XXIV International Baldin Seminar
on High Energy Physics Problems 2018

Highlights from the STAR experiment

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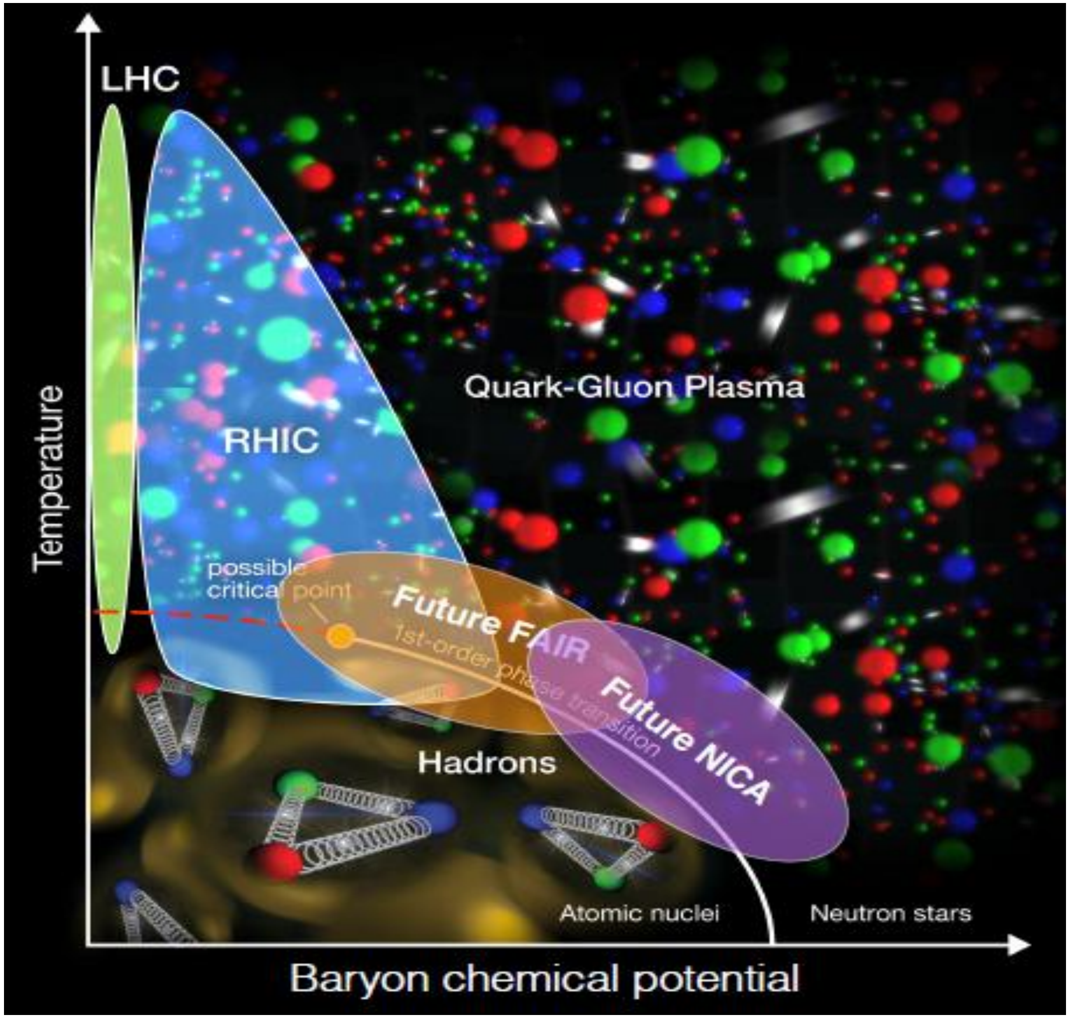
For the STAR collaboration

Joint Institute for Nuclear Research

Outline

- Introduction
- Azimuthal anisotropy
- Heavy flavor
- Global polarization
- Femtoscopy
- Fixed target program
- Hypertriton
- STAR future program

Introduction



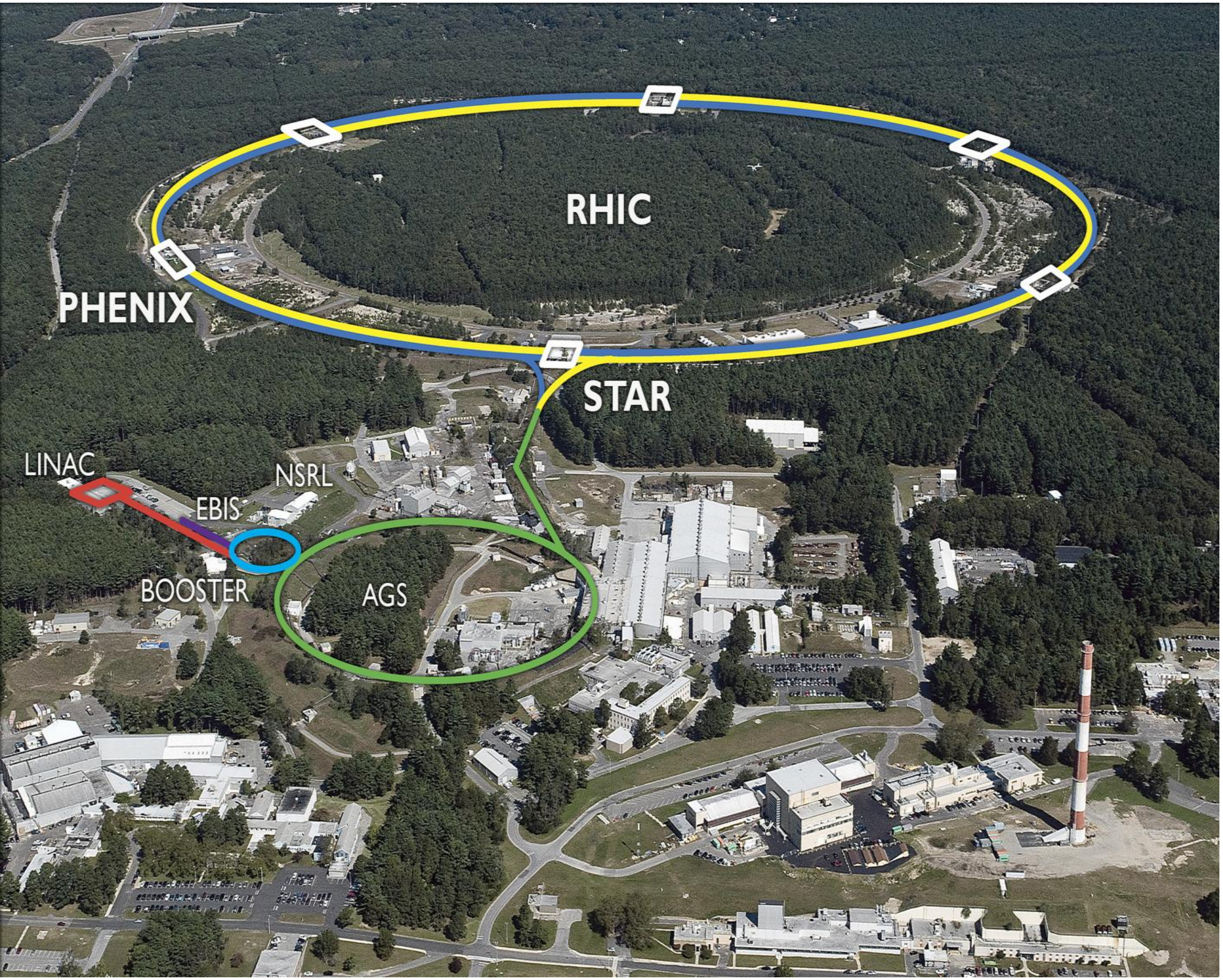
Picture from QM18 presentation by Chun Shen

RHIC Top Energy
p+p, p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U 200 GeV
QCD at high energy density/temperature
Properties of QGP, EoS

Beam Energy Scan
Au+Au 7.7-62 GeV
QCD phase transition
Search for critical point
Turn-off of QGP signatures

Fixed-Target Program
Au+Au 3.0-7.7 GeV
High baryon density regime with 420-720 MeV

Relativistic Heavy Ion Collider



In operation since 1999

3.83 km circumference

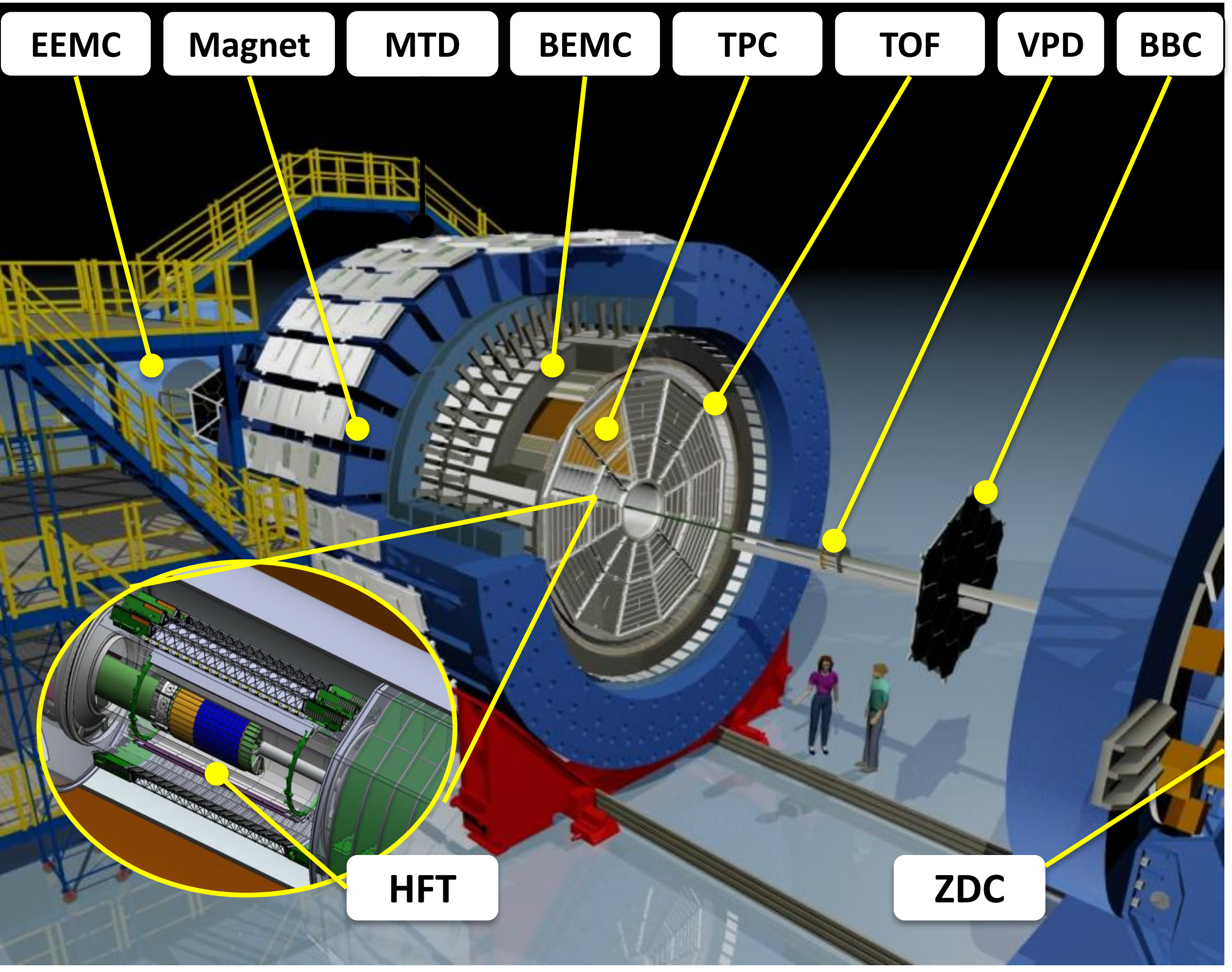
Suitable for p+p, p+A, A+A

Max colliding energy:
200 GeV for Au+Au
510 GeV for p+p

Tuned for exploring QCD matter and it's phase boundary in different colliding systems (Au+Au, U+U, p+Al, Cu+Au, Zr+Zr, Ru+Ru)

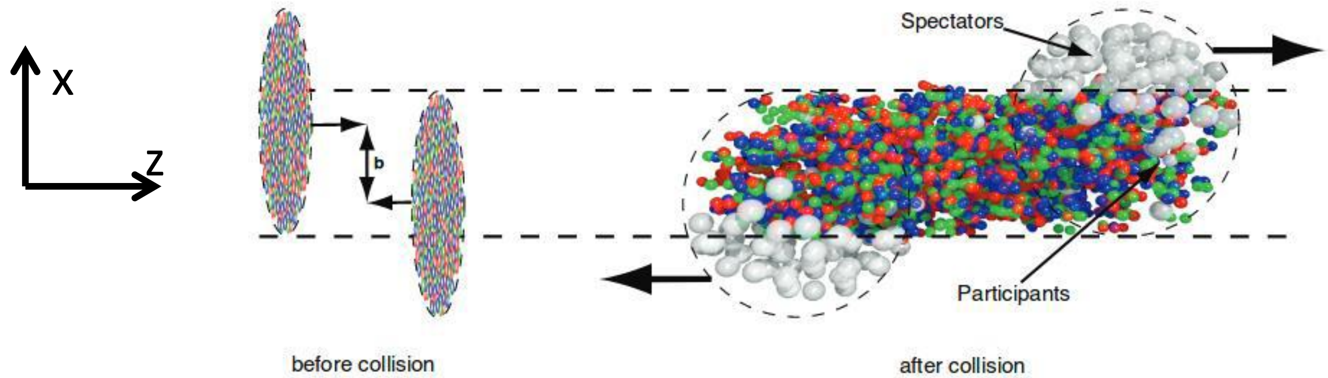
Spin physics on polarized proton-proton beam

STAR detector



- **Tracking and PID (full 2π)**
  - TPC: $|\eta| < 1$
  - TOF: $|\eta| < 1$
  - BEMC: $|\eta| < 1$
  - EEMC: $1 < \eta < 2$
  - HFT (2014-2016): $|\eta| < 1$
  - MTD (2014+): $|\eta| < 0.5$
- **MB Trigger and event plane reconstruction**
  - BBC: $3.3 < |\eta| < 5$
  - EPD(2018+): $2.1 < |\eta| < 5.1$
  - FMS: $2.5 < |\eta| < 4$
  - VPD: $4.2 < |\eta| < 5$
  - ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  - iTPC (2019+): $|\eta| < 1.5$
  - eTOF (2019+): $-1.6 < \eta < -1$
  - FCS (2021+): $2.5 < |\eta| < 4$
  - FTS (2021+): $2.5 < |\eta| < 4$

Azimuthal anisotropy in heavy ion collisions



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\varphi - \Psi_r)\right]\right)$$

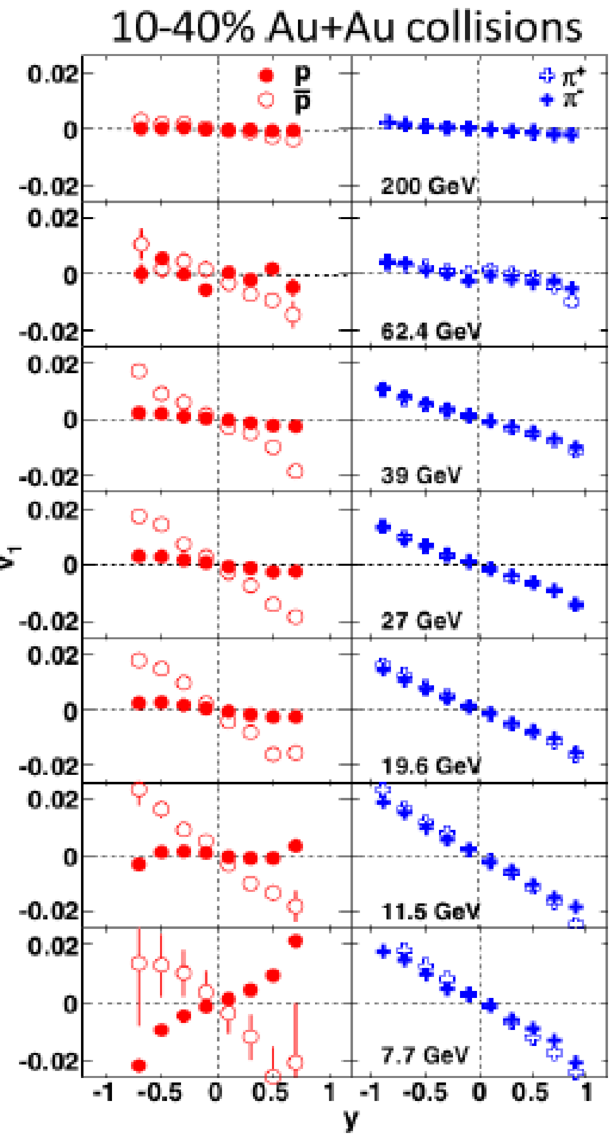
Coordinate space anisotropy transforms to momentum space anisotropy

$v_1 = \langle p_x/p_t \rangle$ describes the sideward collective motion of particles within the reaction plane (x-z)

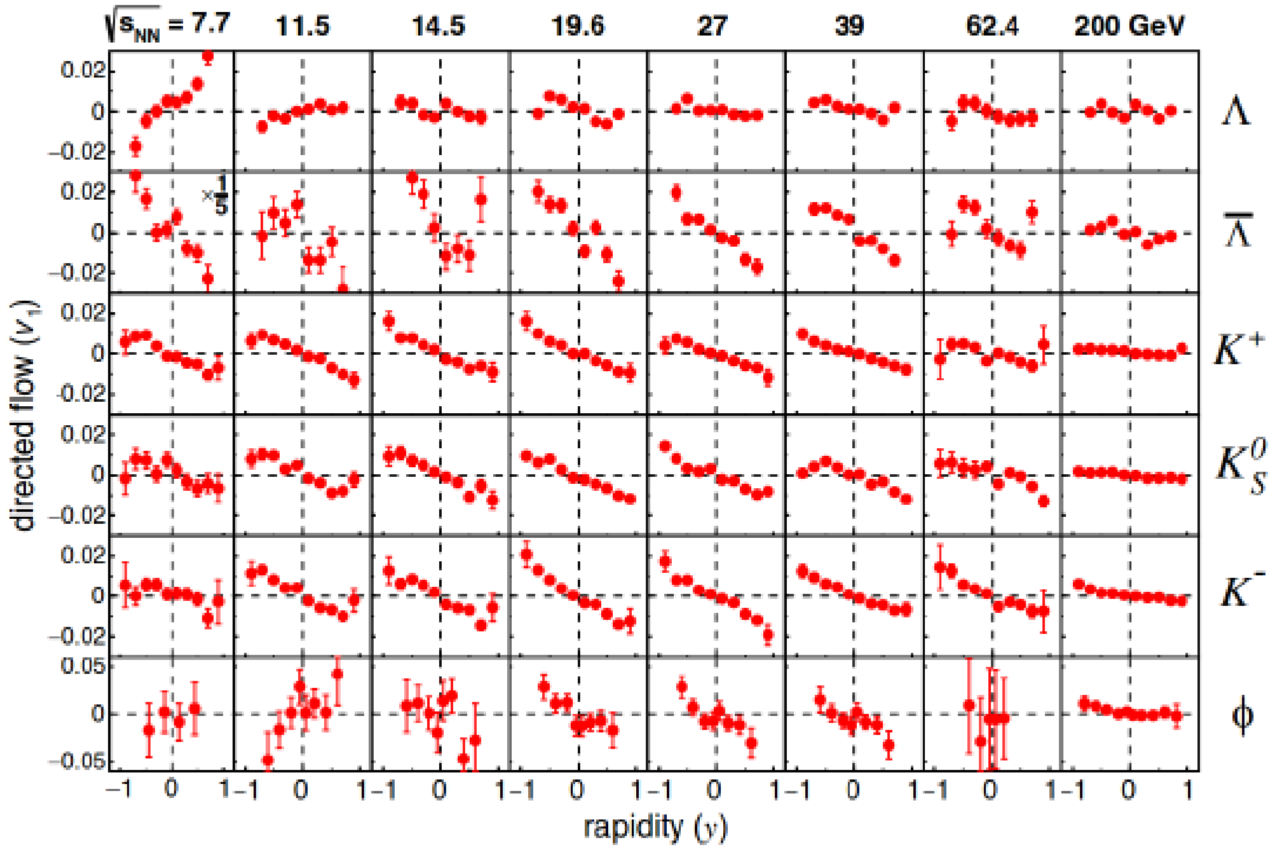
Voloshin, Zhang. Z. Phys. C 70 (1996) 665
Poskanzer, Voloshin. Phys Rev. C 58 (1998) 1671

Probe of the softening of the EoS
- Strong softening consistent with the 1st order phase transition
- Weak softening is more likely due to crossover

Directed flow with light flavors



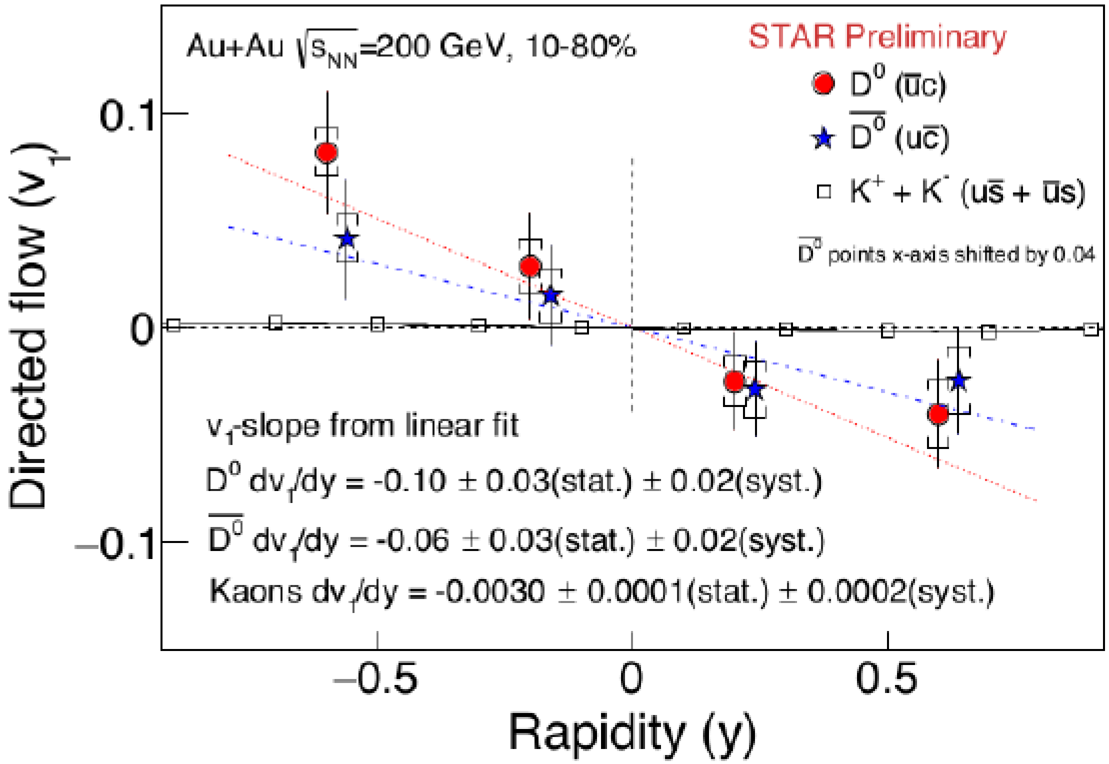
To extract v_1 slope, use linear fit over $|y| < 0.6$ for Φ and over $|y| < 0.8$ for all other species



Phys. Rev. Lett. 112 (2014) 162301
Phys. Rev. Lett. 120 (2018) 062301

Directed flow of D^0

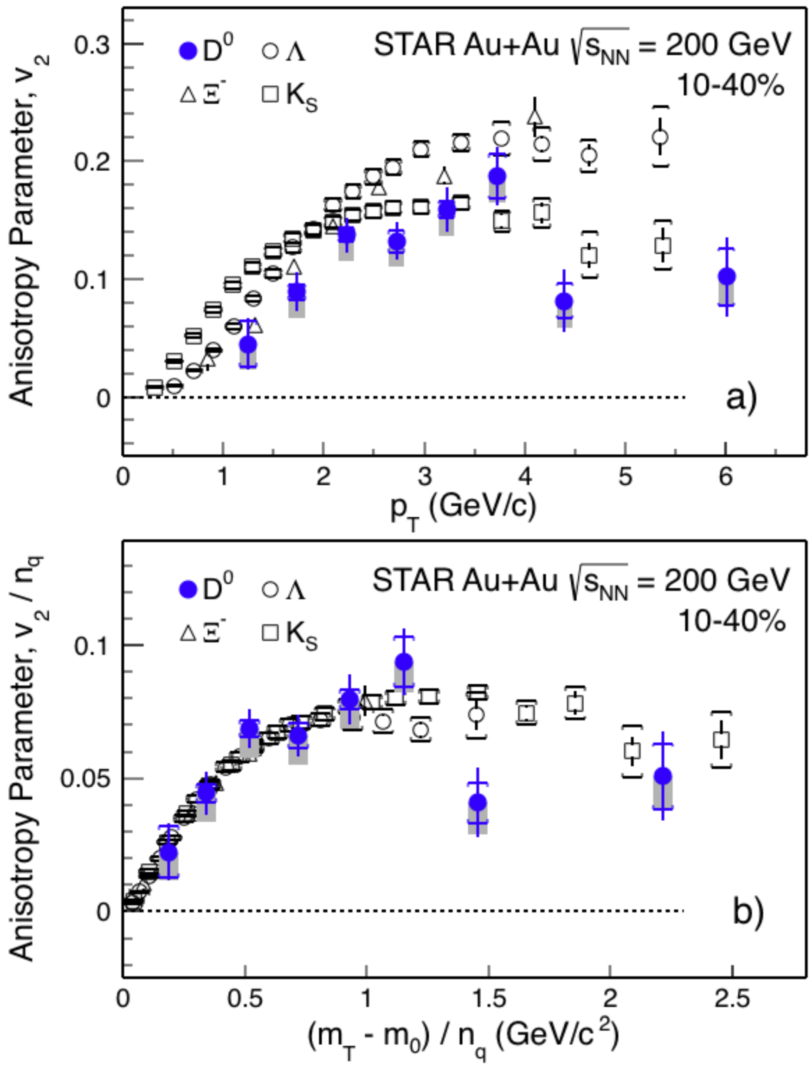
Non-zero v_1 for D^0 observed for the first time

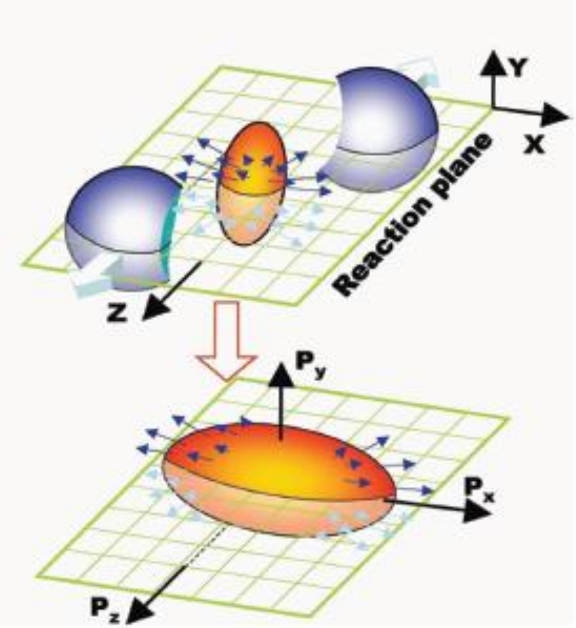


Data from 2014+2016 Heavy Flavor Tracker (HFT)

$$D^0 + \overline{D}^0 dv_1 / dy = -0.081 \pm 0.021(stat.) \pm 0.017(syst.)$$

Elliptic flow of D^0



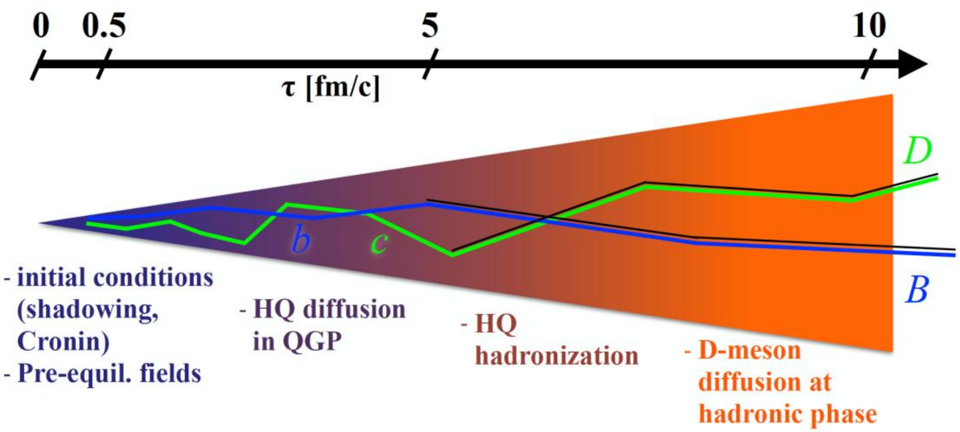


Charm quarks seem to follow NCQ-scaling behavior as light quarks

Charm quarks gain significant flow

Phys Rev. Lett. 118, 212301 (2017)

Nuclear modification and heavy flavor in medium



Partons interact with the medium and lose energy through e.g. gluon radiation

Quarks are expected to exhibit different radiative energy loss depending on their mass **(D.Kharzeev et al. Phys Letter B. 519:1999)**

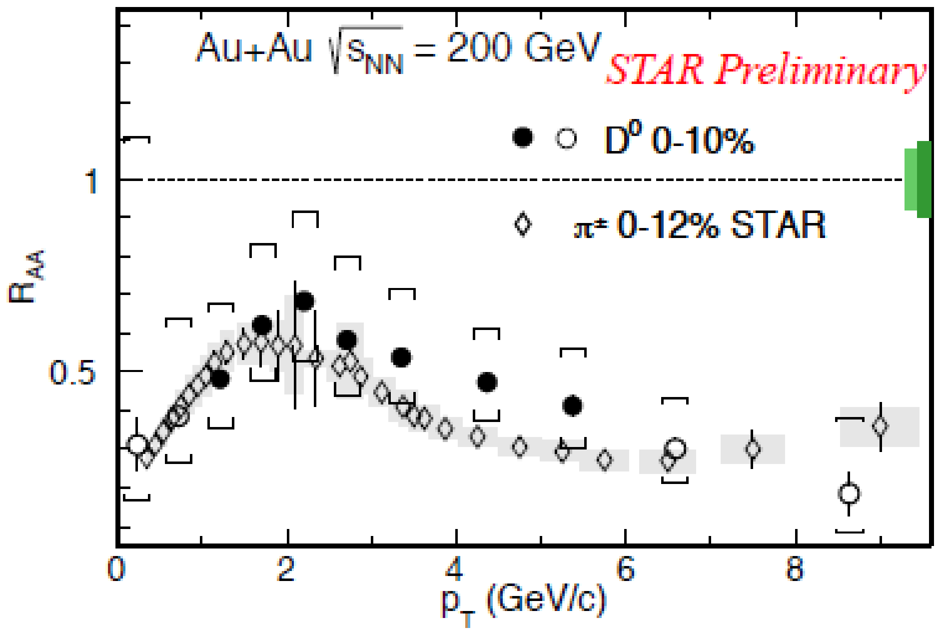
Nuclear Modification factor:

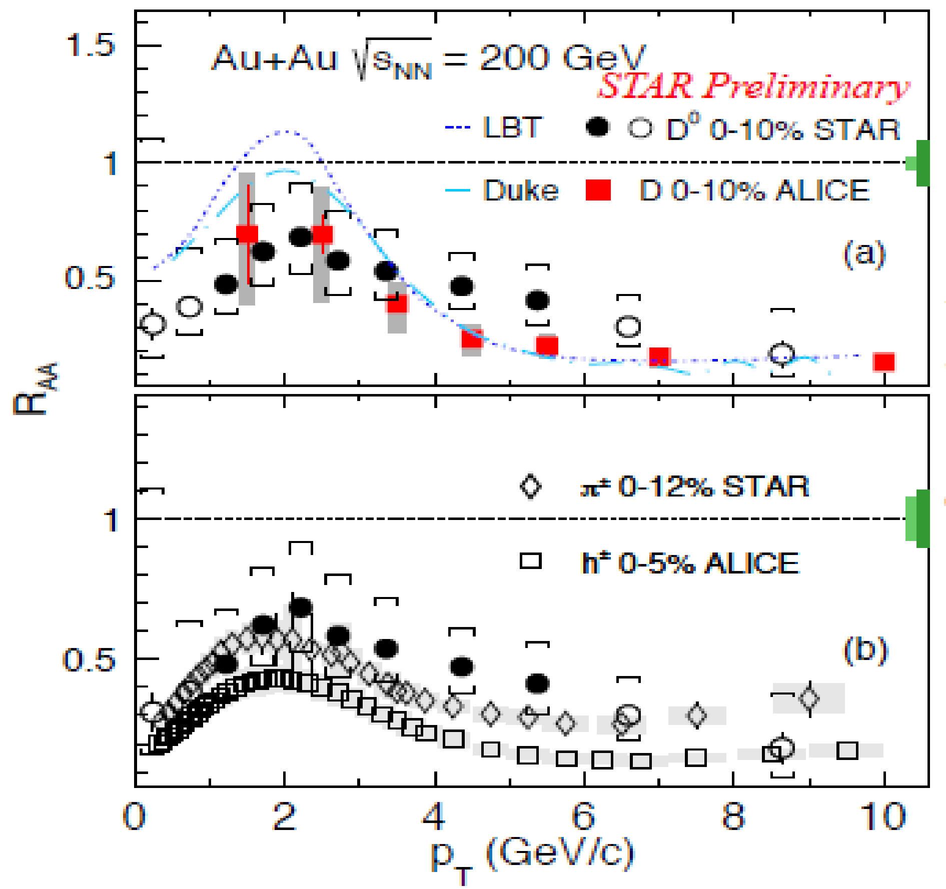
$$R_{AA}(p_t) = \frac{\sigma_{in}^{pp}}{< N_{coll}^{AA} >} \cdot \frac{d^2N_{AA}/dp_t d\eta}{d^2\sigma_{pp}/dp_t d\eta}$$

Large collective flow and modification of yields for charm hadrons in A+A collisions

Understand heavy quark production, transport and hadronization in the presence of QGP

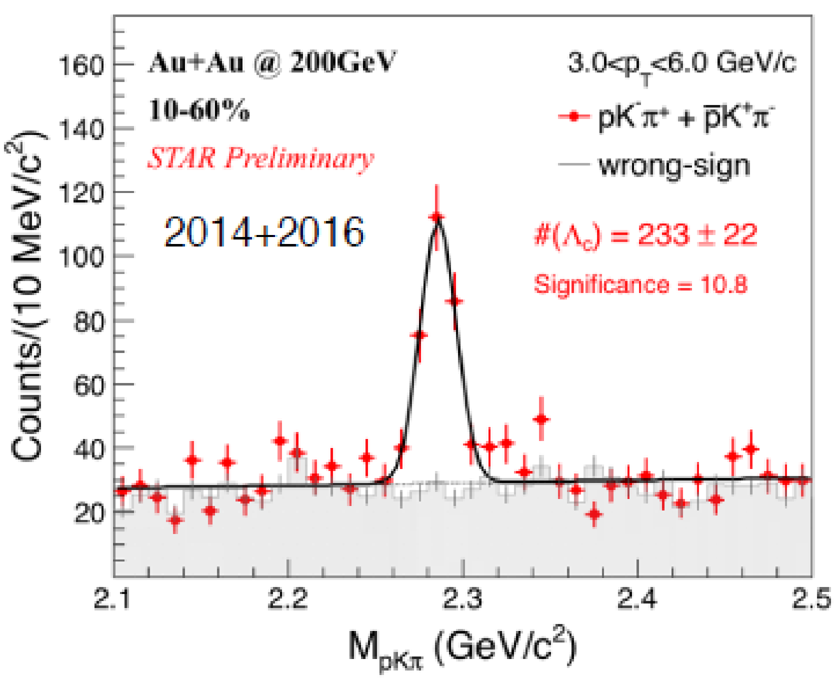
Nuclear modification factor for D^0

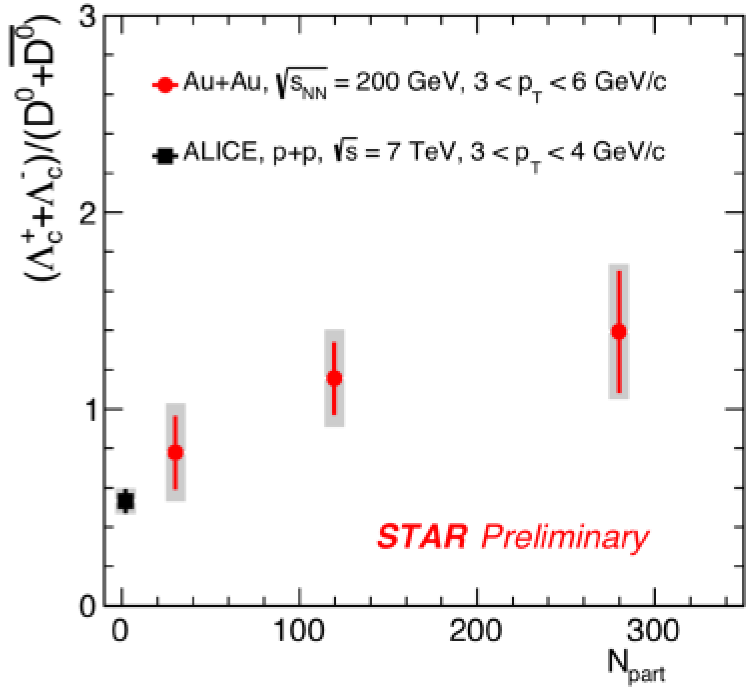




- R_{AA} in central events < 1 at all p_T
- Suppression at high p_T increases with centrality
- Similar to D-mesons at LHC and high-p_T pions at RHIC

Λ_c production at 200 GeV



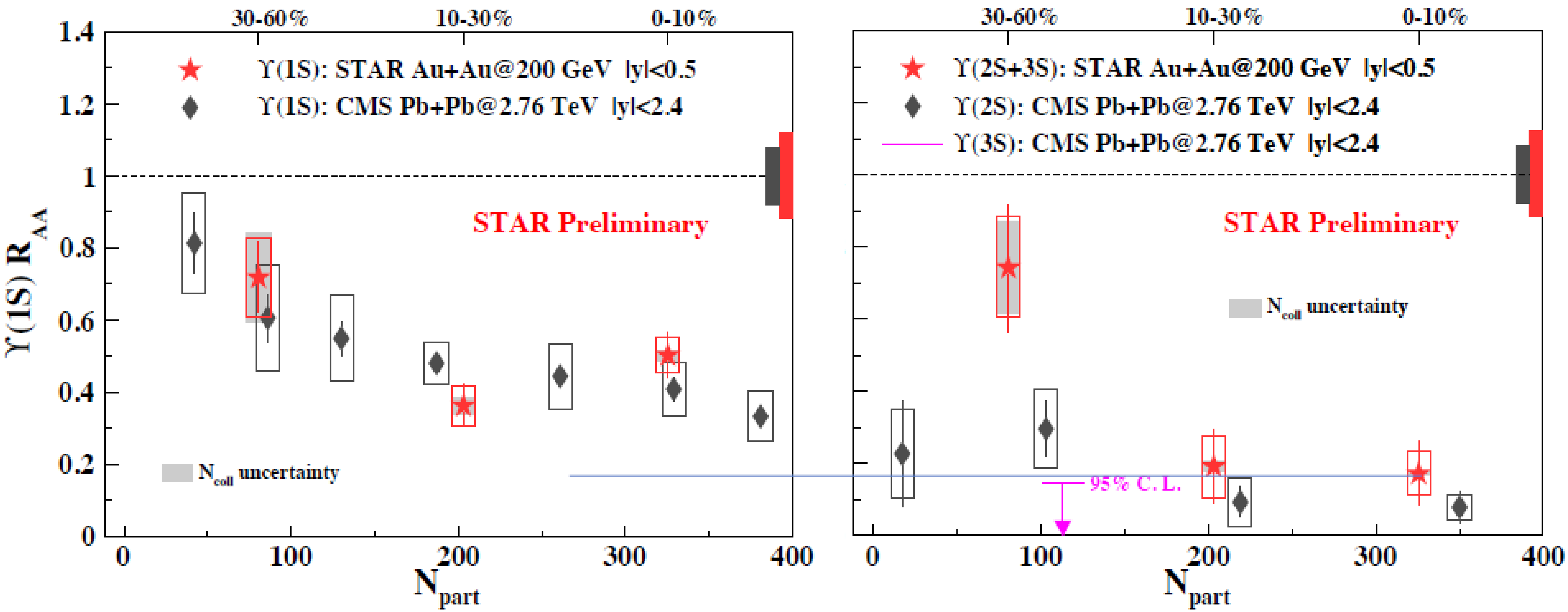


First measurement of centrality dependence of Λ_c production in heavy ion collisions

- Λ_c/D^0 ratio increases from peripheral to central, indicative of hot medium effects
- Ratio for peripheral Au+Au consistent with p+p value at 7 TeV
- Enhancement predicted from coalescence hadronization

Υ suppression at 200 GeV

Combined results from Υ-> e+e- and Υ-> μ+μ- improve precision of Υ measurements



CMS PLB 04, 031 (2017)

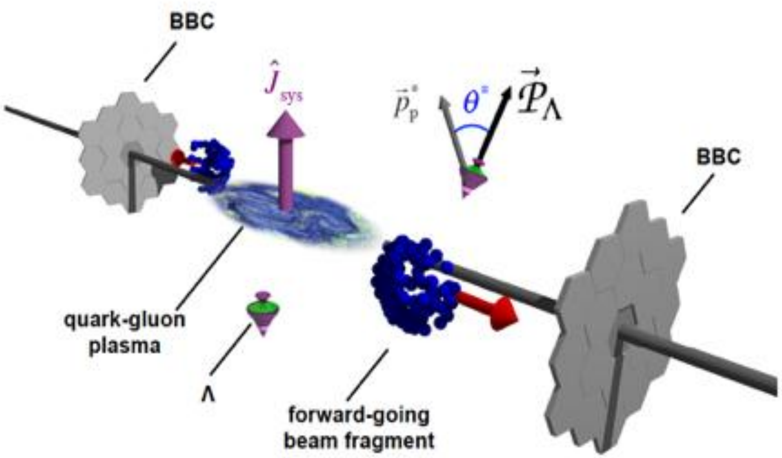
Υ(1S) suppression: similar at RHIC and LHC energies!

Υ(2S+3S) is more suppressed than Υ(1S) in the most central events

Υ(1S) R_{AA}: 0.50 ± 0.06 (stat.) ± 0.05 (sys.)

Υ(2S+3S) R_{AA}: 0.17 ± 0.09 (stat.) ± 0.06 (sys.)

Global Λ polarization



$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1+\alpha_H \,|\, P_H \,|\cos\theta^*\right)$$

P_H : Λ/anti-Λ polarization vector in the hyperon rest frame (H denotes Λ/anti-Λ)

α_H : decay parameter $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

Average vorticity points towards the direction of the angular momentum J_{sys} of the collision

Average projection of the polarization on J_{sys} is extracted:

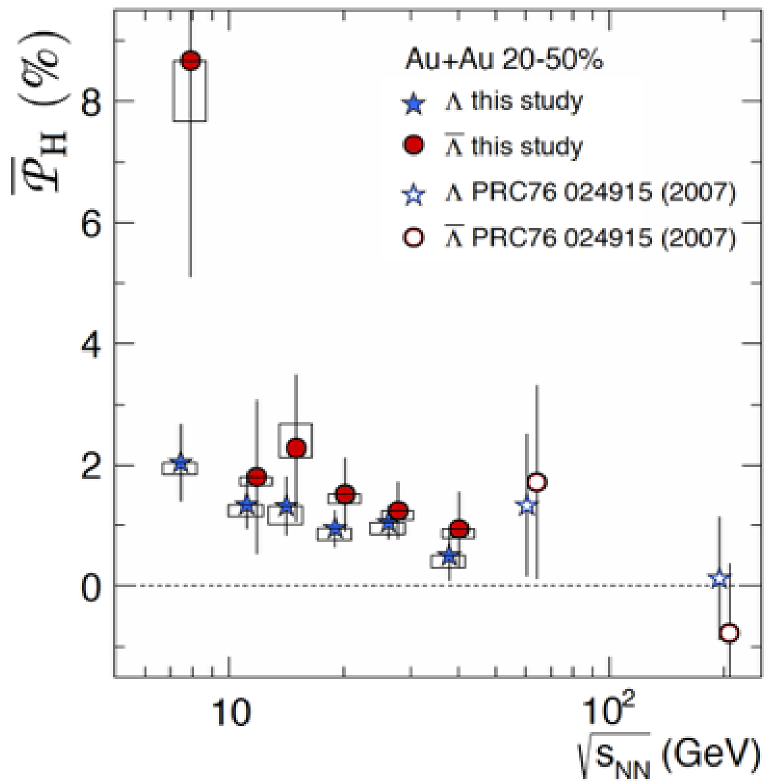
$$\overline{P}_H \equiv \left\langle \vec{P}_H \hat{J}_{sys} \right\rangle = \frac{8}{\pi\alpha_H} \frac{\left\langle \cos(\phi_p^* - \phi_{\hat{J}_{sys}}) \right\rangle}{R_{EP}^1}$$

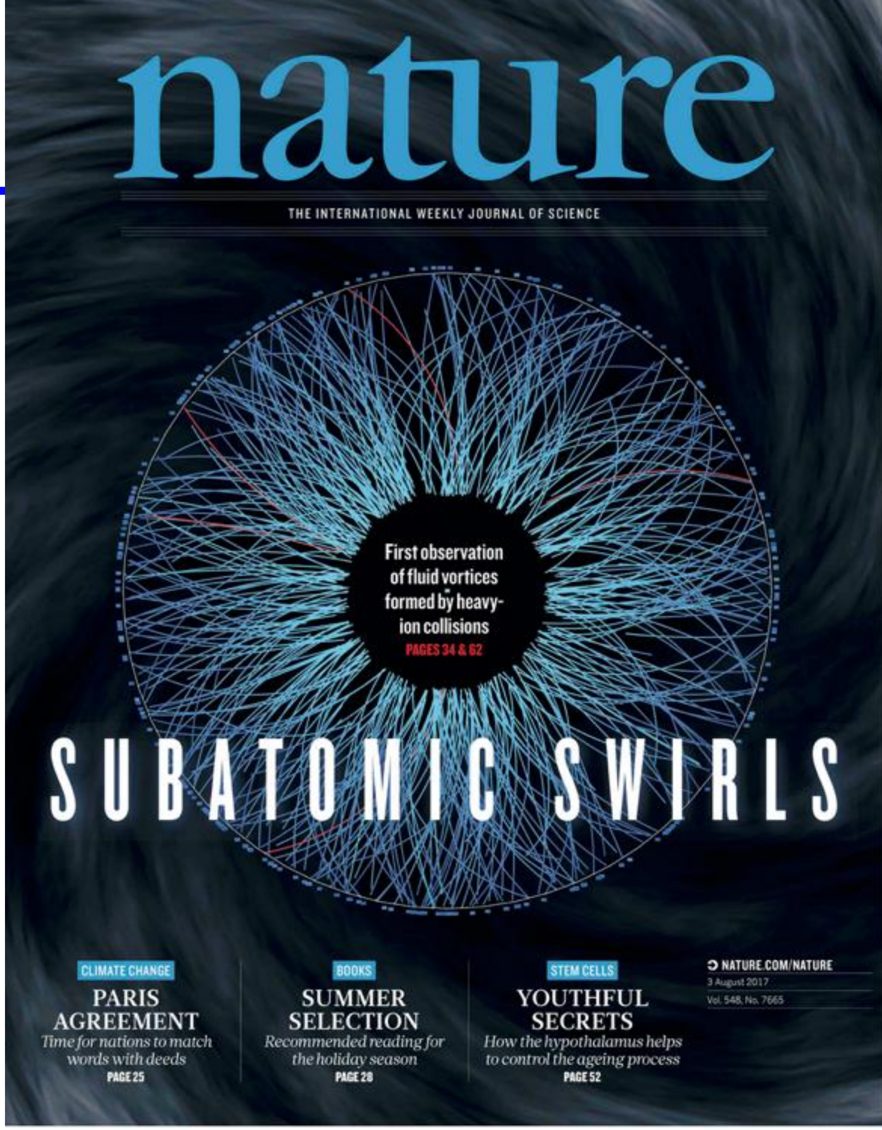
noted here as global polarization

Global Λ polarization

STAR, Nature, 2017, 1701.06657

First observations of Lambda global polarization



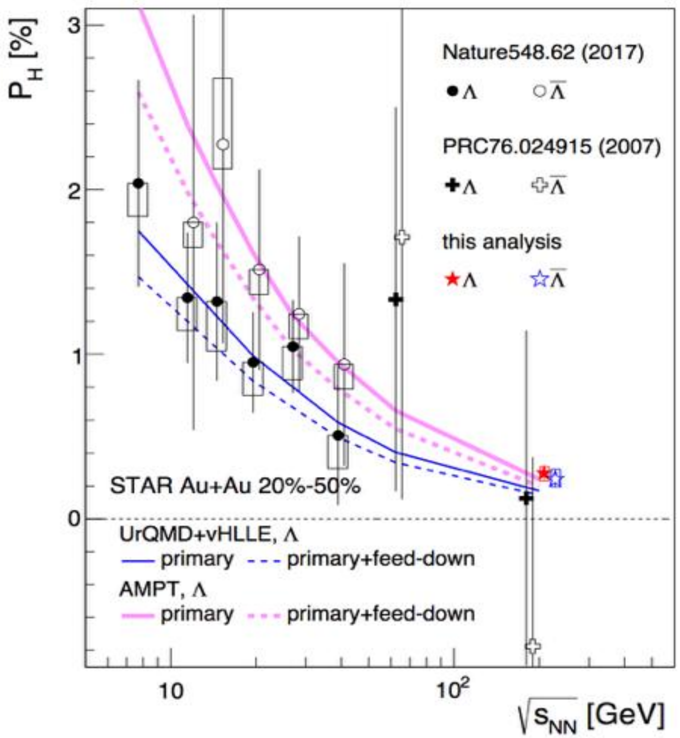


The most vortical fluid

$$\omega = k_B T(\overline{P}_{\Lambda} + \overline{P}_{\overline{\Lambda}})/\hbar = 10^{22} s^{-1}$$

Global Λ polarization

Phys. Rev. C 98 (2018) 014910



Data on polarization from 2010, 2011, 2014

Measurements in Au-Au 200 GeV collisions 20-50 % centrality

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$

$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

5 -7 σ significance, comparable with BES-I results

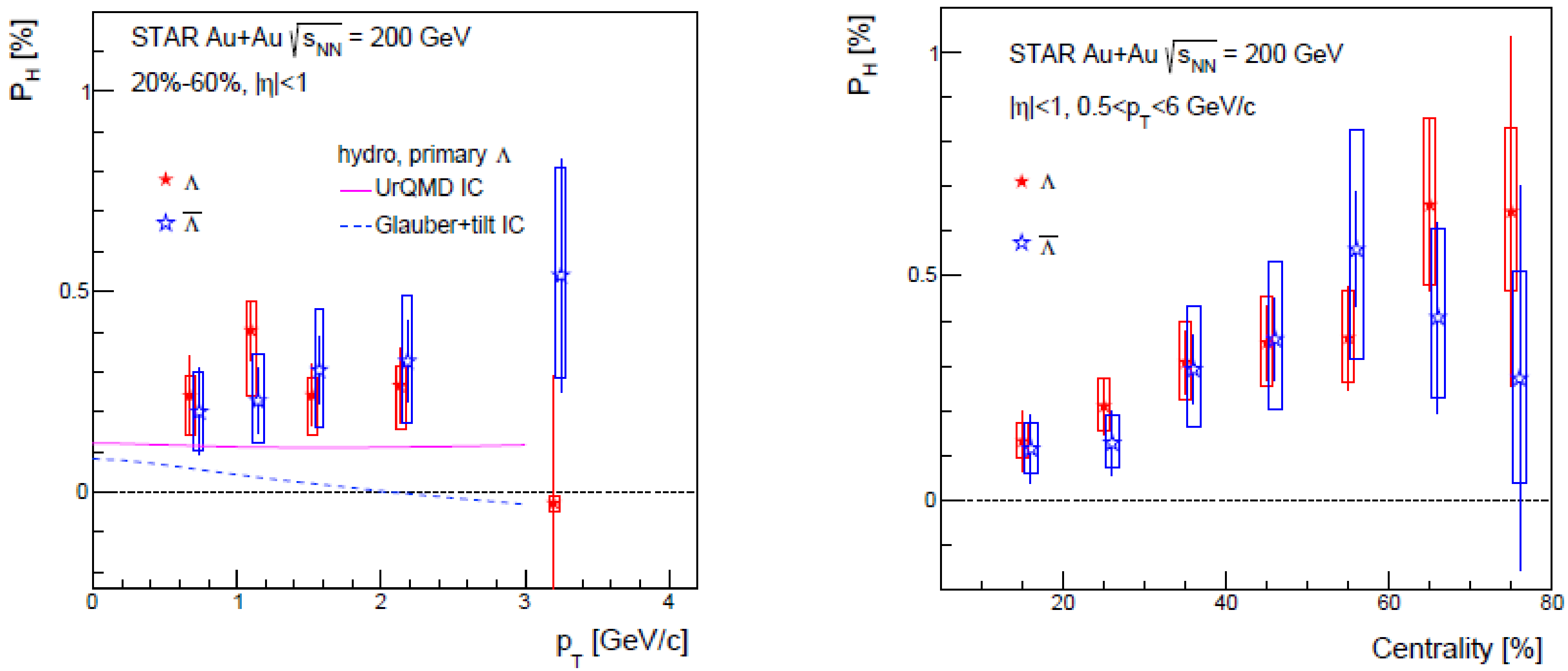
No significant difference between Λ and anti-Λ polarization at $\sqrt{s_{NN}}$ = 200 GeV within the uncertainties.

Within the uncertainties these results agree with predictions from a hydrodynamic model (UrQMD+vHLLE) and the AMPT (A Multi-Phase Transport) model.

UrQMD+vHILLE: I. Karpenko and F. Becattini, EPJC (2017)77:213
AMPT: H. Li et al., Phys. Rev. C 96, 054908 (2017)

Polarization dependence on P_T and centrality

Phys. Rev. C 98 (2018) 014910



The polarization was also studied as function of the collision centrality, the hyperon's transverse momentum, and pseudorapidity.
No significant dependence on centrality or transverse momentum was observed.

I. Karpenko and F. Becattini PRL 120.012302, (2018)

Femtoscopy

Single- and two- particle distributions:

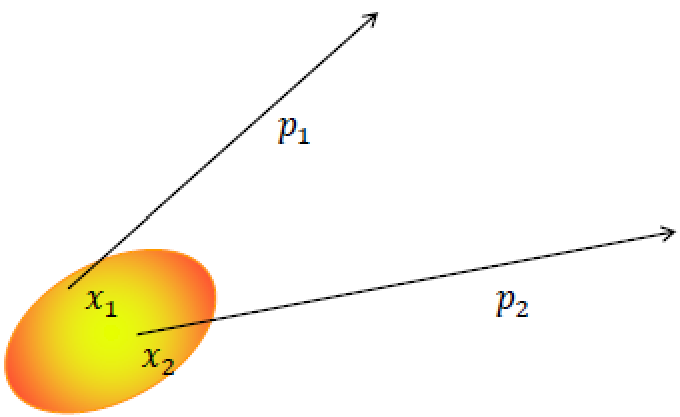
$$P_1(p) = E\frac{dN}{d^3p} = \int d^4x S(x,p)$$

S(x,p) – emission function: the distribution of source density probability of finding particle with given x and p

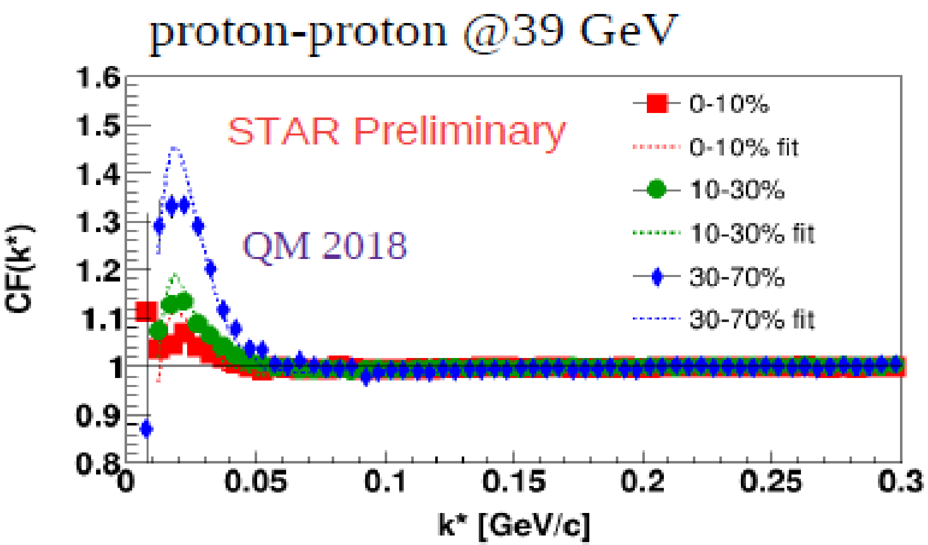
$$P_2(p_1,p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2} = \int d^4x_1 S(x_1,p_1) d^4x_2 S(x_2,p_2) \Phi_2(x_2,p_2|x_1,p_1)$$

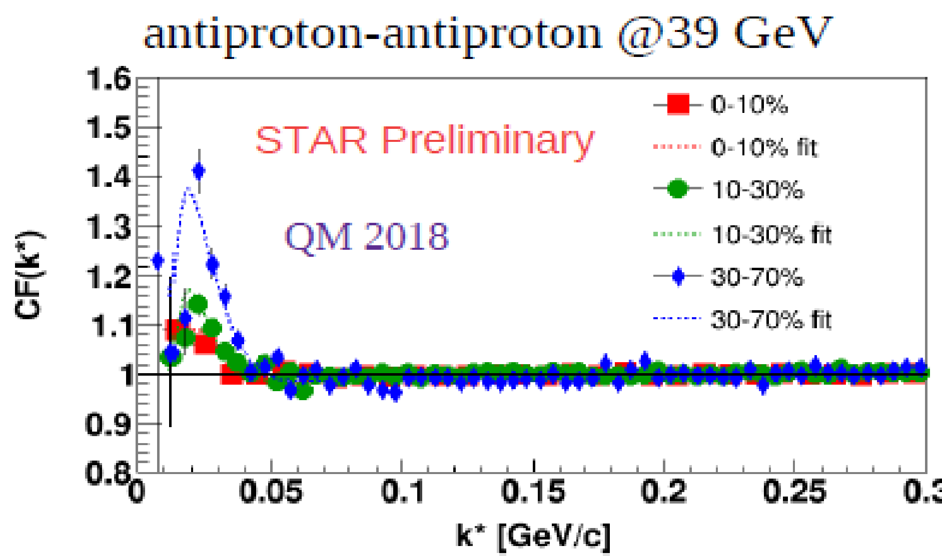
Correlation function

$$C(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1)P_1(p_2)}$$



PP correlations

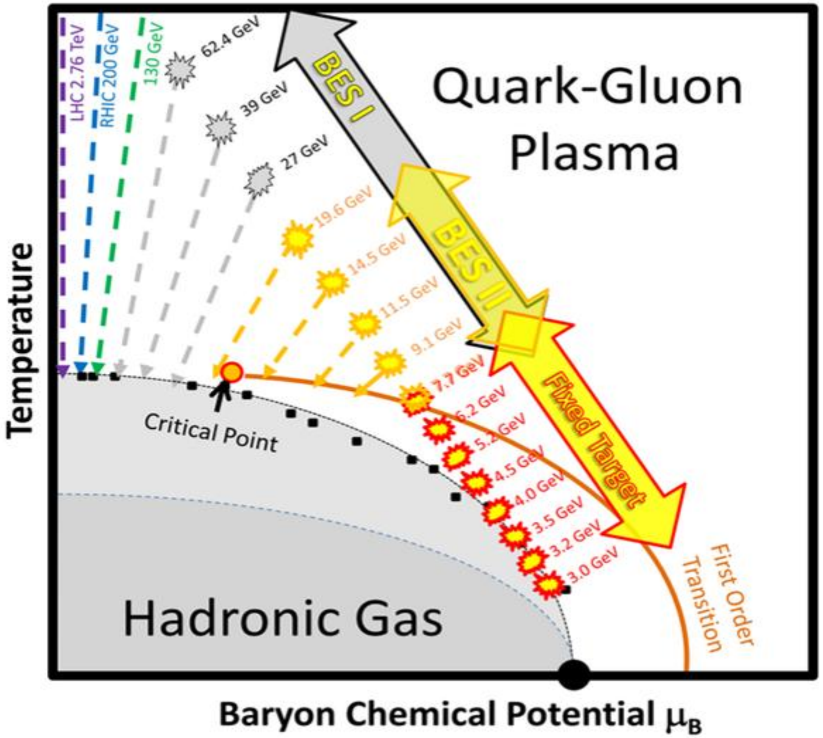




centrality	R_{inv} $p-p$ [fm]	R_{inv} $\overline{p}-\overline{p}$ [fm]	R_{inv} $p-\overline{p}$ [fm]
0-10%	$4.00 \pm 0.15 \pm 0.02$	$3.83 \pm 0.20 \pm 0.03$	$3.39 \pm 0.12 \pm 0.14$
10-30%	$3.61 \pm 0.13 \pm 0.17$	$3.68 \pm 0.15 \pm 0.11$	$2.69 \pm 0.10 \pm 0.12$
30-70%	$2.72 \pm 0.07 \pm 0.07$	$2.95 \pm 0.11 \pm 0.08$	$2.56 \pm 0.09 \pm 0.12$

- R_{inv} smaller for less central collisions as expected
- No significant difference between p p and p-bar p-bar correlation functions
- Systematically R_{inv} (p-bar p) < R_{inv} (p p, p-bar p-bar) which indicates a need to refine low energy p-bar p measurements

Fixed target program at STAR



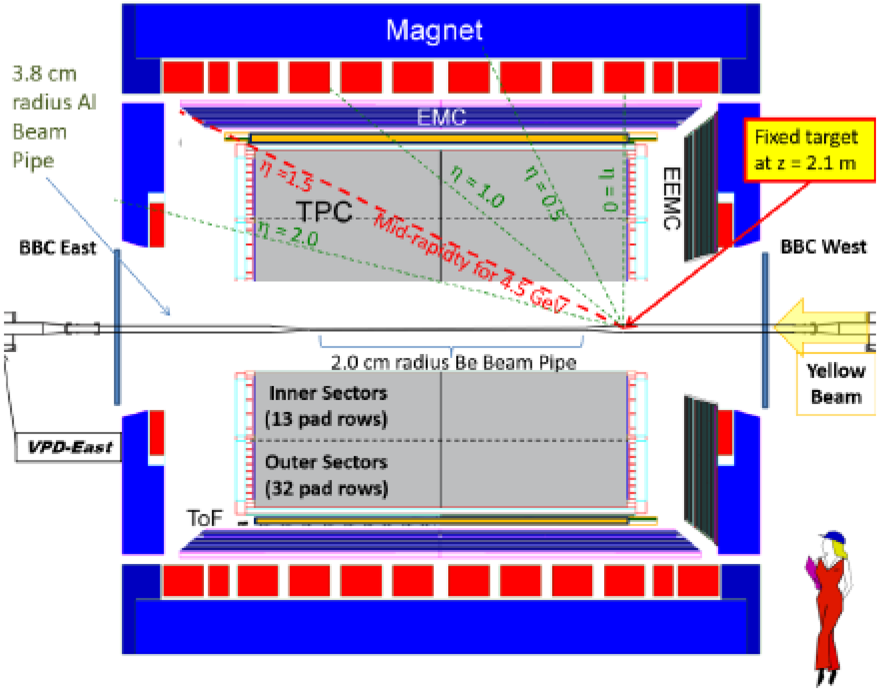
BES-I main goals:
Search for 1st order phase transition
Search for existence of the Critical Point
Search for turn-off of QGP signatures
Finished data taking

Originally BES-I program planed to go down to $\sqrt{s_{NN}}$ = 5 GeV

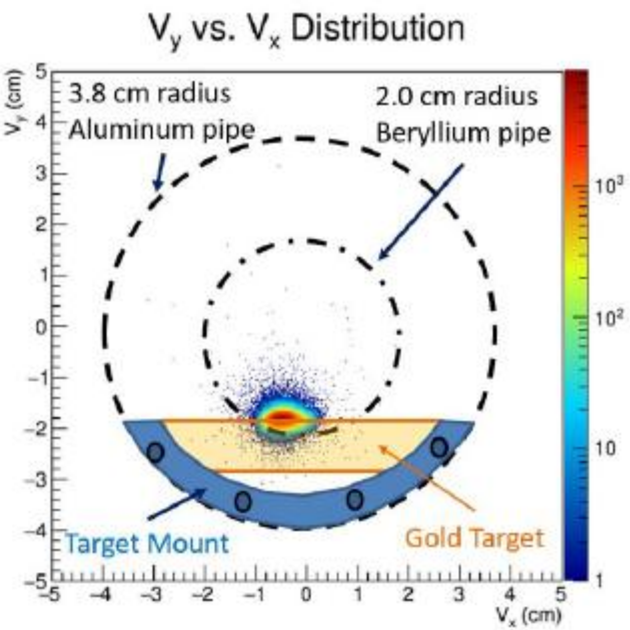
Collider mode
Can not cover energy region $\sqrt{s_{NN}}$ < 7.7 GeV

Fixed target mode
Can cover energy region 3 Gev < $\sqrt{s_{NN}}$ < 7.7 GeV

Fixed target program at STAR



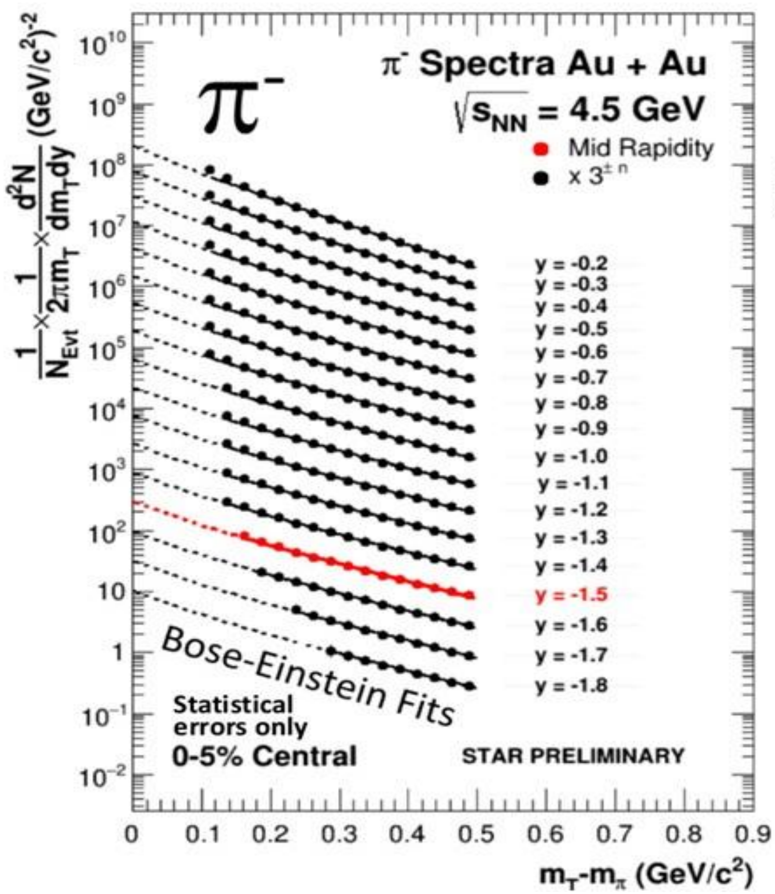
A 1 mm thick (4% inter. prob.) gold target

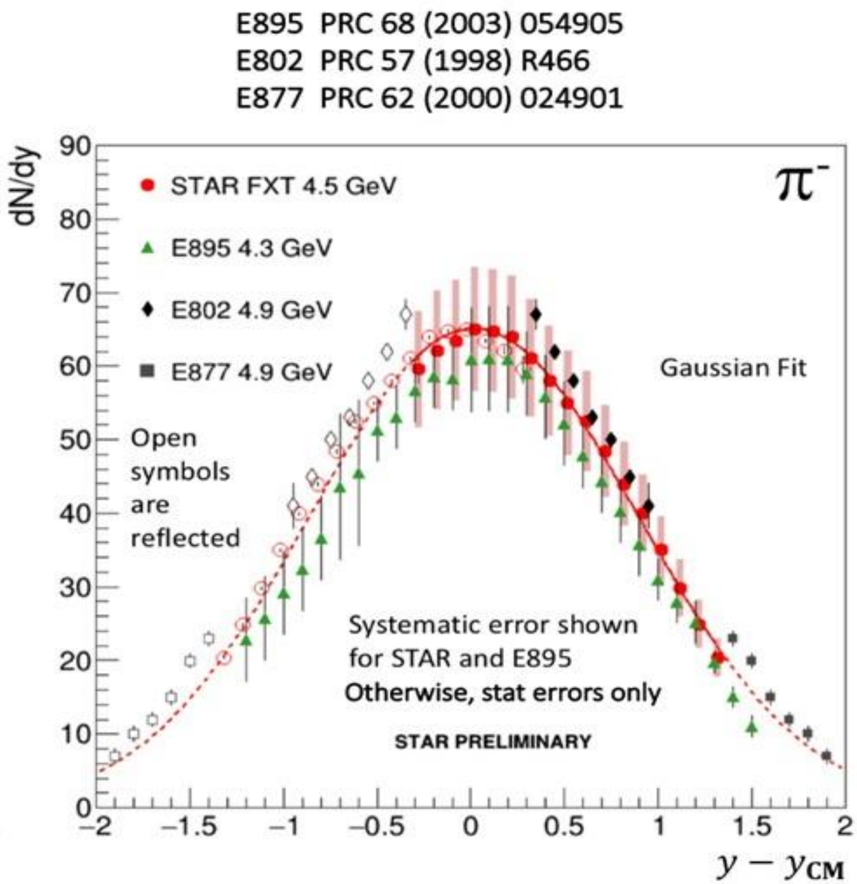


BES Phase II to probe phase diagram of QCD matter, lowest energy is $\sqrt{s_{NN}}$ = 3 GeV and cover region lack of experimental data.

BES-II can extend μ_B range from 400 MeV to about 720 MeV

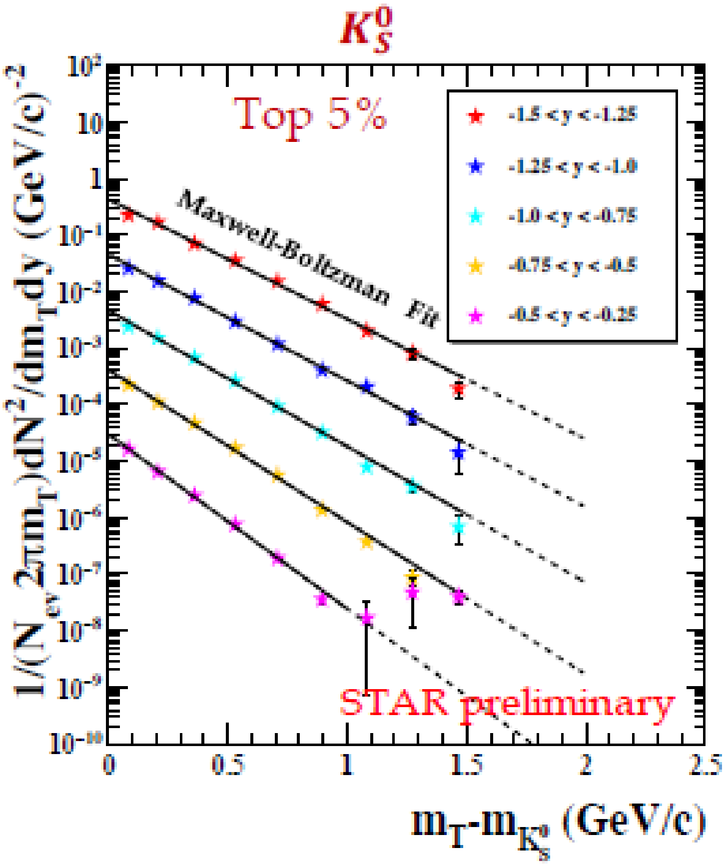
Spectra of π in Au-Au at 4.5 GeV FXT

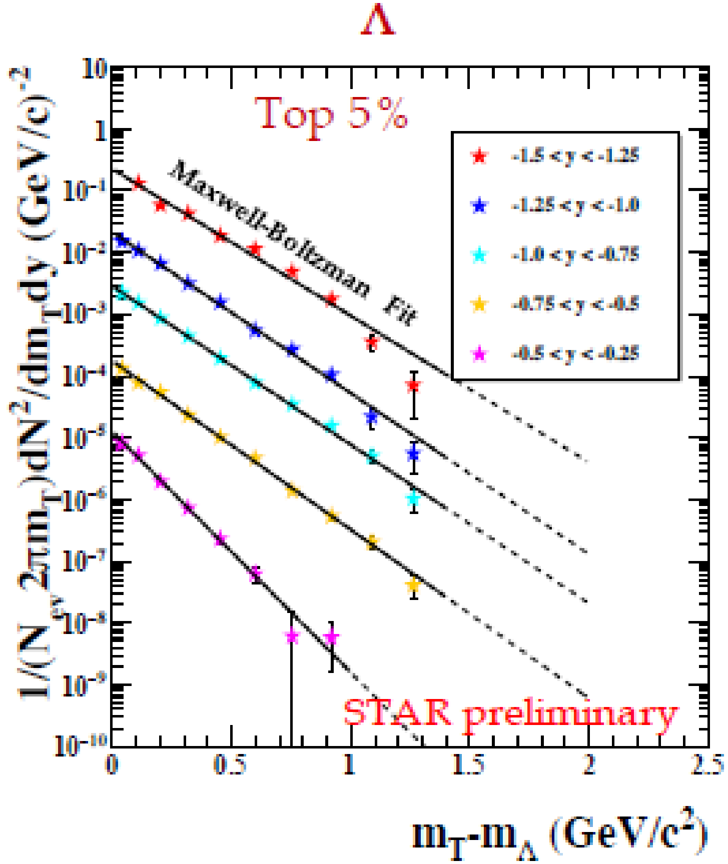




Spectra consistent with AGS results

Spectra of K^0_S and Λ in Au-Au at 4.5 GeV FXT

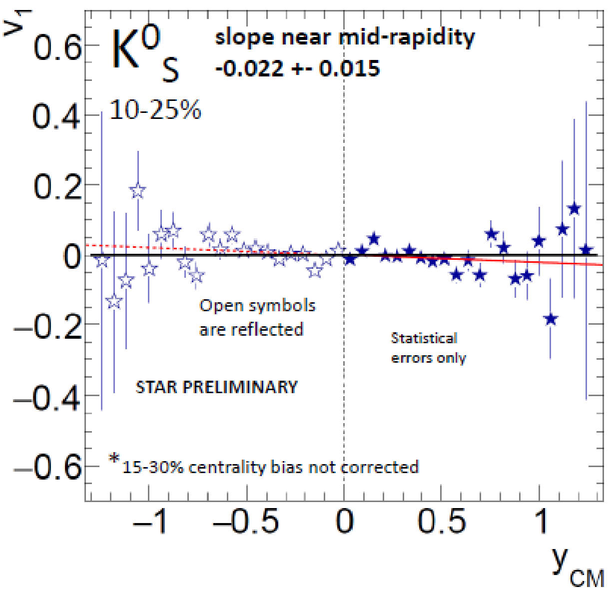


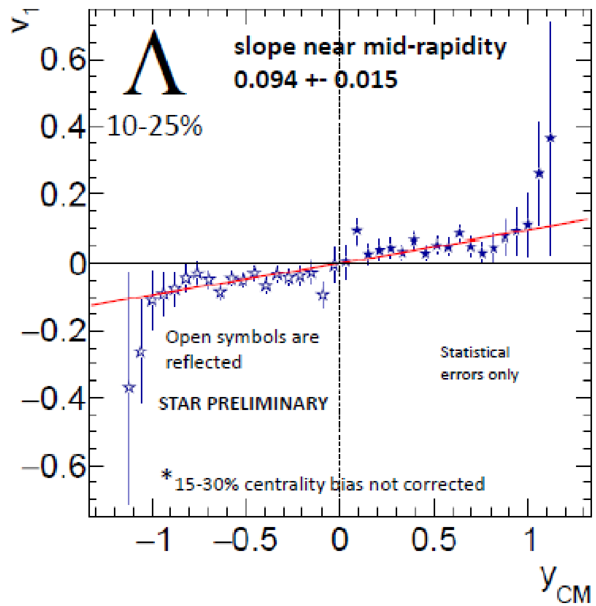


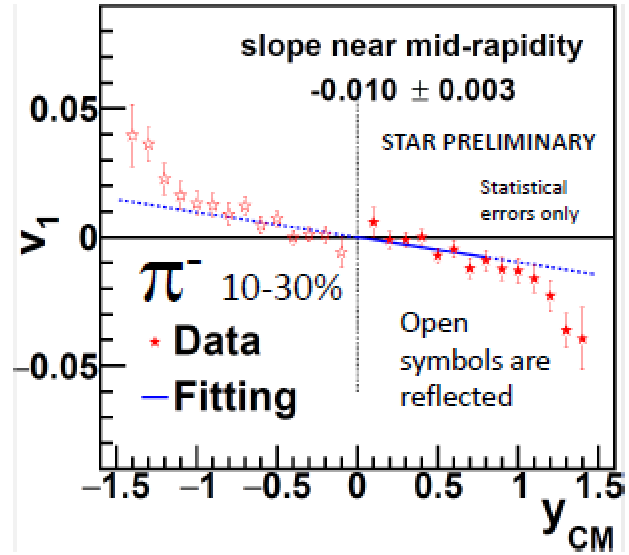
Statistical errors only

Spectra consistent with AGS results

Directed flow v_1 in Au-Au at 4.5 GeV







mesons

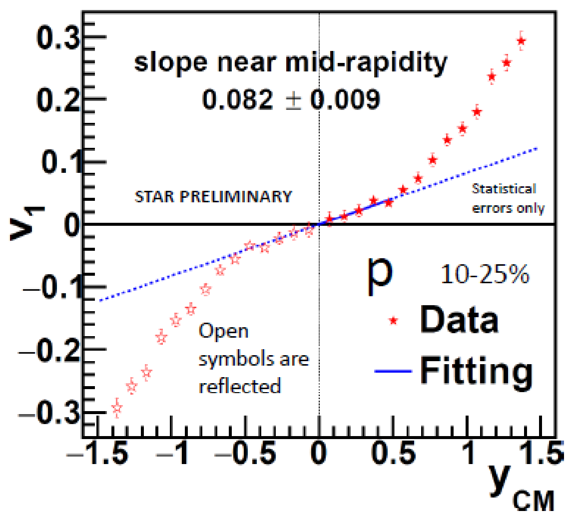
pion flow is “negative”

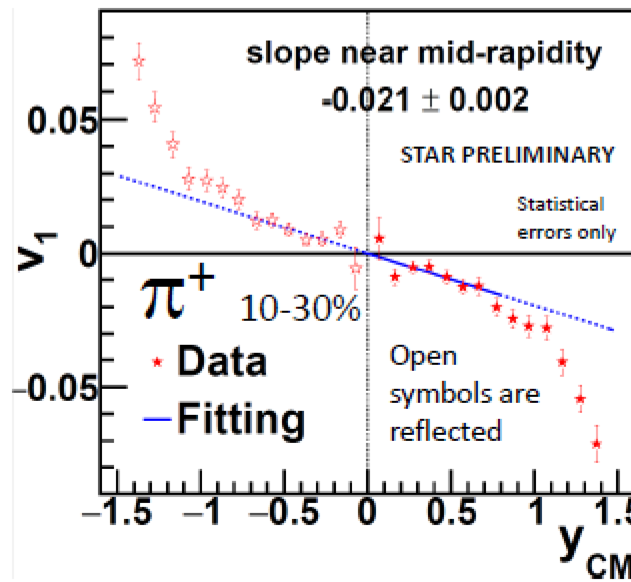
kaon needs more statistics

baryons

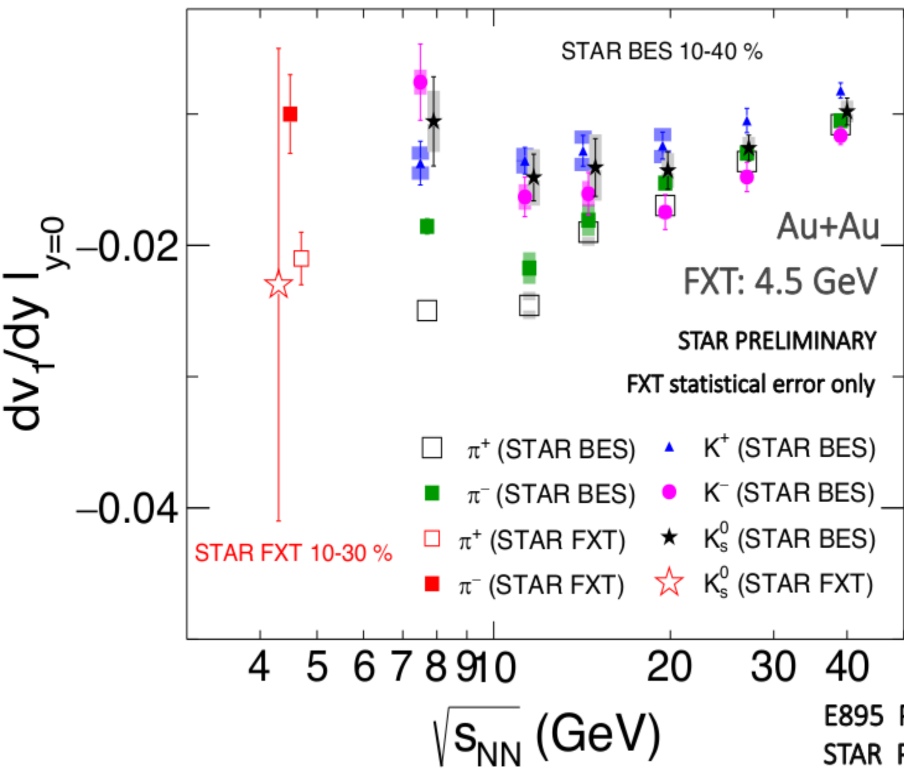
proton flow is “positive”

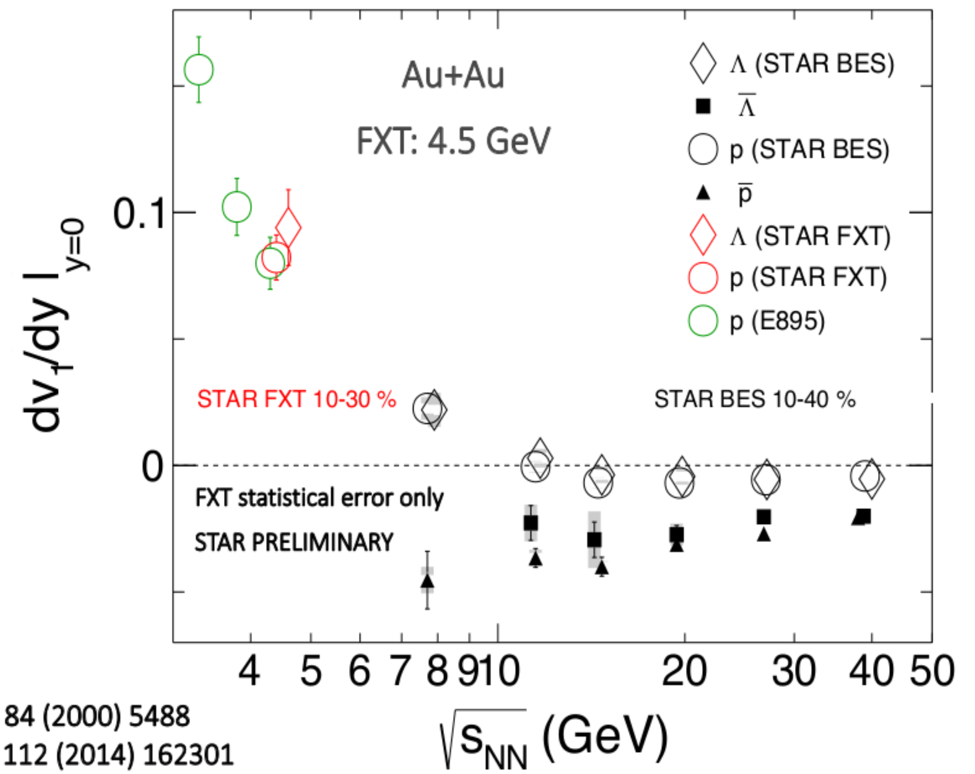
lambda flow is “positive”





Directed flow v_1 energy dependence

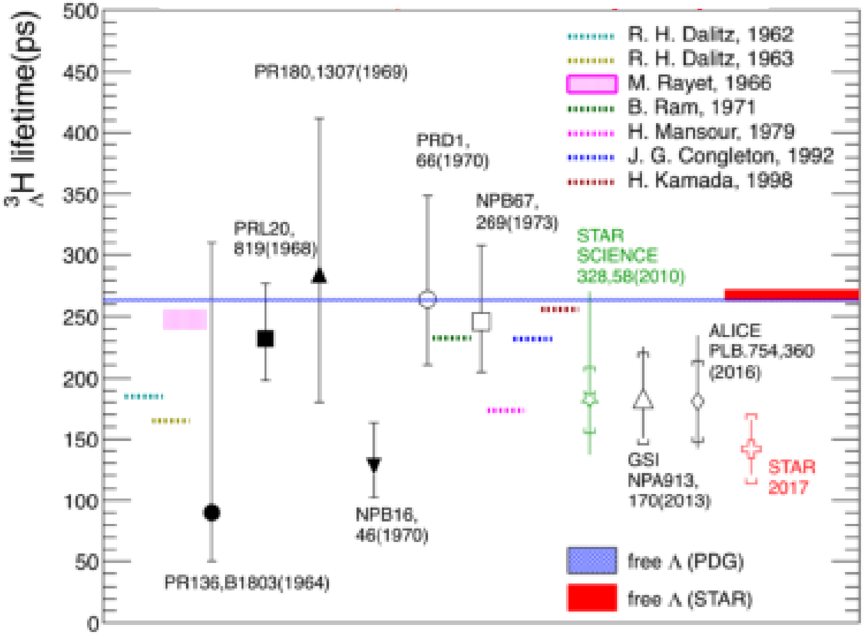




E895 PRL 84 (2000) 5488
STAR PRL 112 (2014) 162301

Proton v_1 agrees with E895; Λ is close to proton

Hypertriton lifetime



[1] R. O. Gomes, V. Dexheimer, S. Schramm, and C. A. Z. Vasconsellos, The Astrophys. J. 808, 8 (2015).
[2] L. L. Lopes and D. P. Menezes, Phys. Rev. C 89, 025805 (2014).
[3] J. Antoniadis et al., Science 340, 448 (2013).
[4] László P. Csernai, Joseph I. Kapusta, Phys. Reps. 131, 223 (1986).
[5] A. Z. Melkjian, Phys. Rev. C 17, 1051 (1978).
[6] Kaijia Sun et al., Phys. Lett. B 774, 103 (2017).

Hyperon-Nucleon interactions play an important role in theory of neutron stars and QCD

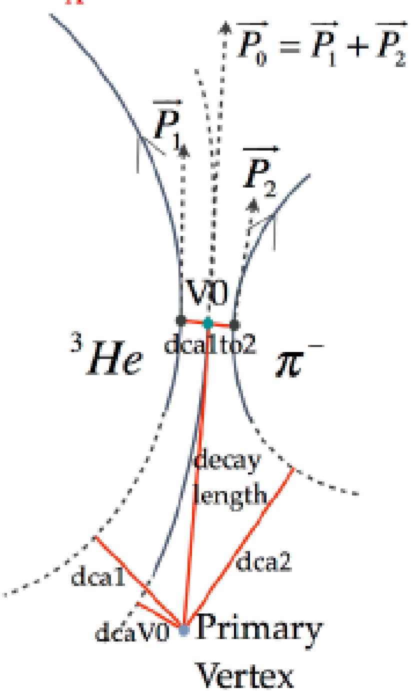
- measurements of masses of hypertriton and anti-hypertriton provide insight into H-N interactions and the CPT symmetry

- measurements sensitive to the temperature and nucleon phase-space of the system freezout

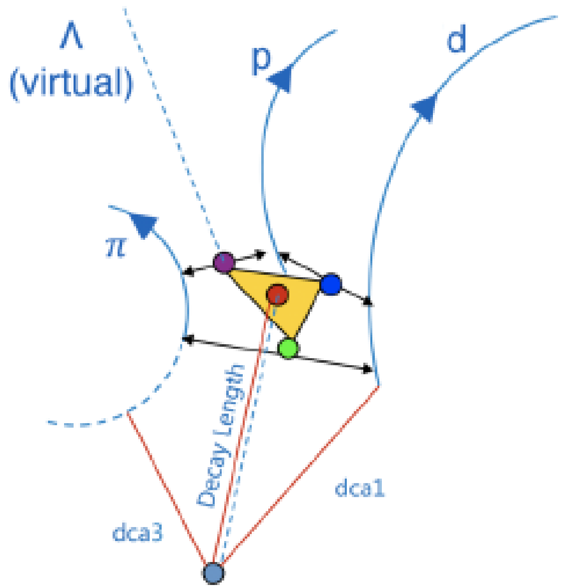
Phys. Rev. C 97 (2018) 54909

Hypertriton reconstruction with HFT

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



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



$^{3}_{\Lambda}H$ has many decay channels:

- ✓ Non-meson decay channels:
  - $^{3}_{\Lambda}H \rightarrow d + n$
  - $^{3}_{\Lambda}H \rightarrow p + n + n$
- ✓ Meson decay channels:
  - $^{3}_{\Lambda}H \rightarrow {}^{3}He\ ({}^{3}H) + \pi^{-}\ (\pi^{0})$
  - $^{3}_{\Lambda}H \rightarrow d + p\ (n) + \pi^{-}\ (\pi^{0})$
  - $^{3}_{\Lambda}H \rightarrow p + n + p\ (n) + \pi^{-}\ (\pi^{0})$

Good PID of charged particles in STAR detector.

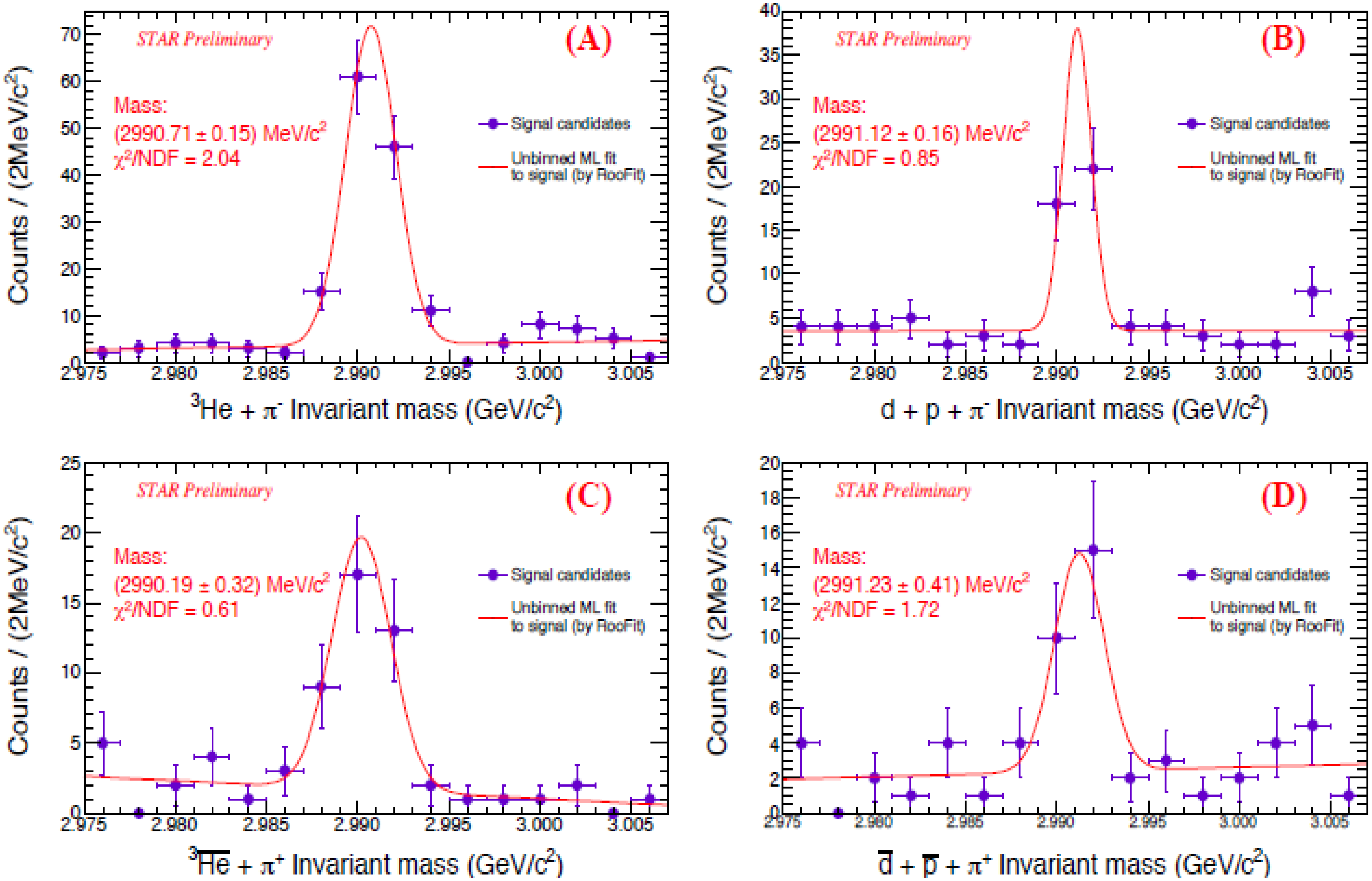
Reconstructing $^{3}_{\Lambda}H$ ($^{3}_{\overline{\Lambda}}\overline{H}$) through:

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

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

High spatial resolution of HFT (< 30 µm) allows precise determination of the decay vertex

${}_{\Lambda}{}^{3}H$ and anti-${}_{\Lambda}{}^{3}H$ mass reconstruction



${}^{3}_{\Lambda}H$ (2-body + 3-body)
2990.90 ± 0.11 (stat.) ± 0.15 (syst.) MeV/c^2

${}^{3}_{\Lambda}\overline{H}$ (2-body + 3-body)
2990.59 ± 0.25 (stat.) ± 0.15 (syst.) MeV/c^2

${}^{3}_{\Lambda}H$ and ${}^{3}_{\Lambda}\overline{H}$ combined
2990.85 ± 0.10 (stat.) ± 0.15 (syst.) MeV/c^2

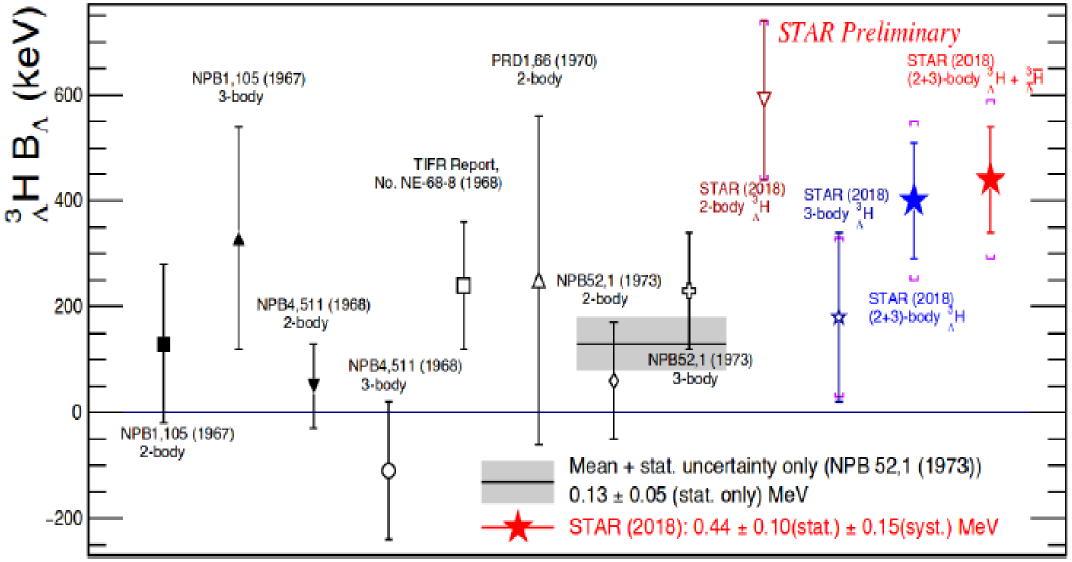
Systematical uncertainty source:
- Energy loss correction.
- Different cuts impact.

Fit Function:

$$N_{sig}\left(\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}\right)+N_{bkg}(ax+b)$$

Energy loss corrections applied

Hypertriton and CPT symmetry



Hypertriton binding energy definition:

$$m_\Lambda + m_d - m_{^3_\Lambda H} = 0.44 \pm 0.10(\text{stat.}) \pm 0.15(\text{syst.})\text{MeV}$$

Mass difference between $_\Lambda{}^3$H and anti-$_\Lambda{}^3$H was measured for the first time

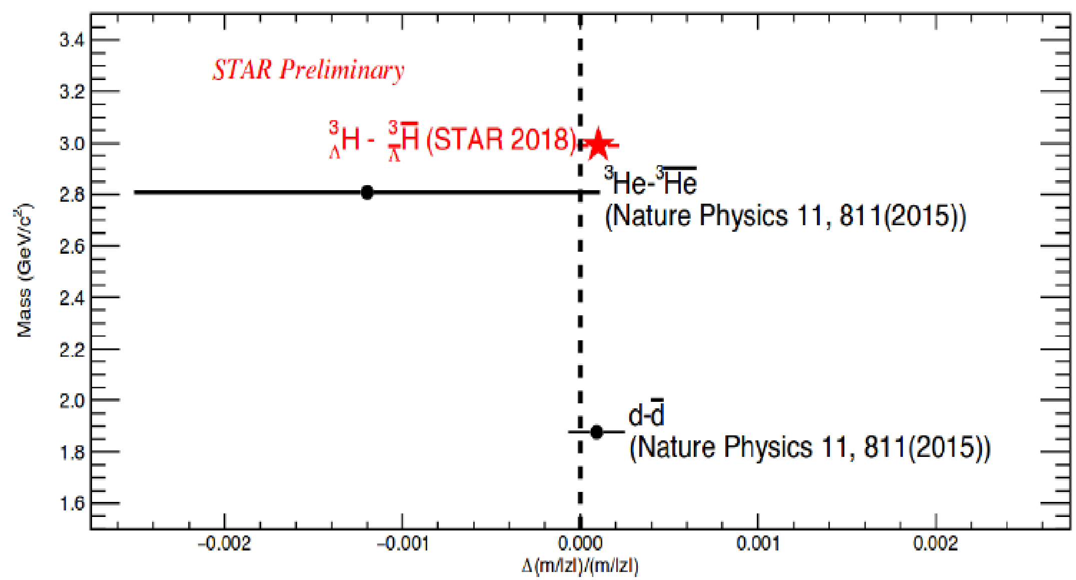
First test of CPT symmetry in light hypernuclei sector.

Mass difference is zero within the uncertainties.

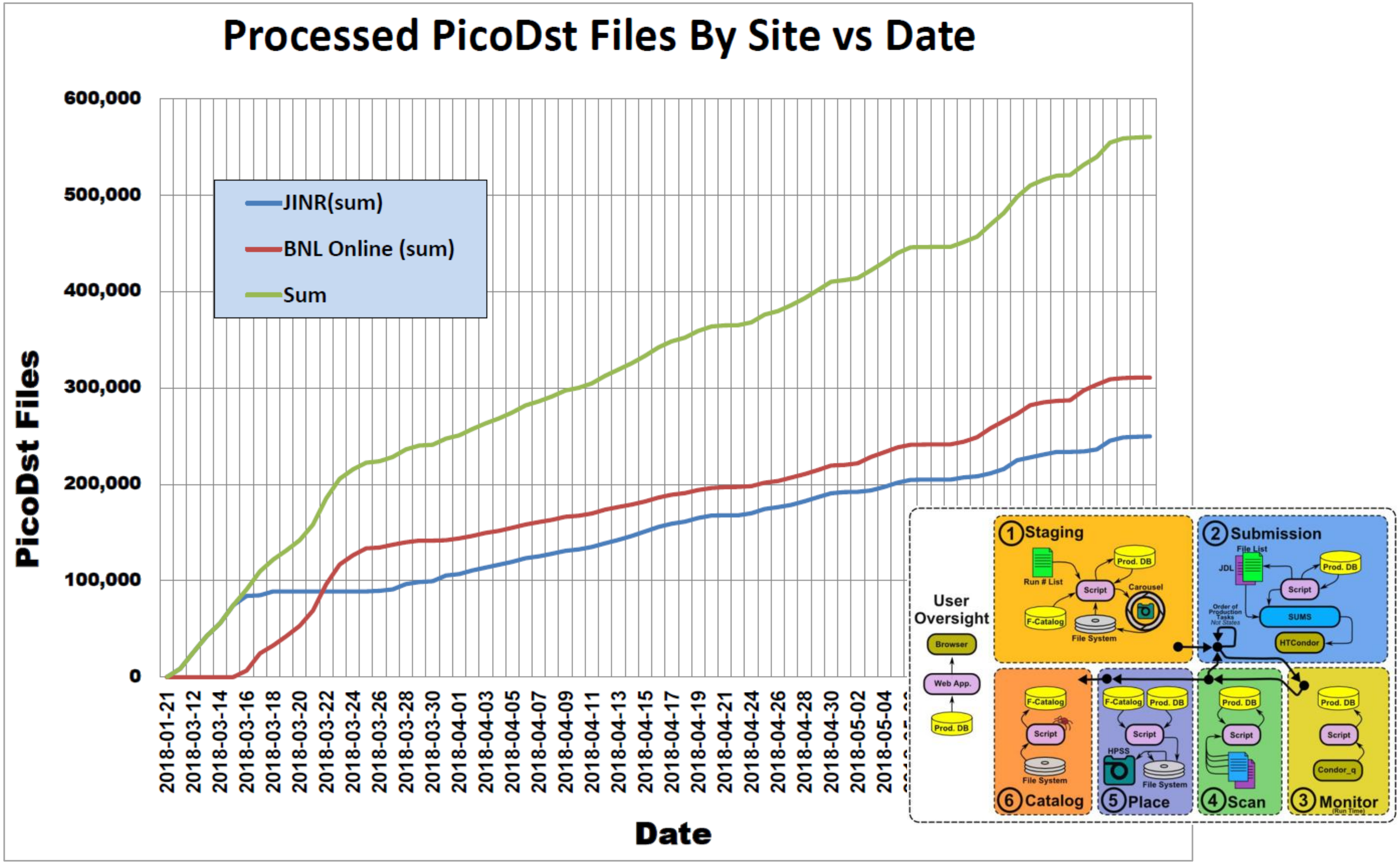
$$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_d = (0.9 \pm 0.5(\text{stat.}) \pm 1.4(\text{syst.})) \times 10^{-4}$$

$$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_{^3He} = (-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$$

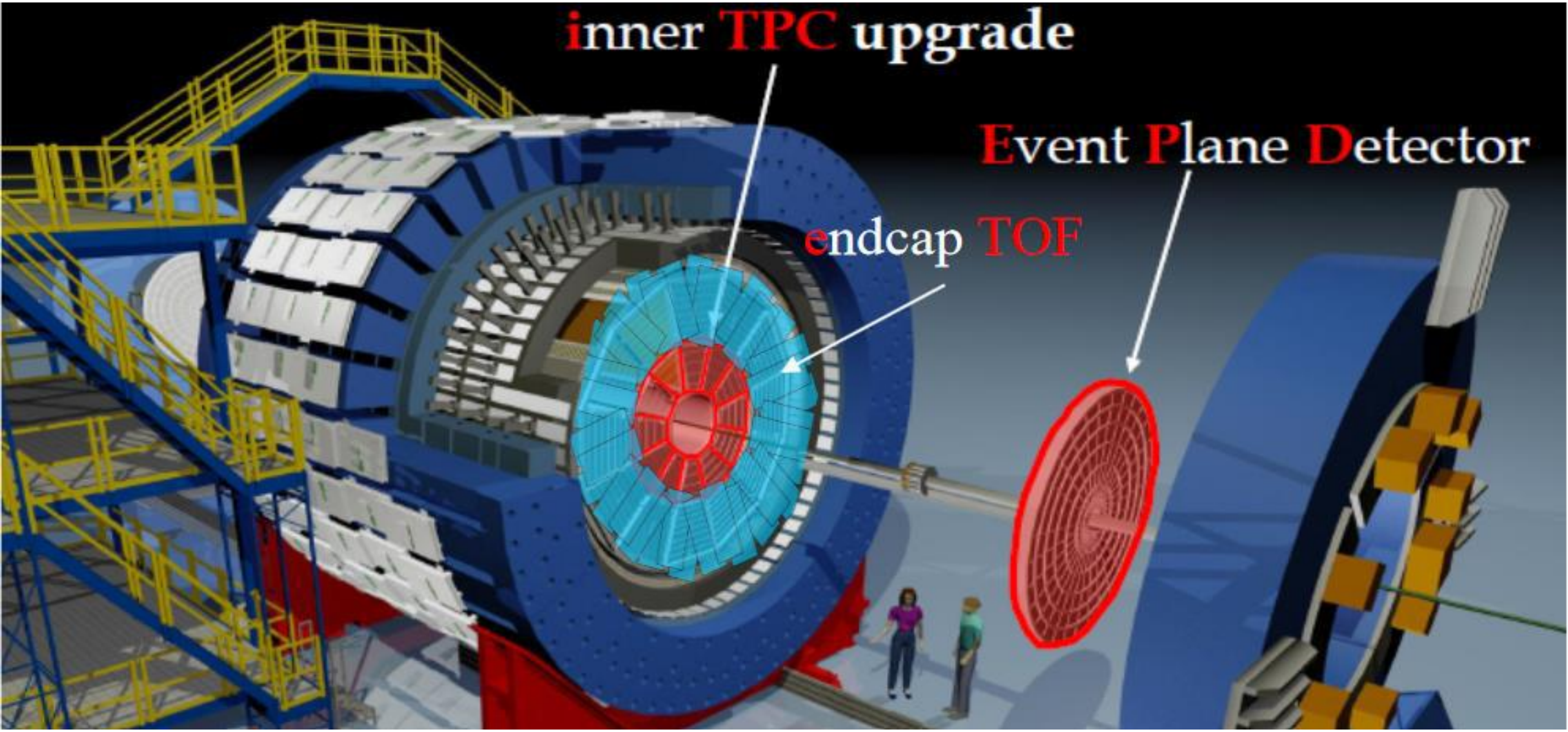
$$\left(\frac{\Delta m}{m}\right)_{^3_\Lambda H} = (1.0 \pm 0.9(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-4}$$



Transfer of production data to PicoDST



Future detector upgrades



EPD installed
- $2.1 < |\eta| < 5.1$
- Improves EP resolution
- Independent trigger

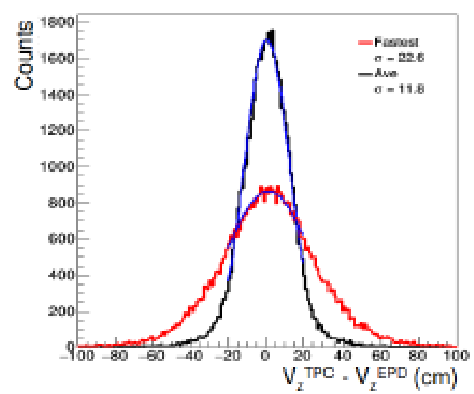
iTPC upgrade 2019
- $p_T > 60$ MeV/c
- $|\eta| < 1.5$
- Improvement of dE/dx resolution

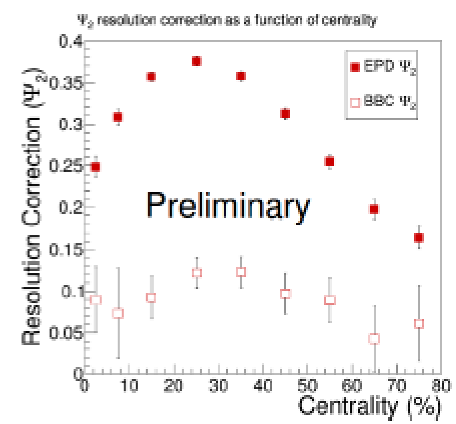
eTOF upgrade 2019
- $-1.6 < \eta < -1.1$
- Extends forward PID capability

Event Plane Detector

- ✓ **2 wheels**
  - East and West EPD ($2.1 < |\eta| < 5.1$)
- ✓ **12 supersectors**
  - Scintilator wedges, milled to form 31 tiles
  - Optically separated by epoxy
- ✓ **Fiber optics**
  - Wavelength shifting fibers
- ✓ **Sensors**
  - Silicon Photon Multipliers (SiMP)

- All 744 tiles are good
- Timing resolution about 0.75 ns with fastest TAC method
- The 2nd order event plane resolution is 0.37 in 20-30% central events in isobar collisions



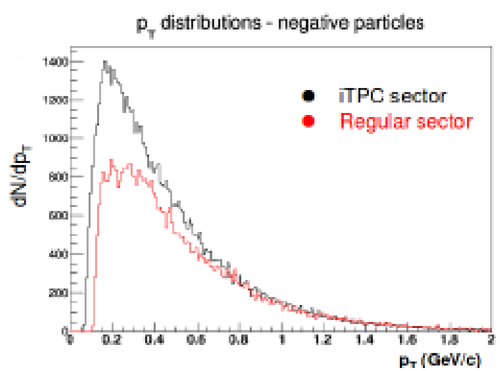


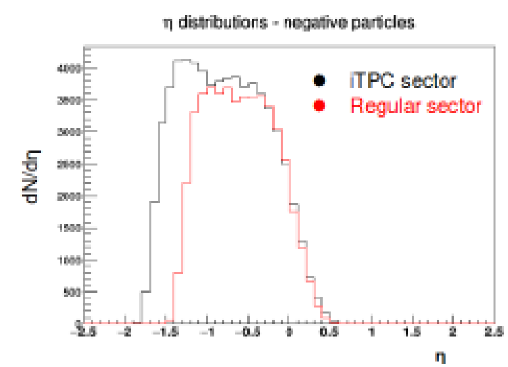
STAR Note 0666: An Event Plane Detector for STAR

iTPC upgrade

- ✓ **Inner sectors**
  - Increase readout pad rows (13 to 40)
  - New wire frames
  - New designed strongback
- ✓ **New electronics for inner sectors**
  - Doubled readout channels. Use ALICE SAMPA chip
- ✓ **New designed insertion tooling**
- ✓ **Replace all 24 inner sectors**
  - One sector has been installed and used in the data taking 2018
  - Full installation in fall 2018

- Maximum hits per track 45 -> 72
- Lower transverse momentum threshold of 60 MeV/c
- Extends |η| coverage 1.1 -> 1.5

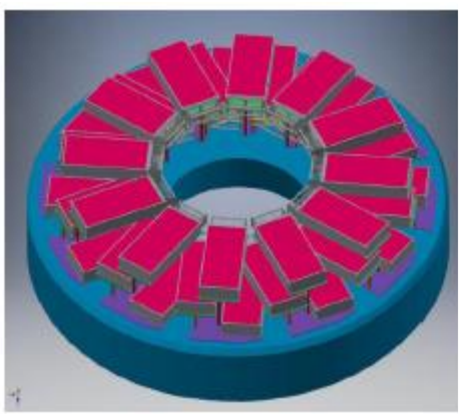


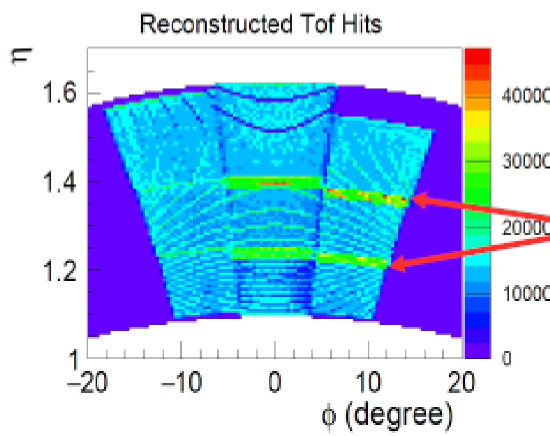


STAR Note 0644: Technical Design Report for the iTPC Upgrade

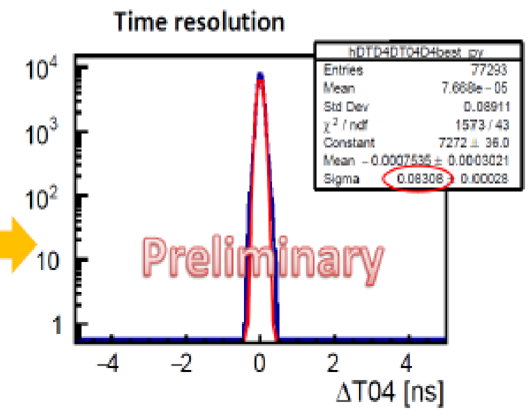
eTOF upgrade

- ✓ **Install, commission and use 10% of the CBM TOF modules in STAR**
- ✓ **Design concept**
  - 3 layers, 12 sectors, 36 modules, 108 MRPCs
- ✓ **PID in the forward direction**
- ✓ **One sector with three modules has been installed and used in the data taking 2018**
- ✓ **Full installation in fall 2018**





Overlap range of two MRPCs



- ✓ System time resolution: 83 ps
- ✓ Counter time resolution: 59 ps

arXiv:1609.05102v1

STAR future program

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Observables					
R_{CP} up to $p_T = 5$ GeV/c	-		160	125	92
Elliptic Flow (ϕ mesons)	80	120	160	160	320
Chiral Magnetic Effect	50	50	50	50	50
Directed Flow (protons)	20	30	35	45	50
Azimuthal Femtoscopy (protons)	35	40	50	65	80
Net-Proton Kurtosis	70	85	100	170	340
Dileptons	100	160	230	300	400
$>5\sigma$ Magnetic Field Significance	50	80	110	150	200
Required Number of Events	100	160	230	300	400

STAR BES-II and FXT programs will cover broad range of interest

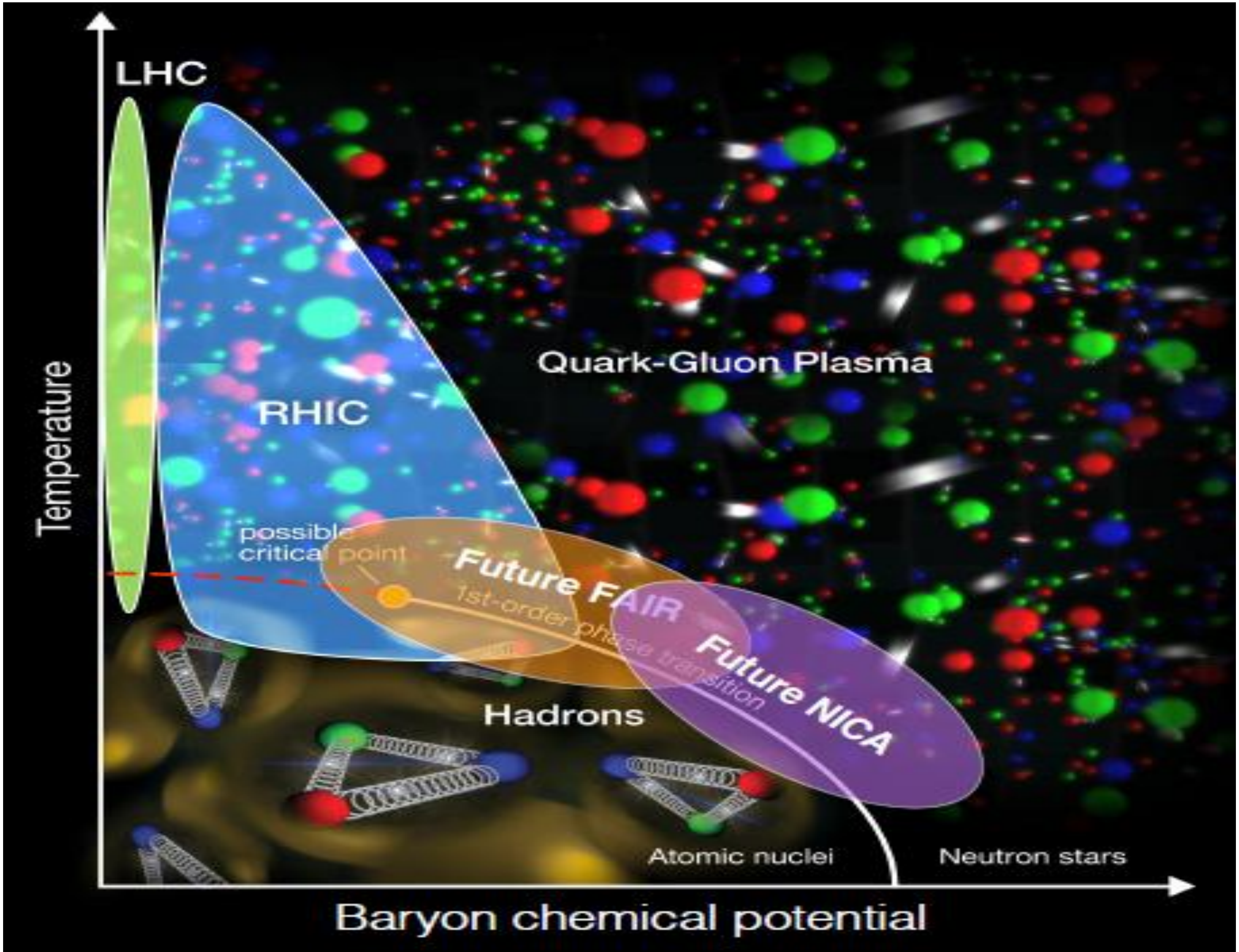
FXT

- Data rate is DAQ limited
- iTPC & eTOF will be available
- Will have an overlap with the collider data for 7.7 GeV

Single Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Year	Run Time	Species	Min-Bias Events Number
5.75	3.5 (FXT)	2020	2 days	Au+Au	100M
7.3	3.9 (FXT)	2019	2 days	Au+Au	100M
9.8	4.5 (FXT)	2019	2 days	Au+Au	100M
13.5	5.2 (FXT)	2020	2 days	Au+Au	100M
19.5	6.2 (FXT)	2020	2 days	Au+Au	100M
31.2	7.7 (FXT)	2019	2 days	Au+Au	100M

STAR Note 0696: Beam Use Request for Run19+

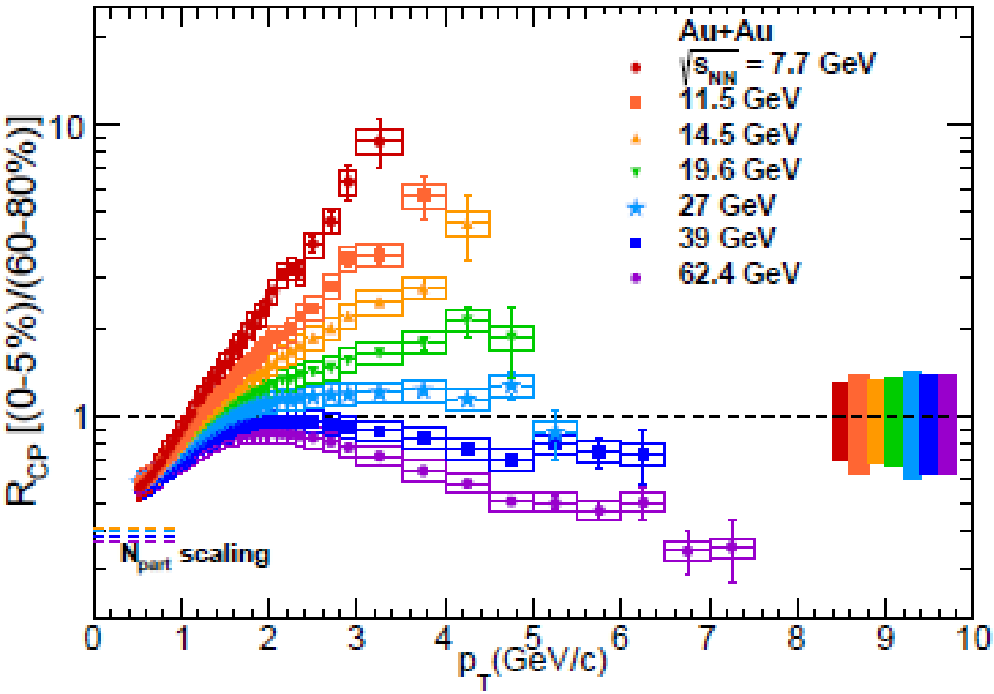
Thank you for the attention!

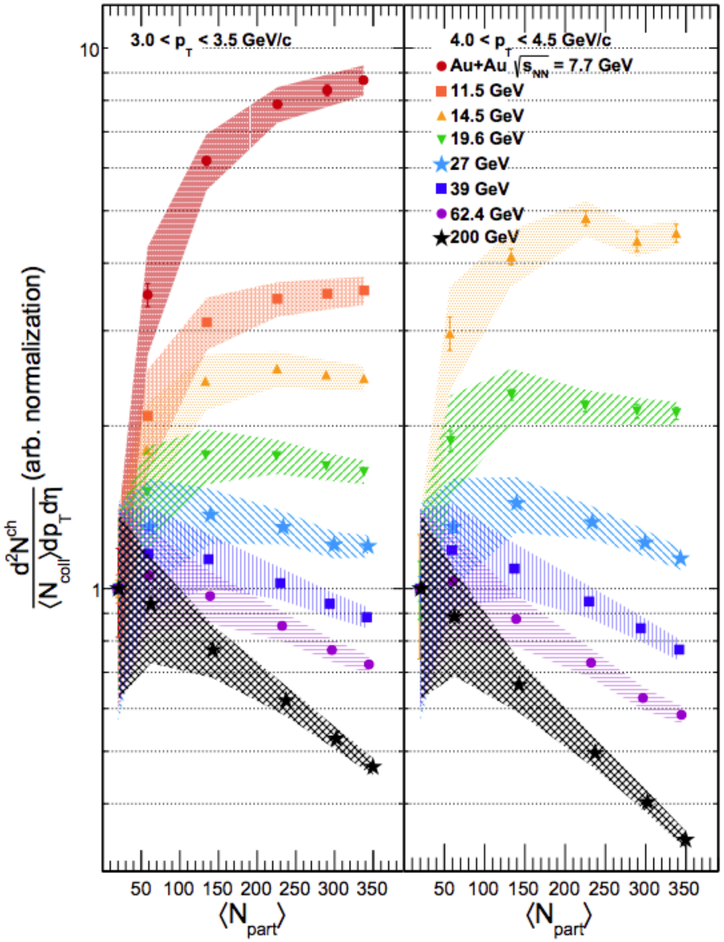


Backup slides

Results from BES-I

$$R_{cp} = \frac{d^2Ndp_t d\eta / < N_{bin} > (central)}{d^2Ndp_t d\eta / < N_{bin} > (peripheral)}$$





R_{CP} of charged hadrons

- Becomes smaller than 1 at 39 GeV and higher
- Reaches plateau at 19.6 GeV and 27 GeV

STAR, Phys. Rev. Lett. **121** (2018) 32301

Present and future HIC experimental programs