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

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Strangeness in Quark Matter 2021 – New York, USA
May 17-21, 2021

The 19th International Conference on Strangeness in Quark Matter

May 17-21, 2021, sponsored by Brookhaven National Laboratory, Upton, New York

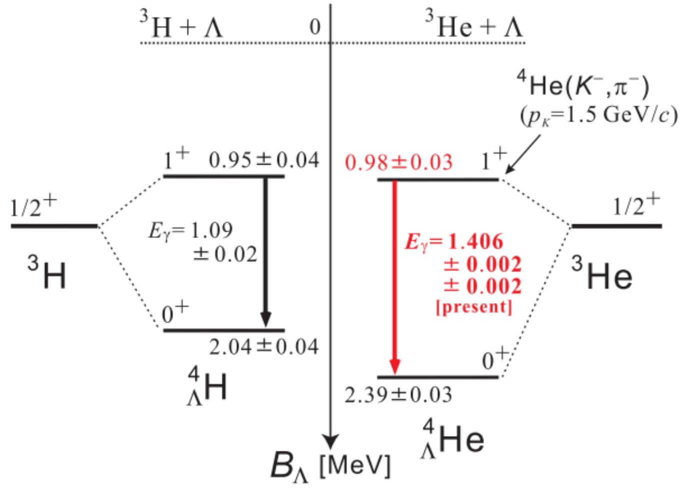
SQM2021

Outline

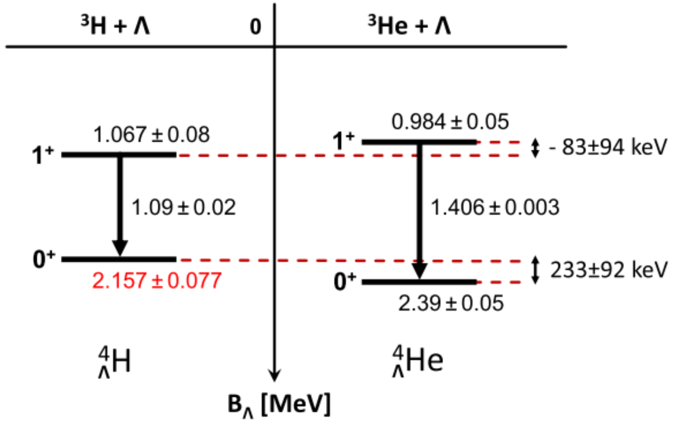
- Motivation
- STAR Fixed Target Program
- ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ Reconstruction
- Corrections and Systematic Uncertainties
- Λ Binding Energy
- Charge Symmetry Breaking
- Summary

Motivation - Experimental Studies

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



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



Nuclear Physics A 754 (2005) 3c–13c

Nuclear emulsion experiment in 1970s

Hypernuclide		B_Λ/MeV
$^{3}_{\Lambda}H$	0.41 MeV (NP2020)	0.13 ± 0.05
$^{4}_{\Lambda}H$		2.04 ± 0.04
$^{4}_{\Lambda}He$		2.39 ± 0.03

$$\Delta B_\Lambda = 350 \pm 60 \text{ keV}$$

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

Motivation - Theoretical Studies

Model calculations

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

- Theoretical calculations including Λ-Σ^0 mixing show that the CSB in ground and excited states are comparable.
- Need independent experiments to test.

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

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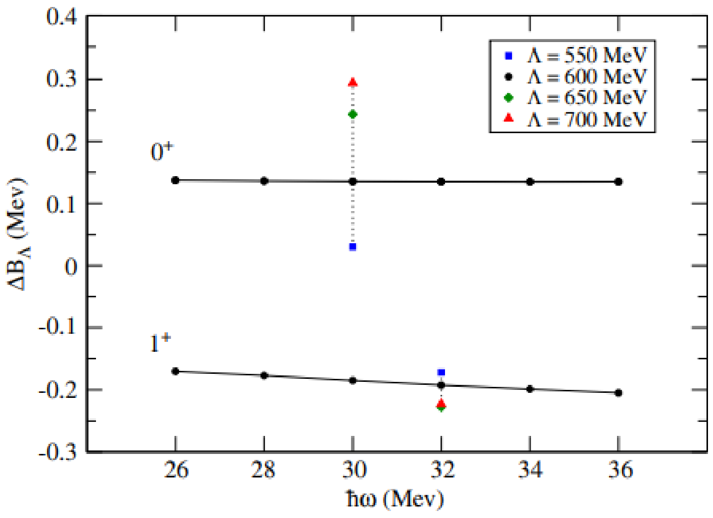
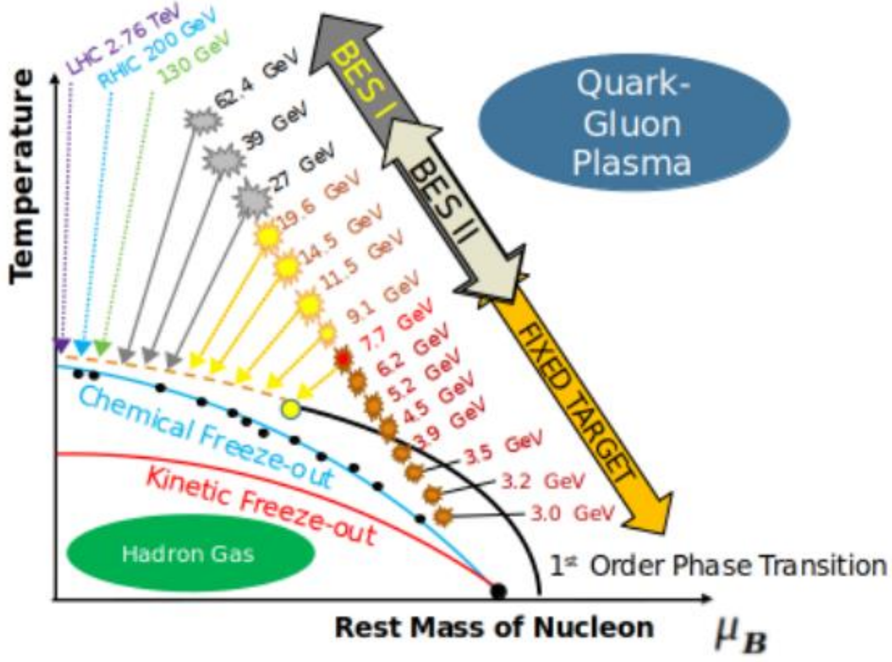
(Received 7 December 2015; published 22 March 2016)

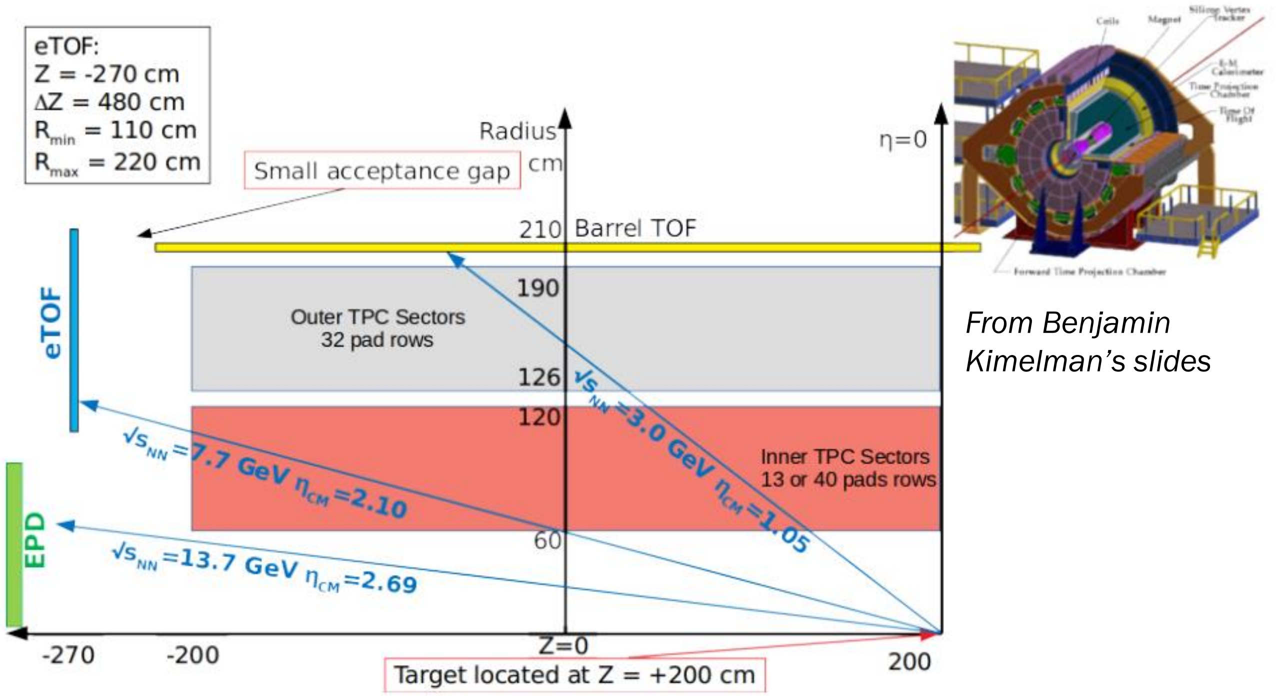


$$\overline{\Delta B}^{J=1}_\Lambda \approx -\overline{\Delta B}^{J=0}_\Lambda < 0.$$

STAR Fixed Target Program



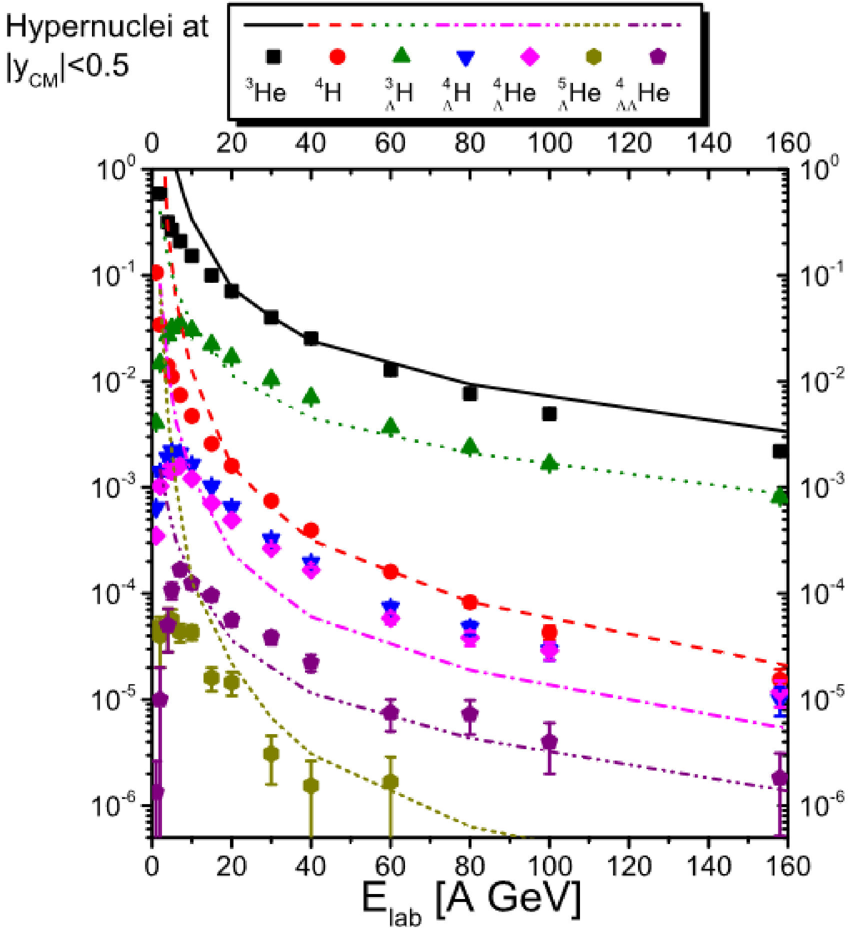
STAR Fixed Target setup



From Benjamin Kimelman's slides

- STAR Au+Au at $\sqrt{s_{NN}}$ = 3 GeV FXT run in 2018, ~ 300M events

STAR Fixed Target Program

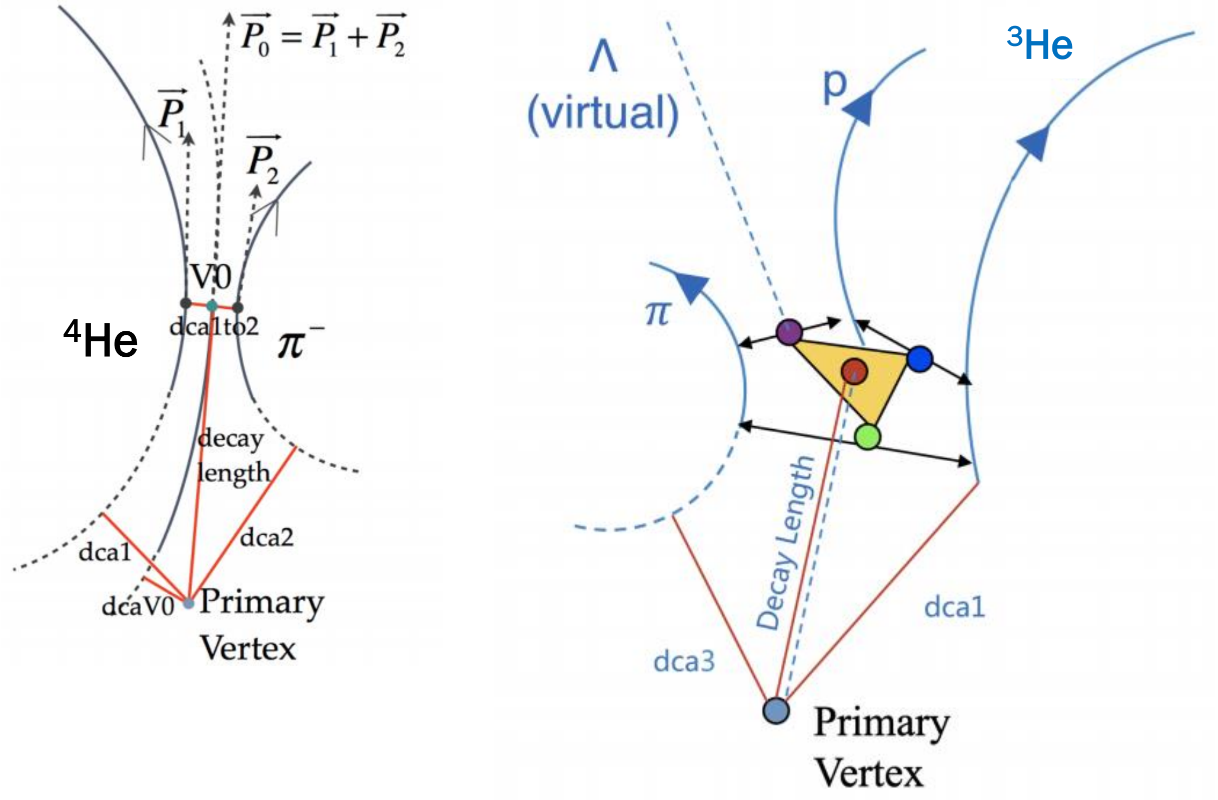


UrQMD (curves) and coalescence (symbols) calculation for hypernuclei yields, PLB 714 (2012) 85-91

- Higher baryon density and higher hypernuclei yields at lower collision energies.

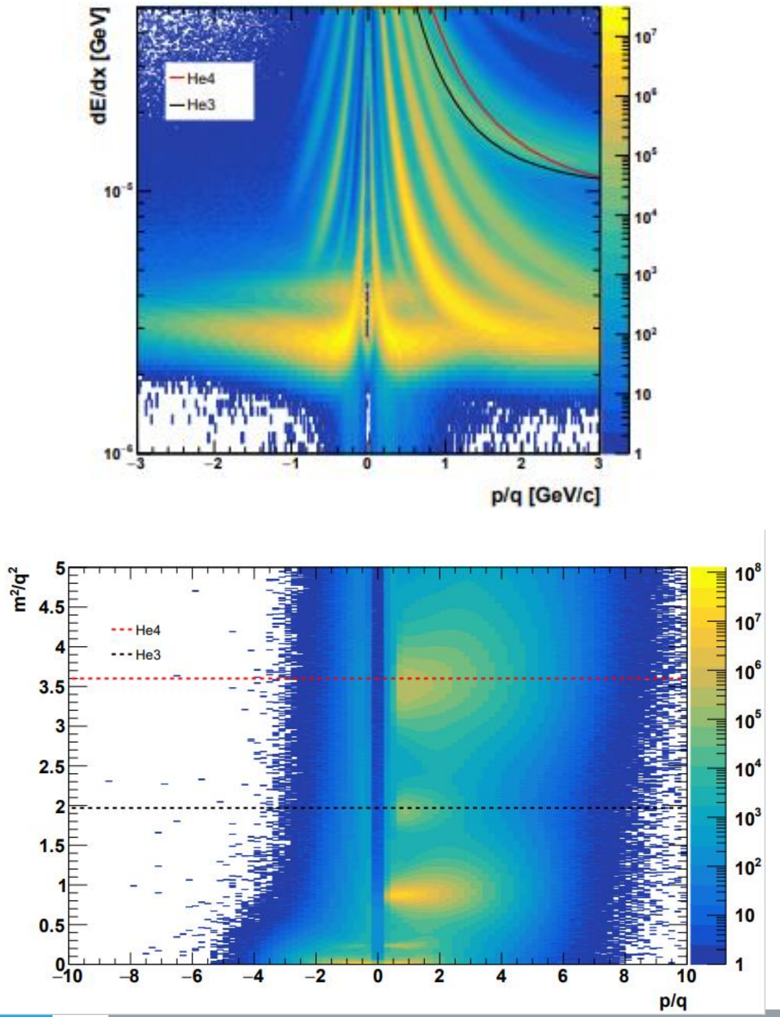
${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ Reconstruction

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



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

Particle Identification with TPC and TOF



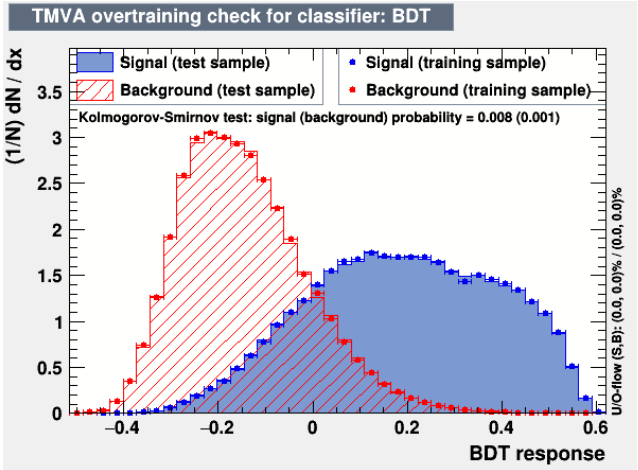
${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ Reconstruction

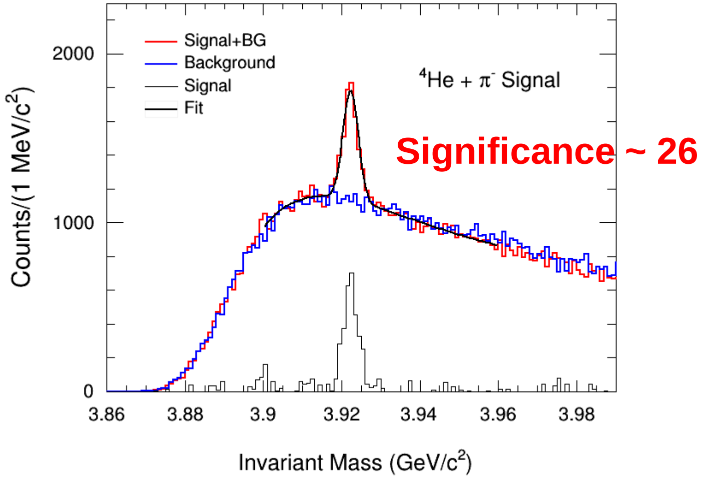
- Using TMVA-BDT to optimize the signal.

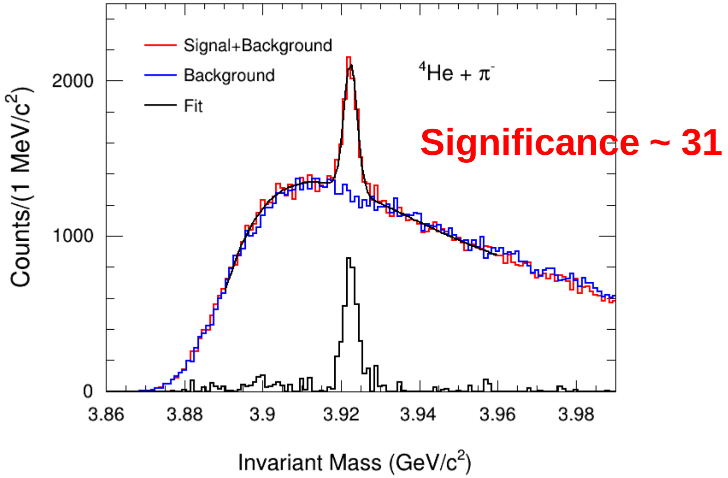
Normal Helix Method

TMVA-BDT

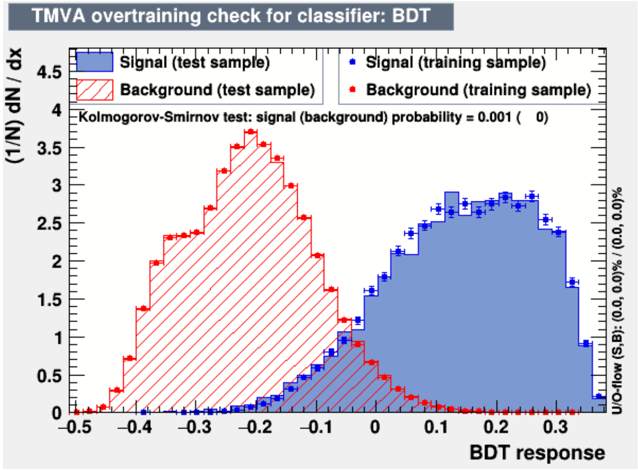
${}^{4}_{\Lambda}H$

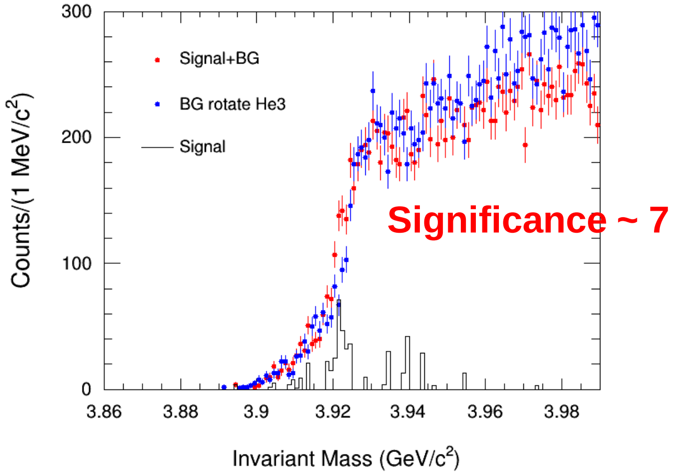


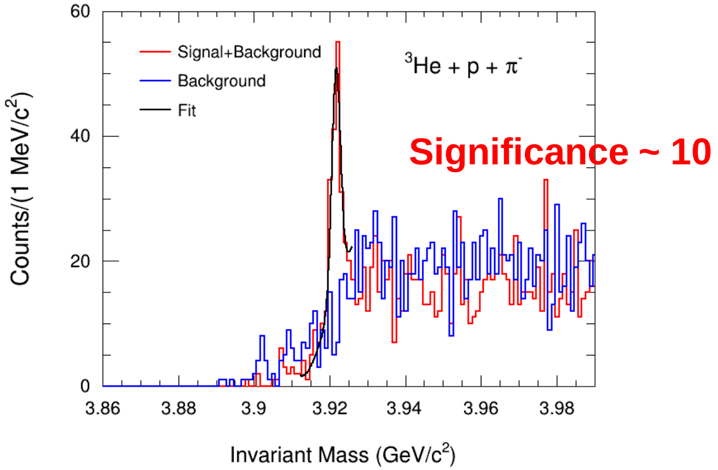




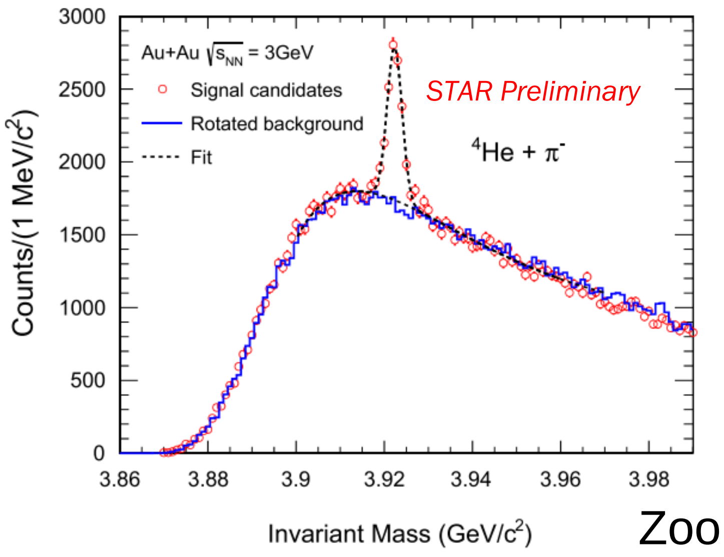
${}^{4}_{\Lambda}He$

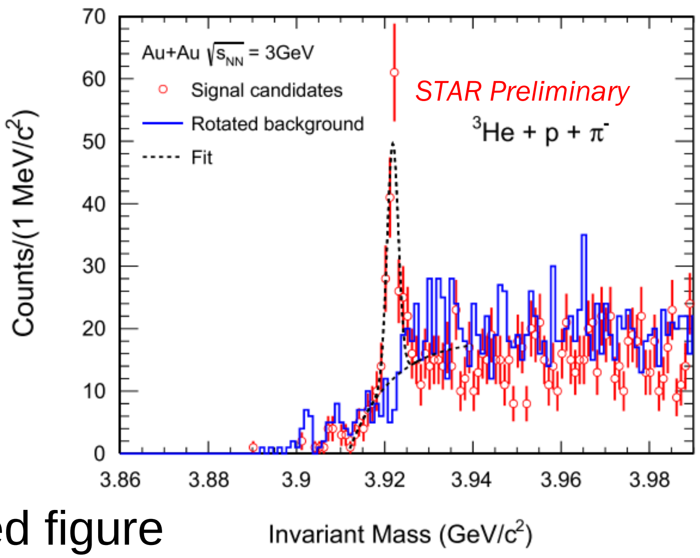




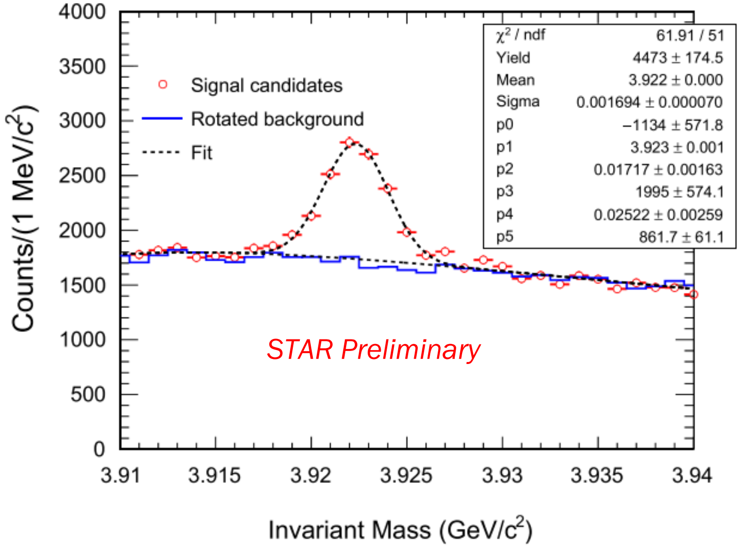


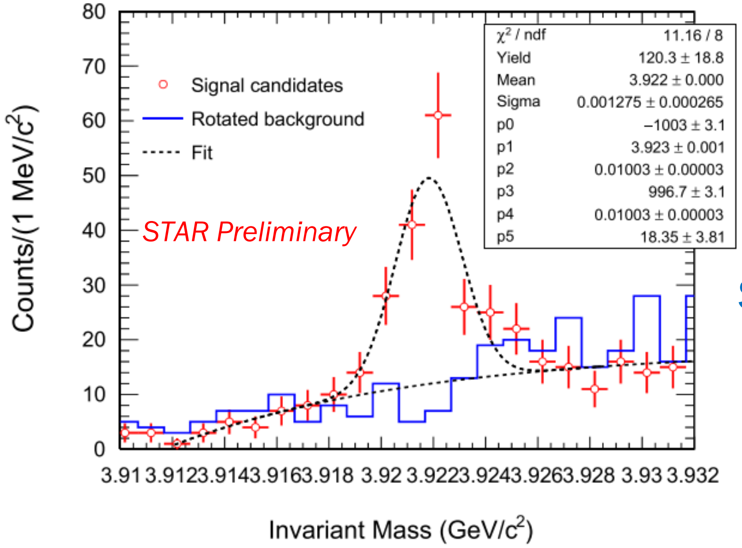
${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ Invariant Mass





Zoomed figure





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

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

$$f(x) = \frac{A}{\sqrt{2\pi}\sigma} exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) + p_0 exp\left(-\frac{x-p_1}{p_2}\right) + p_3 exp\left(-\frac{x-p_1}{p_4}\right) + p_5$$

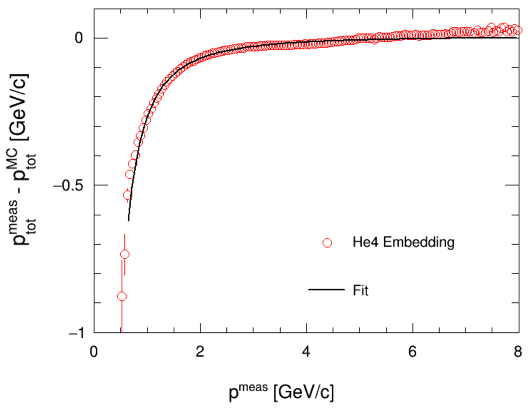
- m(${}^{4}_{\Lambda}H$) = 3922.36 ± 0.06(stat.) ± 0.18(syst.) MeV/c^2
- m(${}^{4}_{\Lambda}He$) = 3921.70 ± 0.12(stat.) ± 0.14(syst.) MeV/c^2

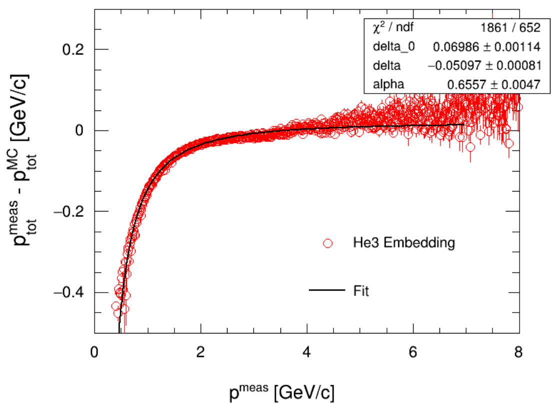
Systematical uncertainties source :

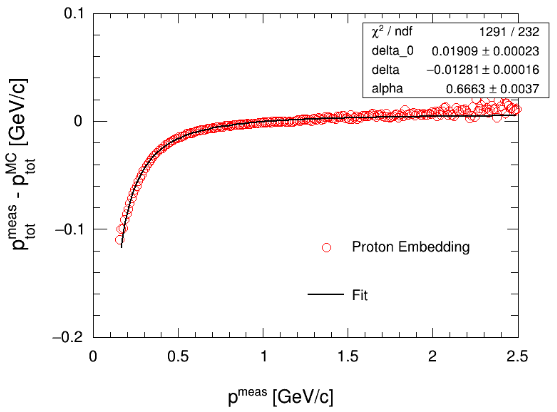
- Magnetic field distortion
- Energy loss correction
- BDT cut
- Fit method

Corrections

Energy loss corrections







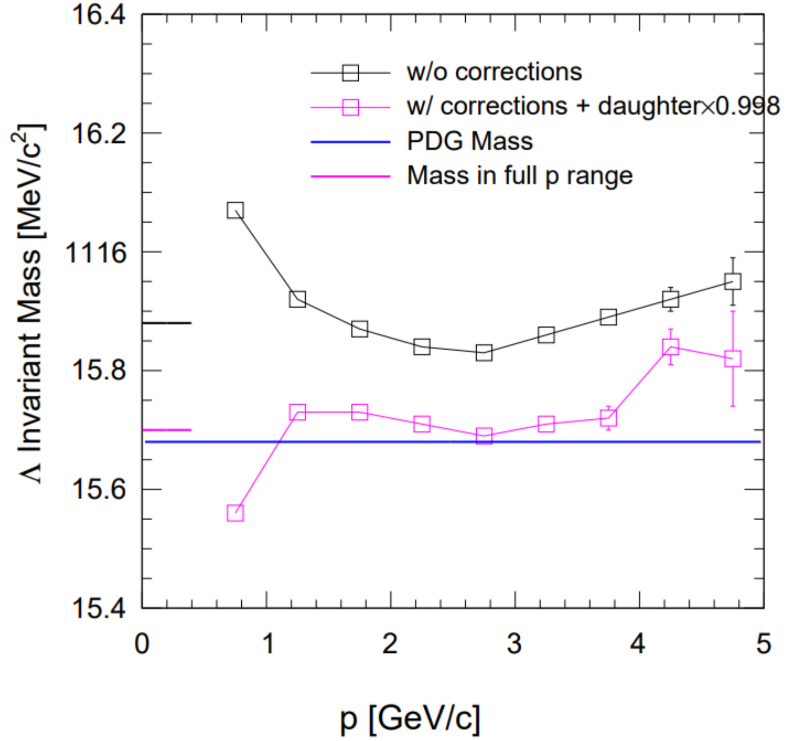
Fit and correct function:

$$y = \delta_0 + \delta\left(1 + \frac{m^2}{x^2}\right)^{\alpha}$$

Check in Λ invariant mass

Correction from magnetic field distortion

Momentum of decay daughters × 0.998



Systematic Uncertainties

Systematic uncertainties for Λ binding energy.

Error source	$^{4}_{\Lambda}\mathrm{H}$ Systematic error (MeV)	$^{4}_{\Lambda}\mathrm{He}$ Systematic error (MeV)
Magnetic field distortion	0.16	0.11
Energy loss correction	0.06	0.07
BDT cut	0.01	0.05
Fit method	0.04	0.02
Total	0.18	0.14

- Systematic uncertainties mainly come from magnetic field distortion.
- Due to the use of the same experiment and the same analysis method, most of the systematic error can be canceled when calculating the binding energy difference. The systematic uncertainties for binding energy difference are mainly from the fit method.

Λ Binding Energy

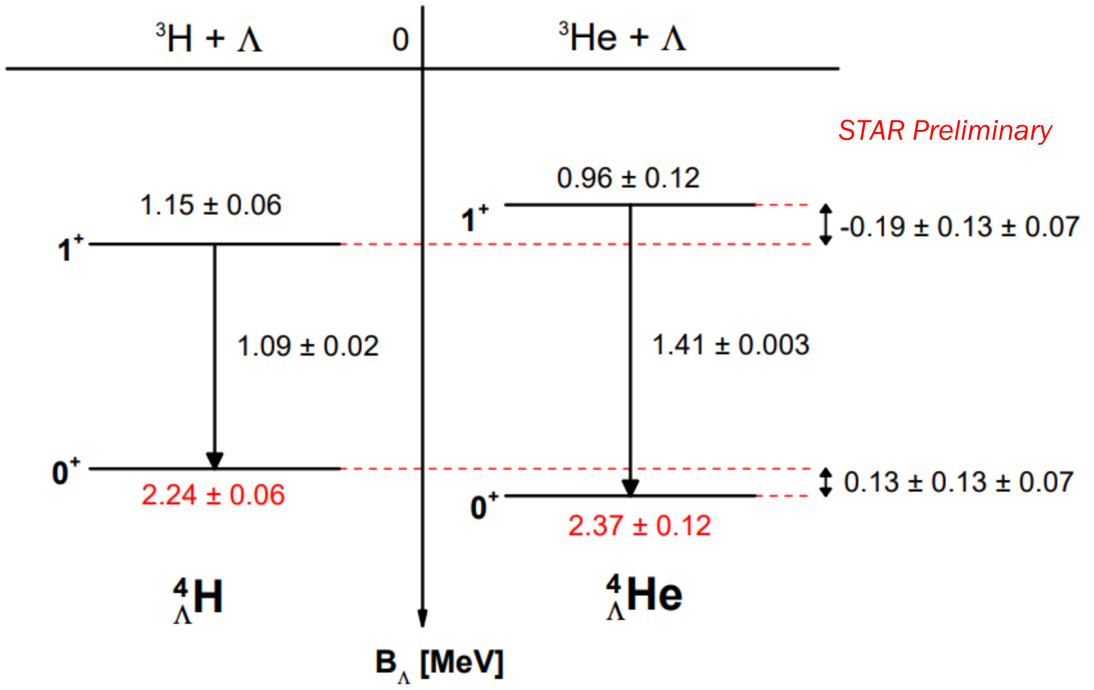
- Calculate the Λ binding energy according to the mass of hypernuclei and its constituents:

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

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

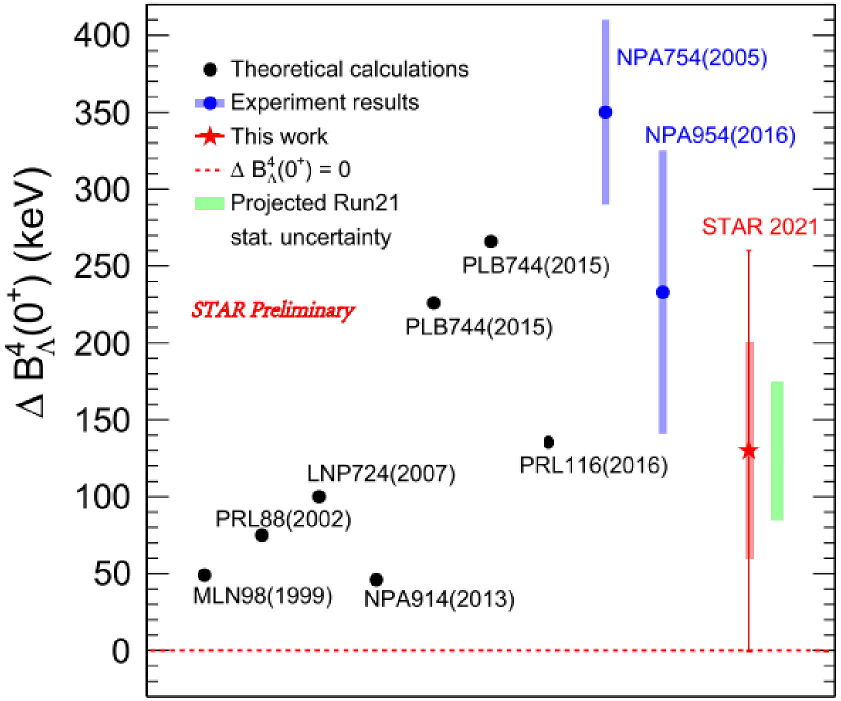
	Λ	Triton	He3
Mass (MeV/c^2)	1115.68	2808.92	2808.39

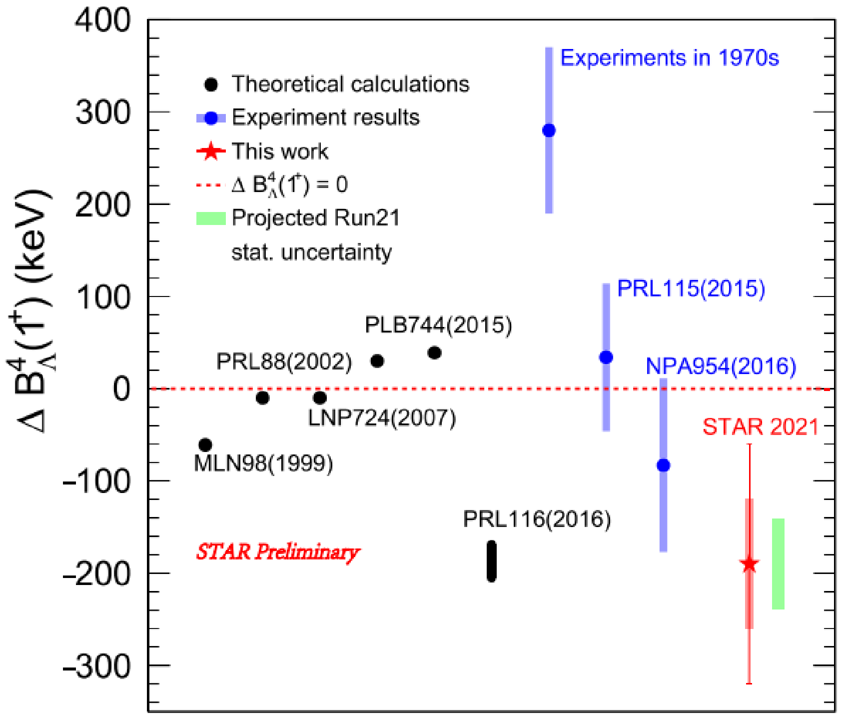
- B_Λ (${}^4_\Lambda H$) = 2.24 ± 0.06(stat.) ± 0.18(syst.) MeV
- B_Λ (${}^4_\Lambda He$) = 2.37 ± 0.12(stat.) ± 0.14(syst.) MeV



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.

Charge Symmetry Breaking





- The Λ binding energy difference between ${}^4_\Lambda H$ and ${}^4_\Lambda He$ in ground states (left figure) and in excited states (right figure). The green shadows are projected statistical uncertainties obtained according to the high statistics from STAR run 2021 3 GeV data (~ 2 billion events).
- $\Delta B_\Lambda(0^+) = 130 \pm 130(\text{stat.}) \pm 70(\text{syst.})$ keV
- $\Delta B_\Lambda(1^+) = -190 \pm 130(\text{stat.}) \pm 70(\text{syst.})$ keV
- Charge symmetry breaking effects in ground states and excited states are comparable.

Summary

- Invariant mass and Λ binding energies of ${}^4_\Lambda H$ and ${}^4_\Lambda He$ have been measured in Au+Au at 3 GeV:
  m(${}^4_\Lambda H$) = 3922.36±0.06(stat.) ±0.18(syst.) MeV/c^2, B_Λ (${}^4_\Lambda H$) = 2.24±0.06(stat.) ±0.18(syst.) MeV
  m(${}^4_\Lambda He$) = 3921.70±0.12(stat.) ±0.14(syst.) MeV/c^2, B_Λ (${}^4_\Lambda He$) = 2.37±0.12(stat.) ±0.14(syst.) MeV
- To address 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 :

  $\Delta B_\Lambda(0^+)$ = 130 ± 130(stat.) ± 70(syst.) keV

  $\Delta B_\Lambda(1^+)$ = -190 ± 130(stat.) ± 70(syst.) keV
- Our results show that the charge symmetry breaking effect in excited states is a negative value and the magnitude is comparable to the ground states.
- Outlook : STAR is taking a factor of 7 more data at 3 GeV fixed target in Run-21. The statistical uncertainties will be reduced.

Back up

Error Source

- Invariant mass : Signal+Background fit
- Statistical error : fit the pure signal count from background subtraction.
- B distortion : the difference between without and within daughter momentum scaling down.
- Energy loss correction : apply this correction in embedding data and look at the difference between reconstructed signal and MC input.
- BDT cut : tune the value of BDT cut, the difference between the mass from different BDT cut.
- Fit method : the difference between Signal+Background fit and pure signal fit.