Status and perspectives of Hypernuclear Physics in ultra-relativistic heavy ion collisions

Stefania Bufalino
Politecnico and INFN Torino

Outlook

- Motivation for the hyper-nuclei search in URHIC
- Introduction about the models
- Experimental method for hypertriton measurement
- Results from ALICE at the LHC
- Results from STAR at RHIC
- Summary and a look to the future

Motivations

The main goal of the URHIC is to study the formation of Quark-Gluon Plasma, its properties and evolution:

- (anti-)hypernuclei **yields are sensitive to the freeze-out temperature** due to their large mass [thermal model]
- light (anti-)hypernuclei have **small binding energy and small Λ separation energy** e.g. $B_\Lambda(^3_\Lambda H$ = 0.13 ± 0.05 MeV) [D.H. Davis Nucl. Phys. A 754, 3c (2005)]
  - light (anti-)hypernuclei should dissociate in a medium with high T_{chem} (~156 MeV) and be suppressed
  - light (anti-)hypernuclei production determined by the entropy per baryon (fixed at chemical freeze-out)
  - if light (anti-)hypernuclei yields equal to thermal model prediction ⇒ sign for adiabatic (isentropic) expansion in the hadronic phase
- **A=3 (anti-)(^{3}He, t, $^3_\Lambda$H), simple systems of 9 valence quarks:**
  1. $^3_\Lambda$H / ^{3}He and $^3_\Lambda$H / t (and anti) ⇒ Λ-nucleon correlation (local baryon-strangeness correlation)
  2. t / ^{3}He (and anti) ⇒ local charge-baryon correlation
  3. YN & YY interaction (strangeness sector of hadronic EOS, cosmology, physics of neutron stars)

(Hyper-)nuclei in URHIC

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Thermal Model

Coalescence Model

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Coalescence Model

- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem})
- (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $e(^{-M/T_{chem}})$
- depends only on T, V and μ_B, which is basically 0 at LHC

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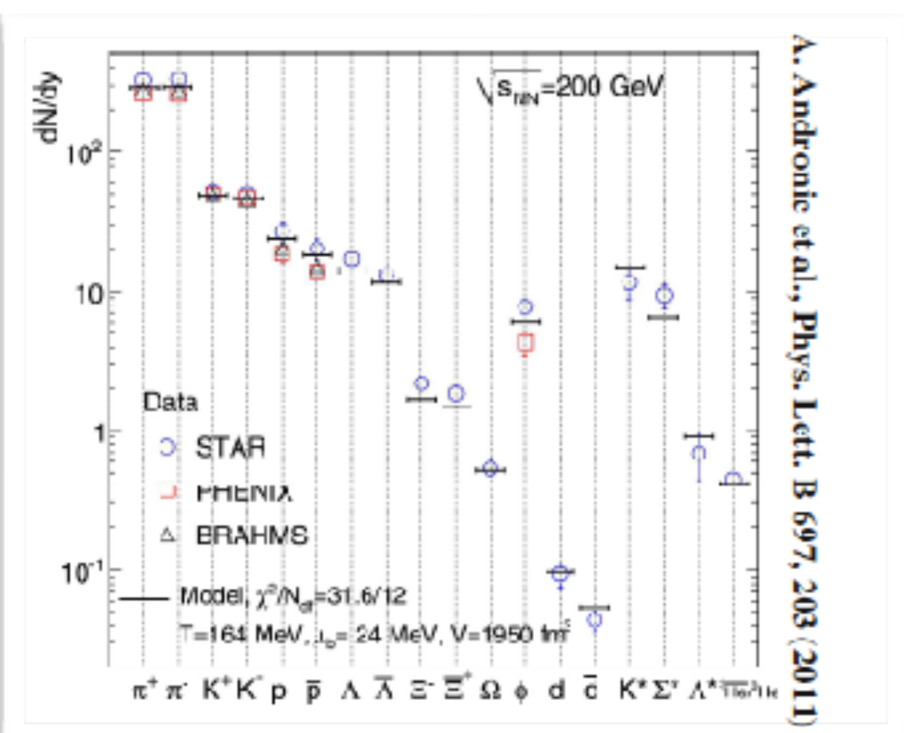

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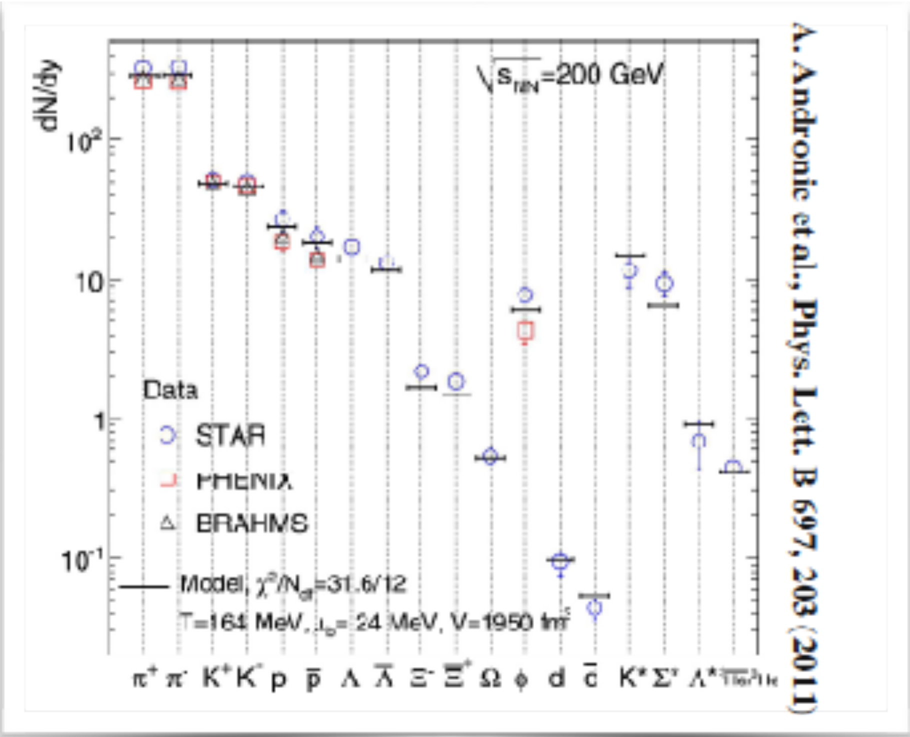

Coalescence Model

- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper-)nucleus can be formed
- (Hyper-)nuclei are formed by protons (Λ) and neutrons which have similar velocities after the freeze-out

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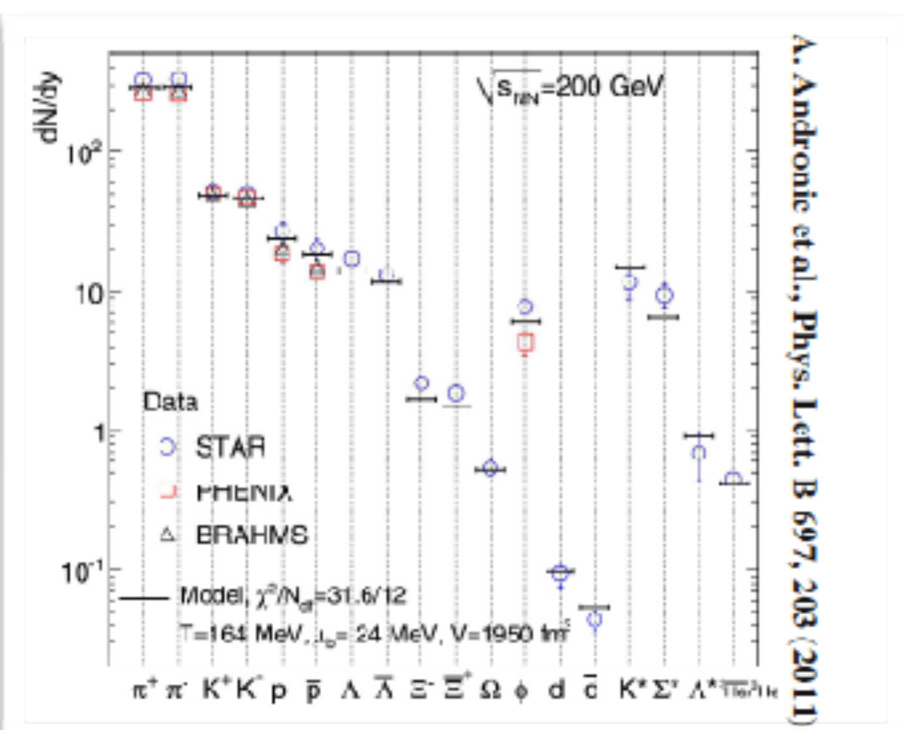

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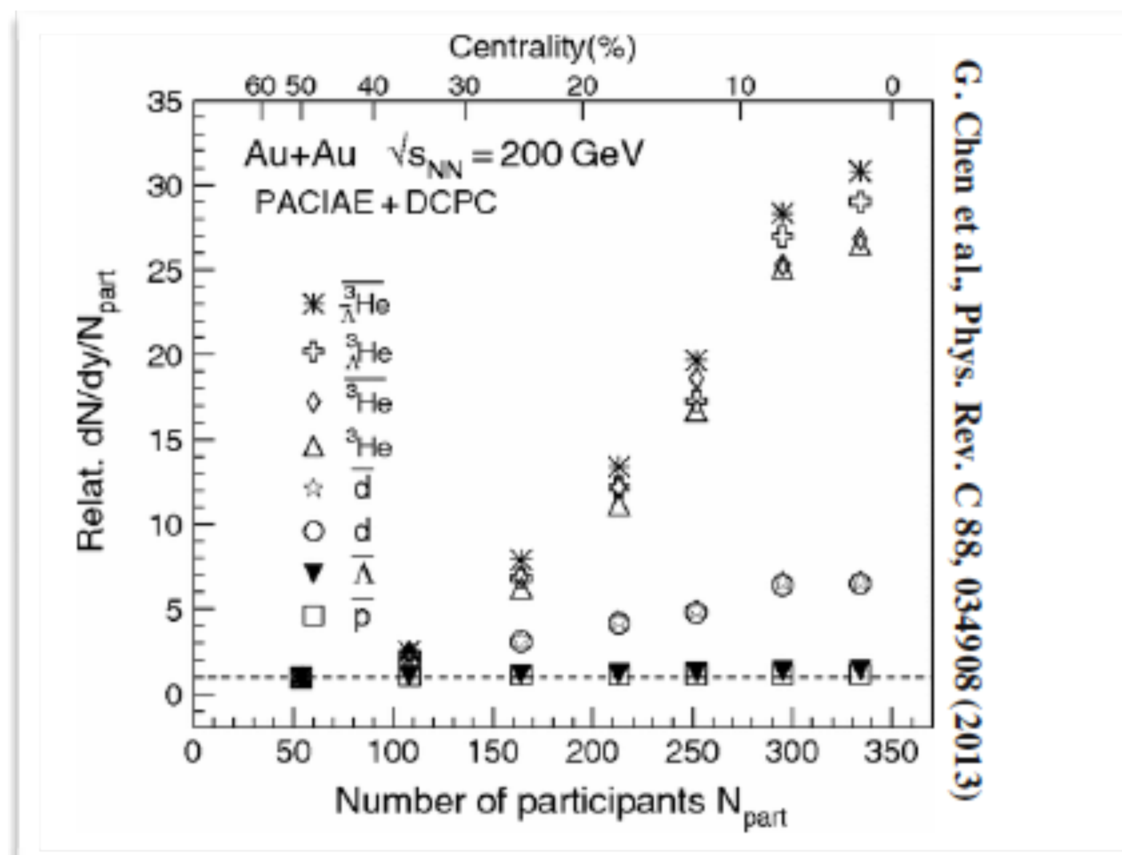
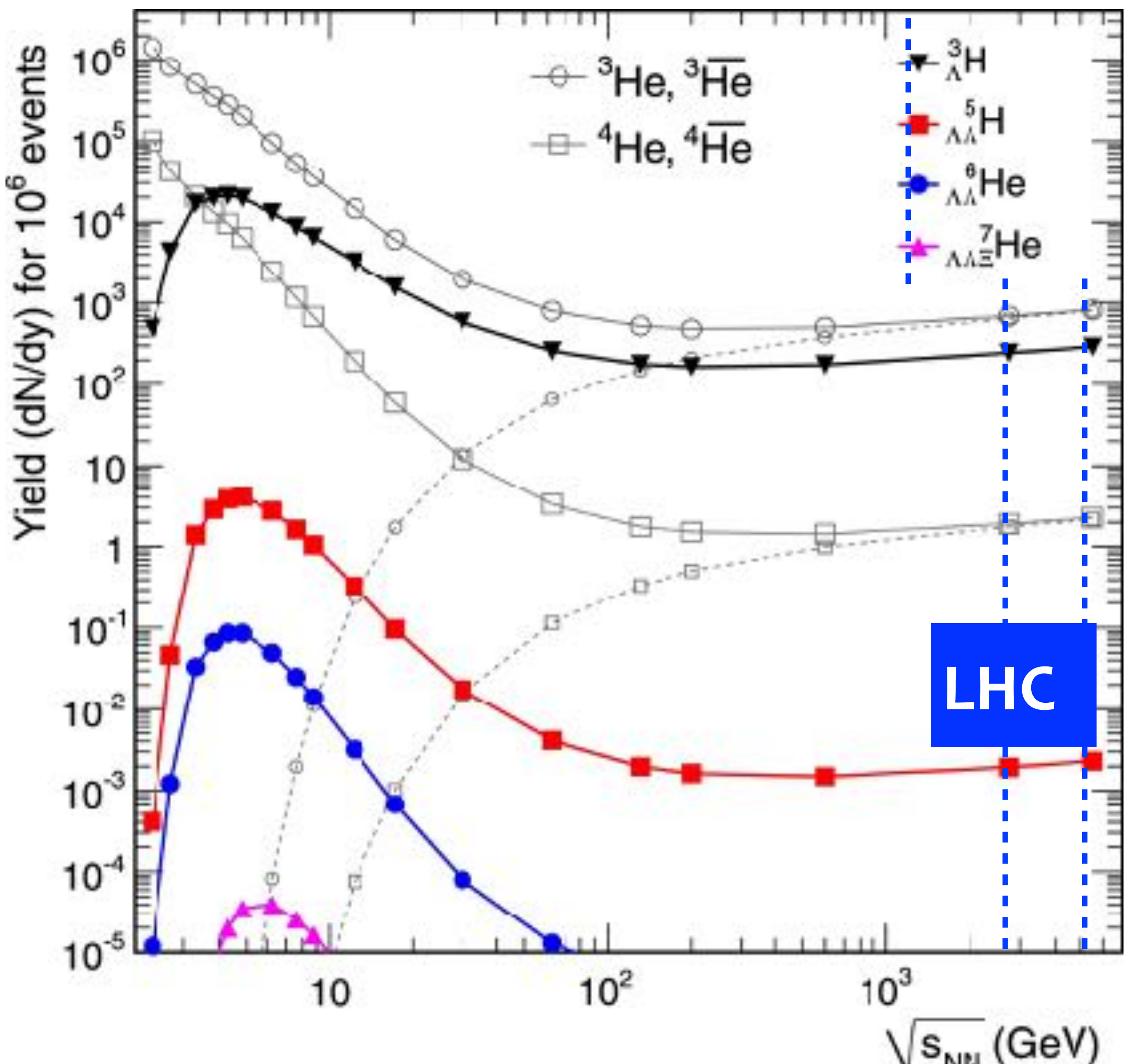


(Hyper-)nuclei in heavy-ion collisions at the LHC

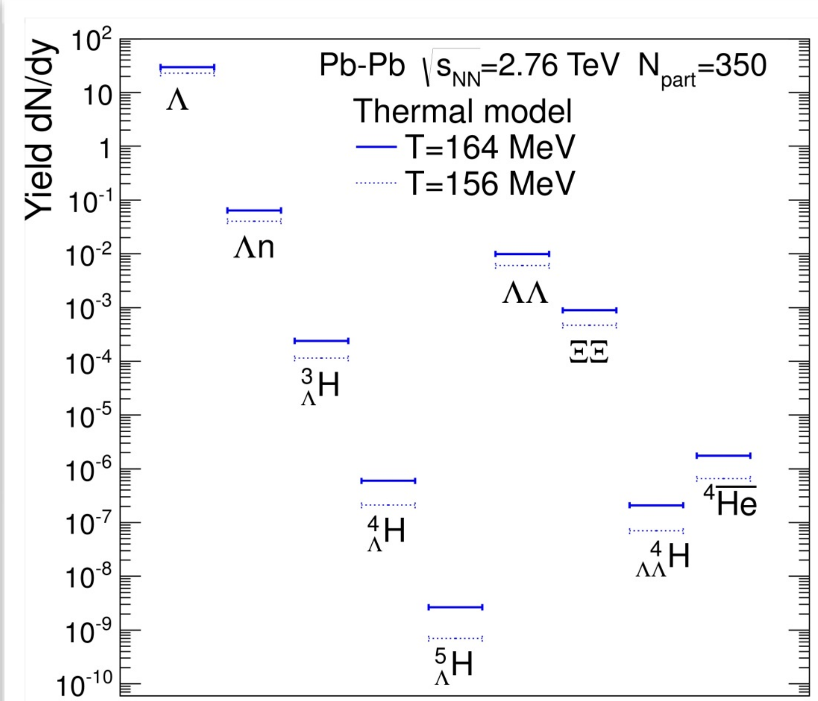


A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker.
B. *Phys. Lett. B* 697, 203 (2011)

A. Andronic et al., Phys. Lett. B 697, 203 (2011)

	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

A. Andronic, Private communication



- Hadrons emitted from the interaction region in statistical equilibrium once the *chemical freeze-out* temperature is reached
- Estimation for central heavy ion collisions at the LHC energies

Hypertriton search: methodology

Hypertriton: lightest know hypernucleus
bound state of **p**, **n** and **Λ**

Mass = 2.992 GeV/c^2

Λ-Lifetime ~263 ps

Decay Channel:

1. Mesonic
2. Non Mesonic

Mesonic decay

Charged	Neutral
$^3_\Lambda H \longrightarrow {}^3He+\pi^-$	$^3_\Lambda H \longrightarrow {}^3H+\pi^0$
$^3_\Lambda H \longrightarrow d+p+\pi^-$	$^3_\Lambda H \longrightarrow d+n+\pi^0$
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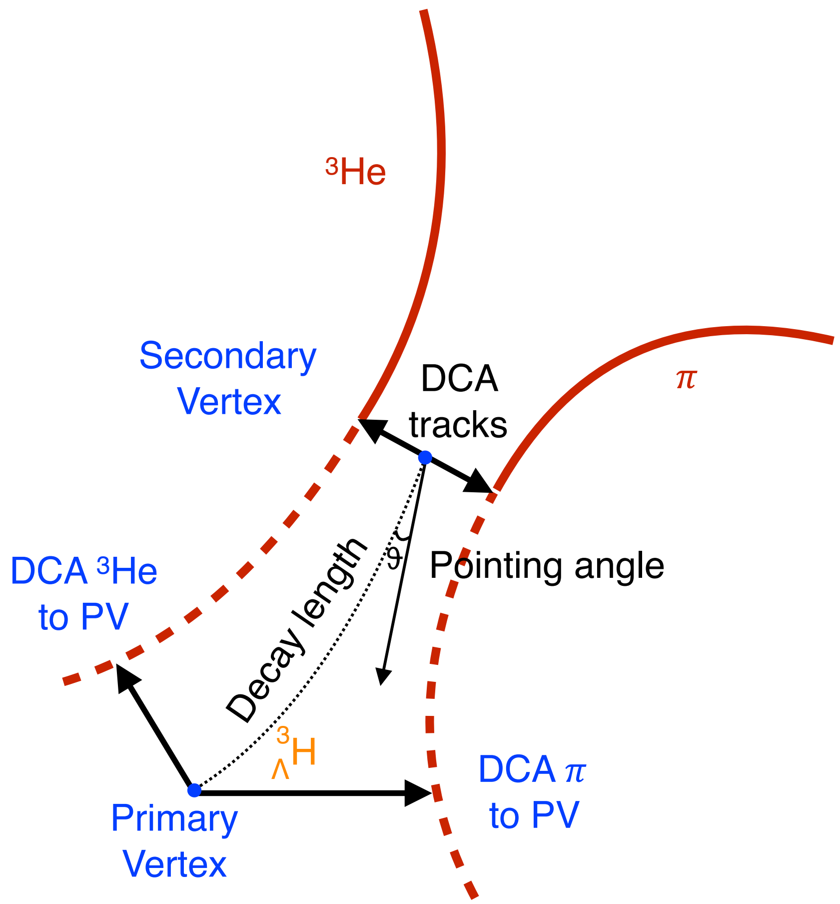

- Anti-hypertriton was first observed by STAR Collaboration
  Science 328,58 (2010)

- Study of the production in the charged decay channel
  - 2 body (B.R.[1] ≅ 25%)
  - 3 body (B.R.[1] ≅ 41%)

- **Phys. Lett. B 754, 360-372 (2016)**

[1] **H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603**

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Signal extraction:

- Identify daughters (^{3}He,π) or (d,p,π)
- Apply topological cuts in order to:
  - Identify secondary decay vertex
  - Reduce combinatorial background
- Evaluate invariant mass

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Hypertriton in ALICE

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Hypertriton in ALICE

Hypertriton: lightest known hypernucleus bound state of **p**, **n** and **Λ**

Mass[4] = 2.99116 ± 0.00005 GeV/c^2

Decay Channels:

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2. Non Mesonic (B.R. < 0.02%)

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Hypertriton in ALICE

- The study of the production of the (anti-)hypertriton is important to constrain **thermal** and **coalescence** models
- Open puzzle on the lifetime of the hypertriton
- Study of the production in the accessible decay channels (charged products only)
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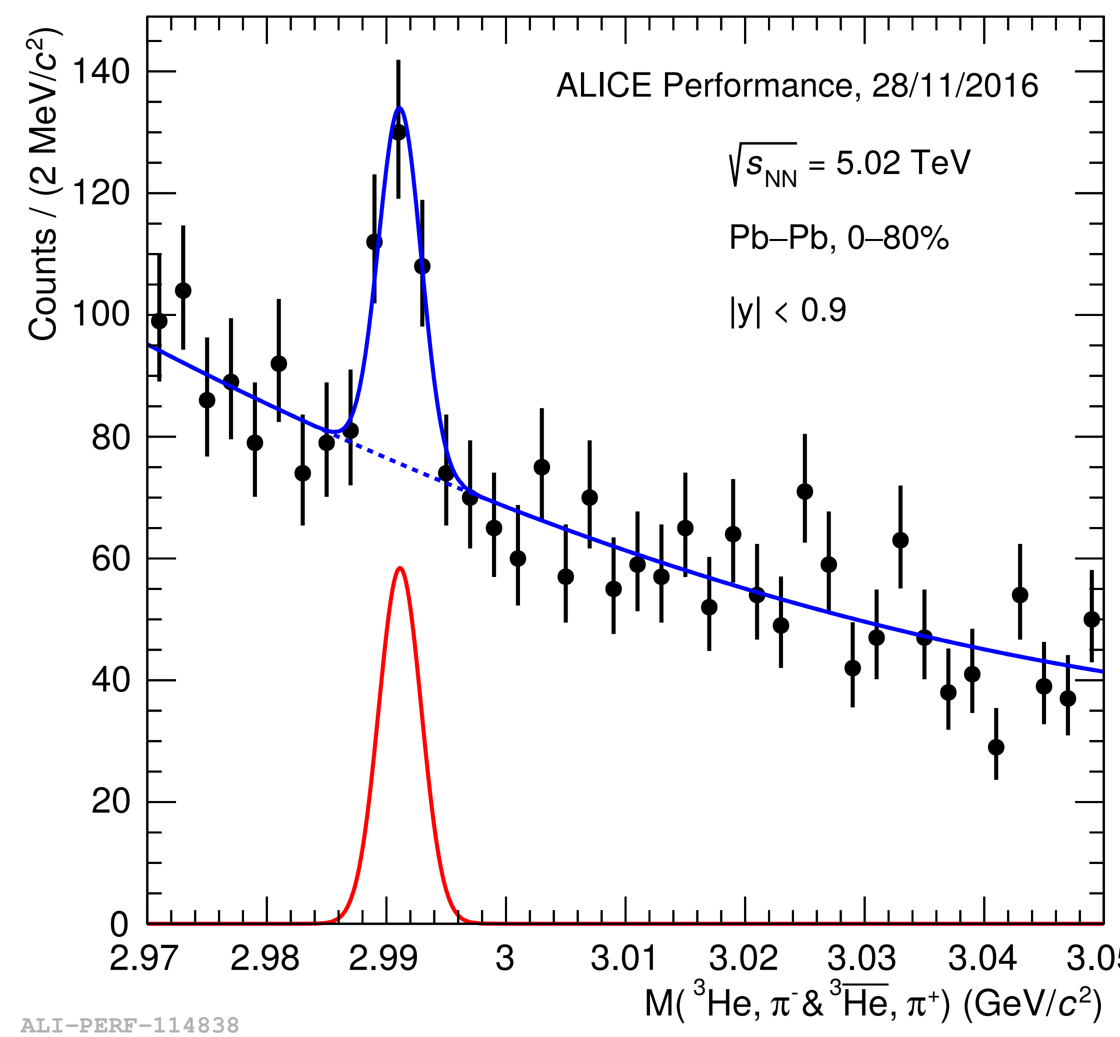

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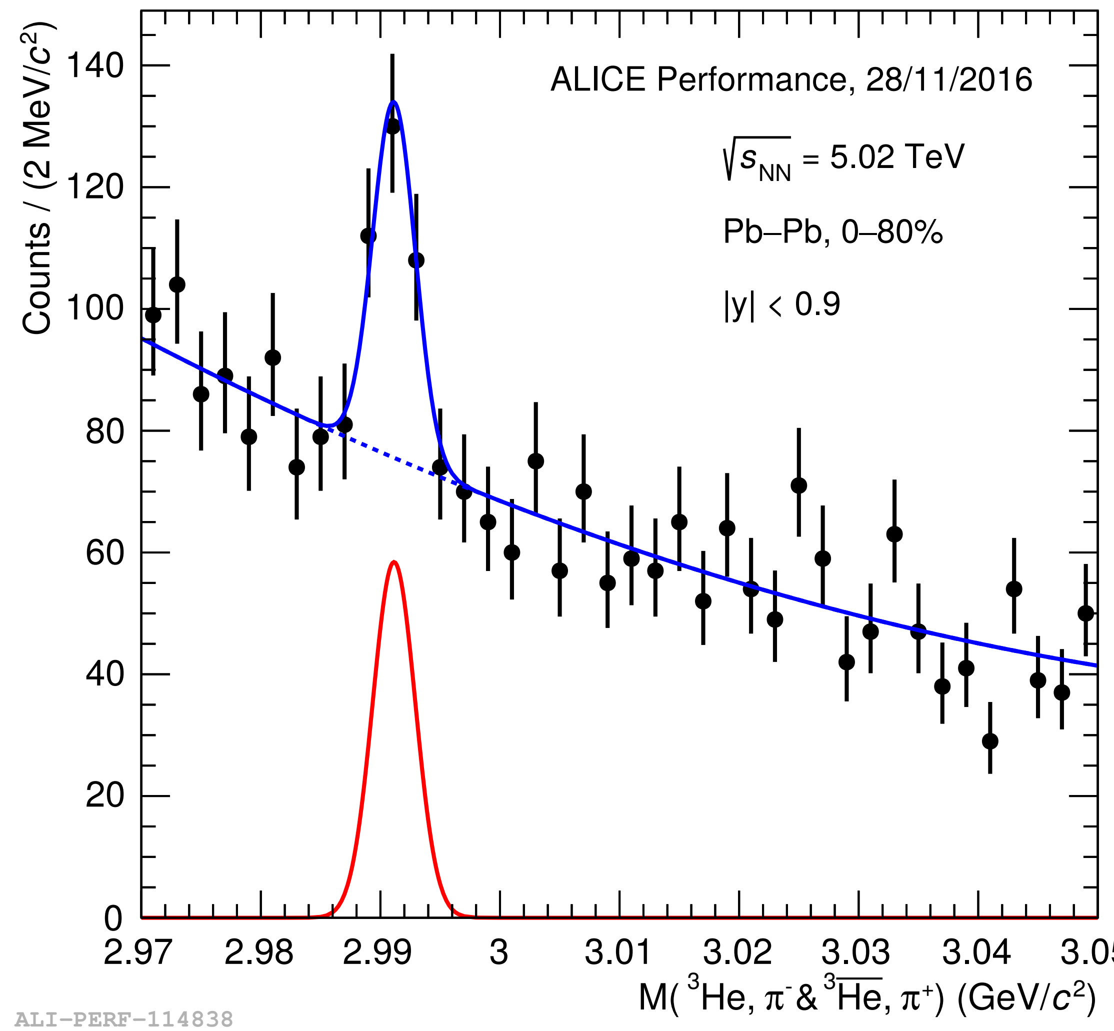

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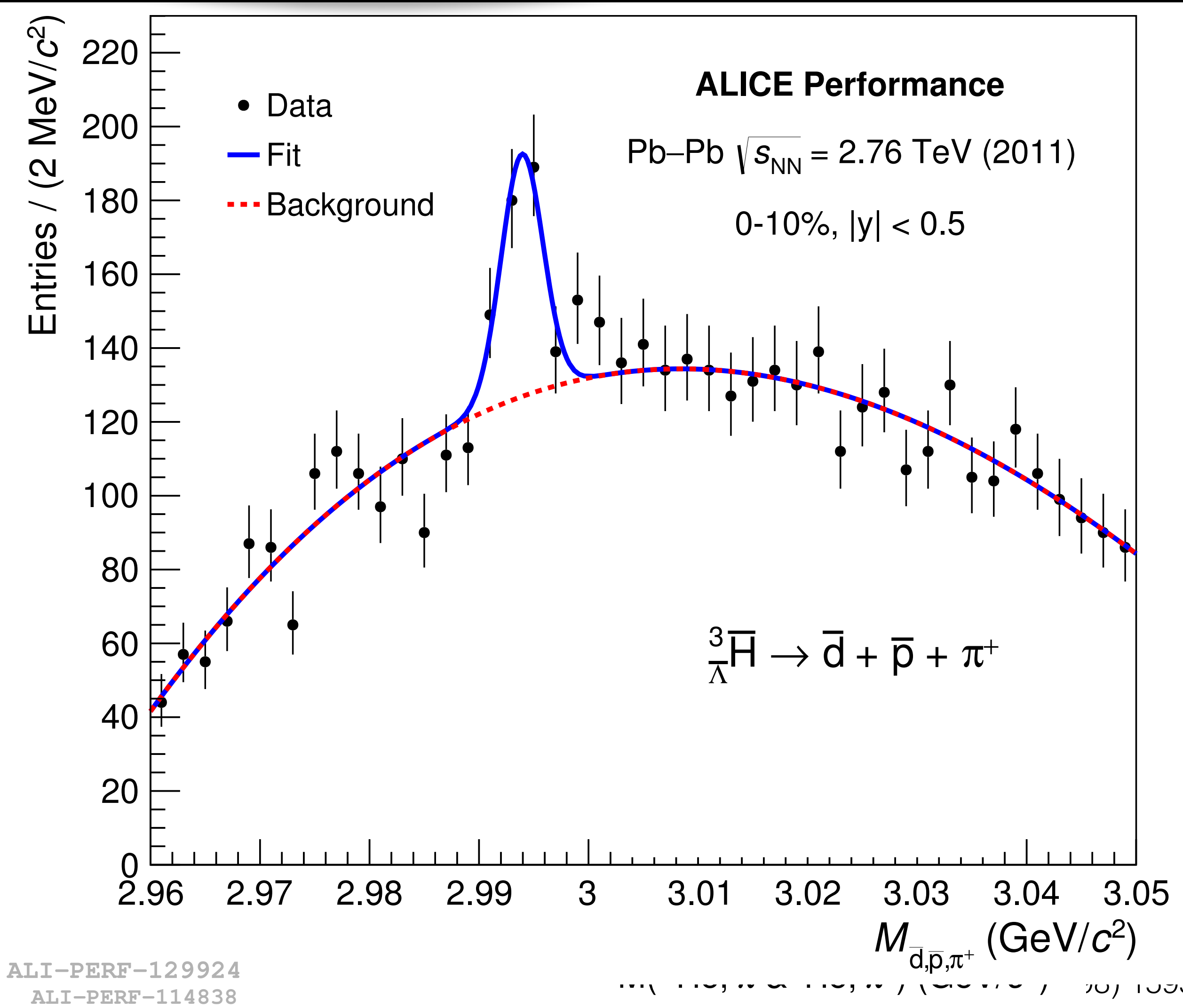
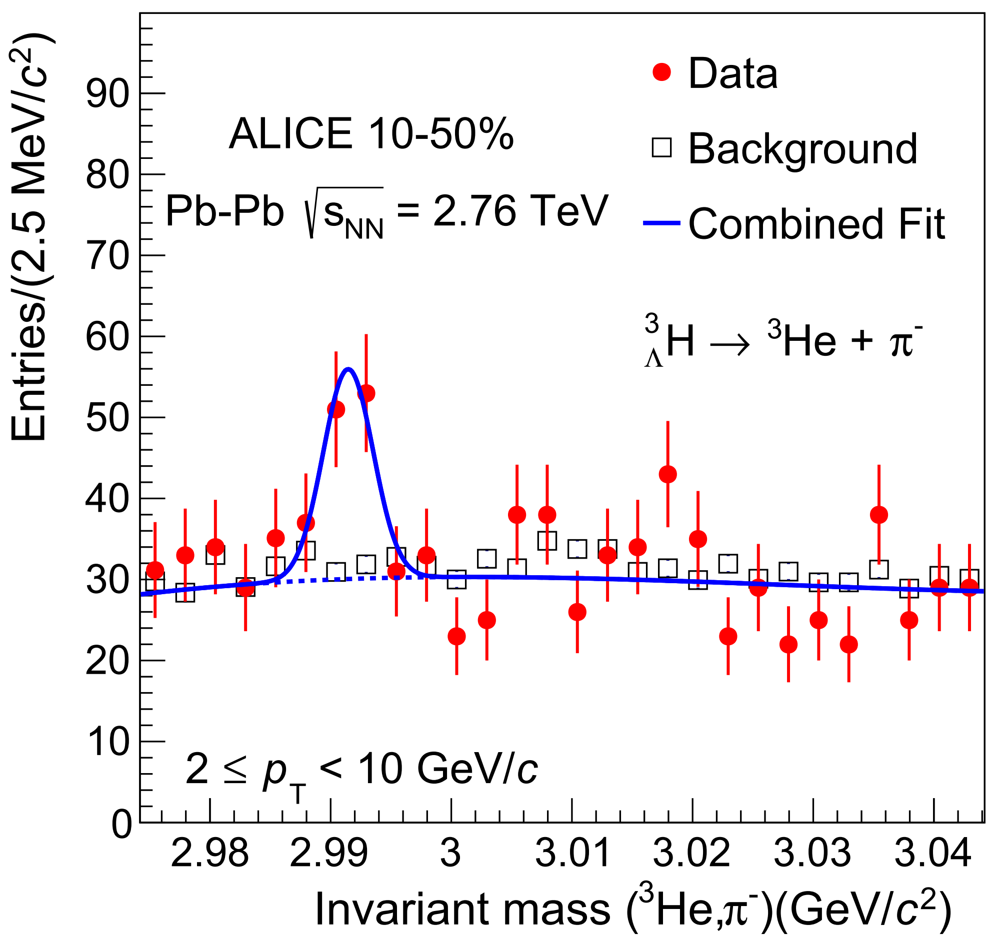
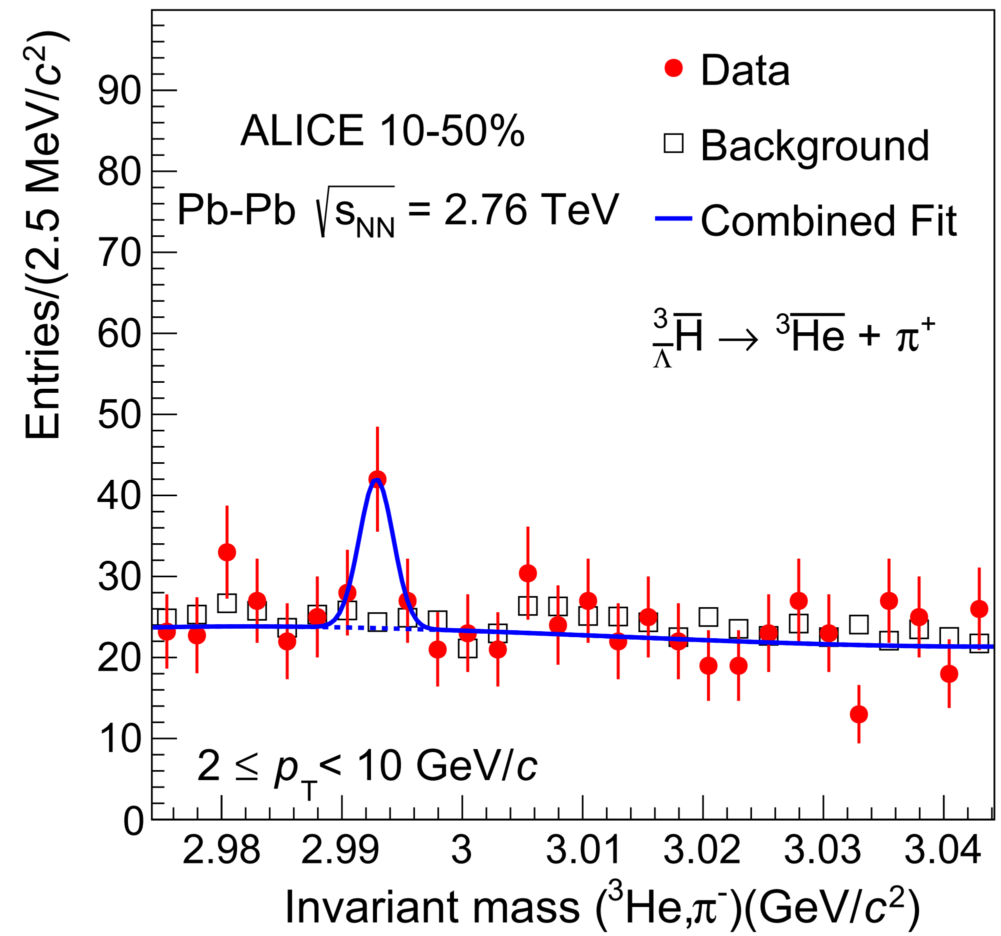


Hypertriton in ALICE: *signal*

ALICE Collaboration, *Phys. Lett. B* 754, 360-372 (2016)



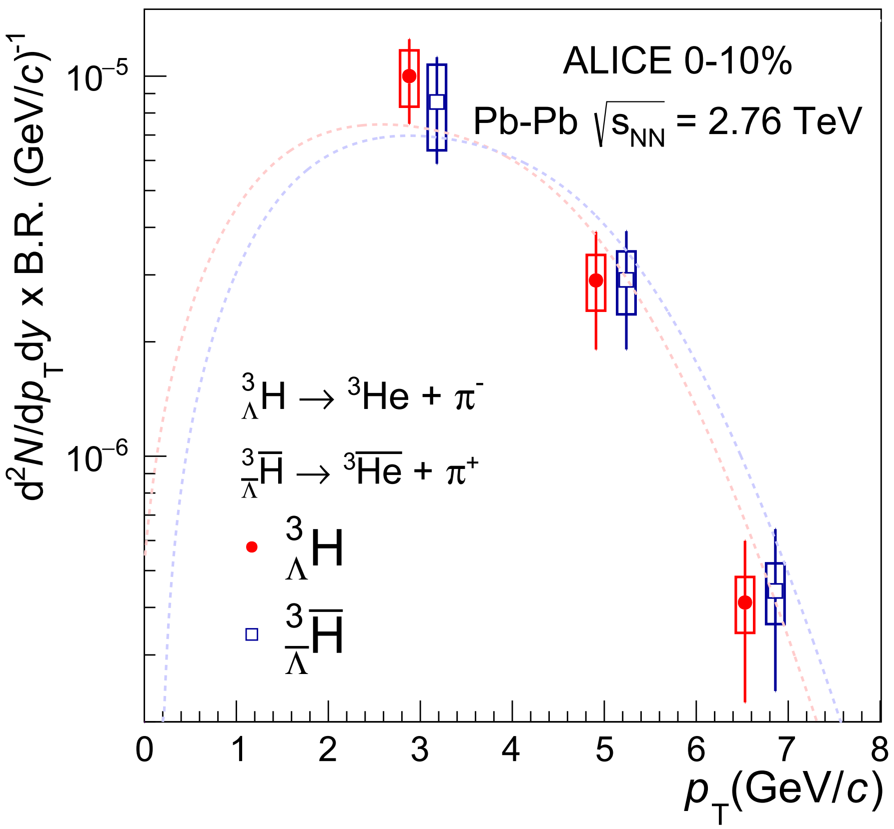


μ = 2.991 ± 0.001 ± 0.003 GeV/c^2
σ= (3.01 ± 0.24)x10^{-3} GeV/c^2

To be compared to literature value:
μ= 2.99131 ± 0.00005 GeV/c^2
[Juric, Nucl. Phys. B 52, 1 (1973)]

- Fit to the invariant mass spectrum
  - *signal*: Gaussian
  - *background*: 3rd degree polynomial
- Open square: background obtained from data and used to tune the polynomial parameters
- Signal obtained for 3 p_T bins and 2 centrality classes (0-10% and 10-50%)

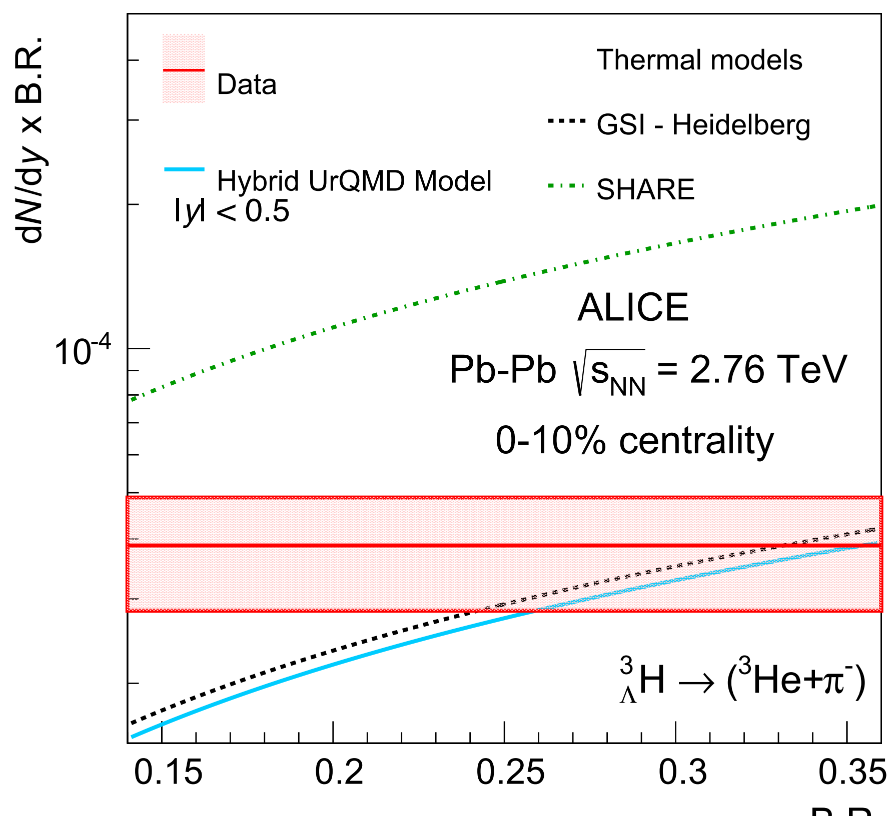
Hypertriton in ALICE: p_T spectra and yields



Points and curves of the anti- hypertiton displaced for visibility

p_T spectra

- differential p_T-spectra for particle and anti-particle in the most central collisions
- Blast-Wave function fits the spectra well and it is used to extrapolate the integrated yield at low and high p_T
- Blast-Wave parameters taken from deuteron analysis, leaving the normalization free



dN/dy x B.R. vs B.R.

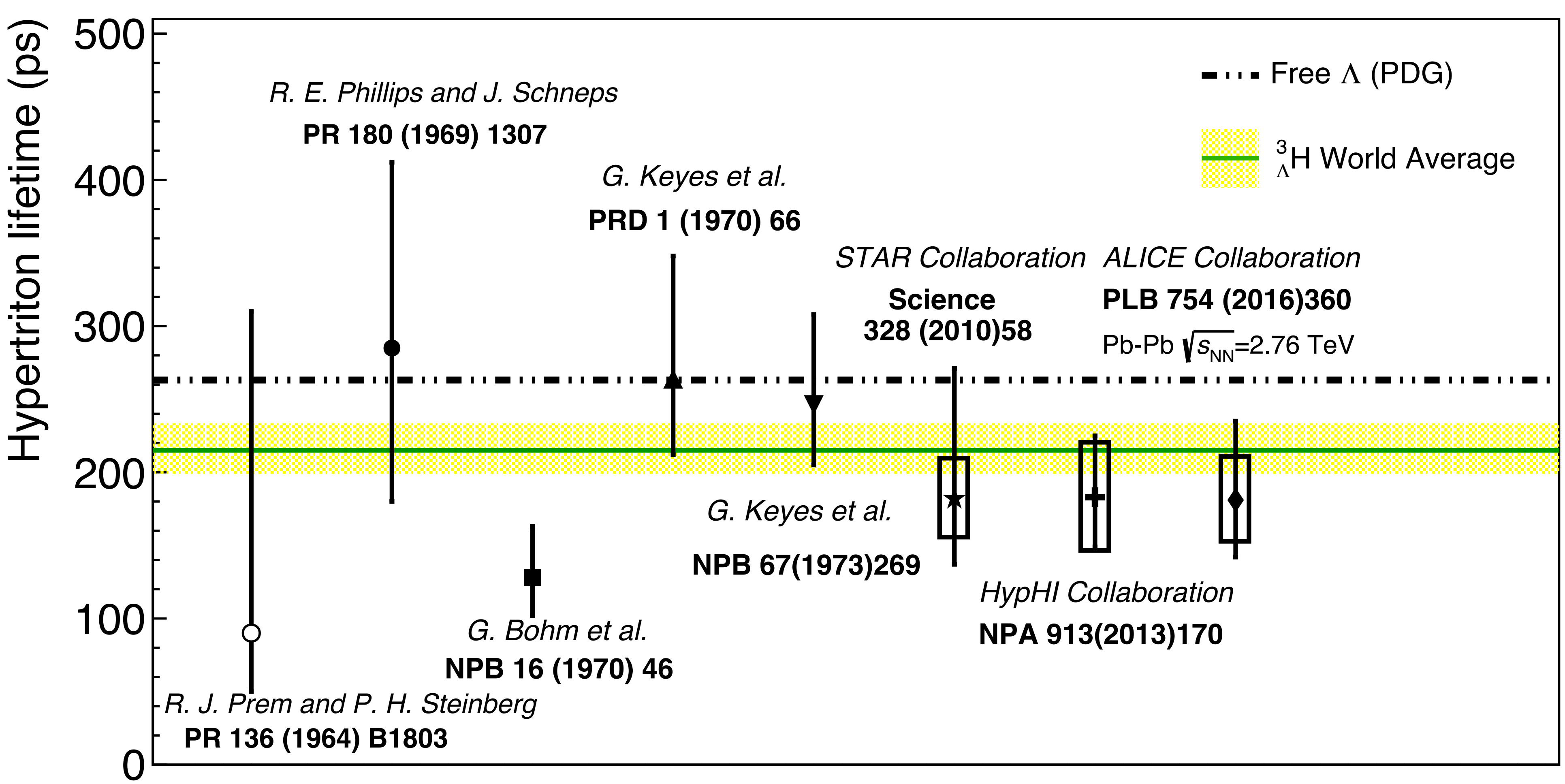
✓ Hybrid UrQMD: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium J. Steinheimer et al. *Phys. Lett. B* 714 (2012) 85–91

✓ GSI-Heidelberg: equilibrium statistical thermal model with T_{chem} = 156 MeV A. Andronic et al. *Phys. Lett. B* 697, 203 (2011)

- SHARE: non-equilibrium thermal model with T_{chem} = 138.3 MeV M. Pétran et al. *Phys. Rev. C* 88 (3) (2013) 034907

Hypertriton: the *lifetime puzzle*

Where we stood last year
only published results



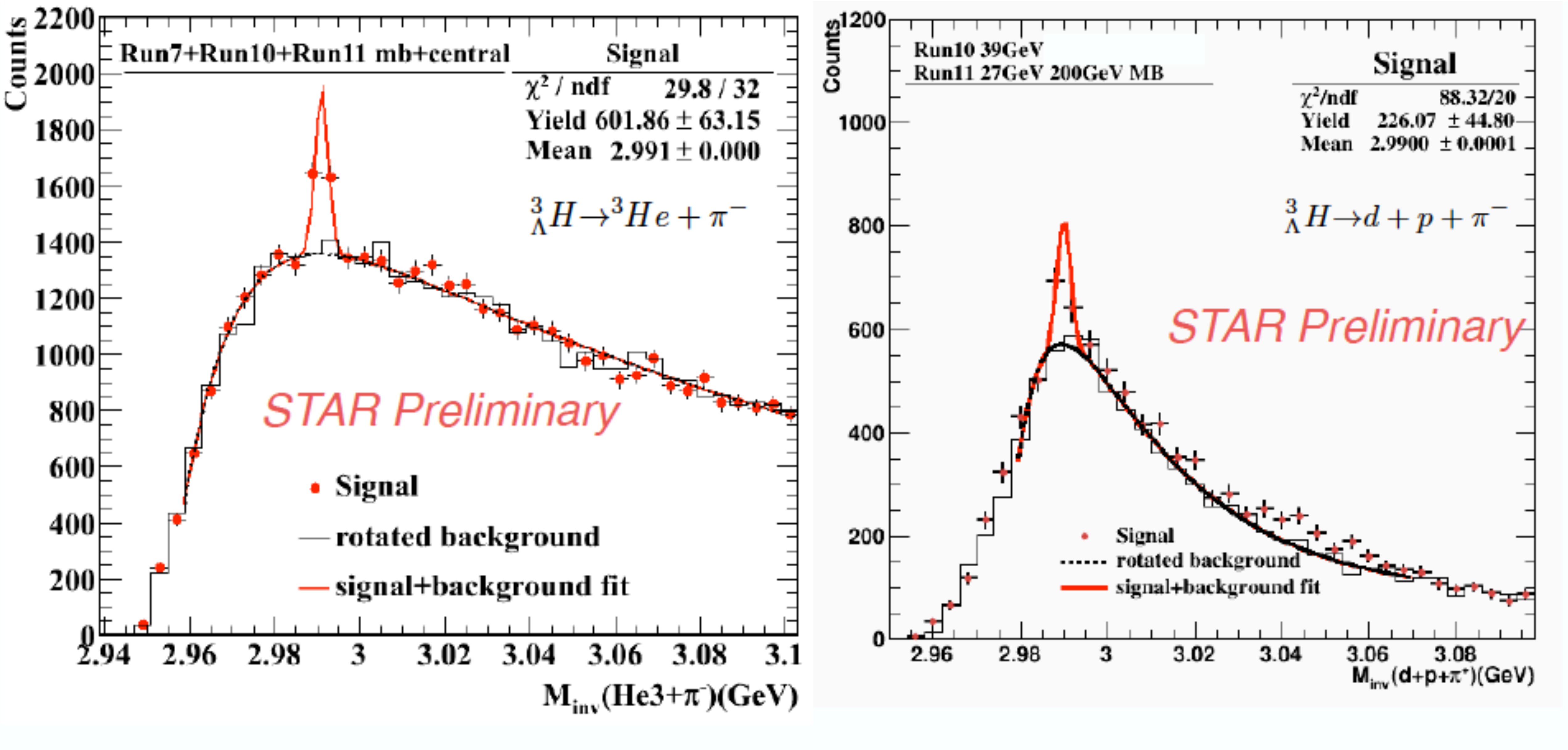
Re-evaluation of world average including ALICE result:

$$\tau = (215^{+18}_{-16})\ ps$$

ALICE value compatible with the computed average

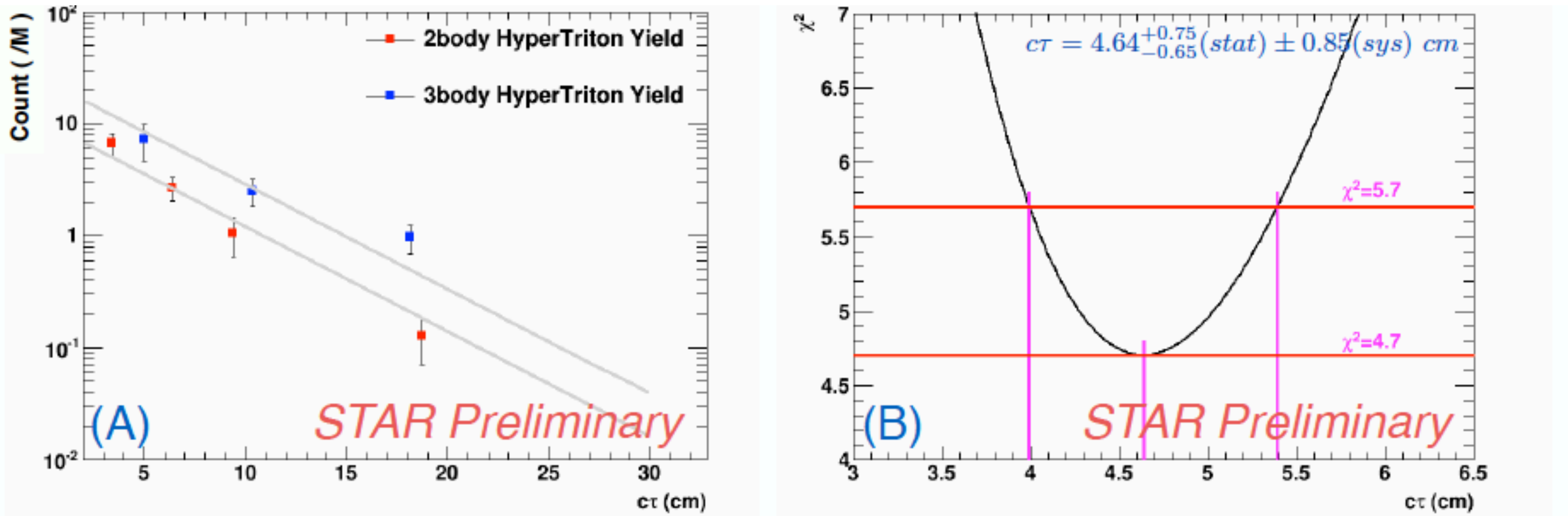
Hypertriton in STAR: Preliminary

Invariant mass spectra from both 2- and 3-body decay



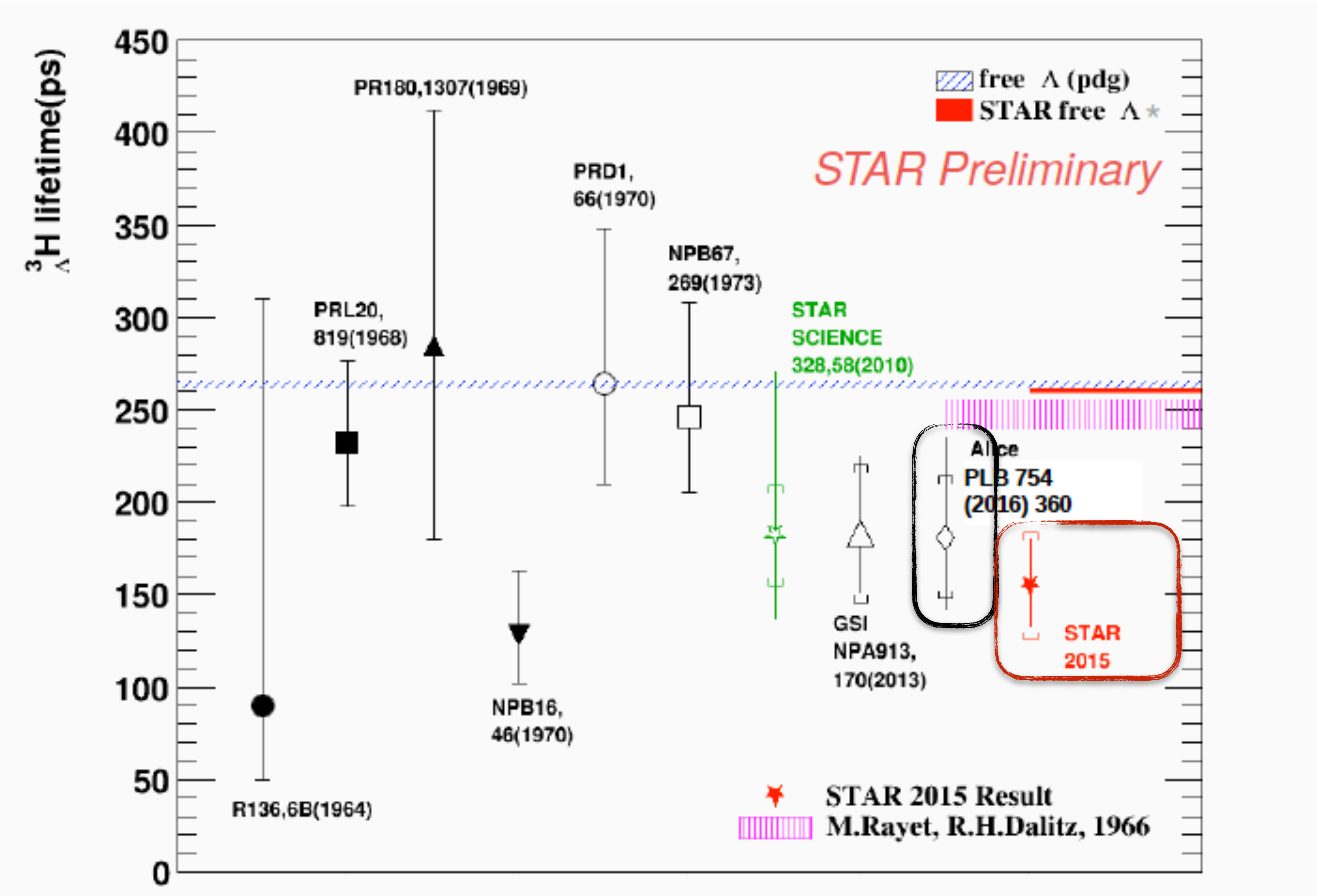
Hypertriton in STAR: Preliminary

Determination of $^3_\Lambda H$ both 2- and 3-body decay



$\tau = 155^{+25}_{-22}(\text{stat}) \pm 29\ (\text{sys})\ ps$

World data adding preliminary STAR results



Hypertriton *lifetime in ALICE: new Preliminary*

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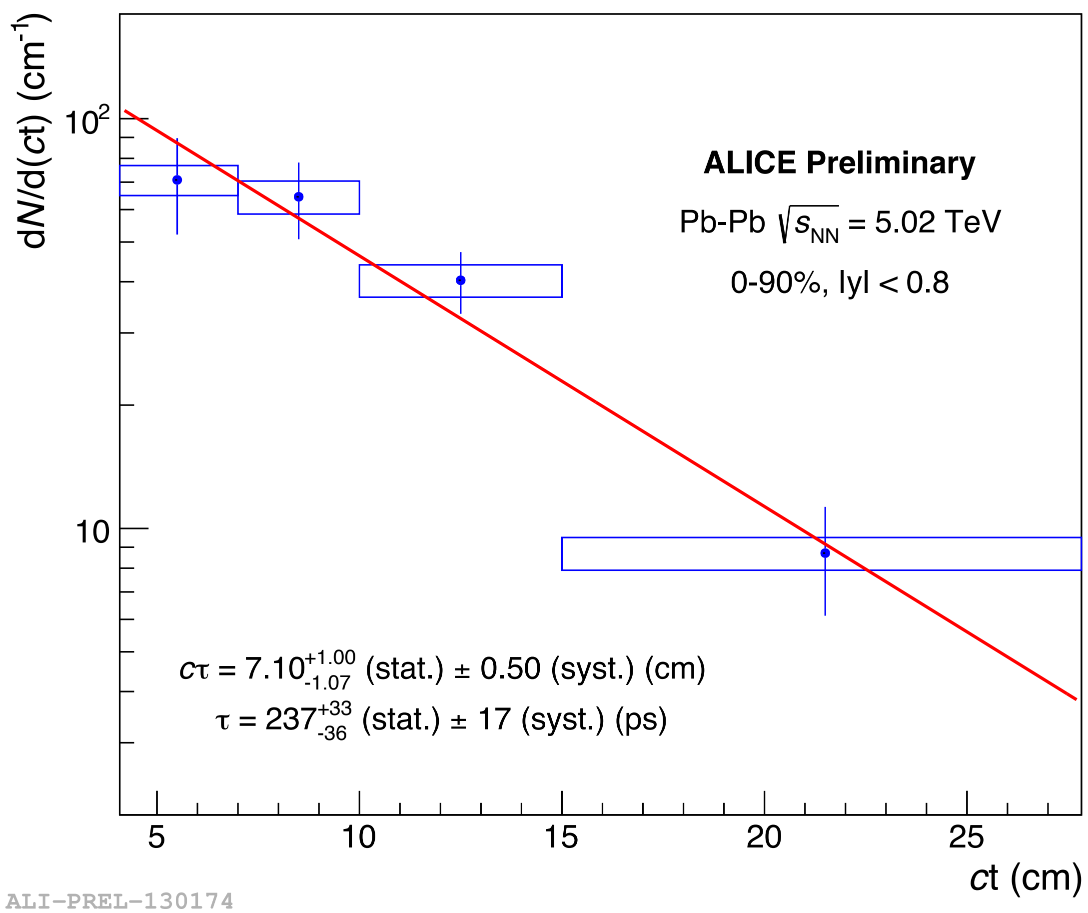

ct spectra (*default*)

- Exponential fit to the differential yield in different *c*t bins

$$\tau = 237^{+33}_{-36}(stat.) \pm 17(syst.)ps$$

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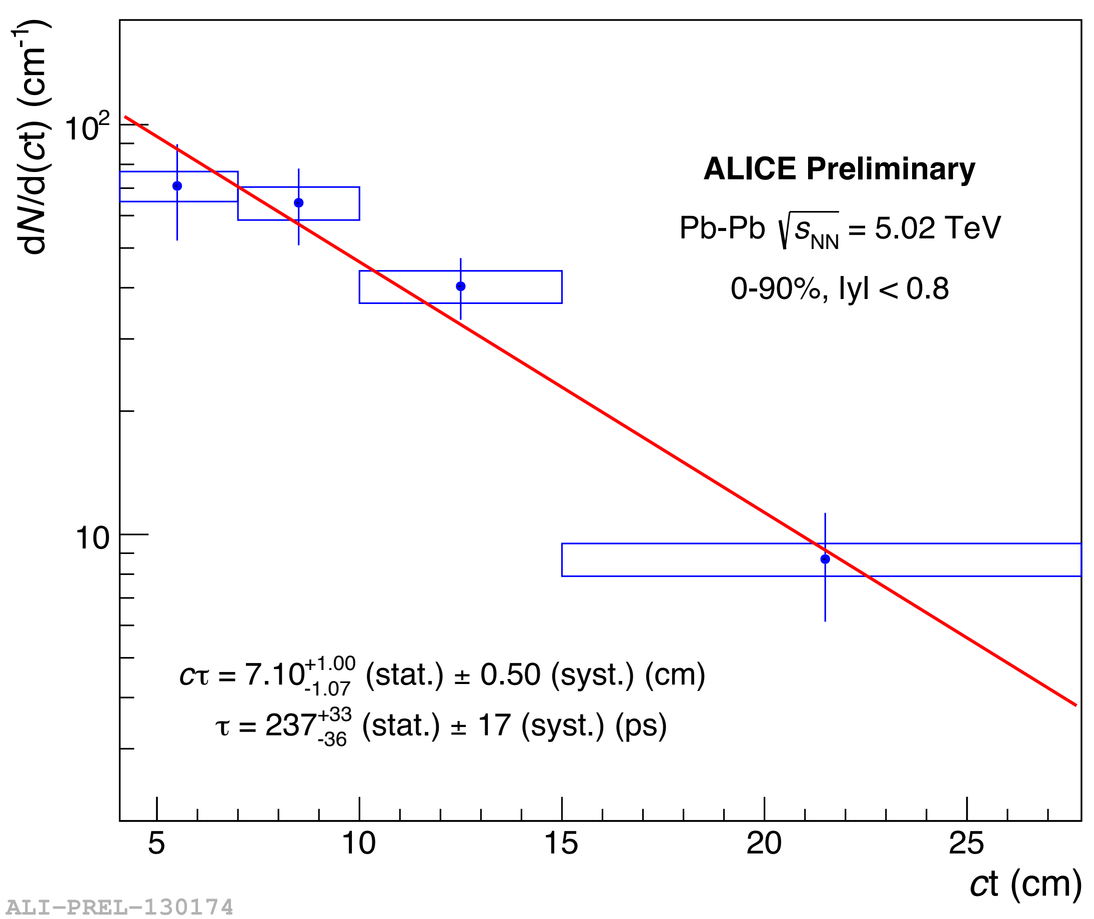

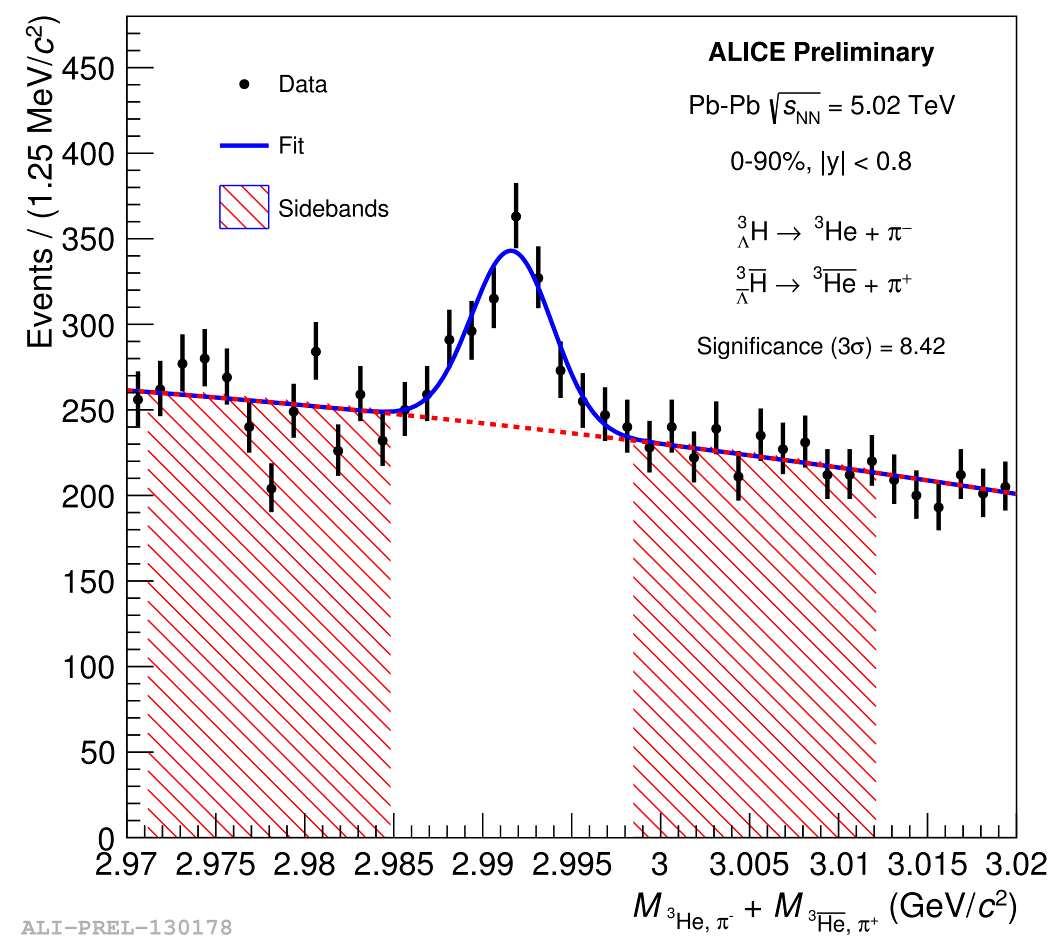

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ct unbinned fit

- Crosscheck method
- Fit to the invariant mass distribution → σ used to define the signal range [+3σ,-3σ]

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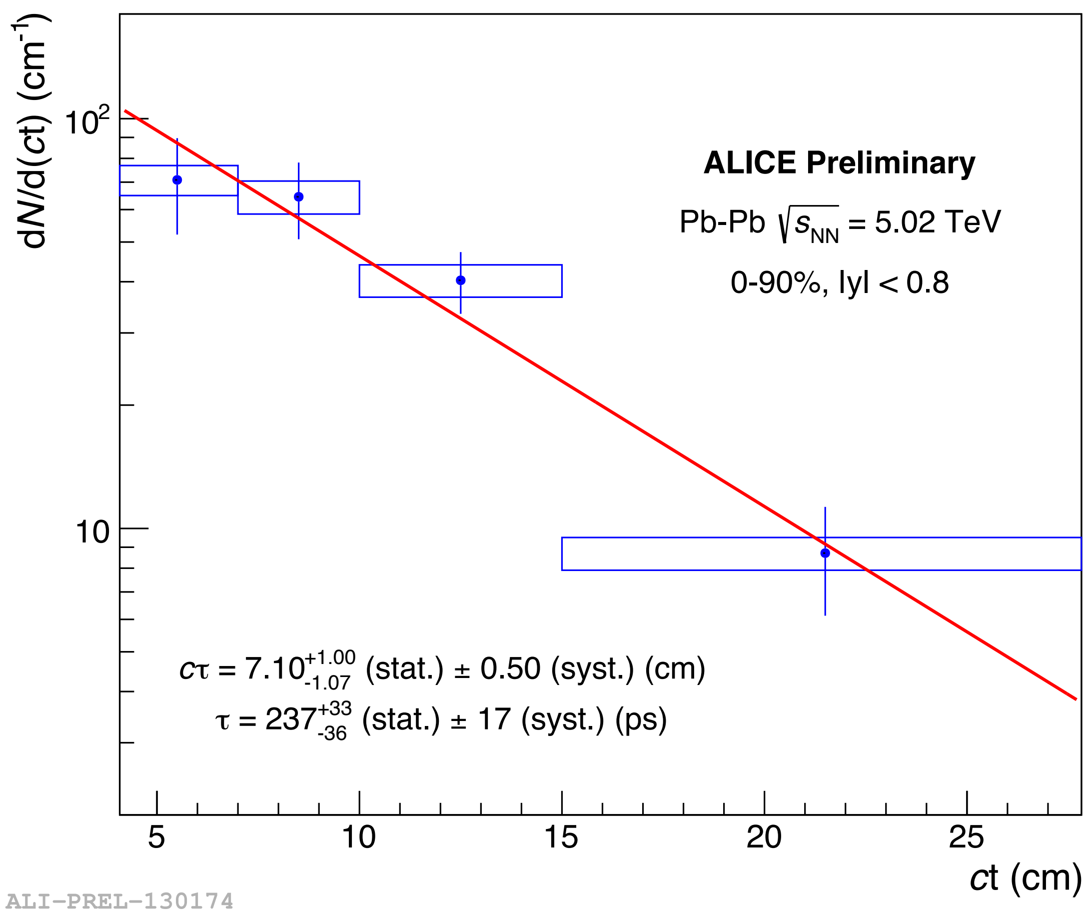

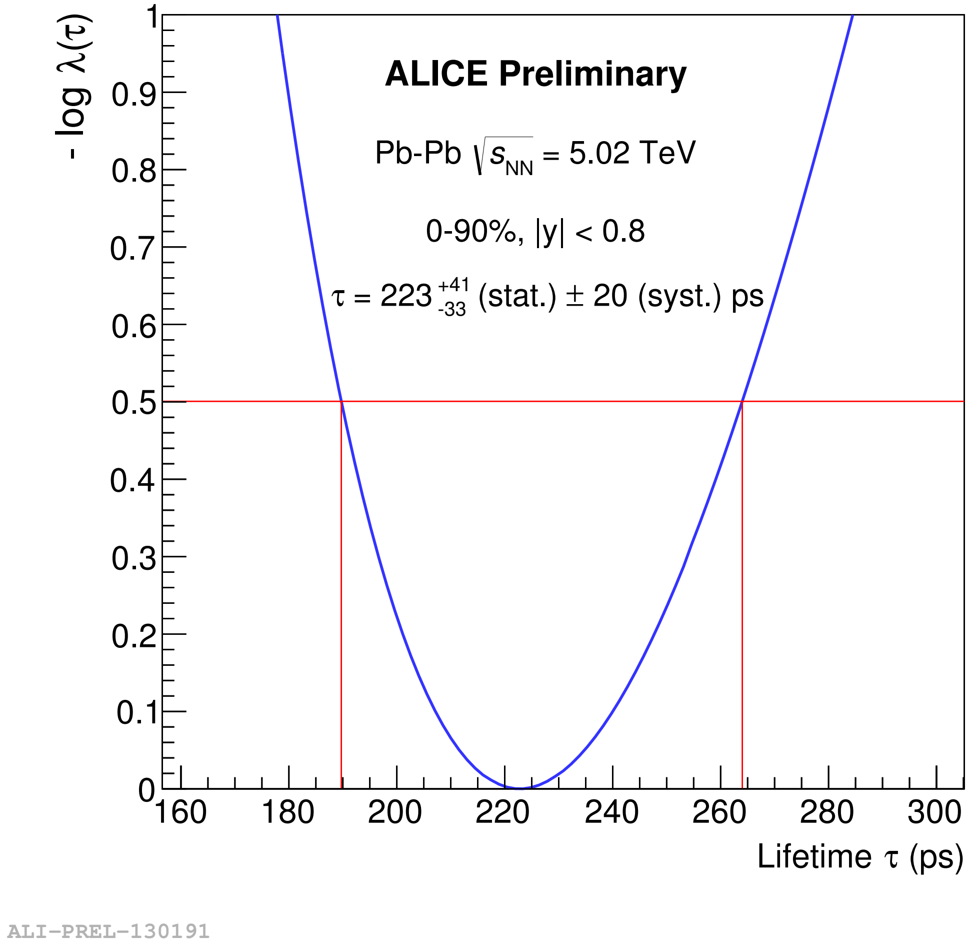

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- Exponential fit to the differential yield in different *c*t bins

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ct unbinned fit

- Fit to the *c*t distribution in the signal range with function:
  - *signal*: single exponential
  - *background*: double exponential

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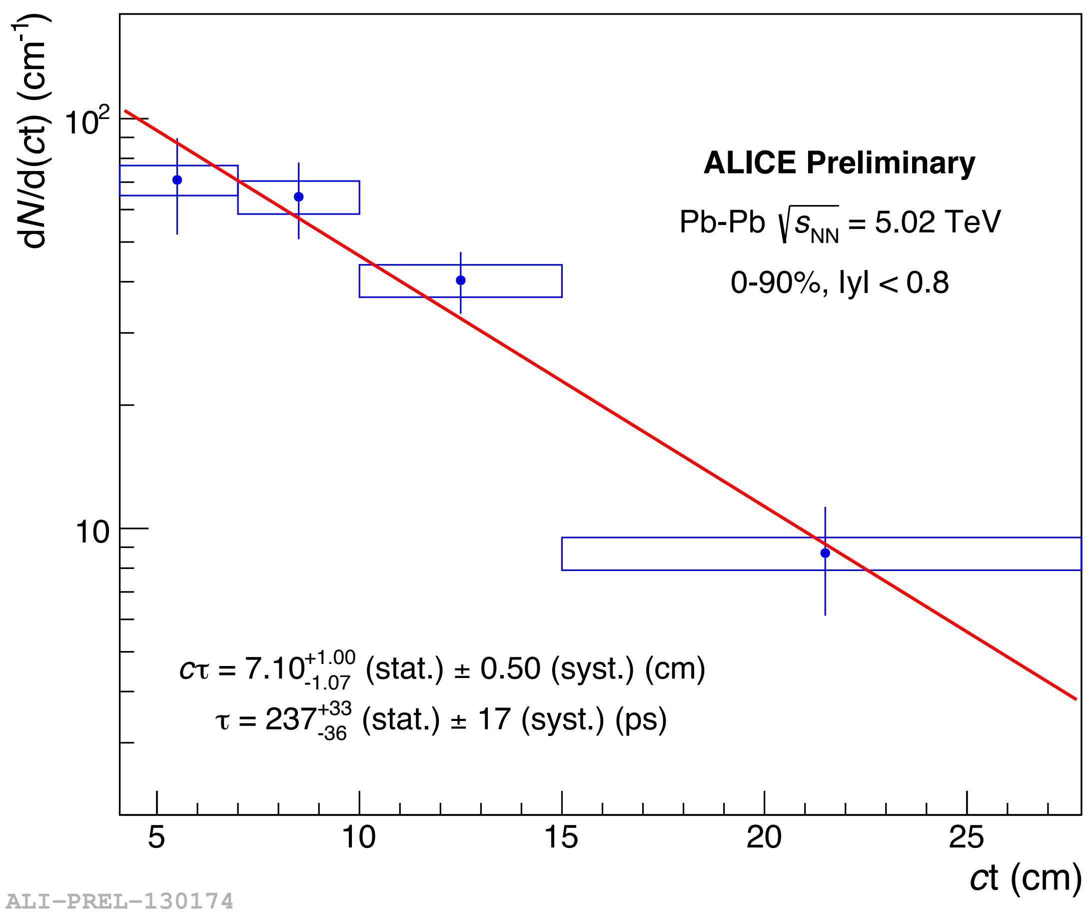

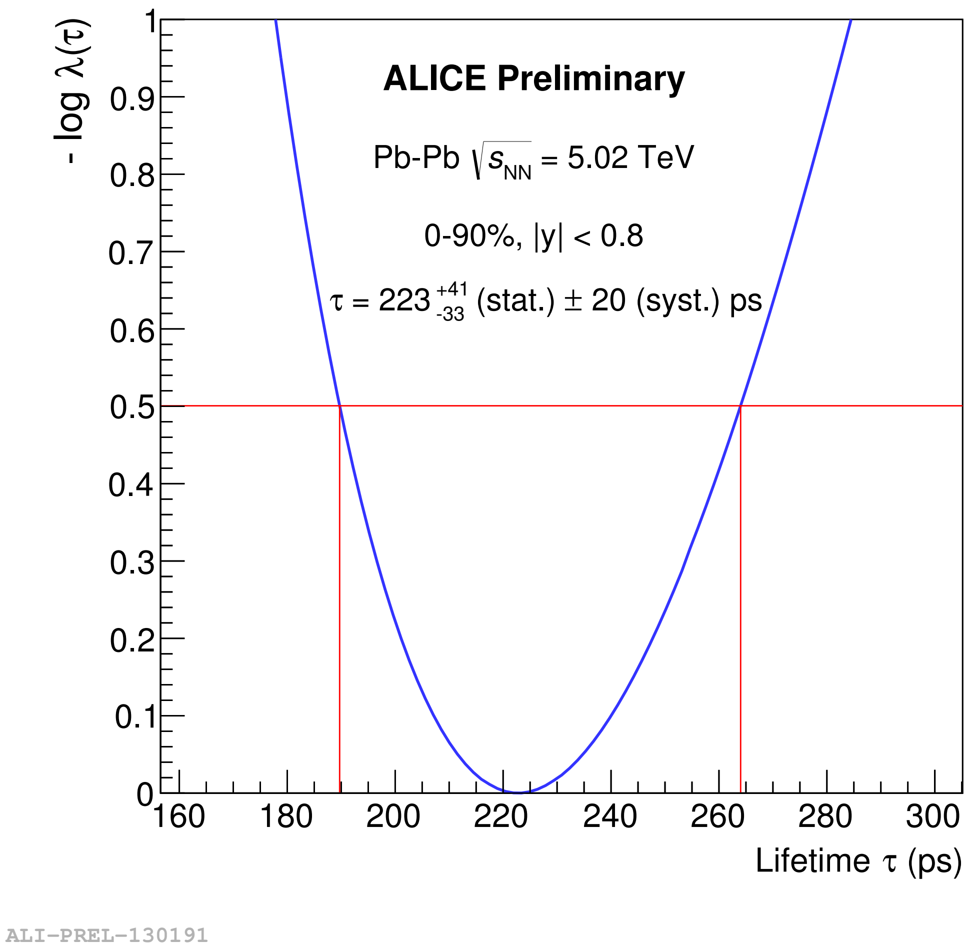

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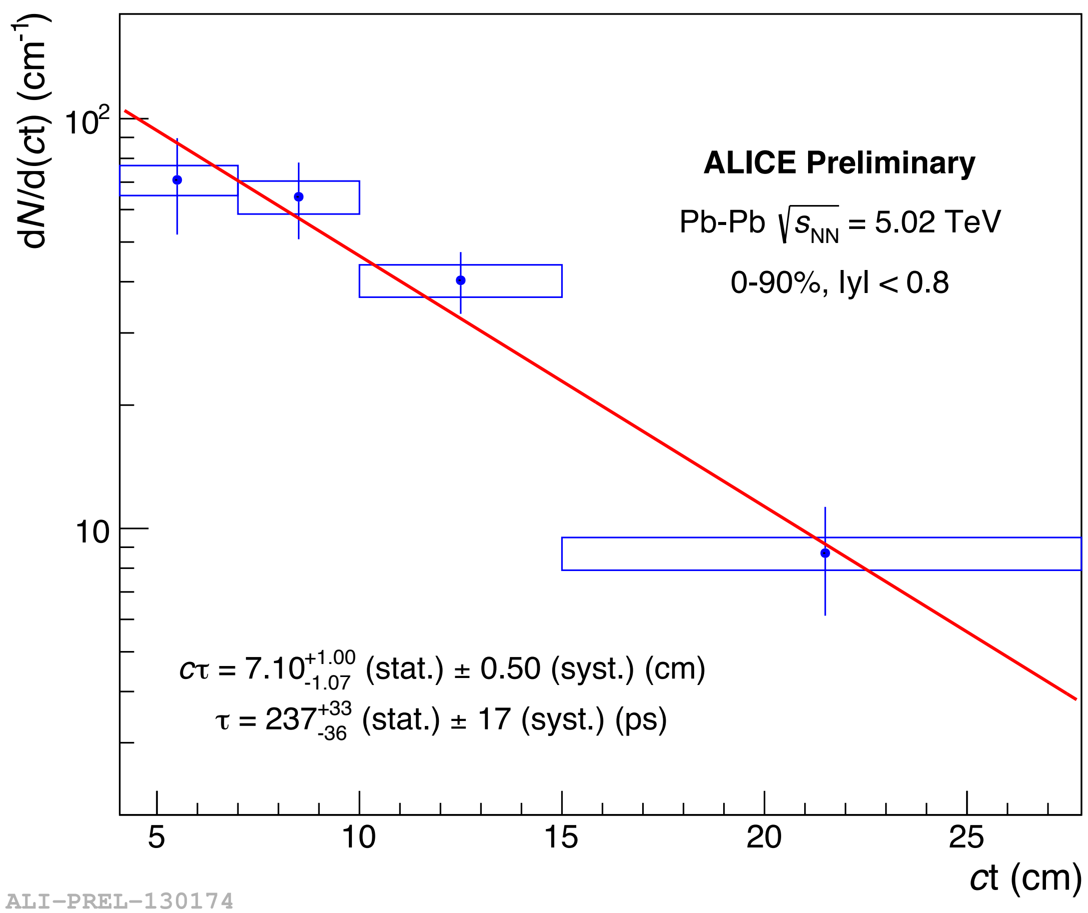

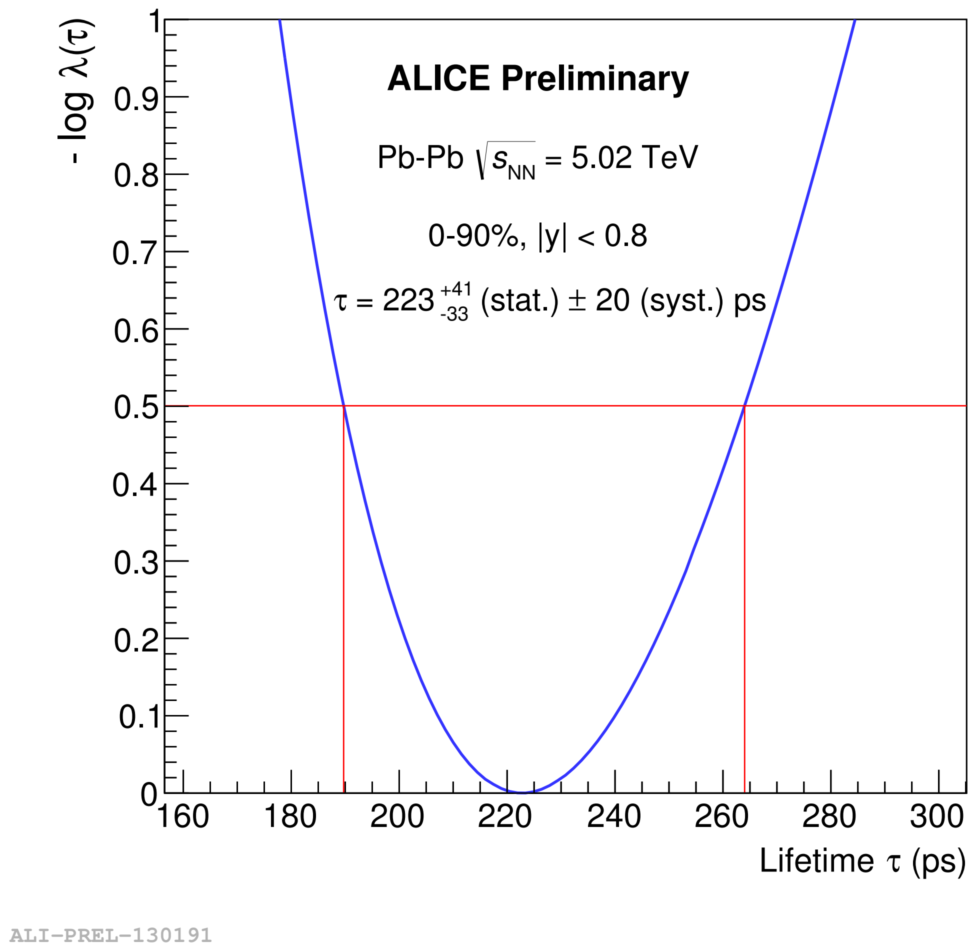

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$$\tau = 223^{+41}_{-33}(stat.) \pm 20(syst.)ps$$

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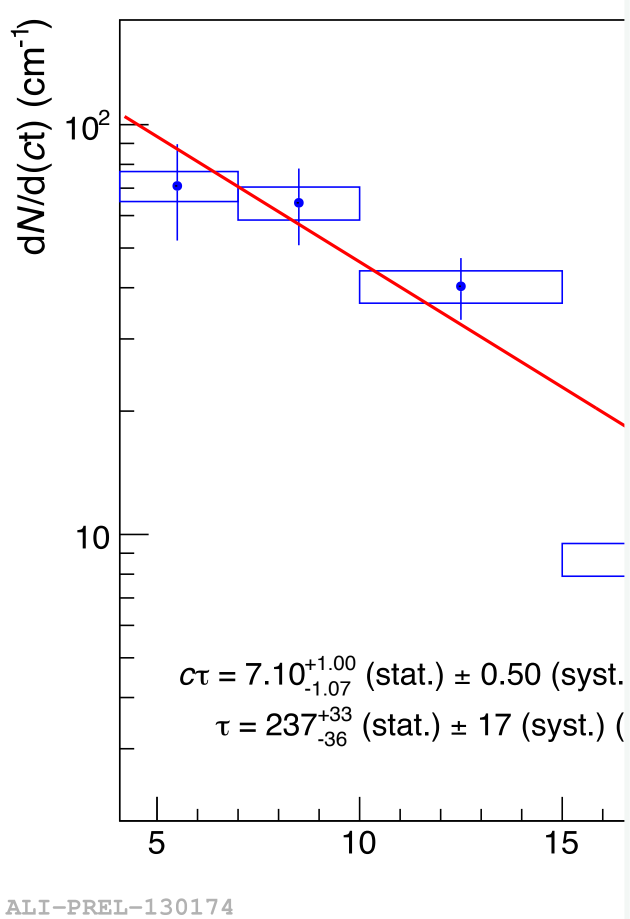

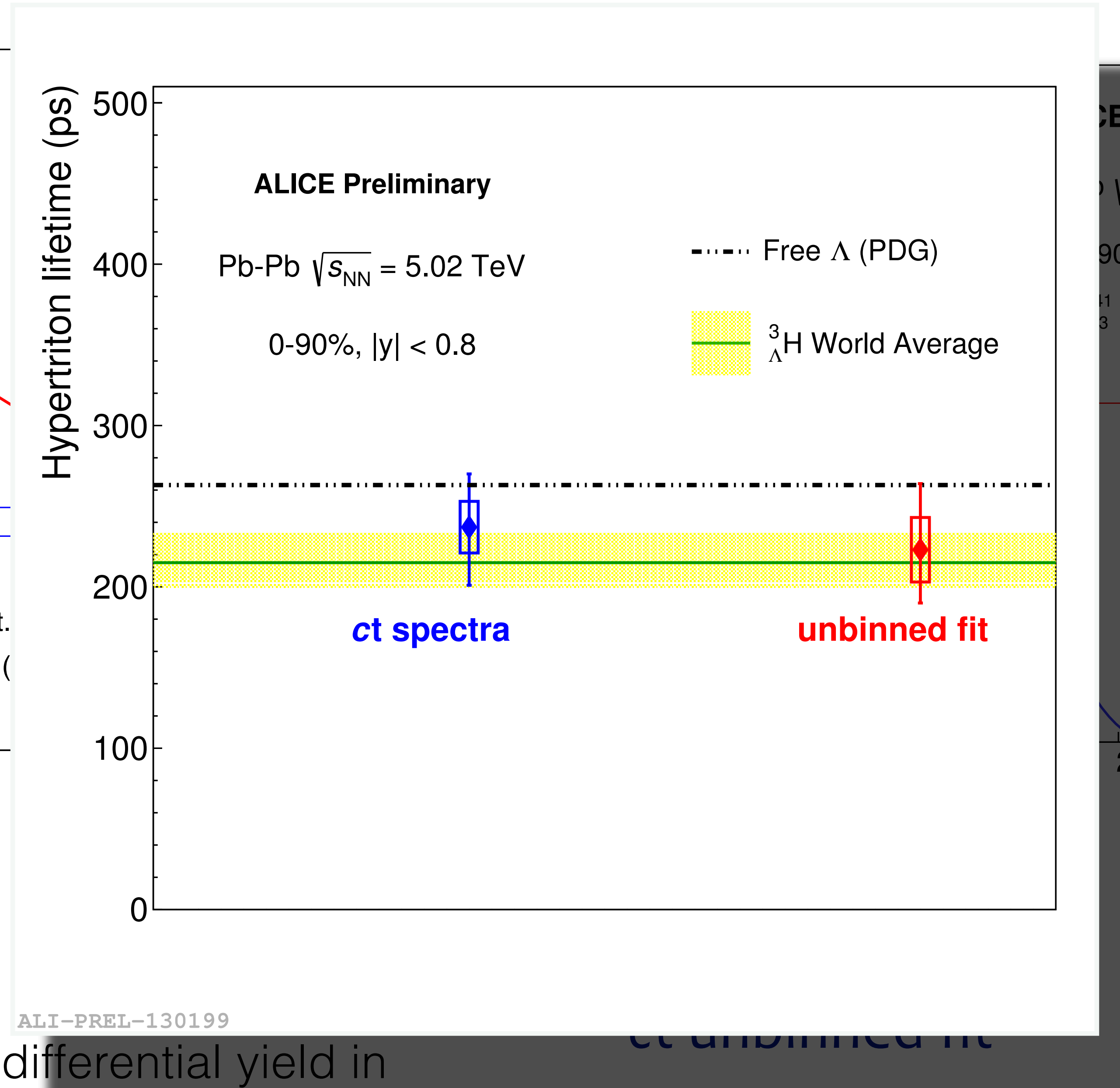

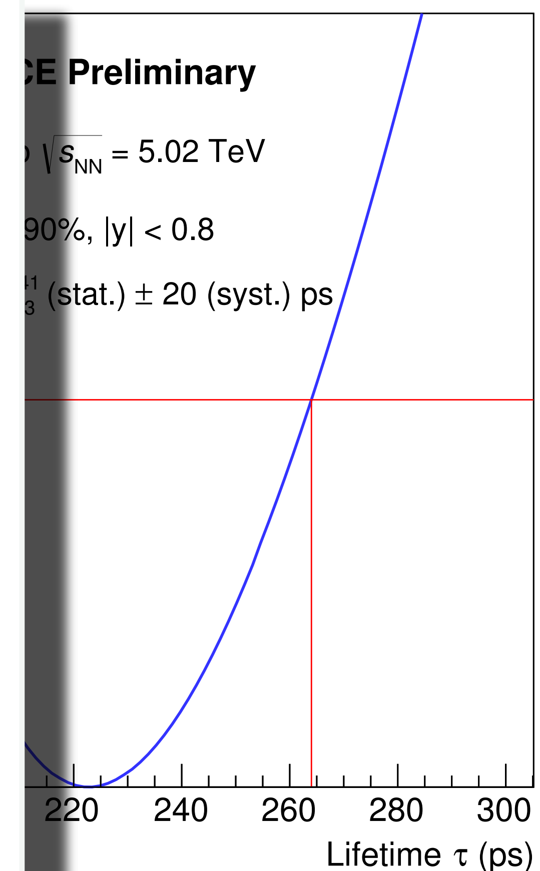

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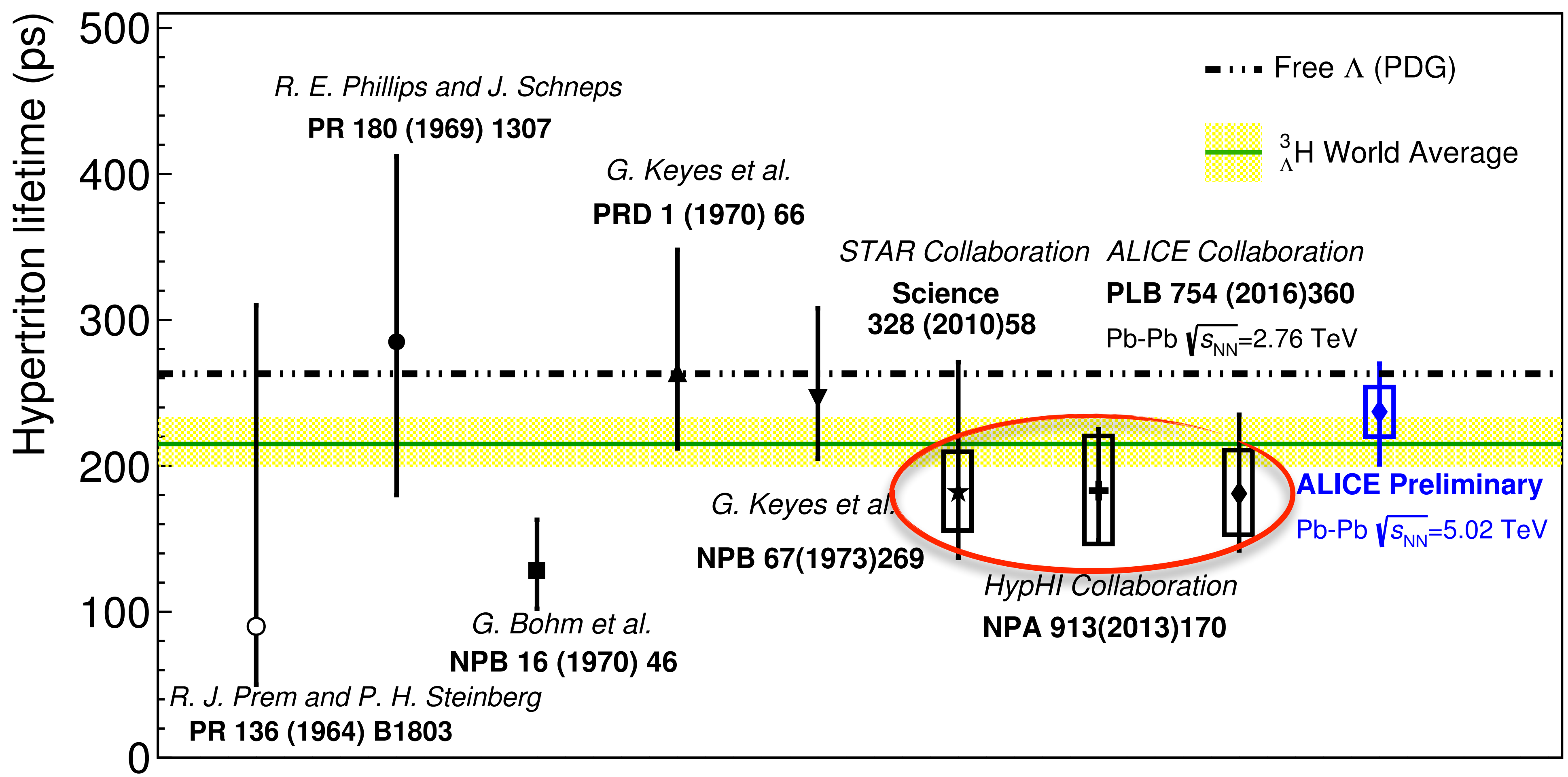
Hypertriton *lifetime world data*



ALI−PREL−130195

- Previous heavy-ion experiment results show a trend **well below** the free Λ lifetime
- ALICE result from Pb-Pb at 5.02 TeV is **closer** to the free Λ
- More **precision**, reducing the statistical uncertainties can be reached:
  - **increasing** the statistics → another Pb-Pb data sample will be collected in 2018 at the LHC
  - lifetime measured in the **3-body** decay channel

Summary and perspectives

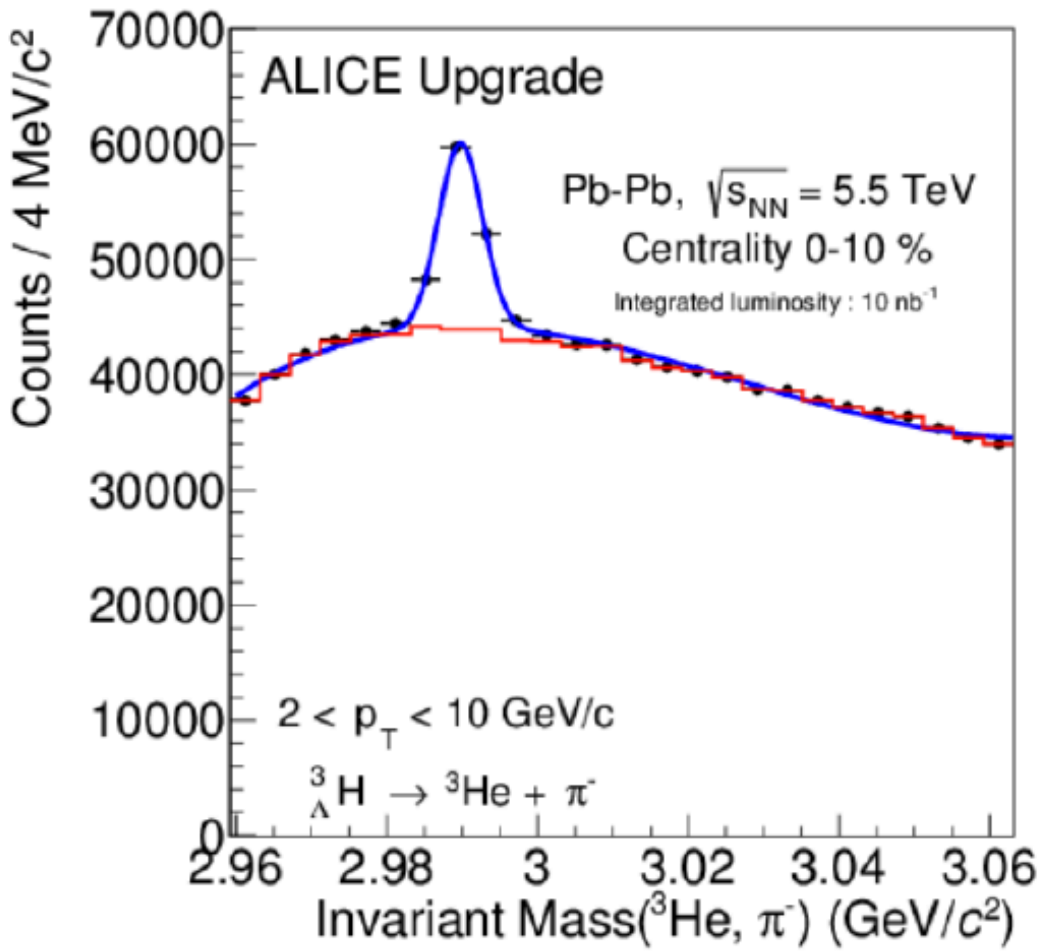
- Measurement of (anti-)hypertriton yields and lifetime is an interesting topic and nice inputs come from the URHIC
- New measurement from HI experiments gives a shorter lifetime than the expected free Lambda lifetime → recently confirmed by ALICE at a new energy (5.02 TeV)
- What about LHC? Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)
  - Upgraded ALICE detector will be able to cope with the high luminosity
  - ITS Upgrade: less material budget and more precise tracking for the identification of hyper-nuclei
  - Physics which is now done for A = 2 and A = 3 (hyper-)nuclei will be done for A = 4 (too low production yields for A>4)

Summary and perspectives

- Measurement of (anti-)hypertriton yields and lifetime is an interesting topic and nice inputs come from the URHIC
- New measurement from HI experiments gives a shorter lifetime than the expected free Lambda lifetime → recently confirmed by ALICE at a new energy (5.02 TeV)
- What about LHC? Run 3 & Run 4 of LHC will deliver much more statistics (50 kHz Pb-Pb collision rate)

State	dN/dy	B.R.	$\langle Acc \times \epsilon \rangle$	Yield
${}^{3}_{\Lambda}H$	1×10^{-4}	25%	11 %	44000
${}^{4}_{\Lambda}H$	2×10^{-7}	50%	7 %	110
${}^{4}_{\Lambda}He$	2×10^{-7}	32%	8 %	130

ITS Upgrade TDR: J. Phys. G 41, 087002 (2014)



BACKUP

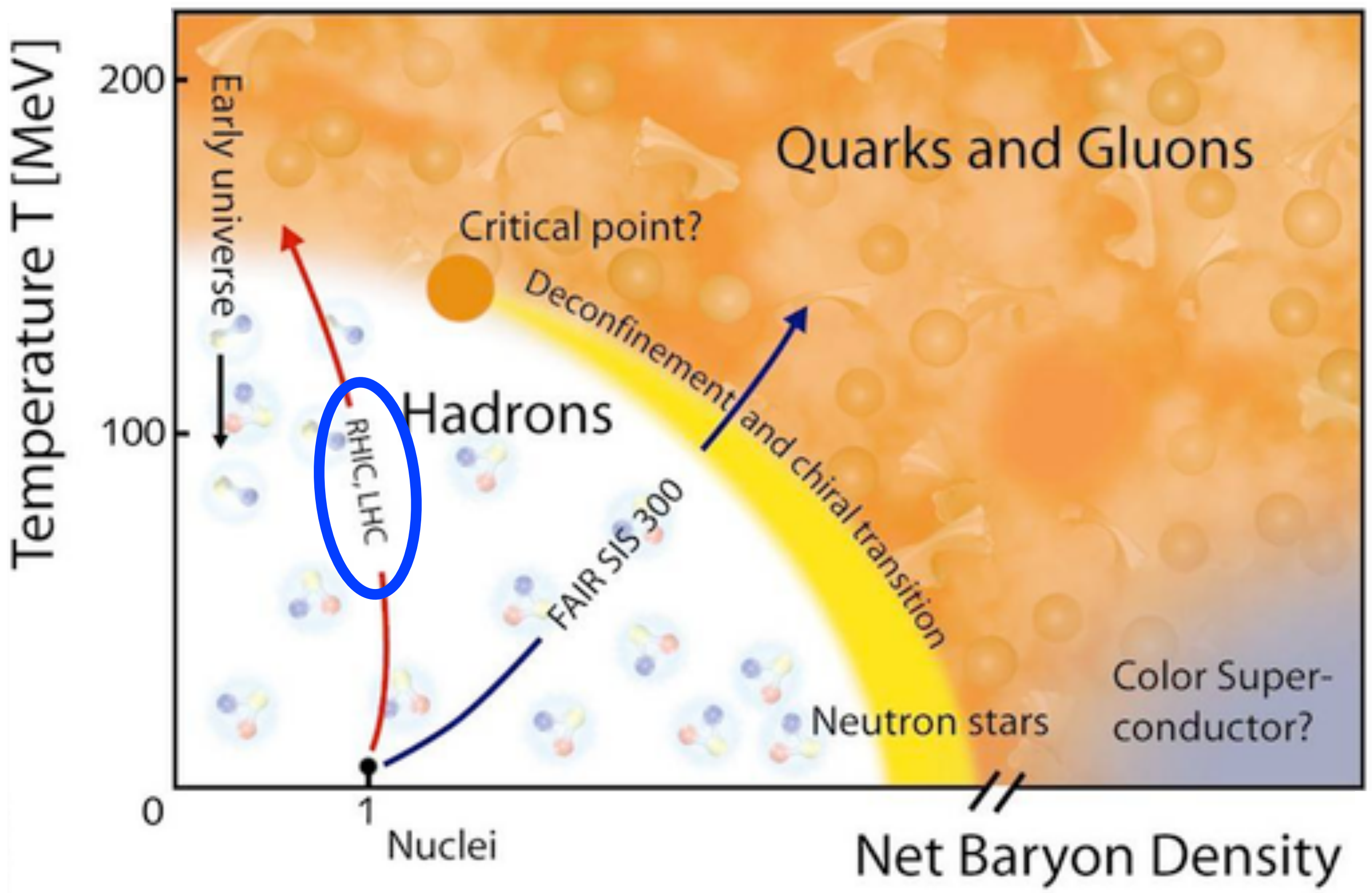
Heavy-ion physics

Study the hadronic matter under extreme conditions:

- compress a large amount of energy in a very small volume
- reach high temperature and energy density
- matter expected to undergo a phase transition

Hadronic matter $\Longrightarrow$ quarks and gluons deconfined (QGP)

ALICE study the deconfined hadronic matter in heavy ion collisions (Pb-Pb) at the LHC



Past

- ✳ SIS ~2 GeV at GSI
- ✳ AGS ~5 GeV at BNL
- ✳ SPS ~20 GeV at CERN

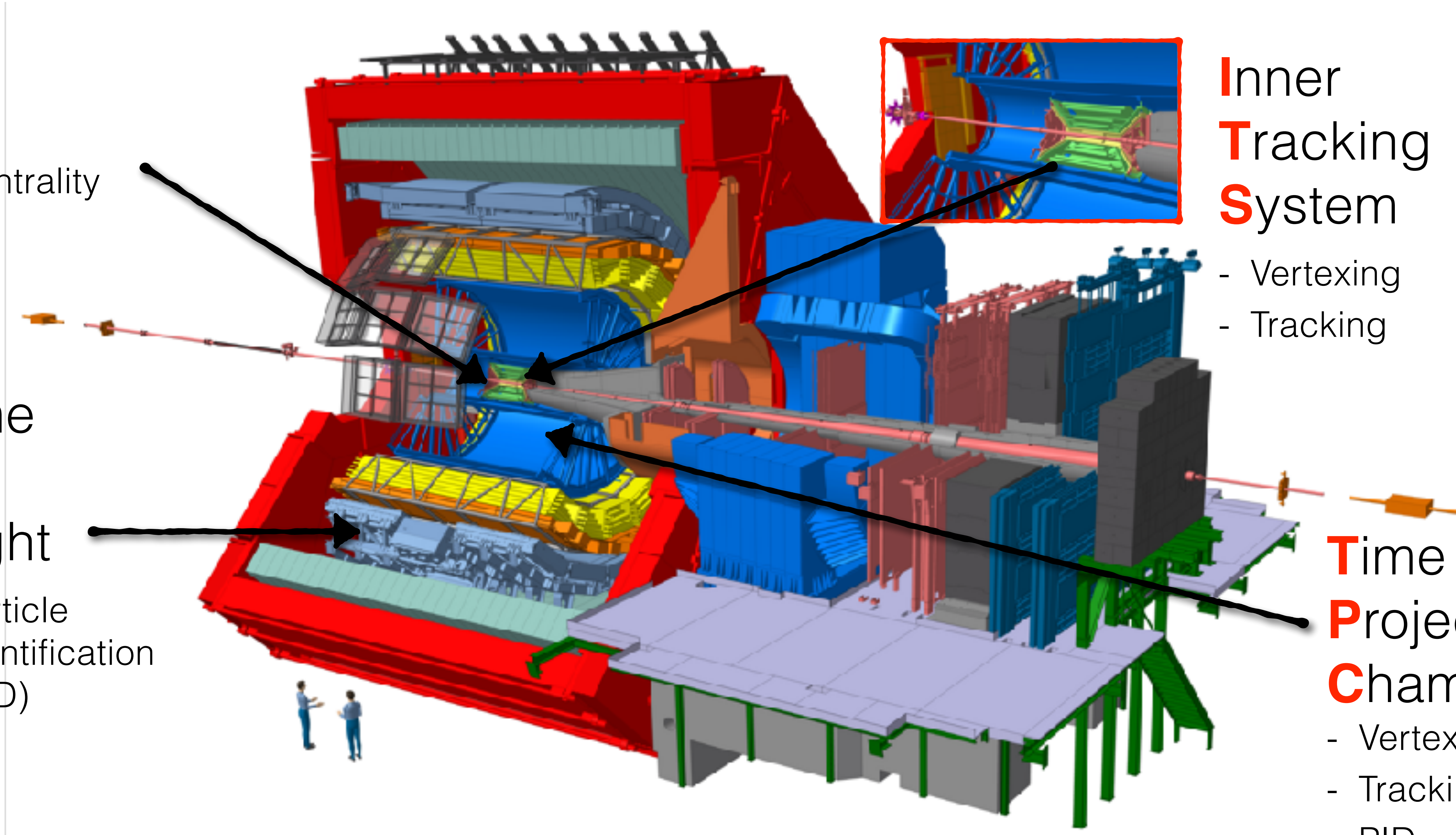
Present

- ✳ RHIC ~200 GeV at BNL
- ✳ LHC ~5 TeV at CERN

Introduction: *ALICE*

V0
- Centrality

Time
Of
Flight
- Particle Identification (PID)



Inner
Tracking
System
- Vertexing
- Tracking

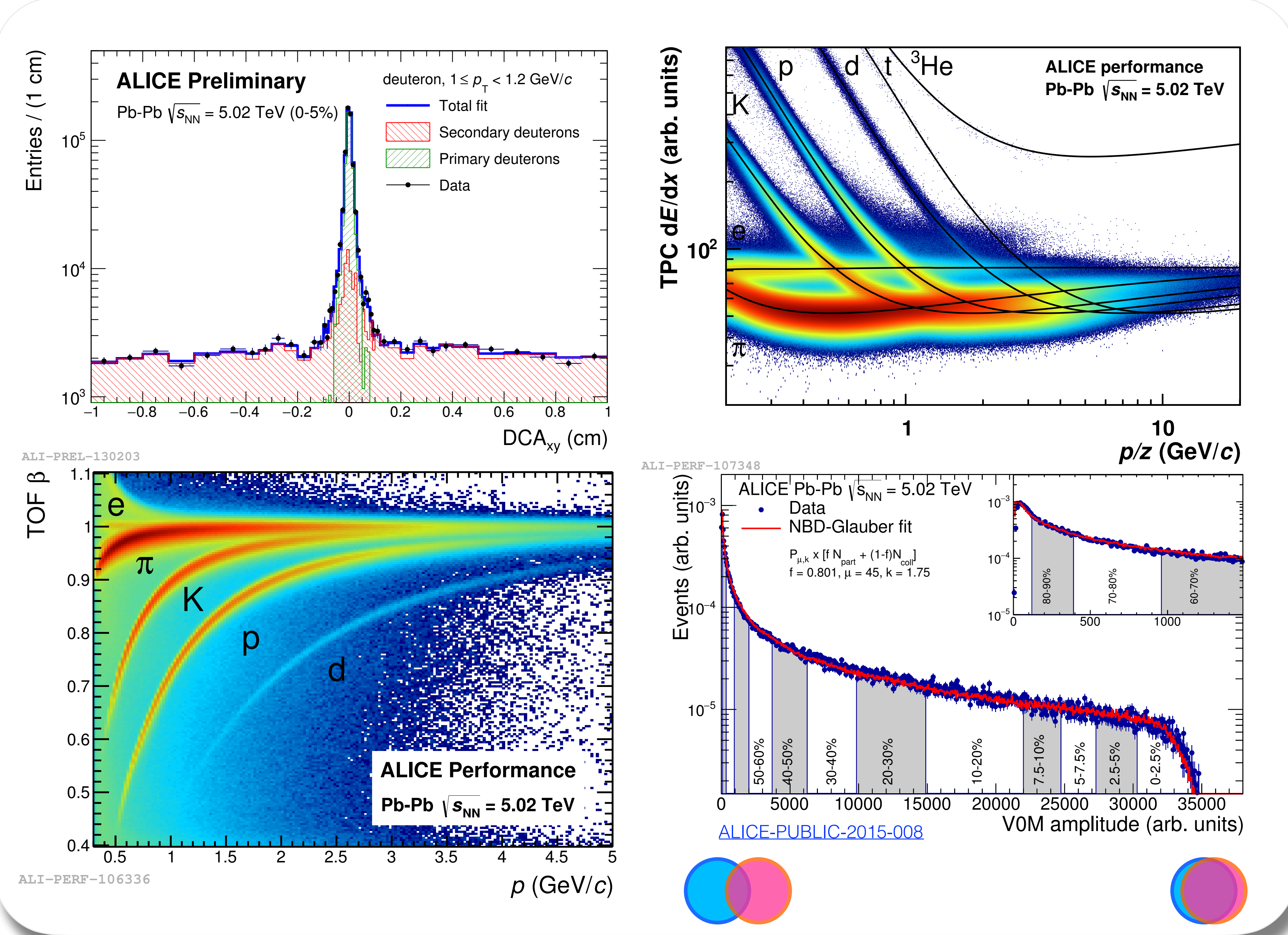
Time
Projection
Chamber
- Vertexing
- Tracking
- PID

- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in the collisions

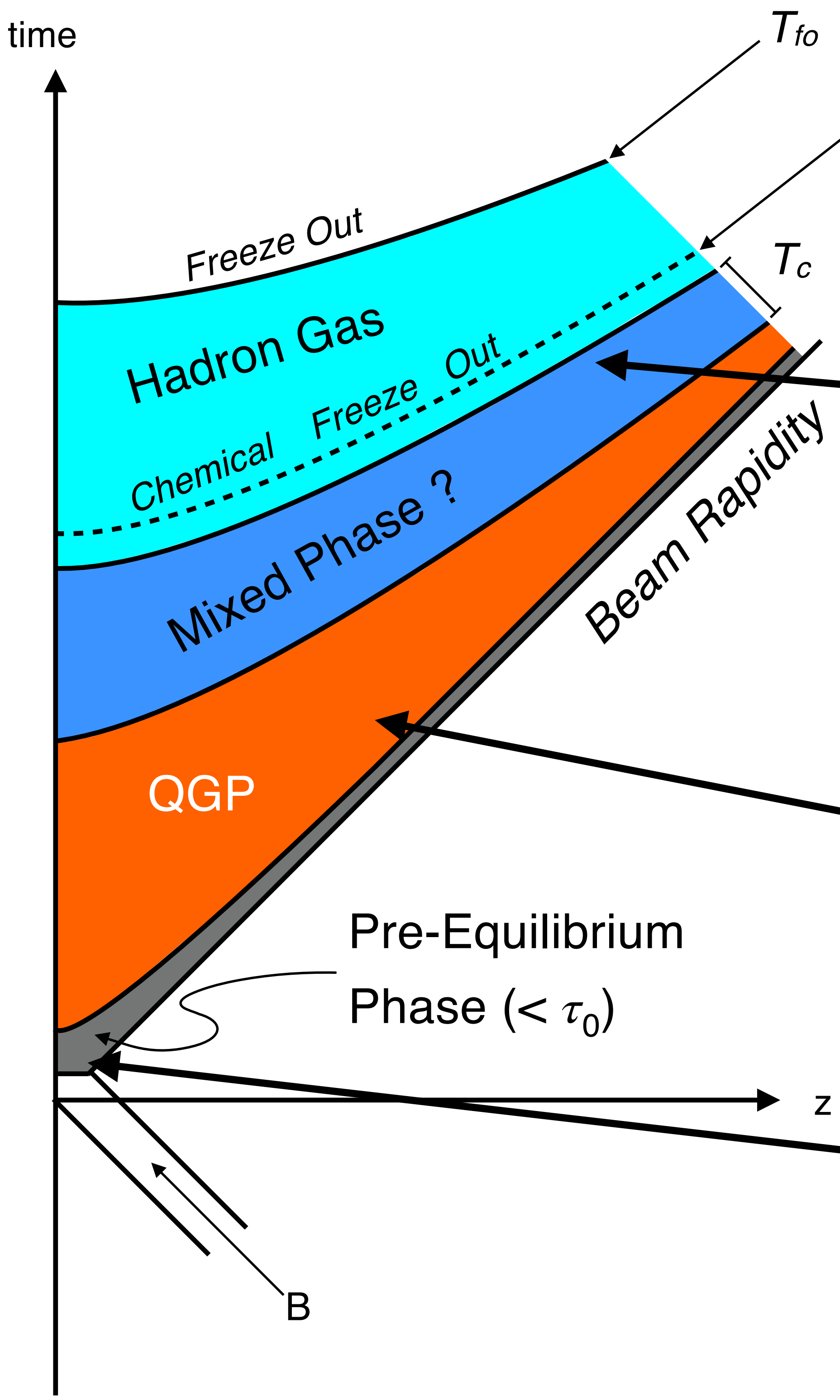
Particle identification in *ALICE*

Detectors used for (anti-)(hyper-)nuclei analysis:

- **ITS**
  - Separation of primary and secondary nuclei from knock-out
  - p_T > 0.5 GeV/c → σ_{DCAxy}<100 μm
- **TPC**
  - dE/dx in gas (Ar-CO_2)
  - $\sigma_{dE/dx}$ ~ 5.5%
- **TOF**
  - Time-of flight measurement
  - σ_{TOF} ~ 80 ps (Pb-Pb), 120 ps (pp)
- **V0**
  - Two arrays of 64 scintillators
  - determination of the centrality of a collision



Nucleus-Nucleus collision



Freeze-out (fo)

- Chemical: particle composition is fixed (no more inel. coll.) $\longrightarrow T_{ch} \cong 160$ MeV
- Kinetic: momentum spectra are fixed (no more elas. coll.) $\longrightarrow T_{fo} \cong 110 \div 130$ MeV

Hadronization

- Soft processes
- high cross section
- indirect signals for QGP

System expansion 0.2 fm/c < τ < 10 fm/c

- Hydrodynamic laws
- Temp. (T) and energy density (ε) drop down

Photons

- insensitive to hadronization process

Thermalization time (LHC) $\tau_0 \cong 0.2$ fm/c

- centre-of-mass energy dependent

Hard processes

- low cross section
- probe the whole evolution of the collision

Heavy-ion collisions

Motivation

- explore QCD and QCD-inspired model predictions for (unusual) multi-baryon states
- search for rarely produced anti- and hyper-matter
- test model predictions, e.g. thermal and coalescence, for both classes of phenomena

Collision systems

- to study the ordinary nuclear matter effects and the QCD matter at high temperature and energy density

ALICE integrated luminosities

p-p

$\sqrt{s}$	$\mathcal{L}_{INT}$
900 GeV	0.33 nb^{-1}
2.76 TeV	46 nb^{-1}
7 TeV	5.4 pb^{-1}
8 TeV	9.7 pb^{-1}
13 TeV	8.02 pb^{-1}

p-Pb and Pb-p

$\sqrt{s_{NN}}$	$\mathcal{L}_{INT}$
5.02 TeV	15 nb^{-1}
5.02 TeV	17 nb^{-1}

Pb-Pb

$\sqrt{s_{NN}}$	$\mathcal{L}_{INT}$
2.76 TeV	155 μb^{-1}
5.02 TeV	433 μb^{-1}

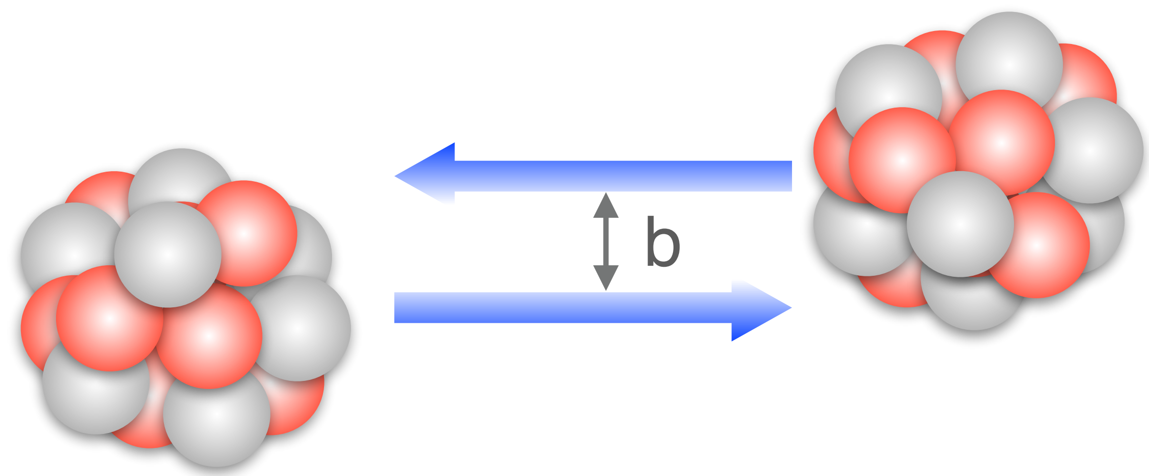
Centrality

Theory

The centrality of the collision is defined by the impact parameter vector ***b***

Most central collision $\Longleftrightarrow$ Smallest ***b***

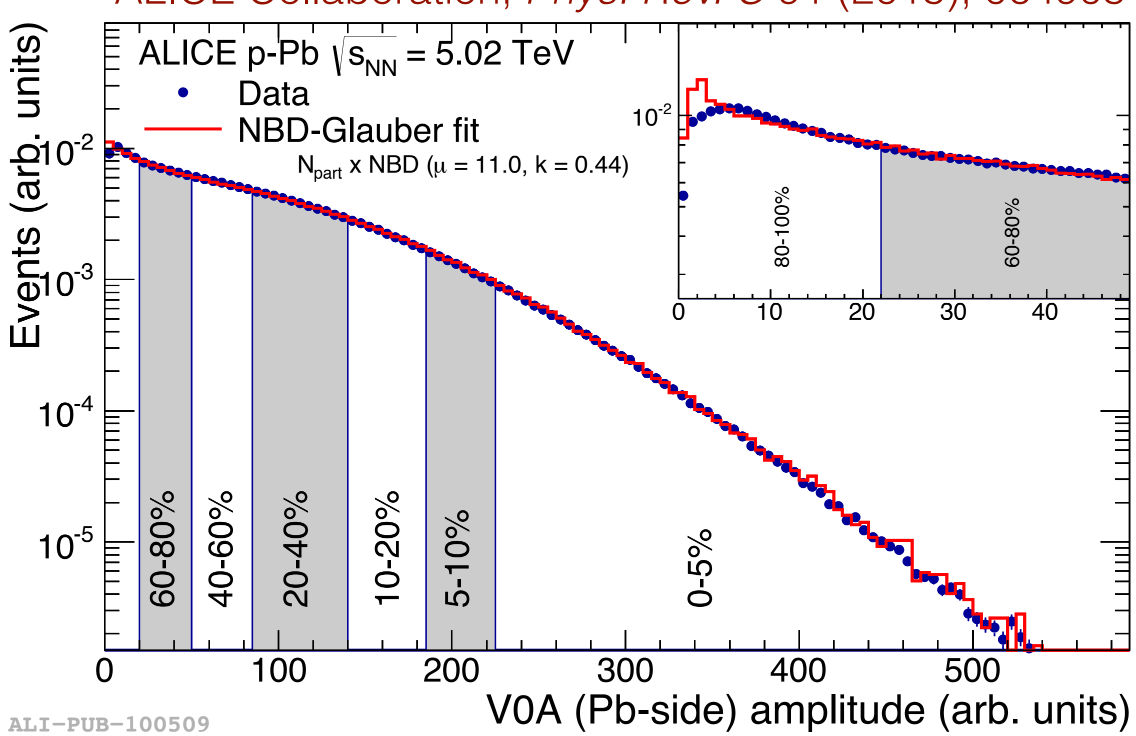
Heavy Ion collision



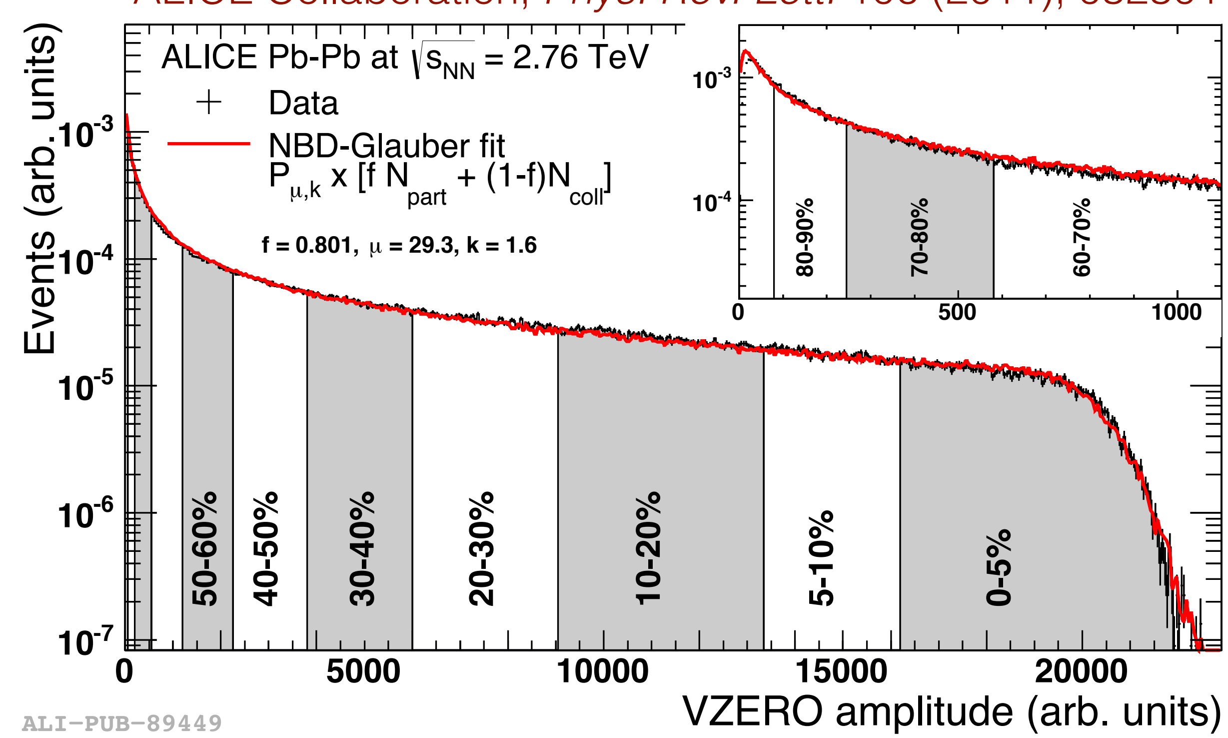
Experimentally

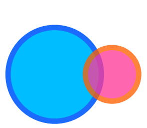
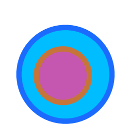
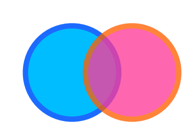
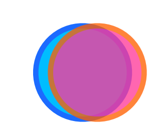
It is possible to correlate the track multiplicity to an impact parameter value by fitting data with predictions from Glauber model.

ALICE Collaboration, *Phys. Rev. C* 91 (2015), 064905

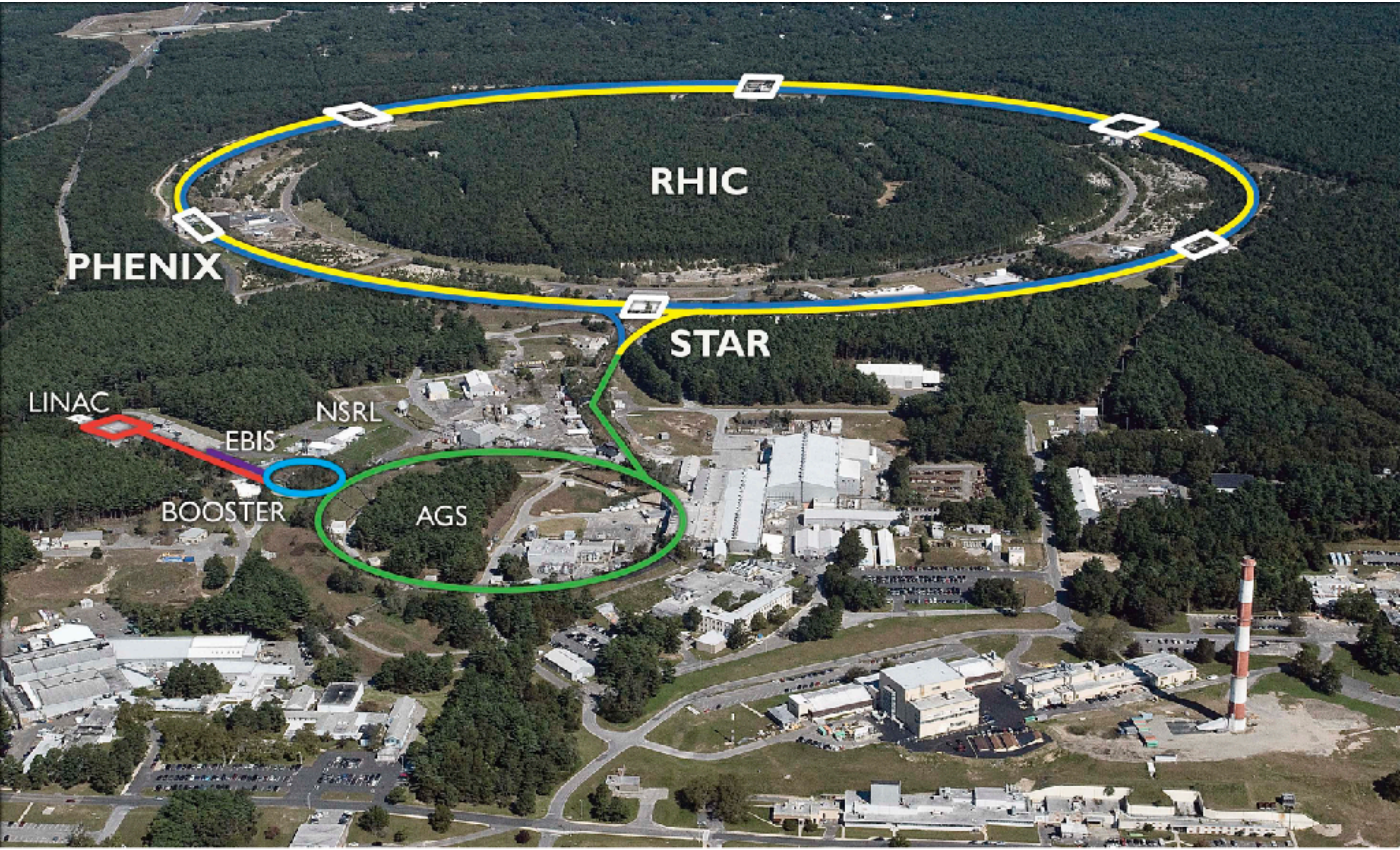


ALICE Collaboration, *Phys. Rev. Lett.* 106 (2011), 032301

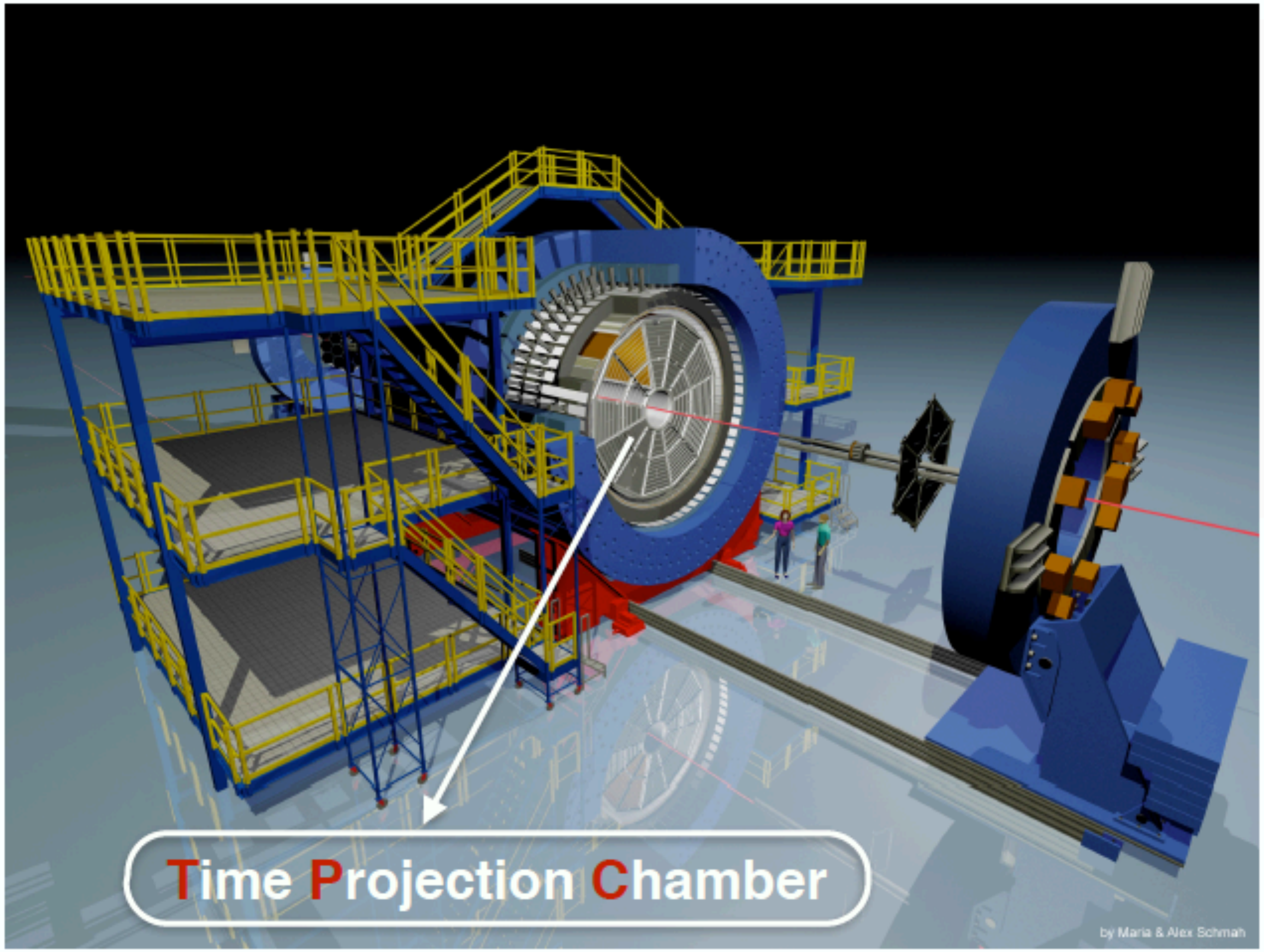


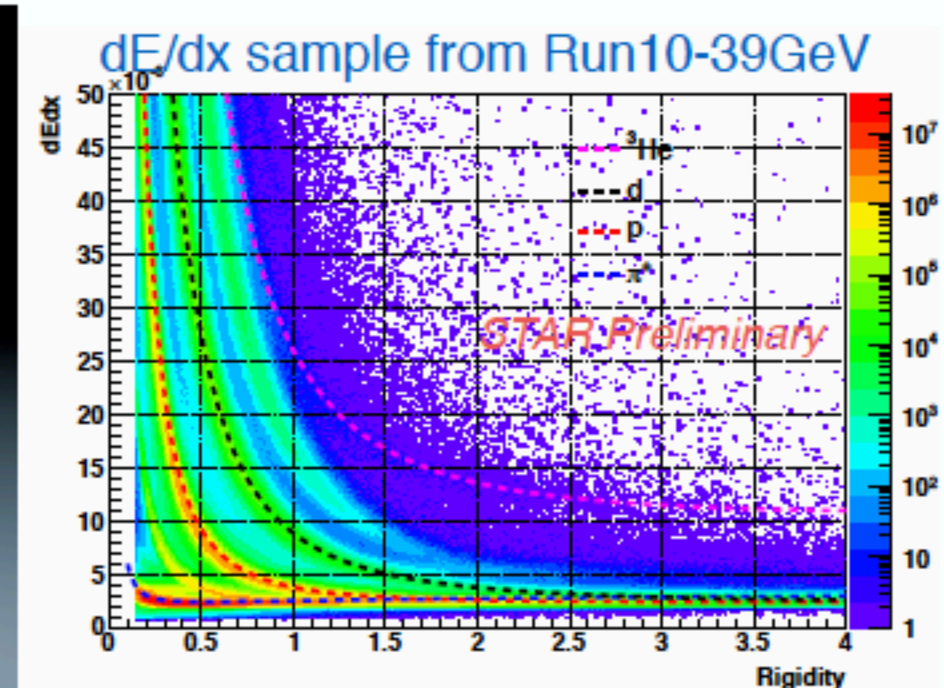
RHIC



STAR Experiment



STAR TPC provides momentum and energy loss information.

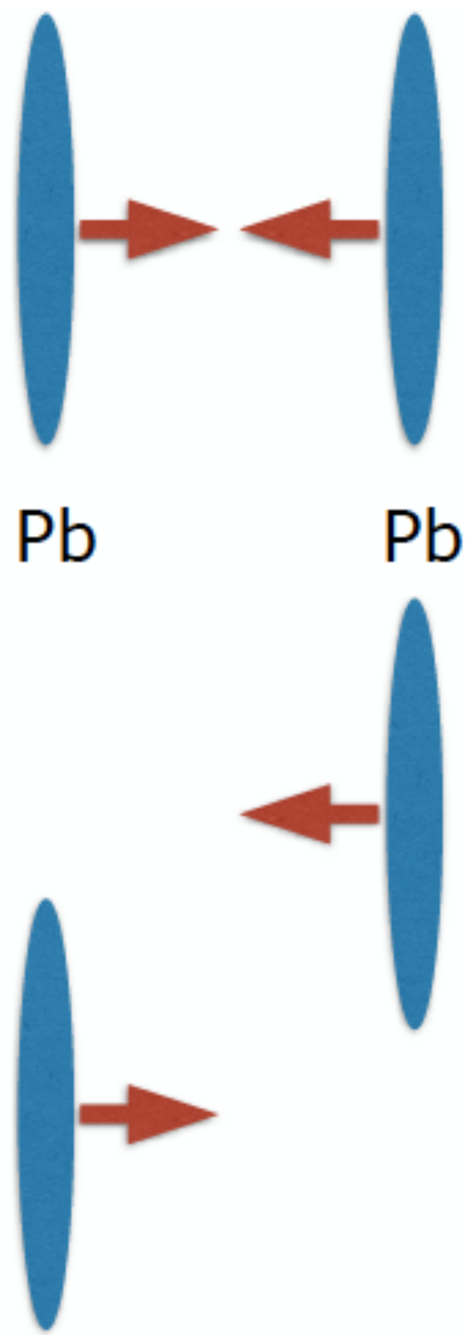


^{3}He, d, p and π can be identified well at STAR, which makes it possible to reconstruct hyper-tritons through its 2 main decay channels:

$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} $$

$$ {}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-} $$

Interlude: Centrality



Central Pb-Pb collision:

High multiplicity = large <dN/dη>

High number of tracks

(more than 2000 tracks in the detector)

Peripheral Pb-Pb collision:

Low multiplicity = small <dN/dη>

Low number of tracks

(less than 100 tracks in the detector)

Blast-Wave model

- How fast is the expansion velocity? Estimate in a simplified hydro model:
  - Consider a thermal source (Boltzmann type p_T-spectrum) of particles:
  - Boost source radially with velocity β and evaluate at y=0:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T \, I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

  - Simple assumption: consider uniform sphere of radius R

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r\,dr \, m_T \, I_0\left(\frac{p_T \sinh(\rho(r))}{T}\right) K_1\left(\frac{m_T \cosh(\rho(r))}{T}\right)$$

  - and parameterize velocity profile as
- Three free parameters: kinetic freeze-out temperature T_{kin}, surface expansion velocity β_S, exponent n of velocity profile.