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

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Outline

- Motivation
- Data analysis
- Corrections and systematic uncertainties
- Λ binding energy results
- 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

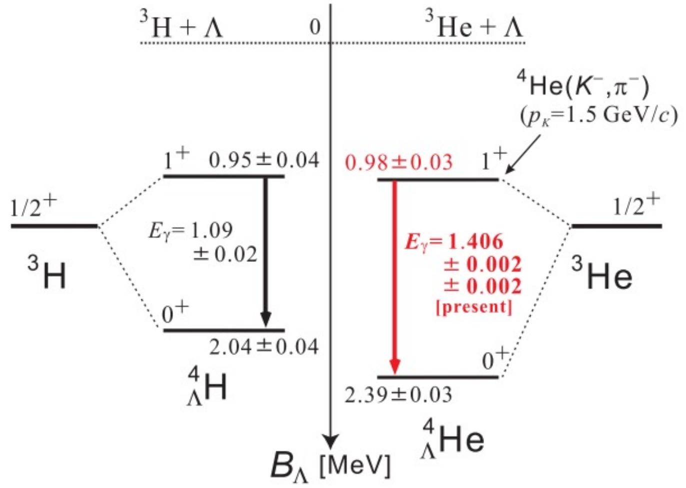
ΔB_Λ (g.s.) = $B_\Lambda ({}^{4}_{\Lambda}H)_{g.s.} - B_\Lambda ({}^{4}_{\Lambda}He)_{g.s.}$ = 350 ± 60 keV

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

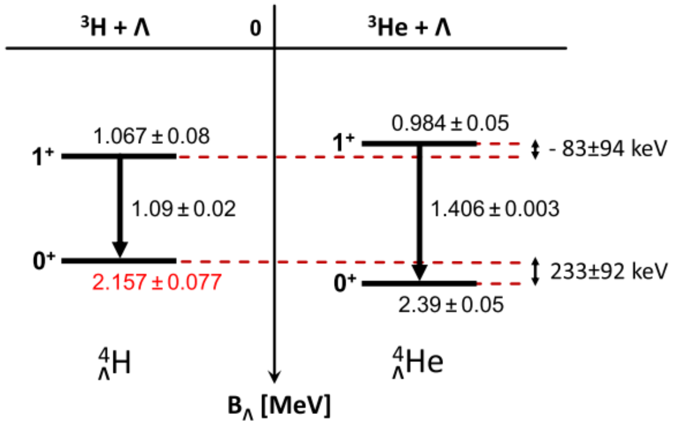
CSB in nucleus system: B(^{3}He) – B(t) ~ 67 keV
(Coulomb removed)

- 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)

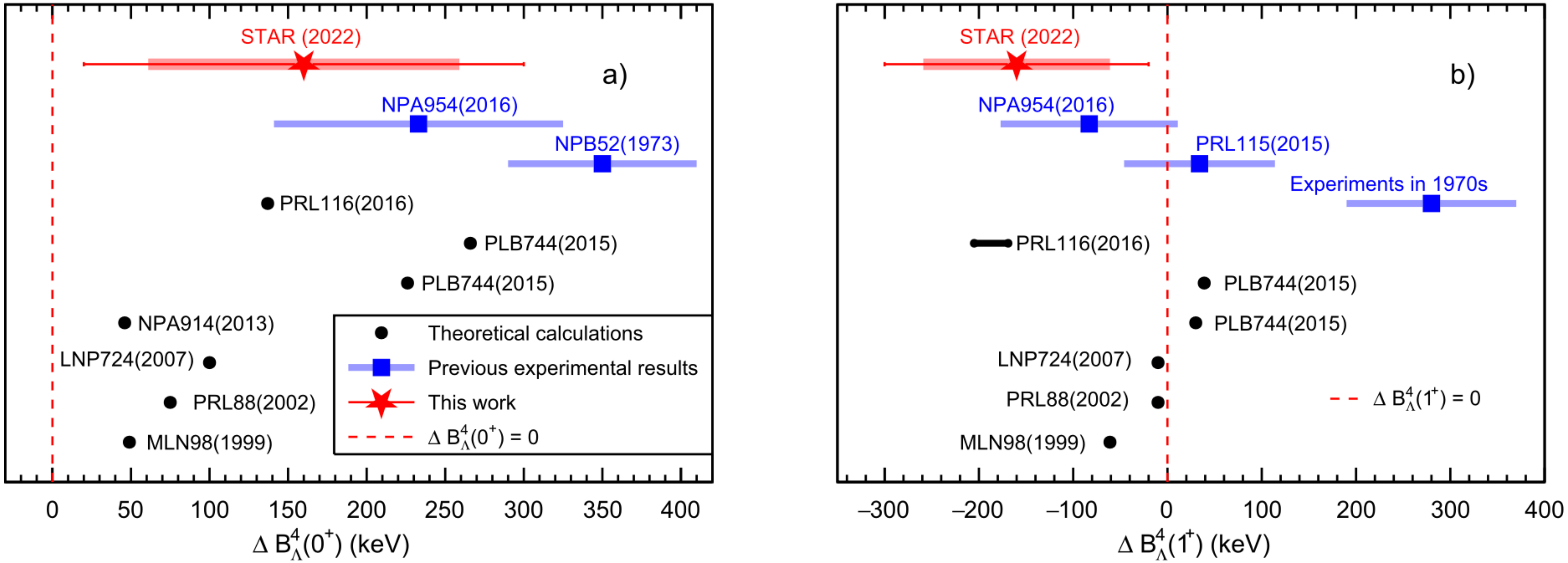


A1 Collaboration, PRL 114, 232501 (2015), NPA 954(2016) 149-160



Previous STAR measurement

- Results from run18 Au+Au at 3GeV show that CSB in ground states and excited states maybe similar in magnitude with opposite sign. However, the statistical uncertainties are large.
- Valuable to continue this study with much larger statistics from run 21.



STAR, PLB 834 (2022) 137449

Motivation - Theoretical studies

Model calculations

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

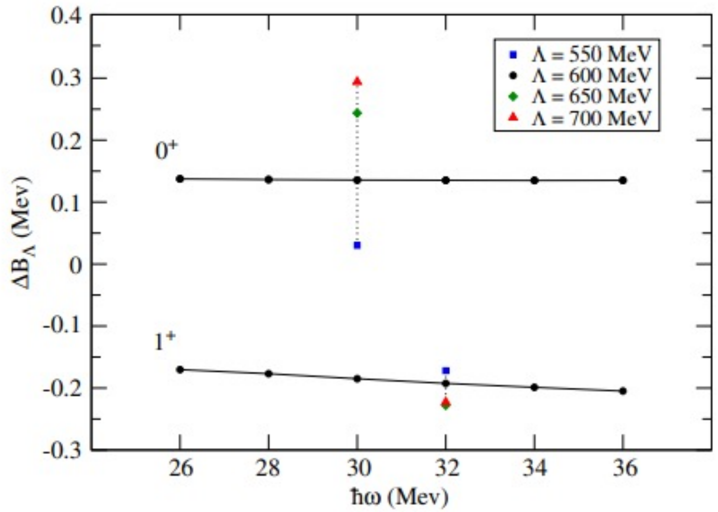
Table 2: Calculated CSB contributions to $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and total values of $\Delta B^4_\Lambda(0^+_{\rm g.s.})$ and $\Delta B^4_\Lambda(1^+_{\rm exc})$, in keV, from several model calculations of the $A = 4$ hypernuclei. Recall that $\Delta B^{\rm exp}_\Lambda(0^+_{\rm g.s.}) = 350 \pm 60$ 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$_e$ [10]	1.6	47	−16	44	75	−10
NSC97$_f$ [11]	1.8				100	−10
NLO chiral [12]	2.1	55	−9	–	46	
$(\Lambda\Sigma)_e$ [present]	0.72	39	−45	232	226	30
$(\Lambda\Sigma)_f$ [present]	0.92	49	−46	263	266	39

keV

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

ab-initio NCSM with CSB Λ-Σ^0 mixing:



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

D. Gazda and A. Gal, NPA 954 (2016) 161-175

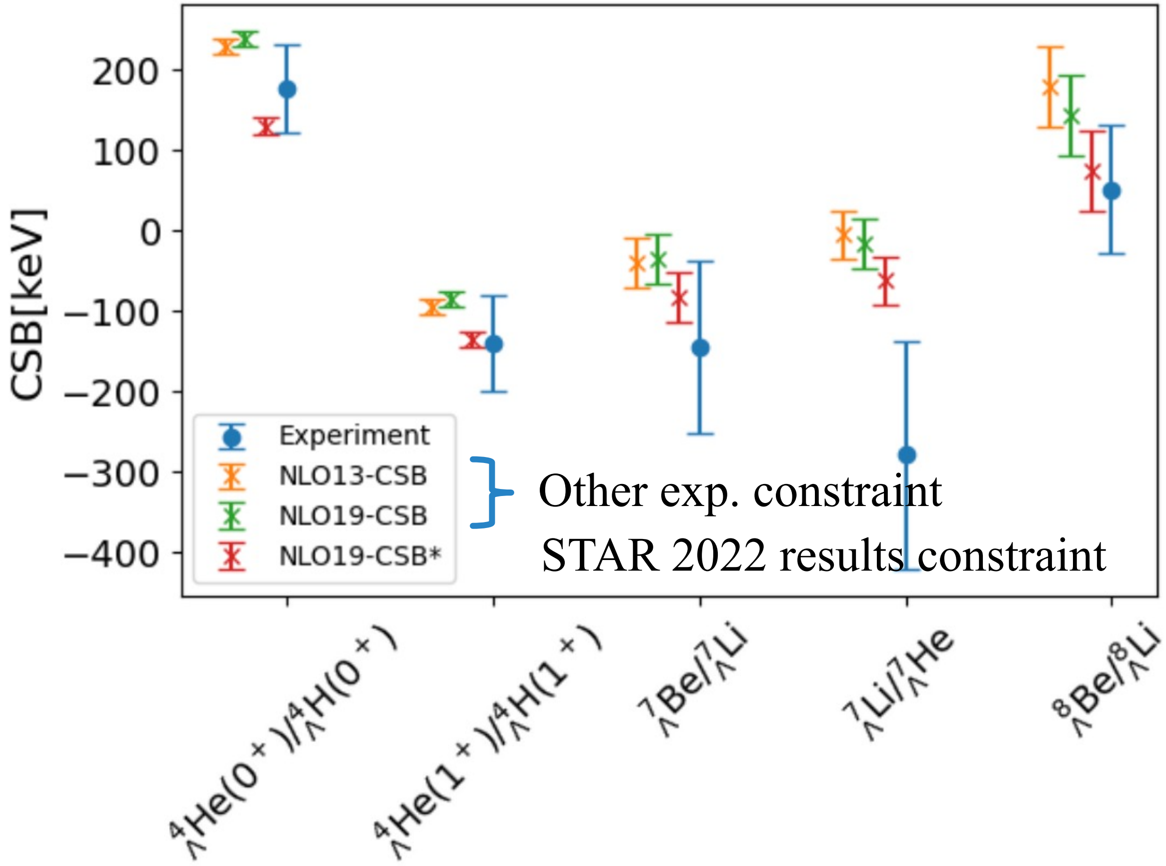
Consider DvH OPE:

$$\Delta B^{J=0}_\Lambda \approx 175 \pm 40\,\text{keV}, \quad \Delta B^{J=1}_\Lambda \approx -50 \pm 10\,\text{keV},$$

- Most of model calculations can not reproduce the experiments.
- Introducing the Λ-Σ^0 mixing in calculation shows that the CSB in ground and excited states are comparable. However, the value in excited states becomes smaller if DvH OPE is considered.
- Need more precise experiments to test.

Motivation - Theoretical studies

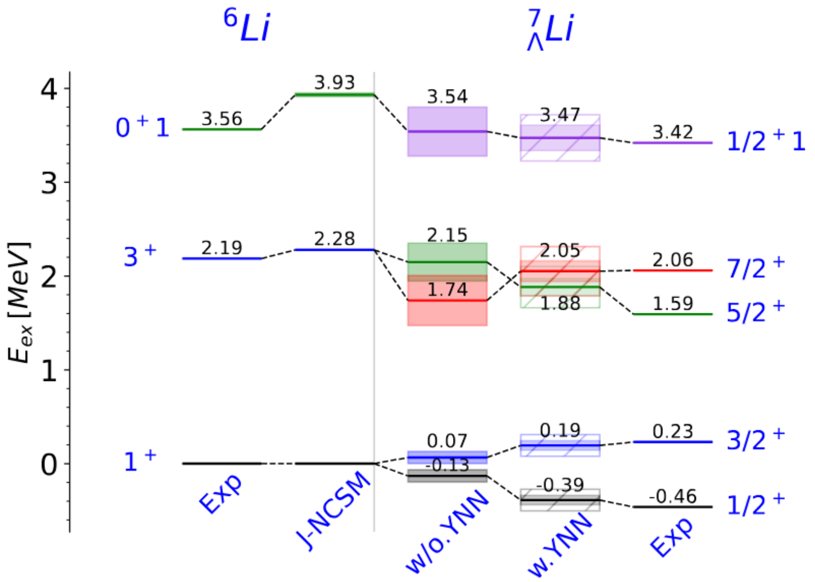
- The CSB in A = 4 hypernuclei can be used to constrain the YN and YNN interactions.



H. Le et. al., PRC 107 (2023) 2, 024002

J. Haidenbauer et. al., arXiv:2508.05243v1

H. Le et. al., PRL 134 (2025) 7, 072502

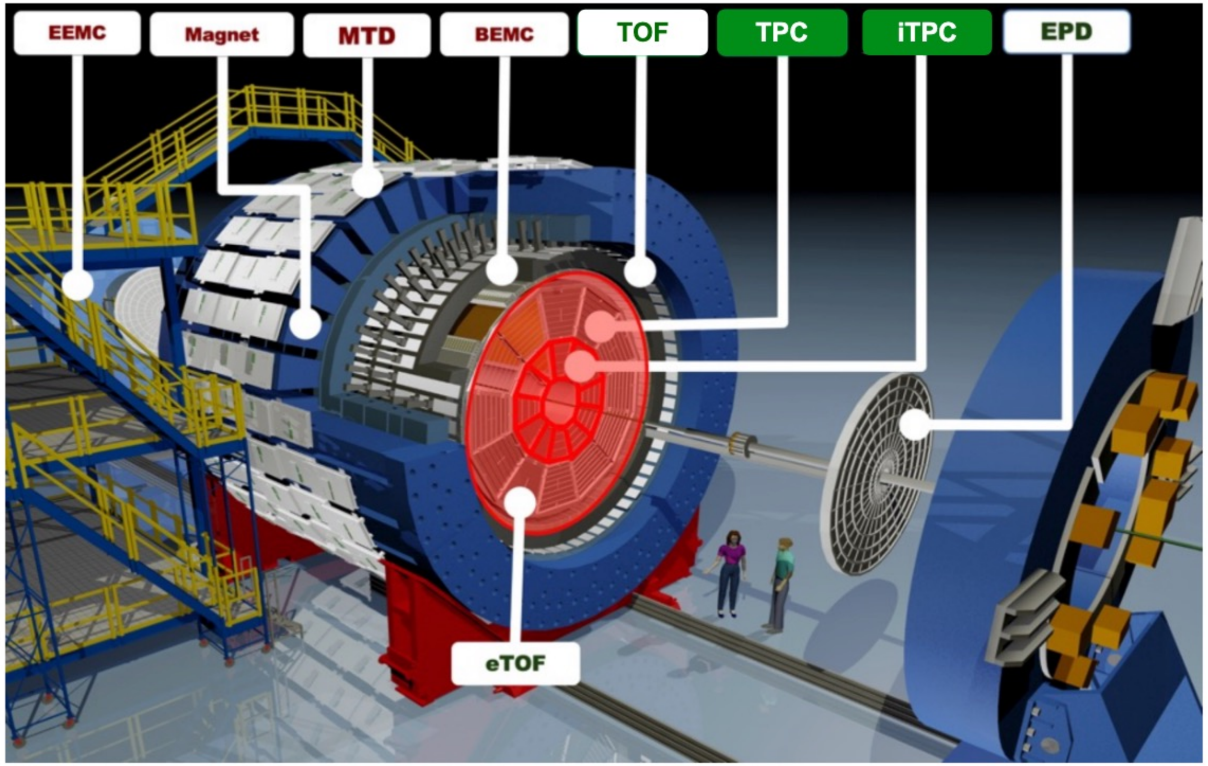


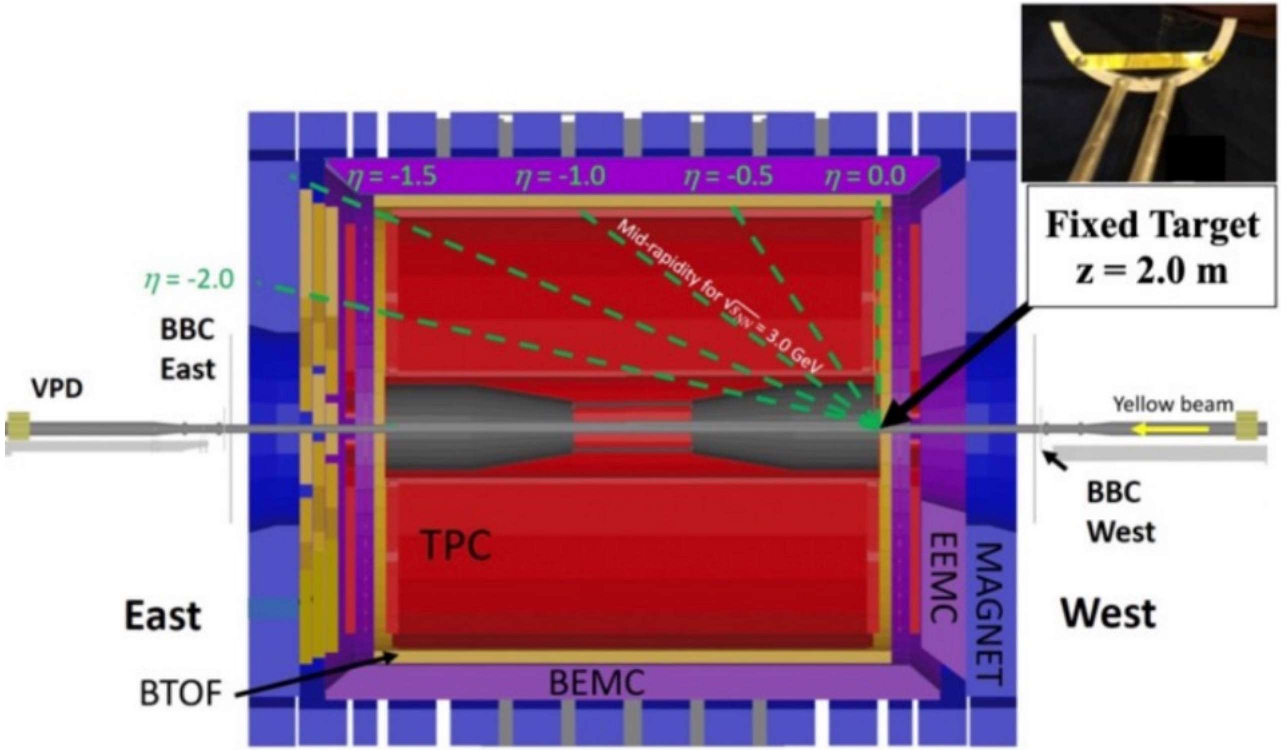
YNN constrained by A = 4 hypernuclei

STAR fixed target program

- STAR Au+Au at $\sqrt{s_{NN}} = 3$ GeV in fixed-target mode
- run18 (~300M events) and run21 (~2B events)

STAR Fixed Target setup

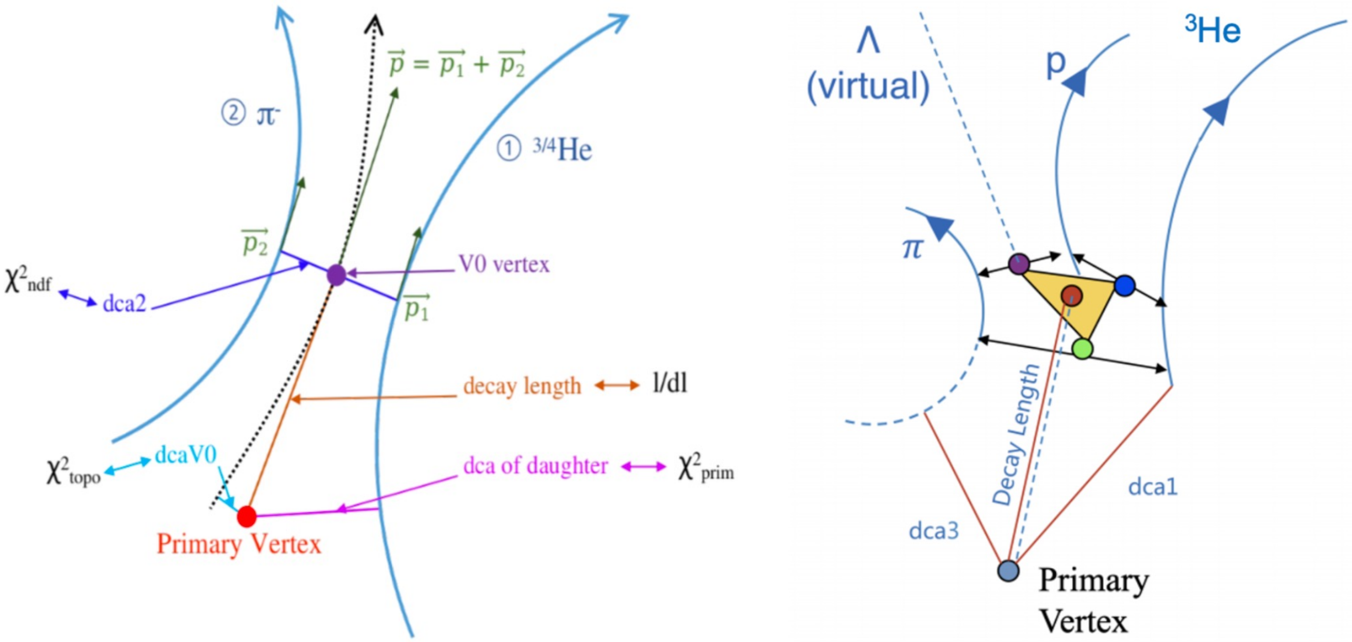




${}^4_\Lambda$H and ${}^4_\Lambda$He reconstruction

STAR ☆

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



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

Reconstructed with KFParticle package

KFParticle class describes particles by:

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

State vector

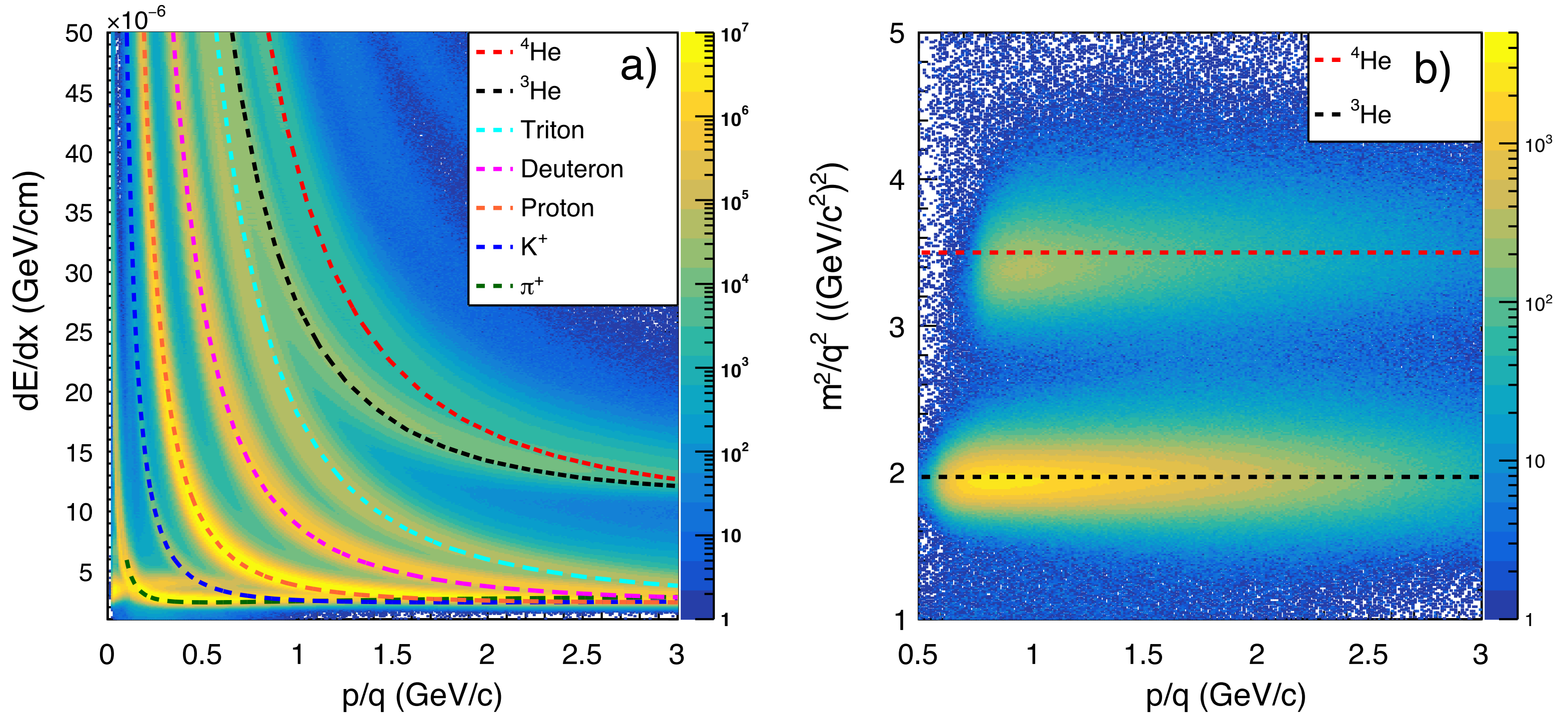
$$\mathbf{C} = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x}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

Covariance matrix

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

X. Ju, et. al., NST 34 (2023) 10, 158

Charged particle identification

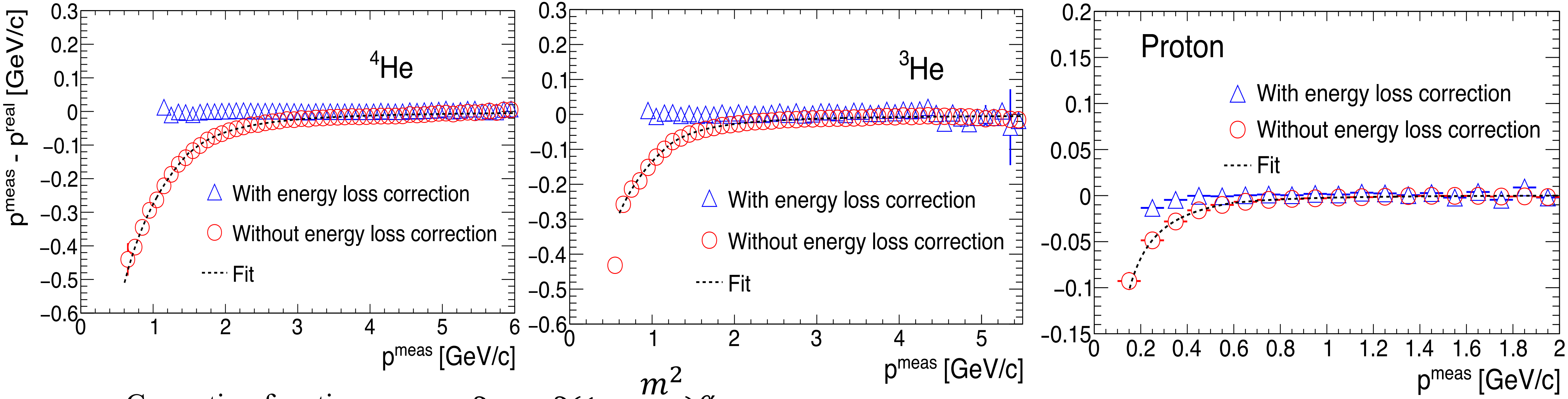


- Charged particle PID is based on the dE/dx from the TPC. ^{3}He and ^{4}He are also selected according to the mass square from the TOF.

Corrections

Corrections from magnetic field, and energy loss in detector system

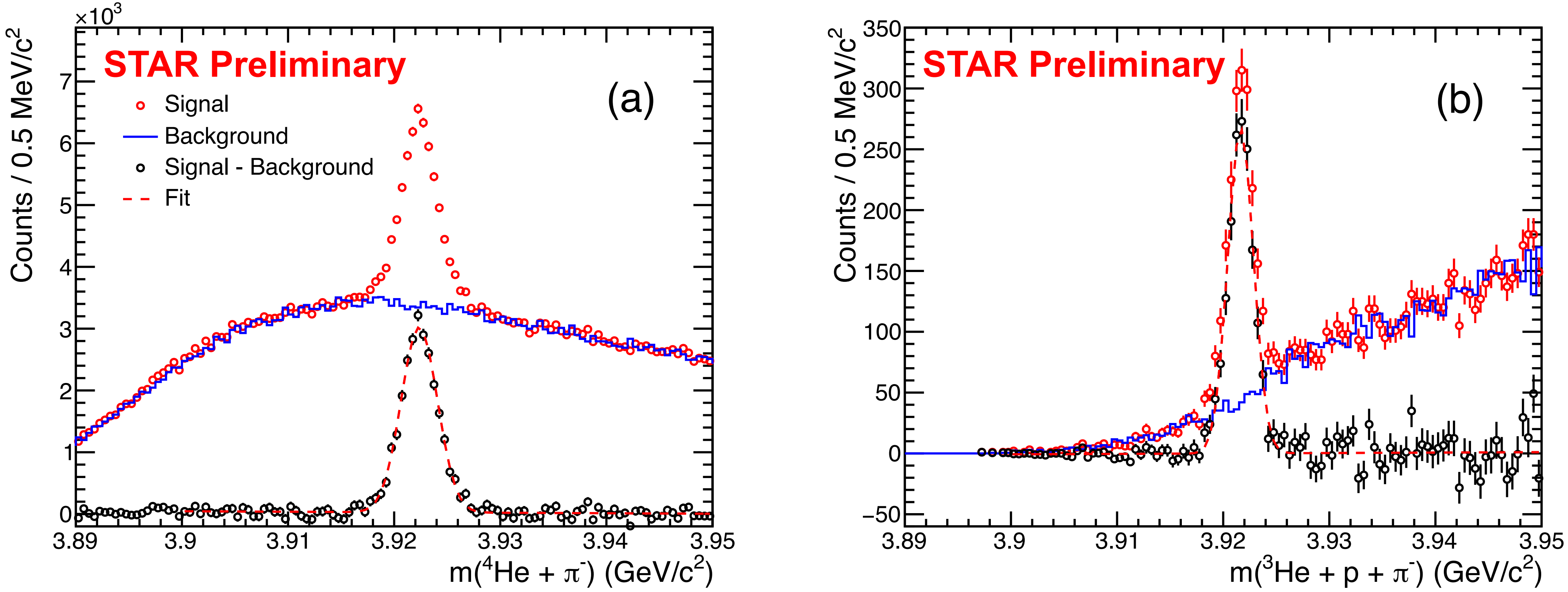
- A 0.2% correction is applied to particle momenta due to the imperfect magnetic field measurement.
- All tracks are assumed to be pions and corrected their energy loss in official tracking algorithm.
- Simulate the tracks in virtual STAR detector constructed by GEANT. Compare the momentum difference between MC input and detector output.



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

Invariant mass measurements

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



- Background : rotate ^{4}He or ^{3}He track by random degrees
- Fit function : $f(x) = \frac{A}{\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) + p_0 x + p_1$
- $m({}^{4}_{\Lambda}\mathrm{H}) = 3922.36 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})\ \mathrm{MeV}/c^2$
- $m({}^{4}_{\Lambda}\mathrm{He}) = 3921.68 \pm 0.05(\text{stat.}) \pm 0.04(\text{syst.})\ \mathrm{MeV}/c^2$

Λ binding energy

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

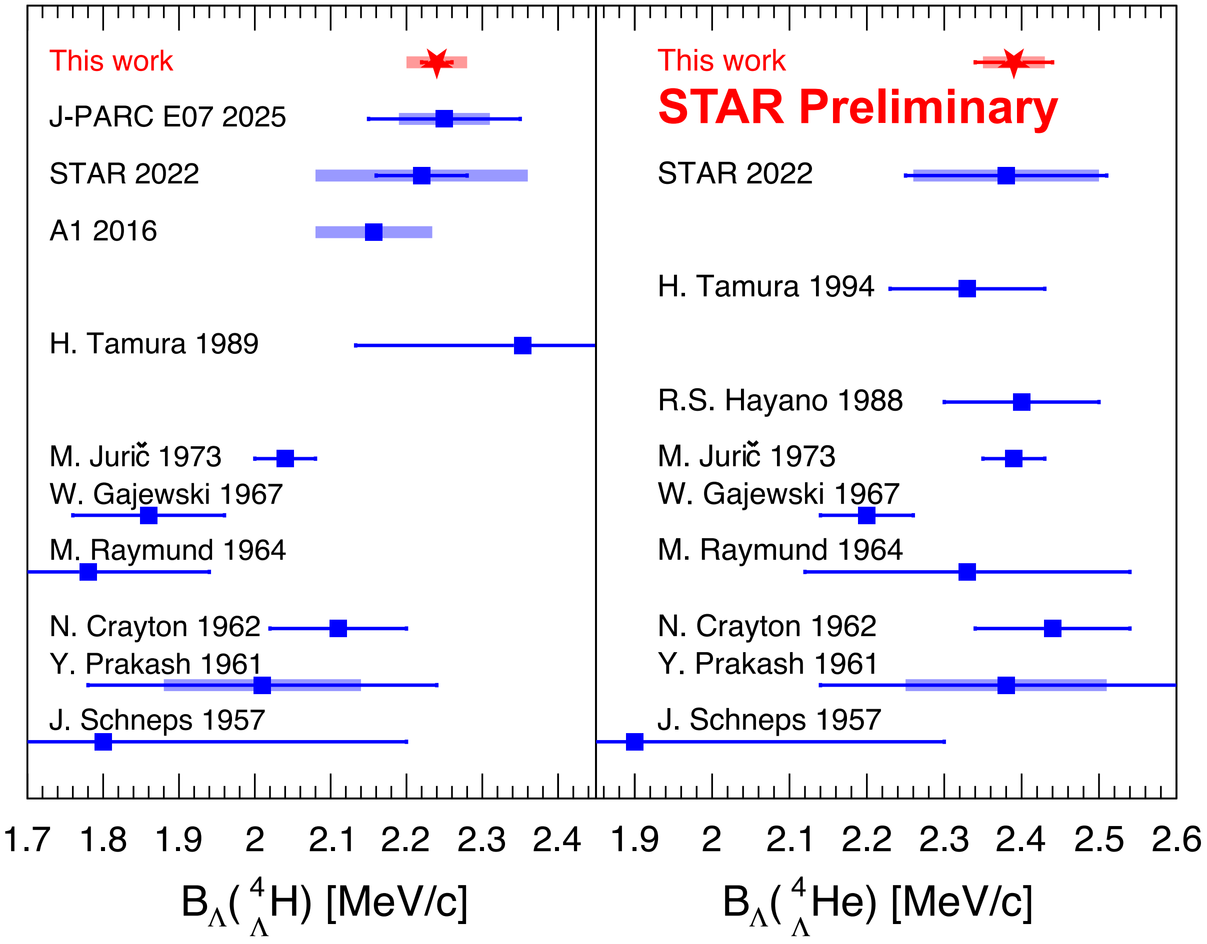
$$B_\Lambda = (M_\Lambda + M_{core} - M_{hypernucleus})c^2$$

$$M_{\text{core}} = M(\text{Triton}) \text{ or } M(^3\text{He})$$

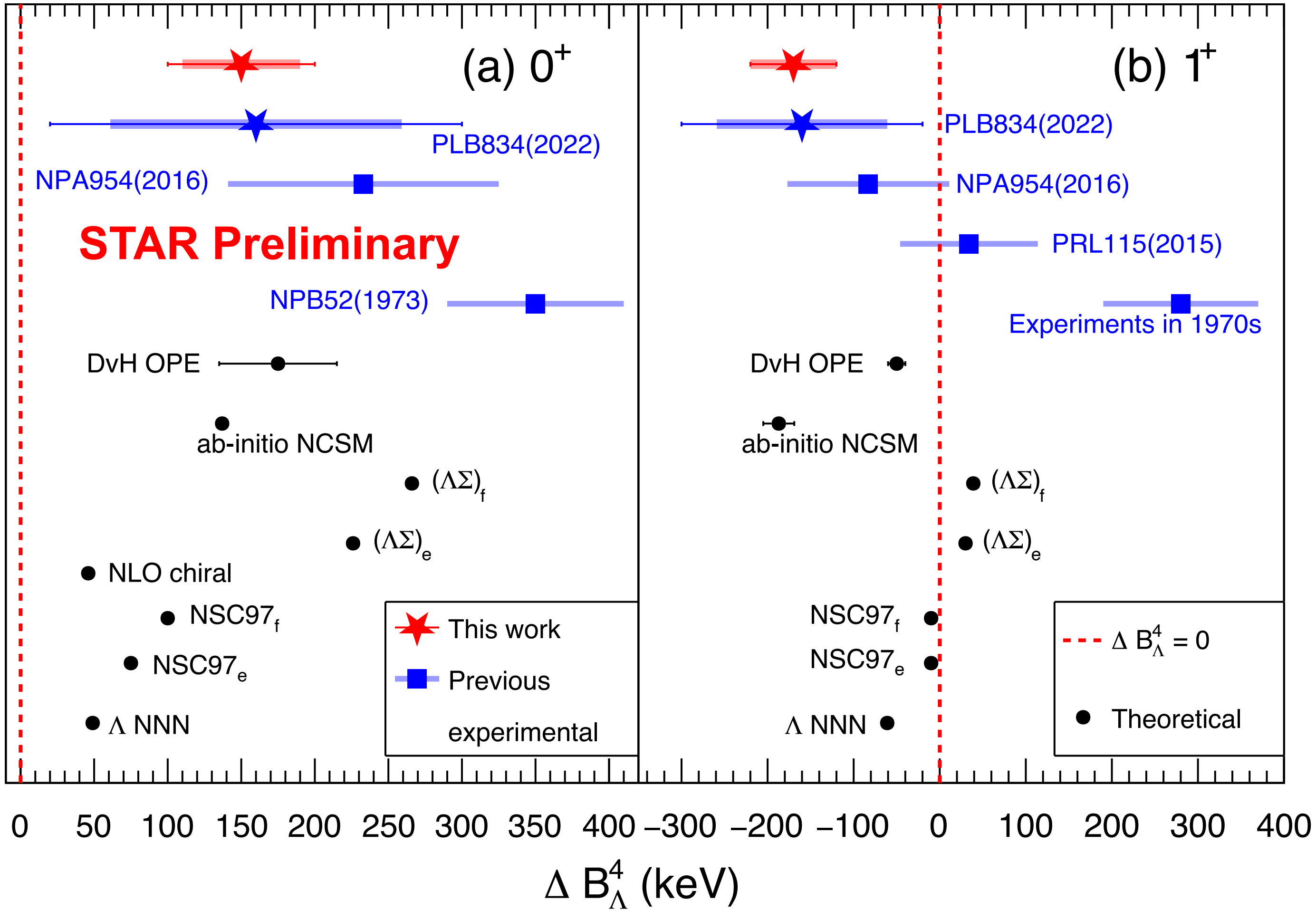
	Λ	Triton	^{3}He
Mass (MeV/c^2)	1115.68	2808.92	2808.39

- $B_\Lambda(^4_\Lambda\text{H}) = 2.24 \pm 0.02(\text{stat.}) \pm 0.05(\text{syst.})$ MeV
- $B_\Lambda(^4_\Lambda\text{He}) = 2.39 \pm 0.05(\text{stat.}) \pm 0.04(\text{syst.})$ MeV
- With the γ-ray transition energies from previous experiments, the values for excited states can also be obtained.

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



Charge symmetry breaking



- $\Delta B_{\Lambda}(0^{+}) = 150 \pm 50(\text{stat.}) \pm 40(\text{syst.})$ keV
- $\Delta B_{\Lambda}(1^{+}) = -170 \pm 50(\text{stat.}) \pm 50(\text{syst.})$ keV
- We confirm that charge symmetry breaking effects in A = 4 hypernuclei ground states and excited states are comparable.
- The ab-initio NCSM calculation with CSB Λ-Σ^0 mixing can describe our results. However, the latest calculation with DvH OPE in excited states is smaller than our measurement with about 2σ.

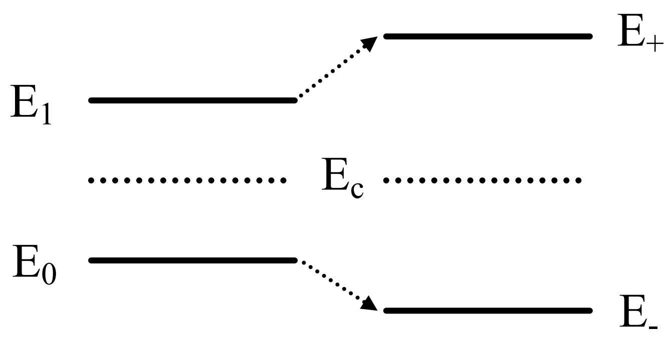
A. Gal, PLB 744 (2015) 352-357
A. Nogga et. al., PRL 88, 172501 (2002)
D. Gazda and A. Gal, PRL 116, 122501 (2016)
J. Haidenbauer et. al., LNP 724, 113-140 (2002)
D. Gazda and A. Gal, NPA 954 (2016) 161-175

Charge symmetry breaking

- How symmetry breaking affects a two-level system in basic quantum mechanics:

Hamiltonian : $H = H_0 + H'$

$$H = \begin{pmatrix} H_{00} & H'_{01} \\ H'_{10} & H_{11} \end{pmatrix}$$

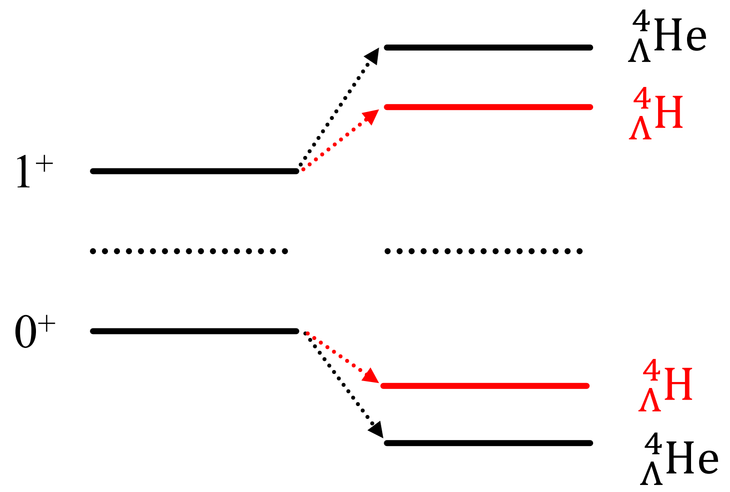


If $|\psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle$

$$\begin{pmatrix} E - E_2 & -H'_{01} \\ -H'_{10} & E - E_1 \end{pmatrix}\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = 0$$

Solve the eigenvalue :

$$\begin{vmatrix} E - E_2 & -H'_{01} \\ -H'_{10} & E - E_1 \end{vmatrix} = 0$$



Symmetric in ground and excited states.

$$E_\pm = E_c \pm \sqrt{d^2 + |H'_{01}|^2} \qquad E_c = \frac{1}{2}(E_0 + E_1) \qquad d = \frac{1}{2}(E_0 - E_1)$$

- Our results favor the basic QM picture.

Summary

- Invariant masses and Λ binding energies of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ have been measured in $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions with higher precision than before:

  $m({}^{4}_{\Lambda}\mathrm{H})$ = 3922.36±0.02(stat.) ±0.05(syst.) MeV/c^2, $B_\Lambda({}^{4}_{\Lambda}\mathrm{H})$ = 2.24±0.02(stat.) ±0.05(syst.) MeV

  $m({}^{4}_{\Lambda}\mathrm{He})$ = 3921.68±0.05(stat.) ±0.04(syst.) MeV/c^2, $B_\Lambda({}^{4}_{\Lambda}\mathrm{He})$ = 2.39±0.05(stat.) ±0.04(syst.) MeV

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

  $\Delta B_\Lambda(0^+)$ = 0.15 ± 0.05(stat.) ± 0.04(syst.) MeV

  $\Delta B_\Lambda(1^+)$ = -0.17 ± 0.05(stat.) ± 0.05(syst.) MeV

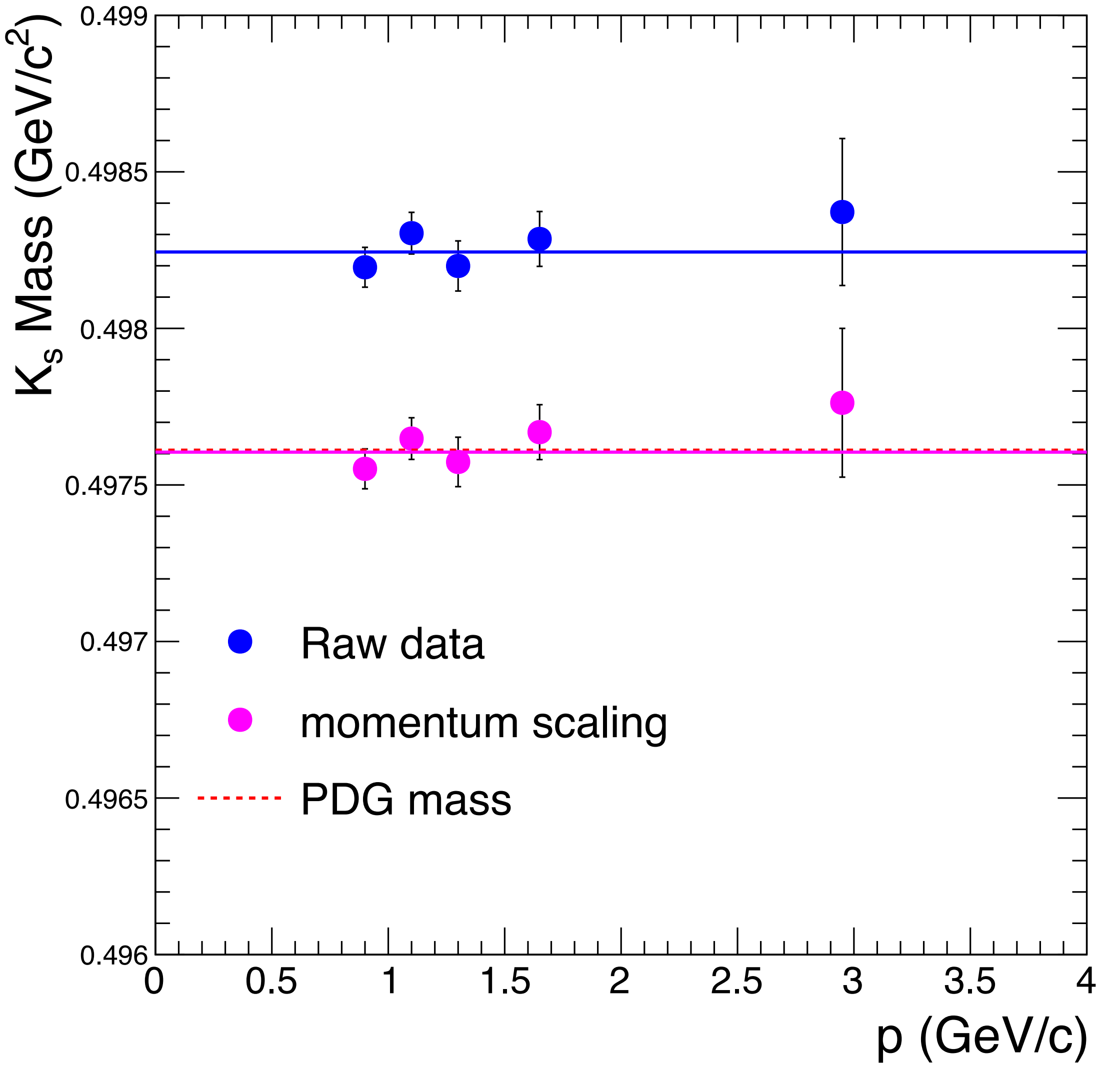
- Our results confirm that the charge symmetry breaking effect in excited states is negative, and the magnitude is comparable to the ground states, which favors the basic quantum mechanics picture.

Backup

Corrections

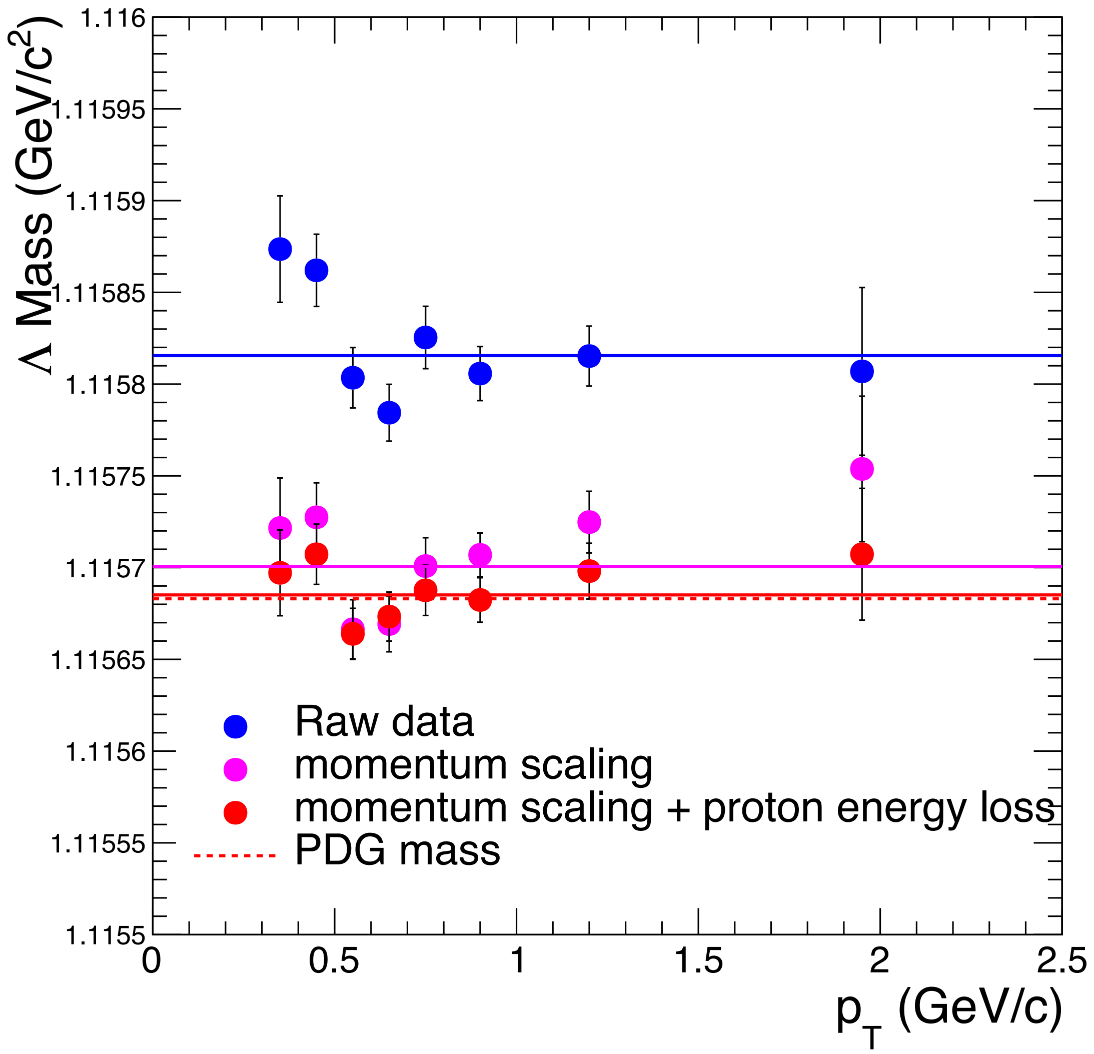
Momentum calibration due to magnetic field measurement

- The track momentum is decide by its curvature in the STAR magnet system.
- Due to the accuracy limitation on the measurement of STAR magnetic field, the reconstructed momentum of track may deviates from the real value.
- We calibrate the track momentum by measuring the mass of $K_s \to \pi^+ + \pi^-$. A 0.2% correction is needed to match the PDG value.
- Consider the uncertainty of the measurement, 0.17% ~ 0.23% correction range are tested to evaluate the systematic uncertainty.



Corrections

- Test the momentum corrections with $\Lambda \rightarrow p + \pi^-$ mass.
- Λ mass with corrections is consistent with PDG value within ~10keV.
- The deviation of the measured Λ mass from PDG value is propagated to the measured mass of hypernuclei.



Systematic uncertainties

Systematic uncertainties for Λ binding energies

Error source	${}^{4}_{\Lambda}$H Systematic error (MeV)	${}^{4}_{\Lambda}$He Systematic error (MeV)
Momentum calibration	0.03	0.03
Energy loss correction	0.02	0.01
Topological cuts	0.02	0.03
Fit method	0.02	0.01
Total	0.05	0.04

Systematic uncertainties for Λ binding energy differences

Error source	Ground state (MeV)	Excited state (MeV)
Energy loss correction	0.02	0.02
Topological cuts	0.04	0.04
γ-ray energy	0.00	0.02
Total	0.04	0.05

Symmetric check