

Measurement of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ binding energy in Au+Au collisions at $\sqrt{s_{NN}} = 3 \text{ GeV}$

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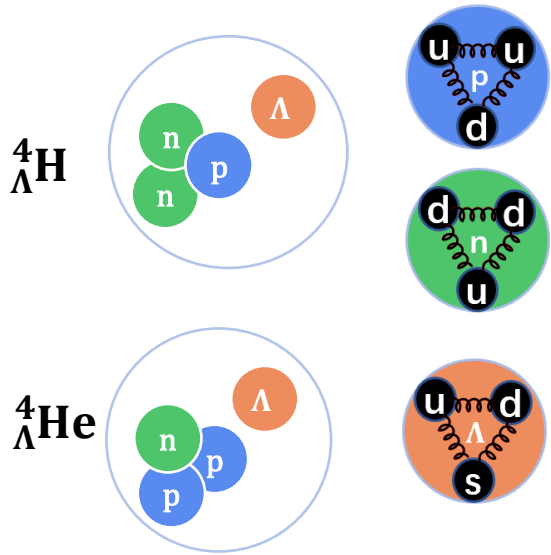
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June 27th, 2023

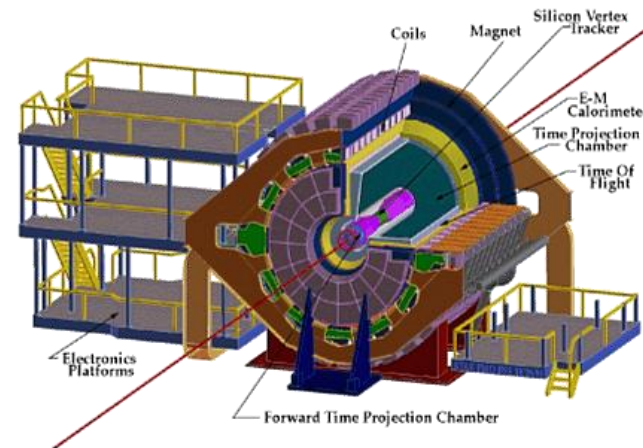
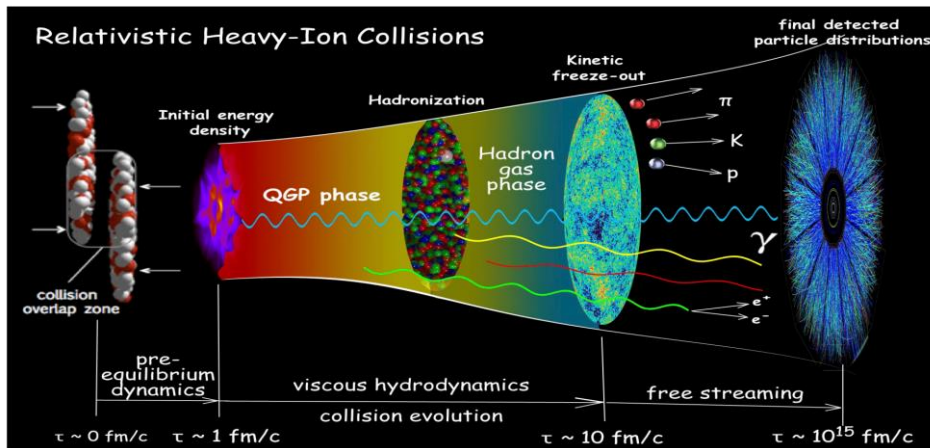
Outline

- **Motivation**
- **Methods**
 - Reconstruction via weak decay
 - Systematic uncertainties
- **Results and Discussion**

Motivation



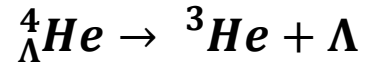
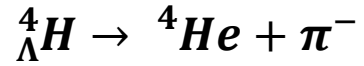
- Hypernuclei are nuclei composed of at least one hyperon
- Natural laboratory to study hyperon-nucleon(Y-N) interaction
 - Binding energy, lifetime, ...
- Mirror (hyper-)nuclei and charge symmetry breaking
 - Prediction on binding energy difference: $\Delta B_{\Lambda}^4(1_{\text{exc}}^+) \approx -\Delta B_{\Lambda}^4(0_{\text{g.s.}}^+)$
 - Consider $\Lambda - \Sigma^0$ mixing [Phys. Rev. Lett. 116, 122501\(2016\)](#)
- Hypernuclei have high production rate in heavy-ion collisions



Methods

- Reconstruction via weak decay

- Decay channel:



- PID with TPC and TOF

- ${}^4\text{He}$, ${}^3\text{He}$, p and π^- are selected with

- dE/dx within 3 standard deviation

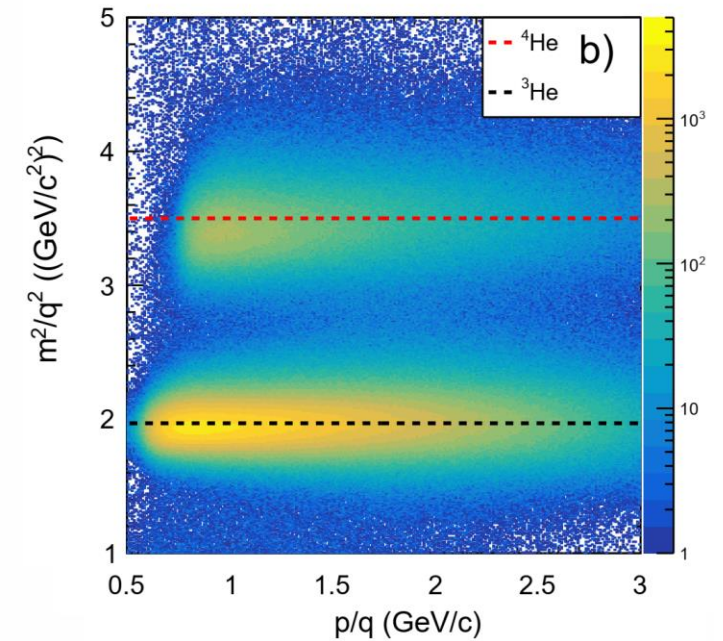
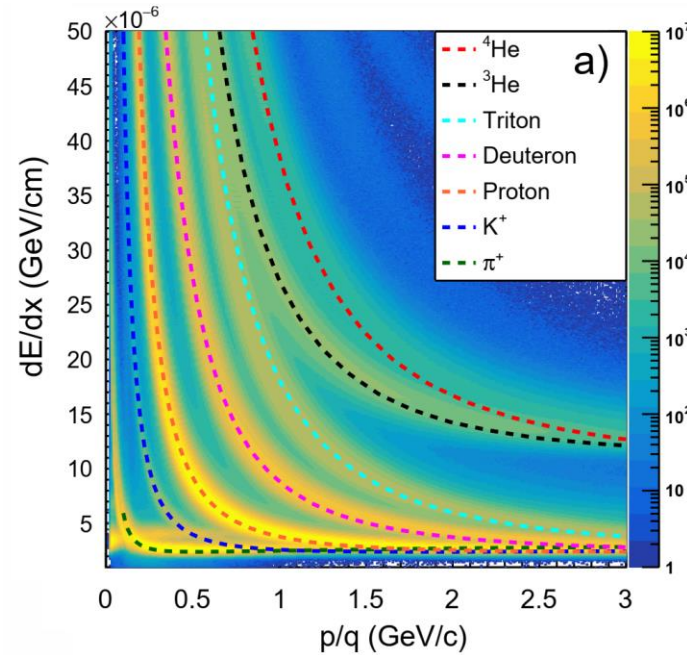
$$n\sigma_x = \frac{1}{R} \log \frac{\langle dE/dx \rangle_{\text{measured}}}{\langle dE/dx \rangle_x}$$

$$|n\sigma_x| < 3, \quad x = {}^4\text{He}, {}^3\text{He}, p, \pi^-$$

- If TOF matched,

$${}^3\text{He}: m^2/q^2 = 1.4 \sim 2.5 \text{ (GeV/c}^2\text{)}^2$$

$${}^4\text{He}: m^2/q^2 = 2.5 \sim 4.5 \text{ (GeV/c}^2\text{)}^2$$



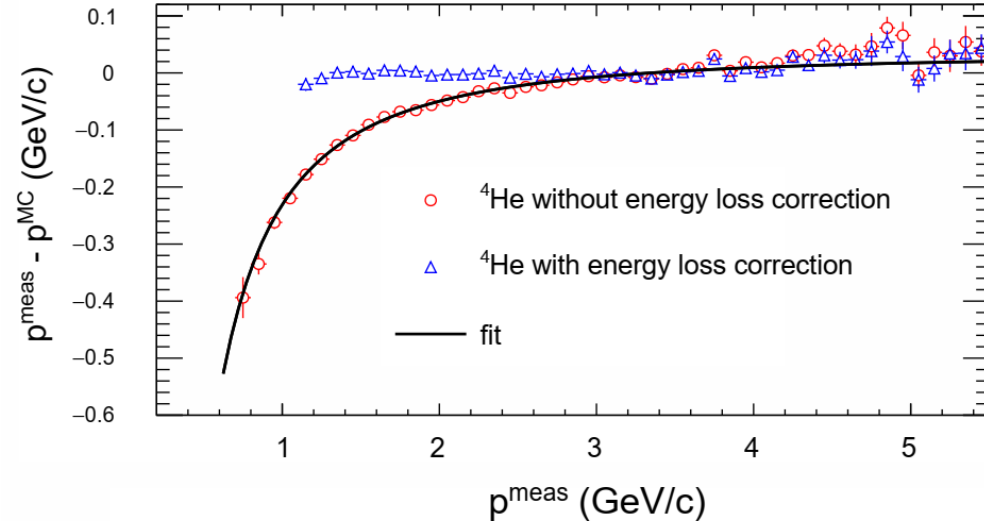
Methods

- Reconstruction via weak decay

- Energy loss correction

- Particles lose energy while traversing the detector material,
- The real momentum $\mathbf{p}_{real} \neq$ TPC raw momentum \mathbf{p}_{raw}
- \mathbf{p}_{mea} : correct \mathbf{p}_{raw} by assuming it's a pion track (track reconstruction algorithm)

➡ Recalibrations on ${}^4\text{He}$, ${}^3\text{He}$, \mathbf{p} momenta with MC

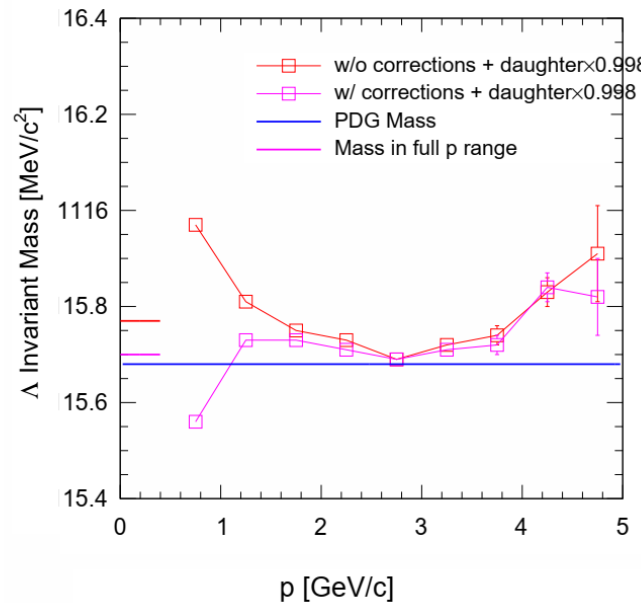
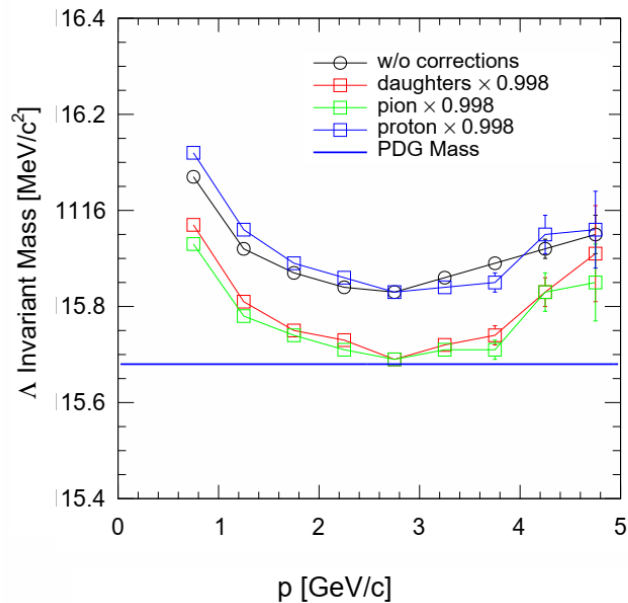


$$\mathbf{p}_{rec} - \mathbf{p}_{mea} = \delta_0 + \delta \left(1 + \frac{m^2}{p_{mea}^2} \right)^\alpha$$

δ_0, δ, α are parameters

Methods

- Reconstruction via weak decay
 - Magnetic distortion correction
 - The magnetic field B is designed to be 5 T
 - Limited readout accuracy $\rightarrow B < 5$ T
 - Overall correction on track momentum $p_{rec} \times 0.998$
 - The scaling factor is calibrated with Λ mass ($\Lambda \rightarrow p + \pi^-$)



Λ mass with energy loss correction and momentum scaling:
 1115.710 ± 0.004 MeV/c²

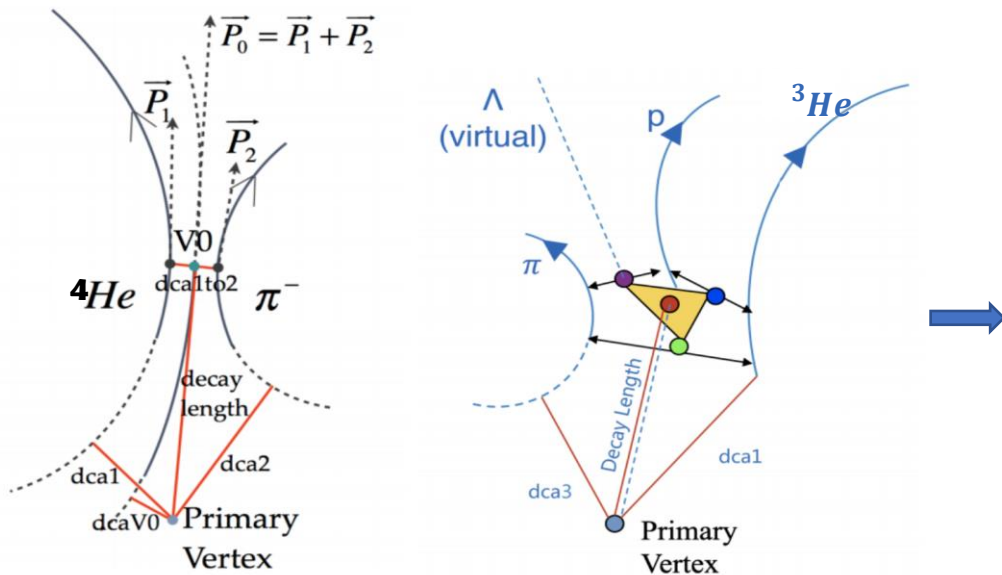
PDG value:
 1115.683 ± 0.006 MeV/c²

Consistent within uncertainties

The difference 0.03 MeV/c² is considered as systematic uncertainty

Methods

- Reconstruction via weak decay
 - A series of topological variables on the decay kinematics
 - Decay length
 - DCA(Distance of the Closest Approach)
 - KFParticle package for reconstruction
 - Kalman filter algorithm
 - The topological variables will be assigned an error



KF Particle variable	Related helix method variable	Description
$\chi_{prim^{3/4}He}^2$	DCA of Helium	DCA of Helium over its error
$\chi_{prim\pi}^2$	DCA of π^-	DCA of π^- over its error
χ_{ndf}^2	DCA 1 to 2	DCA between 2 daughter particle tracks over its error
χ_{topo}^2	DCA V0	DCA from mother particle to primary vertex over its error
l	-	decay length
ldl	-	decay length over its error

Methods

- Reconstruction via weak decay
 - Optimization with TMVA-BDT

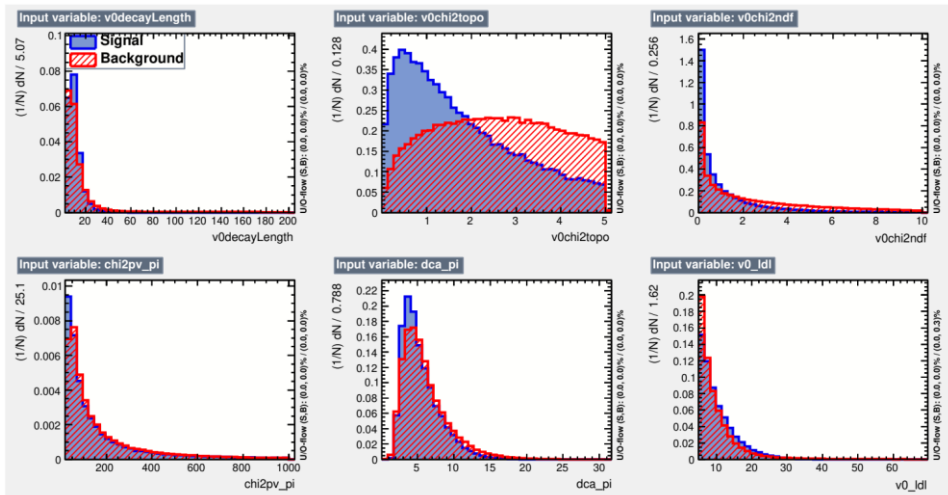


Figure 47: Training results for topological features of ${}^4_{\Lambda}H$ from KFParticle.

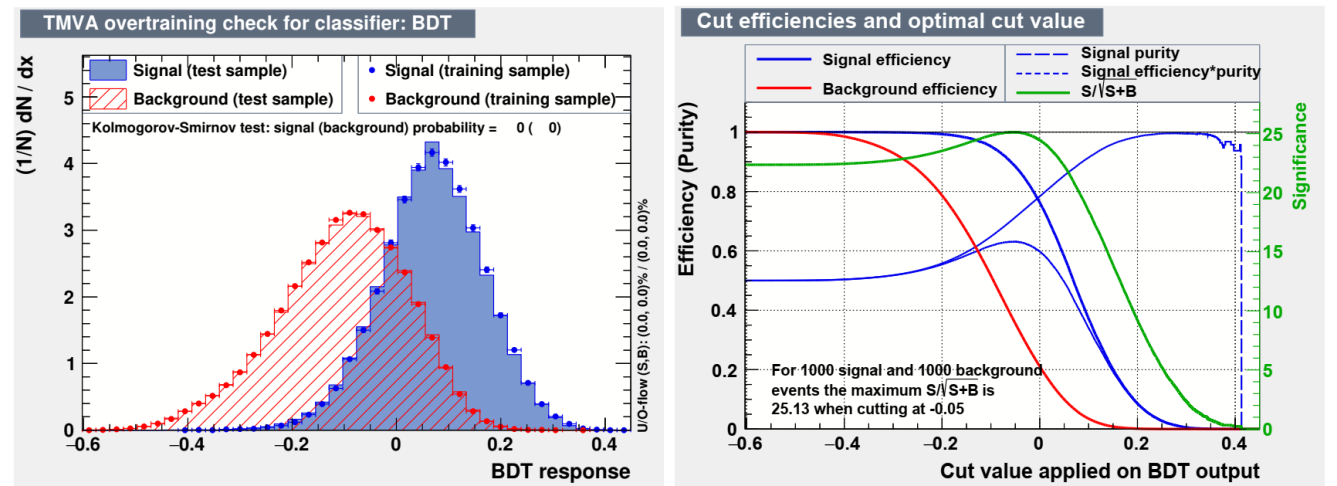
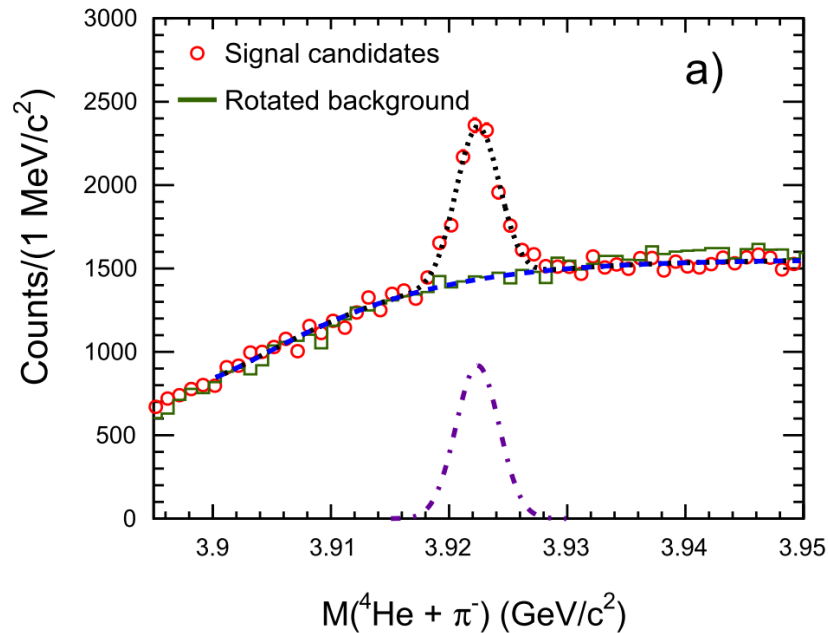


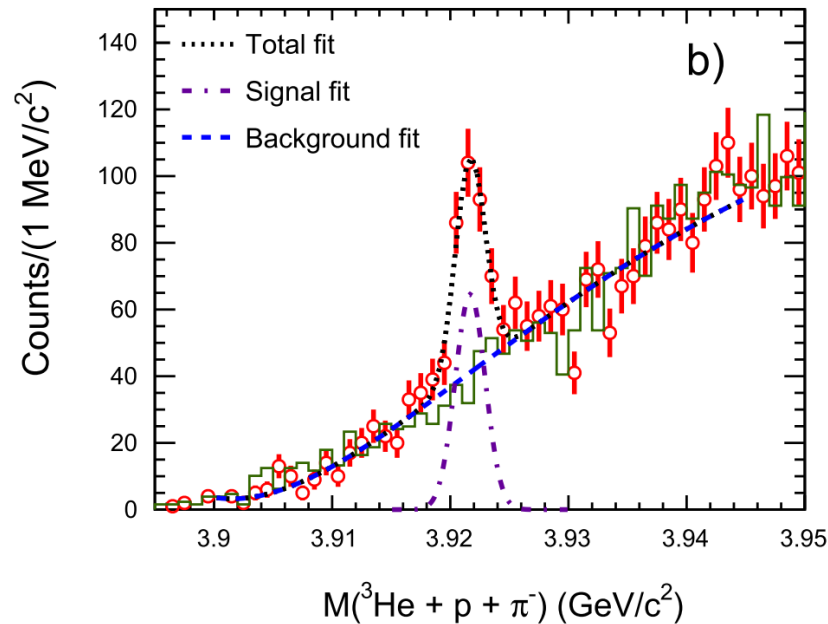
Figure 48: Training results for overtraining (left) and BDT response (right) of ${}^4_{\Lambda}H$ from KFParticle.

Methods

- Reconstruction via weak decay
 - Invariant mass distribution
 - Background reconstructed by rotating ${}^4\text{He}$, ${}^3\text{He}$ momenta with 180 degrees



➔ $M({}^4\text{H}) = 3922.38 \pm 0.06(\text{stat.}) \text{ MeV}/c^2$



$M({}^4\text{He}) = 3921.69 \pm 0.13(\text{stat.}) \text{ MeV}/c^2$

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

Methods

- Systematic uncertainties
 - Sources:
 - Energy loss correction:
 - Vary the fit parameters of the correction function with $\pm 1\sigma$
 - Magnetic distortion correction:
 - The difference between reconstructed Λ mass and PDG value
 - Kinematic cuts on the reconstruction
 - Vary the BDT responses

Sources of systematic uncertainties for the masses and Λ binding energies of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ in MeV/c^2 .

Uncertainty source	${}^4_{\Lambda}\text{H}$	${}^4_{\Lambda}\text{He}$
Momentum scaling factor	0.11	0.11
Energy loss correction	0.08	0.05
BDT response cut	0.03	0.01
Total	0.14	0.12



$$M({}^4_{\Lambda}\text{H}) = 3922.38 \pm 0.06(\text{stat.}) \pm 0.14(\text{syst.}) \text{ MeV}/c^2$$

$$M({}^4_{\Lambda}\text{He}) = 3921.69 \pm 0.13(\text{stat.}) \pm 0.12(\text{syst.}) \text{ MeV}/c^2$$

Results and Discussion

- Binding energy

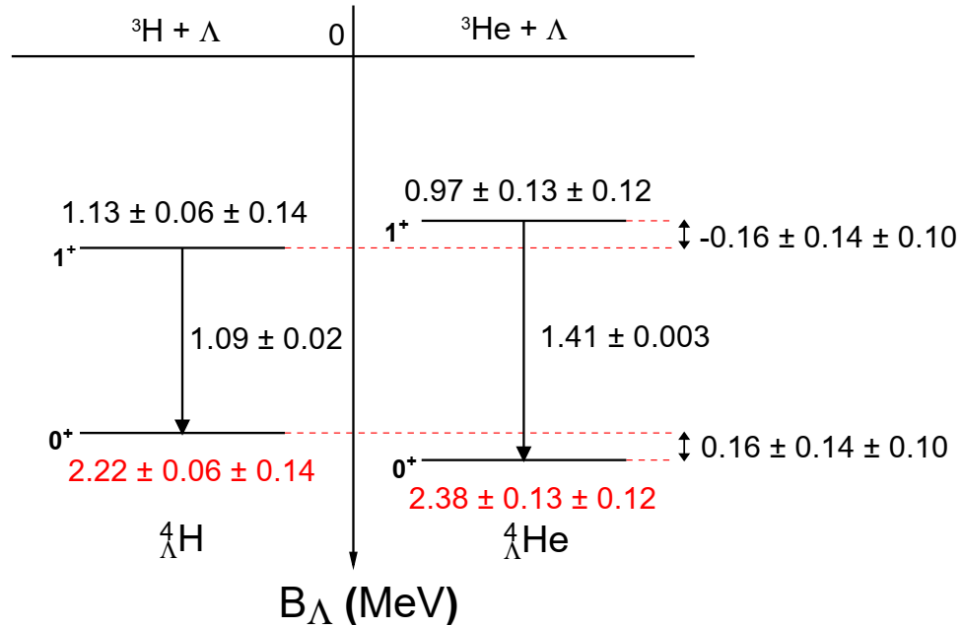
- $B_\Lambda = M_{\text{hypernuclei}} - M_{\text{core}} - M_\Lambda$

- $B_\Lambda(^4_\Lambda\text{H}(0^+)) = 2.22 \pm 0.06(\text{stat.}) \pm 0.14(\text{syst.}) \text{ MeV}$

- $B_\Lambda(^4_\Lambda\text{He}(0^+)) = 2.38 \pm 0.13(\text{stat.}) \pm 0.12(\text{syst.}) \text{ MeV}$

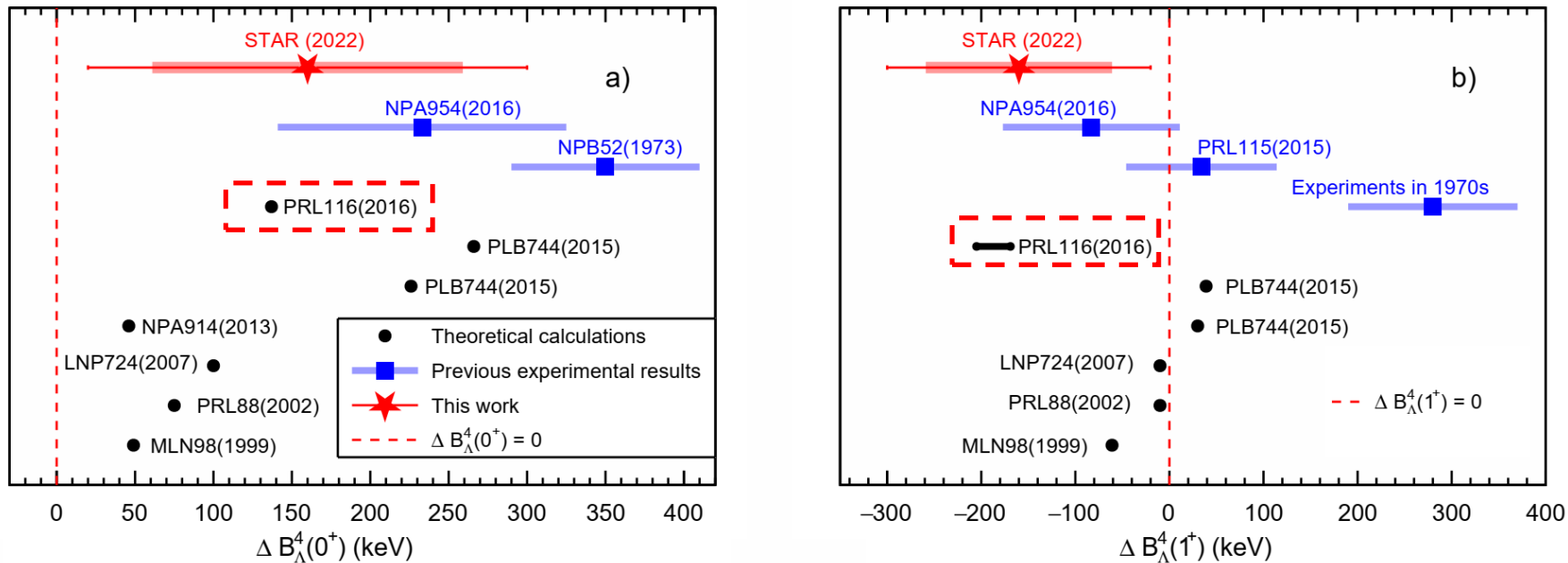
- Also can calculate B_Λ of excited states(1^+), by including the γ -ray transition energy from other measurements

[Phys. Rev. Lett. **115**, 222501 \(2015\)](#)
[Phys. Lett. B **62**, 467 \(1976\)](#)



Results and Discussion

- Binding energy difference between the mirror $A=4$ hypernuclei



- Consistent with Charge Symmetry Breaking effect, but the result is not significant
- Need further study
 - More data being produced (~10 times statistics)
 - More efforts on γ -ray transition energy measurement

Thank you

Backup

Many theoretical model calculations have failed to reproduce the experimental results, with most of them underestimating the CSB effect in both the ground and excited states [7, 19-21]. It has been proposed that $\Lambda - \Sigma$ mixing can account for the large CSB [22]. In 2016, the *ab initio* calculation using chiral effective field theory hyperon-nucleon potentials plus a CSB $\Lambda - \Sigma^0$ mixing vertex of $A = 4$ hypernuclei achieved a large CSB in both ground and excited states, and also concluded that $\Delta B_{\Lambda}^4(1_{\text{exc}}^+) \approx -\Delta B_{\Lambda}^4(0_{\text{g.s.}}^+) < 0$ [23]. Independent experiments are needed to test these calculations. More accurate values of the Λ binding-energy splitting in ground and excited states are needed to constrain the Λn interaction [24].