开题报告——重离子碰撞中超核寿命与产额的测量及寻找新超核

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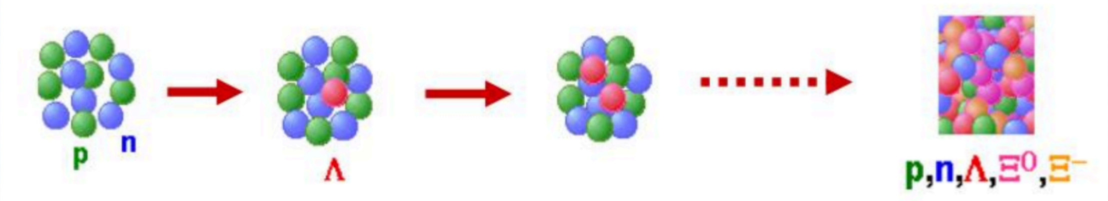
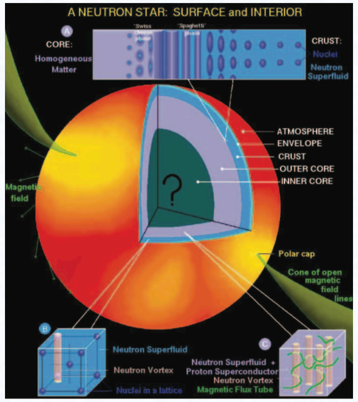
Hypernuclei physics

- Hypernuclei: bound nuclear systems of non-strange and strange baryons



- In 1952, discovery of hypernuclei by Polish physicists
- Around 2000, observations of light double Λ hypernuclei ${}^{4}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{6}_{\Lambda\Lambda}\mathrm{He}$



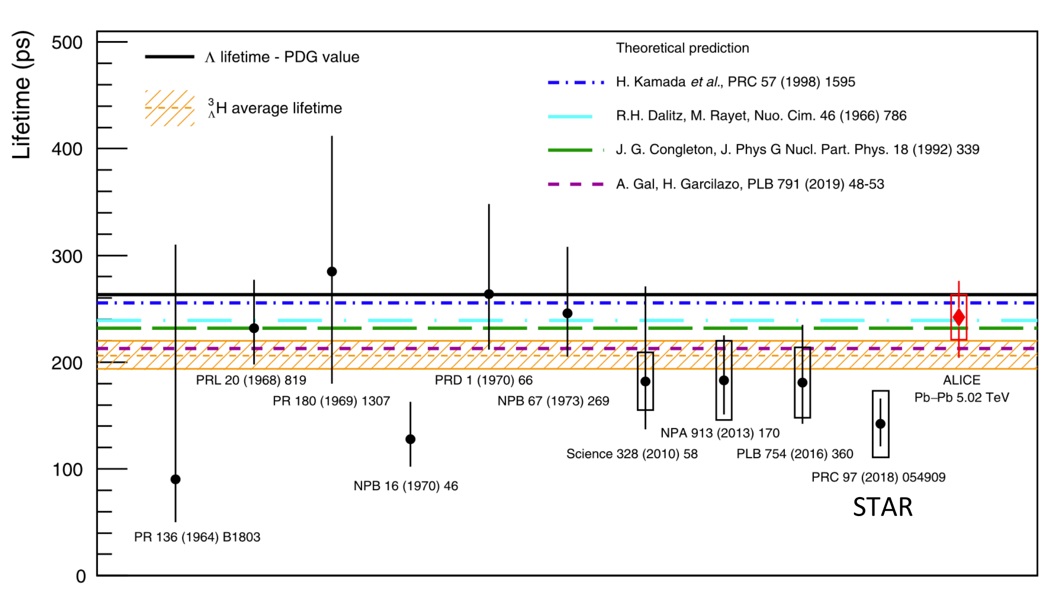
- Hypernuclei are natural hyperon-baryon correlation system

—— an probe to study the hyperon-nucleon(Y-N) interaction

- Strangeness in high density nuclear matter
  - Connected with modelling of the EoS for the dense inner core of neutron stars
    - Do hyperon exists in the neutron star inner core?

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

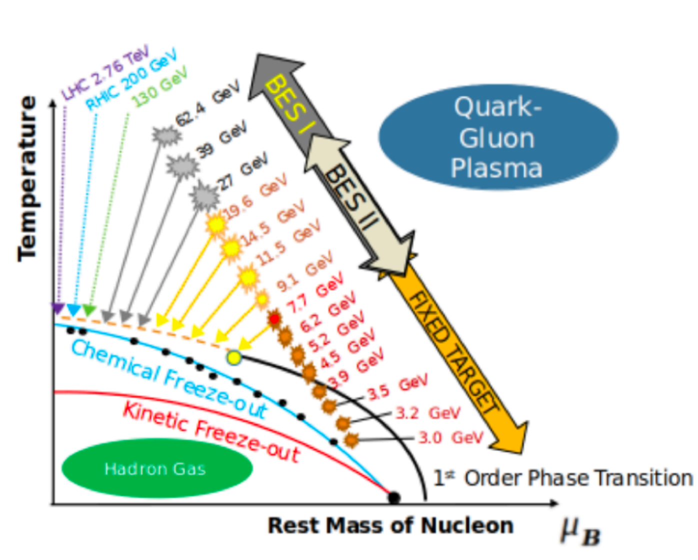
- ${}^{3}_{\Lambda}H$ is characterized by a very small binding energy
  - $B_{\Lambda} = 0.13 \pm 0.05$ MeV
  - Expect that the lifetime of ${}^{3}_{\Lambda}H$ will approximate the free Λ lifetime
- However, recent experimental measurements of ${}^{3}_{\Lambda}H$ lifetime is shorter than the free Λ lifetime by $\sim$ 30%.
  - Great difference between STAR and ALICE

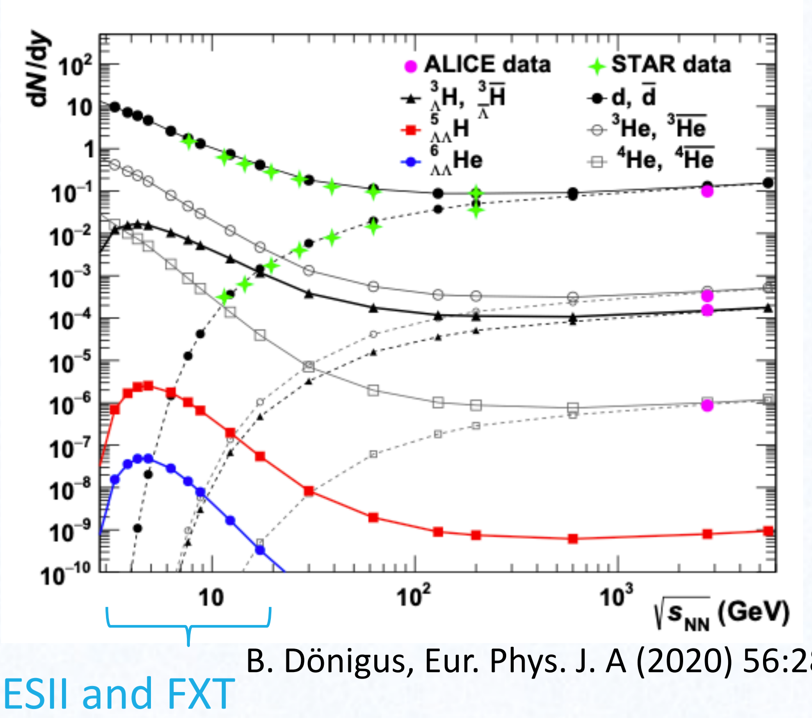


PLB 797,134905 (2019)(ALICE)

STAR BESII and FXT

- Hyper nuclei measurements are scarce in heavy-ion collisions experiments
- At lower beam energies, the hypernuclei production is expected to be enhanced due to high baryon density
  - STAR BESII and FXT → great opportunity to study hypernuclei production

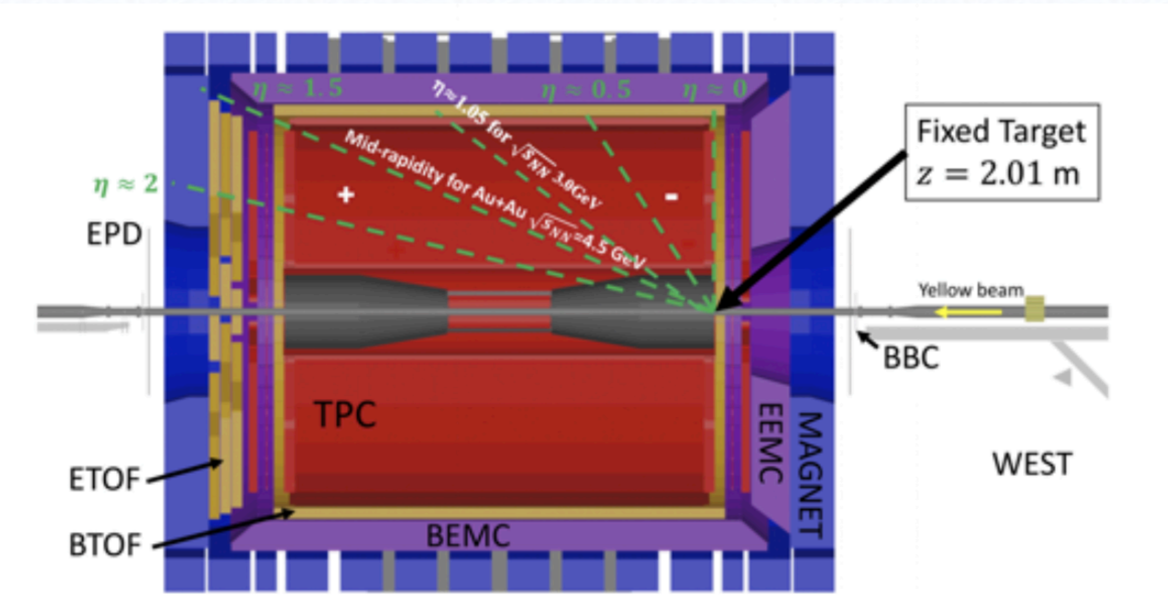


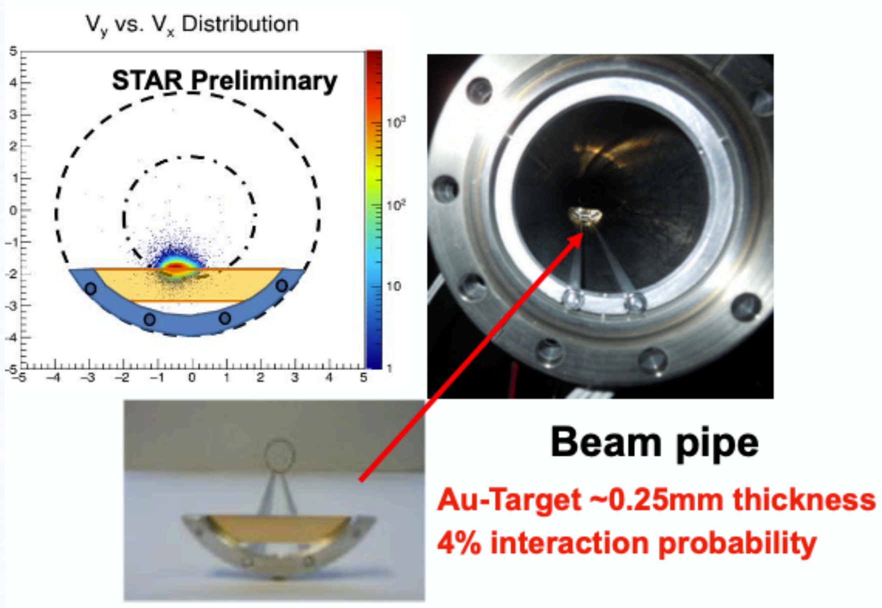


B. Dönigus, Eur. Phys. J. A (2020) 56:280

FXT setup

The beam-going direction is the positive direction



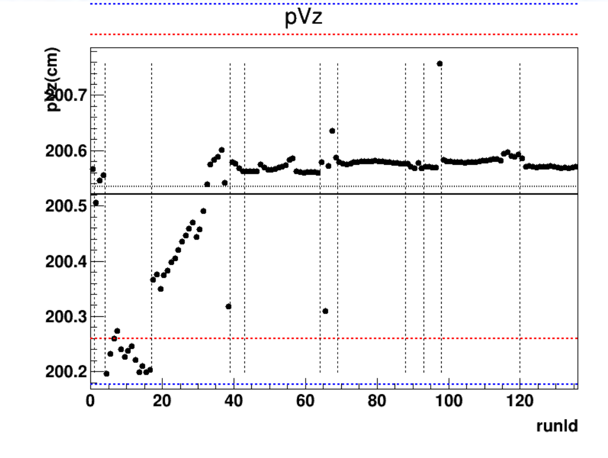


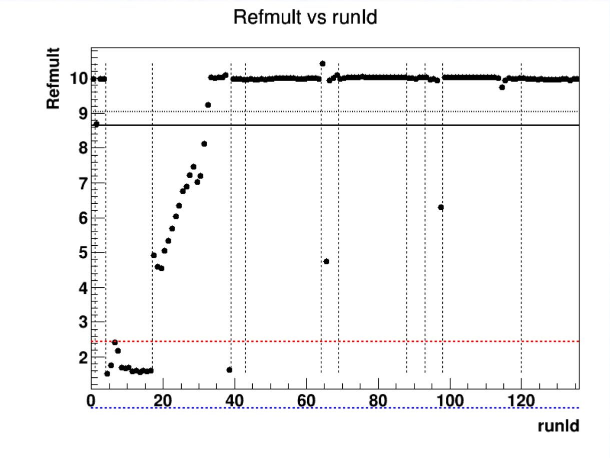
- Rapidity conventions between lab frame and center of mass(CM) frame
  - $y_{MID} = y_{beam}/2$, $y_{beam} = -\cosh^{-1}[\frac{\sqrt{s_{NN}}}{2\, m_p}]$
  - $y_{CM} = -(\, y_{LAB} - y_{MID})$

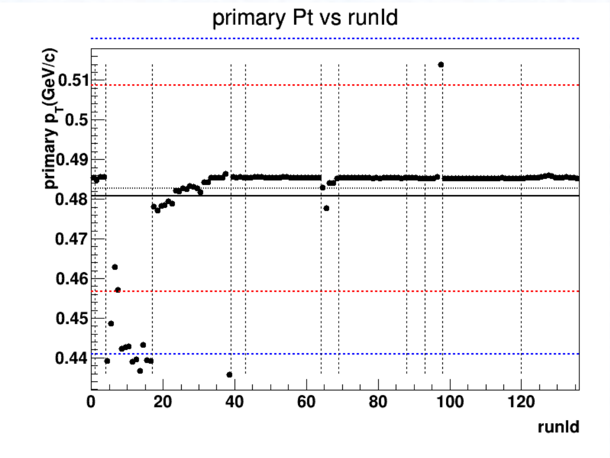
Bad Run selection

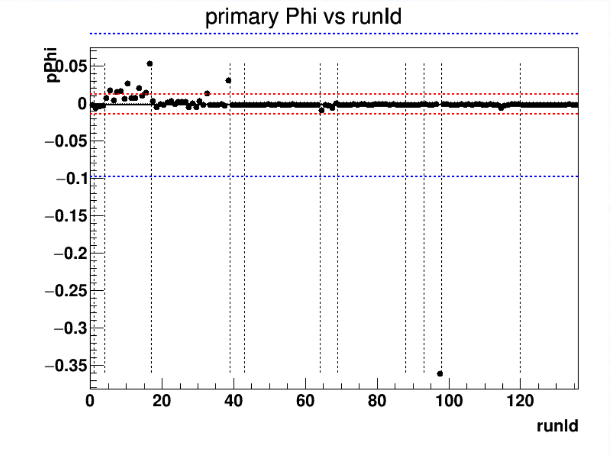
1. Event level and tracking level selection
2. Get the Mean of each variable (<v>) as a function of Run Index
3. Get the Mean and Standard Deviation (SD) for the distribution of <v> from all runs
4. Rejection Window : "|<v>-Mean| > 3*SD"
5. Repeat procedure one time after remove the first round bad run

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N - 1}}$$







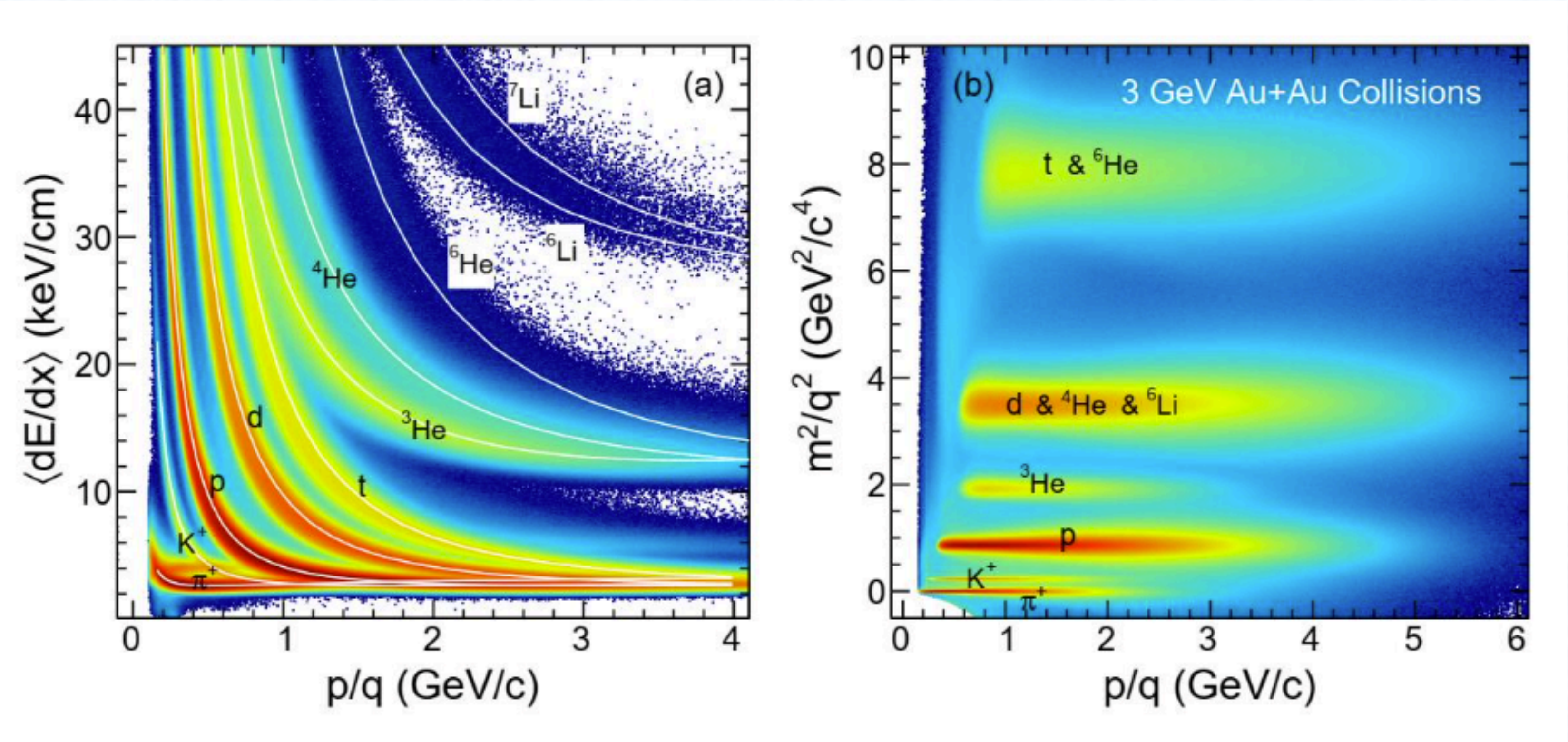


Data set and cuts

- Run18 $\sqrt{s_{NN}}$ = 3.0 GeV Au+Au
  - Trigger 620052
  - MB events ~310M
- Run18 $\sqrt{s_{NN}}$ = 7.2 GeV Au+Au
  - Trigger 630052
  - MB events ~ 150M
- Run19 $\sqrt{s_{NN}}$ = 3.22 GeV Au+Au
  - Trigger 680001
  - MB events ~ 190M

- Event level cut:
  - $V_r(0,-2) < 1.5$ cm
  - $198 < V_z < 202$ cm
- Track level cut:
  - nHits>=15
  - PID: dE/dx selection for Helium, $|n_\sigma| < 3$ for pion and proton
  - Topological cuts for reconstruction

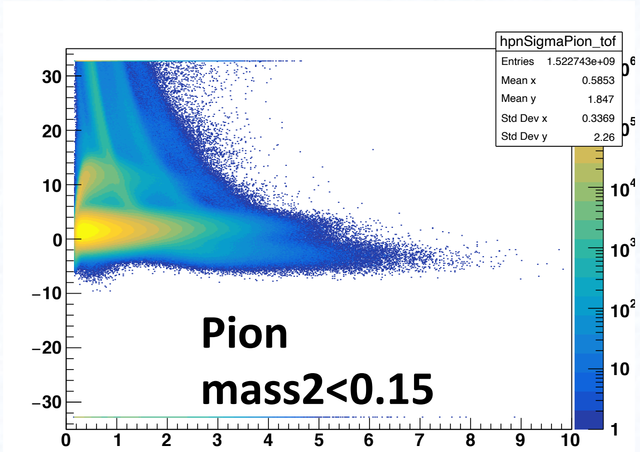
Particle identification(PID) at STAR

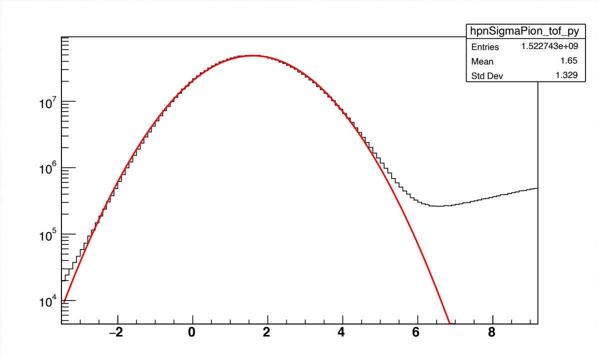


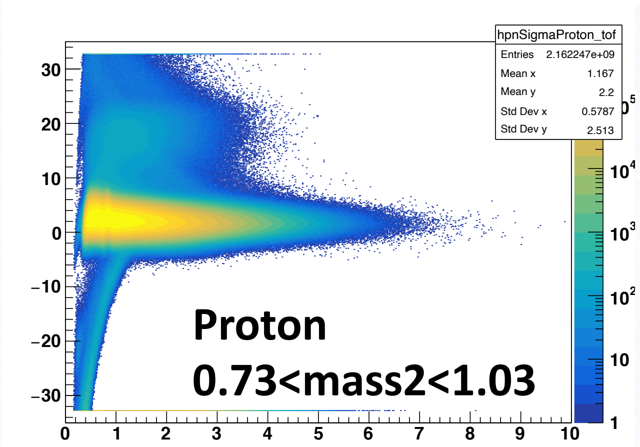
- TPC(dE/dx) and TOF(m2)

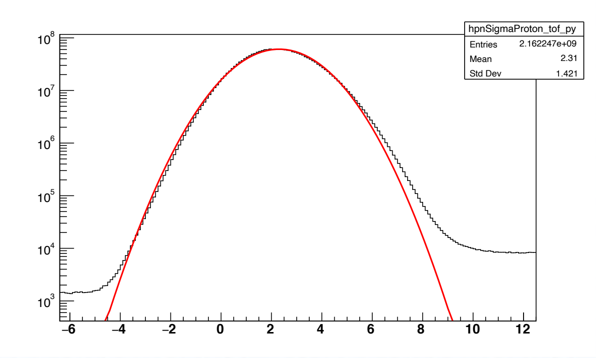
PID check

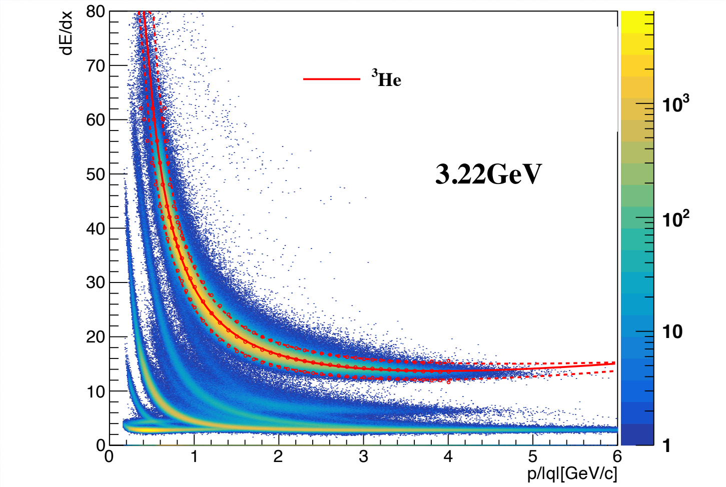
Check the calibration for daughter particles

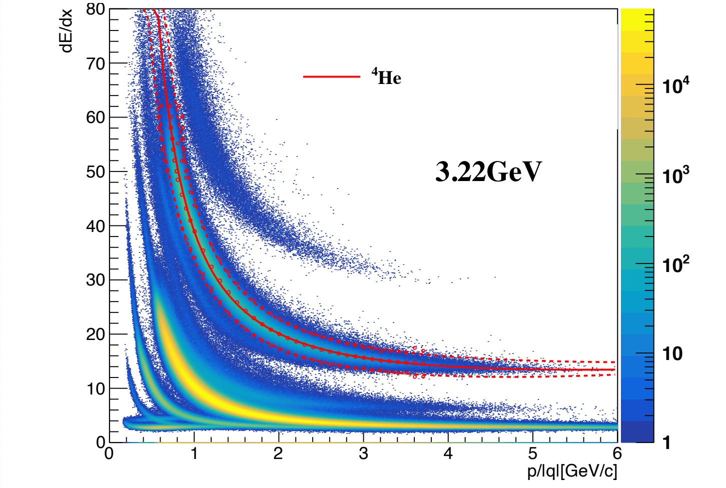




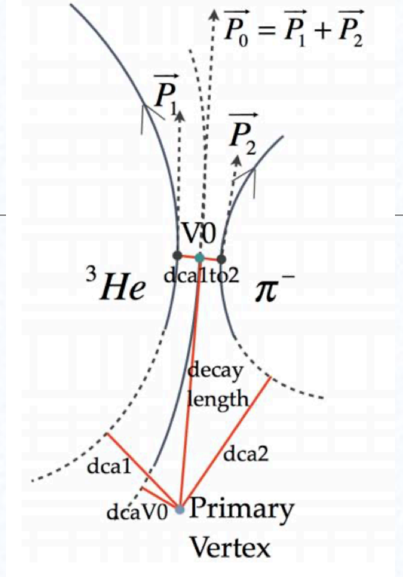








Particle reconstruction



- Use the KFParticle package for particle reconstruction

  State vector — Position, momentum and energy

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

  $\mathbf{C} = \langle \mathbf{r}\mathbf{r}^T \rangle$

  Covariance matrix

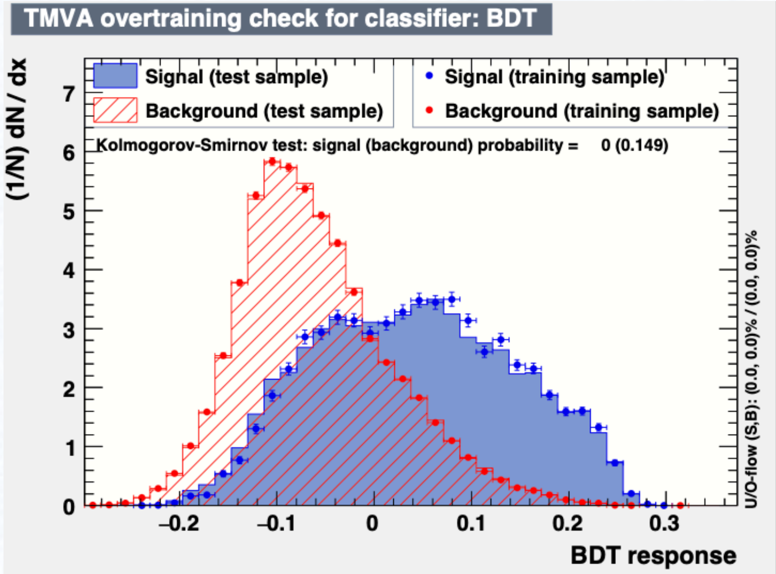
  - Take parameters and their errors into account in reconstruction
  - Analysis cuts based on physical parameters normalized by their respective error:
    - χ^2_{topo}: DCA of mother particle to PV in chi2
    - χ^2_{prim}: DCA of daughter particle to PV in chi2
    - l/dl: normalized decay length

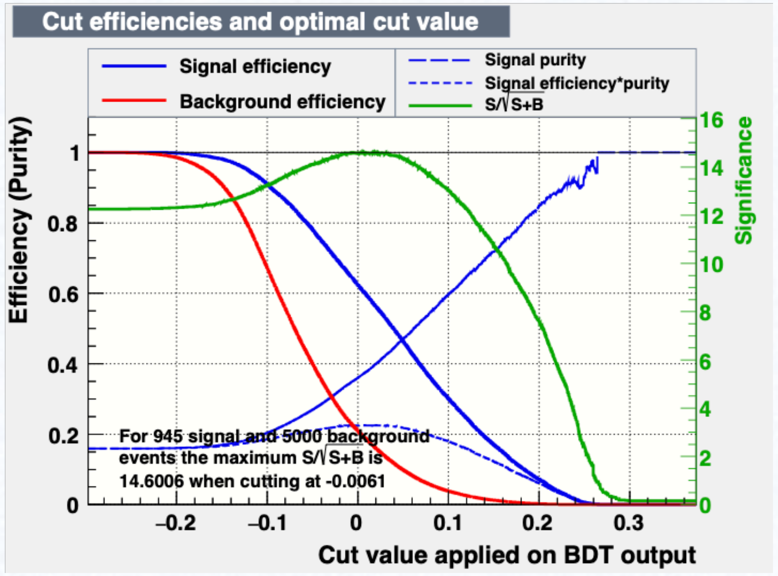
	Decay channels
${}^{3}_{\Lambda}\mathrm{H}$	${}^{3}\mathrm{He} + \pi^-$, ${}^{2}\mathrm{H} + p + \pi^-$
${}^{4}_{\Lambda}\mathrm{H}$	${}^{4}\mathrm{He} + \pi^-$
${}^{4}_{\Lambda}\mathrm{He}$	${}^{3}\mathrm{He} + p + \pi^-$
${}^{5}_{\Lambda}\mathrm{He}$	${}^{4}\mathrm{He} + p + \pi^-$
${}^{4}_{\Lambda\Lambda}\mathrm{H}$	${}^{4}_{\Lambda}\mathrm{He} + \pi^-$, ${}^{3}_{\Lambda}\mathrm{H} + p + \pi^-$
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	${}^{5}_{\Lambda}\mathrm{He} + \pi^-$
${}^{6}_{\Lambda\Lambda}\mathrm{He}$	${}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$

Improve signal: cuts optimization

signal: embedding simulation
background: rotational background from real data

7.2 GeV H4L

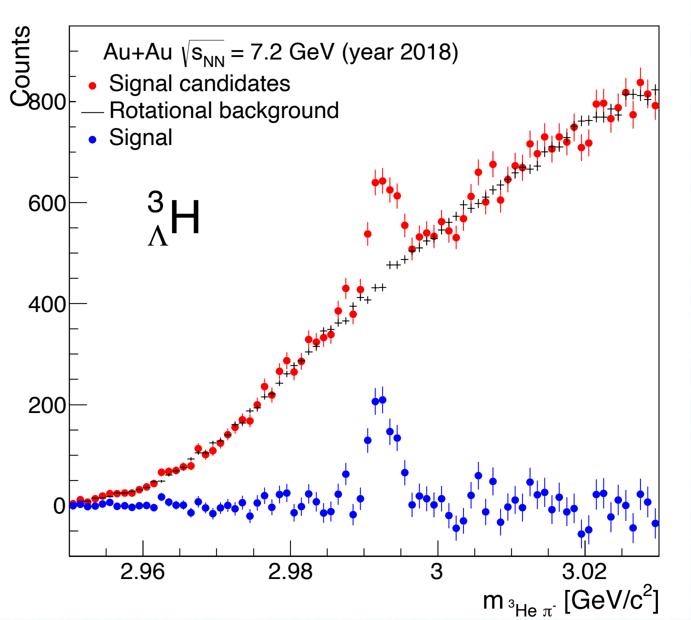


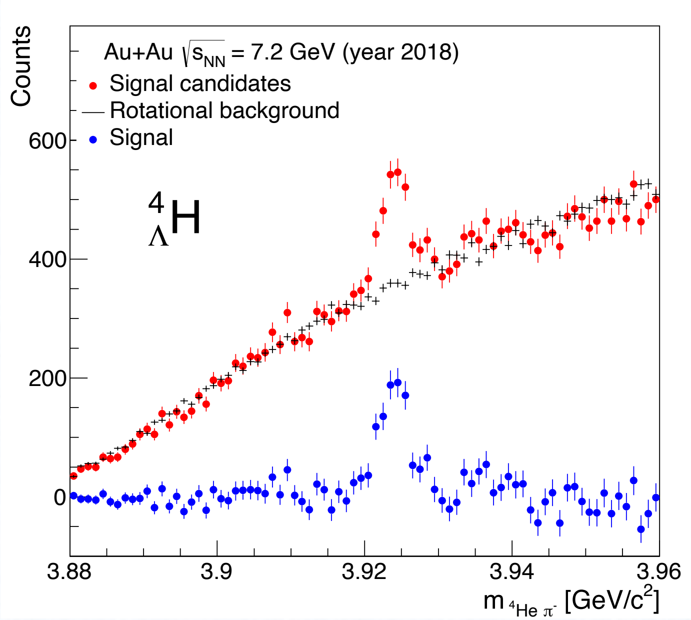


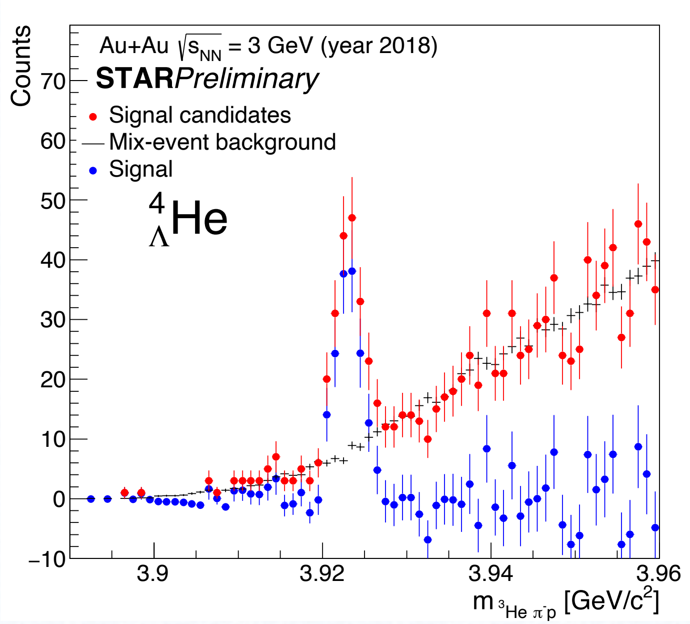
- TMVA (Toolkit for Multivariate Data Analysis)
- Training on multiple variables based on the BDT (Boosted decision tree) method
  - Cut choosing: blance of significance and efficiency

Background reconstruction technics

- Rotational background: rotate daughter particle in transverse plane
- Mix-event background: mix daughter particles from different events
  - For 3-body decay, e.g. for He4L, mix $^{3}\mathrm{He}$ and $p\pi^{-}$ pairs.



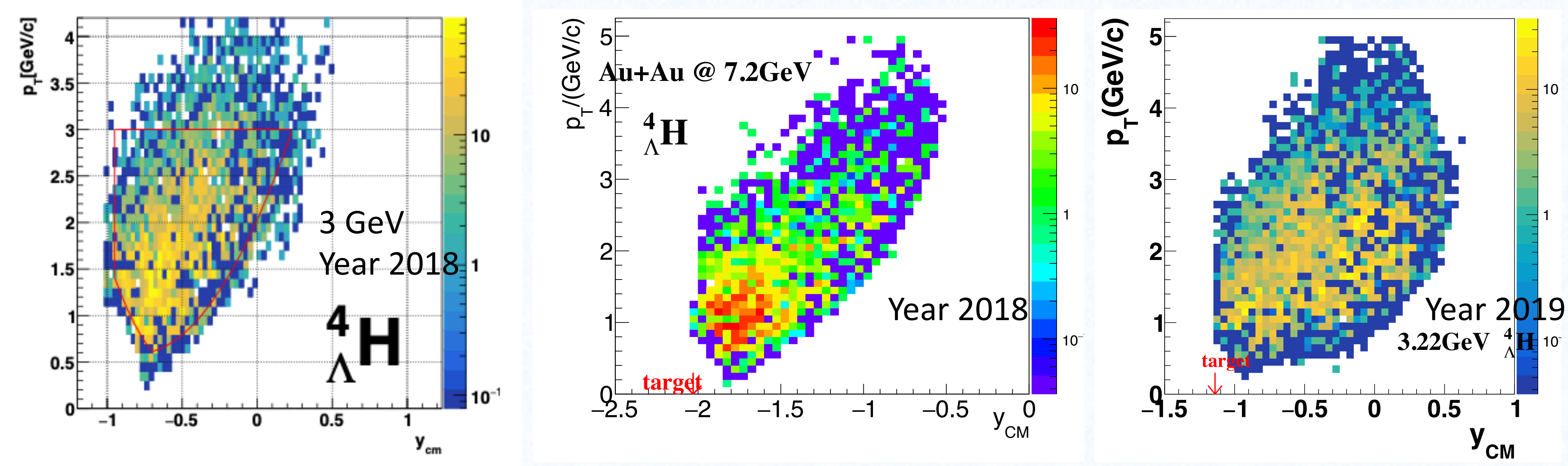




Signal acceptance in CM frame

For FXT collisions,

- $y_{CM} = -(y_{LAB} - y_{MID})$
- for 3GeV, y_{MID}= - 1.05; for 3.22GeV, y_{MID}= -1.14; for 7.2GeV, y_{MID}= - 2.03



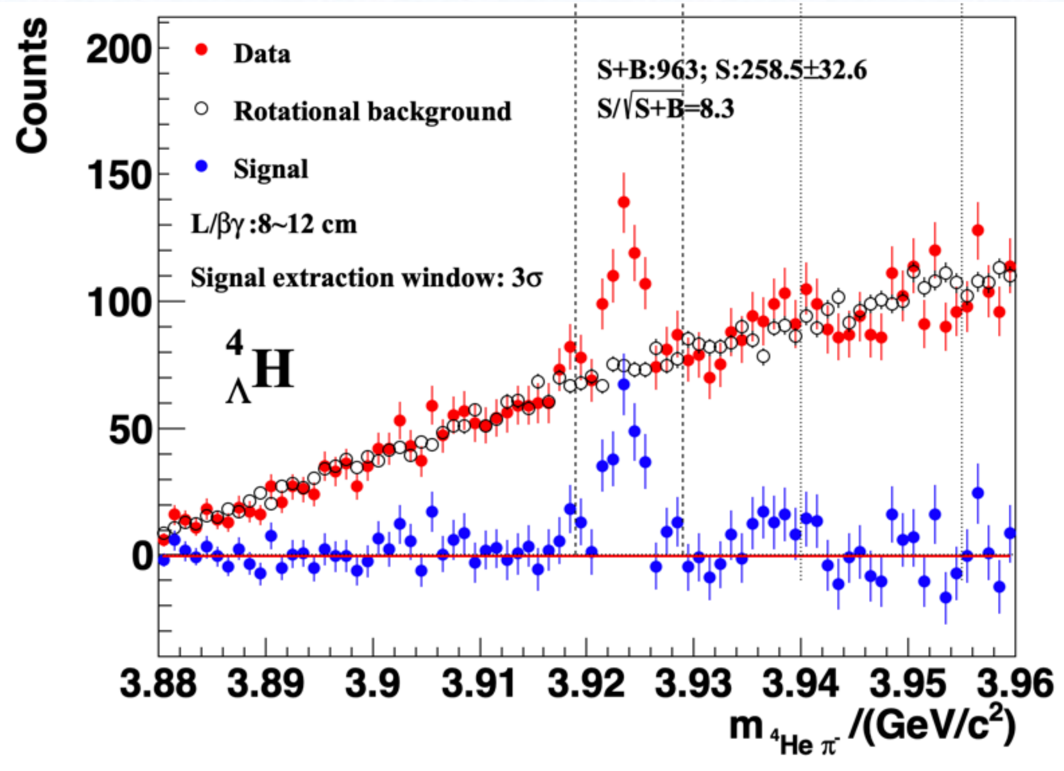
Better coverage for Run2019 with iTPC

Lifetime analysis outline

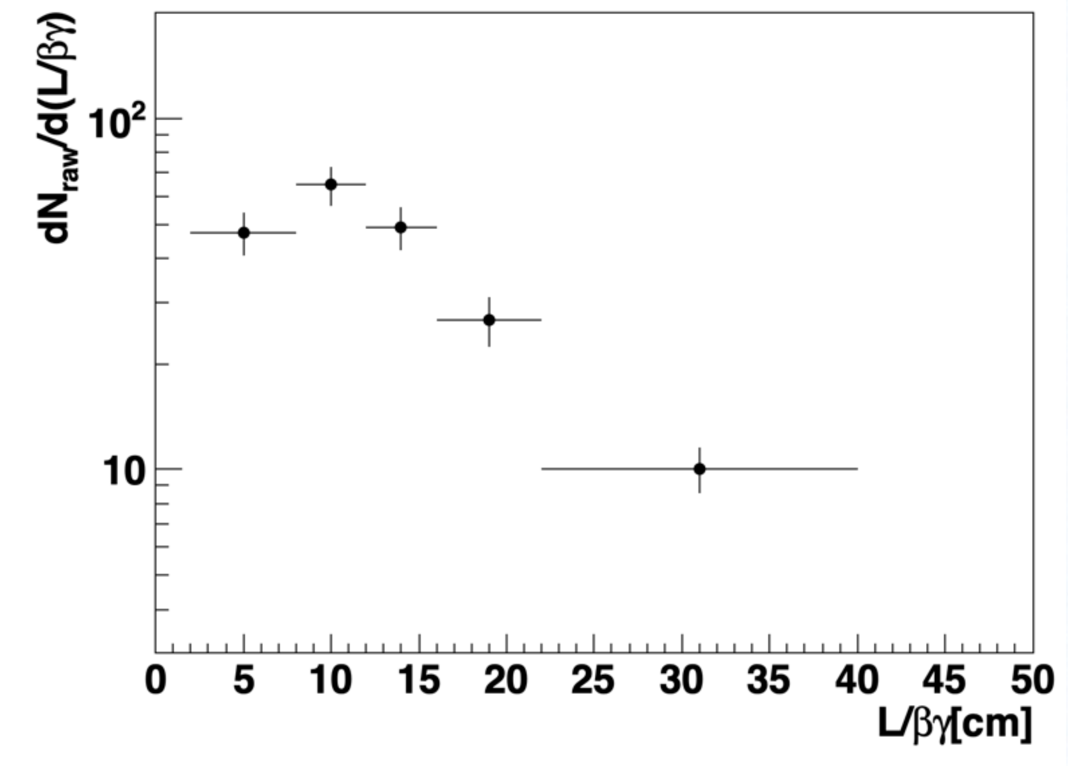
- Measure the signal counts as a function of L/$\beta\gamma$
- Calculate efficiency as a function of L/$\beta\gamma$
- Correct the raw signal counts with efficiency from simulation
- Fit with an exponential to extract the lifetime
  - $\mathrm{N(t)} = \mathrm{N_0 e^{-L/\beta\gamma c\tau}}$, L: decay length
- Systematic uncertainties study

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

An example of H4L @Au+Au 7.2GeV



invariant mass distribution in one L/$\beta\gamma$ bin



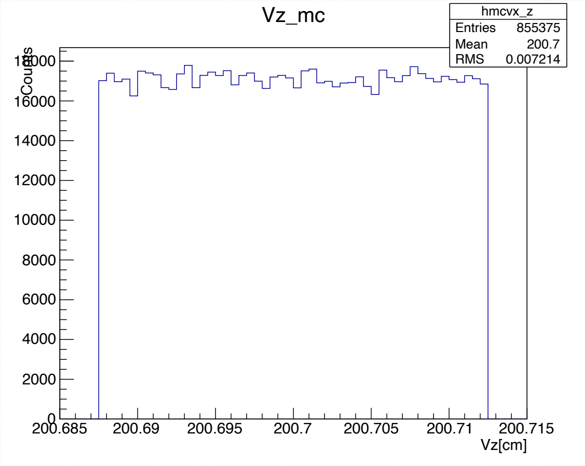
Raw signal counts as a function of L/$\beta\gamma$

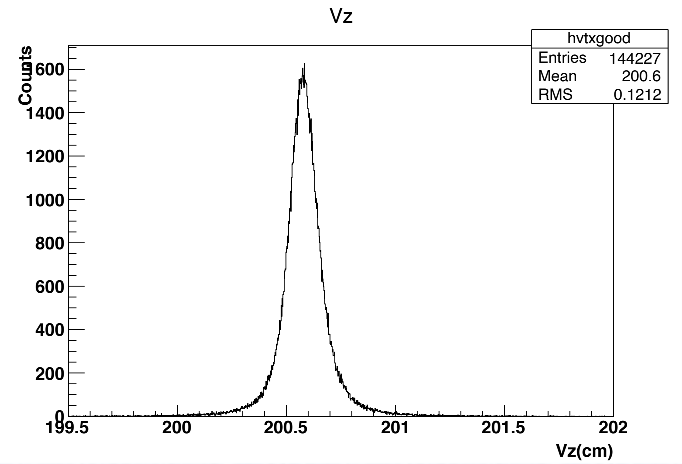
Preparation for efficiency ——embedding QA

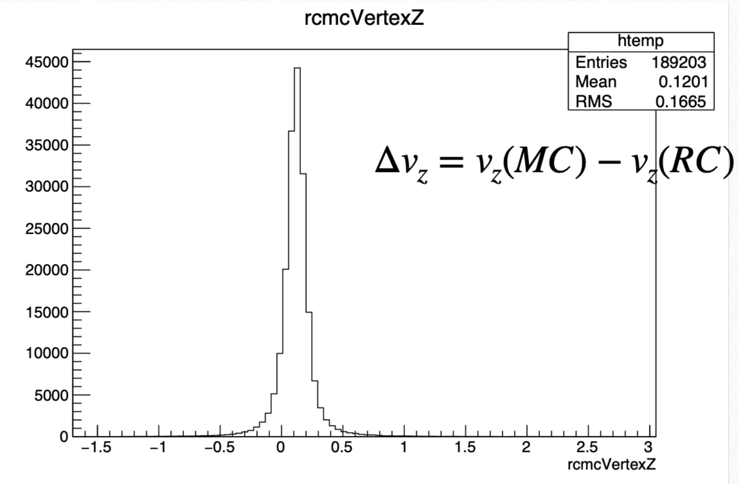
Embedding technique:

- The TPC response to Monte Carlo(MC) hypernuclei and their decay daughters is simulated in the STAR detector deacribed in GEANT3
- Simulated signals are embedded into the real data

Embedding QA: find MC settings that describe the data uncorrectly

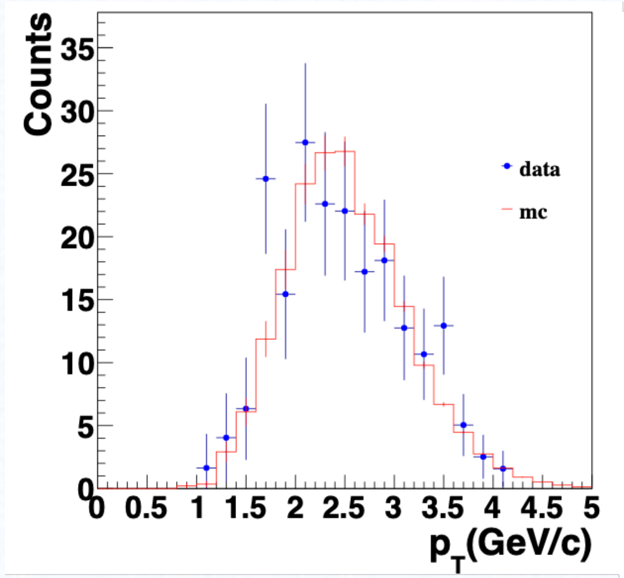


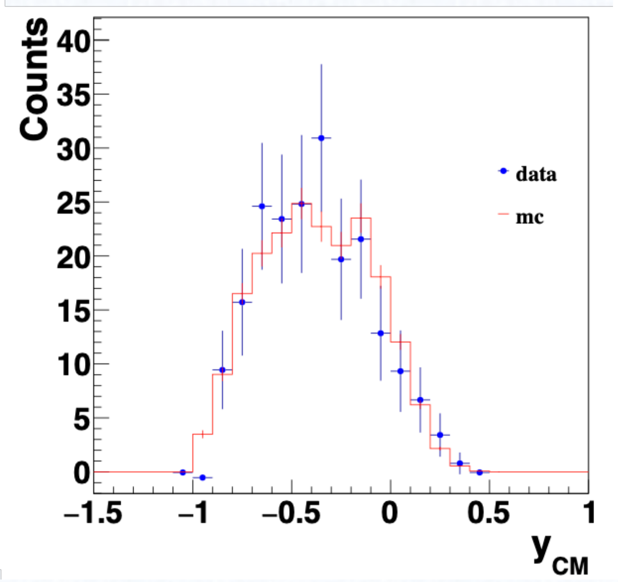


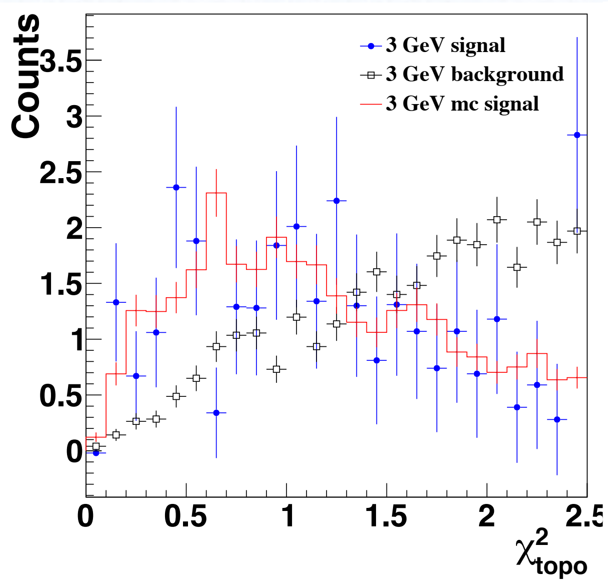


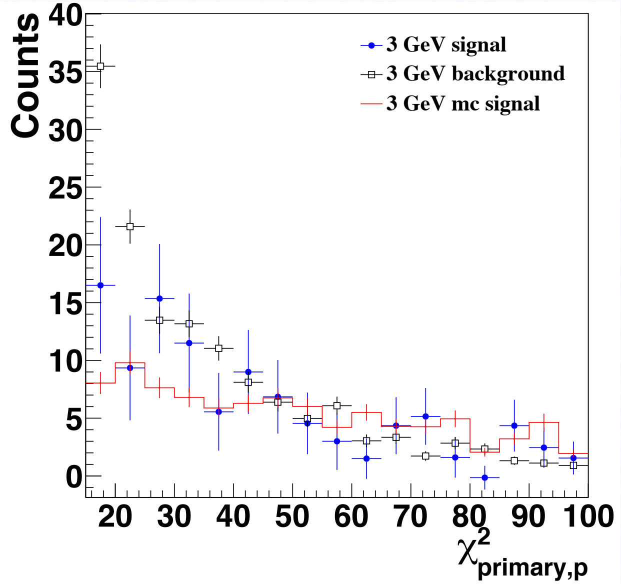
Efficiency from simulation

- Embedding-data tuning:
  - Tune the spectrum in the simulations to match the data
    - Reproduce variable distributions in real data





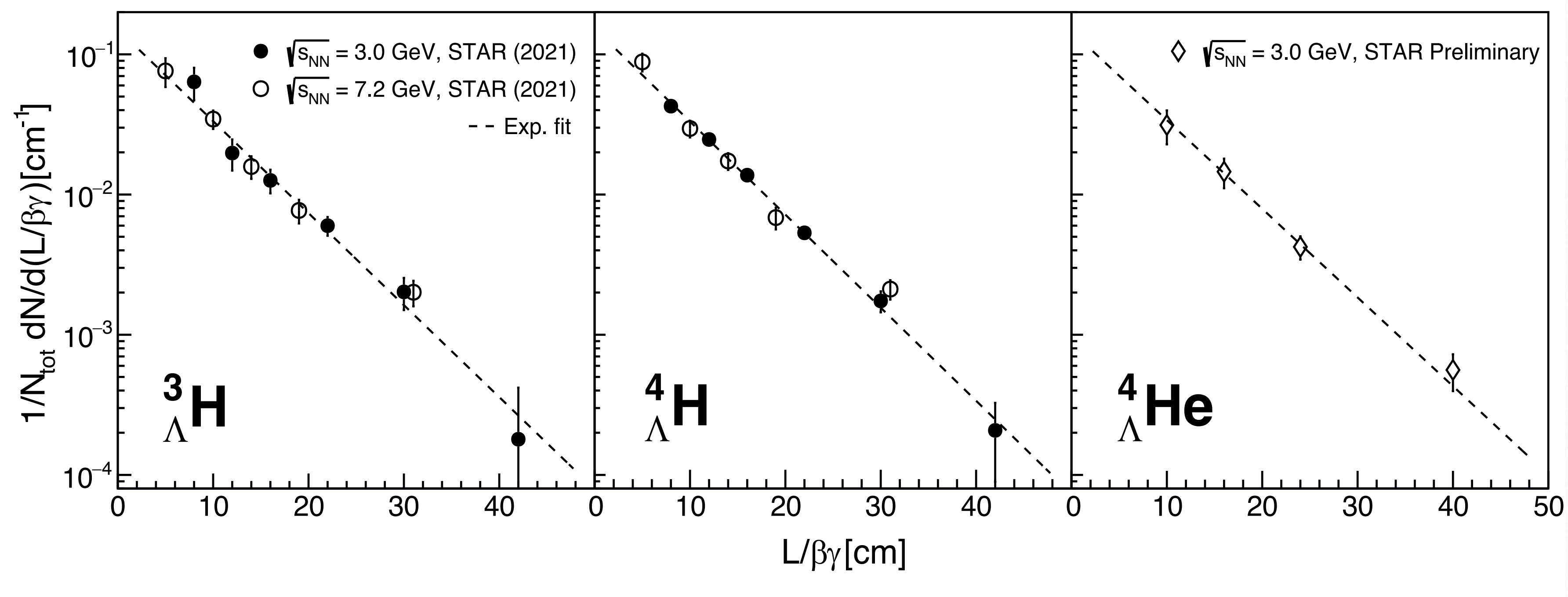




Fit lifetime

Extraction lifetime τ from an exponential fit on the corrected signal counts dN/d(L/$\beta\gamma$) vs. L/$\beta\gamma$

$\tau_{^3_\Lambda H}$ = 221 $\pm$ 15(stat.) $\pm$ 19(syst.) ps
$\tau_{^4_\Lambda H}$ = 218 $\pm$ 6(stat.) $\pm$ 13(syst.) ps
$\tau_{^4_\Lambda He}$ = 229 $\pm$ 23(stat.) $\pm$ 20(syst.) ps



Systematic uncertainties study

Sources taken into account:

- Imperfect description of topological variables between simulations and real data
- Imperfect knowledge in the real kinematic distributions of the hypernuclei
- Mismatch of single track efficiency between simulations and data
- Uncertainties related to the background subtraction technique

7.2 GeV syst. Err:.

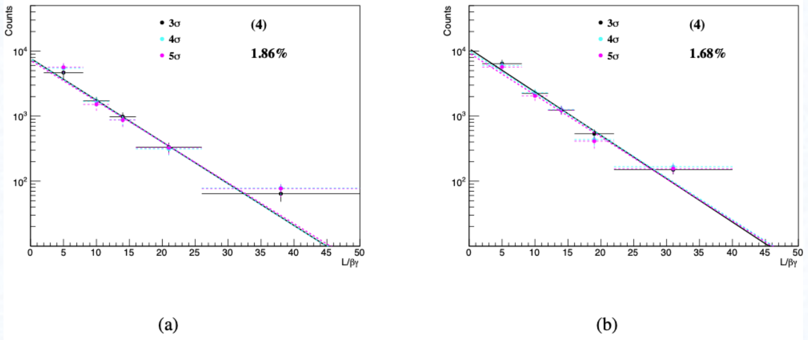


FIG. 20. Extracted lifetime with different counting window for ${}^{3}_{\Lambda}H$ (left) and ${}^{4}_{\Lambda}H$ (right).

syst. uncertainty	${}^{3}_{\Lambda}H$	${}^{4}_{\Lambda}H$
Analysis cuts	3.92%	4.25%
Input MC	5.32%	1.74%
Tracking efficiency	3.27%	1.14%
Signal extraction	1.86%	1.68%
Total	7.60%	5.02%

Eliminate stat. fluctuations from syst. errors

Eliminate errors due to statistical fluctuations:

Difference between default value and variation cut value:

$$\Delta = |\tau_{default} - \tau_{variation}|$$

Statistic error on the difference:

$$\sigma_{\Delta} = \sqrt{|\sigma^2_{default} - \sigma^2_{variation}|}$$

If($\Delta > \sigma_{\Delta}$),systematic err: $\sigma_{sys} = \sqrt{\Delta^2 - \sigma^2_{\Delta}}$

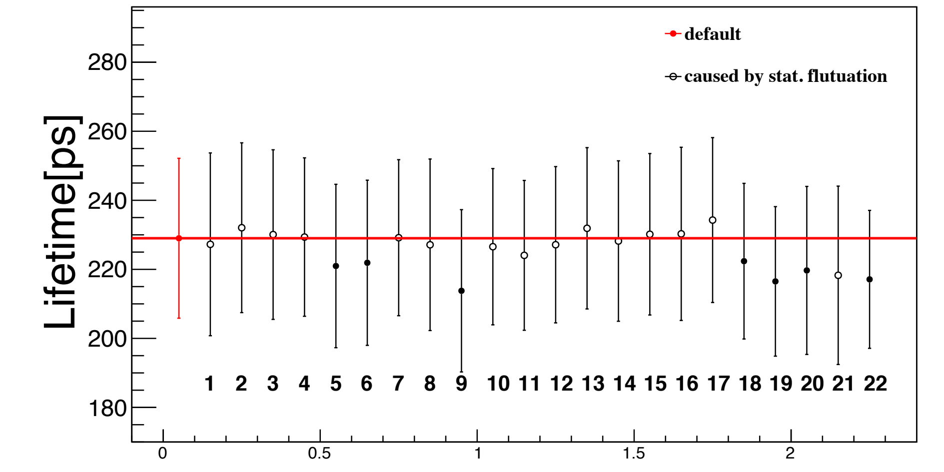
For multiple variations of a variable:

$$\sigma_{sys,var} = \sqrt{\frac{(\sigma^{cut_1}_{sys})^2 + (\sigma^{cut_2}_{sys})^2 + \ldots + (\sigma^{cut_n}_{sys})^2}{n}}$$

Total sys.err: add all systematic source in quadrature

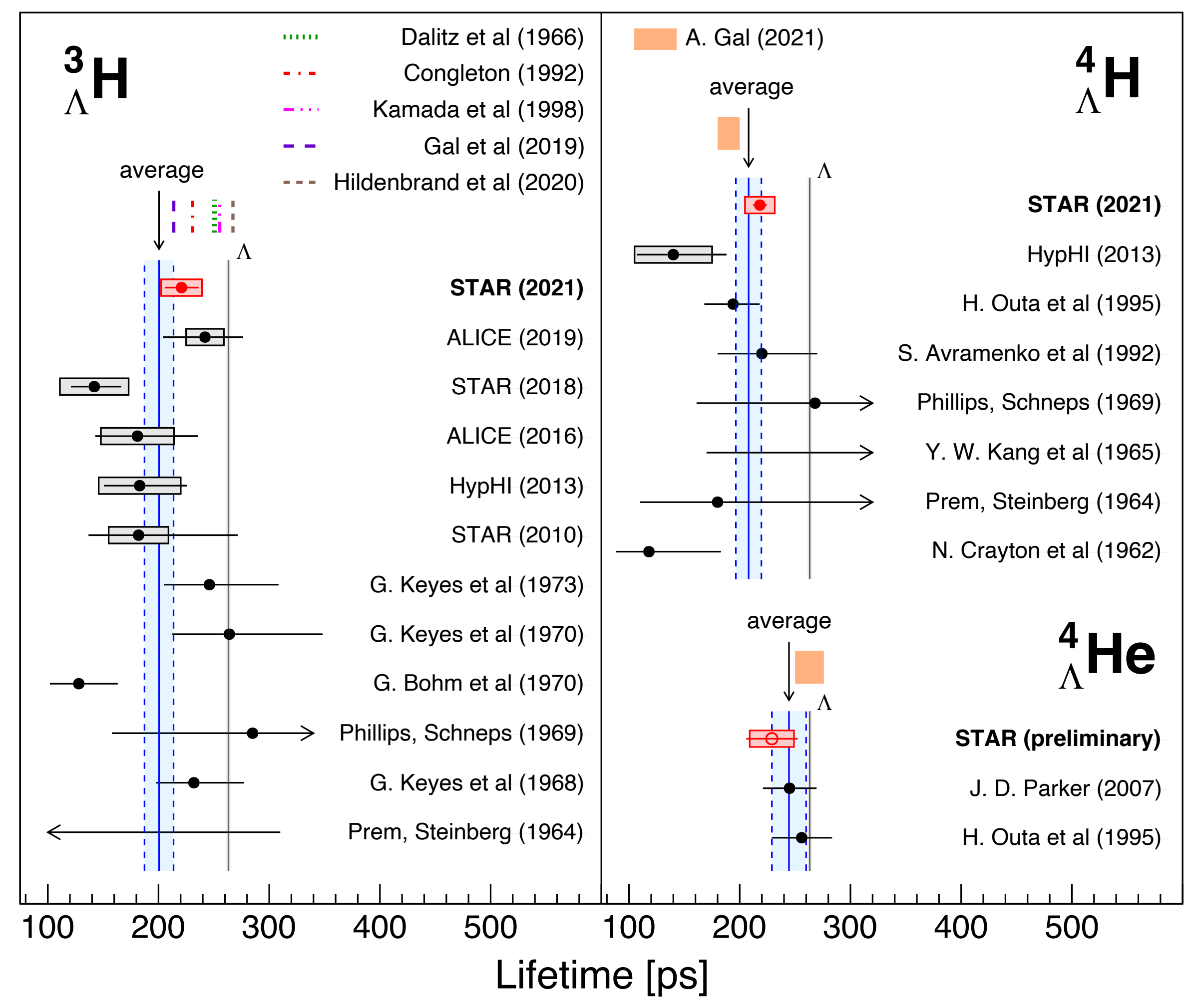
$$\sigma^{tot}_{sys} = \sqrt{(\sigma_{sys,var_1})^2 + (\sigma_{sys,var_2})^2 + \ldots}$$

3GeV He4L syst. err:



systematic uncertainty	
(1) topo cuts	6.81%
(2) input mc	4.11%
(3) minimum nhits	3.38%
(4) signal extraction window	0.91%
Total	8.69%

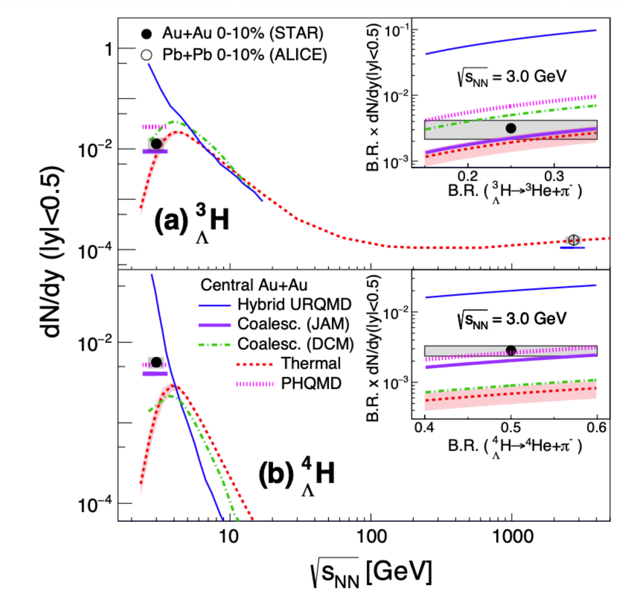
Lifetime results



- **The averaged $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetimes are both shorter than τ_{Λ} by ~ 20%.**
- **The $^{4}_{\Lambda}He$ lifetime is consistent with former measurements and theoretical prediction.**
- **$\frac{\tau_{^{4}_{\Lambda}H}}{\tau_{^{4}_{\Lambda}He}} = 0.85 \pm 0.07$, consistent with theoretical estimations: 0.74 ± 0.04**
  (A. Gal arXiv 2108.10179, 2022)

Motivation - hypernuclei yield

- Investigate hypernuclei yield dependence with energy to give information on production mechanisims
  - Little measurement at low collision energies
  - Expect enhancement of hypernuclei production



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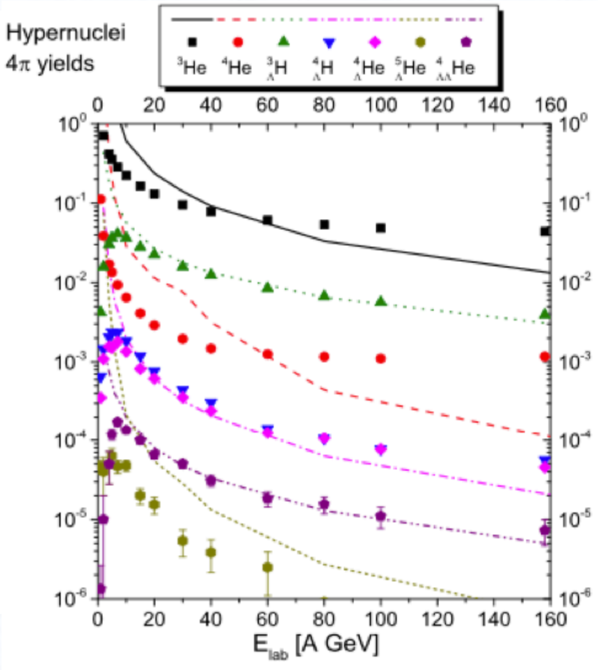


PLB 714(2012)85-91

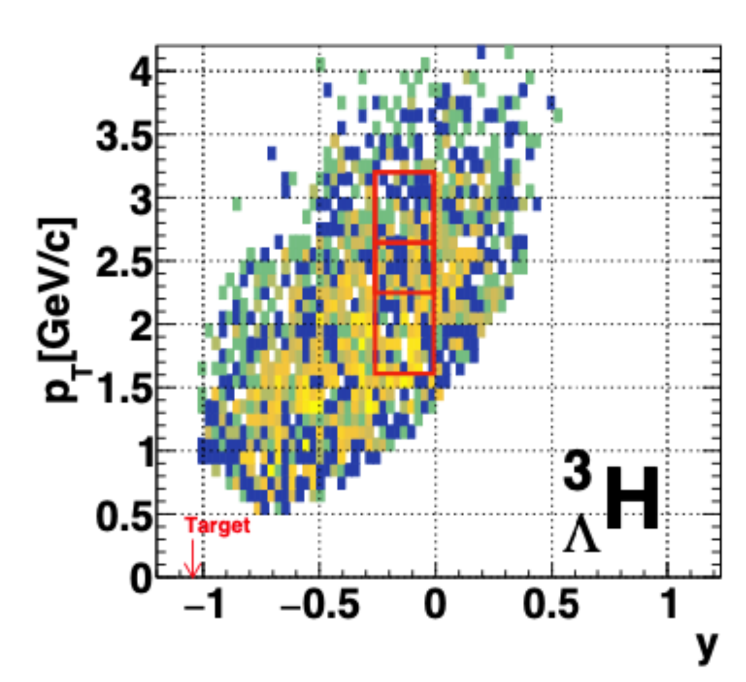
- Isospin effect: $^{4}_{\Lambda}$He and $^{4}_{\Lambda}$H
  - Close Λ binding energy:

$B_{\Lambda}(^{4}_{\Lambda}H)$= 2.22 ± 0.06(stat.) ± 0.09(syst.) MeV

$B_{\Lambda}(^{4}_{\Lambda}He)$= 2.38 ± 0.13(stat.) ± 0.06(syst.) MeV

Yield analysis outline

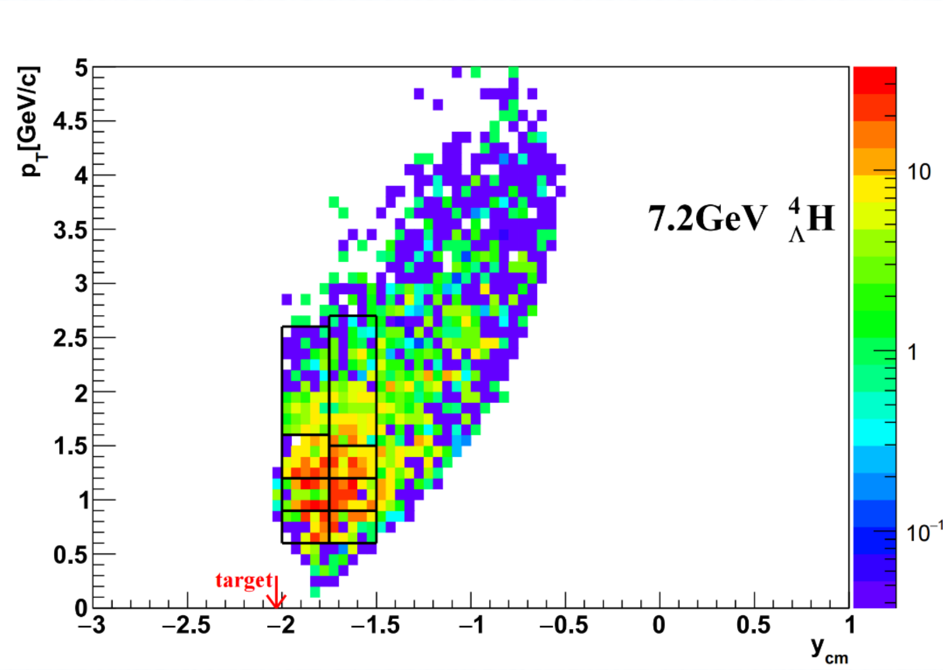
- Measure the signal counts in different y and pt bins
- Calculate efficiency in different y and pt bins
- Correct the raw signal counts with efficiency from simulation
- Fit pt spectrum, get dN/dy

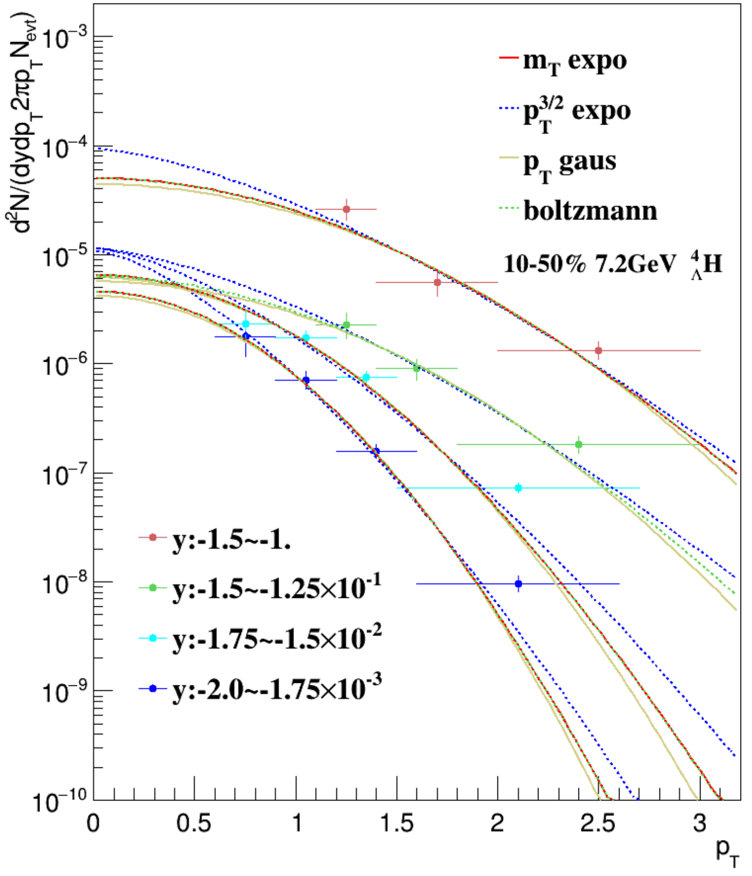


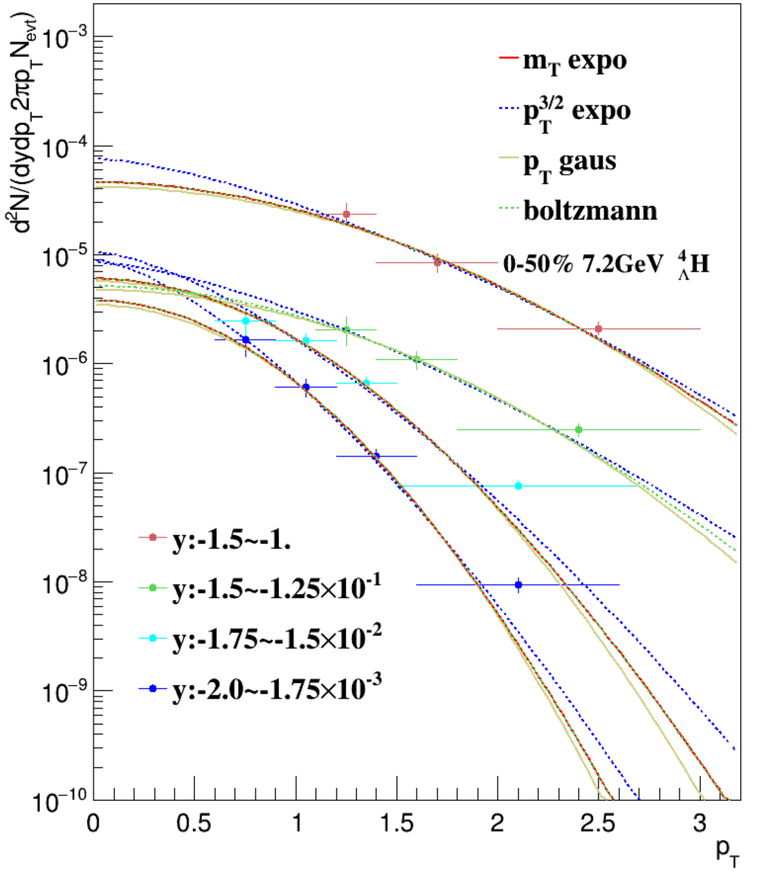
Do these procedures in different centrality

${}^{4}_{\Lambda}\mathrm{H}$ p_T spectrum study at 7.2GeV

Keep significance > 3 for each bin

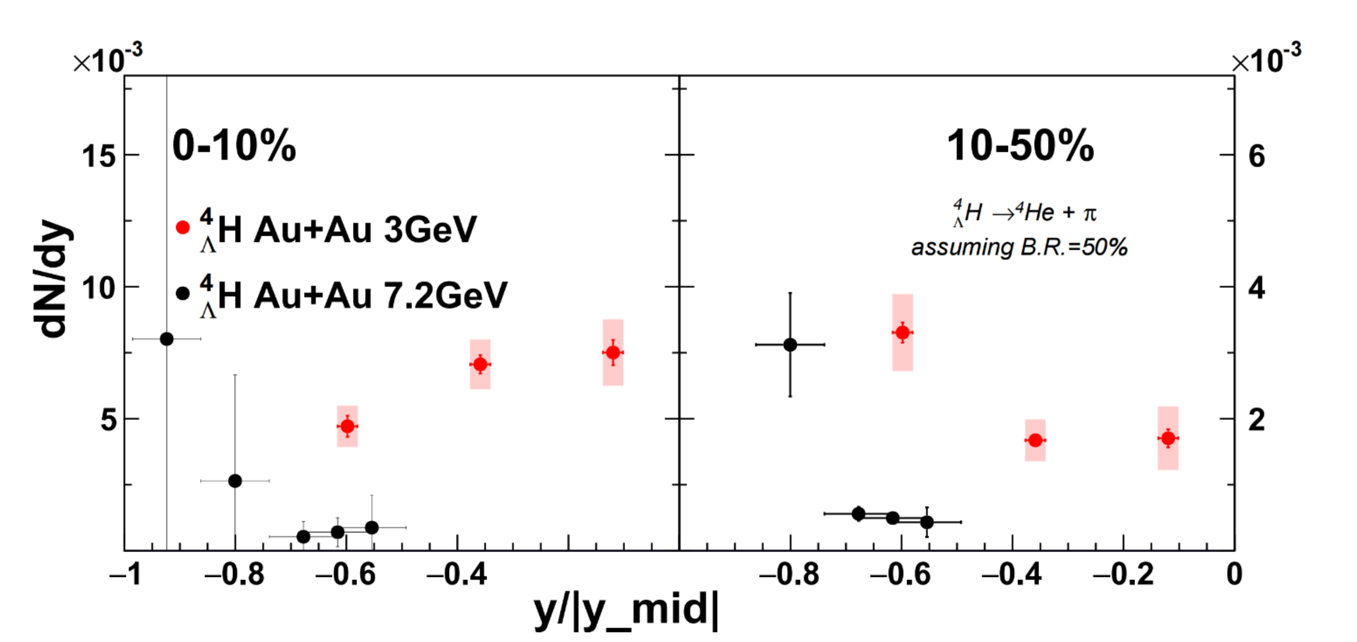


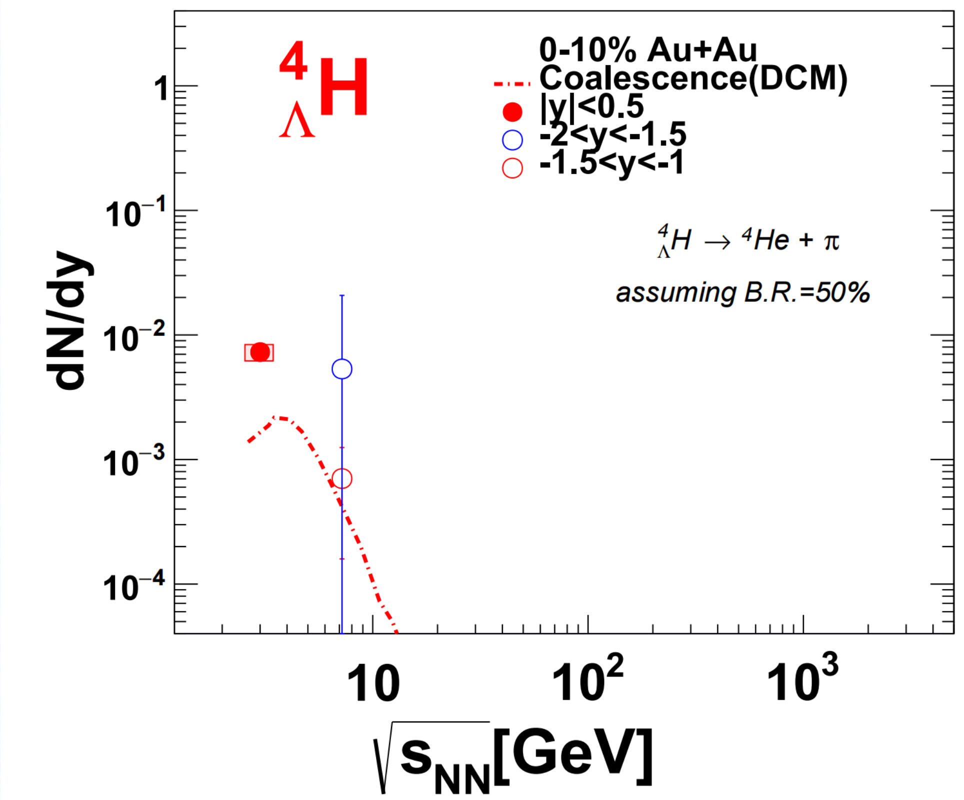




Bad mid-rapidity coverage

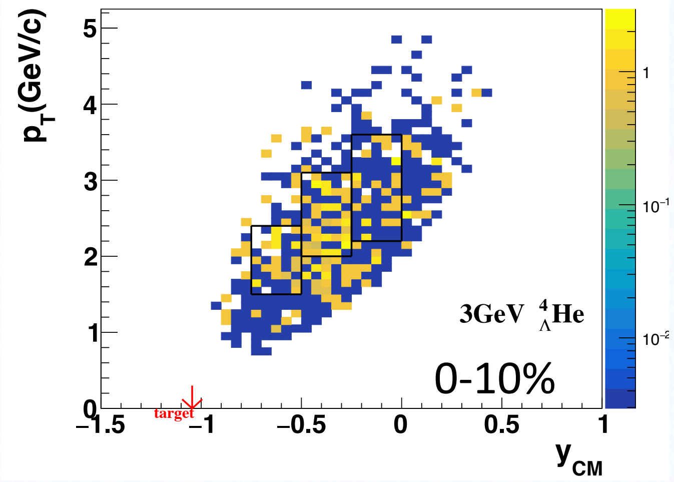
${}^{4}_{\Lambda}H$ yield study at 7.2 GeV

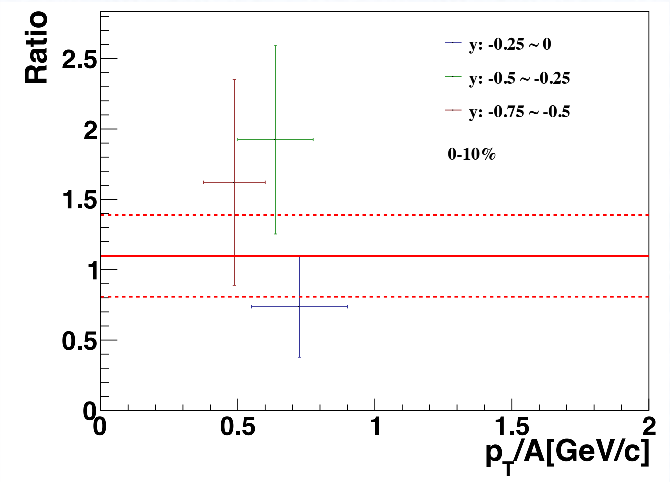


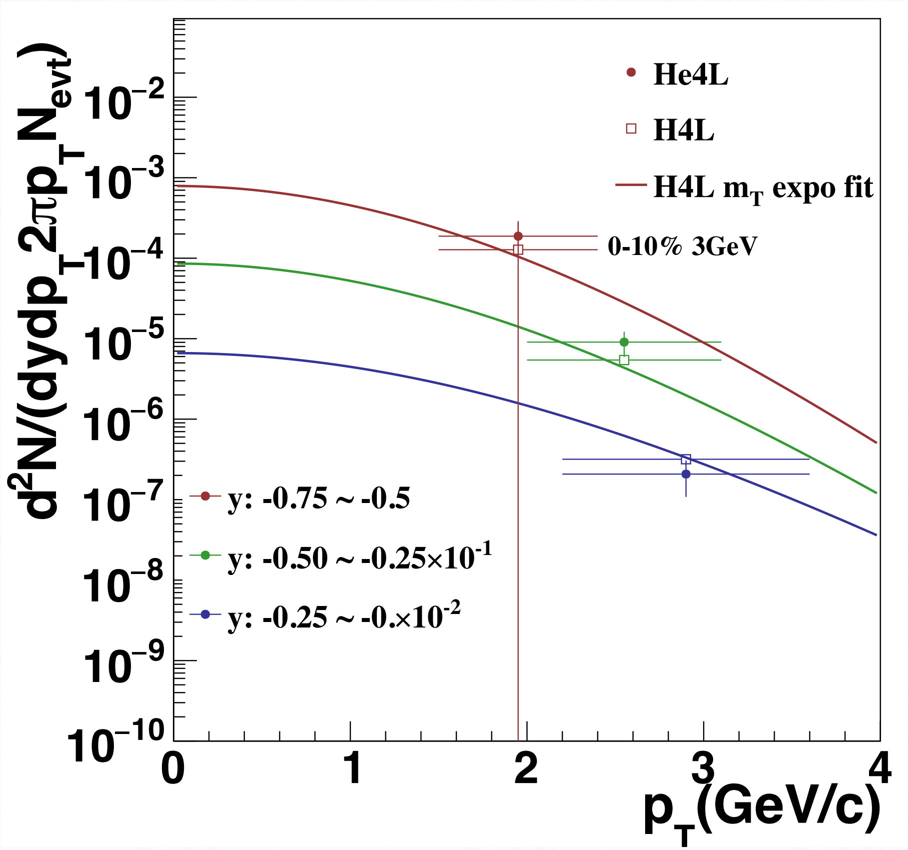


Bad mid-rapidity coverage @7.2GeV

${}^{4}_{\Lambda}$He yield study at 3GeV and ${}^{4}_{\Lambda}$He / ${}^{4}_{\Lambda}$H ratio





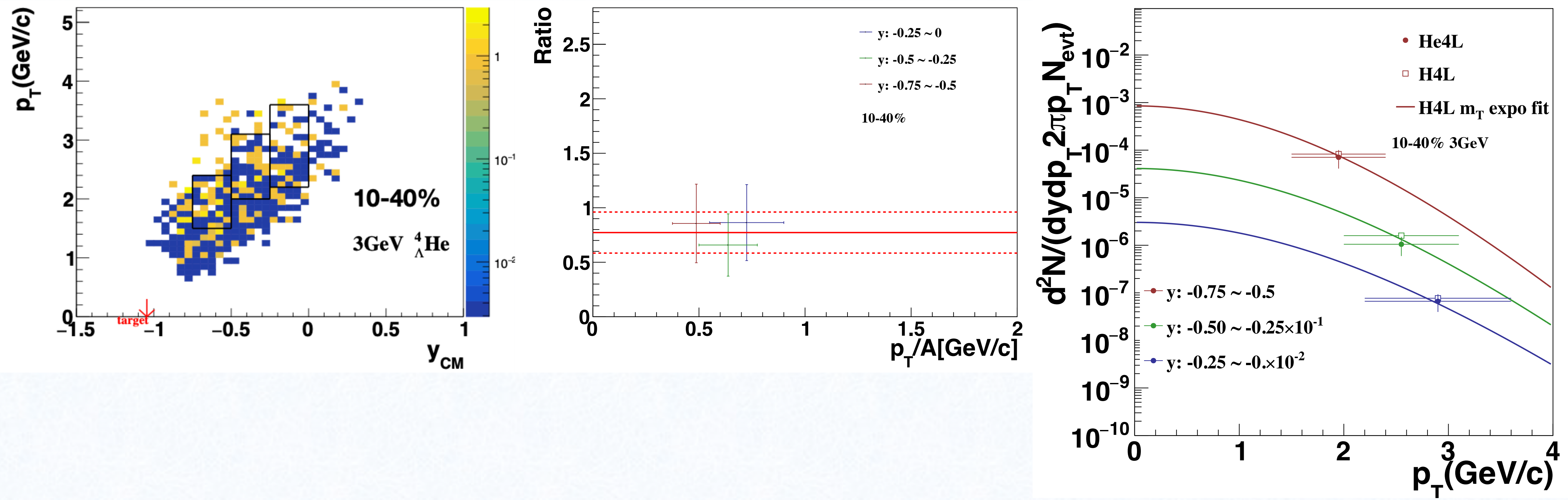


${}^{4}_{\Lambda}$He signal significance is not enough for yield study.

Hard to study ${}^{4}_{\Lambda}$He, ${}^{4}_{\Lambda}$H spectrum difference.

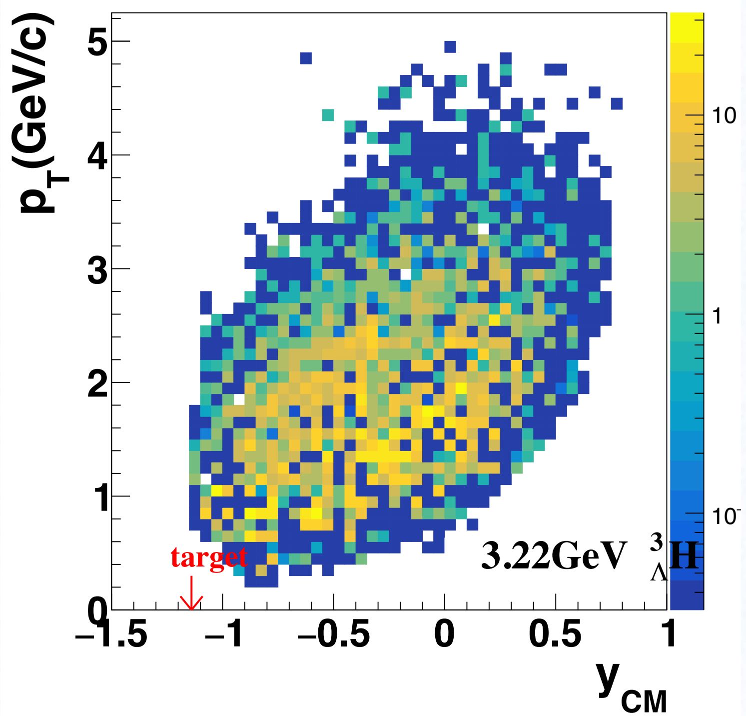
We check ${}^{4}_{\Lambda}$He / ${}^{4}_{\Lambda}$H ratio in same pt and y bins. With large errors, we can't draw a conclusion.

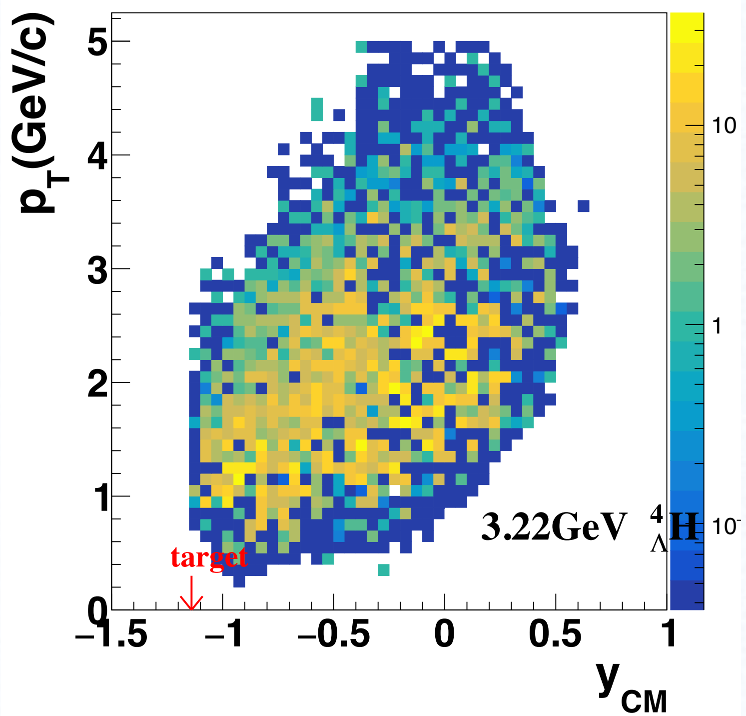
${}^{4}_{\Lambda}He$ yield study at 3GeV and ${}^{4}_{\Lambda}He$ / ${}^{4}_{\Lambda}H$ ratio

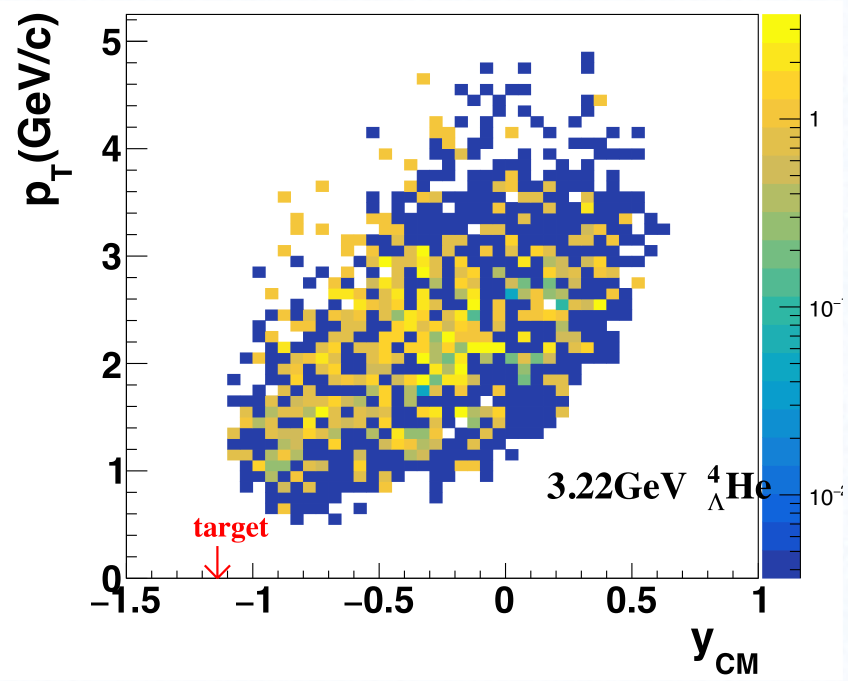


We hope for pt spectrum and yield differences for ${}^{4}_{\Lambda}He$ and ${}^{4}_{\Lambda}H$.

Good acceptance at 3.22 GeV







First look at 3.22 GeV without cut optimization

- Good mid-rapidity coverage
- Hopeful for yield study at 3.22 GeV

To do: energy scan

- Run19 $\sqrt{s_{NN}}$ = 3.22 GeV Au+Au
  - Trigger 680001
  - MB events ~ 190M
- 3.22 GeV hypernuclei cuts optimization
- 3.22 GeV centrality definition
- Request embedding for 3.22 GeV hypernuclei
- Hypernuclei lifetime and yield analysis

$\sqrt{s_{NN}}$ (GeV)	E_{beam} (GeV)	y_{CM}	Year Collected
3.0	3.85	1.05	2018 & 2019
3.2	4.59	1.14	2019
3.5	5.75	1.25	2020
3.9	7.3	1.37	2019 & 2020
4.5	9.8	1.52	2020
5.2	13.5	1.68	2020
6.2	19.5	1.86	2020
7.2	26.5	2.03	2018
7.7	31.2	2.10	2019 & 2020

MORE DATASETS WAITING…

```
pp500_production_2017/      production_19GeV_2019/              production_4p59GeV_fixedTarget_2019/
production_14p5GeV_2019/    production_31GeV_fixedTarget_2019/  production_7.3GeV_fixedTarget_2019/
```

To do: double Λ hypernuclei

Based on ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$ and ${}^{5}_{\Lambda}\mathrm{He}$ reconstruction, we can reconstruct ${}^{4}_{\Lambda\Lambda}\mathrm{H}$, ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ in the mean time.

	Decay channels
${}^{3}_{\Lambda}\mathrm{H}$	${}^{3}\mathrm{He}+\pi^-$, ${}^{2}\mathrm{H}+\mathrm{p}+\pi^-$
${}^{4}_{\Lambda}\mathrm{H}$	${}^{4}\mathrm{He}+\pi^-$
${}^{4}_{\Lambda}\mathrm{He}$	${}^{3}\mathrm{He}+\mathrm{p}+\pi^-$
${}^{5}_{\Lambda}\mathrm{He}$	${}^{4}\mathrm{He}+\mathrm{p}+\pi^-$
${}^{4}_{\Lambda\Lambda}\mathrm{H}$	${}^{4}_{\Lambda}\mathrm{He}+\pi^-$, ${}^{3}_{\Lambda}\mathrm{H}+\mathrm{p}+\pi^-$
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	${}^{5}_{\Lambda}\mathrm{He}+\pi^-$
${}^{6}_{\Lambda\Lambda}\mathrm{He}$	${}^{5}_{\Lambda}\mathrm{He}+\mathrm{p}+\pi^-$

Paper and presentation

- Paper

Xiujun Li et al., Temperature Fluctuation and the Specific Heat in Au+Au Collisions at Collision Energies from 5 to 200 GeV, Nuclear Physics Review 36(4), 395-399, 2019.12.20

STAR Collaboration, Measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ Lifetimes and Yields in Au+Au Collisions in the High Baryon Density Region, arXiv 2110.09513

- Presentation

Poster, CNPC 2019, "Temperature Fluctuation and the Specific Heat in Au+Au Collisions at $\sqrt{s_{NN}} = 7 - 200$ GeV in AMPT model", China, August 16-20, 2019.

Poster, Quark Matter 2019, "Temperature Fluctuation and the Specific Heat in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 7.7 - 200$ GeV from AMPT model and STAR", China, November 3-9, 2019.

Talk, The 14th workshop on QCD phase transition and relativistic heavy-ion physics (QPT 2021), "Lifetime measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 7.2$ GeV from STAR experiment", China, July 26-30, 2021.

Poster, The 13th China Particle Physics Conference, "Lifetime measurements of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 7.2$ GeV from STAR experiment", China, August 16-19, 2021.