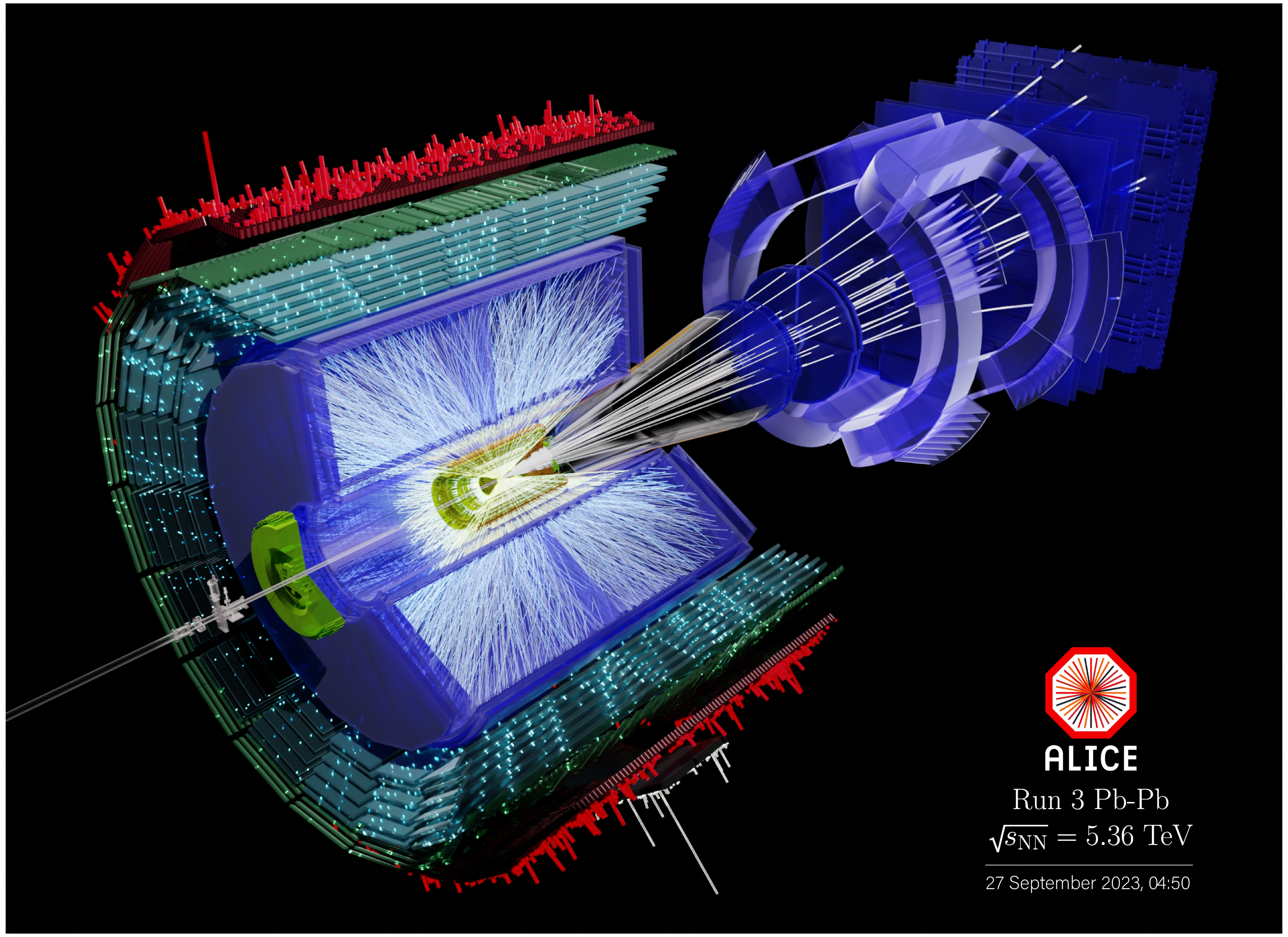
ALICE future plans

Marco van Leeuwen,
Nikhef and CERN

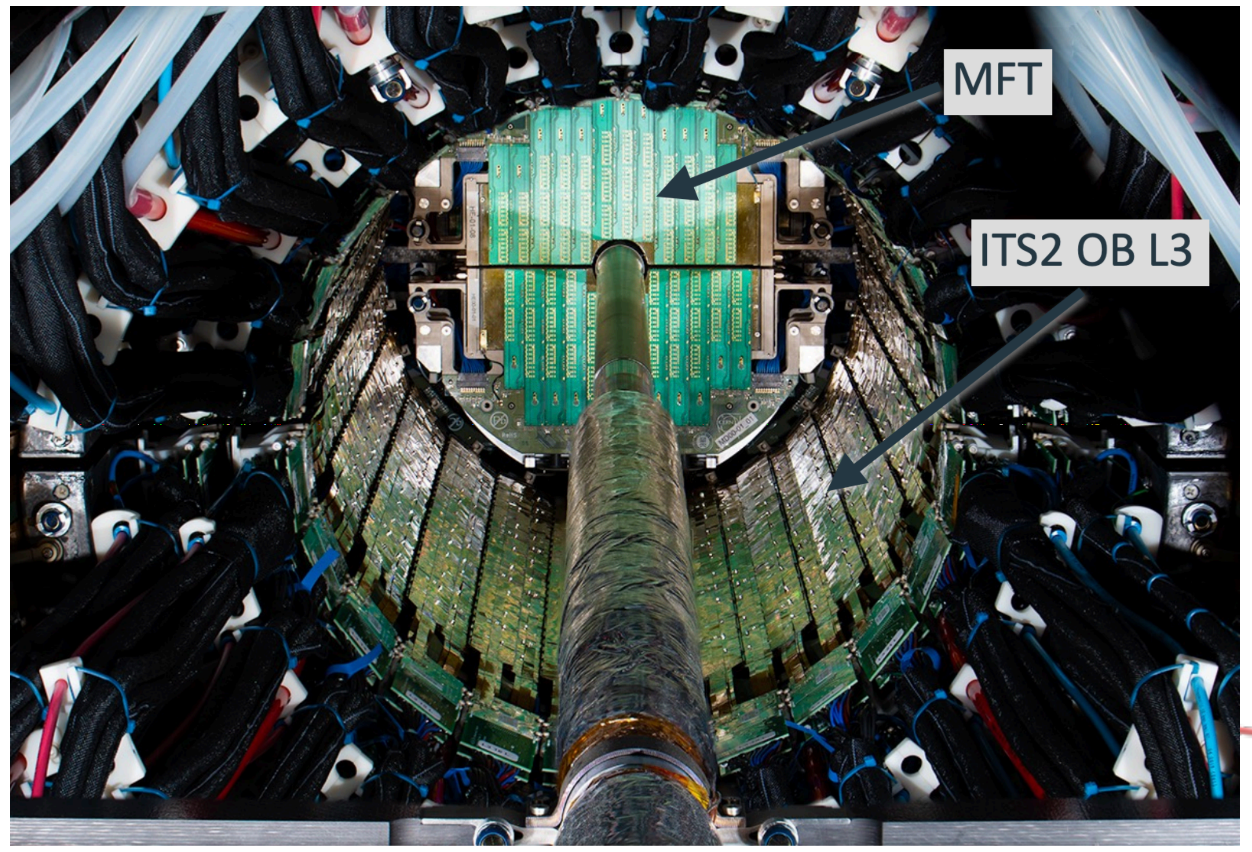


ALICE USA meeting - Open session

Yale University 31 May 2024

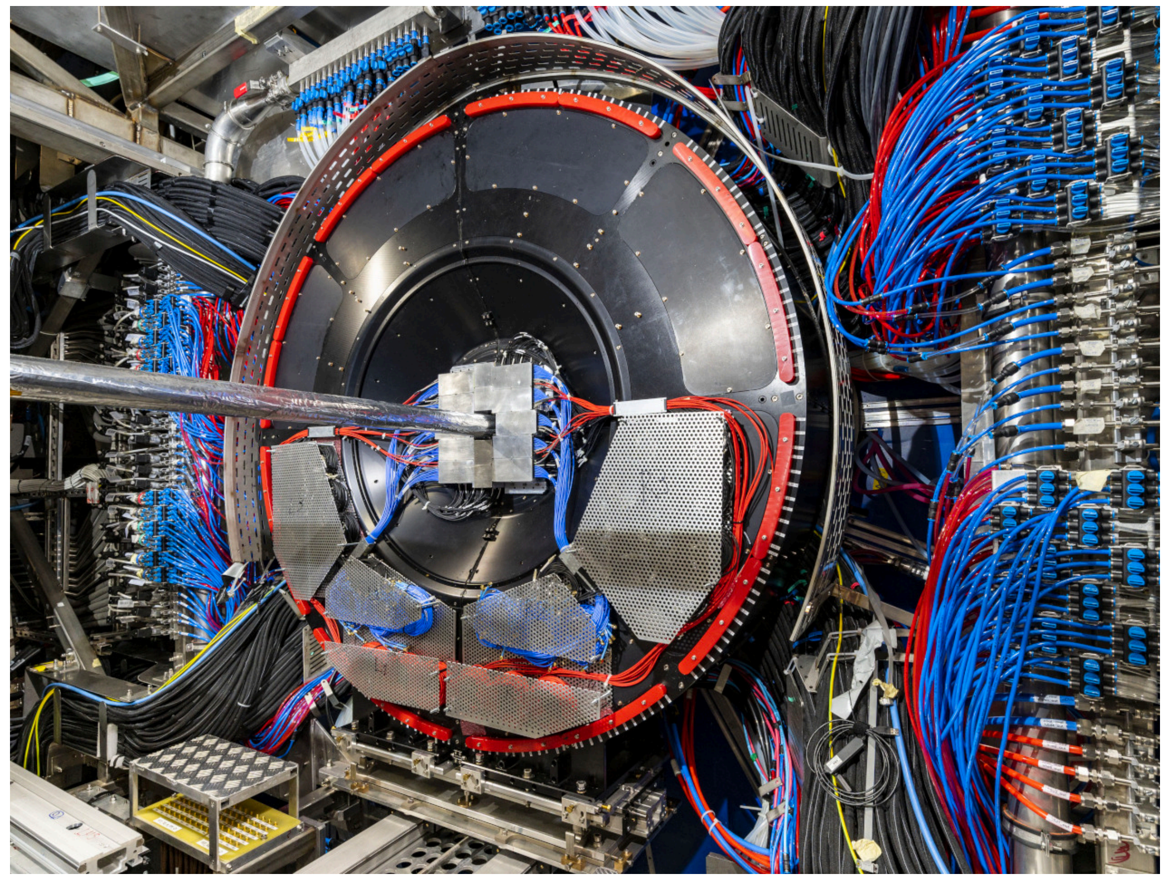
ALICE upgrades in Long Shutdown 2 (2019-2021)

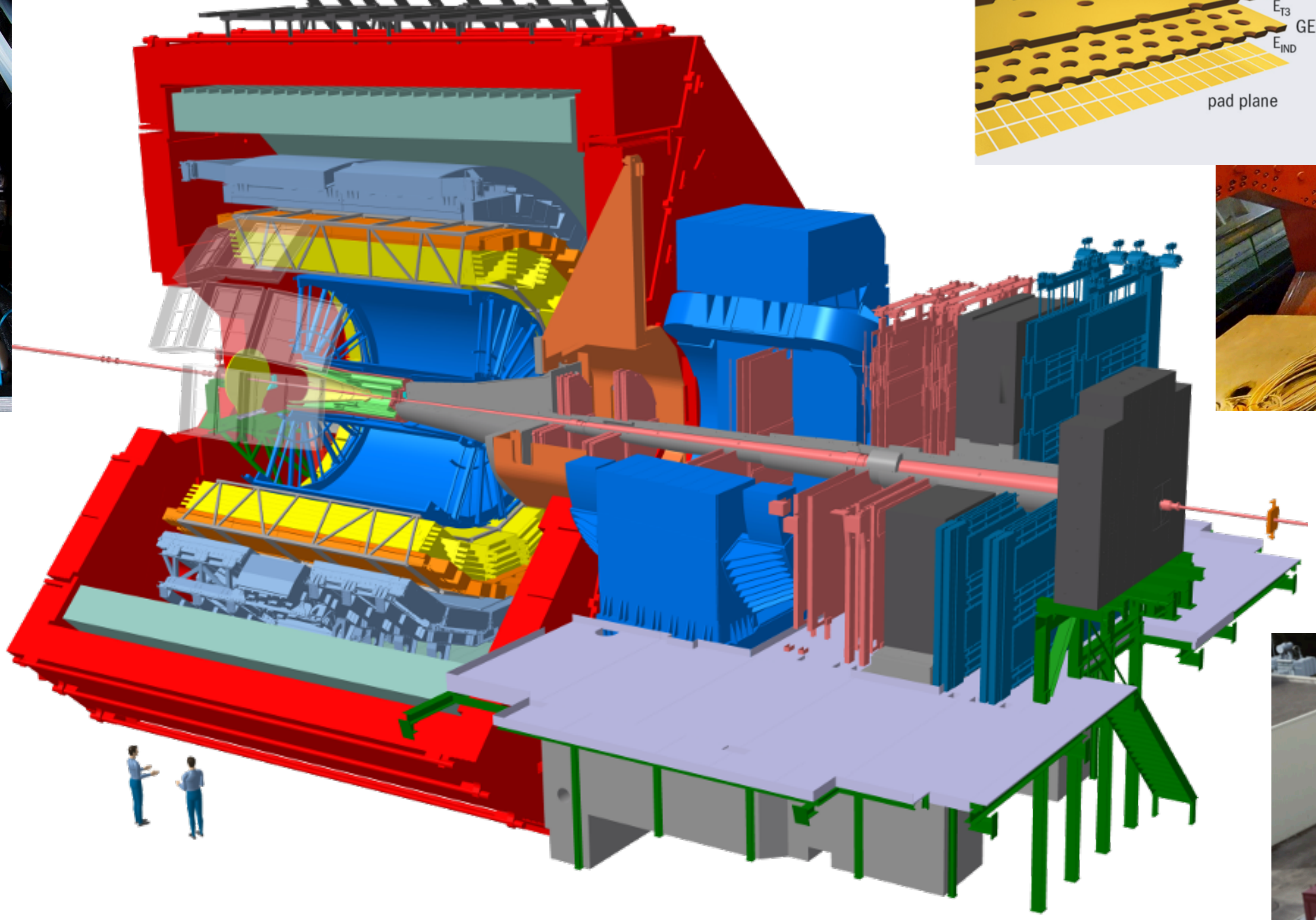
New ITS and MFT

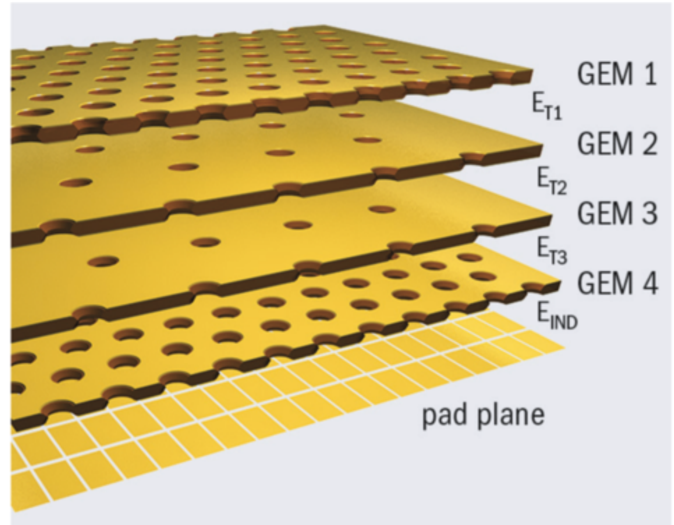


Full pixel detector
Improved spatial resolution

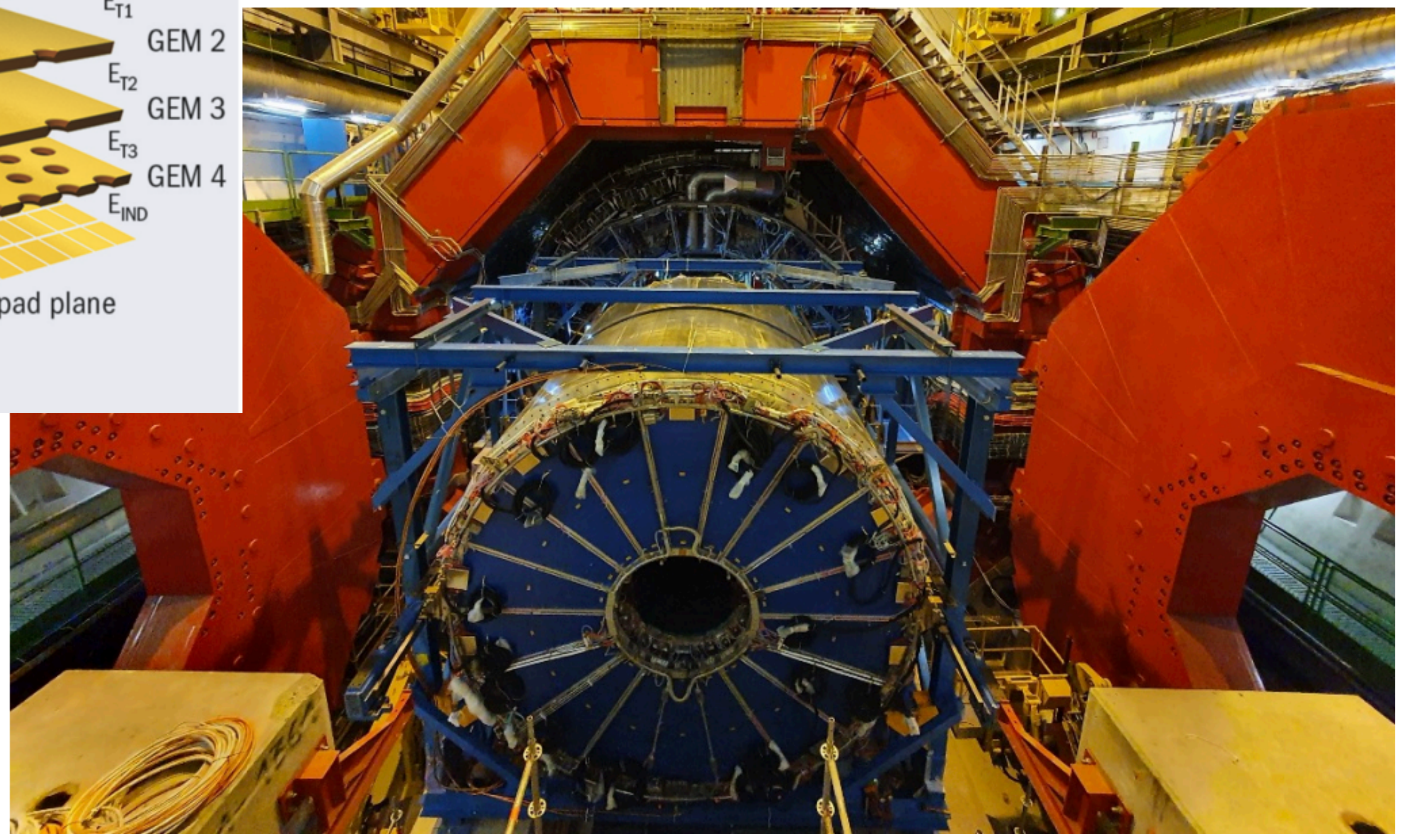
Fast Interaction Trigger







TPC: GEM readout



Continuous readout

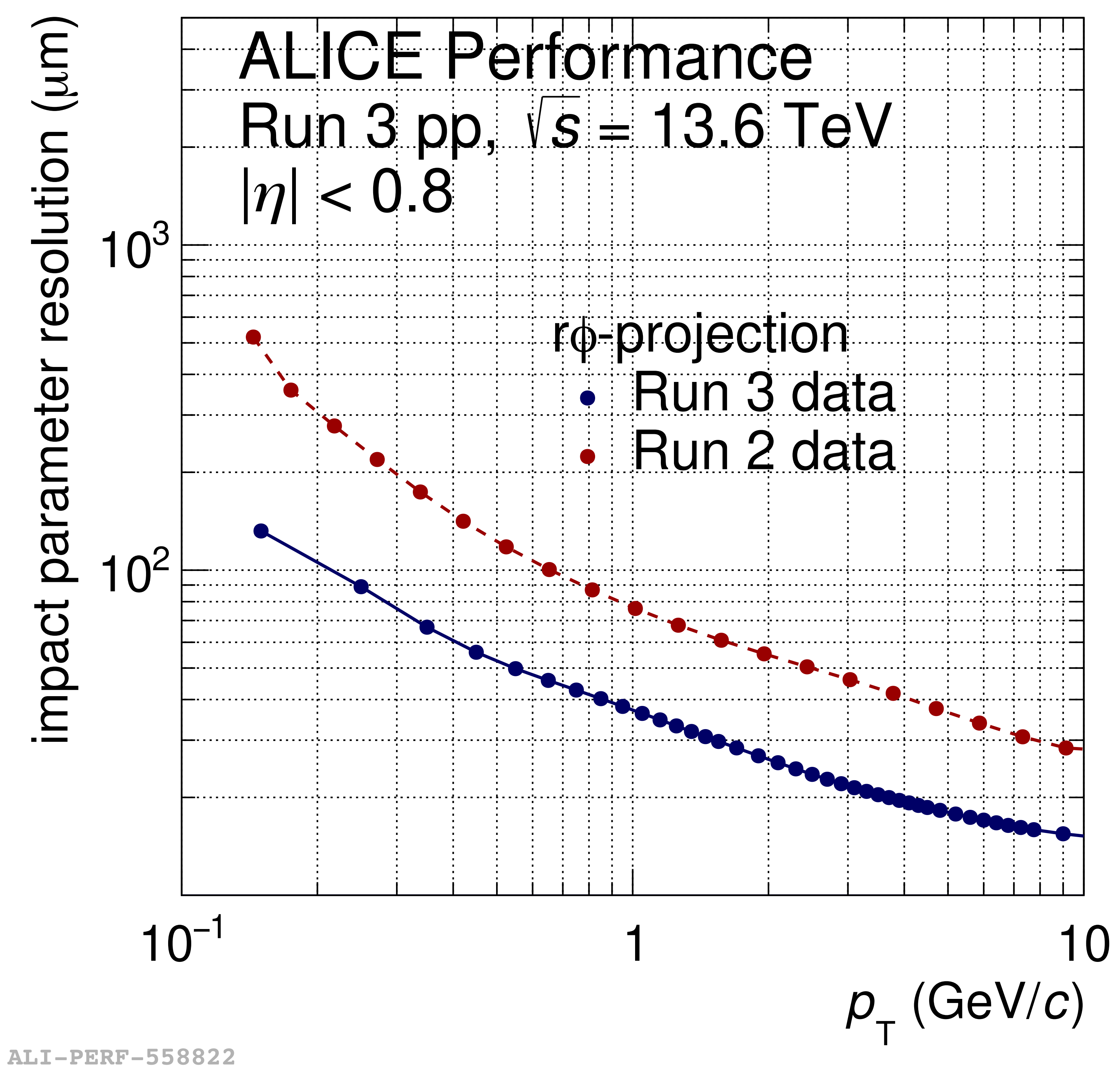
Online event processing

ALICE LS2 upgrade paper: arXiv:2302.01238

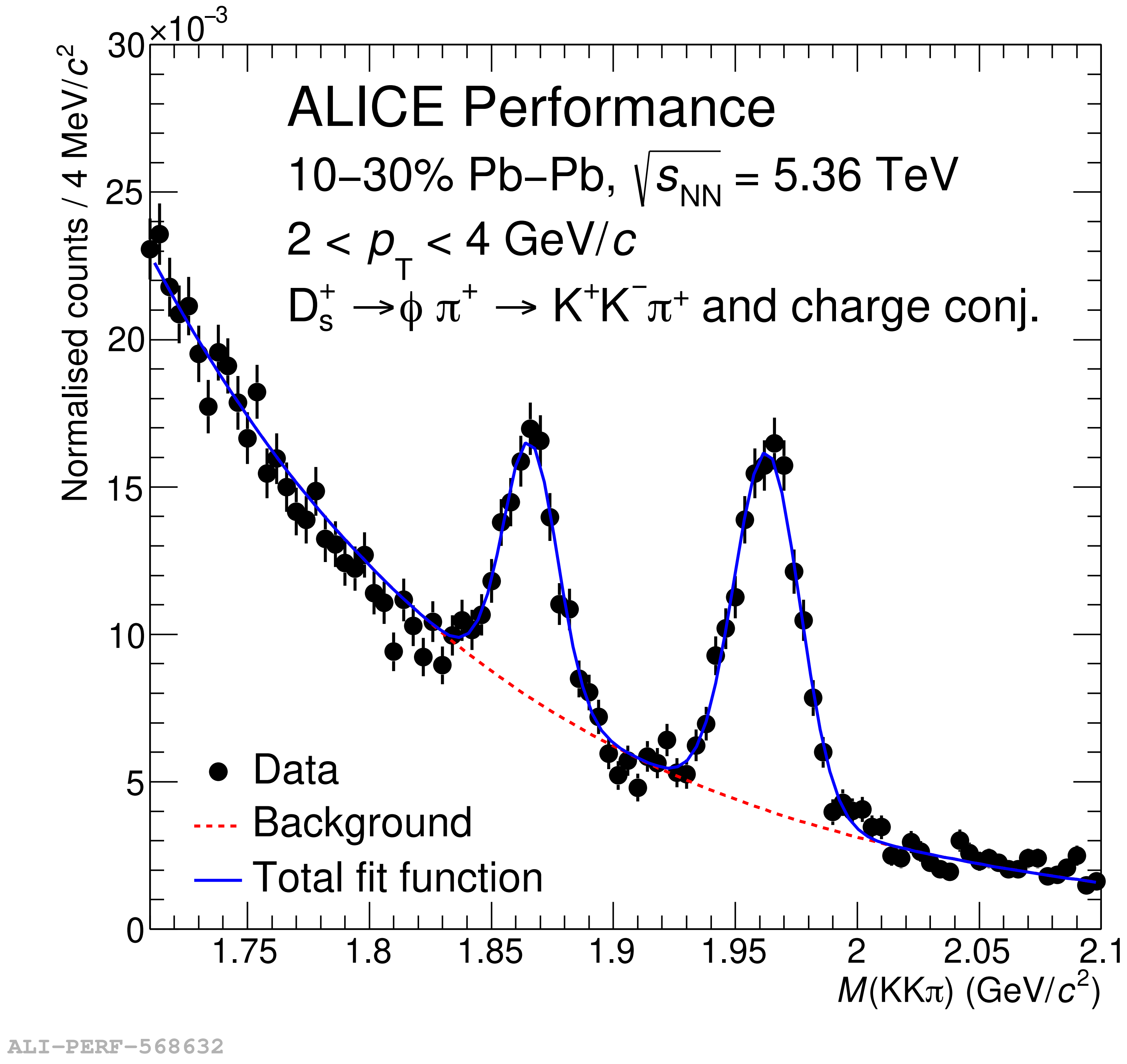
Run 3, 4: collect 13 nb^{-1} Pb-Pb: 50x more minimum bias data; 10x more triggered data

Run-3 physics performance: some examples

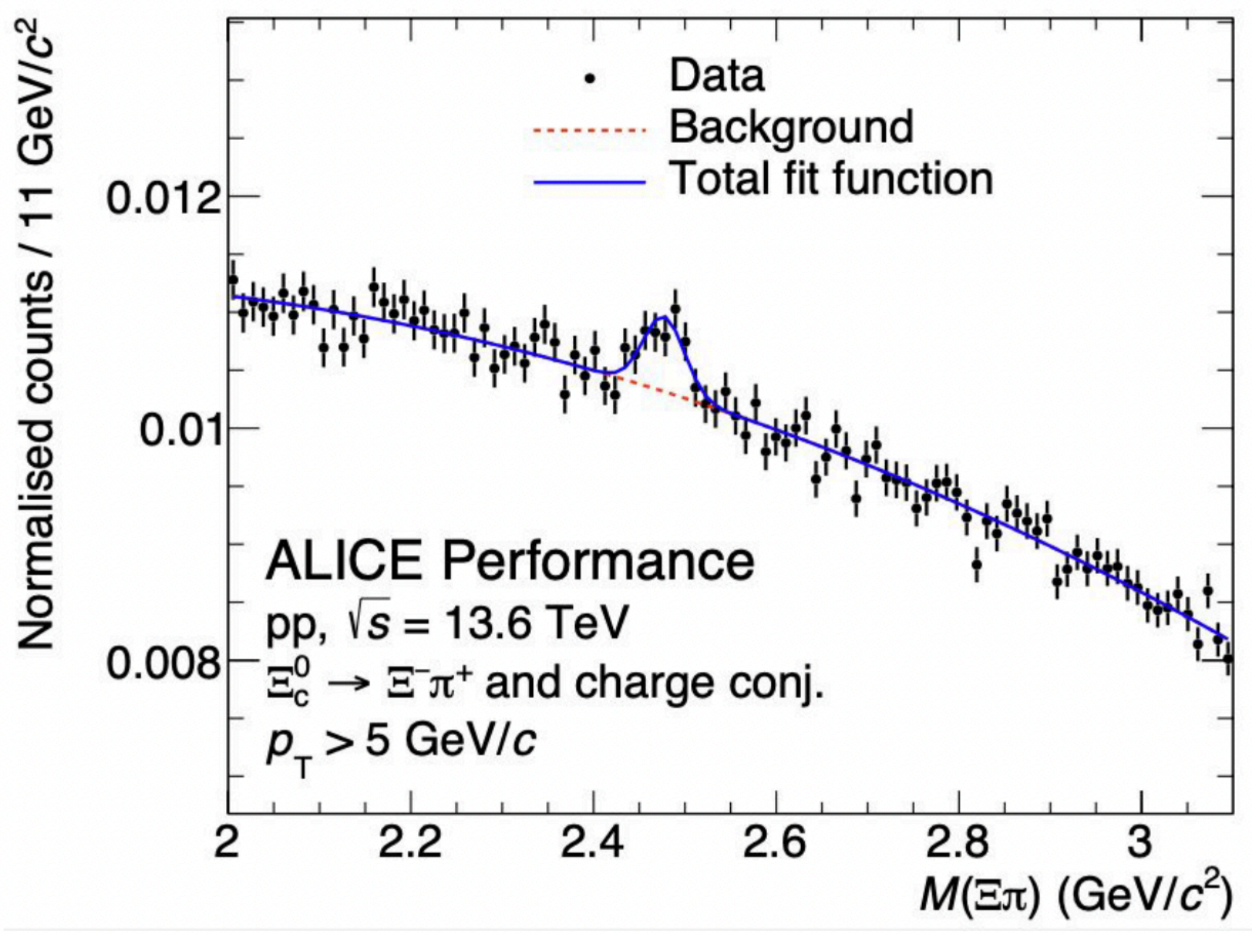
Impact parameter resolution



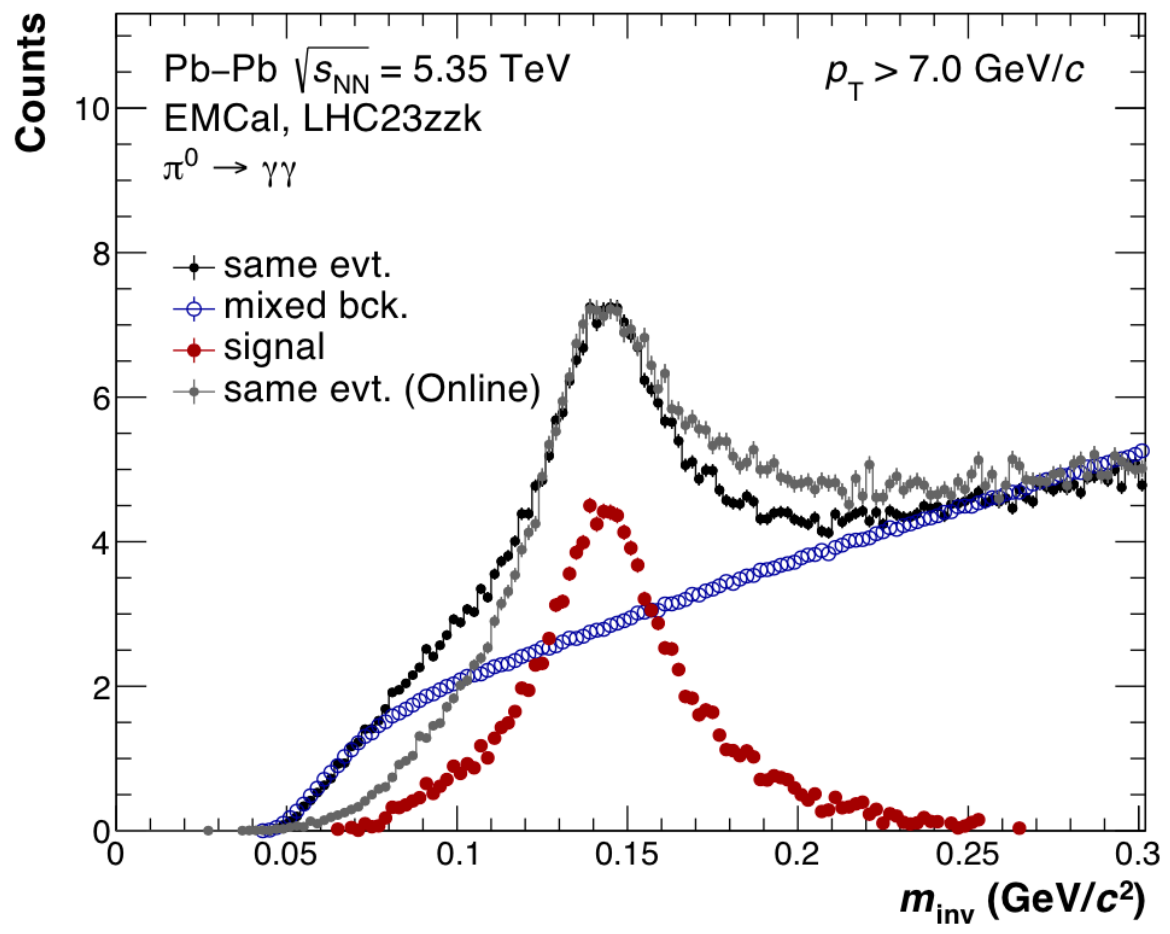
D mesons in Pb-Pb



$\Xi_c^0 \to \Xi^-\pi^+$



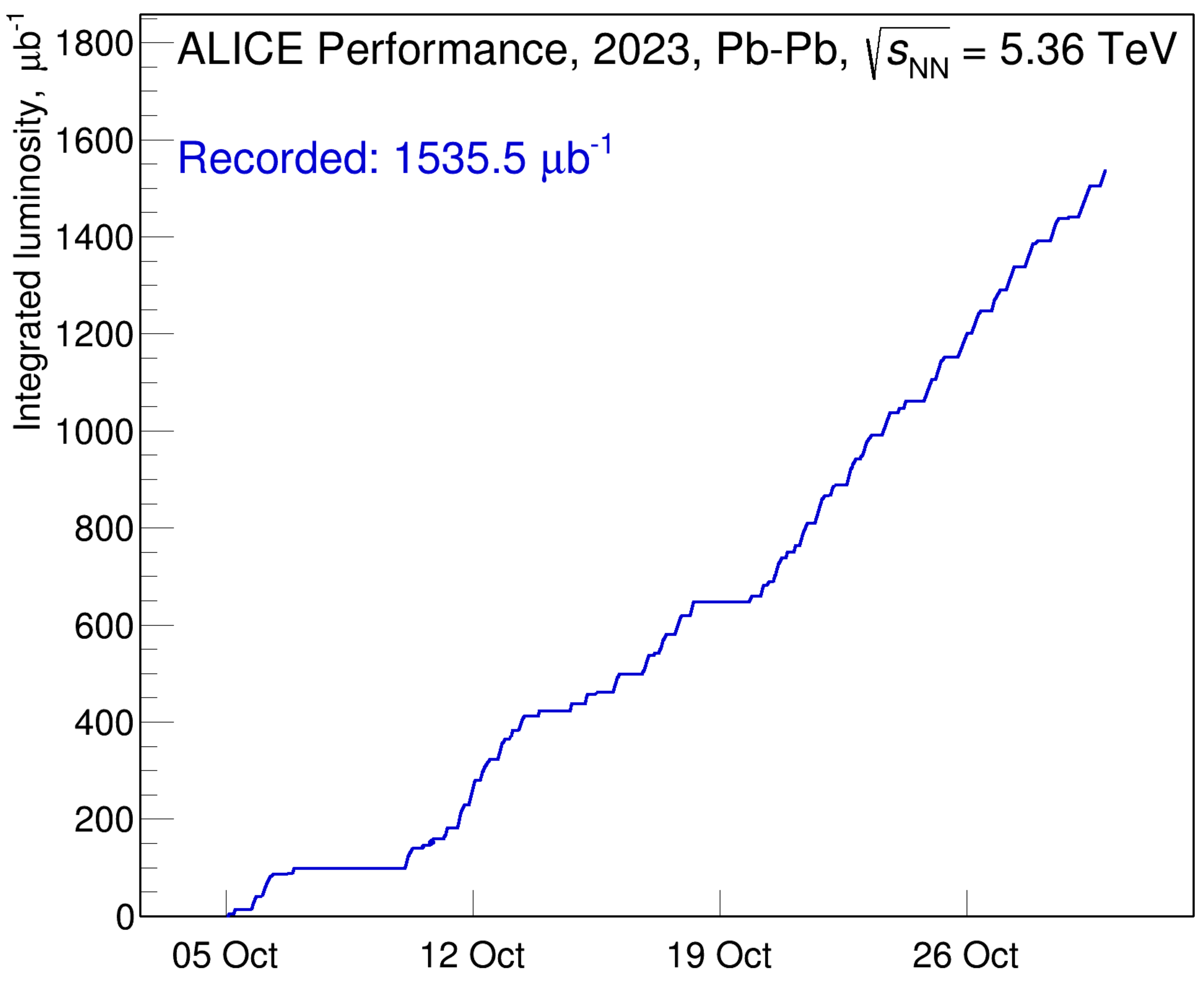
π^0 in Pb-Pb



LS2 upgrades work as expected, first physics results shown at QM last year, more new results at SQM and LHCP

Run 3 data taking

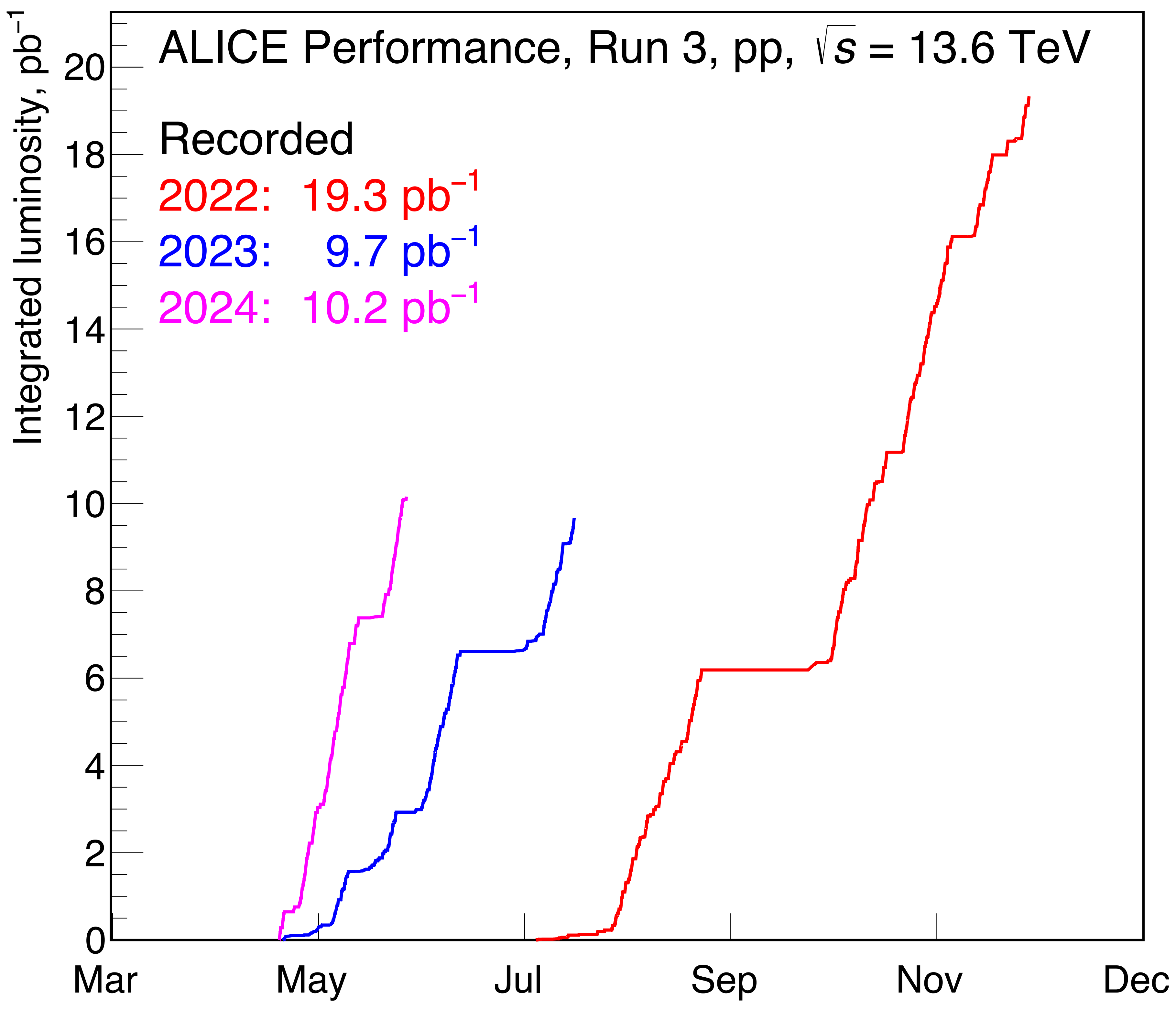
Recorded Pb-Pb luminosity



Successful 2023 heavy-ion run
collected 1.6 nb^{-1}, approx. 11.5 G minimum bias events

~7x more central events than Run 1+2

Run p-p luminosity vs time

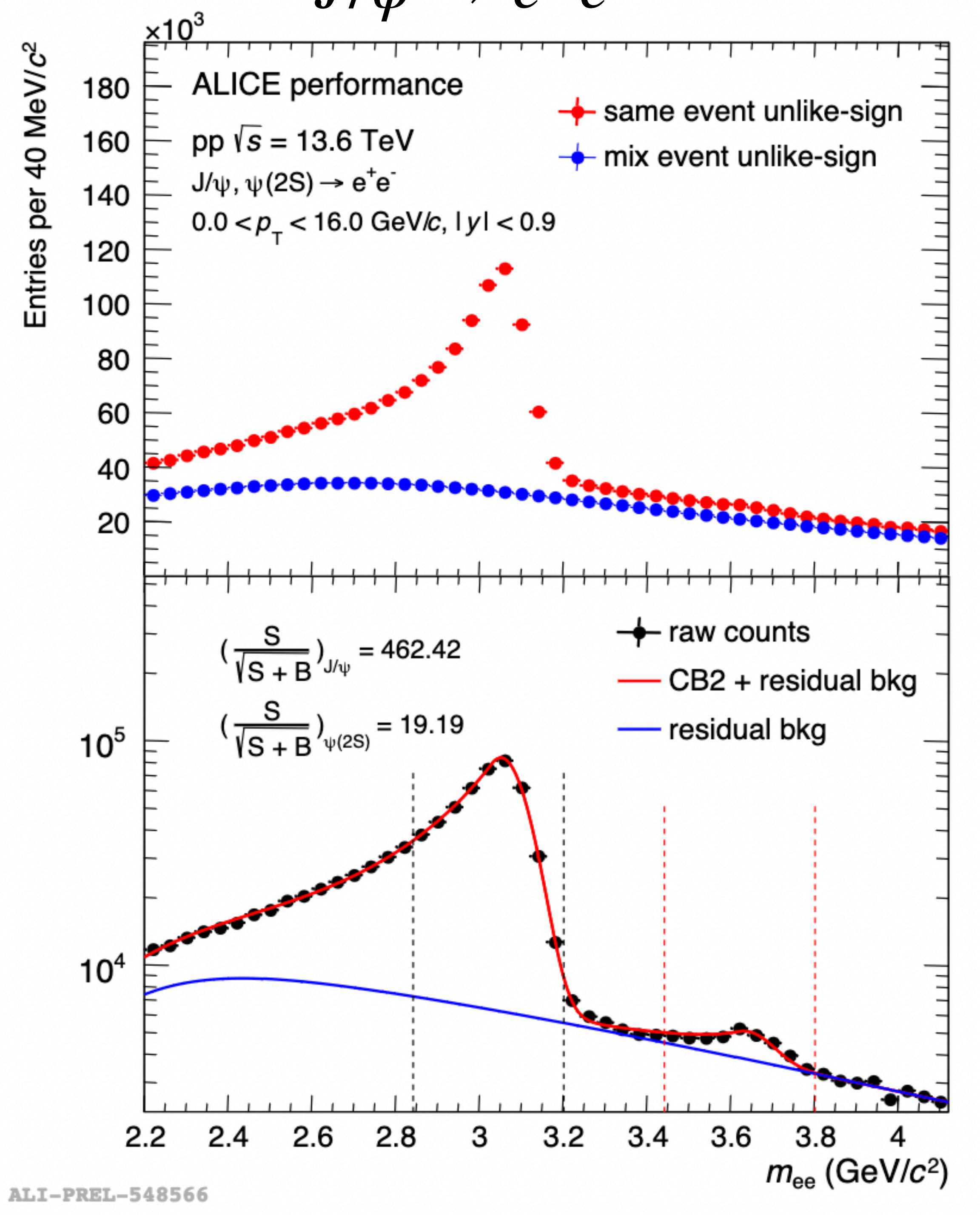


pp 2024 off to a good start: 10.2 pb^{-1} recorded
ALICE operational efficiency: 95%

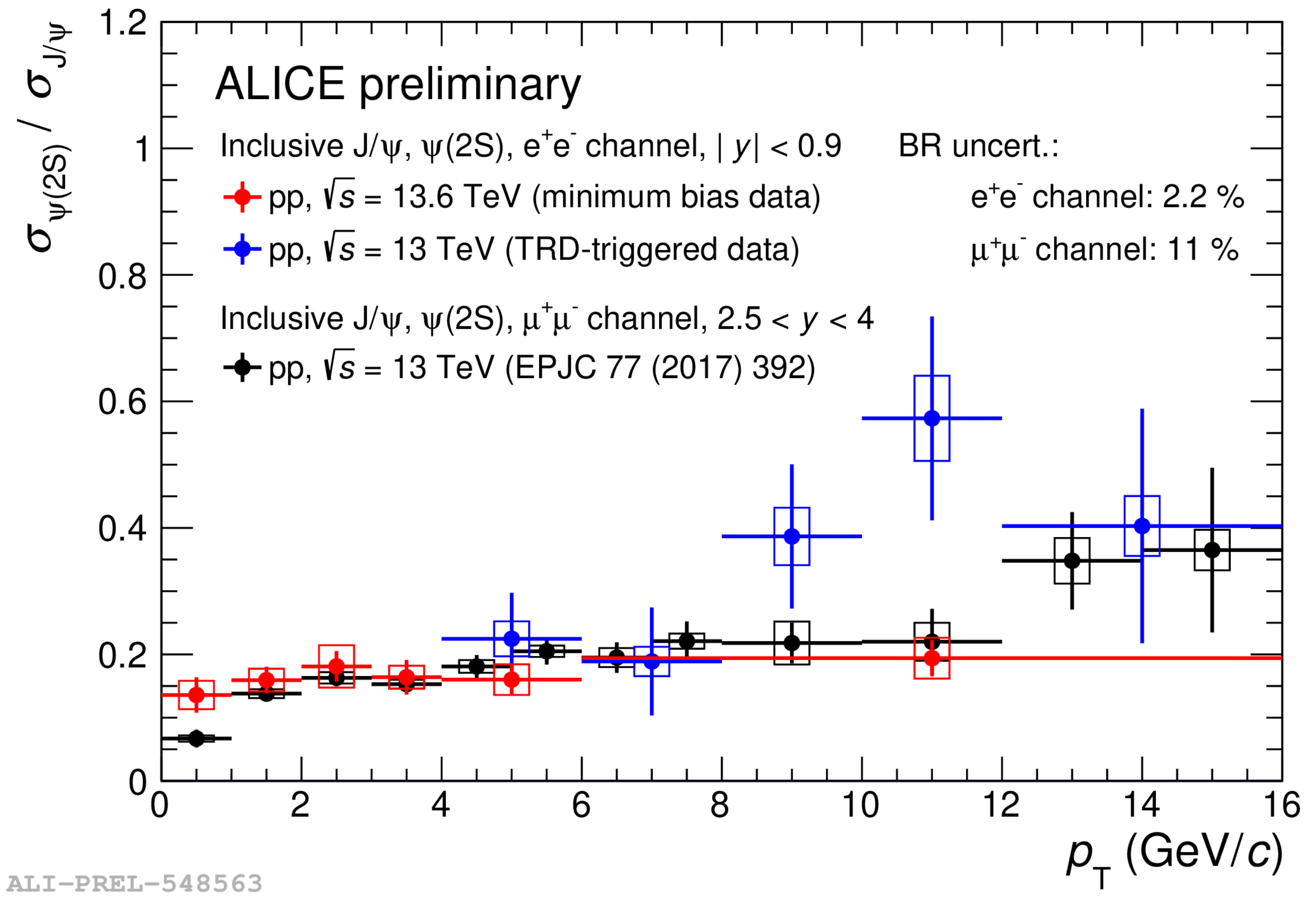
Data taking going very well: significantly more data collected in Run 3 than in Run 1 and 2 combined

Run 3 pp results: ψ(2s) to J/ψ ratio

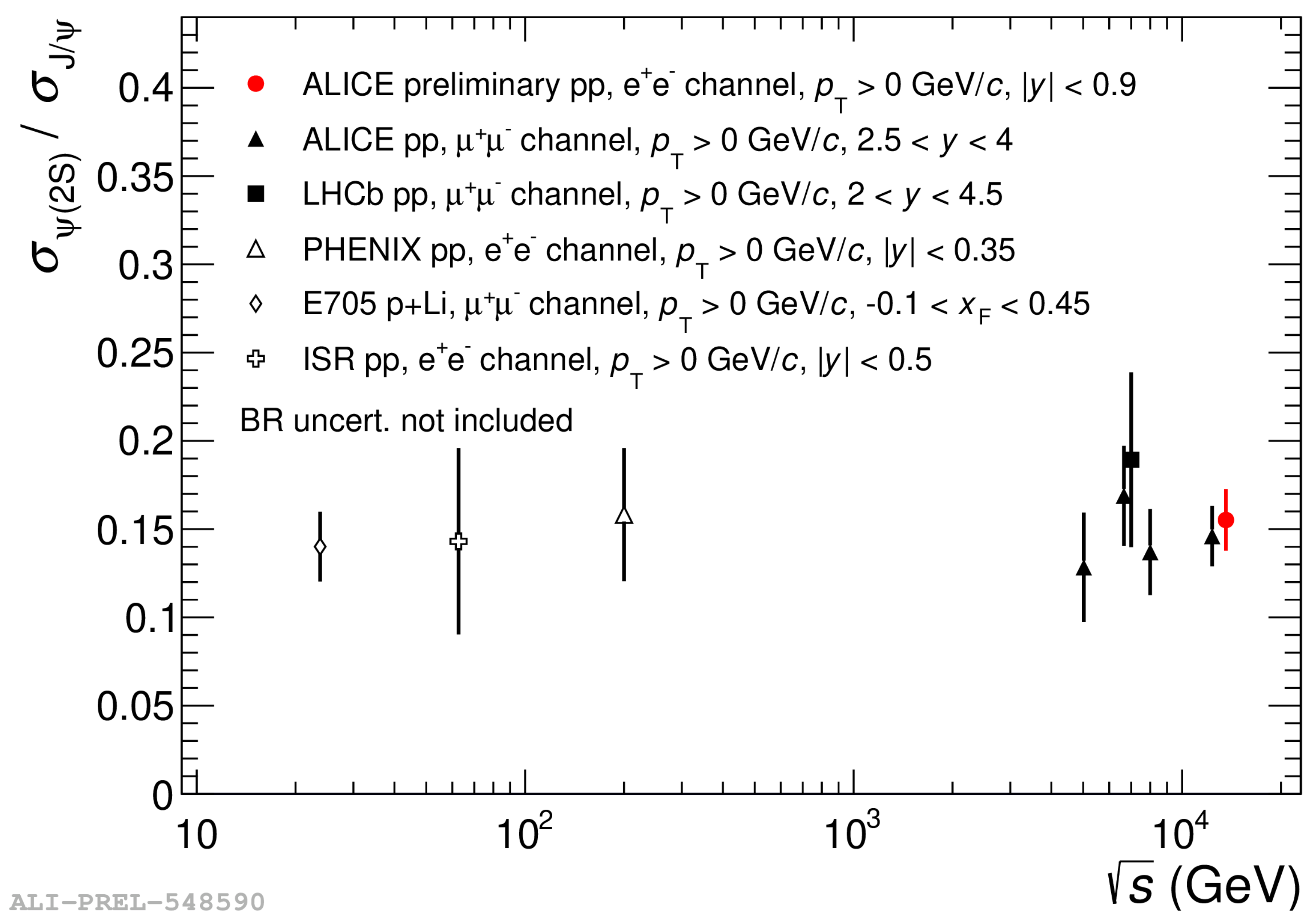
$J/\psi \rightarrow e^+e^-$



$\psi(2S)$ to J/ψ ratio vs p_T



Comparison to world data

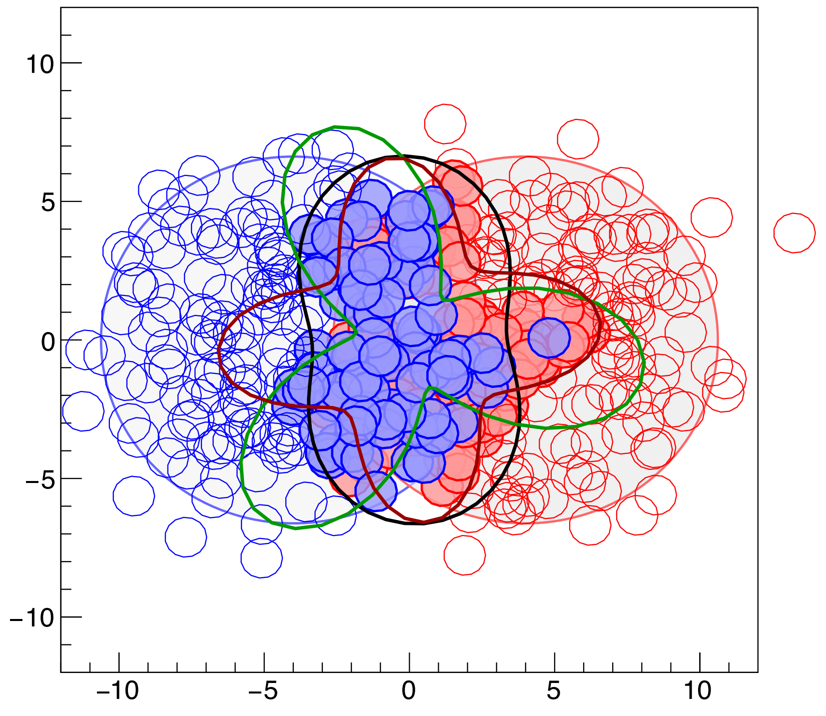


First measurement of ψ(2s) / J/ψ ratio at mid-rapidity down to zero p_T at LHC

Important contribution to available world data — understanding of formation process

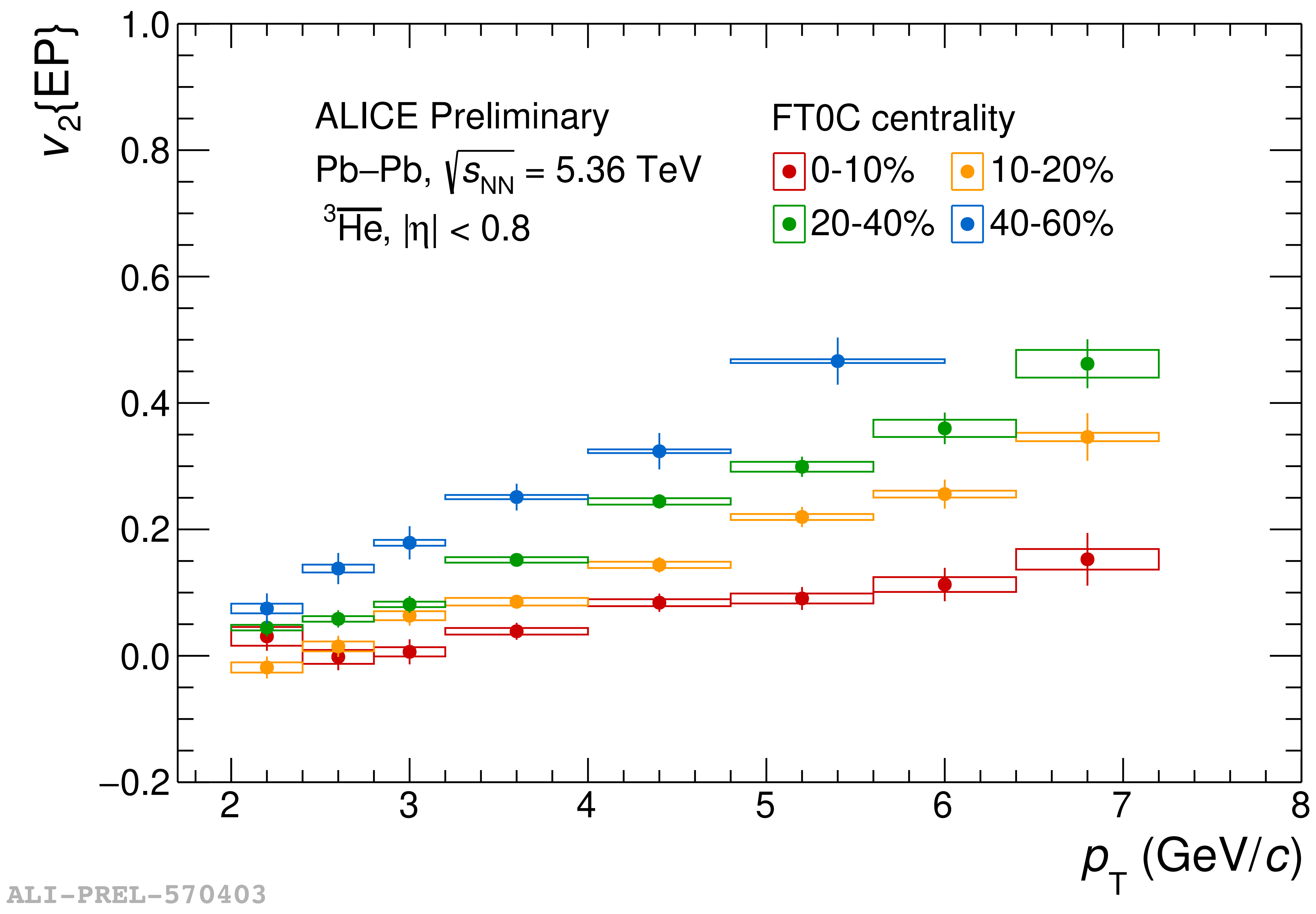
Run 3 results: $^{3}\overline{\mathrm{He}}$ elliptic flow

New run 3 result



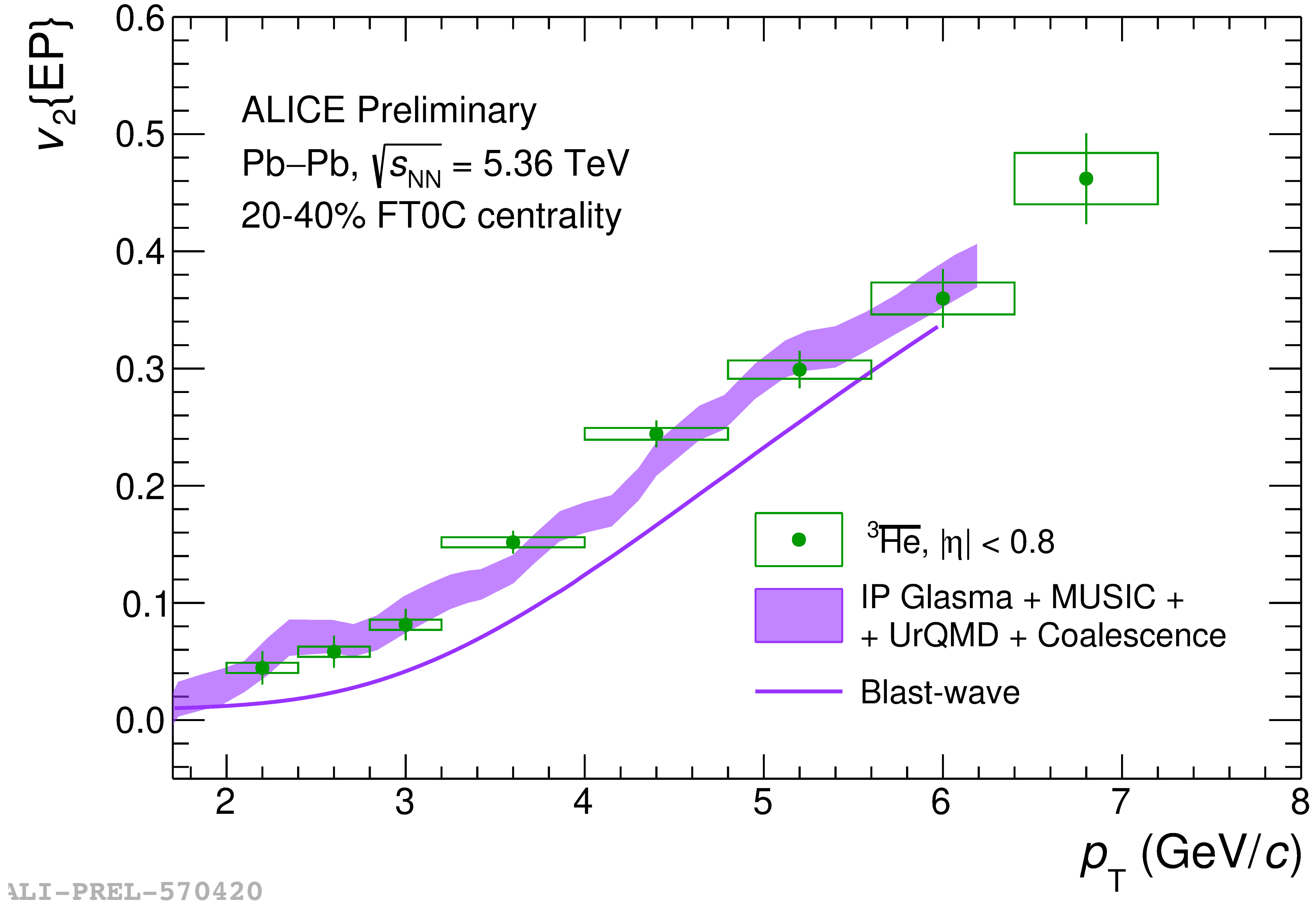
Elliptic flow:
azimuthal anisotropy
due to asymmetry
of initial state

v₂ vs pT



v_2 reflects geometry:
largest for mid-central collisions
small in central collisions

Comparison to models

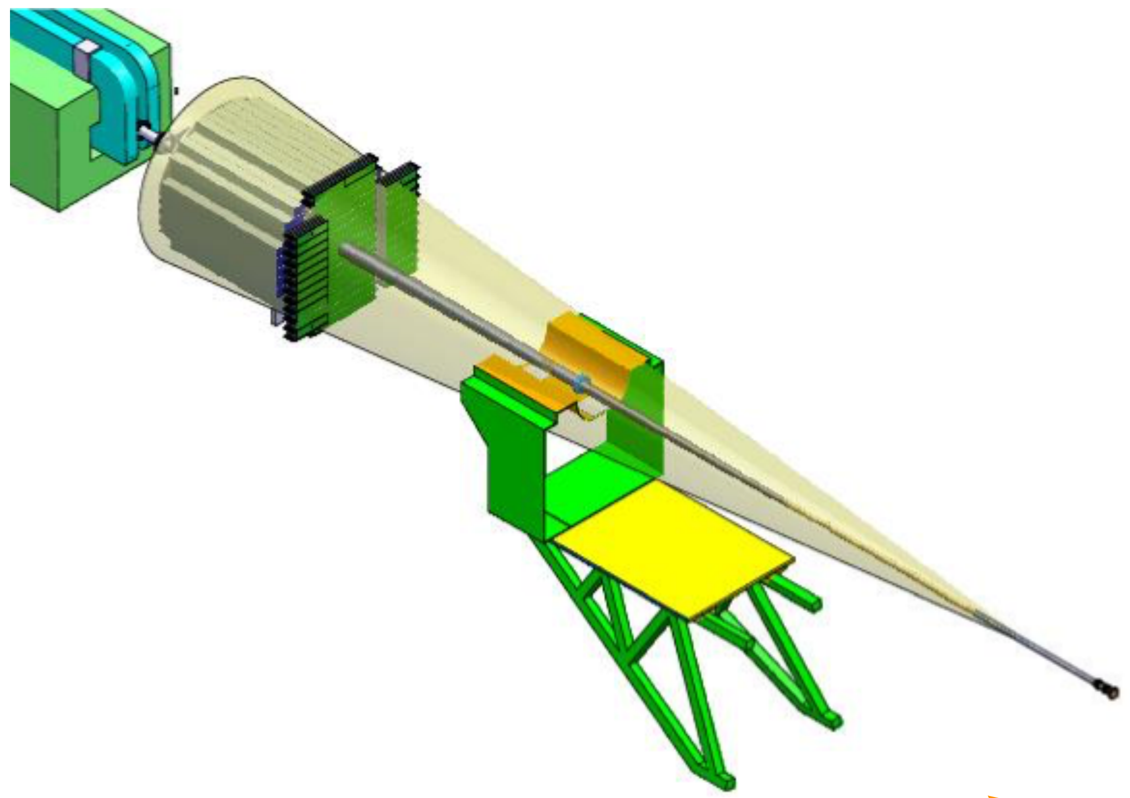


Measured v_2 agrees with coalescence model
Thermal freeze-out model — blast wave —
does not describe data

Upgrade projects

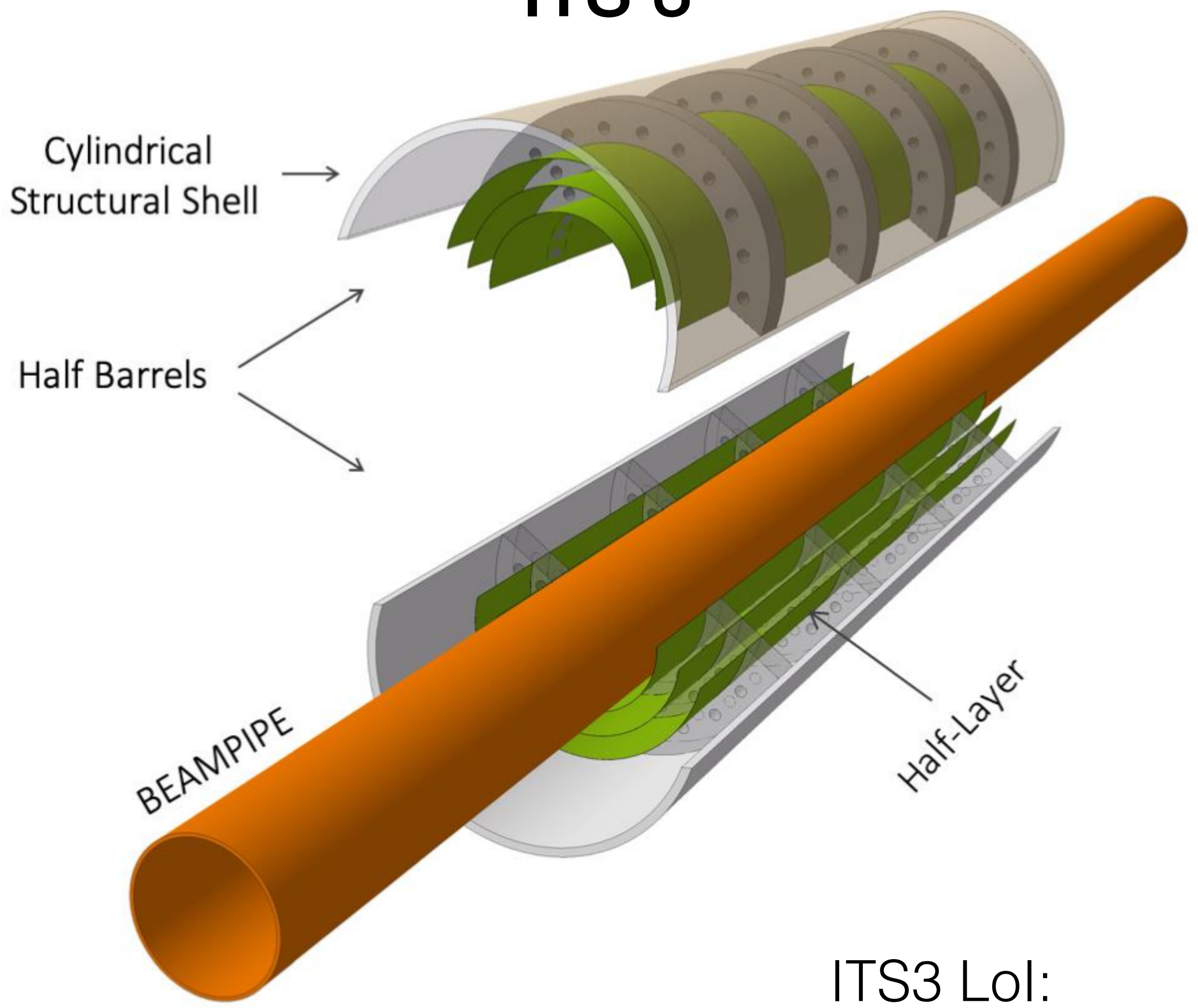
LS3 upgrades

Forward Calorimeter



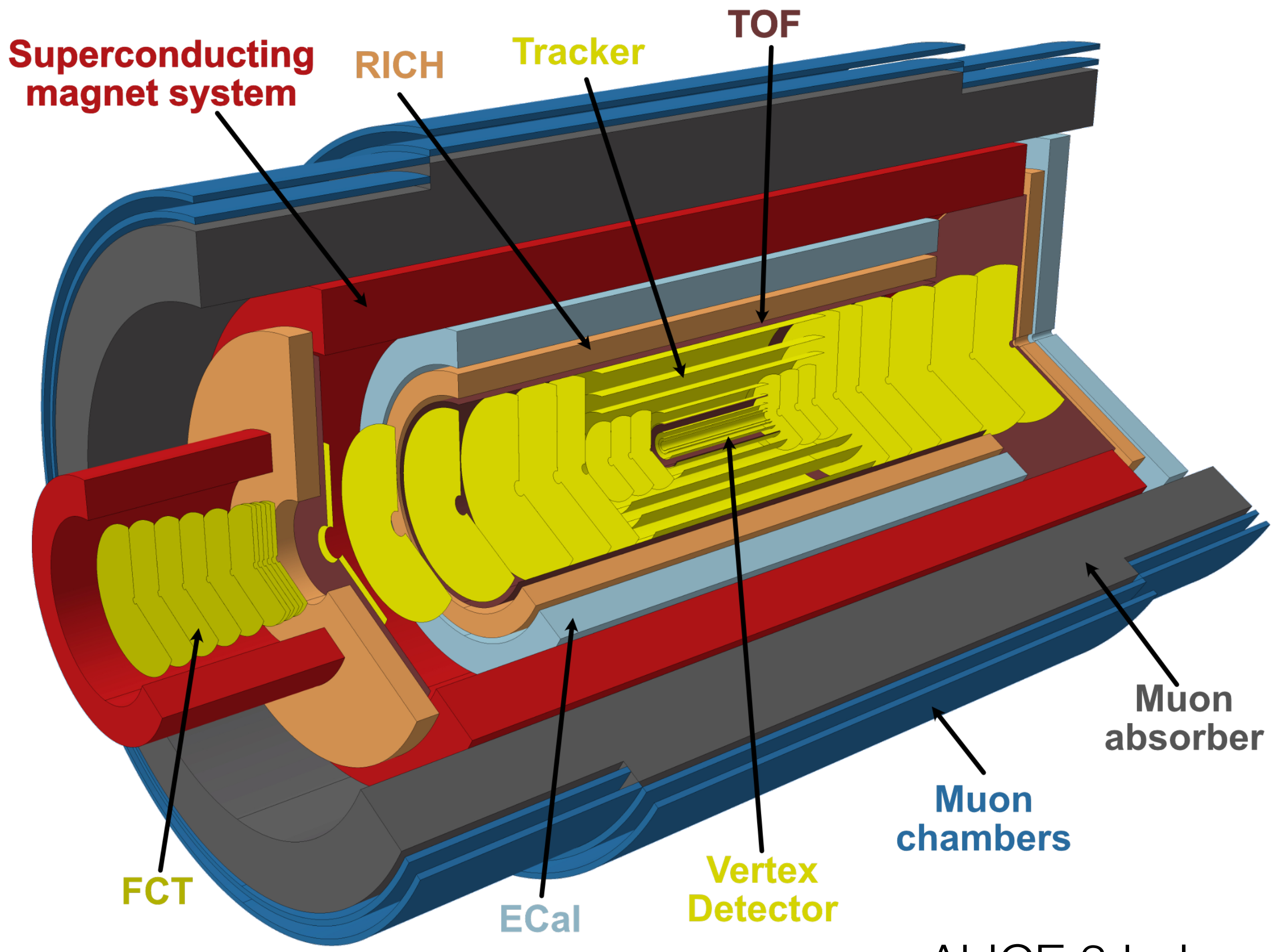
FoCal LoI:
CERN-LHCC-2020-009

ITS 3

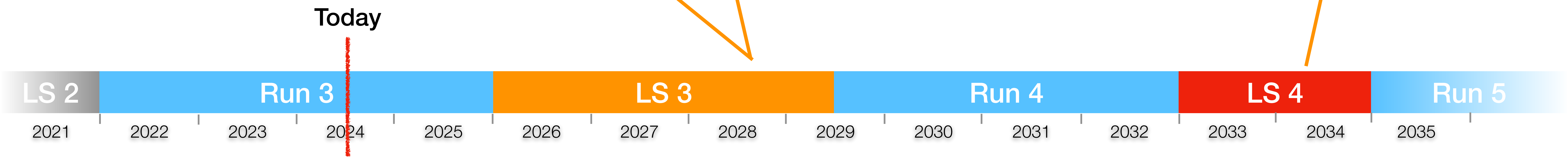


ITS3 LoI:
CERN-LHCC-2019-018

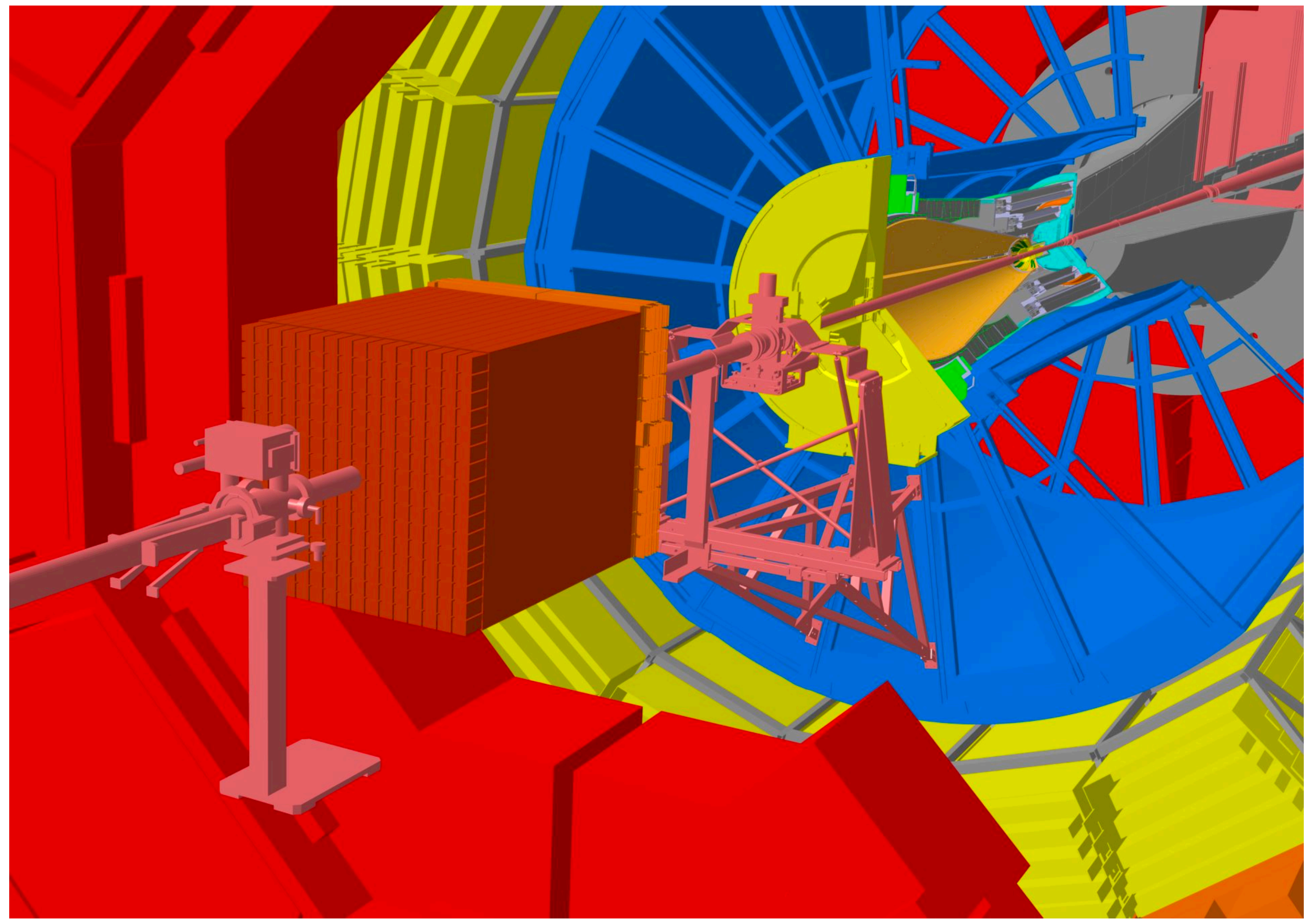
ALICE 3: LS4

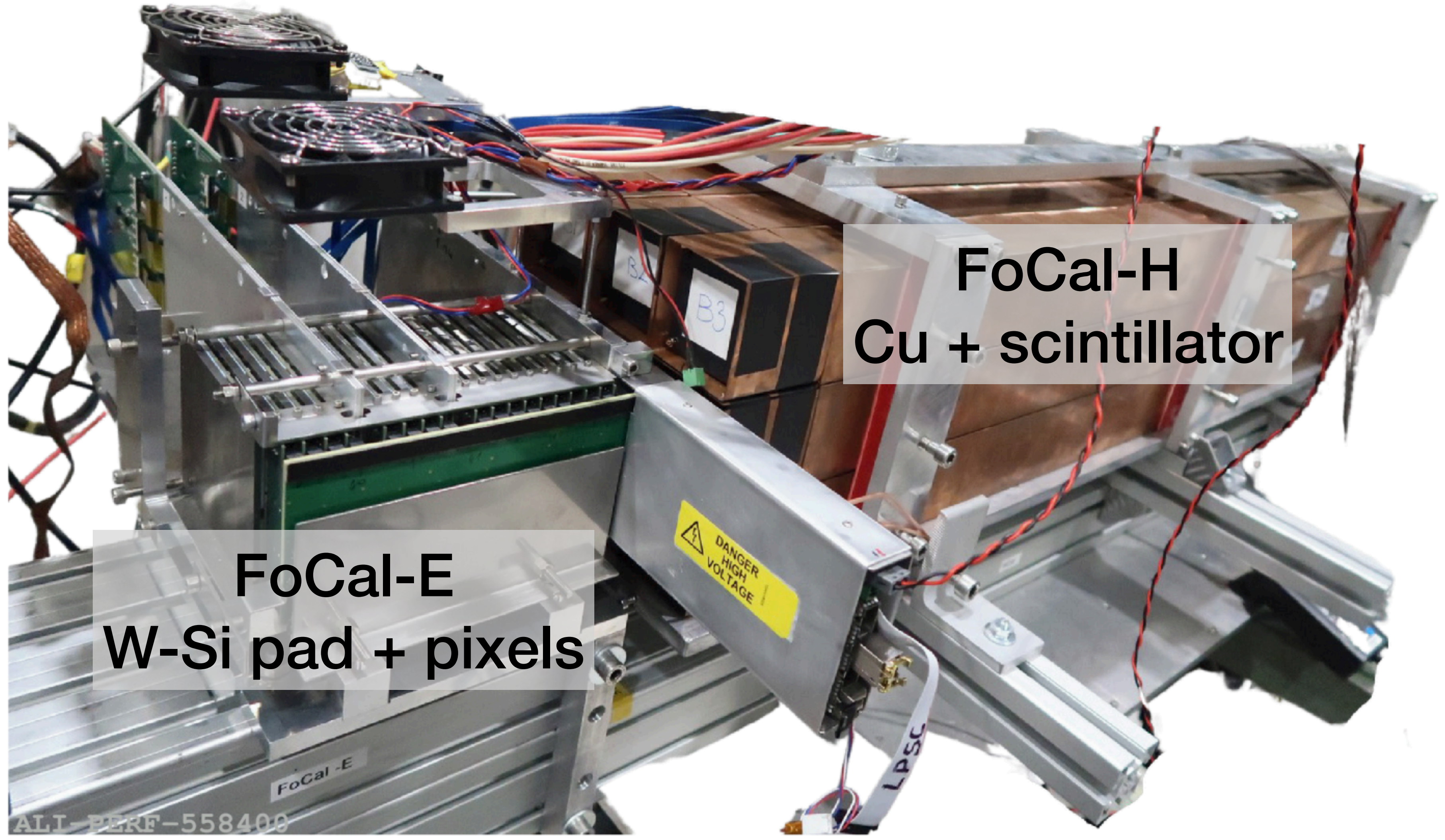


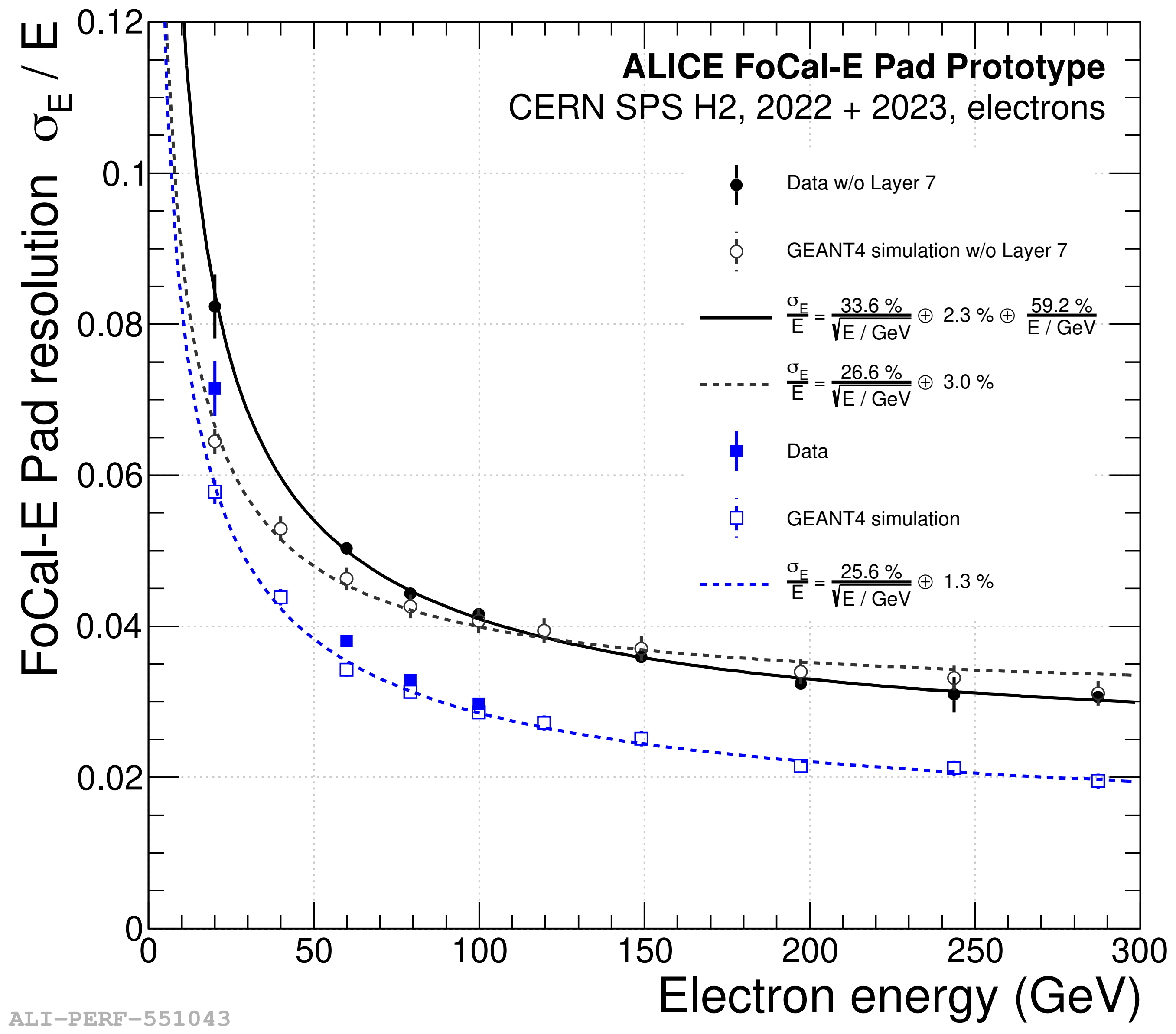
ALICE 3 LoI:
CERN-LHCC-2022-009



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 …

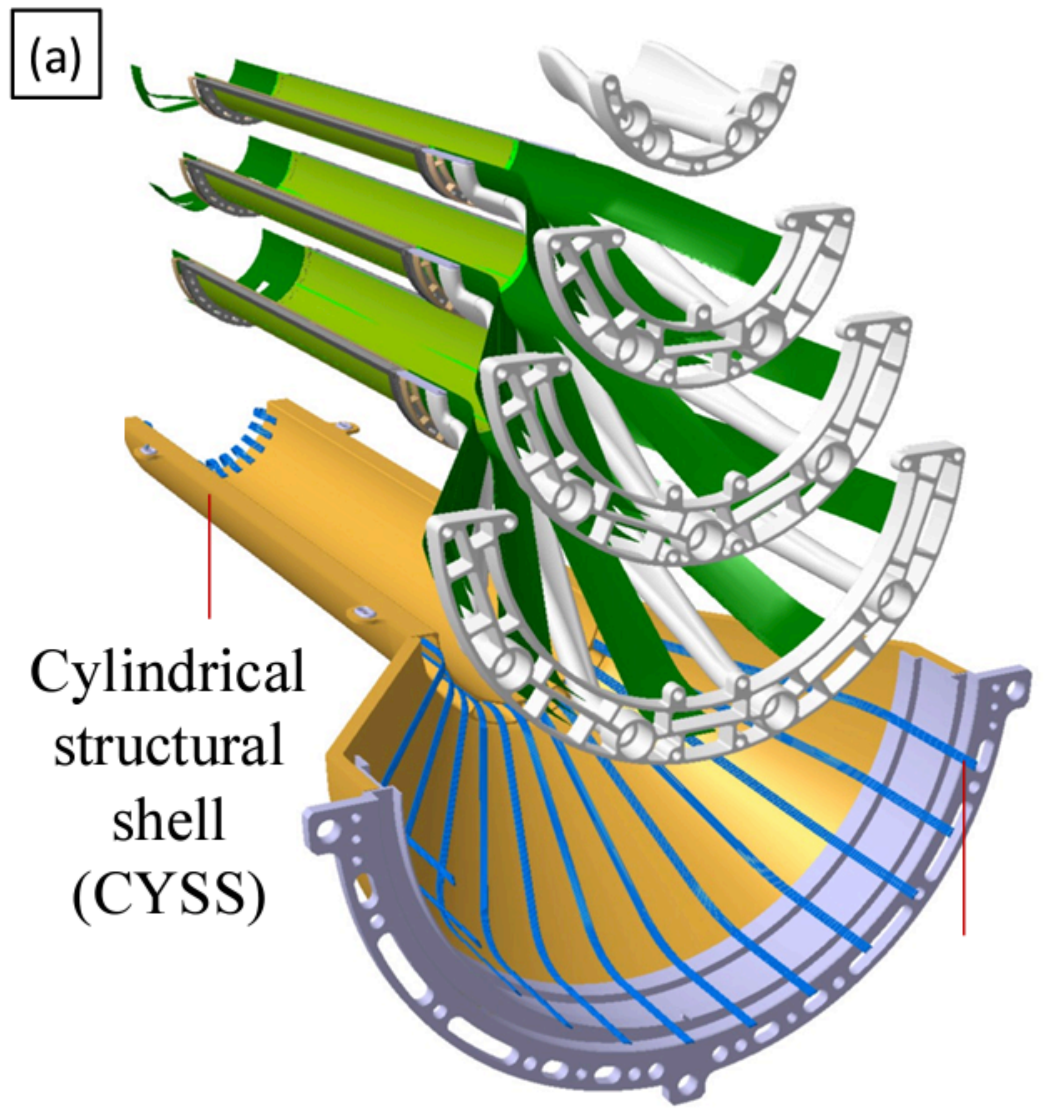
Prototypes produced and tested with beams at PS and SPS

- Meet required performance
- Further radiation testing, tests of pads from second vendor ongoing

TDR approved — moving towards mass production

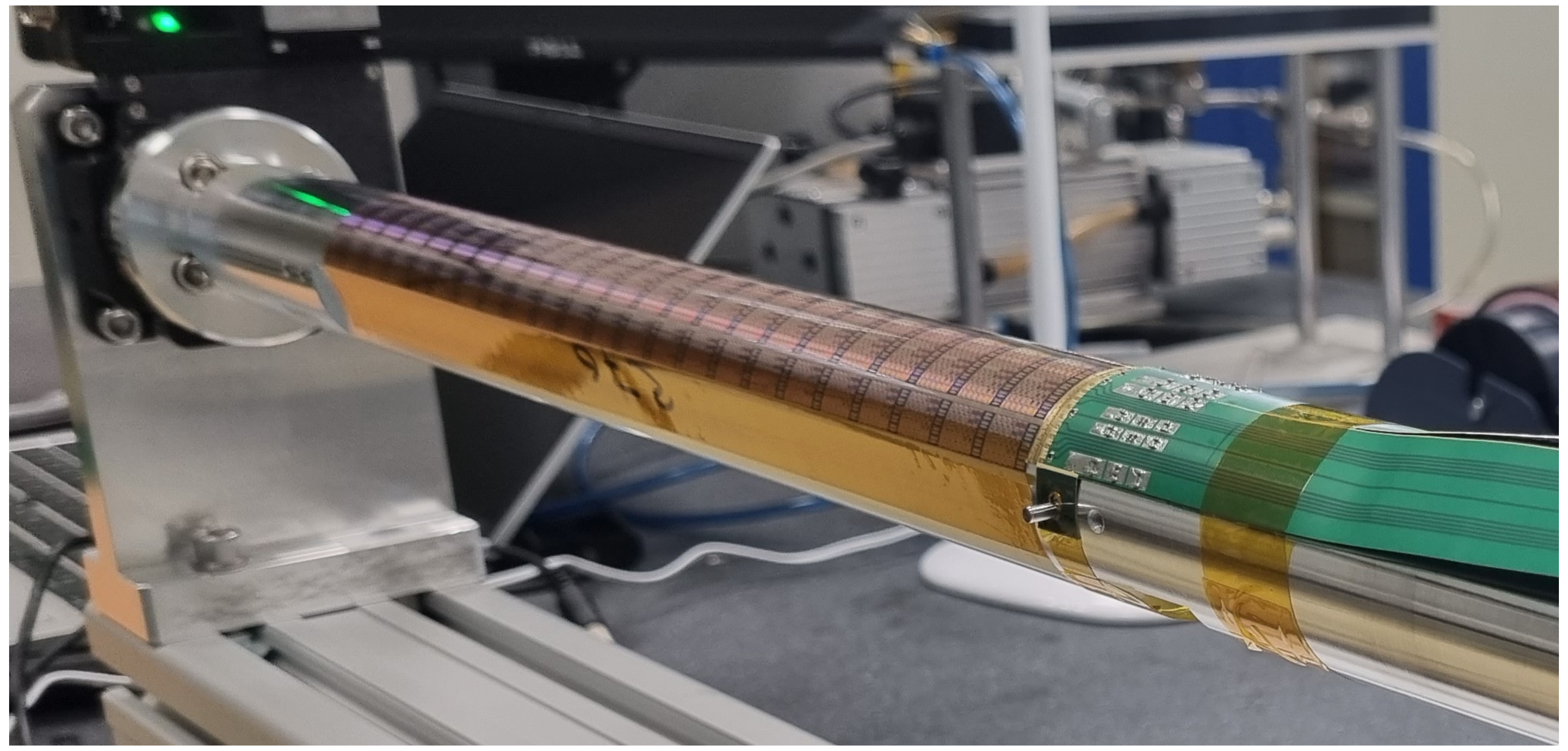
More in presentation Constantin

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

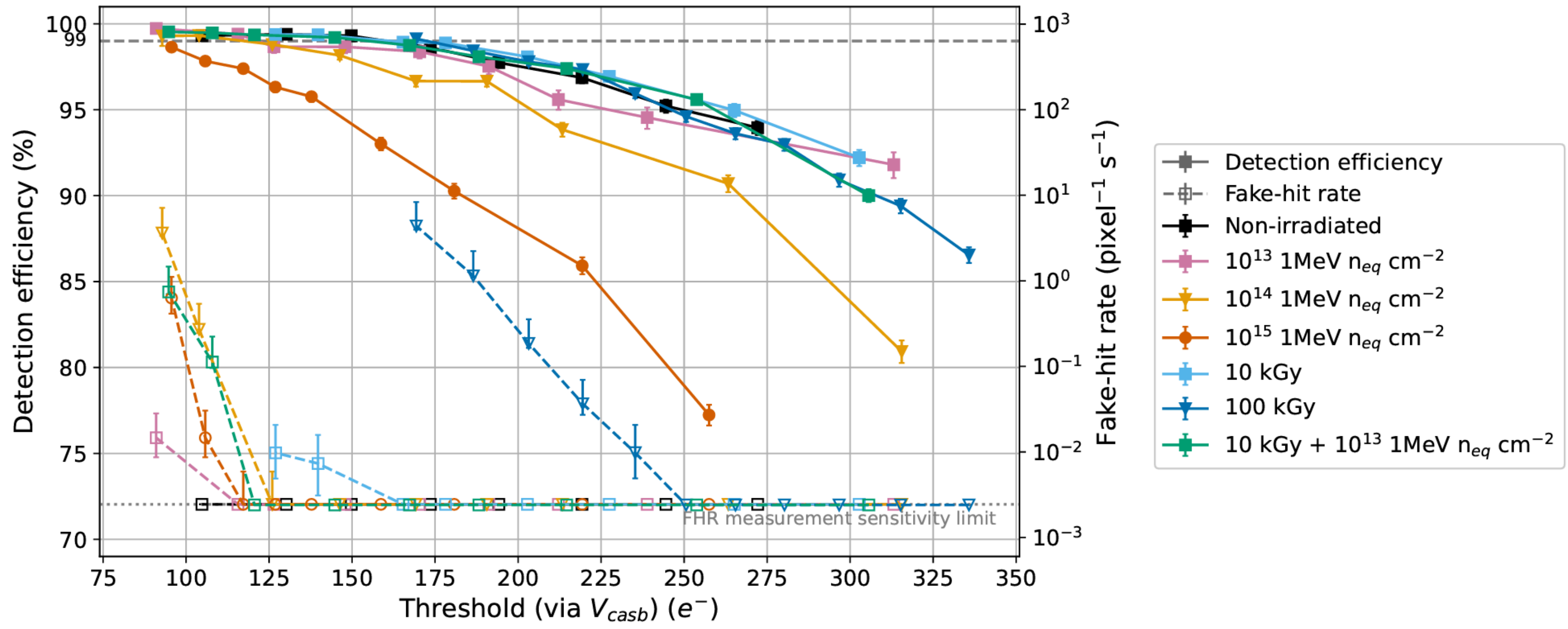


LoI: CERN-LHCC-2019-018

Curved sensor bonding test



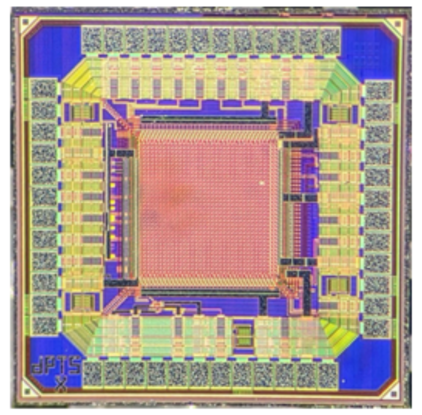
MLR1: 65 nm technology validated



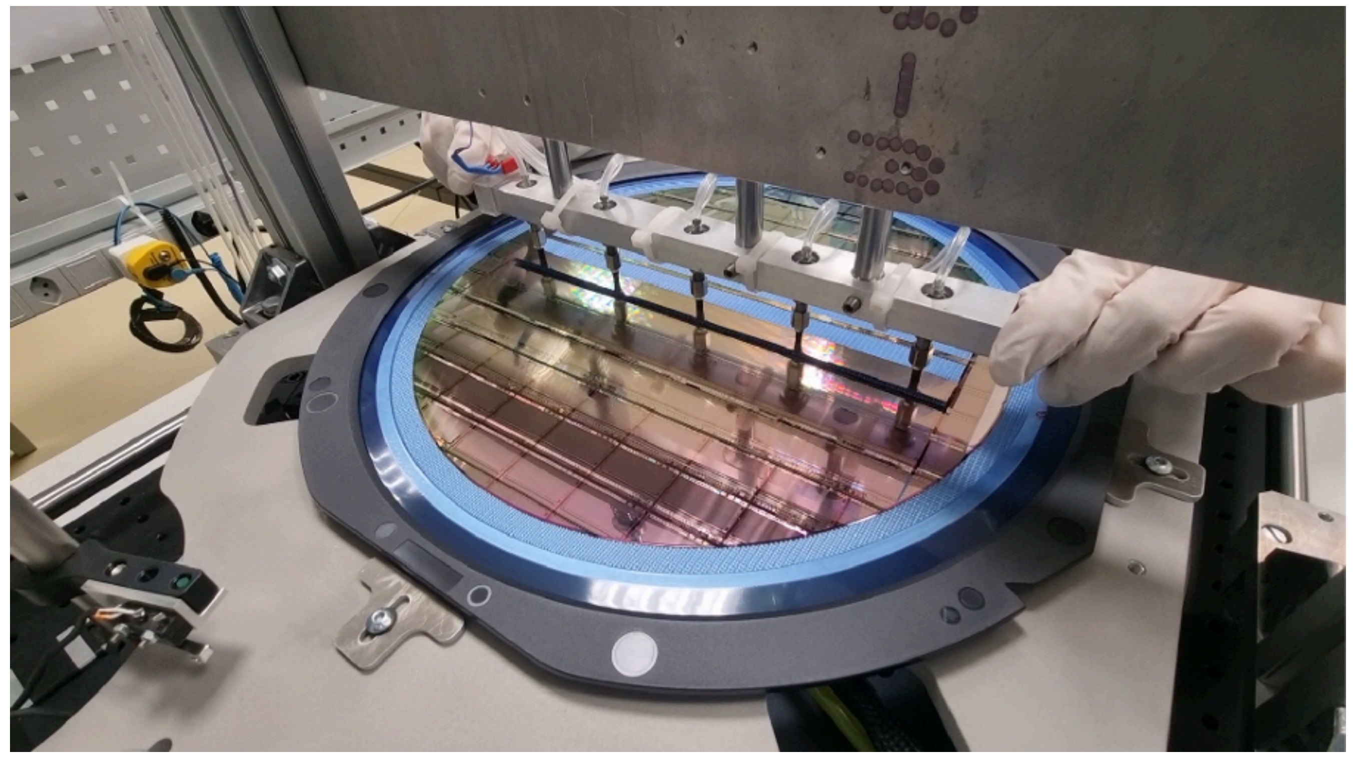
DPTS paper arXiv:2212.08621

ITS3: replace inner 3 tracking layers with ultra-light tracking layers
Improved pointing resolution for
- Heavy flavour reconstruction
- Di-lepton measurements

DPTS test sensor



Handling of stitched structures

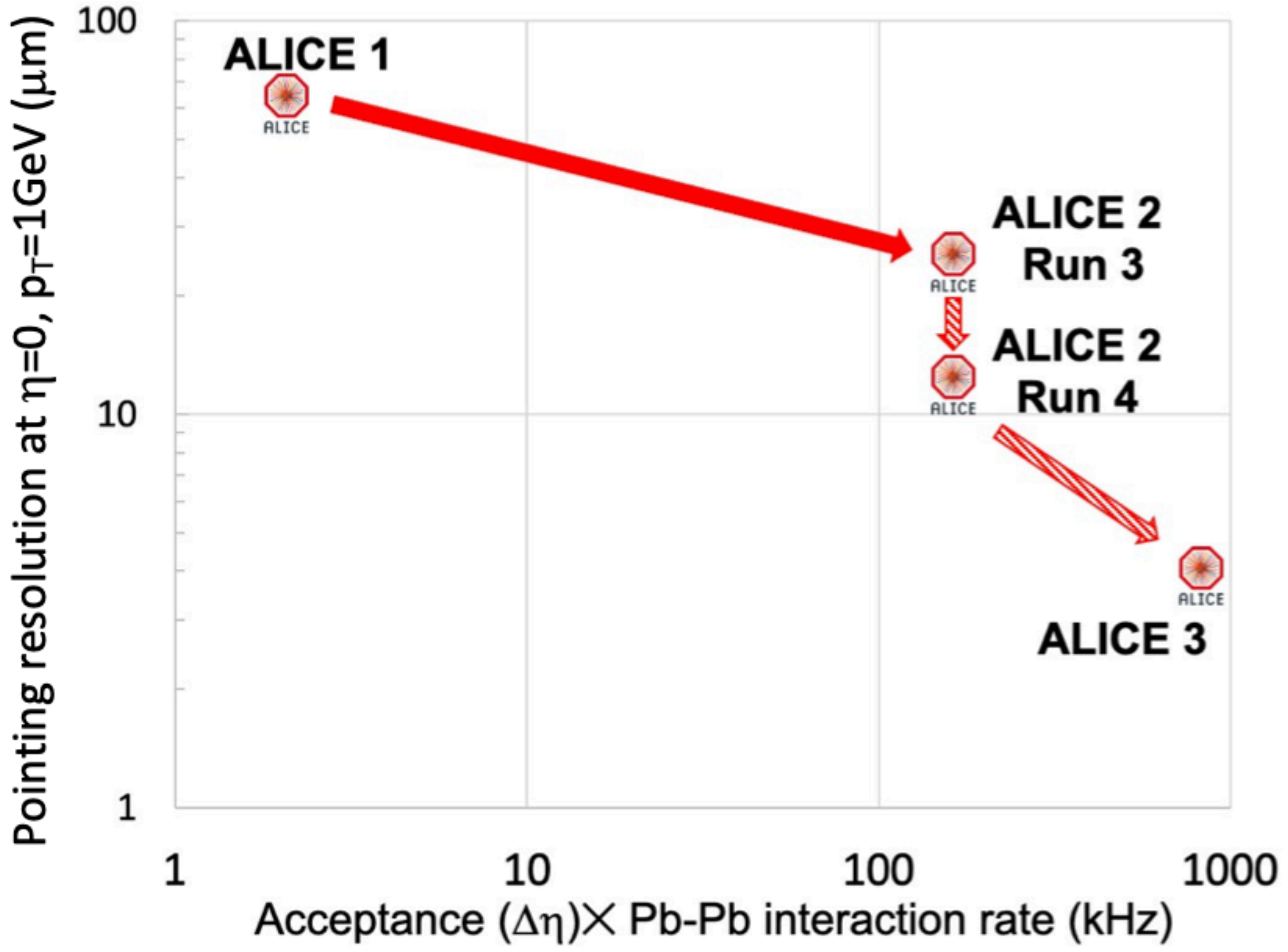


ER1: test of stitched structures
26 x 1.4 cm sensors!

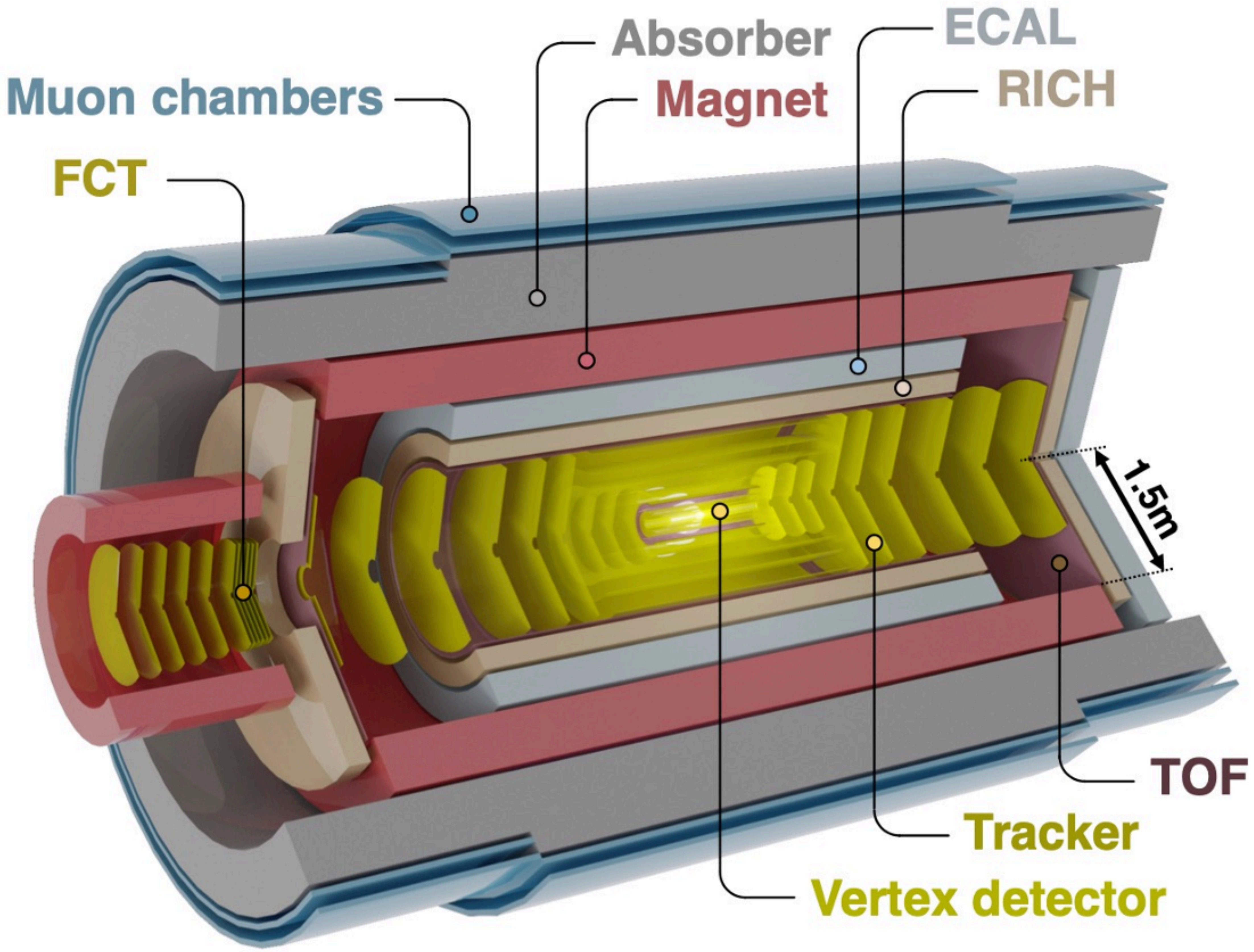
TDR approved — design of final sensor in progress

LHC Run 5 and 6: ALICE 3

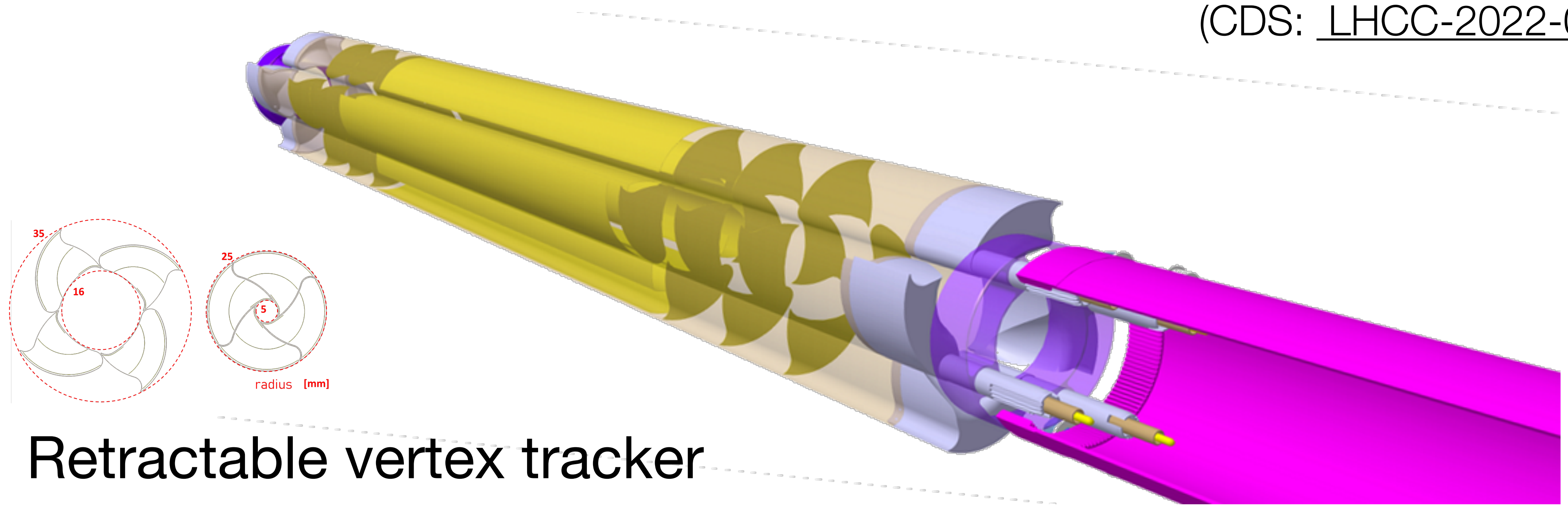
- Compact all-silicon tracker
  with high-resolution vertex detector:
  excellent pointing resolution
- **Particle Identification over large acceptance**:
  muons, electrons, hadrons, photons
- Fast read-out and online processing



Upgrades: improvements in
precision, rate, acceptance



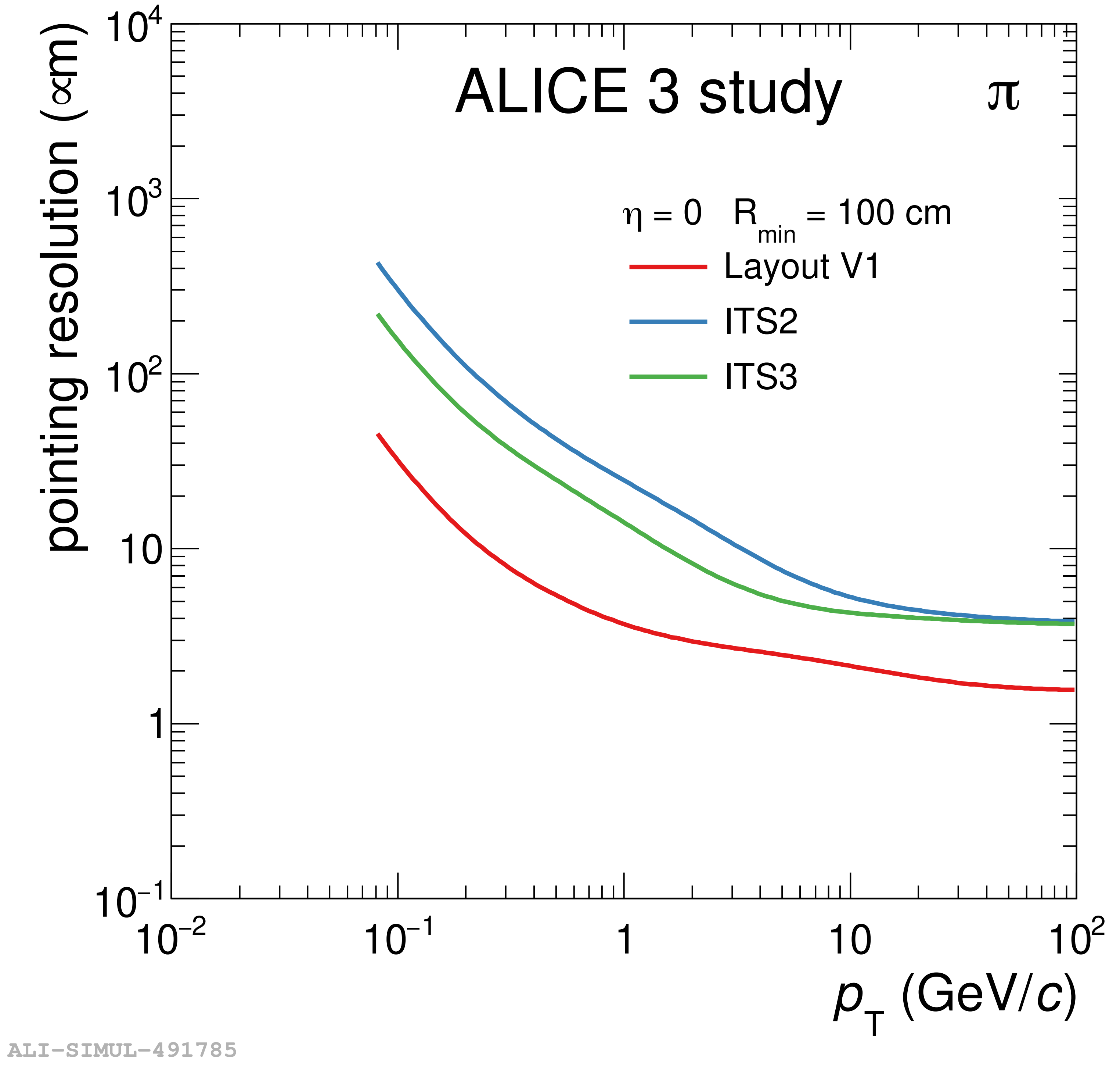
ALICE 3 Letter of Intent
(CDS: LHCC-2022-009)



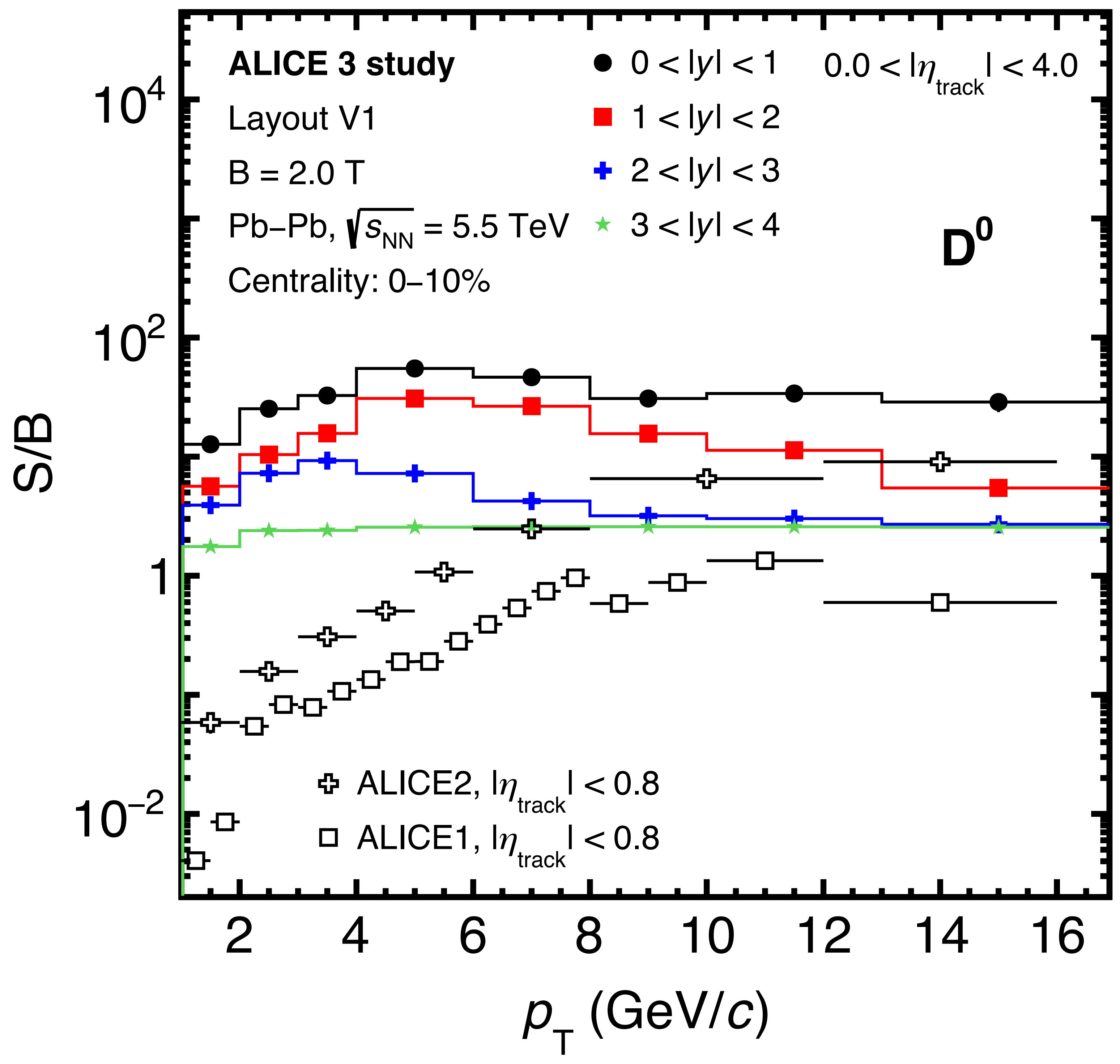
Retractable vertex tracker

Impact parameter resolution — HF benchmarks

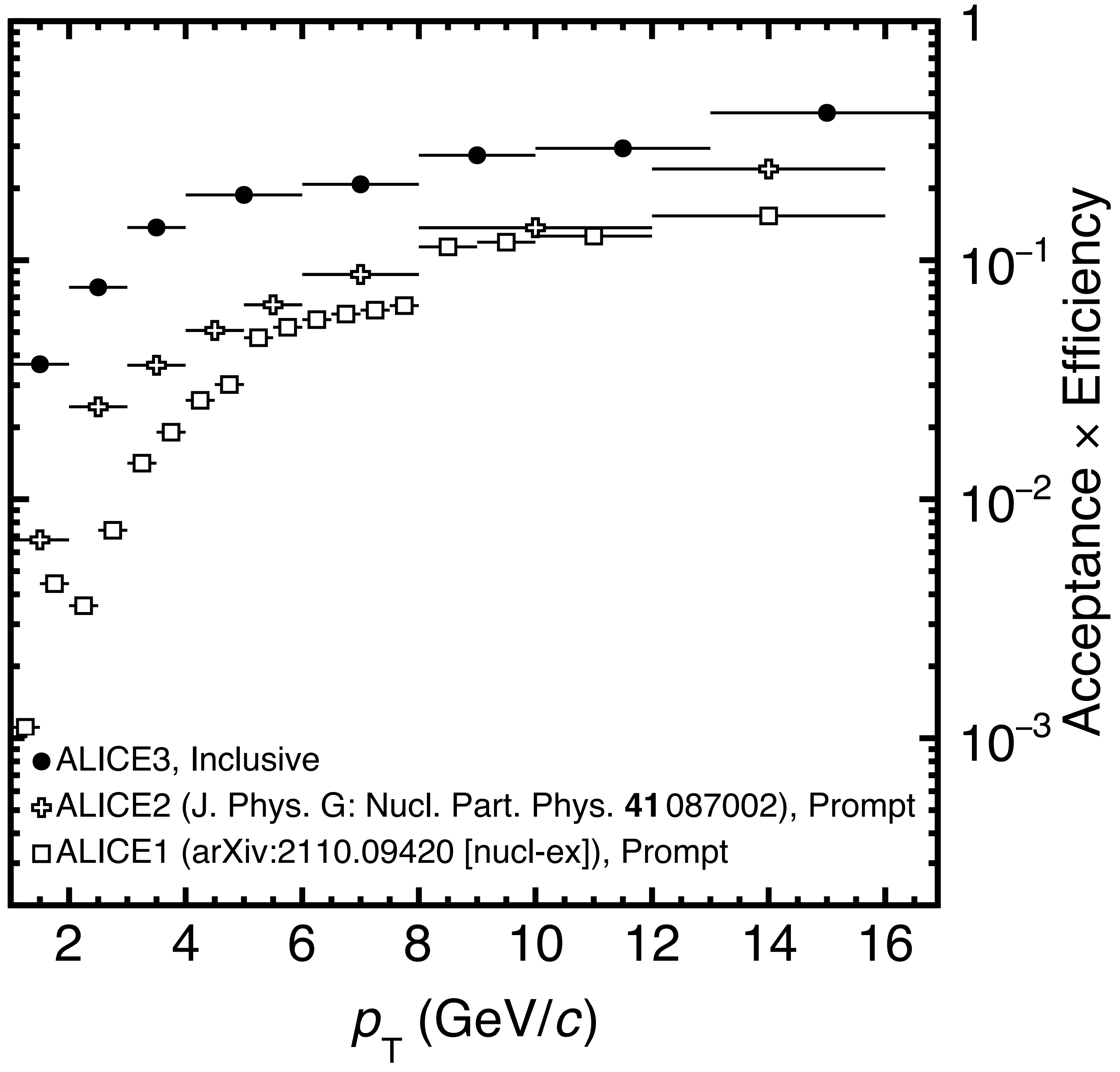
Impact parameter resolution



D meson signal/background



Efficiency

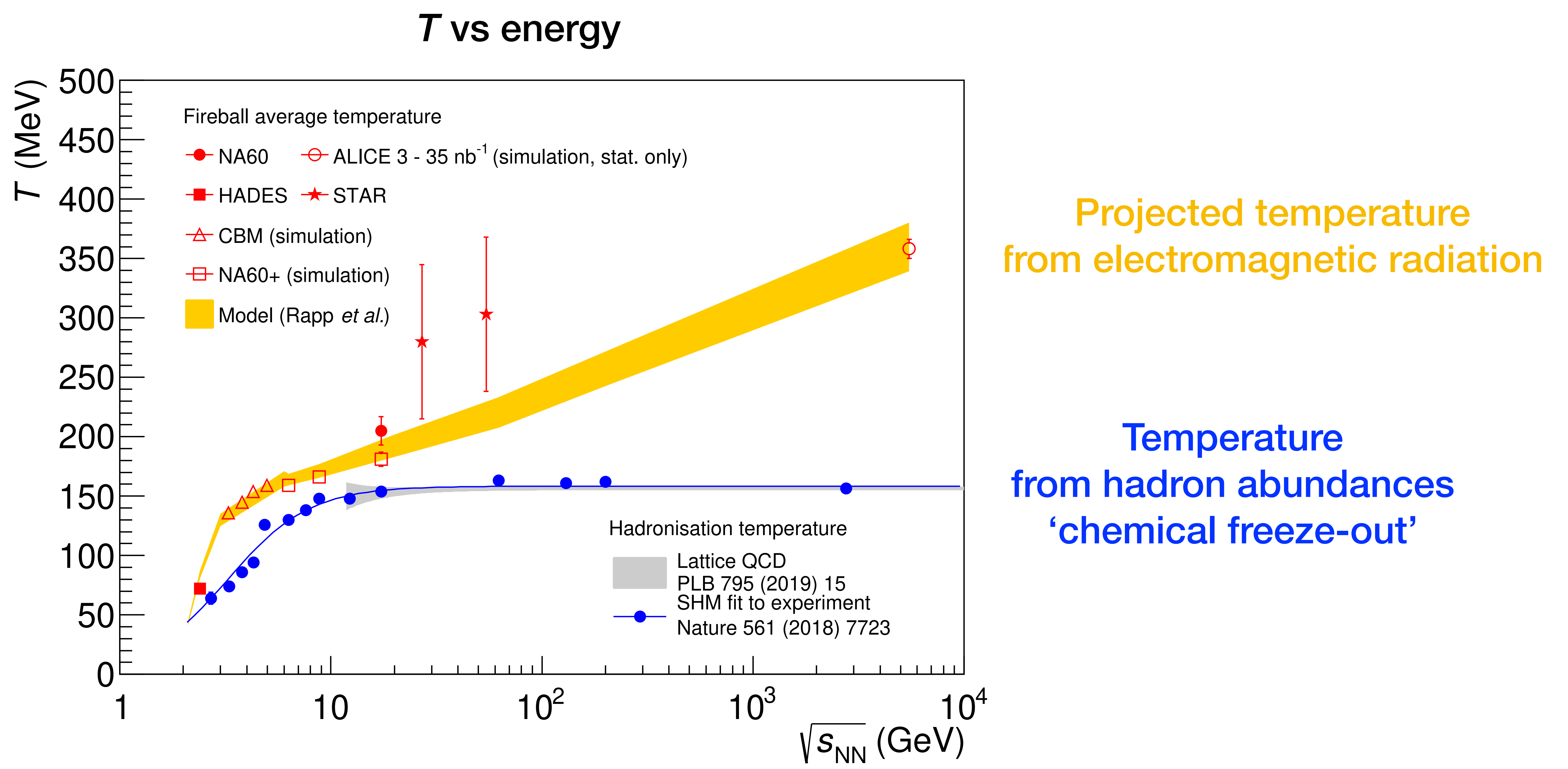


Excellent pointing resolution and PID:
Large S/B and efficiency
10-20x ITS 2 at p_T < 4 GeV

Improves precision for:
- Charm and beauty baryon v_2
- Dielectron spectra

Access to new signals:
- $D\bar{D}$ correlations
- Multi-charm baryons
- Dielectron v_2

Temperature of the QGP: electromagnetic radiation



Light flavour hadron abundances consistent with common chemical freeze-out

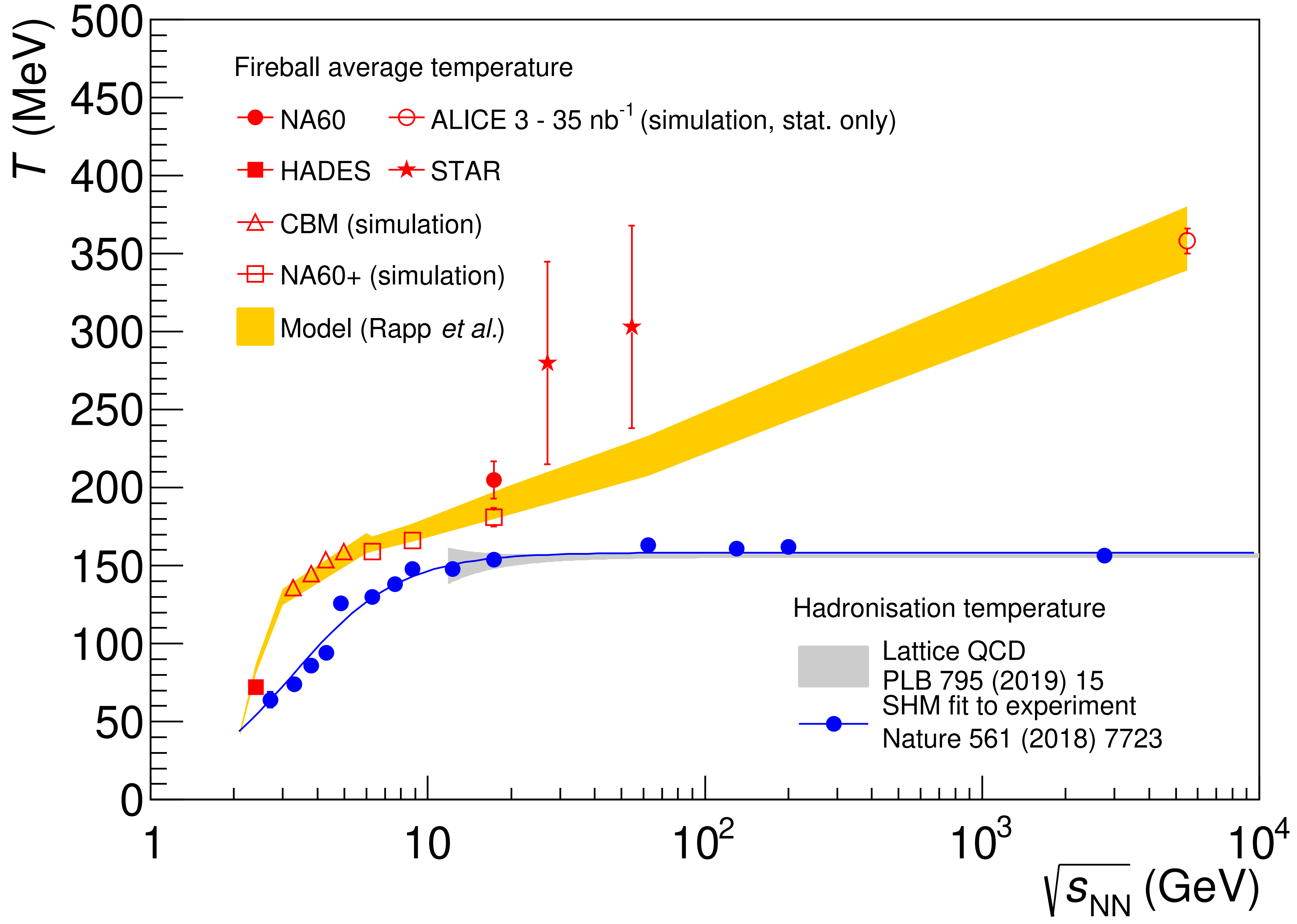
- Limiting temperature: ~155 MeV

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

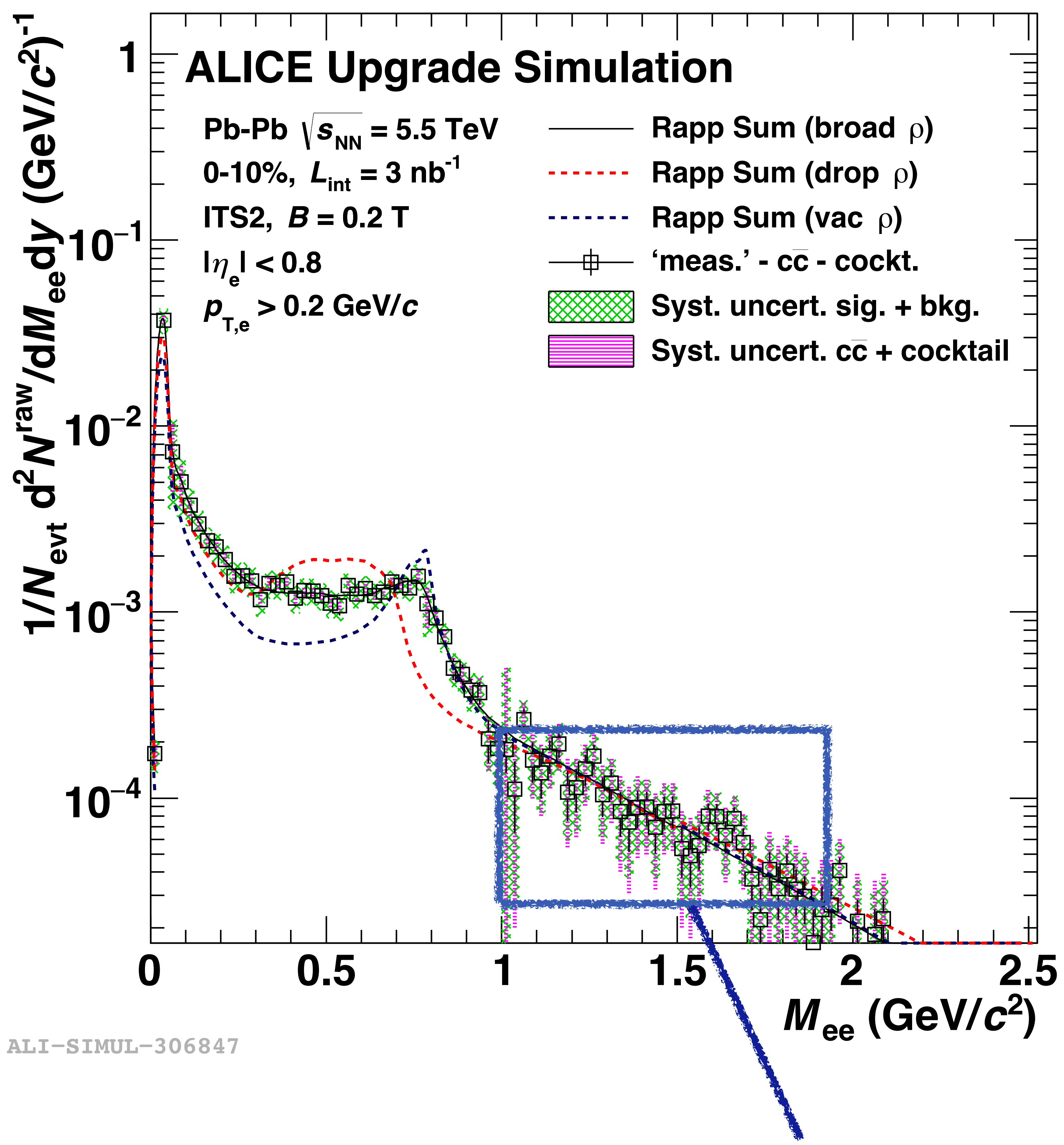
T vs energy



Projected temperature from electromagnetic radiation

Temperature from hadron abundances ‘chemical freeze-out’

Dileptons in run 3 and 4



Slope measures temperature

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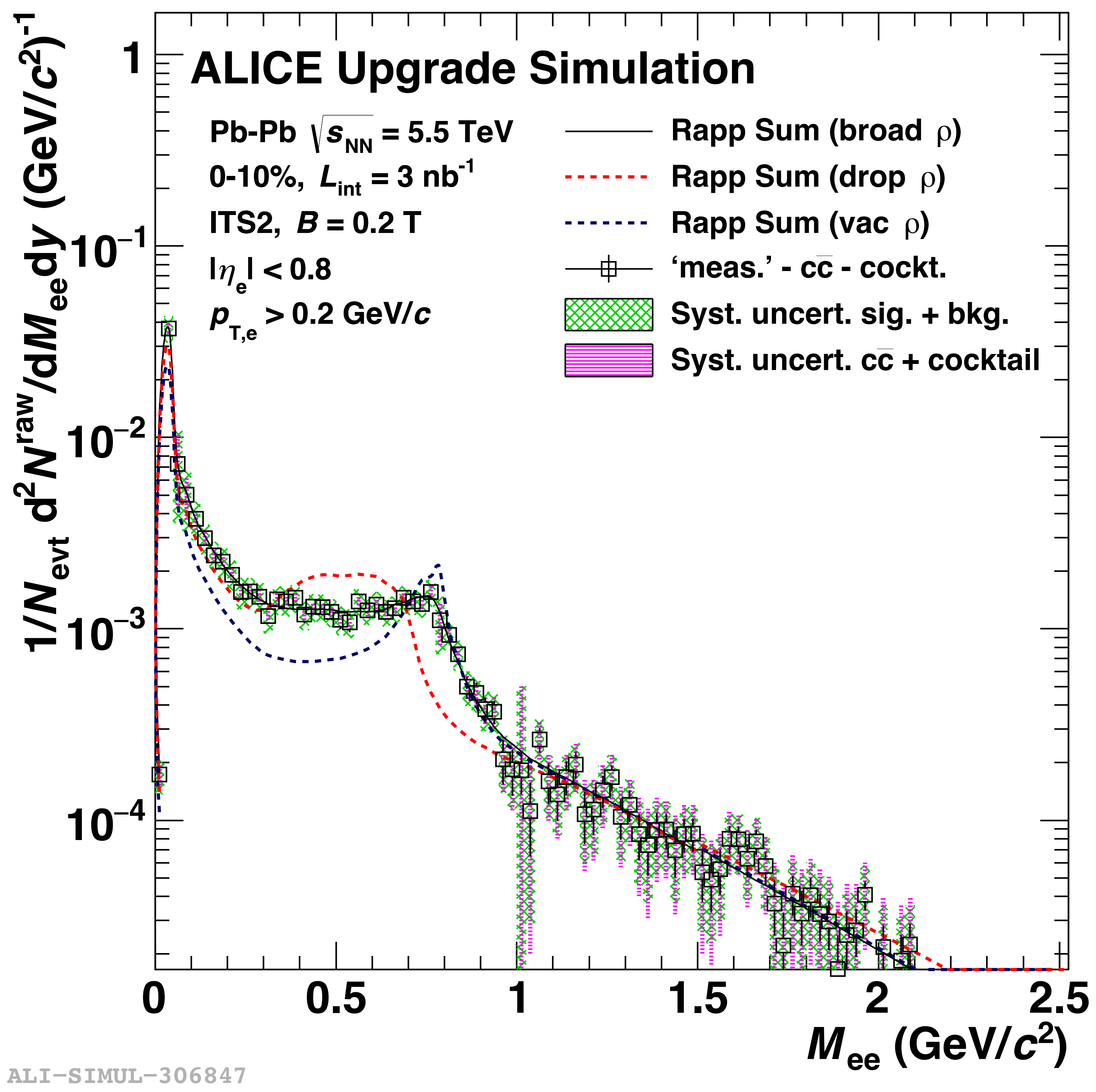
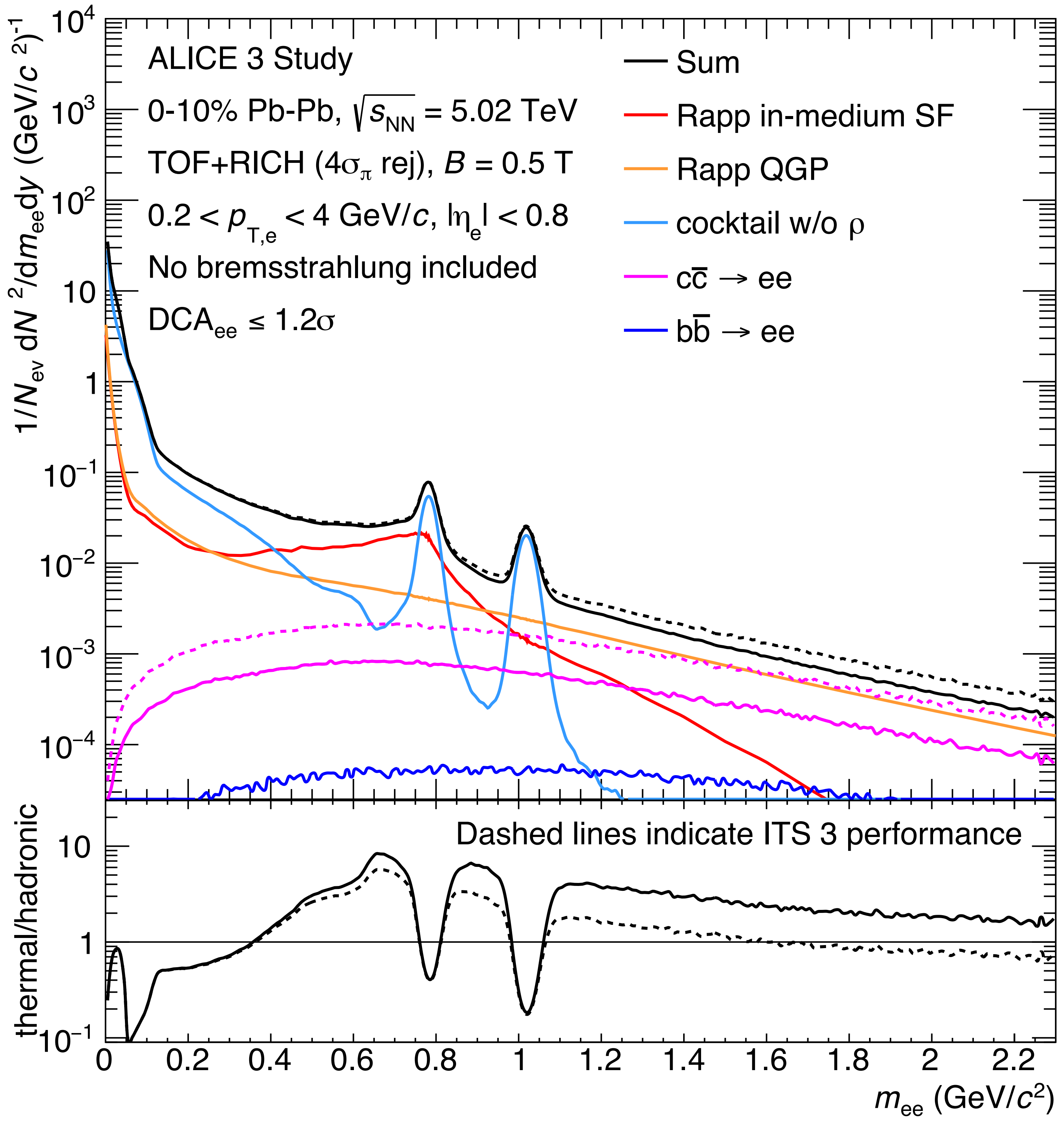
Dielectrons: chiral symmetry and thermal emission

Dielectrons in run 3 and 4



Run 3 and 4: first measurements
of thermal dilepton emission at LHC
→ first access to average T

Dielectron cocktail: HF background

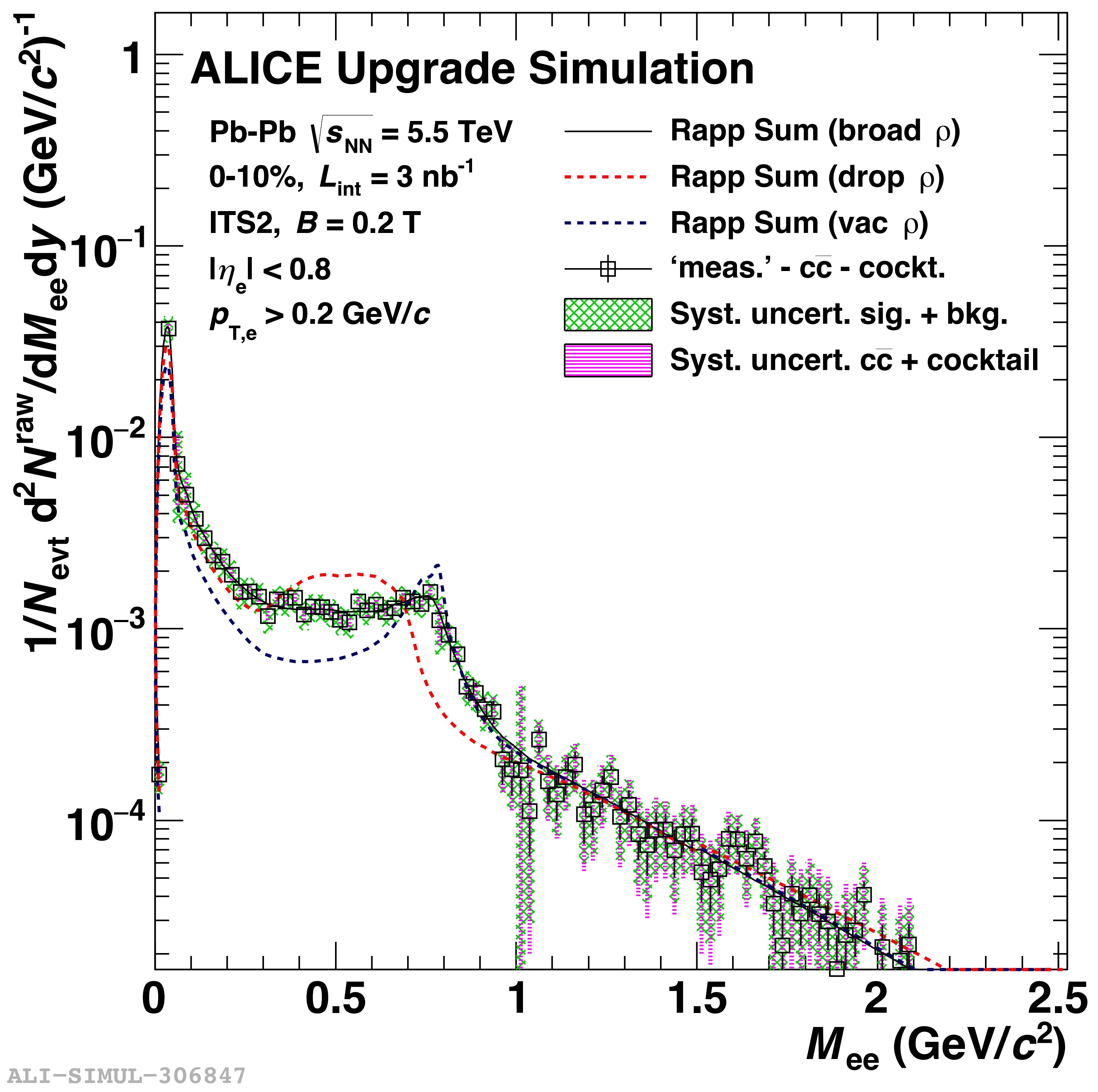


HF decays produce correlated background

- Large for $m_{ee} \gtrsim 1\,\mathrm{GeV}/c^2$
- Can be effectively suppressed in ALICE 3

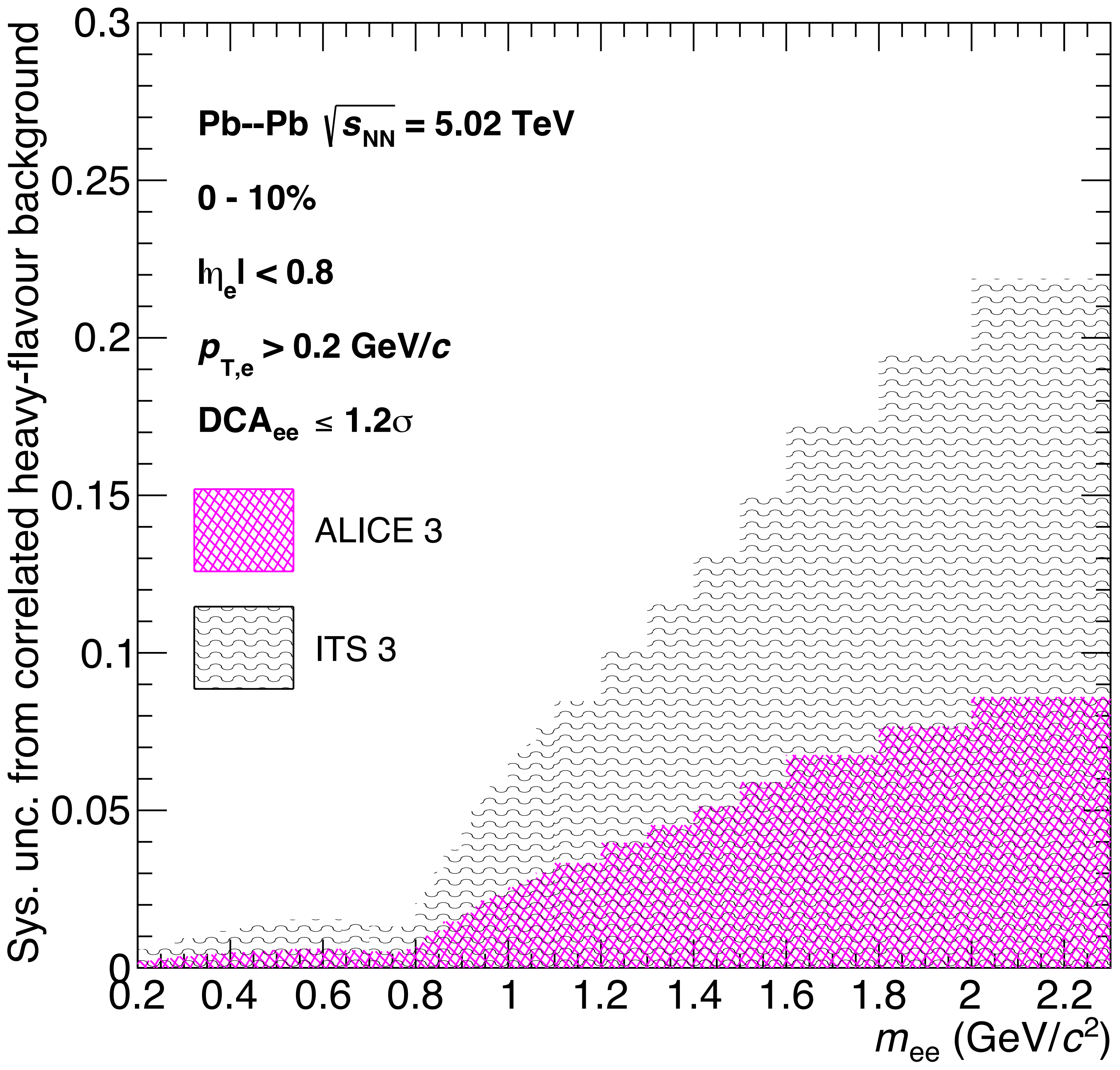
Dielectrons: chiral symmetry and thermal emission

Dielectrons in run 3 and 4



Run 3 and 4: first measurements of thermal dilepton emission at LHC → first access to average *T*

Relative syst uncertainties: ITS3 vs ALICE3



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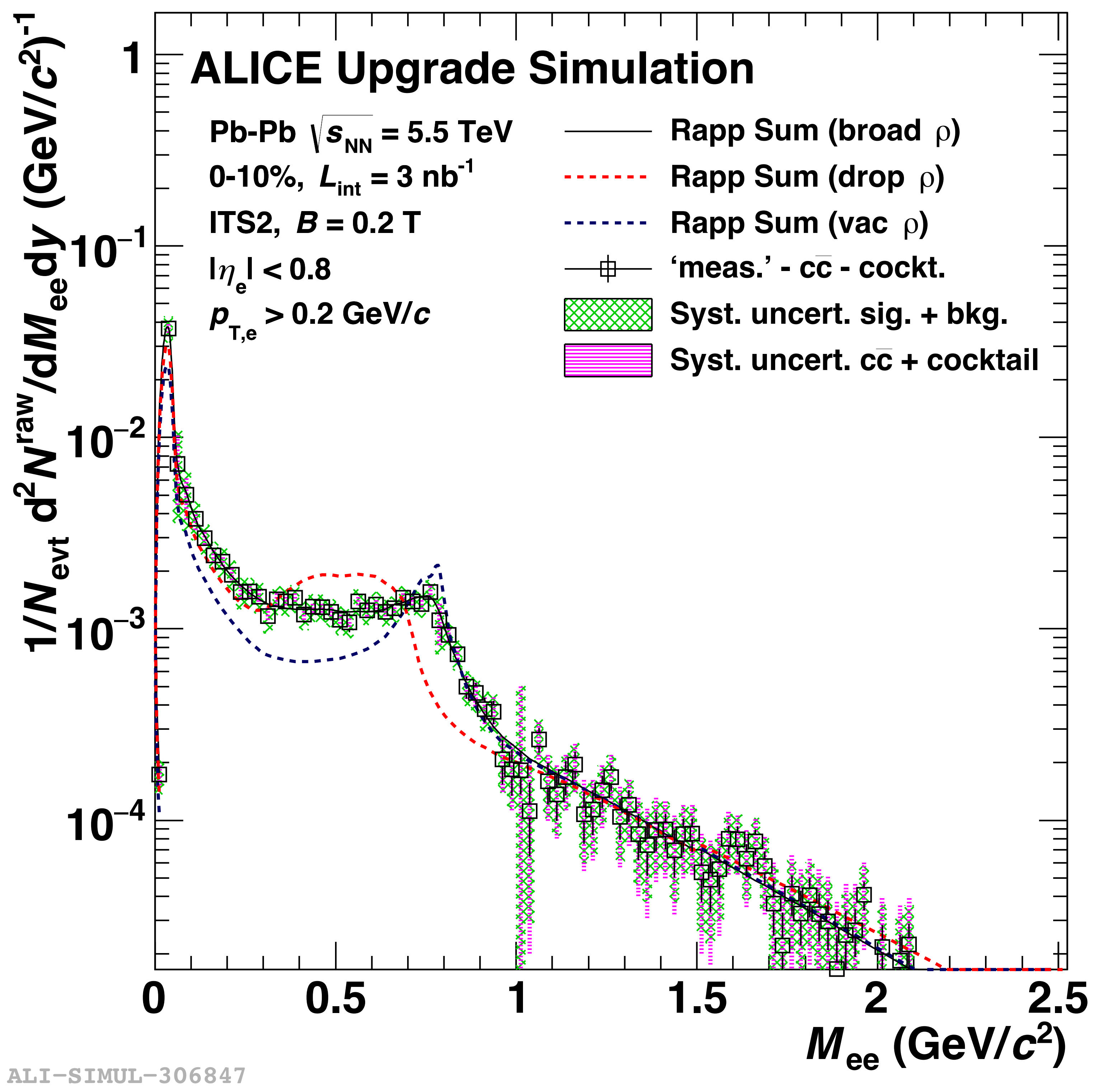

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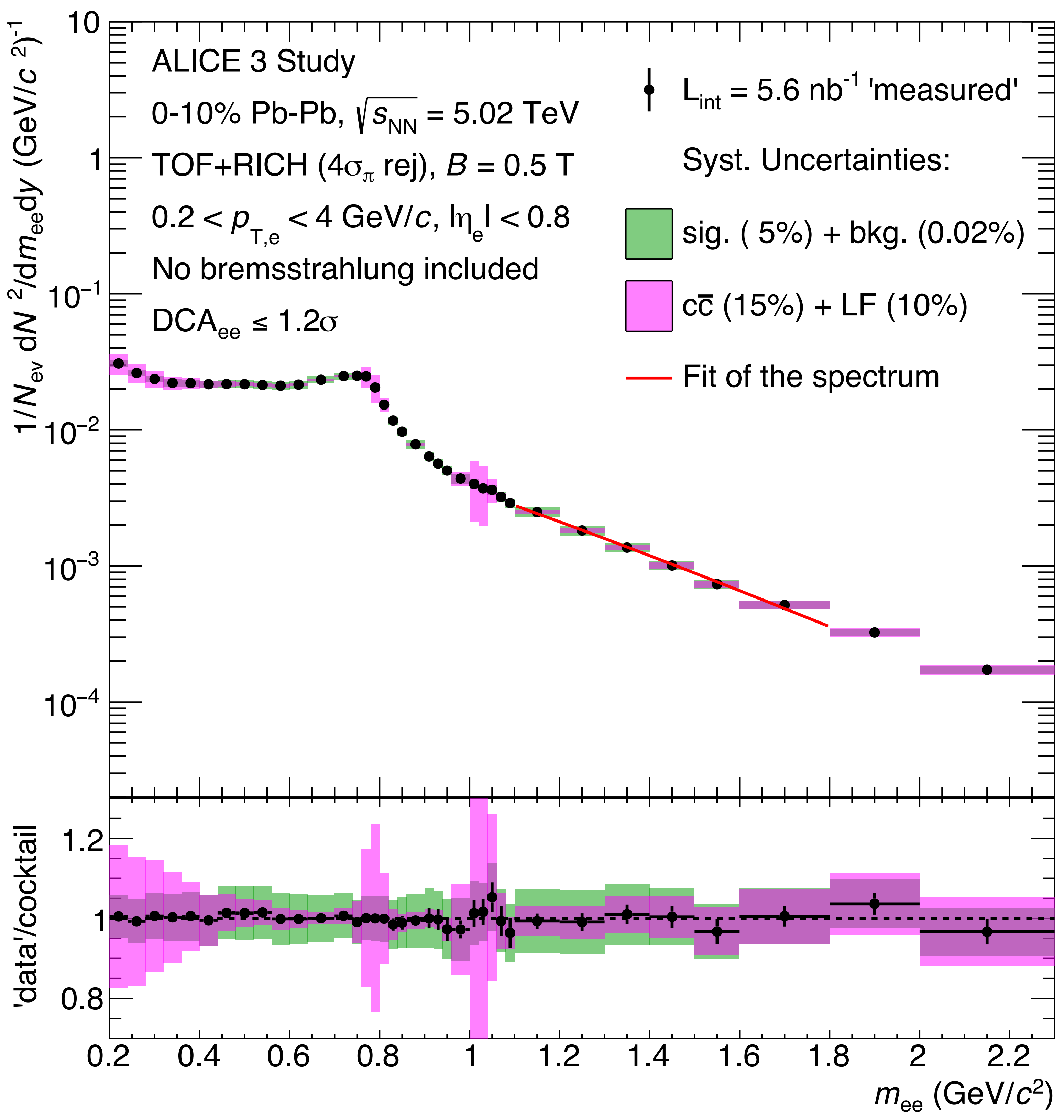
Dielectron mass distribution



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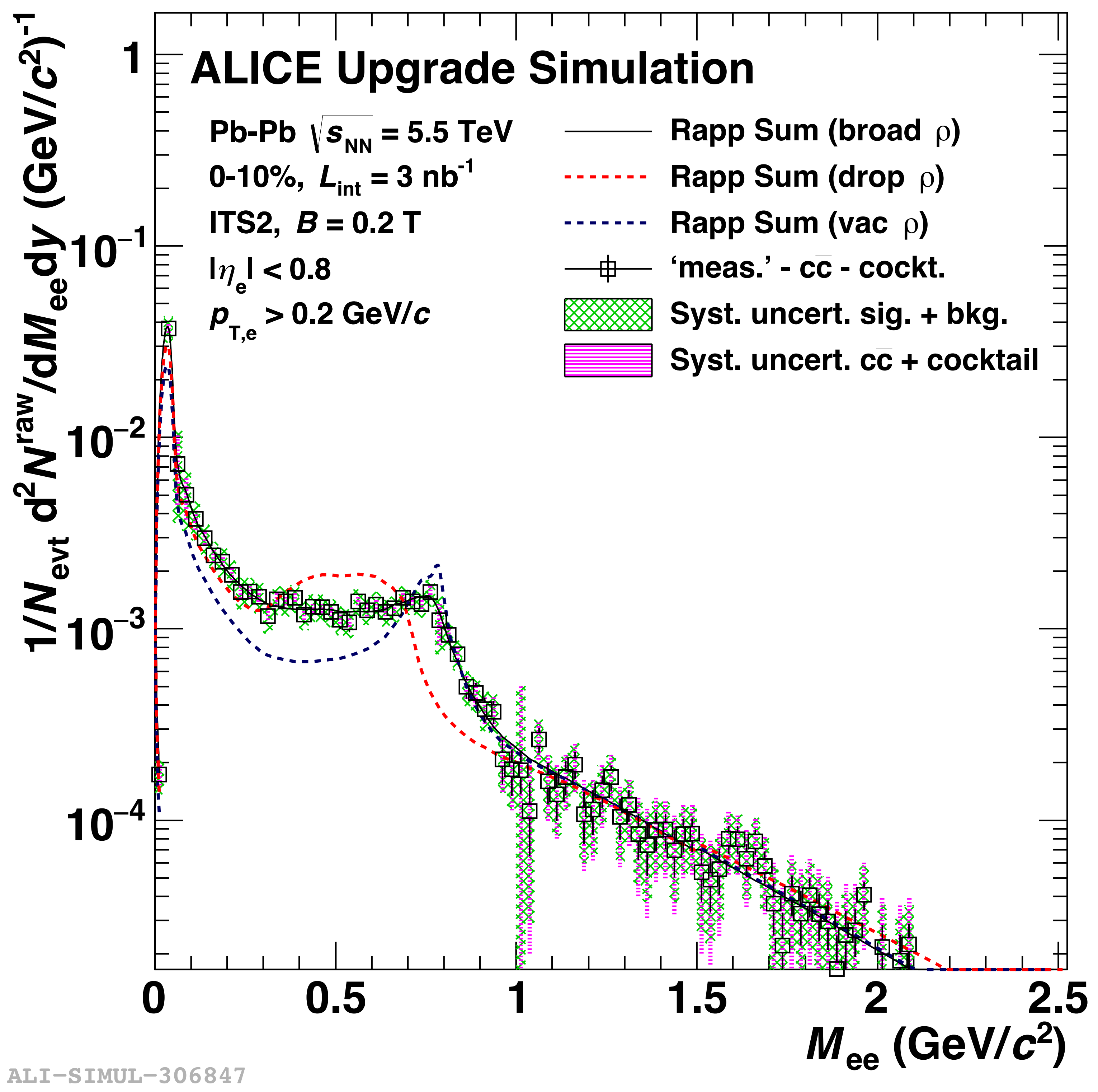
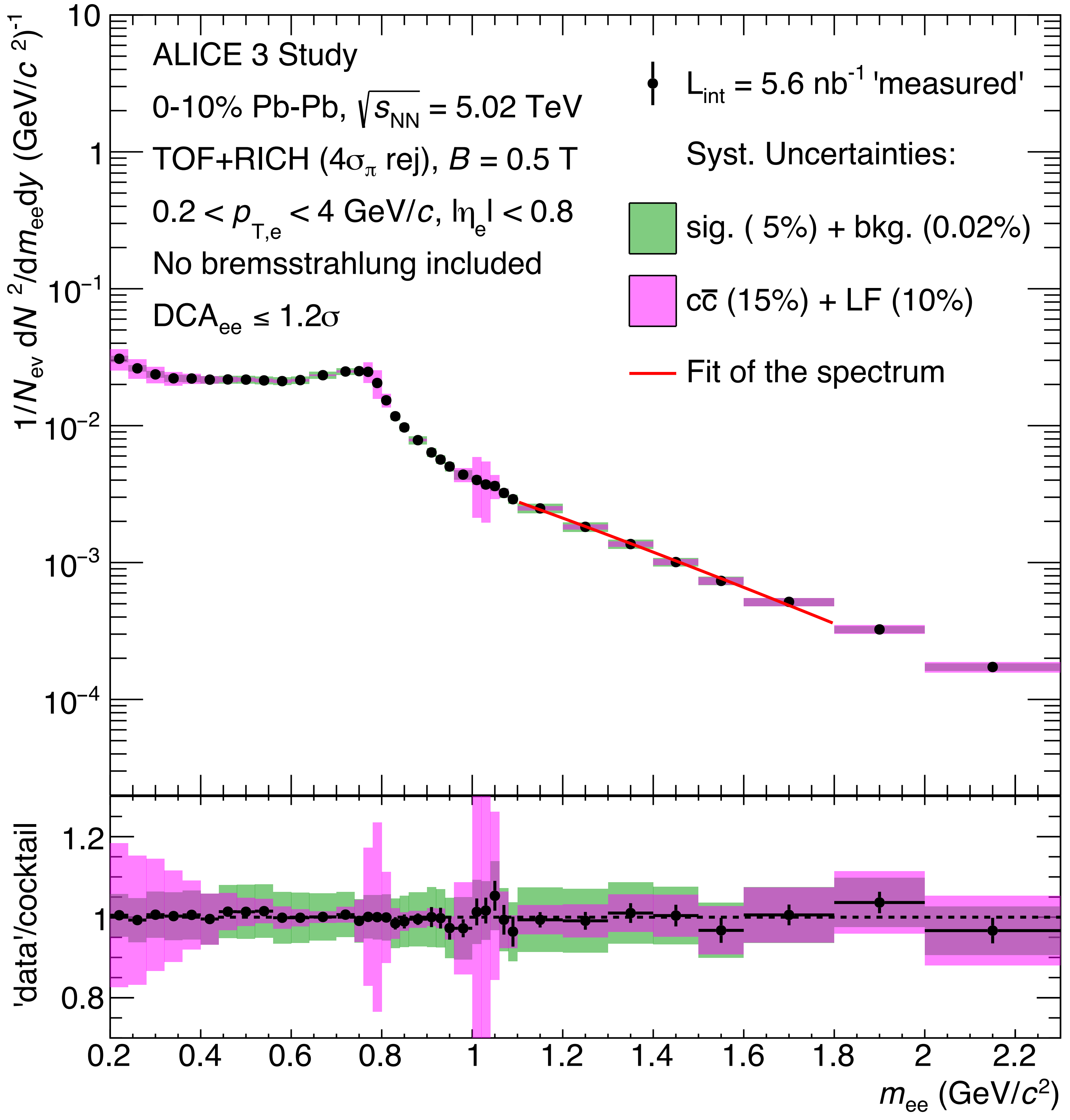
Dielectrons in run 3 and 4



Run 3 and 4: first measurements of thermal dilepton emission at LHC → first access to average *T*

Dielectron mass distribution



HF decays produce correlated background

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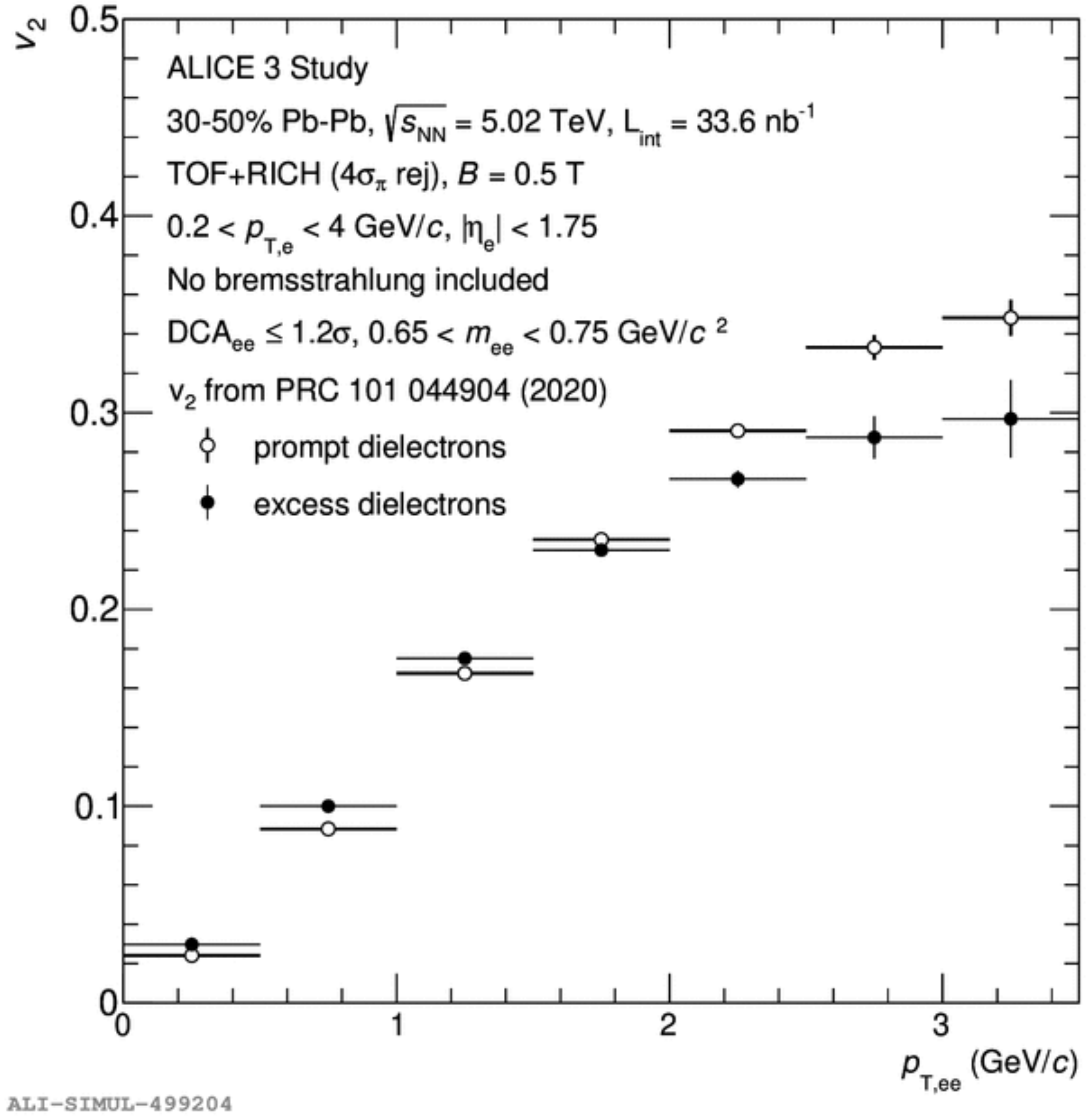
Dielectron v_2

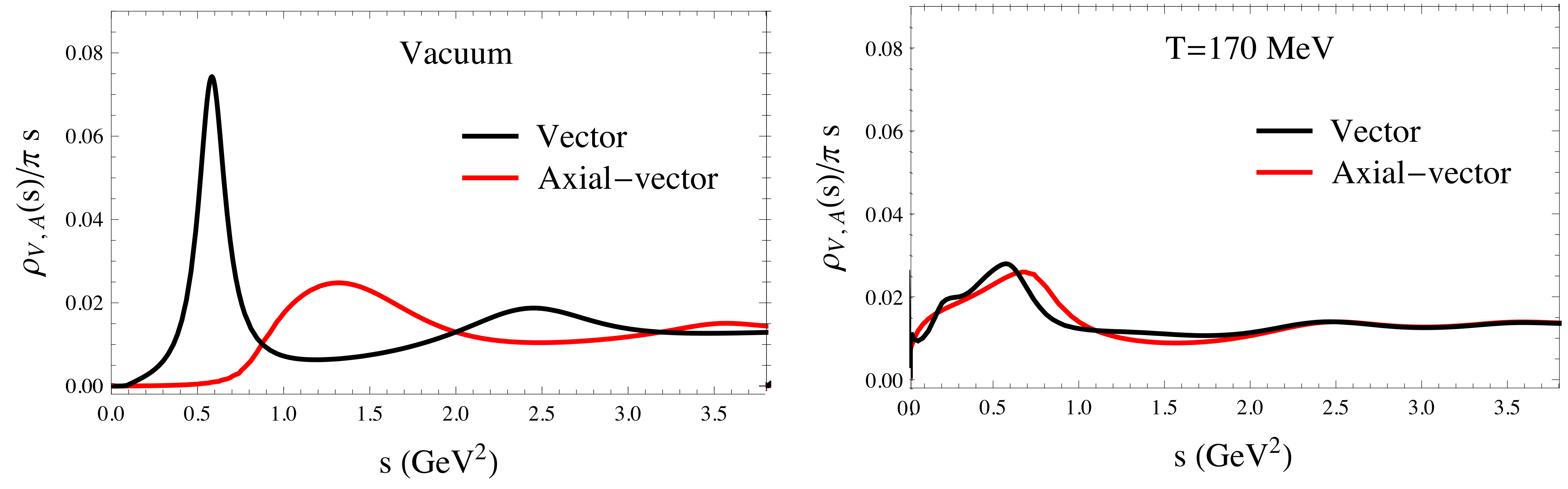


Excellent precision for dilepton v_2 vs p_T in different mass ranges → **time evolution of temperature**

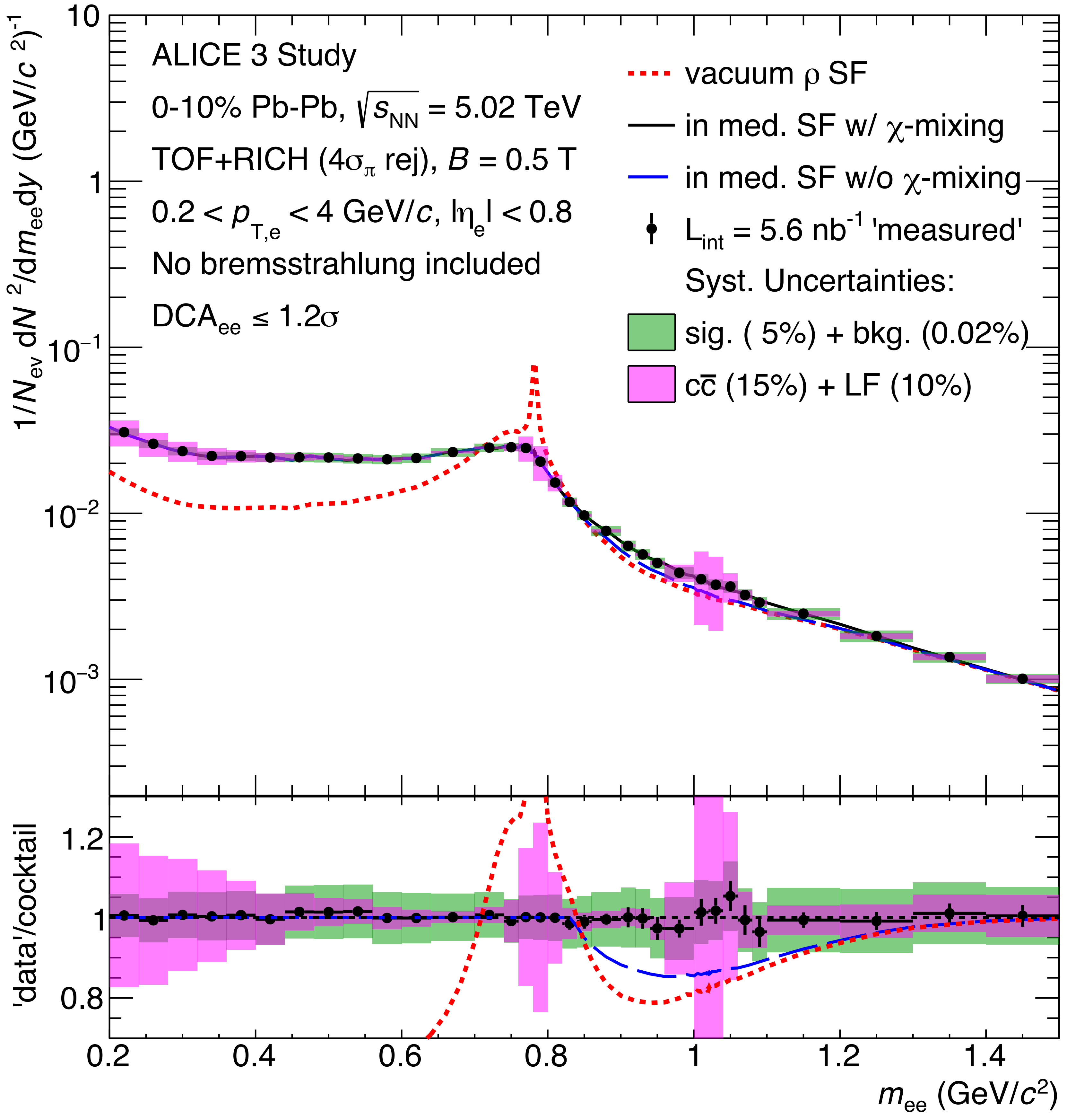
Chiral symmetry restoration: $\rho - a_1$ mixing

- 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

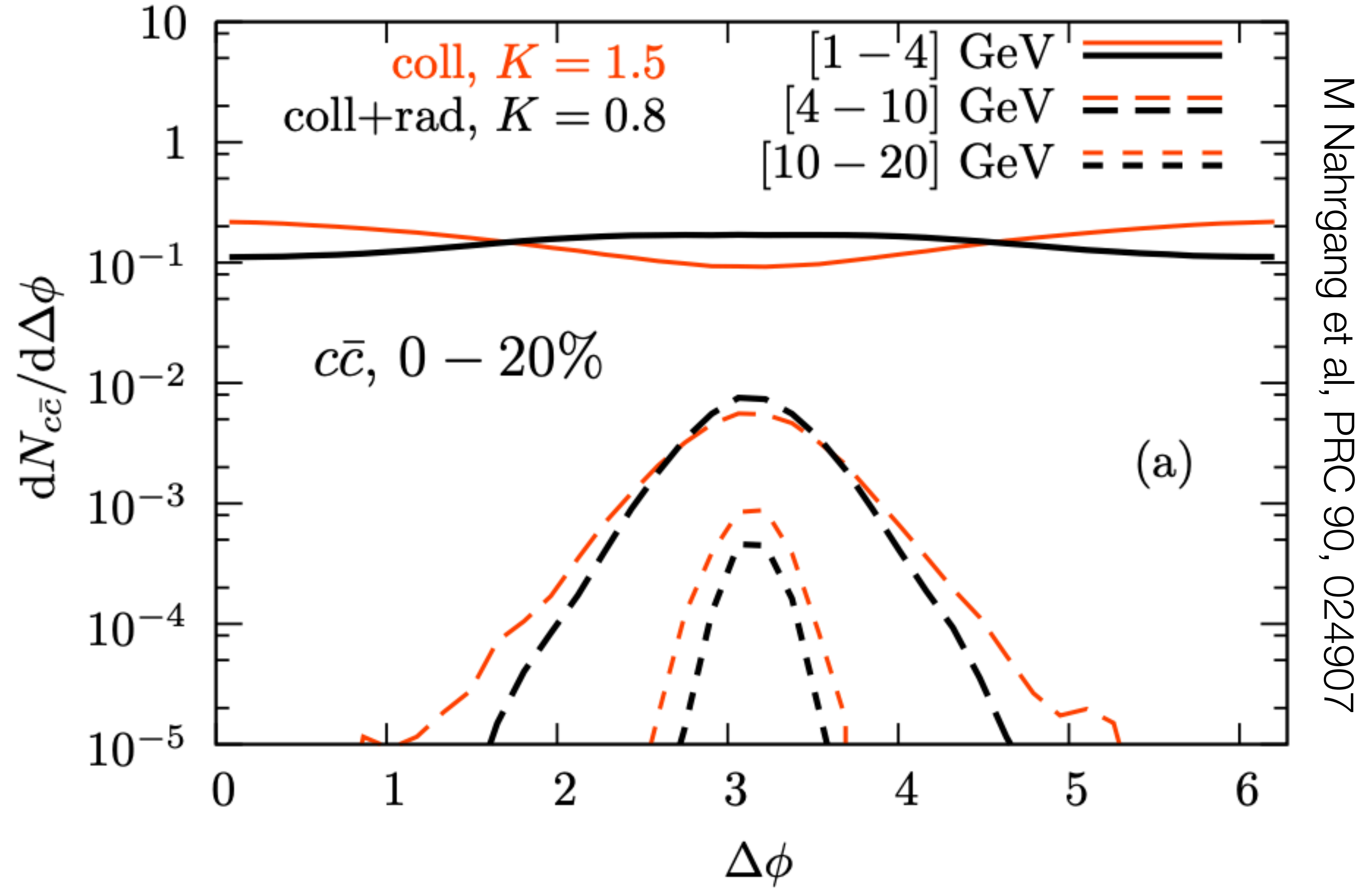


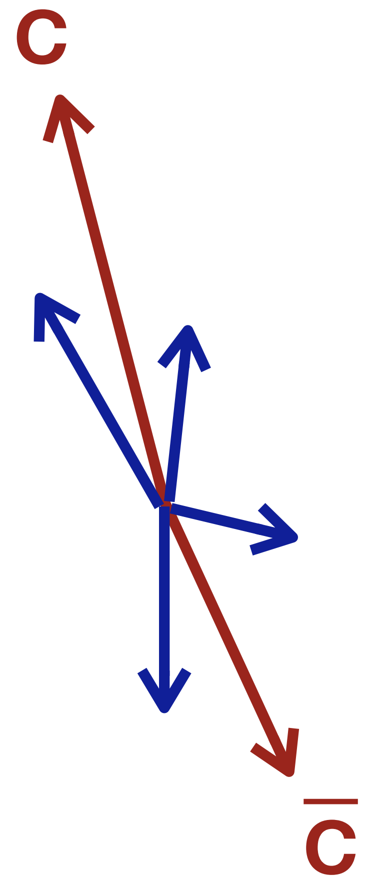
$\rho - a_1$ mixing affects mass spectrum above ρ peak

ALICE 3 provides necessary precision

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

Charm azimuthal correlations

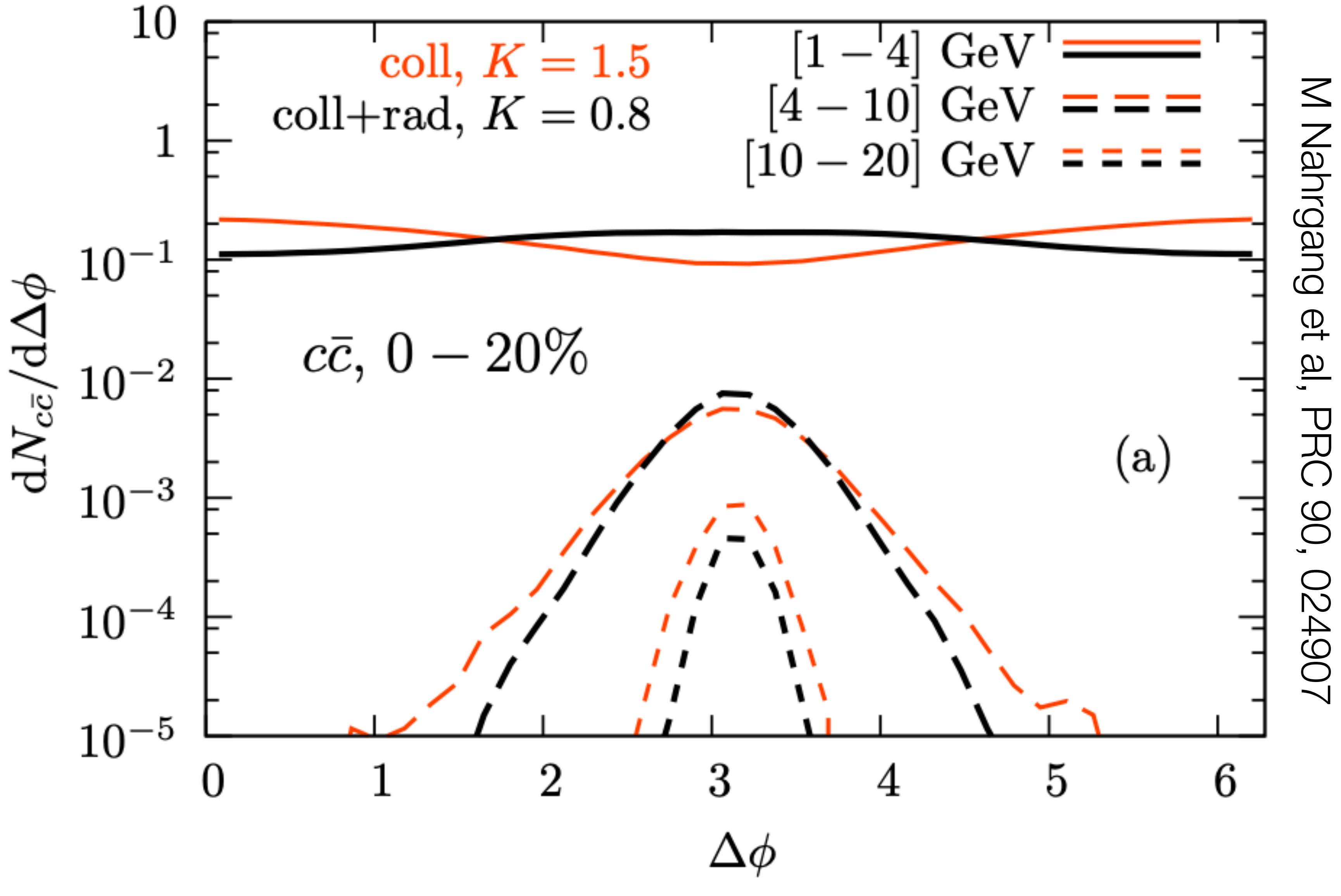


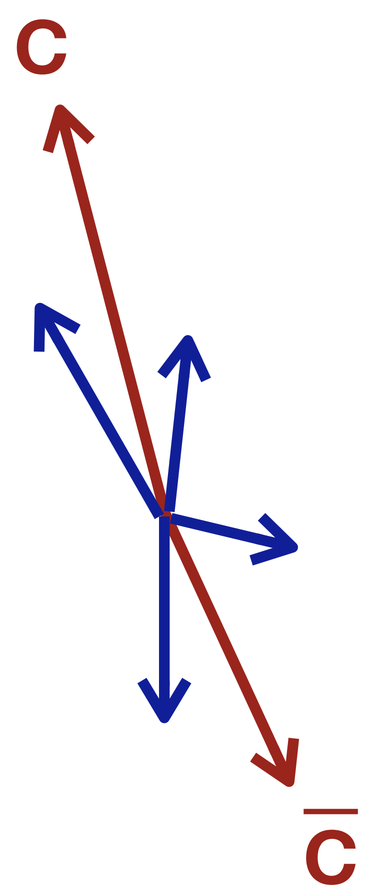


- Angular decorrelation **directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → **heavy-ion measurement only possible with ALICE 3**

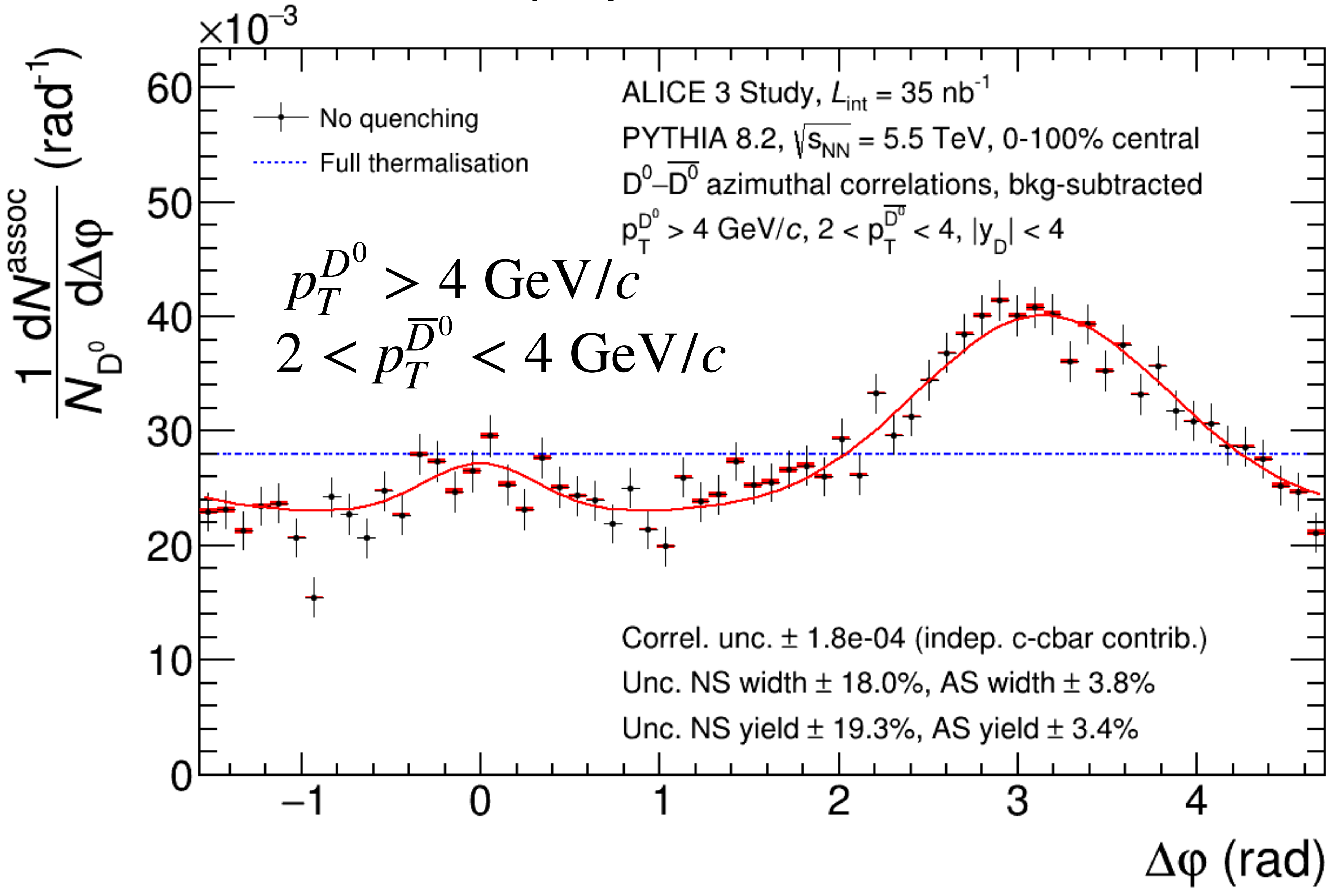
Heavy-flavour transport: $D\bar{D}$ azimuthal correlations

Charm azimuthal correlations





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



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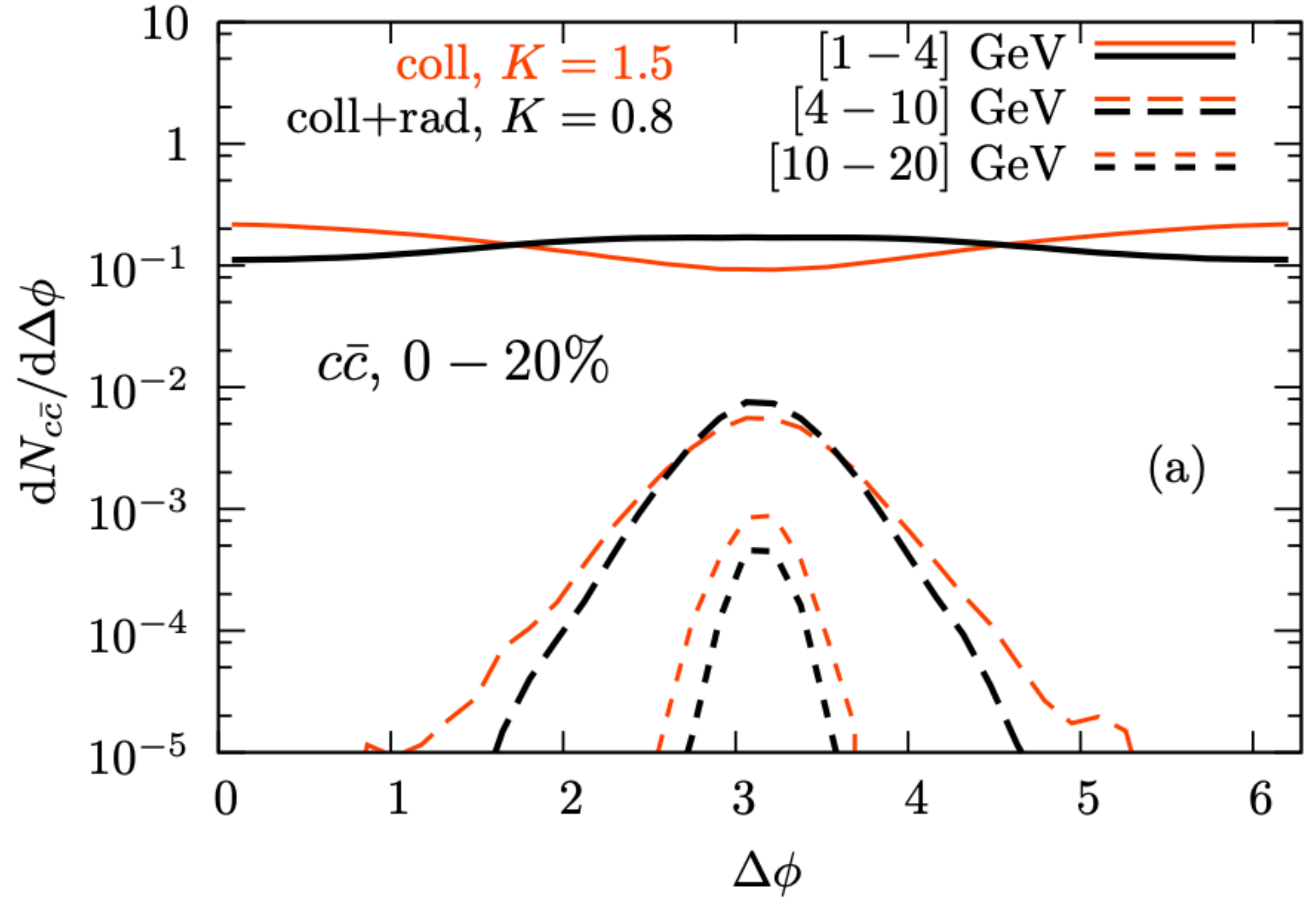
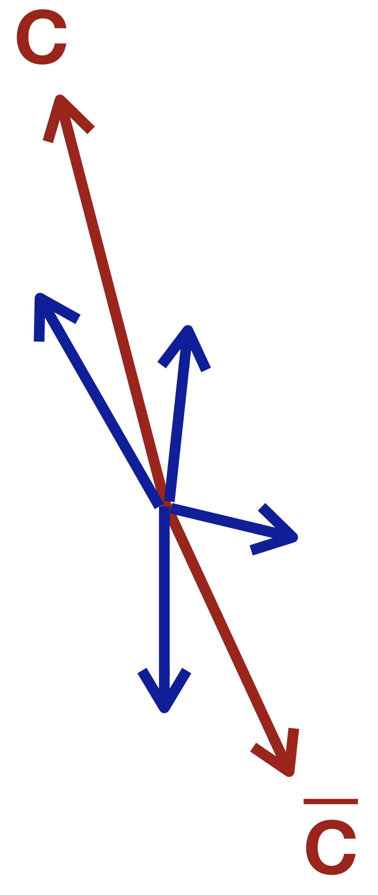
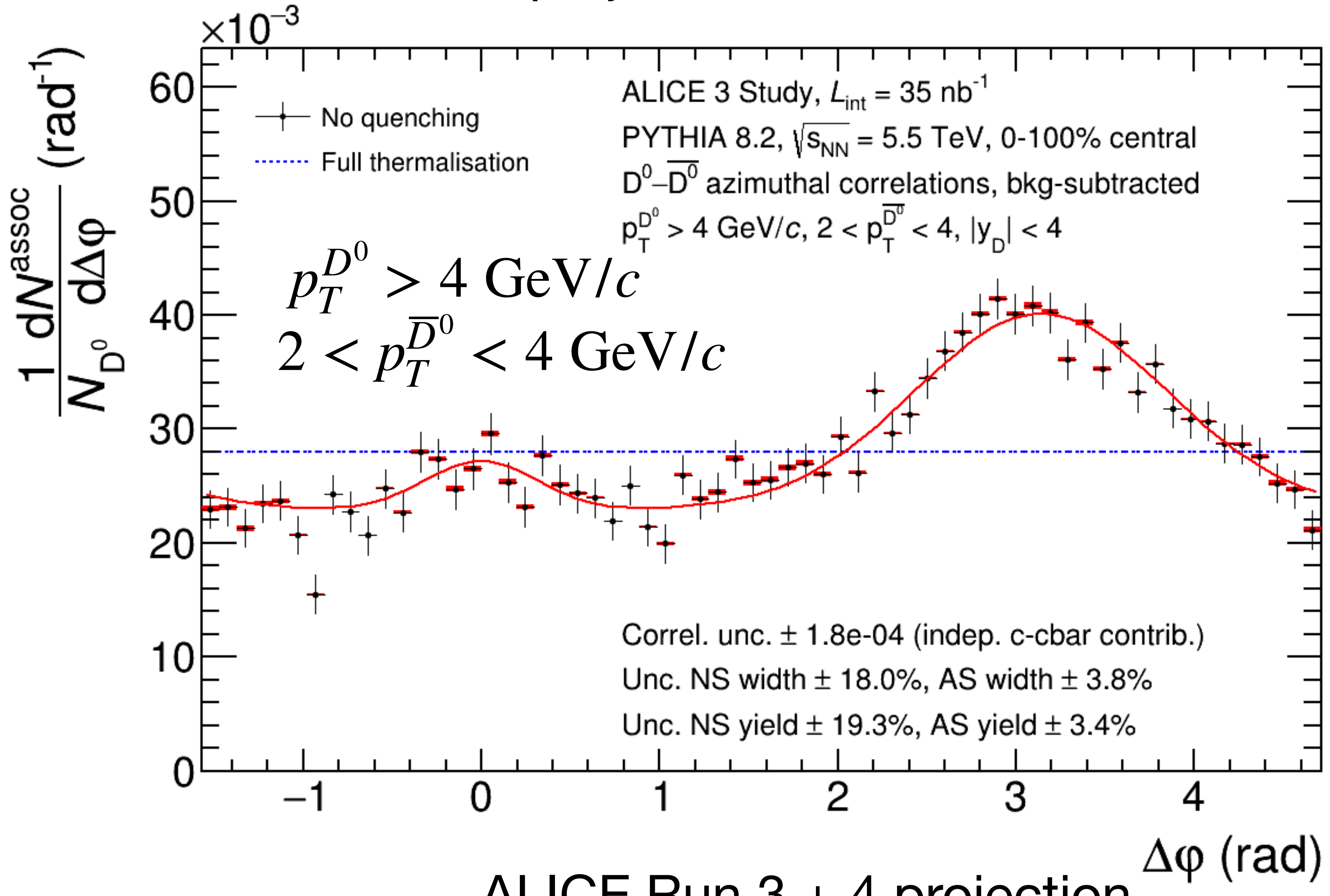
Charm azimuthal correlations



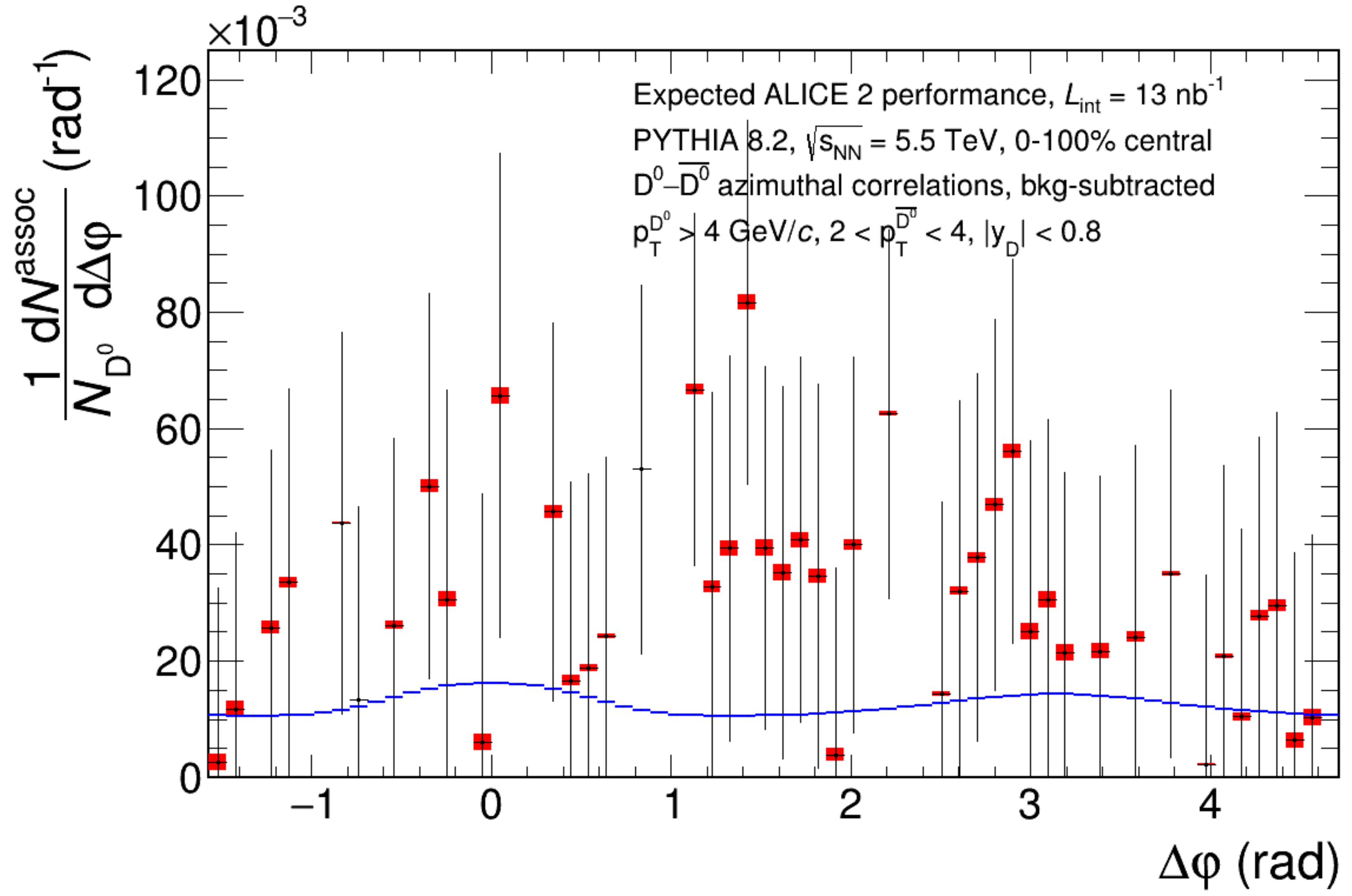
M Nahrgang et al, PRC 90, 024907



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



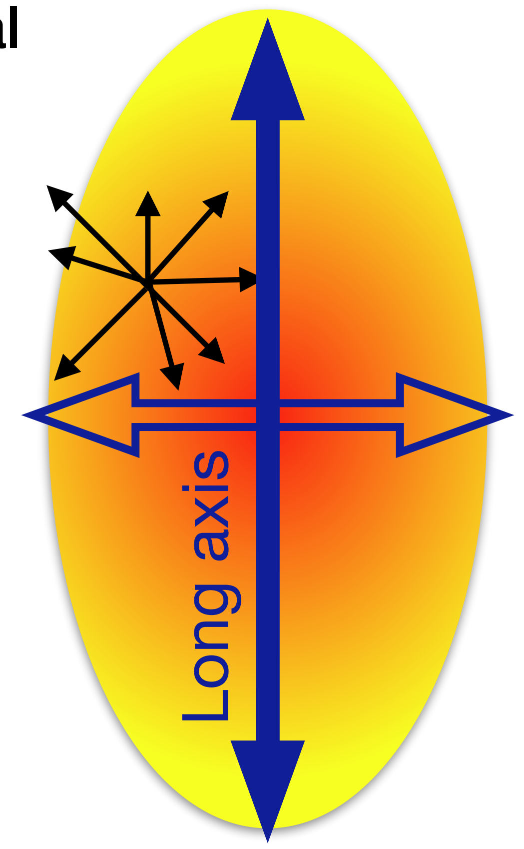
ALICE Run 3 + 4 projection



- 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: elliptic flow v_2

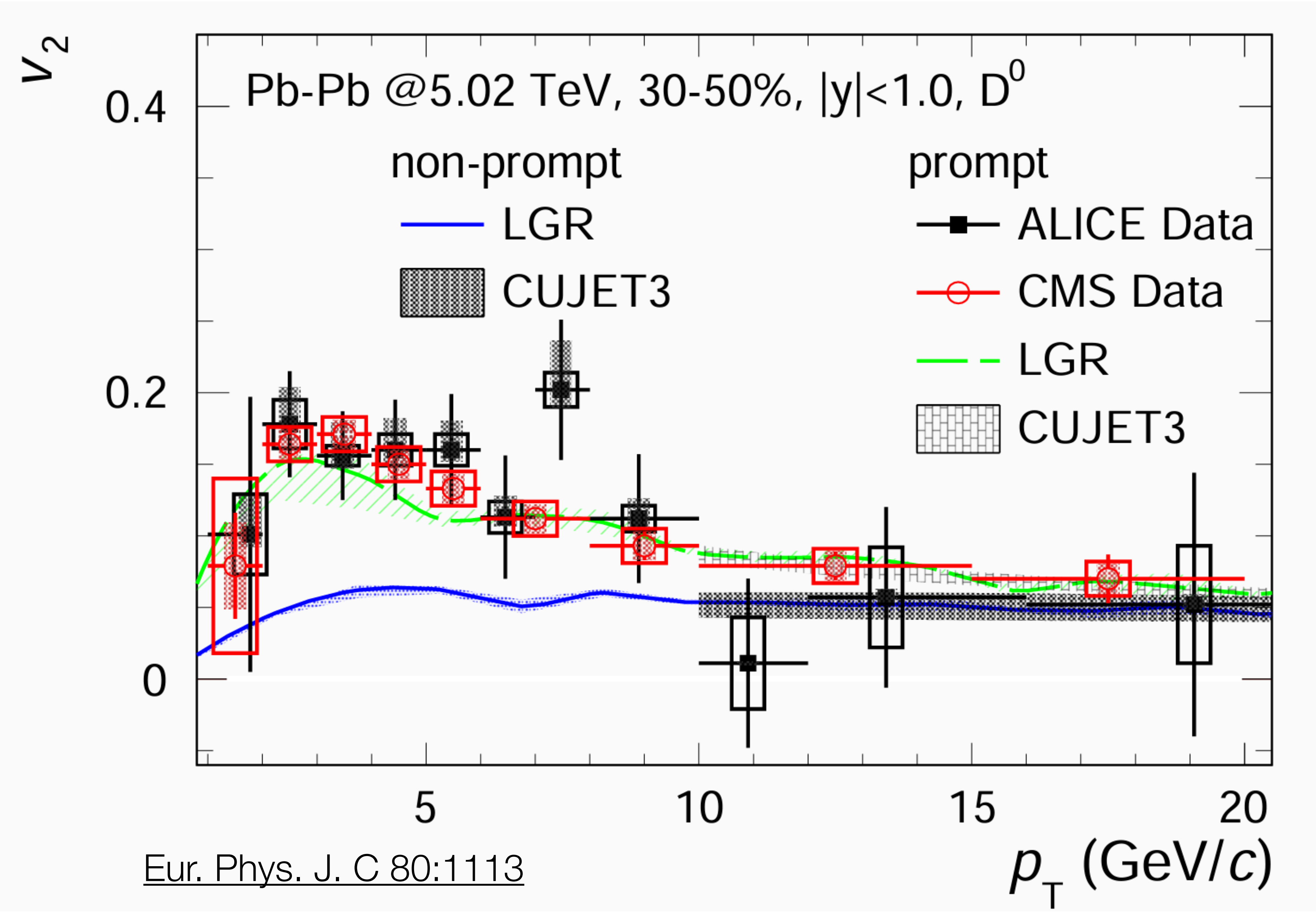
Non-central collision



Interactions with the plasma generate azimuthal anisotropy v_2:

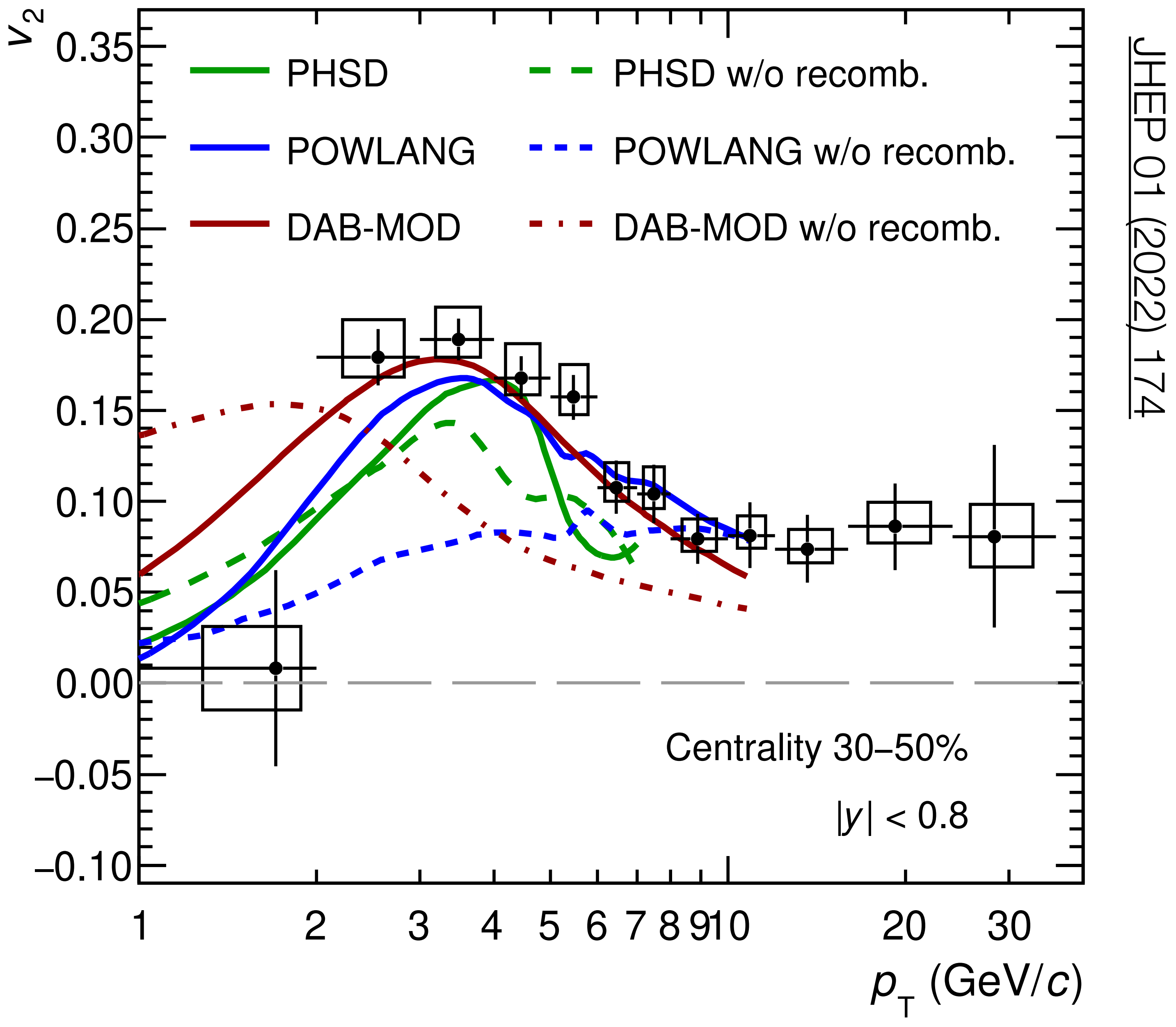
$$\frac{dN}{d\phi} \propto 1 + 2\,v_2 \cos 2(\varphi - \psi)$$

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



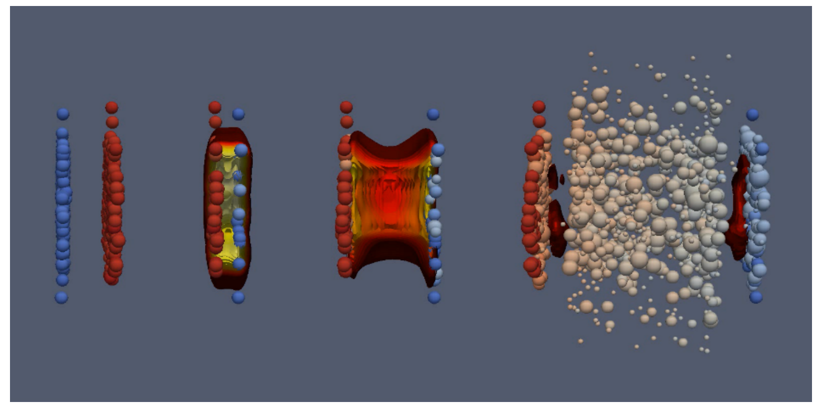
relaxation time: $\tau_Q = (m_Q/T)\,D_s$

Impact of hadronisation (recombination)



Heavy quarks: access to quark transport at hadron level

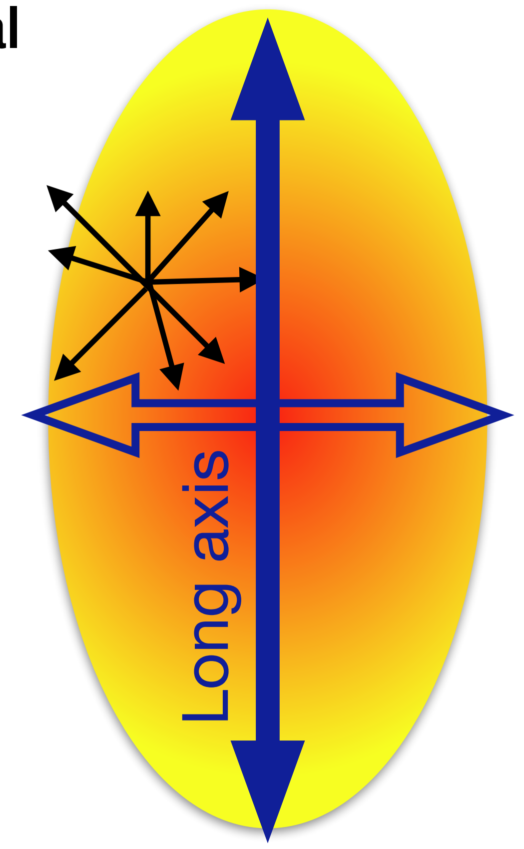
- Expect beauty thermalisation slower than charm — smaller v_2
- Need baryons and mesons to disentangle hadronisation effects: interplay with light quarks



QGP: quark transport Hadronisation

Heavy flavour transport: elliptic flow v_2

Non-central collision



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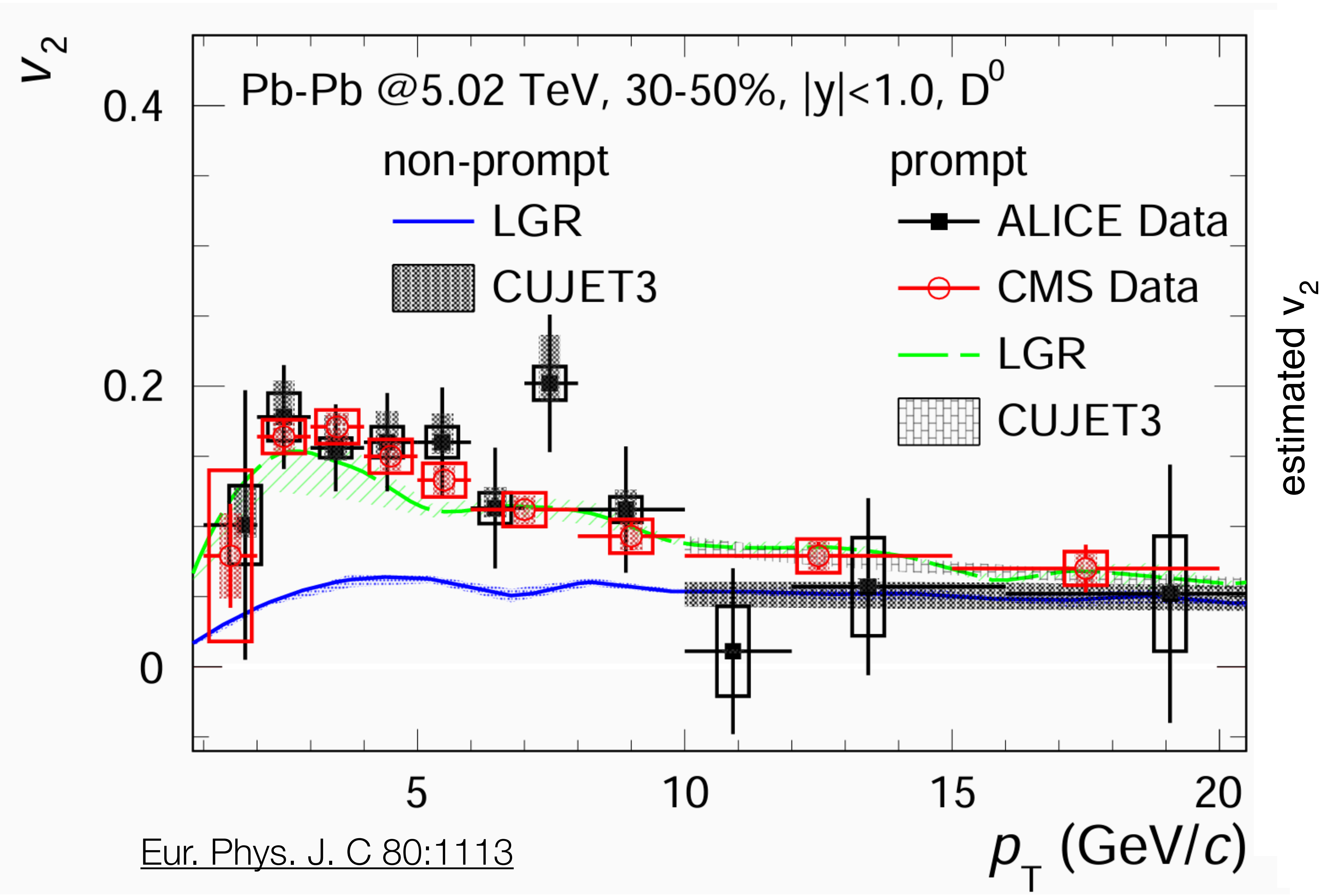
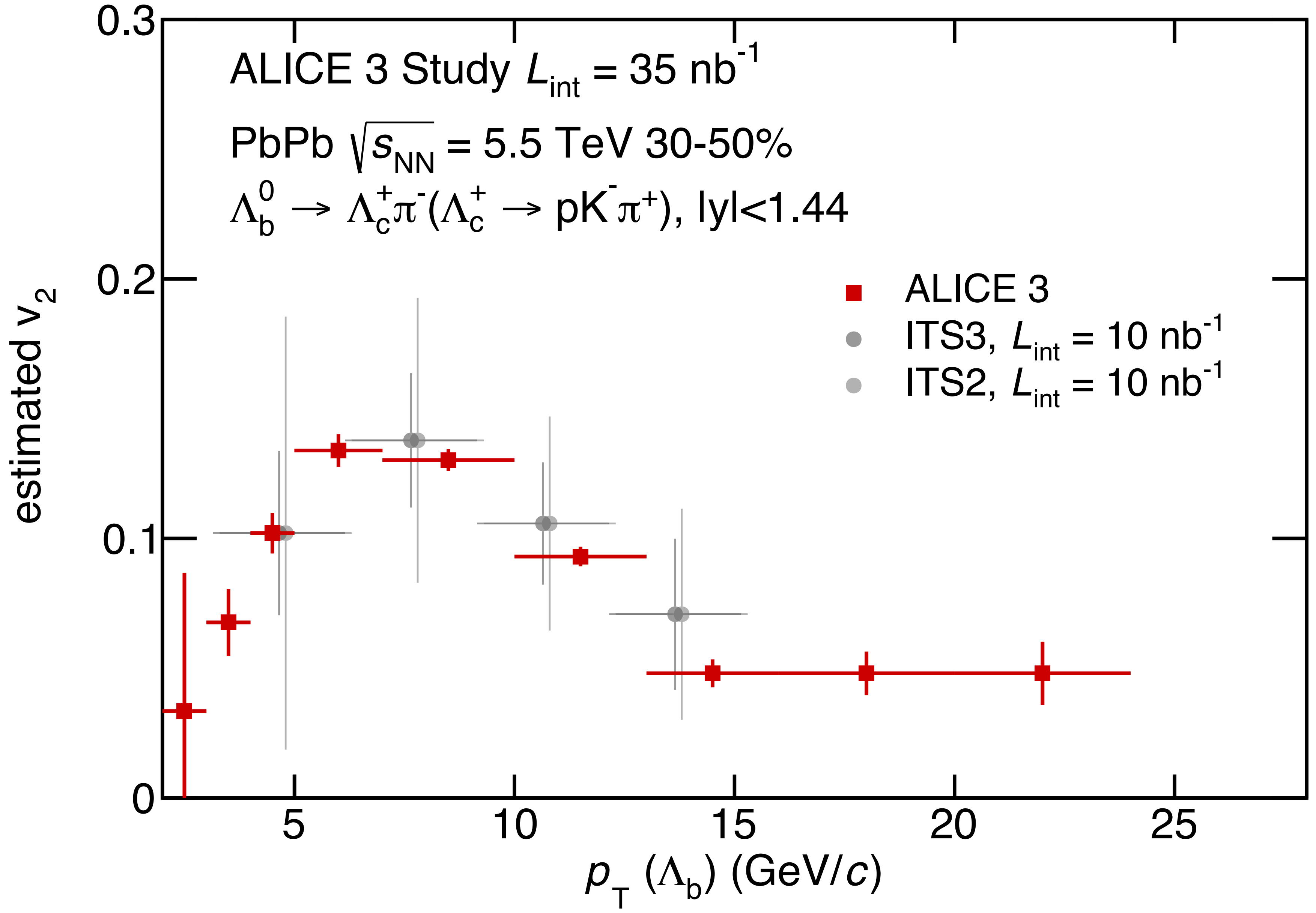


relaxation time: $\tau_Q = (m_Q/T)\,D_s$

Λ_b v_2 performance



Heavy quarks: access to quark transport at hadron level

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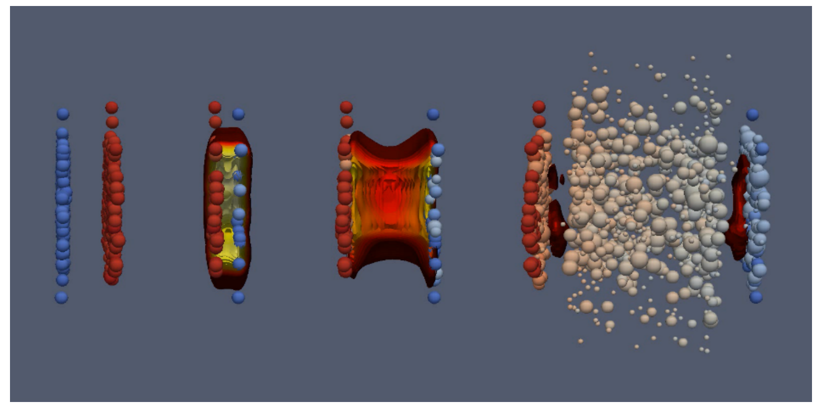
- Need baryons and mesons to disentangle hadronisation effects: interplay with light quarks



QGP: quark transport

Hadronisation

Hadron formation: multi-HF hadrons

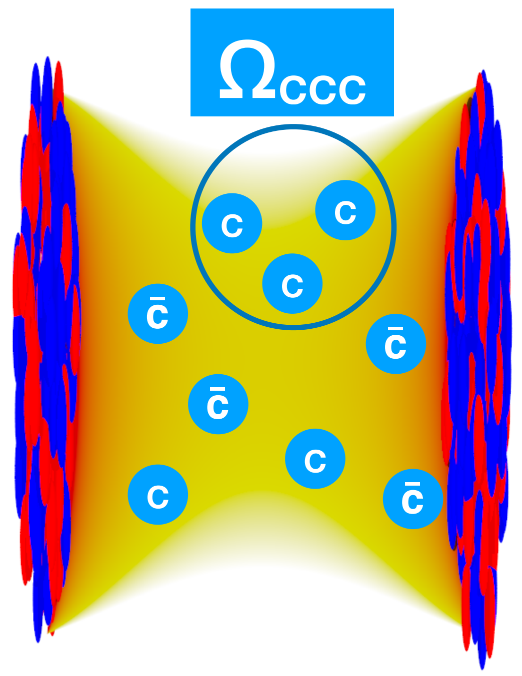
- **Multi-charm baryons**: unique probe of hadron formation
- Statistical hadronisation model: **very large enhancement** in AA
  - Specific relation between yields: g_c^n for n-charm states
- How is thermalisation approached microscopically?
  - Measure multiple states to probe dynamics of thermalisation and hadronisation

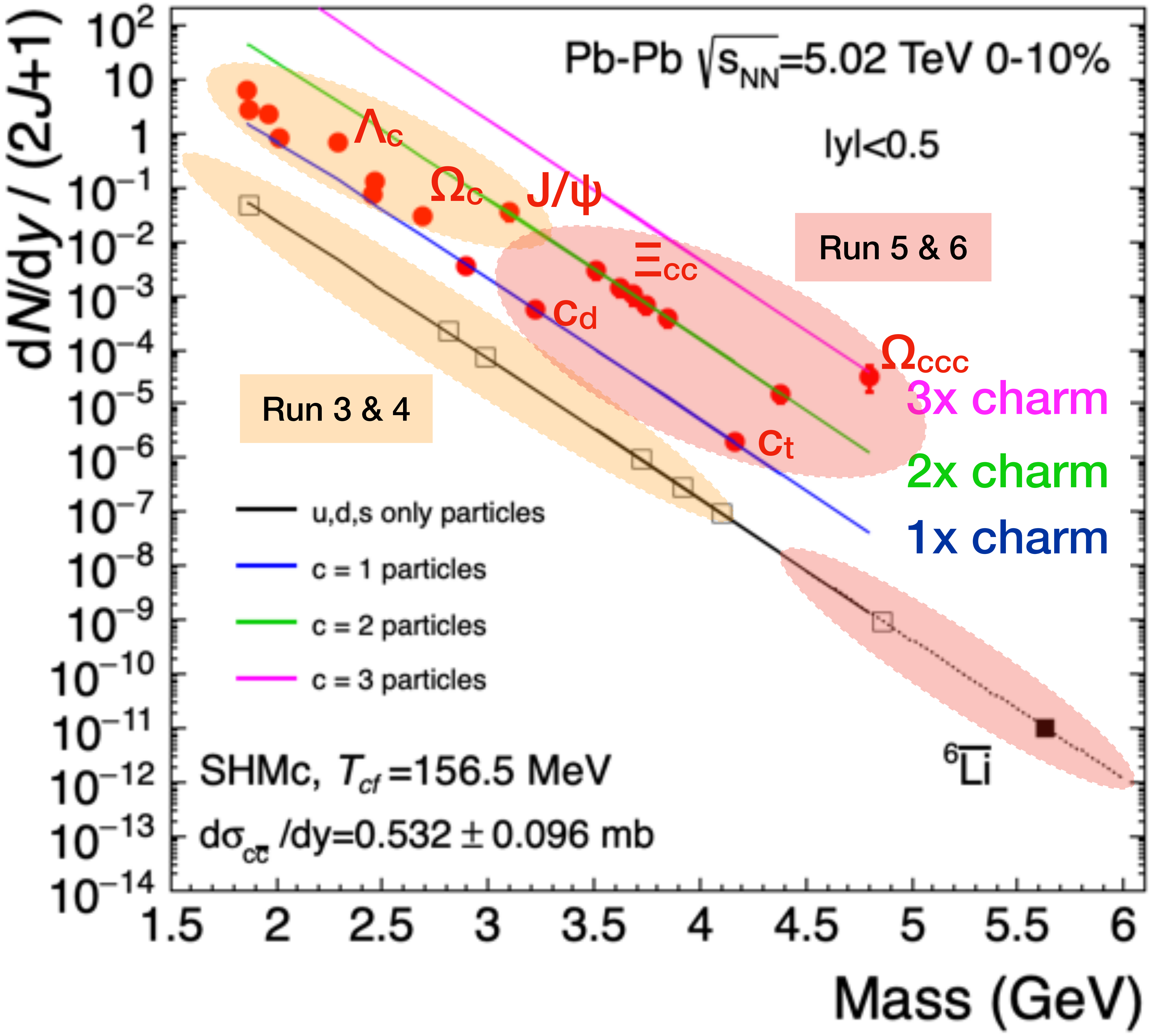
Single and double-charm baryons: Λ_c, Ξ_c, Ξ_{cc}, Ω_{cc}

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

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

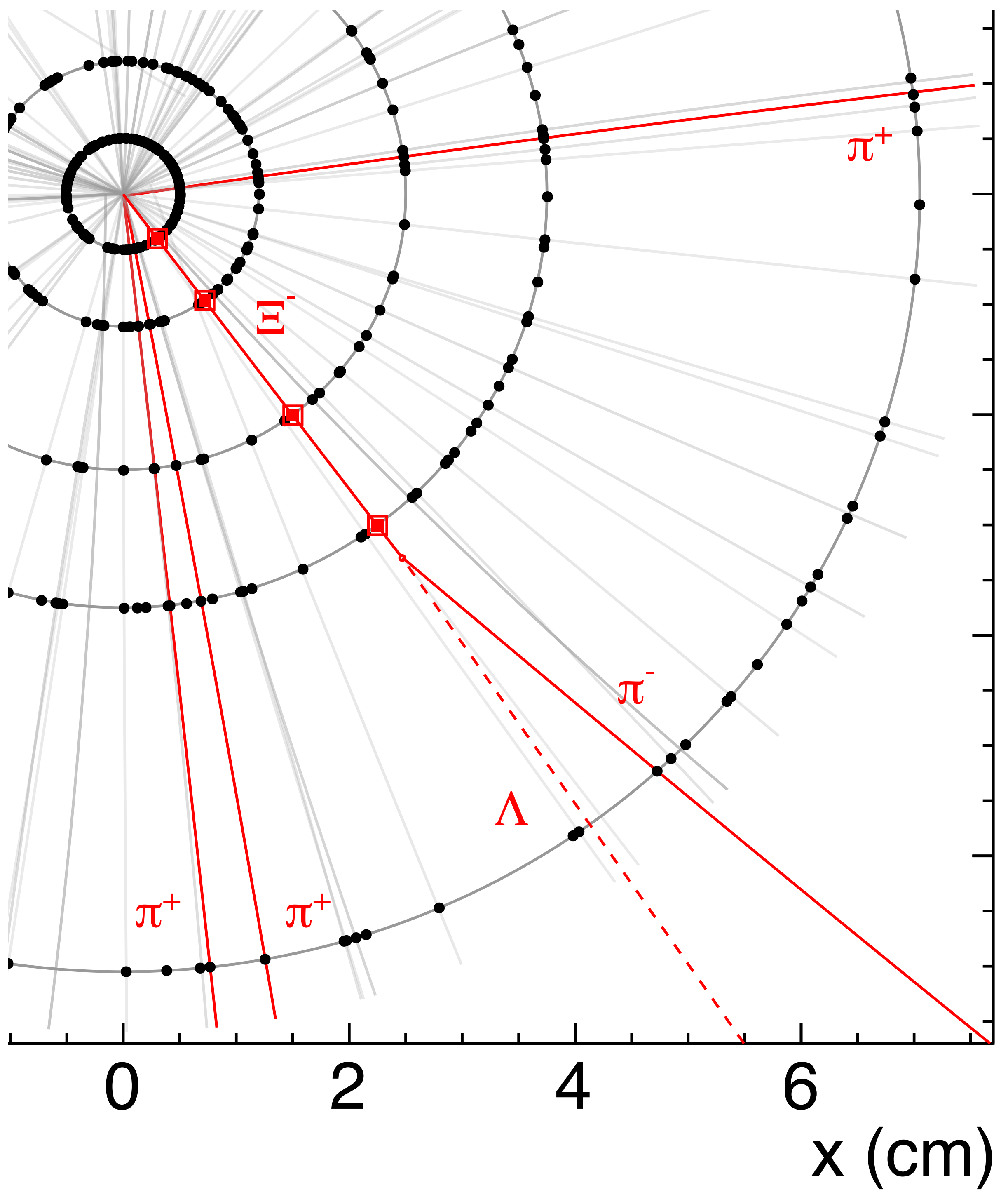
Large mass light flavour particles: nuclei



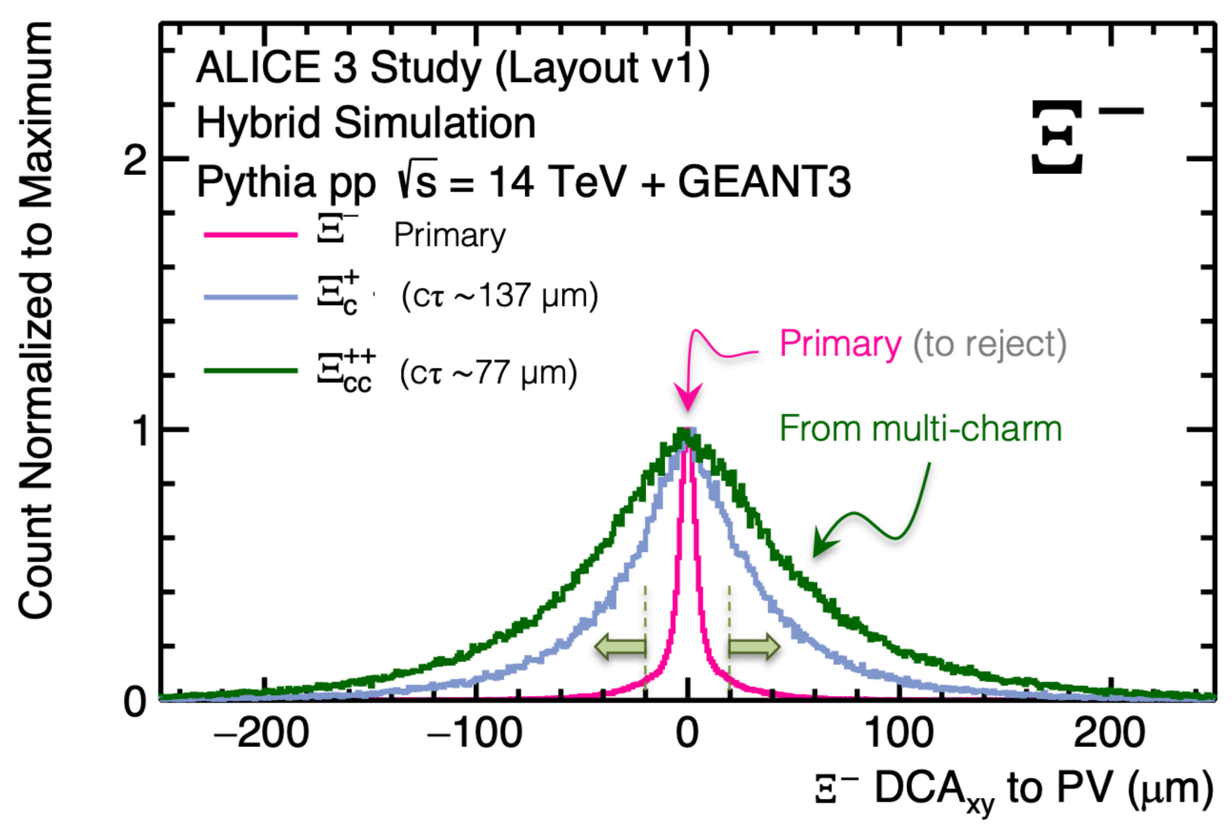


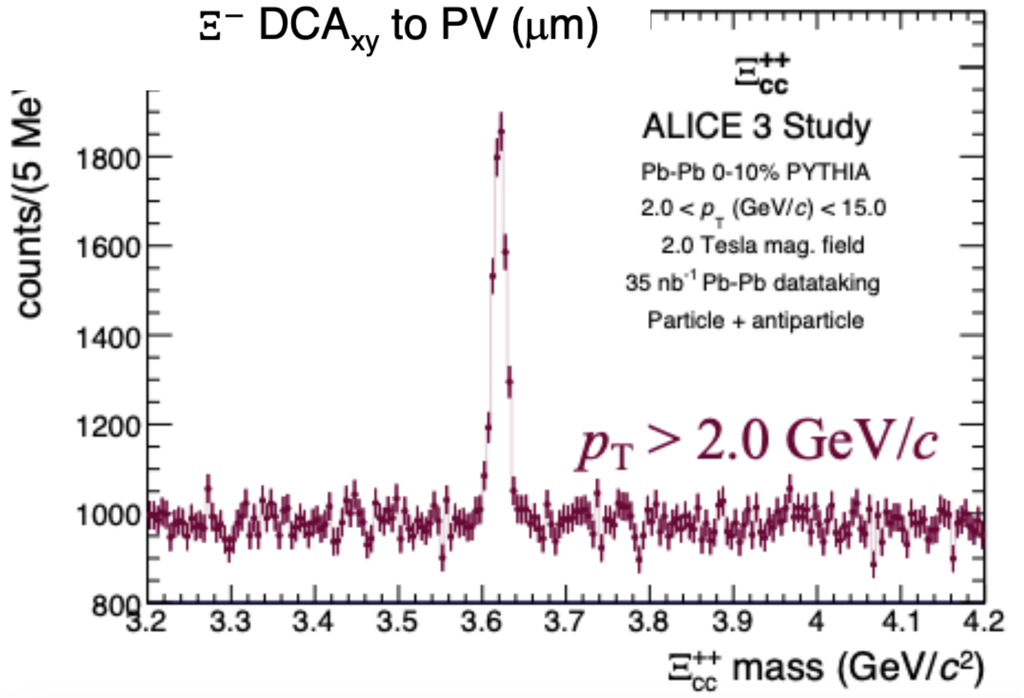
Multi-charm baryons

New technique: strangeness tracking



Impact parameter of Ξ



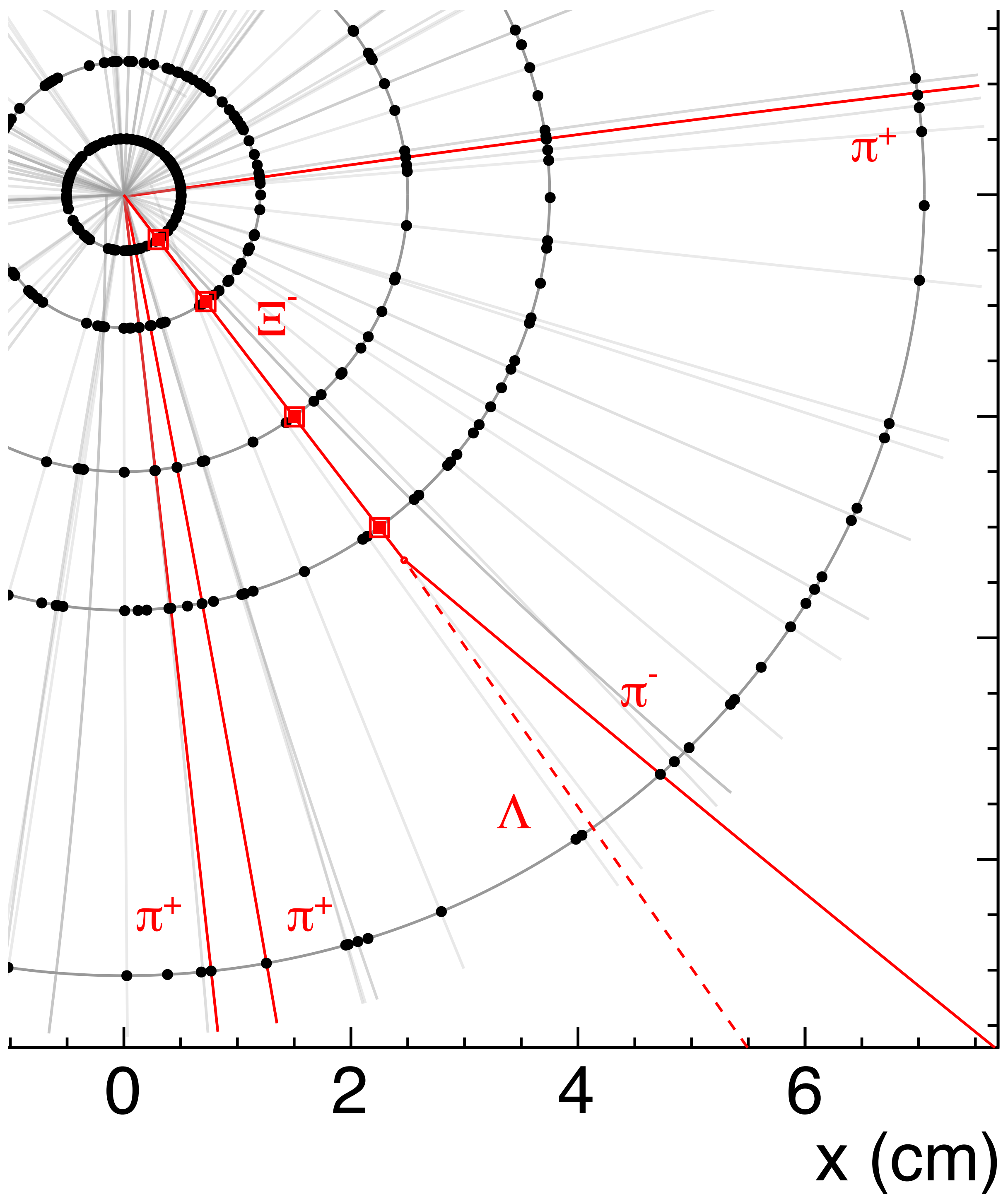


Pointing of Ξ baryon provides high selectivity

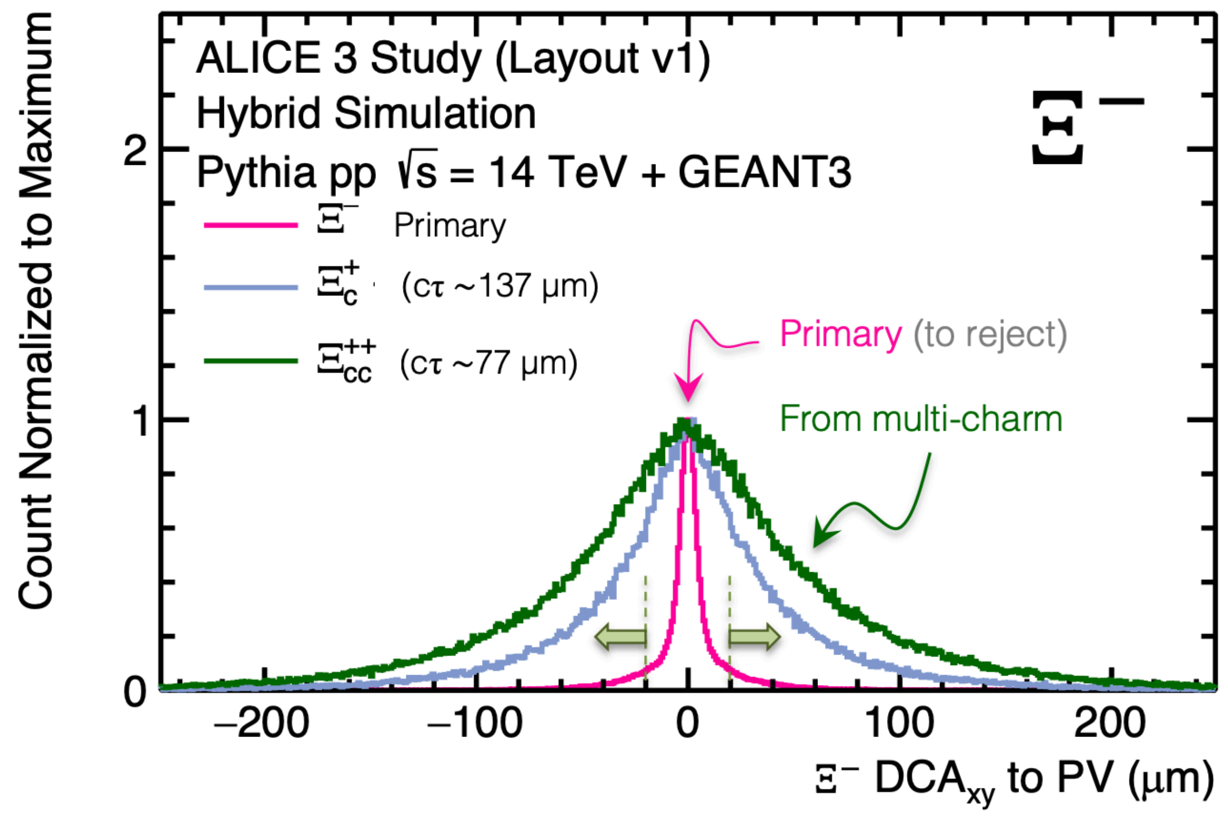
$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+} \qquad \Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

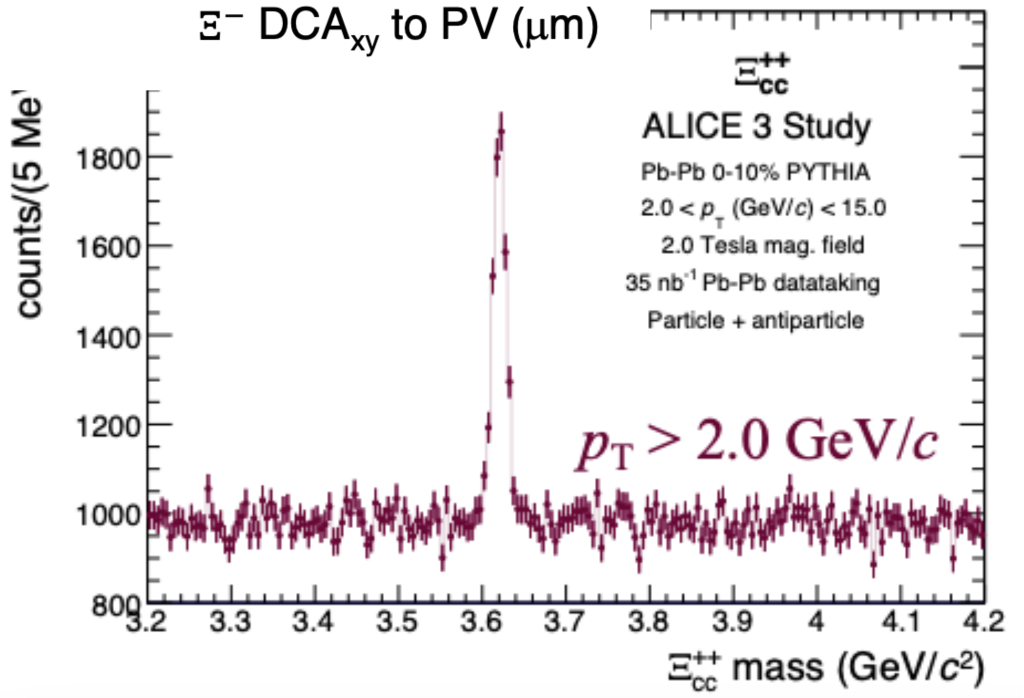
Multi-charm baryons

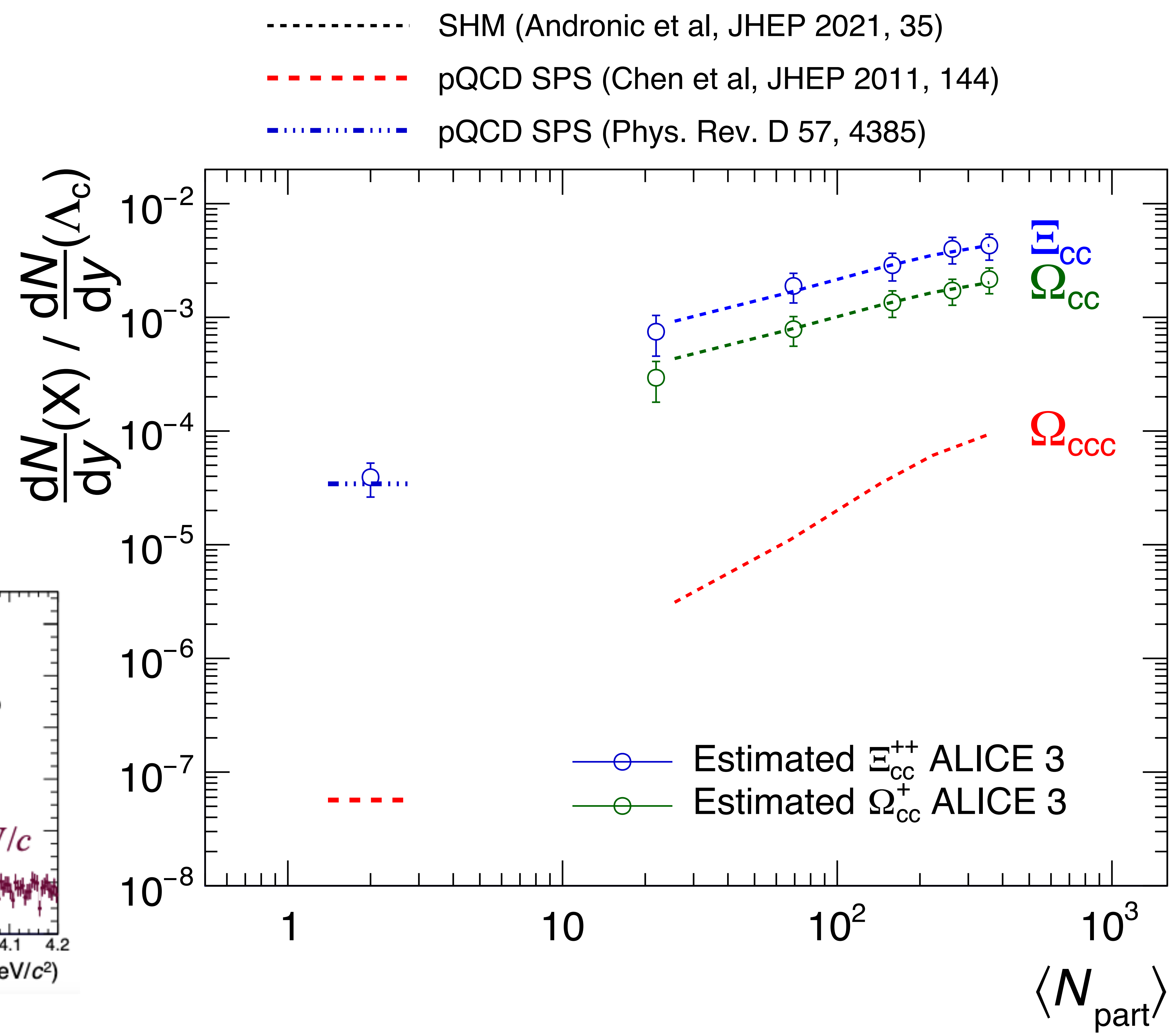
New technique: strangeness tracking



Impact parameter of Ξ







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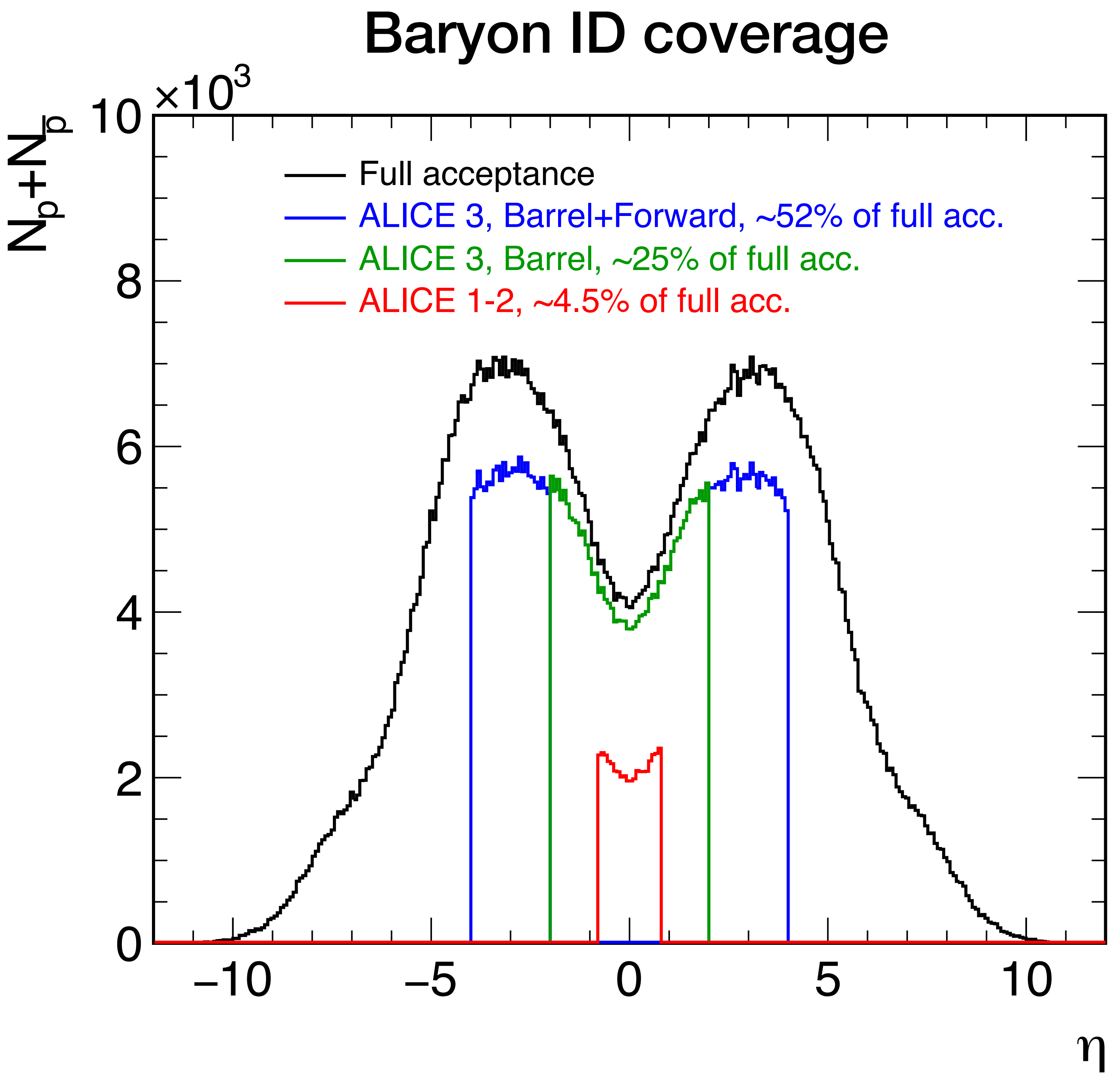
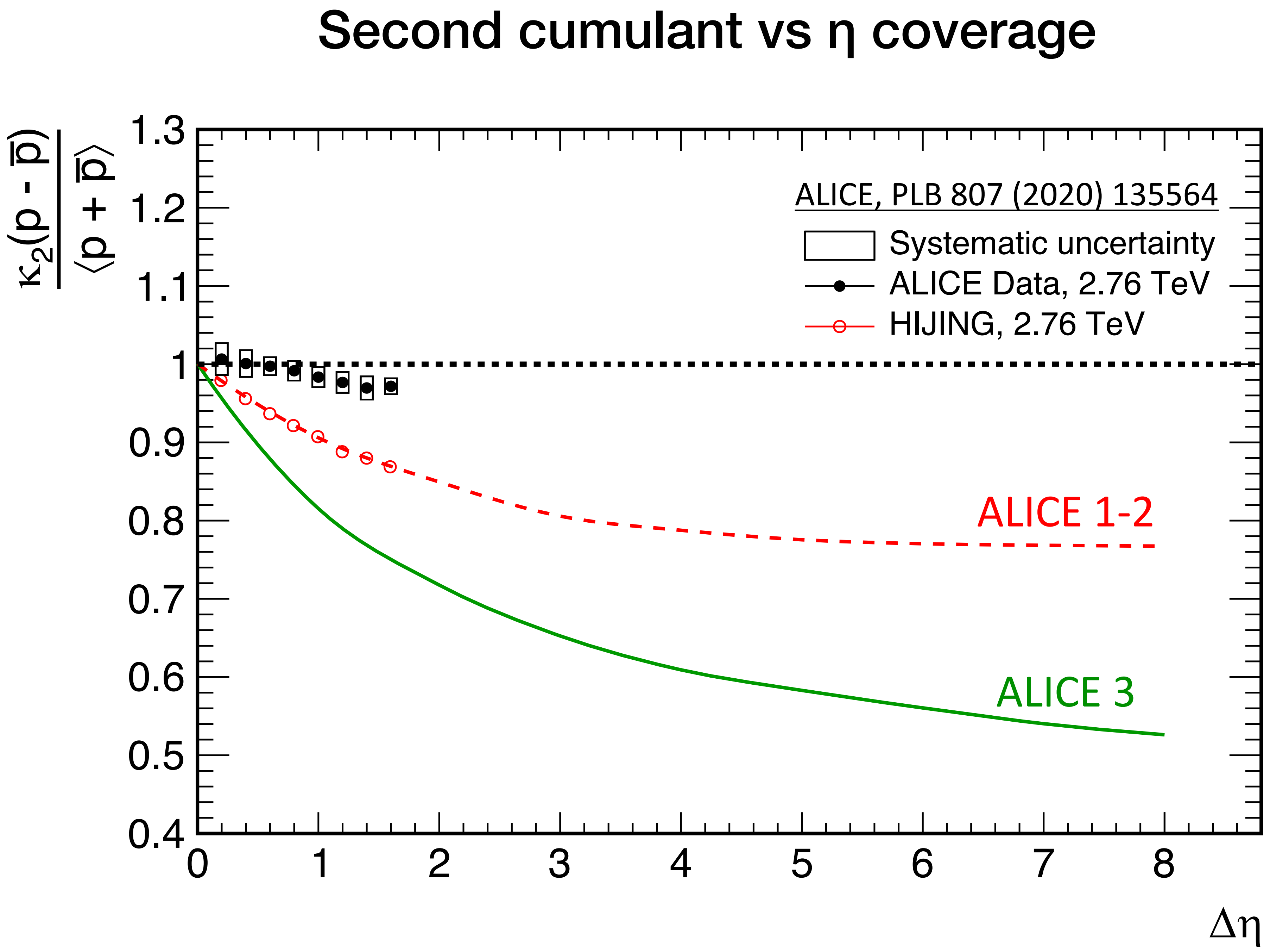
Large enhancements: unique sensitivity to thermalisation and hadronisation dynamics

ALICE 3: unique experimental access in Pb-Pb collisions

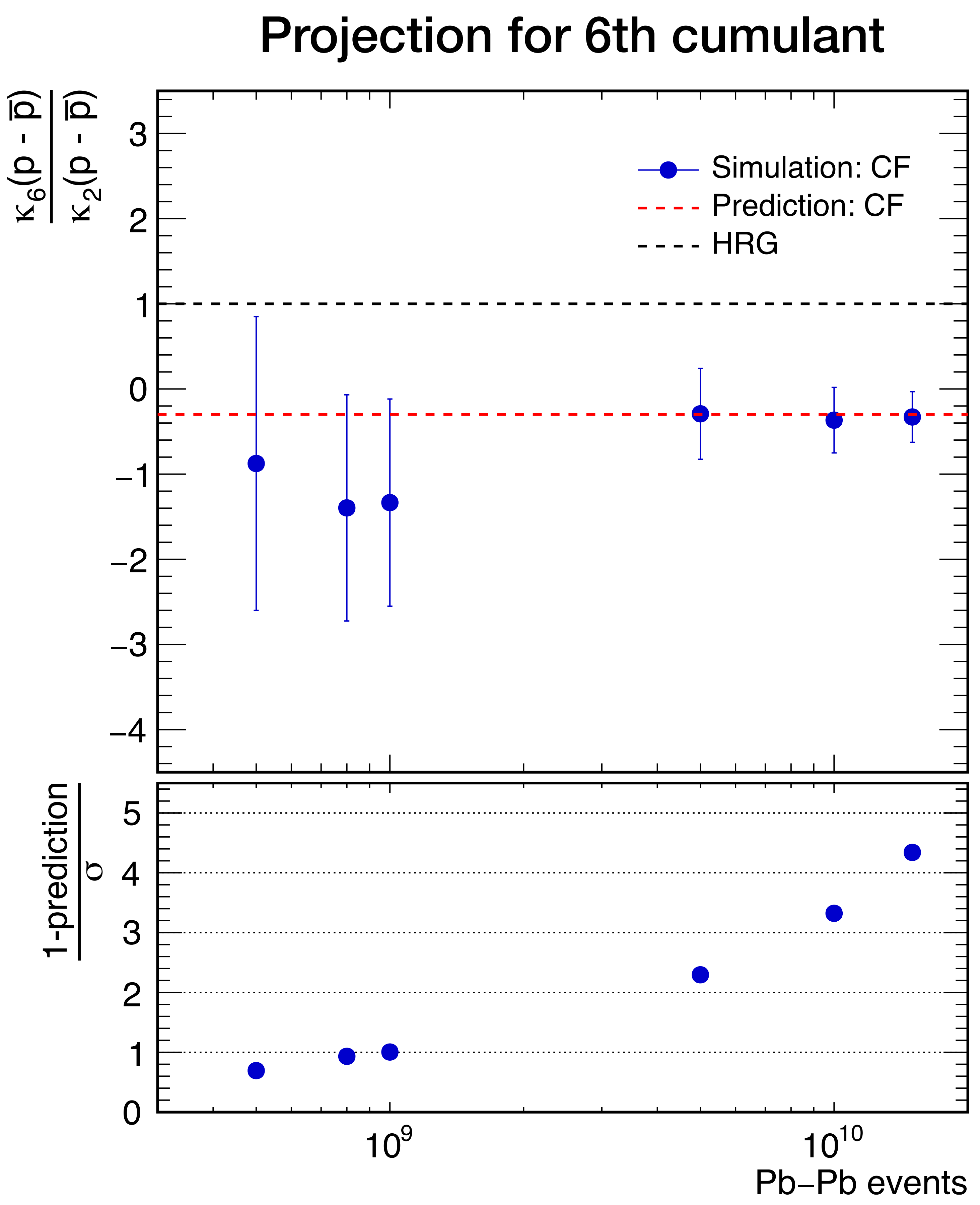
Net-baryon fluctuations



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



Second cumulant probes baryon number conservation — ‘correlation distance’

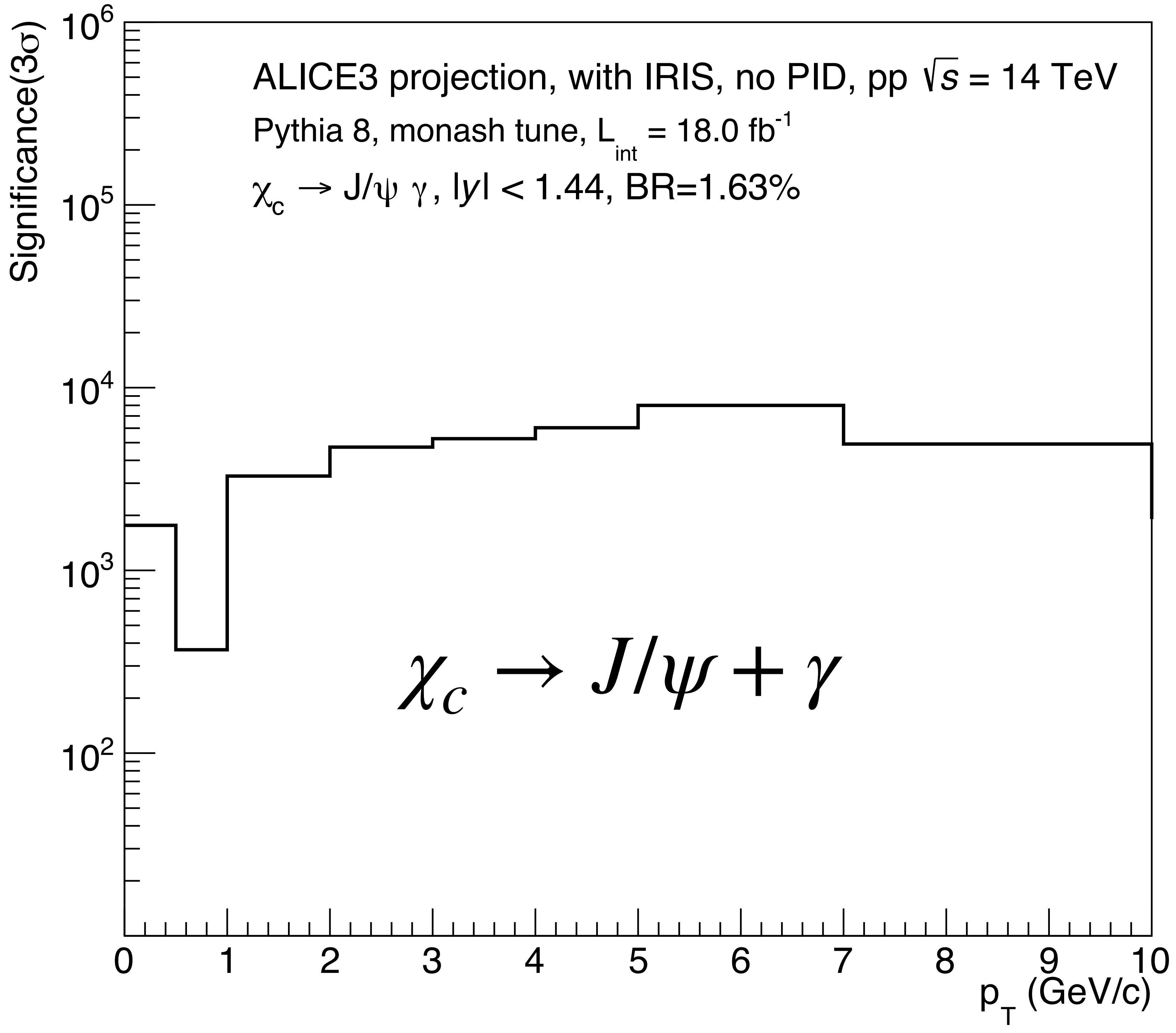


Higher cumulants: sensitive to baryon number susceptibility and critical behaviour

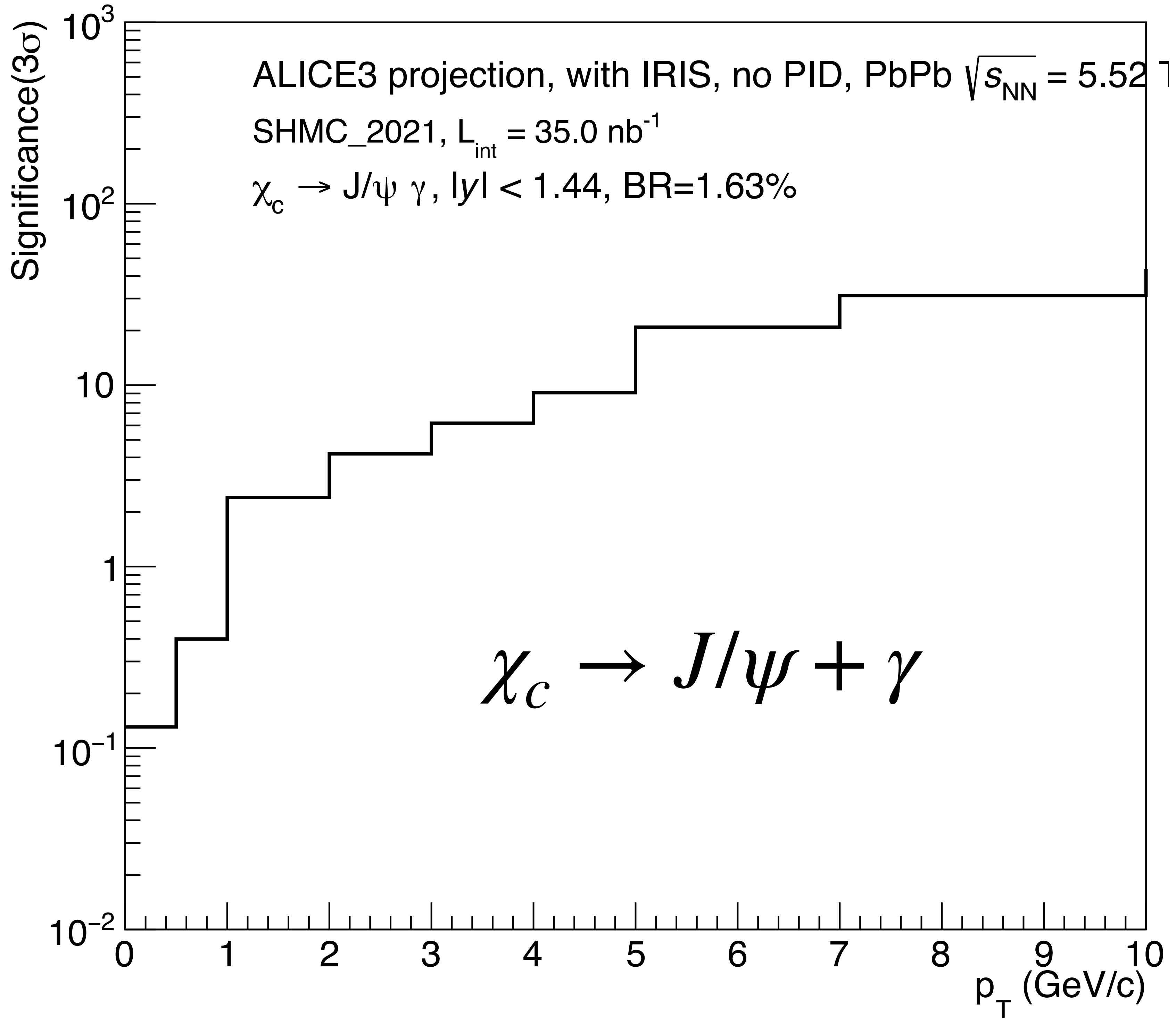
4σ observation in reach with ALICE 3

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

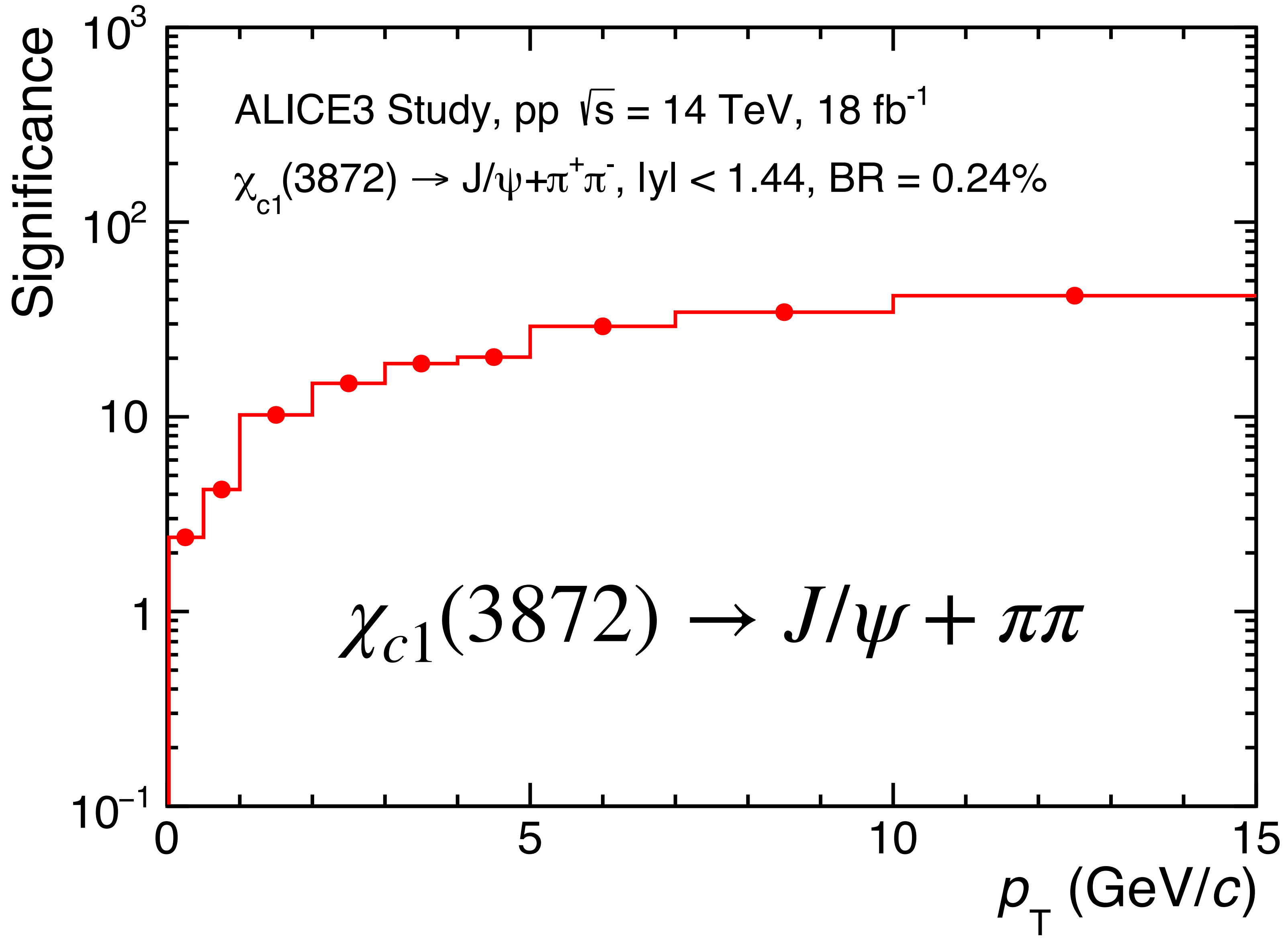
pp significance



Pb-Pb significance



pp significance

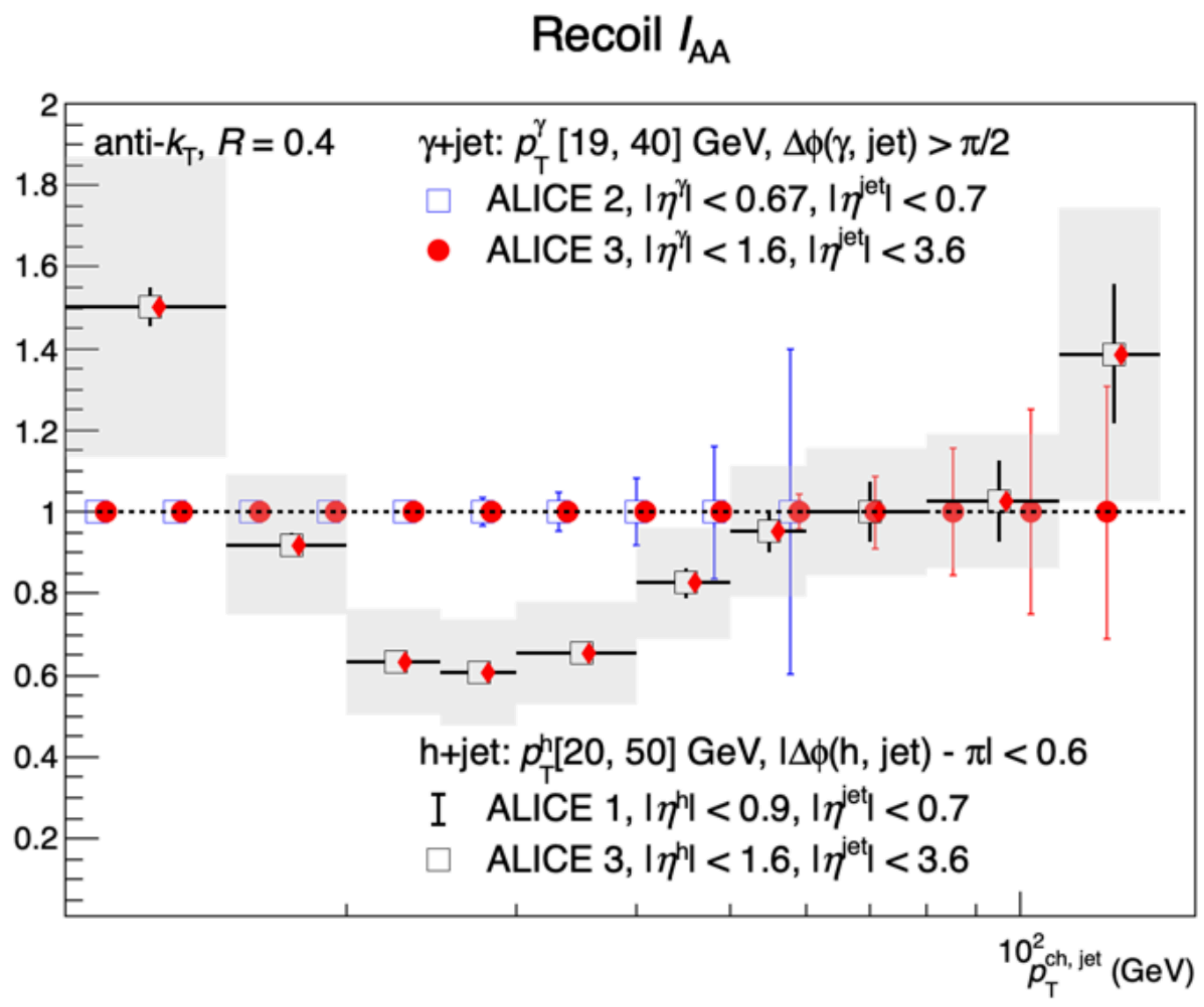


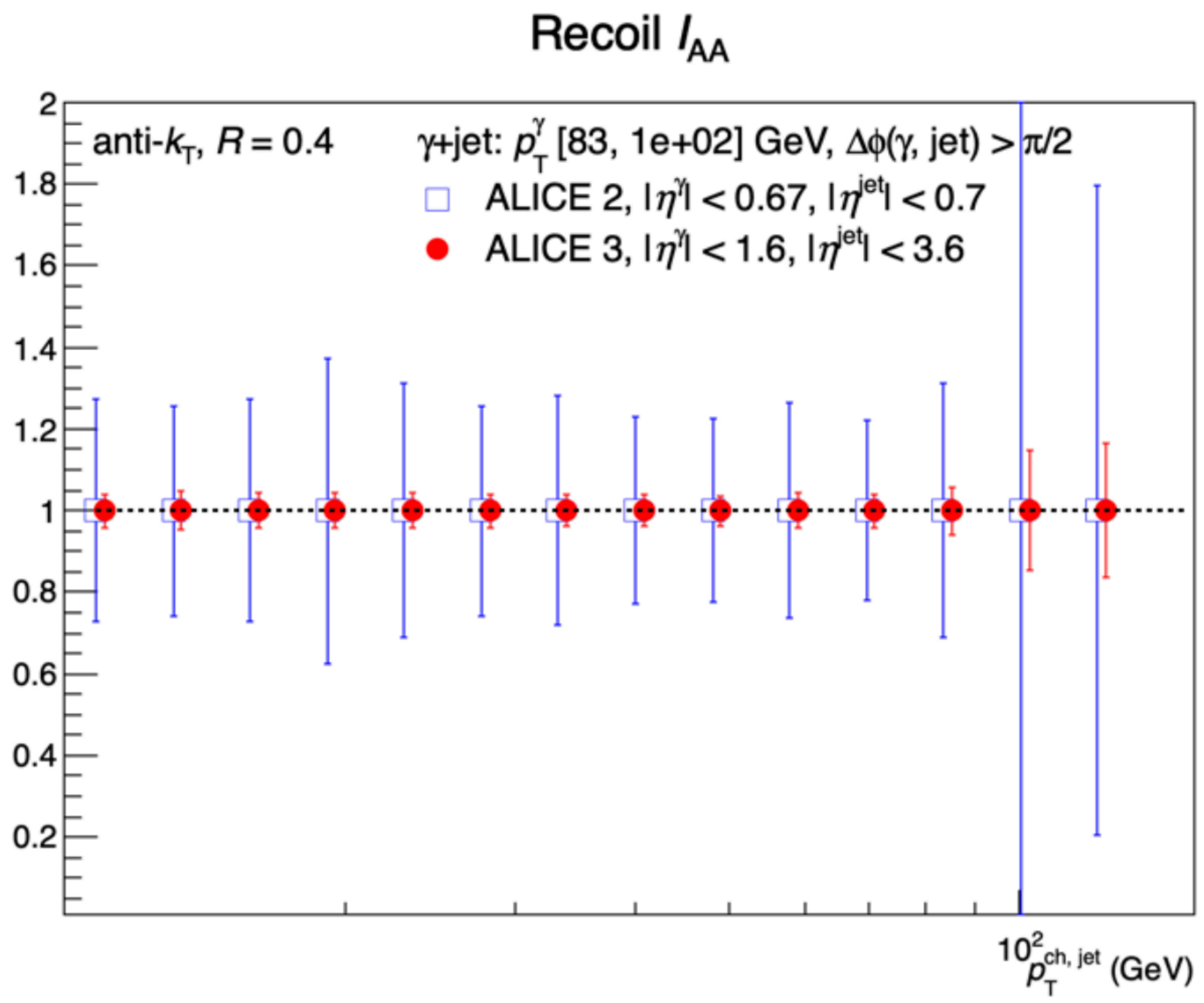
ALICE 3: $\chi_{c1}(3872)$
down to low p_T in pp

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

Hard probes: γ-jet



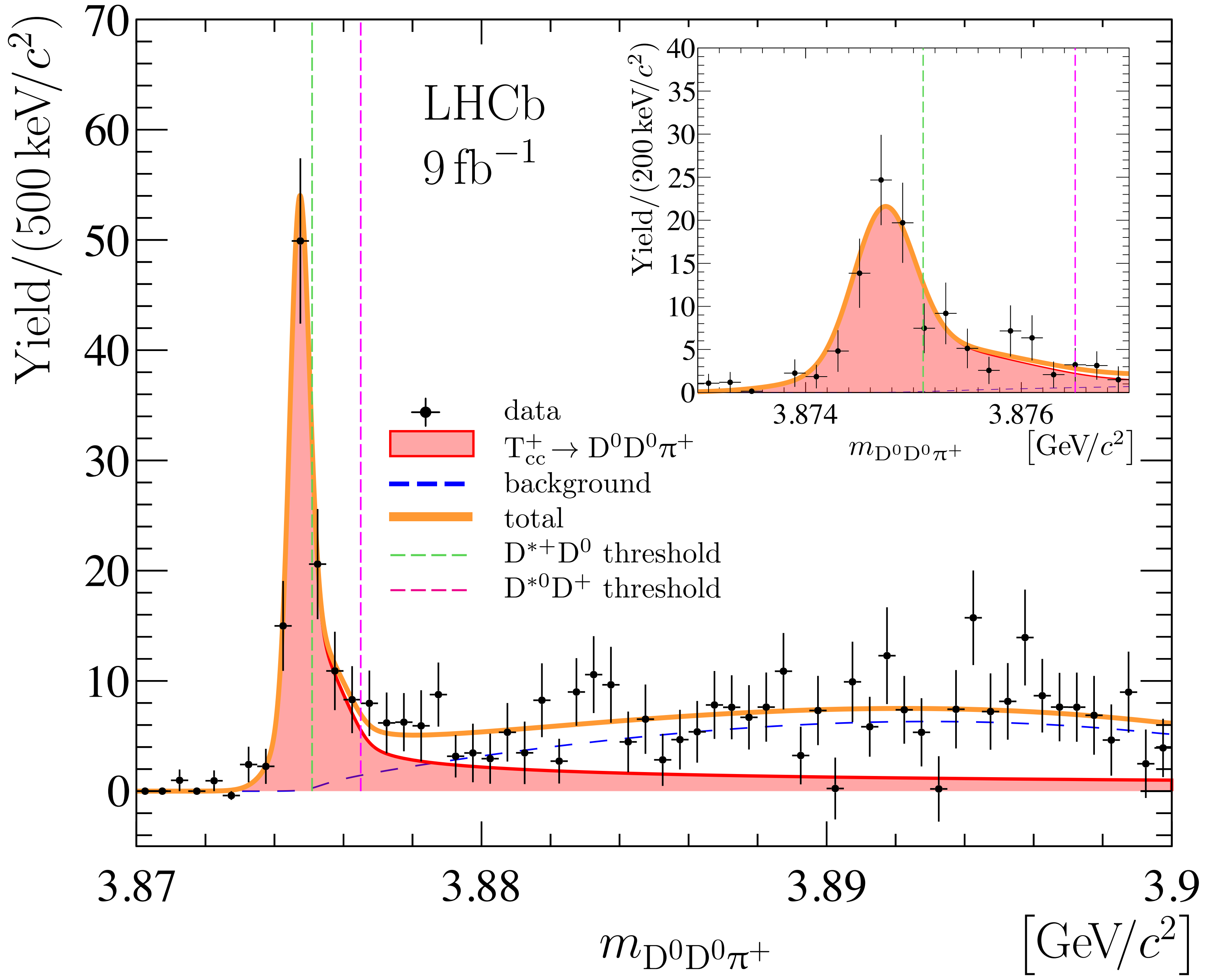


γ-jet, h-jet recoil jet measurements crucial for unbiased study of jet quenching

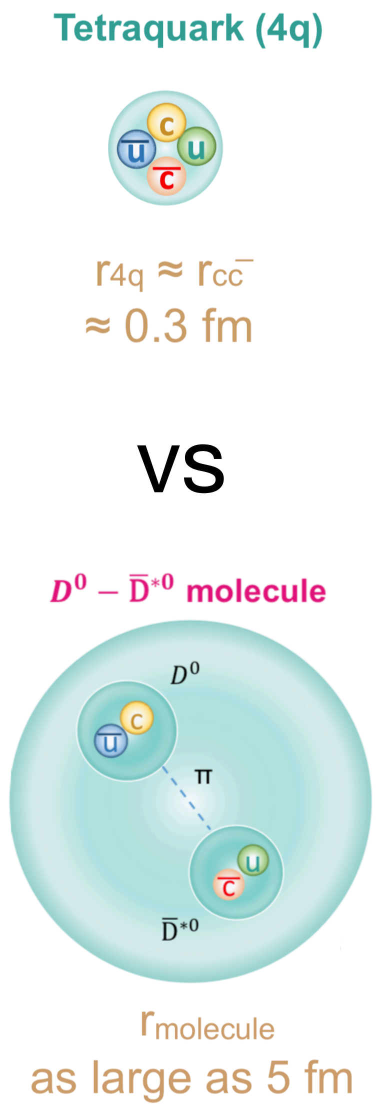
- ALICE 3 acceptance, full coverage EMCal, rate capabilities dramatically improve precision

Heavy-ion collisions as a laboratory for hadron physics

T_{cc}^{+} discovery

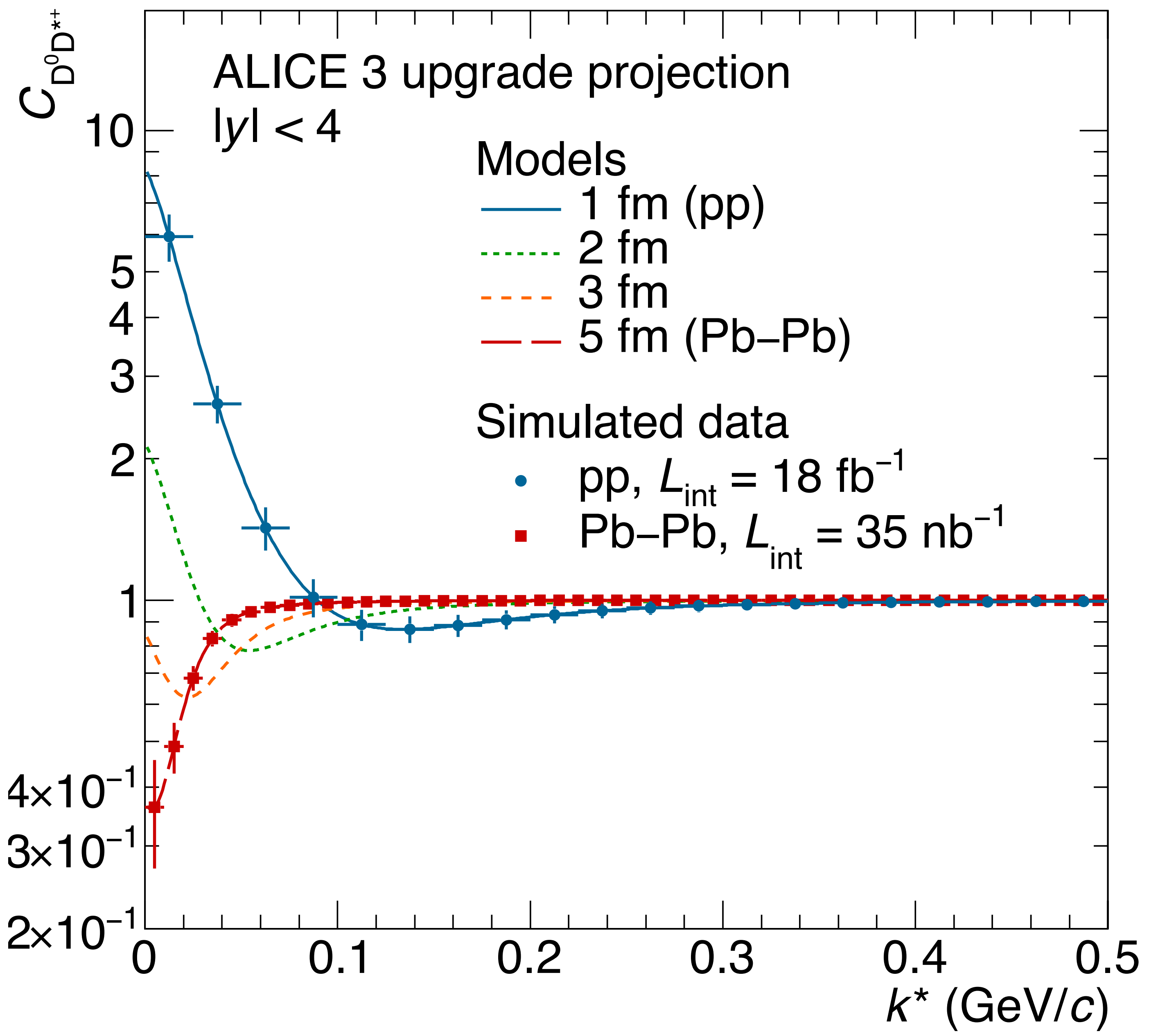


LHCb, Nat Phys 18 (2022) 7, 751

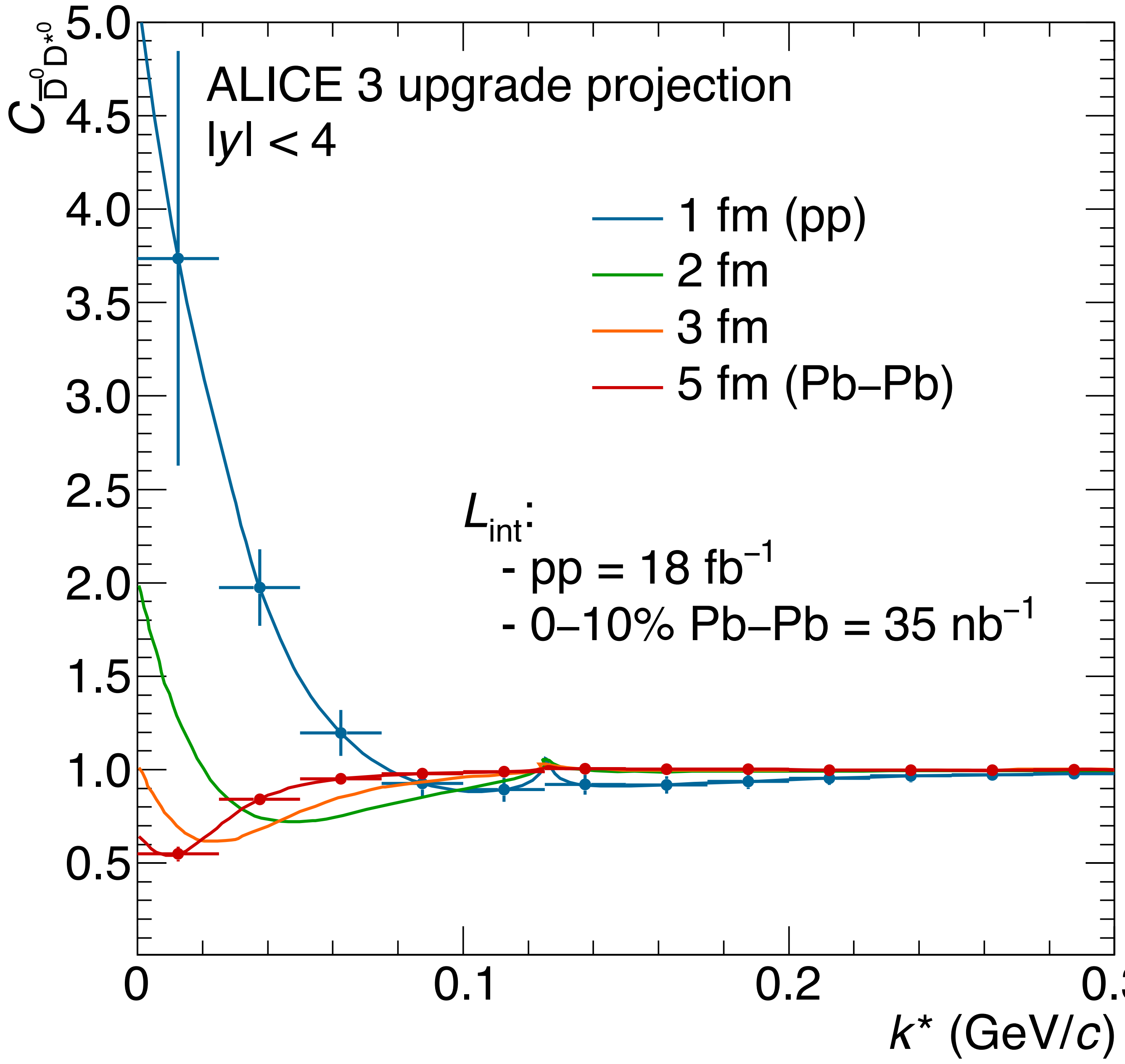


DD* momentum correlation

D^0D^{*+}



$D^0\overline{D}^{*0}$



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

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

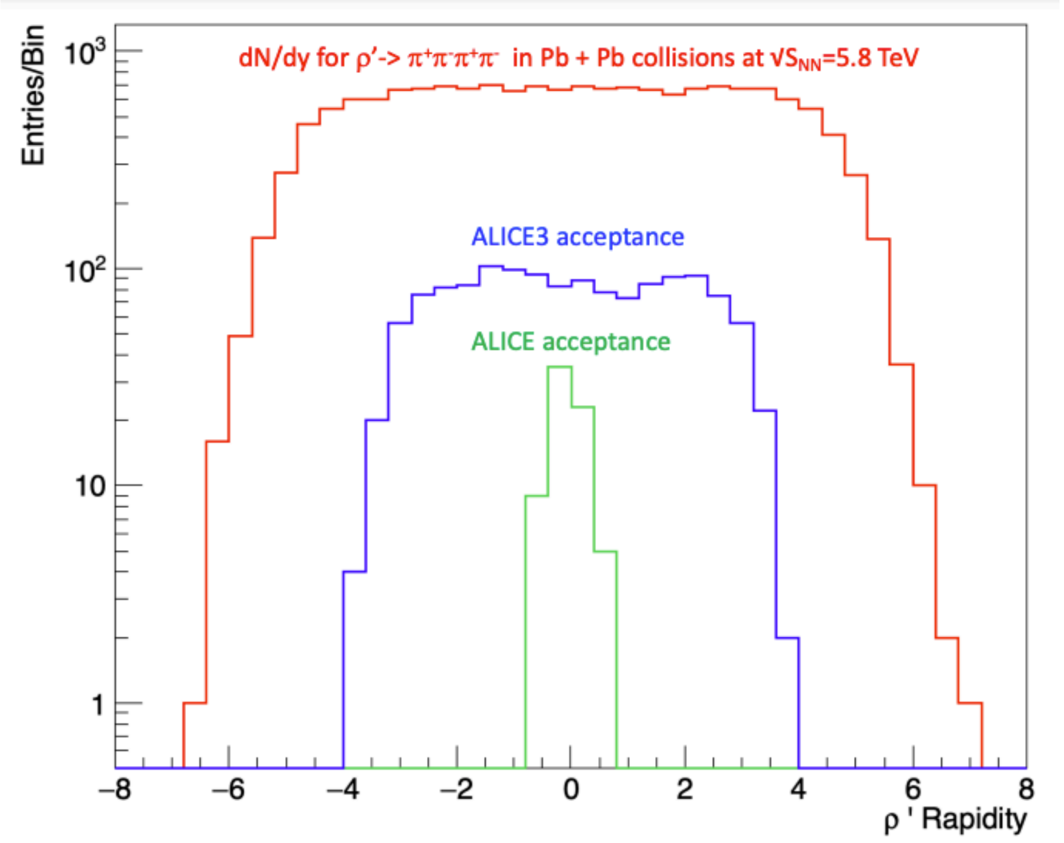
- Several exotic heavy flavour states identified
- Loosely bound meson molecule or tightly bound tetraquark?
- Study binding potential with final state interactions ‘femtoscopic correlations’

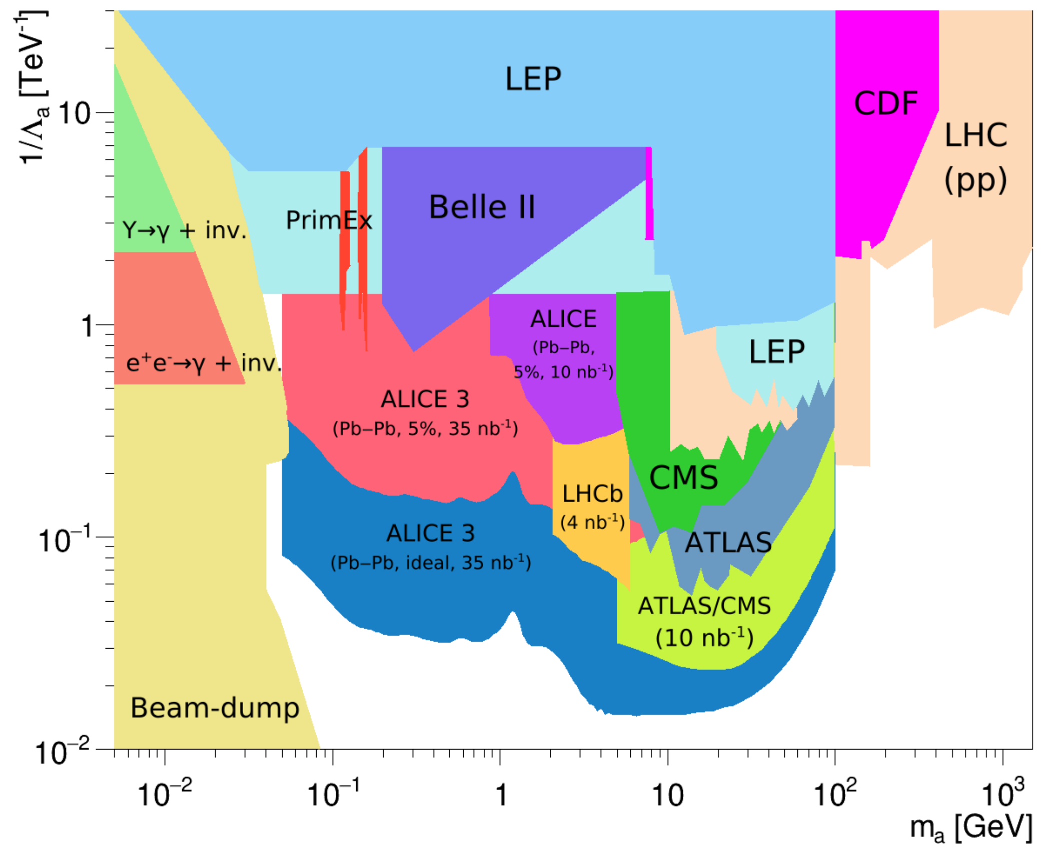
Bound states produce specific pattern vs system size

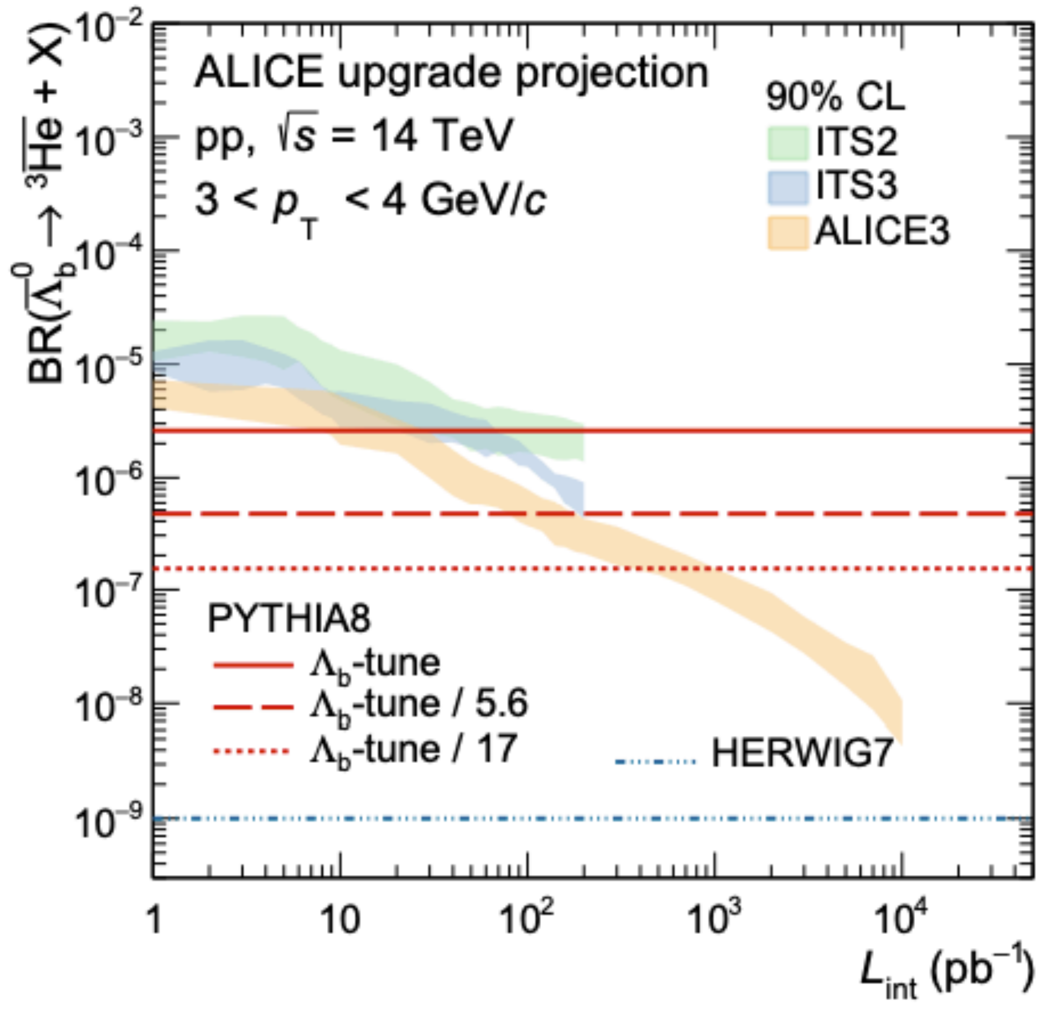
Other physics topics

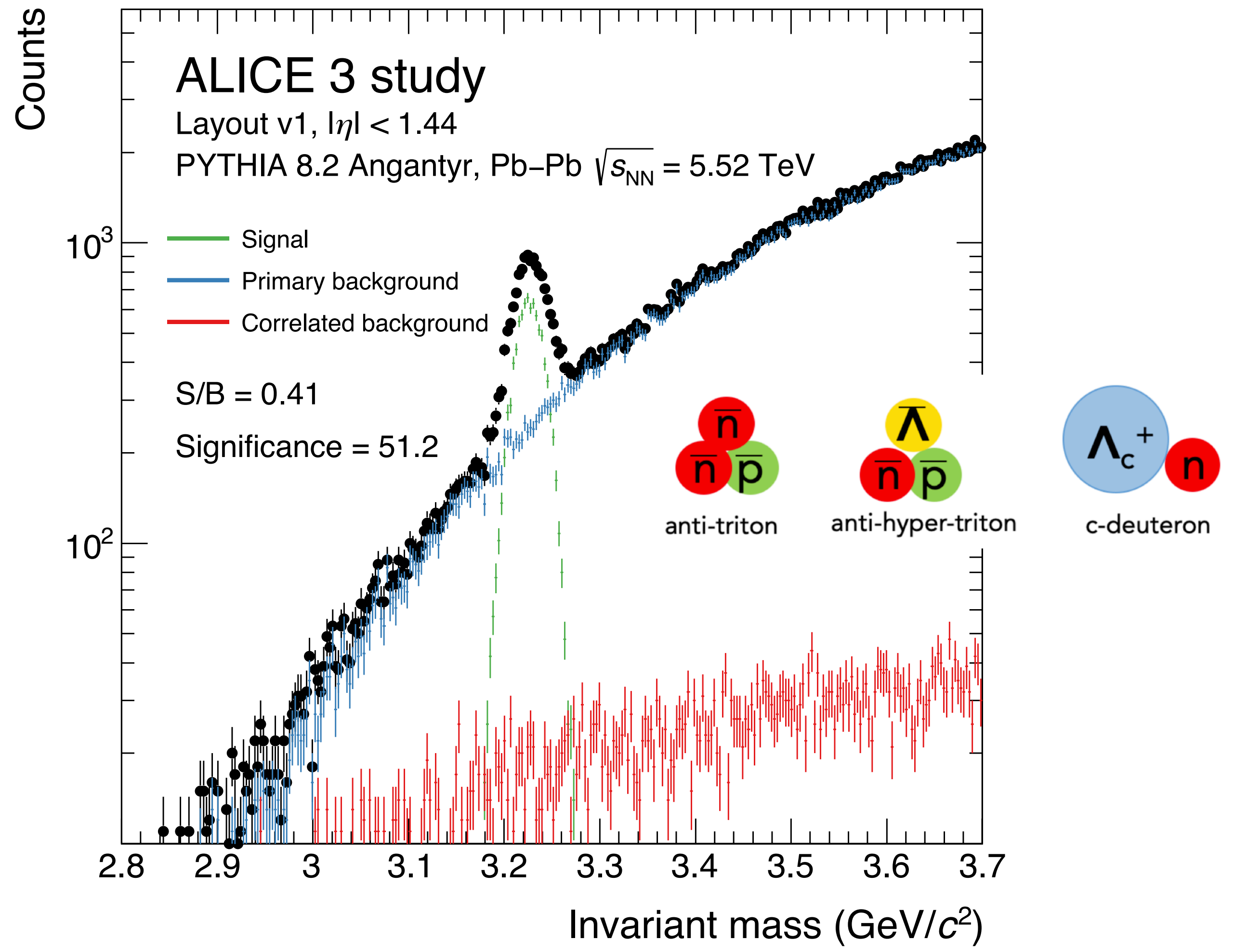
- Resonance production in Ultra-peripheral collisions
- ALP search in $\gamma\gamma$
- Production of nuclei in $\overline{\Lambda}_b \rightarrow^3 \overline{\mathrm{He}}$ decays
- Search for charm-nuclei
- Ultra-soft photons: Low's theorem

See ALICE 3 LoI for details: CERN-LHCC-2022-009



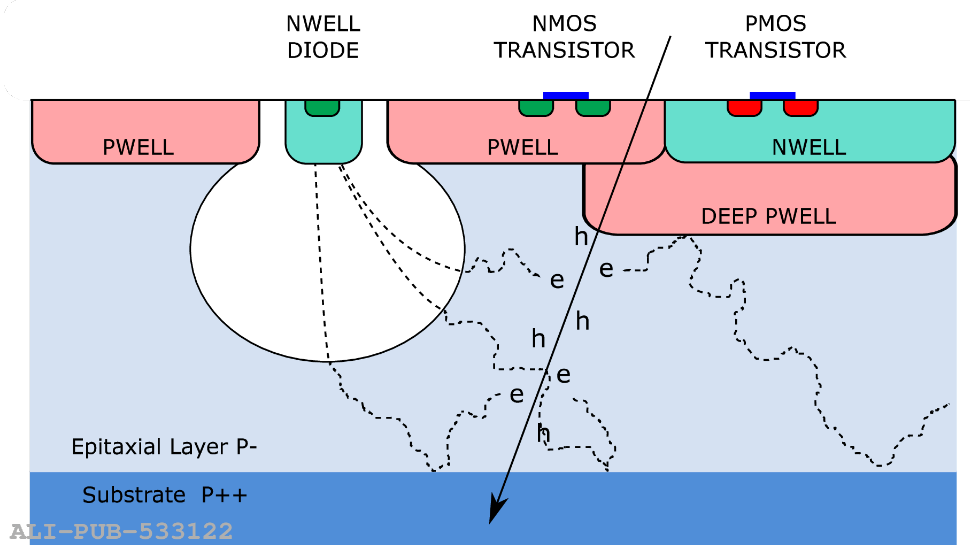




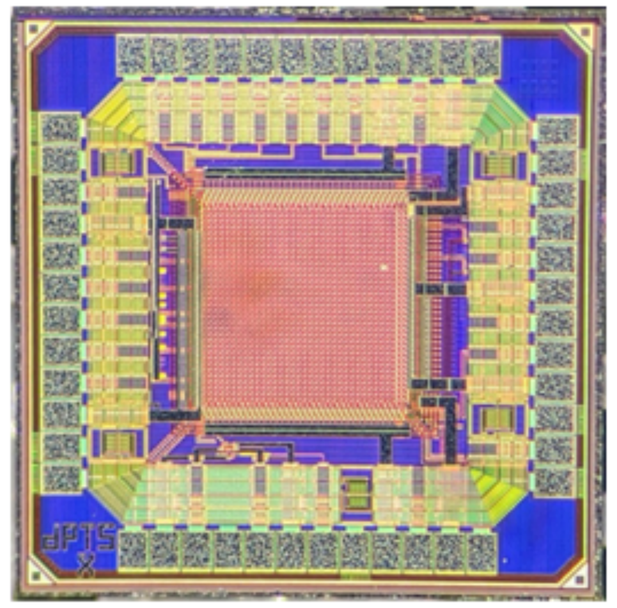


R&D: tracking sensor design

- Key technology: **CMOS monolithic active pixels** (MAPS)
  - Affordable, high-precision sensors with very low noise
- Experience with ITS2: 180 nm Tower-Semi technology
- R&D for ITS3: 65 nm technology
  - Large area stitched sensors
  - Improved radiation hardness (modified process)



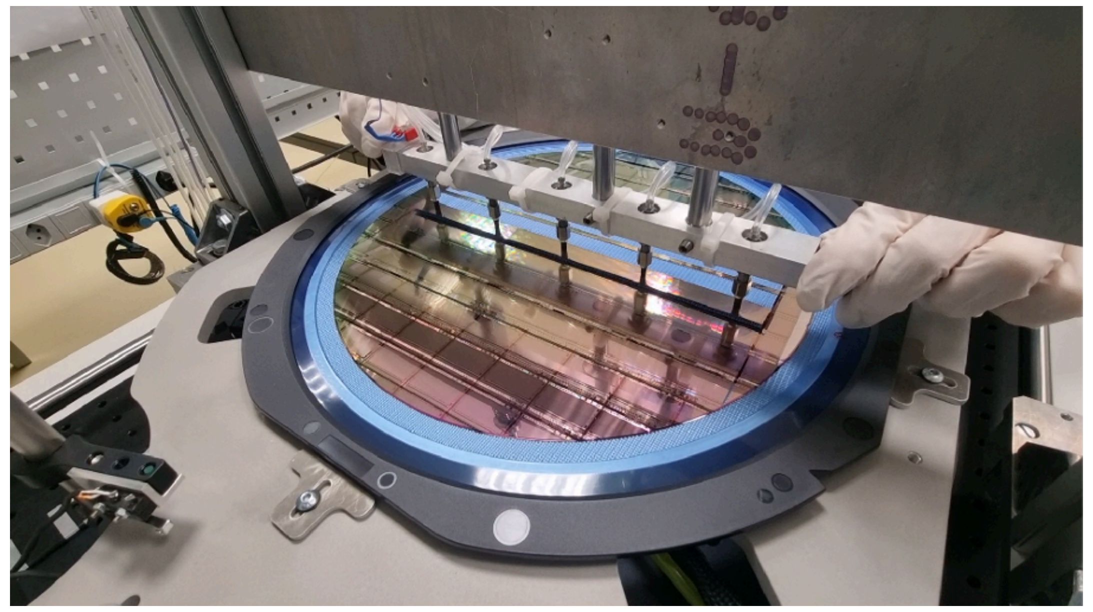
65 nm test structure

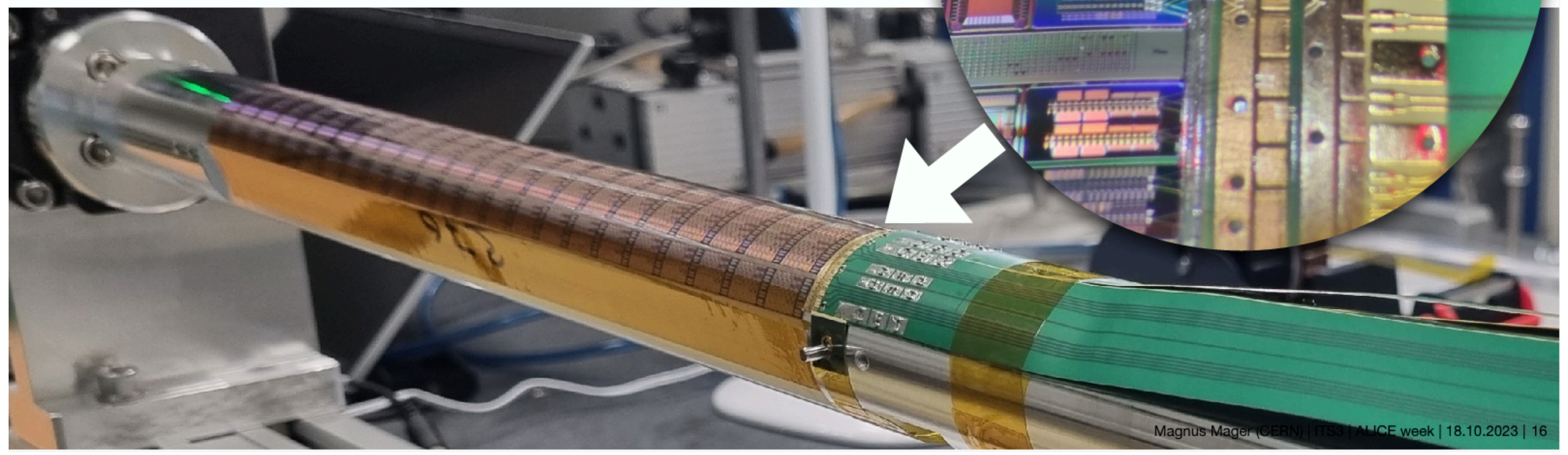


DPTS test paper arXiv:2212.08621

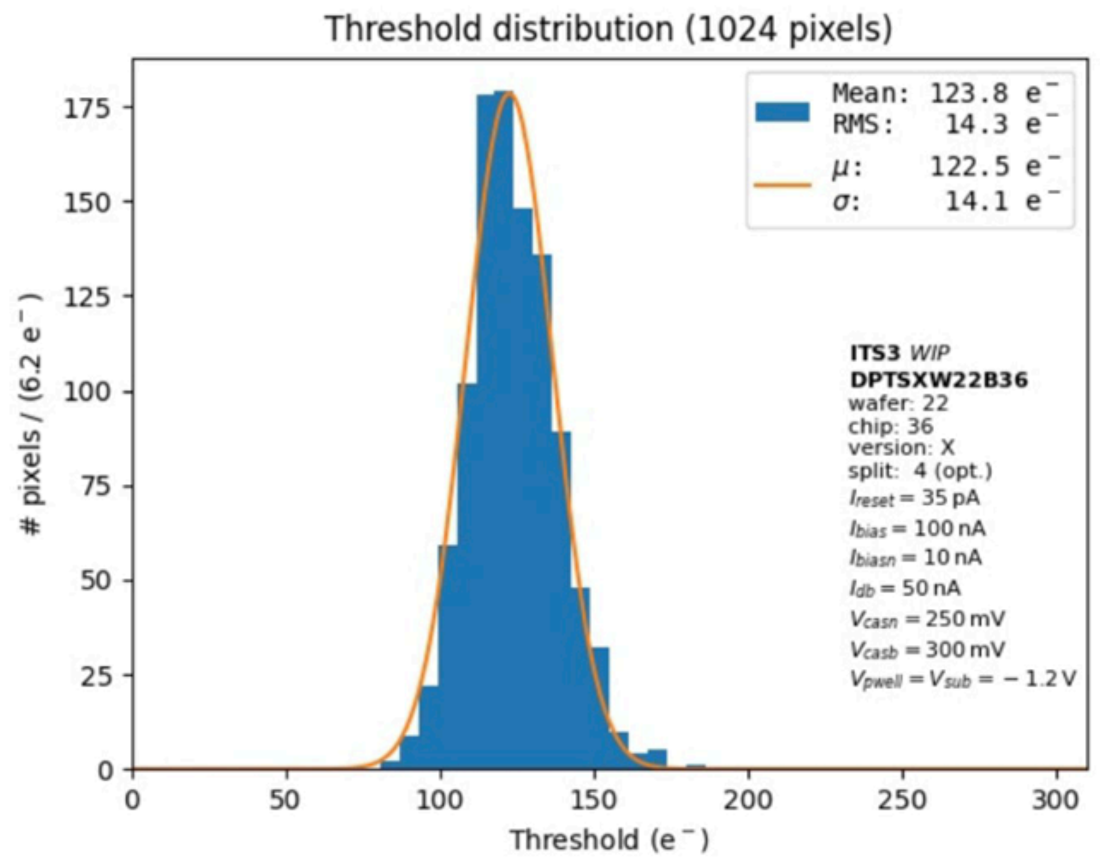
ITS2, 3 development are the starting point for ALICE 3 tracker sensors

Handling of stitched sensors

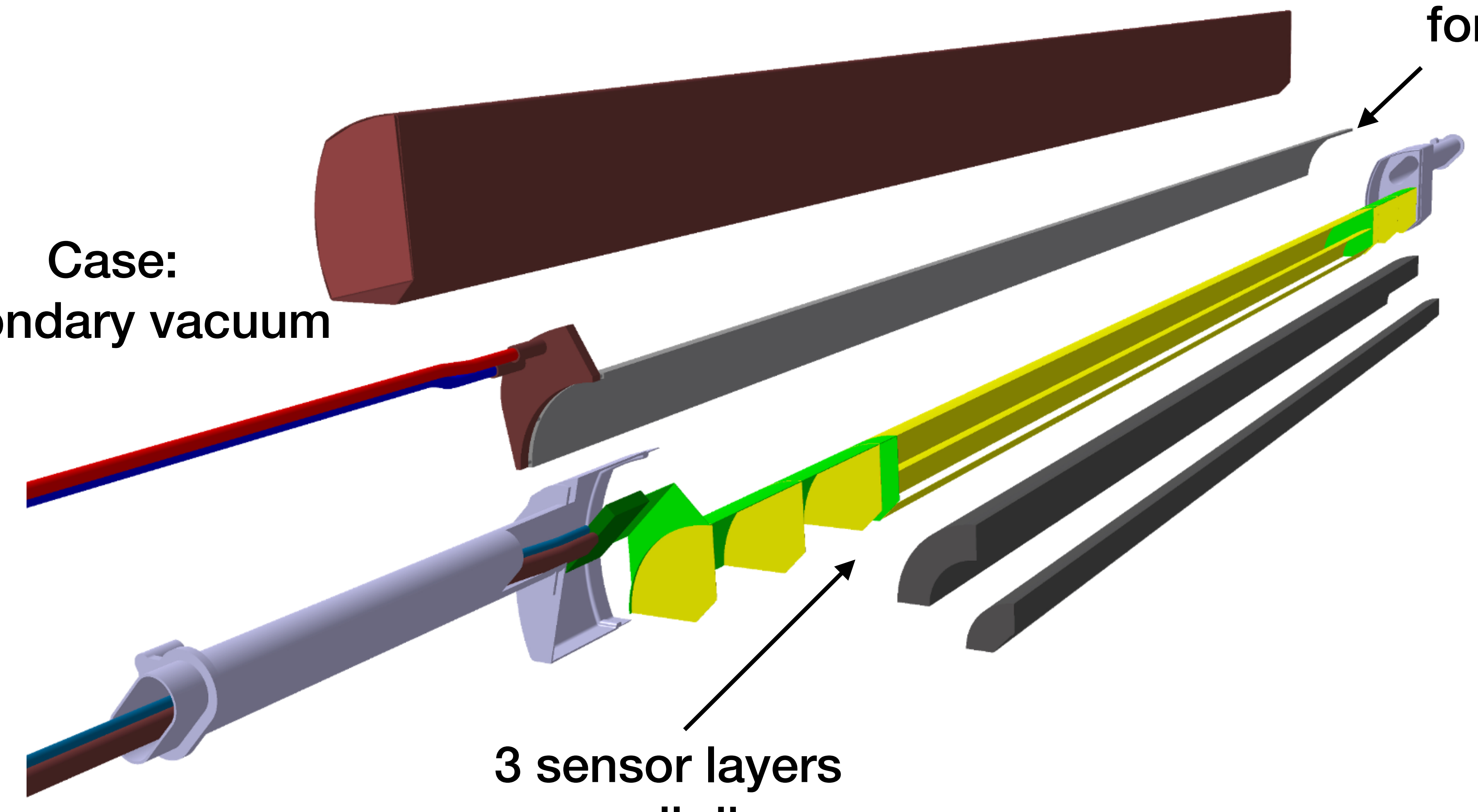




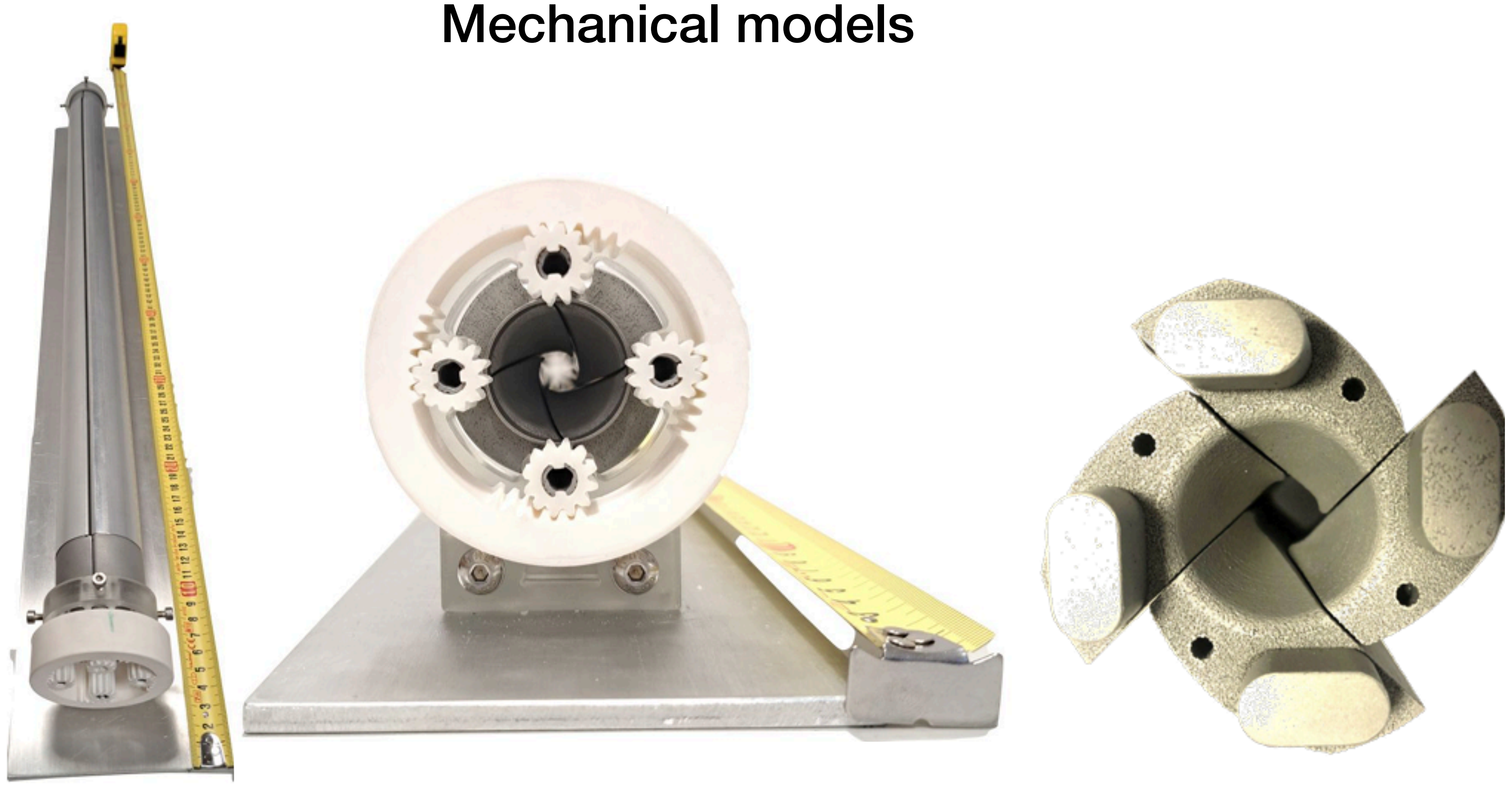
Tests with irradiated sensors show improved radiation tolerance



Vertex detector: mechanics



Mechanical models

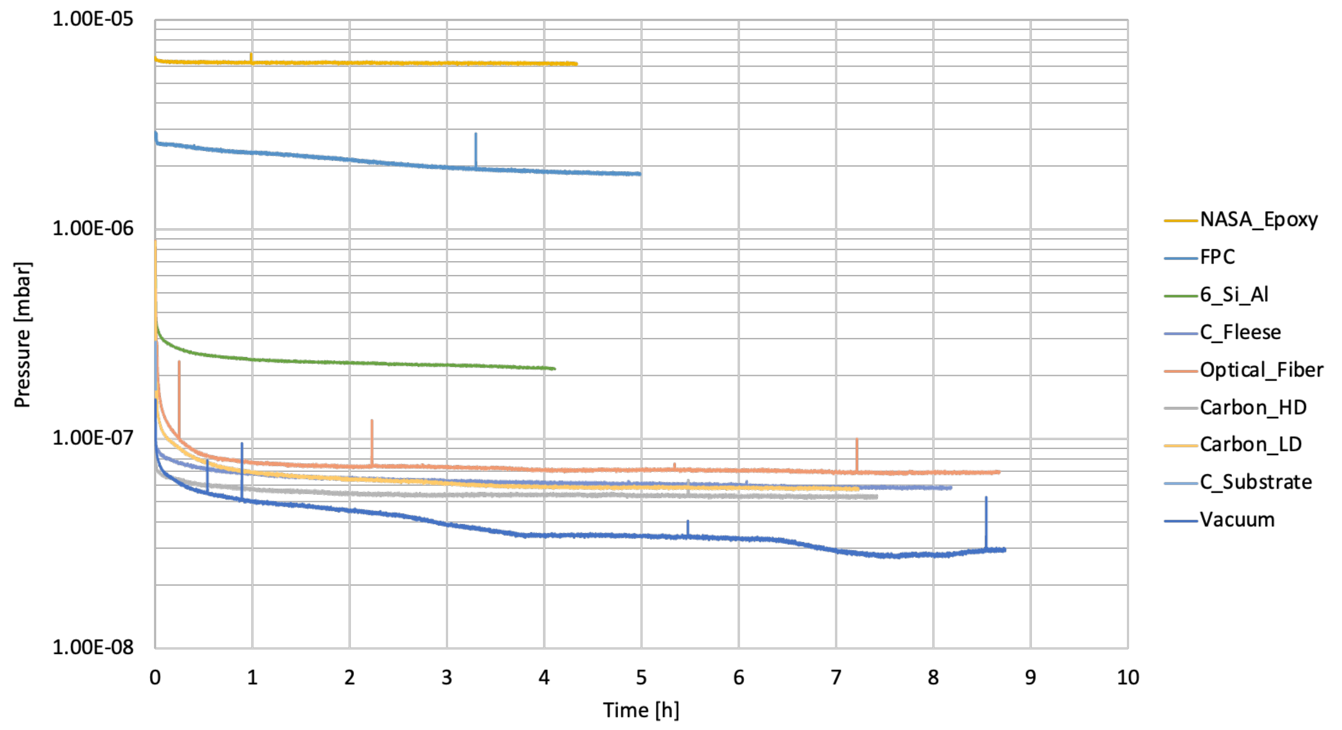


Geometry variants, cooling design being explored

Material outgassing studies for secondary vacuum

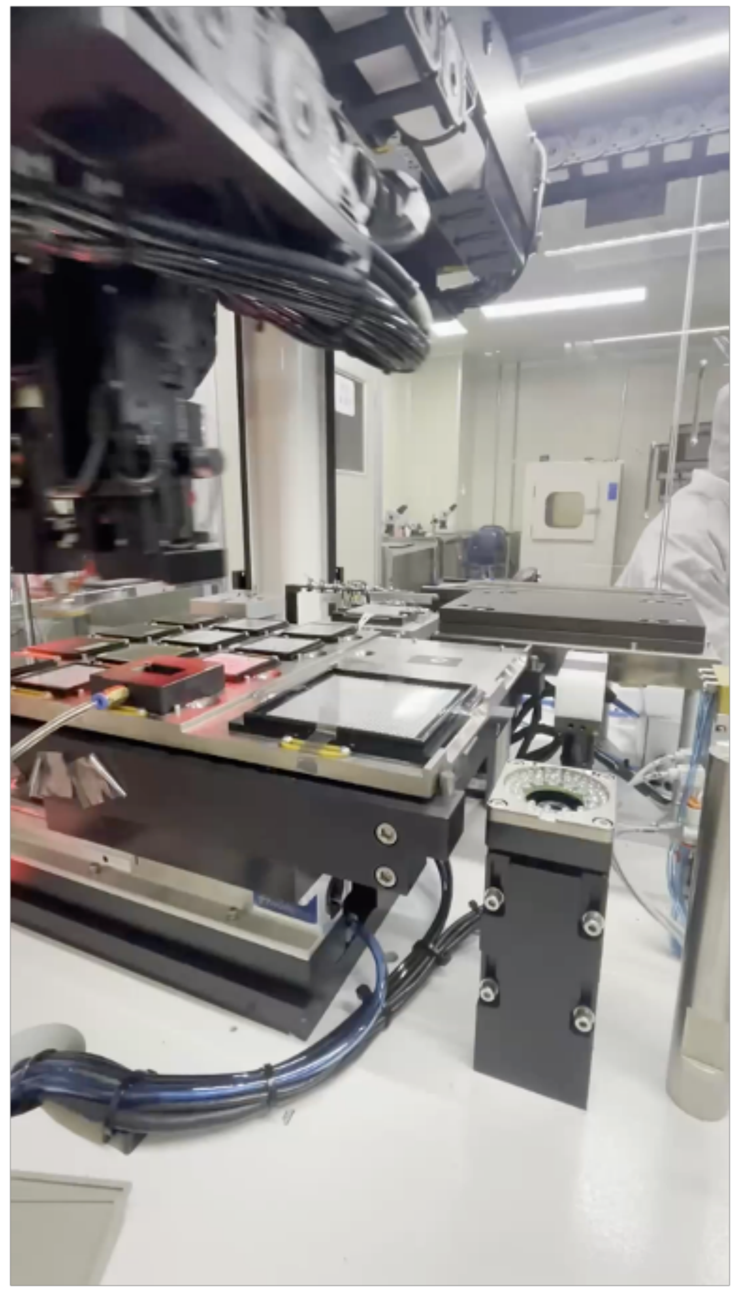
- pressure vs time
- residual gas composition

Outgassing at 10^{-6} mbar

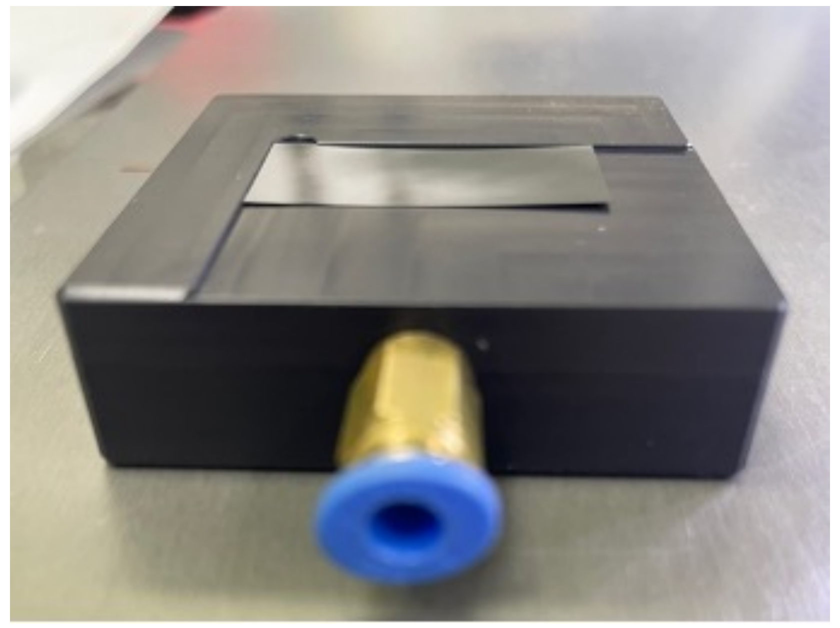


Outer tracker R&D: module production

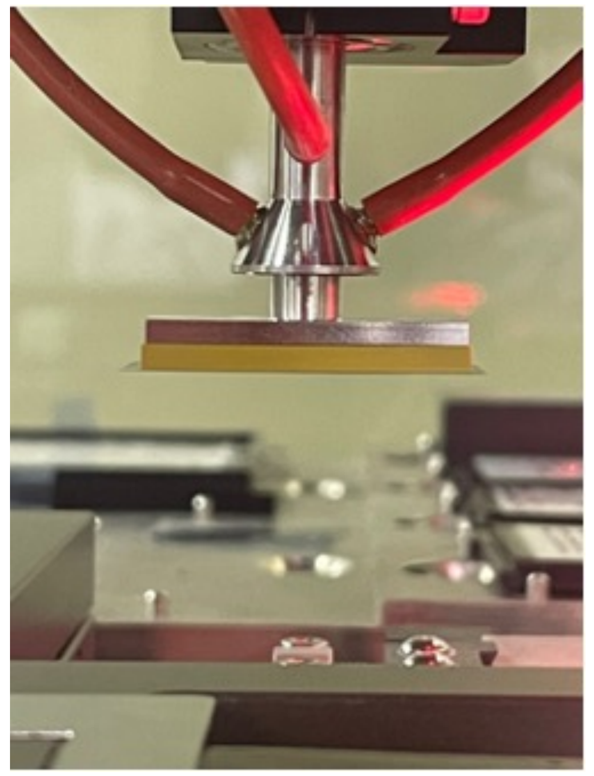
Commercial general purpose die attach machine



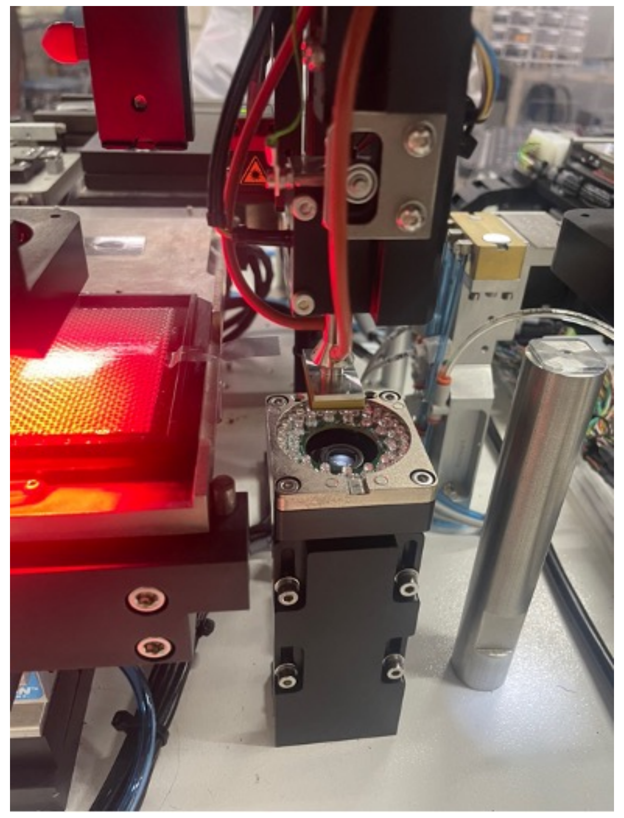
Chip holder



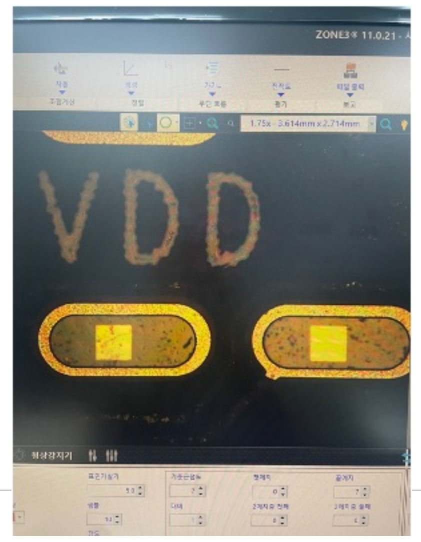
Chip gripper



Marker scan

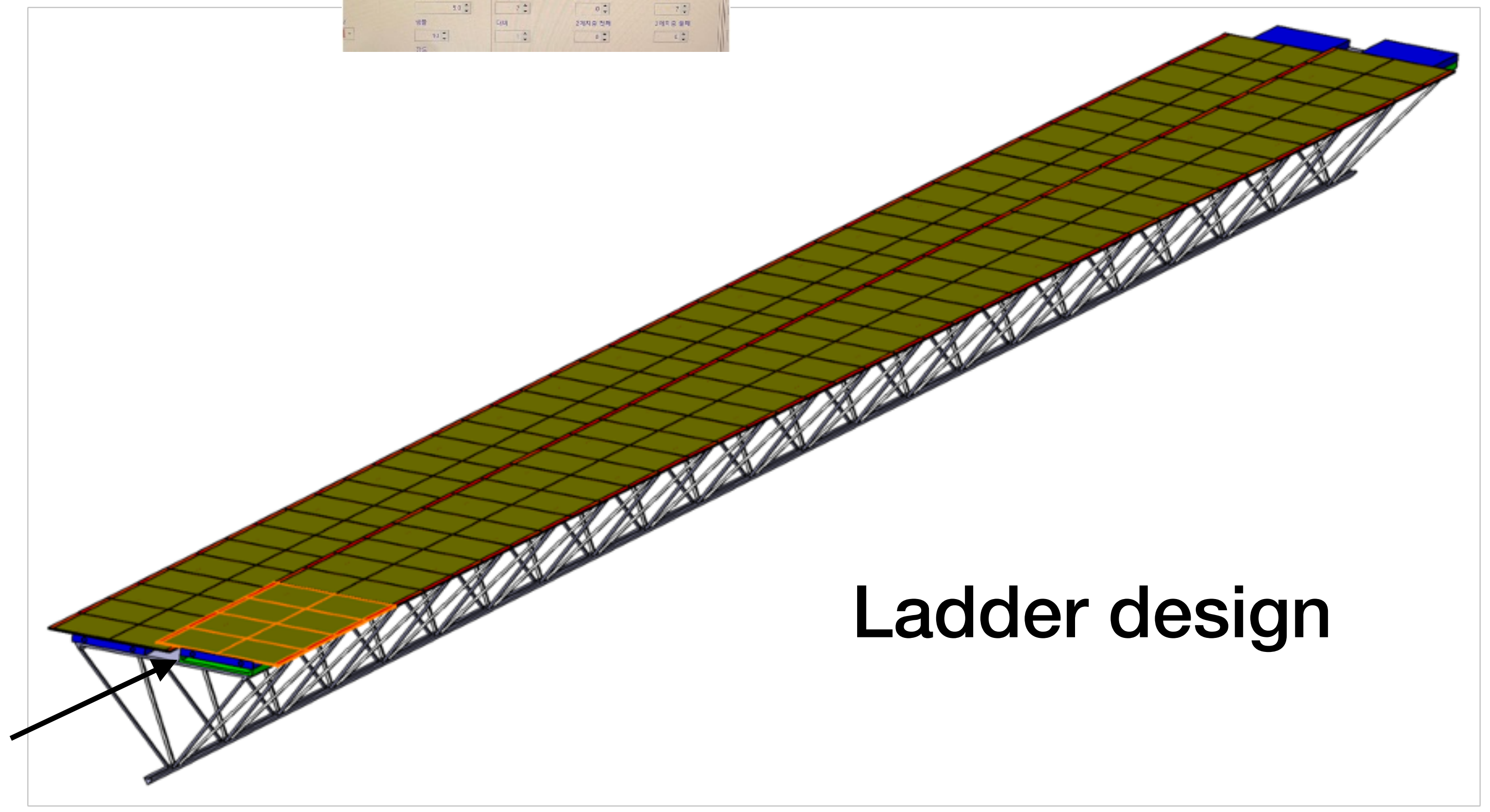


Position reproducible with 5 μm level accuracy



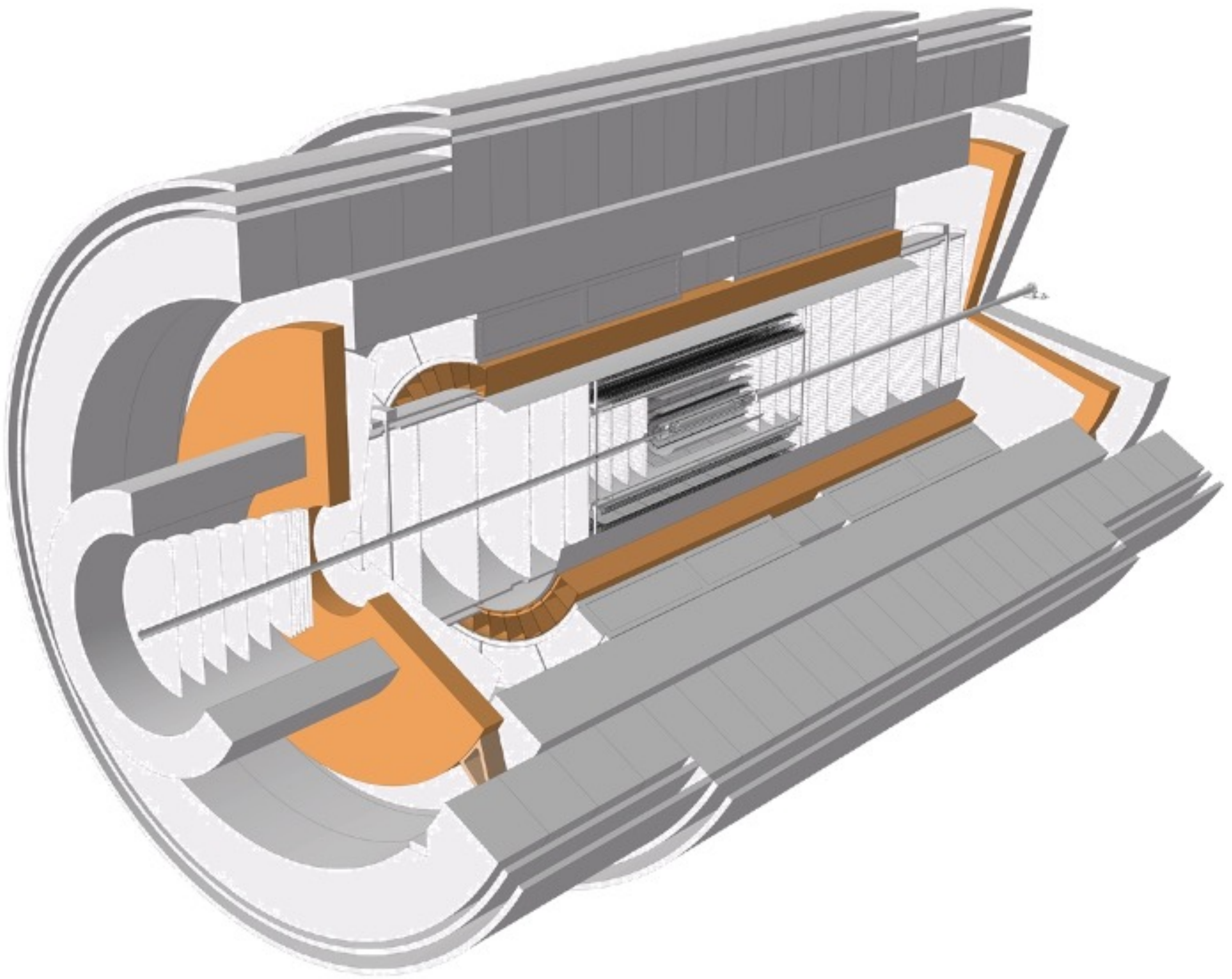
Large area: automated industrial production of multi-chip modules

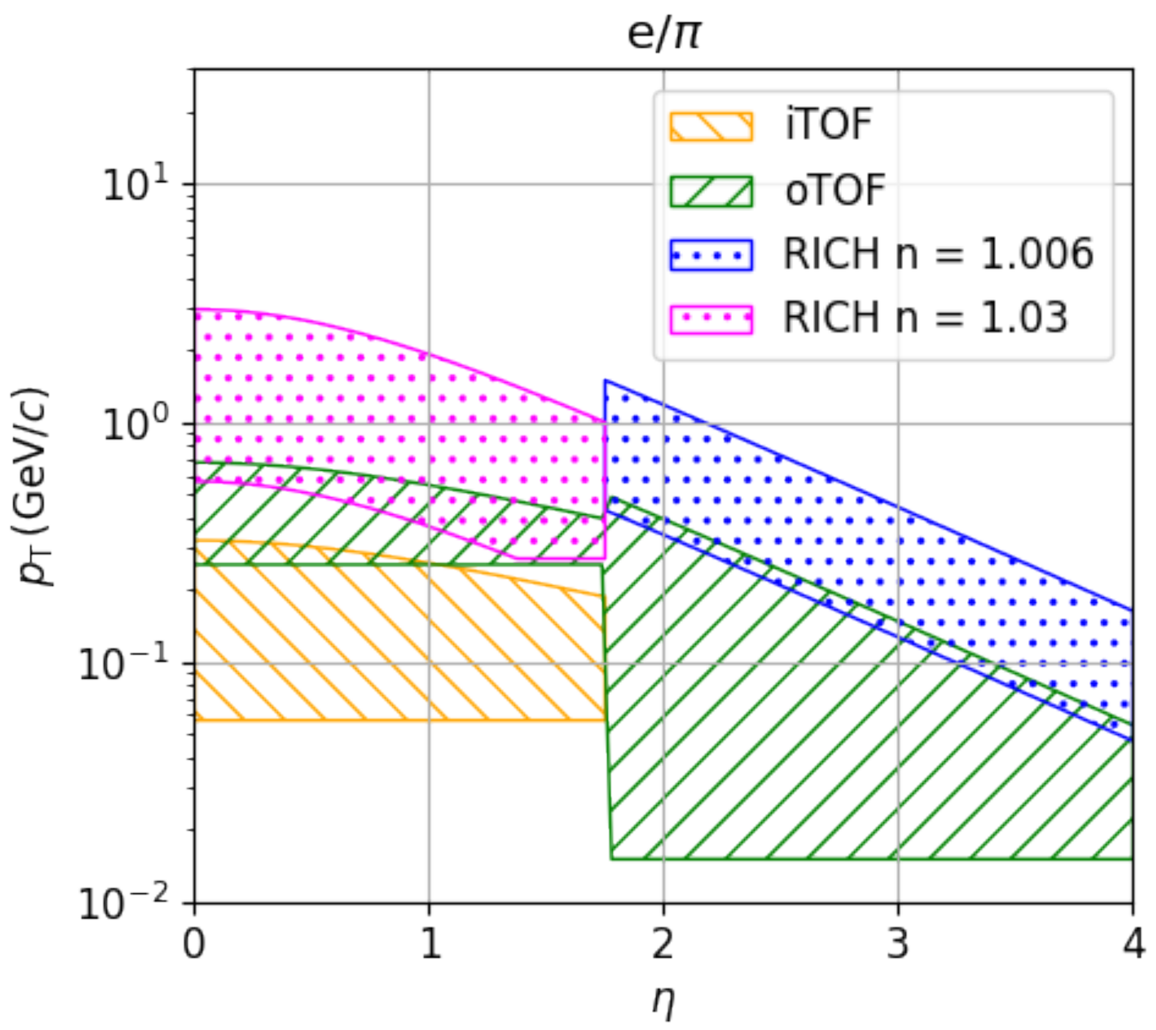
First tests with dummy modules in collaboration with industry



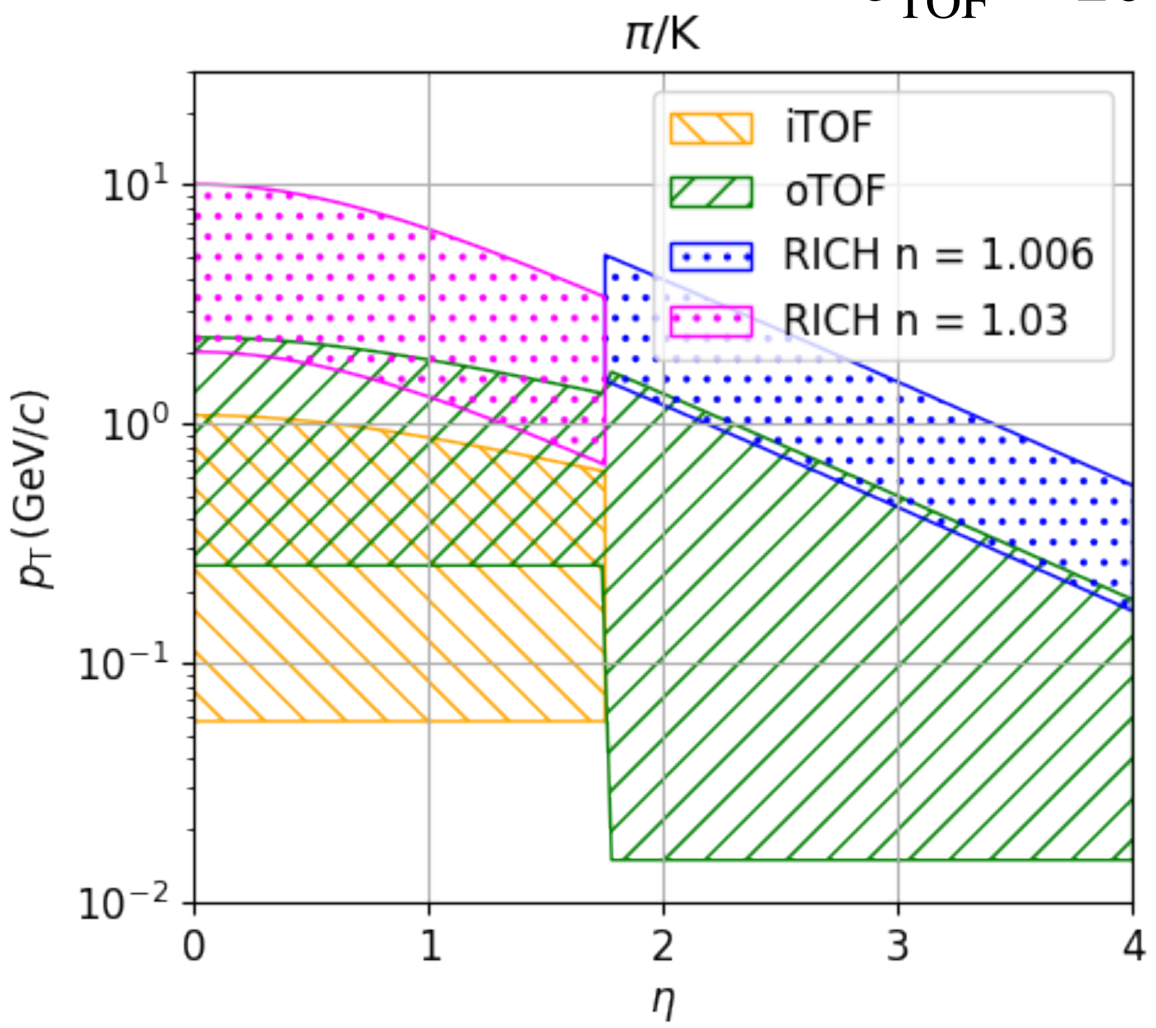
Module

Particle identification





$\sigma_{\mathrm{TOF}} = 20$ ps

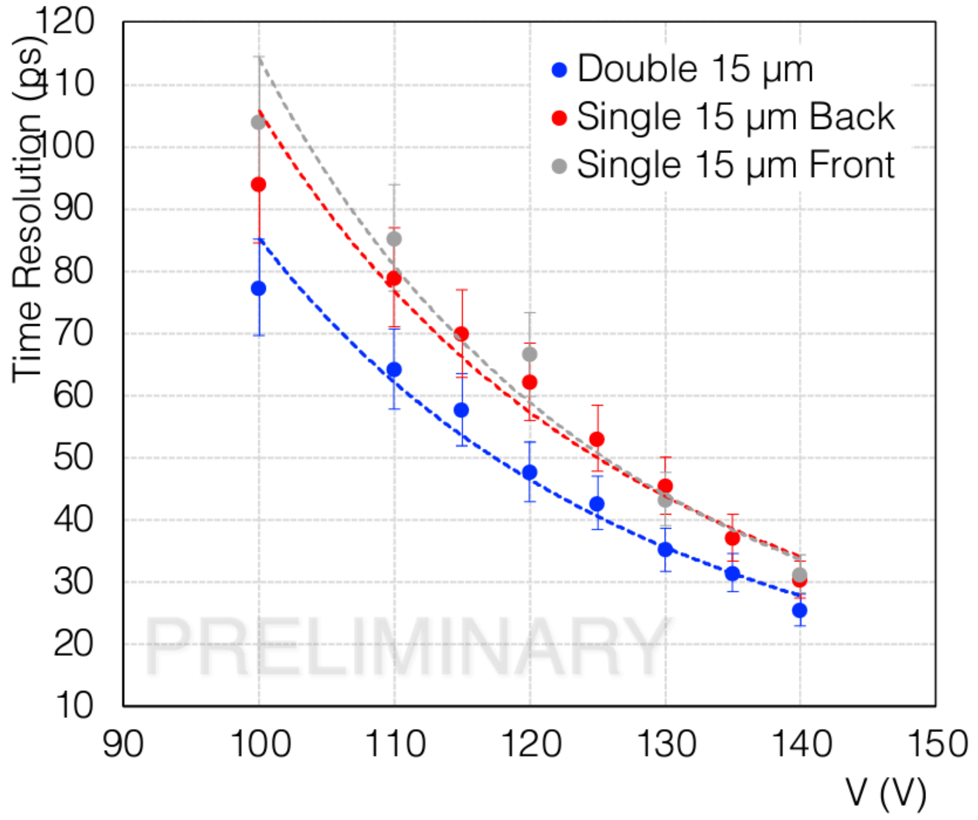


- **TOF** and **RICH** provide hadron and electron identification
  - Complementary p_T ranges
  - Electron ID up to p_T = 1.5 GeV/*c*: thermal dilepton production measurements
  - Kaon and proton PID up to 6-10 GeV/*c*: HF measurement
- **Muon ID**: measurements of J/ψ down to p_T = 0, χ_c, exotic states
- **EMCal** for photon ID: ALPs, χ_c, jets

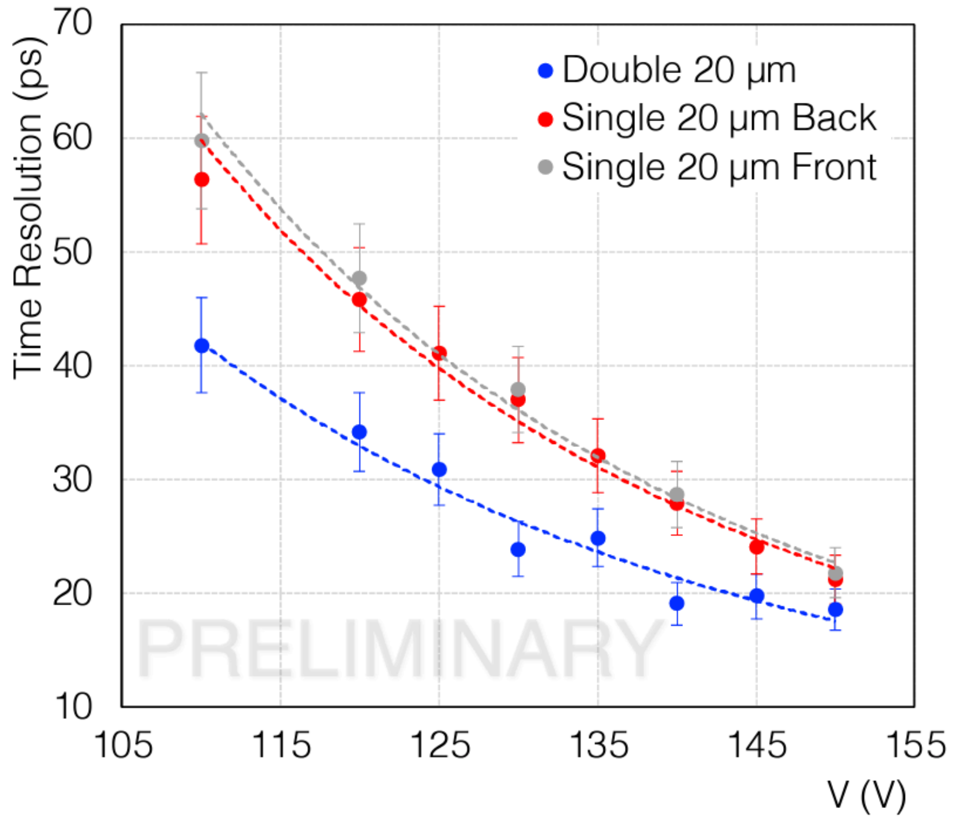
R&D for timing sensors

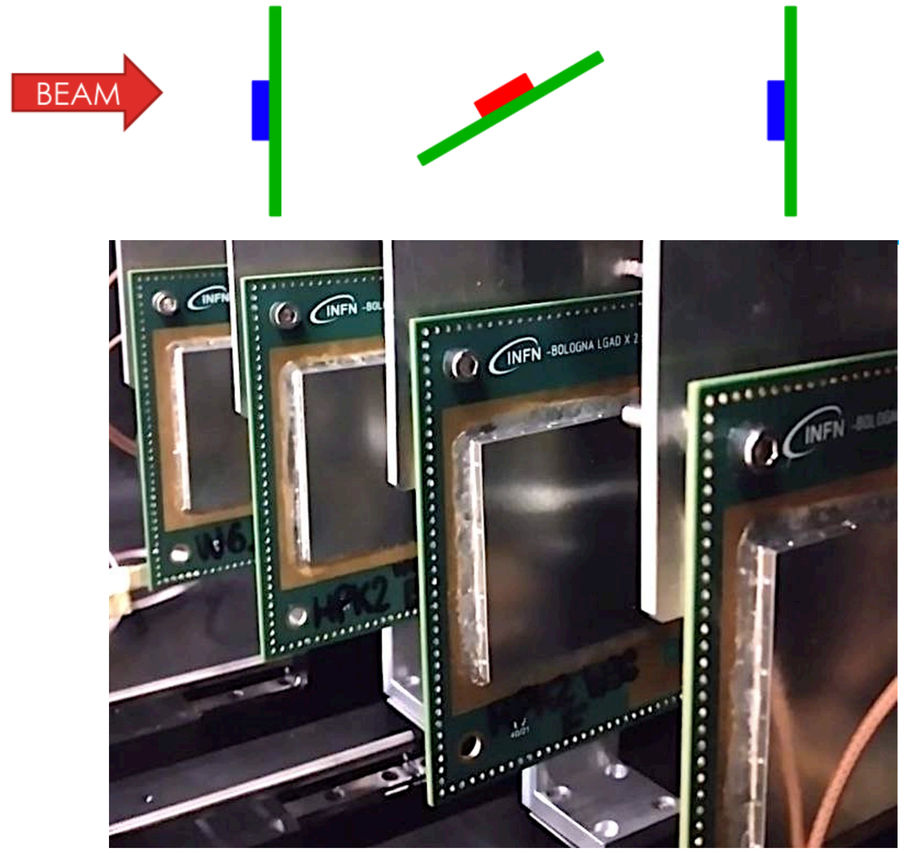
LGAD

15 µm

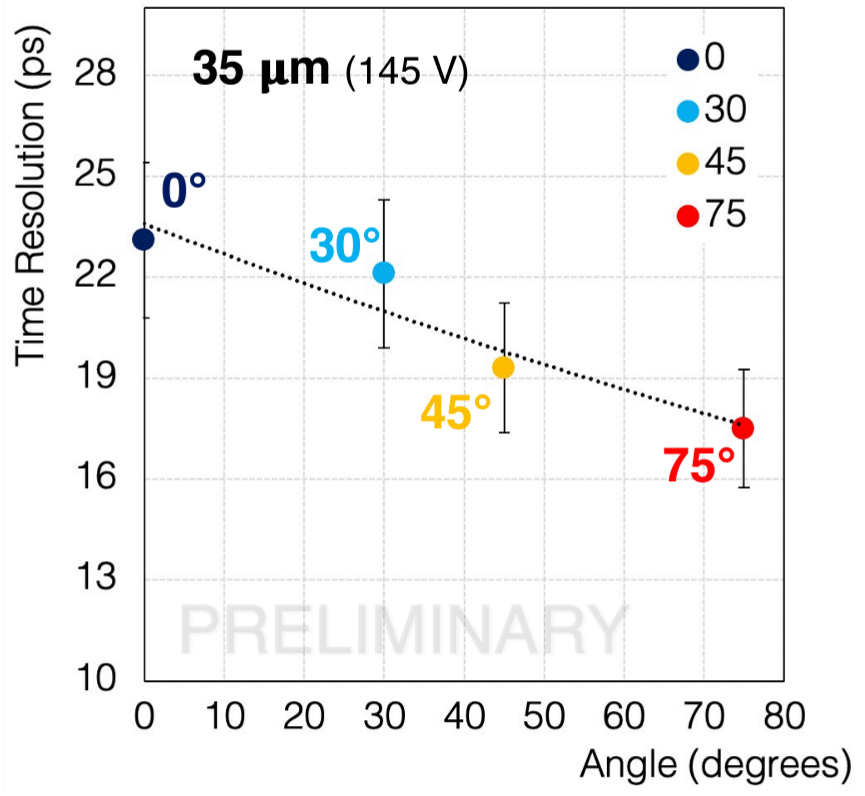


20 µm

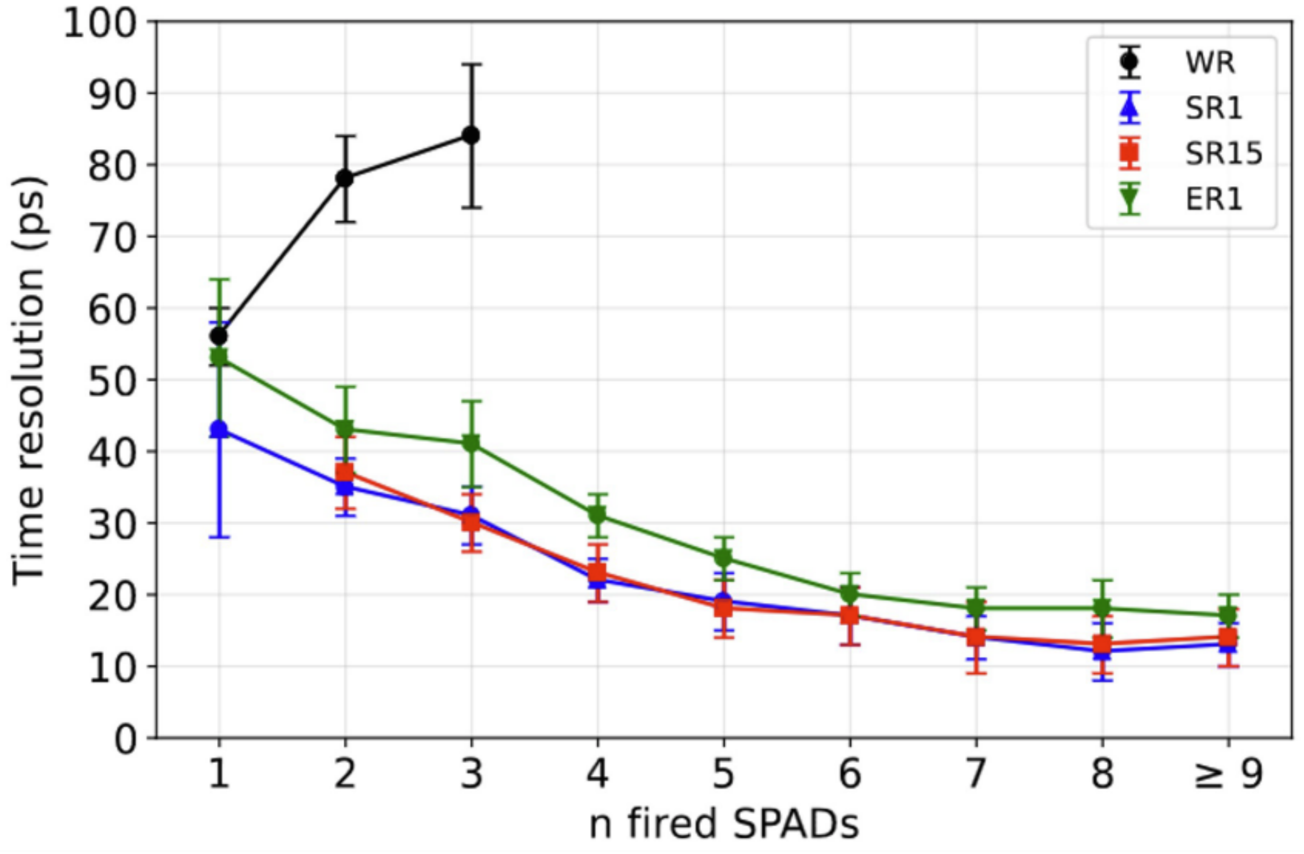




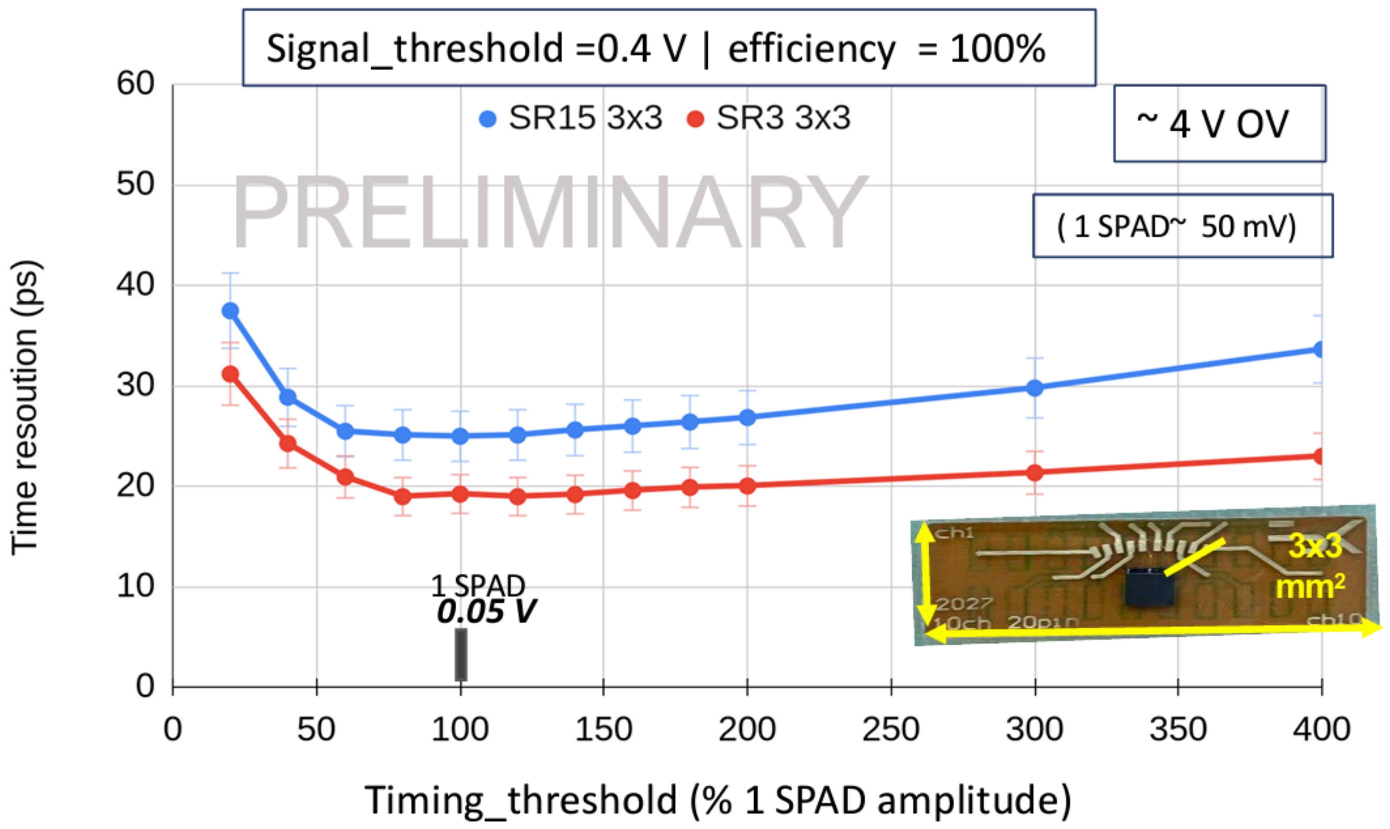
Angle dependence



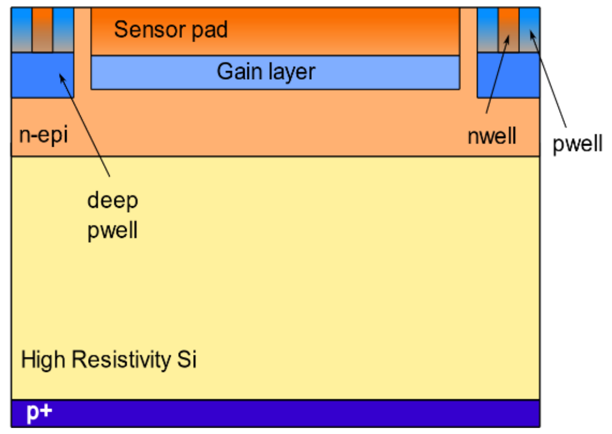
SiPM + Cherenkov layer



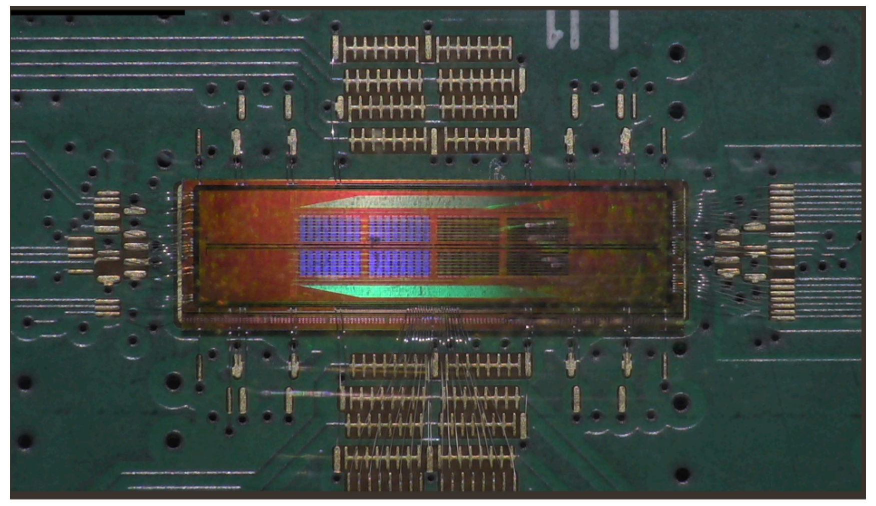
F Carnesecchi, et al EPJ Plus 138, 788 (2023)



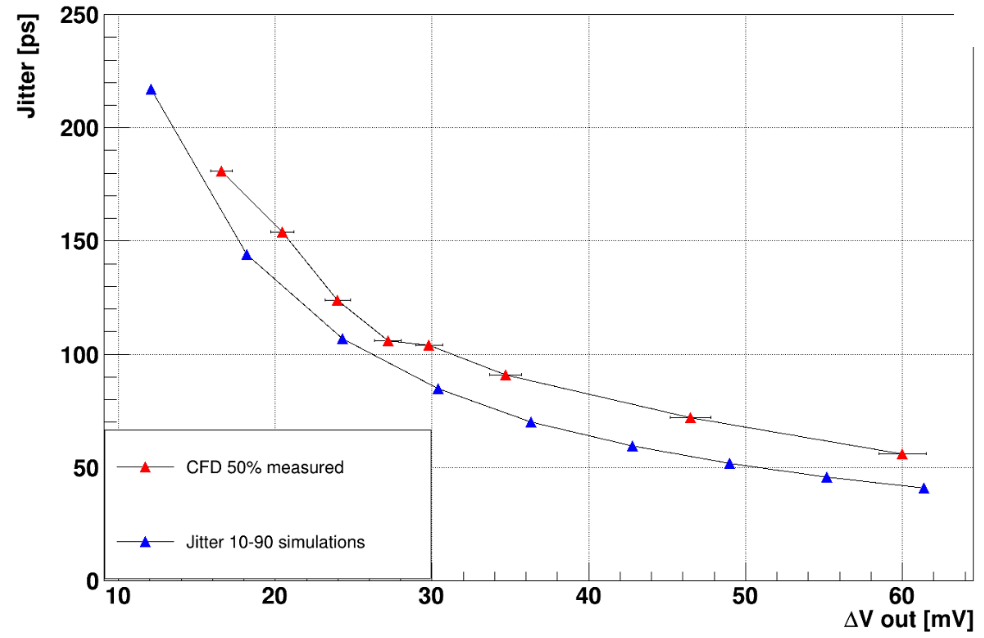
CMOS pixel with gain



Test pixels: MADPIX



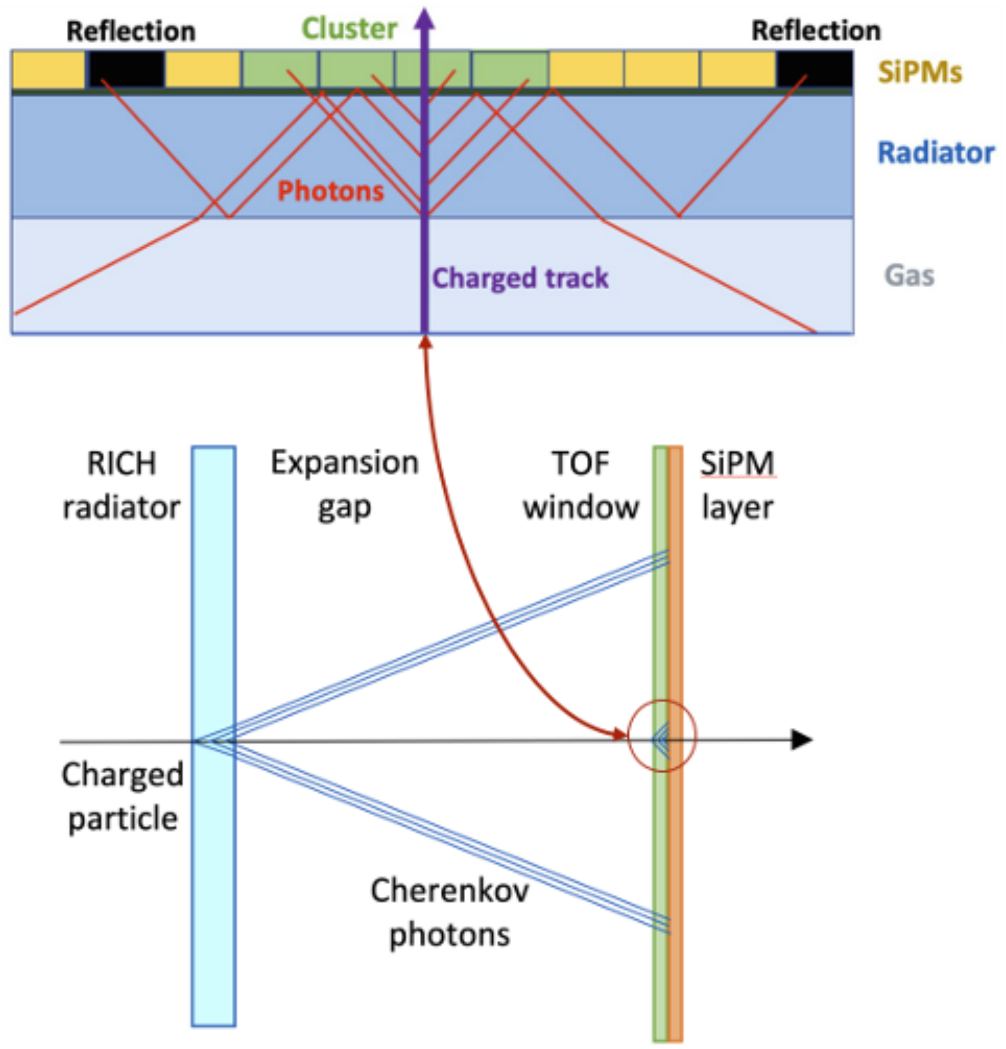
Laser measurement



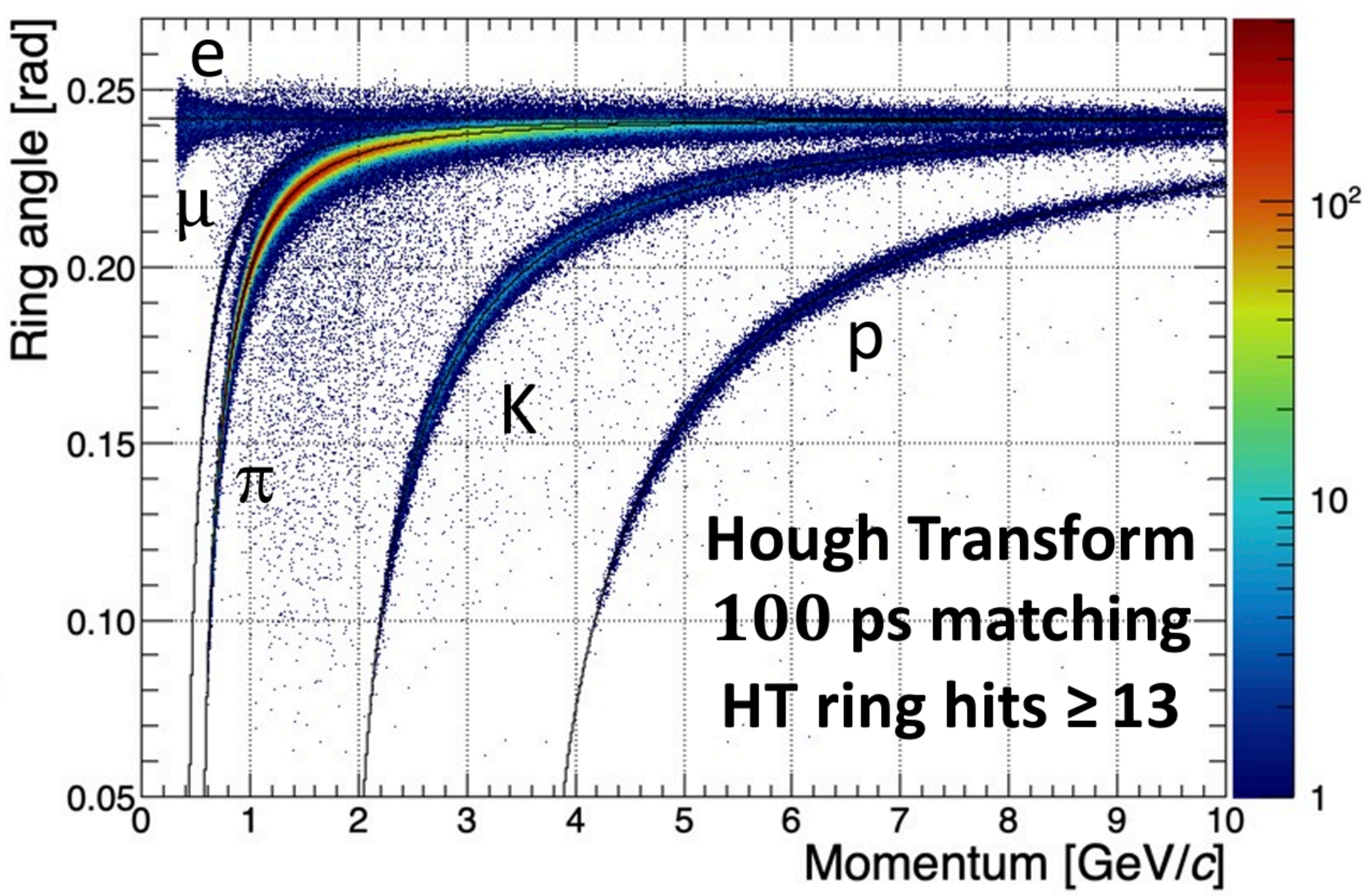
3 technology options:

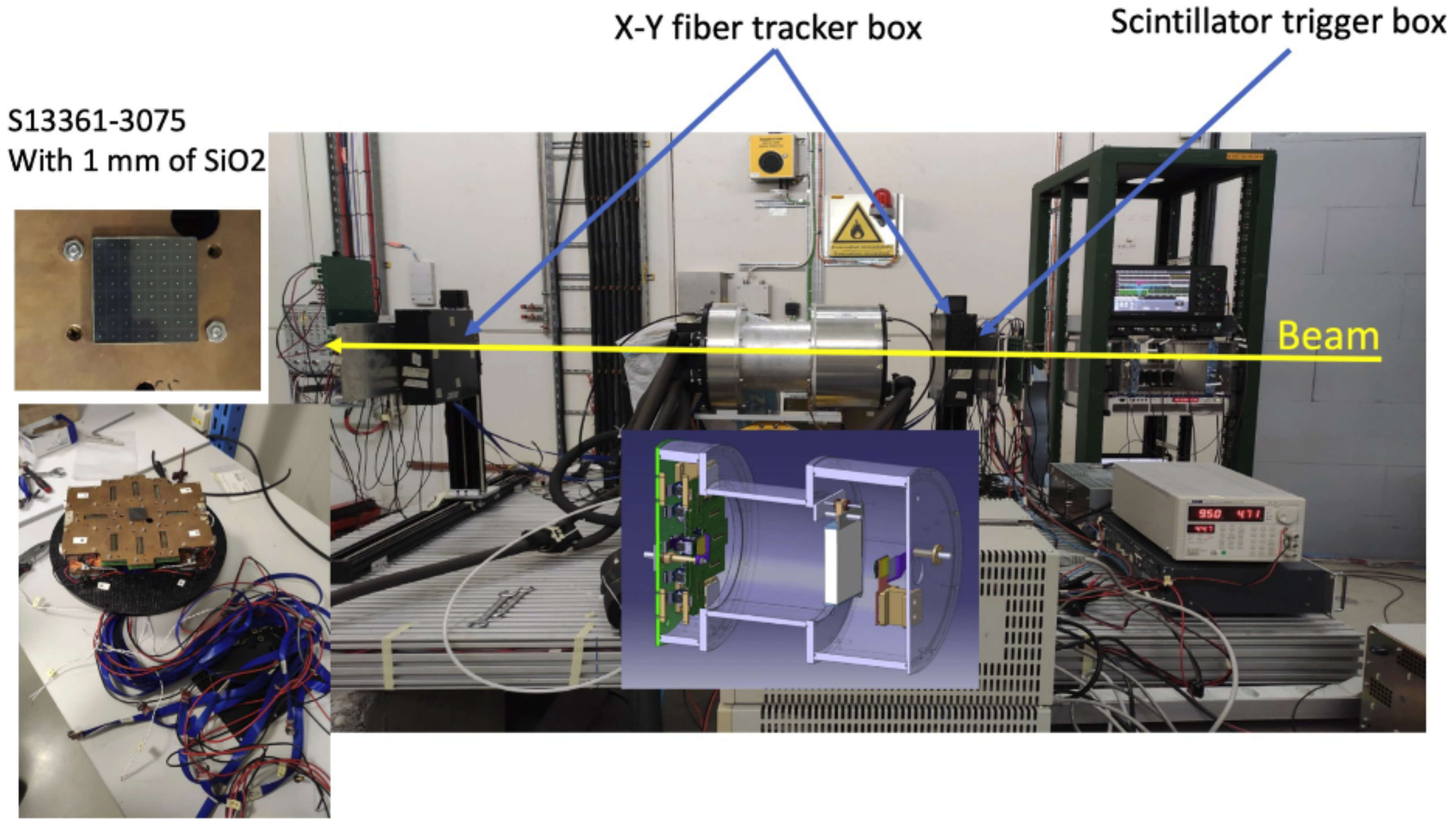
R&D for CMOS sensors ongoing
LGAD, SPAD: 20 ps resolution demonstrated/in reach (sensor only)

Ring Imaging Cherenkov R&D



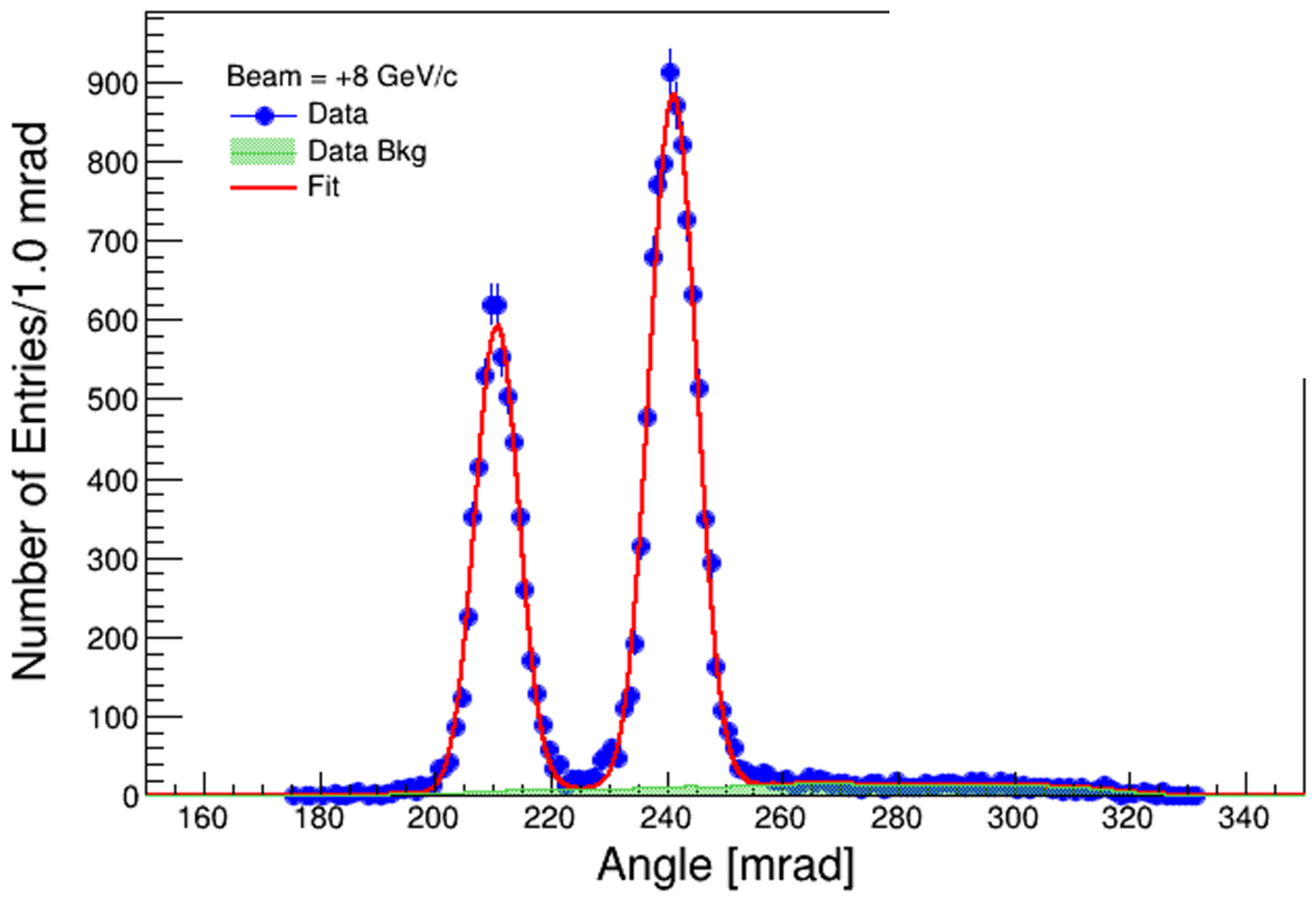
Simulated performance (Pb-Pb)





Principle: aerogel + proximity focusing
SiPM/SPAD integrated readout

Testbeam performance



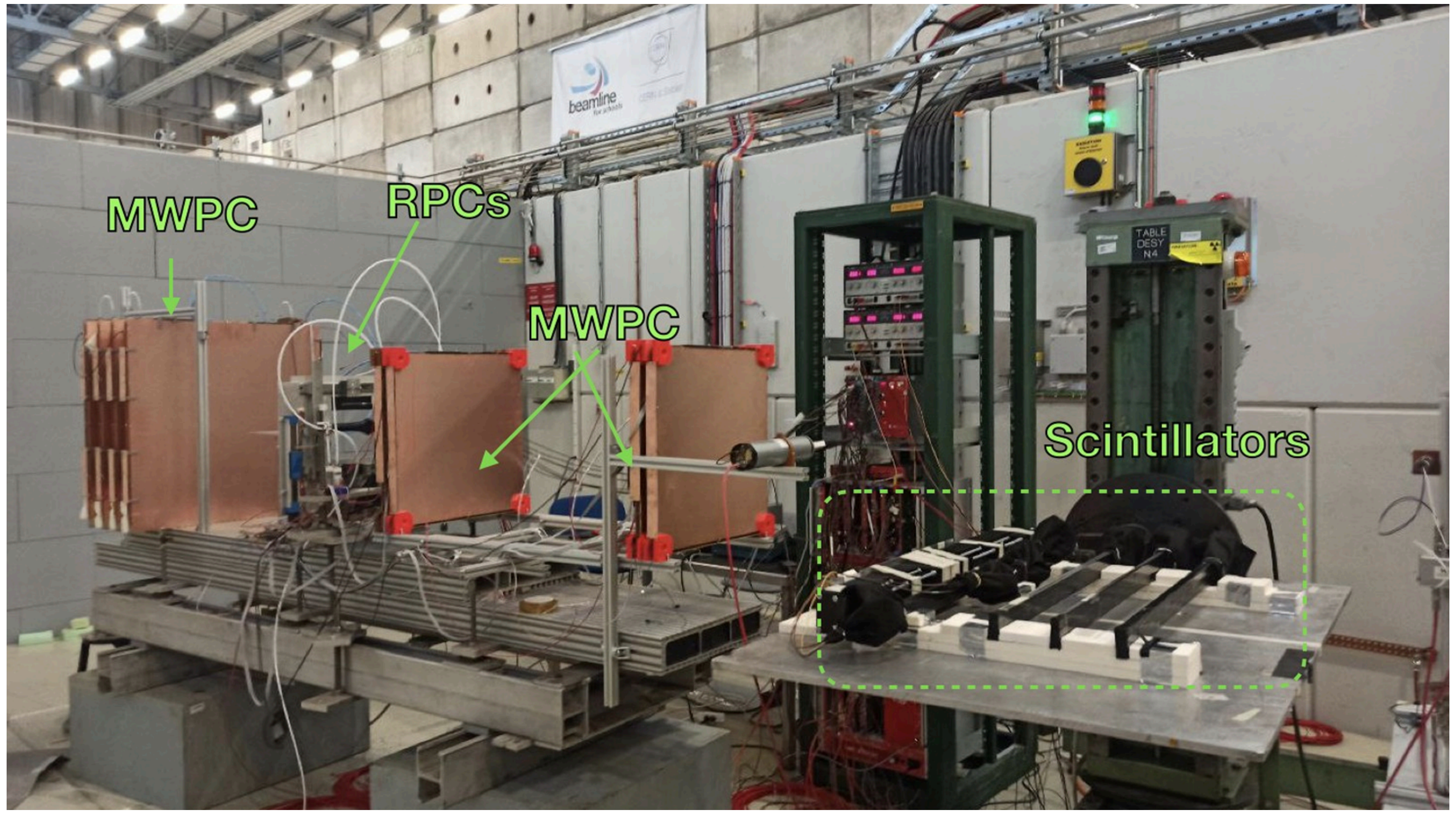
Test beams:

- **Performance verified**
- Characterisation of aerogels and SiPMs ongoing

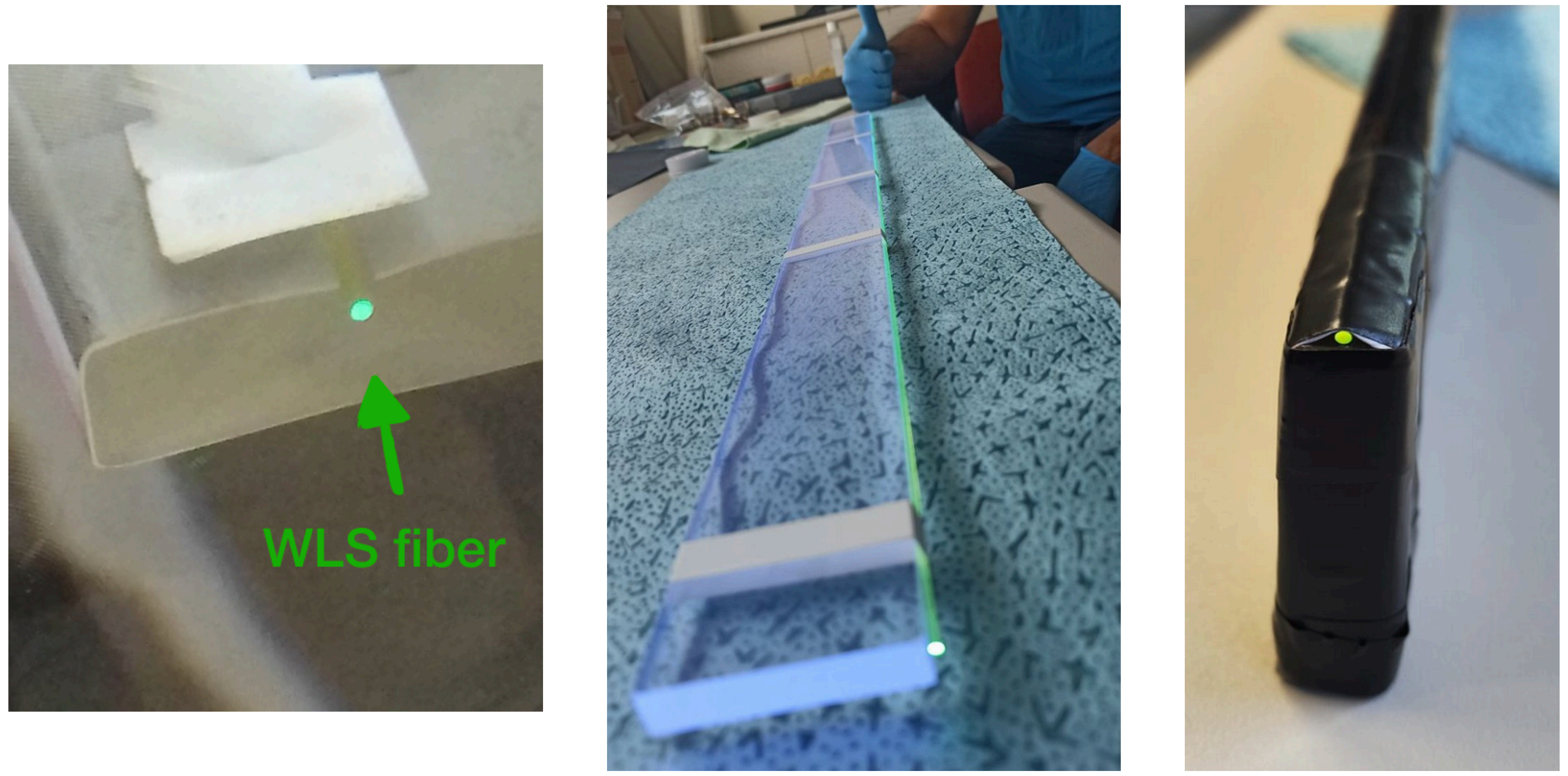
R&D option: combined TOF and RICH readout with SiPMs (SPADs)

R&D for Muon Identifier

Test beam June 2023

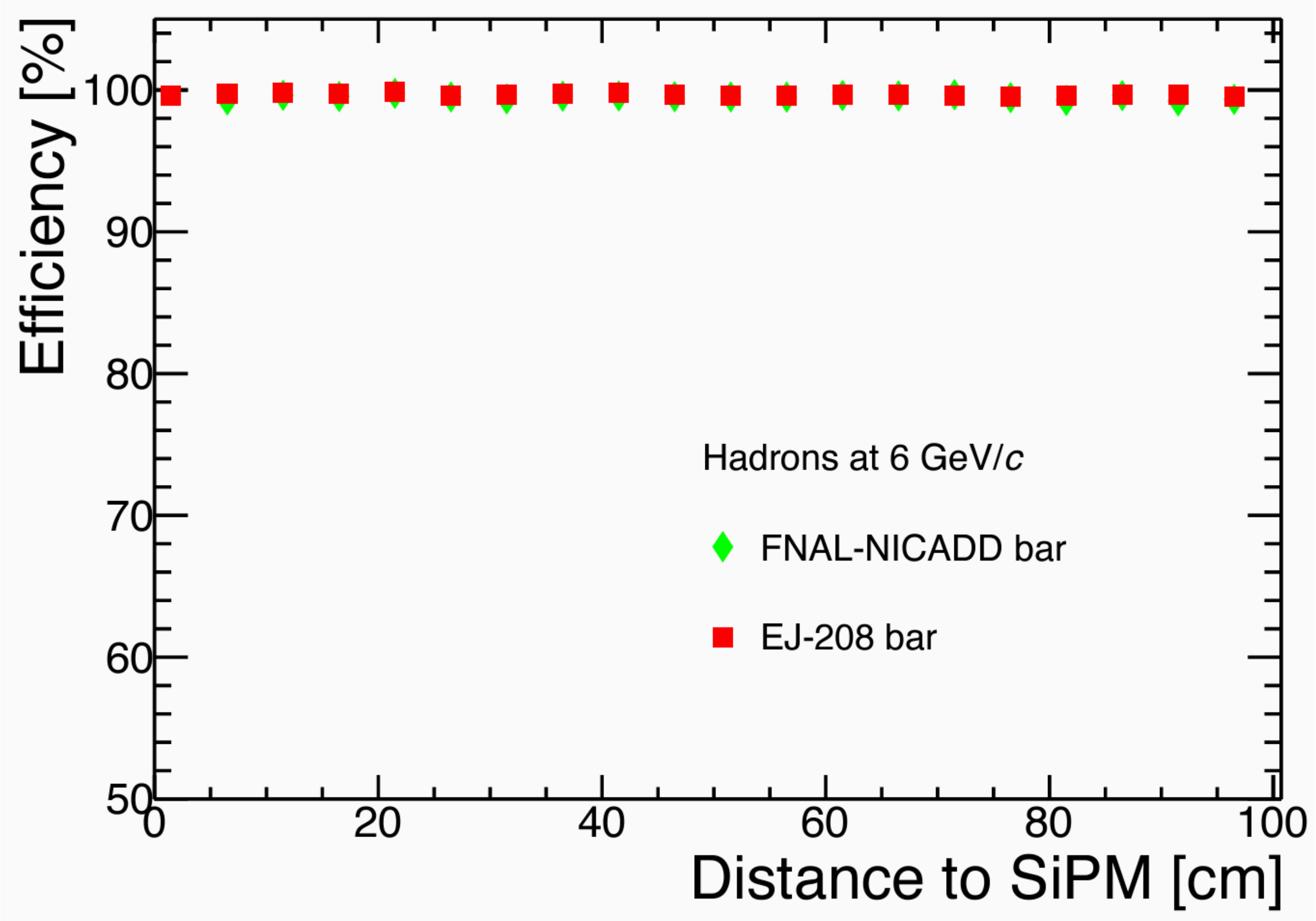


Several geometries under evaluation



JINST 19 (2024) 04, T04006

Efficiency vs distance along bar

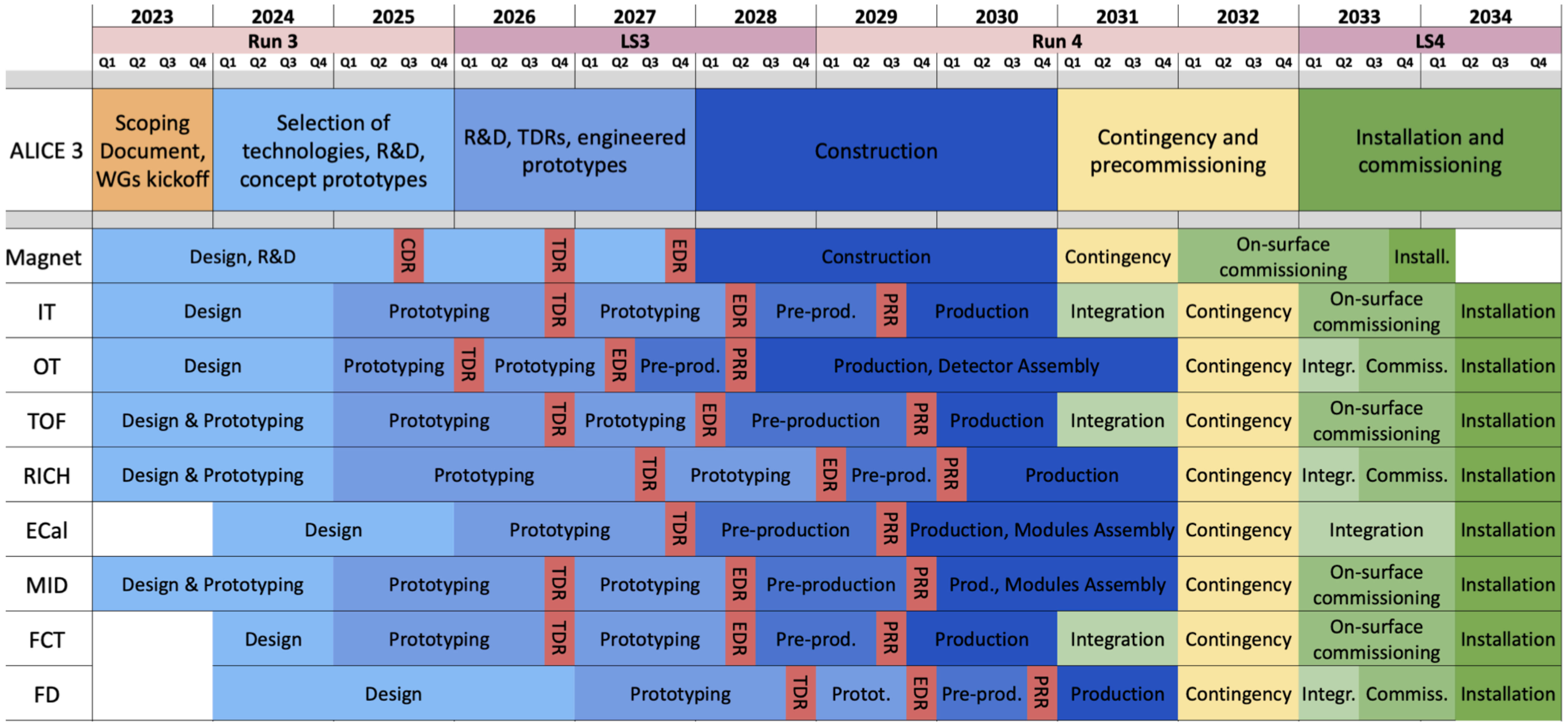


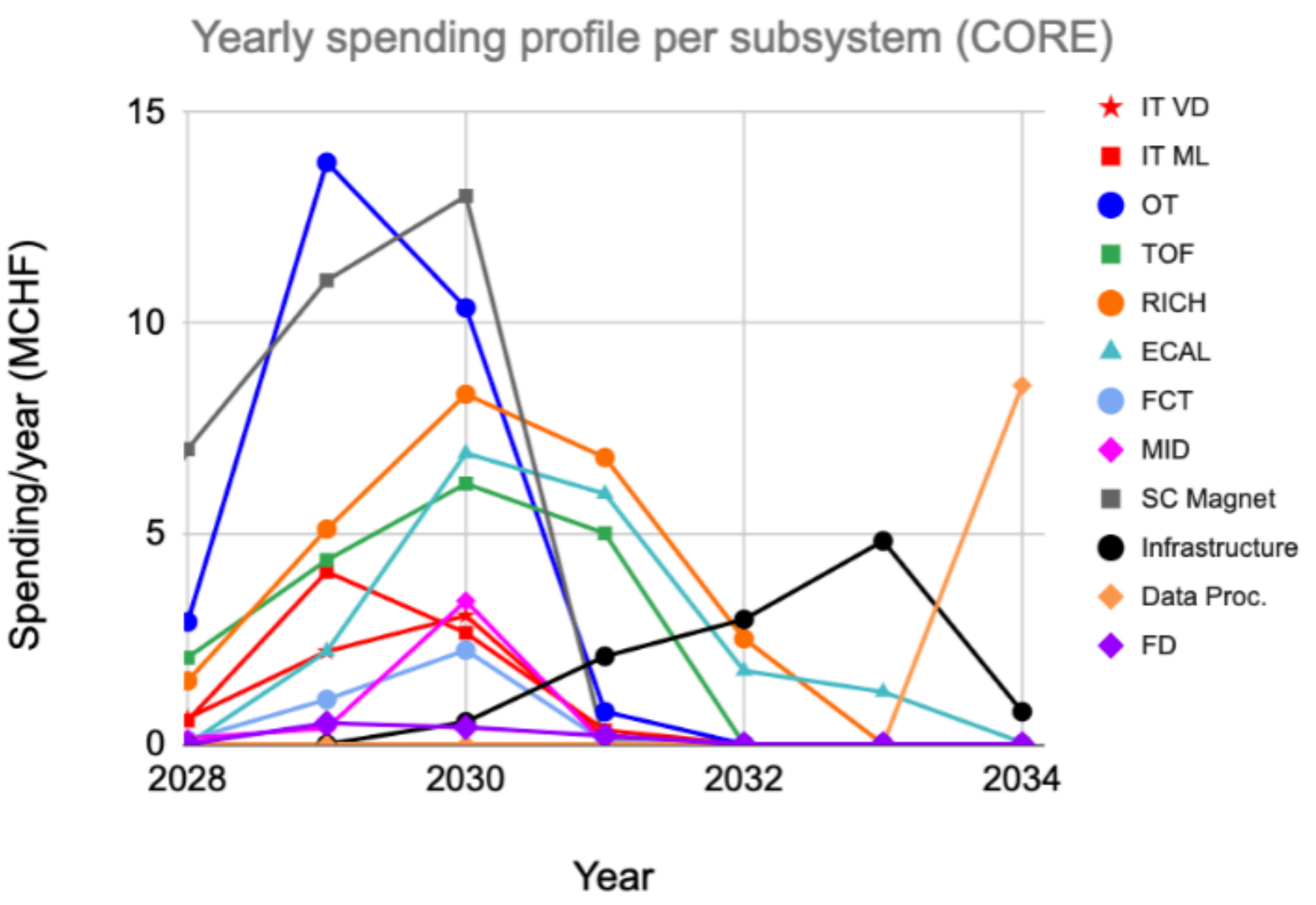
Muon identifier: **absorber followed by muon stations**

- Base line technology: Scintillator bars, SiPM readout
- Alternative technologies: MWPC, RPC
- Muon identification down to $p_T \approx 1.5$ GeV/c

Scoping document: schedule and cost profile

ALICE 3 time time





Preparation of ‘scoping document’ ongoing — draft reviewed internally

- Design considerations, R&D roadmap, preliminary view of planning, cost and resources
  - First TDRs planned by end of 2026

ALICE 3 scoping: cost

More detailed cost projections in preparation

(De)scoping scenarios:

- Without ECal: - 25 MCHF
- B = 1T: - 5 MCHF

Impact on physics programme presented in scoping document

LoI cost table

System	Technology	Cost (MCHF)
Tracker	MAPS	30.5
TOF	Monolithic timing sensors (integrated gain layer)	14.8
	Hybrid LGADs	26.4
RICH	Aerogel and monolithic SiPMs	20.9
	Aerogel, analog SiPMs + read-out	34.0
ECal	Pb-Sci sampling and $PbWO_4$	17.0
Muon ID	Steel absorber, scintillator bars, SiPMs	7.0
FCT	MAPS (solenoid and dipoles)	2.3
	MAPS (solenoid and separate dipole for FCT)	5.3
Magnets	Superconducting solenoid + FCT magnet	25.0
	Superconducting solenoid and dipoles	40.0
Computing	Data acquisition and processing	6.0
Common items	Beampipe, infrastructure, engineering	15.0
Total		**141.4**

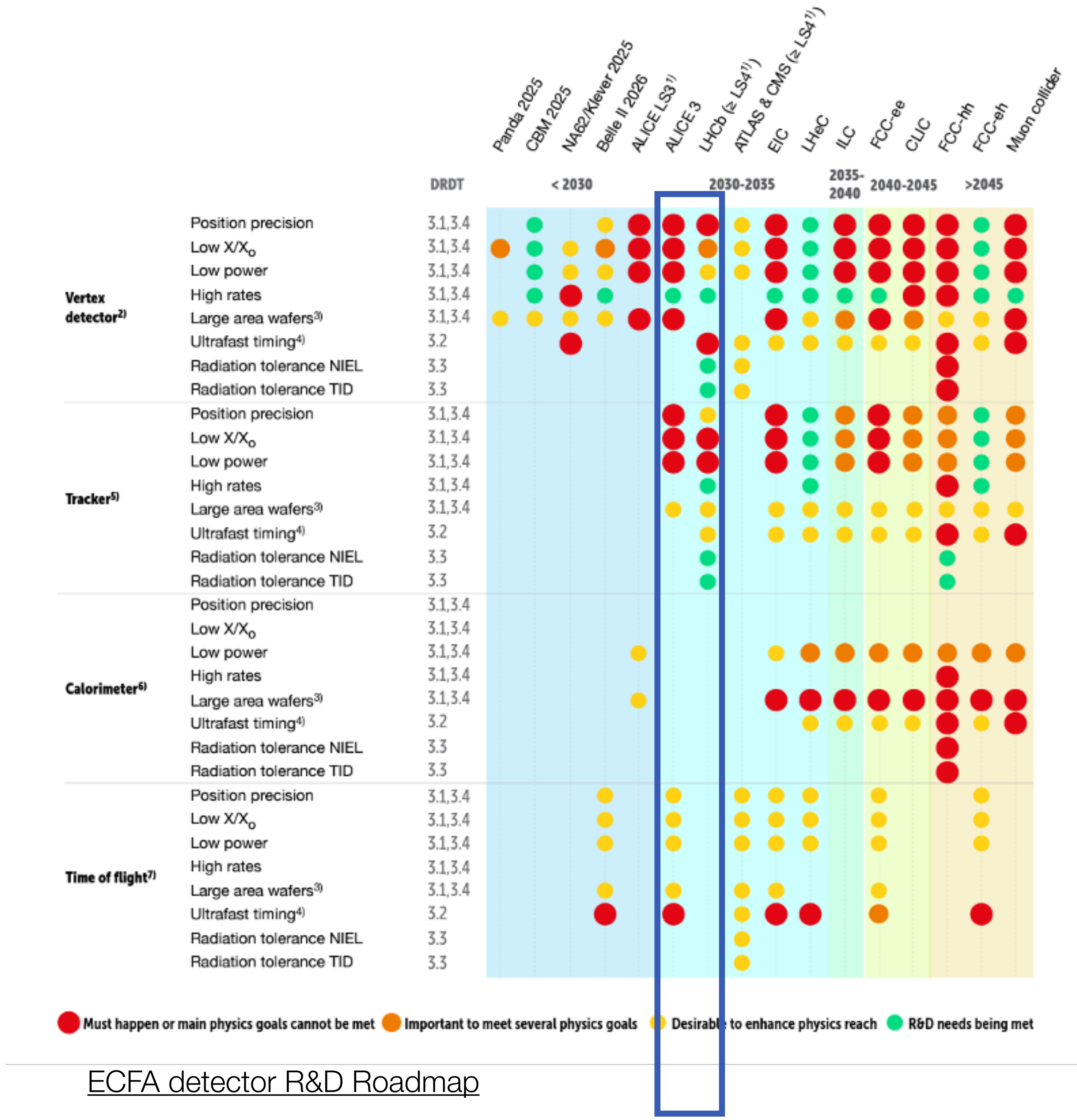
ALICE future plans — summary

Clear path for future upgrades of ALICE

LS3 — smaller upgrades
- **ITS3**: improve pointing resolution, reduce material budget
- **FoCal**: new capability for forward photons, π^0, jets

ALICE 3 in LS 4: Unique pointing resolution and extensive PID to unlock
- High-precision measurements of thermal radiation, chiral symmetry restoration
- Unique access to multi-charm baryon production — chemical equilibrium and coalescence
- Unique precision in heavy-flavour transport — approach to equlibrium
- Unique access to interactions between charm mesons — nature of exotic states

Develop detector technologies of the future
- High-performance CMOS MAPs for tracking
- Integrated TOF sensors
- Next-generation photon sensors



ECFA detector R&D Roadmap

ALICE 3 and LHCb IIb R&D well aligned with EIC, ILC, FCC-ee needs

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Let’s build this program together!

ECFA detector R&D Roadmap

ALICE 3 and LHCb IIb R&D well aligned with EIC, ILC, FCC-ee needs


WELCOME TO THE
FUTURE

Parton interactions in the medium: Collisional + radiative

Different formulations exist in literature — use this as an example

Y. Xu et al, PRC 97, 014907

'Improved Langevin model':

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g.$$

Drag

(often not used/present in light flavour models)

Thermal force

Radiative loss

(fluctuations are modelled as well)

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Thermal force

Radiative loss (fluctuations are modelled as well)

Transport coefficients:

$$\begin{cases} \frac{d}{dt}\langle p \rangle \equiv -\eta_D \langle p \rangle , \\ \frac{1}{2}\frac{d}{dt}\left\langle (\Delta p_T)^2 \right\rangle \equiv \kappa_T , \\ \frac{d}{dt}\left\langle (\Delta p_z)^2 \right\rangle \equiv \kappa_L . \end{cases}$$

Drag

Transverse and longitudinal momentum diffusion

Parton interactions in the medium: Collisional + radiative

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'Improved Langevin model':

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Drag (often not used/present in light flavour models) — Thermal force — Radiative loss (fluctuations are modelled as well)

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Drag

Transverse and longitudinal momentum diffusion

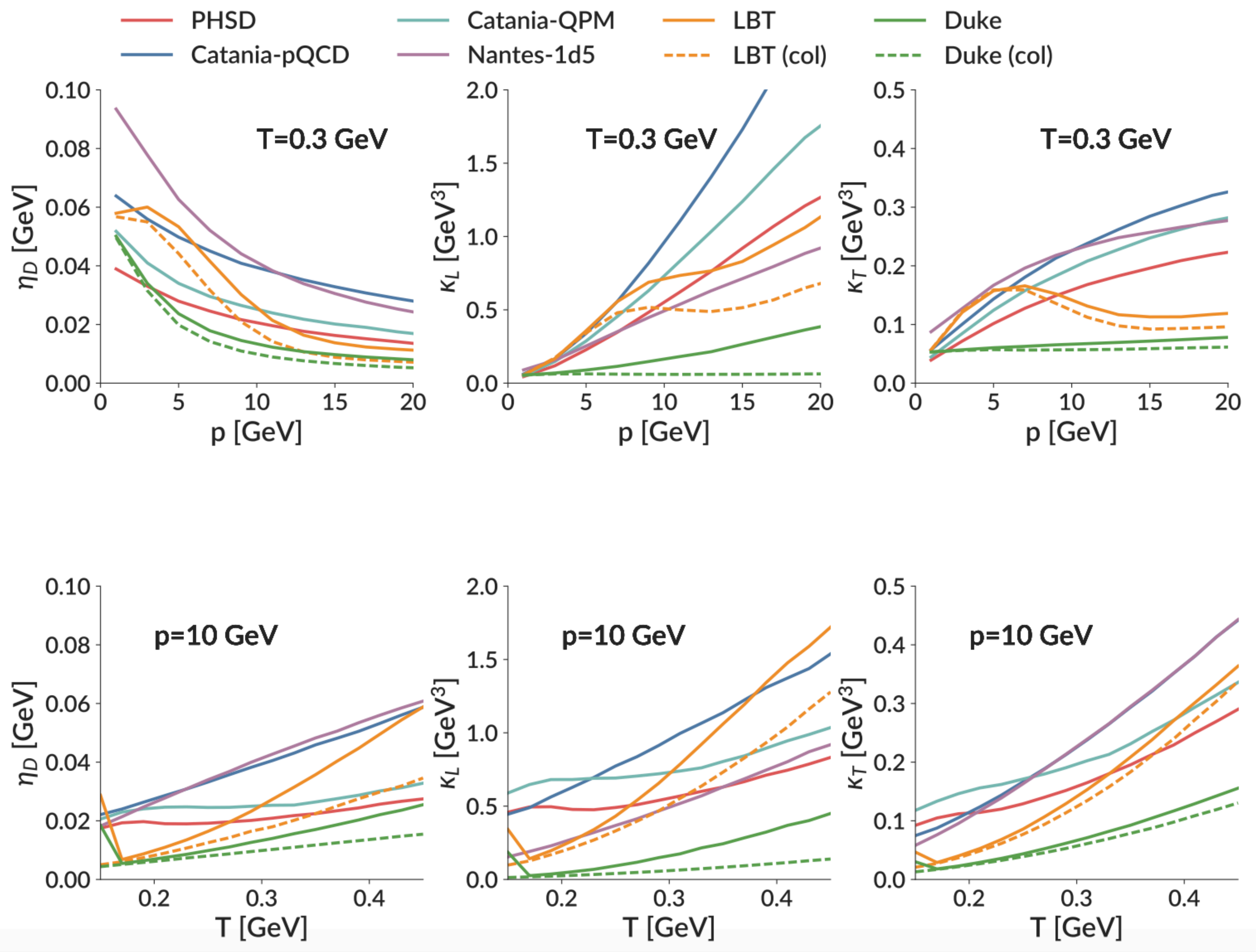
Over time: approach thermalisation

'limiting behaviour'

Mass and momentum dependence of transport coefficients

Heavy quark spatial diffusion coefficient D_s $\langle r^2 \rangle = 6\, D_s\, t$

Mass independent, limit $p \to 0$



Other key quantities do depend on mass:

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

Drag coefficient $\gamma = \dfrac{T}{m_Q\, D_s}$

⇒ Beauty thermalises more slowly than charm

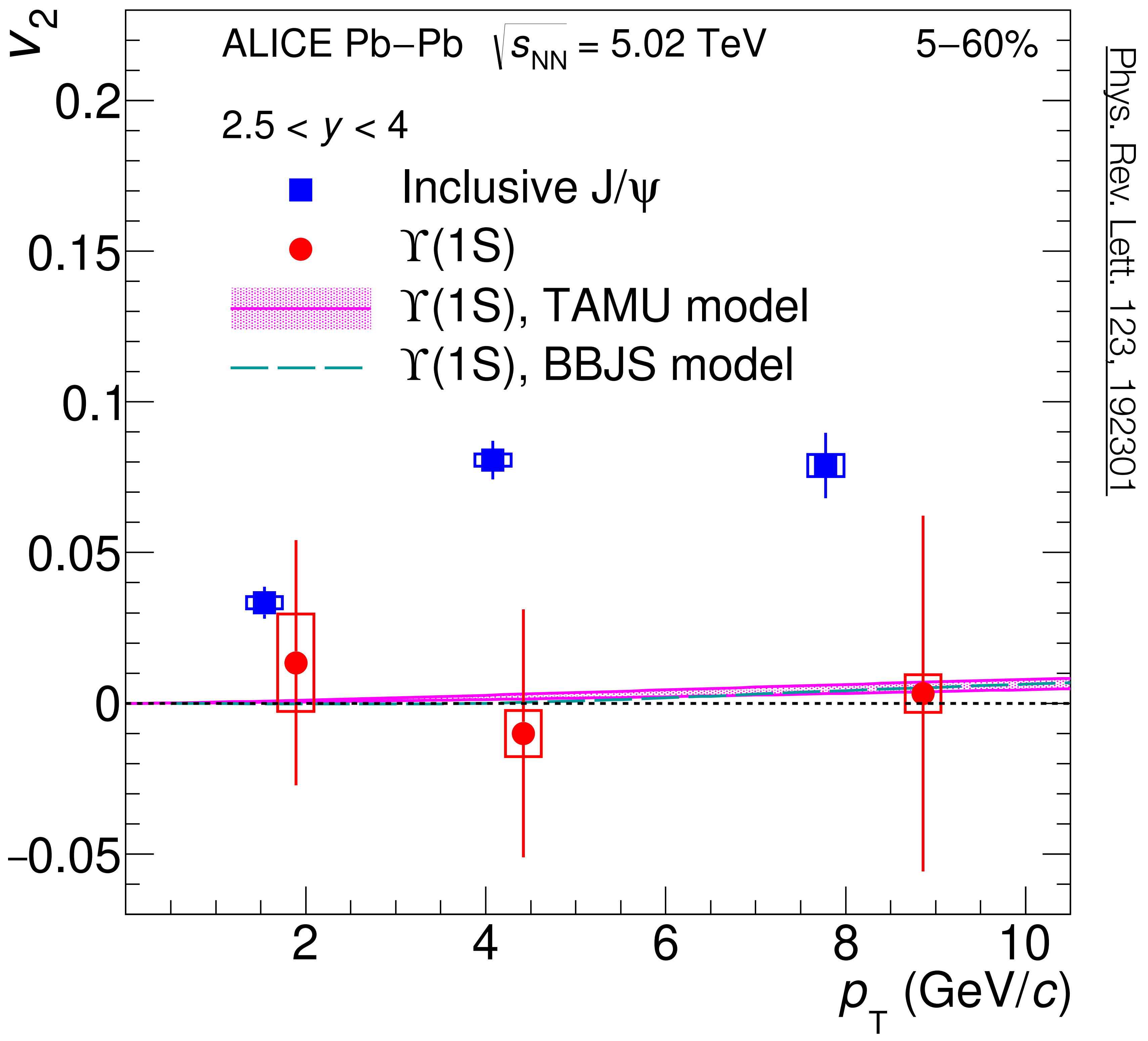
Rapp et al, arXiv:1803.03824

Xu, Y and Bass, S er at, PRC 99, 1, 014902

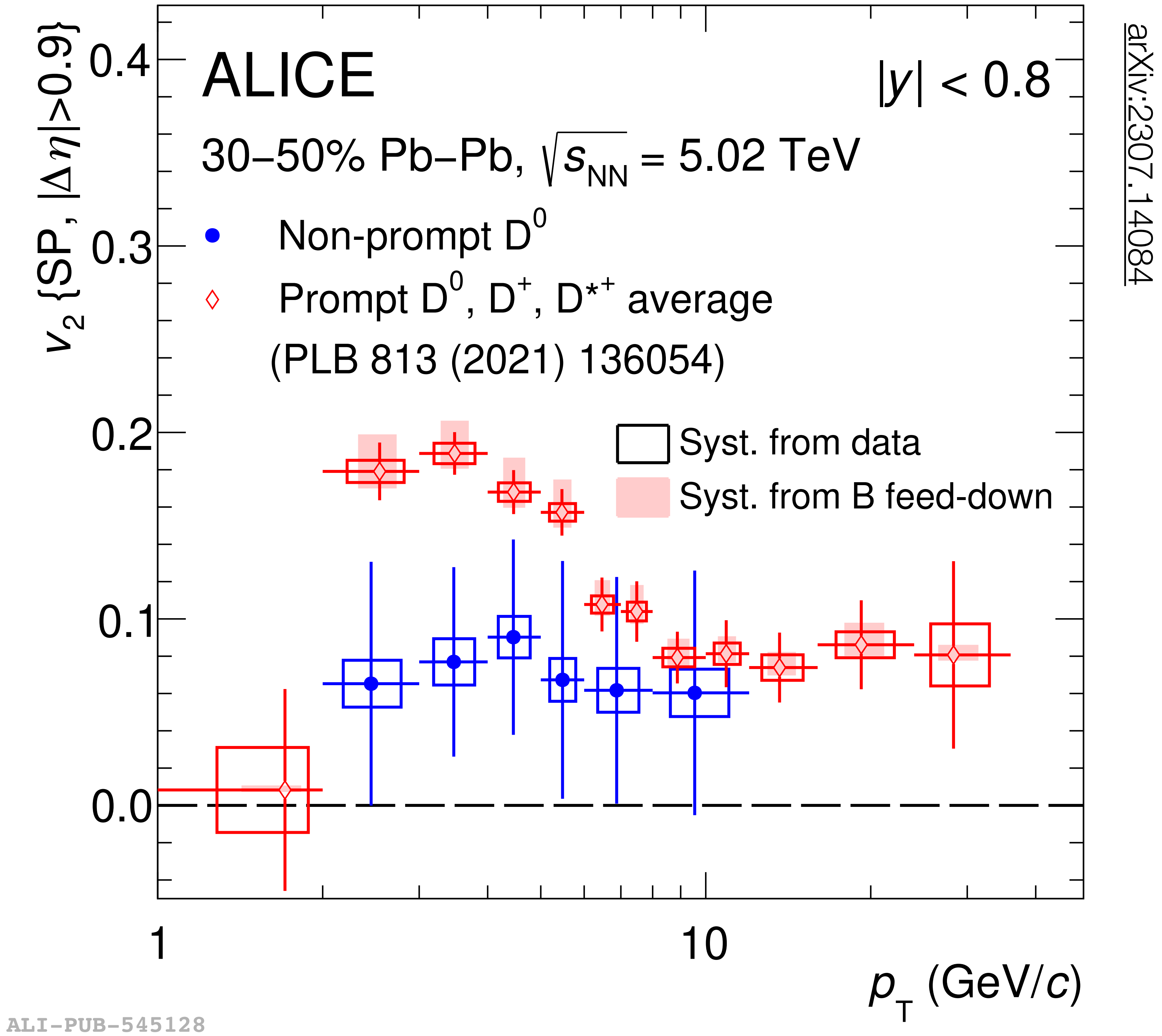
Beauty vs charm: important handle on understanding phenomenology

Elliptic flow of charm beauty quarks: impact of mass

J/ψ and Υ elliptic flow



Open charm, beauty elliptic flow

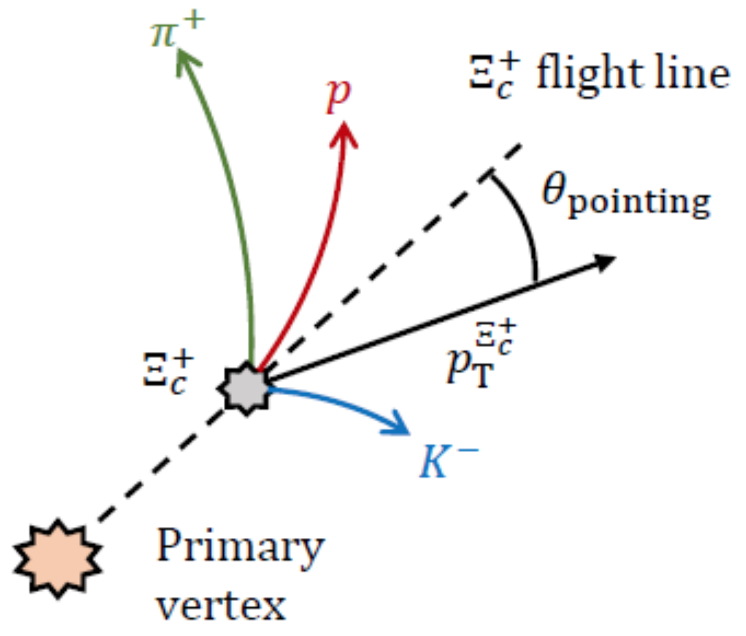


Quarkonia: flow generated by quark flow and coalescence
Charmonia: large elliptic flow — Bottomonia: compatible with no flow

Non-prompt D mesons (open beauty) show smaller v_2

Beauty quarks flow less than charm quarks: larger mass, smaller kicks
Impact of hadronisation, light quark flow, to be further understood

ITS3 performance example: $\Xi_c \rightarrow$ p, K, π



- ITS3 will largely improve the reconstruction capabilities of the Ξ_c
- Lifetime: cτ ≈ 135 μm
  - spatial resolution is key

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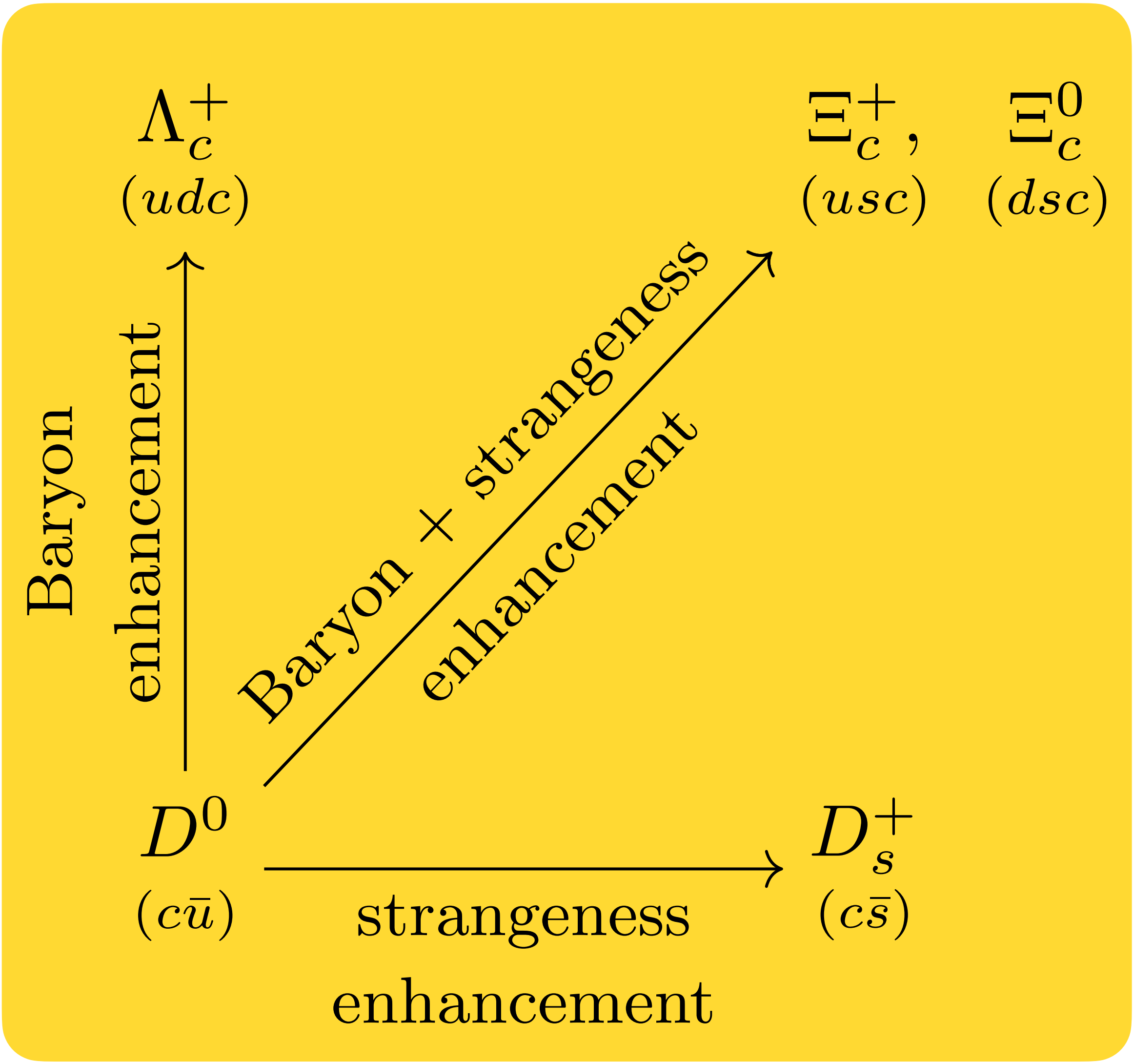
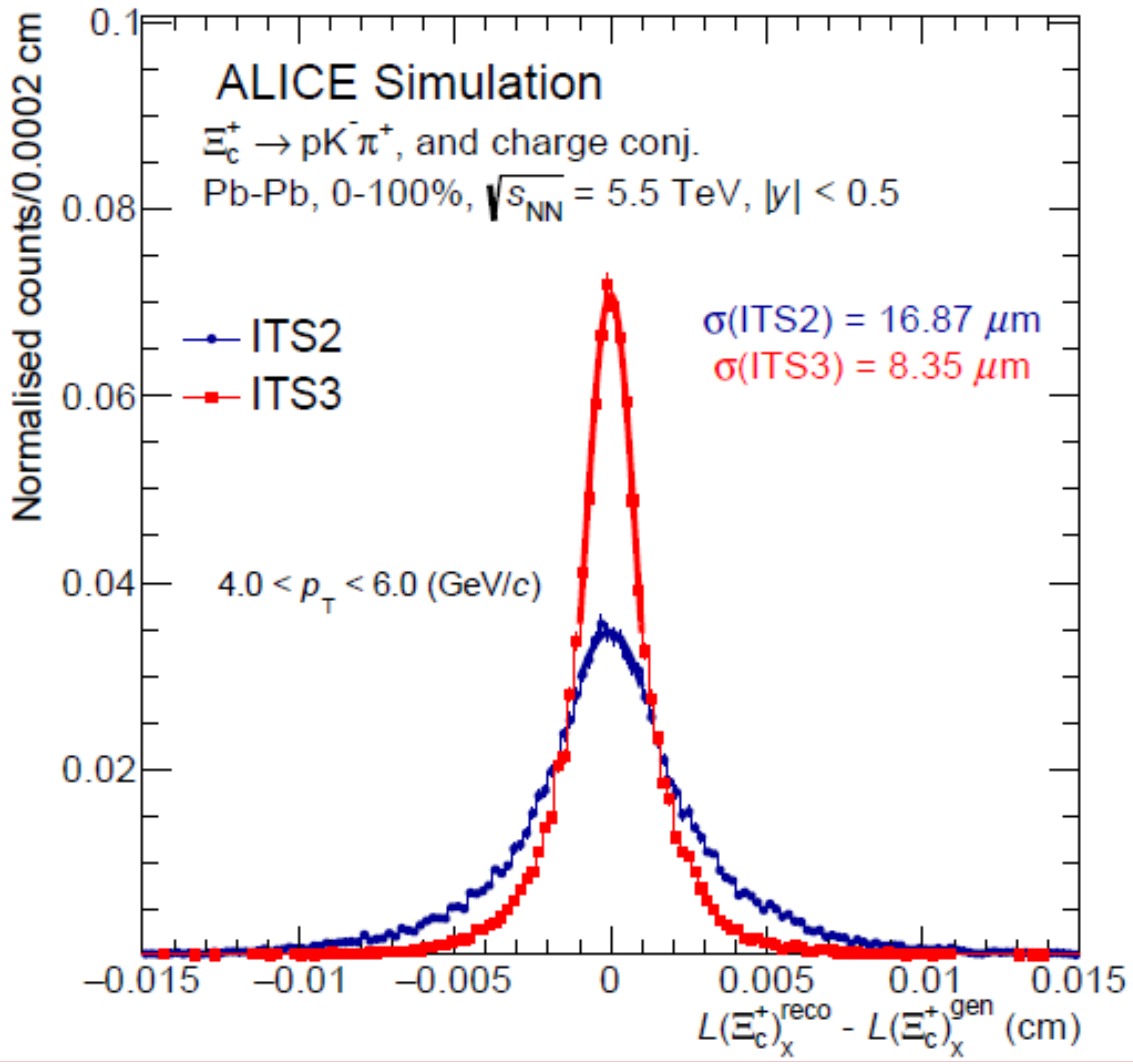
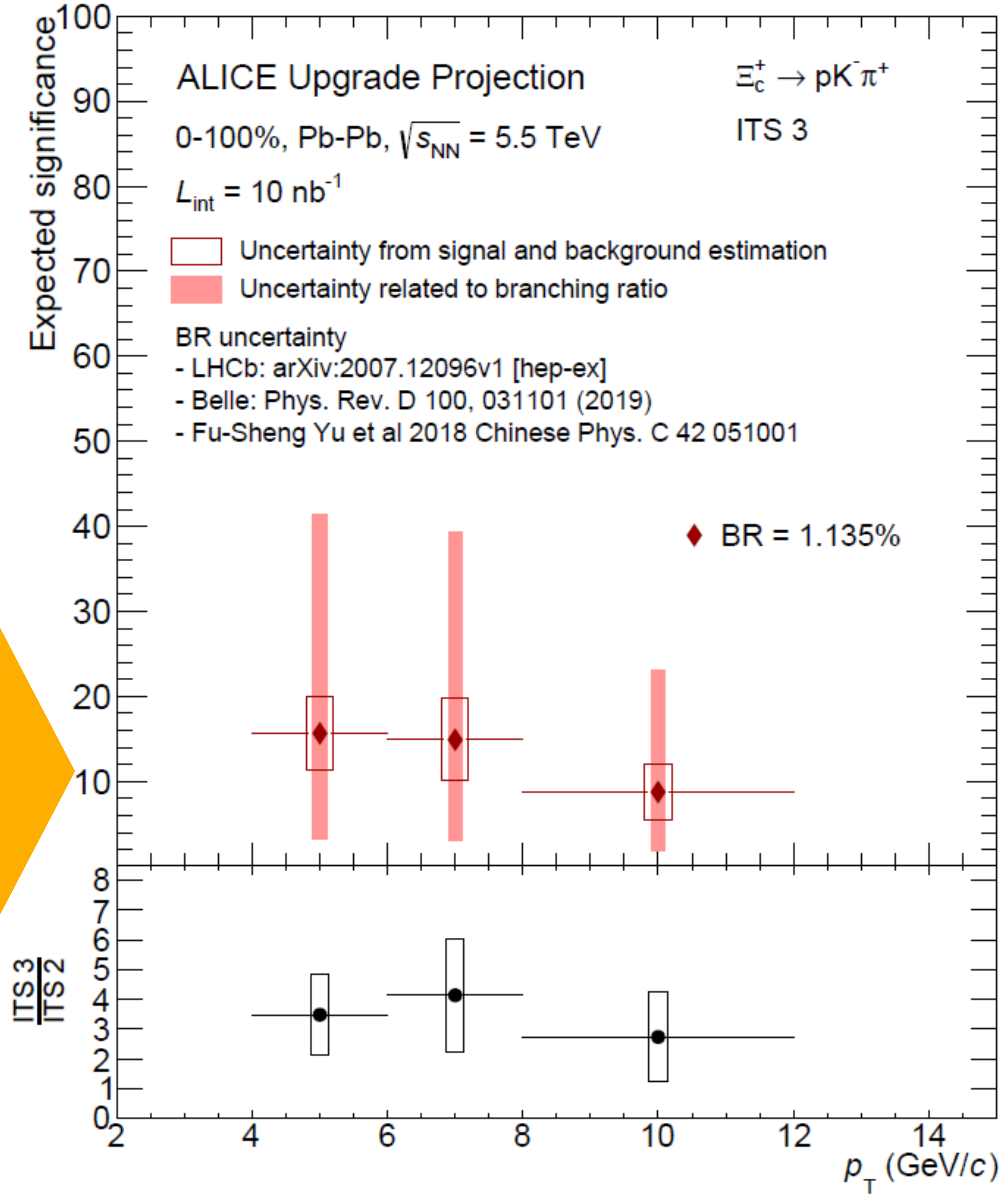
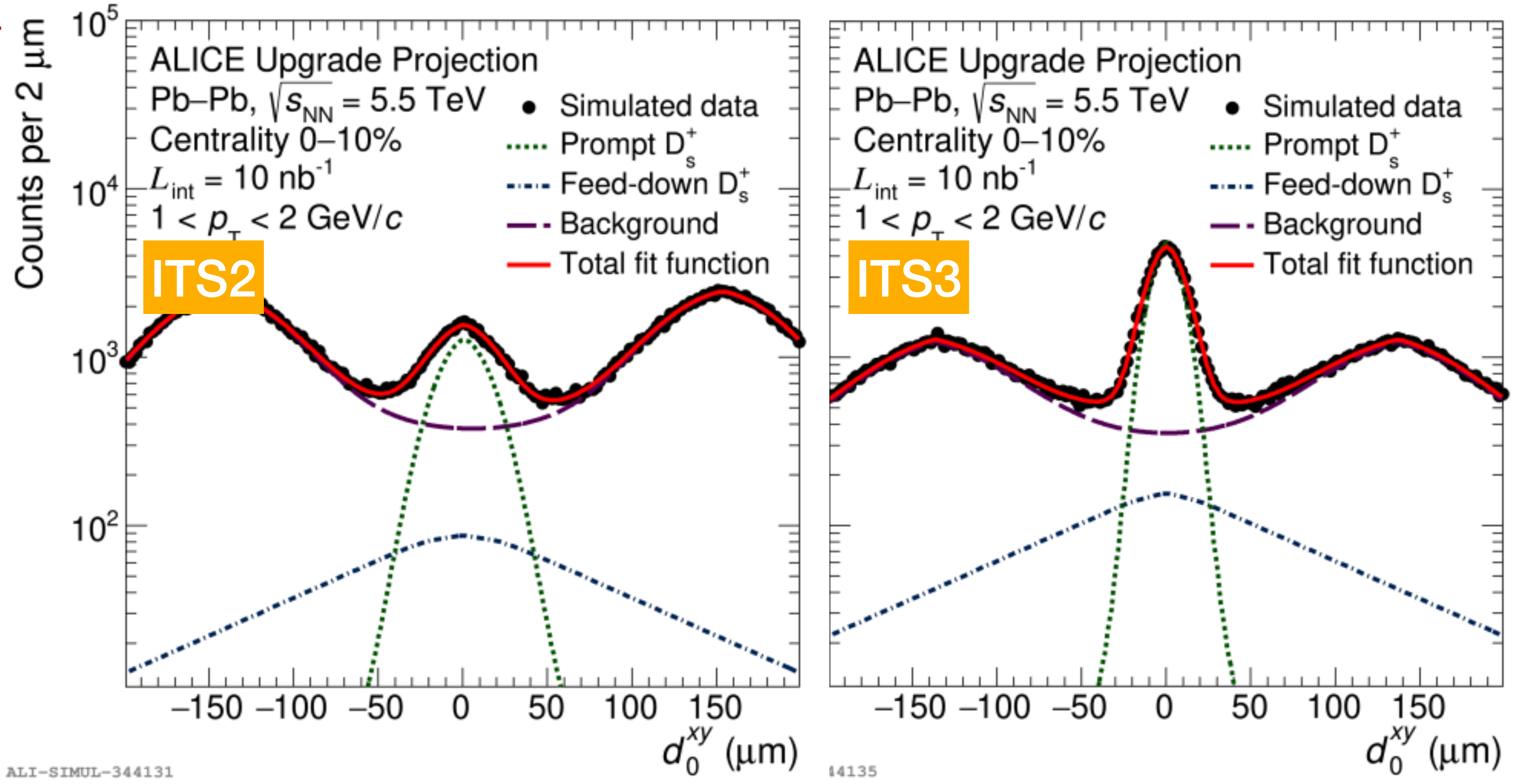
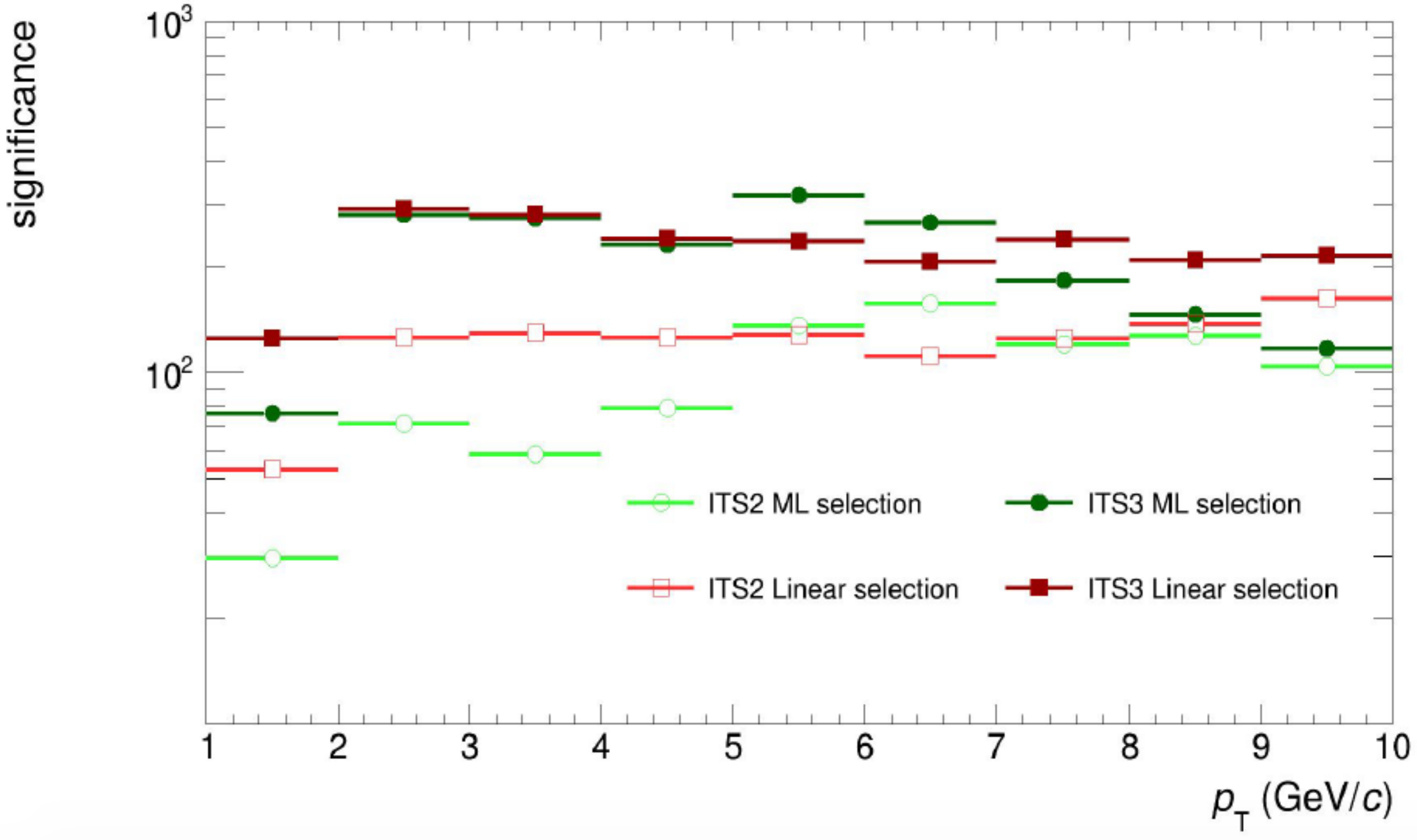






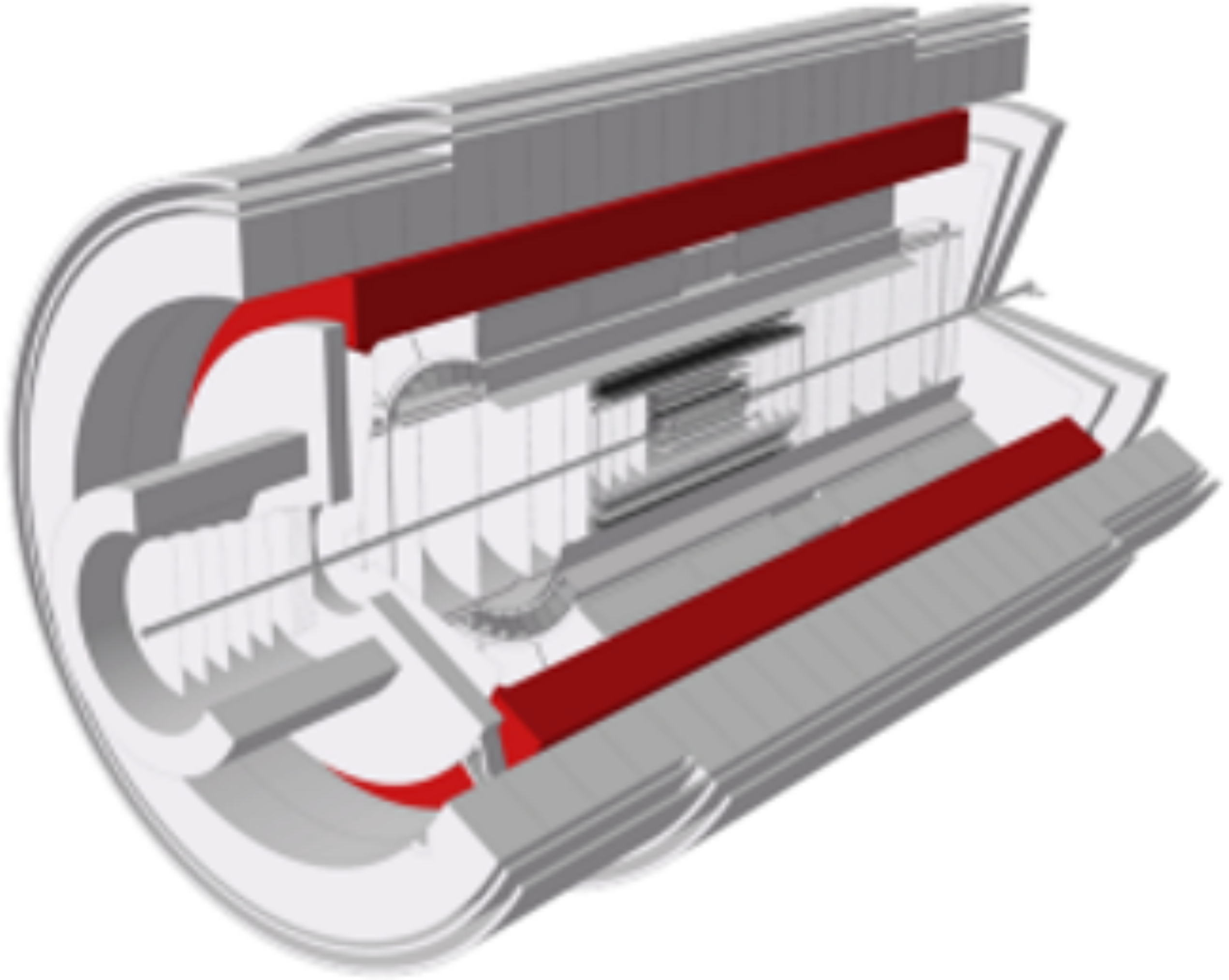
ITS3 performance: non-prompt D_s^+





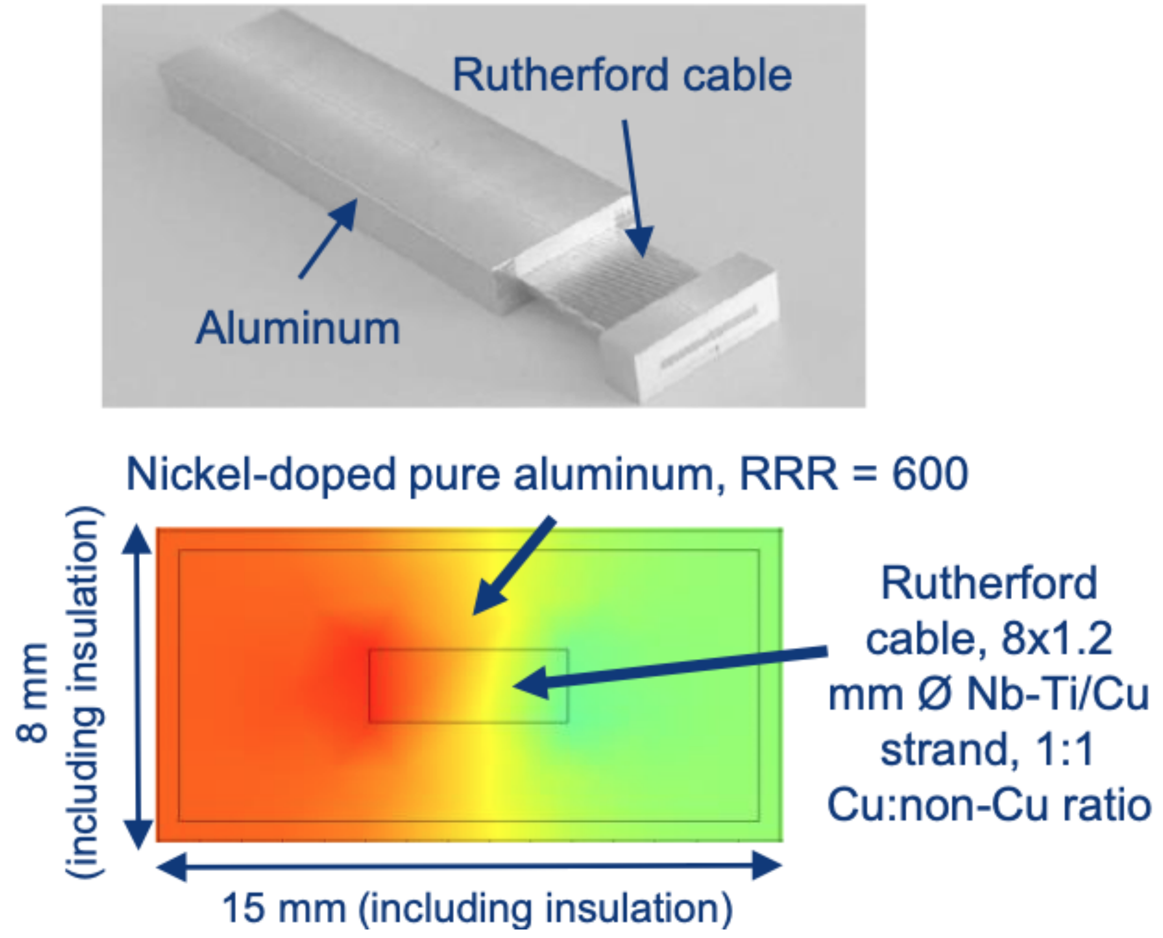
- The much better tracking resolution of ITS3 allows a much cleaner identification of the different templates
- Machine learning allows to select a high fraction of non-prompt D_s^+ even with ITS2
- However, with ITS2 one then pays a prize in significance while this does not happen for ITS3

Magnet design



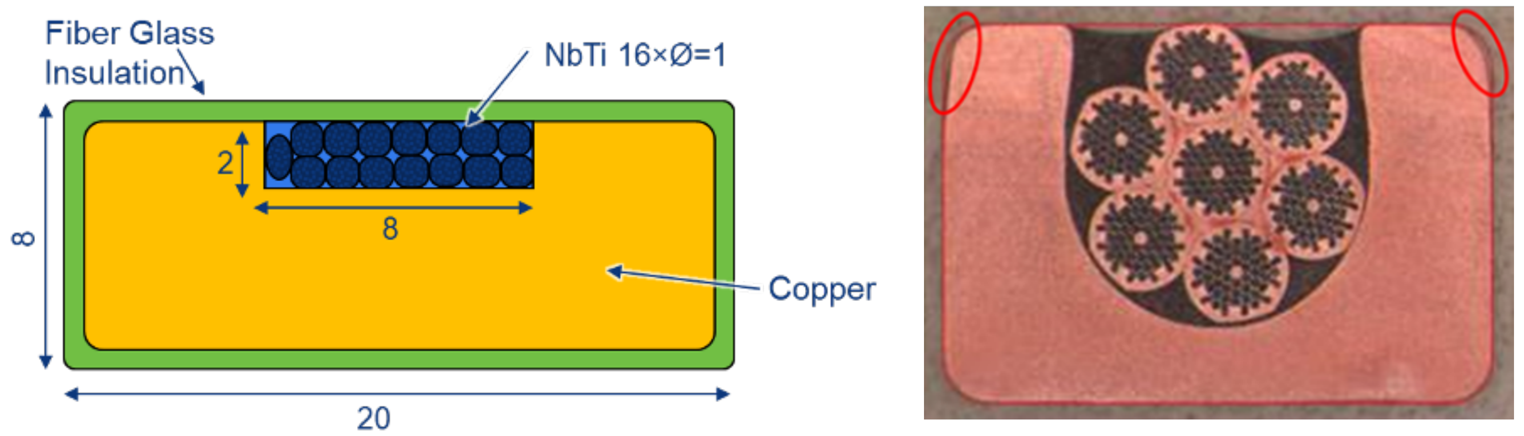
Superconducting solenoid B = 2T

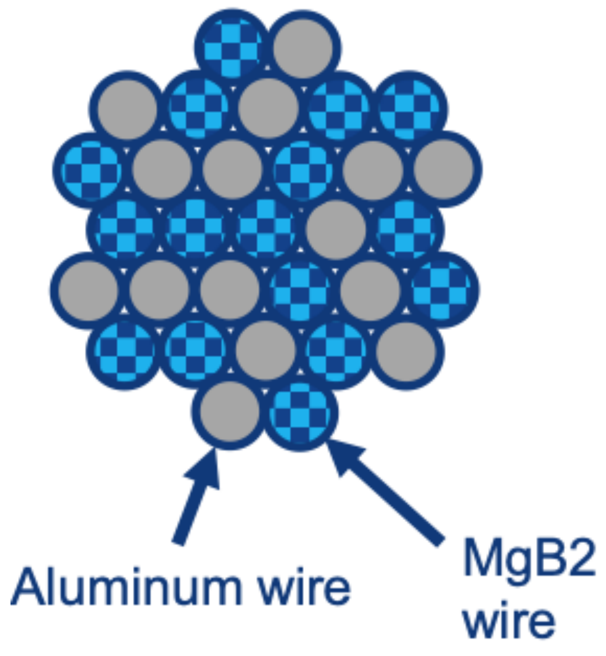
R=1.8m, L=7.5m



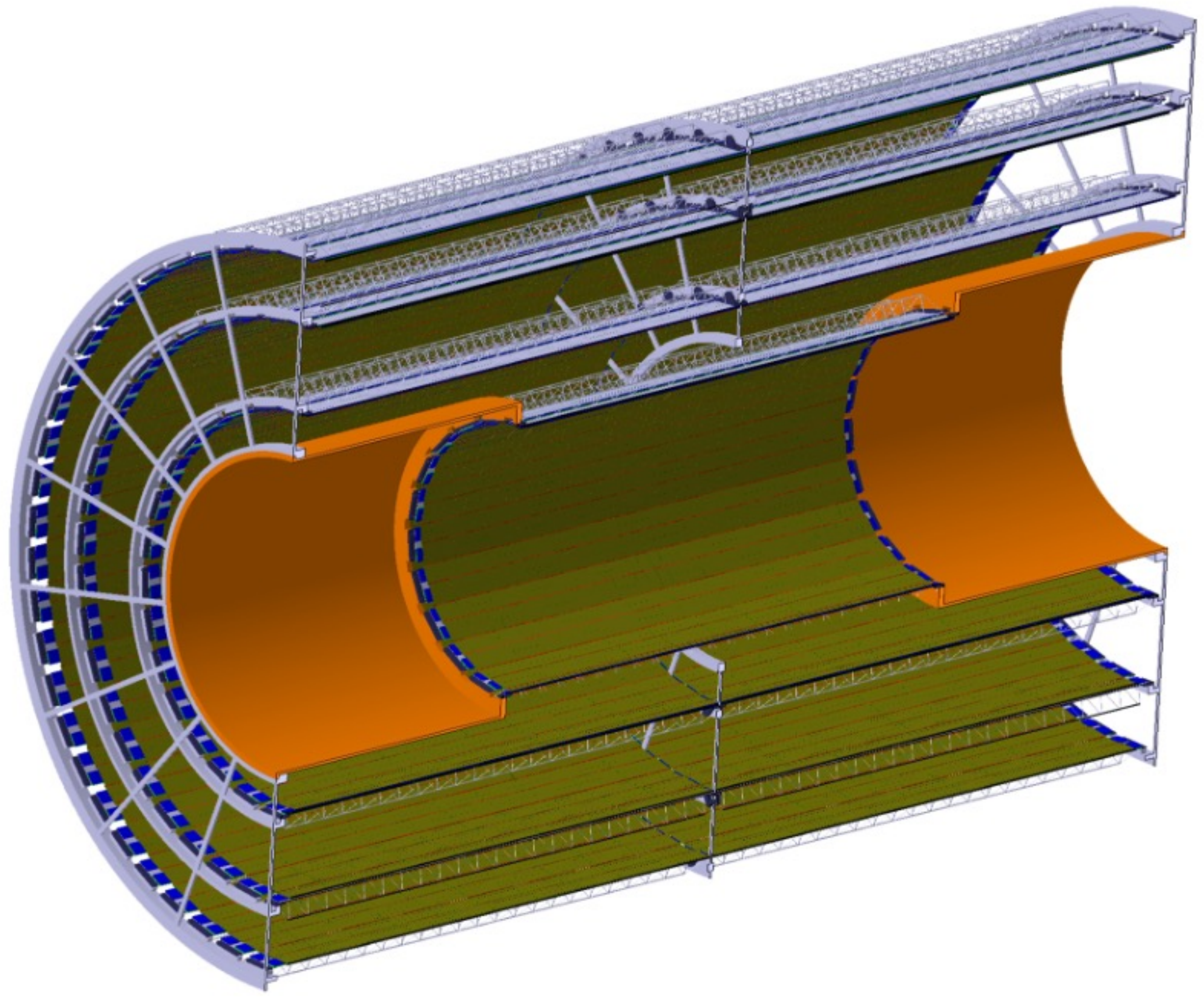
Superconducting cable options being explored:

- Nb-Ti
  - Al co-extruded cable not commercially available anymore; R&D at CERN to re-establish production
  - Cu stabilised cable being produced for EPIC@EIC
- MgB_2
  - Commercially available (e.g. ASG – former Ansaldo), R&D needed for experiment magnet implementation

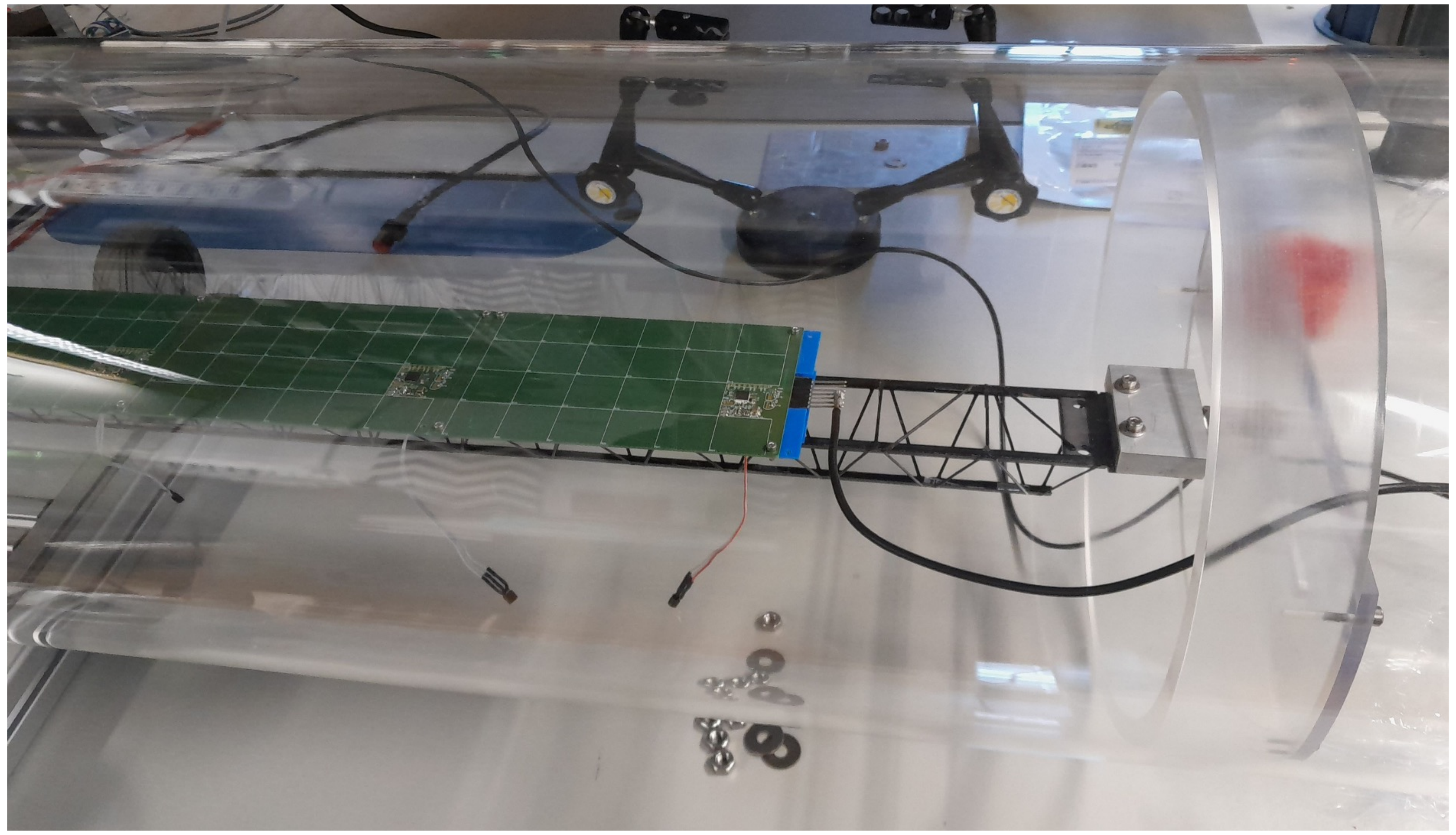


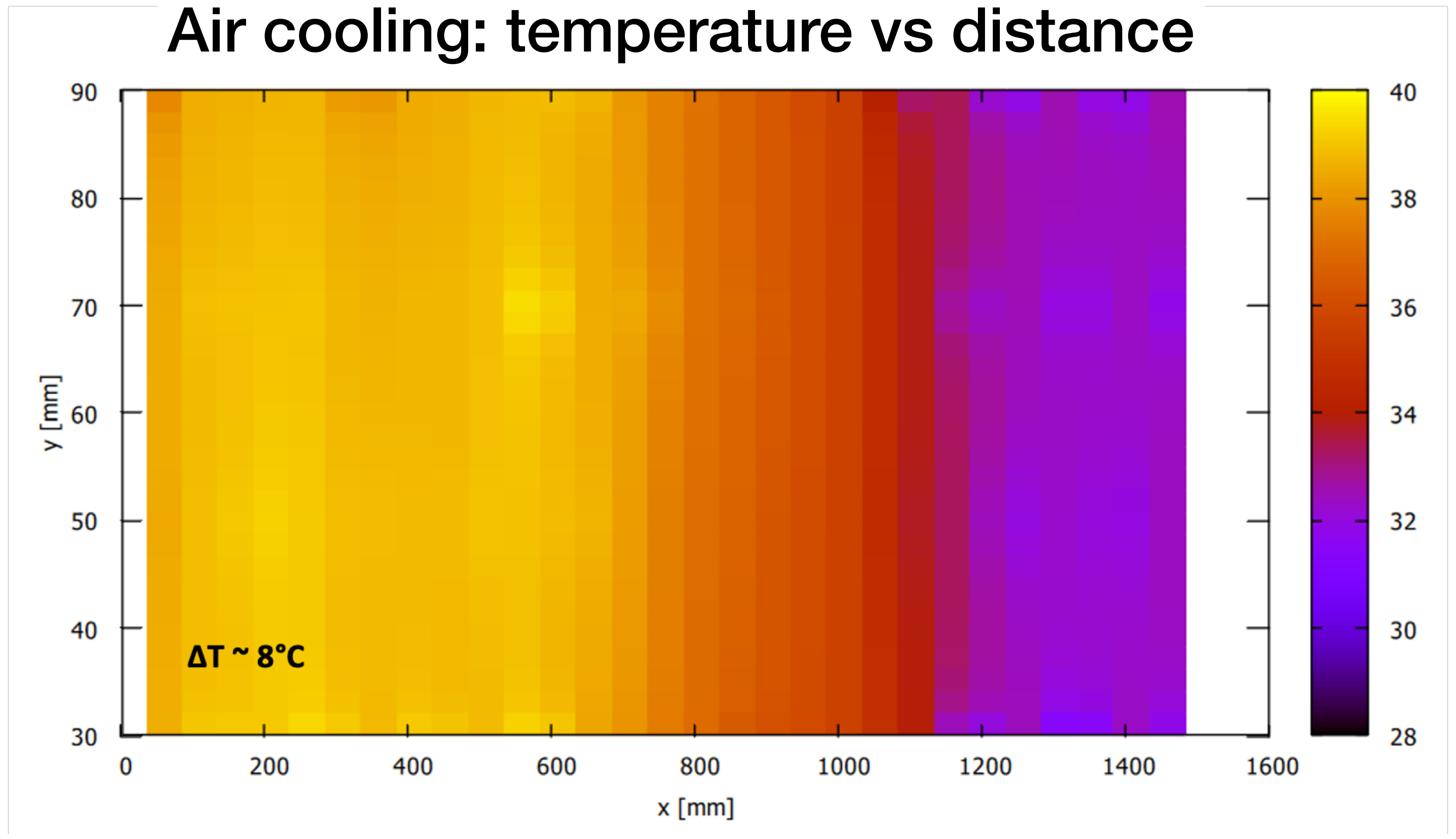


Outer tracker R&D: thermal testing



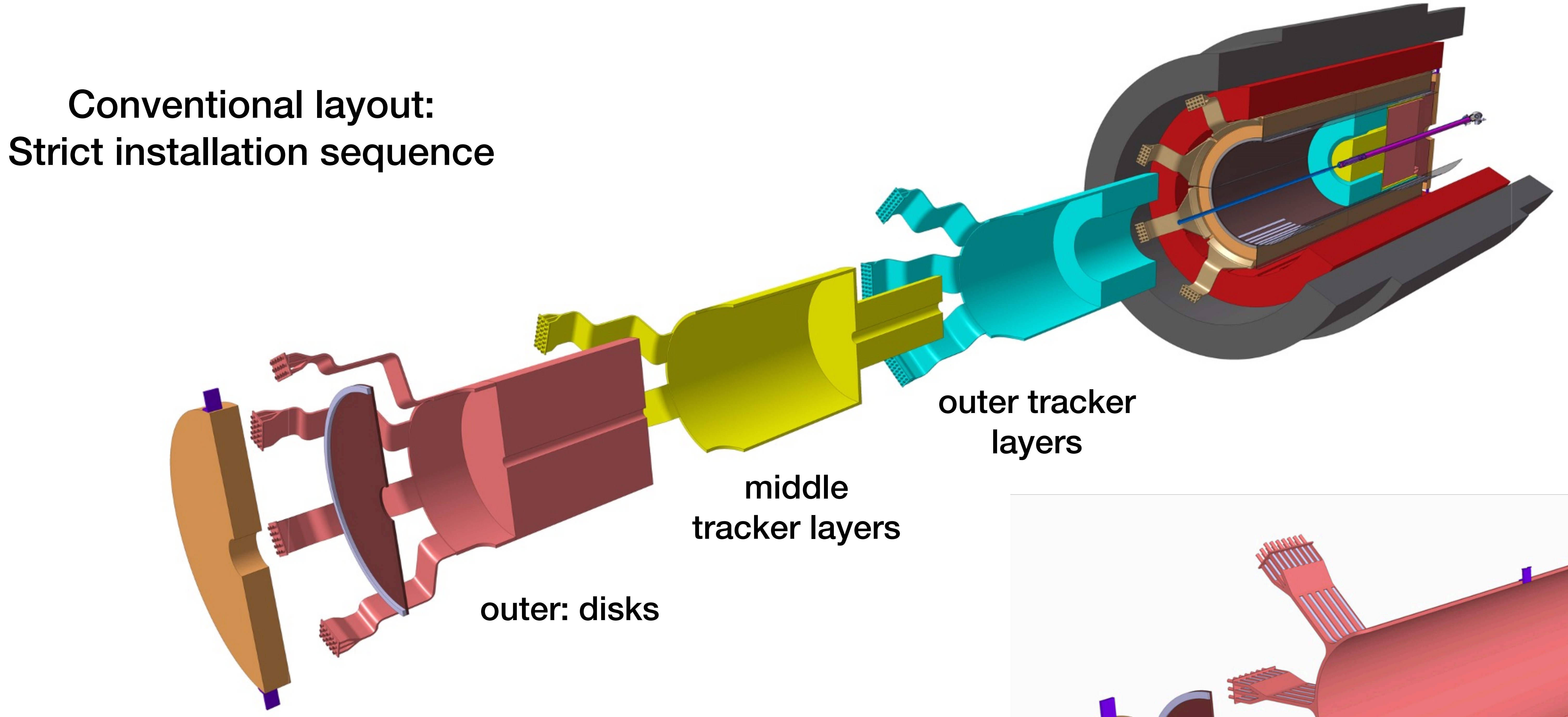
Test setup with heater boards

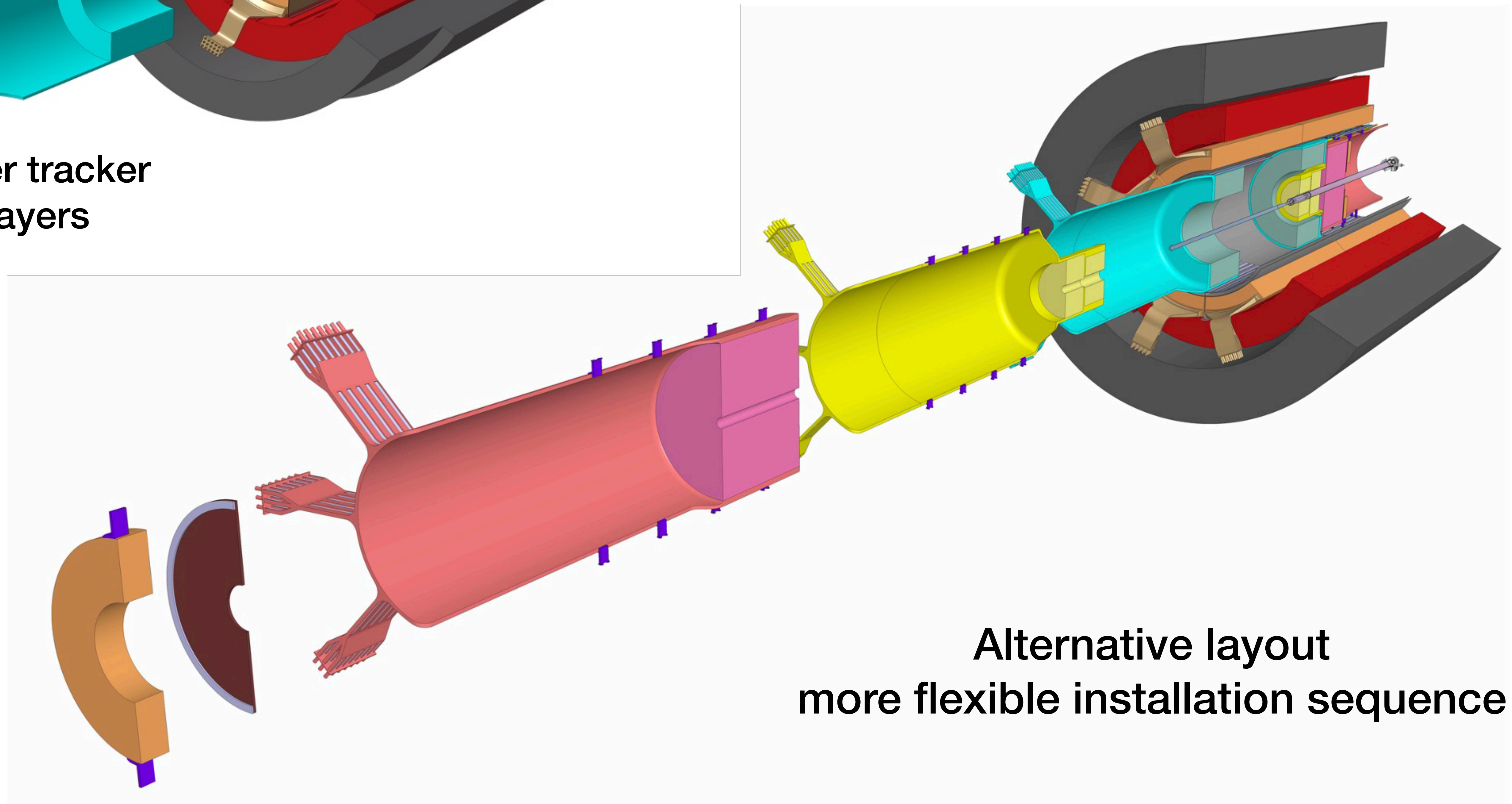




- Layout concept for outer tracker: optimise module geometry
- Lab tests of cooling: air vs water vs hybrid cooling

Overall mechanics, integration, and installation



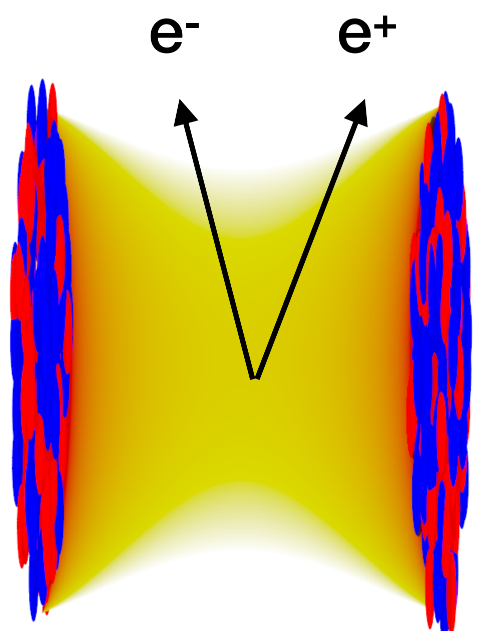


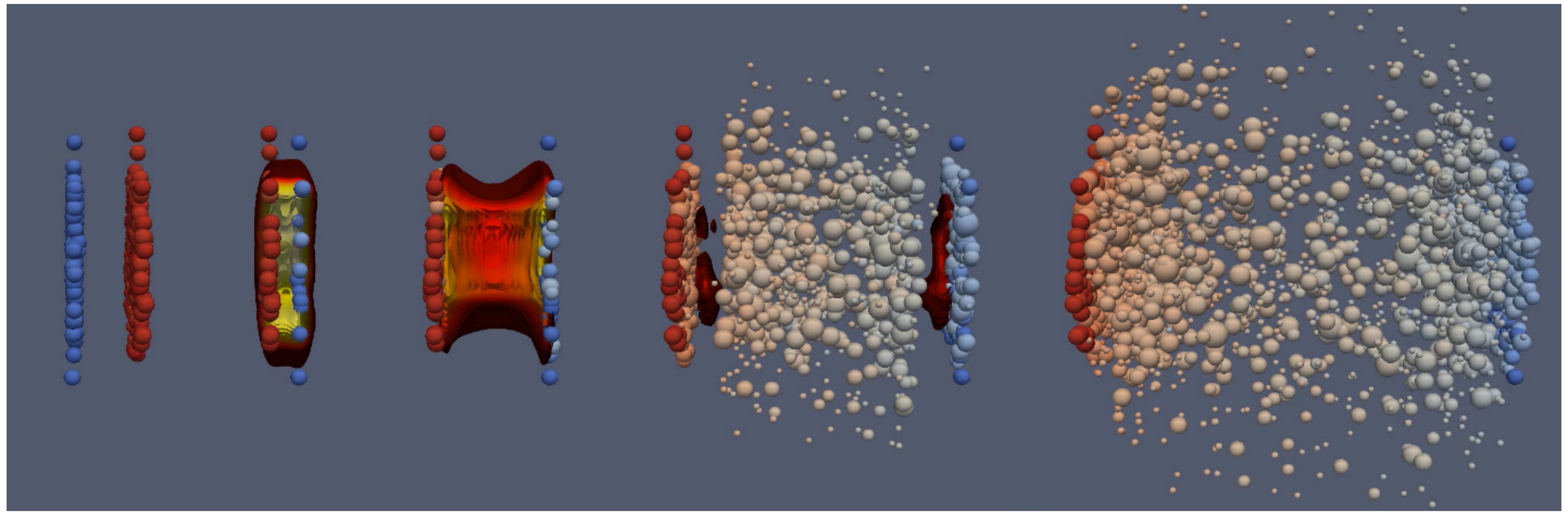
Overall mechanical concepts being studied: impact on installation sequence

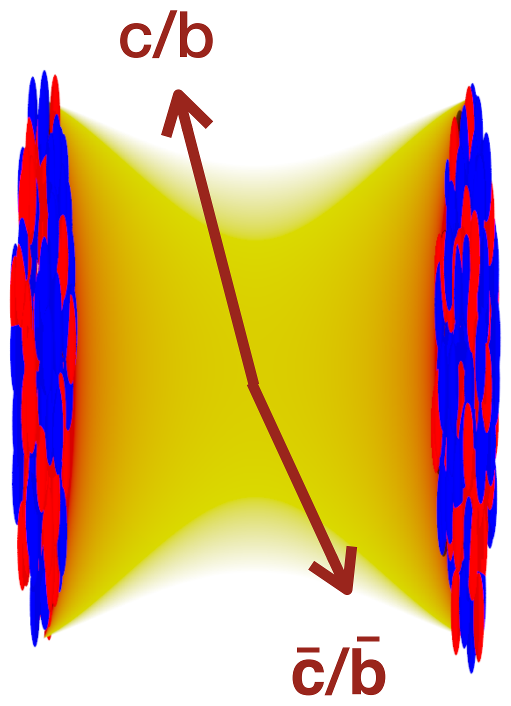
Goal: flexible installation order; ability to install outer detectors last

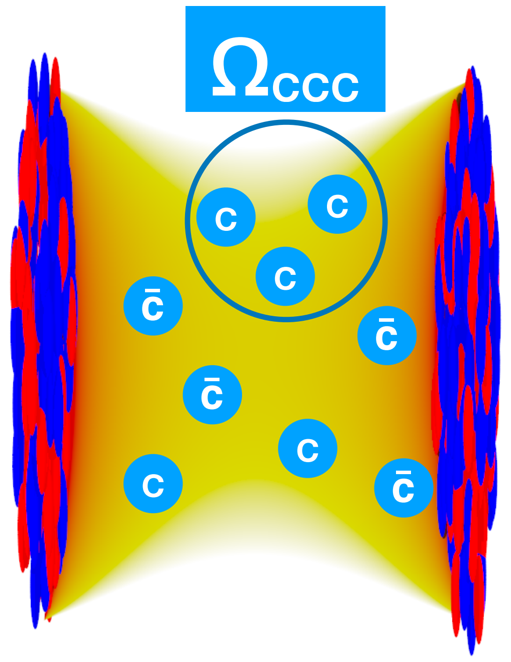
Physics beyond Run 4

- Progress beyond run 3 and 4 relies on
  - **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
    - ➟ susceptibilty to conserved charges
  - …









Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances ‘hadrochemistry’

Hadron correlations, fluctuations