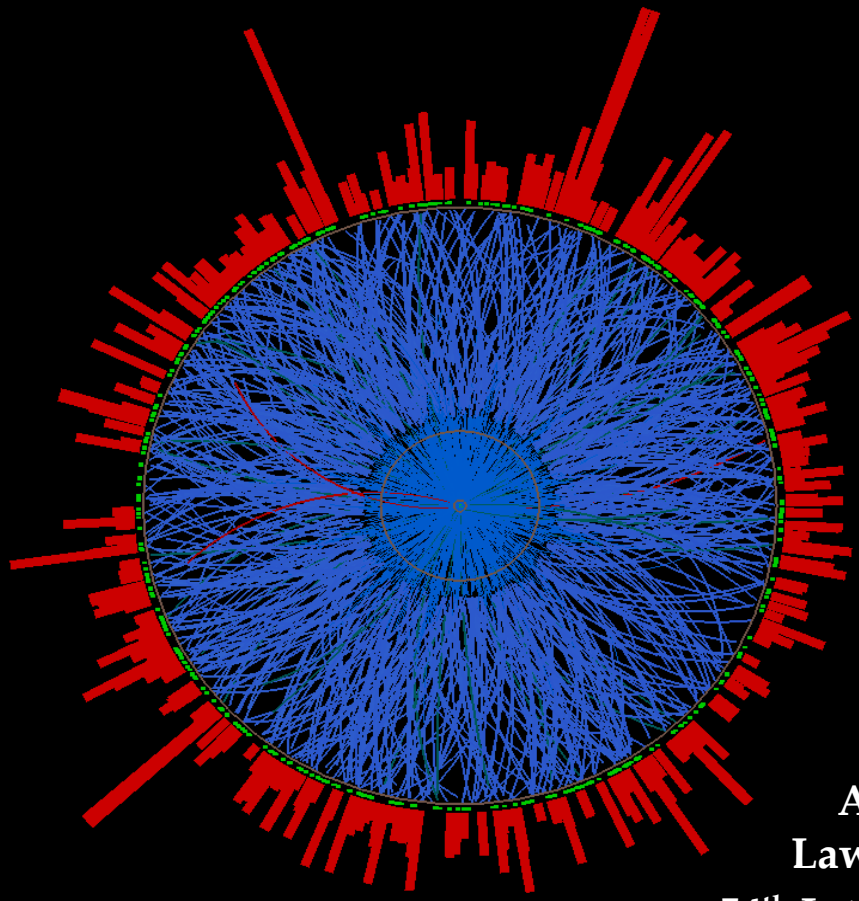
# News from RHIC



**Alexander Schmah**
**Lawrence Berkeley National Lab**

**54th International Winter Meeting on Nuclear Physics - Bormio**

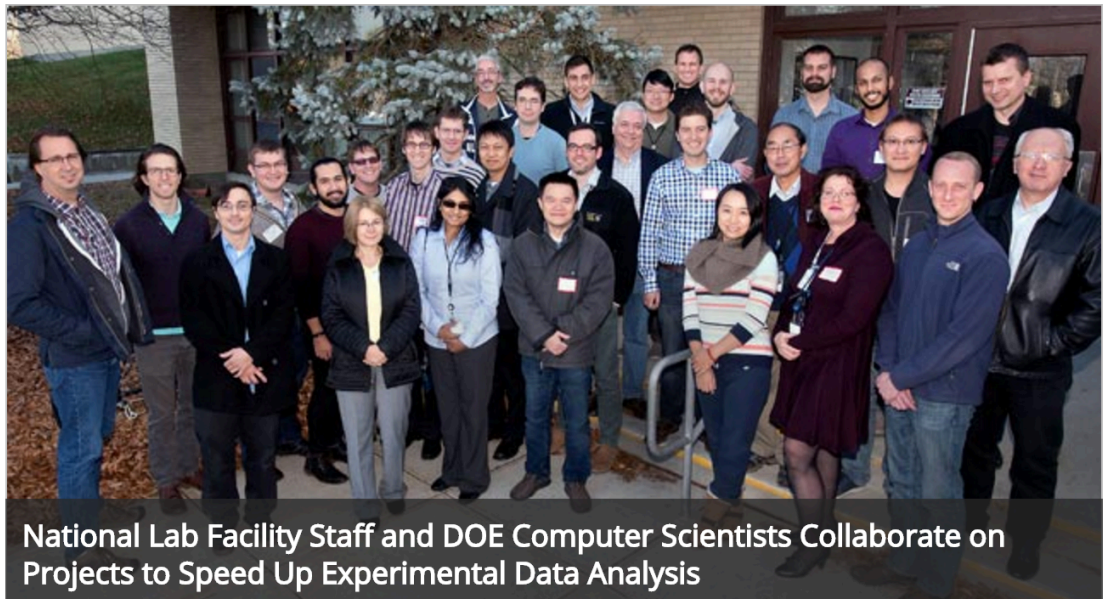
BERKELEY LAB

U.S. DEPARTMENT OF ENERGY

# Most Recent News…

BROOKHAVEN NATIONAL LABORATORY *a passion for discovery* U.S. DEPARTMENT OF ENERGY

**BROOKHAVEN LAB SITE TO REMAIN CLOSED UNTIL 1 P.M., 1/25. MAIN GATE WILL OPEN AT 12 NOON (update as of 4:15 p.m. 1/24)** The Brookhaven Lab site will remain closed to non-essential personnel until 1 p.m., Jan. 25, to allow crews to clean the site following the weekend's winter storm. The Main Gate will open for all staff at 12 noon. Essential personnel should continue to report for their scheduled shifts. Non-essential personnel must not attempt to enter the Lab site before 12 noon.



National Lab Facility Staff and DOE Computer Scientists Collaborate on Projects to Speed Up Experimental Data Analysis

Happening Now See all

Brookhaven Lab to Partner on Electric Grid Modernization Projects

New Theory of Secondary Inflation Expands Options for Avoiding an Excess of Dark Matter

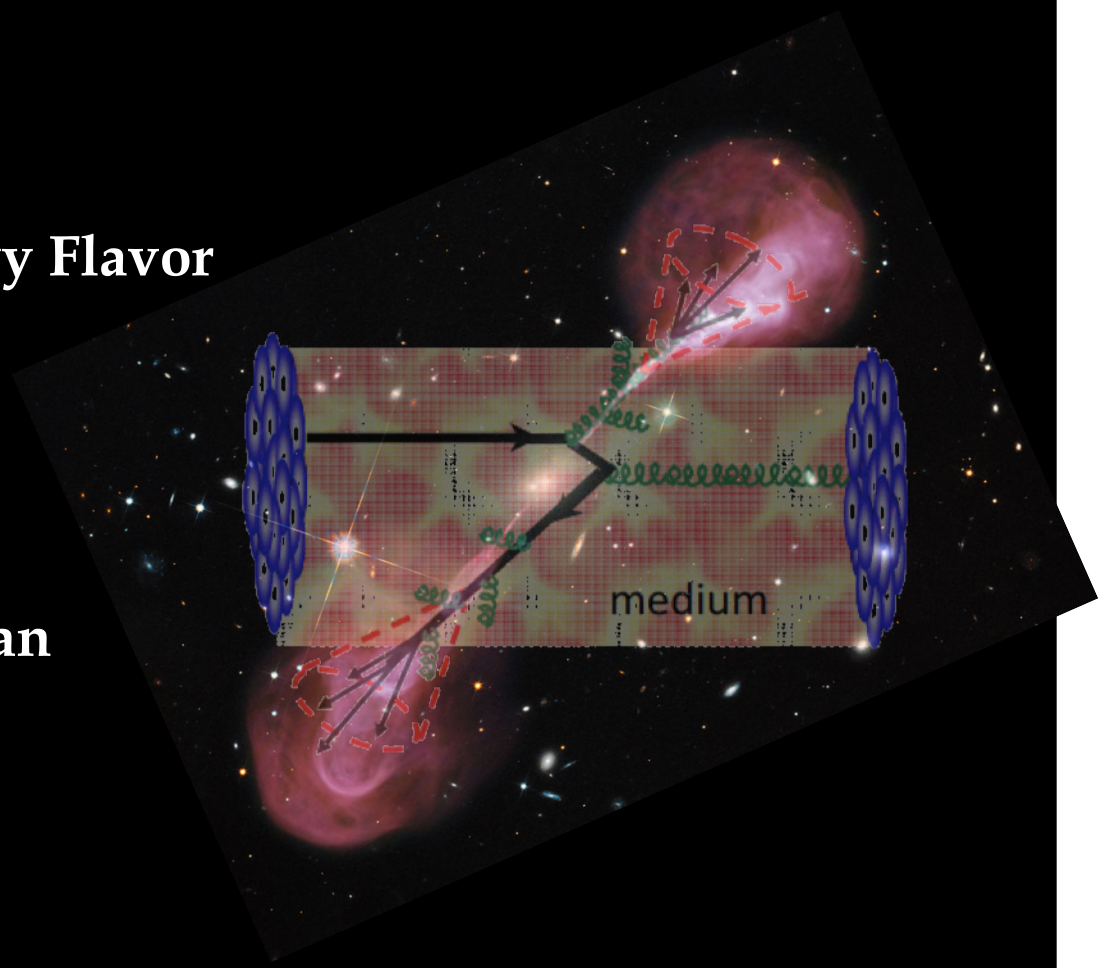
Bright High School Students Get An Insider Look at the National Synchrotron Light Source II

Our Mission

We advance fundamental research in nuclear and

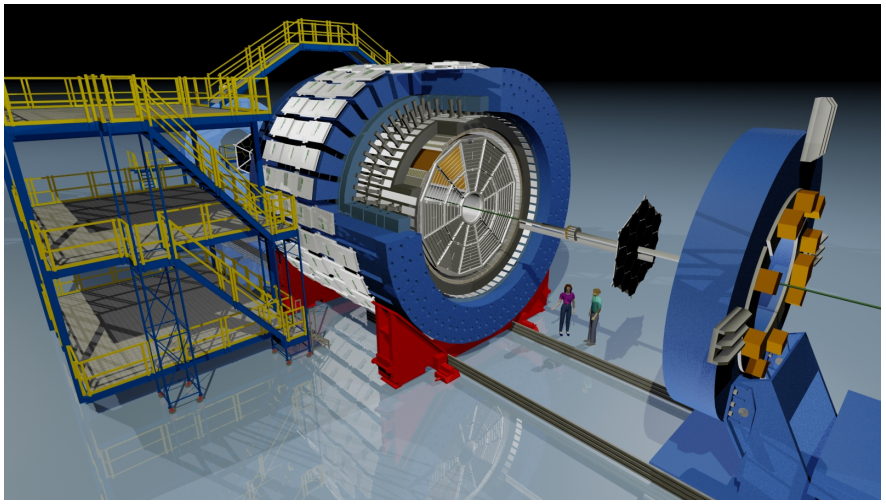
# Outline

- **Penetrating Probes and Heavy Flavor**
- **Bulk Observables**
- **Outlook for Beam Energy Scan phase II and sPHENIX**



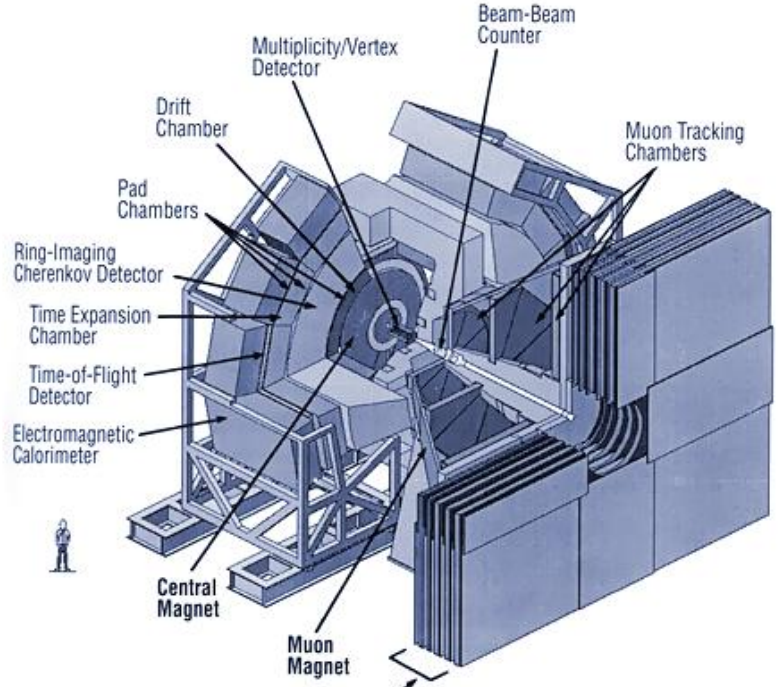
# Detectors at RHIC

## STAR



- Full azimuthal coverage
- -1 < η< 1 coverage
- Electromagnetic calorimeter
- Heavy Flavor Tracker
- Muon Tracking Detector
- PID

## PHENIX



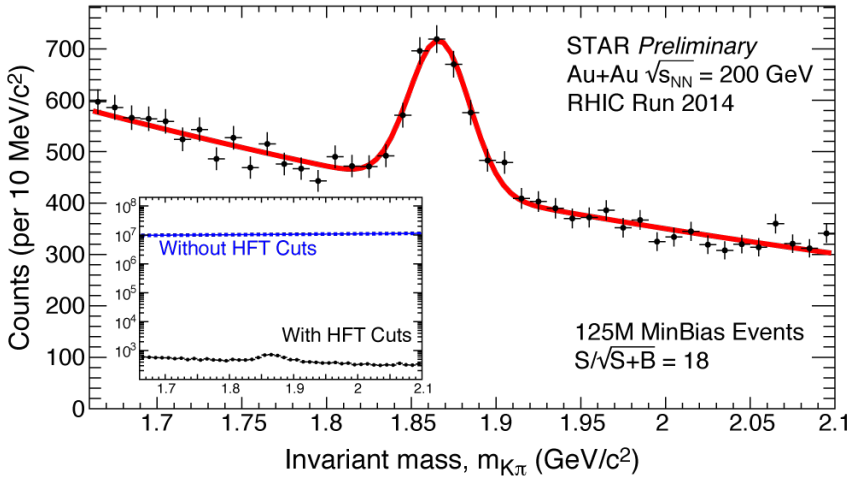

- High granularity calorimeter
- Silicon Tracker
- PID

# Open Heavy Flavor

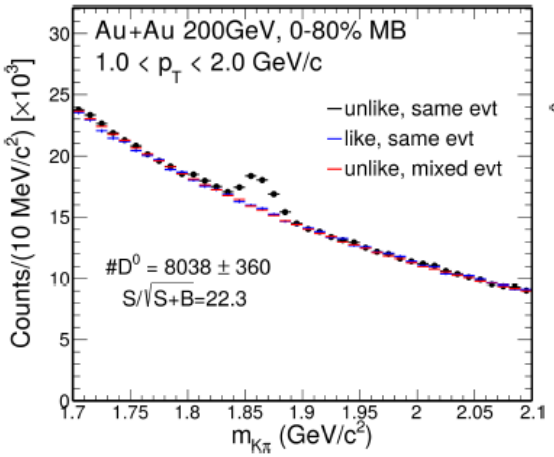
First results from the STAR **H**eavy **F**lavor **T**tracker

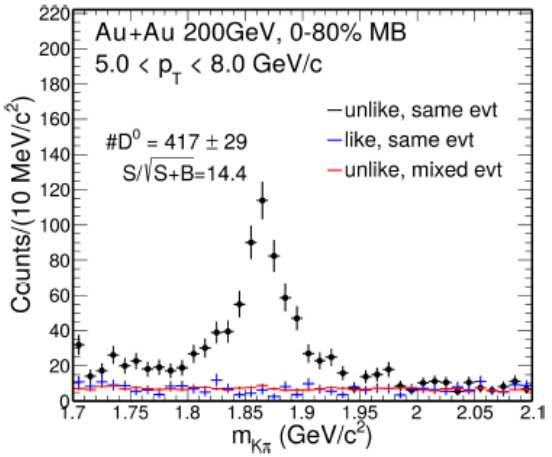
**PiXeL detector (PXL)**
- Monolithic Active Pixel Sensor
- 20.7 mum pitch pixels
- radii: 2.8 and 8 cm, 20 cm length

$D^0 \rightarrow K\pi$

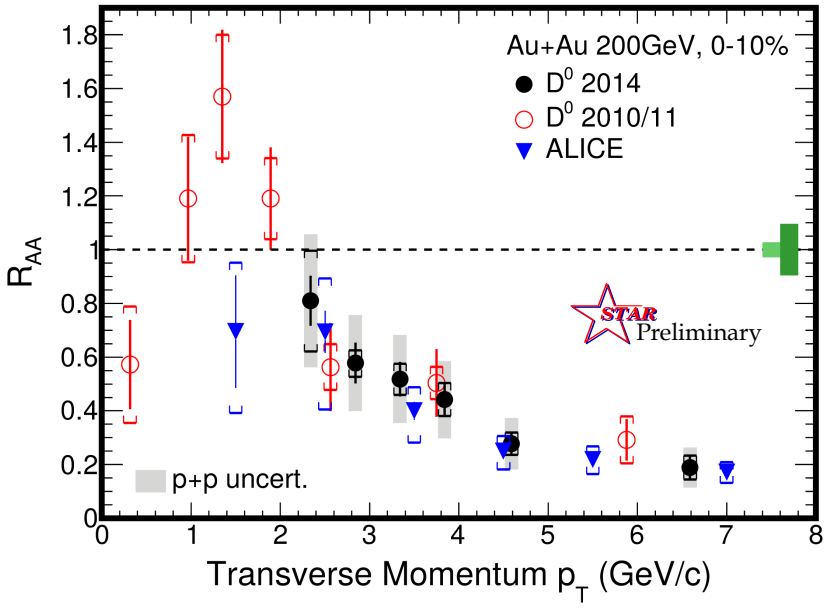


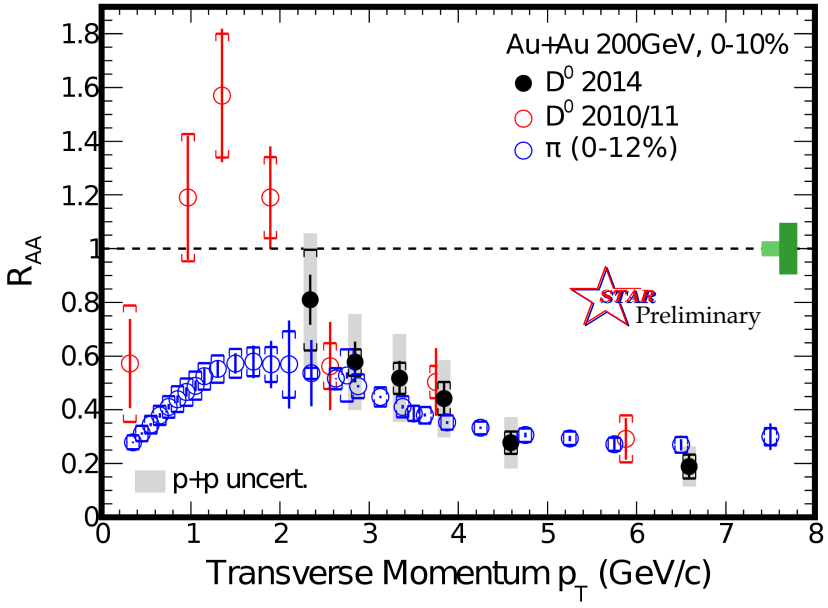

- Topological reconstruction of D0 mesons (~120 mum) with the STAR Heavy Flavor Tracker



# Nuclear Modification Factor

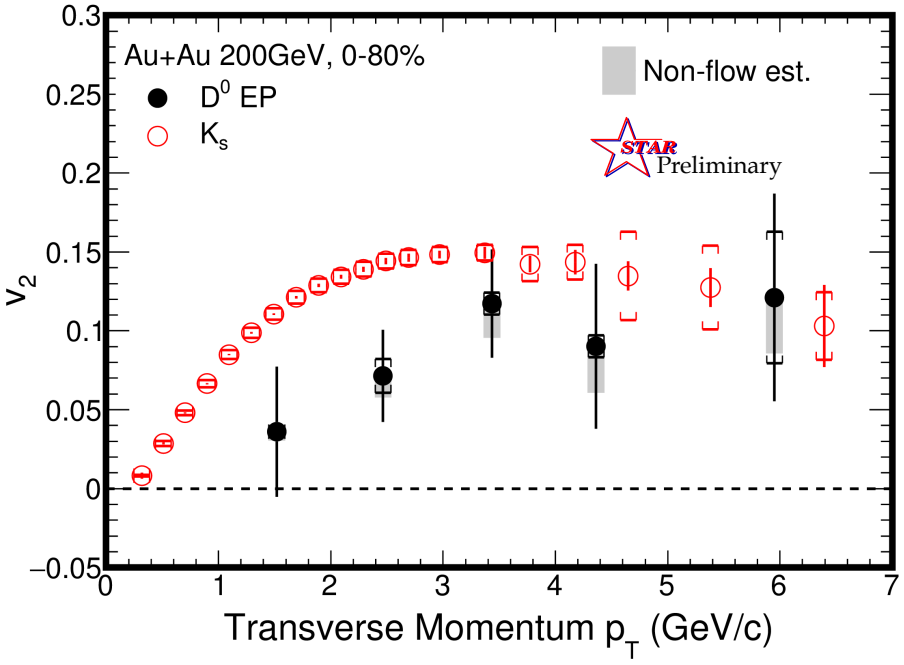


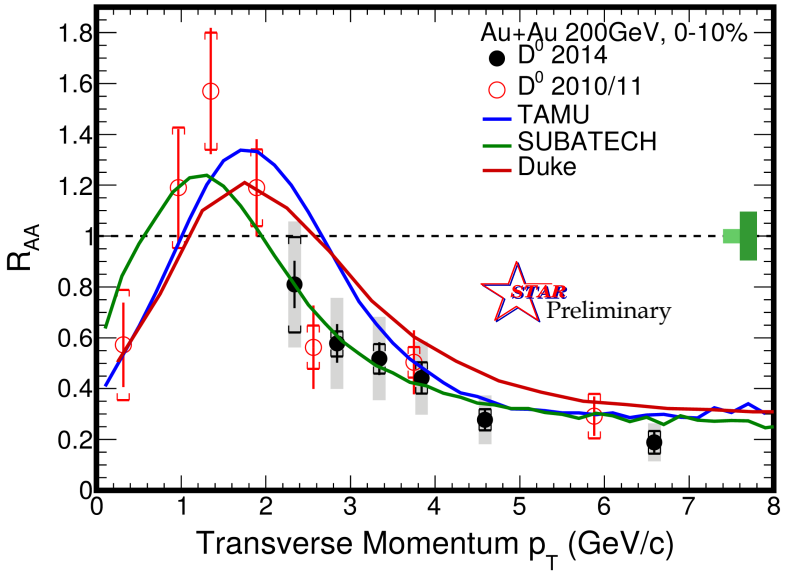

- Improved $D^0$ data with HFT
- Enhanced D meson $R_{AA}$ for low transverse momenta
  → Charm coalescence and flowing medium
- Suppression at high $p_T$ similar to pion $R_{AA}$
- $R_{AA}$ at RHIC similar to LHC

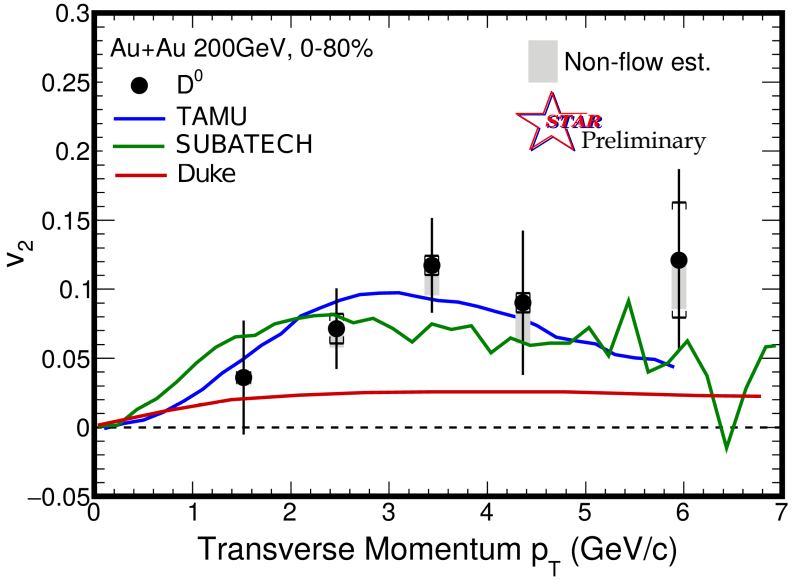
# $D^0$ Azimuthal Anisotropy

- $D^0$ elliptic flow is finite at top RHIC energies
- $D^0$ $v_2$ is lower than light hadron $v_2$
  → Some kind of charm thermalization with the medium?



# Comparison to Theory



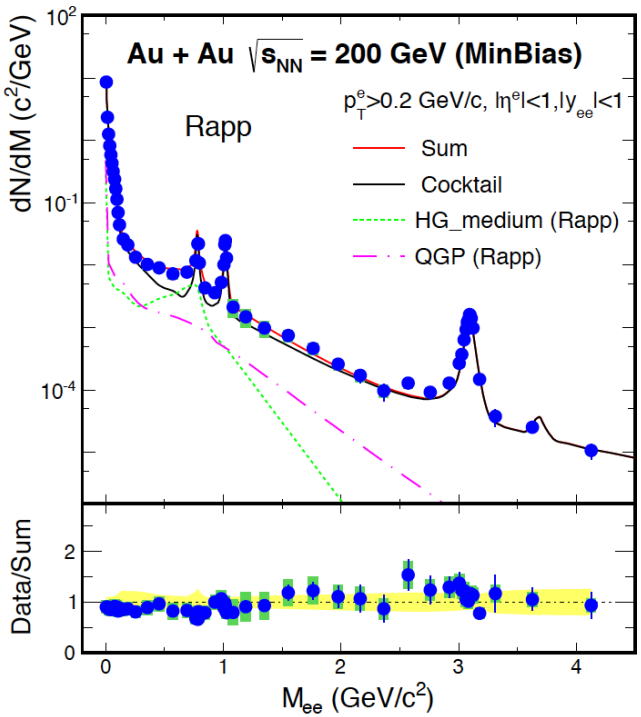




- Data favors models with charm diffusion
  → charm exhibits collectivity with the medium

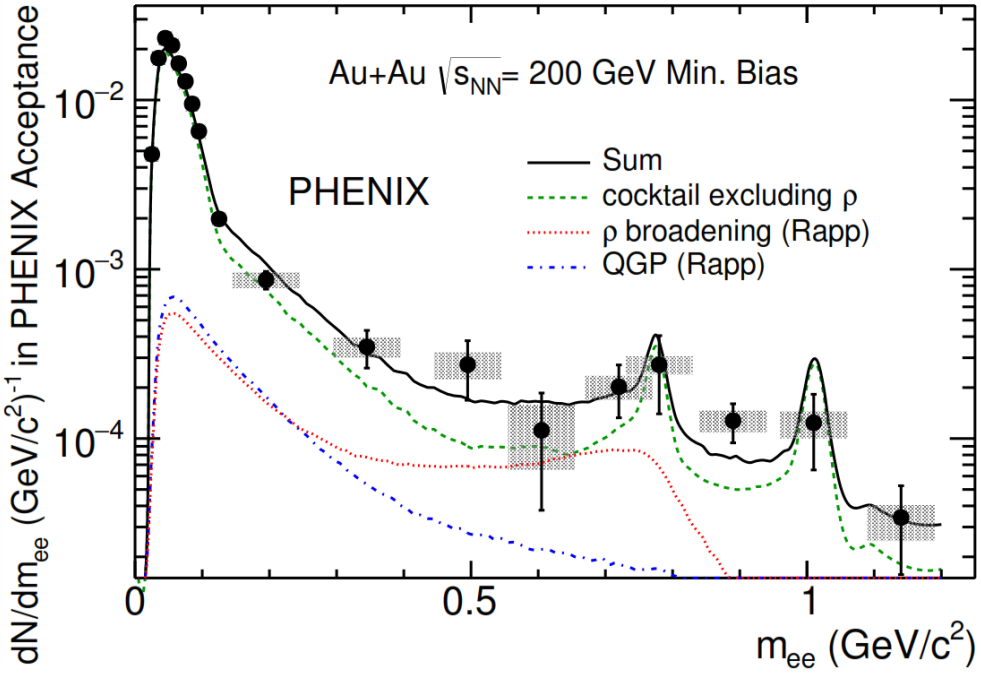
| | D × 2πT | Diff. Calculation |
|---|---|---|
| TAMU | 2-11 | T-Matrix |
| SUBATECH | 2-4 | pQCD+HTL |
| Duke | 7 | Free parameter |

arXiv:1506.03981 (2015) & private comm.

# Di-Electrons at 200 GeV



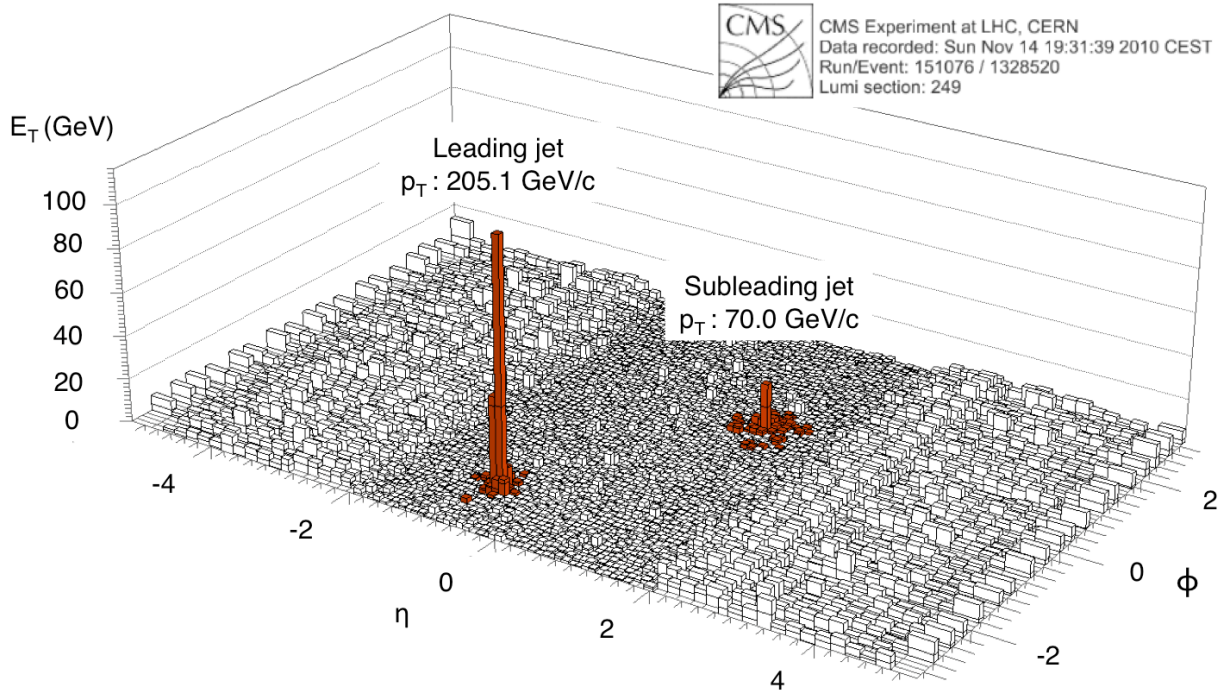

*PHENIX: arXiv1509.04667 (2015)*




- Consistent results between STAR and PHENIX
  → previous large PHENIX enhancement is not reproduced

- Good description of data by model calculations
  → in-medium rho

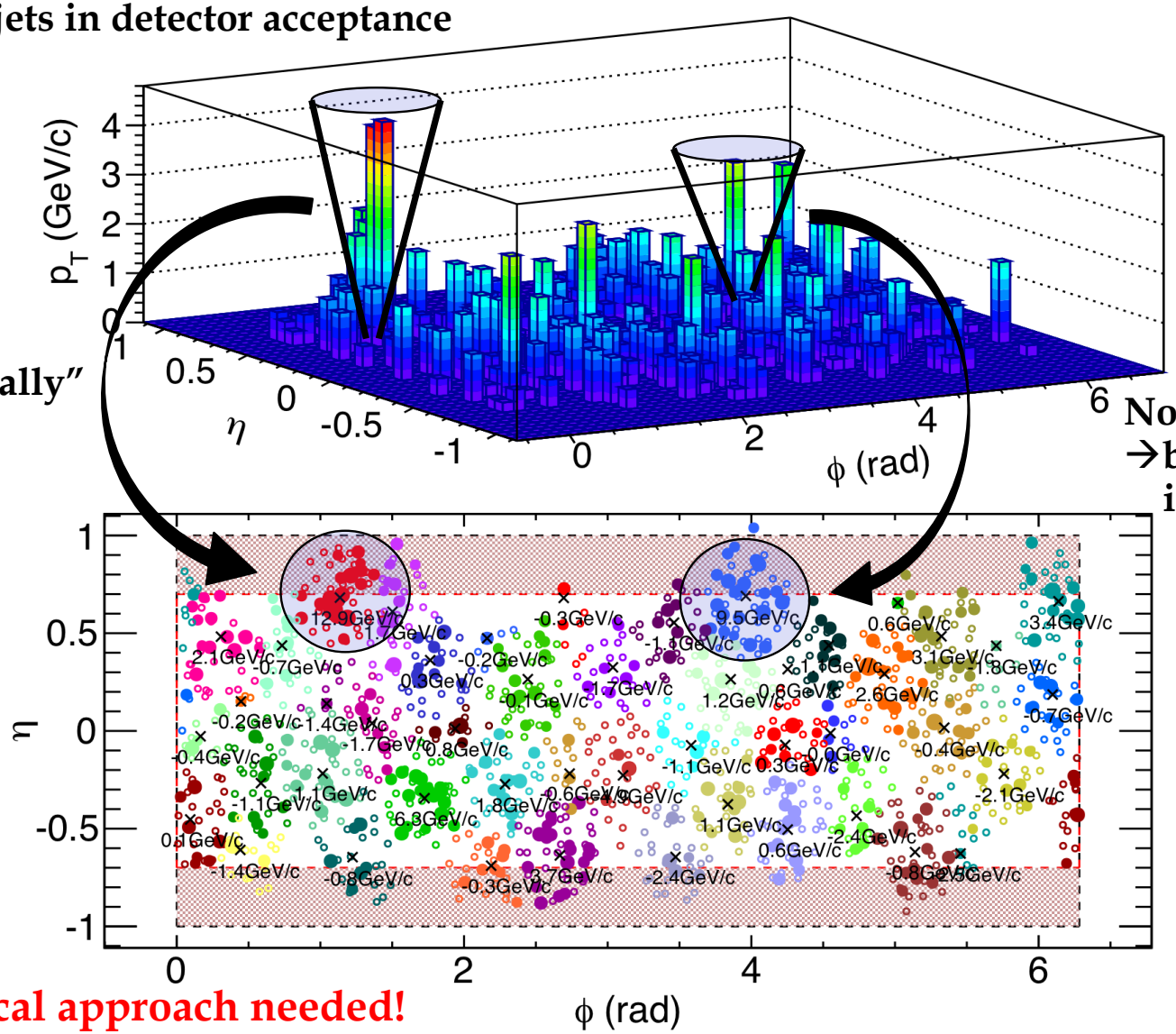
# Jet Finding at LHC




- High $p_T$ objects, clearly seen over of heavy-ion background
  → Clear jet identification (at high $p_T$)
  → But measuring is not straight forward

# Jet Finding at RHIC

**Tracks and jets in detector acceptance**

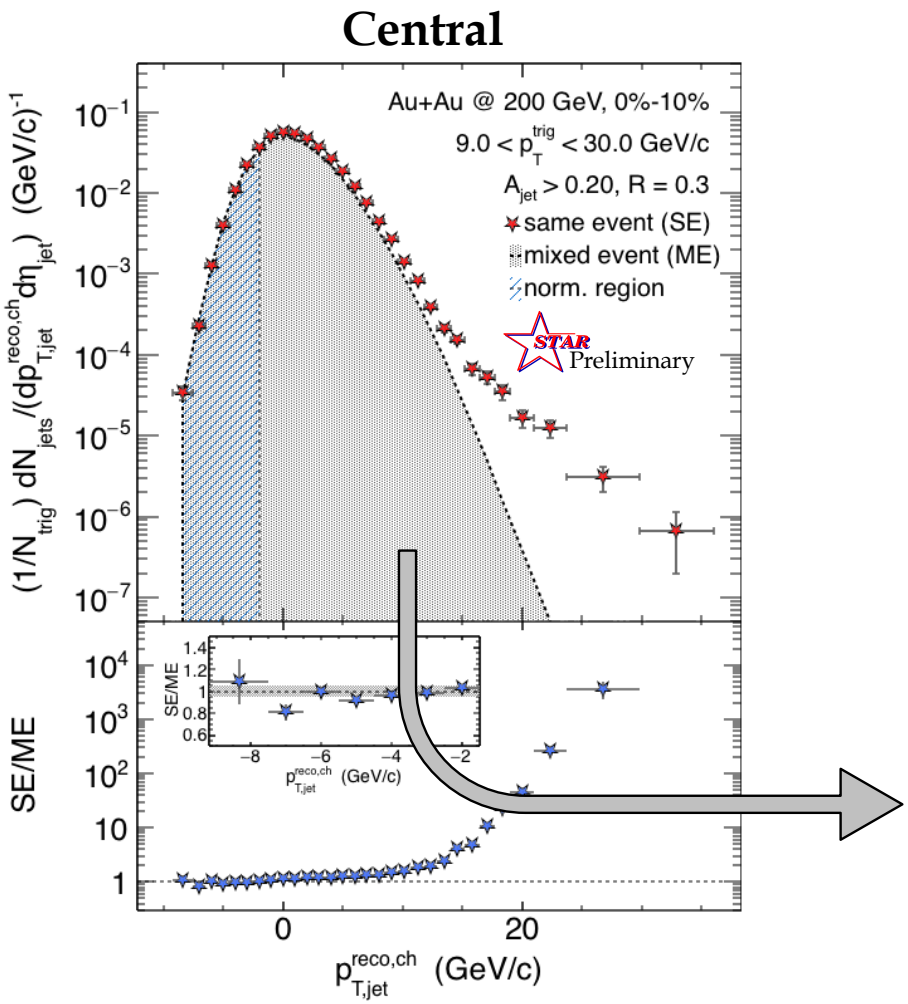


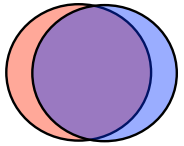

**Can be "visually" identified**

**Not obvious →background is huge!**

**→ Statistical approach needed!**

# Charged Raw Recoil Jet Spectrum: Central

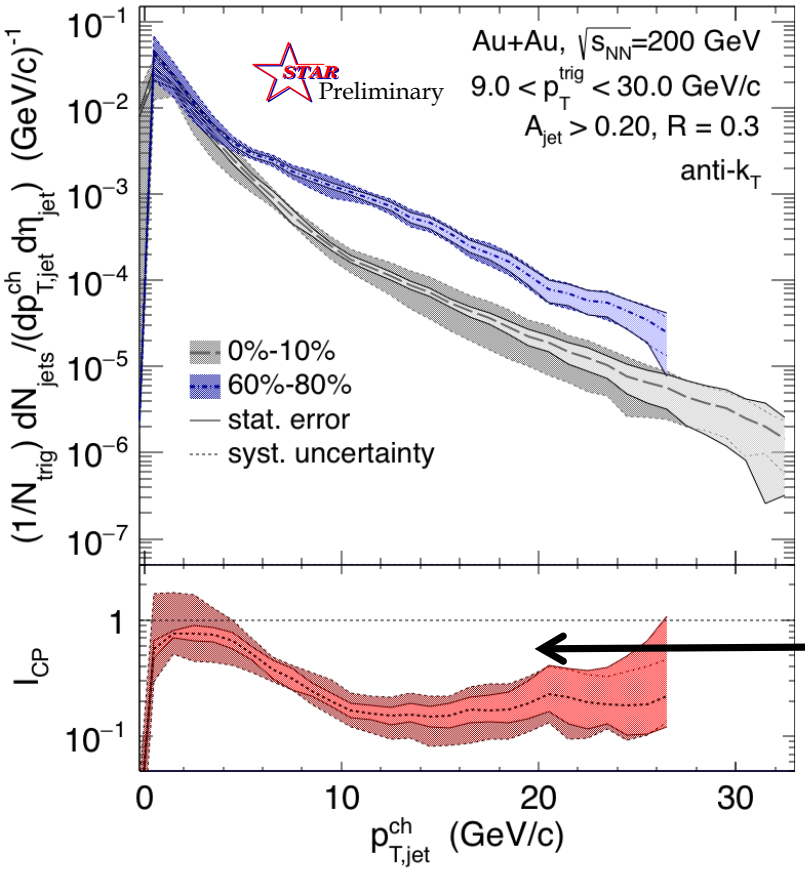


- Excellent description of low $p_T$ SE spectrum with ME
- Normalization region varied systematically
- Significant jet signal at $p_T$-ρA > 10 GeV/c

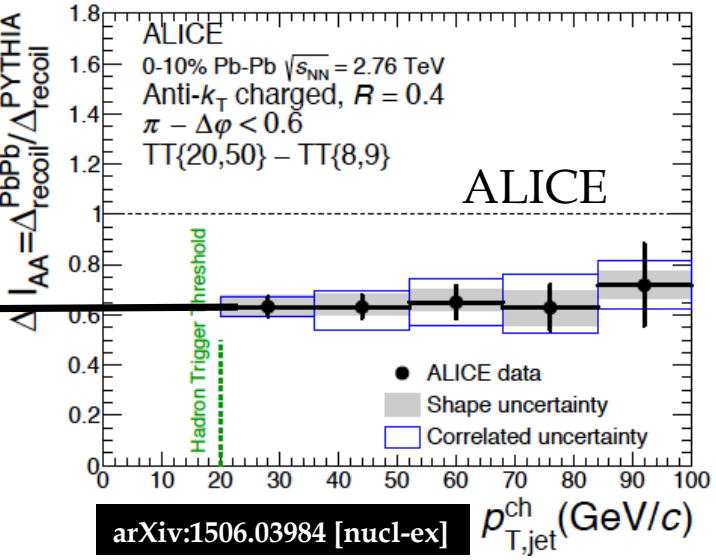
Combinatorial jet background → statistically described by mixed event technique

# Comparison Central-Peripheral: $I_{CP}$



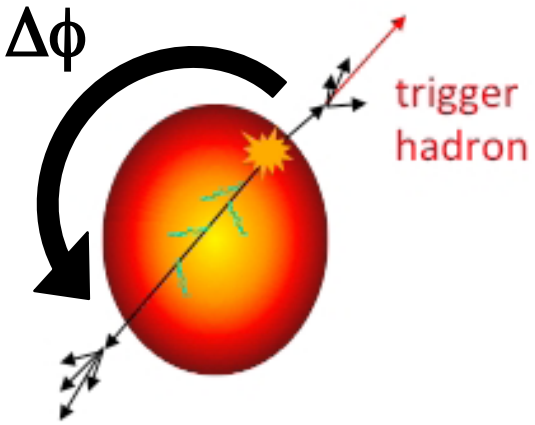

- Errors show combined systematics of unfolding (see previous slide) and track reconstruction

- Significant suppression (~0.2) at $p_T > 10$ GeV/c
- $I_{CP}$ close to 1 at low $p_T$
- Larger suppression compared to LHC energies!
  → but similar shift in $\Delta p_T$

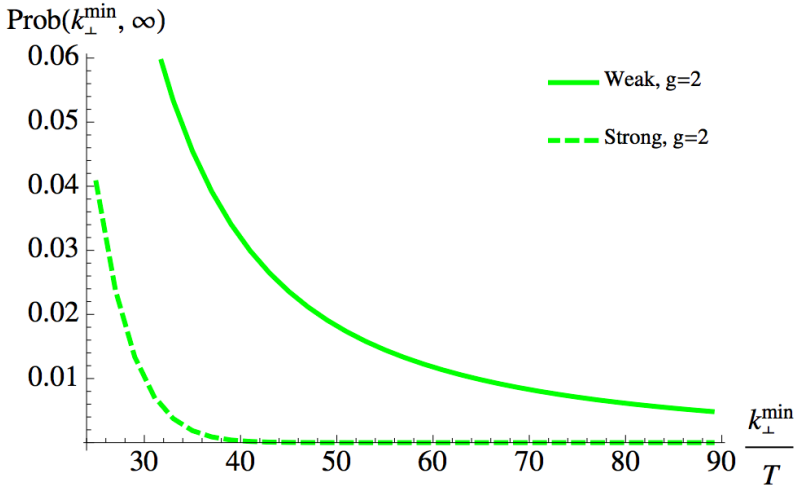



arXiv:1506.03984 [nucl-ex]

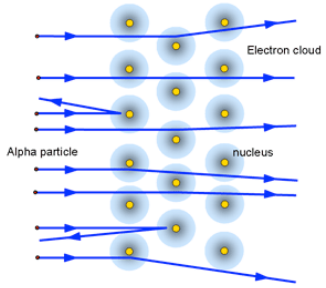
# Large Angle Scattering off the QGP?



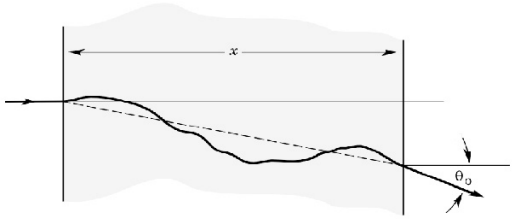

JHEP 1305 (2013) 031




Discrete scattering centers or effectively continuous medium?



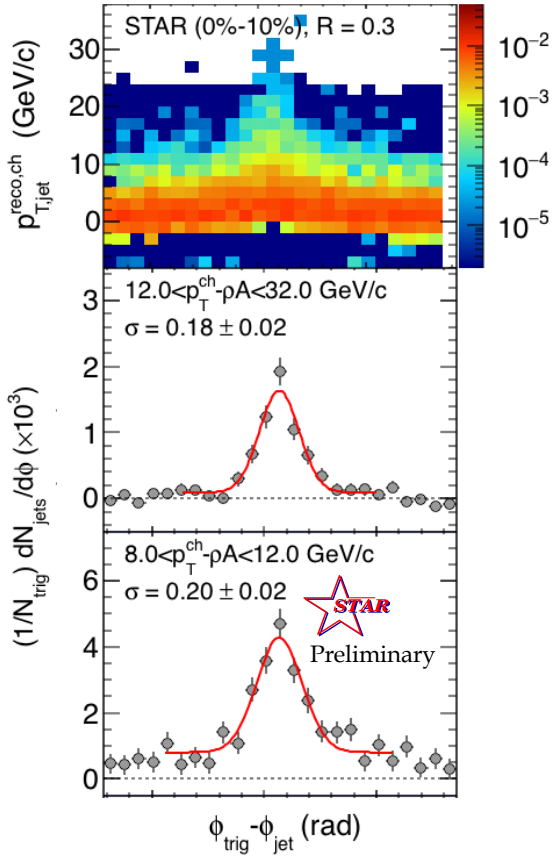

"Weak"




"Strong"

- Scattering probability can give us important information about coupling
  → strongly/weakly coupled QGP
  → quasiparticles?

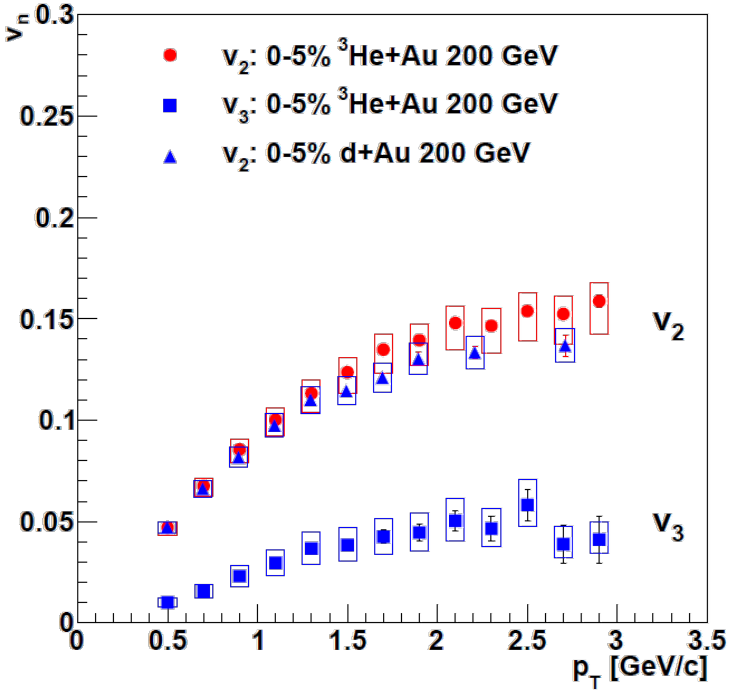
# ΔΦ, 0%-10%, R = 0.3

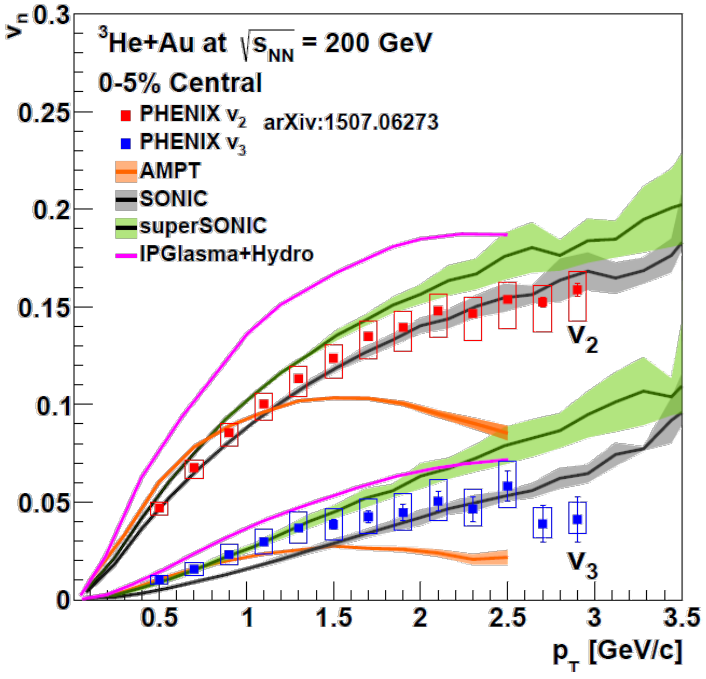



- $\Delta\phi = \phi_{trig} - \phi_{jet}$
- Projections for different recoil jet $p_T$
- Gaussian + $0^{th}$ order polynomial
- Fit results do not depend on ME normalization
- Some pedestal for 0%-10% but uncertainties still under investigation

# Elliptic Flow in small Systems

**PHENIX 3HeAu: Phys. Rev. Lett. 115, 142301 (2015)**
**PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)**



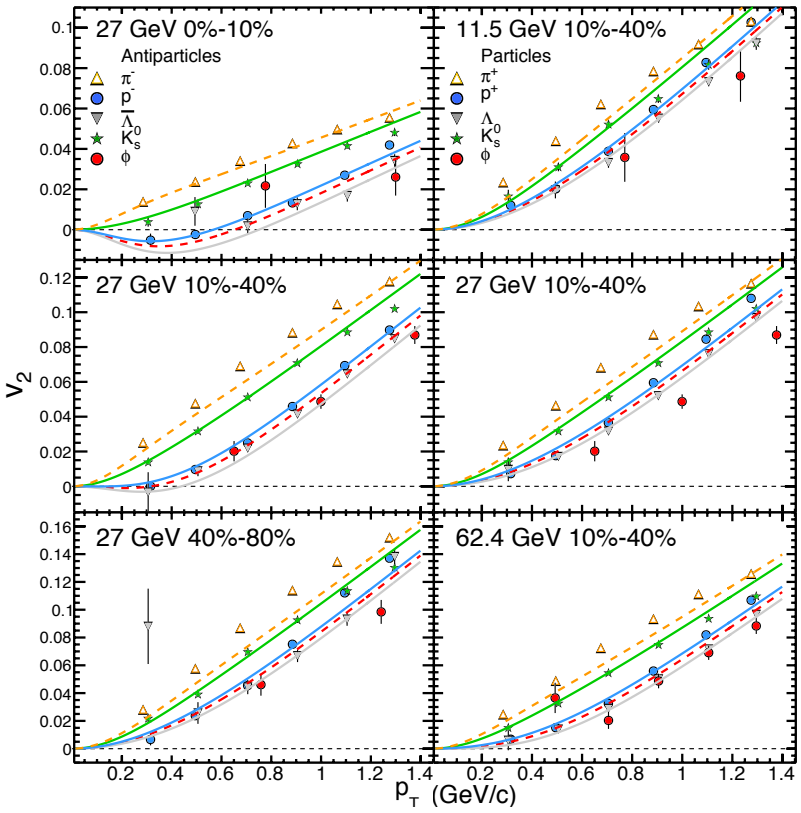



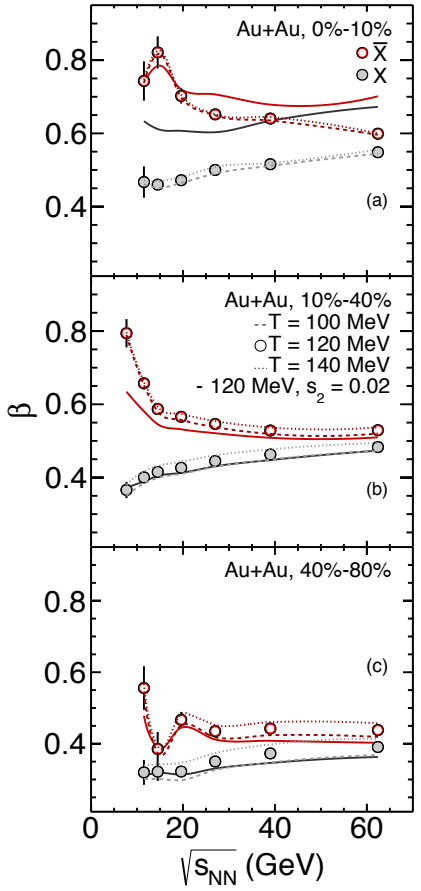

- Large anisotropy in small systems
- Models show sensitivity to initial conditions and early time evolution

SONIC Glauber + hydro + hadron cascade
super SONIC + pre-equilibrium
IPGlasma + hydrodynamic
AMPT parton + hadron cascade

# Elliptic Flow in the Beam Energy Scan

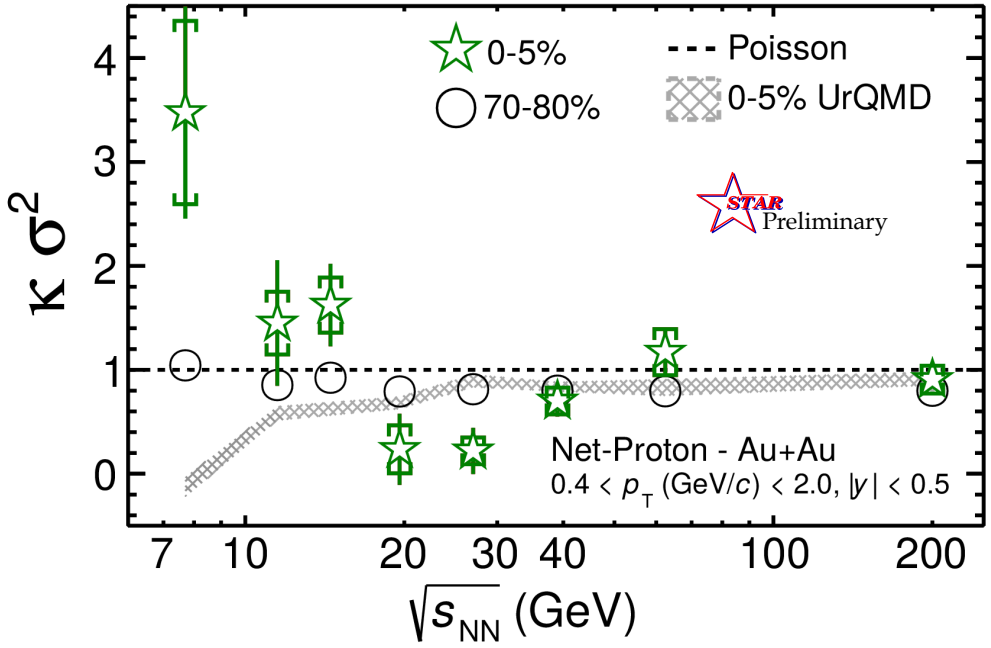
Phys.Rev. C93 (2016) 1, 014907




- Centrality and energy dependence published
- Particle – antiparticle difference in $v_2$ observed
- Blast wave model can simultaneously fit the data

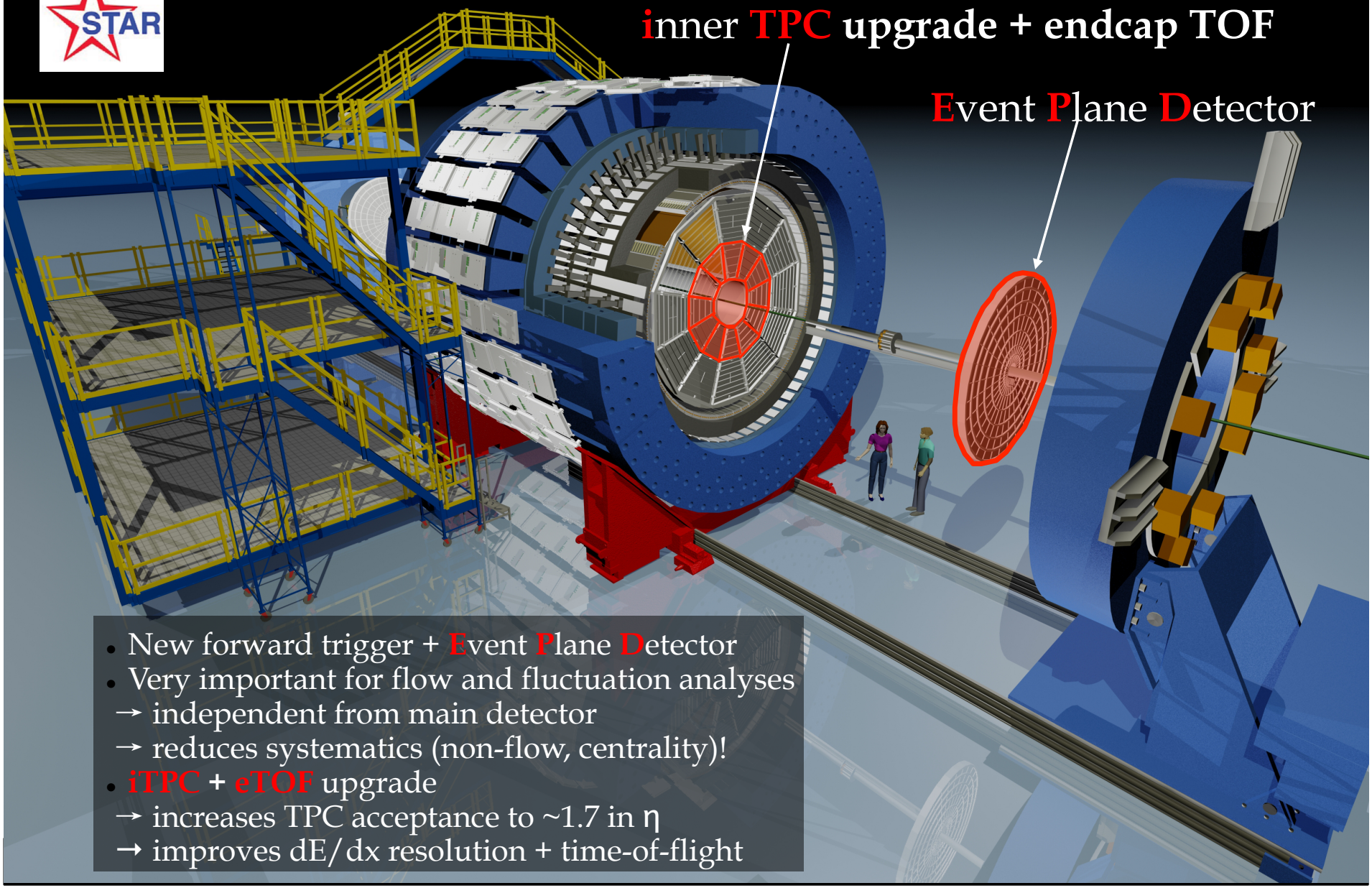
# Search for the QCD Critical Point




- Higher moments of conserved quantities might be sensitive to the QCD critical point

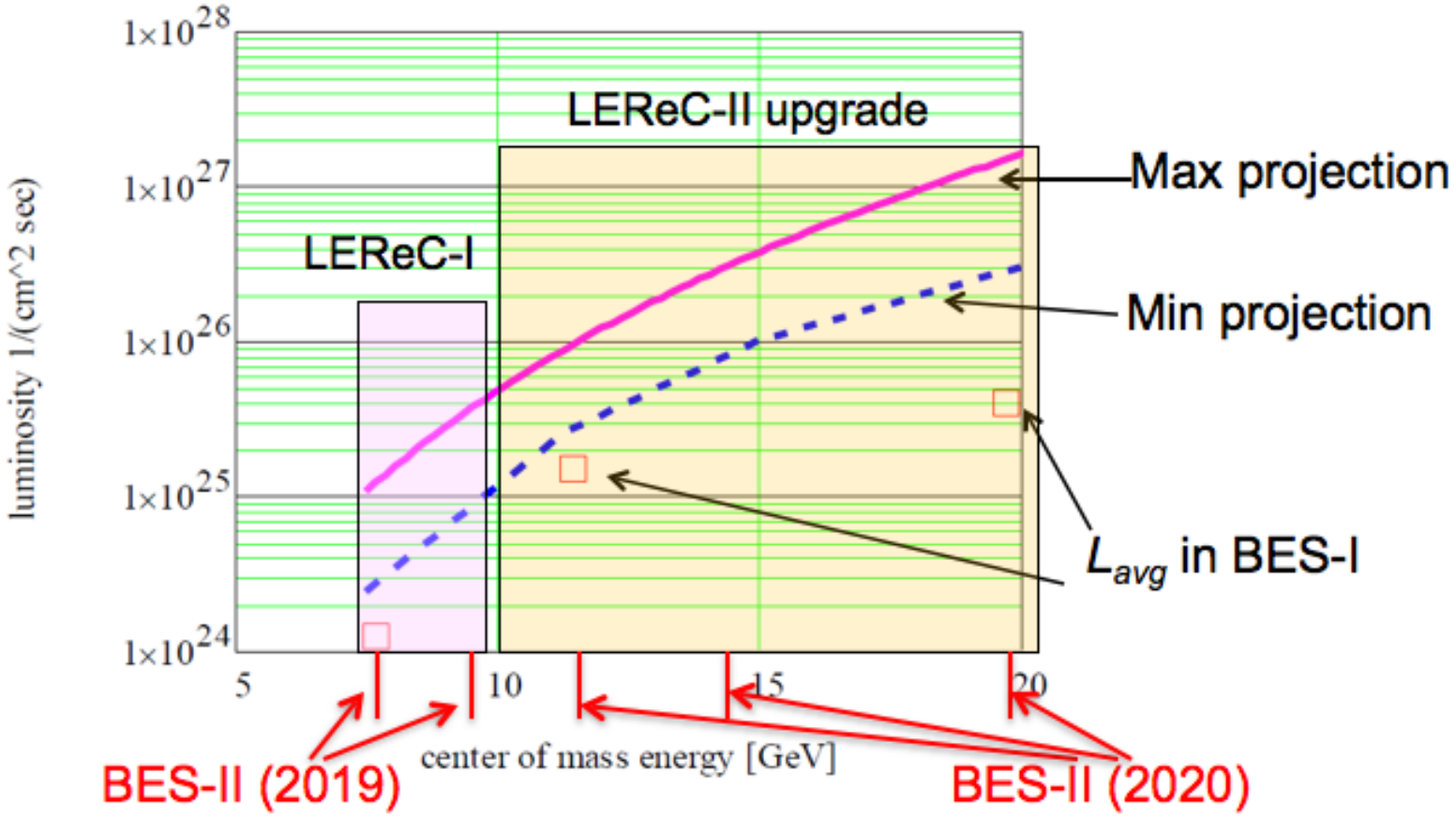
- Increased $p_T$ range: 0.4-2.0 GeV/c (from 0.4-0.8 GeV/c)
  → non monotonic behavior

# Detector Developments for BES II




- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses
  → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC + eTOF upgrade
  → increases TPC acceptance to ~1.7 in η
  → improves dE/dx resolution + time-of-flight

# Electron Cooling for BES II

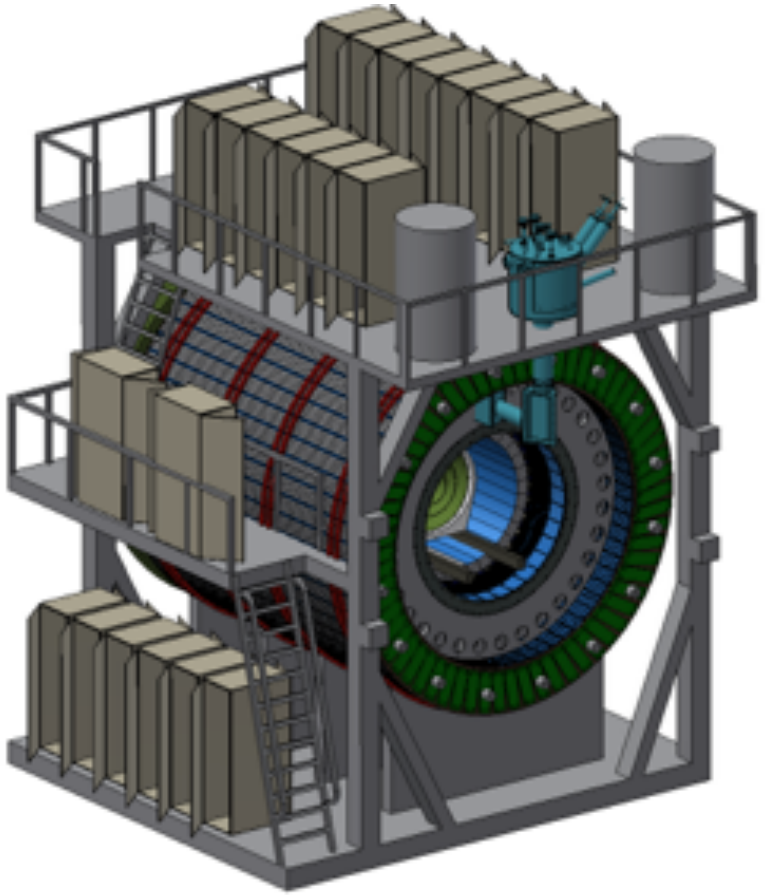



- Up to a factor 10 luminosity increase for BES II

# sPHENIX

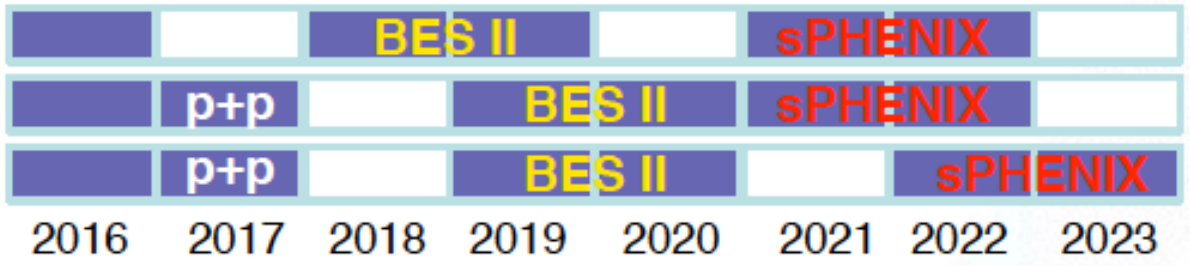
Detector overview:
- Inner/outer HCal
- EMCal
- Tracking (only silicon or silicon and TPC)
- 1.5 T magnetic field based on the SC BaBar magnet

Observables (high statistics):
Jets, D mesons, and Upsilons



# RHIC Timeline

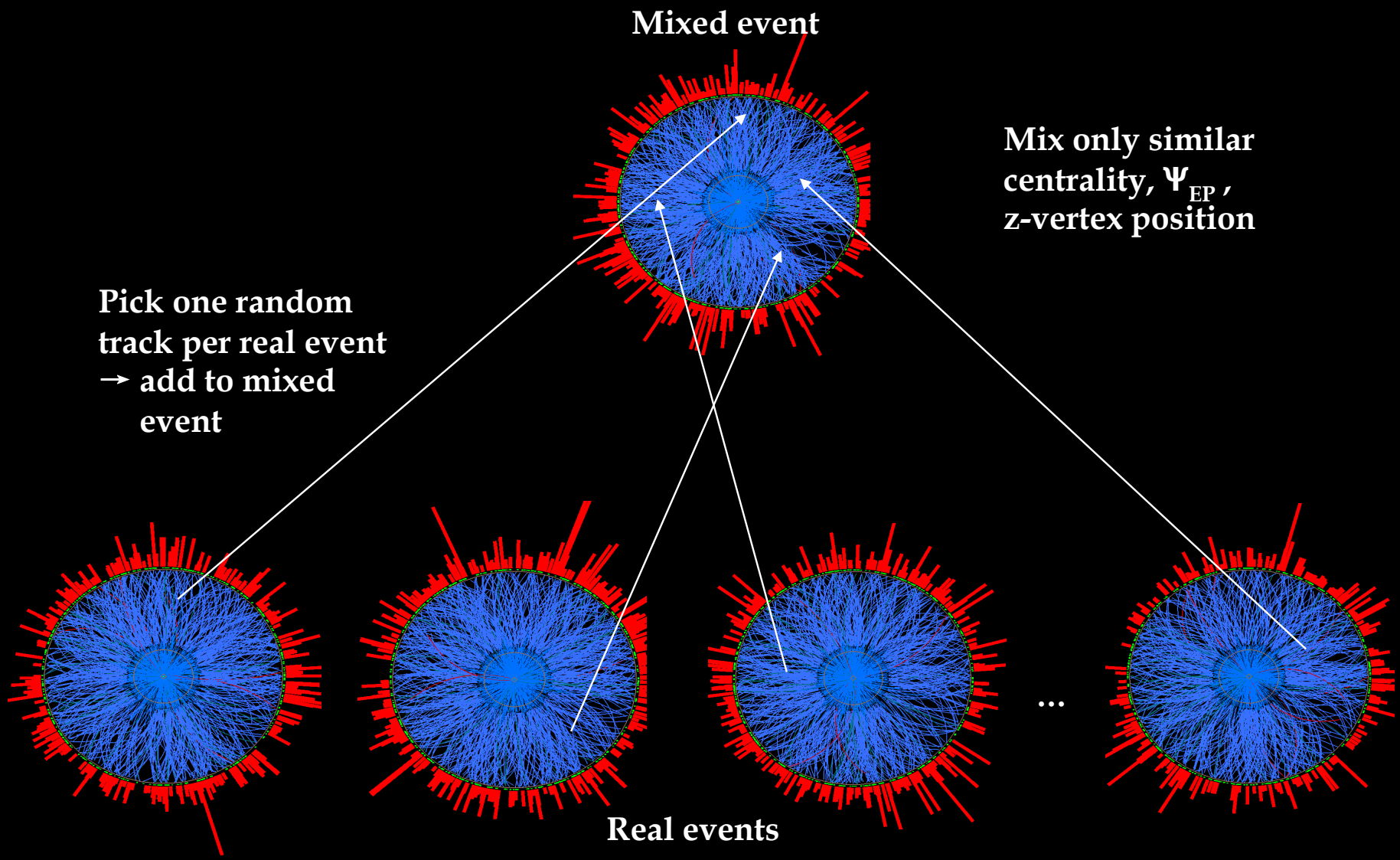
Berndt Mueller, sPHENIX collaboration meeting Dec/2015




- 2014-2017: Heavy-flavor probes (silicon trackers), transverse spin physics
- 2018: Install low energy electron cooling
- 2019-2020: Beam Energy Scan phase II, precision scan of QCD phase diagram (only STAR)
- 2021: Install sPHENIX
- 2022-2023: sPHENIX: jet and Upsilon physics
- After 2023: Transition to eRHIC?


Thanks!

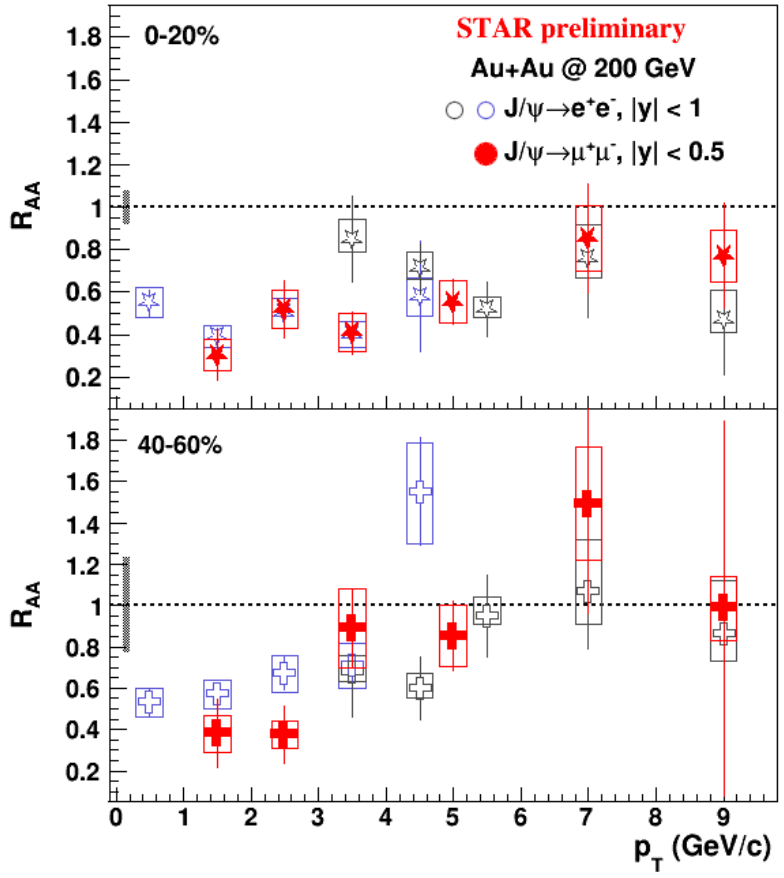
# Mixed Event Generation for Jets



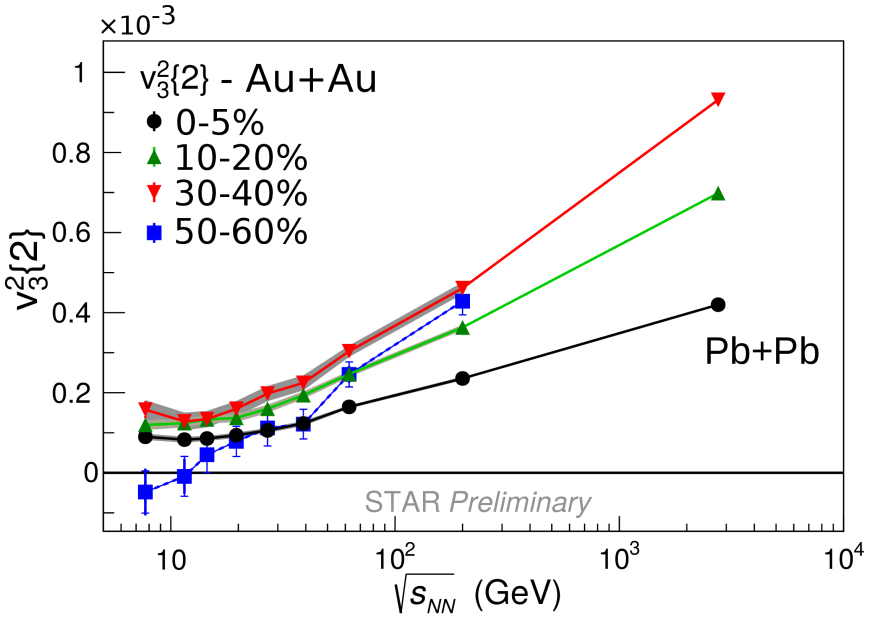
# Quarkonia in Au+Au

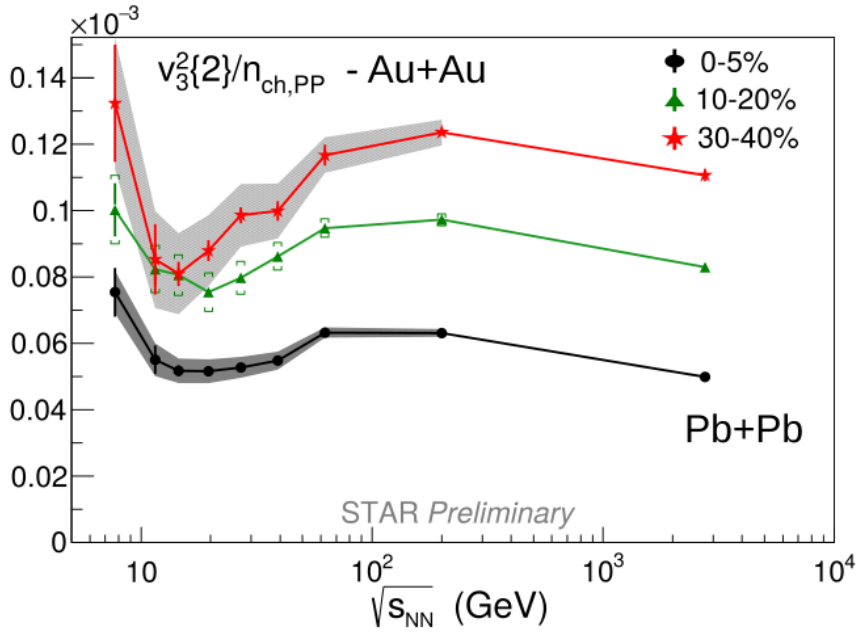
First results from the STAR **M**uon **T**elescope **D**etector

- Di-electron and di-muon results are consistent
- Almost constant suppression for all $p_T$ in central collisions
- Suppression only at low $p_T$ in peripheral collisions



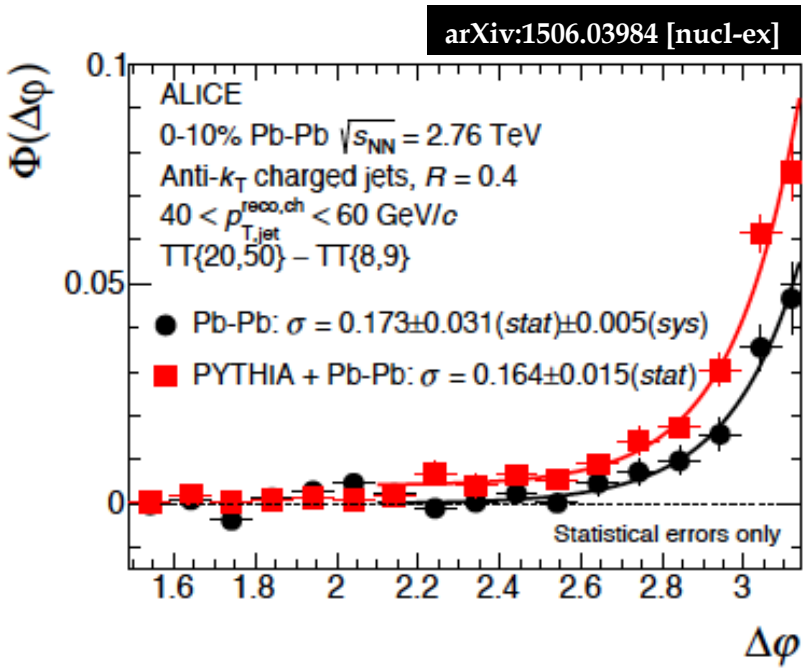
# Triangular Flow in the Beam Energy Scan

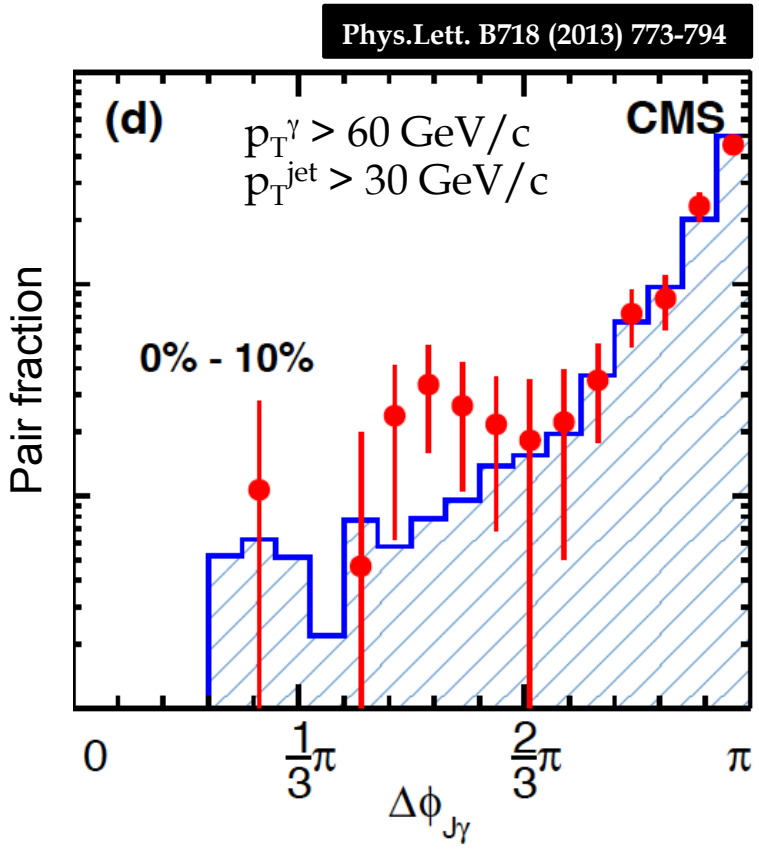



- ~ Monotonic increasing $v_3^2\{2\}$ with collision energy for all centralities
- Scaling with multiplicity per participant pair (~ energy density) reveals a dip at about 10-20 GeV
  → Signature for the softening of the EOS?

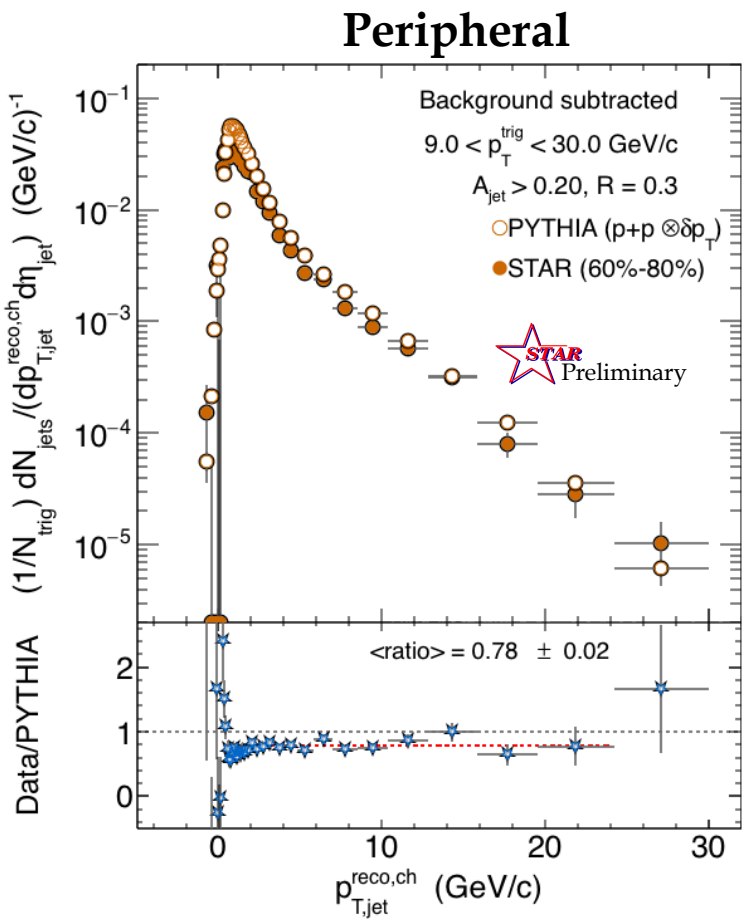
# Large Angle Scattering at LHC

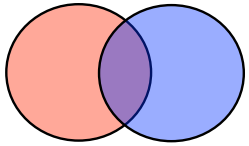



- No additional broadening observed in Pb+Pb compared to p+p so far

# Reference vs. PYTHIA

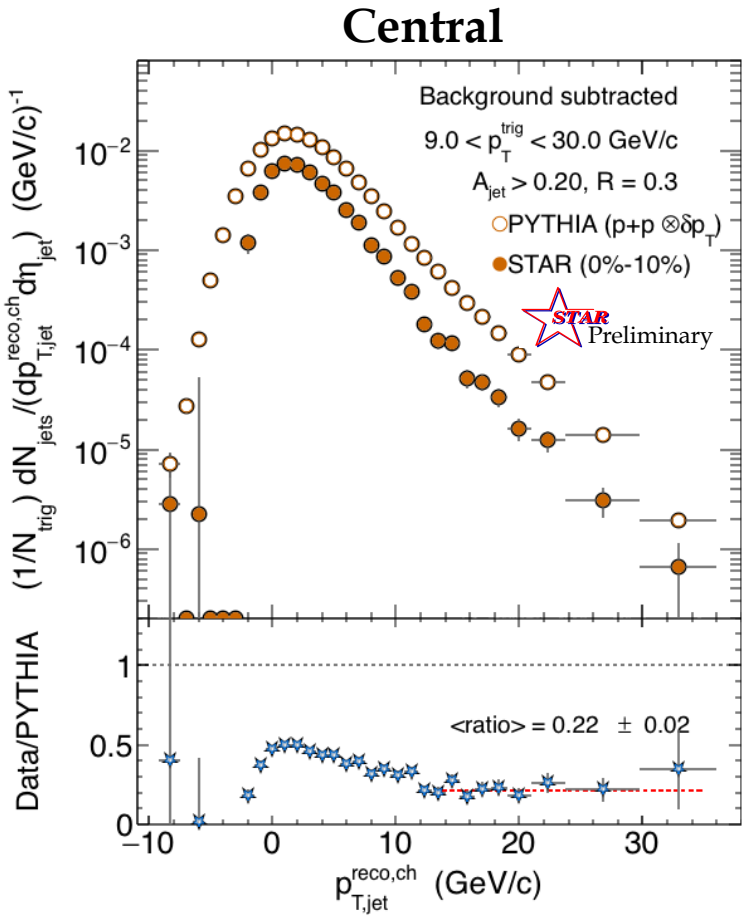


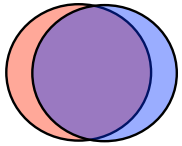



- Background subtracted 60%-80% spectrum in comparison to smeared* PYTHIA
- PYTHIA shape + yield in good agreement 60%-80% data

*PYTHIA $\otimes \delta p_T$

# Recoil Jet Energy Loss

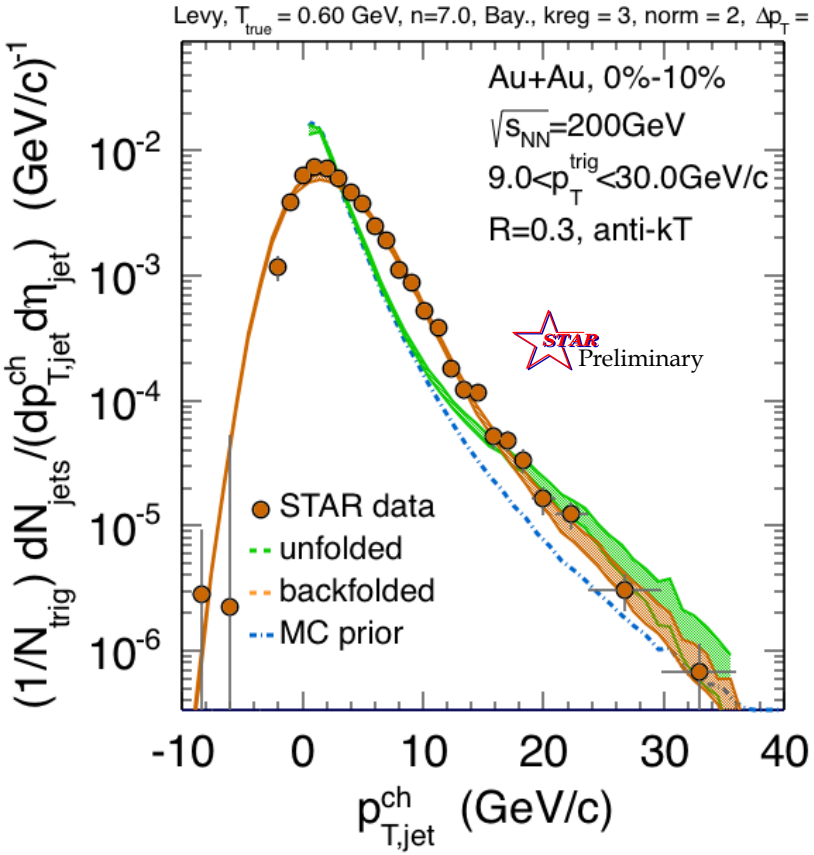


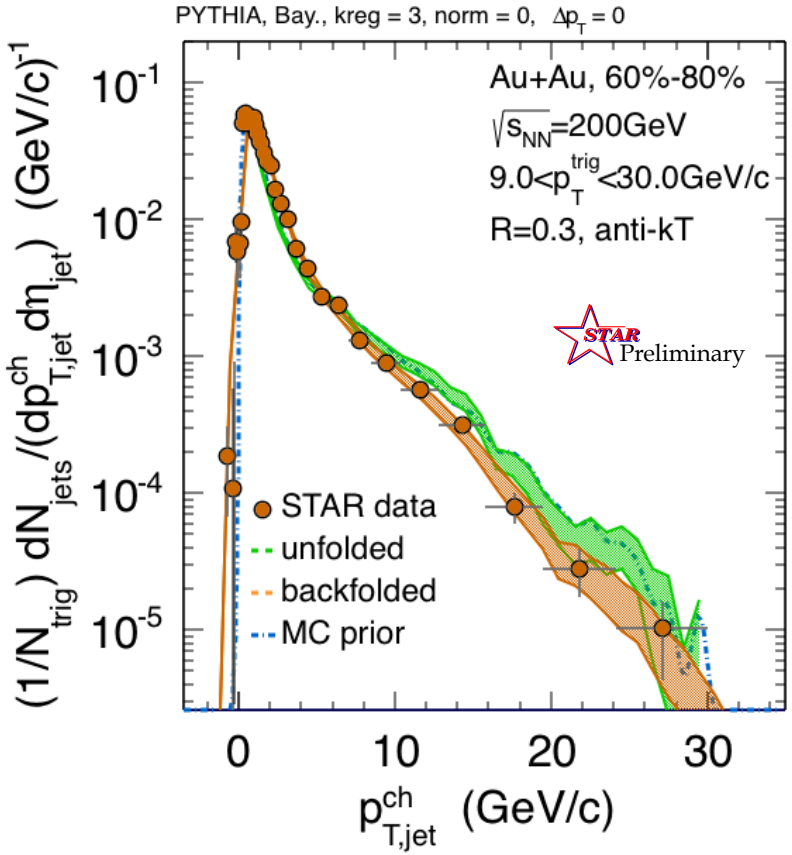
- Significant suppression (central/smeared PYTHIA) over whole $p_T$ range
  → energy loss
- Very similar shape over 4 orders of magnitude

# Unfolding Examples

**Central (Levy prior example)**

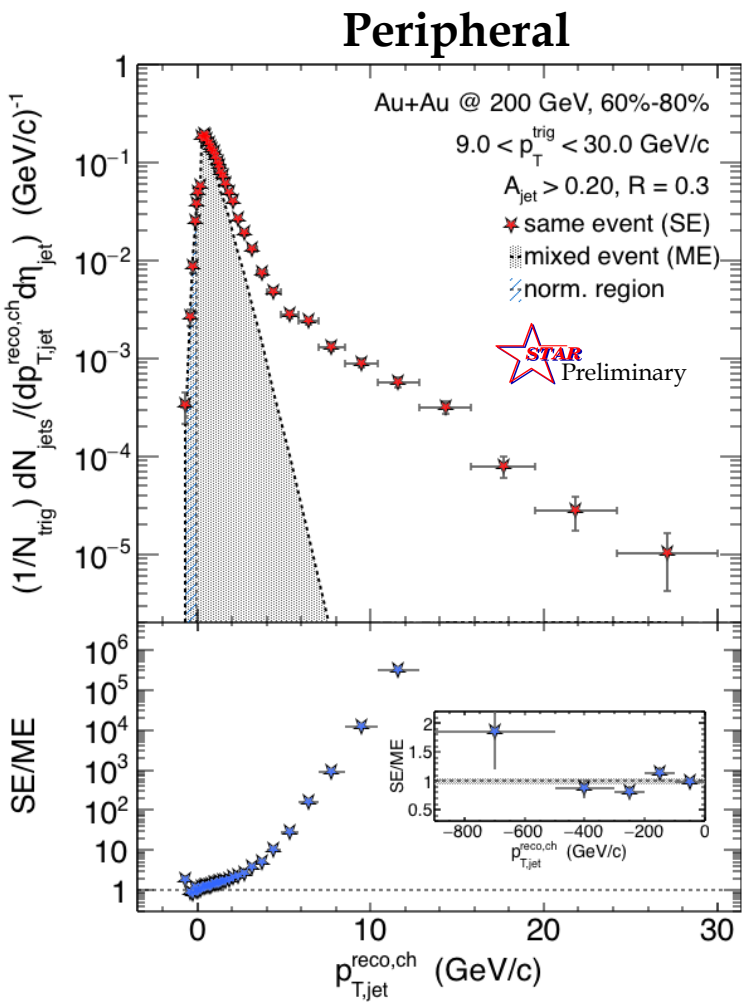


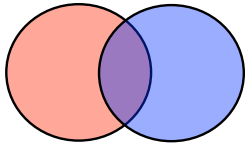

**Peripheral (PYTHIA prior example)**




- SVD and Bayesian unfolding used
- Systematic variation of: Prior → {Levy function (T, n), PYTHIA}, regularization parameter, +/-5% efficiency variation, ME normalization, $\delta p_T$ distribution (single particle embedding, PYTHIA jet embedding)
- Check based on backfolding $\chi^2$

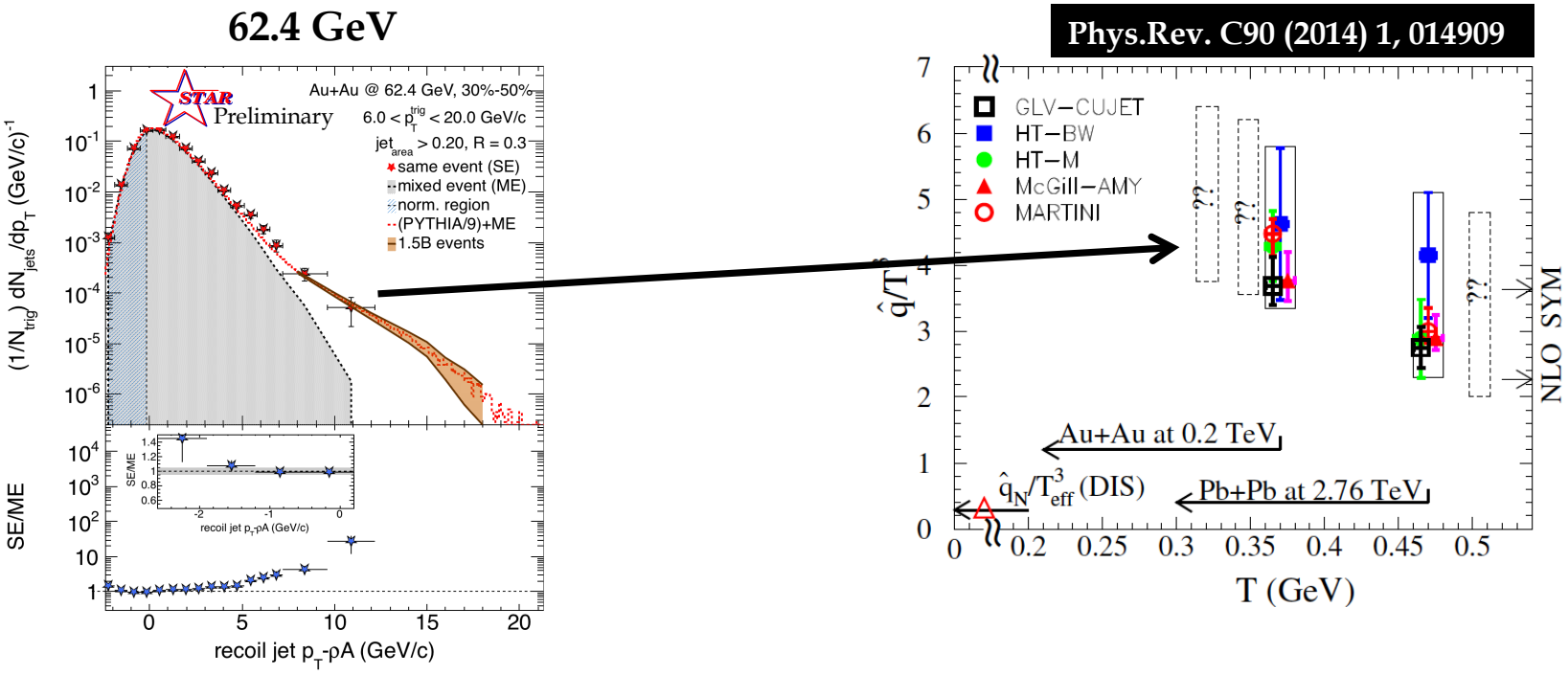
# Charged Raw Recoil Jet Spectrum: Reference



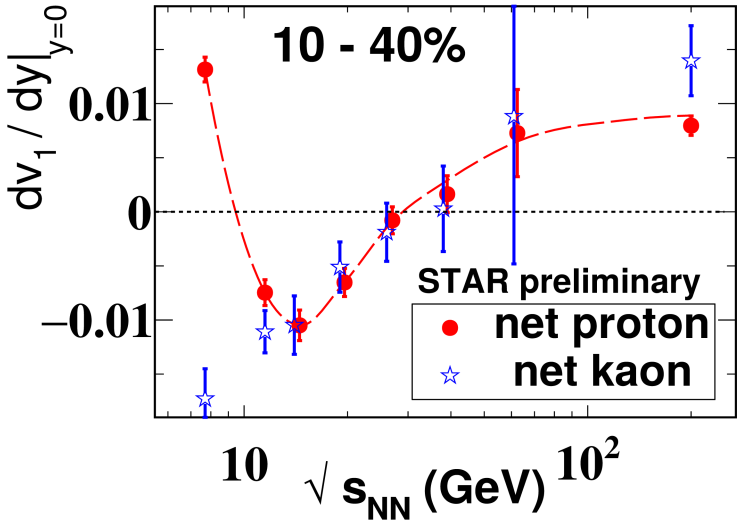
- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c

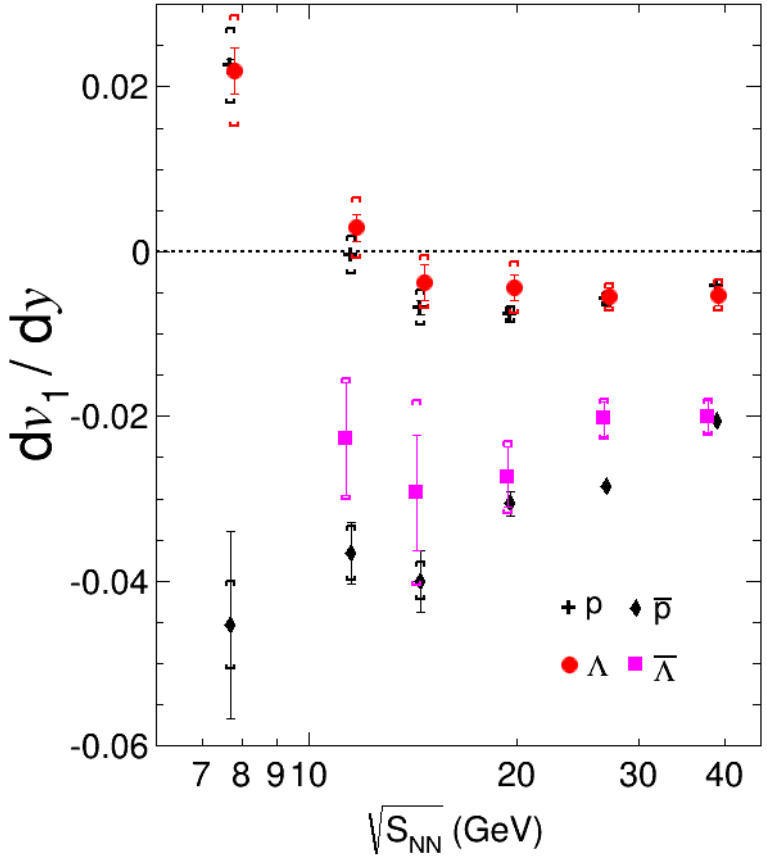
# Outlook



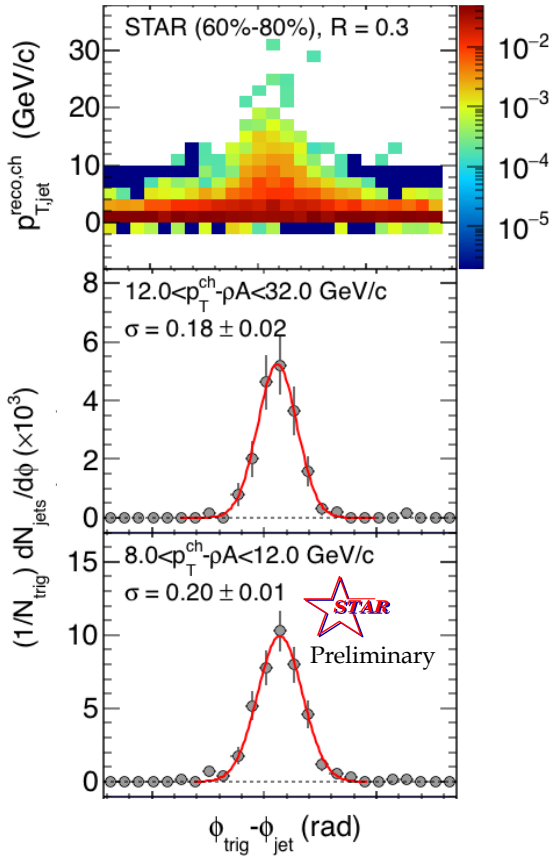

- Jet transport parameter has most likely a Temperature dependence
  → high statistics 62.4 GeV + full jet reconstruction!
  → Beam Use Request for 1.5 B events for next year (under discussion)

# Directed Flow in the Beam Energy Scan



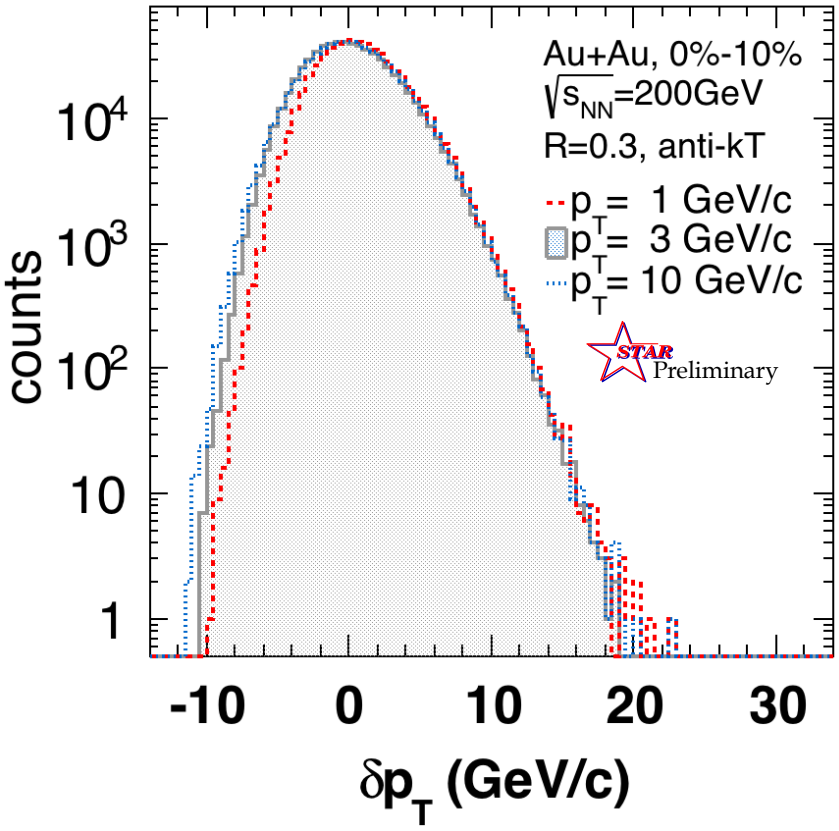
# ΔΦ, 60%-80%, R = 0.3




- $\Delta\phi = \phi_{trig} - \phi_{jet}$
- Projections for different recoil jet $p_T$
- Gaussian + $0^{th}$ order polynomial
- Fit results do not depend on ME normalization
- Almost no pedestal for 60%-80%

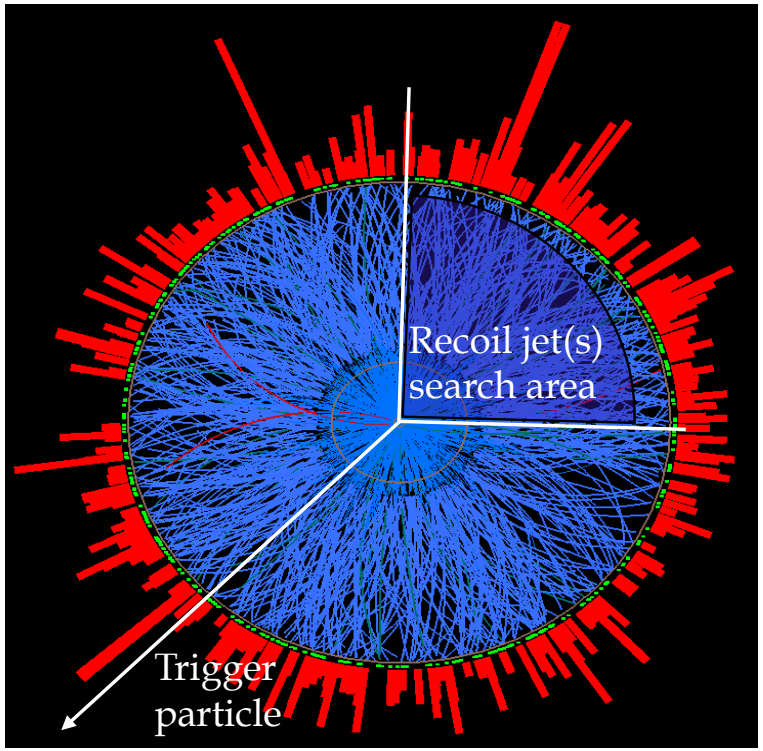
# Background Fluctuations

**Smearing of "true" recoil jet due to underlying thermal background**




- True jet candidate is still contaminated by thermal background
  → jet momentum is smeared
  → $\delta p_T$
- Embed particles into real events to determine fluctuation
- Depends little on embedded particle momentum
- $\delta p_T$ used to unfold the spectrum

# Semi-Inclusive Recoil Jets




Semi-inclusive yield of jets* recoiling from a high $p_T$ hadron trigger

$$\frac{1}{N^h_{trig}}\frac{dN_{jet}}{dp_{T,jet}} = \frac{1}{\sigma^{pp\to h+X}}\frac{d\sigma^{pp\to h+jet+X}}{dp_{T,jet}}$$

Measured  Calculable in fixed-order pQCD

- Trigger on high $p_T$ hadron → Selection of a high $p_T$ process
- Use all jet candidates on the other azimuthal hemisphere within +/- 45 degree → **no fragmentaion bias on recoil side**!
- **How to deal with combinatorial recoil jets?**

*charged jets