Measurements of $({}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$ $(dN/dy, c\tau, v_1)$ from 3 GeV Au+Au collisions with the STAR detector

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Outline

- Introduction
- Hypernuclei Lifetime
- Hypernuclei yields
- Hypernuclei v_1
- Summary and Outlook

REIMEI-THEIA Webseminar
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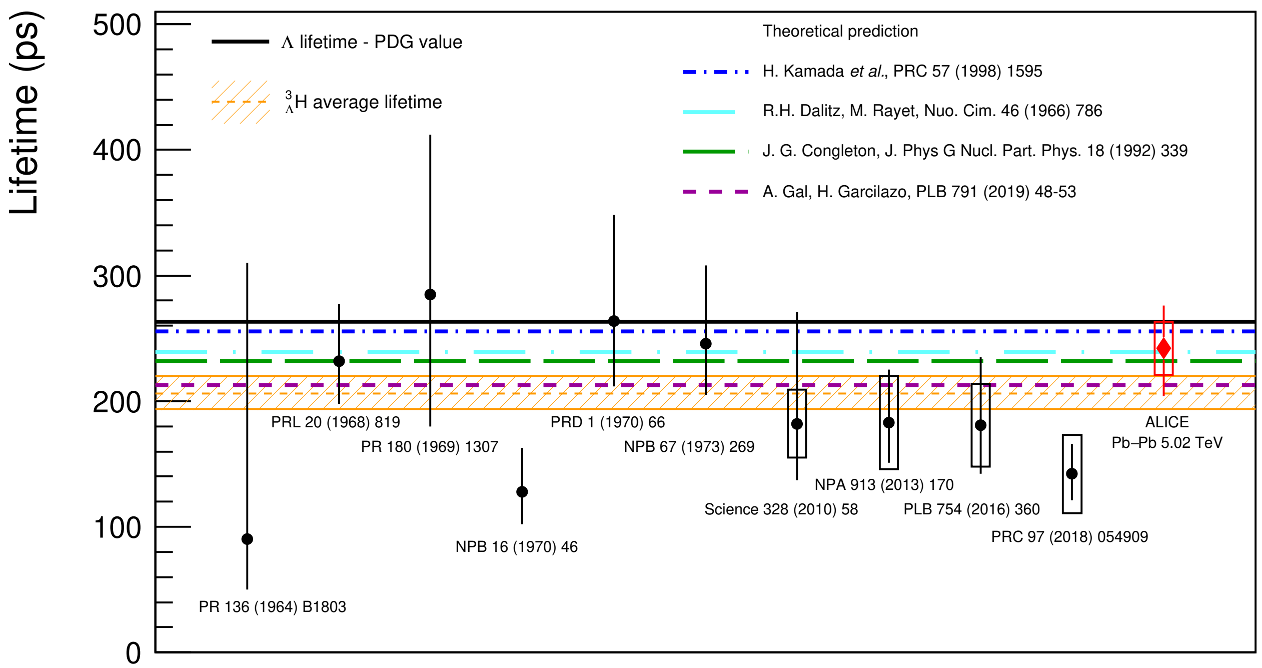
STAR

Introduction

- **Hypernuclei -> experimental probe to study the hyperon-nucleon (YN) interaction**
    - Modeling the EOS of astrophysical objects
    - Lifetime, branching ratios, and binding energy measurements provide key information to understand the YN potential

- ${}^{3}_{\Lambda}\mathrm{H}$ (Λpn) is the lightest hypernuclei
    - Binding energy~0.4 MeV
    - Theory predicts lifetime close to the free lambda lifetime

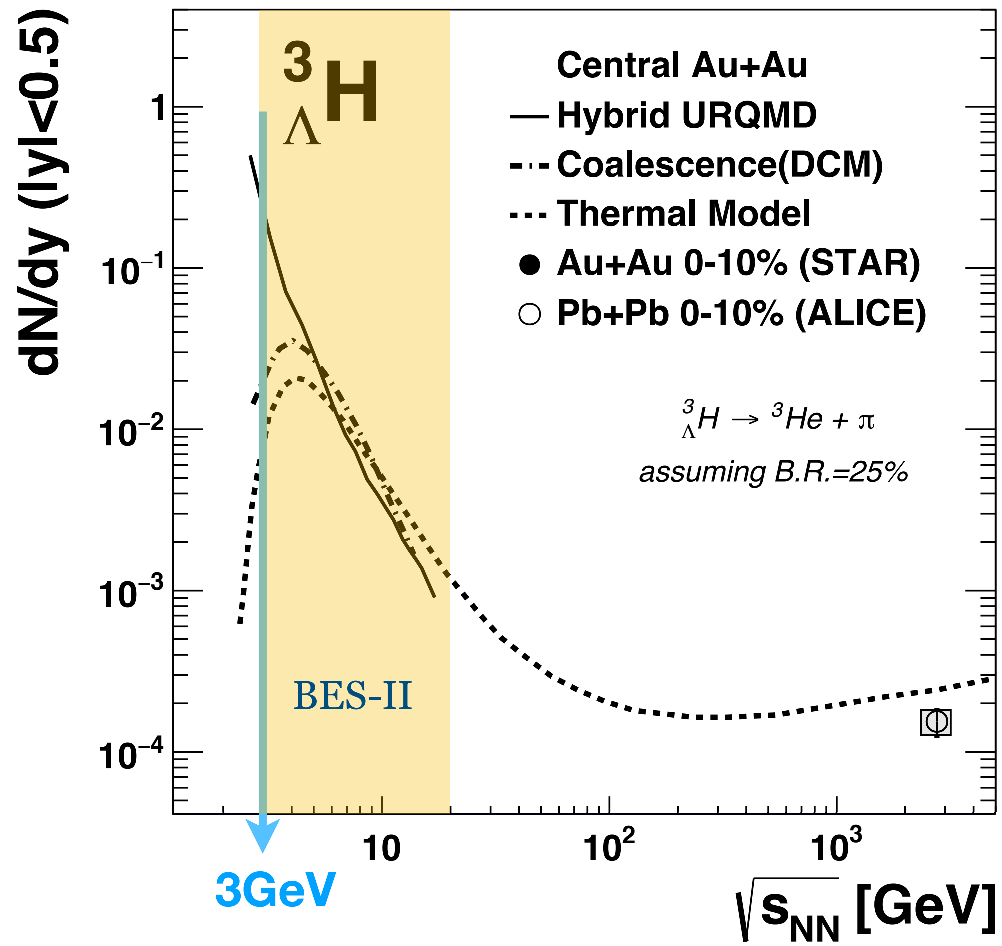


PLB797 (2019) 134905 (ALICE)

- Few measurements of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ in heavy-ion collisions
    - Yield and flow -> insight on the production mechanisms and hyperon contribution to the EoS

STAR BES-II

- Higher baryon density at lower beam energies
  - STAR BES-II -> great opportunity to study hypernuclei production

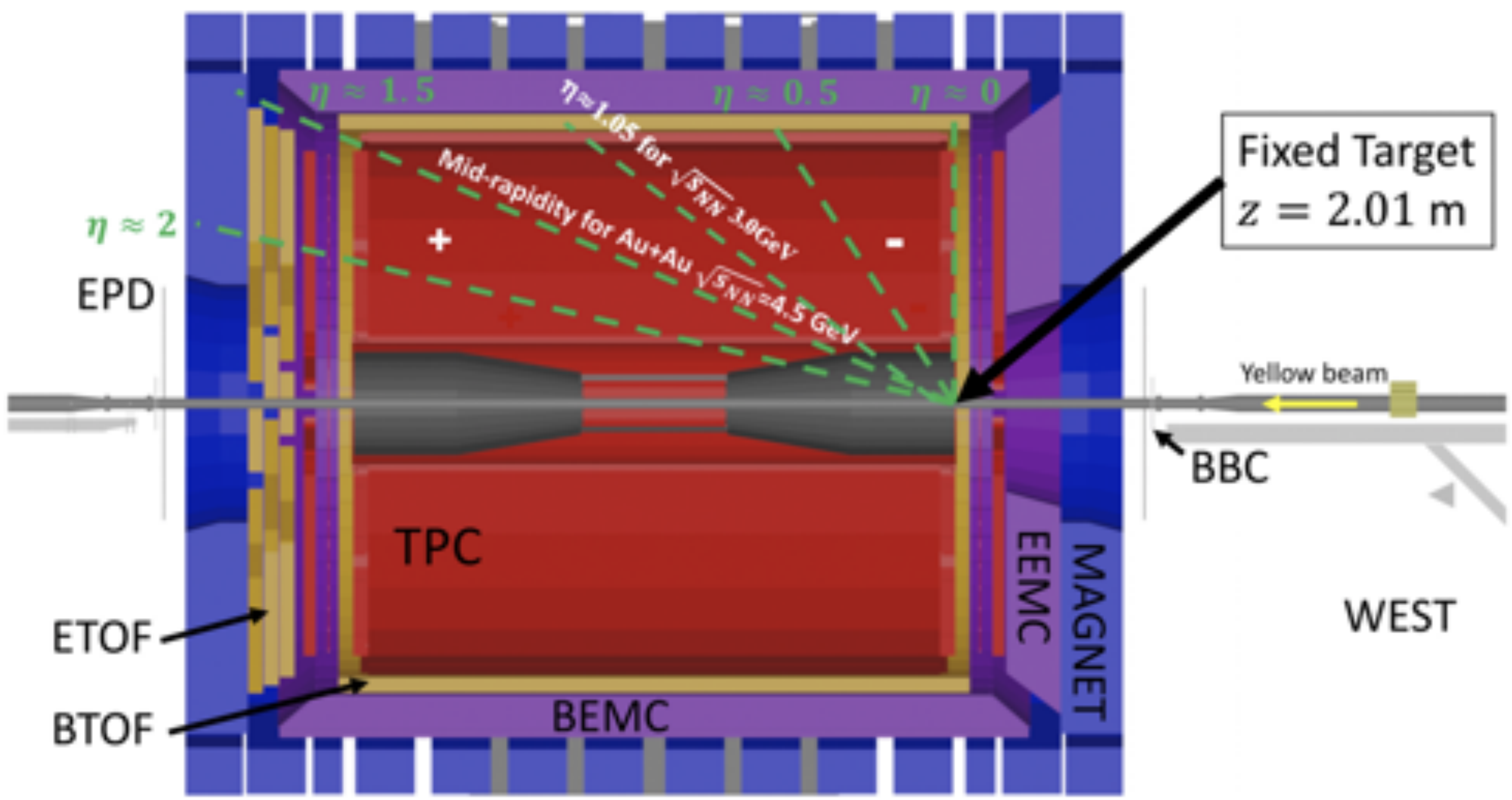


PLB714(2012),85 (Hybrid URQMD, Coalescence(DCM))

PLB 697 (2011)203 (Thermal Model)

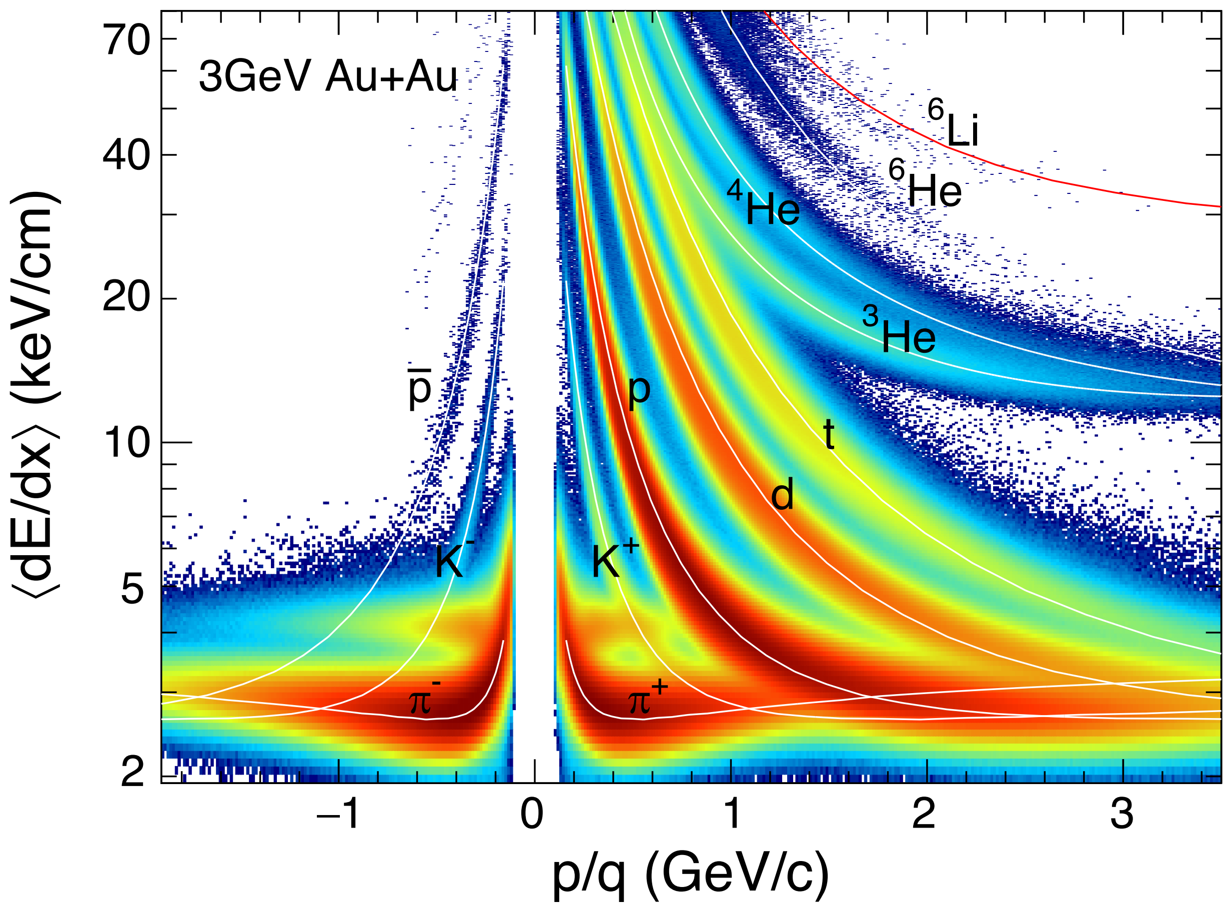
PLB 754 (2016)360 (ALICE)

STAR Fixed-target Experiment Setup



- 250M events at $\sqrt{s_{NN}} = 3$ GeV with STAR fixed target mode

Particle identification



- Main detector used for the analysis is Time Projection Chamber (TPC)
    - Track reconstruction
    - Provides high quality dE/dx measurement for particle identification

KFParticle finder

- Kalman Filter based reconstruction

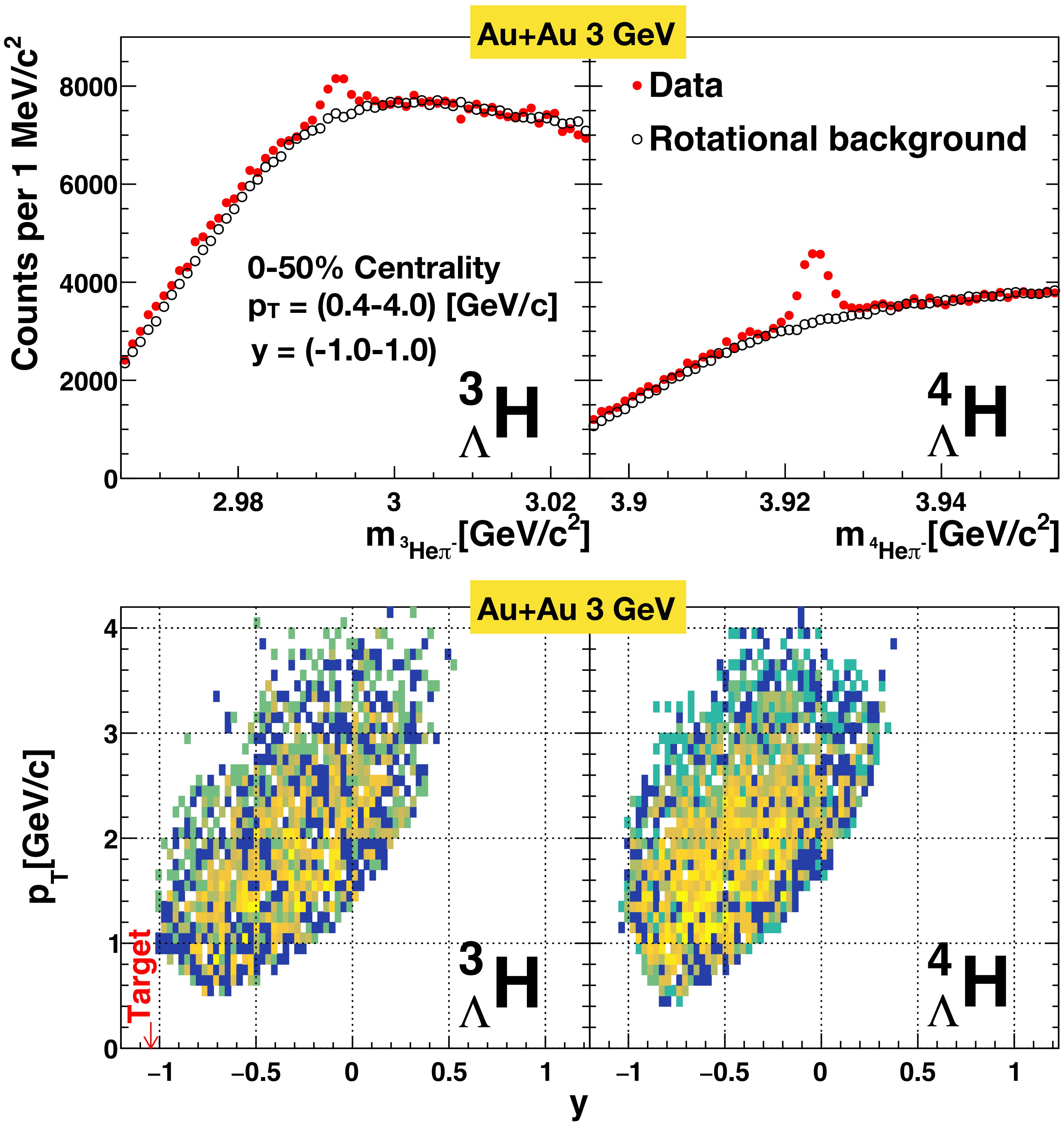
- All particles (mother and daughter) described by state vectors and covariance matrix

Covariance matrix contains essential information about tracking and detector performance

- Higher significance compared to traditional (helix swimming) method

KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, http://publikationen.ub.uni-frankfurt.de/frontdoor/index/index/docId/41428

Hypernuclei reconstruction and acceptance



- Decay channels

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi \quad (B.R. \approx 25\%)$$

[PRC57(1998)1595](#)

~2900 candidates

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi \quad (B.R. \approx 50\%)$$

~6300 candidates

[NPA585(1995) 365c](#)
[NPA639(1998) 251c](#)

$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi \quad (B.R. \approx 40\%)$$

[PRC57(1998)1595](#)

~7000 candidates

- Good mid-rapidity coverage at 3 GeV

**KFParticle package used for reconstruction*

*M. Zyzak, “Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR”, thesis, urn:nbn:de:hebis:30:3-414288

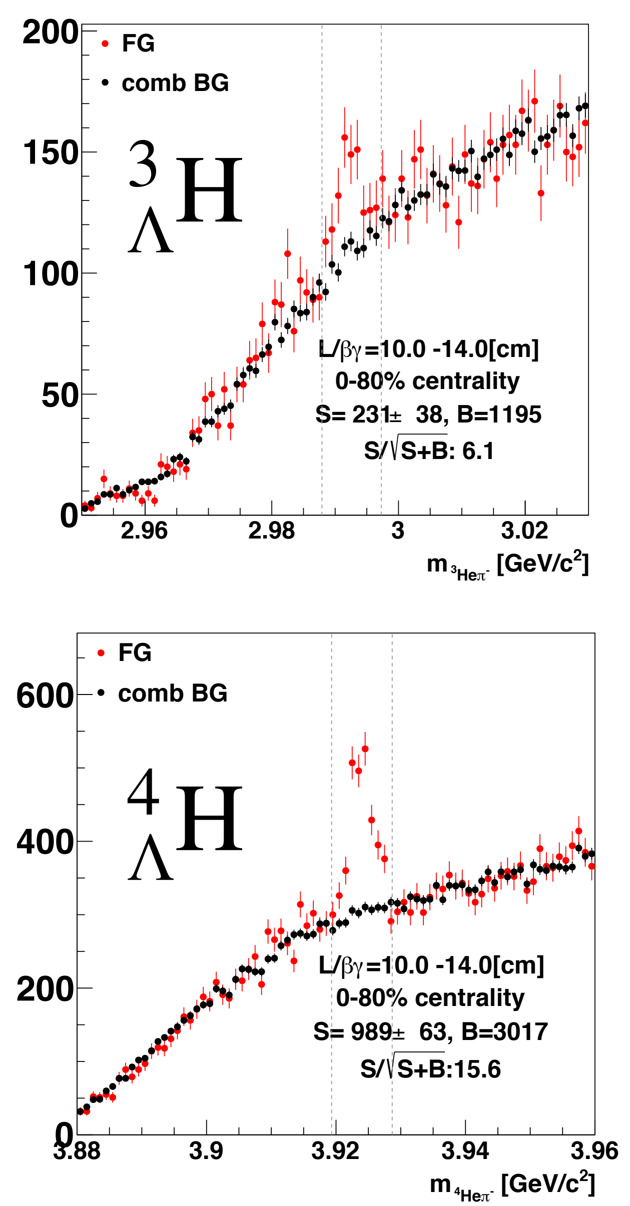
Lifetime analysis

- 1. Measure the signal counts as a function of $L/\beta\gamma$
  - Background estimated by rotating pion tracks

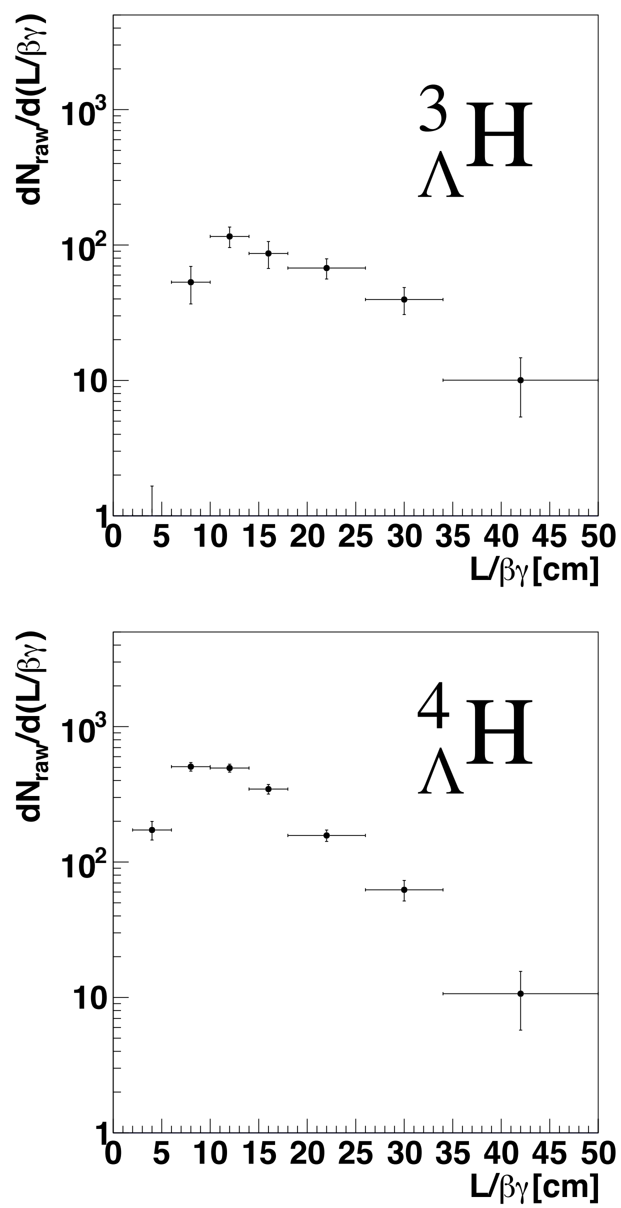
$L/\beta\gamma = ct$

L : decay length

t : proper time



$He-\pi^-$ invariant mass distribution in one $L/\beta\gamma$ bin

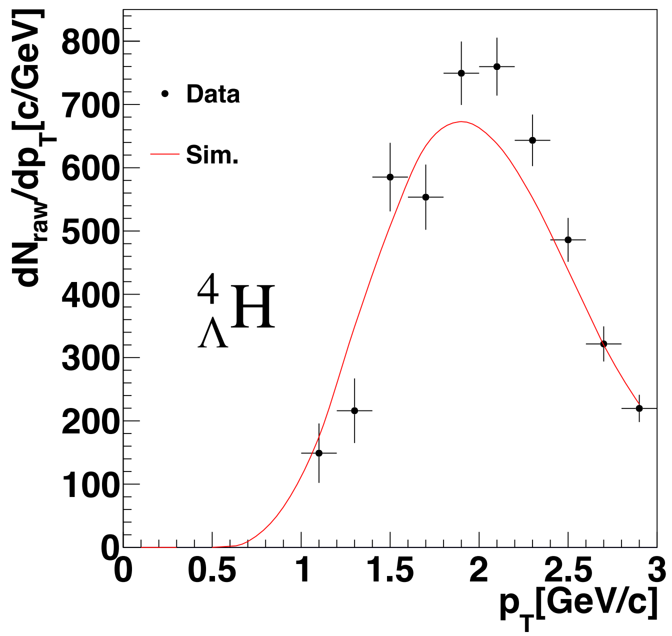


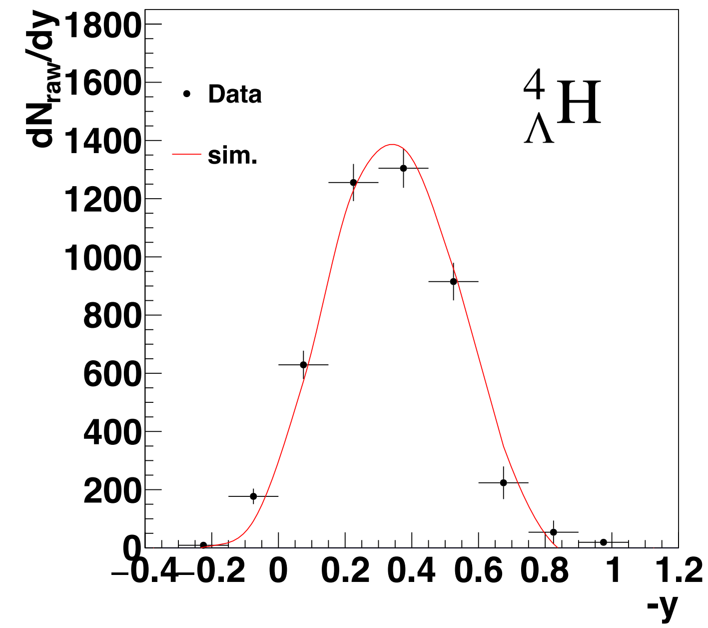
Raw signal counts as a function of $L/\beta\gamma$

Lifetime analysis (cont.)

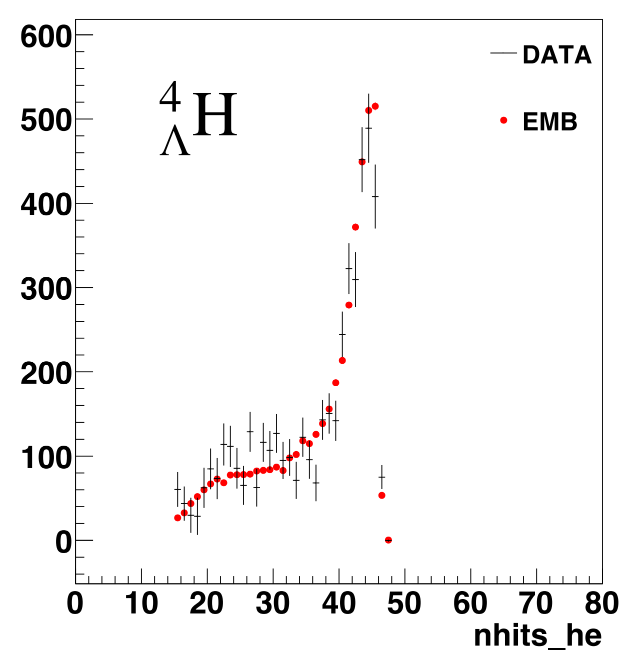
- 2. Correct for efficiency as a function of $L/\beta\gamma$
  - GEANT3 simulations: simulated hypernuclei embedded into real data

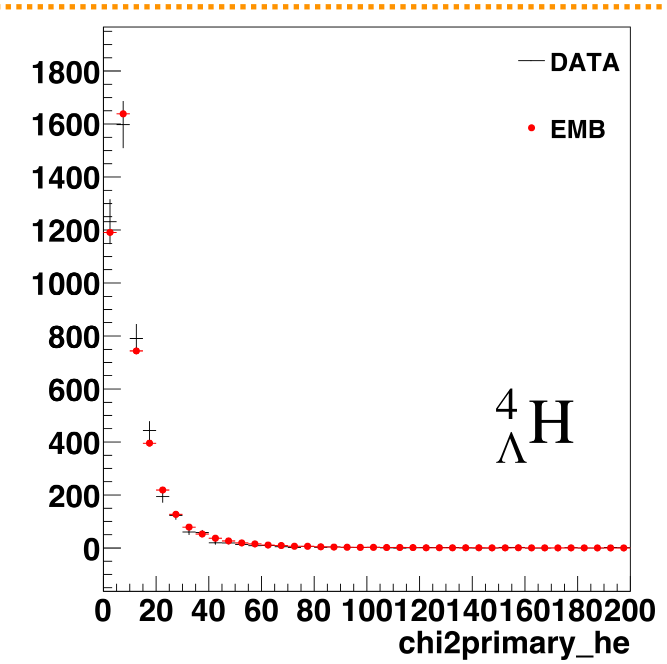
- Apply weighting to simulations to describe p_T and rapidity distributions in real data





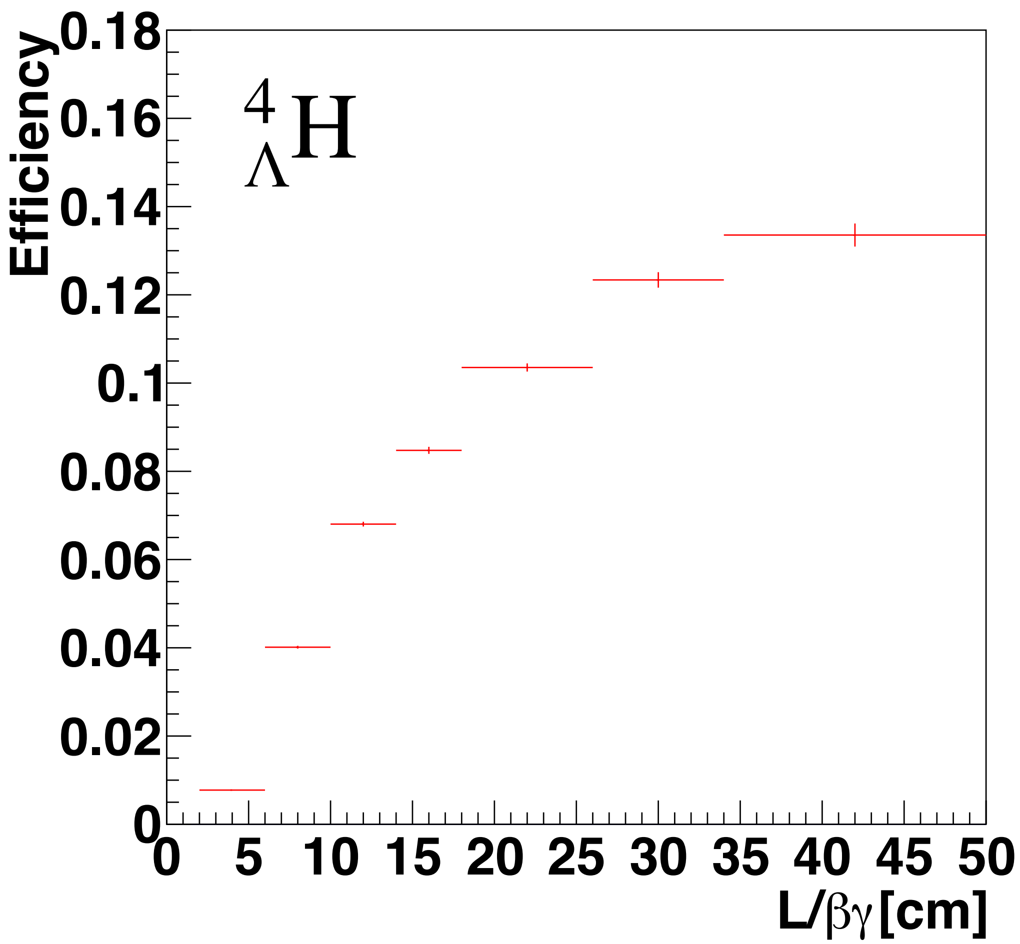
- Distributions of topological variables/ nhits described by our simulations





Lifetime analysis (cont.)

- Efficiency obtained by ratio of reconstructed particles to input particles

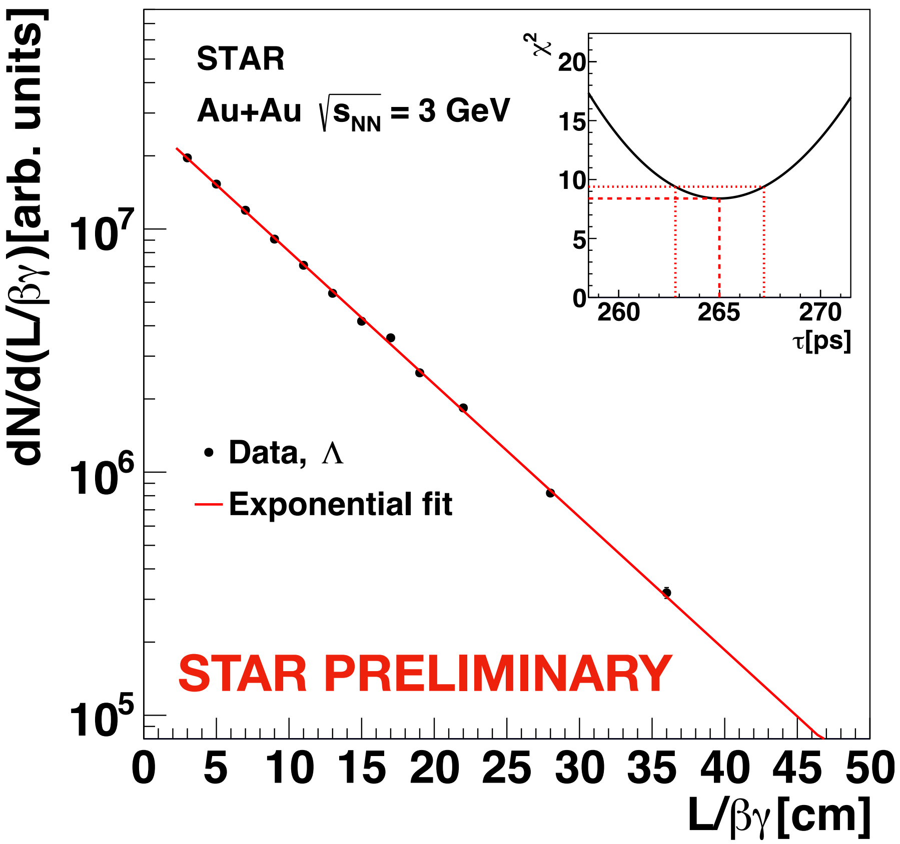


- <u>3. Fit with an exponential to extract the lifetime</u>

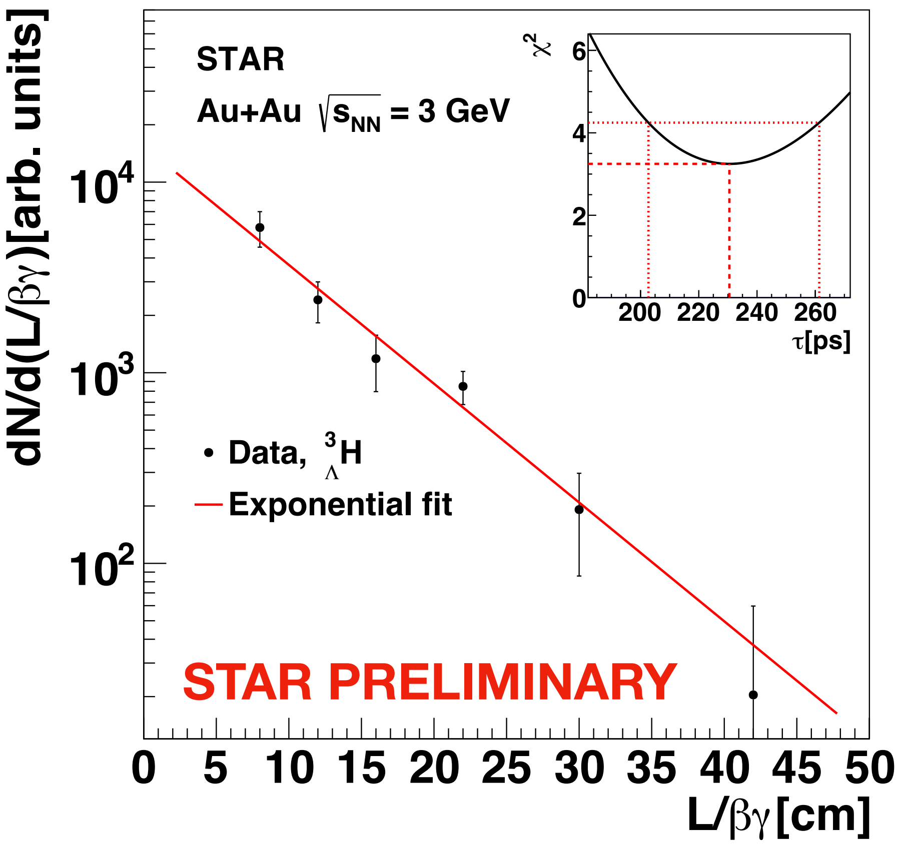
$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-L/\beta\gamma c\tau}$$

Lifetime analysis (cont.)

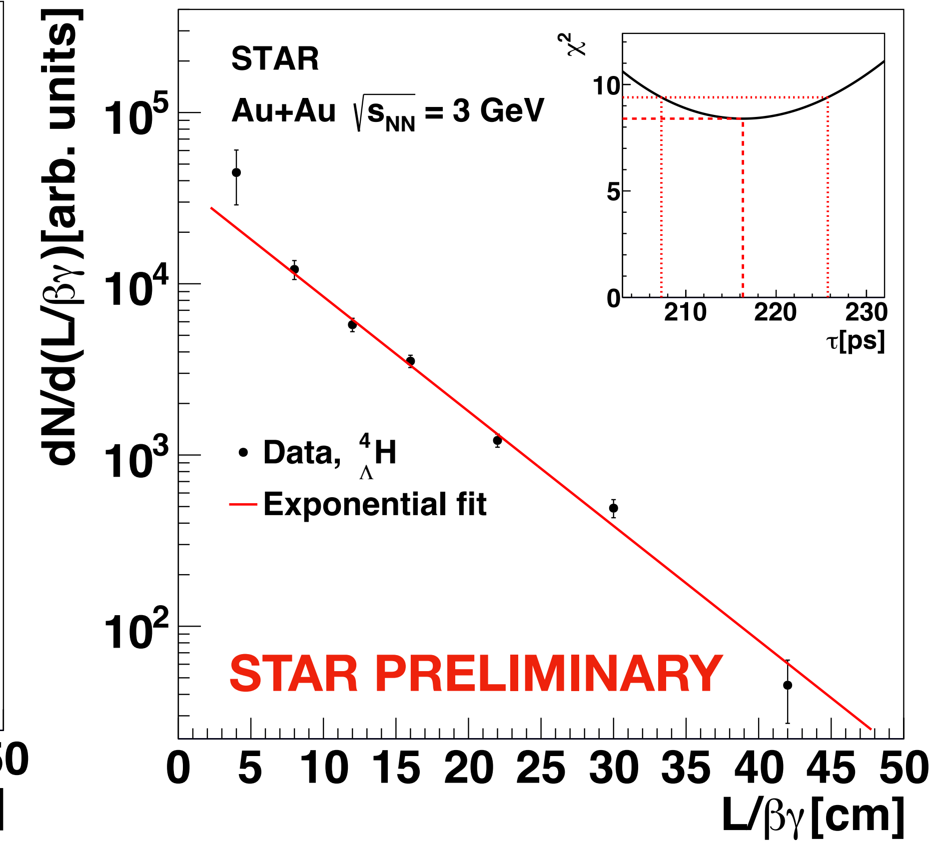
Λ



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



${}^{4}_{\Lambda}H$

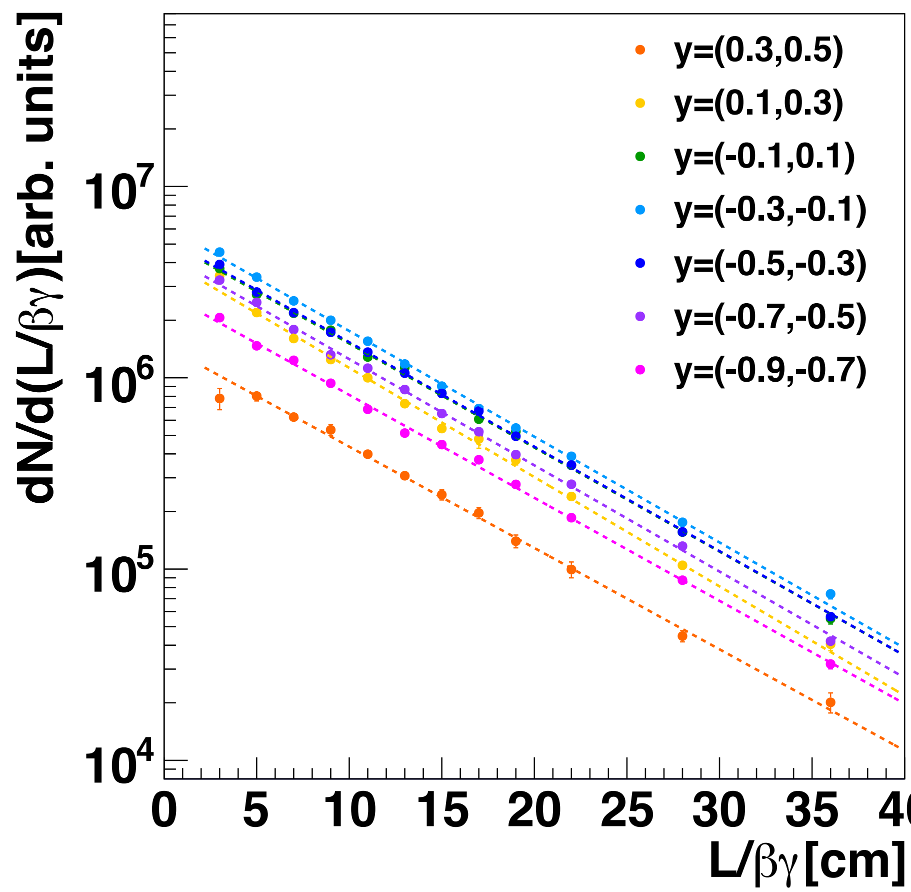


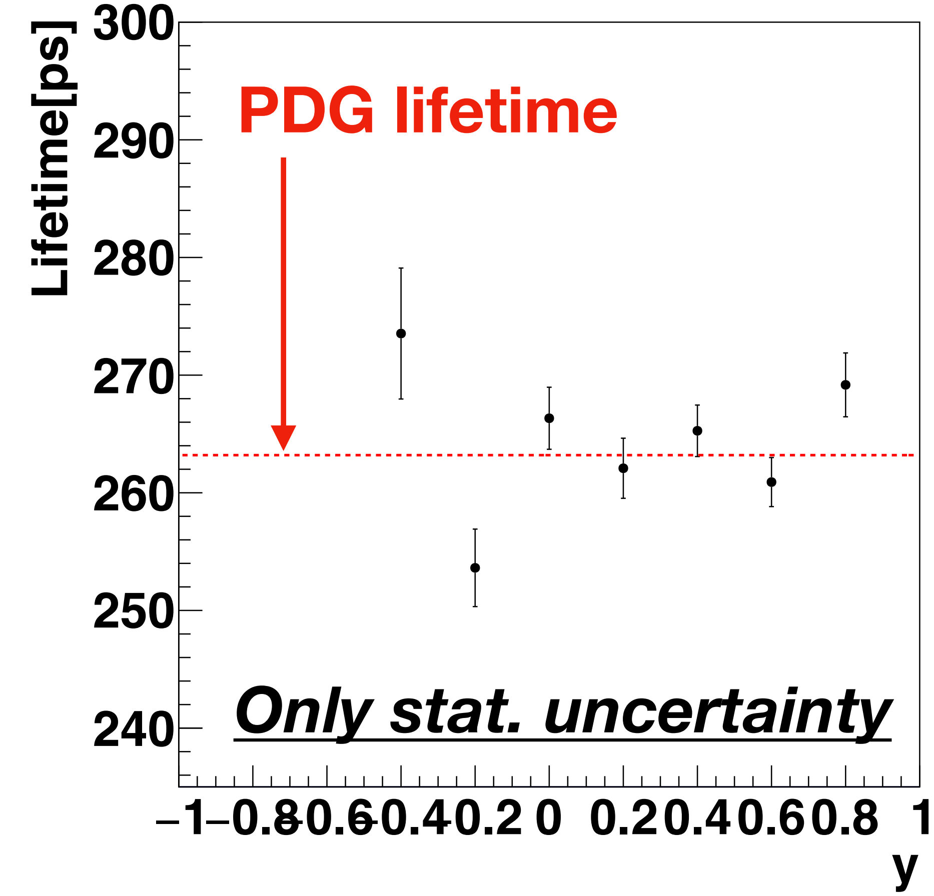
- **Yields of** Λ, ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ **as a function of** $L/\beta\gamma$
    - **Well described by exponential functions** $N(t) = N_0 e^{-L/\beta\gamma c\tau}$
- **Lifetime extracted with** χ^2 **fit**
- **Extracted** Λ **lifetime** $(265.0 \pm 2.2)[\text{ps}]$ **consistent with PDG value** $(263.1 \pm 2.0)[\text{ps}]$

Lambda lifetime crosscheck

- We extract $dN/d(L/\beta\gamma)$ <u>in different rapidity slices</u> for Λ

- The extracted lifetimes are consistent with PDG value.





- <u>Analysis procedure is robust using different regions of the detector</u>

Systematic uncertainties on the lifetime

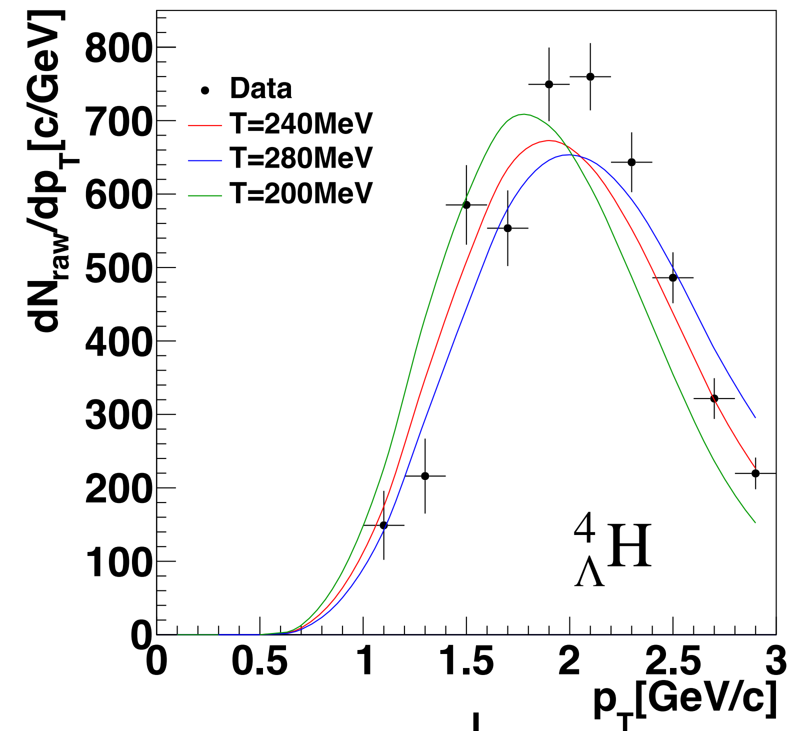
- (1) Analysis cuts
  - Imperfect description of topological variables between simulations and real data
- (2) Input MC p_T/rapidity/lifetime
  - Imperfect knowledge in the real kinematic distributions of the hypernuclei
- (3) Single track efficiency
  - Mismatch of single track efficiency between simulations and data
- (4) Signal extraction
  - Uncertainties related to the background subtraction technique

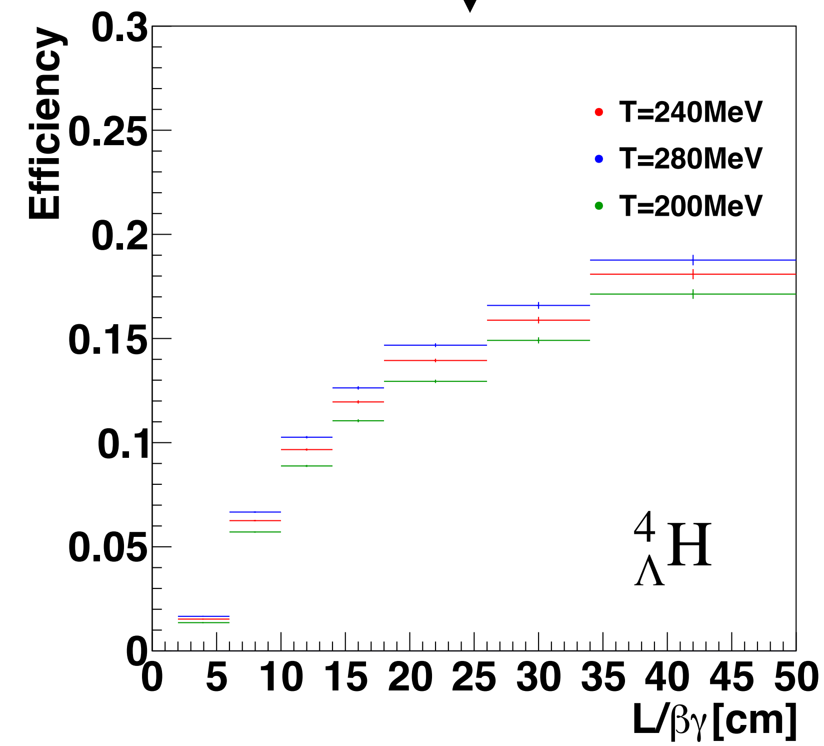
syst. uncertainty	$^{3}_{\Lambda}H$	$^{4}_{\Lambda}H$
Analysis cuts	9.7%	5.0%
Input MC	9.1%	1.3%
Tracking efficiency	7.7%	1.1%
Signal extraction	3.8%	0.9%
Total	15.8%	5.4%

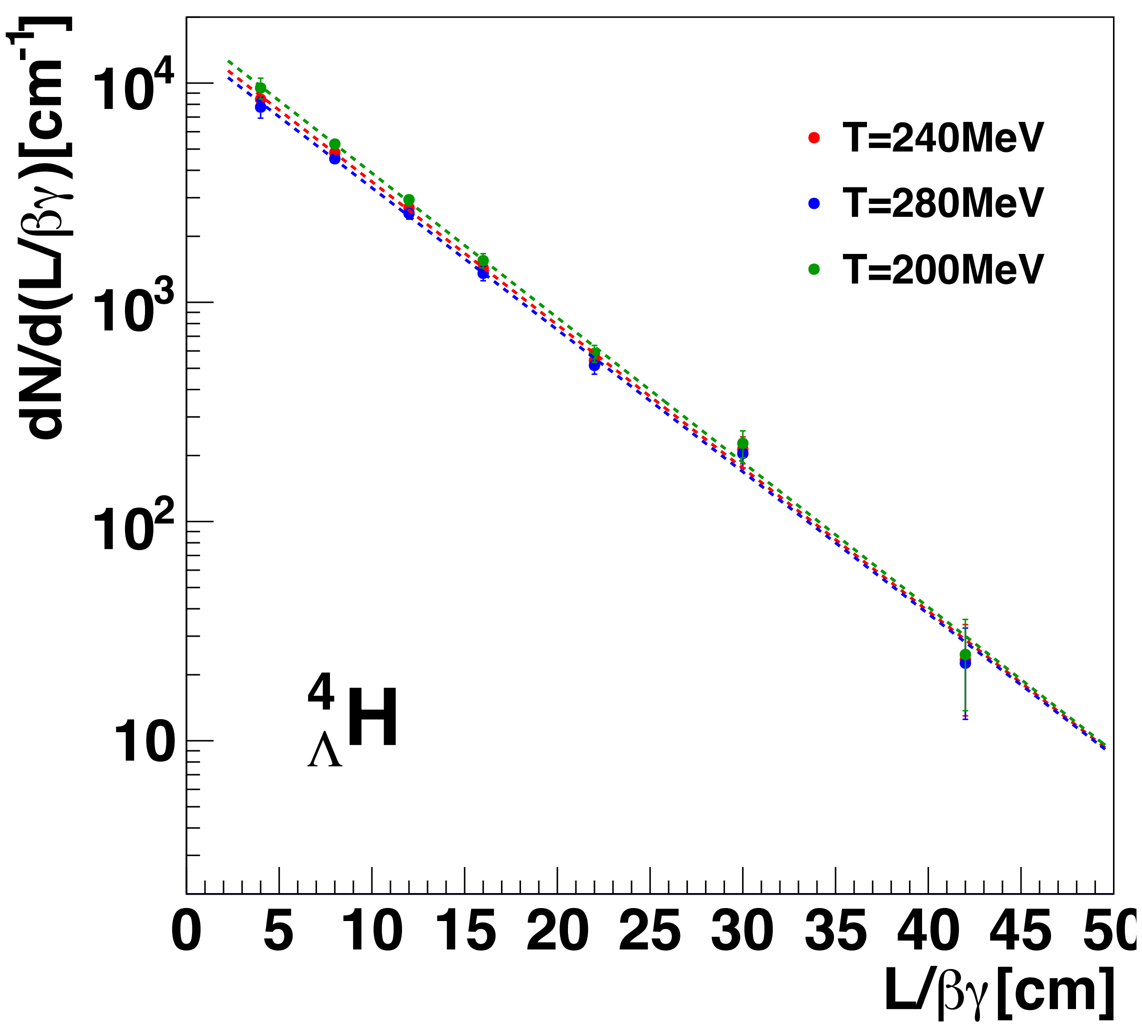
Table: Syst. uncertainty for $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetime

Systematic uncertainties: input weighting

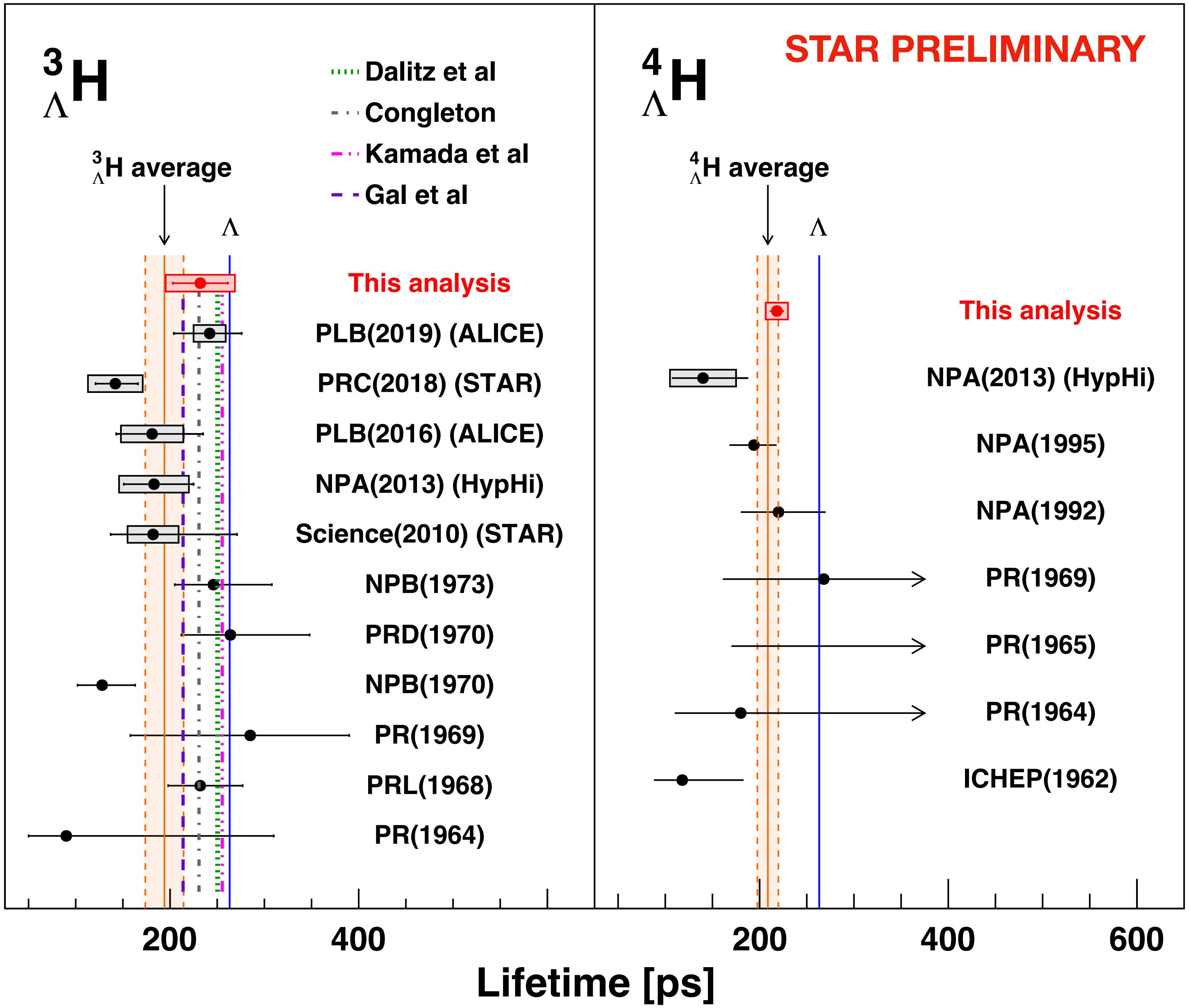
- Efficiency as a function of $L/\beta\gamma$ depends on weighting applied to the simulations
    - Systematic uncertainties assigned by varying the weighting function used







New results on ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ lifetime



$$ {}^{3}_{\Lambda}\mathrm{H} : \tau = 232.1 \pm 29.2(\mathrm{stat}) \pm 36.7(\mathrm{syst})[\mathrm{ps}] $$

$$ {}^{4}_{\Lambda}\mathrm{H} : \tau = 218.3 \pm 7.5(\mathrm{stat}) \pm 11.8(\mathrm{syst})[\mathrm{ps}] $$

- ${}^{4}_{\Lambda}\mathrm{H}$:
  - **Most precise measurement to date.**
  - **Consistent with previous measurements.**
- ${}^{3}_{\Lambda}\mathrm{H}$:
  - **Consistent with theoretical calculations including pion FSI.**

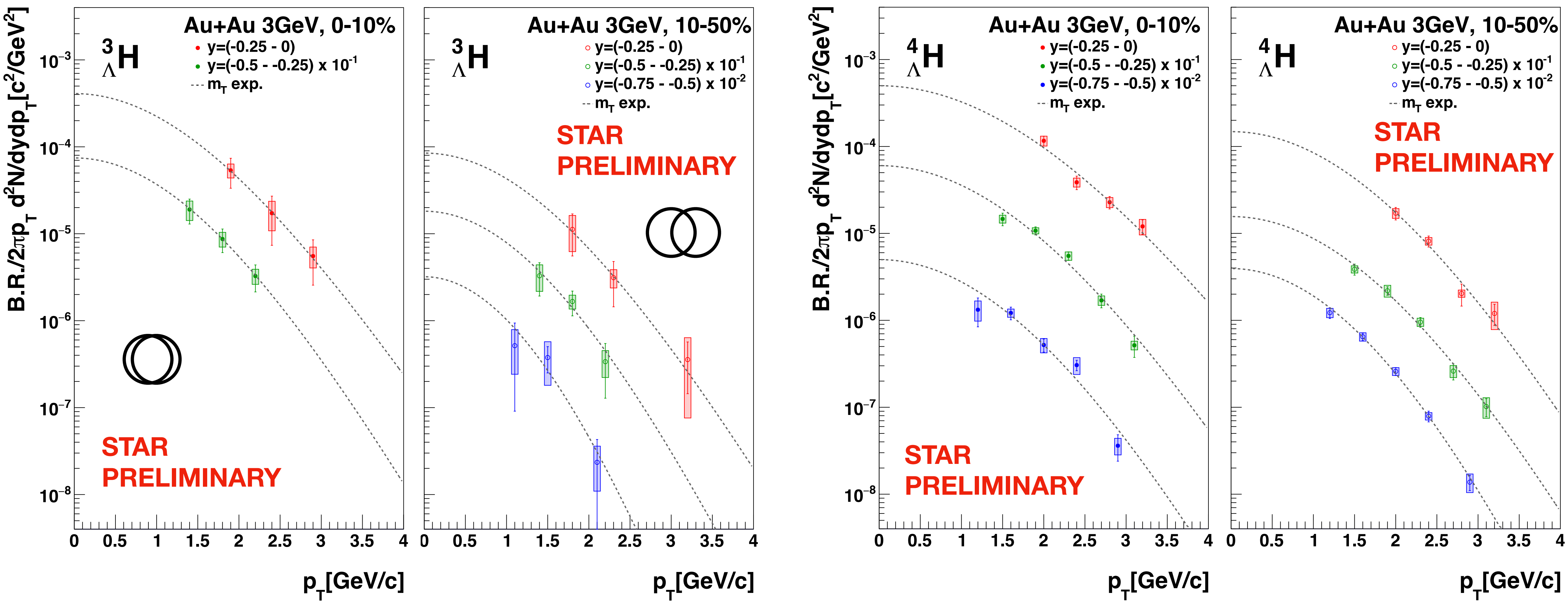
NC46(1966)786 (Dalitz et al)

JPG NPP 18(1992)339 (Congleton)

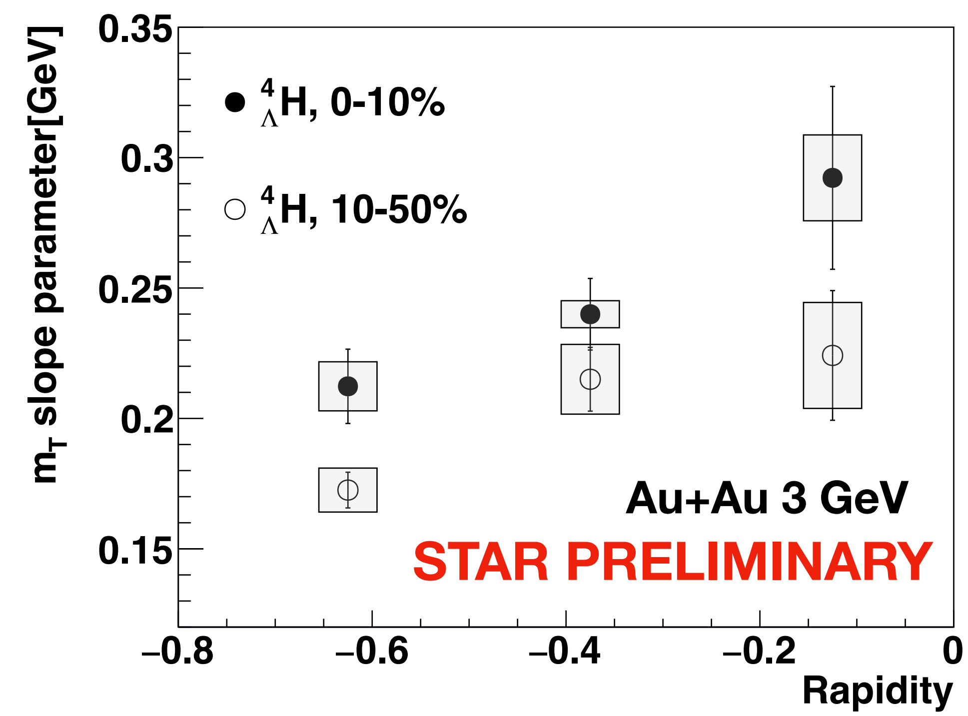
PRC57(1998)1595 (Kamada et al)

PLB791(2019)48 (Gal et al)

${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ p_T spectra



- **Extract ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ spectra in 0-10% and 10-50% centralities.**
  - **${}^{4}_{\Lambda}\mathrm{H}$ spectra becomes softer at more backward rapidities.**
- **Extrapolate to p_T = 0 GeV/c to obtain dN/dy**



Systematic uncertainties on the spectra

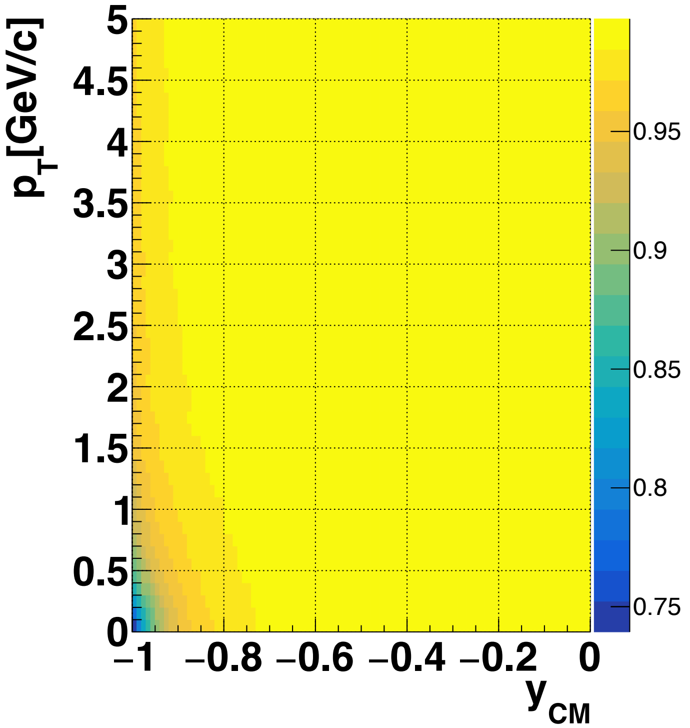
- Additional sources of systematic uncertainties considered:
- <u>Extrapolation</u>
  - Different functions for extrapolation to estimate uncertainty
    - m_T exponential, blast wave, Boltzmann, etc.
- <u>Target material</u>
  - Took into account possible Coulomb dissociation when traversing target material

    Physics of Atomic Nuclei, 2007, Vol. 70, No. 9, pp. 1617–1622
  - Survival probability >95% in kinematic regions analyzed

*Target thickness = 0.25mm

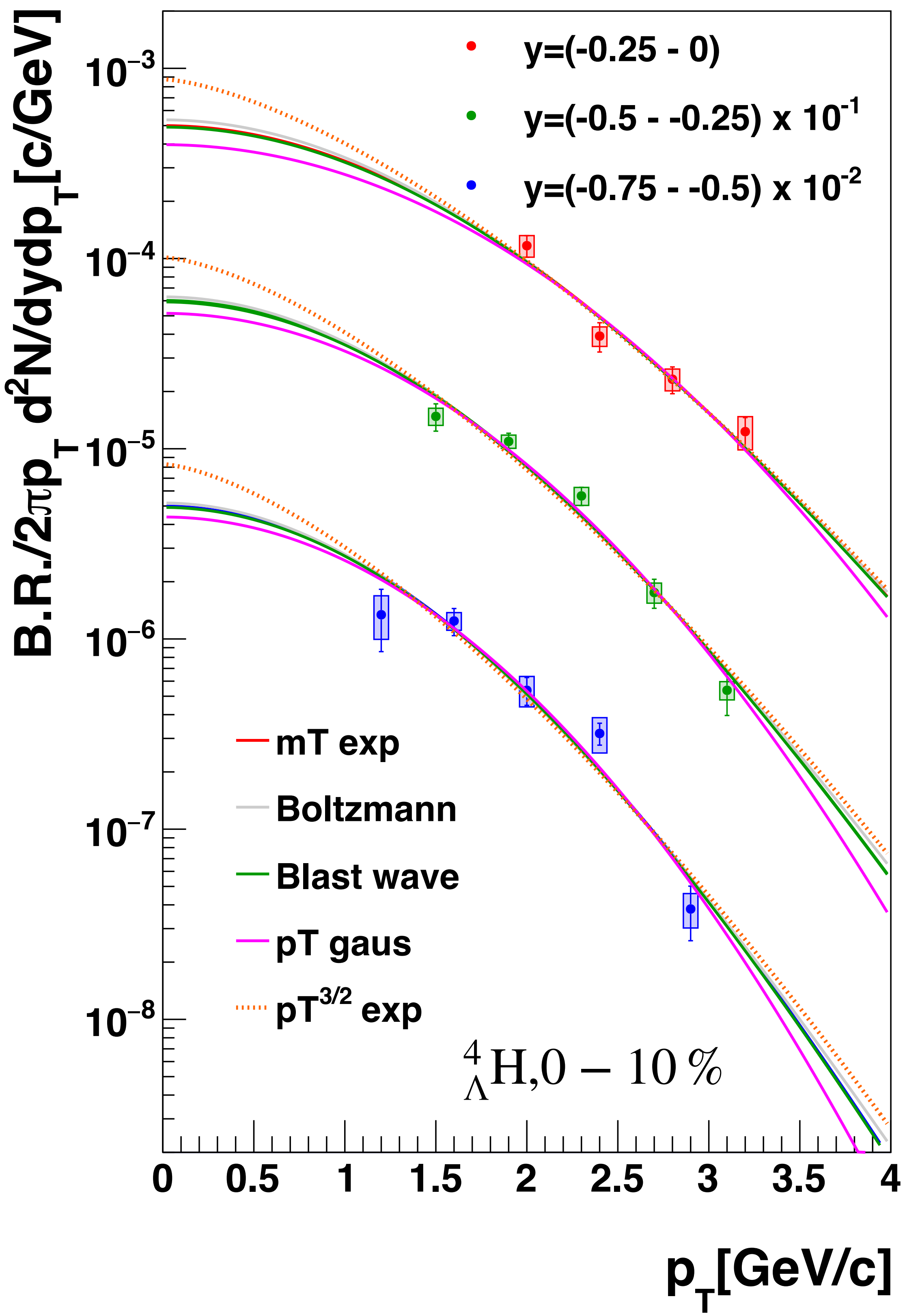
syst. uncertainty	${}^{3}_{\Lambda}$H	${}^{4}_{\Lambda}$H
Analysis cuts	19.3%	4.1%
Input MC	10.0%	4.0%
Tracking efficiency	3.7%	2.9%
Signal extraction	6.0%	4.0%
Extrapolation	11.8%	12.8%
Detector material	4.0%	$<$ 1%
Total	26.0%	14.9%
Branching ratio	40.0%	20.0%

<u>Table: Syst. uncertainty for ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H dN/dy at |y|<0.5 in Au+Au 0-10%.</u>



<u>Fig: Survival prob. for ${}^{3}_{\Lambda}$H estimated from MC study</u>

Systematic uncertainties: Extrapolation



- Use different functions for extrapolation to estimate systematic uncertainty

Systematic uncertainties: Coulomb dissociation

- Hypernuclei may experience coulomb dissociation when traversing target material **Target thickness = 0.25mm*

- Coulomb dissociation of weakly bound relativistic (hyper)nuclei within two cluster model

$$\sigma = \frac{\pi}{3}(Z\alpha)^2 z^2 \frac{m_2}{v^2 M m_1 \epsilon_{\rm bin}}\left[\ln\left(\frac{8\gamma^2 v^2 M m_1}{m_2 \epsilon_{\rm bin}}\right) - (2A - C) - v^2 - \Delta B(Z)\right]. \quad (21)$$

Here, $2A - C \approx 2.12$; the quantity $\Delta B(Z)$ is determined according to Eq. (8).

Z: charge of target
m_2: mass of lambda
m_1: mass of deuteron/triton
M: mass of hypernuclei
e_{bin}: binding energy
v: velocity of hypernuclei

ΔB(Z): correction term connected with the finite size of the target nucleus

ISSN 1063-7788, Physics of Atomic Nuclei, 2007, Vol. 70, No. 9, pp. 1617–1622. c Pleiades Publishing, Ltd., 2
https://inis.iaea.org/collection/NCLCollectionStore/_Public/22/054/22054069.pdf?r=1

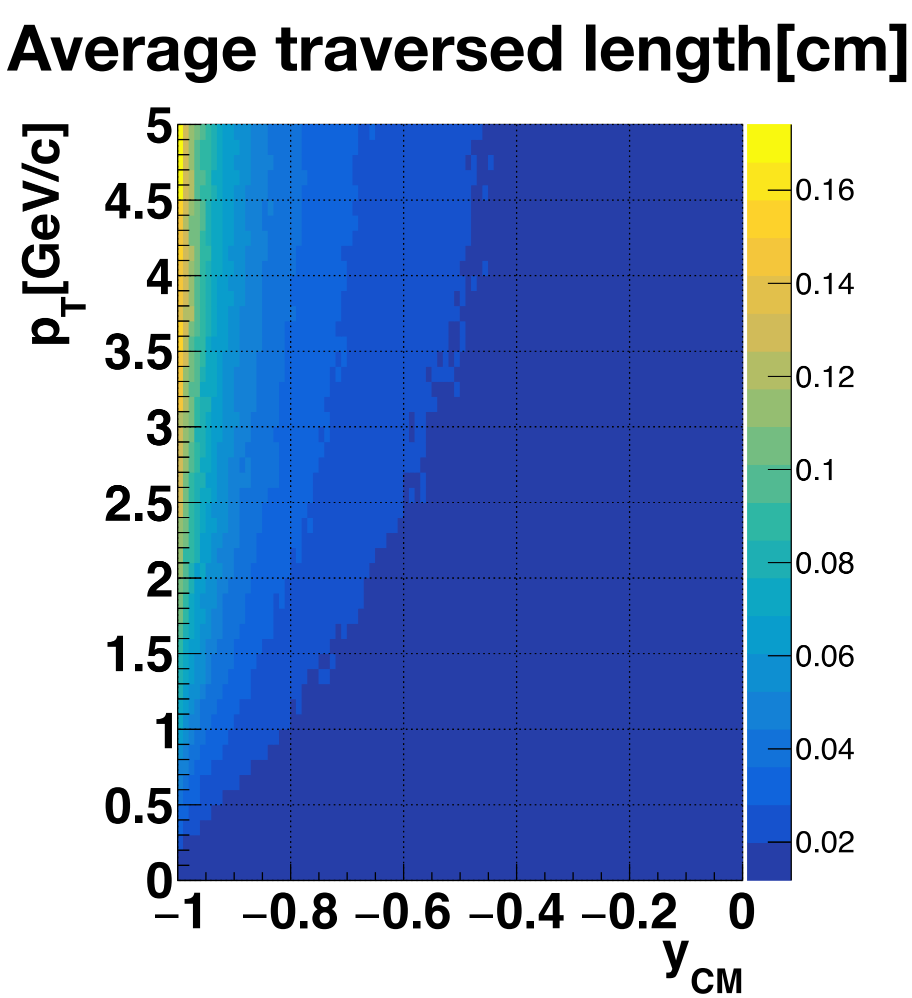
- Probability to survive length d of material

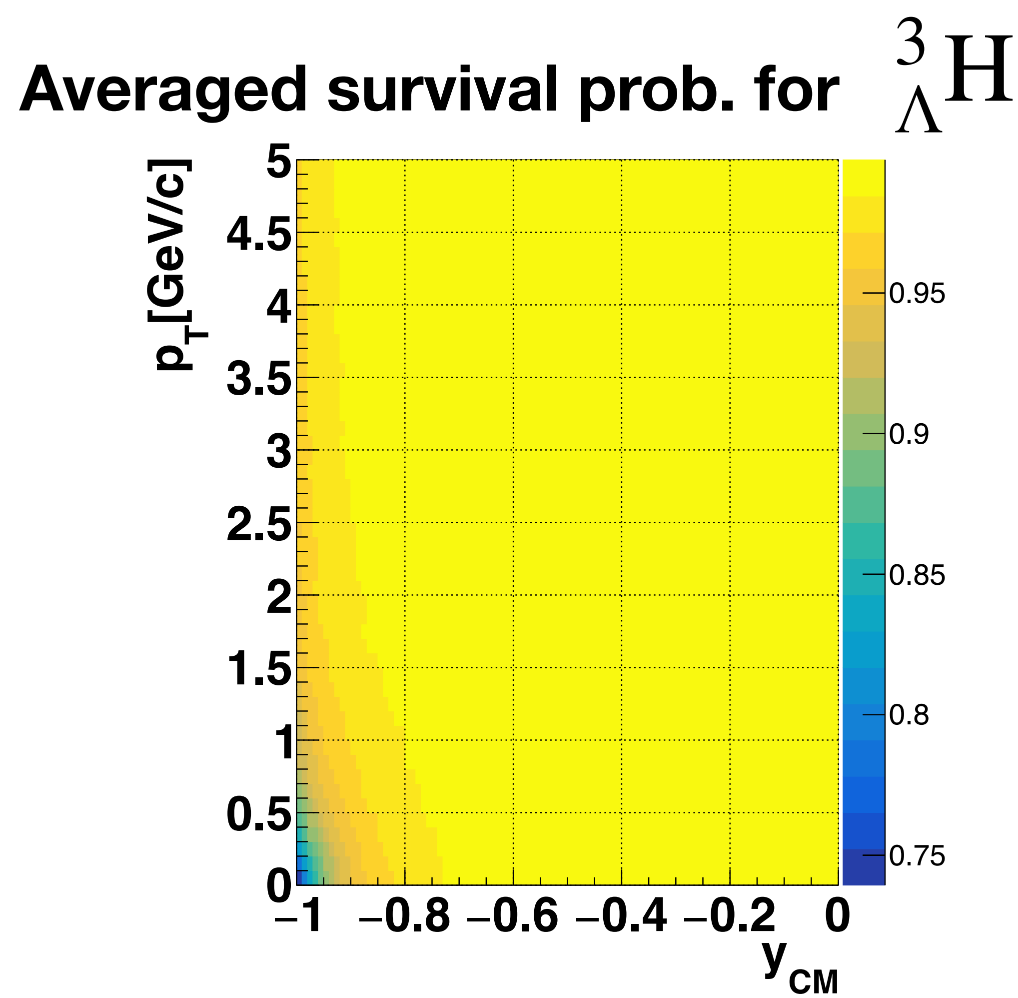
$$P(d) = exp(-\sigma * n * d)$$

n: atomic density
(5.90×10^{28} m^{-3} for Au)

Systematic uncertainties: Coulomb dissociation

- Dissociation xsection -> depends on momentum
- Traversed length -> depends on direction + collision vertex
- <u>We use a MC to calculate this effect as a function of momentum and rapidity</u>





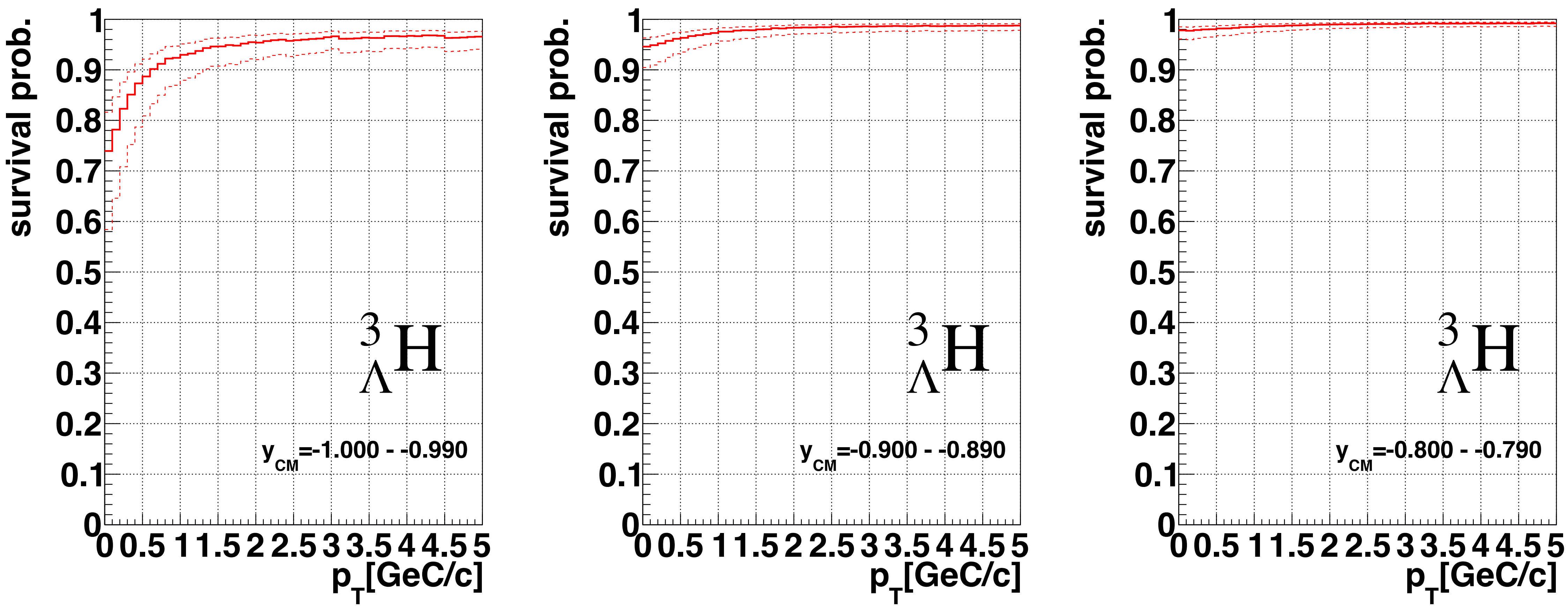
- Survival probability > 95% for y > -0.8
- Dissociation effect is negligible for ${}^{4}_{\Lambda}\mathrm{H}$

Systematic uncertainties: Coulomb dissociation

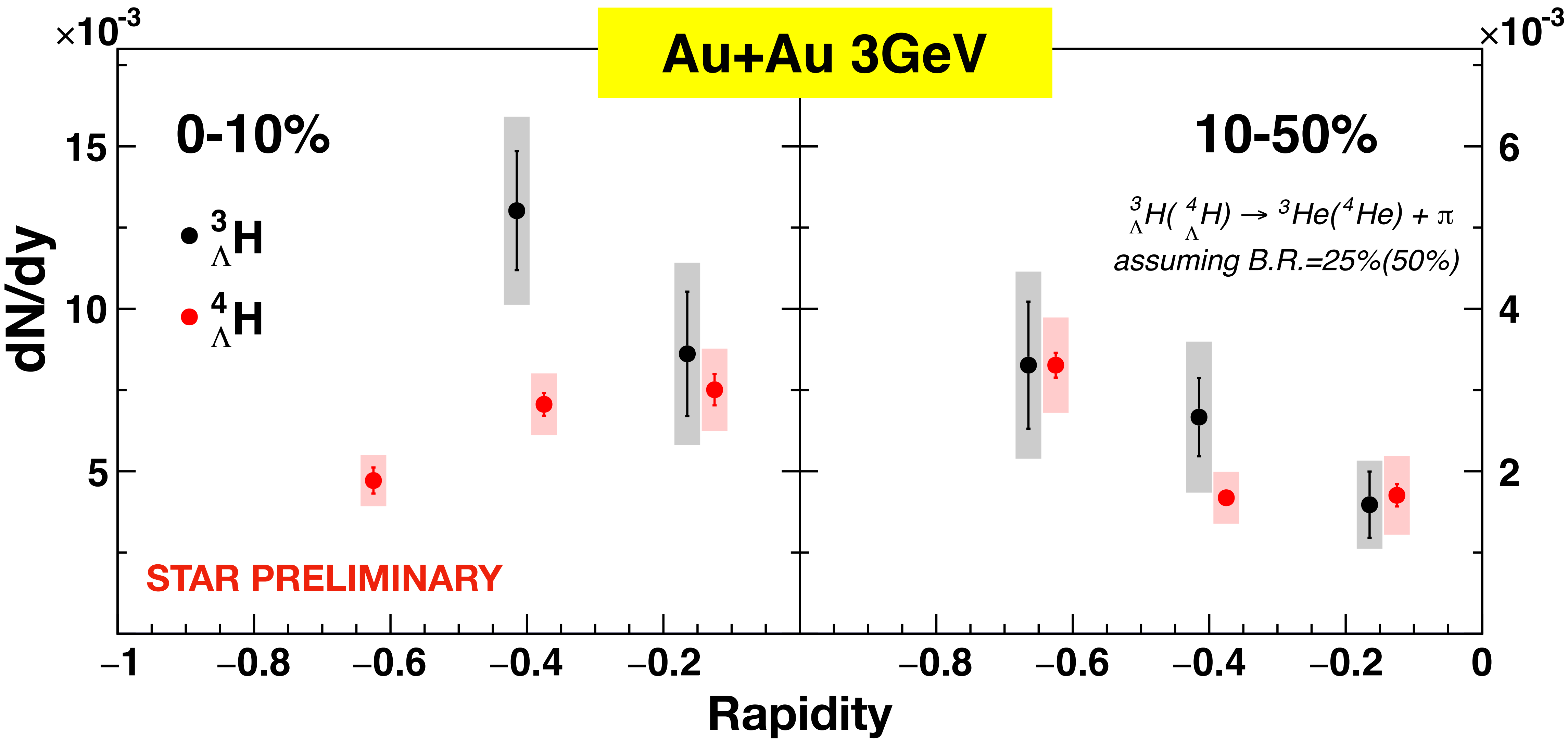
- Dissociation cross section depends on the binding energy of hypertriton: 0.11 ± 0.05 MeV

NPB1(1967)
NPB4(1968)
PRD(1970)
NPB52(1973)
Nature Physics 16 (2020) 409

- Correction applied as a function of rapidity and momentum
  - Uncertainties due to precision in binding energy of ${}^{3}_{\Lambda}H$



${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ dN/dy at $\sqrt{s_{NN}} = 3$ GeV



- **First measurement of dN/dy of hypernuclei in HI collisions**
  - **Different trends in the ${}^{4}_{\Lambda}H$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions**

PRC57(1998)1595
NPA585(1995) 365c
NPA639(1998) 251c

Light nuclei dN/dy at 3 GeV

- ^{4}He spectra at 3 GeV
  - Softening of spectra from mid-rapidity to target rapidity
  - dN/dy show centrality dependence
  - **Qualitatively similar to $^{4}_{\Lambda}H$**

Au+Au Collisions

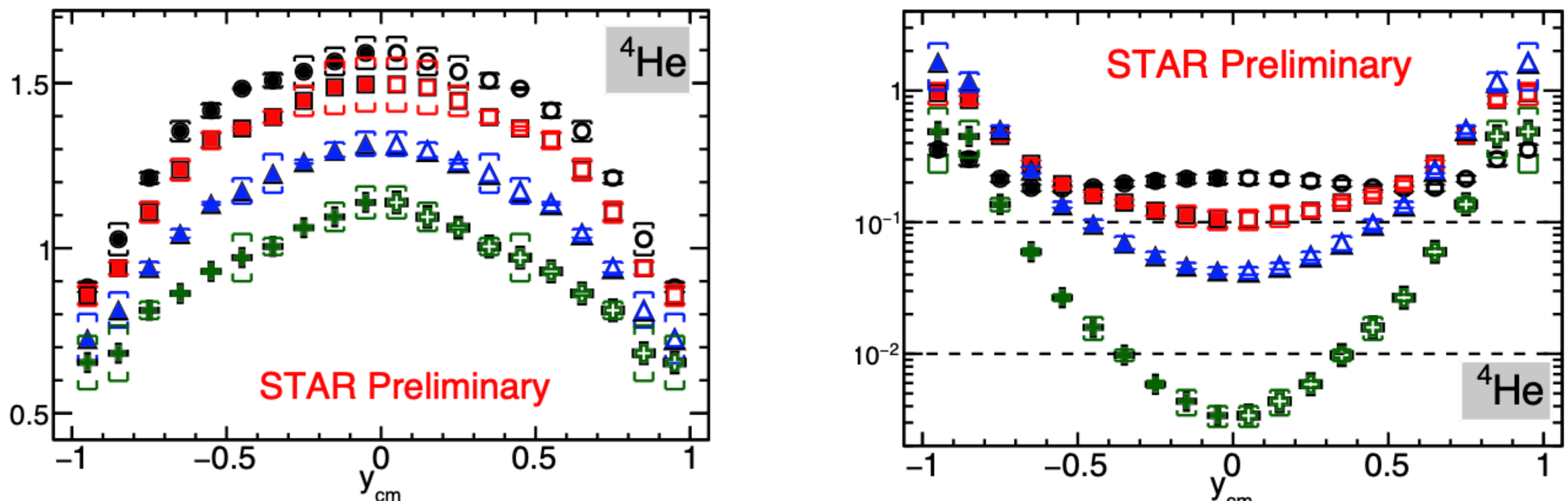
FXT $\sqrt{s_{NN}}$ = 3 GeV

● 0-10% ▲ 20-40%

■ 10-20% ✚ 40-80%

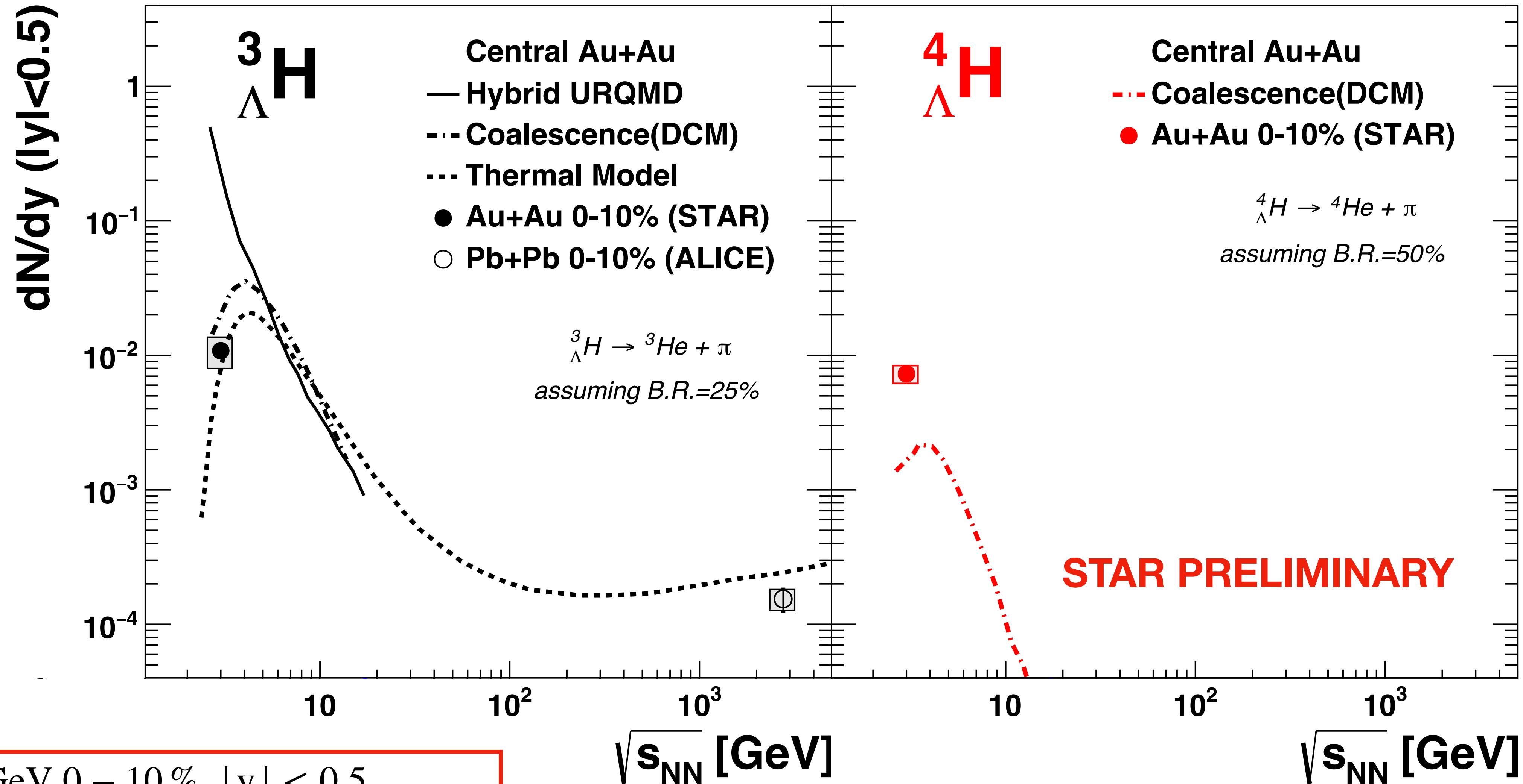
○ □ △ ✚ reflection

<p$_T$>[GeV/c] **dN/dy**



Liu Hui, APS April Meeting 2021

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ |y|<0.5 yield vs beam energy



Au + Au@3GeV,0 – 10 %, |y| < 0.5

${}^{3}_{\Lambda}H$: $dN/dy = 1.1 \pm 0.1(stat) \pm 0.3(syst) \times 10^{-2}$

${}^{4}_{\Lambda}H$: $dN/dy = 7.3 \pm 0.3(stat) \pm 1.1(syst) \times 10^{-3}$

- **Thermal model (GSI-Heidelberg) which adopts the canonical ensemble, describes ${}^{3}_{\Lambda}H$ yield at 3 GeV**
- **Yield of ${}^{4}_{\Lambda}H$ not described by coalescence (DCM) model**

PLB714(2012),85 (Hybrid URQMD, Coalescence(DCM))

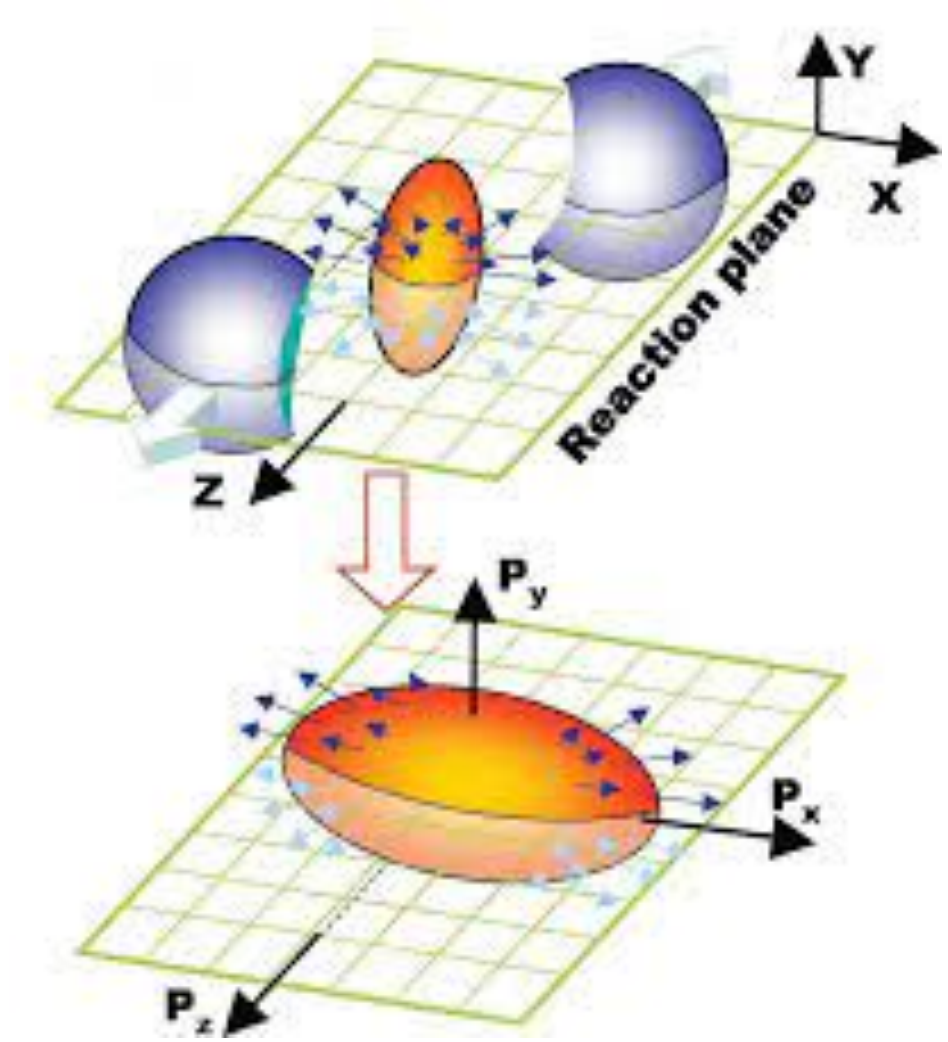
PLB 697 (2011)203 (Thermal Model)

PLB 754 (2016)360 (ALICE)

Directed flow of hypernuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$

- **Anisotropic flow commonly used for studying the properties of matter created in high energy nuclear collisions**
  - **Sensitive to early stage of system evolution**

$$\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\inf} 2v_n cos(n(\phi - \Psi))$$



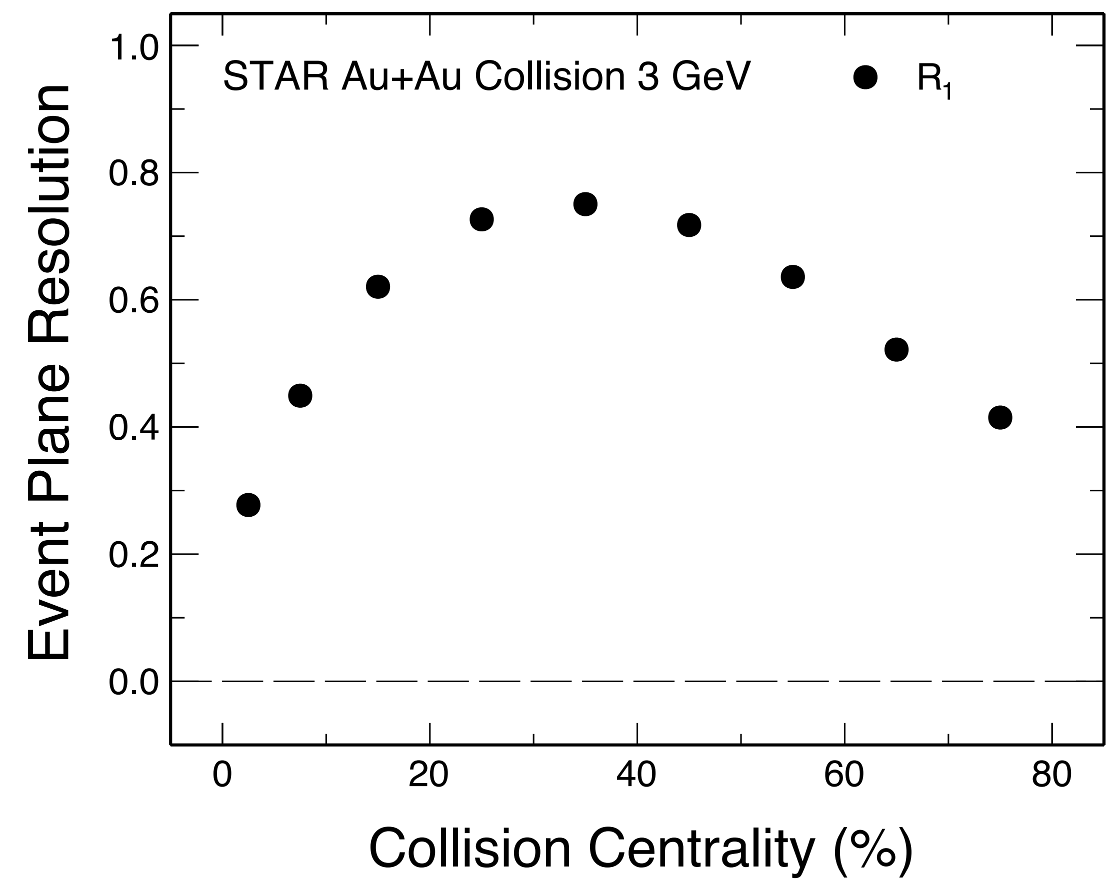
- **Directed flow v_1 generated during the nuclear passage time, probes the earliest stage of the collision**

$$v_1 = \langle cos(\phi - \Psi) \rangle$$

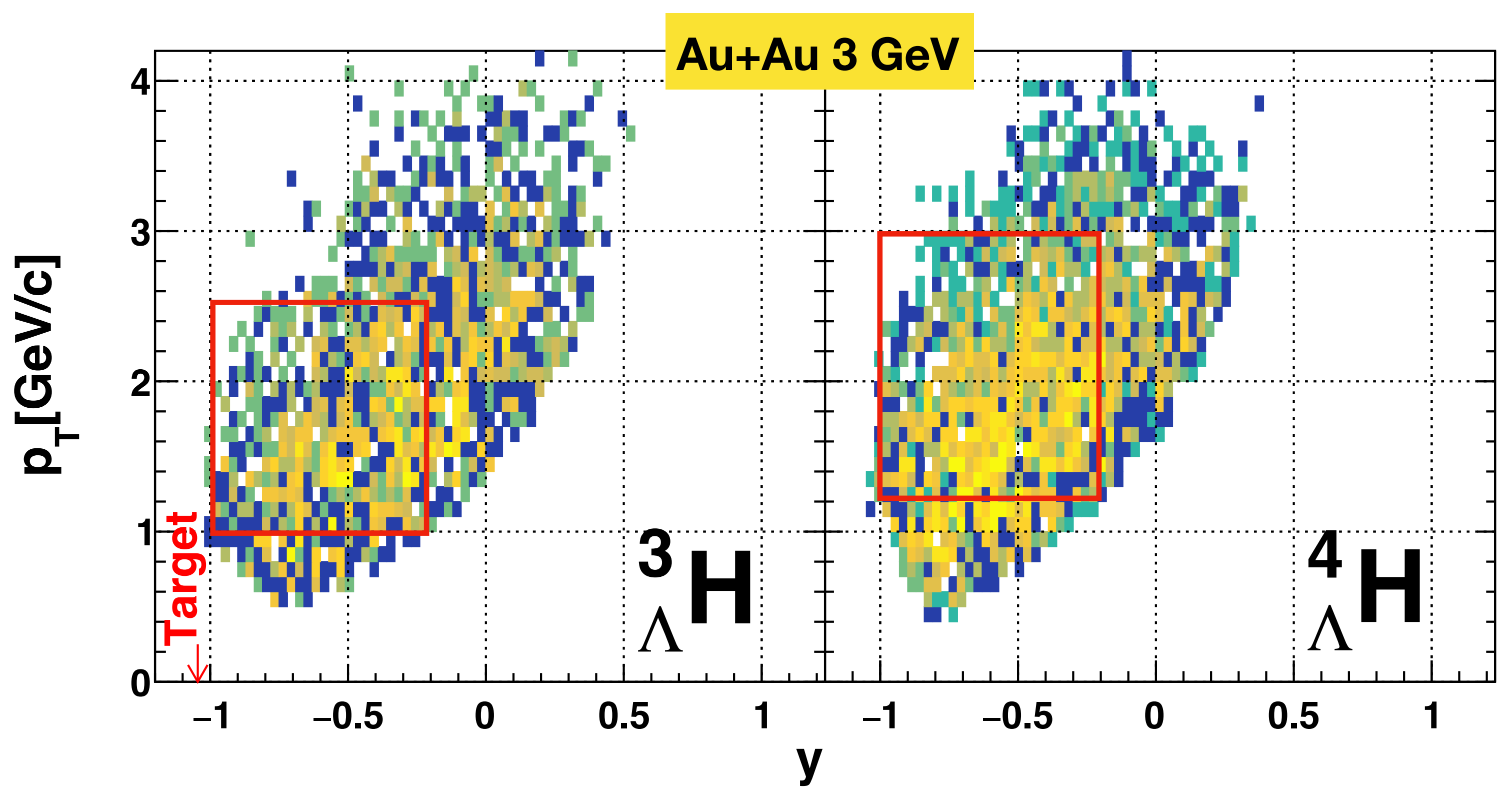
ϕ **: azimuthal angle of particle**
Ψ **: reaction plane angle**

Directed flow of hypernuclei ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$

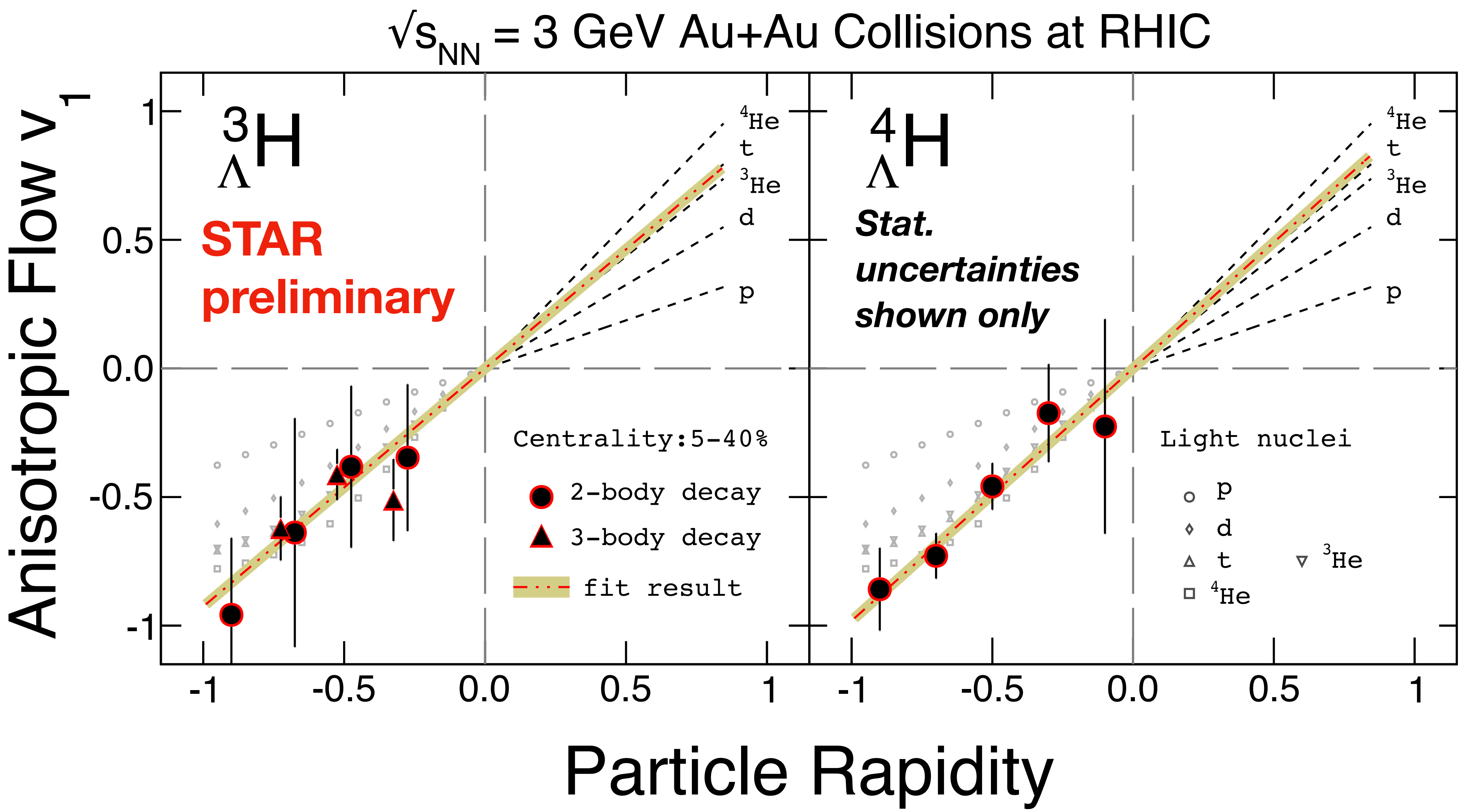
- **We use the <u>event plane method</u> to extract the v_1 of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$**
  - **1st order event plane angle measured by Event Plane Detector (EPD)** $(-5.3 < \eta < -2.6)$
  - **Event plane resolution R_1 from 3-sub-event method**



- **Kinematic range for extraction of v_1 slope:**



Directed flow of hypernuclei ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$



- **First observation of hypernuclei collectivity v_1 in HI collisions.**
- **v_1 slope follow baryon number scaling in 5-40% 3 GeV Au+Au collisions**
    - **Results consistent with hypernuclei production from coalescence of hyperons and nucleons**

Summary 1

- First measurement of hypernuclei dN/dy in HI collisions
  - Different trends in the ${}^{4}_{\Lambda}\mathrm{H}$ rapidity distribution in central (0-10%) and mid-central (10-50%) 3 GeV Au+Au collisions
  - Thermal model describes ${}^{3}_{\Lambda}\mathrm{H}$ yield, while coalescence (DCM) model does not describe ${}^{4}_{\Lambda}\mathrm{H}$ yield.
- First observation of hypernuclei collectivity v_1 in HI collisions
  - v_1 slope of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ follow baryon number scaling in 5-40% collisions.
- Improved precision on ${}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H}$ lifetimes

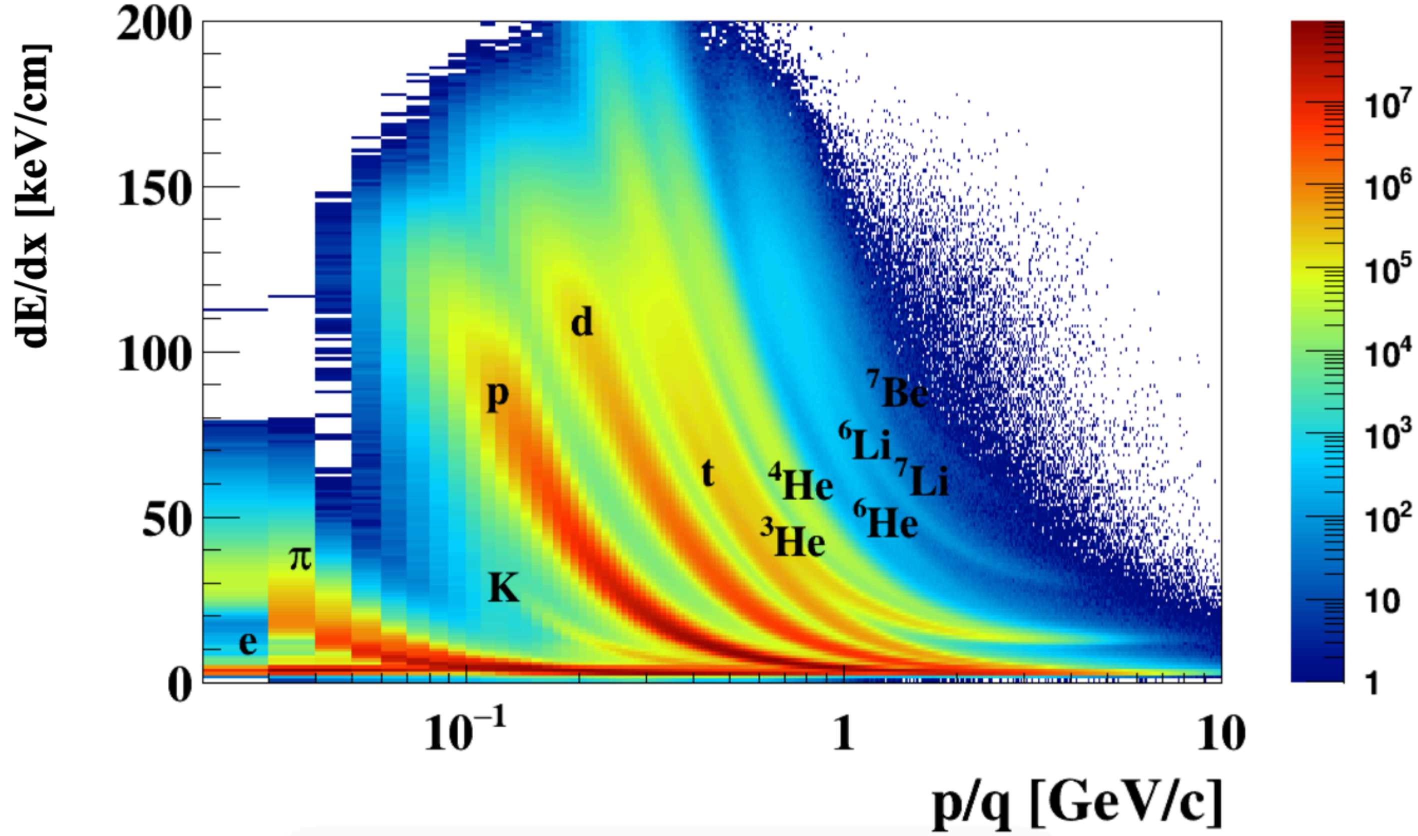
Outlook: Energy dependence

STAR	$\sqrt{s_{NN}}$	Beam E	# of Good Events
2017	54.4		1350 M
2018	27		1550 M
	7.2	26.5 (FXT)	155 M
	3.0	3.85 (FXT)	258 M
2019	19.6		582 M
	14.6		324 M
	7.7	31.2 (FXT)	50.6 M
	3.9	7.3 (FXT)	52.7 M
	3.2	4.59 (FXT)	200 M
2020	11.5		235 M
	9.2		58 M
	7.7	31.2 (FXT)	112 M
	6.2	19.5 (FXT)	118 M
	5.2	13.5 (FXT)	103 M
	4.8	11.5 (FXT)	235 M
	4.5	9.8 (FXT)	108 M
	3.9	7.3 (FXT)	117 M
	3.5	5.75 (FXT)	116 M

- **High statistics runs covering 3.0 - 54.4 GeV**
  - **Study energy dependence of hypernuclei production**
- **2019 onwards: iTPC + eTOF**
  - **Improve low momentum reach**

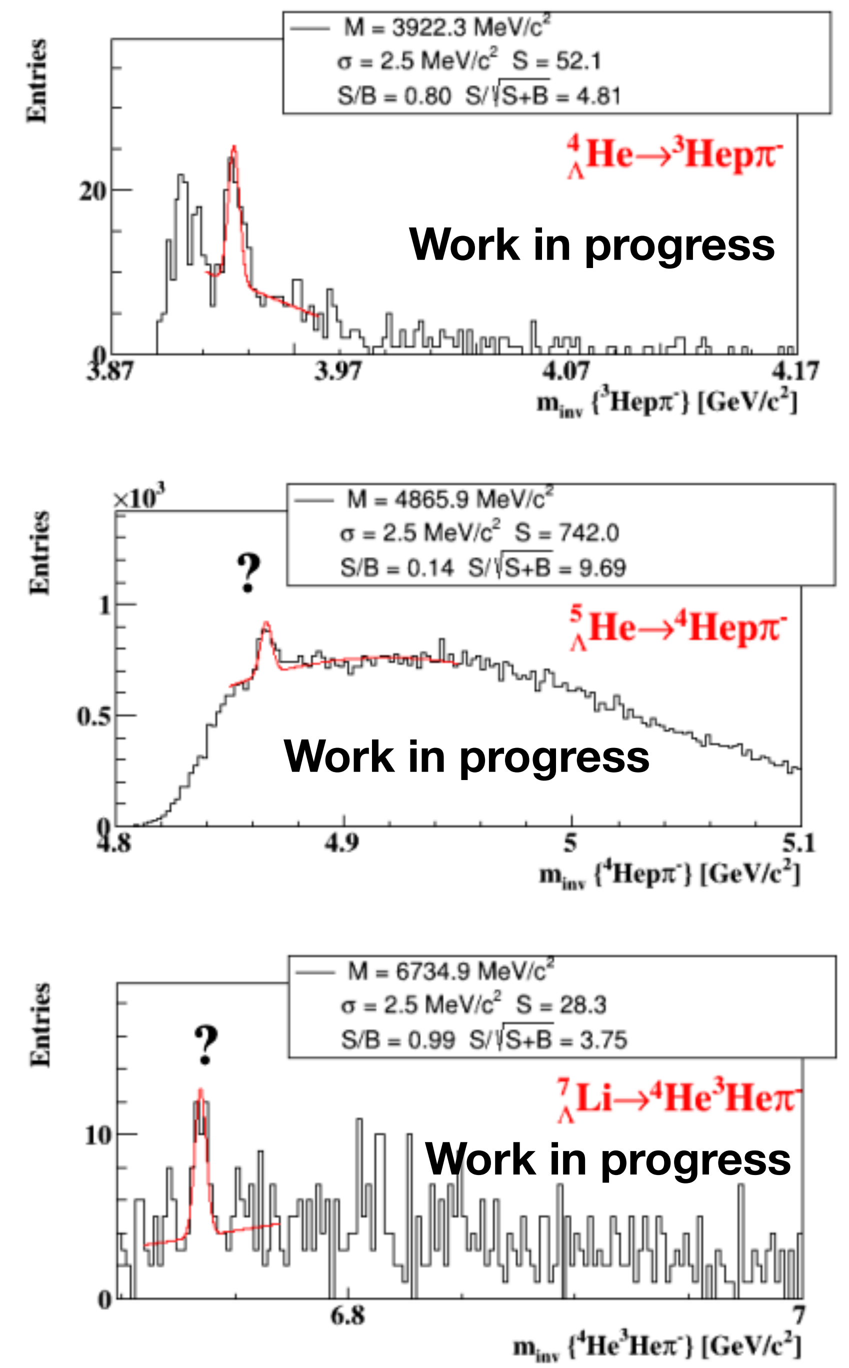
Outlook: Heavier hypernuclei

3 GeV, 2018



From Maksym Zyzak, Iouri Vassiliev et al.

3 GeV, 2018



From Maksym Zyzak, Iouri Vassiliev et al.

- **High quality dE/dx measurement from TPC**
- **At 3 GeV, heavy fragments up to ^{7}Be are seen**
    - **Opportunity to study heavier hypernuclei**

Outlook: Discovery potential for double-Λ hypernuclei

- Access $\Lambda\Lambda$ interaction through double-Λ hypernuclei

- Search for ${}^{5}_{\Lambda\Lambda}\mathrm{H}$

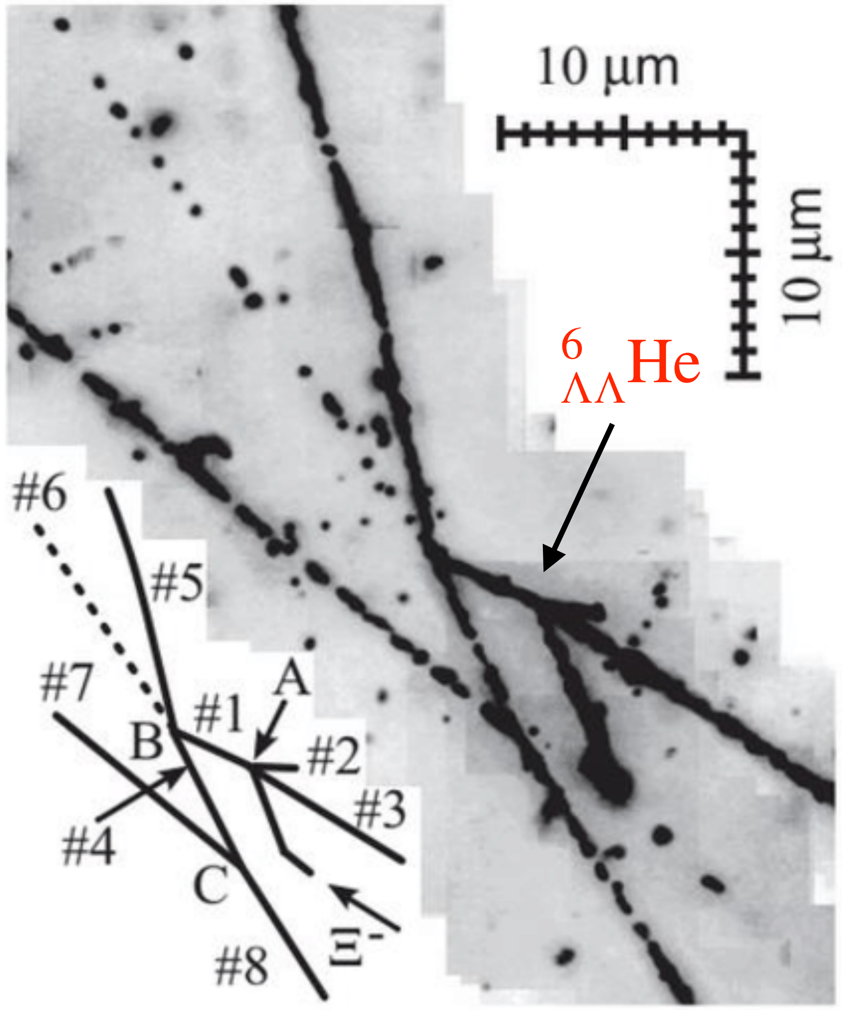
$$ {}^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^- \rightarrow {}^{4}\mathrm{He} + \mathrm{p} + \pi^- + \pi^- $$

  - Fast MC study in ideal STAR conditions:
    - 2B events at 3 GeV
    - Ideal iTPC conditions
    - Yields based on thermal model

gives an estimate of ~27 counts

- Search for ${}^{4}_{\Lambda\Lambda}\mathrm{H}$
    - Existence under debate due to low binding energy

"Nagara" event



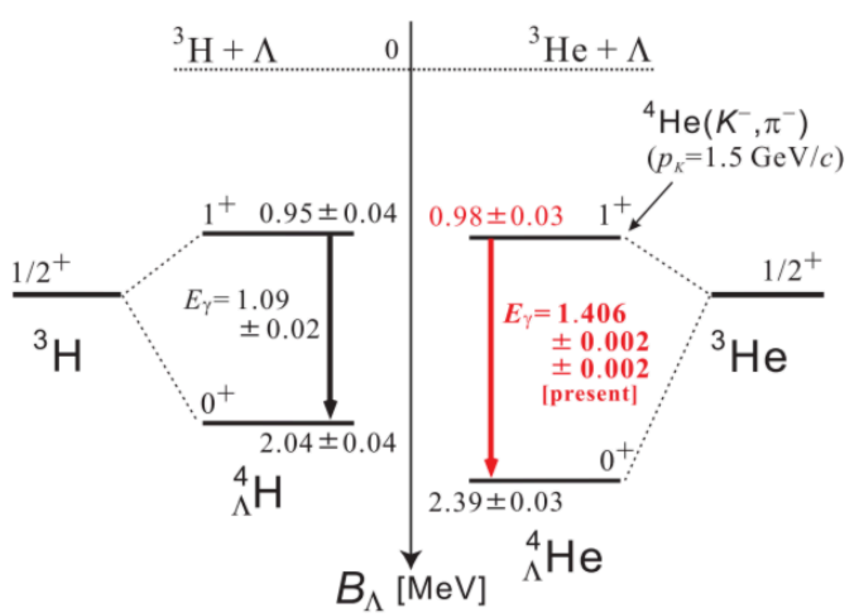
E373, PRL 87(2001)212502

Summary 2

- BES-II + FXT : $\sqrt{s_{NN}} = 3 - 20$ GeV
    - Energy dependence, heavier hypernuclei, S=2 hypernuclei
    - Binding energy, particle ratios, etc.

Moving towards a quantitative understanding of QCD matter in the high baryon density region

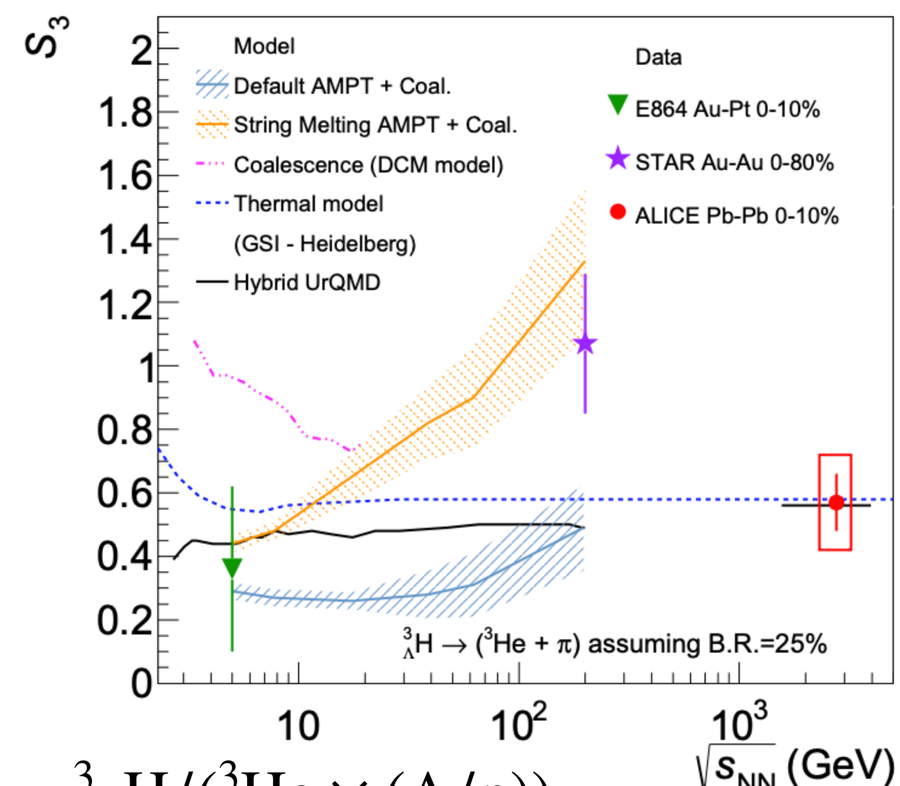
Charge symmetry breaking in hypernuclei



J-PARC E13 Collaboration, PRL 115, 222501 (2015)

Phys.Lett. B744 (2015) 352-357

Particle ratios



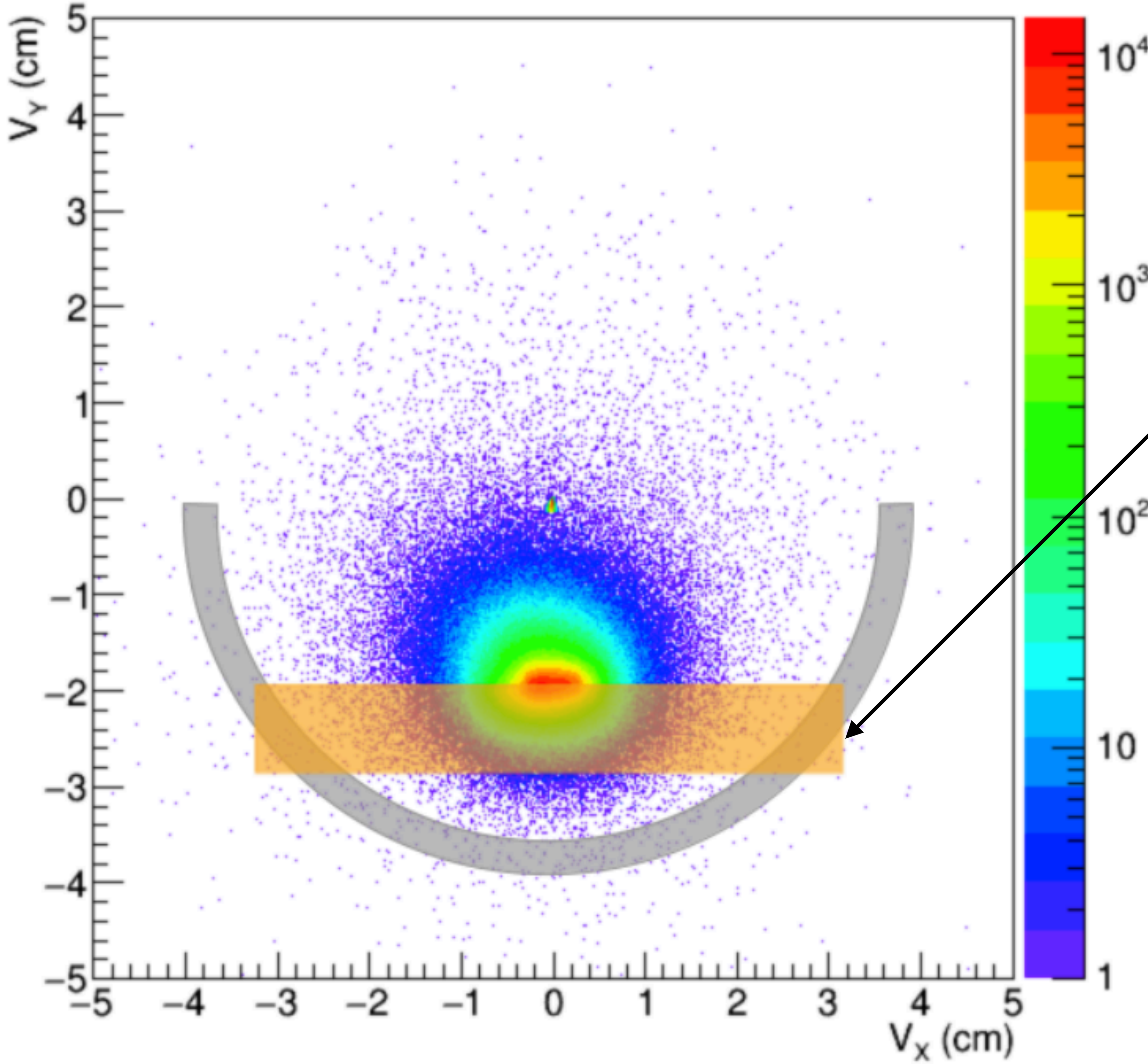
$$S_3 = {}^3_\Lambda\mathrm{H}/({}^3\mathrm{He} \times (\Lambda/\mathrm{p}))$$

PLB 754 (2016)360 (ALICE)

Thank you for listening!

Backup slides follow

Primary vertex in 3 GeV collisions



Dimensions of target

0.25mm thick

6.0cm X 1.0cm