Observation of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ @ RHIC

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(for the STAR Collaboration)

- Introduction & Motivation
- Evidence for first antihypernucleus
  - ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ signal (for discovery)
  - Mass and Lifetime measurements
- Production rate and ratios
  - Yields as a measure of correlation
  - A case for RHIC energy scan
- Conclusions and Outlook

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a passion for discovery
Office of Science
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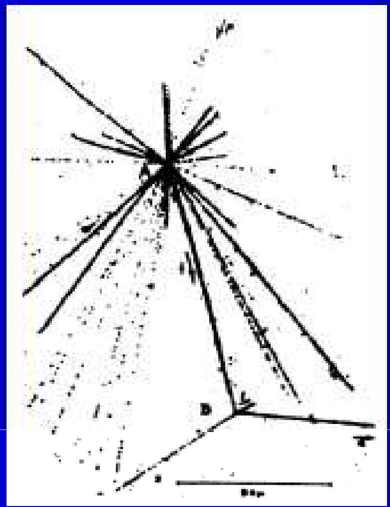
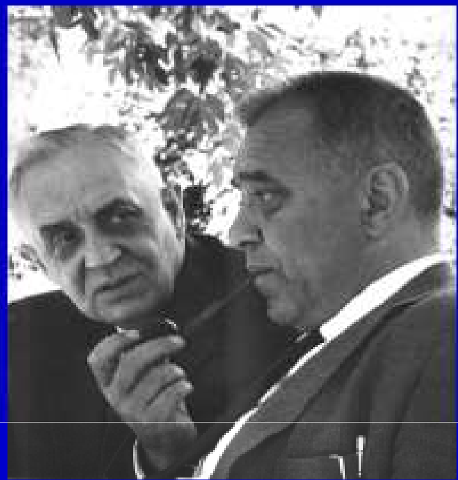
What are hypernuclei?

Nucleus which contains at least one hyperon in addition to nucleons.





The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

No one has ever observed **any** antihypernucleus

Hypernuclei of lowest A

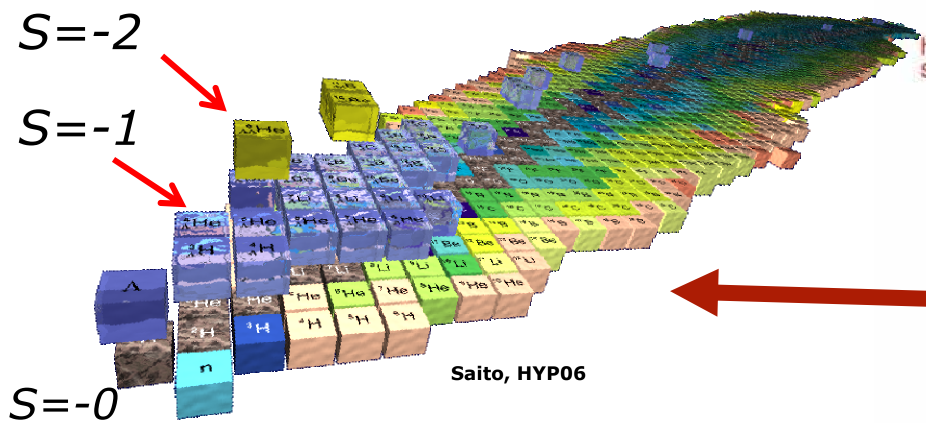
$${}^{3}_{\Lambda}H(n+p+\Lambda)$$

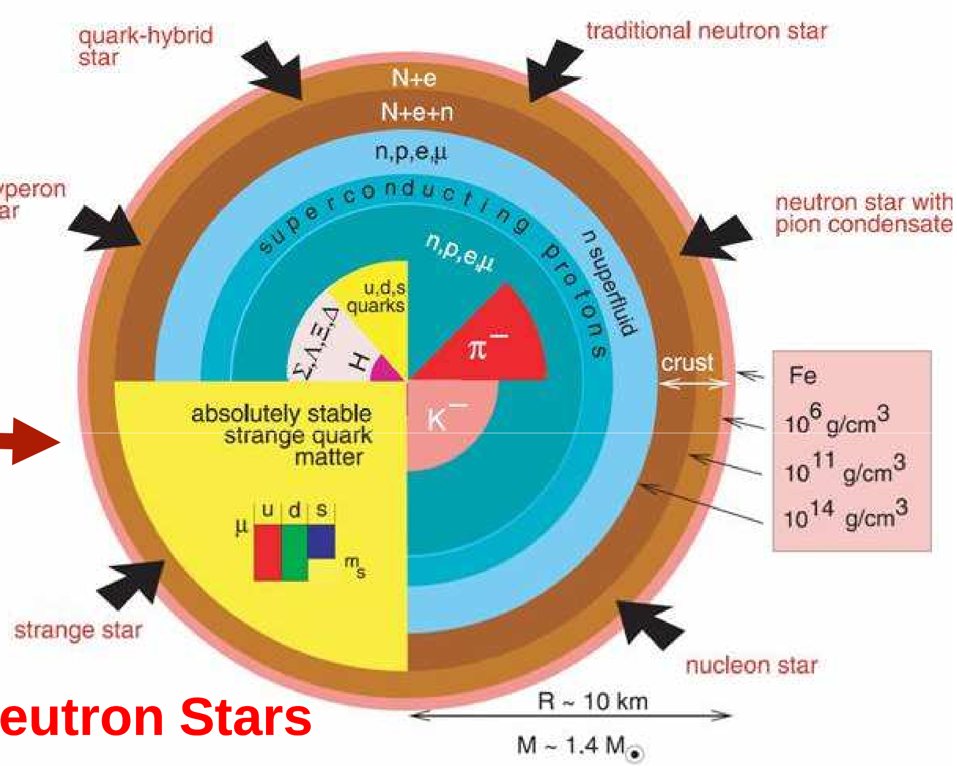
$${}^{3}_{\bar{\Lambda}}\overline{H}(\bar{n}+\bar{p}+\bar{\Lambda})$$

- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to Y-N interactions
- Hypertriton: **$\Delta B=130\pm50$ KeV; r~10fm**
- Production rate via coalescence at RHIC depends on overlapping wave functions of **n+p+Λ** in final state
- Important first step for searching for other exotic hypernuclei (double-Λ)

from Hypernuclei to Neutron Stars

hypernuclei ⟵ Λ-B Interaction ⟶ Neutron Stars





Several possible configurations of Neutron Stars

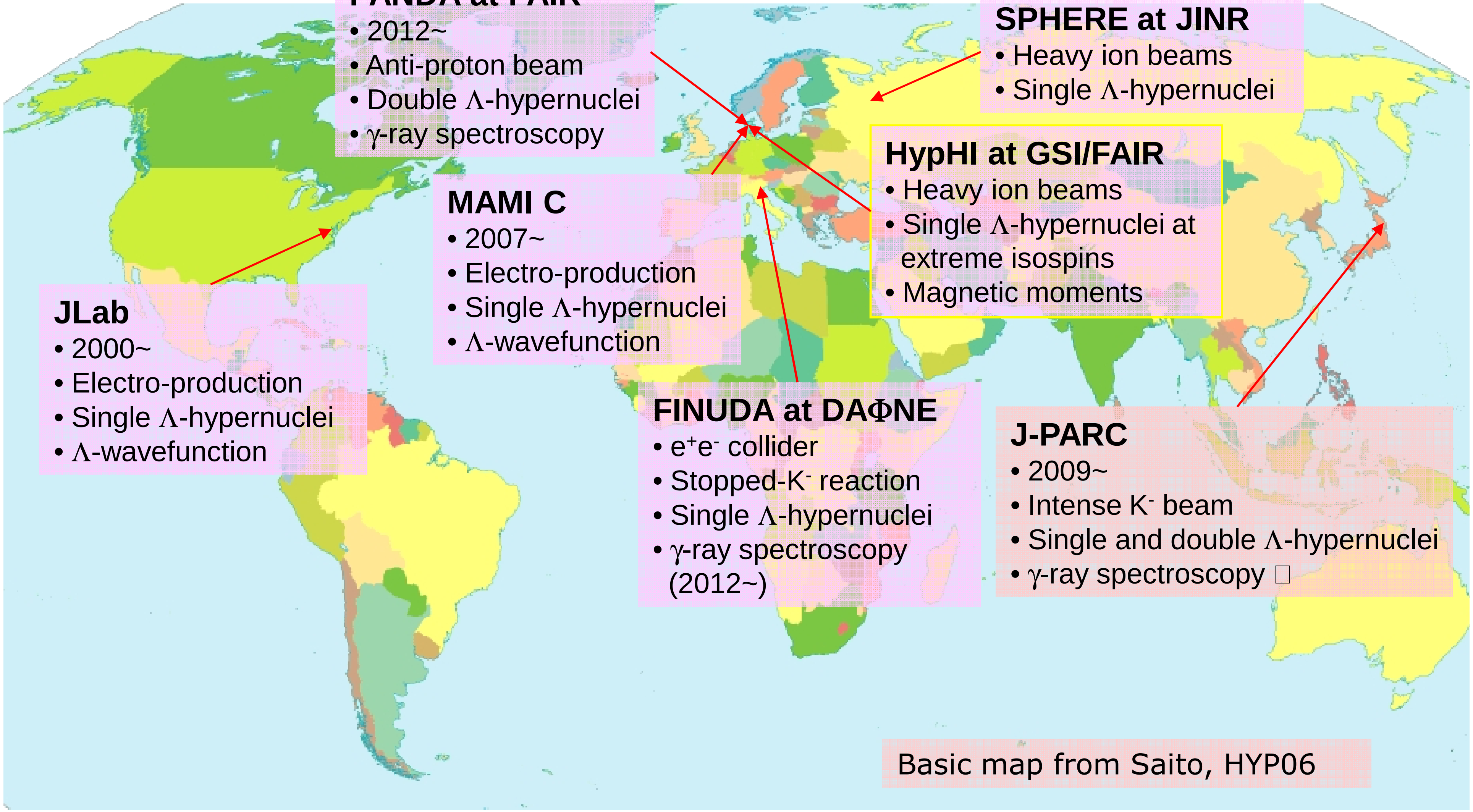
- **Kaon condensate, hyperons, strange quark matter**

J.M. Lattimer and M. Prakash,
"The Physics of Neutron Stars", Science 304, 536 (2004)
J. Schaffner and I. Mishustin, *Phys. Rev. C* 53 (1996):
Hyperon-rich matter in neutron stars

Single **and** ***double*** **hypernuclei in the laboratory:**

- **study the strange sector of the baryon-baryon interaction**
- **provide info on EOS of neutron stars**

Current hypernucleus experiments



PANDA at FAIR
- 2012~
- Anti-proton beam
- Double Λ-hypernuclei
- γ-ray spectroscopy

SPHERE at JINR
- Heavy ion beams
- Single Λ-hypernuclei

HypHI at GSI/FAIR
- Heavy ion beams
- Single Λ-hypernuclei at extreme isospins
- Magnetic moments

MAMI C
- 2007~
- Electro-production
- Single Λ-hypernuclei
- Λ-wavefunction

JLab
- 2000~
- Electro-production
- Single Λ-hypernuclei
- Λ-wavefunction

FINUDA at DAΦNE
- e^+e^- collider
- Stopped-K^- reaction
- Single Λ-hypernuclei
- γ-ray spectroscopy (2012~)

J-PARC
- 2009~
- Intense K^- beam
- Single and double Λ-hypernuclei
- γ-ray spectroscopy

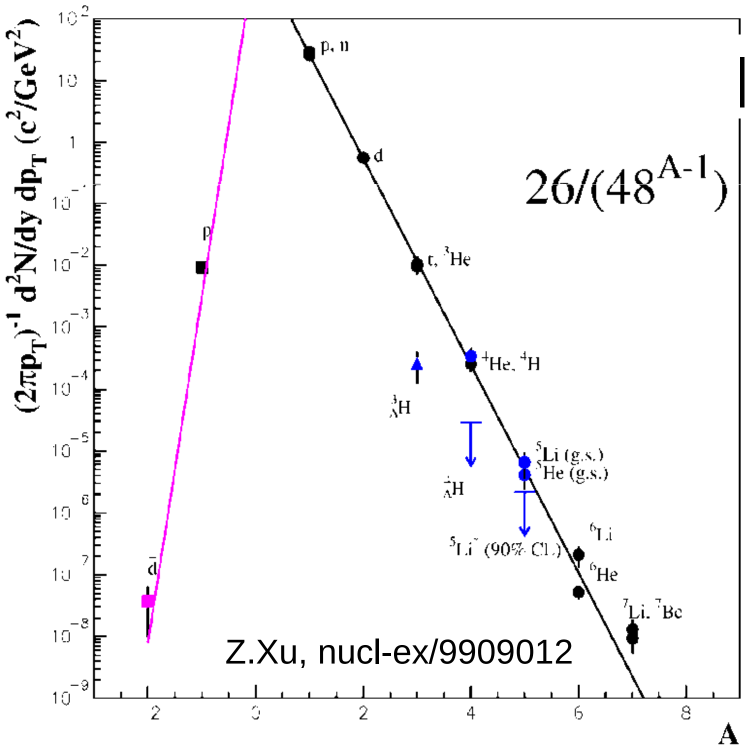
Basic map from Saito, HYP06

Can we observe hypernuclei at RHIC?

- Low energy and cosmic ray experiments (wikipedia):

  hypernucleus production via
  - Λ or K capture by nuclei
  - the direct strangeness exchange reaction

  hypernuclei observed
  - energetic but delayed decay,
  - measure momentum of the K and π mesons

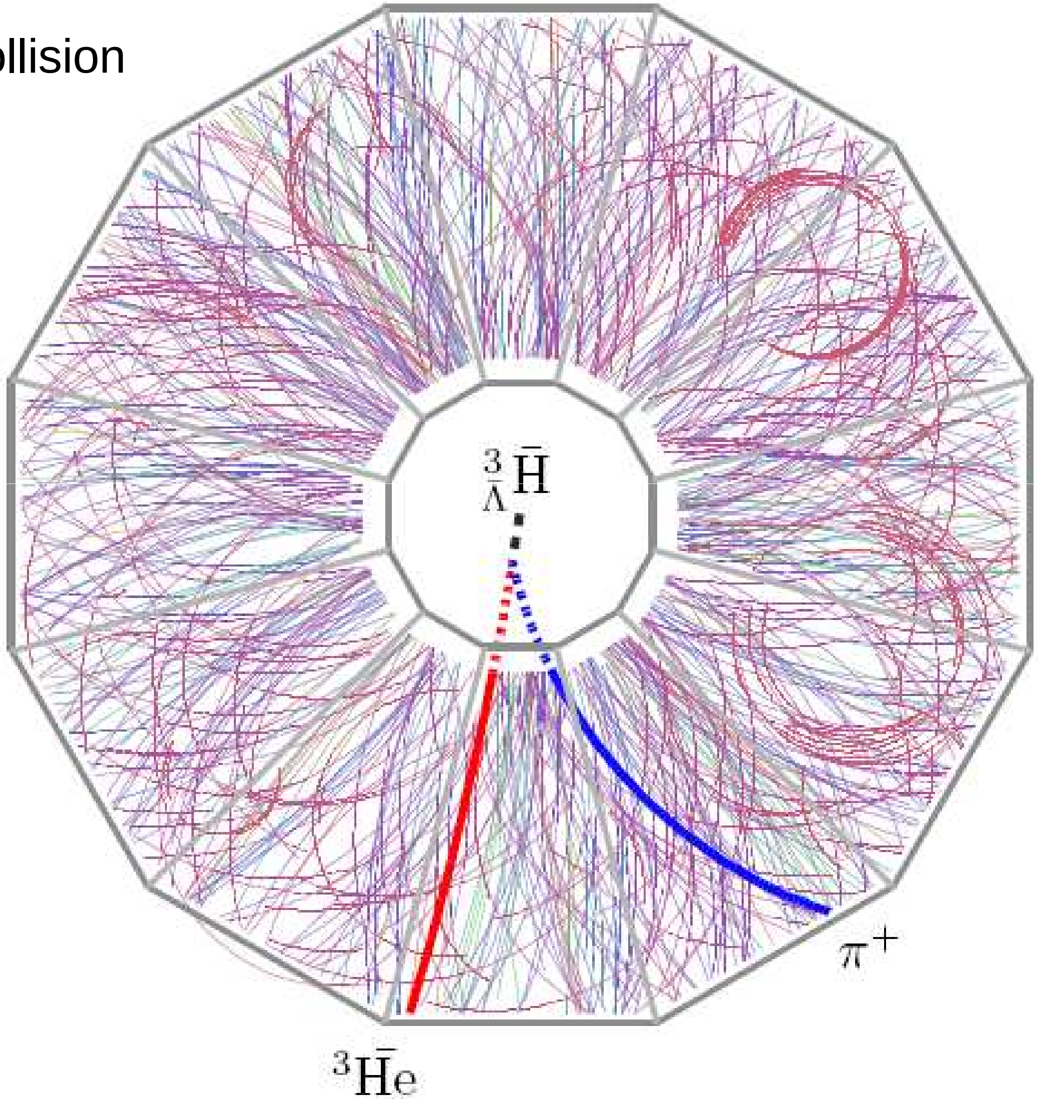


- In high energy heavy-ion collisions:
  - nucleus production by coalescence, characterized by penalty factor.
  - AGS data[1] indicated that hypernucleus production will be further suppressed.
  - What's the case at RHIC?

[1] AGS-E864, Phys. Rev. C70,024902 (2004)

A candidate event at STAR

Run4 (2004)
200 GeV Au+Au collision



Data-set and track selection

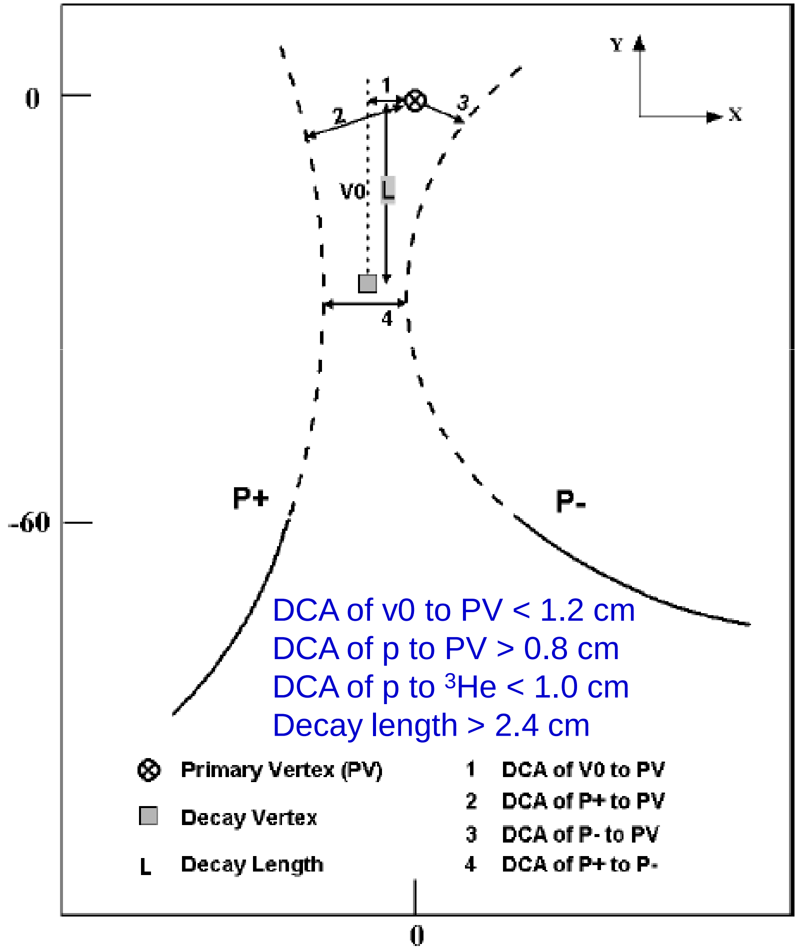
$^{3}_{\Lambda}H$ mesonic decay, m=2.991 GeV, B.R. 0.25;

$$^{3}_{\overline{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$

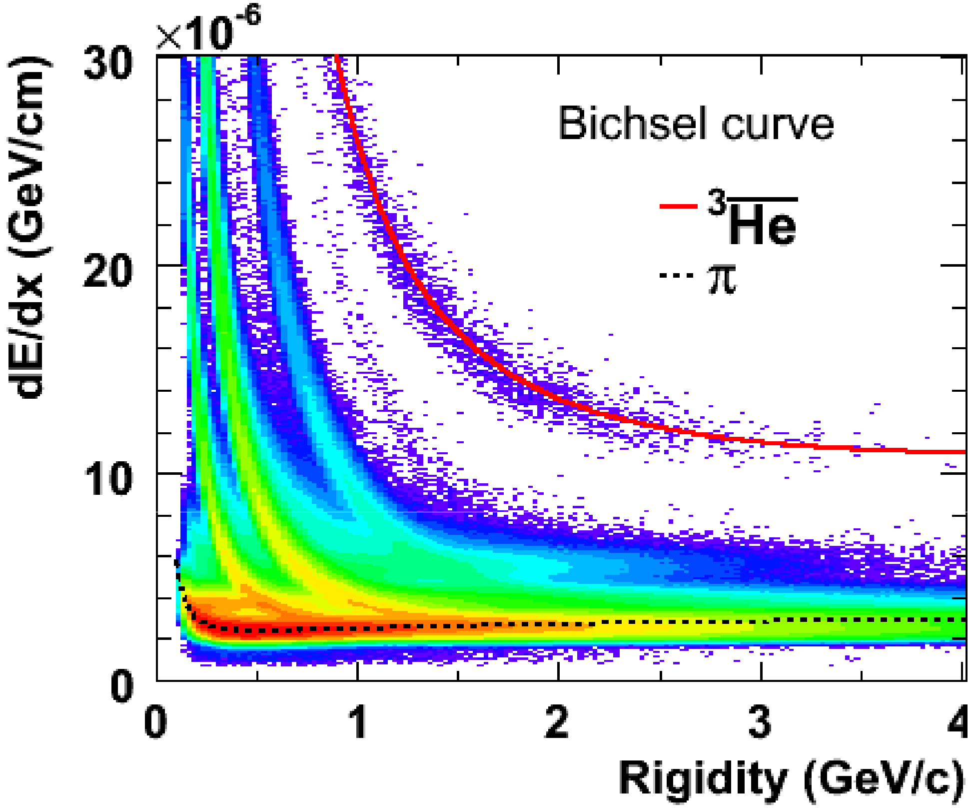
$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

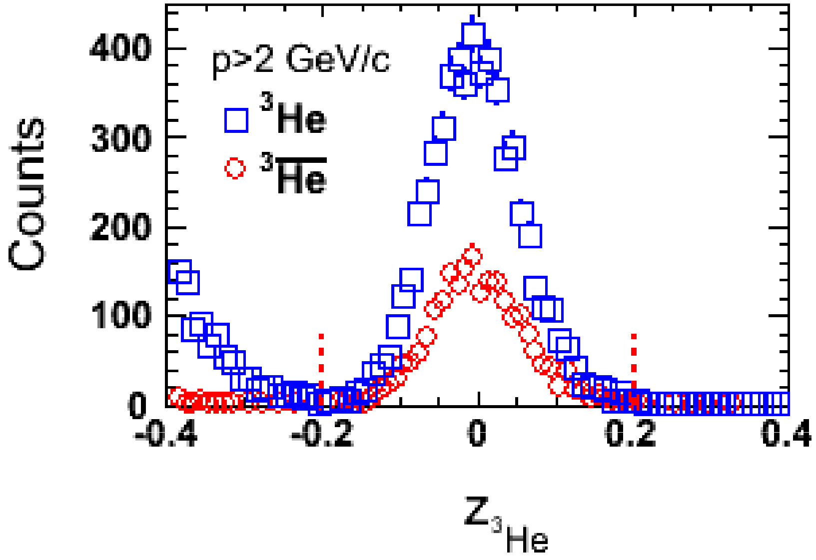
- Data-set used, Au+Au 200 GeV
  - ✓~67M Run7 MB,
  - ✓~23M Run4 central,
  - ✓~22M Run4 MB,
  - ✓|VZ| < 30cm
- Track quality cuts, global track
  - ✓nFitsPts > 25, nFitsPts/Max > 0.52
  - ✓nHitsdEdx > 15
  - ✓P_t > 0.20, |eta| < 1.0
  - ✓Pion n-sigma (-2.0, 2.0)

Secondary vertex finding technique



^{3}He & anti-^{3}He selection





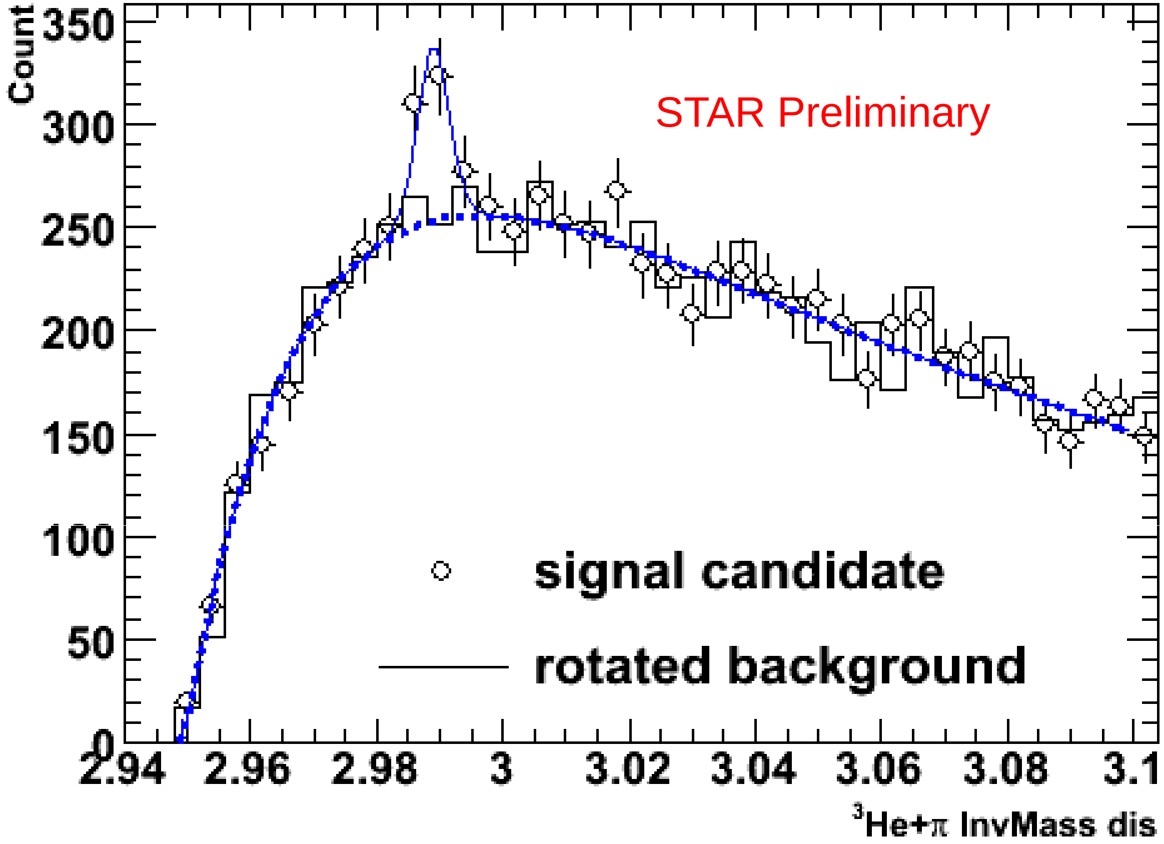
$$Z = \ln\left(\frac{\langle dE/dx \rangle}{\langle dE/dx \rangle^{Bichsel}}\right)$$

Select pure ^{3}He sample: -0.2<Z<0.2 & dca <1.0cm & p >2 GeV

^{3}He: 2931(MB07) + 2008(central04) + 871(MB04) = 5810

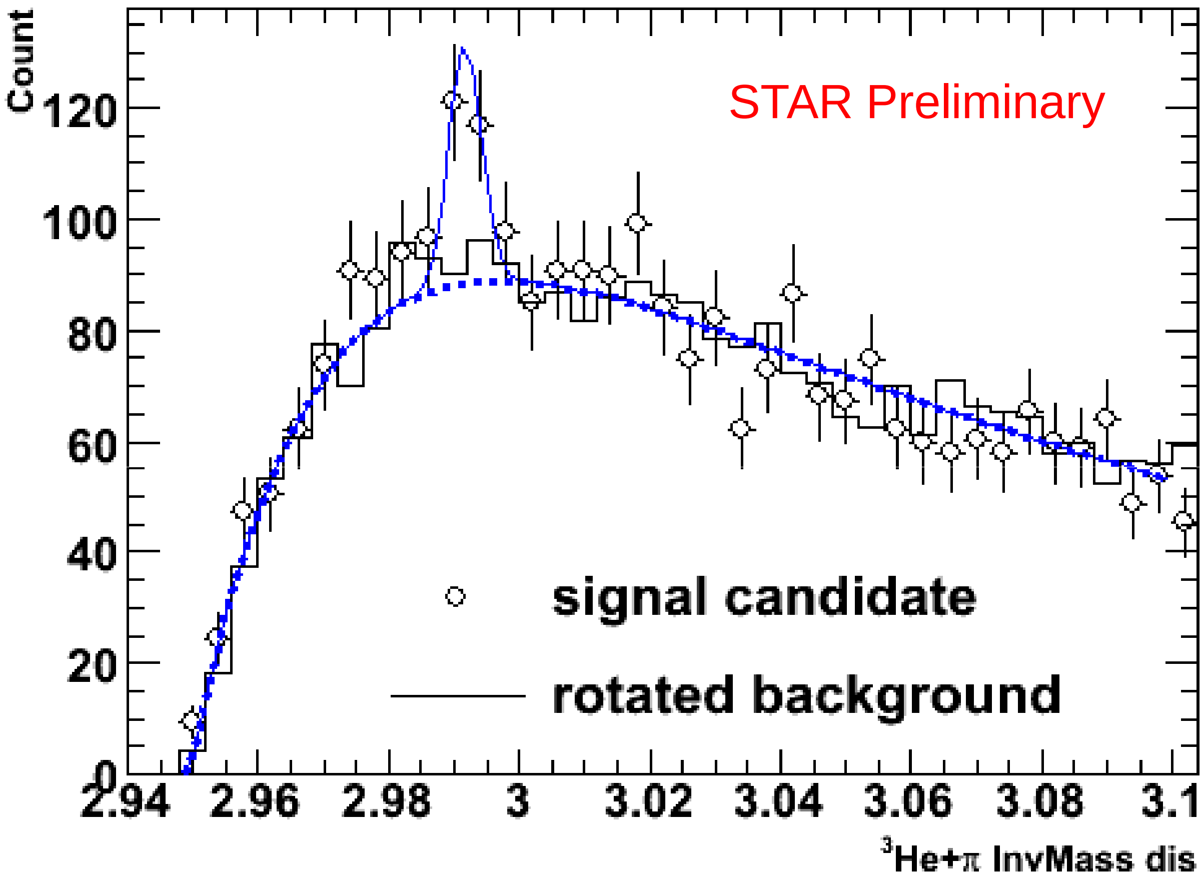
Anti-^{3}He: 1105(MB07) + 735(central04) + 328(MB04) = 2168

$^{3}_{\Lambda}H$ signal from the data



- background shape determined from rotated background analysis;
- Signal observed from the data (bin-by-bin counting): **157 ± 30** ;
- Projection on antihypertriton yields: $^{3}_{\Lambda}\overline{H} = {}^{3}_{\Lambda}H * {}^{3}\overline{He} / {}^{3}He = 157 * 2168 / 5810 = 59 \pm 11$
  constraint on antihypertriton yields without direct observation

$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ signal from the data

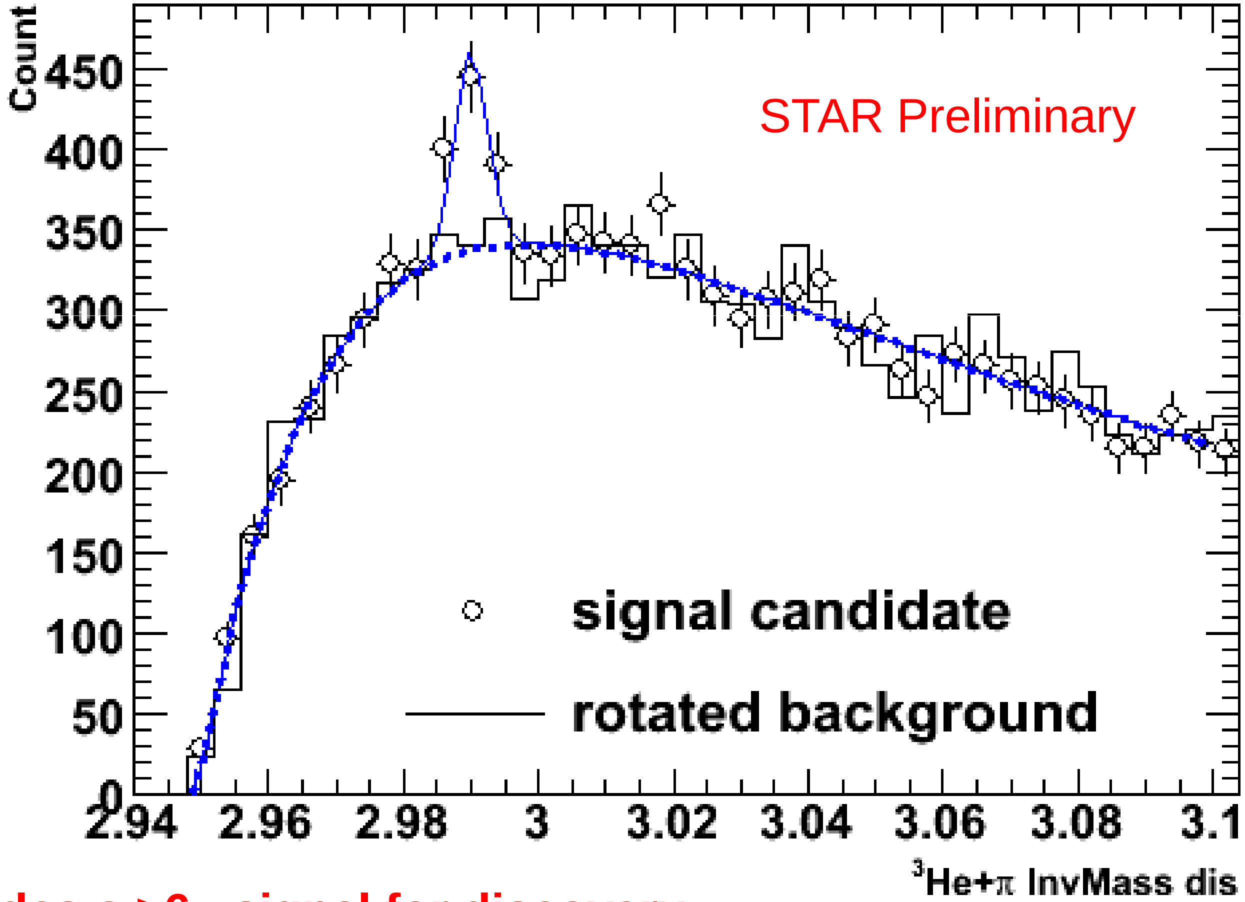


- Signal observed from the data (bin-by-bin counting): **70±17**;

  Mass: 2.991±0.001 GeV; Width (fixed): 0.0025 GeV;

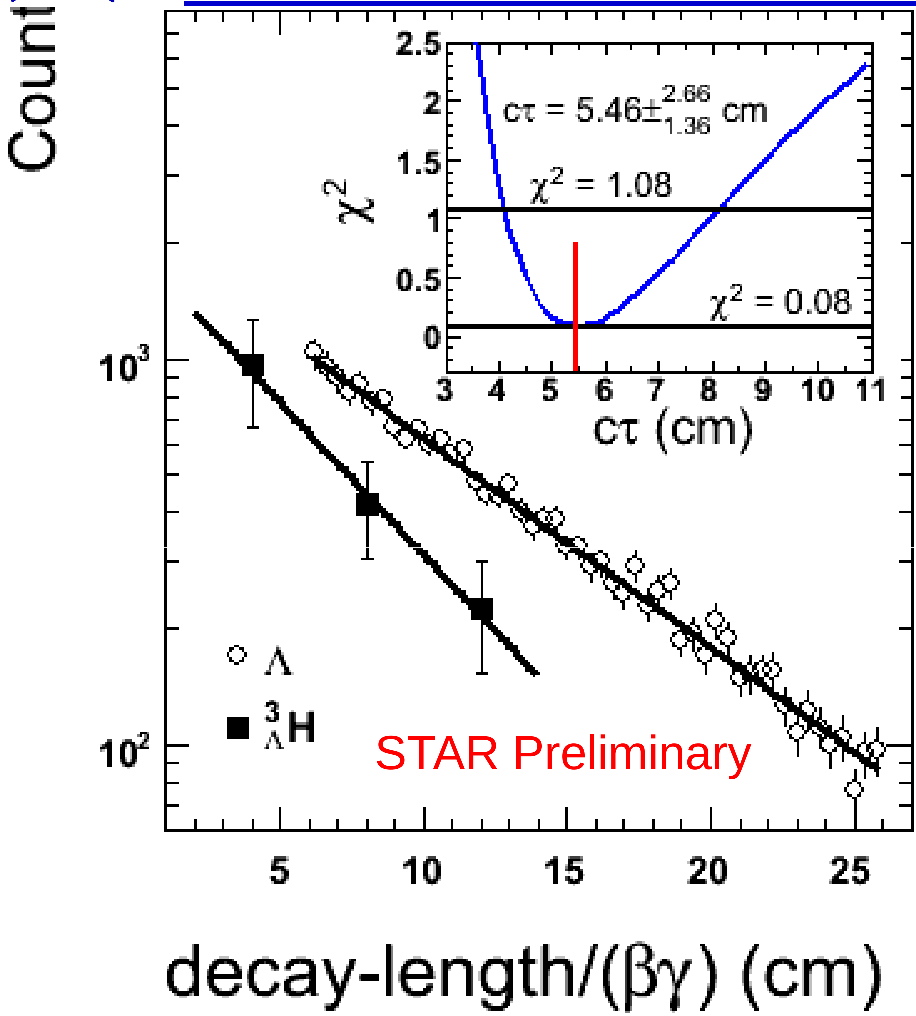
Combined signals

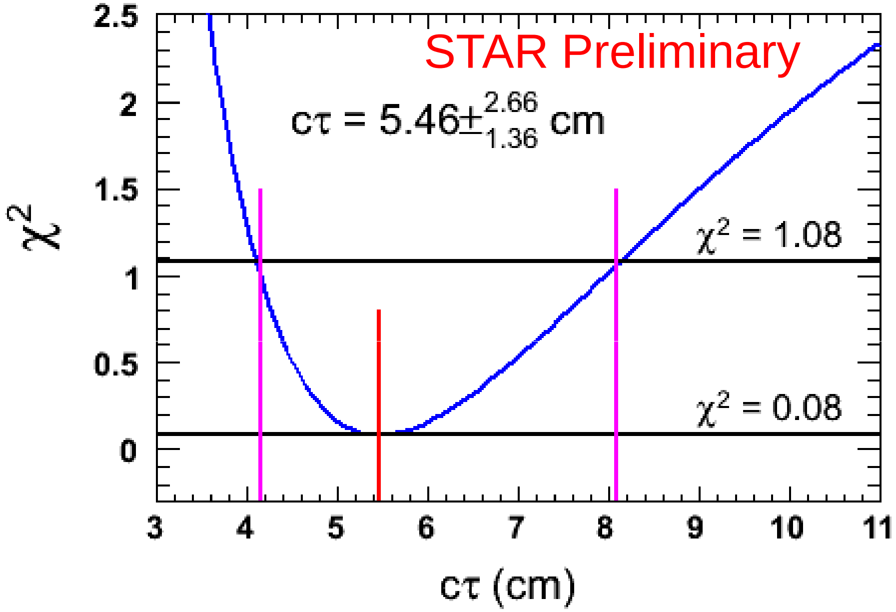
Combine hypertriton and antihypertriton signal:
225±35



This provides a >6σ signal for discovery

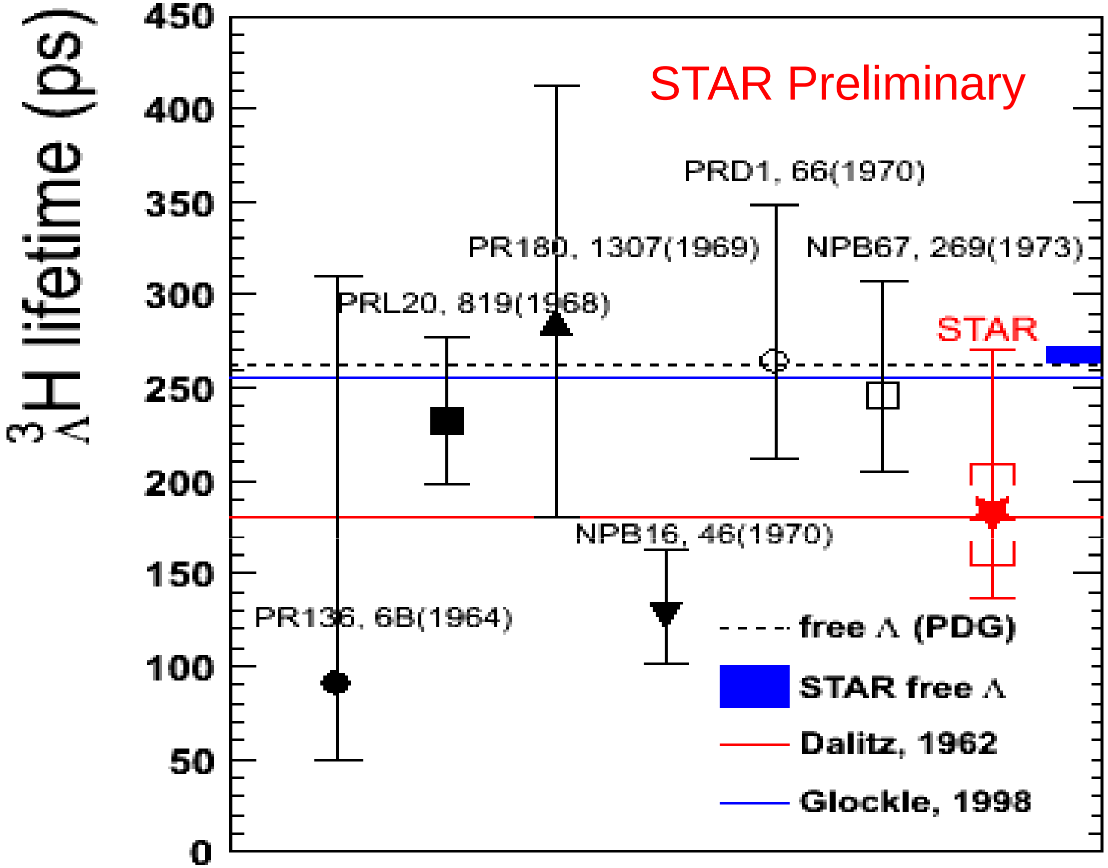
Lifetime





- Our data: $\tau = 182 \pm^{89}_{45} \pm 27\, ps$
- Consistency check on Λ lifetime yields τ(Λ)=267±5 *ps* *[PDG: 263 ps]*.

Comparison to world data



- Lifetime related to binding energy
- Theory input: the Λ is lightly bound in the hypertriton

[1] R. H. Dalitz, *Nuclear Interactions of the Hyperons* (Oxford Uni. Press, London, 1965).

[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).

[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

Measured invariant yields and ratios

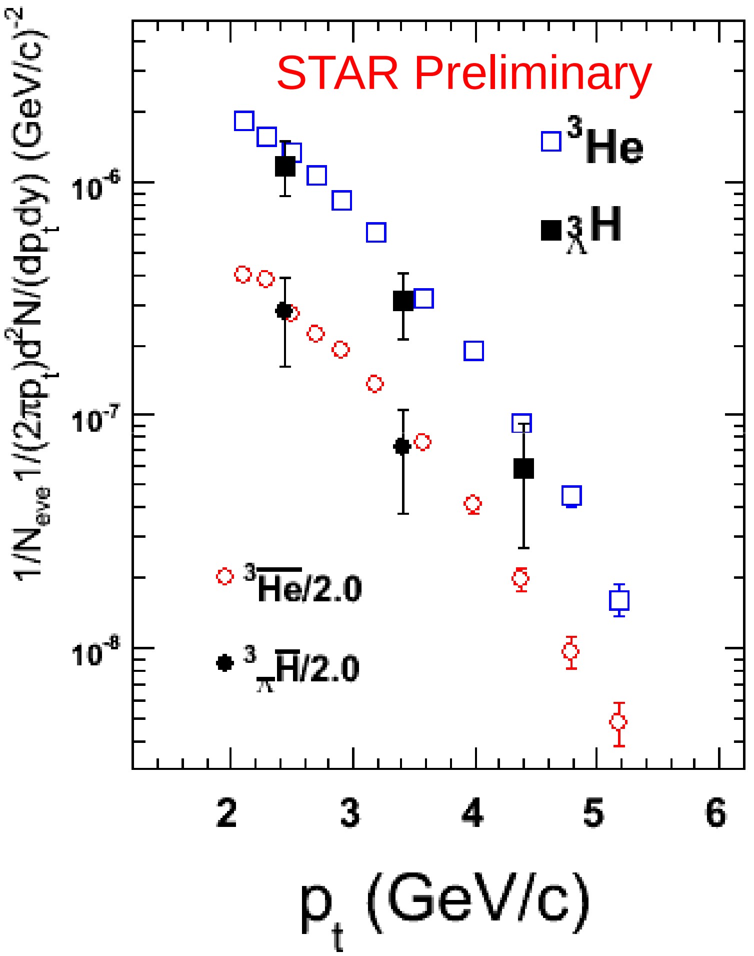


TABLE I: Particle ratios from Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV/c. The ^{3}He ($^3\overline{\text{He}}$) yield have been corrected for $^3_\Lambda$H ($^3_{\bar\Lambda}\overline{\text{H}}$) feed-down contribution.

Particle type	Ratio
$^3_{\bar\Lambda}\bar{\mathrm{H}}/^3_\Lambda\mathrm{H}$	$0.49 \pm 0.18 \pm 0.07$
$^3\bar{\mathrm{He}}/^3\mathrm{He}$	$0.45 \pm 0.02 \pm 0.04$
$^3_{\bar\Lambda}\bar{\mathrm{H}}/^3\bar{\mathrm{He}}$	$0.89 \pm 0.28 \pm 0.13$
$^3_\Lambda\mathrm{H}/^3\mathrm{He}$	$0.82 \pm 0.16 \pm 0.12$

In a coalescence picture:

$$^3_{\Lambda}\overline{H}/^3_{\Lambda}H \propto (\overline{p}/p)(\overline{n}/n)(\overline{\Lambda}/\Lambda)$$

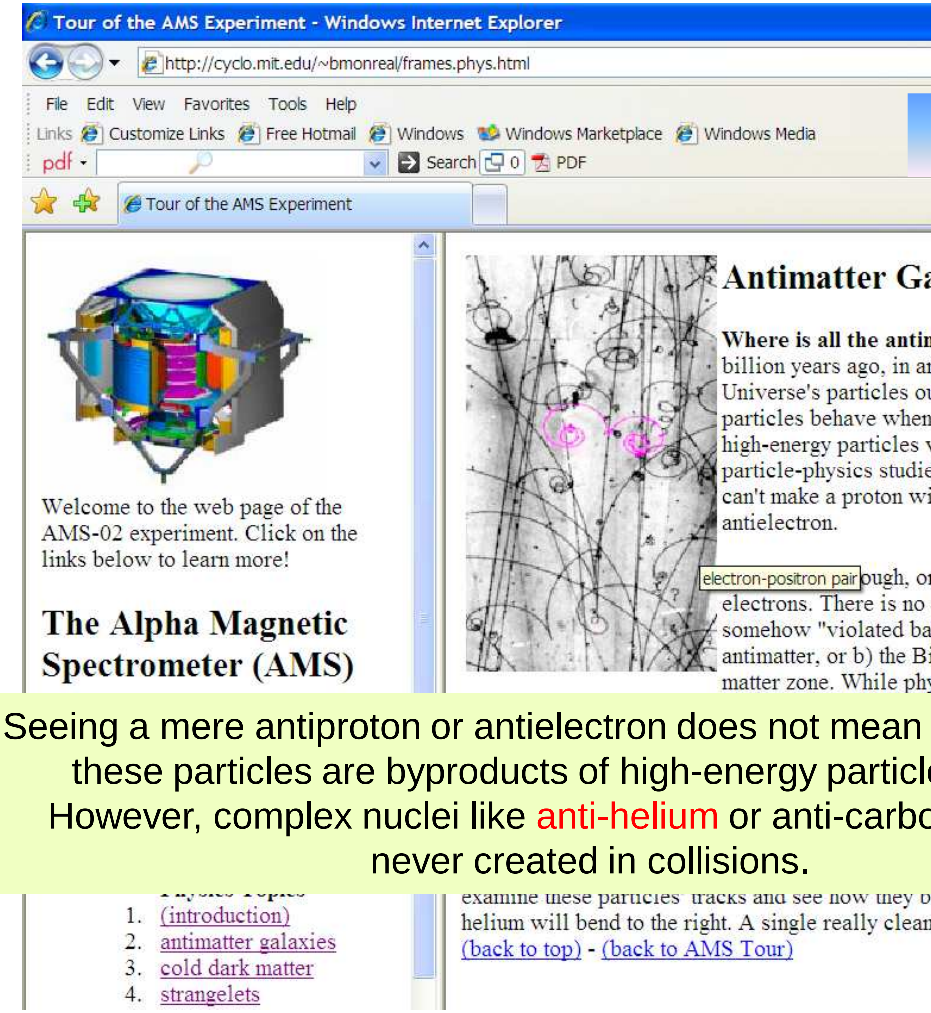
$$^3\overline{He}/^3He \propto (\overline{p}/p)^2(\overline{n}/n)$$

$0.45 \sim (0.77)^3$

Antinuclei in nature (new physics)

To appreciate just how rare nature produces antimatter (strange antimatter)

RHIC: an antimatter machine



Seeing a mere antiproton or antielectron does not mean much– after all, these particles are byproducts of high-energy particle collisions. However, complex nuclei like anti-helium or anti-carbon are almost never created in collisions.

Dark Matter, Black Hole➔ antinucleus production via coalescence

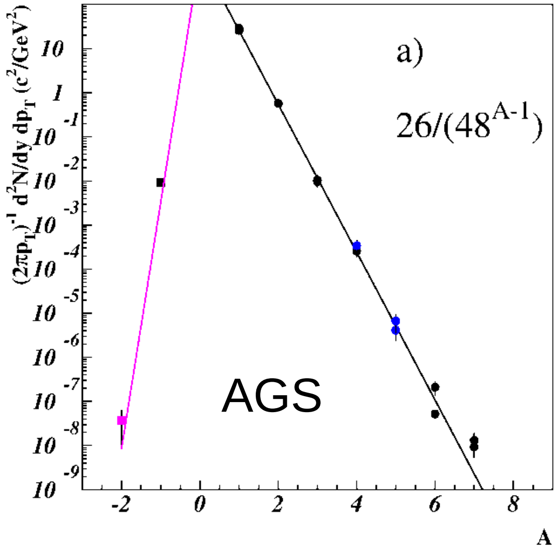
Matter and antimatter are not created equal

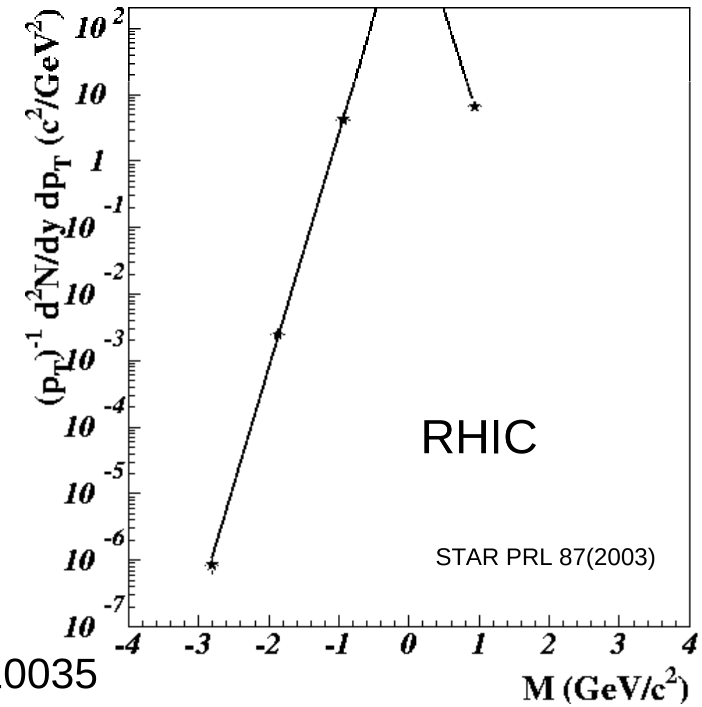
But we are getting there !

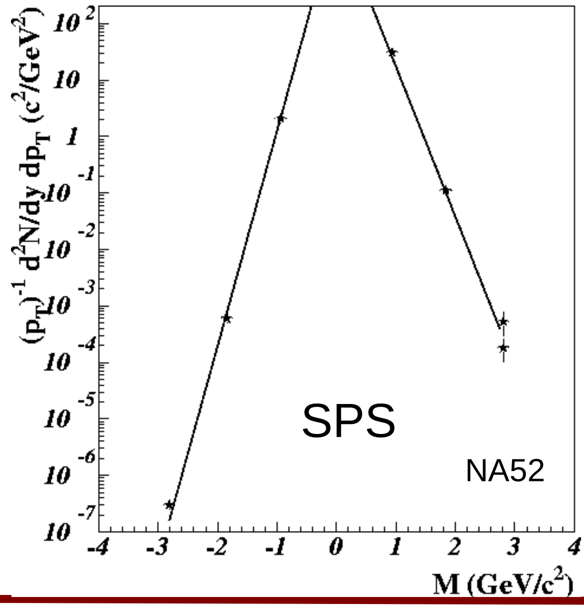
$$^3\overline{He}/^3He \approx 10^{-11}\text{(AGS,Cosmic)}$$

$$^3\overline{He}/^3He \approx 10^{-3}(SPS)$$

$$^3\overline{He}/^3He \approx 0.5(RHIC)$$





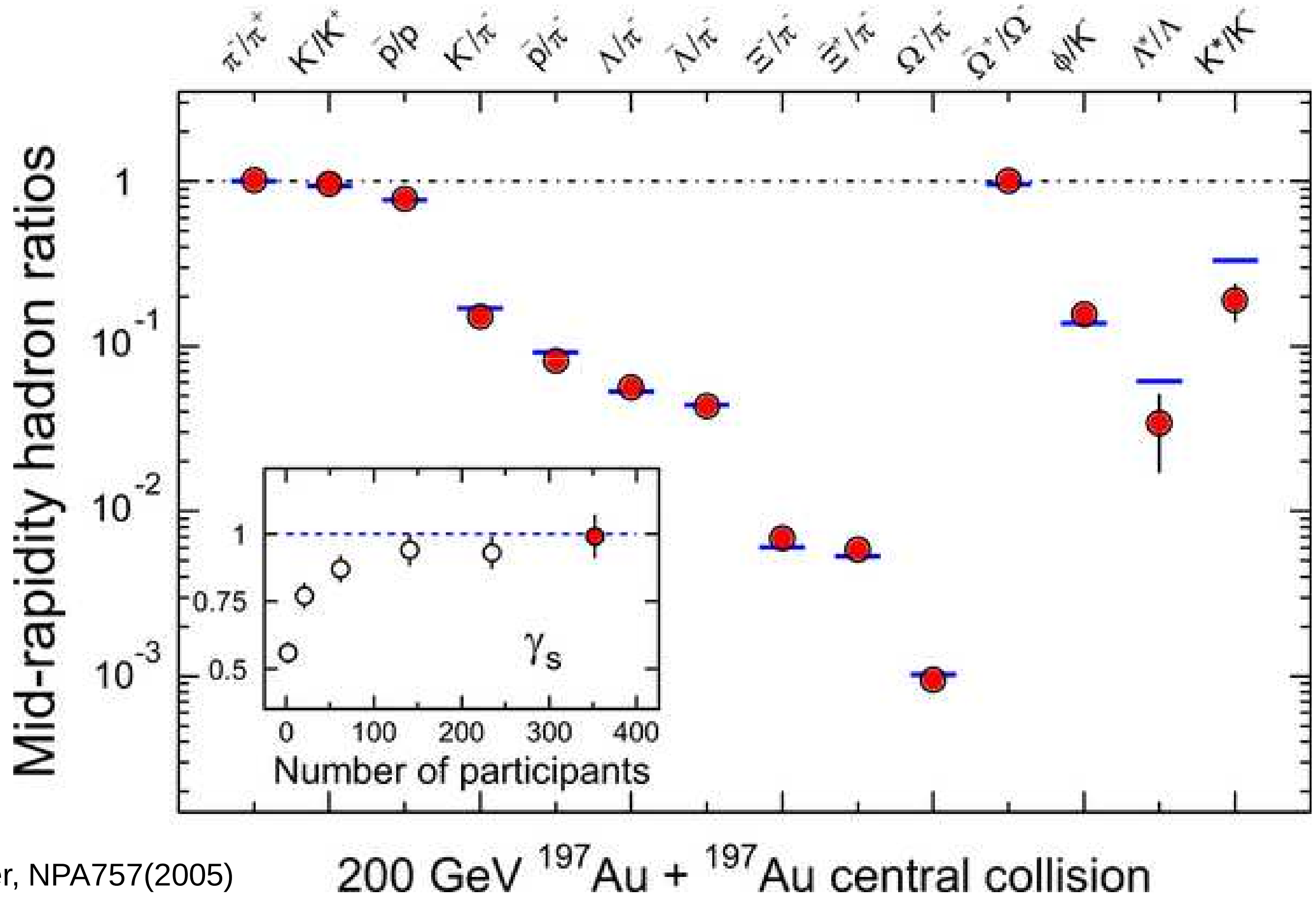


Nucl-ex/0610035

Flavors (u,d, s) are not created equal

except in possible QGP

J. Rafelski and B. Muller, Phys.Rev.Lett.48:1066,1982



STAR whitepaper, NPA757(2005)

Yields as a measure of correlation

Volume 98B, number 3 PHYSICS LETTERS 8 January 1981

probability $F_d(\boldsymbol{p})$, which is determined by the deuteron internal wave function ψ_d and the spatial distribution functions D_p and D_n through eq. (9). If the $\boldsymbol{k}$-dependences of $P_p(\boldsymbol{k})$ and $P_n(\boldsymbol{k})$ are weak compared with the $\boldsymbol{p}$-dependence of $F_d(\boldsymbol{p})$, eq. (8) becomes equivalent to eq. (1) for $Z = N = 1$ with

$$\tfrac{4}{3}\pi p_0^3 = \int \mathrm{d}\boldsymbol{p}\, F_d(\boldsymbol{p})\,. \qquad (10)$$

Using eq. (9), one can express the coalescence volume in terms of ψ_d, D_p and D_n as

$$\tfrac{4}{3}\pi p_0^3 = 2^3\cdot\tfrac{3}{4}\cdot(2\pi)^3 \int \mathrm{d}\boldsymbol{r}\,|\psi_d(\boldsymbol{r})|^2 D_2(\boldsymbol{r})\,, \quad D_2(\boldsymbol{r}) \equiv \int \mathrm{d}\boldsymbol{r}'\, D_p(\boldsymbol{r}-\boldsymbol{r}')D_n(\boldsymbol{r}')\,. \qquad (11,12)$$

$D_2(\boldsymbol{r})$ gives the distribution of the p–n relative coordinate in the HX and is closely related to the interaction volume introduced by Mekjian [6]. In fact, if the spatial size of the internal wave function ψ_d is much smaller than that of the HX, then eq. (11) gives

$$\tfrac{4}{3}\pi p_0^3 \simeq 2^3\cdot\tfrac{3}{4}\cdot(2\pi)^3 D_2(0)\,. \qquad (13)$$

A=2➔Baryon density $\langle\rho_B\rangle$

$D_2(0)$ thus corresponds to the inverse of the interaction volume. In the actual situation, however, the size of the deuteron is comparable to that of the HX and therefore one has to use eq. (11) to relate the coalescence volume with the spatial size of the HX.

Expressions analogous to eqs. (8–10) can be obtained for the other composite particles such as ^{3}H, ^{3}He and ^{4}He. In the case of triton (^{3}H) one gets

$$P(1,2;\boldsymbol{k}) = \int \mathrm{d}\boldsymbol{p}_1\,\mathrm{d}\boldsymbol{p}_2\, F_t(\boldsymbol{p}_1,\boldsymbol{p}_2)P_p(\boldsymbol{k}+\boldsymbol{p}_1)P_n(\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{p}_1+\boldsymbol{p}_2)P_n(\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{p}_1-\boldsymbol{p}_2)\,, \qquad (14)$$

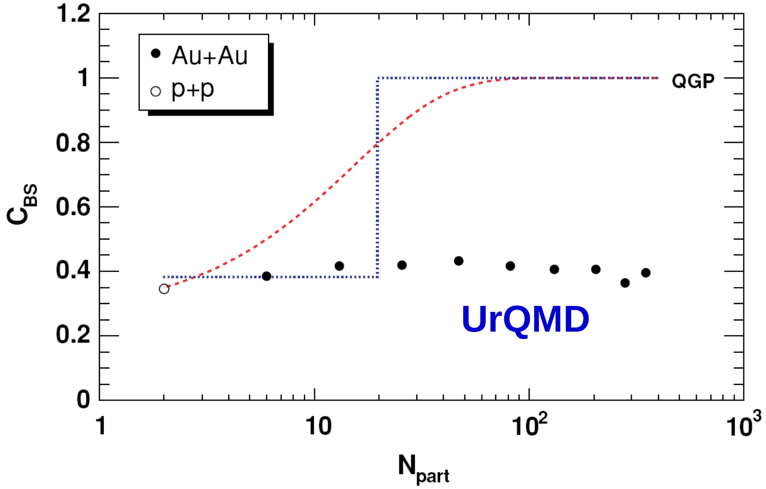
$$F_t(\boldsymbol{p}_1,\boldsymbol{p}_2) = 3^3\cdot\tfrac{1}{4}\int\frac{\mathrm{d}\boldsymbol{q}_1\mathrm{d}\boldsymbol{q}_2}{(2\pi)^6}\,\tilde{\psi}_t^*(\boldsymbol{p}_1+\tfrac{1}{2}\boldsymbol{q}_1,\boldsymbol{p}_2+\tfrac{1}{2}\boldsymbol{q}_2)\tilde{\psi}_t(\boldsymbol{p}_1-\tfrac{1}{2}\boldsymbol{q}_1,\boldsymbol{p}_2-\tfrac{1}{2}\boldsymbol{q}_2)$$

$$\times\,\tilde{D}_p(\boldsymbol{q}_1)\tilde{D}_n(-\tfrac{1}{2}\boldsymbol{q}_1+\boldsymbol{q}_2)\tilde{D}_n(-\tfrac{1}{2}\boldsymbol{q}_1-\boldsymbol{q}_2)\,, \qquad (15)$$

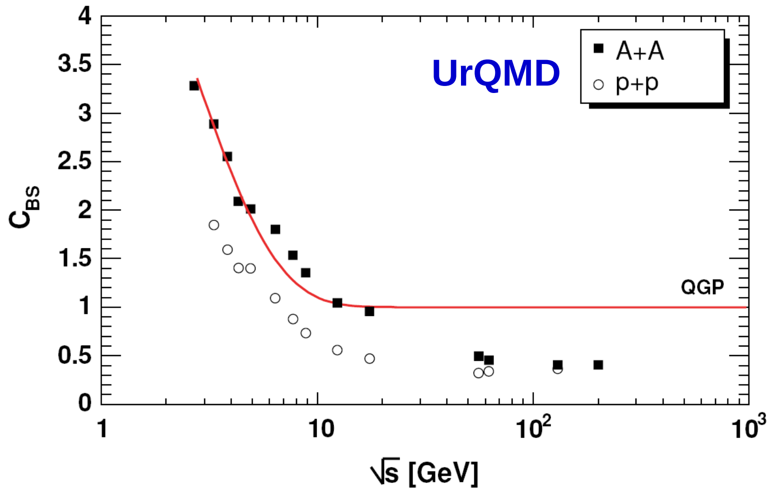
where $\tilde{\psi}_t$ is the Fourier transform of the triton internal wave function ψ_t. The coalescence volume is related to F_t as

$$\tfrac{1}{2}(\tfrac{4}{3}\pi p_0^3)^2 = \int \mathrm{d}\boldsymbol{p}_1\,\mathrm{d}\boldsymbol{p}_2\, F_t(\boldsymbol{p}_1,\boldsymbol{p}_2)\,. \qquad (16)$$

A=3 ➔ $\langle\rho^2_B\rangle$; $\langle\rho_\Lambda\rho_B\rangle$



S. Haussler, H. Stoecker, M. Bleicher, PRC73

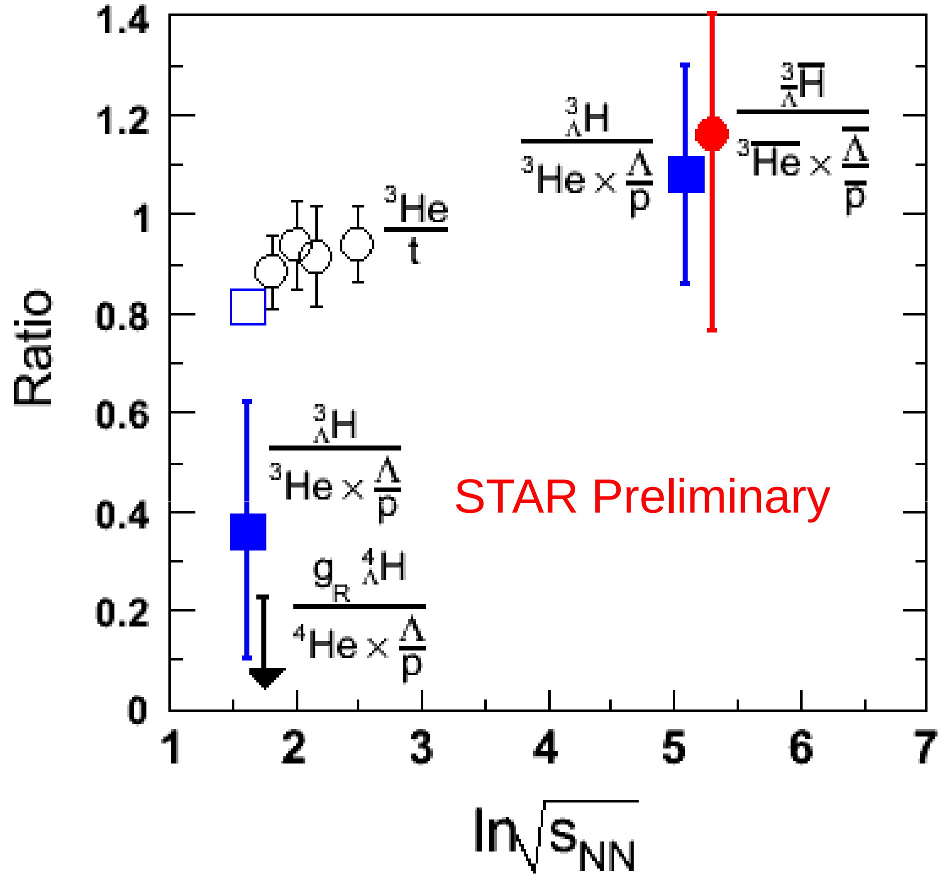


Caution:

measurements related to **local** (strangeness baryon)-baryon correlation

Simulations of (all strangeness)—(all baryon) correlation

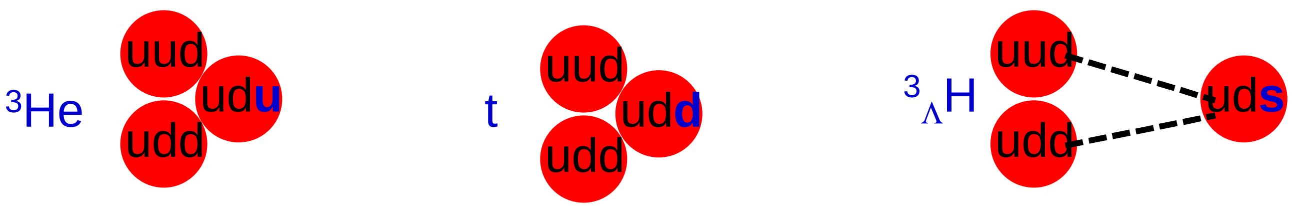
(^{3}He, t, $^3_\Lambda$H)➔(u, d, s)



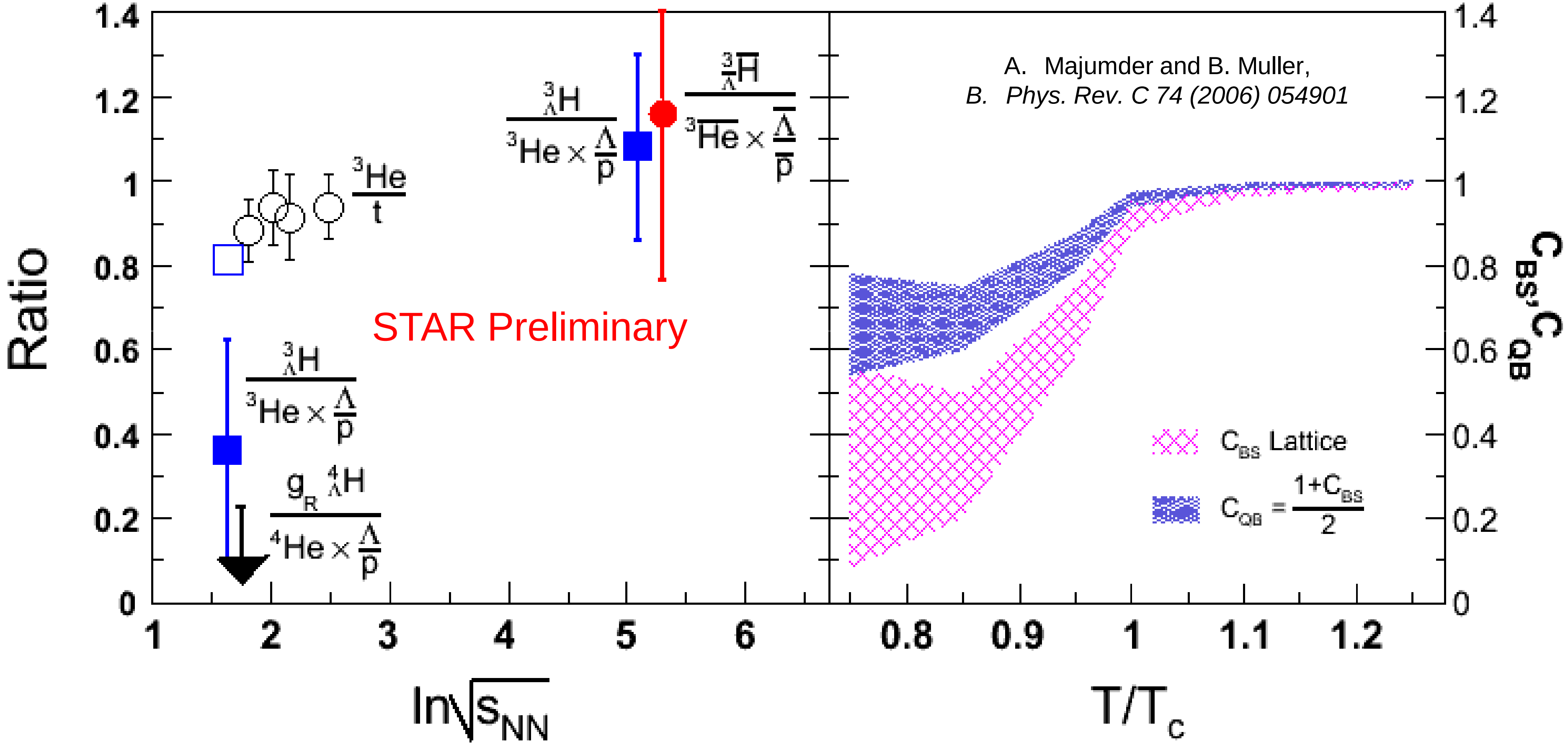
- A=3, a simple and perfect system
  9 valence quarks,
  (^{3}He, t, $^3_\Lambda$H)➔(u, d, s)+4u+4d
- Ratio measures Lambda-nucleon correlation
- RHIC: Lambda-nucleon similar phase space
- AGS: systematically lower than RHIC

➔Strangeness phase-space equilibrium

- ^{3}He/t measures charge-baryon correlation



${}^{3}_{\Lambda}H/{}^{3}He$: Primordial Λ-B correlation

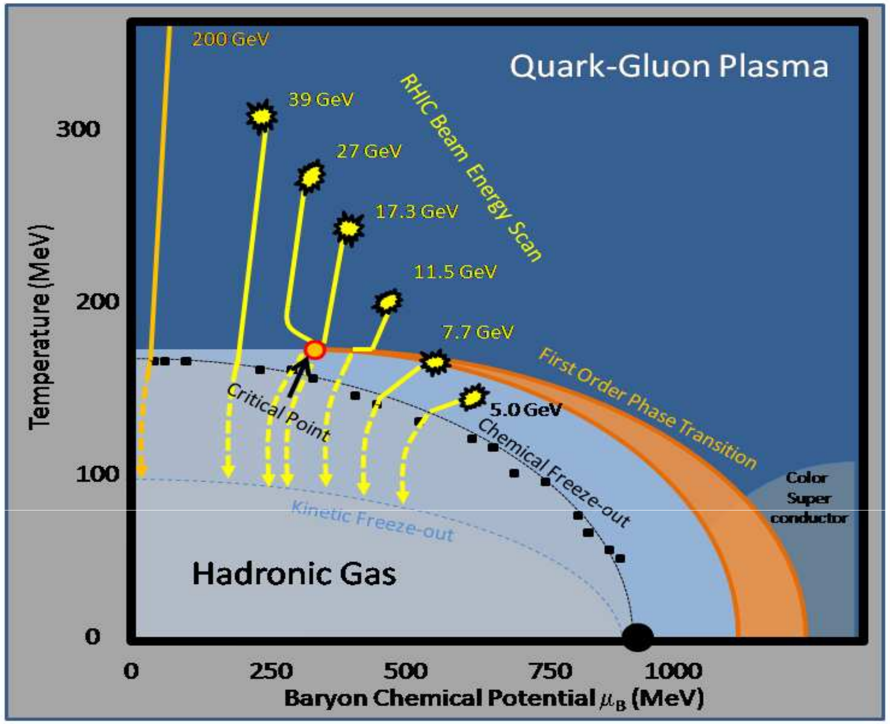


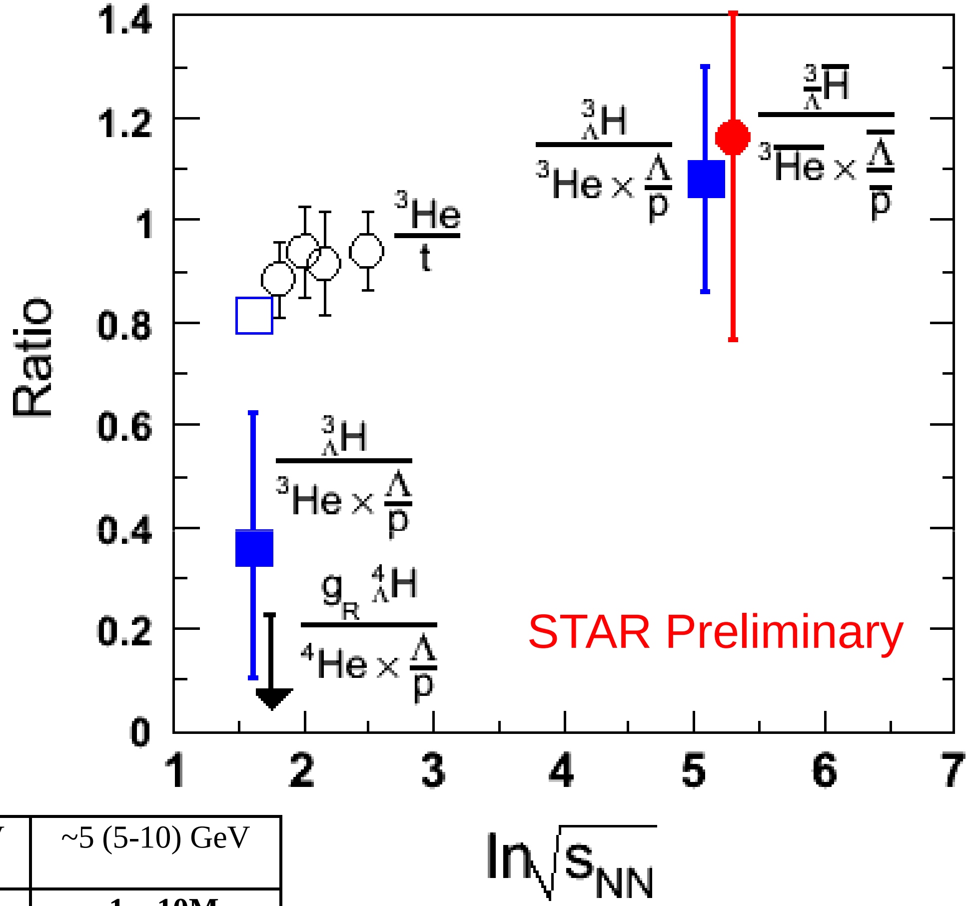
Caution:

measurements related to local (strangeness baryon)-baryon correlation

Lattice Simulations of (all strangeness)—(all baryon) correlation at zero chemical potential

Energy scan to establish the trend





Beam energy	200(30—200) GeV	~17 (10—30)GeV	~5 (5-10) GeV
Minbias events# (5σ)	300M	**~10—100M**	**~1—10M**
Penalty factor	1448	368	48
^{3}He invariant yields	1.6×10^{-6}	2×10^{-4}	0.01
$^3_\Lambda H/^3He$ assumed	1.0	0.3	0.05

Hypertriton only
STAR: DAQ1000+TOF

Conclusions

- ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ has been observed for 1^{st} time; significance ~4σ.
- Consistency check has been done on ${}^{3}_{\Lambda}\mathrm{H}$ analysis; significance is ~5σ
- The lifetime is measured to be $\tau = 182 \pm^{89}_{45} \pm 27\ ps$
- The ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}\,/\,{}^{3}_{\Lambda}\mathrm{H}$ ratio is measured as 0.49$\pm$0.18, and $^{3}\overline{\mathrm{He}}$ / ^{3}He is 0.45$\pm$0.02, favoring the coalescence picture.
- The ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ / $^{3}\overline{\mathrm{He}}$ ratio is determined to be 0.89 $\pm$ 0.28, and ${}^{3}_{\Lambda}\mathrm{H}$ / ^{3}He is 0.82 $\pm$ 0.16. No extra penalty factor observed for hypertritons at RHIC.
  Strangeness phase space equilibrium

Outlook

- **Lifetime:**
  - **data samples with larger statistics**

- **Production rate:**
  - **Strangeness and baryon correlation**
    Need specific model calculation for this quantity
  - **Establish trend from AGS—SPS—RHIC—LHC**

- **$_{\Lambda}^{3}H \rightarrow d+p+\pi$ channel measurement: *d* and dbar via ToF.**

- **Search for other hypernucleus: $^{4}_{\Lambda}H$, double Λ-hypernucleus.**

- **Search for anti-α**

- **RHIC: best antimatter machine ever built**

International Hyper-nuclear network