
Gatchina, Russia, August 6 – 10, 2018
*Hadron Structure and QCD:*
*from Low to High Energies*
Dedicated to the memory of Lev N. Lipatov

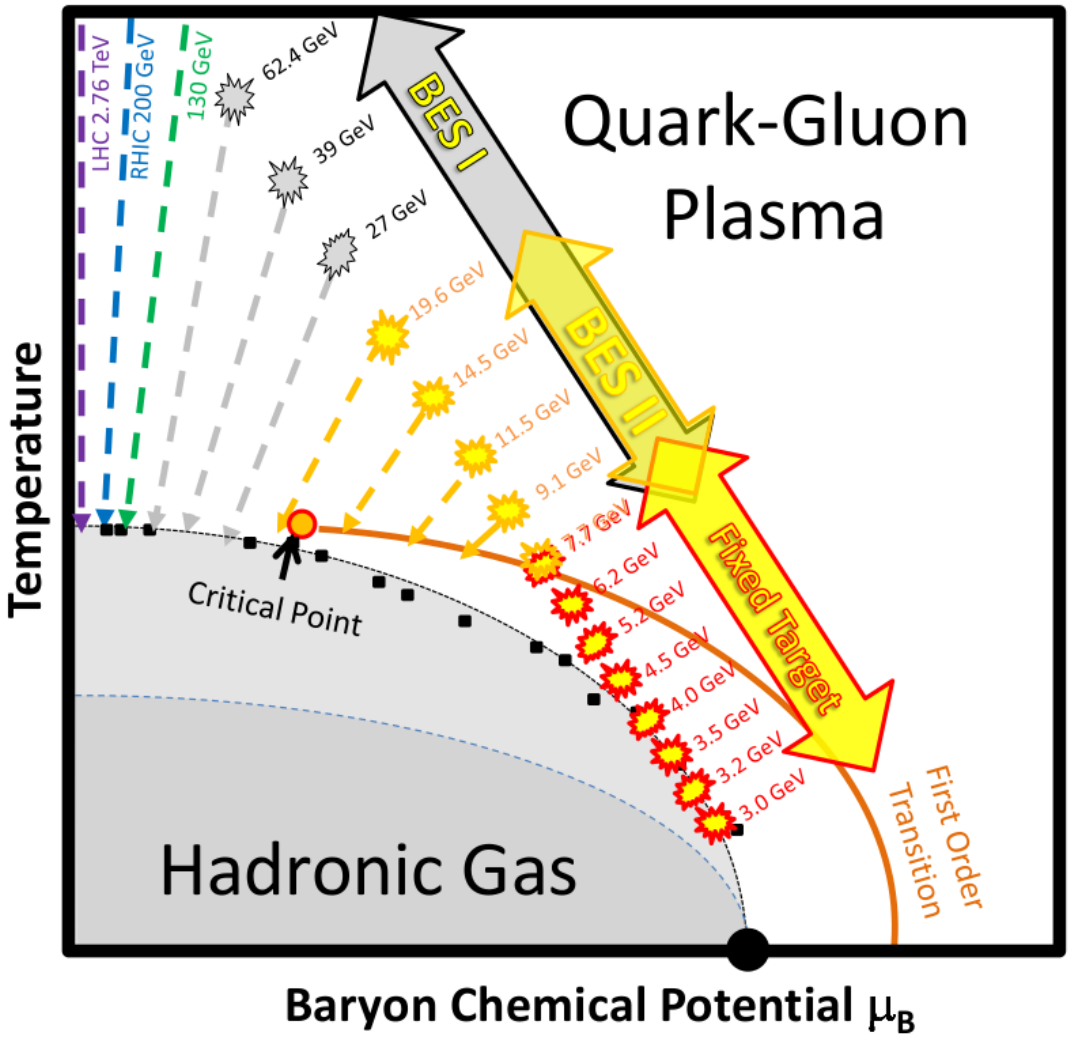
# Recent results from STAR

Grigory Nigmatkulov
(for the STAR Collaboration)
National Research Nuclear University
MEPhI

# Outline

- Introduction
- The STAR Experiment
- Collective Dynamics and Correlations
- Particle Production
- High-$p_T$ Hadrons and Jet Modification
- The STAR Fixed-Target Program
- Detector Upgrades
- Summary

# Introduction




**Top RHIC energy**

p+p, p+Al, p+Au, d+Au, $^3$He+Au, Cu+Cu, Cu+Au, Ru+Ru, Zr+Zr, Au+Au, U+U

- QCD at high energy density/temperature
- Properties of QGP, Equation of State (EoS)
- Proton spin structure

**Beam Energy Scan**

Au+Au $\sqrt{s_{NN}}$=7.7-62.4 GeV

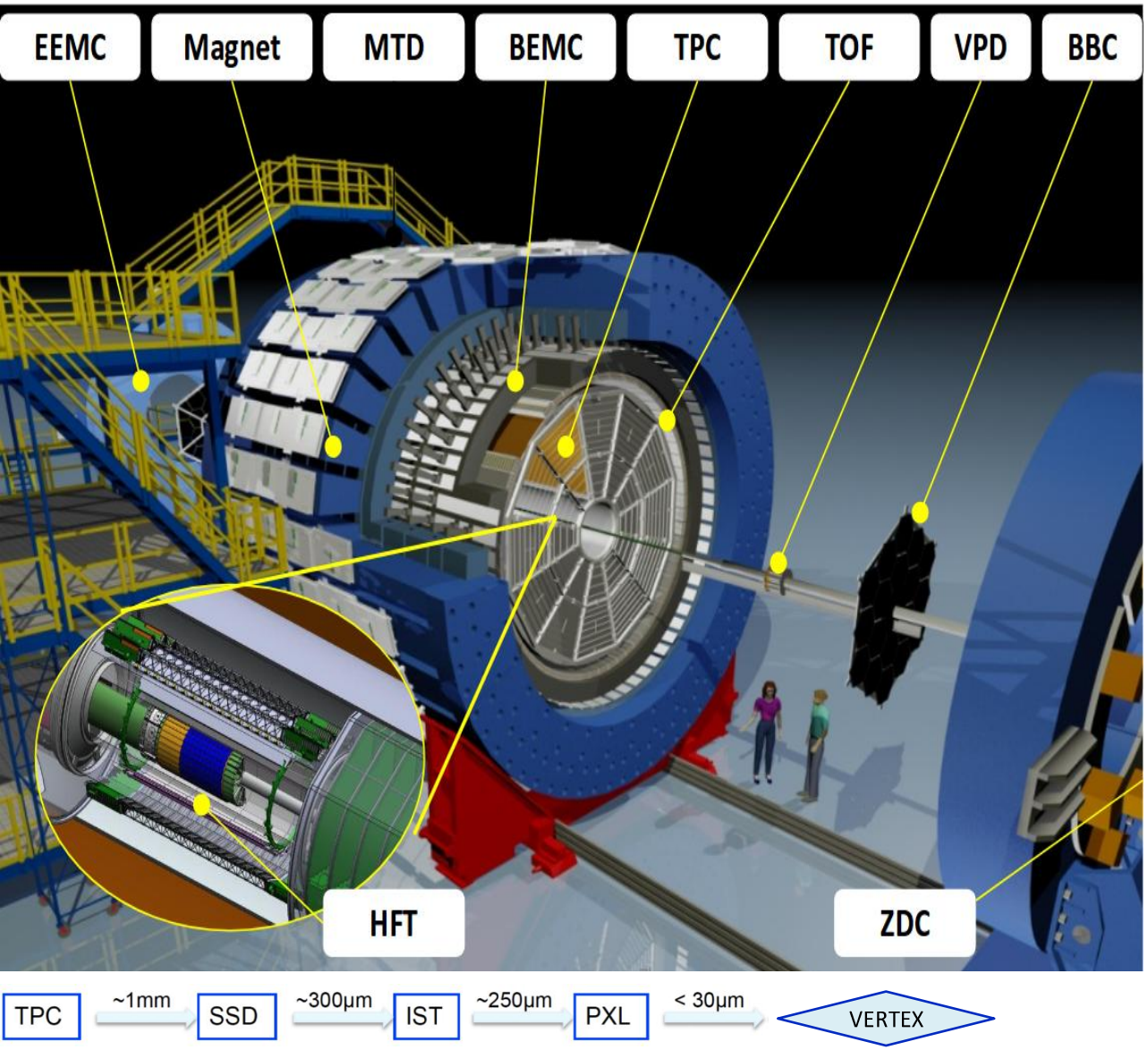
- Search for critical point
- QCD phase transition
- Turn-off of QGP signatures

**Fixed-Target Program**

Au+Au $\sqrt{s_{NN}}$=3.0-7.7 GeV

- High baryon density ($\mu_B$~420-720 MeV)

# The STAR ☆ Experiment

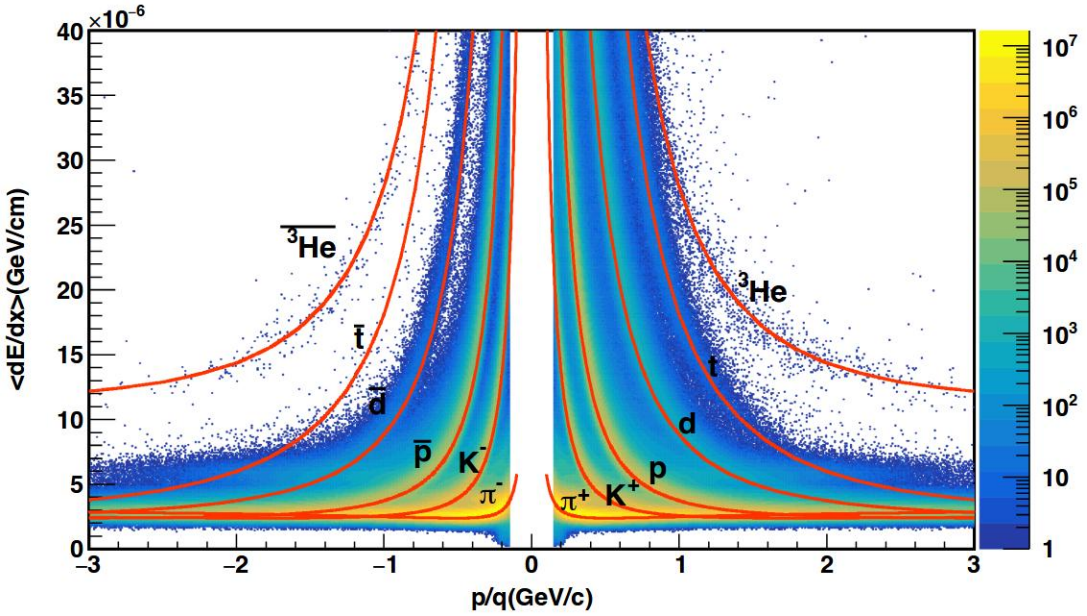


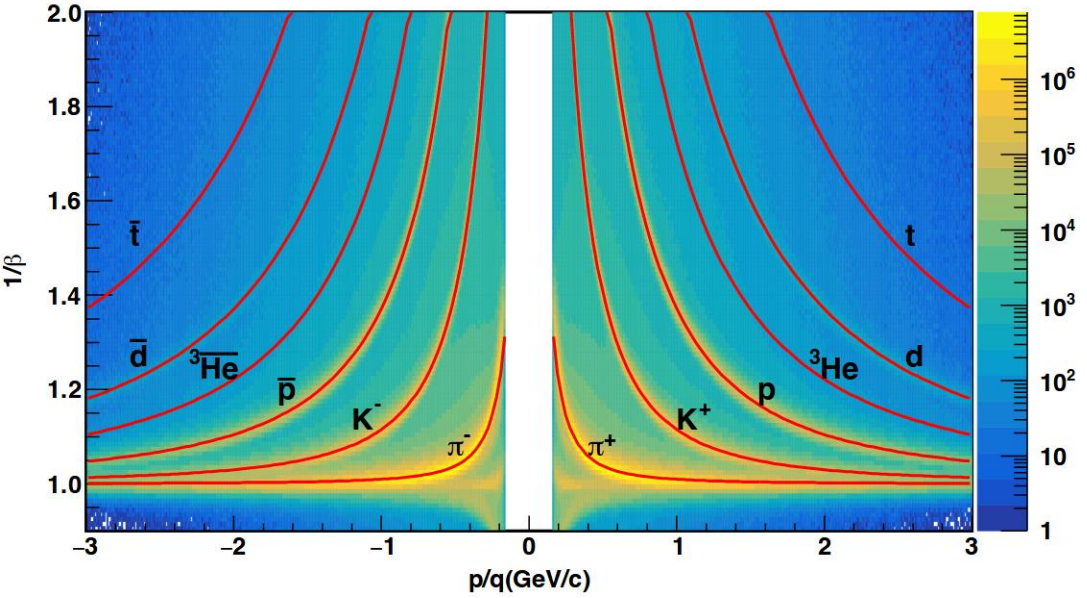

- **Tracking and PID (full 2π)**
  TPC: |η|<1
  TOF: |η|<1
  BEMC: |η|<1
  EEMC: 1<|η|<2
  HFT (2014-2016): |η|<1
  MTD (2014+): |η|<0.5

- **MB trigger and event plane reconstruction**
  BBC: 3.3<|η|<5
  EPD (2018+): 3.1<|η|<5.1
  FMS: 2.5<|η|<4
  VPD: 4.2<|η|<5
  ZDC: 6.5<|η|<7.5

- **On-going/future upgrades**
  iTPC (2019+): |η|<1.5
  eTOF (2019+): -1.6<η<-1
  FCS (2021+): 2.5<η<4
  FTS (2021+): 2.5<η<4

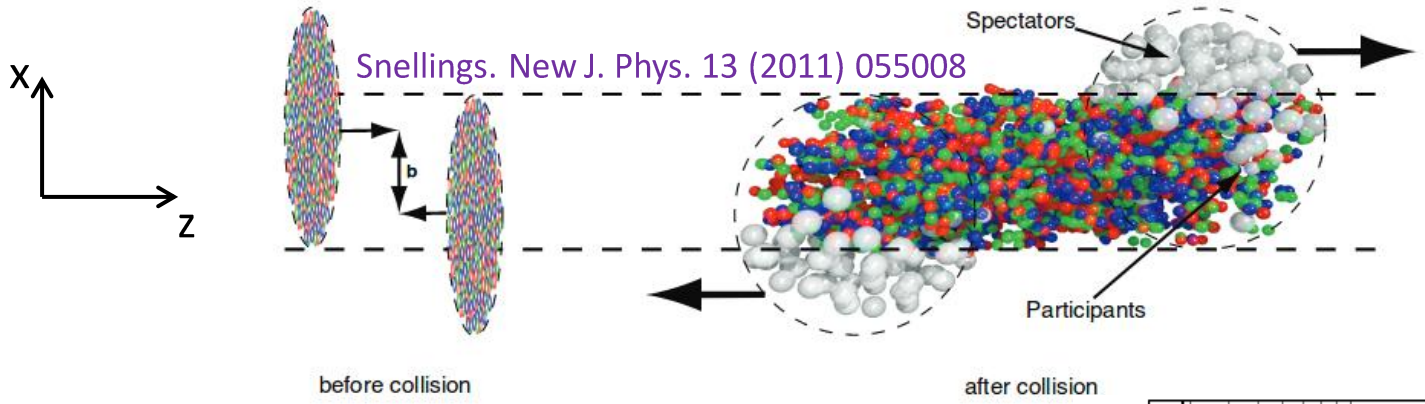
# Particle Identification with TPC and TOF




- The <dE/dx> versus rigidity measured by TPC in 2014 Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
- The 1/β versus rigidity measured by TOF in 2014 Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV

# Azimuthal Anisotropy in Heavy-Ion Collisions

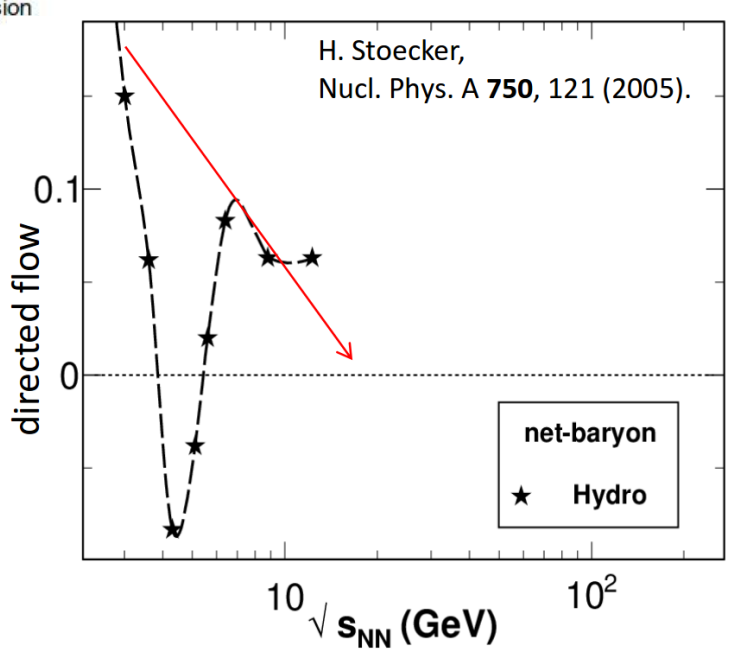



Snellings. New J. Phys. 13 (2011) 055008

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

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

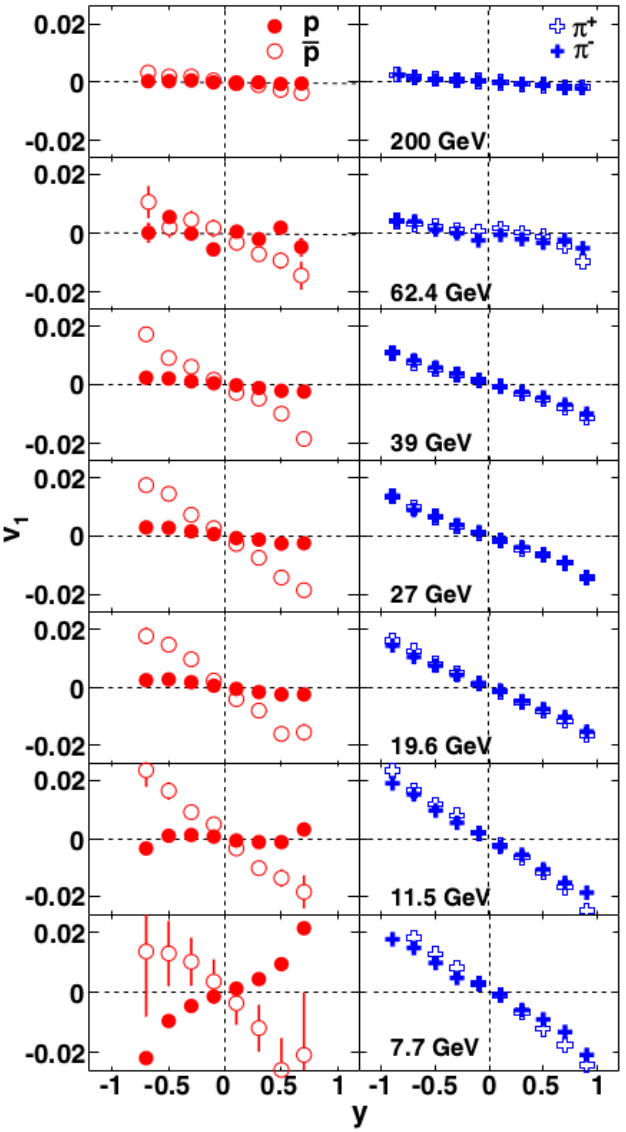
- $v_1=\langle p_x/p_t\rangle$ – directed flow
- Describes the sideward collective motion of particles within the reaction plane (x-z)
- Probe of the softening of the EoS:
  - Strong softening: consistent with the 1st-order phase transition
  - Weaker softening: more likely due to crossover




Nara, Niemi, Steinheimer, Stöker. Phys. Lett. B 769 (2017) 543
Ivanov, Soldatov. Phys. Rev. C 91 (2015) 024915

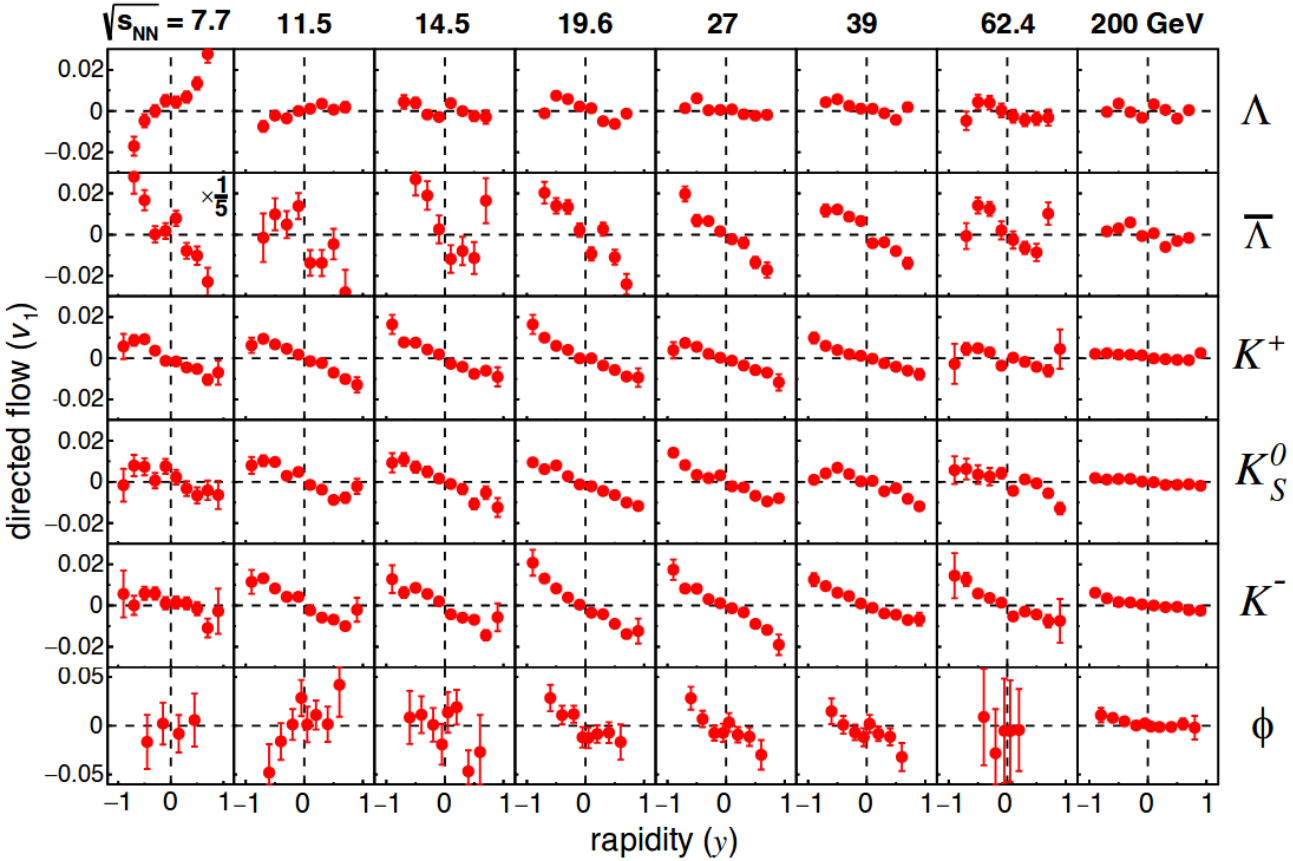
# Directed flow measurements

10-40% Au+Au collisions

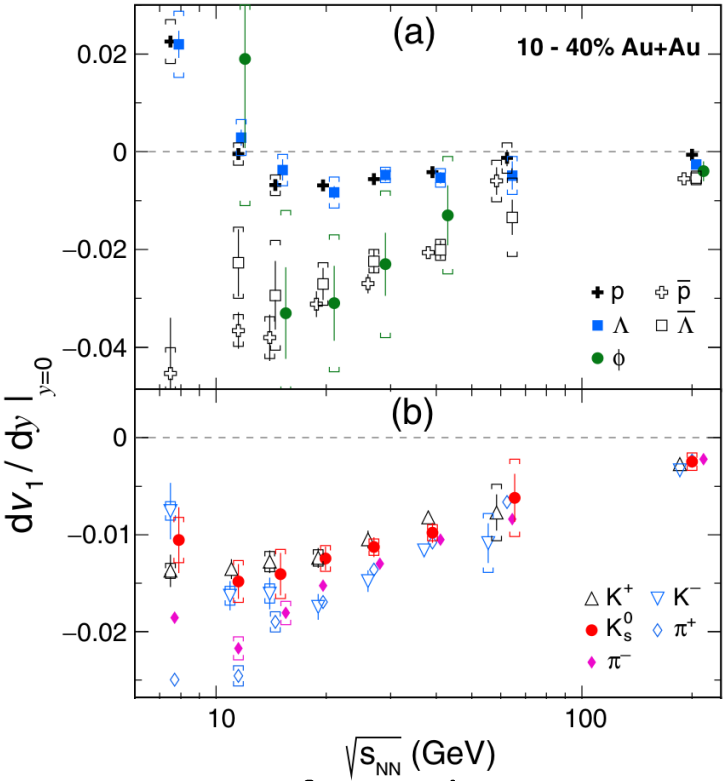



To extract $v_1$ slope, linear fit was used over $|y|<0.6$ for $\phi$ meson and over $|y|<0.8$ for all other species

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

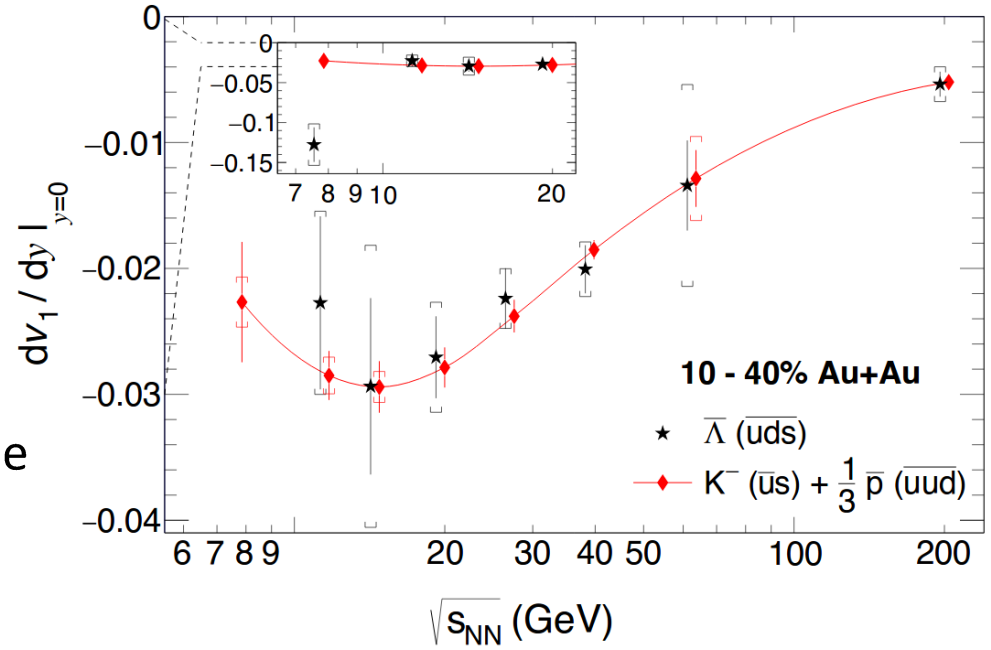


# Beam energy dependence of directed flow




- $dv_1/dy$ for $\Lambda$ and p agree within uncertainties
- $dv_1/dy$ slope for baryons changes sign in the region $\sqrt{s_{NN}}$<14.5 GeV
- Particles (anti-p, anti-$\Lambda$, and $\phi$) with produced quarks show similar behavior for $\sqrt{s_{NN}}$>14.5 GeV
- Mesons show negative $dv_1/dy$

STAR. Phys. Rev. Lett. 120 (2018) 062301



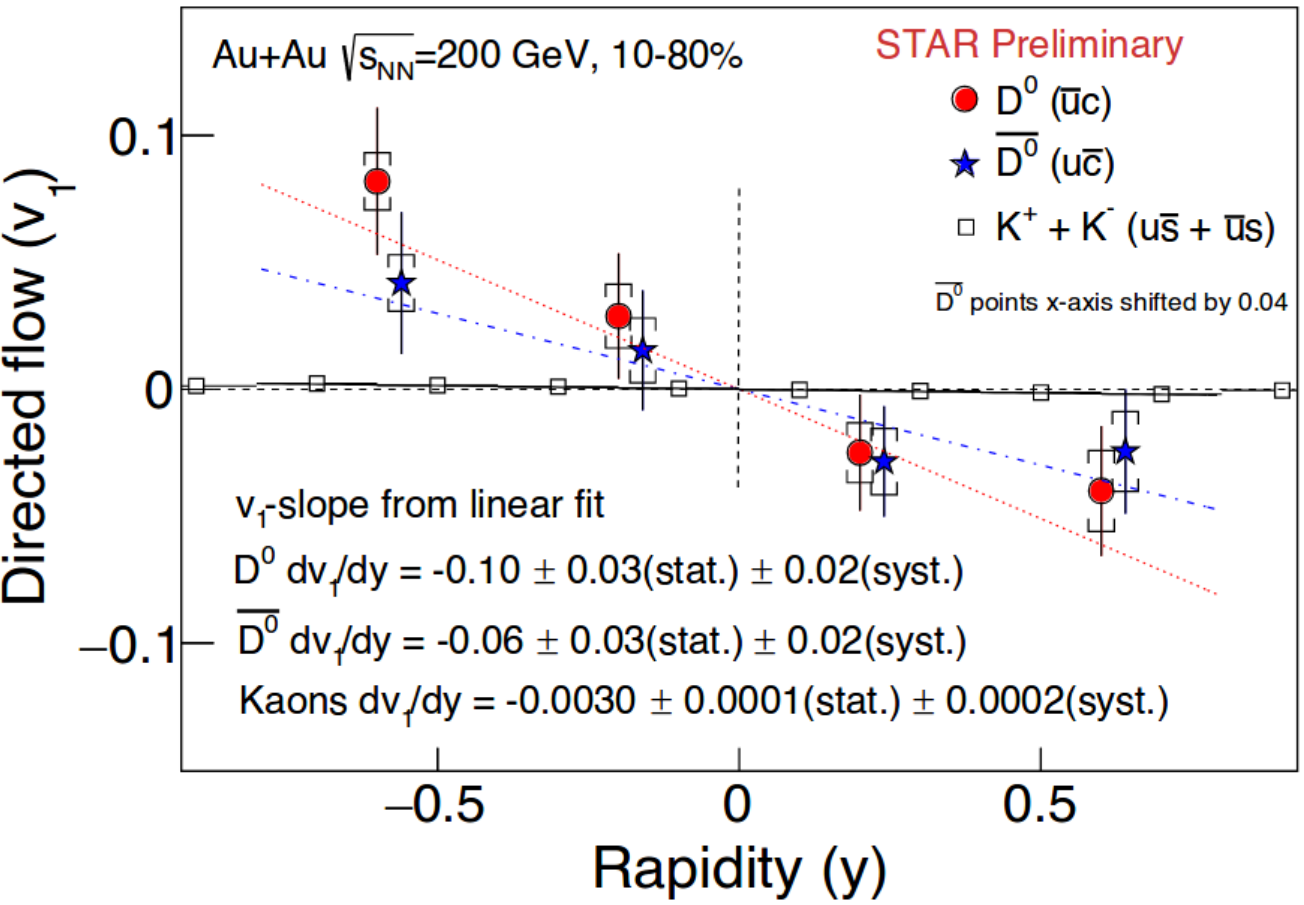

Assumptions for coalescence sum rule:

- $v_1$ is developed at prehadronic stage
- Specific types of quarks have the same $v_1$
- Hadrons are formed via coalescence

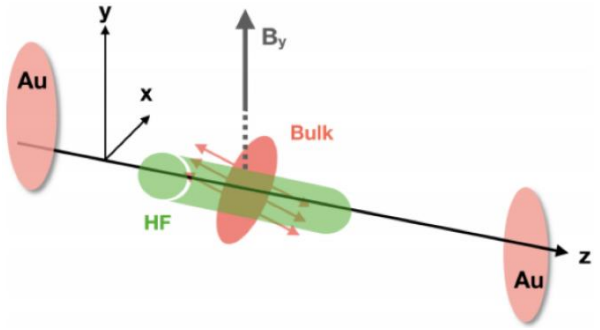
$$(v_n)_{hadron} = \Sigma(v_n)_{\text{constituent quarks}}$$

For anti-Lambdas, prediction using coalescence sum rule agrees with measured v1 above $\sqrt{s_{NN}}$=11.5 GeV

# $v_1$ of $D^0$ in Au+Au at 200 GeV




Interplay between the drag by the tilted bulk and the EM field




Chatterjee, Bozek. Phys. Rev. Lett. 120 (2018) 192301

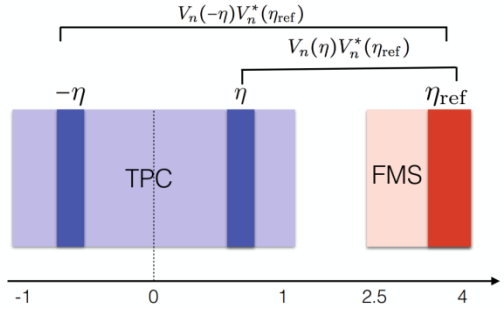
First evidence for non-zero $D^0$ $v_1$ from 2014+2016 Heavy Flavor Tracker (HFT) data:

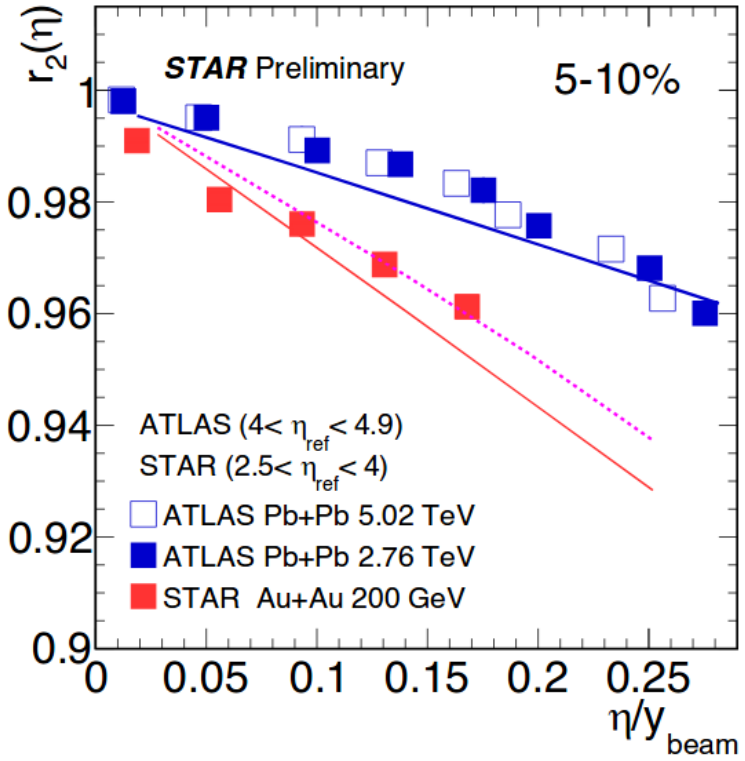
$$\boldsymbol{D^0 + \overline{D^0}\ dv_1/dy = -0.081 \pm 0.021(stat.) \pm 0.017(syst.)}$$

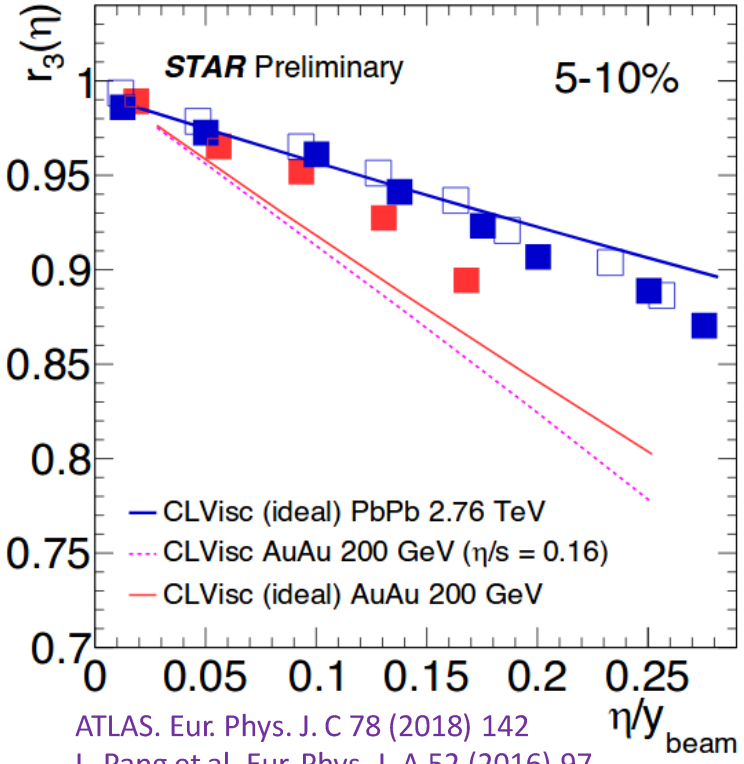
# Longitudinal Flow Decorrelation in 200 GeV Au+Au Collisions

CMS. Phys. Rev. C 92 (2015) 034911

$$r_n(\eta) = \frac{\langle v_n(-\eta)v_n(\eta_{\rm ref})\cos n(\Psi_n(-\eta)-\Psi_n(\eta_{\rm ref}))\rangle}{\langle v_n(\ \eta)v_n(\eta_{\rm ref})\cos n(\Psi_n(\ \eta)-\Psi_n(\eta_{\rm ref}))\rangle}$$



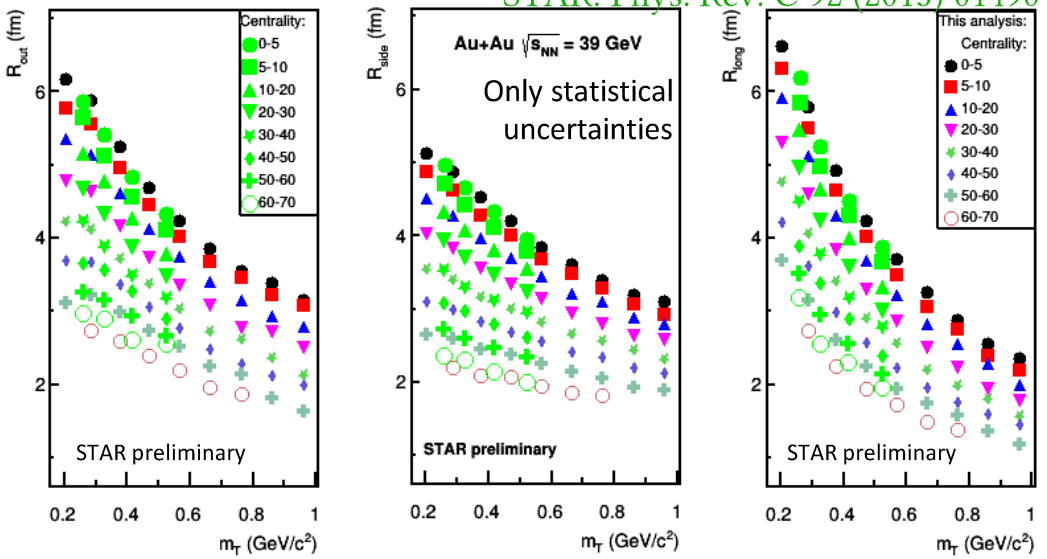

ATLAS. Eur. Phys. J. C 78 (2018) 142
L. Pang et al. Eur. Phys. J. A 52 (2016) 97
L. Pang et al. arXiv: 1802.04449

- Stronger longitudinal flow decorrelation at RHIC than at LHC
- Hydrodynamic calculations can not simultaneously describe LHC and RHIC data

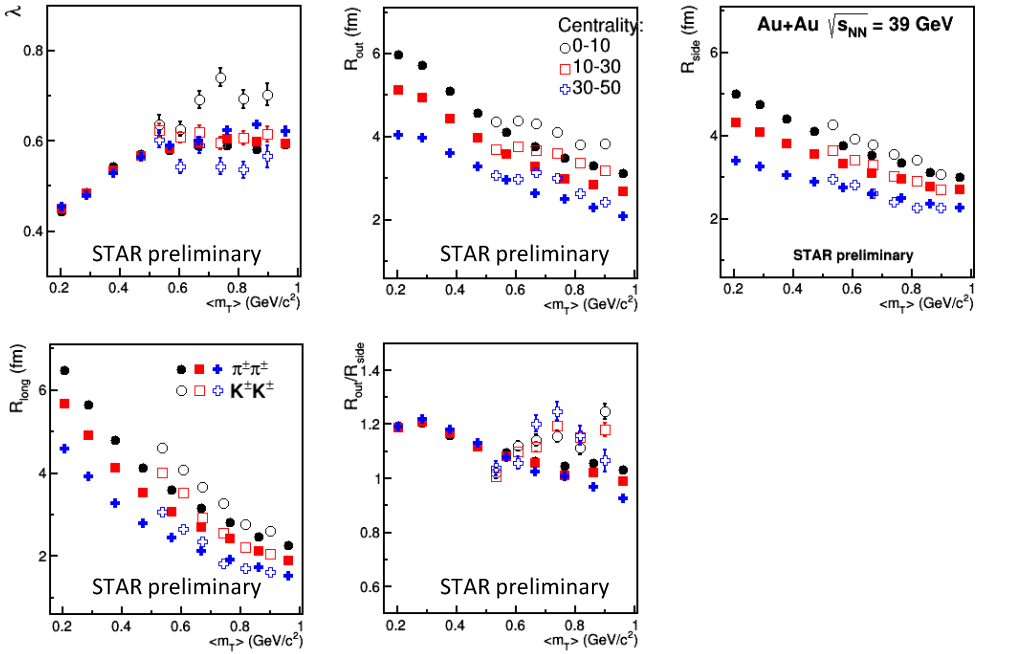
# Femtoscopic measurements

STAR. Phys. Rev. C 92 (2015) 014904

- Use two-particle momentum correlations to measure spatial and temporal properties of the source at kinetic freeze-out
- Utilizing the information from the TOF detector to extend measurement to higher transverse mass ($m_T$) region




- Kaon femtoscopic radii in outward and longitudinal directions are generally larger than those for pions at the same $m_T$ → breaking of the $m_T$-scaling
- In the sideward direction, the pion and kaon radii are similar

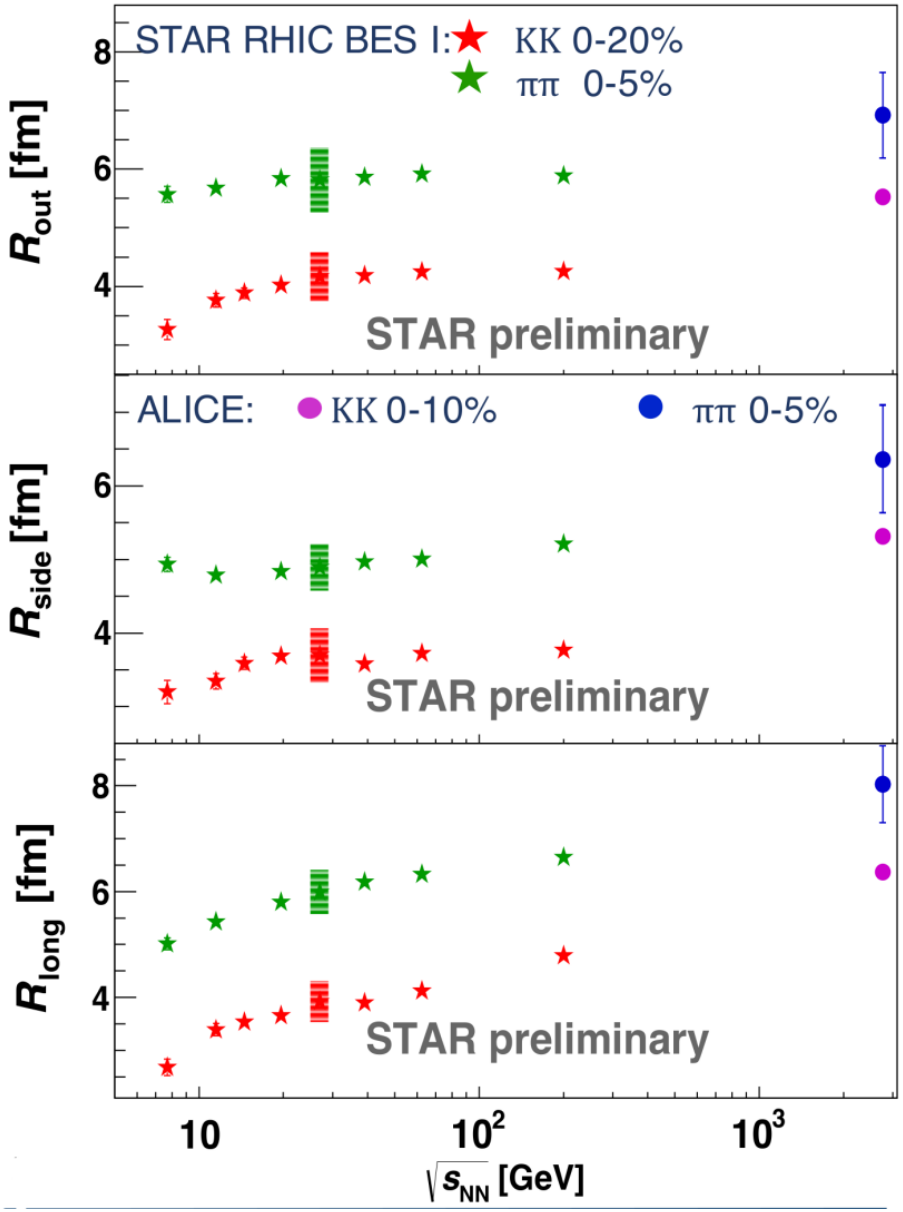


# Femtoscopic measurements

The extracted femtoscopic radii smoothly increase with increasing collision energy

The values of $R_{out}$ and $R_{side}$ for both pions and kaons show a very small increase at the RHIC energies and slightly larger at the LHC

The values of $R_{long}$ suggest that the system lives longer at the LHC energy



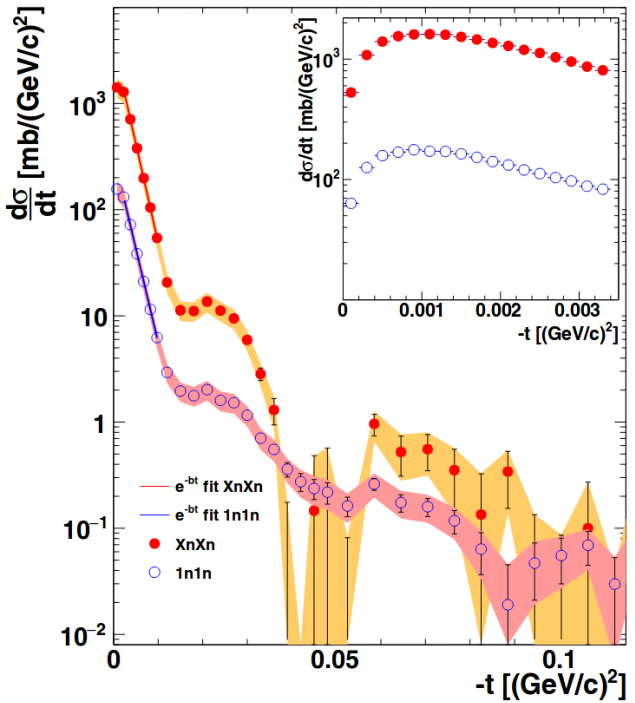
# Ultra-Peripheral Collisions

## Diffraction in $\rho^0$ photoproduction

- -t is the square of transferred 4-momentum
- Diffractive dips at $-t=0.018$ and $0.043$ $(GeV/c)^2$
- Two cases of nuclear breakup:
  - 1n1n: one neutron at (+) and (-) rapidity
  - XnXn: one or more neutrons at (+) and (-) rapidity
- Exponential slope in dσ/dt is consistent with LHC (ALICE. JHEP 1509 (2015) 095)

**Similarity in exponential parts implies no evidence for increase of nuclear size with photon energy**

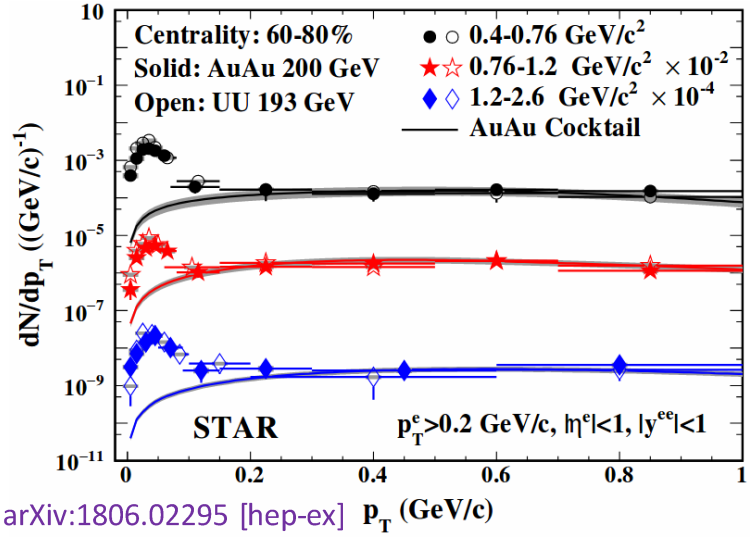
STAR. Phys. Rev. C 96 (2017) 054904




## Electromagnetic processes in peripheral collisions

- Data on $e^+e^-$ pairs in peripheral Au+Au and U+U collisions
- Yield enhanced at low $p_T$ with respect to hadronic expectation
- Shape of the excess is consistent with $e^+e^-$ from photoproduction

**Novel probe to electromagnetic fields of the nuclei**




STAR. arXiv:1806.02295 [hep-ex]

# (Anti)Hypertriton Binding Energy

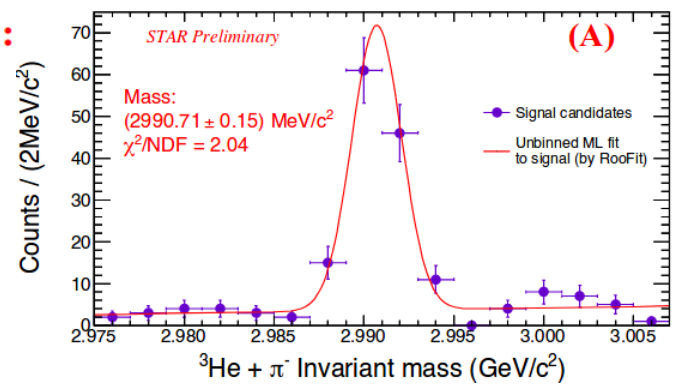
**Reconstructing ${}^{3}_{\Lambda}\mathrm{H}$ (${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$) through:**

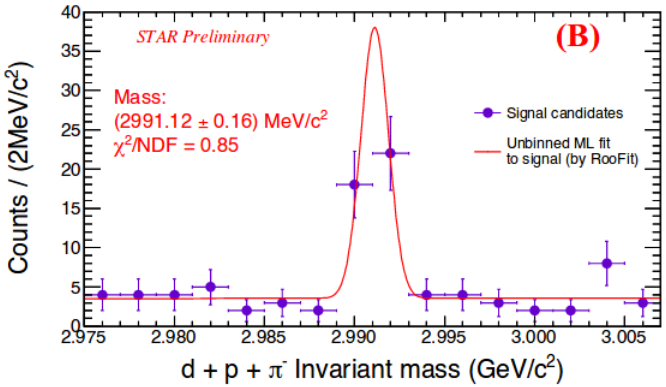
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$

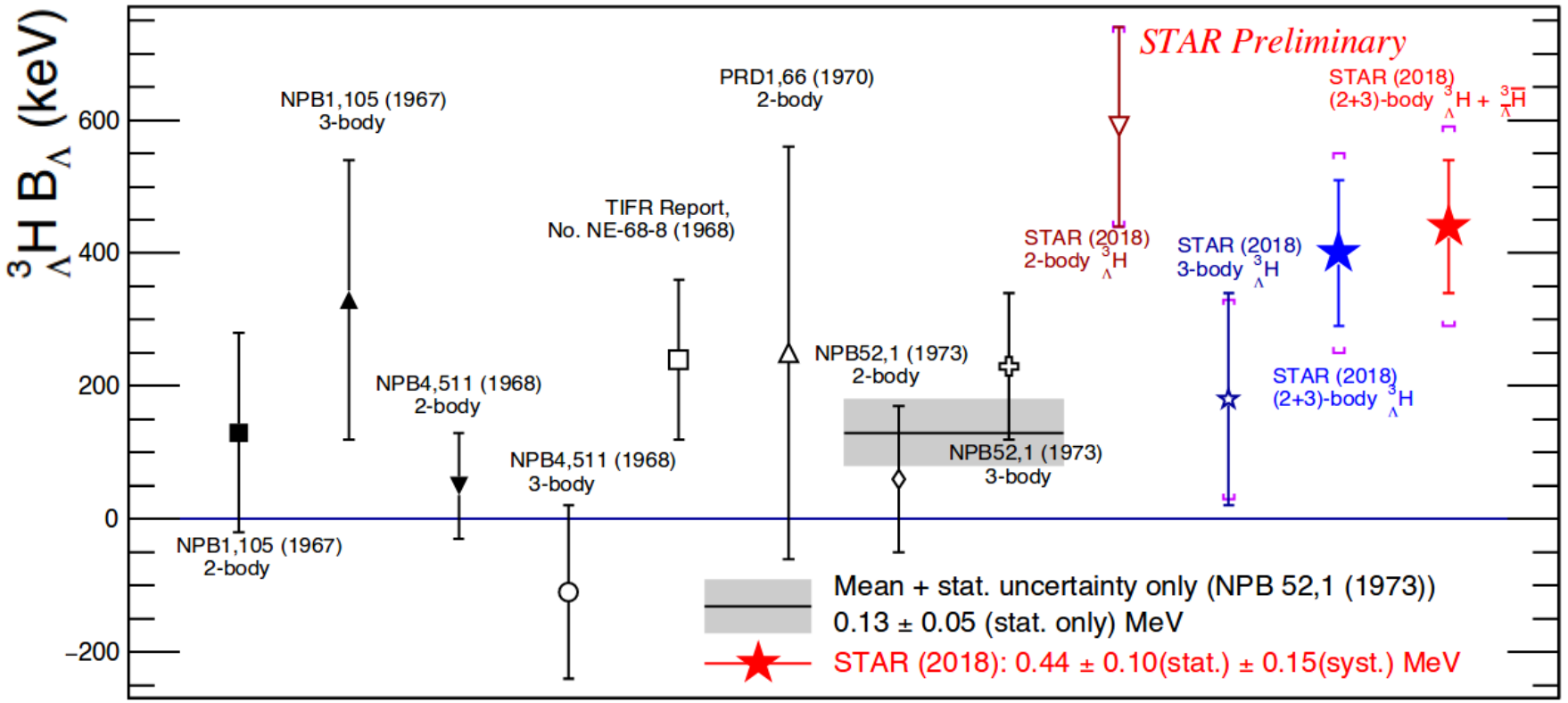
$${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$$

Binding energy ($B_\Lambda$) definition:

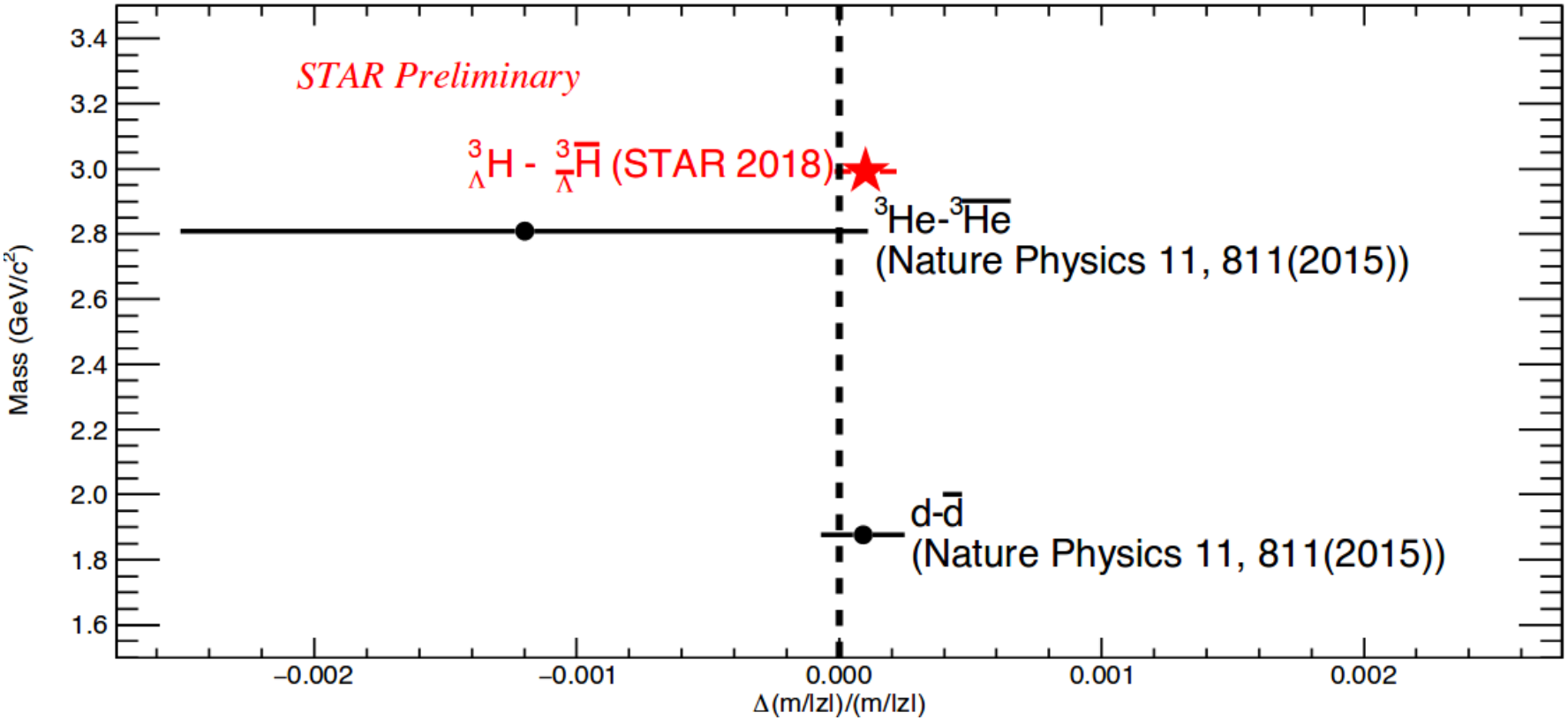
$$m_\Lambda + m_d - m_{{}^{3}_{\Lambda}\mathrm{H}}$$



# Mass difference between ${}^{3}_{\Lambda}H$ and ${}^{3}_{\bar{\Lambda}}\bar{H}$




- First measurement of the hypertriton and antihypertriton mass difference
- Test of CPT symmetry in the light hypernuclei sector

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

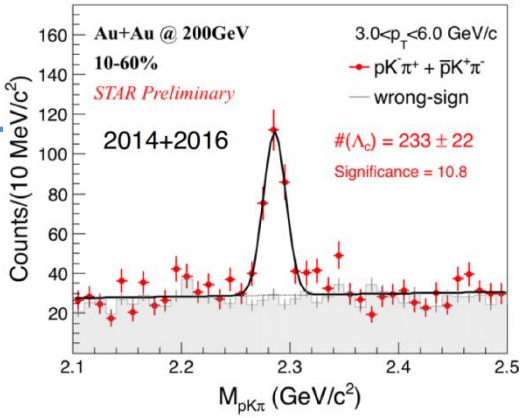
$$\left(\frac{\Delta(m/|z|)}{m/|z|}\right)_{^3\text{He}} = (-1.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.}))\times 10^{-3}$$

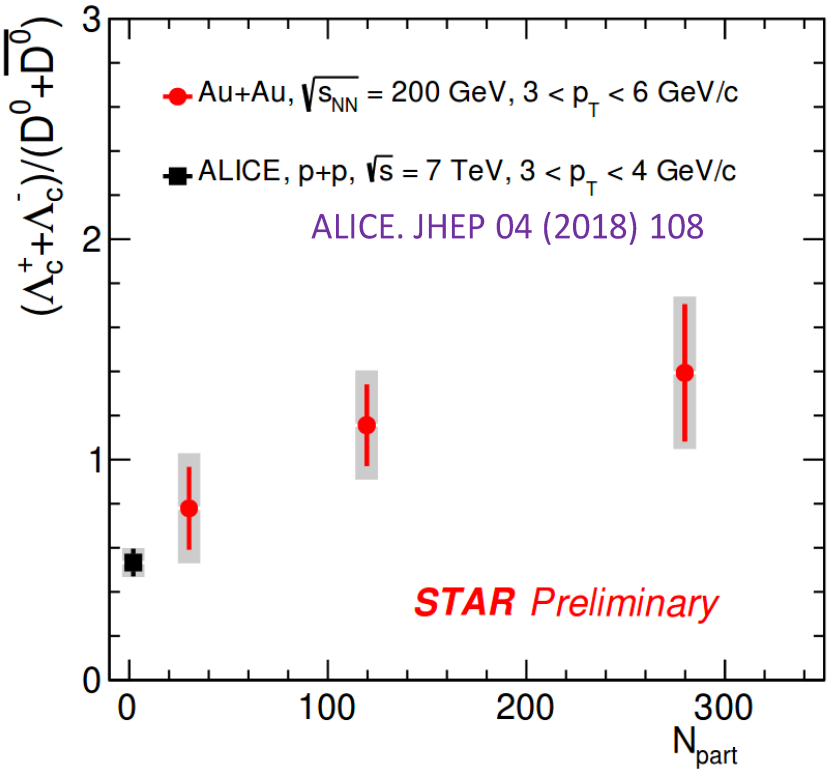
$$\left(\frac{\Delta m}{m}\right)_{^3_\Lambda\text{H}} = (1.0 \pm 0.9\,(\text{stat.}) \pm 0.7\,(\text{syst.}))\times 10^{-4}$$

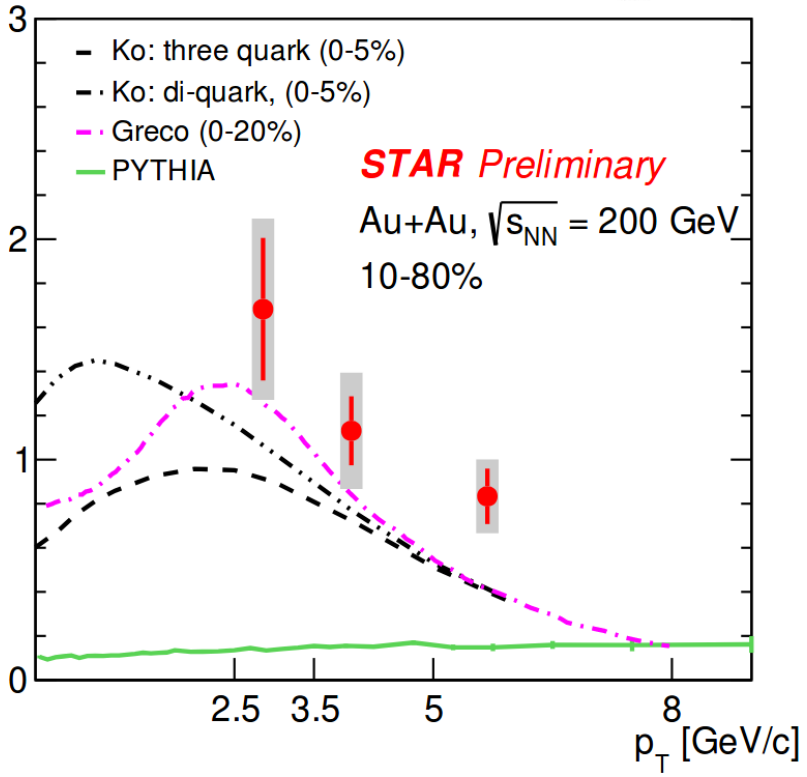
- The mass difference is consistent with the CPT expectation

# $\Lambda_c$ production

Adding data from year 2016 and using TMVA BDT allowed to obtain more than 2 times improvement in the signal significance than 2014 data alone

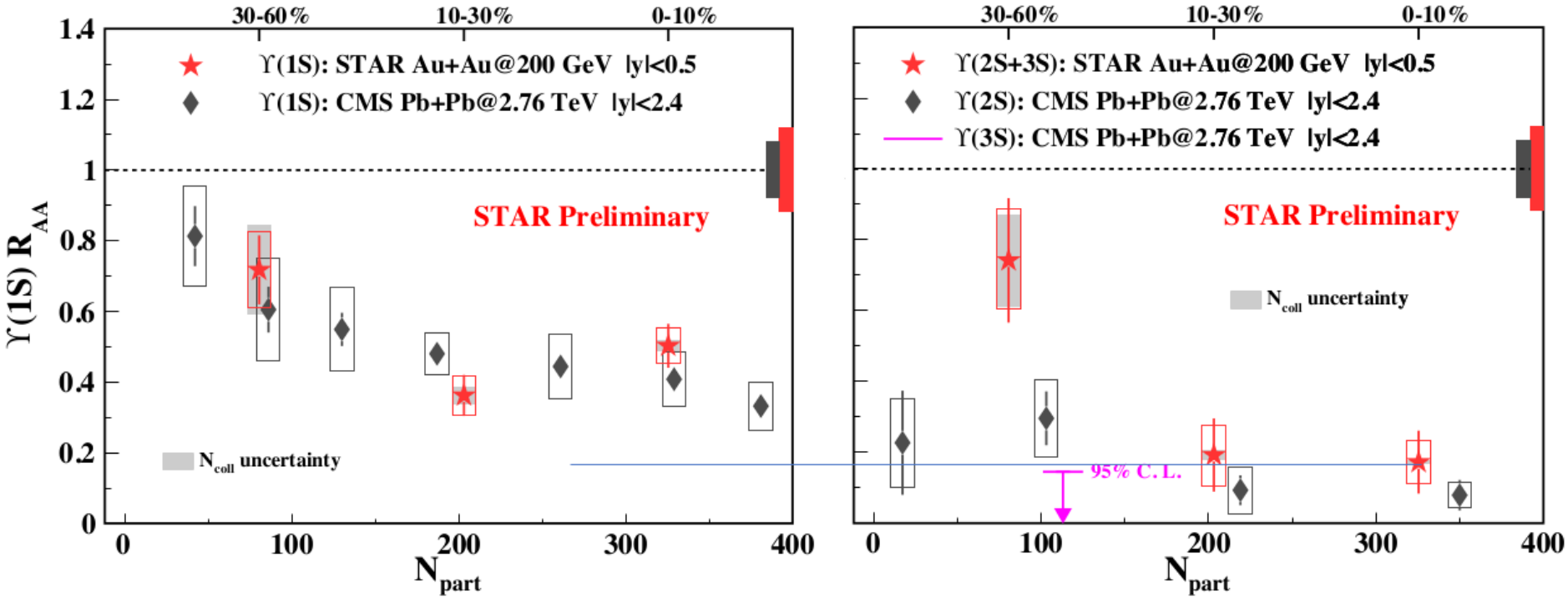



- $\Lambda_c/D^0$ ratio increases from peripheral to central collisions
- Enhancement of $\Lambda_c$ production increases towards low $p_T$
- Large $\Lambda_c$ contribution to the total charm cross-section in heavy-ion collisions

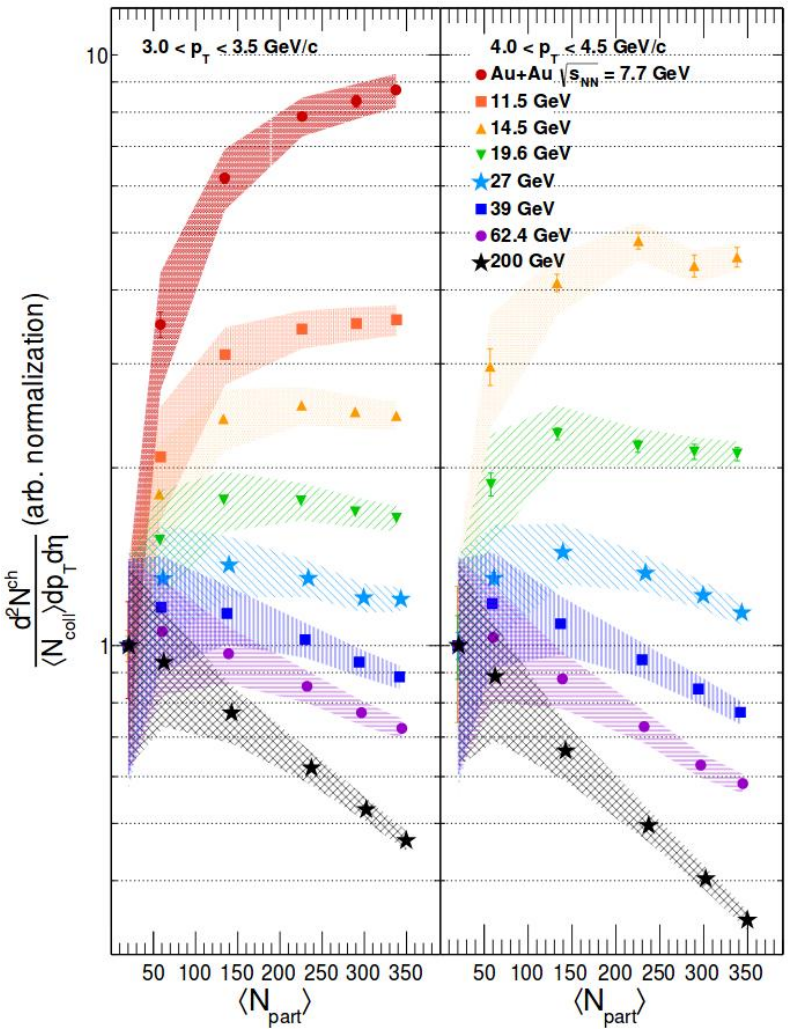
# Upsilon Suppression in Au+Au @ 200 GeV




CMS. Phys. Lett. B 04 (2017) 031

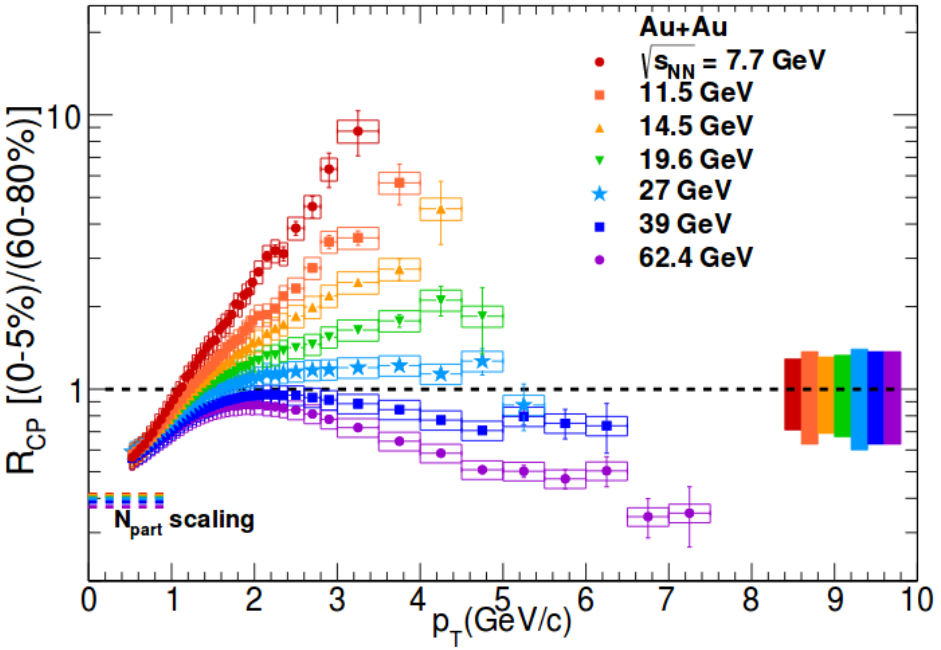
- Improved precision by combining 2011 di-electron, 2014+2016 di-muon
- $\Upsilon$(2S+3S) $R_{AA}$ smaller that $\Upsilon$(1S) in 0-10%
  - "Sequential melting" at RHIC

# Nuclear modification in BES-I



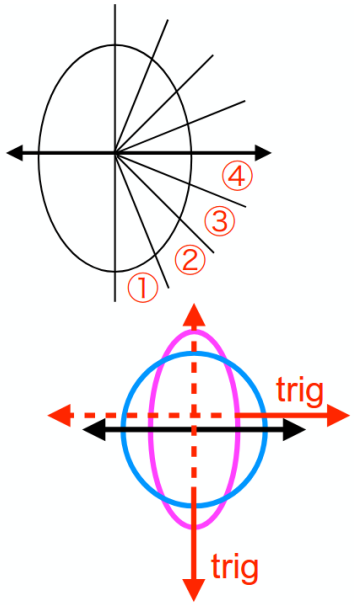

STAR. arXiv: 1707.01988v1

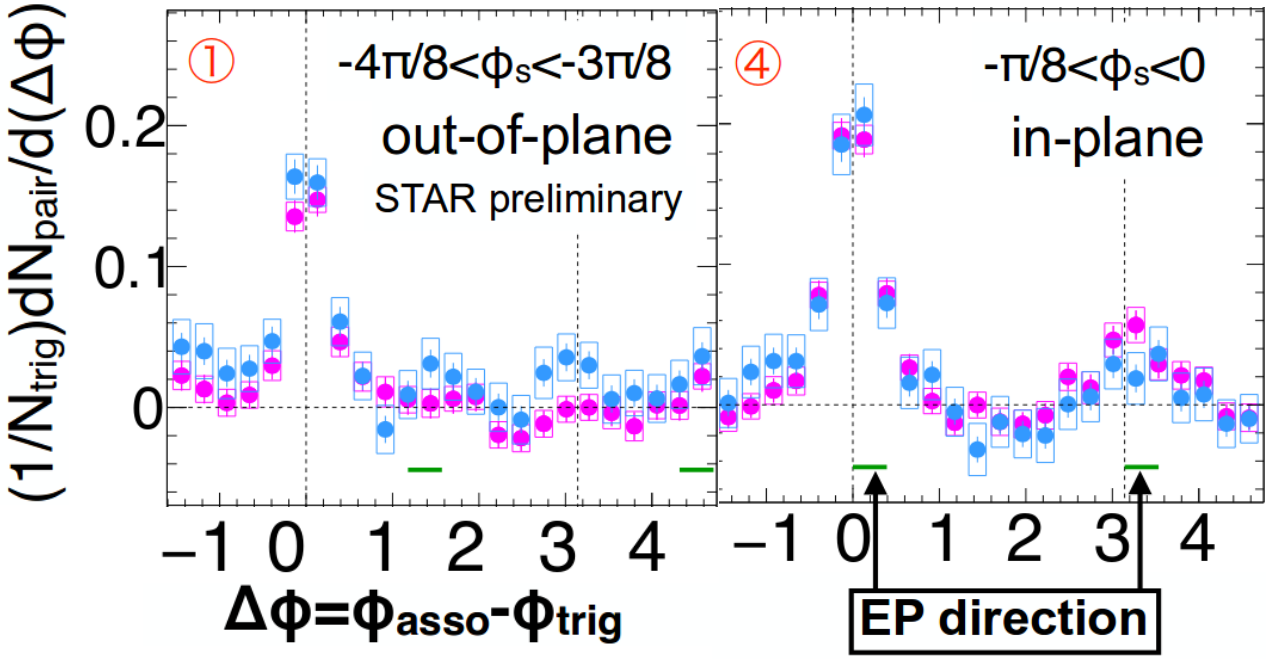
- $R_{CP}$ for hadrons and for charged particles probes partonic energy loss in the medium
- BES-I results Indicate disappearance of suppression bellow 14.5 GeV
- Would like to explore this with identified hadrons (to isolate baryon stopping)



# Di-hadron Correlations in Au+Au @ 200 GeV

Au+Au $\sqrt{s_{NN}}$ = 200 GeV
0-10%
- $q_2$ top 20%
- $q_2$ bottom 20%

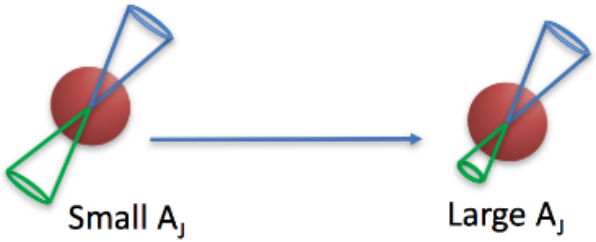


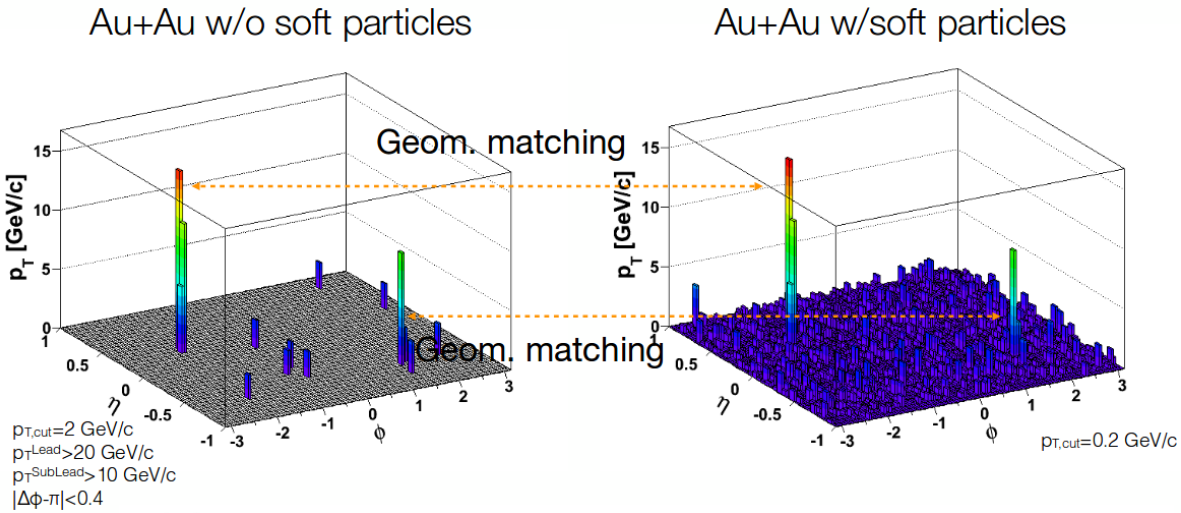




- High-$p_T$ particles penetrate more with short pathlength
- Low-$p_T$ particles are pushed toward in-plane direction and this effect is stronger in large $q_2$
  - Pathlength-dependent jet-medium interaction

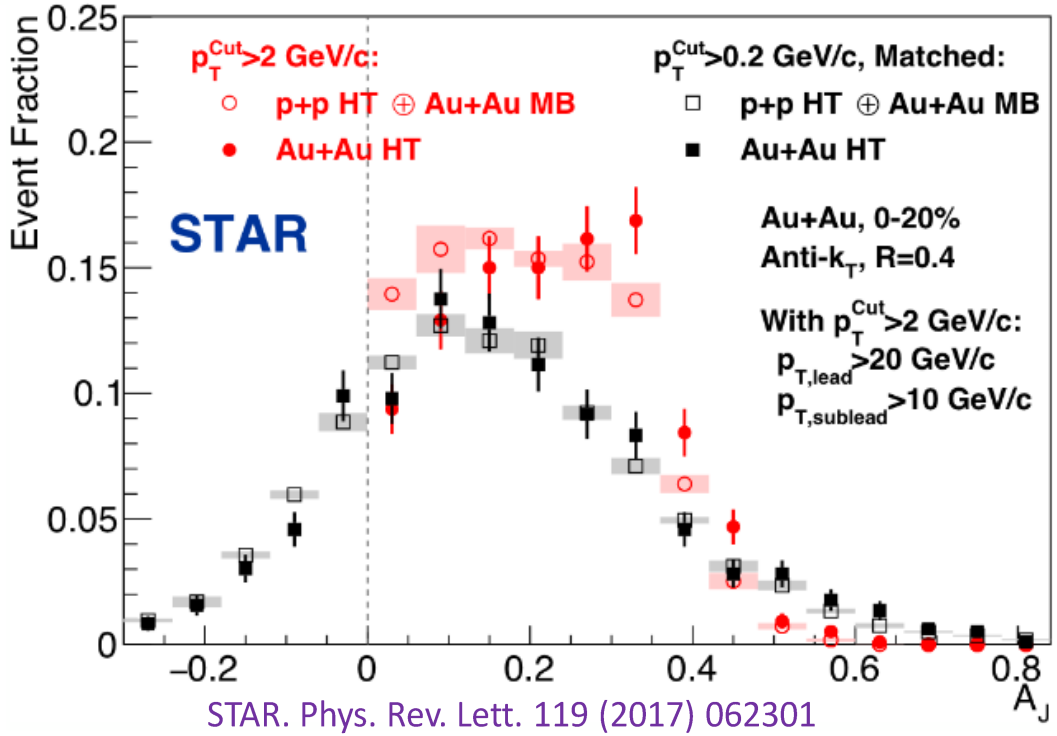
# “Hard Core” Di-Jets

$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$



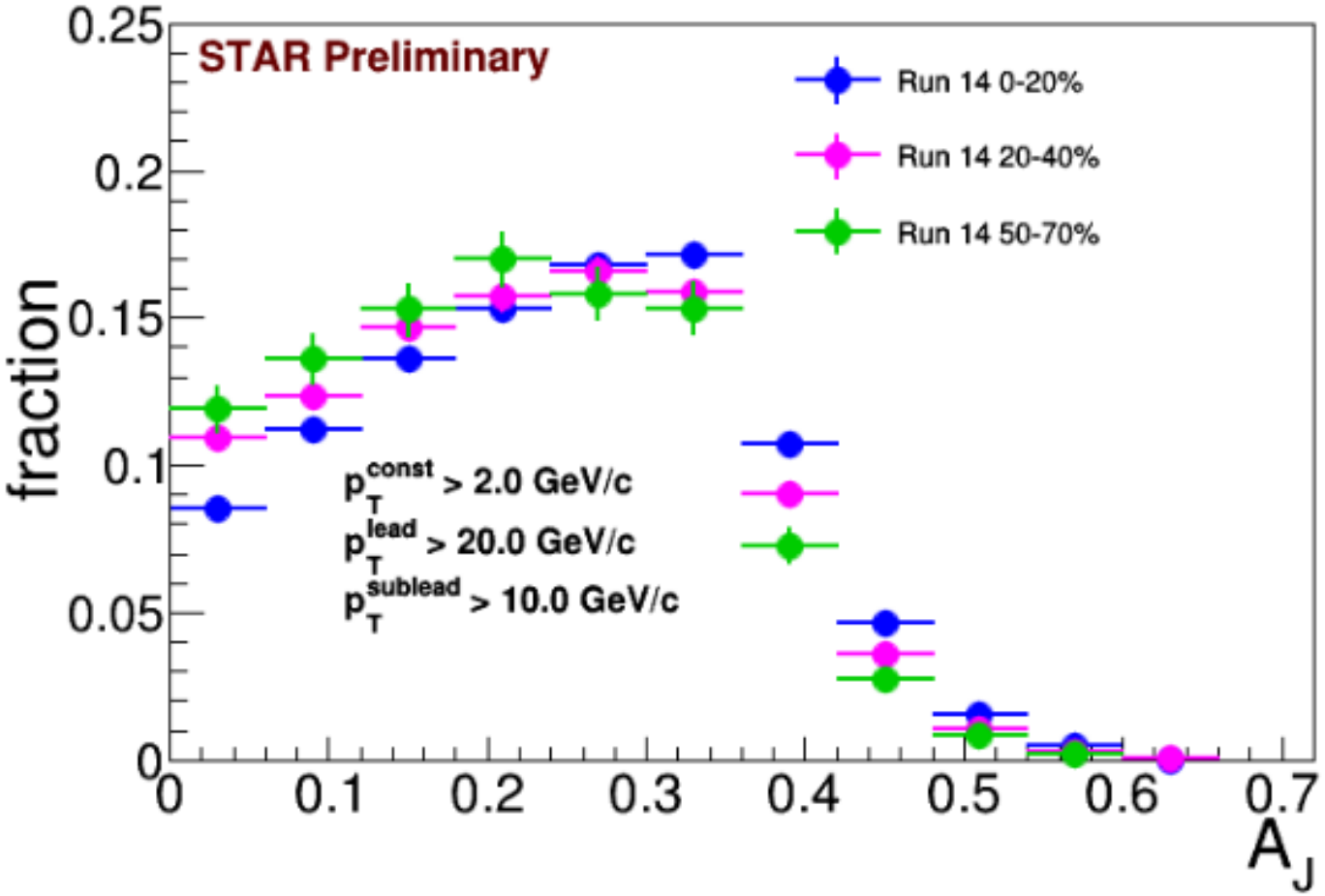




Momentum balance restored to p+p baseline for R=0.4, after adding particles with p<2 GeV/c



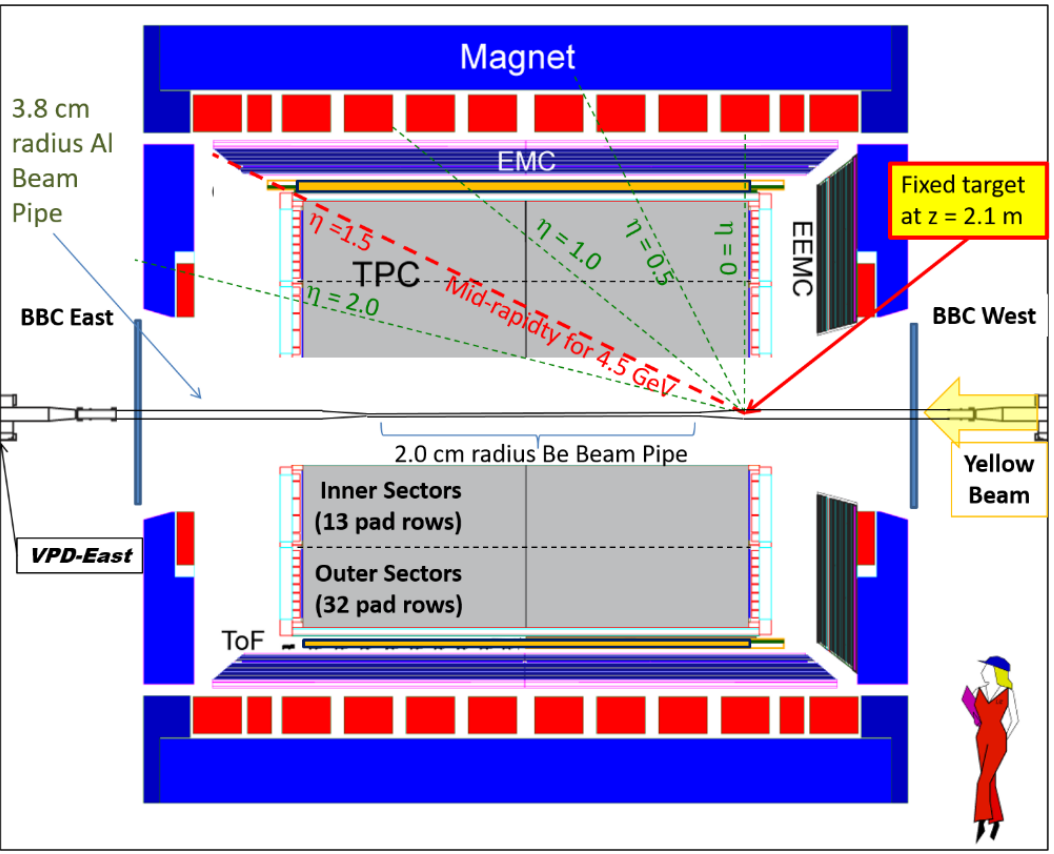

STAR. Phys. Rev. Lett. 119 (2017) 062301

# Centrality dependence of $A_J$ in Au+Au@200 GeV

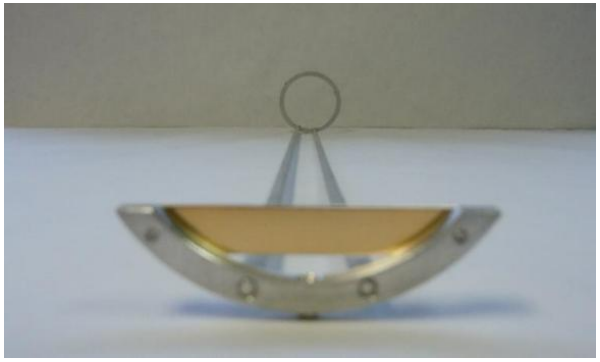



- The first measurement of centrality dependence of $A_J$ at RHIC
- Smaller di-jet imbalance in more peripheral collisions

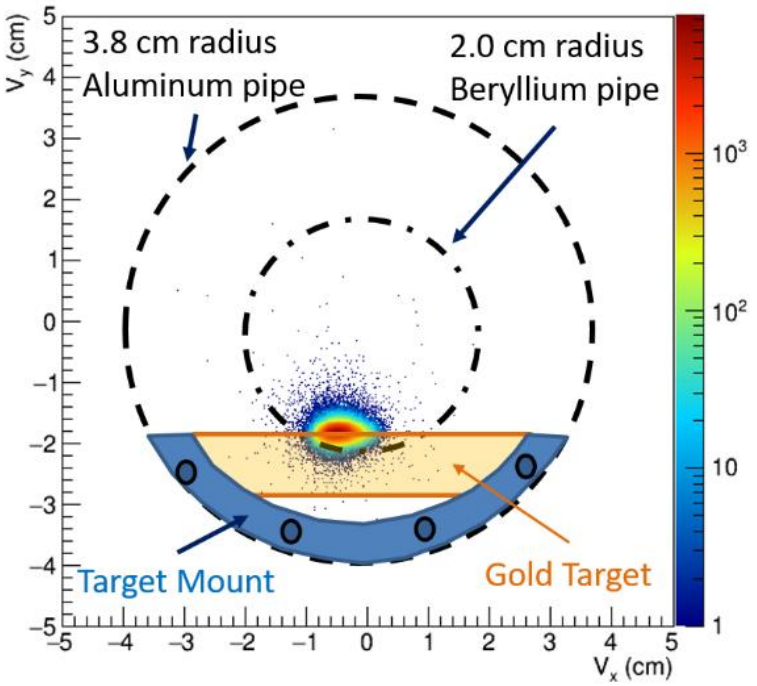
# STAR Fixed-Target Program




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



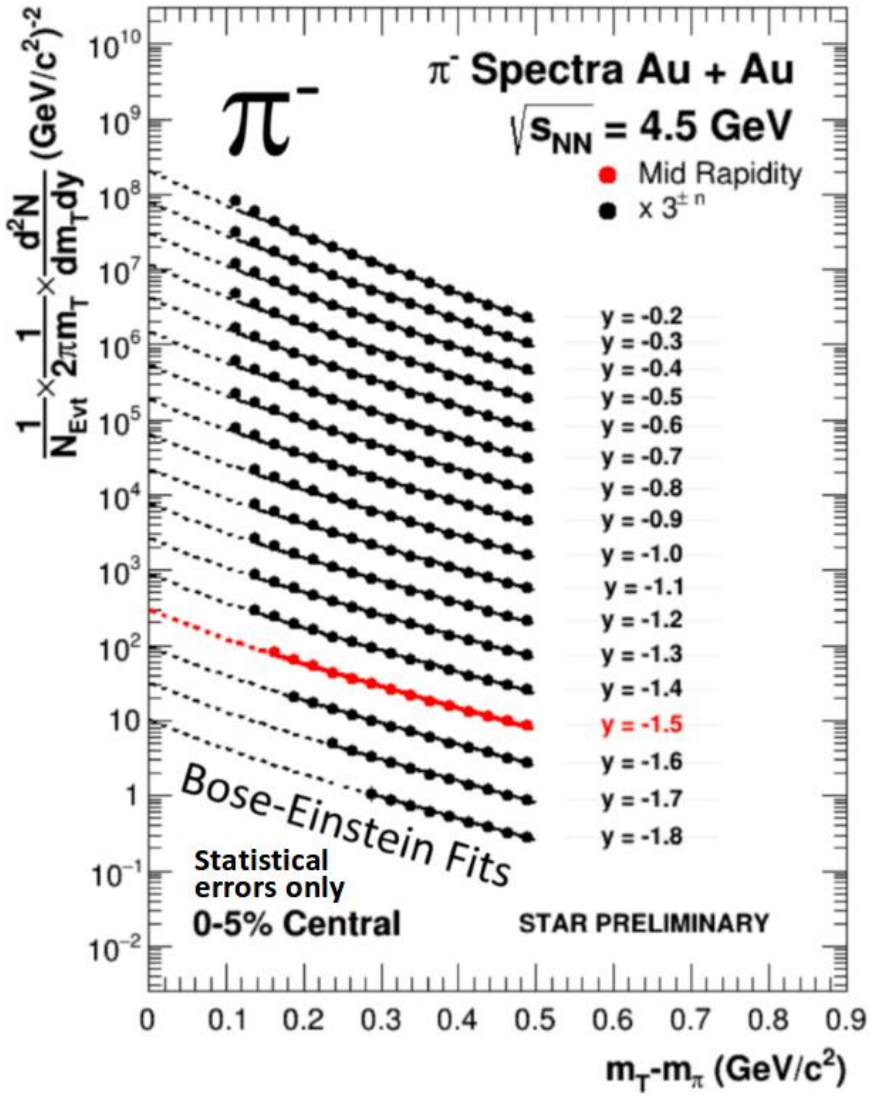
$V_y$ vs. $V_x$ Distribution



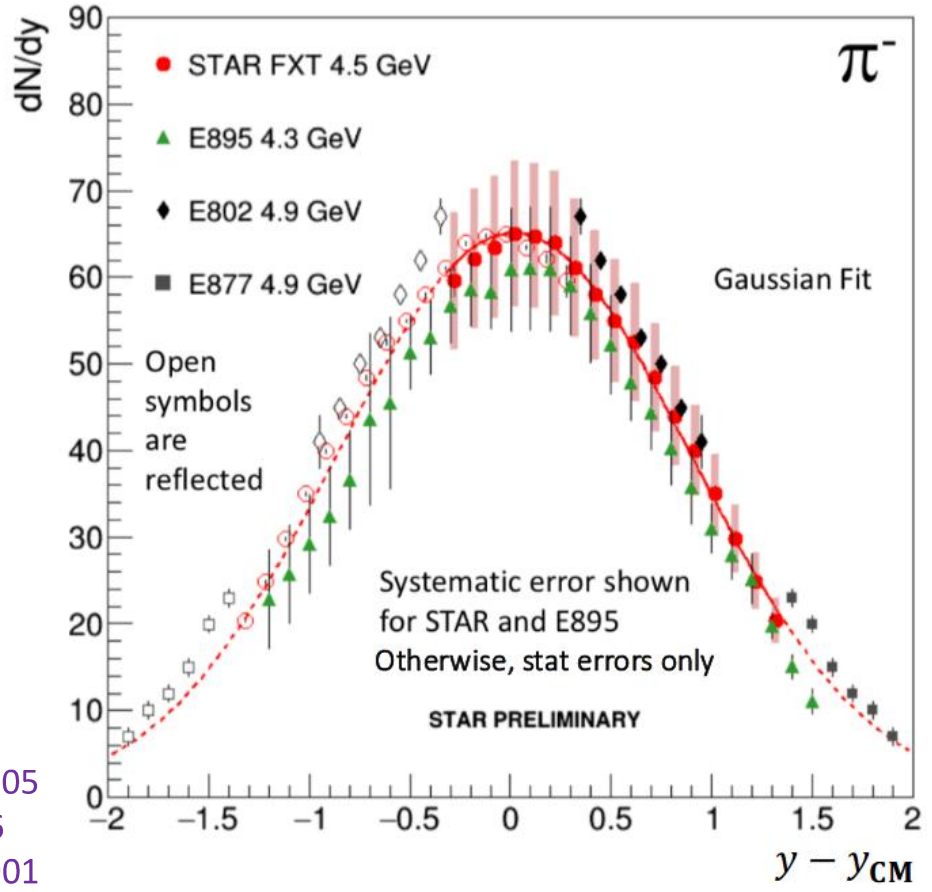

1.3M events from half hour test run, top 30% central trigger, Au+Au $\sqrt{s_{NN}}$=4.5 GeV

3.4M events from two hour test run, top 30% central trigger, Al+Au $\sqrt{s_{NN}}$= 4.9 GeV

# Pion spectra and dN/dy in Au+Au at $\sqrt{s_{NN}}$=4.5 GeV




- Amplitudes & widths of rapidity densities are consistent with AGS experiments
- $m_T - m_0$ and y range will be extended by eTOF & iTPC upgrade

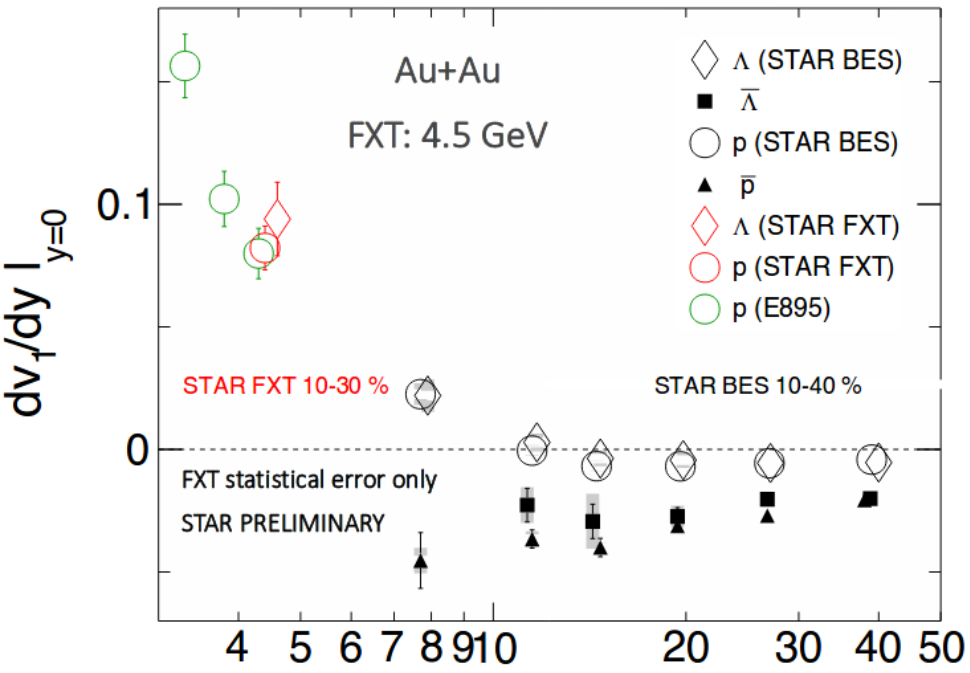


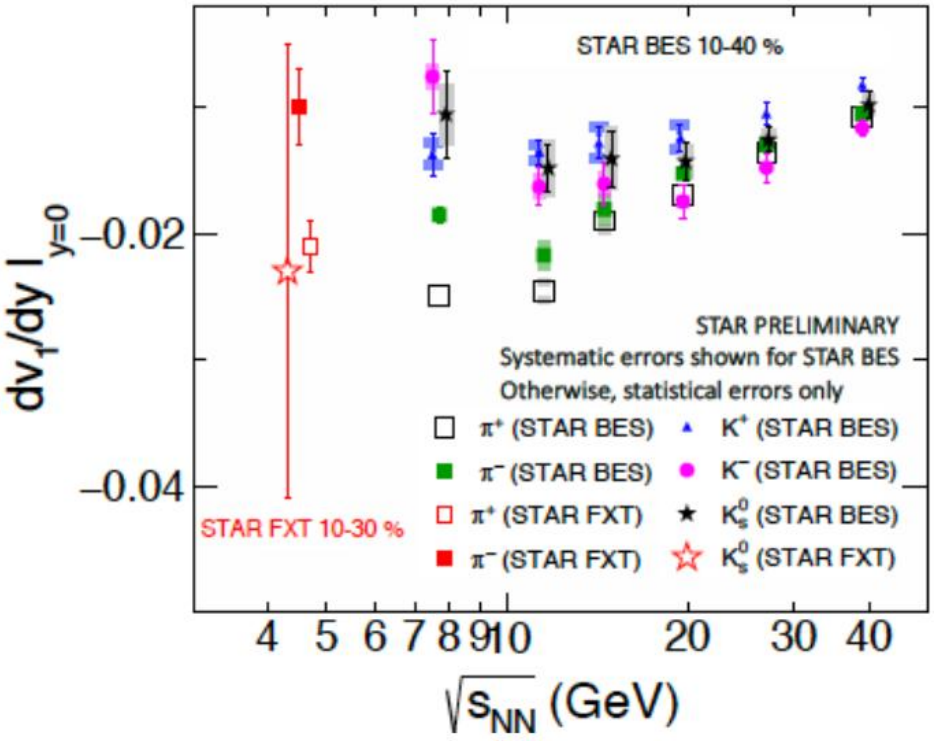


E895. Phys. Rev. C 68 (2003) 054905
E802. Phys. Rev. C 57 (1998) R466
E877. Phys. Rev. C 62 (2000) 024901

# Directed flow measurements from FXT

E895. Phys. Rev. Lett. 84 (2000) 005488
STAR . Phys. Rev. Lett. 112 (2014) 162301

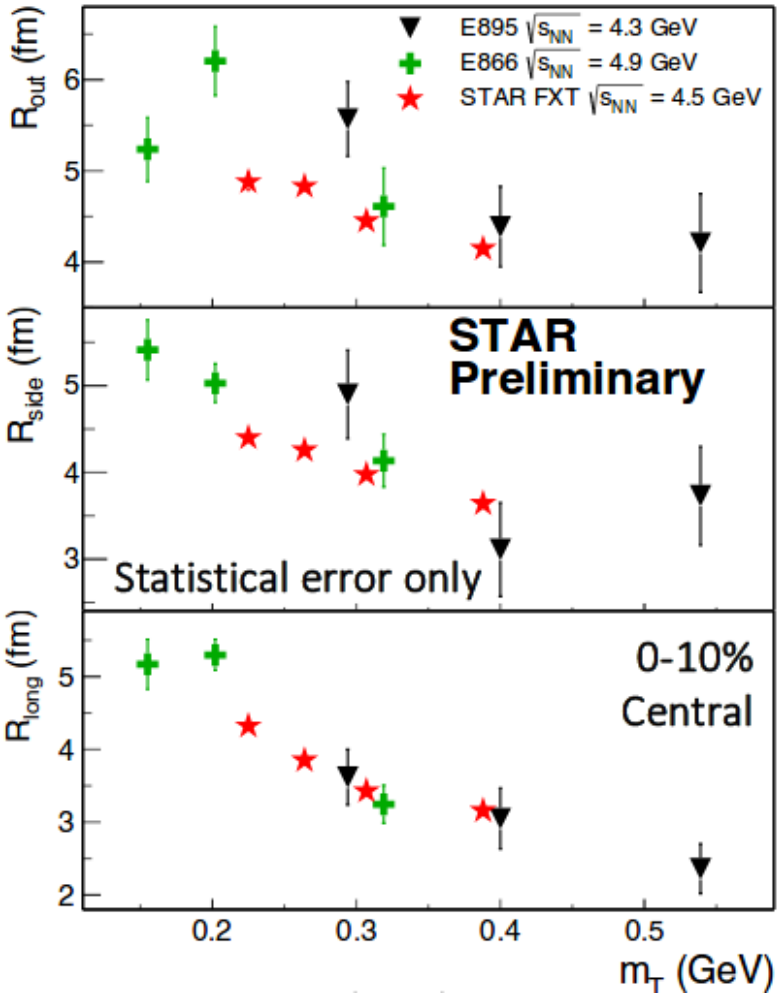


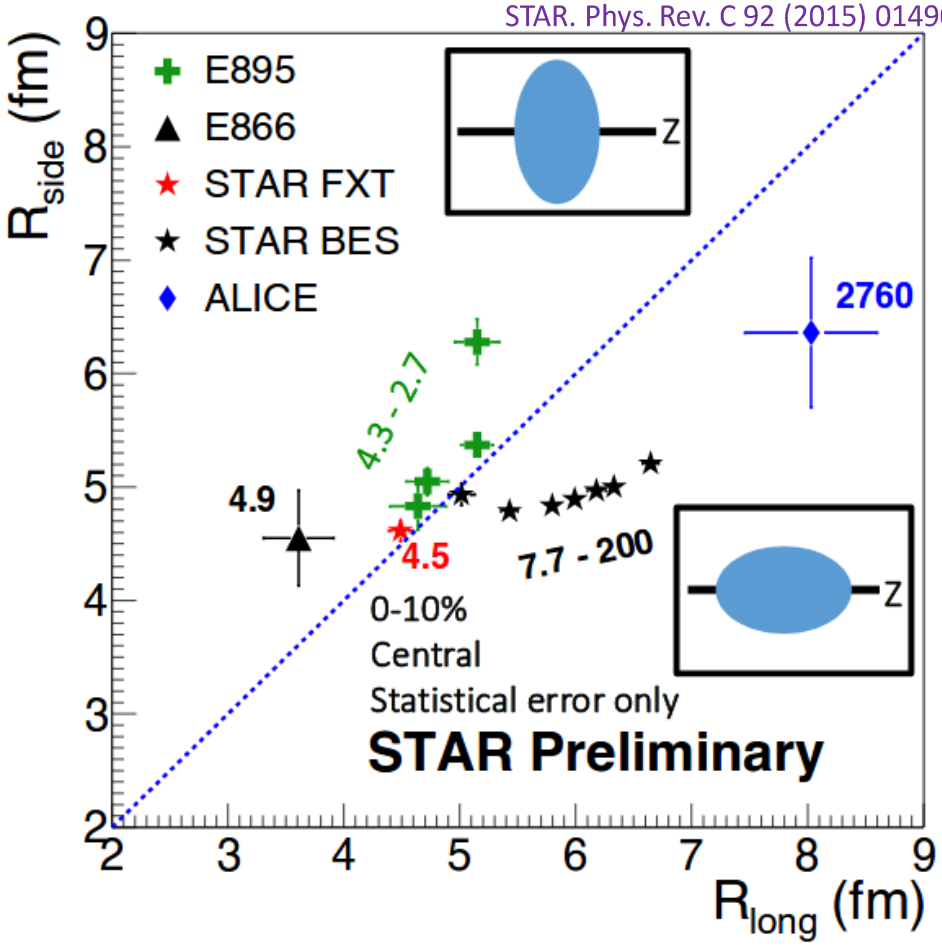




- Proton $v_1$ is consistent with E895. $\Lambda$ $v_1$ is close to that of proton
- First pion $v_1$ measurements in this energy range
- $\pi^+$ $\pi^-$ ordering supports the idea that transported quarks have bigger effect on $\pi^-$

# Femtoscopic measurements in FXT

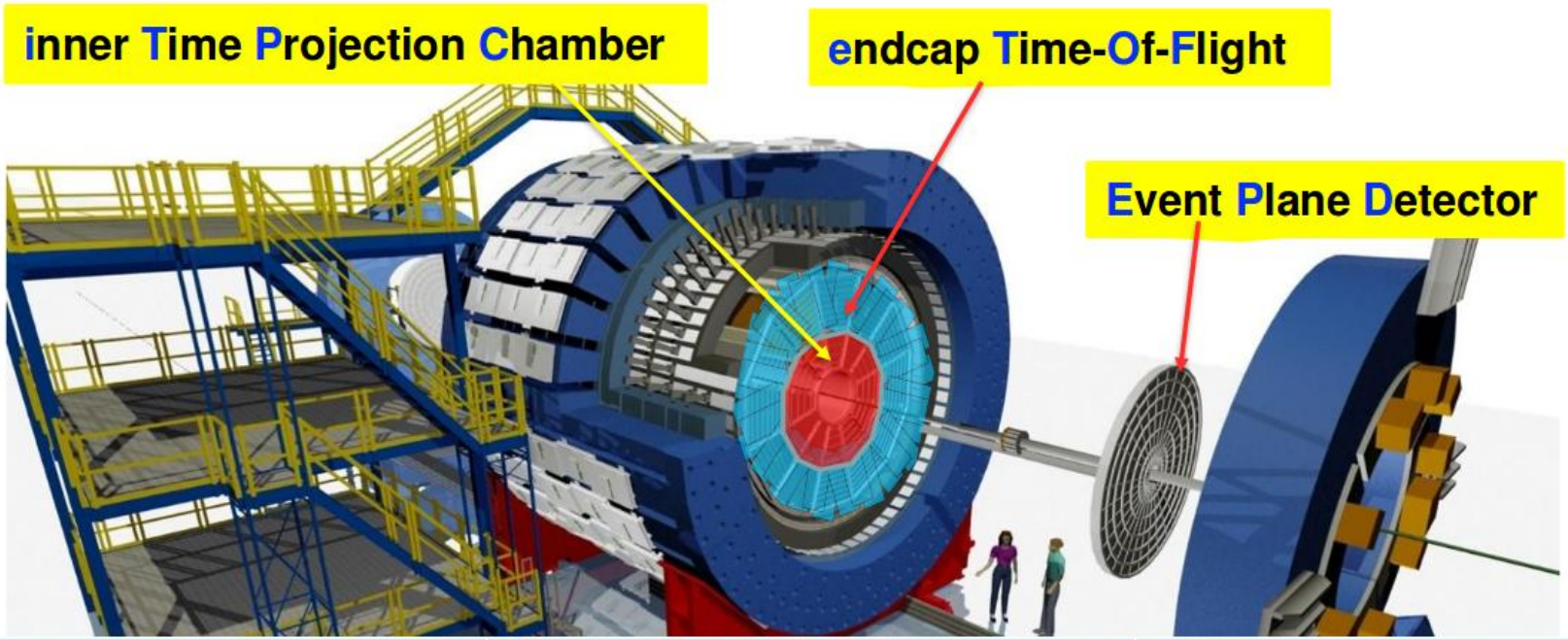
E866. Phys. Rev. C 66 (2002) 054096
E895 .Phys. Rev. Lett. 84 (2000) 2798
ALICE. Phys. Rev. B 696 (2011) 328
STAR. Phys. Rev. C 92 (2015) 014904



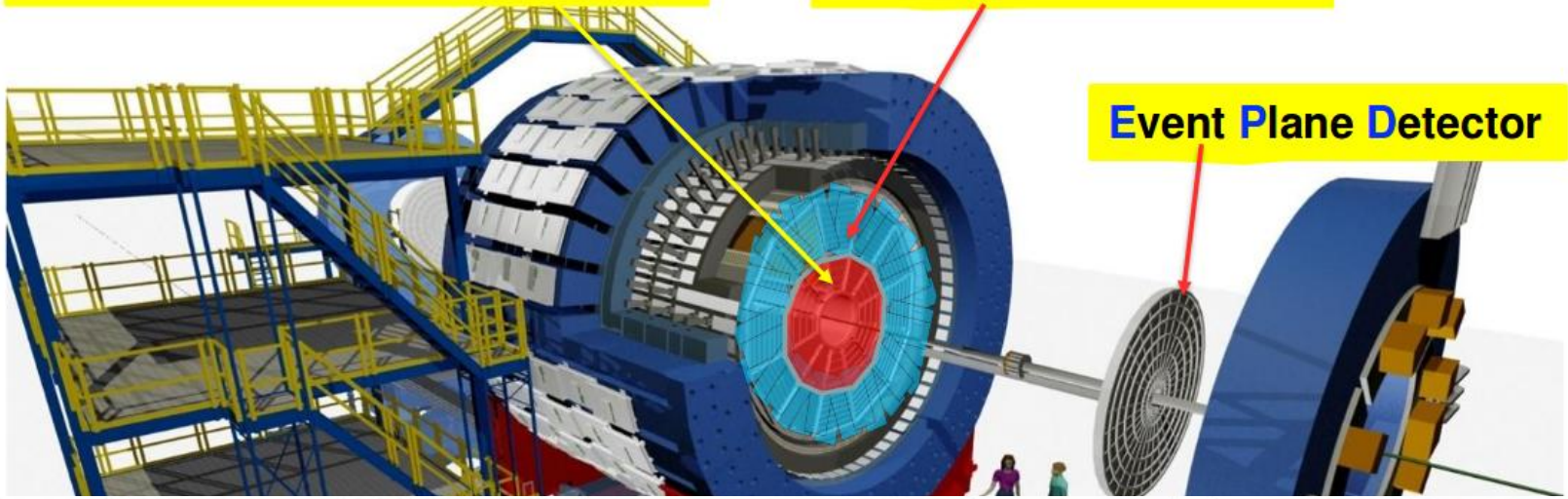

- Consistent with results from AGS experiments, with smaller stat. errors
- Apparent source shape evolves from oblate to prolate, as energy increases
- Increased longitudinal expansion above FXT energy

# Upgrades for BES-II




| iTPC upgrade | eTOF upgrade | EPD upgrade |
|---|---|---|
| **Continuous pad rows<br>Replace all inner TPC sectors** | **Add CBM TOF modules and electronics (FAIR Phase 0)** | **Replace Beam-Beam Counter** |
| **$\|\eta\| < 1.5$** | **$-1.6 < \eta < -1.1$** | **$2.1 < \|\eta\| < 5.1$** |
| $p_T > 60$ MeV/c | Extend forward PID capability | Better trigger & b/g reduction |
| Better dE/dx resolution<br>Better momentum resolution | Allows higher energy range of Fixed-Target program | Greatly improved Event Plane info (esp. 1st-order EP) |

# Upgrades for BES-II






# The inner TPC upgrade

- **Inner Sectors**
  - New designed strongback
  - New wire frames
  - Increase readout pad rows (13 to 40)
- **New electronics for inner sectors**
  - Doubled readout channels. Using ALICE SAMPA chip
- **New designed insertion tooling**
  - Removal and insertion of inner sectors
- **Replace all 24 inner sectors**
  - 2018: One sector has been installed and used in the physics run
  - Full installation in autumn 2018

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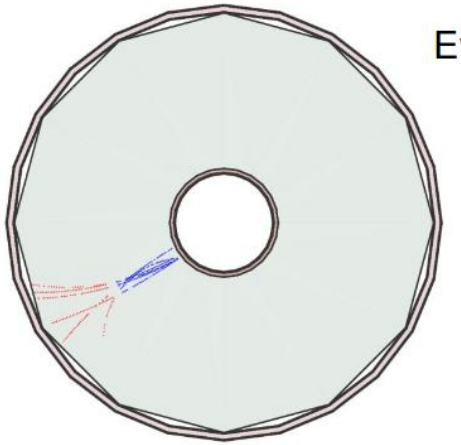
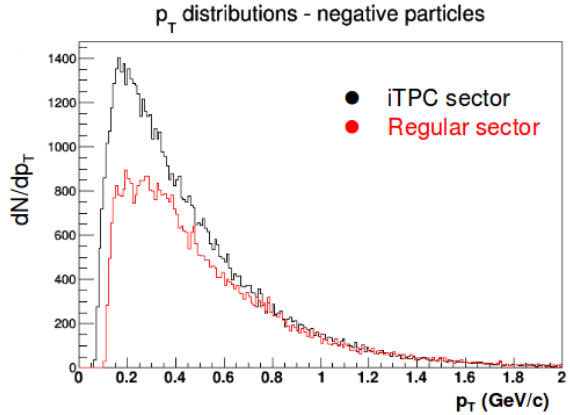
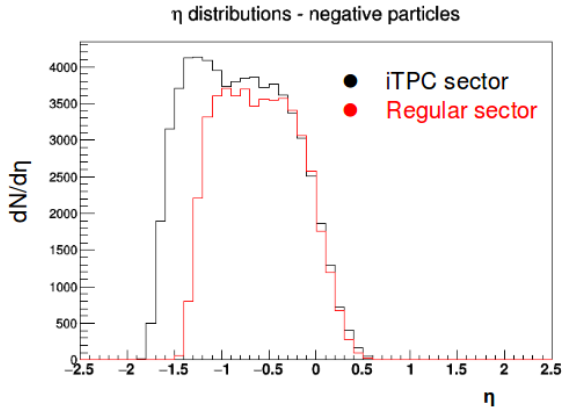
**iTPC (one sector) performance in the current isobar collisions**




- Maximum hits per track: 45⟶72
- Lower transverse momentum threshold of 60 MeV/c
- η coverage extended by 0.4 units



# The endcap Time-Of-Flight

- **Install, commission and use 10% of the CBM TOF modules in STAR**
- **Design concept**
  - 3 layers, 12 sectors, 36 modules, 108 MRPCs
- **Provides PID in the forward direction**
  - Extended rapidity and yields
- **One sector with three modules has been installed for runs in 2018**
- **Full installation in autumn 2018**

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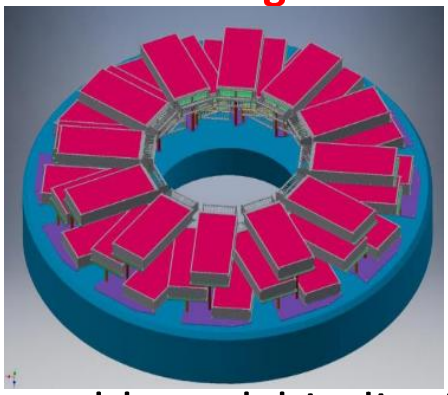
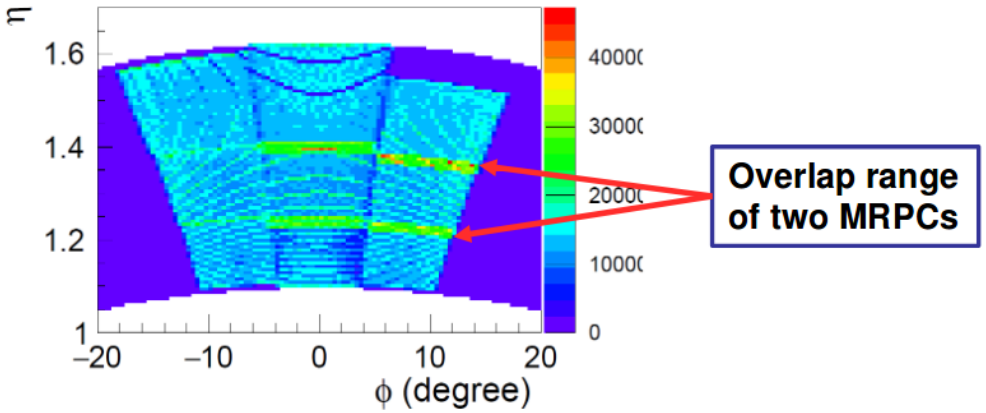
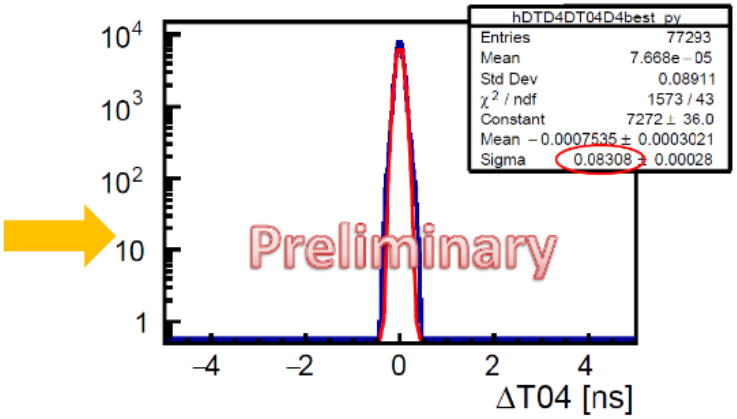
**eTOF (three modules) commissioned, integrated and participated in data taking**



- Reasonable η-ϕ hit distribution
  - eTOF works properly
- Time resolution 59 ps




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

# The Event Plane Detector

**Event Plane Detector**

- **2 wheels**
  - East and West EPD ($2.1<|\eta|<5.1$)
- **12 super sectors**
  - Scintillator wedges, milled to form 31 tiles
  - Optically separated by epoxy
- **Fiber optics**
  - Wavelength-shifting fibers
  - Grouped in 3D-printed connectors
- **Sensors**
  - Silicon Photon Multipliers (SiPM)

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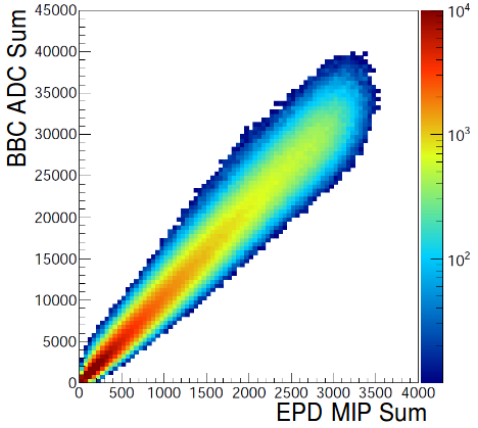
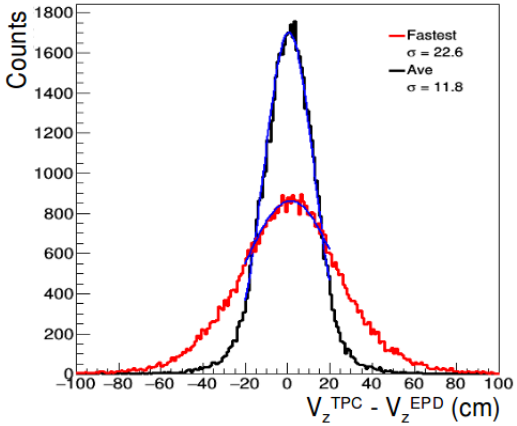
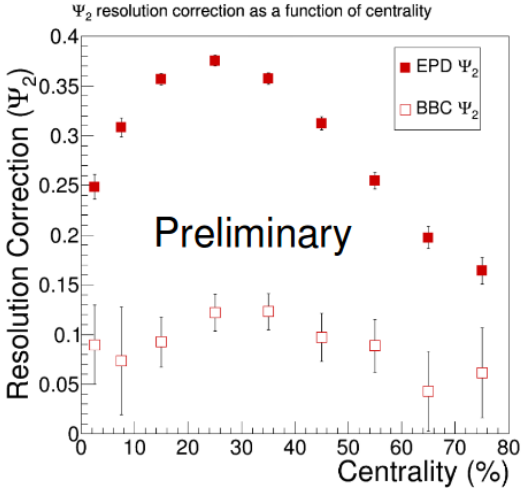
**EPD is fully installed and took part in data taking in 2018**

- All 744 tiles are good
- Good correlation between BBC and EPD
  - Correct timing
- Timing resolution is about 0.75 ns with fastest TAC method
  - 0.35 ns with average TAC method, raw slewing correction
- The 2nd-order event plane resolution is 0.37 in 20-30% central events at top energy isobar collisions



# Short term plan

Year 2018:

- Took ~1.5B events for Zr+Zr and Ru+Ru collision systems each
- Au+Au data at 27 GeV (~500M events) and 3.0 GeV (~300M events)

✓ Physics goals: Chiral Magnetic Effect, global polarization, dileptons, etc..

Plan for 2019-2021:

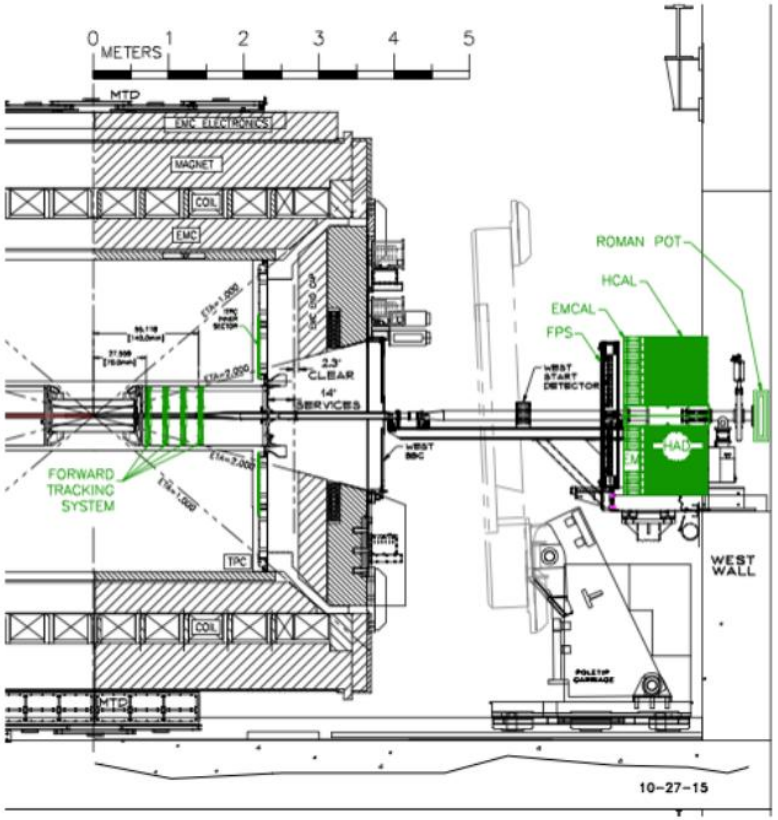
| Beam Energy (GeV/nucleon) | $\sqrt{s_{NN}}$ (GeV) | $\mu_B$ (MeV) | Run Time | Number Events |
|---|---|---|---|---|
| 9.8 | 19.6 | 205 | 4.5 weeks | 400M |
| 7.3 | 14.5 | 260 | 5.5 weeks | 300M |
| 5.75 | 11.5 | 315 | 5 weeks | 230M |
| 4.55 | 9.1 | 370 | 9.5 weeks | 160M |
| 3.85 | 7.7 | 420 | 12 weeks | 100M |
| 31.2 | 7.7 (FXT) | 420 | 2 days | 100M |
| 19.5 | 6.2 (FXT) | 487 | 2 days | 100M |
| 13.5 | 5.2 (FXT) | 541 | 2 days | 100M |
| 9.8 | 4.5 ( FXT) | 589 | 2 days | 100M |
| 7.3 | 3.9 (FXT) | 633 | 2 days | 100M |
| 5.75 | 3.5 (FXT) | 666 | 2 days | 100M |
| 4.55 | 3.2 (FXT) | 699 | 2 days | 100M |
| 3.85 | 3.0 (FXT) | 721 | 2 days | 100M |

# STAR Forward Upgrade

- STAR is proposing to install a Forward Calorimeter System (FCS), including an electromagnetic calorimeter and a hadron calorimeter, and a Forwarding Tracking System (FTS) in 2021+.

- Di-jet measurements with one or both jets in the forward region ($2.8 < \eta < 3.7$) will be one of the highlights of this upgrade.

- FCS will provide gluon polarization at very low x
  - x $\sim 5\times10^{-3}$ with FCS-EEMC di-jets
  - $x \leq 10^{-3}$ with FCS-FCS di-jets



# Summary

- Collective dynamics and correlations
  - $v_1$, longitudinal flow decorrelation, femtoscopy
- Particle production
  - Ultra-peripheral collisions, (anti)hypertriton, $\Lambda_C$, $\Upsilon$(1S,2S+3S)
- High-pT particles and jet
  - $R_{CP}$ from BES-I, di-jet imbalance
- The STAR fixed-target results
- Detector upgrades