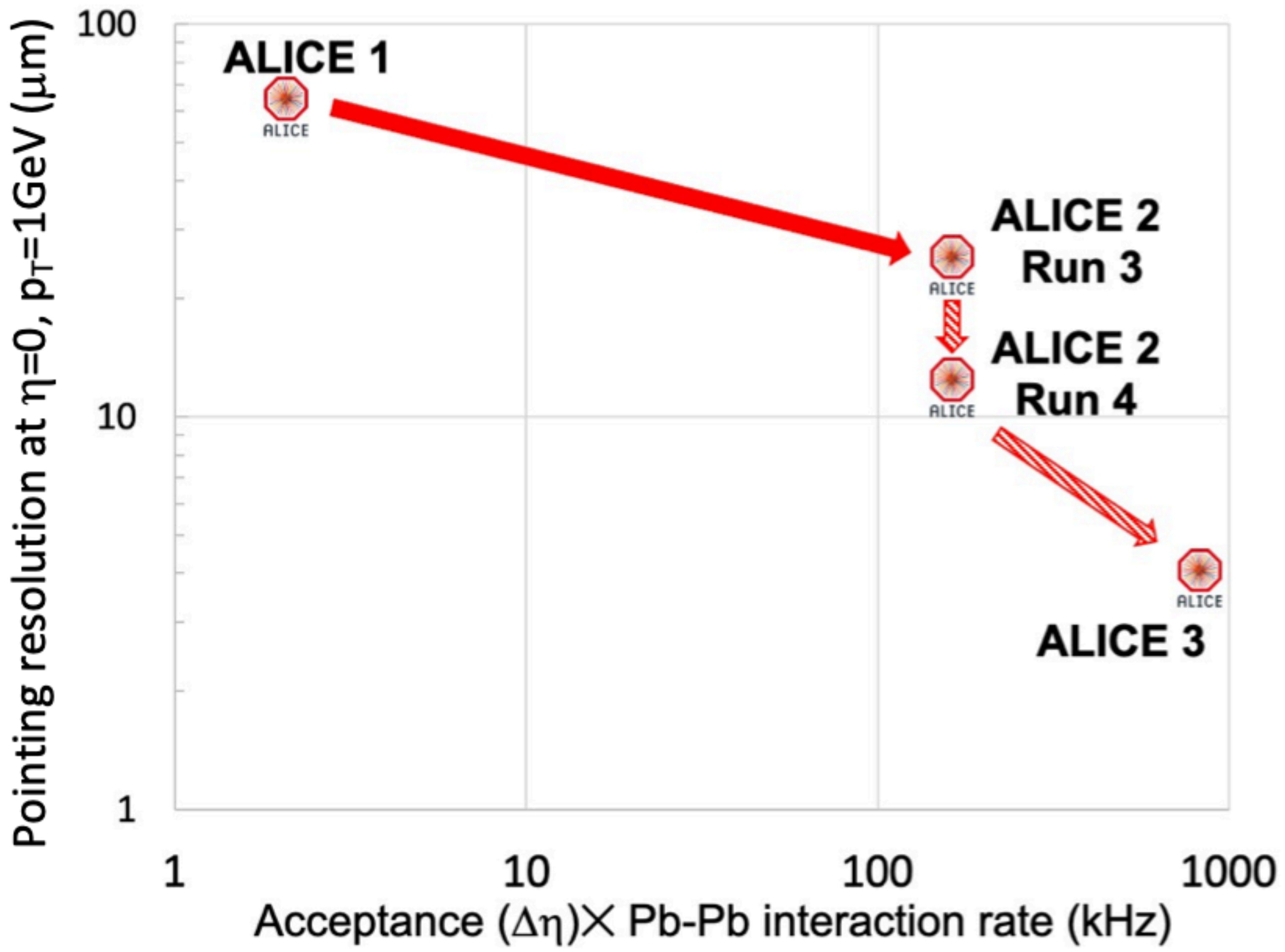
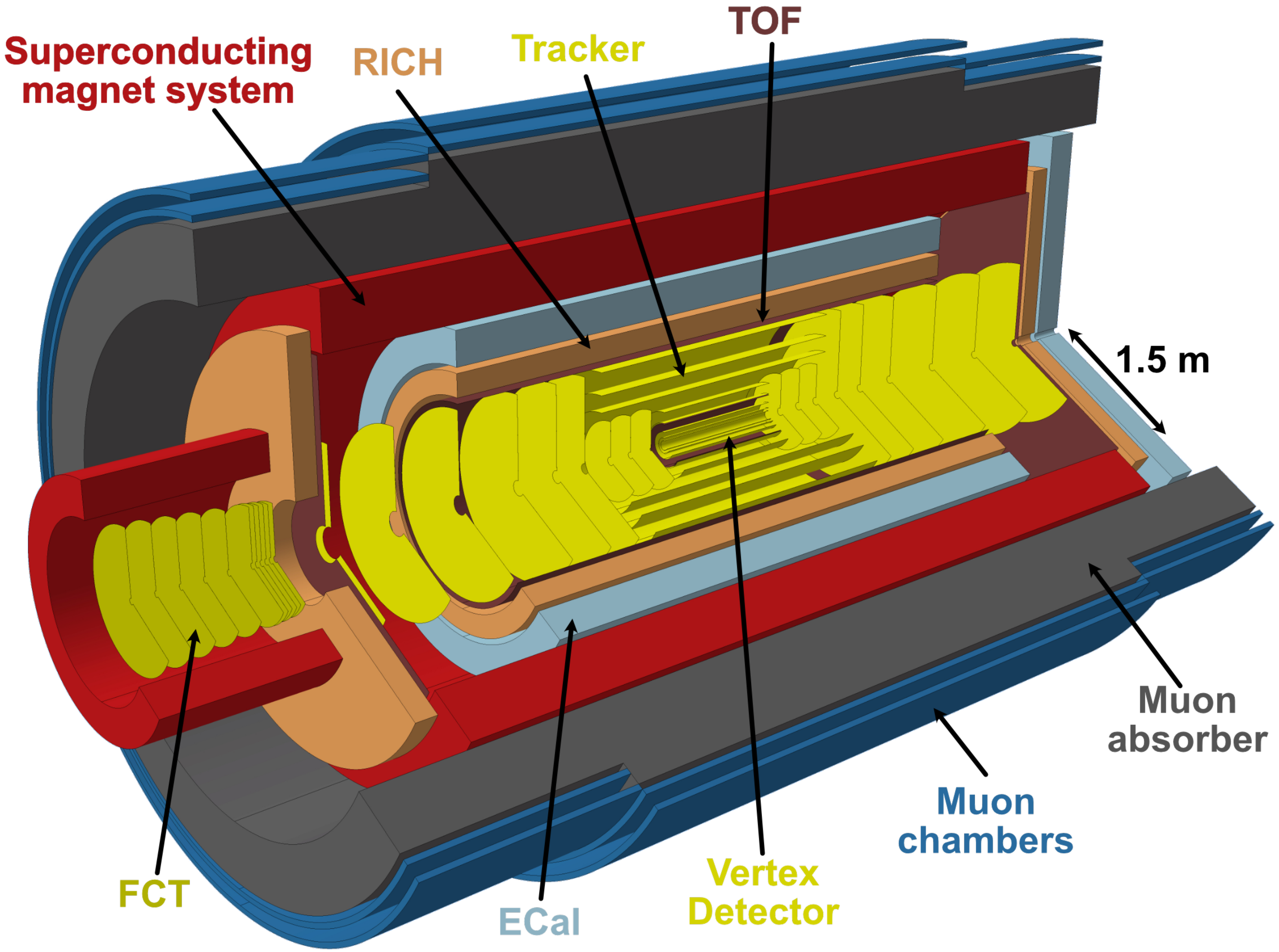
ALICE 3: a next-generation heavy-ion programme

Marco van Leeuwen,
Nikhef and CERN

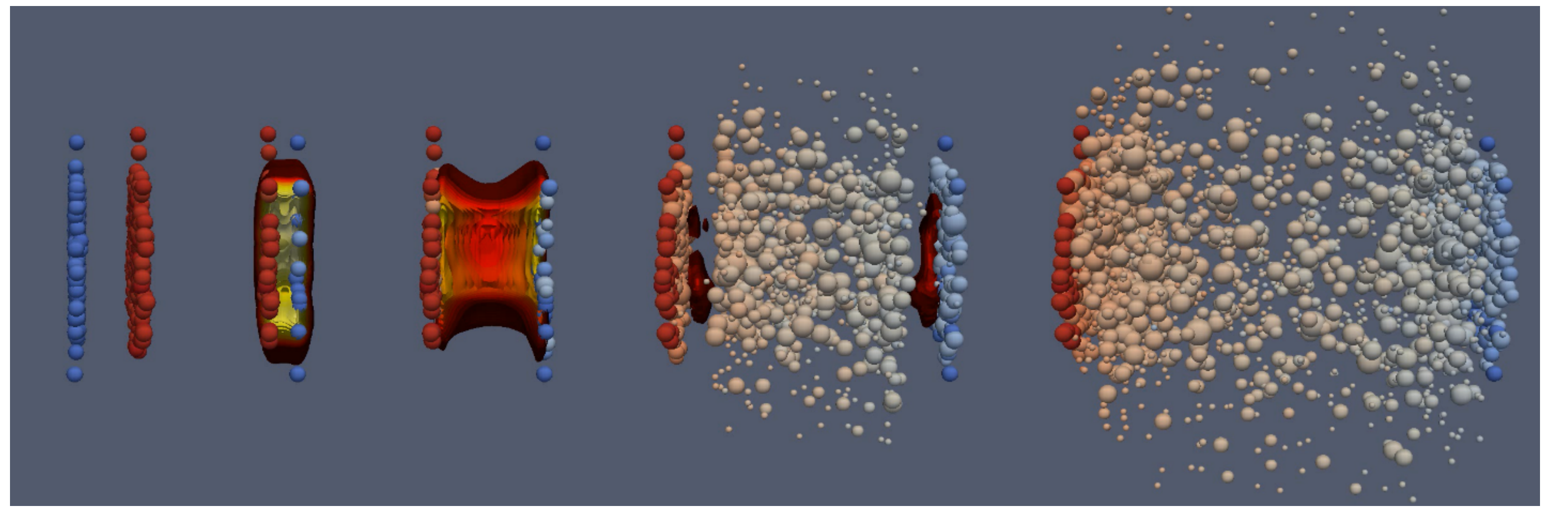
ALICE 3: A next-generation heavy ion detector

- Compact and lightweight all-silicon tracker
  - Excellent pointing resolution with a retractable vertex detector
- Extensive particle identification: TOF, RICH
- Large acceptance





ALICE 3 key physics questions



Key questions in our field

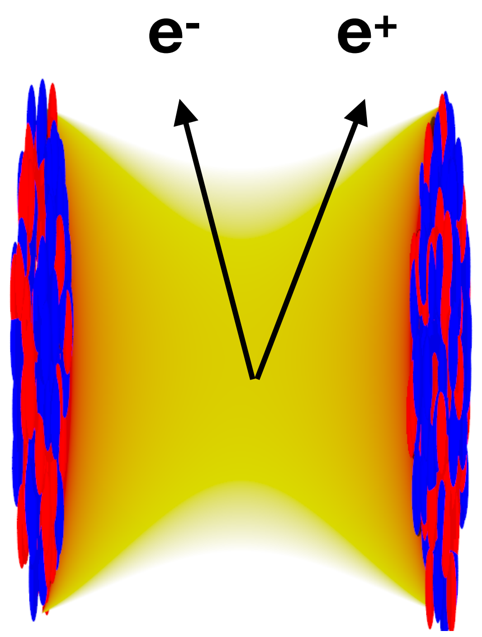
- What is the nature of **interactions between high-energy quarks and gluons and the the quark-gluon plasma**? How do transport properties arise from first-principle quantum chromodynamics?
- Which mechanisms **drive strongly-interacting matter towards thermal equilibrium**? To what extent do heavy quarks of different mass reach thermal equilibrium with the plasma? How do they behave close to the diffusion regime?
- What is the process of the **formation of hadrons emitted by the quark-gluon plasma**?
- What are the **mechanisms for the restoration of chiral symmetry in the quark-gluon plasma**?

Most of these will not be fully addressed by the end of Run 3 and 4

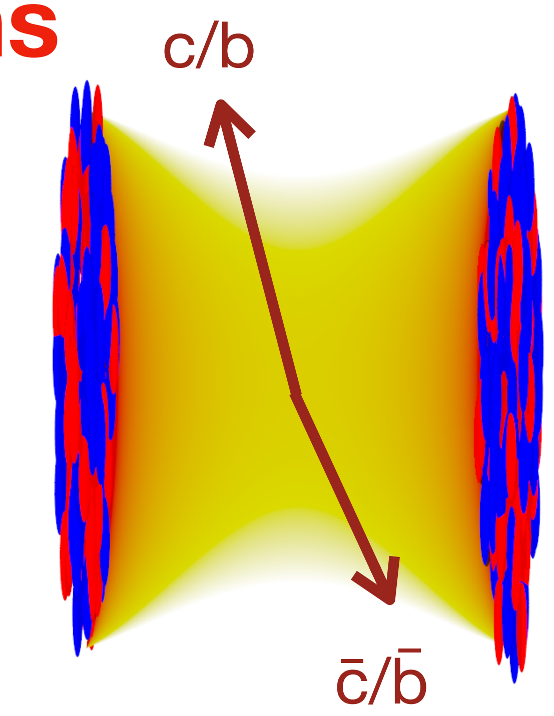
ALICE 3 provides unique opportunities to answer some of these questions

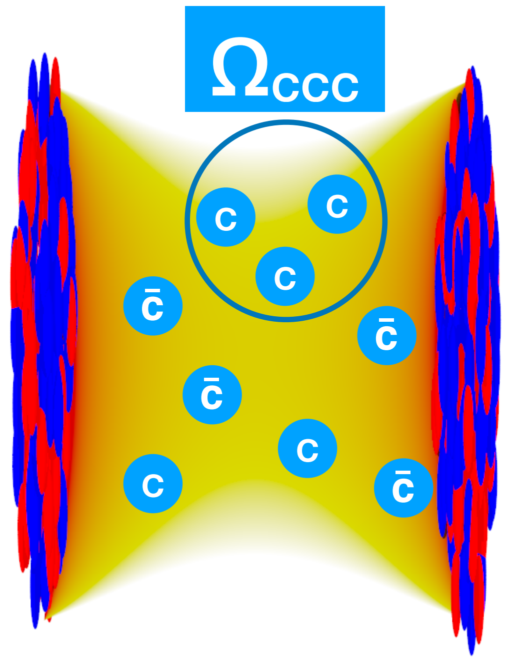
ALICE 3 programme

- **precision measurements of dileptons**
  - ➡ evolution of the quark gluon plasma
  - ➡ mechanisms of chiral symmetry restoration in the quark-gluon plasma

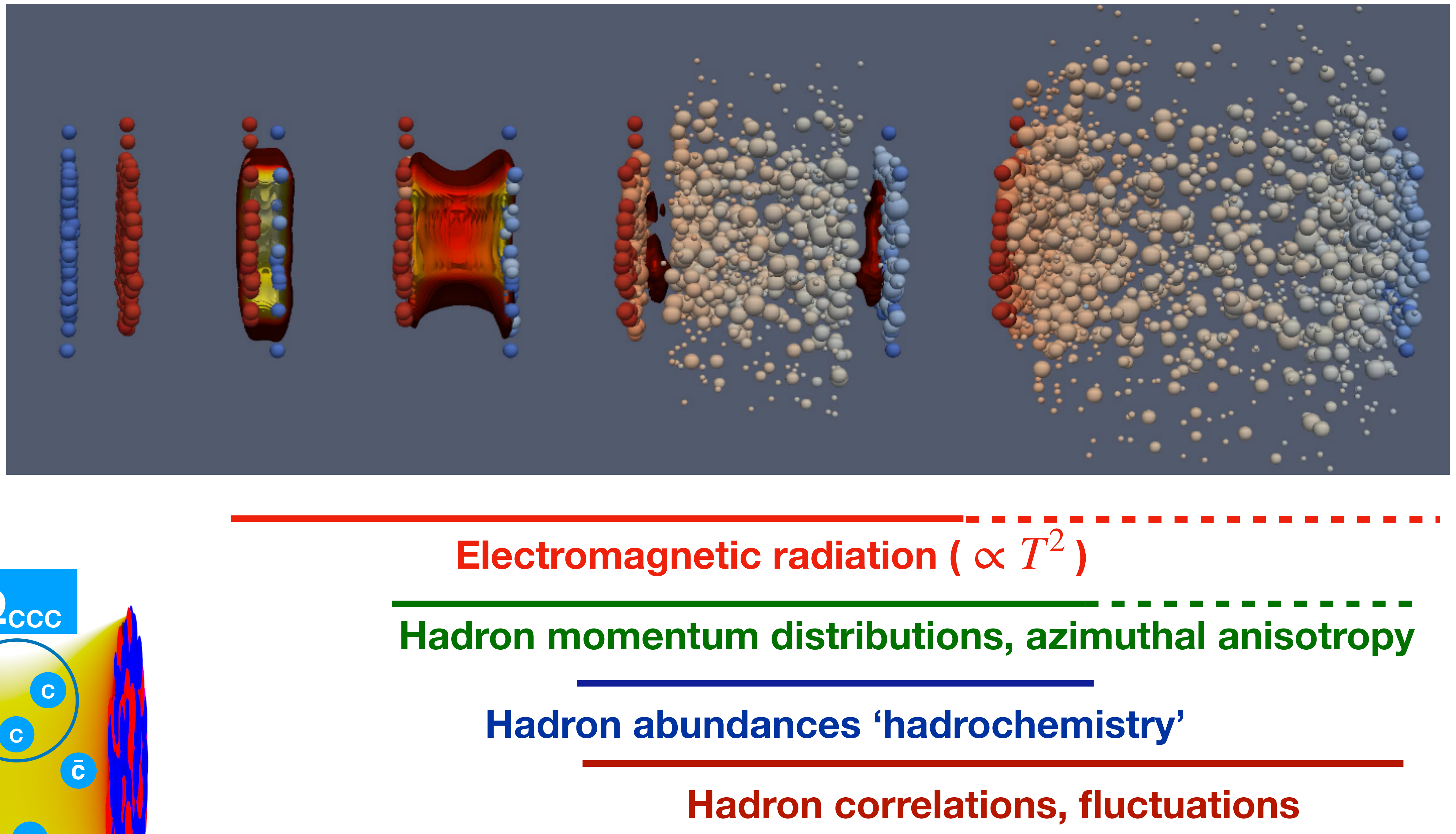


- **systematic measurements of (multi-)heavy-flavoured hadrons**
  - ➡ transport properties in the quark-gluon plasma
  - ➡ mechanisms of hadronisation from the quark-gluon plasma





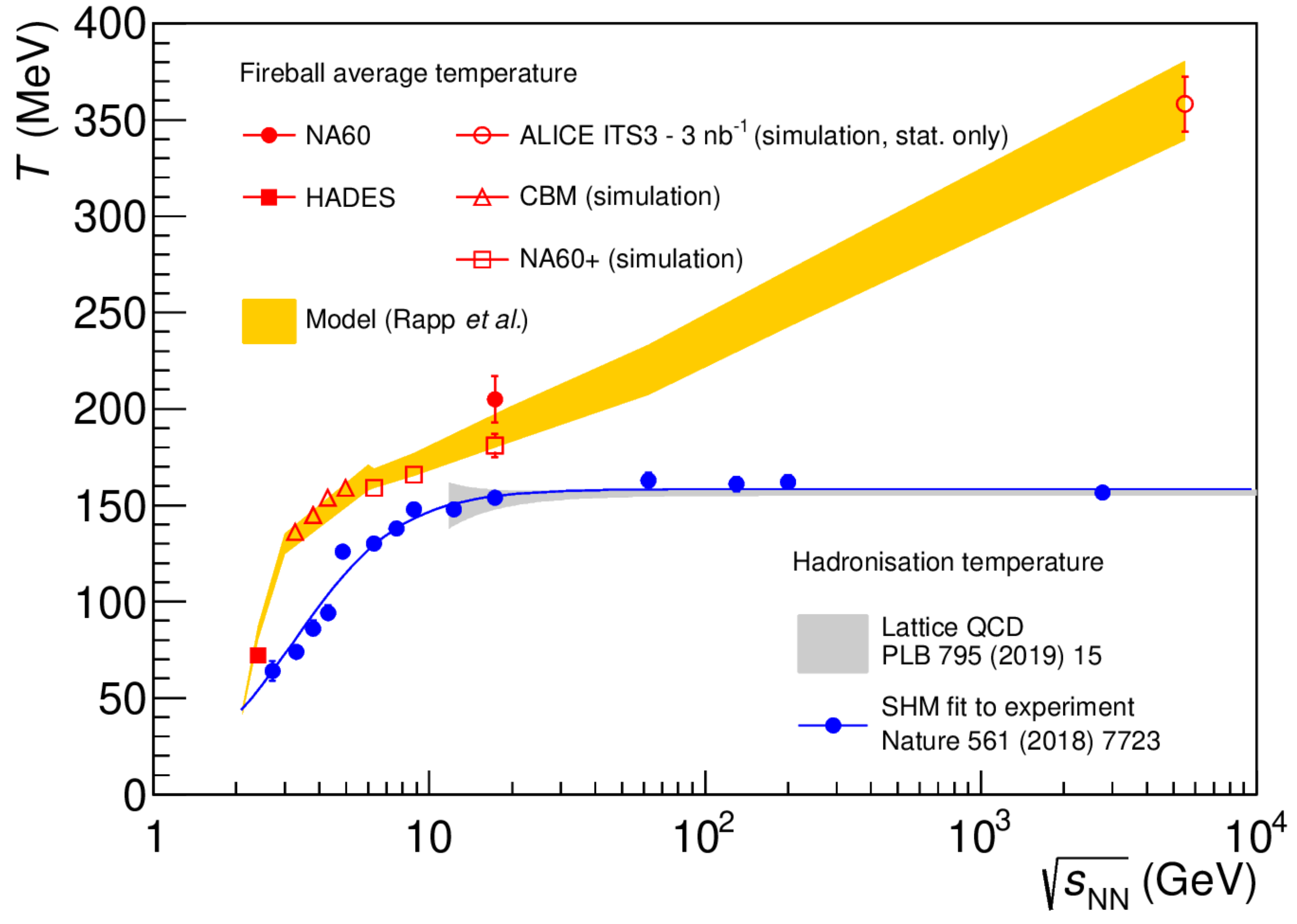
- **hadron correlations**
  - ➡ interaction potentials
  - ➡ fluctuations
- …



Electromagnetic radiation

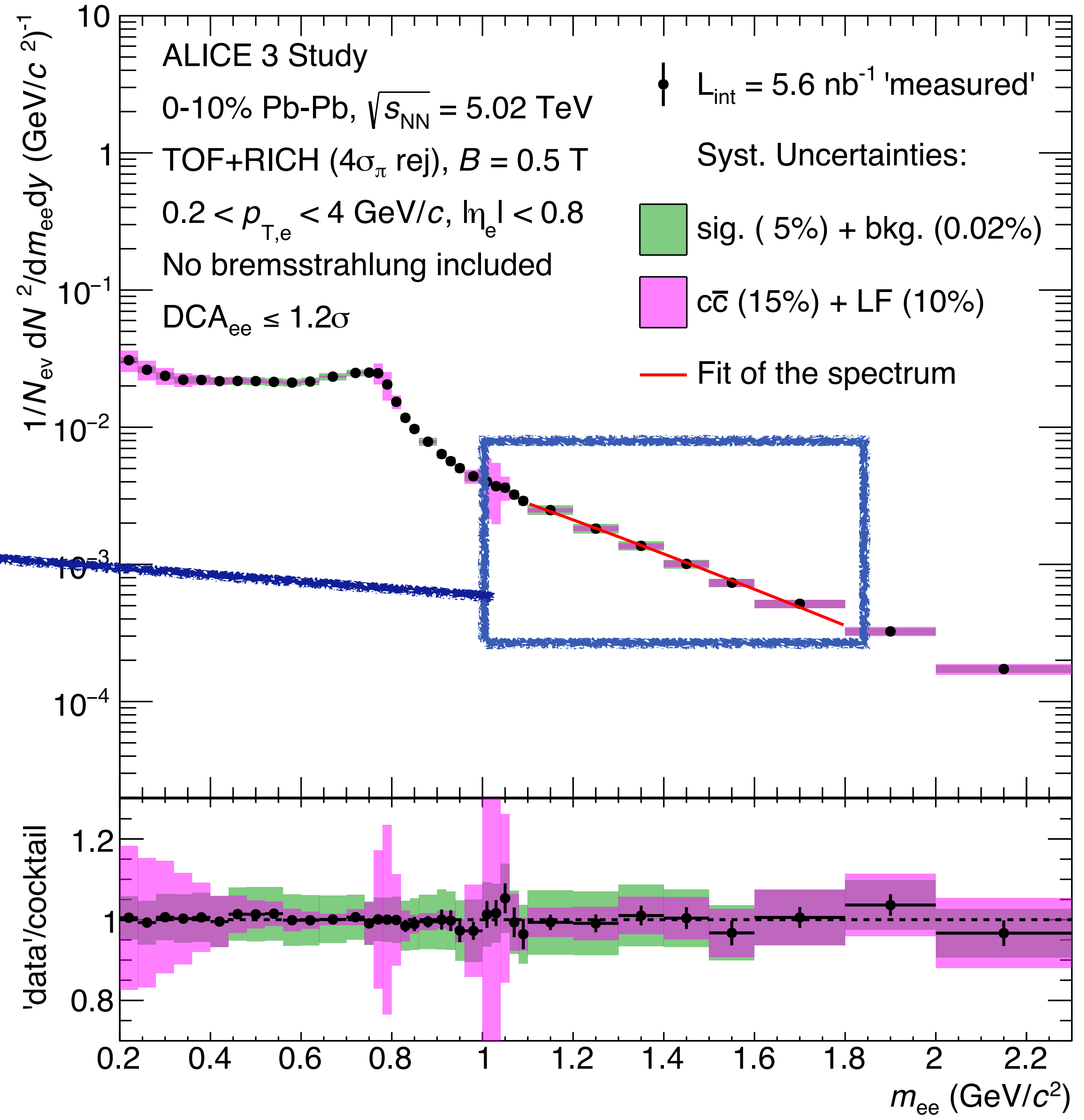
- Access to precise QGP temperature
  - First measurements in Run 3 and 4
- **ALICE 3**: access time evolution and flow field ('photon puzzle')
  - Dilepton v_2 vs mass and p_T
  - Double-differential spectra: T vs mass, p_T
- **ALICE 3**: high precision in ρ-a_1 mixing region
- Complementary measurements with photons

T vs energy



Dilepton mass

Direct measure of temperature



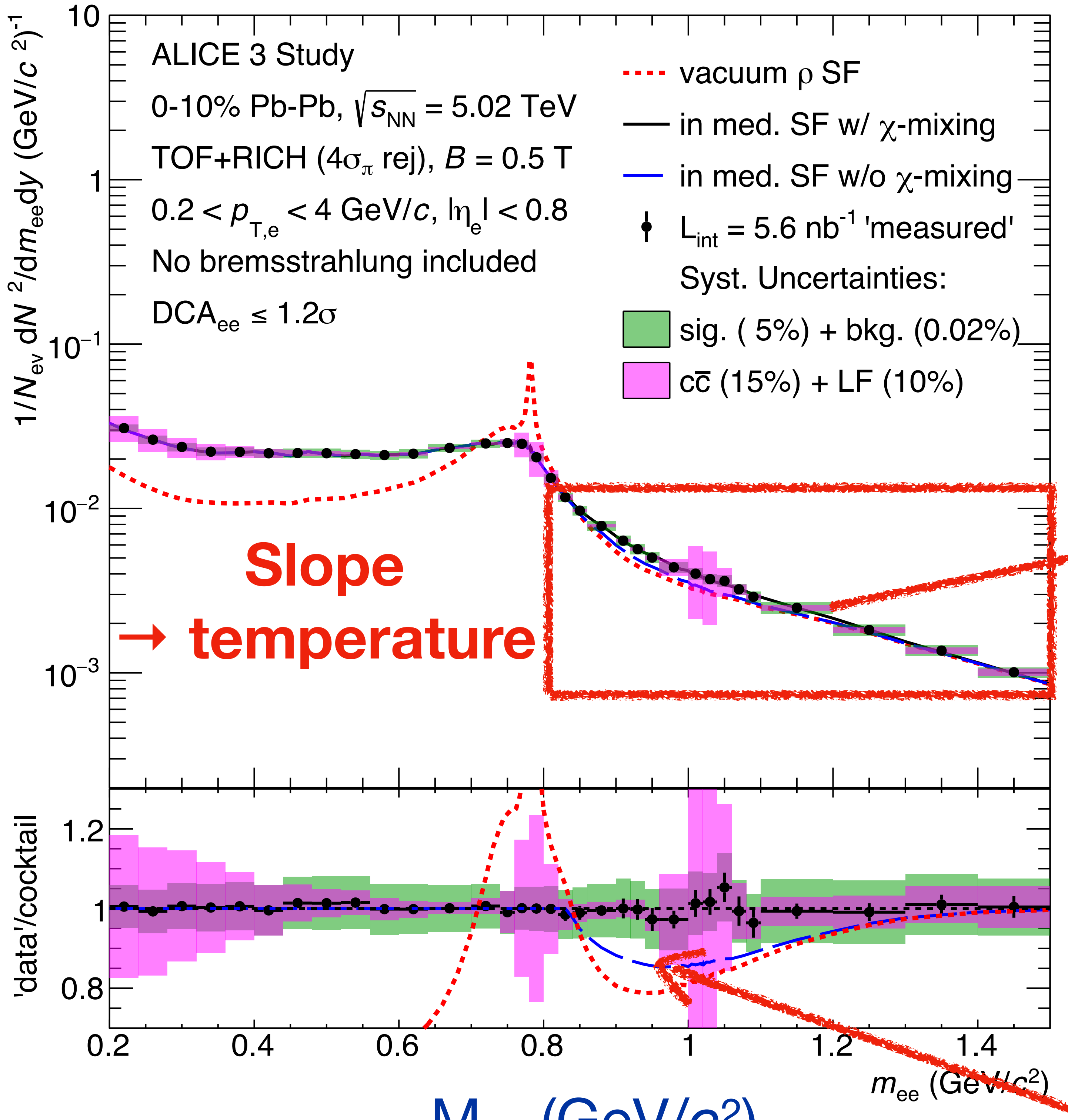
Need excellent electron ID (hadron rejection),
low-mass detector (conversion bkg),
excellent pointing resolution (HF decay bkg)
Photon detection: conversions + ECAL

Time evolution & chiral symmetry

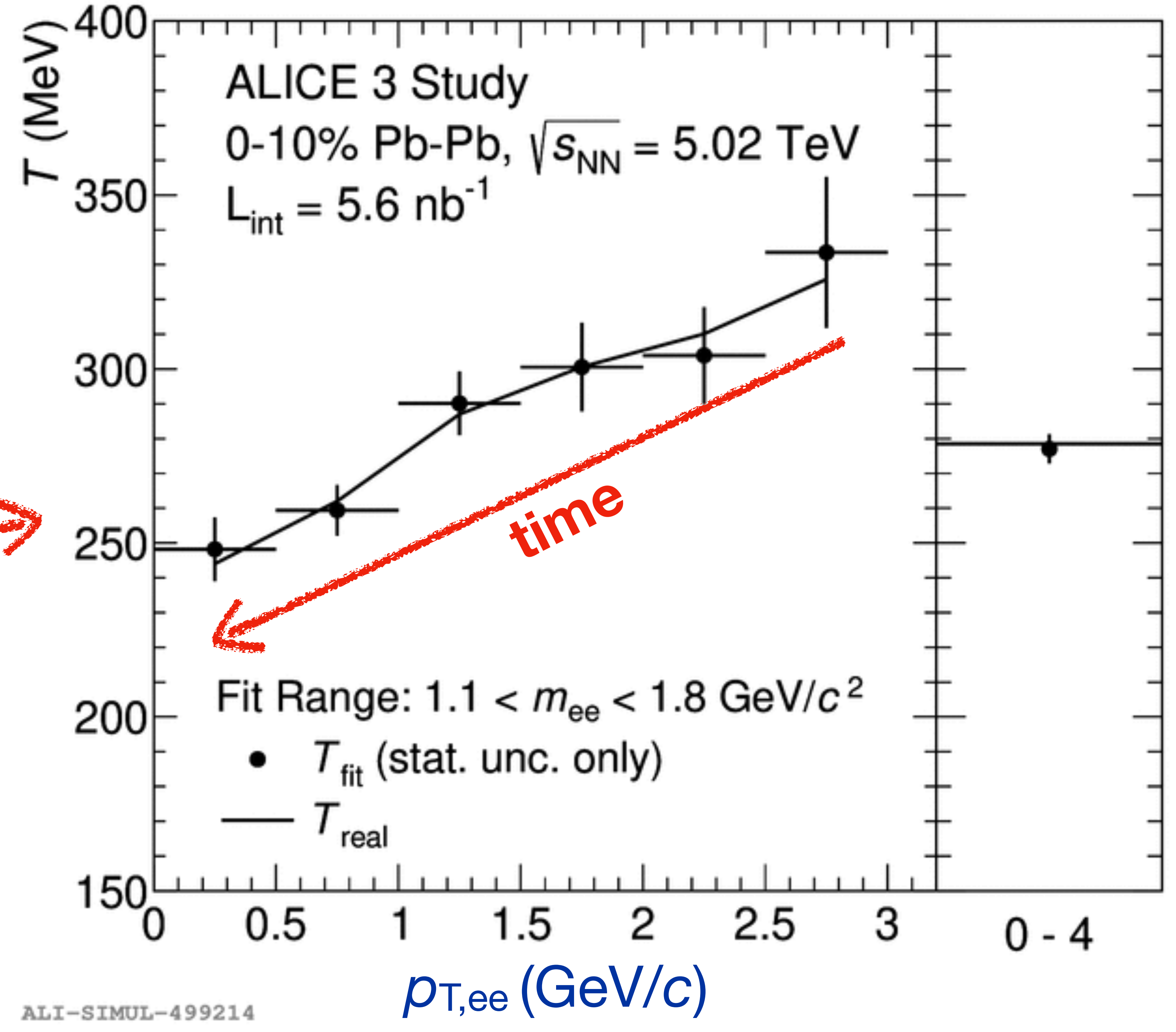
- **Understand time evolution and mechanisms of chiral symmetry restoration**
  → high-precision measurements of dileptons, also multi-differentially
  → further reduced material; excellent heavy-flavour rejection

[CERN-LPCC-2018-07]

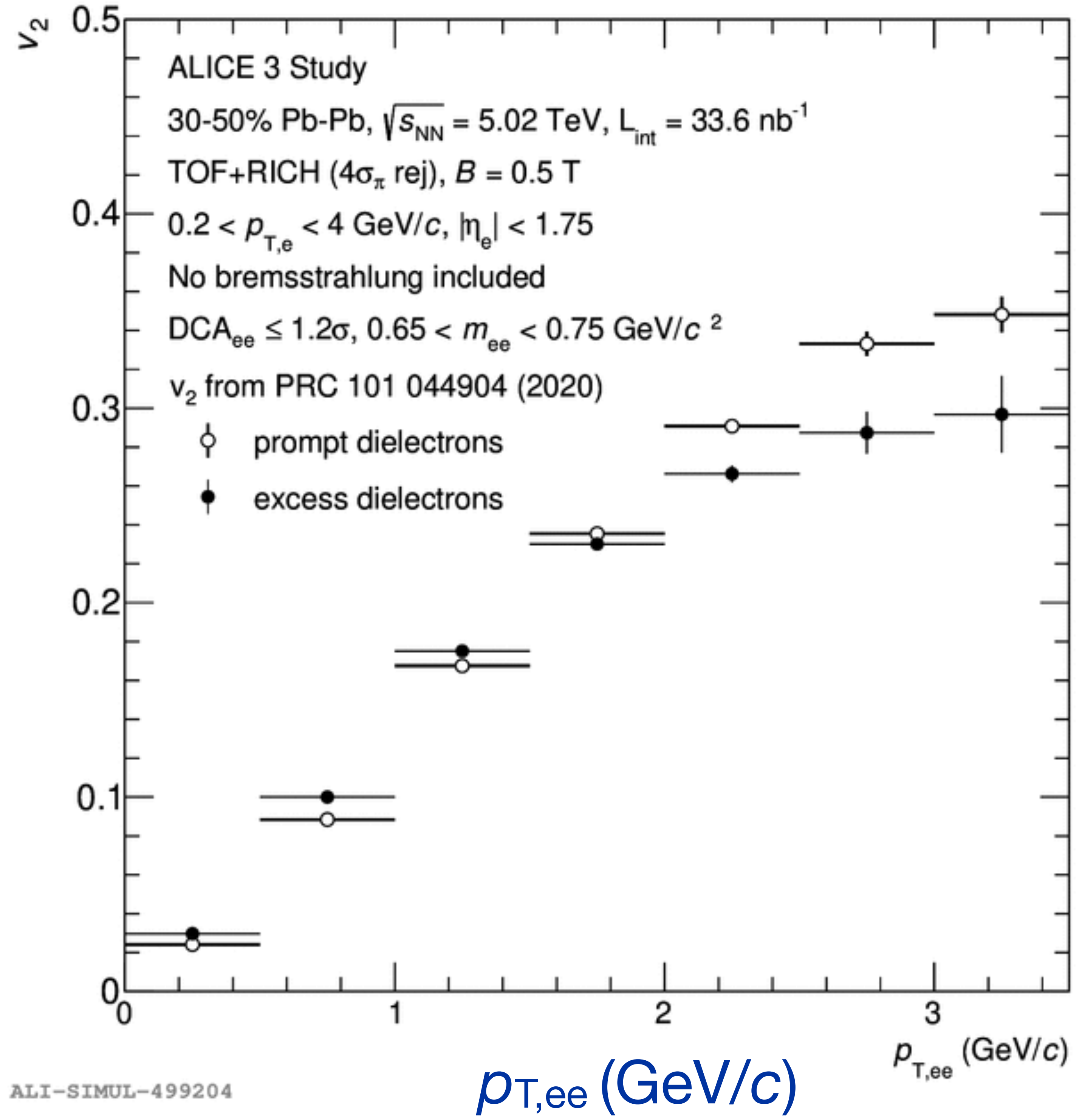
Invariant mass spectrum of dielectrons



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



Dilepton v_2
→ time dependence of emission



Without ρ-a_1 mixing
→ dip in thermal spectrum

Time evolution & chiral symmetry

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  → high-precision measurements of dileptons, also multi-differentially
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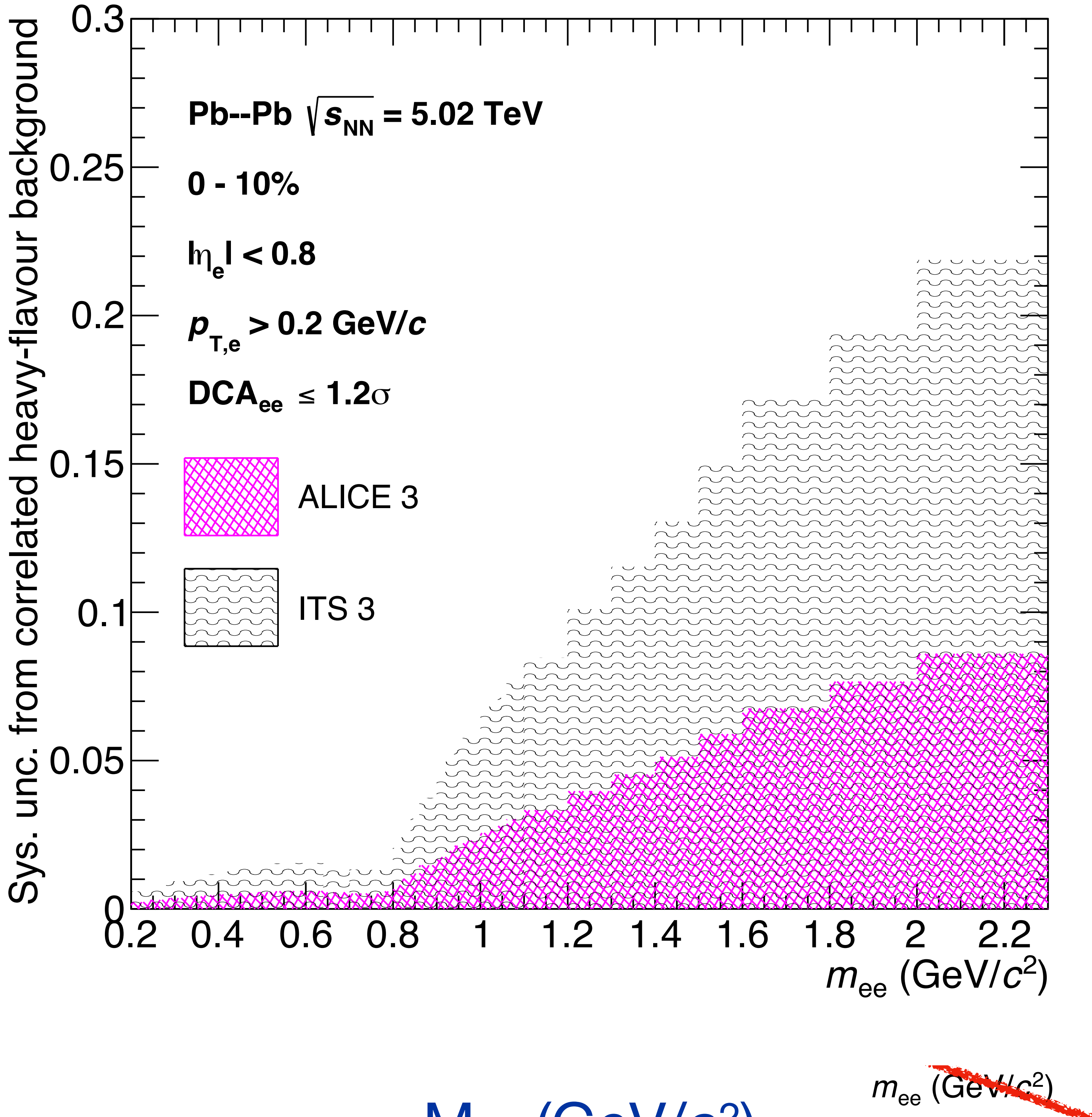
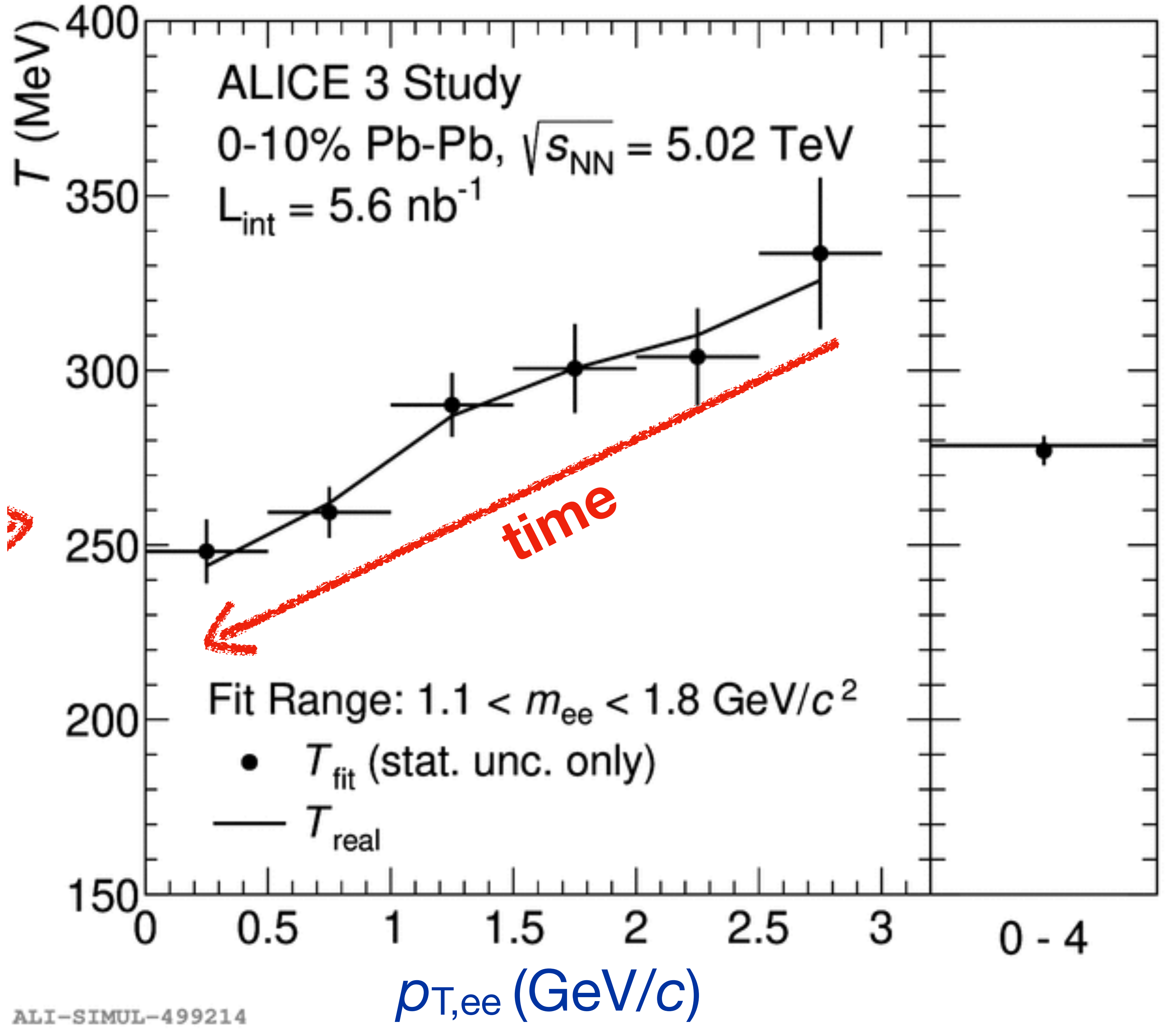
Uncertainty on mass spectrum

[CERN-LPCC-2018-07]



M_{ee} (GeV/c^2)

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



$p_{T,ee}$ (GeV/c)

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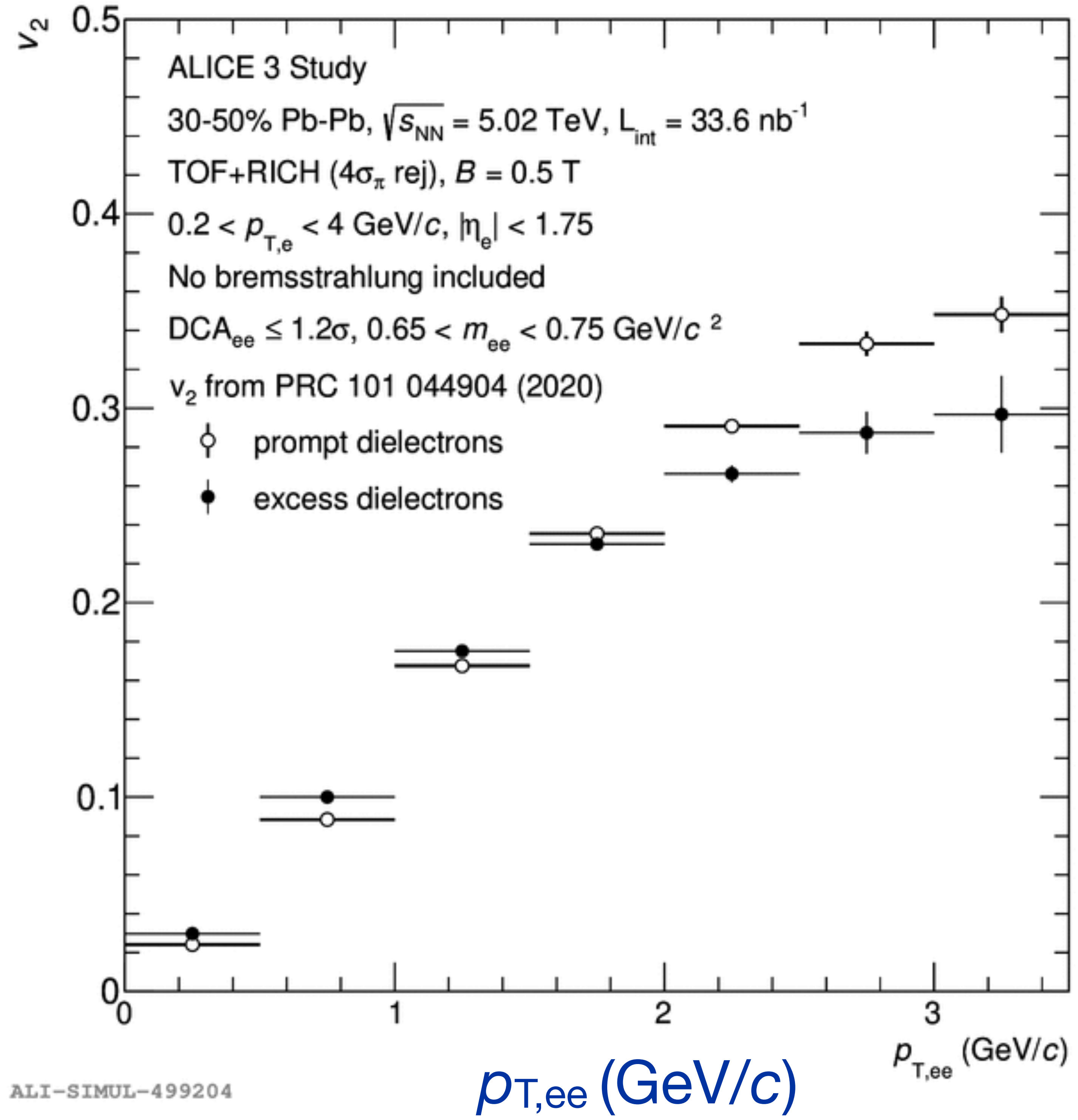
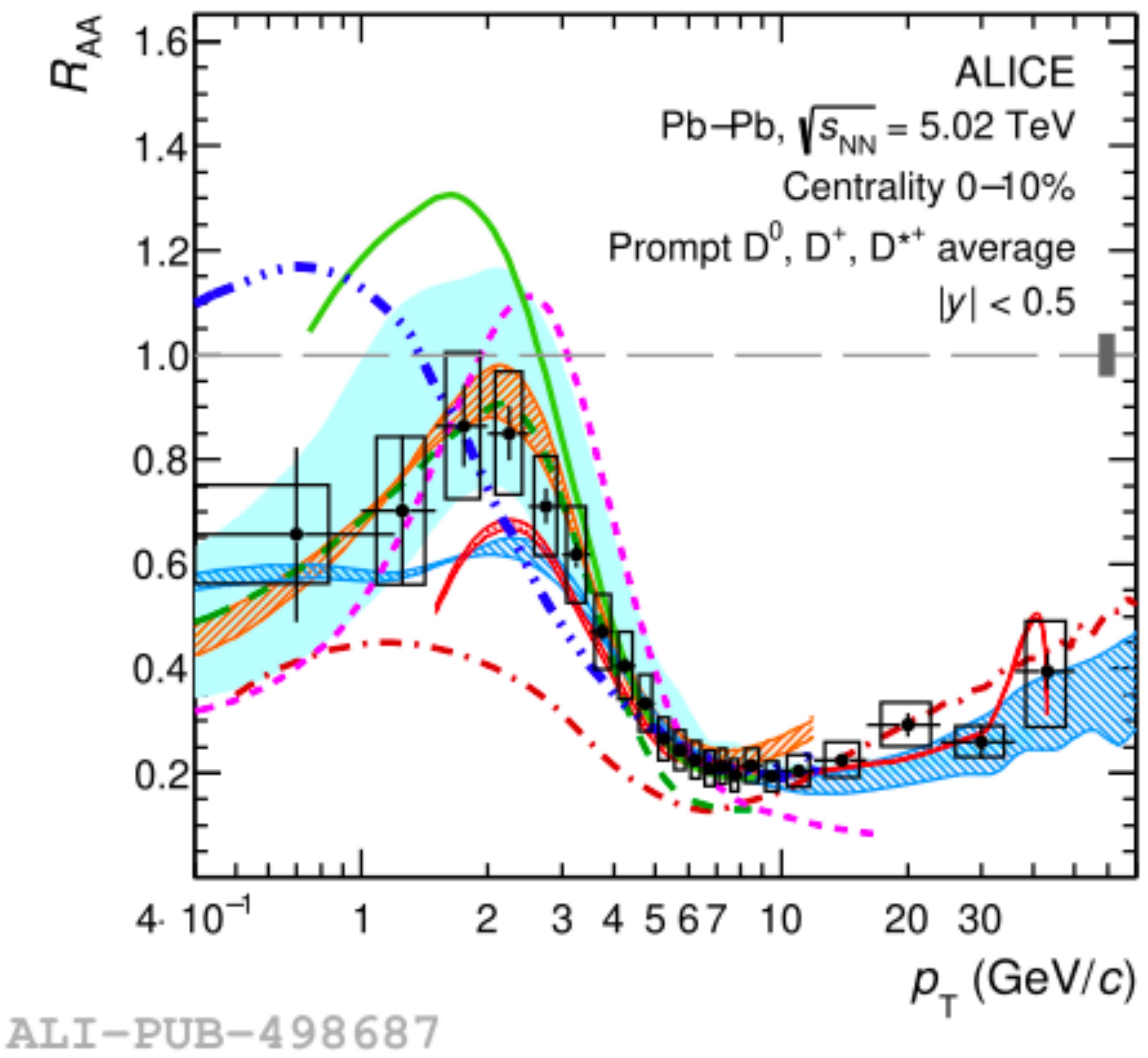


$p_{T,ee}$ (GeV/c)

Without ρ-a_1 mixing
→ dip in thermal spectrum

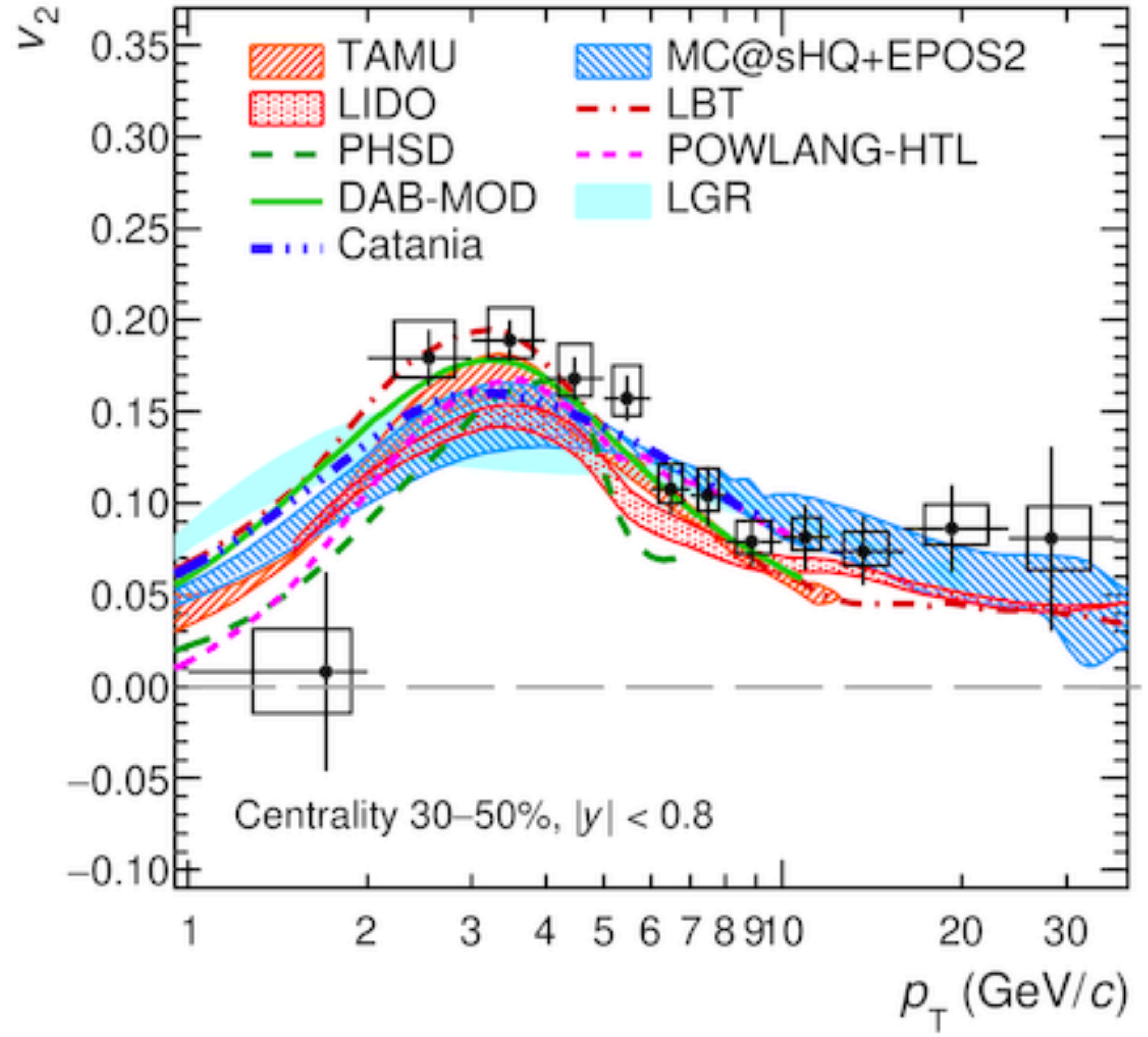
Nuclear modification and elliptic flow of D mesons

Nuclear modification factor



ALICE, arXiv:2110.09420

Elliptic flow v_2



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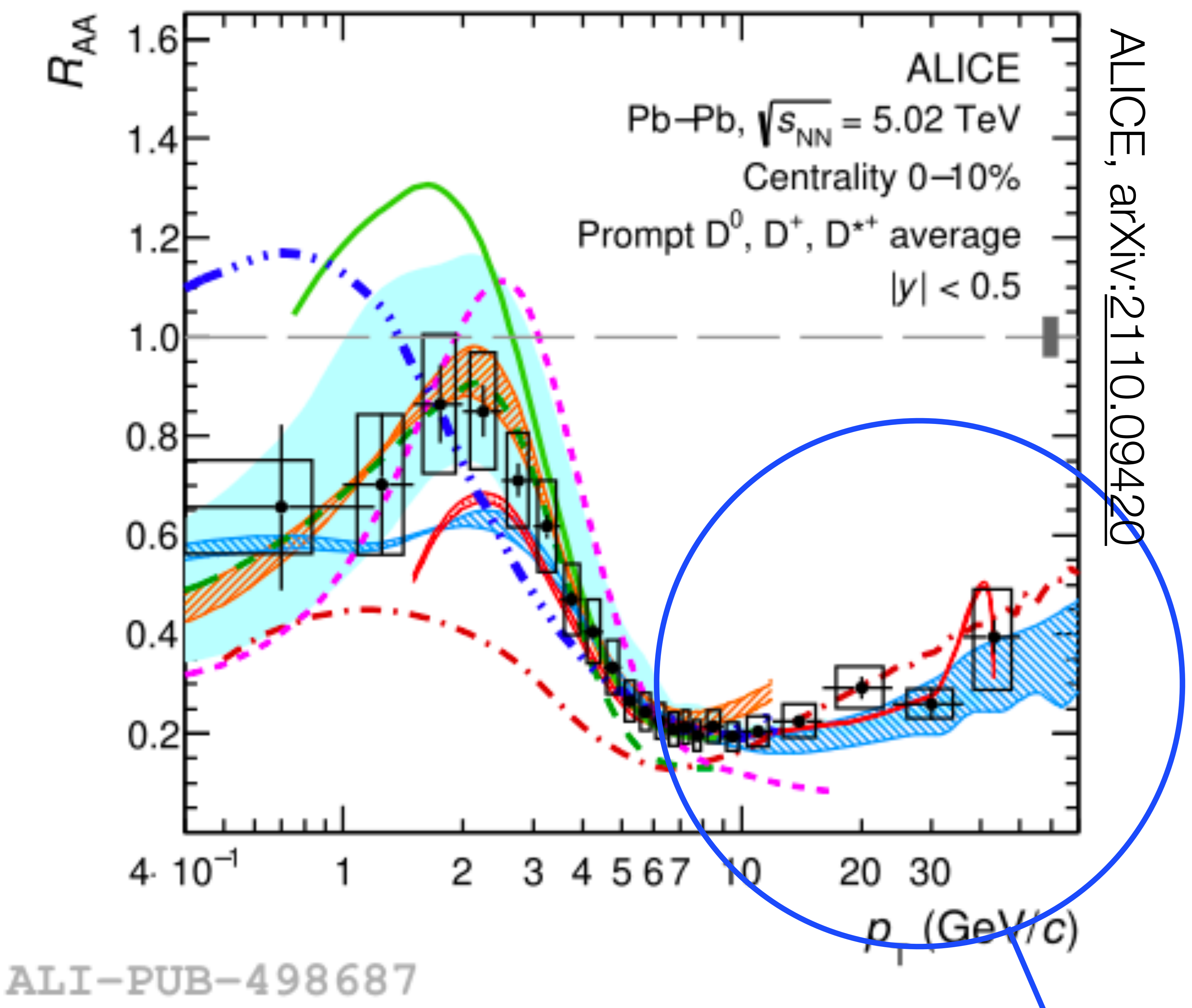

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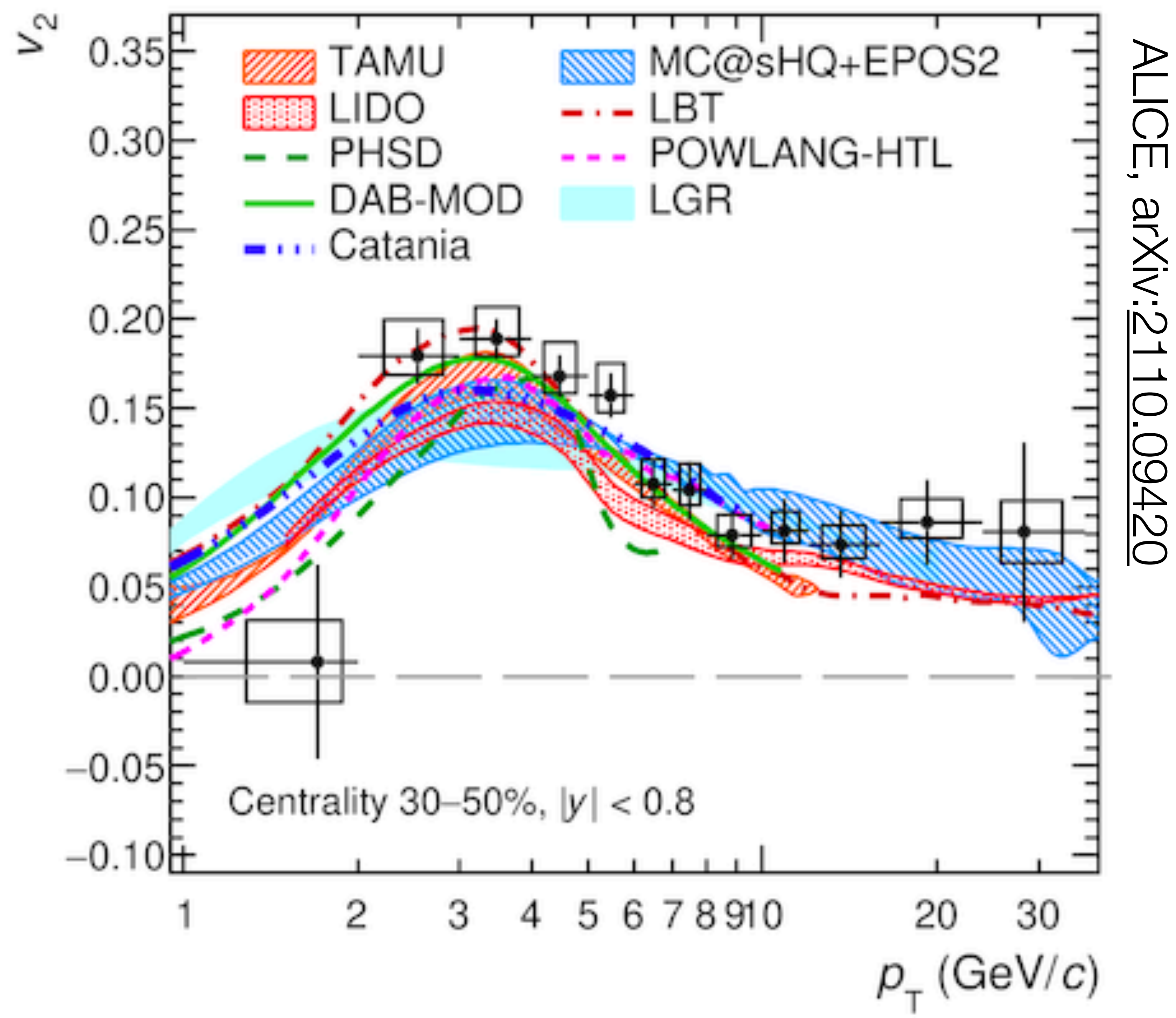

High-p_T suppression:
due to energy loss/thermalisation

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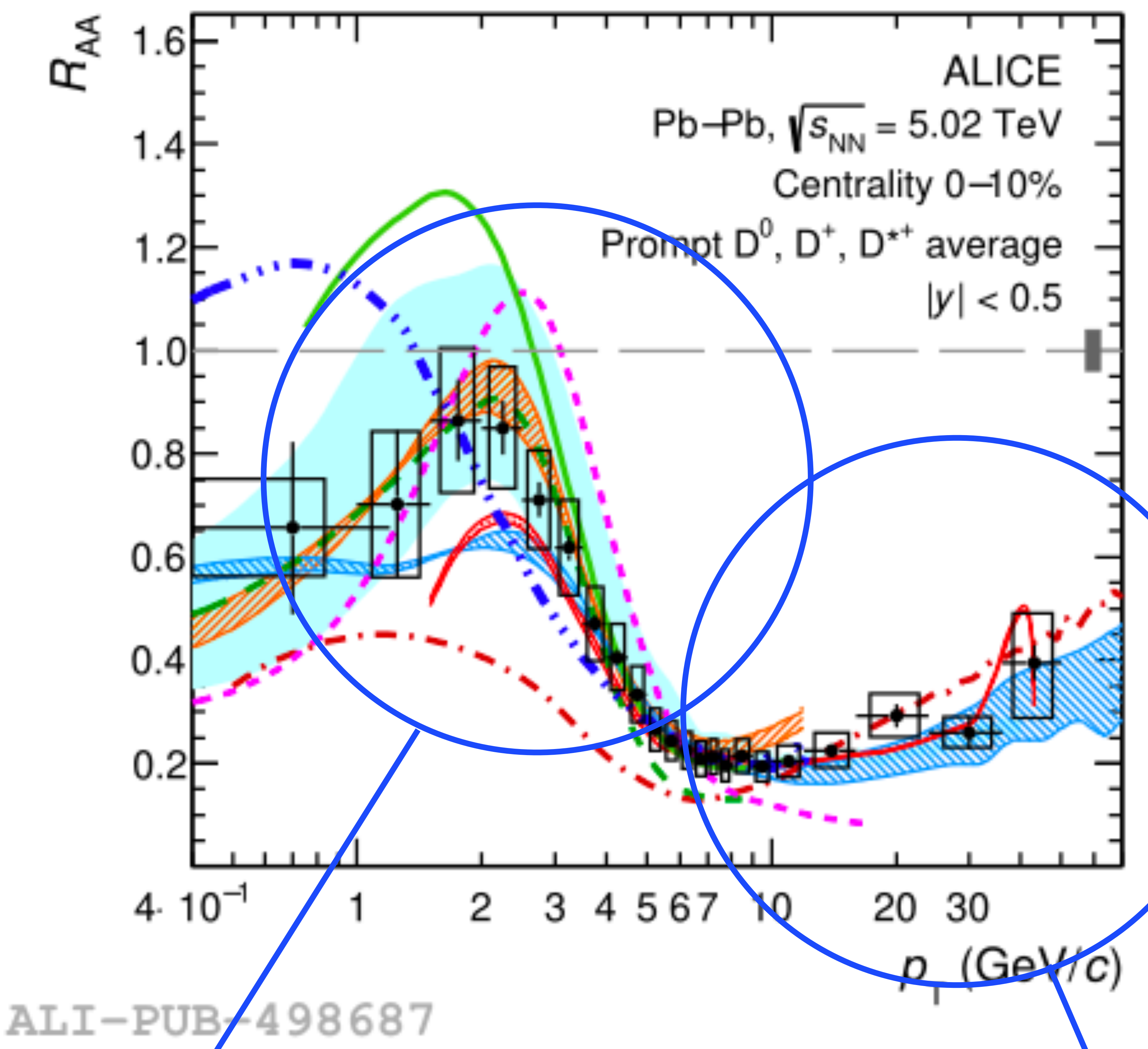
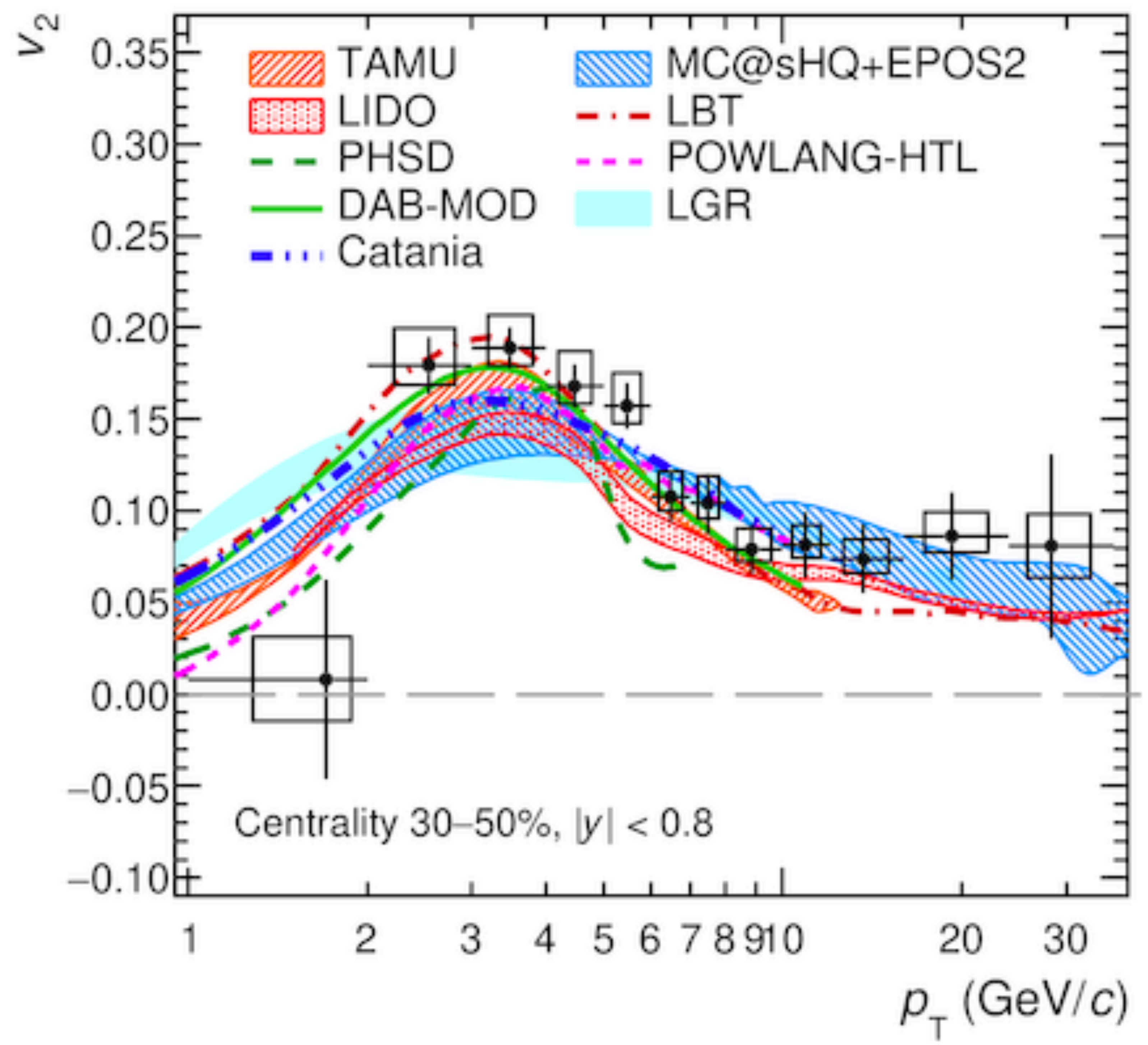


ALICE, arXiv:2110.09420

Elliptic flow v2



ALICE, arXiv:2110.09420

Low p_T: no change/enhancement: charm conservation + energy loss

High-p_T suppression: due to energy loss/thermalisation

Nuclear modification and elliptic flow of D mesons

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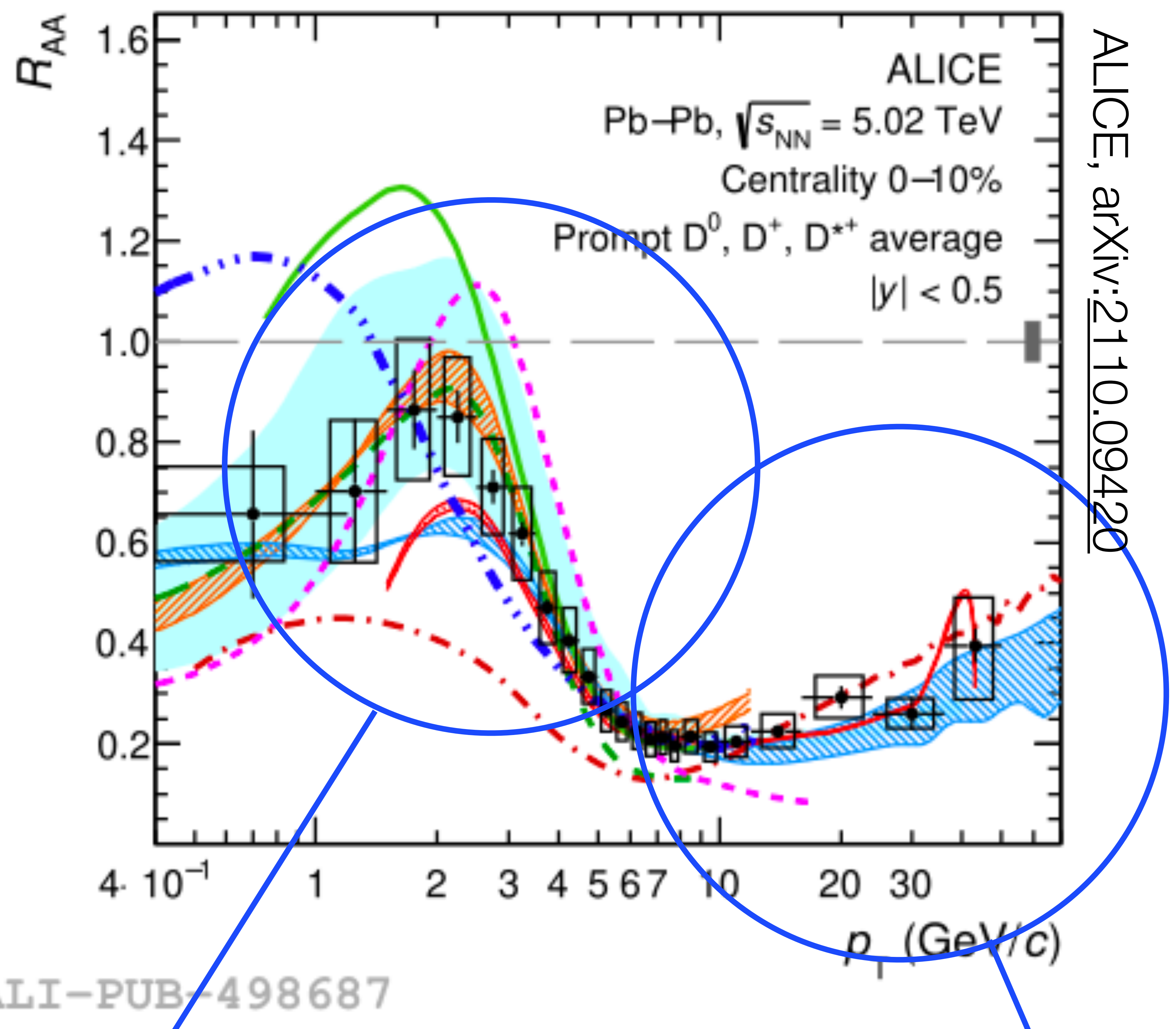

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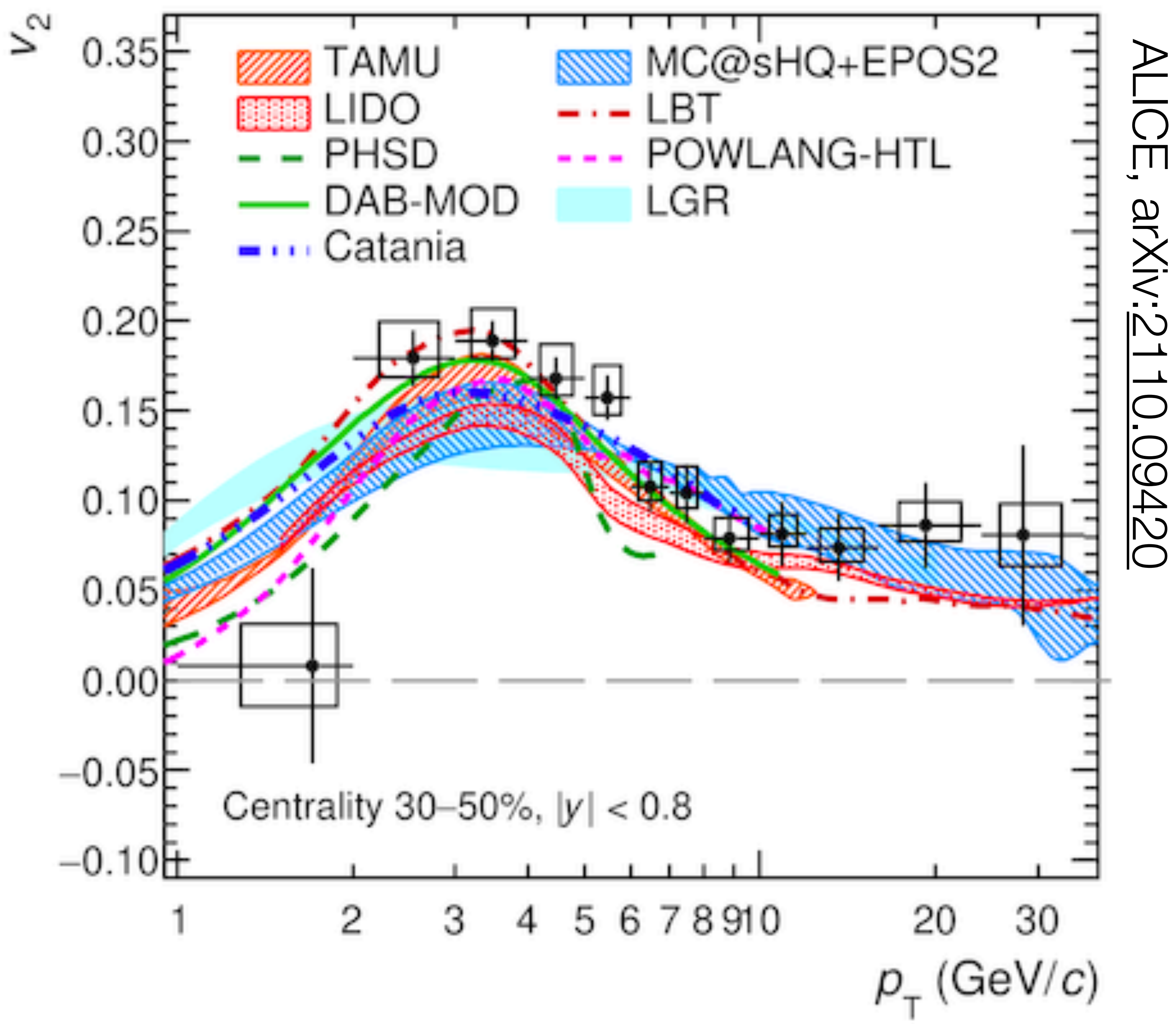


Azimuthal anisotropy:
Full effect generated by interactions
- High p_T: ‘energy loss regime’
- Low p_T: ‘thermal regime’

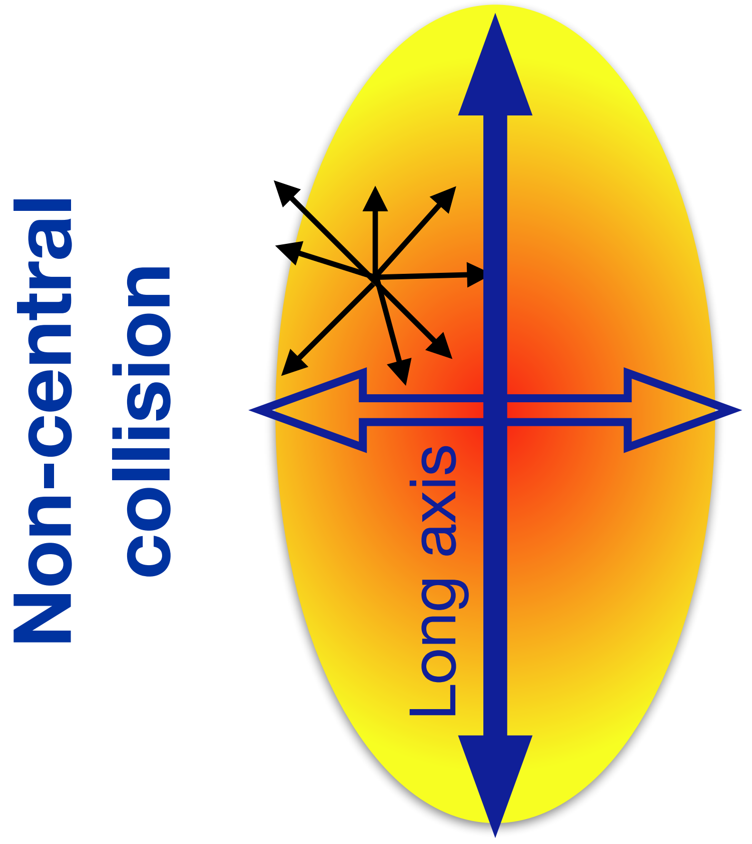
Heavy flavour transport

- **Heavy quarks: access to quark transport at hadron level**
  - Expect beauty thermalisation slower than charm — smaller v_2
- Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2

relaxation time

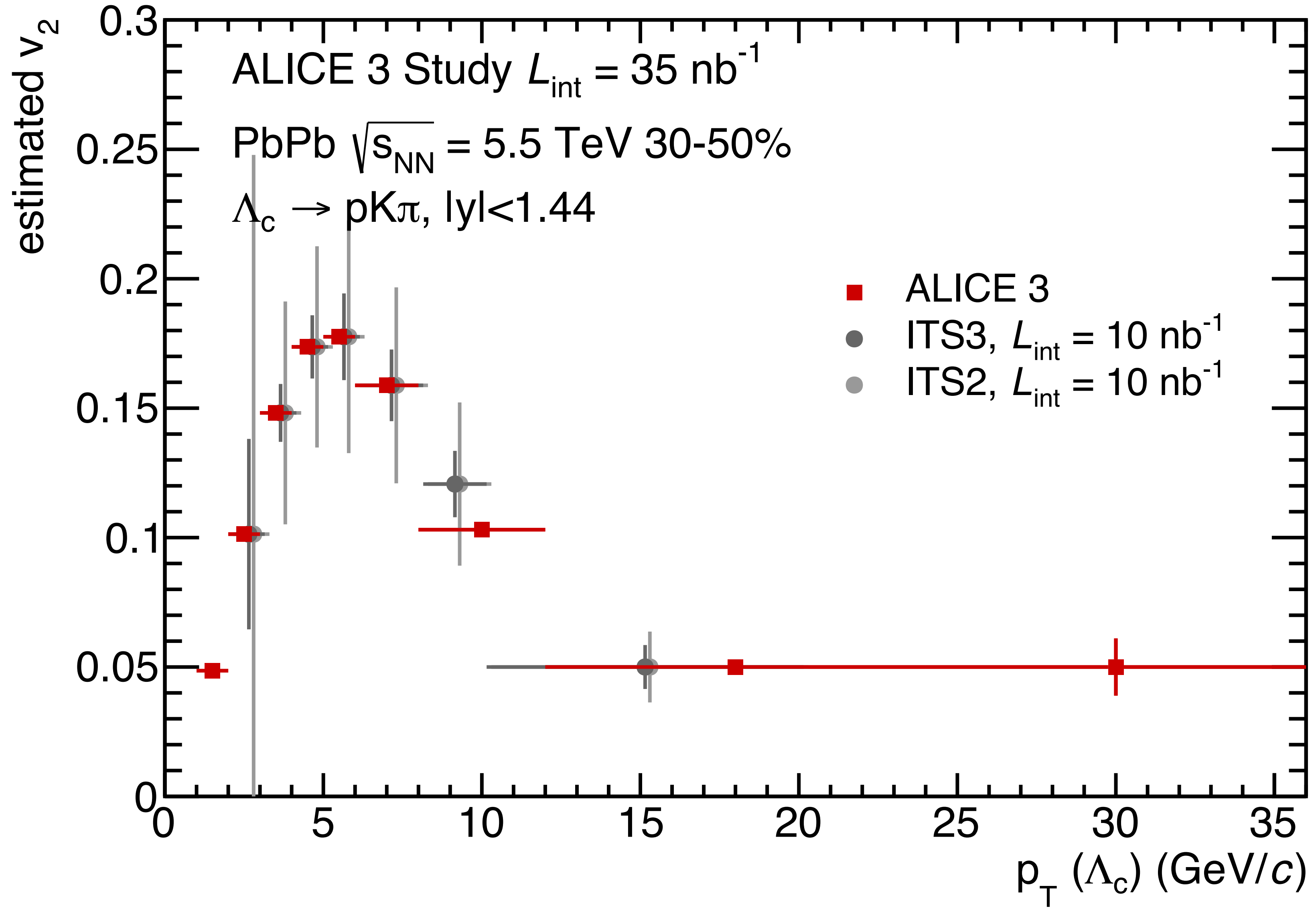
$$\tau_Q = (m_Q/T)\, D_s$$

Interactions with the plasma generate azimuthal anisotropy v_2:

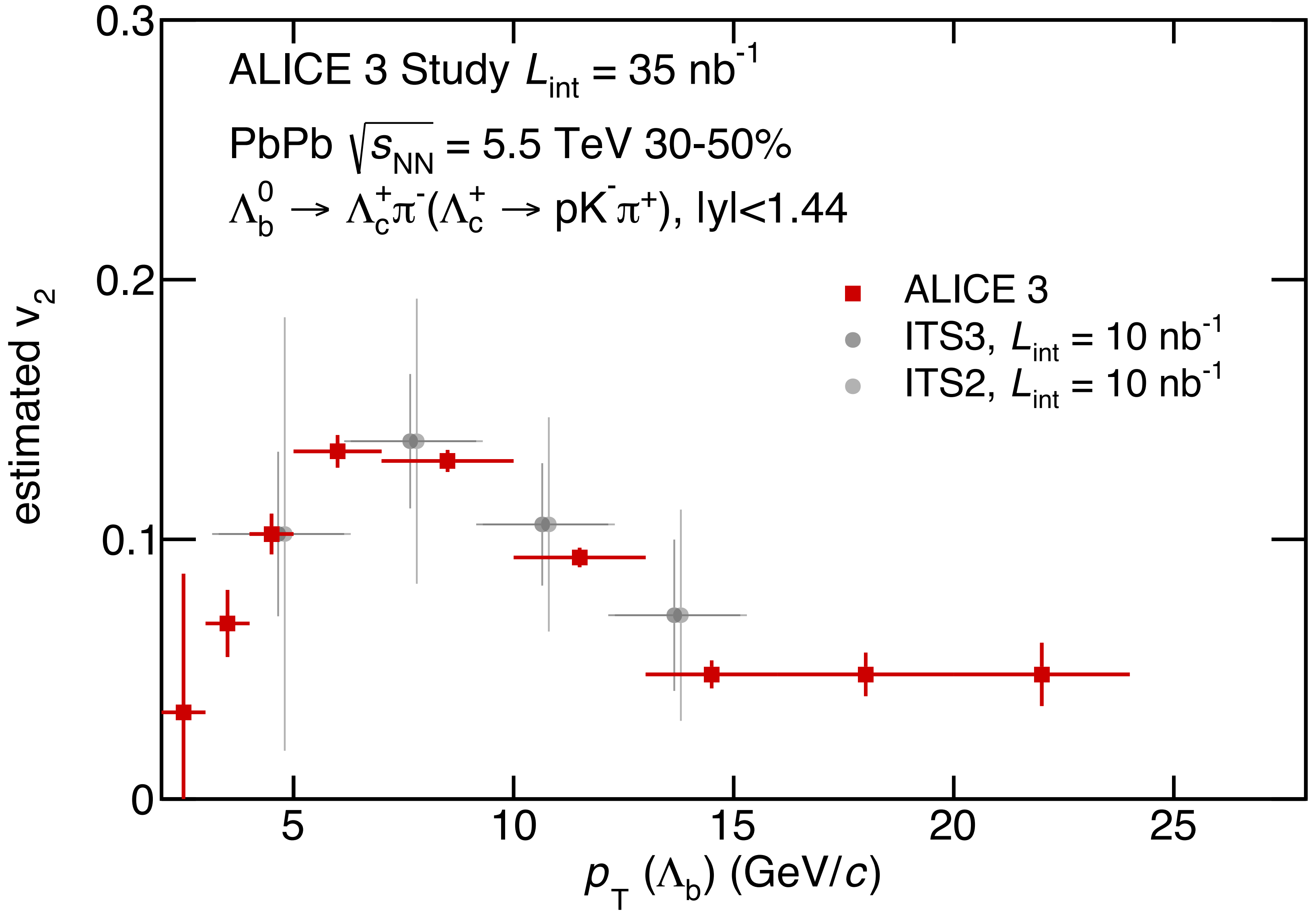


$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos 2(\varphi - \psi)$$

Λ_c v_2 performance

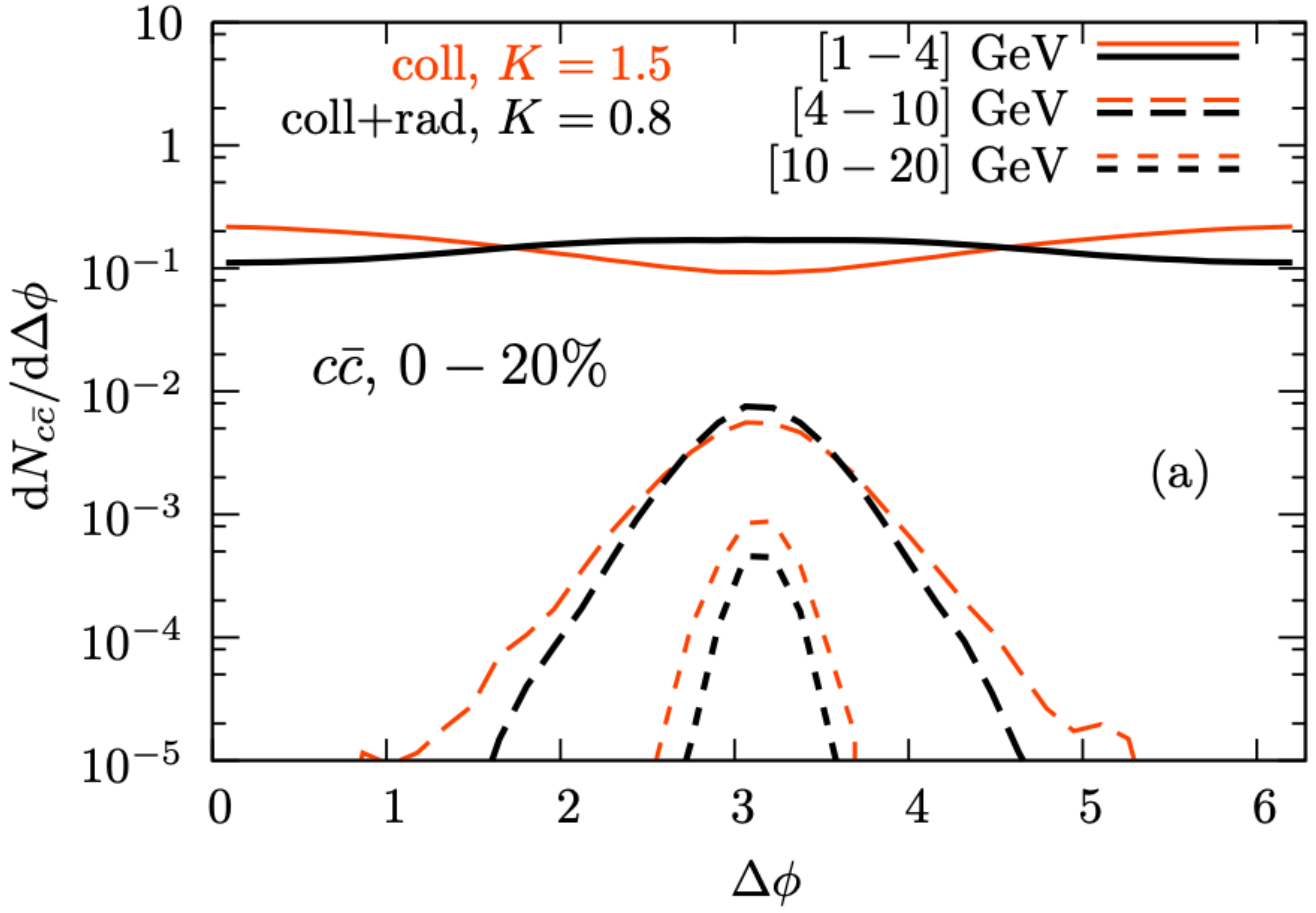


Λ_b v_2 performance

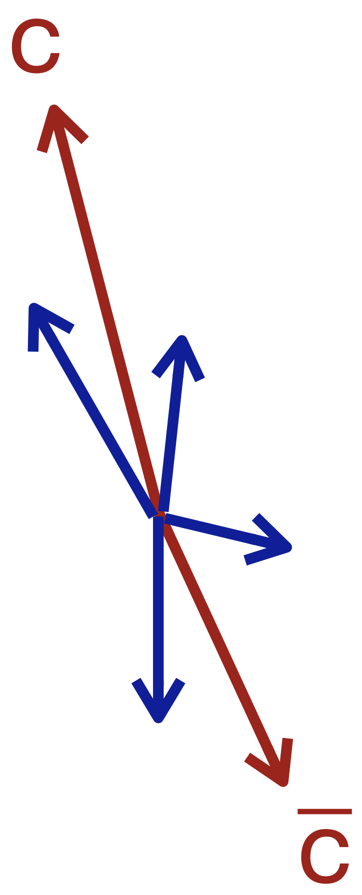


DD̄ azimuthal correlations

Charm azimuthal correlations



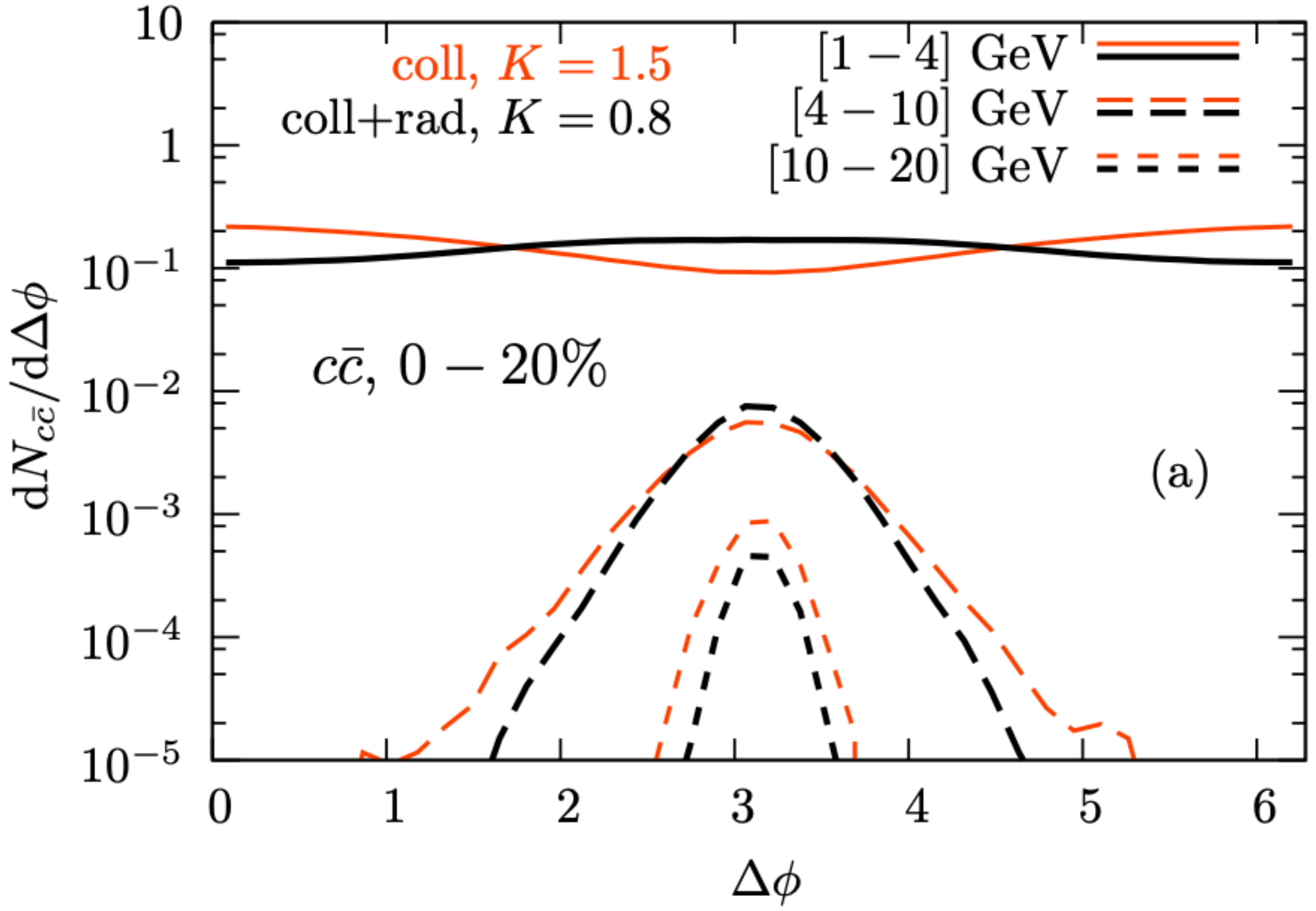
M Nahrgang et al, PRC 90, 024907



- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T

$D\bar{D}$ azimuthal correlations

Charm azimuthal correlations



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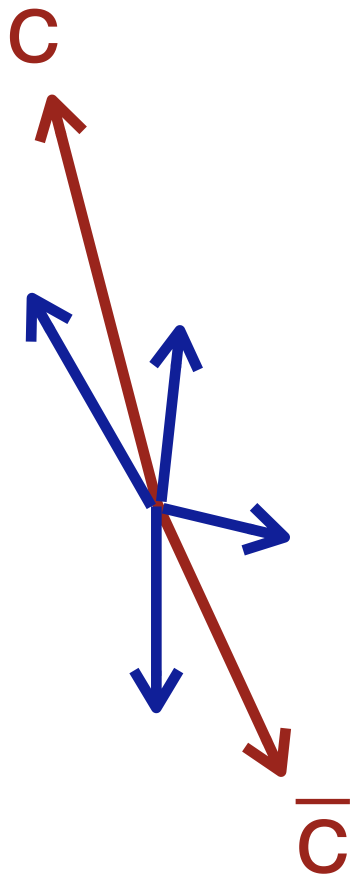
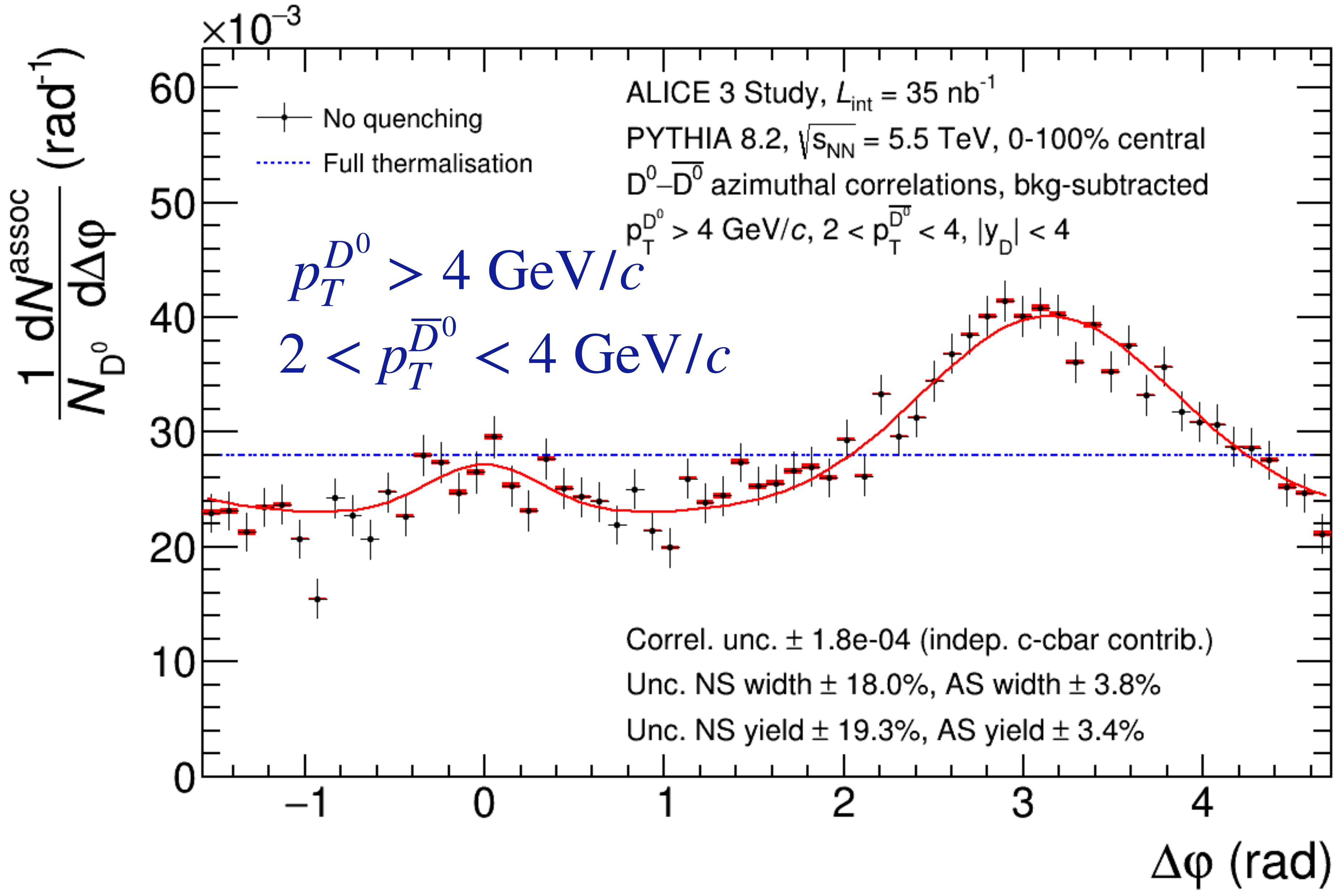


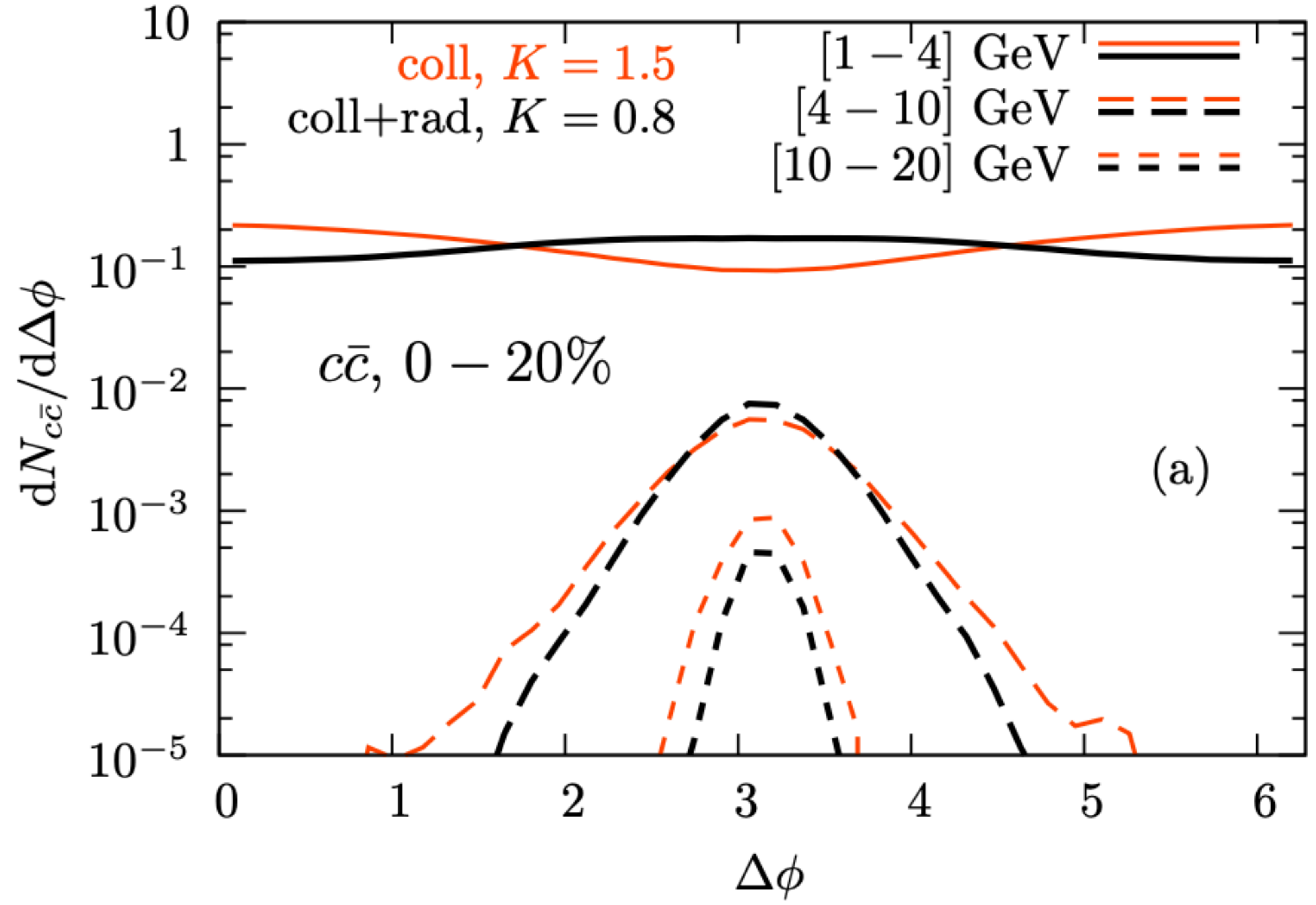
ALICE 3 projection: $D\bar{D}$ correlations



- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → heavy-ion measurement only possible with ALICE 3

$D\bar{D}$ azimuthal correlations

Charm azimuthal correlations



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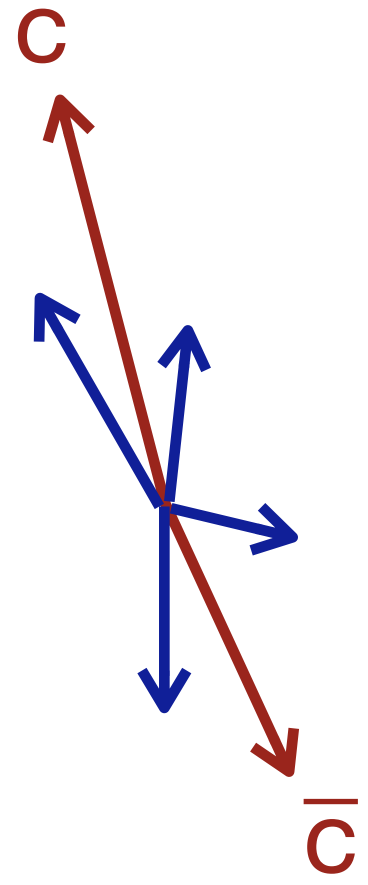

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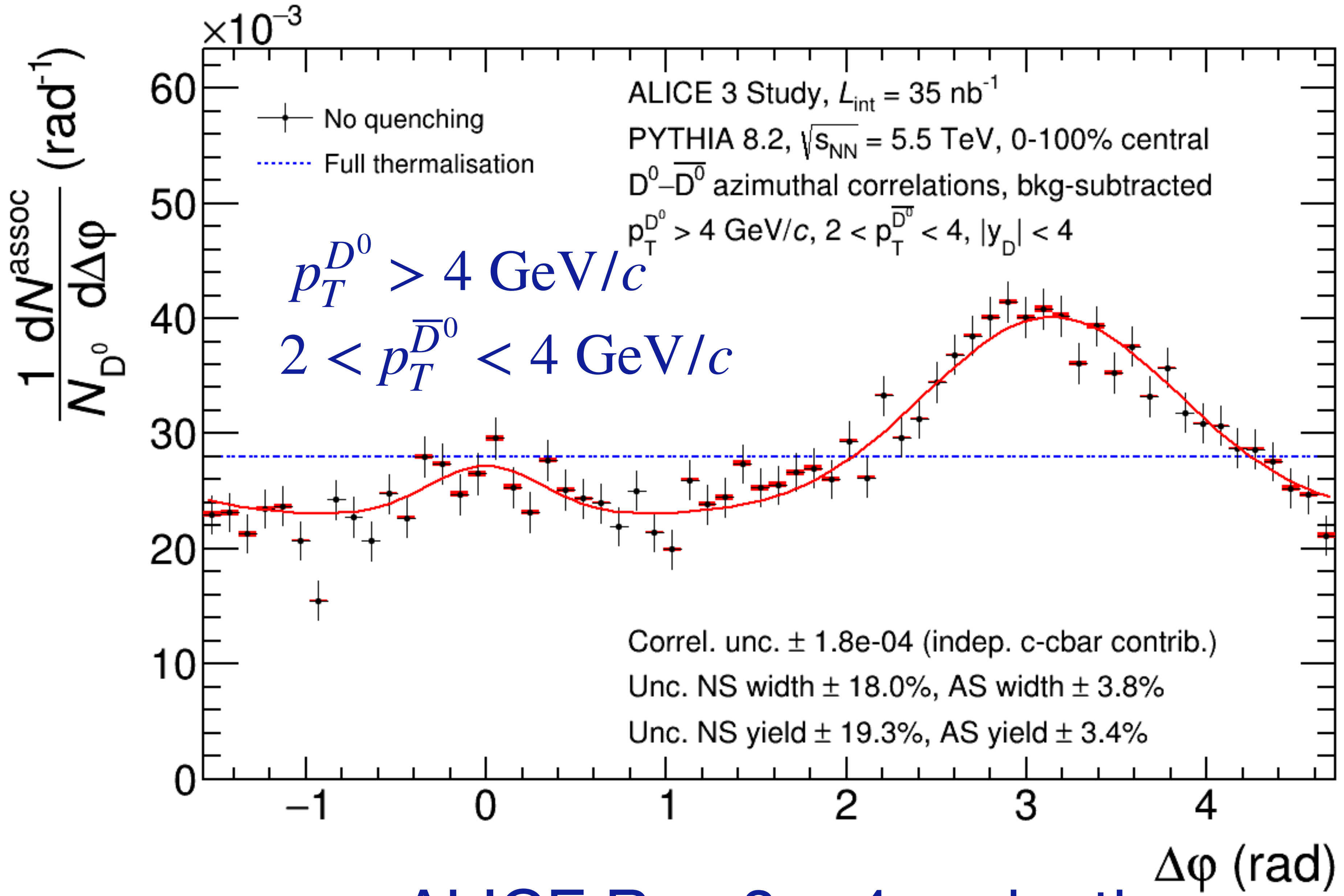
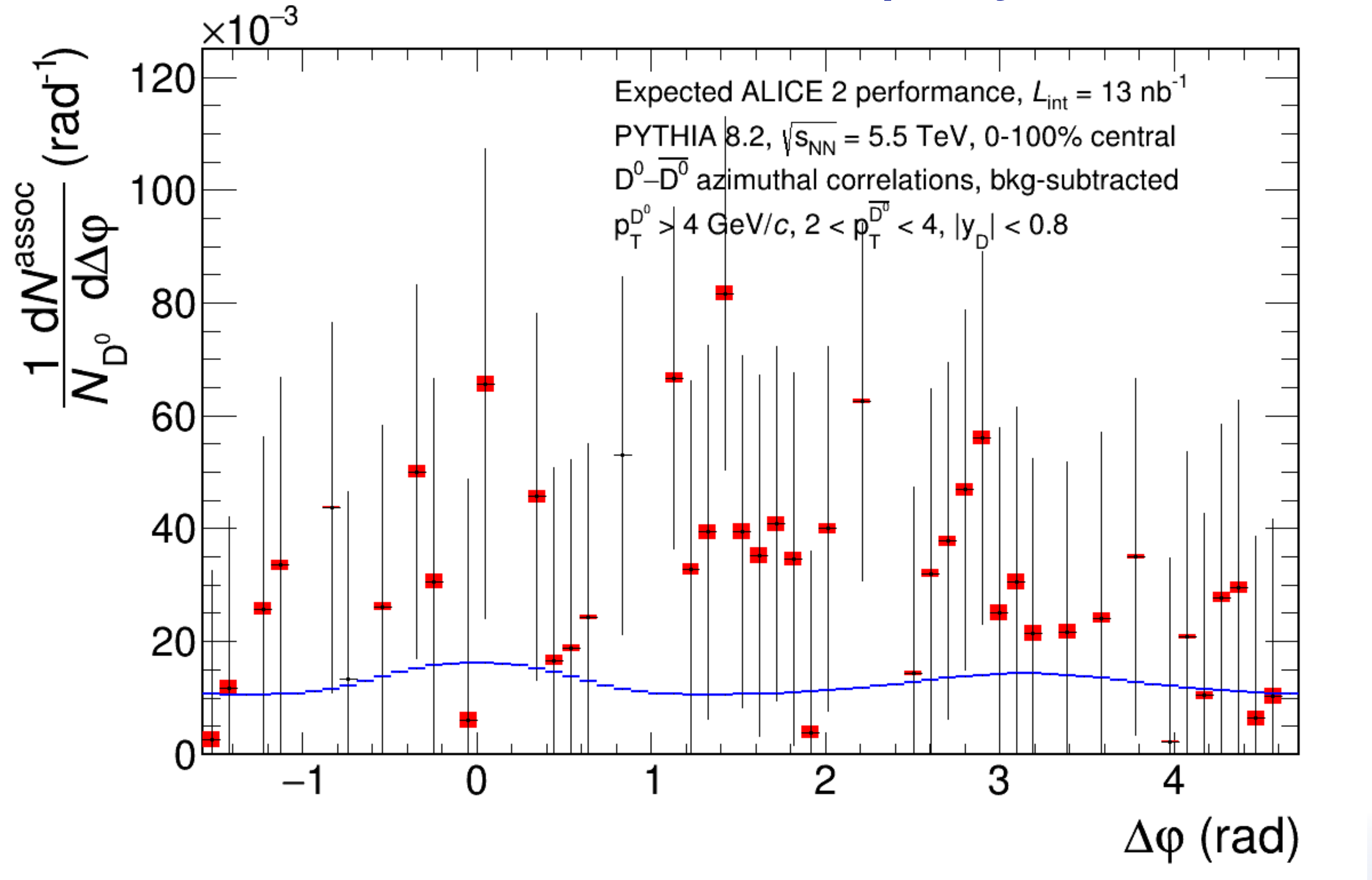


ALICE Run 3 + 4 projection



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  - Signal strongest at low p_T
- Very challenging measurement:
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Hadronisation

- **Multi-charm baryons**: unique probe of hadron formation
  - Requires **production of multiple charm quarks**
  - Single-scattering contribution very small (unlike e.g. J/ψ)
- Statistical hadronisation model:
  very large enhancement in AA
  - Specific relation between yields: g_c^n for *n*-charm states
  - How is thermalisation approached microscopically?

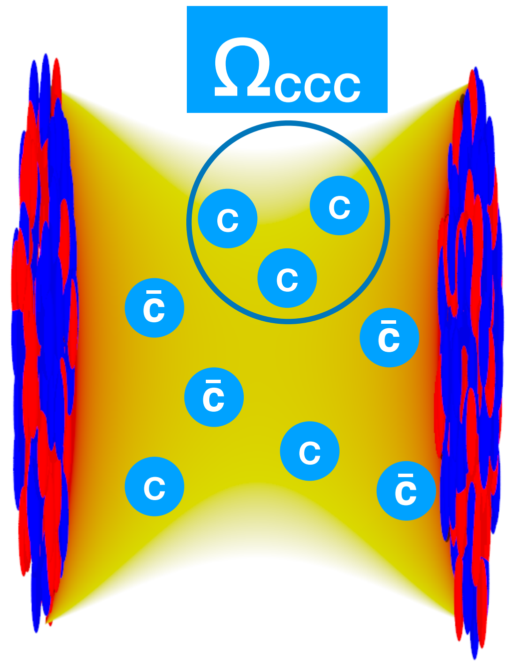
Measure additional states to test physical picture:

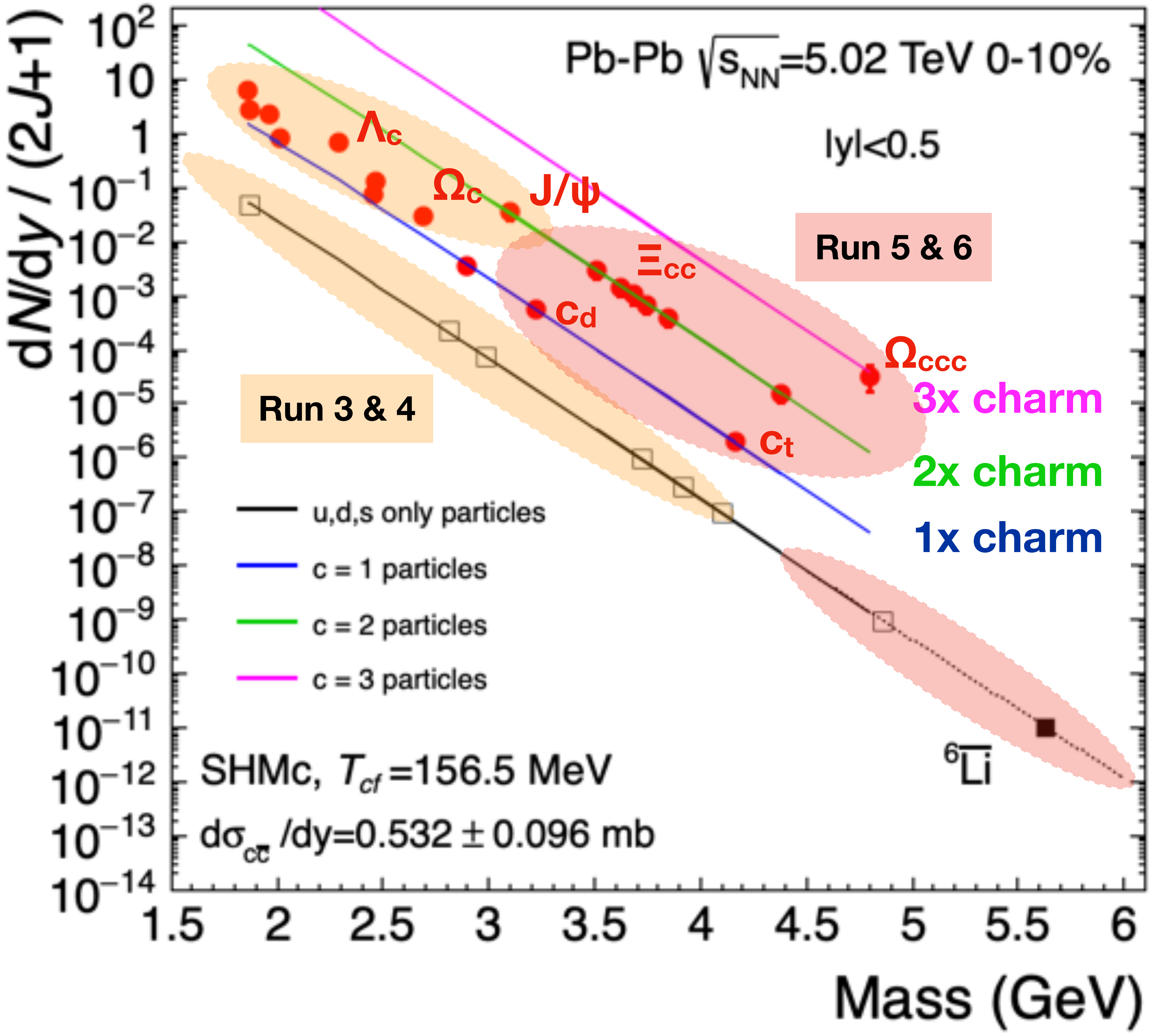
Single and double-charm baryons: Λ_c, Ξ_c, Ξ_{cc}, Ω_{cc}

Multi-flavour mesons: B_c, D_s, B_s, …

Tightly/weakly bound states J/ψ, $\chi_{c1}(3872)$, T_{cc}^+

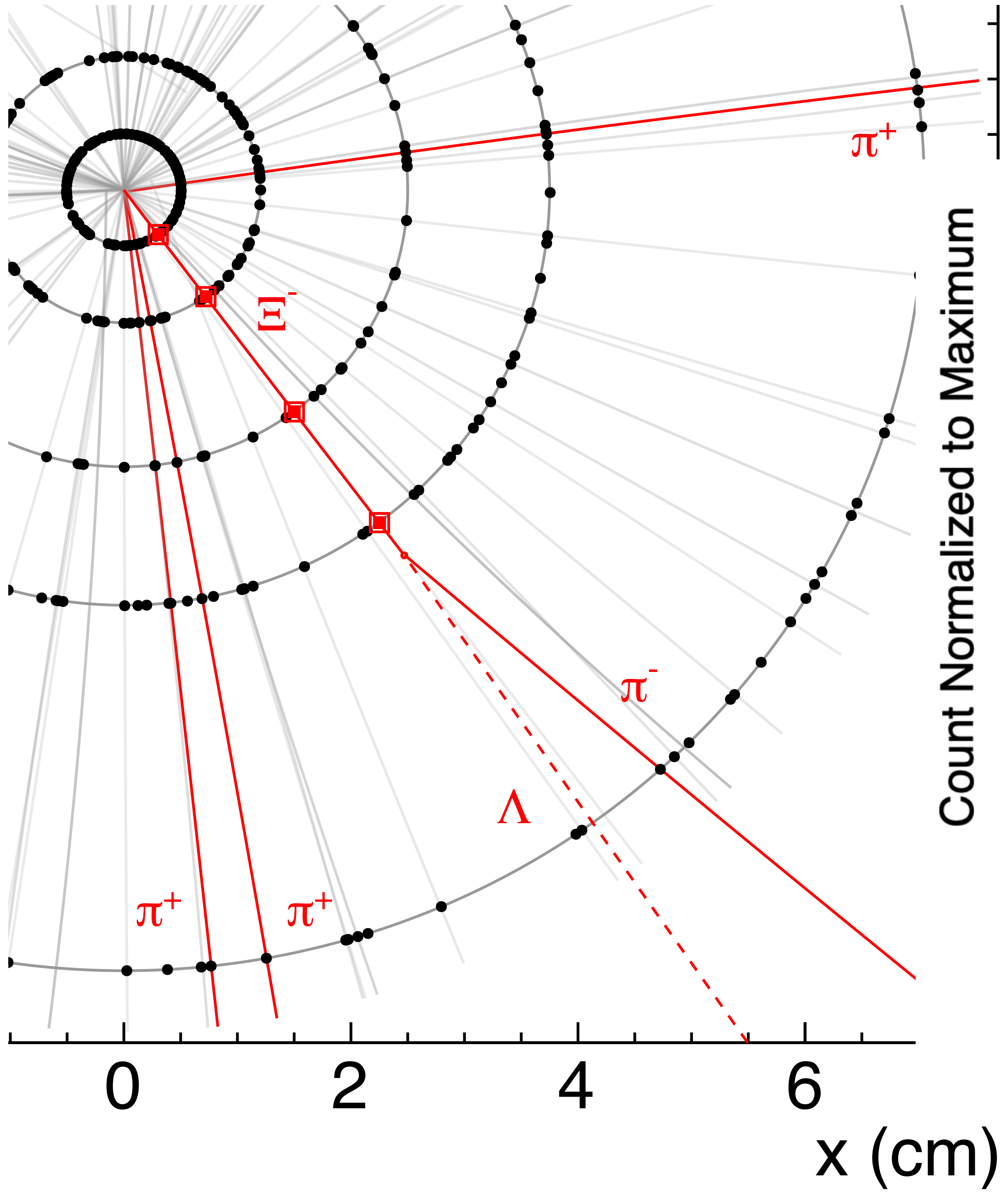
Large mass light flavour particles: nuclei



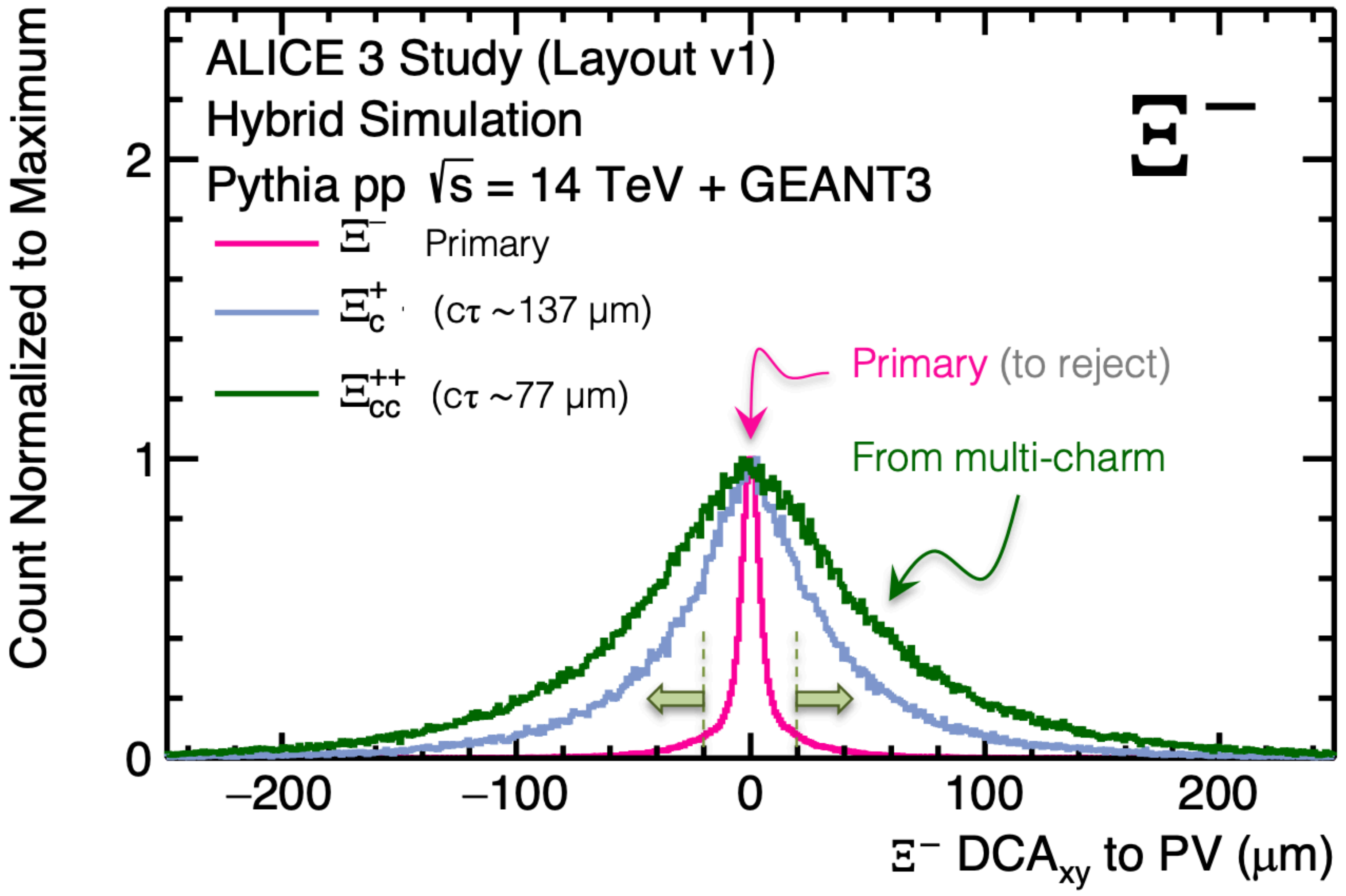


Multi-charm baryon detection

New technique: strangeness tracking



Impact parameter of Ξ



Pointing of Ξ baryon provides high selectivity

$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+} \qquad \Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

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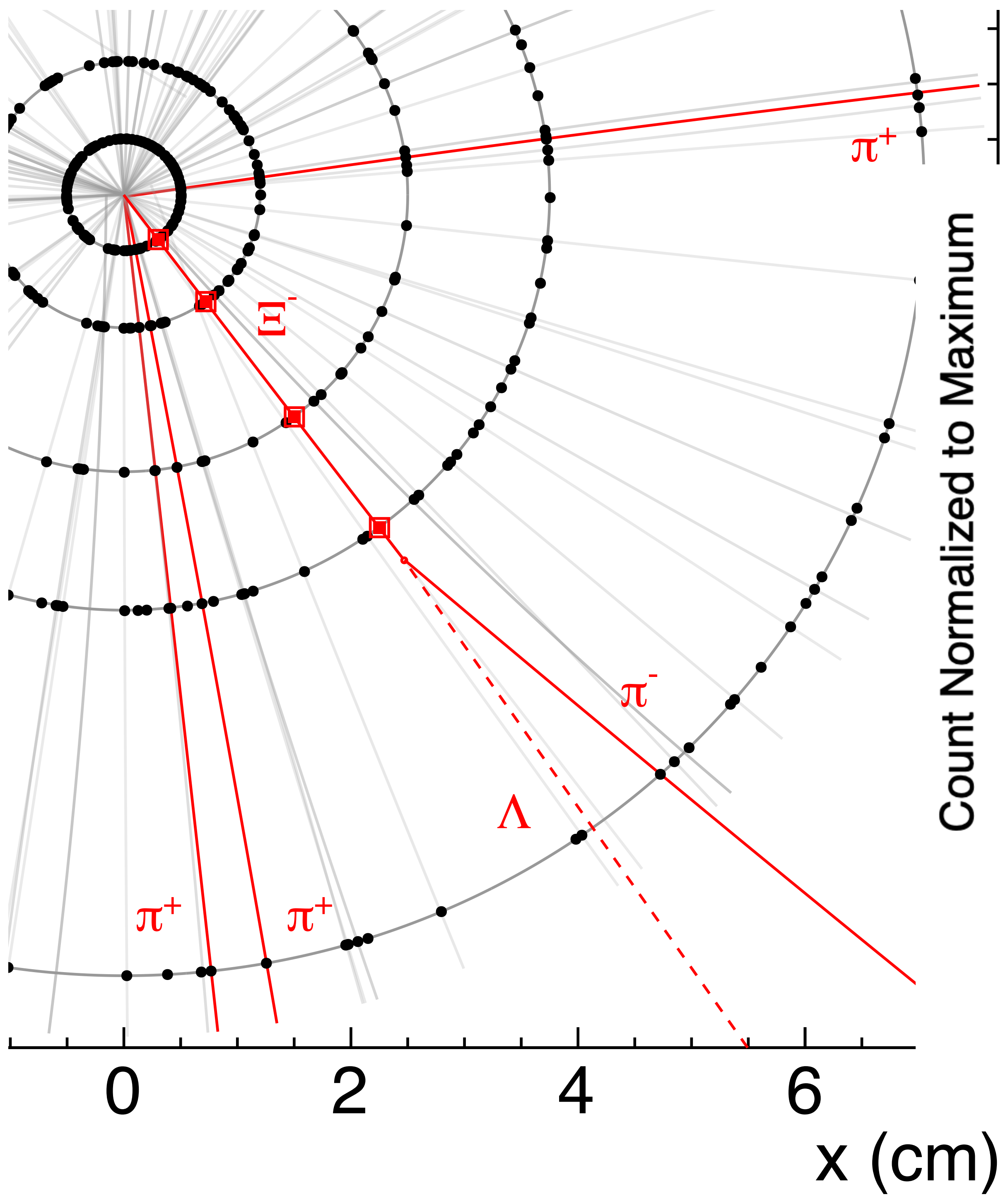

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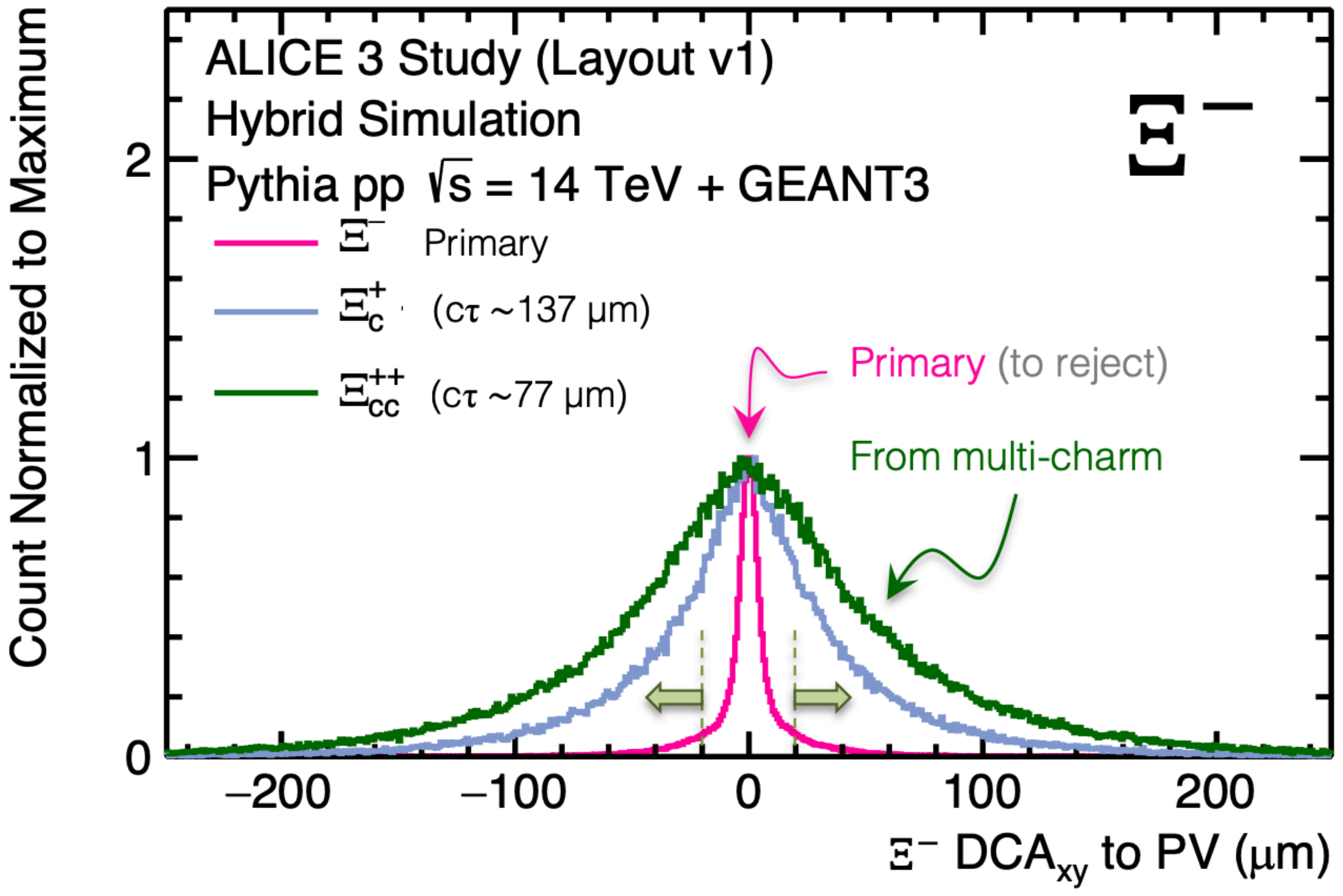

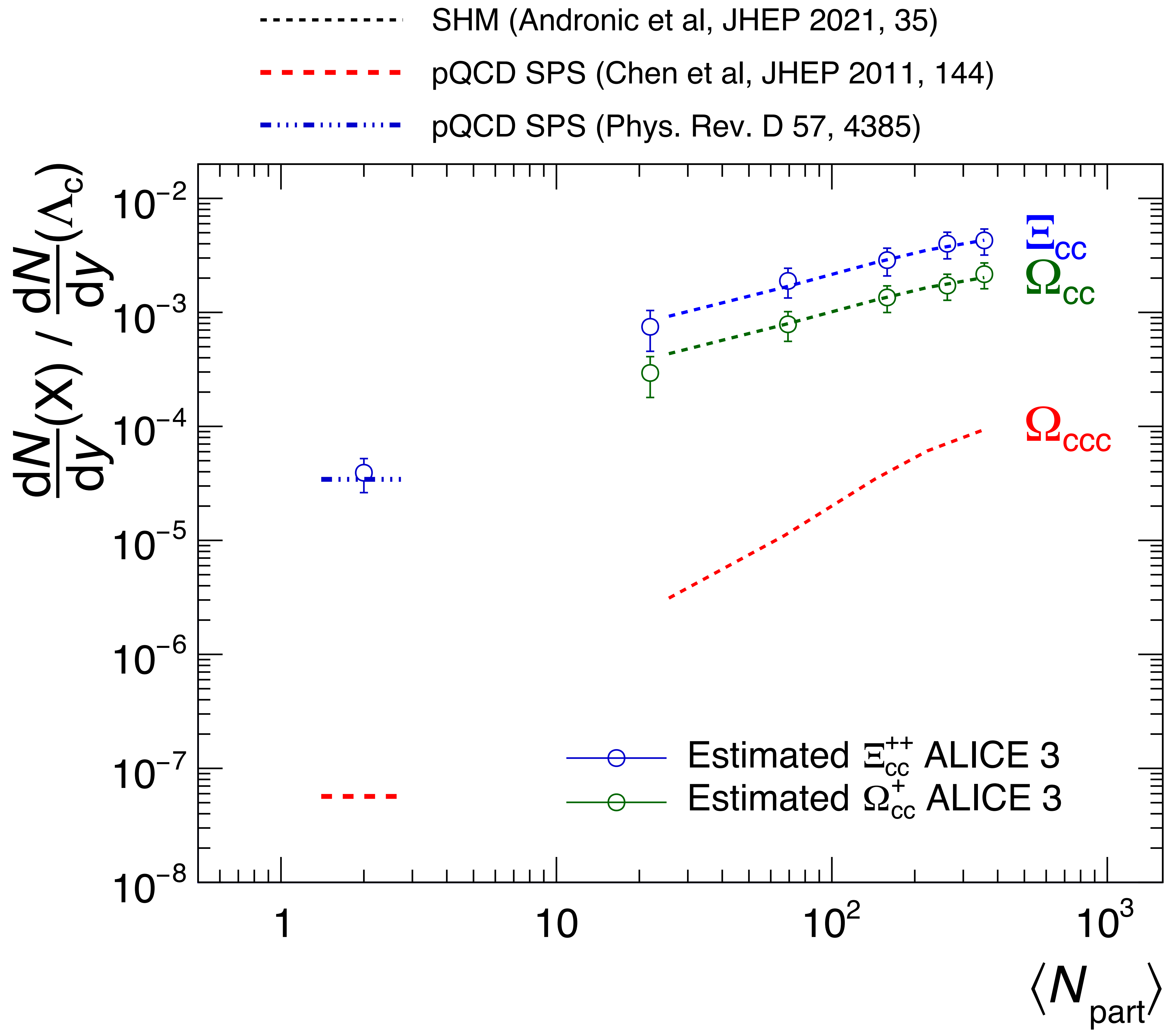

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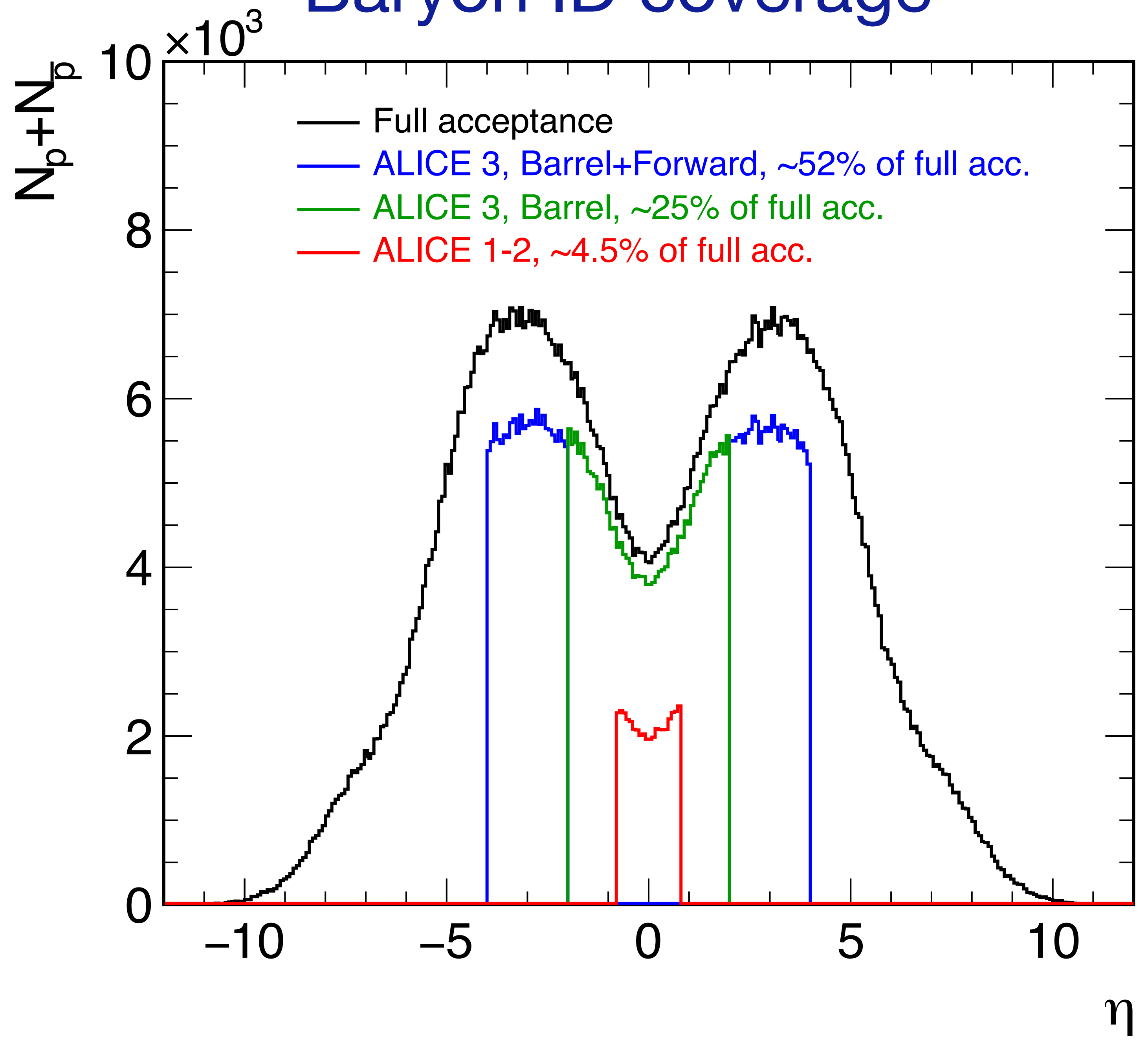
Large enhancements: unique sensitivity to thermalisation and hadronisation dynamics

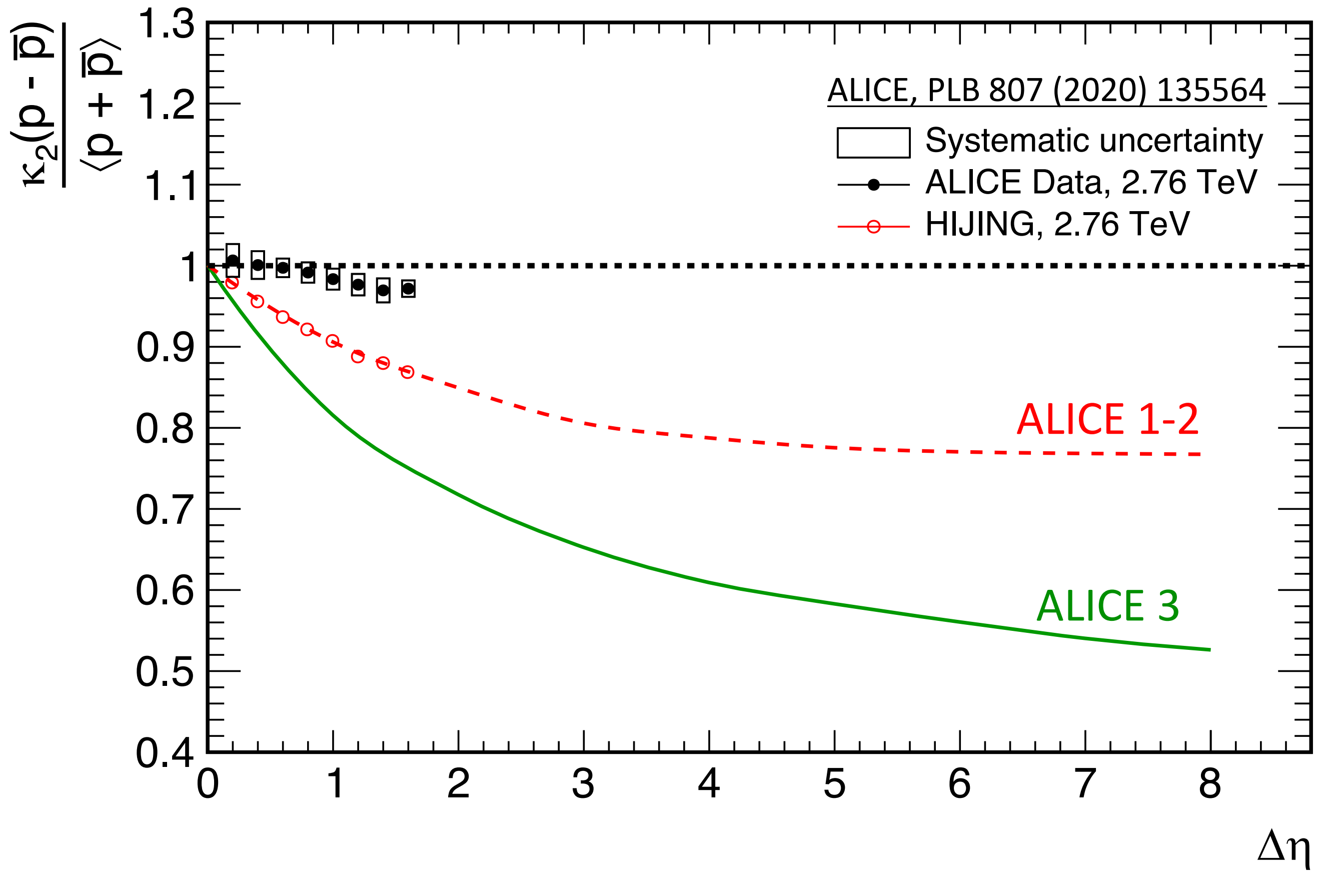
Unique access in Pb-Pb collisions with ALICE 3

Net-quantum number fluctuations

Baryon ID coverage

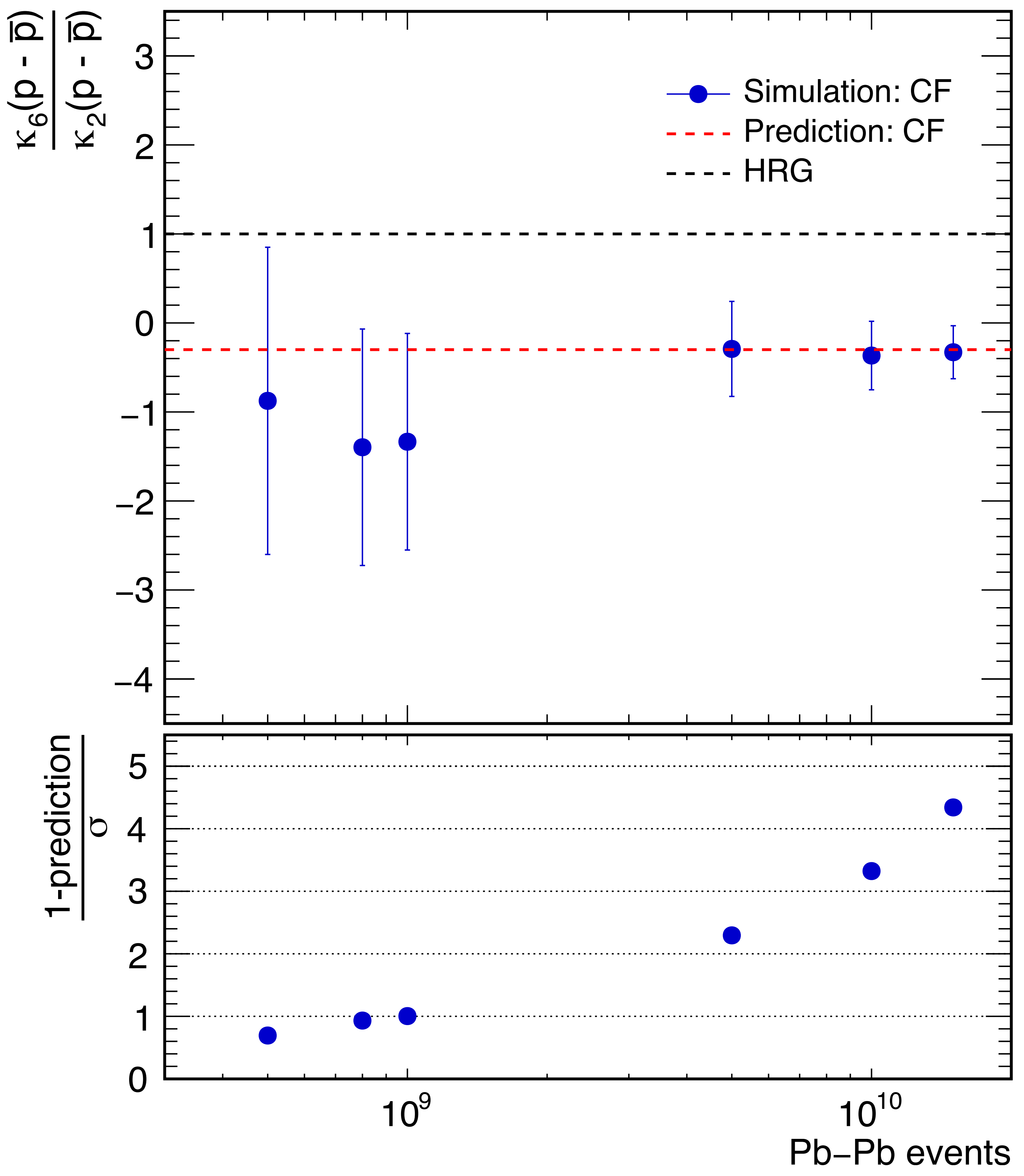


Second cumulant vs η coverage



Sensitive to baryon conservation dynamics

6th net-proton cumulant



Expect deviations from HRG expectation due to baryon number susceptibility

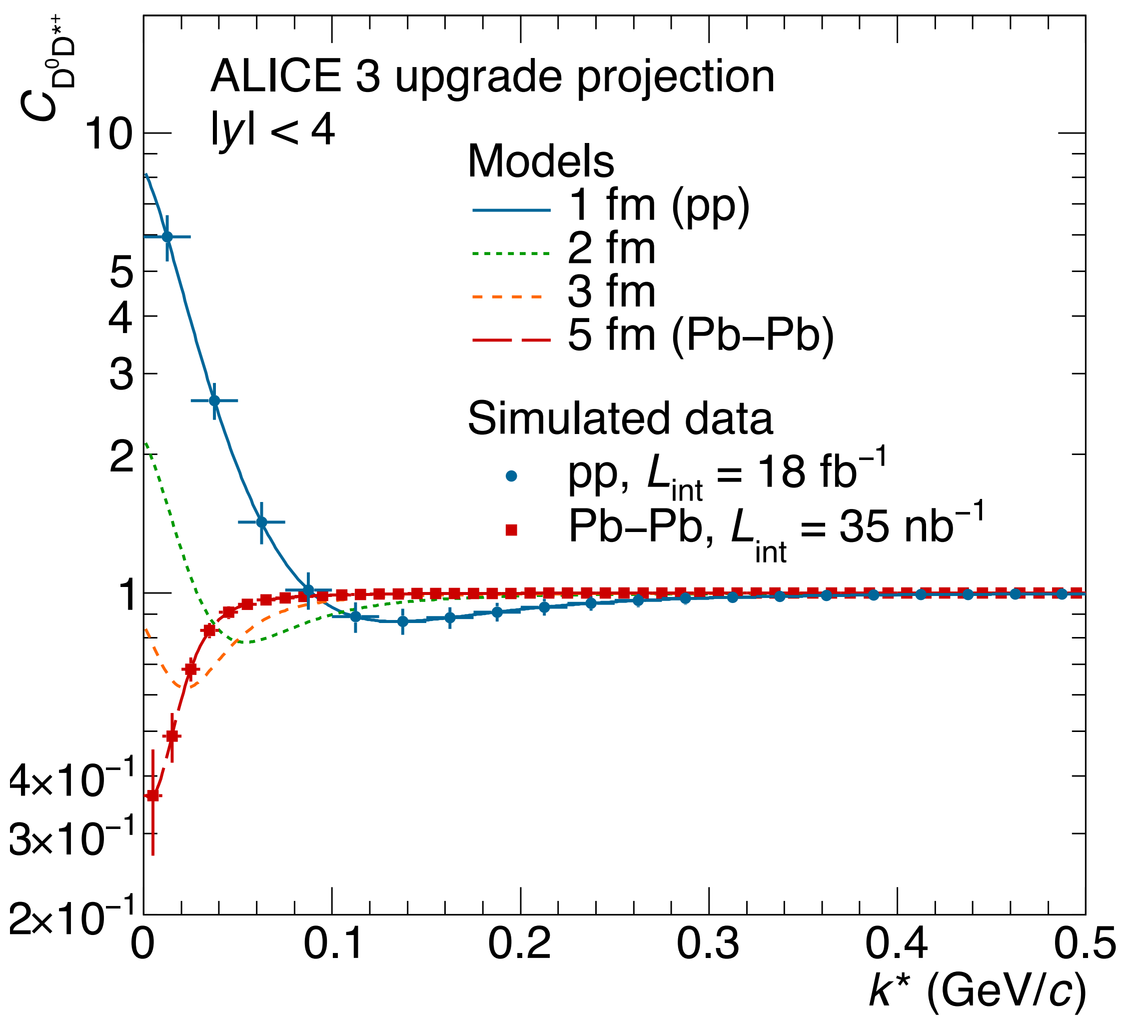
Goal: determine susceptibility of QGP — test lattice QCD predictions

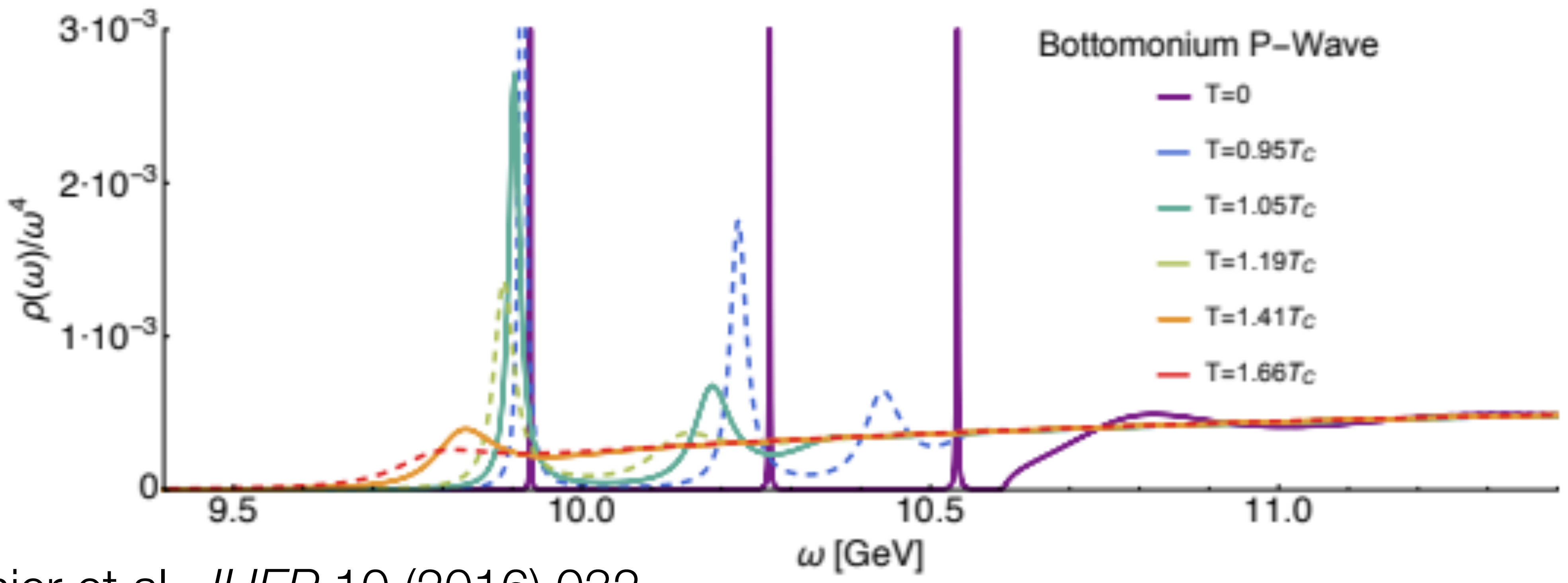
- Need high-purity PID over large range
- Large η acceptance: differential measurements vs Δη
- ALICE 3: 4σ observation in reach with ALICE 3

Bound states: quarkonia and exotica

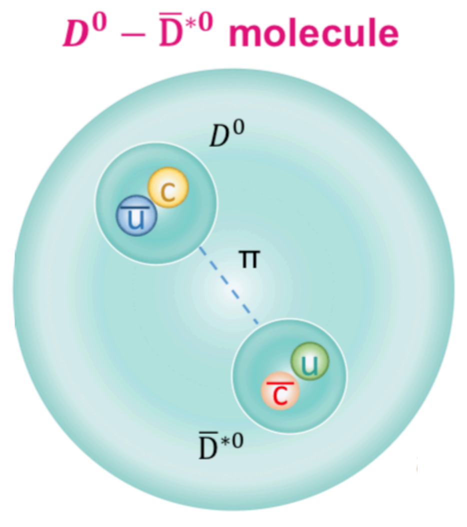
- Exotic states: $\chi_{c1}(3872)$, T_{cc}^{+}, …
  - Include double charm states, potentially weakly-bound states
  - Investigate structure with femtoscopic momentum correlations
  - Understand dissociation and regeneration in QGP
- Quarkonium states
  - Explore new states: P-wave and pseudoscalars
  - Melting temperature depends on angular momentum
  - Measurements of χ_c ; χ_b test theory
    - e.g. are there bound states above T_c?

$D^0 D^{*+}$: nature of T_{cc}^{+}



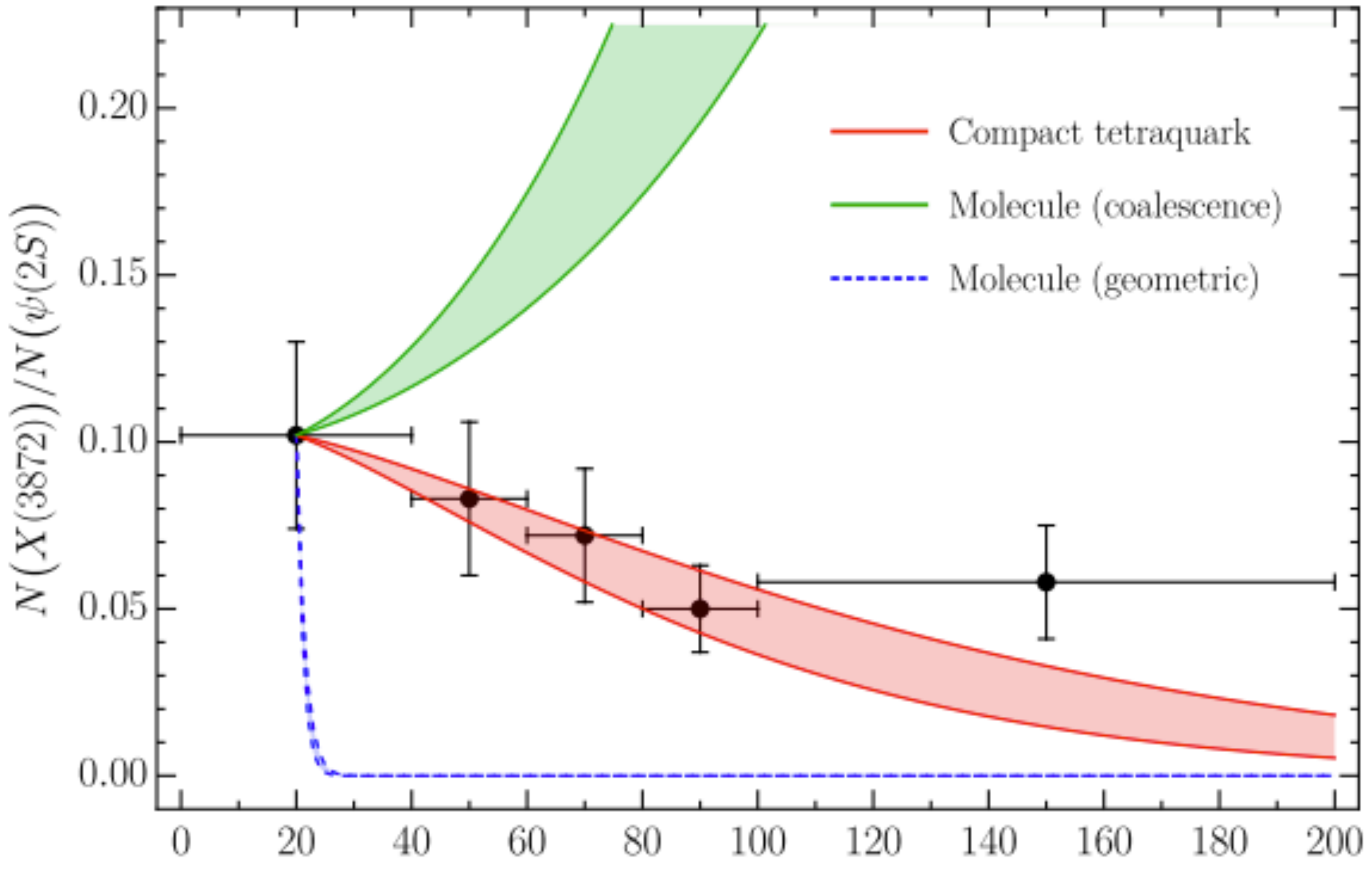


Burnier et al, *JHEP* 10 (2016) 032



$r_{molecule}$
as large as 5 fm

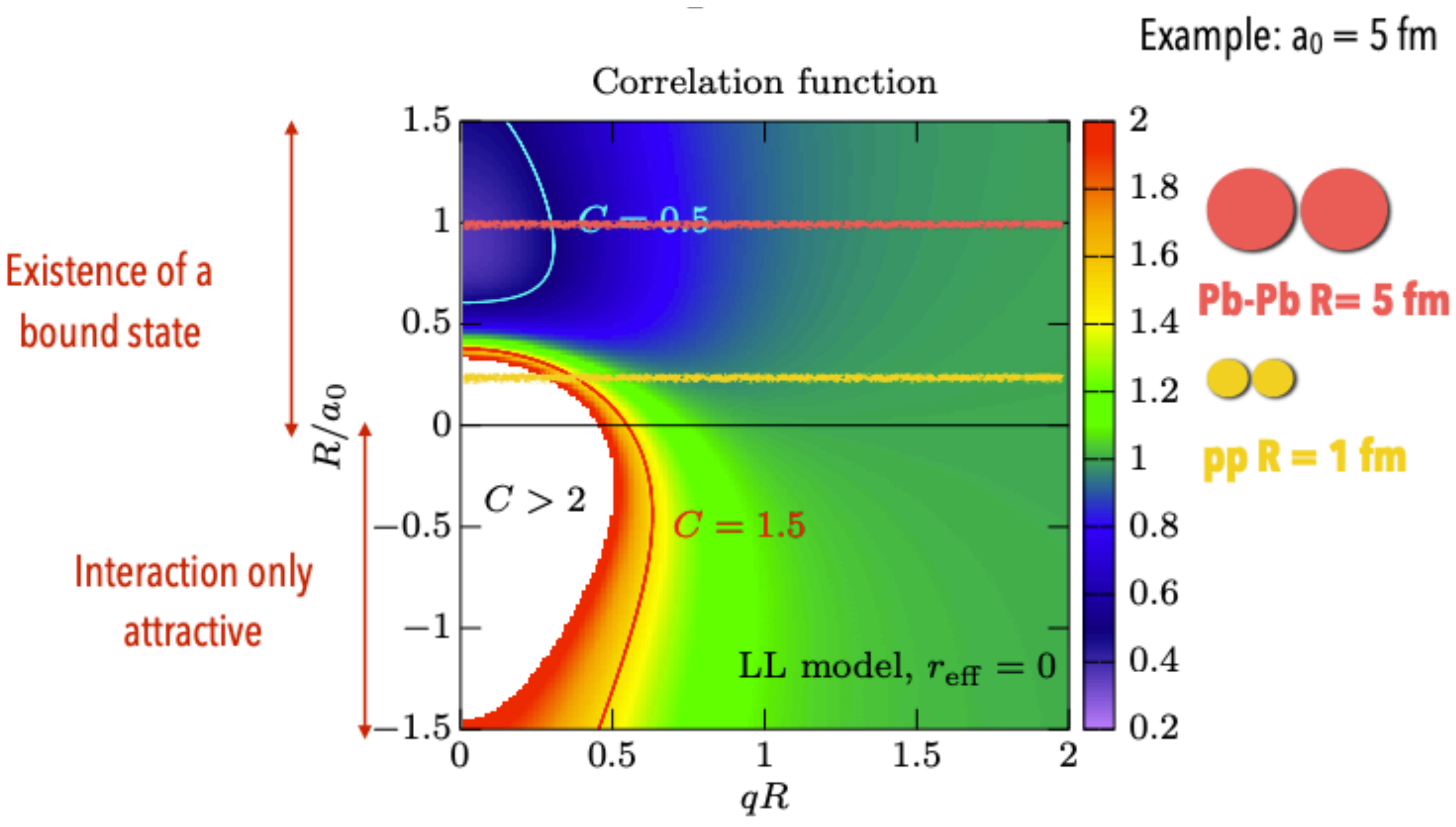
Dissociation and regeneration vs multiplicity



A Esposito et al, *EPJ.C* 86, 669

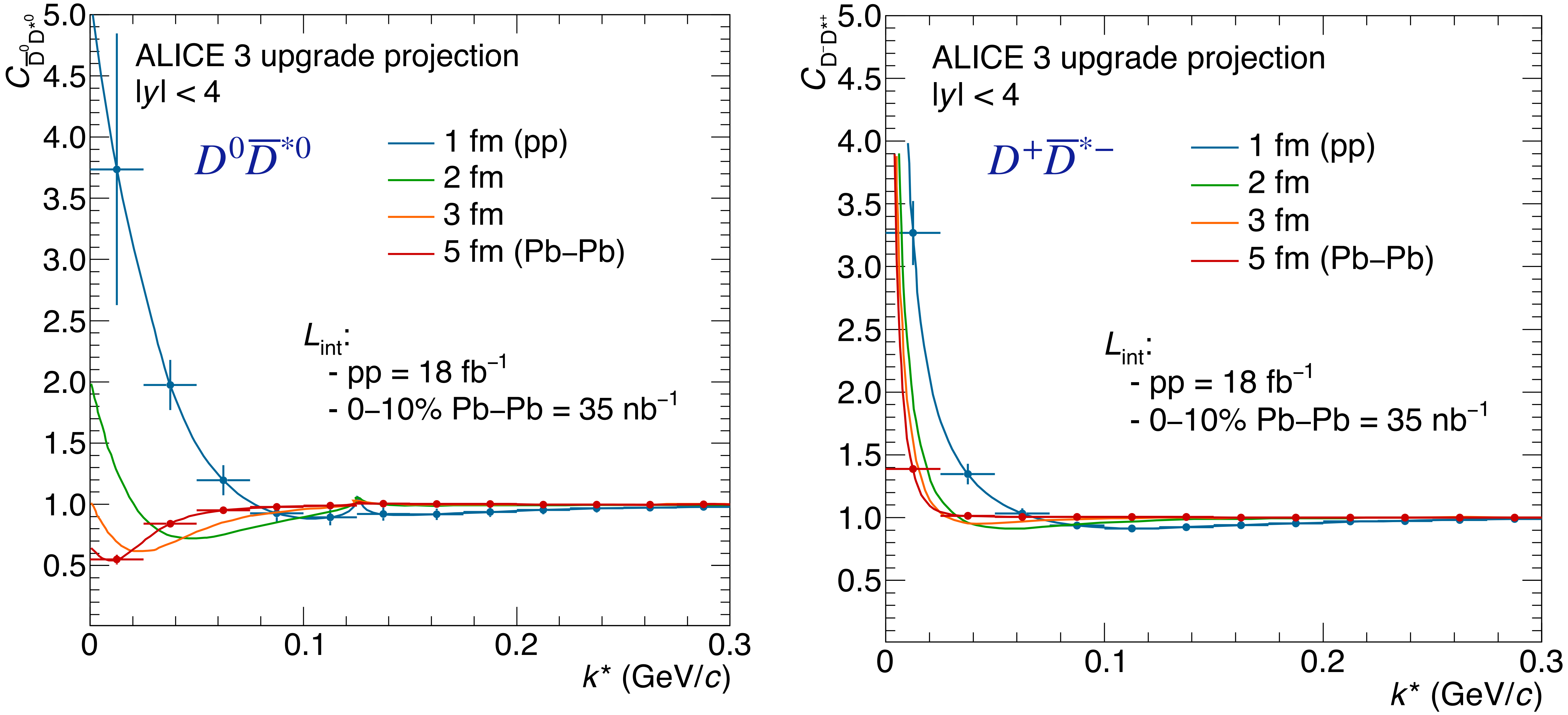
Requires: muon ID down to 1.5 GeV/c, photon detections

Bound states: DD* momentum correlations



Y. Kamiya et al. arXiv:2108.09644v1

DD* momentum correlation



- Study interaction between hadrons trough momentum correlation
- Carries information about existence of bound states

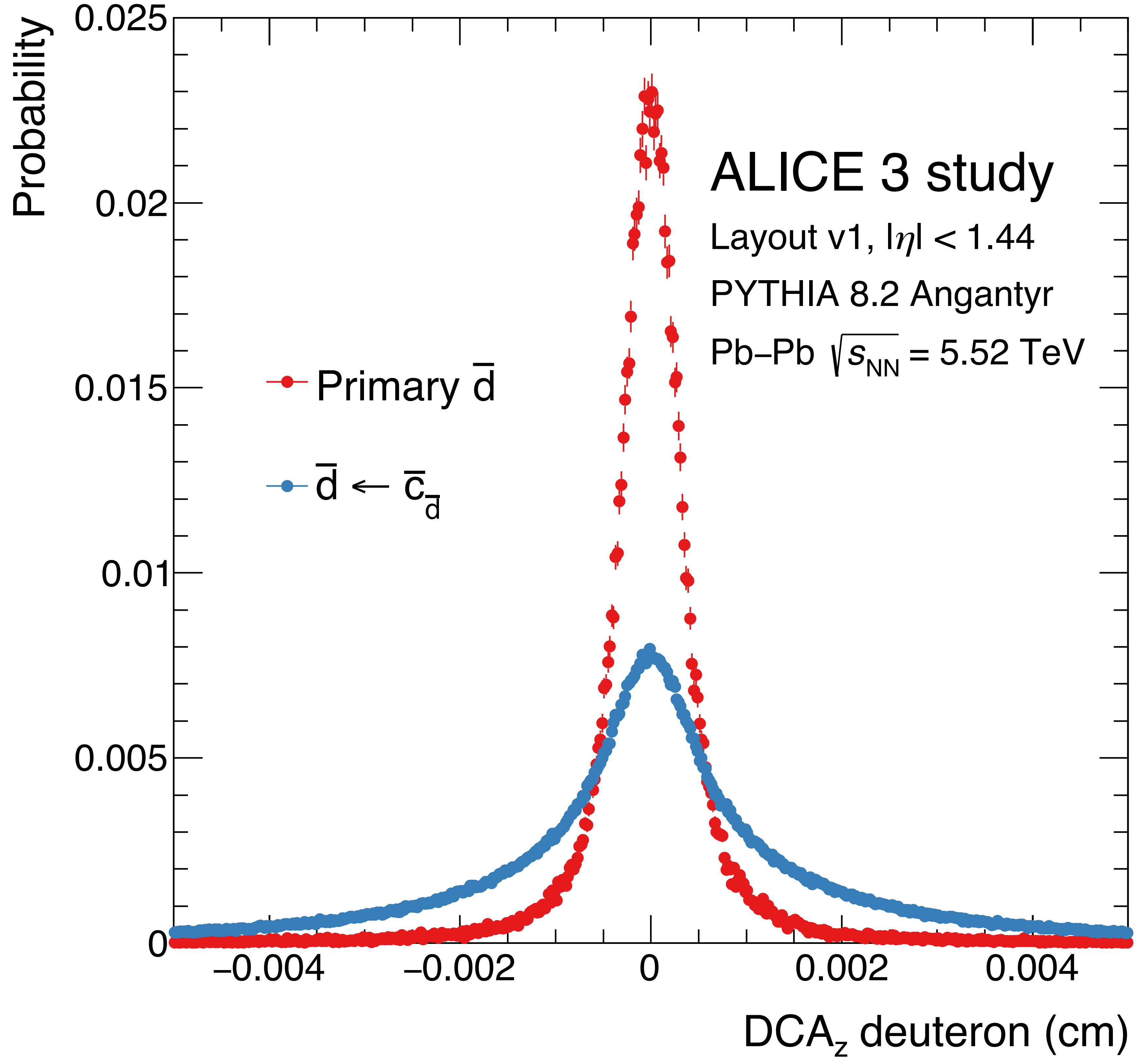
$D^0\overline{D}^{*0}$ probes nature of $\chi_{c1}(3872)$

Nuclear states: charm-deuteron

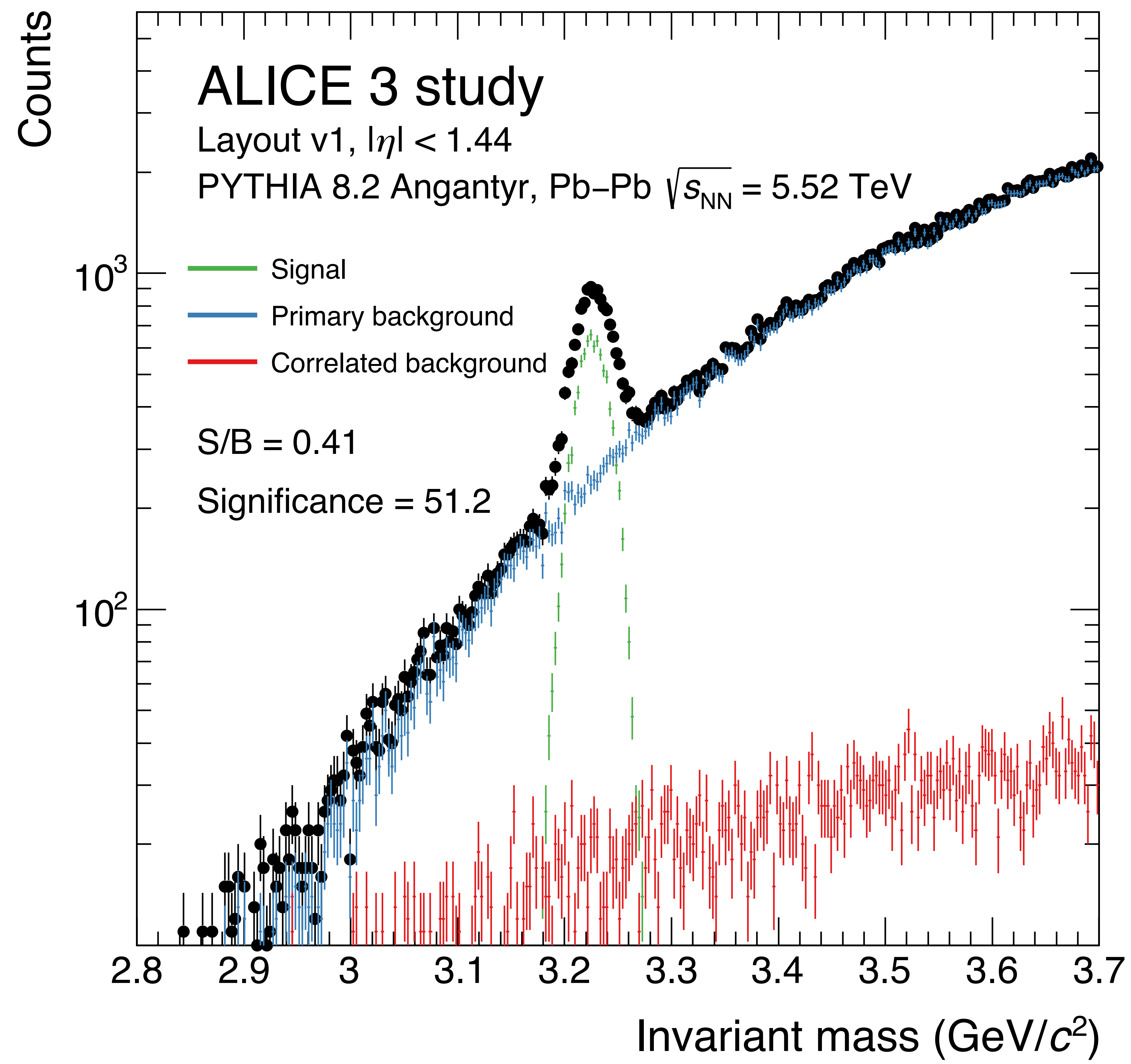
Decay channel:

$$c_d \rightarrow d + K^- + \pi^+$$

Impact parameter distributions



Invariant mass distribution



Unique sensitivity to undiscovered charm-nuclei:
charm-deuteron and higher nuclear states

Physics programme

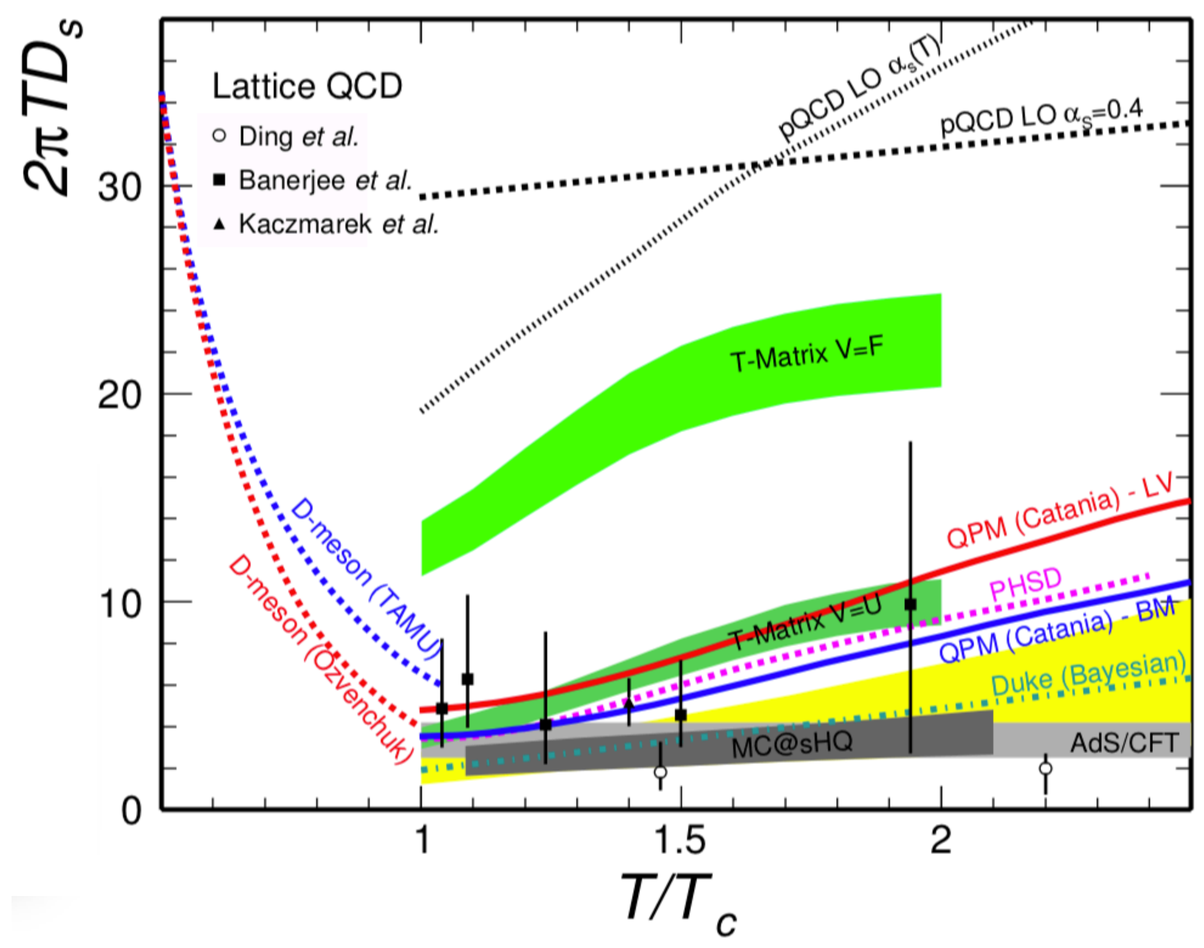
- **Early stages**: temperature of QGP before hadronisation
  - Di-lepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron correlations
- **Hadronisation**, final state interactions in heavy-ion collisions
  - Multi-charm baryon production: thermal processes/quark recombination
  - Quarkonia and exotic mesons: dissociation and regeneration
- Structure of **exotic hadrons**
  - Momentum correlations (femtoscopy)
  - Production yields — dissociation in final state scattering
  - Decay studies in ultra-peripheral collisions
- New **nuclear states**: charm nuclei
- **Susceptibilities**
- **Ultra-soft photons**: experimental test of Low's theorem
- **BSM searches**: ALPs, dark photons
- …

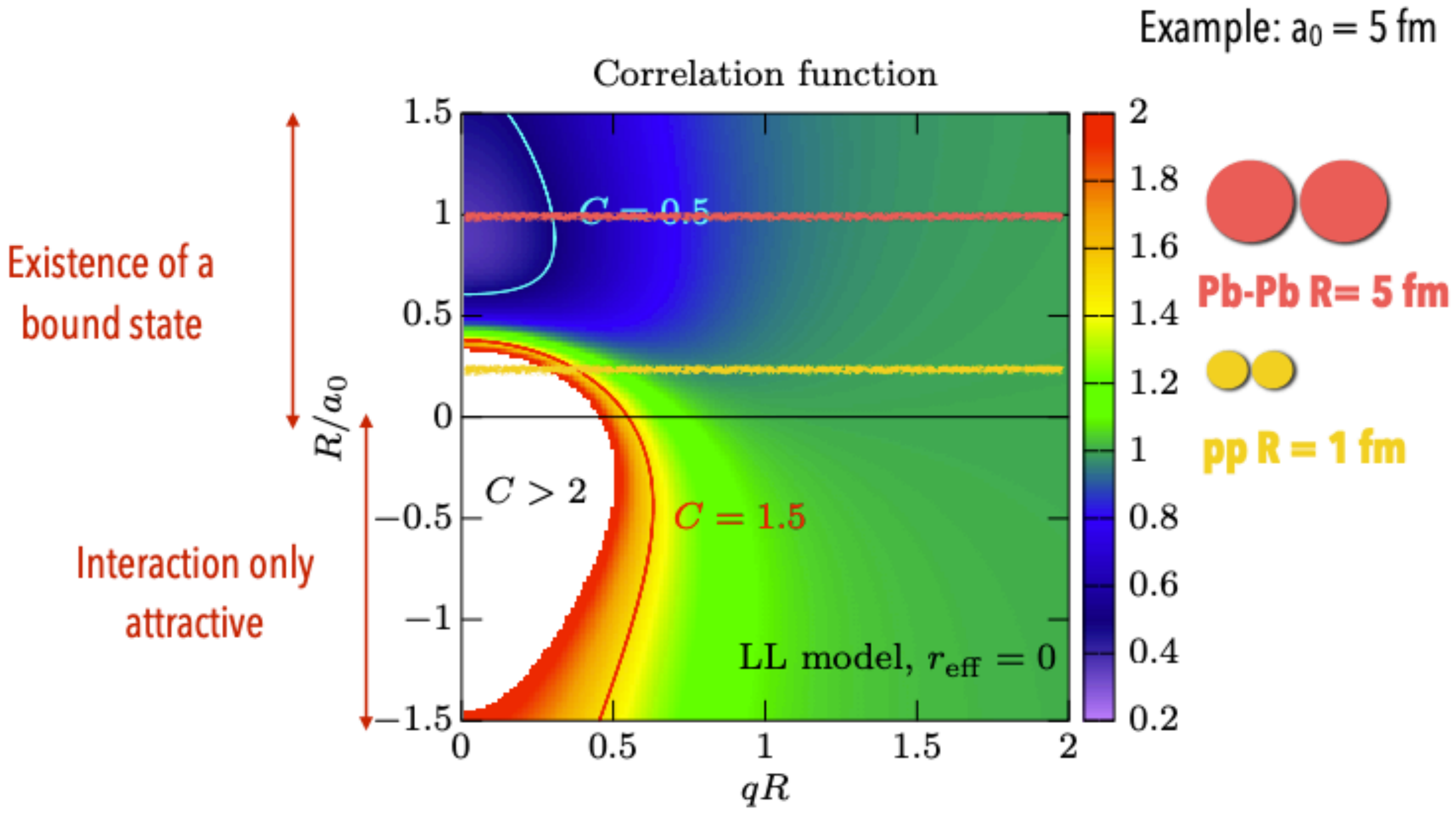
[CERN-LHCC-2022-009]

D_s: heavy quark diffusion coefficient

$$\langle r^2 \rangle = 6\, D_s\, t$$

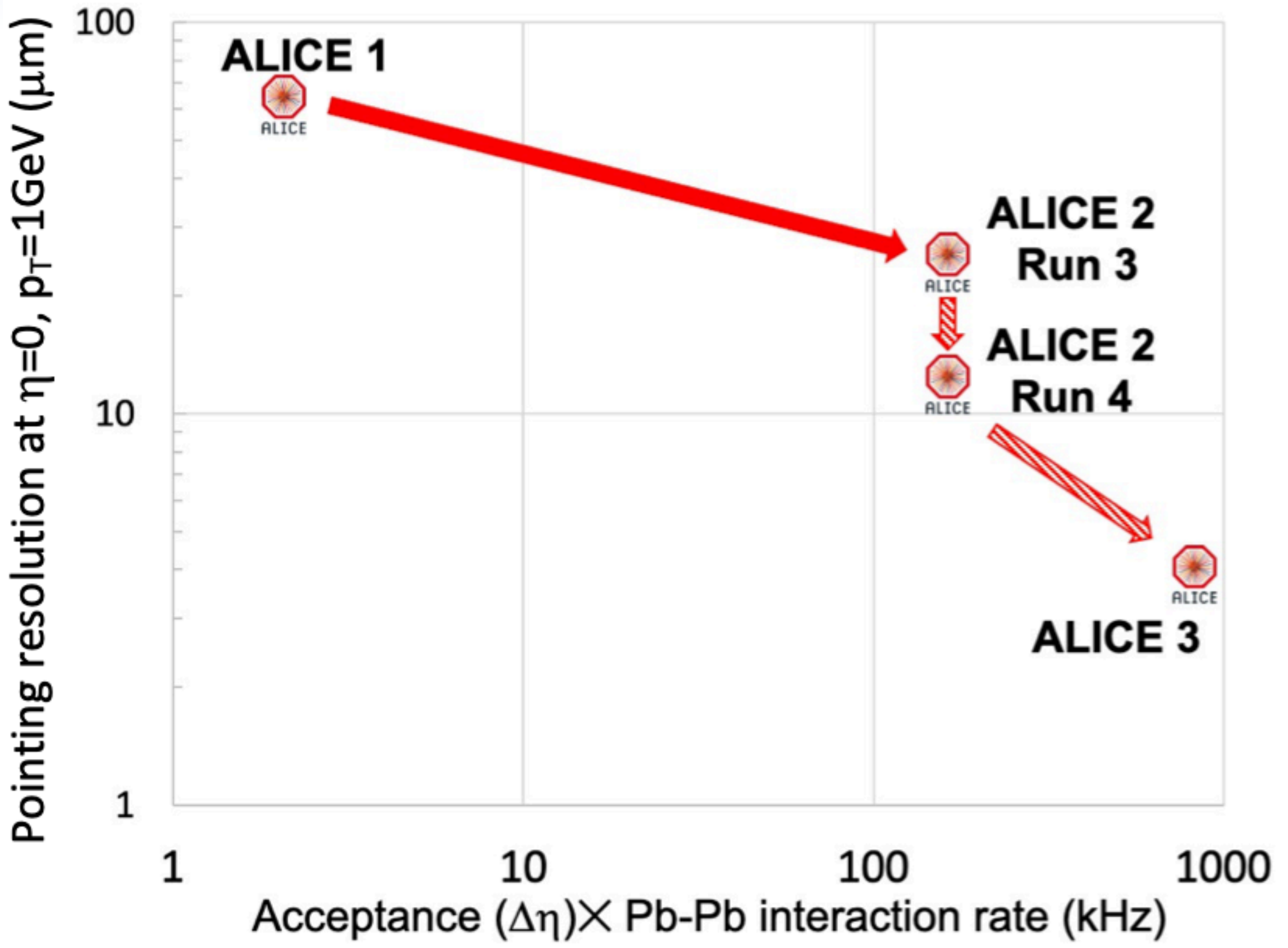
$$\tau_Q = (m_Q/T)\, D_s$$

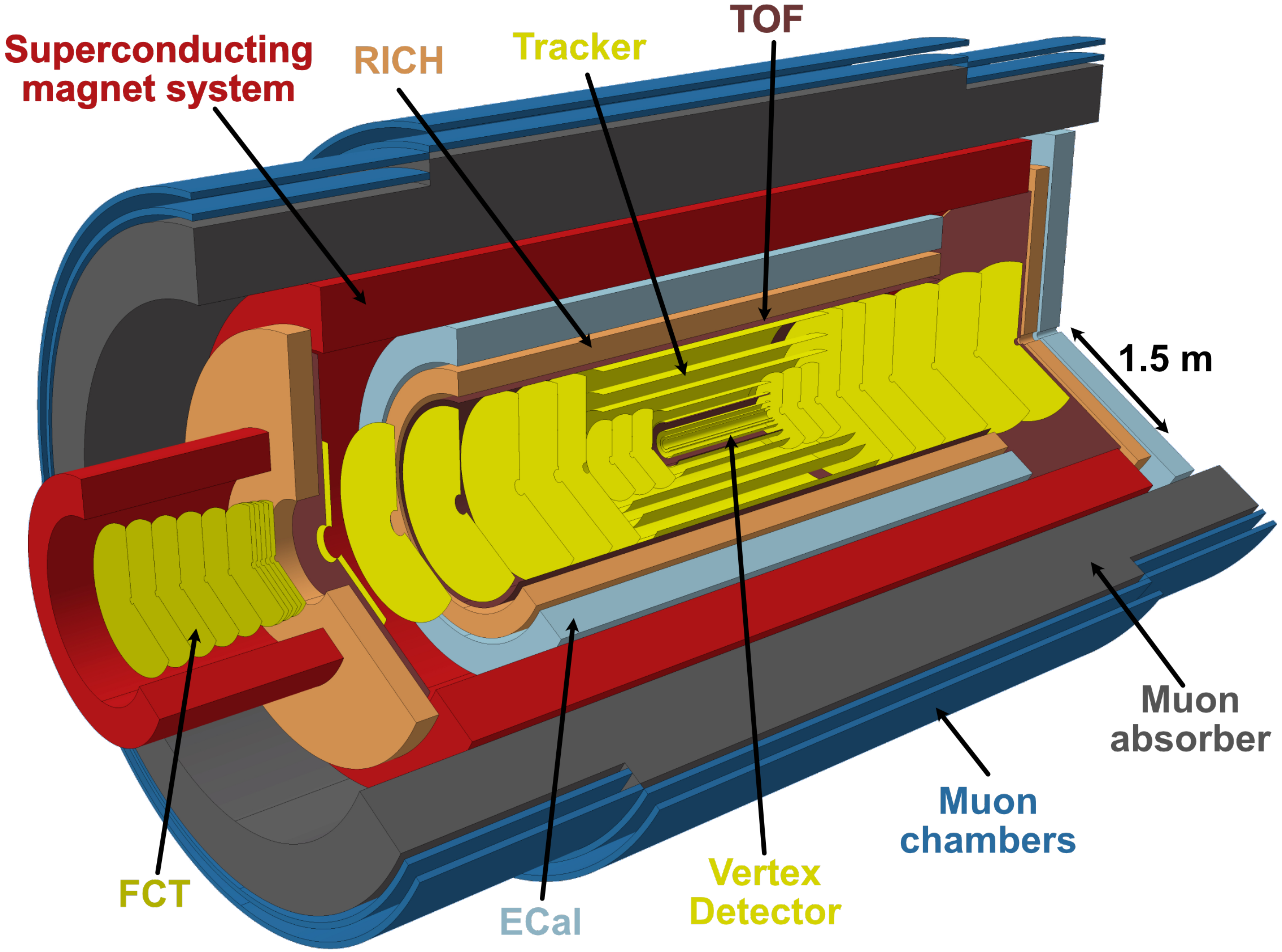




Y. Kamiya et al. arXiv:2108.09644v1

ALICE 3



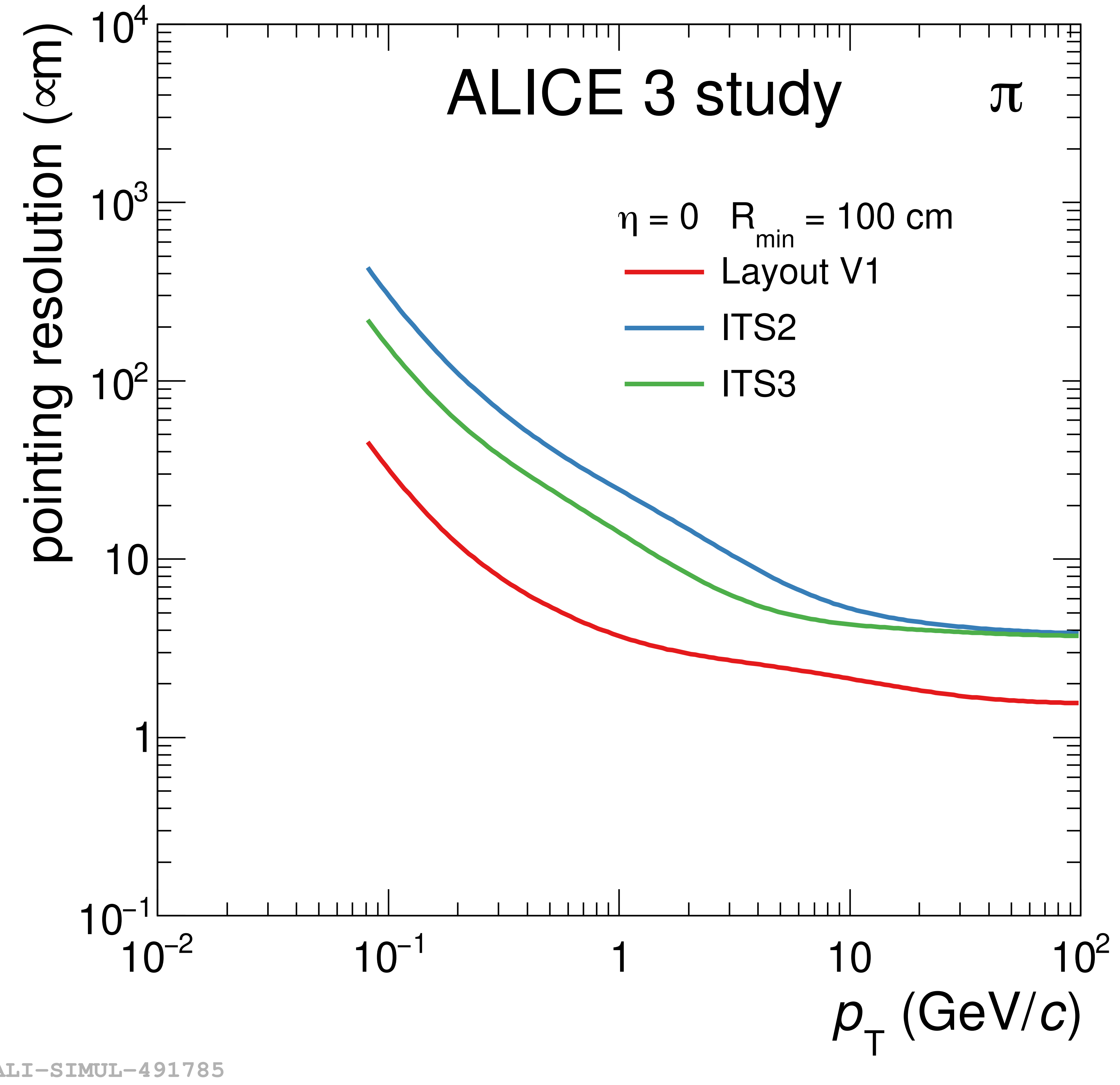


Innovative detector concept

- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Extensive particle identification
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing

Pointing resolution

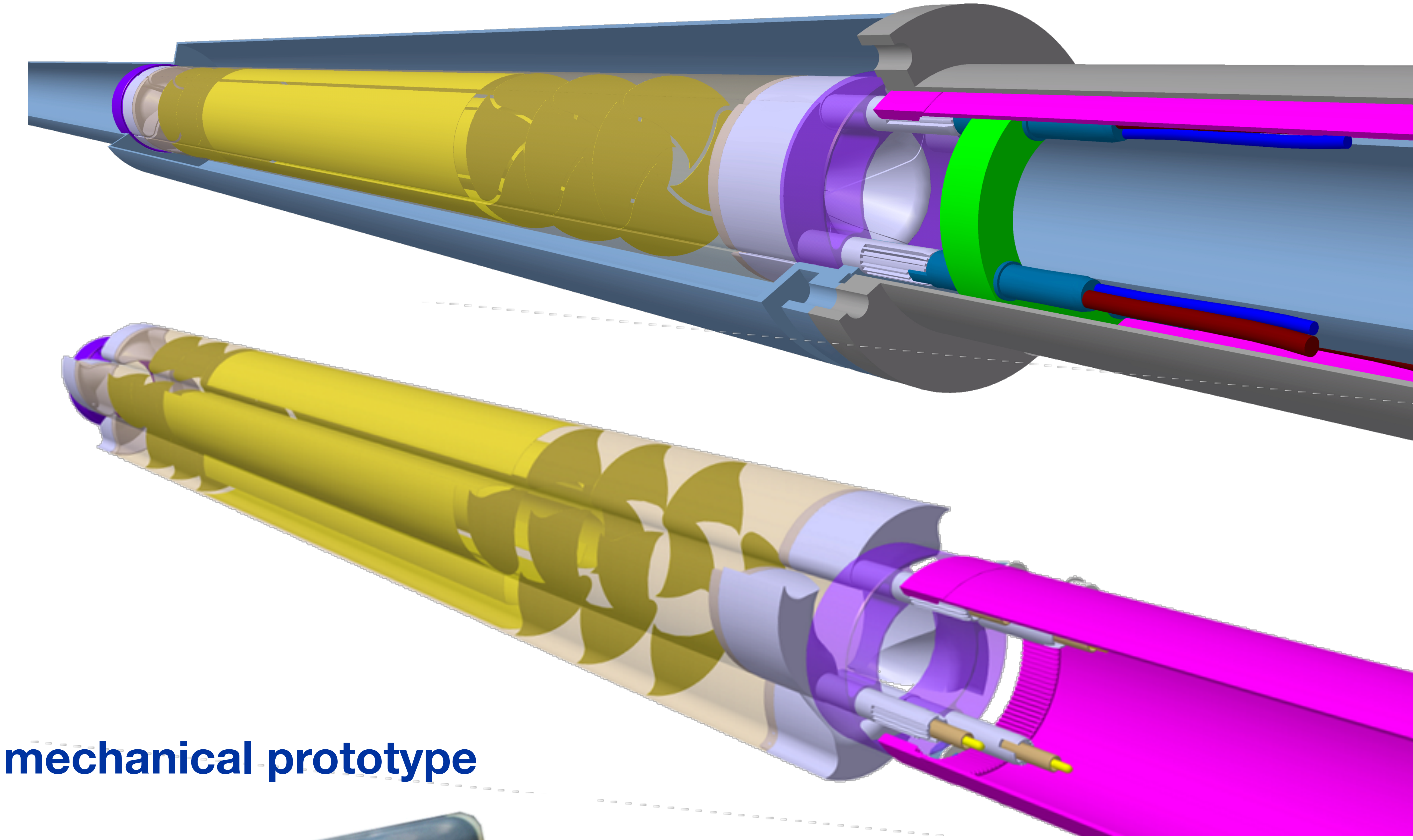
- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  (multiple scattering regime)
  ➟ 10 μm @ p_T = 200 MeV/*c*
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex detector**
- **3 layers within beam pipe** (in secondary vacuum)
  at radii of 5 - 25 mm
  - wafer-sized, bent Monolithic Active Pixel Sensors
  - σ_{pos} ~2.5 μm → 10 μm pixel pitch
  - 1 ‰ X_0 per layer



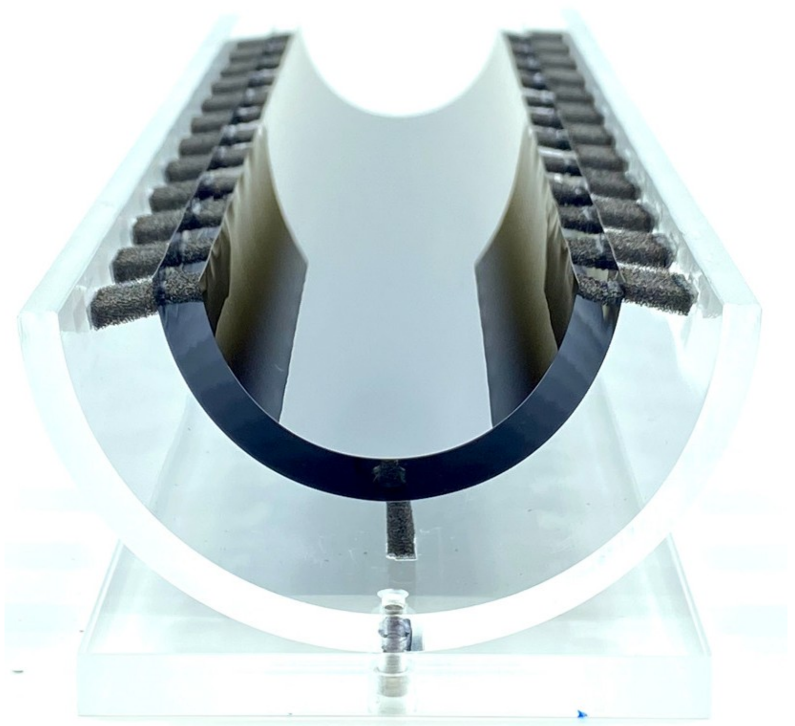
5x better than ALICE 2.1
(ITS3 + TPC)

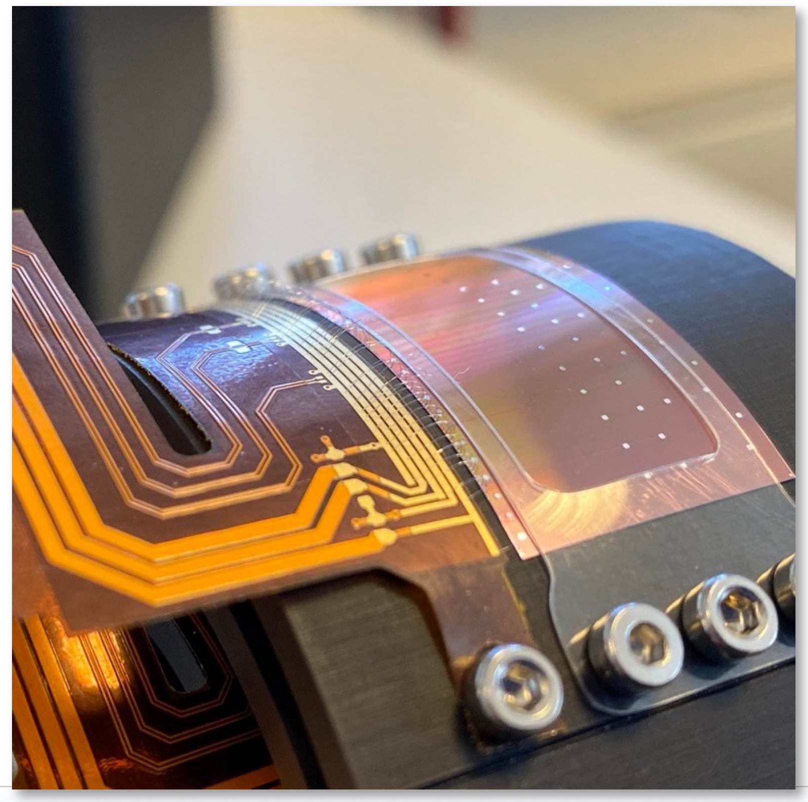
Vertex Detector

- **Retractable design for proximity to beam**
  - wafer-sized, bent MAPS (ITS3 technology)
  - rotary petals for secondary vacuum
- **R&D challenges**
  - feed-throughs for power, cooling, data
  - radiation tolerance

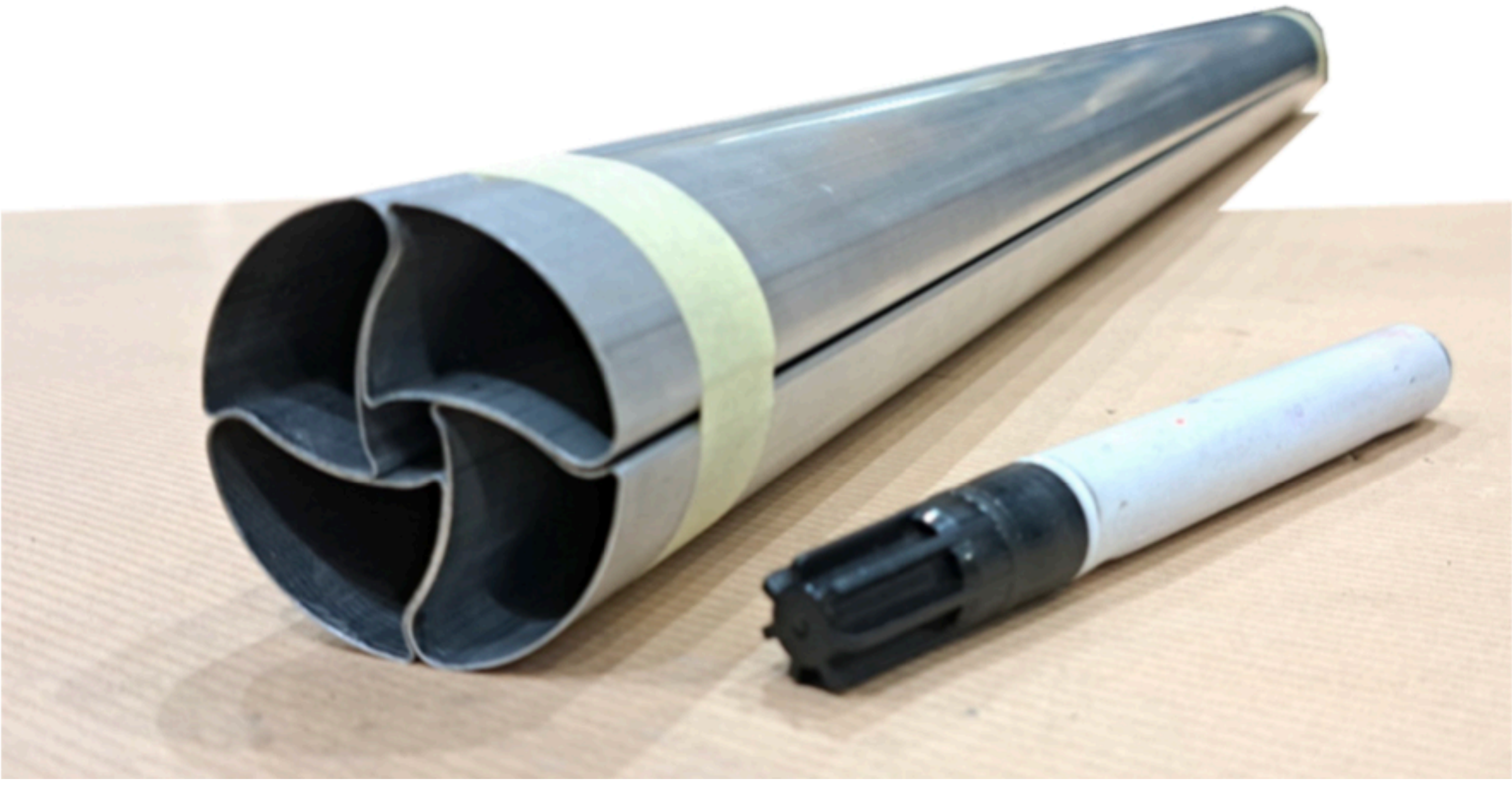


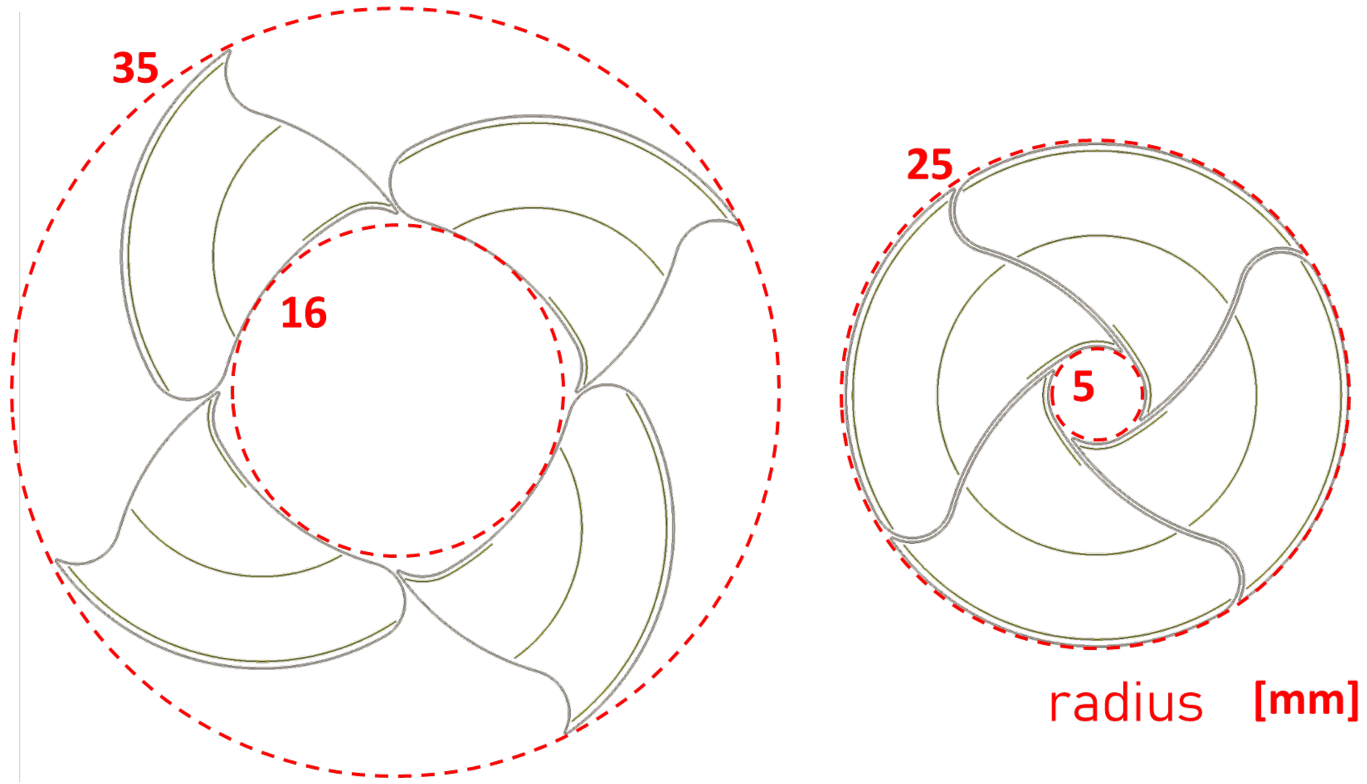
ITS3 R&D





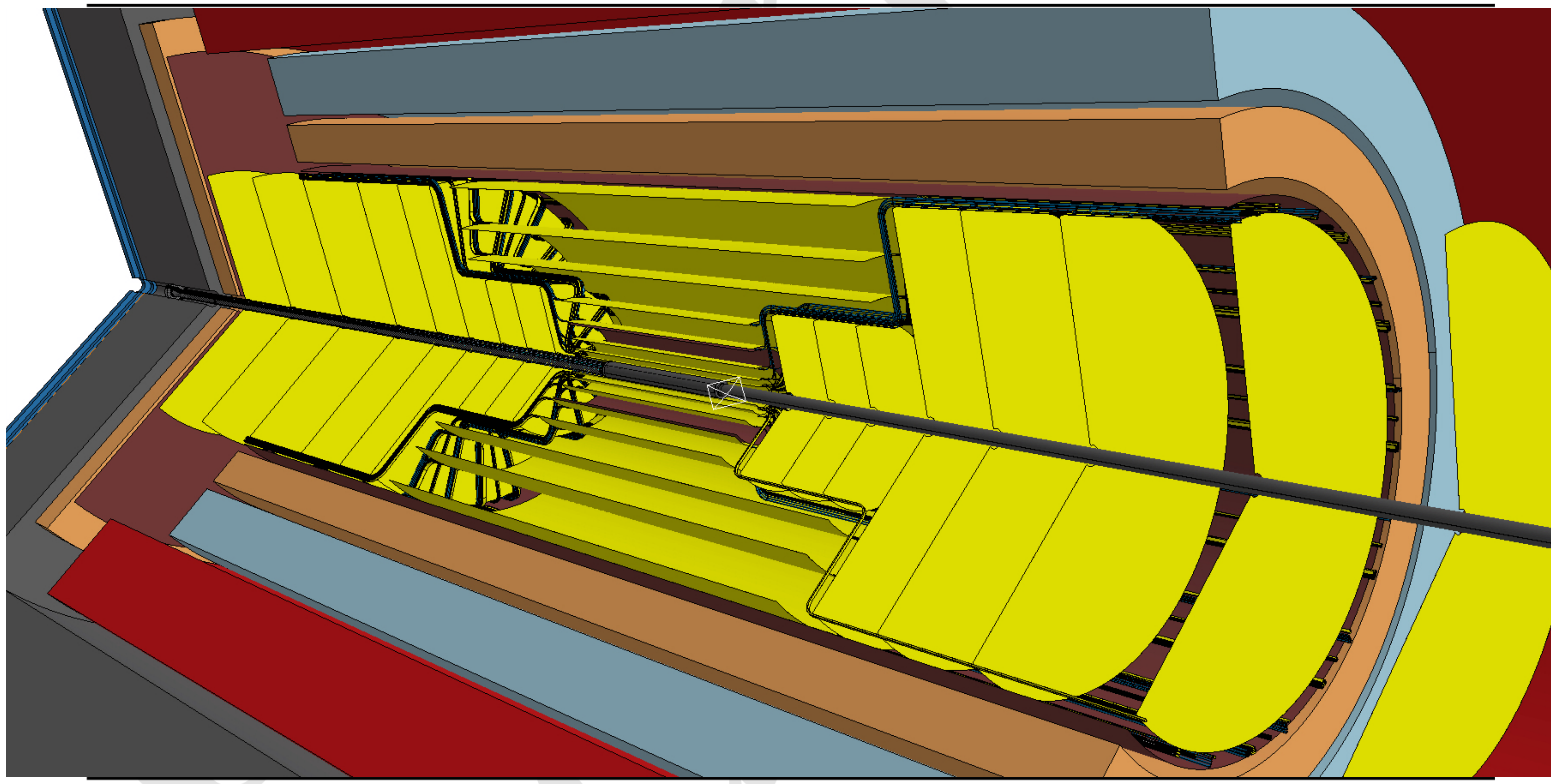
Extruded mechanical prototype

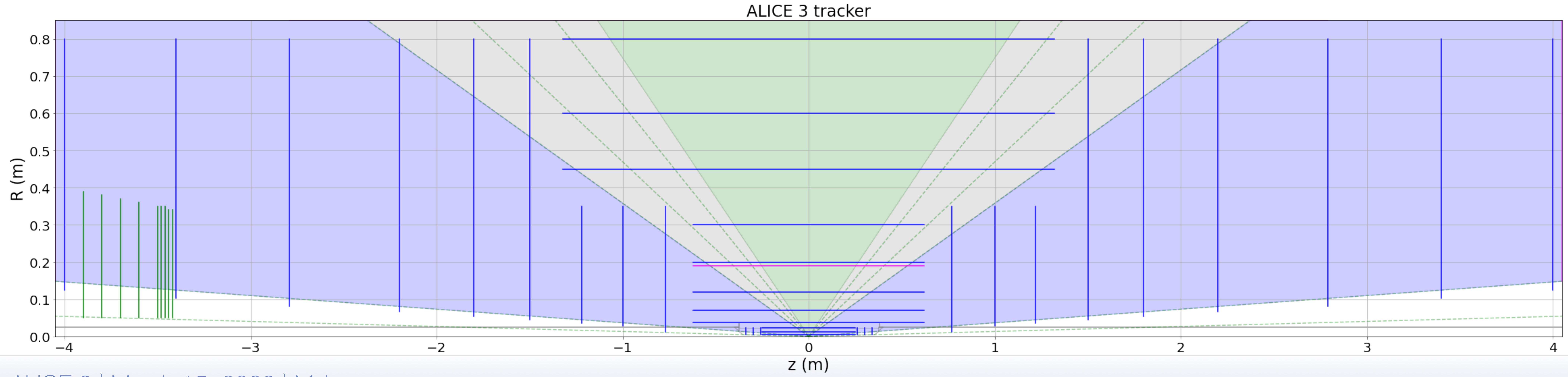




Outer Tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- Carbon-fibre space frame for mechanical support
- **R&D challenges** on
  - powering scheme (→ material)
  - industrialisation

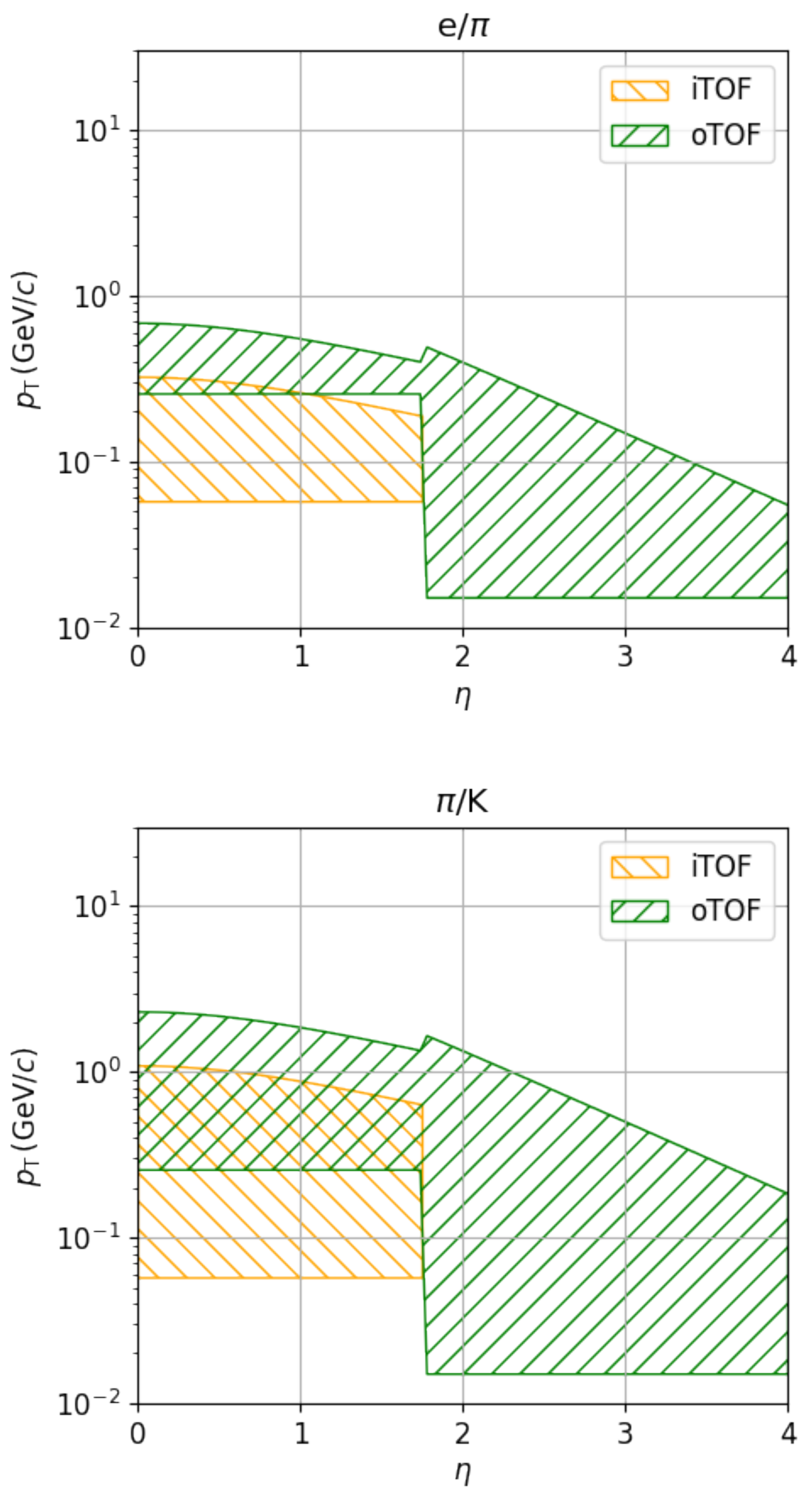




Total silicon surface ~60 m²

Time of flight

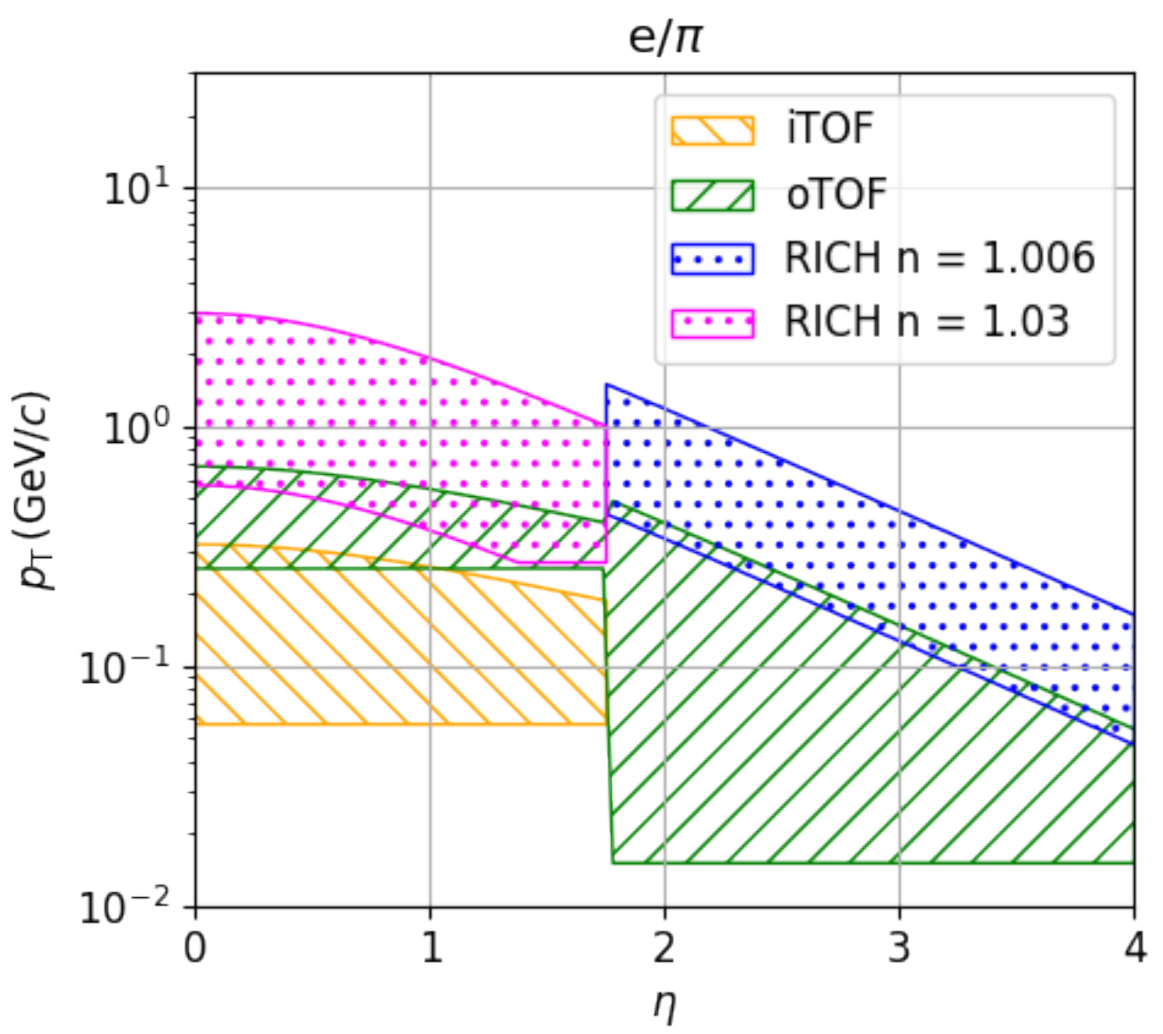
- **Separation power** $\propto \dfrac{L}{\sigma_{\text{tof}}}$
  - distance and time resolution crucial
  - larger radius results in lower p_T bound
- **2 barrel + 1 forward TOF layers**
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm
  - total surface ~45 m^2
- **Silicon timing sensors** ($\sigma_{TOF} \approx$ 20 ps)
  - R&D on monolithic CMOS sensors with integrated gain layer

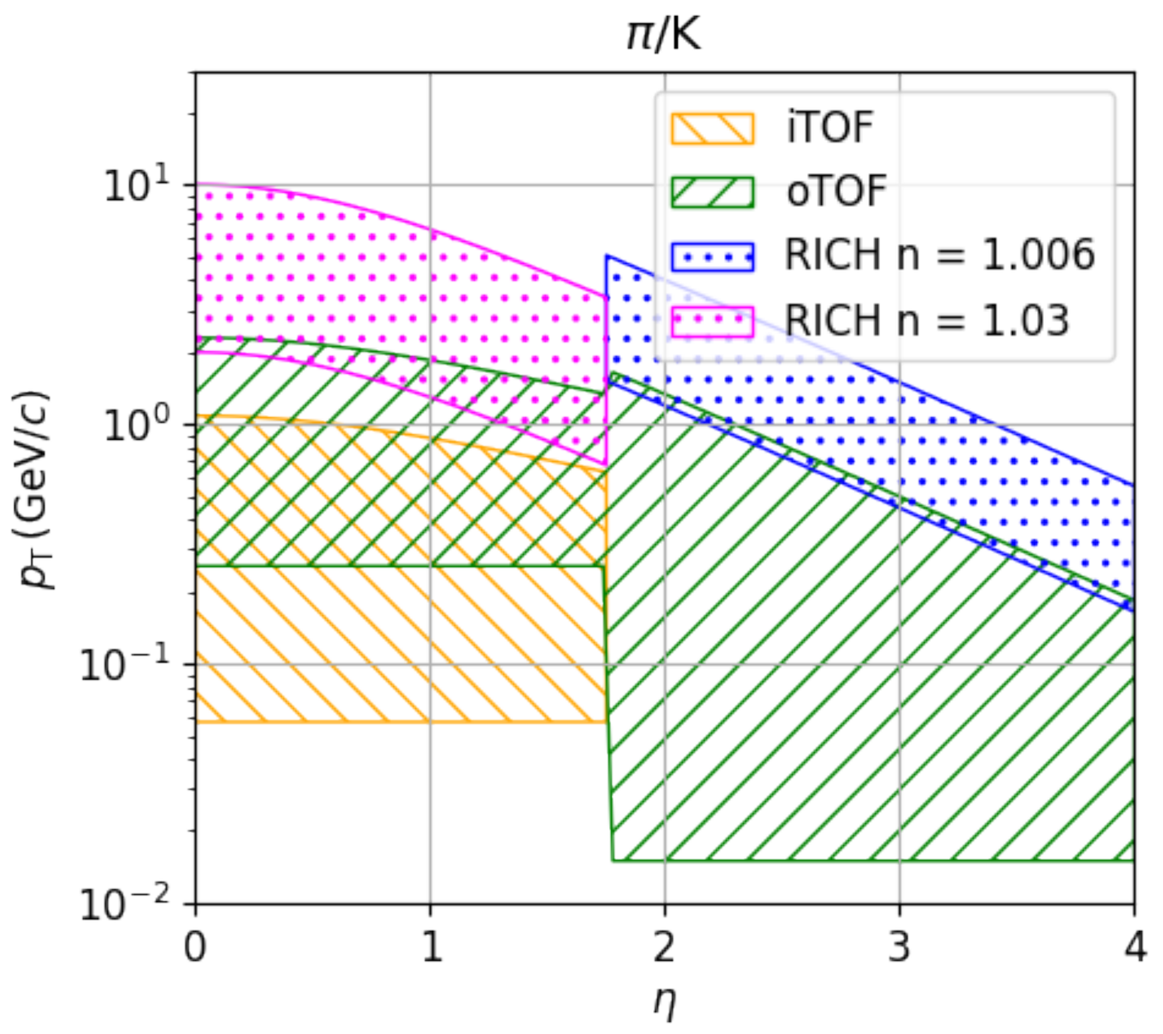


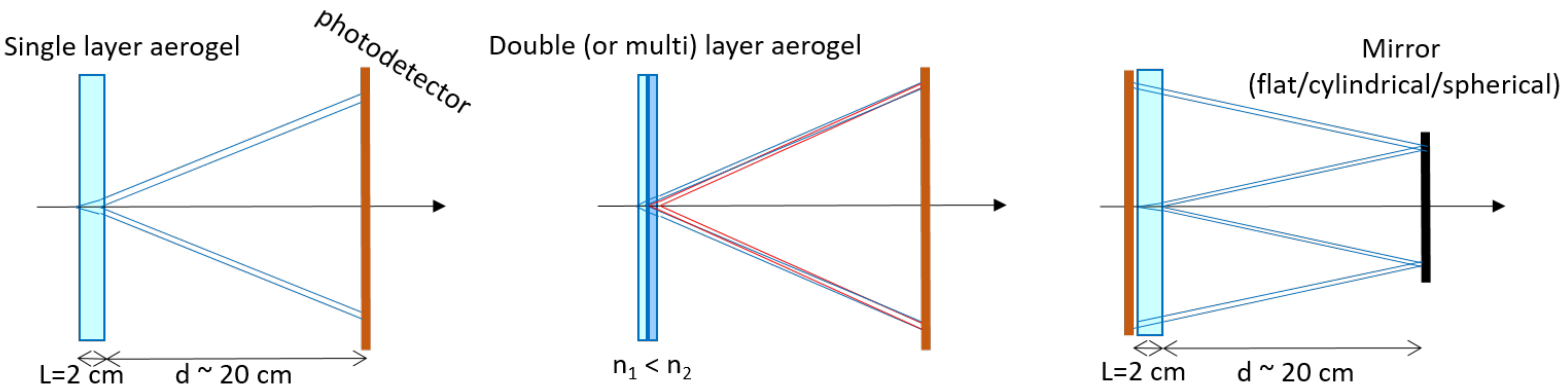
Ring-Imaging Cherenkov

- **Extend PID reach of outer TOF to higher p_T**
  ➟ Cherenkov
  - **aerogel radiator**
    to ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - **silicon photon sensors**
    - R&D on monolithic photon sensors
    - Possibility to use photon sensors for charges particle detection: combine RICH and outer TOF?

Total SiPM surface ~60 m²

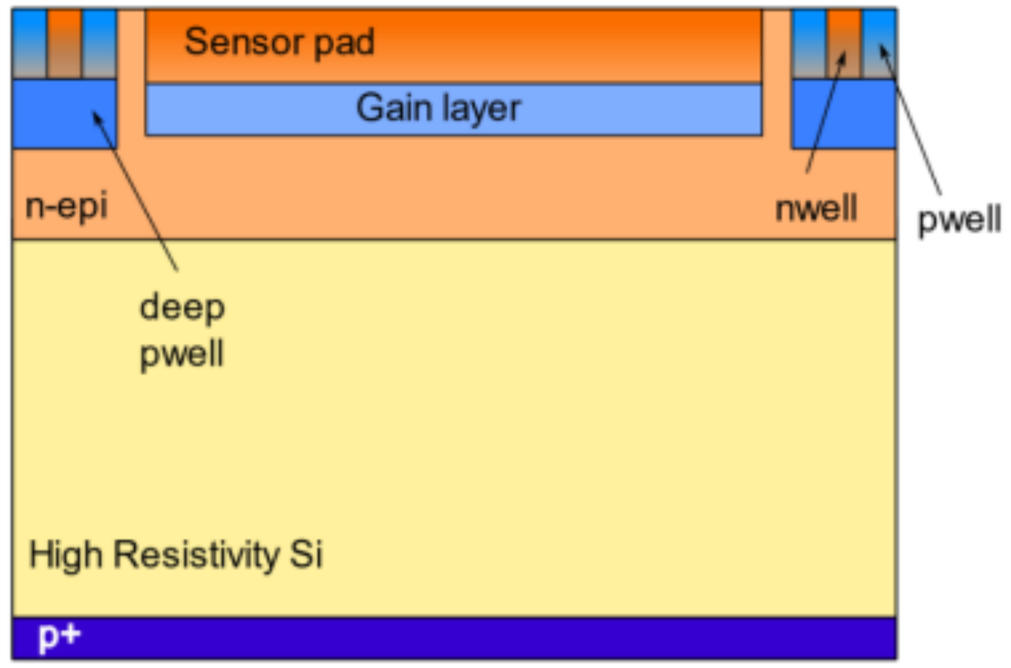






Timing sensor R&D

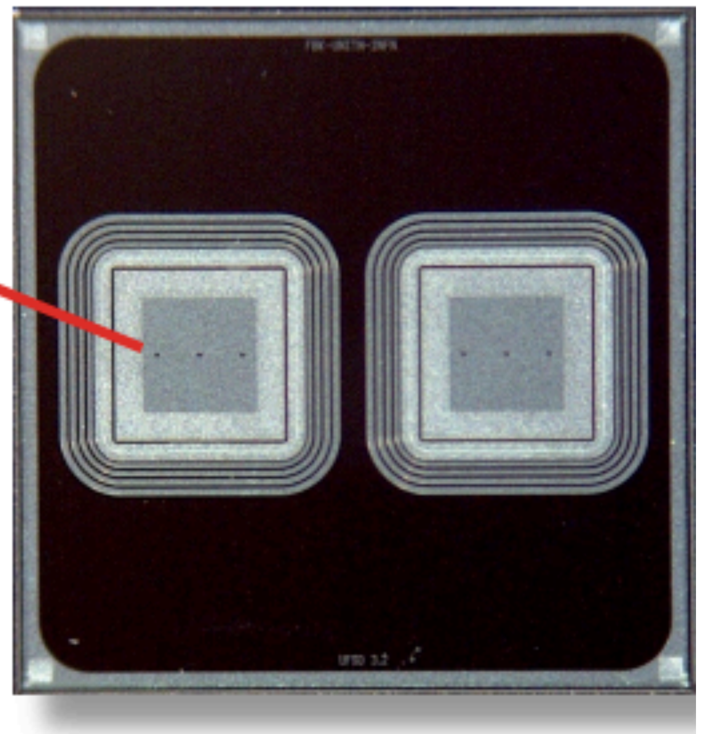
- R&D for monolithic timing sensor
  - Implement/test gain layer in L-foundry process
- Fallback: thin hybrid LGAD sensors



First very thin LGAD prototypes produced by FBK

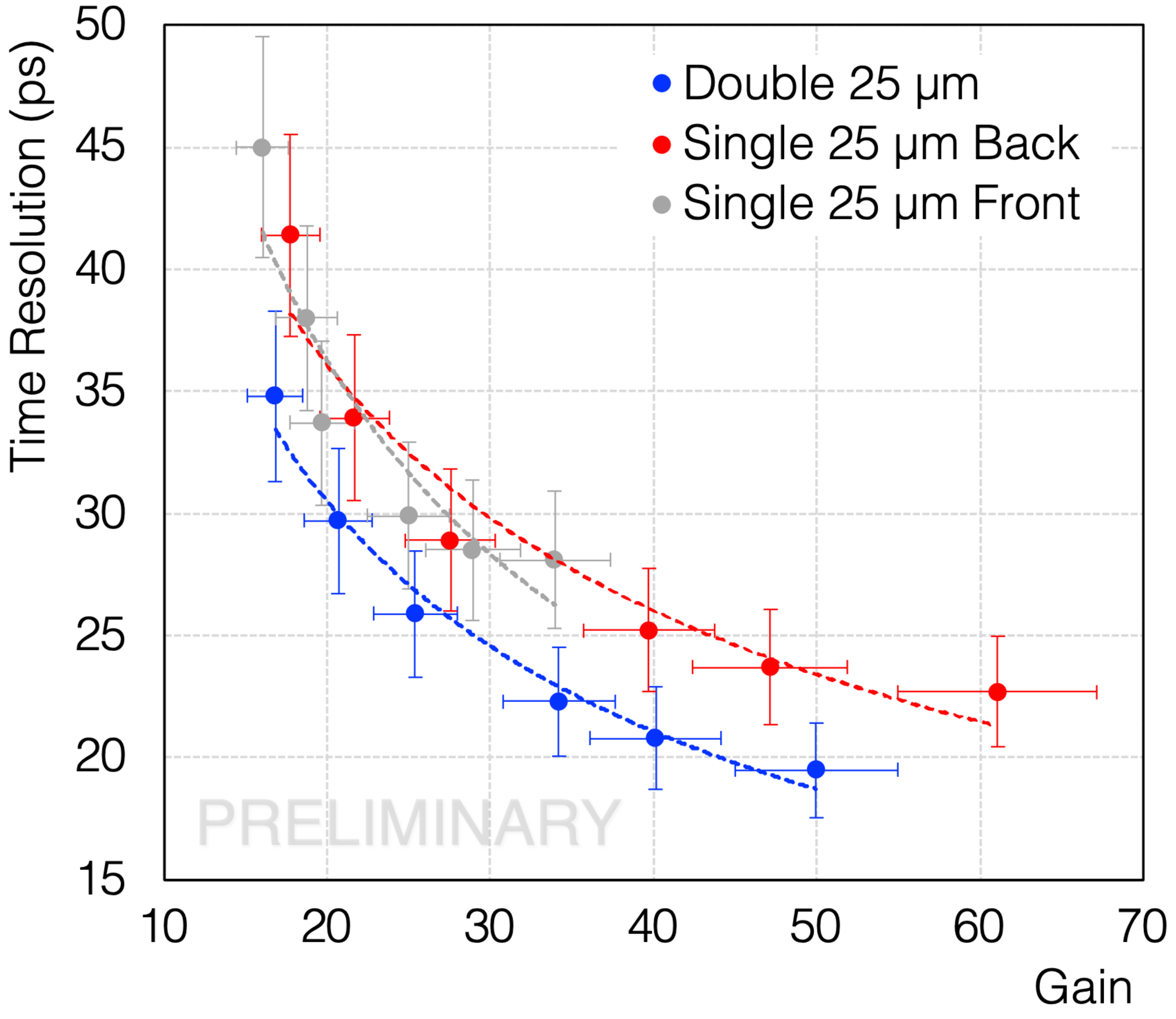
25 µm and
35 µm-thick FBK
single channel

Area = **1x1 mm²**

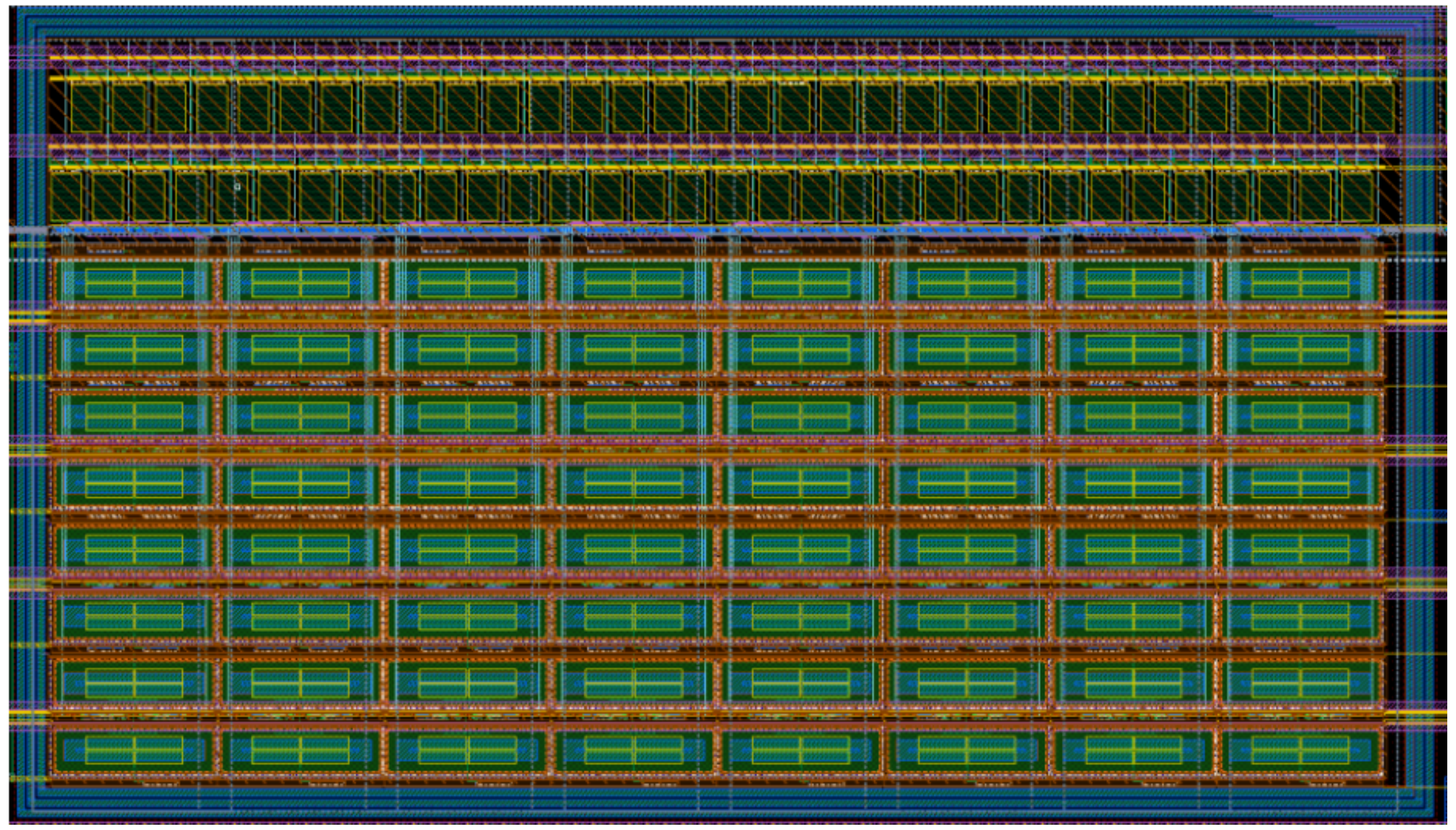


F. Carnesecchi et al, EPJ Plus 138 1, 99

LGAD time resolution



Demonstrator submitted to L-foundry

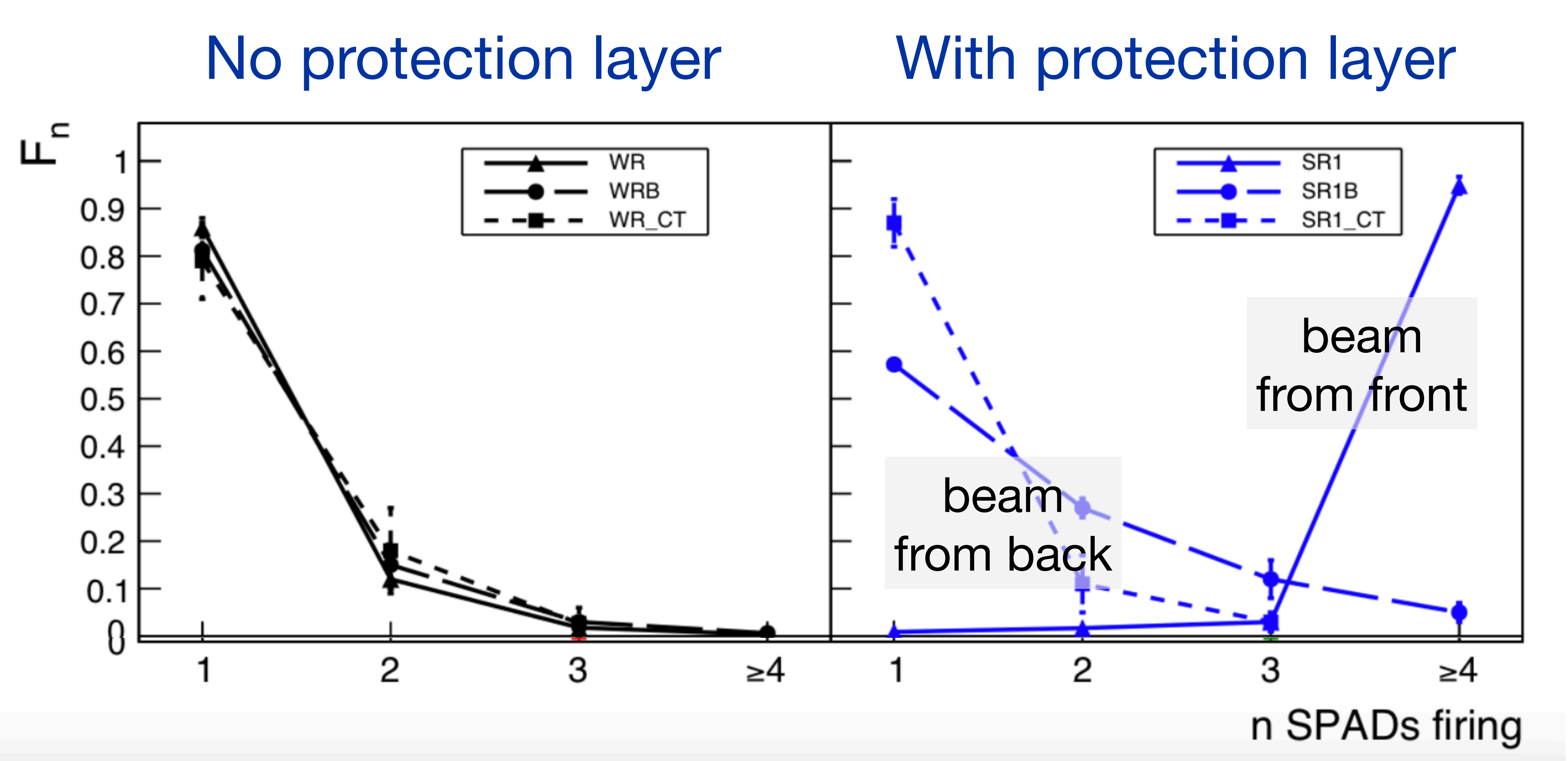


First devices delivered — tests ongoing

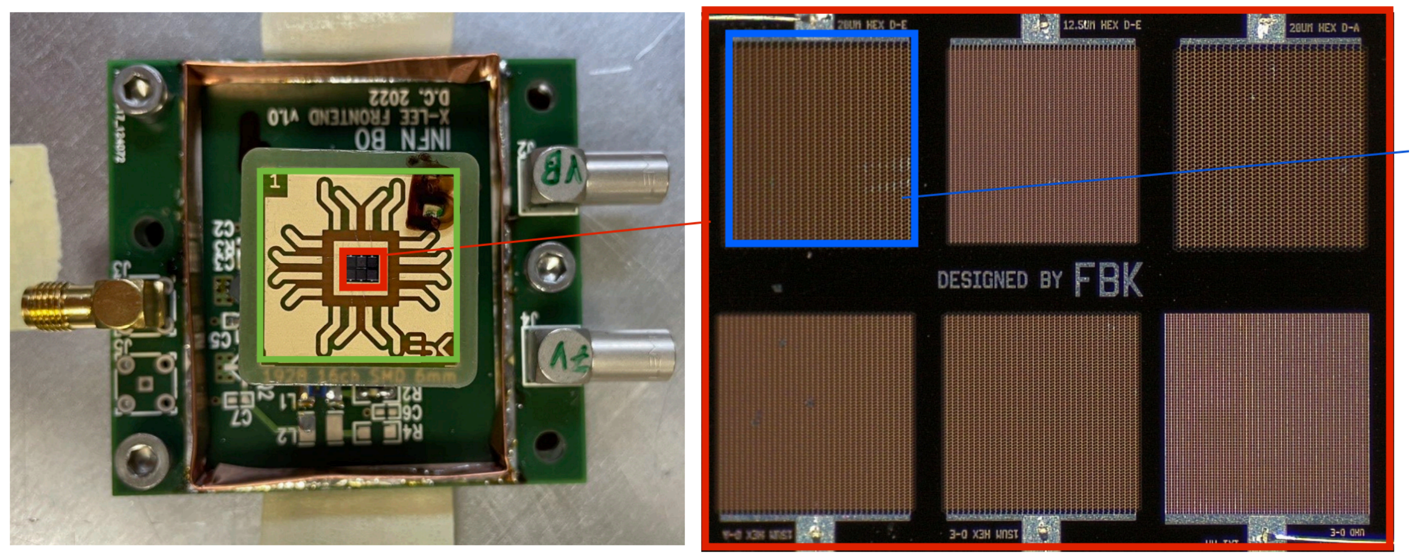
R&D: SiPM response studies

- Ongoing R&D with SiPM for photon and hadron detection and good time resolution
- First results encouraging:
  - Multi-pixel response for charged particles: Cherenkov radiation in protection layer
  - Good time resolution, in particular for large clusters ⇒ important for dark count suppression

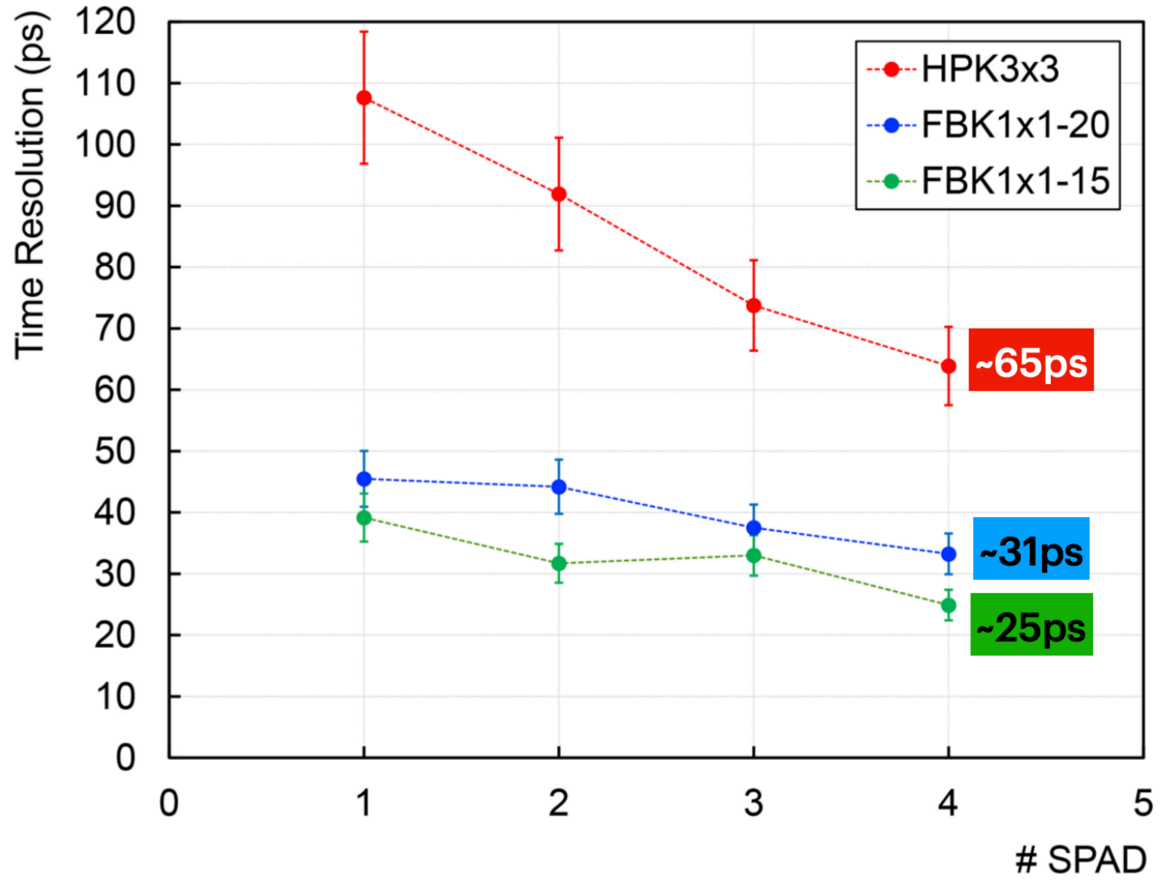
Cluster size distribution



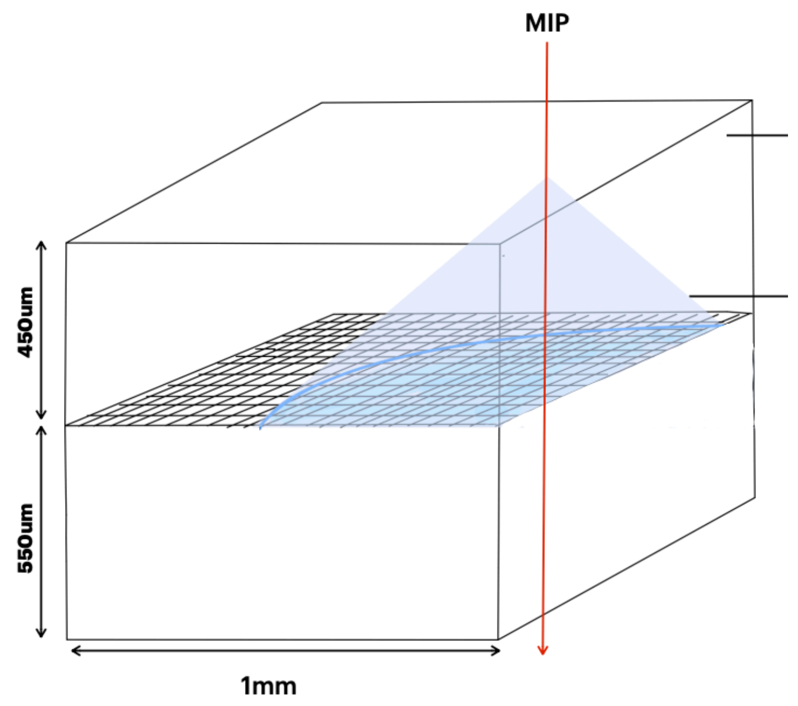
With protection layer, front-side beam shows large clusters: Cherenkov radiation in protection layer



Time resolution



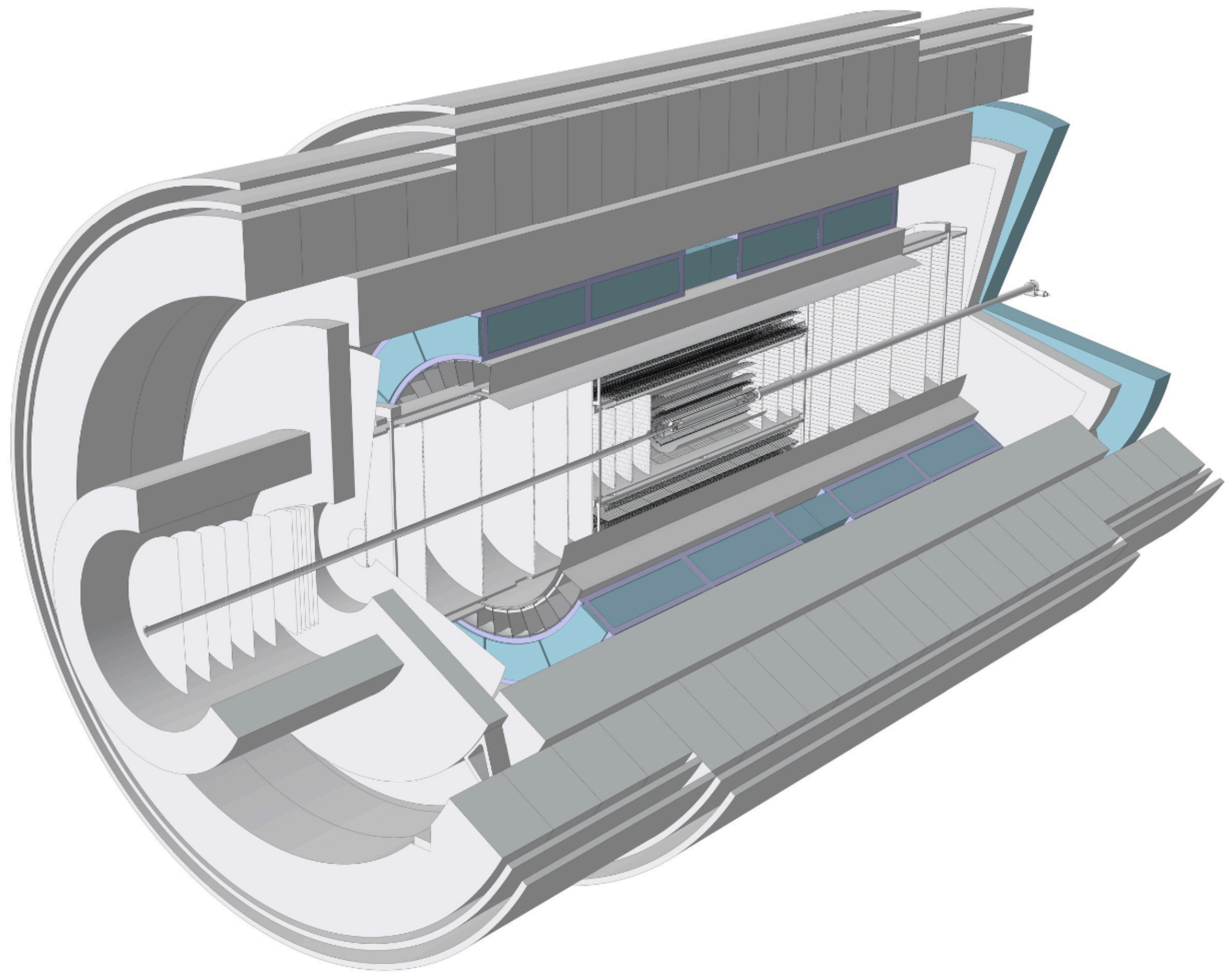
arXiv:2202.04169



EM calorimeter

- **Large acceptance ECal**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)
- **Additional high energy resolution segment** at midrapidity or forward
  → $PbWO_4$-based

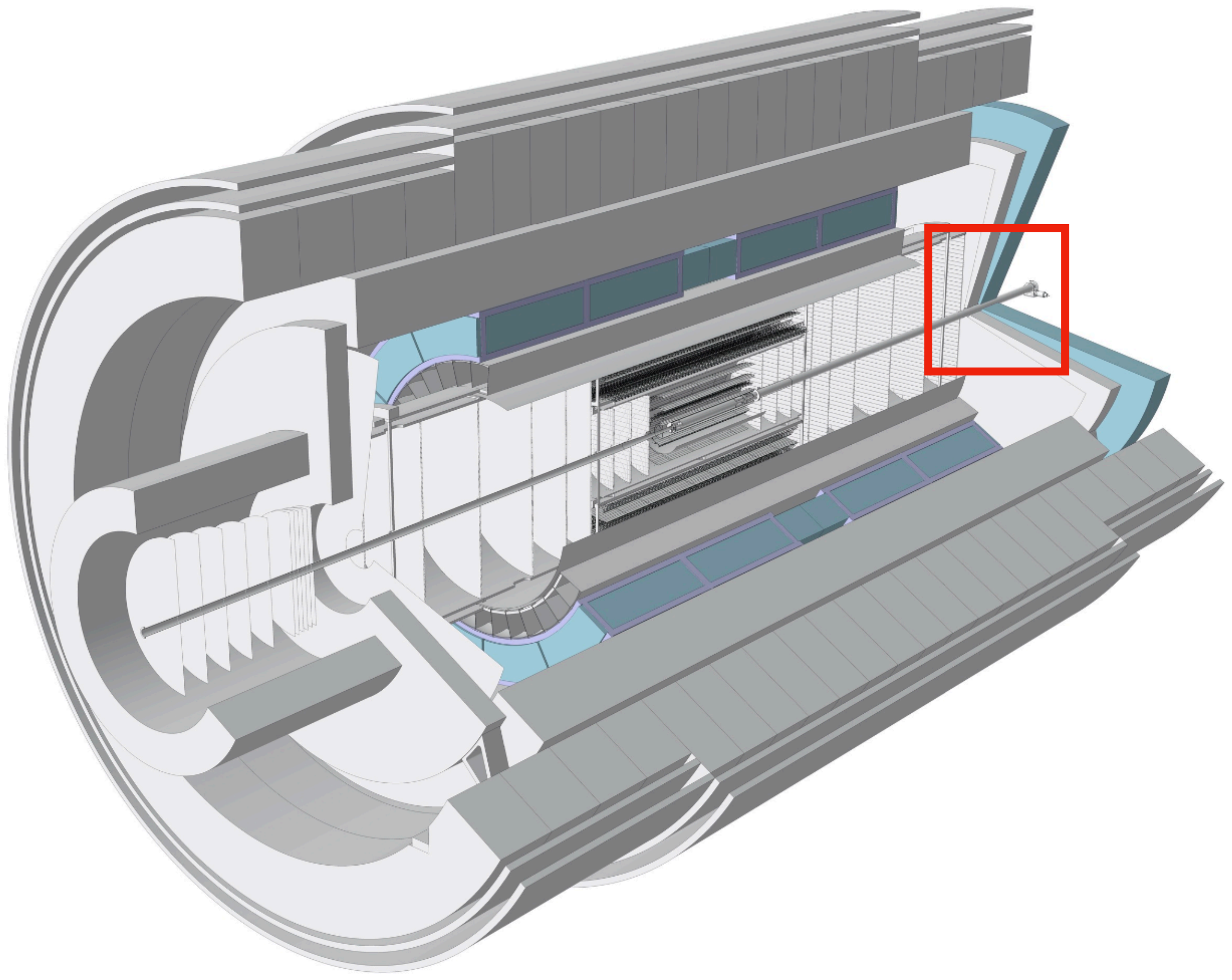
ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\|\eta\| < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\|\eta\| < 0.33$
geometry	$R_{in} = 1.15$ m, $\|z\| < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\|z\| < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV



Strong interest from JINR

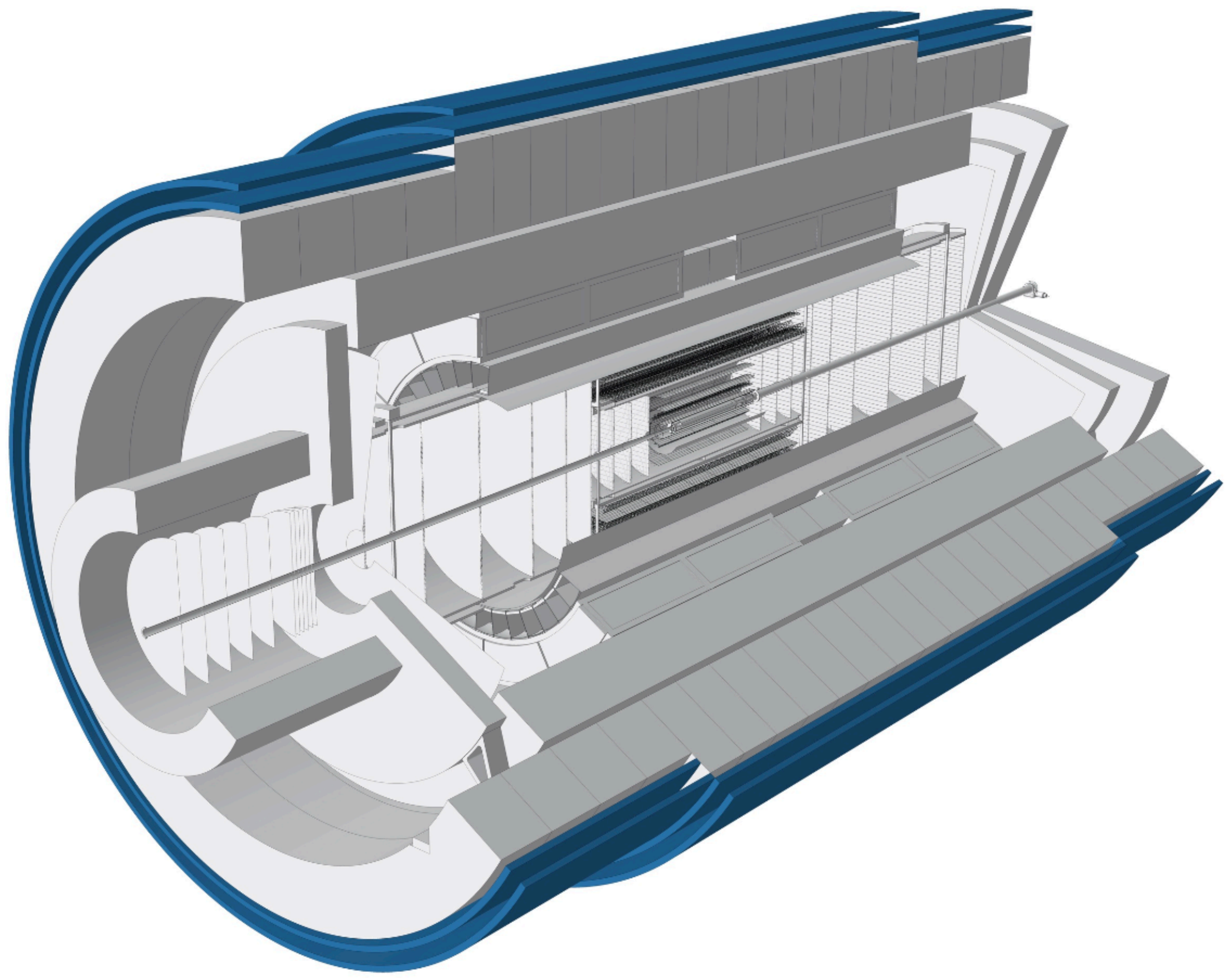
FoCal in ALICE 3

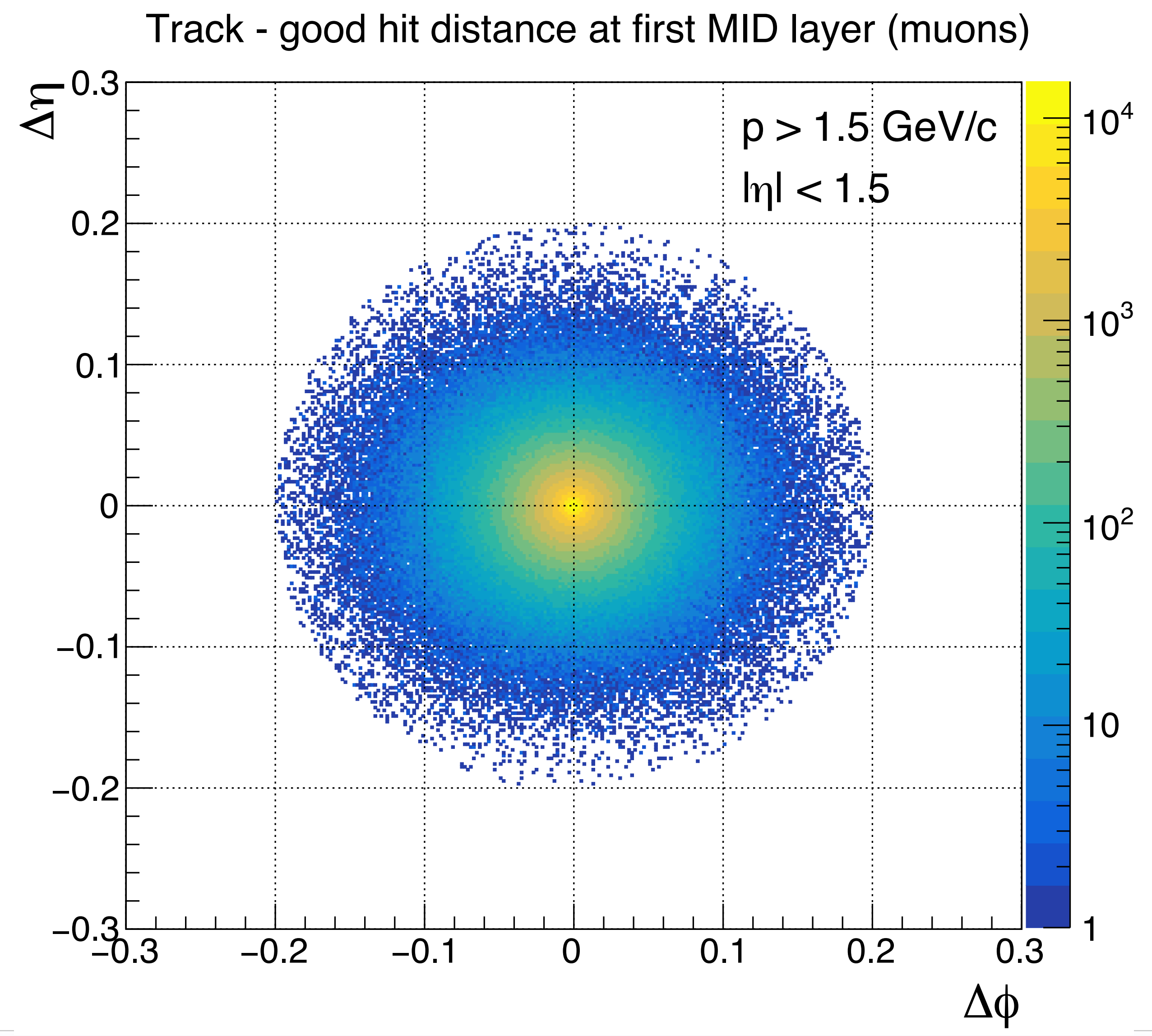
- FoCal technology would be a natural fit for ALICE 3 forward EM calorimetry
  - Change/extend coverage to match barrel?
- Needs upgrades for **higher event rates**
  - Replace pixel layers?
  - PAD trigger
- Baseline FoCal measurements not statistics limited
- Investigate new physics opportunities
  - Extended acceptance for correlations
  - With tracking (up to y = 4?):
    - improved J/ψ mass resolution
    - radiative decays
    - non-prompt quarkonia
  - UPC with higher mass states?



Muon ID

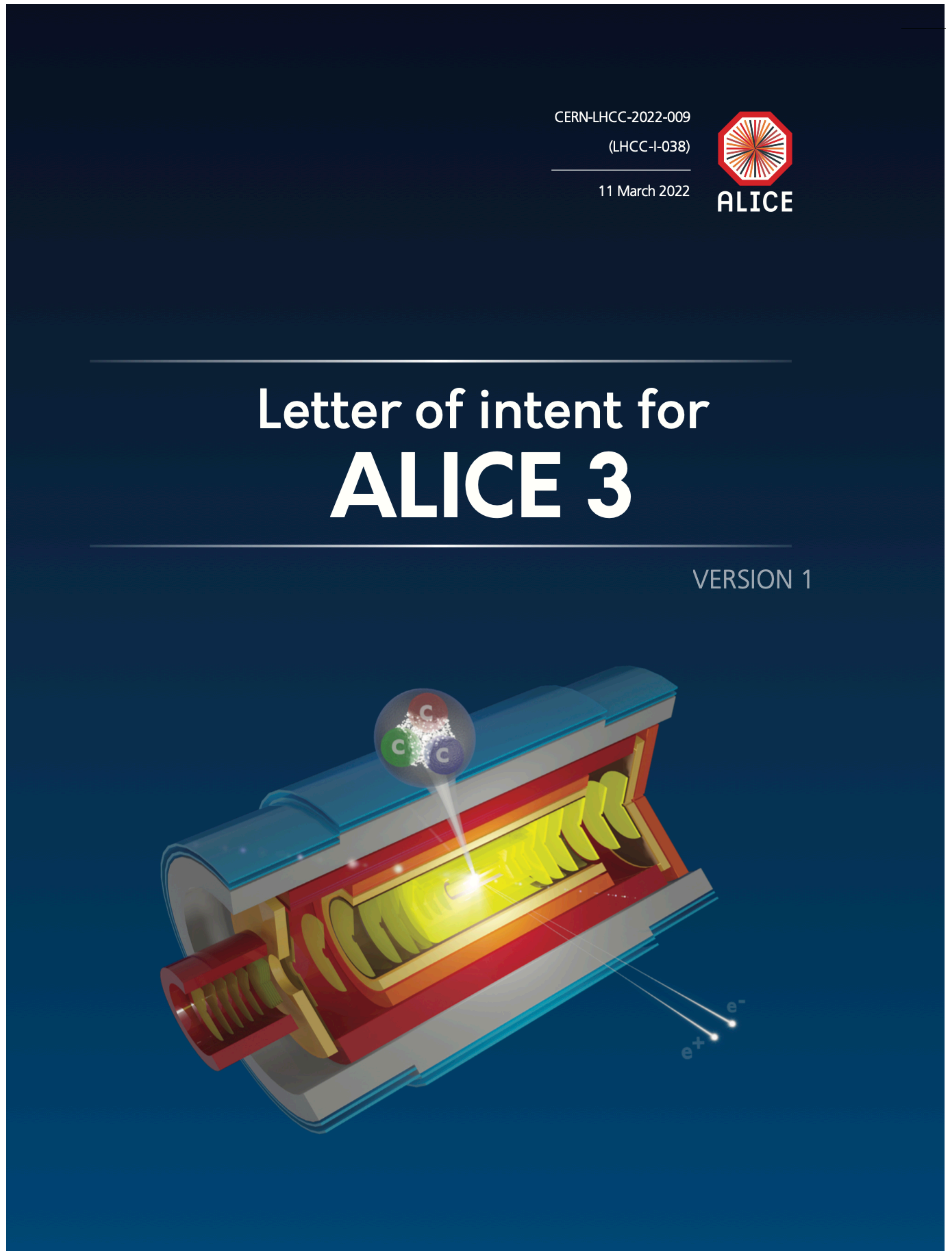
- **Hadron absorber** outside of the magnet
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm^2 cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars with SiPM read-out
    - resistive plate chambers
  - R&D for scintillator setup started by Mexican groups





Status and planning

- Letter of Intent reviewed by LHCC in March 2022
  - → **very positive evaluation** [LHCC-149]
    - Exciting physics program
    - Detector well matched with physics program and strategically interesting R&D opportunities
  - **R&D activities** have started, already with promising results
- **Timeline**
  - **2023-25**: selection of technologies, small-scale proof of concept prototypes
  - **2026-27**: large-scale engineered prototypes → Technical Design Reports
  - **2028-30**: construction and testing
  - **2031-32**: contingency
  - **2033-34**: Preparation of cavern and installation of ALICE 3



[CERN-LHCC-2022-009]
[arXiv:2211.02491]

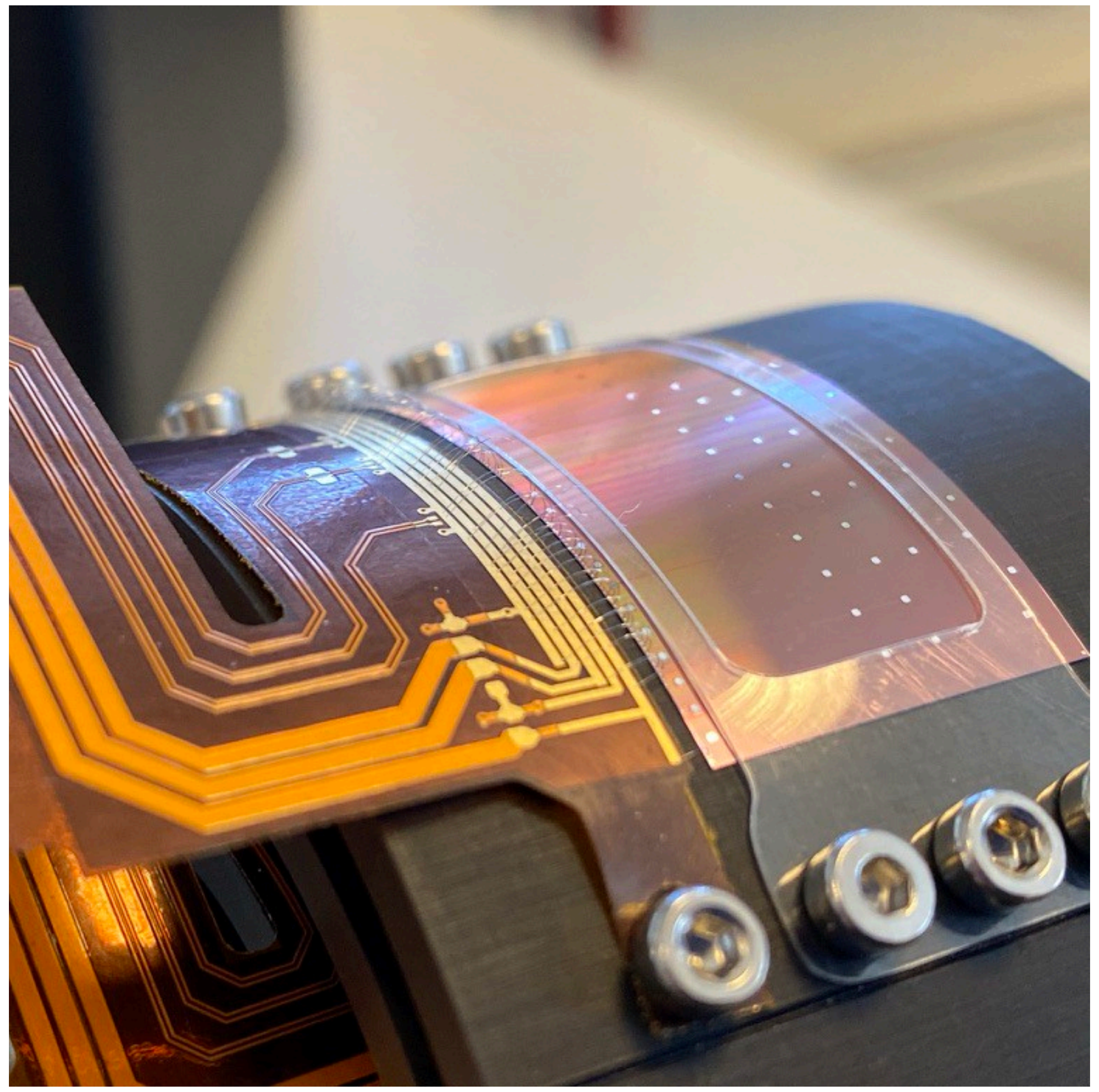
Summary

- ALICE 3 opens up new physics opportunities:
  - Thermal radiation and chiral symmetry restauration
  - Heavy flavour (charm + *beauty*) transport and thermalisation
  - Exploring the nature of exotic hadronic states
  - Quantum number conservation over large rapidity range
  - and more …
- Using novel detector concepts, opening up R&D opportunities
  - Next-generation silicon sensors for tracking and PID
  - Retractable vertex tracker at mid-rapidity
  - Effective construction silicon sensor layers with large area
  - PID with TOF, RICH, MID, EMCal

Thank you for you attention!

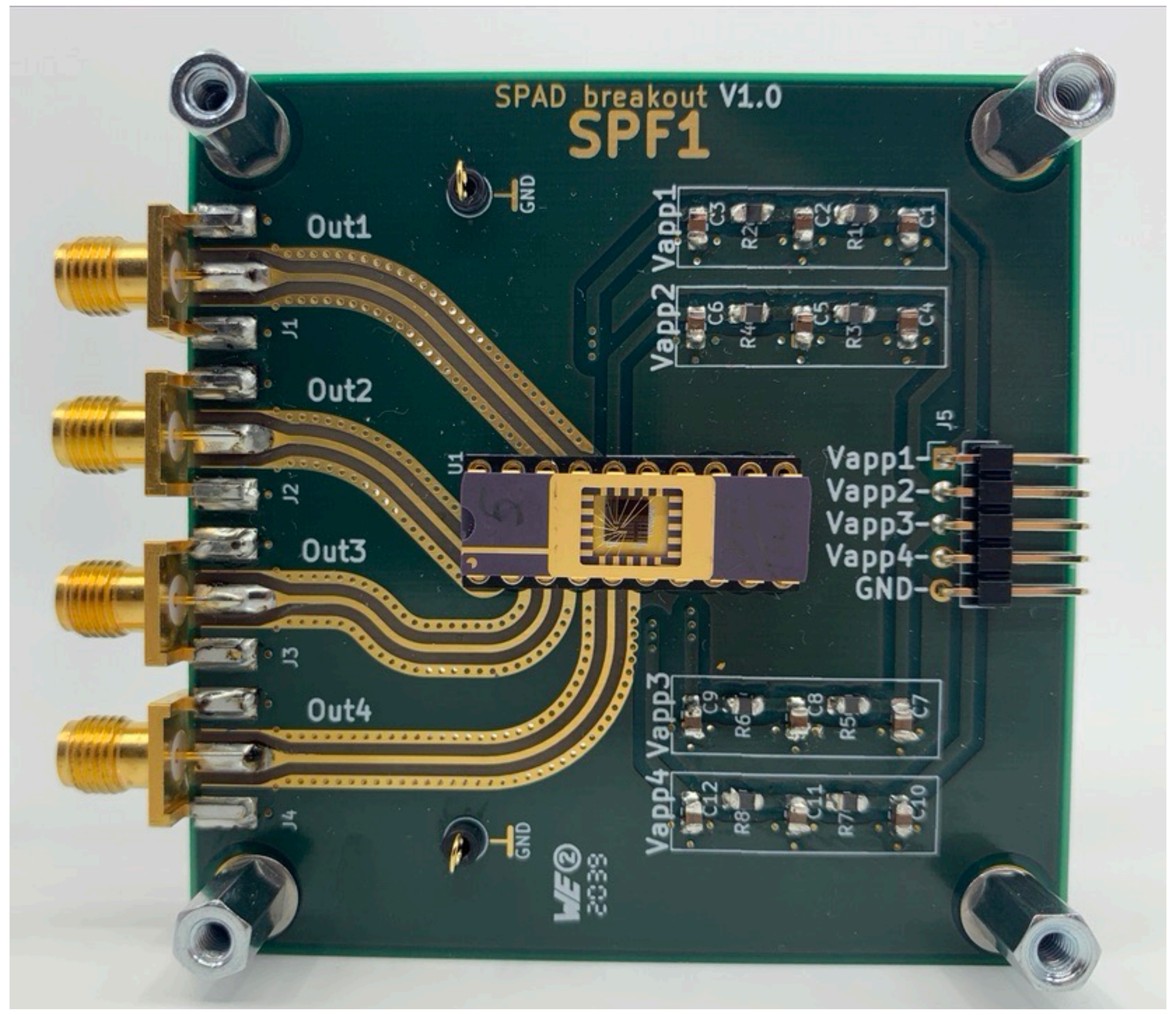
Strategic R&D

- **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



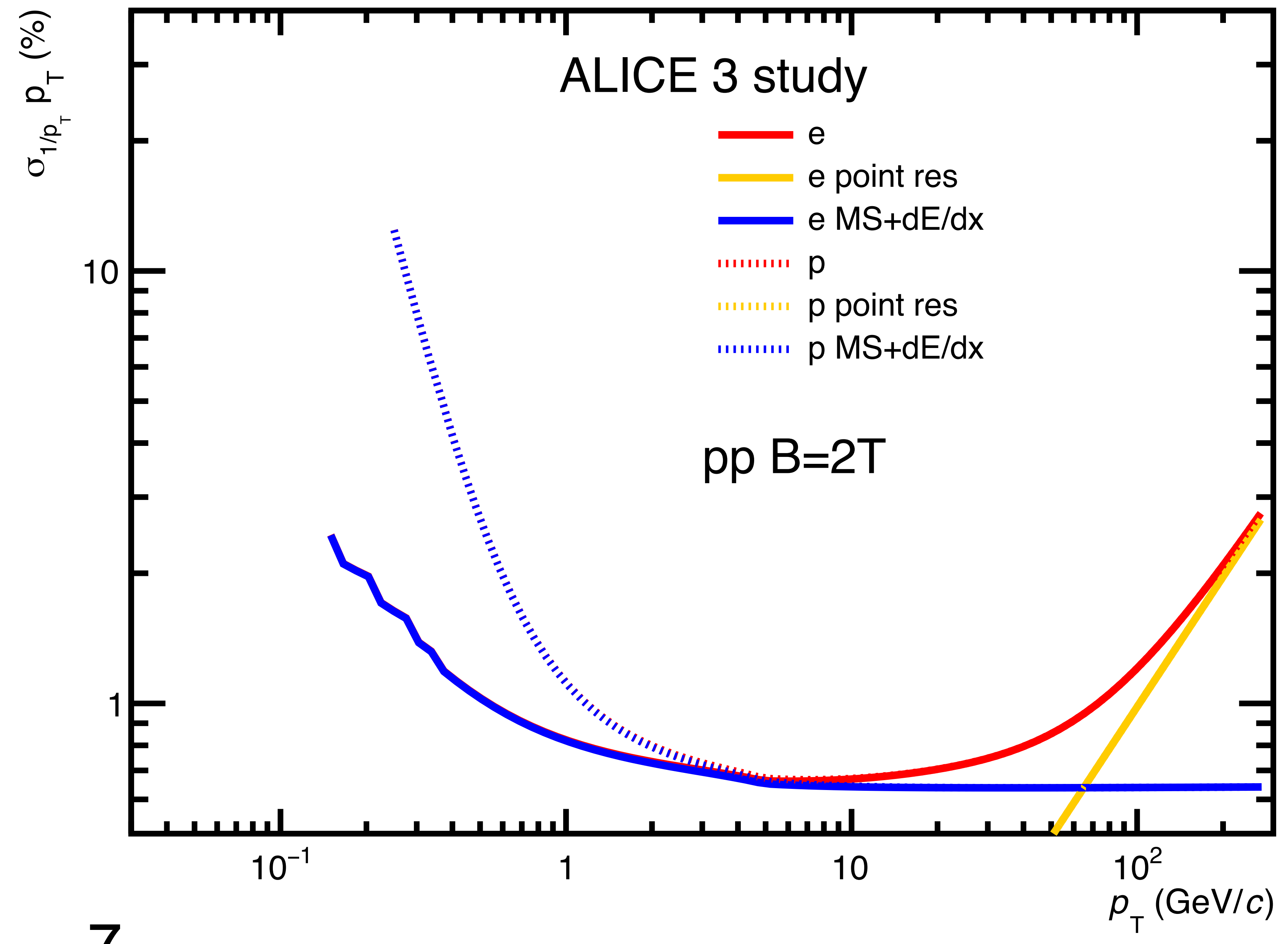
Unique and relevant technologies

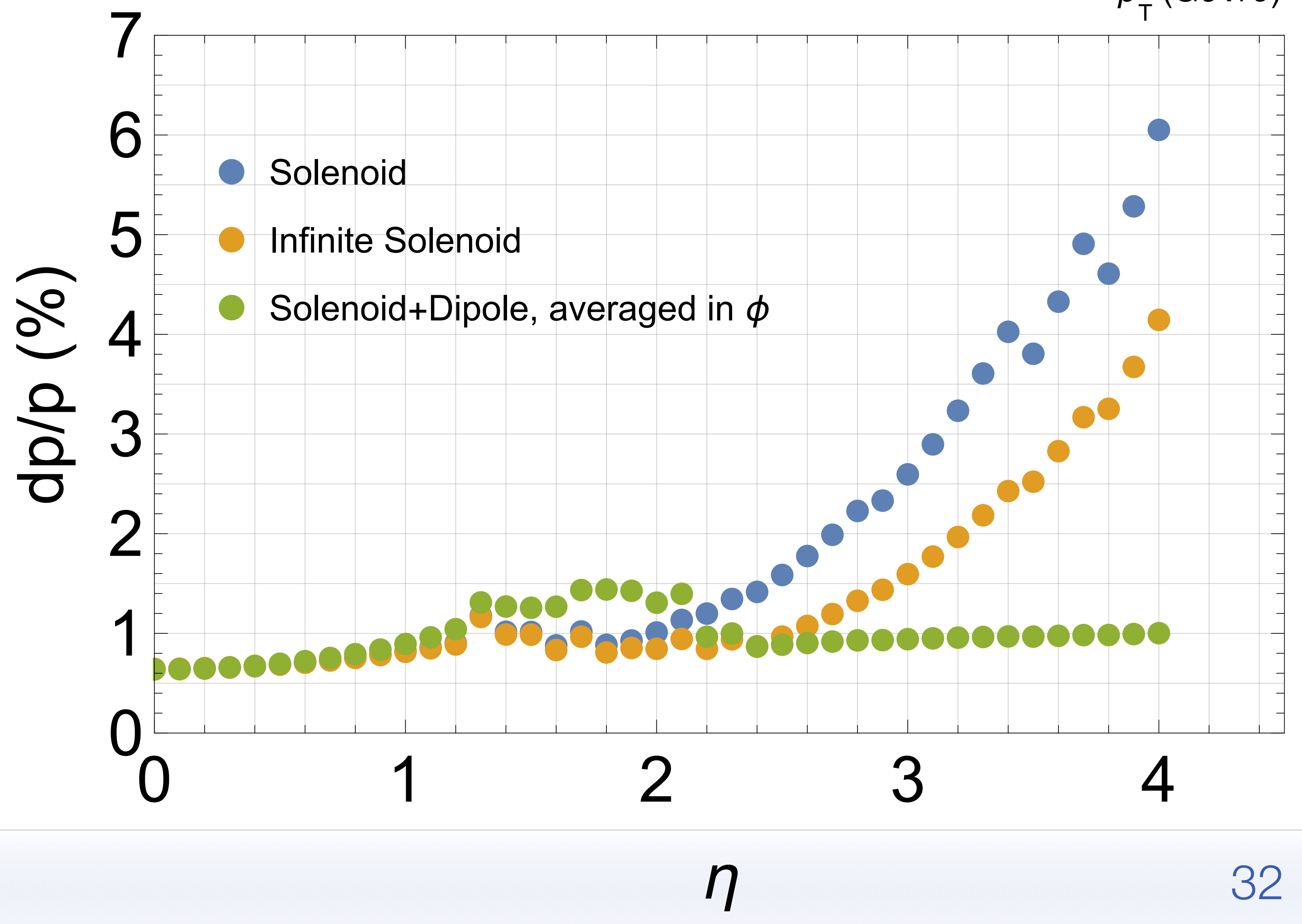
→ Synergies with LHC, FAIR, EIC, …



Tracking

- **Relative p_T resolution** $\propto \frac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  ➟ ~1 % up to η = 4
  - integrated magnetic field crucial
  - overall material budget critical
- **~11 tracking layers (barrel + disks)**
  - MAPS
  - σ_{pos} ~10 μm → 50 μm pixel pitch
  - R_{out} ≈ 80 cm and L ≈ 4 m (→ magnetic field integral ~1 Tm)
  - timing resolution ~100 ns (→ reduce mismatch probability)
  - material ~1 % X_0 / layer → overall X/X_0 = ~10 %



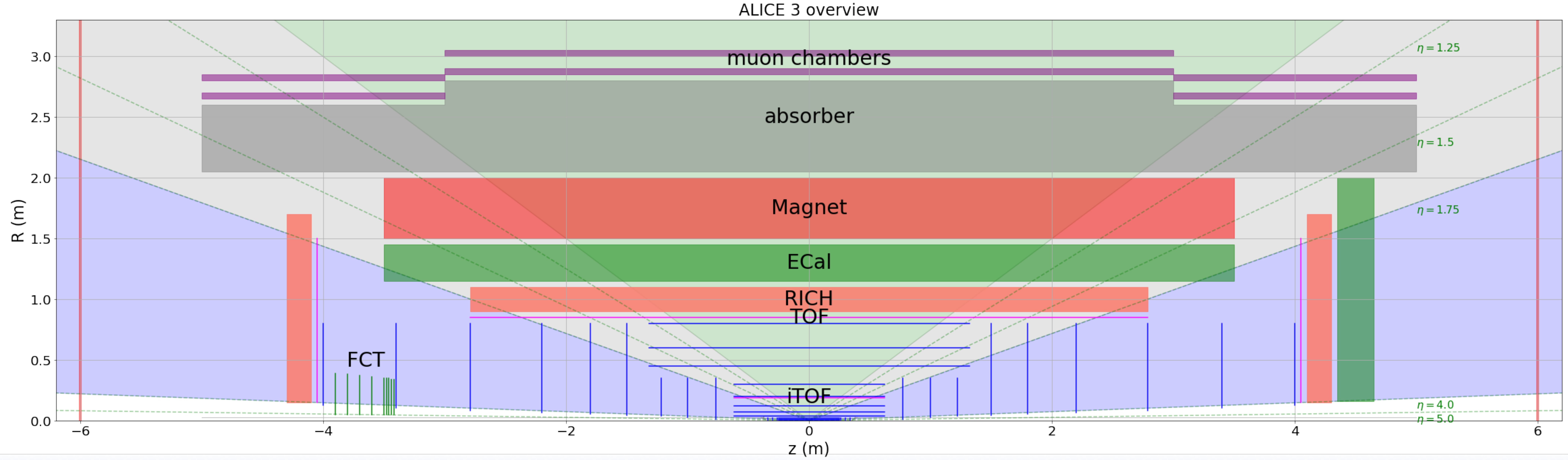


Detector concept

- Compact and low-mass all-silicon tracker:
  - High-resolution retractable vertex detector
  - Outer tracker: large rapidity coverage, $|\eta| < 4$
- Superconducting magnet system (1-2T)
- Untriggered readout and online processing

- Particle identification:
  - Silicon TOF
  - RICH
  - Muon ID down to $p_T \approx 1.5$ GeV/c
  - ECal: photon detection, jets

R&D/innovation areas: vertex tracker mechanics, MAPS development, large scale integration, Monolithic Si timing sensors, Si photon detection, …



Luminosity improvements

- **Studies in LoI based on Pb-Pb**
  - Most challenging in terms of multiplicity
  - Lowest nucleon-nucleon luminosity
- Preliminary studies on achievable luminosities performed by machine groups
  - Main li
- **Furthe**
  optima

Nucleon-nucleon luminosity:

$$\mathscr{L}_{NN} = A^2 \cdot \mathscr{L}_{AA}$$

[https://indico.cern.ch/event/1078695/]

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathscr{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathscr{L}_{NN}$ (pb^{-1} / month)	**409**	**550**	**500**	**510**	**512**	**434**	**242**

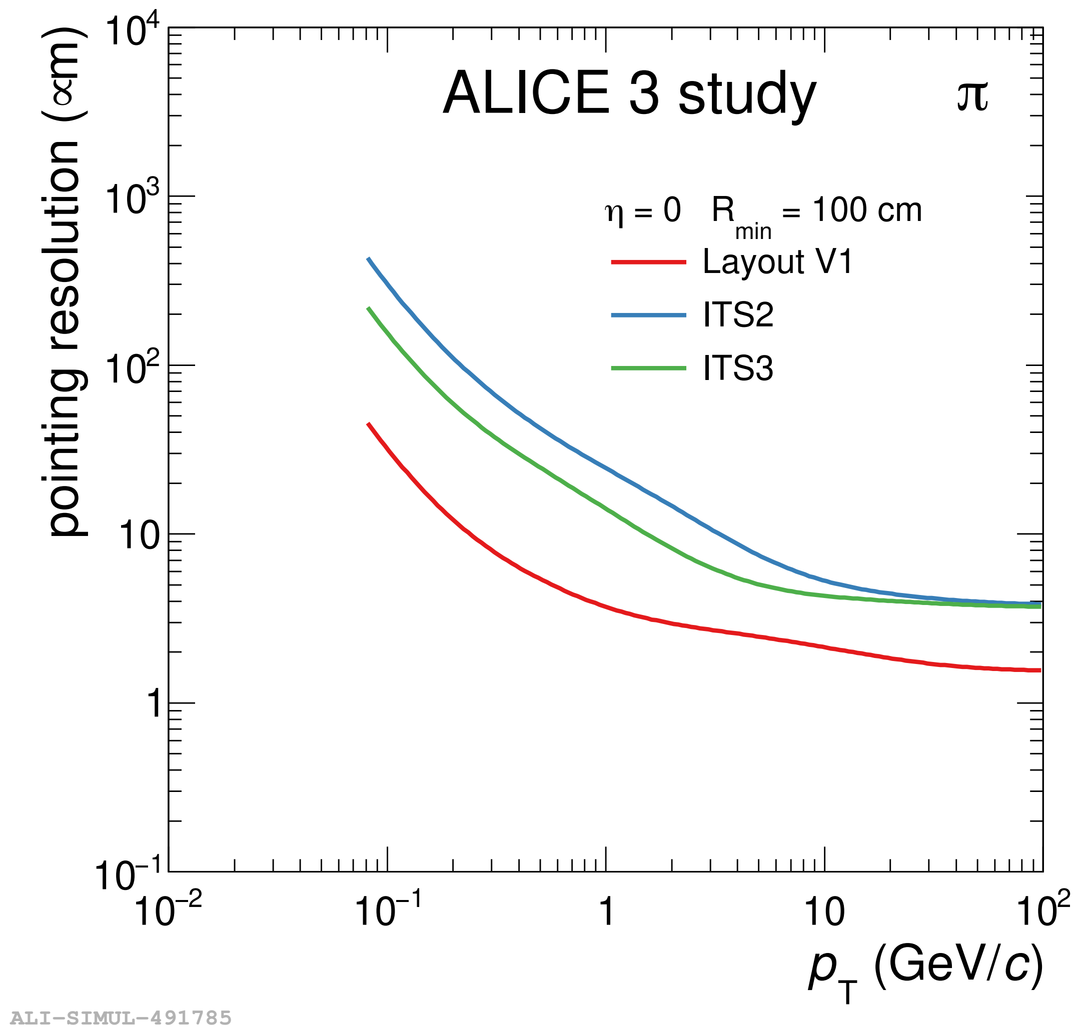
Strength of QGP effects
(e.g. charm abundance, quenching, also background)

Detector requirements

Component	Observables	$\|\eta\| < 1.75$ (barrel)	$1.75 < \|\eta\| < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10\ \mu m$ at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30\ \mu m$ at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5\ \mu m$, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10\ \mu m$, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer
Hadron ID	Multi-charm baryons	**π/K/p separation up to a few GeV/*c***		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to ~2 - 3 GeV/*c*		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*		steel absorber: $L \approx 70$ cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/*c*	Forward Conversion Tracker based on silicon pixel sensors

Open heavy flavour performance

Impact parameter resolution

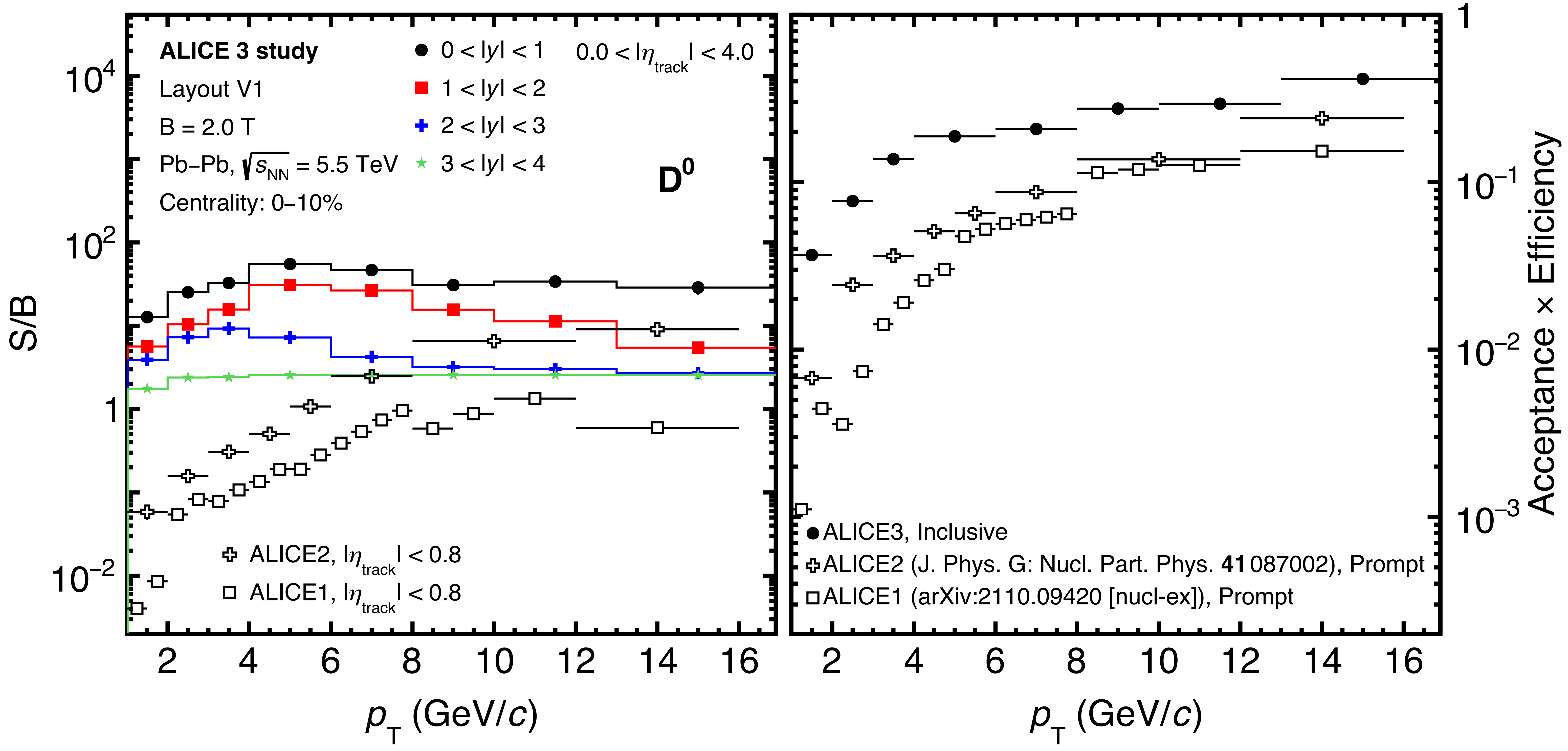


Excellent pointing resolution and PID:

Large S/B and efficiency

10-20x ITS 2 at p_T < 4 GeV

Signal/background   Efficiency



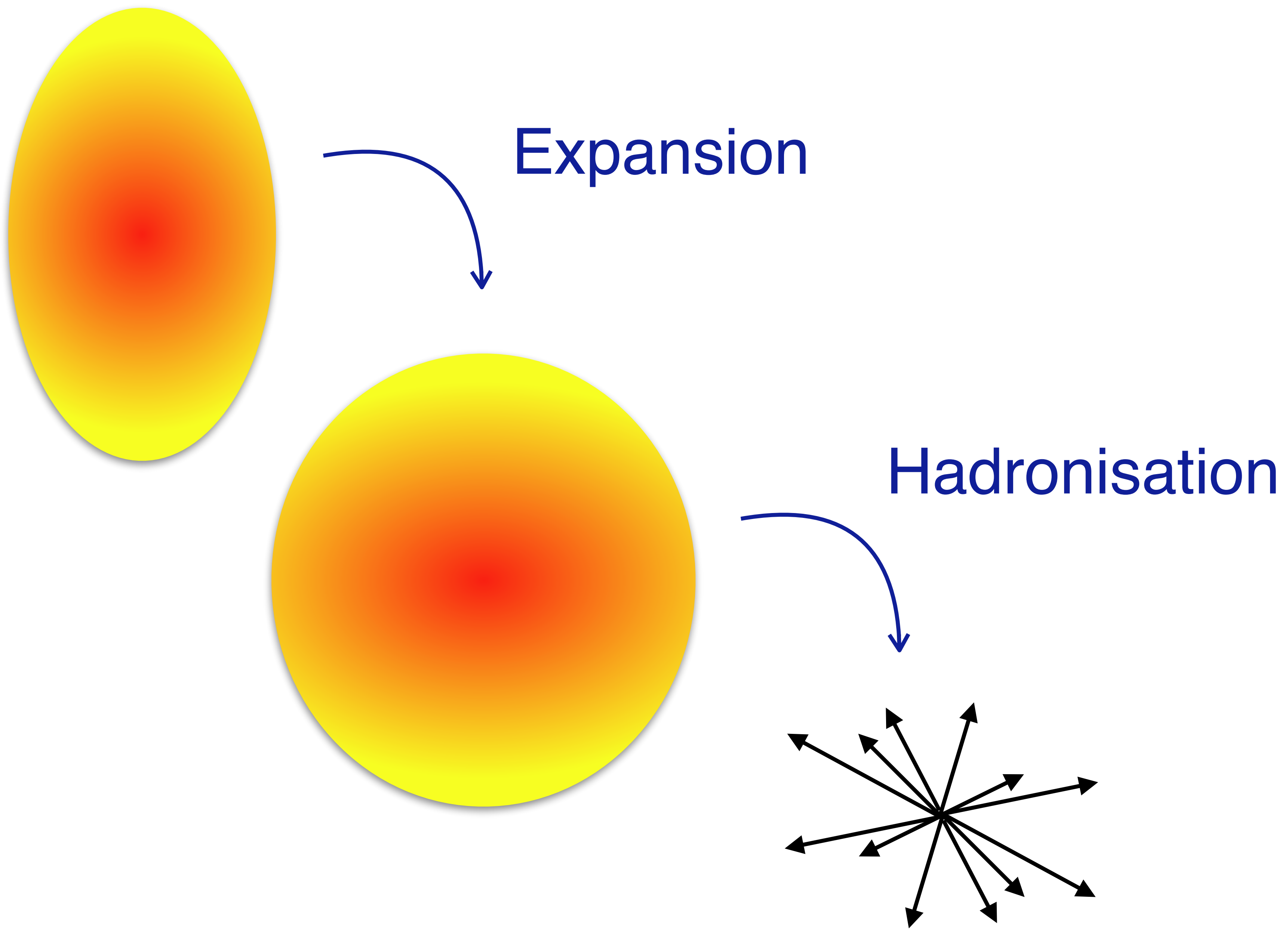
Gives access to further signals:

- Beauty meson and baryon v_2
- $D\overline{D}$ correlations
- Multi-charm baryons

Azimuthal anisotropy: two mechanisms

Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy

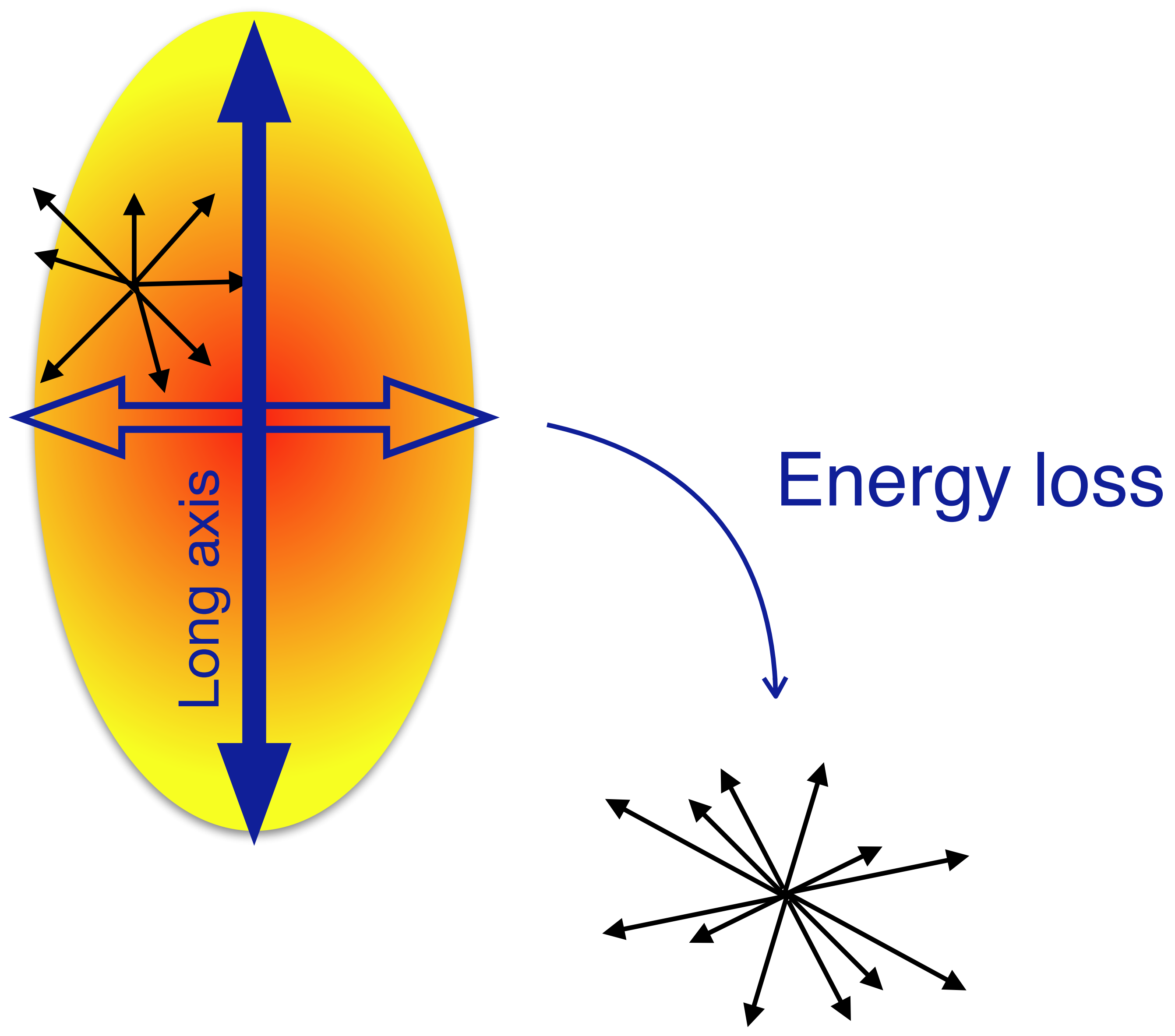


$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Dominant effect for thermalised probes:
di-electrons, light flavour, HF at low p_T

Parton energy loss

Anisotropy due to energy loss and path length differences



More energy loss along long axis than short axis

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Dominant effect for non-thermal probes
(early formation times)
heavy flavour, high p_T probes

Adding beauty

- Do not expect full thermalisation for beauty
  - Retain memory of initial distribution: more sensitive
  - Also affects hadronisation by recombination?
- Theory uncertainties reduced
  - Langevin approach more justified
  - Lattice QCD calculations more reliable

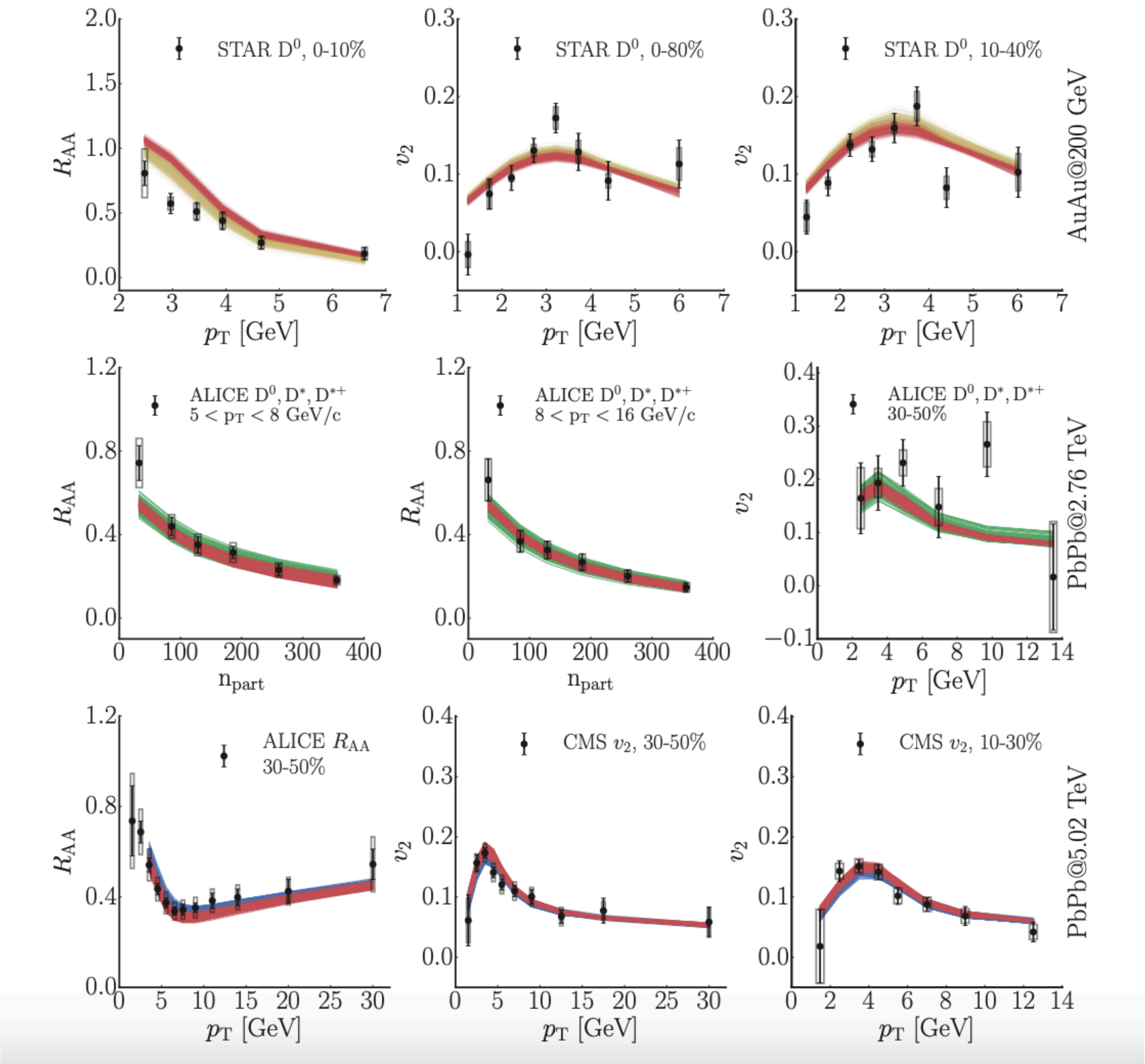
relaxation time

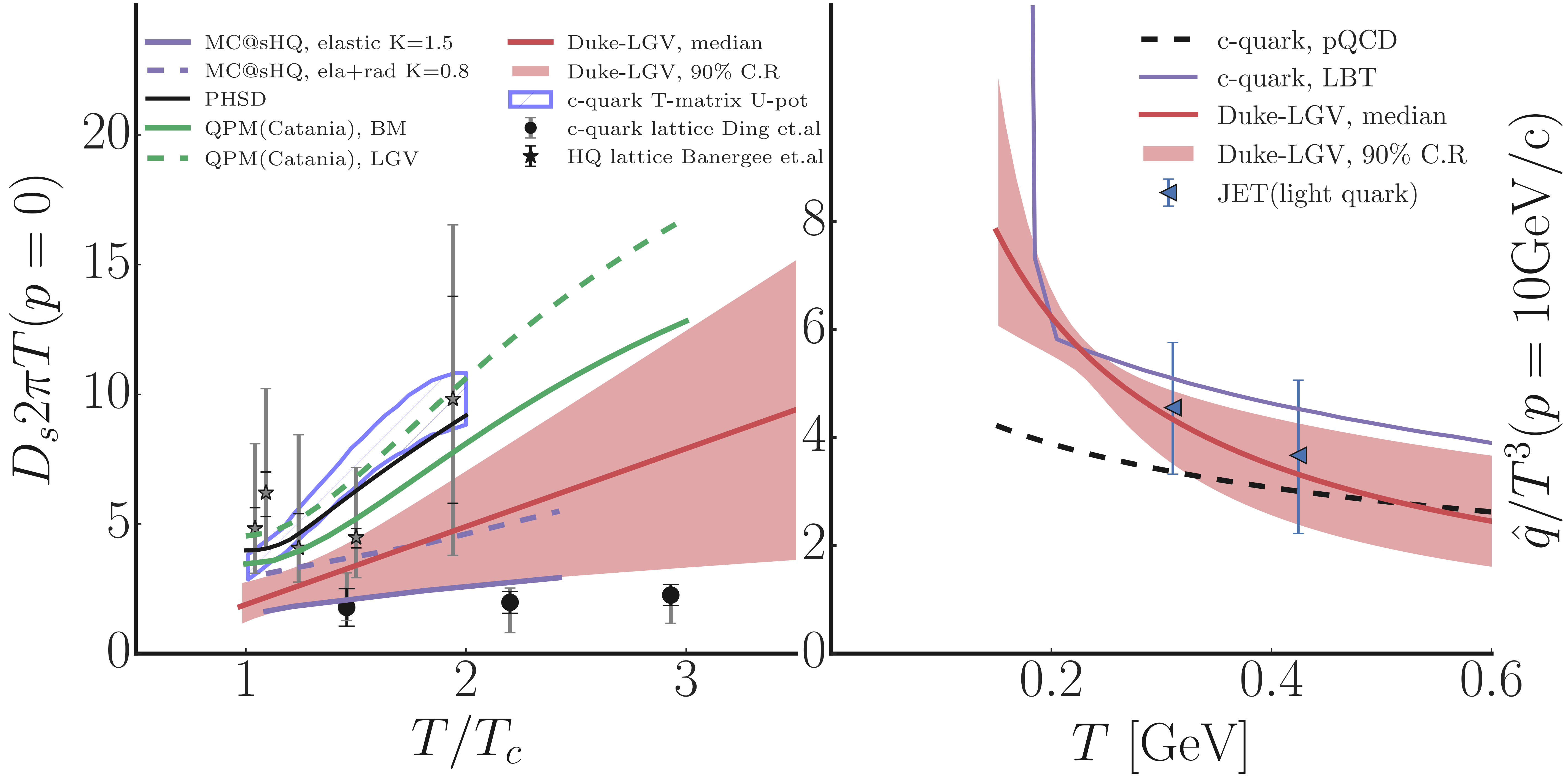
$$\tau_Q = (m_Q/T)\, D_s$$

Beauty measurements test transport, hadronisation in a different regime

Multi-observable fits to constrain

Input: R_{AA}, v_2, …



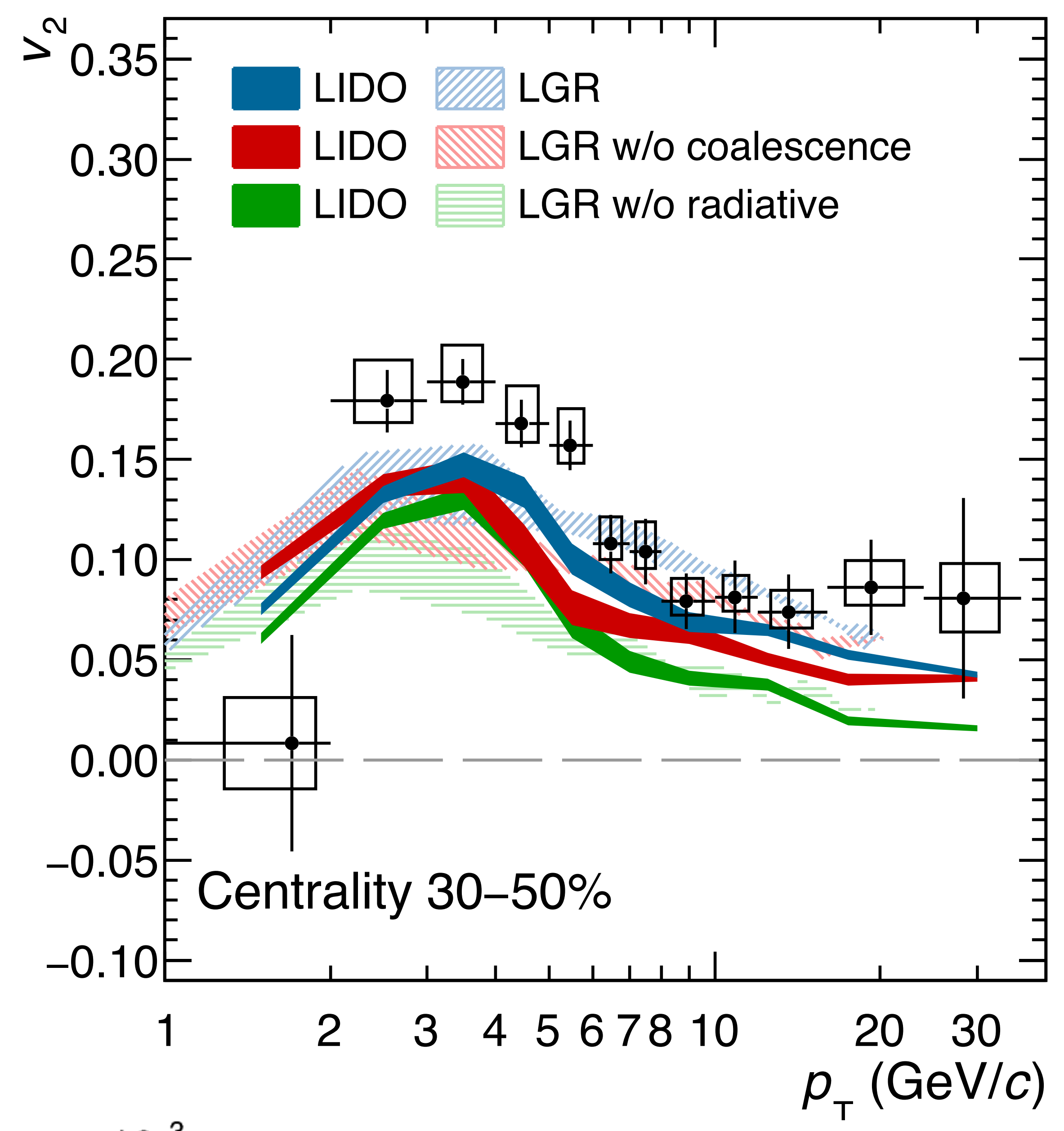


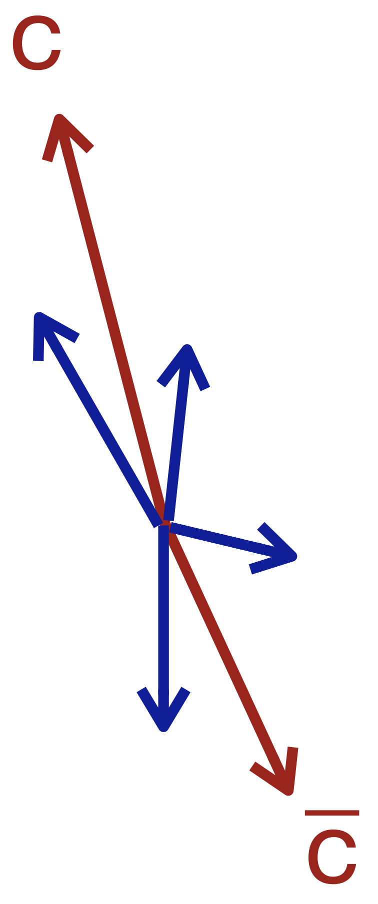
Y. Xu et al, PRC 97, 014907

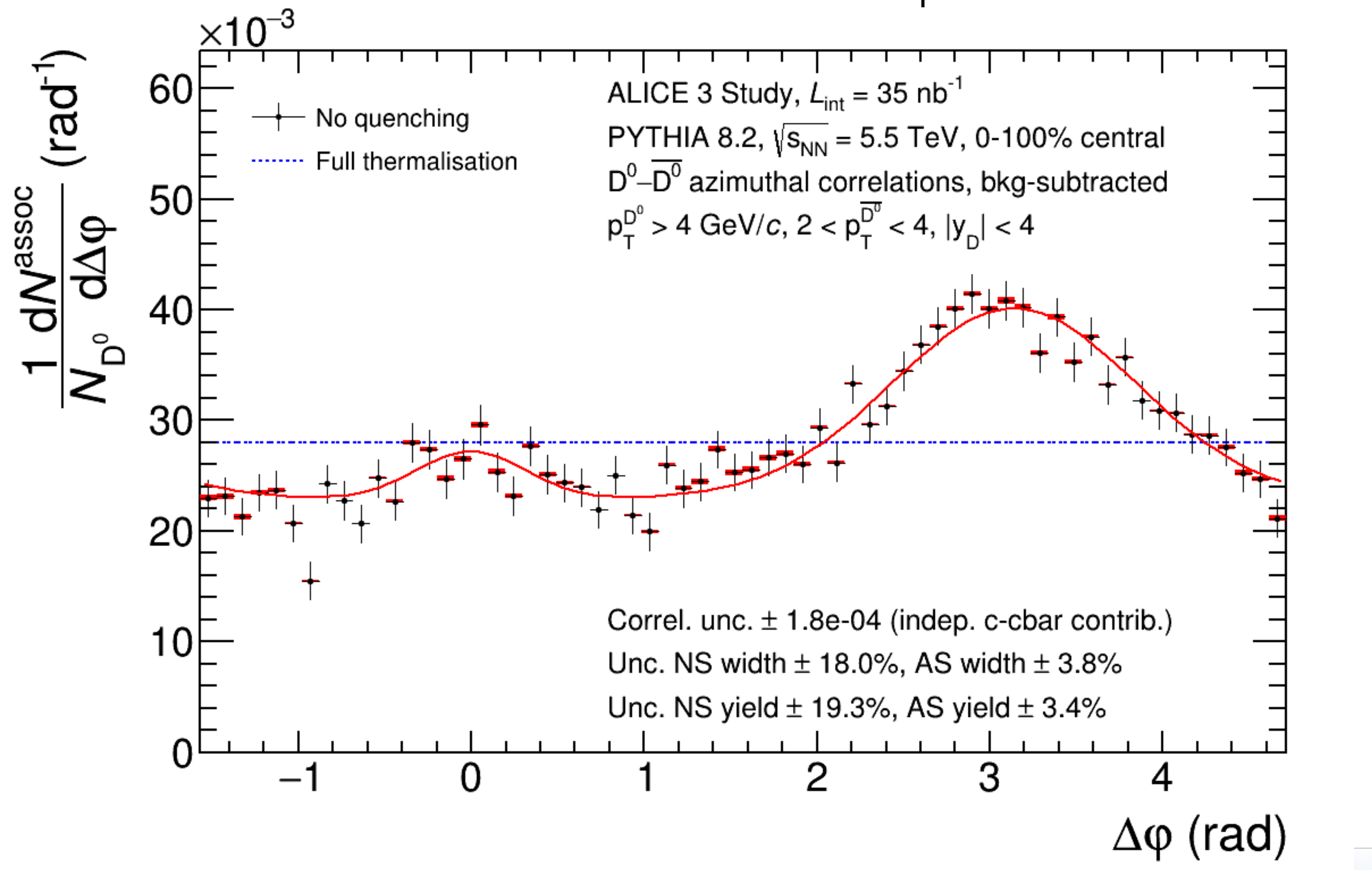
Tools to derive derive transport coefficients from measurements exist:
Gaussian Process emulators + Bayesian inference

Heavy flavour transport coefficient: Bayesian fit

- Simultaneous confrontation of models with multiple measurement to constrain multiple model aspects
    - Tools exist: gaussian process emulators + Bayesian inference
- Needs exploration of 'model space' for relevant model aspects, e.g.:
    - Hadronisation via recombination vs fragmentation
      ⇒ expect that baryon vs meson v_2 provides constraints
    - ALICE 3: include $D\overline{D}$ correlations — probe momentum broadening
    - …





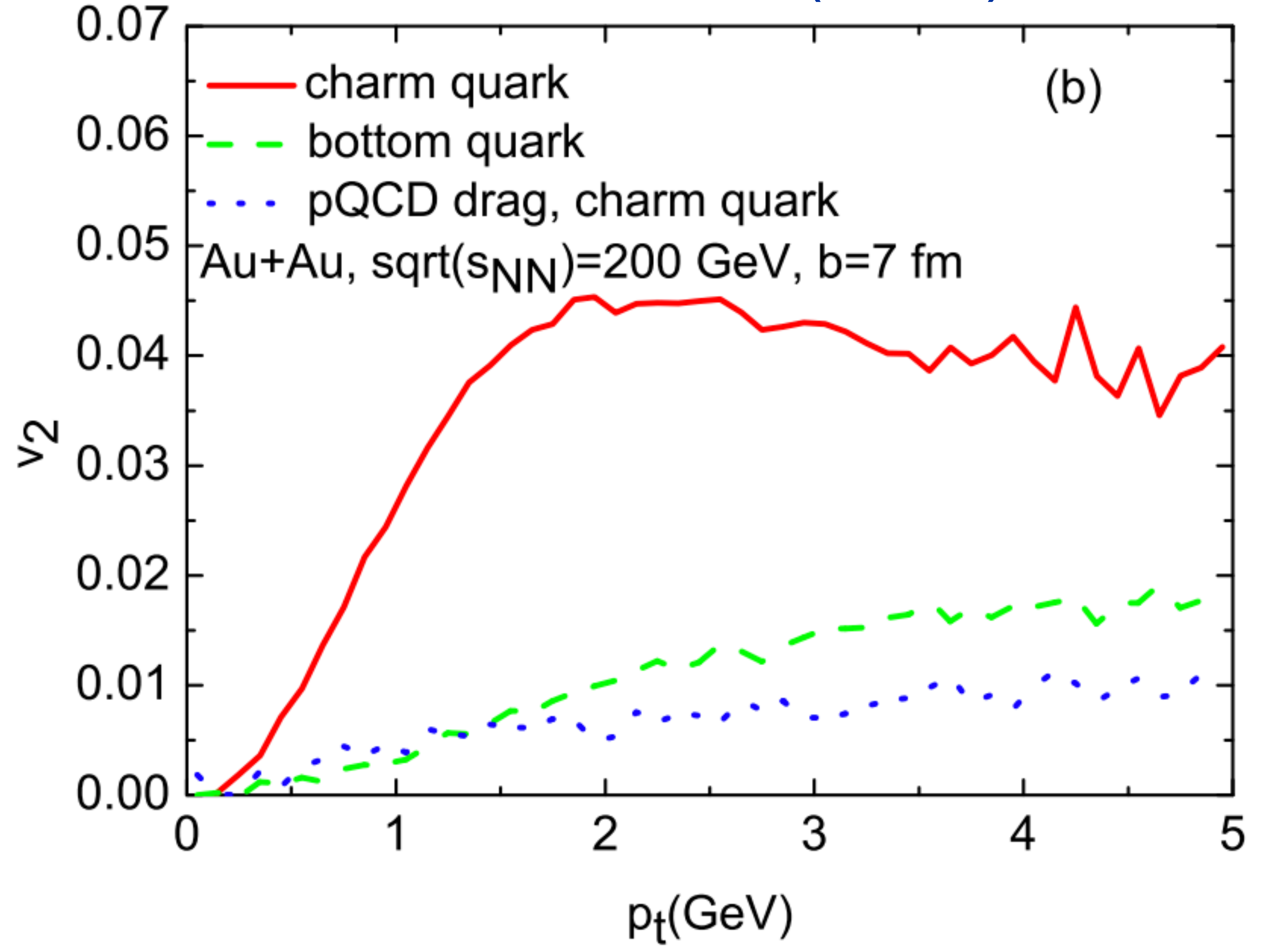


Charm vs beauty flow

ALICE

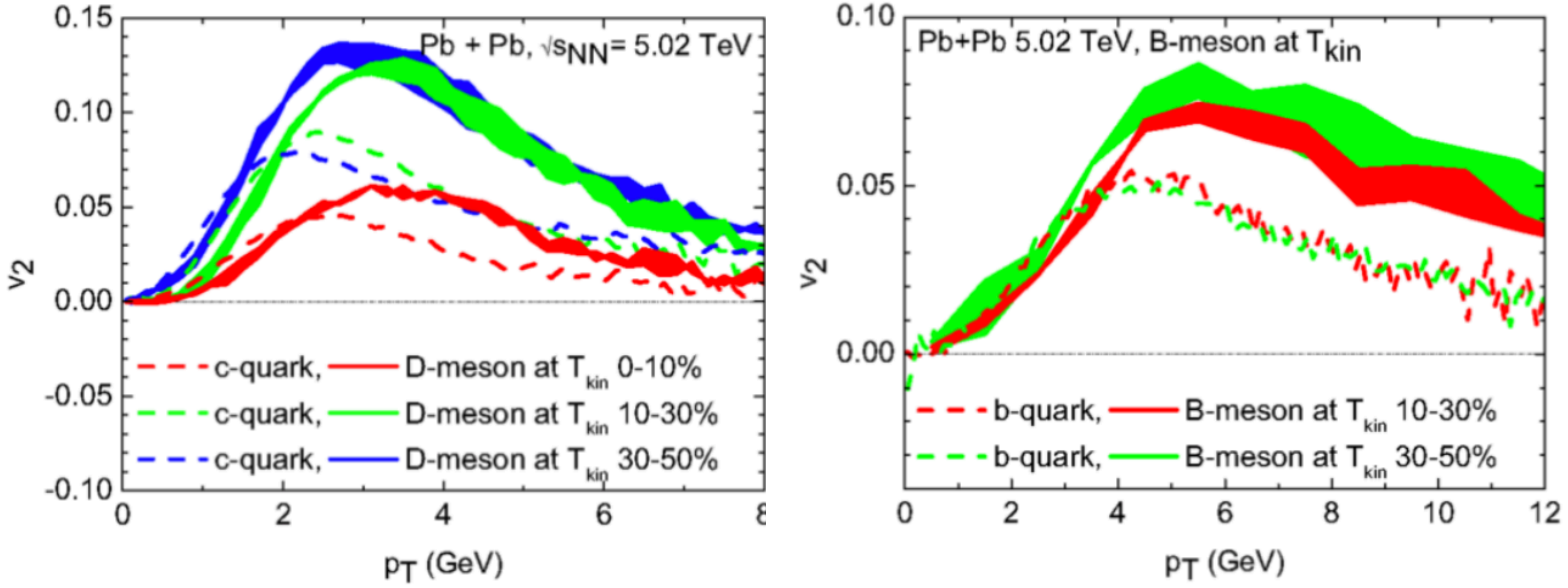
Q: How will beauty add? Does the mass dependence help, or is it just 'heavier charm' ?

Quark level (RHIC)



He, Rapp and Fries, arXiv:1106.6006

Hadron level (LHC)



He, Rapp and Fries, Nucl Part Phys Proc

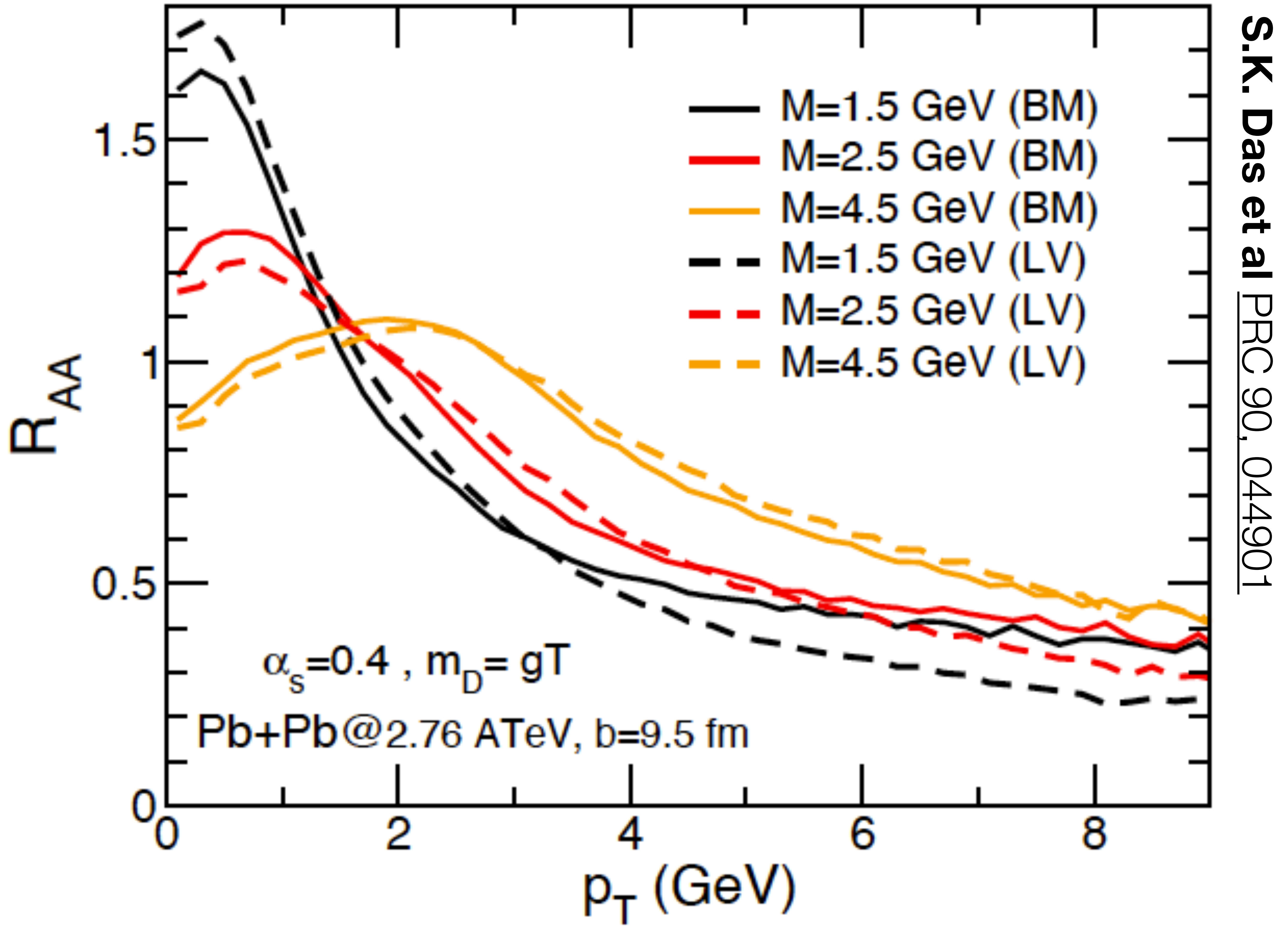
Beauty expected to thermalise more slowly; smaller drag coefficient

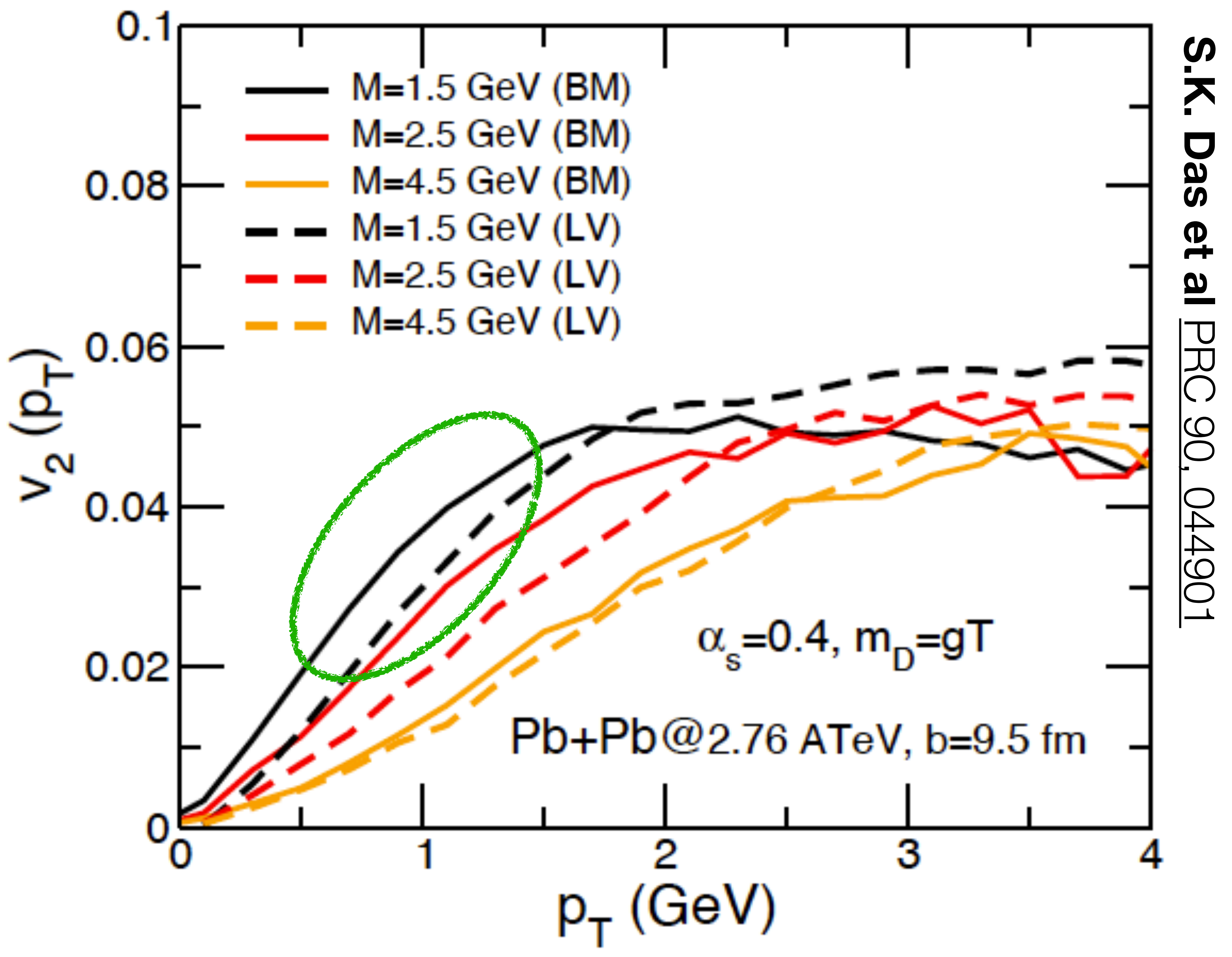
⇒ Smaller v_2, larger R_{AA}

Ongoing discussions with TAMU/Nanjing for updated predictions — groups interested, needs work

Transport theory uncertainties

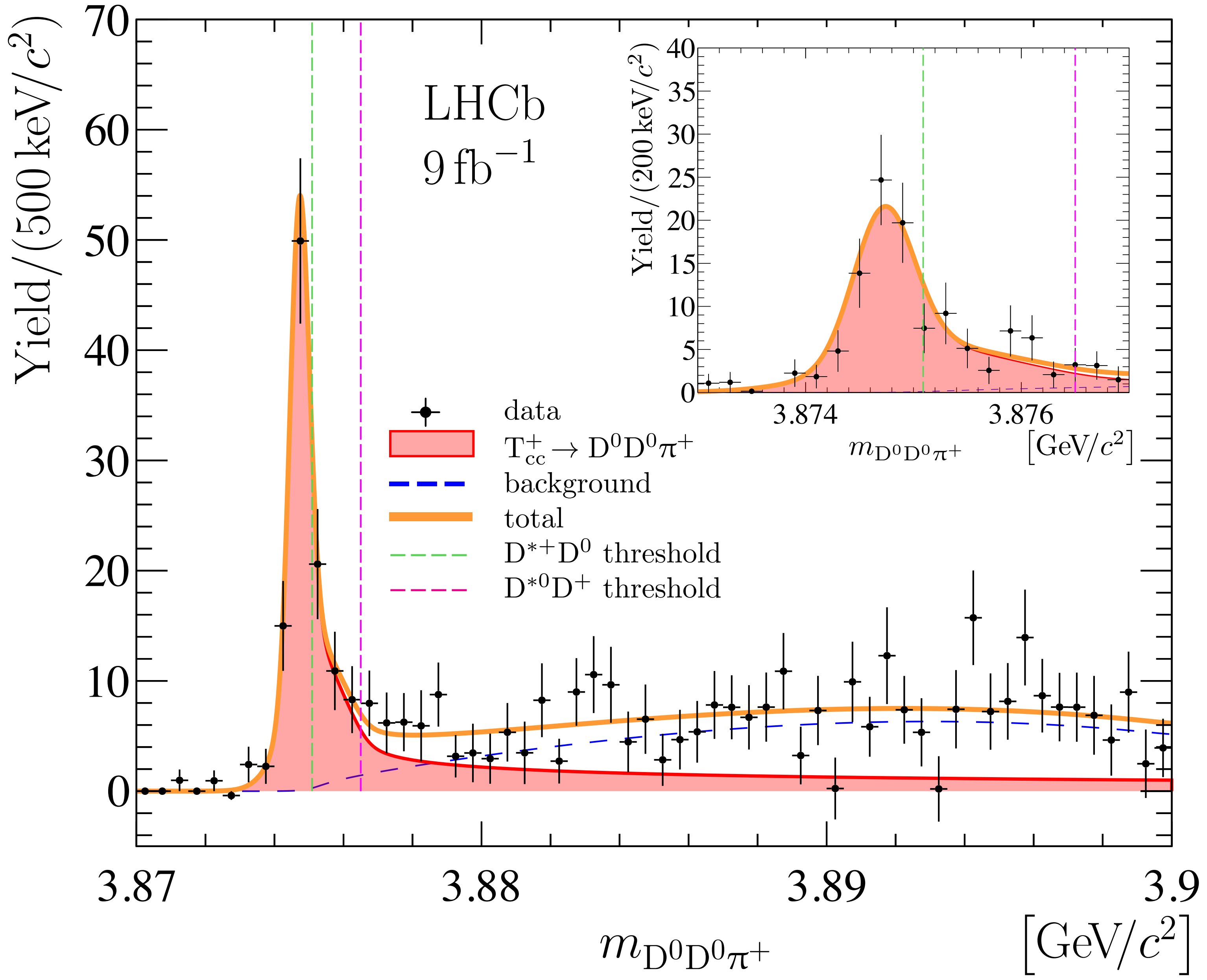
Q: How will beauty add? Does the mass dependence help, or is it just 'heavier charm'?

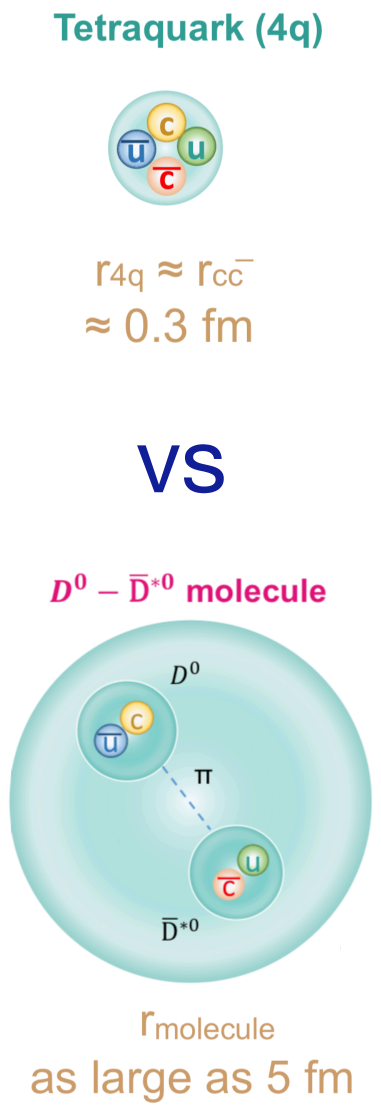




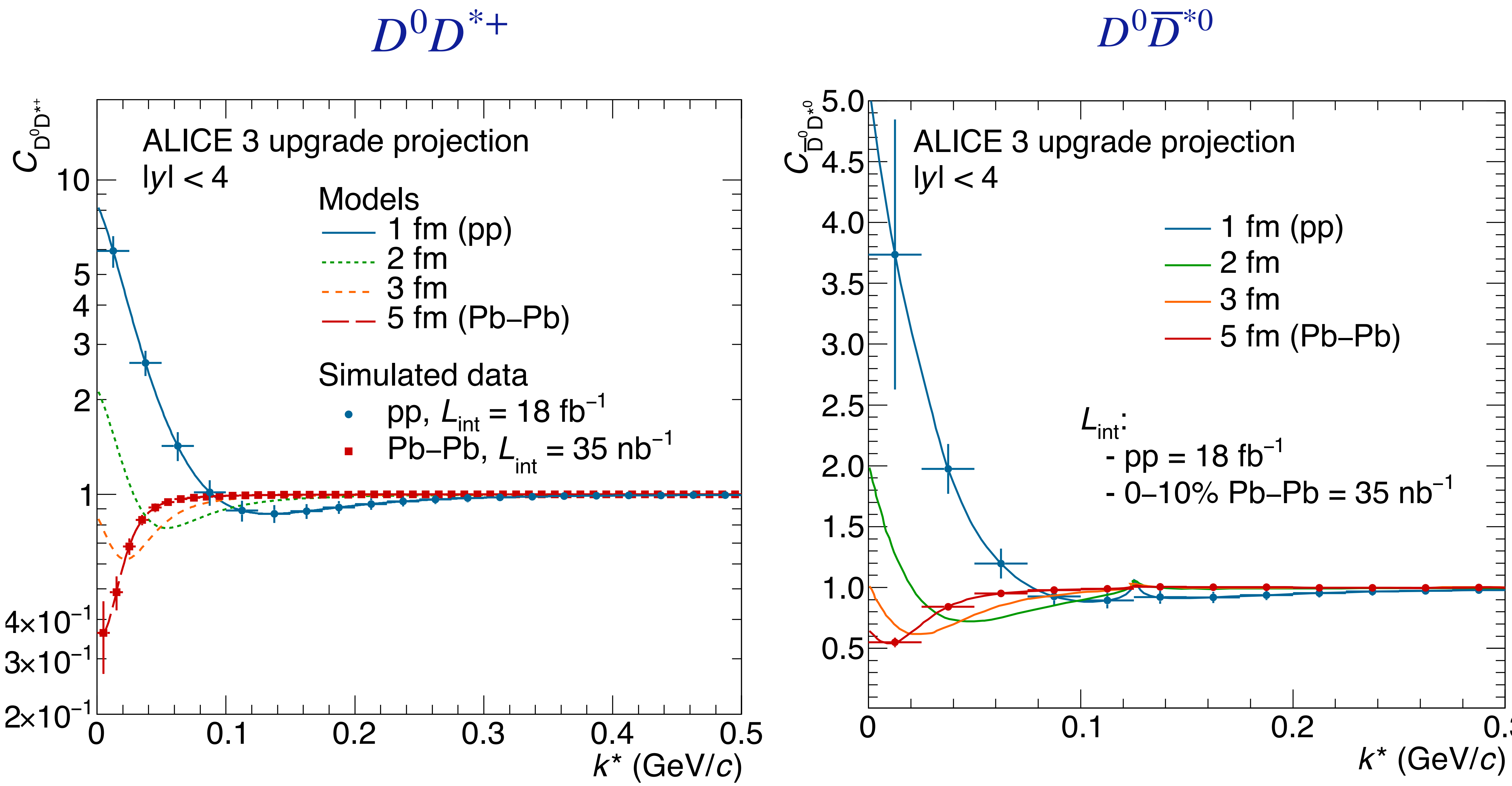
- Sizeable uncertainties in transport theory calculations of (R_{AA} and) v_2 for charm ($m \approx 1.5$ GeV/c^2)
- Uncertainties reduced for beauty ($m \approx 3.5$ GeV/c^2)

DD* momentum correlations





DD* momentum correlation



- Several exotic heavy flavour states identified
- Loosely bound meson molecule or tightly bound tetraquark?
- Study binding potential with final state interactions ‘femtoscopic correlations’

D^0D^{*+}: nature of T_{cc}^+