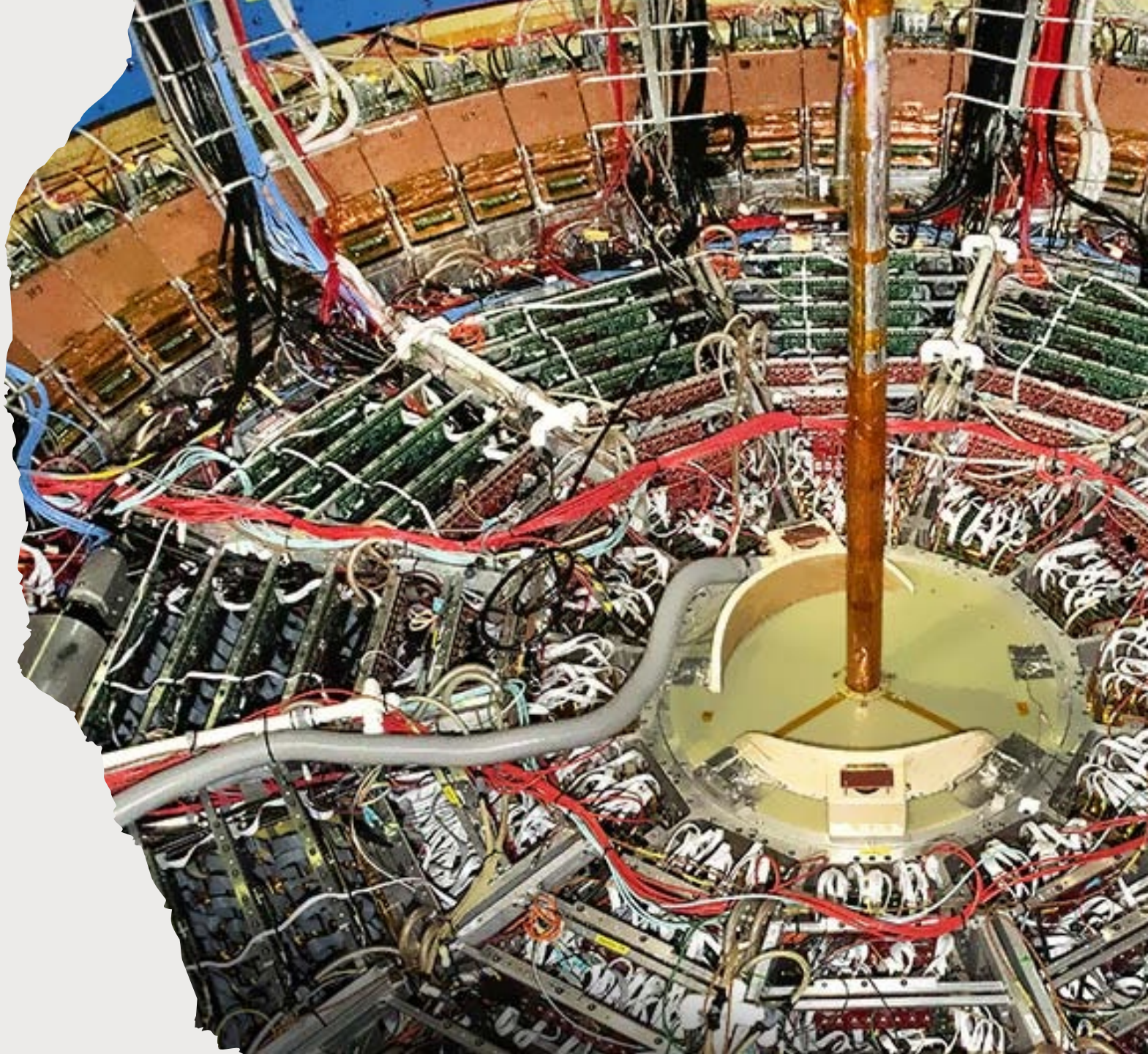
STAR:
HIGH P_T AND JET PHYSICS

Olga Evdokimov (UIC)



JET QUENCHING — THE STAR PERFORMANCE

🌟 Cast & Crew

Directors:

1991–2002: John Harris
2002–2008: Tim Hallman
2008–2014: Nu Xu
2014–2017: Zhangbu Xu
2017–2020: Helen Caines and Zhangbu Xu
2020–2023: Helen Caines and Lijuan Ruan
2023–now: Lijuan Ruan and Frank Geurts

Lead Roles:

the STAR Collaboration

Supporting Ensemble:

CAD/RHIC/BNL

Special Thanks: DOE, NSF, International Funding Entities

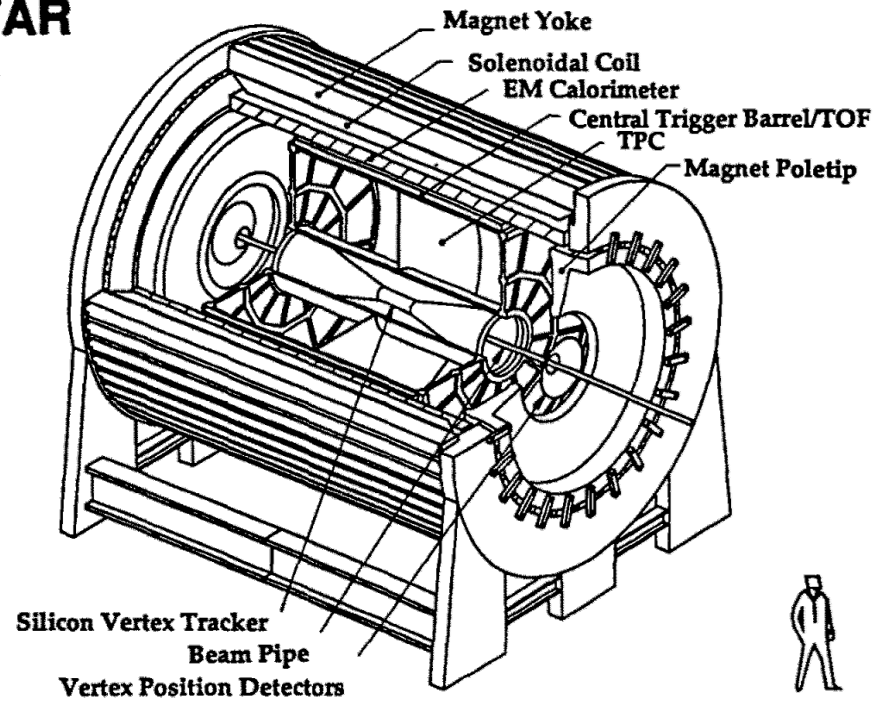
PREAMBLE: STAR BEFORE RHIC

- J. Harris, Quark Matter 1993:

"The experiment will utilize two aspects of hadron production that are fundamentally new at RHIC: correlations between global observables on an event-by-event basis and the use of hard scattering of partons as a probe of the properties of high-density nuclear matter."

"A systematic study of (high-pT) particle and jet production will be carried out over a range of colliding nuclei from pp through p-nucleus up to Au-Au, over a range of impact parameters from peripheral to central, and over the range of energies available at RHIC."

NPA 566 (1994) 277



3. PHYSICS OF STAR
3.1 Parton Physics from Jets, Mini-Jets and High pt Particles
3.2 Particle Spectra
3.3 Strangeness Production
3.4 Hanbury-Brown and Twiss (HBT) Interferometry
3.5 Electromagnetic/Charged The measurement Particle Energy Ratio
3.6 Fluctuations in Energy, Entropy, Multiplicity, and Transverse Momentum

EARLY DISCOVERIES

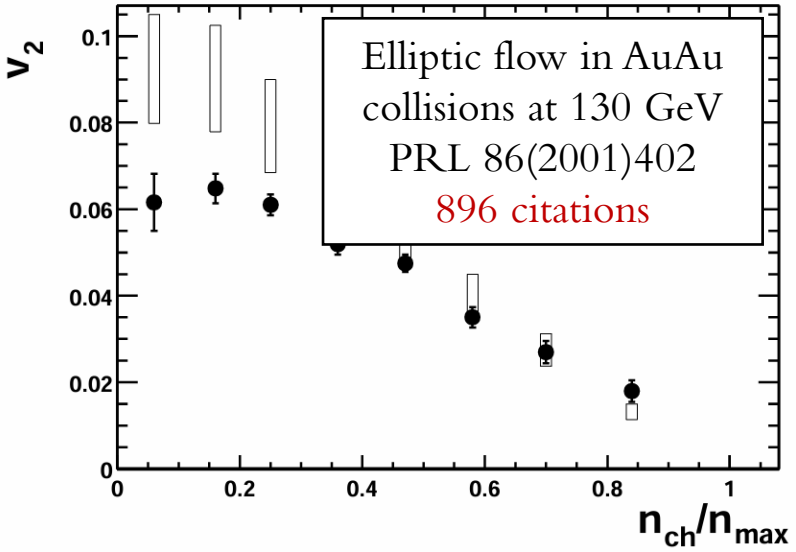
Iconic plots from STAR!

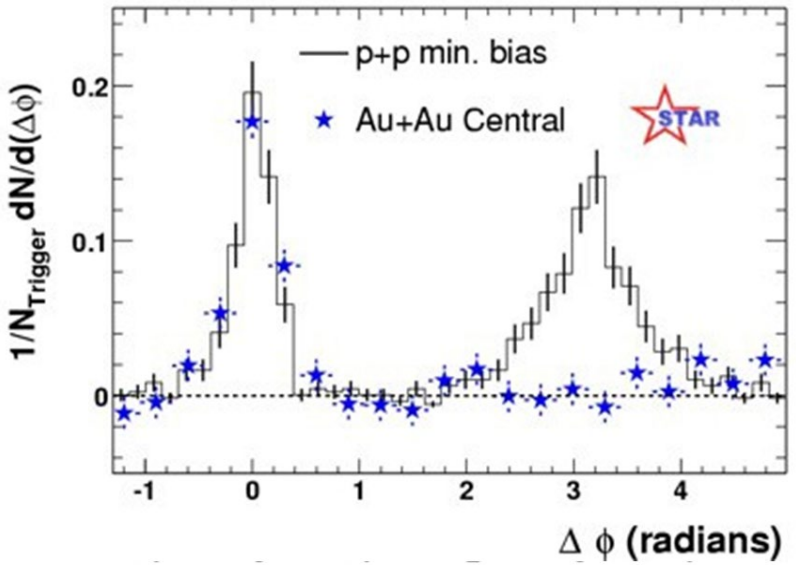
- Discovery of the strong elliptic flow

  → the very first step to the "perfect fluid."

- Discovery of the jet quenching: Disappearance of back-to-back high p_T correlations in central AuAu collisions at 200 GeV

  → a major impact on shaping future HIN programs



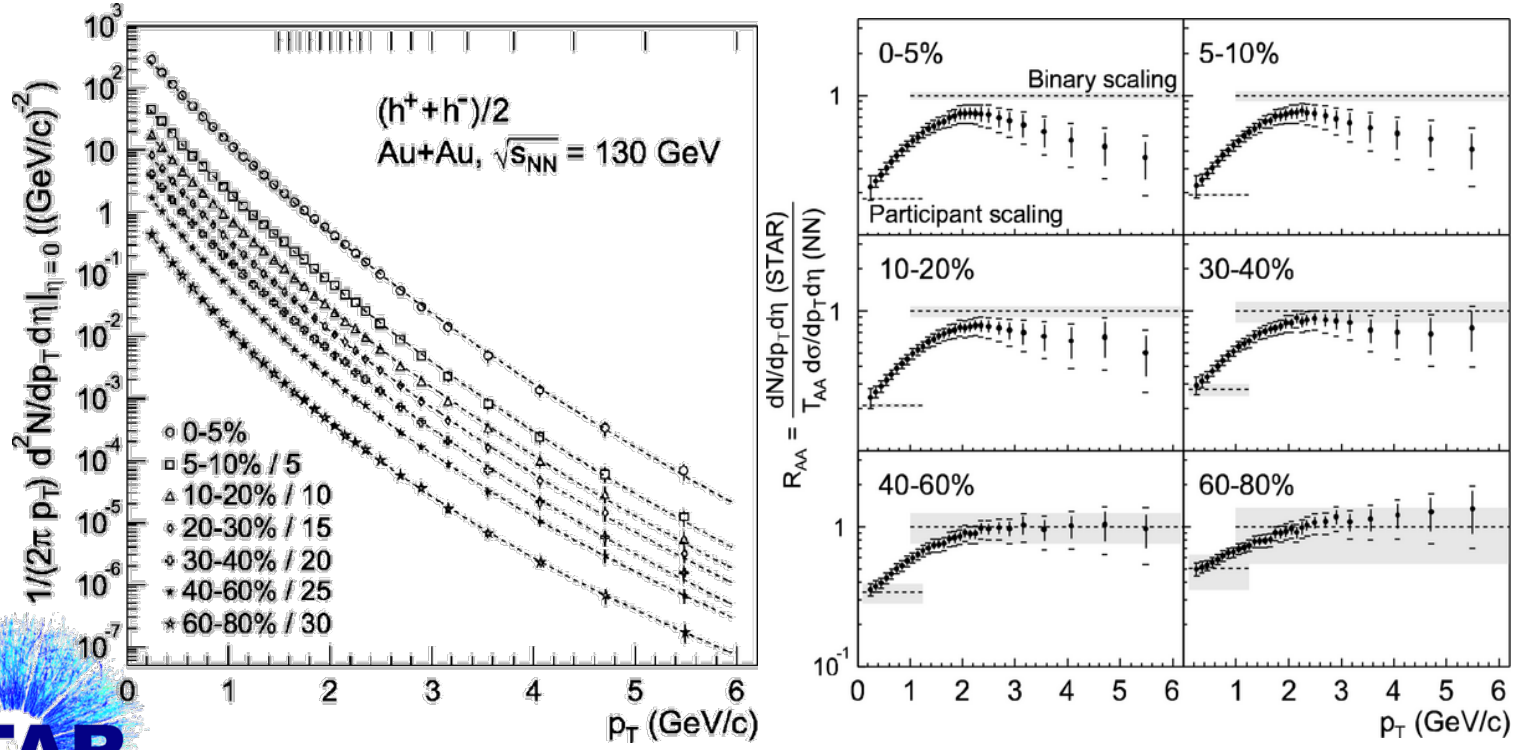


PRL 90(2003)082302
February 26, 2003

David Hardtke, John Harris, Mike Miller

BUT FIRST THINGS FIRST

- Published just a few months earlier, it was the first STAR nuclear modification measurement from 130 GeV AuAu data:



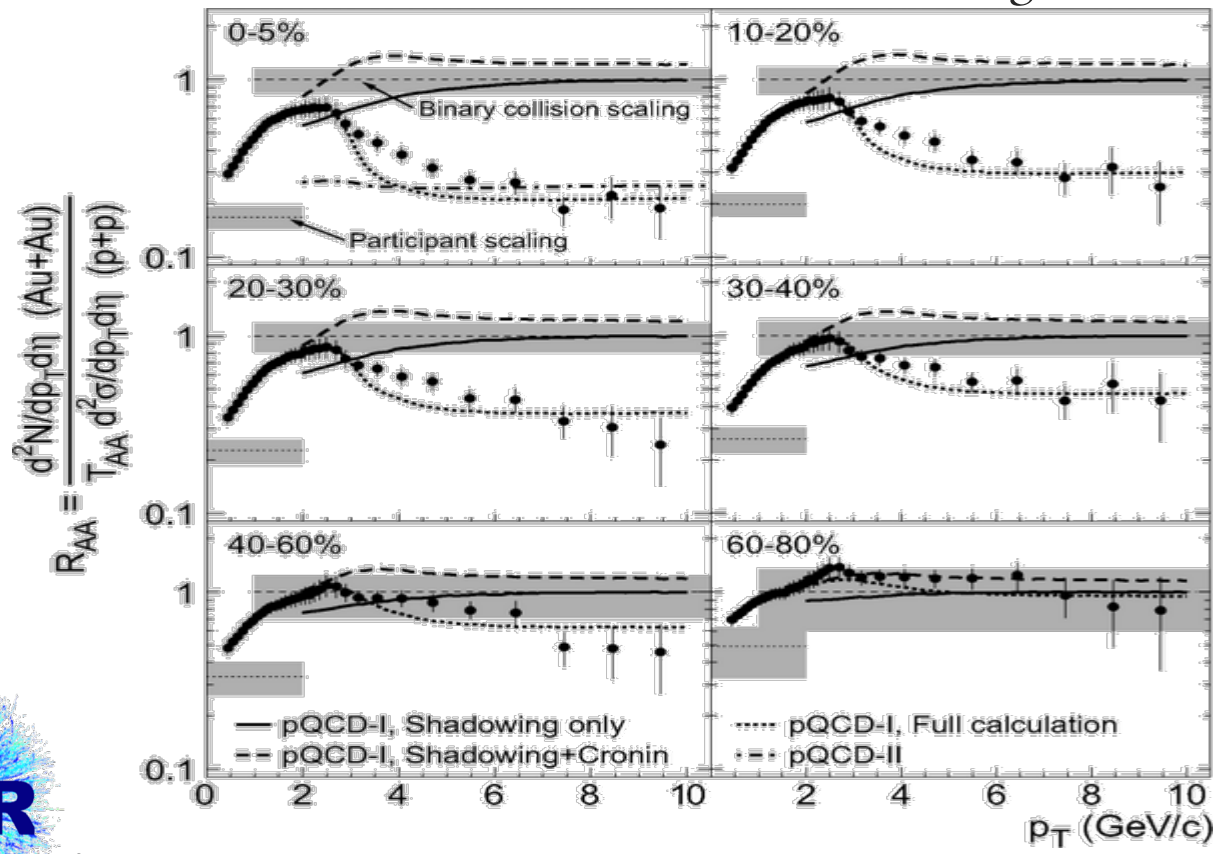
PRL **89** (2002) 202301
November 11, 2002

- Significant suppression at high-p_T
- Reference: parametrization and fit to UA1 $p\bar{p}$ data at $\sqrt{s}$=200-900

Peter Jacobs, Bum Choi, Jamie Dunlop, Kirill Filimonov, Jennifer Klay, Gerd Kunde, Frank Laue, Mike Miller

R_{AA} WITH MEASURED REFERENCE

- Transverse momentum and collision energy dependence of high p_T hadron suppression in AuAu collisions at ultra relativistic energies:



PRL **91** (2003) 172302
October 24, 2003

- Factor of 5 hadron suppression in central collisions at high p_T
- The suppression level was accurately predicted by the pre-RHIC theory.

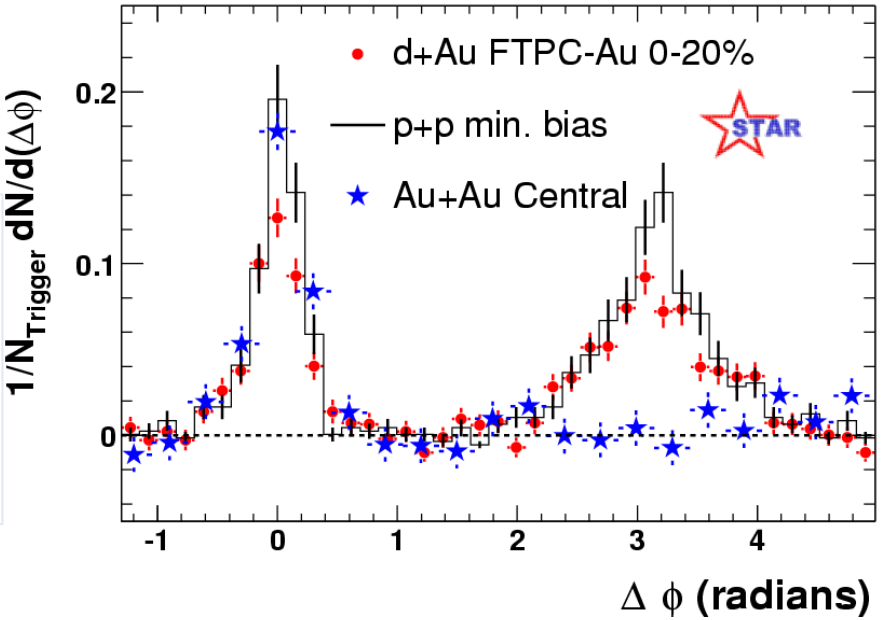
(X.N. Wang, "Last Call for RHIC Predictions," NPA 661 (1999) 205c)

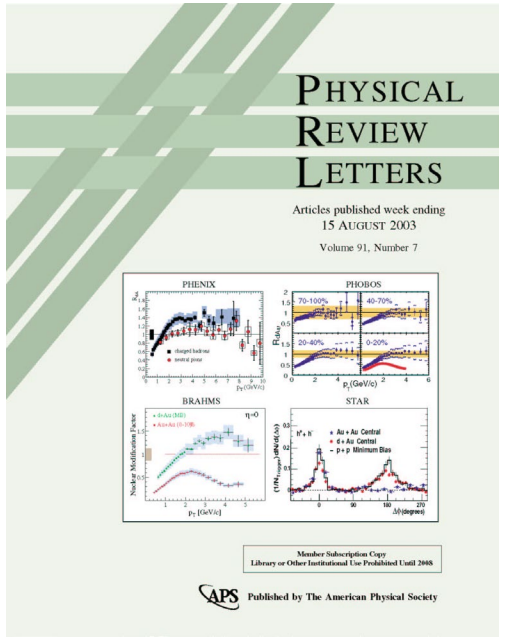
Carl Gagliardi, Peter Jacobs, Jon Gans, Jennifer Klay, Jamie Dunlop

THE OFFICIAL QUENCHING DISCOVERY

PRL 91 (2003) 072304
August 15, 2003

Joern Putschke, Peter Jacobs, Bum Choi, Jamie Dunlop, Patricia Fachini, Jon Gans, David Hardtke, Jennifer Klay, Dan Magestro, Mike Miller, Frank Simon, Zhangbu Xu





PHENIX: PPRL 91 (2003) 072303
STAR: PRL 91 (2003) 072304
PHOBOS: PRL 91 (2003) 072302
BRAHMS: PRL 91 (2003) 072303

QGP discovery: combined efforts of RHIC's Collaborations

- "Missing" particle yields in central AuAu collisions: evidence for strongly interacting medium
- Evidence of **non**-quenching (the effect vanishes in cold nuclear matter) was equally important to claim the discovery!

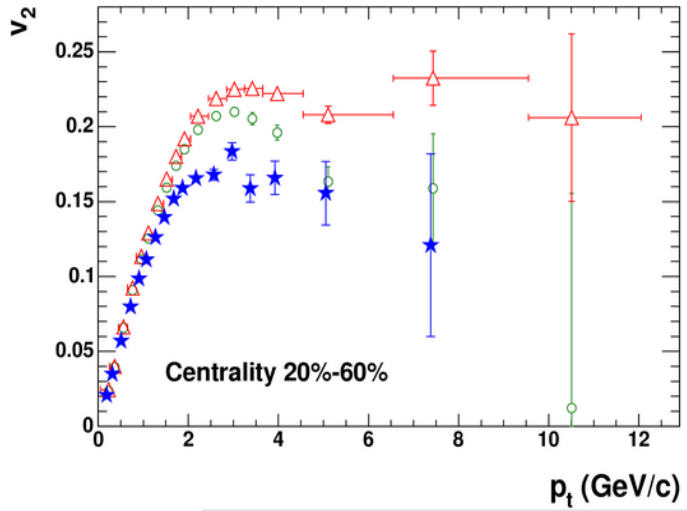
PROBING PATH-LENGTH EFFECTS

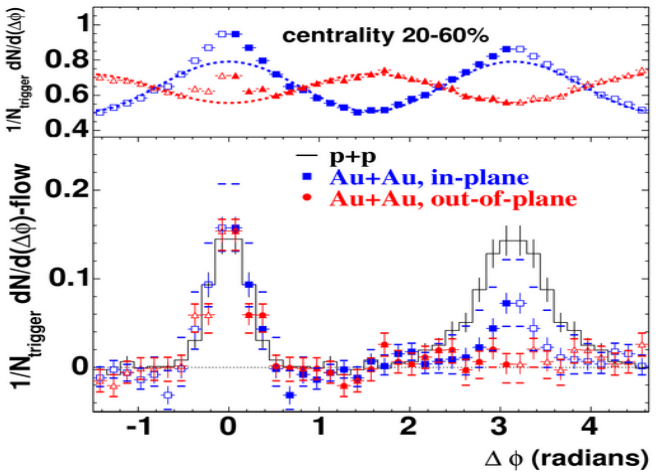
- Explosion of jet-like correlations!

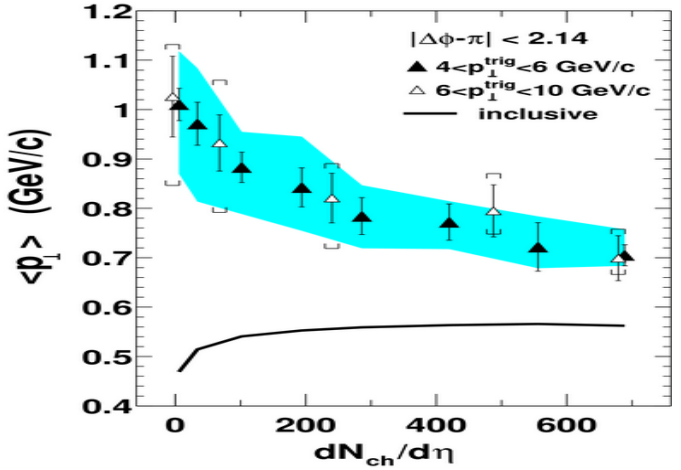
  High-p_T charged hadron v_2 from multi-particle correlations

  Stronger suppression of the back-to-back high-p_T yields for out- vs. in-plane triggers

  Centrality-dependent "softening" of associate hadron p_T distributions







Kirill Filimonov, Vitaly Okorokov, Raimond Snellings, Aihong Tang, Sergei Voloshin

PRL **93** (2004) 252301
Dec. 15, 2004

Olga Barannikova, Tim Herston, Fuqiang Wang, Aihong Tang

PRL **95** (2005) 152301
Oct. 6, 2005

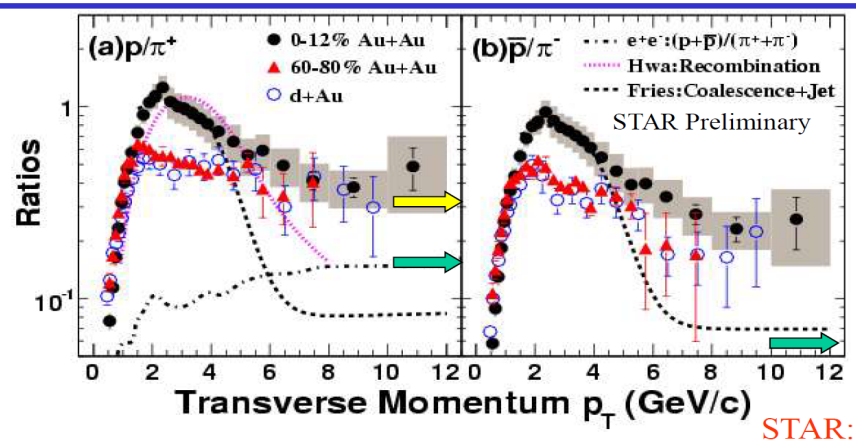
PROBING COLOR-CHARGE EFFECTS

- High p_T:
  $R_{AA}(p) \sim R_{AA}(\pi)$
  $p/\pi^+, \bar{p}/\pi^-, \bar{p}/p$ from central AuAu ~ pp and dAu
- Similar fragmentation patterns AA and pp
- No evidence for the q/g energy loss differences

PRL 97 (2006) 152301
June 6, 2006

Olga Barannikova, Haidong Liu, Lijuan Ruan, Zhangbu Xu

Proton over pion ratios



STAR: nucl-ex/0606003

At p_T>5 GeV/c at RHIC at 200 GeV:

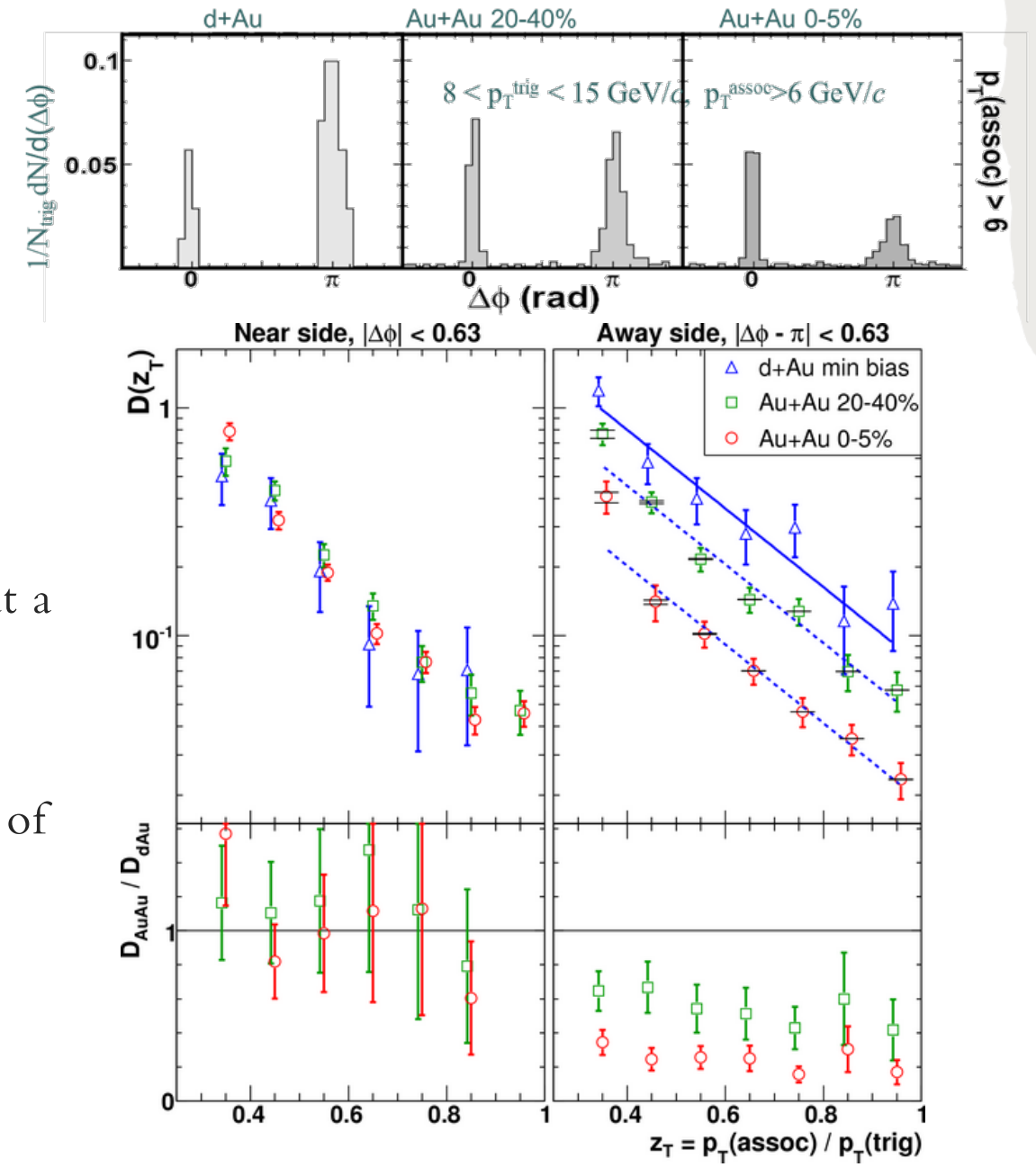
1. **p(pbar)/π are larger than the ratios from quark jet.** ***→ gluon jet plays a dominant role for protons production at RHIC.***
2. **p(pbar)/π (Au+Au) ~ p(pbar)/π (d+Au, p+p). No centrality dependence of p(pbar)/π ratios.** ***→No clear color charge dependence of energy loss.***
3. **We expect pbar/π (Au+Au) < pbar/π (d+Au, p+p).** **(X.N. Wang, PRC 58 (2321) 1998)**

R.J. Fries, et al., PRL 90 202303 (2003); R. C. Hwa, et al., PRC 70, 024905 (2004); DELPHI Collaboration, Eur. Phy. J. C 5, 585 (1998), Eur. Phy. J. C 17, 207 (2000).

06/14/2006 Hard Probes 2006, Lijuan Ruan 11

ARE THERE JETS?

- Direct observation of dijets in central AuAu collisions at 200 GeV:
- Reemergence on a back-to-back dijet peak (at a suppressed rate ~ R_{AA})
- Near and away sides: little to no modification of the away-sided azimuthal and p_T distributions



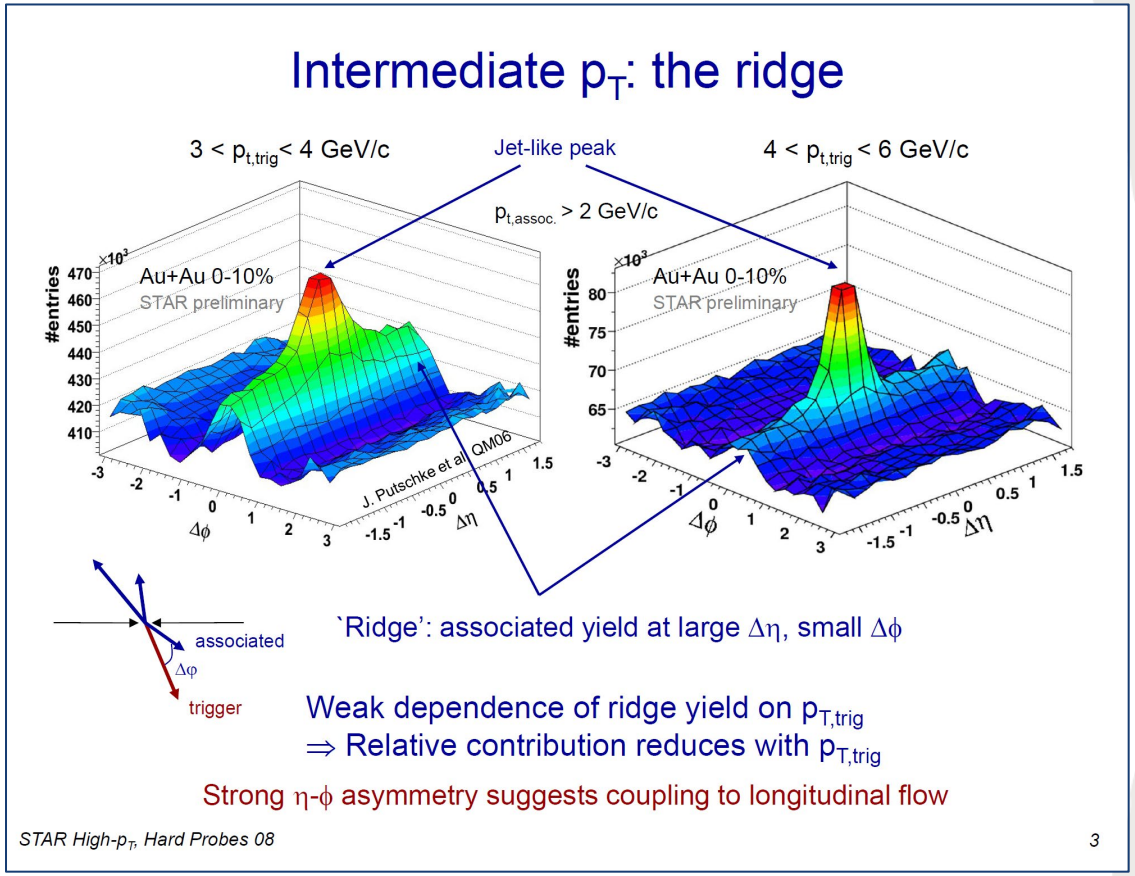
Peter Jacobs, Dan Magestro

PRL 97 (2006) 162301

THE RIDGE

Marco van Leeuwen,
for the STAR collaboration

- Long-range rapidity correlations and jet production in high-energy nuclear collisions.
- Previously unseen feature, many theoretical proposals:
  - coupling of induced gluon radiation to the longitudinal flow of bulk matter
  - coupling of radiation to transverse chromo-magnetic fields
  - elastic scattering of the jet in the flowing medium
  - medium heating by a jet
  - CGC
  - ...



PRC **80** (2009) 64912
Dec. 29, 2009

Joern Putschke, Oana Catu, Marco van Leeuwen, Peter Jacobs

ACT I: RECAP

Early 2000s, Initial evidence for jet quenching:

- Inclusive Hadron Suppression: significant suppression in high-p_T hadron yields in central AuAu collisions compared to the scaled pp reference
- Correlations: away-side suppression of back-to-back correlations at high-p_T, excess near-side yields at low p_T, similar fragmentation patterns, no hints of q/g suppression differences, path-length dependence of suppression, ridge, Mach-cone searches

Act II: The Jet Era →

IN THE MEANTIME:

- The ColdQCD/Spin collaborators of STAR were already doing physics with "real" jets:

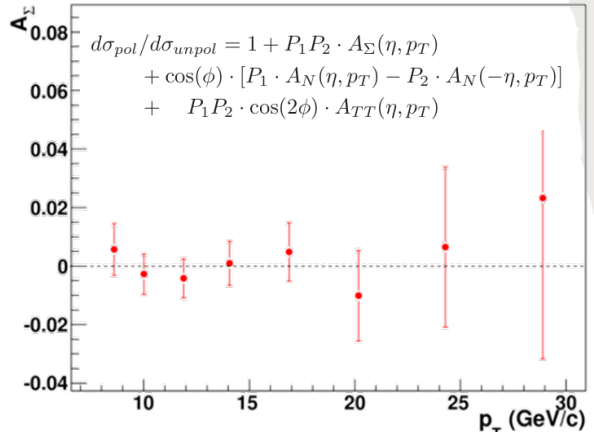
  - Longitudinal Double-Spin Asymmetry and Cross Section for Inclusive Jet Production in Polarized Proton Collisions at 200 GeV (PRL 97 (2006) 252001)

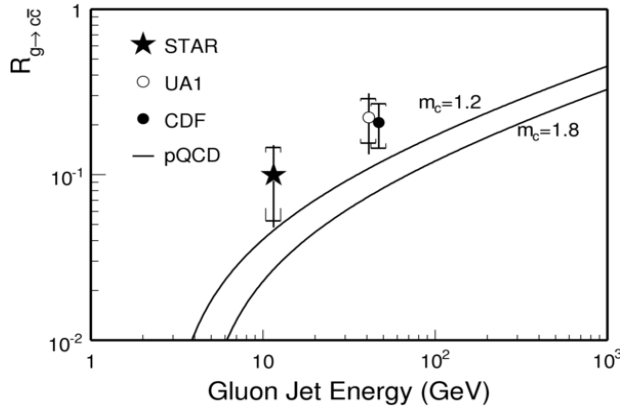
  - Measurement of Transverse Single-Spin Asymmetries for Di-Jet Production in Proton-Proton Collisions at 200 GeV (PRL 99 (2007) 142003)

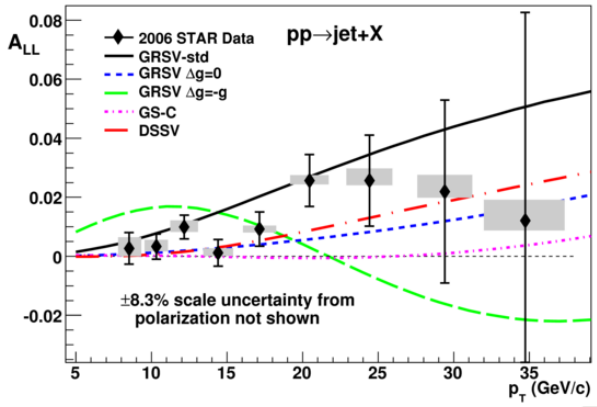
  - Longitudinal double-spin asymmetry for inclusive jet production in polarized pp collisions at 200 GeV (PRL 100 (2008) 232003)

  - Measurement of D* Mesons in Jets from pp Collisions at 200 GeV (PRD 79 (2009) 112006)

  - Longitudinal and transverse spin asymmetries for inclusive jet production at mid-rapidity in polarized pp collisions at 200 GeV (PRD 86 (2012) 32006)

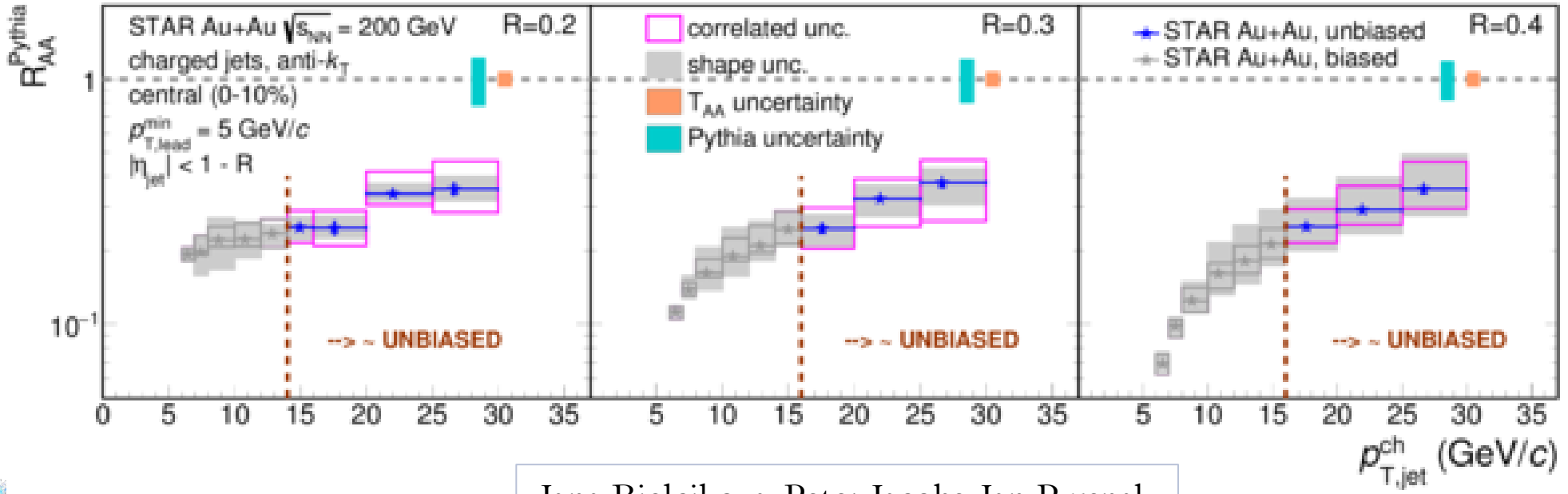






INCLUSIVE JET PRODUCTION

- Anti-k_T charged particle jets, various R
- Inclusive jet R_{AA}: suppression observed in abundancies of the fully-reconstructed jets



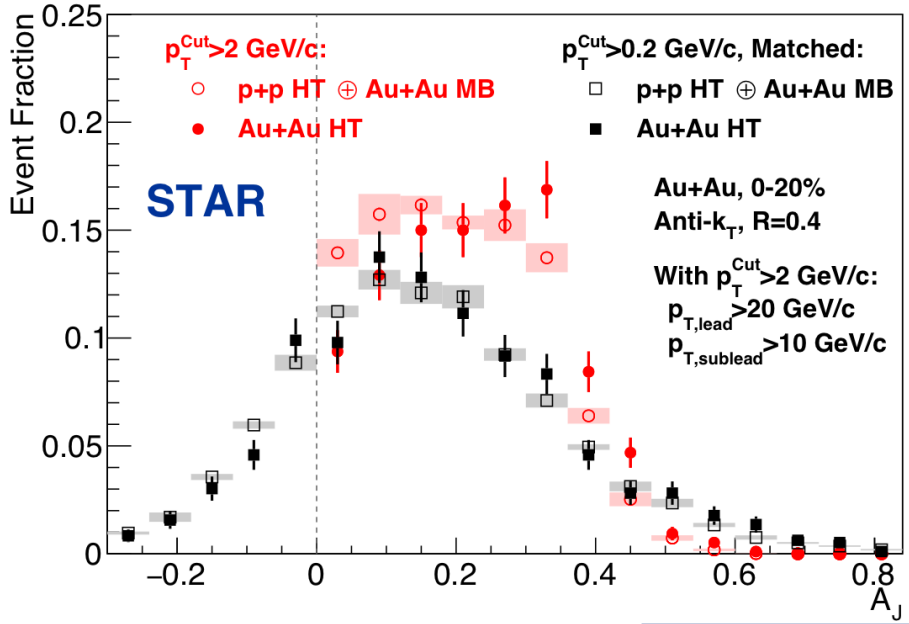
Jana Bielcikova, Peter Jacobs, Jan Rusnak

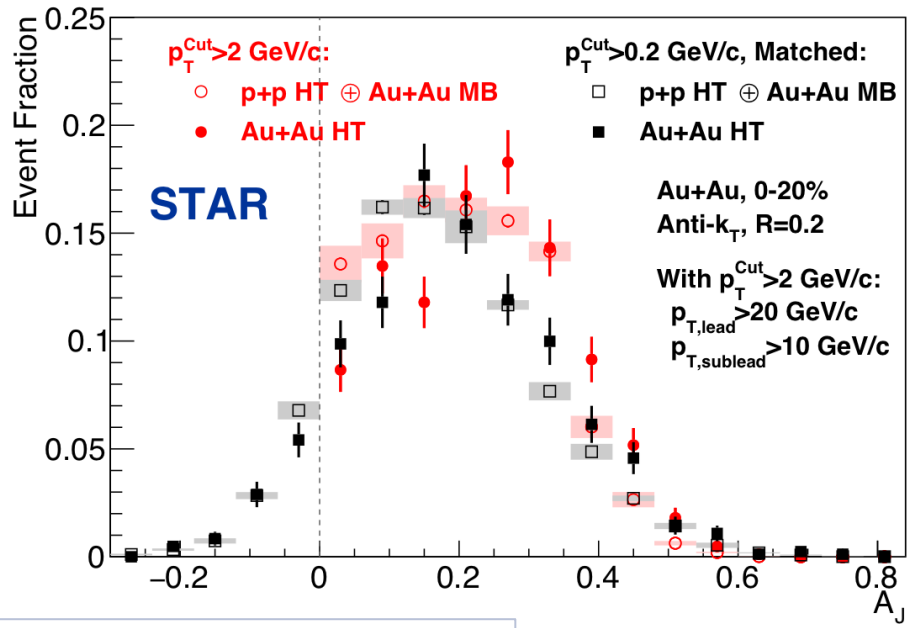
PRC **102** (2020) 54913
Nov. 30, 2020

FIRST DIJET ASYMMETRY AT RHIC

- Anti-k_T R=0.4, 0.2 dijets with hard cores:
  Increased imbalance in AuAu vs pp for 2GeV+ constituents
  Balance is ~ restored for constituents of 0.2GeV+
- Unique at RHIC:
  Lost energy recovered in the soft fragments in the cone of 0.4, but not 0.2

PRL **119** (2017) 62301
August 10, 2017





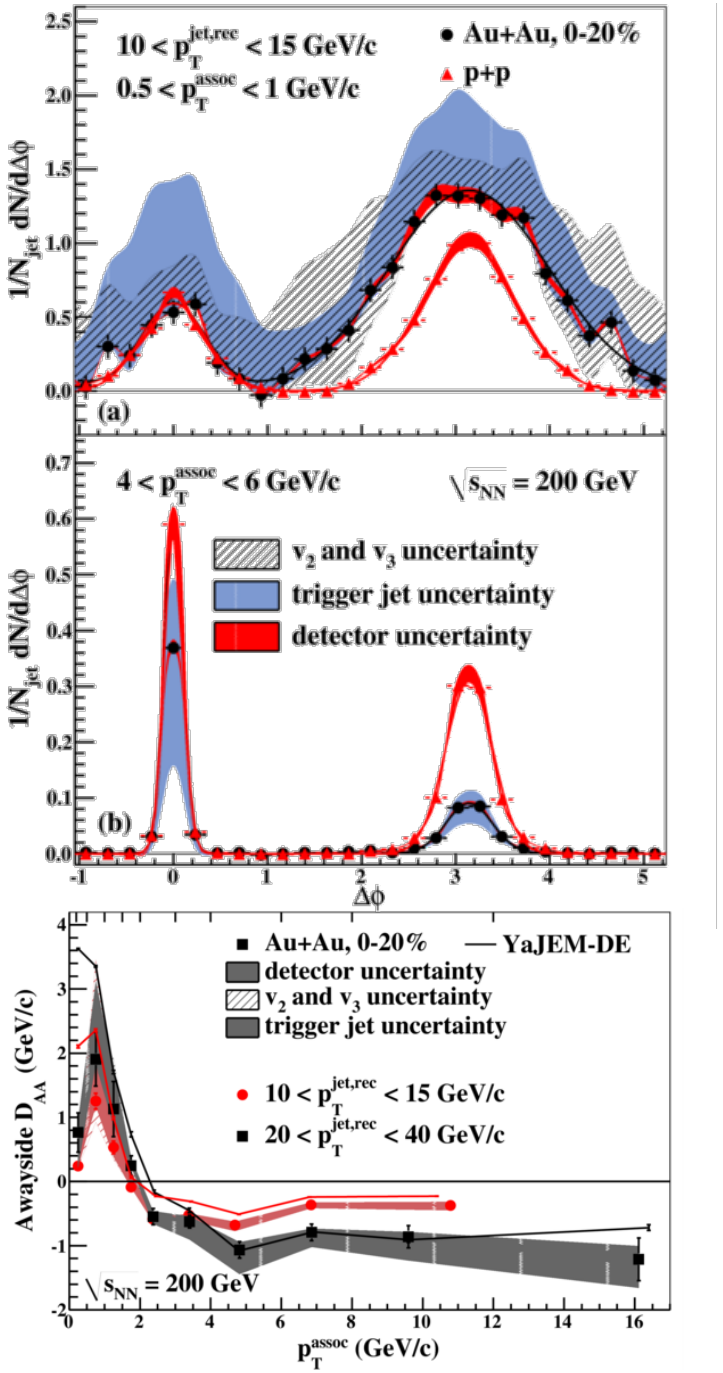
Joern Putschke, Helen Caines, Kolja Kauder

JET + HADRON

- Full jet reconstruction: anti-k_T R=0.4 jets from charged tracks and BEMC towers above 2 GeV
- Jet-hadron correlations in 200 GeV pp and AuAu, away-side energy balance:

  Suppression of high-p_T hadrons is ~ balanced by low-p_T enhancement

$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$



PRL **112** (2014) 122301
February 7, 2014

Alice Ohlson, Joern Putschke

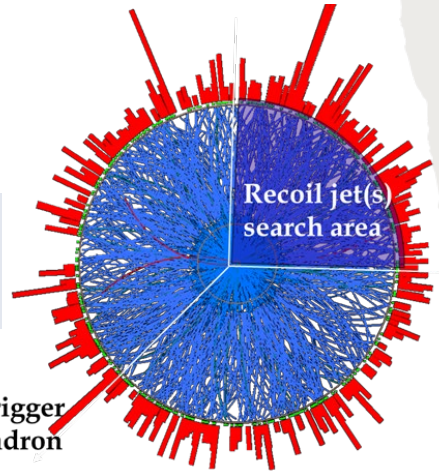
HADRON + JET

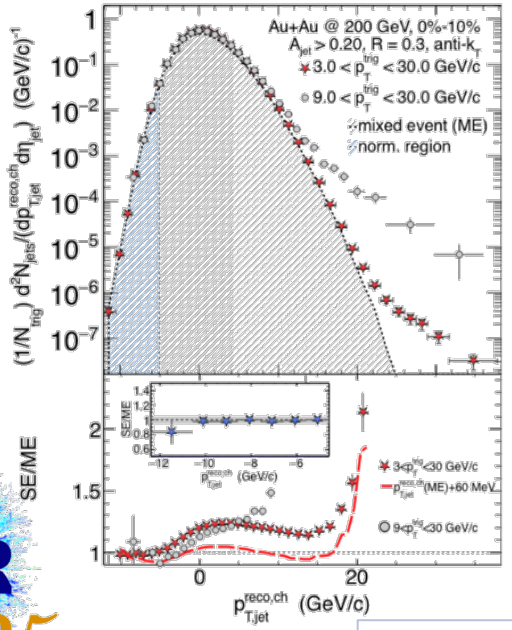
High p_T trigger hadron → hard process with surface bias

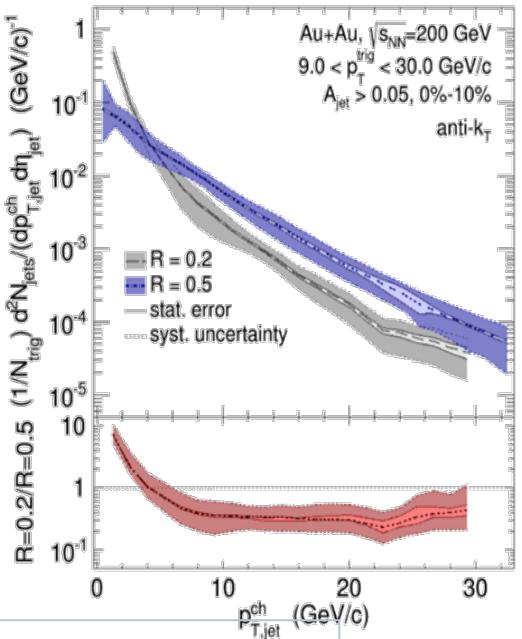
Recoil jets → no fragmentation bias on the away side!

Sophisticated treatment of combinatorial background

PRC **96** (2017) 24905
Aug. 14, 2017







Peter Jacobs, Alex Schmah

- Similar jet yield suppression for all R
- No evidence for large-angle in-medium jet scattering →
- First quantitative limit on Moliere scattering in AA collisions at RHIC

ACT II: RECAP

Jet quenching with jets:

- Significant suppression of jet yields in inclusive and semi-inclusive measurements
- Softening of recoil jets; unchanged hard part, consistency between coincidence and correlation measurements
- Emerging understanding/ control over fragmentation biases
- Input for radiative vs. collisional energy loss scenarios

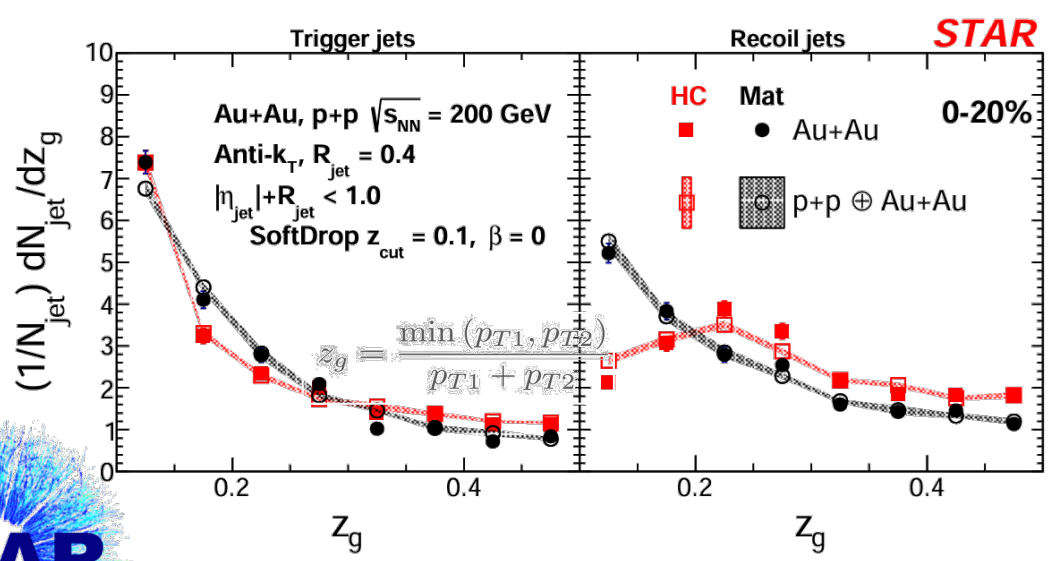
Act III: Precision Era →

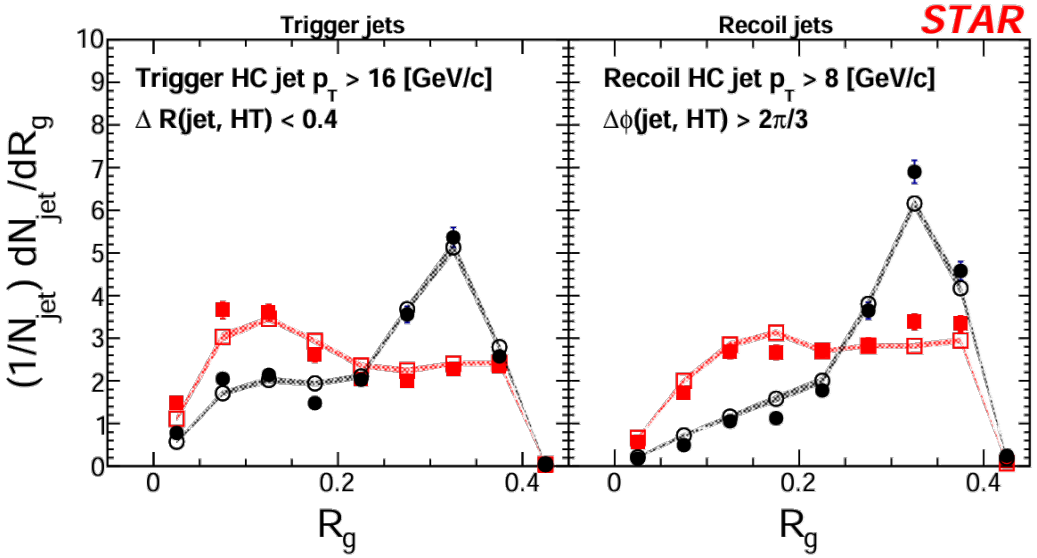
LOOKING INTO THE JETS

PRC **105** (2022) 44906
April 21, 2022

Jets substructure studies with jets:

- First, testing waters in pp (e.g., "*Invariant Jet Mass Measurements in pp Collisions at 200 GeV at RHIC*" and "*Measurement of Two-Point Energy Correlators Within Jets in pp Collisions at 200 GeV,*"…)
- Then, AuAu: Differential measurements of jet substructure and partonic energy loss – probing coherence effects in energy loss

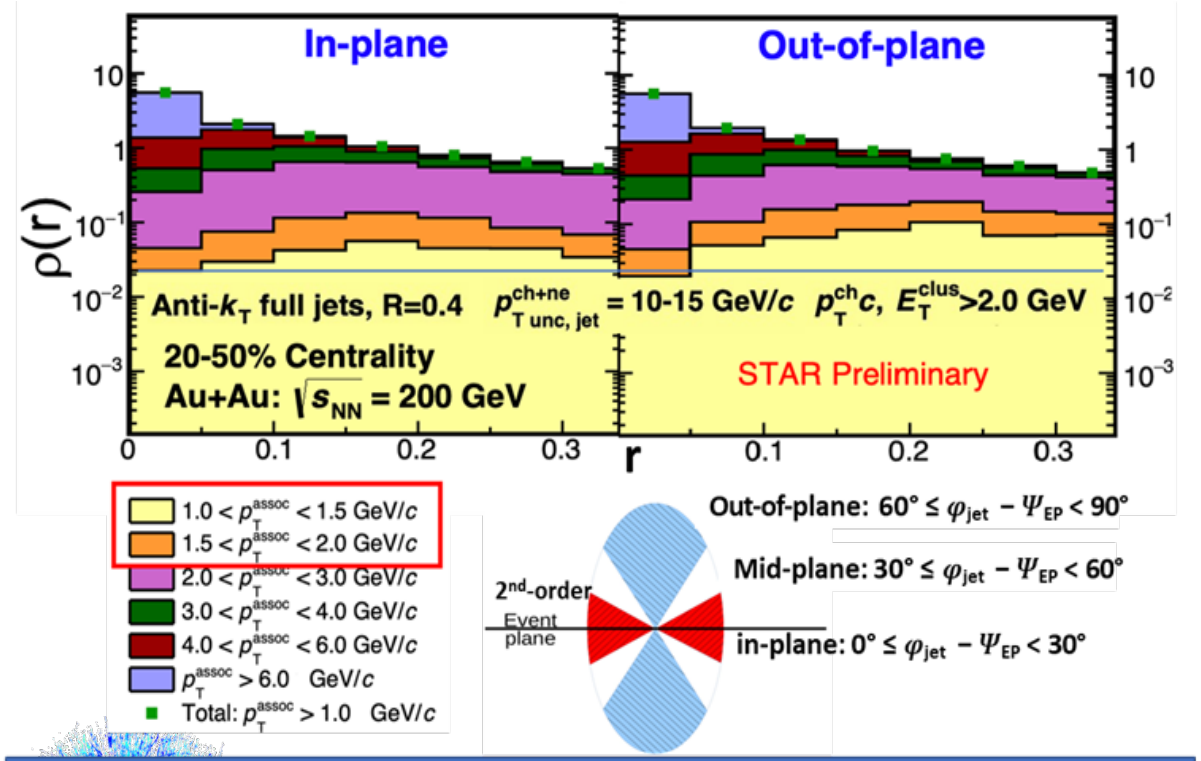




Raghav Kunnawalkam Elayavalli, Joern Putschke, Kolja Kauder

JET SUBSTRUCTURE AT RHIC

Joel Mazer, Tanmay Pani, Sevil Salur

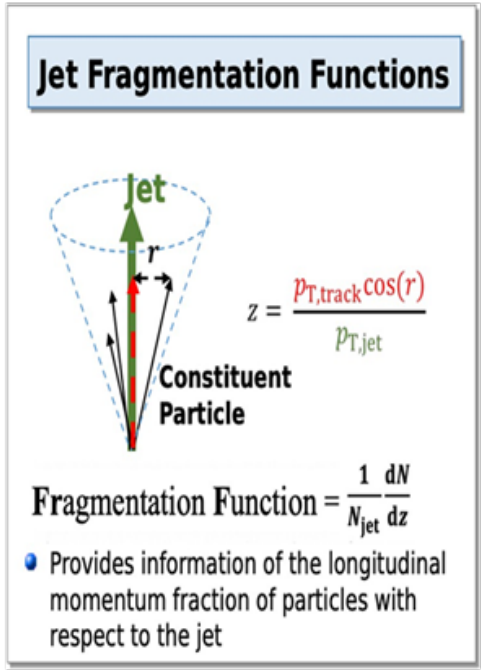


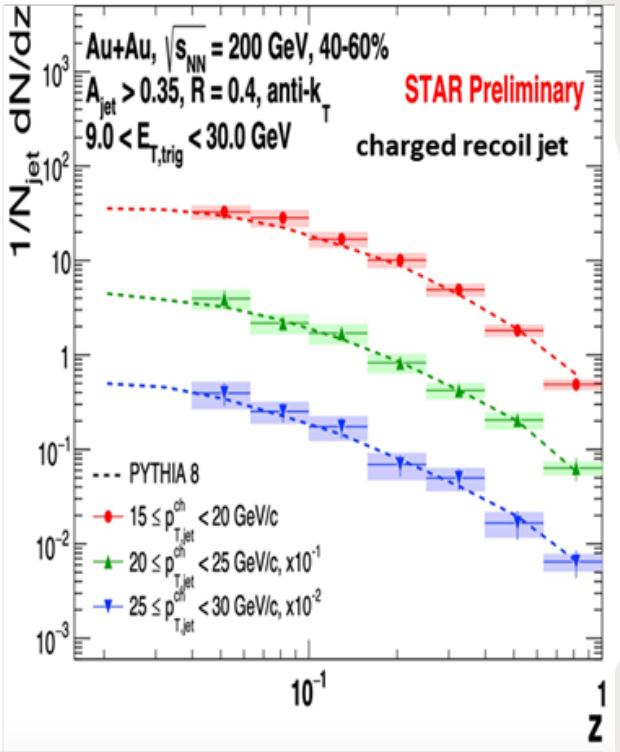
First full-jet (charged+neutral) shapes in Au+Au at RHIC:

- Low-p_T particles have larger yields, and are pushed toward larger r in the out-of-plane direction

→ Hint of path-length dependent jet quenching

Joel Mazer, Sevil Salur





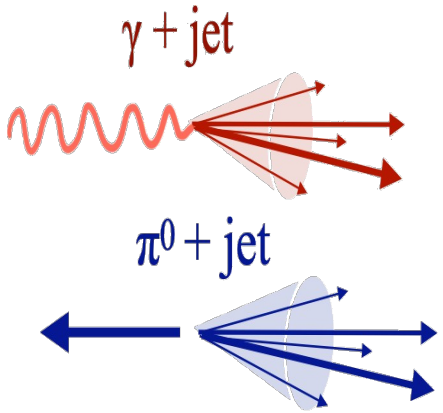
Semi-inclusive jet fragmentation functions between 15 and 30 GeV/c: Unfolded results (40-60%) are comparable to PYTHIA8 predictions

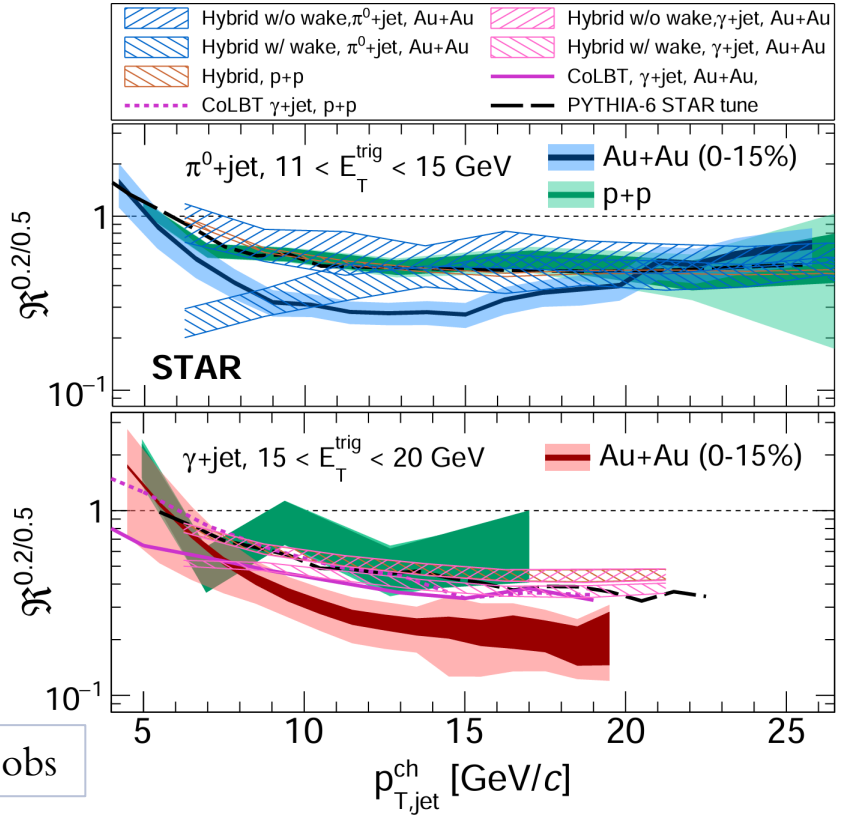
"STANDARD CANDLE" OF QUENCHING

- First: "*Jet-like Correlations with Direct-Photon and Neutral-Pion Triggers at 200GeV*"
- Now: "*Measurement of in-medium jet modification using direct-γ +jet and π^0 +jet correlations in pp and central AuAu collisions at 200 GeV*"
- Vary:

  Parton initiating recoil jets

  Average path length





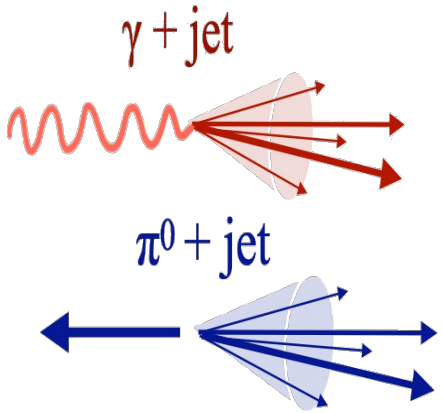
- New constraints on various jet-quenching models

PRL **134** (2025) 232301
June 11, 2025

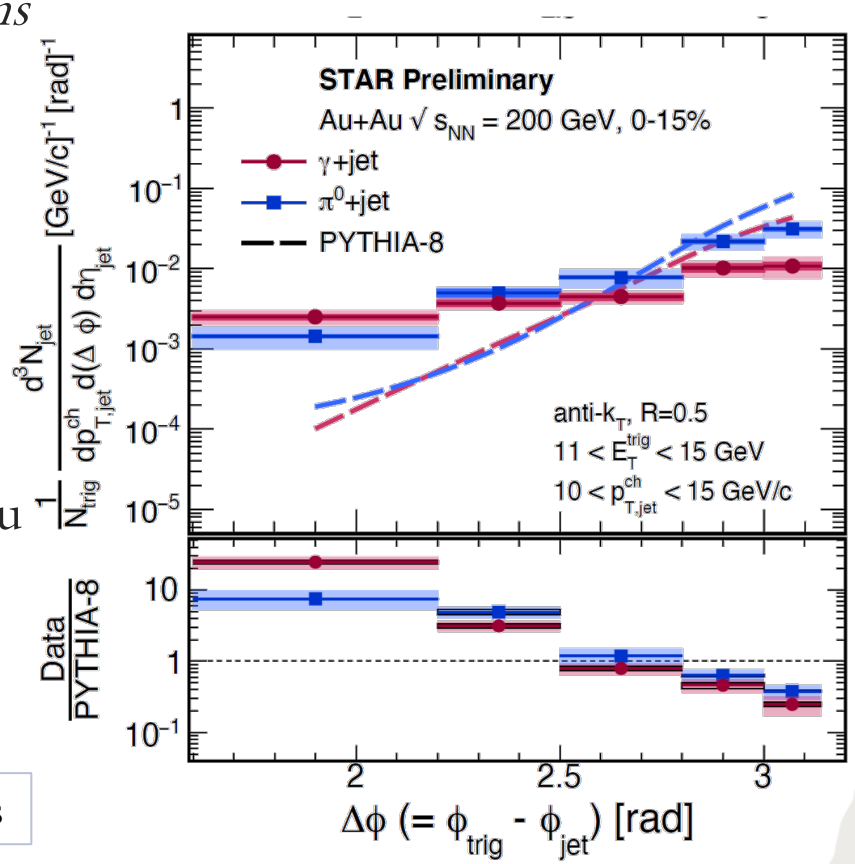
Nihar Sahoo, Derek Anderson, Saskia Mioduszewski, Peter Jacobs

"STANDARD CANDLE" OF QUENCHING

- First: "*Jet-like Correlations with Direct-Photon and Neutral-Pion Triggers at 200GeV*"
- Now: *Measurement of medium-induced acoplanarity in central AuAu and pp collisions at 200 GeV using direct-γ +jet and π^0 +jet correlations*
- Vary:
  - Parton initiating recoil jets
  - Average path length



- Large off-axis jet yield/modified acoplanarity in AuAu
  - Probing constituents of the medium



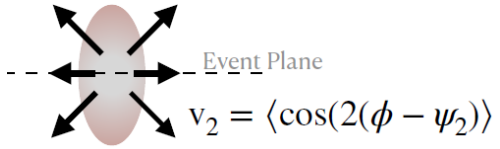
arXiv:2505.05789

Nihar Sahoo, Derek Anderson, Saskia Mioduszewski, Peter Jacobs

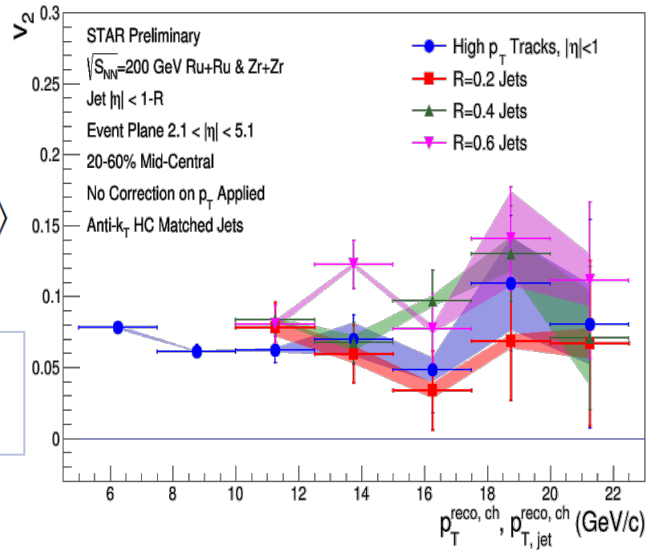
PATH-LENGTH DEPENDENCE WITH JETS

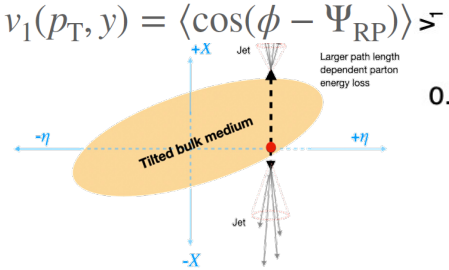
- Jet v_2: 200 Gev isobar data
  - Non-zero v_2 of high-p_T jets
  - Consistent with high-p_T hadrons
  - No radius dependence

- Jet v_1: 200 GeV AuAu data
  - New observable for pathlength-dependence
  - None-zero v_1 for high-p_T jets
  - (Similar for isobar data)

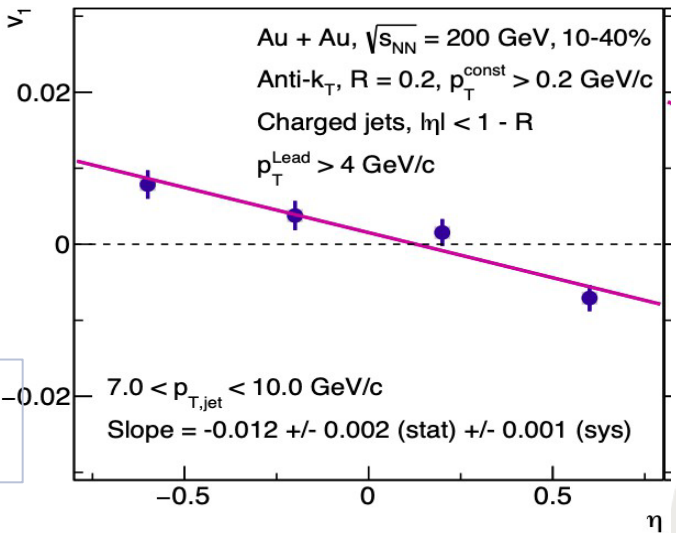


Tristan Protzman
HP2023





Sooraj Radhakrishnan
HP2024



ACT III: RECAP

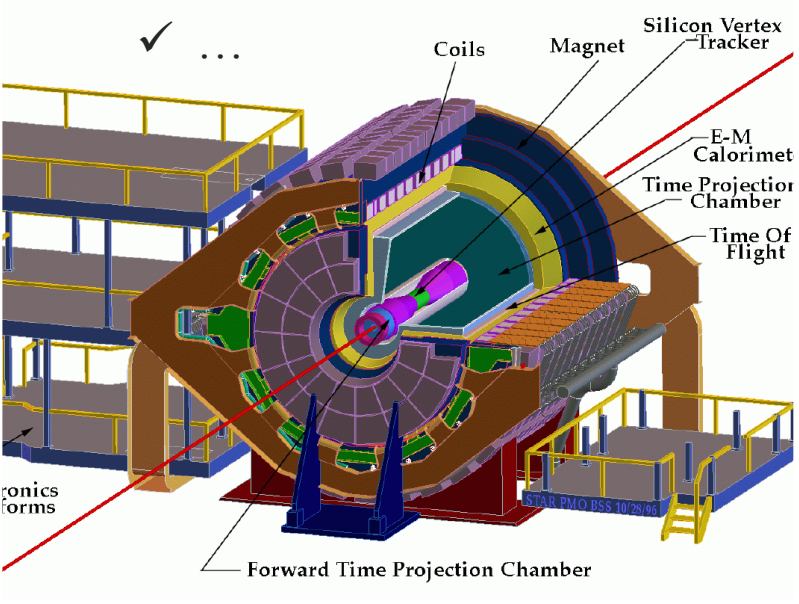
Studies advanced to jet substructure observables and jet-coincidence measurements:

- Jet shapes and Jet fragmentation functions explore energy redistribution with/by the medium: energy "lost" from the jet cone is recovered at larger angles
- Semi-inclusive measurements of jets recoiling from a hard hadron or a photon allow a better/different handle on initial parton energy before it traverses the medium
- Path-length dependence of quenching assessed with jets
- System size dependence: recent OO collision studies show quenching evidence in smaller (symmetric) systems, bridging the gap between pp and heavy ions.

Outlook →

EVOLUTION OF THE STAR DETECTOR

- Continuous investment in detector advancement, adding new/improved capabilities on:
  - ✓ Calorimetry
  - ✓ Particle identification
  - ✓ Vertex reconstruction/identification
  - ✓ Extended tracking coverage
  - ✓ …

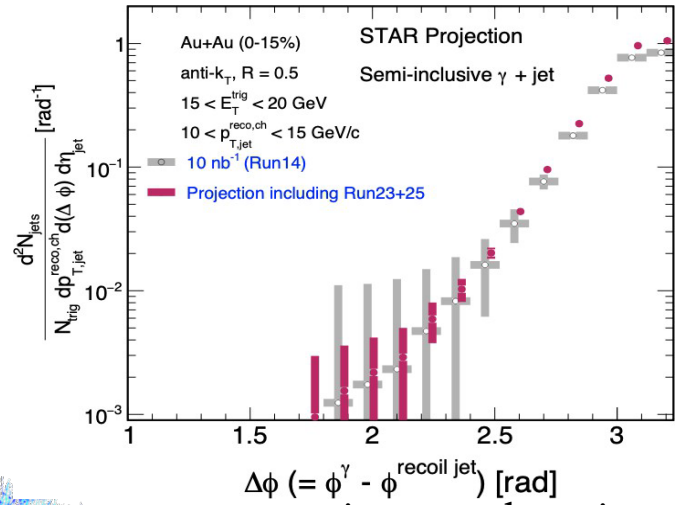


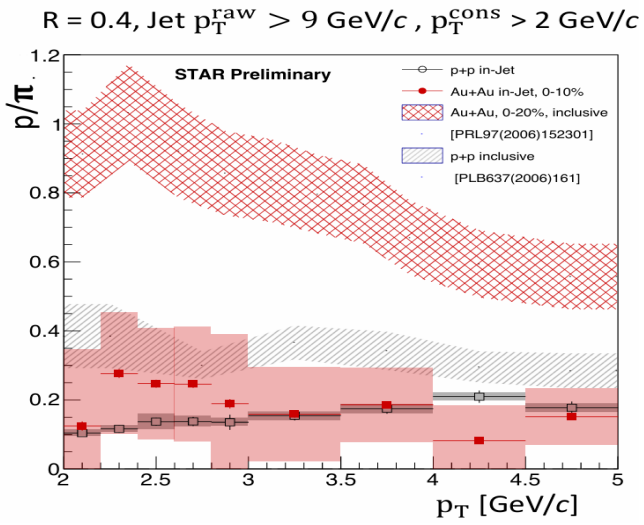
Detector	primary functions	DOE+(in-kind)	year
TPC+Trigger	$\|\eta\|$ <1 Tracking		1999-
Barrel EMC	$\|\eta\|$ <1 jets/γ/π^0/e		2004-
FTPC	forward tracking	(Germany)	2002-2012
L3	Online Display	(Germany)	2000-2012
SVT/SSD	V0/charm	(France)	2004-2007
PMD	forward photons	(India)	2003-2011
EEMC	1< η <2 jets/π^0/e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

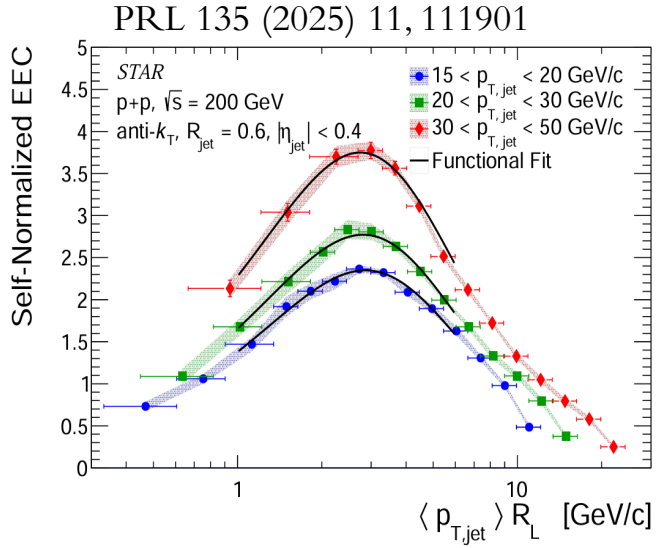
From L. Ruan

FUTURE JET OPPORTUNITIES

- Improved angular and momentum resolution; extended forward coverage – jet quenching studies
- Runs 23+25 factor of ~3 increase in hard probes sample from AuAu (vs. Run 14)







- γ+jet acoplanarity: probing constituents of the medium
- PID-in-jet: in-medium modification of hadronization/fragmentation
- Jet substructure: coherence effects in energy loss
- EEC: locate hadronization transition, separate perturbative/ non-perturbative regimes

OUTLOOK

- RHIC operated phenomenally and now is in its final run before (full-blown) transition to the EIC will begin.
- STAR is the only experiment that is up and running at RHIC from day one to lights-out.
- Through many historical developments discussed at this meeting, STAR has provided compelling, quantitative evidence for the formation of QGP and jet quenching phenomena.
- With its proven track record of creativity and scientific throughput, and the largest AuAu dataset now on tape, STAR has many celebrations to come!

THANK YOU, ALL!

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