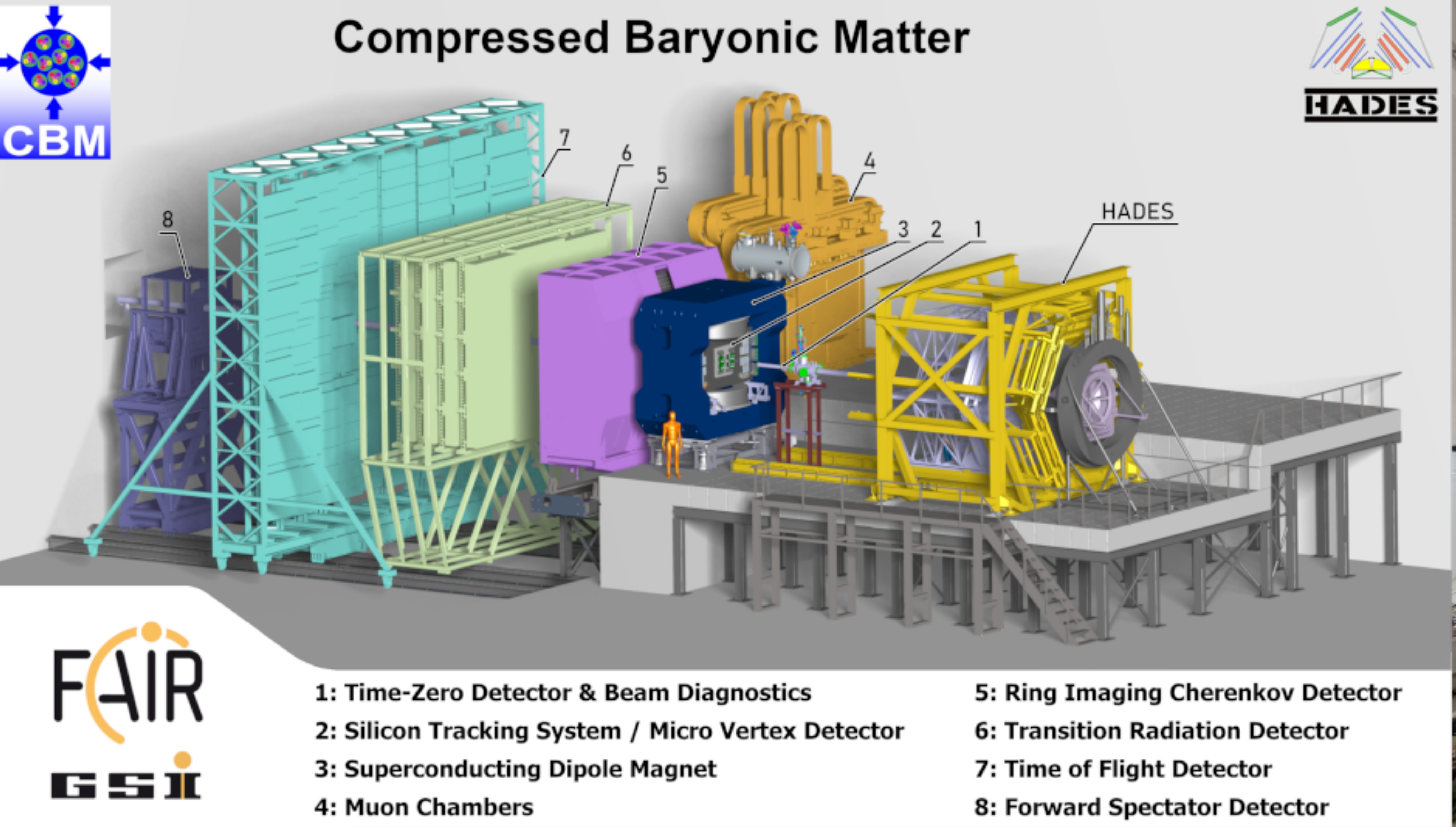
EMMI Workshop "5th Workshop on Anti-Matter, Hyper-Matter and Exotica Production"

Perspectives on Hypernuclei Physics with the CBM Experiment at FAIR



10–14 Nov 2025
Comune di Salerno

Yingjie Zhou, for the CBM Collaboration

Motivation

STAR results:
Mon. Y.X. Jin

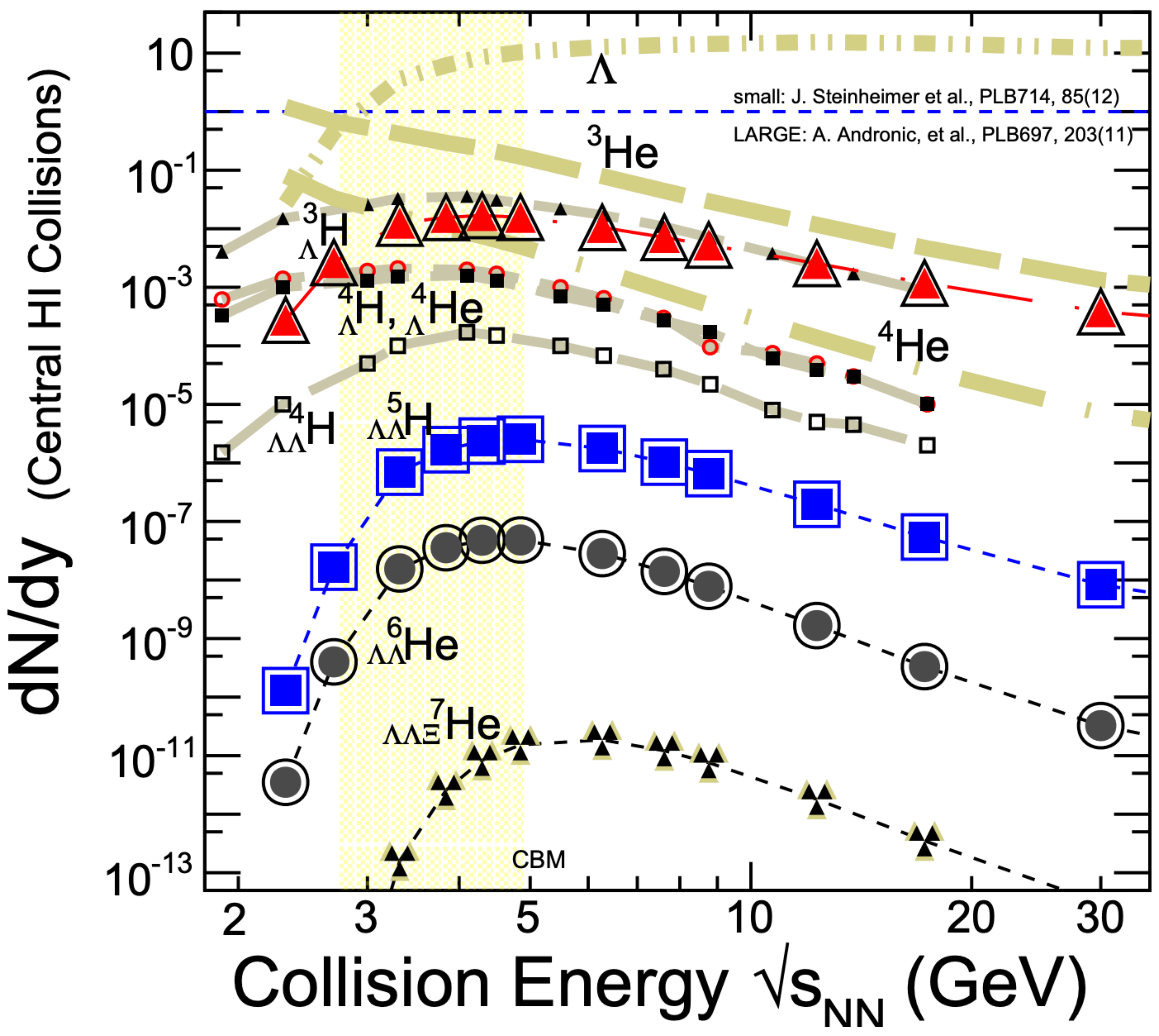
One of the key physics cases of the CBM experiment is study of hypernuclei:

1. Hyperon puzzle: understanding of YN, YNN interactions
2. Probing medium properties, possible signatures of phase transition
3. Searching for exotic hyper-systems

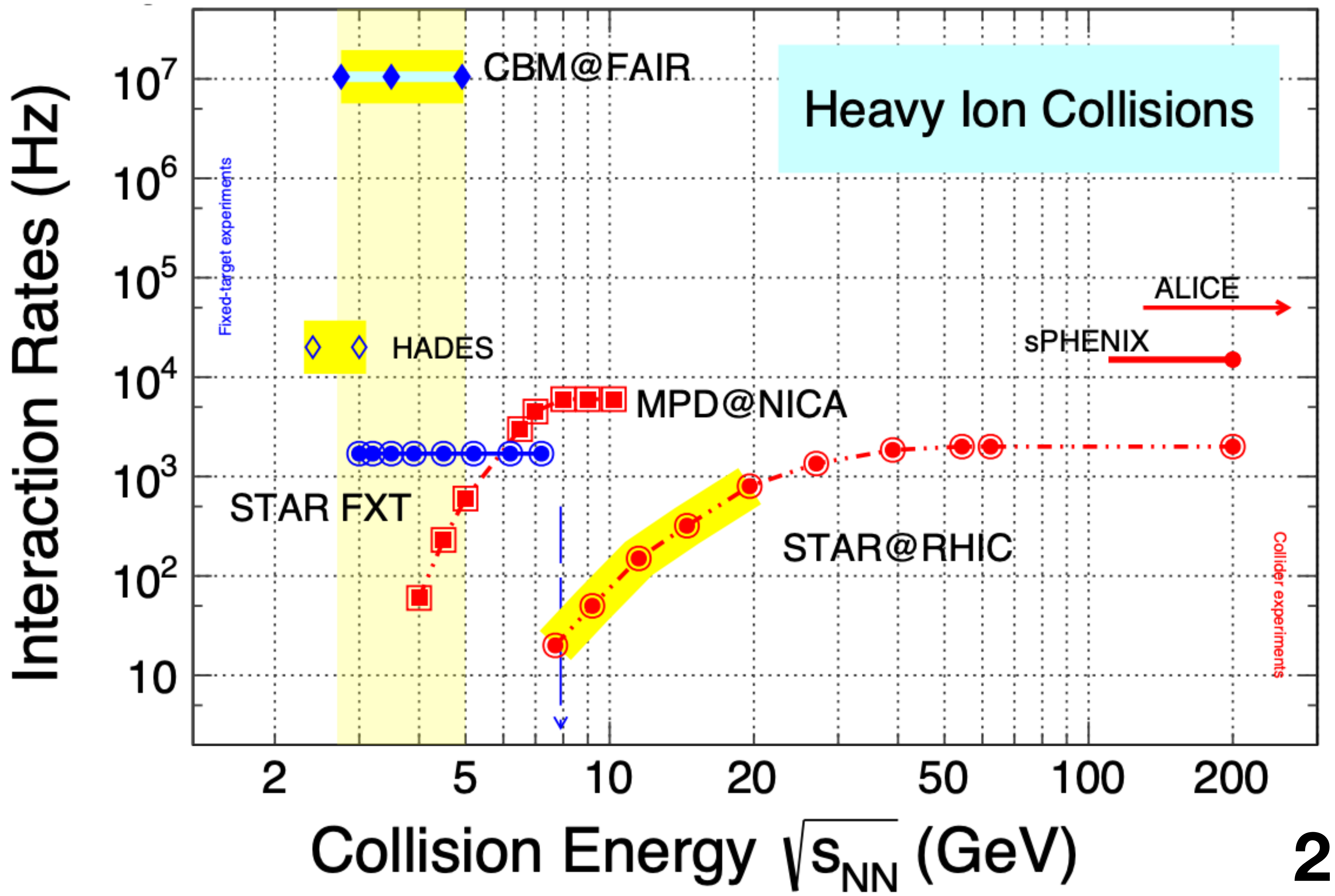
Advantages of CBM:

1. **Optimal beam energies** for hypernuclei production
2. **Excellent vertexing** and particle identification
3. **High interaction rates** capability enabling rare-signal studies, including double-Λ hypernuclei

Interaction rates up to 10MHz



Nu Xu et al., arXiv:2209.05009

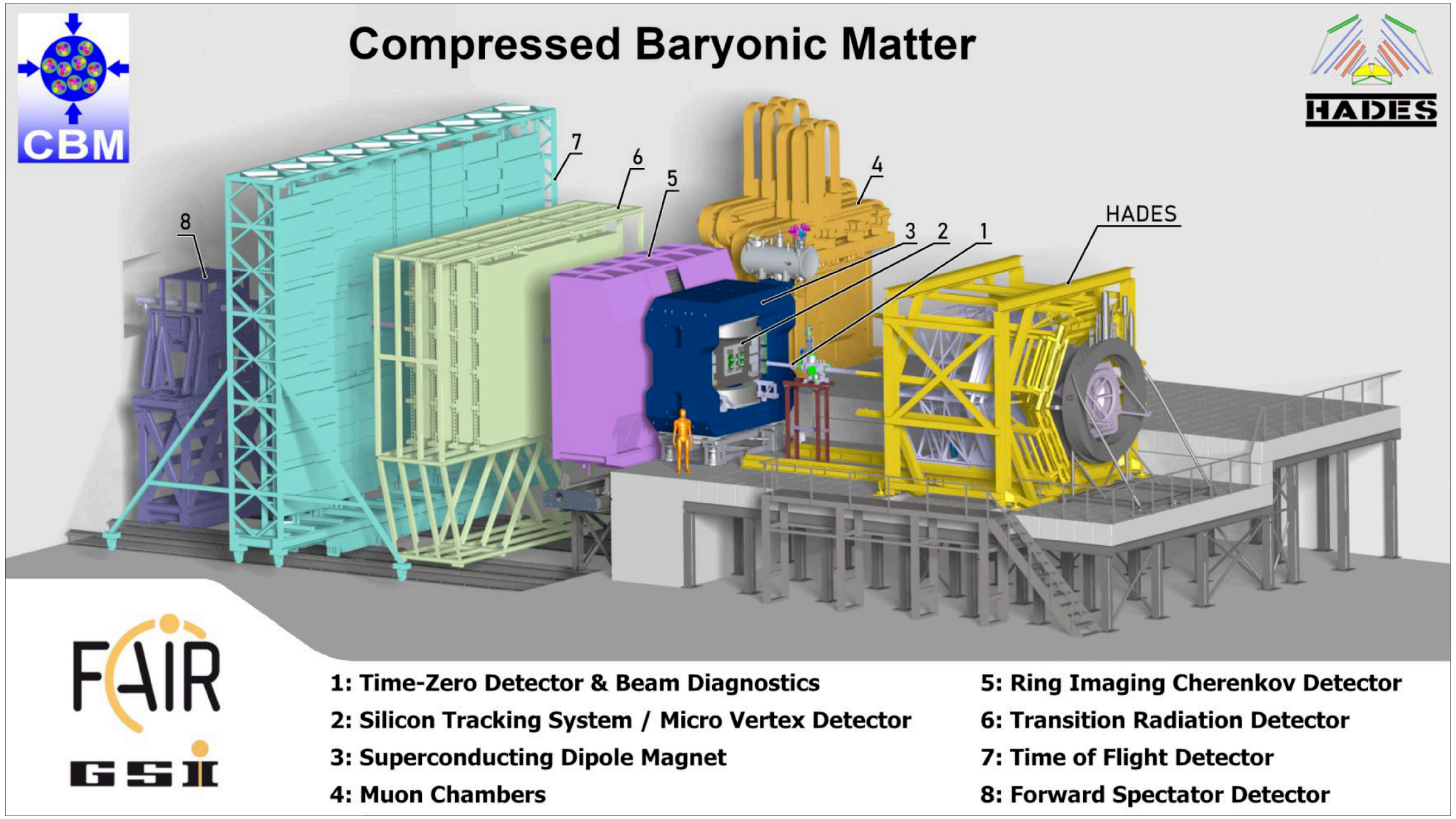


Compressed Baryonic Matter (CBM)

$\sqrt{s_{NN}}$ = 2.5-4.9 GeV Au+Au

Fixed target experiment

- Polar coverage 2° < θ_{lab} < 25° , full ϕ coverage
- Mid-rapidity coverage for all energies, extending to low p_T



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Fixed target experiment

- Polar coverage 2° < θ_{lab} < 25° , full ϕ coverage
- Mid-rapidity coverage for all energies, extending to low p_T

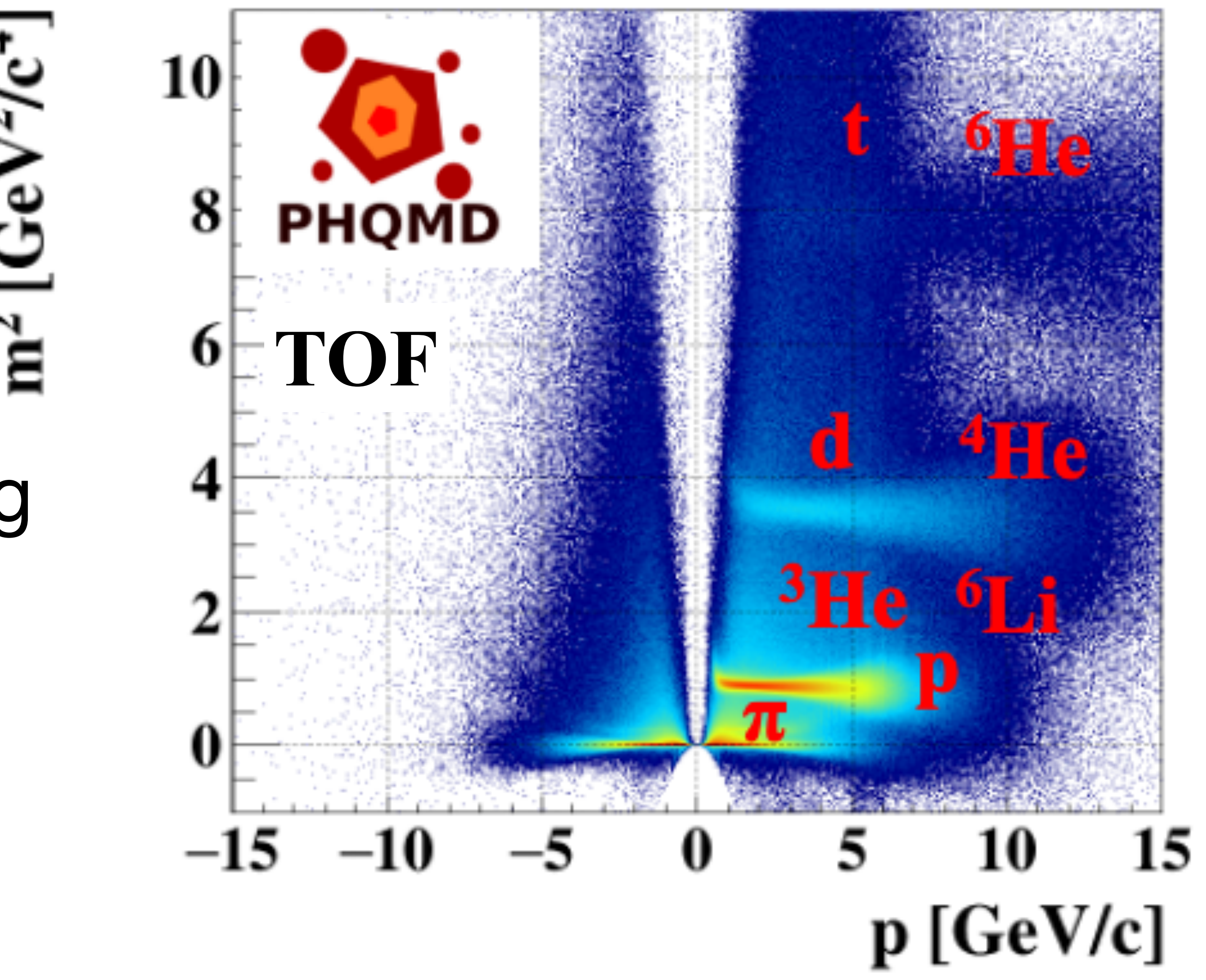
Versatile detector systems

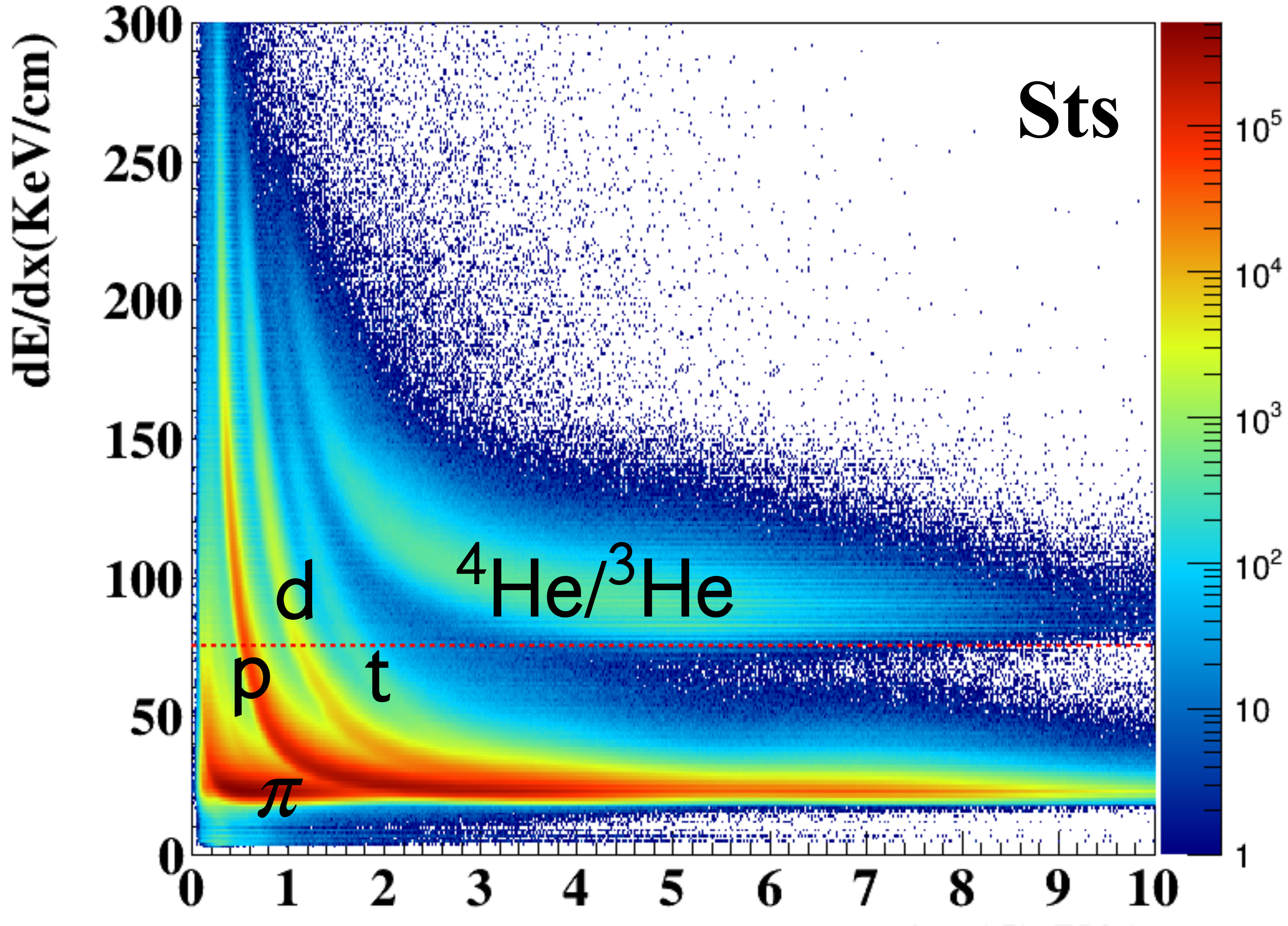
- MVD (Micro-Vertex Detector) — track reconstruction, excellent secondary vertex
- TOF (Time of Flight) — hadron identification
- STS (Silicon Tracking System) — heavy fragments identification by dE/dX
- TRD (Transition Radiation detector) — electron and heavy fragments identification

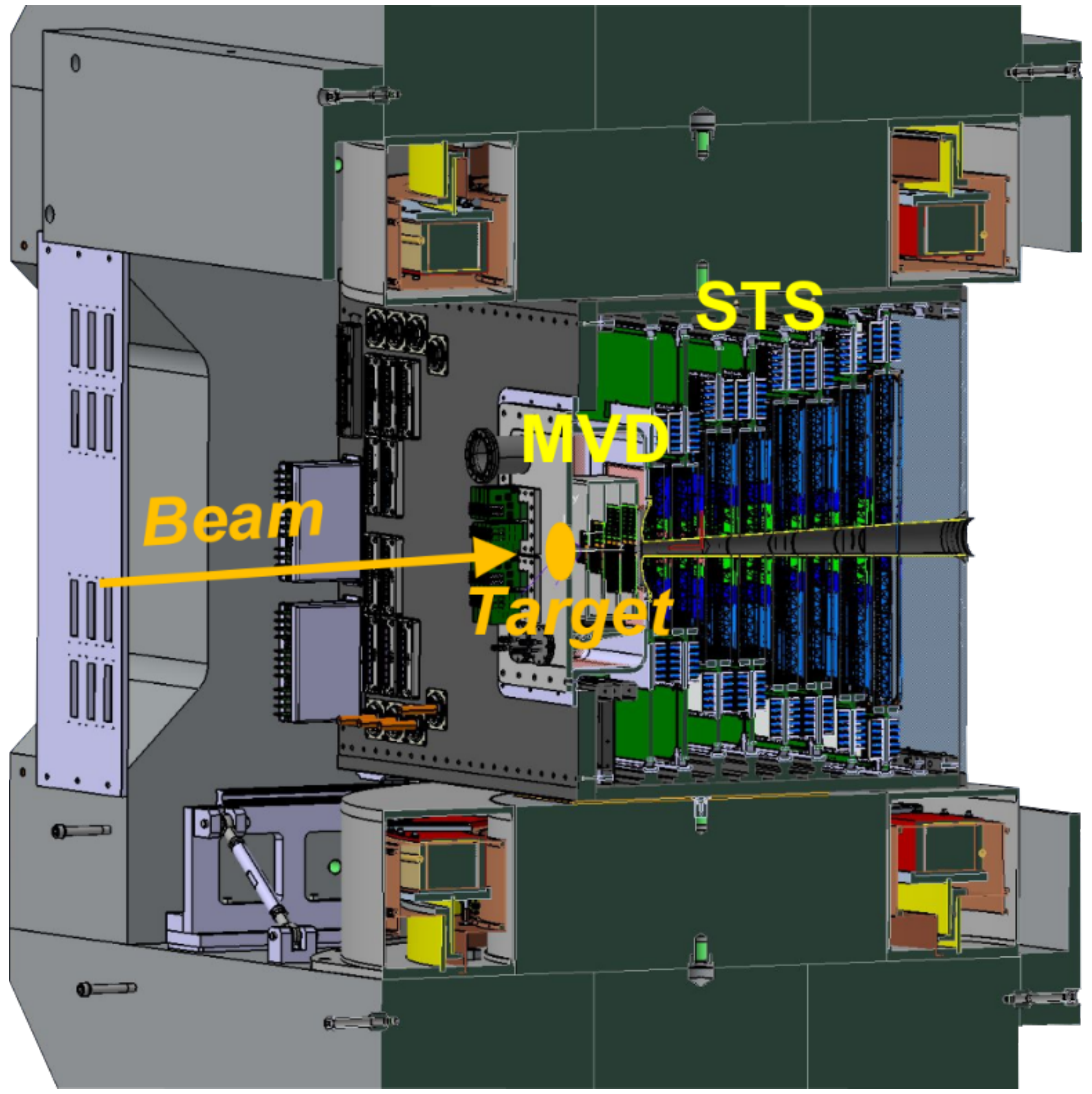
Tracking fully silicon-based

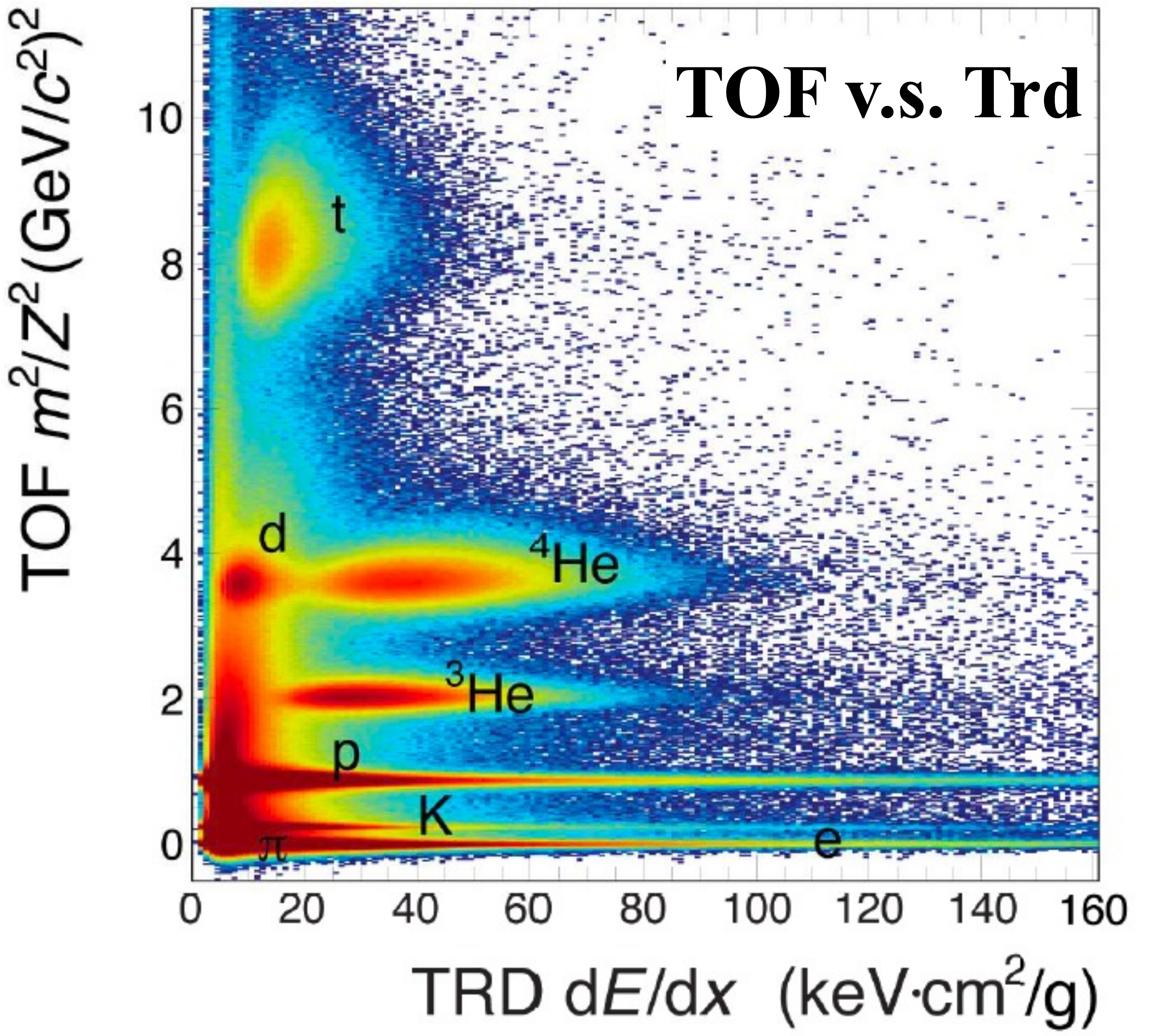
- Fast and precise track reconstruction

Online event selection and data reduction





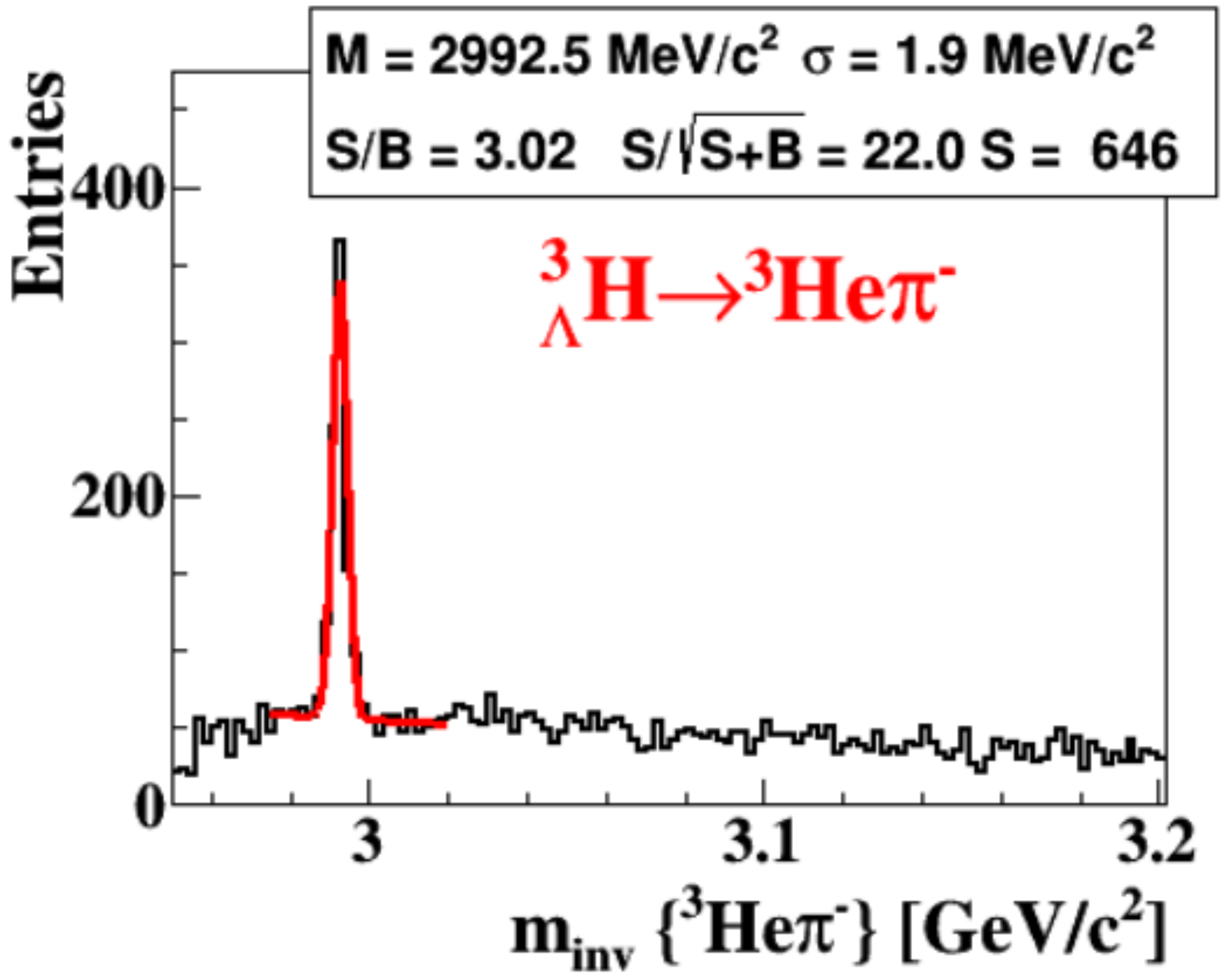


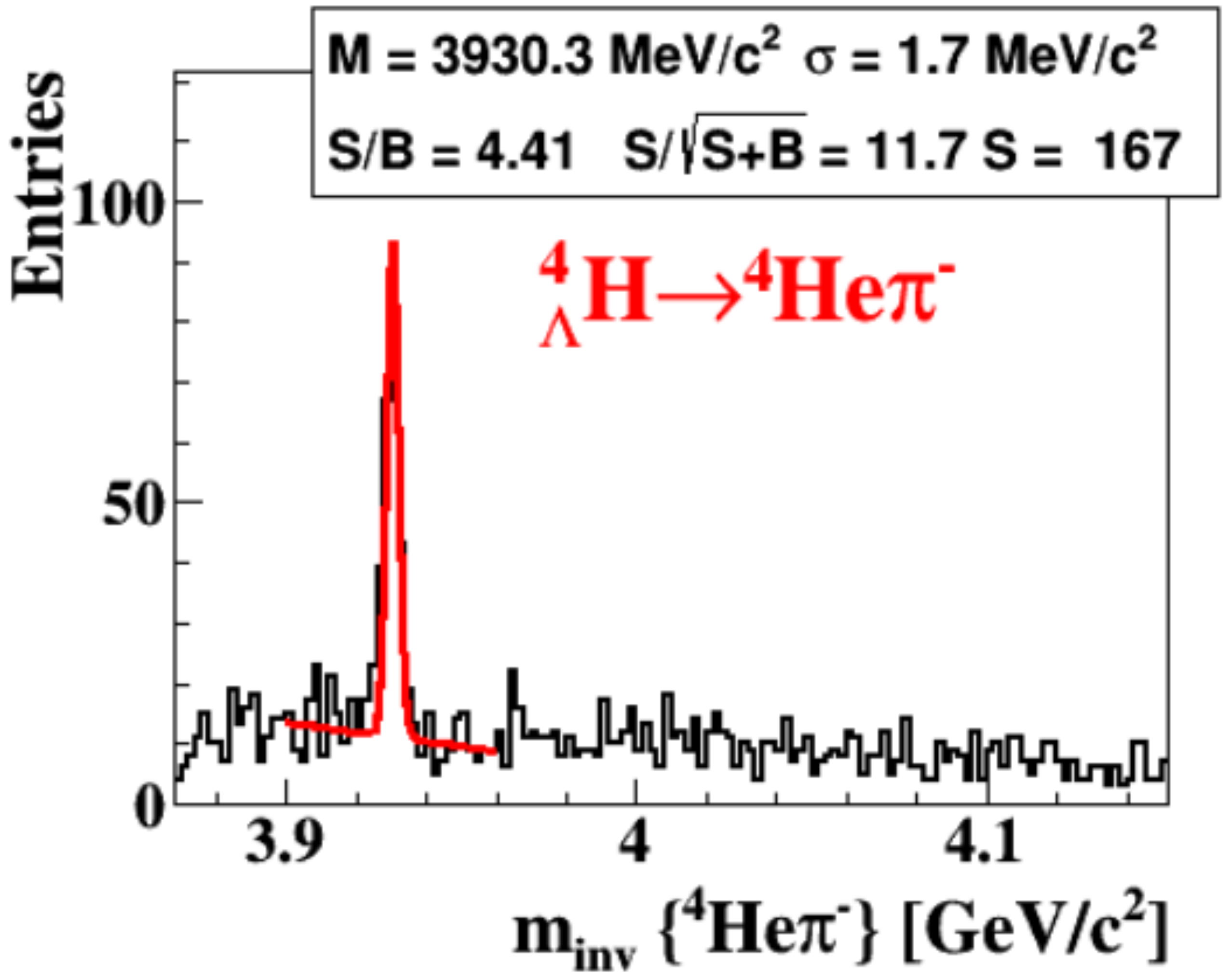


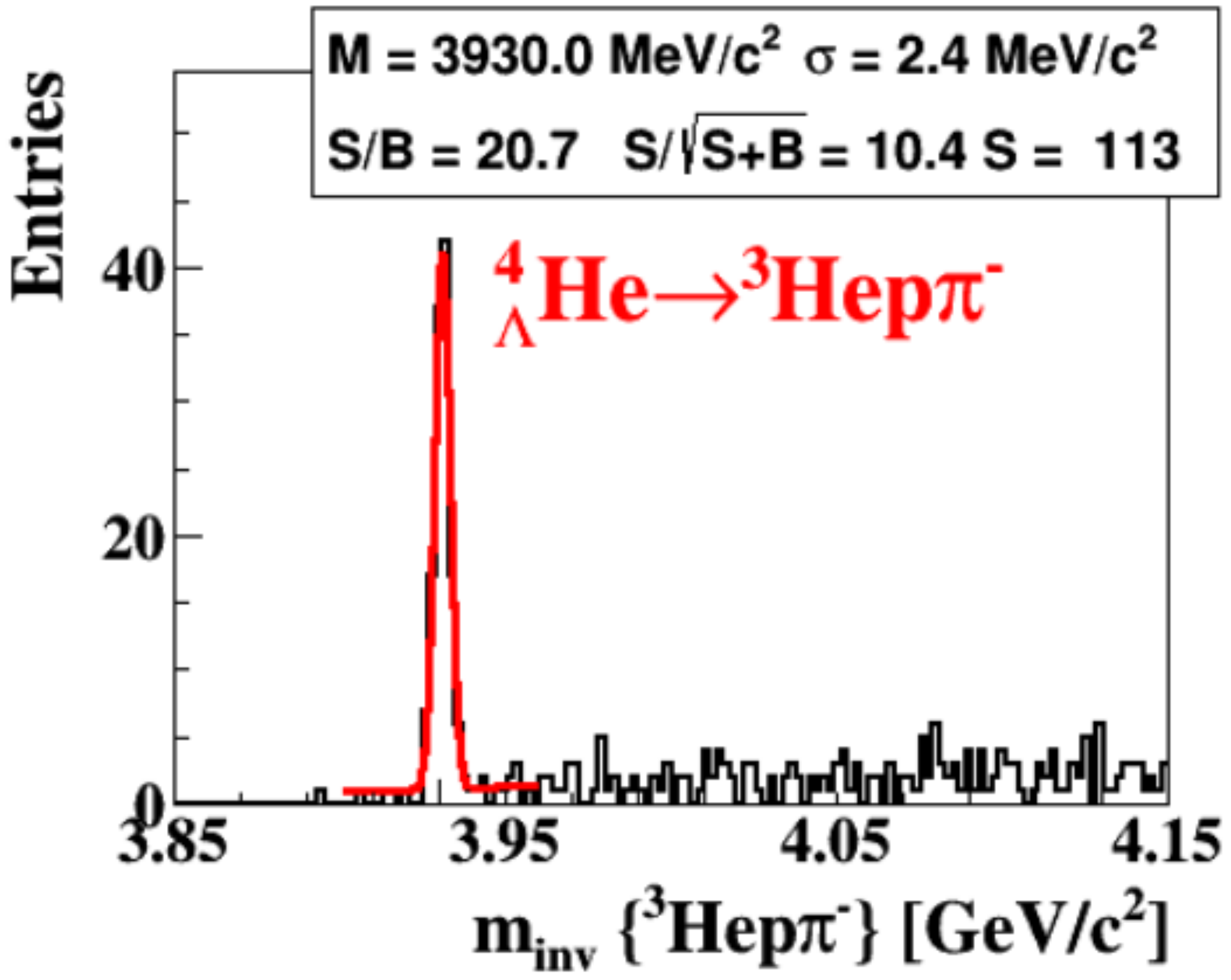
Hypernuclei in CBM at SIS100

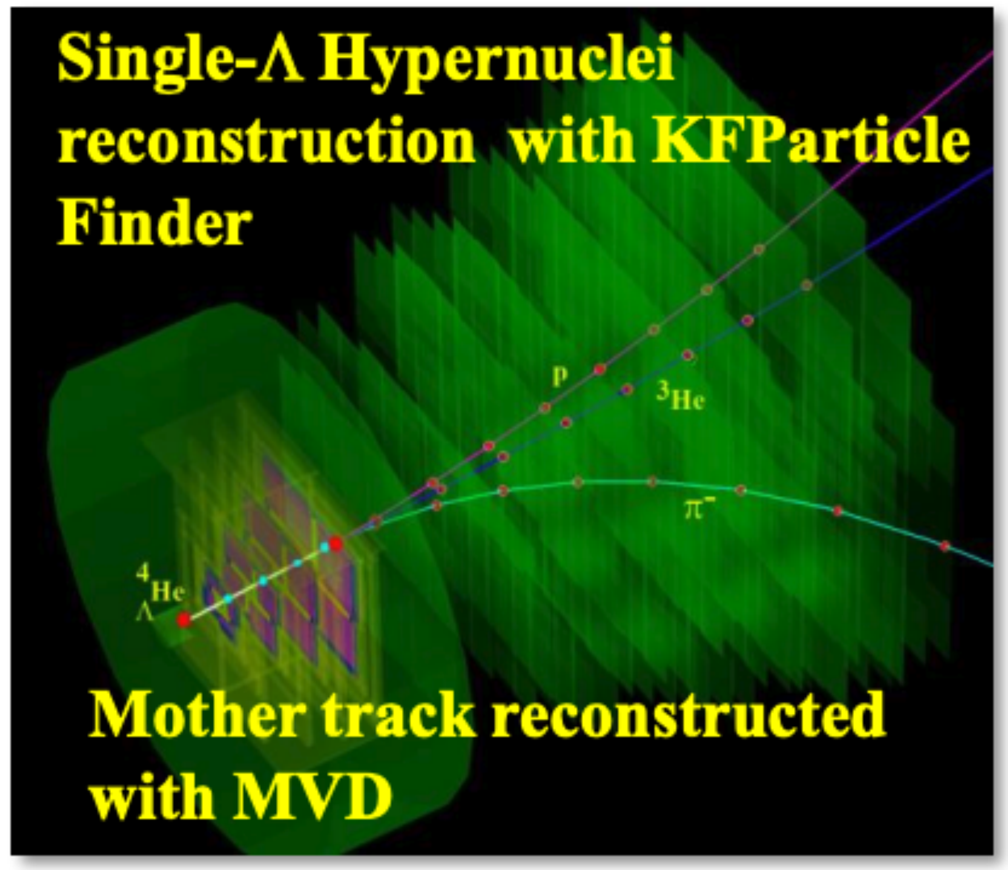
UrQMD events, thermal isotropic signal:

Au + Au, 4.72 GeV, 10^{12} central (b = 0)

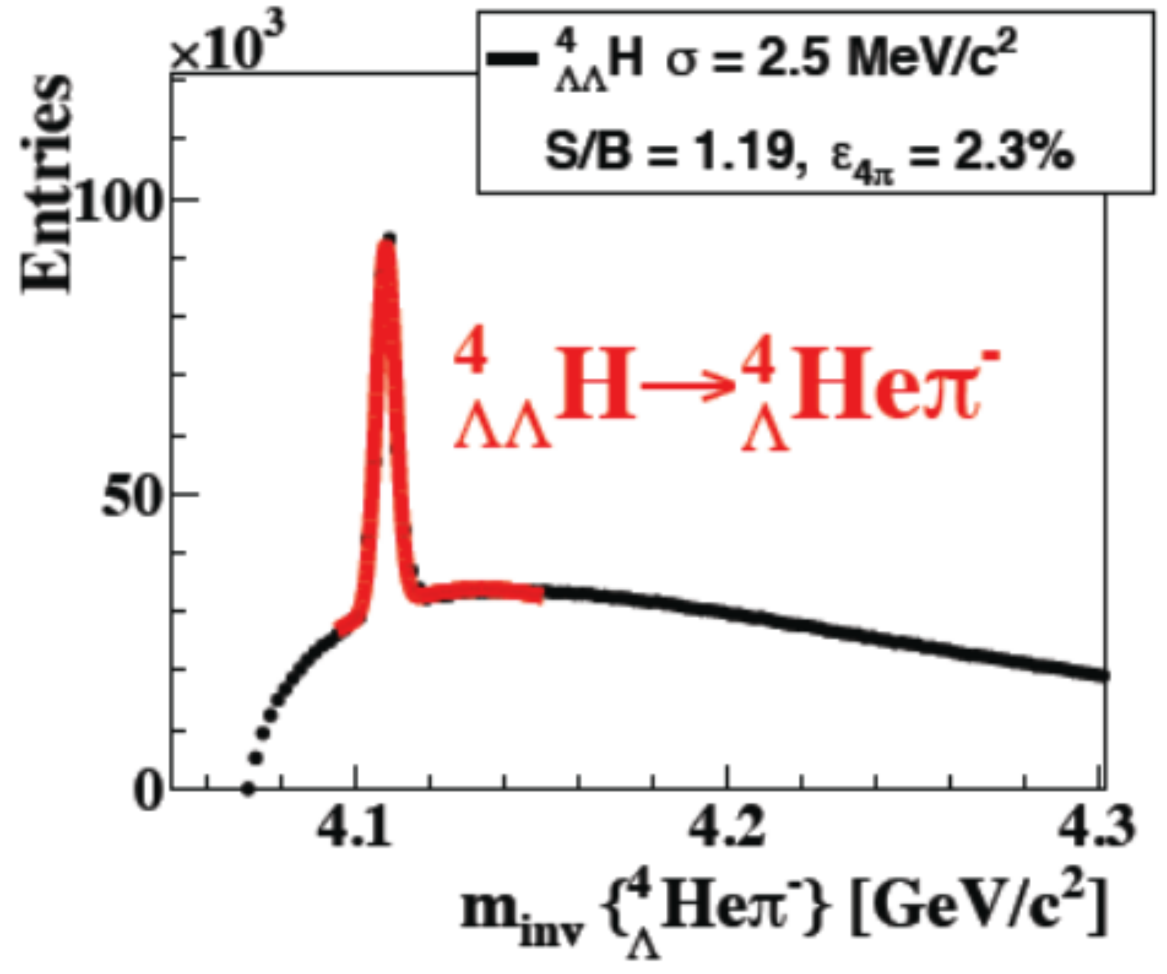


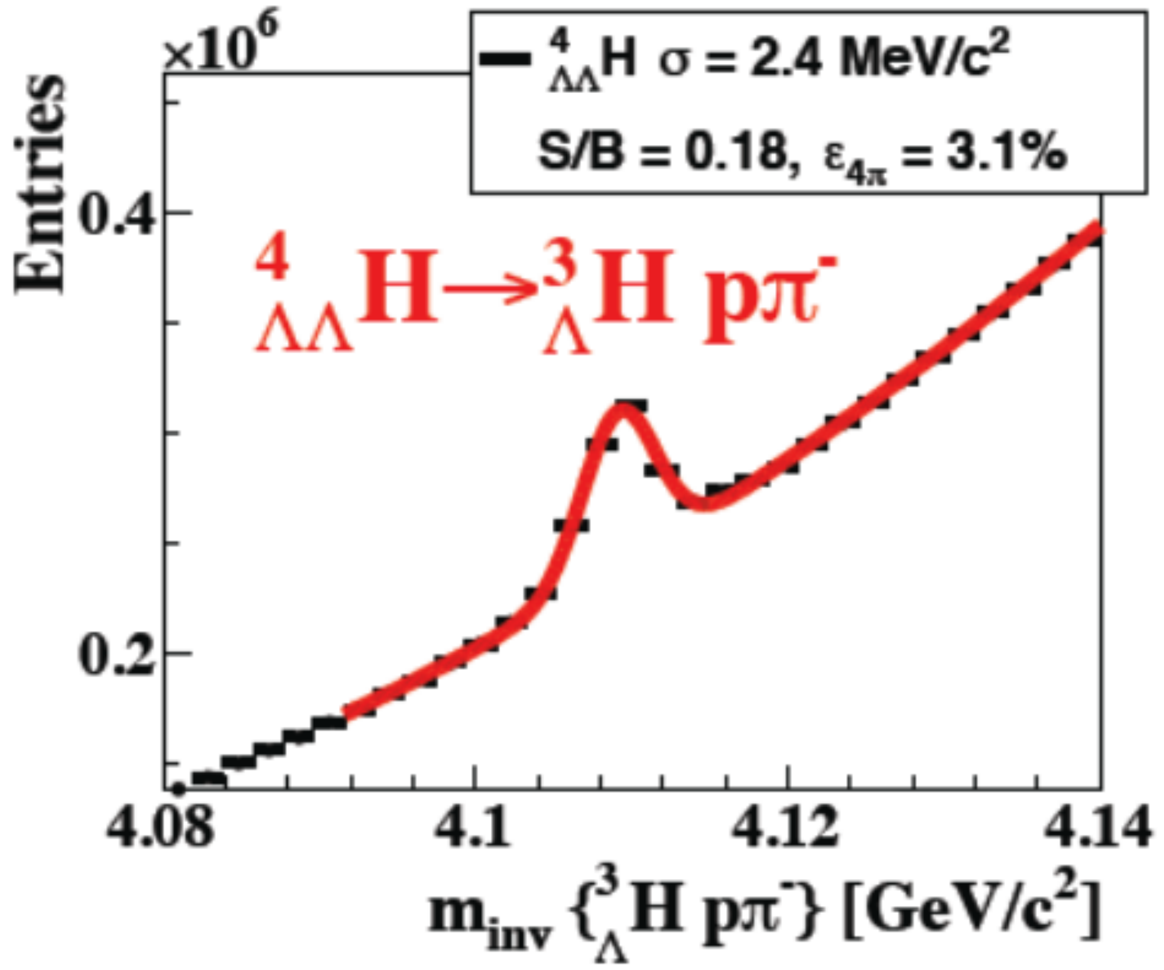


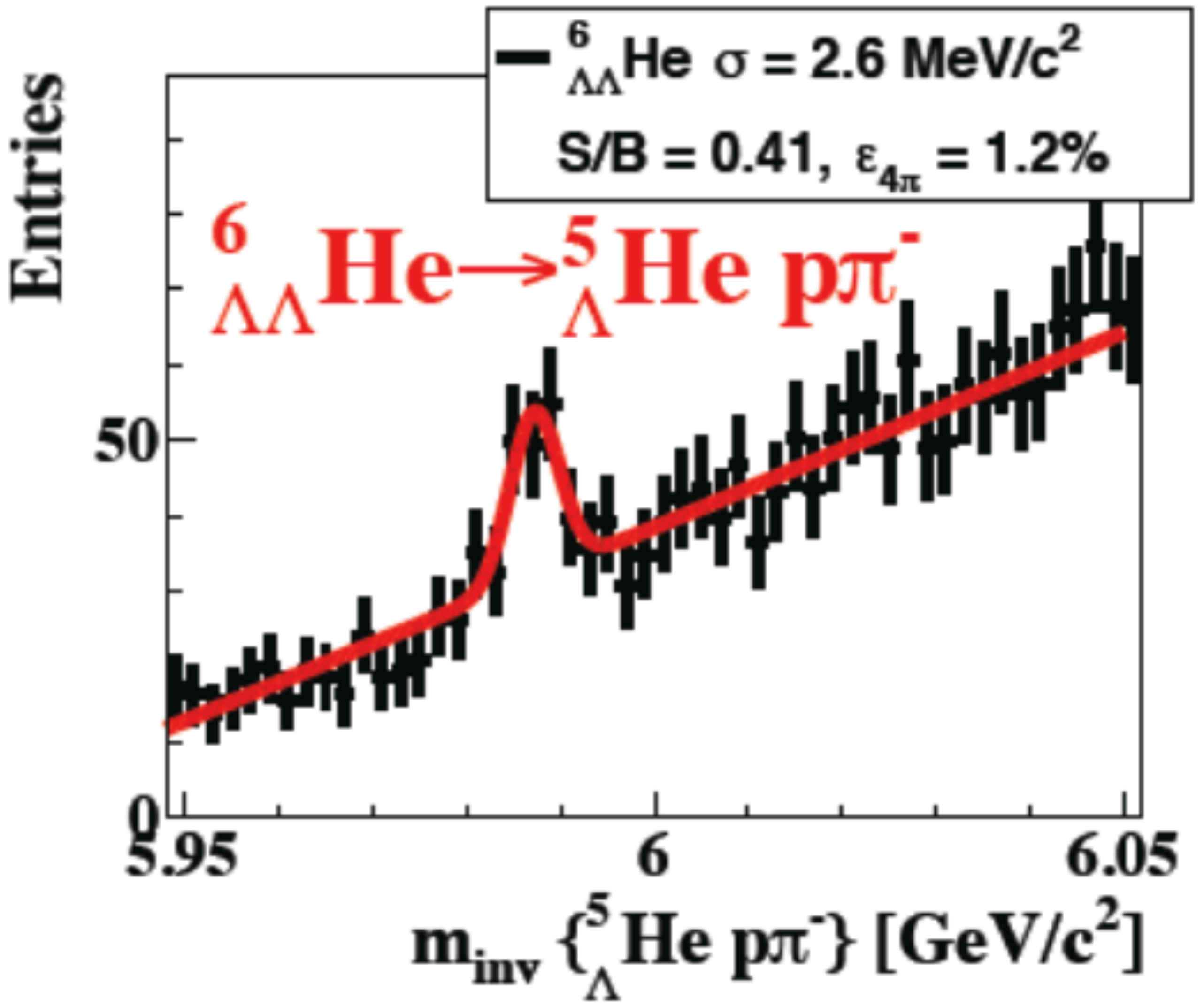


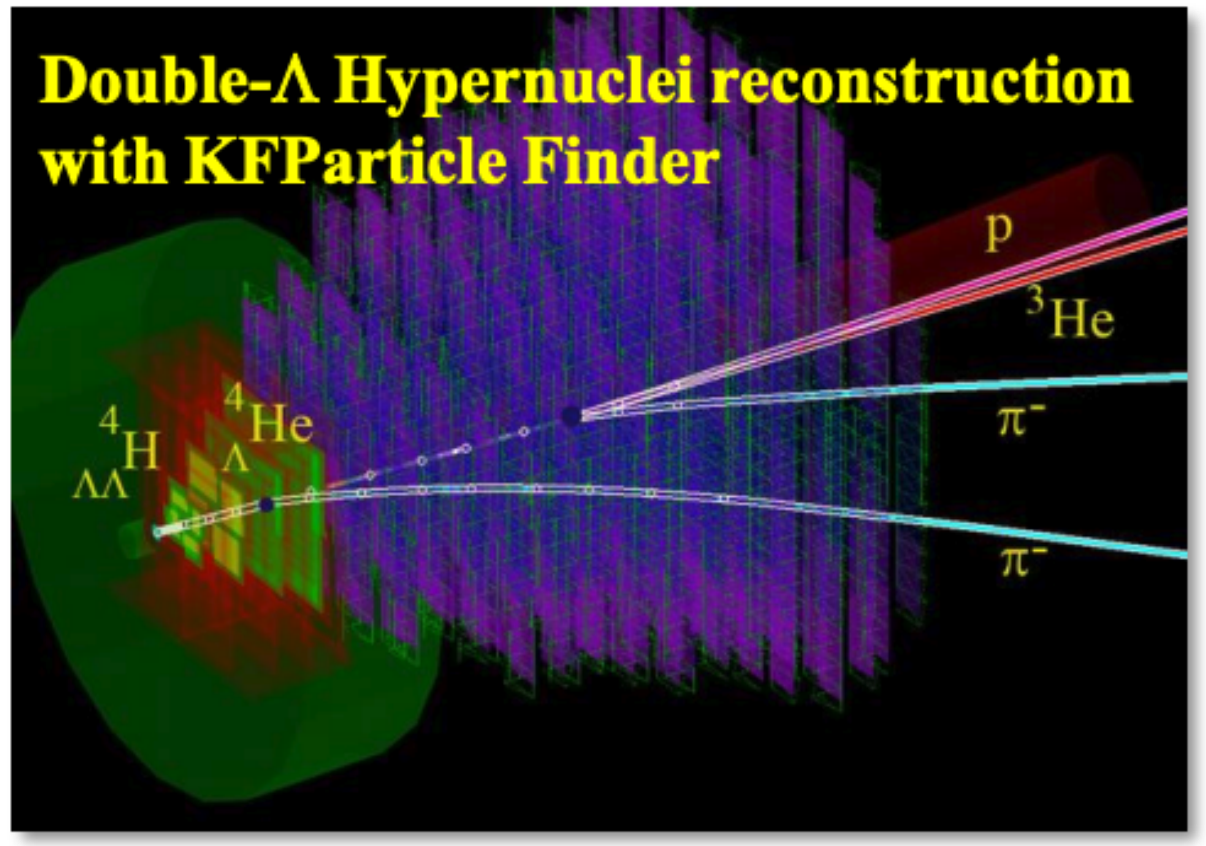


Expected collection rate: ~60 $^6_{\Lambda\Lambda}$He in 1 week at **10MHz IR**





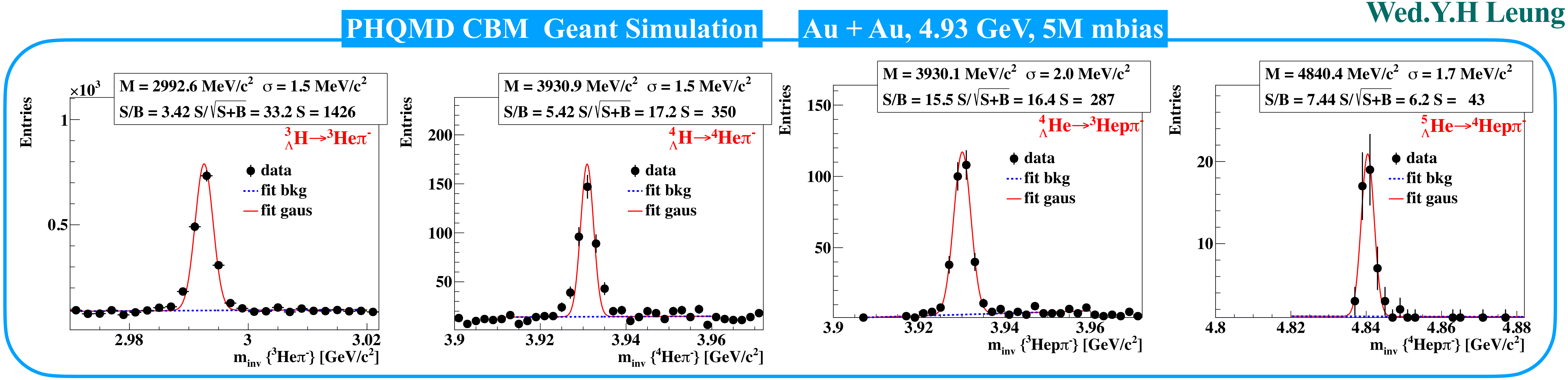


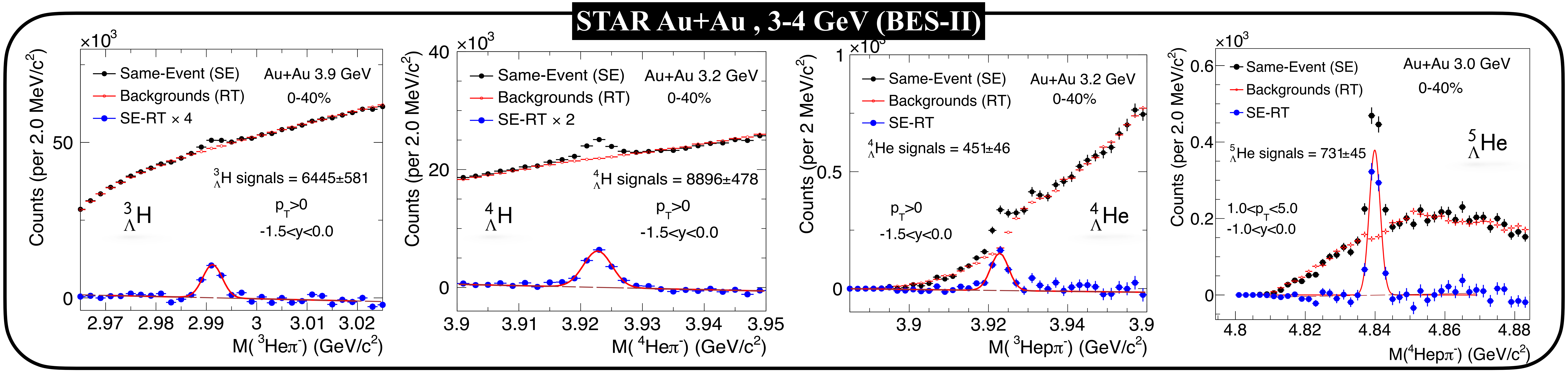


- Simulated with UrQMD + thermal source; reconstruction via KFParticle maximizes signal significance

Hypernuclei in CBM at SIS100

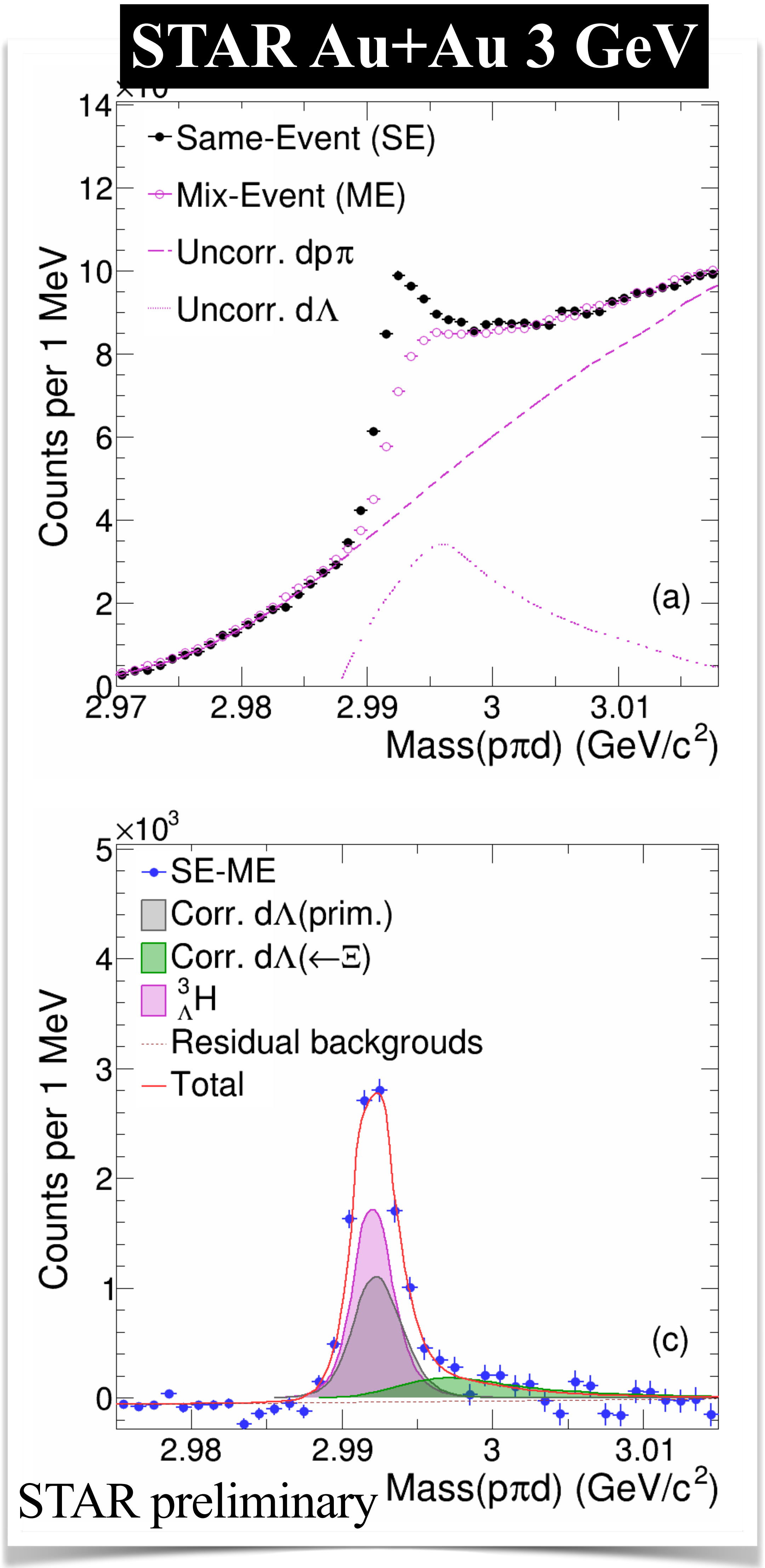
PHQMD:
Tue. S. Glessel
Wed.Y.H Leung



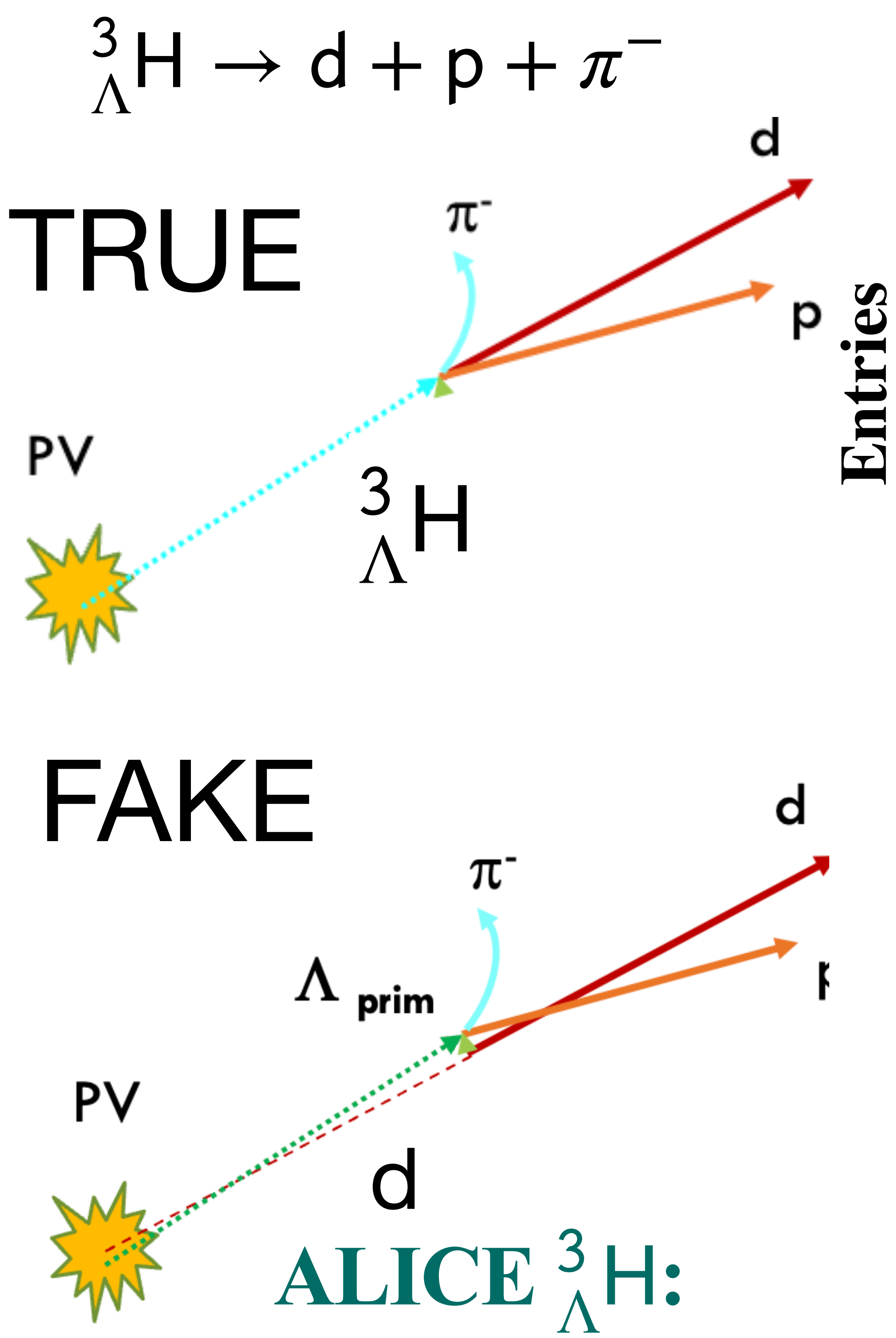


- Background largely suppressed with the MVD detector — excellent DCA and vertex resolution

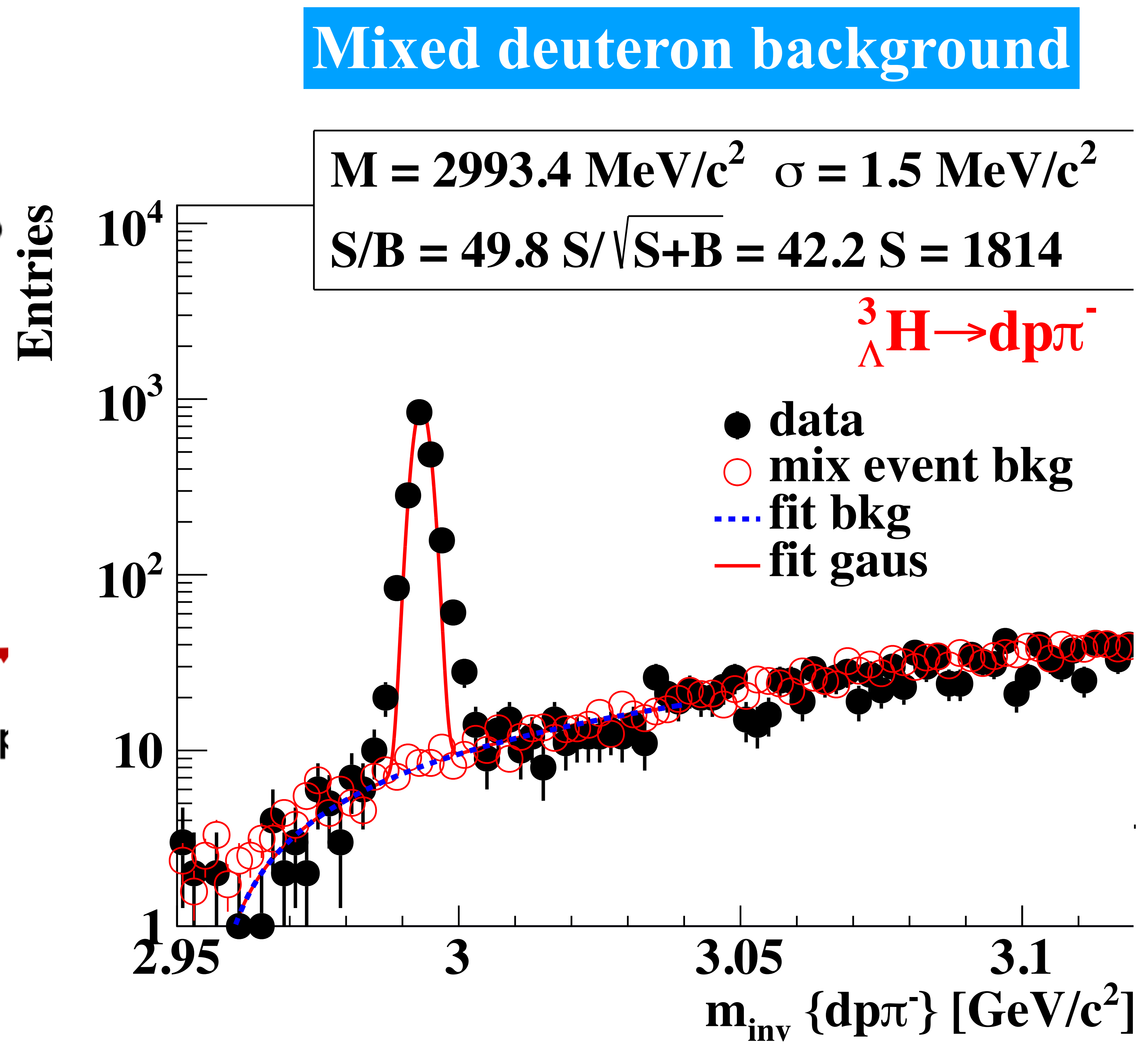
Background Subtraction – Event Mixing Technique with MVD Suppression

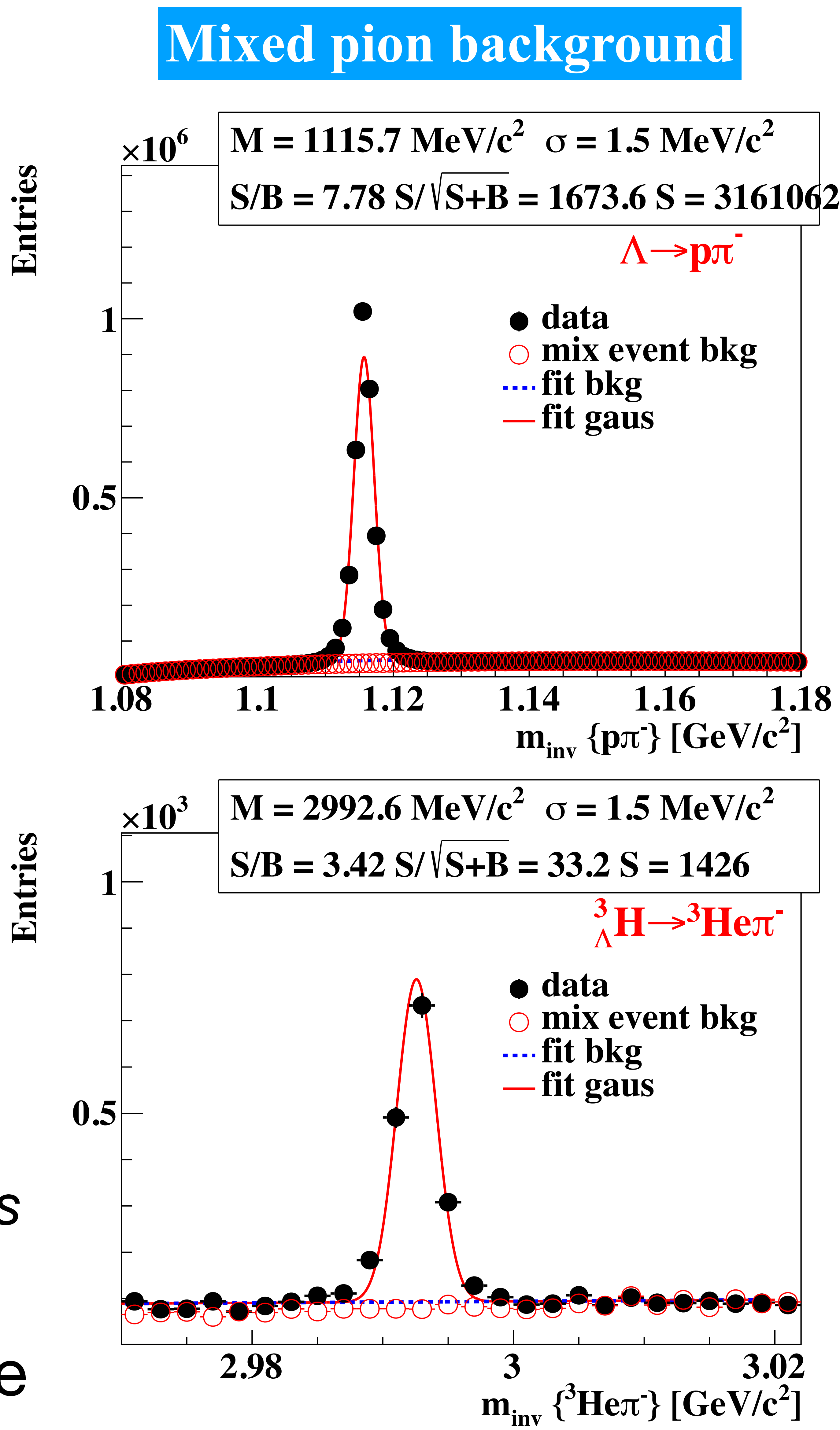


$$M(\Lambda) + M(d) \sim 2.9913 GeV/c^2$$
$$M({}^{3}_{\Lambda}H) \sim 2.991 GeV/c^2$$



ALICE ${}^{3}_{\Lambda}H$:
Mon. C. Jauch





- Primary Λ background strongly suppressed by MVD's excellent vertex resolution

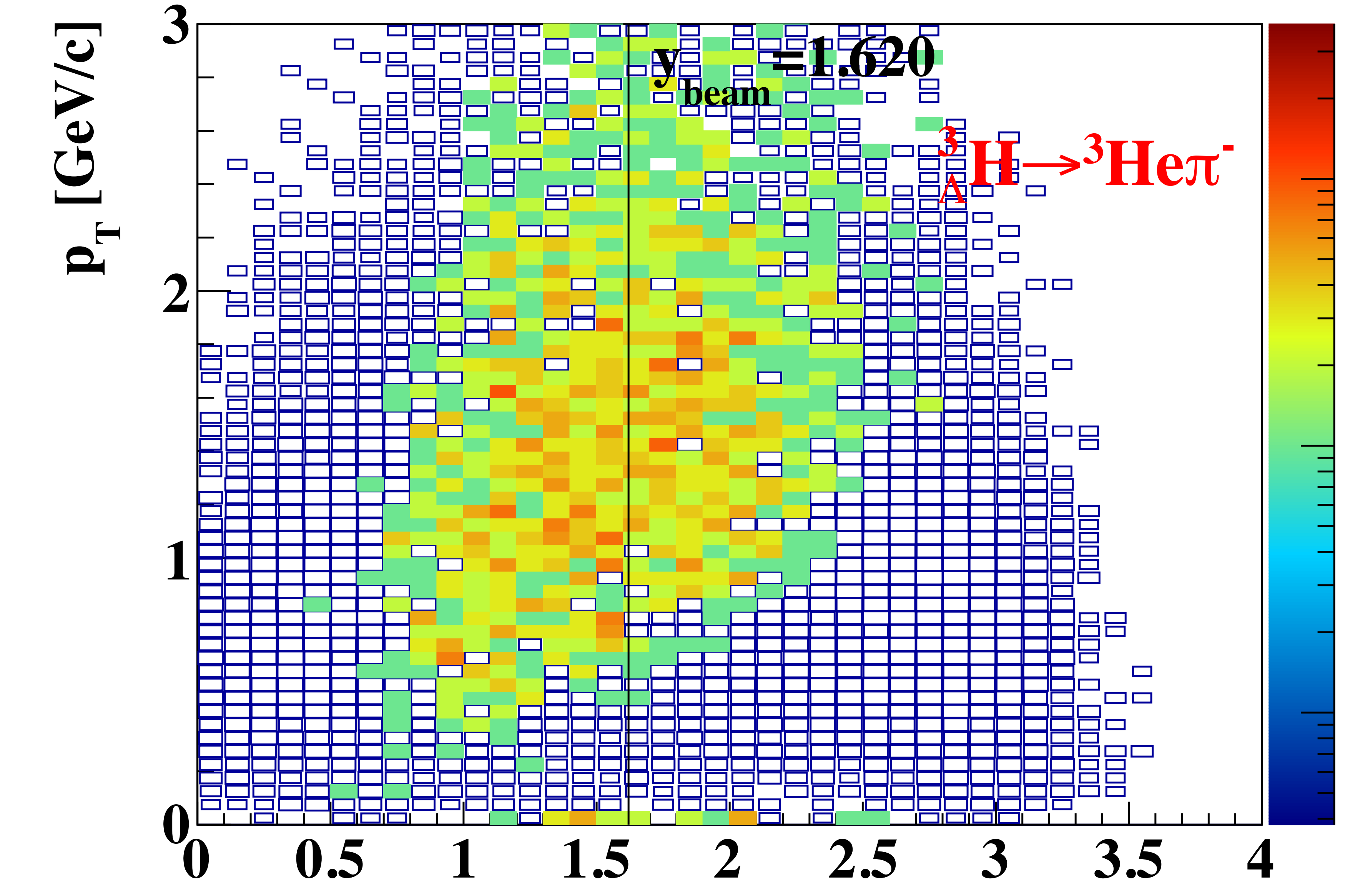
  Reduces both correlated and uncorrelated d–Λ backgrounds

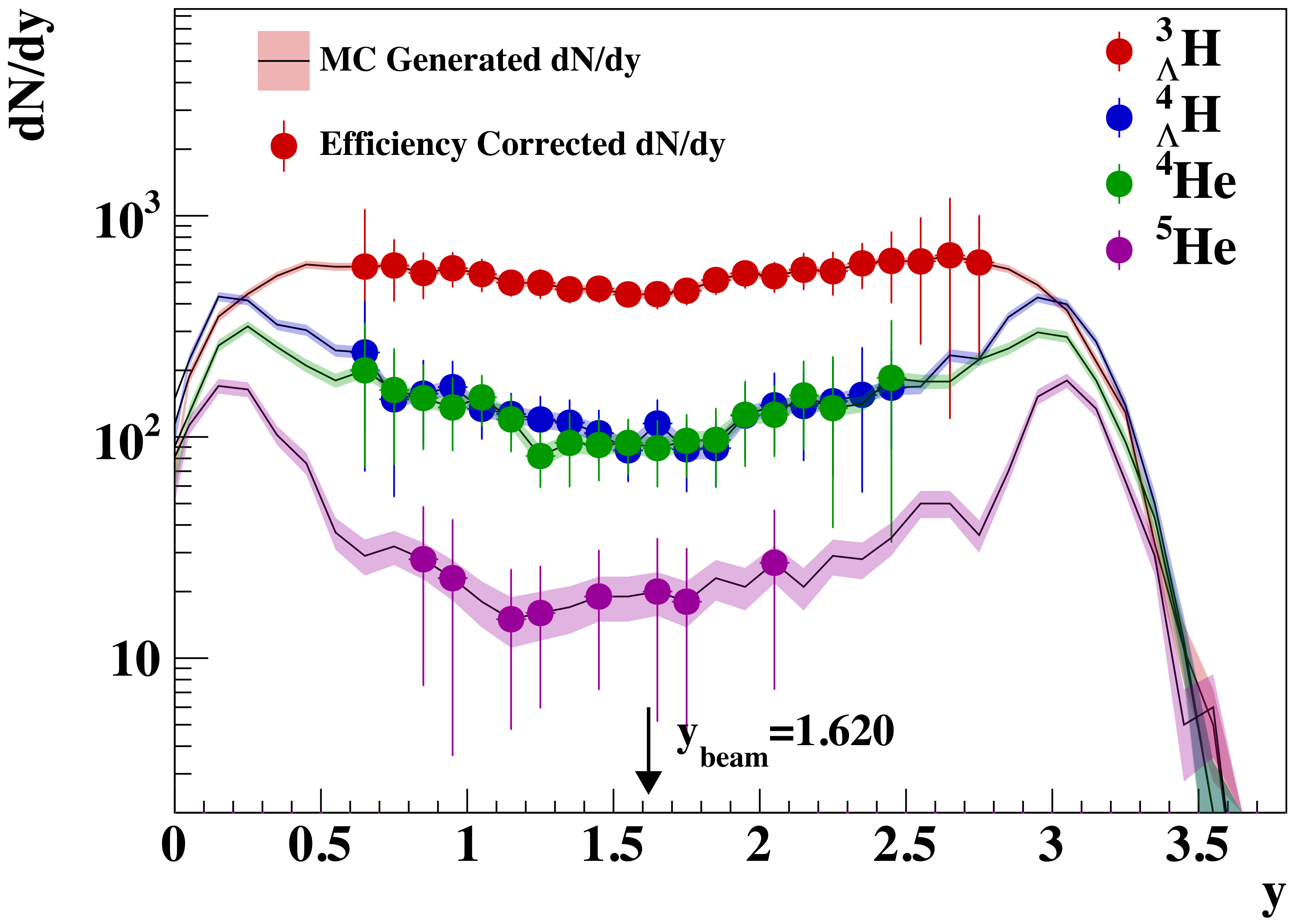
- Mixed-event technique models the combinatorial background; its shape smoothly matches that of true events

  Allows clean signal extraction!

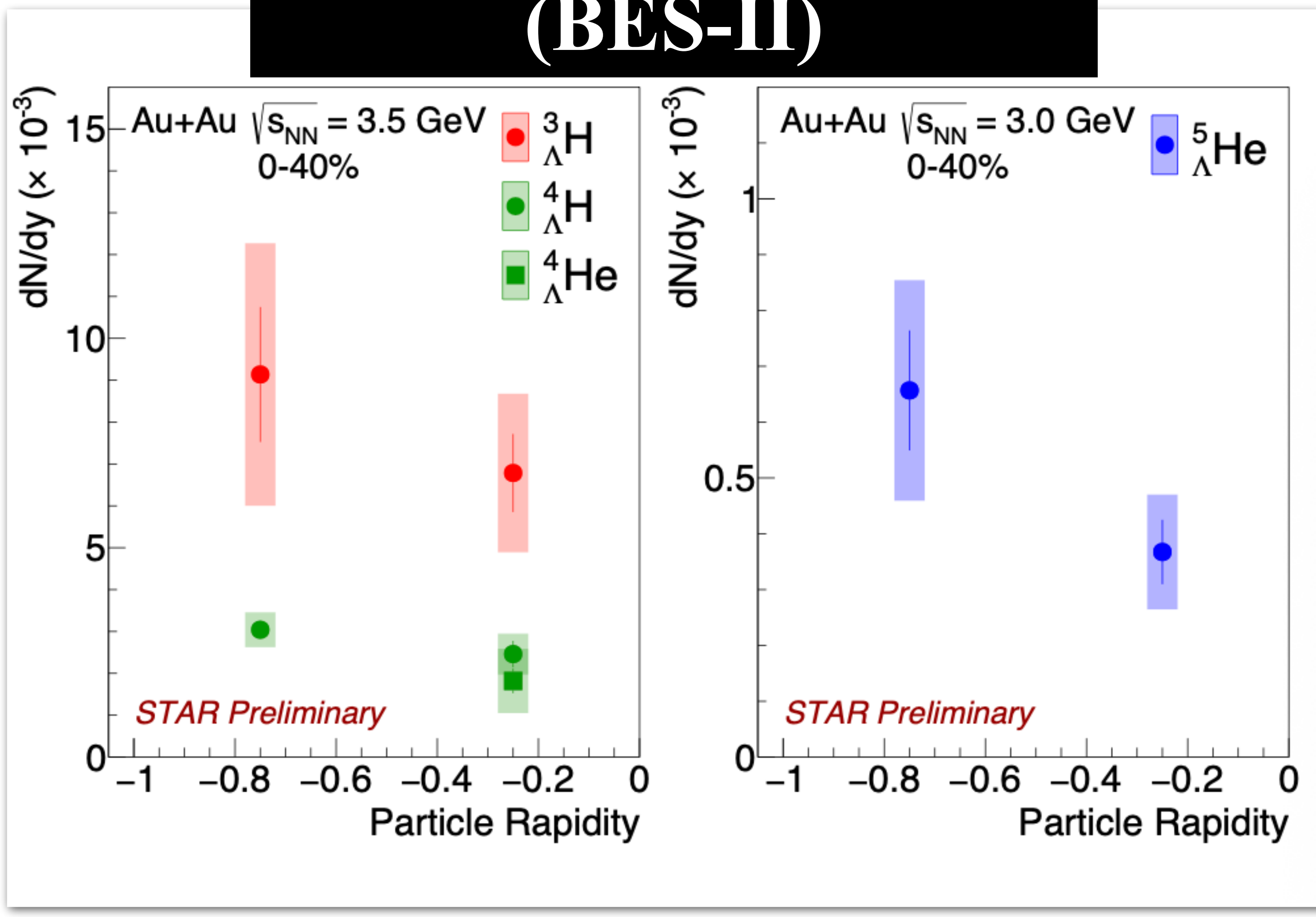
e.g. ${}^{4}_{\Lambda}H \rightarrow t + p + \pi^{-}$
${}^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$
${}^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$

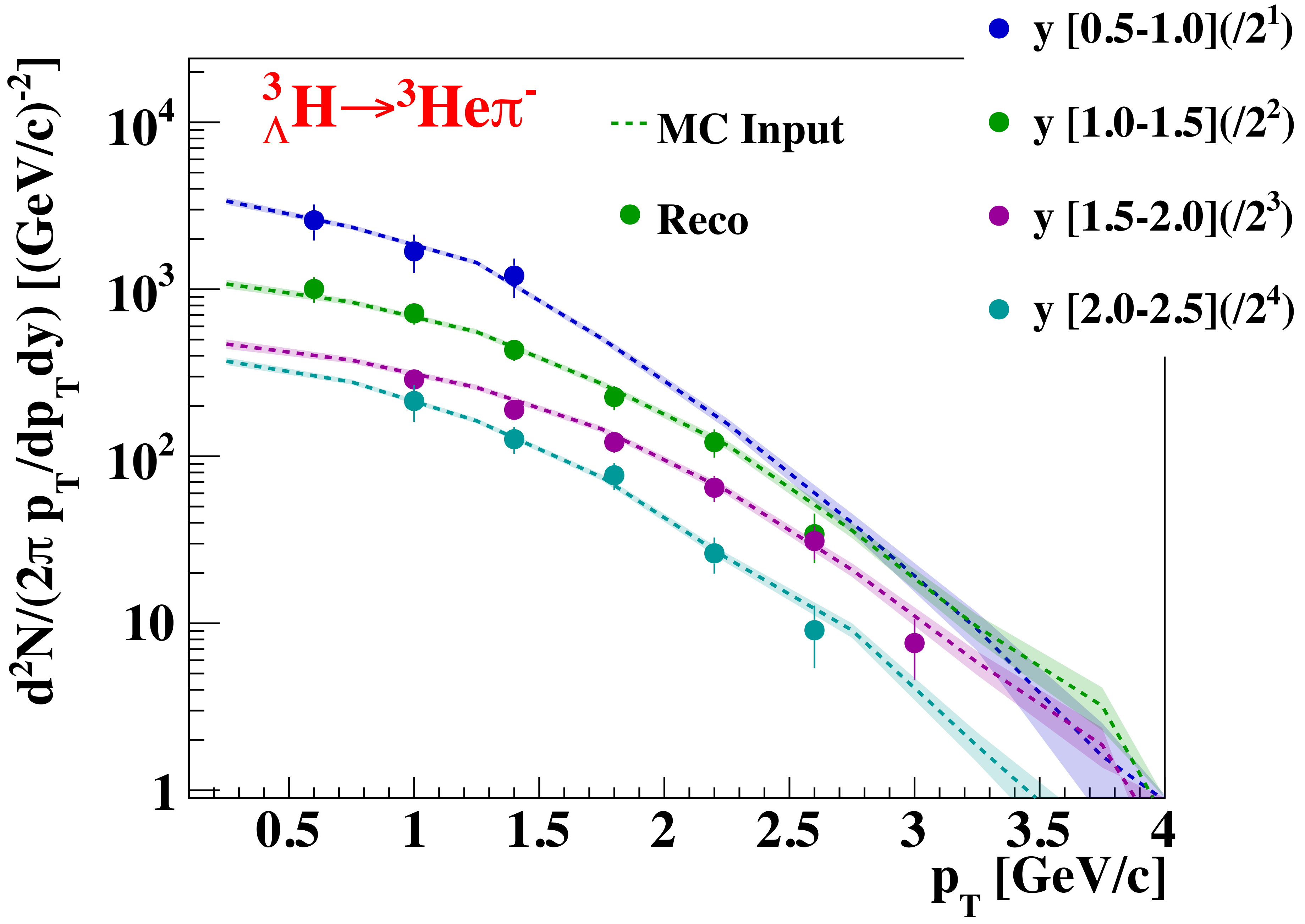
Differential p_T Spectrum and Rapidity Dependence





STAR Au+Au 3-4 GeV (BES-II)

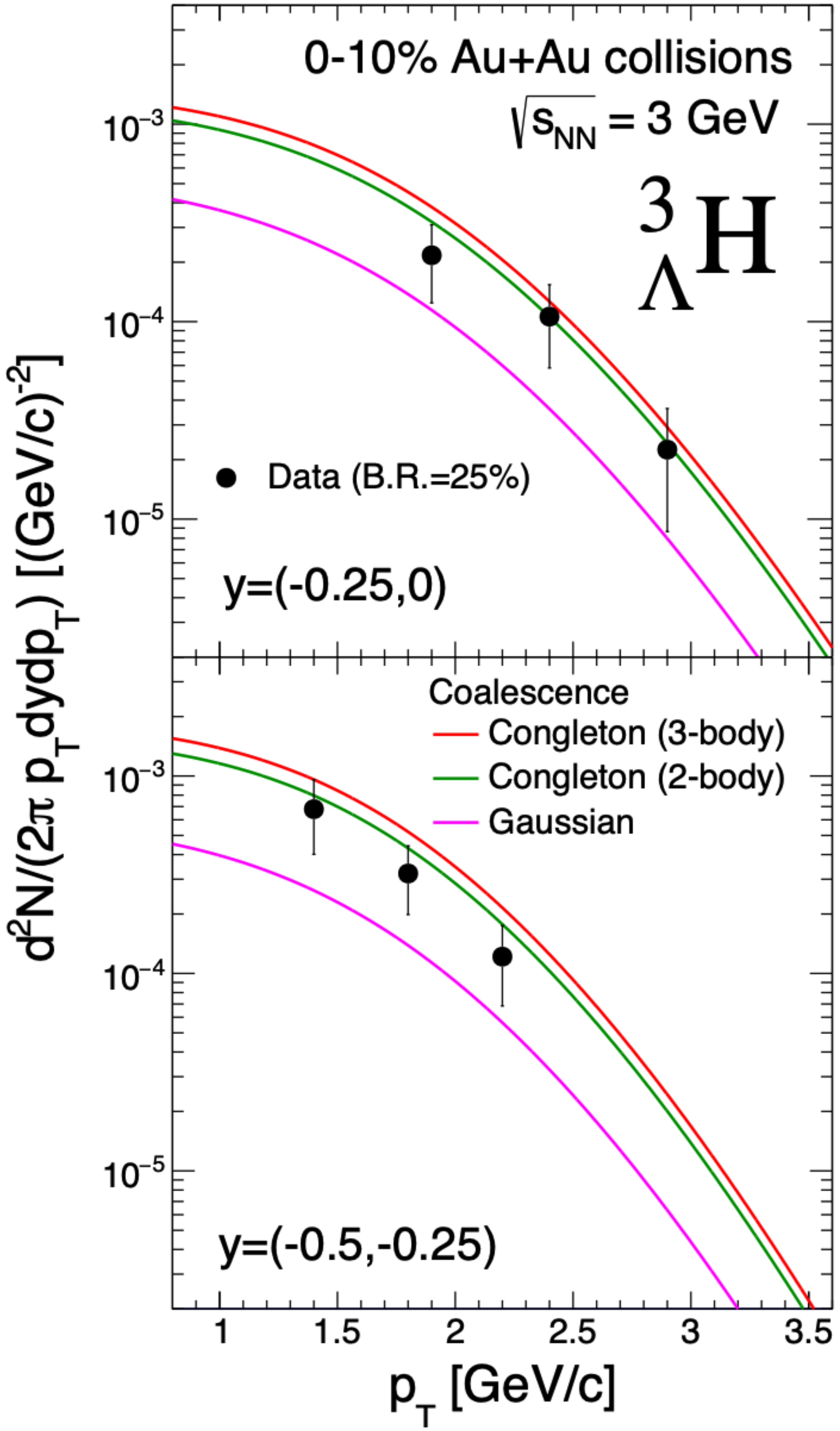




- High precision enables study of the detailed shape of dN/dy, probing possible changes in production mechanisms toward target rapidity
  - Spectator fragments may play an important role in hypernuclei production — Λ capture + fragmentation?

Differential p_T Spectrum — Probing the Hypertriton Wave Function

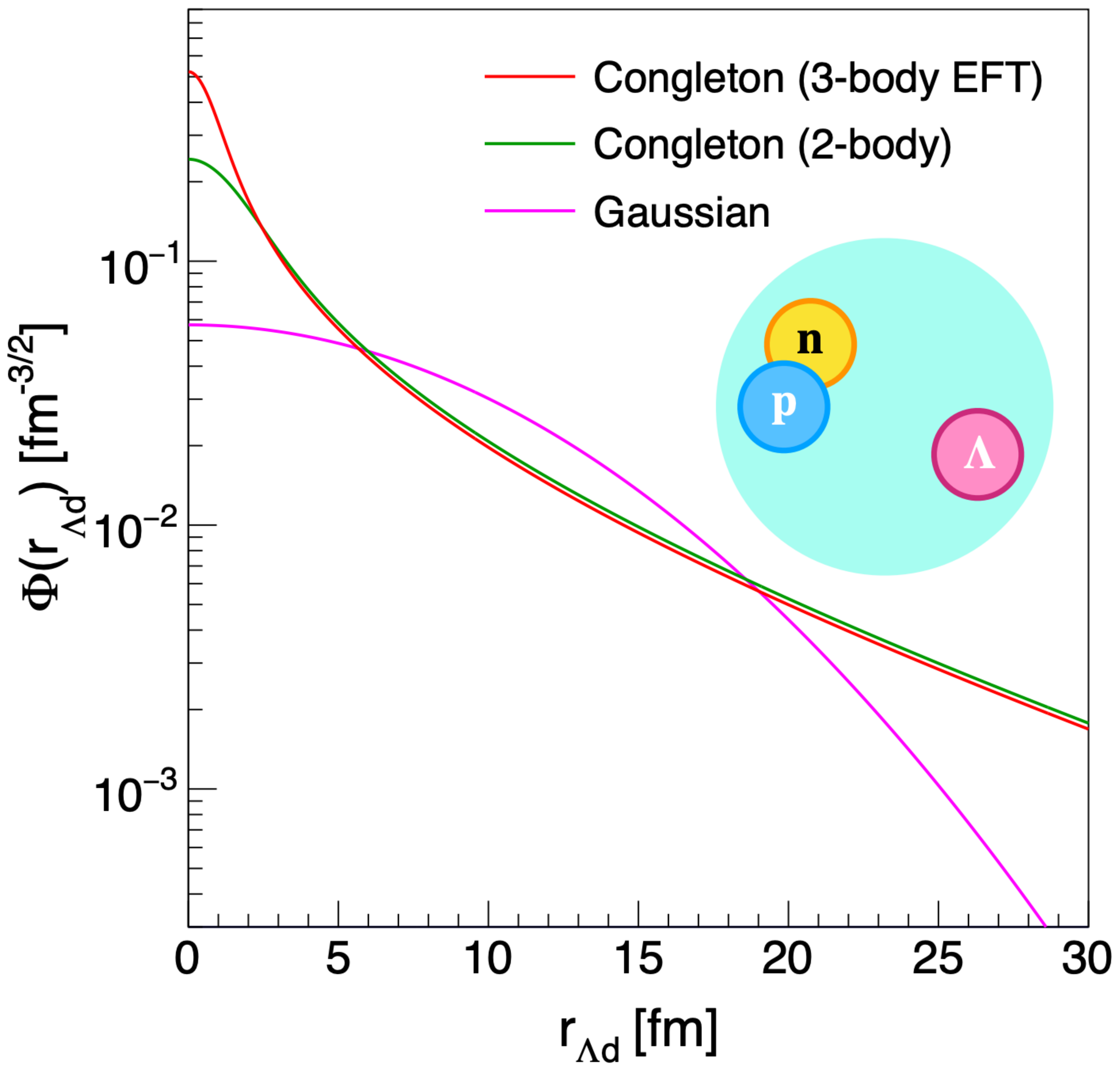
Coalescence: arXiv: 2510.06758



- Wigner-function coalescence: coalescence probability given by overlap between $^{3}_{\Lambda}$H **wave function** and **nucleon/hyperon distributions** at freeze out

F. Bellini et al., PRC 103 (2021) 014907

$$B_3(^3_\Lambda\text{H}) \approx \frac{3}{m^2}\frac{2s_{^3_\Lambda\text{H}}+1}{(2s_N+1)^3}(2\pi)^6\int d^3r_{pn}\int d^3r_\Lambda\,|\Phi_{^3_\Lambda\text{H}}(r_{pn},r_\Lambda)|^2\,\mathcal{S}_3(r_{pn},r_\Lambda)$$

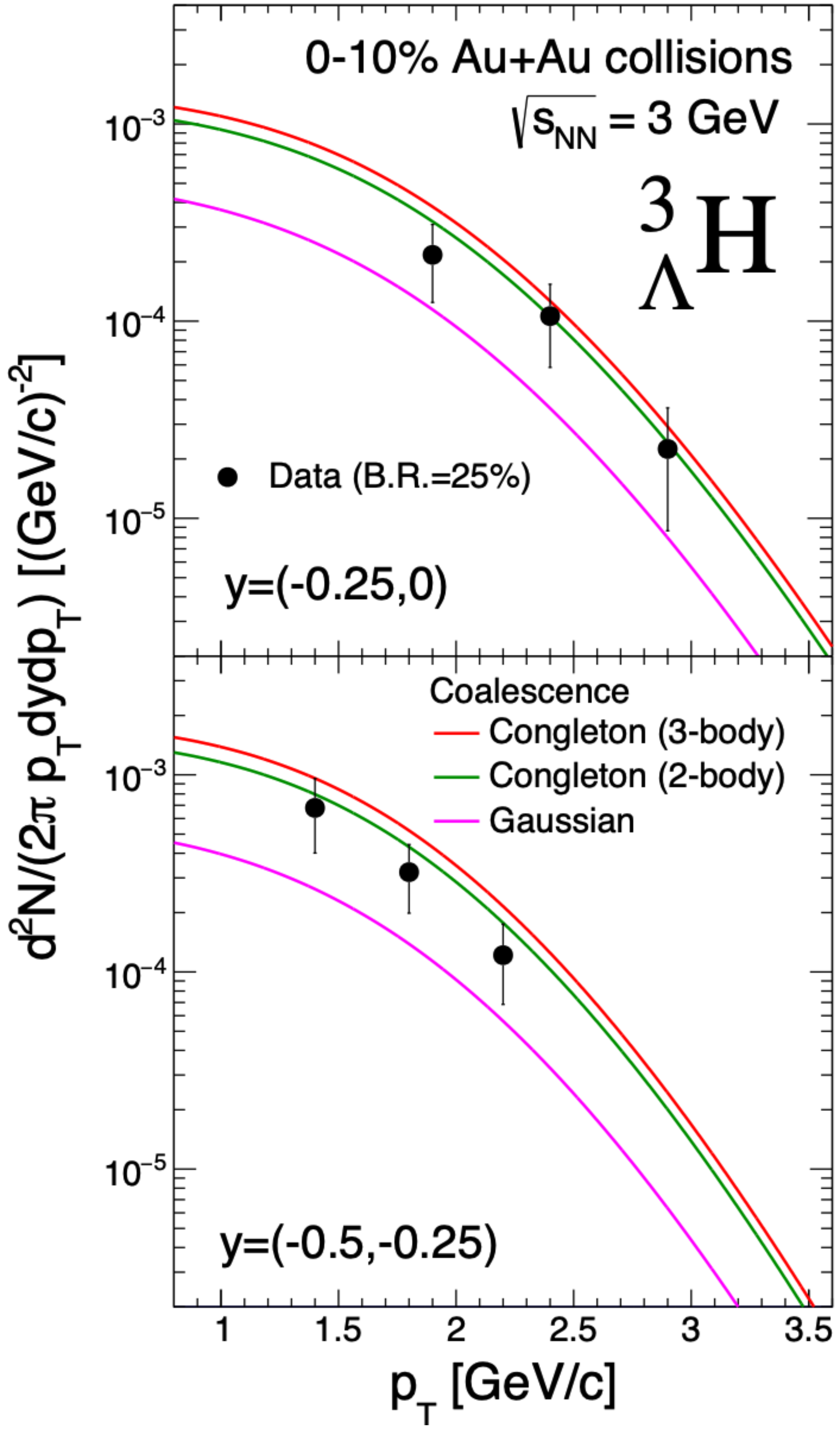


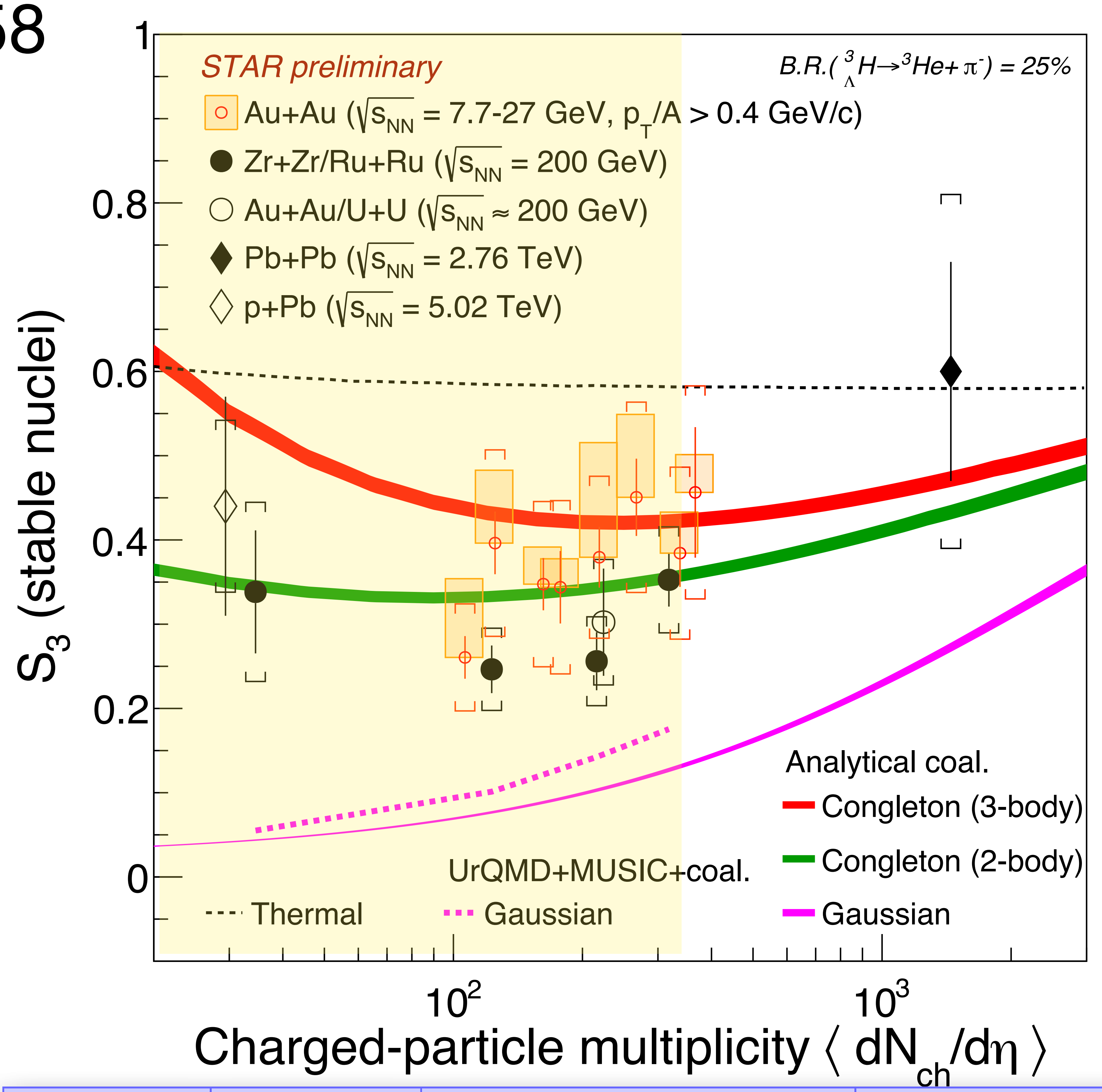
- $^{3}_{\Lambda}$H yields are sensitive to the short-distance structure of the wave function
  - Congleton wave function describes $^{3}_{\Lambda}$Hspectra at 3 GeV

F. Hildenbrand, H.-W. Hammer, PRC 100(2019)034002

Multiplicity Dependence S_3

Coalescence: arXiv: 2510.06758





$$S_3 = \frac{^{3}_{\Lambda}\mathrm{H}}{^{3}\mathrm{He} \times \frac{\Lambda}{p}}$$

Reflect relative production probabilities of nuclei (^3He) and hypernuclei ($^3_\Lambda H$)

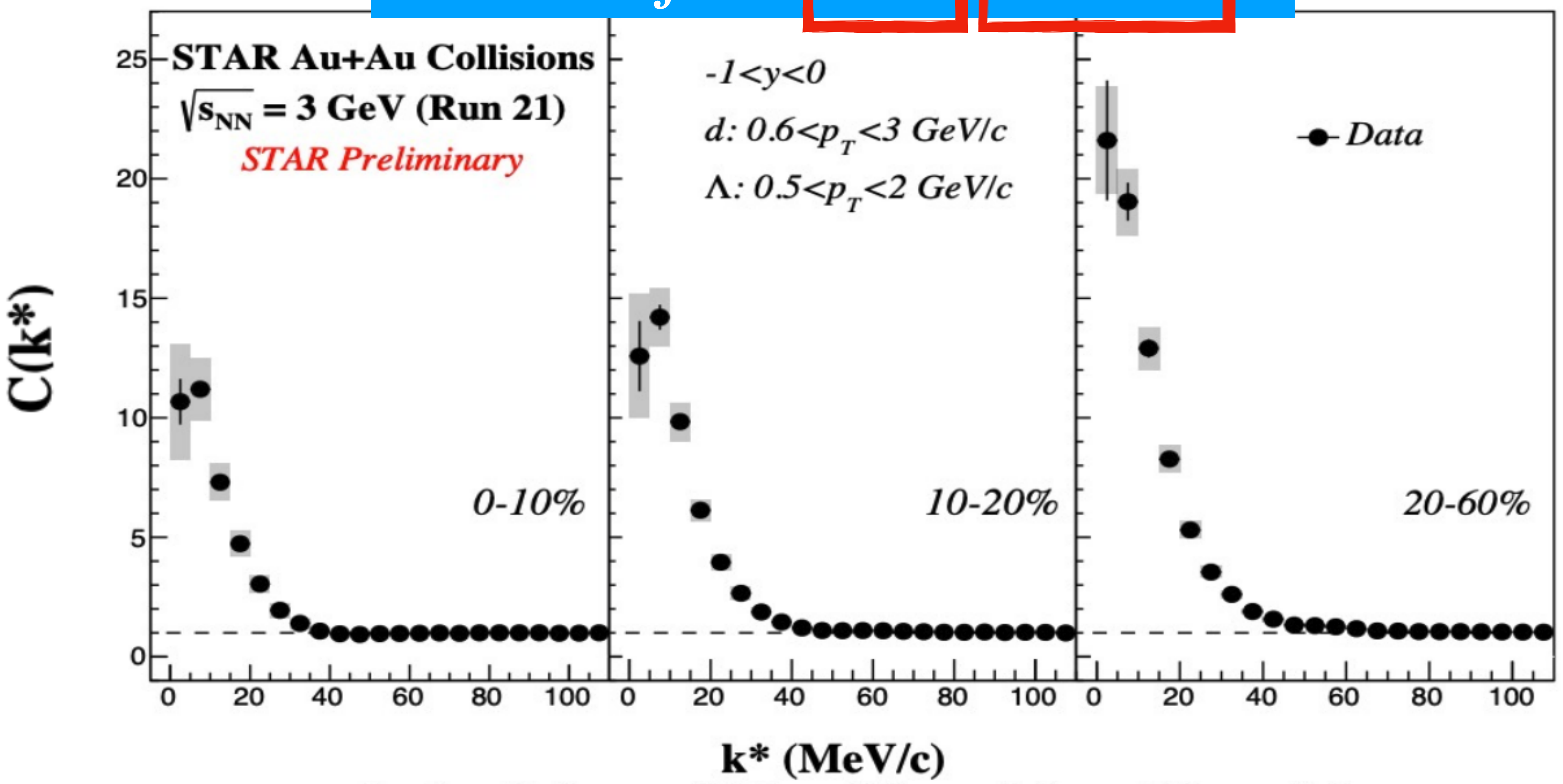
- CBM's high precision across different energies and system sizes will better constrain the $^{3}_{\Lambda}$H wave function

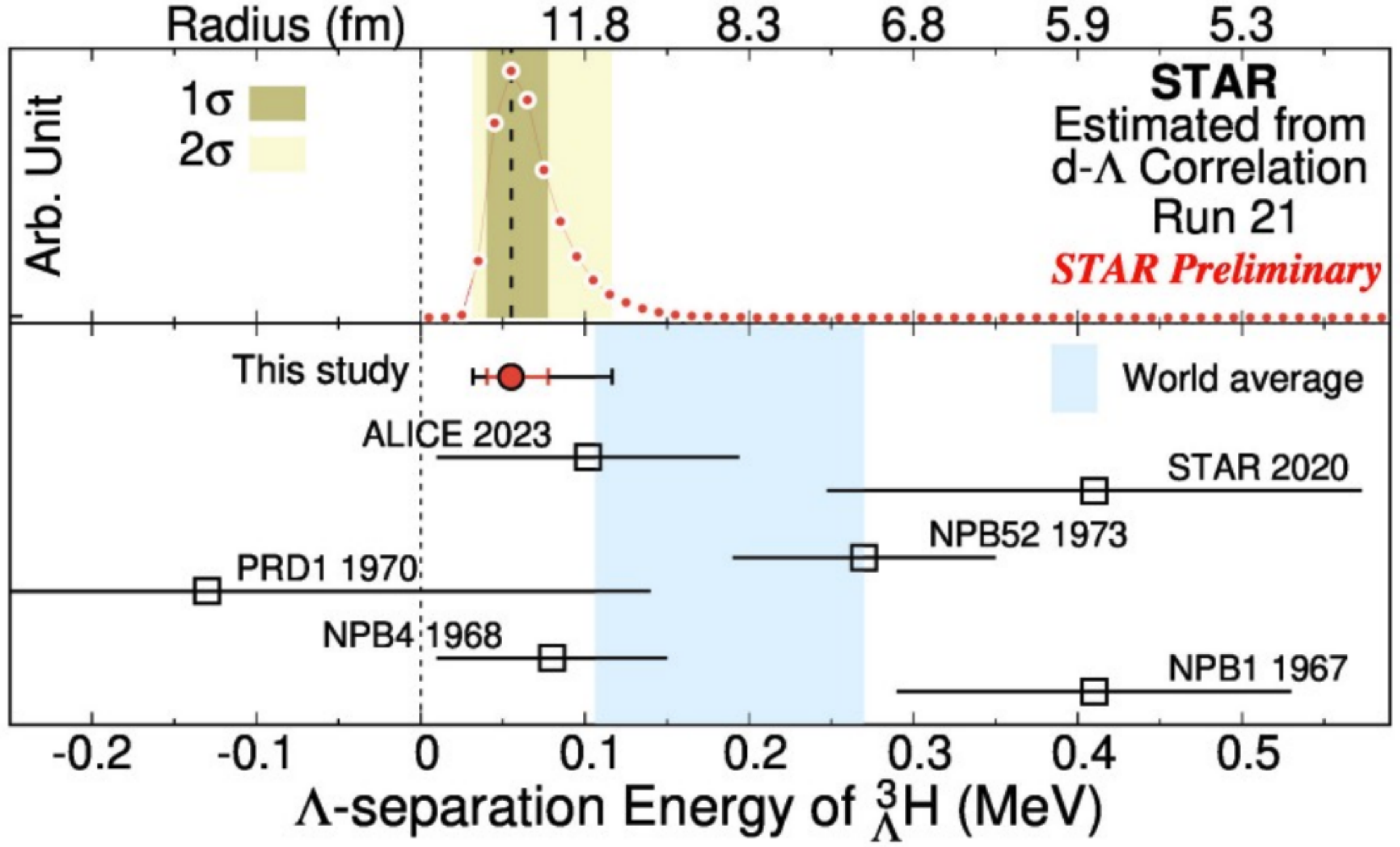
N.Herrmann, Theme Meeting on CBM: Science and Technology, Jatni, India, Feb. 2023

Year	Setup	Reaction	T_{Lab} (AGeV)	Days on Target	Number of events	Remarks
0 (2028*)	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60	–	Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	2×10^{10} each	EB mBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	4×10^{10} each	mBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	2×10^{11} each	mBias
2	MUON	Au+Au	2,4,6,8,10,max	30 (5 each)	2×10^{11} each	mBias
2	MUON	C+C	2,4,6,8,10,max	18 (3 each)	4×10^{11} each	mBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	2×10^{12} each	mBias
3	HADR	Au+Au	2,4,6,8,10,max	12 (2 each)	4×10^{11} each	EB + Selectors
3	HADR	C+C	2,4,6,8,10,max	6 (1 each)	8×10^{11} each	–
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	–
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	2×10^{10} each	mBias

Light Nuclei - Λ Correlation

$$CF(k^*) = \int d^3r^*\, S(r^*)\, |\psi(r^*, k^*)|^2$$





- **Formalism with Lednicky-Lyuboshitz (L-L) model:**
  - Only consider s-wave
  - Effective range expansion for $\psi(r^*, k^*)$
  - Static and spherical Gaussian source assumed

R. Lednicky and V. L. Lyuboshitz, Sov. J. Nucl. Phys. 35, 770 (1982)

- **Wave function:**
  - $\psi(r^*, k^*) = e^{-ik^*r^*} + f(k^*)\frac{e^{-ik^*r^*}}{r^*}$

- **Scattering amplitude:**
  - $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - ik^*]^{-1}$ (No Coulomb)
  - $f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0k^{*2} - \frac{2}{a_c}h(\eta) - ik^*A_c(\eta)]^{-1}$(Include Coulomb)

  a_c: Bohr radius $\quad \eta = (k^*a_c)^{-1}$

  A_c, h: Coulomb interaction factor

- Light nuclei - Λ correlation functions provide further insights to hyper-nuclei structure and properties

Bethe formula:

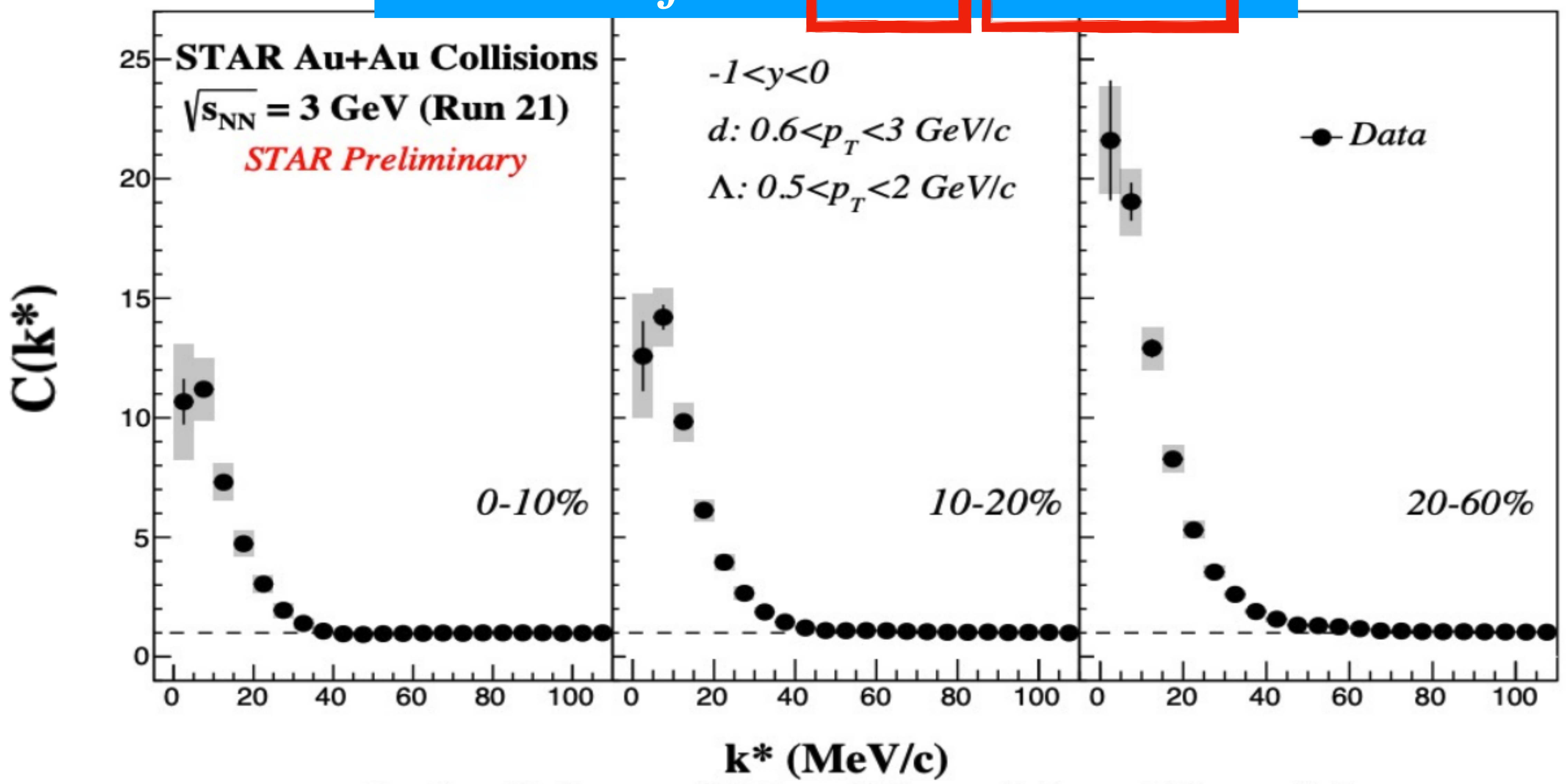
$$BE_{^3_\Lambda\mathrm{H}} = \frac{1}{2m_{d\text{-}\Lambda}d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2 \qquad r = \sqrt{\frac{\hbar^2}{4\mu B_\Lambda}}$$

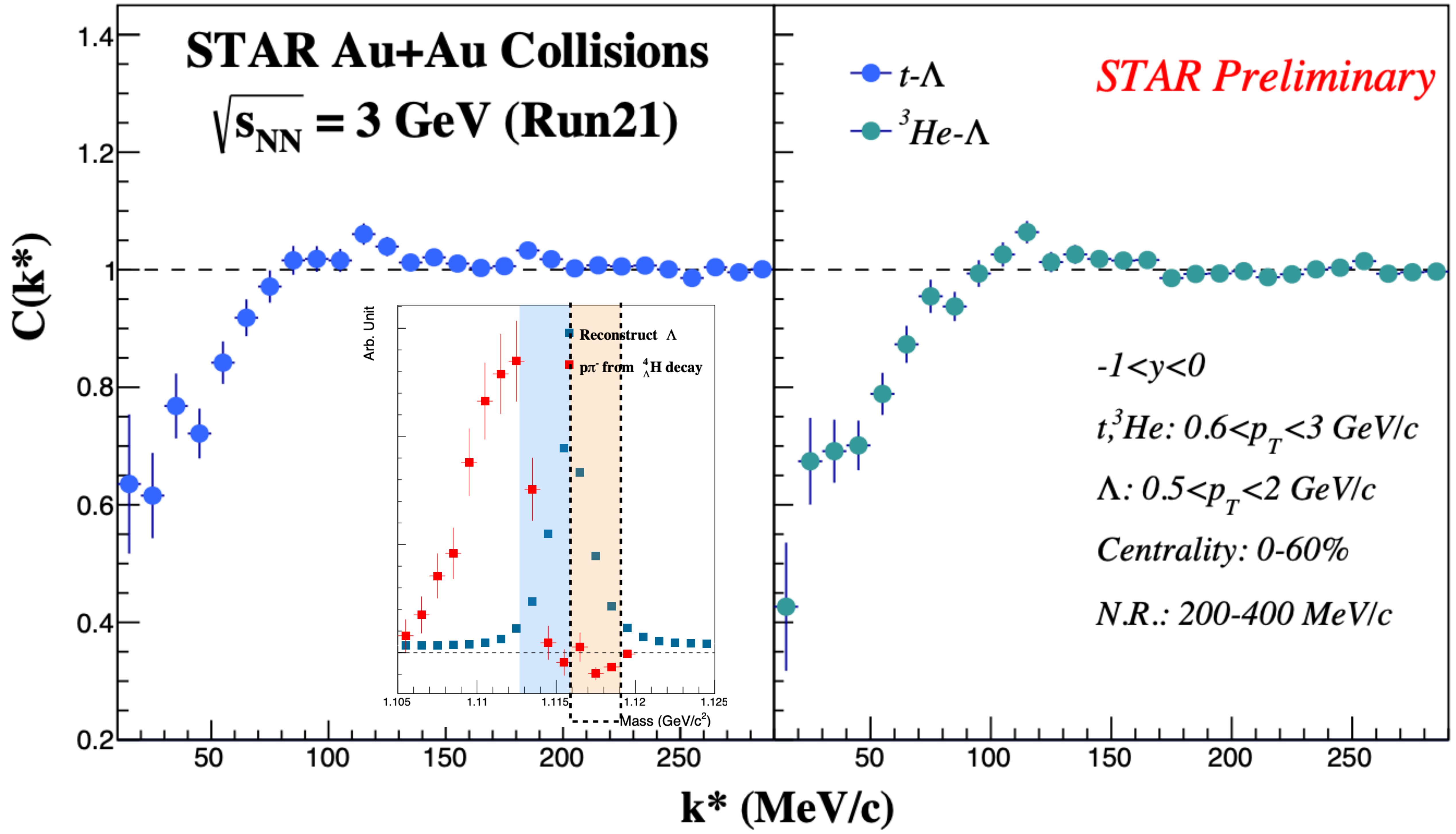
Light Nuclei - Λ Correlation

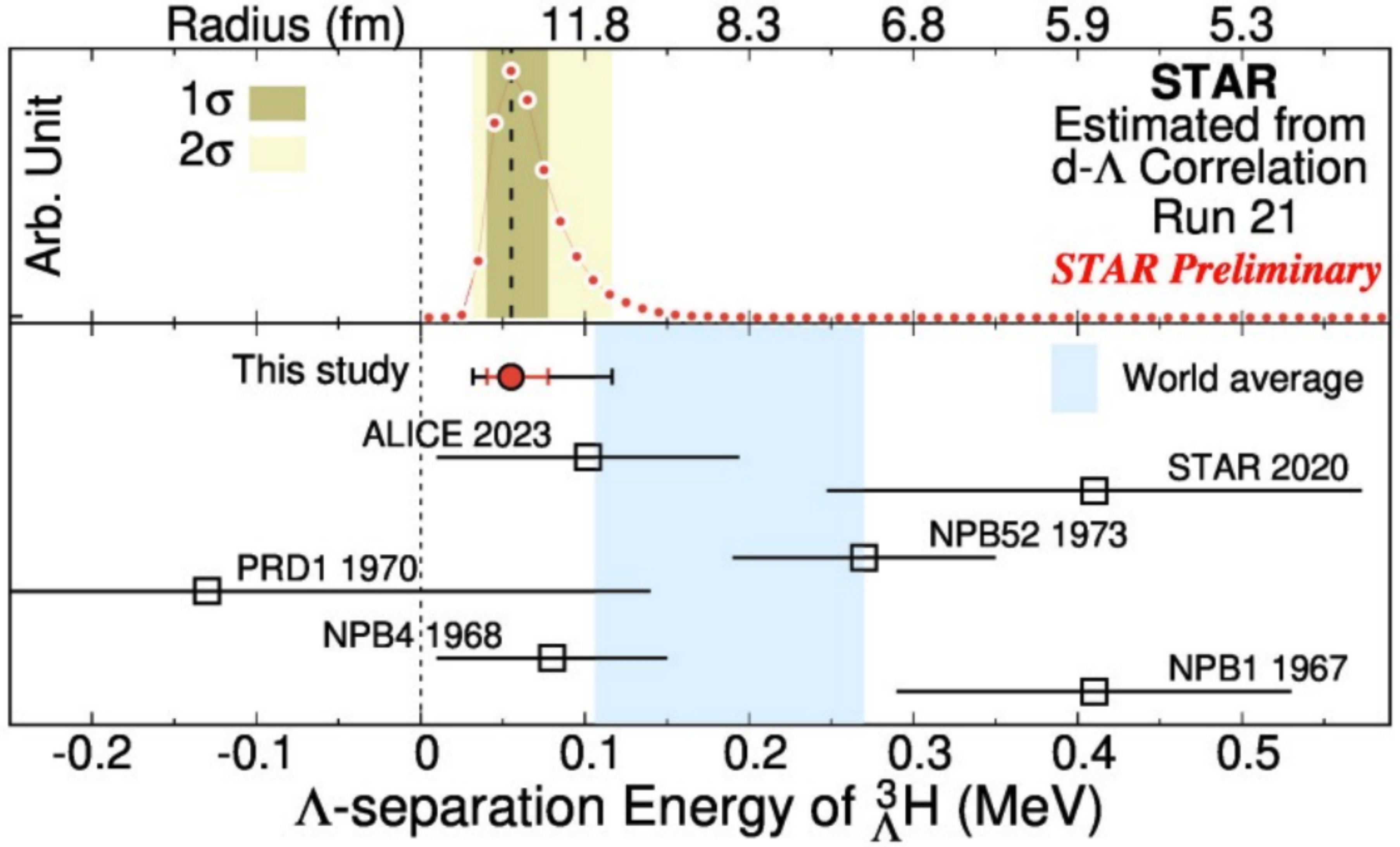
$$CF(k^*) = \int d^3r^* \, S(r^*) \, |\psi(r^*, k^*)|^2$$

QM 2025, X. Jiang

STAR Au+Au 3 GeV (BES-II)







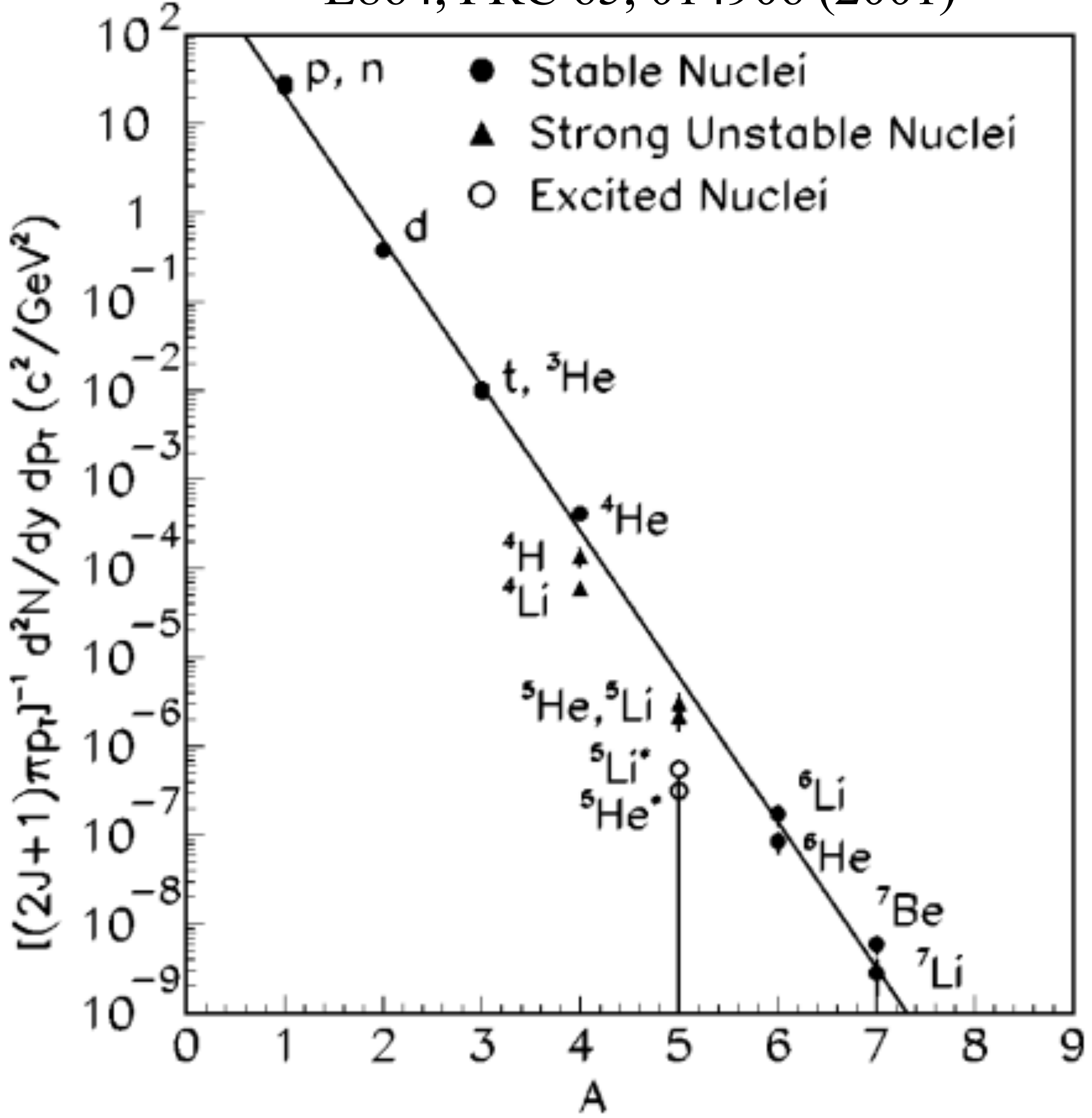
- Light nuclei - Λ correlation functions provide further insights to hyper-nuclei structure and properties
- STAR has measured d/t–Λ and ^{3}He–Λ correlations at 3 GeV

Bethe formula:

$$BE_{^3_\Lambda H} = \frac{1}{2m_{d\text{-}\Lambda} d_0^2}\left(1 - \sqrt{1 + \frac{2d_0}{f_0}}\right)^2 \qquad r = \sqrt{\frac{\hbar^2}{4\mu B_\Lambda}}$$

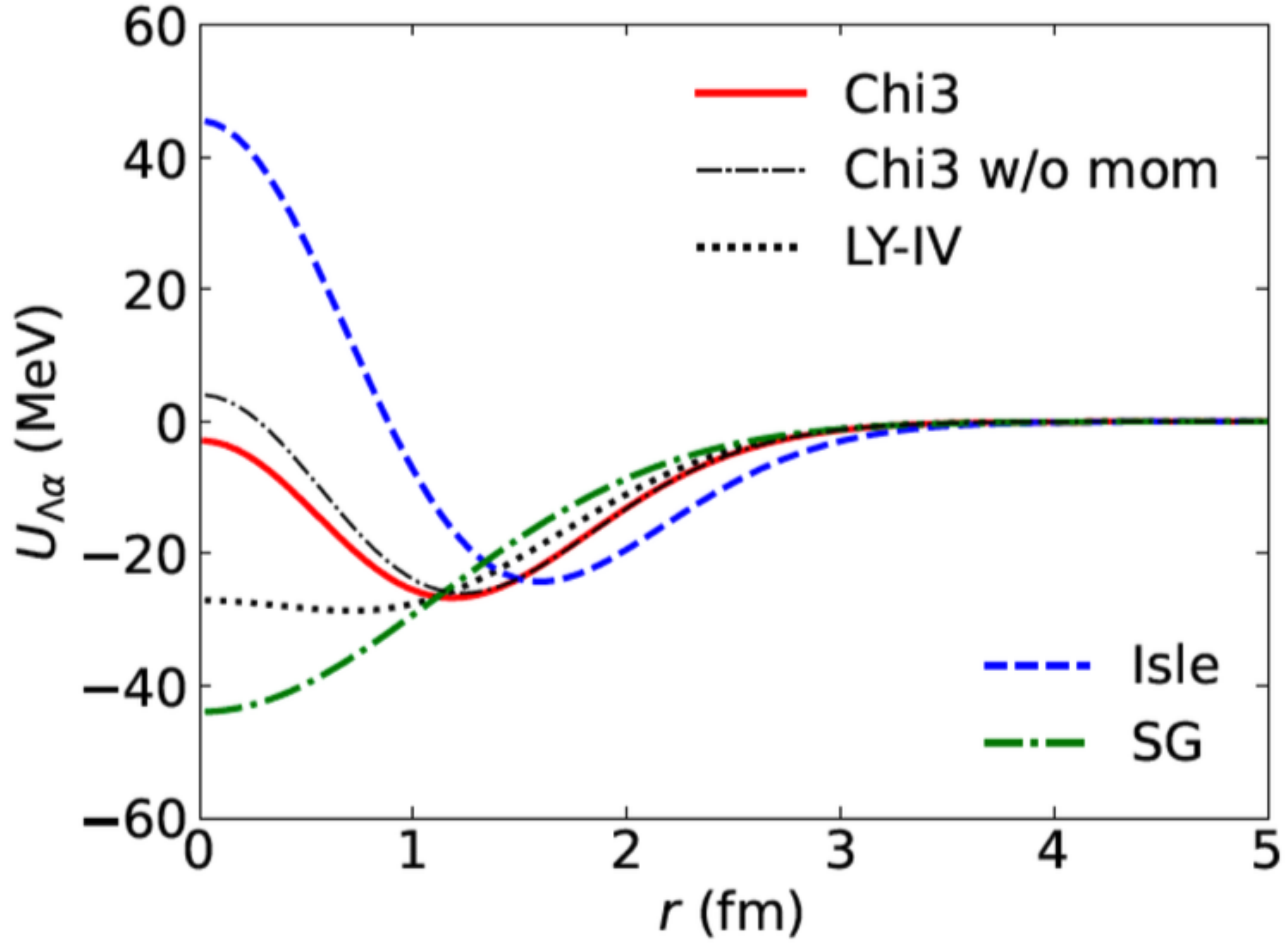
Light Nuclei - Λ Correlation

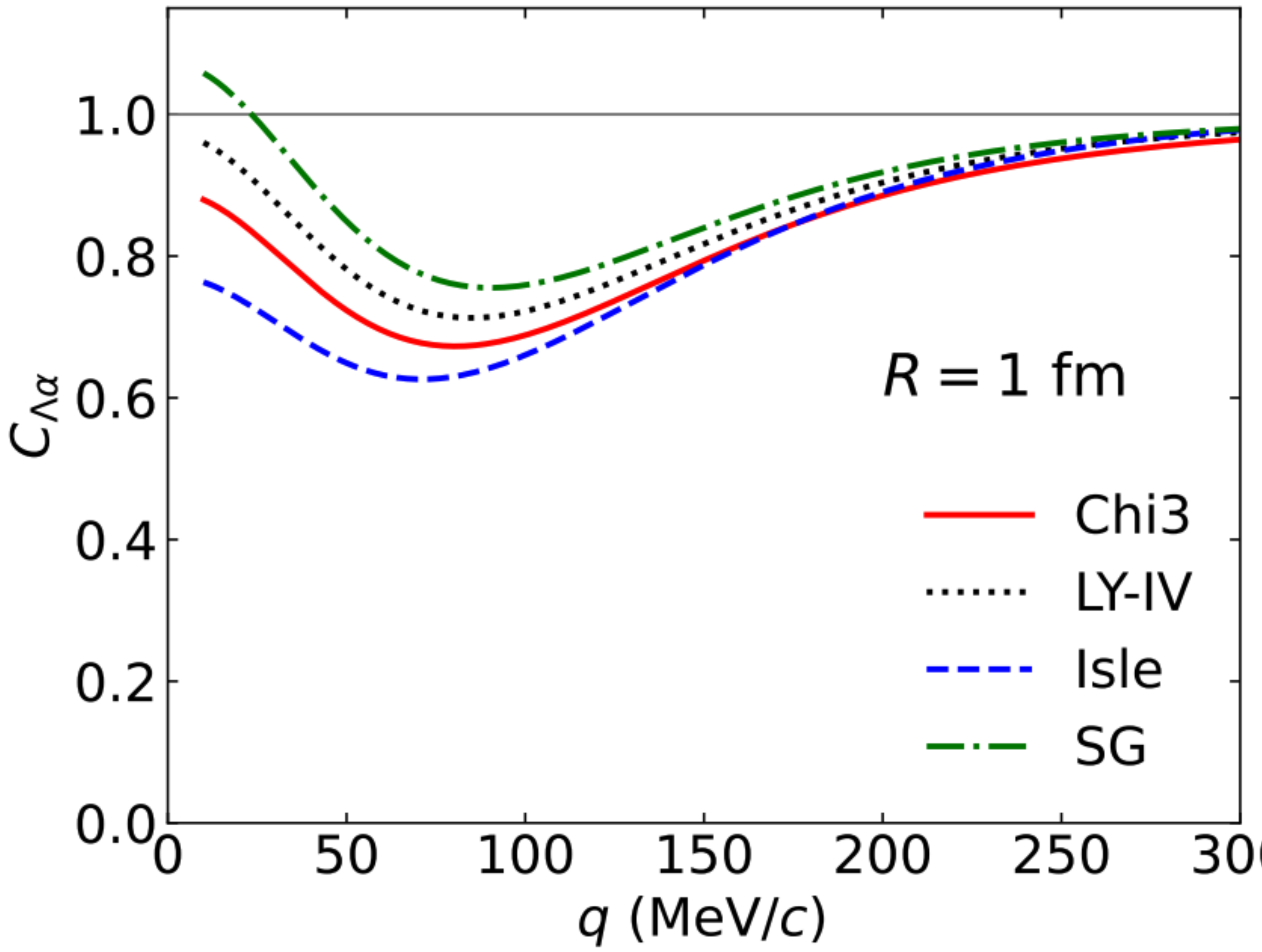
E864, PRC 65, 014906 (2001)



A. Jinno et al., PRC 110, 014001 (2024)

$U_{\Lambda\alpha}$: (Λα potential)





- CBM's higher statistics will extend these studies to heavier systems such as α–Λ for the first time

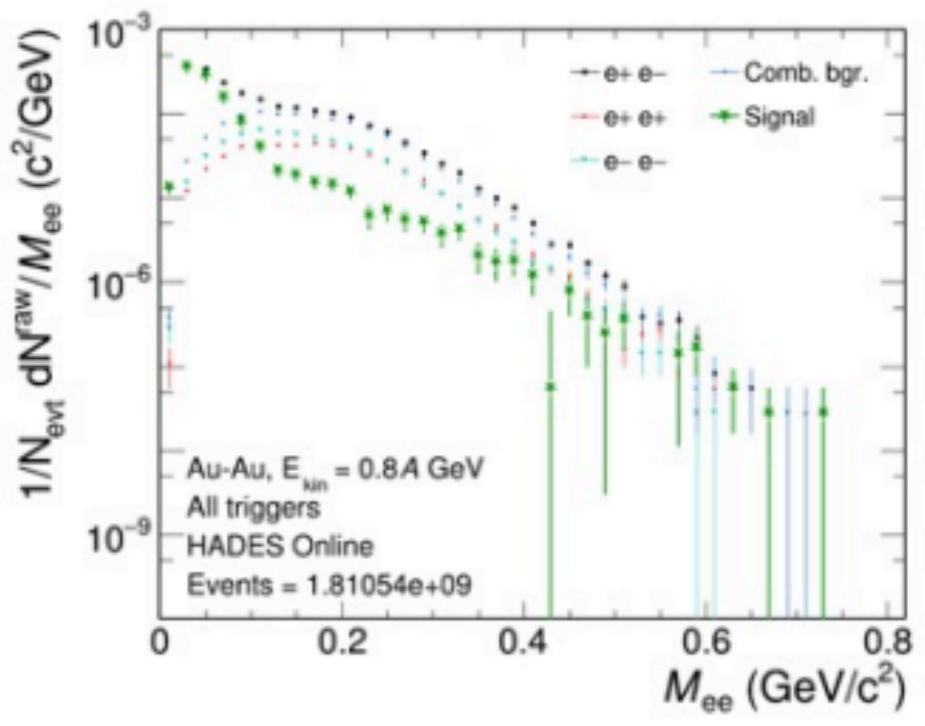
- Overall Λ–α interaction is constraint by B_Λ of $^{5}_{\Lambda}$He, but the short-range part still differs among models
- $C_{\Lambda\alpha}$ at small size is highly sensitive to short range part of $U_{\Lambda\alpha}$

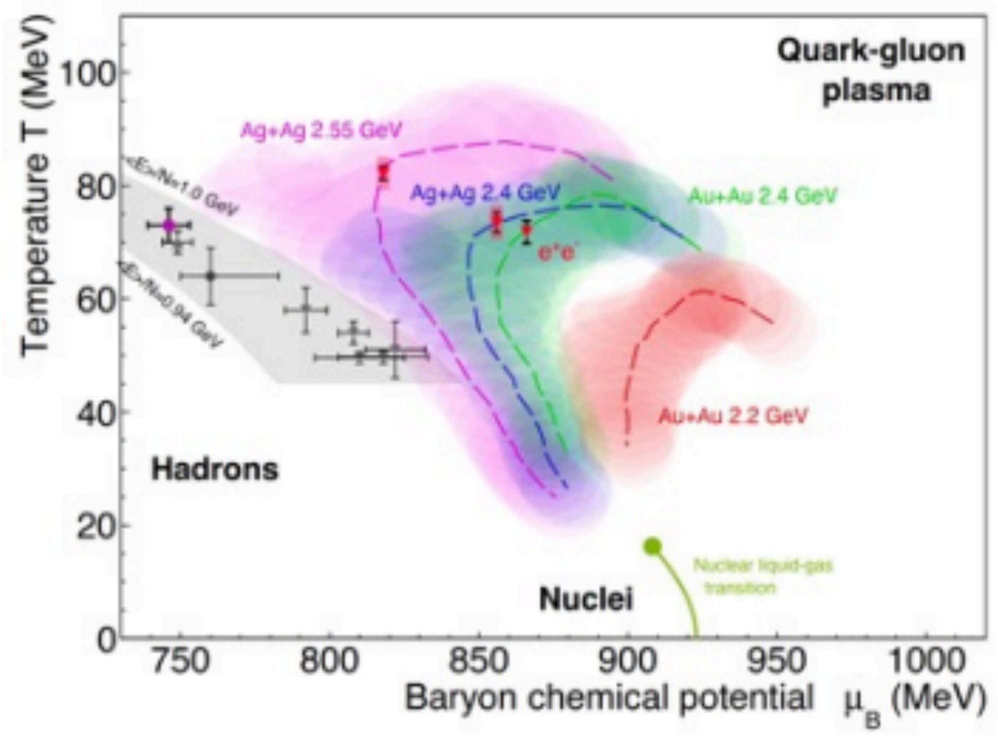
- With multiple system sizes and higher statistics, CBM will better constrain the short-range YN interaction

Successful Phase-0: HADES, STAR, E16

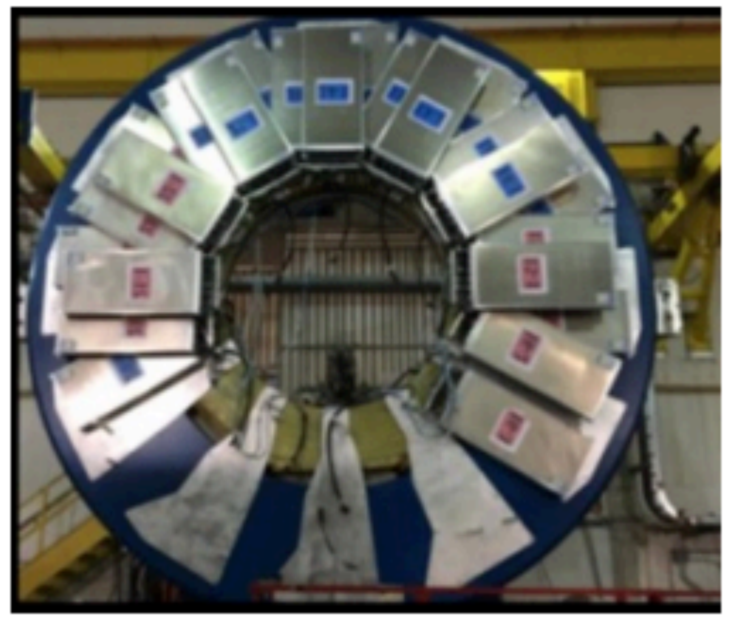
HADES RICH photodetector upgrade employing CBM technology

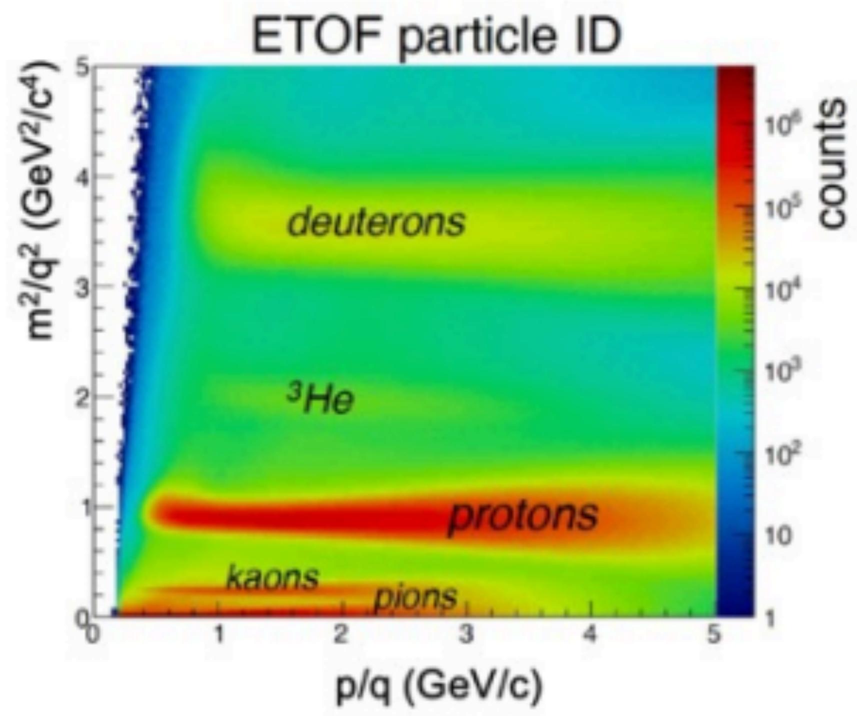
Fast on-line dilpton spectra from 2025 Au+Au, 800 AMeV



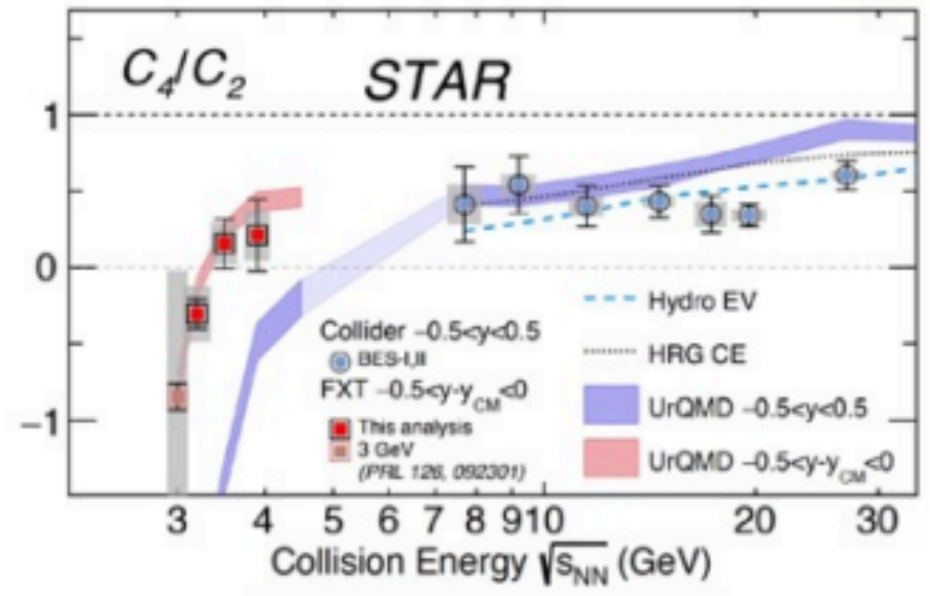


N. Schild, S. Kim, QM25

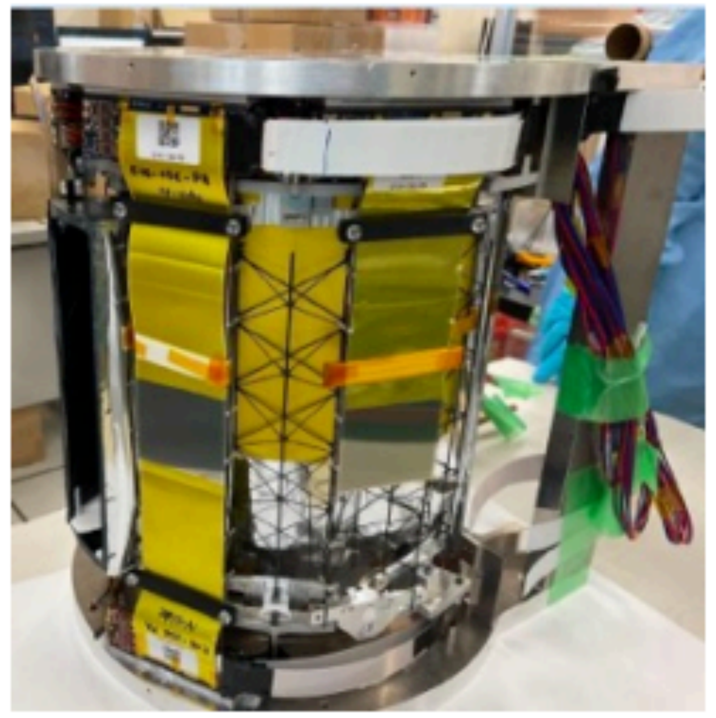


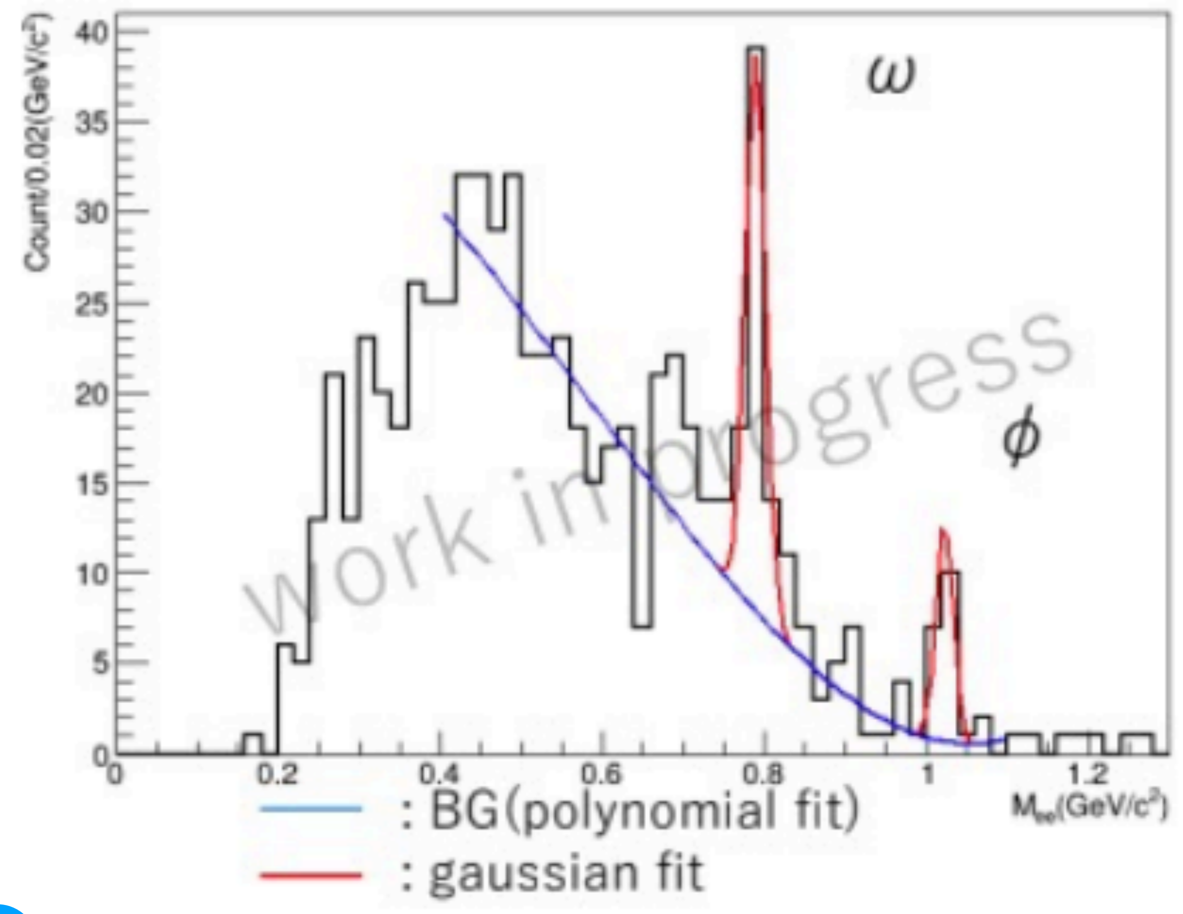


eTOF provided by CBM-FAIR, crucial for BES-II, especially for the FXT program



Zachary Sweger, QM25





Result of E16 pilot run (p+A collision) ~20h data taking

Yuhei Morino, QM25

10 pre-series STS modules were built, assembled and tested at GSI and are installed as innermost tracking detector of the ***E16*** *experiment at J-PARC*

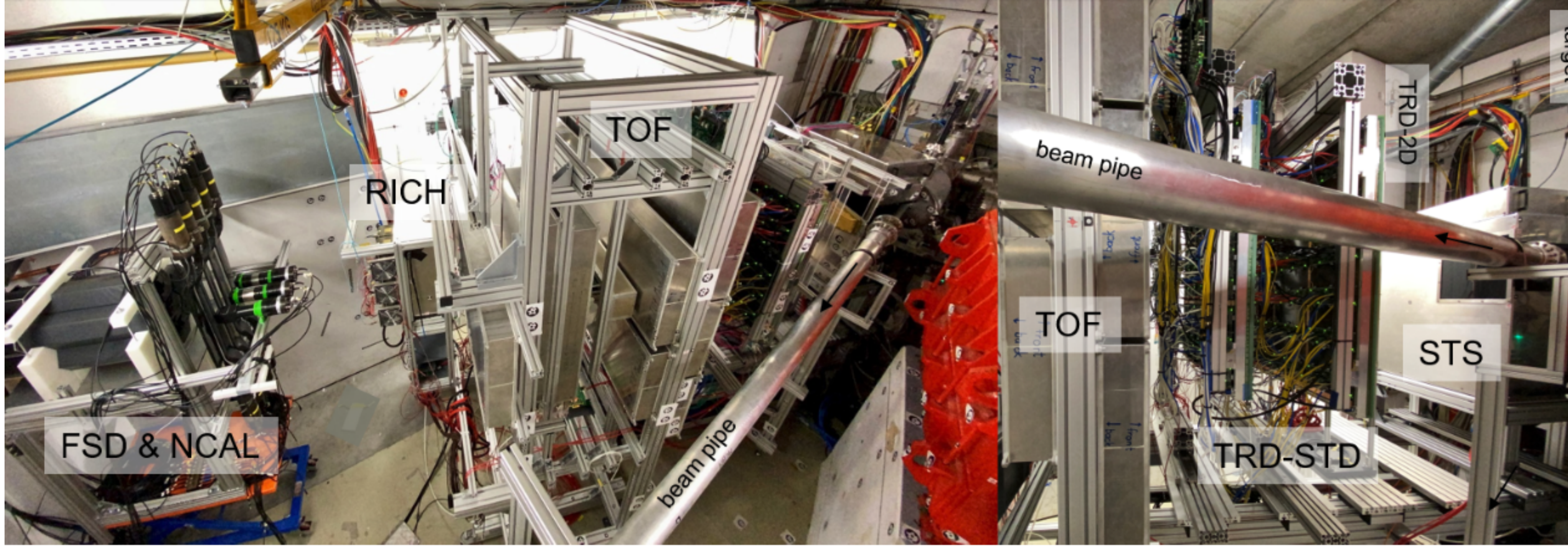
- Demonstrate performance of major detector subsystems
- Physic results validate CBM detector systems and software framework

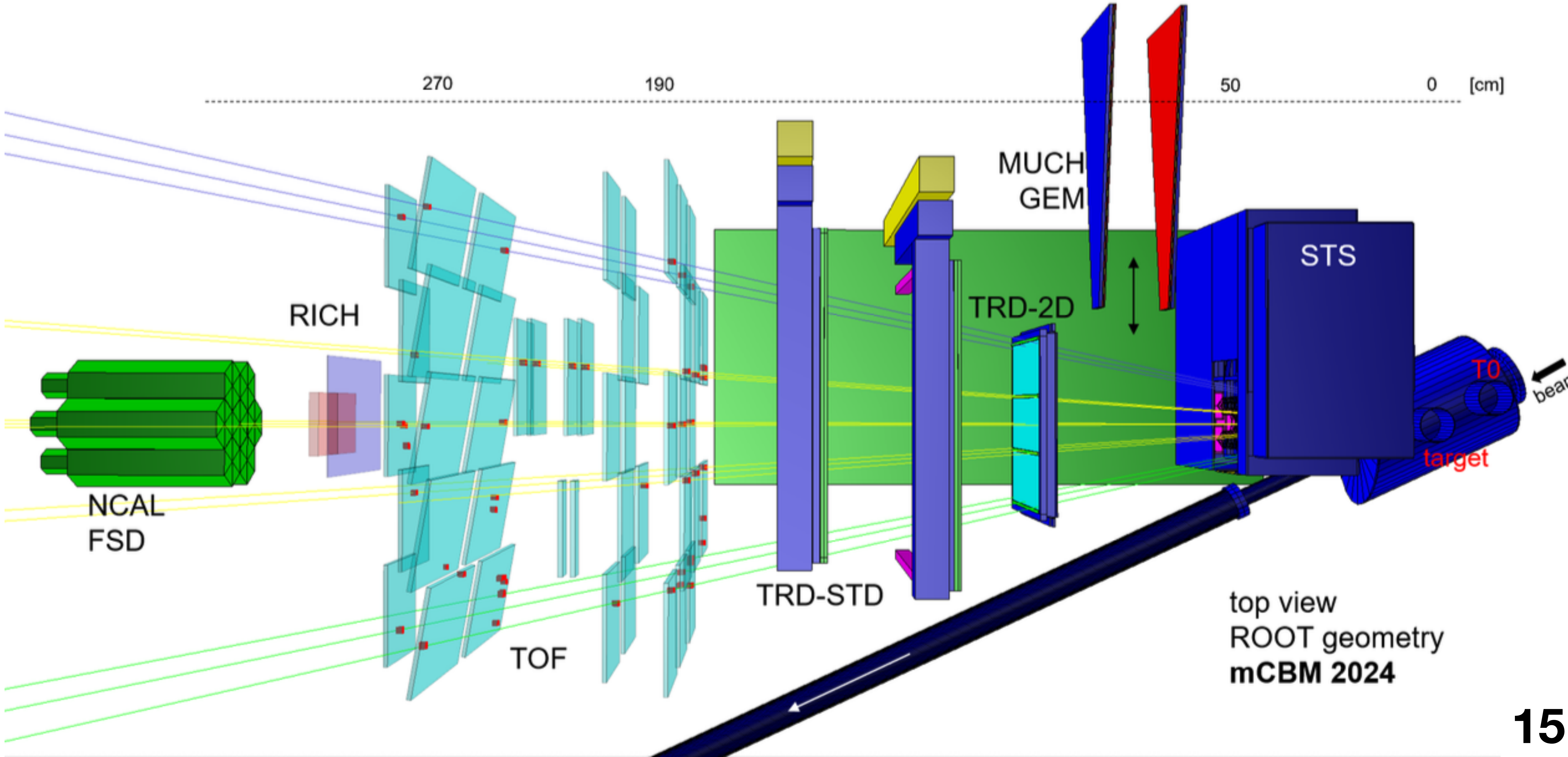
Testing to Scale

miniCBM test setup

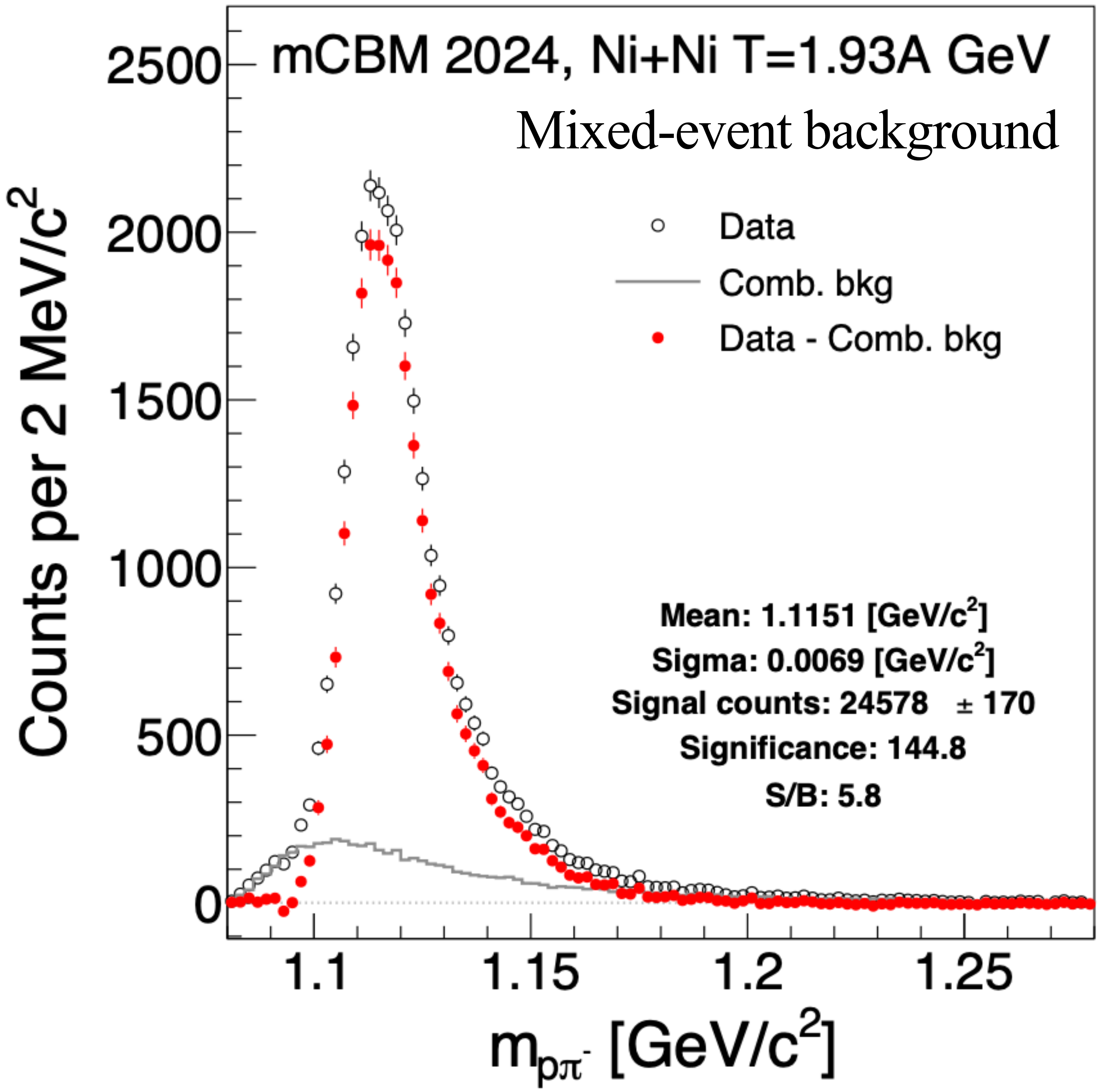
No B-field

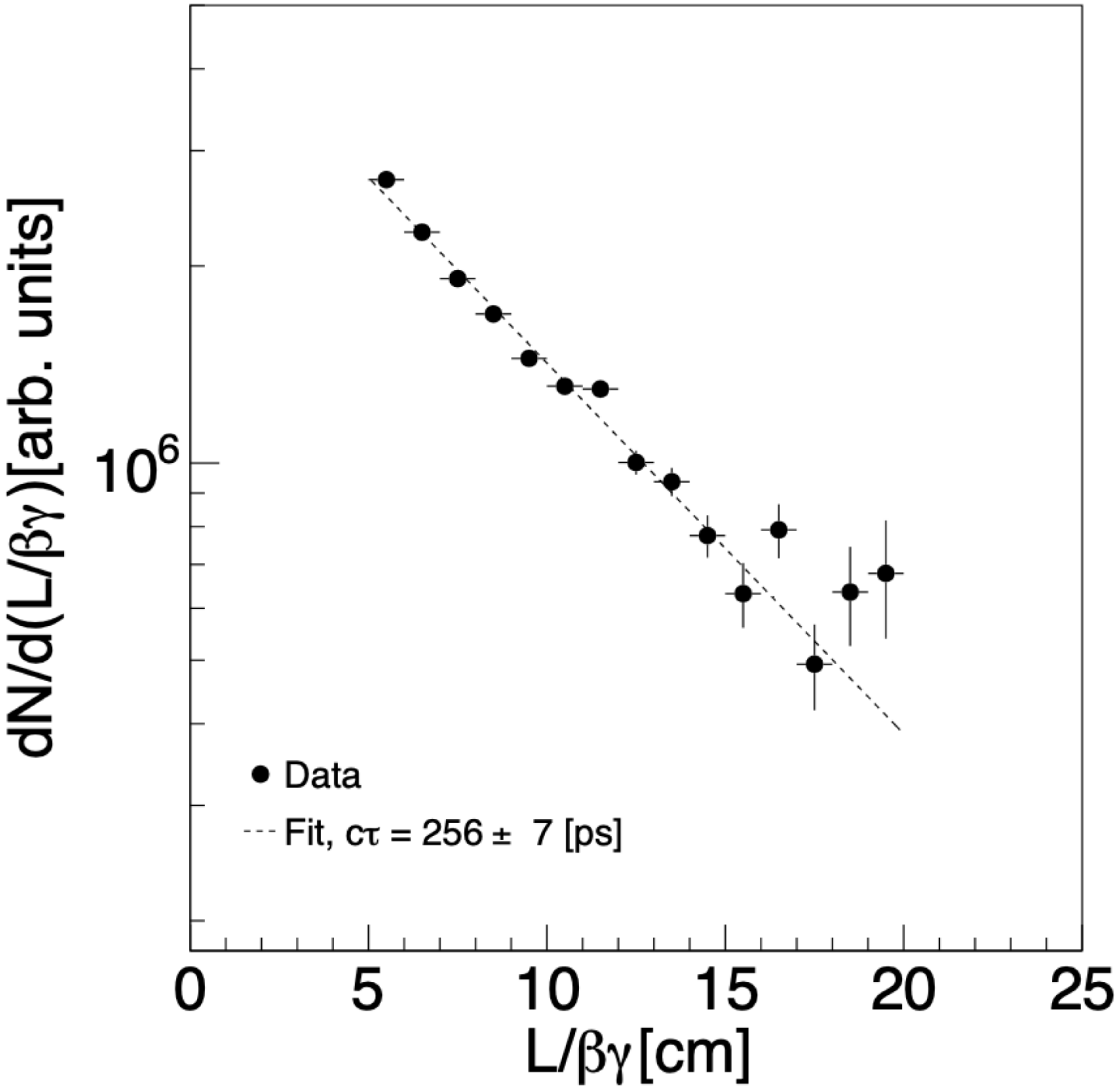
- Silicon Tracking System (STS)
- Muon Chamber system (MUCH)
- Transition Radiation Detector system (TRD)
- Time-Of-Flight detector system (TOF)
- Ring Imaging Cherenkov detector system (RICH)
- Forward Spectator Detector system (FSD) with the Neutron Calorimeter (NCAL)
- Time-zero detectors of the Beam Monitoring system (BMON)





Testing to Scale





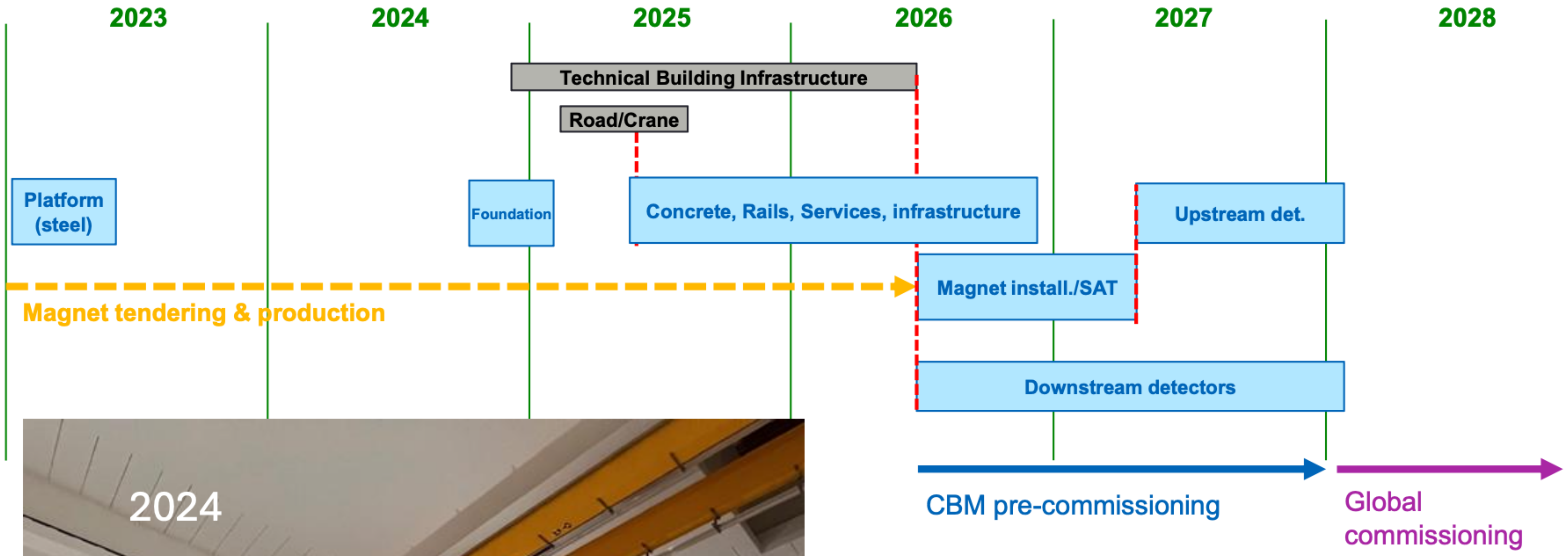
- Λ reconstructed using KFParticle in CBMRoot
- Topological cuts suppress combinatorial background from primary tracks

- Measured Λ lifetime: 256 ± 7(stat.) ± 27(syst.) ps — consistent with literature

Demonstrated the complete data processing chain — from front-end acquisition to high-level analysis of a rare signal — validating the performance and **readiness of hardware and software components** for **CBM measurements**

Towards Detector Installation

CBM Cave
- A dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM Cave/Building shell completed
- Technical Building Infrastructure in 2025/2026



CBM Installation
- CBM installation activities (platform) started in June 2023
- Ready for beam by 2028, ~ 12 months contingency for CBM global commissioning

All major detector subsystems are under installation, keeping CBM on track for physics data taking by 2028!

Backup

Probing the Hypertriton (${}^{3}_{\Lambda}\mathrm{H}$) Wave Function

- **Wigner-function coalescence:** coalescence probability given by overlap between ${}^{3}_{\Lambda}\mathrm{H}$ **wave function** and **nucleon/hyperon distributions** at freeze out

- ${}^{3}_{\Lambda}\mathrm{H}$: loosely bound hypernuclei
  ($B_\Lambda = 0.164 \pm 0.043$ MeV)

- Gaussian: $\Phi_{{}^{3}_{\Lambda}\mathrm{H}}(r_{pn}, r_\Lambda) = \left(\frac{1}{3\pi^2 b_{pn}^2 b_\Lambda^2}\right)^{\frac{3}{4}} e^{-\frac{r_{pn}^2}{4b_{pn}^2} - \frac{r_\Lambda^2}{3b_\Lambda^2}}$

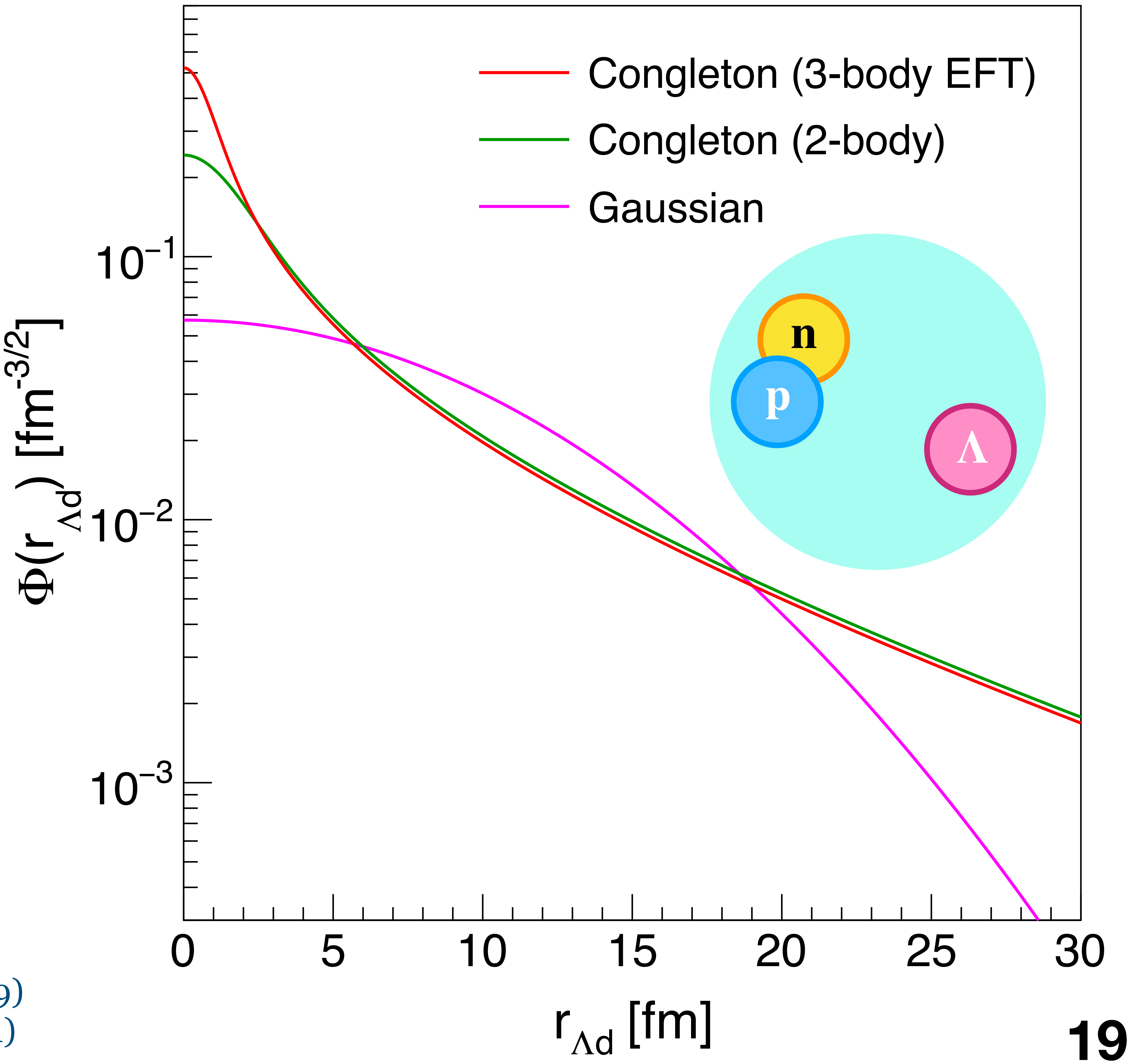
  $b_\Lambda = 7.2\mathrm{fm}$ Phys.Rev.C 103, 014907 (2021)

- Congleton: $\hat{\Phi}_{{}^{3}_{\Lambda}\mathrm{H}(d\Lambda)}(q) = A\frac{e^{-\frac{-q^2}{Q_\Lambda^2}}}{q^2 + \alpha_\Lambda^2}$
  - 2-body model of ${}^{3}_{\Lambda}\mathrm{H}$ J.Phys.G 18, 339-357 (1992)

    $(Q_\Lambda, \alpha_\Lambda) = (1.17, 0.068)\mathrm{fm}^{-1}$
  - 3-body effective field theory

    $(Q_\Lambda, \alpha_\Lambda) = (2.5, 0.068)\mathrm{fm}^{-1}$

    Phys.Rev.C 100, 034002 (2019)
    Phys.Rev.C 103, 014907 (2021)



Coalescence calculations (arXiv:2510.06758)

Phys.Rev.C 103, 014907 (2021)

$$B_3({}^3_\Lambda\mathrm{H}) \approx \frac{3}{m^2}\frac{2s_{{}^3_\Lambda\mathrm{H}}+1}{(2s_N+1)^3}(2\pi)^6\int d^3r_{pn}\int d^3r_\Lambda \left|\Phi_{{}^3_\Lambda\mathrm{H}}(r_{pn},r_\Lambda)\right|^2 \mathcal{S}_3(r_{pn},r_\Lambda)$$

Wave function: $\left|\Phi_{{}^3_\Lambda\mathrm{H}}(r_{pn},r_\Lambda)\right|^2$

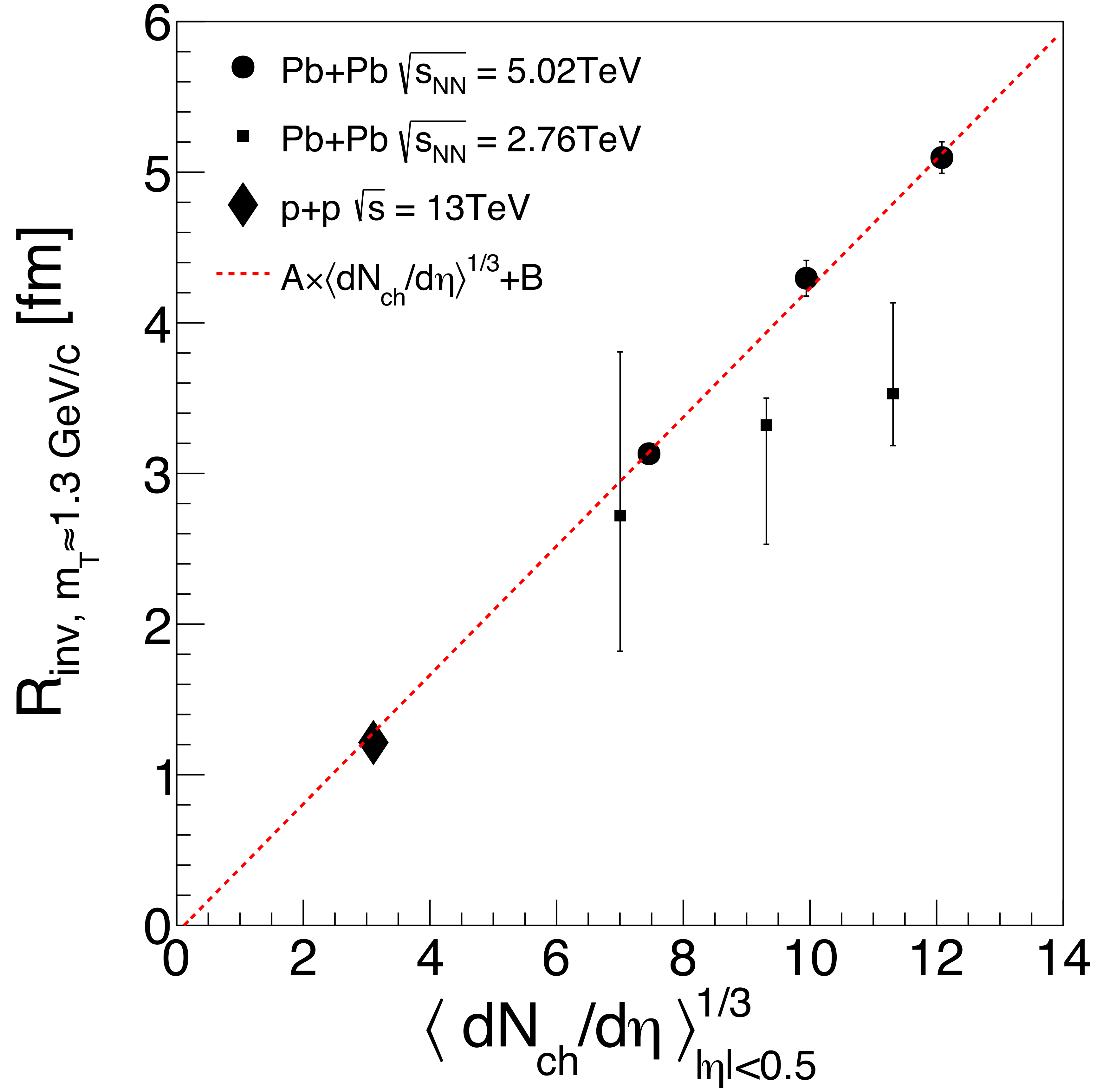
Nucleon source: $\mathcal{S}_3(r_{pn},r_\Lambda)$

- Assuming an isotropic Gaussian nucleon source

$$\mathcal{S}_3(r_{12},r_3) = \frac{1}{(12\pi^2 R_{\mathrm{inv}}^4)^{3/2}}\exp\left(-\frac{r_{12}^2+\frac{4}{3}r_3^2}{4R_{\mathrm{inv}}^2}\right)$$

- Use ALICE baryon-baryon **correlation function data** to estimate R_{inv} for **high energy collisions**

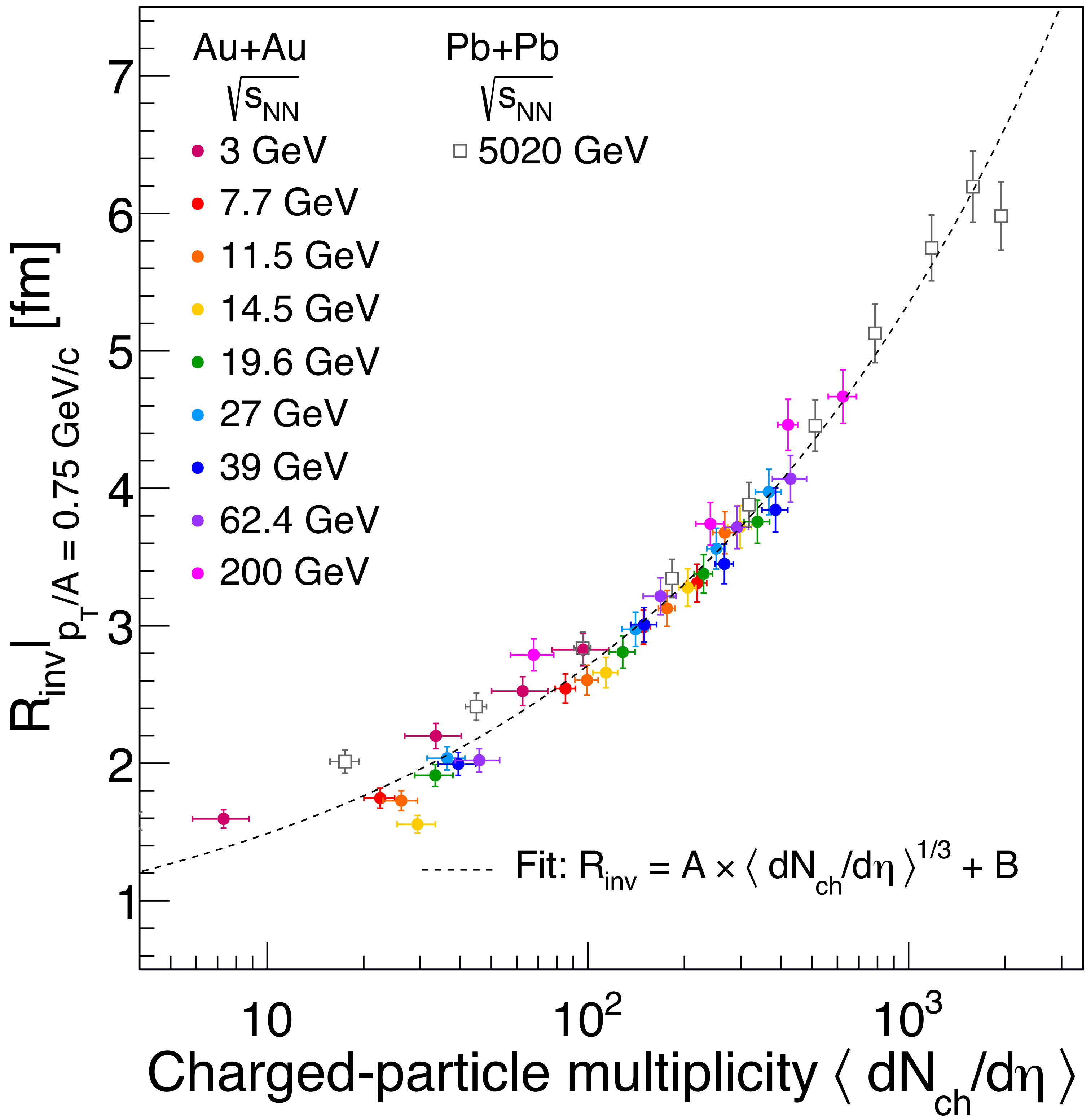
ALICE, arXiv:2505.01061

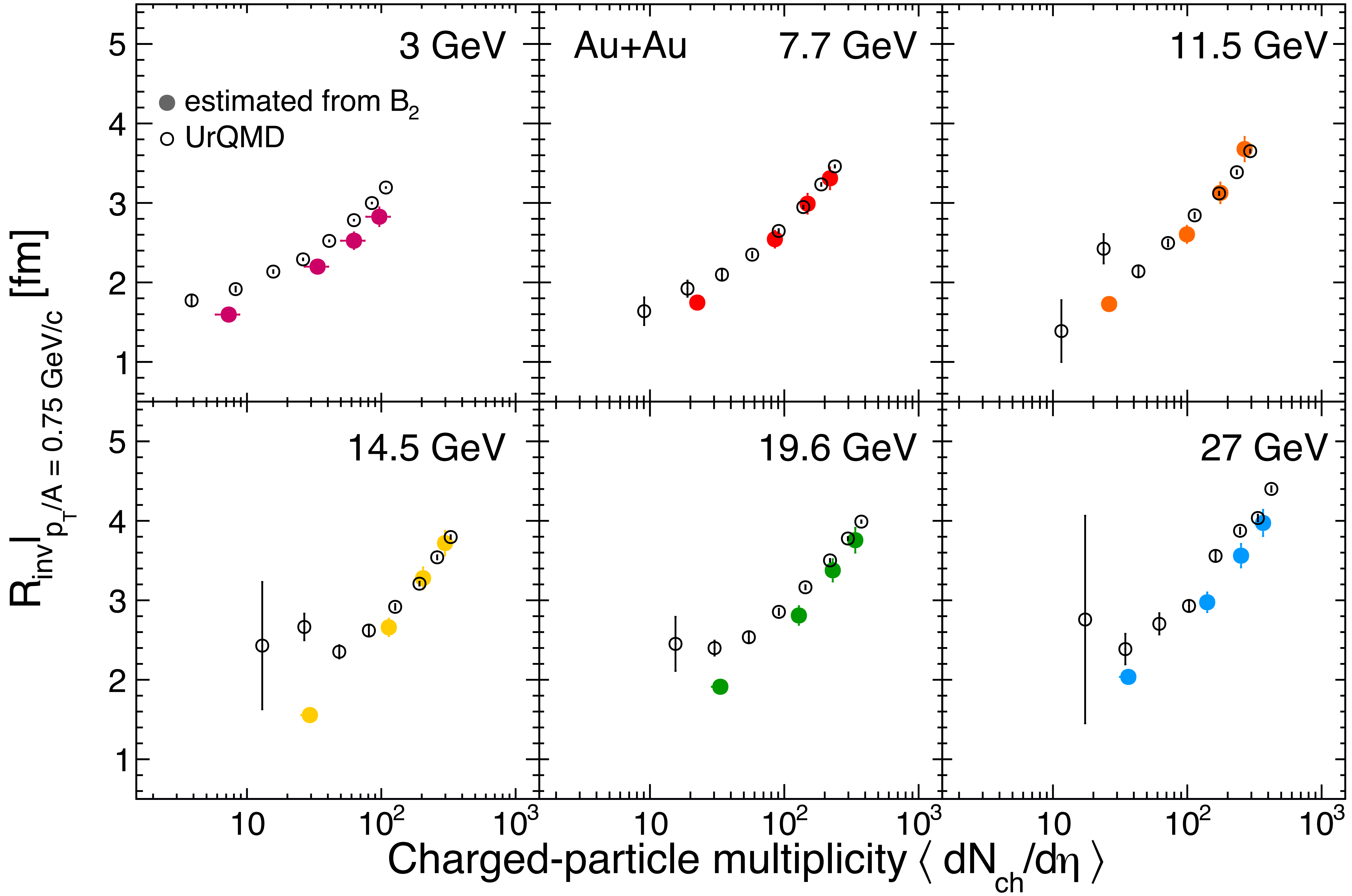


Coalescence calculations (arXiv:2510.06758)

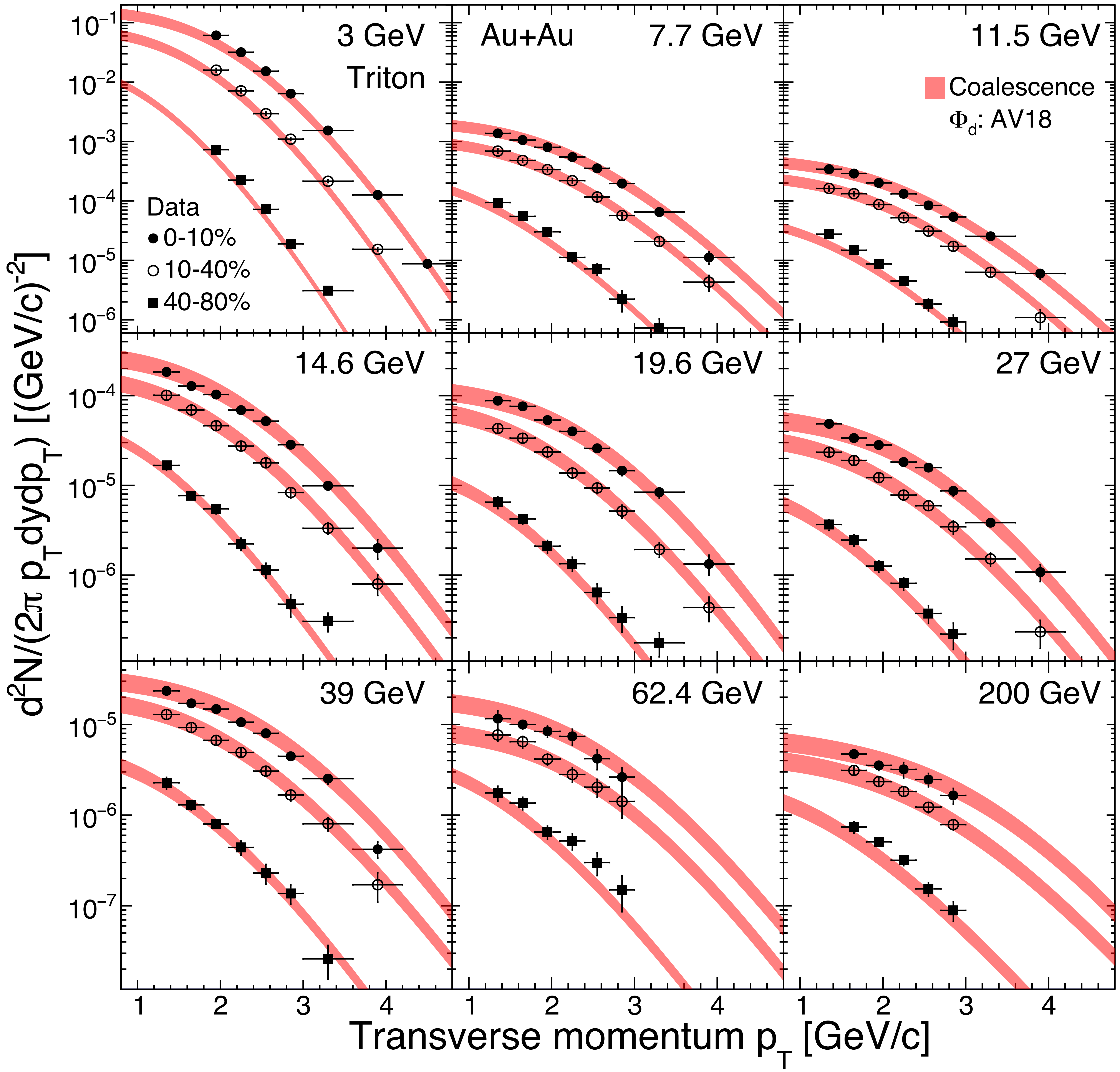
- Use deuteron data to estimate R_{inv} **for BES energies**
- Calculate B_2 as function for pT and centrality using data
- Use coalescence formula with Argonne v_{18} wave function to obtain R_{inv}

$$B_2(d) \approx \frac{2(2s_d + 1)}{m\,(2s_N + 1)^2(2\pi)^3} \int d^3r |\Phi_d(r)|^2\, \mathcal{S}_2(r)$$





Coalescence calculations (arXiv:2510.06758)



- Calculations describe triton data well