My journey at STAR

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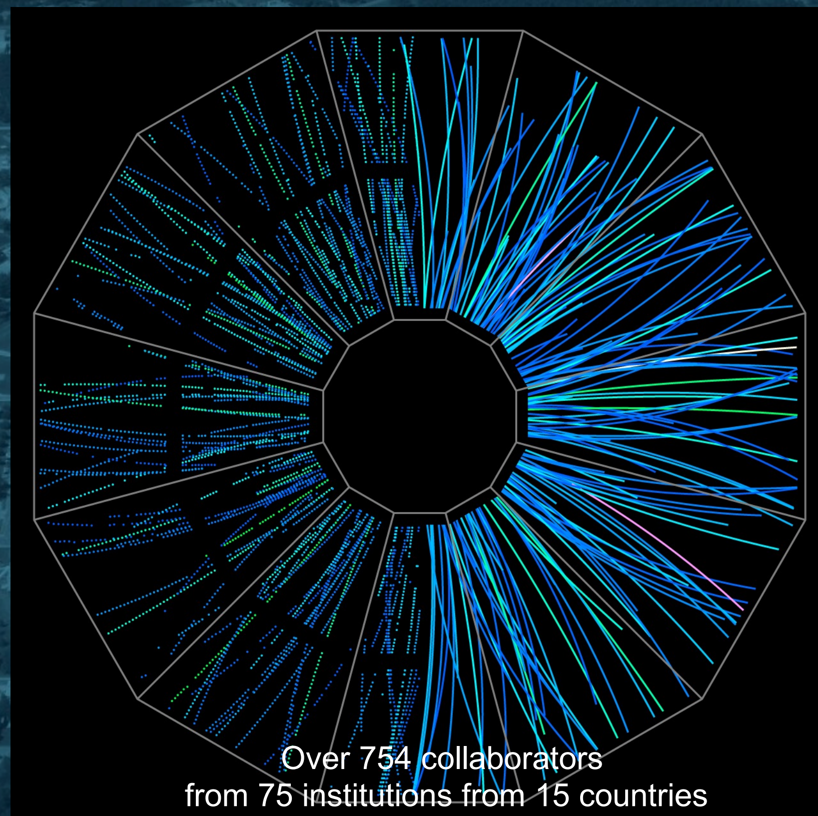
U.S. DEPARTMENT OF ENERGY

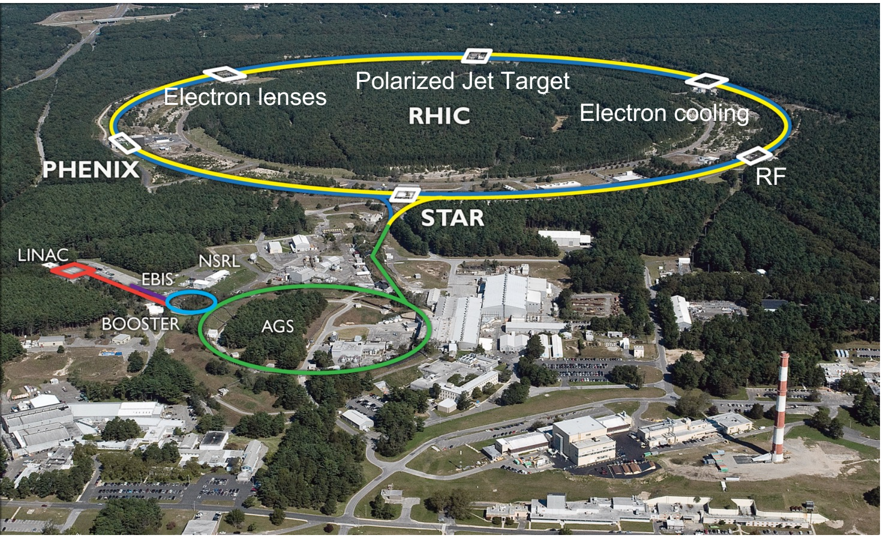


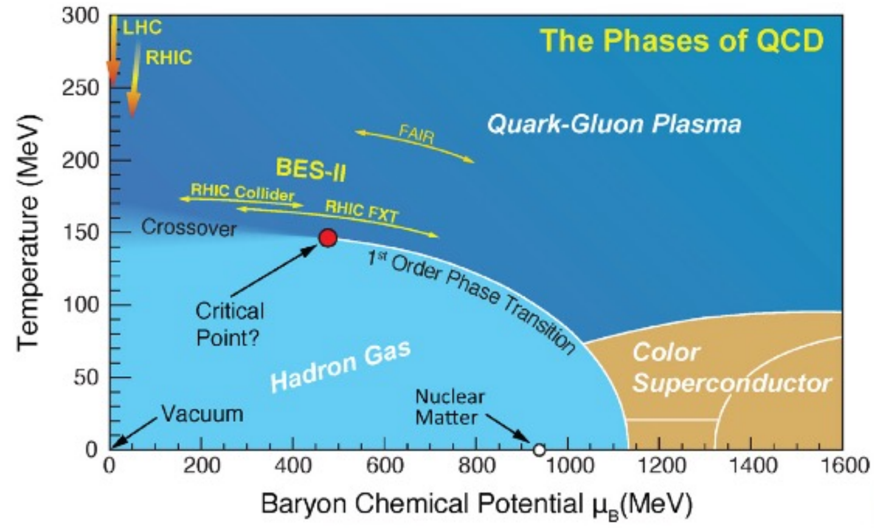
@BrookhavenLab

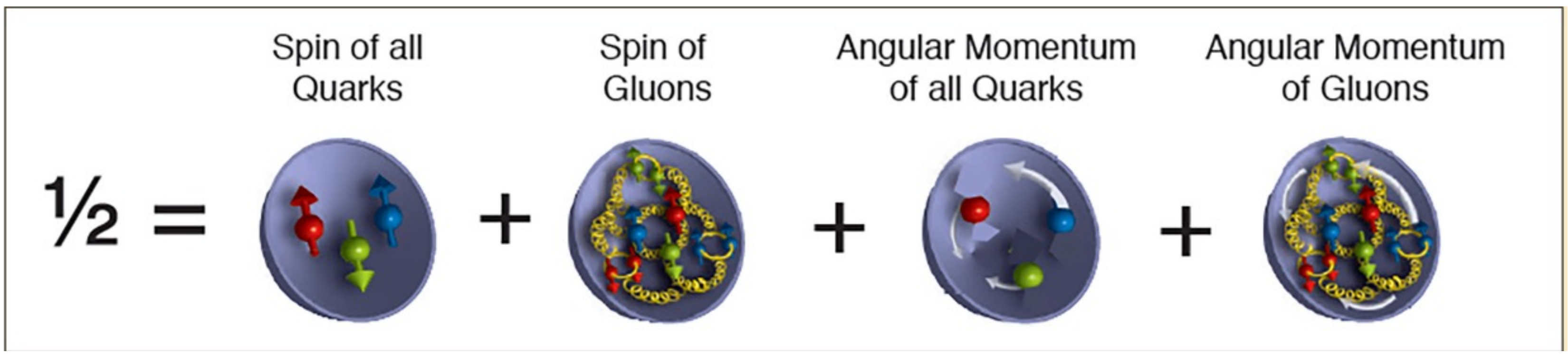
RHIC @ Brookhaven National Laboratory

24 years of RHIC operation

The mission of RHIC







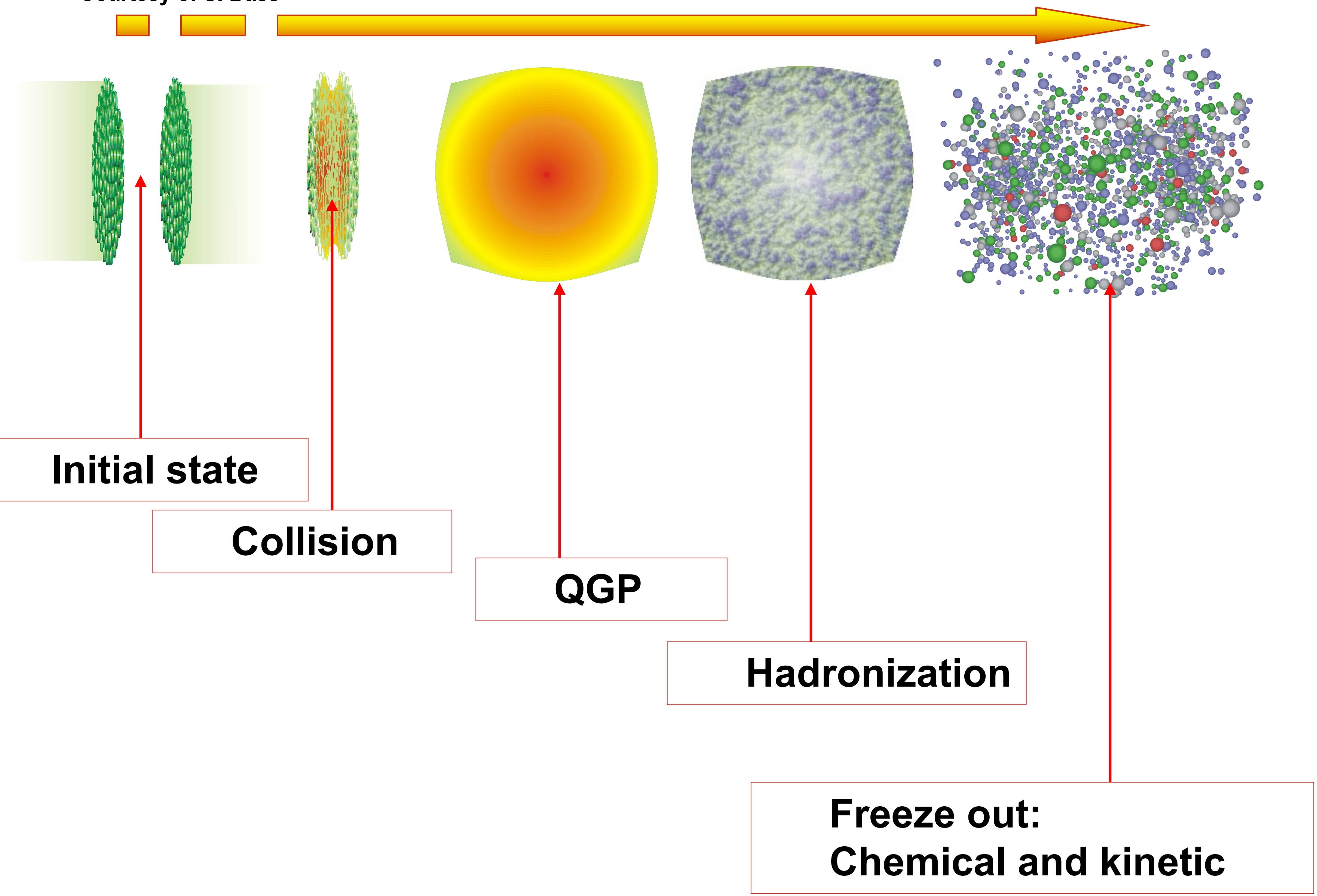
To probe the inner workings of the Quark-Gluon Plasma

To map the phase diagram of QCD

To study the spin puzzle of proton

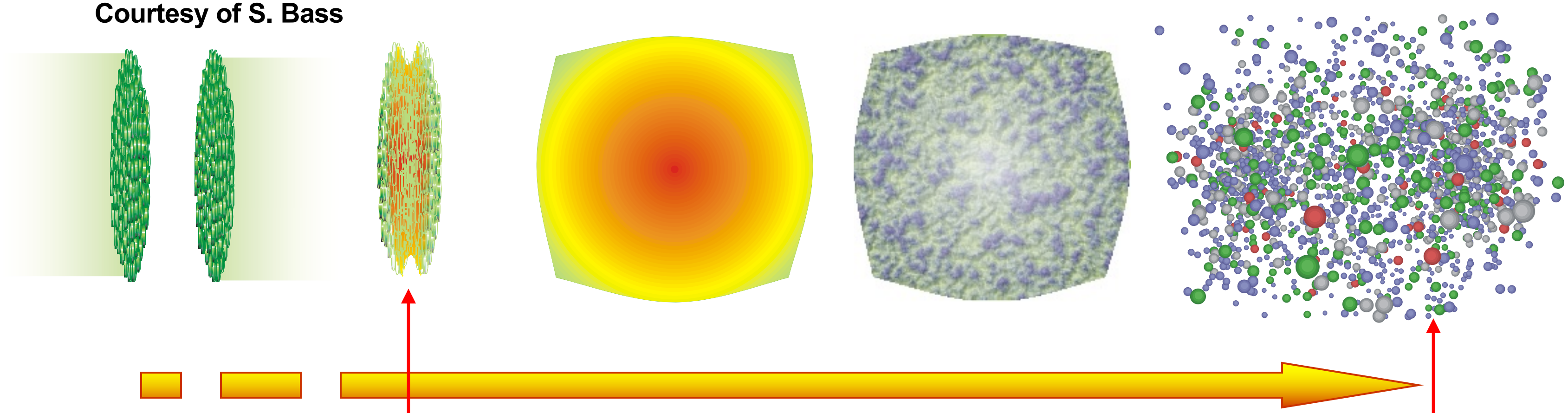
Relativistic heavy ion collision

Courtesy of S. Bass



Physics Goals at RHIC

Courtesy of S. Bass



Identify and study the properties of matter with partonic degrees of freedom.

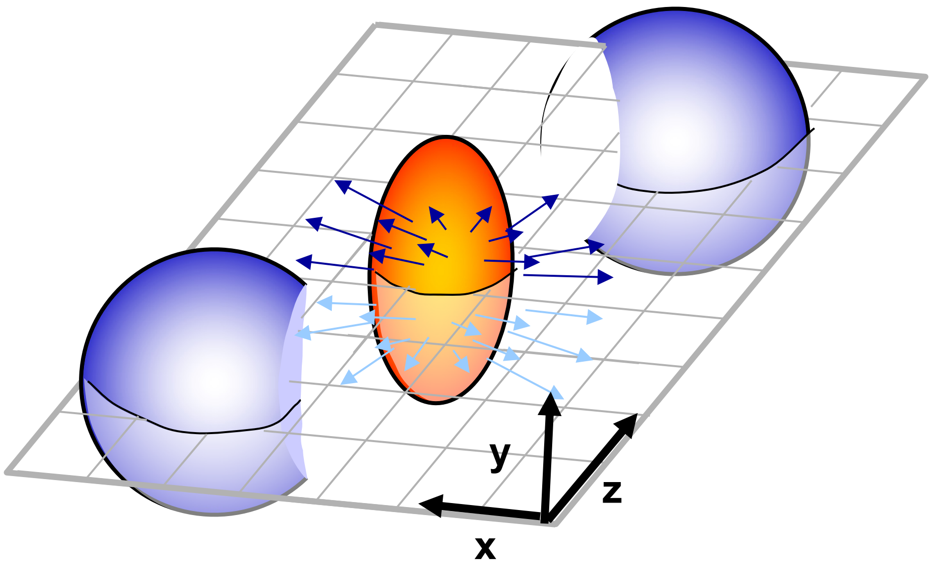
Penetrating probes

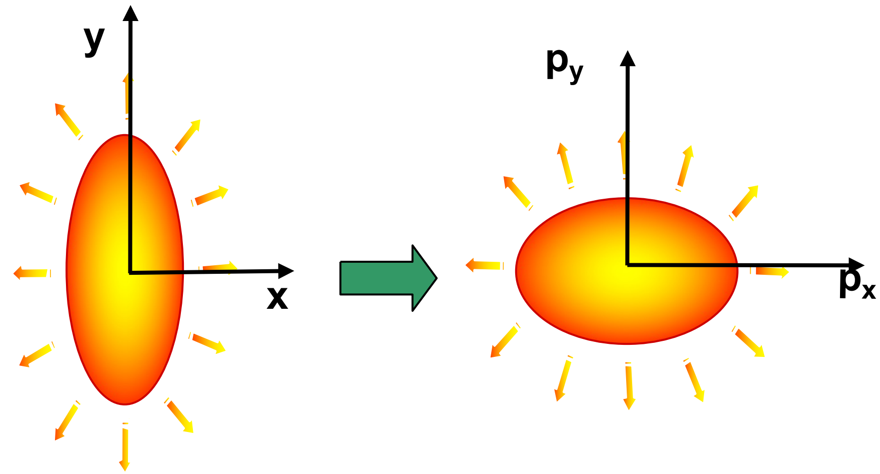
- "jets" and heavy flavor

Bulk probes

- v_2 → partonic collectivity
- spectra at low p_T, particle ratios.

Elliptic flow v_2





Non-central collisions: azimuthal anisotropy in coordinate-space
Interactions → asymmetry in momentum-space
Sensitive to early time in the system's evolution

Measurement: Fourier expansion of the azimuthal p_T distribution

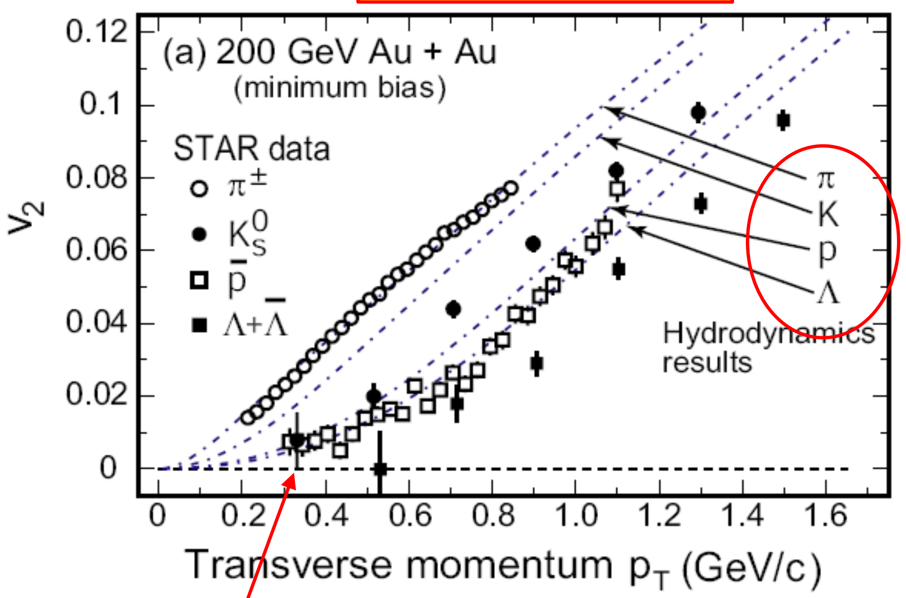
$$E\frac{d^3N}{d^3p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2 dy}\left[1 + 2v_1 \cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right]$$

→

$$v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

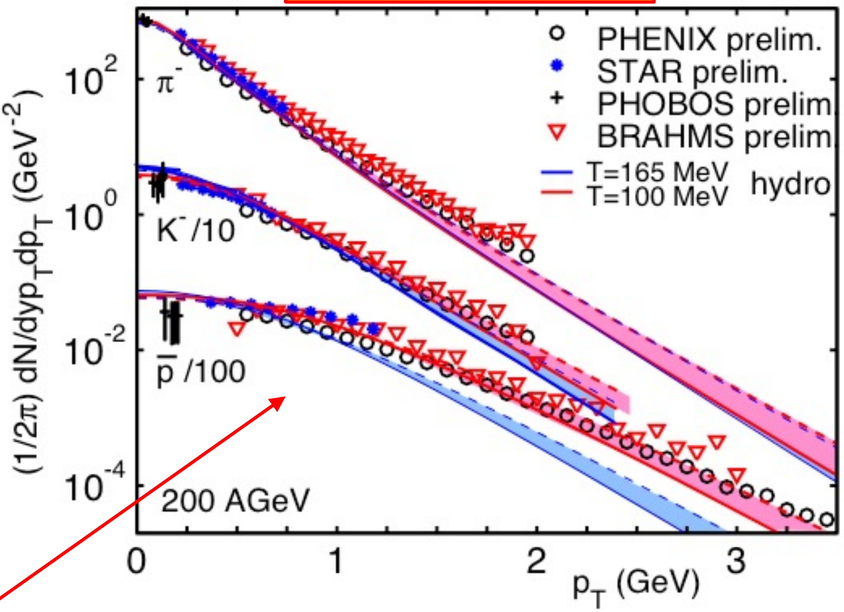
Low p_T: bulk property

Elliptic flow v_2



STAR: Nucl. Phys. A 757 (2005) 102

p_T distributions

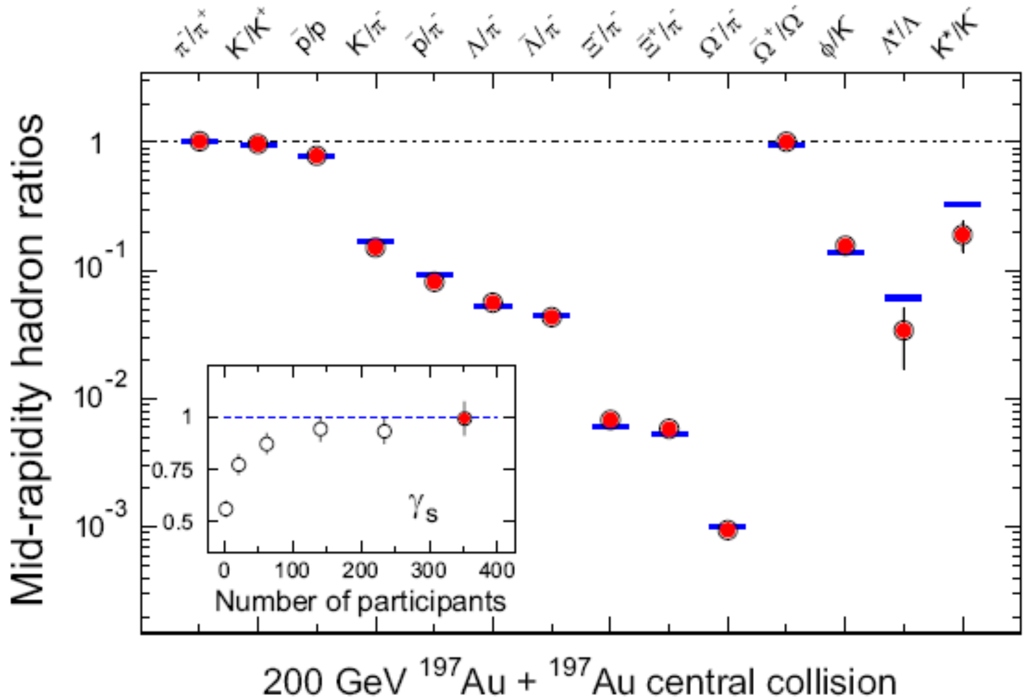


M. Calderon de la Barca Sanchez, ISMD2003

Hydrodynamical models can reproduce mass dependence of v_2 and spectra at p_T<2 GeV/c.

Low p_T: bulk property

Particle ratios: chemical freeze out



STAR: Nucl. Phys. A 757 (2005) 102

A few parameters in the model:

Chemical freeze out temperature T_{ch}

Baryon chemical potential μ_B (μ_B=0 if pbar/p=1)

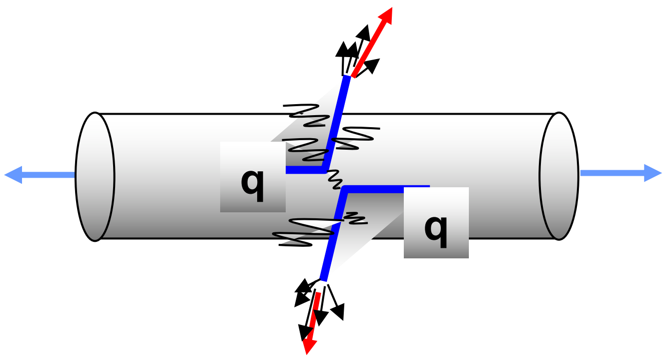
Strangeness saturation factor: γ_s

T_{ch}=163±4 MeV, μ_B=24±4 MeV

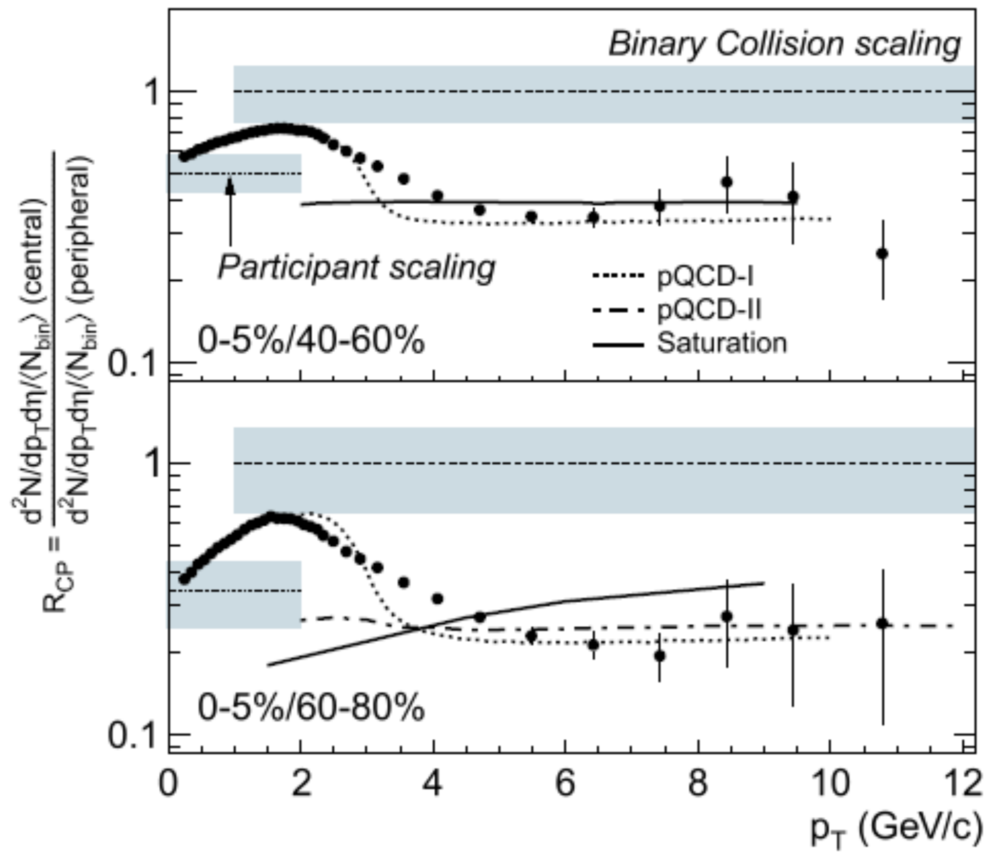
γ_s=0.99±0.07

γ_s approach 1 in central Au+Au collisions: thermalization within the framework of this model.

High p_T: penetrating probe



$$R_{cp} = \frac{(d^2N/(2\pi p_T dp_T dy)/N_{bin})\,|\,central}{(d^2N/(2\pi p_T dp_T dy)/N_{bin})\,|\,peripheral}$$

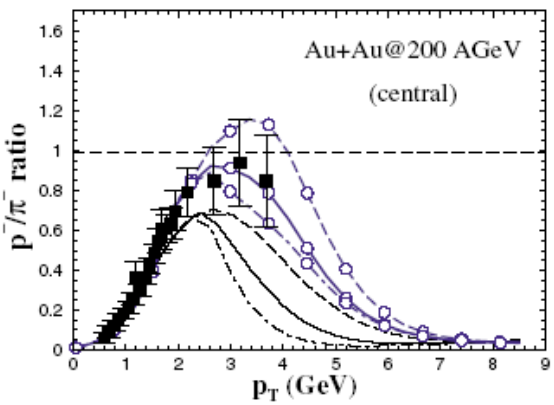


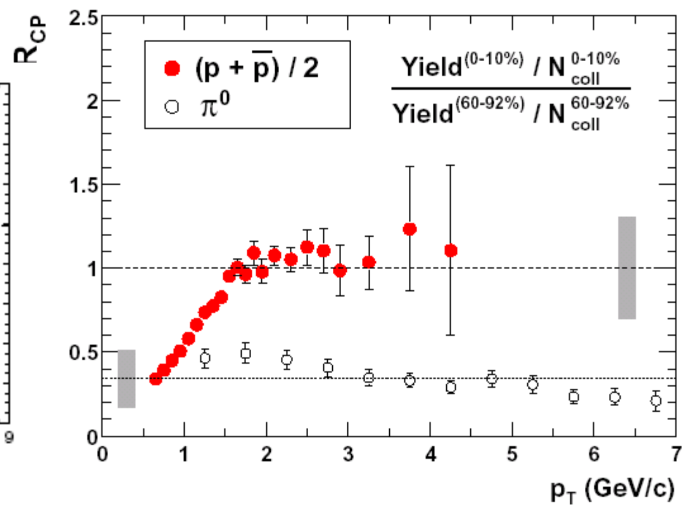
STAR: Nucl. Phys. A 757 (2005) 102

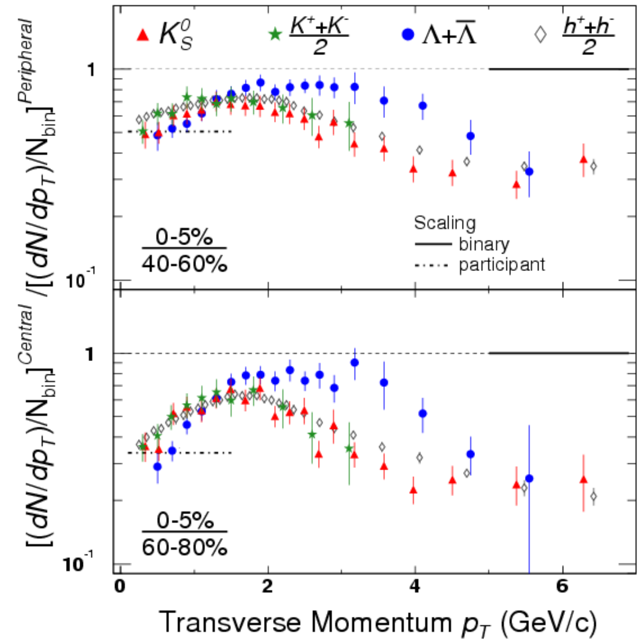
In central Au+Au collisions at RHIC: Fragmentation (q/g→hadrons) + energy loss at p_T > 6 GeV/c:

Significant suppression of inclusive charged hadron observed at p_T>6 GeV/c: dN_g/dy~1000. **M. Gyulassy et al., nucl-th/0302077.**

Intermediate p_T: baryon/meson pattern



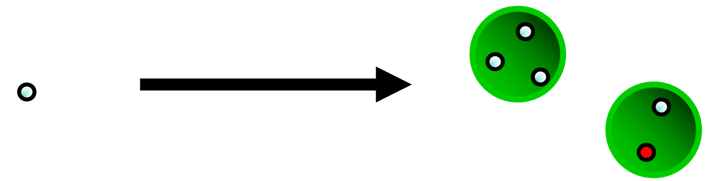




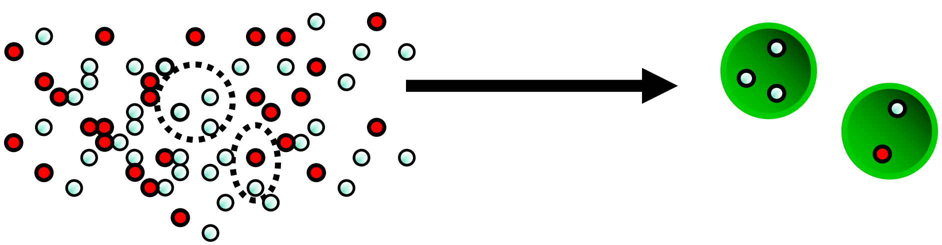
At p_T~2 GeV/c, pbar/π ratio ~1. →It can not be factorized jet fragmentation.

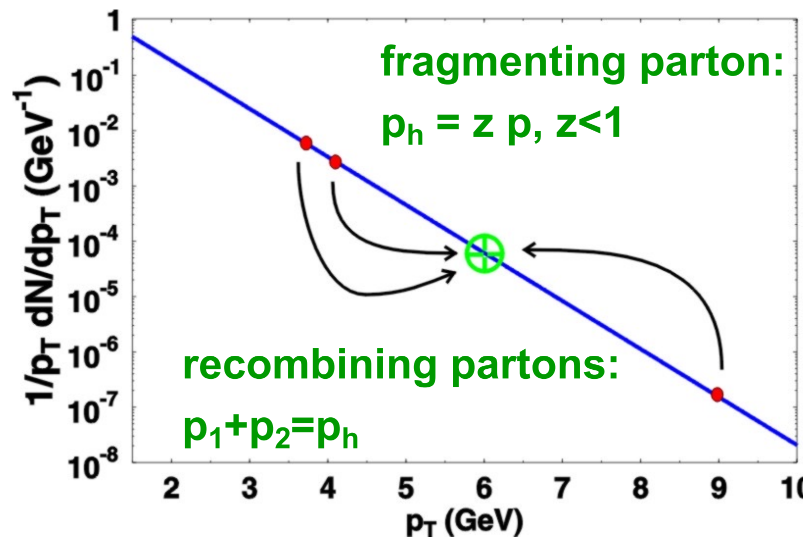
At 2<p_T<6 GeV/c, p, Λ increase faster than π, K_S, K from peripheral to central collisions. **STAR: Phys. Rev. Lett. 92 (2004) 052302; PHENIX: Phys. Rev. Lett. 91 (2003) 172301; V. Greco, et al., Phys. Rev. Lett. 90, 202302 (2003).**

Recombination/Coalescence at hadronization



Fragmentation works for p+p collisions for hadrons at $p_T > 2$ GeV/c

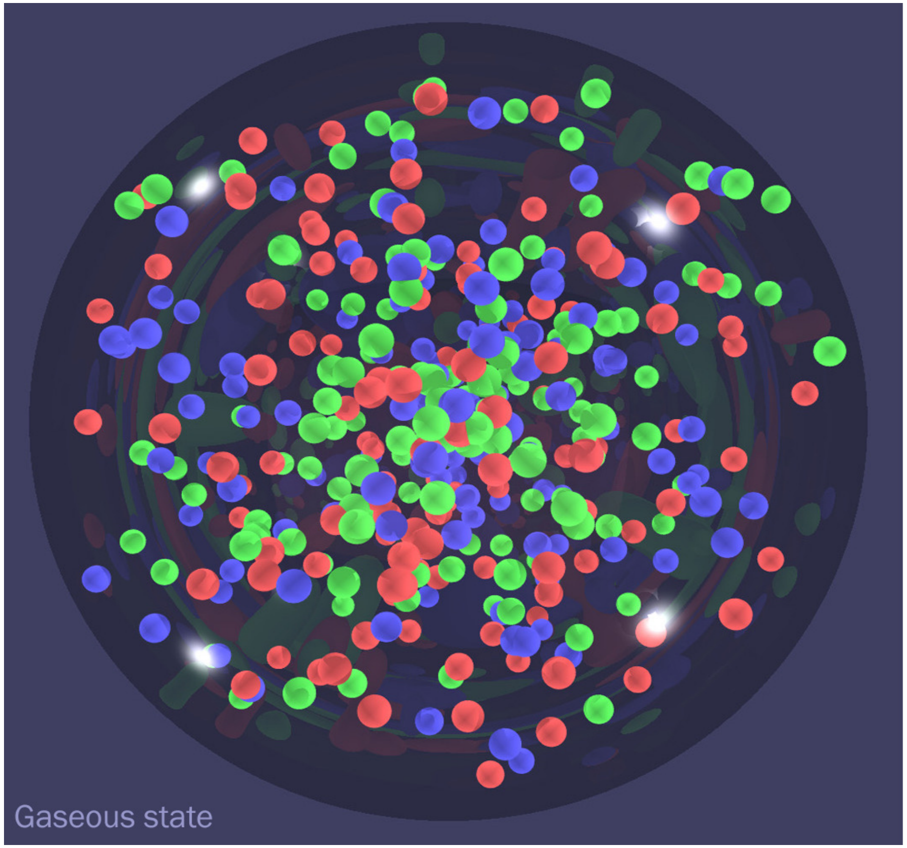


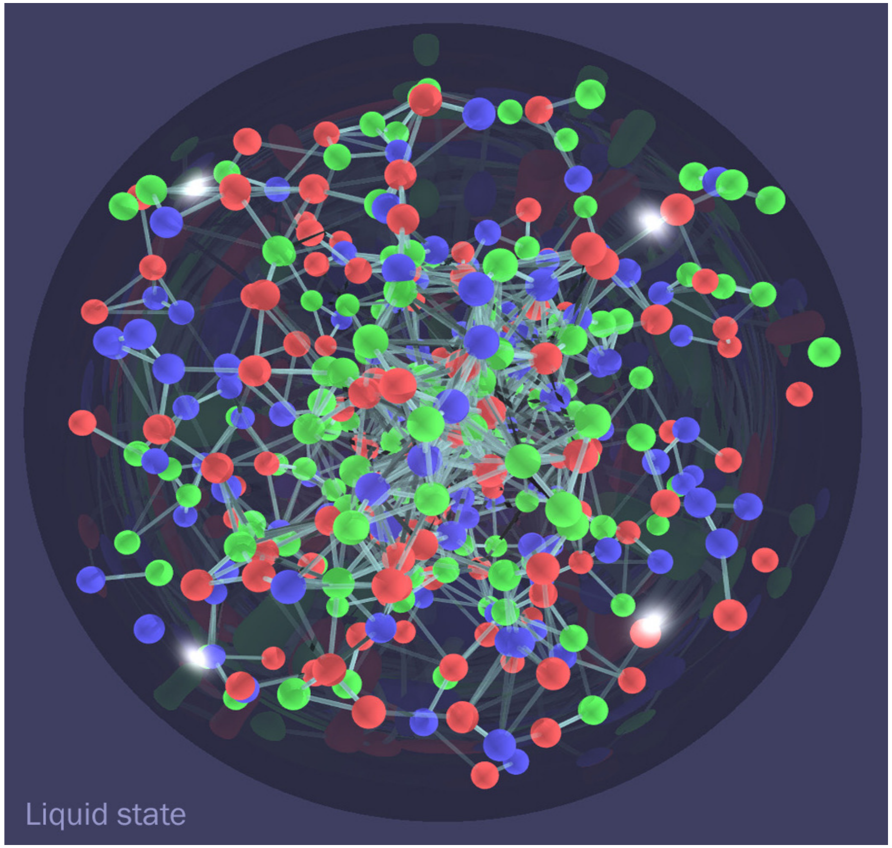


R.J. Fries, QM2004

If phase space is filled with partons, recombine/coalesce them into hadrons. At $2 < p_T < 6$ GeV/c, baryon enhancement, v_2 number of constituent quark scaling.

Perfect Liquid discovery

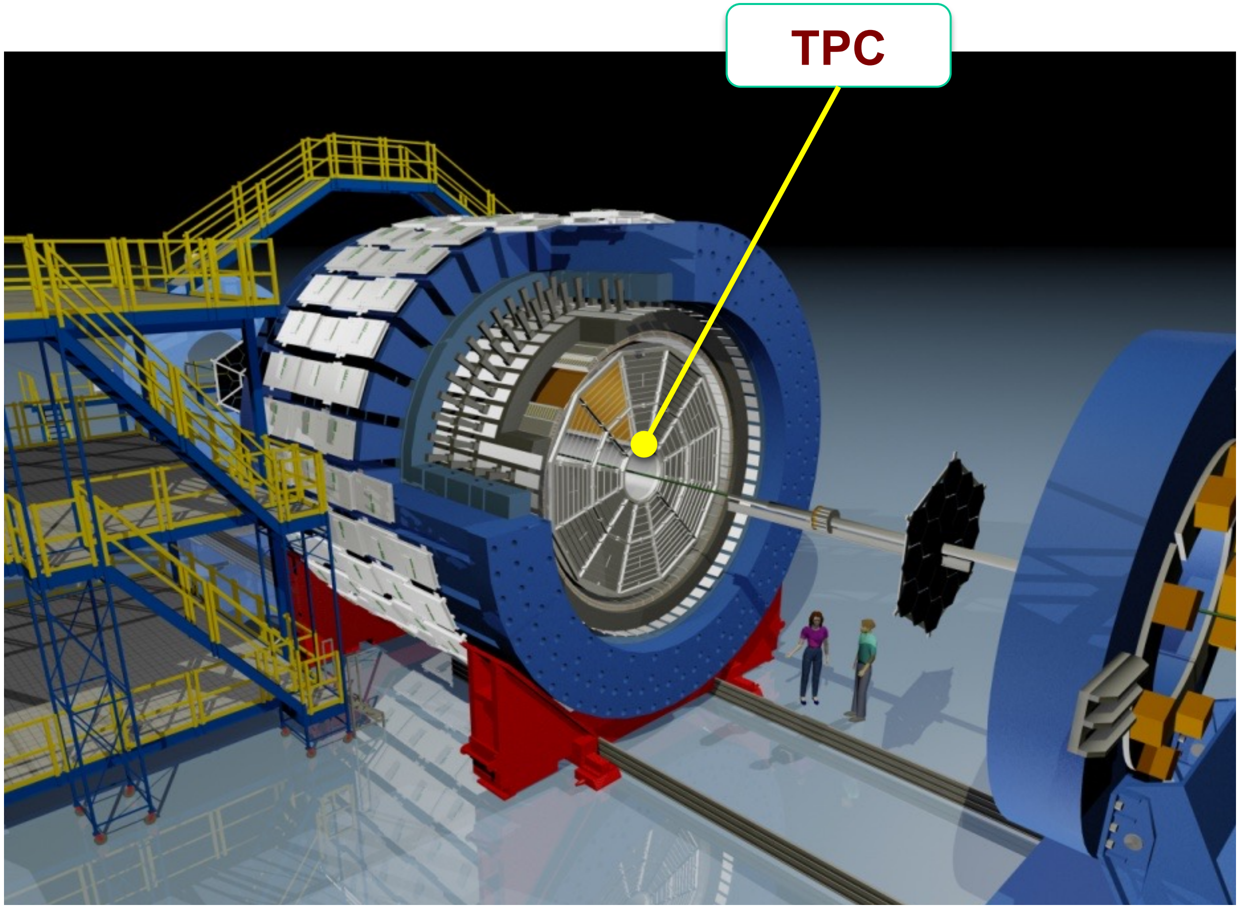




In 2005, BNL announced a discovery of perfect liquid at RHIC

https://www.bnl.gov/newsroom/news.php?a=110303

The STAR Detector

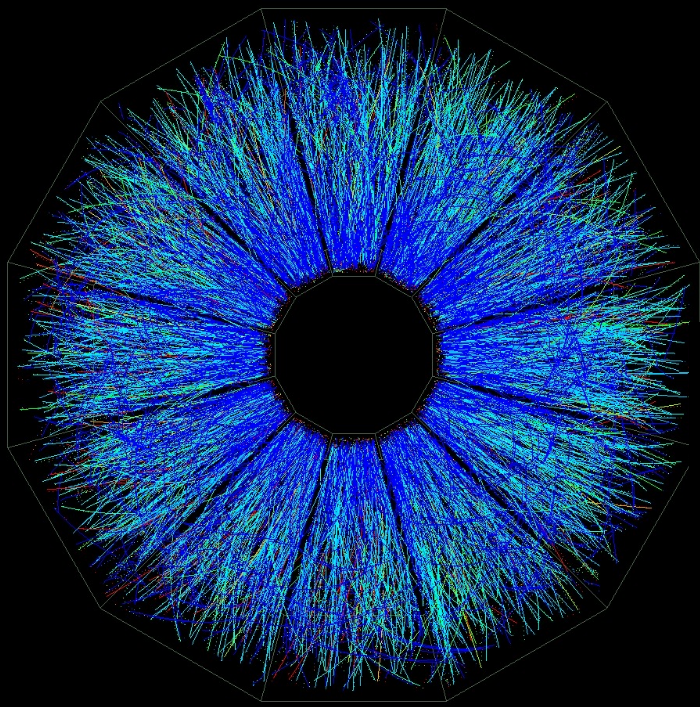


[Solenoidal Tracker at RHIC (1200 tons)]

Time Projection Chamber

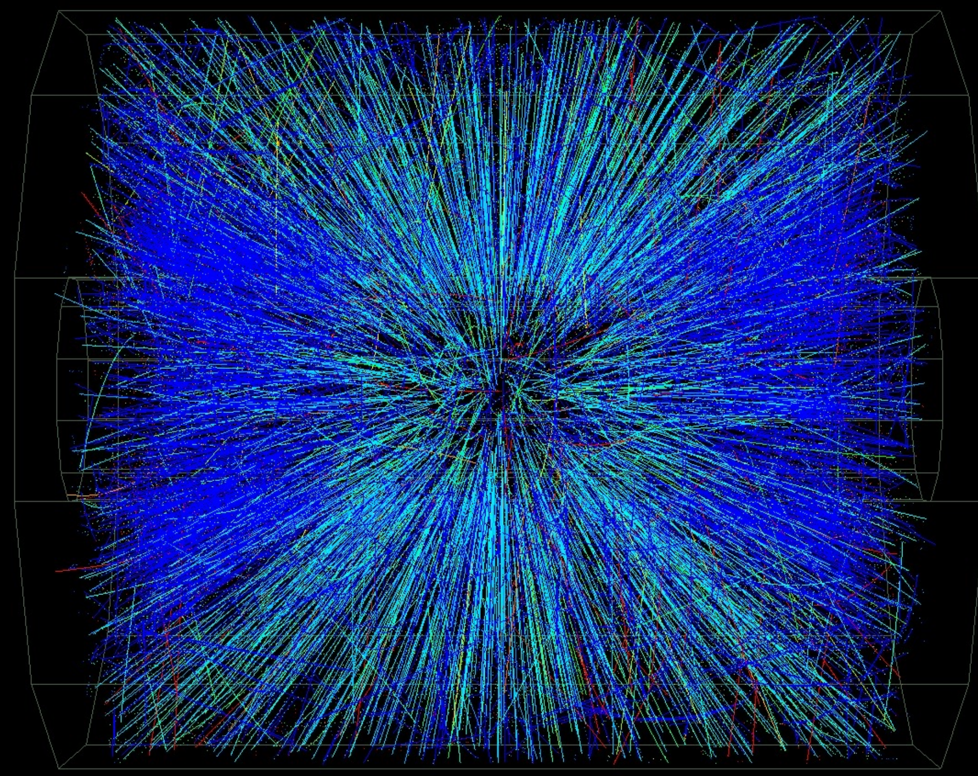
1. **Second largest device of its kind ever built**
2. **3D camera to take photos of the collisions**
3. **Measure ionization energy loss (dE/dx) and momentum**

$^{197}Au + ^{197}Au$ Collisions at RHIC



Central Event

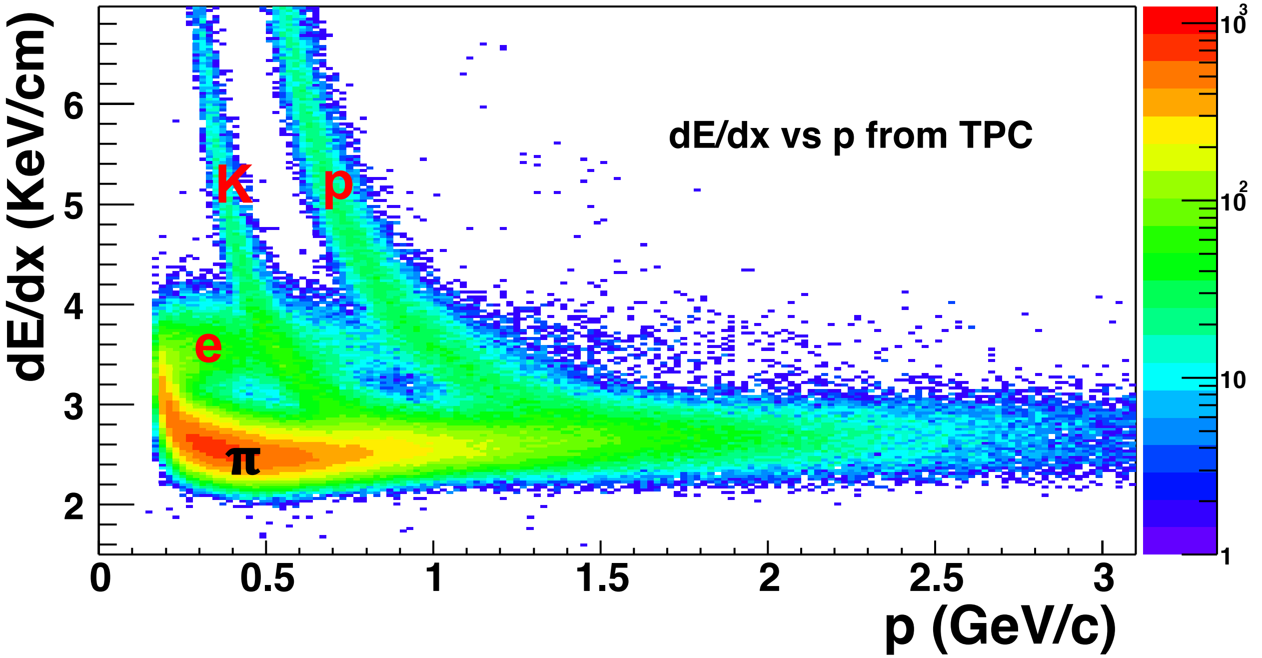
$E = m c^2$



STAR

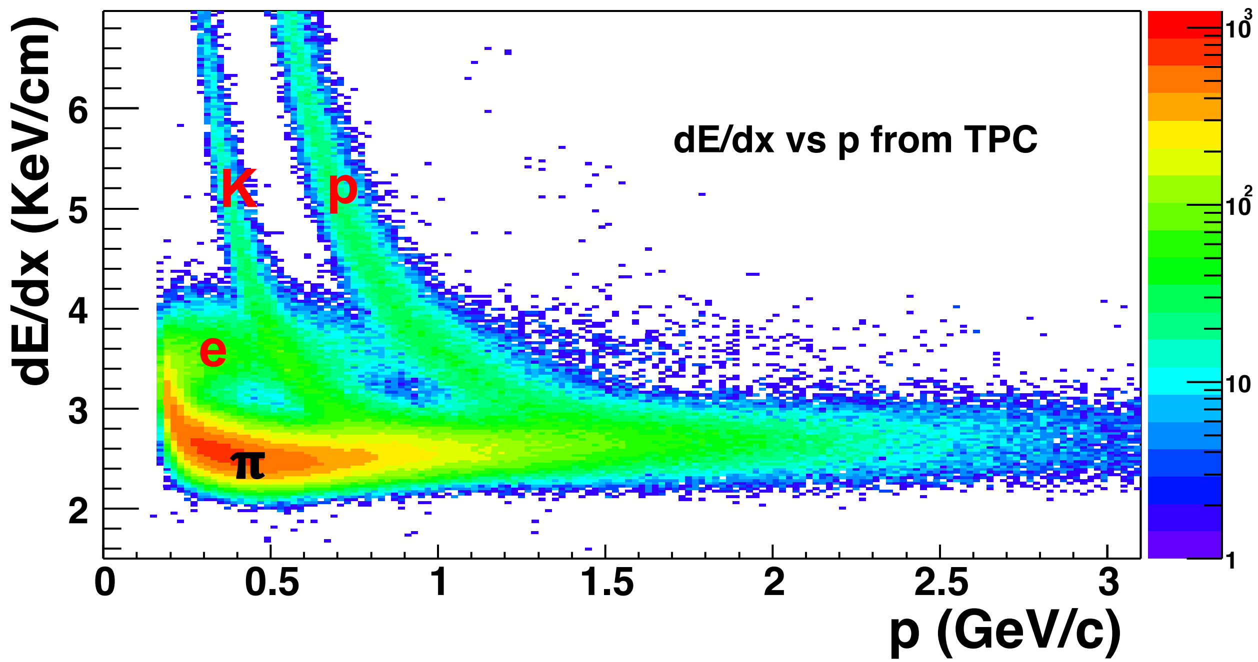
(real-time Level 3)

Particle identification



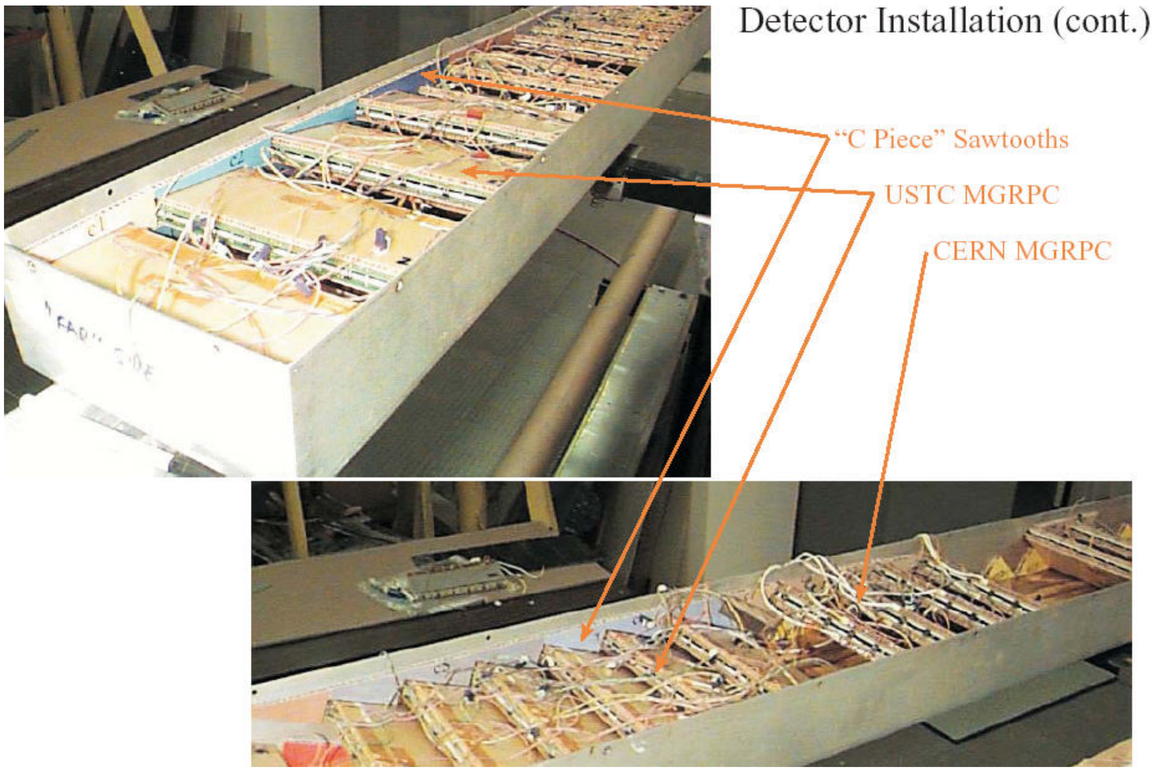
Pion/kaon identification less than 1 GeV/c, proton identification less than 1.5 GeV/c

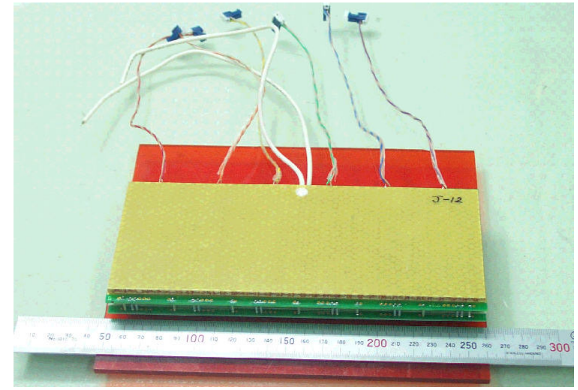
A need to extend particle identification

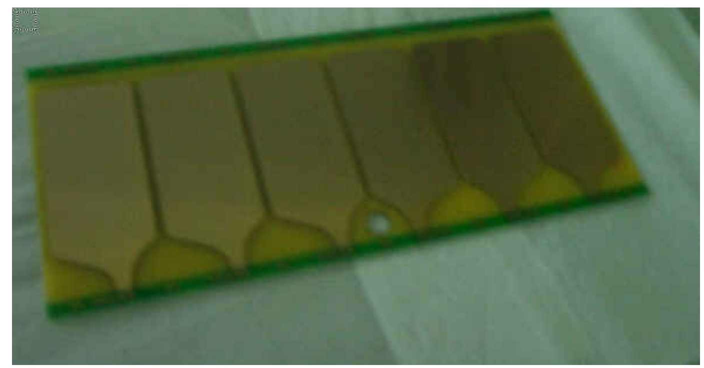


Need new experimental tool to extend particle identification to higher momentum and separate electrons from hadrons

MRPC TOFr 2003





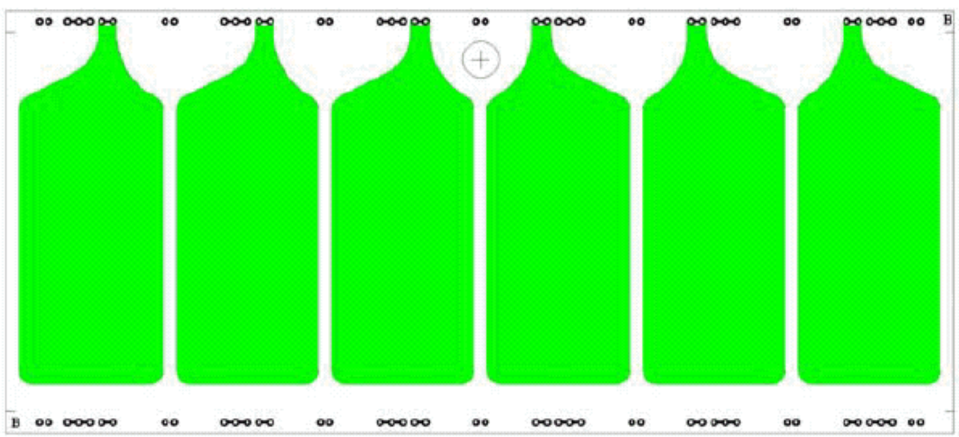


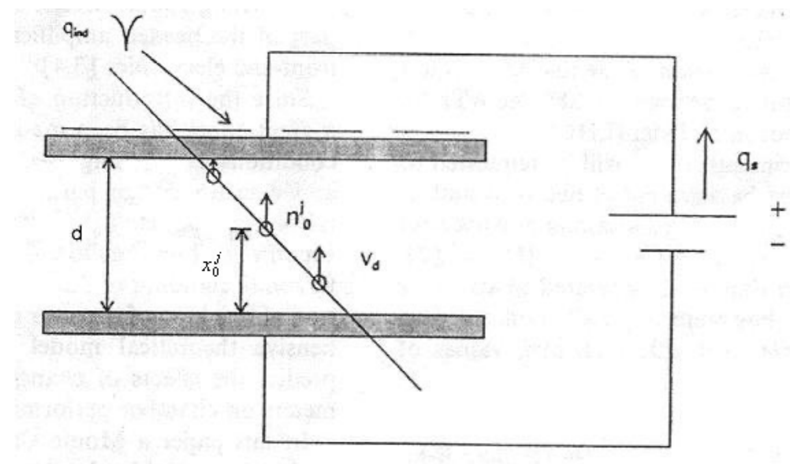
Multigap Resistive Plate Chamber (MRPC) Technology

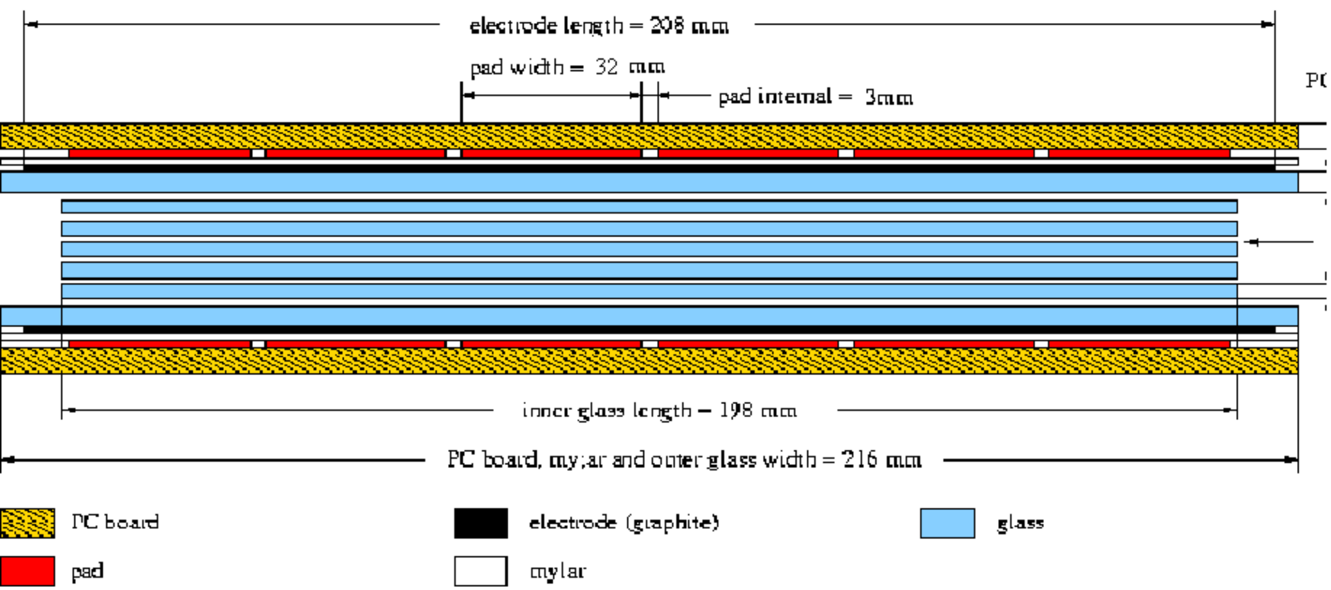
low cost, high timing resolution <100 × 10^{-12} second

A prototype tray (TOFr) was installed in 2002-2003

Structure of MRPC Module



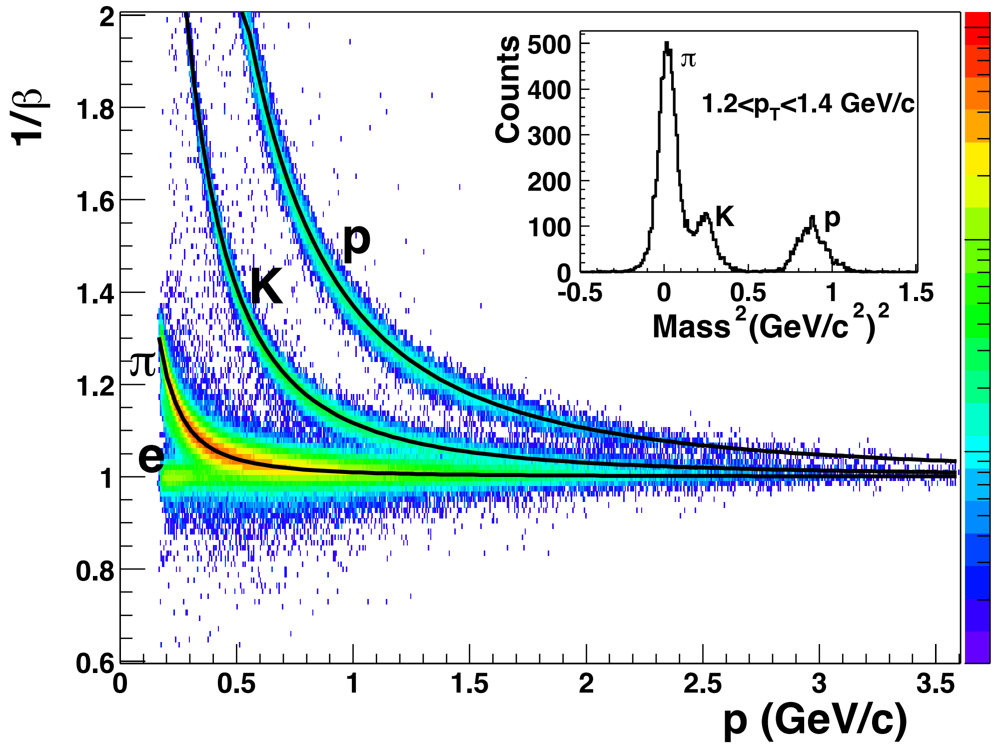




Read out pad size：3.15cm×6.3cm, gap：6×0.22mm

M. Abbrescia et al., Nucl. Instr. and Meth. A 398 (1997) 173-179
M. Abbrescia et al., Nucl. Instr. and Meth. A 431 (1999) 413-427

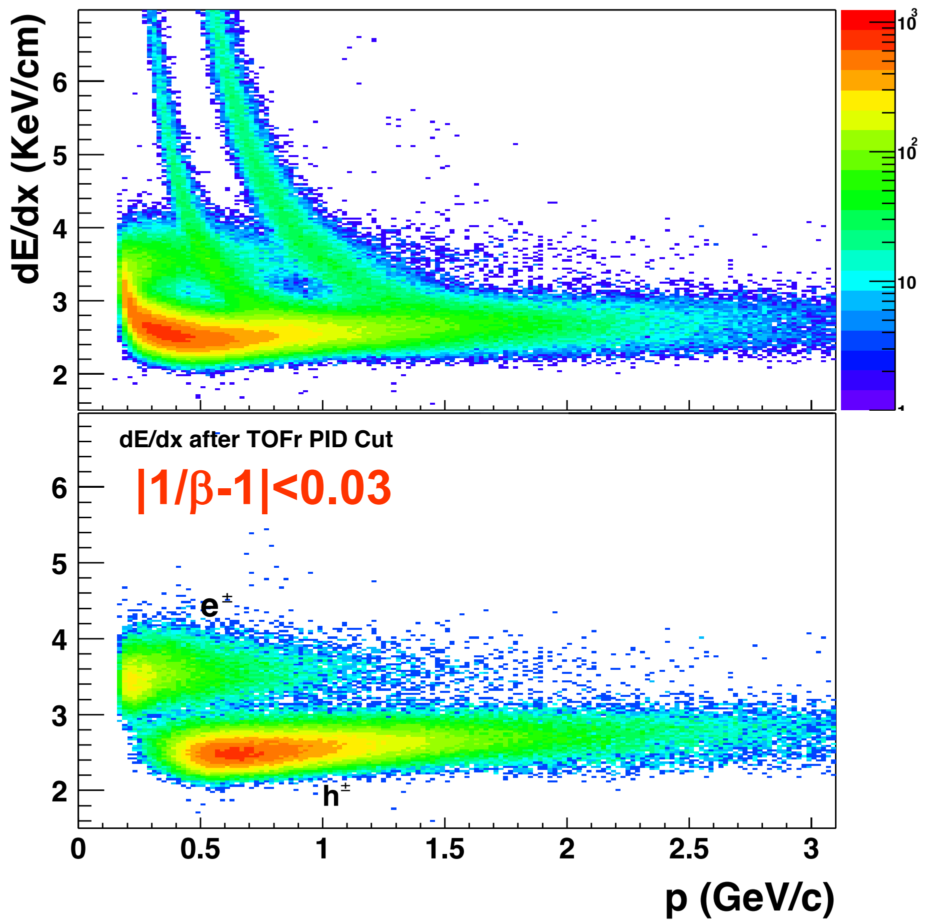
Particle identification from TOFr



STAR Collaboration, PLB616(2005)8

Curve: $$\frac{1}{\beta} = \sqrt{\frac{m^2}{p^2}+1}$$

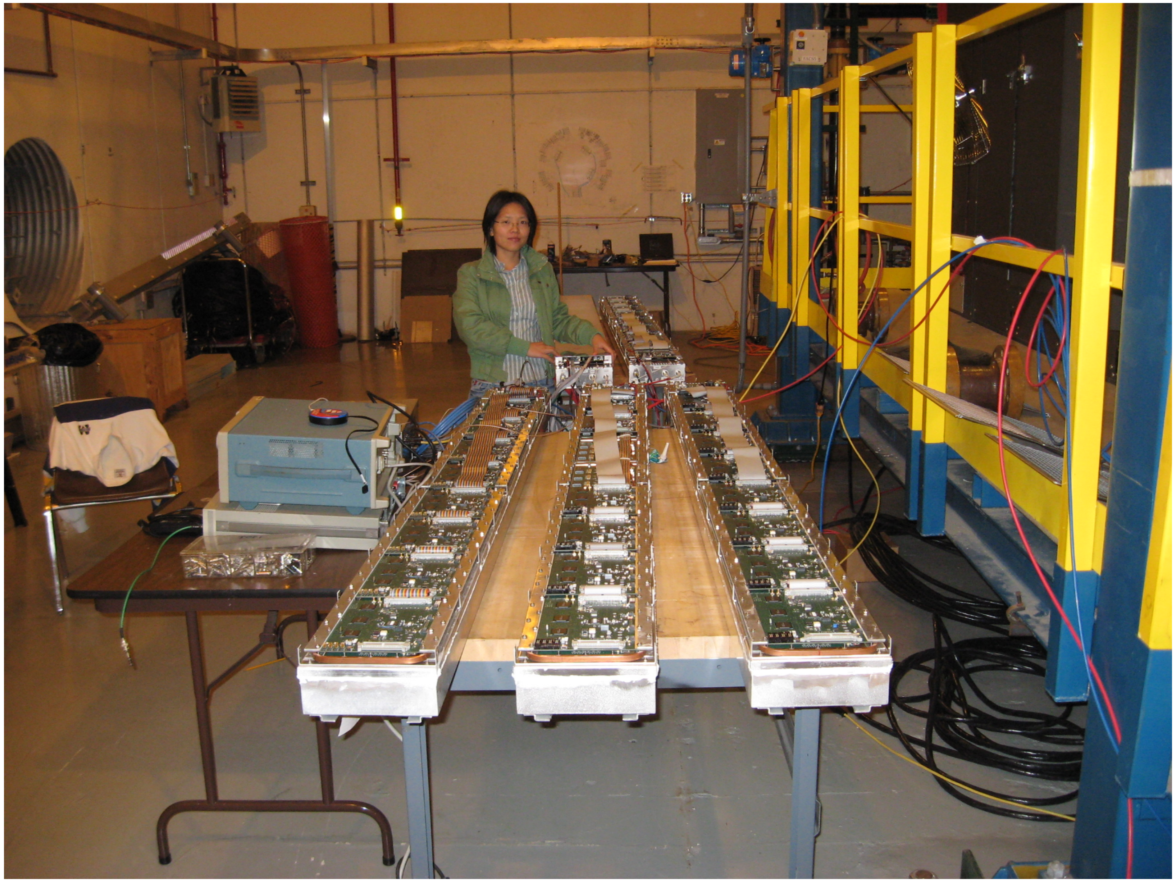
Electron identification



STAR Collaboration, PRL94(2005)062301

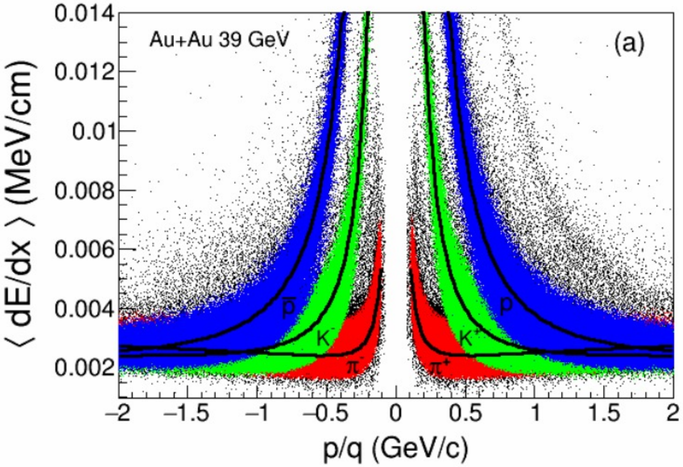
Clean electron samples!

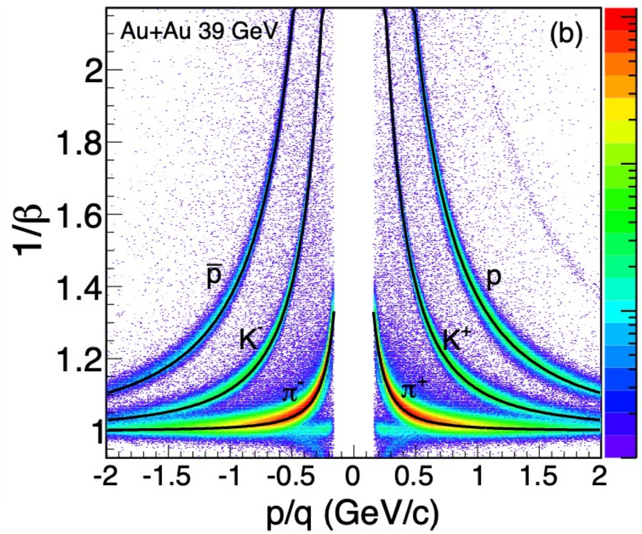
Time of Flight Detector upgrade

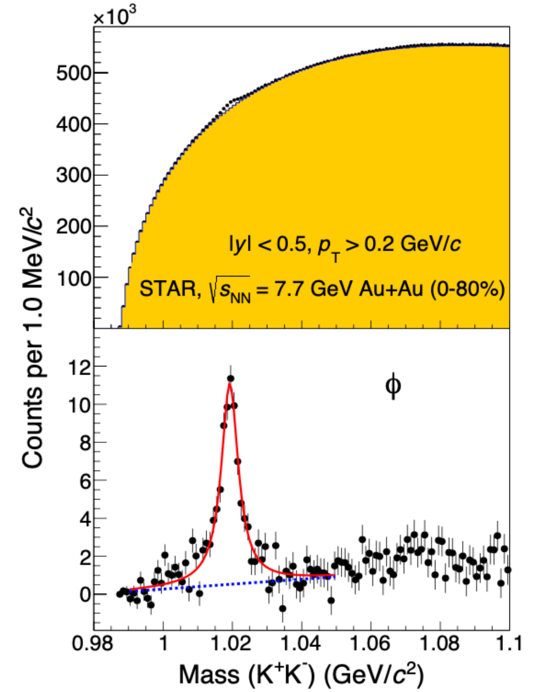


US-China Collaboration, 120 units in total:
2008: 4%; 2009: 72%; 2010: 100%

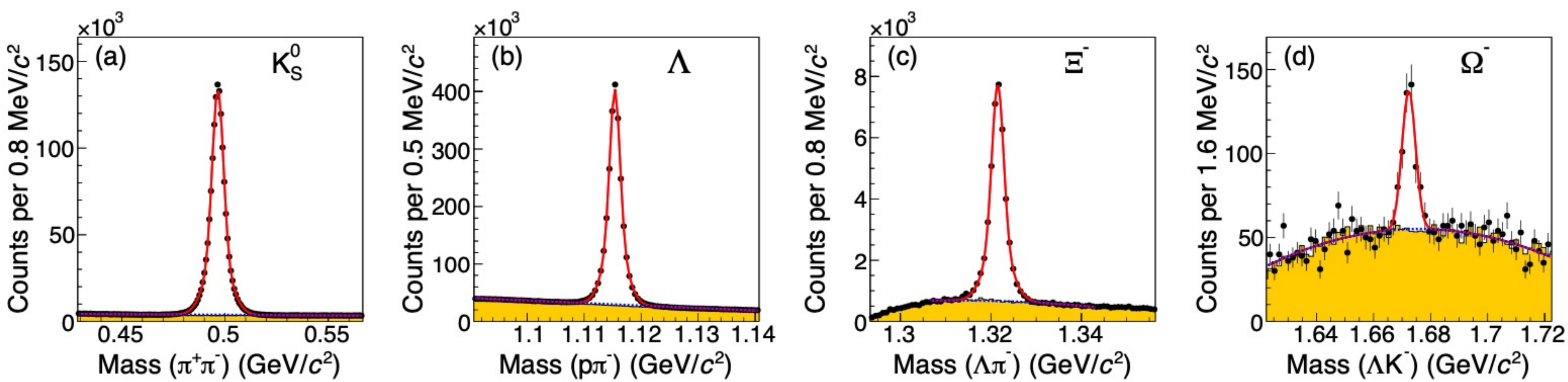
Beautiful particle identification at STAR



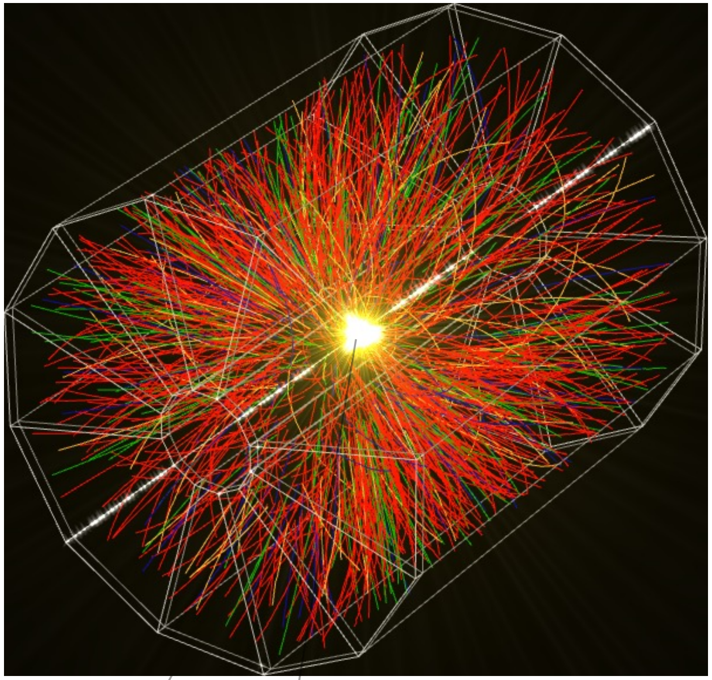


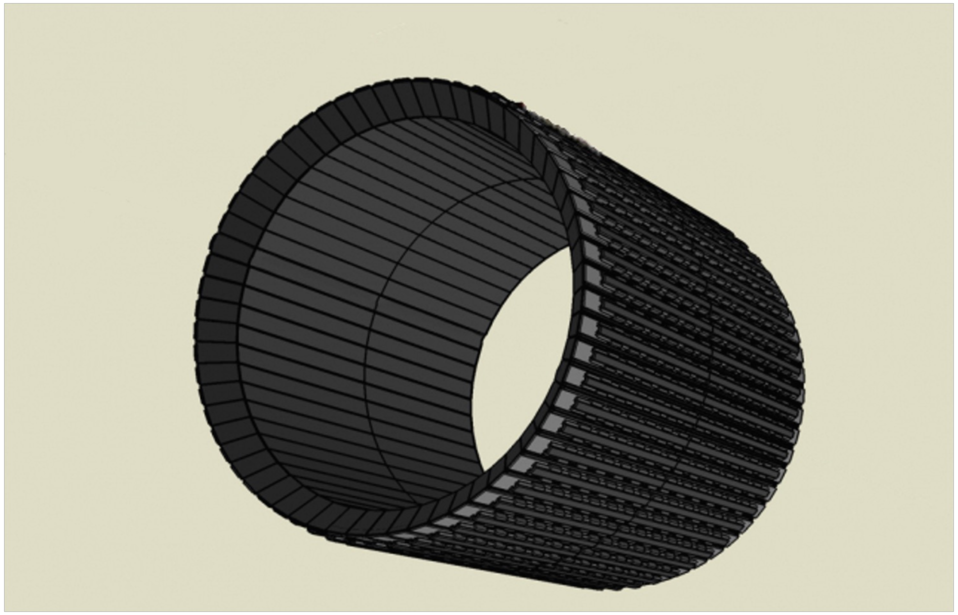


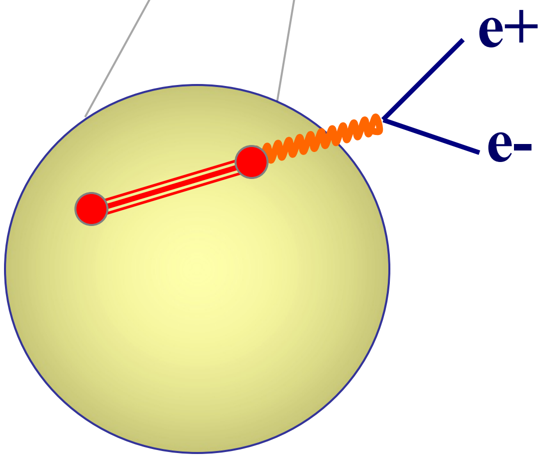
STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), |y|<0.5



The electron-positron tomography

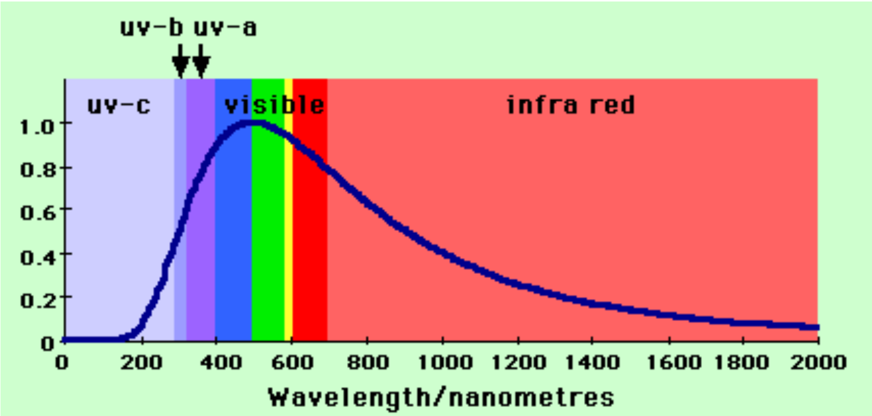


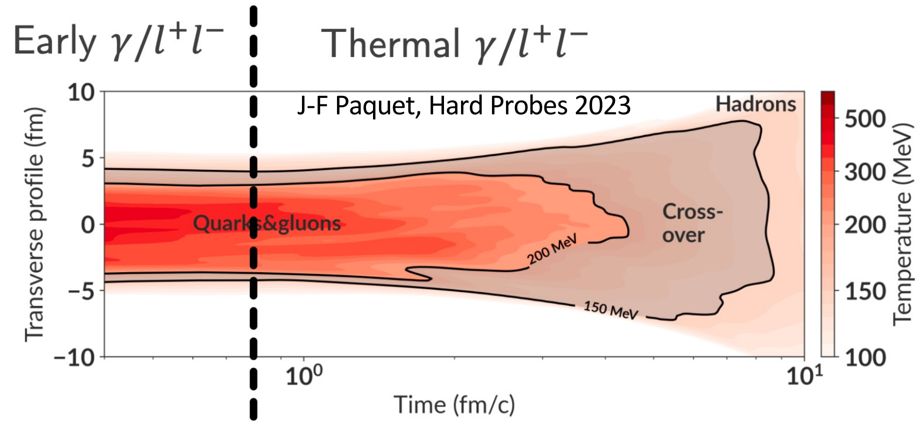




The Time of Flight Detector completes the experimental tool for electron-positron (dielectron) tomography.

Thermal dileptons

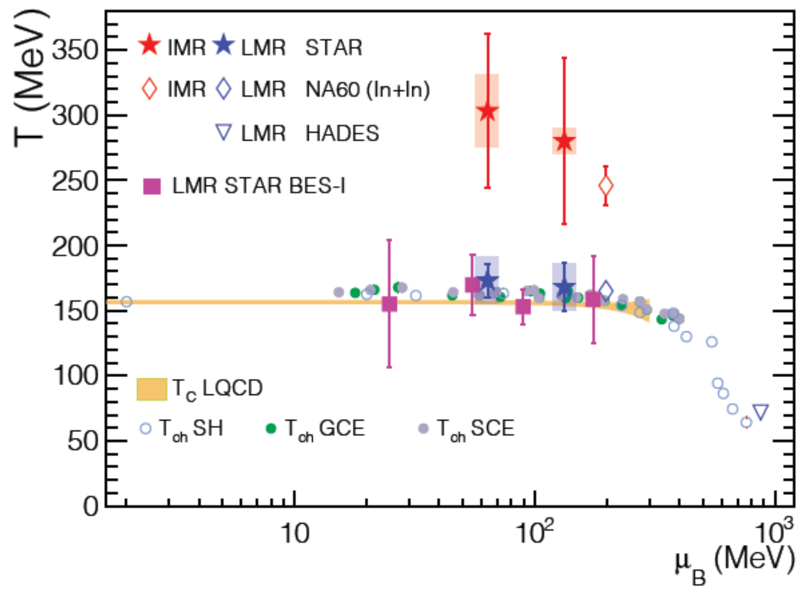




Sun emission spectrum:
Photon energy a few electron volts.

Quark-Gluon Plasma emission spectrum: photon energy a few 10^9 electron volts

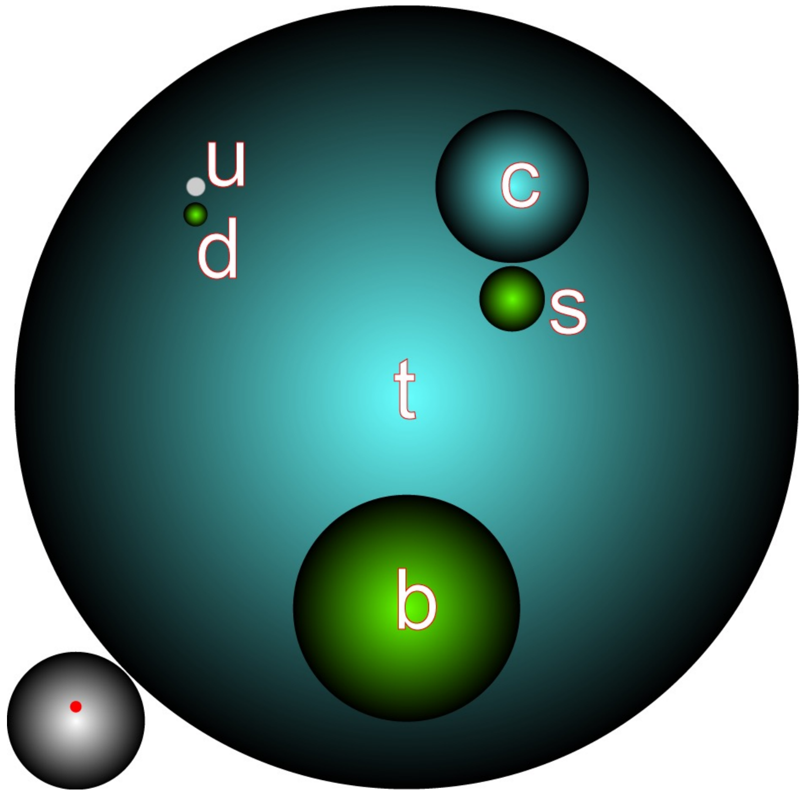
Hottest matter in the universe: a few trillion degree Celsius!



arXiv: 2402.01998, submitted to Nature

My journey continues

We would like to use heavy flavor particles to probe medium properties.



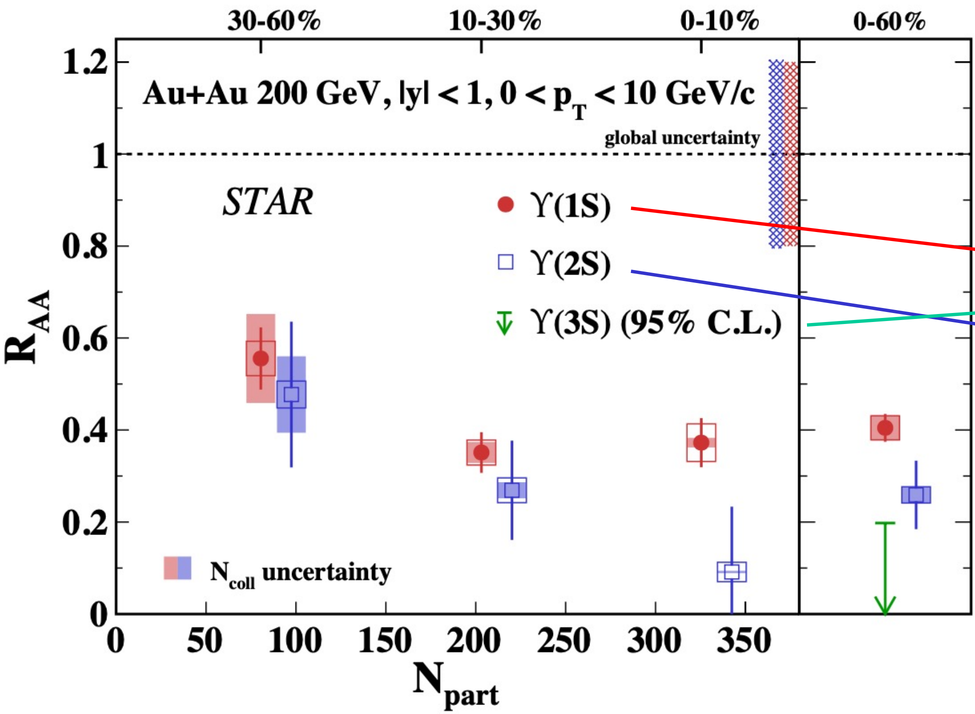
Muon Telescope Detector

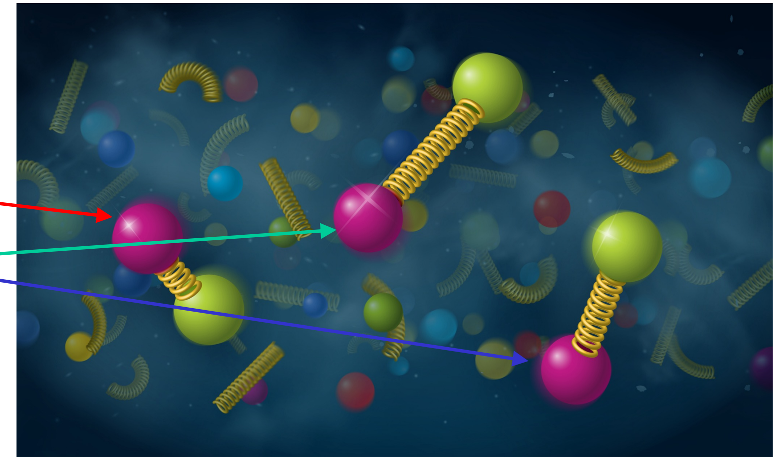
Muon Telescope Detector
– MRPC technology

Measuring quarkonia, bound states composed of a heavy quark and anti-heavy quark held together by gluons

Sequential Upsilon suppression

PRL 130 (2023) 112301





https://www.bnl.gov/newsroom/news.php?a=121097

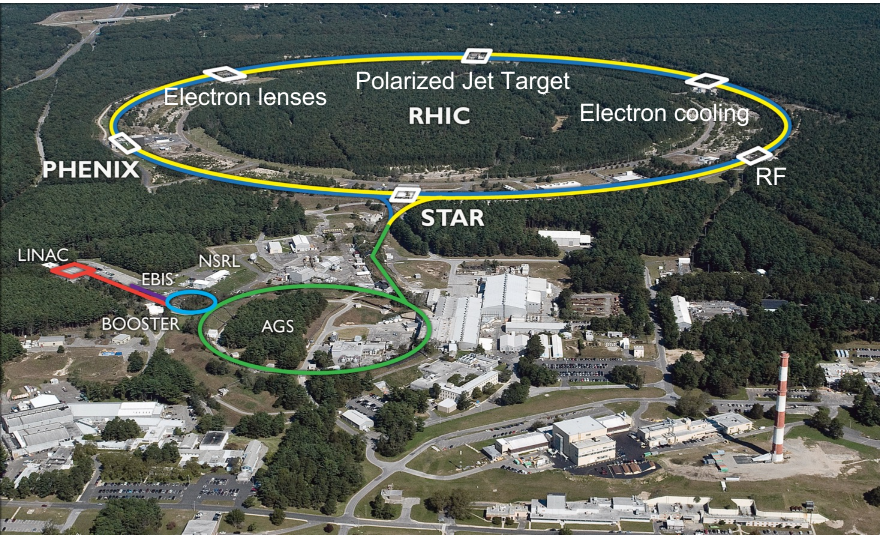
ϒ(1S) R_{AA} = 0.40 ± 0.03 (stat.) ± 0.03 (sys.) ± 0.07 (norm.)

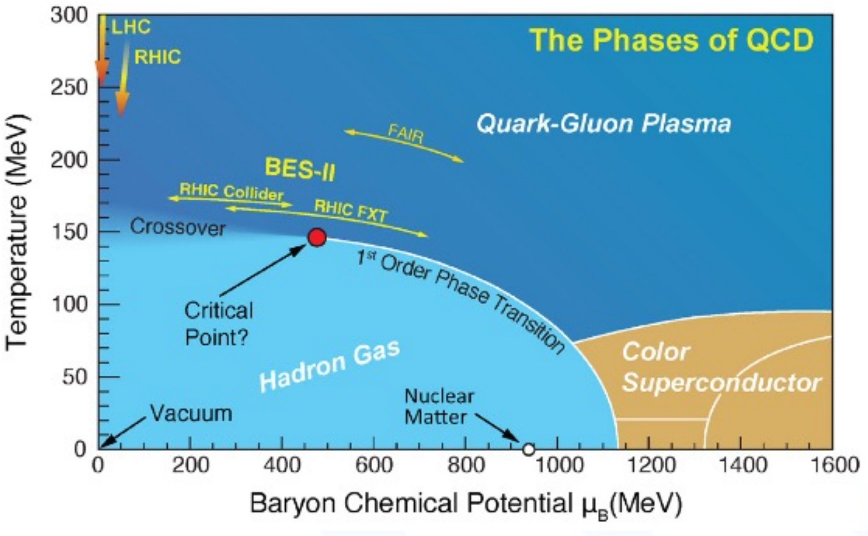
ϒ(2S) R_{AA} = 0.26 ± 0.07 (stat.) ± 0.02 (sys.) ± 0.04 (norm.)

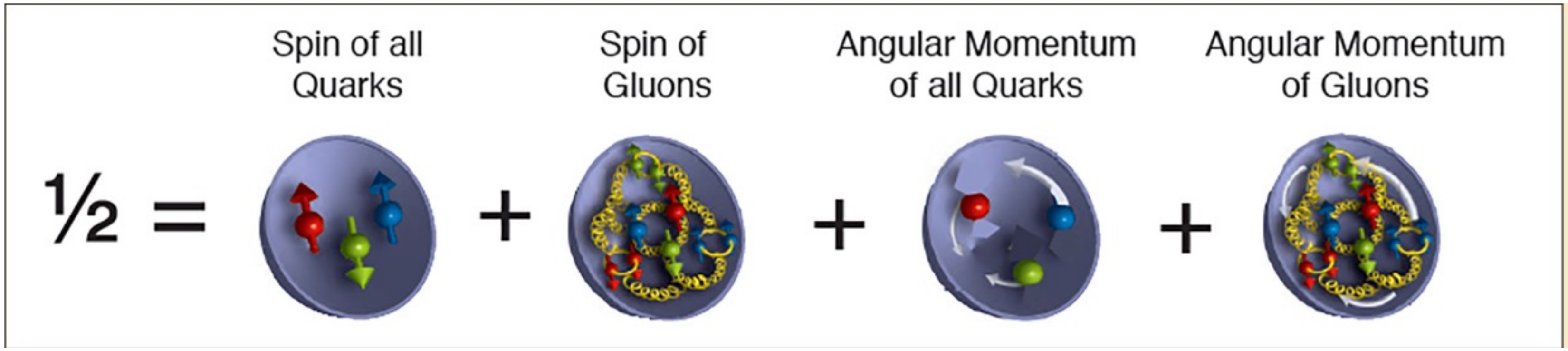
ϒ(3S) R_{AA} upper limit: 0.20 at a 95% confidence level

Sequential ϒ suppression at RHIC

The mission of RHIC







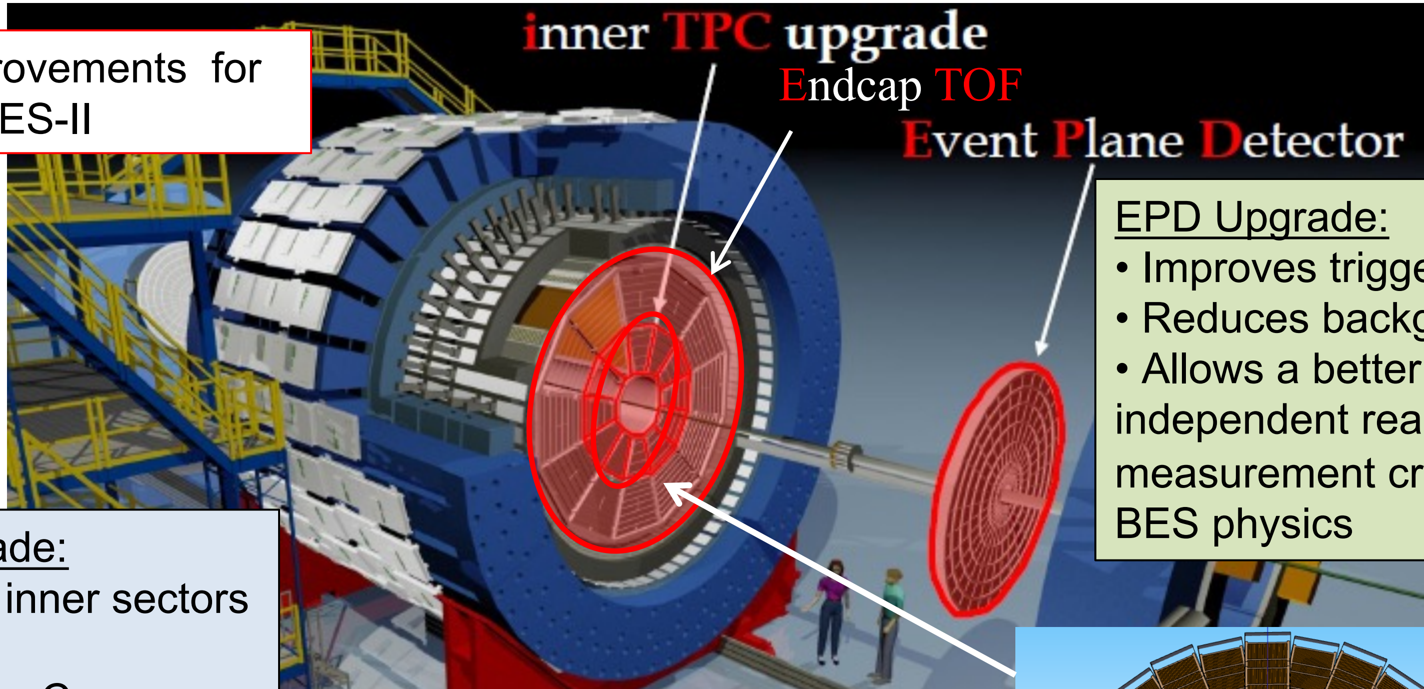
To probe the inner workings of the Quark-Gluon Plasma

To map the phase diagram of QCD

To study the spin puzzle of proton

STAR detector at Beam Energy Scan Phase II (BES-II)

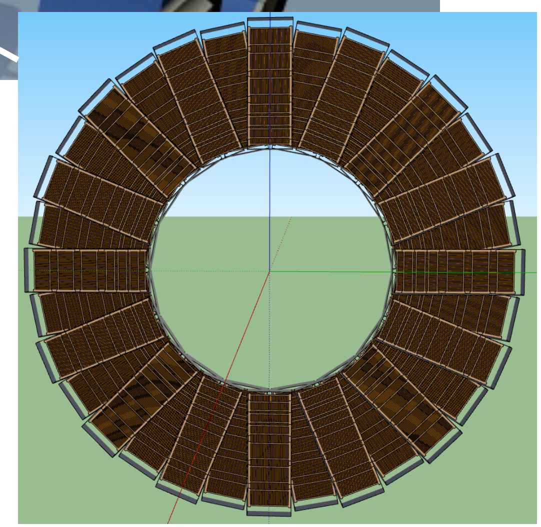
Major improvements for BES-II



EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

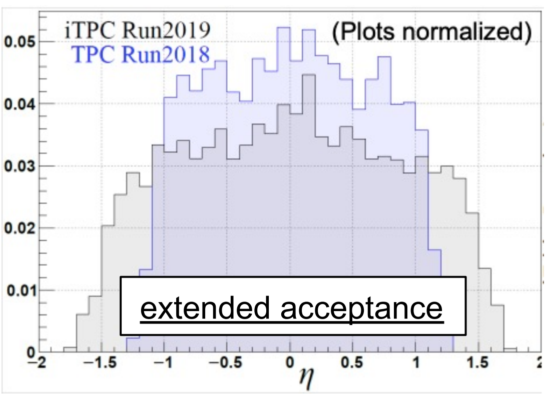
iTPC Upgrade:
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut from 125 MeV/c to 60 MeV/c

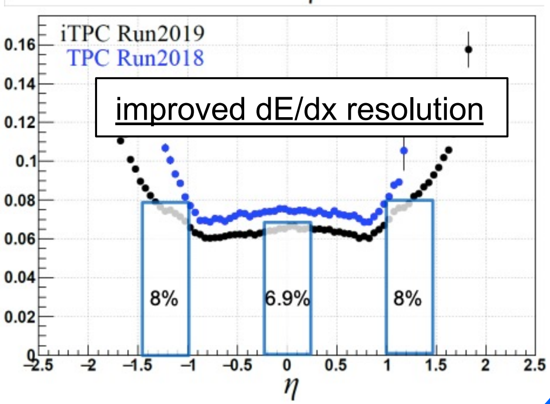
EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



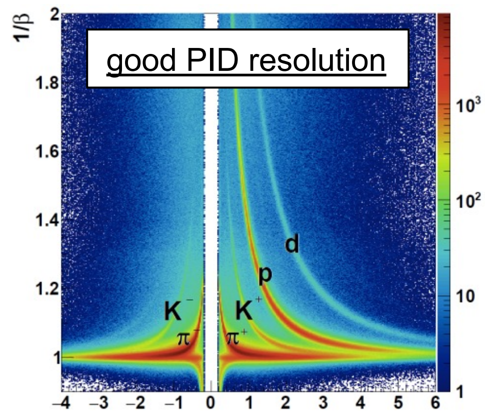
Detector performance

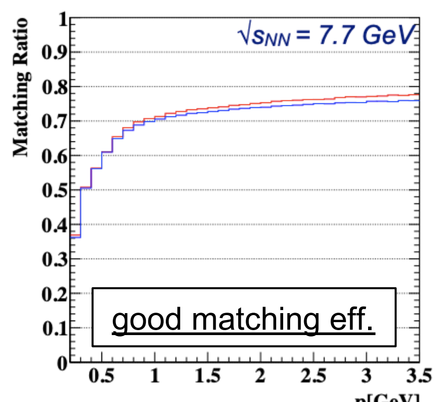
iTPC (2019+)



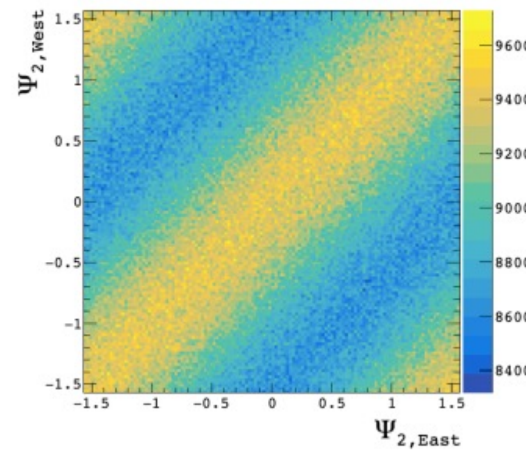


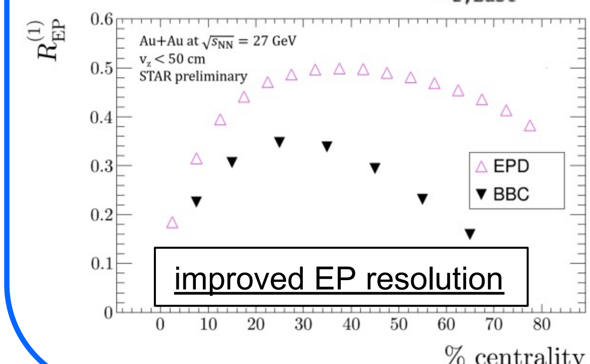
eTOF (2019+)



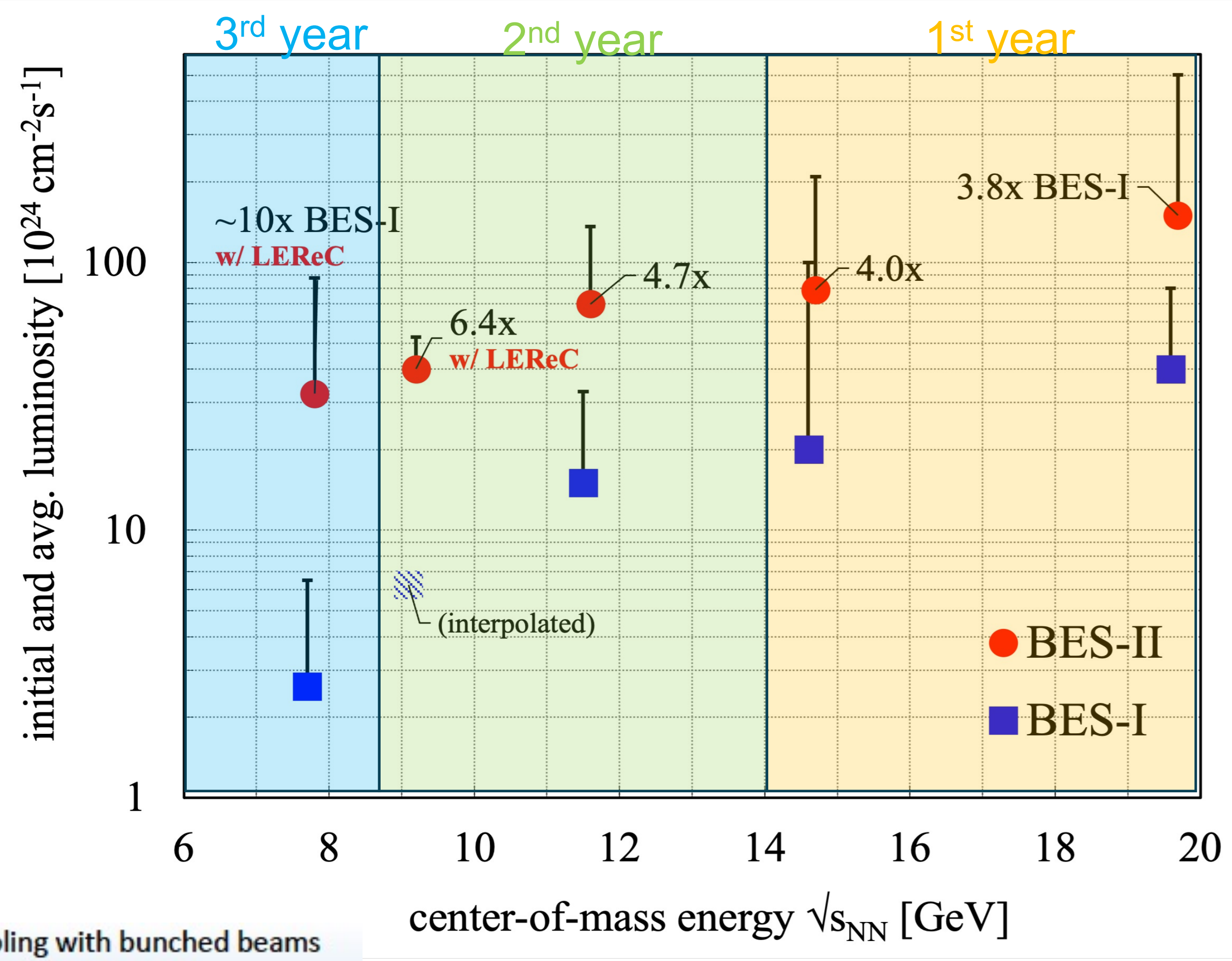


EPD (2018+)





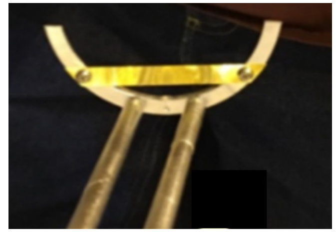
Beam Energy Scan II in 2019-2021

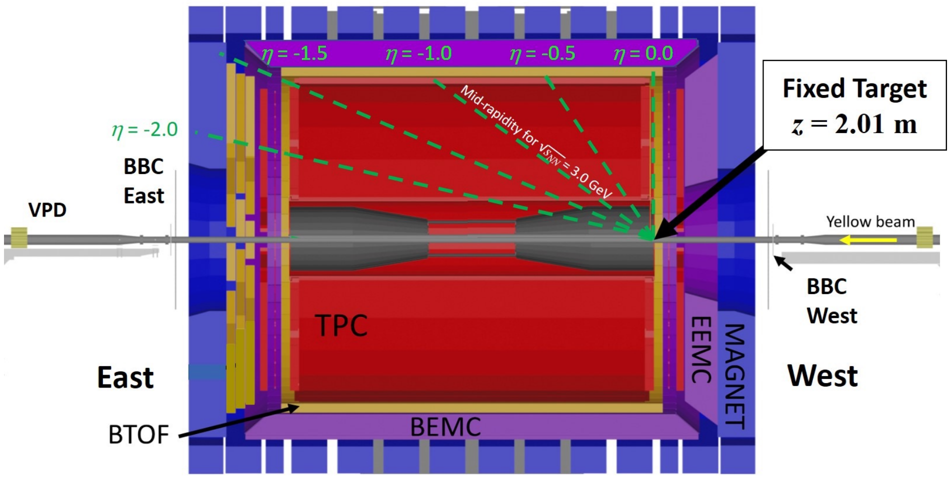


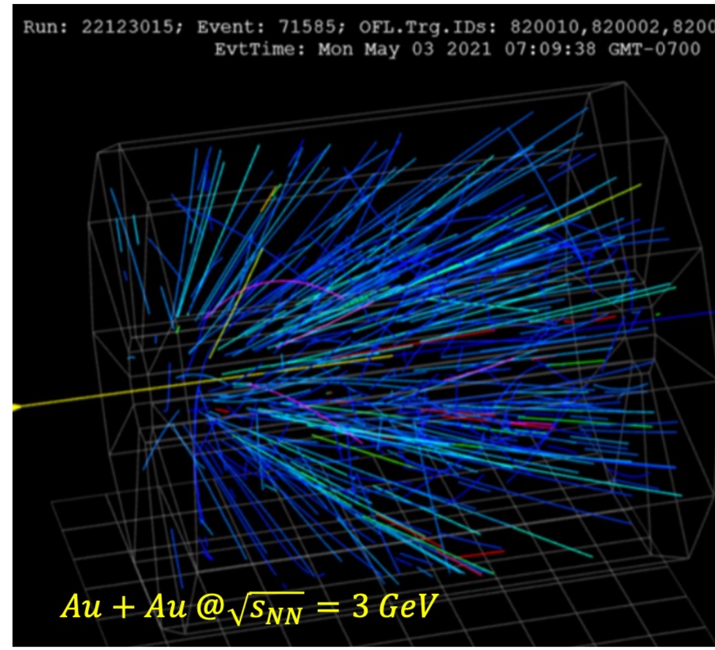
LEReC: First-ever electron cooling with bunched beams
Test case for electron cooling at EIC

LEReC: low energy RHIC electron cooling

STAR as a fixed-target experiment

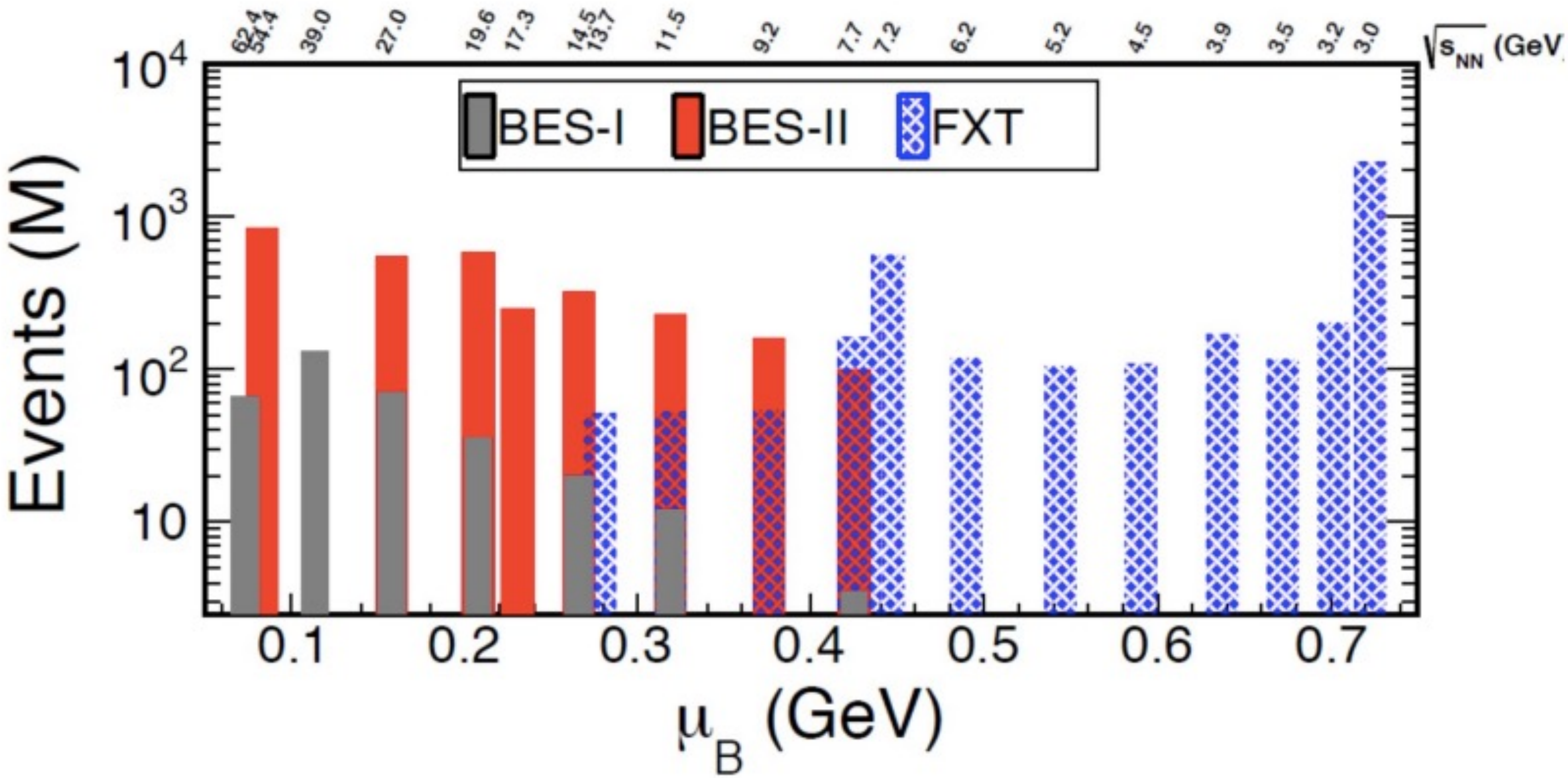






A gold target was installed inside the beam pipe in 2014

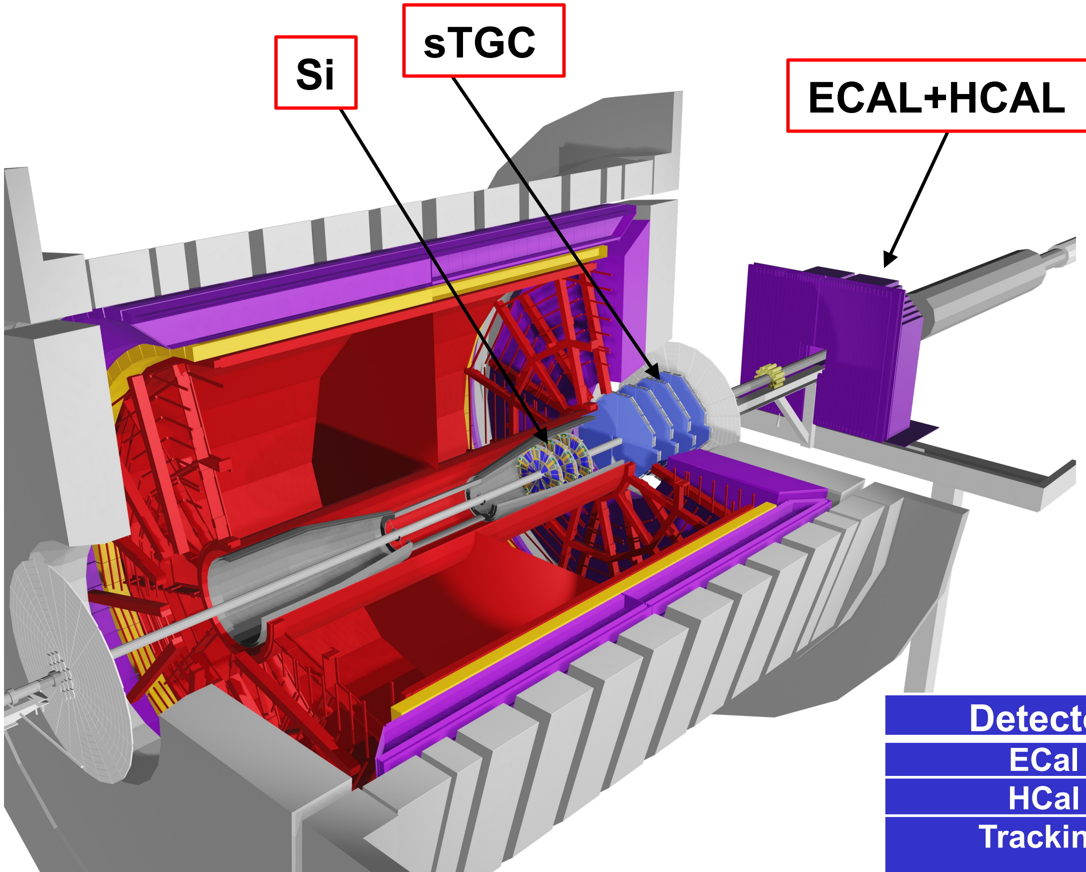
BES-II datasets



A broad μ_B coverage: $20 < \mu_B < 720$ MeV

BES-II data collected at RHIC will cover a broad and interesting range of μ_B for the critical point search

STAR forward upgrades for 2022-2025



At $2.5<\eta<4$

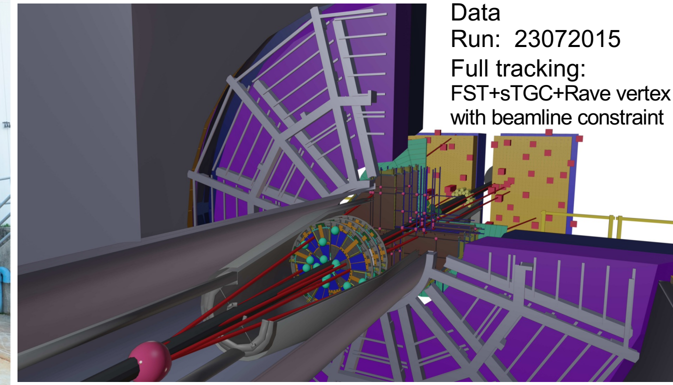
- Jets
- PID (π^0, γ, e, Λ)
- charged particle momentum resolution 20-30% at $0.2<p_T<2$ GeV/c
- event-plane reconstruction and trigger capability

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

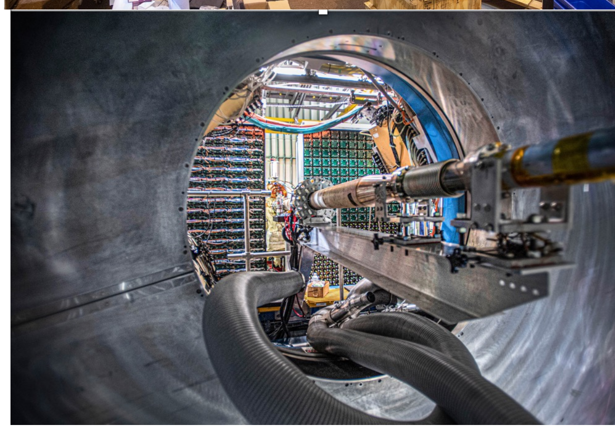
To probe the inner workings of the Quark-Gluon Plasma
To study the spin puzzle of proton, to bridge RHIC physics and EIC science

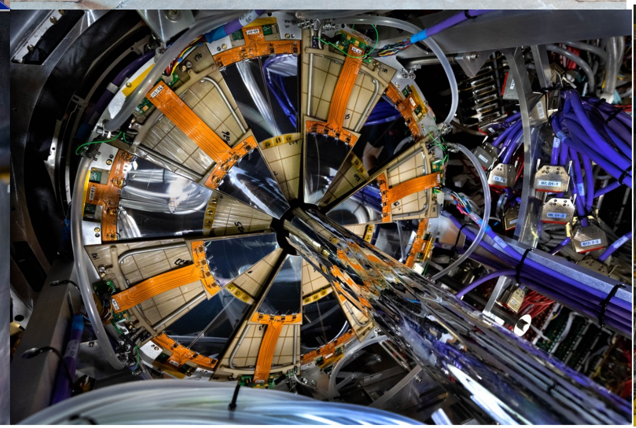
Enormous efforts to make forward upgrades on schedule during pandemic
Successfully commissioned and collected data for Runs 2022 and 2023

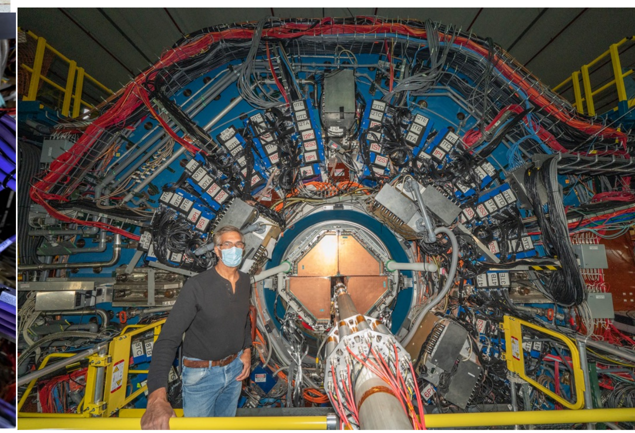
STAR forward upgrades



Zero Field Alignment Data
Run: 23072015
Full tracking:
FST+sTGC+Rave vertex with beamline constraint





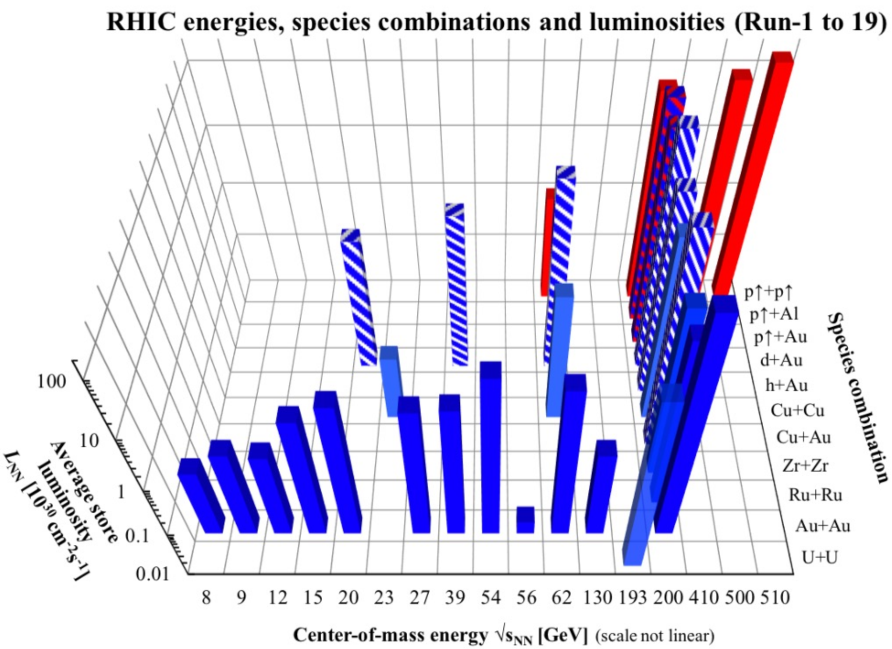


FCS **FST** **sTGC**

It is an amazing journey

Evolution of the STAR Detector

major upgrades over the last twenty years to improve particle identification and vertex reconstruction, and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.



Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\| <1$ Tracking		1999-
Barrel EMC	$\|\eta\| <1$ jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	$1< \eta <2$ jets/π^0/e	(NSF)	2005-
Roman Pots	diffractive		2009-
TOF	PID	(China)	2009-
FMS/Preshower	$2.5< \eta <4.2$	(Russia)	2008-2017
DAQ1000	x10 DAQ rate		2008-
HLT	Online Tracking	(China/Germany)	2012-
FGT	$1< \eta <2$ $W^\pm$		2012-2013
GMT	TPC calibration		2012-
HFT/SSD	open charm	(France/UIC)	2014-2016
MTD	muon ID	(China/India)	2014-
EPD	event plane	(China)	2018-
RHICf	$\eta >5$ π^0	(Japan)	2017
iTPC	$\|\eta\| <1.5$ Tracking	(China)	2019-
eTOF	$-2< \eta <-1$ PID	(Germany/China)	2019-
FCS	$2.5< \eta <4$ calorimeter	(NSF)	2021-
FTS	$2.5< \eta <4$ Tracking	(NCKU/SDU)	2021-

Zhangbu Xu, STAR Collaboration meeting, September 2020

STAR is a discovery machine

RHIC Scientists Serve Up "Perfect" Liquid
https://www.bnl.gov/newsroom/news.php?a=110303

Exotic Antimatter Detected at Relativistic Heavy Ion Collider
https://www.bnl.gov/newsroom/news.php?a=111075

RHIC Physicists Nab New Record for Heaviest Antimatter
https://www.bnl.gov/newsroom/news.php?a=111259

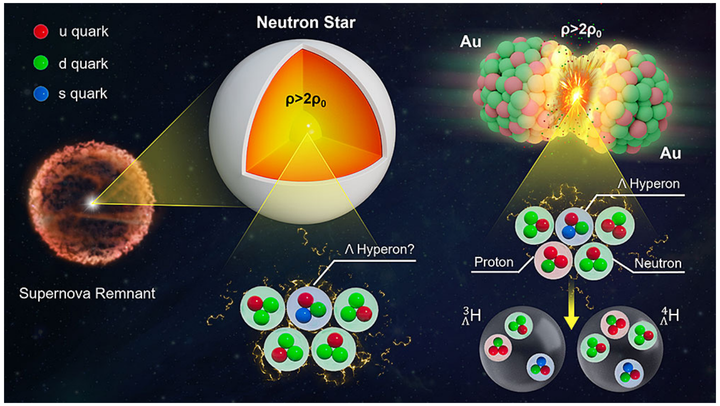
Physicists Measure Force that Makes Antimatter Stick Together
https://www.bnl.gov/newsroom/news.php?a=111786

'Perfect Liquid' Quark-Gluon Plasma is the Most Vortical Fluid
https://www.bnl.gov/newsroom/news.php?a=112068

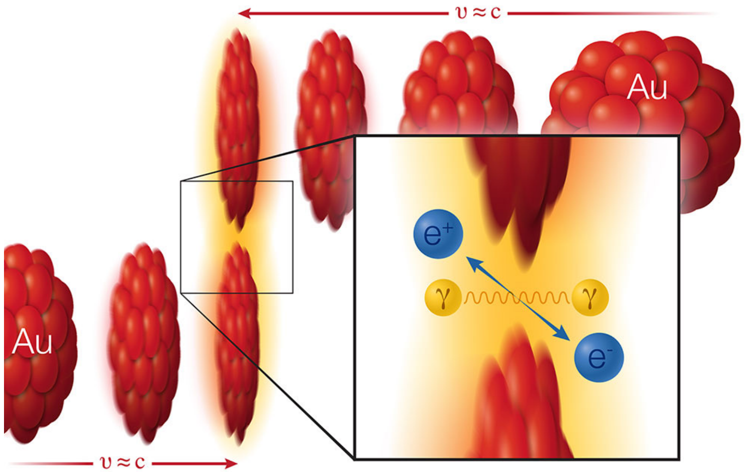
'Strange' Glimpse into Neutron Stars and Symmetry Violation
https://www.bnl.gov/newsroom/news.php?a=116983

Collisions of Light Produce Matter/Antimatter from Pure Energy
https://www.bnl.gov/newsroom/news.php?a=119023

…



Picture credit:
BNL news article
https://www.bnl.gov/newsroom/news.php?a=121192



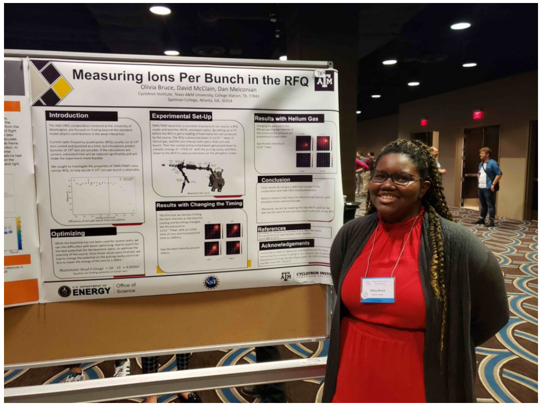
The journey continues with both existing and future data sets

Workforce

People are essential to accomplishing the goals in all areas of physics described in the Long Range Plan.

Programs such as the NSF REU and DOE SULI are essential to attracting talented students to nuclear science.

Central to our proposals is the necessity to reduce barriers to participation in nuclear science.



Our community is committed to establishing and maintaining an environment where all feel welcome and are treated with respect and dignity.

The training our students receive is very valuable in industry, national labs, and in critical areas of national need, such as nuclear nonproliferation and security