

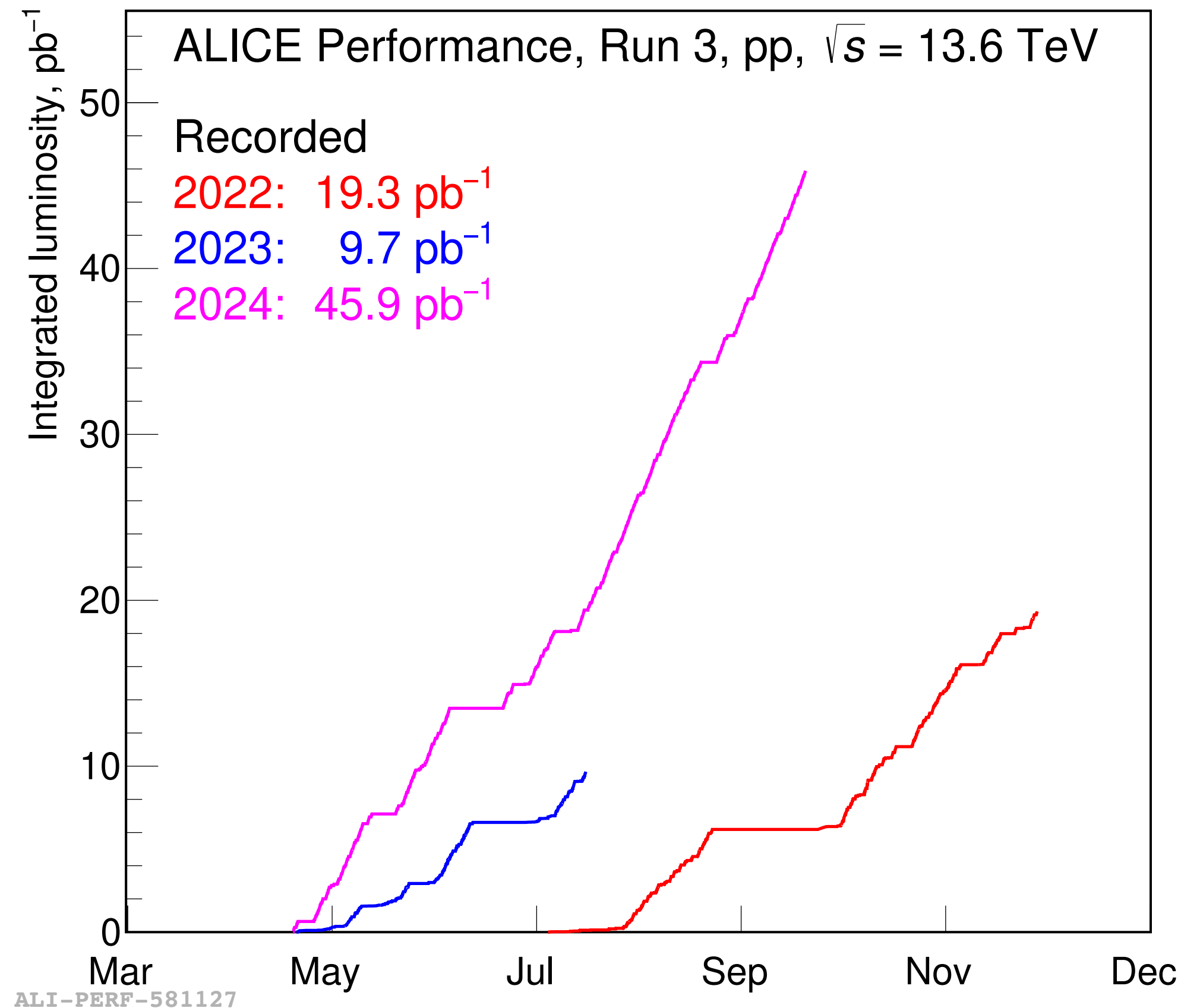
ALICE upgrades

Marco van Leeuwen, Nikhef and CERN

Upgrade Week, 7-11 October 2024, Cracow, Poland

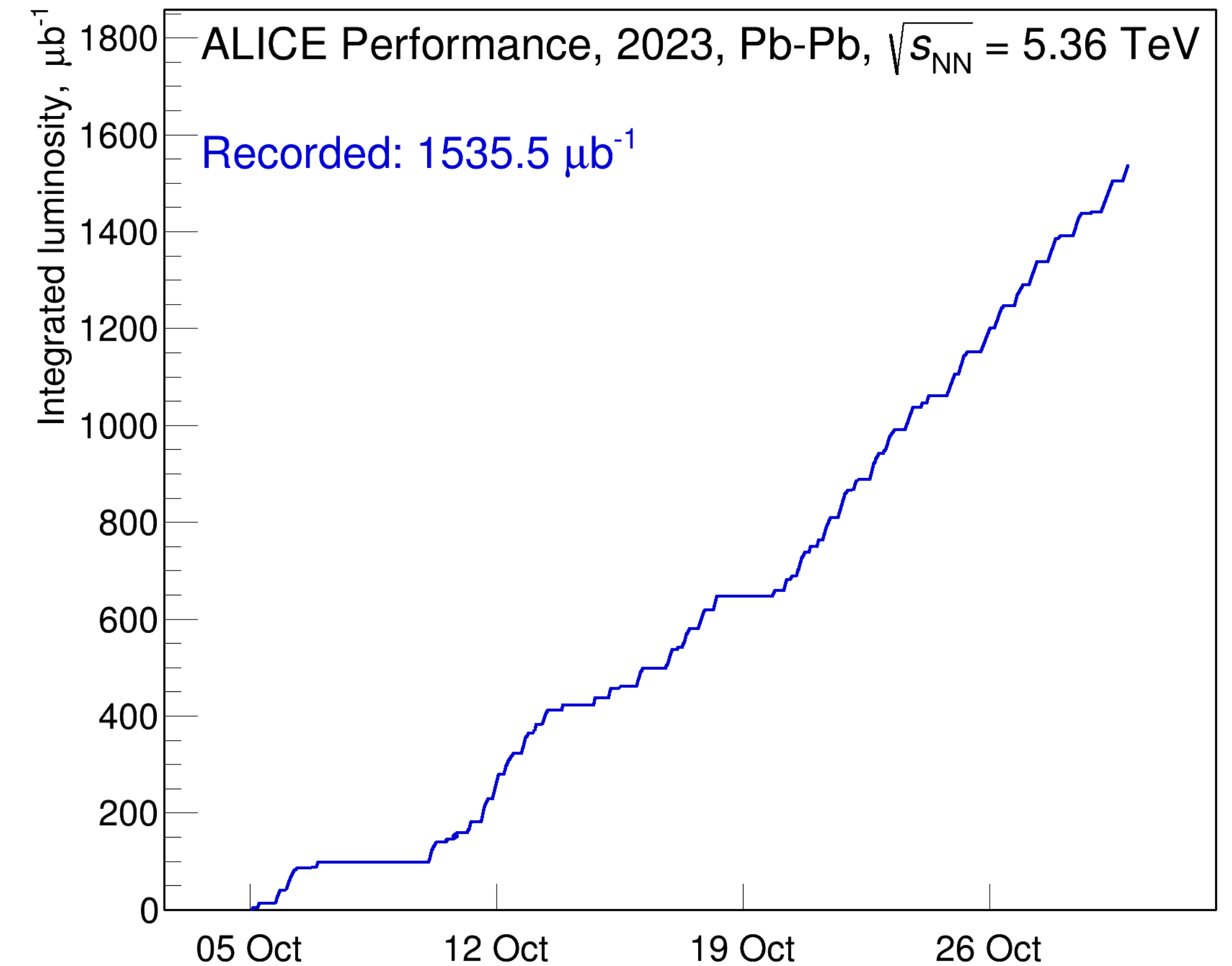
Run 3 data taking

Recorded p-p luminosity



Large pp samples collected (with offline trigger selections)
2024 data taking progressing very well

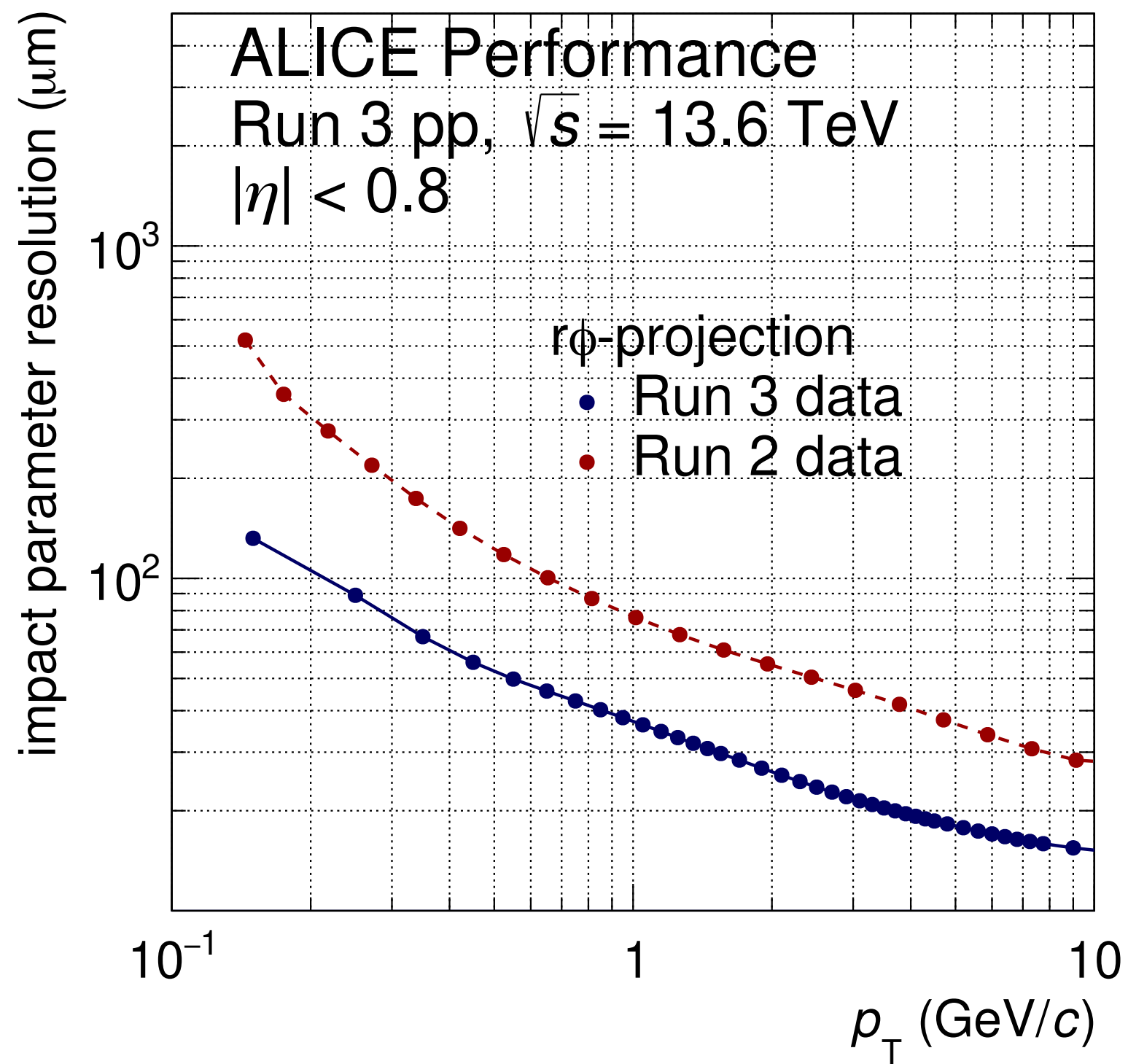
Recorded Pb-Pb luminosity



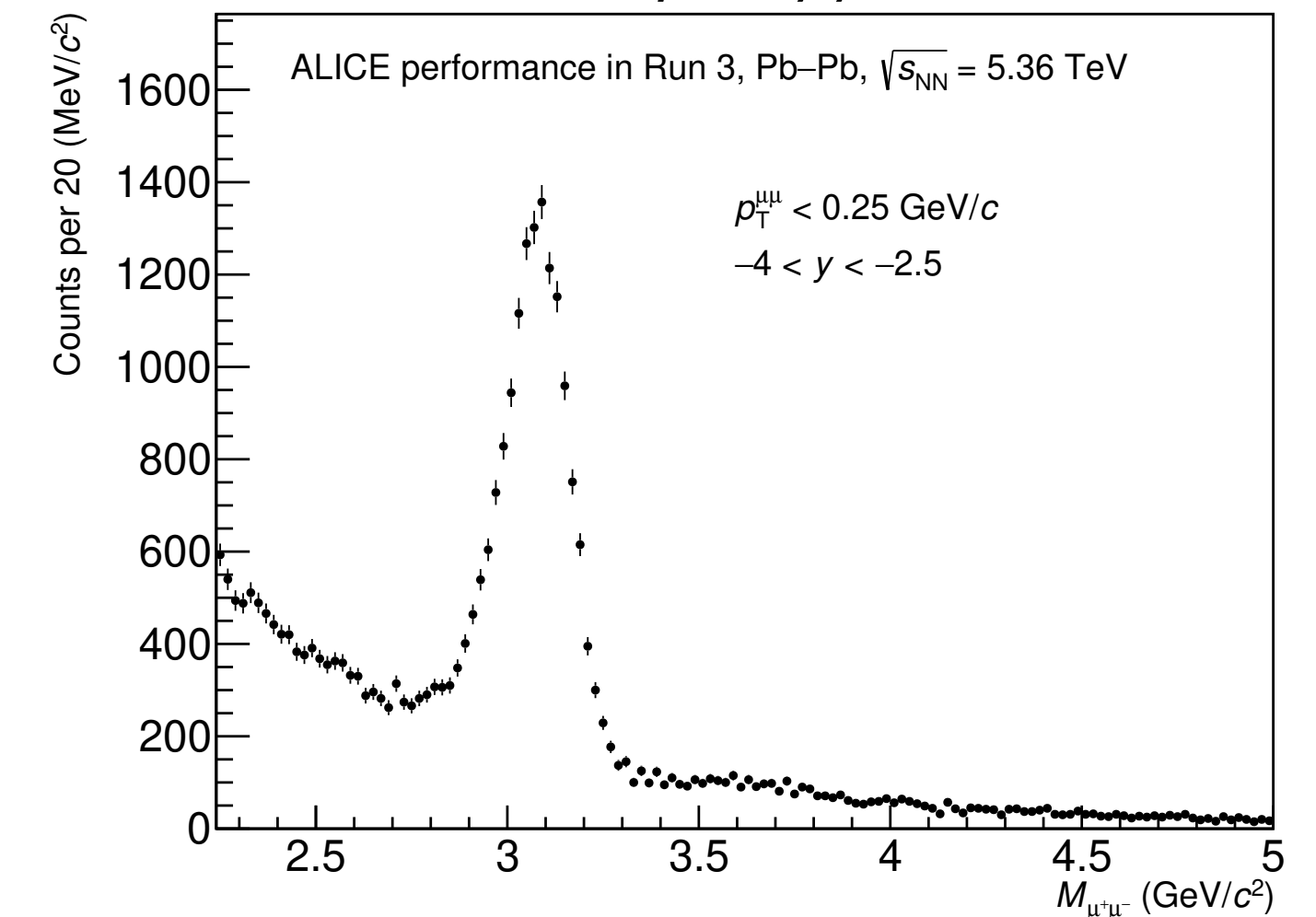
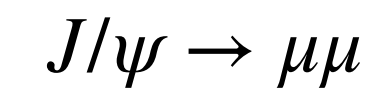
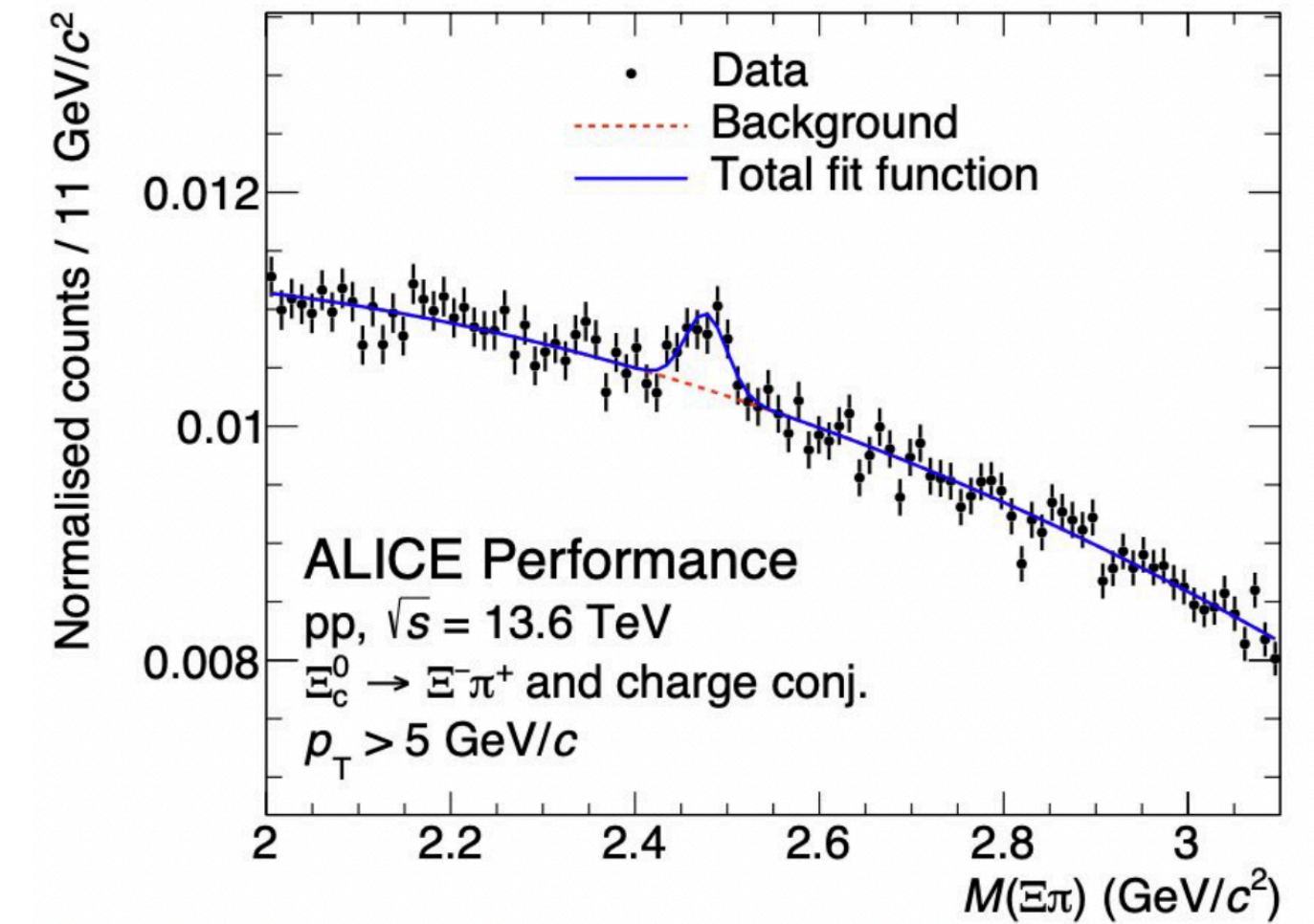
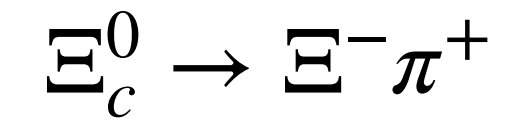
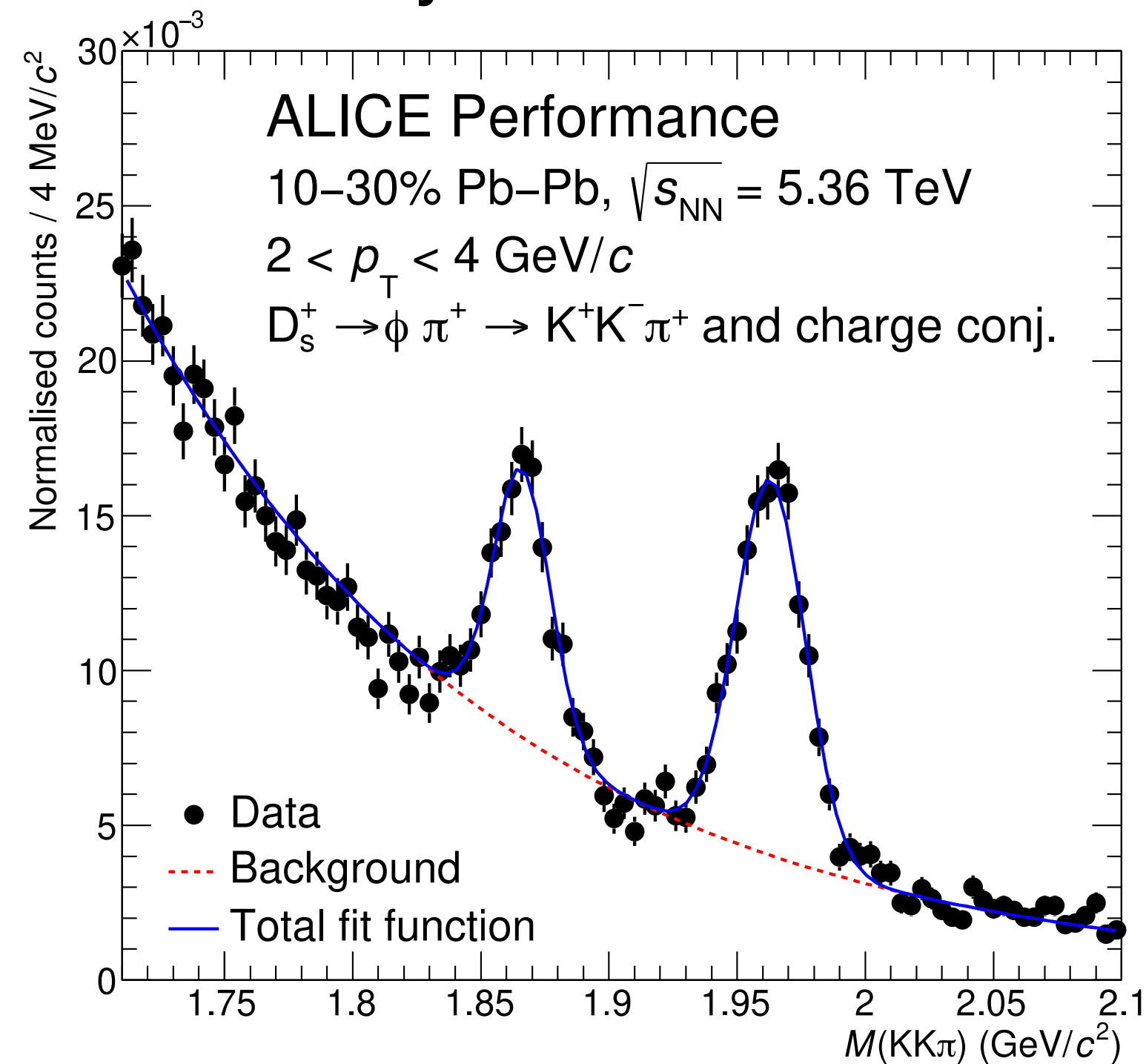
Large heavy-ion data sample collected
in 2023; first results shown at conferences

Run-3 physics performance examples

Impact parameter resolution

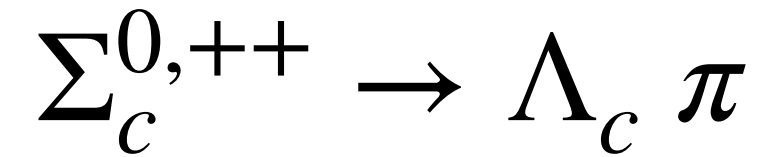


Heavy flavour mesons

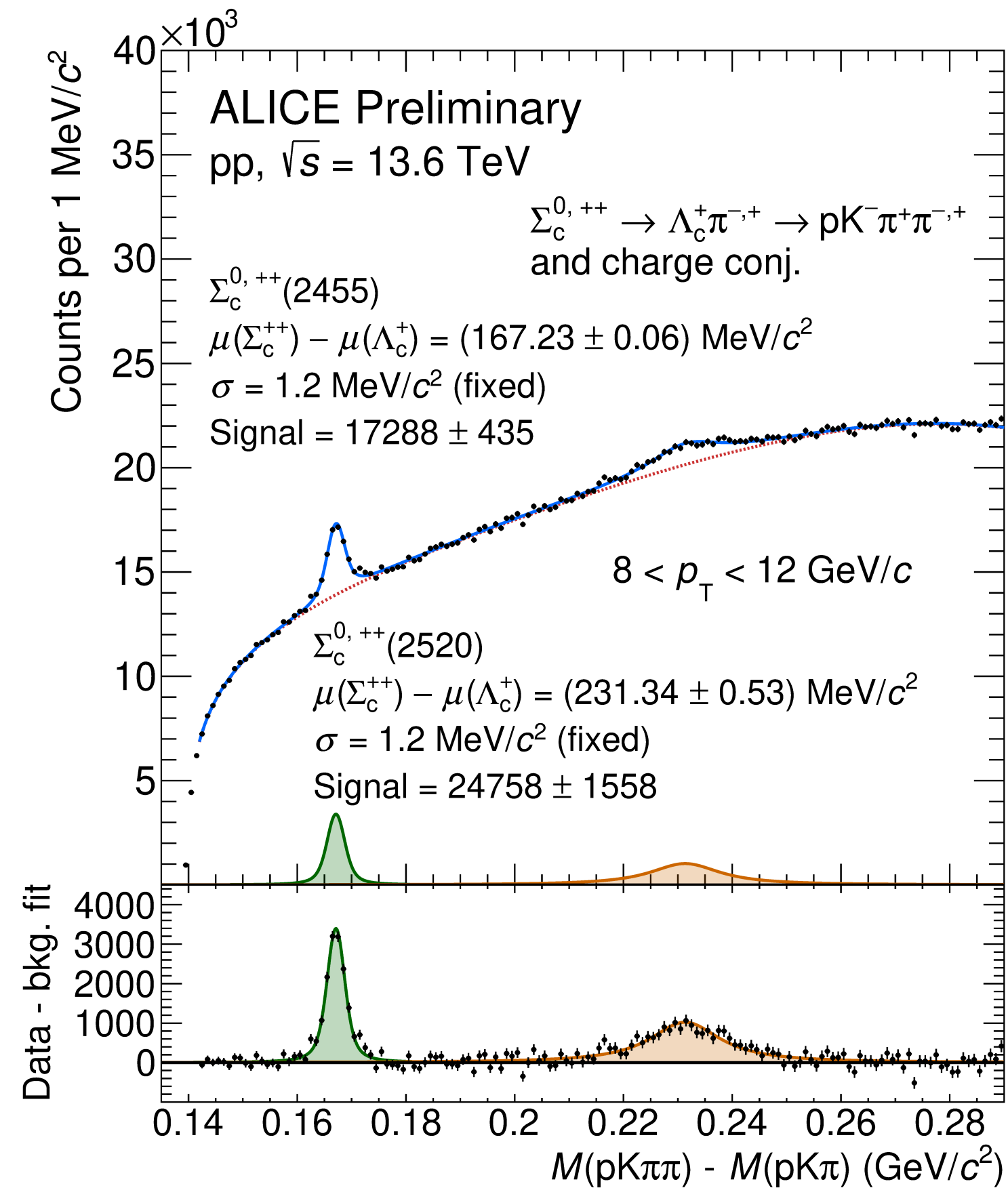


LS2 upgrades: improved pointing resolution and larger data samples

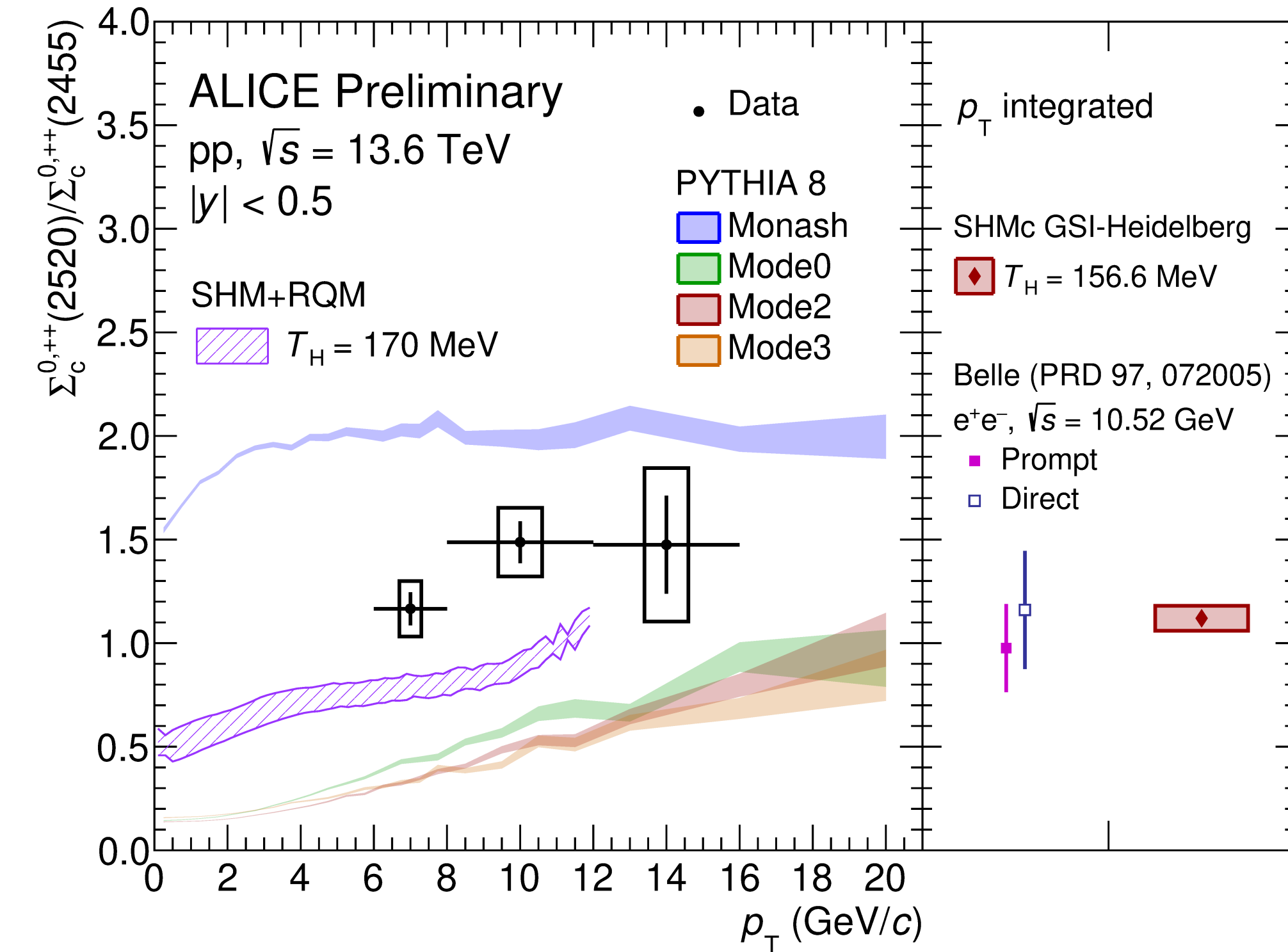
Run 3 results: charm baryon resonance production: $\Sigma_c^{0,++}$



$\Sigma_c^{0,++}$ yield ratio vs p_T



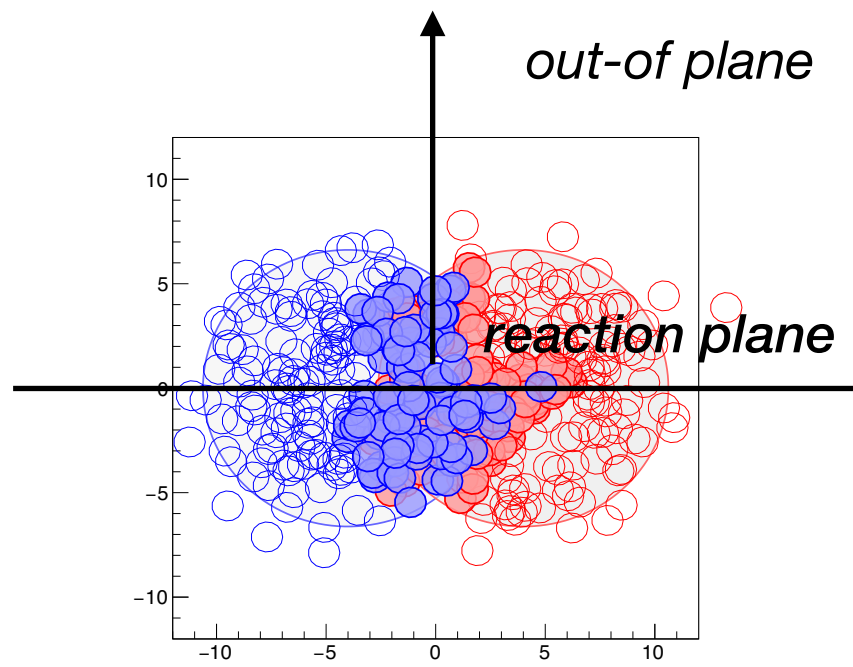
ALI-PREL-571534



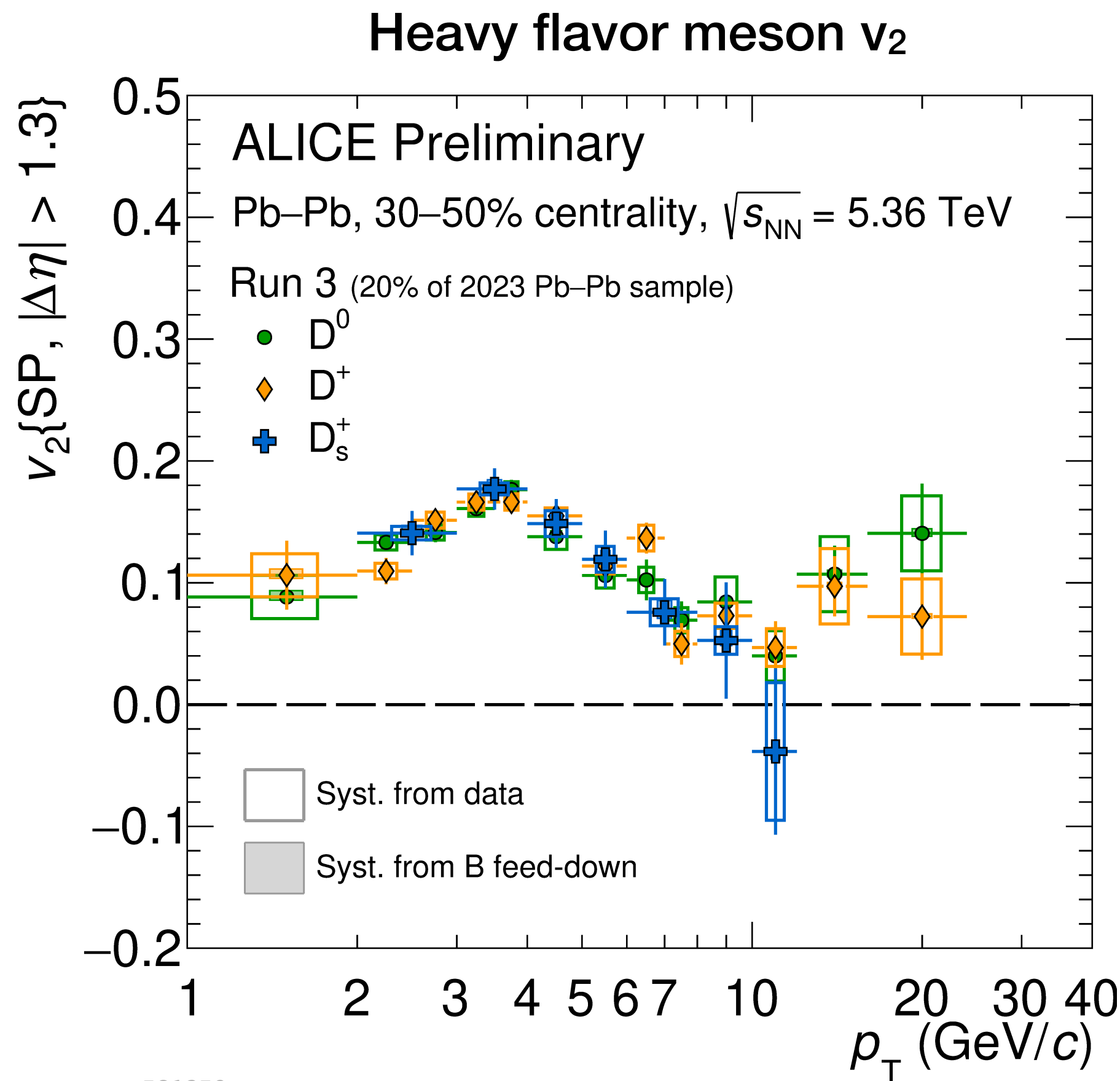
ALI-PREL-574270

Similar yield of both resonances
 Not described by Pythia hadronisation
 in line with statistical model expectation

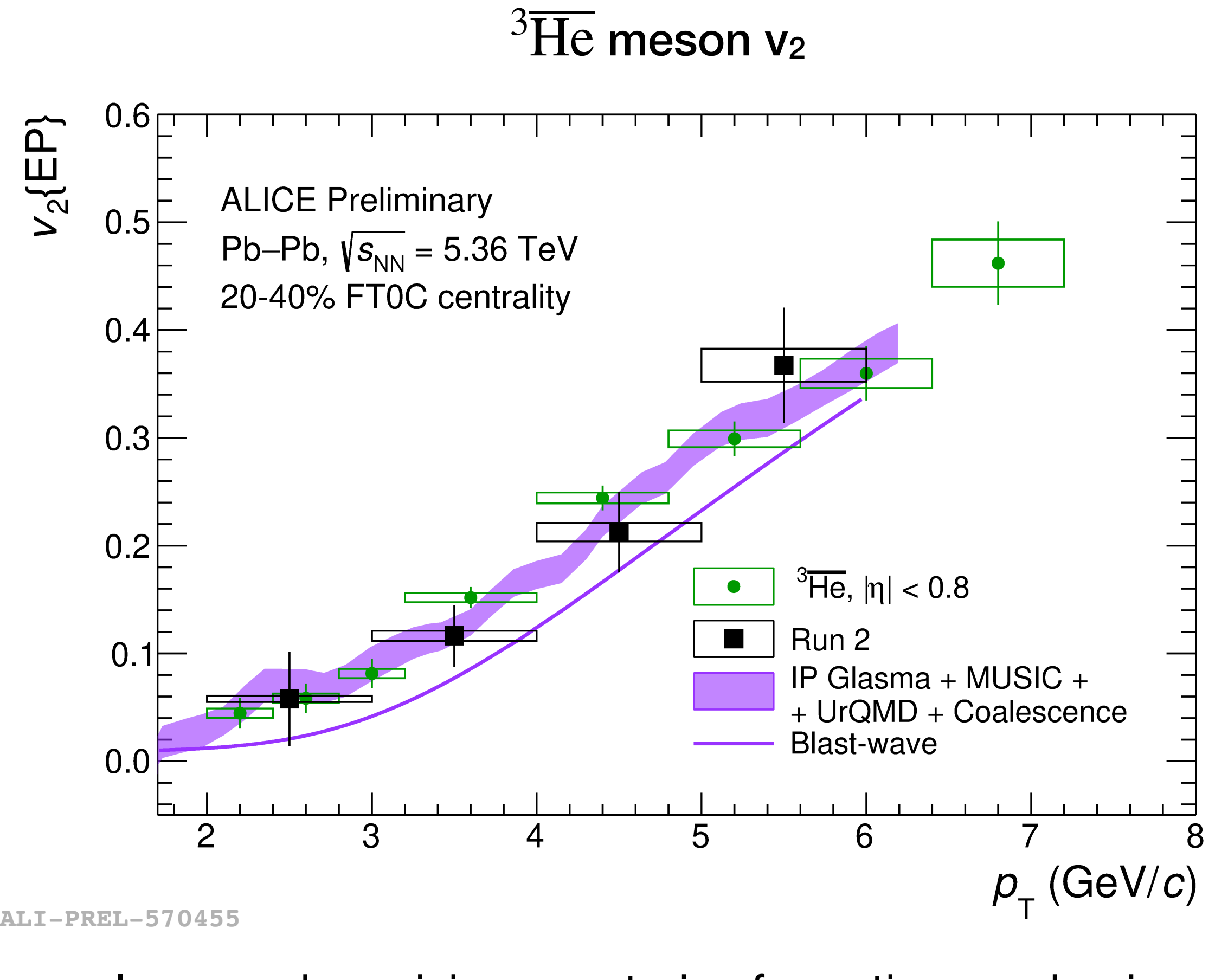
Run 3 Pb-Pb results: elliptic flow



Asymmetric initial state produces momentum asymmetry



ALI-PREL-581279



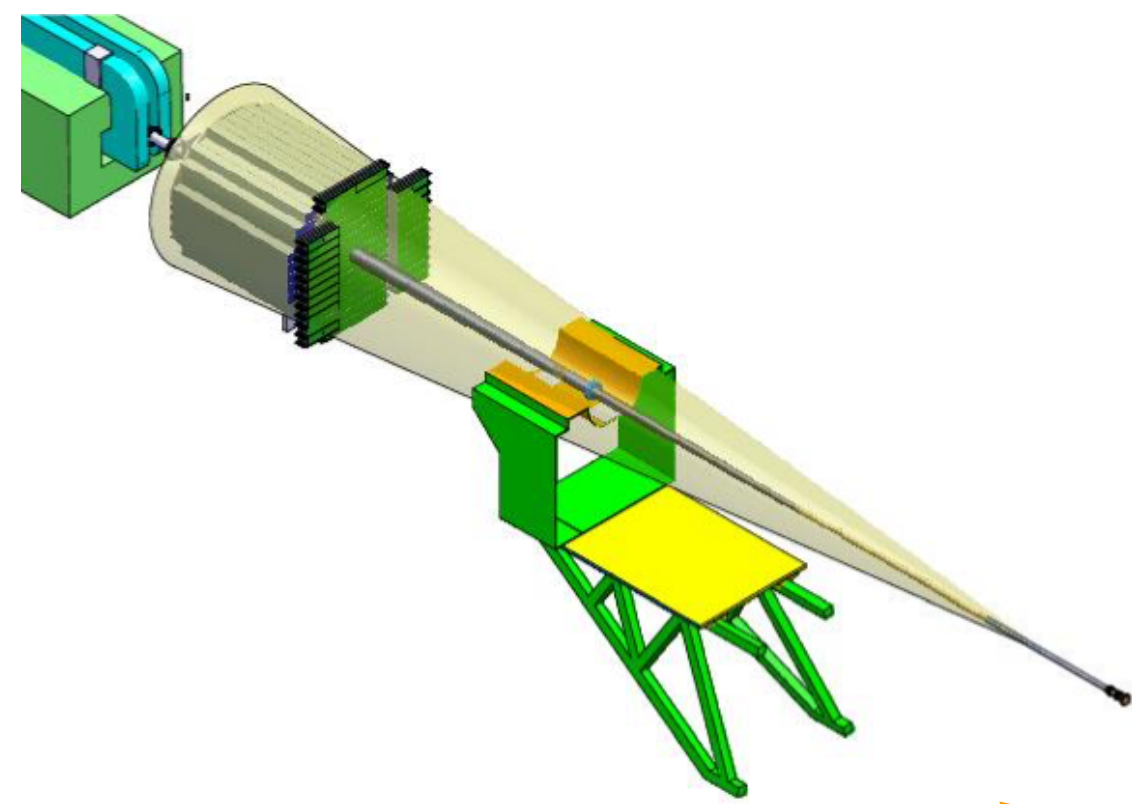
Improved precision constrains formation mechanism

More results shown at SQM, LHCP, ICHEP, Hard Probes this summer
Some based on partial statistics — analysis of full sample ongoing

ALICE upgrade projects

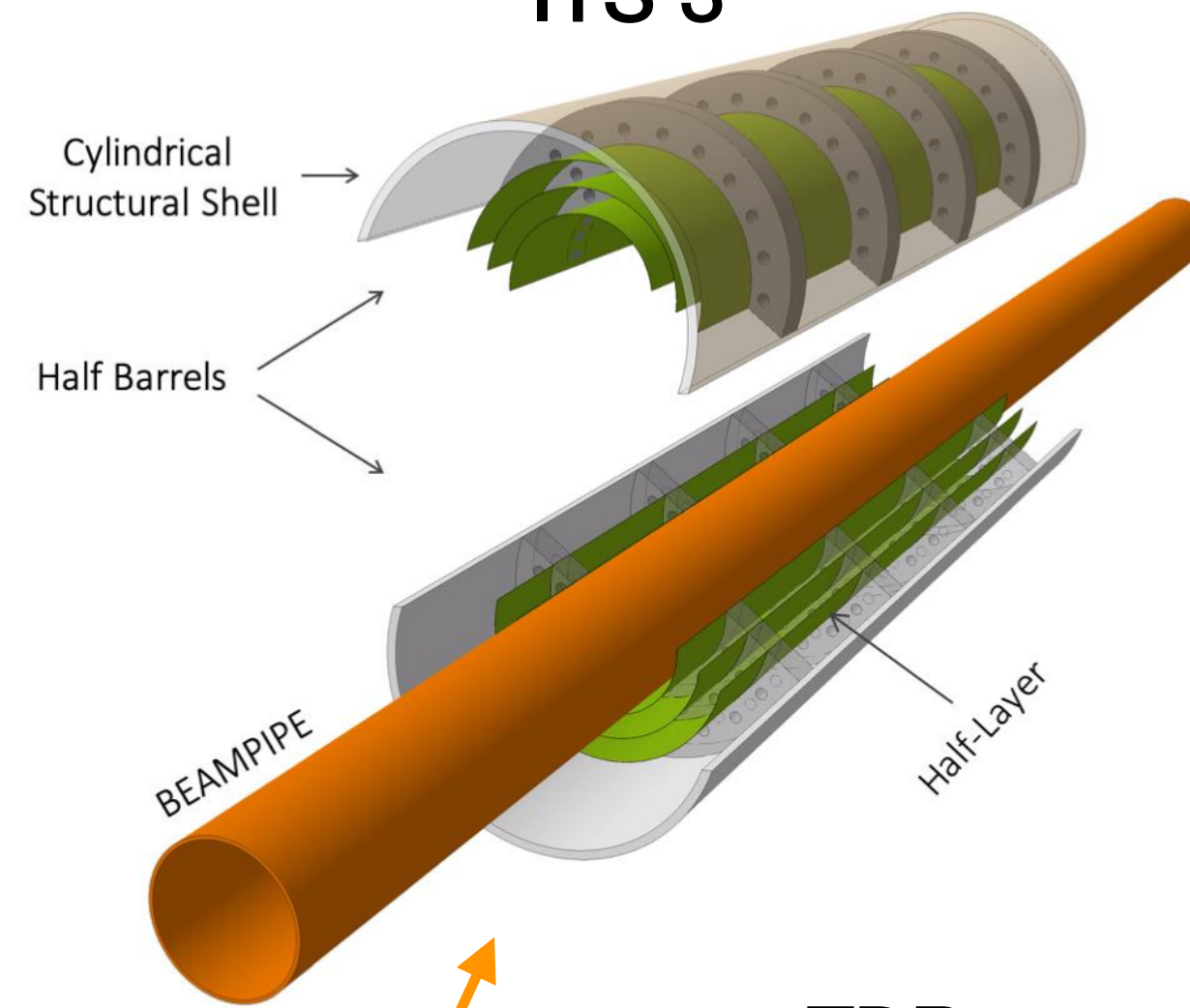
LS3 upgrades

Forward Calorimeter



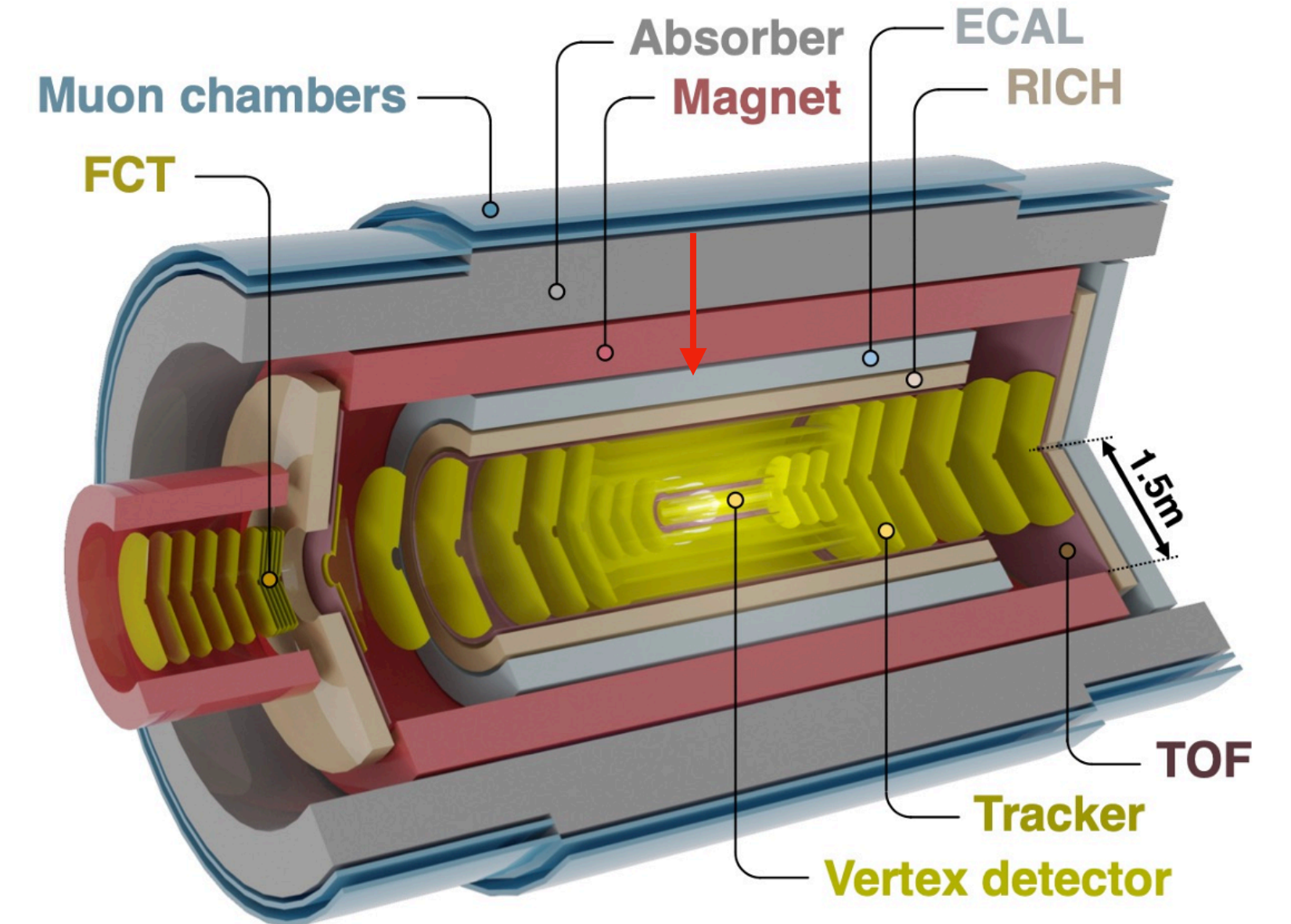
TDR approved

ITS 3

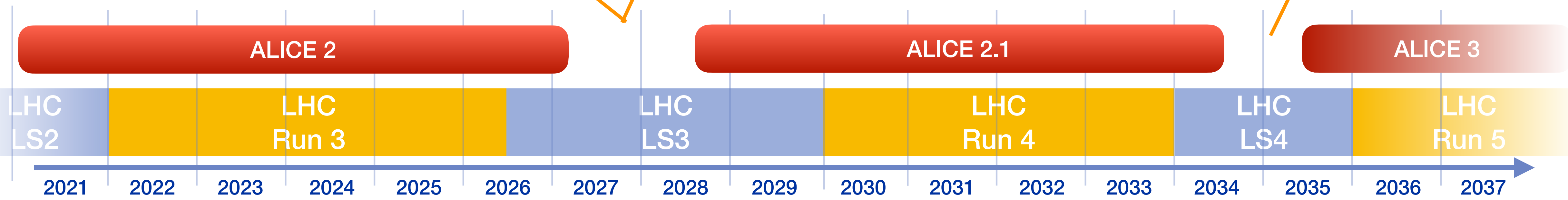


TDR approved

LS4: ALICE 3



ALICE 3 Lol:
CERN-LHCC-2022-009

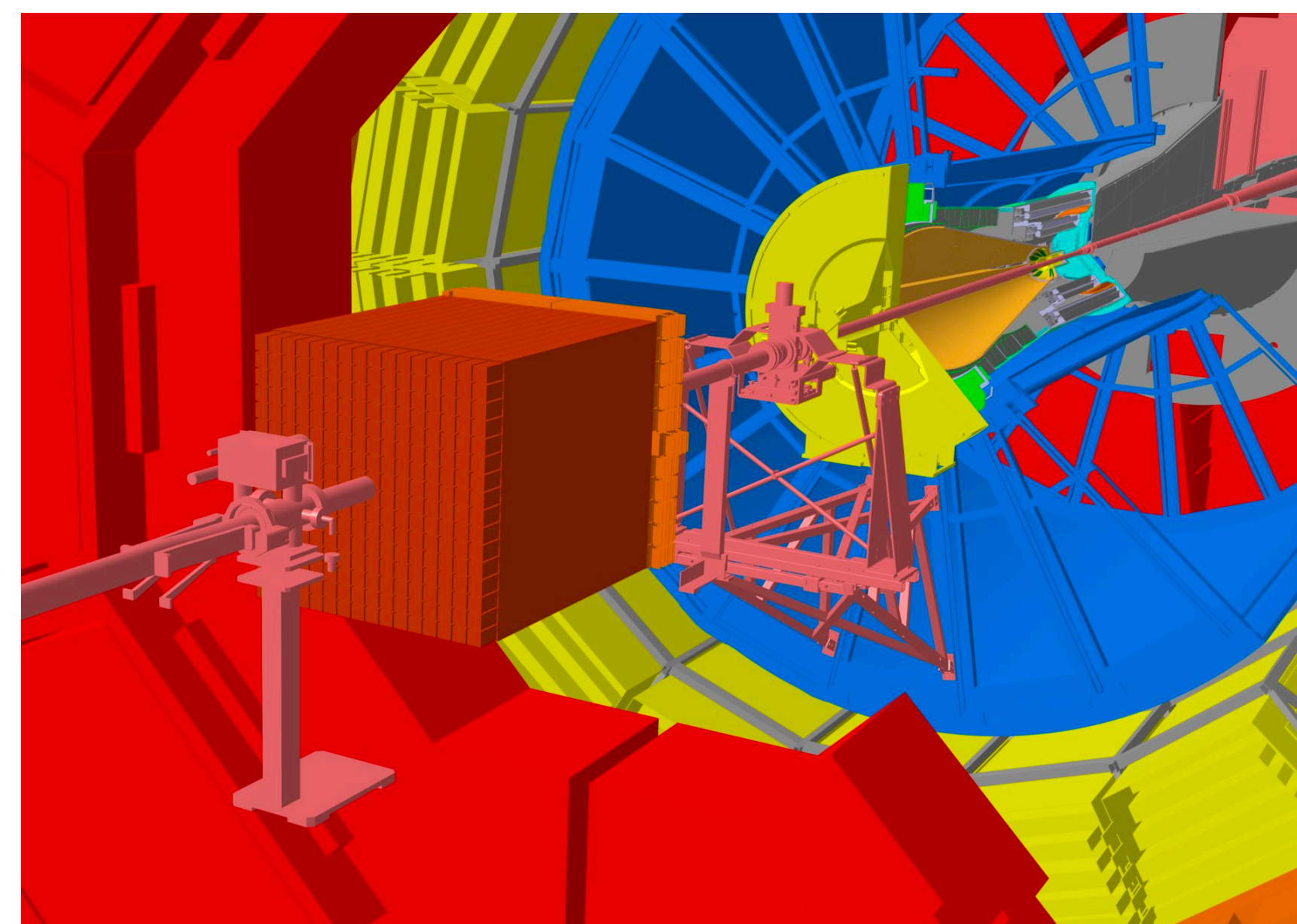


NB: schedule update: LS3 moved by half a year

Forward Calorimeter upgrade

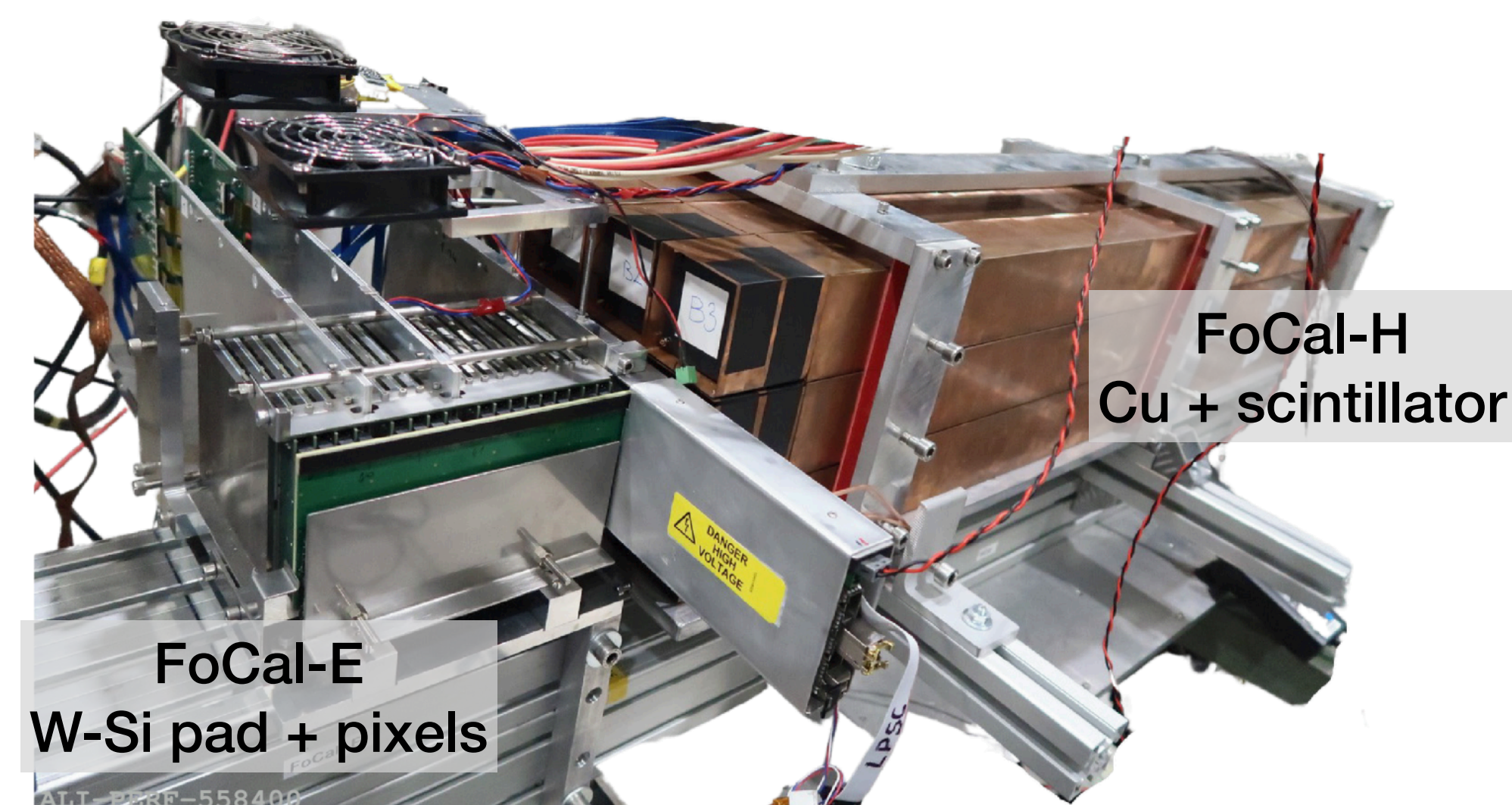
Forward Calorimeter upgrade: $3.4 < \eta < 5.8$

- High-granularity Si-W electromagnetic calorimeter
- Hadron calorimeter: Cu-scintillator
- Goal: *determine small-x gluon density in the nucleus* by measuring forward production of isolated direct photons, π^0 , jets ...



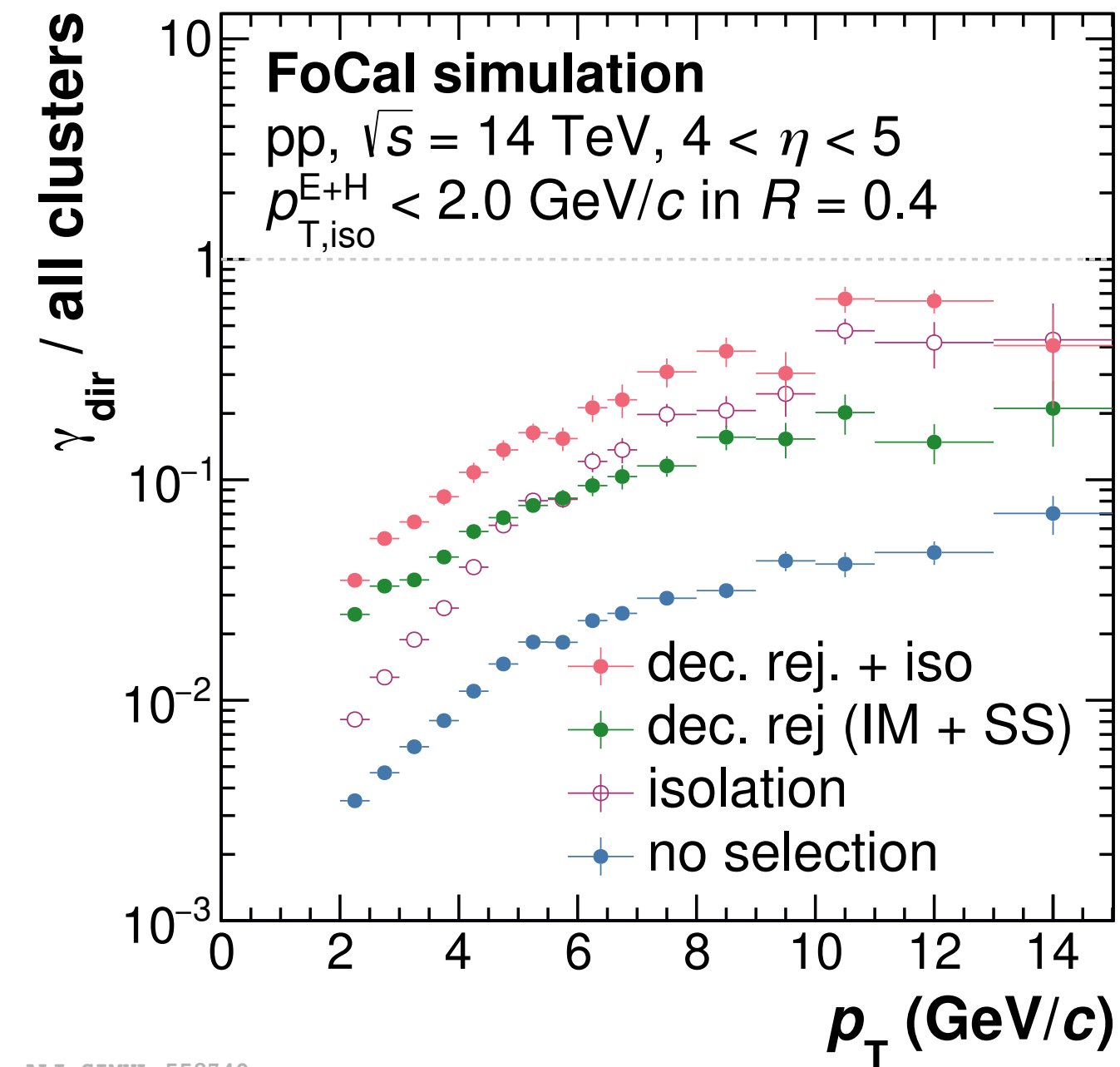
Prototype test campaigns at PS and SPS

- Pad sensors + readout validated
- p-type sensors from Indian vendor being tested
- Pixel readout validated
- HCAL readout with H2GCROC validated

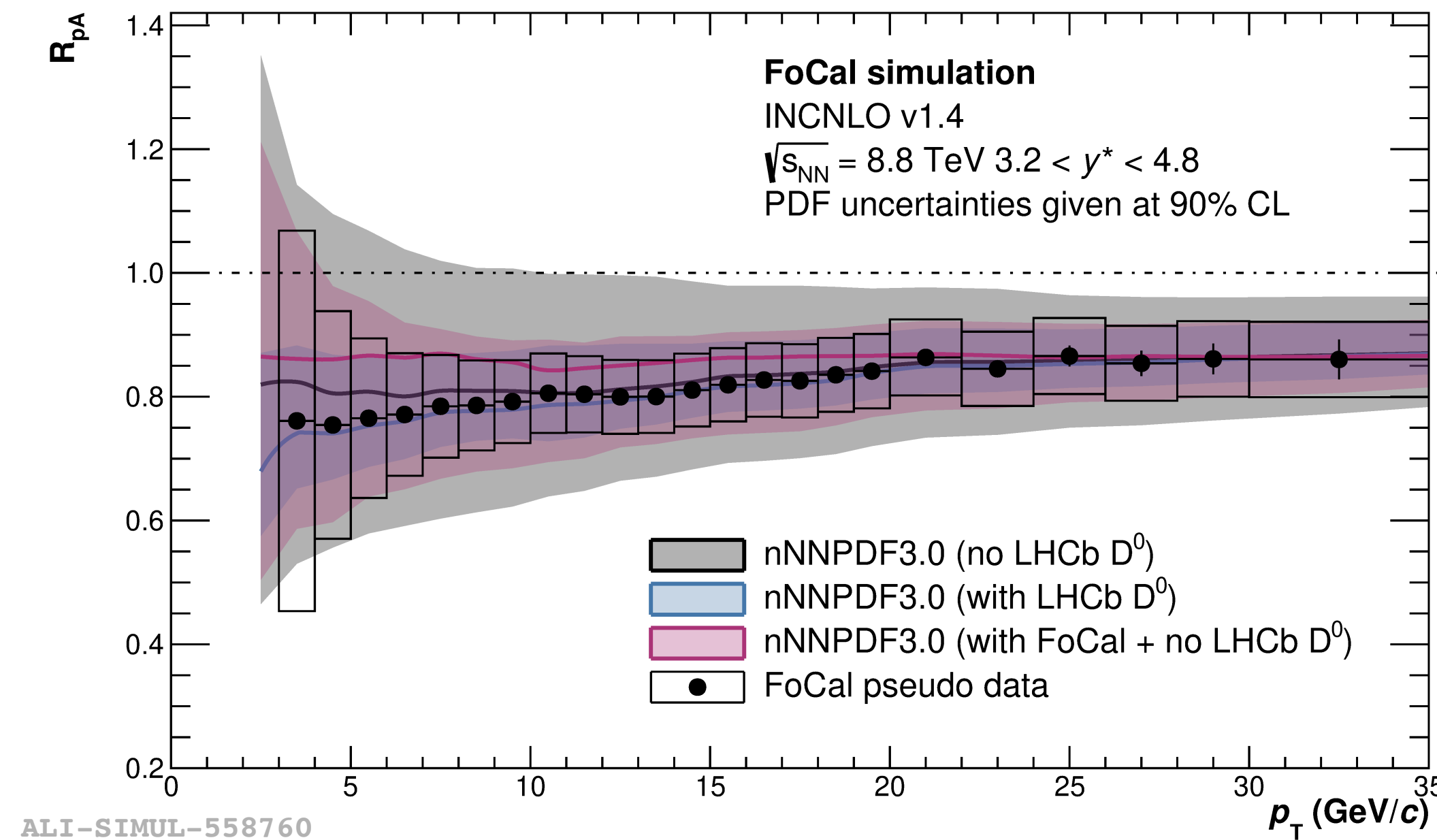


FoCal physics program

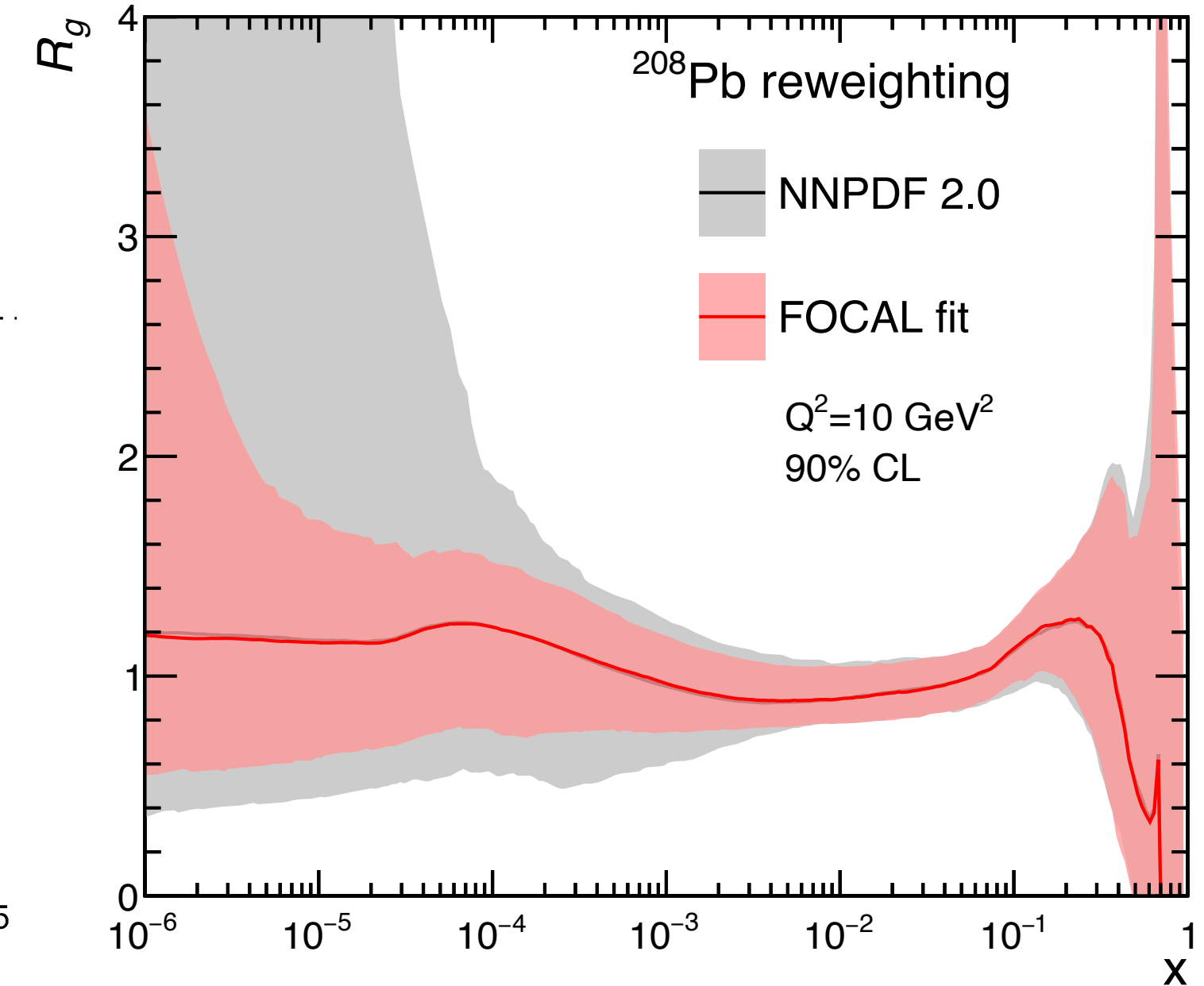
Signal photon fraction



Projected photon uncertainties



Projected PDF uncertainties

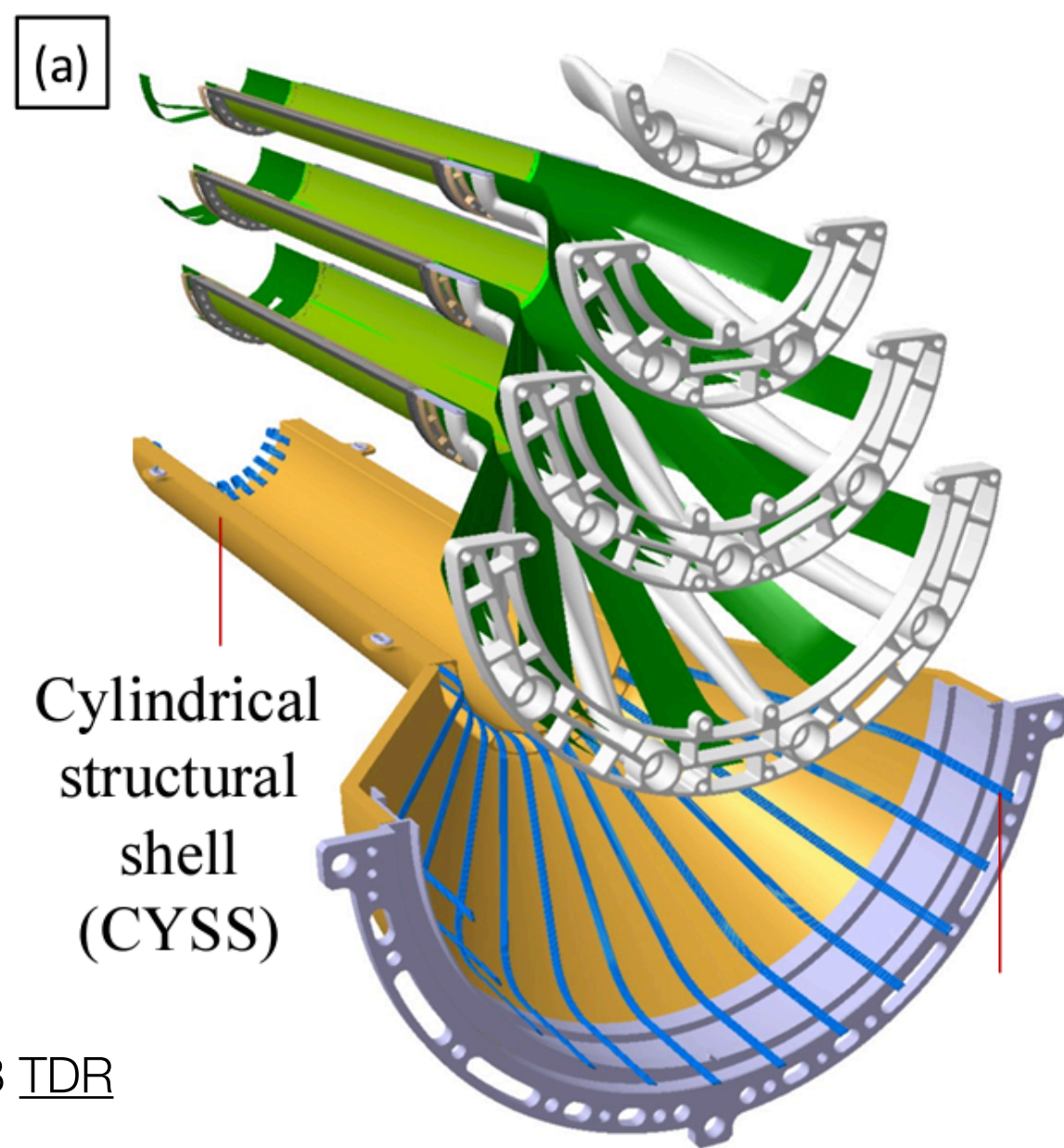


High granularity to reject decay background

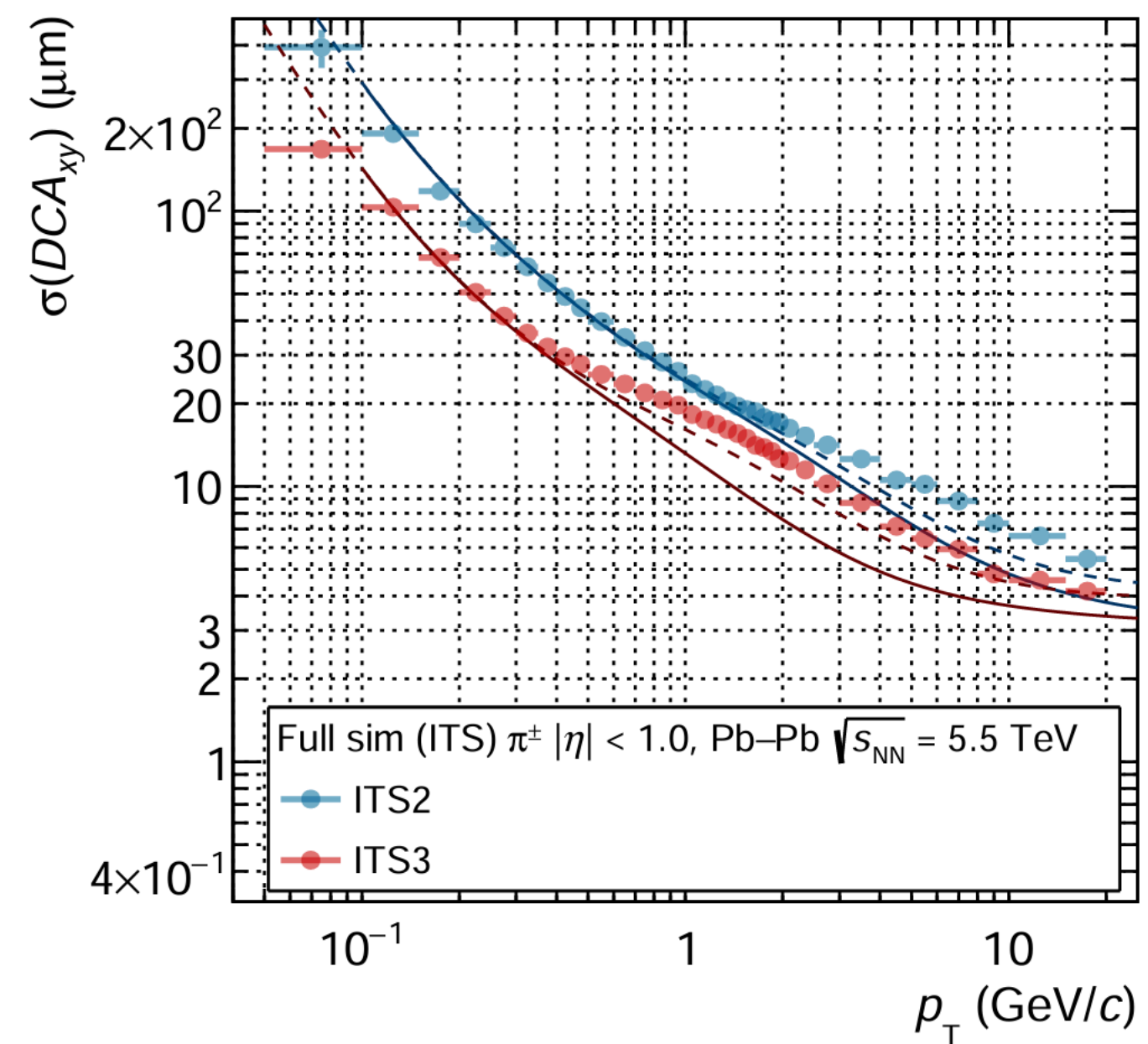
High precision direct photon measurements down to low p_T to constrain gluon density down to small $x \approx 10^{-5}$

Larger program: π^0 , jets, UPC

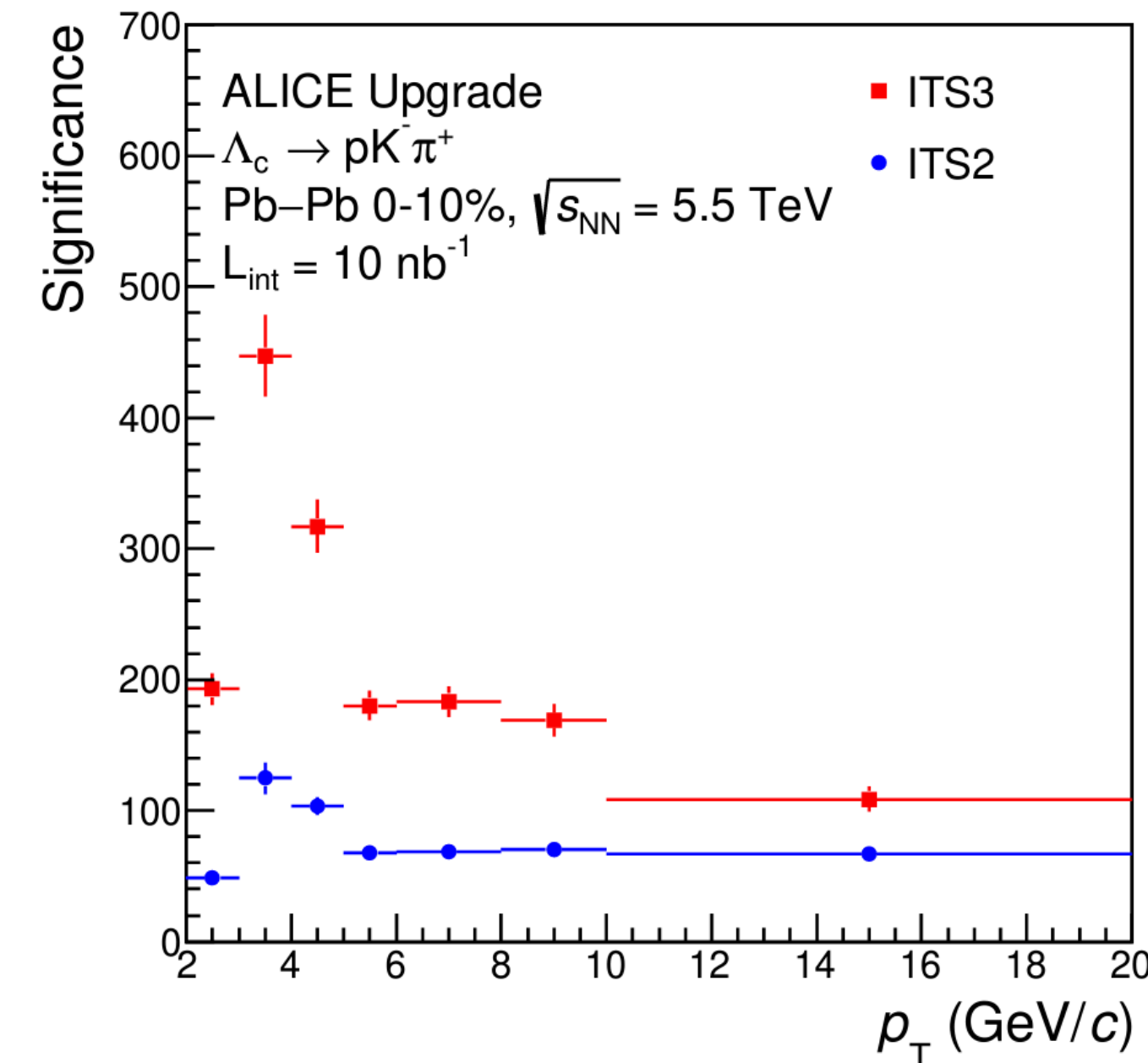
LS3 upgrades: ITS 3 – ultra-light fully cylindrical tracking layers



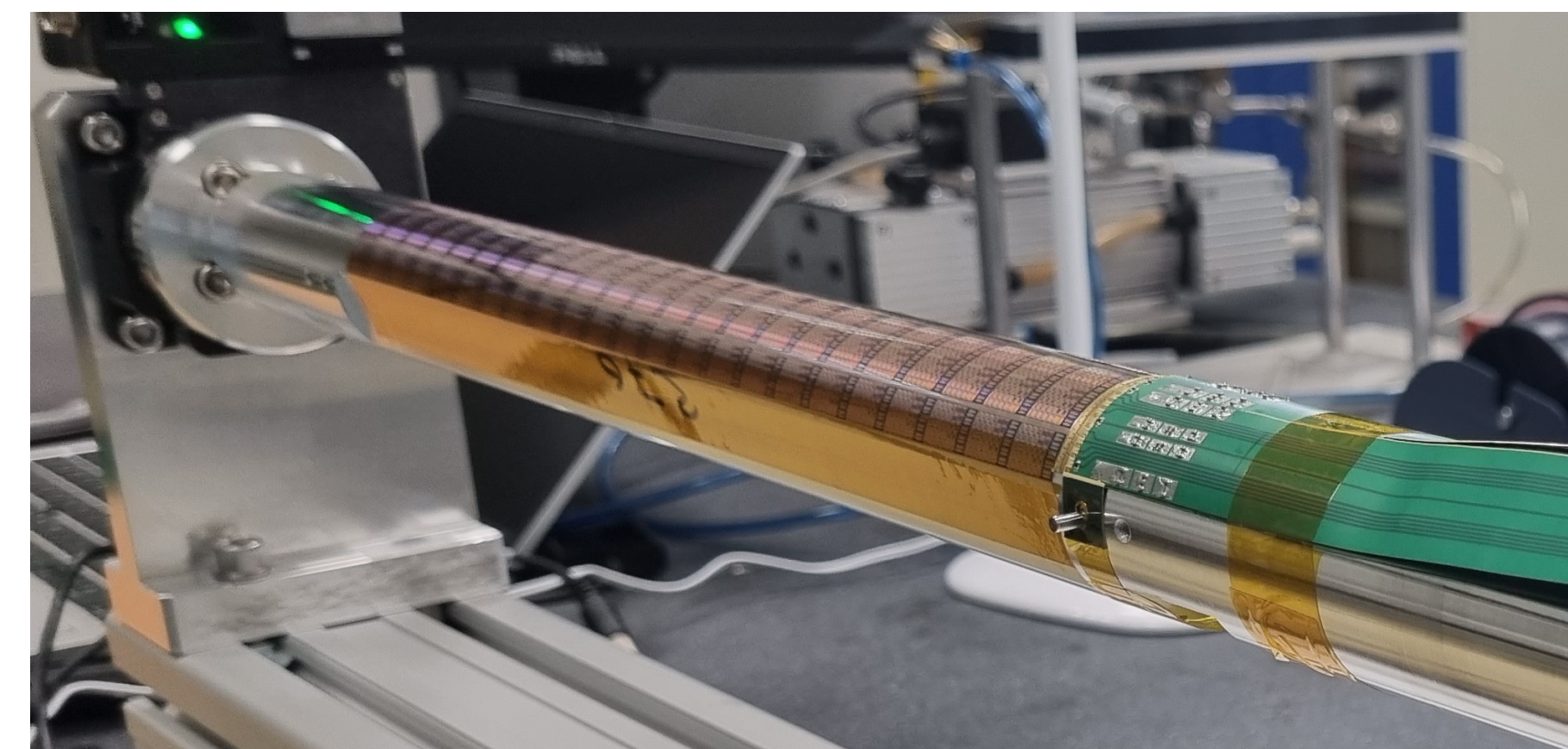
Impact parameter resolution



Λ_c significance



Curved sensor bonding test



Replace inner 3 tracking layers with ultra-light tracking layers

- Large area sensors, curved around beam pipe, carbon foam support

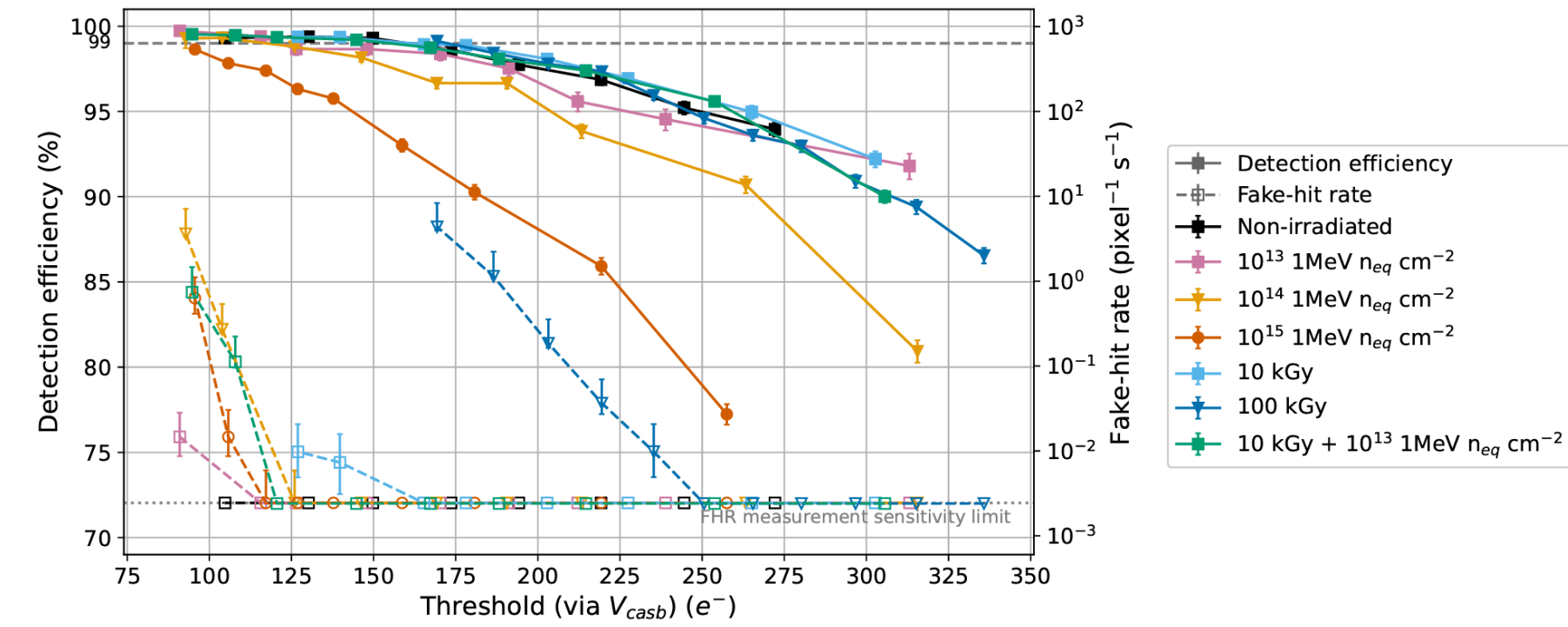
Improved pointing resolution for

- Heavy flavour reconstruction
- Di-lepton measurements

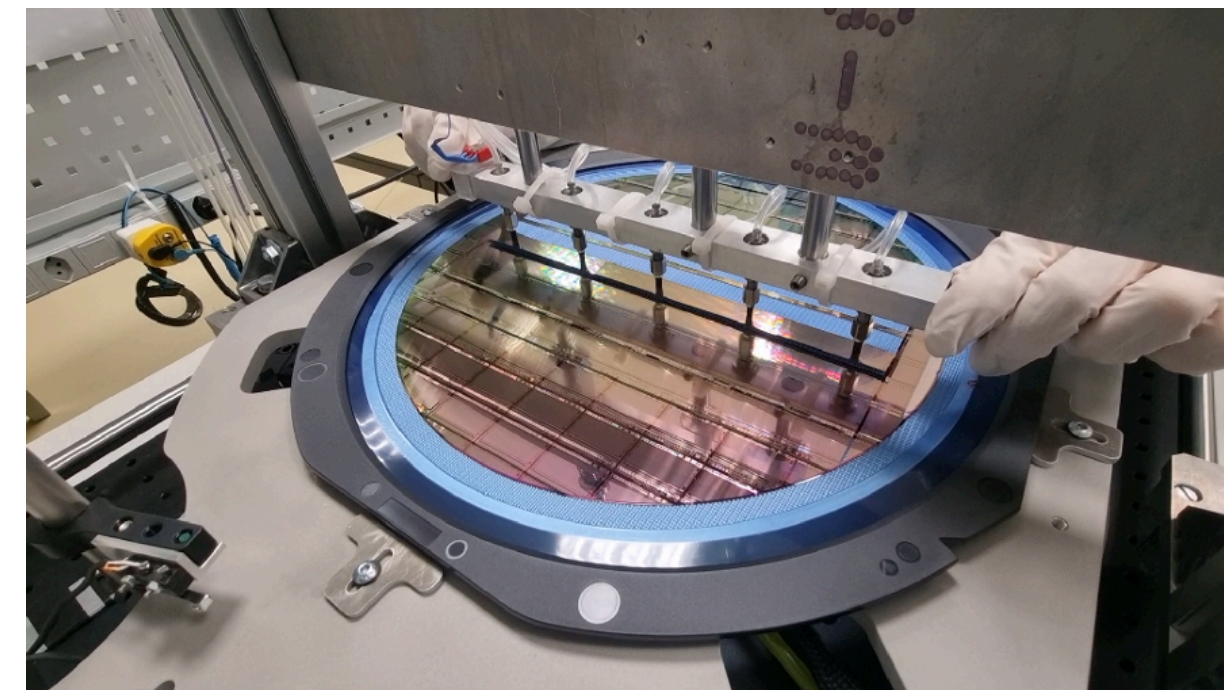
ITS3 R&D

- Development of stitched sensors: 65 nm technology
 - Engineering runs (MLR1, ER1) completed
 - optimise design, test stitching
- Mechanical prototypes produced
- Air cooling strategy tested and validated

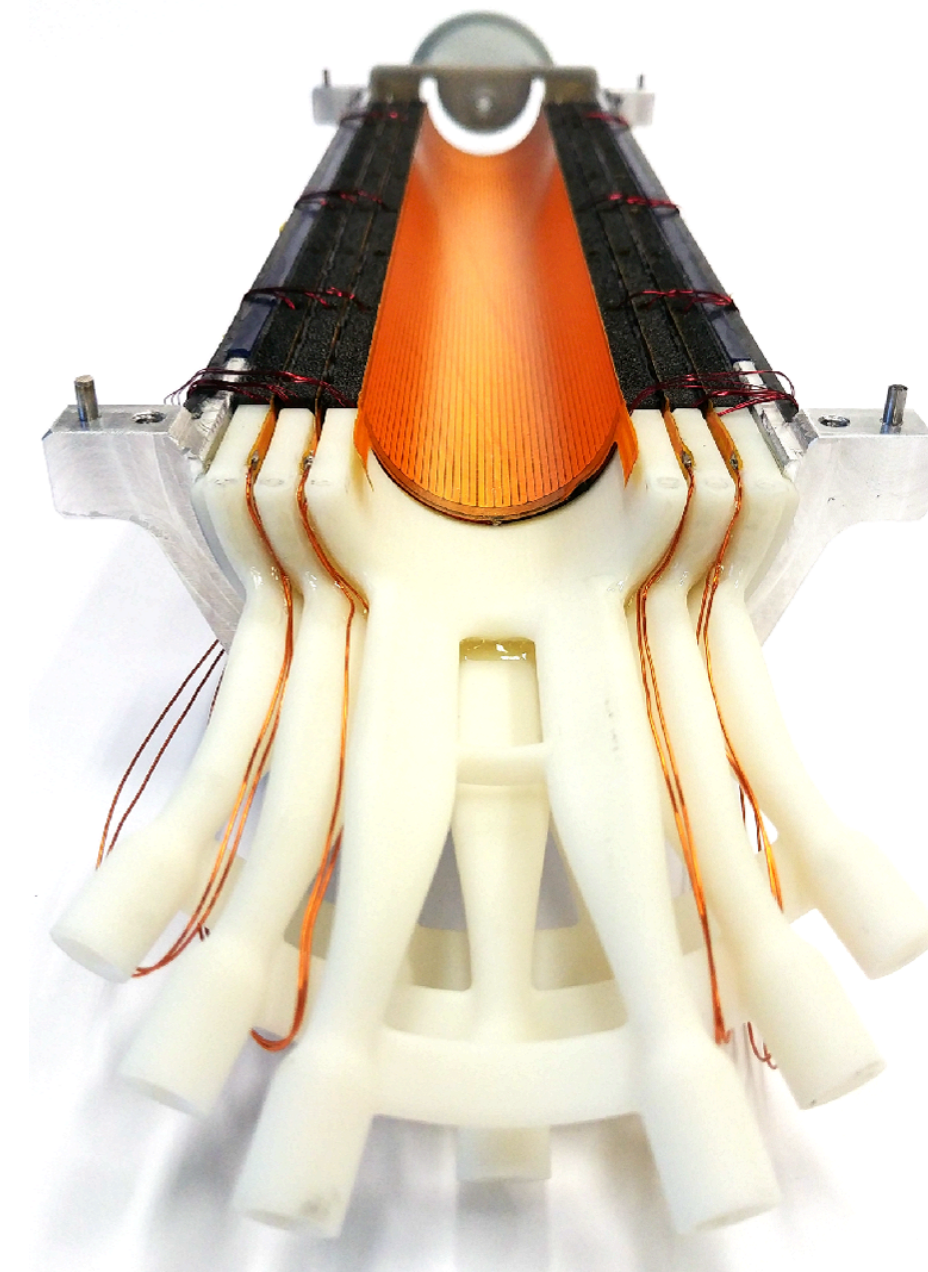
MLR1 efficiency and fake rate



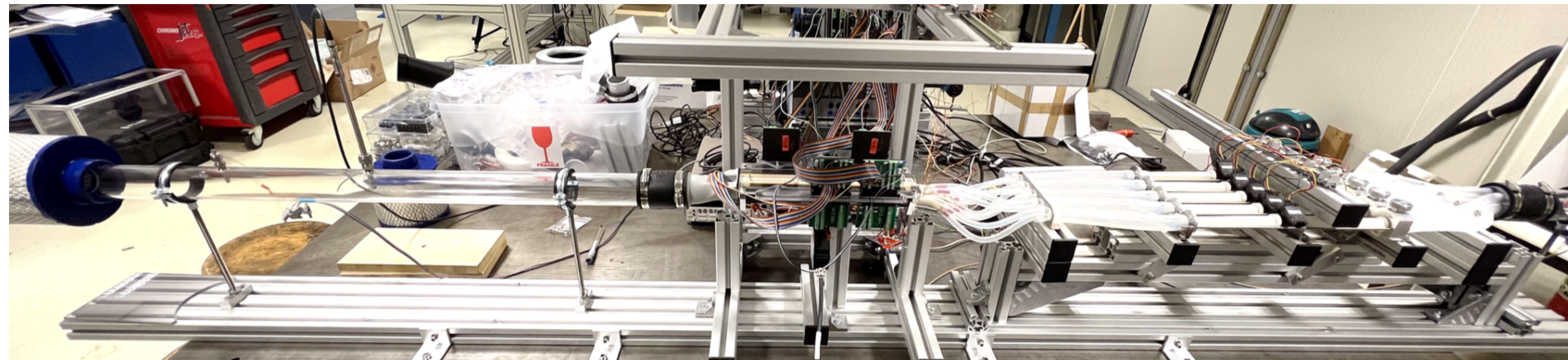
Handling of stitched structures



Engineering model for thermal tests

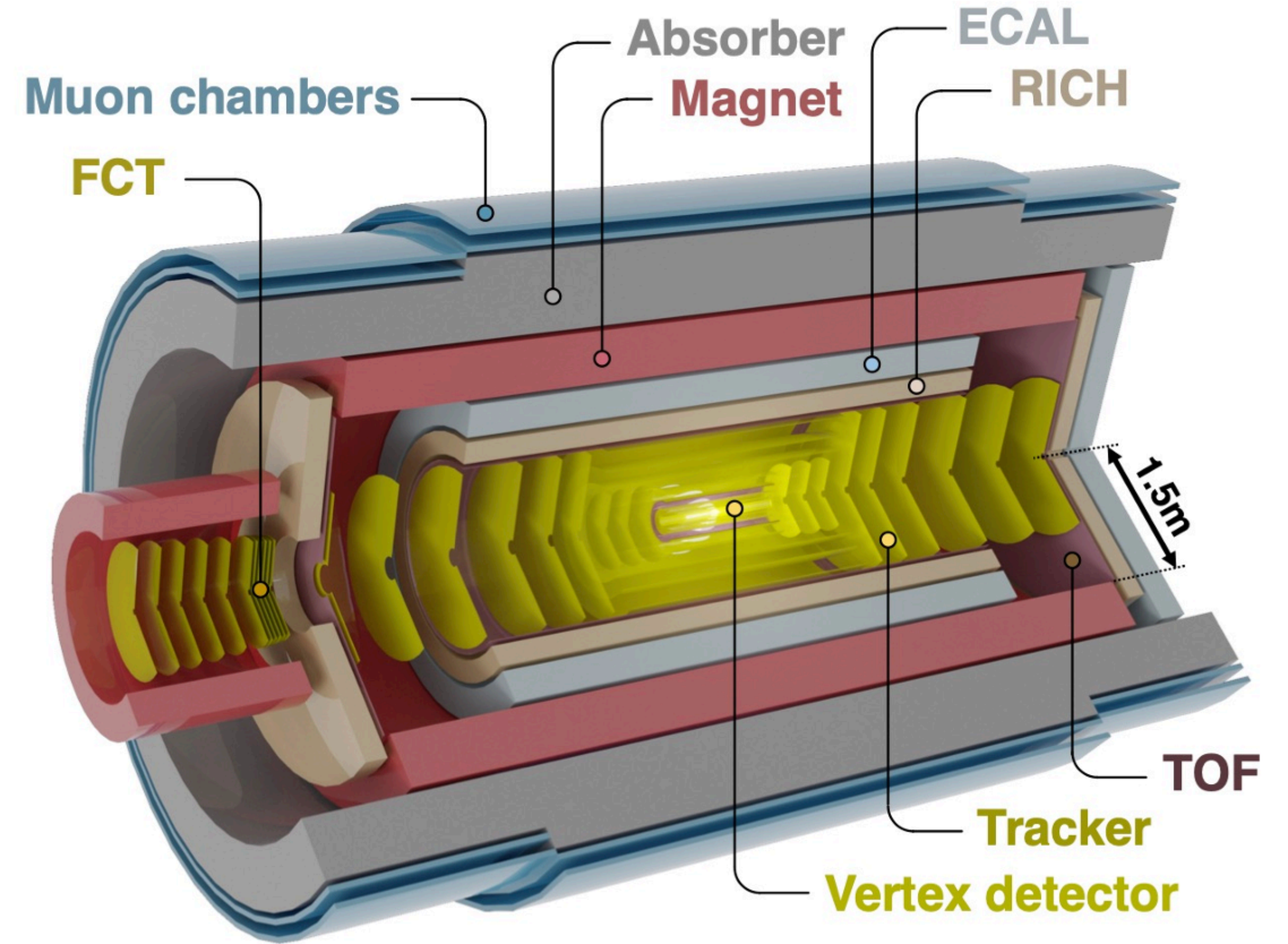


Air cooling test setup

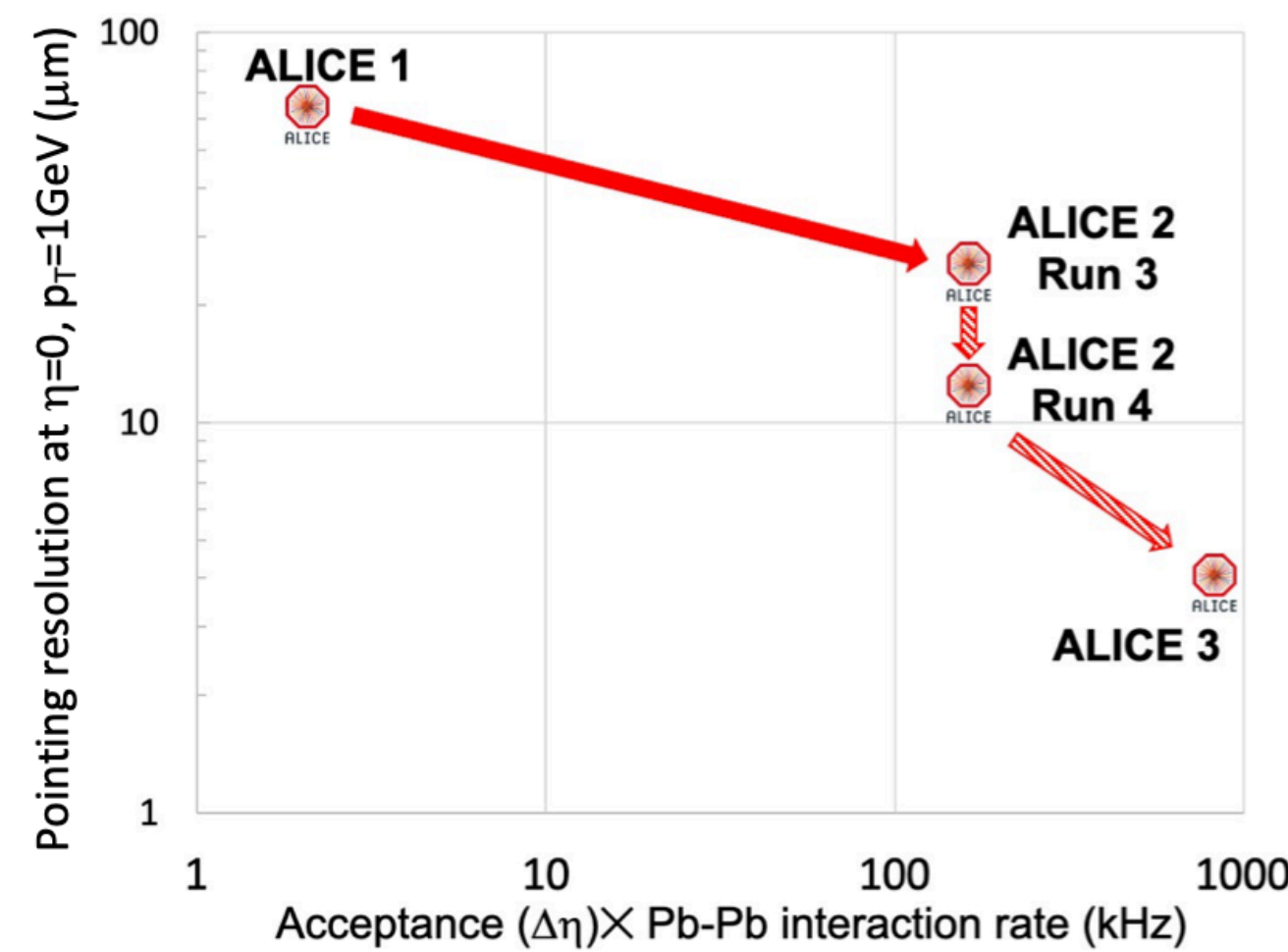
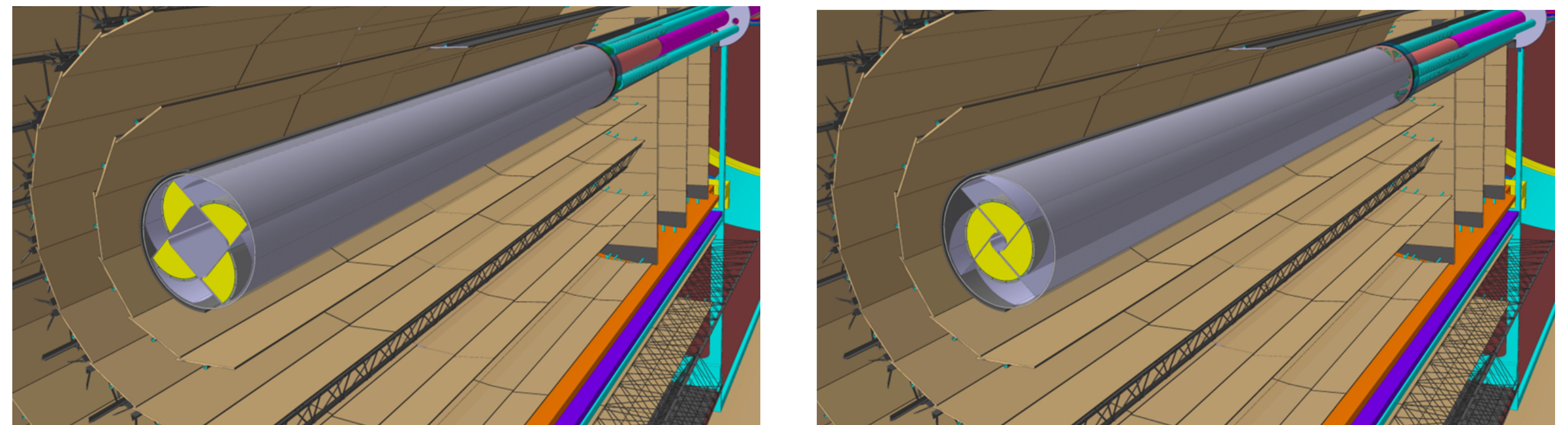


LHC Run 5 and 6: ALICE 3

- Compact all-silicon tracker with high-resolution vertex detector:
excellent pointing resolution
- **Particle Identification over large acceptance:** muons, electrons, hadrons, photons
- Fast read-out and online processing



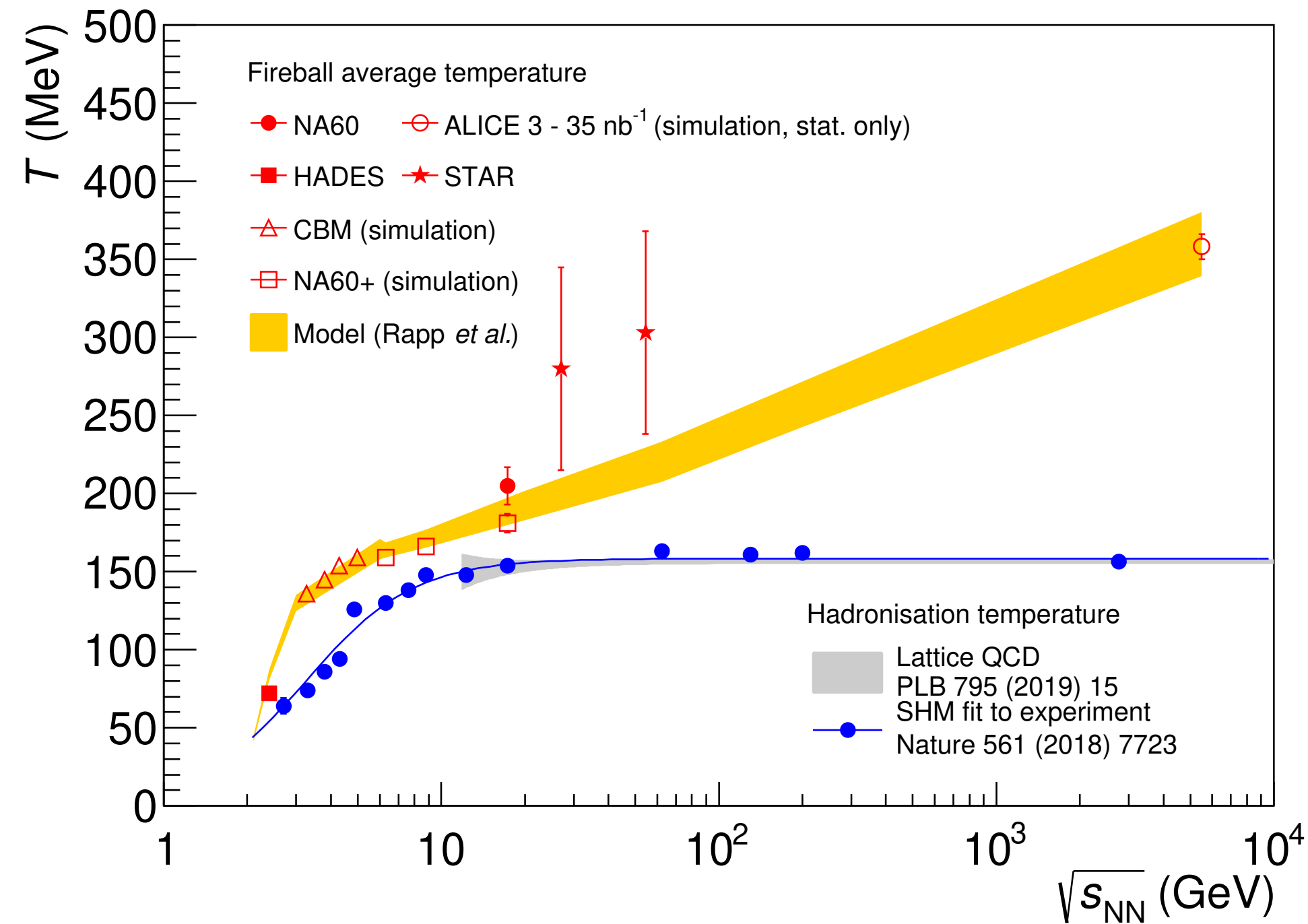
Retractable vertex tracker



Upgrades: improvements in precision, rate, acceptance

Temperature of the QGP: electromagnetic radiation

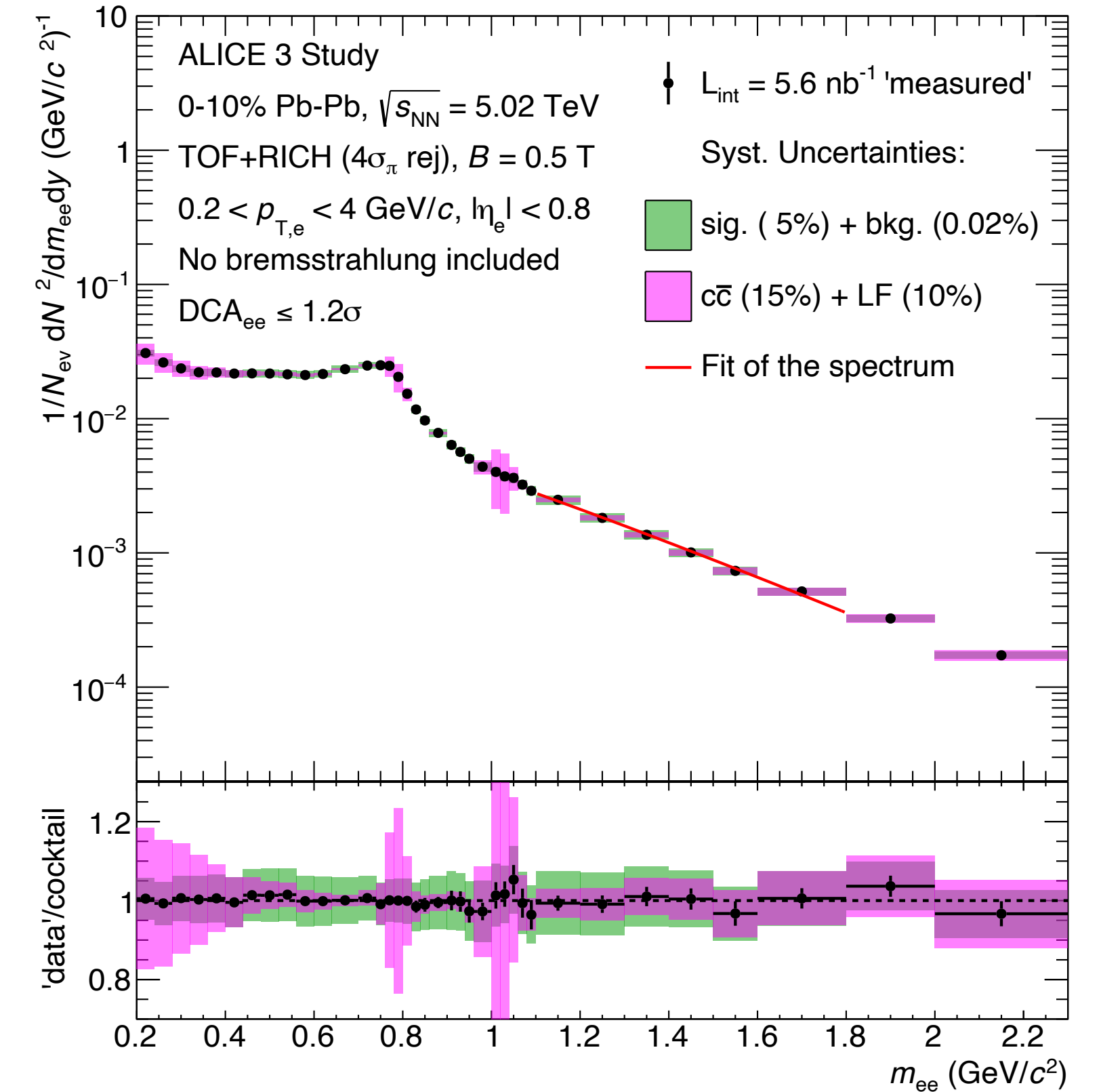
T vs energy



Projected temperature from electromagnetic radiation

Temperature from hadron abundances 'chemical freeze-out'

Dielectron mass distribution



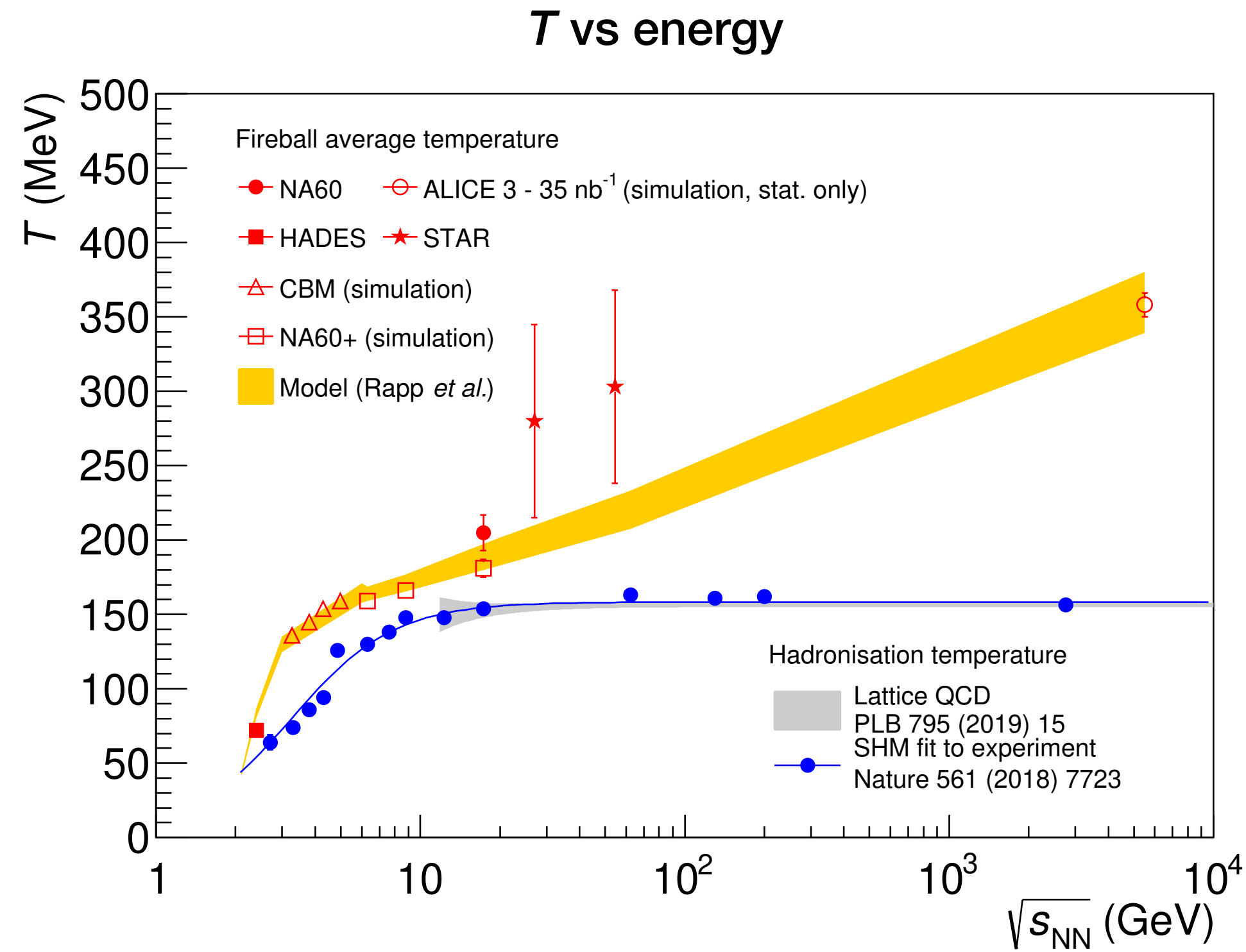
Light flavour hadron abundances consistent with common chemical freeze-out

- Limiting temperature: ~155 MeV

Electromagnetic radiation gives access to **temperature of QGP before hadronisation**

- Cleanest signal: dilepton pairs
- Expected T at LHC: 300-400 MeV

Temperature of the QGP: electromagnetic radiation



Projected temperature from electromagnetic radiation

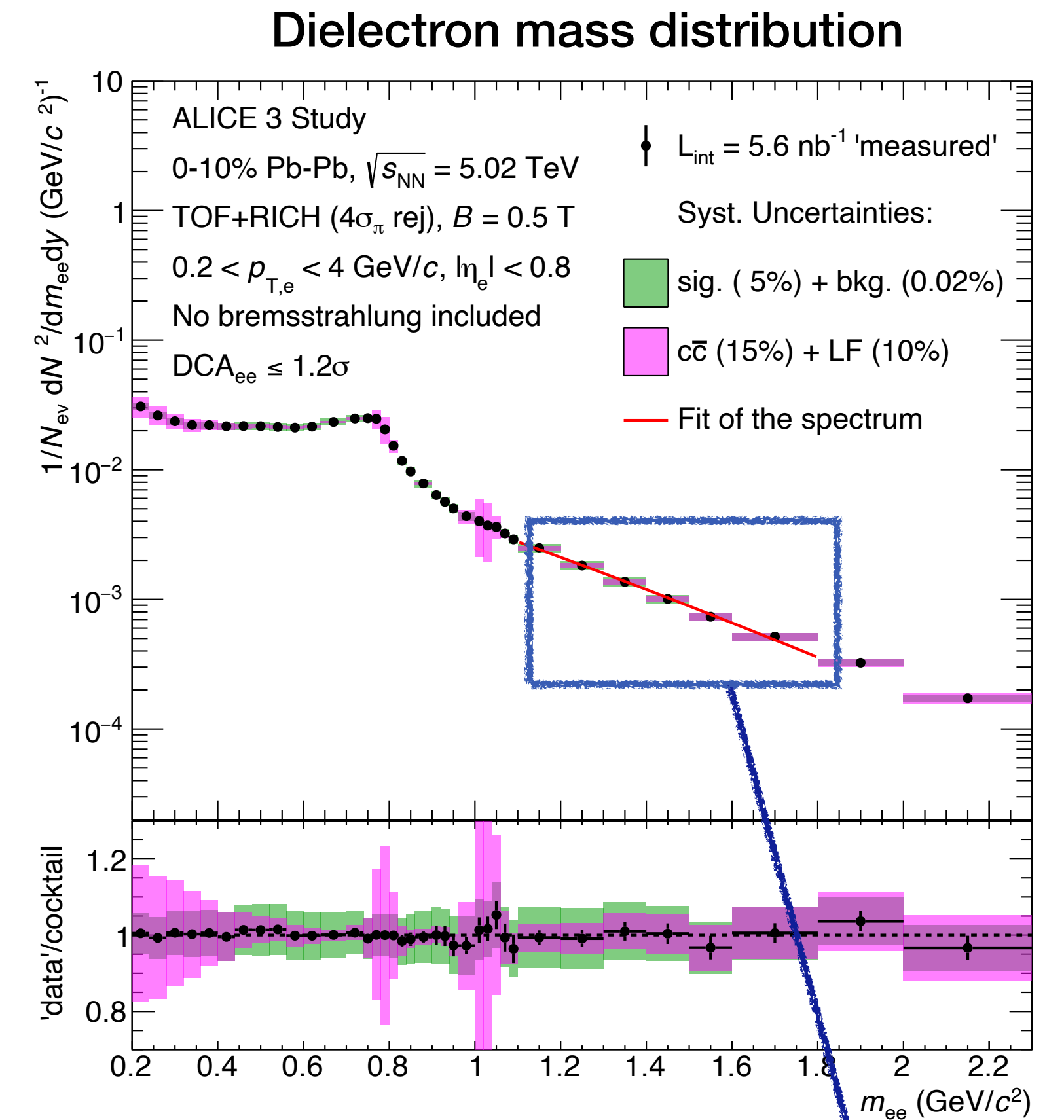
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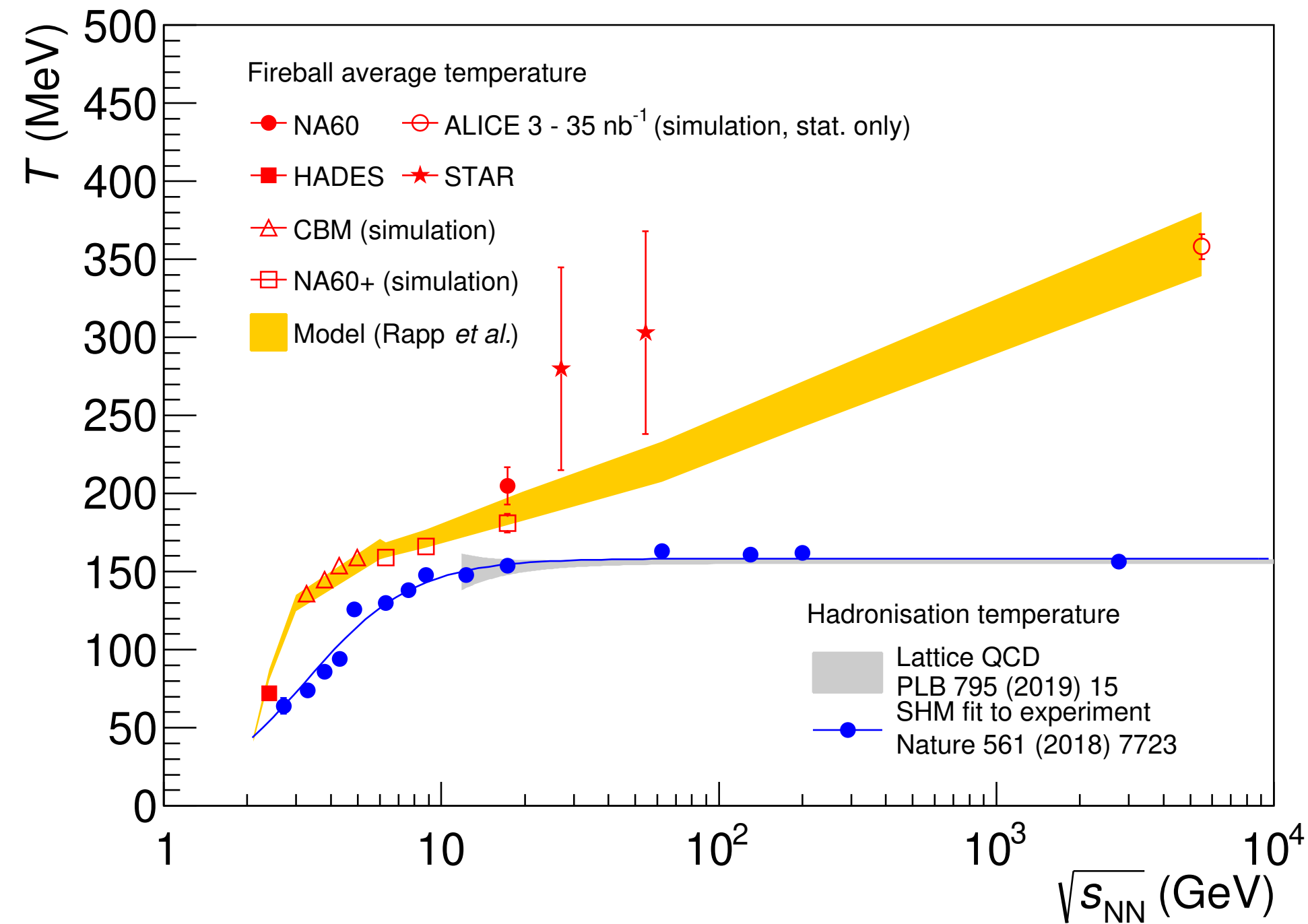
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Slope measures temperature

Temperature of the QGP: electromagnetic radiation

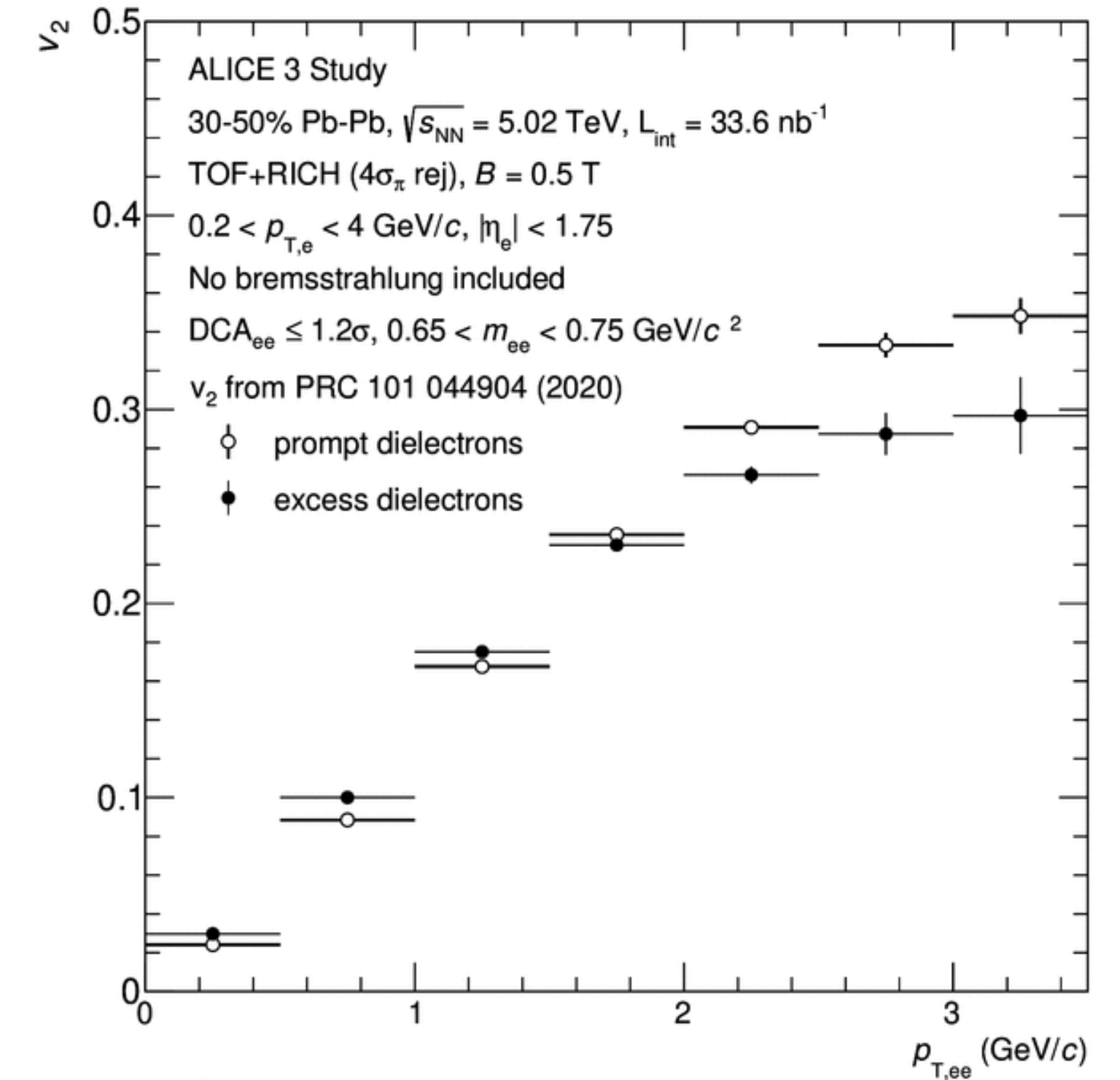
T vs energy



Projected temperature from electromagnetic radiation

Temperature from hadron abundances 'chemical freeze-out'

Dielectron *v*₂



ALI-SIMUL-499204

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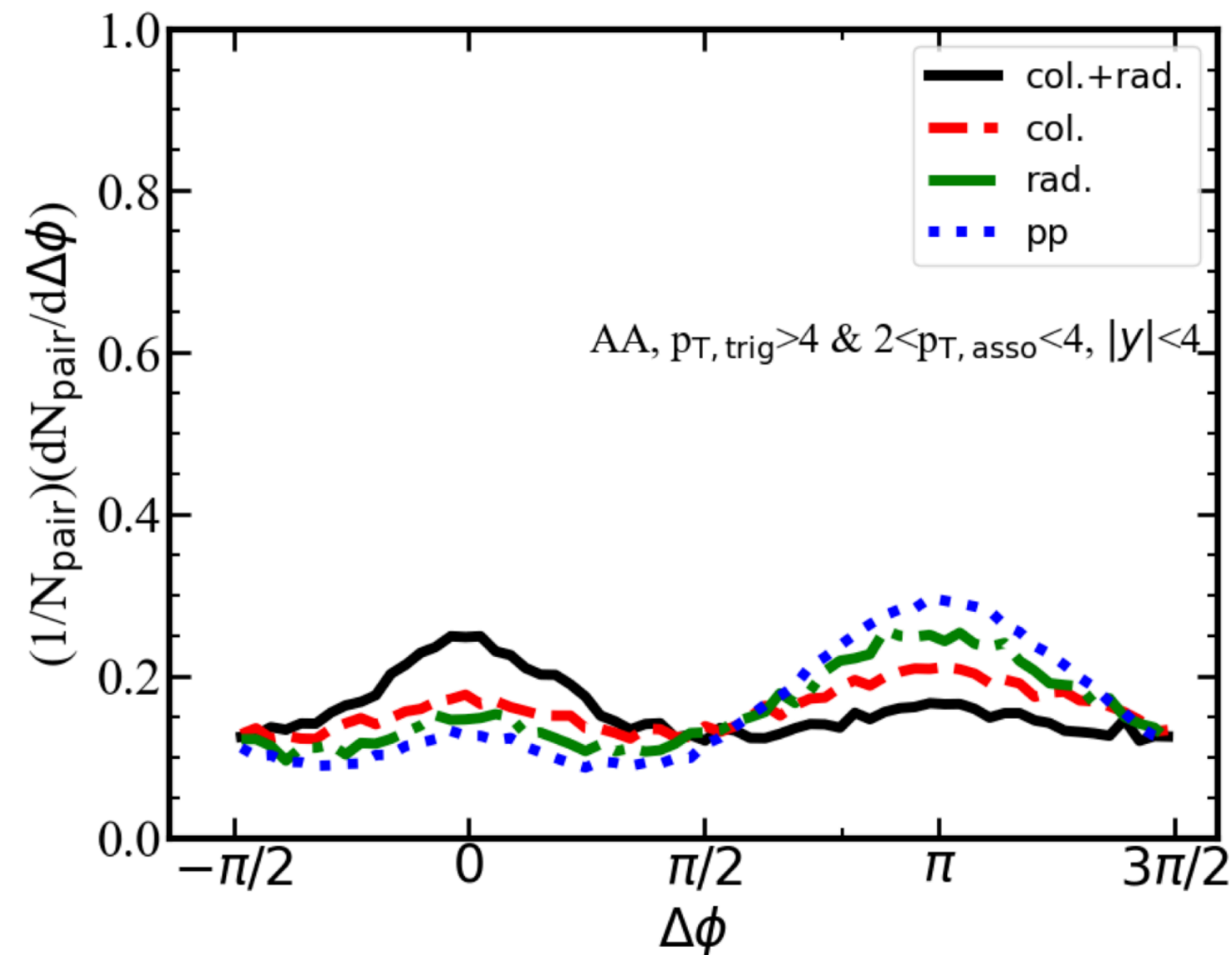
- Cleanest signal: dilepton pairs
- Expected *T* at LHC: 300-400 MeV

Unique access to **time evolution of temperature**

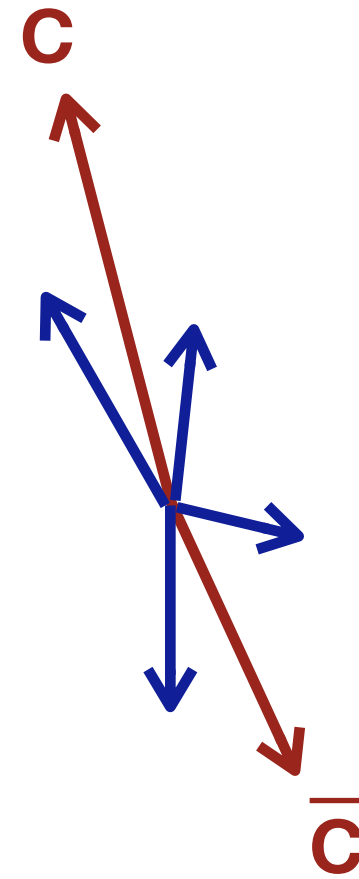
via *v*₂, *p*_T dependence of *T*

Heavy-flavour transport: $D\bar{D}$ azimuthal correlations

Charm azimuthal correlations



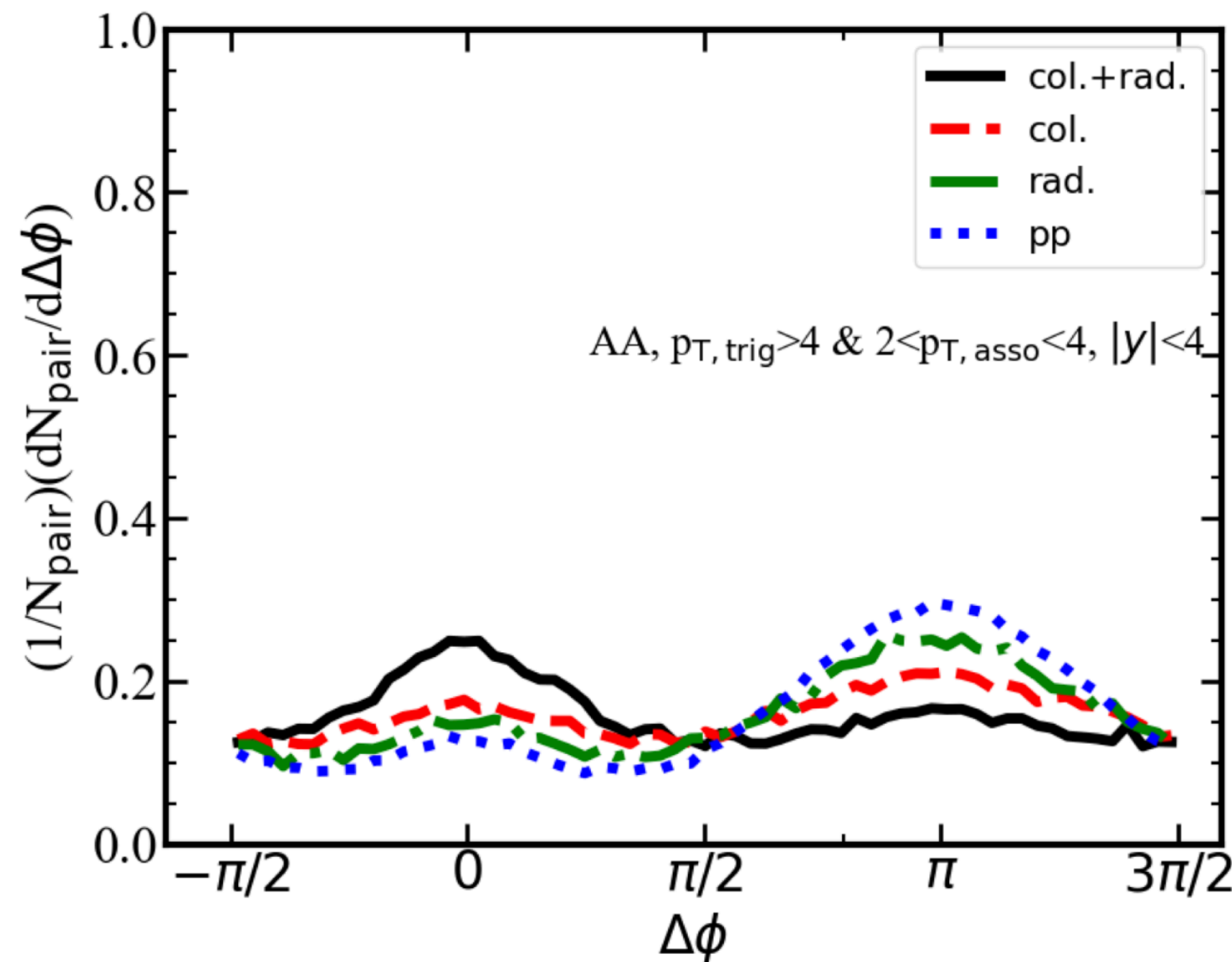
S. Cao et al., private comm.,
based on PLB 838 (2023) 137733



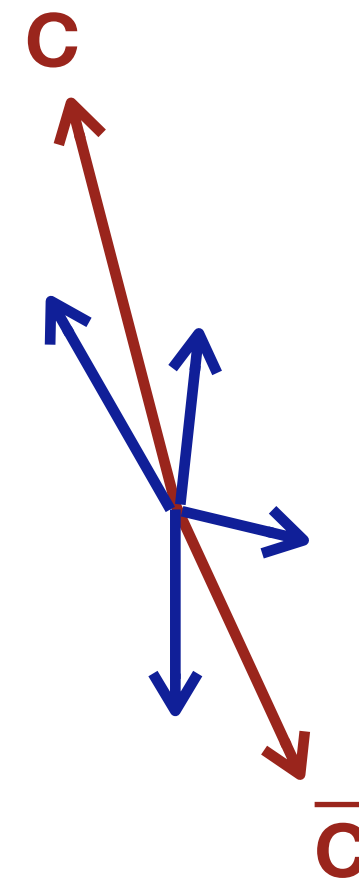
- Angular decorrelation **directly probes QGP scattering**
 - Signal strongest at low p_T
- Very challenging measurement:
 - need good purity, efficiency and η coverage
 - **heavy-ion measurement only possible with ALICE 3**

Heavy-flavour transport: $D\bar{D}$ azimuthal correlations

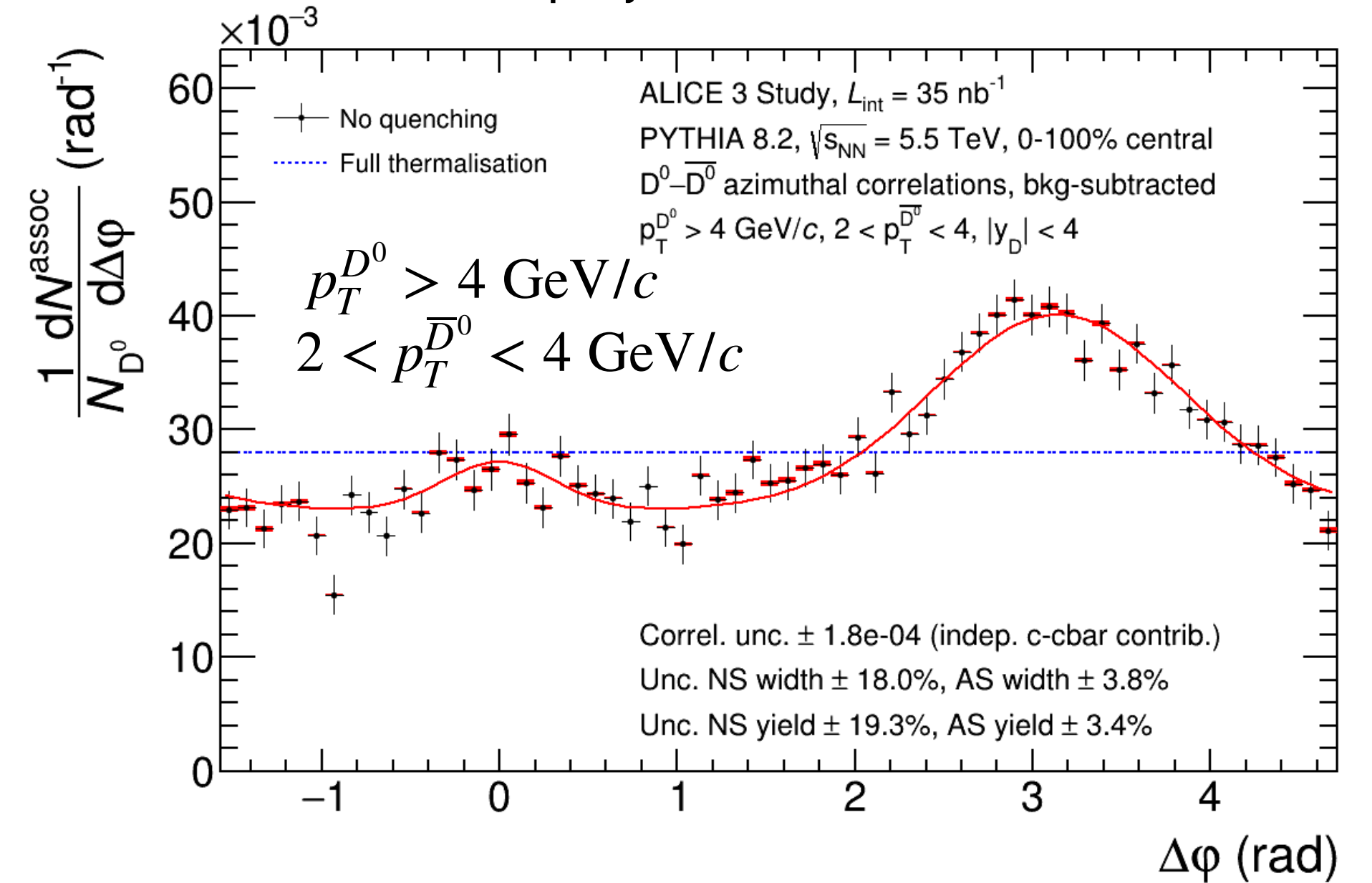
Charm azimuthal correlations



S. Cao et al., private comm.,
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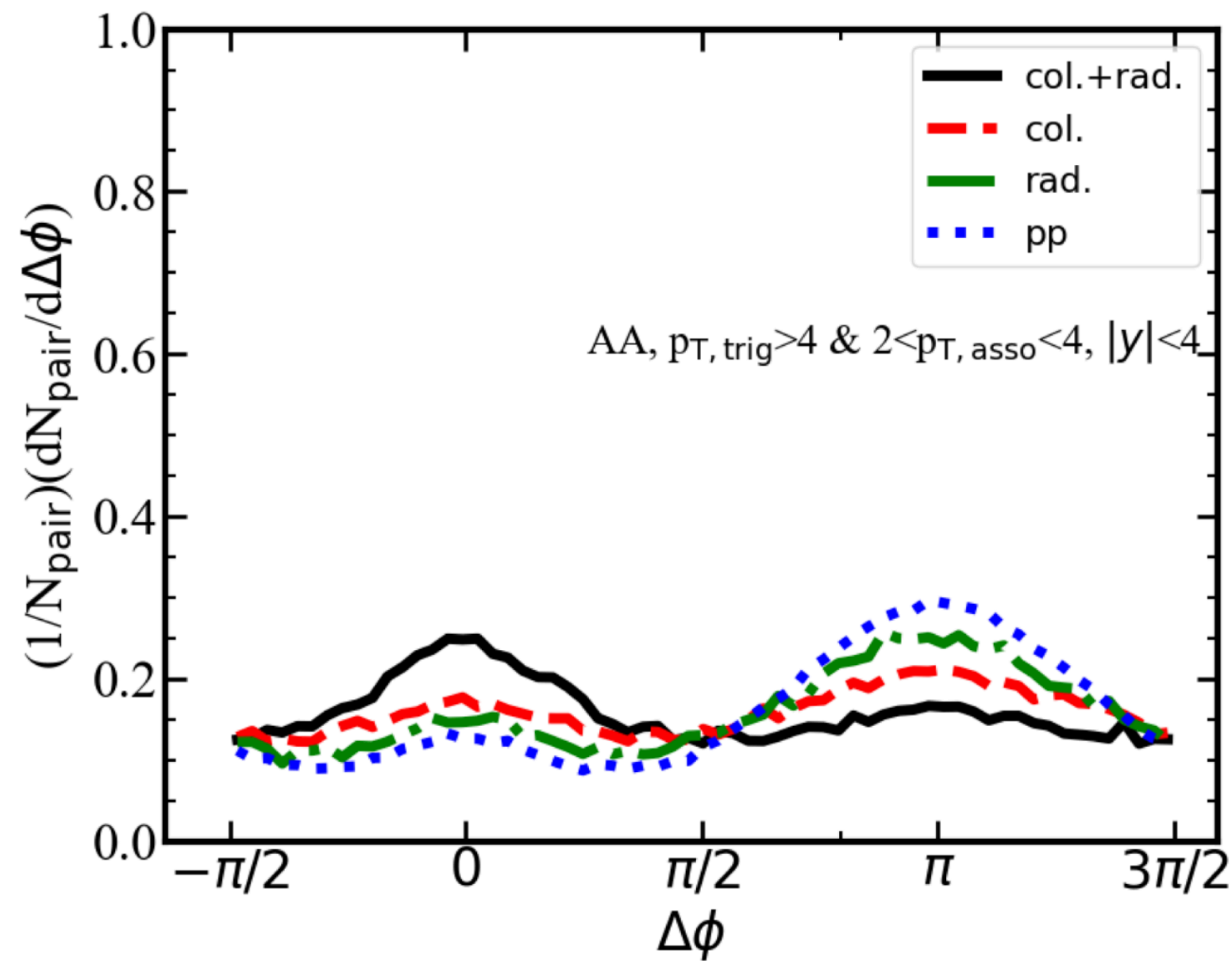
ALICE 3 projection: $D\bar{D}$ correlations



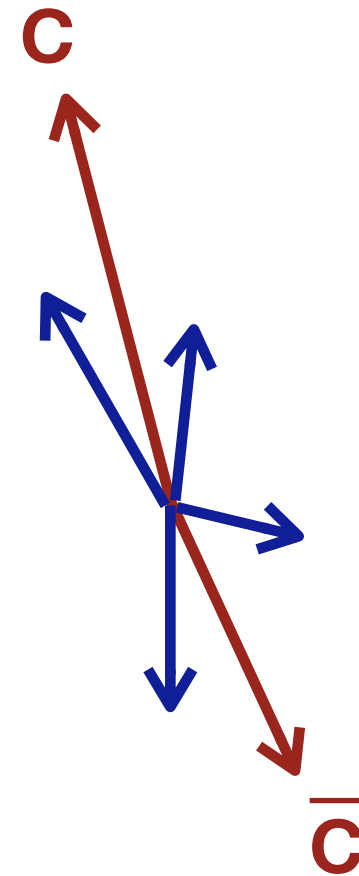
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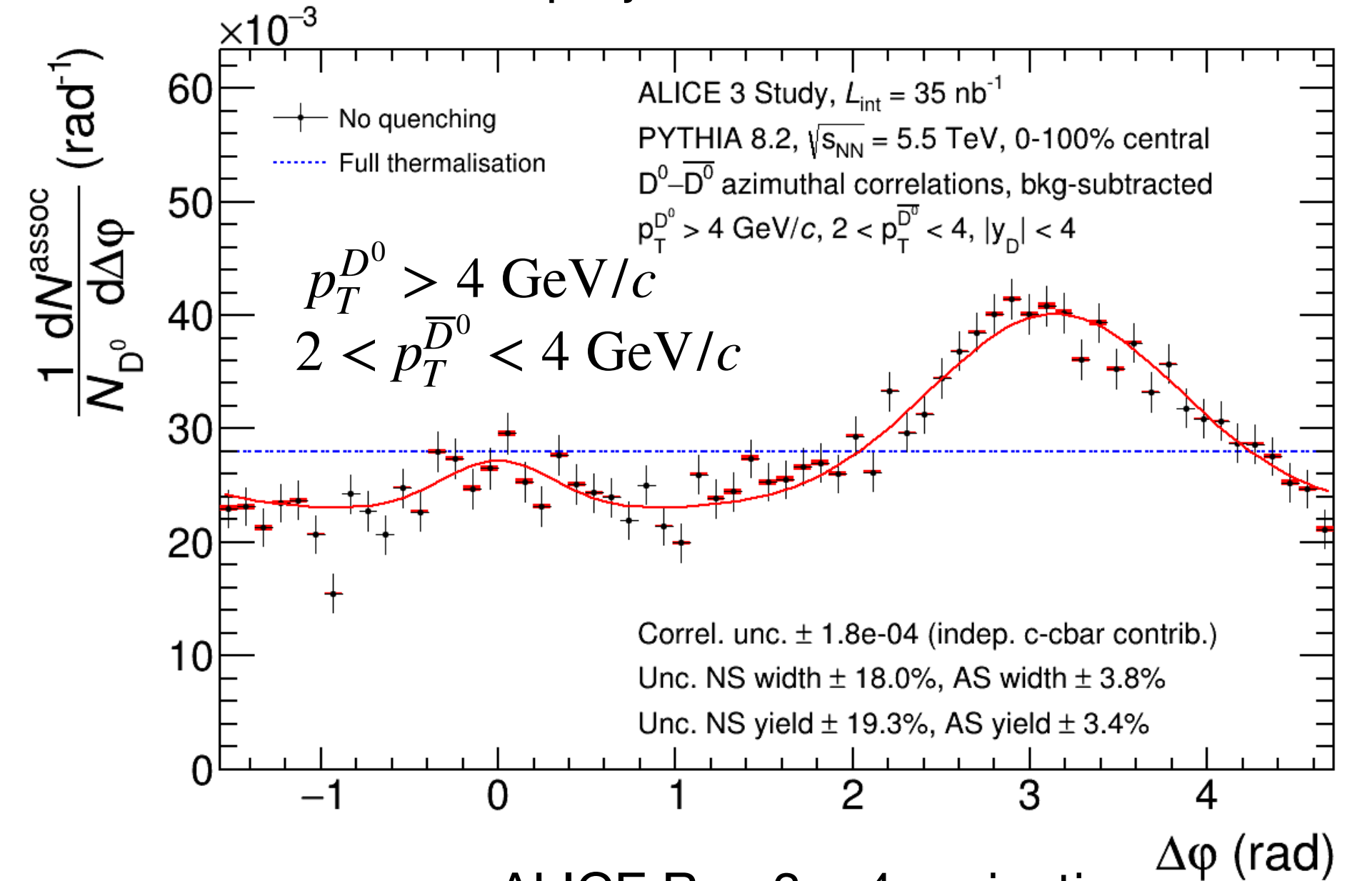


S. Cao et al., private comm.,
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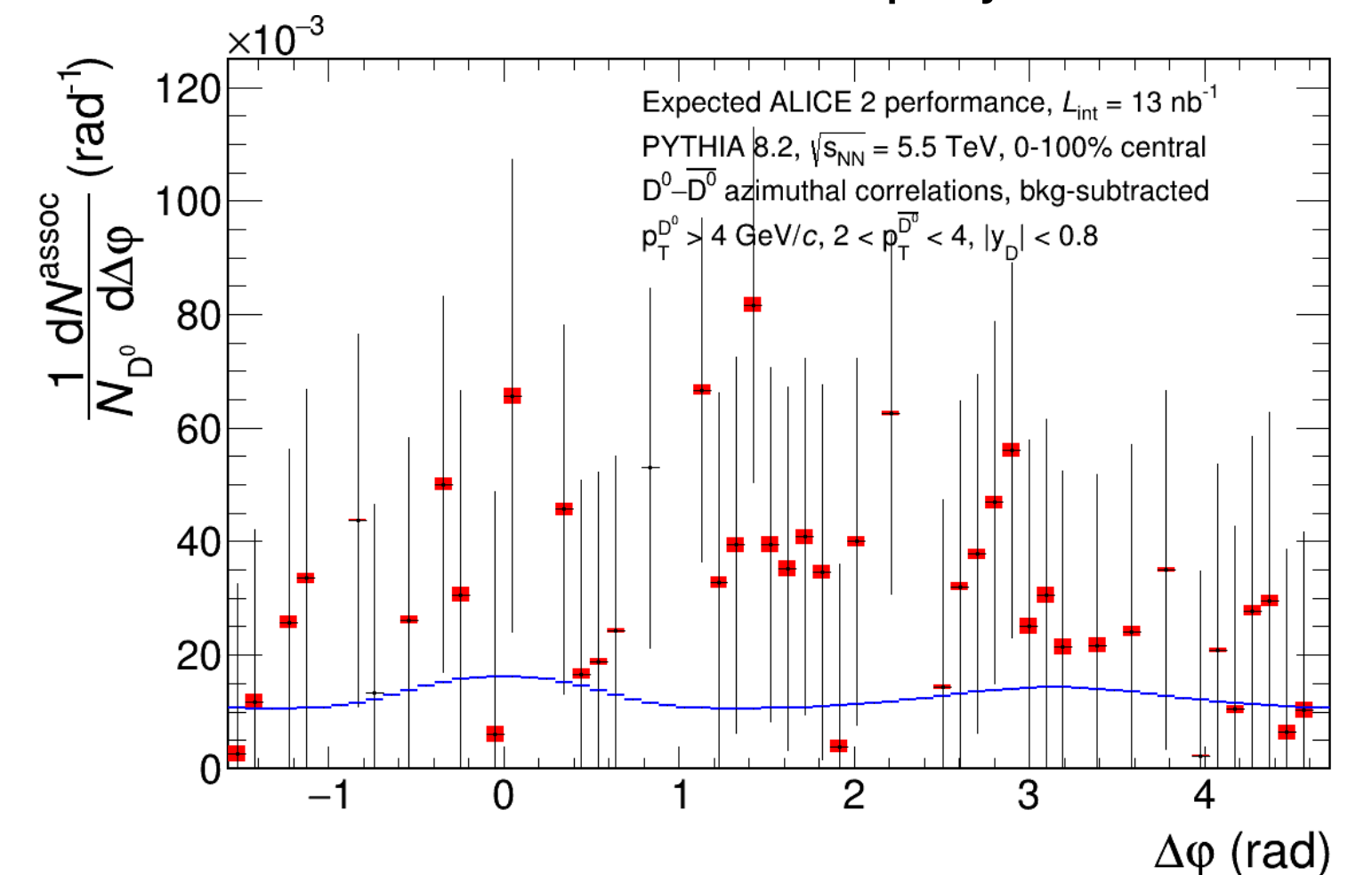


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ALICE 3 projection: $D\bar{D}$ correlations

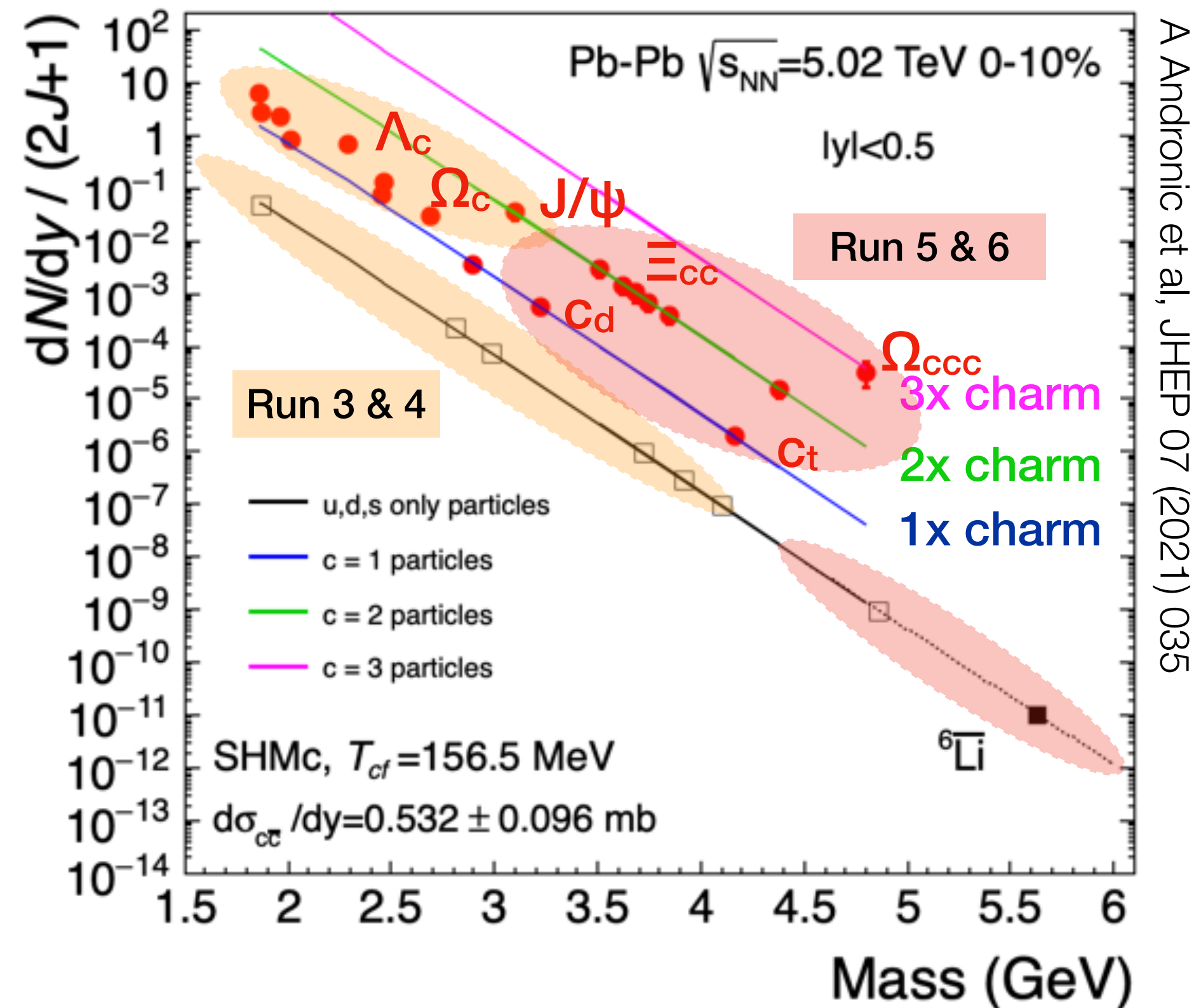


ALICE Run 3 + 4 projection

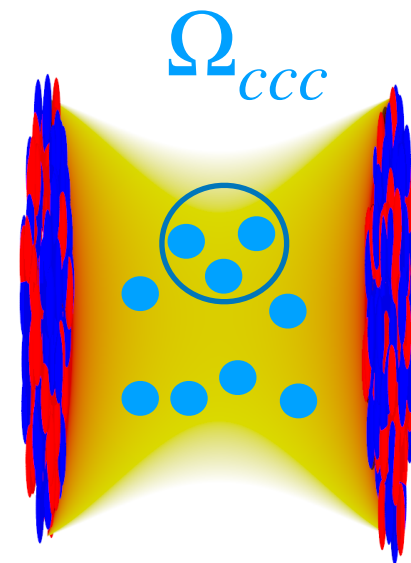


Hadron formation: multi-HF hadrons

Yield vs mass



A Andronic et al, JHEP 07 (2021) 035



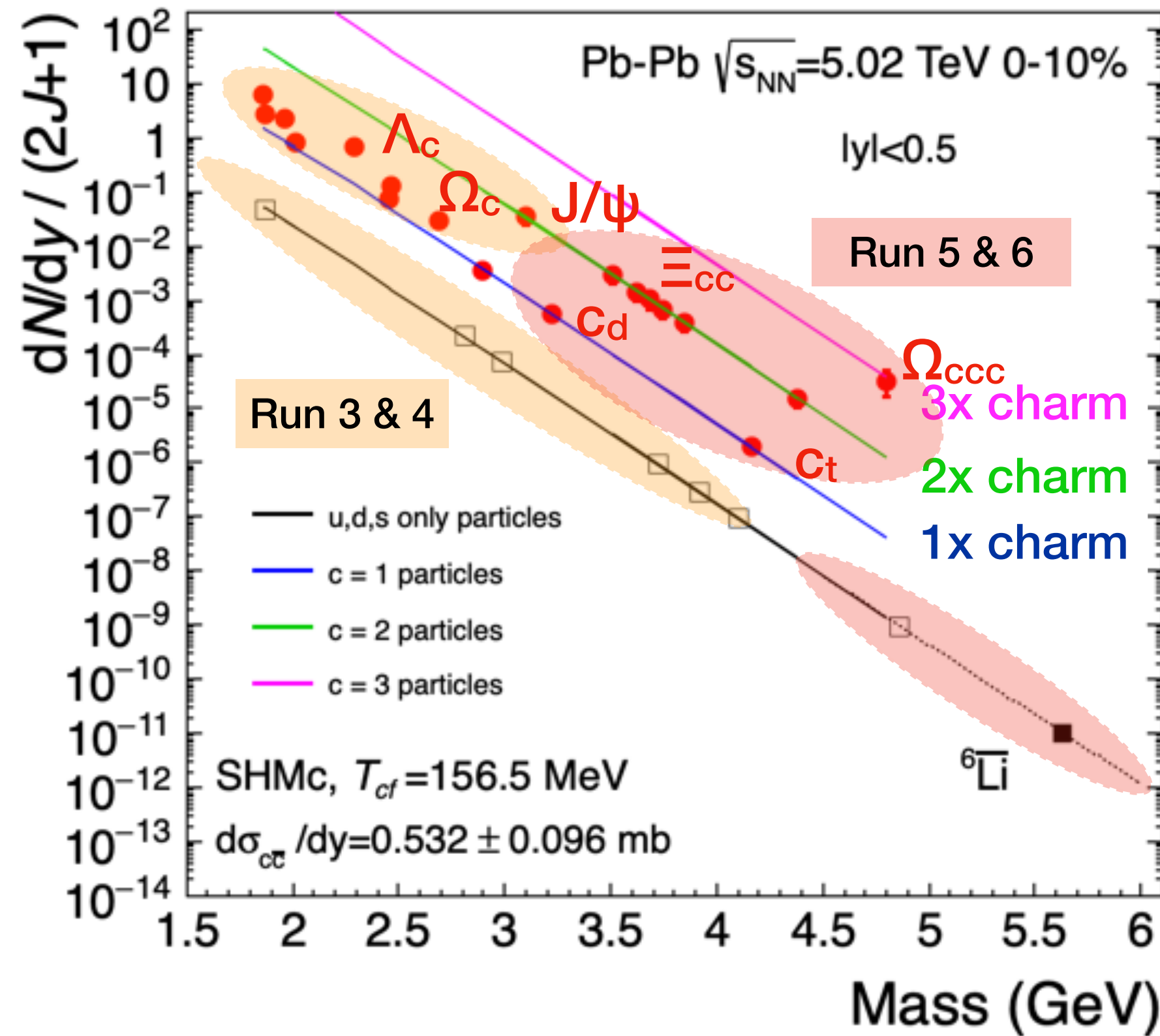
Multi-charm baryons: unique probe of hadron formation

Statistical hadronisation model: **very large enhancement** in AA

- Specific relation between yields: g_c^n for n -charm states

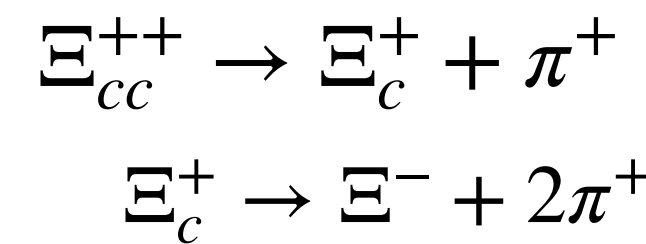
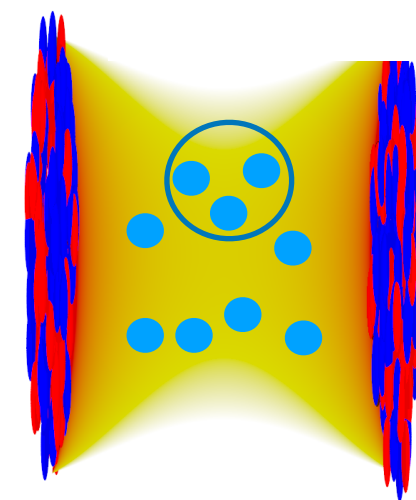
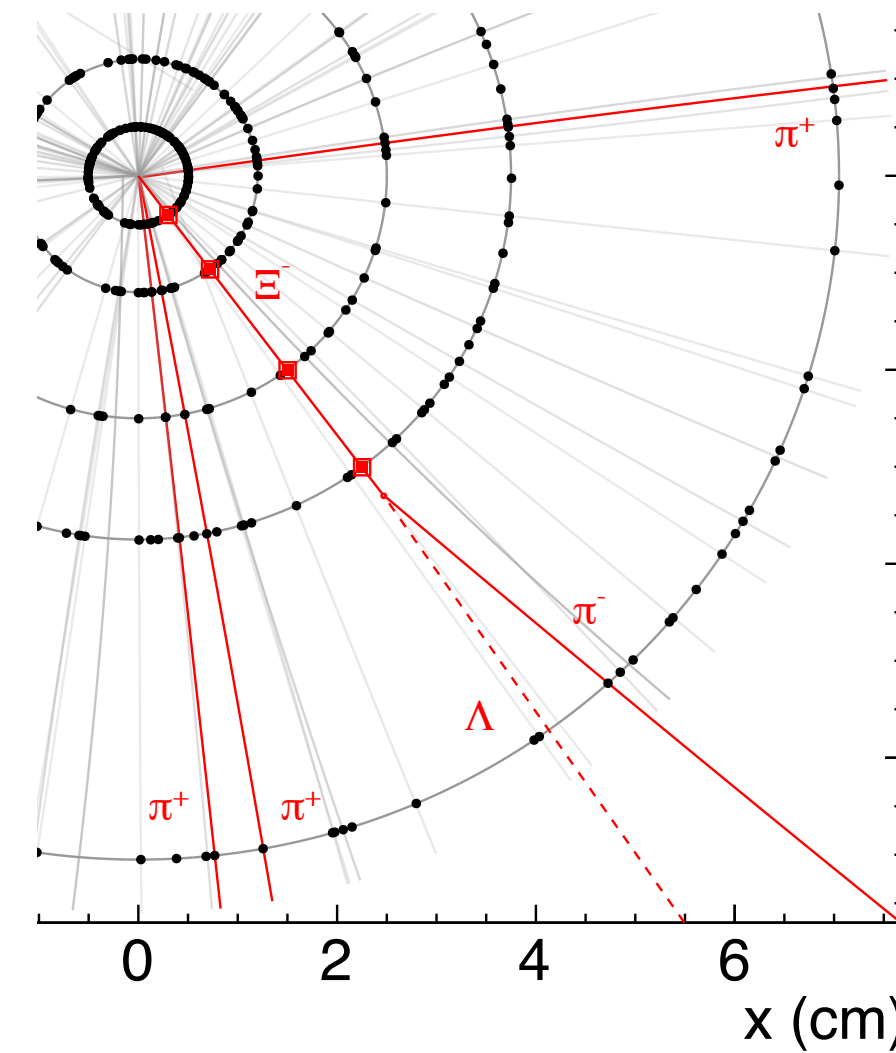
Hadron formation: multi-HF hadrons

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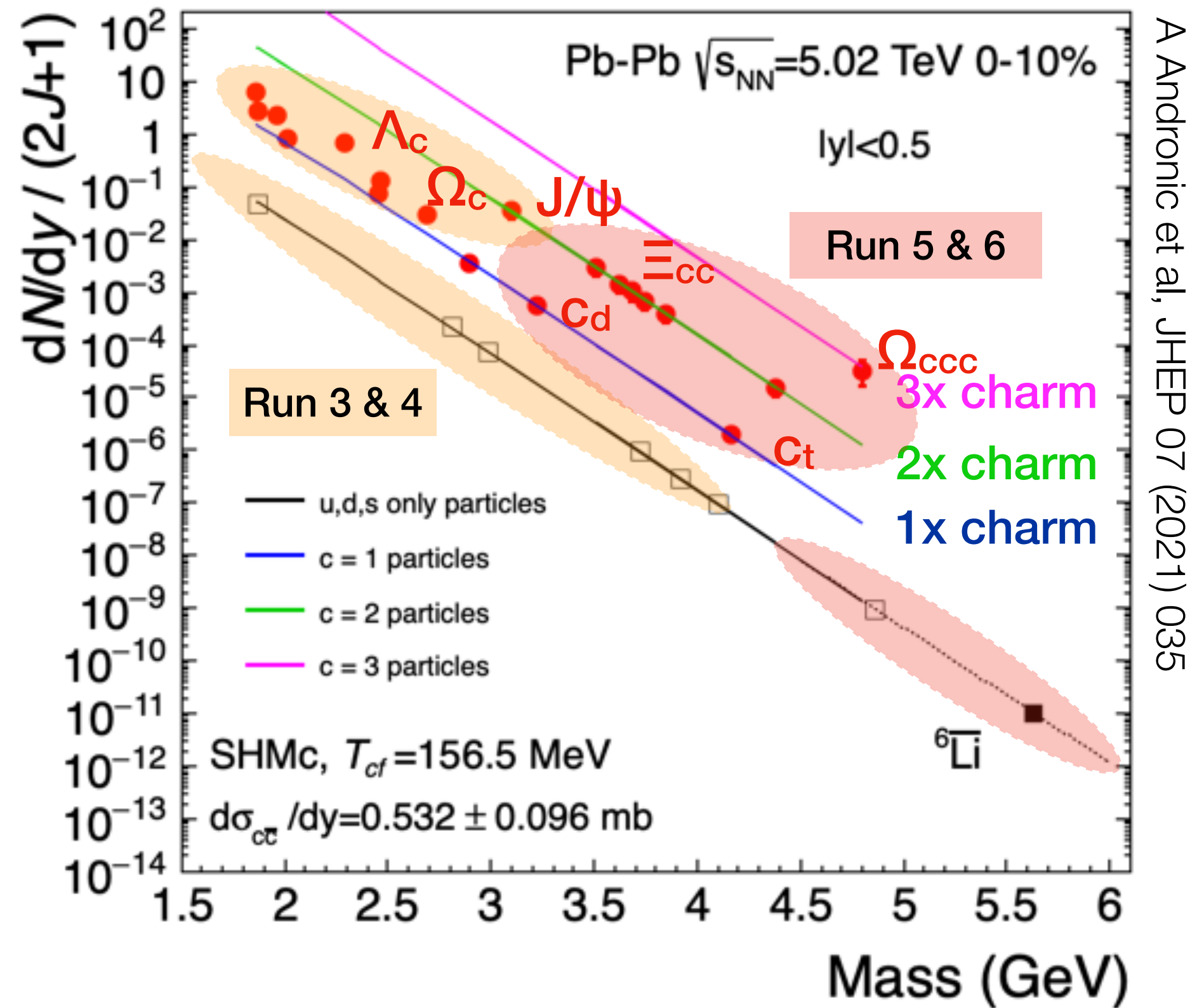
Strangeness tracking



- Multi-charm baryons: unique probe of hadron formation
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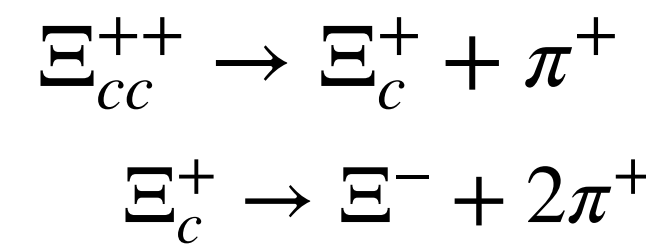
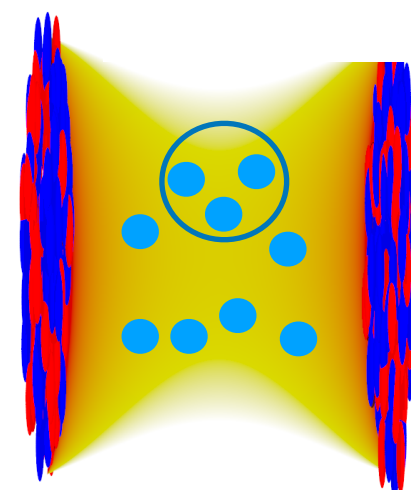
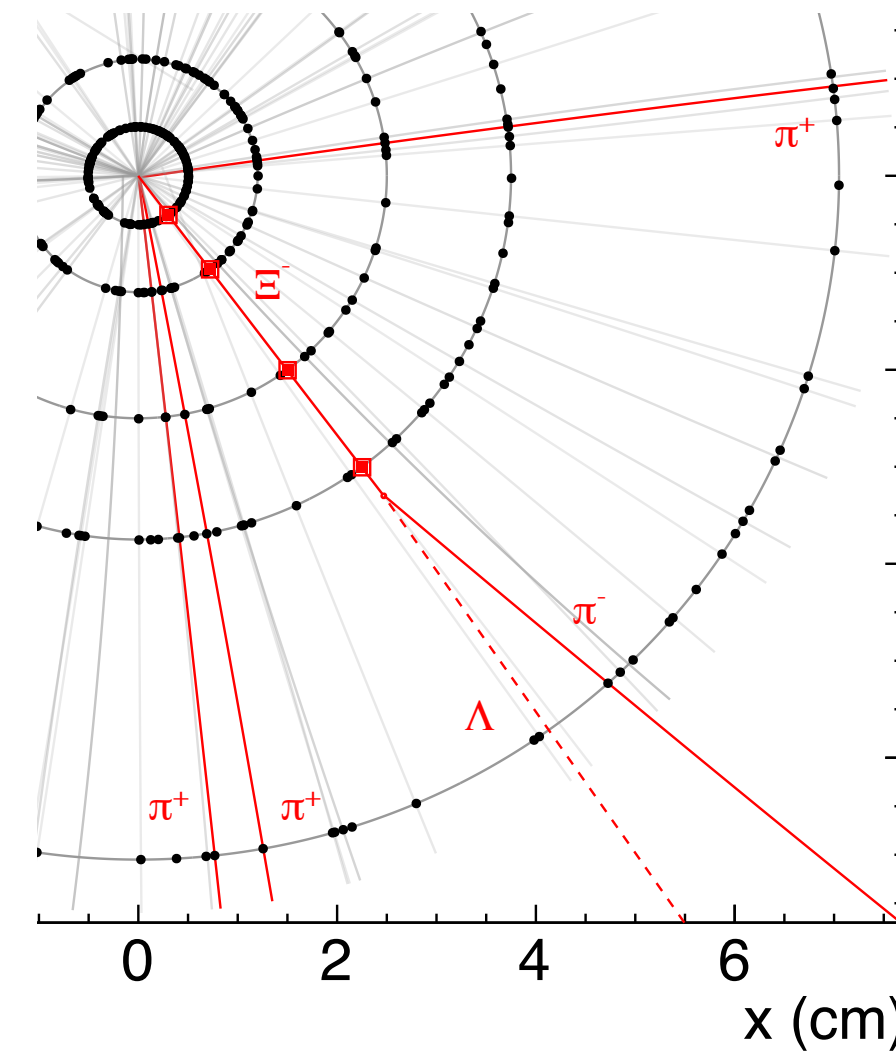
Hadron formation: multi-HF hadrons

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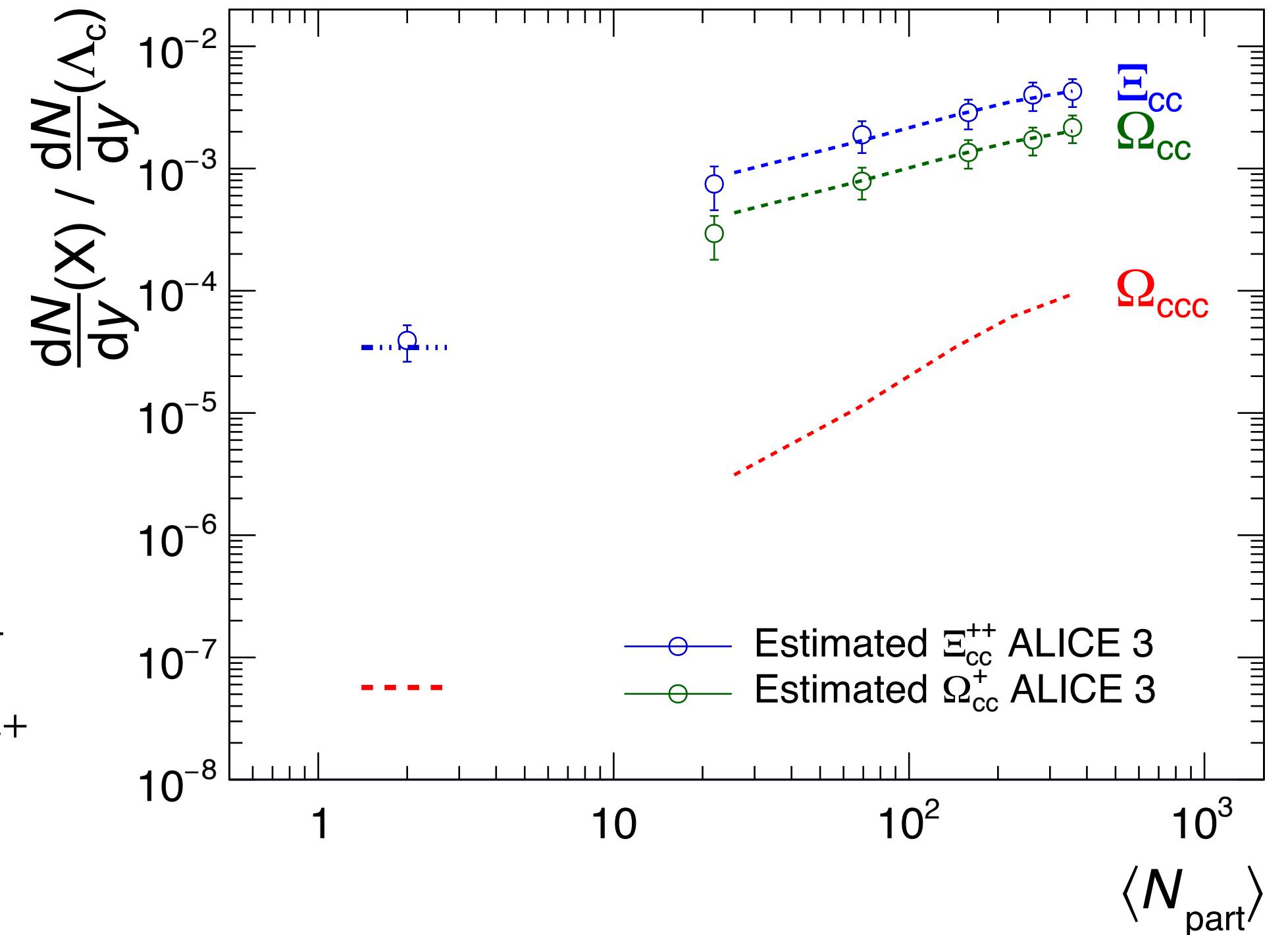


A Andronic et al, JHEP 07 (2021) 035

Strangeness tracking



----- SHM (Andronic et al, JHEP 2021, 35)
 - - - - - pQCD SPS (Chen et al, JHEP 2011, 144)
 - · - · - pQCD SPS (Phys. Rev. D 57, 4385)

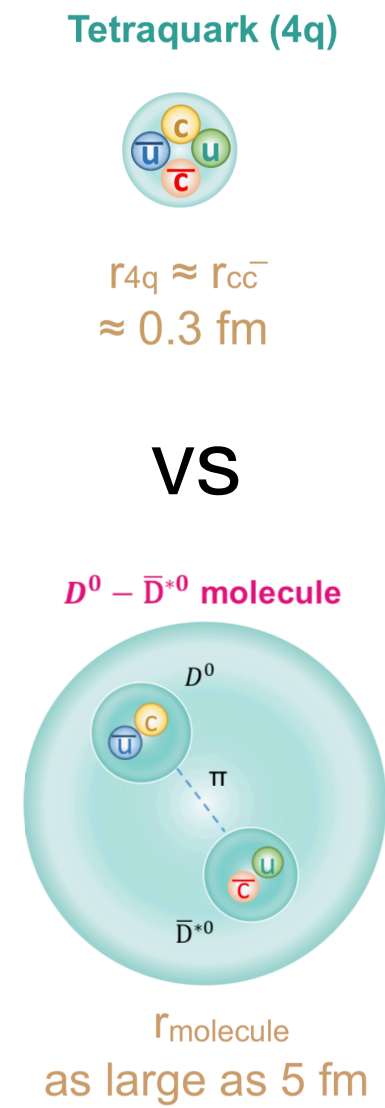
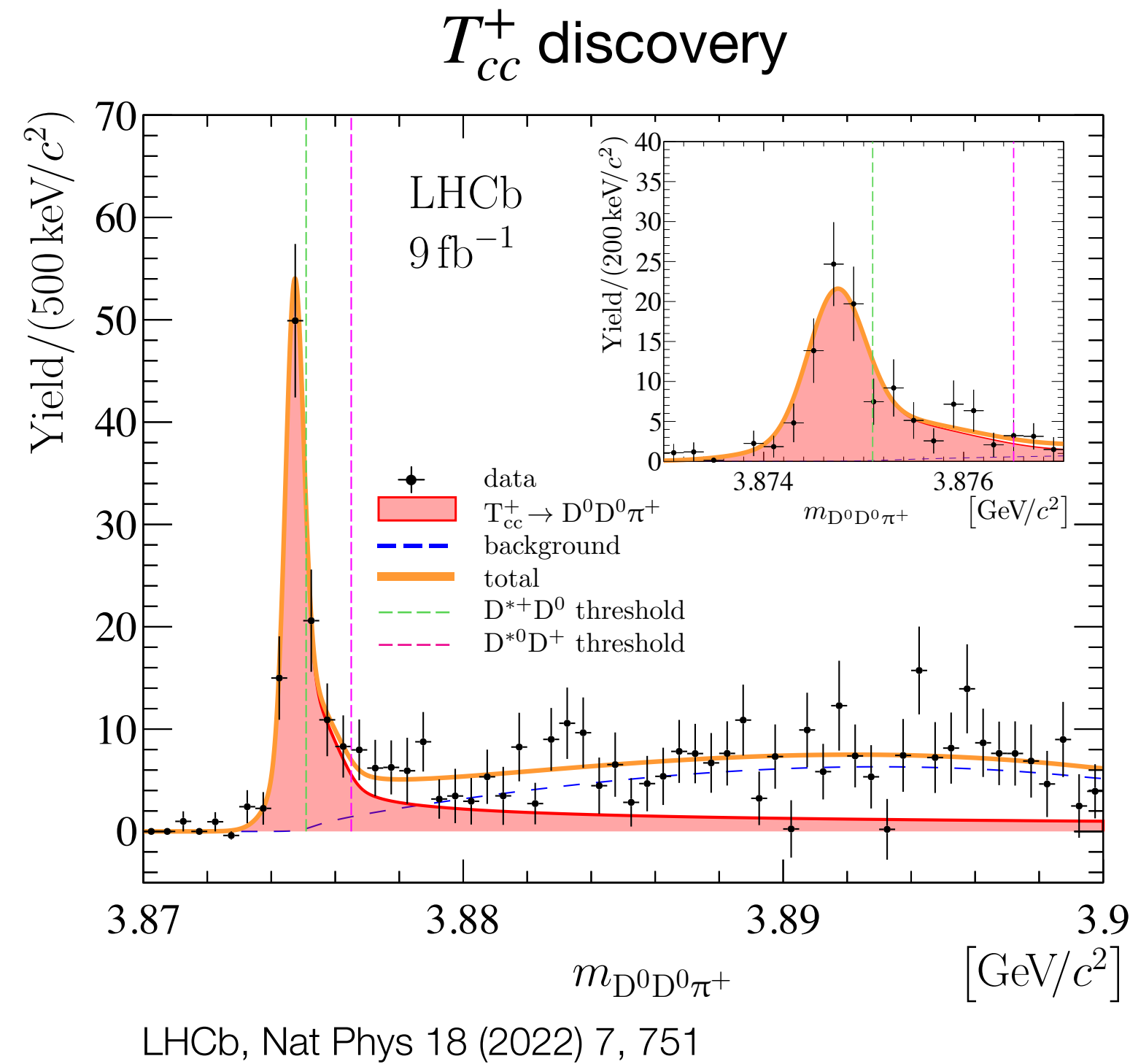


Multi-charm baryons: unique probe of hadron formation
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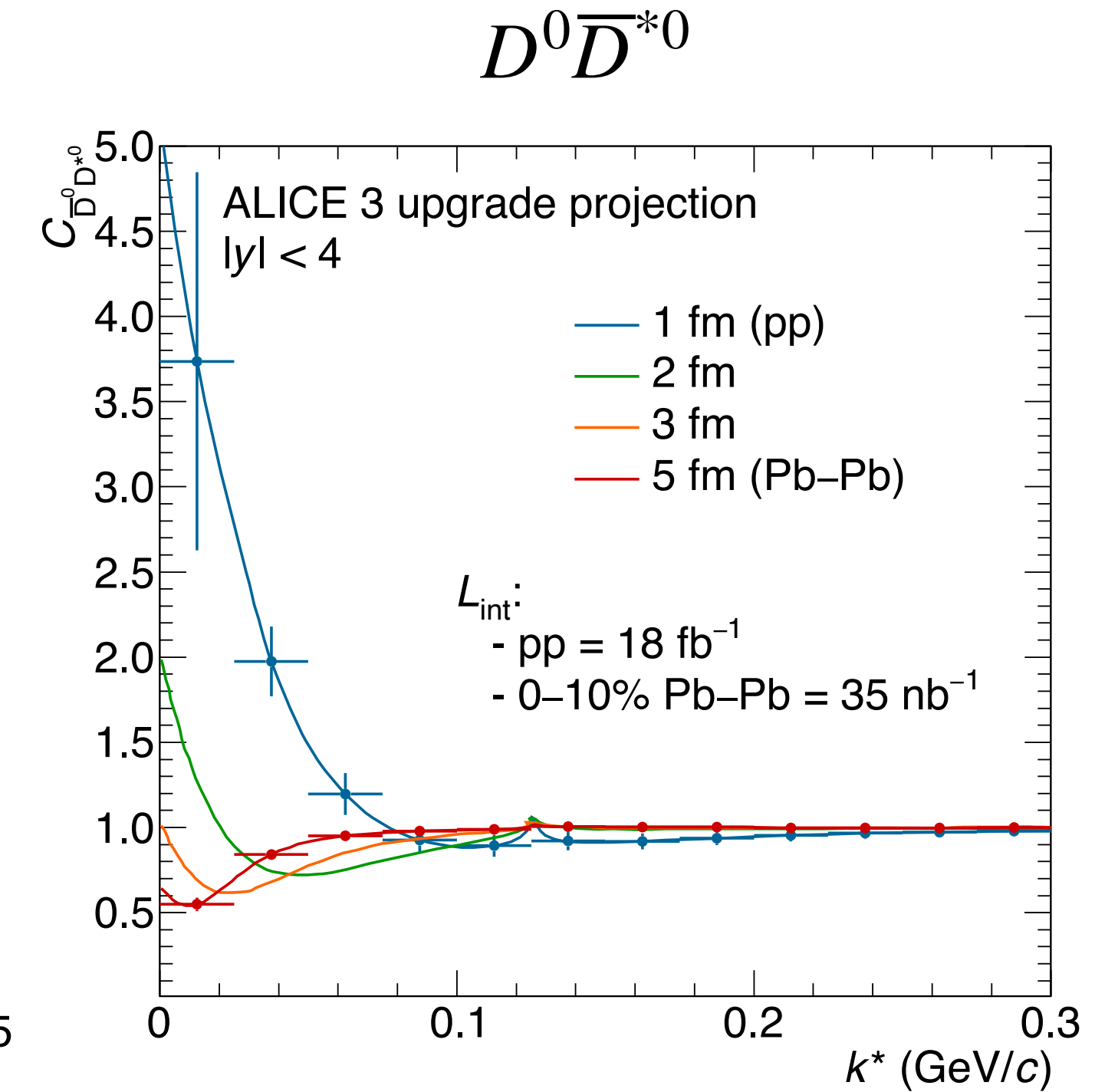
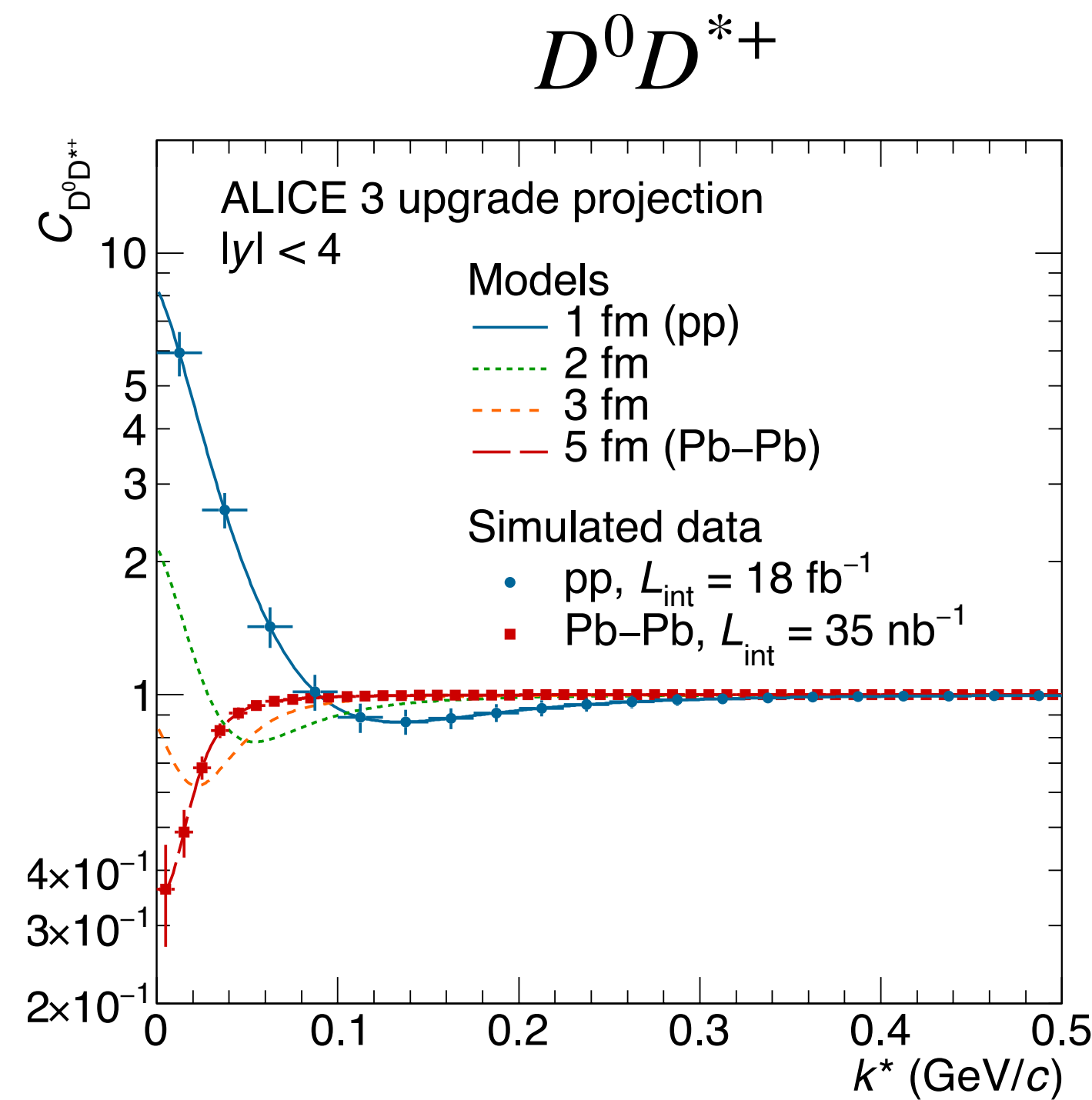
- Specific relation between yields: g_c^n for n -charm states

ALICE 3: unique experimental access to multi-charm baryons

Heavy-ion collisions as a laboratory for hadron physics



DD* momentum correlation



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

$D^0 \bar{D}^{*0}$: nature of $\chi_{c1}(3872)$

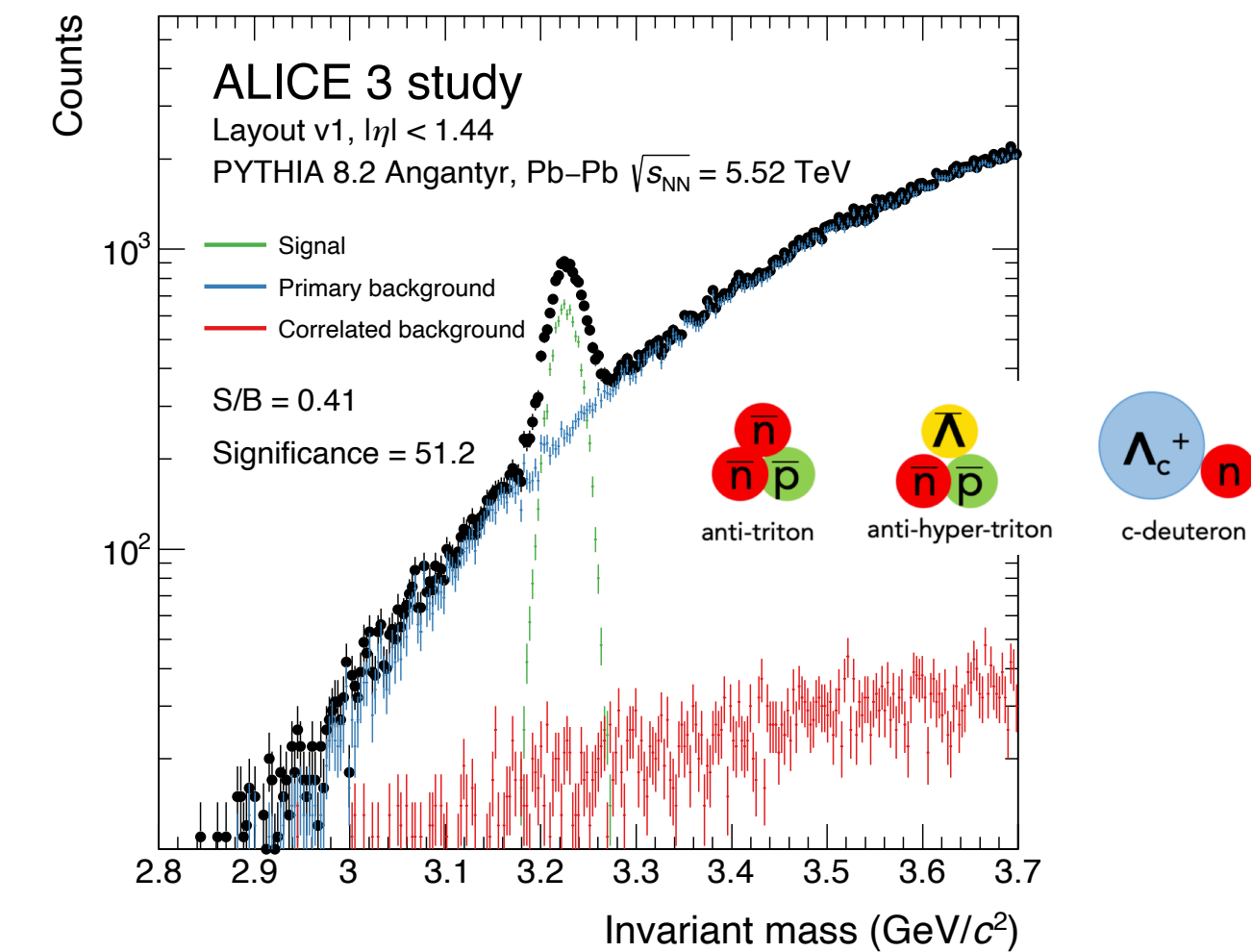
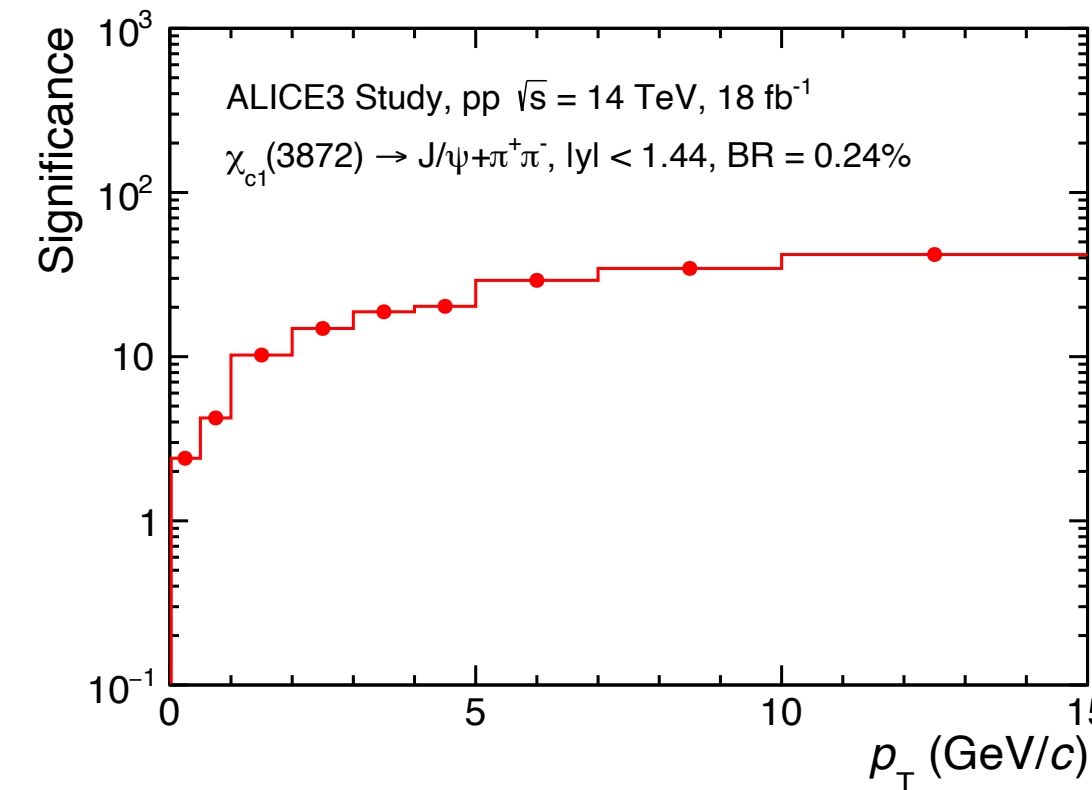
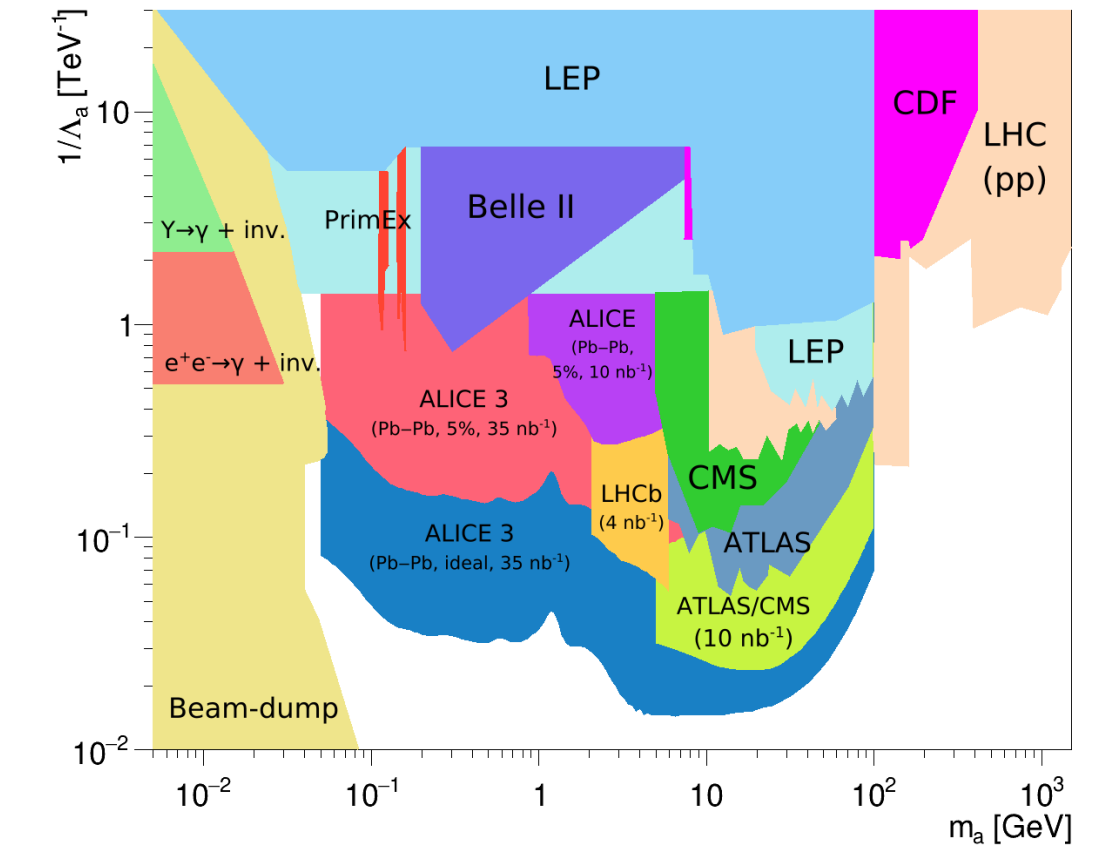
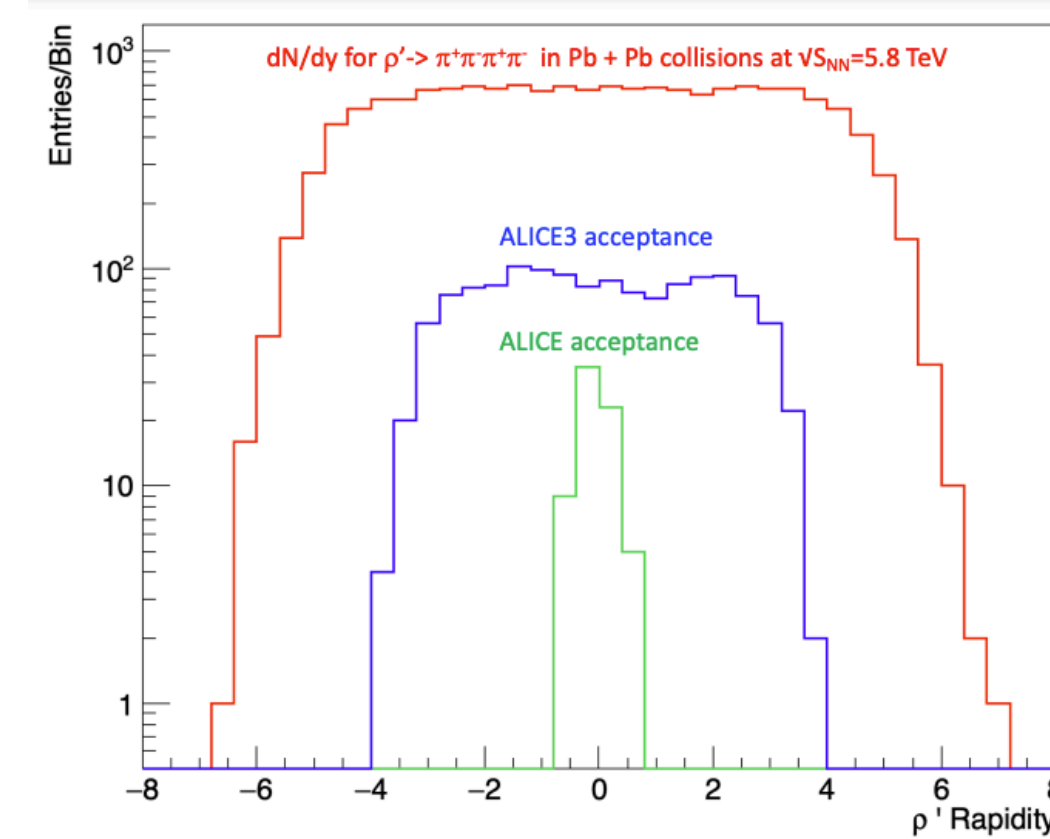
- Several exotic heavy flavour states identified
- Loosely bound meson molecule or tightly bound tetraquark?
- Study binding potential with final state interactions ‘femtoscopic correlations’

Bound states produce specific pattern vs system size

Other physics topics

- Susceptibility of the QGP: net-baryon fluctuations
- Resonance production in Ultra-peripheral collisions
- ALP search in $\gamma\gamma$
- Measurements of χ_c, χ_{c1}
- Production of nuclei in $\bar{\Lambda}_b \rightarrow {}^3\bar{H}e$ decays
- Search for charm-nuclei
- Ultra-soft photons: Low's theorem

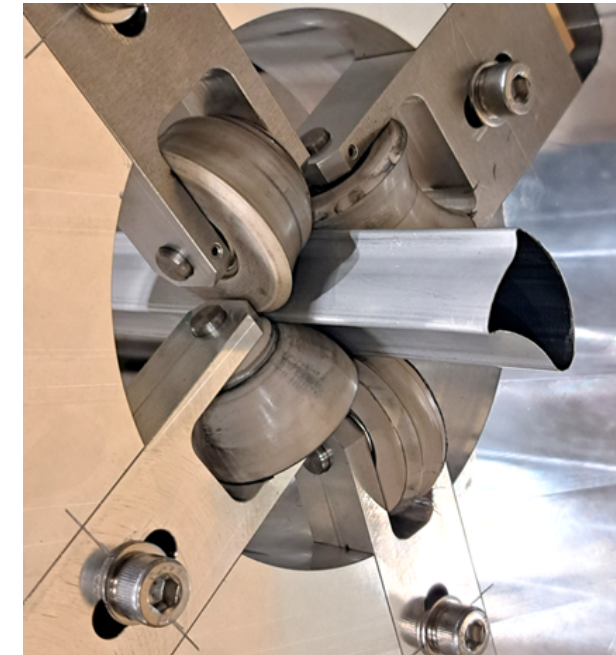
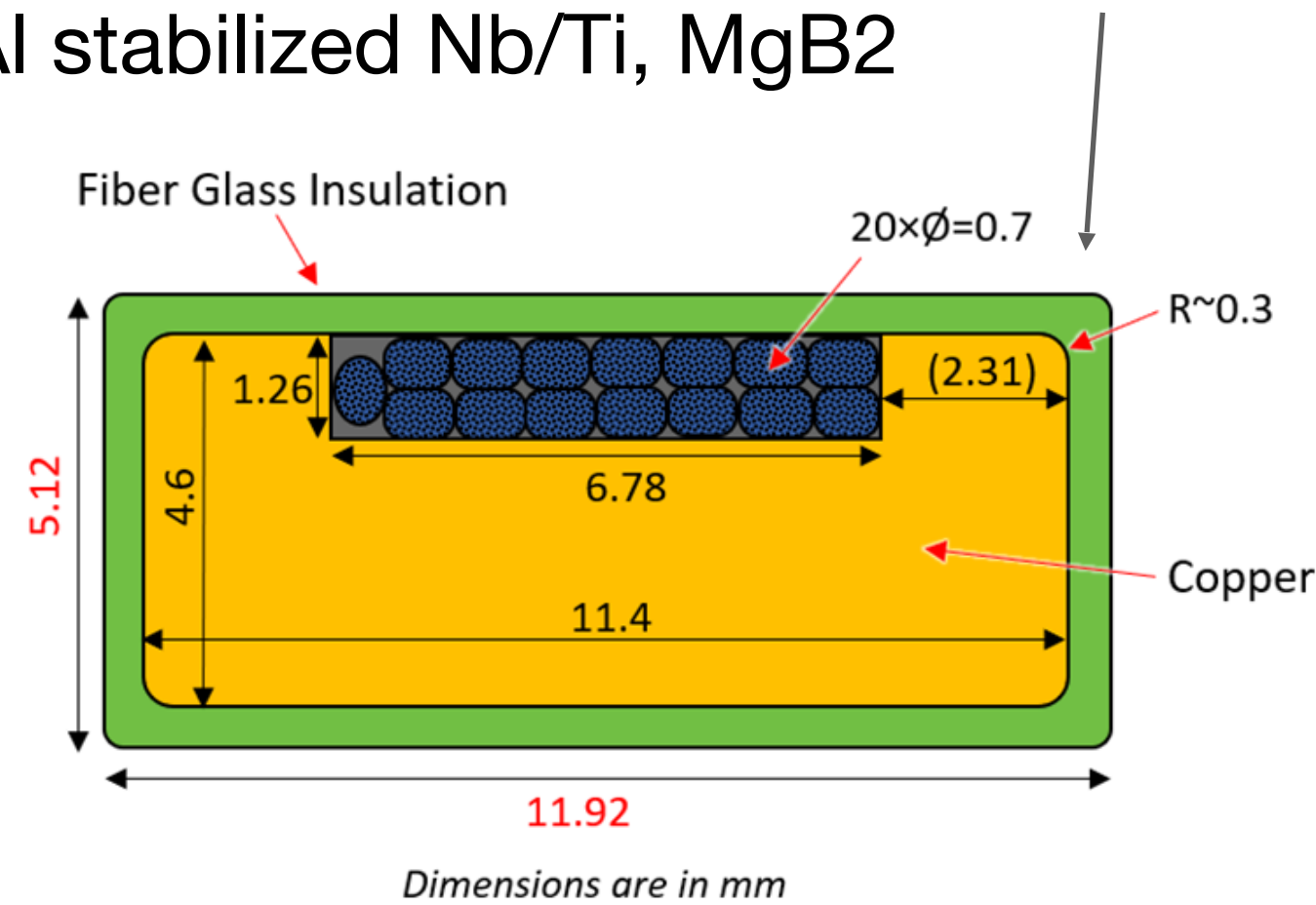
See ALICE 3 Lol for details: [CERN-LHCC-2022-009](https://cds.cern.ch/record/2811000)



ALICE 3 R&D

Superconducting magnet

- Design
- SC cable options: Cu stabilized Nb/Ti, Al stabilized Nb/Ti, MgB2

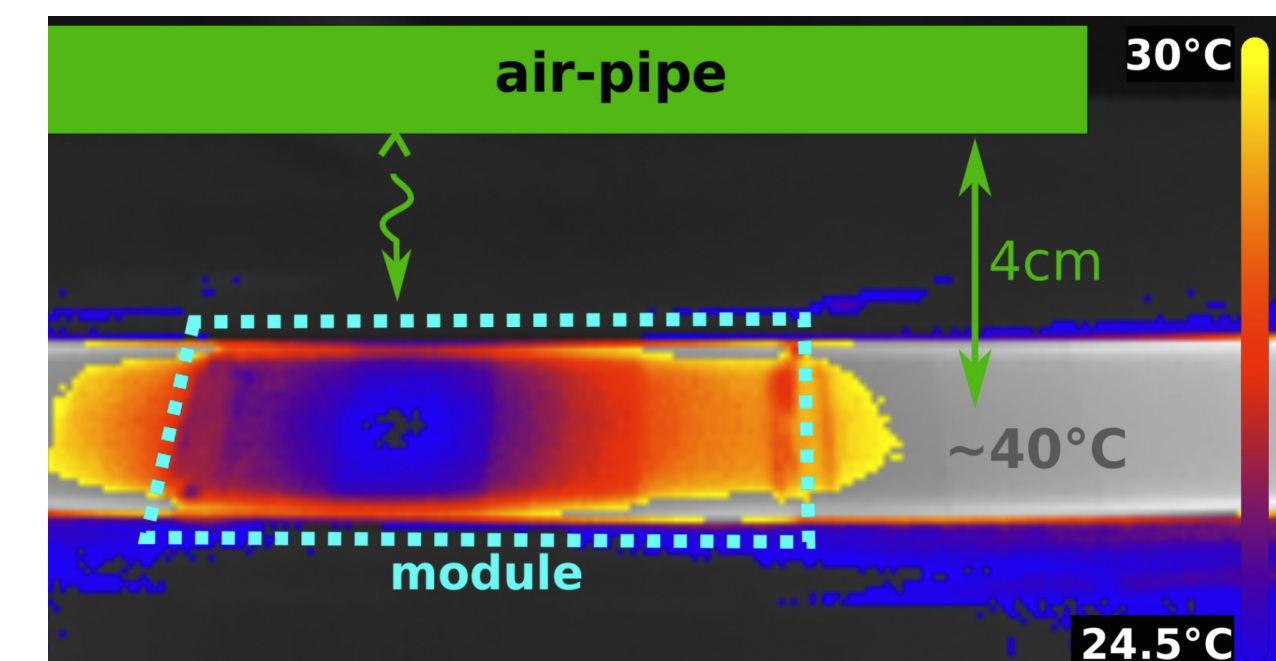
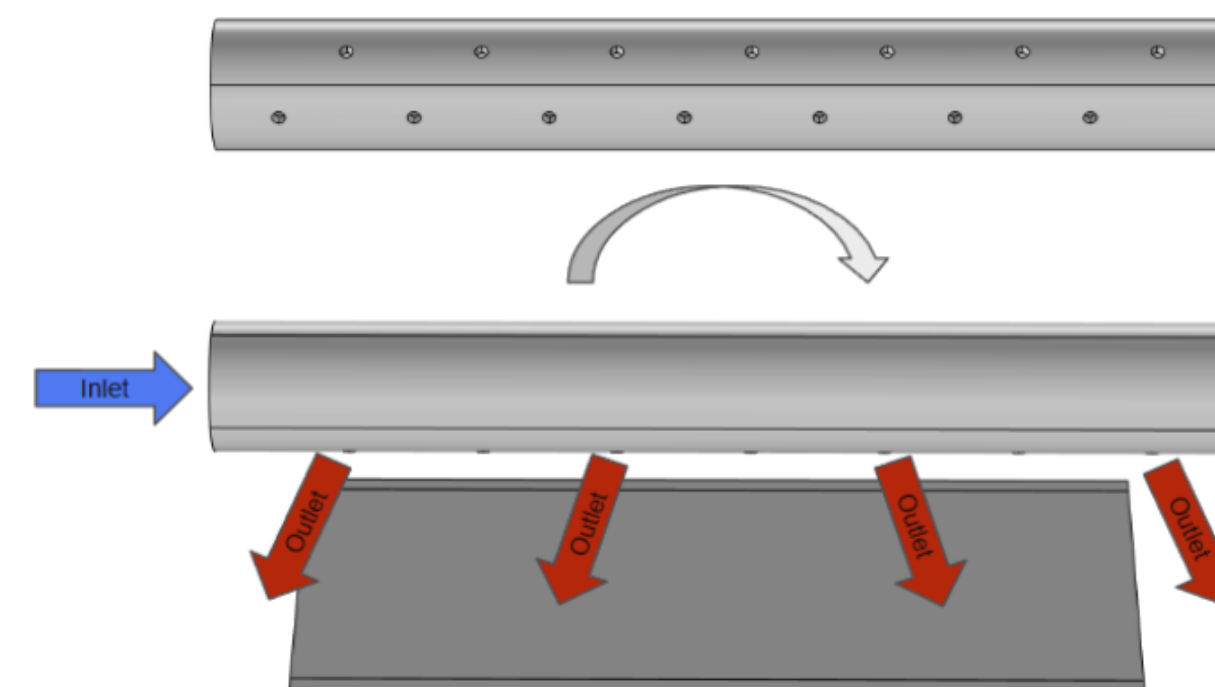
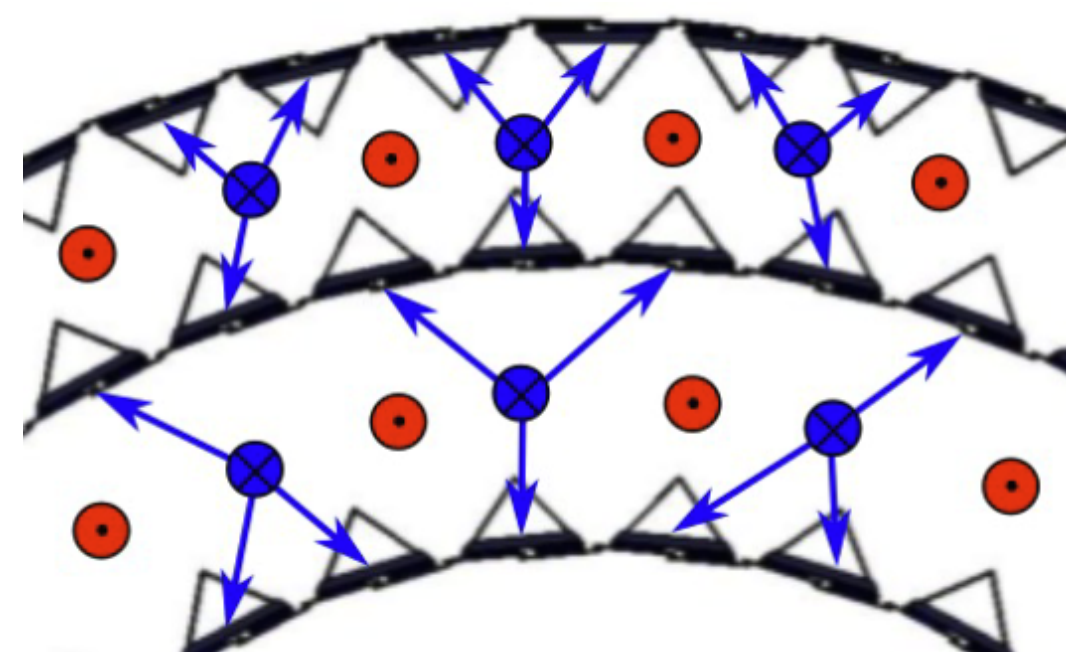


Inner Tracker

- vertex IRIS retractable system: mock-ups of petals and rotation system, primary and secondary vacuum systems design CO₂ cooling studies
- middle layers: module design, ultra-light version with stitched sensor

Outer Tracker

Module, stave and barrel design, air cooling system, module assembly for industrial production

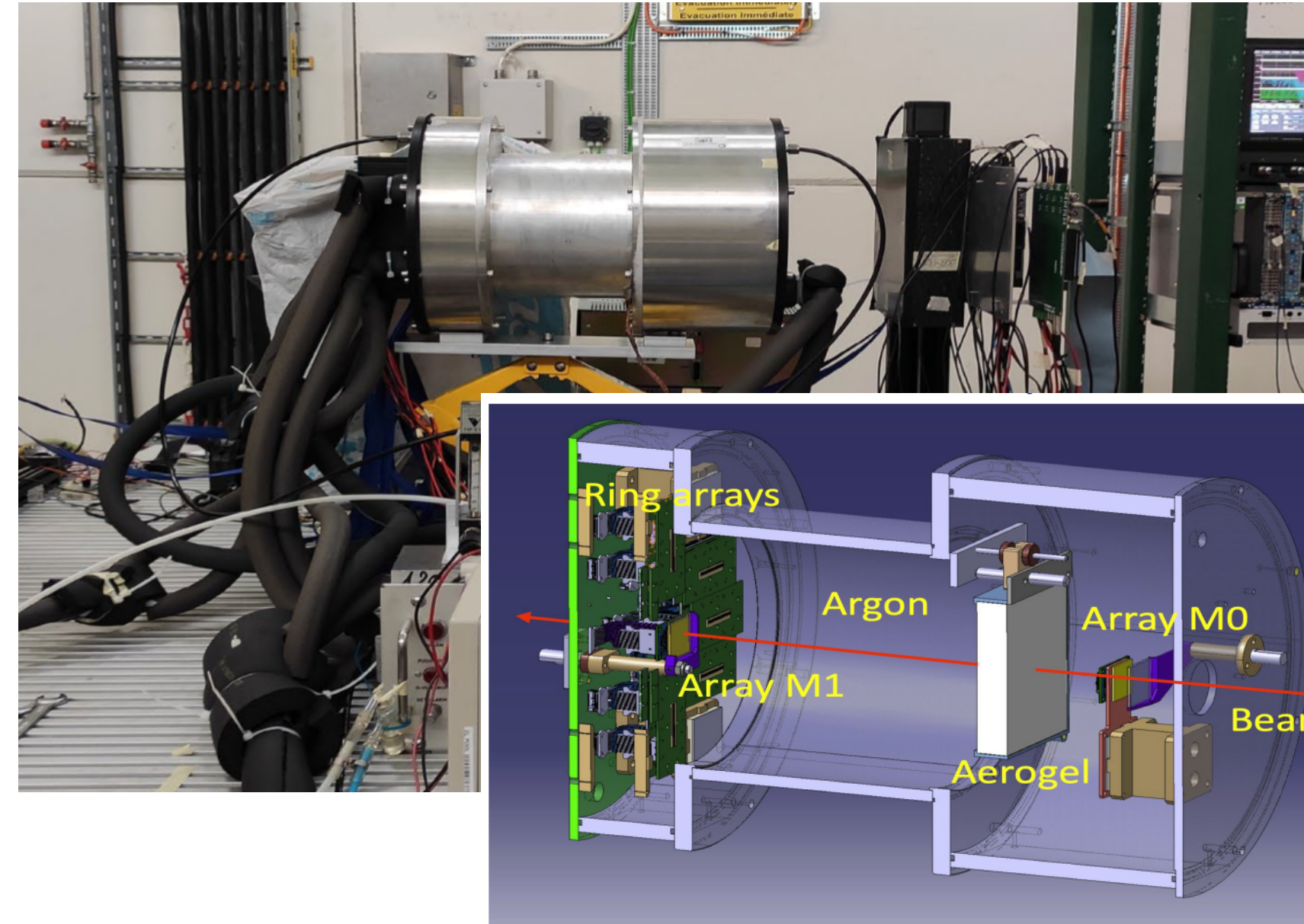
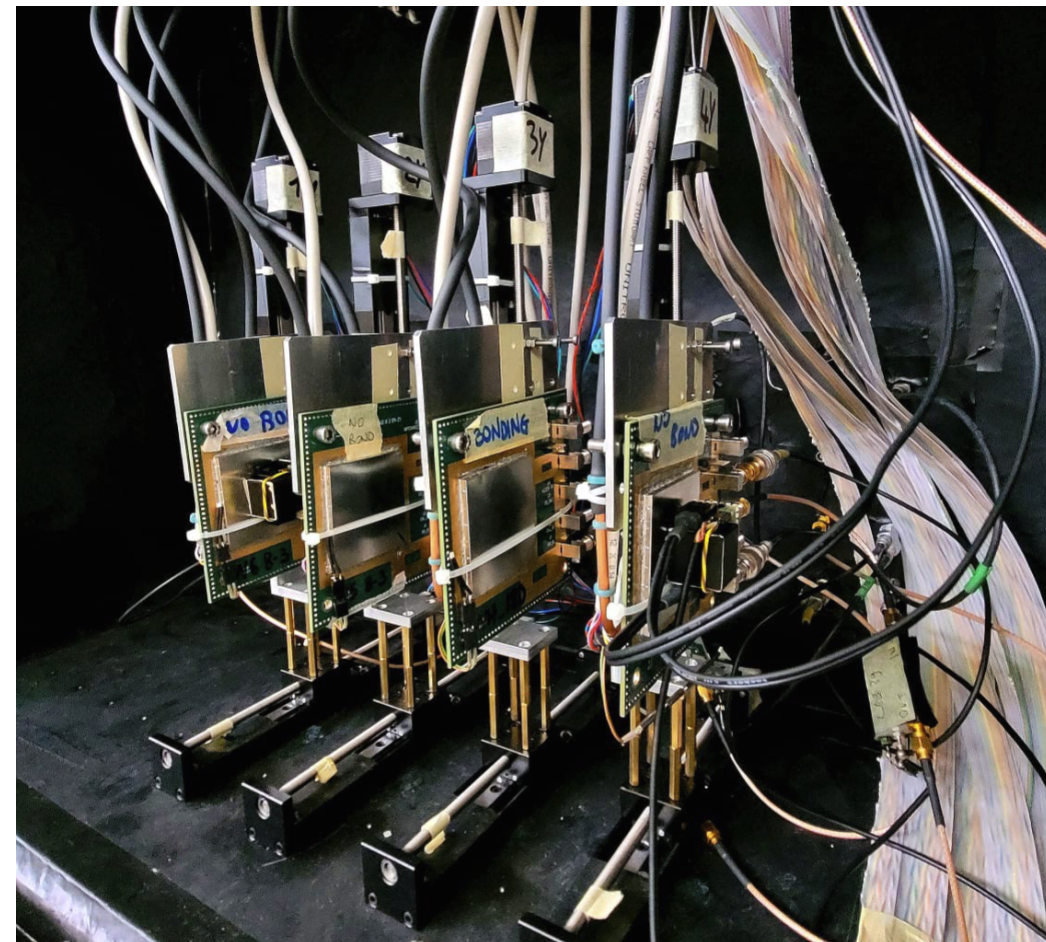
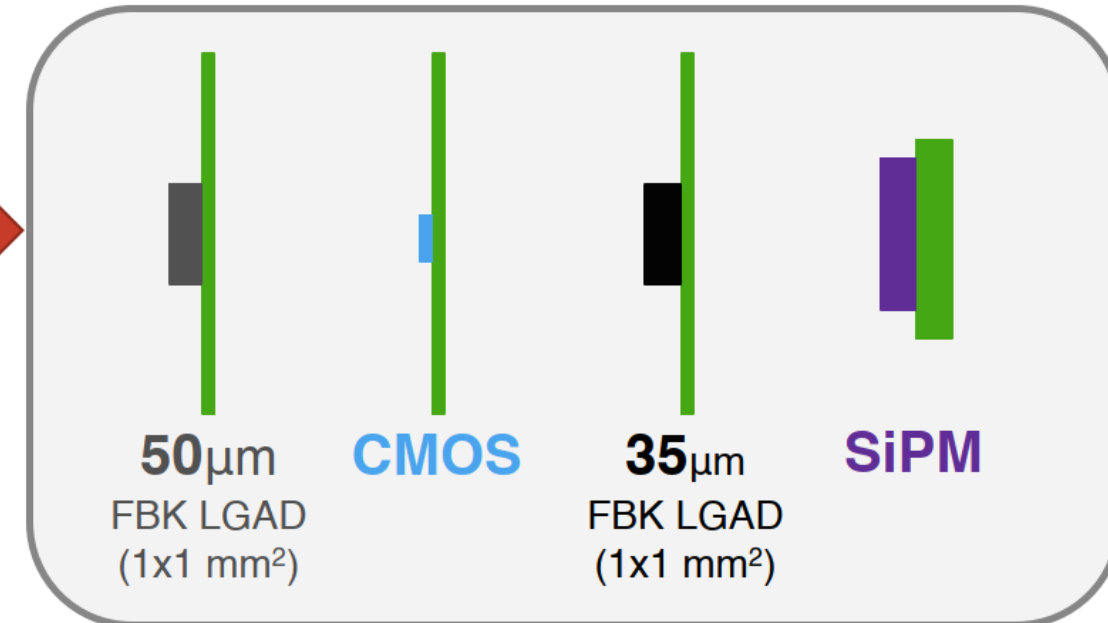


ALICE 3 R&D

TOF

sensor technologies under study:

- hybrid LGAD
- monolithic CMOS LGAD
- SiPM



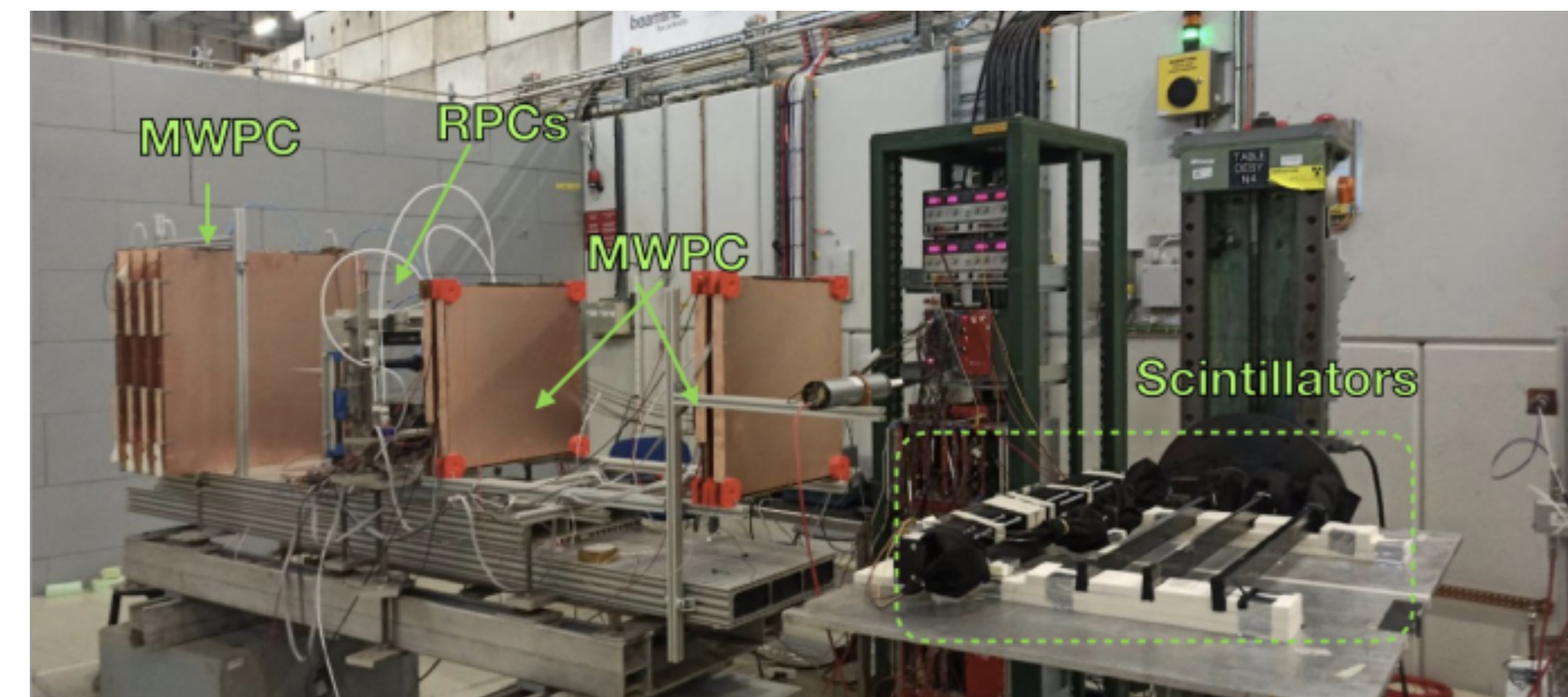
RICH

- aerogel Cherenkov radiator
- SiPM radiation hardness
- SiPM timing properties for MIP detection (combined TOF measurement)

MID

technologies under study:

- scintillators + SiPM
- multi-wire chambers
- resistive plate chambers



Summary

- Run 3 data taking: large data samples, improved momentum resolution open new physics opportunities
- LS3 upgrades: ITS3 and FoCal progressing well
- ALICE 3: unique physics program enabled by
 - Excellent pointing resolution
 - Increased rapidity coverage and rate
 - Excellent PID

An interesting and productive week ahead!

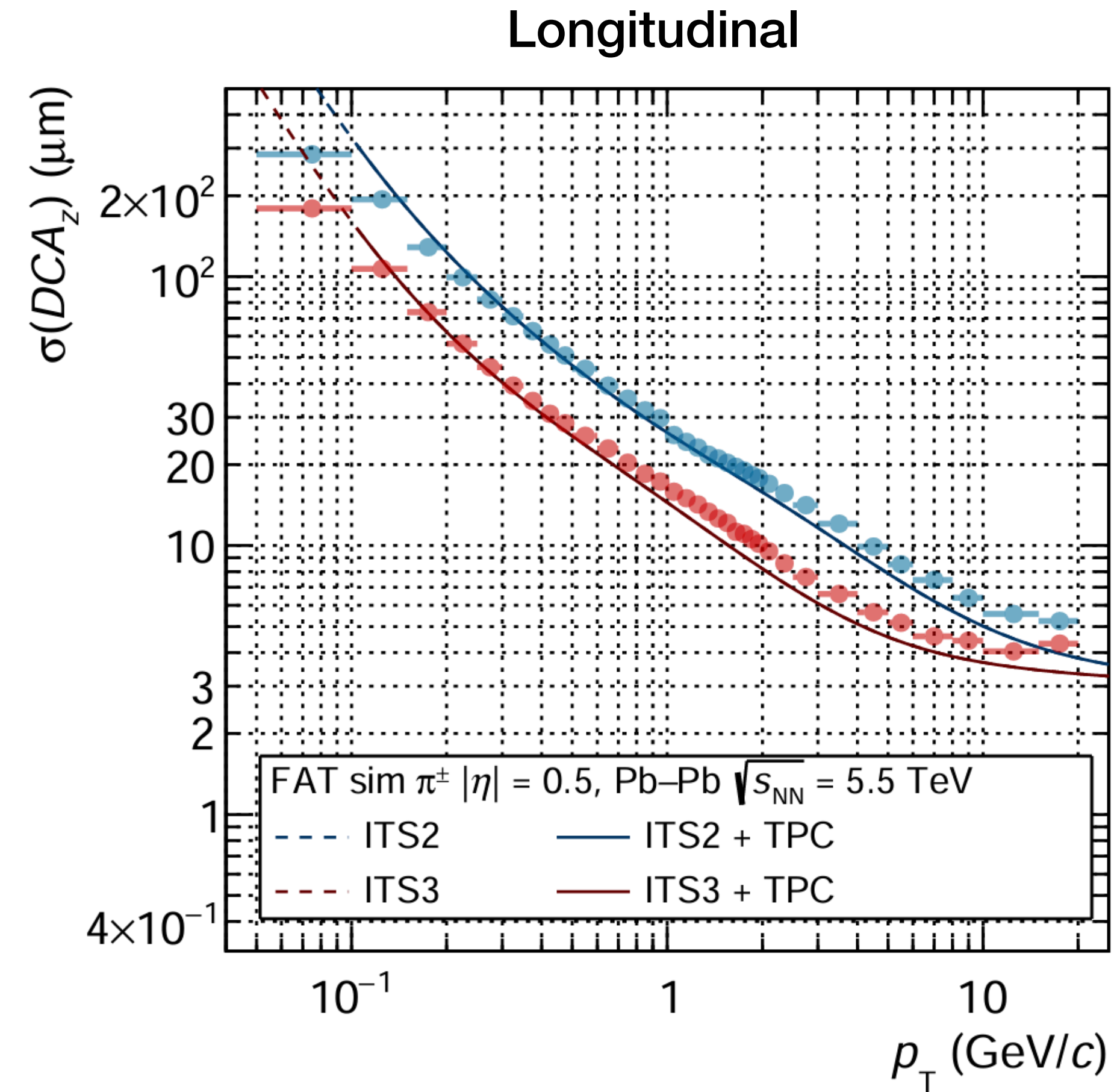
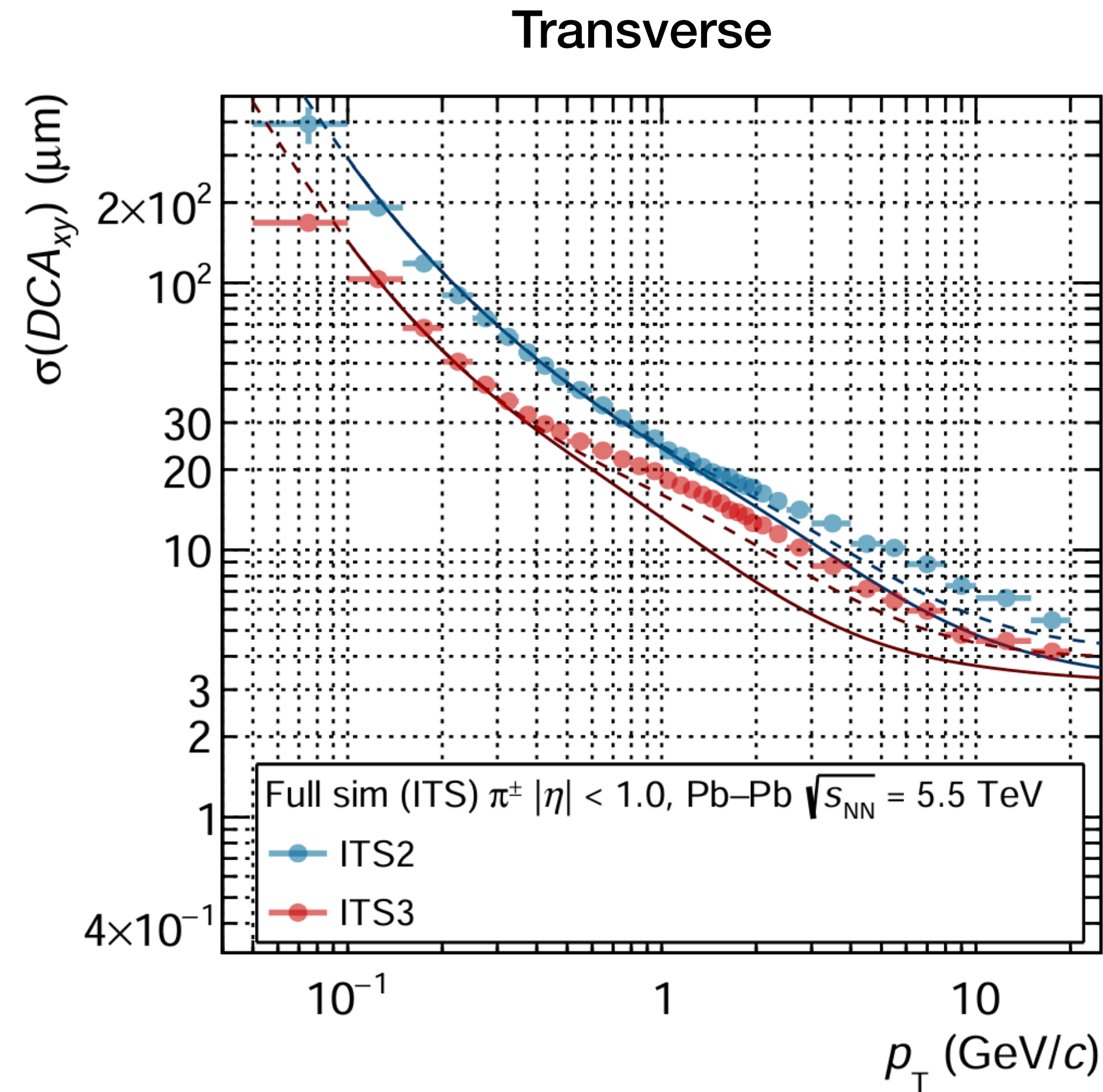
Summary

- Run 3 data taking: large data samples, improved momentum resolution open new physics opportunities
 - LS3 upgrades: ITS3 and FoCal progressing well
 - ALICE 3: unique physics program enabled by
 - Excellent pointing resolution
 - Increased rapidity coverage and rate
 - Excellent PID
- Upgrade events in 2025:
- ALICE 3 Days, 17-19 February
 - ALICE 3 Days, 19-21 May
 - Upgrade week, 29 Sept-3 Oct

An interesting and productive week ahead!

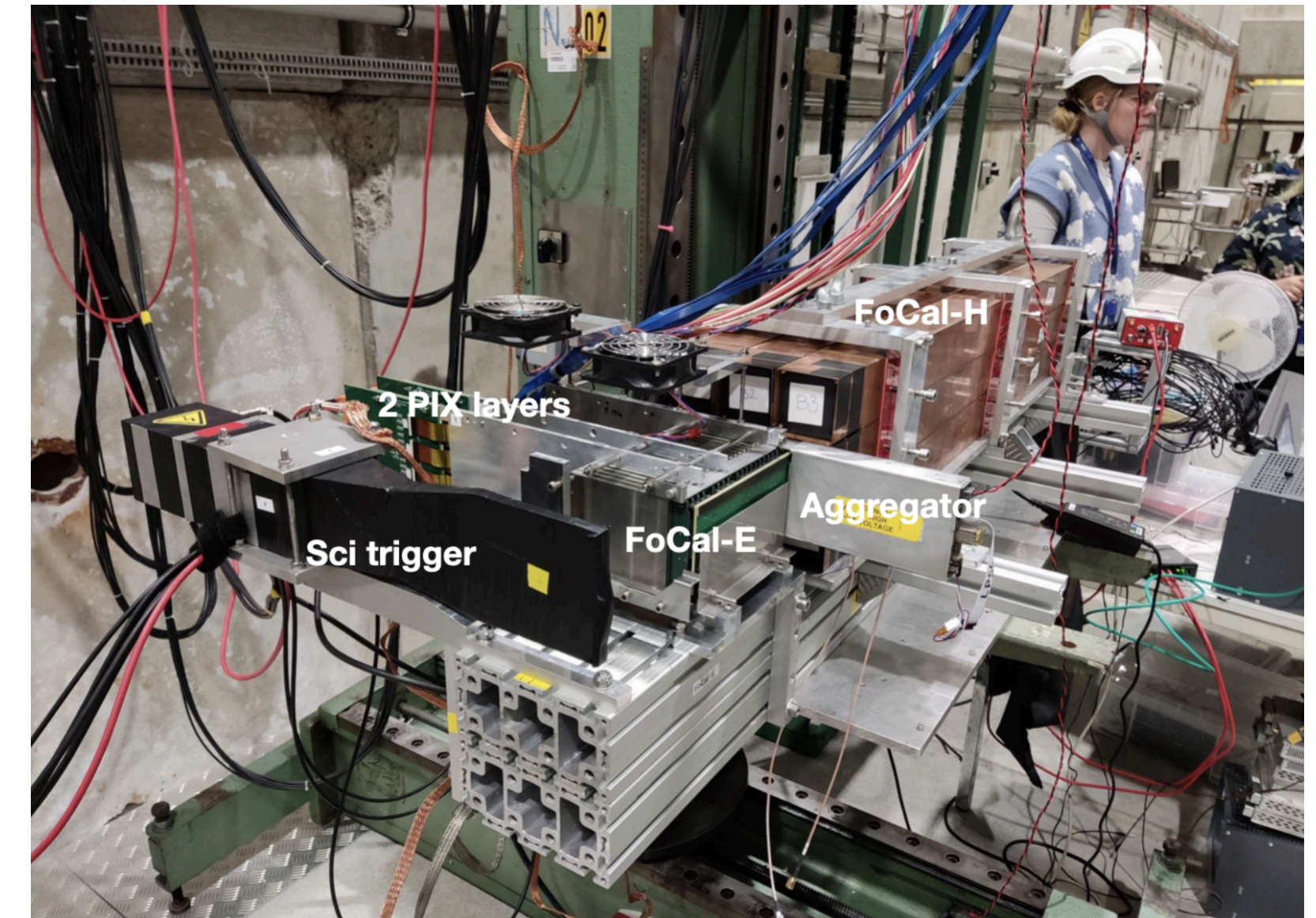
Thank you for your attention

ITS3 impact parameter resolution

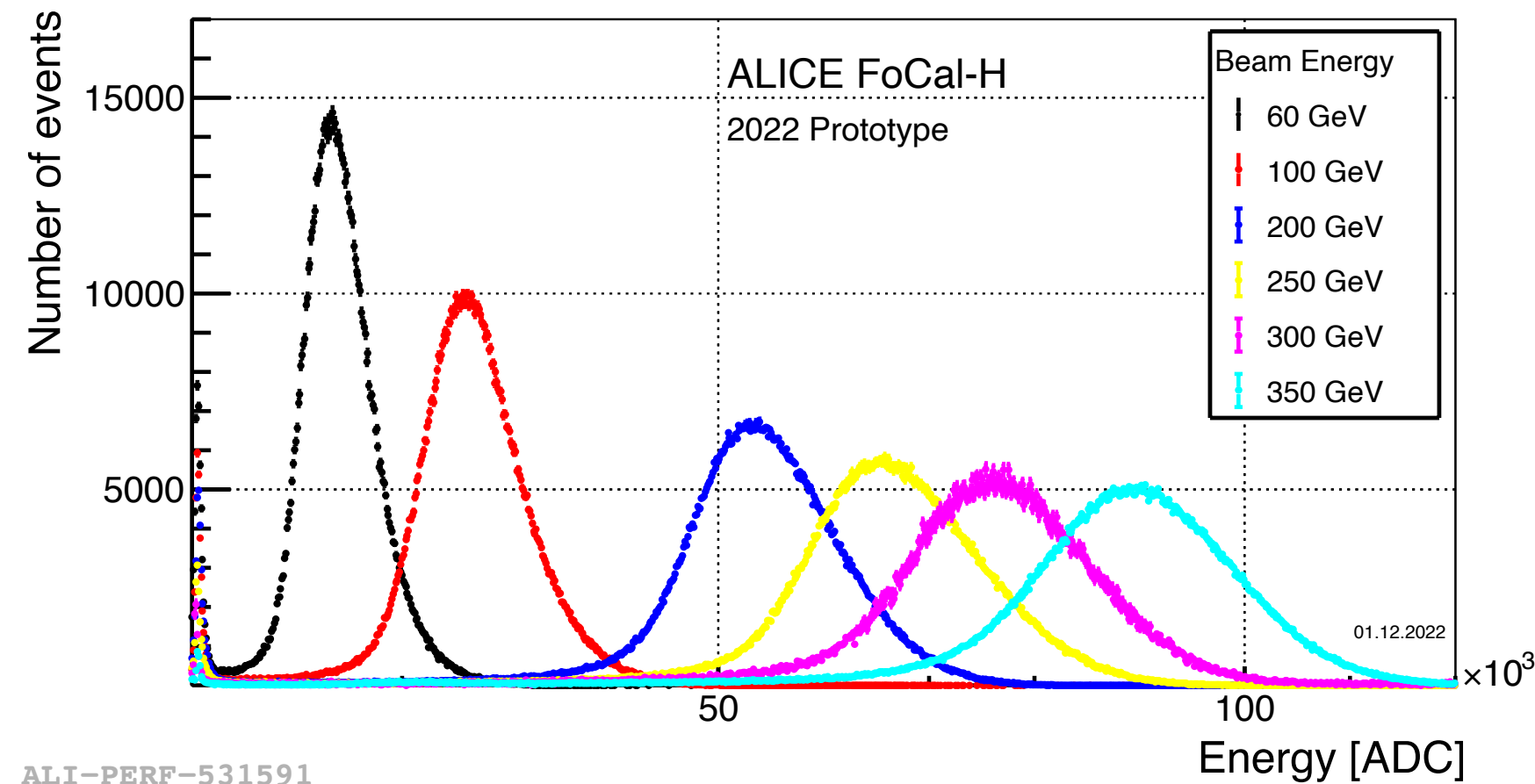


ALICE LS3 upgrades: Forward Calorimeter

- Prototype tests at PS, SPS:
 - ECAL pad and pixel layers
 - HCAL Cu-scintillator spaghetti design
- Analysis ongoing — encouraging first results

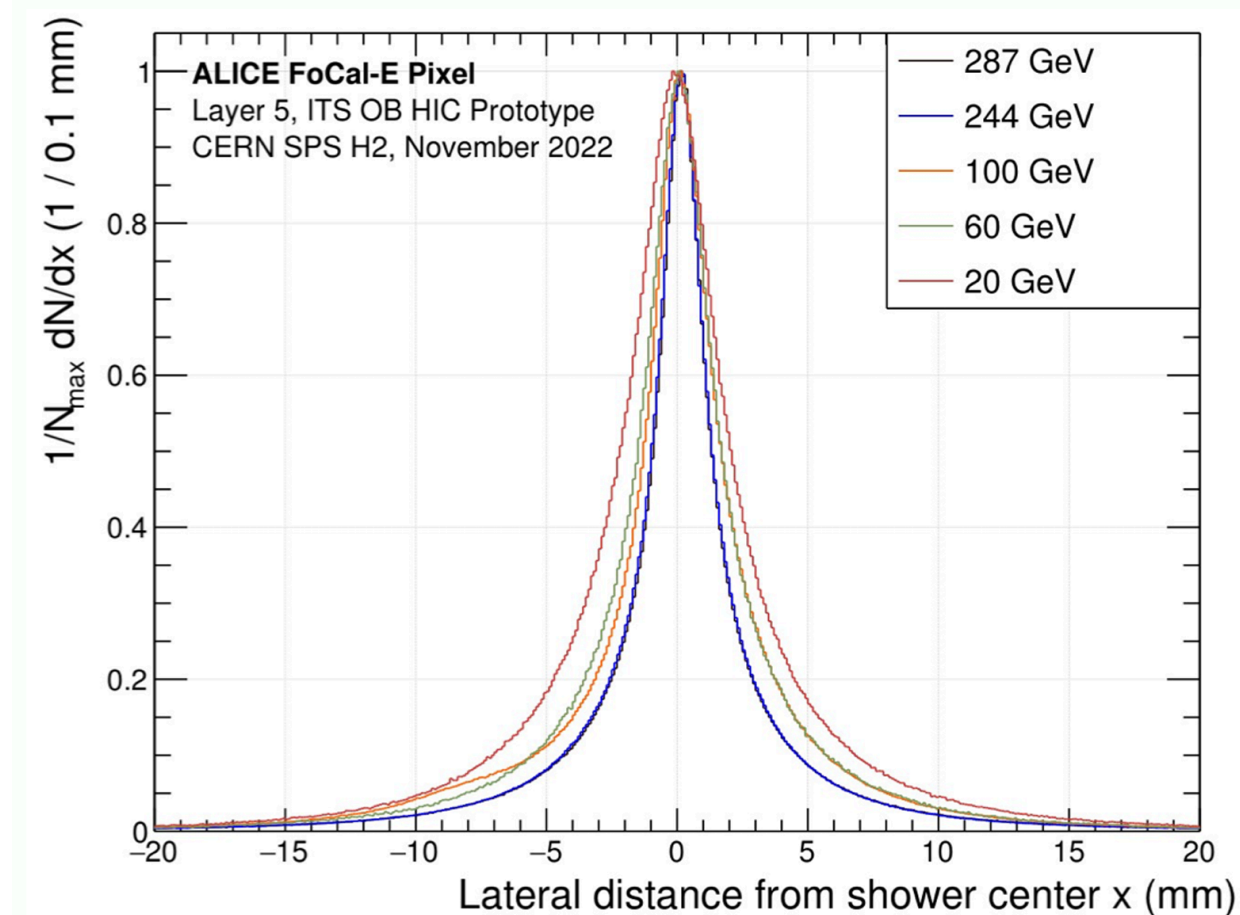


HCAL response



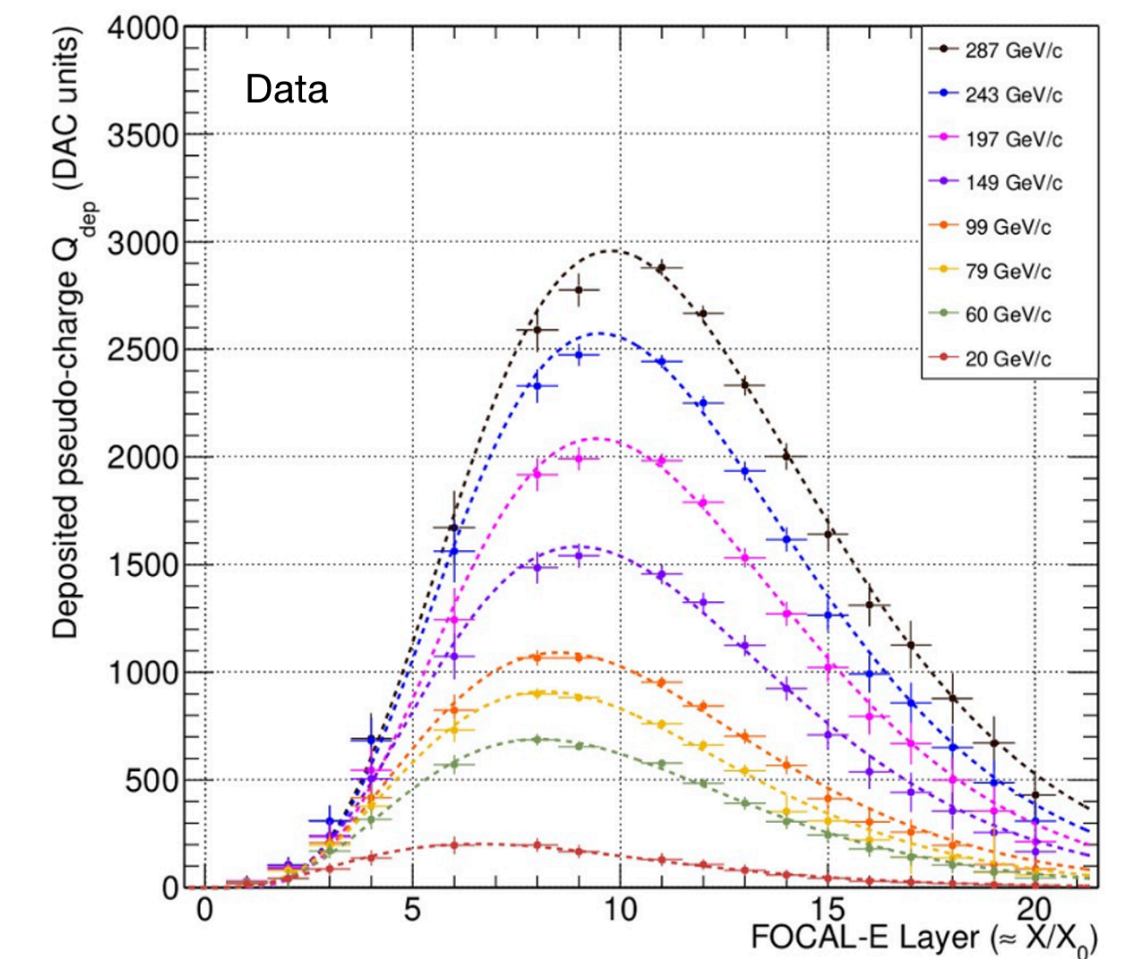
ALI-PERF-531591

ECAL pixels: lateral distribution



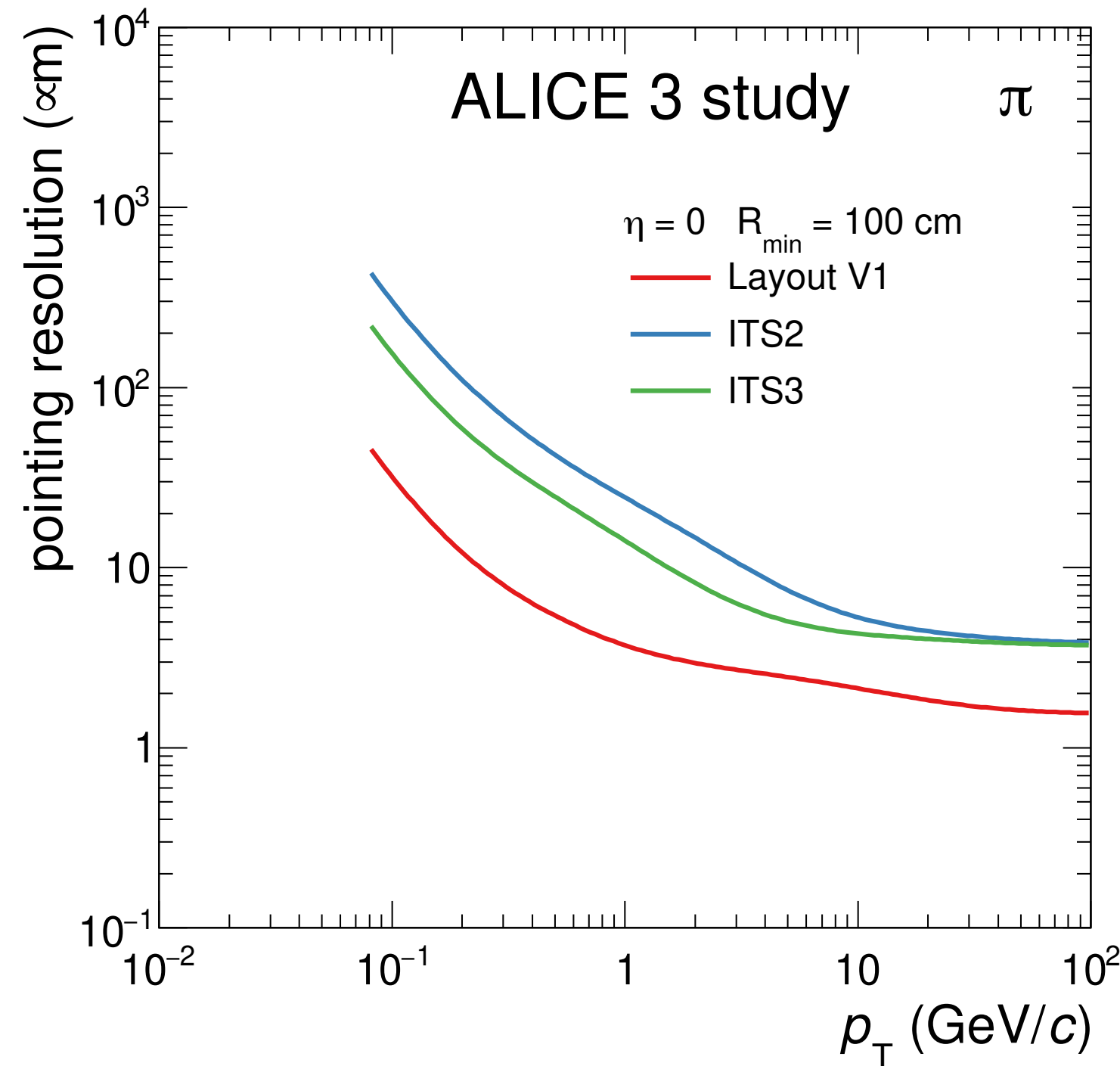
mm-scale spatial precision

ECAL pads: longitudinal profile



Impact parameter resolution – HF benchmarks

Impact parameter resolution

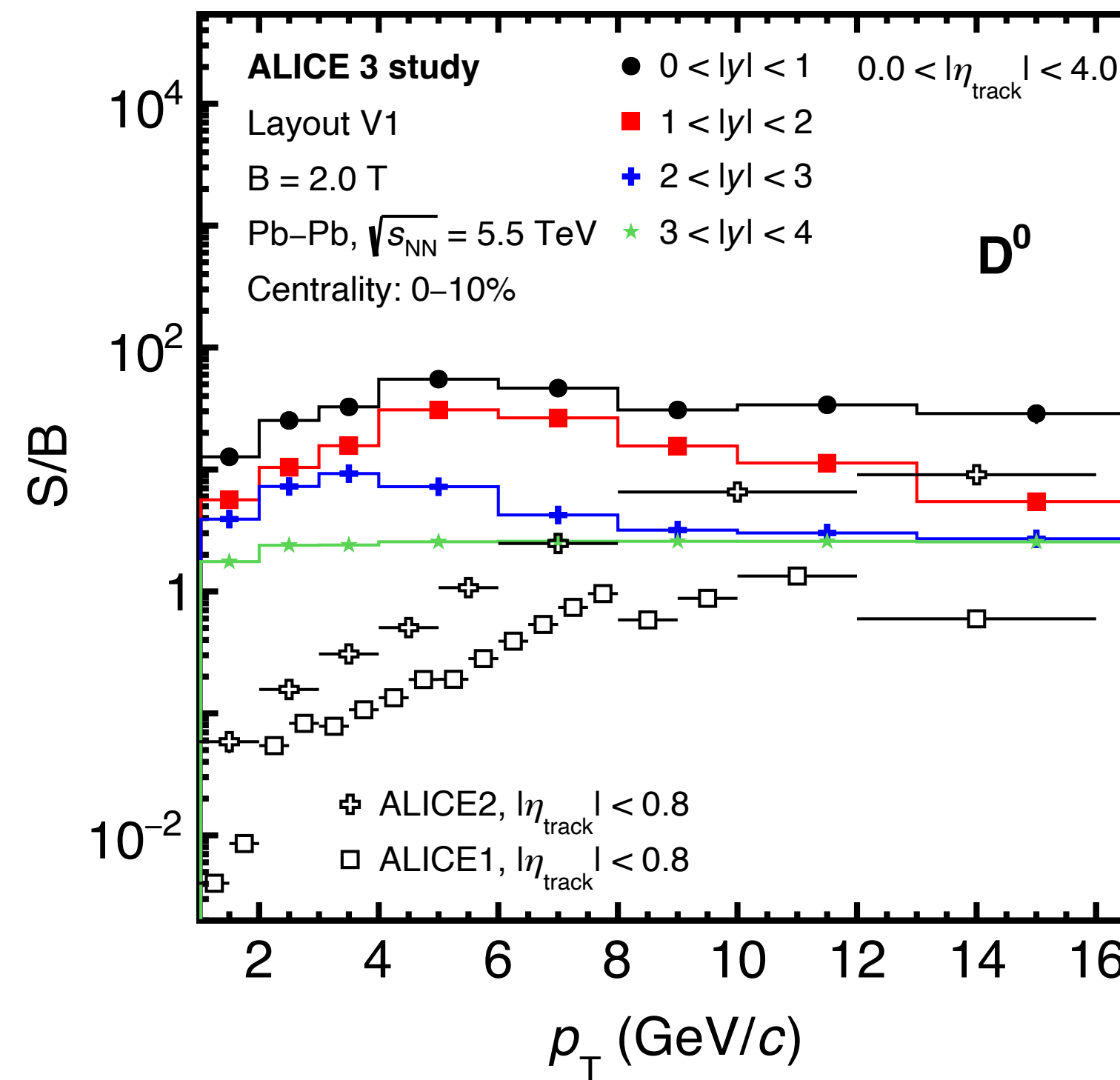


ALI-SIMUL-491785

Excellent pointing resolution and PID:

Large S/B and efficiency
 10-20x ITS 2 at $p_T < 4$ GeV

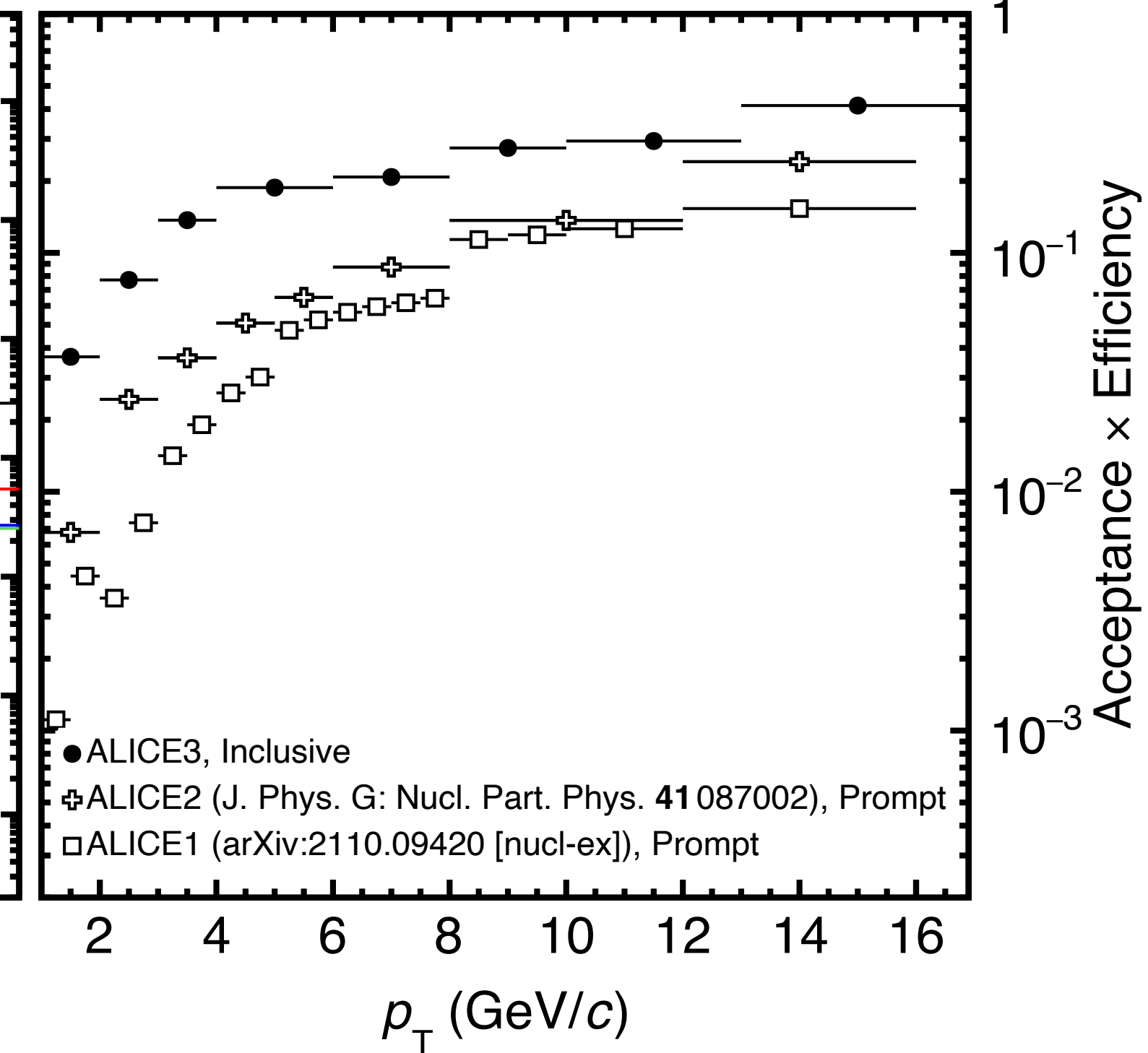
D meson signal/background



Improves precision for:

- Charm and beauty baryon v_2
- Dielectron spectra

Efficiency

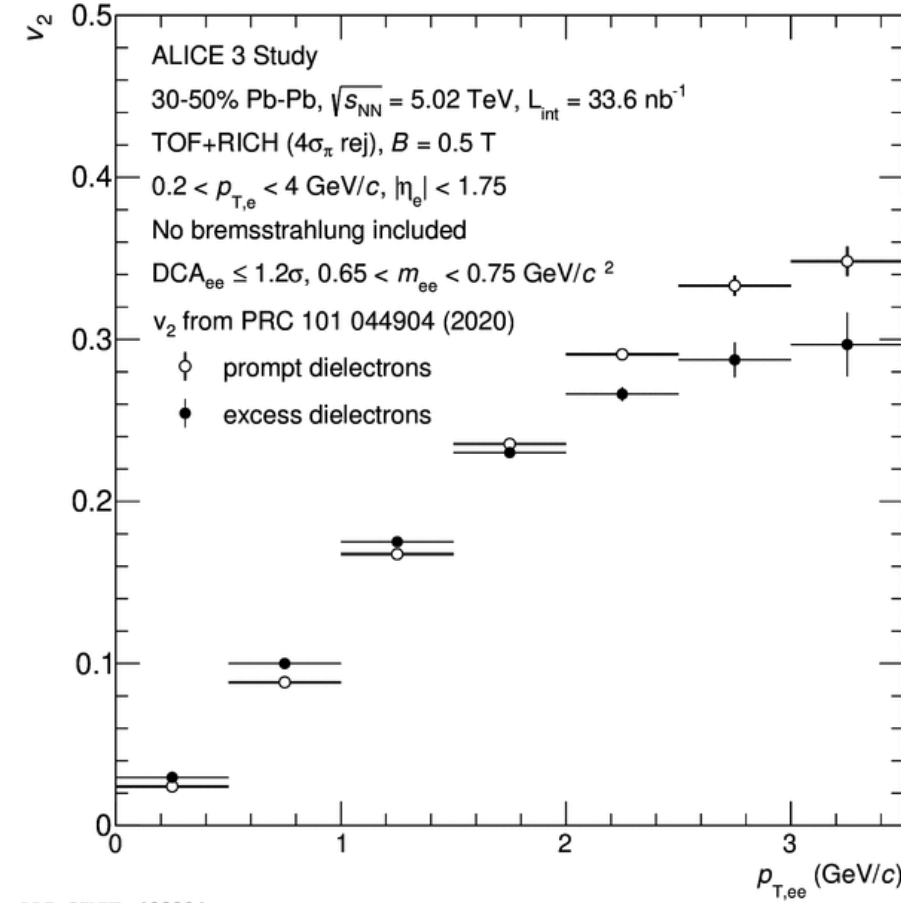


Access to new signals:

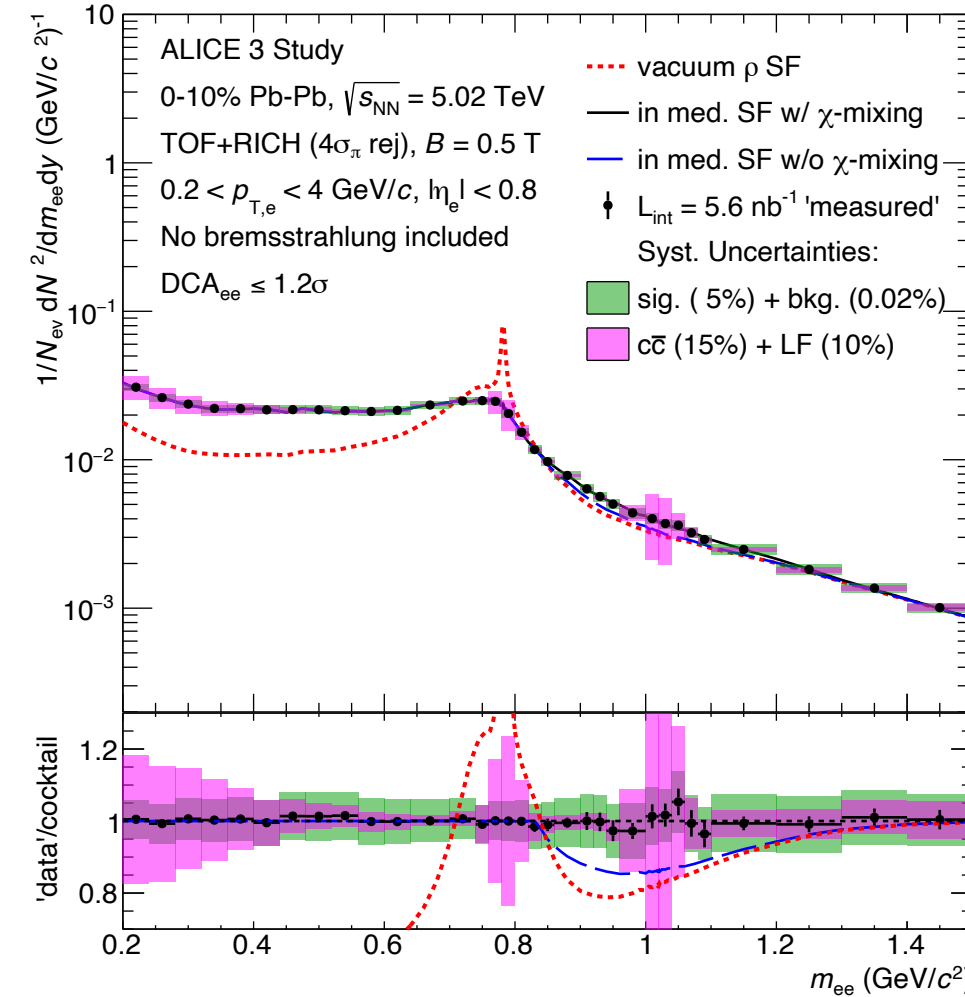
- $\overline{D}D$ correlations
- Multi-charm baryons
- Dielectron v_2

ALICE 3: an ambitious physics program ...

Dielectrons

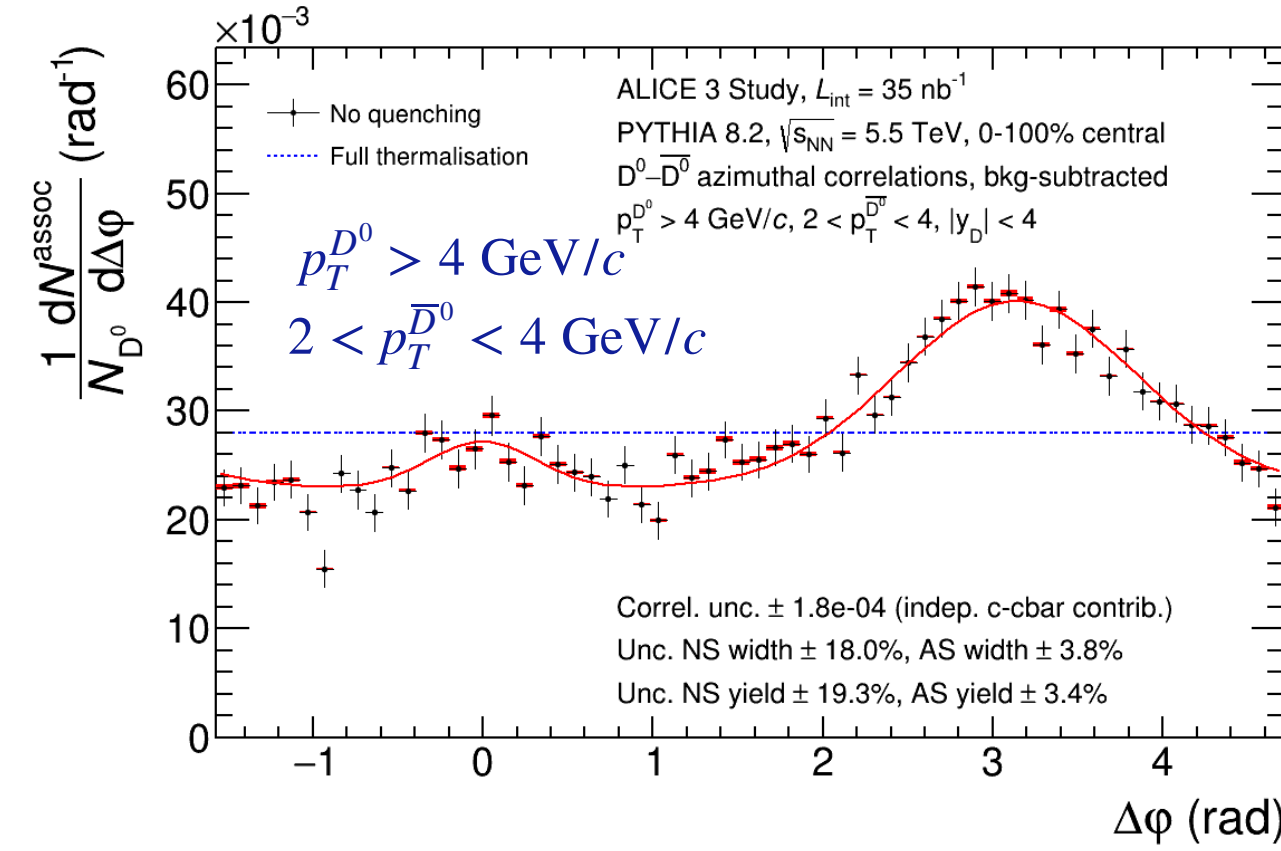


Direct measure of temperature and expansion of early stage



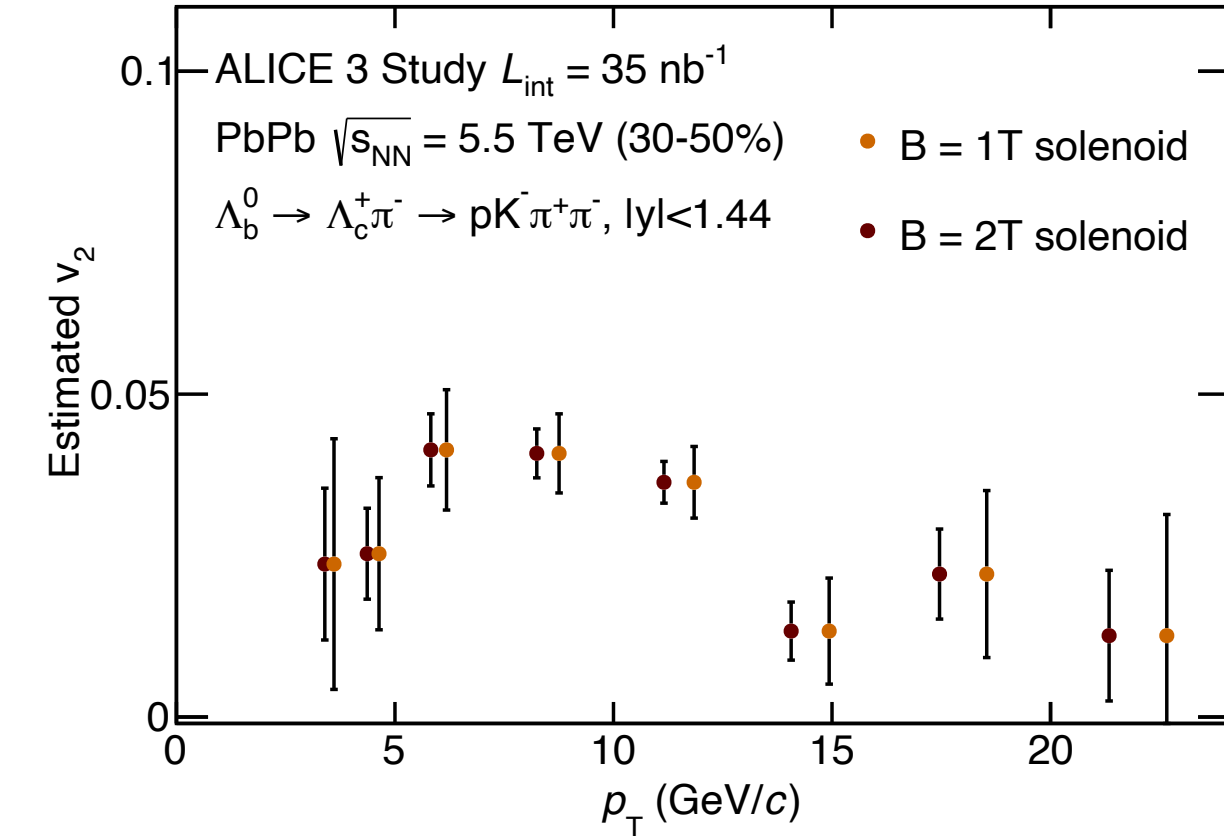
Chiral symmetry restoration

DD correlations: charm diffusion

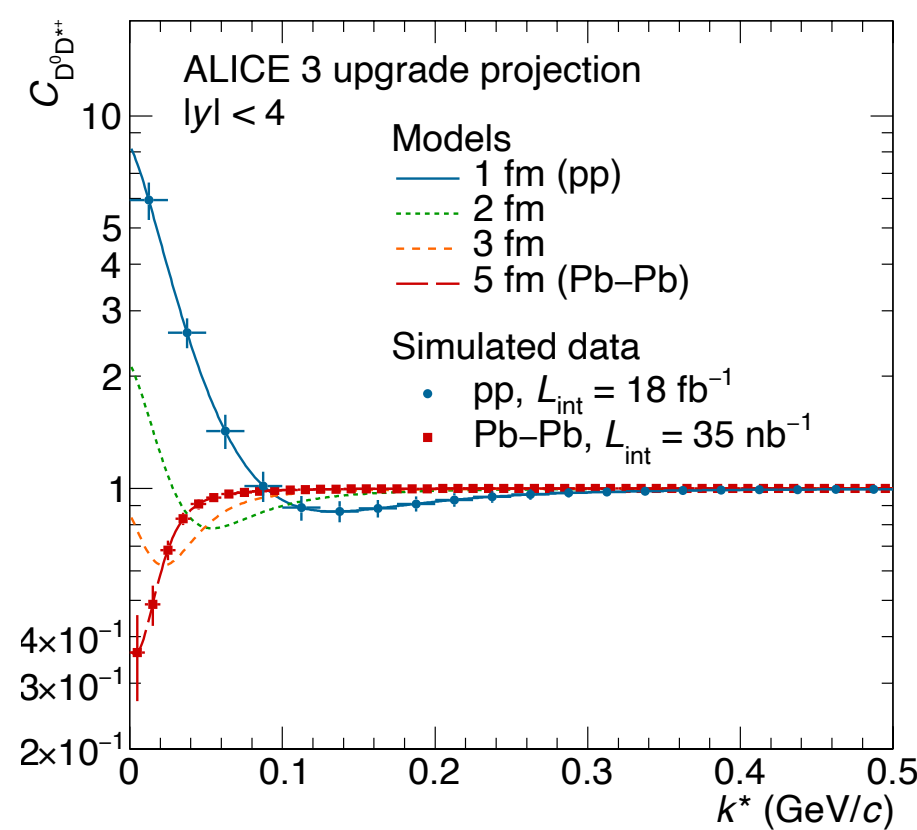


Thermalisation of heavy quarks

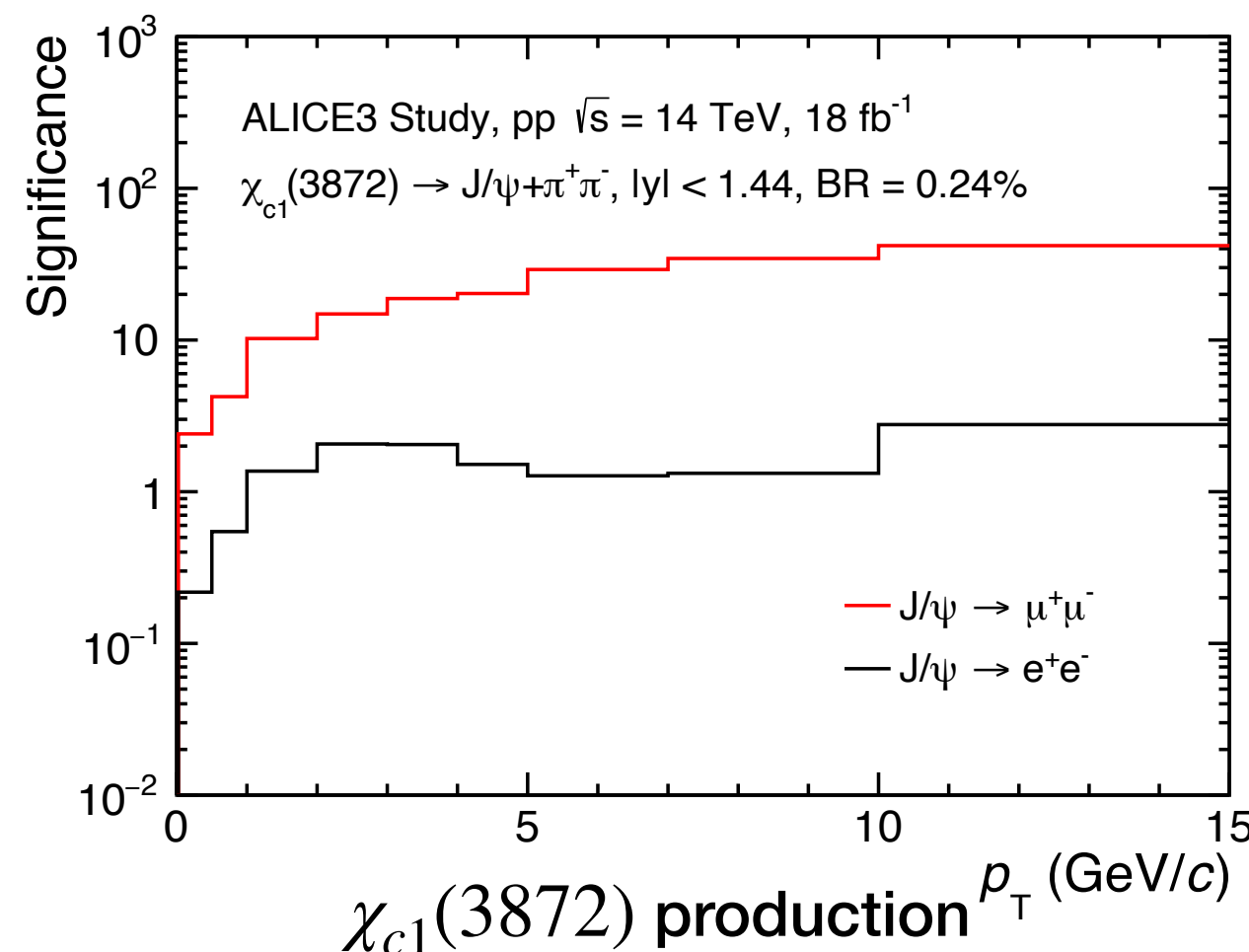
Heavy flavour v2



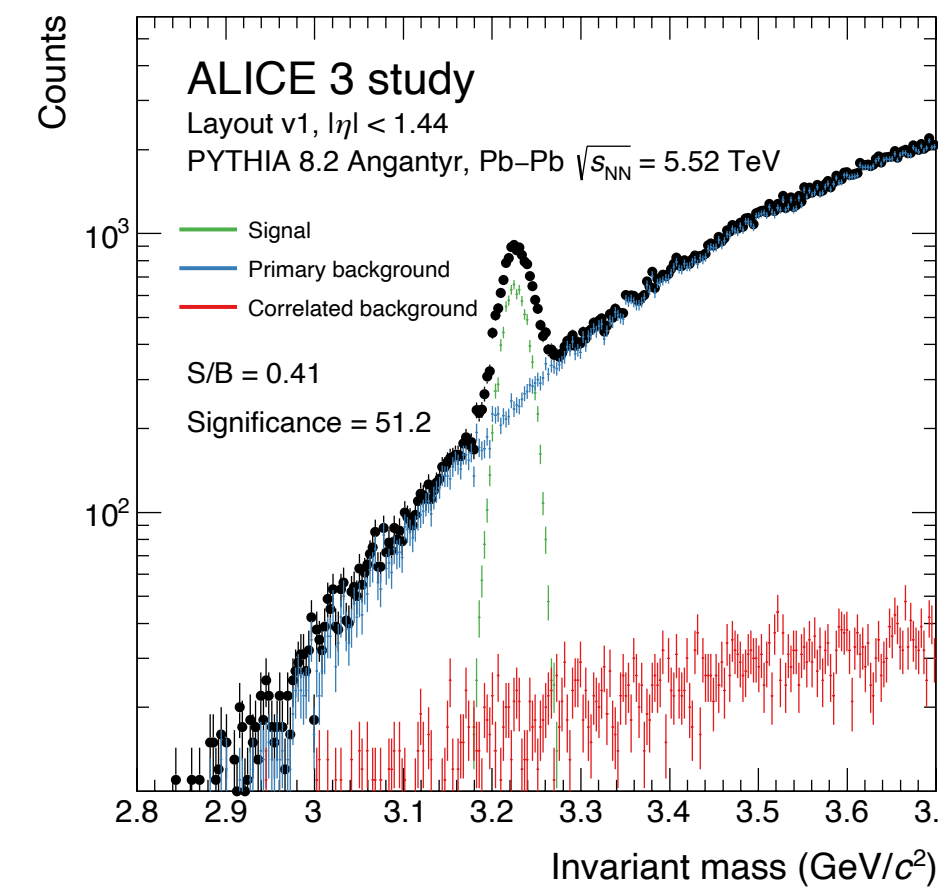
Exotic states and hadron interactions



$D^0 D^{*+}$ momentum correlations

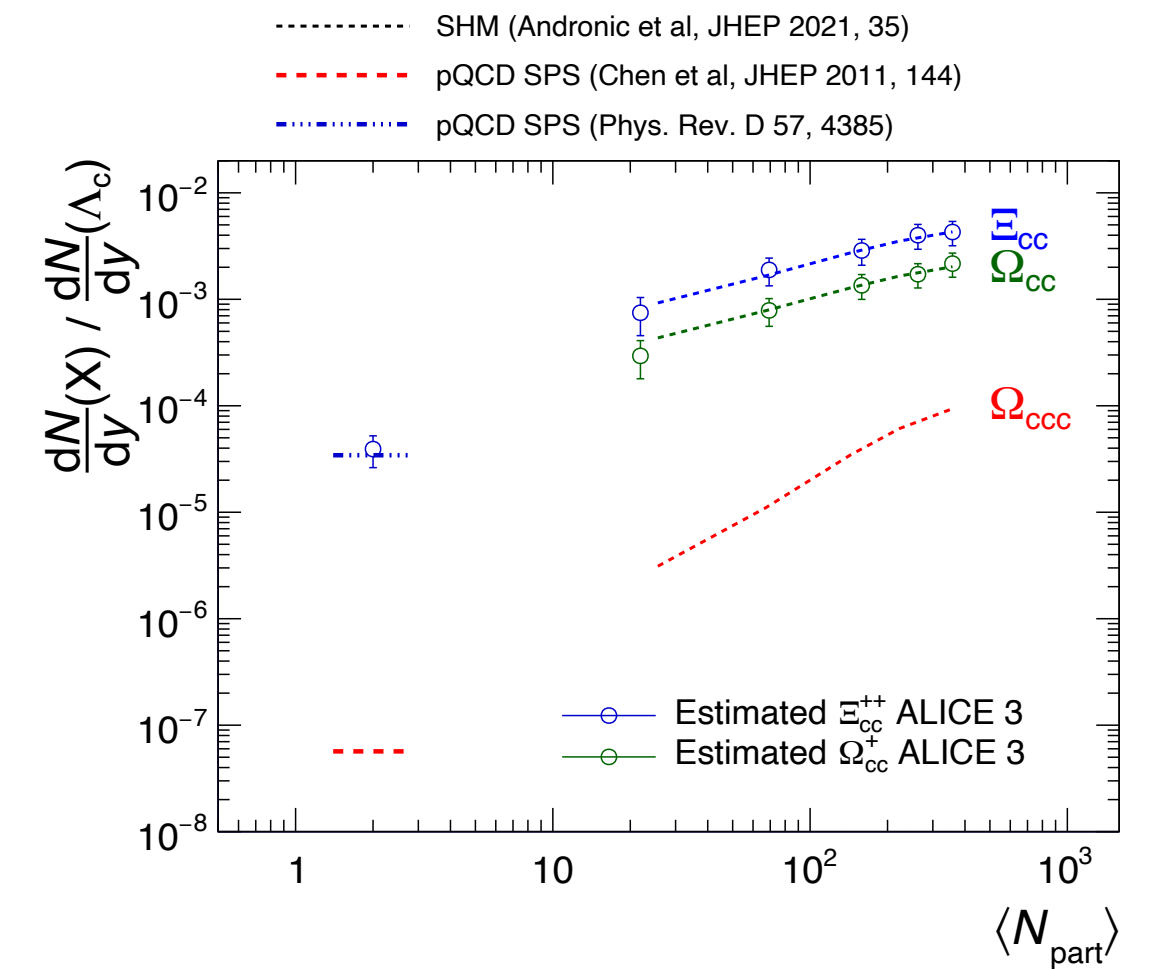


$\chi_{c1}(3872)$ production p_T (GeV/c)



c-deuteron

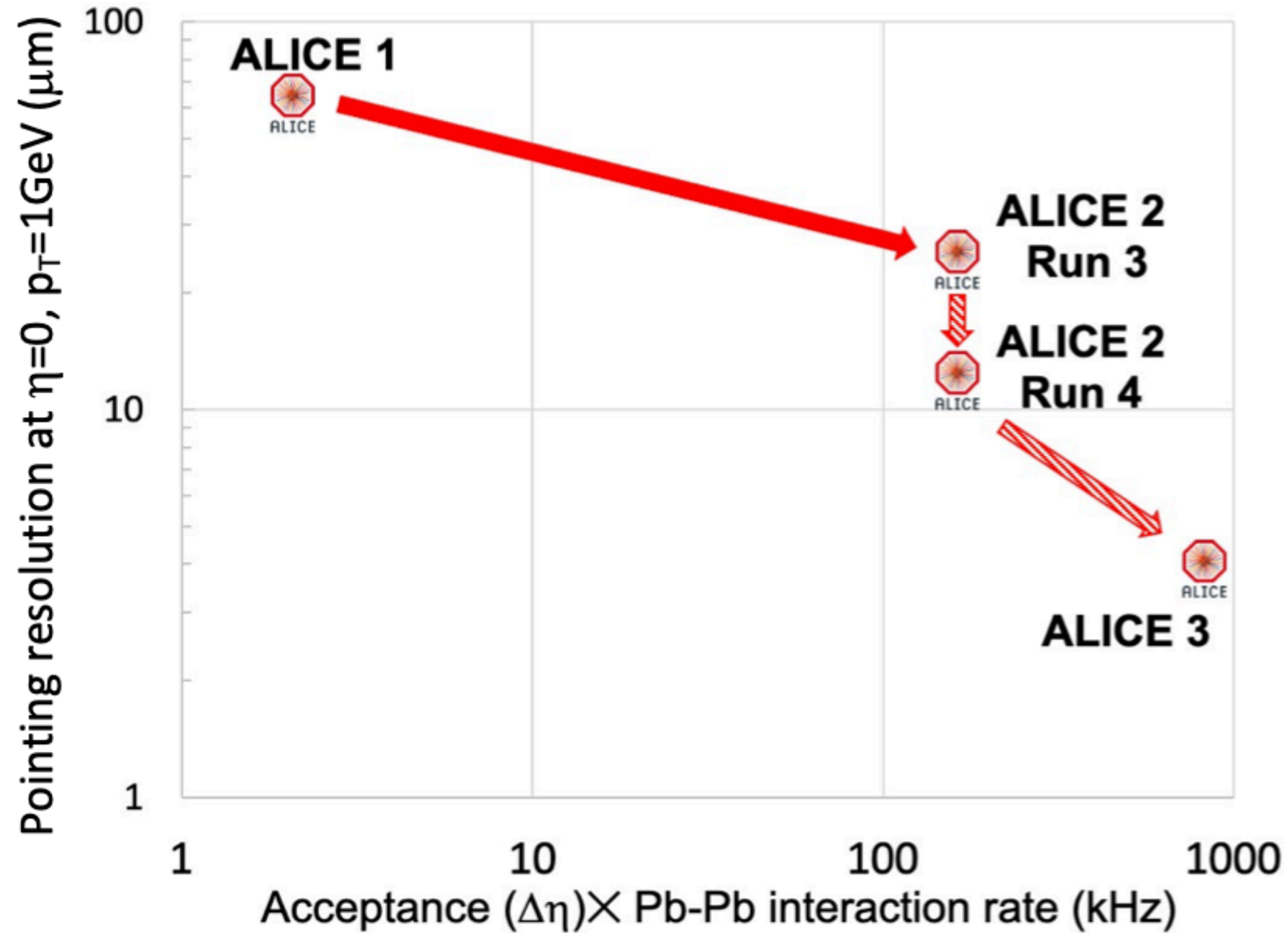
Multi-charm baryons



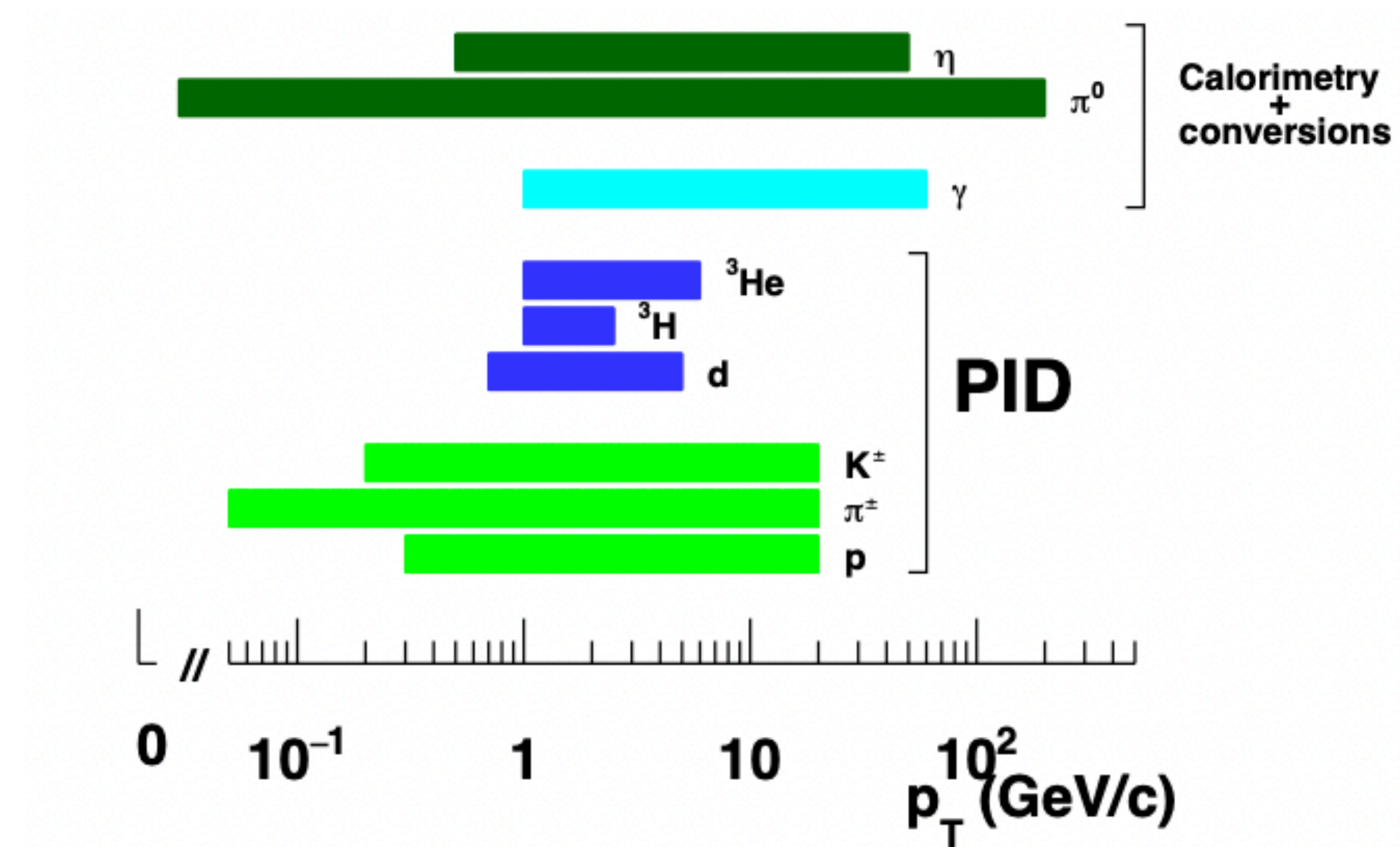
... and more

ALICE upgrades strategy

Large steps in pointing precision and “effective acceptance”



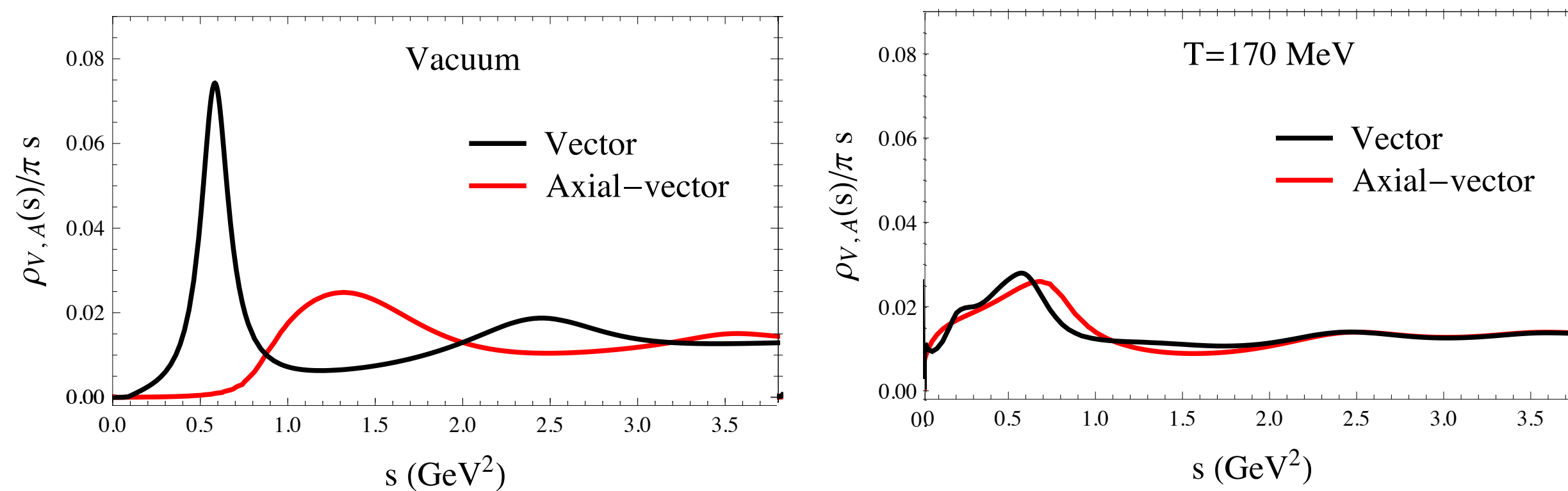
+
Keep/strengthen ALICE unique reach in particle identification



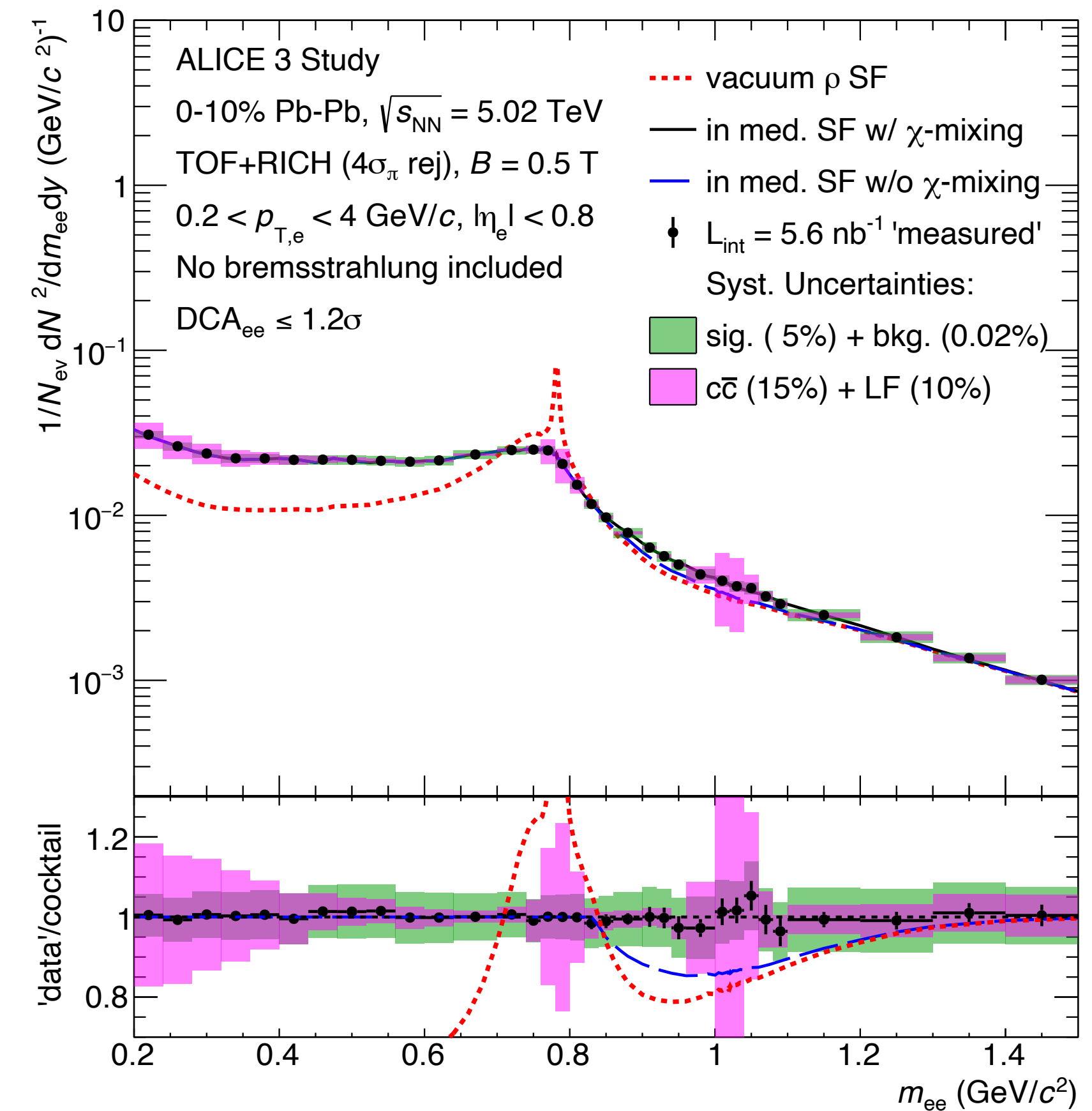
Chiral symmetry restoration: $\rho - a_1$ mixing

- Spontaneous breaking of chiral symmetry generates **hadron masses in QCD**
 - Large mass difference between ρ (770 MeV) and a_1 (1260 MeV)
- Chiral symmetry restored in QGP**
 - ρ and a_1 degenerate: mixing
- ALICE 3 provides experimental access to chiral symmetry restoration mechanism

ρ and a_1 spectral function



Hohler and Rapp, [PLB 731,103](#)

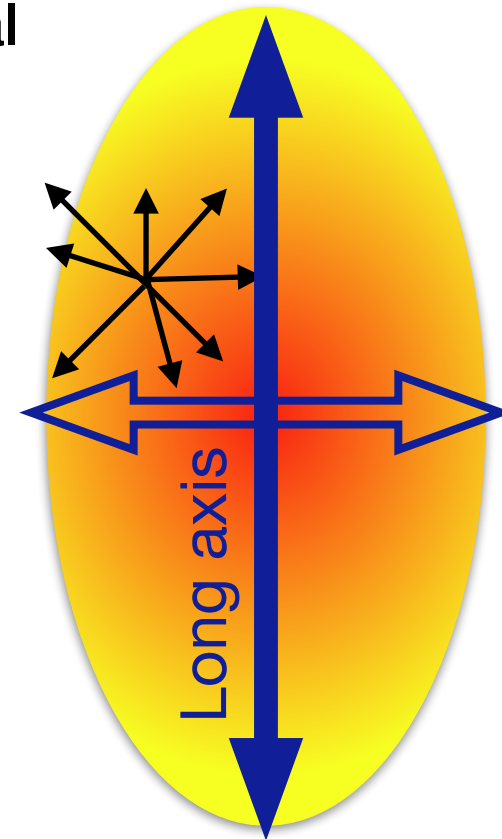


$\rho - a_1$ mixing affects mass spectrum above ρ peak

ALICE 3 provides necessary precision

Heavy flavour transport: elliptic flow v_2

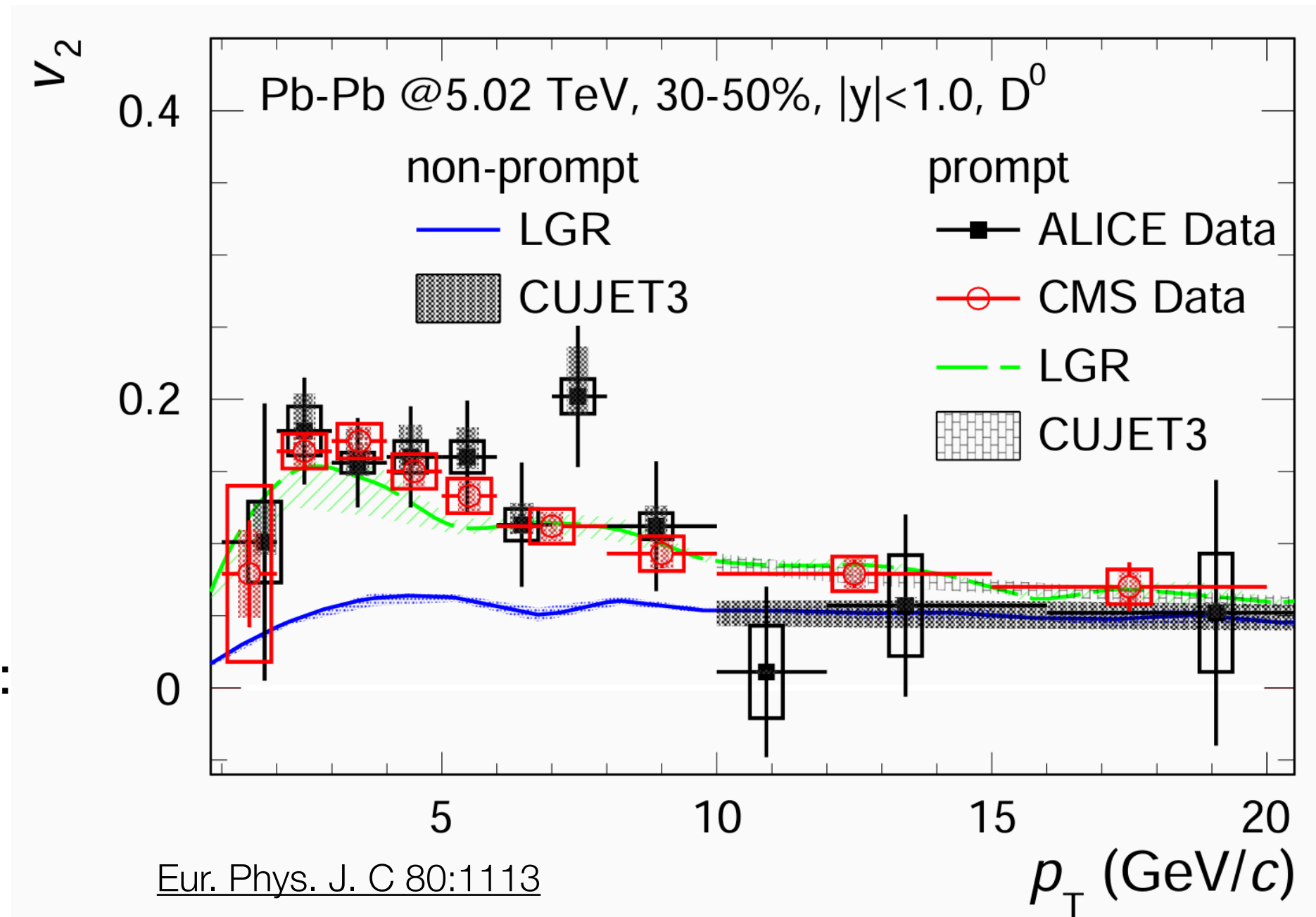
Non-central collision



Interactions with the plasma generate azimuthal anisotropy v_2 :

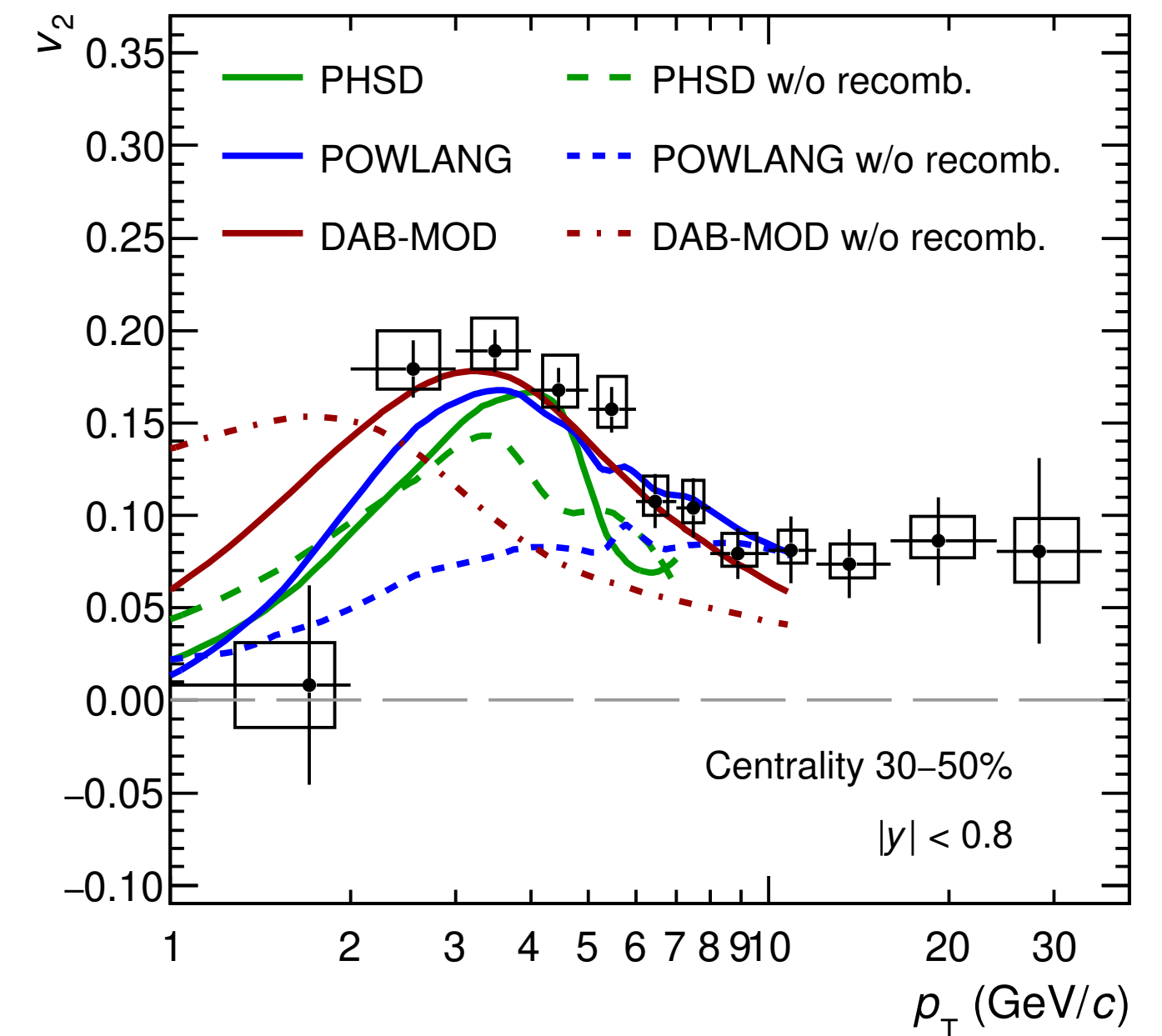
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \psi)$$

Charm and beauty v_2 (via non-prompt D mesons)



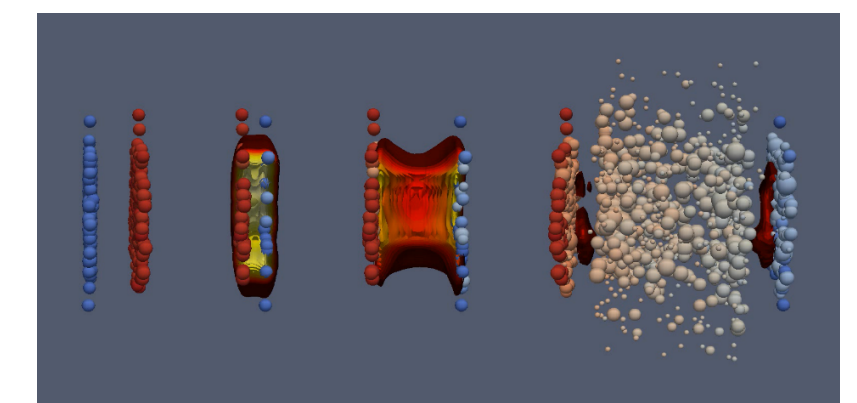
relaxation time: $\tau_Q = (m_Q/T) D_s$

Impact of hadronisation (recombination)



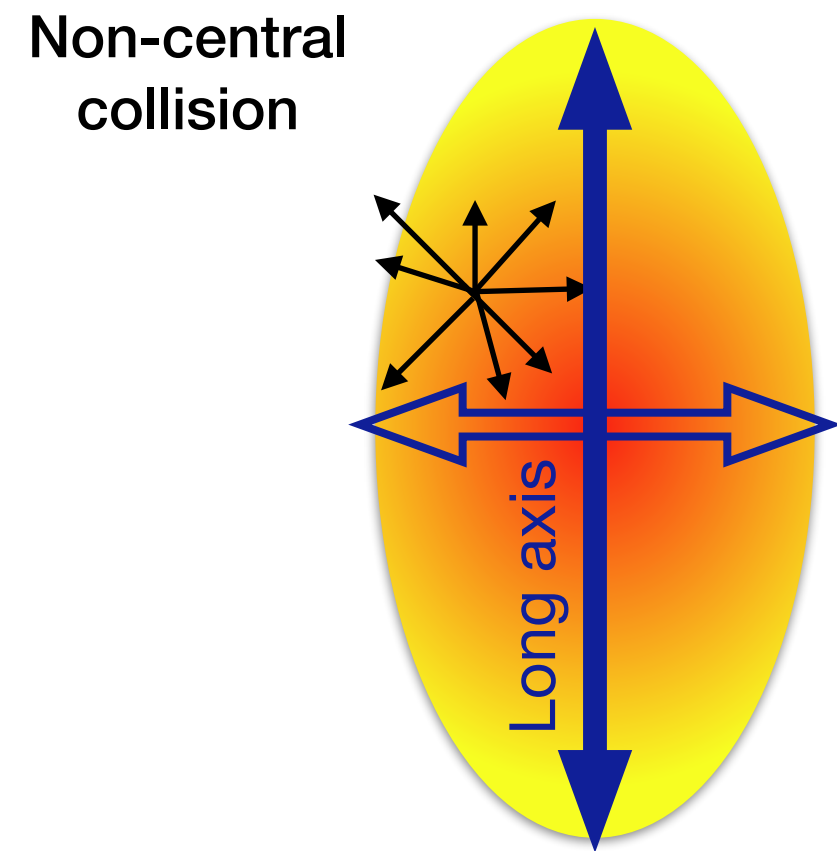
Heavy quarks: access to quark transport at hadron level

- Expect beauty thermalisation slower than charm — smaller v_2
- Need baryons and mesons to disentangle hadronisation effects: interplay with light quarks



QGP: quark transport Hadronisation

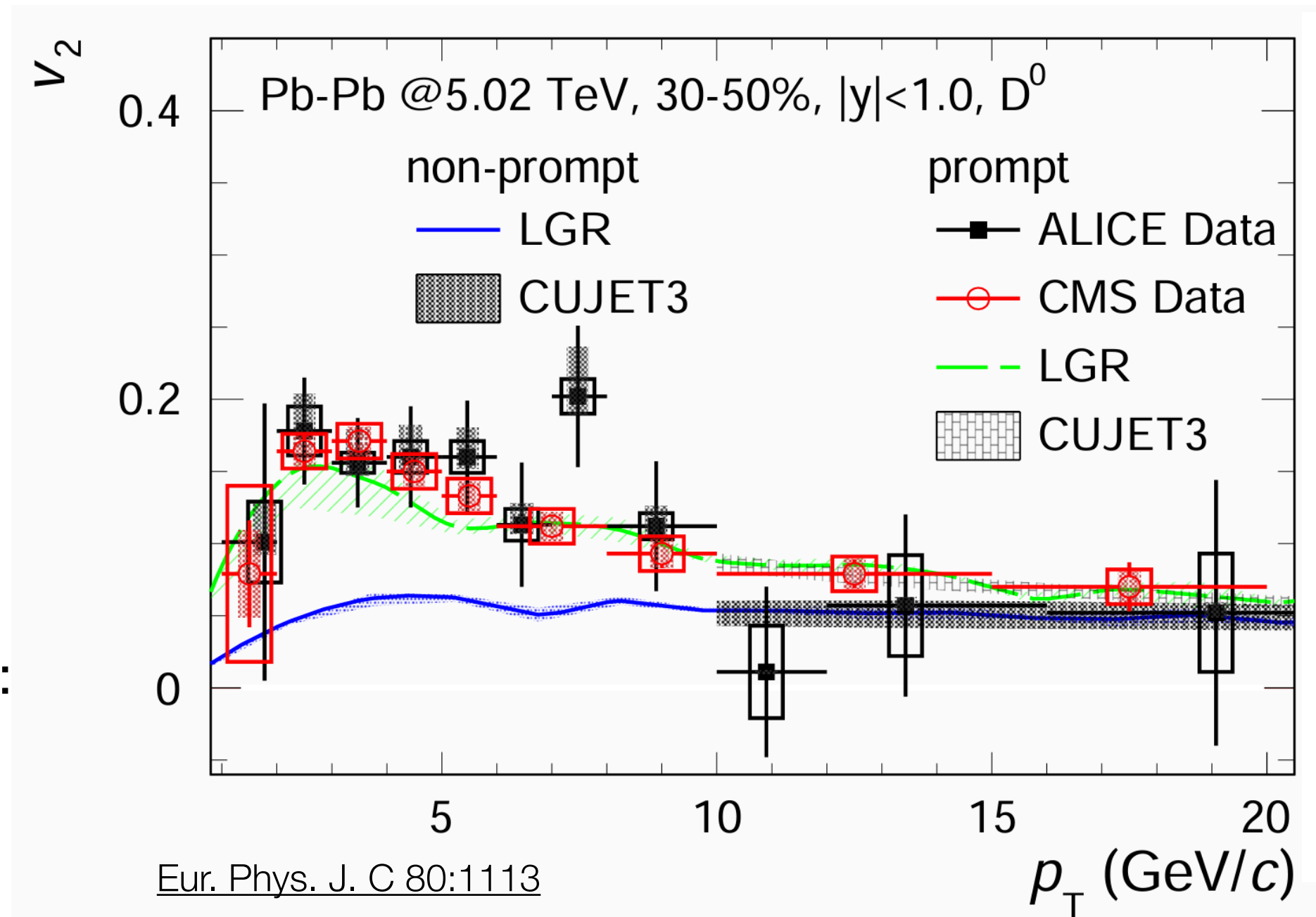
Heavy flavour transport: elliptic flow v_2



Interactions with the plasma generate azimuthal anisotropy v_2 :

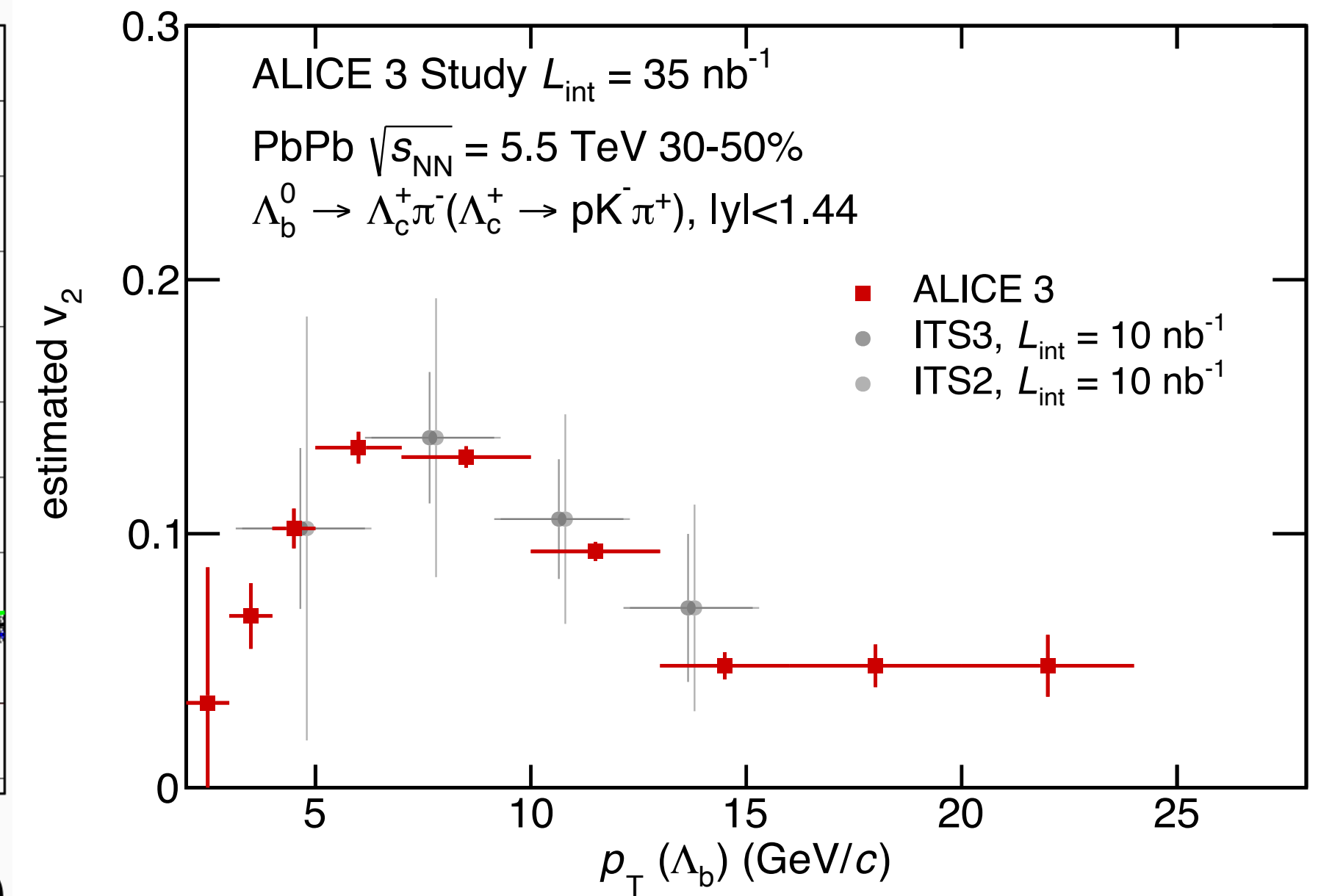
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Charm and beauty v_2 (via non-prompt D mesons)



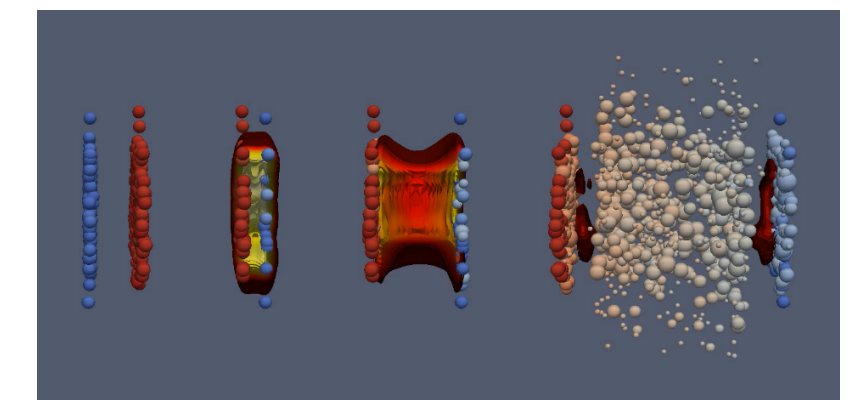
relaxation time: $\tau_Q = (m_Q/T) D_s$

Λ_b v_2 performance



Heavy quarks: access to quark transport at hadron level

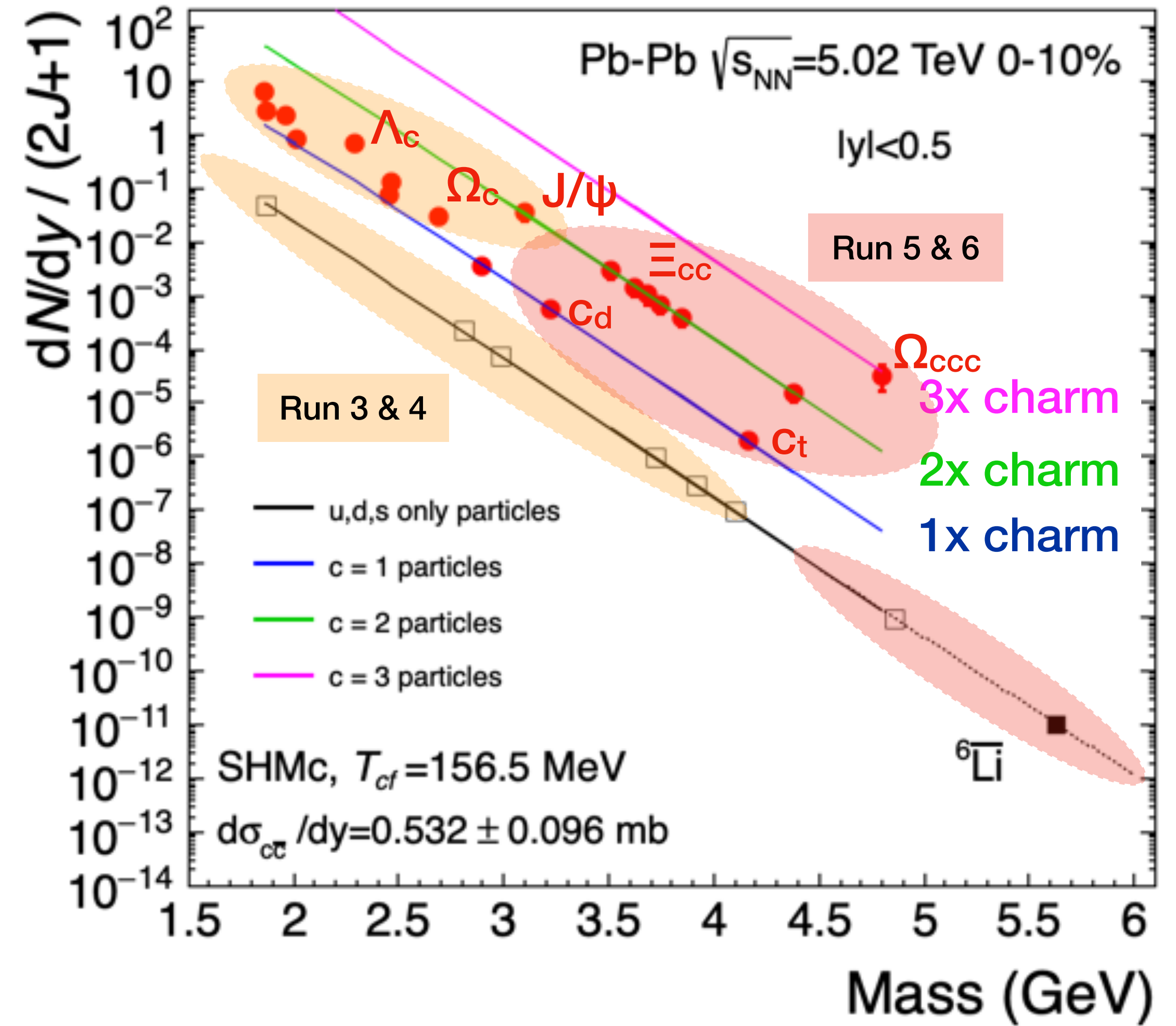
- Expect beauty thermalisation slower than charm — smaller v_2
- Need baryons and mesons to disentangle hadronisation effects: interplay with light quarks



QGP: Hadronisation
quark transport

Hadron formation: multi-HF hadrons

- **Multi-charm baryons:** unique probe of hadron formation
- 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 multiple states to probe dynamics of thermalisation and hadronisation

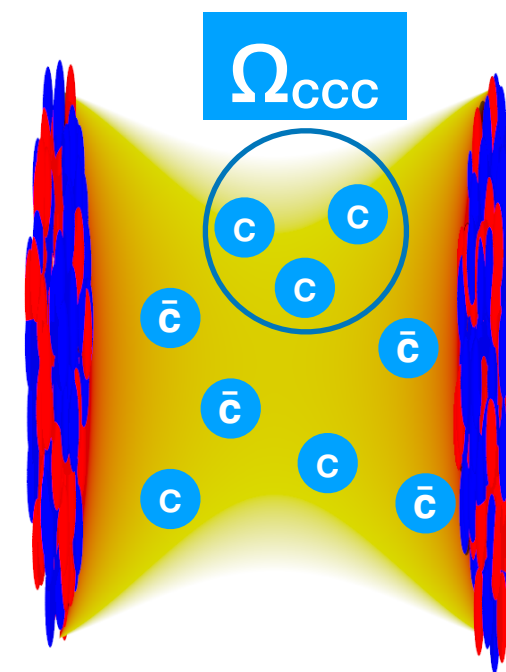


Single and double-charm baryons: Λ_c , Ξ_c , Ξ_{cc} , Ω_{cc}

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

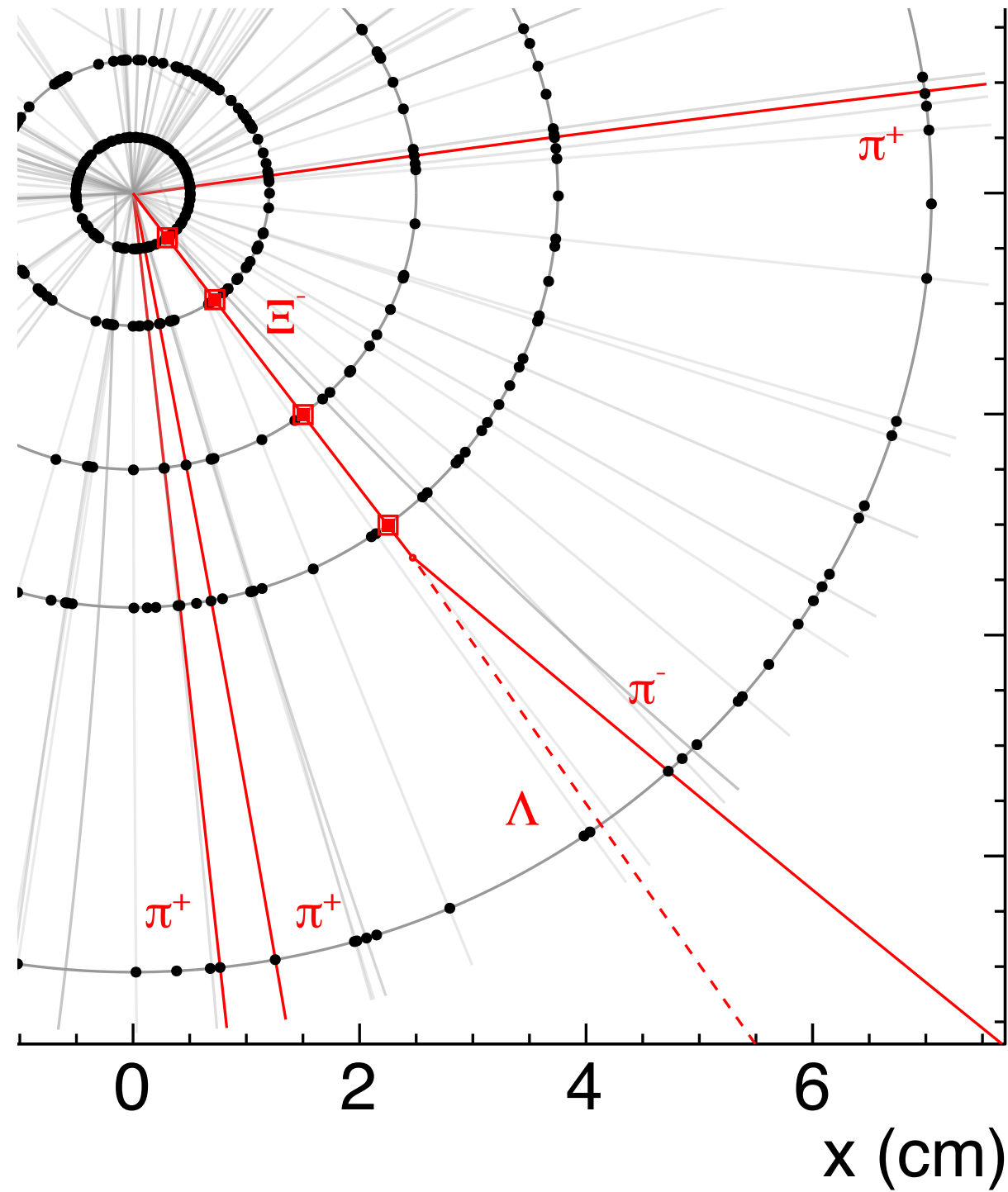
Tightly/weakly bound states J/ψ , $\chi_{c1}(3872)$, T_{cc}^+

Large mass light flavour particles: nuclei

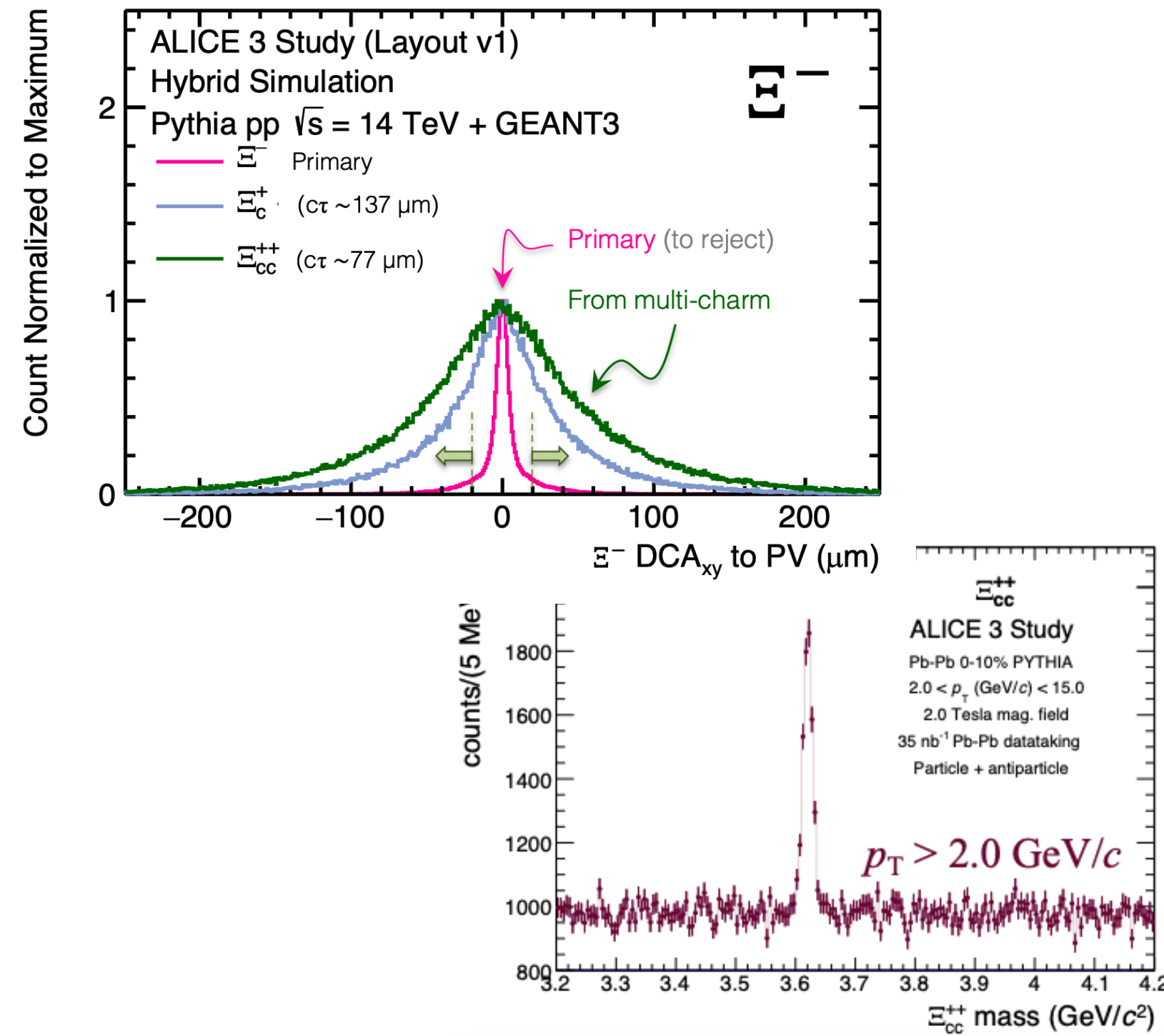


Multi-charm baryons

New technique: strangeness tracking



Impact parameter of Ξ

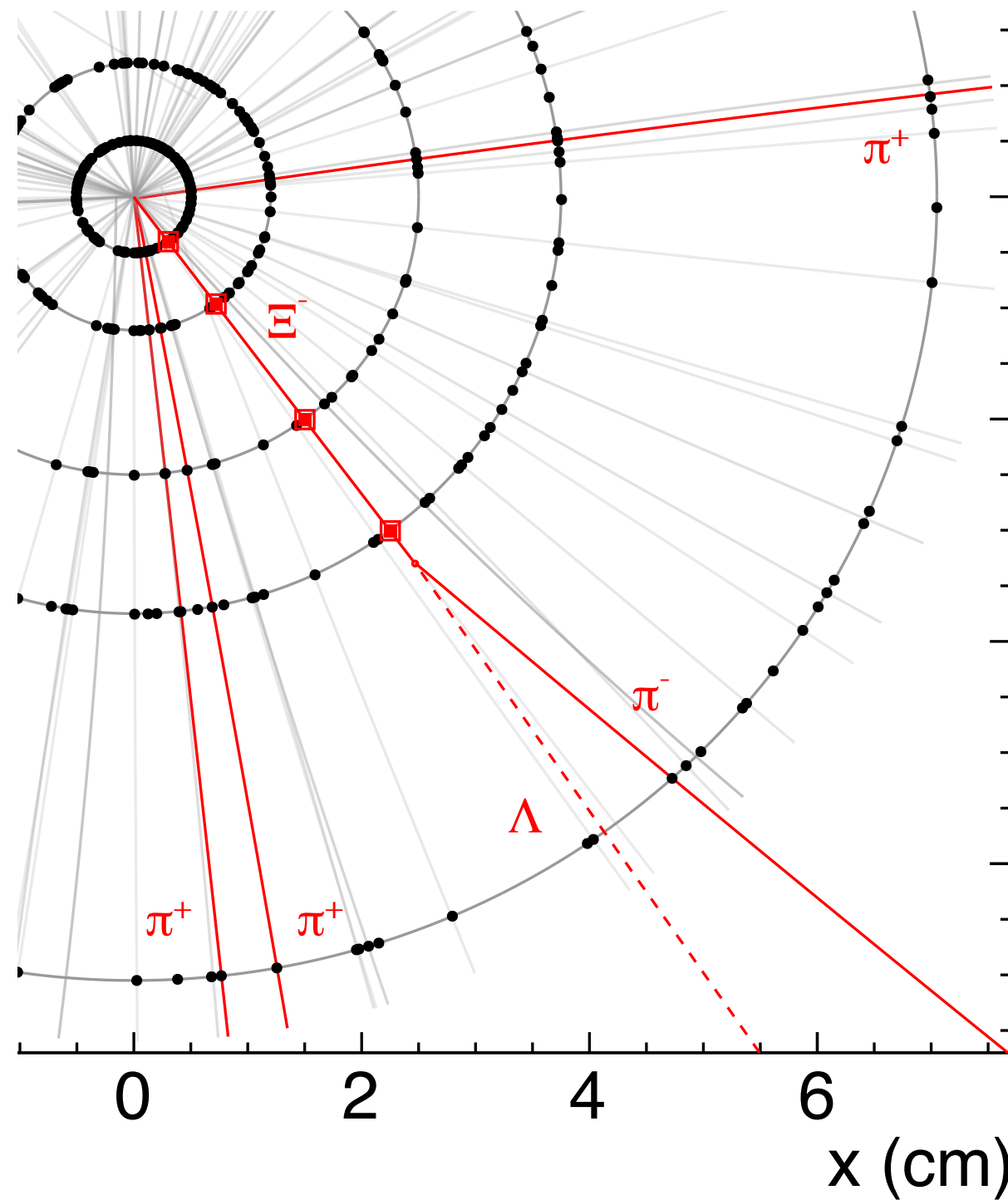


Pointing of Ξ baryon provides high selectivity

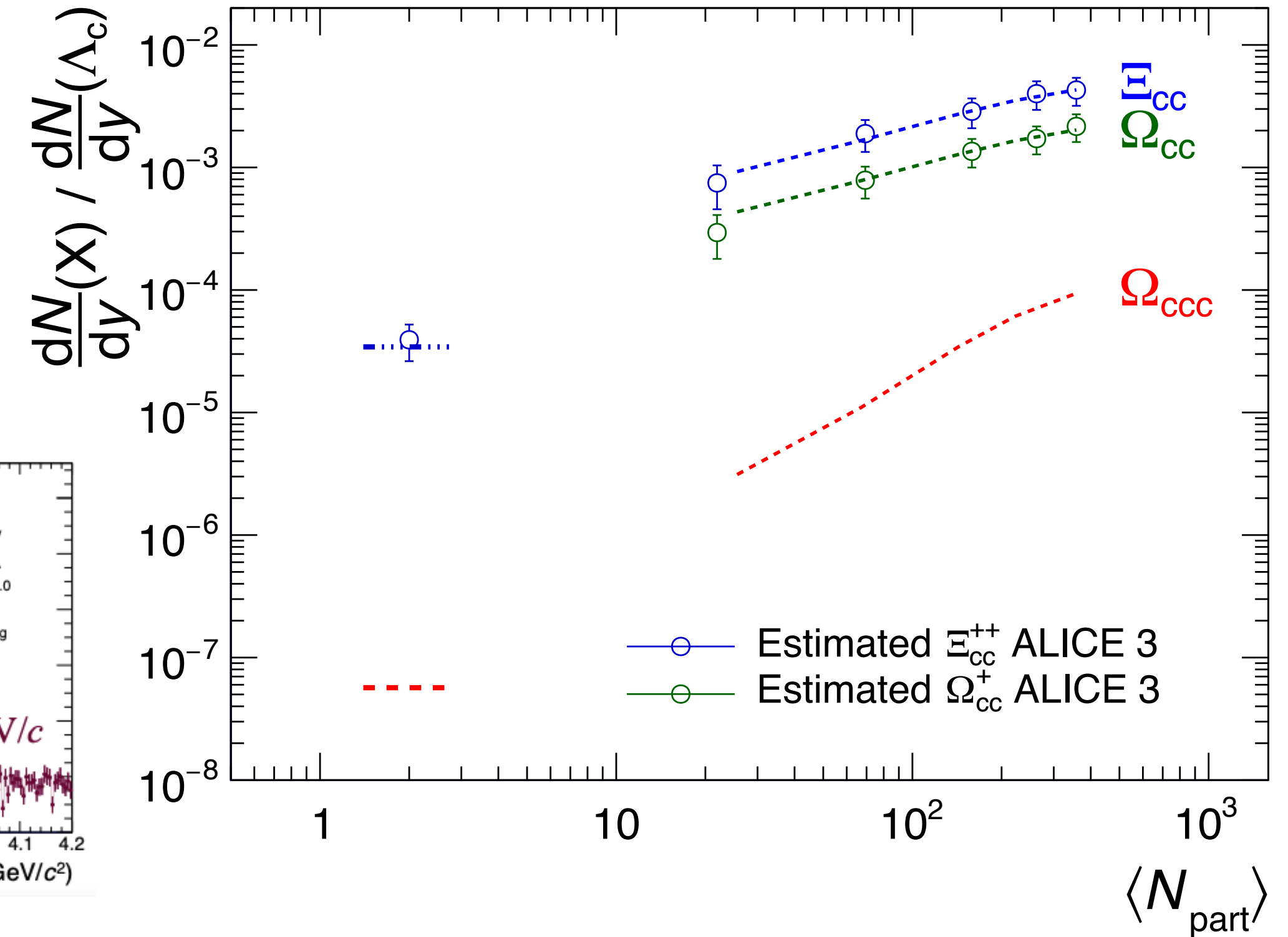
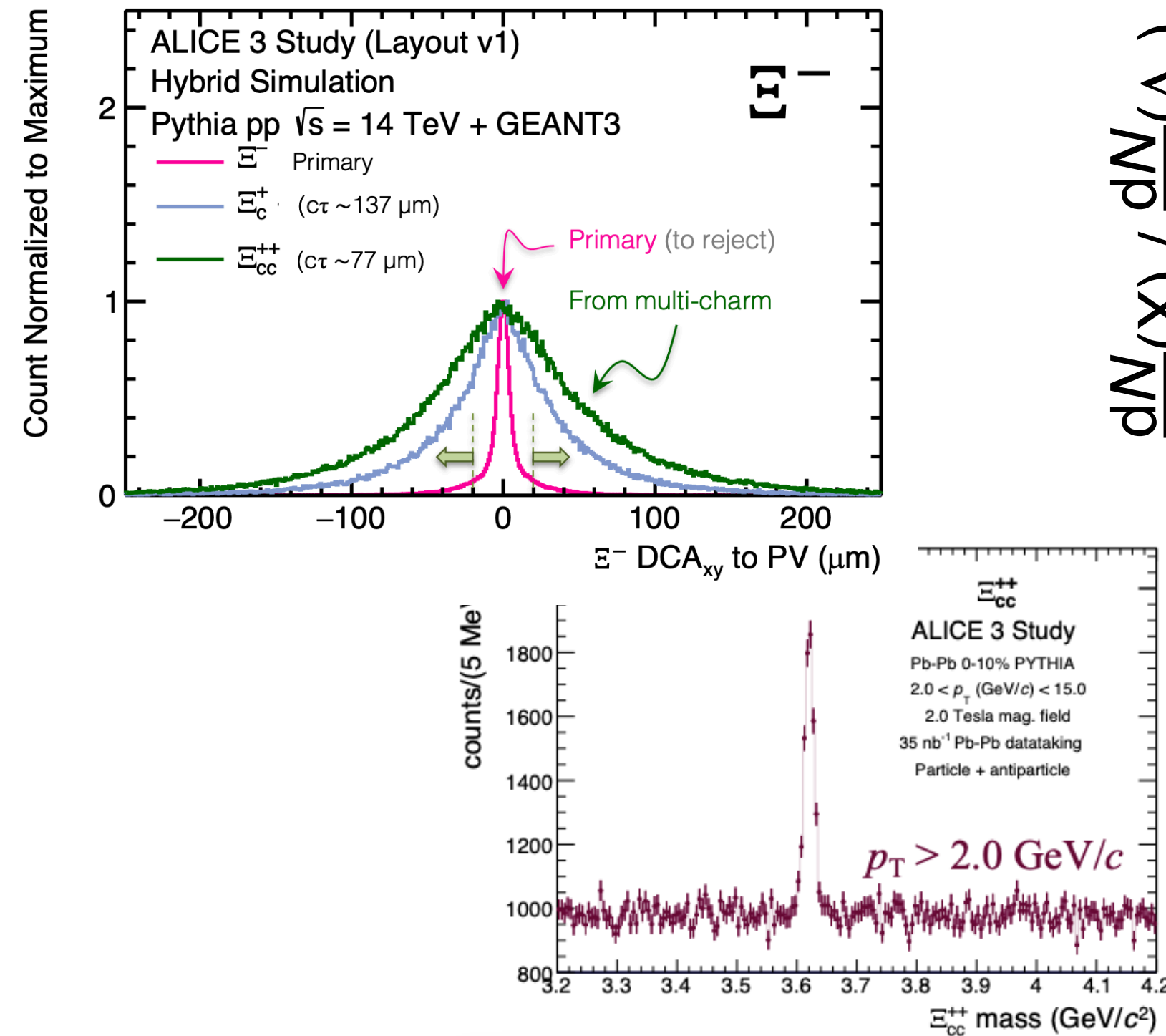


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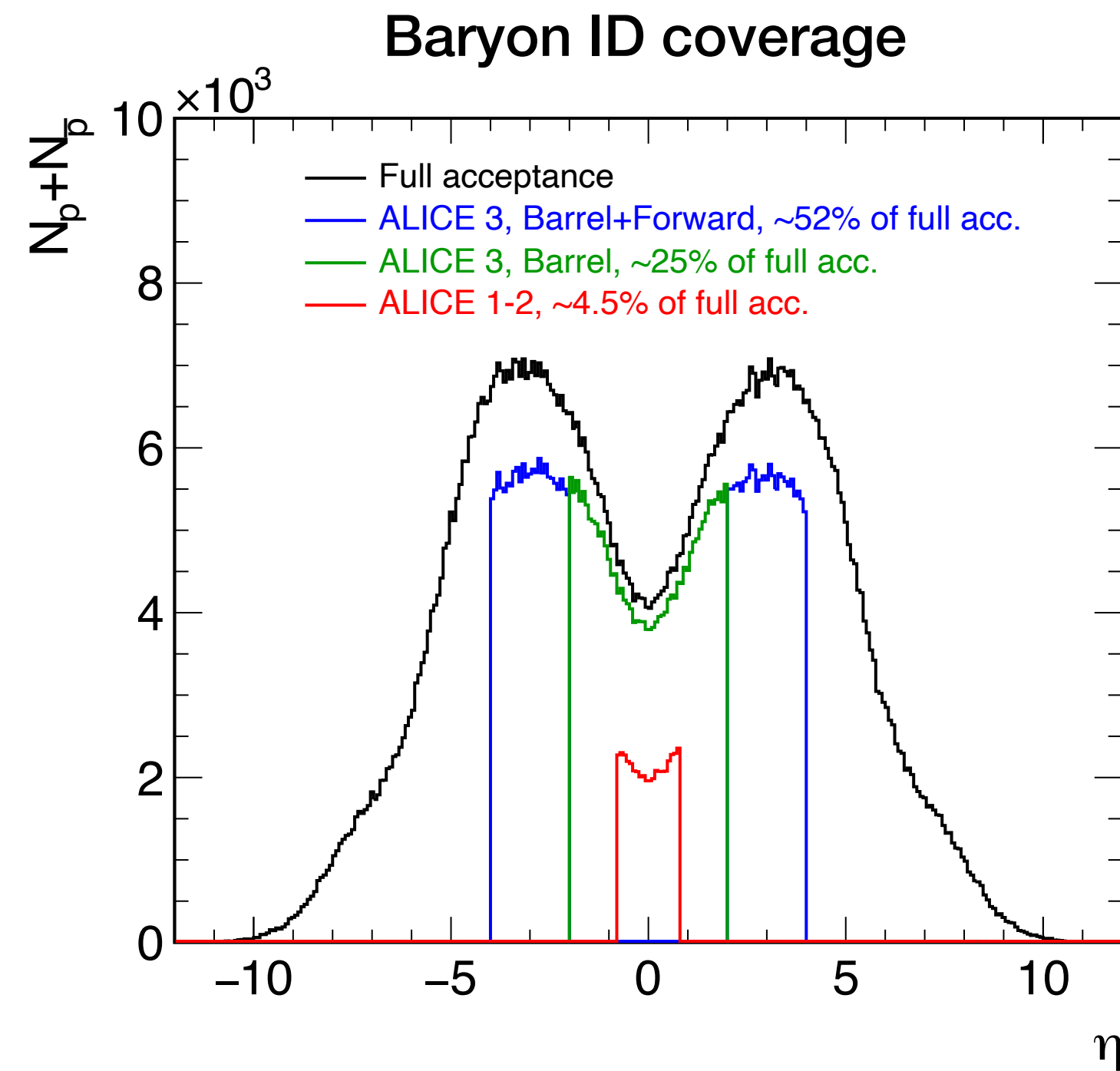
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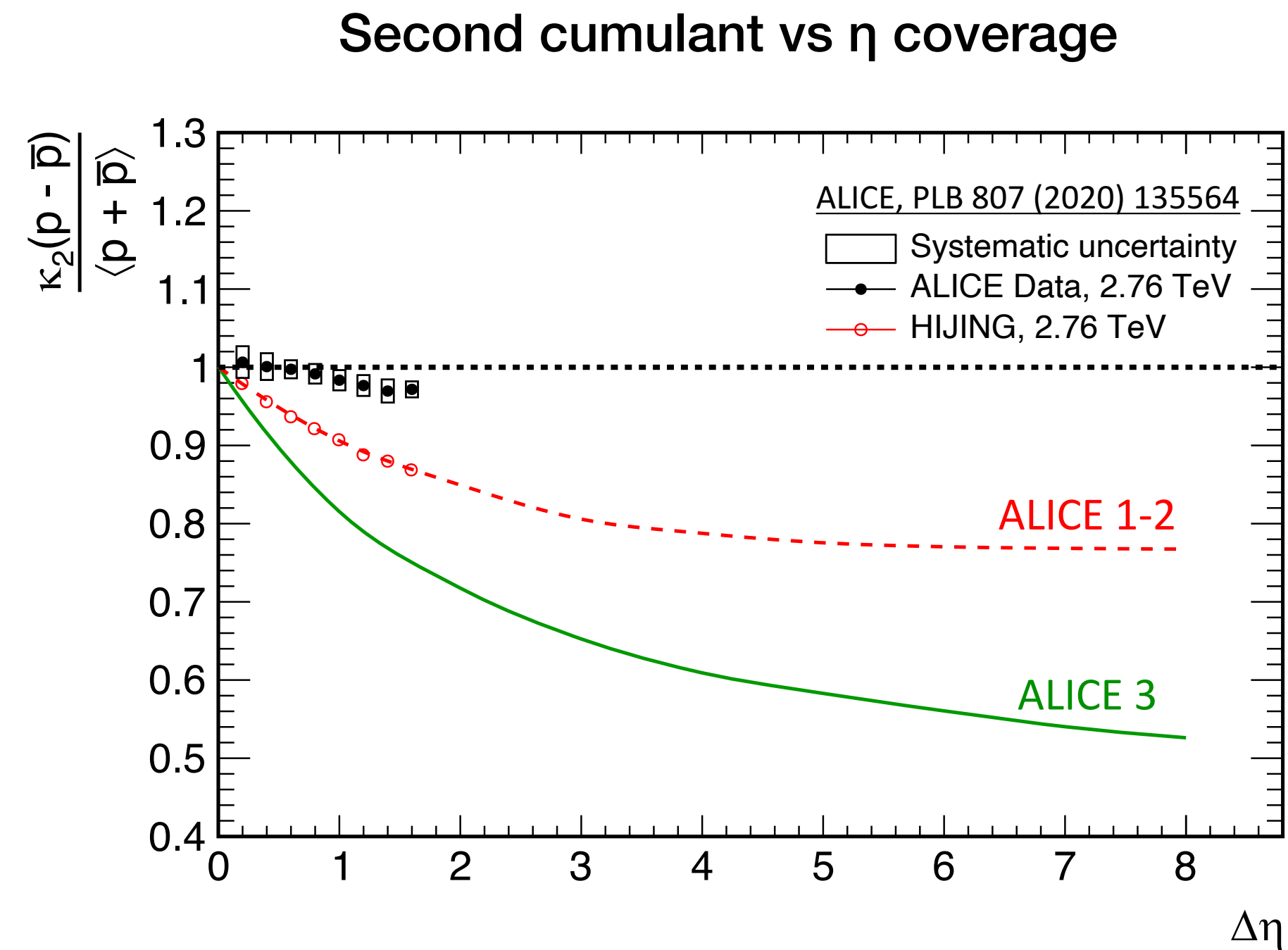
Large enhancements: unique sensitivity to thermalisation and hadronisation dynamics

ALICE 3: unique experimental access in Pb-Pb collisions

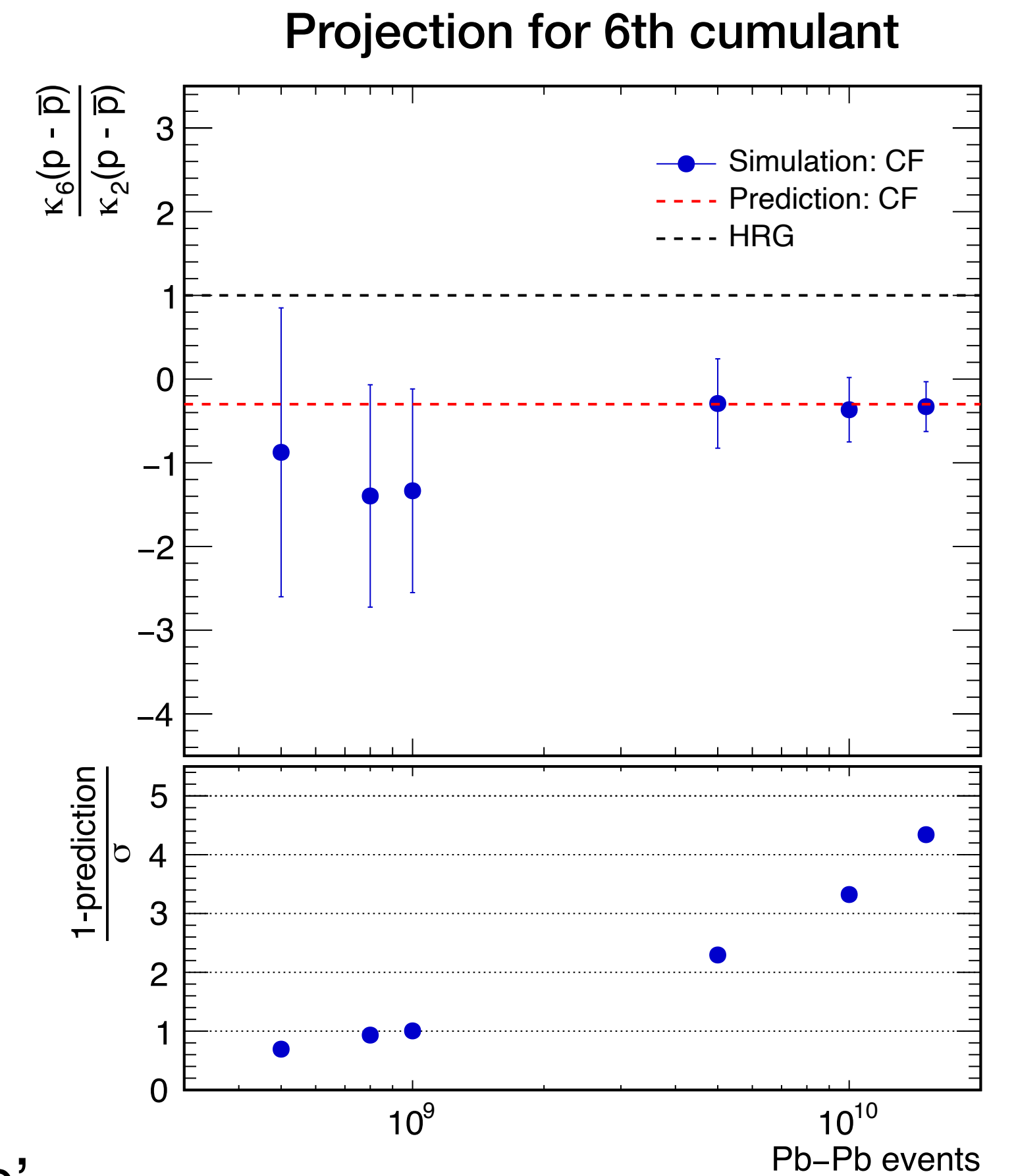
Net-baryon fluctuations



ALICE 3: much larger baryon ID coverage in p_T and η



Second cumulant probes baryon number conservation — ‘correlation distance’

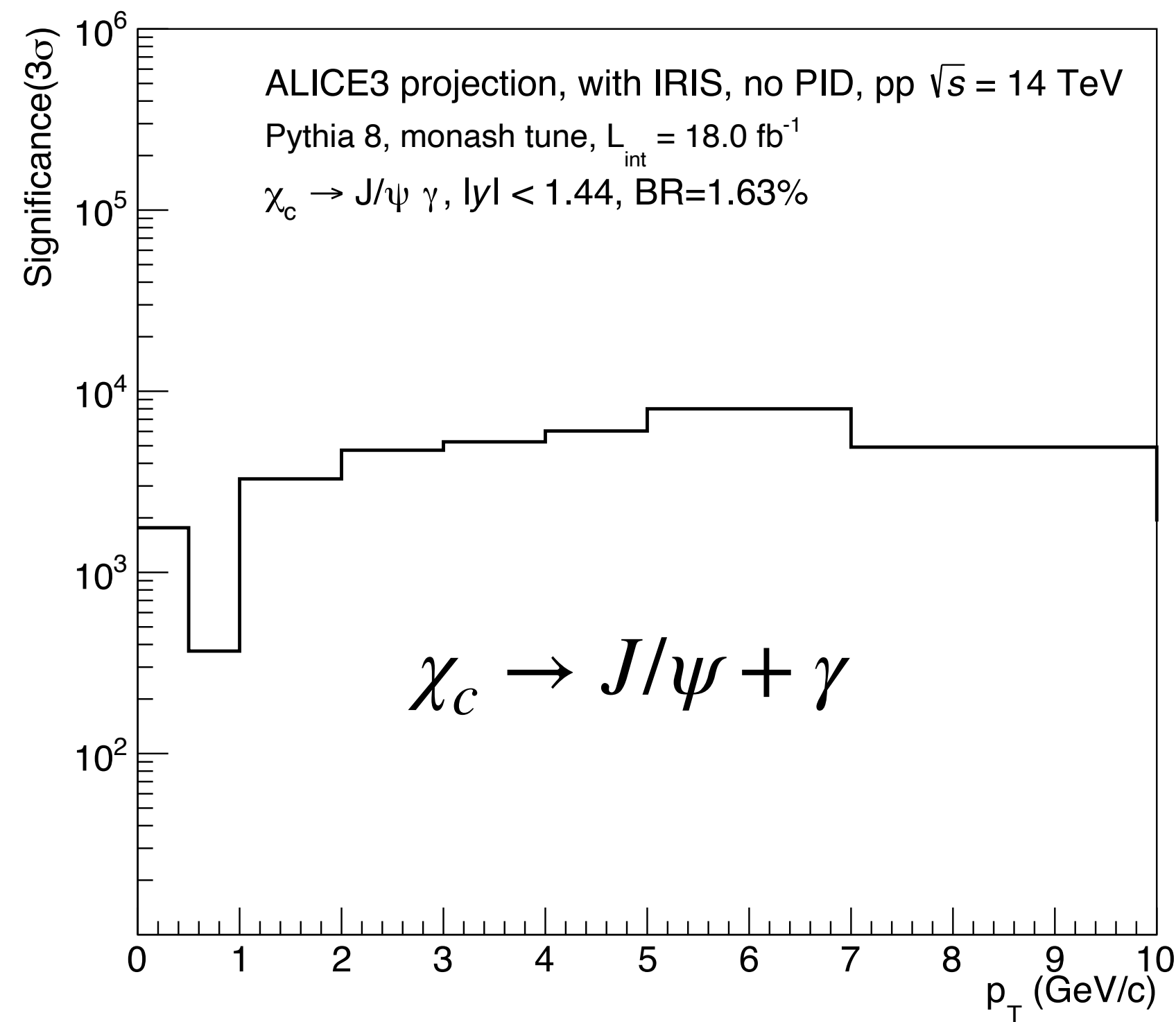


Higher cumulants: sensitive to baryon number susceptibility and critical behaviour

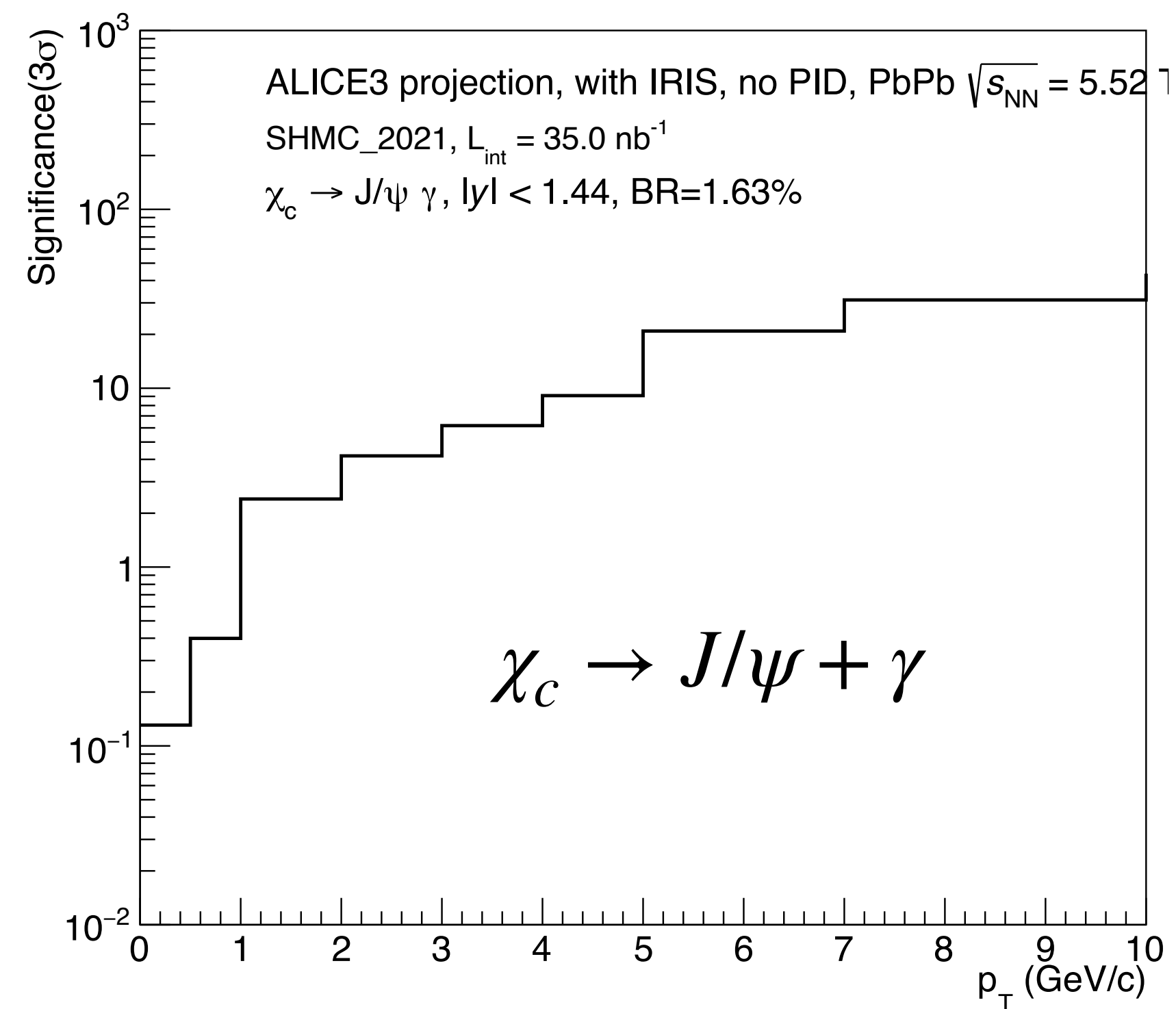
4 σ observation in reach with ALICE 3

Quarkonia and $\chi_{c1}(3872)$

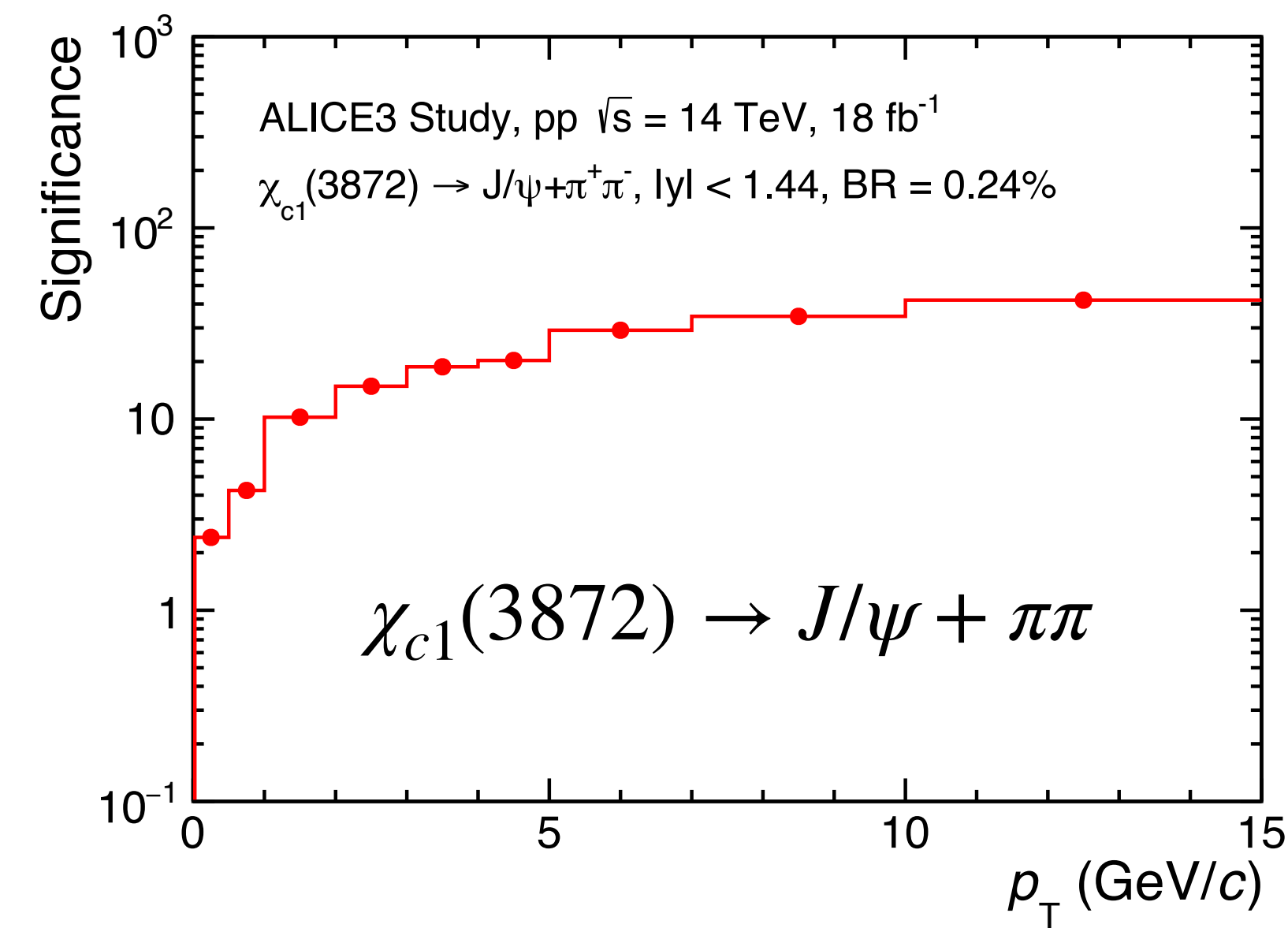
pp significance



Pb-Pb significance



pp significance

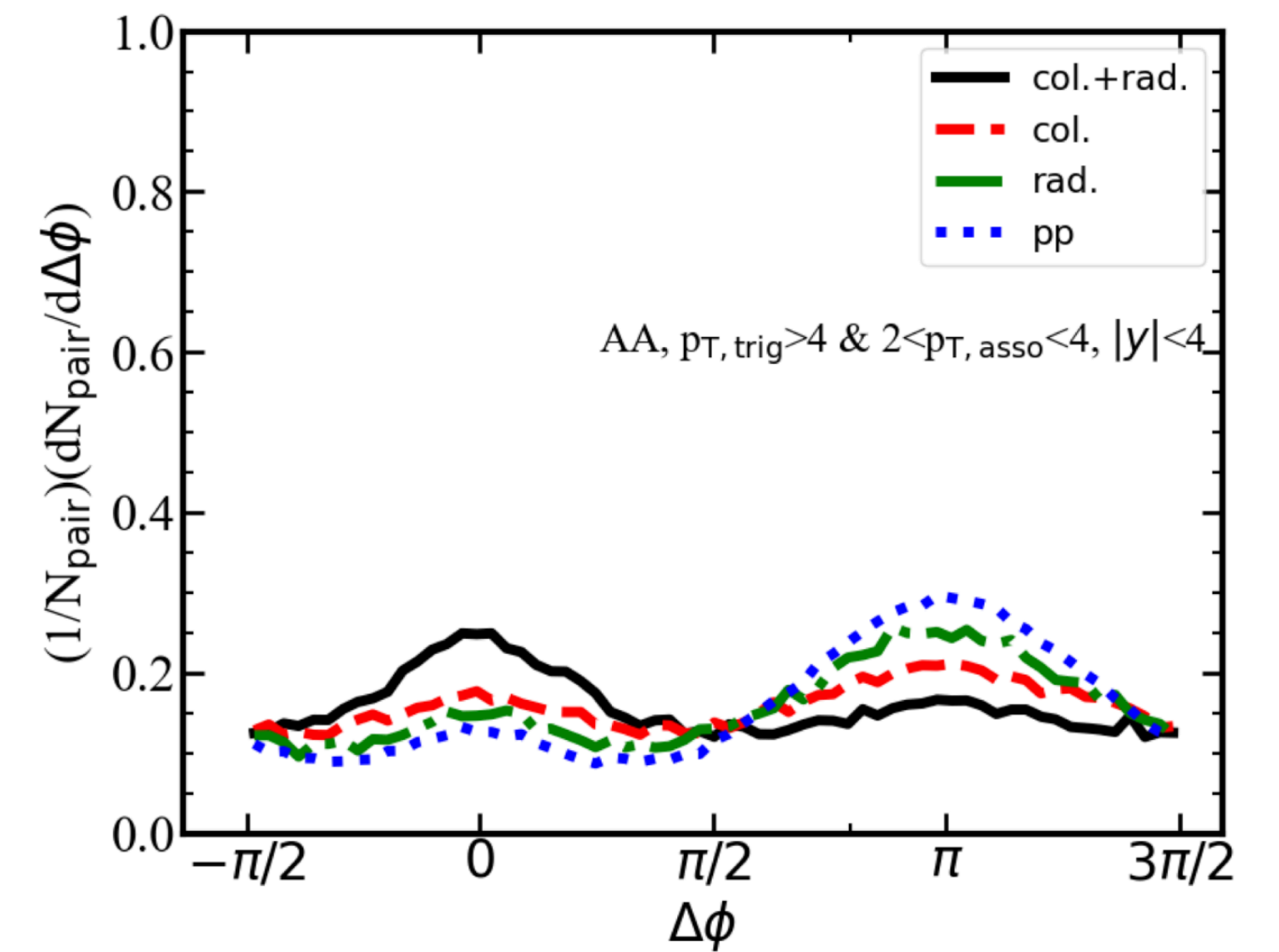
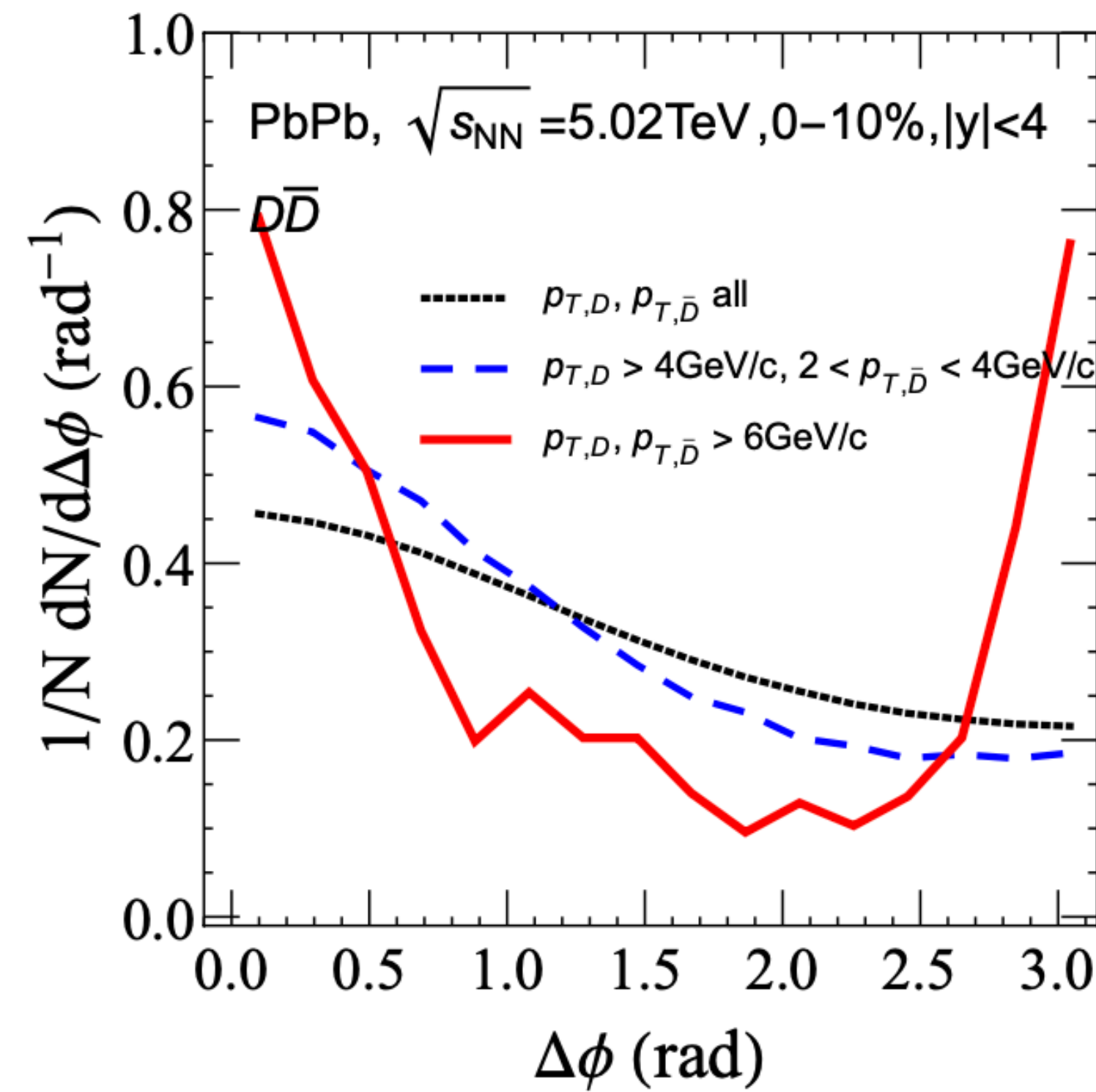
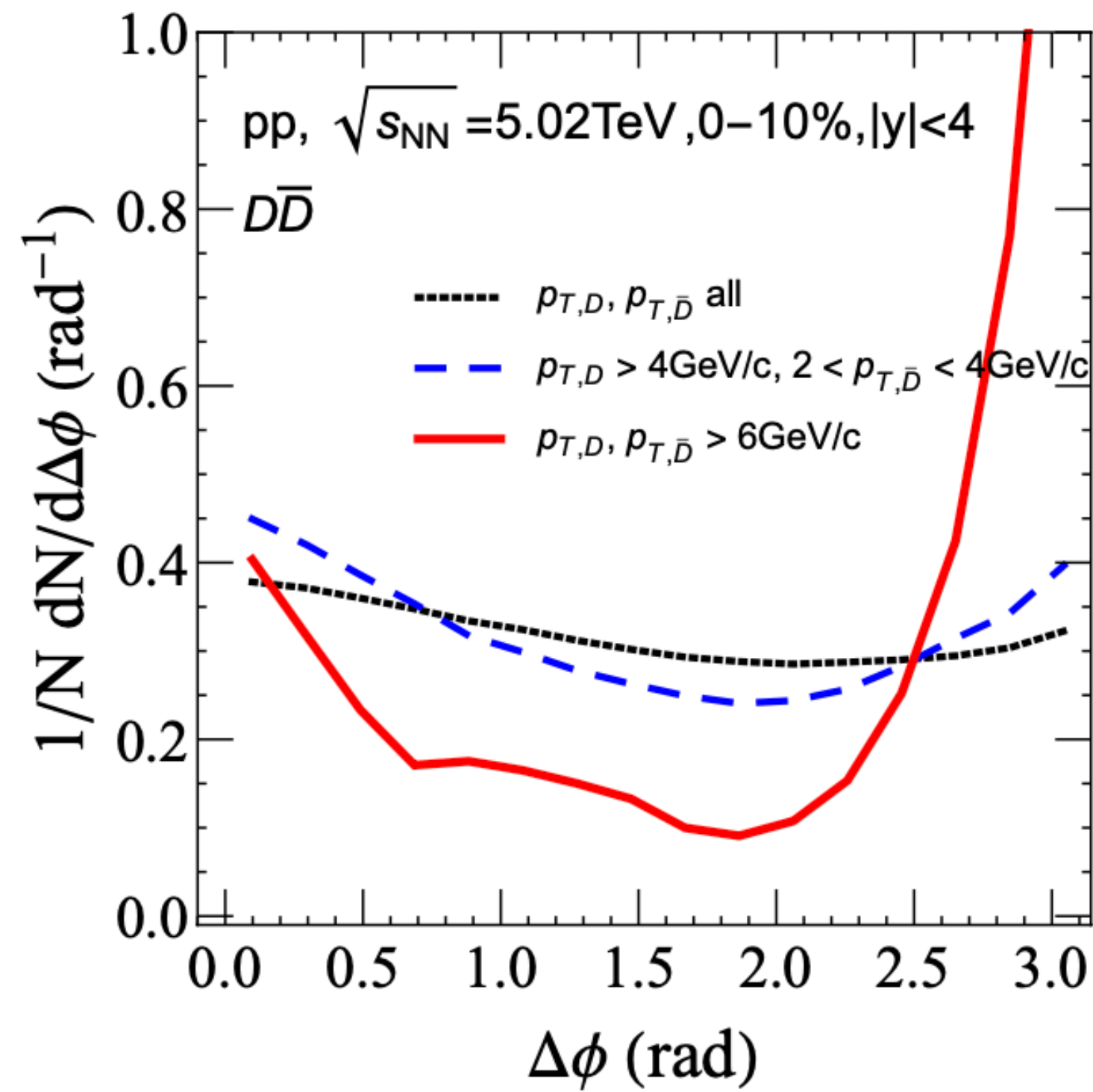


ALICE 3: $\chi_{c1}(3872)$
 down to low p_T in pp

Goal: understand formation and dissociation of $c\bar{c}$ states

ALICE 3 muon ID and ECal enable measurement of χ_c in Pb-Pb collisions

Charm azimuthal correlations



EPOS4HQ, in prep.

S. Cao et al.,
 private comm.,
 based on
PLB 838 (2023)
 137733