Study on heavy-flavour and strangeness with ALICE

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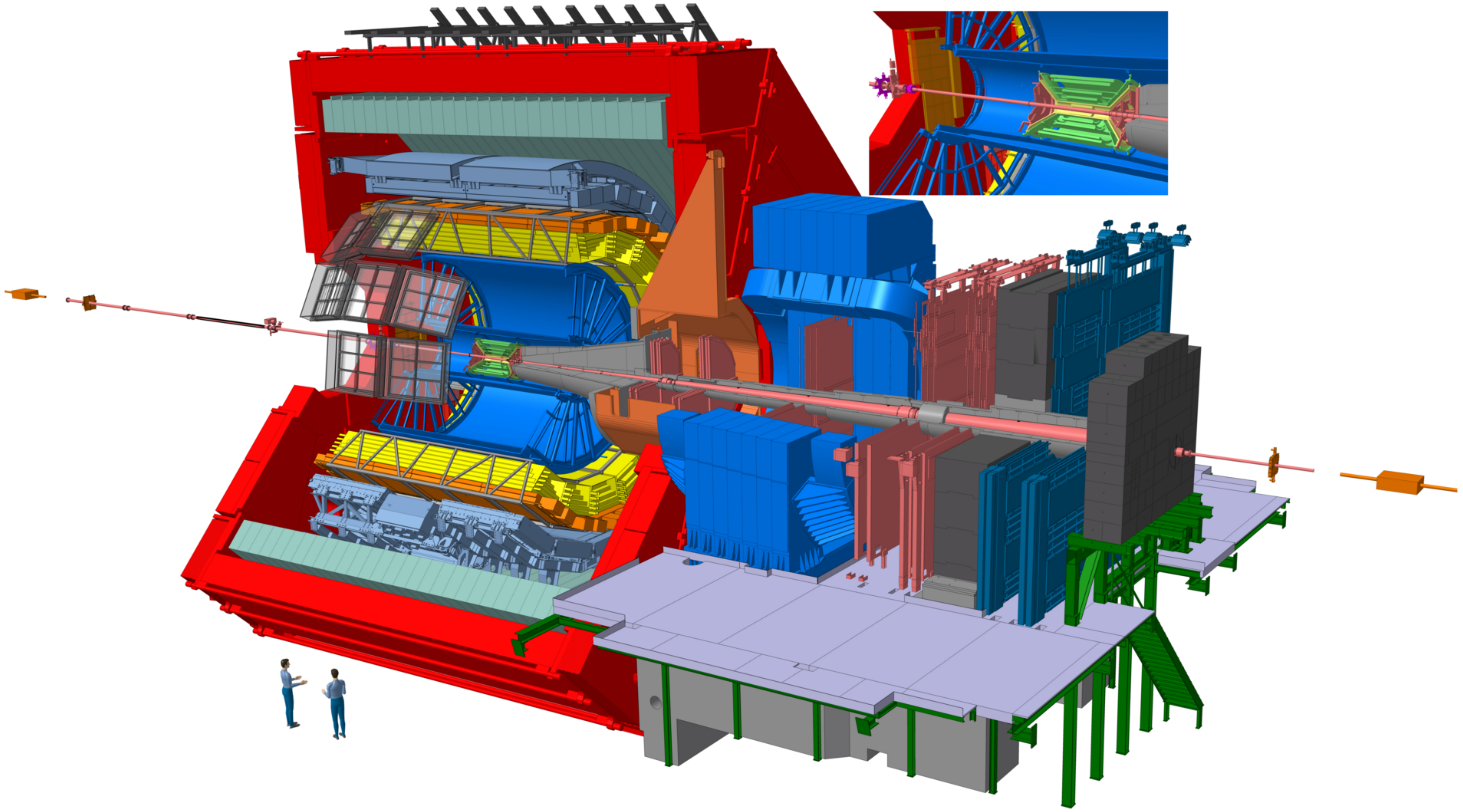
ALICE apparatus



ALICE apparatus

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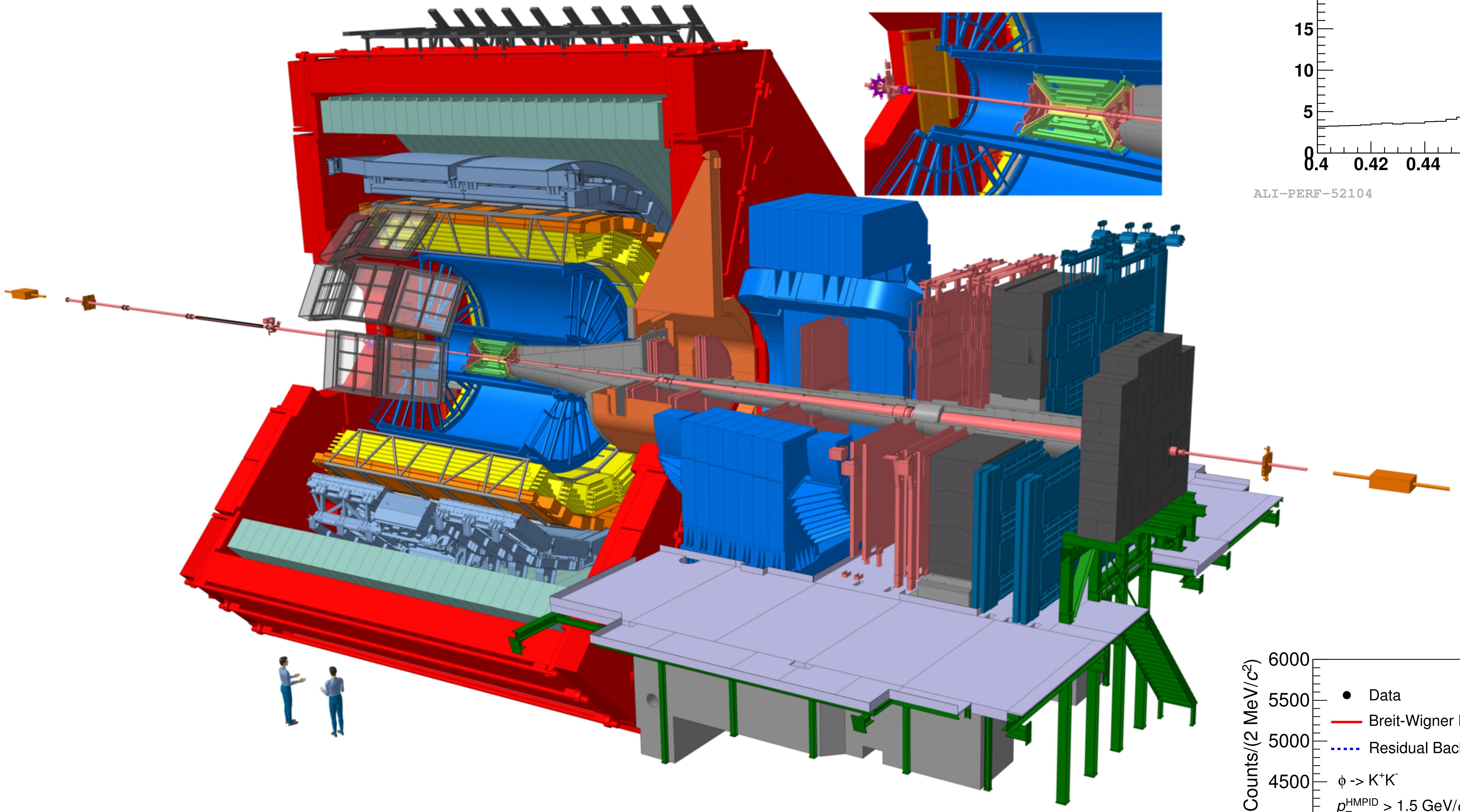

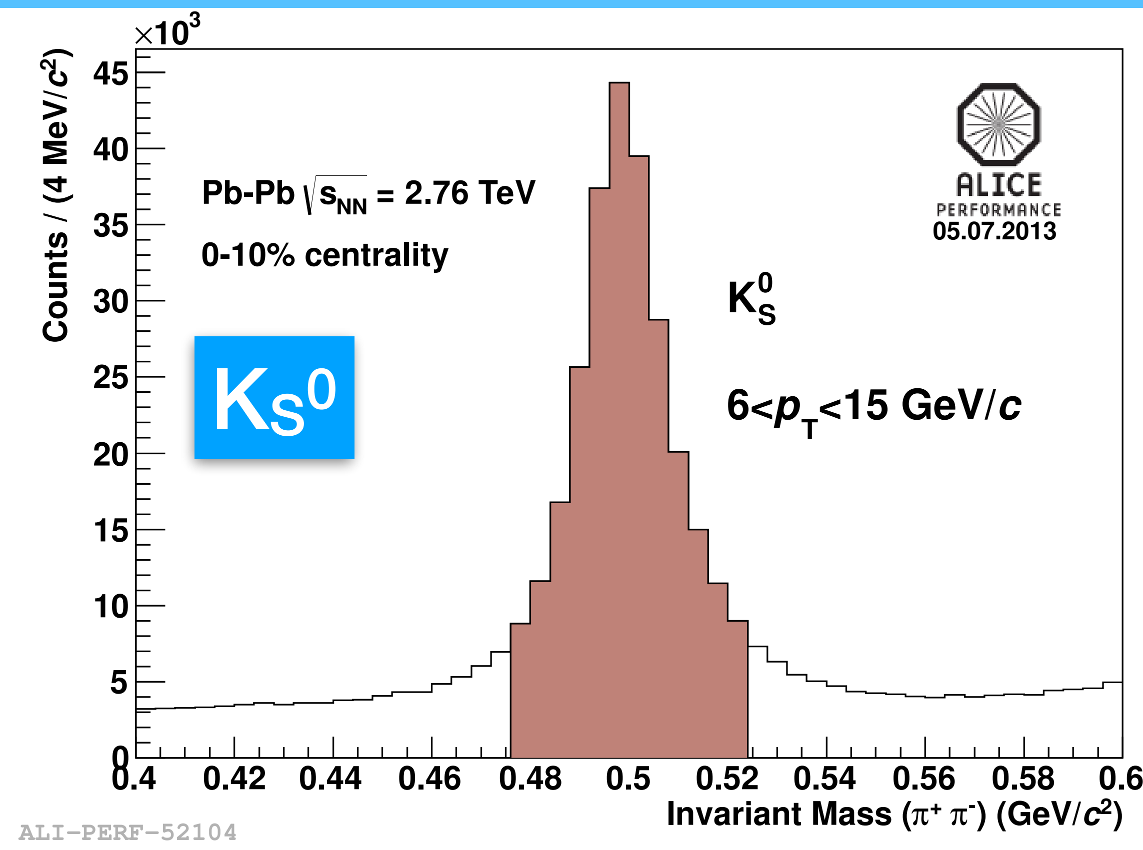

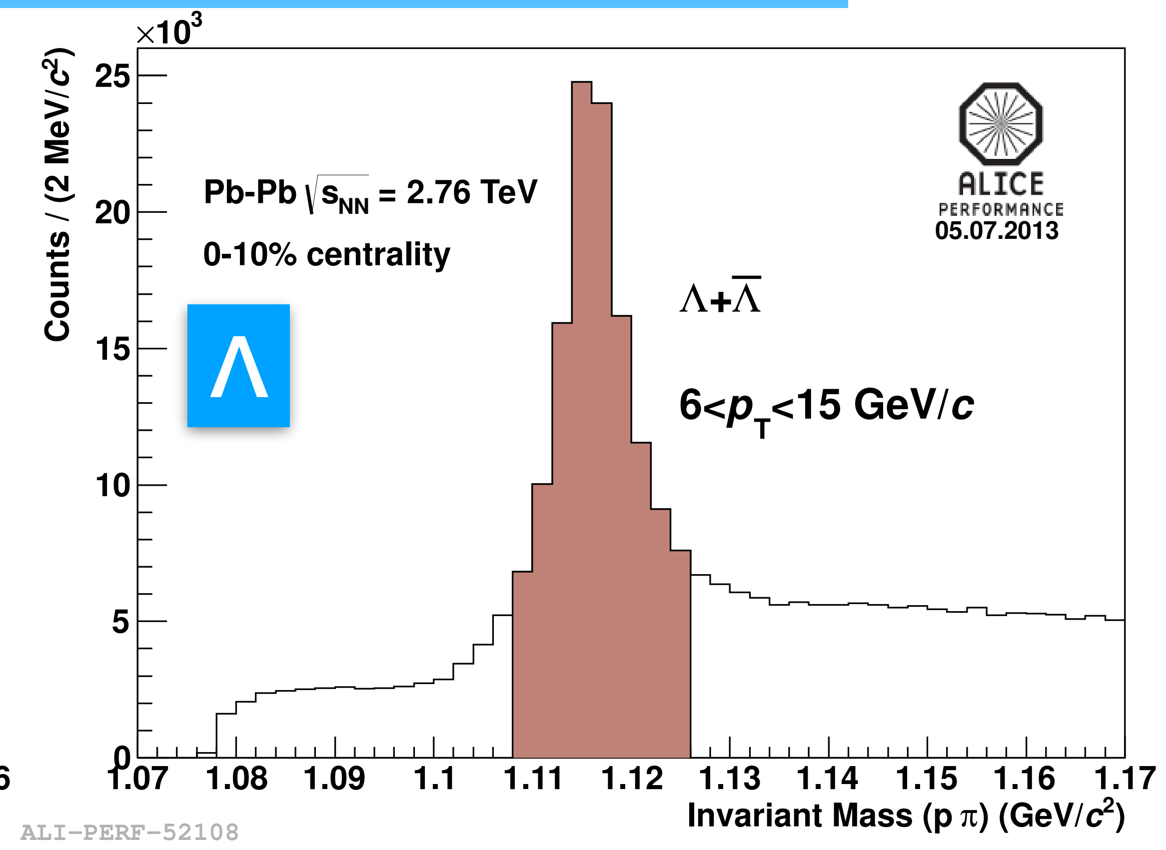

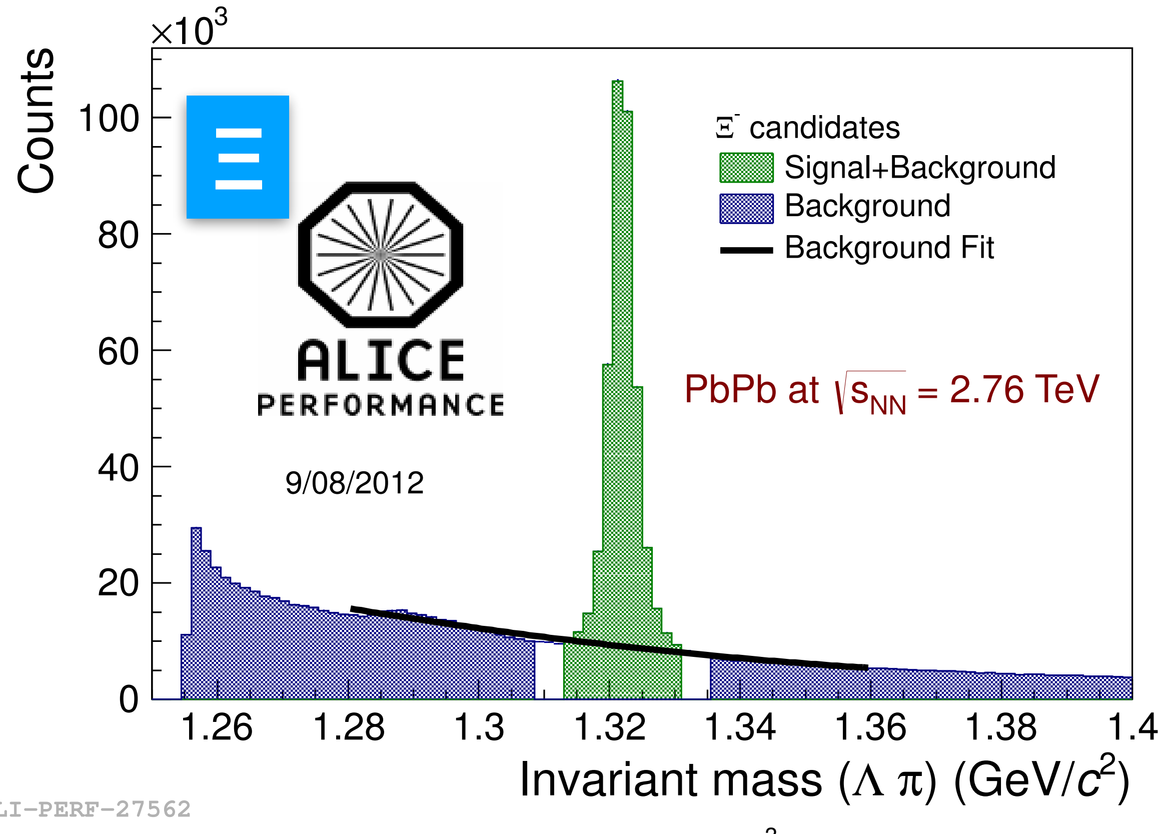

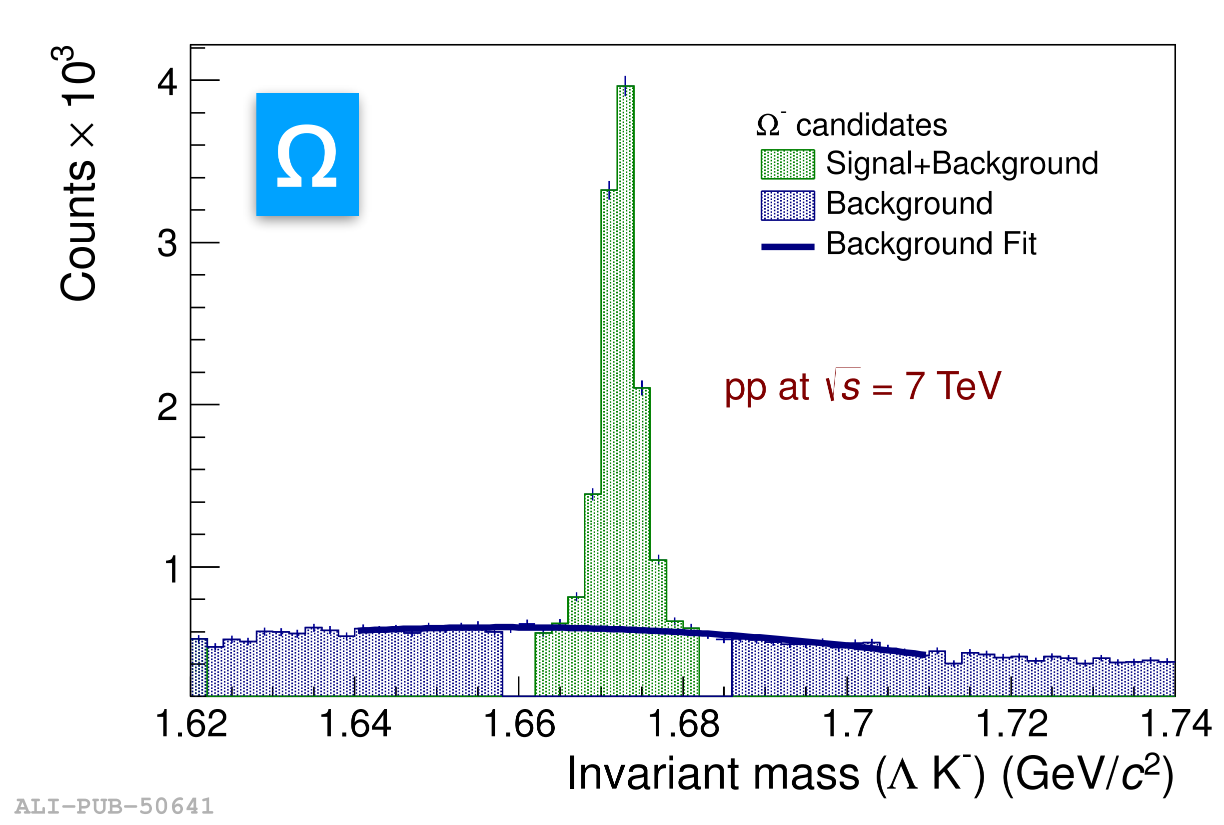

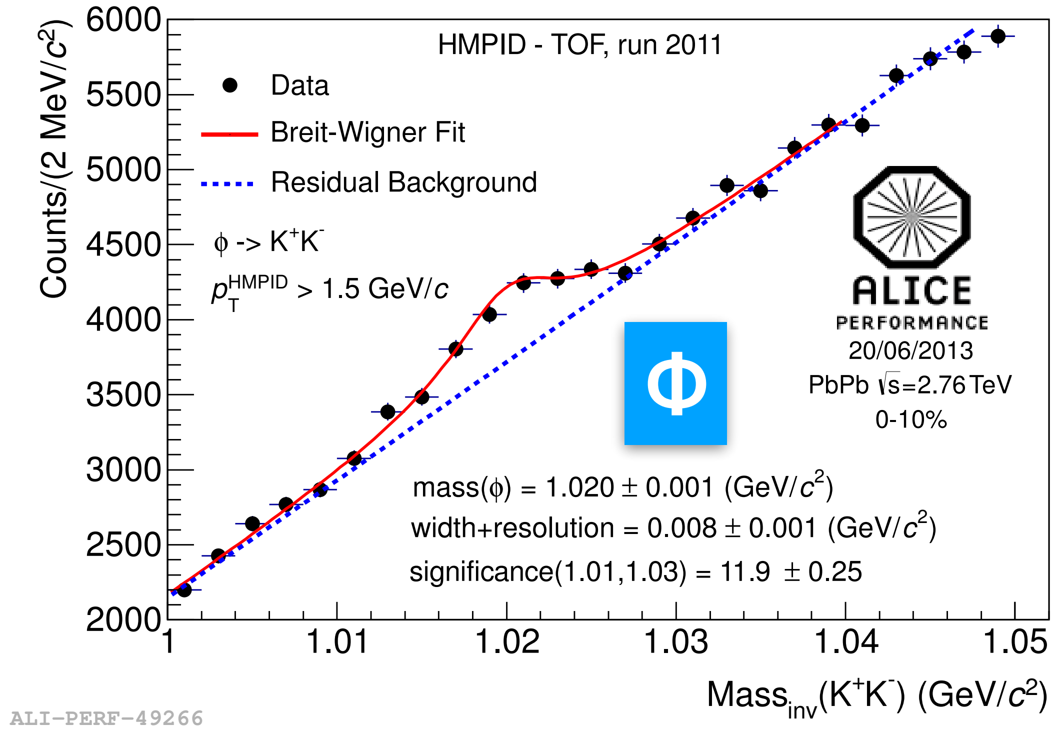

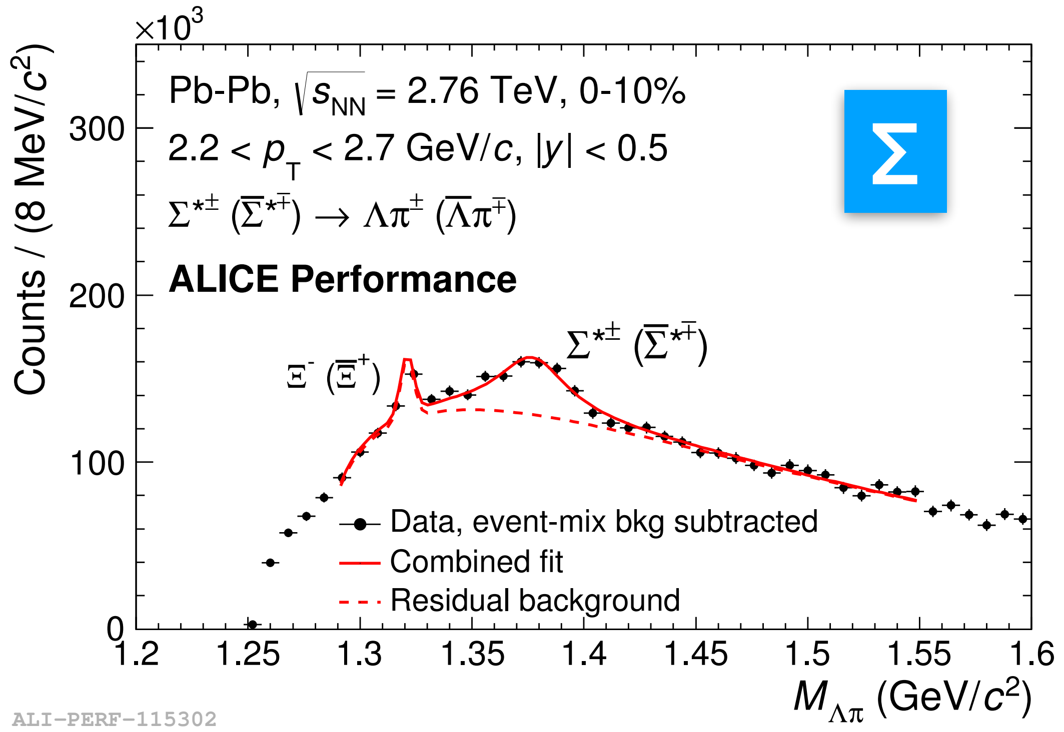

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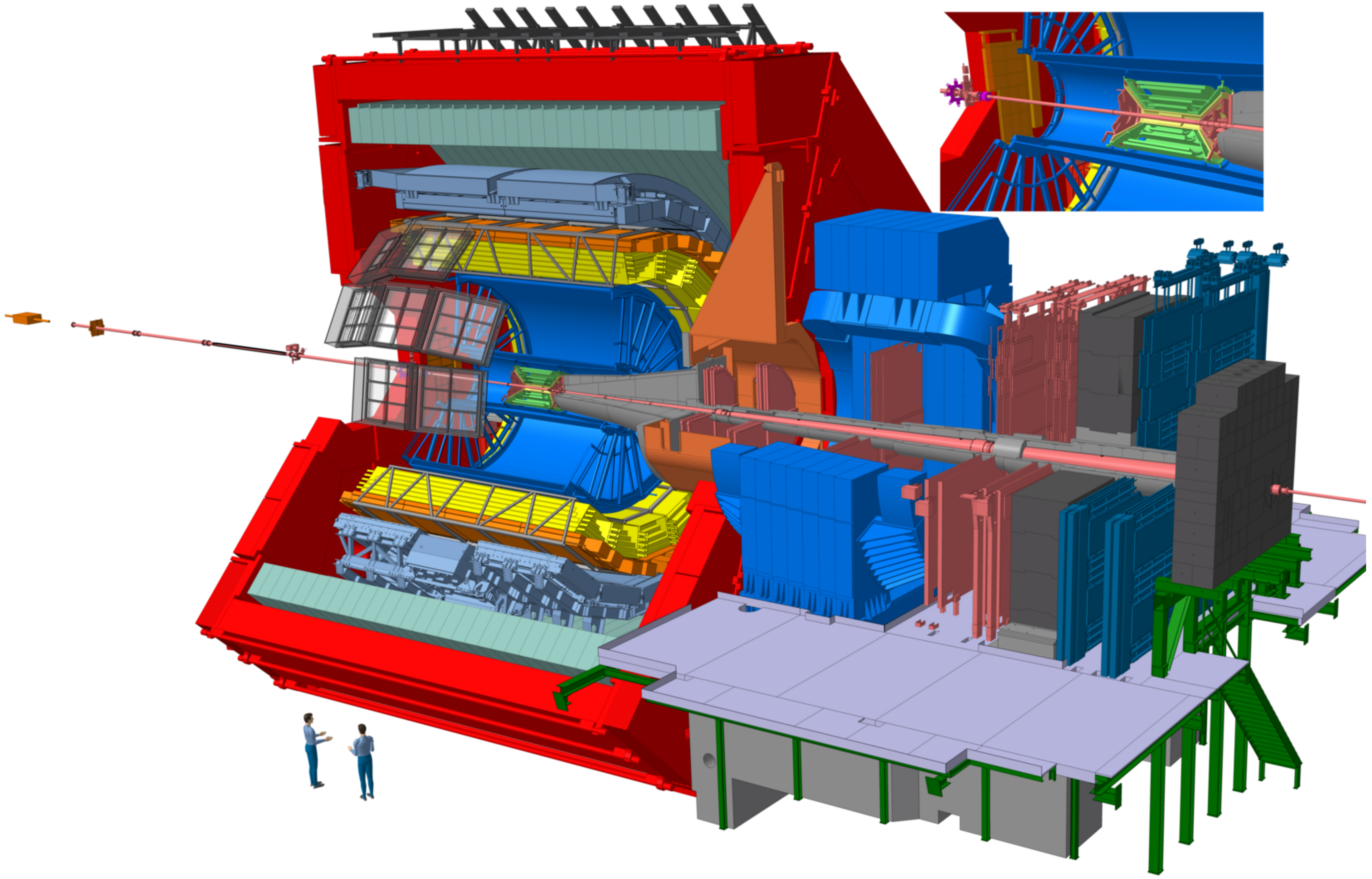

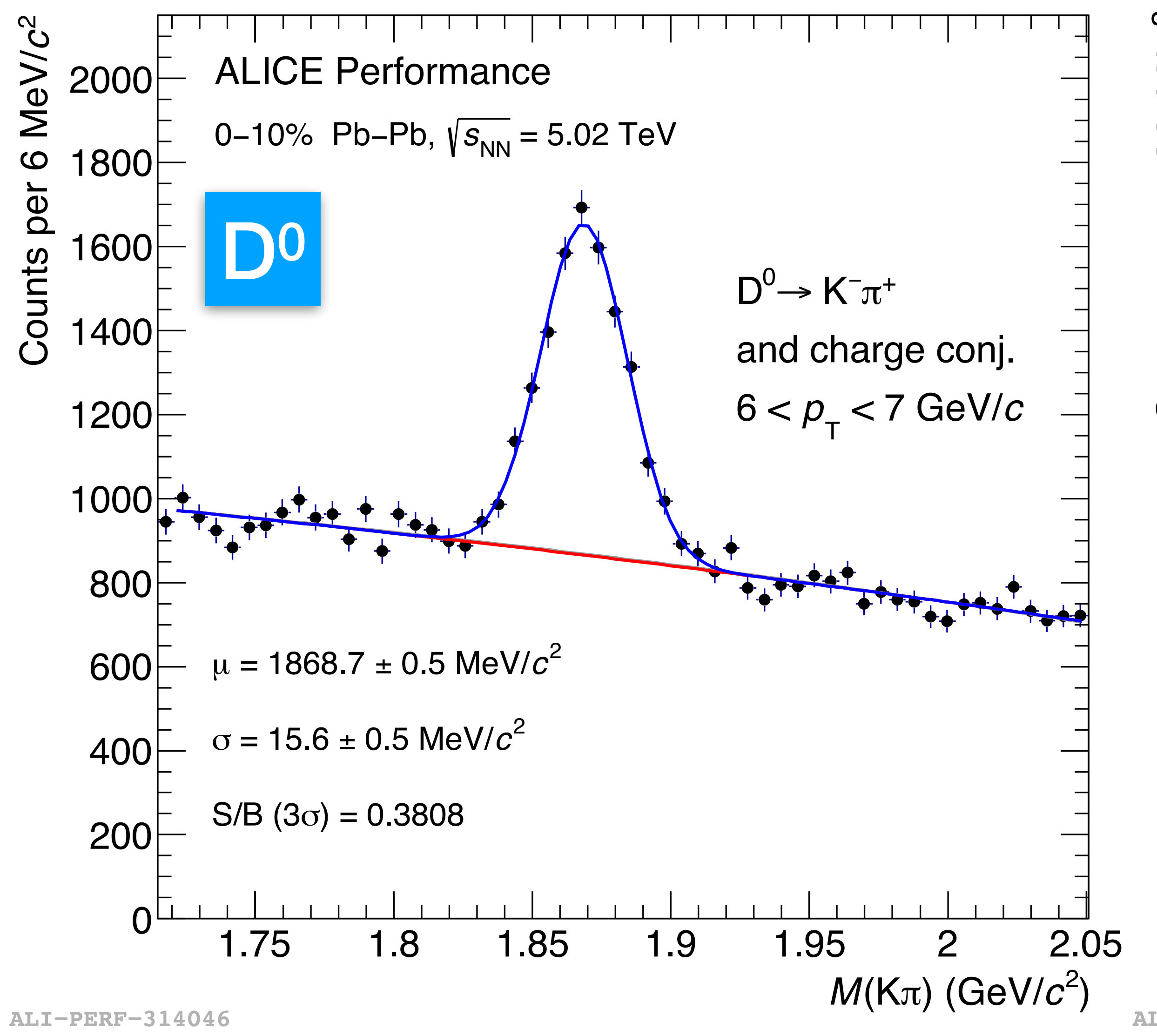

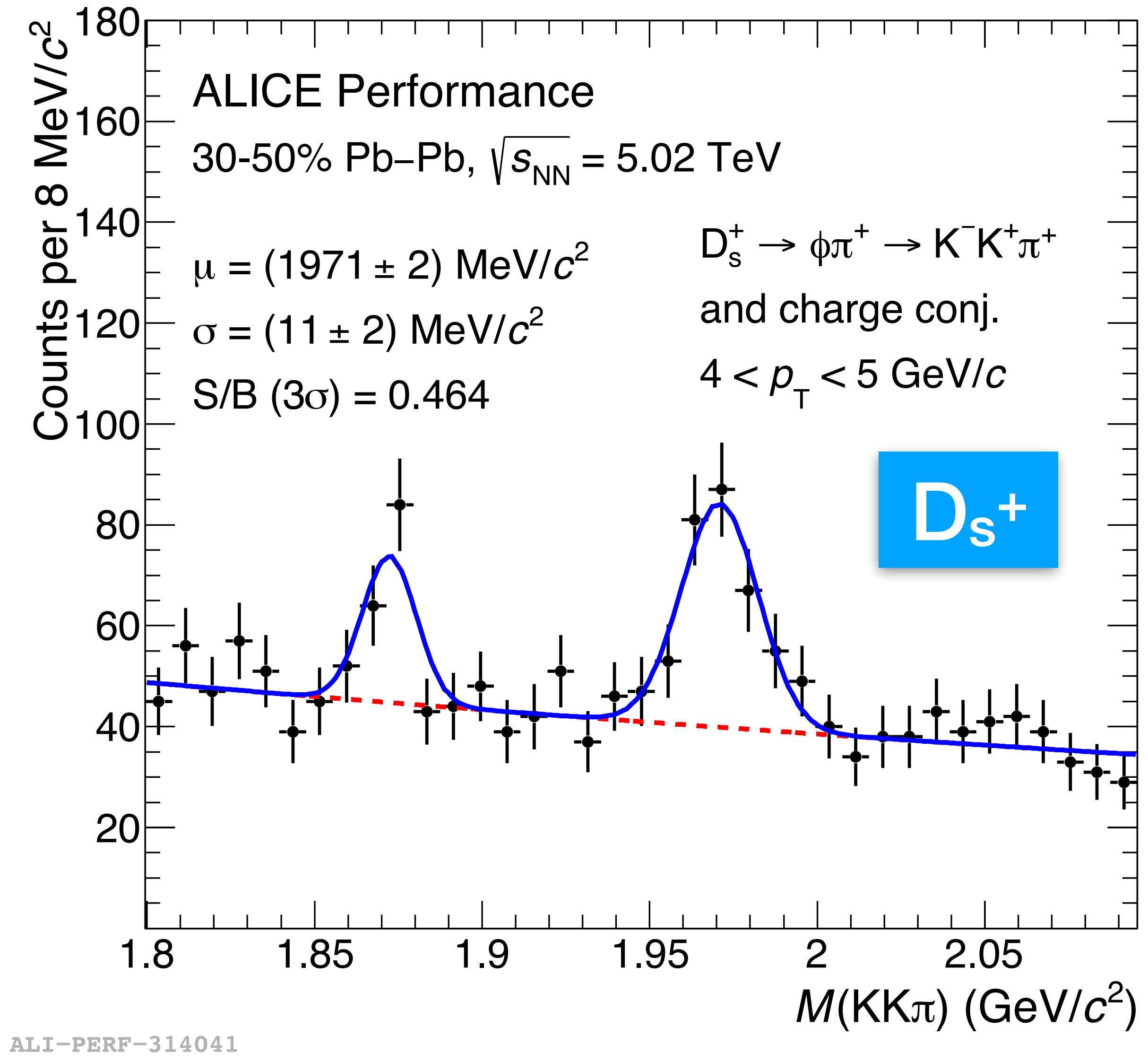

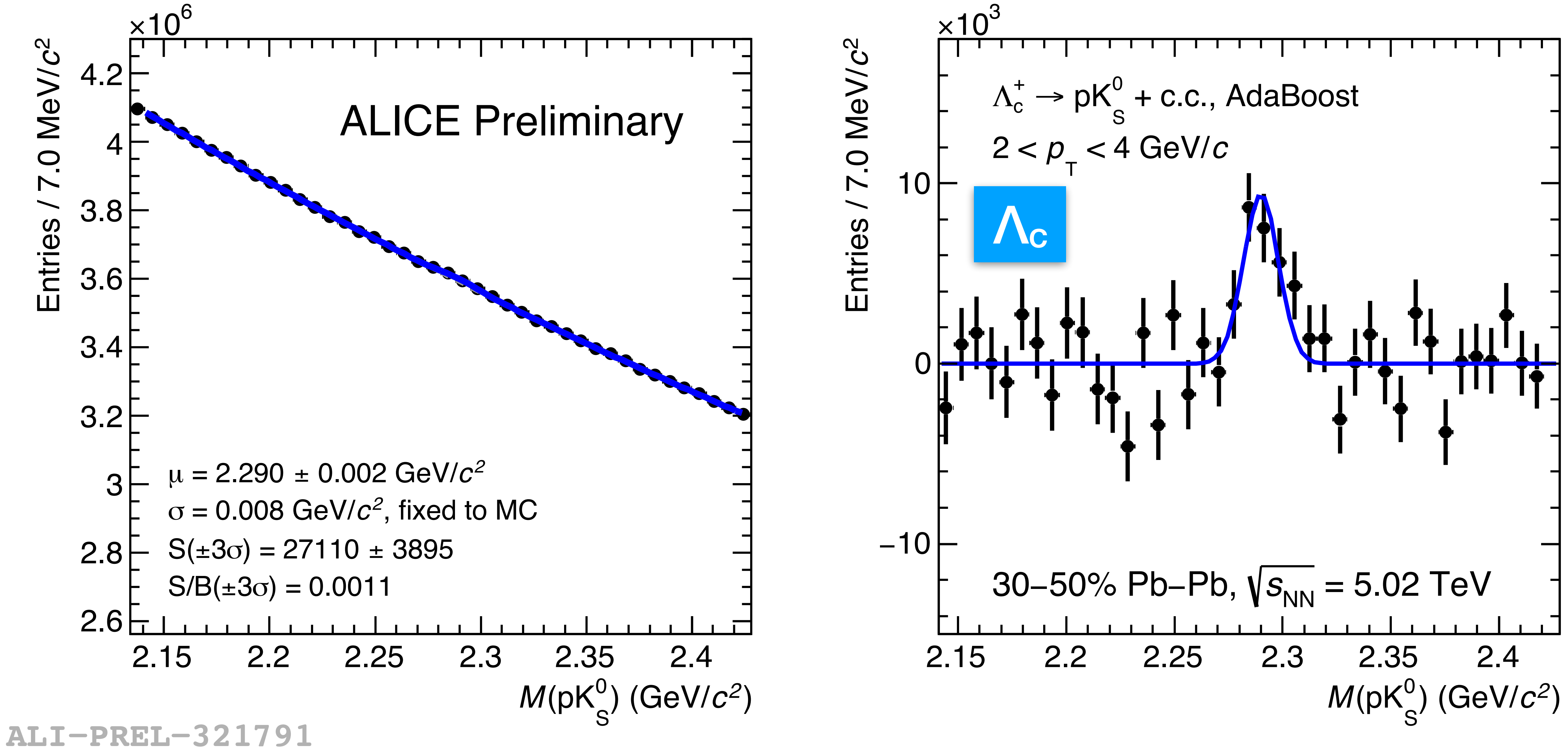

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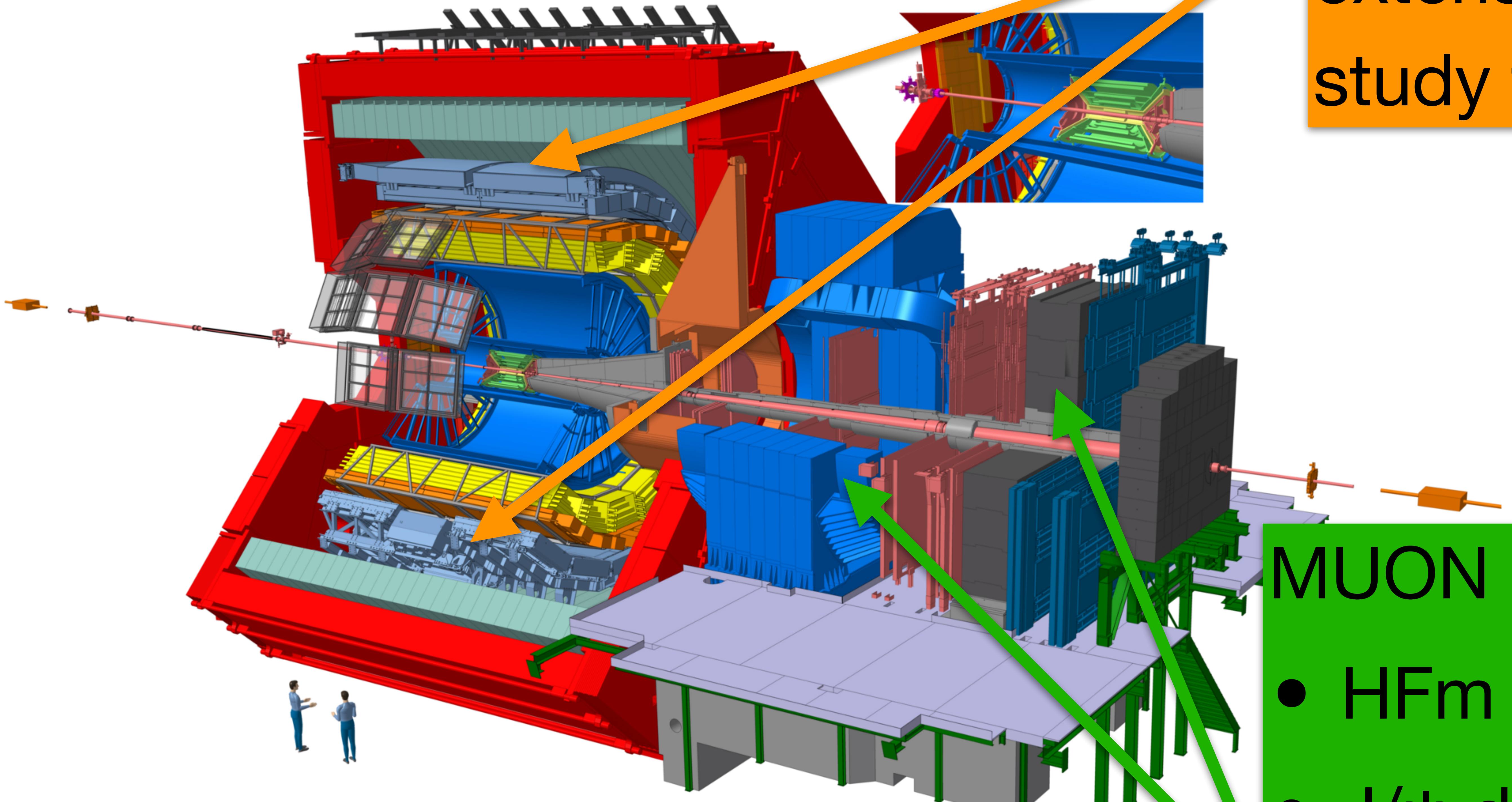
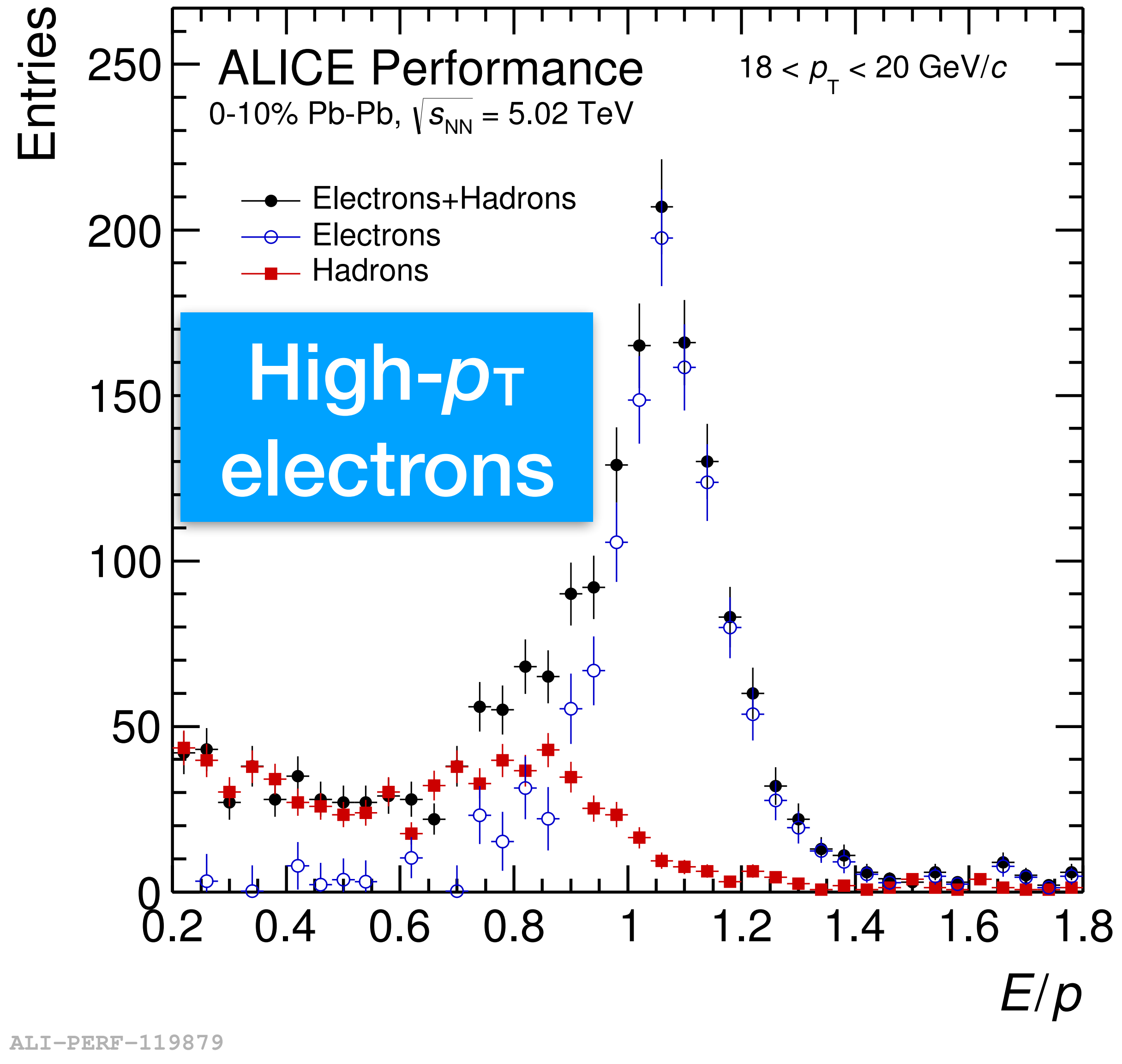
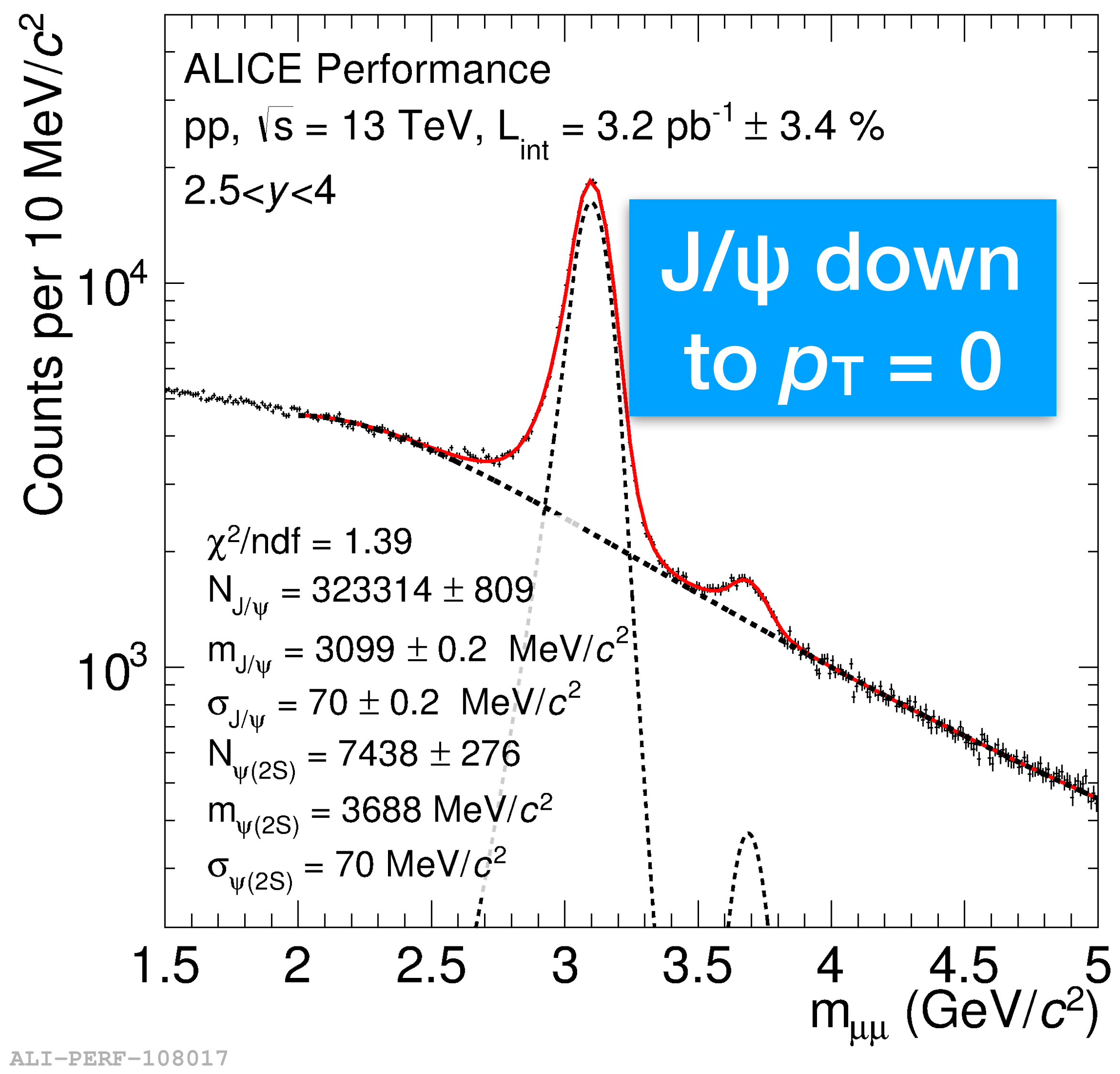


EMCal ($|y| < 0.7$): extension of HFe study to higher p_T

MUON ($2.5 < y < 4$)
- HFm muons
- J/ψ down to $p_T = 0$
- W/Z decay muons





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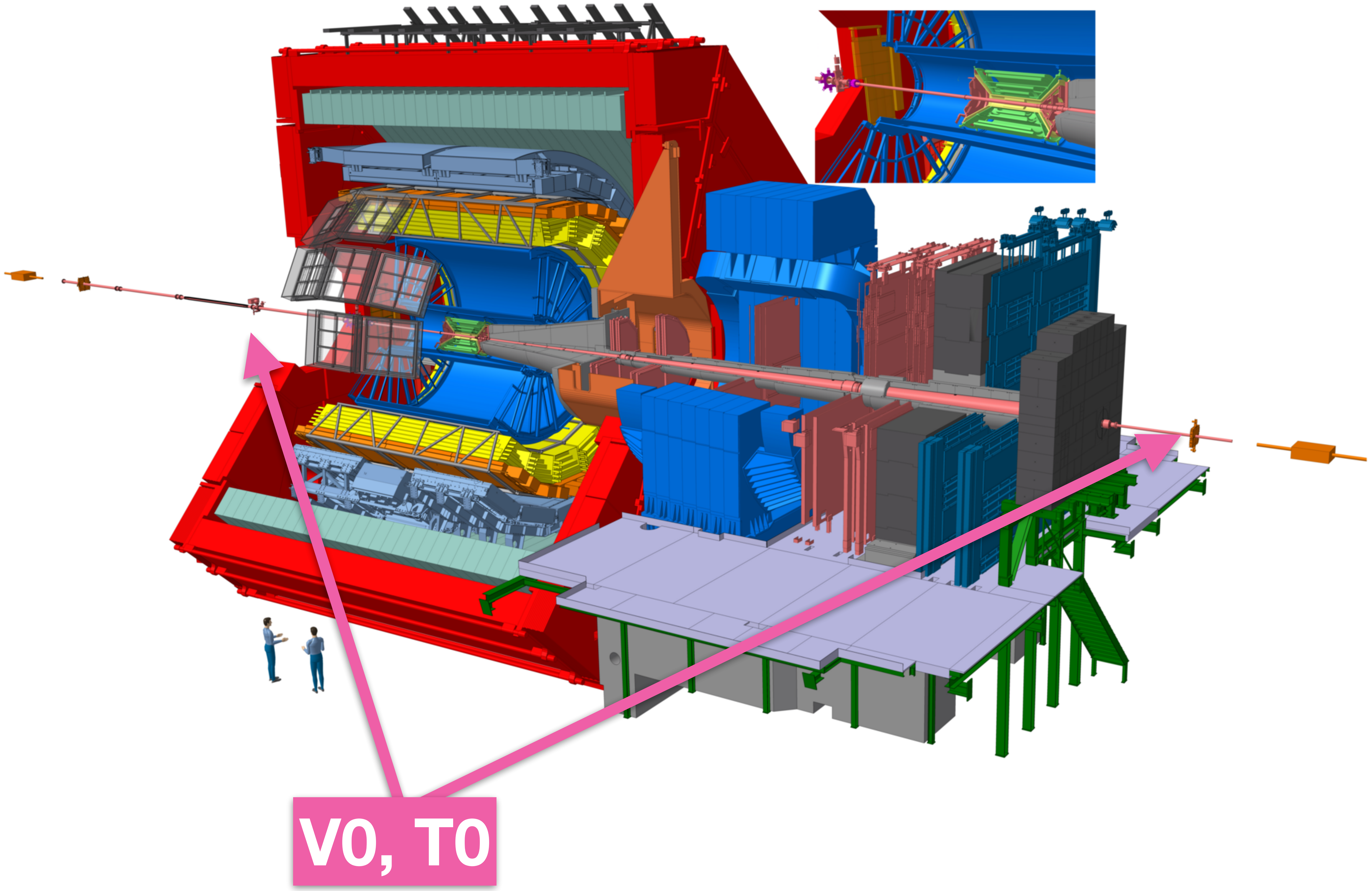
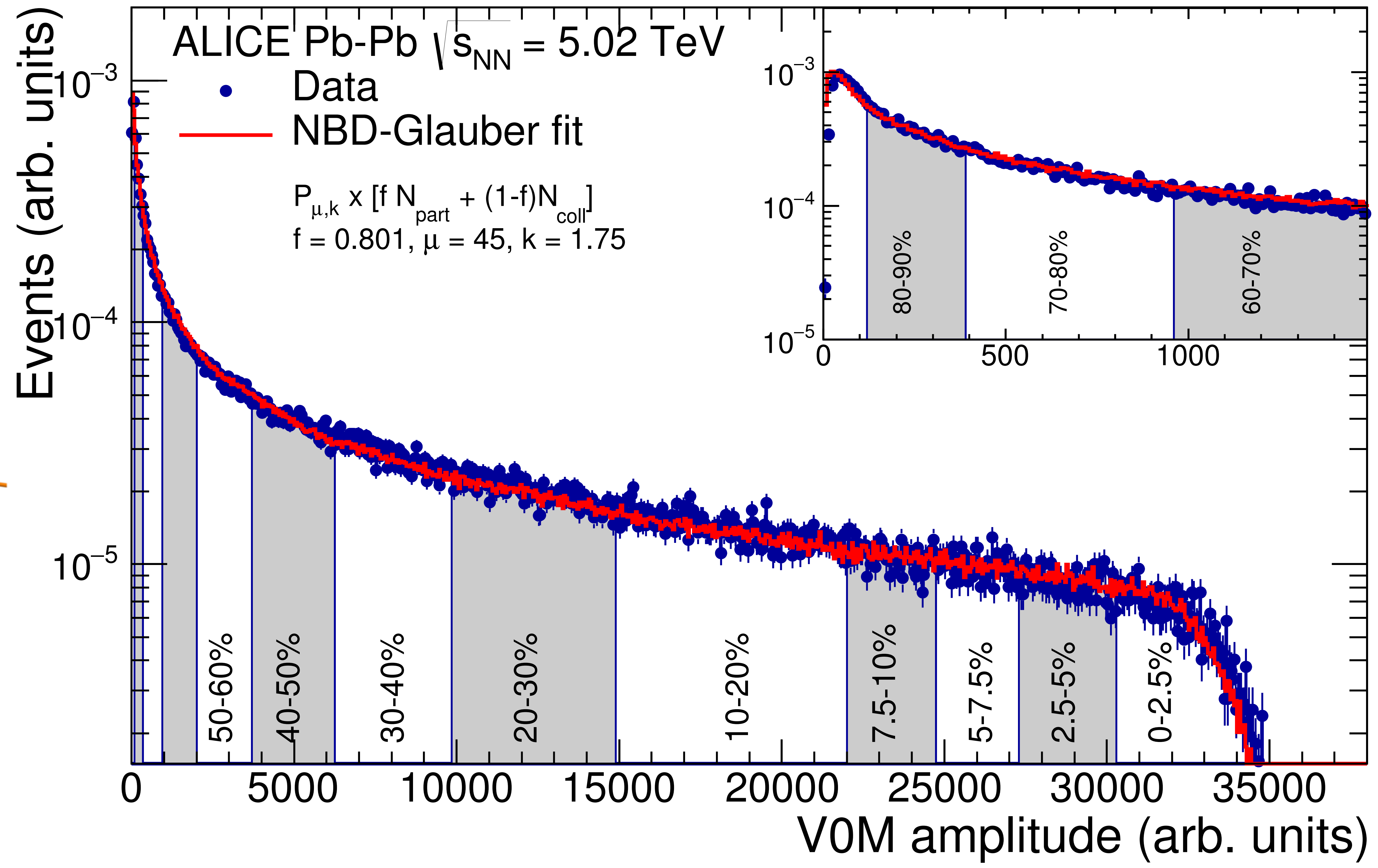
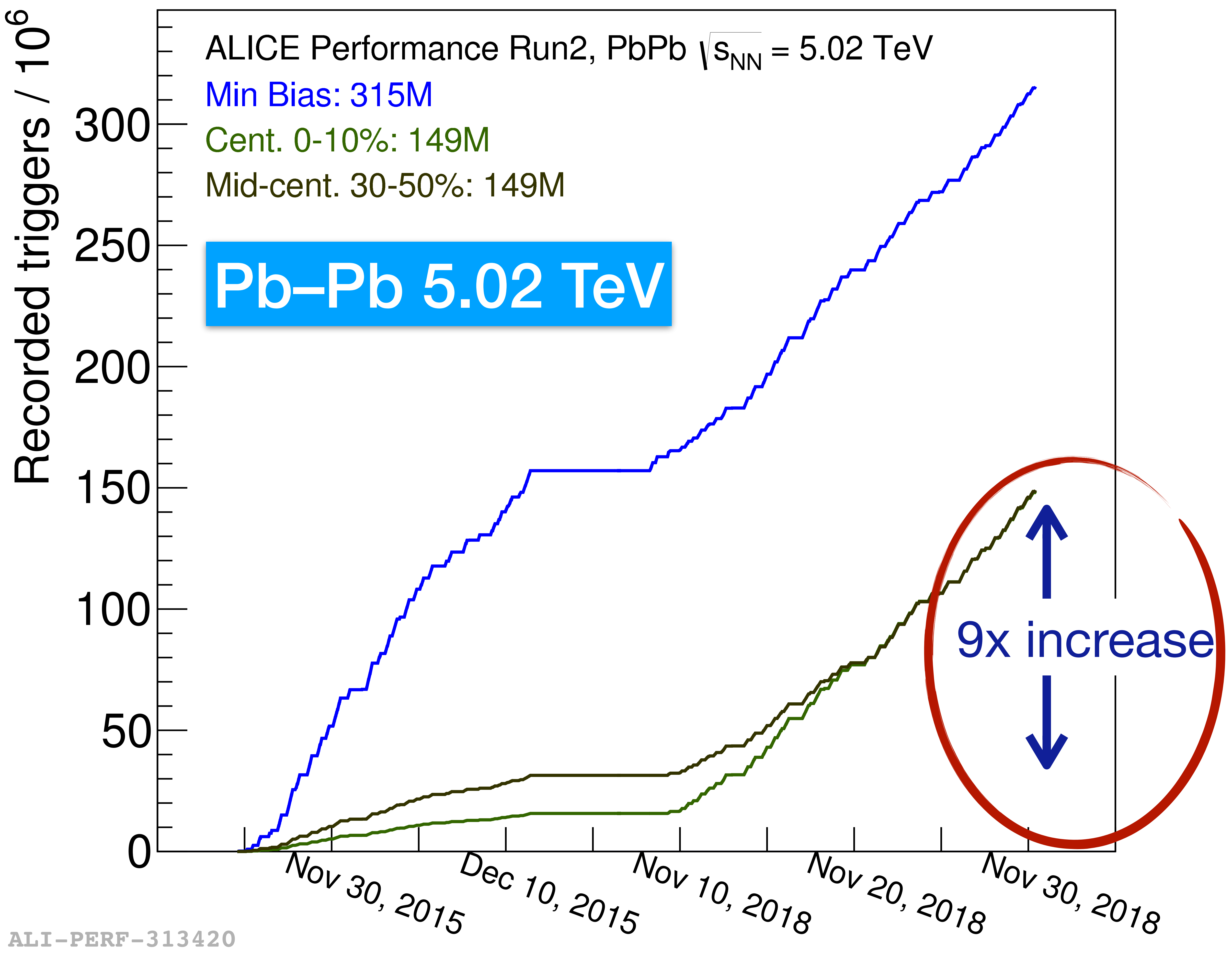




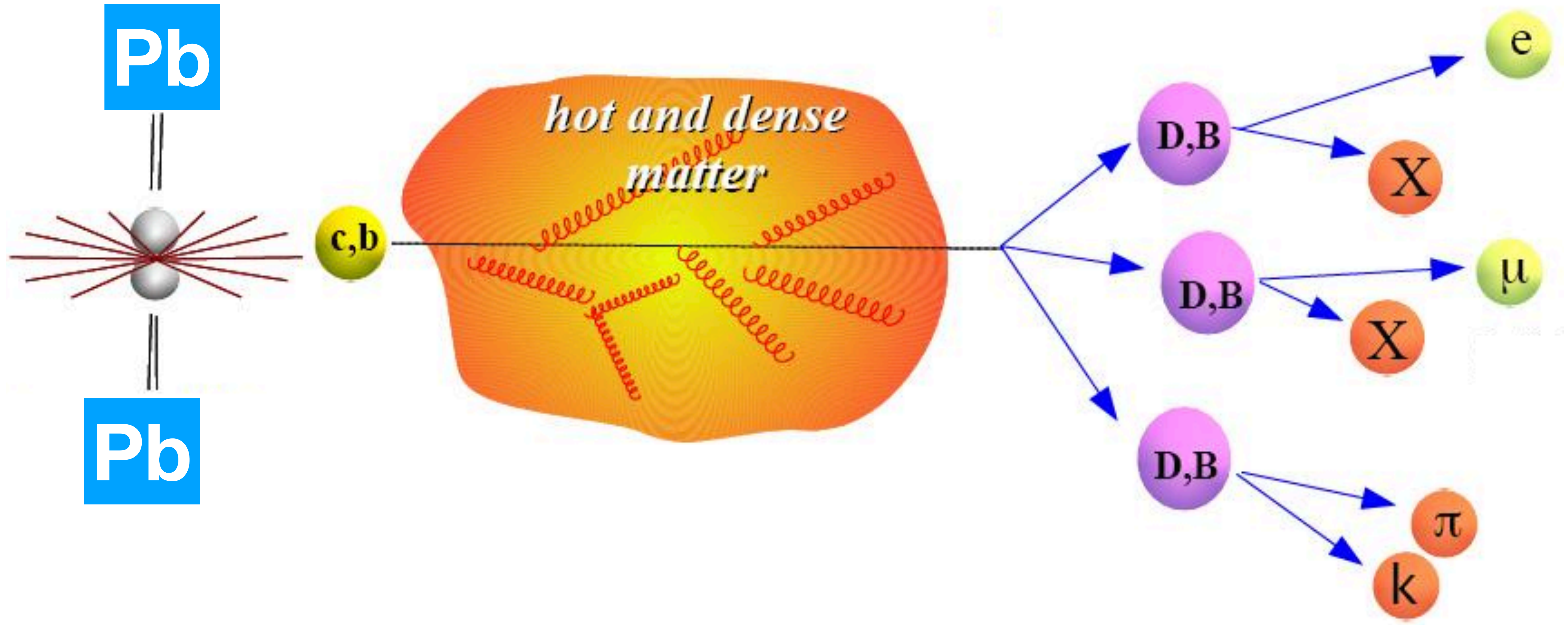
ALICE data collection

System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb–Pb	2018	5.02	~0.9 nb^{-1}
	2015	5.02	~250 μb^{-1}
	2010—2011	2.76	~75 μb^{-1}
Xe–Xe	2017	5.44	~0.3 μb^{-1}
p–Pb	2016	8.16	~25 nb^{-1}
		5.02	~3 nb^{-1}
	2013	5.02	~15 nb^{-1}
pp	2015—2018	13	~59 pb^{-1}
		5.02	~1.3 pb^{-1}
	2009—2013	8	~2.5 pb^{-1}
		7	~1.5 pb^{-1}
		2.76	~100 μb^{-1}
		0.9	~200 μb^{-1}



Open heavy-flavour production

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



Total charm cross section in HIC is expected to scale w. r. t. the number of binary collisions in pp-like collisions

- Produced in initial hard scatterings (high Q^2) at the early stage of heavy-ion collisions: $\tau_{c/b}$ ~0.01 — 0.1 fm/c < τ_{QGP} (~0.3 fm/c)
- Production cross section calculable with pQCD (m_c, $m_b \gg \Lambda_{QCD}$)
- Experience the entire evolution of the QCD medium — probe transport properties of the deconfined medium

Open heavy-flavour production

Nuclear modification factor (R_{AA}): heavy quark in-medium energy loss

- Elastic (radiative) vs. inelastic (collisional) processes
- Color charge (Casimir factor) and mass (eg dead-cone effect) dependence
- Sensitive to the presence of the medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

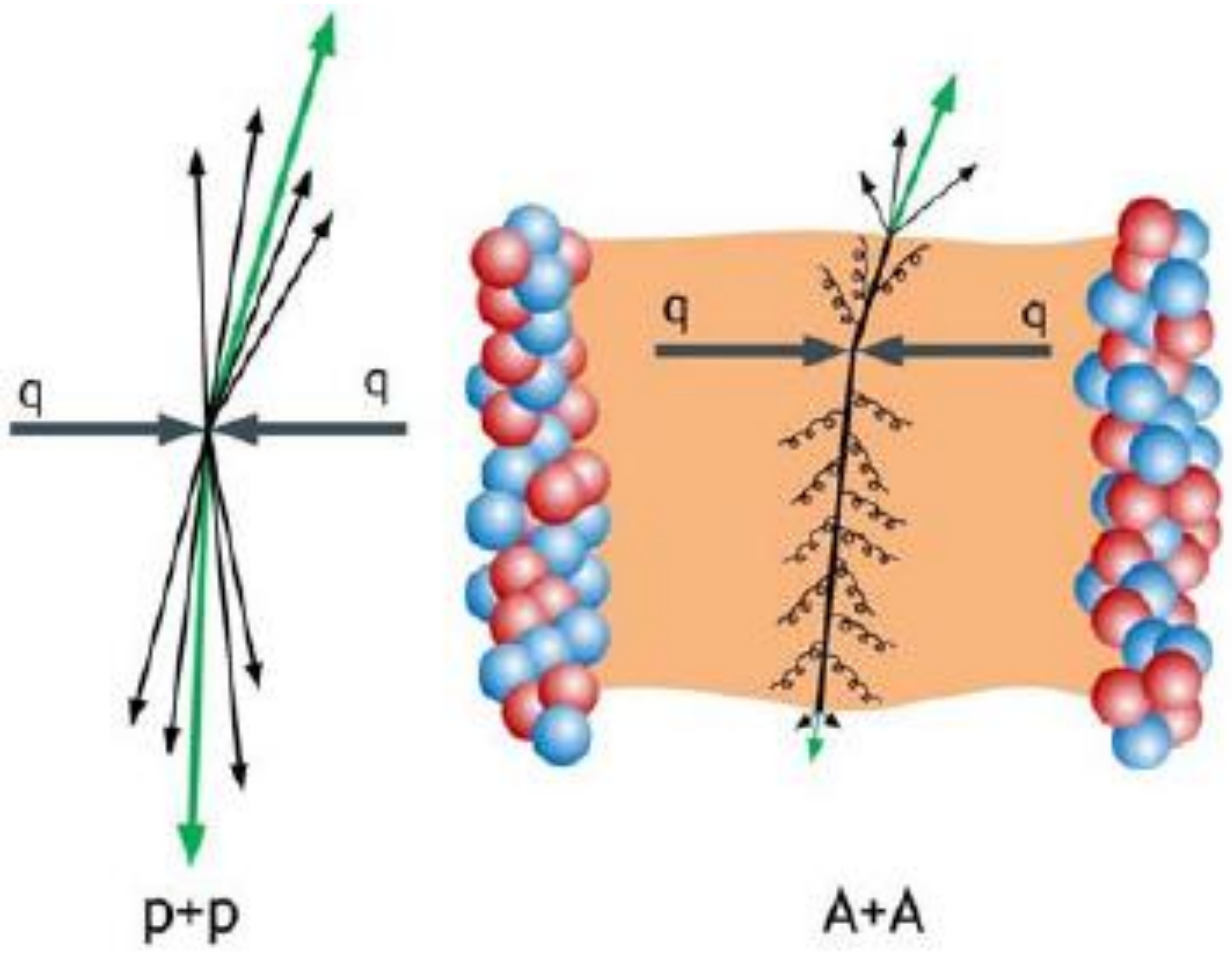
QCD medium

QCD vacuum

- R_{AA} = 1, if no medium modification

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

➡ R_{AA}(light hadron) < R_{AA}(D) < R_{AA}(B) ?

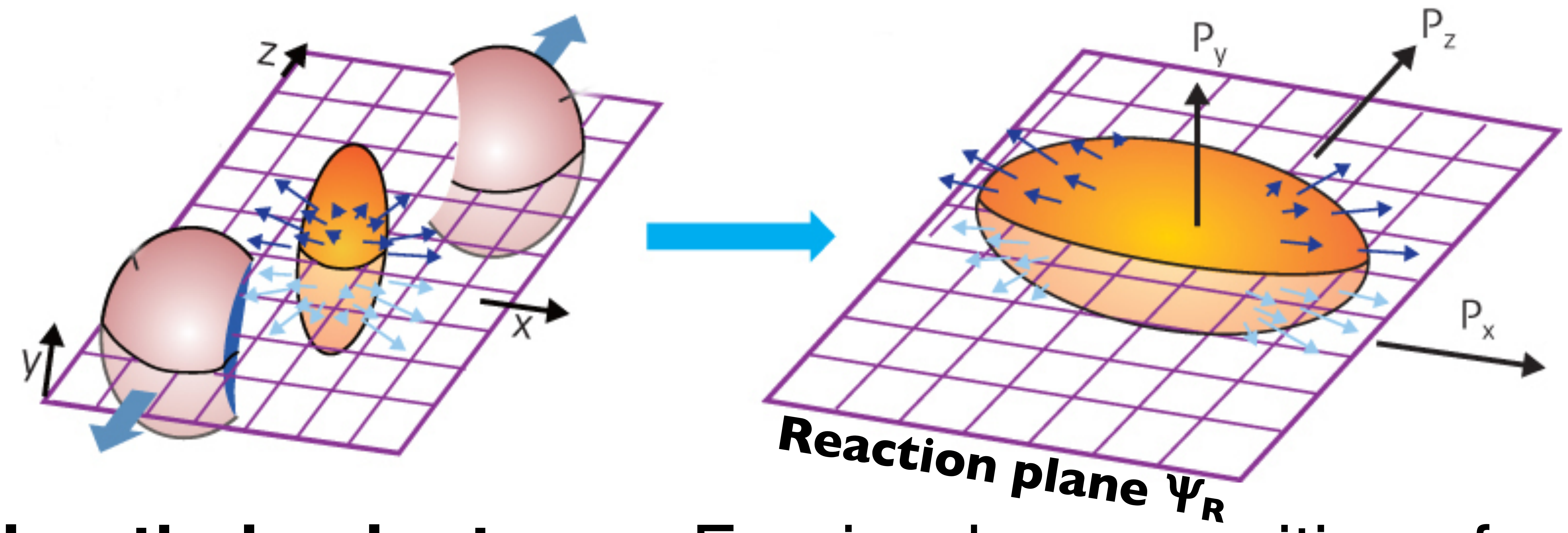


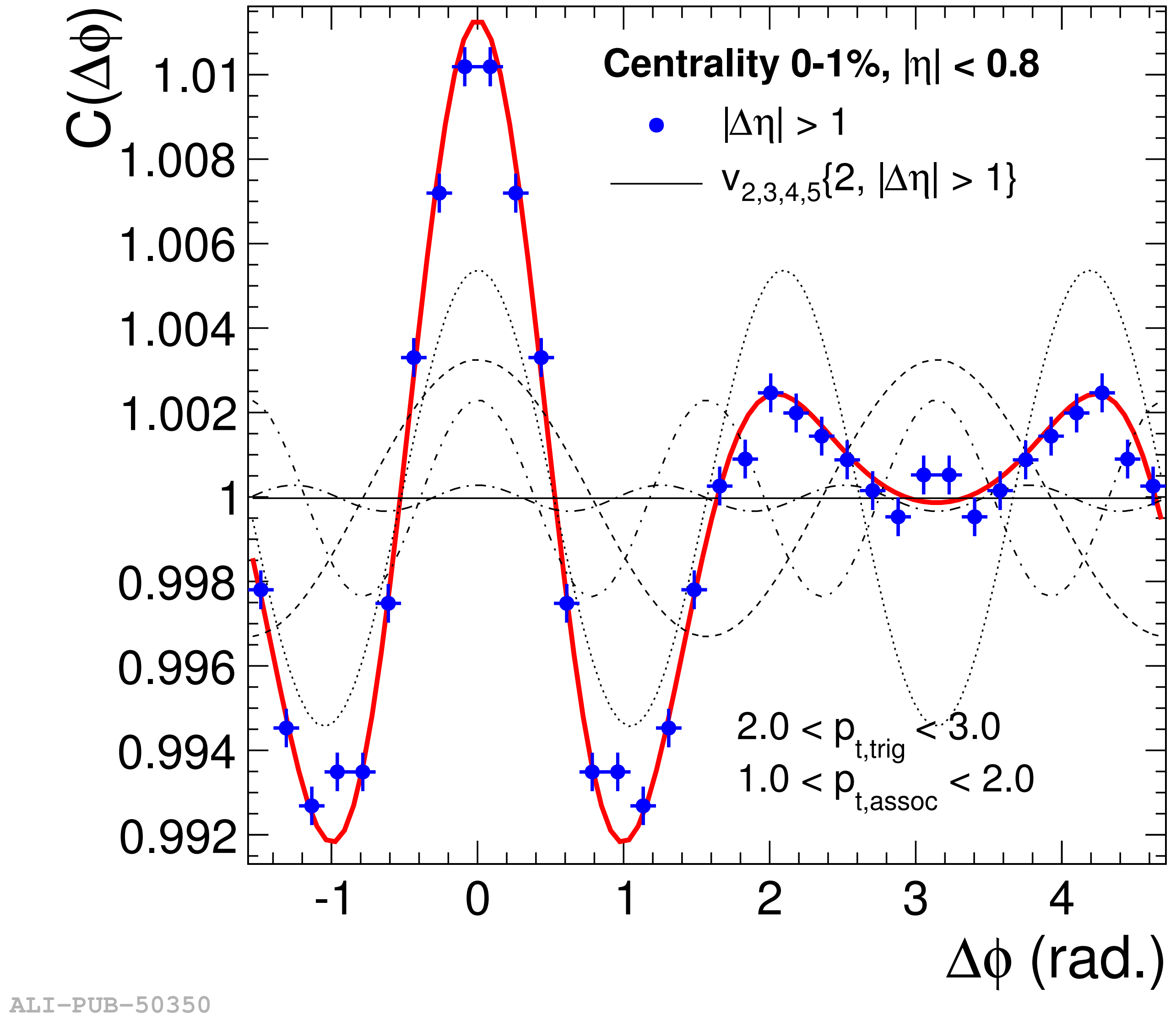
Medium modification of heavy-flavour hadron production

- Hadronization via coalescence may modify the D_s^+ / non-strange D and Λ_c / D ratios

Open heavy-flavour production

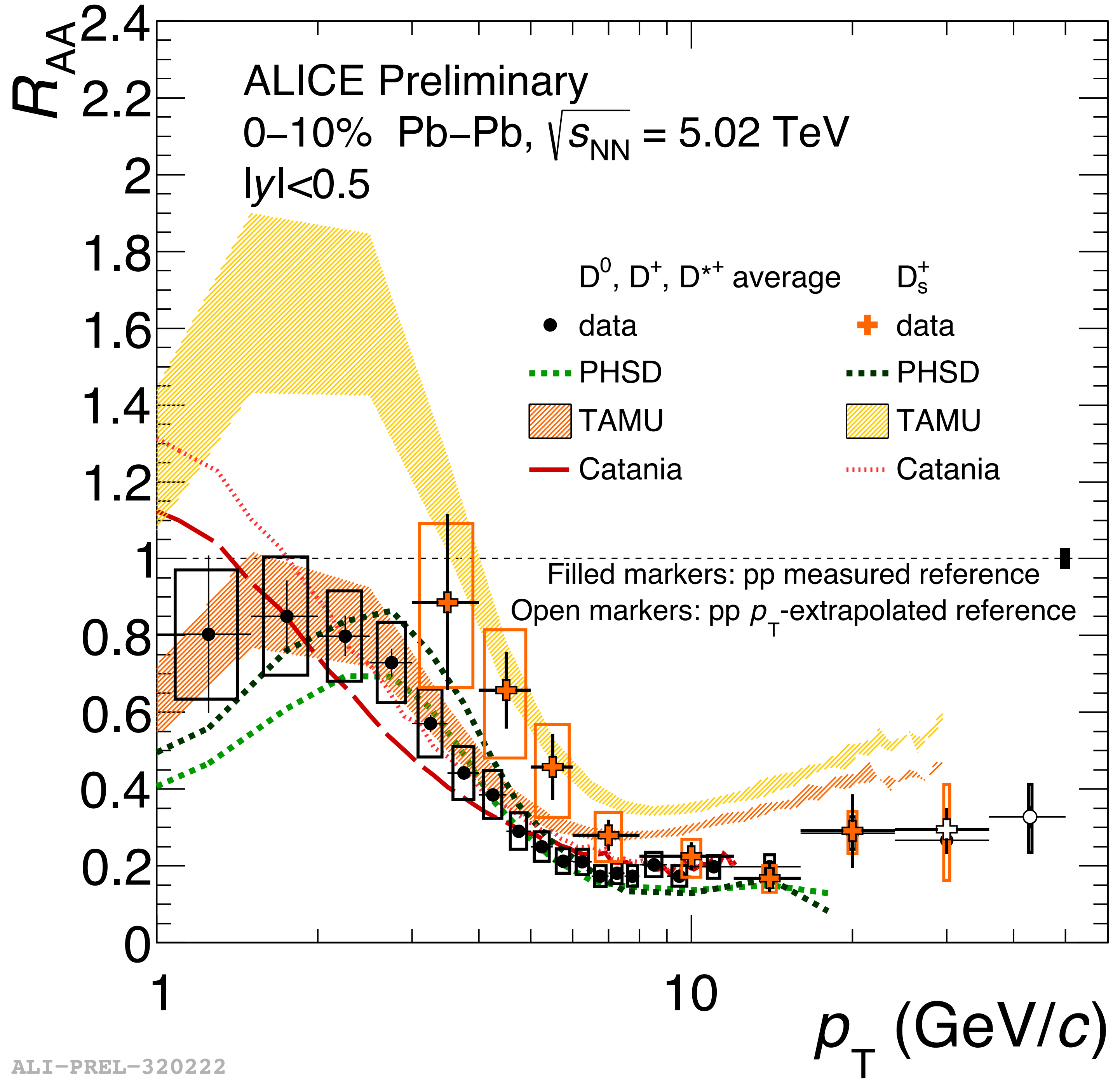
$$E\frac{d^3\sigma}{d^3\vec{p}} = \frac{d^2\sigma}{2\pi p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos n(\varphi - \Psi_R)\right]$$

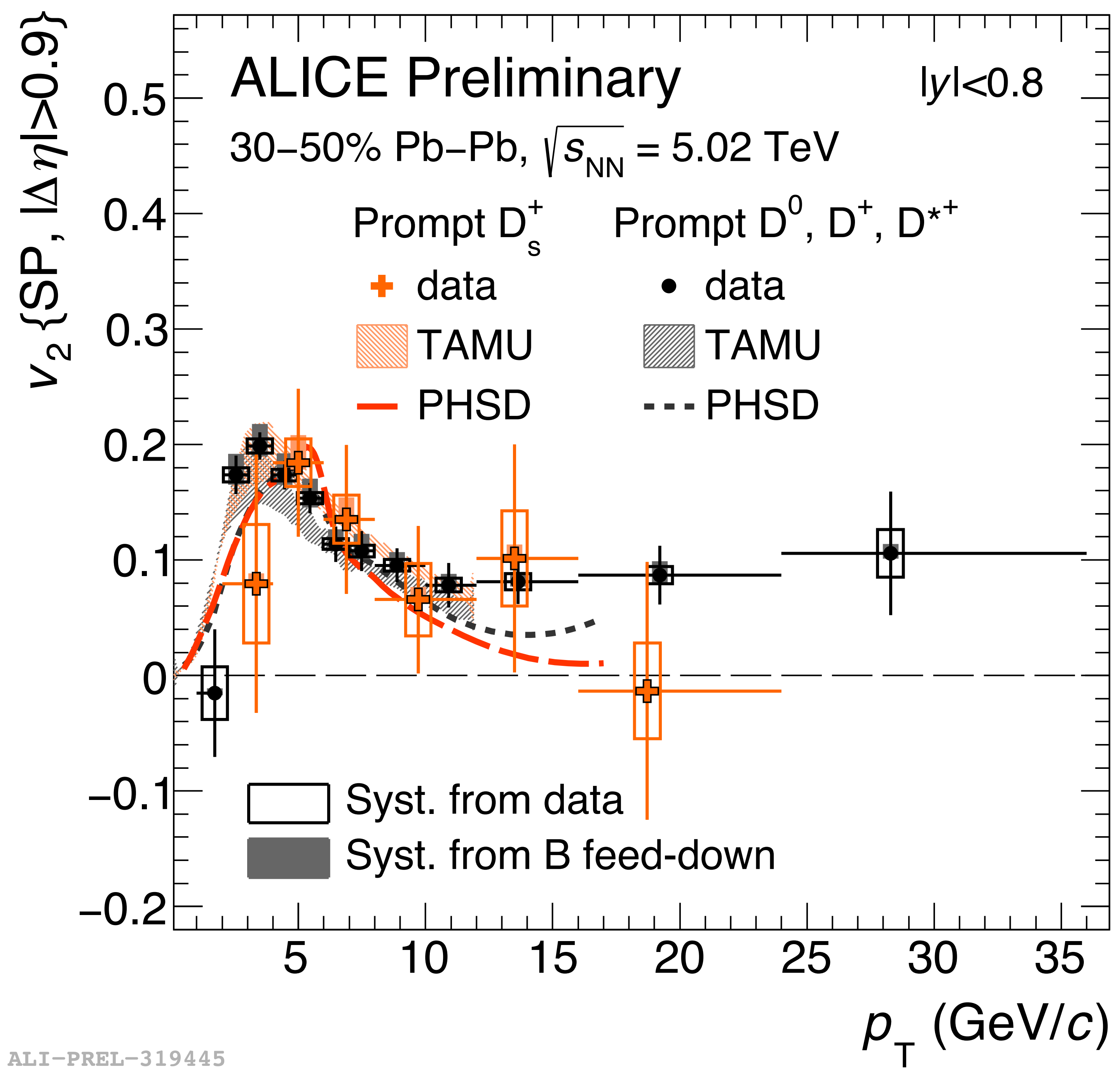




Azimuthal anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP})

- Elliptic flow (v_2): second order Fourier coefficient
  - ➡ Low and intermediate p_T: collective motion and possible heavy-quark thermalization in the QCD medium
  - ➡ High p_T: path-length dependence of heavy-quark in-medium energy loss

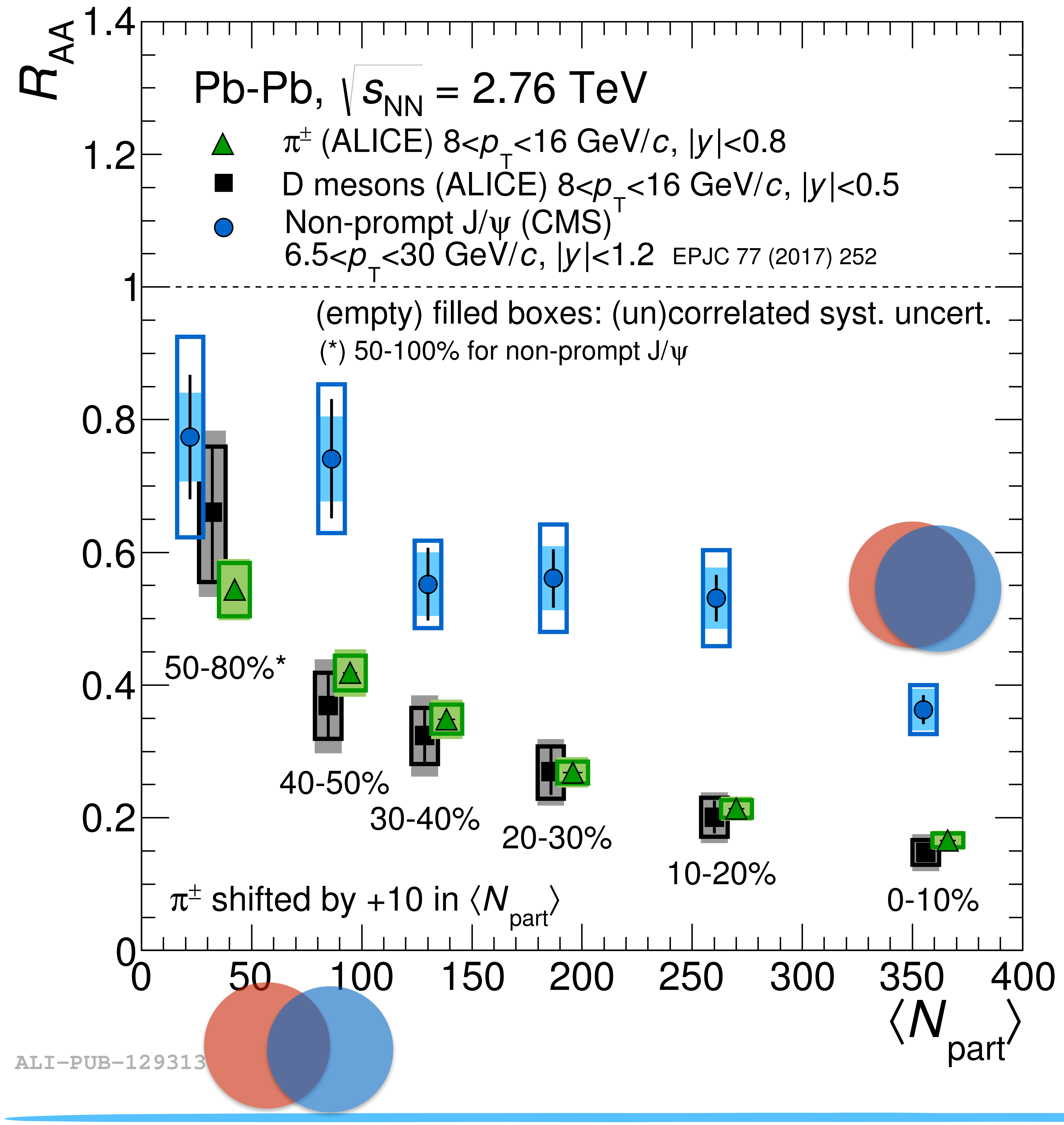




- Simultaneous description D_s^+ and non-strange D R_{AA} and v_2
  - ➡ Constrain interplay of coalescence and collisional energy loss + medium flow
  - ➡ Charm quark diffusion coefficient at the LHC: (1.5 – 7) / $2\pi T_c$

- Strong suppression: charm undergone significant interactions in the QGP
  - ➡ Indication of $R_{AA}(D_s^+)$ > R_{AA}(non-strange D): charm hadronization through recombination in medium
- Same v_2 of D_s^+ and non-strange D mesons within uncertainties in p_T > 3 GeV/c

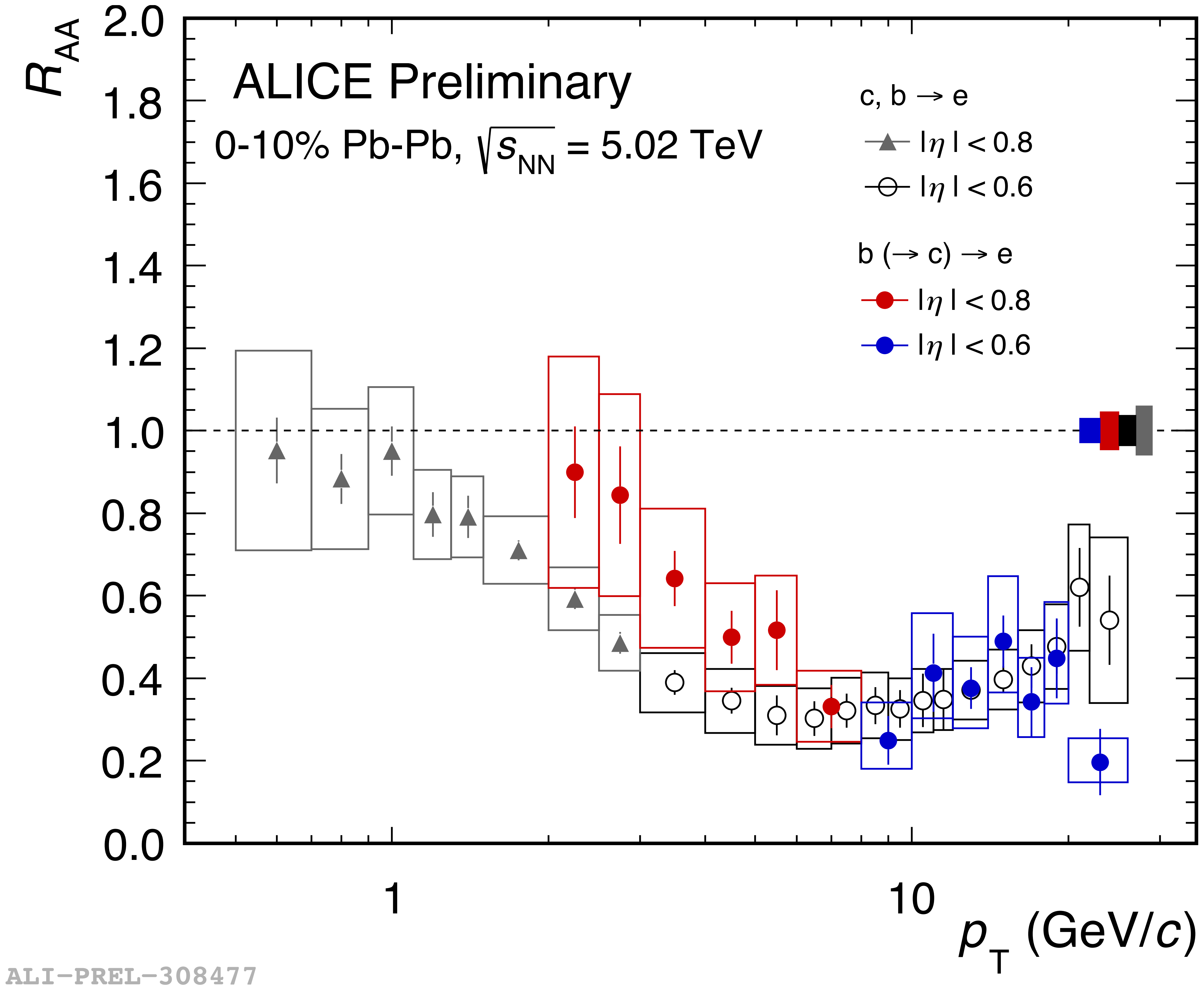
Open heavy-flavour energy loss

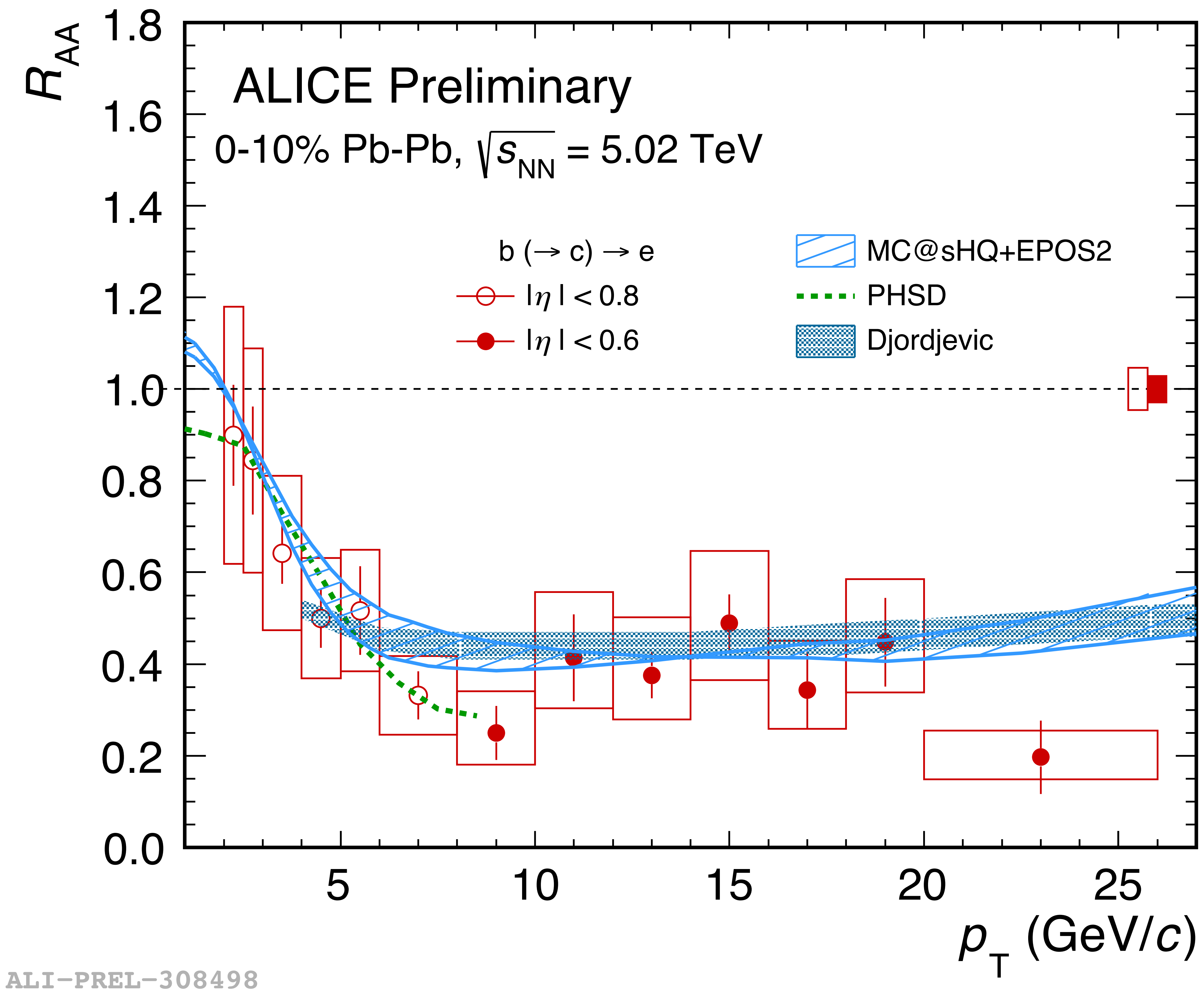


- R_{AA} of D mesons systematically smaller than non-prompt J/ψ at high p_T
  - ➡ Indication of mass-dependent suppression for charm and beauty

- R_{AA}(D) ~ R_{AA}(π) — different parton p_T distribution and fragmentation

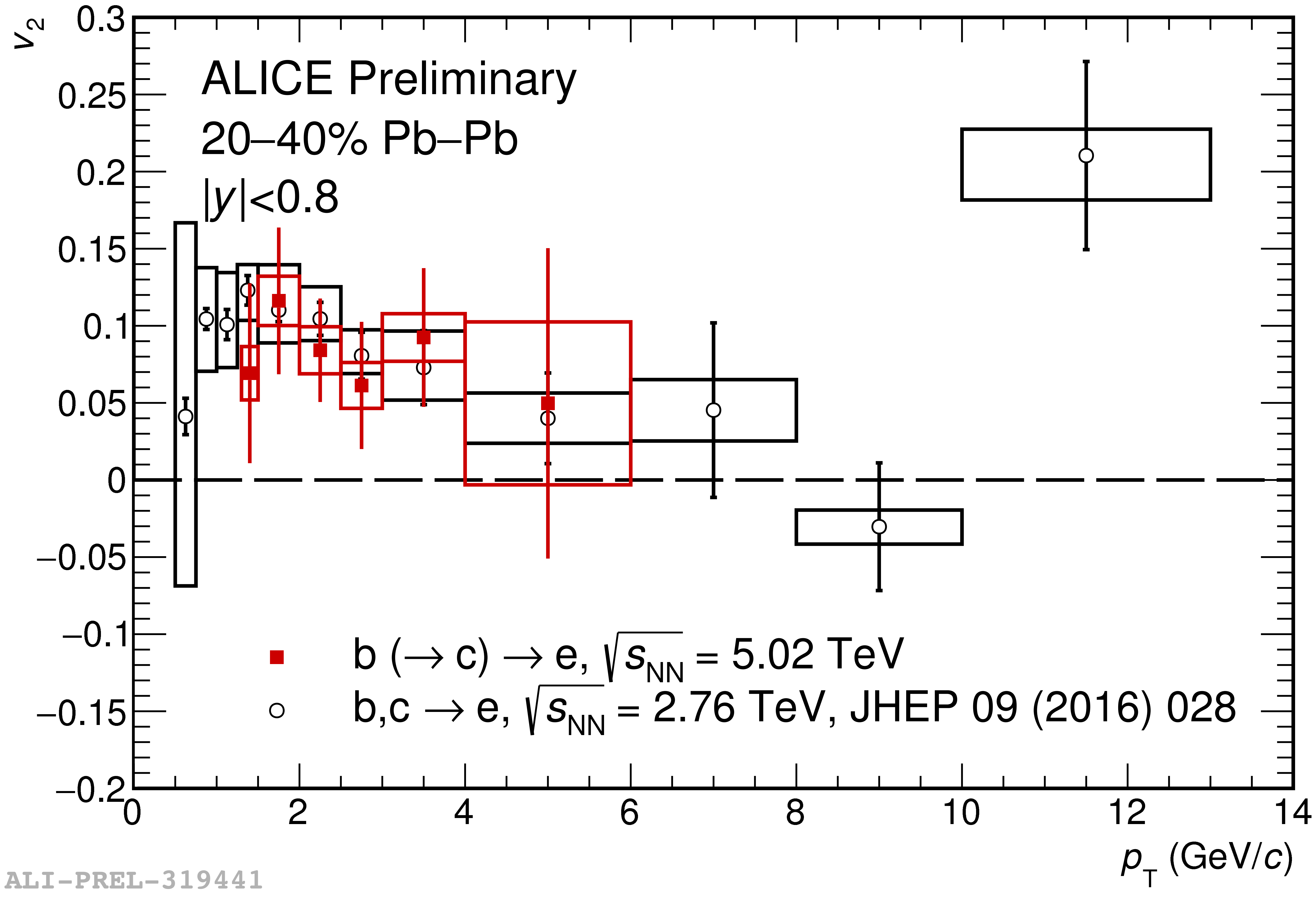
R_{AA}(e←b)





- Hint of a smaller suppression for beauty-decay electrons for $p_T < 6$ GeV/c
- Data is reproduced by models within uncertainties, implementing quark mass dependent energy loss

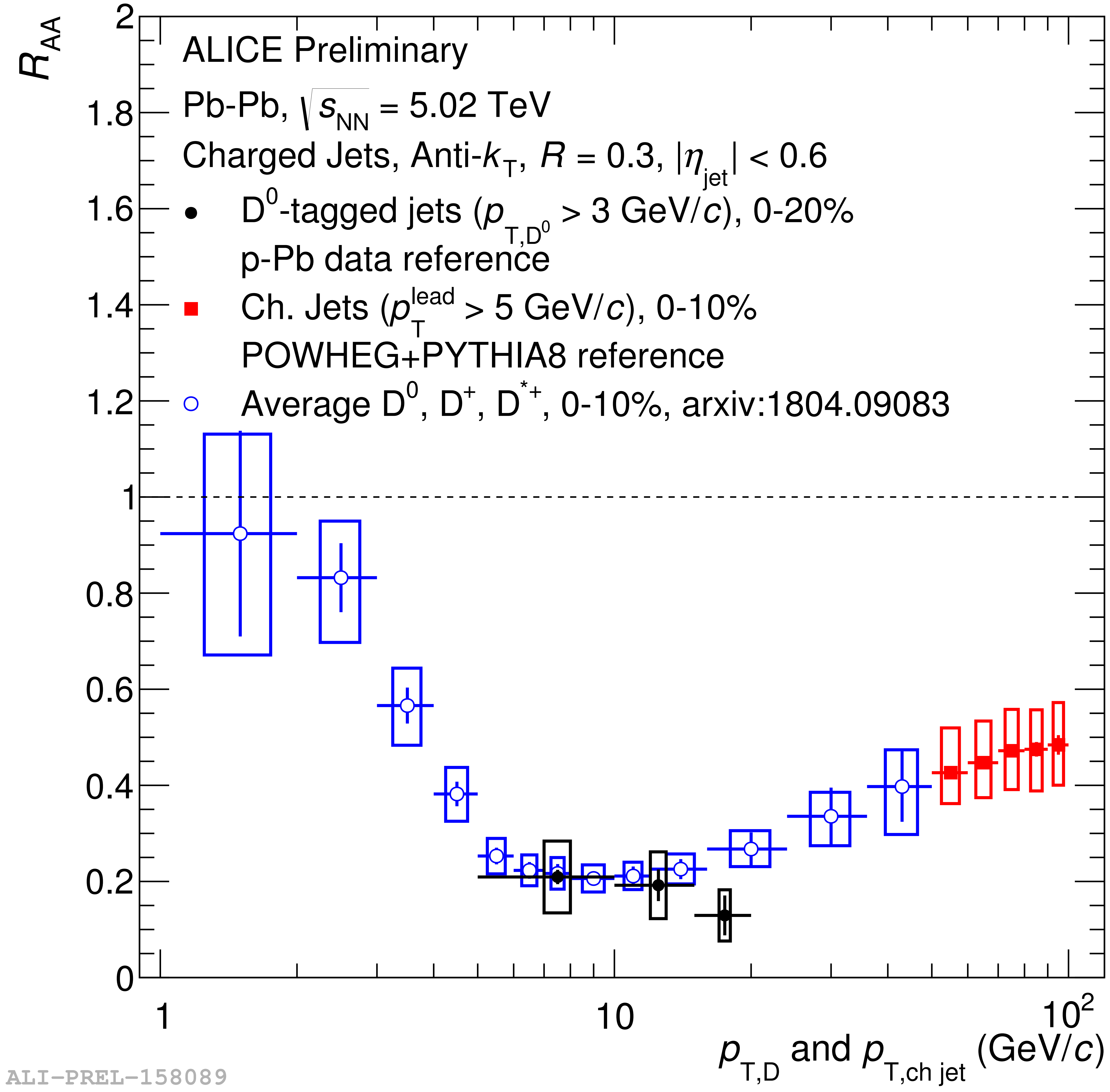
Open-beauty elliptic flow



- $v_2 > 0$ (~3.5σ effect) for e←b in 20-40% centrality
- Similar than e←c,b

- From analysis of 2015 data — can reduce uncertainties with 2018 data

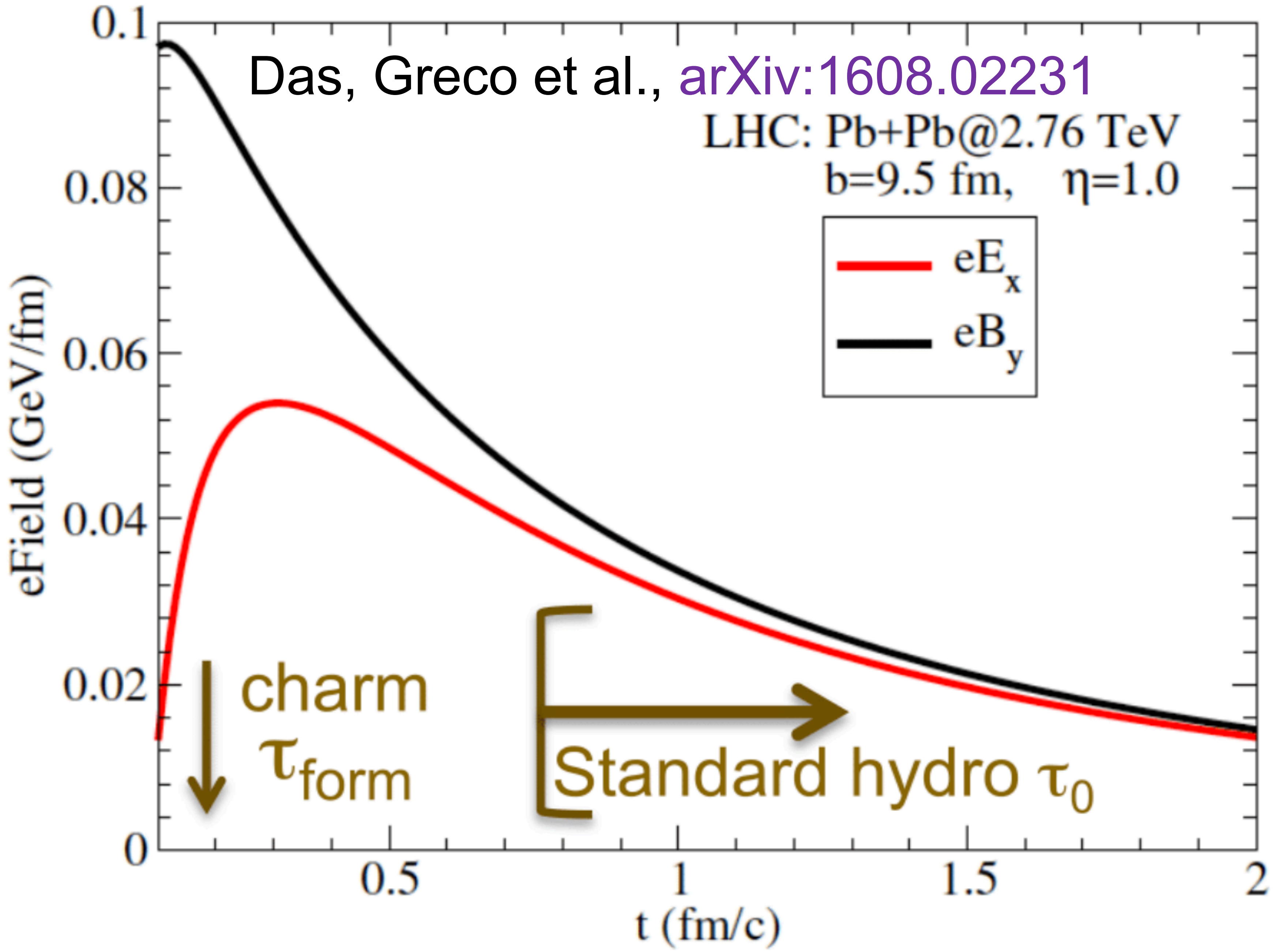
D^0-tagged jets R_{AA}

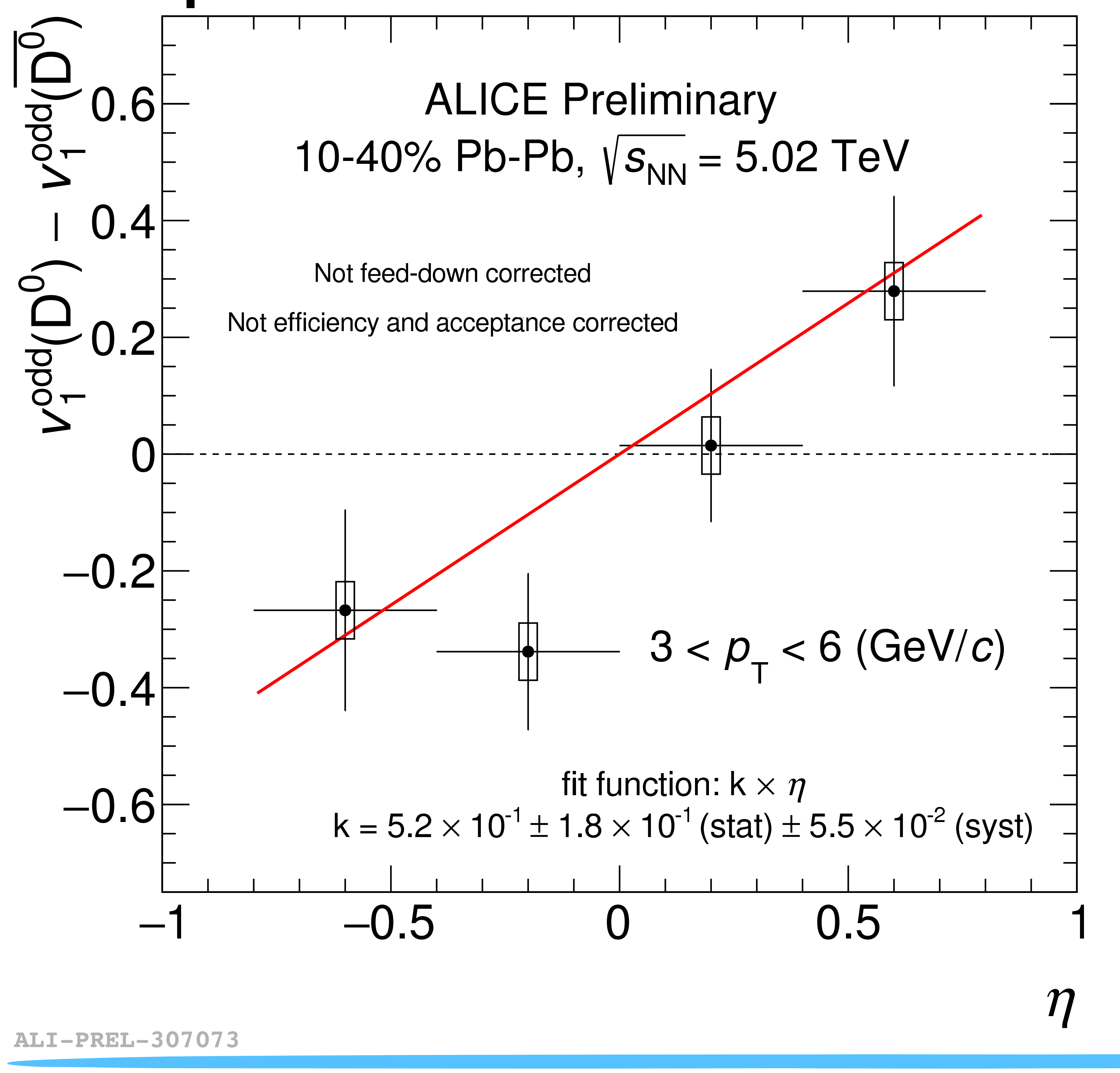


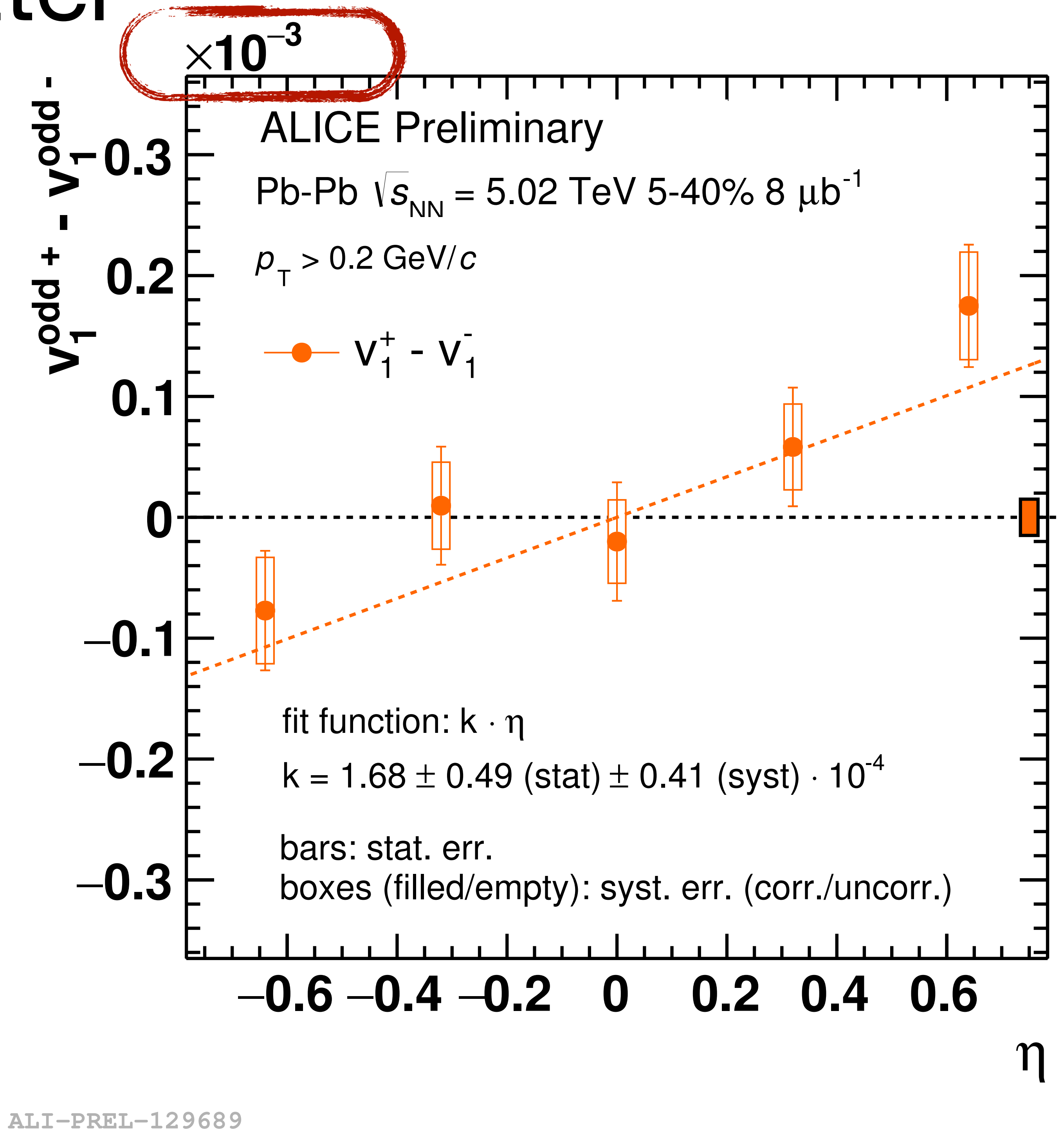
- Strong suppression of D^0-tagged jets in the most 10% central Pb–Pb collisions
- Hint of more suppression of low p_T D^0-tagged jets than inclusive jets at higher p_T
- D^0-tagged jets: more quark-seeded jets compared to inclusive jets
- Similar suppression of D^0-jets and D mesons

Direct flow of open charm

- Sensitive to the early time EM fields in the collisions
  - ➡ Provide constraint for CME related physics
- Charm dragged by tilted bulk
  - ➡ Larger v_1 for D mesons, probe the longitudinal profile of the initial matter



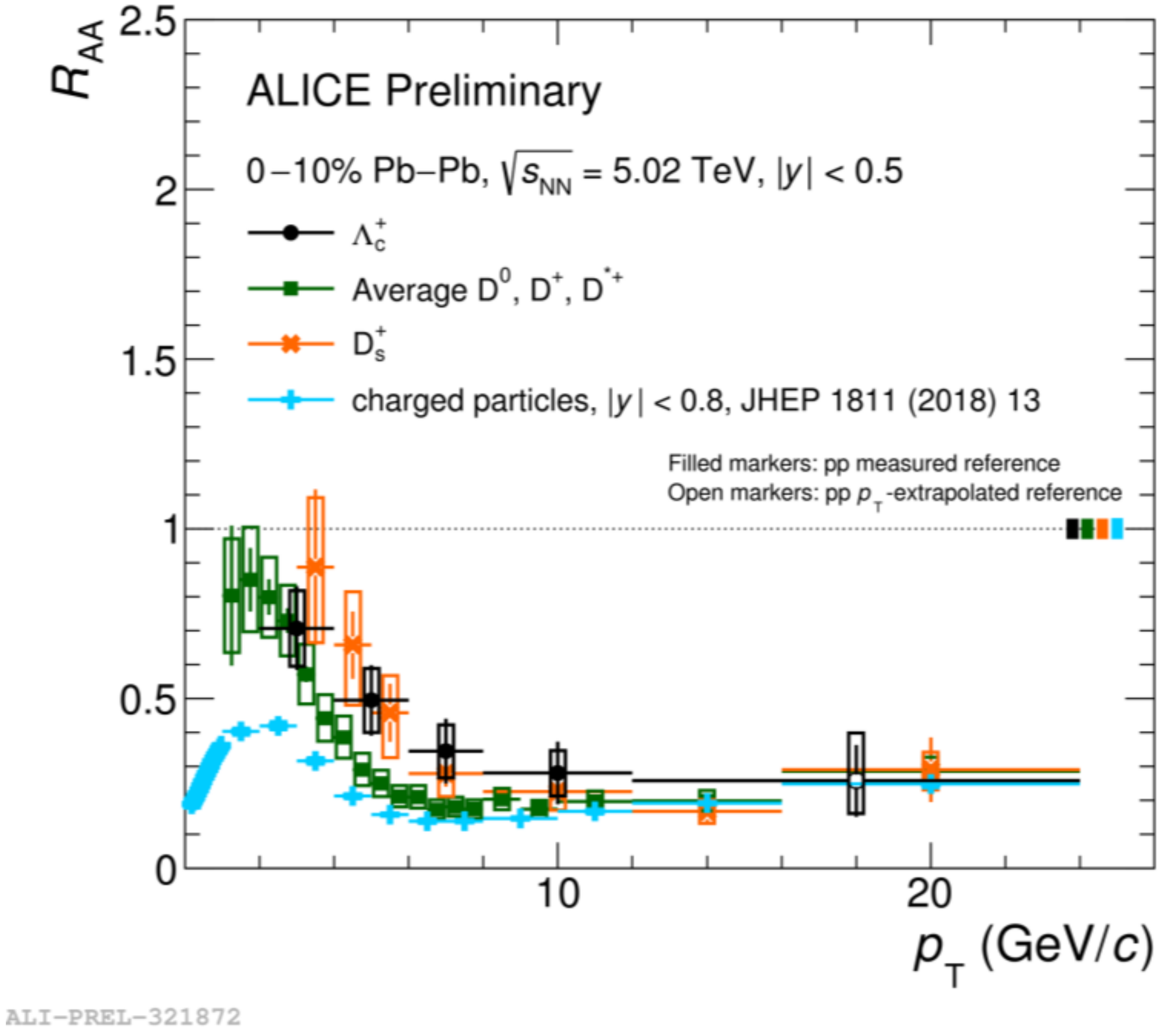


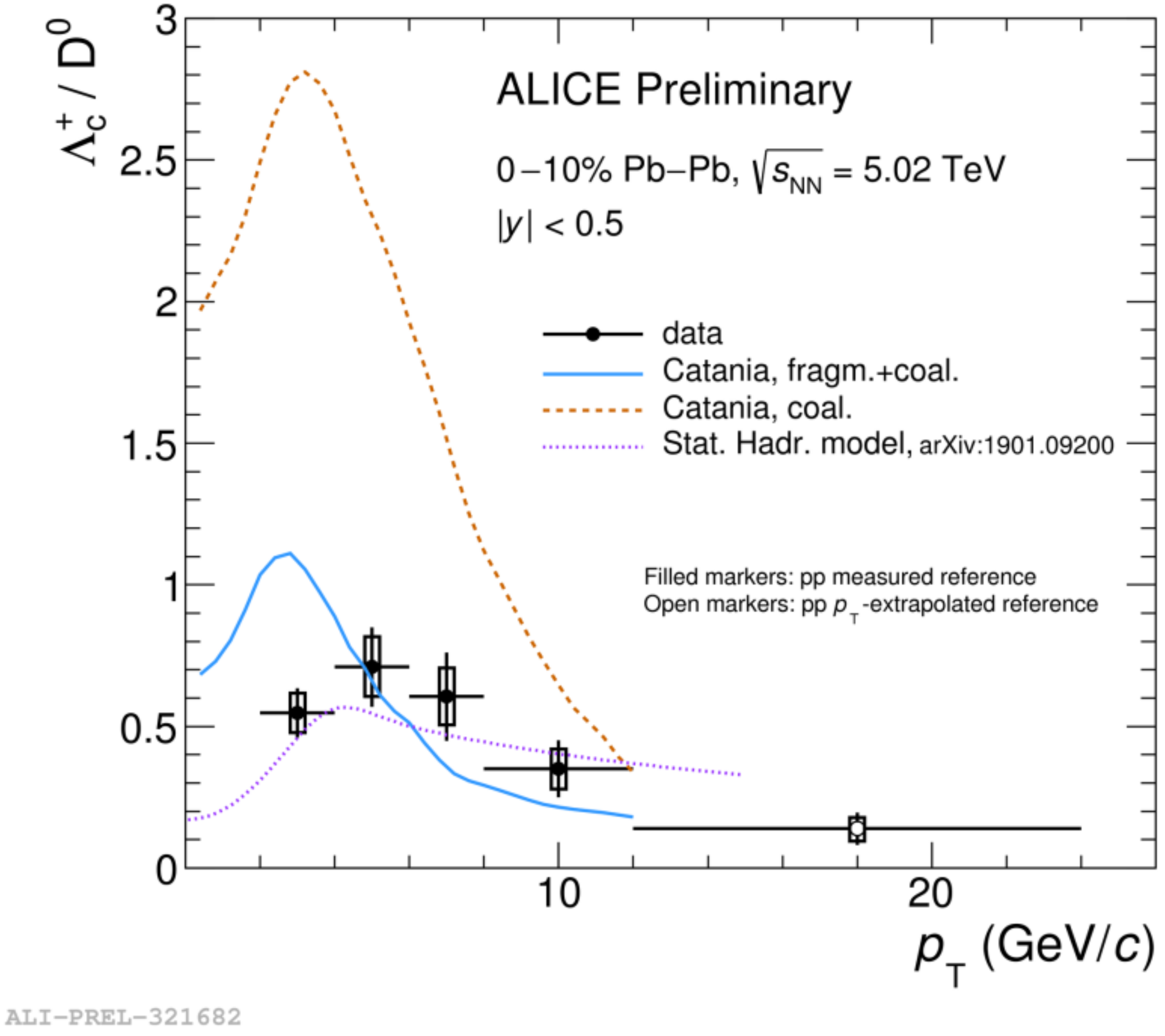


Hint of positive slope with a significance of 2.7σ at low p_T

Similar trend observed for charged particles, but different magnitude

Λ_c production in Pb–Pb collisions





- New Λ_c R_{AA} in 2018 Pb–Pb data, similar suppression as D_s^+
- Hint of higher Λ_c / D^0 ratio in Pb–Pb collisions than small systems

➡ Described by model including both coalescence and fragmentation

More rare probes…

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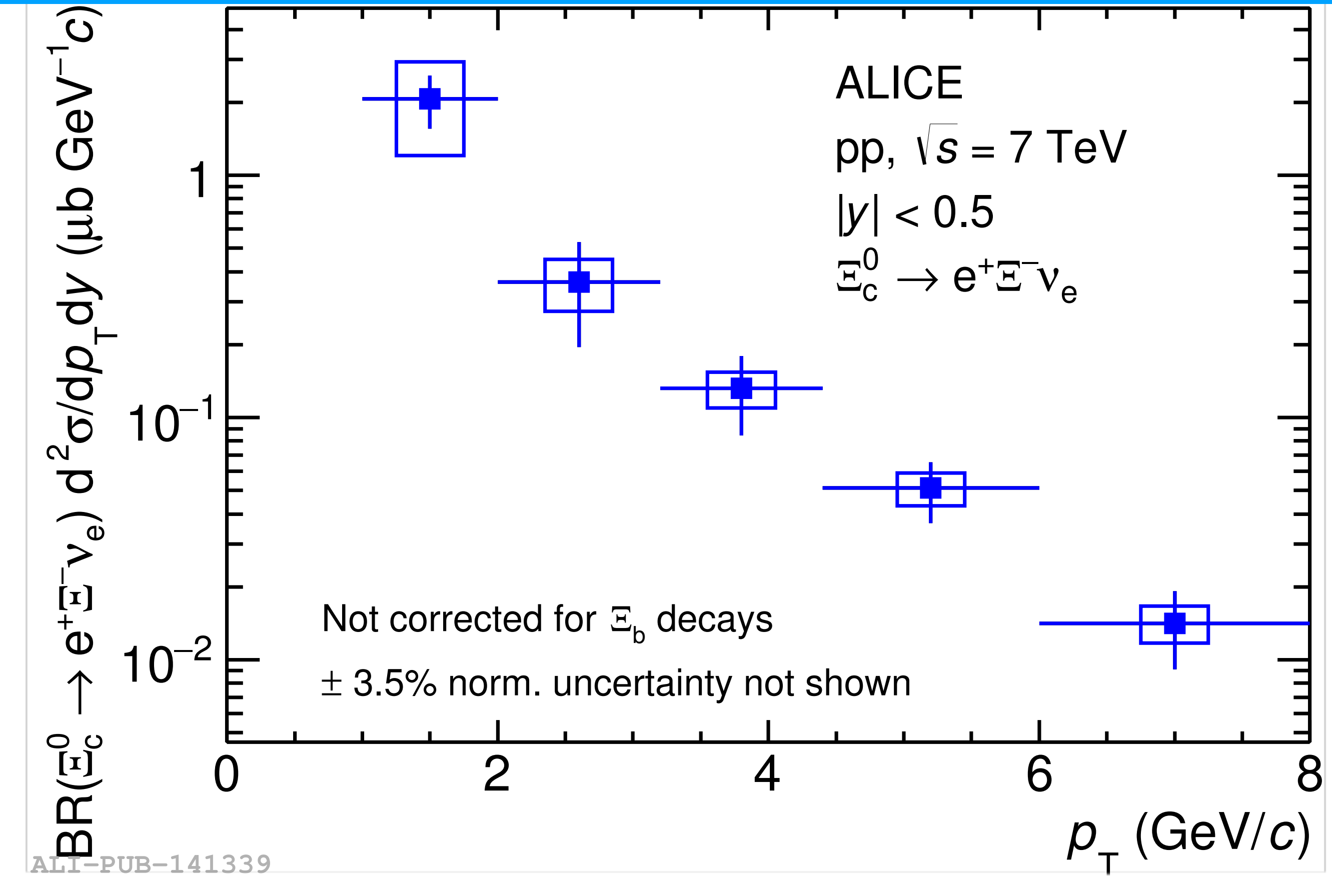

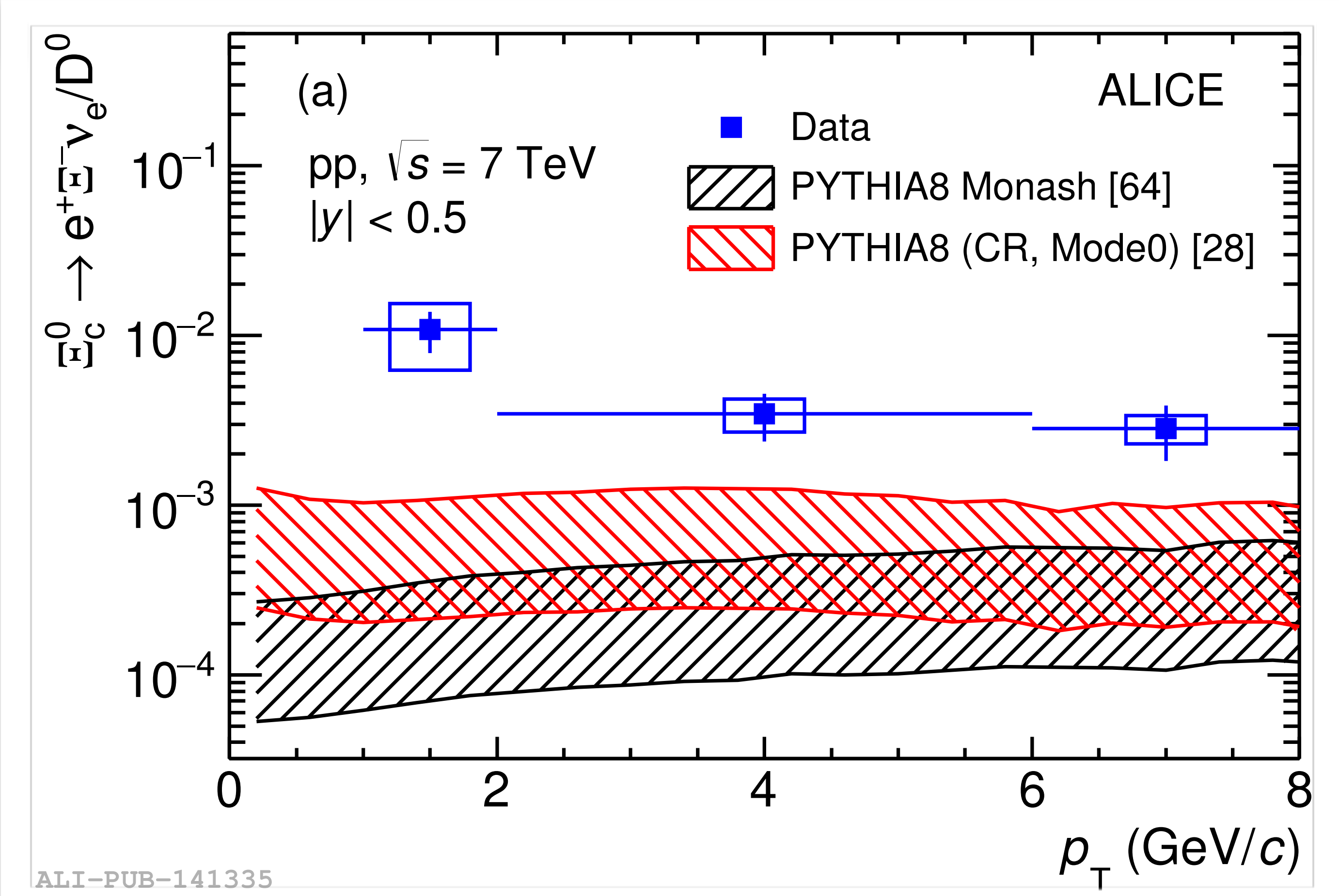

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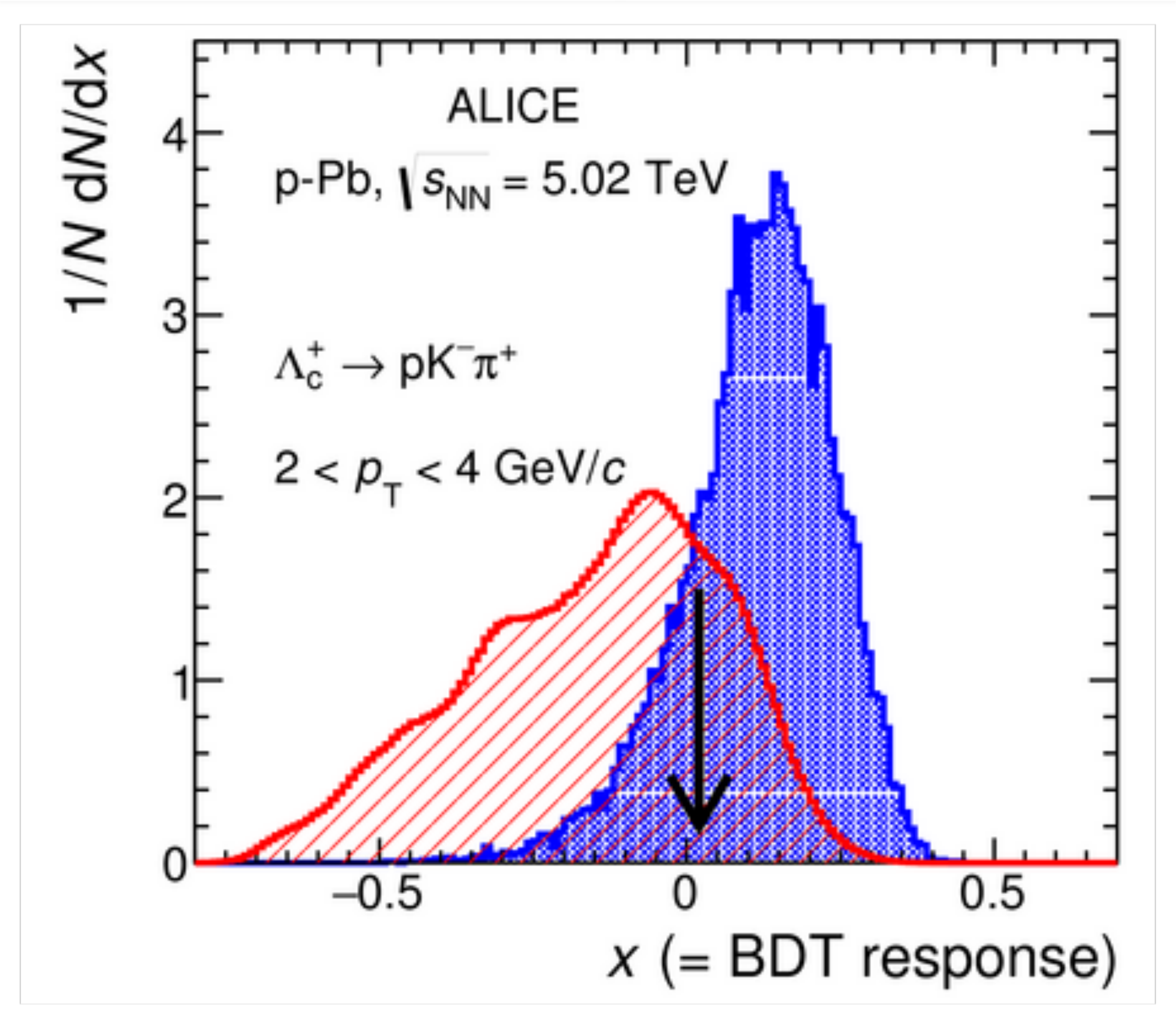
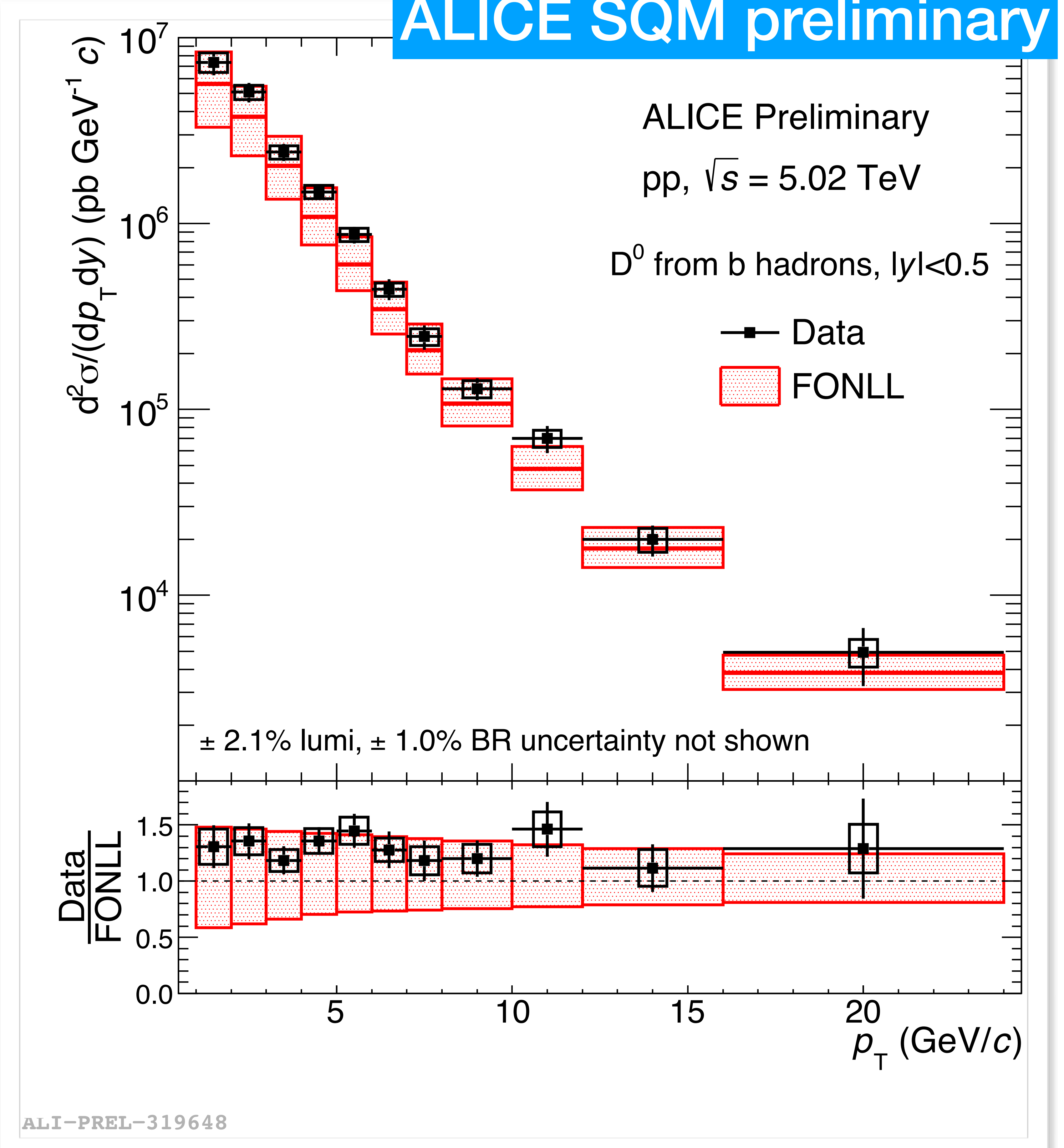


ALICE SQM preliminary



- **Study of rare probes, non-prompt D mesons, Σ_c, Ξ_c… are on the road**
- **Exploring new techniques, such as machine learning…**

J/ψ production in Pb–Pb collisions

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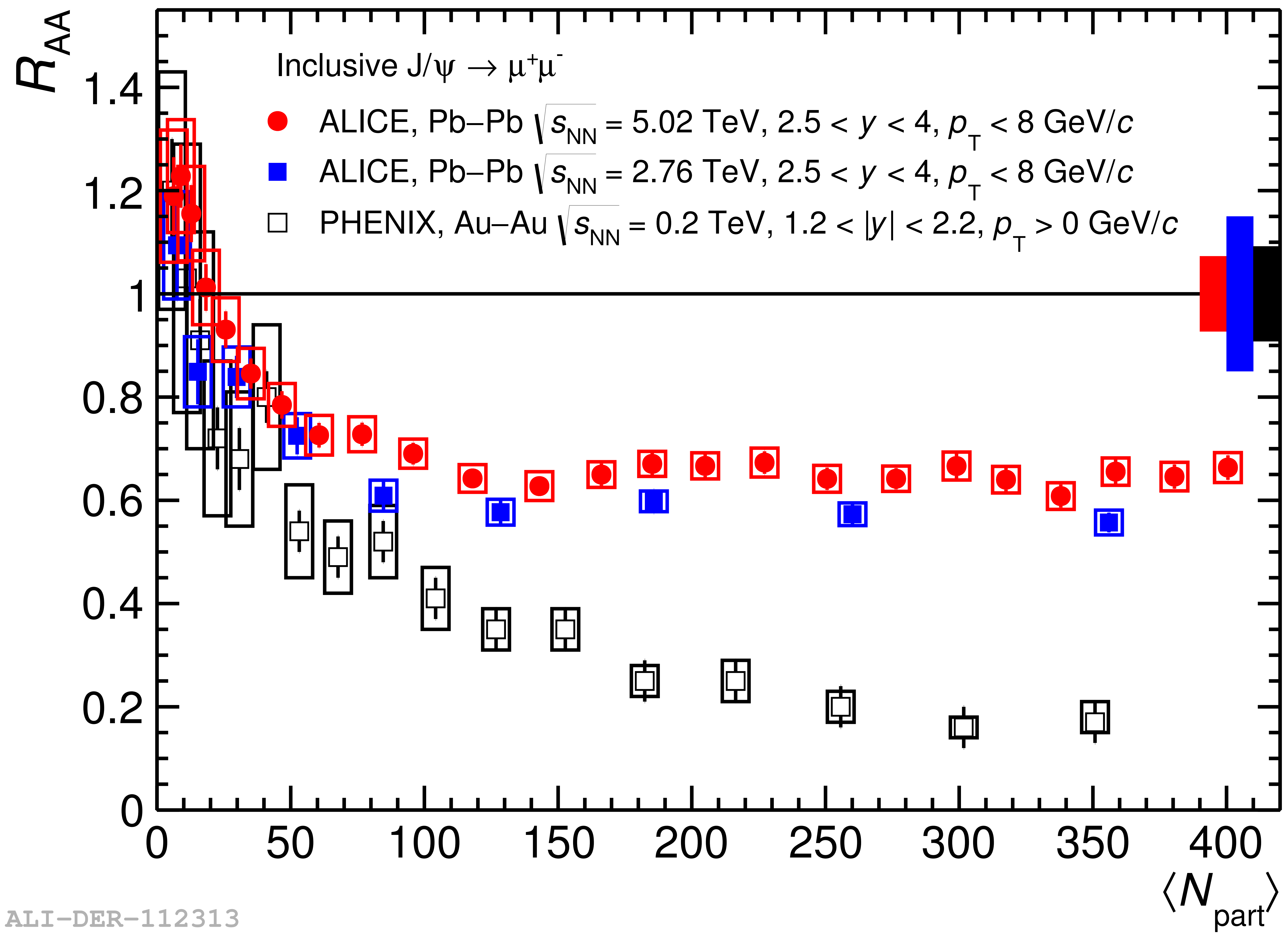
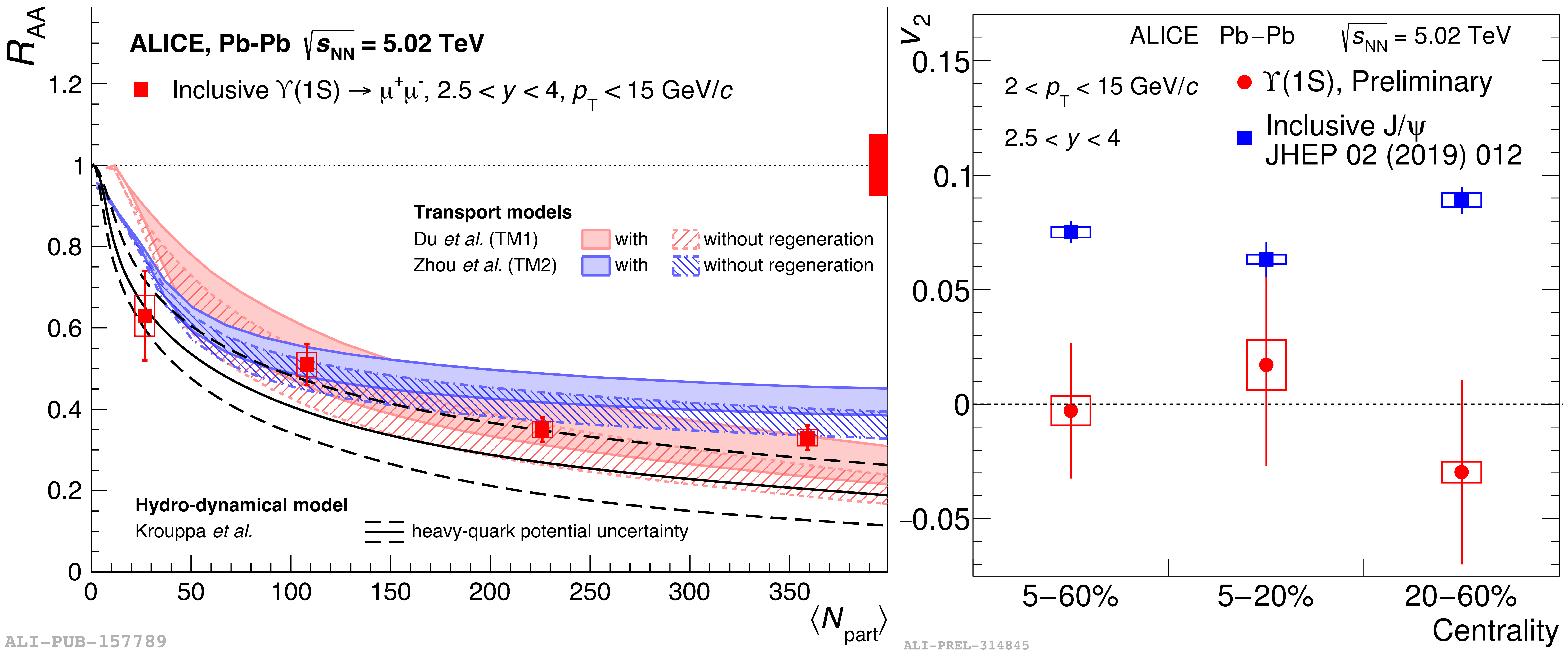


- Suppression is insensitive on centrality in central and semi-central collisions

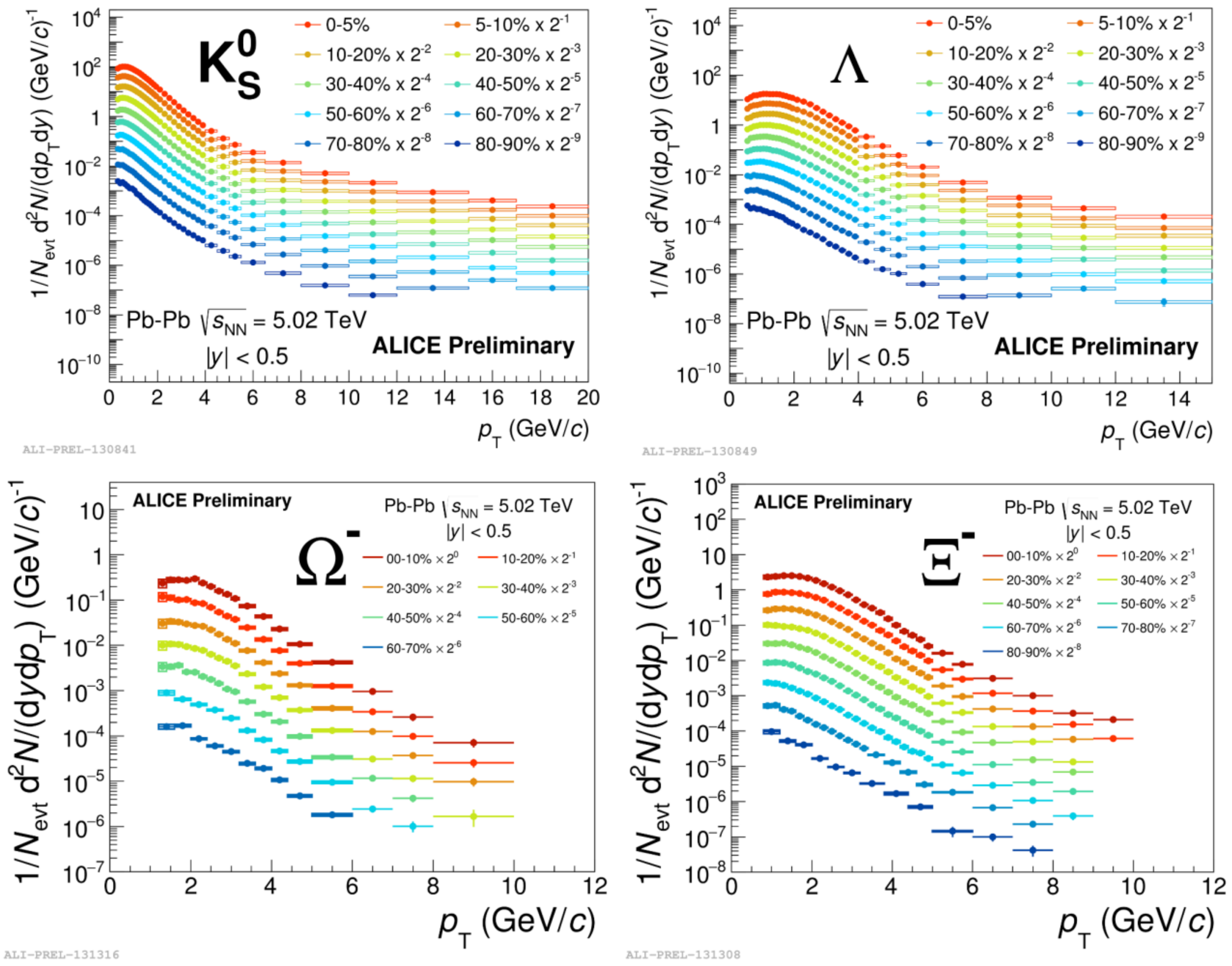
- Recombination plays important roles on J/ψ production on top of the Debye screening at the LHC energies

Υ(1S) production in Pb–Pb collisions



- Significant Υ(1S) suppression, increasing from peripheral to central collisions
- Positive v2 of J/ψ: suggest J/ψ are formed by flowing charm quarks
- First measurement of Υ(1S) elliptic flow at forward rapidity - consistent with zero

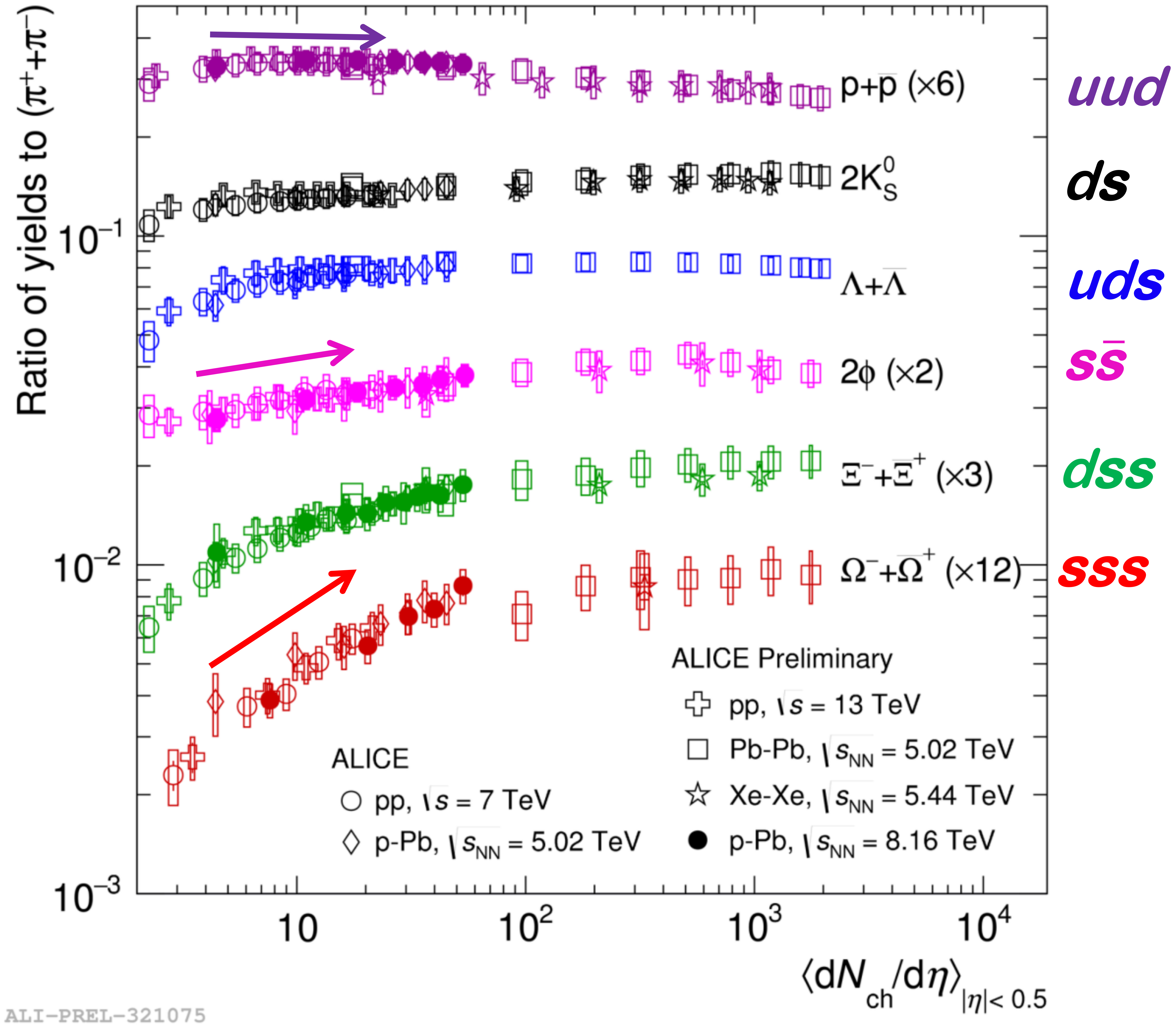
(Multi-)strange particle spectra



- Spectra in Pb-Pb: **spectra become harder** as the multiplicity increases (flattening visible at low pT)

➡ The change is most pronounced for **heavier particles — Radial flow**

p_T-integrated ratio vs. multiplicity



- Steep increase with multiplicity in pp and p–Pb
- Saturation at higher multiplicities
- No significant evolution with the collision energy and collision system
- Slope of the increase depends on strangeness content

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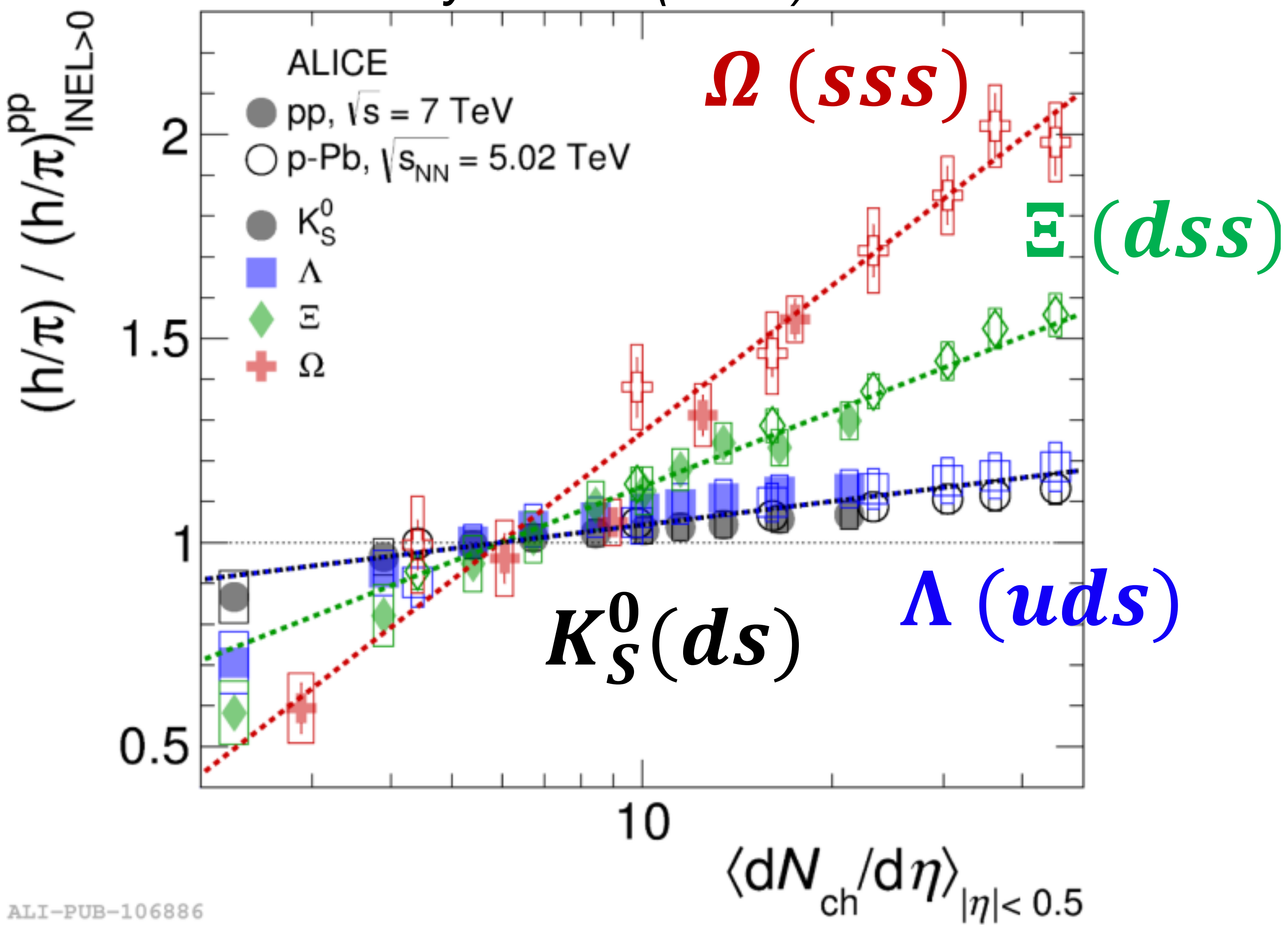
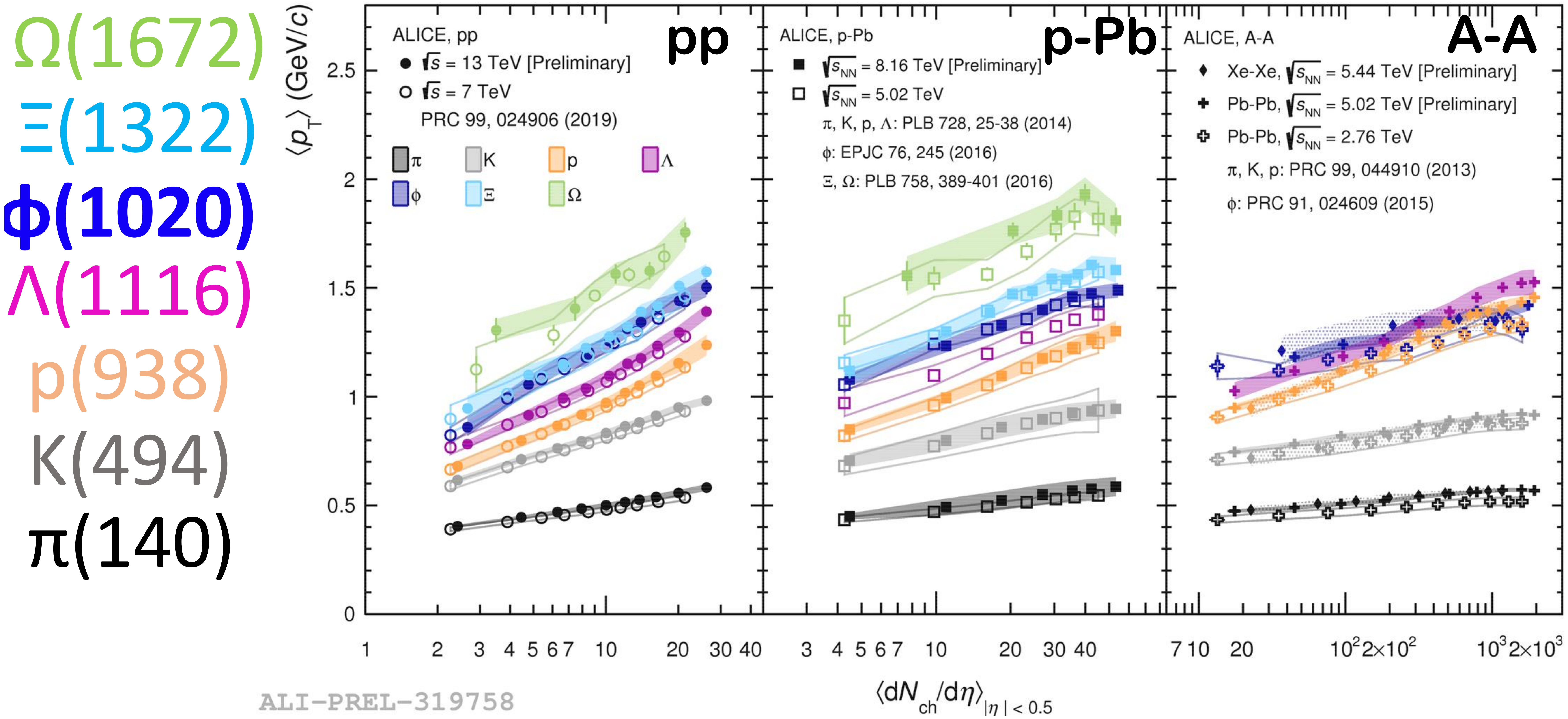


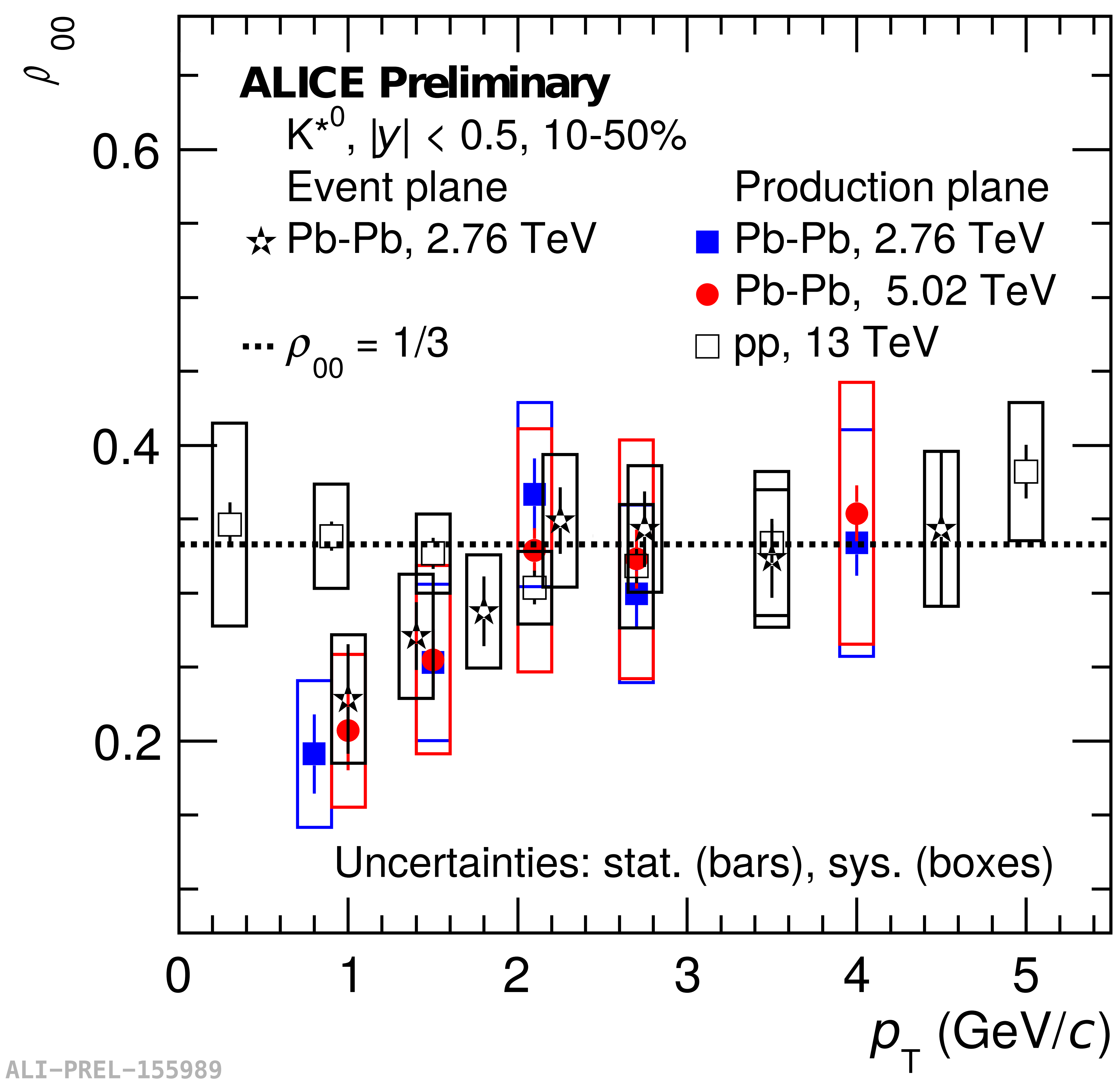
Mean transverse momenta



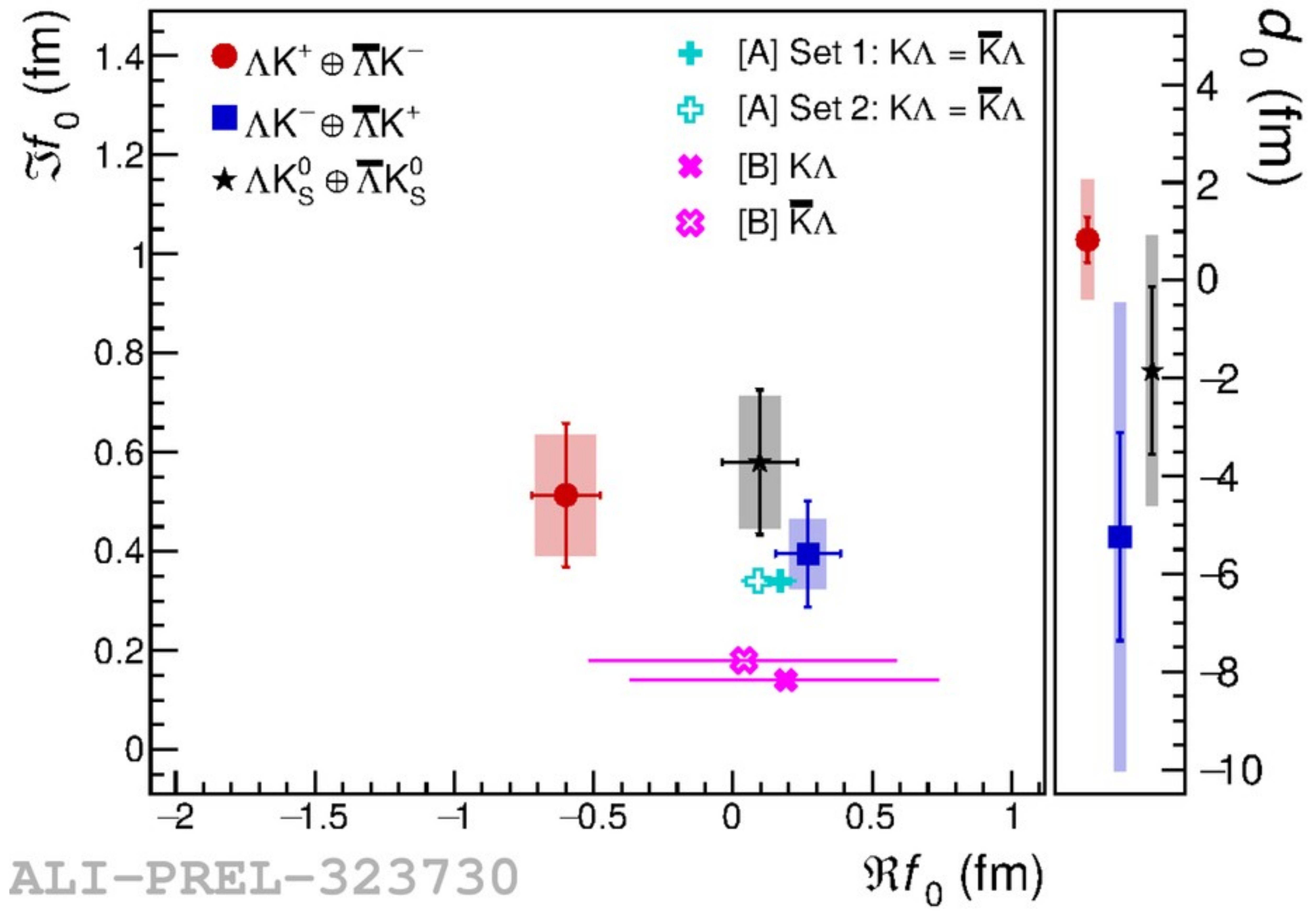
- Similar hierarchy is observed in pp, p–Pb and peripheral A–A
  - ➡ Saturation at higher multiplicities
- In central A–A collisions: particles with similar masses have similar p_T
- The moderate increase is usually attributed to increasing collective radial flow

More on strangeness studies

Spin alignment



Femto-scopy correlations



Conclusion

Heavy-flavour production

- Interplay of CNM (shadowing), collisional and radiative energy loss, coalescence, radial flow required to describe (rather) precise D-meson flow and R_{AA} data
- Intriguing results from charm-chemistry (Λ_c/D, D_s/D) — ALICE upgrade crucial
- J/ψ flow and D-meson flow set together stringent constraints on cause of charm flow
- Beauty-electron $v_2 > 0$… but bottomonia $v_2 \sim 0$

Thanks for your attention!

Strangeness production

- Hints of radial **flow in small systems** (high multiplicity pp)
- Hadron chemistry driven by multiplicity and not by collision energy
- **Yields and <p_T> show a hierarchy** based on particle strangeness content