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Study of Charge Symmetry Breaking in A = 4 hypernuclei in $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions at RHIC

Tianhao Shao (邵天浩)

For the STAR Collaboration

Fudan University

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Outline

- Motivation
- STAR fixed target program
- Particle identification and signal reconstruction
- Corrections and systematic uncertainties
- Λ binding energy
- Charge symmetry breaking
- Summary

Motivation - Experimental studies

M. Juric et. al., Nuclear Physics A 754 (2005) 3c–13c

Nuclear emulsion experiment in 1970s

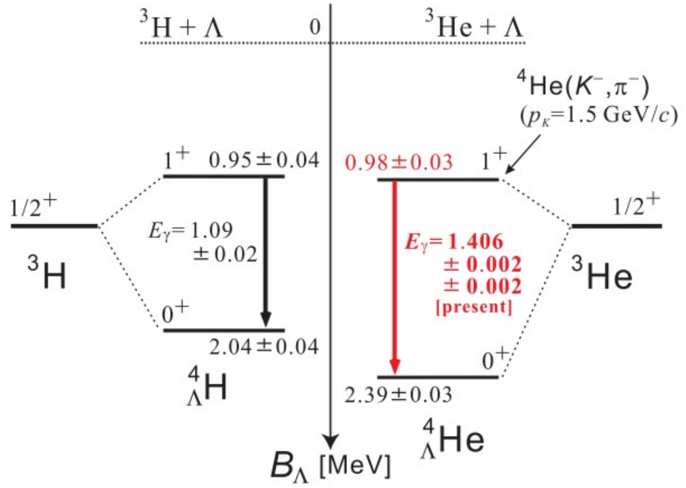
Hypernuclide	B_Λ/MeV
${}^{3}_{\Lambda}$H	0.13 ± 0.05
${}^{4}_{\Lambda}$H	2.04 ± 0.04
${}^{4}_{\Lambda}$He	2.39 ± 0.03

ΔB_Λ (g.s.) = $B_\Lambda ({}^{4}_{\Lambda}\mathrm{H})_{g.s.}$ - $B_\Lambda ({}^{4}_{\Lambda}\mathrm{He})_{g.s.}$ = 350 ± 60 keV

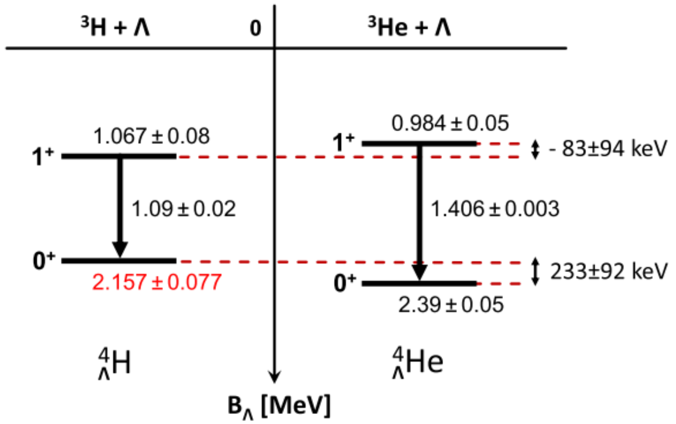
ΔB_Λ (exc) = $B_\Lambda ({}^{4}_{\Lambda}\mathrm{H})_{exc}$ - $B_\Lambda ({}^{4}_{\Lambda}\mathrm{He})_{exc}$ = 30 ± 50 keV

- The charge symmetry breaking (CSB) in A = 4 hypernuclei shows a large value in ground states while it is quite small in excited states.

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



A1 Collaboration, PRL 114, 232501 (2015), NPA 954(2016) 149-160



Motivation - Theoretical studies

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Model calculations

A. Gal, PLB 744 (2015) 352-357

Table 2: Calculated CSB contributions to $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and total values of $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and $\Delta B^4_\Lambda(1^+_{\rm exc})$, in keV, from several model calculations of the $A=4$ hypernuclei. Recall that $\Delta B^{\rm exp}_\Lambda(0^+_{\rm g.s.}) = 350 \pm 60$ keV [3].

${}^4_\Lambda$He–${}^4_\Lambda$H model	$P_\Sigma(\%)$ $0^+_{\rm g.s.}$	ΔT_{YN} $0^+_{\rm g.s.}$	ΔV_C $0^+_{\rm g.s.}$	ΔV_{YN} $0^+_{\rm g.s.}$	ΔB^4_Λ $0^+_{\rm g.s.}$	ΔB^4_Λ $1^+_{\rm exc}$
ΛNNN [9]	–	–	−42	91	49	−61
NSC97$_{\rm e}$ [10]	1.6	47	−16	44	75	−10
NSC97$_{\rm f}$ [11]	1.8				100	−10
NLO chiral [12]	2.1	55	−9	–	46	
$(\Lambda\Sigma)_{\rm e}$ [present]	0.72	39	−45	232	226	30
$(\Lambda\Sigma)_{\rm f}$ [present]	0.92	49	−46	263	266	39

keV

- Most of model calculations can not reproduce the experimental results.
- D. Gazda and A. Gal introduced the Λ-Σ^0 mixing in calculation and show that the CSB in ground and excited states are comparable.
- Need independent experiments to test.

D. Gazda and A. Gal, PRL 116, 122501 (2016)

PRL **116**, 122501 (2016) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2016

***Ab initio* Calculations of Charge Symmetry Breaking in the $A = 4$ Hypernuclei**

Daniel Gazda[1,2,3,*] and Avraham Gal[4,†]
[1]*Nuclear Physics Institute, 25068 Řež, Czech Republic*
[2]*ECT*, Villa Tambosi, 38123 Villazzano (Trento), Italy*
[3]*Department of Fundamental Physics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*
[4]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
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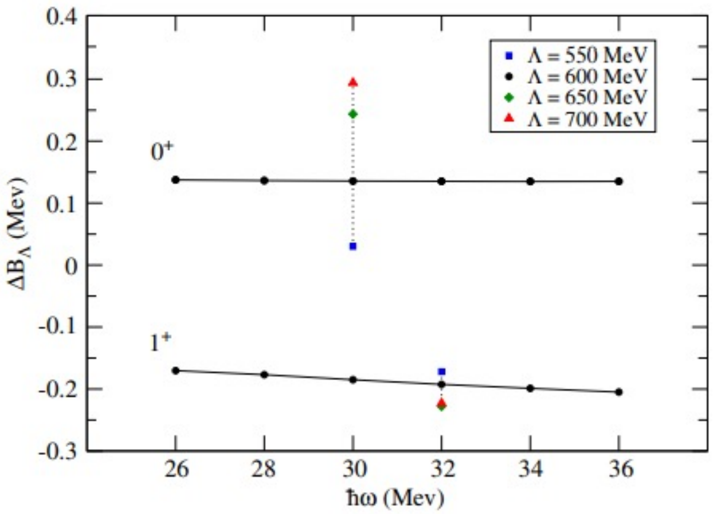
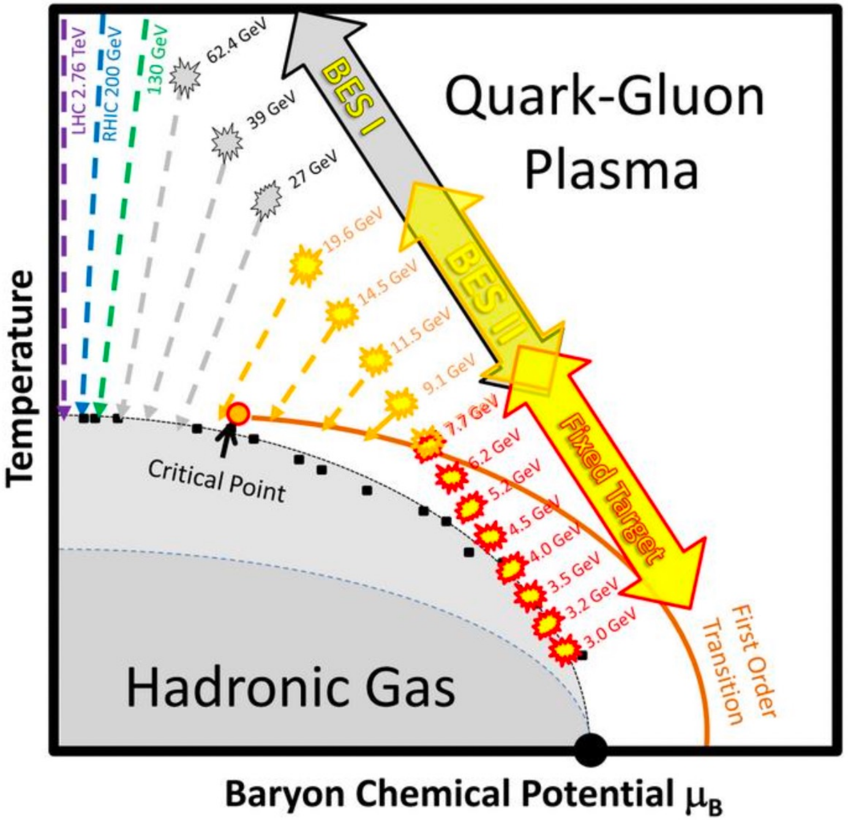
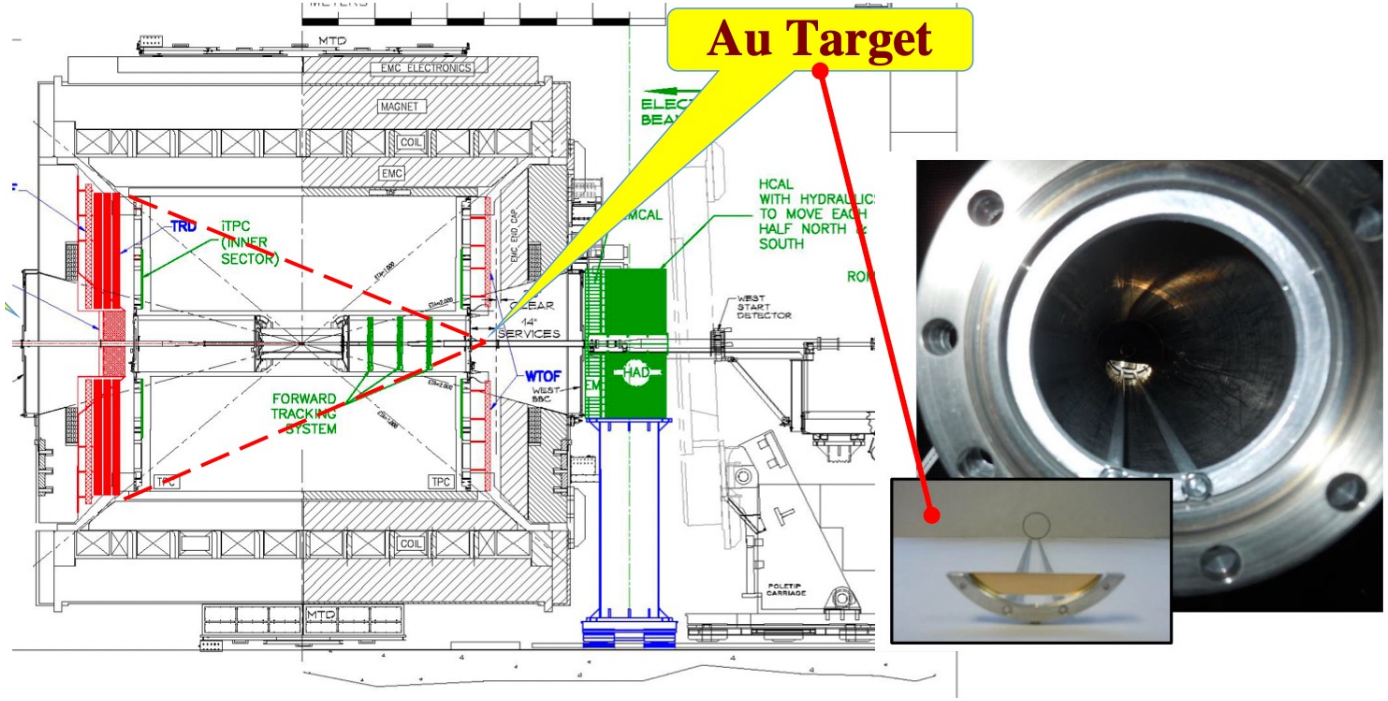


$$\overline{\Delta B}^{J=1}_\Lambda \approx -\overline{\Delta B}^{J=0}_\Lambda < 0.$$

STAR fixed target program

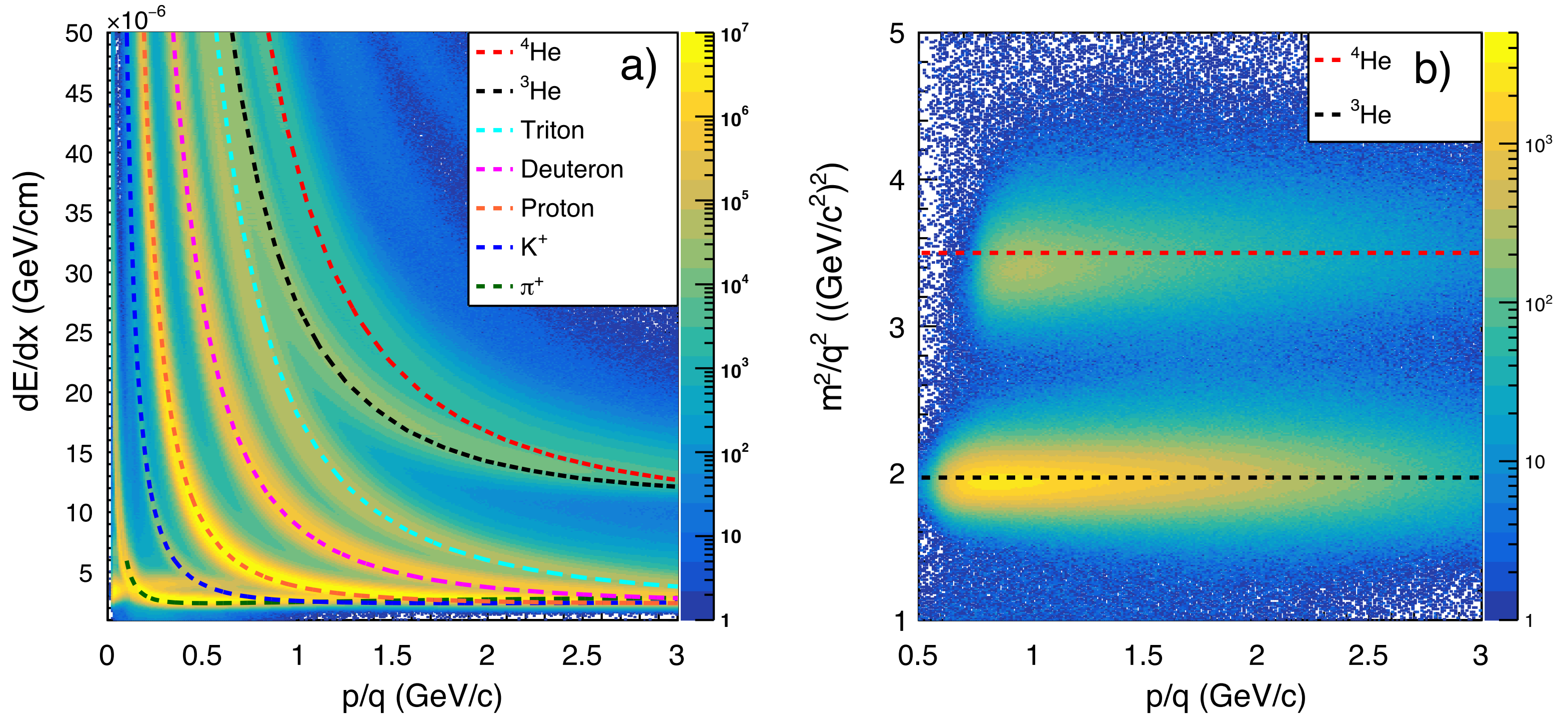


STAR Fixed Target setup



- STAR Au+Au at $\sqrt{s_{NN}}$ = 3 GeV FXT run in 2018, ~ 317M events

Charged particle identification



- Charged particle PID is based on the dE/dx from the TPC. ^{3}He and ^{4}He are also selected according to the mass square from the TOF.

${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ reconstruction

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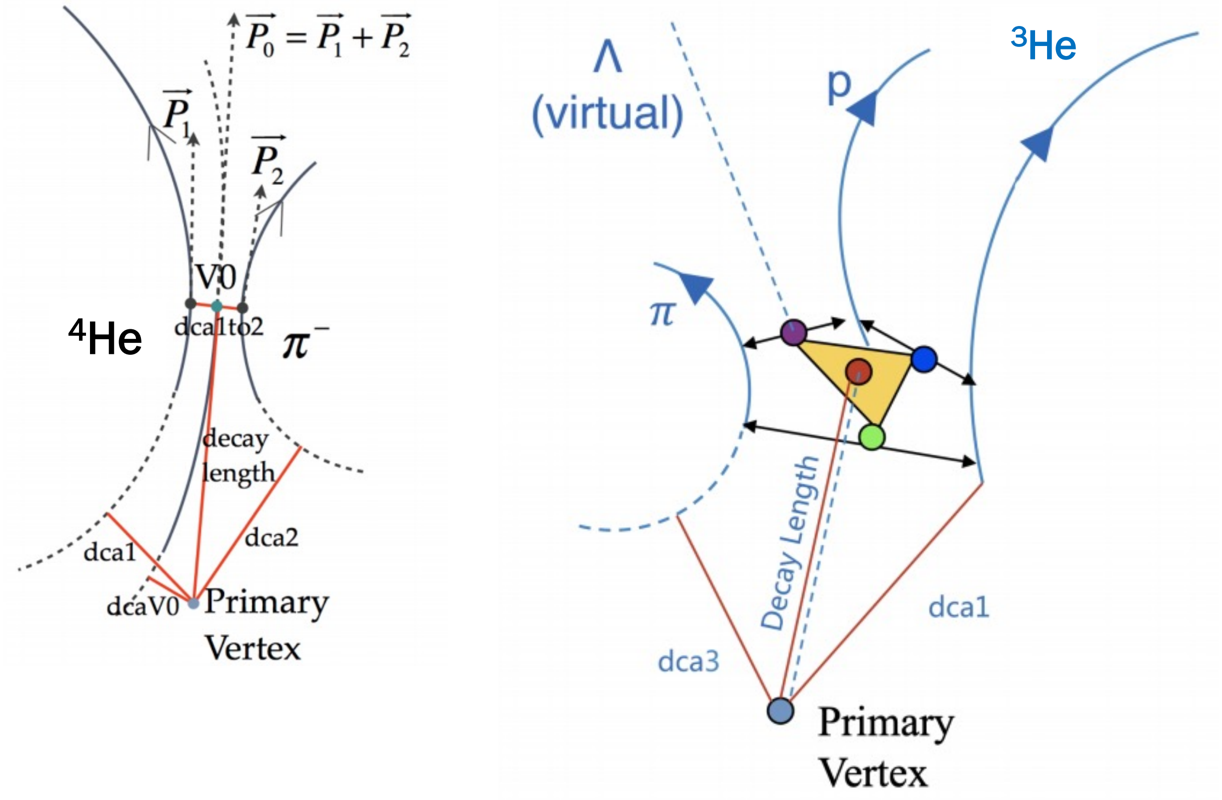
$${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$

$${}^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$$



Decay topology of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$.

Reconstructed with KFParticle package

KFParticle class describes particles by:

$$\mathbf{r} = \{\, x, y, z, p_x, p_y, p_z, E \,\}$$

State vector

$$\mathbf{C} = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_yE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

Covariance matrix

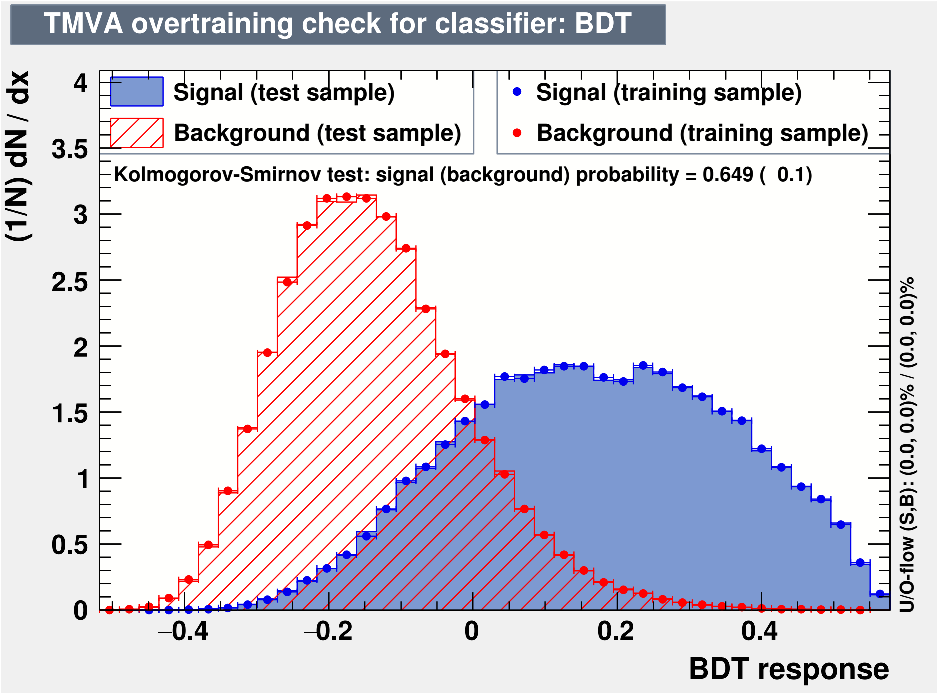
- KFParticle package shows a high quality of the reconstructed particles, high effciencies, and high signal to background ratios.

KFParticle 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

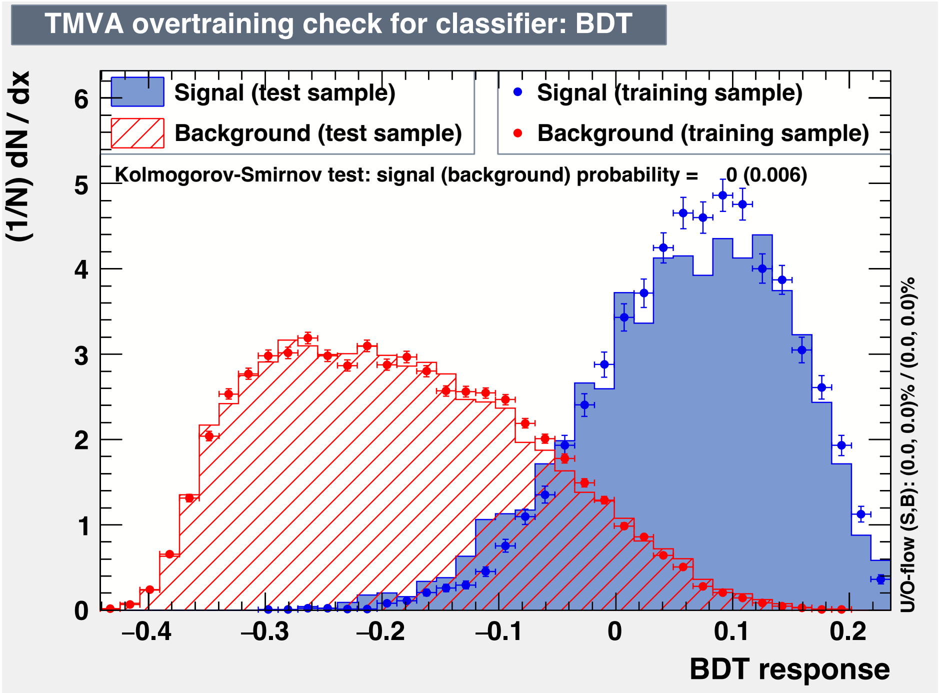
${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ reconstruction

- Using TMVA-BDT to optimize the signal.
- Training samples:
  - Signal: MC simulation
  - Background: rotate ^{4}He or ^{3}He track by 180 degrees

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

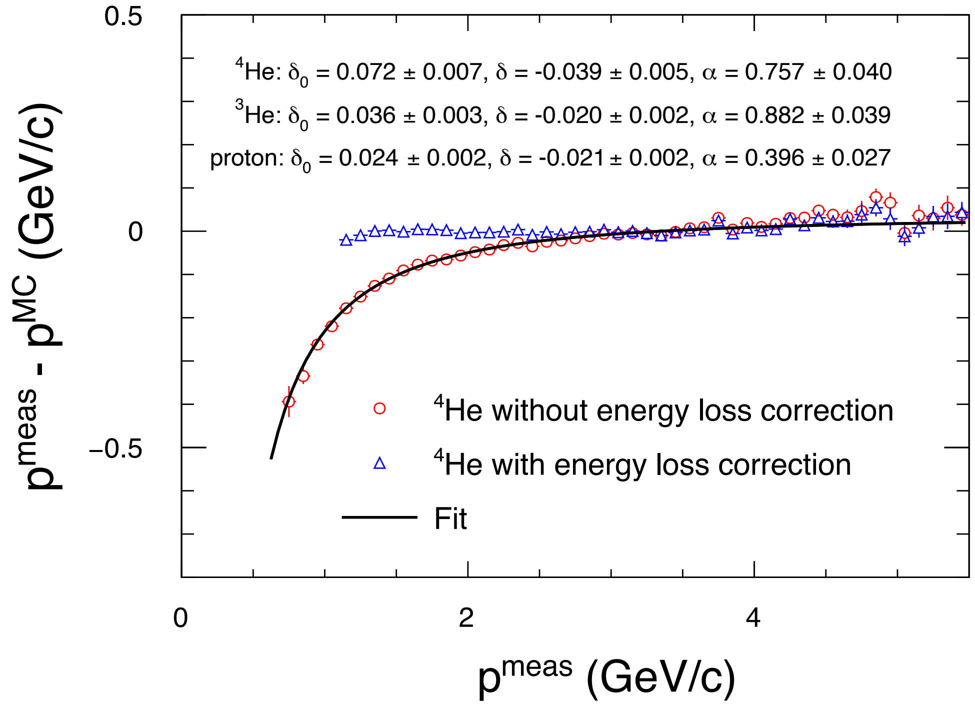


${}^{4}_{\Lambda}He$



Corrections

Energy loss correction

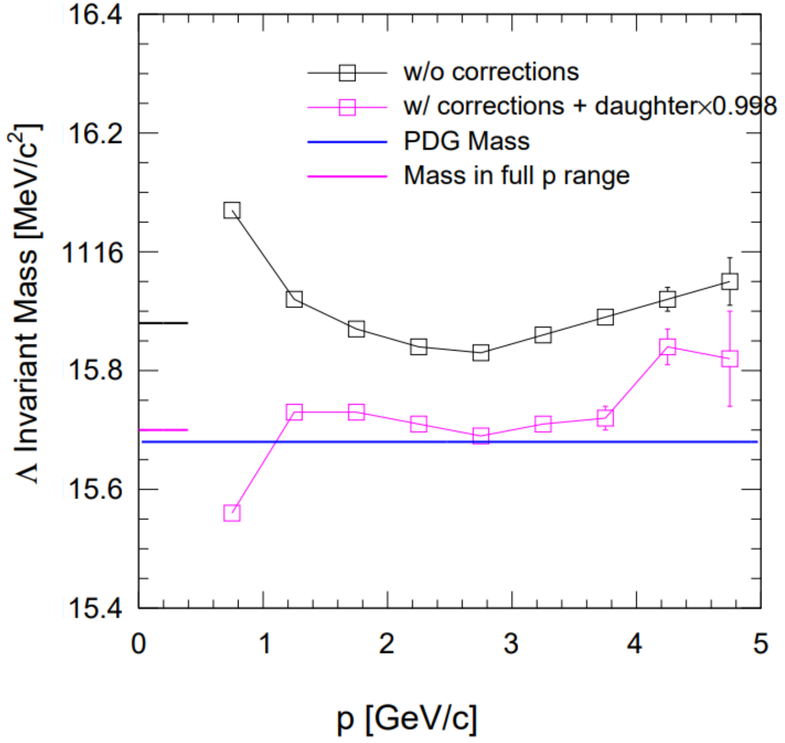


Fit function: $y = \delta_0 + \delta(1 + \frac{m^2}{x^2})^\alpha$

Correction due to magnetic field distortion

Momentum of decay daughters × 0.998

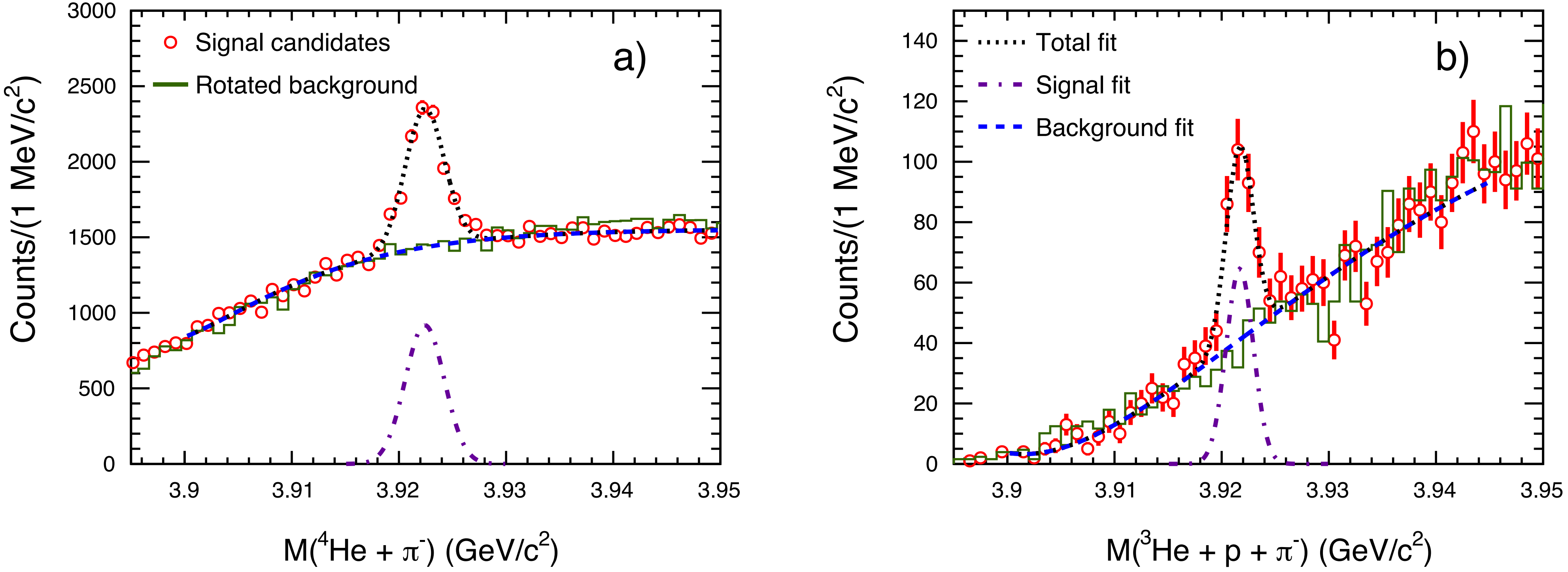
Cross check with Λ invariant mass



${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He invariant mass

STAR, arXiv:XXXX

The invariant mass distributions of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He with corrections.



- Background : rotate ^{4}He or ^{3}He track by 180 degrees
- Fit function :

$$f(x)=\frac{A}{\sqrt{2\pi}\sigma}exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)+p_0exp\left(-\frac{x-p_1}{p_2}\right)+p_3exp\left(-\frac{x-p_1}{p_4}\right)+p_5$$

- $m({}^{4}_{\Lambda}H)$ = 3922.38 ± 0.06(stat.) ± 0.14(syst.) MeV/c^2
- $m({}^{4}_{\Lambda}He)$ = 3921.69 ± 0.13(stat.) ± 0.12(syst.) MeV/c^2

Systematic uncertainties

Systematic uncertainties for Λ binding energies.

Error source	${}^{4}_{\Lambda}\mathrm{H}$ Systematic error (MeV)	${}^{4}_{\Lambda}\mathrm{He}$ Systematic error (MeV)
Momentum scaling factor	0.11	0.11
Energy loss correction	0.08	0.05
BDT cut	0.03	0.01
Total	0.14	0.12

- Systematic uncertainties mainly come from momentum corrections.
- As tested in the MC simulation, the systematic uncertainty from the momentum scaling factor can be mostly canceled when we calculate the binding energy difference between ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$.

Λ binding energy

- Calculate the Λ binding energy according to the masses of hypernuclei and their constituents:

$$B_\Lambda = (M_\Lambda + M_{core} - M_{hypernucleus})c^2$$

M_{core} = M(Triton) or M(He3)

	Λ	Triton	He3
Mass (MeV/c^2)	1115.68	2808.92	2808.39

- B_Λ (${}^4_\Lambda$H) = 2.22 ± 0.06(stat.) ± 0.14(syst.) MeV
- B_Λ (${}^4_\Lambda$He) = 2.38 ± 0.13(stat.) ± 0.12(syst.) MeV

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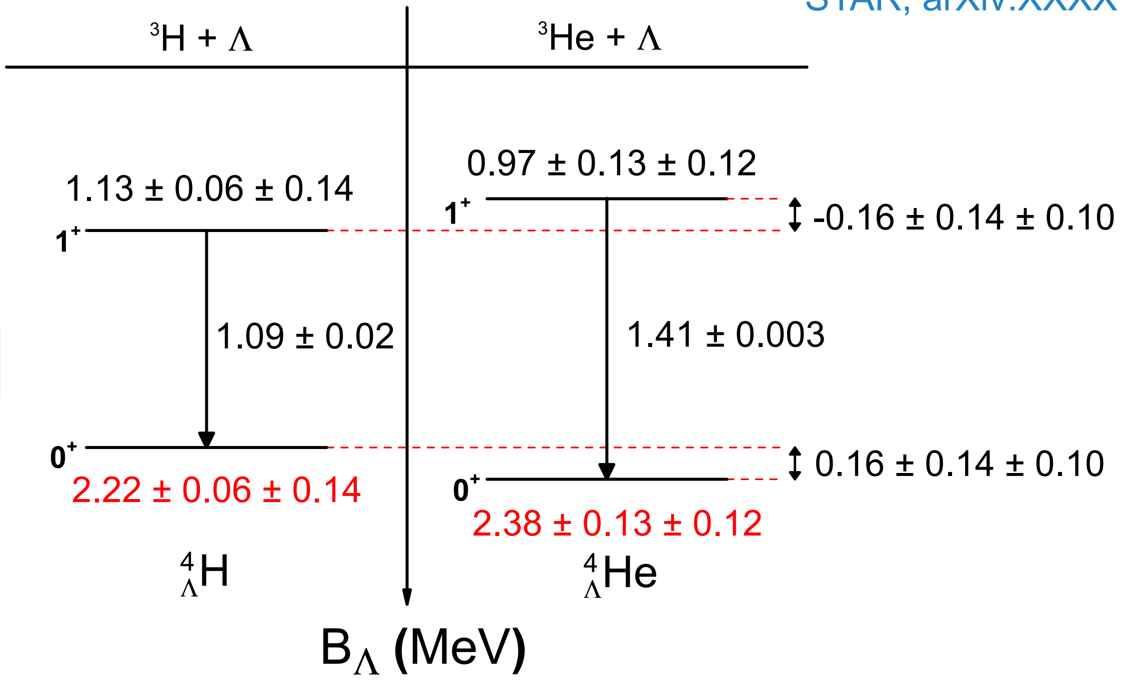
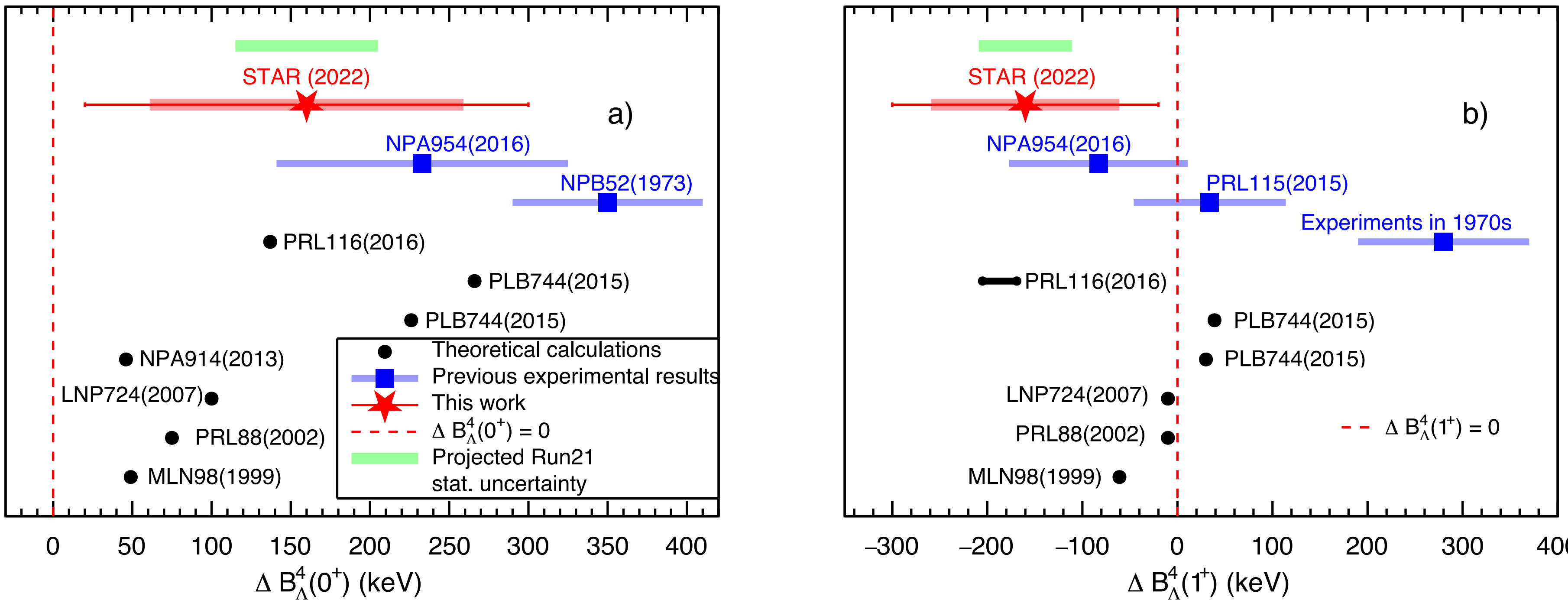


Energy level schemes of ${}^4_\Lambda$H and ${}^4_\Lambda$He in terms of Λ binding energies. The ground states binding energies are from this analysis. The values for excited states are obtained from the γ-ray transition energies.

M. Bedjidian et al., PLB 62, 467-470
J-PARC E13 Collaboration, PRL 115, 222501 (2015)

Charge symmetry breaking

STAR, arXiv:XXXX



- The Λ binding energy difference between ${}^4_\Lambda\mathrm{H}$ and ${}^4_\Lambda\mathrm{He}$ in ground states (left figure) and in excited states (right figure). The green shadows are projected statistical uncertainties obtained according to the high statistics run 2021 3 GeV data (~ 2 billion events).
- $\Delta B_\Lambda(0^+) = 160 \pm 140(\text{stat.}) \pm 100(\text{syst.})$ keV
- $\Delta B_\Lambda(1^+) = -160 \pm 140(\text{stat.}) \pm 100(\text{syst.})$ keV
- Charge symmetry breaking effects in ground states and excited states are comparable.

Summary

- Invariant masses and Λ binding energies of ${}^4_\Lambda H$ and ${}^4_\Lambda He$ have been measured in 3 GeV Au+Au collisions :

$m({}^4_\Lambda\mathrm{H})$ = 3922.38±0.06(stat.) ±0.14(syst.) MeV/c^2, B_Λ (${}^4_\Lambda\mathrm{H}$) = 2.22±0.06(stat.) ±0.14(syst.) MeV

$m({}^4_\Lambda\mathrm{He})$ = 3921.69±0.13(stat.) ±0.12(syst.) MeV/c^2, B_Λ (${}^4_\Lambda\mathrm{He}$) = 2.38±0.13(stat.) ±0.12(syst.) MeV

- To study the charge symmetry breaking in A = 4 hypernuclei, the Λ binding energy differences between ${}^4_\Lambda H$ and ${}^4_\Lambda He$ in ground states and excited states have been measured/extracted :

$\Delta B_\Lambda(0^+)$ = 0.16 ± 0.14(stat.) ± 0.10(syst.) MeV

$\Delta B_\Lambda(1^+)$ = -0.16 ± 0.14(stat.) ± 0.10(syst.) keV

- Our results show that the charge symmetry breaking effect in excited states is negative, and the magnitude is comparable to the ground states.

Acknowledgement:

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