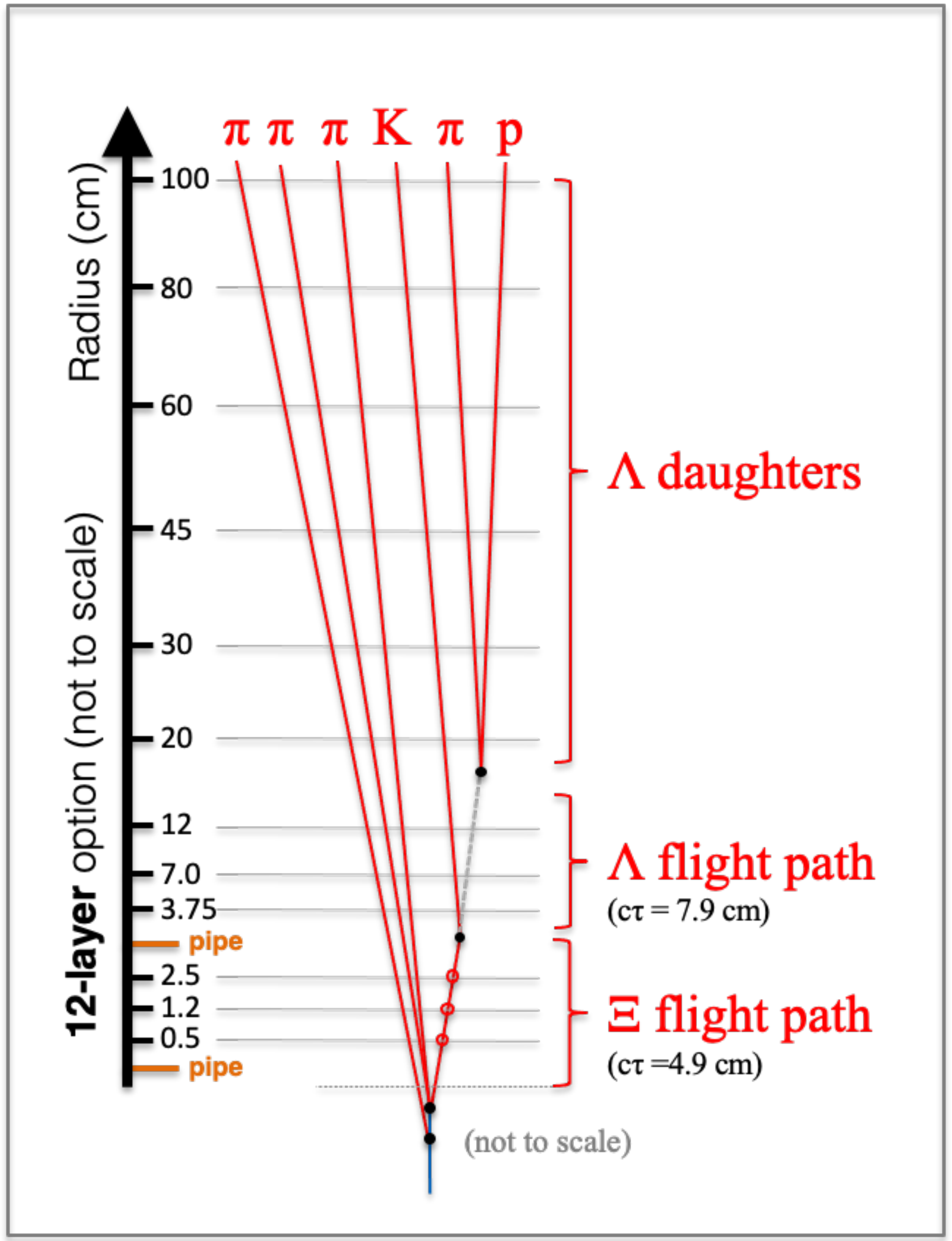
Ξ_{cc}, Ω_{cc}, B_c



→ Extreme benchmarks for mechanisms of hadronization beyond "leading color" in small and large systems

→ **Dynamic connection between "equilibrium" properties of charm quarks and hadronization modifications**

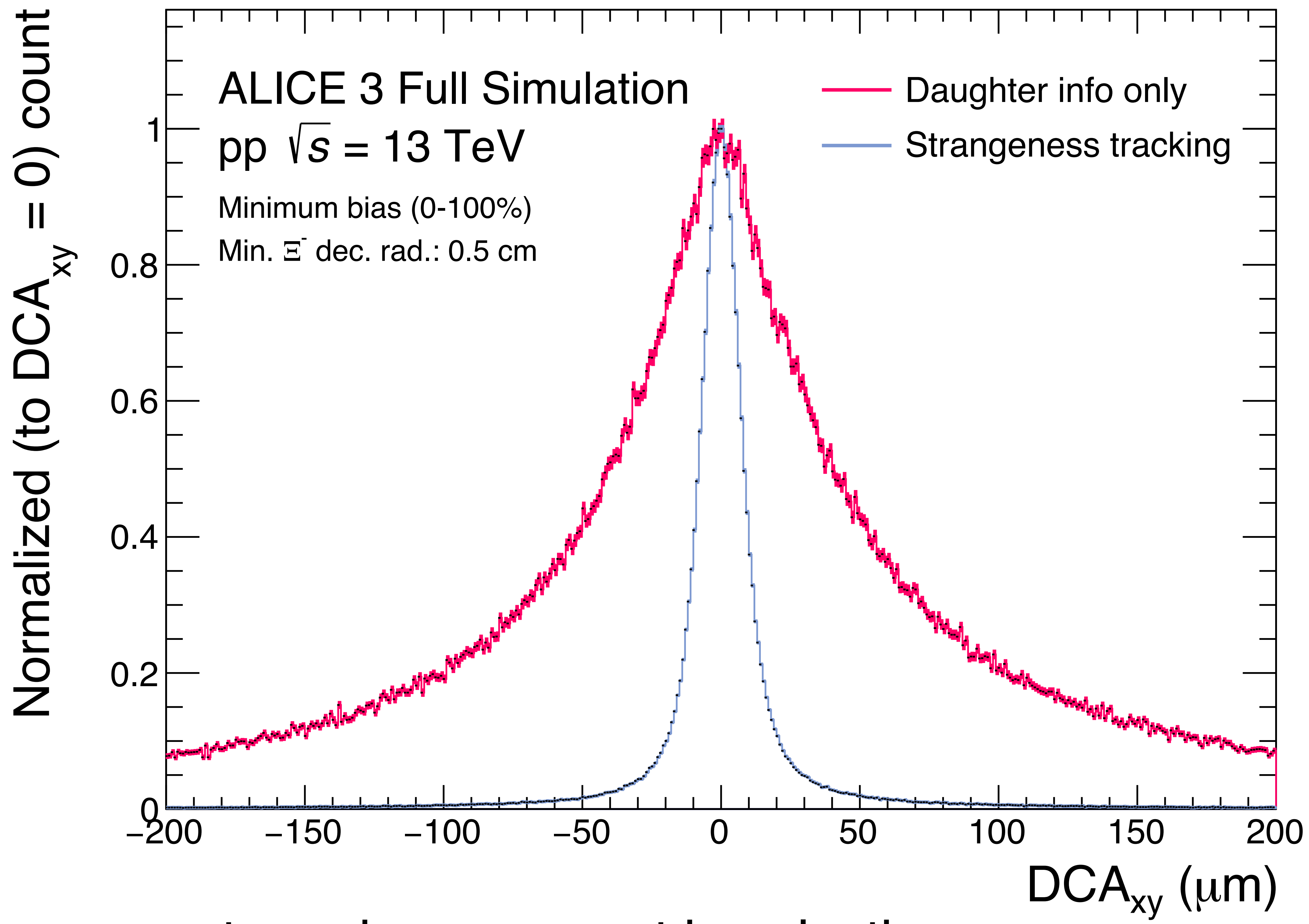
Ξ^{++}_{cc} with strangeness tracking



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

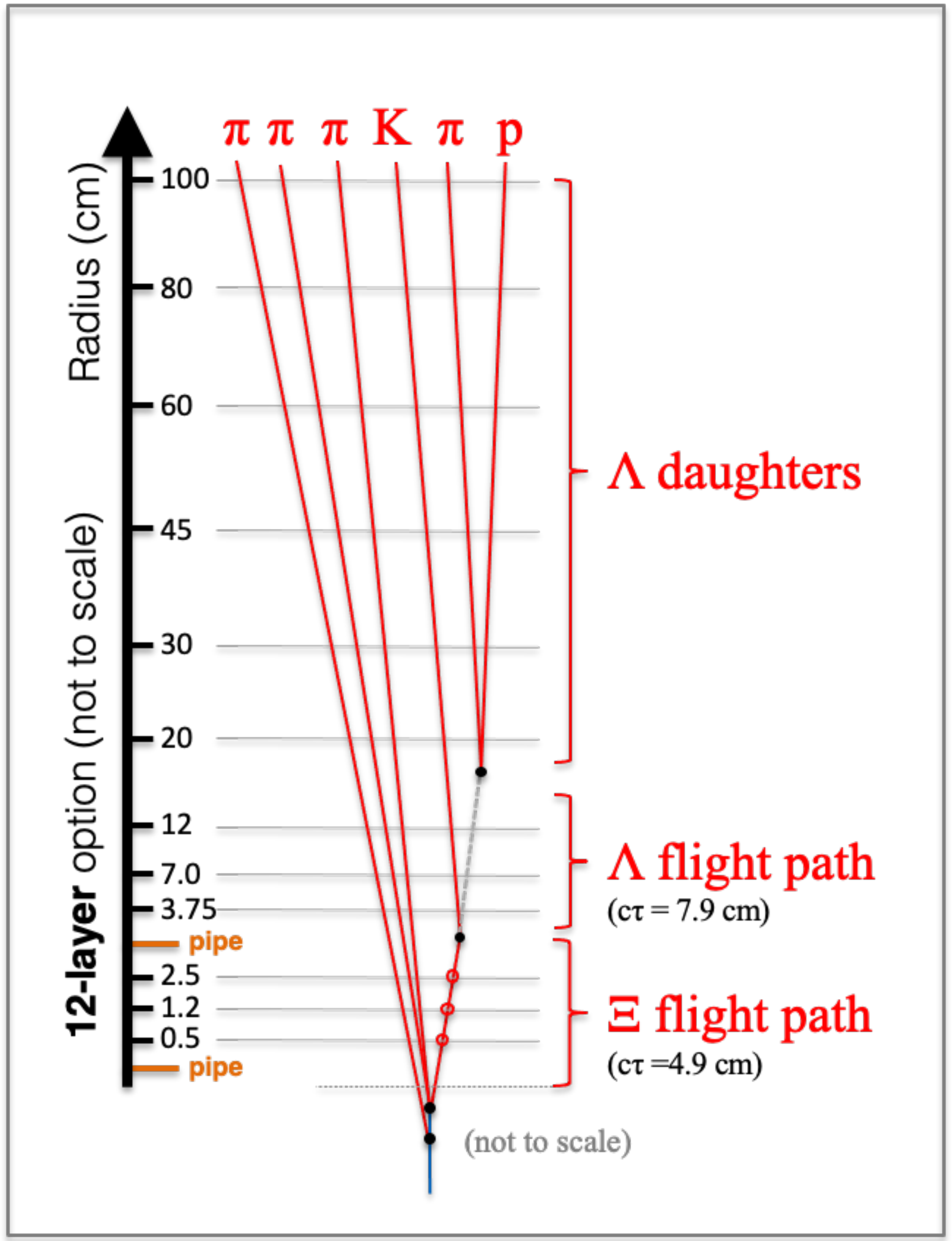
$\Xi^{+}_{c} \rightarrow \Xi^{-} + 2\pi^{+}$ $(c\tau \approx 132\ \mu m)$

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



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

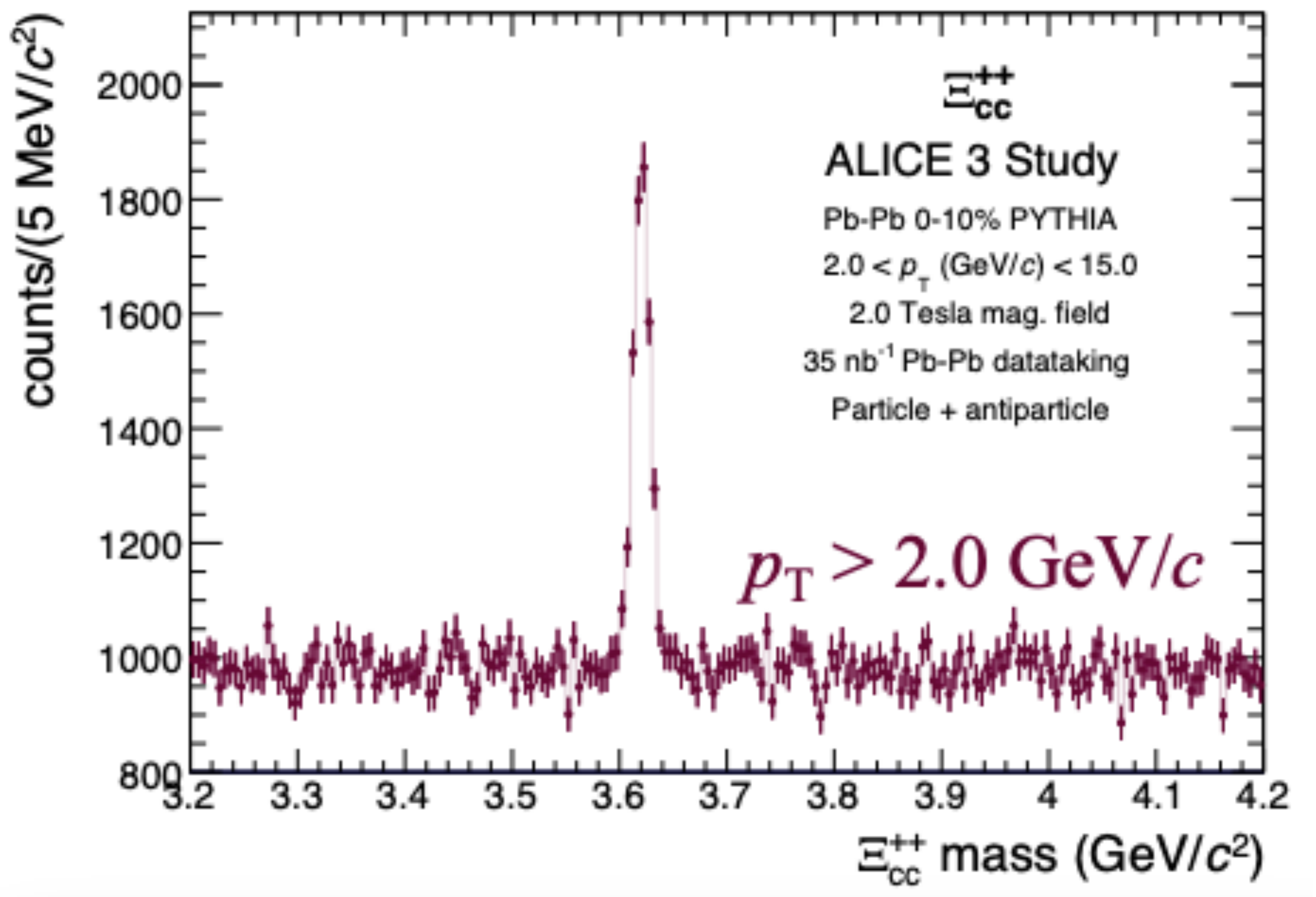
Ξ^{++}_{cc} with strangeness tracking



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

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

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



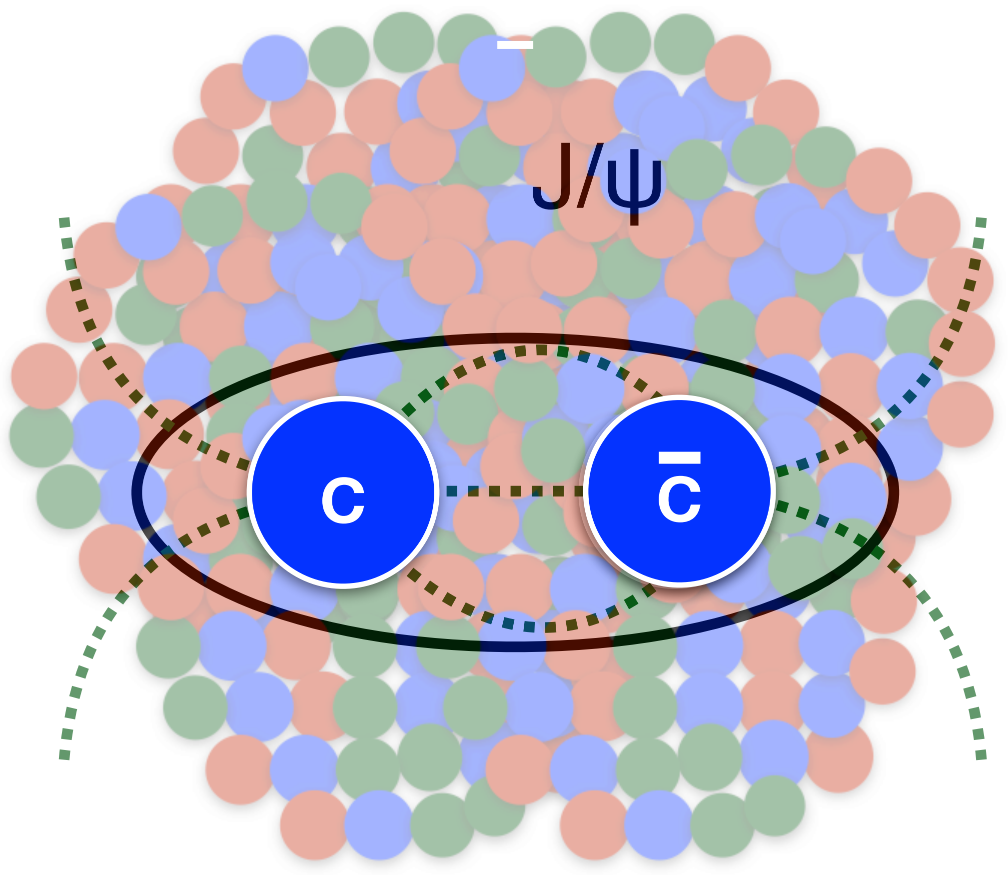
- strong improvement in selection accuracy
- large reduction of combinatorial background

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

Bound states in the QGP

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

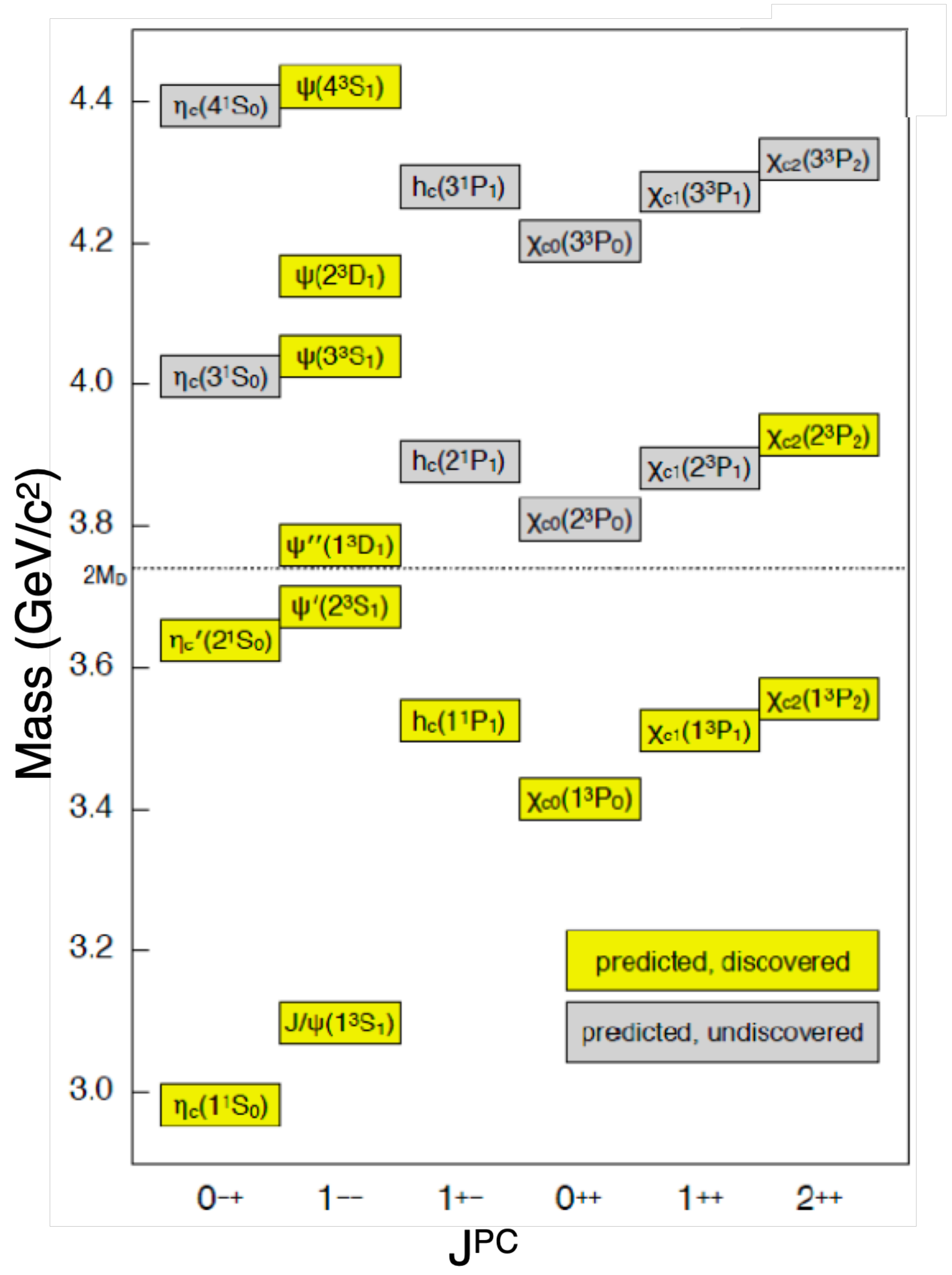


Pseudo-scalars (η_c)

- never measured in HI collisions

χ_c and χ_b → $J/\psi+\gamma$ (L=1):

- different bound-state stability and sensitivity to thermal fluctuations
  → **significant discrepancies among different theoretical predictions**



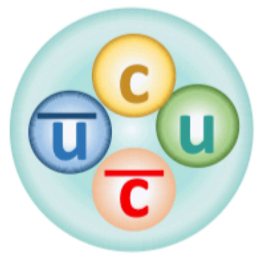
- Photon reconstruction down to ~ 0.5 GeV with good resolution:
- J/ψ and Y reconstruction **down to low p_T**

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

Exotic hadrons in HI collisions

CMS: arXiv.2102.13048

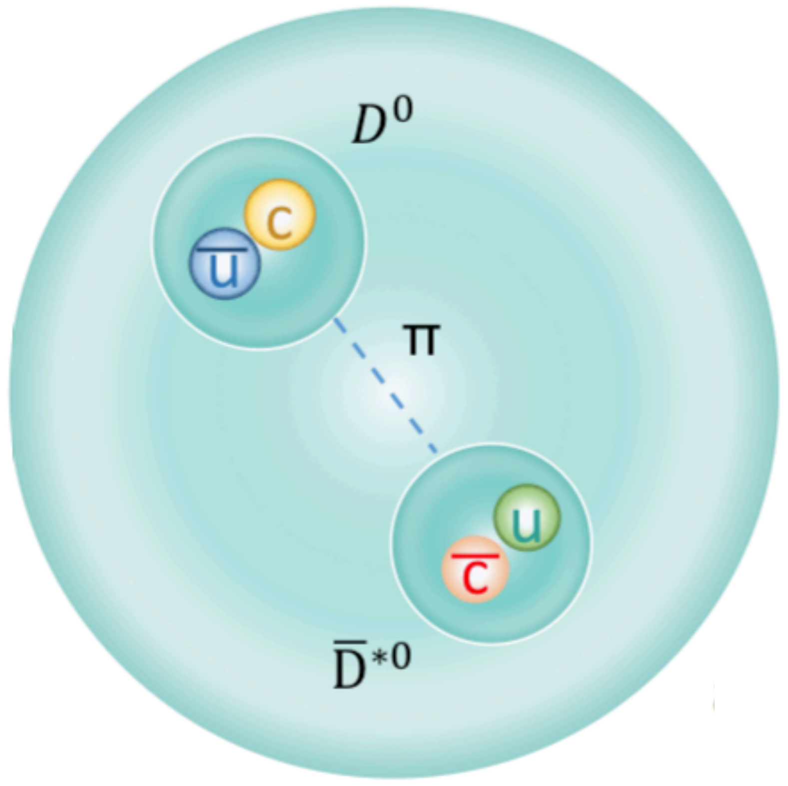
Tetraquark (4q)



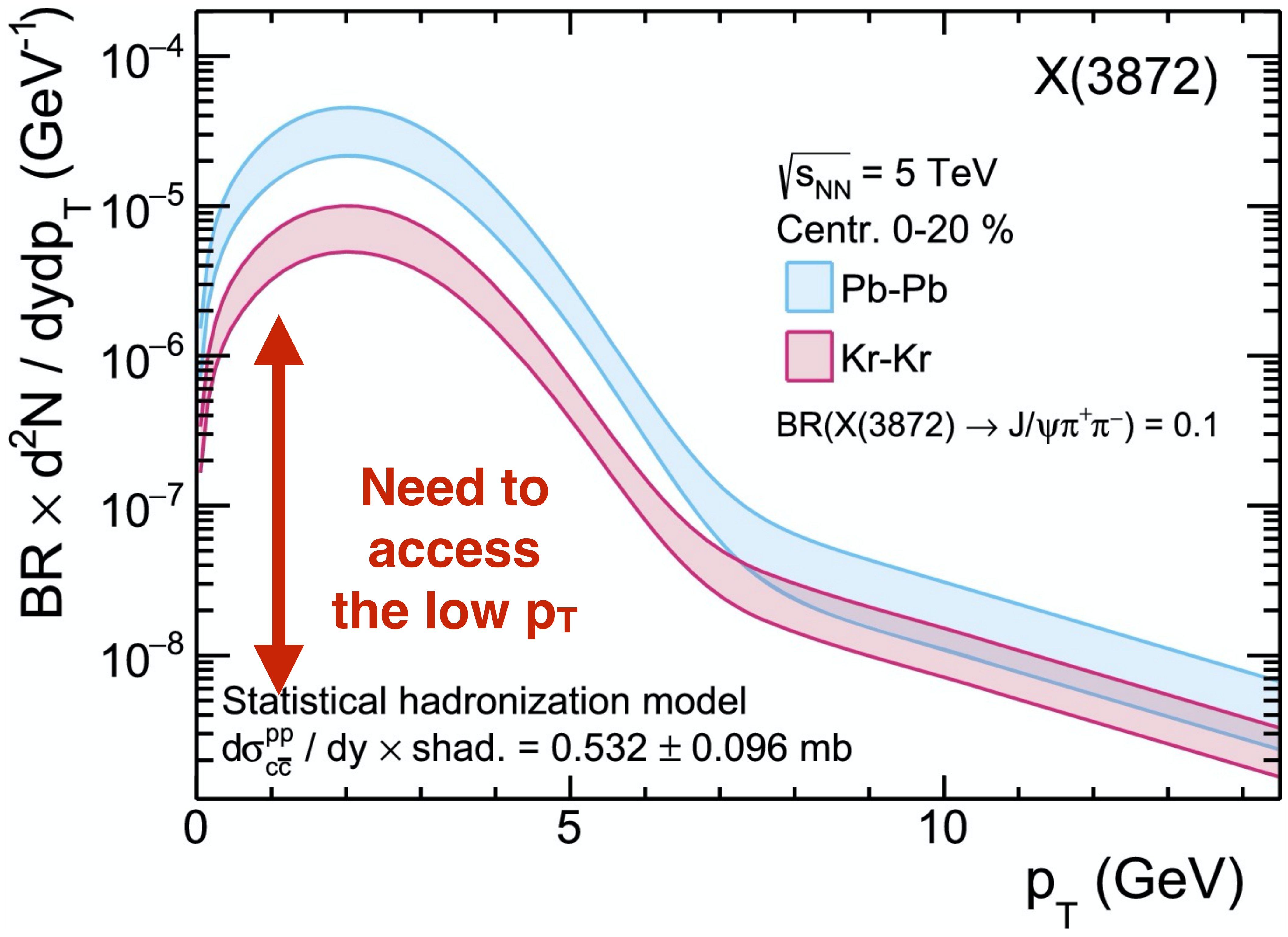
$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

VS

$D^0 - \bar{D}^{*0}$ molecule



$r_{molecule}$
as large as 5 fm



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

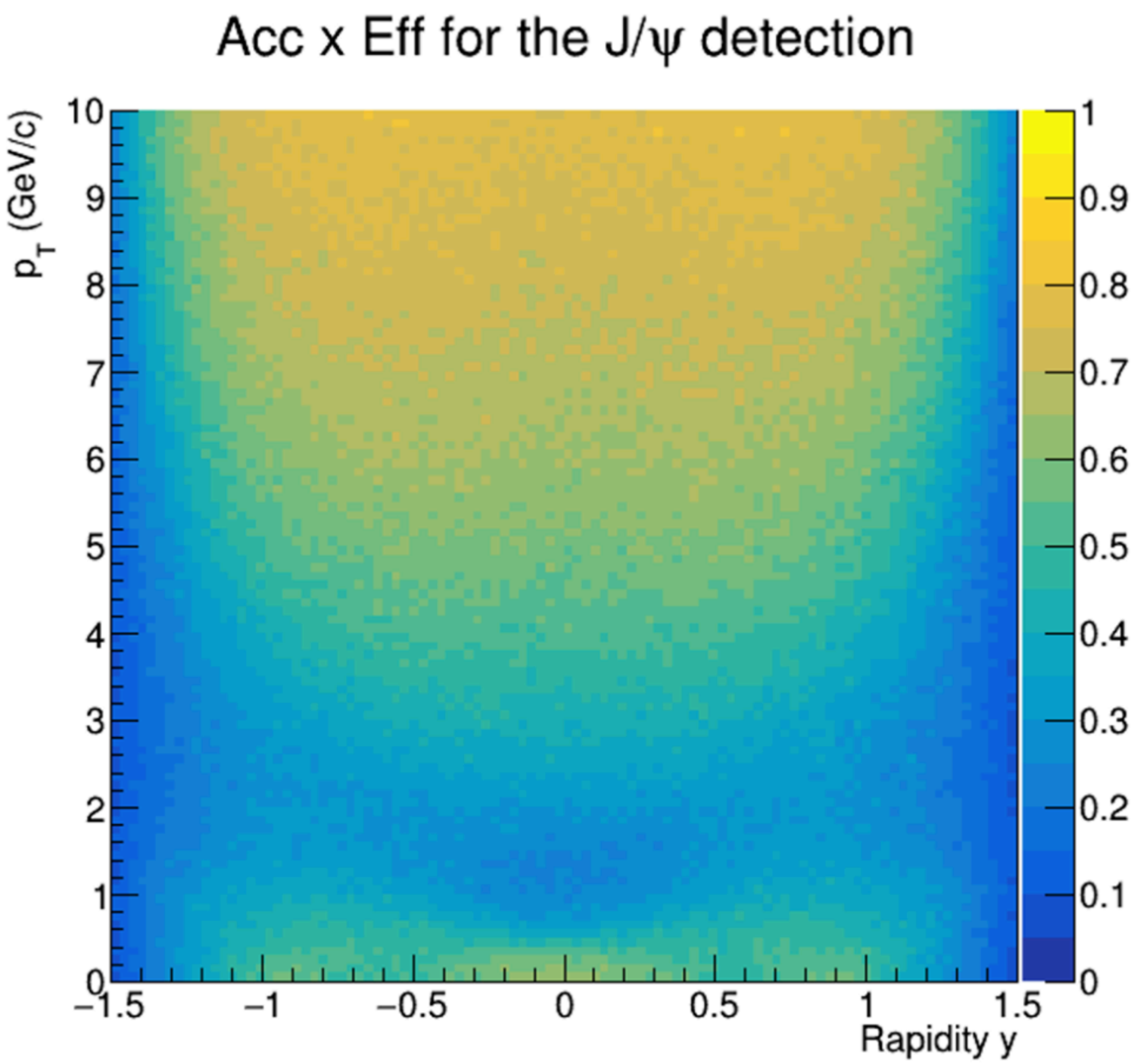
- J/ψ and Y reconstruction **down to 0 at mid- and forward rapidities**
- **low p_T reach for measuring soft pions**

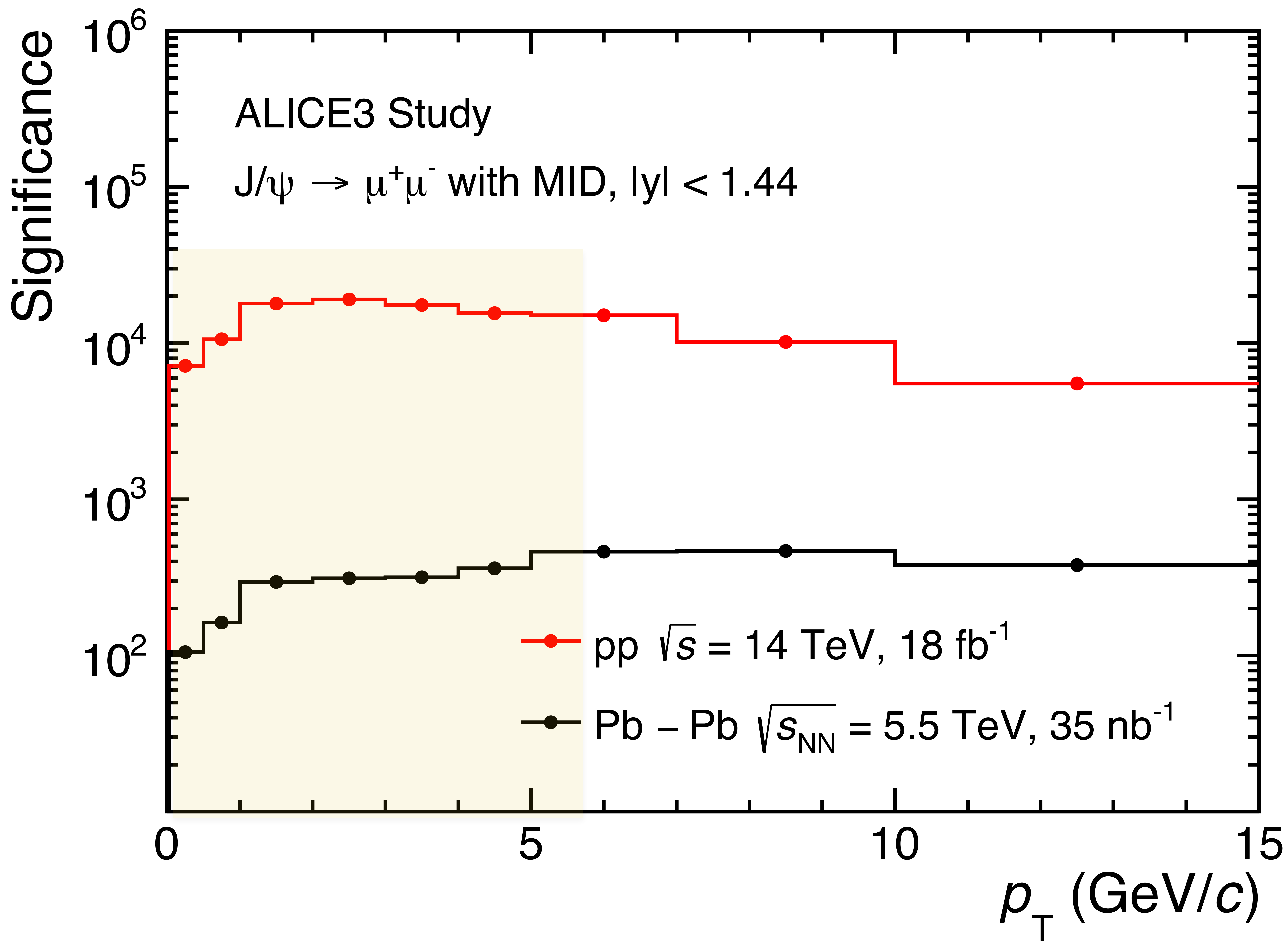
Wu, B., et al.: Eur. Phys. J. A 57, 122 (2021)

J/ψ performance as a benchmark

- J/ψ reconstruction down to p_T=0 as a building block of the quarkonia/exotic program of ALICE 3

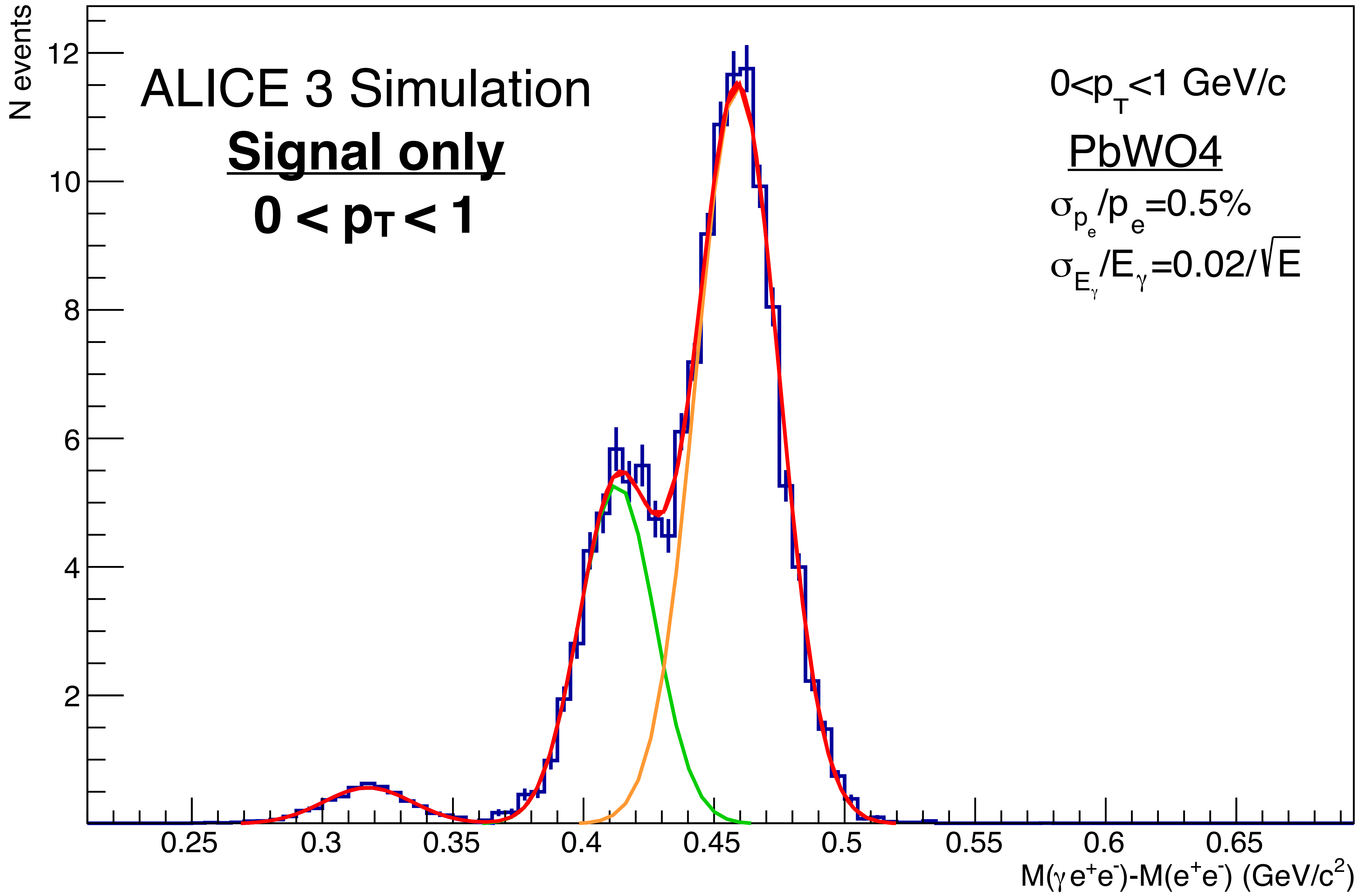
Geant4 study for ***Muon Identification detector***

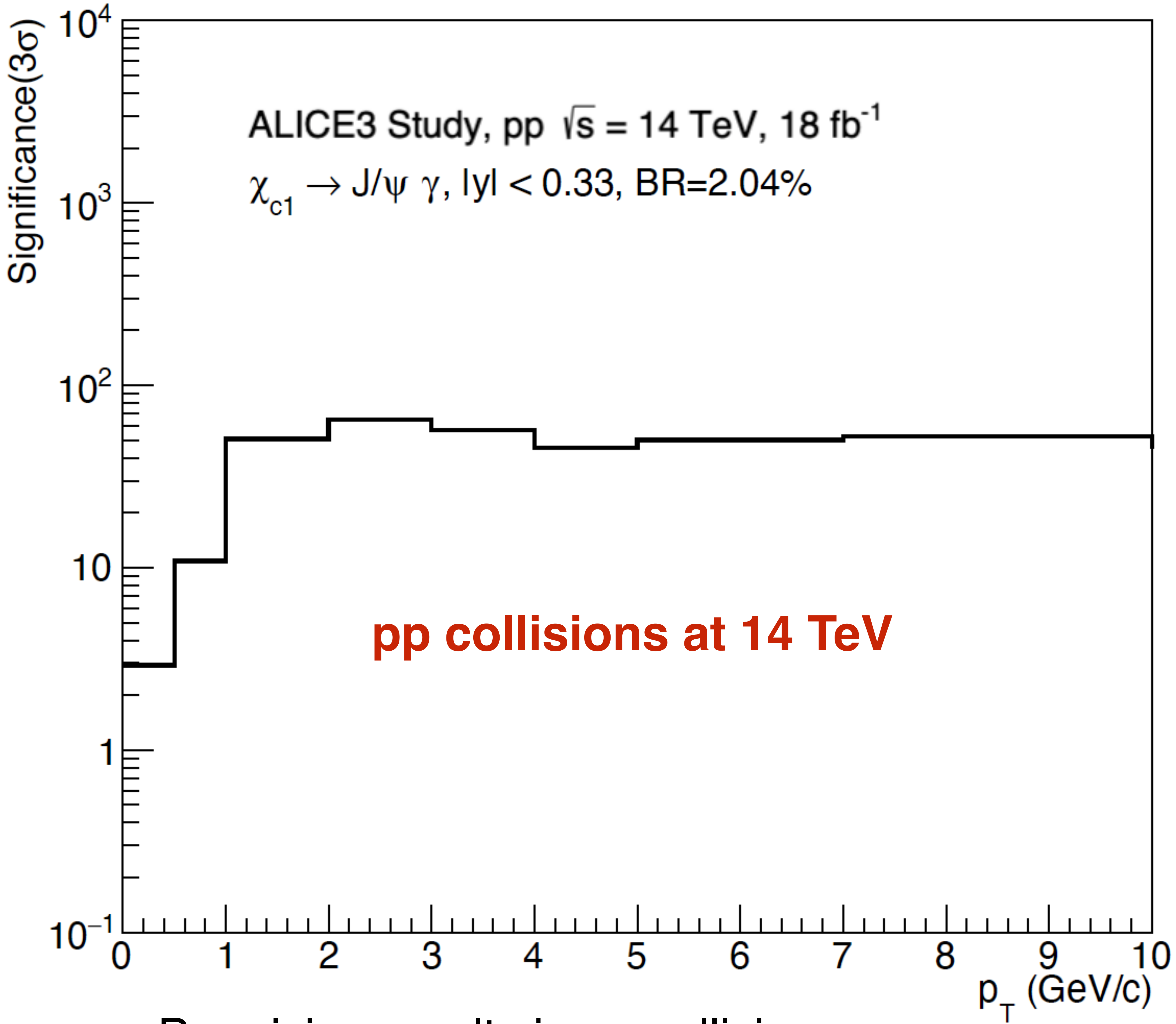




- **J/ψ reconstruction at y=0 down to p_T = 0 GeV/c as a unique feature of the ALICE 3 detector**

P-wave measurements with ALICE3





Photon identification performed with ECAL:

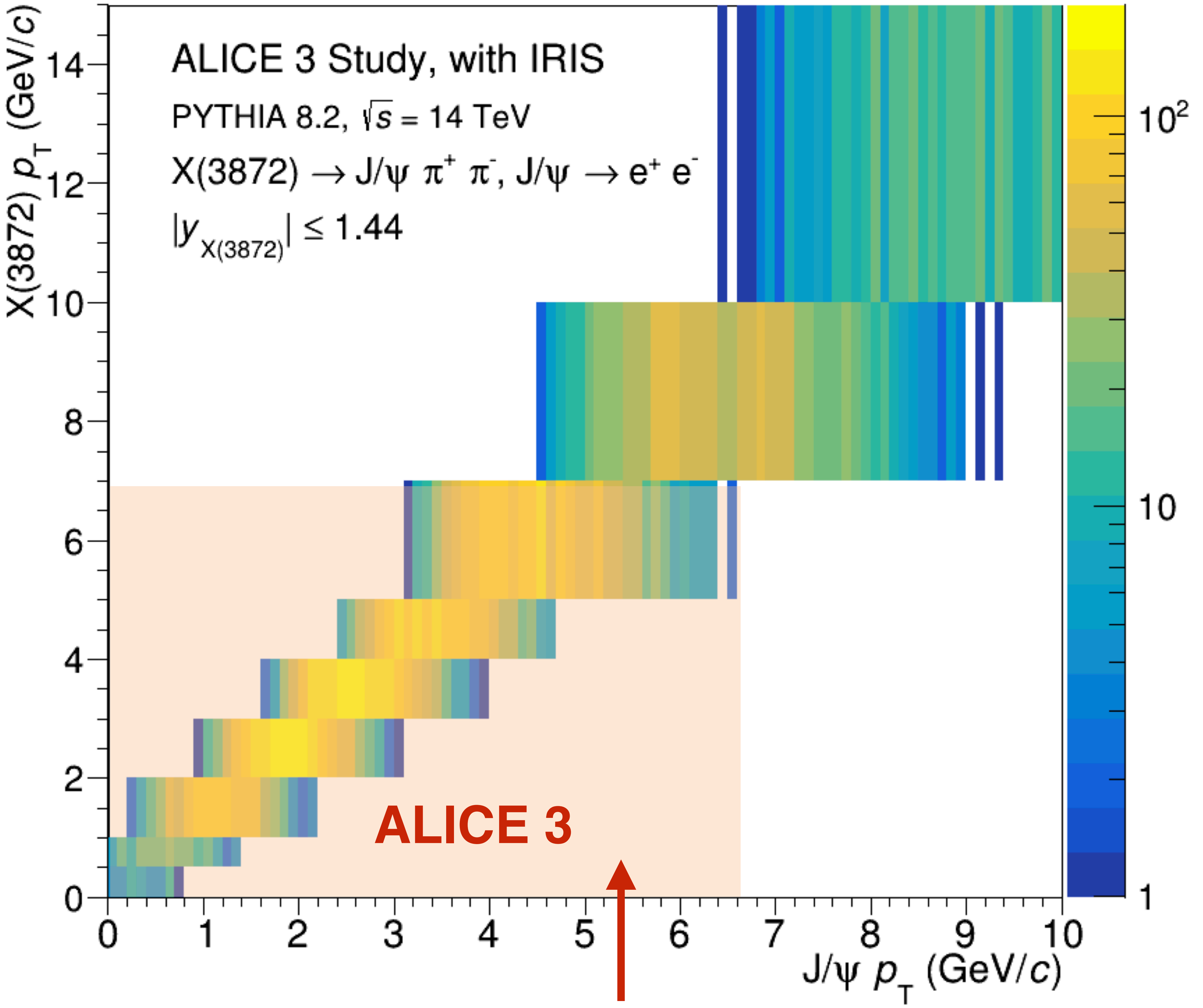
- high-resolution crystals at mid rapidity (no boost)
- sampling calorimeter at more forward rapidities

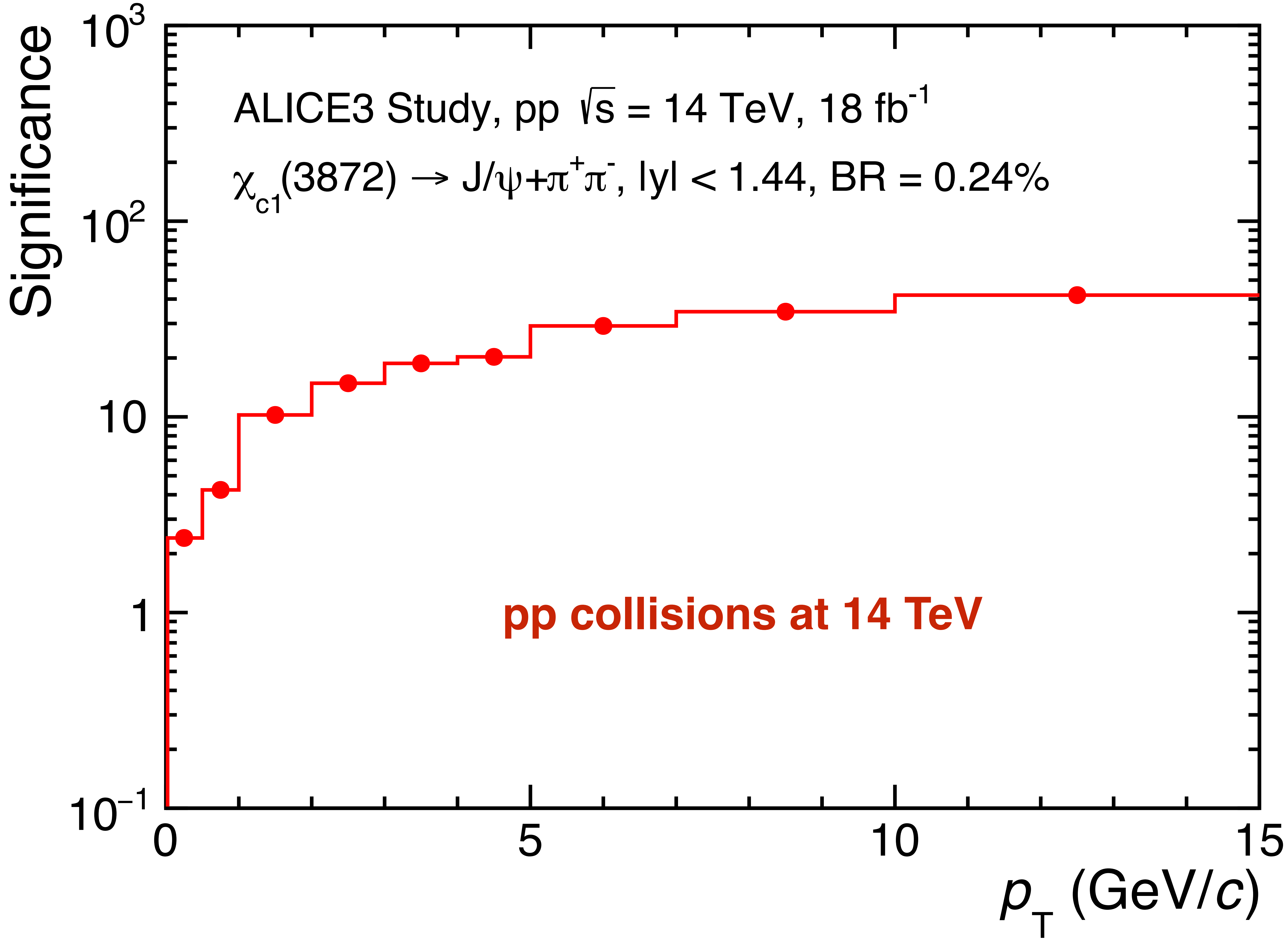
→ **maximize photon reconstruction efficiency**

- Promising results in pp collisions

→ **access to low p_T at mid rapidity**

χ_{c1}(3872) measurements with ALICE 3

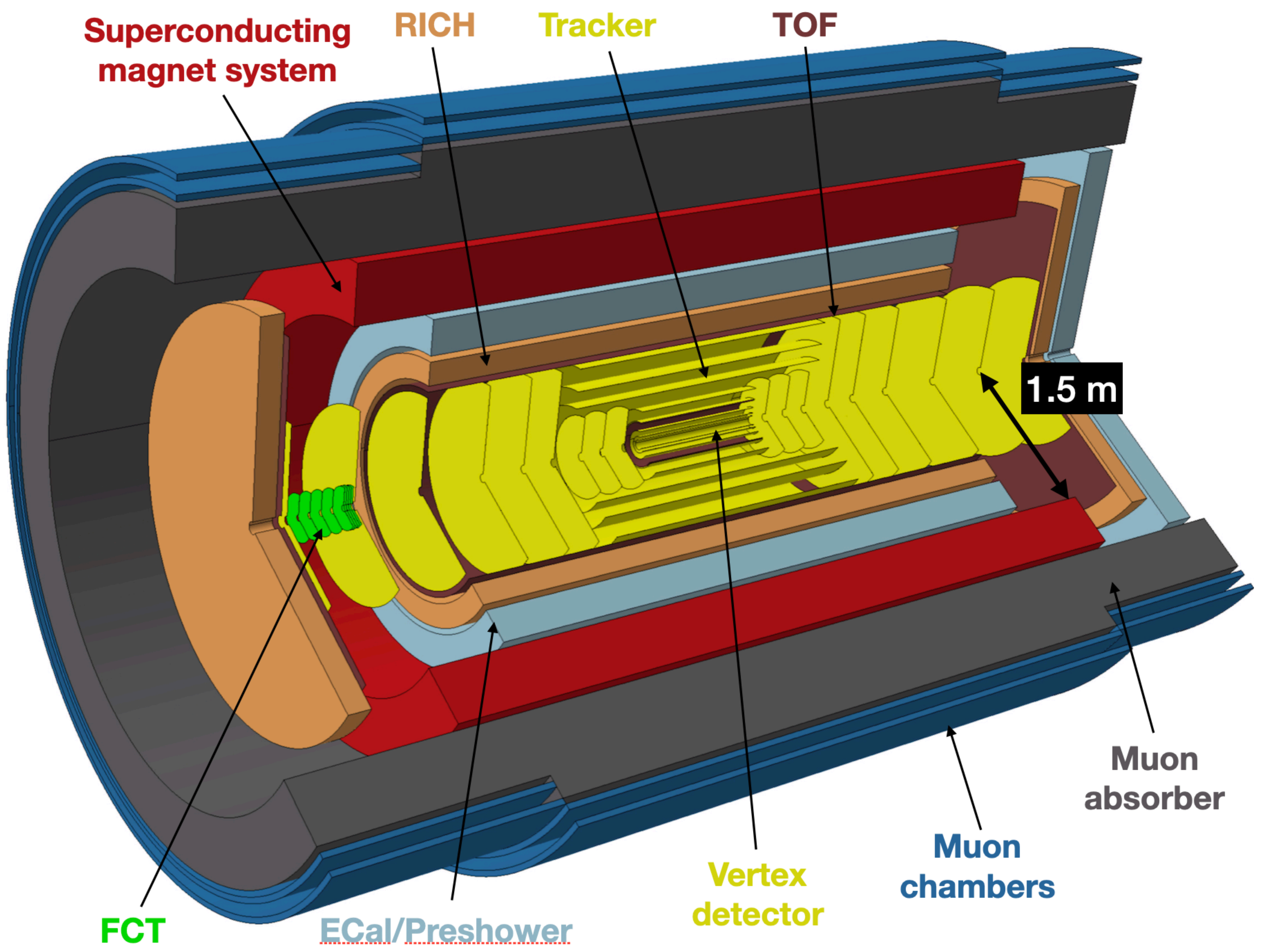




→ **Low p_T reach for J/ψ and charged tracks could allow for a unique kinematic reach at the LHC**

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

Conclusions and outlook

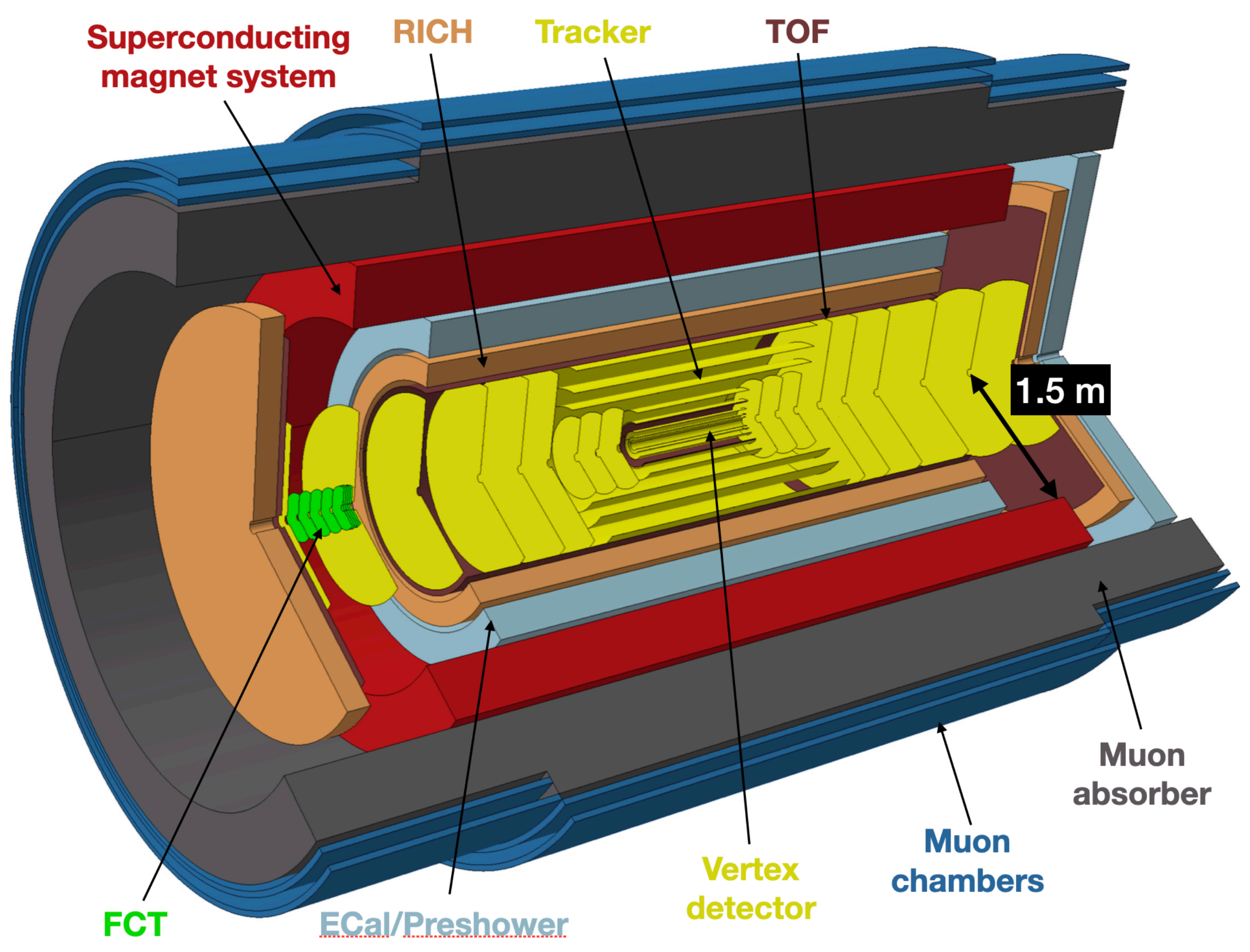


Unique apparatus for untriggerable QCD probes:
- resolution + high-rate + pseudorapidity coverage

→ understanding heavy quark diffusion in the QGP
→ thermalisation and hadronisation
→ bound states' interactions and nature of the states

Several new physics areas are being explored in collaboration with several theory groups

Conclusions and outlook



Unique apparatus for untriggerable QCD probes:
- resolution + high-rate + pseudorapidity coverage

→ understanding heavy quark diffusion in the QGP
→ thermalisation and hadronisation
→ bound states' interactions and nature of the states

An intense activity of R&D is foreseen for the next few years. Some examples:

Tracker sensors:
- thinning and bending of silicon sensors (relying on ITS3 experience)
- modularization and industrialisation (outer tracker)
- readout bandwidth vs power-consumption limitations
- inner-layer mechanics

Silicon timing detector:
- characterization of SPADs/SiPMs, with first beam tests
- monolithic timing sensors R&D
- …

ALICE 3 "schedule"

Long-term schedule

- **2023-25**: selection of technologies, small-scale proof of concept prototypes (~ 25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (~75% of R&D funds) → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of cavern, installation

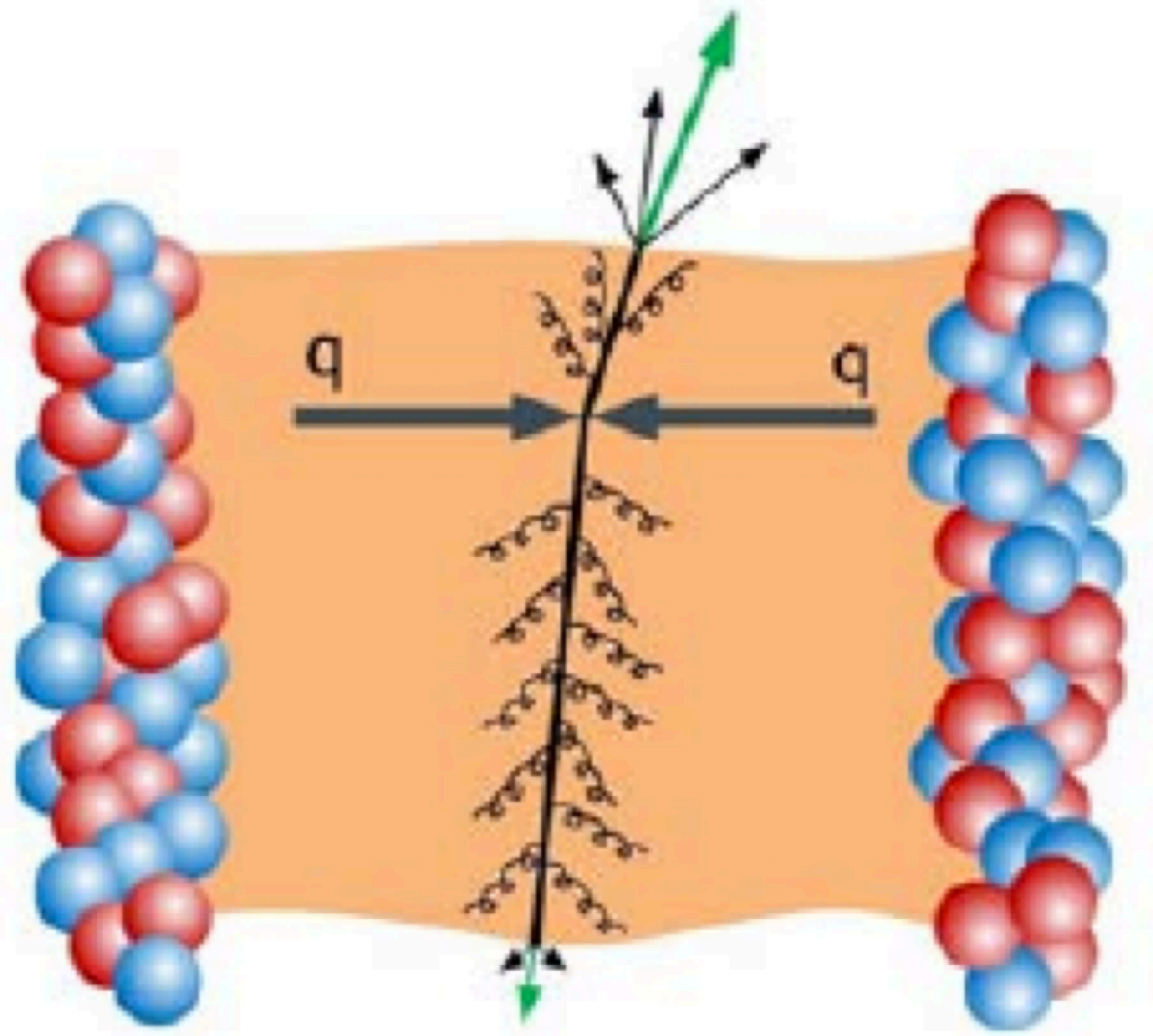
Next 12 months

- Mapping of R&D topics to groups → Upgrade week (next week)
- Preparation of **scoping document**
  - studies for scoping considerations
  - definition of R&D lines
  - resource planning

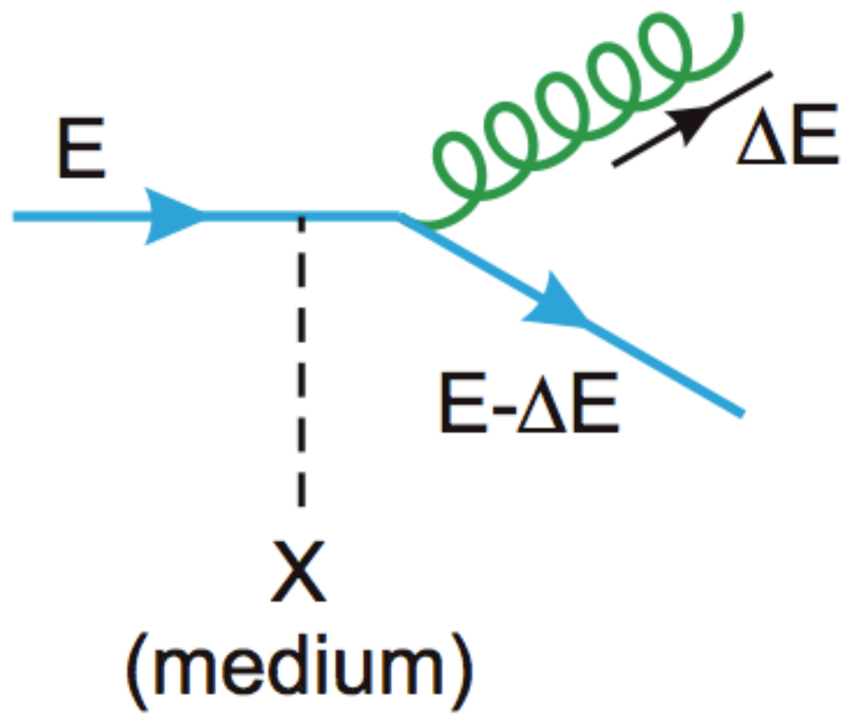
BACKUP

Characterizing the QGP with parton "energy loss"

→ **Characterize QGP properties** (e.g. interaction strength) **by measuring the energy lost by high-p_T partons while traversing it**



In pQCD, described for high-p_T partons by:
→ enhances splitting probability in the QGP
→ high-p_T partons lose energy via **medium-induced gluon radiation**



BDMPS, Nucl.Phys., B484:265–282, 199
B.G. Zakharov, JETP Lett., 63:952–957, 1996.

pQCD calculations in the presence of QGP (e.g. BDMPS-Z):
1. $E_{loss} \propto C_R$ (Casimir factor, = 3 for gluons and 4/3 for quarks)
2. Collinear radiation reduced for heavy quarks ("dead-cone" effect)

↓

"Flavor"-dependence of energy loss:
→ **E_{loss} (gluons)** > **E_{loss} (c-quark)** > **E_{loss} (b-quark)**

Characterizing the QGP with parton “energy loss”

How to observe it experimentally?

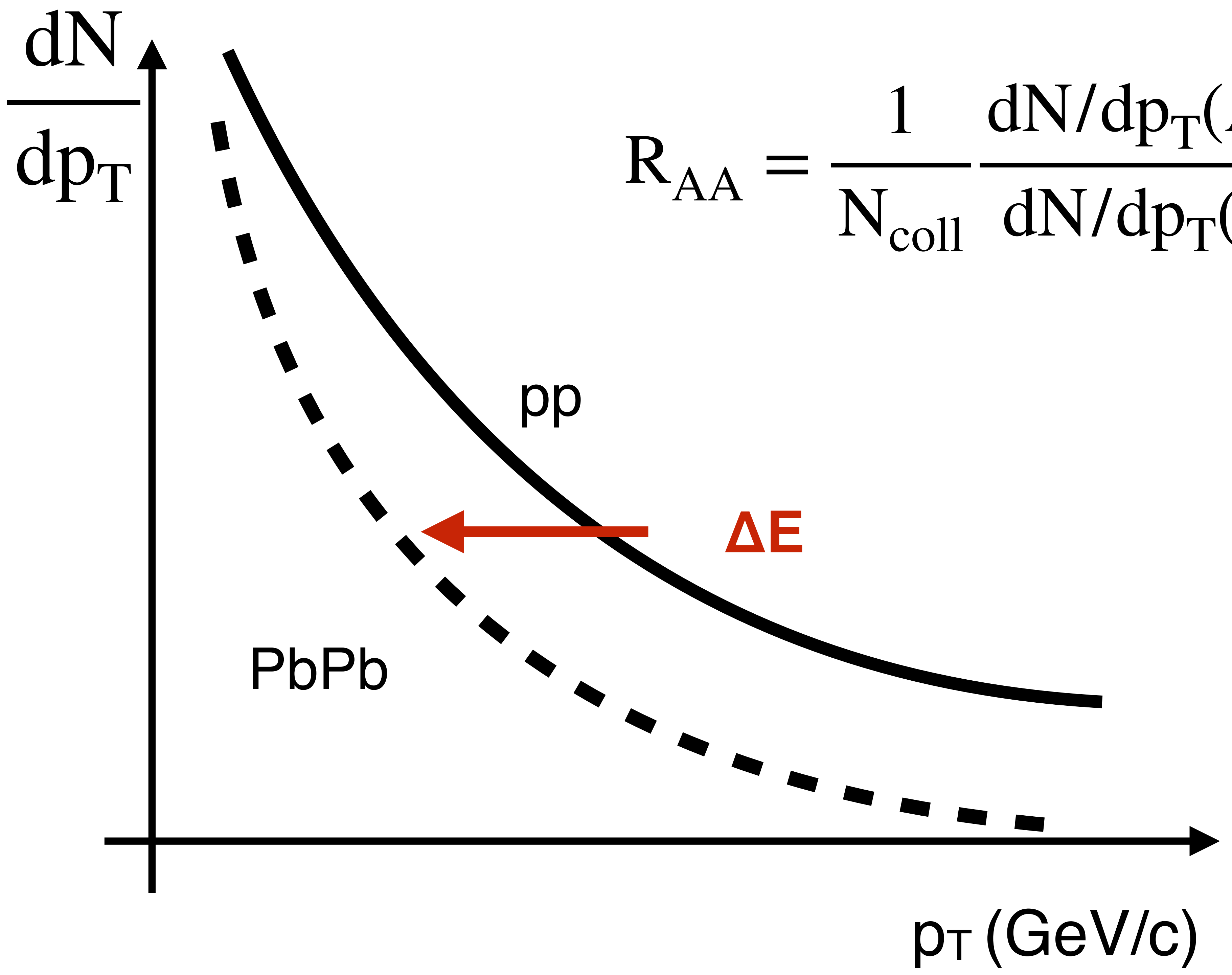
→ measurements **of light, charm and beauty hadrons**

gluon → light hadrons
c→D mesons
b→ B mesons

For each hadron, PbPb/pp

→ Nuclear modification factor R_{AA}

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$



A. Buzzatti, M. Gyulassy, NPA, Vol 910–911, 2013, 490-493

Characterizing the QGP with parton "energy loss"

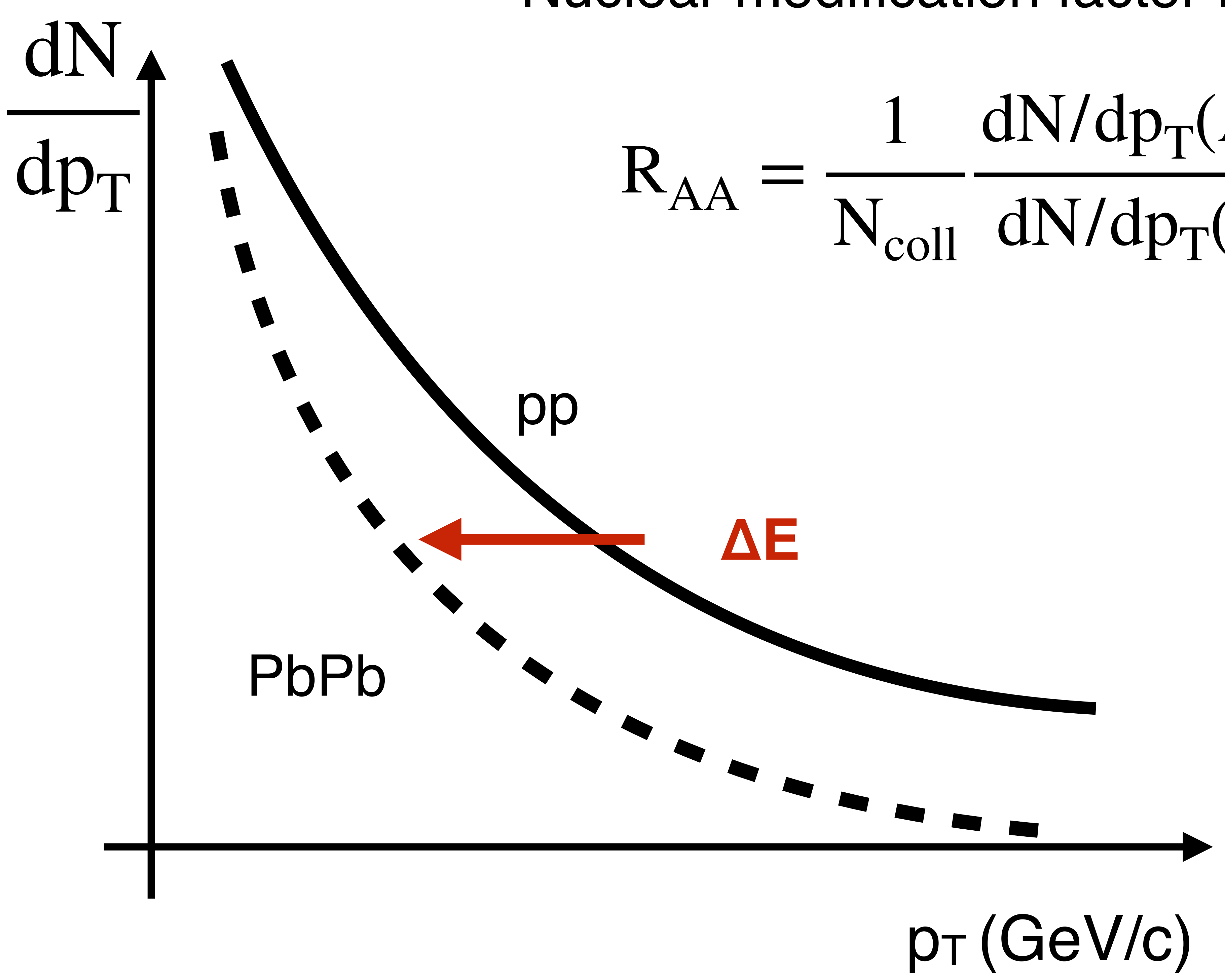
How to observe it experimentally?
→ measurements **of light, charm and beauty hadrons**

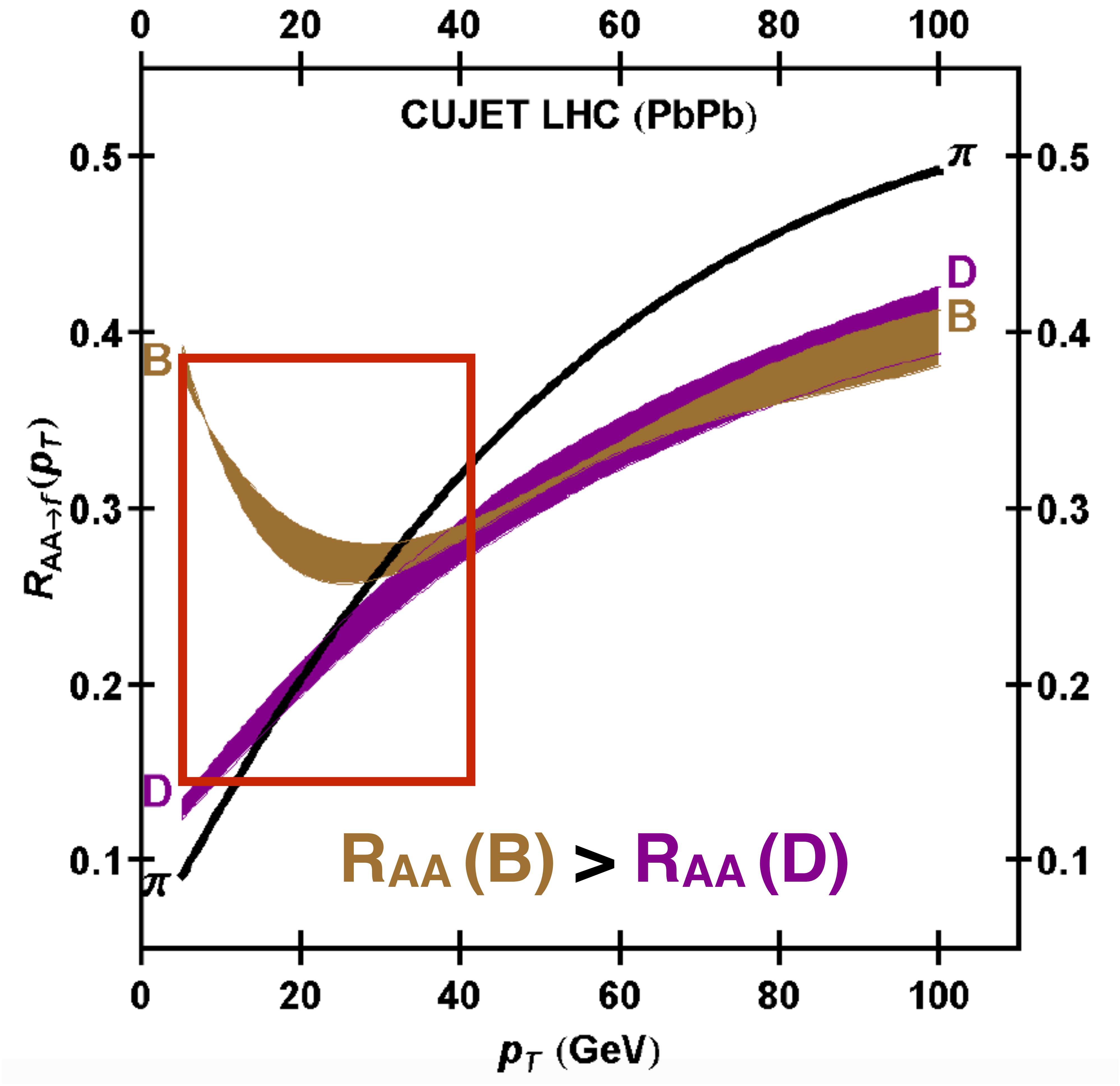
→ **test the pQCD expectations!**

gluon → light hadrons
c→D mesons
b→ B mesons

For each hadron, PbPb/pp
→ Nuclear modification factor R_{AA}

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

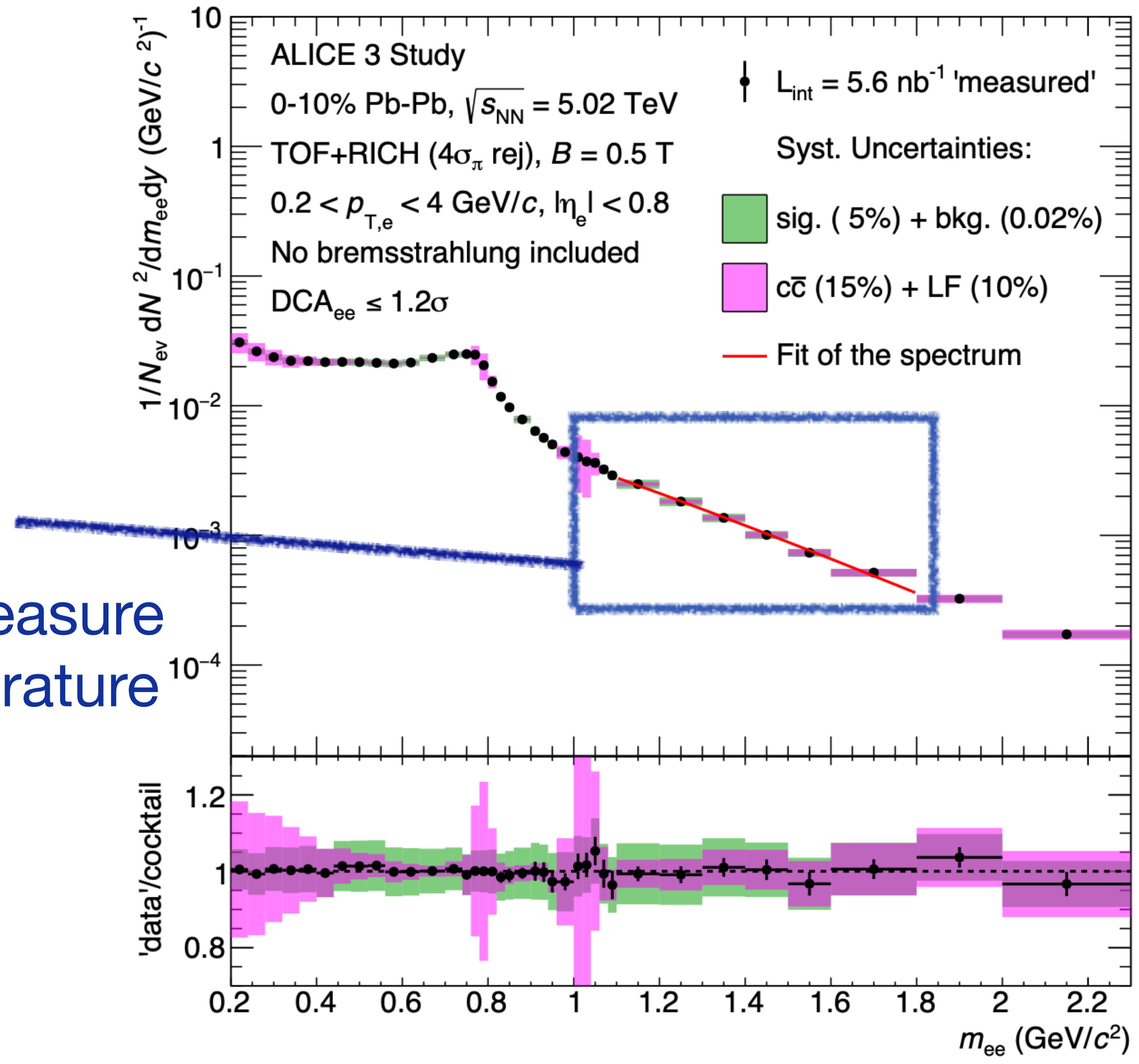




A. Buzzatti, M. Gyulassy, NPA, Vol 910–911, 2013, 490-493

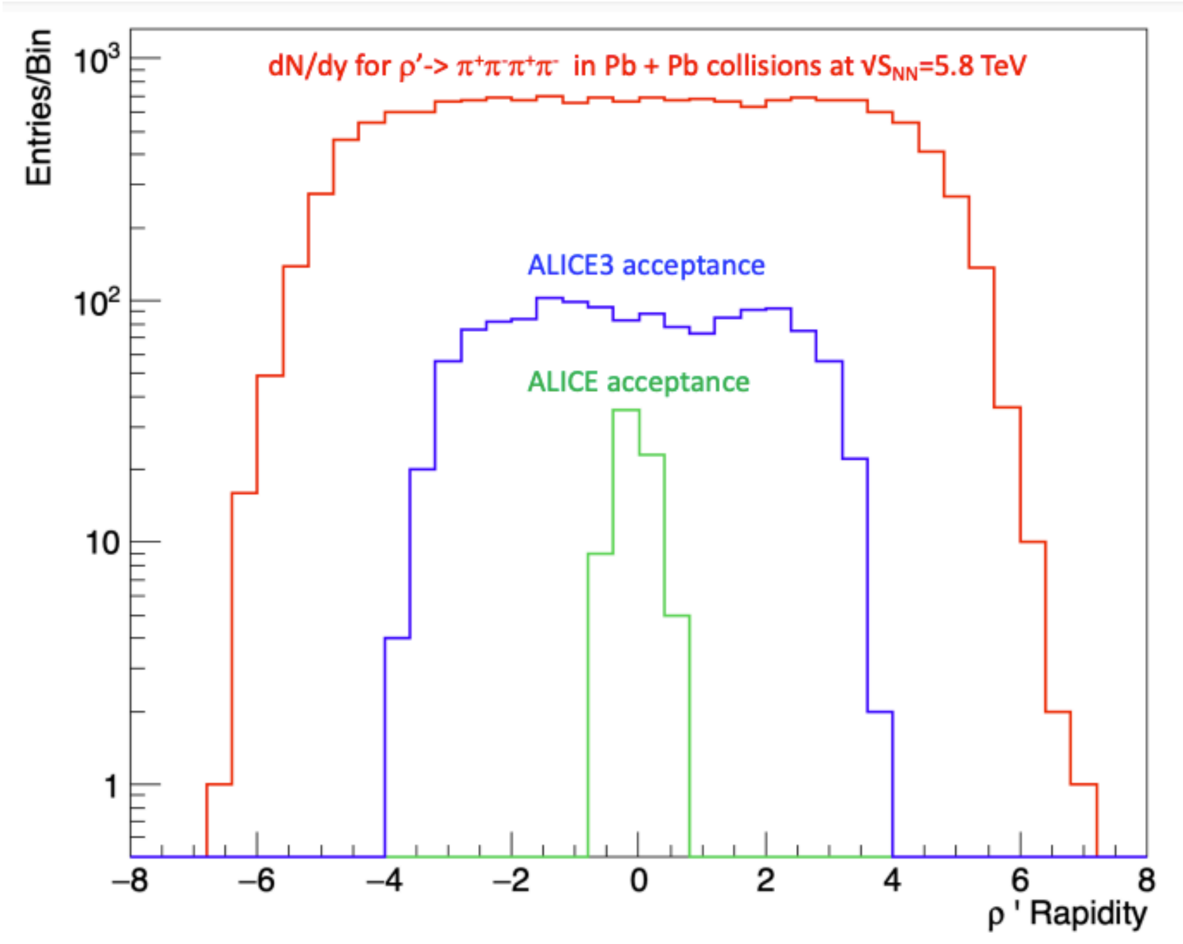
A wide program beyond heavy-flavour measurements

Dielectron mass

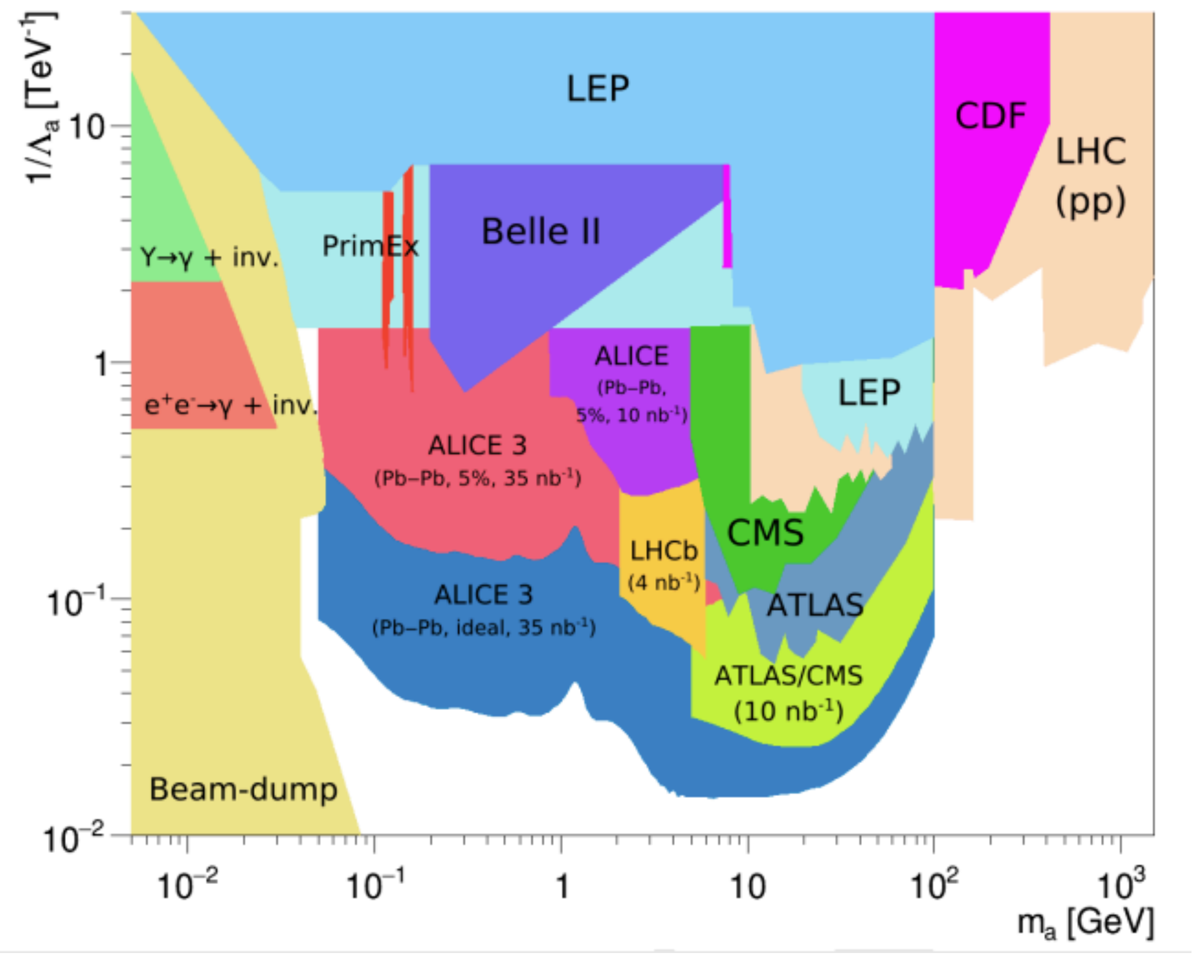


Direct measure of temperature

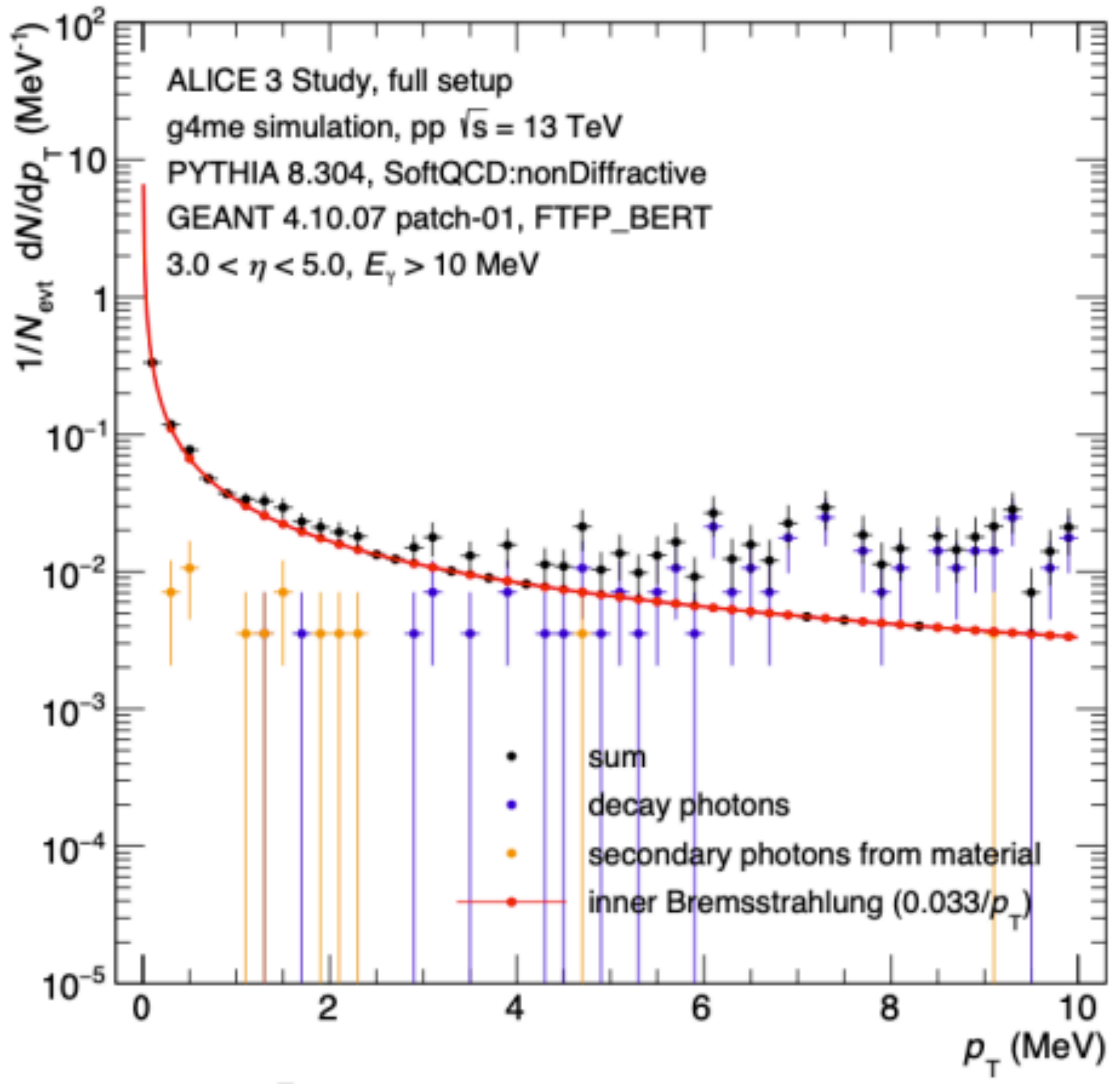
ρ' acceptance



ALP search



Ultra-soft photons



- Access to the initial phase of the QGP to measure its early radiation
- mechanisms of chiral symmetry restoration in the quark-gluon plasma

→precision measurements of dileptons

ALICE 3 Letter of Intent (CERN-LHCC-2022-009)

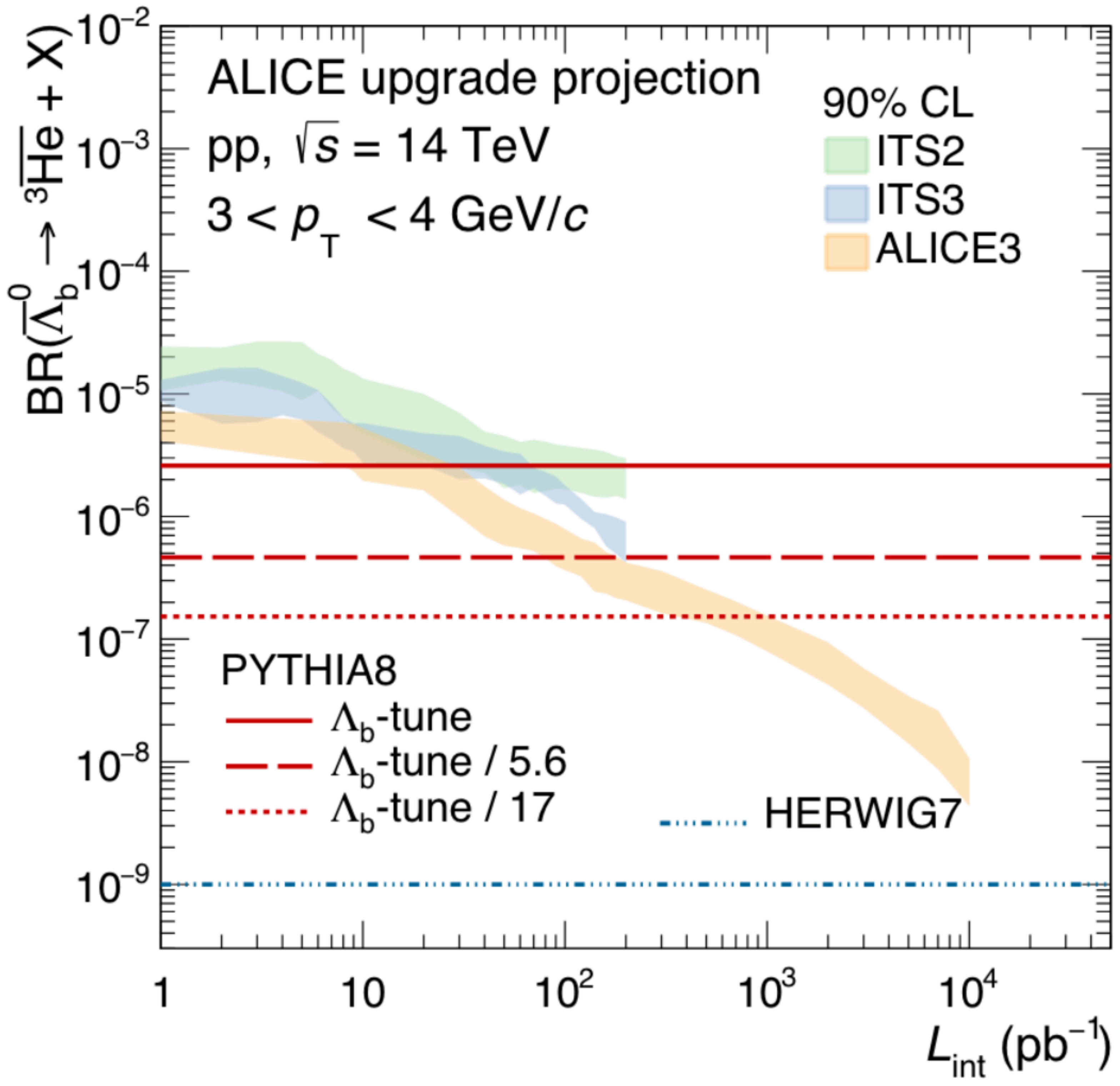
More HF observables with ALICE 3

- **HF flow in small and large systems up to very large Δη**
  → relevance of initial and final state effects

- **HF-γ and HF-HF correlations:**
  → absolute measurement of heavy-quark energy loss
  → Moliere scatterings with the medium constituents with HF-tagged jets

- **Jet measurements with single and double-tagged heavy-hadrons:**
  → characterize heavy-hadron fragmentation patterns
  → time-dependent probes for in-medium broadening

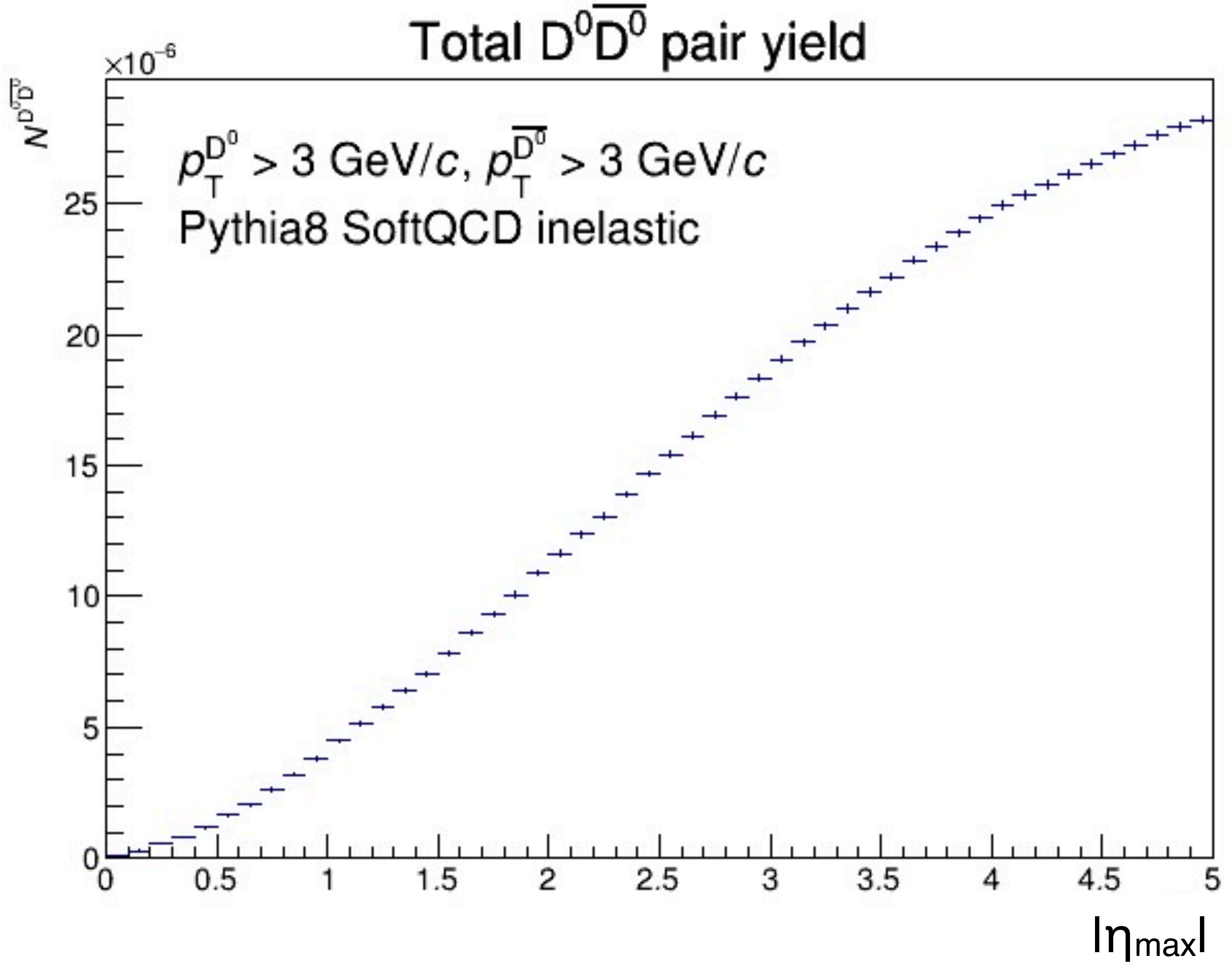
AMS Days at La Palma (2018)
M. W. Winkler, T. Linden, Phys. Rev. Lett. 126, 101101 (2021)



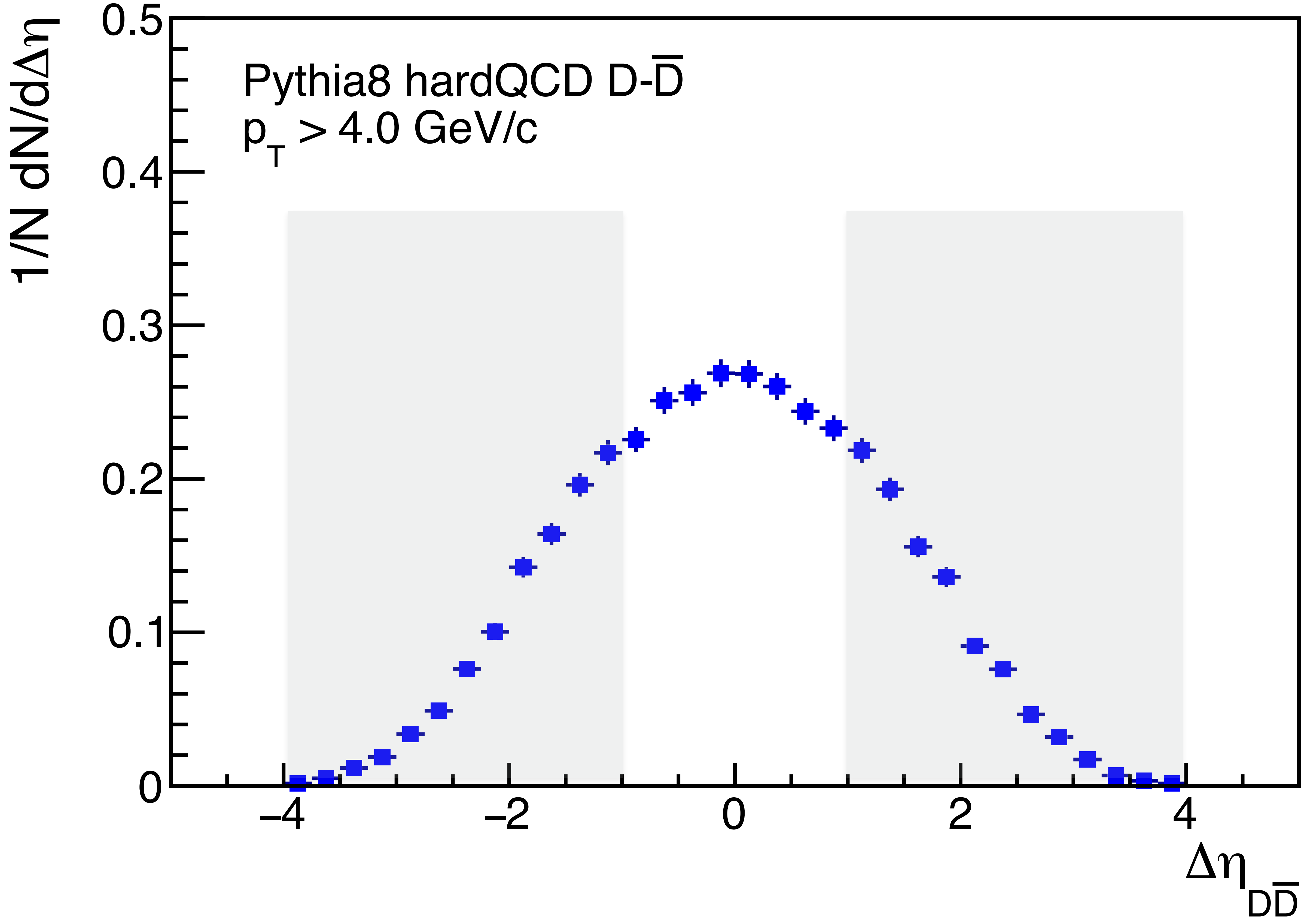
Beyond QGP physics:
- Constraints on branching ratios for rare decays relevant to Dark Matter studies
- Study of the strong interaction between heavy flavour hadrons
- search for charmed hyper and super nuclei in HI collisions
- Exotic production in UPC collisions

η coverage and correlation analyses

Large acceptance plays a critical role in low p_T correlation analyses



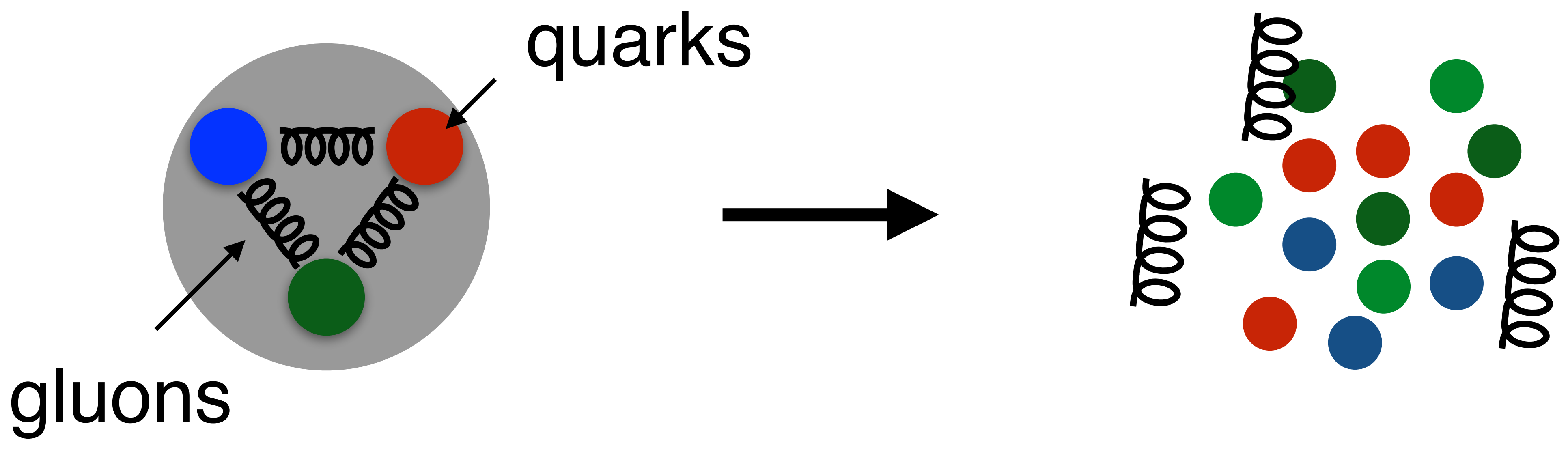
→ Significant increase of signal yield



Access to unexplored region of large Δη (> 2)
→ longitudinal properties of medium evolution

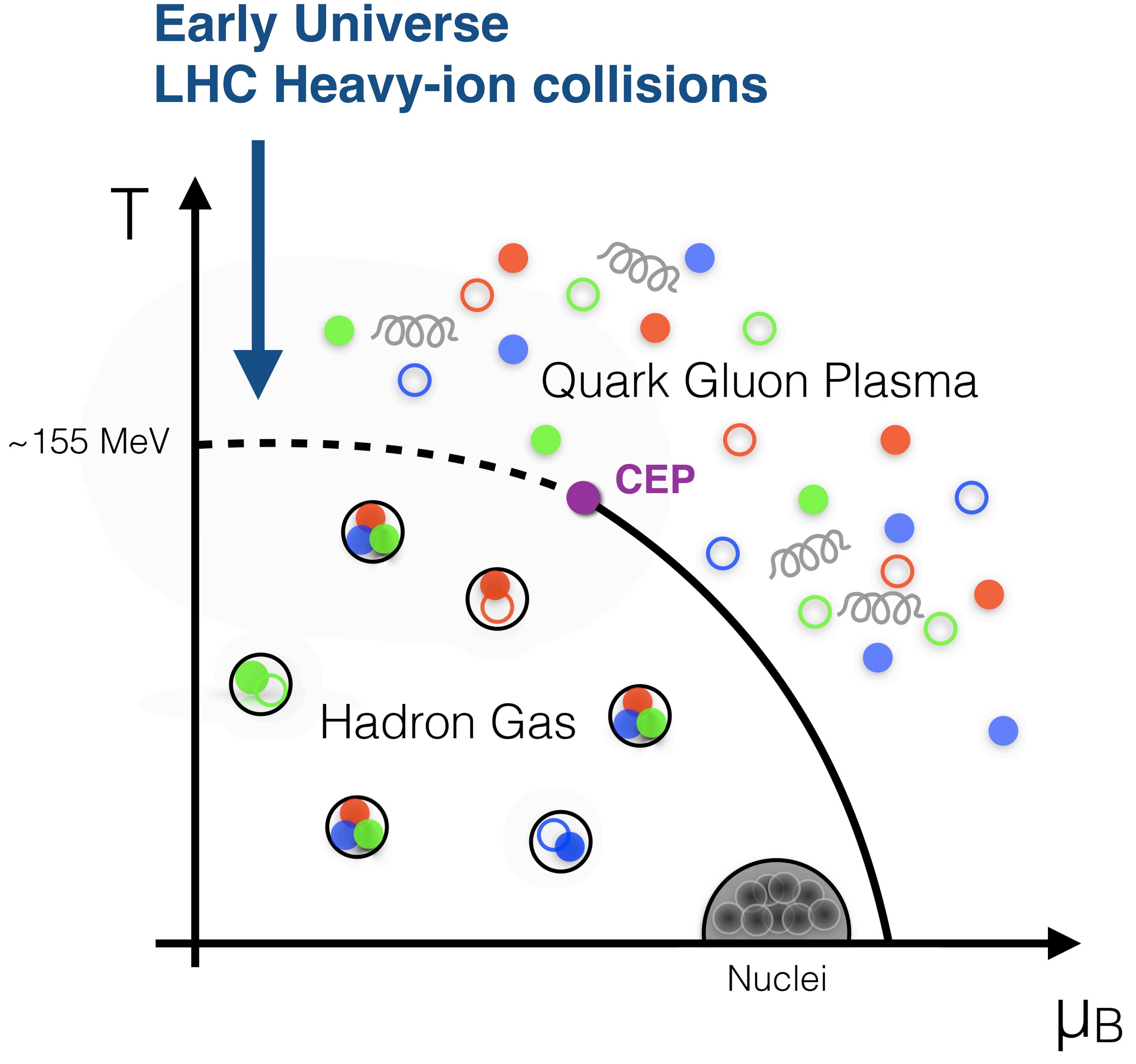
Why heavy-ion collisions: a historical perspective

What are the properties of nuclear matter at high temperature (~Λ_{QCD})?



hadronic matter

Quark Gluon Plasma (QGP)
“deconfined” quarks and gluons

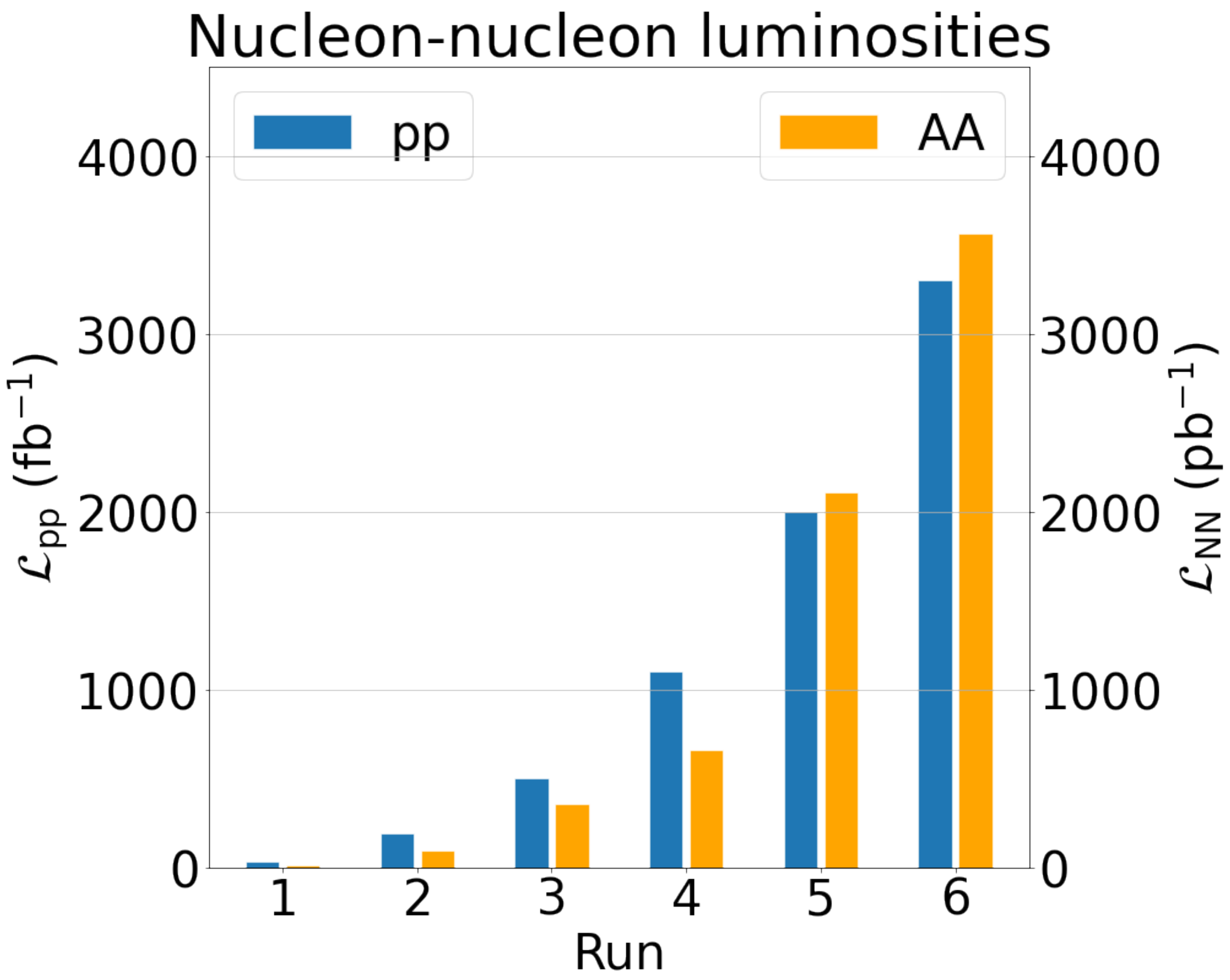


How are hadrons formed in the presence of such a phase?

→ **map the equilibrium phase diagram of nuclear matter**

H-.T. Ding et al., arXiv 1504.05274
W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018

Heavy-ion program at the LHC



Pb-Pb luminosity limited by LHC
~1-2·10^{27} cm^{-2} s^{-1}

Run 3 → high luminosity for ions (~7·10^{27} cm^{-2} s^{-1}) and **OO**

- improved collimation systems
  - ➟ lifted limitation in the LHC from bound-free pair production
  - ➟ ion luminosities now limited by bunch intensities from injectors

Run 4 → HL-LHC

- push pp luminosity to 4·10^{34} cm^{-2} s^{-1}

Run 5 → higher luminosities for ions

- mitigate SC effects in SPS & LEIR, e.g. with lighter species

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
LHC schedule	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA

Detector needs

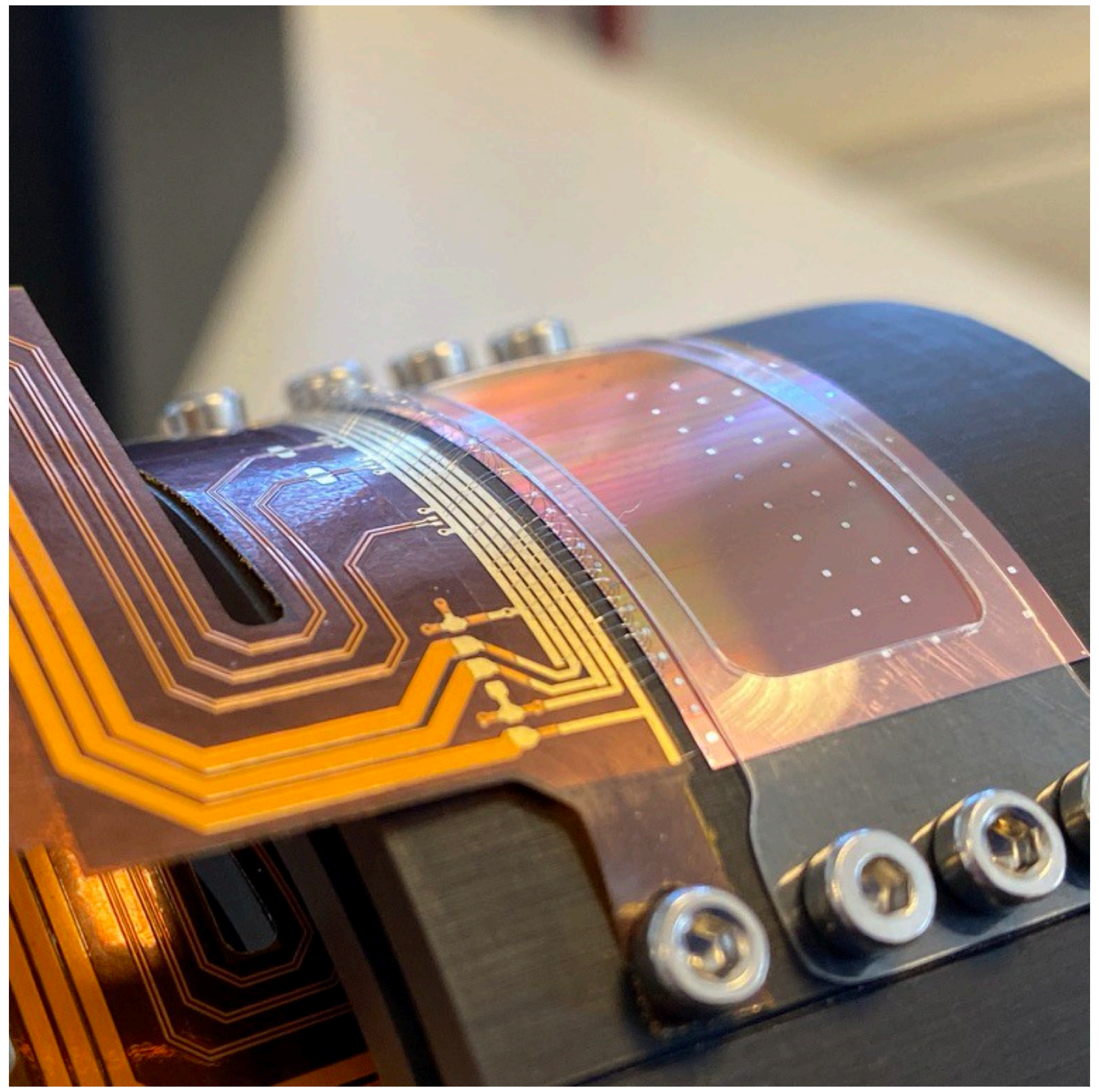
System	Physics areas	Requirements	Specifications	Detectors
Vertexing	Multi-charmed baryons, dielectrons (HF rejection)	DCA resolution ~10 µm (p_T > 200 MeV/c)	P.R. ~1 µm, R_{in} ~5 mm, X/X_0 ~0.1 % / layer	inner tracker based on MAPS w/ pitch ≲ 10 µm
Tracking	Multi-charmed baryons, di-electron mass reso	σ_{p_T} / p_T ~2 %	P.R. ~10 µm, X/X_0 ~1 % / layer	outer tracker based on MAPS w/ pitch 30-50 µm
h-ID	Multi-charmed baryons	π/K/p separation up to 4-5 GeV/c	π/K/p separation up to 4-5 GeV/c	TOF (20 ps) + RICH TOF + DIRC
e-ID	Dielectrons, quarkonia, χ_{c1}(3872)	pion rejection by 1000x up to ~2 - 3 GeV/c	3σ separation of e and π up to 3 GeV/c	TOF (20 ps) + RICH TOF + preshower
***µ*-ID**	New quarkonia, χ_{c1}(3872)	efficient from p_T ~1.0 GeV/c	under study	iron absorber + muon chambers
ECal	Photons, jets, χ_c	under study	under study	PbWO4 + GAGG:Ce
low-p_T photons	Low's theorem	identification and energy determination of photons in p_T range 10 - 50 MeV/c	under study	Forward conversion tracker high-resolution ECal?

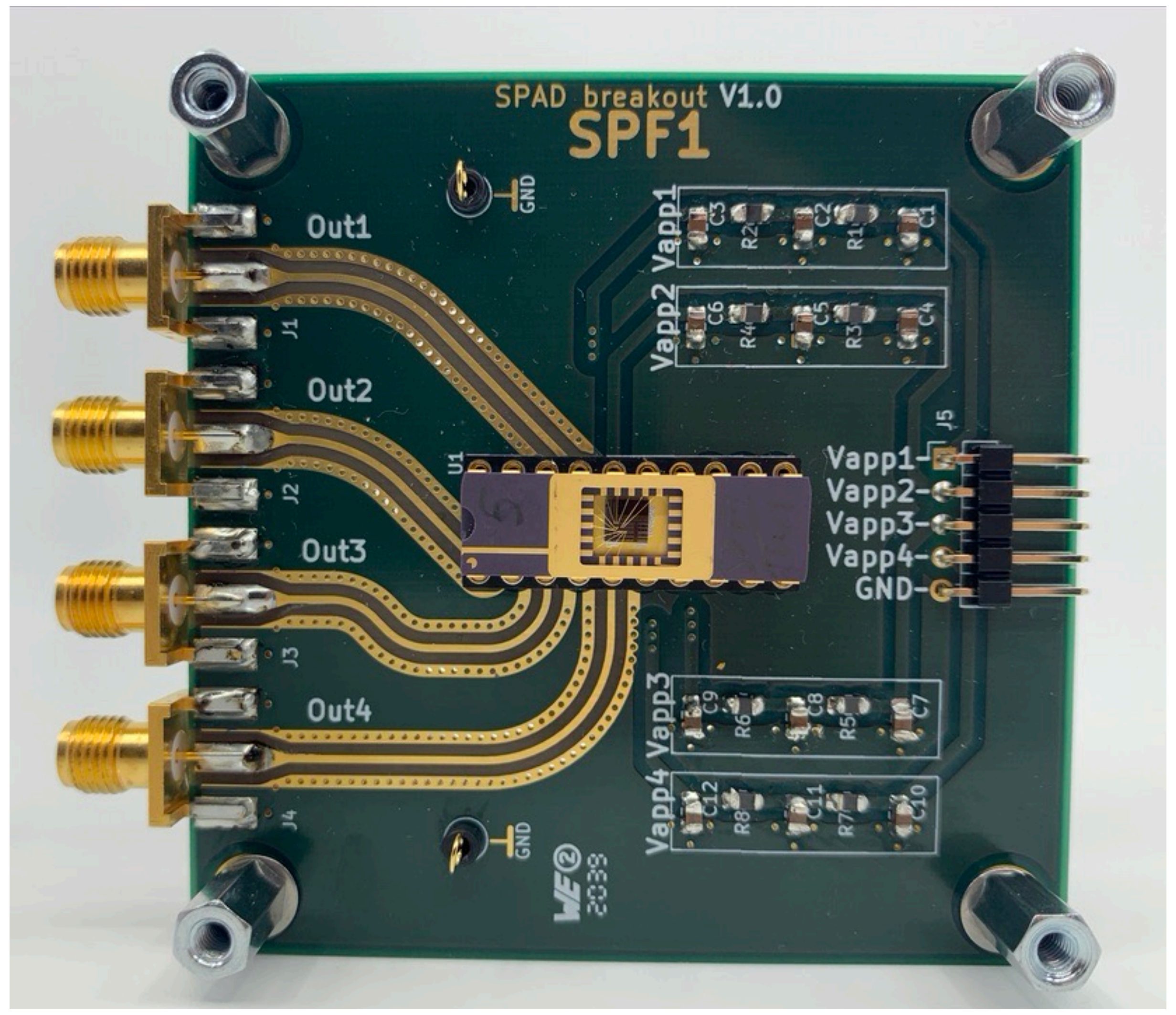
Strategic R&D

- **Silicon pixel sensors**
  - thinning and bending of silicon sensors
    → expand on experience with ITS3
  - exploration of new CMOS processes
    → first in-beam tests with 65 nm process
  - modularisation and industrialisation
- **Silicon timing sensors**
  - characterisation of SPADs/SiPMs
    → first tests in beam
  - monolithic timing sensors
    → implement gain layer
- **Photon sensors**
  - monolithic SiPMs
    → integrate read-out
- **Detector mechanics and cooling**
  - mechanics for operation in beam pipe
    → establish compatible with LHC beam
  - minimisation of material in the active volume
    → micro-channel cooling

Unique and relevant technologies

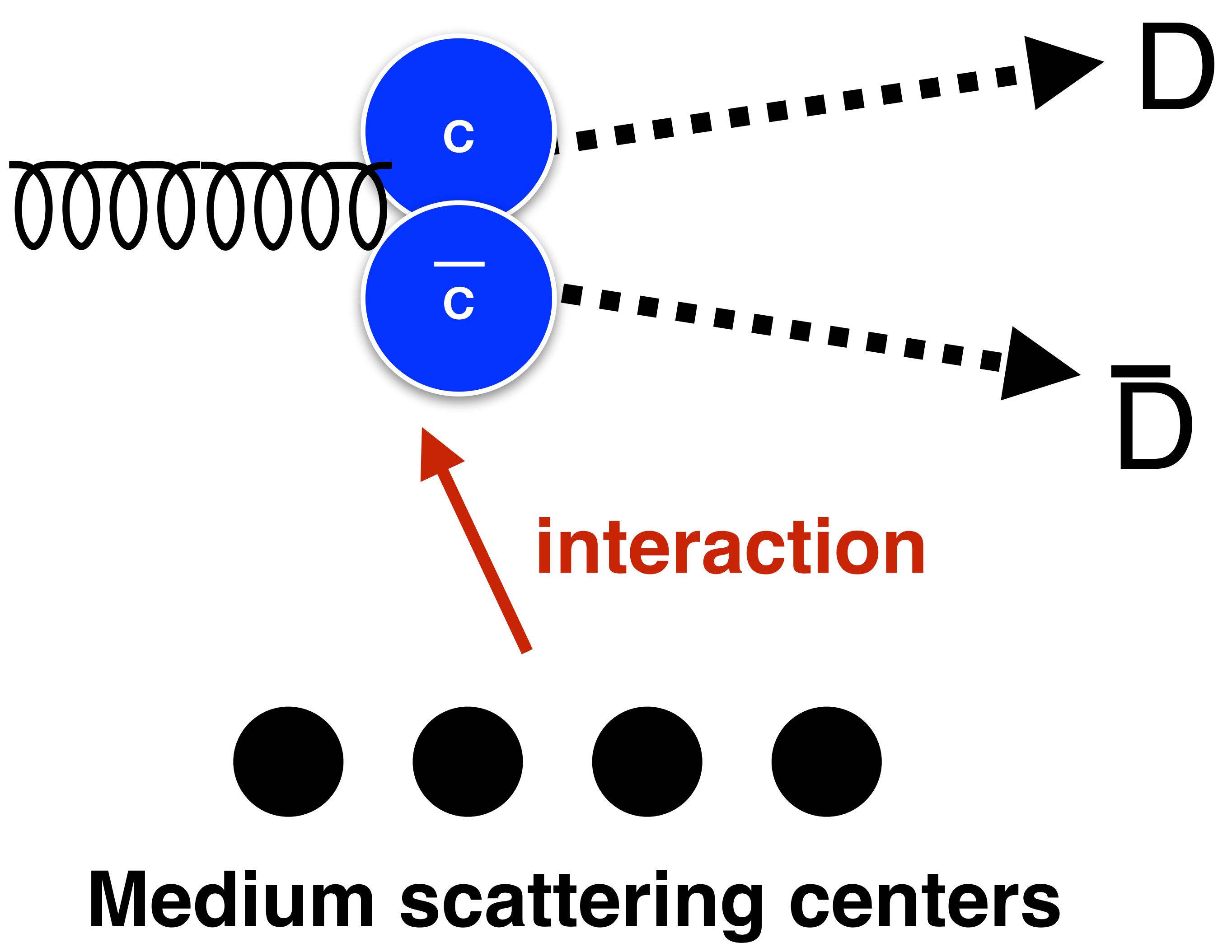
→ Synergies with LHC, FAIR, EIC, …

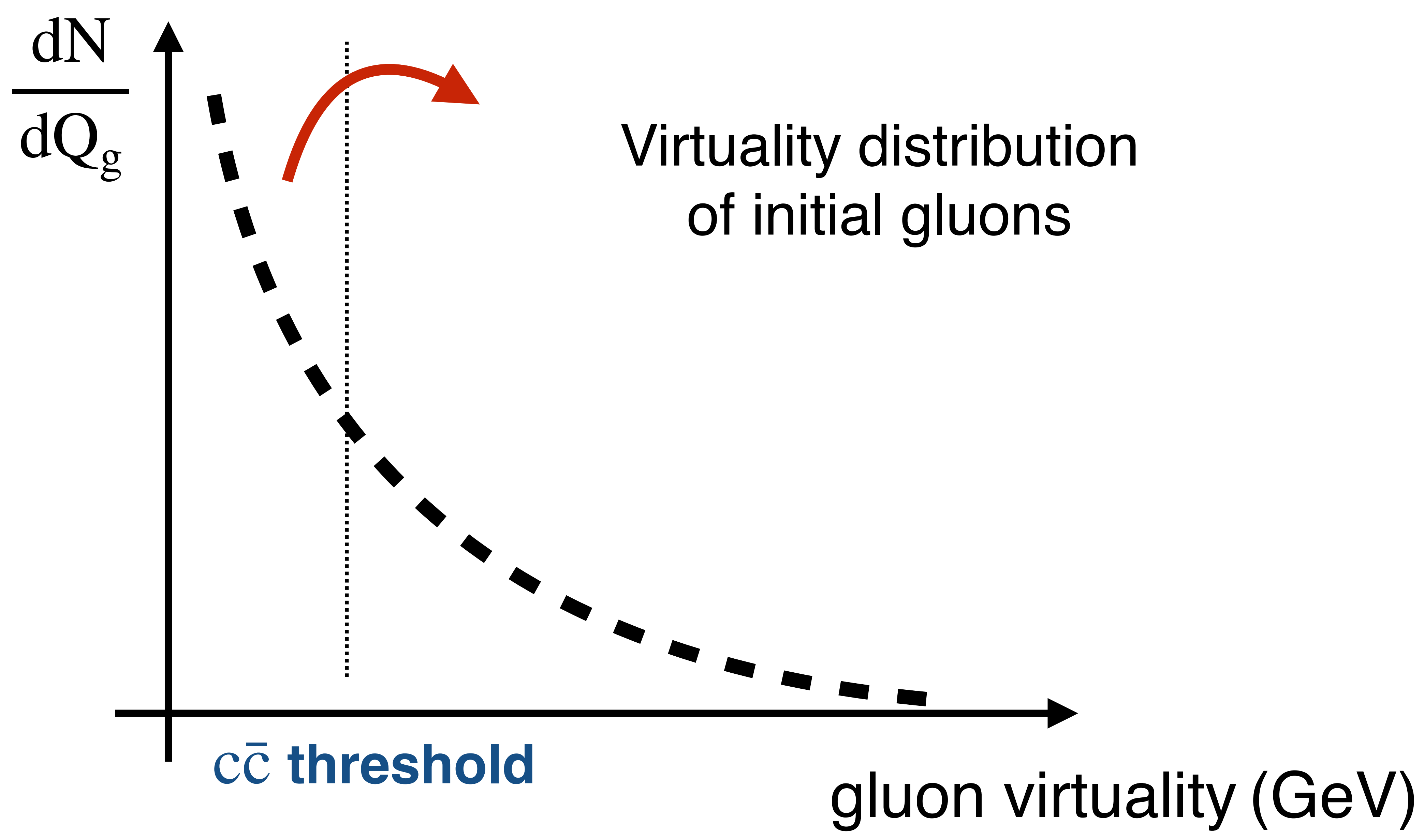




Enhancement of the $g \rightarrow c\bar{c}$ splitting probability

With BDMPS-Z, **first calculation of $P^{medium}(g \rightarrow c\bar{c}) = P^{vac} + P^{mod}$**





Significant increase of the $g \rightarrow c\bar{c}$ in medium:

- interaction with QGP increases production of a traceable quantity → **measurable**

→ **Yields of $D\bar{D}$ tagged jets in pp and PbPb collisions would allow to explore these mechanisms**
→ **Measurements to be explored with the upcoming high-luminosity data**

Papers in preparation, QM 2022