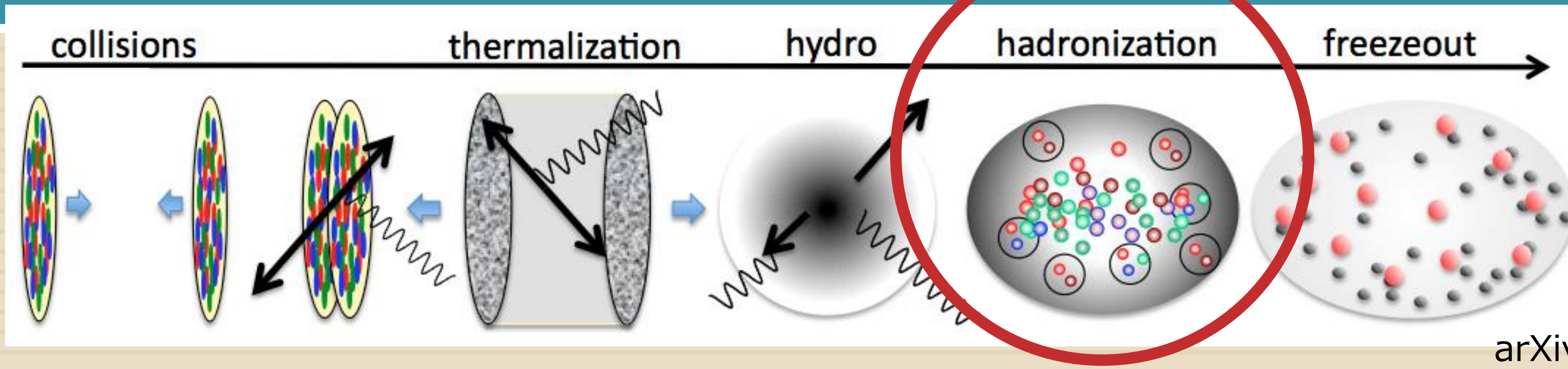
Charmed and exotic hadron measurements with ALICE at the LHC

Yosuke Watanabe (CNS, University of Tokyo)
for the ALICE collaboration

Outline

- Motivation
- ALICE detector
- Results
- Future plans
- Summary

Particle production in heavy-ion collisions



arXiv:1204.4795

- Statistical model
  - Thermodynamic approach assuming thermally and chemically equilibrated system
- Coalescence model
  - Hadrons (or nuclei) are formed by quarks (or nucleons) which are close in phase space
  - Yields of hadrons provide insights into their internal structure and also into the degrees of freedom in the QGP
    - Λ_c production is related to the abundance of di-quark structures in the QGP (S.H.Lee et al PRL100(2008)222301)
    - Different hadrons probe different degrees of freedom
  - Abundant strange quarks coalesce into exotica, such as H-dibaryon?
- Heavy-quark vacuum fragmentation

Hadrons

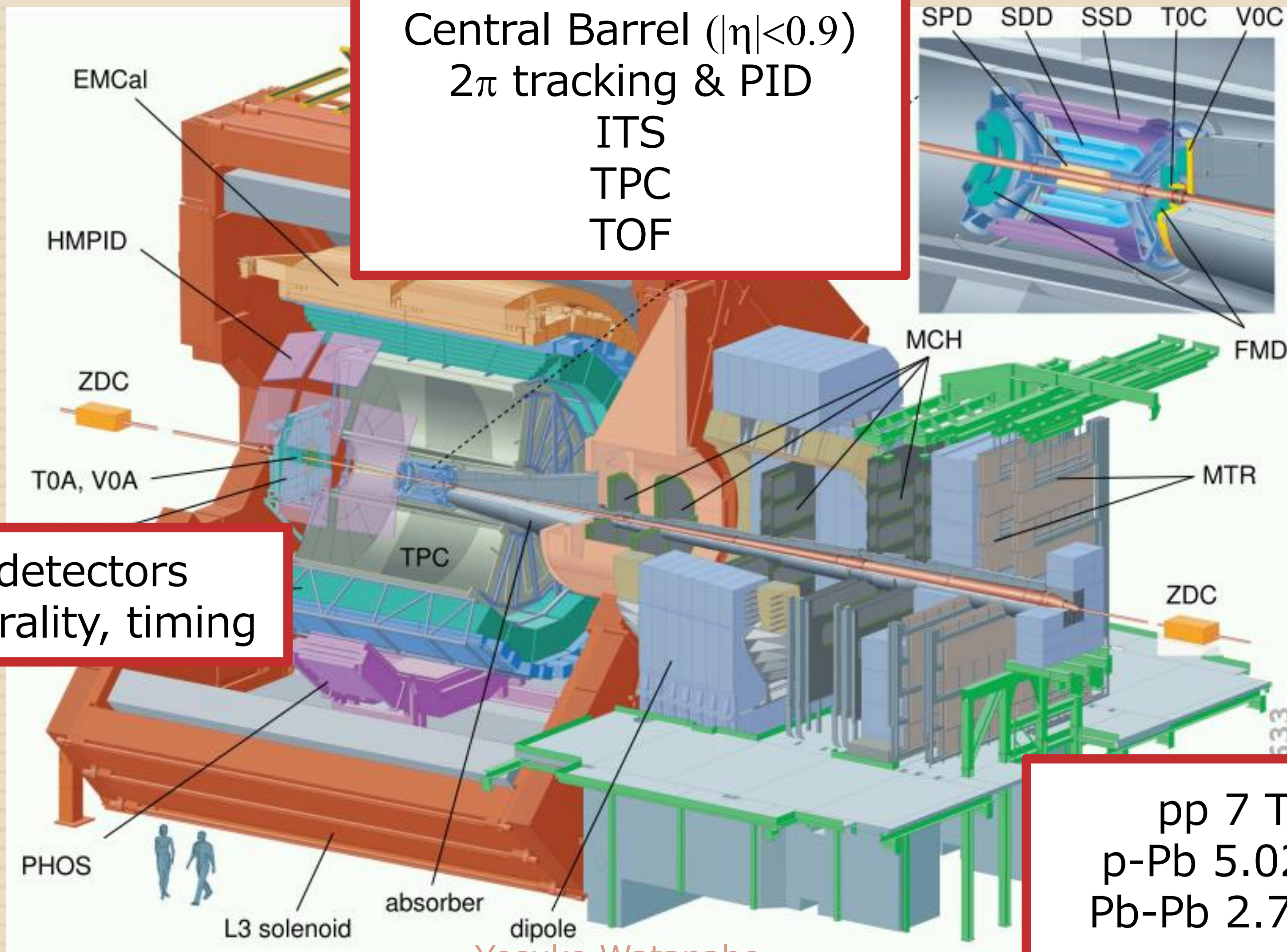
	Light	**Charm**	**Bottom**
Mesons	See Jihye's talk	D mesons	B mesons
Baryons		Λ_c, Ξ_c, Ω_c	Λ_b, Ξ_b, Ω_b
Exotics	Hypernuclei, Dibaryons, , ⋯	T_{cc}, Ω_{ccc}, ⋯	T_{cb}, ⋯

Hadrons

	Light	Charm	Bottom
Mesons	See Jihye's talk	D mesons	B mesons B→J/ψ+X B→e + X
Baryons		Λ_c, Ξ_c, Ω_c	Λ_b, Ξ_b, Ω_b
Exotica	Hypernuclei, Dibaryons, …	T_{cc}, Ω_{ccc}, …	T_{cb}, …

ALICE detector

Central Barrel ($|\eta|<0.9$)
2π tracking & PID
ITS
TPC
TOF

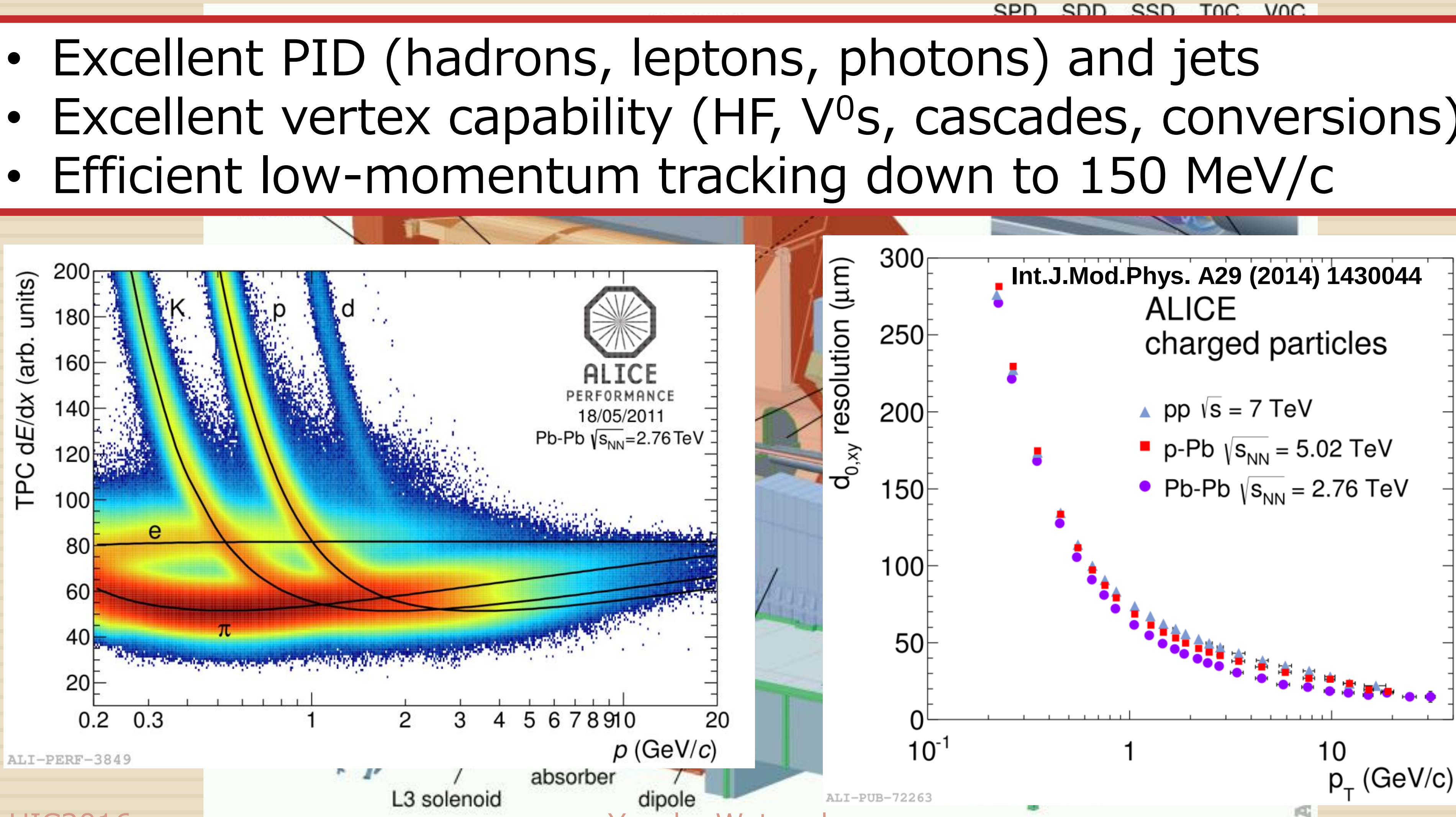


Forward detectors
Trigger, centrality, timing

pp 7 TeV
p-Pb 5.02 TeV
Pb-Pb 2.76 TeV

ALICE detector

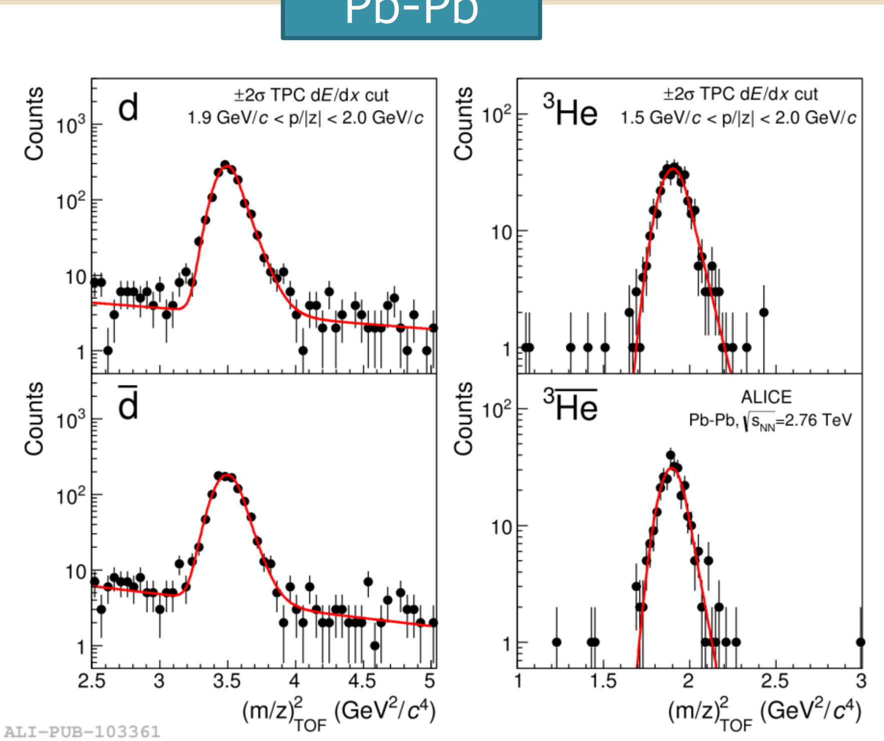
- Excellent PID (hadrons, leptons, photons) and jets
- Excellent vertex capability (HF, V^0s, cascades, conversions)
- Efficient low-momentum tracking down to 150 MeV/c

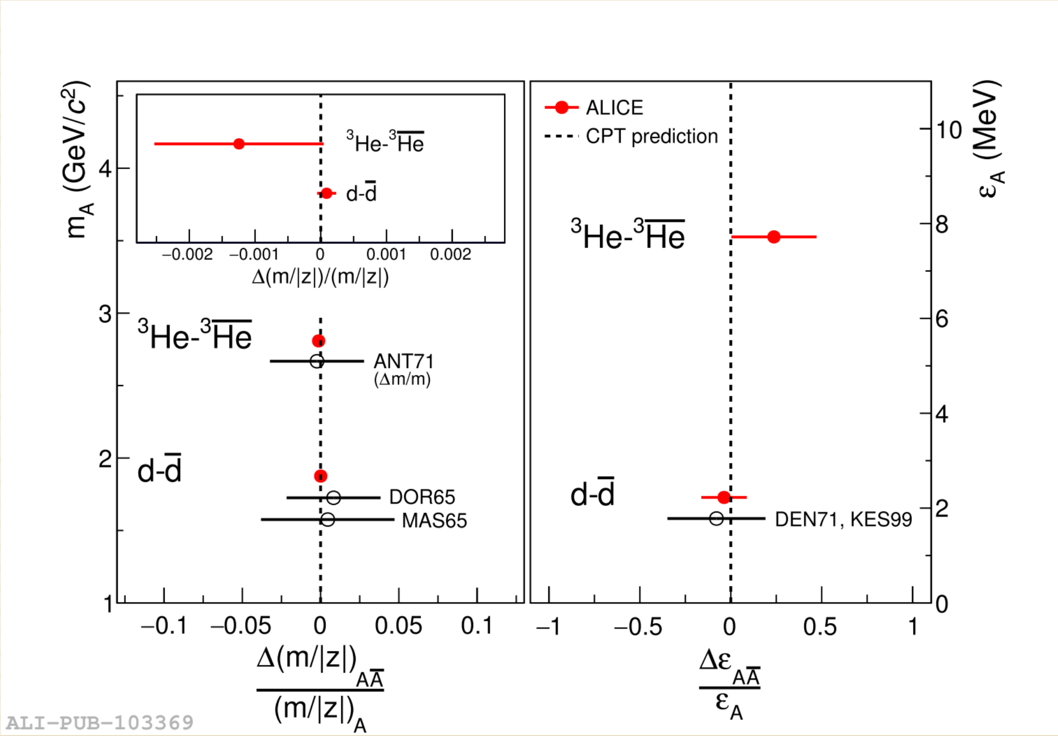


Anti-nuclei

Pb-Pb

Nature Phys. 11 (2015) 811

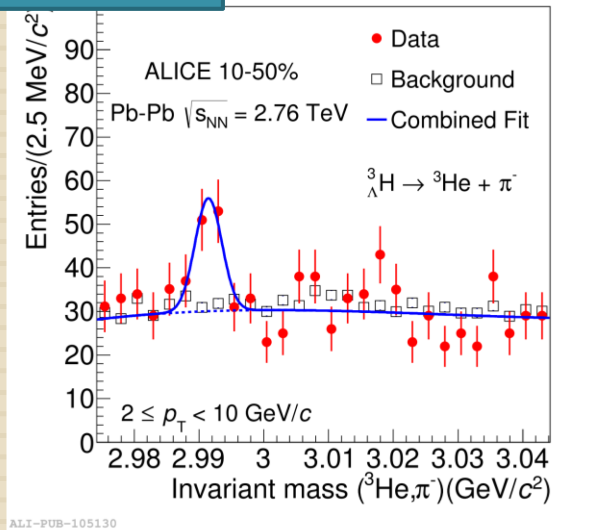




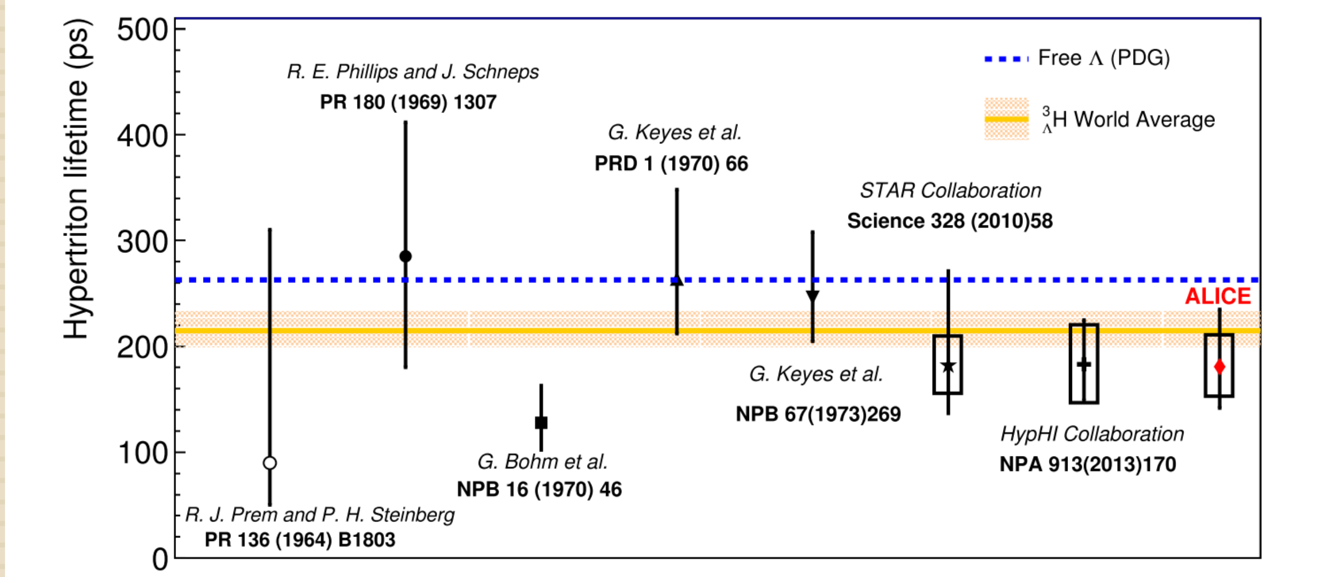
- Anti-nuclei are abundantly produced in heavy-ion collisions
- Mass difference between nuclei and anti-nuclei provides a test of the CPT invariance
- Mass and binding energies of nuclei and anti-nuclei are compatible within experimental uncertainties

$^{3}_{\Lambda}H$ identification

Pb-Pb PLB 754 (2016) 360

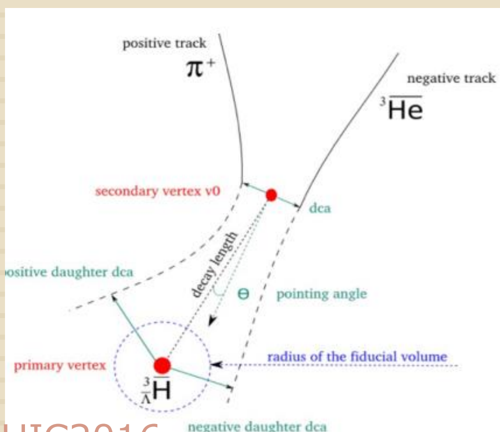


PLB 754 (2016) 360



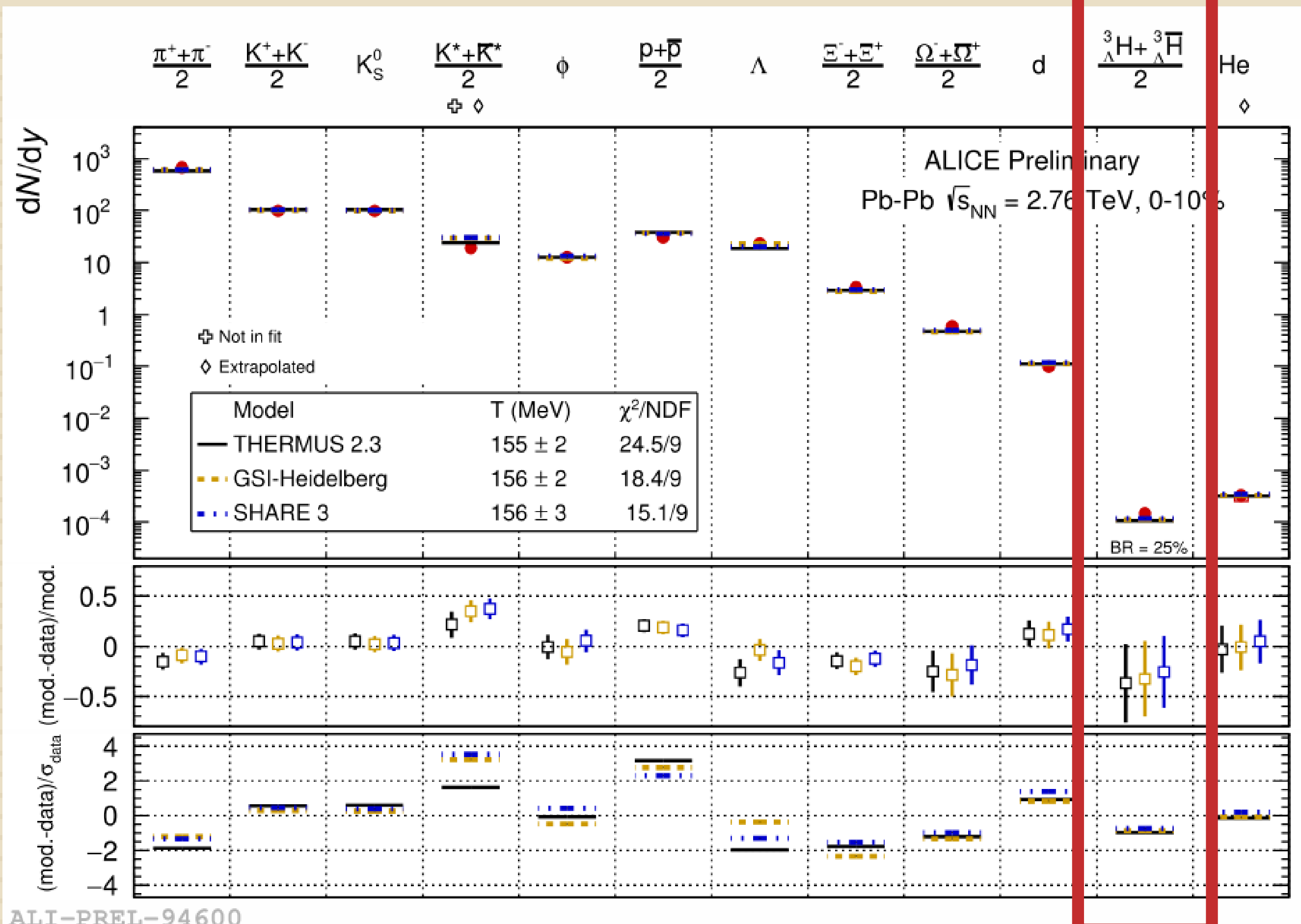
ALI-PUB-105150

$$\tau = 181^{+54}_{-39}(stat) \pm 33(syst)\ \text{ps}$$



- Hypertriton (pnΛ) is measured in ^{3}He+π decay mode
- Topological cuts are applied to reduce combinatorial background
- Measured hypertriton lifetime is compatible with other measurements

$^{3}_{\Lambda}H$ yield vs statistical models



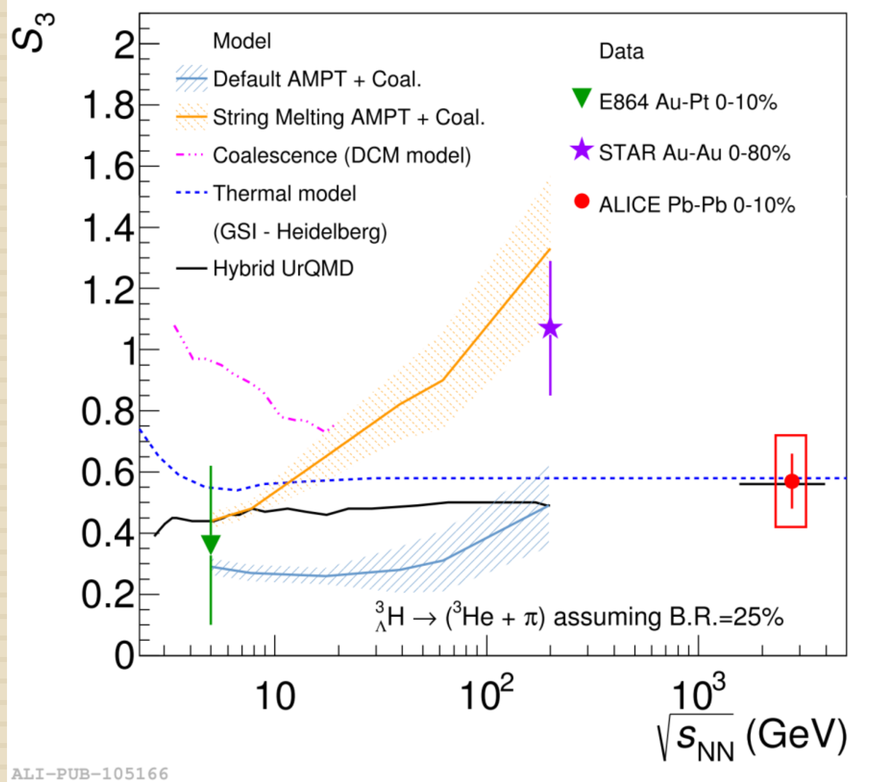
- Different statistical models describe light particle yields with T_{chem} ~ 156 MeV
- Hypernuclei production is also compatible with the models

$^{3}_{\Lambda}H$ S_3 factor

$$S_3 = \frac{^{3}_{\Lambda}H}{^{3}He \times \Lambda/p}$$

- S_3 ~ 1 in a simple coalescence model
- Sensitive also to local baryon-strangeness correlation of the medium (PLB 684 (2010) 224)

PLB 754 (2016) 360

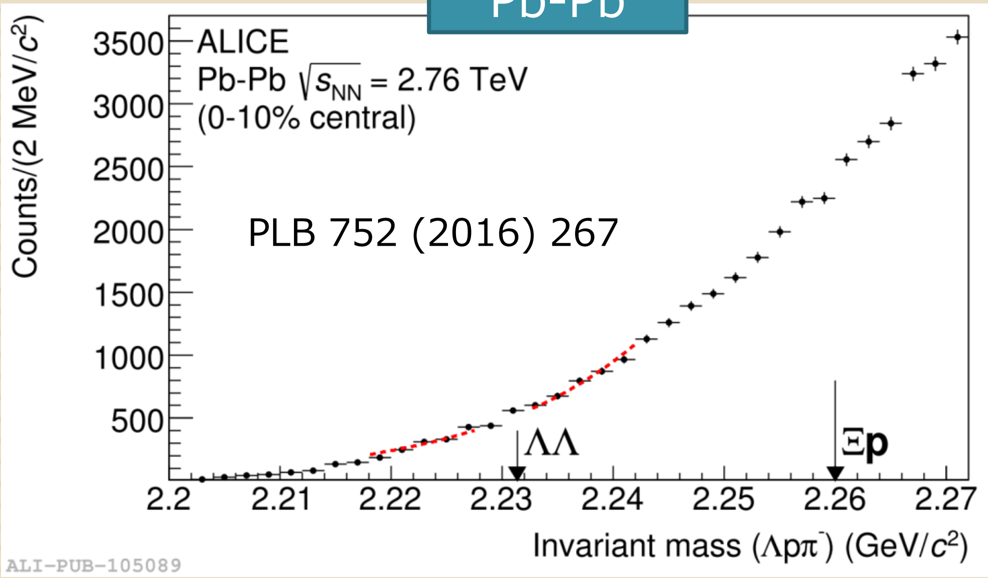


- The S_3 measurements at AGS, RHIC and LHC are compatible
- Thermal model and hybrid UrQMD describe the ALICE data

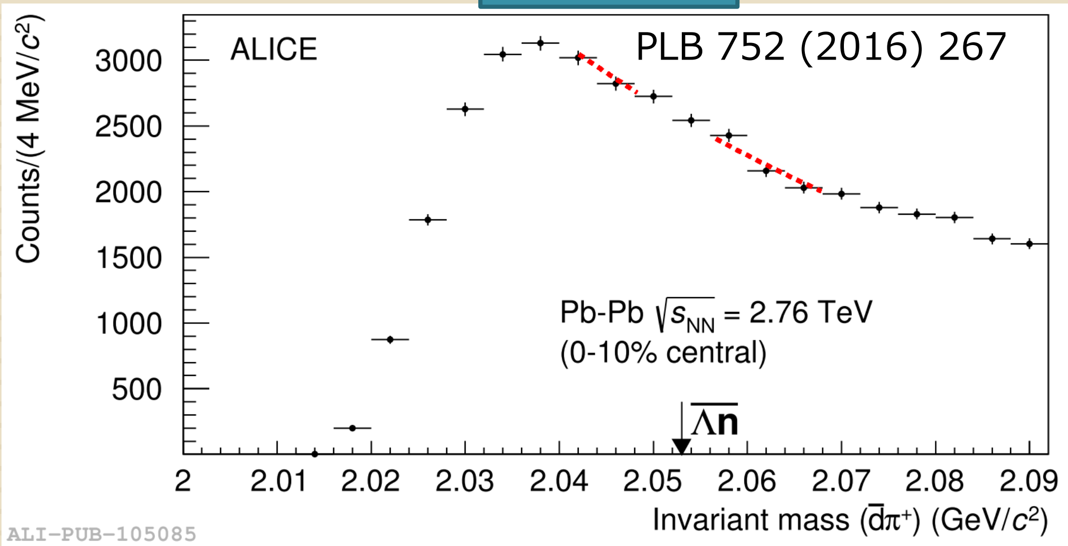
Searches for dibaryons

- ΛΛ: Predicted by Jaffe in bag model calculation (PRL 38 (1977) 195)
  - $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$
- Λn-bar → d-bar + π^+
- Both ΛΛ and Λn-bar are expected to be seen with the analyzed statistics (if they exist)

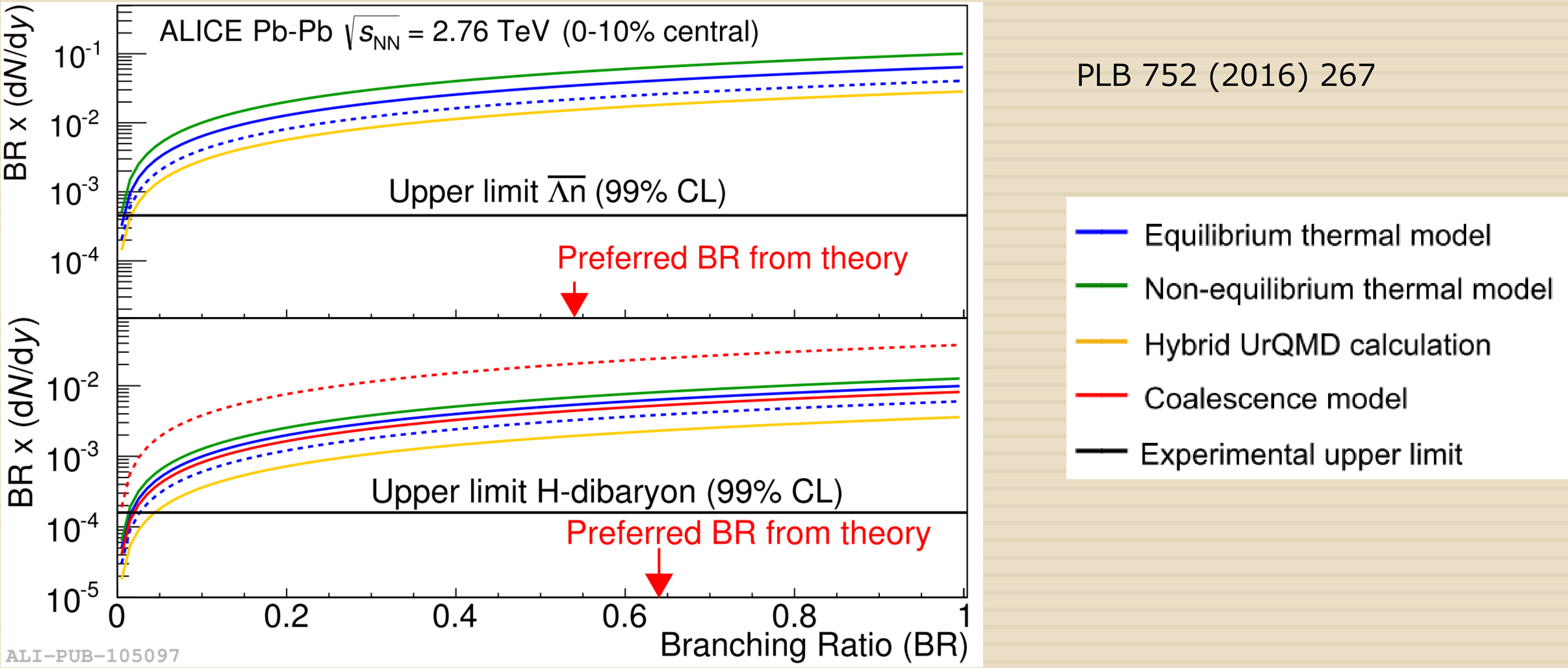
Pb-Pb



Pb-Pb



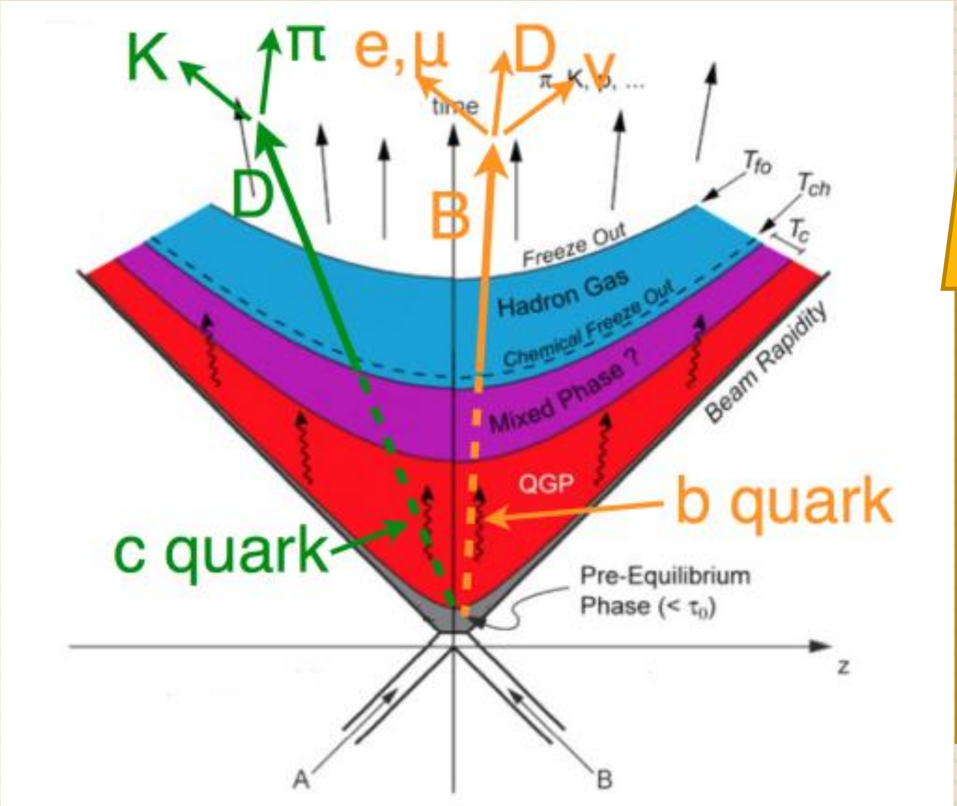
Upper limits on dN/dy



PLB 752 (2016) 267

- No peak observed → Set upper limits on dN/dy
- Upper limits are compared to various model calculations as a function of BR
  - Upper limits are one order of magnitude smaller than model calculations

Heavy-flavor hadrons



- Fragment into hadrons
  - Same as vacuum fragmentation?
  - Recombination with surrounding light quarks?
- Lose energy while traversing the medium
  - Collisional energy loss?
  - Radiative energy loss?
- Heavy quarks are produced in initial hard scattering processes
  - They will experience the whole system evolution

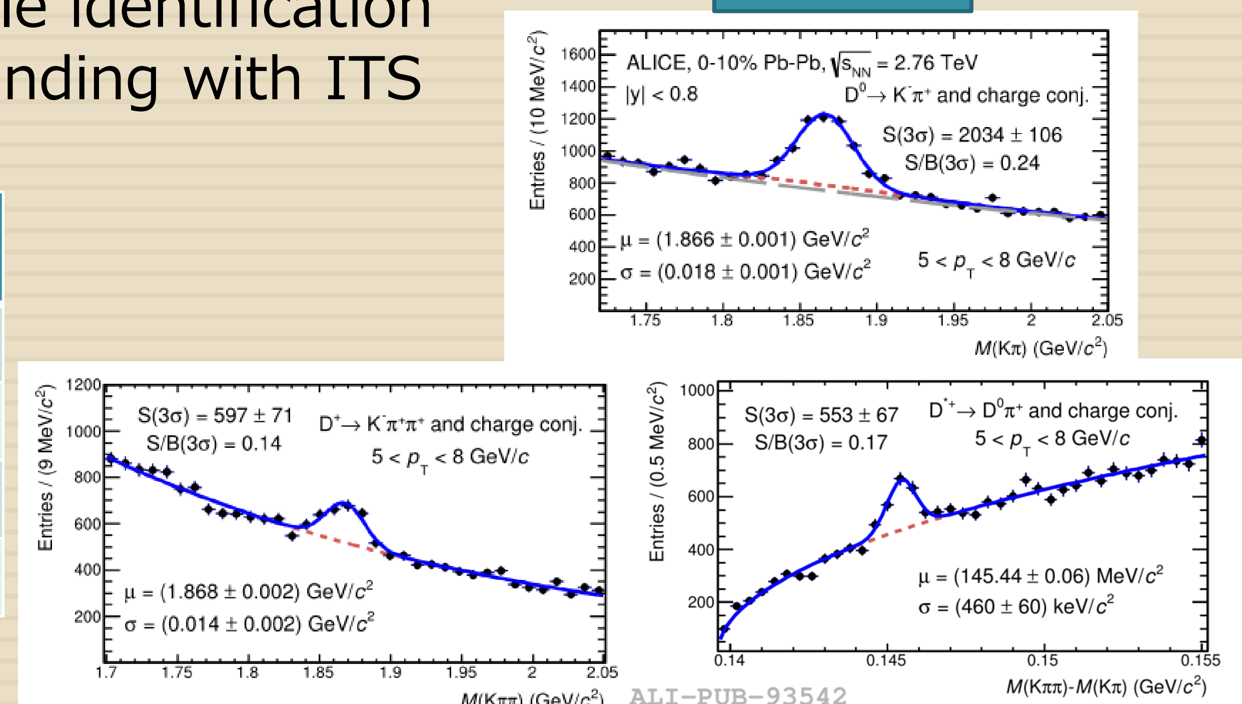
D-meson reconstruction

ALICE

- Only full reconstruction studies are presented
- Signal extraction is performed through invariant mass analysis
- S/B improvement
  - TPC and TOF particle identification
  - Secondary vertex finding with ITS

	$c\tau$ (μm)	BR (%)
$D^0 \to K^- \pi$	123	3.88
$D^+ \to K^- \pi^+ \pi^+$	312	9.13
$D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$		67.7
$D_s^+ \to \phi \pi^+ \to K^+ K^- \pi^+$	150	2.28

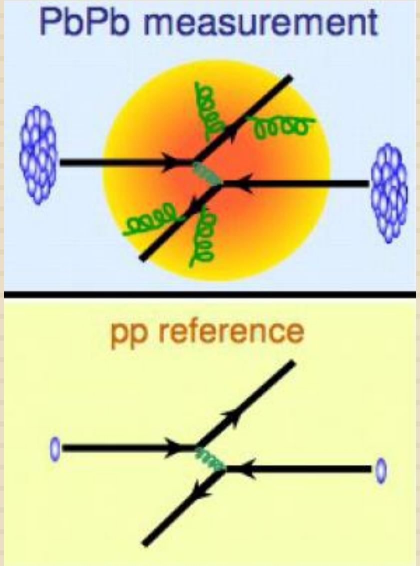
Pb-Pb



arXiv 1506.06604

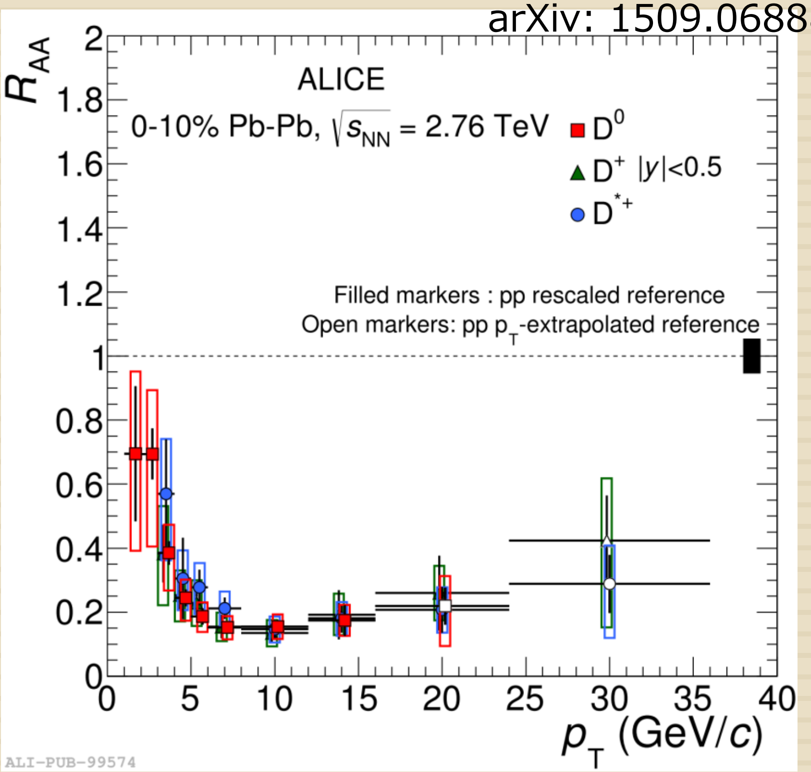
Nuclear modification factor R_{AA}

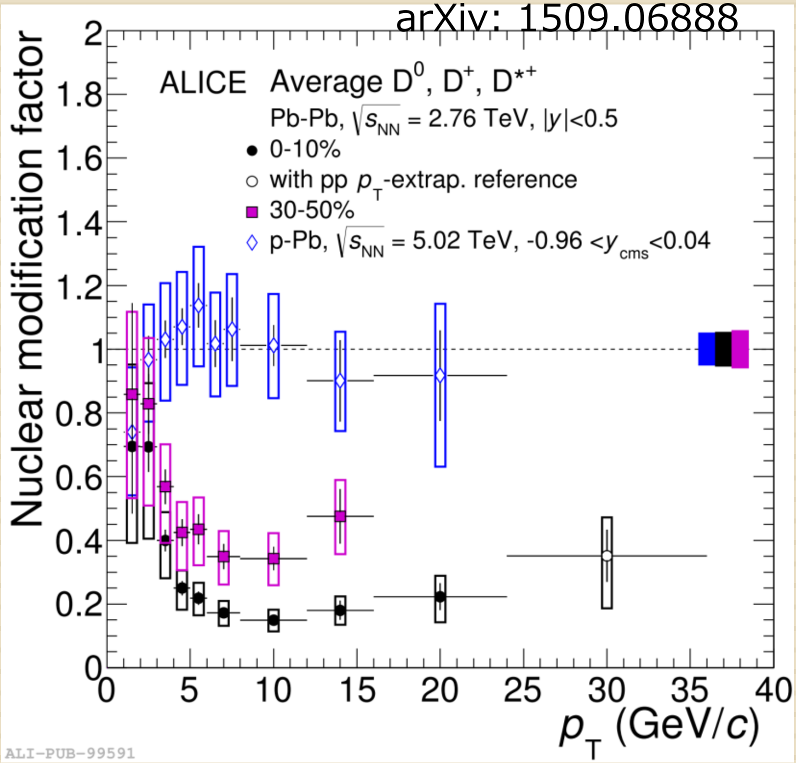
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$



- Charm production in heavy-ion collisions is expected to scale with N_{coll}
- $R_{AA} = 1$: no medium effects
- $R_{AA} \neq 1$:
  - Cold-nuclear-matter effects
  - Energy loss of charm quark in the QGP
  - Change in hadronization
  - etc

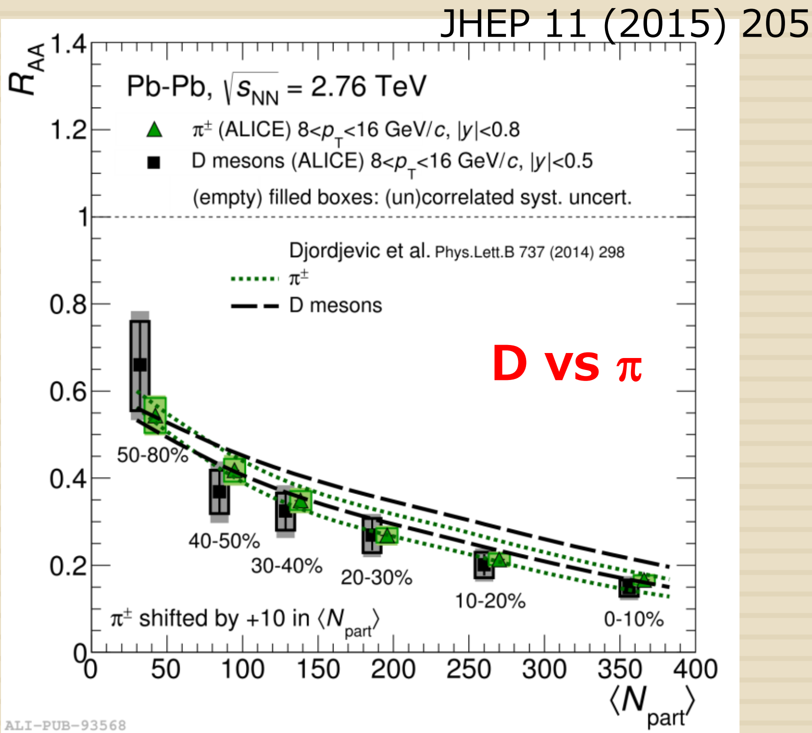
D-meson R_{AA} and R_{pA}

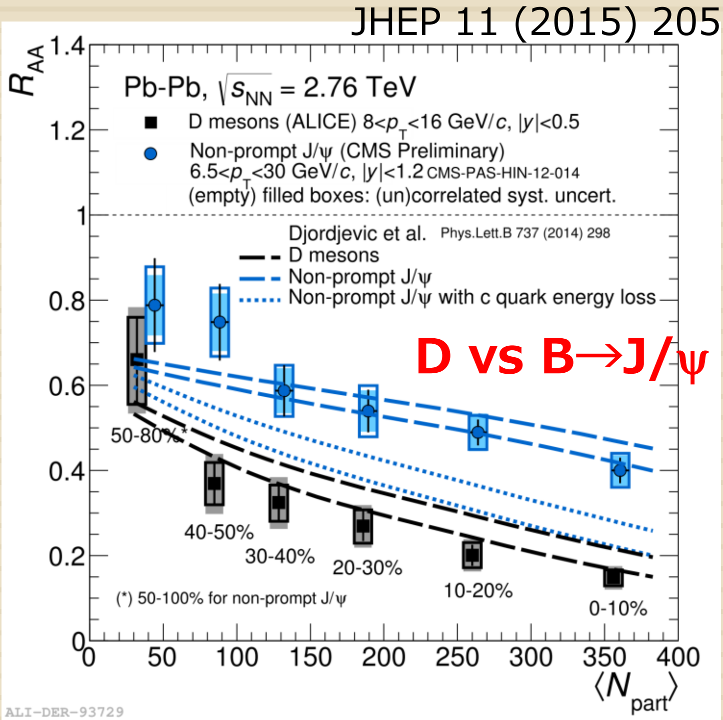




- Strong suppression of D mesons at high p_T in Pb-Pb collisions
  - Not seen in p-Pb collisions
    - Strong suppression is due to final-state effects
  - Stronger suppression in central than in semi-central collisions
    - In-medium energy loss of charm quarks

Comparison with other hadrons



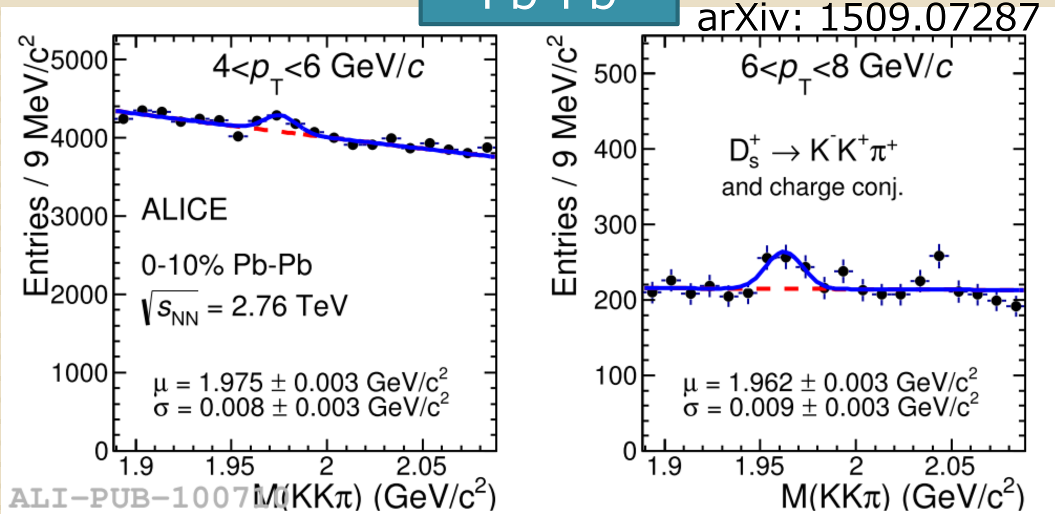


- R_{AA} integrated over high p_T region, $8 < p_T < 16$ GeV/c
- Expected hierarchy in the energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- What we see: $R_{AA}(\pi) \sim R_{AA}(D) < R_{AA}(B)$
  - Different shapes of the parton p_T spectra
  - Different parton fragmentation functions
  - Different energy loss for charm and beauty is confirmed

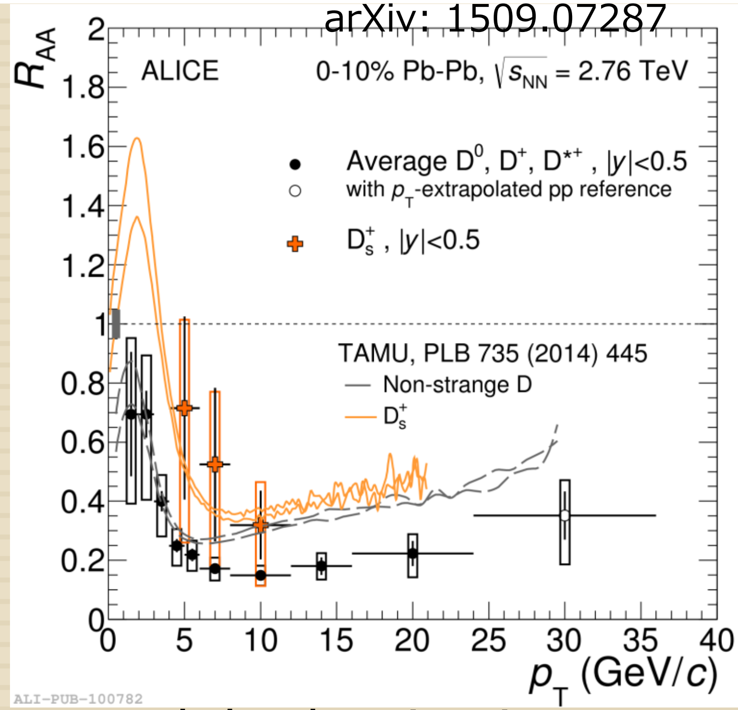
D_s^+

Pb-Pb

arXiv: 1509.07287

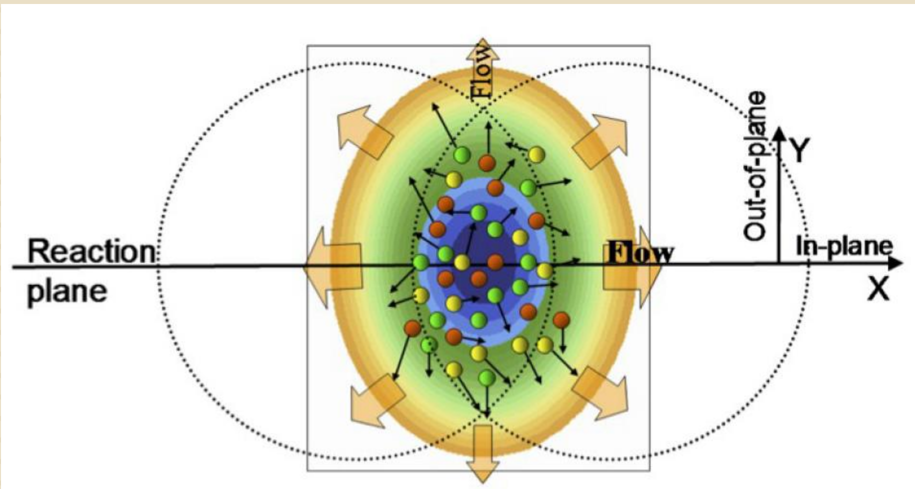


arXiv: 1509.07287



- D_s^+ provides a unique insight into charm-quark hadronization mechanism
  - Strangeness enhancement in heavy-ion collisions affects charm-quark hadronization in the coalescence picture
- p_T>8 GeV/*c*: compatible with other D mesons
- p_T<8 GeV/*c*: hint of less suppression

D-meson azimuthal anisotropy



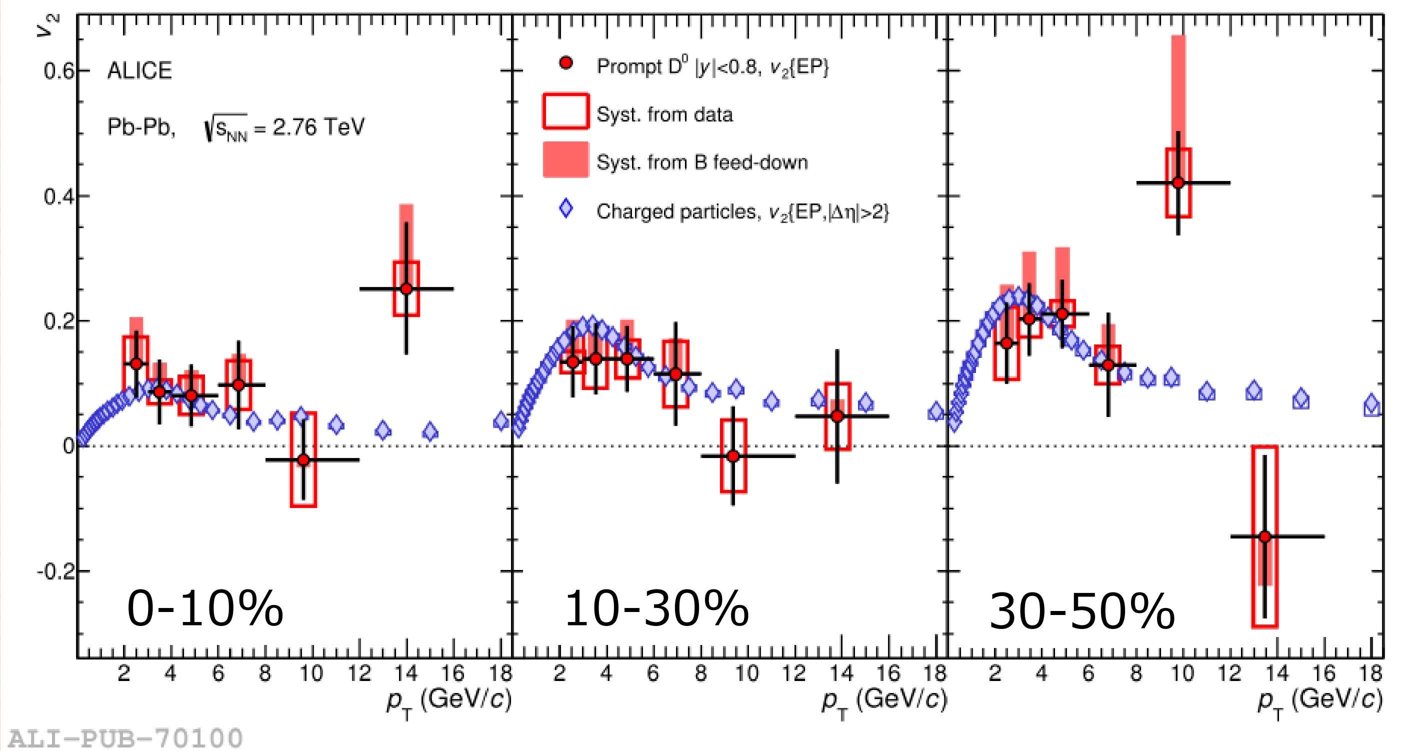
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

v_2: elliptic flow

- Low and intermediate p_T
  - Rescattering of charm quarks with the surrounding medium
    - Degree of charm-quark thermalization
  - Hadronization mechanisms
- High p_T
  - Path-length dependence of charm-quark energy loss

D-meson v_2

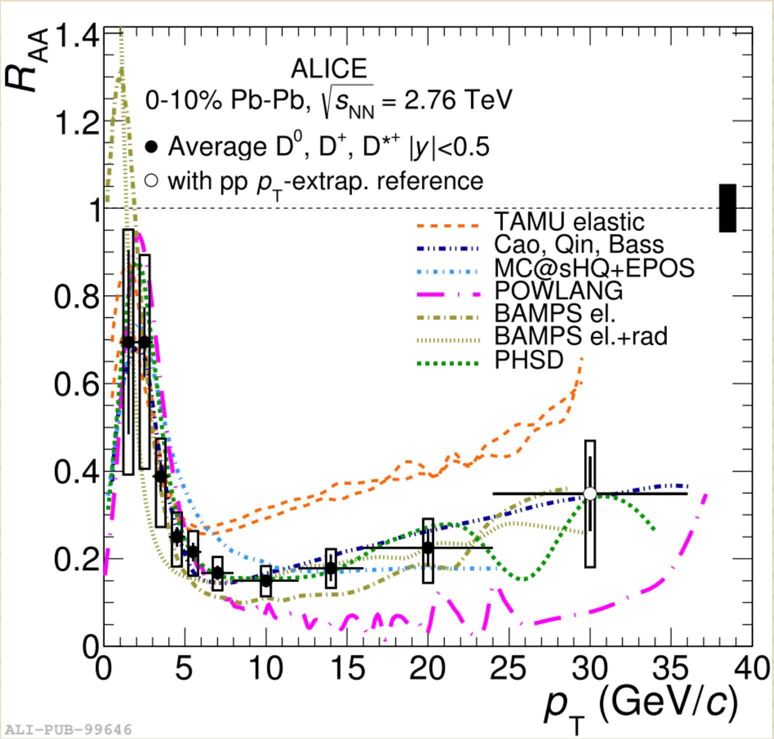
PRC90 (2014) 034904

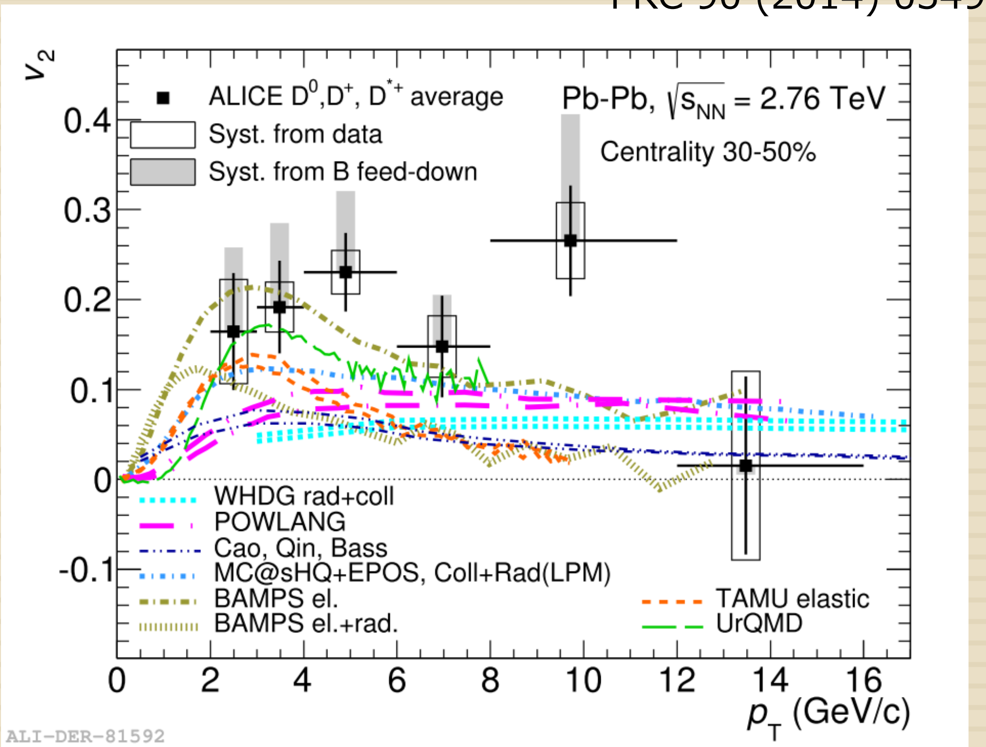


- Positive v_2 is observed (5σ effect for $2 < p_T < 6$ GeV/c in 30-50% centrality bin)
- D-meson v_2 tends to be larger in semi-central than in central collisions
- D-meson v_2 is similar to that of charged particles
  - Significant interaction of charm quarks with the medium (PRL 111 (2013) 102301)

Model comparisons

PRC 90 (2014) 034904



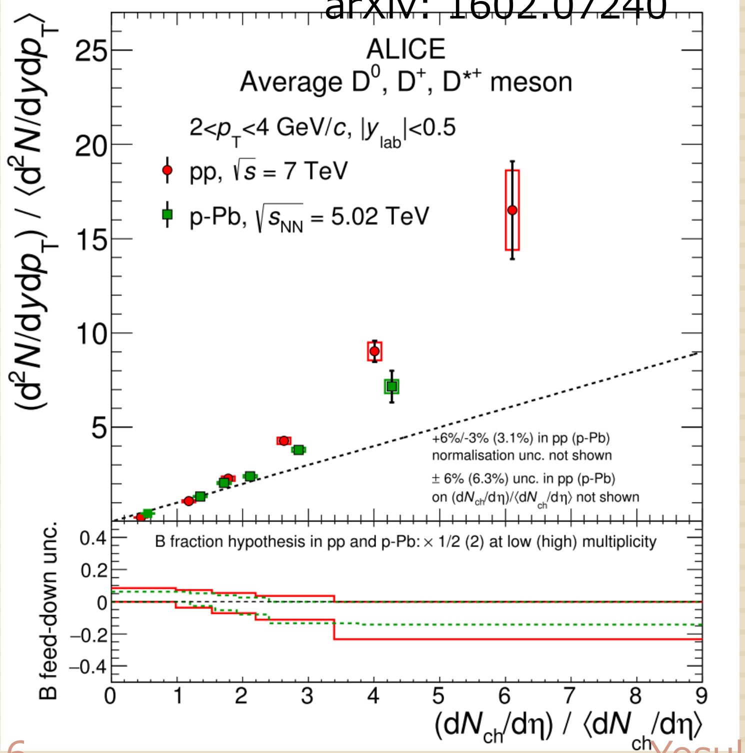


- Various models with different energy-loss mechanisms, fireball evolution, hadronization, etc
- Simultaneous description of R_{AA} and v_2 seems challenging for models

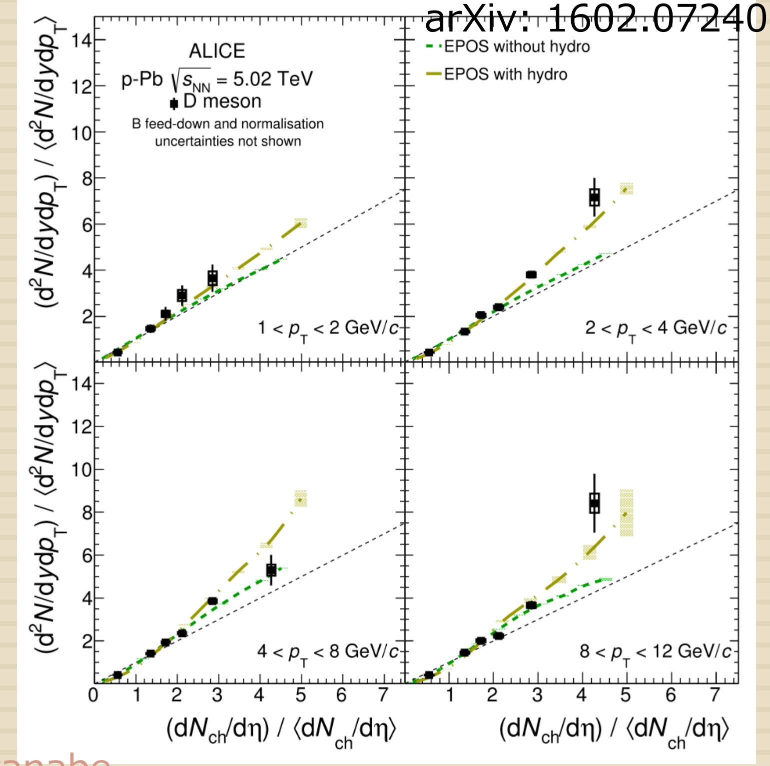
D mesons in small systems

- D-meson production is studied as a function of multiplicity in pp and p-Pb collisions
  - Study the interplay between hard and soft processes of particle production
- The increase of self-normalized yields with multiplicity is faster than linear
- EPOS 3 including hydro describes the data slightly better than the one without hydro

arXiv: 1602.07240



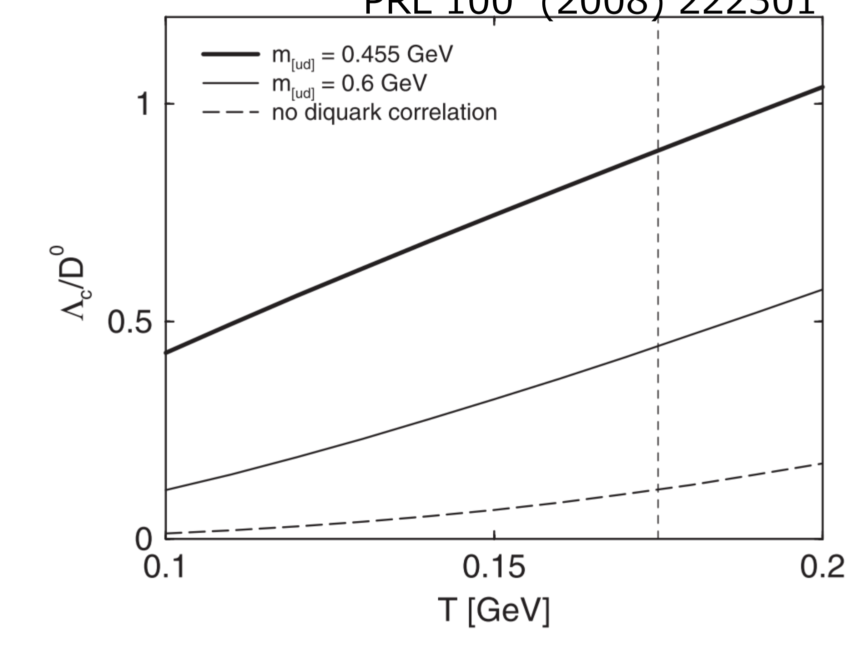
arXiv: 1602.07240



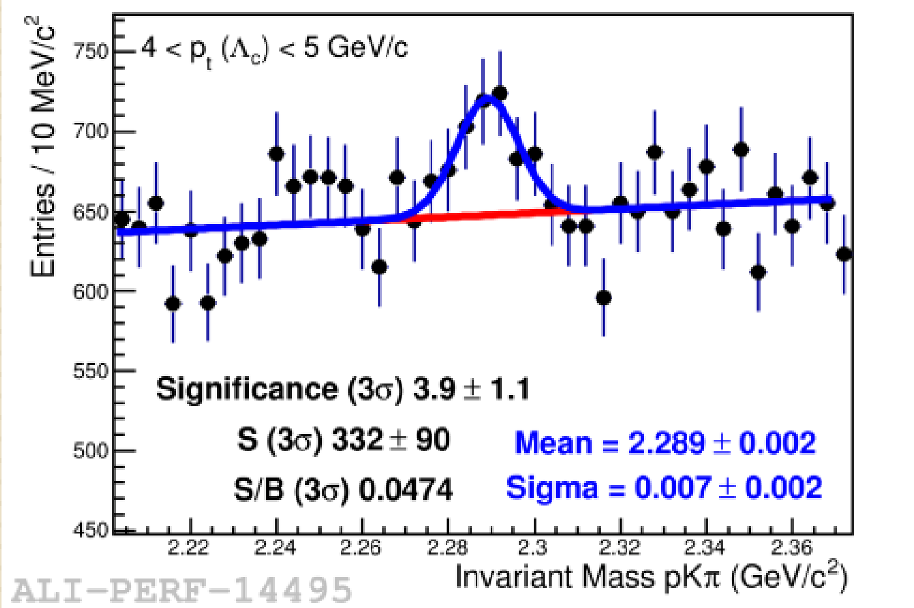
Λ_c^+

- Λ_c production is sensitive to the abundance of di-quark structures in the QGP
- Λ_c production is not well known even in elementary collisions at LHC energies
  - We are currently working on its measurement in pp and p-Pb collisions

PRL 100 (2008) 222301

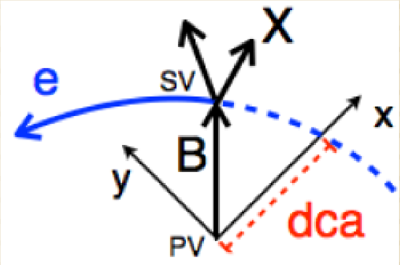


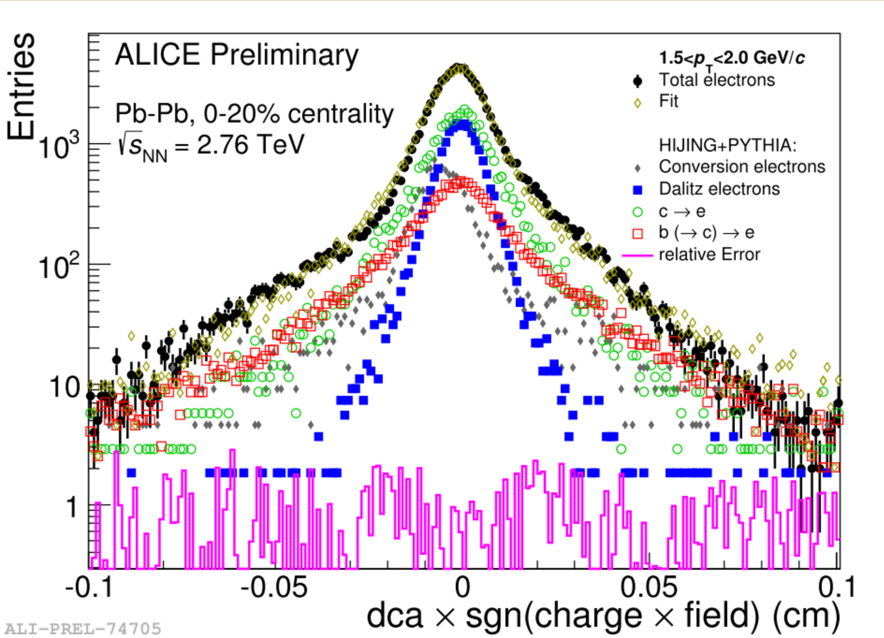
pp √s = 7 TeV

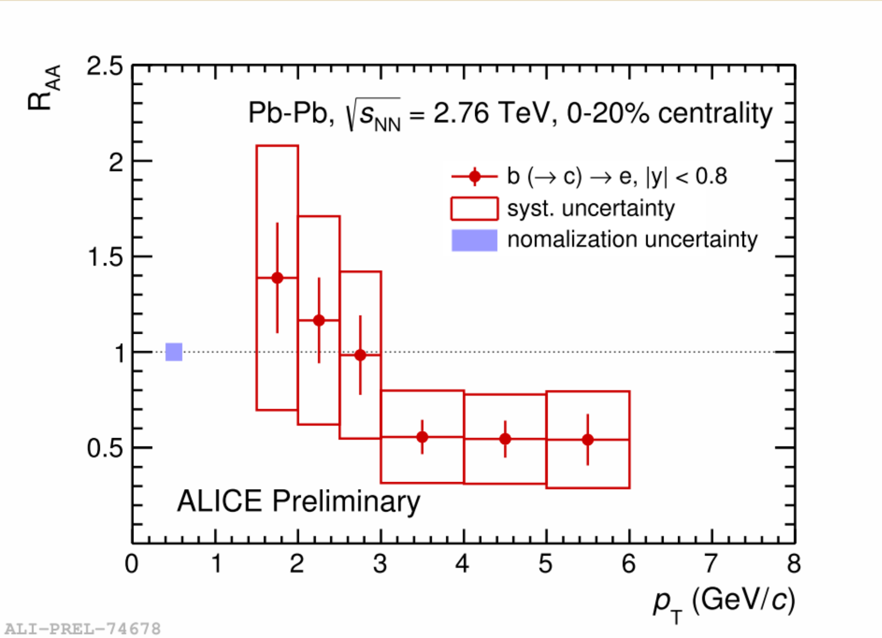


Beauty hadron's R_{AA}

- Beauty-hadron measurements are currently limited to semileptonic decay and B→J/ψ+X (JHEP 1507(2015)051)
- Semileptonic decay analysis
  - Electrons from beauty can be identified with their large impact parameter
  - Hint of R_{AA}<1 for p_T > 3 GeV/c

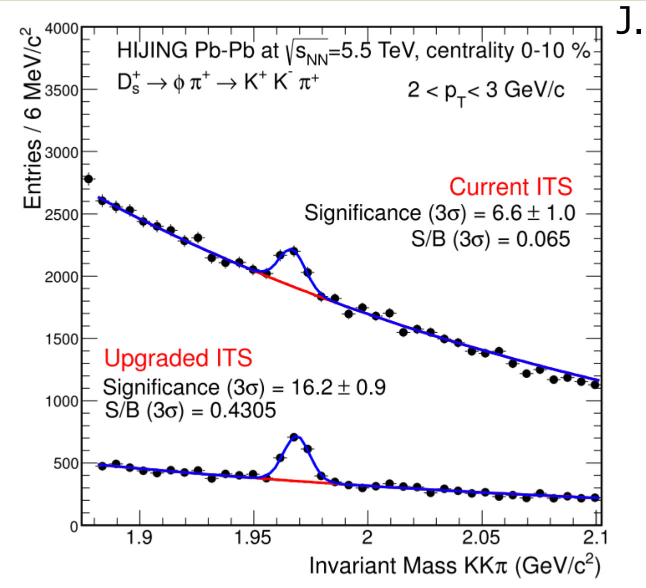






Planned upgrades (2021-)

~100 times larger statistics
~3 times better impact parameter resolution



J. Phys. G 41 (2014) 087001

Observable	Upgrade: p_T^{Umin} (GeV/c)	Upgrade: statistical uncertainty
D meson R_{AA}	0	0.3 % at p_T^{Amin}
D meson from B decays R_{AA}	2	1 % at p_T^{Amin}
D meson elliptic flow ($v_2 = 0.2$)	0	2.5 % at p_T^{Amin}
D from B elliptic flow ($v_2 = 0.1$)	2	20 % at p_T^{Umin}
Charm baryon-to-meson ratio	2	15 % at p_T^{Umin}
D_s meson R_{AA}	1	1 % at p_T^{Amin}

- These are possible only with significant upgrade of detectors
  - TPC: continuous readout using GEM technology
  - ITS: High resolution, low material budget

Hadrons

	Light	Charm	Bottom
Meson	See Jihye's talk	D mesons	B mesons +X X
Baryon	See Jihye's talk	Λ_c, Ξ_c, Ω_c	Λ_b, Ξ_b, Ω_b
Exotics	Hypernuclei, Dibaryons, …	Tcc, Wccc, …	Tcb, …

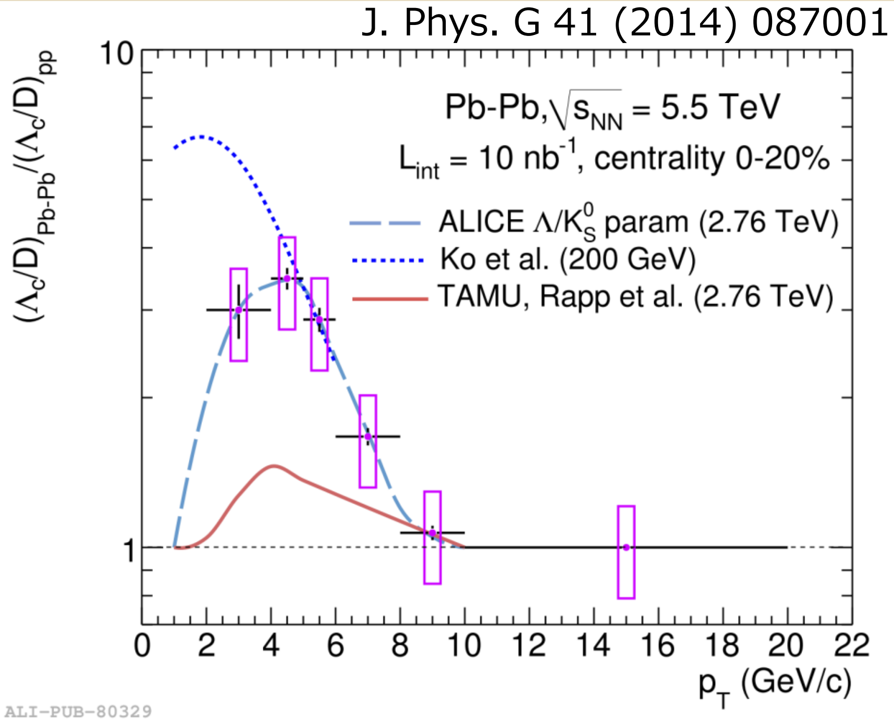
Hypernuclei + Exotica

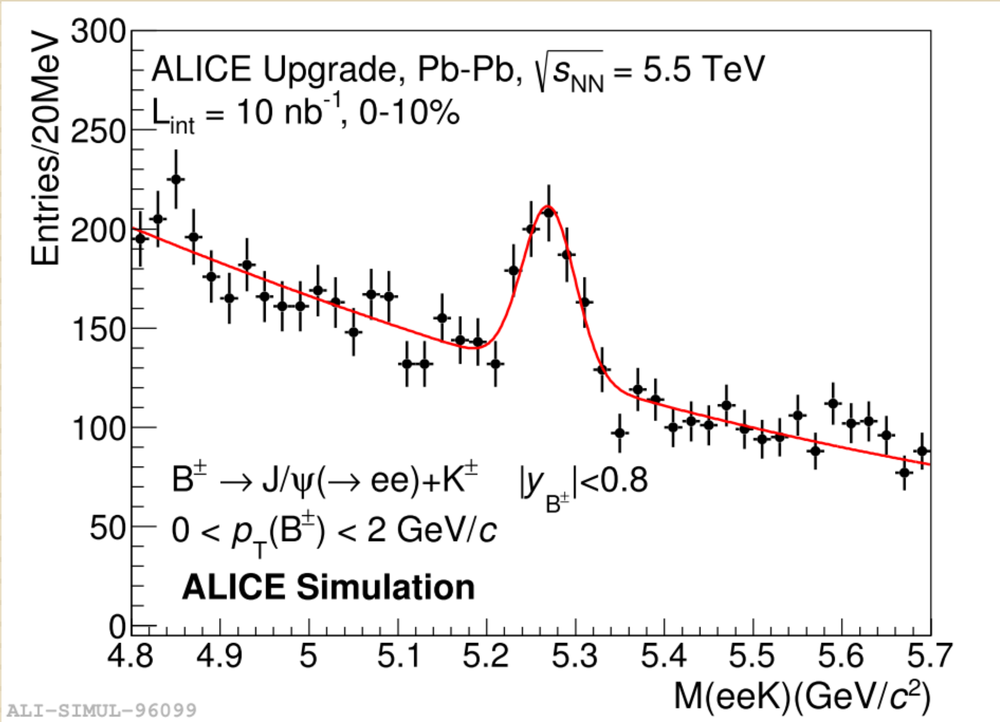
J. Phys. G 41 (2014) 087001

	Expected yields
Anti-α	30,000
$^{3}_{\Lambda}H$	300,000
$^{4}_{\Lambda}H$	800
$^{4}_{\Lambda\Lambda}H$	**34**
$\Xi\Xi$	150,000

10^{10} central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV
8% efficiency per detected baryon is assumed

Charm and beauty hadrons





- Increased statistics + better vertexing capability will enable further studies of Λ_c
- Beauty hadrons can also be fully reconstructed

Summary

- ALICE is an ideal place to measure rare hadron production in heavy-ion collisions
- Hypertriton yield and lifetime are measured
- Our data do not support the existence of ΛΛ and Λn
  - Our upper limits are one order of magnitude smaller than model calculations
- D-meson production in Pb-Pb collisions is intensively studied
  - Strong suppression (R_{AA} < 1)
    - R_{AA} (π) ~ R_{AA} (D) < R_{AA} (B)
  - Positive v_2
  - Combination of R_{AA} and v_2 starts constraining theoretical models
  - Hint of less suppression for D_s^+
- More to come from existing data, e.g. Λ_c
- ··· much more to come after ALICE upgrade

BACKUP