

# In Pursuit of Knowledge and Wisdom

— My Story with Declan Keane



KENT STATE  
UNIVERSITY



Brookhaven  
National Laboratory

Aihong Tang, Keane Symposium,  
Kent State U., Dec.1-2 2023



# Back in the Day

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When I knew little but thought  
I was capable of anything ...

# Back in the Day

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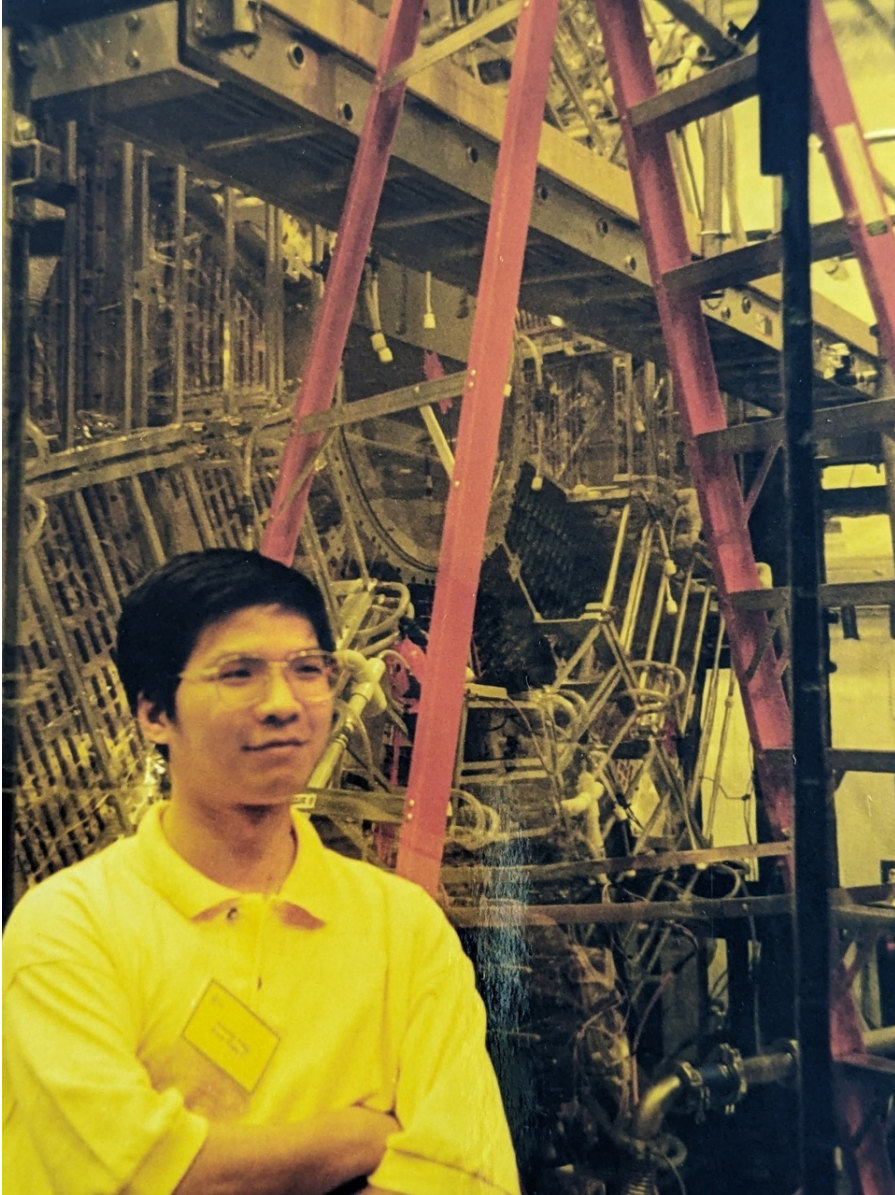


Lost and found in the RHIC tunnel ...



# Back in the Day

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Decided to be powered by  
“STAR”-bucks !

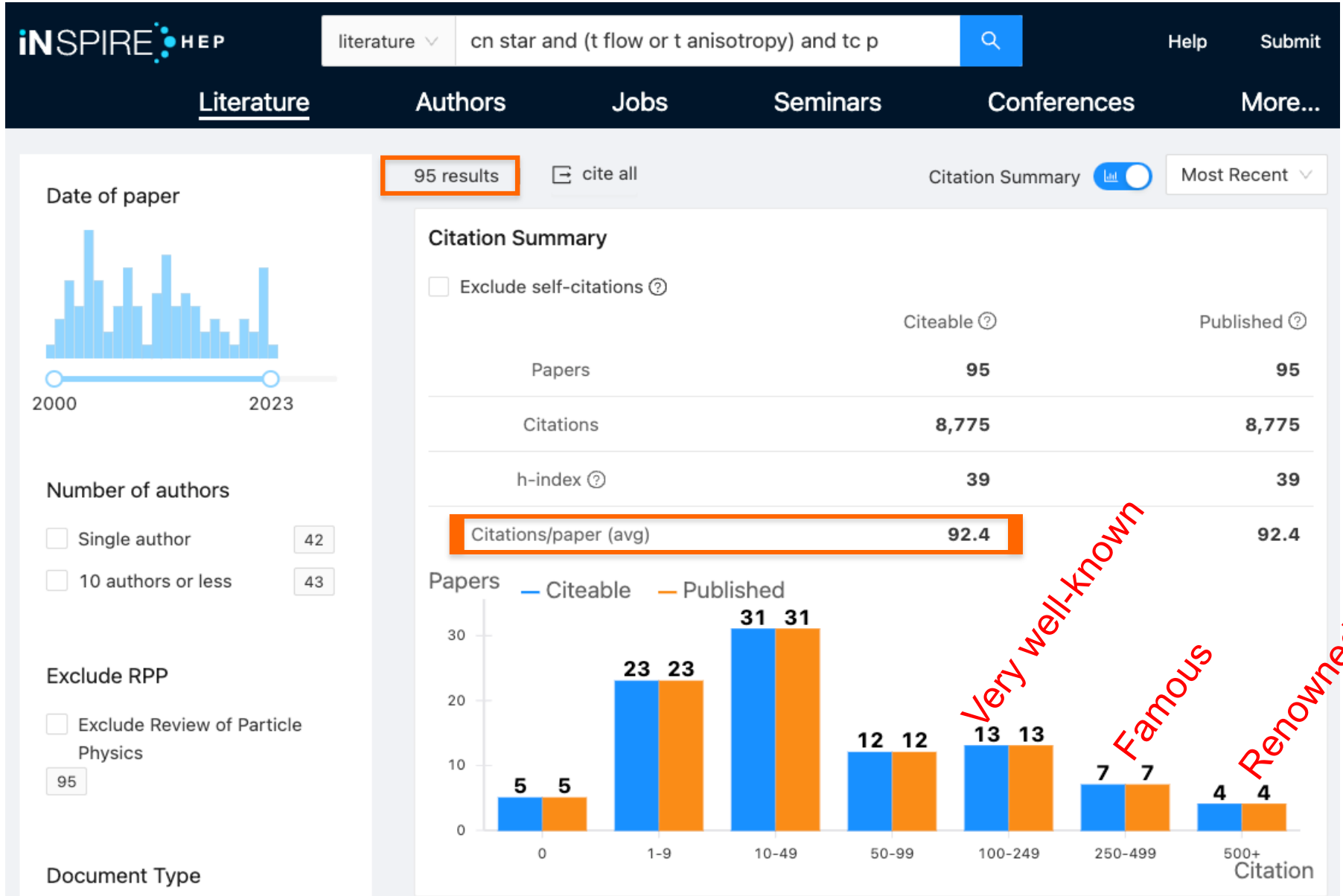


# Flow Dynamics

A large, curling blue wave with white foam, illustrating flow dynamics. The wave is captured from a low angle, showing its powerful, curling structure. The water is a deep blue, and the foam is bright white. The sky is a clear, light blue.

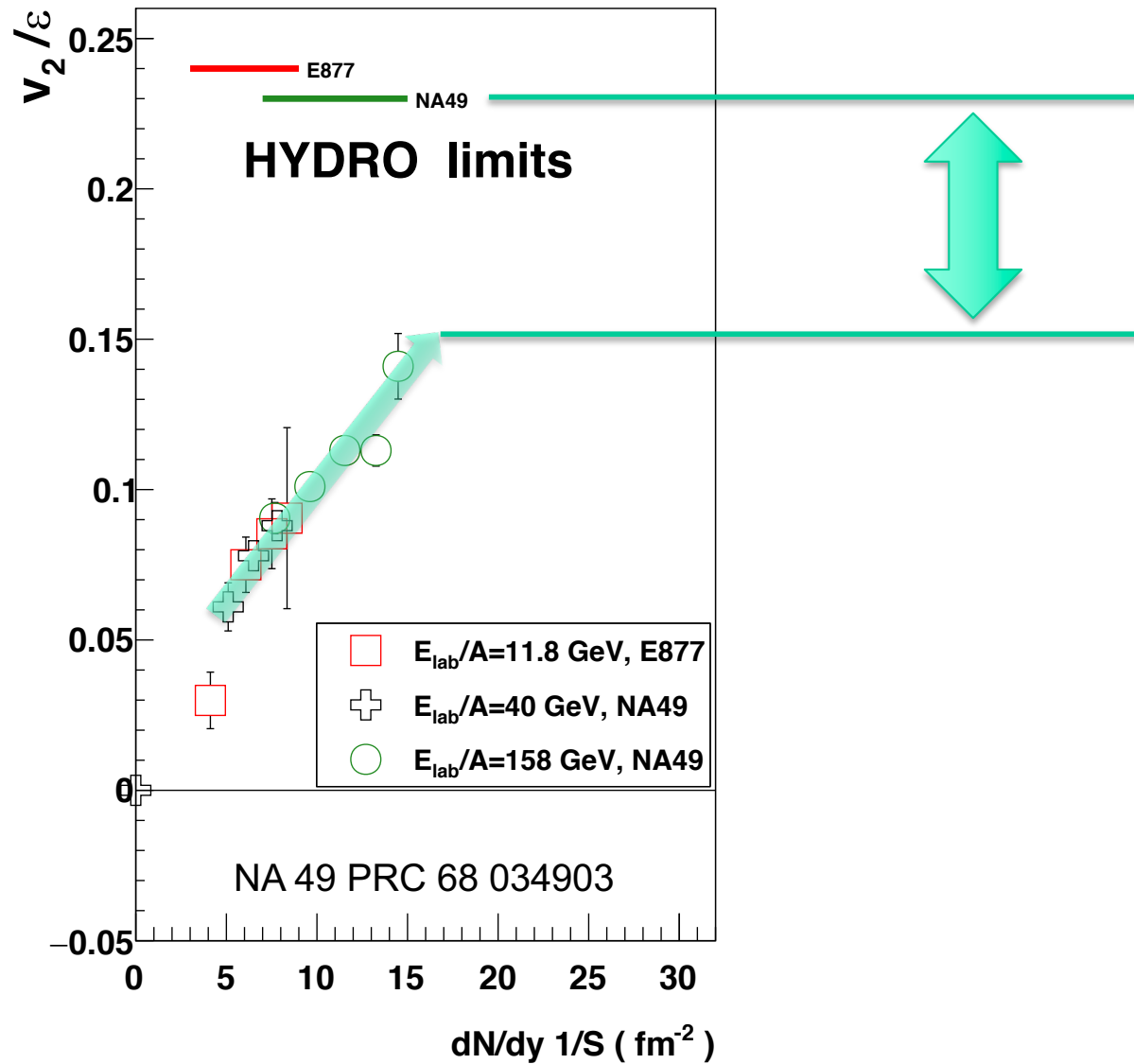


# STAR Flow Publications





# The March to Hydro

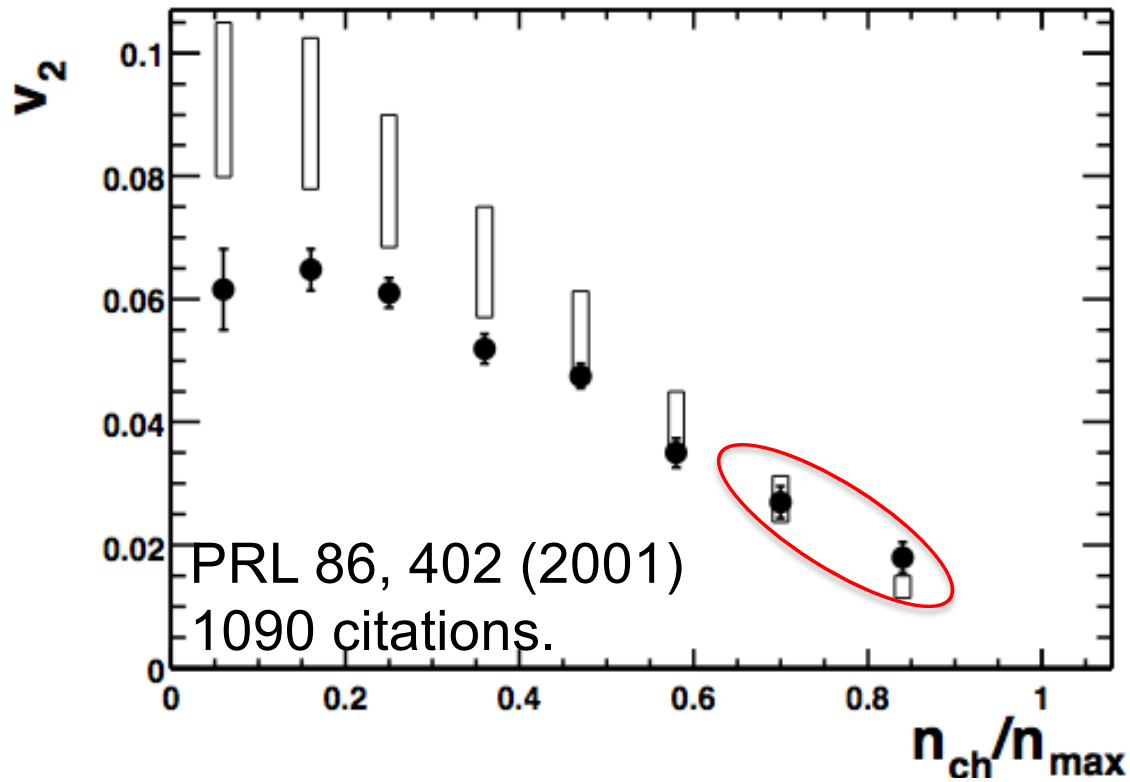




# The March to Hydro



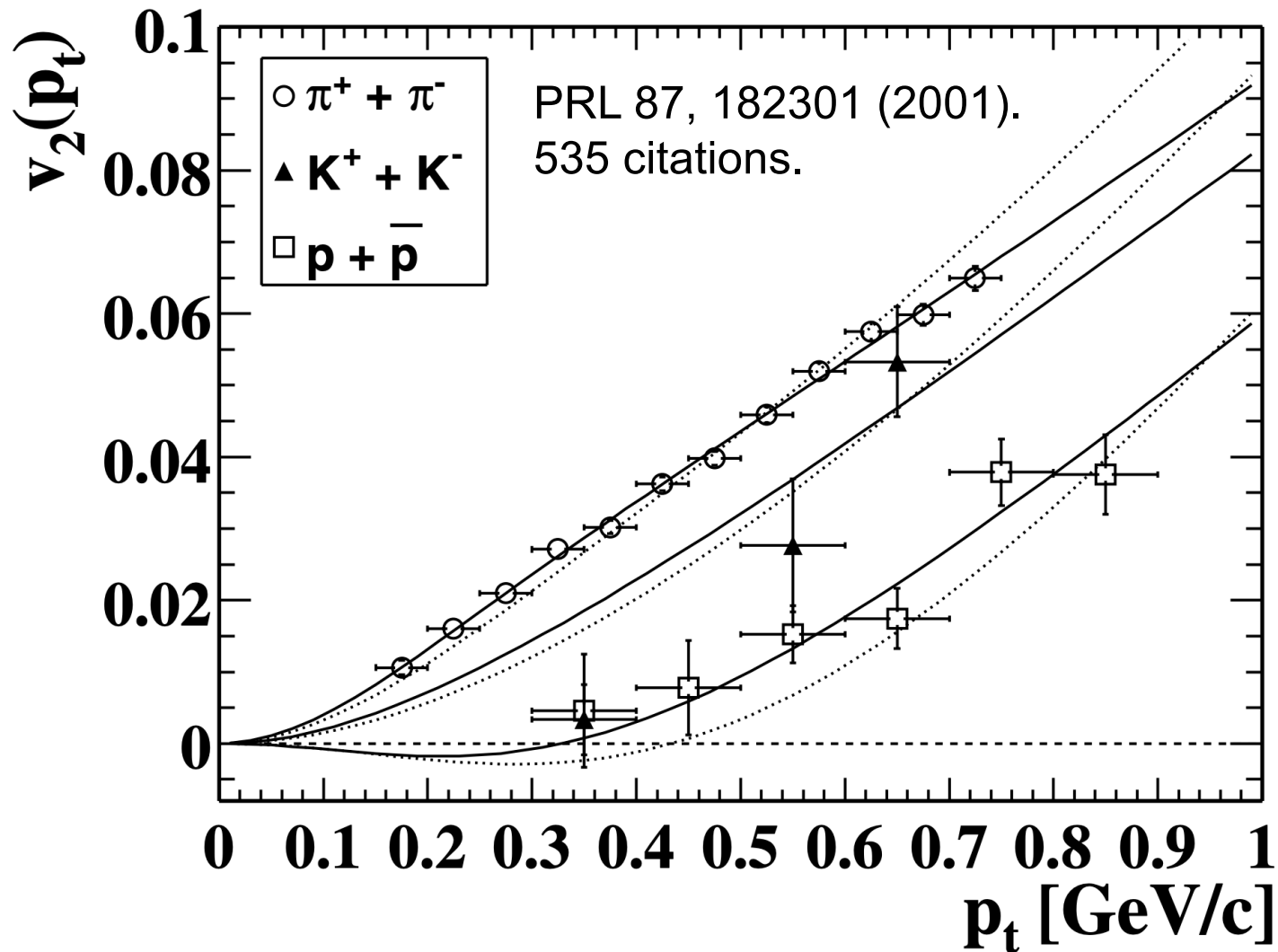
# The first sign of Hydro flow



Approaching Hydro for central collisions.



# Hydro flow in differential view



Mass splitting consistent with collective flow

# The nearly perfect liquid

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## New State of Matter Is 'Nearly Perfect' Liquid

By Sarah Graham

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.



Pin it

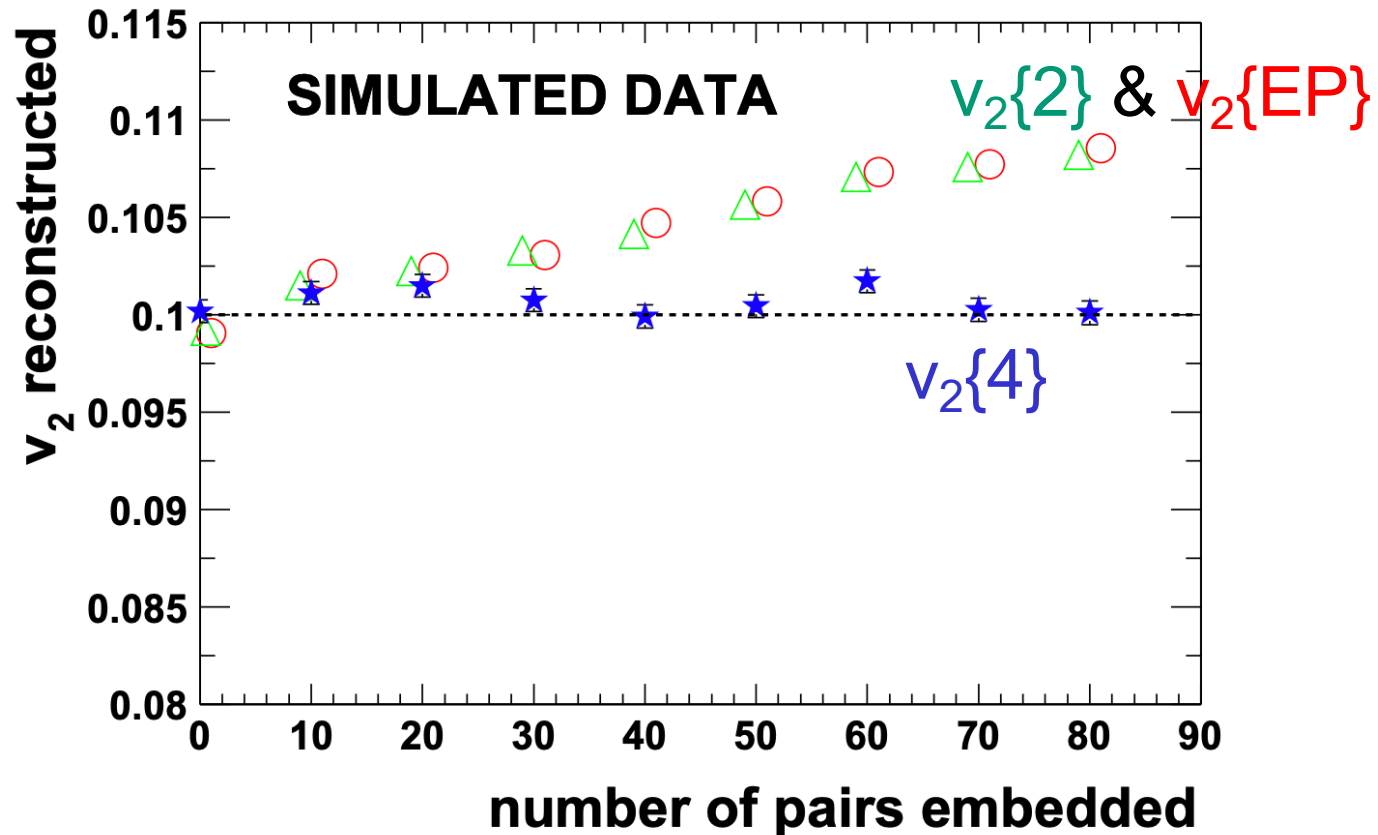
Image: BNL



# Not Everything Flows



# Nonflow and Cumulants

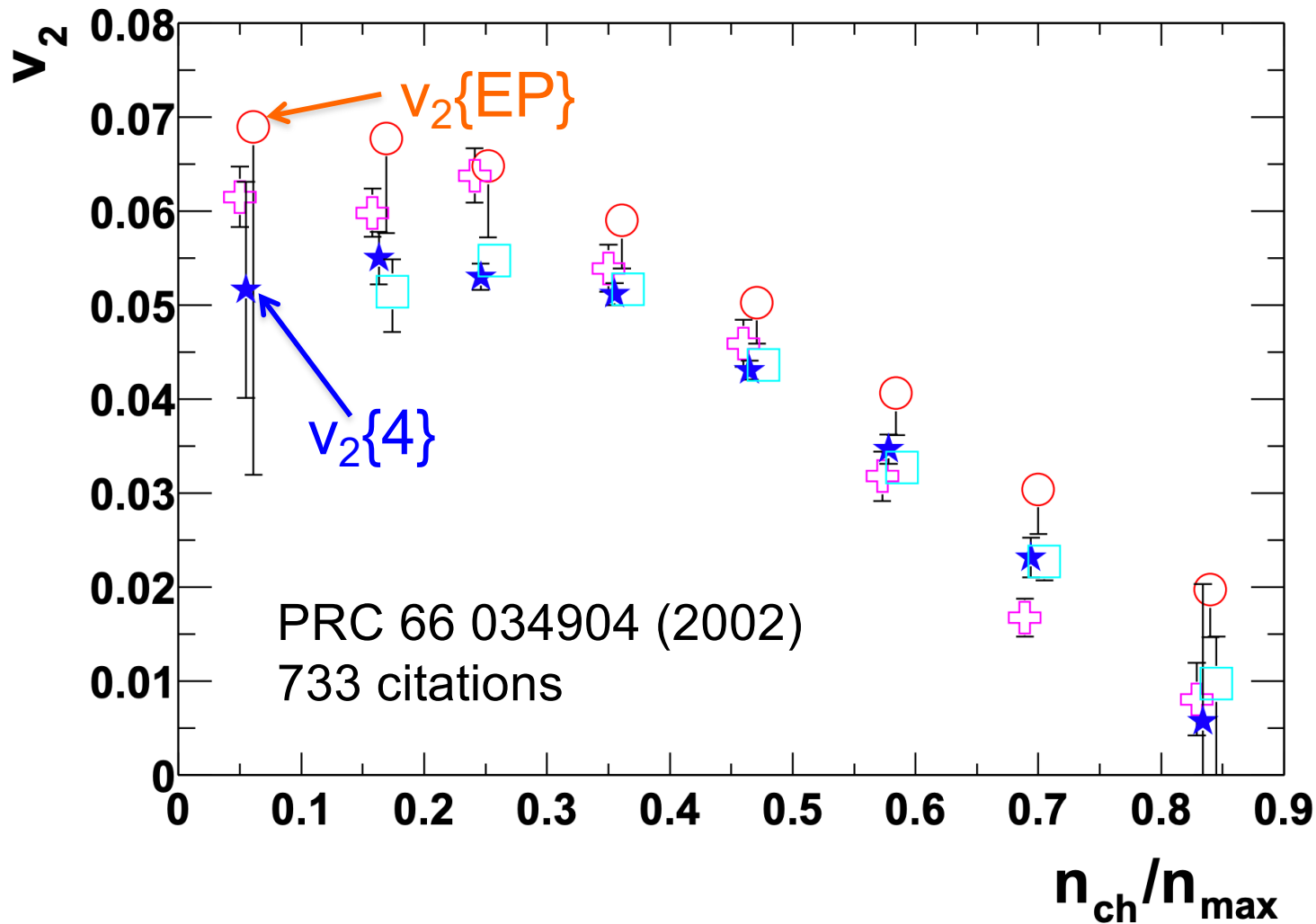


Borghini, Dinh and Ollitrault, PRC 63 054906 (2001) ...  
STAR PRC 66 034904 (2002)

Considerable nonflow in conventional flow method.  
Going for 4<sup>th</sup> order cumulants !

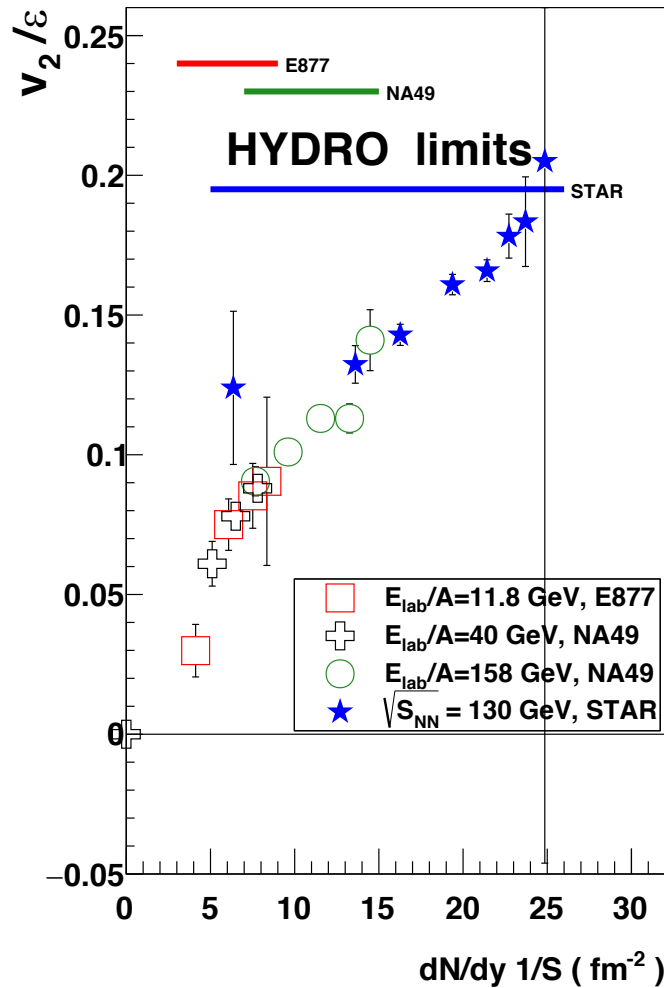


# Sharpen the flow probe



Considerable nonflow in conventional flow method.  
Going for 4<sup>th</sup> order cumulants !

# How close to Hydro ?



PRC 66 034904 (2002)  
733 citations

Eccentricity scaled  $v_2$  reveals important information on how data approaching Hydro limit



# The Strangelet



Aihong Tang. Keane Symposium,  
Kent State U., Dec.1-2 2023

---

# The Strangelet

## Review of Speculative “Disaster Scenarios” at RHIC

R.L. Jaffe<sup>a</sup>, W. Busza<sup>a</sup>, J. Sandweiss<sup>b</sup>, and F. Wilczek<sup>c</sup>

*a) Laboratory for Nuclear Science and Department of Physics  
Massachusetts Institute of Technology  
Cambridge, Massachusetts 02139*

*b) Yale University  
New Haven, Connecticut 06520*

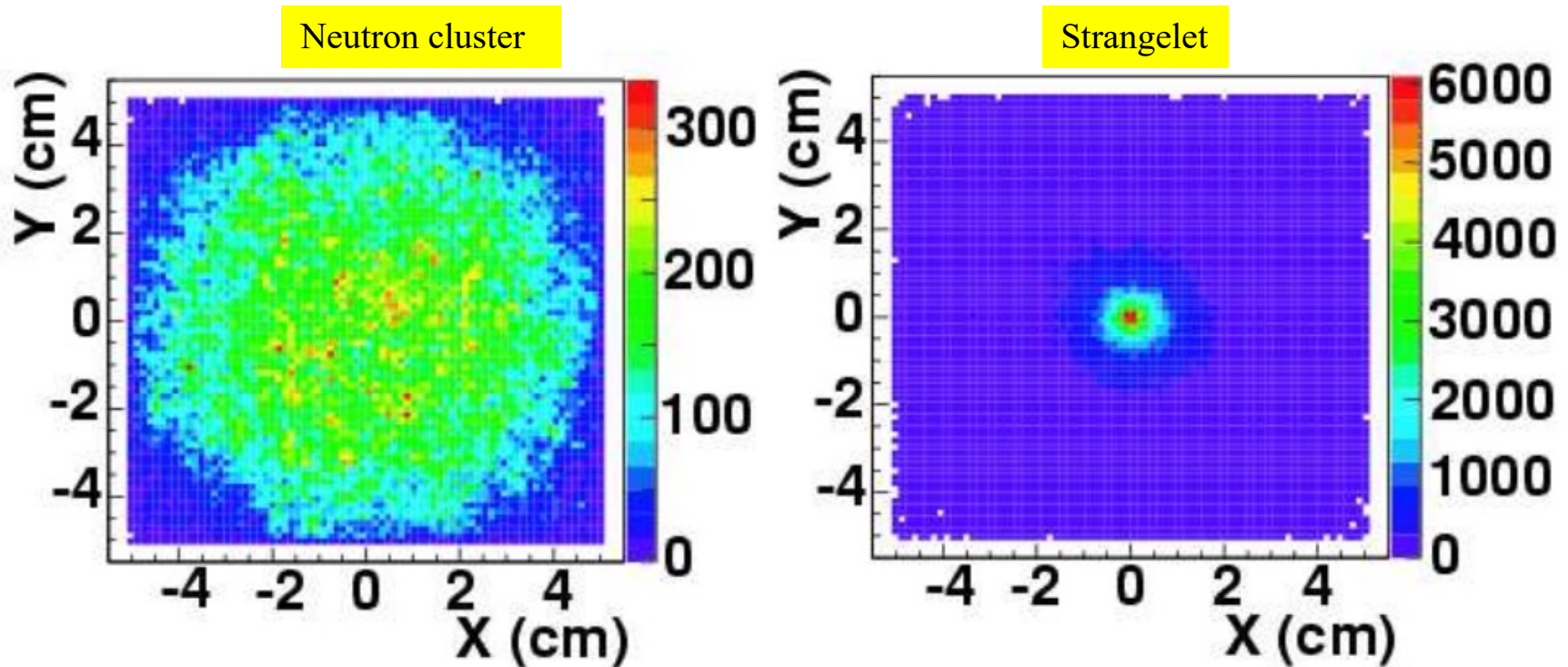
*c) School of Natural Sciences, Institute for Advanced Study  
Princeton, New Jersey 08540*

14 Jul 2000



# ZDCSMD and Strangelet Search

Geant simulation of a normal event and a strangelet event



With position sensitive ZDC, we can distinguish a strangelet event from neutron cluster  $\Rightarrow$  ZDC upgrade !

# A Shower Max Detector at ZDC for STAR

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version 2.5, November 4, 2003  
Revised December 2, 2003

## Proposed Addition of a Shower Max Detector to the STAR Zero Degree Calorimeters

Hank Crawford<sup>1</sup>, Declan Keane<sup>2</sup>, Spencer Klein<sup>3</sup>, Mikhail Kopytine<sup>2</sup>,  
Bernd Surrus<sup>4</sup>, Aihong Tang<sup>4,5</sup>, Sergei Voloshin<sup>6</sup>, Gang Wang<sup>2</sup>, Zhangbu Xu<sup>4</sup>

<sup>1</sup>*UC Berkeley Space Sciences Laboratory*

<sup>2</sup>*Kent State University*

<sup>3</sup>*Lawrence Berkeley National Laboratory*

<sup>4</sup>*Brookhaven National Laboratory*

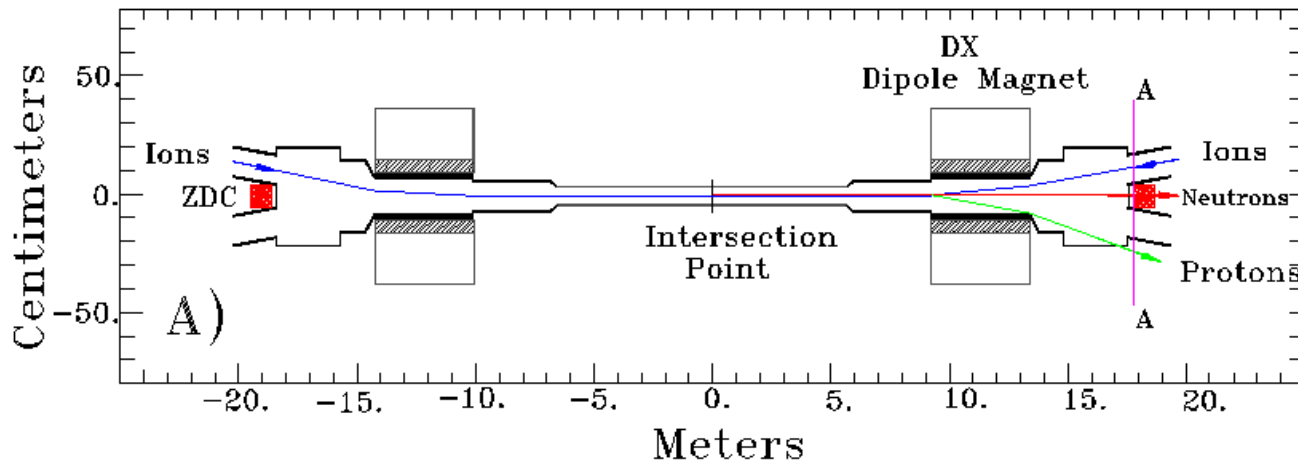
<sup>5</sup>*NIKHEF*

<sup>6</sup>*Wayne State University*

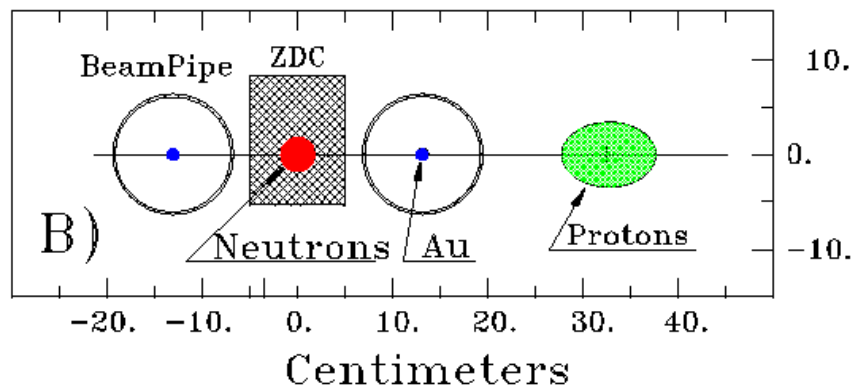
### I. EXECUTIVE SUMMARY

We propose the addition of a Shower Maximum Detector (one plane of 7 vertical slats and another of 8 horizontal slats) to the STAR Zero Degree Calorimeters, closely resembling the ZDC-SMD already used by PHENIX in RHIC run III. The SMD would add significant capability to STAR in four areas of physics: anisotropic flow, strangelet searching, ultra-peripheral collisions, and spin physics. The modest funding needed to implement this upgrade has been identified, and an ample manpower effort is available to complete the installation in time for RHIC run IV.

# A Shower Max Detector at ZDC for STAR



- STAR installed a shower max detector (SMD) between the first and second elements of the ZDCs at STAR during early run 2004.
- The SMDs measure the angular distribution of neutrons on the face of the ZDCs

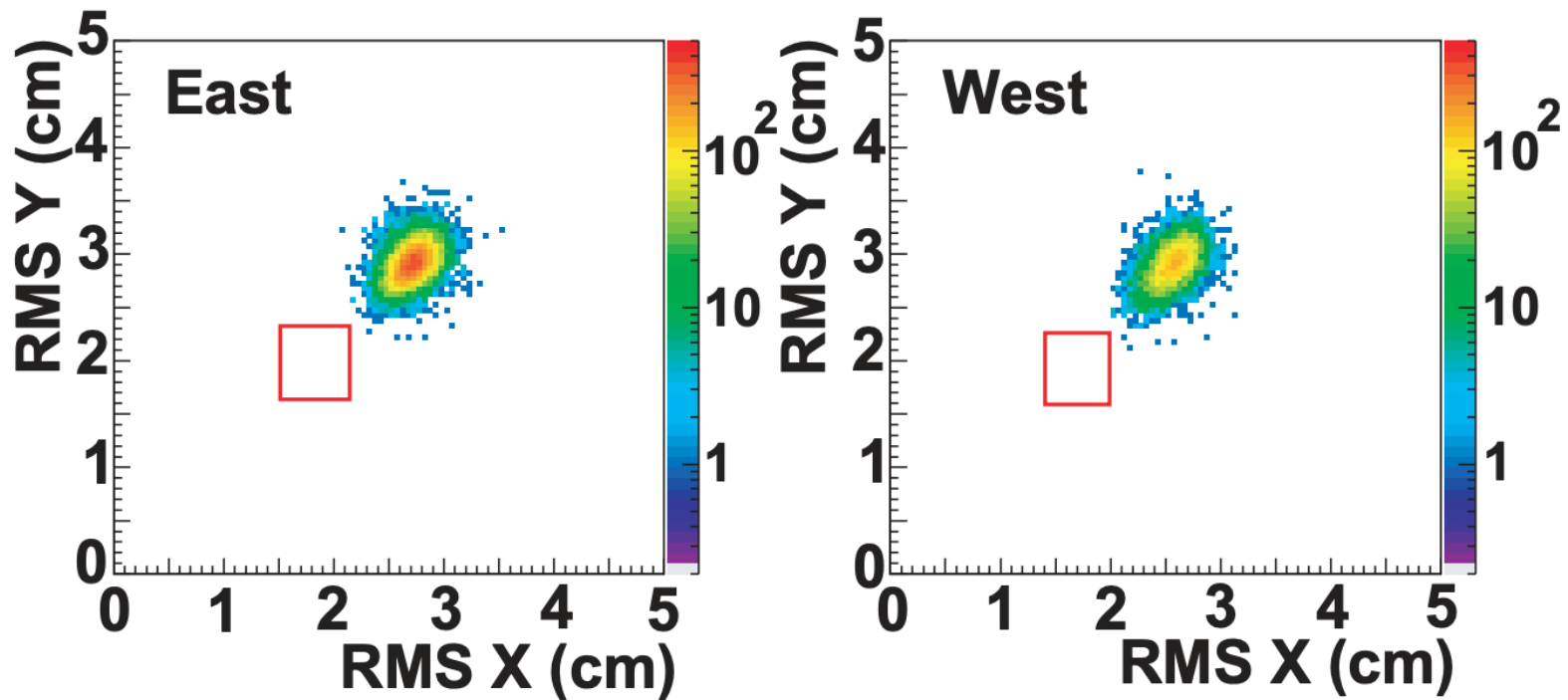


- It is a segmented scintillator detector lying in the path of the beam but coming after the DX magnets. 24 horizontal strips and 21 vertical strips.
- The SMD measures the shower profile inside the ZDC



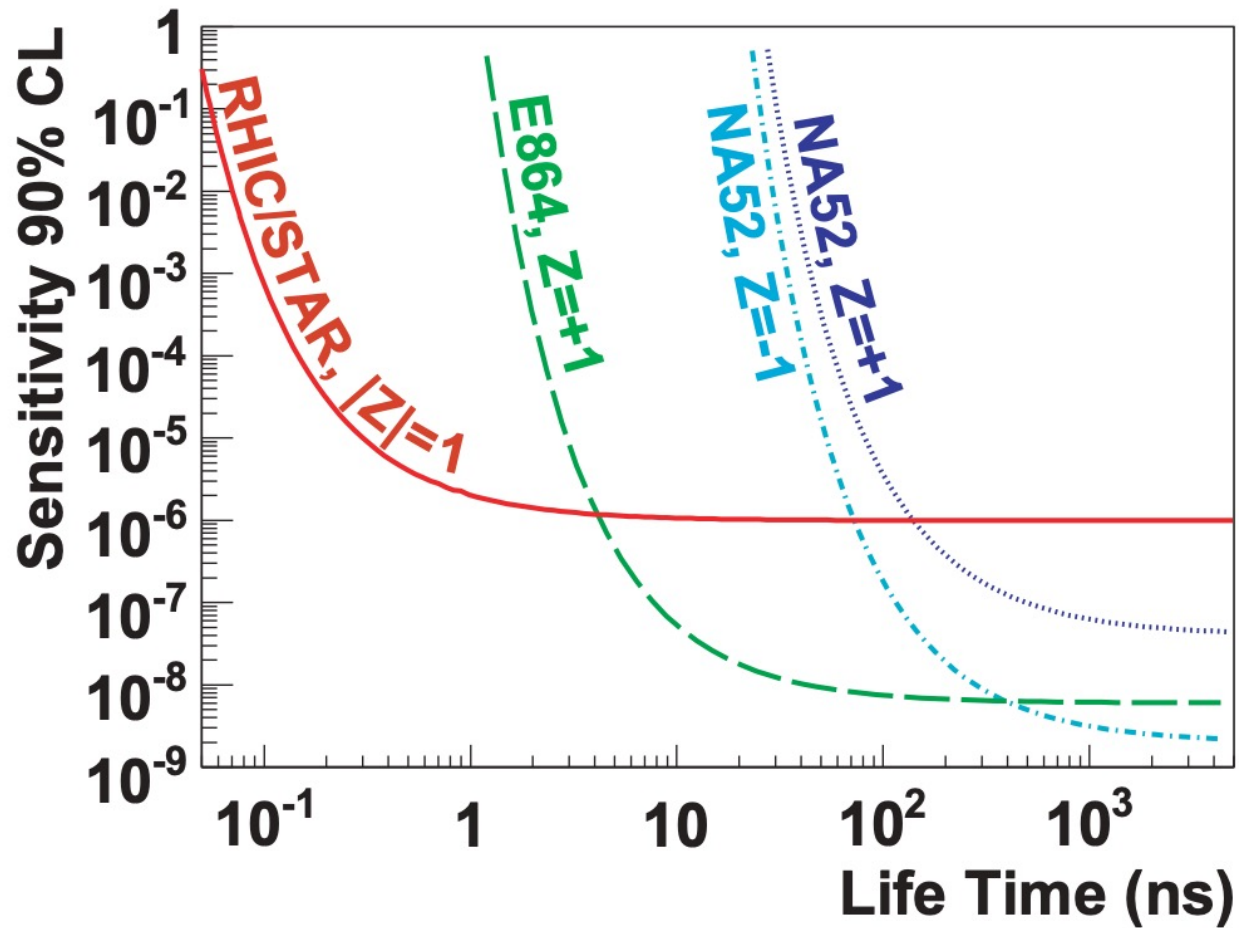
# Strangelet Search

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STAR, PRC 76, 011901 (R) (2007)

# Strangelet Search



STAR, PRC 76, 011901 (R) (2007)

# Antimatter

RHIC

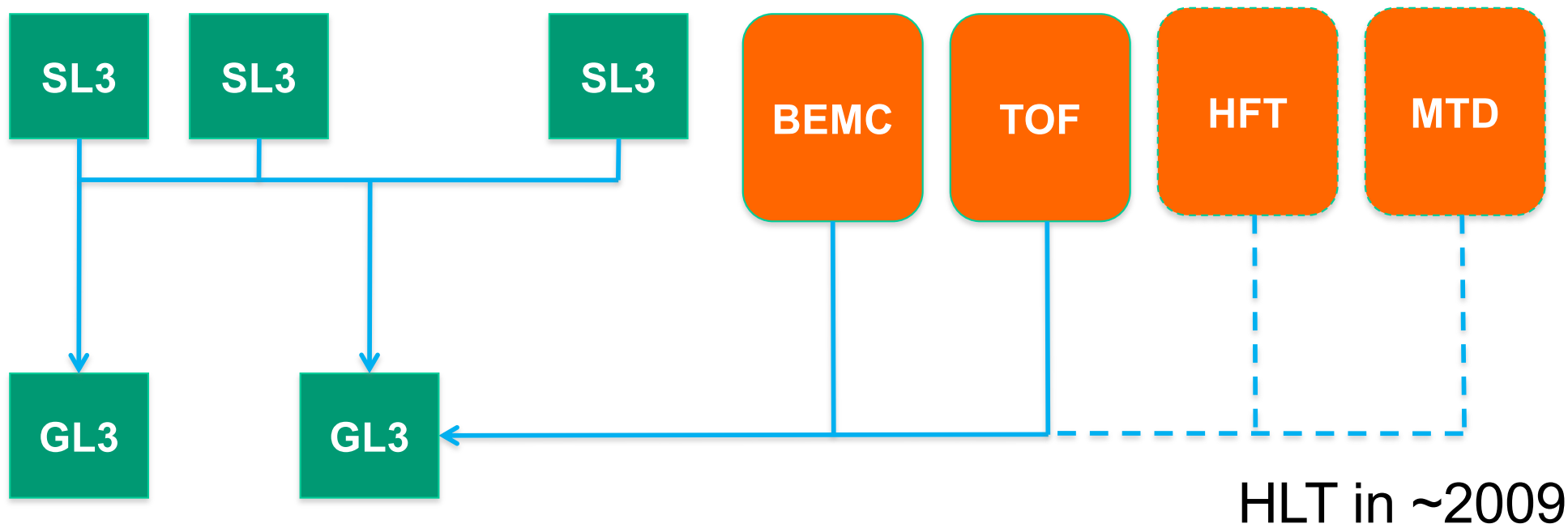


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# STAR's High Level online tracking Trigger (HLT)

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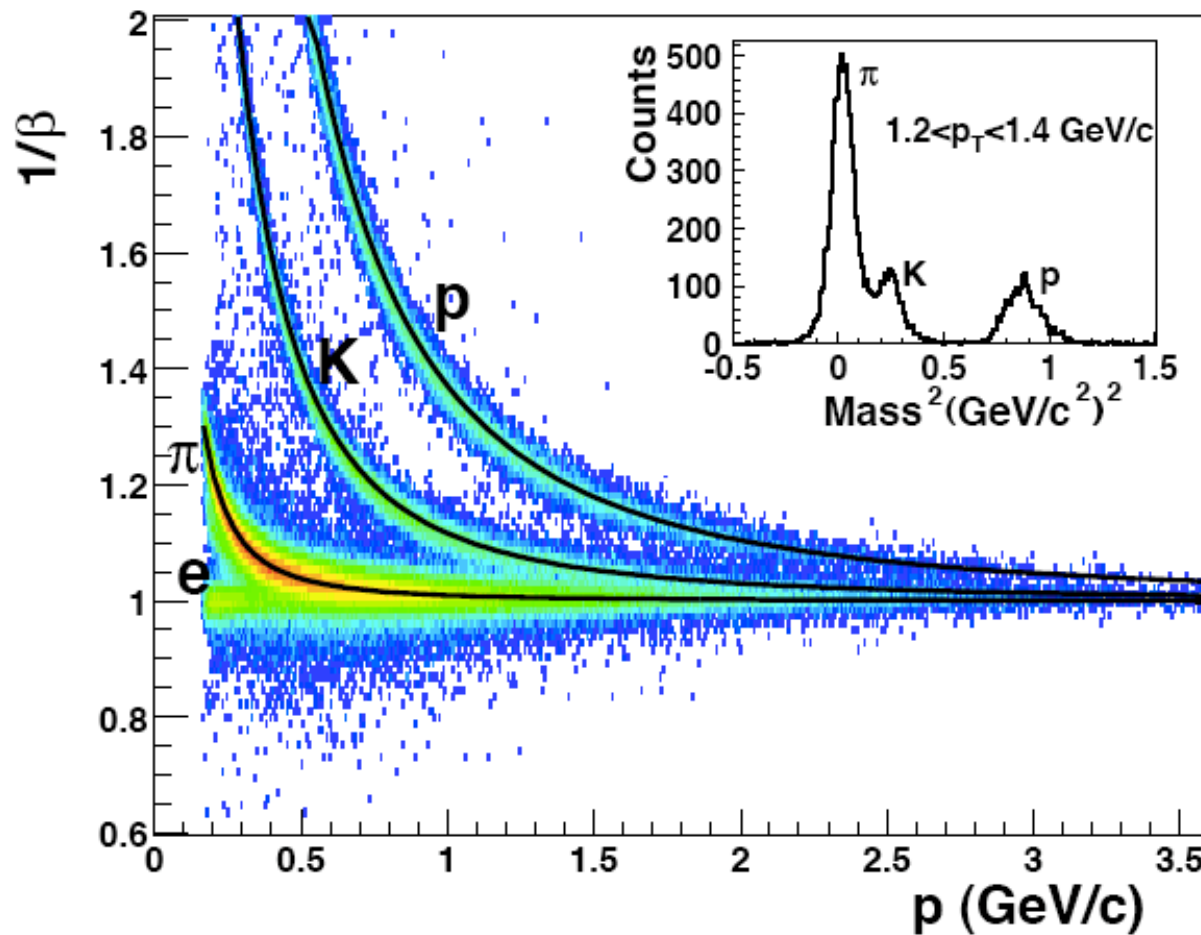


- Sector tracking (SL3) in DAQ machines (24 in total, each for a TPC sector).
- Information from subsystems (SL3 and others) are sent to Global L3 machines (GL3) where an event is assembled and a trigger decision is made.

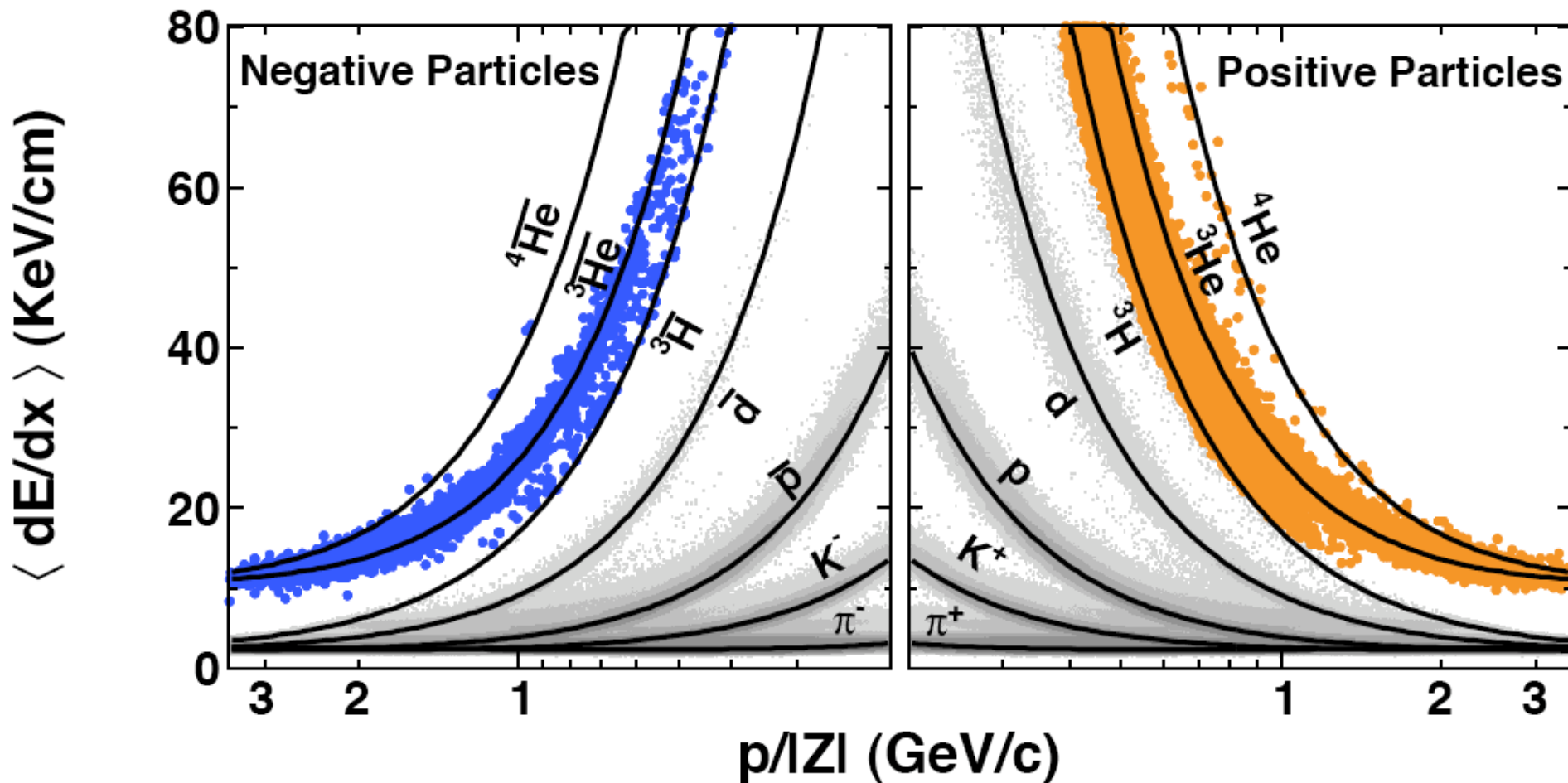
## Fast physics output with HLT

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# PID : TPC + TOF



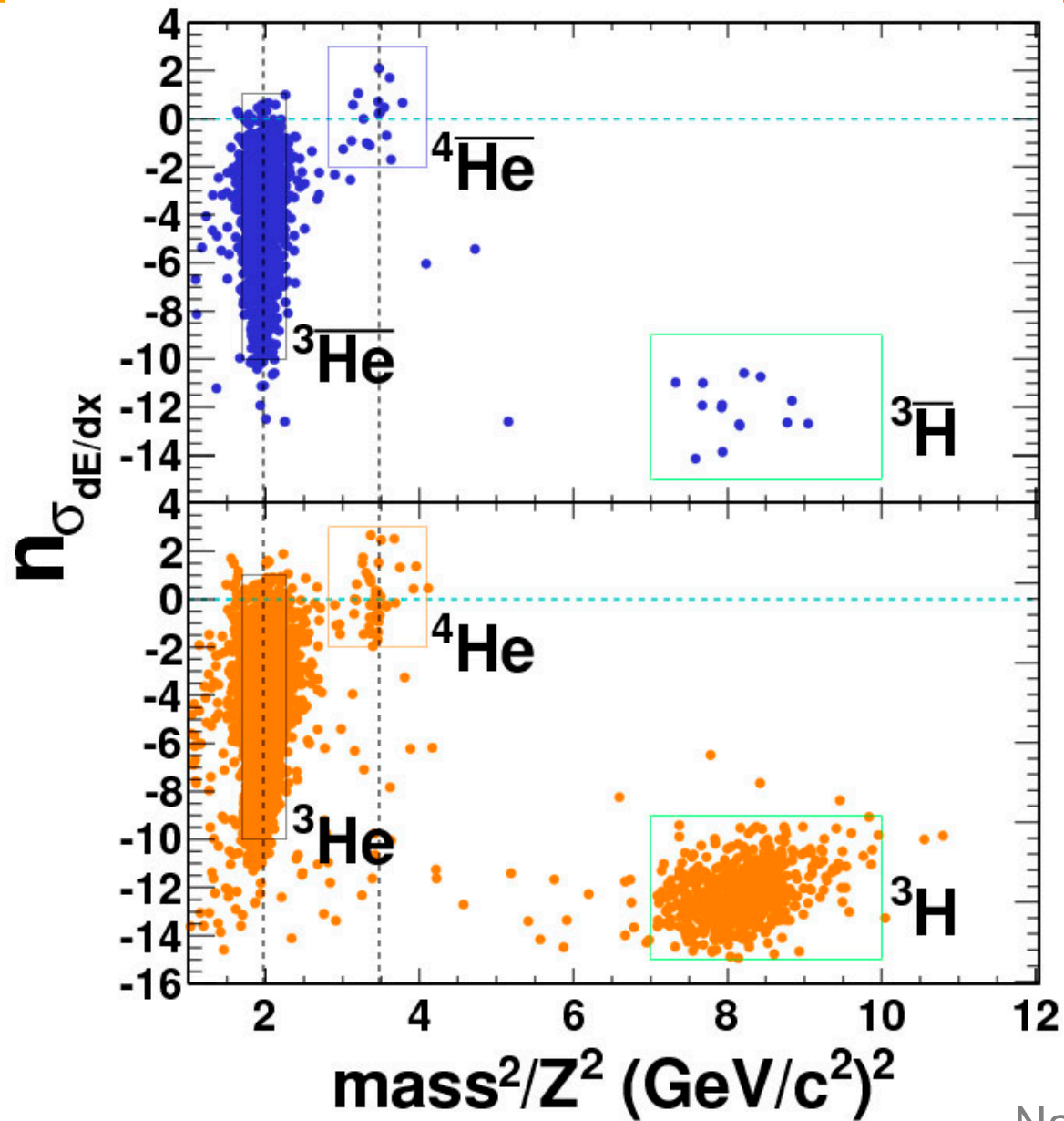
# dE/dx vs Rigidity



HLT has processing power to do rudimentary event reconstruction in real time, allowing events with a  $|Z| = 2$  track to be tagged and fast-tracked via the normal offline calibration & reconstruction chain.



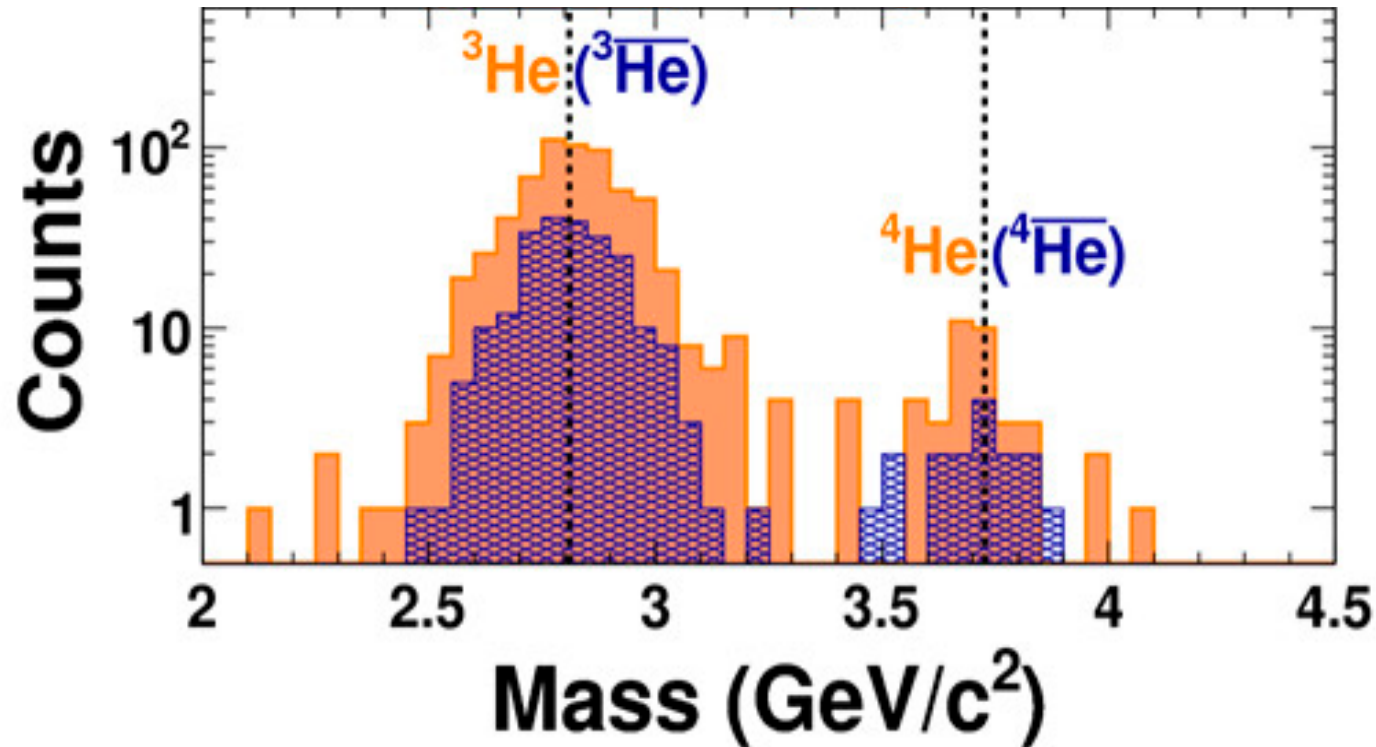
# Combined PID (TPC+TOF)



Nature 473 353 (2011)

# Combined PID (TPC+TOF)

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Very clean identification after search of > half-trillion tracks from almost one billion gold-gold collisions.

In total 18 counts observed.

Nature 473 353 (2011)

# News Coverage

IOP A website from the Institute of Physics

## physicsworld.com

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- 2011
  - April 2011
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- 2001
- 2000
- 1999
- 1998

### Heaviest ever antimatter

Mar 25, 2011 5 comments



The STAR detector

Physicists at the Relativistic Heavy Ion Collider (RHIC) have produced several nuclei of the heaviest antimatter yet.

### 宇宙探秘

## 宇宙探秘

yuzhoutanmi.cn

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## Discovery News

... has gone fishing.

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Discovery News > Space News > Antimatter

### ANTIMATTER GETS HEAVIEST

Analysis by Jennifer Ouellette  
Wed Mar 30, 2011 01:03 PM EST

### technology review

Published by MIT

English | en Español | auf Deutsch | in Italiano

### The Physics arXiv Blog

First Observation of the creation of 18 nuclei of energy physics.

## SCIENTIFIC AMERICAN

Winner of the 2011 National Magazine Award for General Excellence

### Antimatter of Fact: Collider Generates Most Massive Nucleus Yet

Collider has produced several nuclei of the heaviest antimatter yet.

Antimatter of Fact: Collider Generates Most Massive Nucleus Yet

Kent State

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### US scientists get glimpse of antihelium

Heaviest particles of antimatter seen in a lab survive for about 10 billionths of a second before crashing into collider's detector

Article history

Science correspondent

guardian.co.uk, Sunday 24 April 2011 17.59 BST

the production of 18 antinuclei of helium-4, the antimatter opposite of the common chemical element. This is a tremendous achievement and breakthrough in this branch of physics, analysts say.

Using data obtained from in-depth analysis of these nuclei could allow experts to understand why normal matter prevailed over antimatter shortly after the Big Bang, and why the Universe exists.

# 3 story by DISCOVERY magazine for the year 2011 under physics and math



# Synergy with Major Scientific Anniversary

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Year 2011 : the 100<sup>th</sup> anniversary of Rutherford's  $\alpha$  particle scattering experiments which marked the dawn of modern sub-atomic physics.

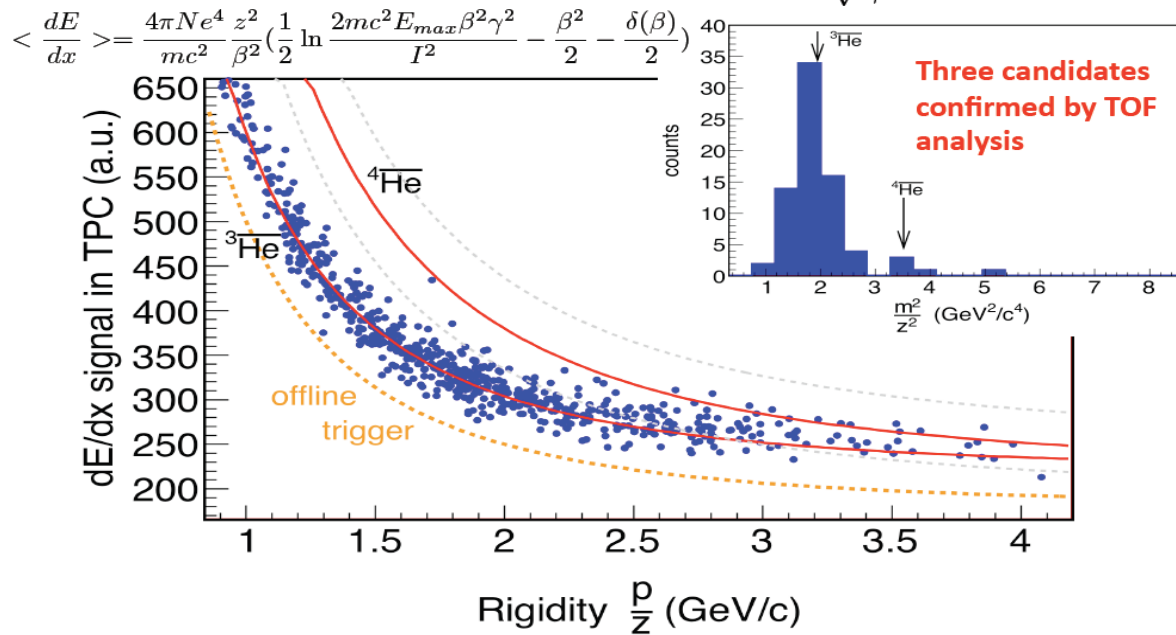
1911 : Rutherford used  $\alpha$  + gold to discover the nucleus;  
2011 : RHIC used gold + gold to discover the anti- $\alpha$ .

# The Competition



## Anti-Alpha candidates in Pb-Pb

Time of flight (sensitive to  $m/z$ -ratio):  $m = \frac{z \cdot R}{\sqrt{\gamma^2 - 1}}$



STAR :

Paper submitted to Nature on March 14<sup>th</sup>, 2011

Posted on arXiv on March 16<sup>th</sup>

Alice :

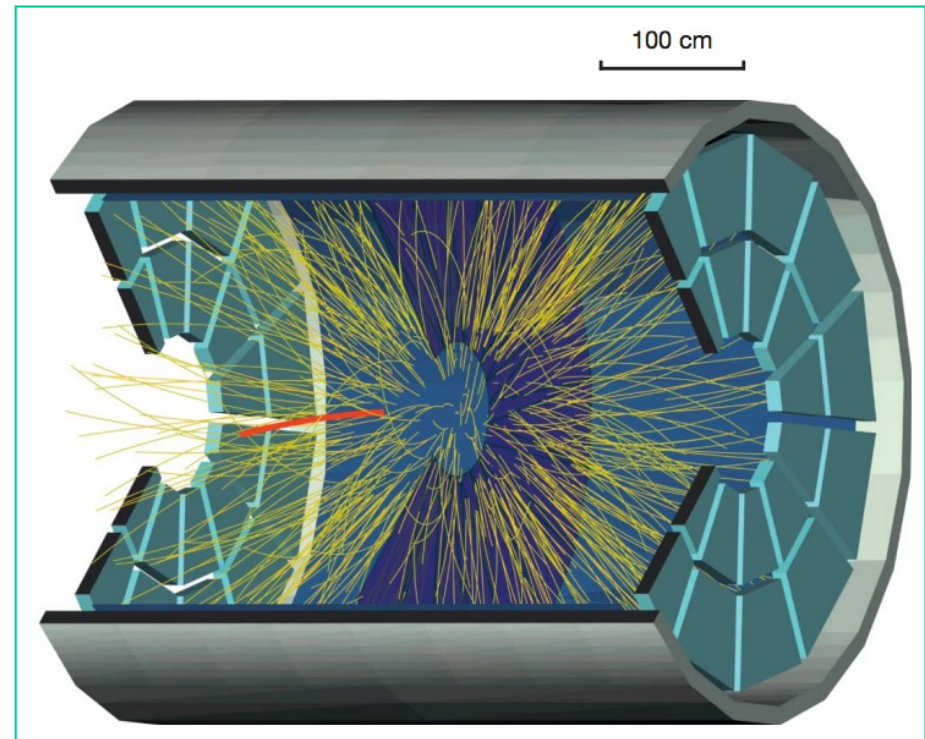
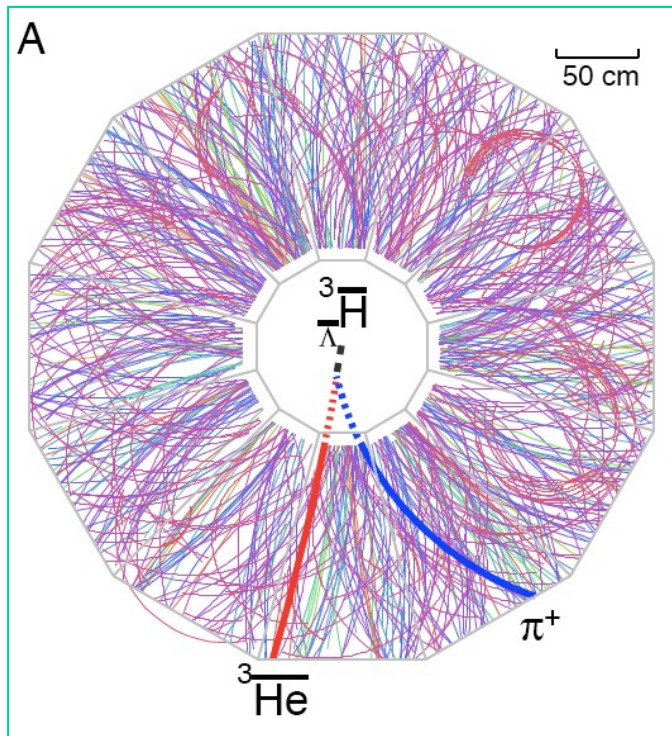
Candidates presented to public on March 23<sup>rd</sup>

March 23, 2011

105th LHCC Meeting, ALICE Collaboration

Without STAR's High Level Trigger, anti-helium 4 would be eventually observed at RHIC, but LHC would claim the prize for sure.

# RHIC : an ideal environment for antimatter production



Science

STAR ☆ *Science* 328, 58 (2010)

nature

STAR ☆ *Nature* 473, 353 (2011)

- With abundantly produced antinucleons, RHIC (and LHC too) has the excellent capability of conducting this study.

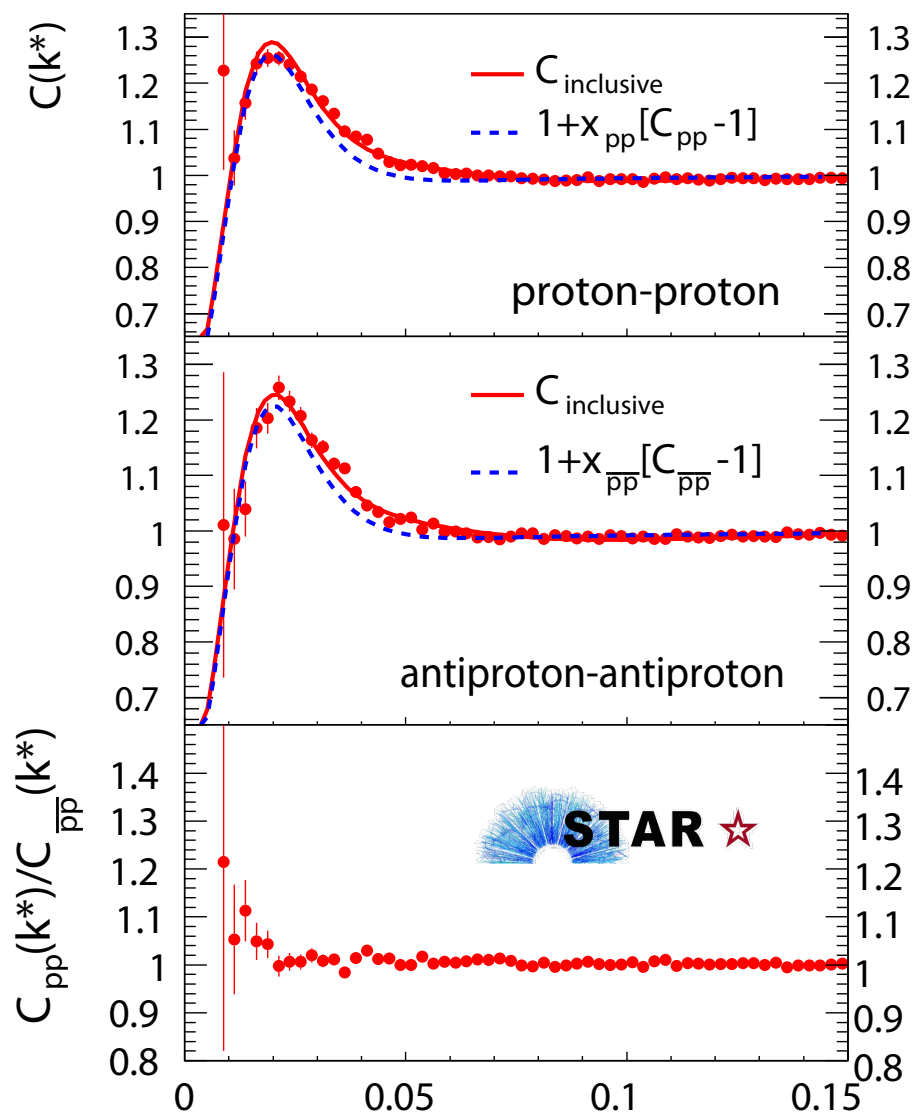


# Antimatter Interaction

The image features a central illustration of an antimatter interaction. Two large, glowing yellow spheres are positioned on the left side. The upper sphere is labeled with a white 'p' and a horizontal bar above it, representing an antiproton ( $\bar{p}$ ). The lower sphere is labeled with a white 'p', representing a proton. Three white, zigzag lines connect the two spheres, symbolizing the exchange of a gluon. The background is a vibrant blue and purple gradient with a radial light effect emanating from the right side. Scattered throughout the scene are numerous smaller, semi-transparent spheres in various shades of blue and purple, some appearing to be in motion or part of a larger field.

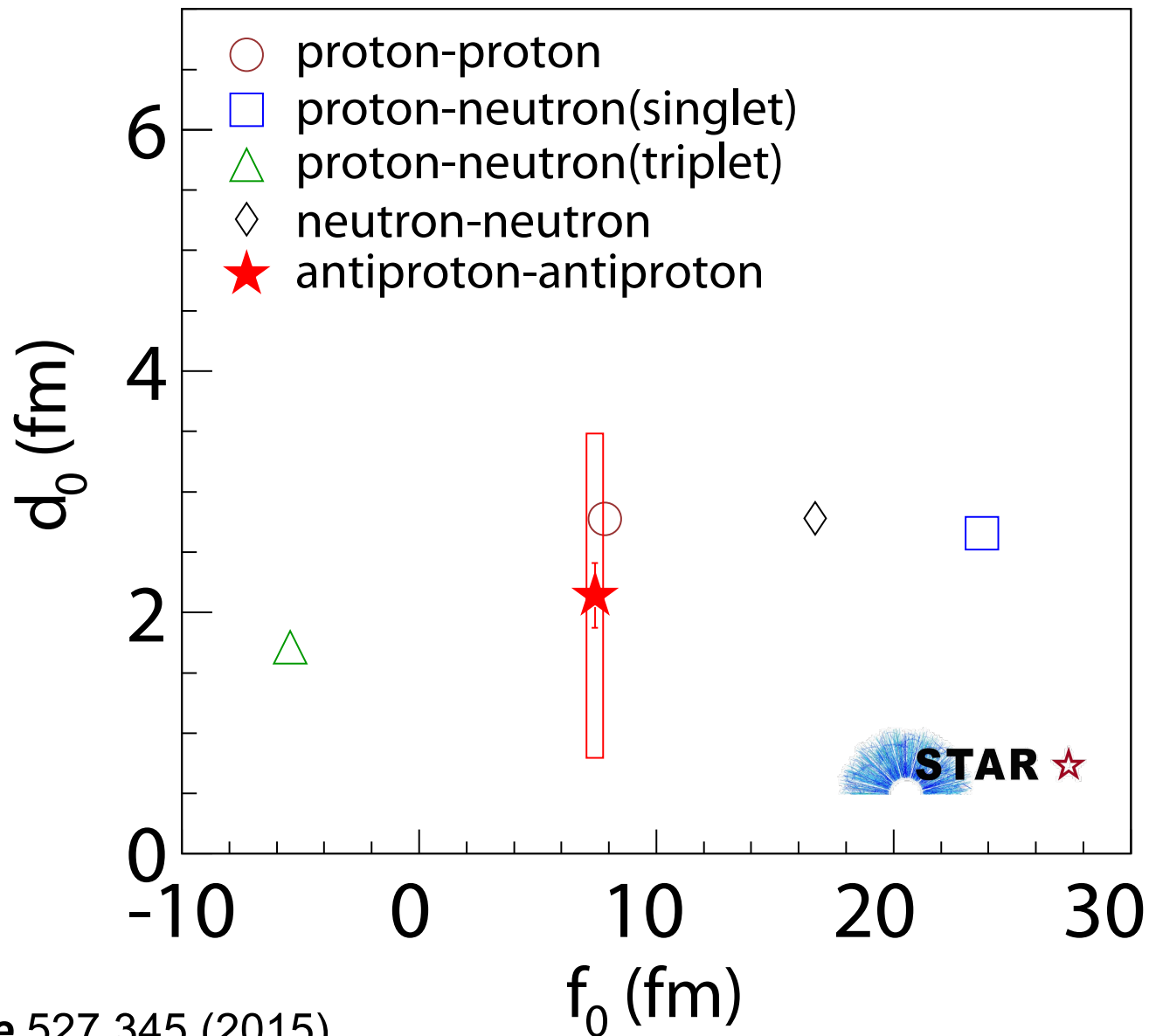


# Antiproton-antiproton correlation



*Nature* 527 345 (2015)  $k^*(\text{GeV}/c)$

# Antiproton-antiproton correlation



*Nature* 527 345 (2015)

# Antiproton-antiproton correlation



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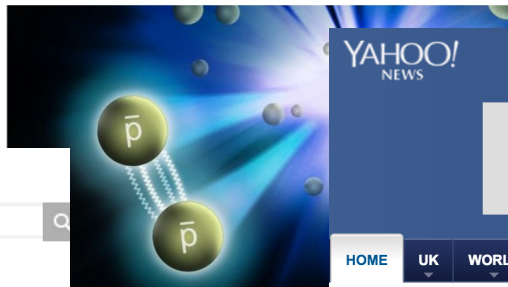


## Science & Environment

### Strong forces make antimatter stick

### Physicists Probe Antimatter For Clues To How It All Began

Physicists have shed new light on one of the greatest mysteries in science: Why the Universe consists primarily of matter and not antimatter.



**YAHOO! NEWS**

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### the antimatter go? Force between s discovered in step towards solving

### Physicists Probe Antimatter For Clues To How It All Began

NOVEMBER 04, 2015 4:06 PM ET

GEOFF BRUMFIEL

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Osborne | International Business Times - 9 hours ago

msn 뉴스

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사이에도 강한 핵력"...반입자 간 상호작용 첫 규명

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## Forbes / Tech

NOV 5, 2015 @ 11:31 AM 14,749 VIEWS

# Antimatter Obeys the same Law of Attraction As Matter

中美首次测量到反质丁向相与下用刀 成本行反衣

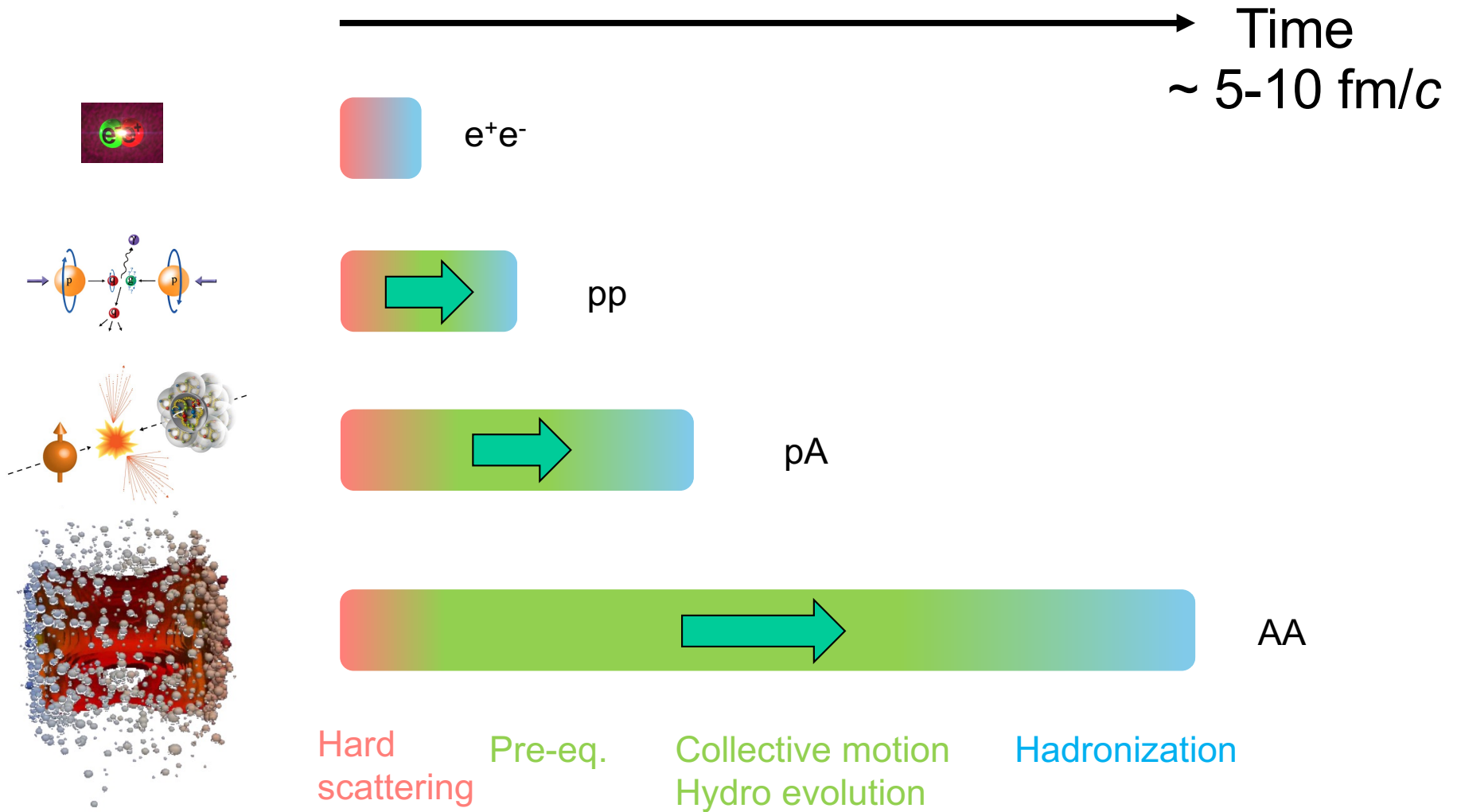
взаимодействия частиц антиматерии

# Spin in Heavy Ion Collisions

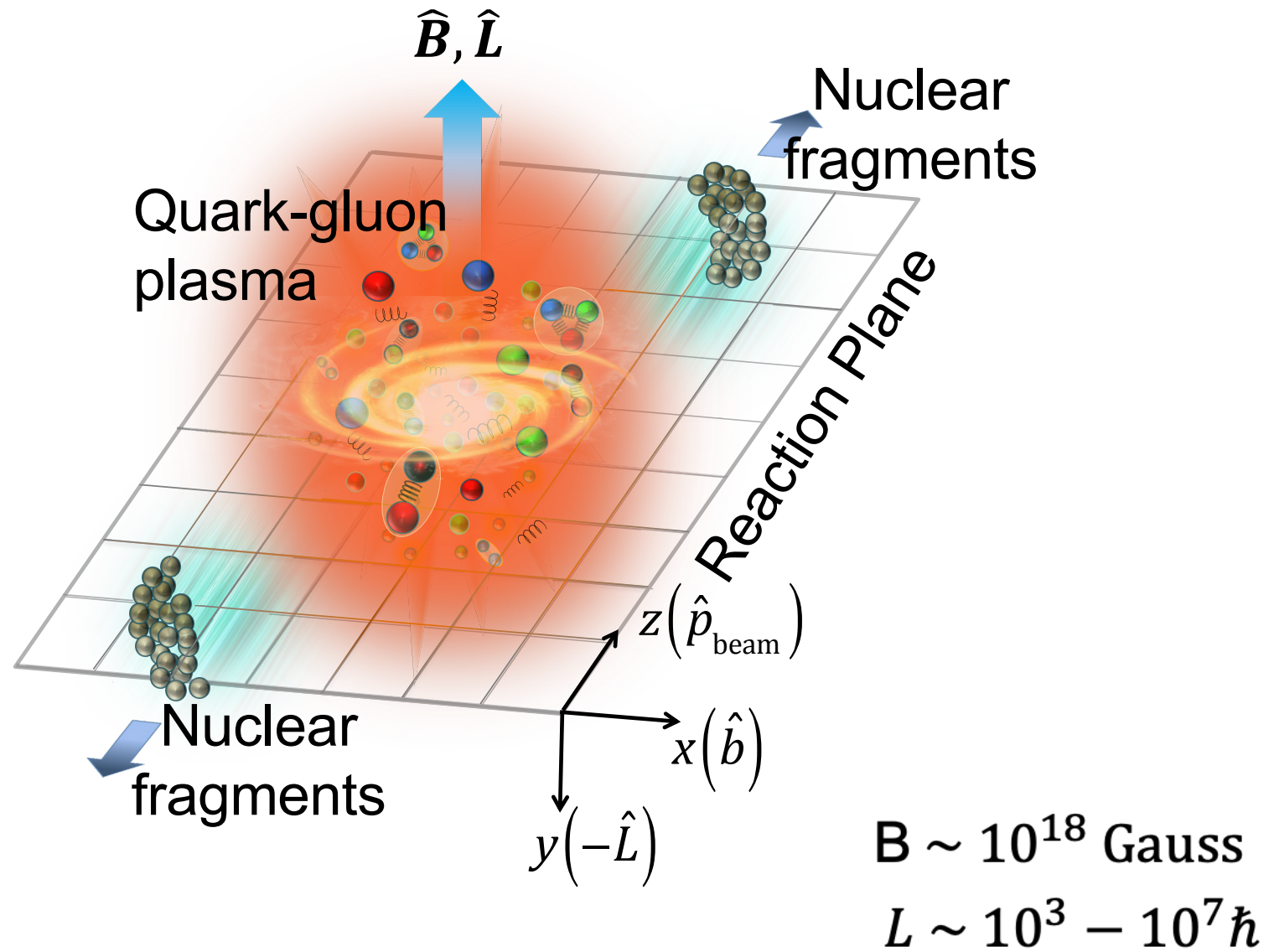




# Temporal Evolutions



# Strongly Interacting QGP under Rotation

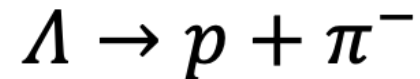
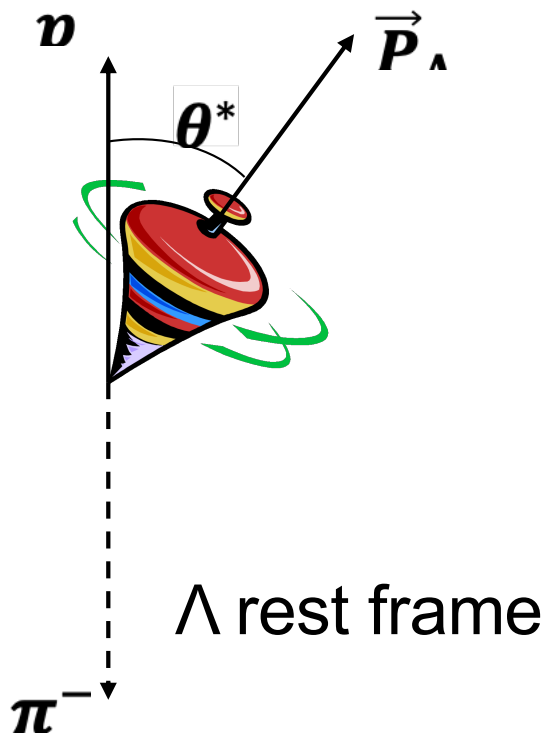


# $\Lambda$ Global Polarization

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Parity-violating weak decay of hyperons (“self-analyzing”)

Daughter baryon is preferentially emitted in the direction of hyperon’s spin (opposite for anti-particle)



$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H P_H \cos \theta^*)$$

$P_H$  :  $\Lambda$  polarization

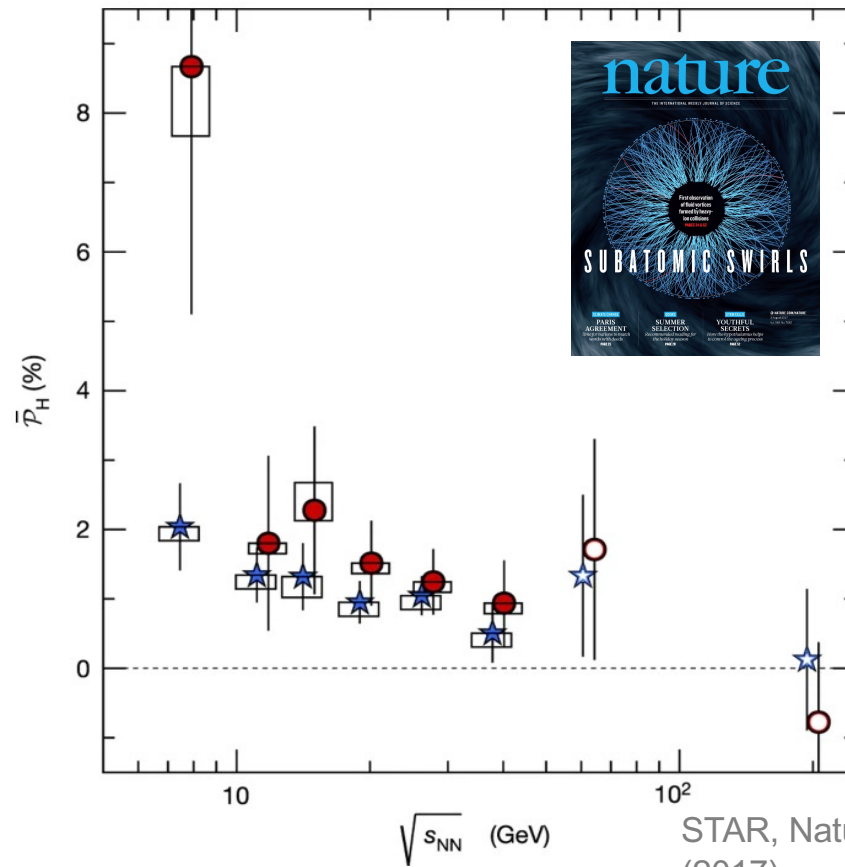
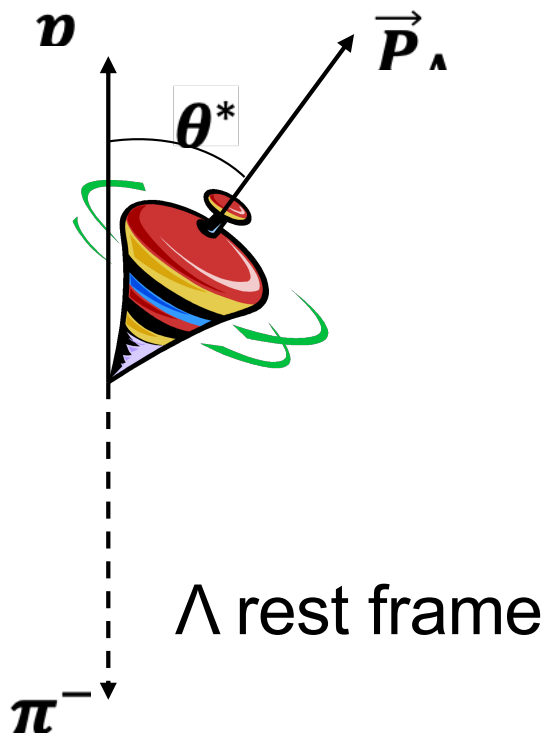
$\theta^*$  : polar angle of daughter w.r.t. polarization direction

$\alpha_H$  :  $\Lambda$  decay parameter ( $0.732 \pm 0.014$ )

# $\Lambda$ Global Polarization

Parity-violating weak decay of hyperons (“self-analyzing”)

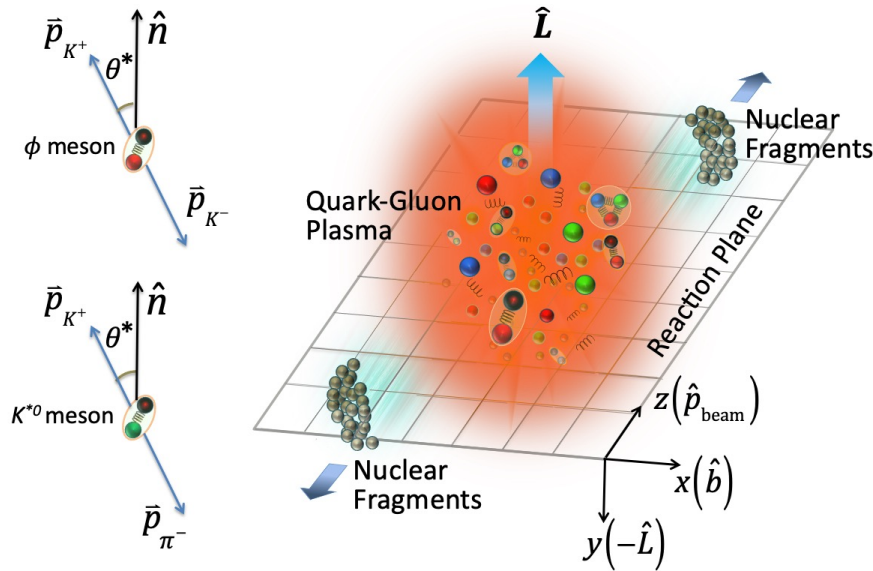
Daughter baryon is preferentially emitted in the direction of hyperon’s spin (opposite for anti-particle)



STAR, Nature 548 62 (2017)



# Global Spin Alignment



The spin state of a vector meson can be described by a 3x3 spin density matrix.

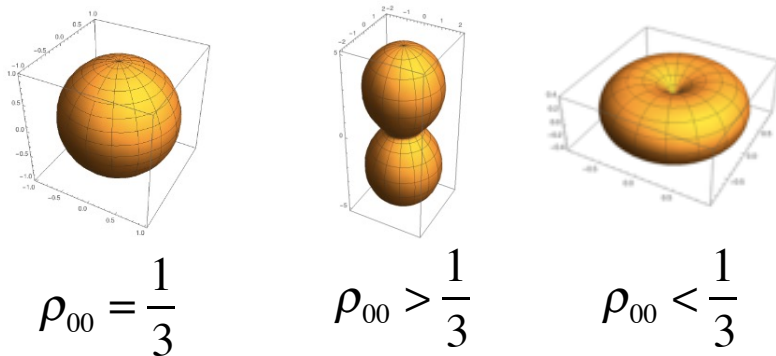
The diagonal element  $\rho_{00}$  corresponds to the probability of finding a vector meson in spin state 0 out of 3 possible spin states of -1, 0 and 1.

A deviation of  $\rho_{00}$  from 1/3 would indicate a non-zero spin alignment.

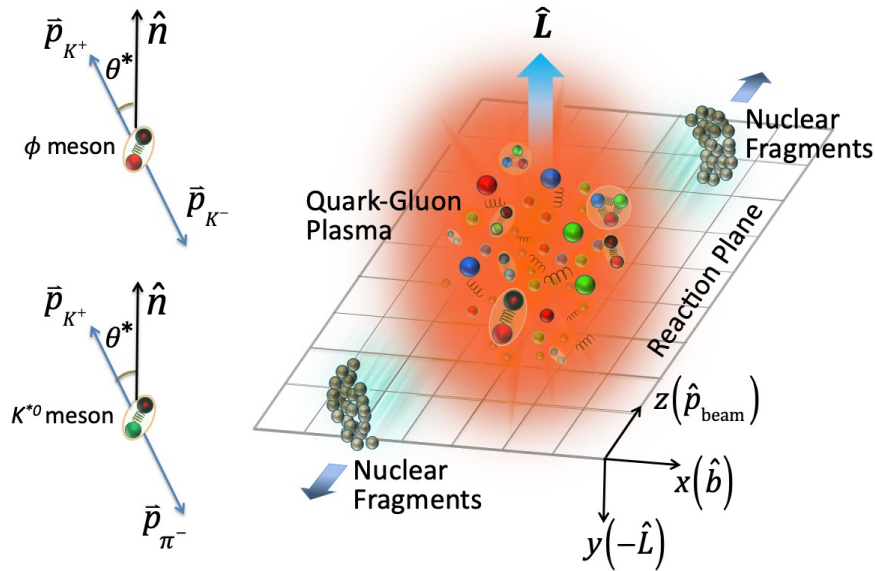
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[ (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^* \right]$$

From quark combination :

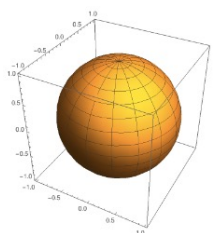
$$\rho_{00}^V = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle} \approx \frac{1}{3} - \frac{4}{9} \langle P_q P_{\bar{q}} \rangle$$



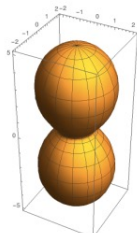
# Global Spin Alignment



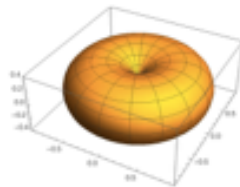
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[ (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^* \right]$$



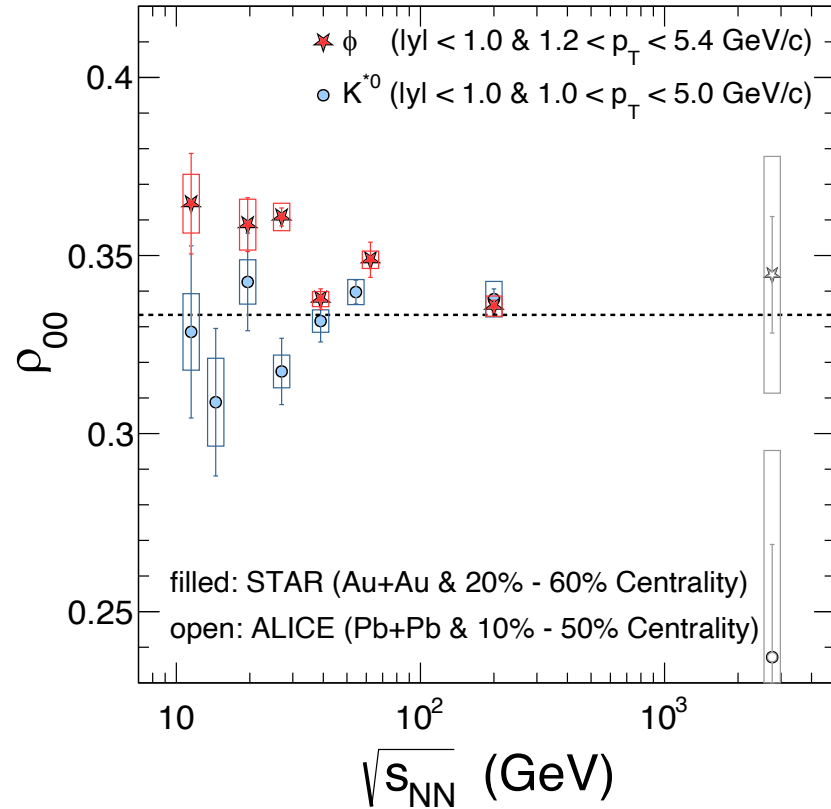
$$\rho_{00} = \frac{1}{3}$$



$$\rho_{00} > \frac{1}{3}$$



$$\rho_{00} < \frac{1}{3}$$



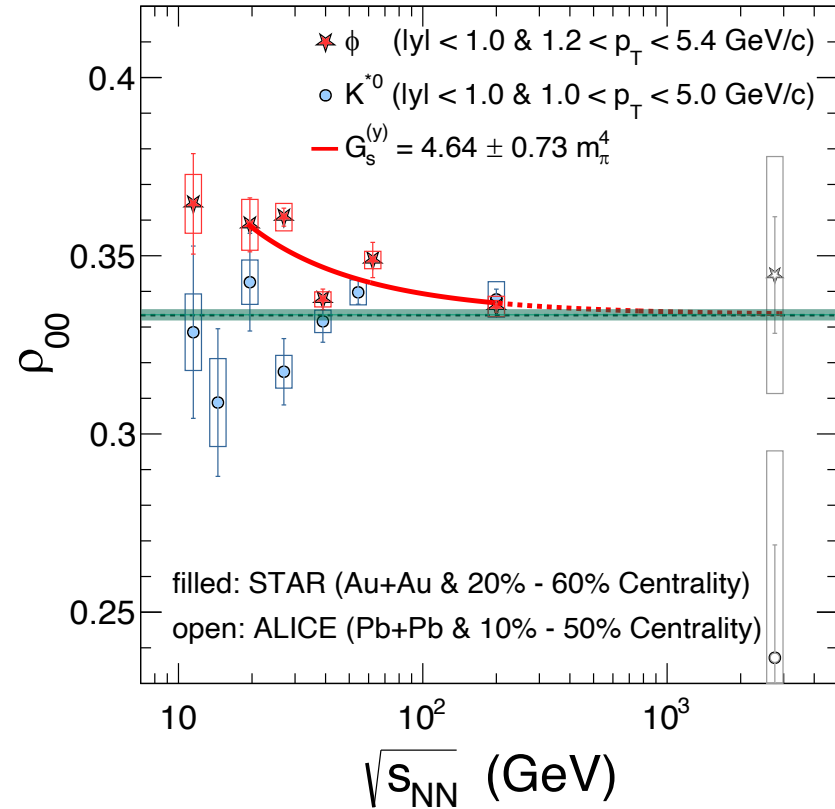
STAR, Nature 614 244 (2023)

$\phi$  exhibits surprisingly large global spin alignment while  $K^*$  displays little.

# Global Spin Alignment

$$\rho_{00} \approx \frac{1}{3} + C_{\Lambda} + C_{\varepsilon} + C_E + C_F + C_L + C$$

Physics Mechanisms	$\langle \rho_{00} \rangle$
$C_{\Lambda}$ : Quark coalescence vorticity & magnetic field <sup>[1]</sup>	$< 1/3$ (Negative $\sim 10^{-5}$ )
$C_{\varepsilon}$ : E-comp. of Vorticity tensor <sup>[1]</sup>	$< 1/3$ (Negative $\sim 10^{-4}$ )
$C_E$ : Electric field <sup>[2]</sup>	$> 1/3$ (Positive $\sim 10^{-5}$ )
$C_F$ : Fragmentation <sup>[3]</sup>	$> \text{or}, < 1/3$ ( $\sim 10^{-5}$ )
$C_L$ : Local spin alignments <sup>[4]</sup>	$< 1/3$
$C_A$ : Turbulent color field <sup>[5]</sup>	$< 1/3$
$C_{\phi}$ : Vector meson strong force field <sup>[6]</sup>	$> 1/3$ (Can accommodate large positive signal)
$C_g$ : Glasma fields + effective potential	could be significant



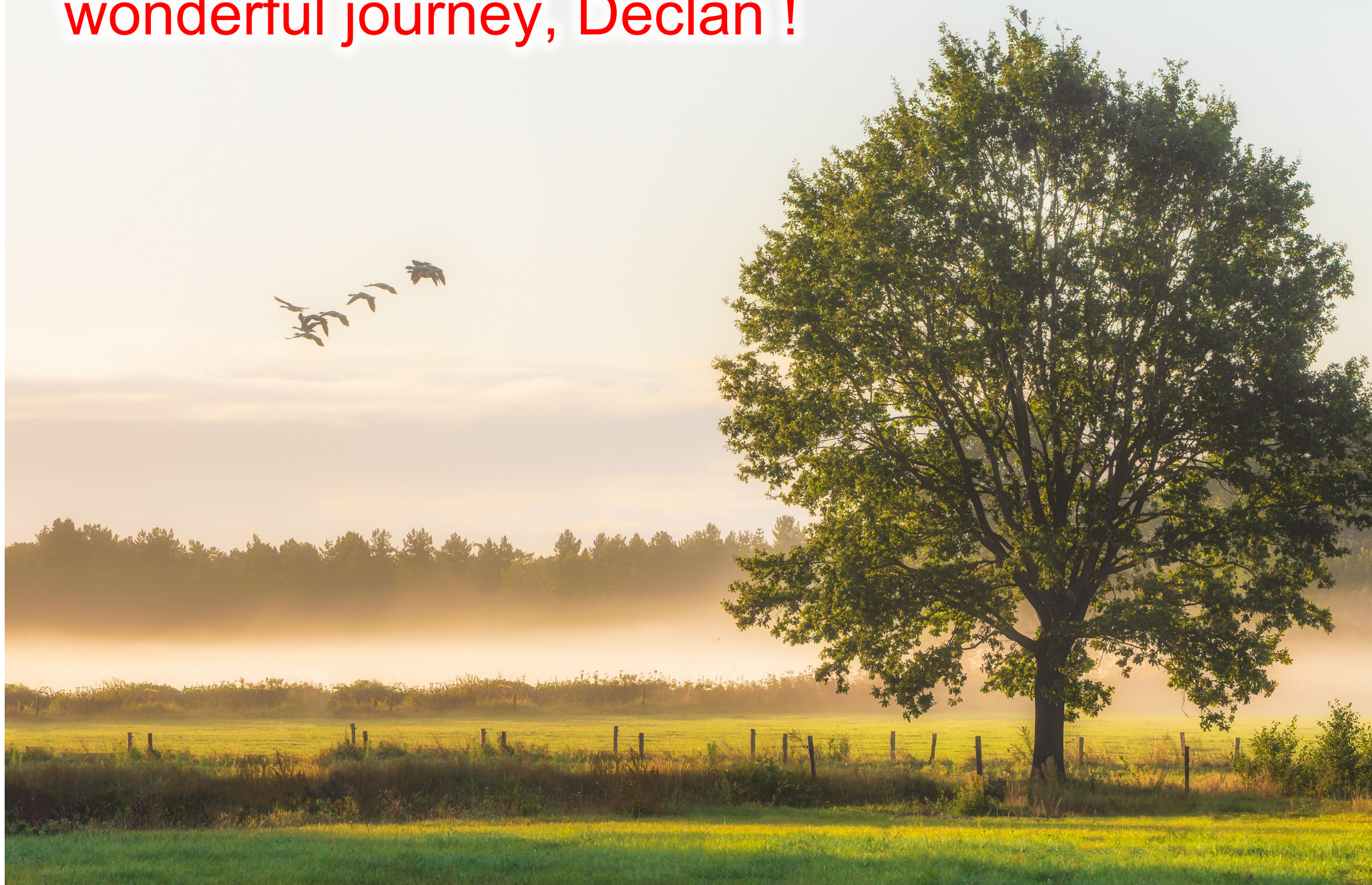
STAR, Nature 614 244 (2023)

strong force

$\phi$  exhibits surprisingly large global spin alignment while  $K^*$  displays little.



Grateful for standing on your shoulders in this wonderful journey, Declan !

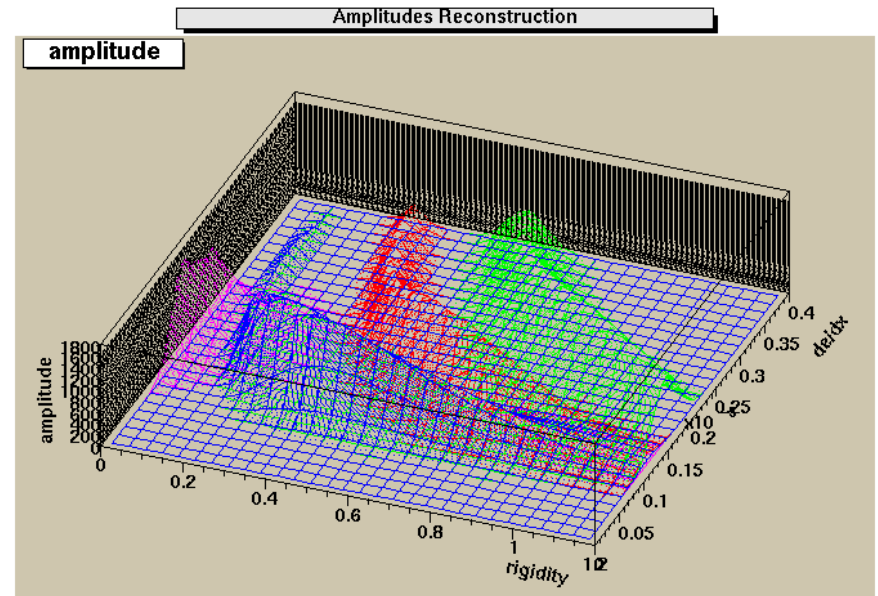
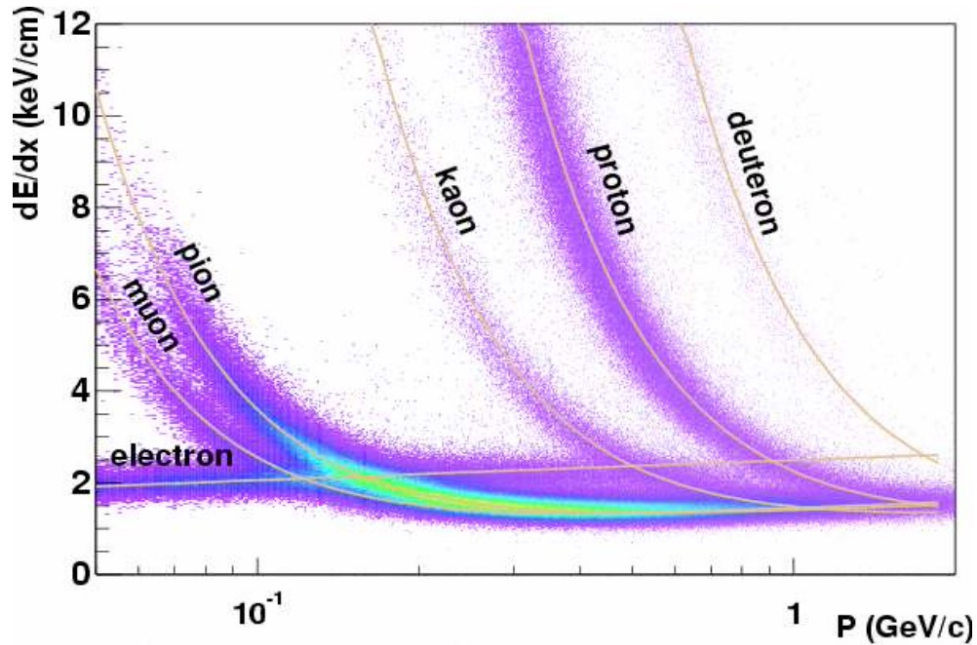




# Backup Slides

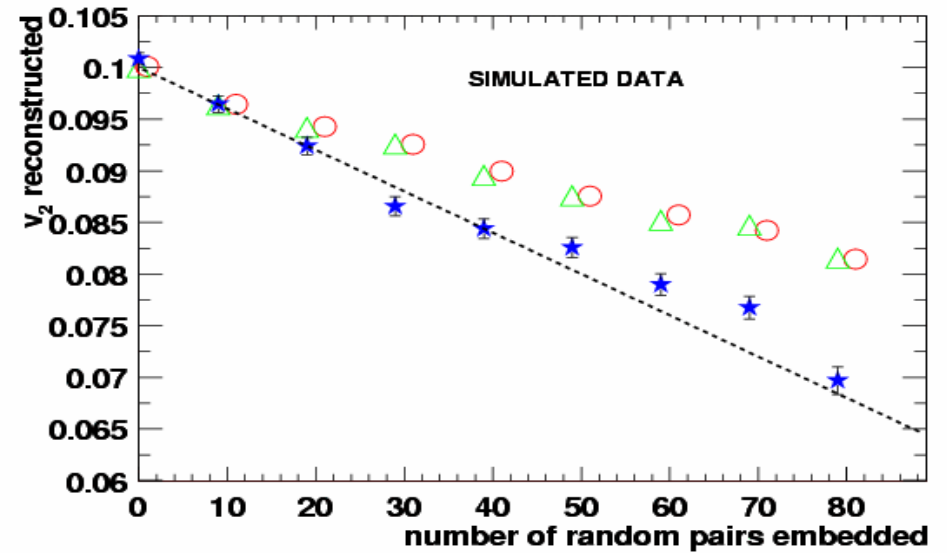
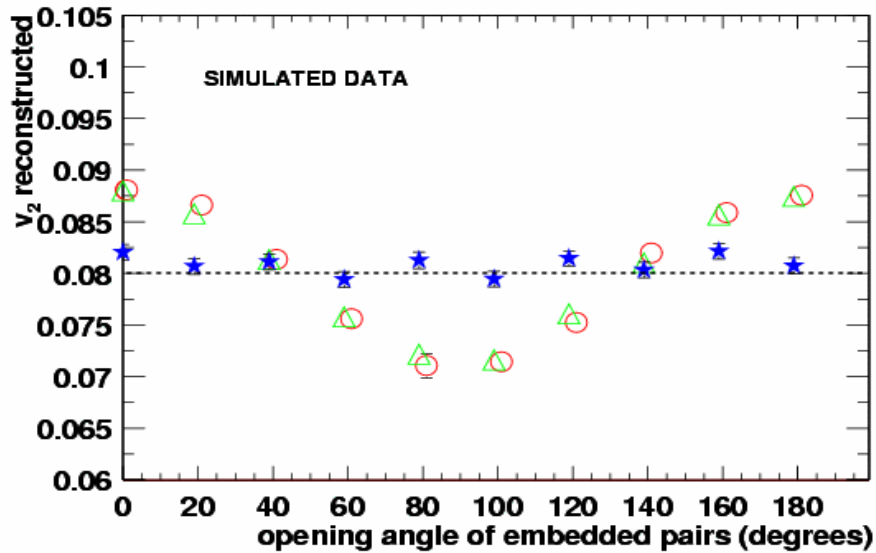
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# First Task @ STAR



Probability PID, used in first PID flow paper.  
Was hoping to use it for extended spectra, but it did not happen.

# Nonflow and Cumulants



Borghini, Dinh and Ollitrault, PRC 63 054906 (2001) ...  
STAR PRC 66 034904 (2002)

Considerable nonflow in conventional flow method.  
Going for 4<sup>th</sup> order cumulants !

## Nuclear force between antimatter

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- So far the large body of knowledge on nuclear force was derived from studies made on nucleons or nuclei, little is known directly about the nuclear force between antinucleons.
- The knowledge of interaction among two anti-protons, one of the simplest system of antinucleons(nuclei), is a fundamental ingredient for understanding the structure of more-complex antinuclei and their properties.



## Nuclear force : scattering length ( $f_0$ ) and effective range ( $d_0$ )

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$f_0$  is related to the cross section.

At low energy limit, the scattering cross section is given by

$$\sigma = 4\pi f_0^2$$

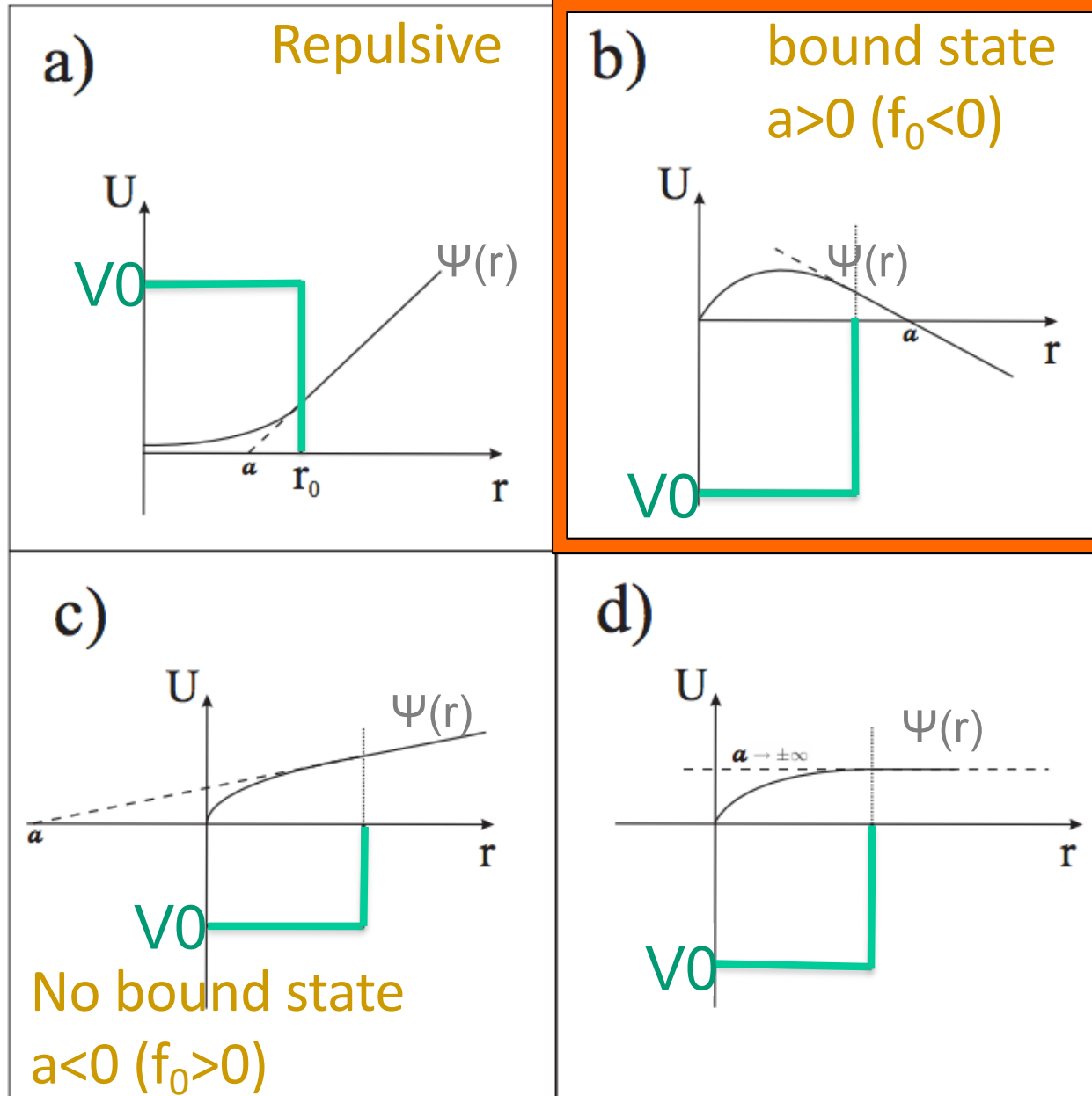
$d_0$  is related to the range of the potential.

In the case of square well potential,  $d_0$  is the range (radius) of the potential.

For a short range potential,  $f_0$  and  $d_0$  are related to the s-wave scattering phase shift  $\delta_0$  and the collision momentum  $k$  by :

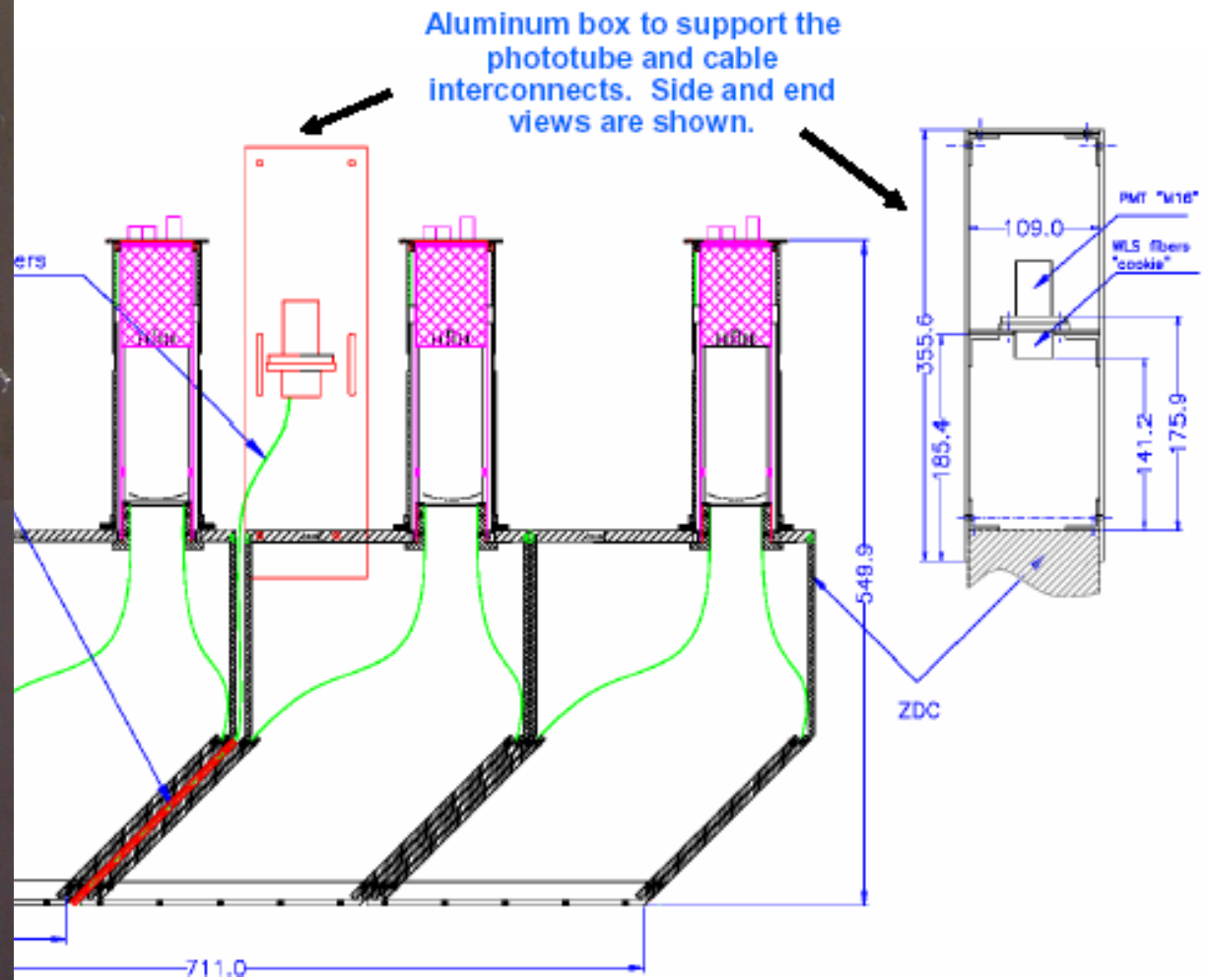
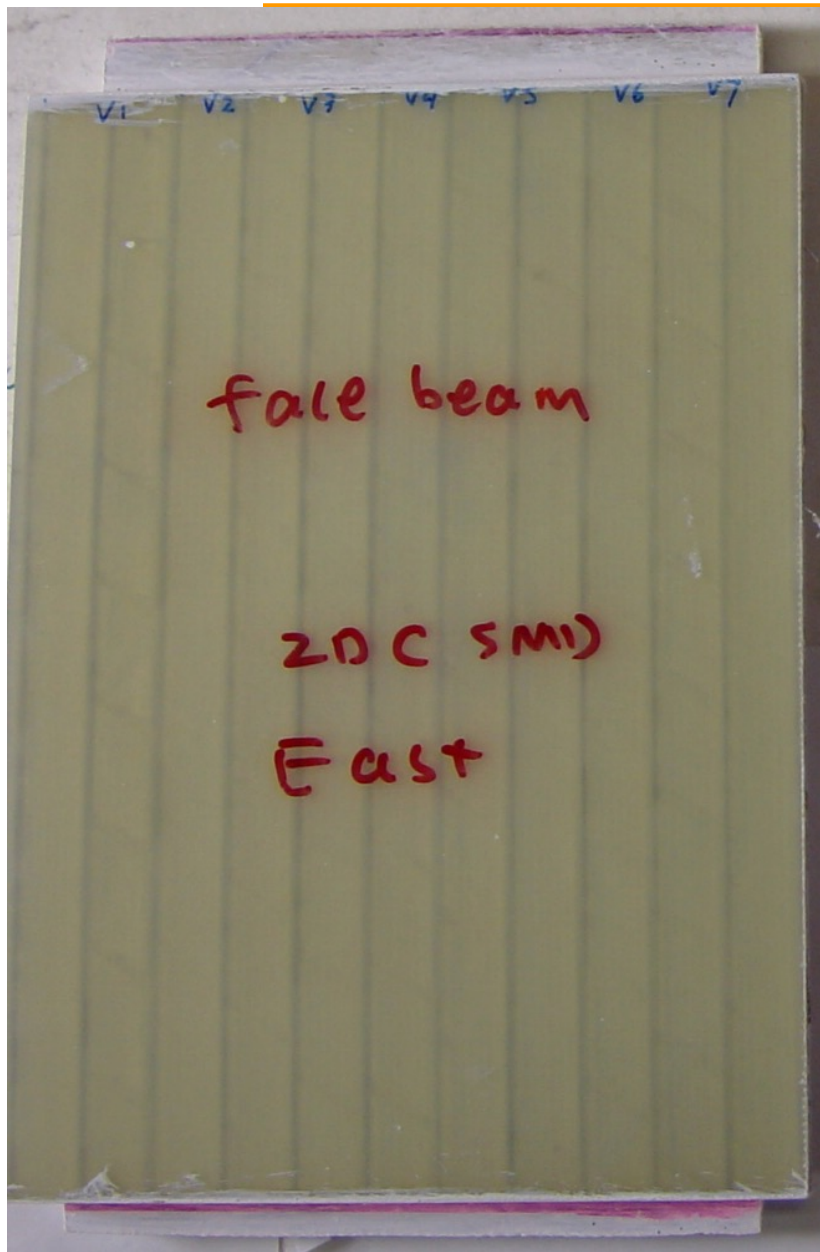
$$k \cot(\delta_0) \approx \frac{1}{f_0} + \frac{1}{2} d_0 k^2$$

# $f_0$ and $d_0$ : characterizing the nuclear force

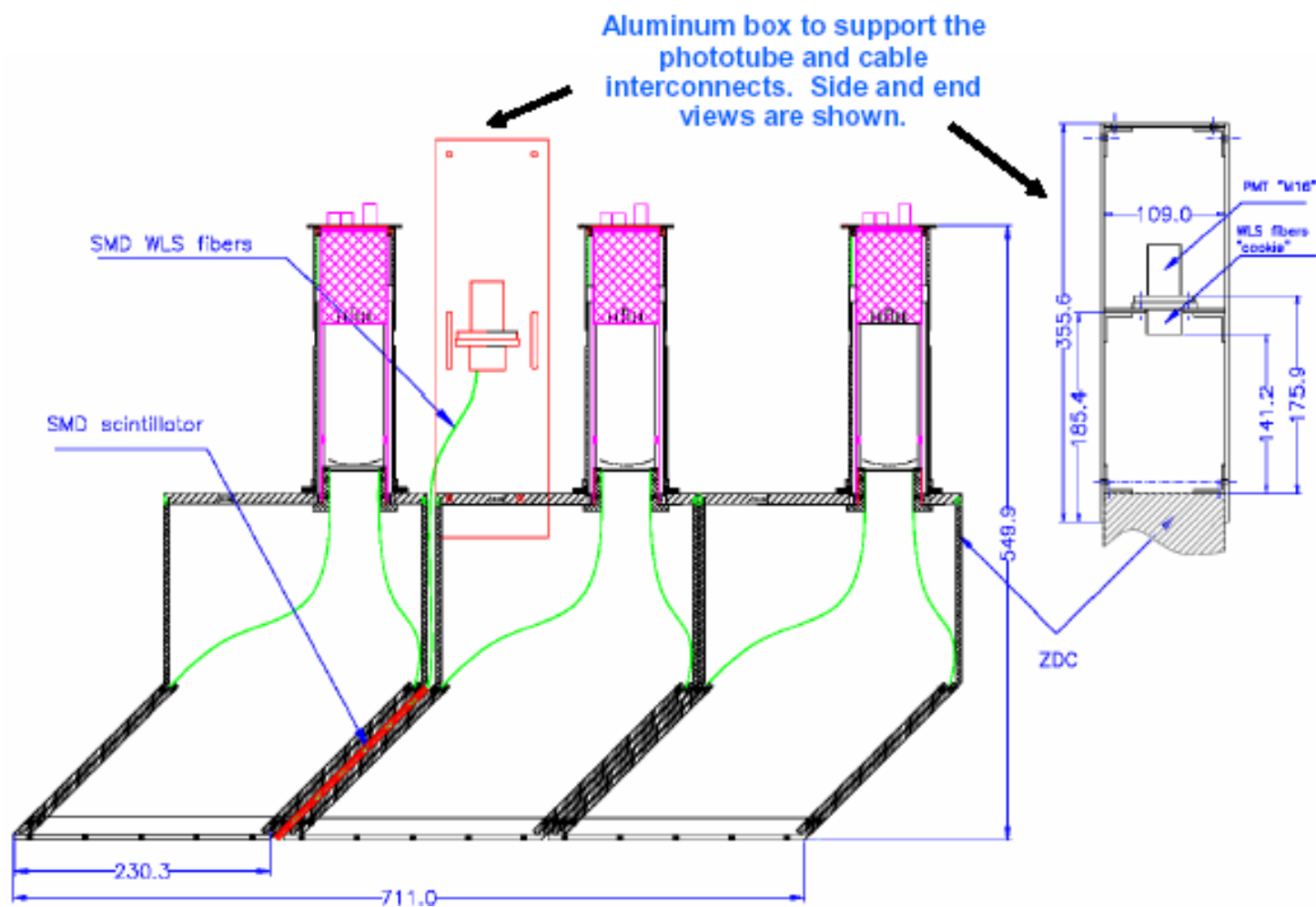


$kr \ll 1$   
 $k \rightarrow 0$   
 $f_0 \equiv -a$   
 $d_0 \equiv r_0$

# A Shower Max Detector at ZDC for STAR



# A Shower Max Detector at ZDC for STAR





# A Shower Max Detector at ZDC for STAR

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