Multiplicity dependence of hyperon and hypertriton production in Zr+Zr and Ru+Ru collisions at $\sqrt{s_{NN}}$ = 200 GeV

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Strasbourg 2024

Hypernuclei and their production mechanisms

◉ Hypernuclei: bound state of hyperon and nucleon

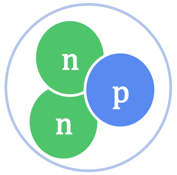
- Natural laboratory to study hyperon-nucleon (Y-N) interactions

◉ Hypernuclei production

- Cosmic ray
- e/K beams bombard onto the fixed nuclear target
- Heavy-ion collisions
  - Forward rapidity: projectile fragmentation + hyperon capture
  - Mid-rapidity: still not clear

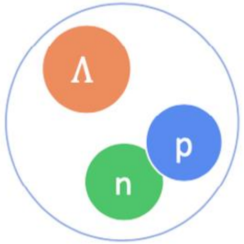
Triton

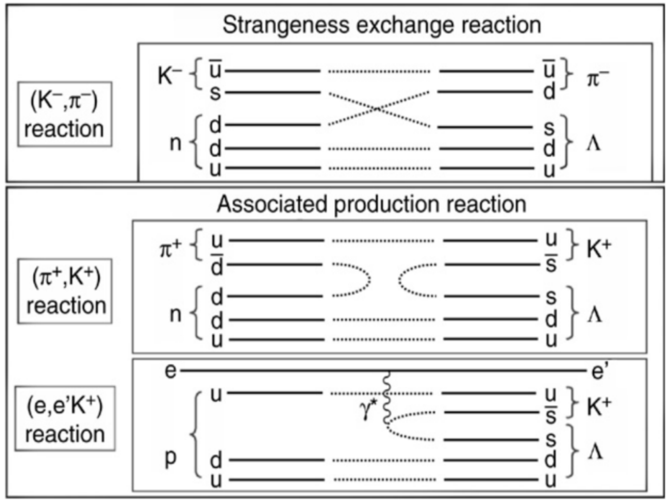
$^{3}\mathrm{H}$



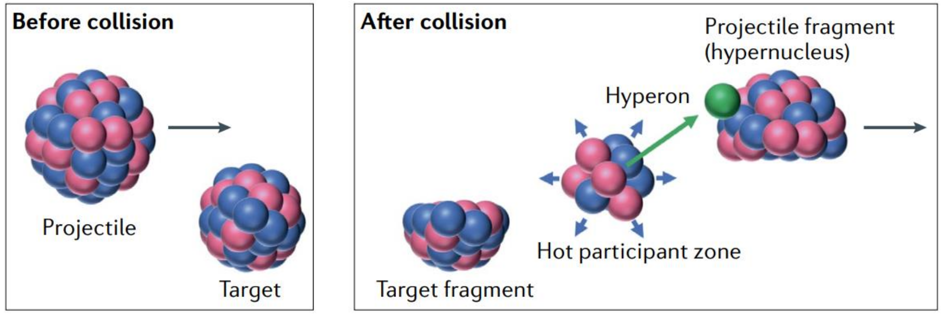
Hypertriton

$^{3}_{\Lambda}\mathrm{H}$





A. Feliciello, T. Nagae
Prog.Part.Nucl.Phys. 57, 564-653 (2006)



T. R. Saito et.al. ,
Nature Reviews Physics 3, 803–813 (2021)

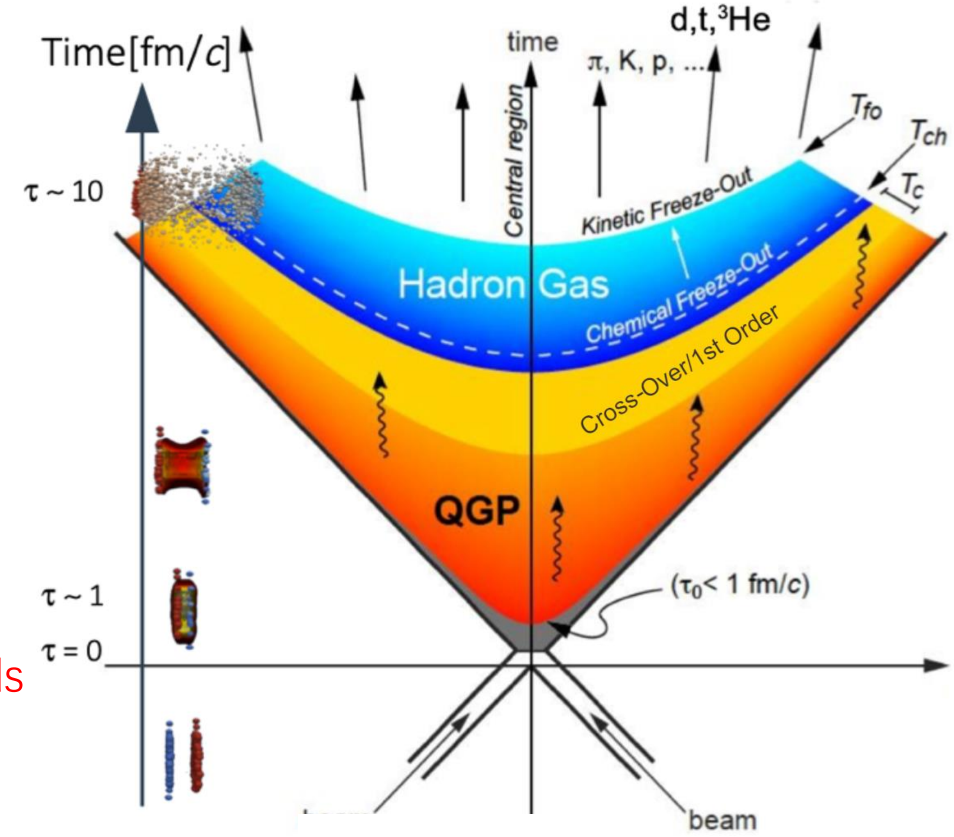
First observation on $^{3}_{\Lambda}\mathrm{H}$ in 1952
Left: Jerzy Pniewski Right: Marian Danysz

Hypernuclei and their production mechanisms

Hypernuclei production mechanism at mid-rapidity of HIC is important
- The nucleosynthesis of the little bang
- Thermal production v.s. nucleon coalescence

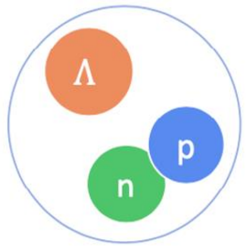
Thermal model
- Hadrons and (hyper-)nuclei are treated equally
- Yields are predicted with thermal equilibrium assumptions

Coalescence model
- (Hyper-)nuclei formation after kinetic freeze-out
- Nucleon coalescence
  - Wigner function
  - The emission source size and the nuclear radius affect the yields



Hypertriton ($^3_\Lambda$H) is special
- Small binding energy and large nuclear radius
- Interesting to study its production in systems with different sizes

$^3_\Lambda$H

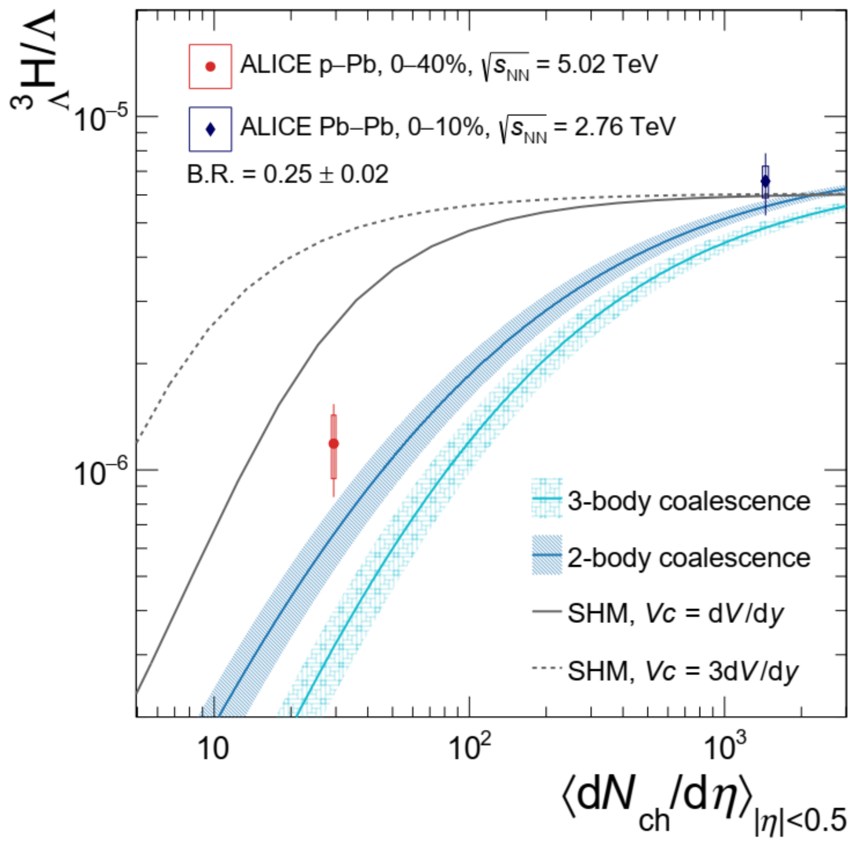


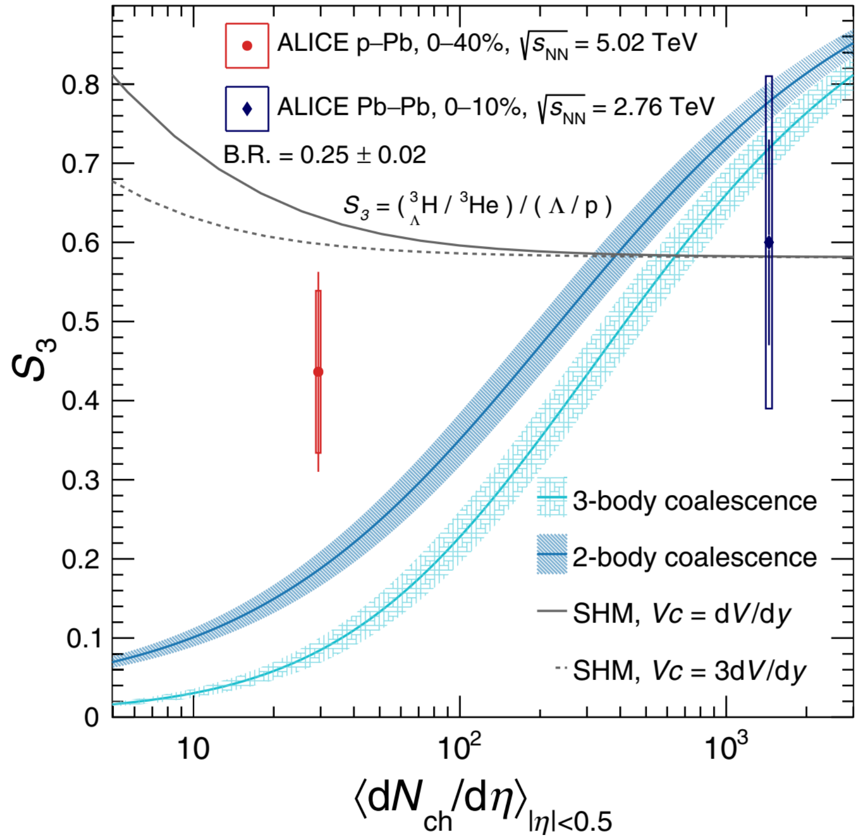
$B_\Lambda \sim 0.15$ MeV

$r_{\Lambda d} \sim 10$ fm

System size dependence of hyperon and ${}^{3}_{\Lambda}H$ production

- **Multiplicity dependence of ${}^{3}_{\Lambda}H$ yield ratios**
  - Powerful test on the models
  - Only two measurements available
  - Can we expect a more differential study with higher precison?





The ALICE collaboration, PRL 128, 252003 (2022)

System size dependence of hyperon and ${}^{3}_{\Lambda}\mathrm{H}$ production

- **Multiplicity dependence of ${}^{3}_{\Lambda}\mathrm{H}$ yield ratios**
  - Powerful test on the models
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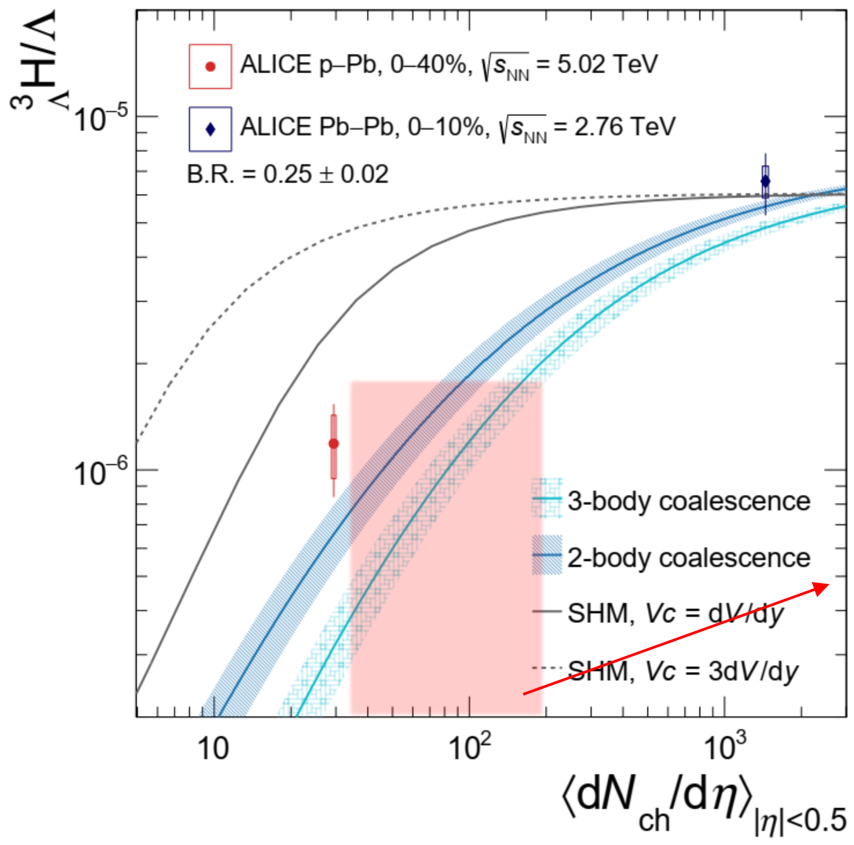
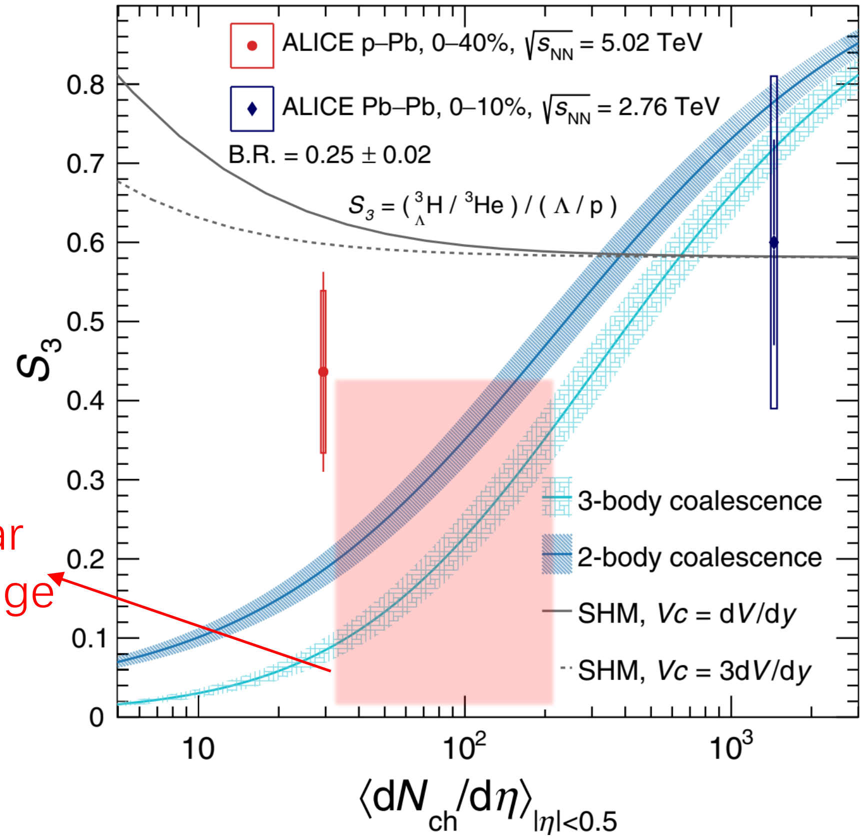
  - Can we expect a more differential study with higher precison?
- **STAR recorded a large sample of isobar collisions (Zr+Zr & Ru+Ru) at $\sqrt{s_{NN}}$ = 200 GeV in 2018**



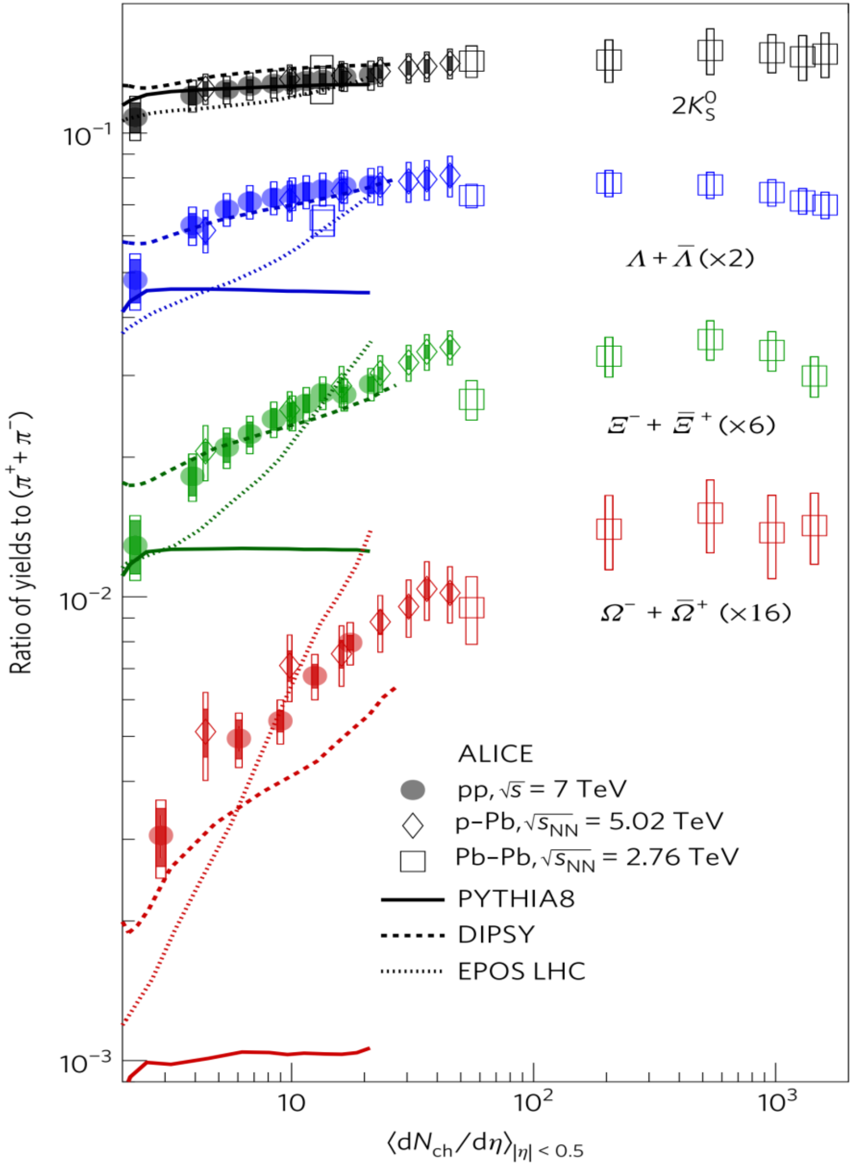
Isobar coverage



The ALICE collaboration, PRL 128, 252003 (2022)

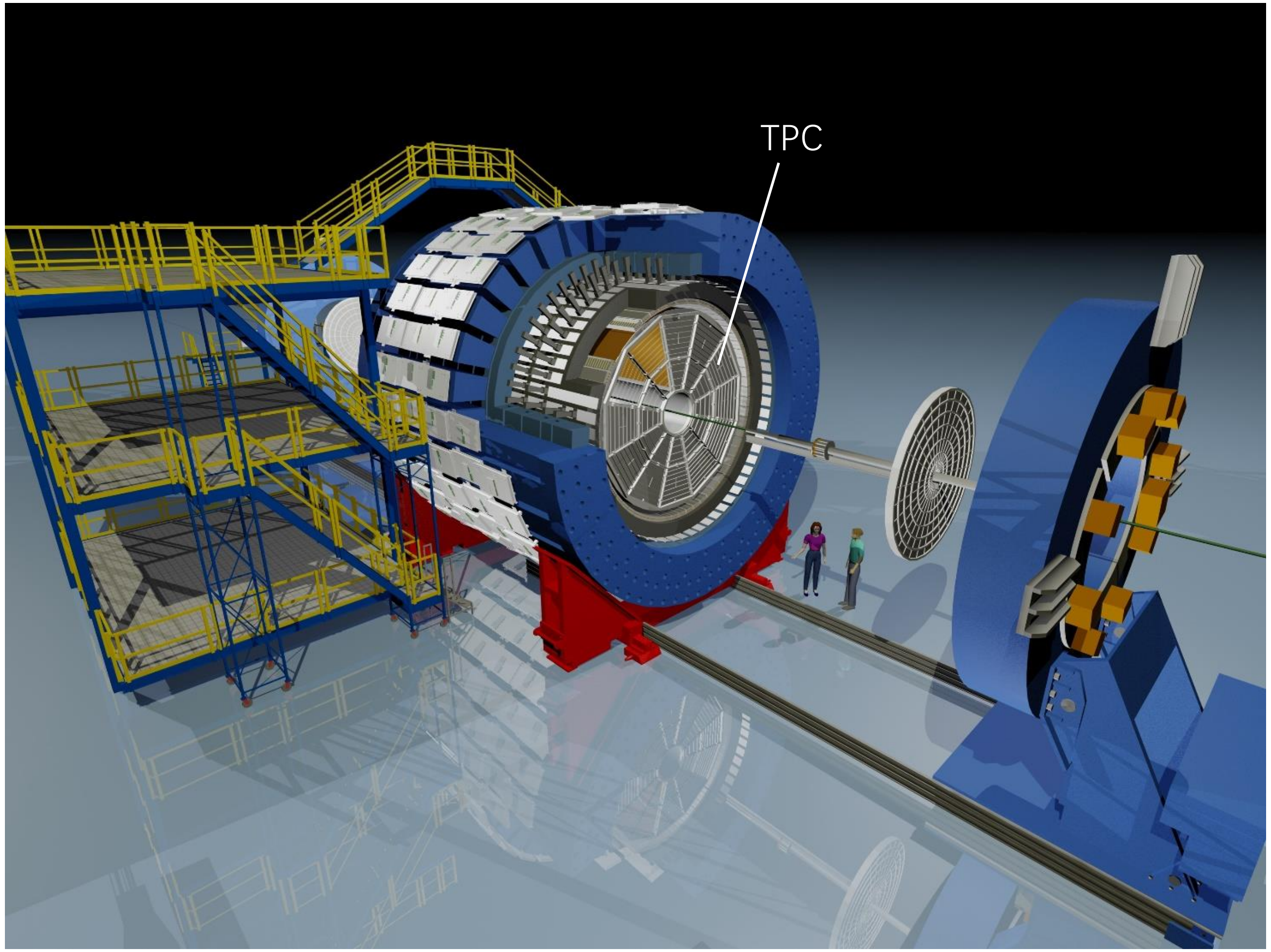
System size dependence of hyperon and ${}^{3}_{\Lambda}\mathrm{H}$ production

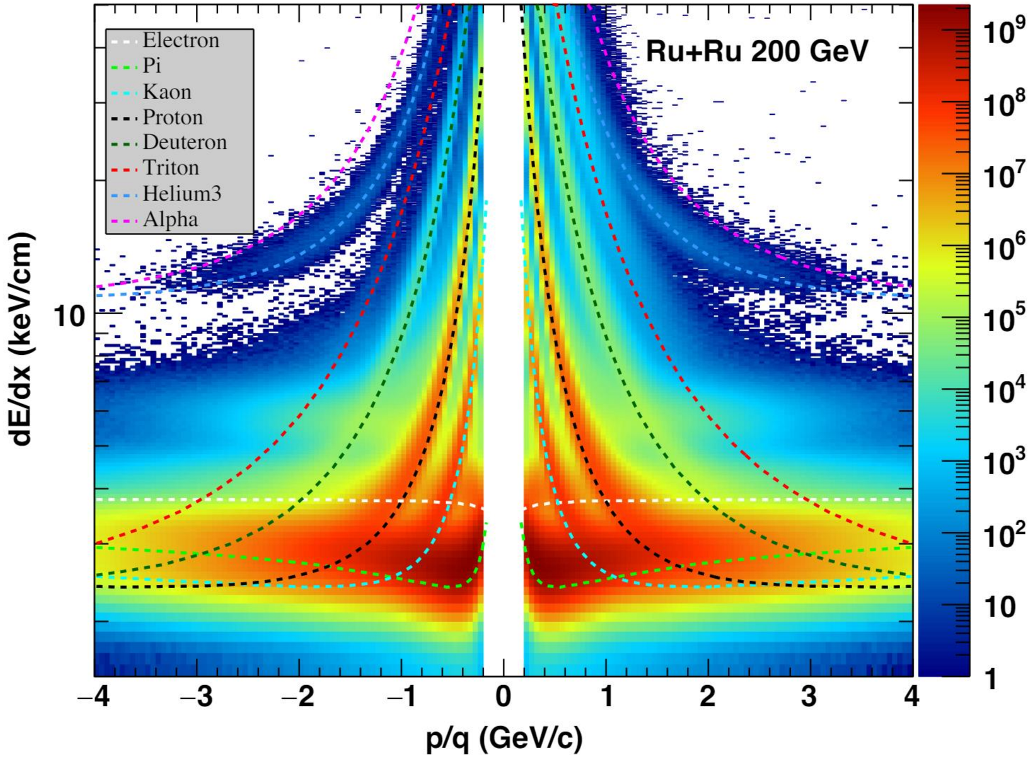
- **Need hyperon yields as reference to ${}^{3}_{\Lambda}\mathrm{H}$ production**
- **Anything else to learn from a hyperon measurement?**
- **Strange hadron yield scaling with system size at LHC energy**
  - Common multiplicity dependence of hyperon-to-pion ratios in different collision systems
  - Strangeness enhancement in high multiplicity p+p collisions
- **How about testing this scaling property at RHIC energy?**
  - Isobar collision is a good choice



The ALICE collaboration, Nature Phys 13, 535–539 (2017)

STAR detector

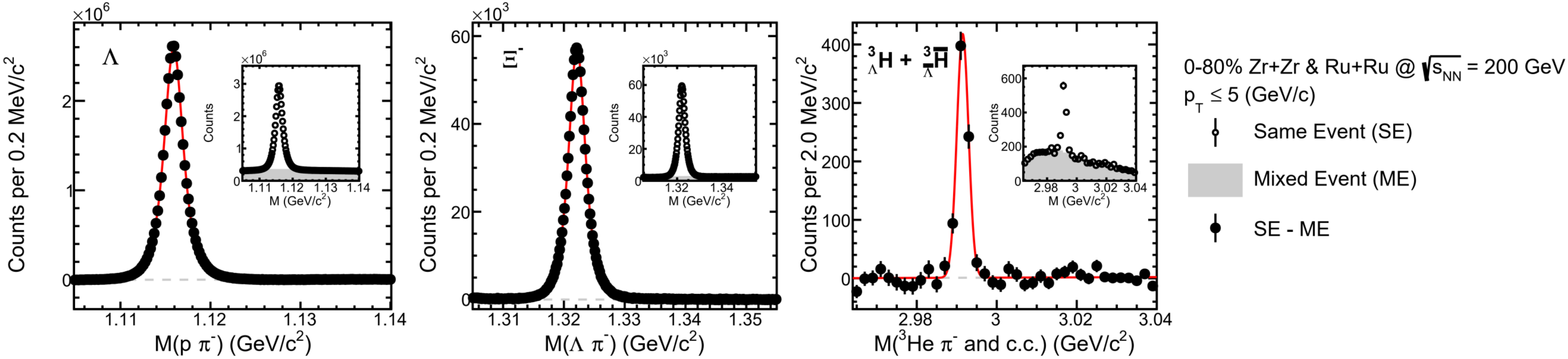




- Time Projection Chamber (TPC)

  Large acceptance, good performance within |y| < 0.8 for hypernuclei reconstruction

Signal reconstruction

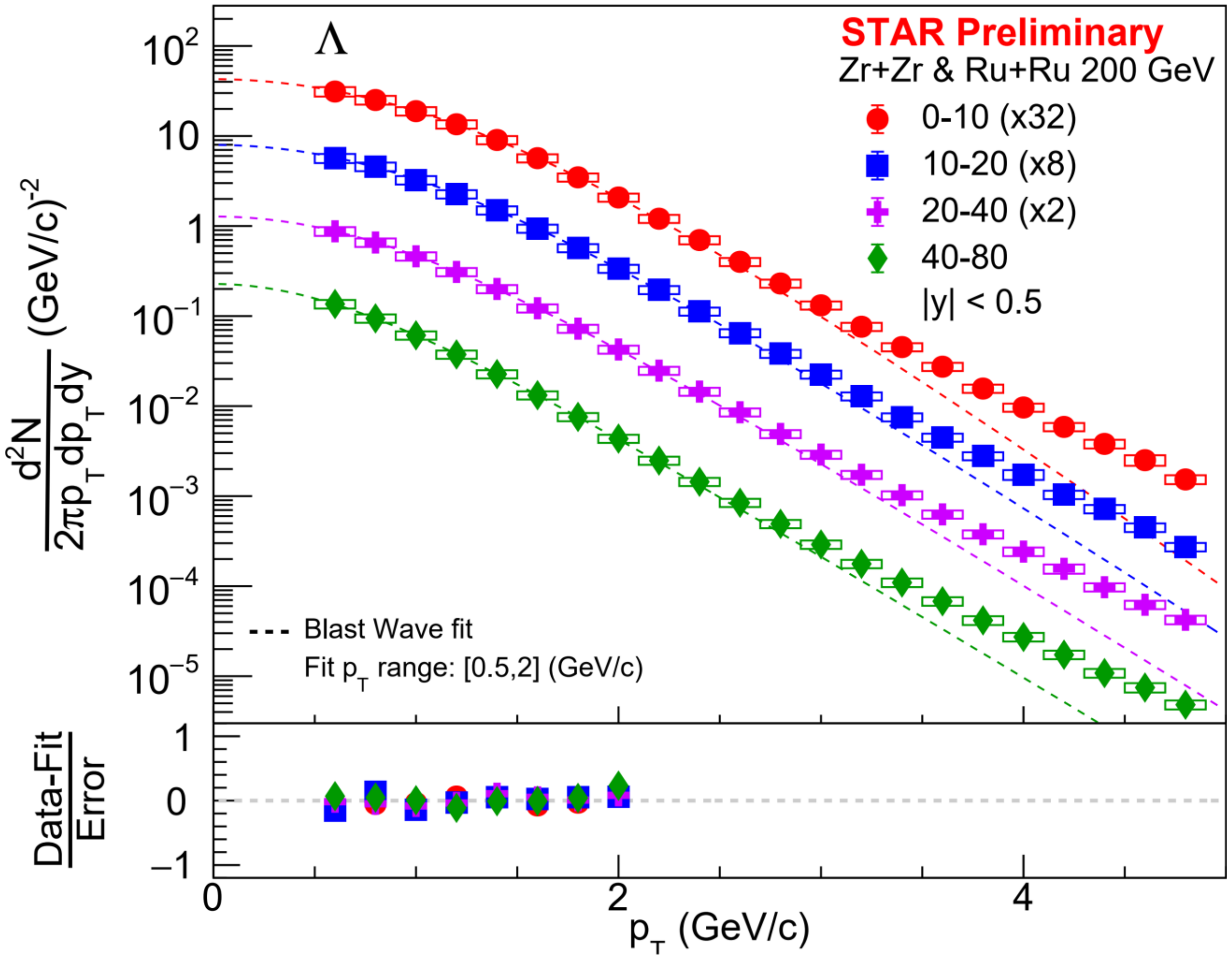


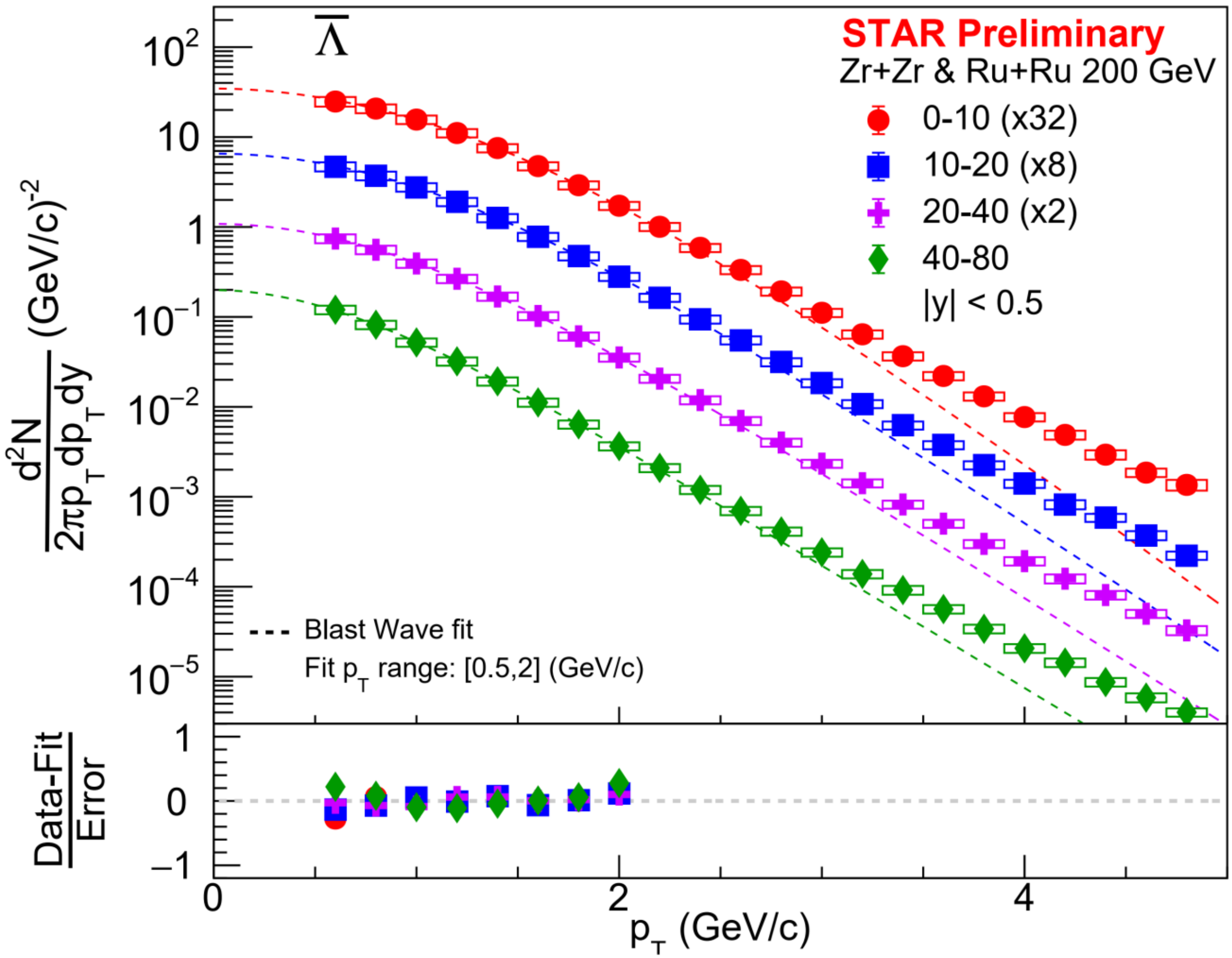
- Signal is extracted via an invariant-mass analysis
- KFParticle[*] + Machine Learning method (XGBDT as core) for ${}^{3}_{\Lambda}\mathrm{H}$ reconstruction
- The mixed event method can reproduce the combinatorial backgrounds well

V0 particle	Decay channel	Method
$\Lambda(\bar{\Lambda})$	$\Lambda \to p + \pi^{-}$ (*and c.c.*)	KFParticle
$\Xi^{-}(\bar{\Xi}^{+})$	$\Xi^{-} \to \pi^{-} + \Lambda$ (*and c.c.*)	KFParticle
${}^{3}_{\Lambda}\mathrm{H}({}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}})$	${}^{3}_{\Lambda}\mathrm{H} \to \pi^{-} + {}^{3}\mathrm{He}$ (*and c.c.*)	KFParticle XGBDT

[*] X.-Y. Ju et.al., NST 34, 158, 2023

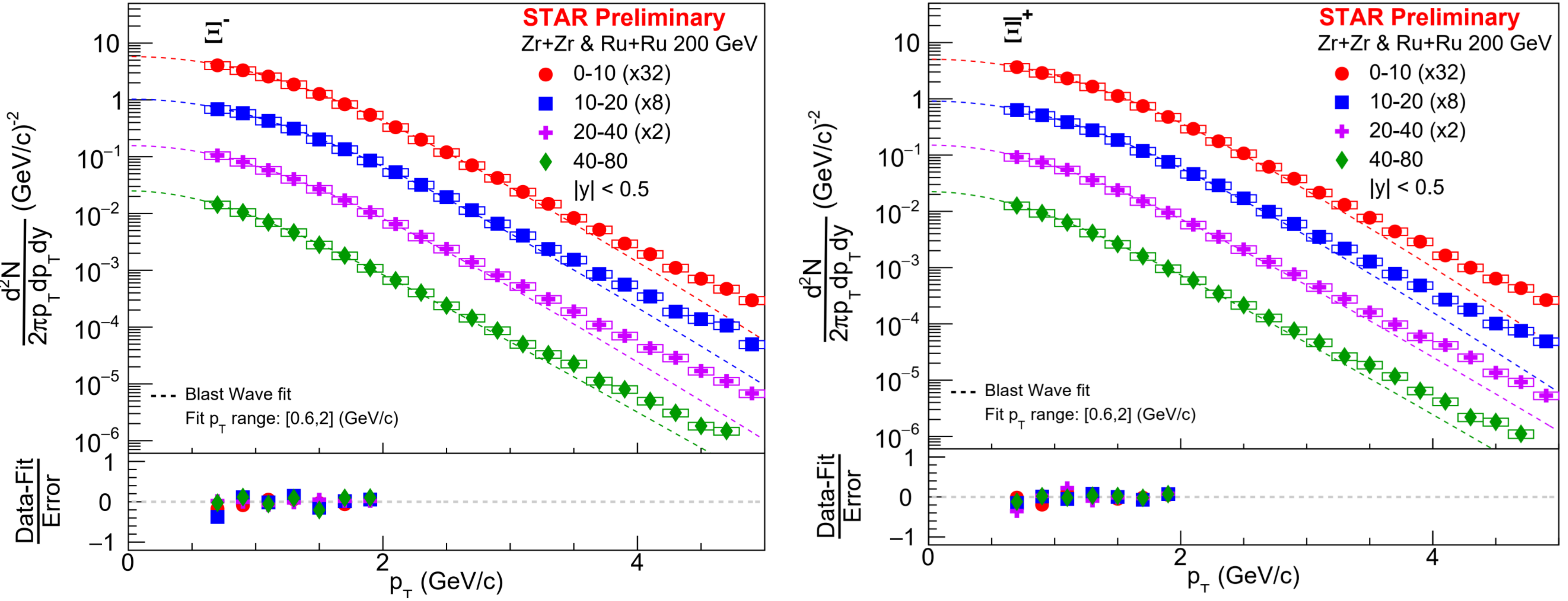
Λ and $\bar{\Lambda}$ production in isobar collisions





- Measurement within 4 different centralities
- Extrapolation down to p_T = 0 GeV/c with Blast Wave function
- Feed-down correction ($\Xi \rightarrow \pi + \Lambda$) on Λ candidates with MC simulation

Ξ^- and $\bar{\Xi}^+$ production in isobar collisions



- Measurement within 4 different centralities
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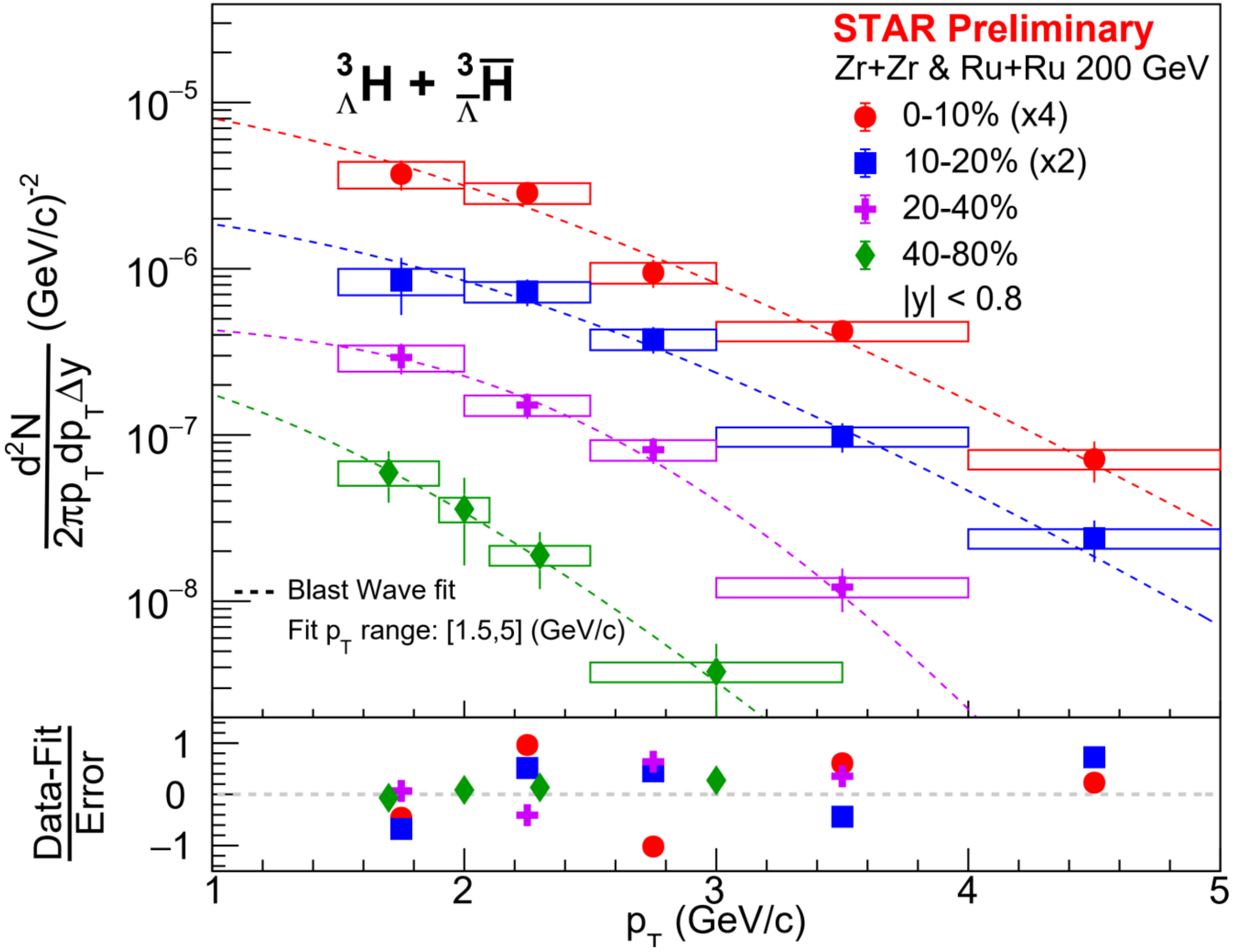
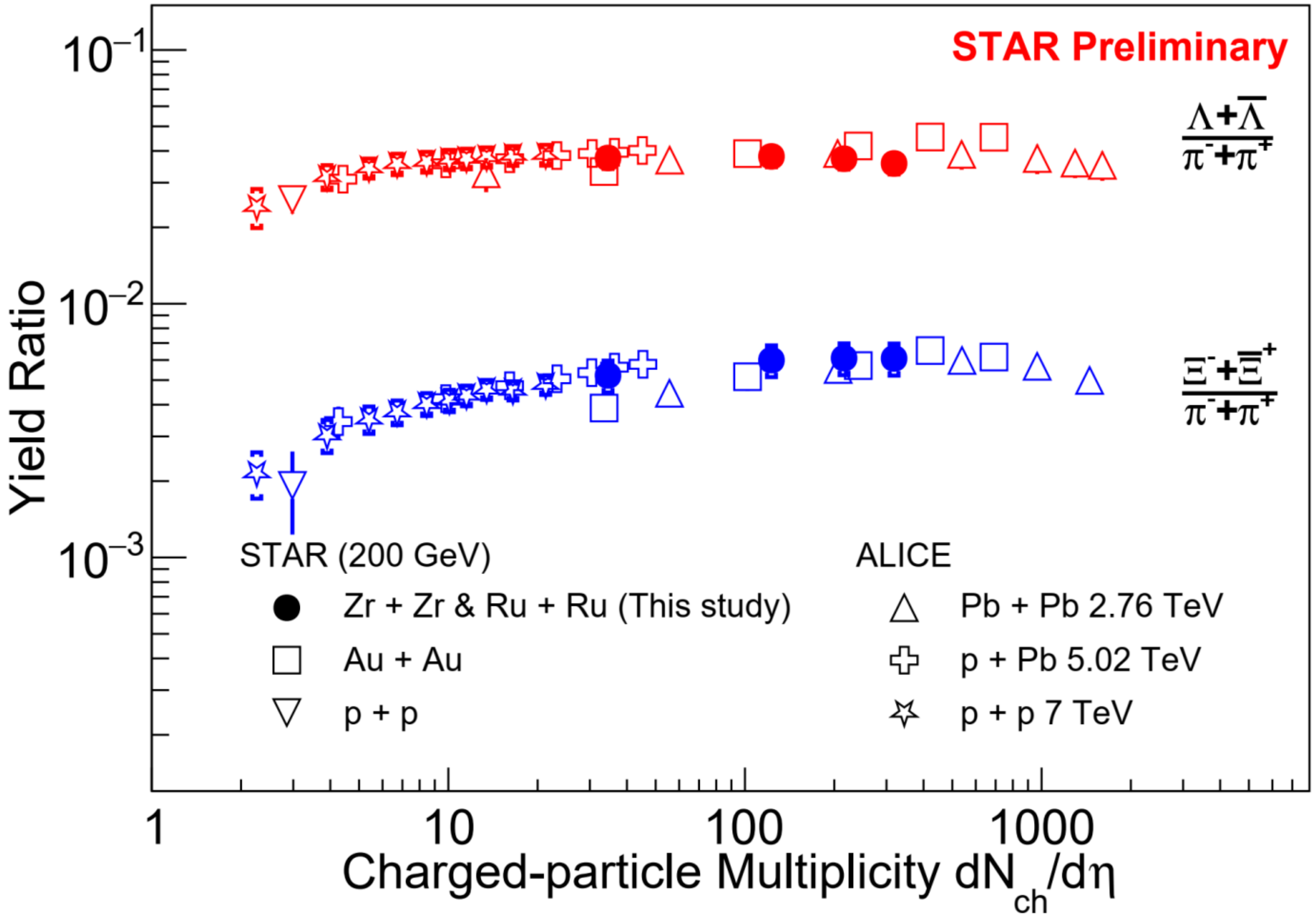
${}^{3}_{\Lambda}H + {}^{3}_{\bar{\Lambda}}\bar{H}$ production in isobar collisions



- Measurement within 4 different centralities
- Extrapolation down to p_T = 0 GeV/c with Blast Wave function

Hyperon production dependence on system size

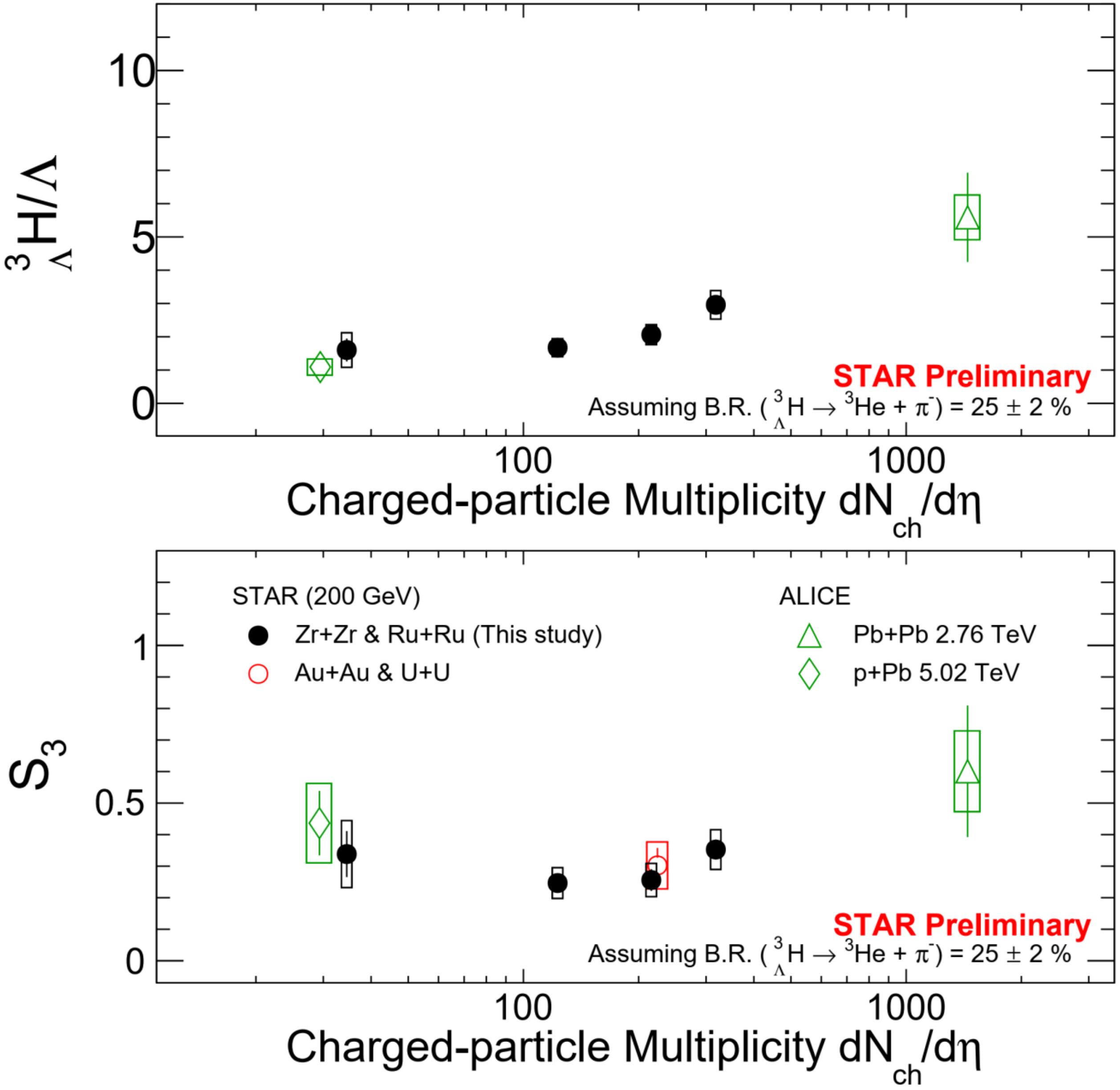


- Hyperon-to-pion ratios follow the same trend as a function of $dN_{ch}/d\eta$ for different collision systems
- Similar Hyperon production mechanism for systems with same multiplicity despite differences in collision energy or system

STAR:
PRL 98, 062301 (2007)
PRC 75, 064901 (2007)
PRC 79, 034909 (2009)

ALICE:
PLB 728, 216–227 (2014)
PLB 728, 25–38 (2014)
PLB 758, 389–401 (2016)
Nature Phys 13, 535–539 (2017)

${}^{3}_{\Lambda}\mathrm{H}$ production dependence on system size: ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ and S_3

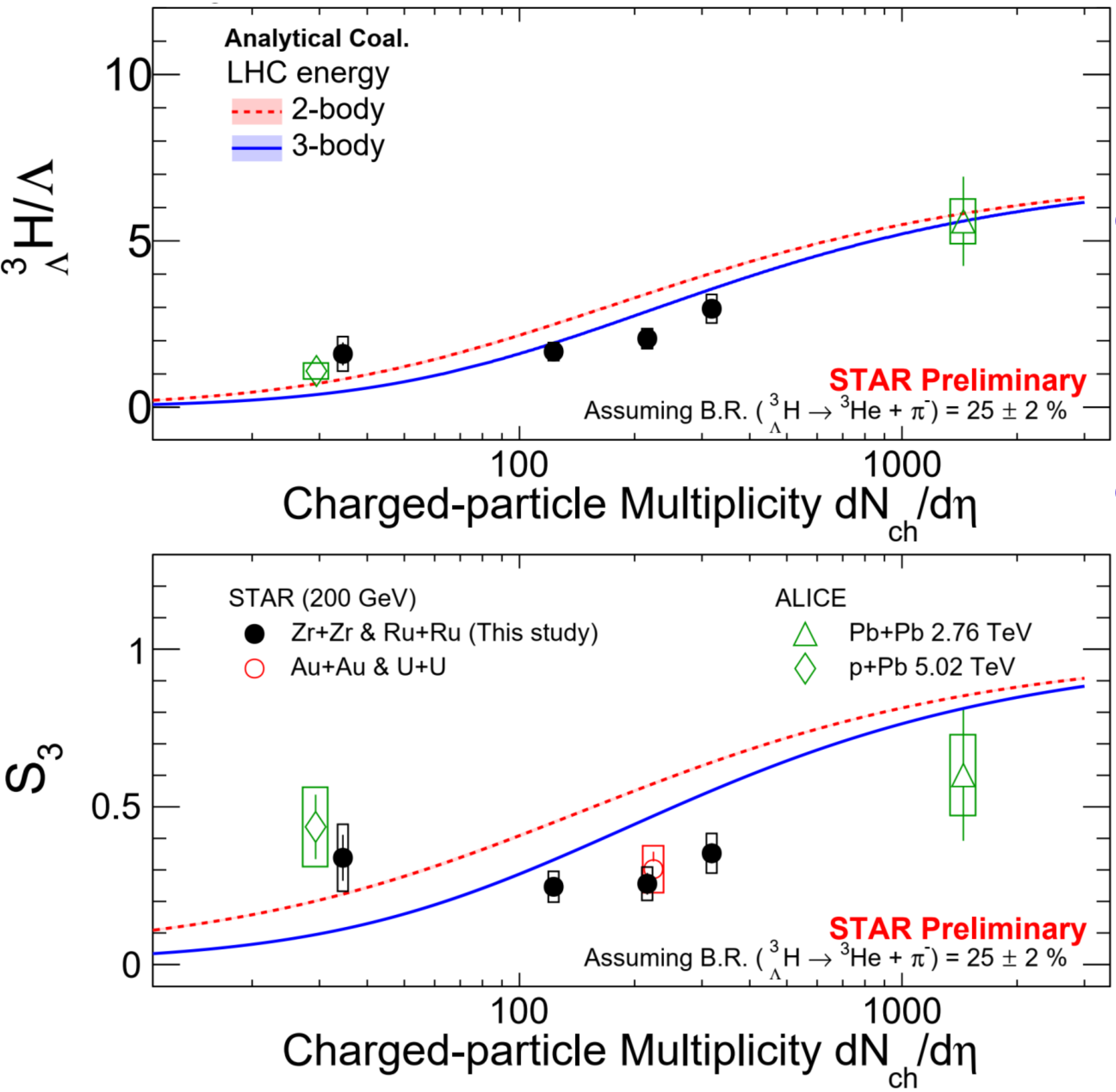


- STAR and ALICE data are consistent for both ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ and $S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H}/\Lambda}{{}^{3}\mathrm{He}/p}$
- Similar mechanisms for hypernuclei production at RHIC and LHC energies

STAR:
arXiv:2310.12674

ALICE:
PRL 128, 252003 (2022)
PLB 754, 360–372 (2016)

${}^{3}_{\Lambda}H$ production dependence on system size: ${}^{3}_{\Lambda}H/\Lambda$ and S_3

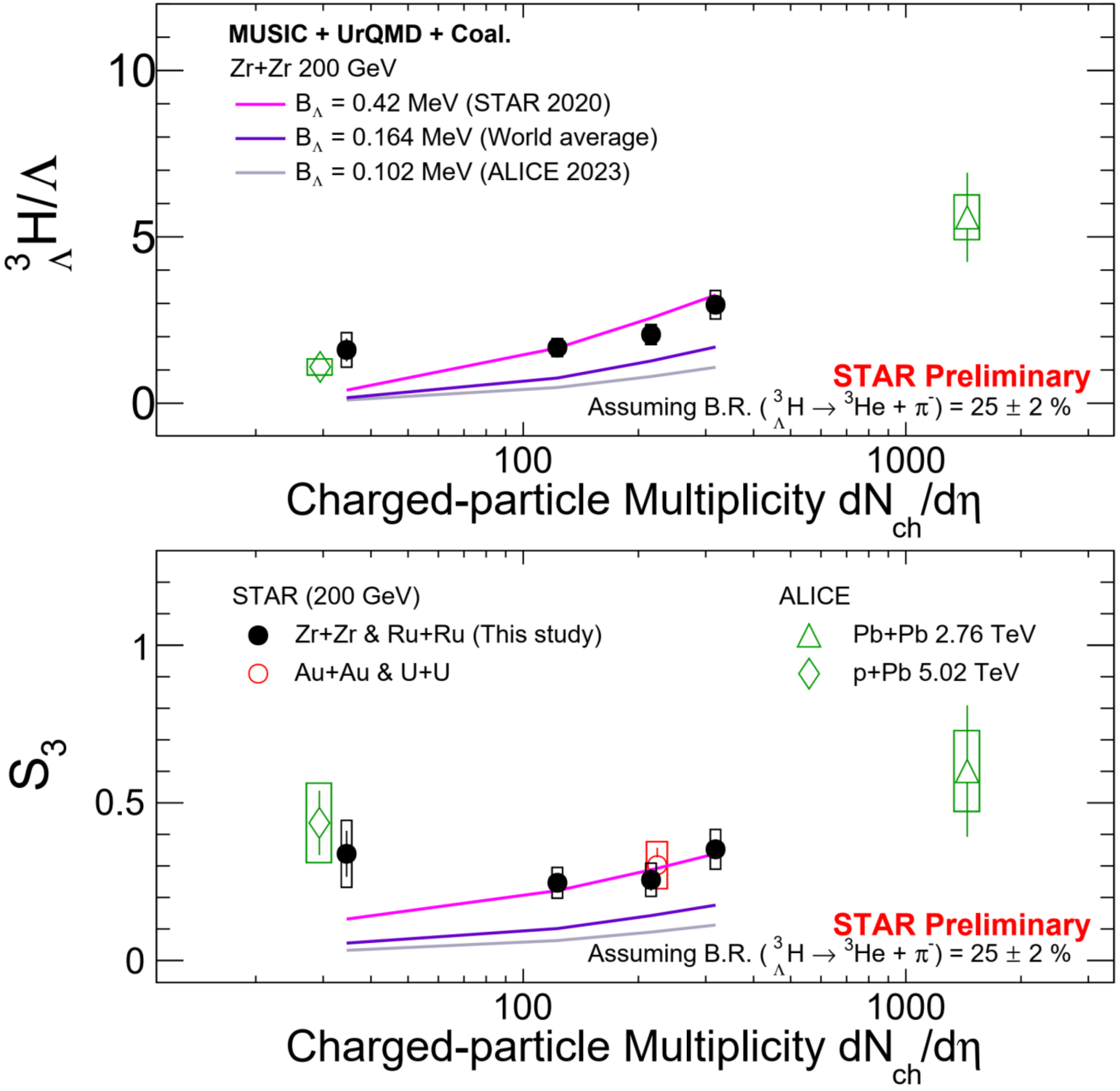


- Analytical Coalescence
  - Assumptions on the thermalized emission source
  - Wigner function approach
  - Consider 2-body and 3-body coalescence
- Qualitatively reproduce the trend of ${}^{3}_{\Lambda}H/\Lambda$ but still have large deviations on S_3

Analytical Coalescence:

K.-J. Sun et.al. ,
PLB 792, 132–137 (2019)

${}^{3}_{\Lambda}H$ production dependence on system size: ${}^{3}_{\Lambda}H/\Lambda$ and S_3

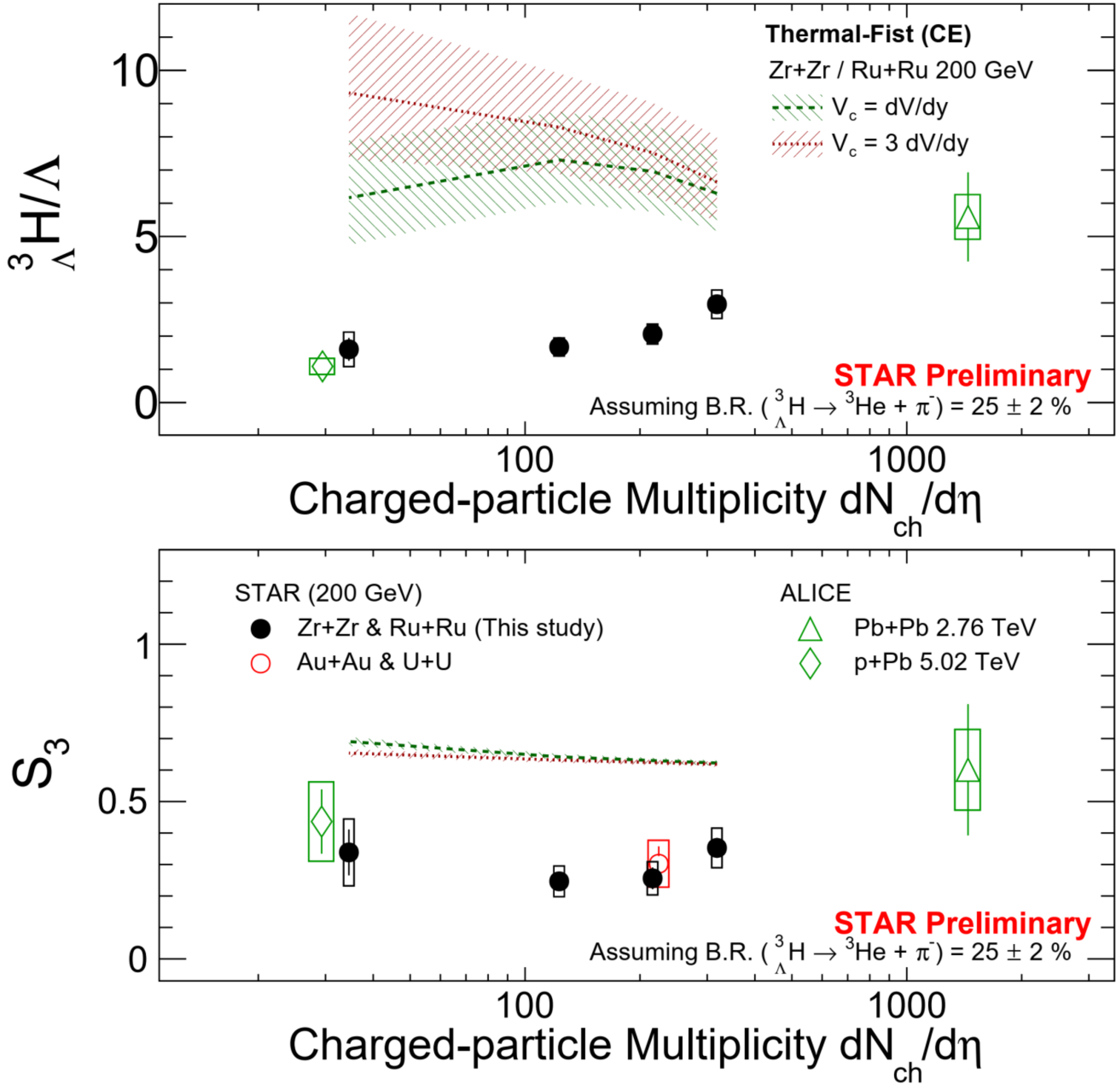


- MUSIC + UrQMD + Coalescence
  - More realistic treatment with QGP evolution, hadronic rescattering …
  - 3-body coalescence with wigner function using different inputs on ${}^{3}_{\Lambda}H$ binding energy
- Significant deviation from isobar data with world average binding energy
- Better description with larger binding energy input

MUSIC + UrQMD + Coalescence:

K.-J. Sun et.al.
arXiv:2404.02701

${}^{3}_{\Lambda}H$ production dependence on system size: ${}^{3}_{\Lambda}H/\Lambda$ and S_3

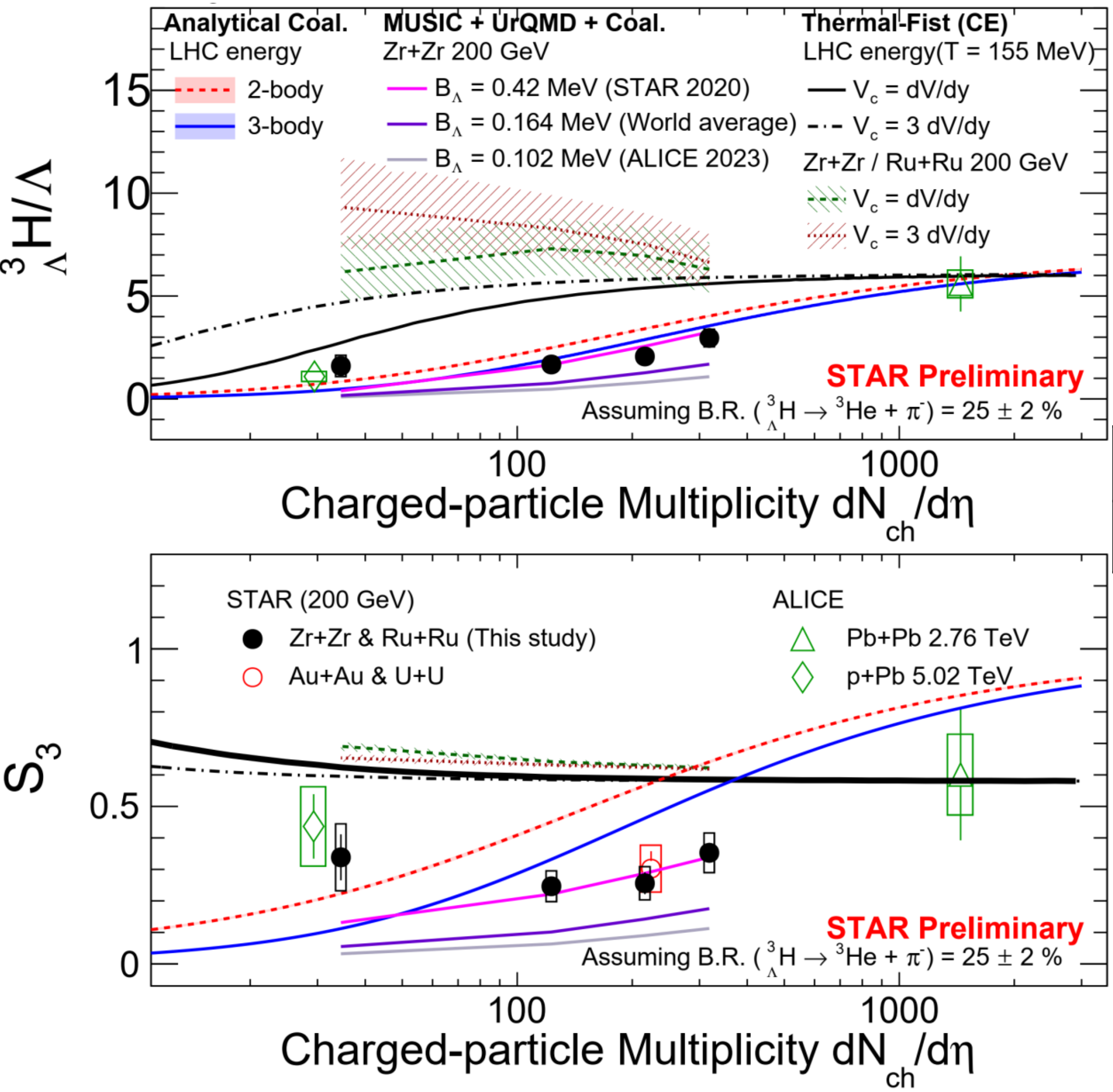


- Thermal model
  - Canonical Ensemble (CE) of the Thermal-Fist Package
  - Variations on the configurations of kinetic freeze-out temperature (T_{ch}) and correlation volume (V_c)
- Significant deviation from isobar data

Thermal-Fist:

V. Vovchenko, H. Stoecker
Comput. Phys. Commun. 244, 295-310 (2019)

$^{3}_{\Lambda}H$ production dependence on system size: $^{3}_{\Lambda}H/\Lambda$ and S_3



Significance of deviation	Ana. coal. (2-body)	Ana. coal. (3-body)	MUSIC+UrQMD+Coal (average B_Λ)	Thermal
$^{3}_{\Lambda}H/\Lambda$	3.8σ	1.9σ	3.8σ	$> 5\sigma$
S_3	6.6σ	3.9σ	3.6σ	$> 8\sigma$

Analytical Coalescence:

K.-J. Sun et.al. ,
PLB 792, 132–137 (2019)

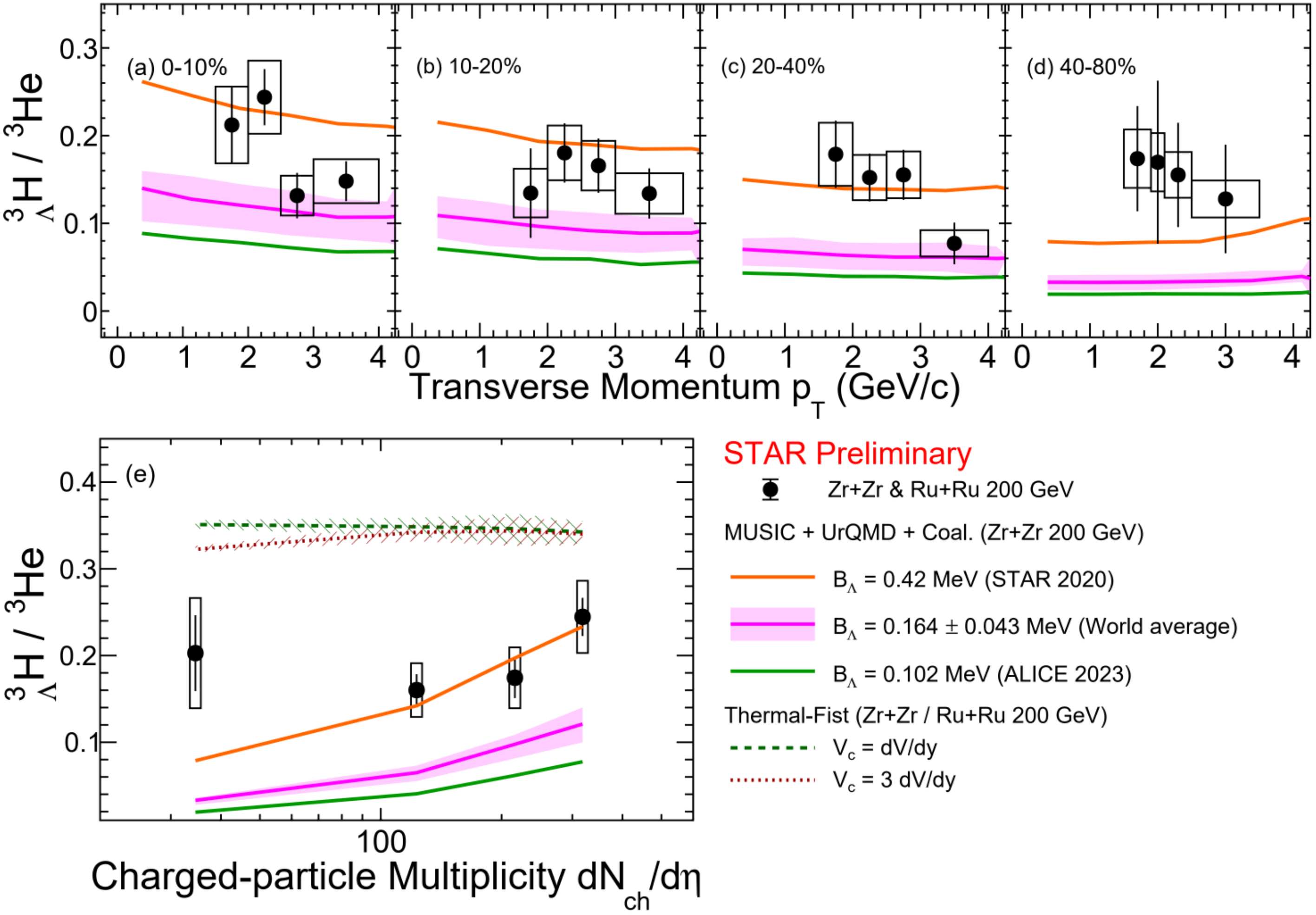
MUSIC + UrQMD + Coalescence:

K.-J. Sun et.al.
arXiv:2404.02701

Thermal-Fist:

V. Vovchenko, H. Stoecker
Comput. Phys. Commun. 244, 295-310 (2019)

$^3_\Lambda$H production dependence on system size: $^3_\Lambda\text{H}/^3\text{He}$



- No significant $\mathbf{p_T}$ dependence nor multiplicity dependence
- Over-estimated by thermal model
  (>5σ deviation)
- Significant deviations between isobar data and MUSIC + UrQMD + Coalescence model with world average binding energy
  (3.6σ deviation for the integrated ratio)
- Suppression effects on hypertriton production which arise from its large radius predicted by coalescence models are not observed from data

Thermal-Fist:
V. Vovchenko, H. Stoecker
Comput. Phys. Commun. 244, 295-310 (2019)

MUSIC + UrQMD + Coalescence:
K.-J. Sun et.al.
arXiv:2404.02701

Summary

- **Hyperon (Λ, Ξ^-) and Hypertriton (${}^{3}_{\Lambda}\mathrm{H} + {}^{3}_{\Lambda}\overline{\mathrm{H}}$) yield measurement in Zr+Zr & Ru+Ru collisions @ $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV at STAR**

  - p_T spectra are shown for each particle species

- **Hyperon-to-pion ratios shown as a function of multiplicity**

  - Consistent trend for collision systems from RHIC to LHC energy
  - Similar hyperon production mechanisms at same multiplicity for different collision systems

- **${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$, ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ and S_3 are shown as a function of multiplicity, while ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ is shown also as a function of p_T**

  - No significant p_T and multiplicity dependence on ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ within current precision
  - No significant multiplicity dependence on S_3 within current precision
  - More efforts are needed to explain the deviations between the isobar data and the model calculations

Outlook

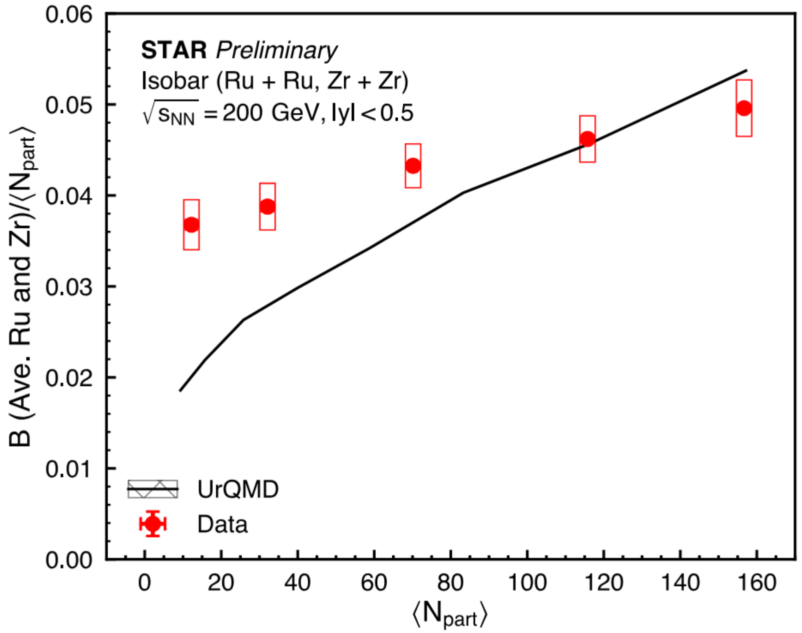
Many new data are coming out

Hyperon production in small collision systems @ $\sqrt{s_{NN}}$ = 200 GeV
- O+O collision
- High multiplicity p+p collision

Hypernuclei production in Au+Au collision @ $\sqrt{s_{NN}}$ = 200 GeV (2023-2025)
- Would allow a more precise measurement on multiplicity dependence
  - Better statistics for ${}^{3}_{\Lambda}\mathrm{H}$
  - Even possible for A = 4 hypernuclei study

Backup

Thermal model configuration on conserved charges

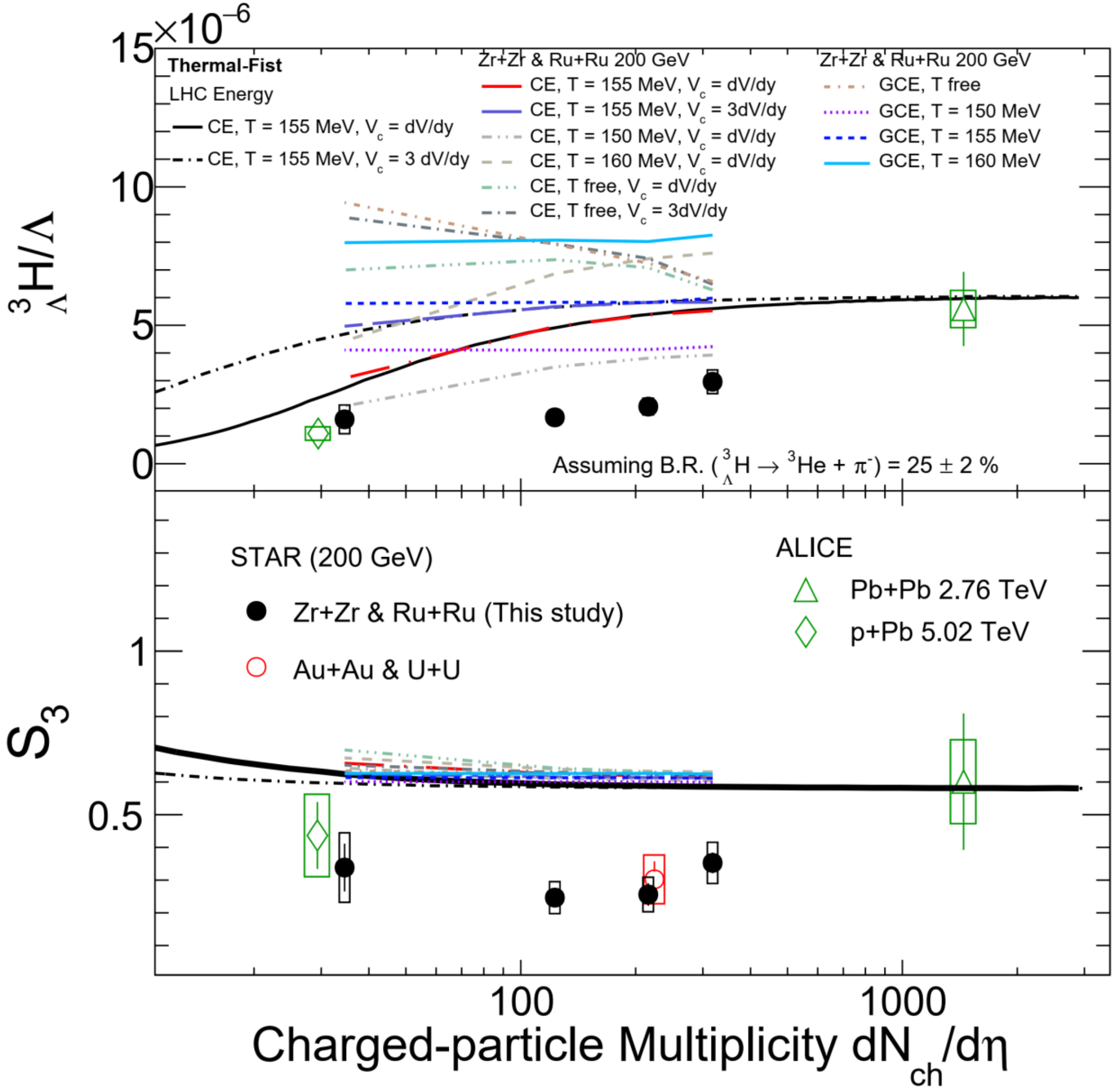


R. Ma, WWND2024

https://indico.cern.ch/event/1345629/contributions/5799495/attachments/2797889/4881261/RMa_WWND2024_v4.pdf

- In each centrality, to execute a Thermal-Fist fit with CE, we need to set the number of conserved charges within the correlation volume V_c (take $V_c = dV/dy$ as an example)
- Net-baryon B from the interpolation of the baryon stopping measurement
- Net-electric charge Q from Q/B = 0.45 (for Ru or Zr, Z/A ~ 0.45)
- Net-strangeness S = 0

Thermal model with different settings for Isobar



- The Thermal-Fist results are obtained by fitting the hadron yields (π^-, K^-, p, Λ, Ξ^- and their anti-particles)
- The thermal prediction on $^3_\Lambda H/\Lambda$ is very sensitive to the configurations
- While S_3 and $^3_\Lambda H/^3He$ only show weak dependence on the configuration details
- By setting T as a free parameter, we find it will slightly vary with centrality
- So we draw error bands by fixing T to the central value and values of 1-σ difference

Centrality	T (MeV) with CE fit
0-10%	157±3
10-20%	159±3
20-40%	161±3
40-80%	165±4

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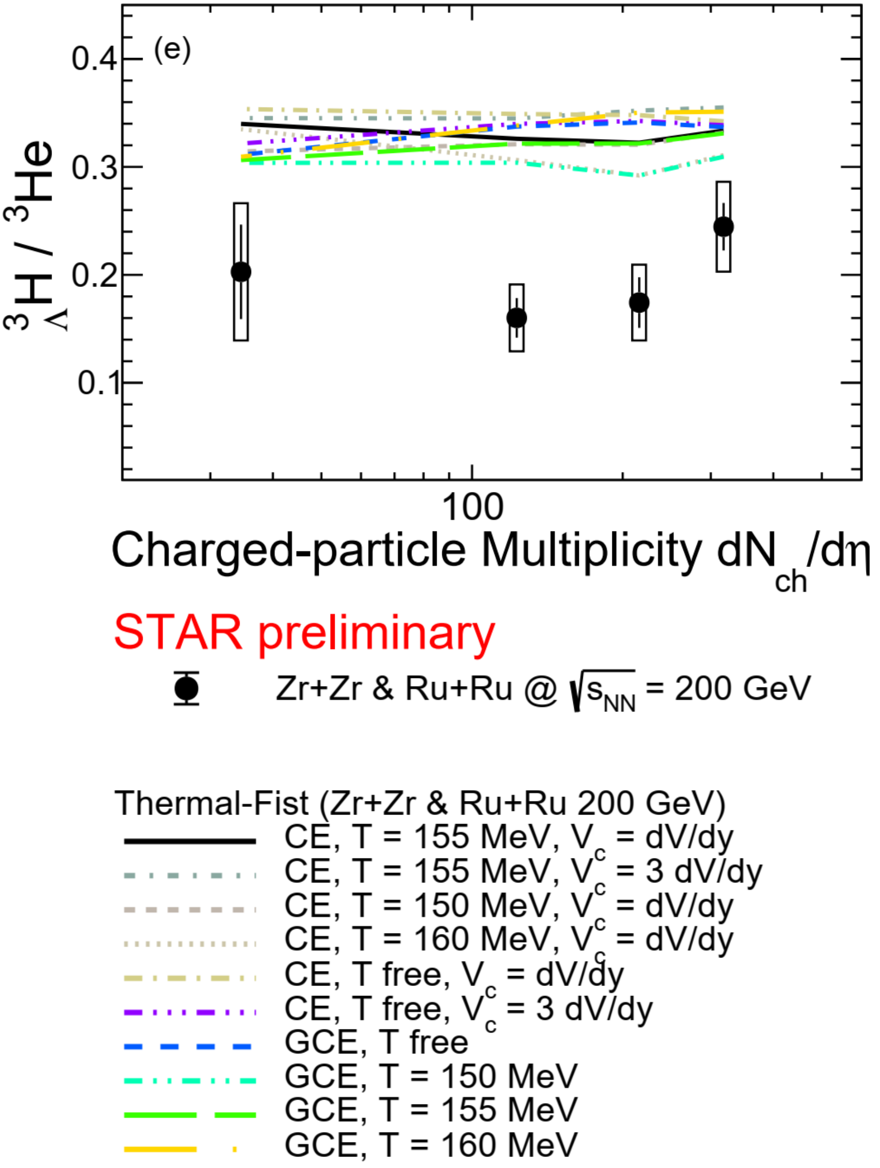

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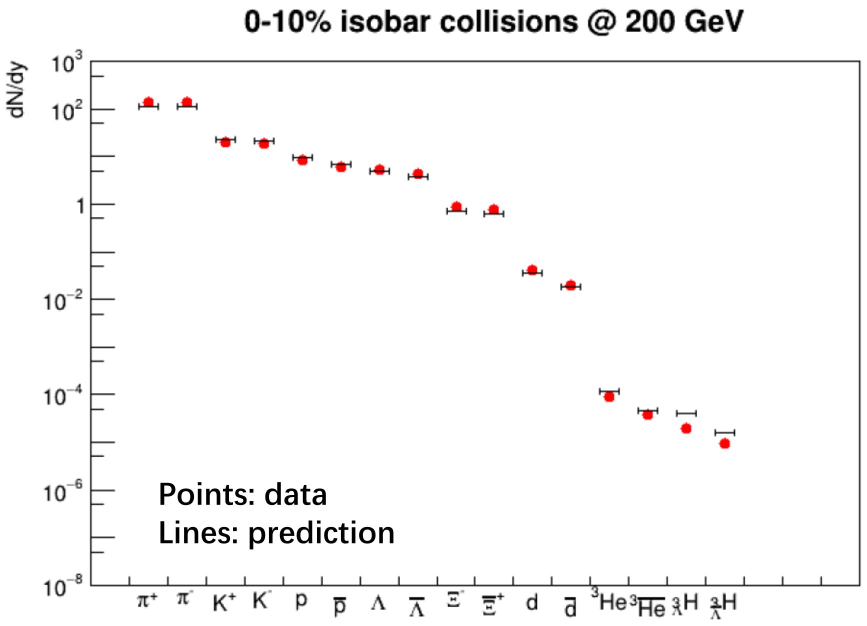
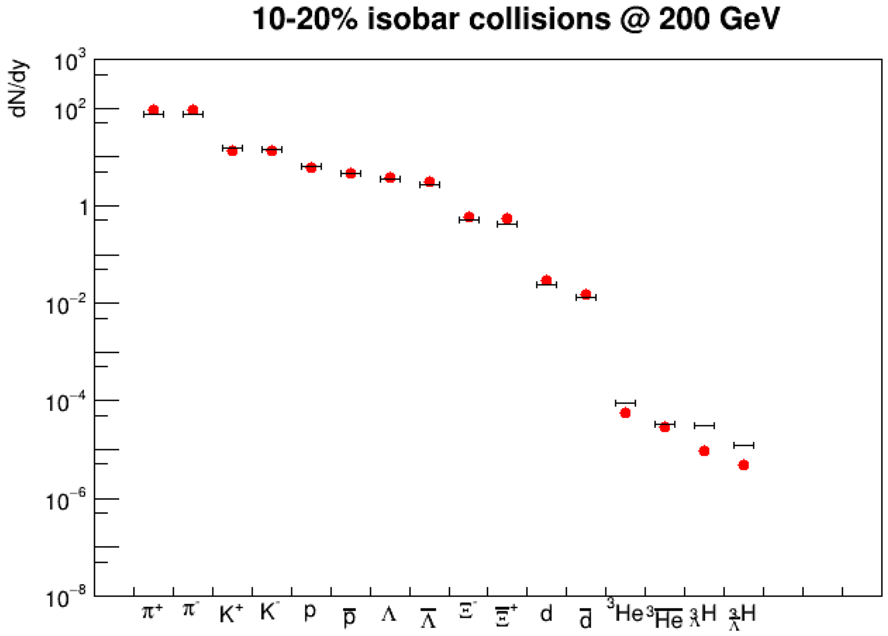
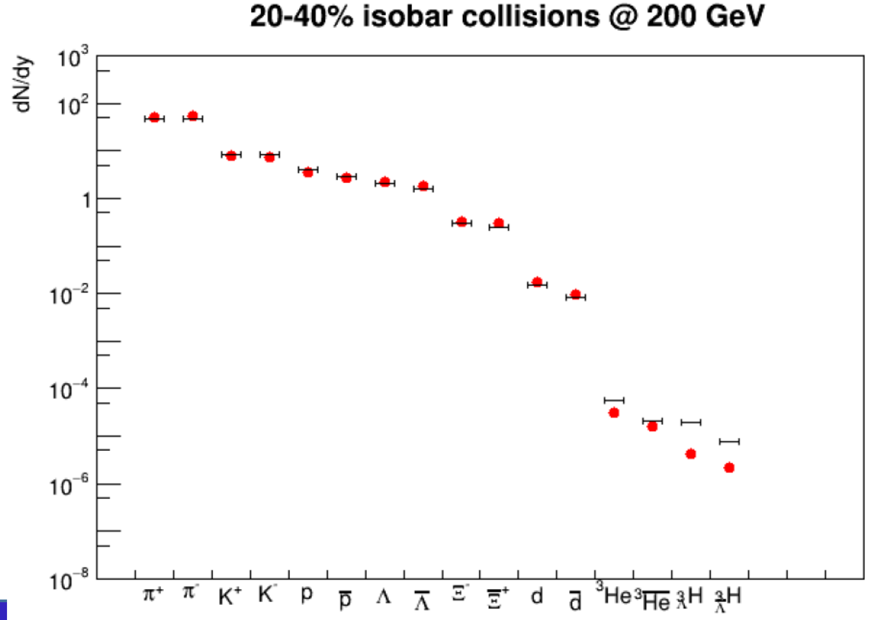
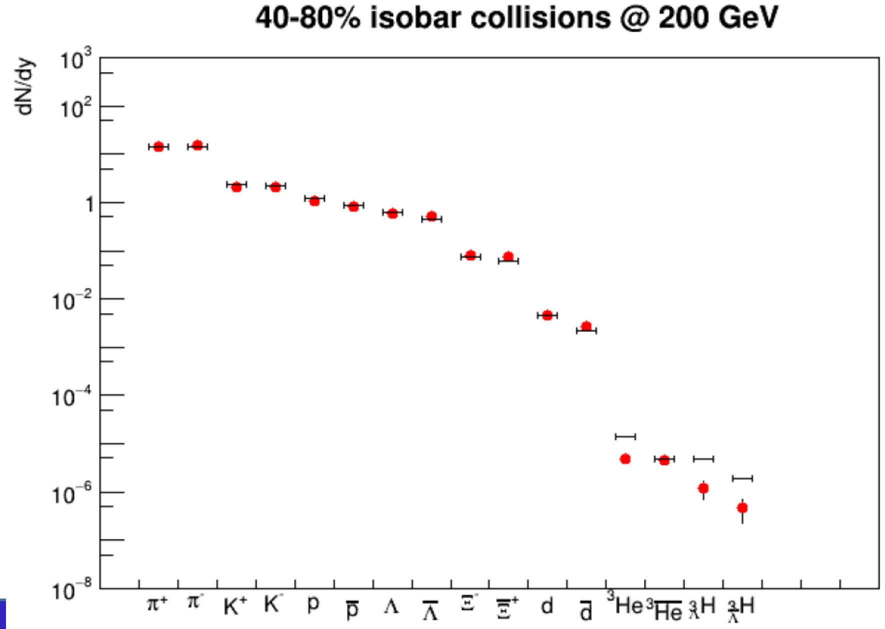
Thermal model predictions









XGBDT training with hipe4ml package

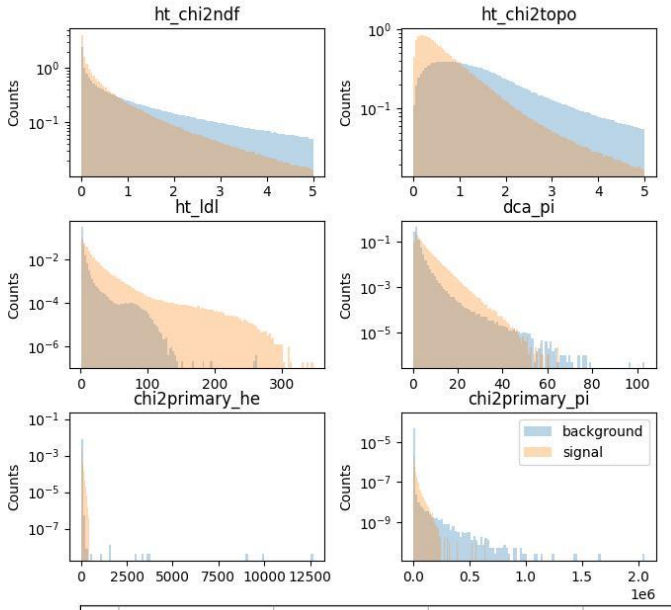
- Using the hipe4ml Package
  - https://github.com/hipe4ml/hipe4ml
  - XGBDT + optuna

hipe4ML

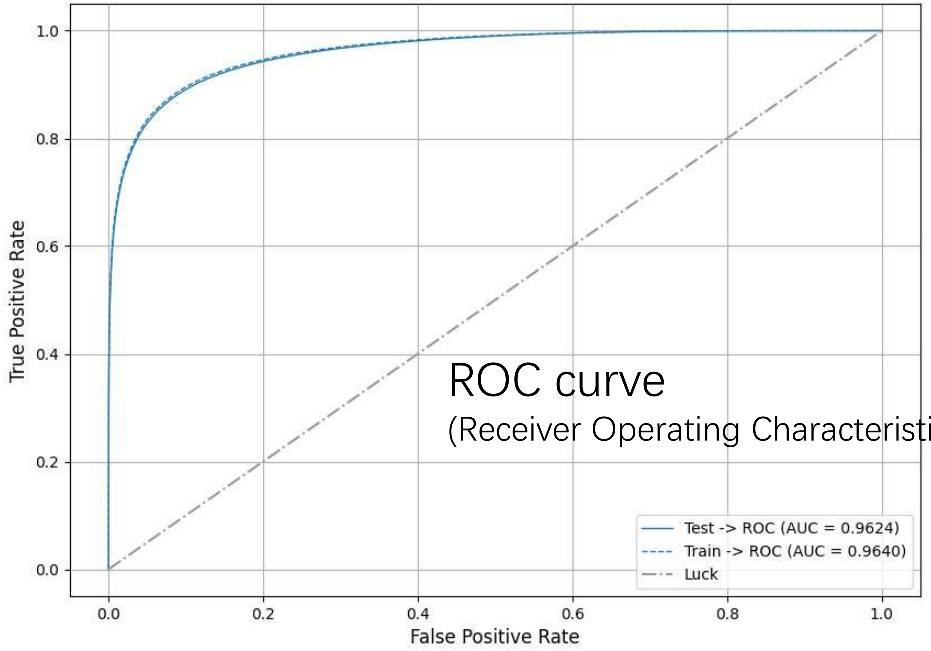
Test package passing | license GPL-3.0 | python 3.8 | 3.9 | 3.10 | 3.11 | pypi v0.0.15 | DOI 10.5281/zenodo.5070131

Minimal heavy ion physics environment for Machine Learning

XGBDT training with hipe4ml package

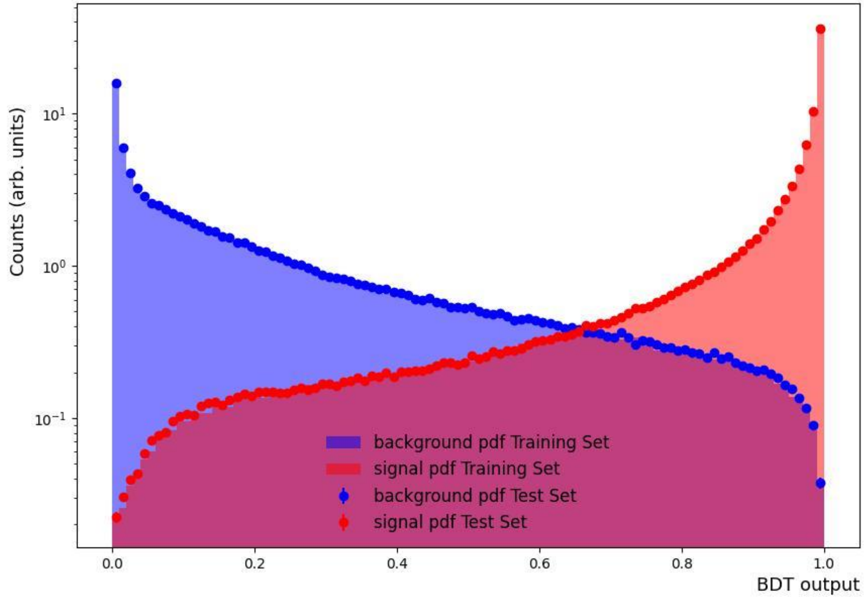


Input features from KFParticle



ROC curve

(Receiver Operating Characteristic)



BDT output distributions on the training and testing sample of signal and background

Hyperon yields zoom-in