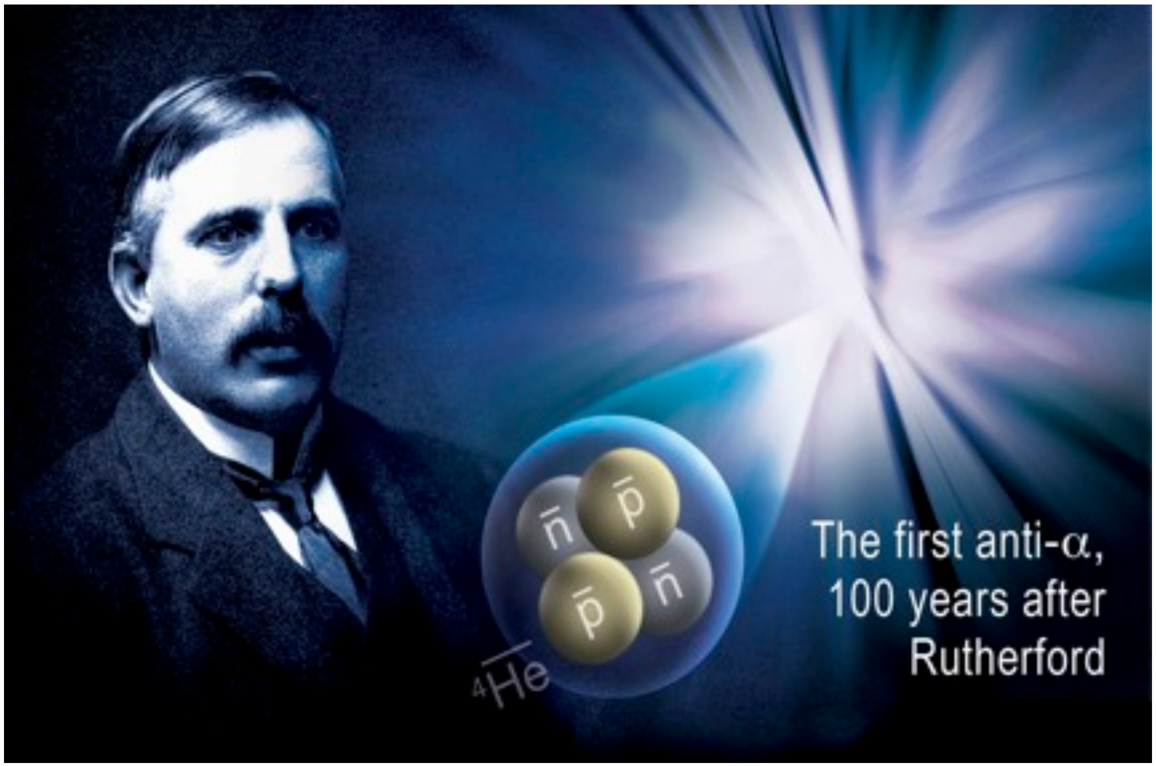
Observation of the antimatter Helium-4 (anti-α) nucleus



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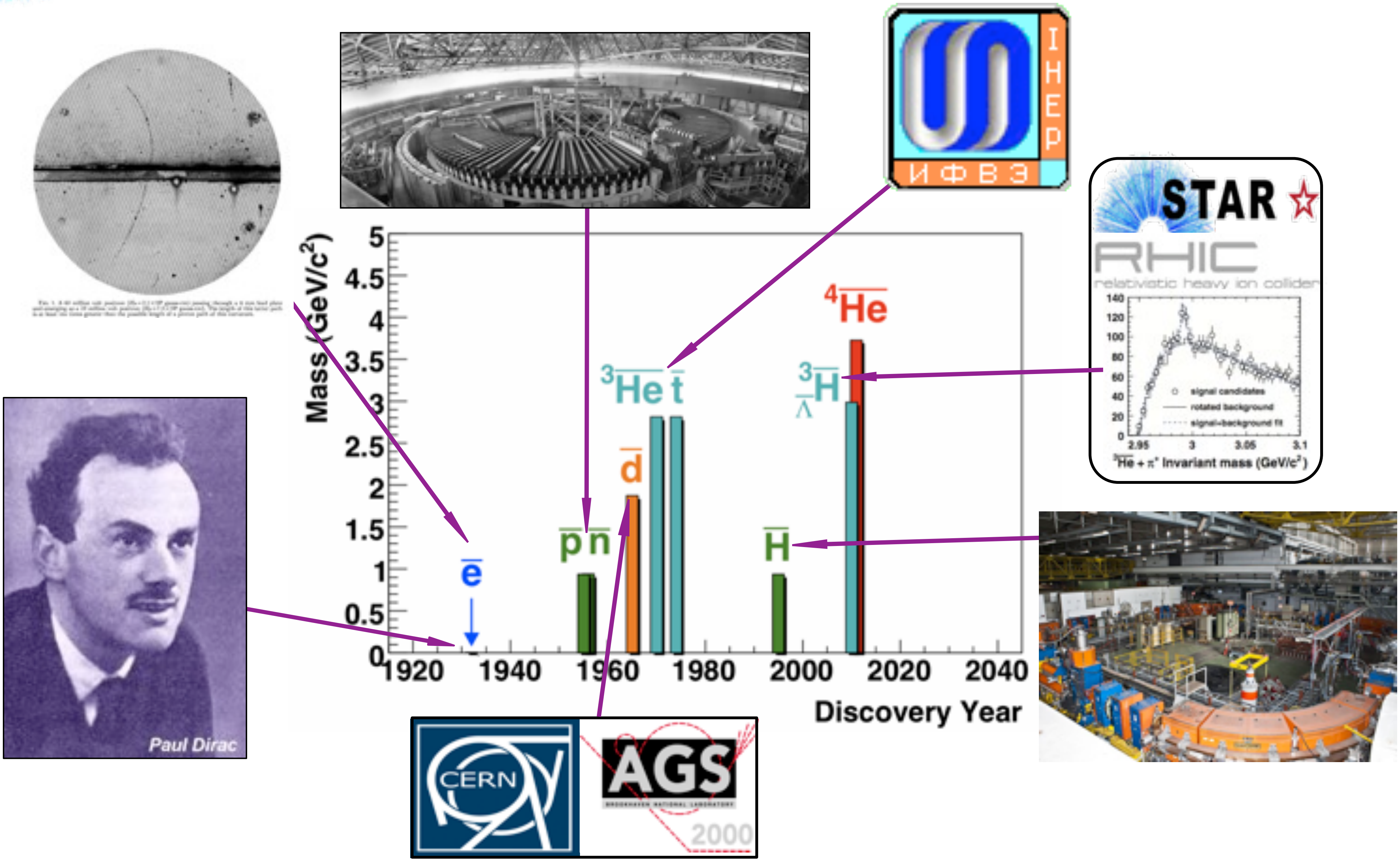
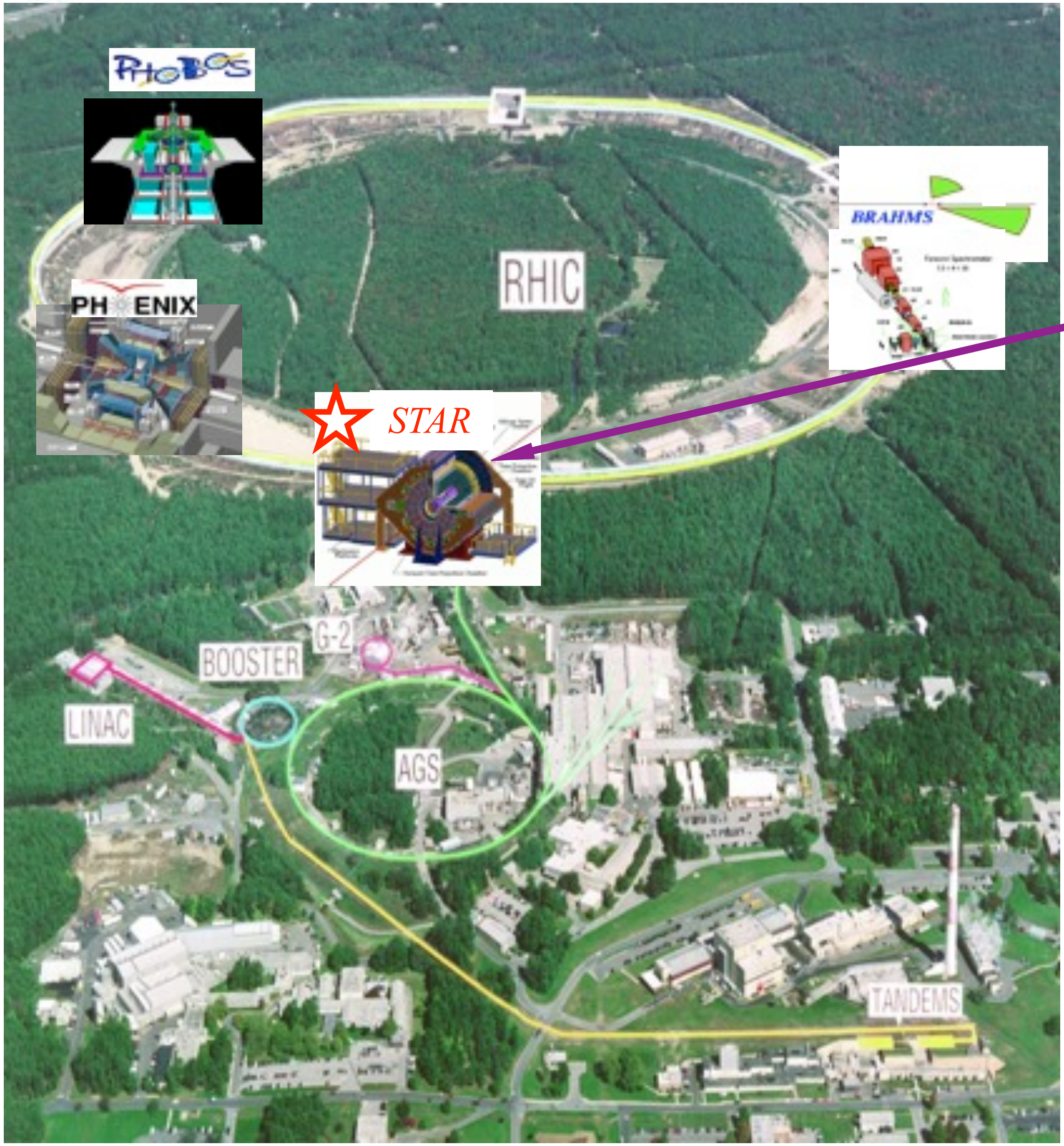
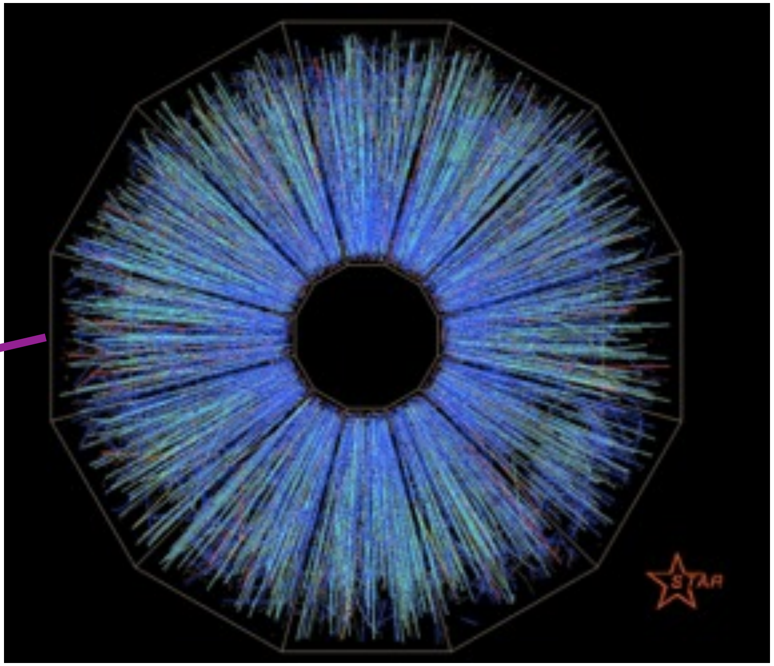
- Introduction & Motivation
- Evidence of the observation of $^4\overline{He}$
- Quality check for $^4\overline{He}$
- $^4\overline{He}$ invariant yields
- Summary

History of antimatter



Relativistic heavy ion collider (RHIC)

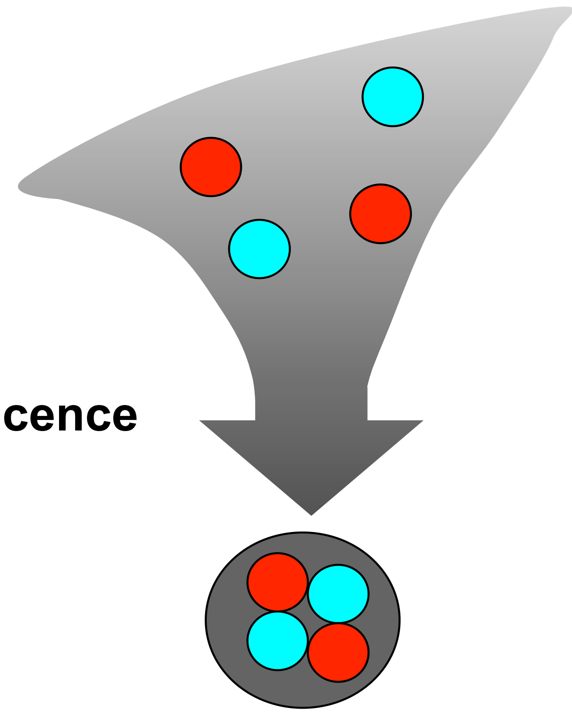




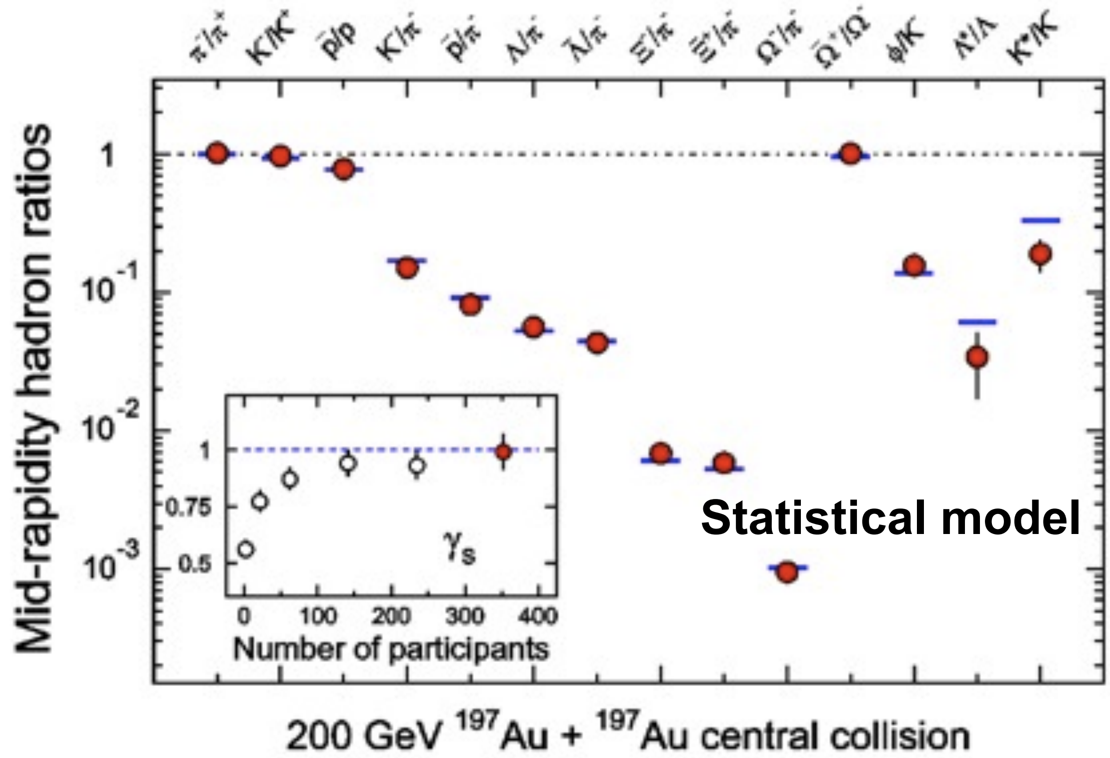
- RHIC as an antimatter production facility, can create controllable, repeatable "little bangs".
- Determine whether $^4\overline{He}$ exists, provide a point of reference for future observations in cosmic radiation.

Production mechanisms

Coalescence



Sato, H. & Yazaki, K. Phys. Lett. B 98, 153-157 (1981)
Butler, S. T. & Perarson, C. A. Phys. Rev. Lett. 7, 69-71 (1961)

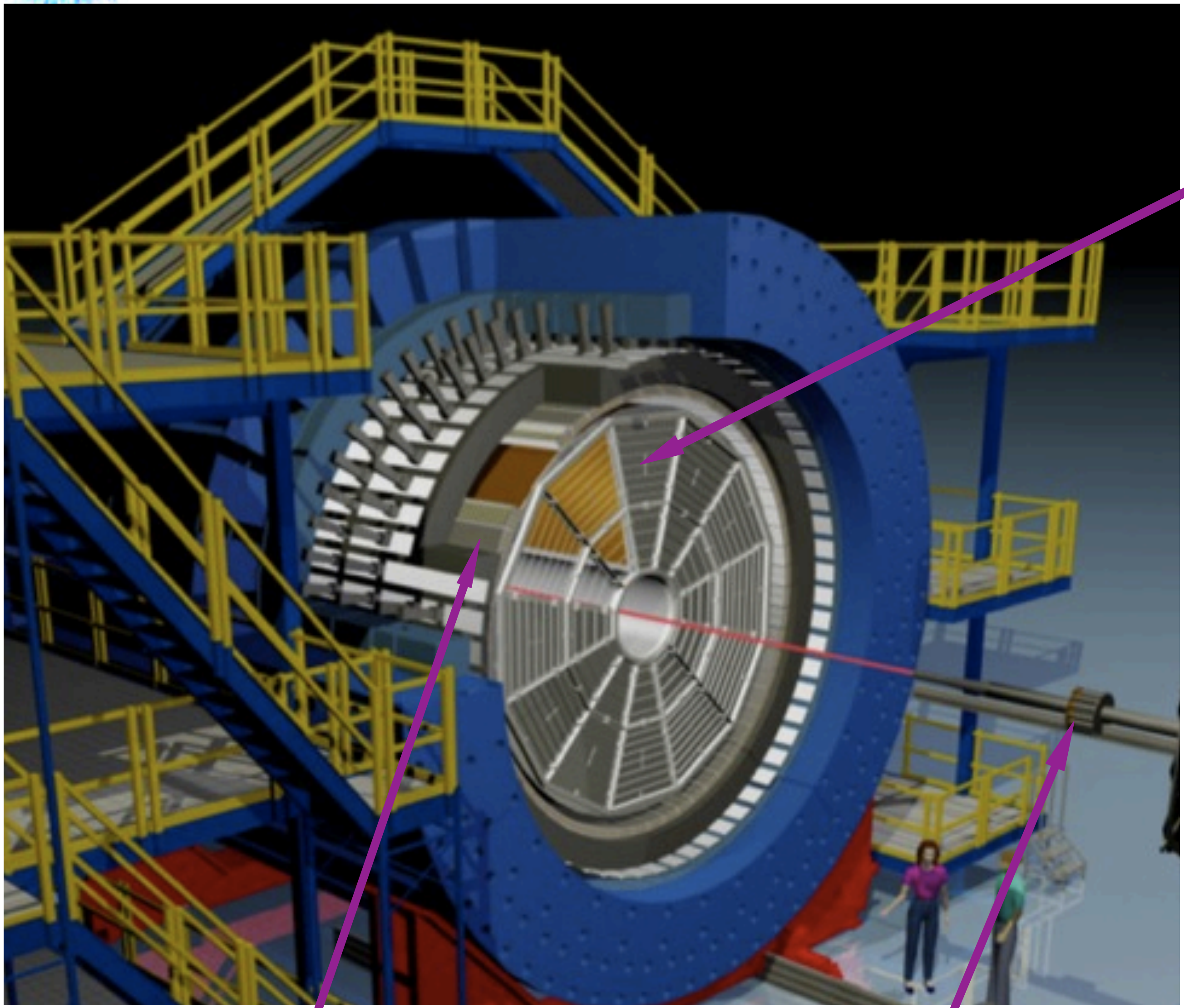


STAR White paper NPA 757, (2005) 102-183

$$N_i = V g_i \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

- **Relativistic Heavy Ion collisions :**
  - **High antibaryon density**
  - **High temperature**
- **Favorable environment for both production mechanisms.**

STAR detectors



Time Projection Chamber (TPC) - momentum & dE/dx

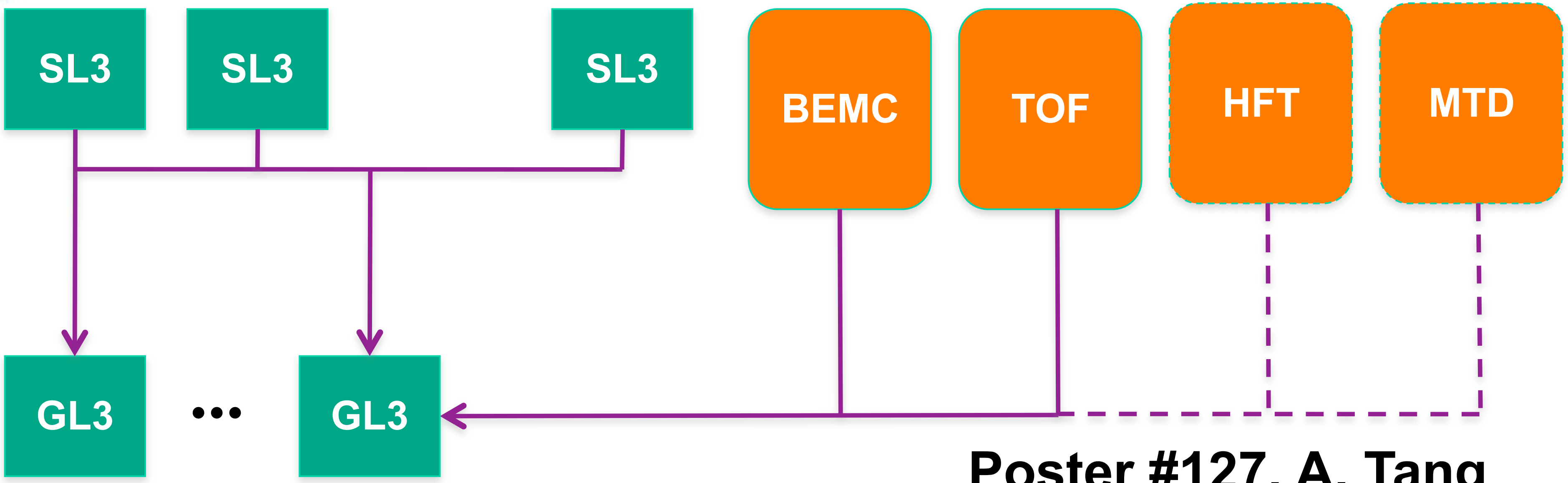
Online High Level tracking Trigger (HLT) - Select events with charge-2 tracks

TOF - stop time measurement

VPD - start time measurement

- 2007 AuAu 200GeV (TPC).
- 2010 AuAu 200GeV and 62GeV selected by HLT (TPC +TOF).
- One billion AuAu collisions.

STAR high level trigger



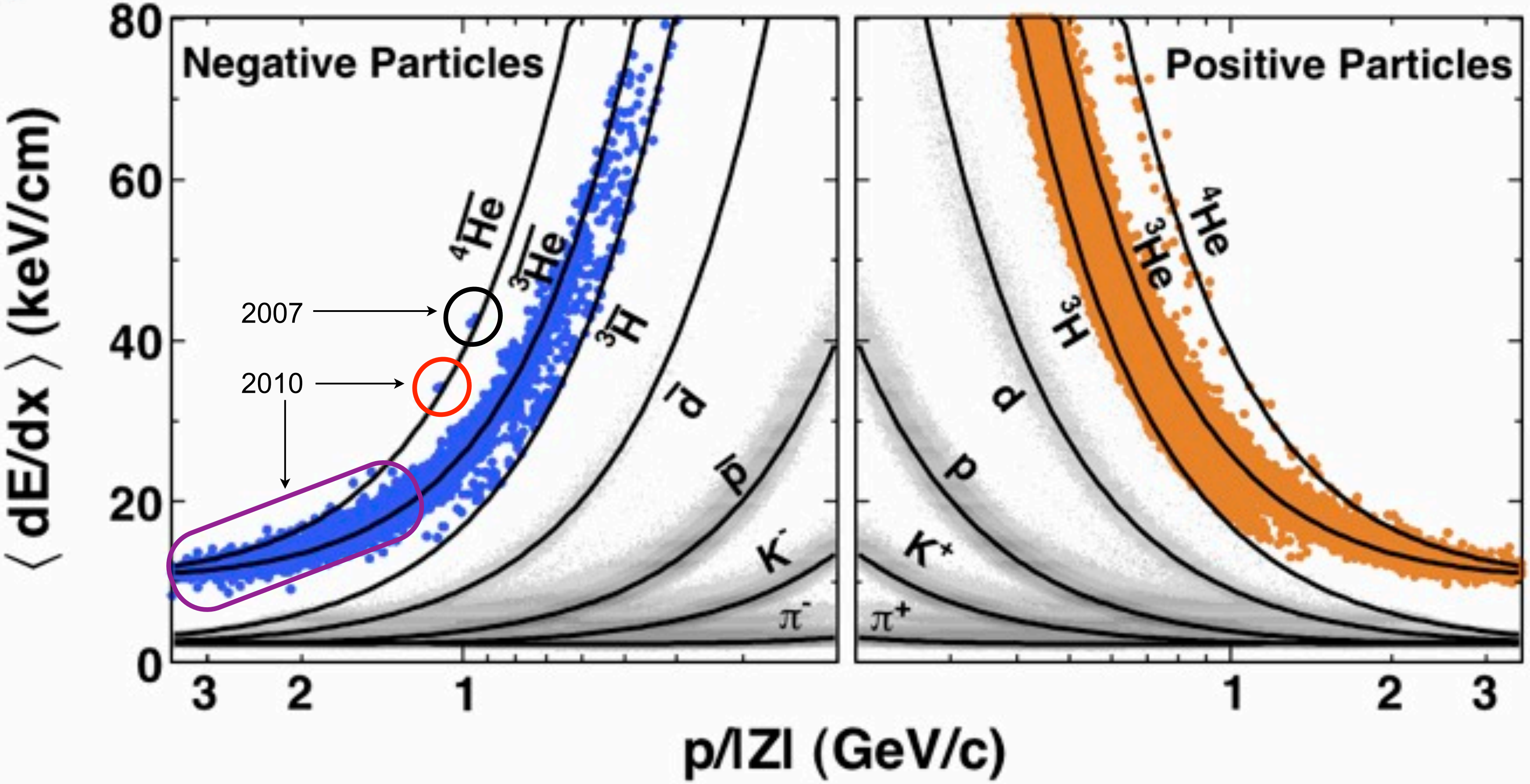
Poster #127, A. Tang

- Sector level 3 (SL3).
  - 24 in total, each for a TPC sector.
  - data acquisition.
  - hit reconstruction.
  - online sector tracking

- Global level 3 (GL3).
  - event reconstruction.
  - selecting events with charge-2 tracks.

- **~70% efficiency for events with charge-2 tracks, compared to offline reconstruction.**
- **Select ~0.4% of events.**

Particle identification



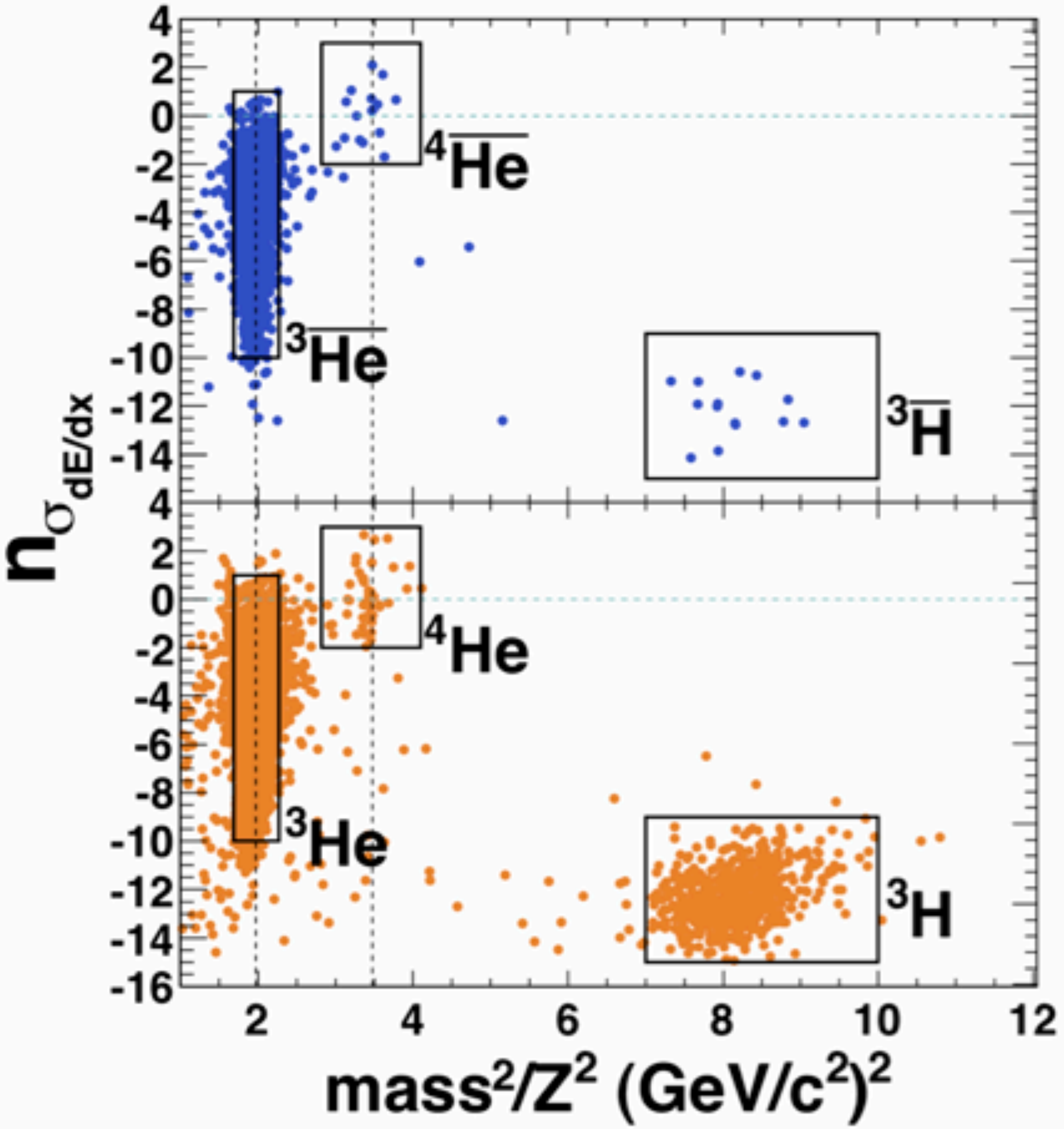
$$n\sigma_{dE/dx} = \frac{1}{R_{dE/dx}} ln(\frac{< dE/dx >^{measured}}{< dE/dx >^{expected}})$$

$R_{dE/dx}$ ~ 7.5%

H. Bichsel, Nucl. Inst. & Meth. A. 562 (2006) 154

- **2 counts from year 2007 are identified by TPC alone.**
- **dE/dx merge together at higher momentum region, TOF information is needed.**

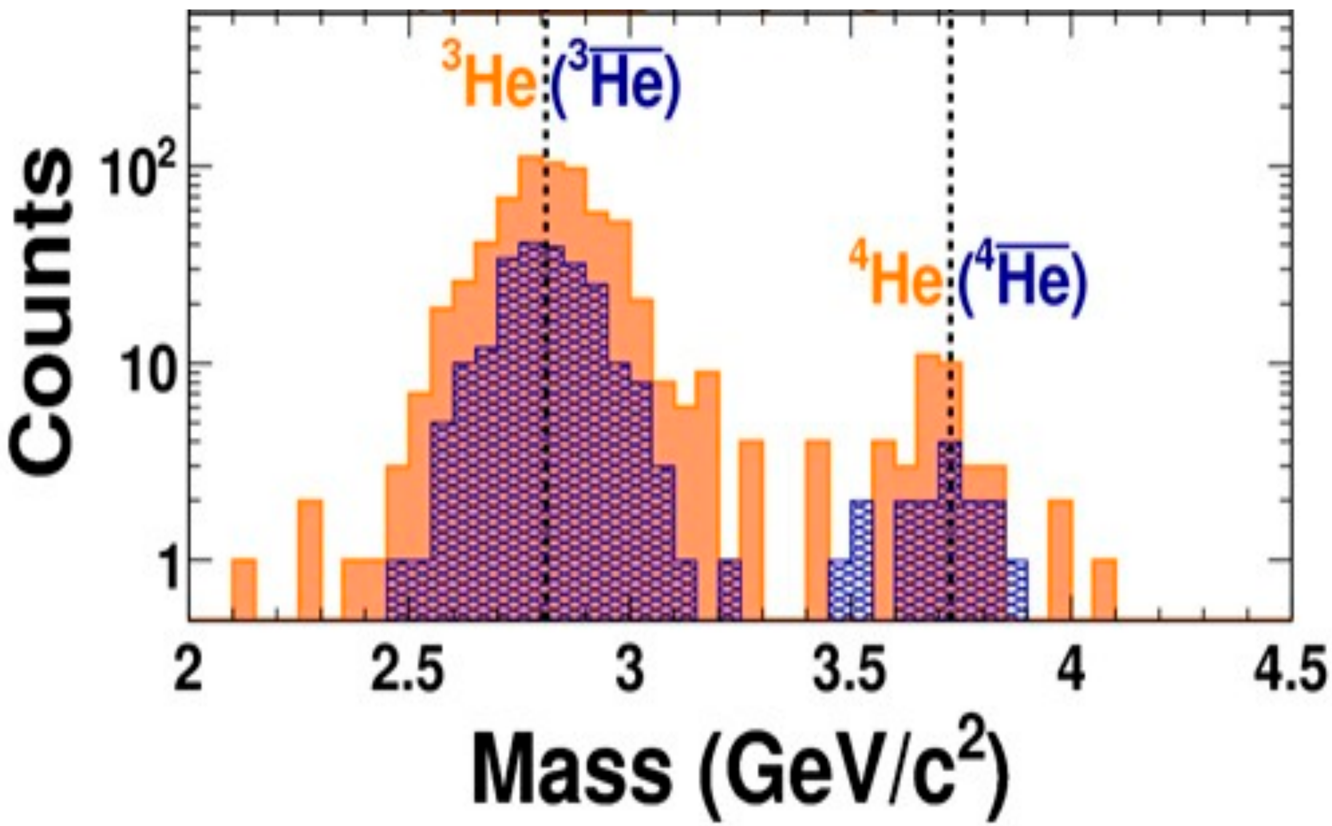
Particle identification



- TPC:
  - Track path length: L
  - Magnetic rigidity: $p/|Z|$
- TOF,VPD:
  - Time of flight: Δt
  - Velocity: $\beta = L/\Delta t$

$$m^2/Z^2 = p^2/Z^2(\frac{1}{\beta^2} - 1)$$

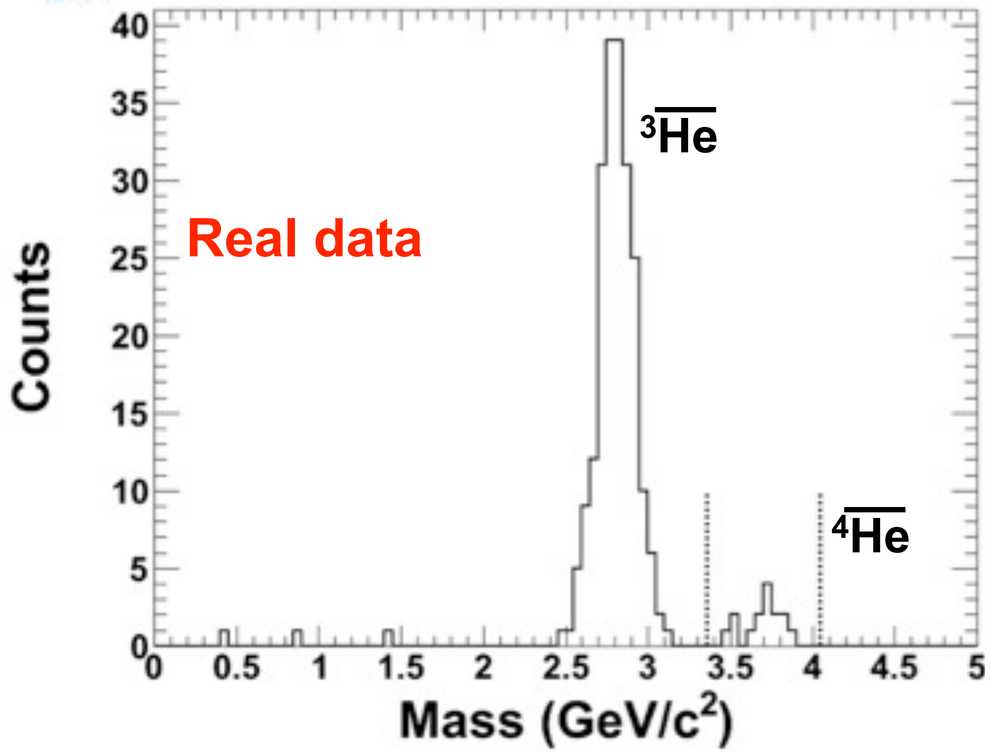
Particle identification

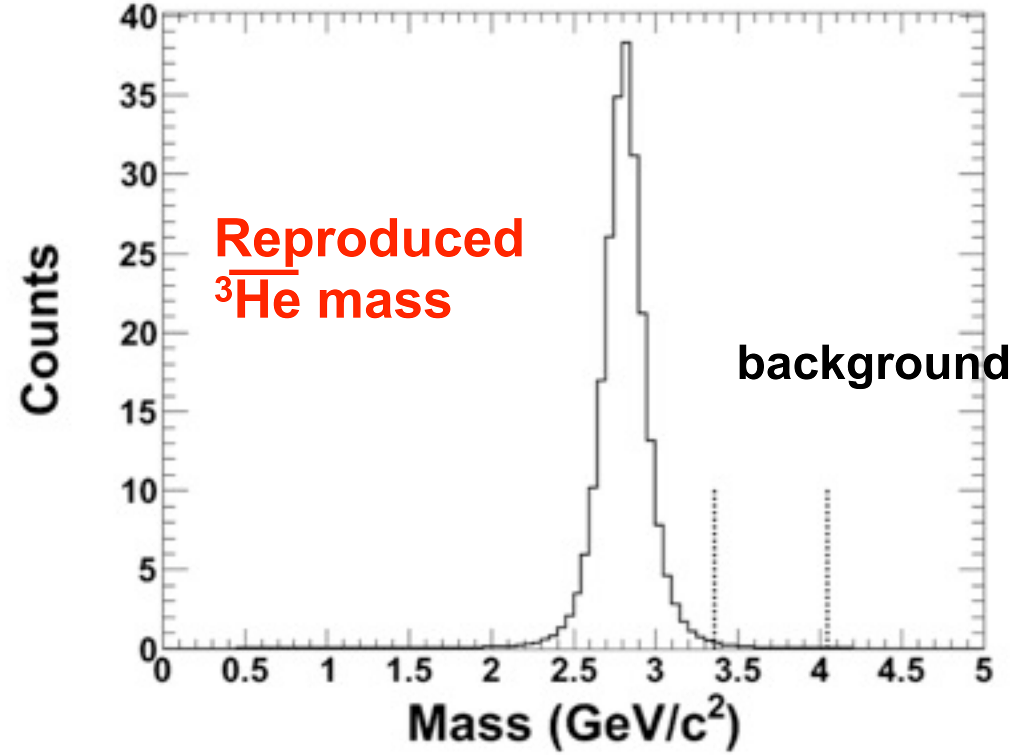


16+2 $^4\overline{He}$ counts in total.

- **An clean separation for $^3\overline{He}$ and $^4\overline{He}$ can be seen by projecting to mass axis.**
- **Candidates counted within the windows of, -2. $<n\sigma_{dE/dx}<$ 3., and, 3.35GeV/c^2 <mass< 4.04GeV/c^2.**

Background estimation





$$t^{expected} = l\sqrt{1. + m^2/p^2}, \quad t_A = t_A^{expected} + t_B - t_B^{expected}, \quad m_A = p_A\sqrt{(t_A^2/L_A^2 - 1)}$$

- $^3\overline{He}$ expands its mass distribution to $^4\overline{He}$ area because of TOF timing resolution, and , contributes to the backgrounds of $^4\overline{He}$.
- We reproduce $^3\overline{He}$ mass distribution using a "t" calculated with "$t_{expected}$"and time deviation (Δt) from other tracks.
- 1.4(0.05) backgrounds in 15(1) from 200GeV(62GeV) Au+Au collisions recorded in 2010.

➡ The miss-identification probability is ~10^{-11} (a significance more than 6σ).

Quality check for $^{4}\overline{He}$

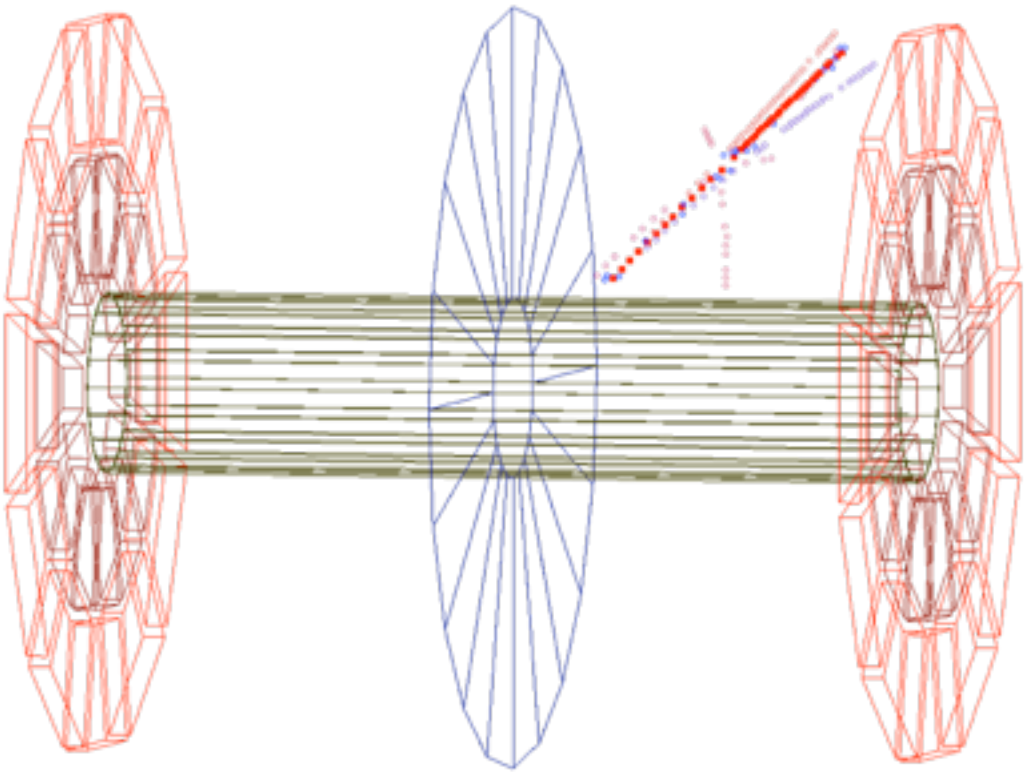
Anti-α track qualities and event display figures

Anti-α information:

- Run10 200GeV Au+Au collisions

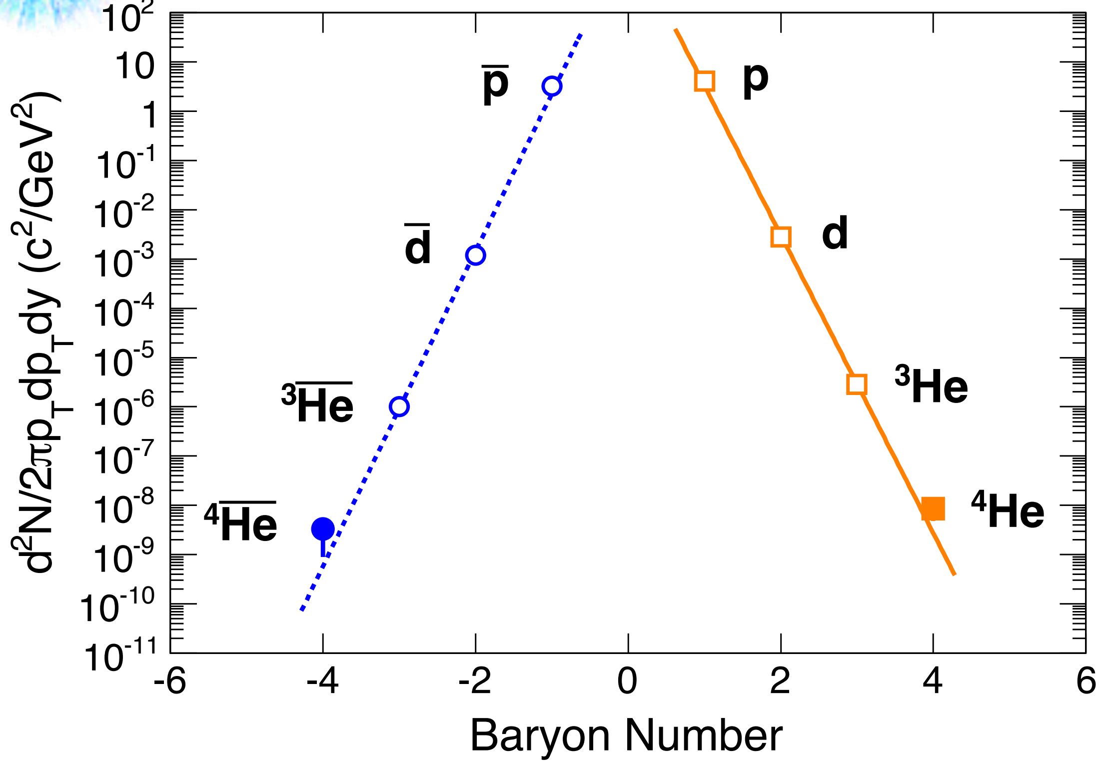
1. First anti-α candidate track qualities.

Global quality				TPC quality									TOF quality				
runID	evtID	vtxZ	RefMult	nHits	nHitsdEdx	p/|Z|	eta	phi	dca	L	chi2	$n\sigma_{4He}$	toflocalZ	toflocalY	tof	β	M
11073003	164108	-4.21	478	41	20	2.319	0.791	2.835	0.789	250.75	1.62	2.11	-0.92	-1.49	12.14	0.78	3.726



- Red dots highlights the $^{4}\overline{He}$ candidate.
- Hits and tracks within 5cm around the candidate are shown.
- Different colors stand for tracks with different magnitude of momentum.

$^4\overline{He}$ invariant yields



- An exponential trend is predicted by both coalescence and statistical model.
- Production rate reduce by 1.6×10^3 (1.1×10^3) for each additional anti-nucleon (nucleon) added to the anti-nucleus (nucleus).
- The yield of the stable antimatter nucleus next in line (B = -6) is predicted to be down by a factor of 2.6×10^6 compared to $^4\overline{He}$ and is beyond the reach of current accelerator technology.

Particle ratios:

- **Measured:**
  - **$^4He/^3He \sim (3.0\pm1.3(stat))\times10^{-3}$**
  - **$^4\overline{He}/^3\overline{He} \sim (3.2\pm2.3(stat))\times10^{-3}$**
- **Statistical model:**
  - **$^4He/^3He$ is ~ 3.1×10^{-3}**
  - **$^4\overline{He}/^3\overline{He}$ is ~ 2.4×10^{-3}**

Andronic, A. et al., Phys. Lett. B 697, 203 (2011)

$$E_A \frac{d^3N_A}{d^3p_A} \propto B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A$$

$$E_A \frac{d^3N_A}{d^3p_A} = \frac{gV}{(2\pi)^3} E e^{-m_p A/T}$$

R. Scheibl. PRC 59:1585, (1999)

E. Schnedermann. PRC 48, (1999), 2462

Antimatter search in the Universe

$^{4}\overline{He}$ in the Cosmos, hint of the existence of massive antimatter in the Universe.

Summary

- $^{4}\overline{He}$ were observed in AuAu collisions with data from year 2007 and year 2010. Considering the background, the probability of miss-identification is 10^{-11} (a significance more than 6σ).
- The invariant yields of ^{4}He and $^{4}\overline{He}$ were calculated with central events. An exponential trend was observed, consistent with the expectations from coalescence and thermodynamic models.
- Barring the dramatic discovery of heavier stable anti-nucleus in the Universe, or a new breakthrough in accelerator technology, it is likely that $^{4}\overline{He}$ will remain the heaviest stable antimatter nucleus observed in the foreseeable future .
- RHIC is an ideal antimatter production facility, and, with TOF and HLT, STAR is in a good position to study exotic nuclei production.

Thank you !

Back up

$^4\overline{He}$ counts

- 18 counts in total.
  - 15 from Run 10 Au+Au 200 GeV collisions
    5 minbias + 5 central with 1 tagged by both triggers
    6 from other triggers.
  - 1 from Run10 Au+Au 62 GeV collisions
  - 2 from Run7 Au+Au 200 GeV collisions

- In Run 10 200 GeV Au+Au collisions.

	Counts	Background	Significance
^4He	26	3.5	7.6
$^4\overline{He}$	15	1.4	6.5

$^{4}\overline{He}$ yields

- $^{4}\overline{He}/^{3}\overline{He}$ ratio is measured with Run10 200GeV central collisions.
- Using $^{3}\overline{He}$ invariant yields $dN/(2\pi p_T dp_T d\eta)$ from previous measurements to calculate $^{4}\overline{He}$ yields.
- p_T/A : 0.75 ~ 1 GeV/c
- ^{4}He: 5 $^{4}\overline{He}$: 2
- ^{3}He: 953 $^{3}\overline{He}$: 352

α/primary He3 : 3.0 +- 1.3 (stat) + 0.5 - 0.3 (sys) e-3

anti α/primary anti He3 : 3.2 +- 2.3 (stat) + 0.7 - 0.2 (sys) e-3

helium3	2.85e-06 ± 0.30e-6(stat) + 0.29-1.14e-06(sys)
anti-helium3	1.02e-06 ± 0.11e-06(stat) + 0.10-0.41e-06
helium4	8.6e-09 ± 3.8e-09(stat) + 0.9-2.8e-09(sys)
anti-helium4	3.3e-09 ± 2.4e-09(stat) + 0.5-0.9e-09(sys)

Miss-identification probability & Significance

- **The miss-identification probability can be calculated with Poisson distribution as bellow :**

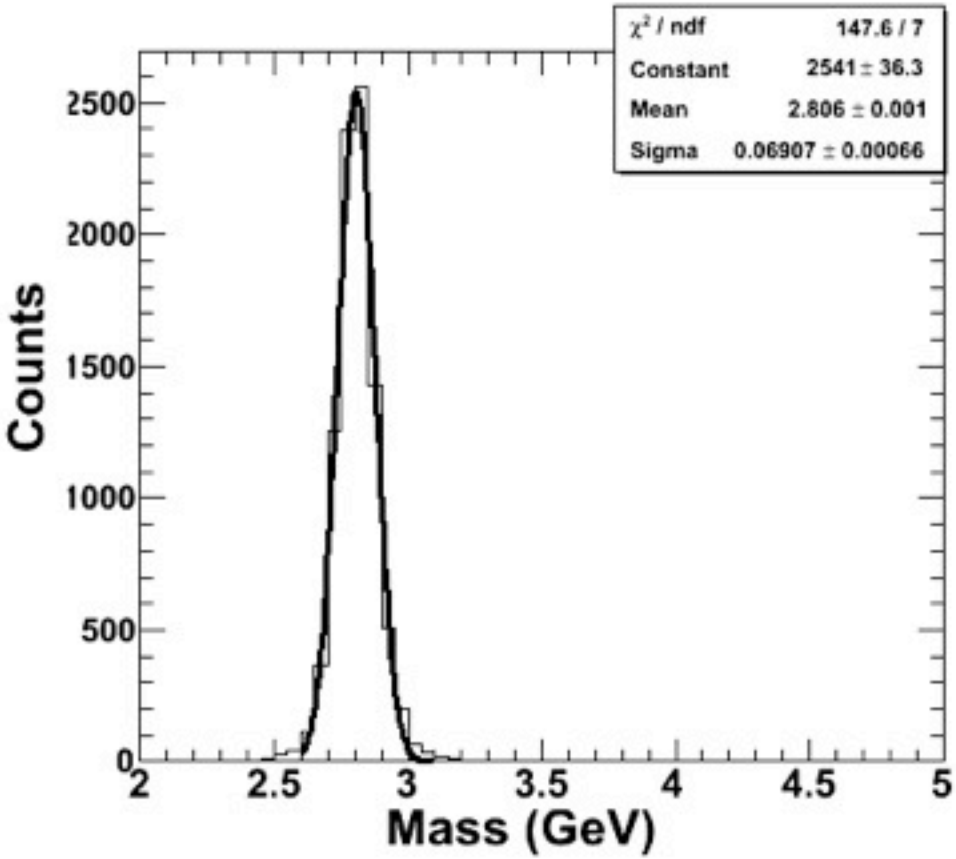
$$p = \frac{m^k}{k!} e^{-m}$$

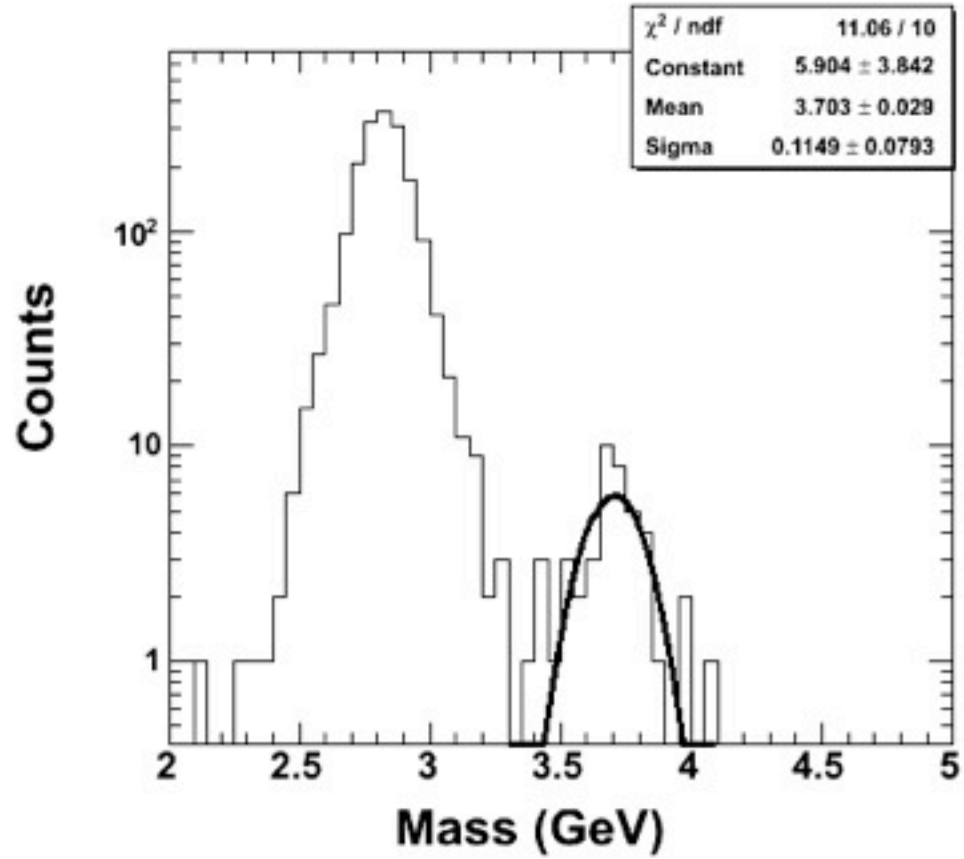
$$p(15/1.4) = \frac{1.4^{15}}{15!} e^{-1.4} \sim 3.0\text{x}10^{-11}$$

- **With the miss-identification probability, the significance "n" can be calculated with formula :**

$$P(x >= S + B) = \int_n^{+\propto} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \qquad n \sim 6.5$$

Mass resolution





$$m^2 = p^2(t^2/l^2 - 1)$$

$$m\delta m = p^2 t\delta t/l^2$$