ALICE + ALICE 3 & other experiments beyond Run 4

Anthony Timmins

Many thanks to ALICE and LHC collaborators for input

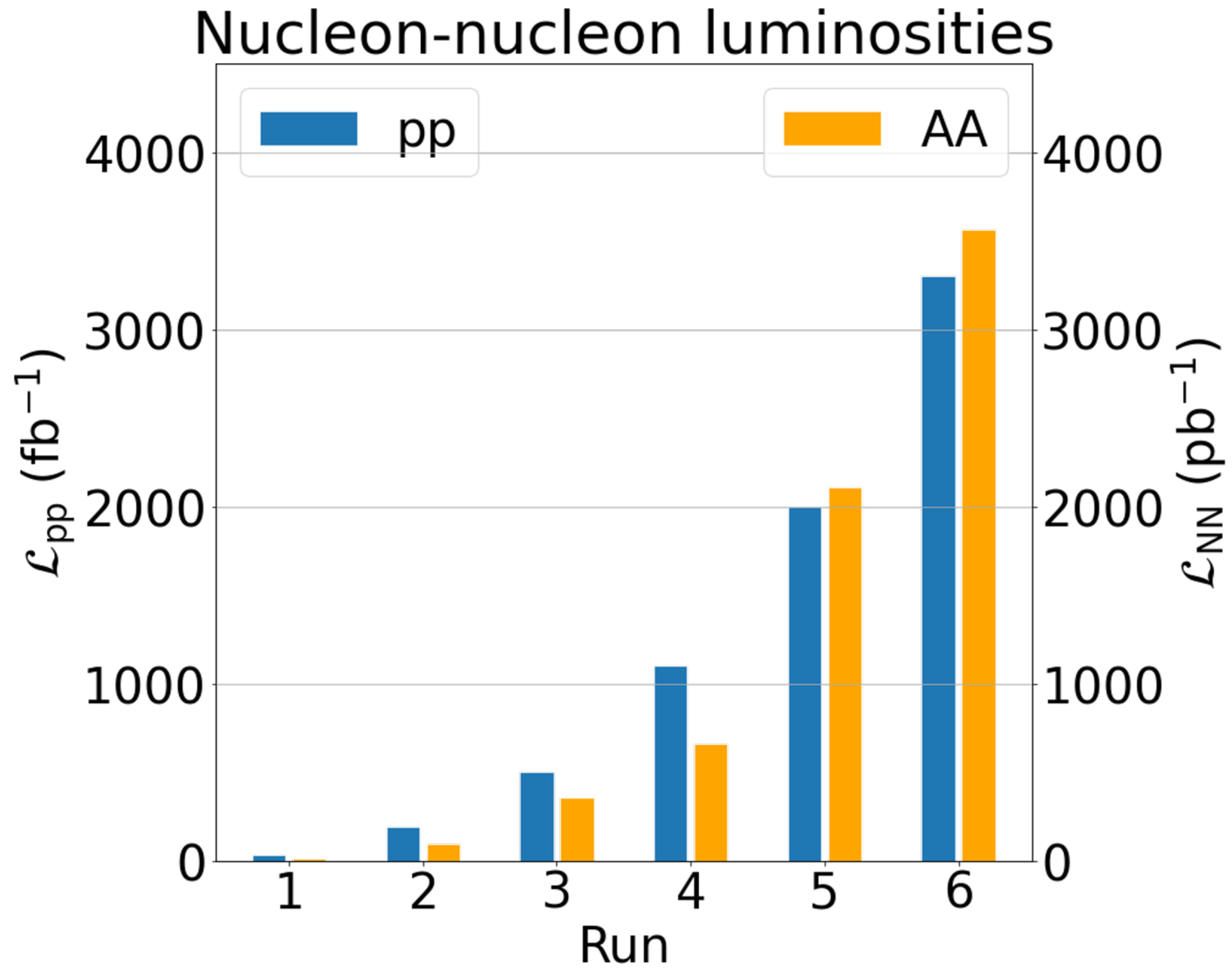
LHC program at CERN

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

High luminosity for ions (Run 3, Run 4)

HL-LHC (Run 4)

Higher luminosities for ions (Run 5, Run 6)



- European Particle Physics Strategy Update recommends full exploitation of the LHC incl. heavy-ion program…
- **Compelling reasons for US Hot QCD community to take advantage**

LHC experiments and upgrades

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

High luminosity for ions

HL-LHC

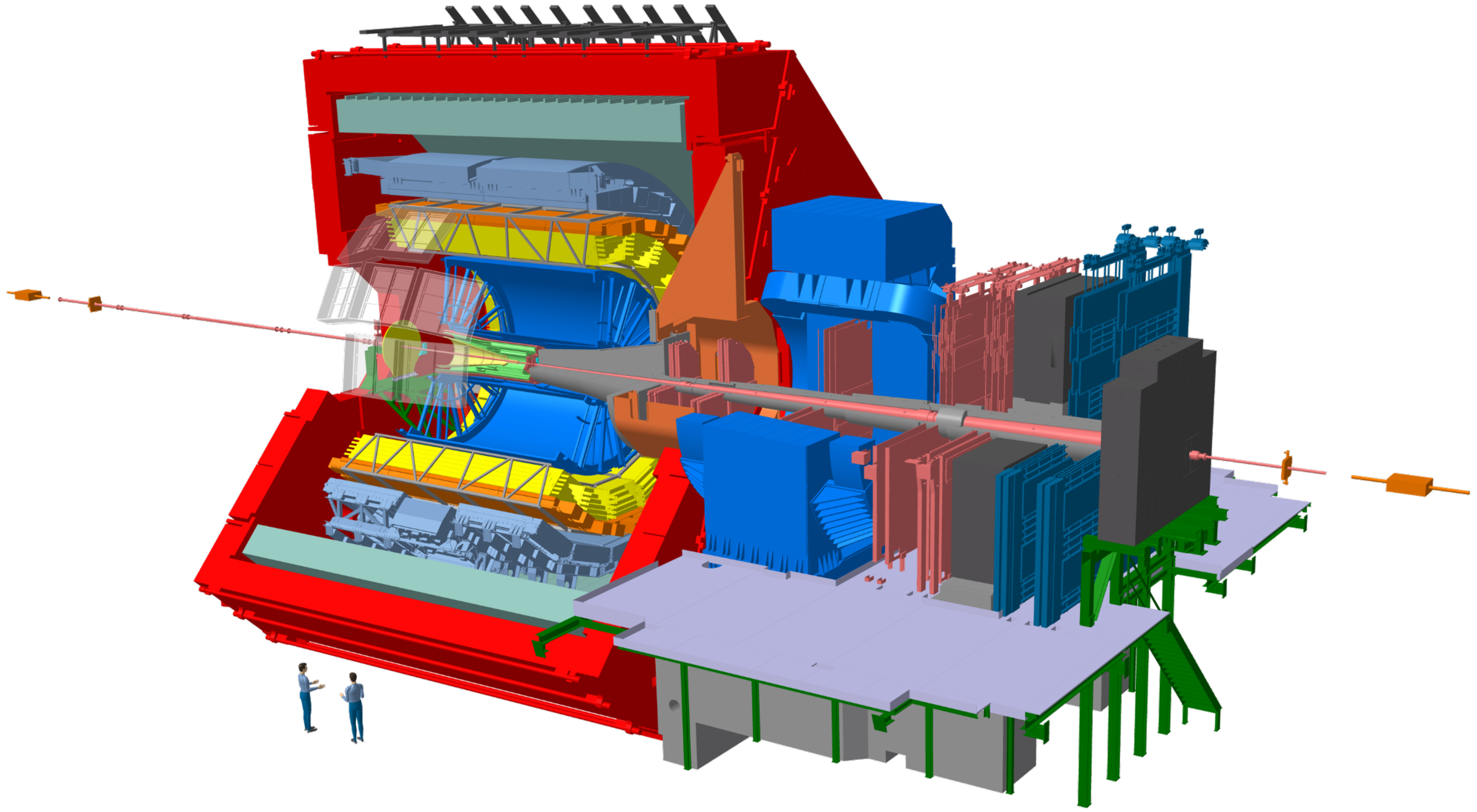
Higher luminosities for ions

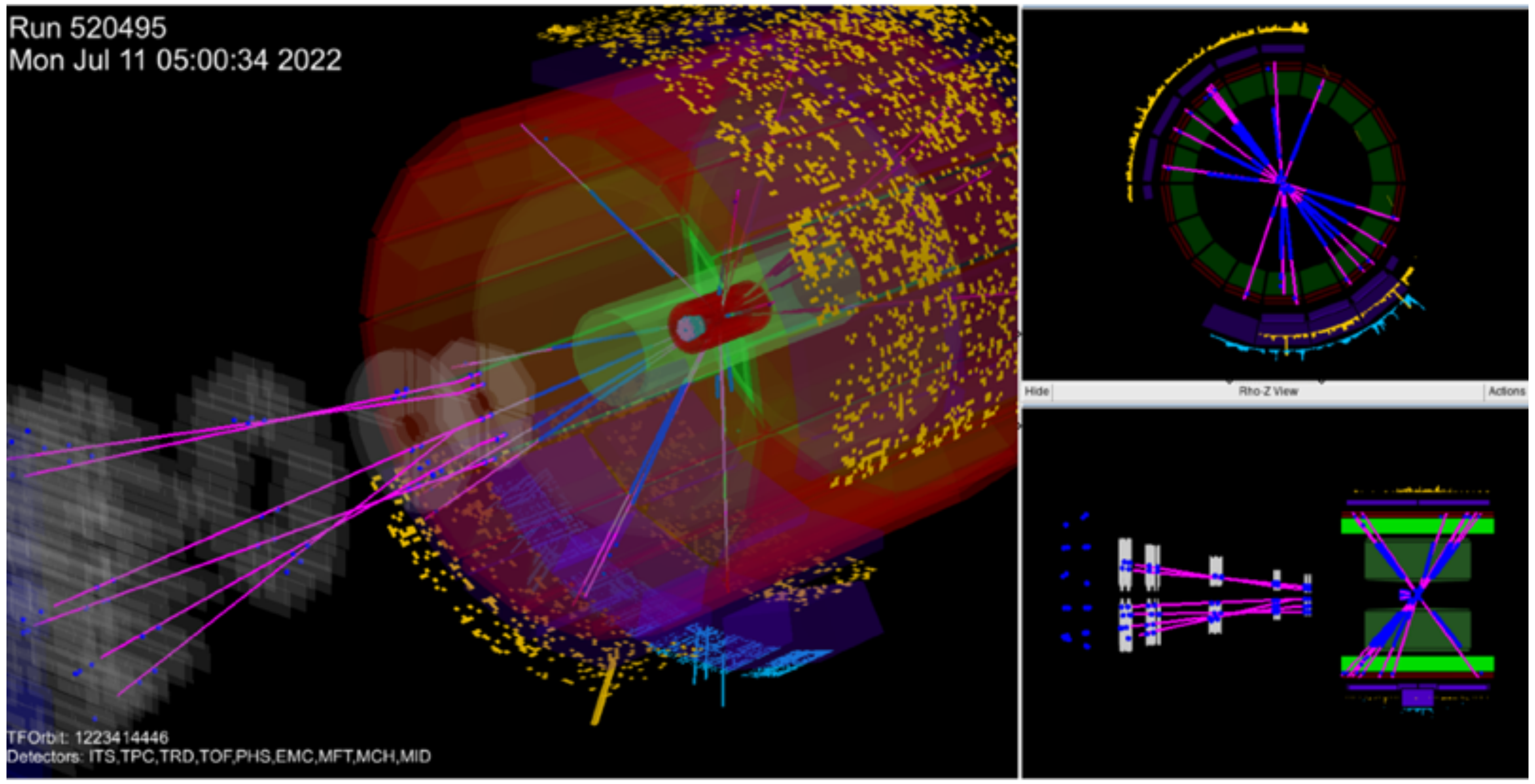
ATLAS	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades
CMS	CMS	CMS phase I upgrades	CMS phase II upgrades
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

intermediate upgrade

major upgrade

ALICE 2 - Upgrades for Run 3



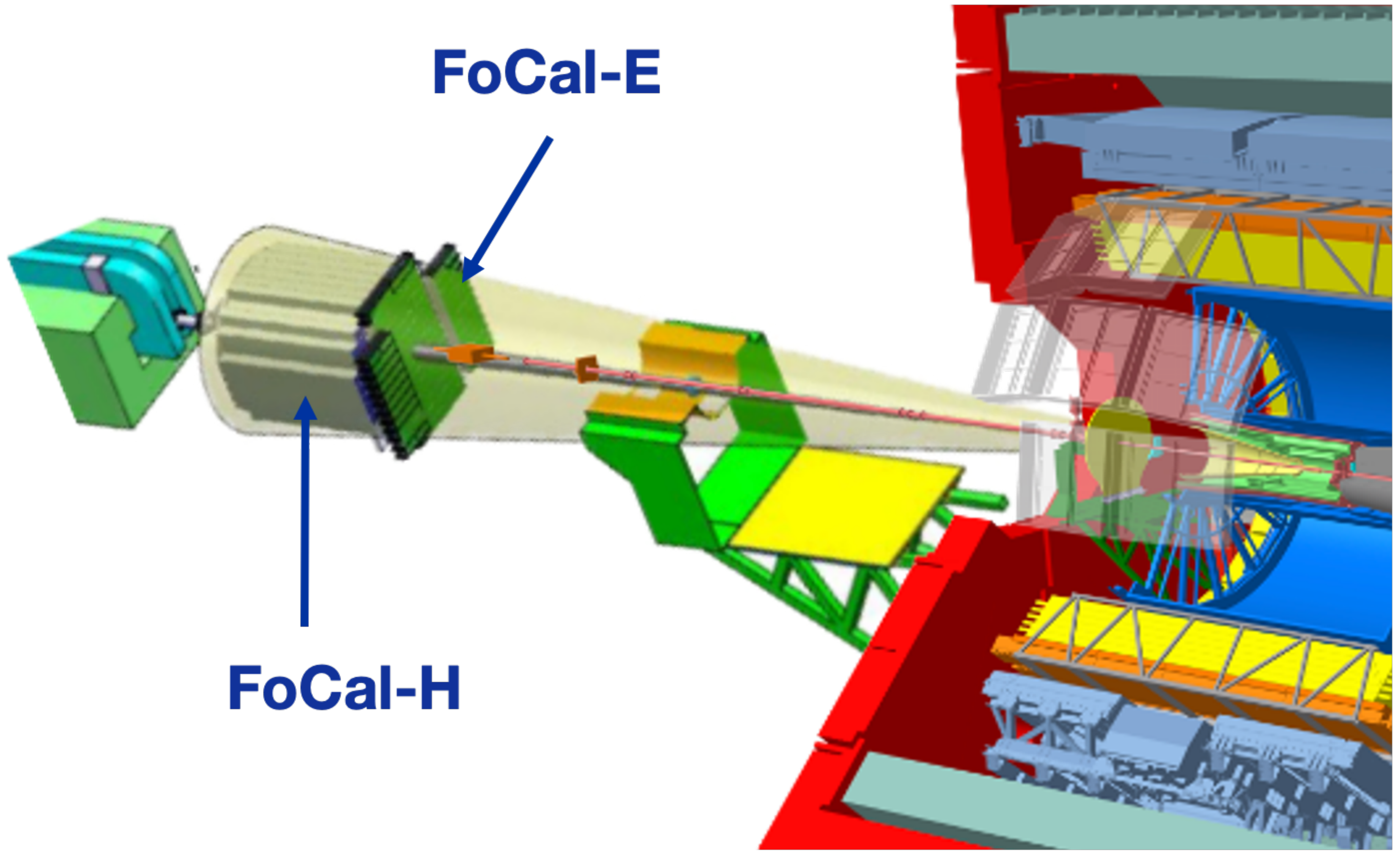


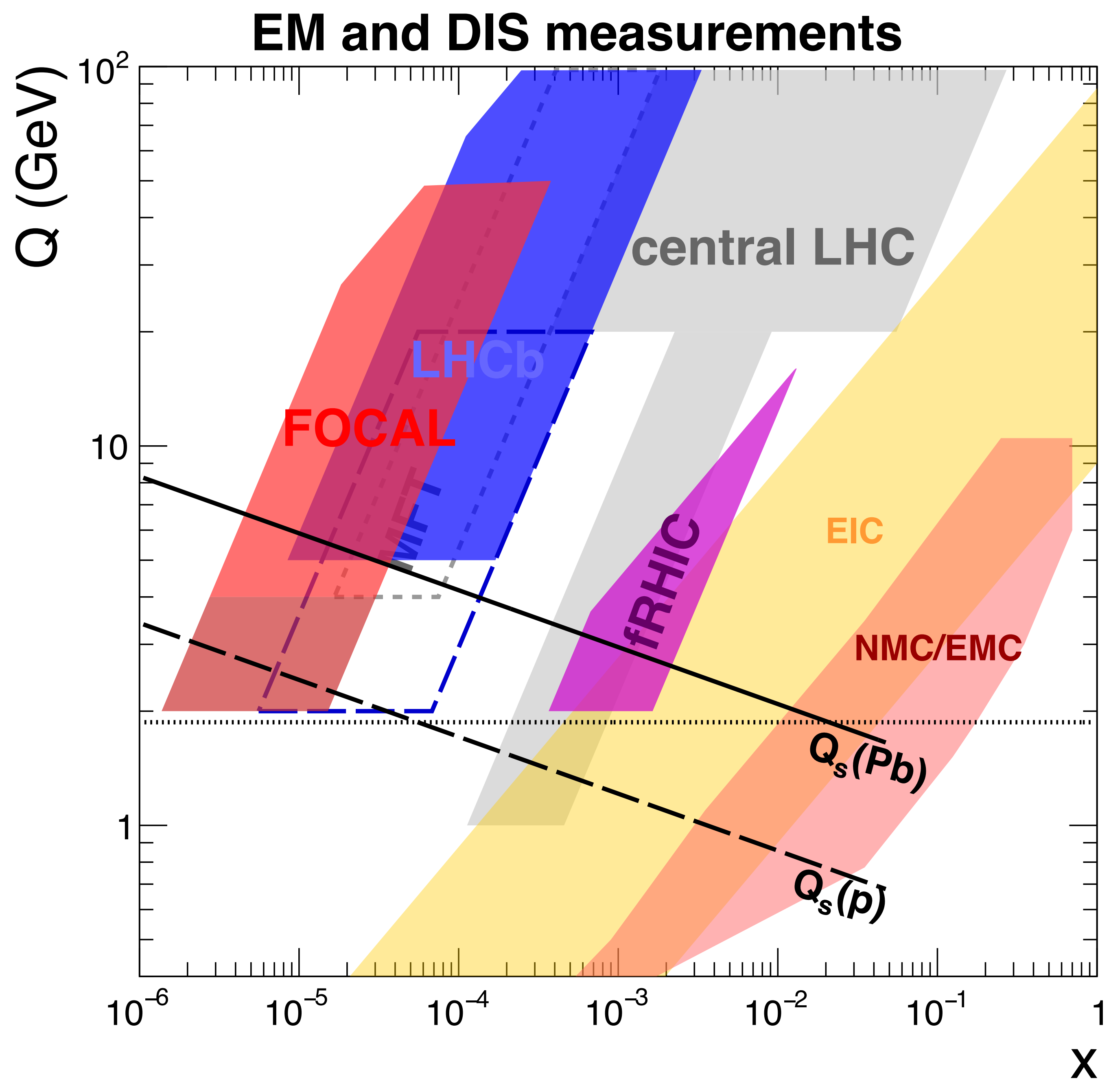
- New Gem based **TPC detector** for continuous readout
  - ✓ Two orders of magnitude increase in collected Pb-Pb data (10/nb)
- New **Inner Tracking System (ITS2)**
  - ✓ Factor 3 improvements in pointing resolution

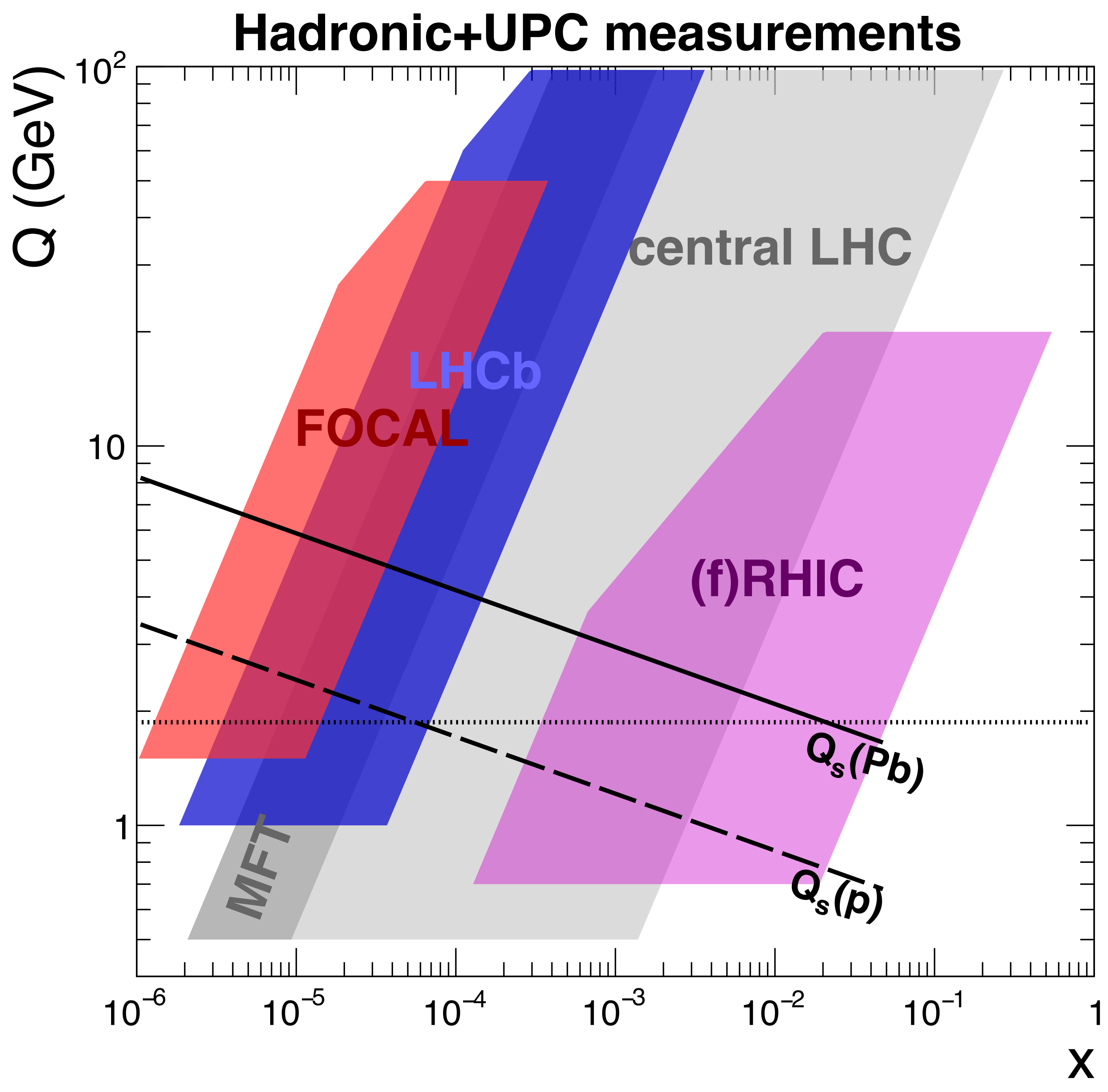
US ALICE BTU project

- **Muon Forward Tracker** at $-3.6 < \eta < -2.5$ and **overhaul in online systems/processing**

ALICE 2.1 - Upgrades for Run 4







Focal Calorimeter (FoCal)

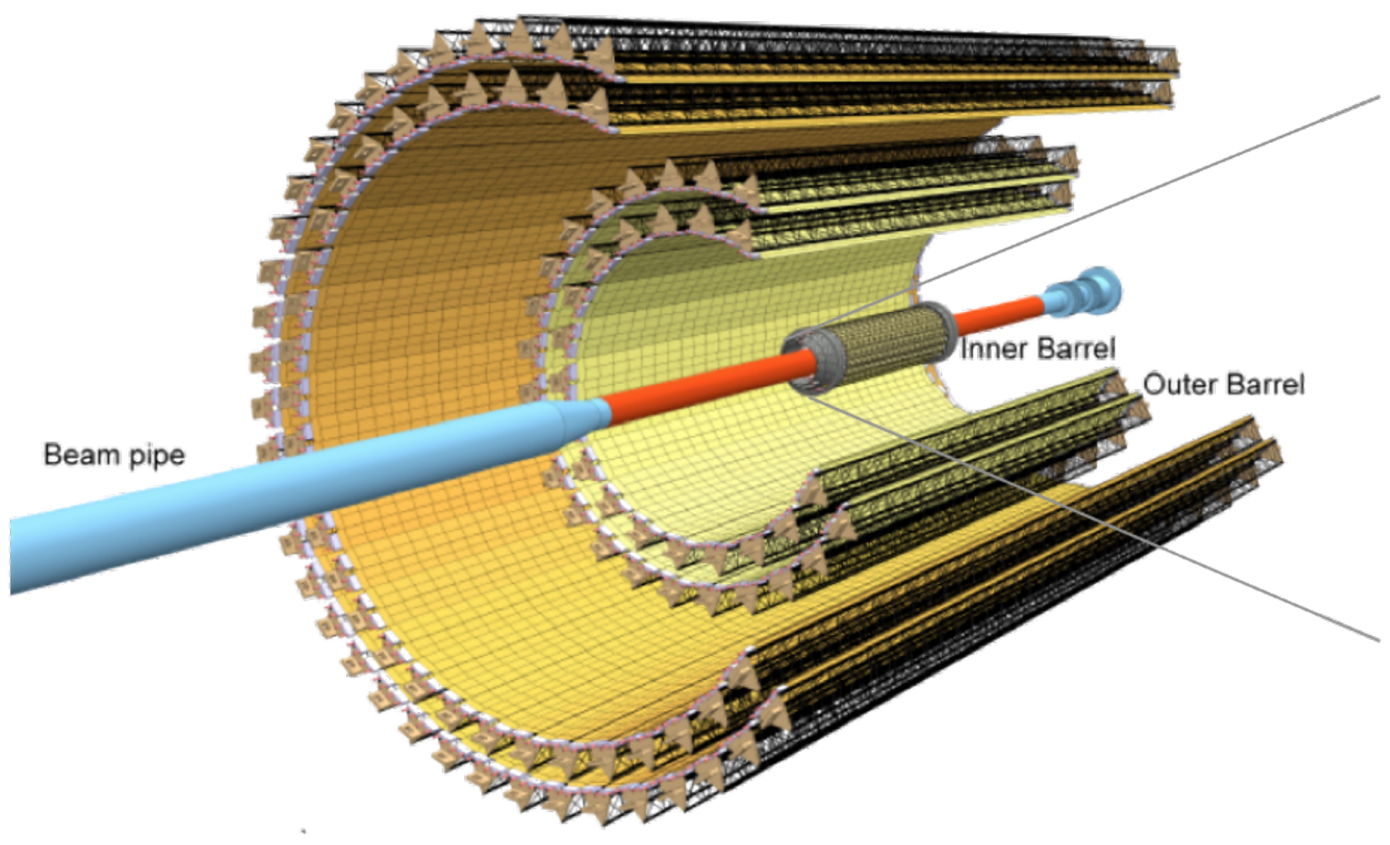
- ✓ Electromagnetic and hadronic calorimeters covering $3.4 < \eta < 5.8$
- ✓ Probes parton densities down to x ~10^{-6}
- ✓ Complementary to EIC and LHCb

US ALICE Focal project

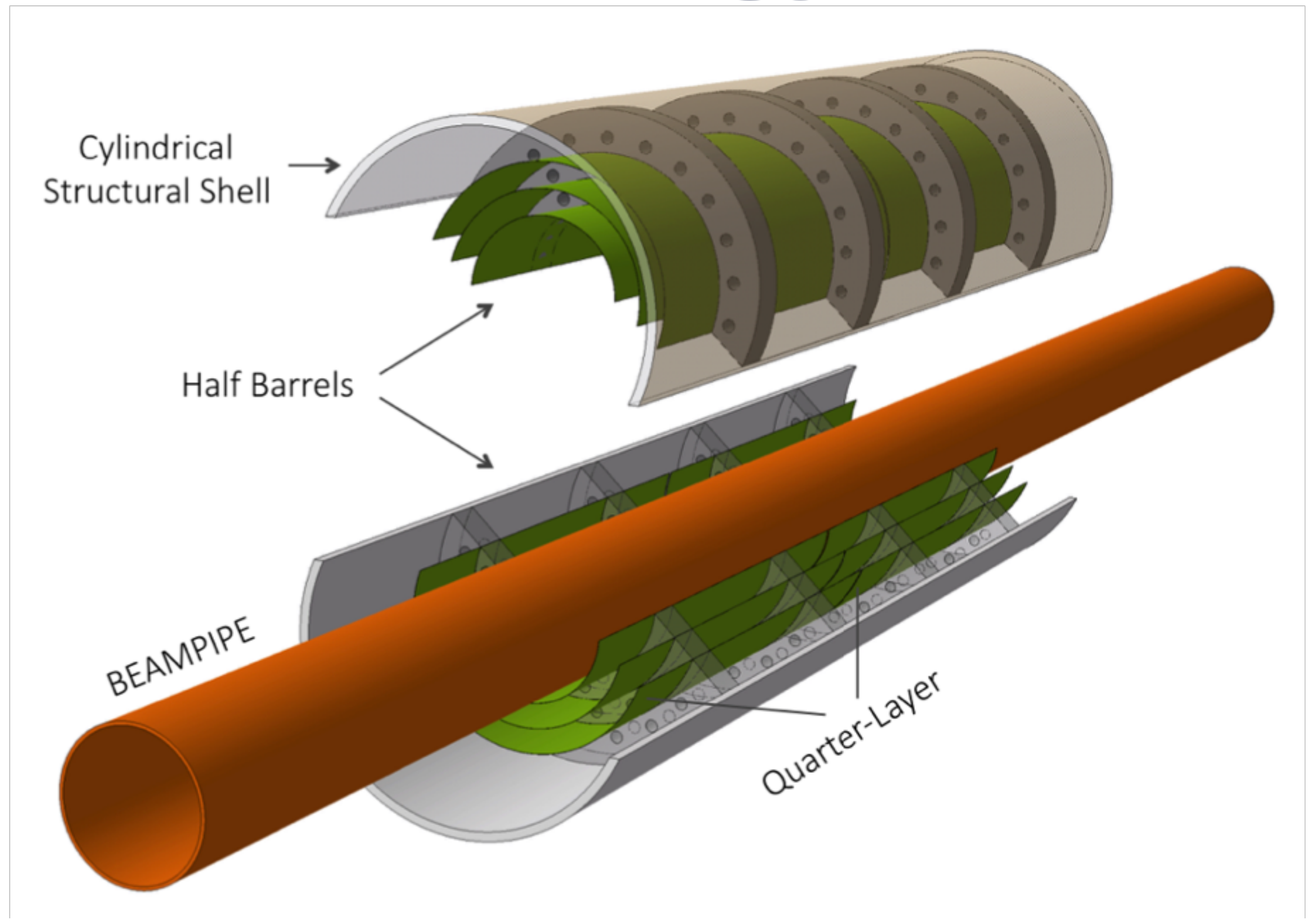
New HCAL prototype

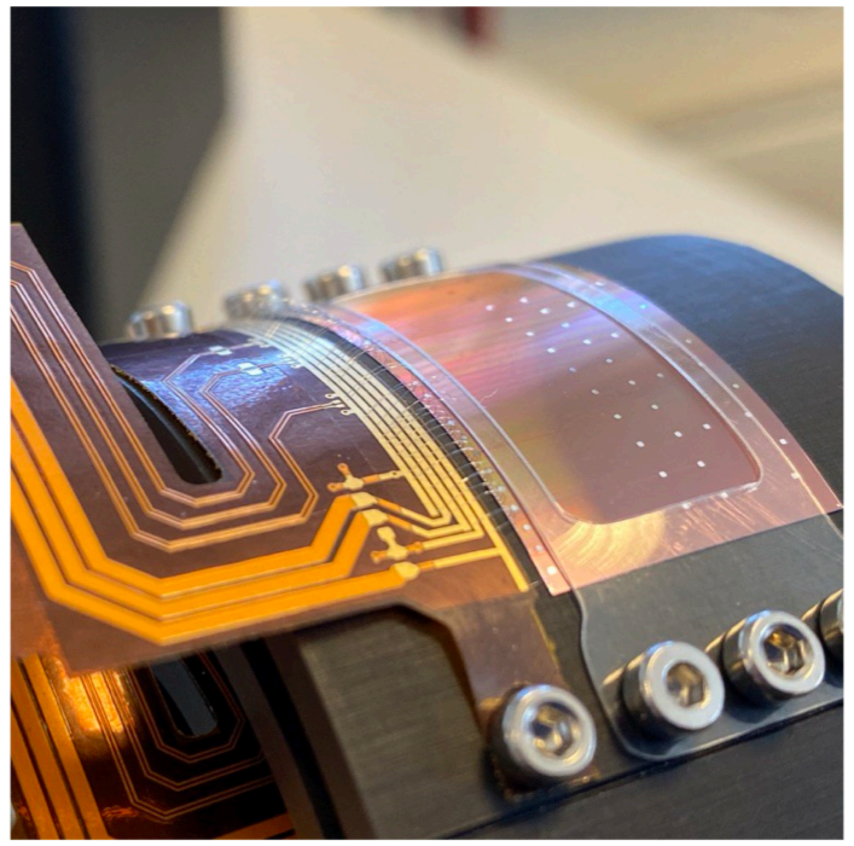
ALICE 2.1 - Upgrades for Run 4

ITS2



ITS3



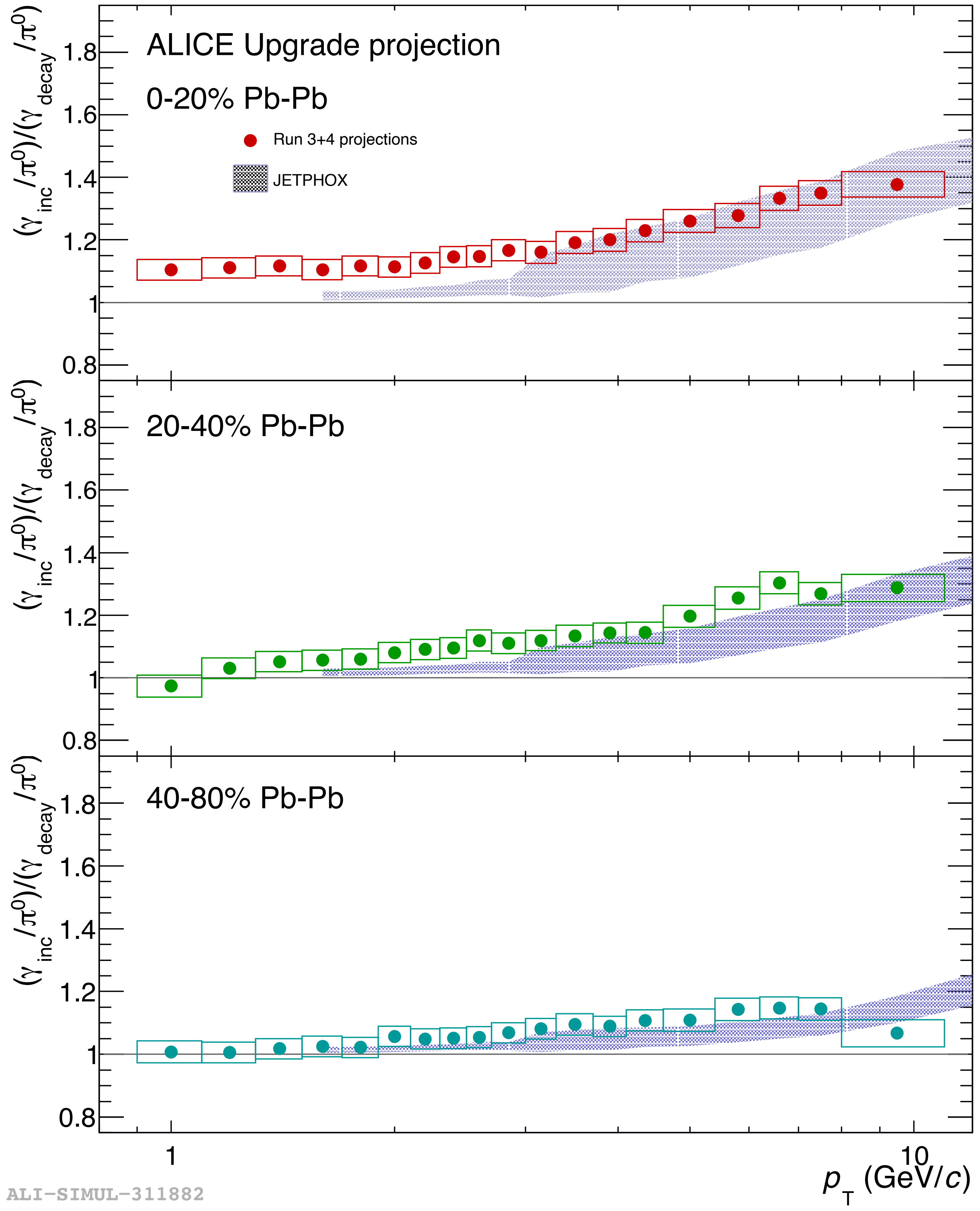


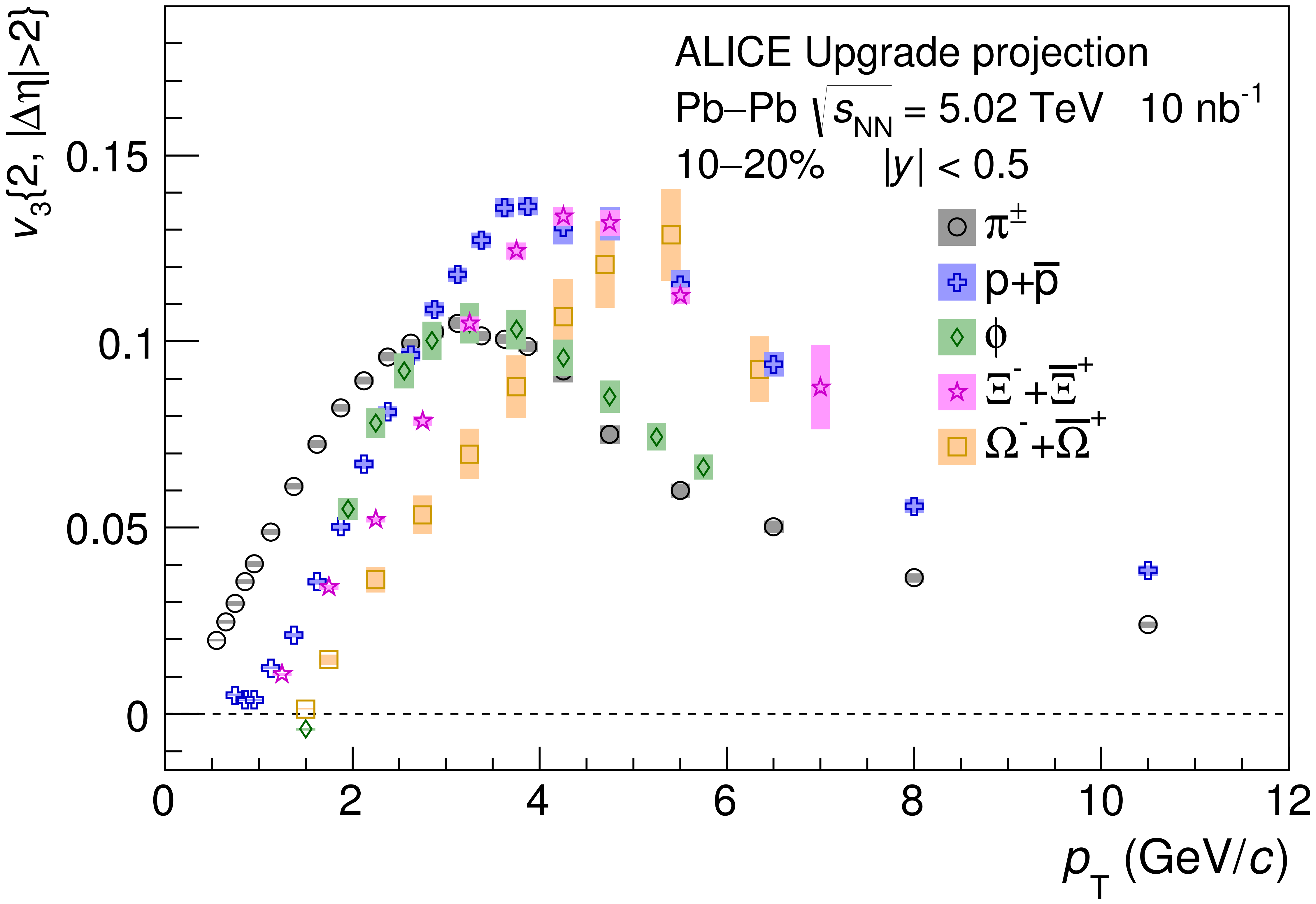
Inner Tracking System (ITS3)

✓Three new inner new layers
✓Further improved (x2) pointing resolution
✓Pioneering wafer thin sensors - 0.03% of radiation length

Synergies with EIC R&D

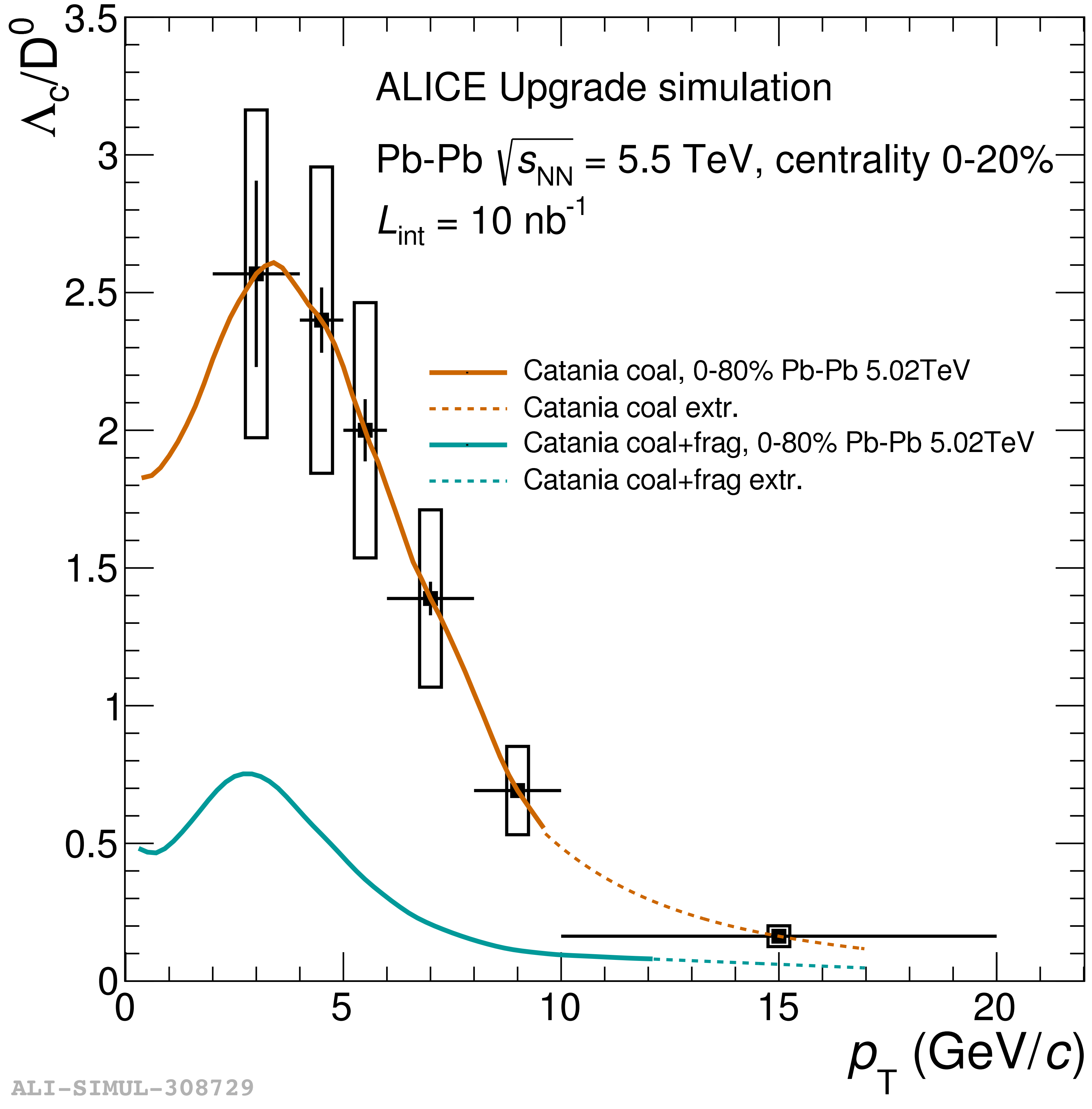
Thermal radiation and flow in Run 3 & 4

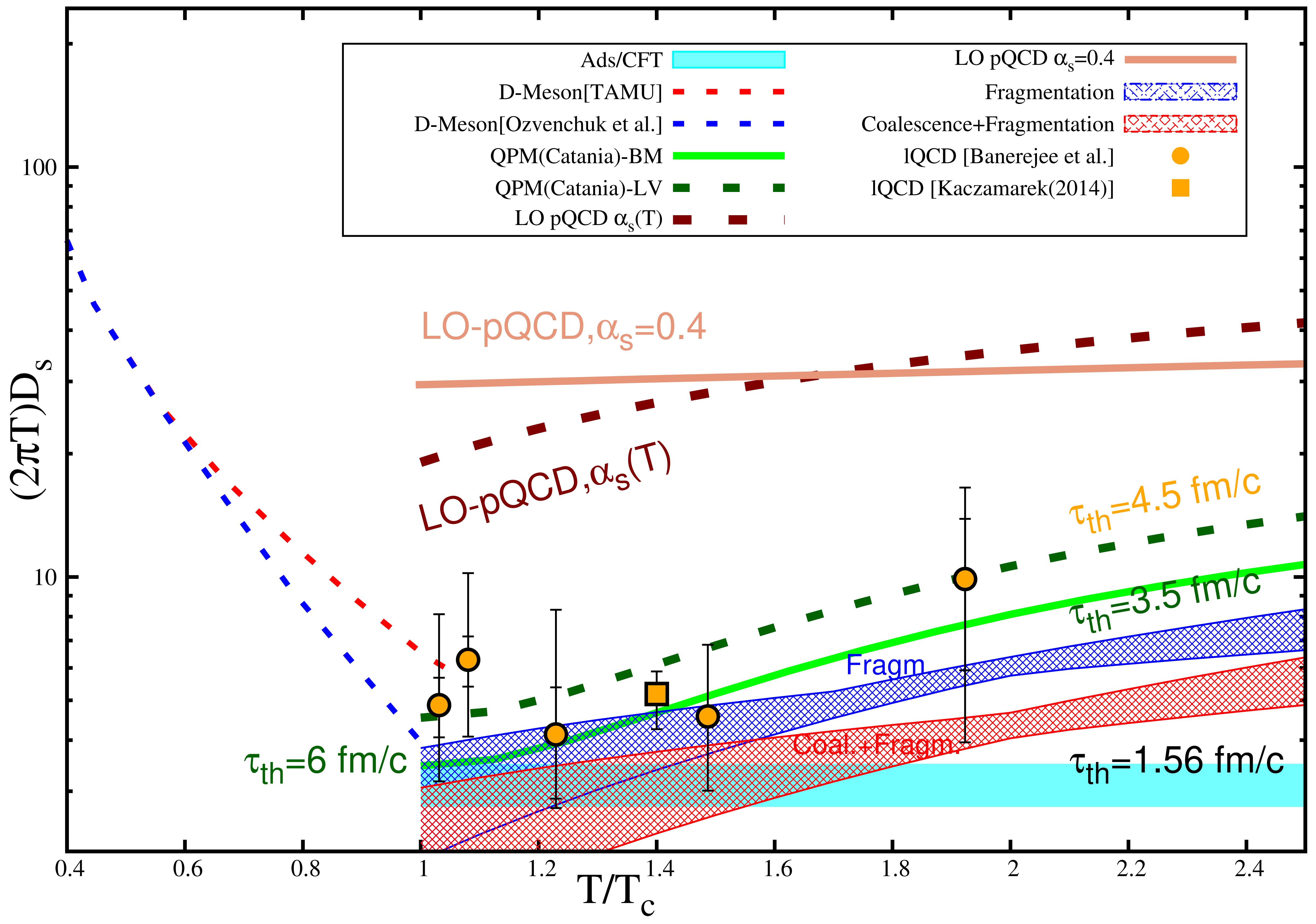




- Inclusive γ and di-electron invariant mass probe **QGP thermal radiation**
- High precision identified particle v_n vs p_T **constrain η/s and ζ/s simultaneously**

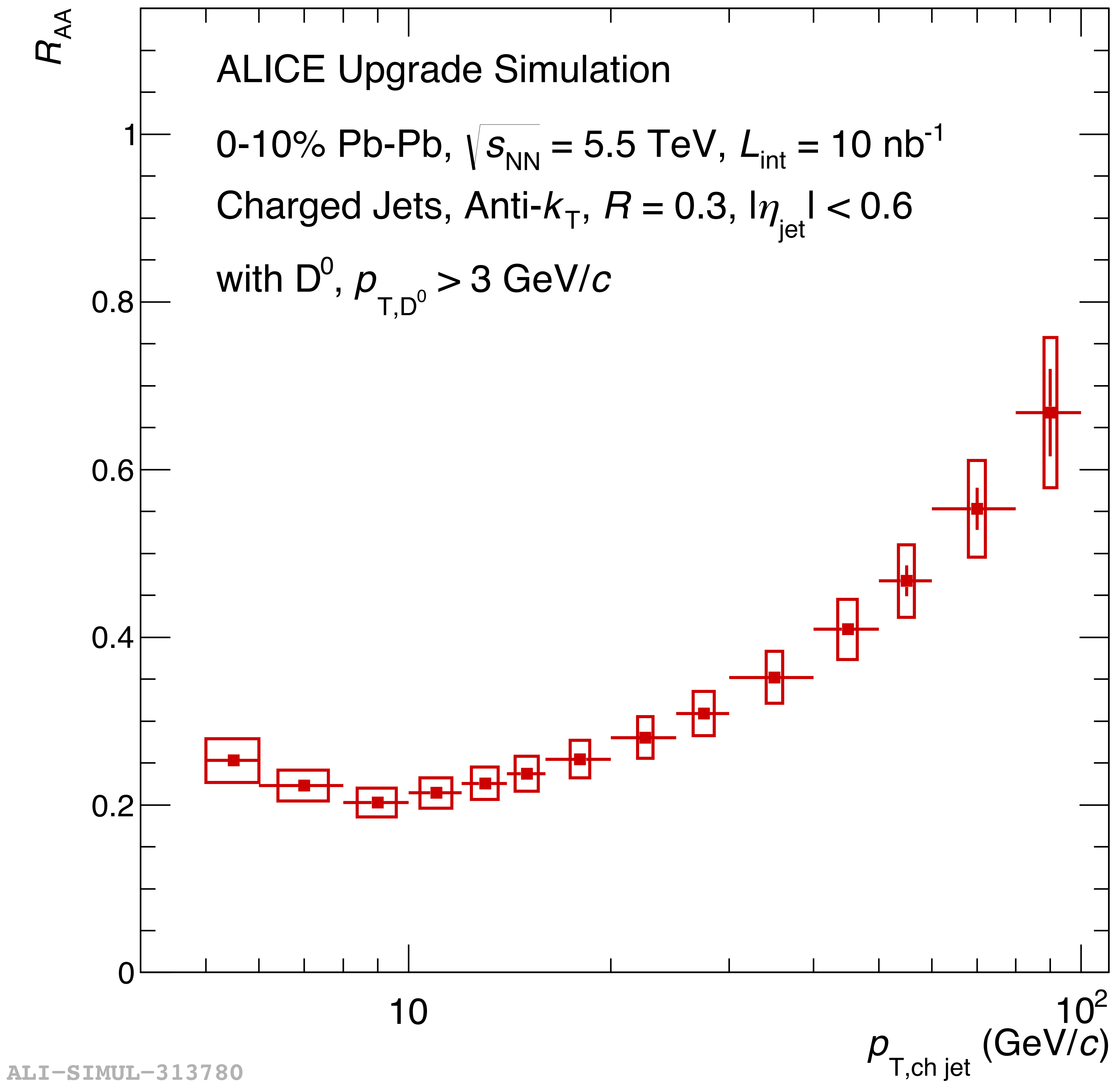
Charm hadronization and QGP transport in Run 3 & 4

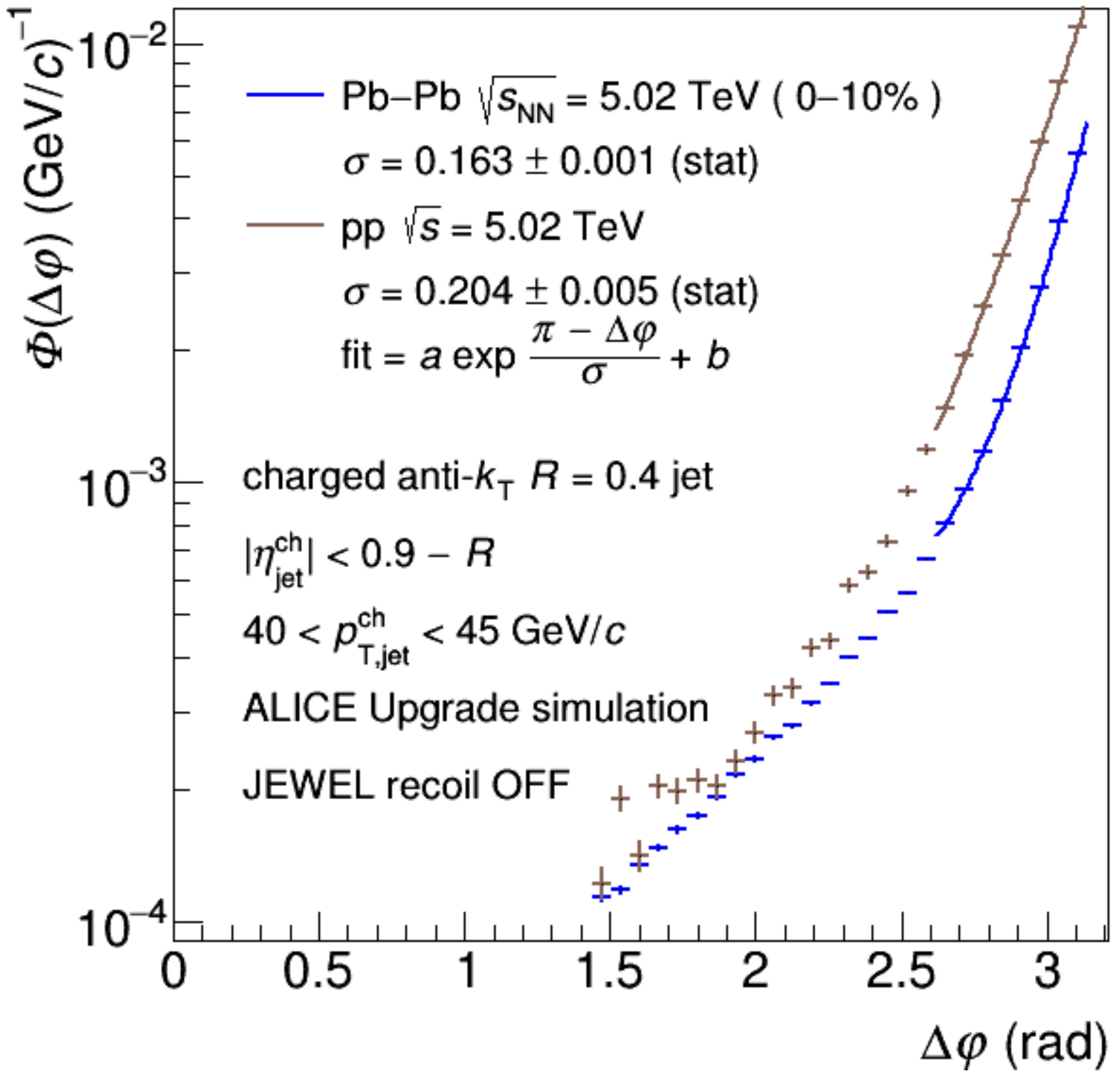




- Charmed baryon/meson ratios probe **collective flow and hadronization mechanisms**
- Pinning down **hadronization important for QGP charm diffusion** D_s constraints

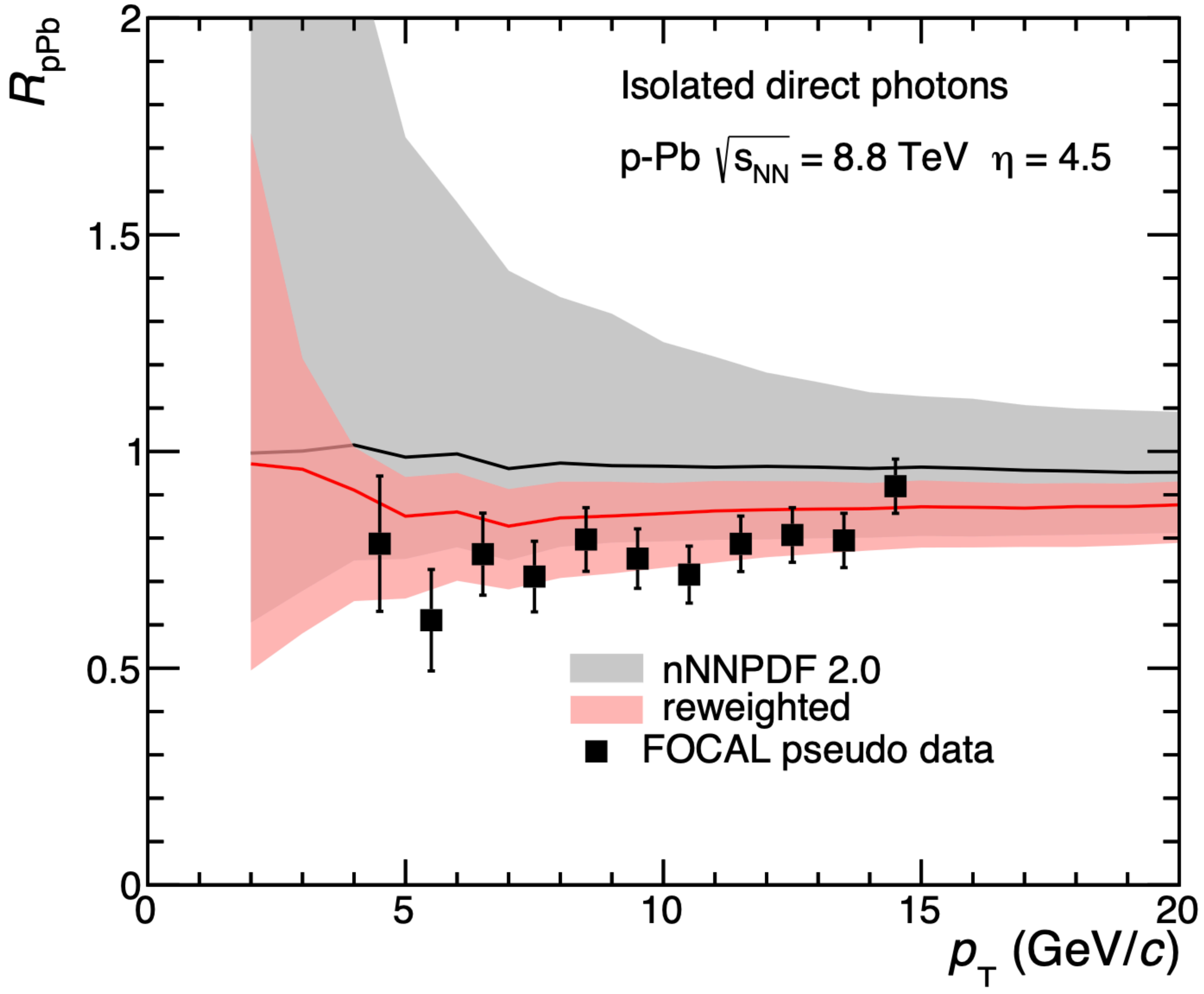
Heavy-flavor jets and di-jets in Run 3 & 4

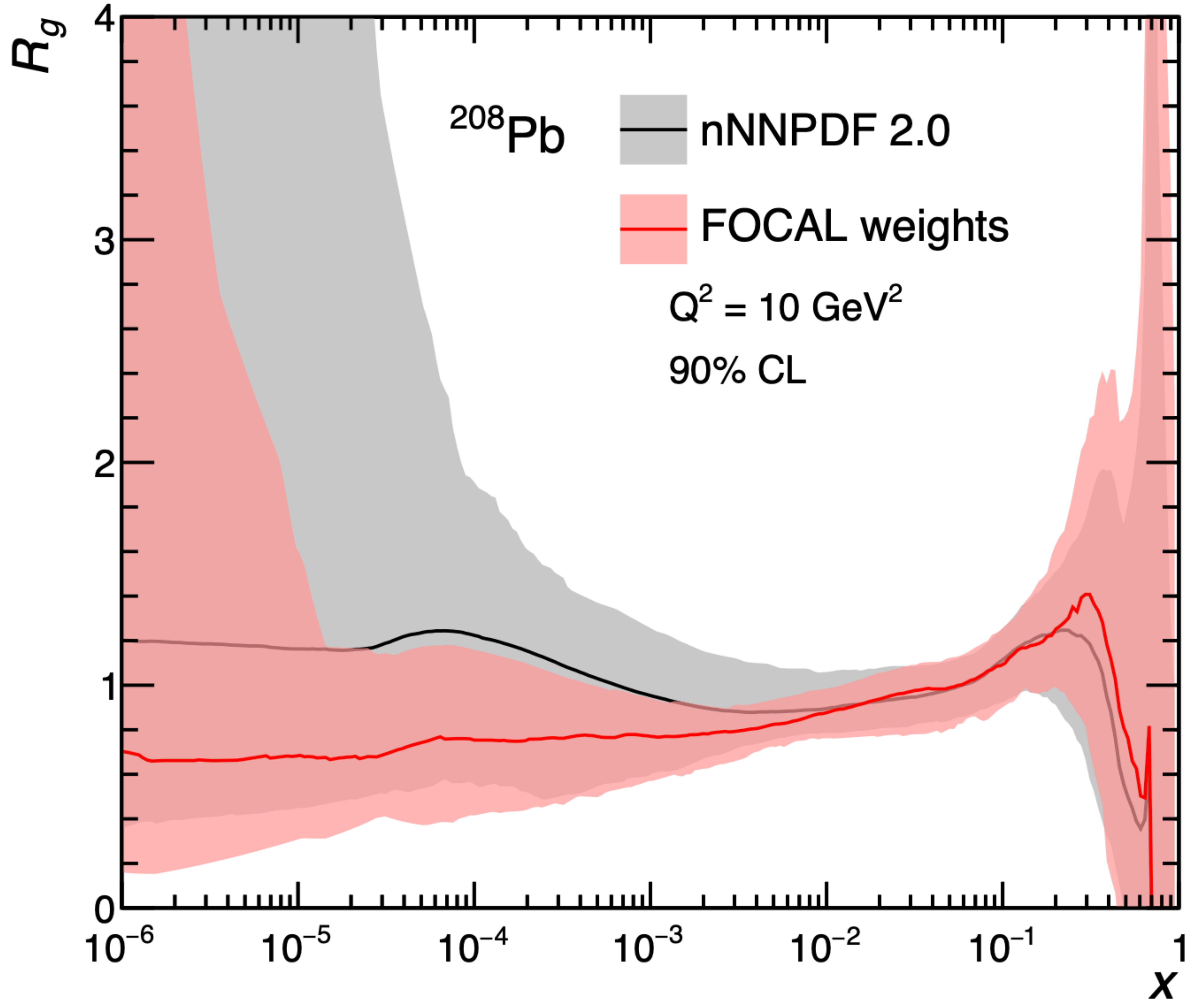




- Heavy-flavor tagged jets probe **QCD dead-cone effect** over large momentum in **QGP**
- Large angle (Moliere) scatterings off **QGP scattering centers explorable**

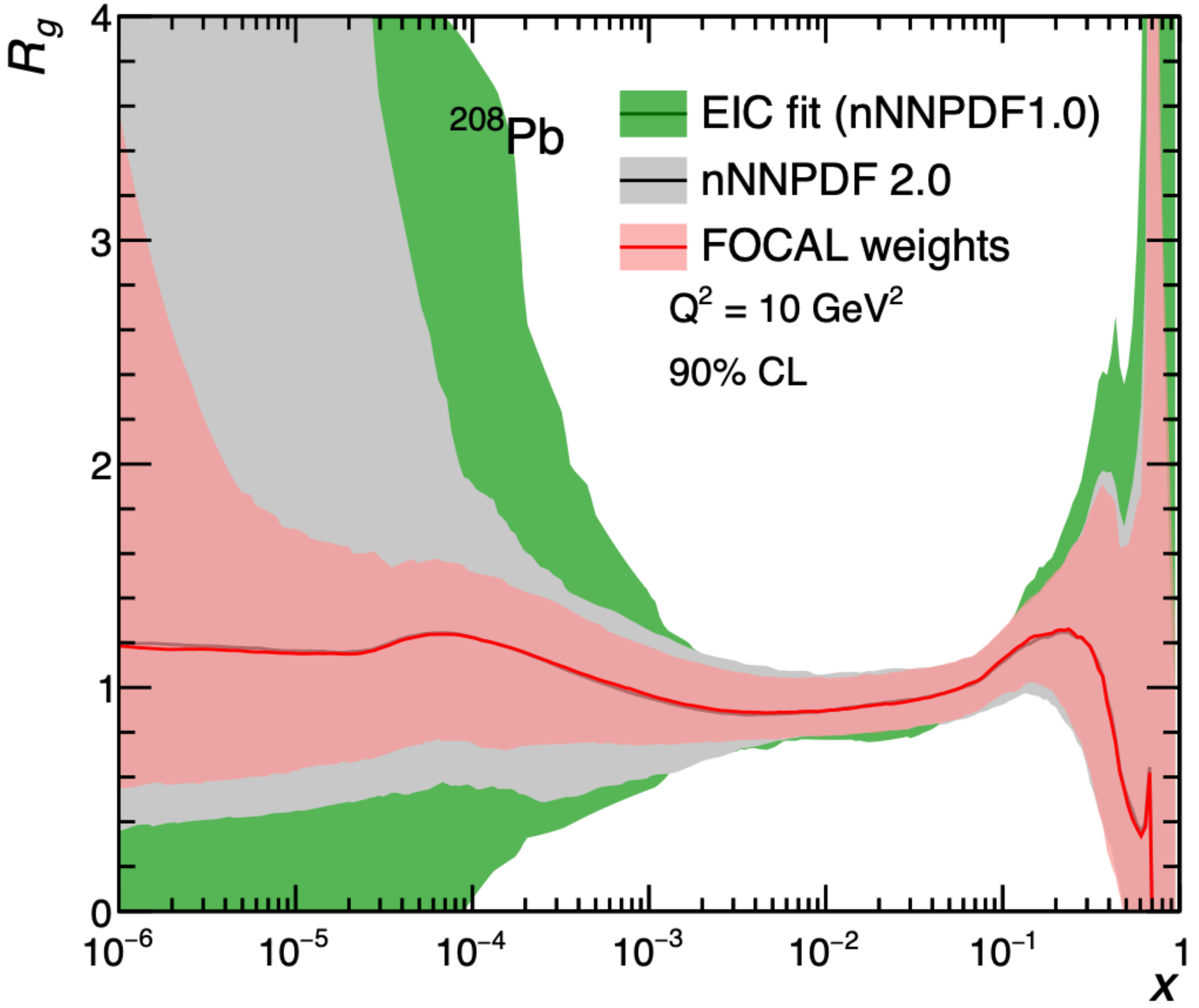
Nuclear parton distribution functions in Run 4

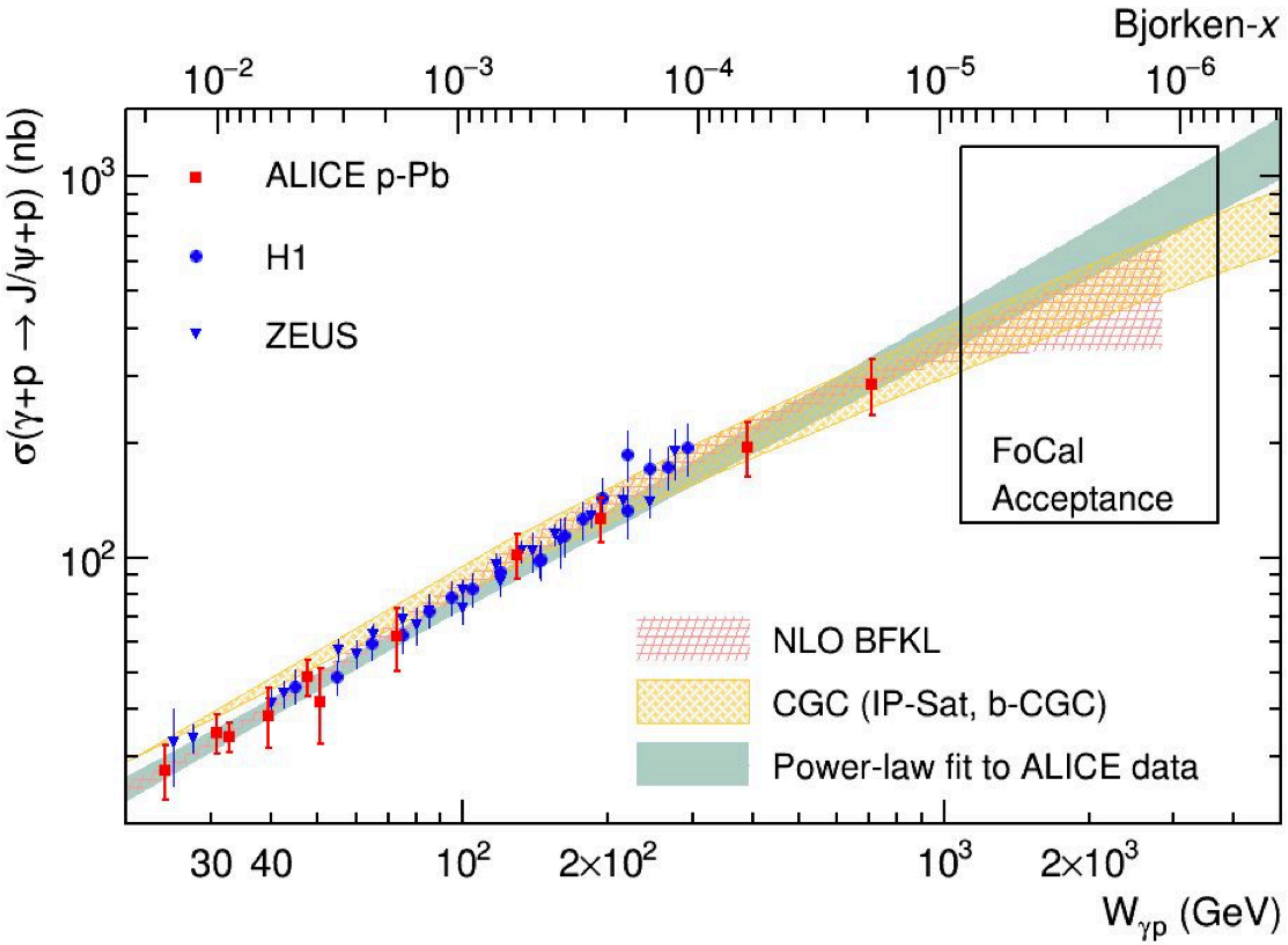




- Isolated γ R_{pPb} performance by FoCal provides **large constraints for gluon nPDFs.**

Nuclear parton distribution functions in Run 4

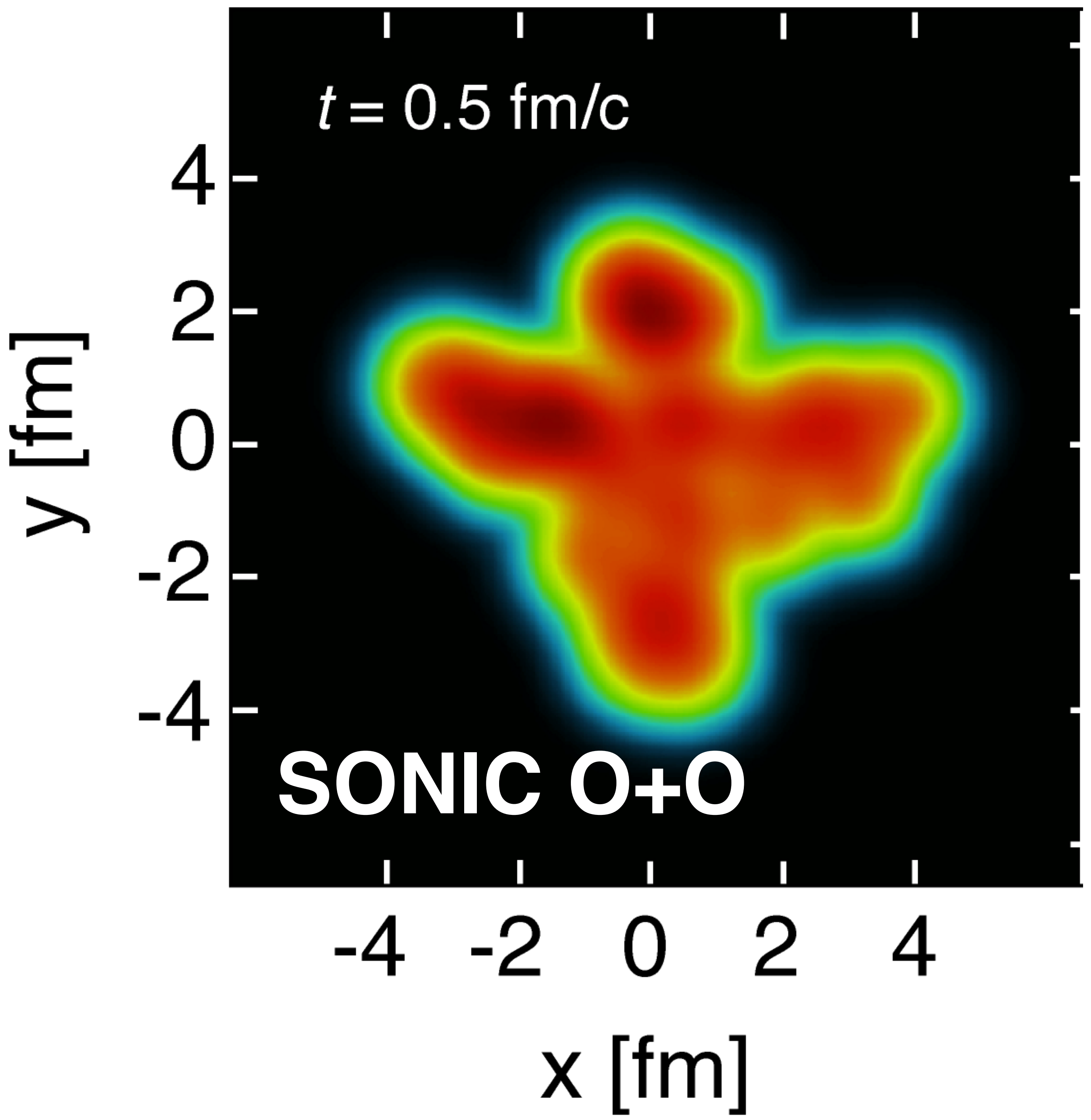




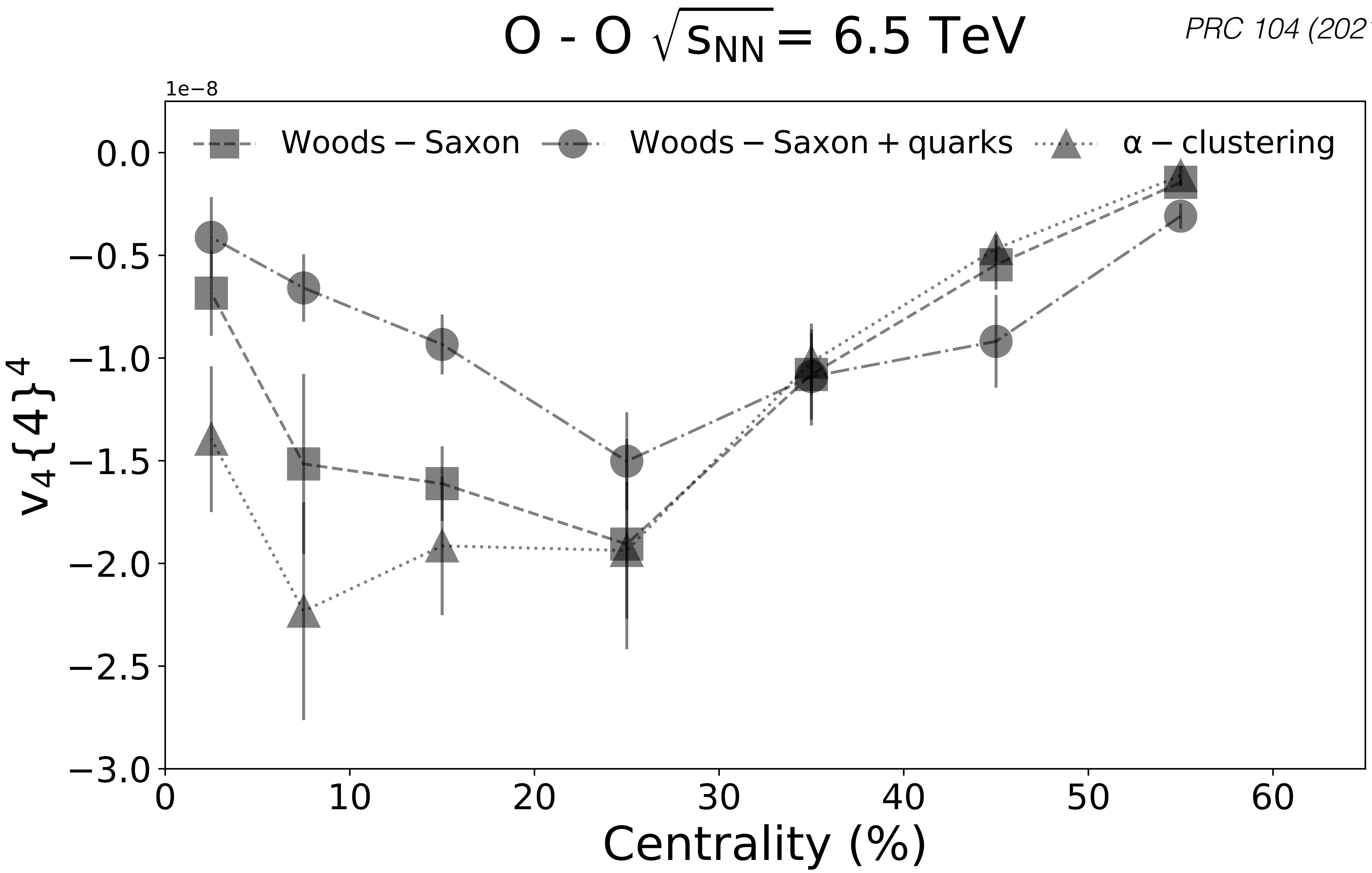
- Isolated γ R_{pPb} performance by FoCal provides **large constraints for gluon nPDFs.**
- Vector meson photo-production from UPC explores **proton saturation to x~10^{-6}**

Small system nuclear properties in Run 3

PRC 99 (2019) 044904

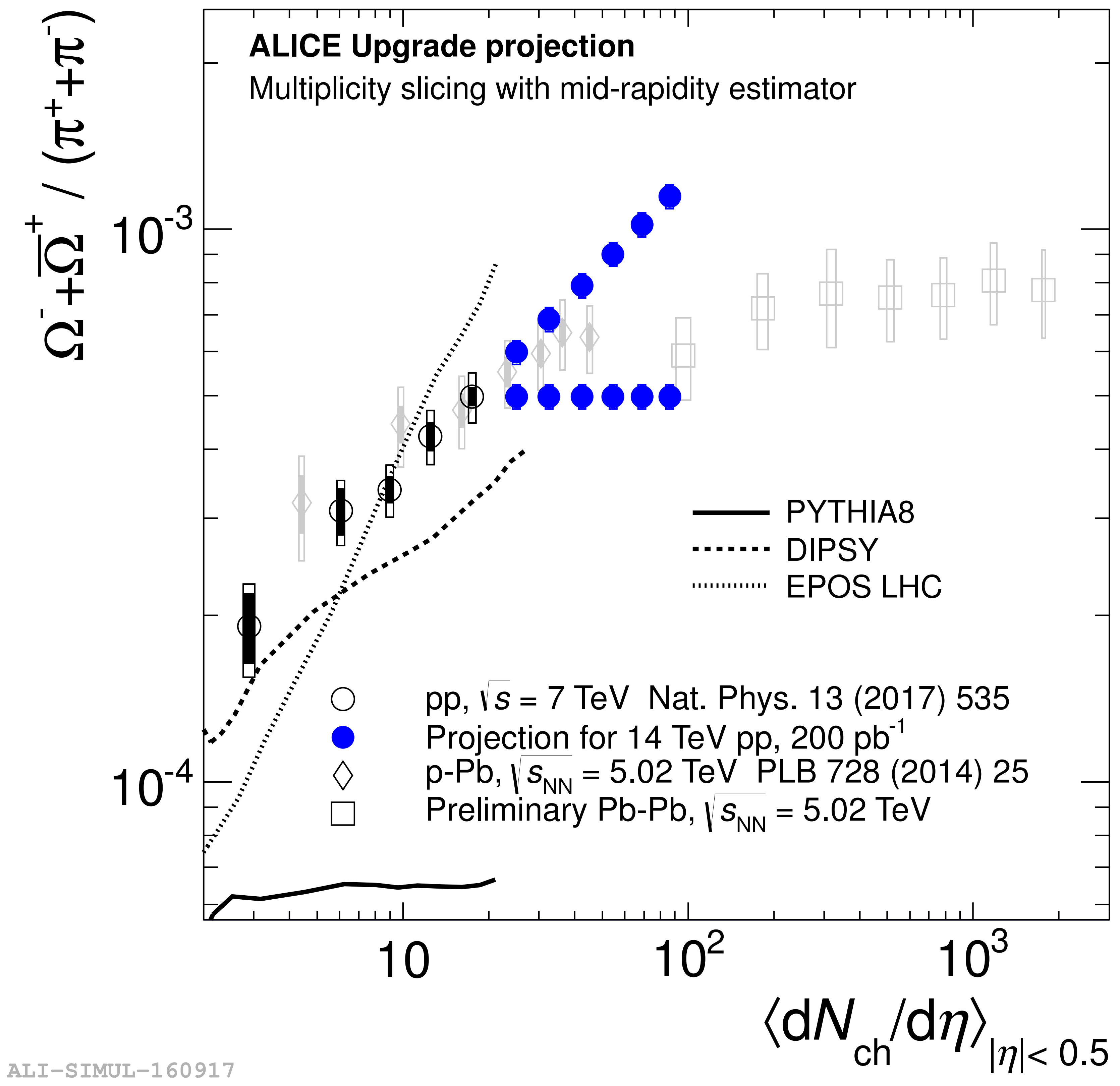


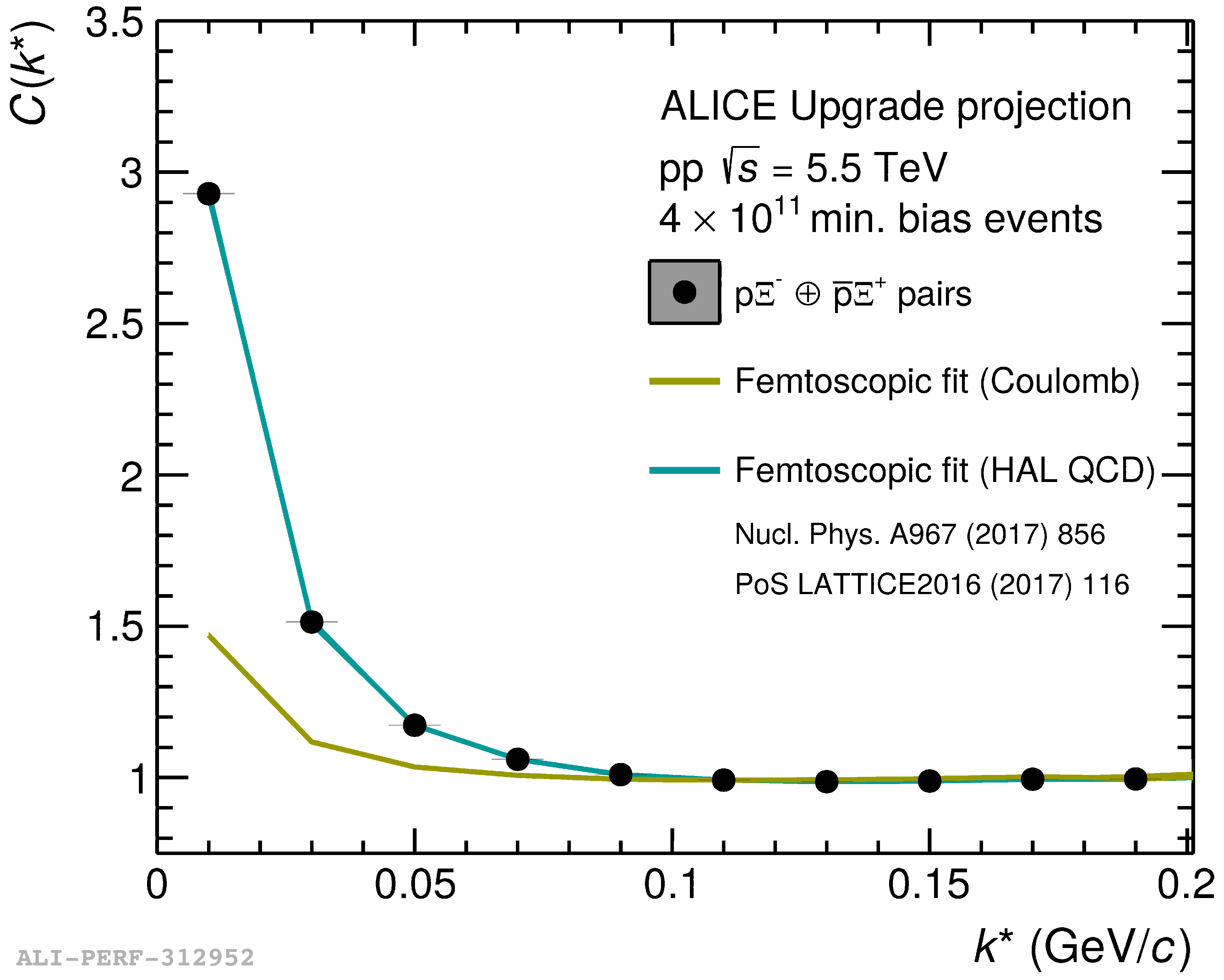
PRC 104 (2021) 041901



- O-O collisions will allow for **searches for α clustering in ^{16}O**
- **Comprehensive tests of hydro in p-O and O-O** possible with suite of low p_T ALICE measurements

Particle production in small systems in Run 3 & 4



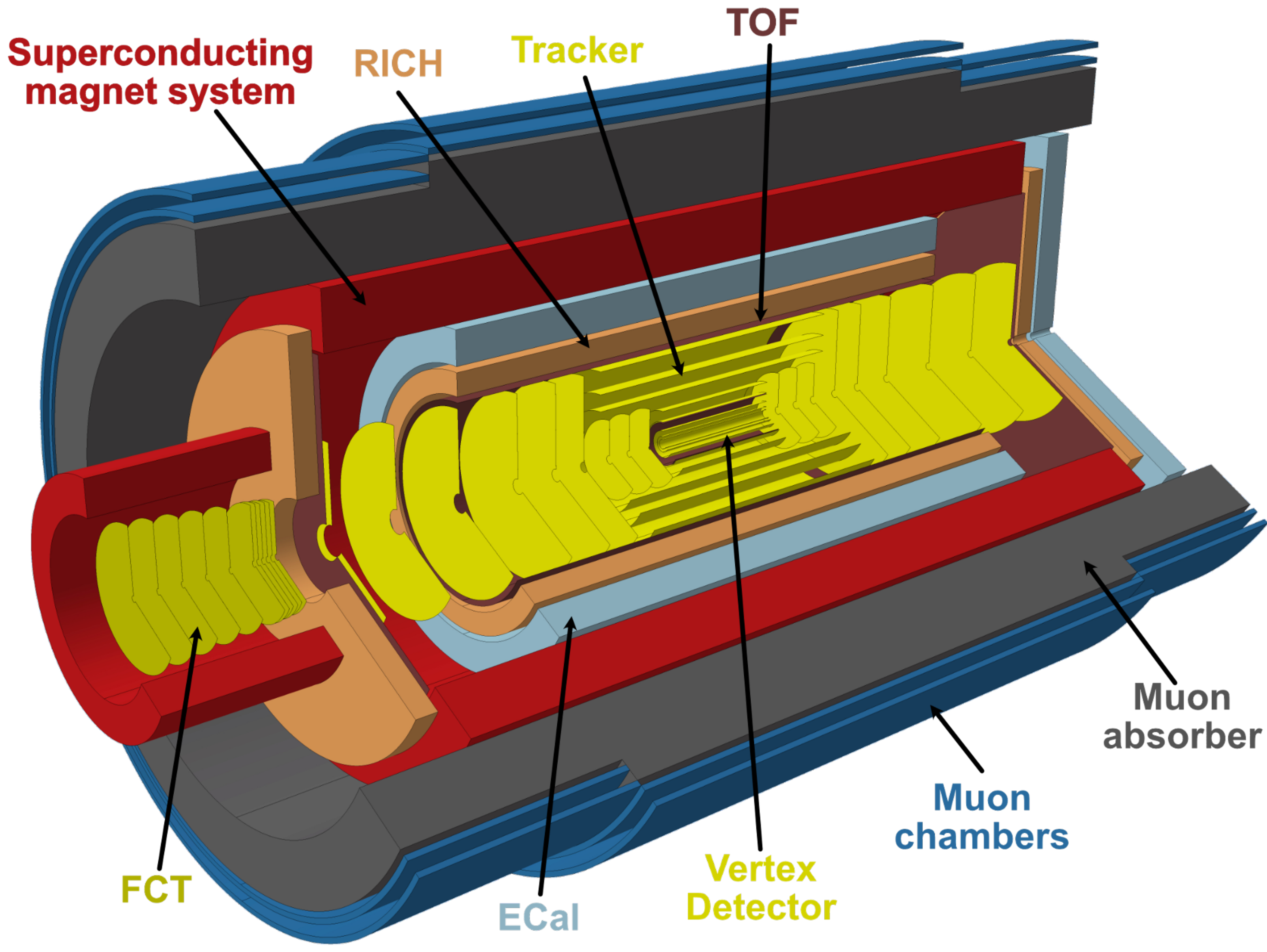


- Enhanced pp statistics enable Ω/π **with x6 larger** $dN_{ch}/d\eta$ than Runs 1 & 2
  - ✓Resembles Pb-Pb in overlap? Increase due to non-QGP effects i.e. color ropes?

- **Precision probes of proton-hyperon interactions** → implications for LQCD, neutron star EOS

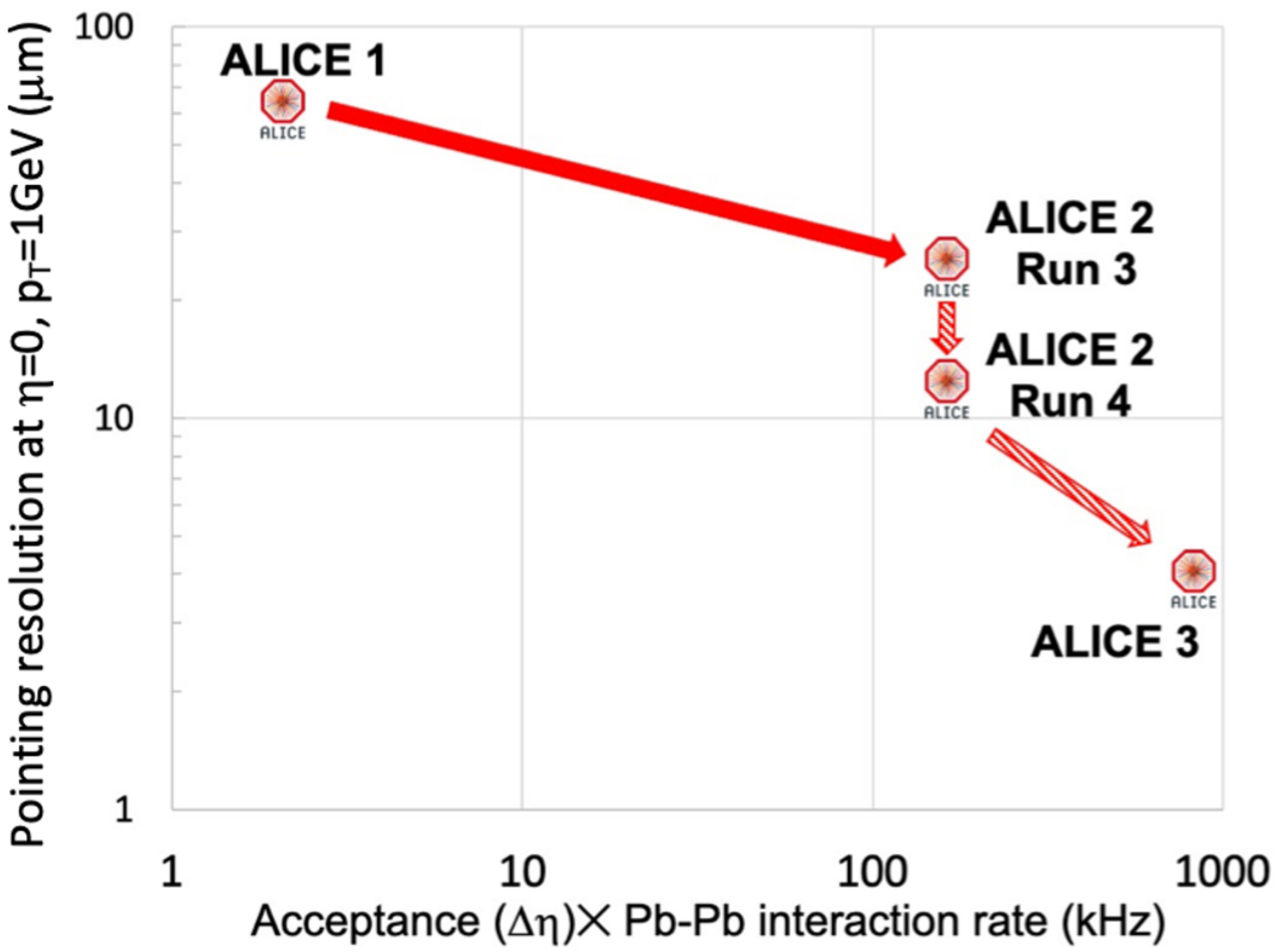
ALICE 3 - next generation heavy-ion detector in Run 5

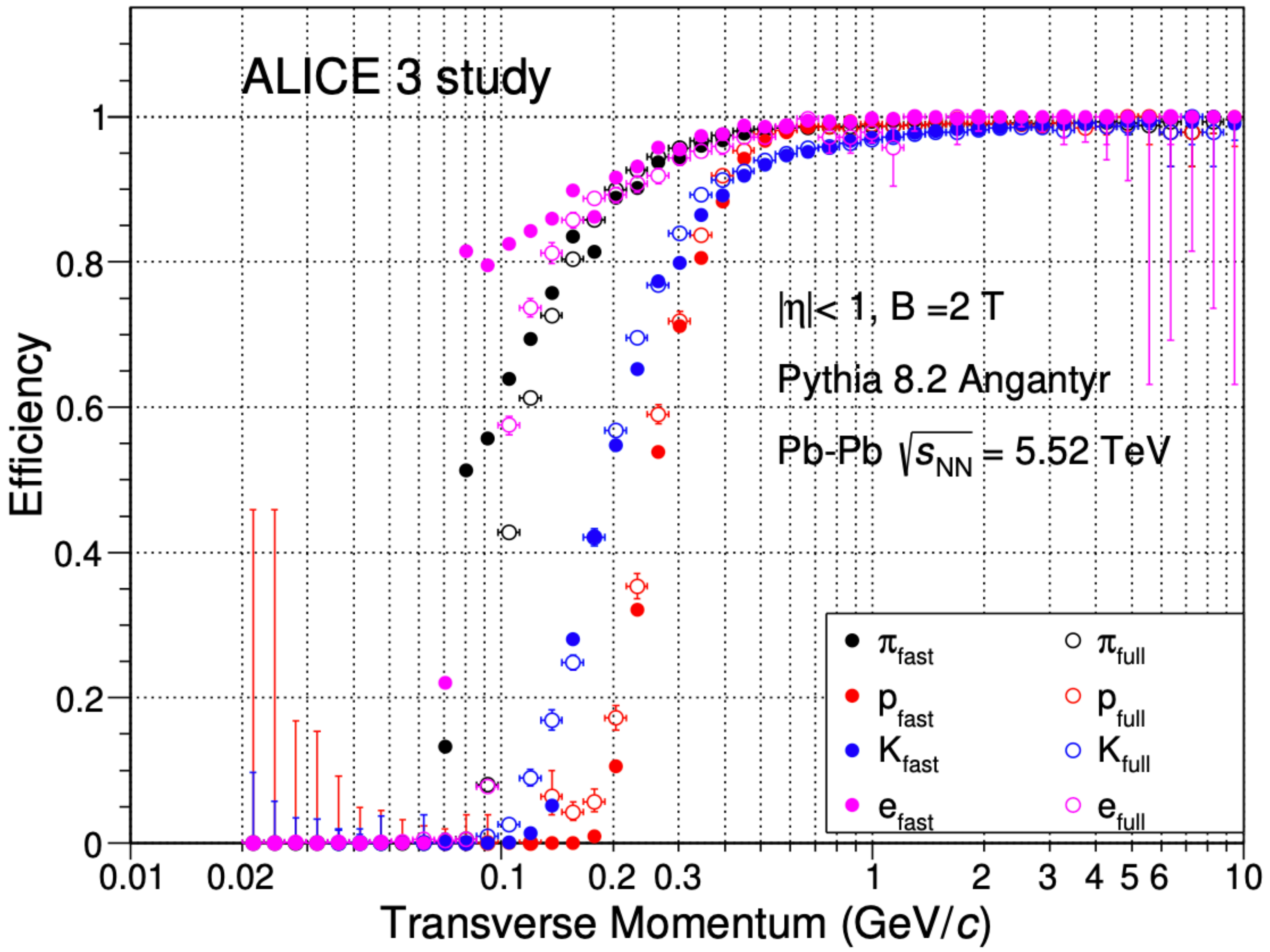
- Compact all-silicon tracker with high-resolution vertex detector and low material budget
- Superconducting magnet system up to B=2T
- Particle Identification over large acceptance: muons, electrons, hadrons, photons
- Fast read-out and online processing



ALICE 3 - expected luminosities and performance

System	$\mathscr{L}^{\text{month}}$	$\mathscr{L}^{\text{Run5+6}}$
pp	$0.5\,\text{fb}^{-1}$	$18\,\text{fb}^{-1}$
pp reference	$100\,\text{pb}^{-1}$	$200\,\text{pb}^{-1}$
A–A		
Xe–Xe	$26\,\text{nb}^{-1}$	$156\,\text{nb}^{-1}$
Pb–Pb	$5.6\,\text{nb}^{-1}$	$33.6\,\text{nb}^{-1}$

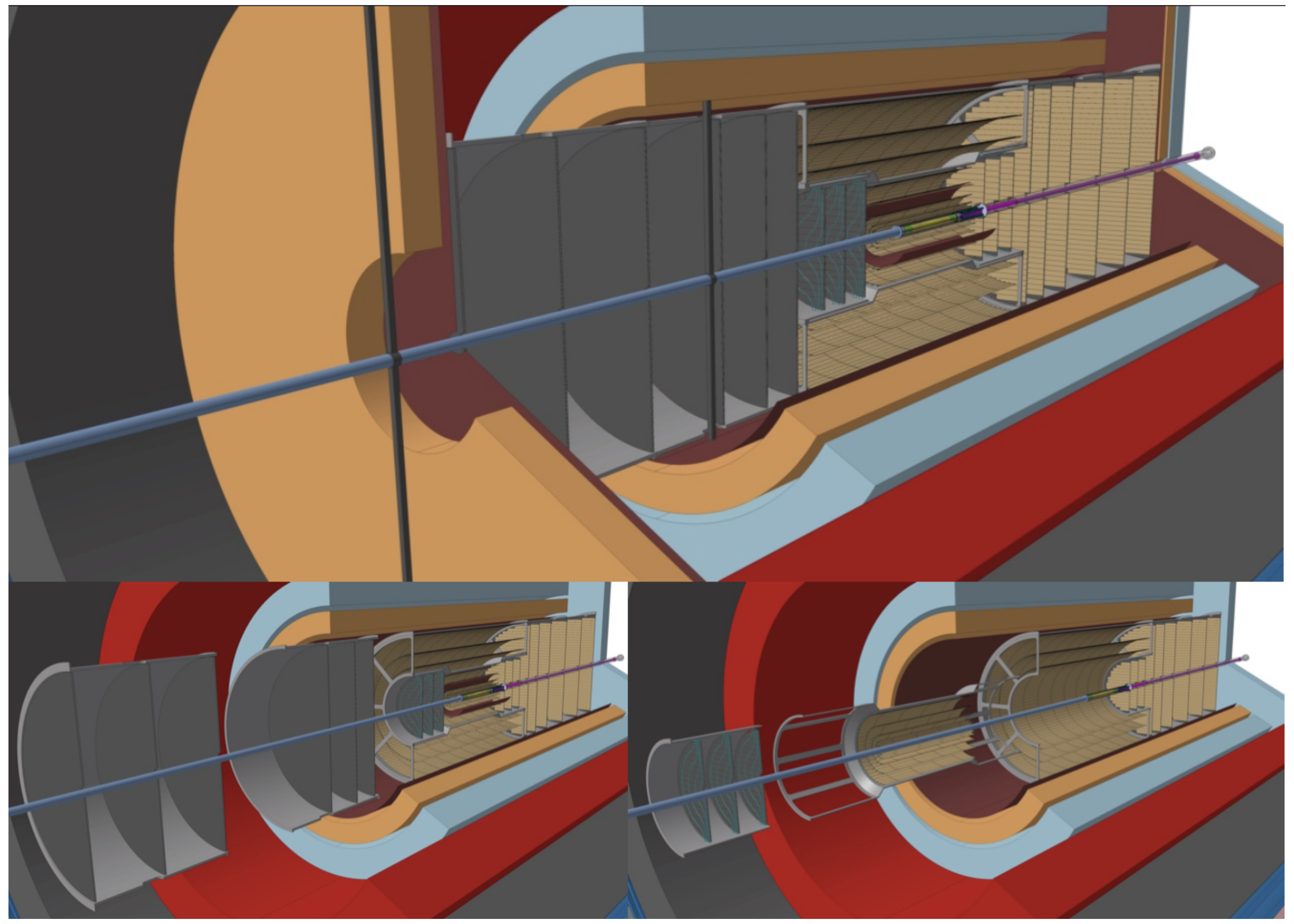




- **Will collect all ion luminosity provided by LHC** →100s billions of Pb-Pb events!
- Factor 3 improvement in pointing resolution compared to ALICE ITS3 in Run 4
- Momentum resolution 1-2% over broad **0.2 < p_T < 100 GeV/c and $-4 < \eta < 4$ range**

ALICE 3 planning

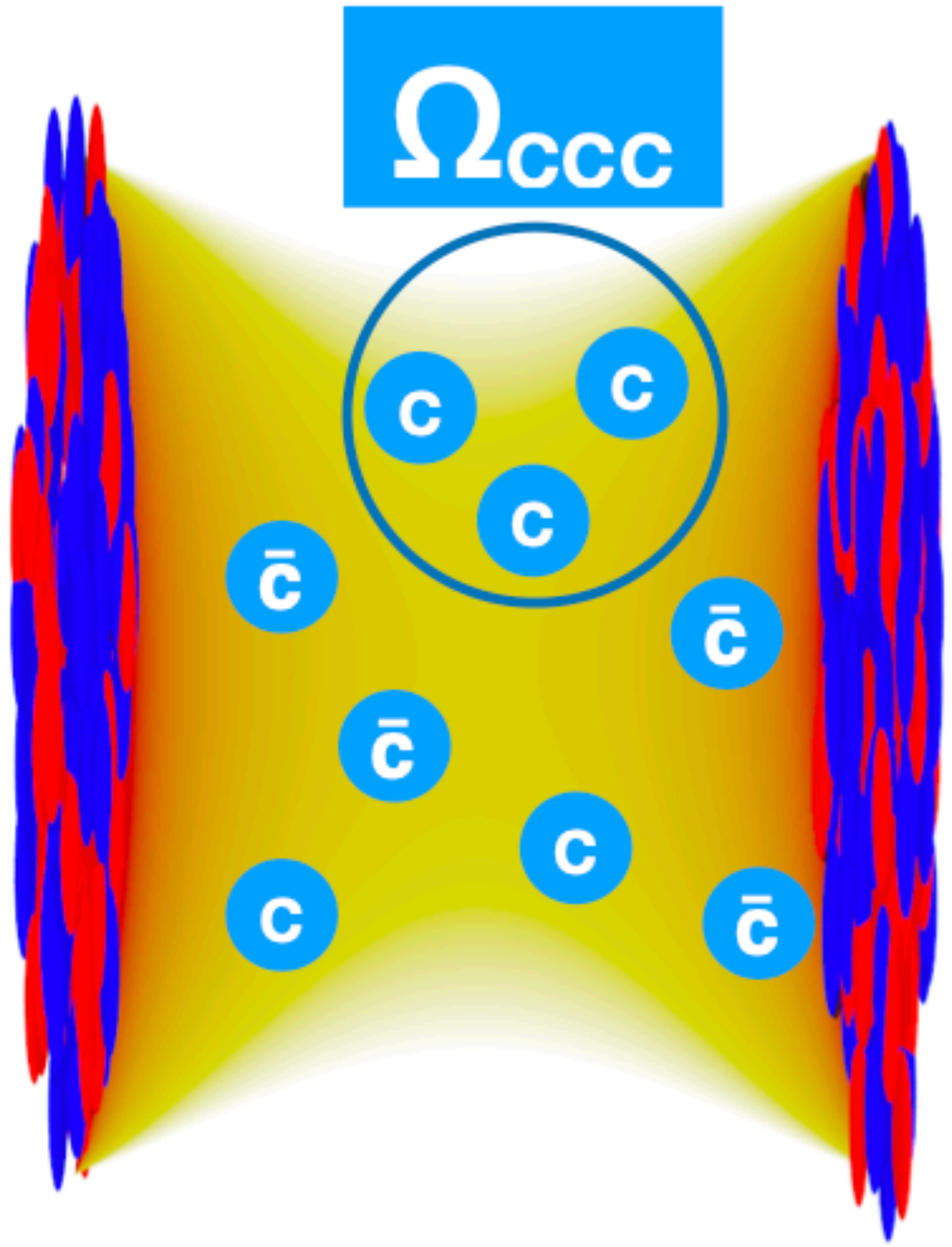
- **2023-25:** Selection of technologies, small-scale proof of concept prototypes
- **2026-27:** Large-scale engineered prototypes
  ✓Technical Design Reports
- **2028-31:** Construction and testing
- **2032:** Contingency
- **2033-34:** Preparation of cavern and installation of ALICE 3



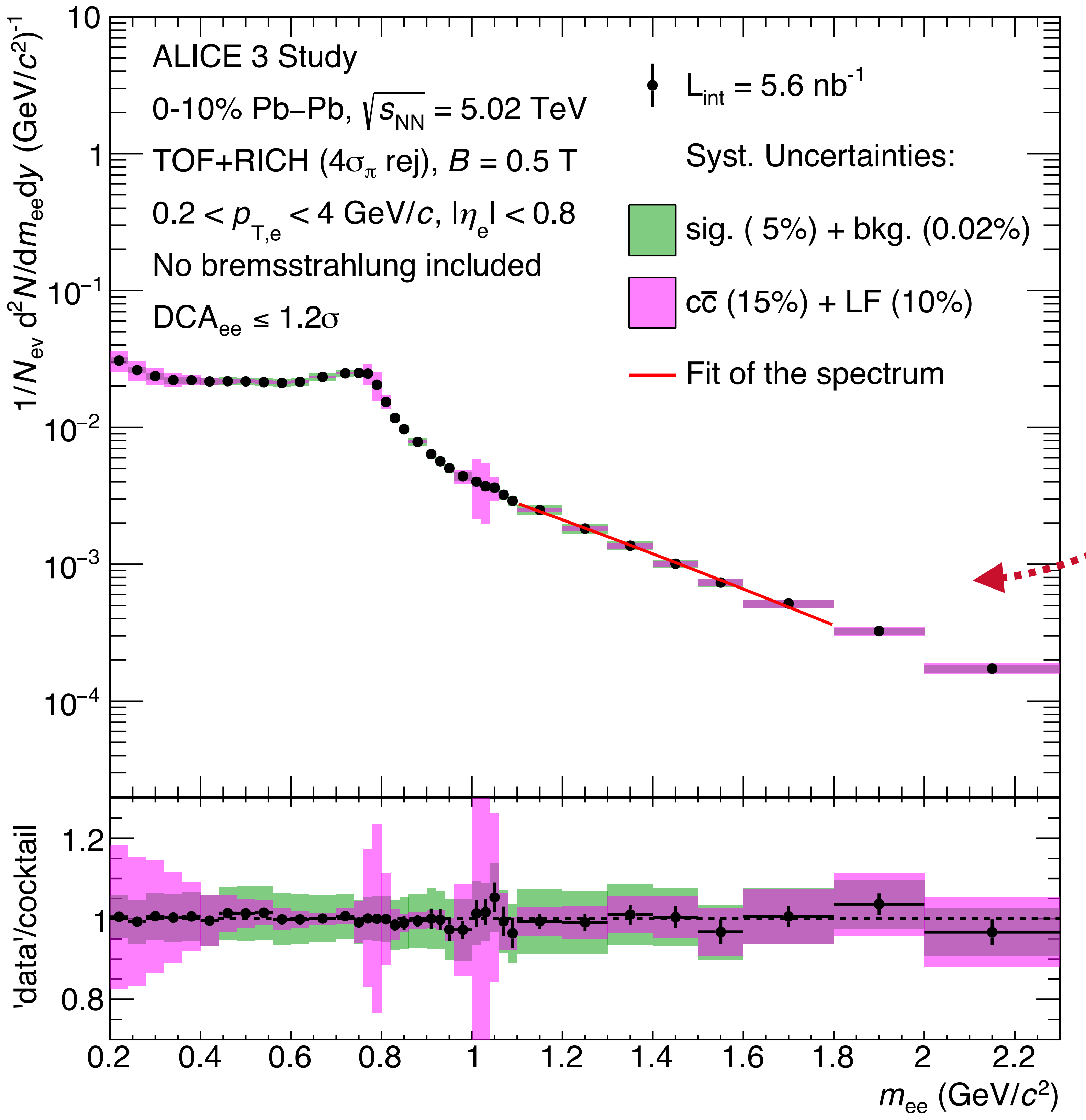
Retractable vertex detector
✓5mm from beam

Physics topics to be explored in ALICE 3

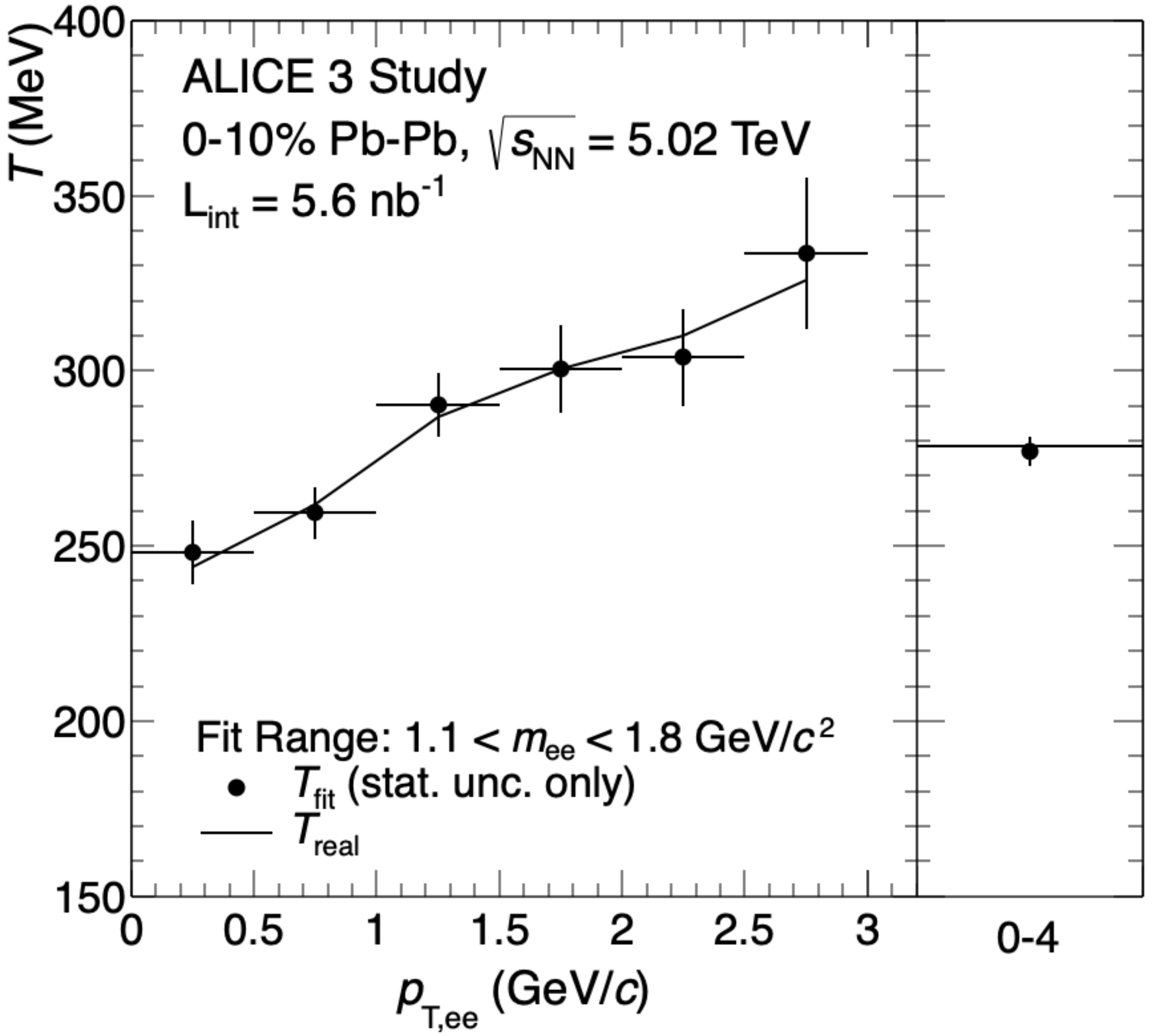
- Thermal radiation, chiral symmetry restoration
- Heavy flavor transport, thermalisation, production
- Net-quantum-number fluctuations
- Hadron structure and interactions
- Ultra-soft photon production
- Beyond Standard Model searches
- **Not exclusive!**



Di-leptons and thermal radiation in ALICE 3



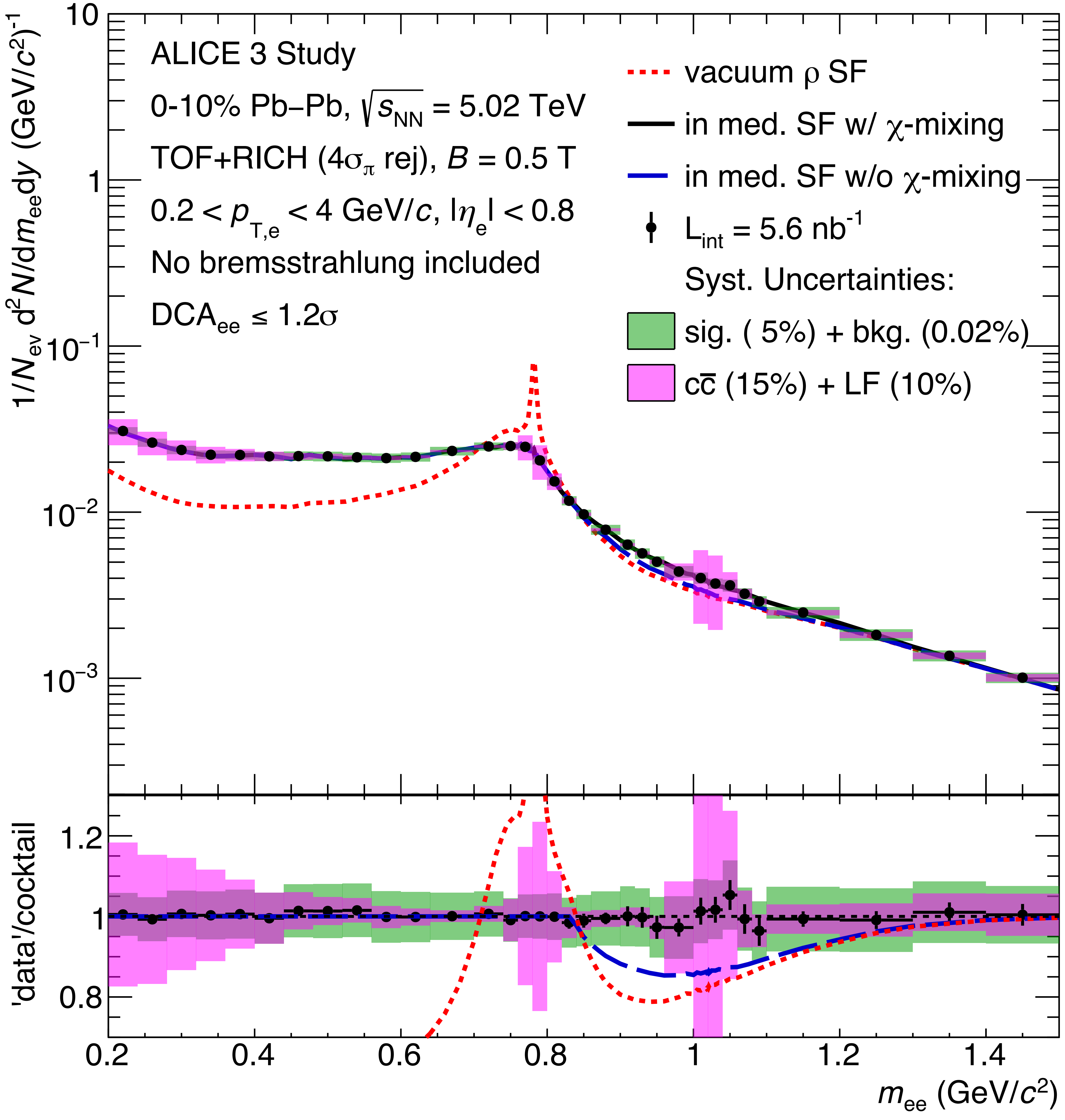
Slope = Temperature



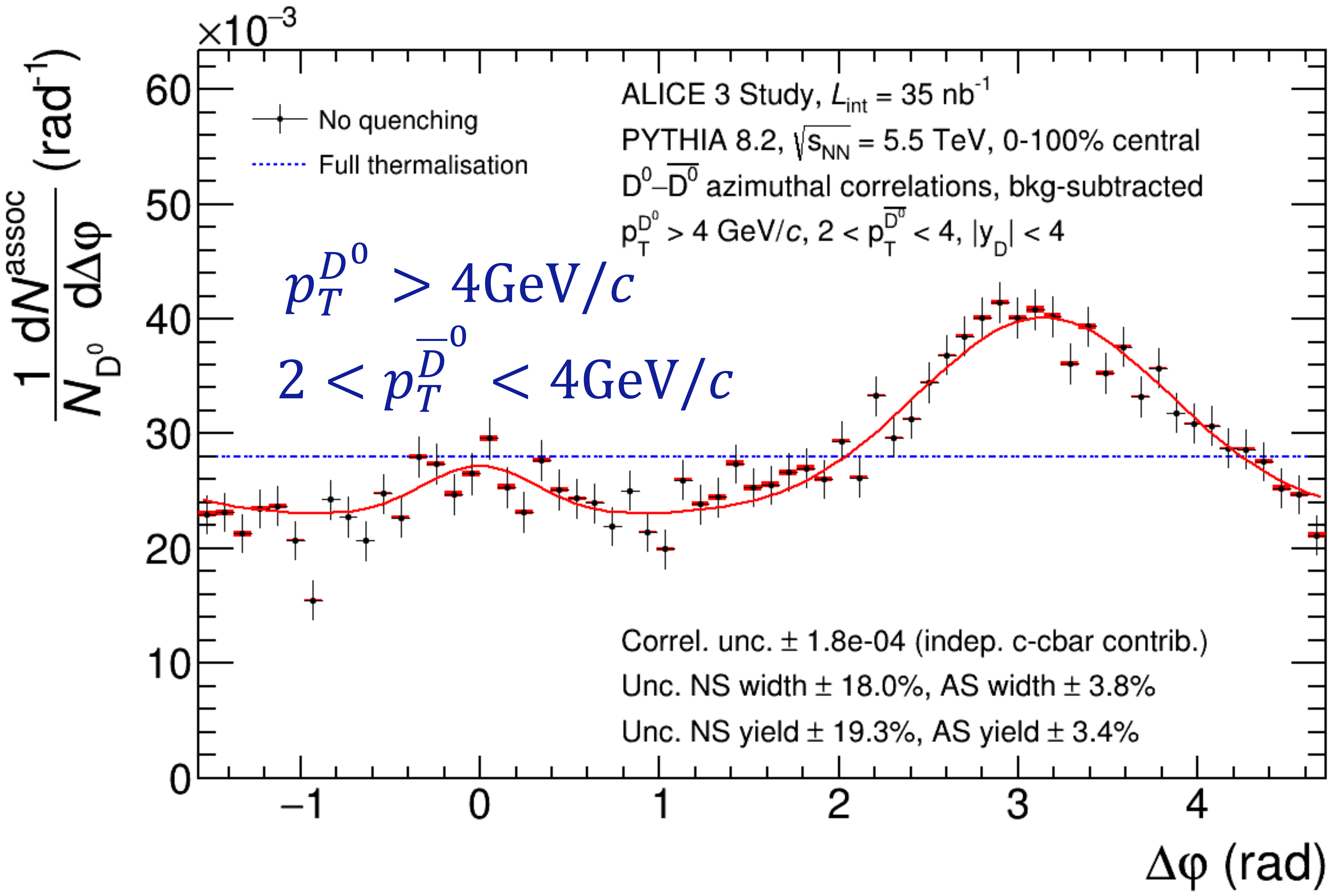
- **Direct QGP temperatures** from intermediate di-electron invariant mass spectrum
- Increasing electron p_T probes earlier times → **possible window to pre-equilibrium stage**

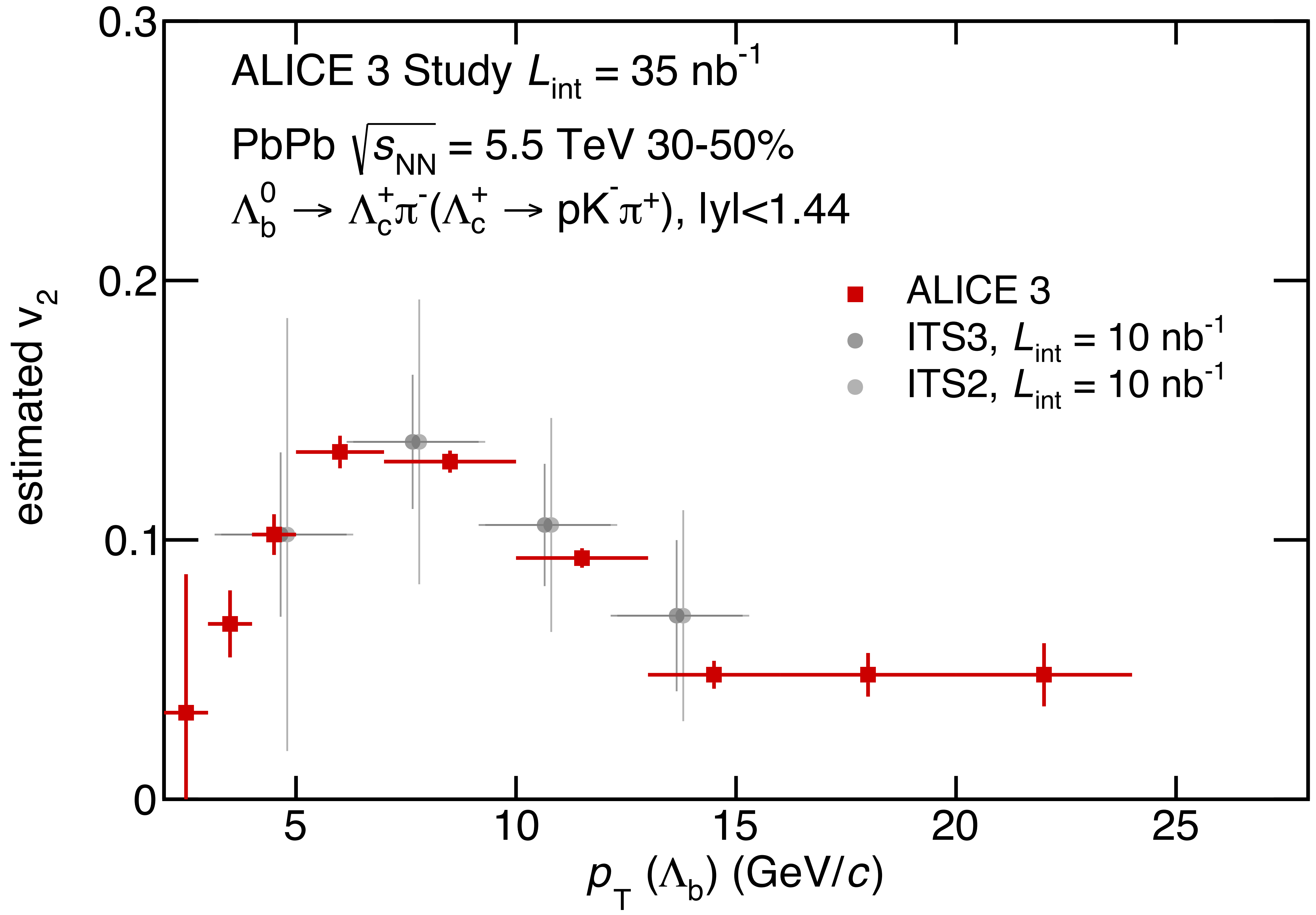
Searches for Chiral Symmetry Restoration in ALICE 3

- **Long sought** after evidence of **QGP formation**
  - ✓Fundamental in high temperature LQCD
  - ✓Breaking responsible for nuclear mass generation
- Deviations from exponential for m_{ee} ~0.9 GeV/C indicative of **Chiral Symmetry Restoration**
- Major topic for NA60+ experiment at CERN at lower energy (2029+)



Heavy-flavor transport in ALICE 3

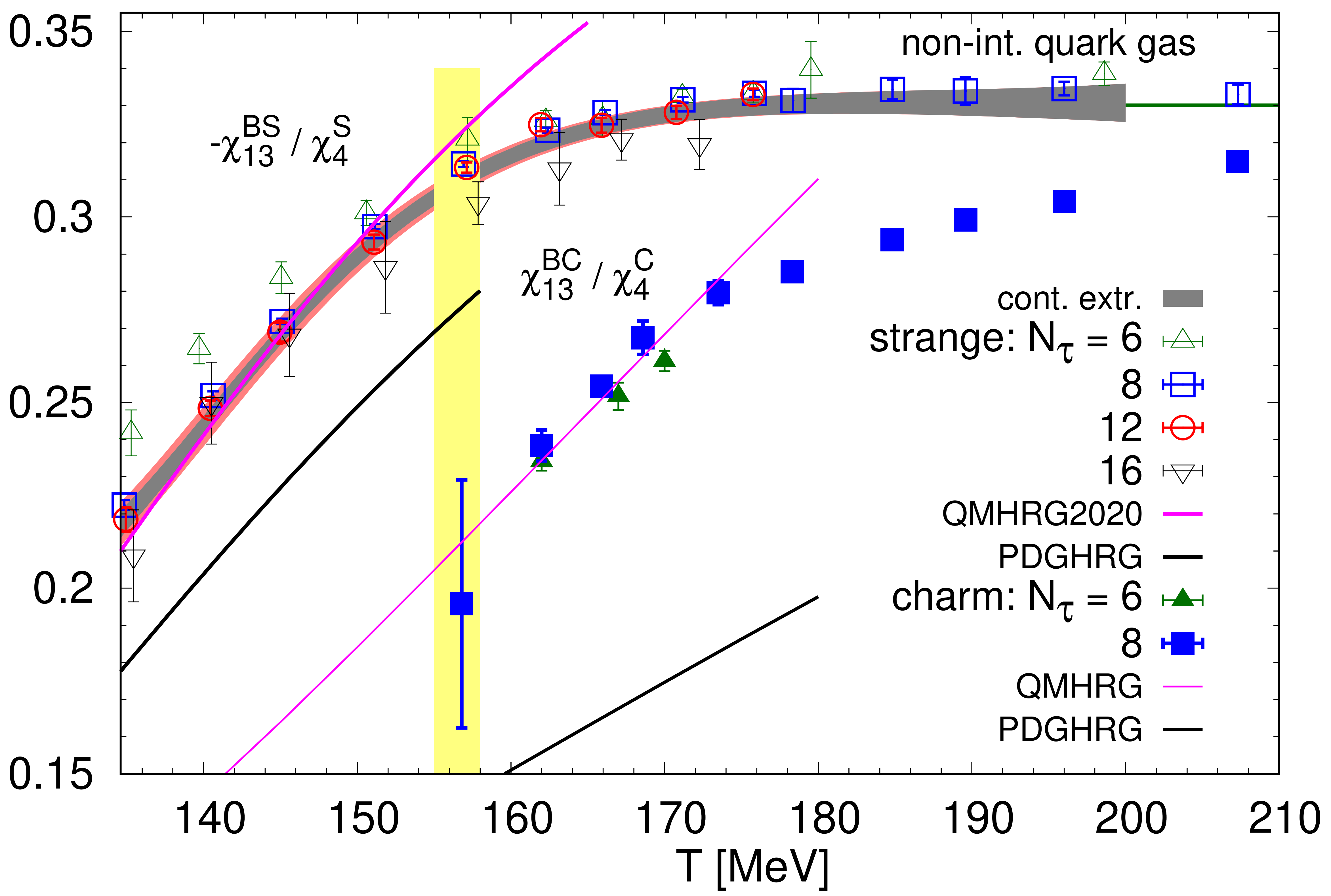


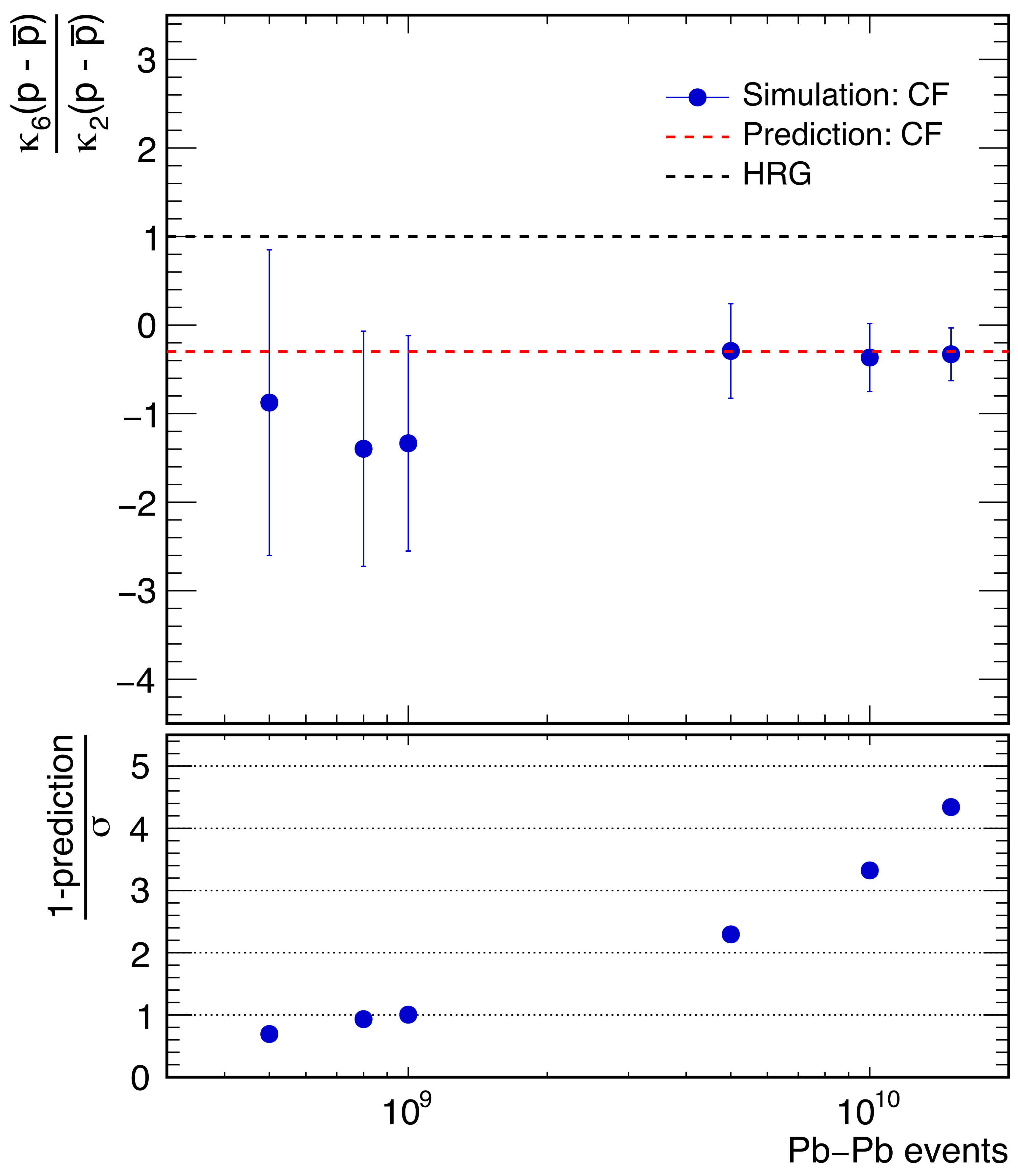


- Two particle D^0 correlations probe **microscopic aspects of charm diffusion more directly**
- Beauty hadron v_n will provide **ultimate constraints on bottom quark diffusion coefficient D_s**

Quantum number fluctuations in ALICE 3

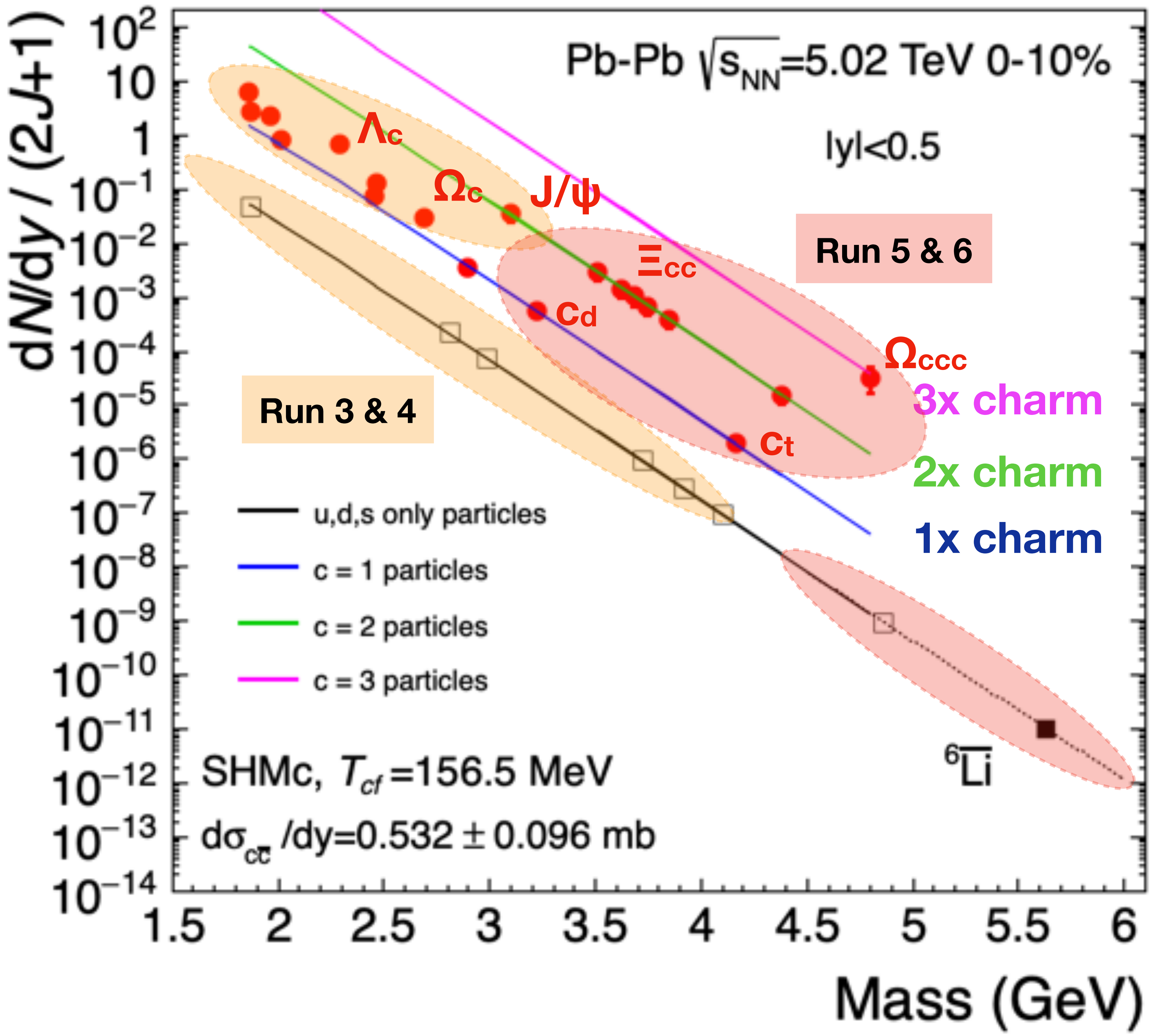
PRC 104 (2021) 041901

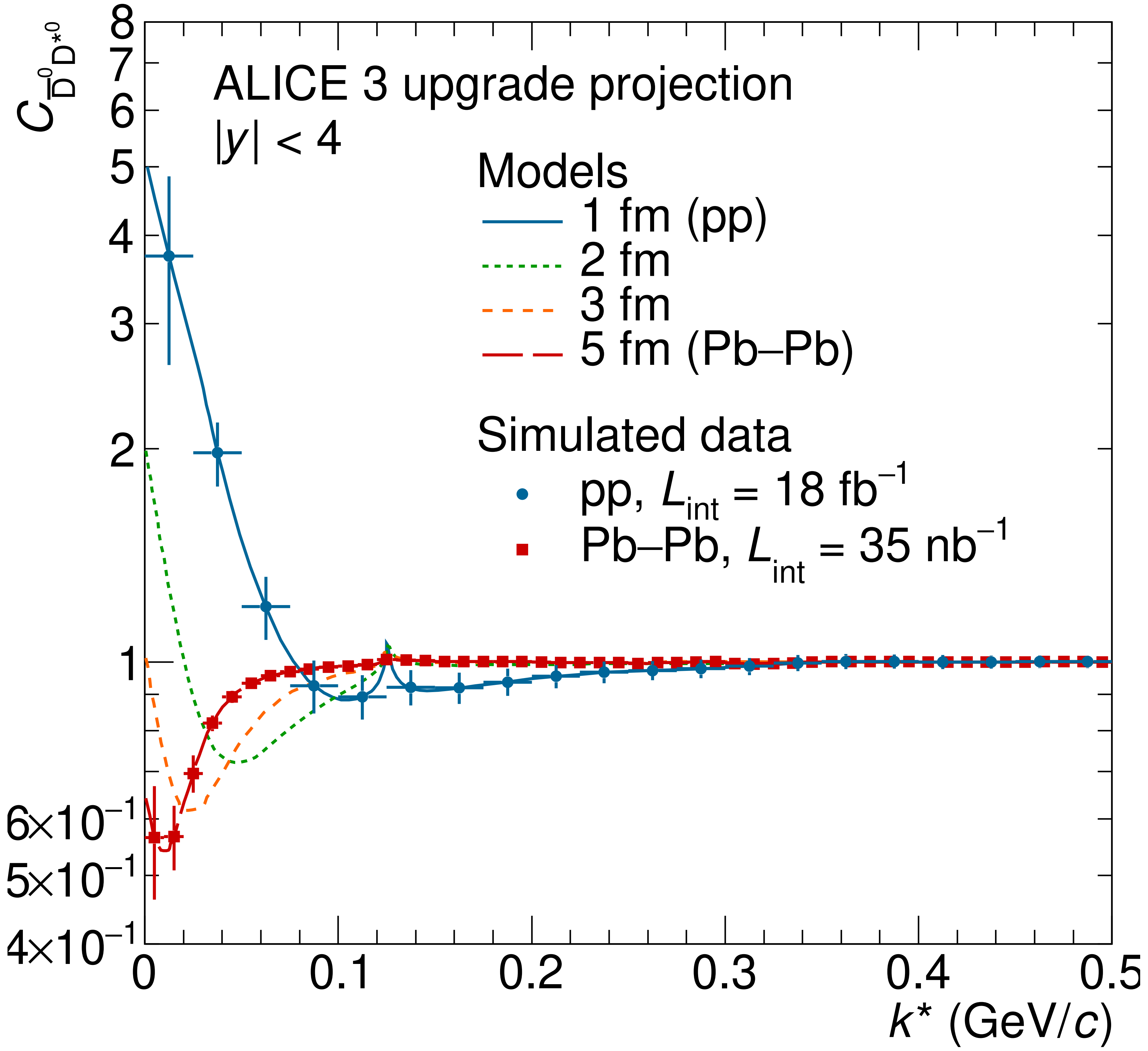


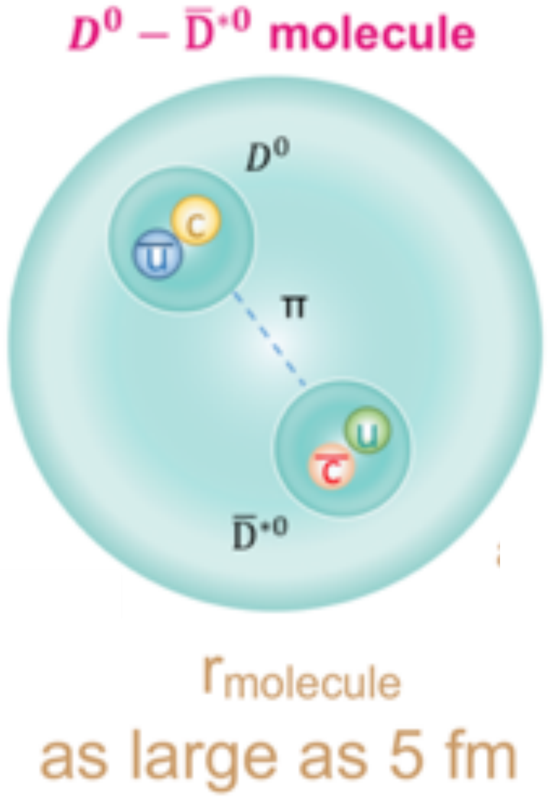


- Measurements of **net-charm fluctuations** open new window to test Lattice QCD
- ALICE 3 necessary for **higher order net-proton fluctuations** to be explored at LHC

Heavy-flavor production and interactions in ALICE 3

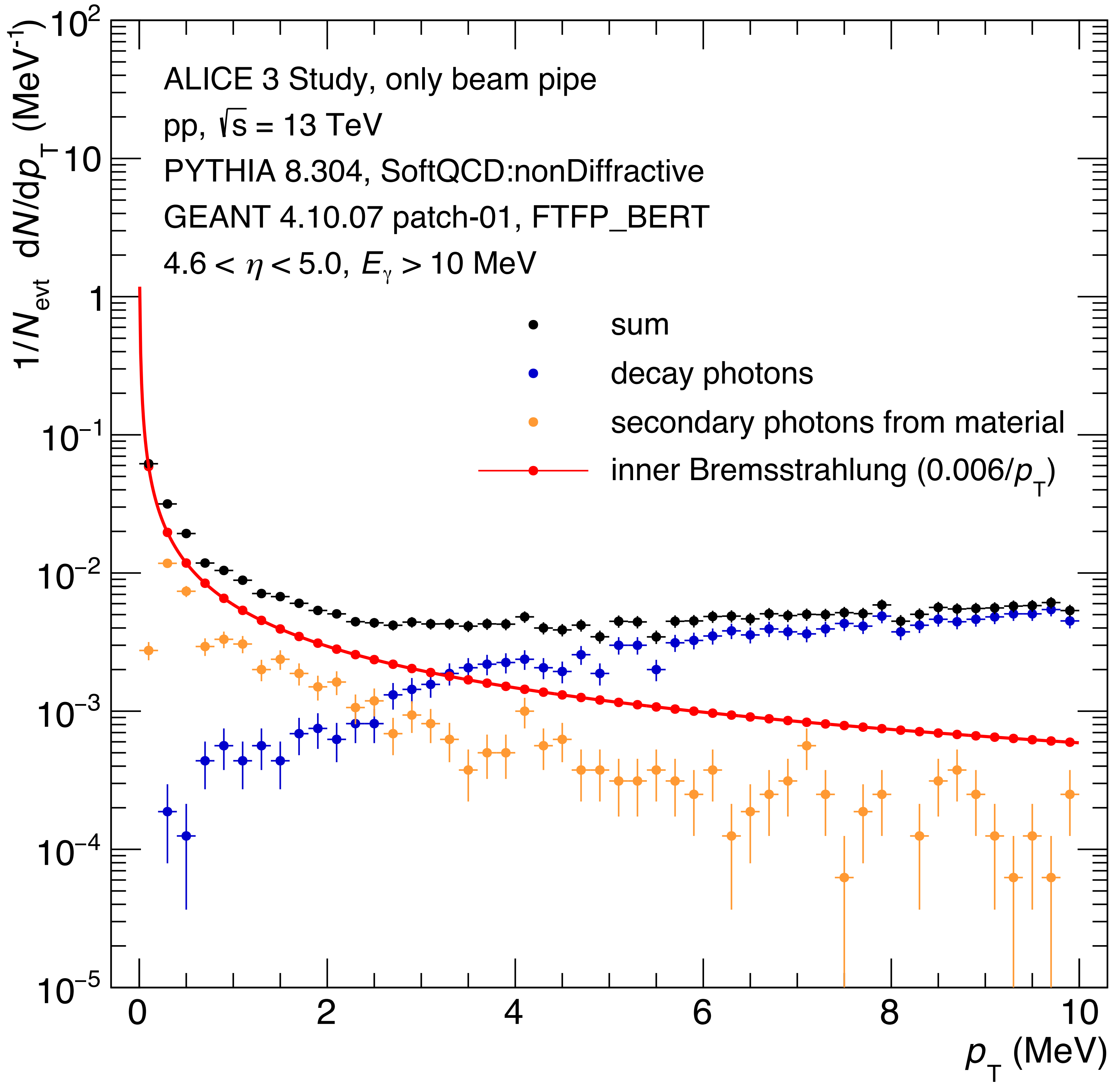


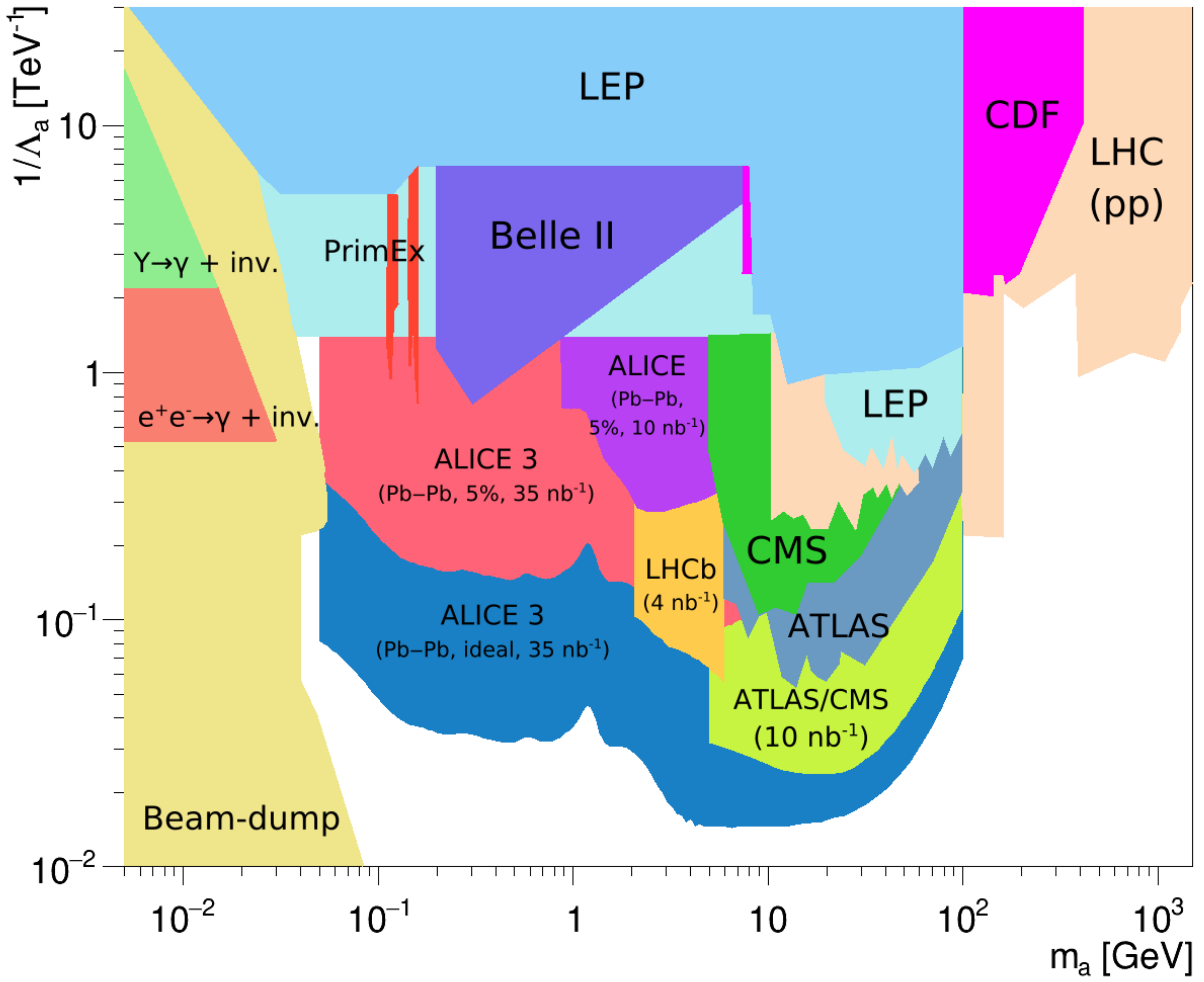




- Multi-charm baryons accessible → **novel tests of hadronization mechanisms**
- Two particle D^0 femto correlations can be used to **explore formation of D^0 molecules**

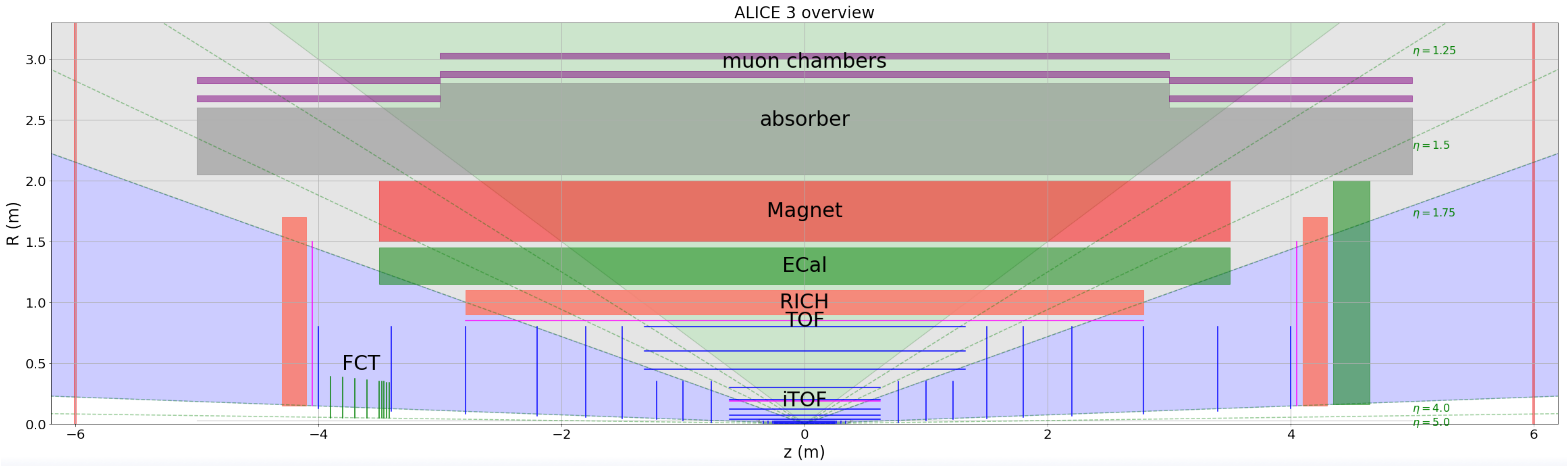
Ultra soft photons and BSM searches in ALICE 3





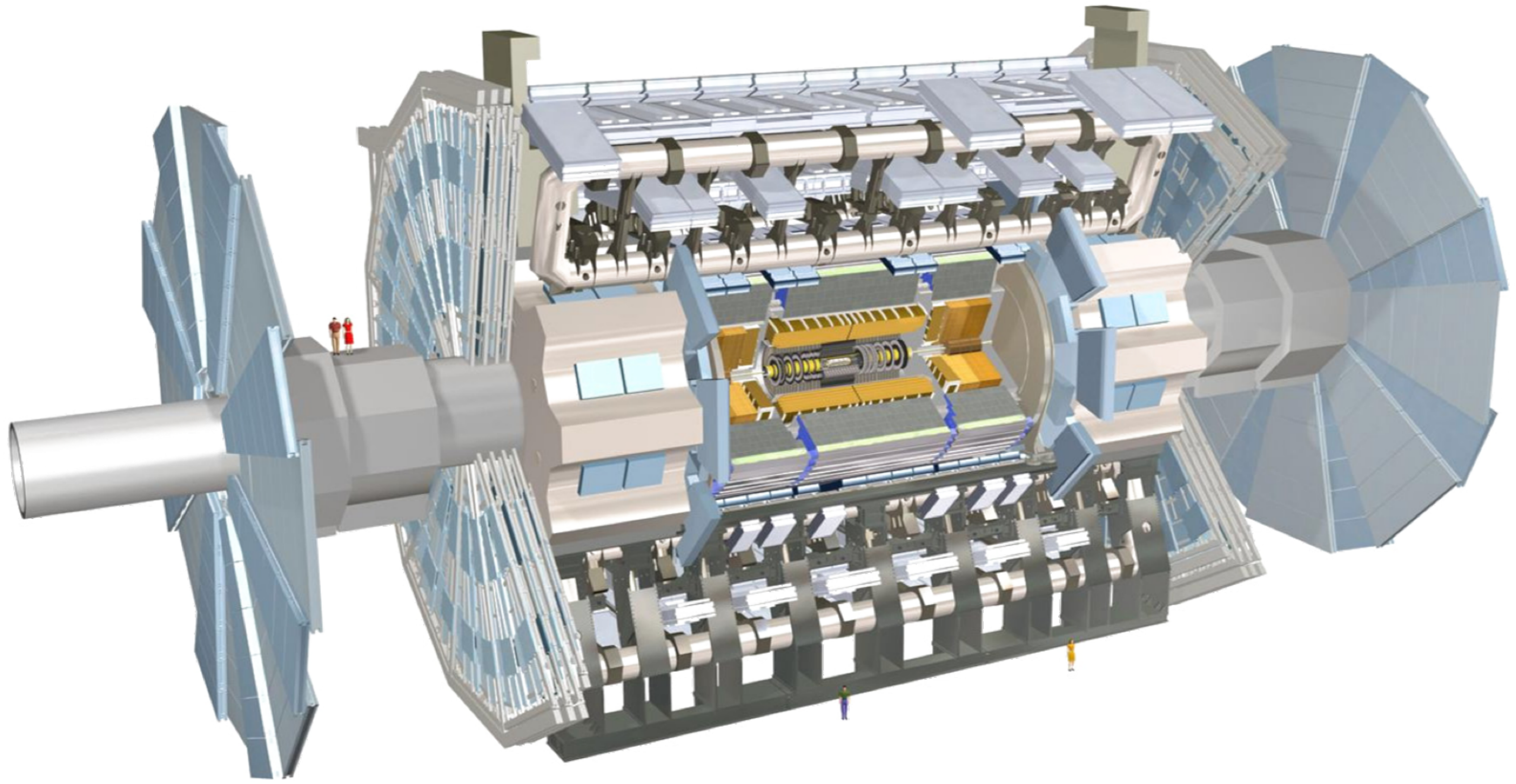
- Forward Conversion Tracker used to measure ultra-soft photons very forward
  - ✓ Low's theorem can be used to **test infrared limits of quantum field theories**
- Light by light scattering via UPC events provide **competitive limits on axion searches**

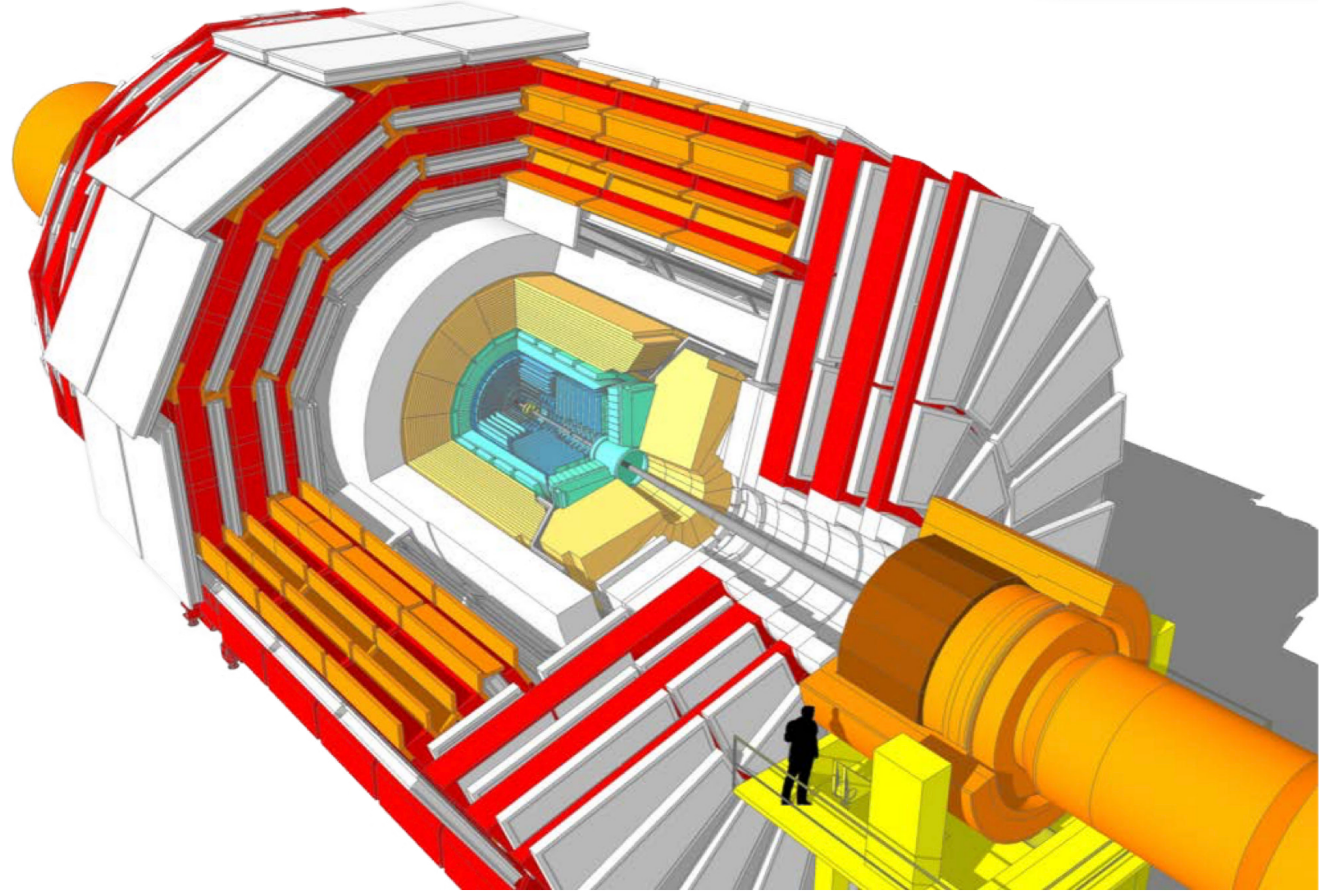
Many more physics topics opportunities with ALICE 3

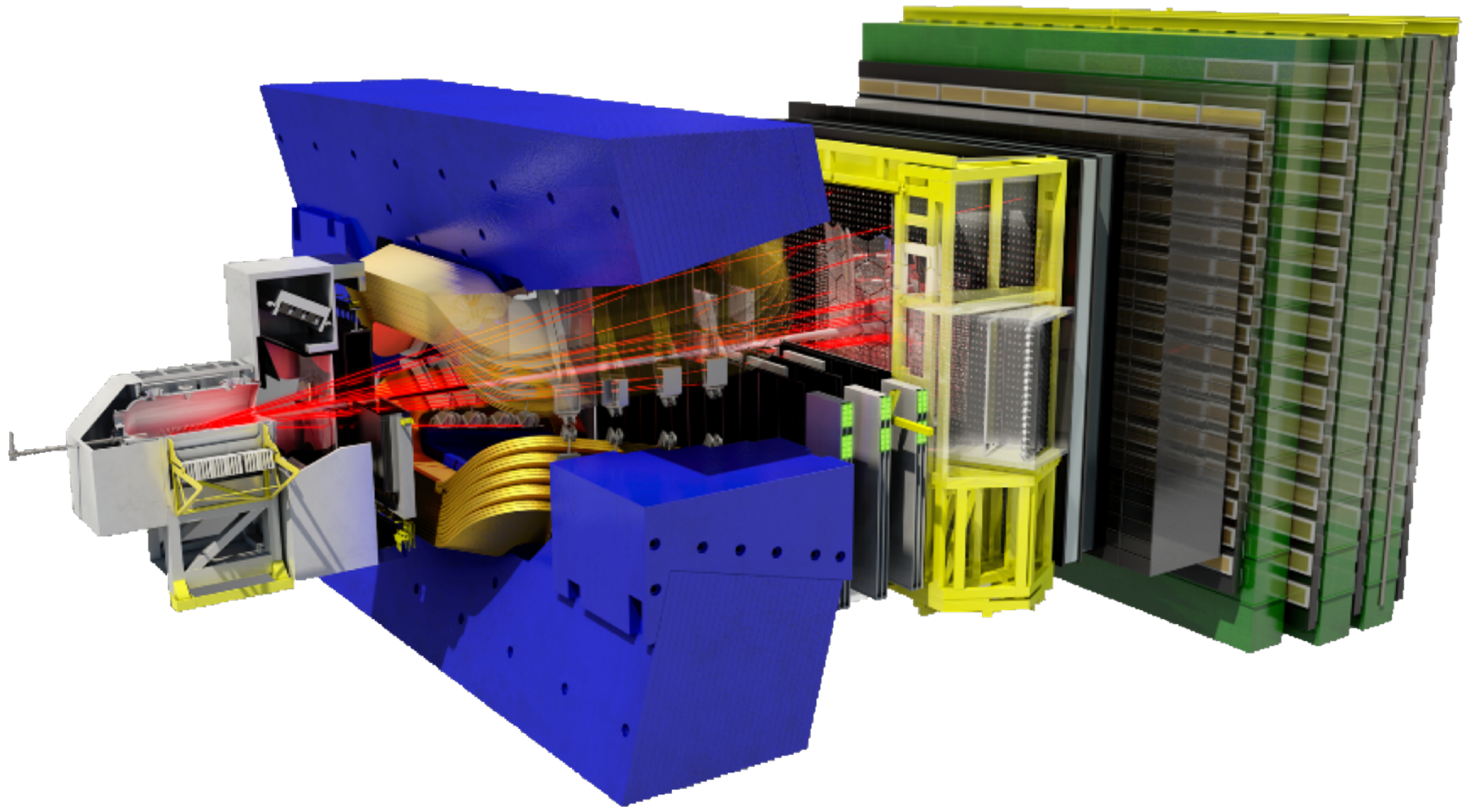


- Large η and p_T acceptance + excellent PID enable for example:
  - ✓ **Heavy-flavor jet correlations** or **photon-heavy-flavor jet correlations** with unprecedented purity at low transverse momentum scales
  - ✓ **Full 3D imagining of nuclear collisions** via anisotropic flow measurements
  - ✓ Two-particle correlations with **large $\Delta\eta$ to probe early time dynamics and diffusion**

ATLAS, CMS, LHCb in Runs 5 and beyond







ALTAS

- ✓ Improved ZDC
- ✓ Extend tracker acceptance to $|\eta| < 4$
- ✓ Time-of-flight PID $2.5 < |\eta| < 4$
- ✓ Endcap calorimeters with higher granularity

CMS

- ✓ Charged particle tracking up to $|\eta| < 4$, muons up to $|\eta| < 3$
- ✓ Time-of-flight PID up to $|\eta| < 3$
- ✓ High-precision vertexing
- ✓ Wide coverage calorimetry

LHCb

- ✓ 50 kHz for Pb-Pb and no centrality limitation
- ✓ Excellent vertexing capabilities
- ✓ Fixed target

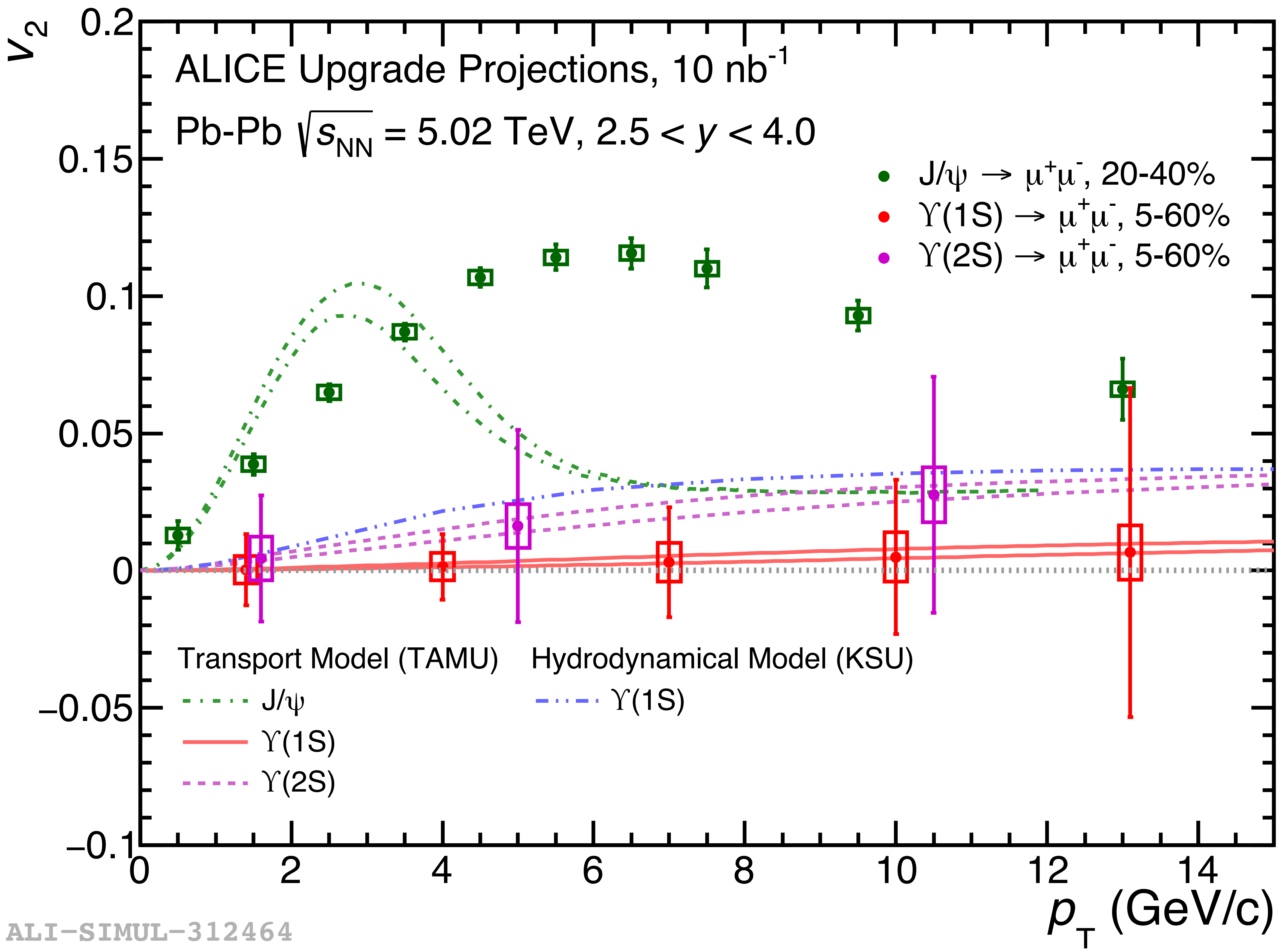
Summary

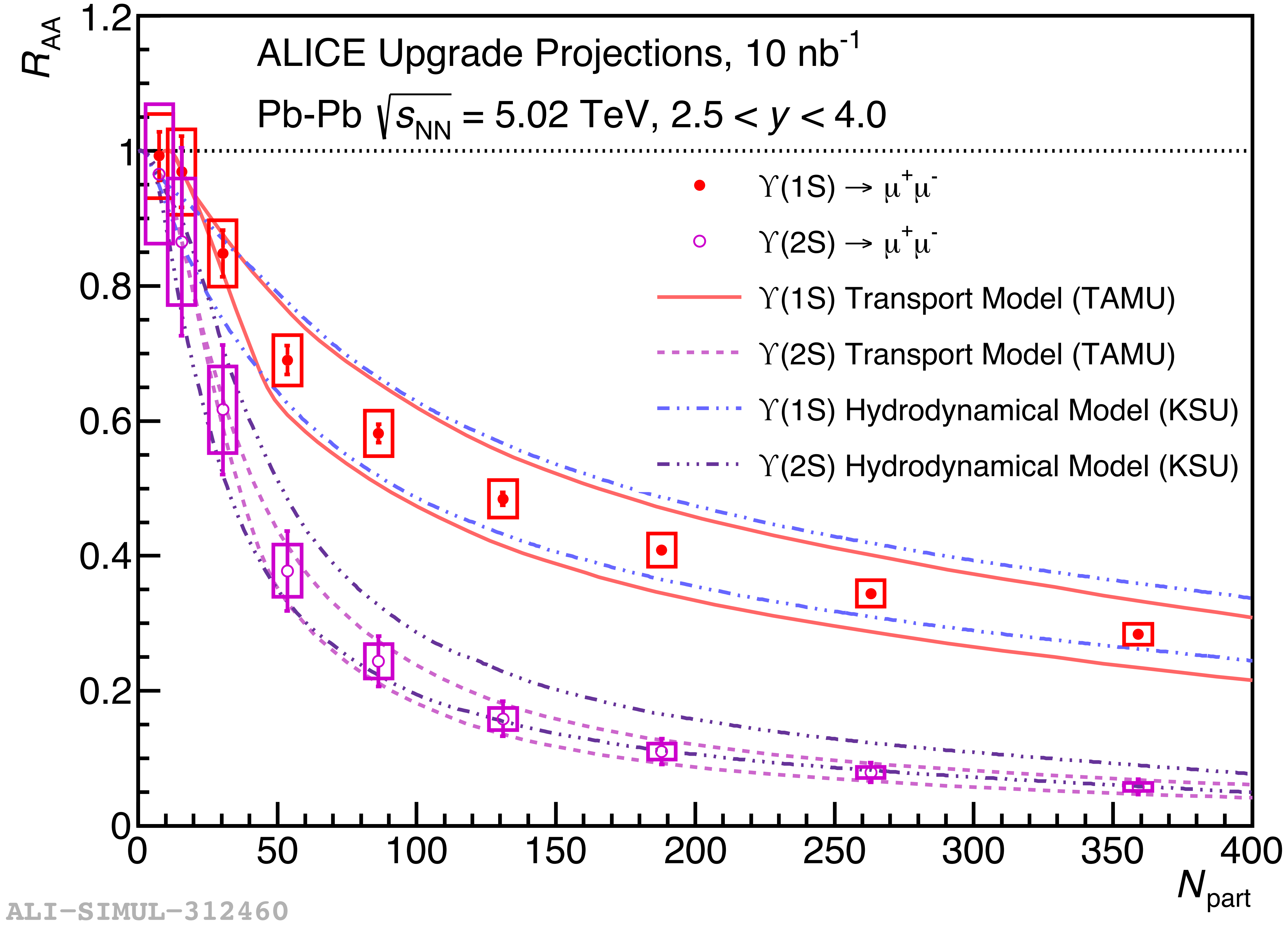
- **Rich physics plan ahead for ALICE** in **Runs 3 & 4 (2023-2032)**:
  - ✓Improvements in detector performance thanks to vital U.S. contributions
  - ✓Unique opportunity for Hot and Cold measurements QCD after RHIC and before EIC
  - ✓Continued support for all US LHC upgrades e.g. FoCal essential.

- **ALICE 3** → designed by heavy-ion physicists for heavy-ion physics:
  - ✓Opens new era of **discovery potential** and **precision** in QCD
  - ✓Technology selection, prototypes, beginning of construction in 2023 LRP period

- Runs 5 and beyond → **Major expansion of capabilities for all LHC detectors**
  - ✓US participation essential for realization of physics opportunities in Hot QCD
  - ✓**Opportunities for growth of US contributions** and leadership

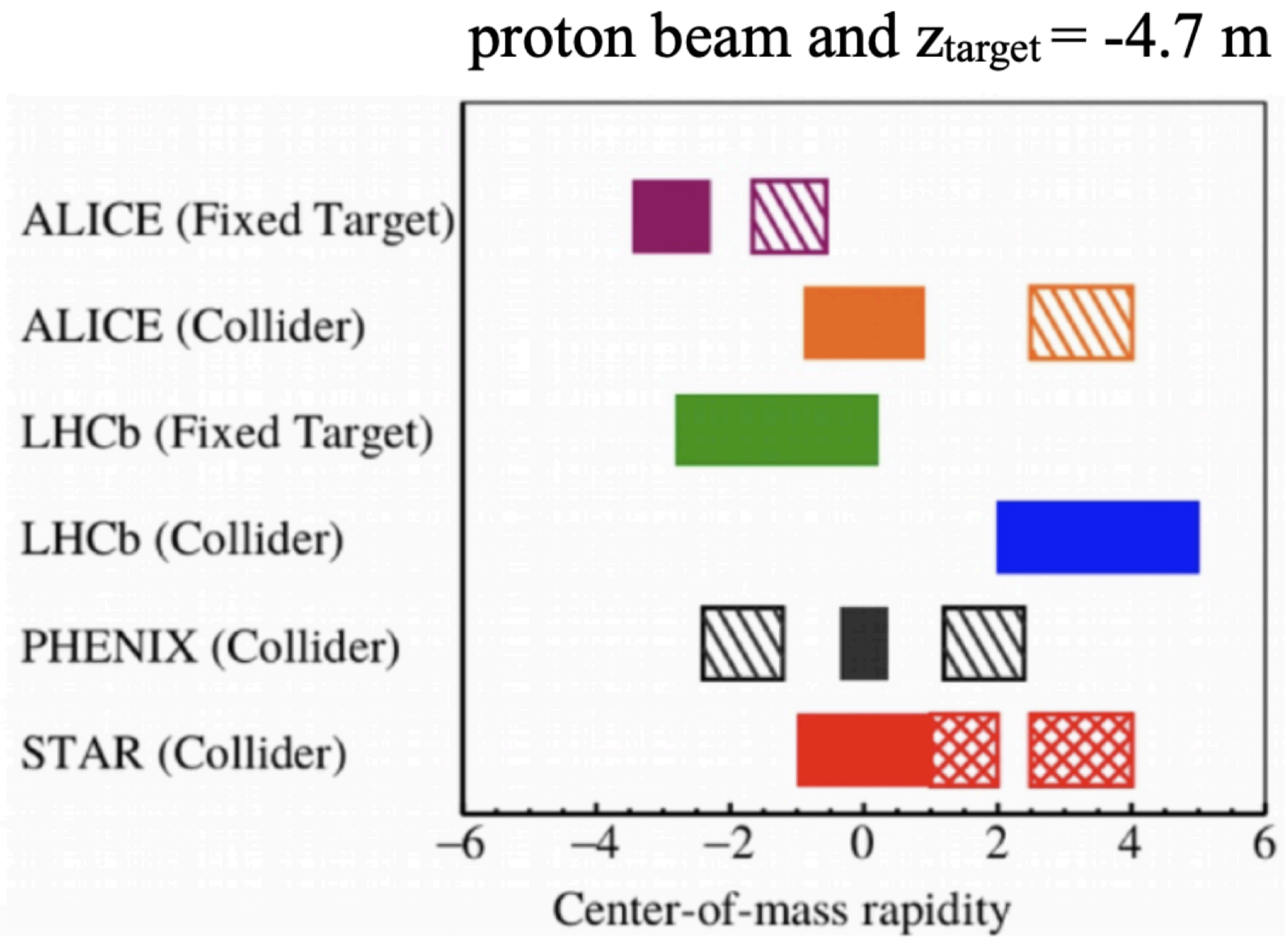
Back-up - Quarkonia in Run 3 & 4





- MFT improves allows separation of prompt and B decays for J/ψ

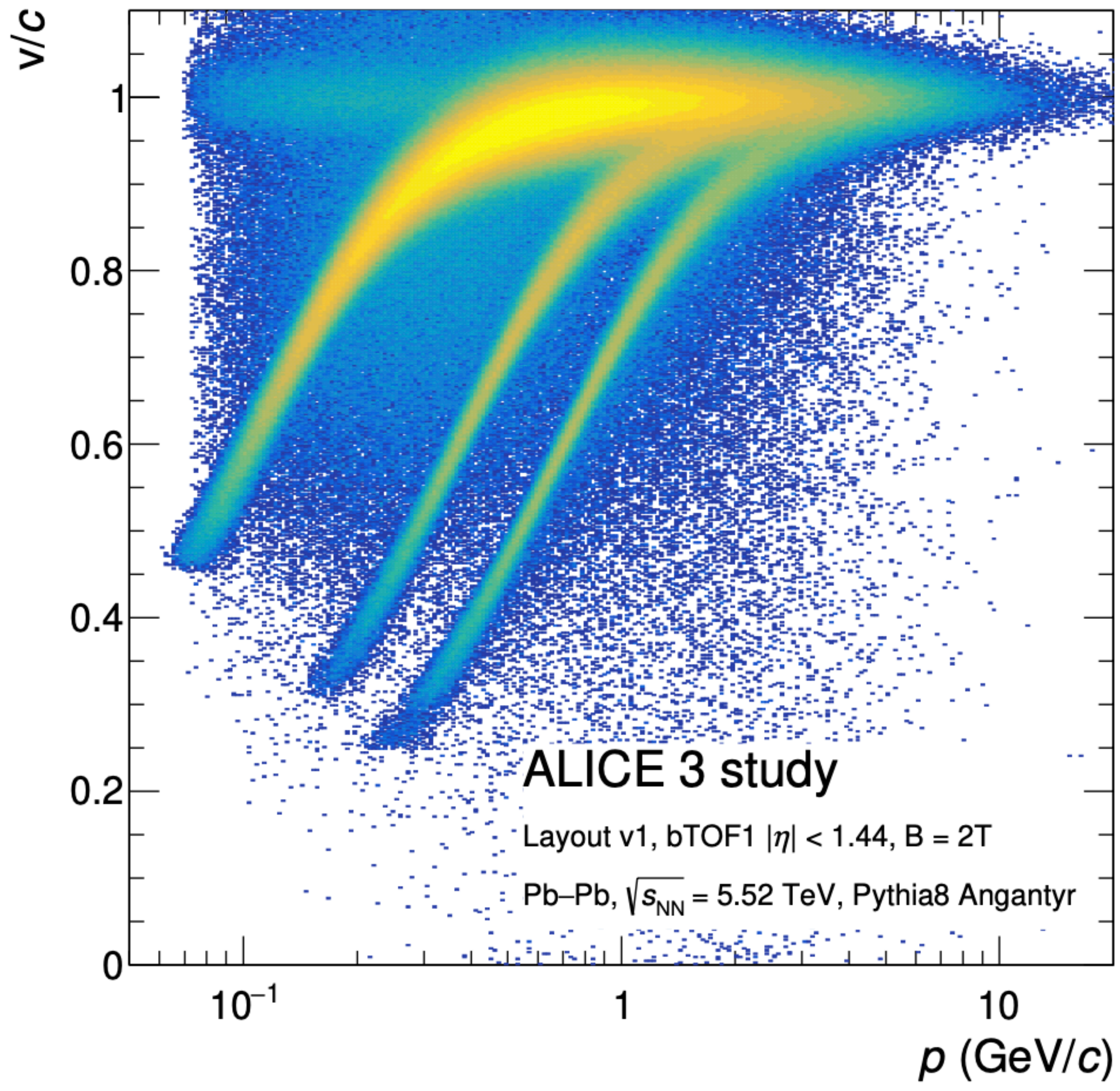
Back-up - Fixed target in Run 4?

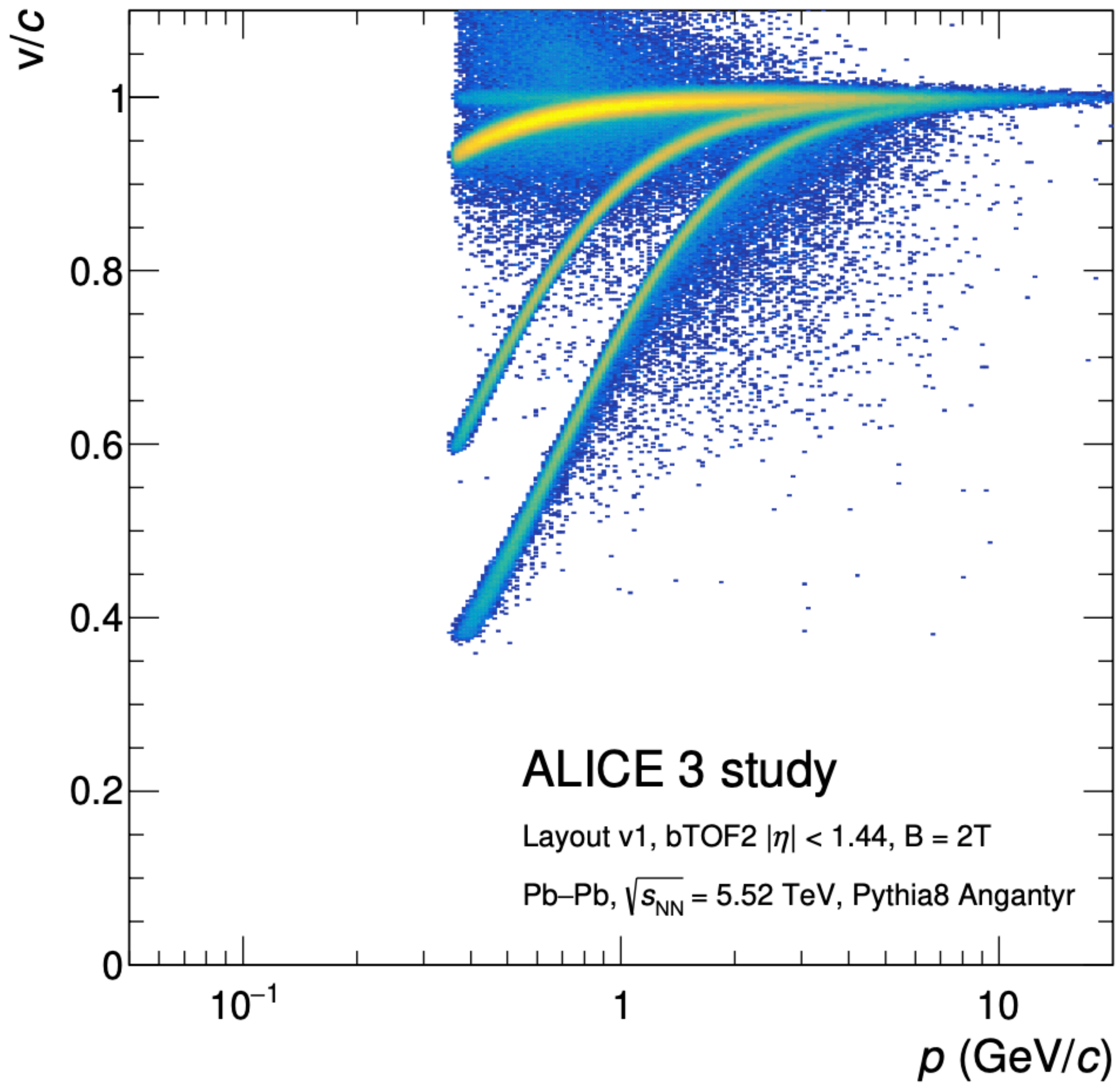


Back-up - ALICE 3 luminosities

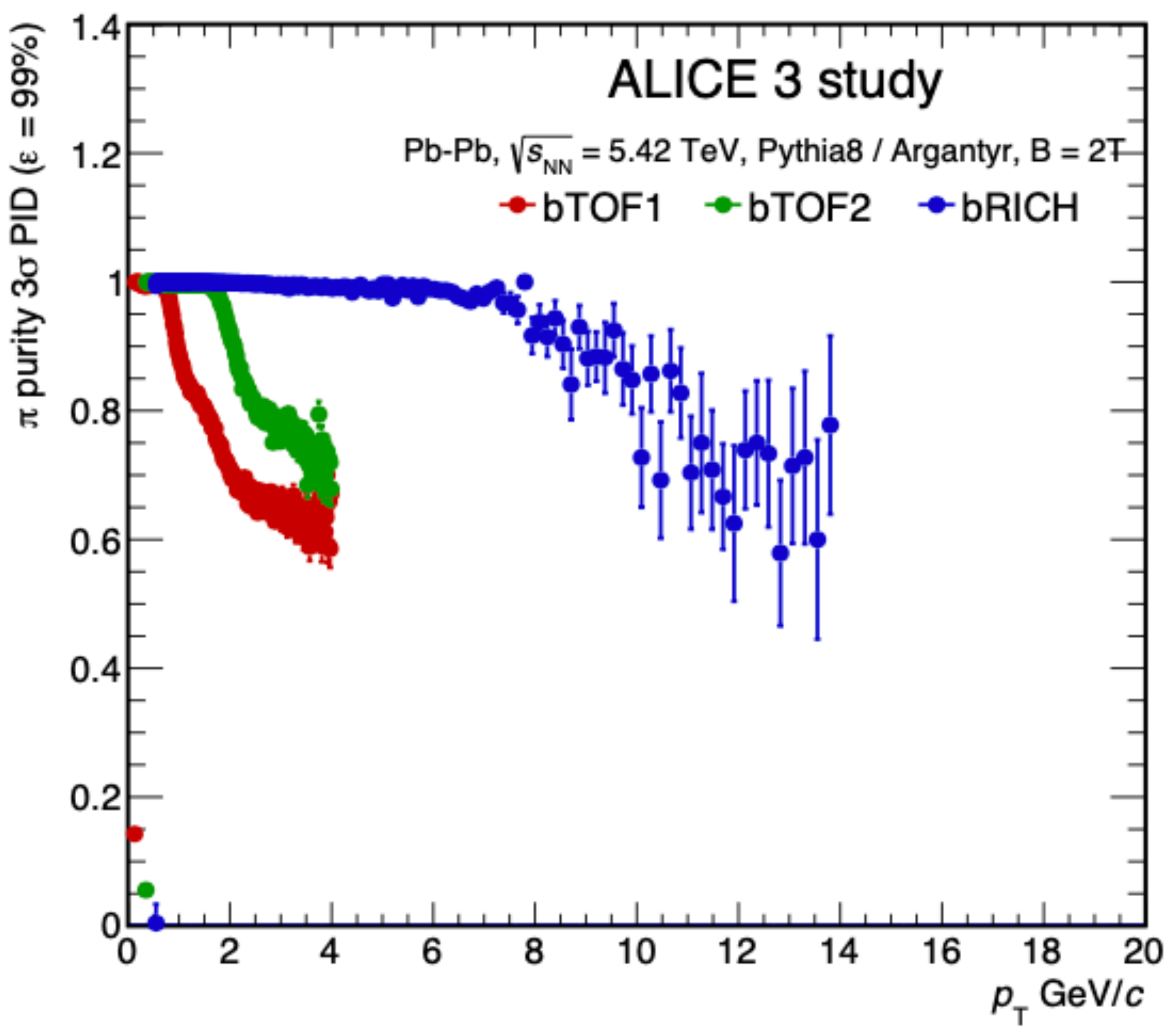
Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	$3.0 \cdot 10^{32}$	$1.5 \cdot 10^{30}$	$3.2 \cdot 10^{29}$	$2.8 \cdot 10^{29}$	$8.5 \cdot 10^{28}$	$5.0 \cdot 10^{28}$	$3.3 \cdot 10^{28}$	$1.2 \cdot 10^{28}$
$\langle L_{AA} \rangle$ ($cm^{-2}s^{-1}$)	$3.0 \cdot 10^{32}$	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	$5.1 \cdot 10^{5}$	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
				at $R = 0.5$ cm				
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	$1.8 \cdot 10^{14}$	$1.0 \cdot 10^{14}$	$8.6 \cdot 10^{13}$	$7.9 \cdot 10^{13}$	$6.0 \cdot 10^{13}$	$3.3 \cdot 10^{13}$	$4.1 \cdot 10^{13}$	$1.9 \cdot 10^{13}$
TID (Rad)	$5.8 \cdot 10^{6}$	$3.2 \cdot 10^{6}$	$2.8 \cdot 10^{6}$	$2.5 \cdot 10^{6}$	$1.9 \cdot 10^{6}$	$1.1 \cdot 10^{6}$	$1.3 \cdot 10^{6}$	$6.1 \cdot 10^{5}$
				at $R = 100$ cm				
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	$4.9 \cdot 10^{9}$	$2.5 \cdot 10^{9}$	$2.1 \cdot 10^{9}$	$2.0 \cdot 10^{9}$	$1.5 \cdot 10^{9}$	$8.3 \cdot 10^{8}$	$1.0 \cdot 10^{9}$	$4.7 \cdot 10^{8}$
TID (Rad)	$1.4 \cdot 10^{2}$	$8.0 \cdot 10^{1}$	$6.9 \cdot 10^{1}$	$6.3 \cdot 10^{1}$	$4.8 \cdot 10^{1}$	$2.7 \cdot 10^{1}$	$3.3 \cdot 10^{1}$	$1.5 \cdot 10^{1}$

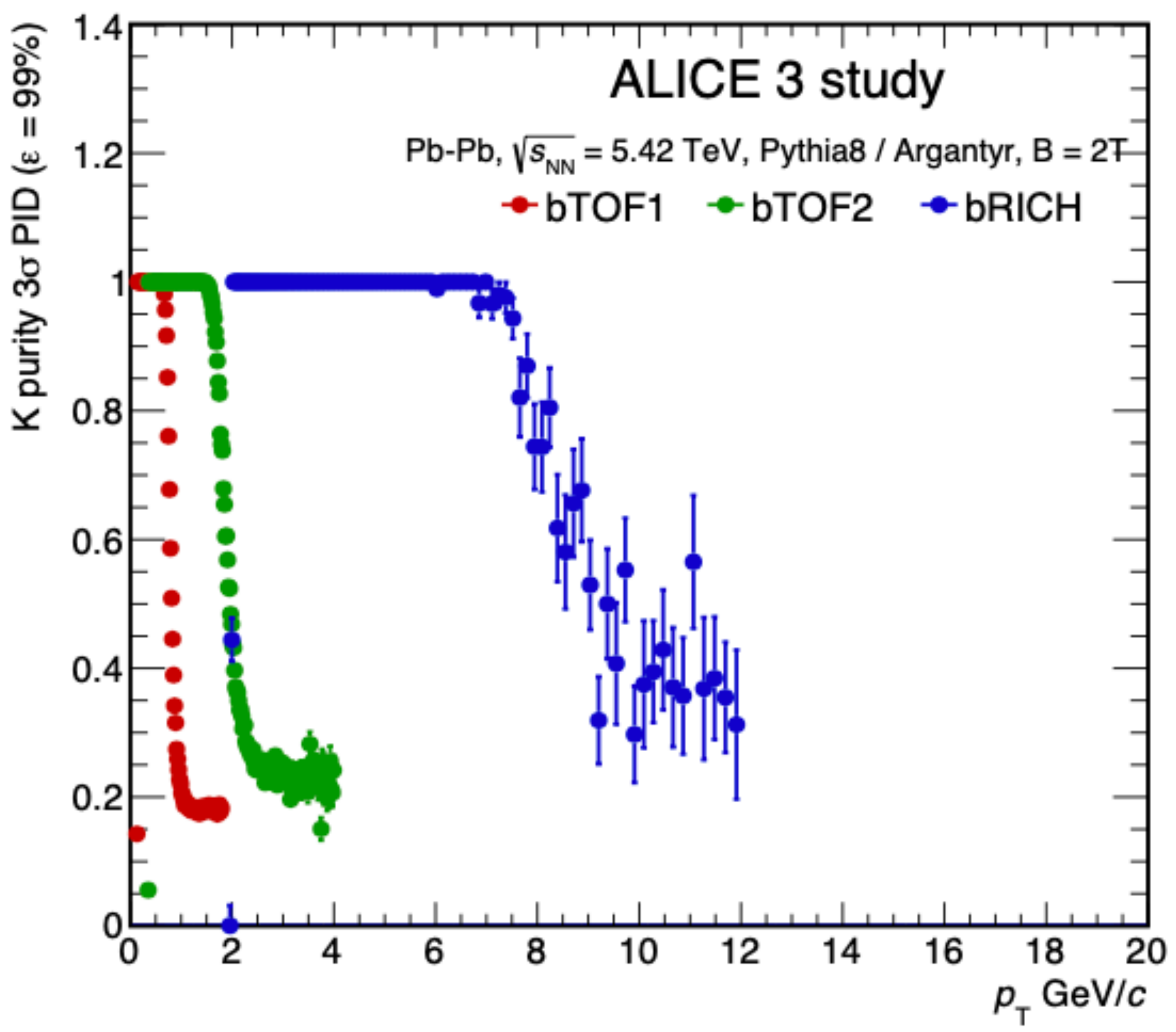
Back-up - ALICE 3 PID

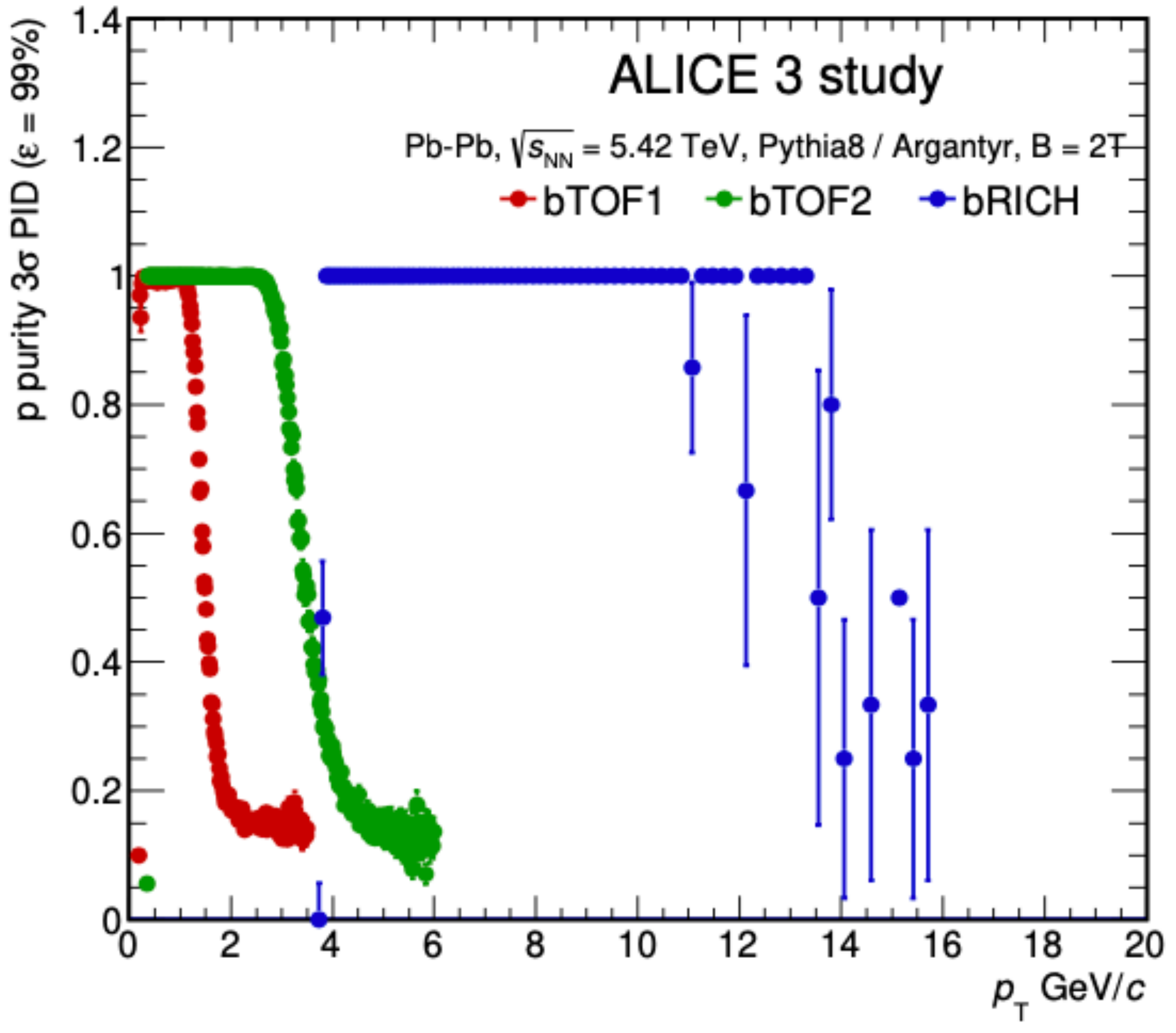


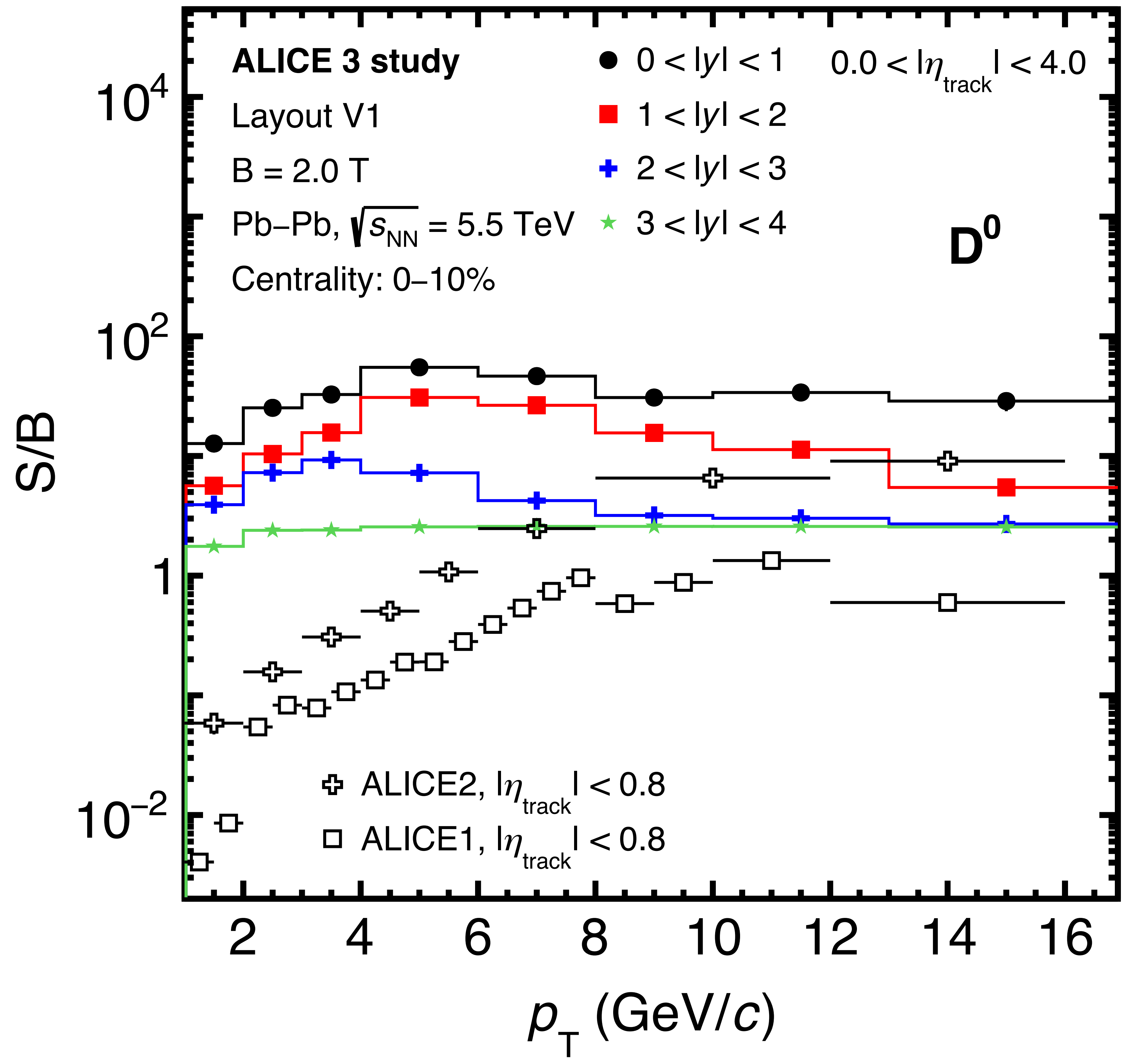


Back-up - ALICE 3 PID

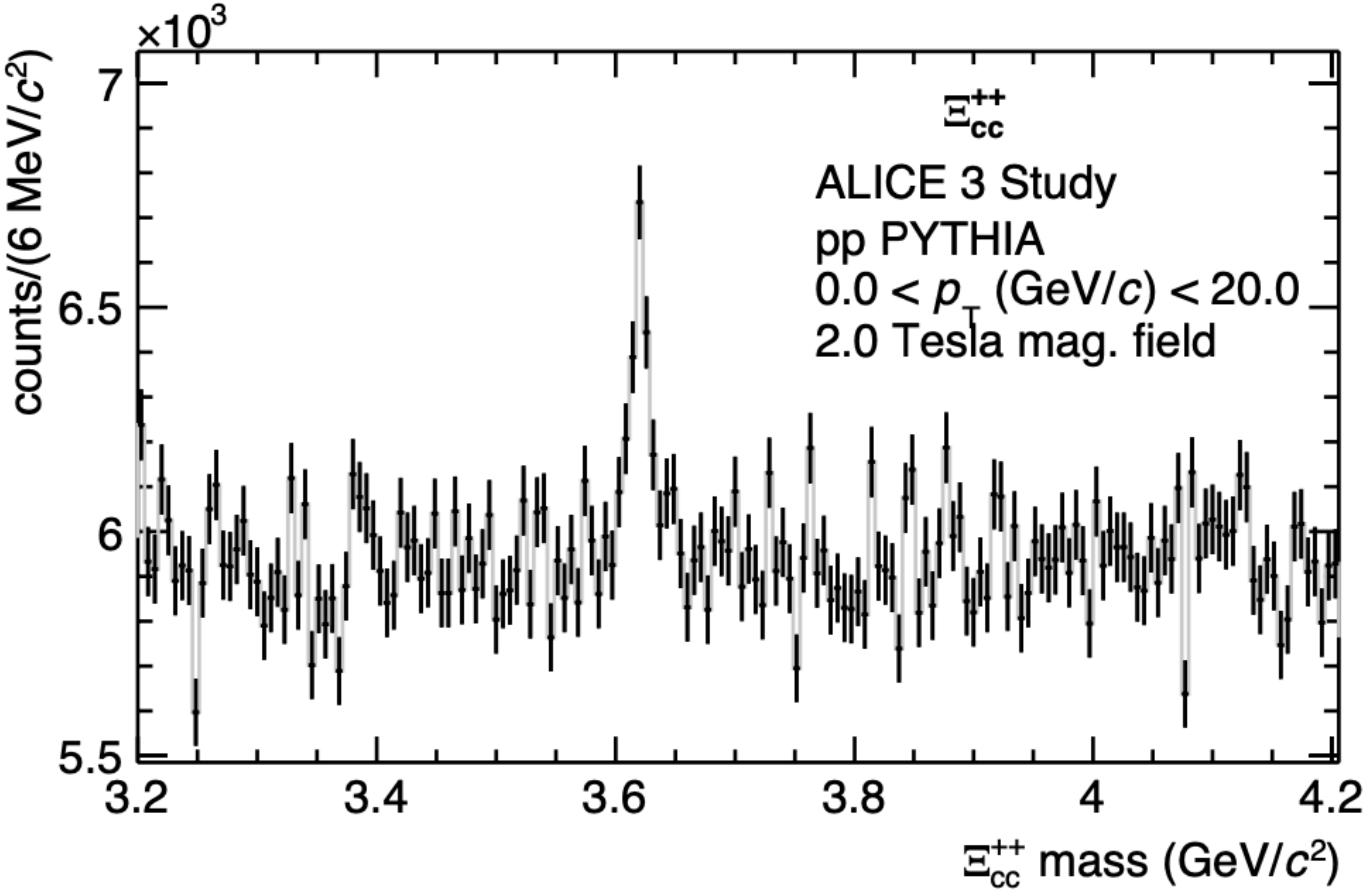








Back-up - Multi-charm



Back-up - ALICE 3 detector requirements

Component	Observables	Barrel ($\|\eta\| < 1.75$)	Forward ($1.75 < \|\eta\| < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	retractable Si-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, photons ...	$\sigma_{p_T}/p_T \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
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: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_T \sim 1.5\,GeV/c$ at $\eta = 0$		steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker