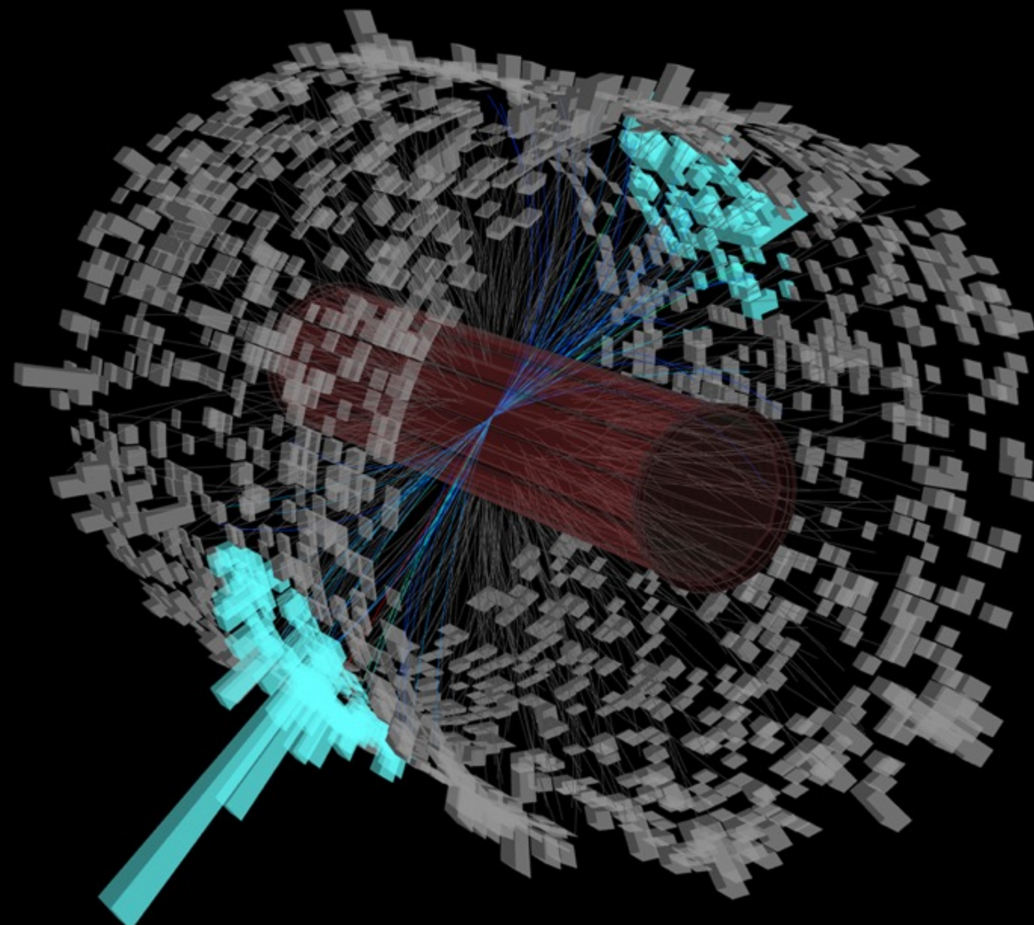
Jet Quenching Dependence on Angularities and Flavor at RHIC

Sevil Salur

for STAR

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY



Supported in part by:

U.S. DEPARTMENT OF ENERGY | Office of Science

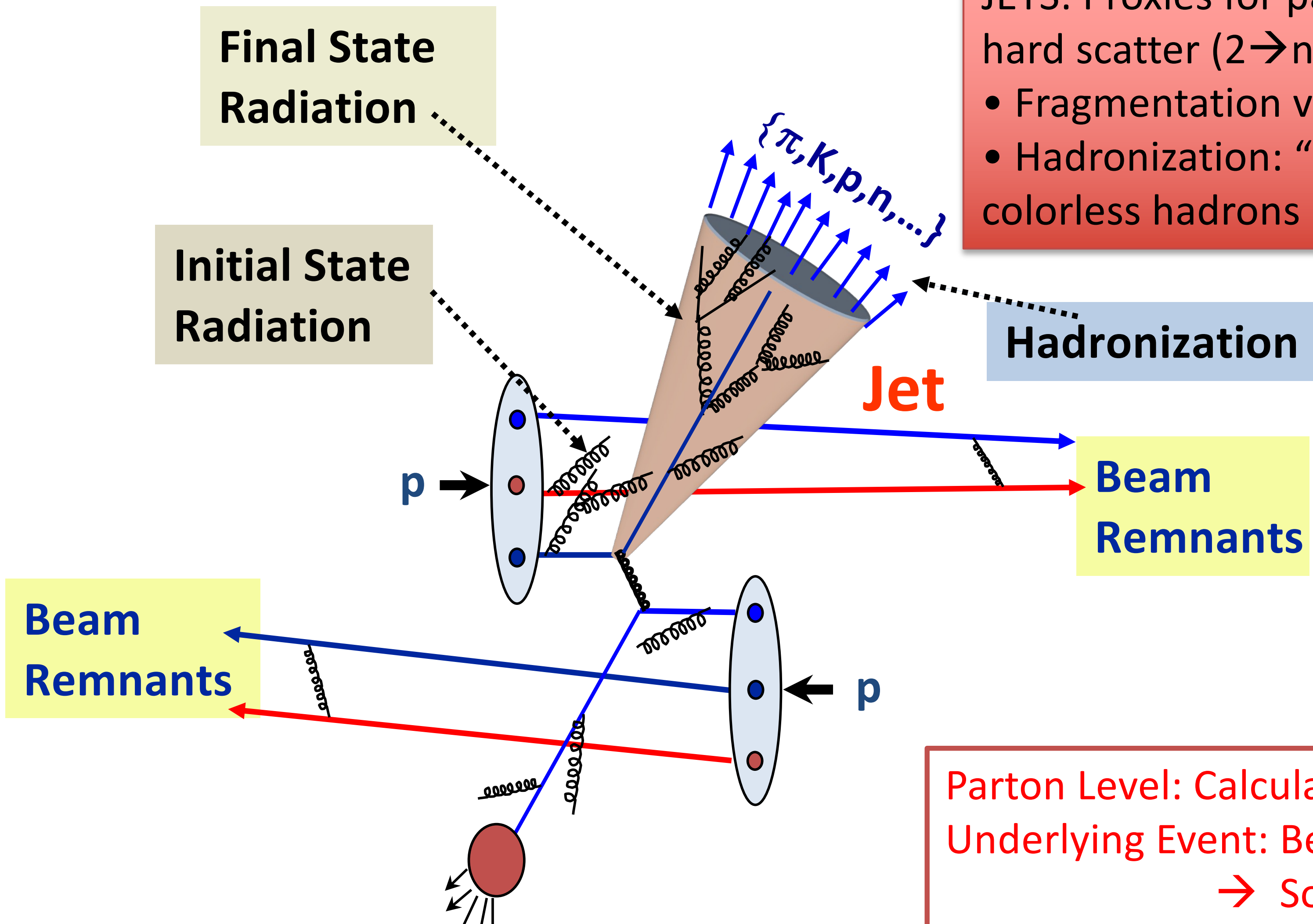
STAR Experiment at the Relativistic Heavy Ion Collider
2014-04-15 09:30:43 EDT
Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV
Run Number / Event ID:15105019 / 204002

The 39th Winter Workshop on Nuclear Dynamics, Feb 11-17, 2024

Jets:

JETS: Proxies for partons from the hard scatter (2→n)

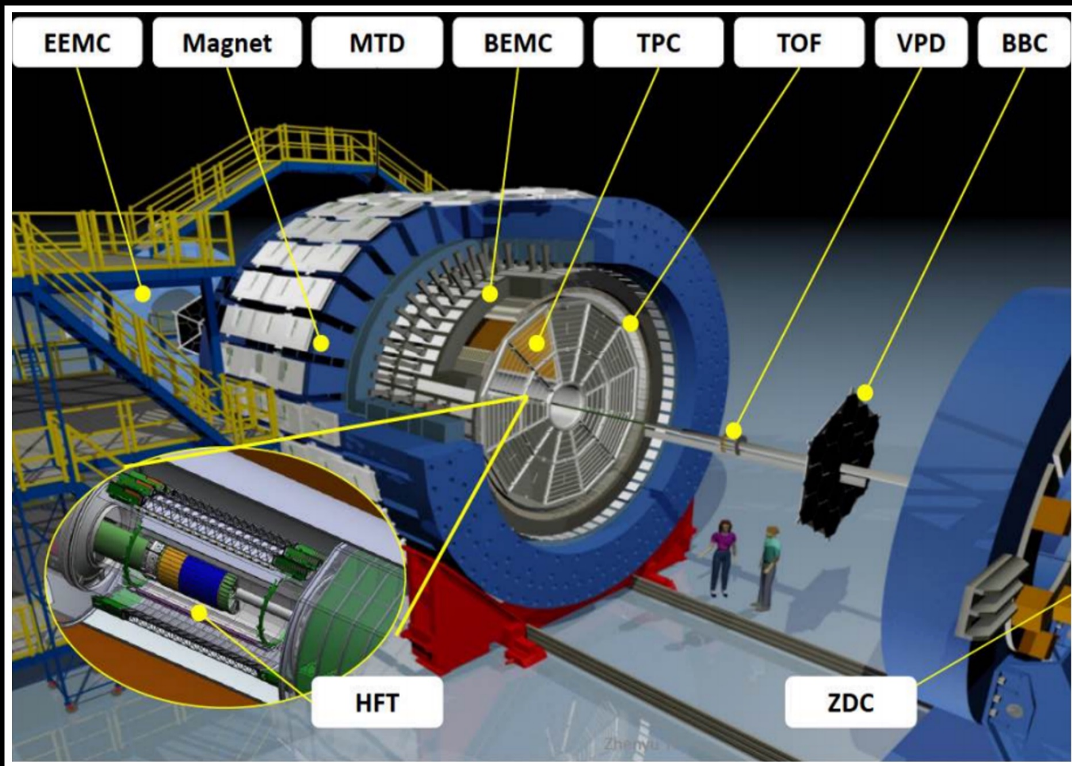
- Fragmentation via gluon radiation
- Hadronization: “spray” of colorless hadrons

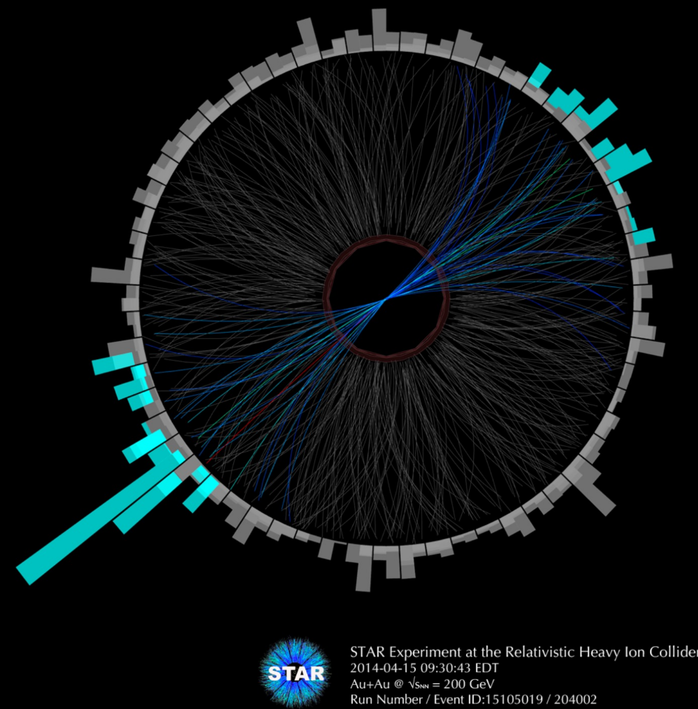


Parton Level: Calculable with pQCD
Underlying Event: Beam remnants
→ Soft Background

S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977)
... and many more

Jets with STAR:

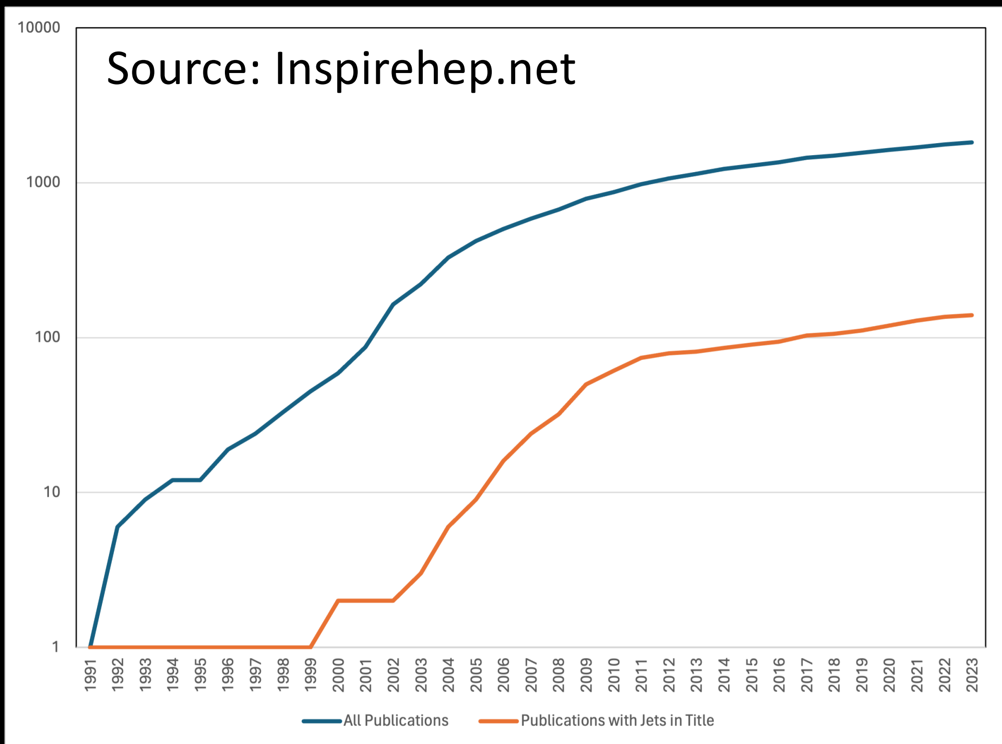




- PID possible through TPC, TOF and MTD
- HFT facilitate precision measurements of particles containing heavy quarks.
- Jet measurements through the clustering of energy deposits using BEMC for neutral particles and the precise momentum of charged tracks measured by inner detectors.

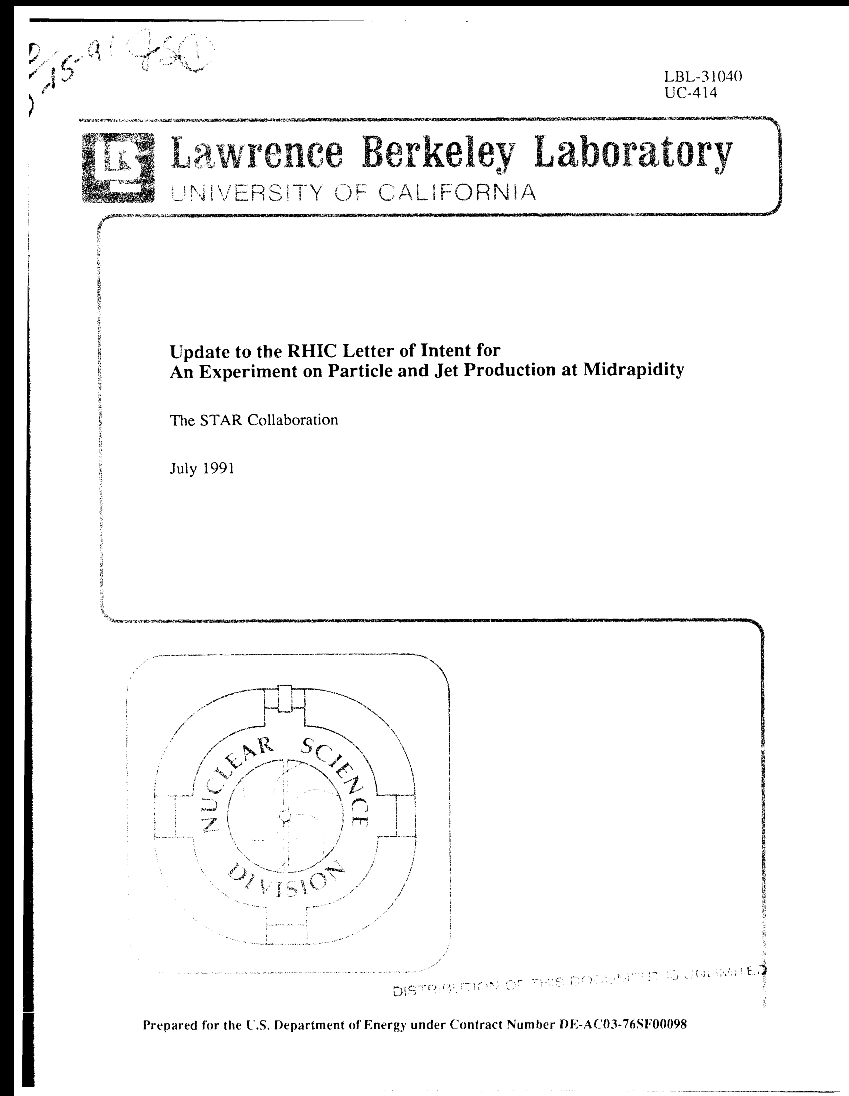
Jets with STAR:

STAR Publications



Years

STAR's vibrant scientific program continues! Publications that utilize jets are steadily growing.



LBL-31040
UC-414

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Update to the RHIC Letter of Intent for
An Experiment on Particle and Jet Production at Midrapidity

The STAR Collaboration

July 1991

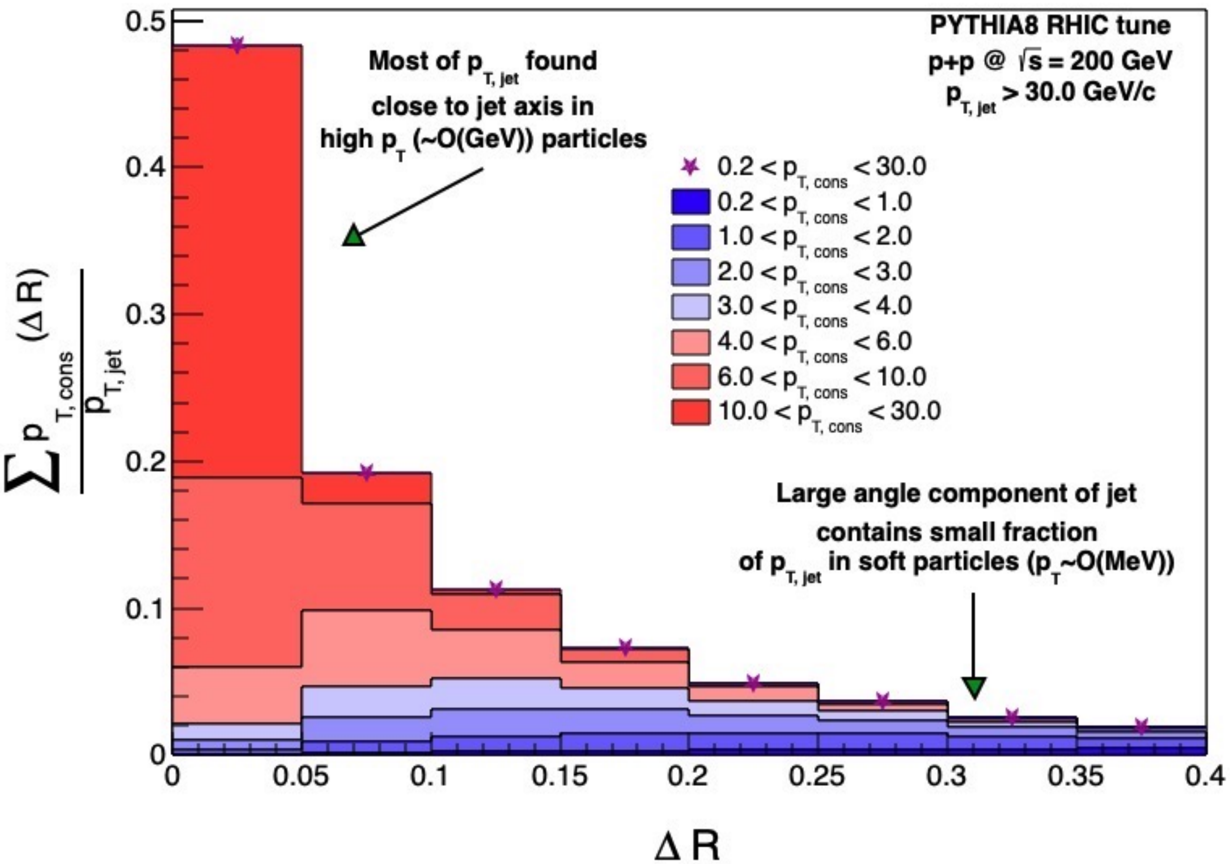
NUCLEAR SCIENCE DIVISION

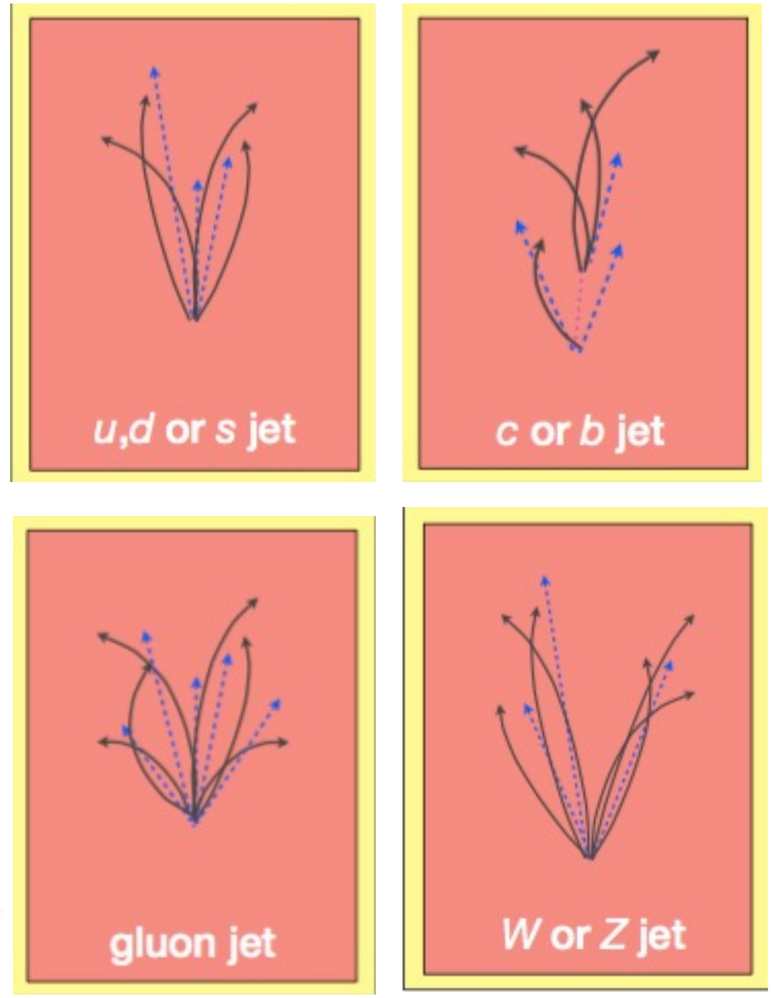
Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

Jet Morphology:

Angular and Momentum Structures

Explore jet inner-workings.





To what extent can the identities of underlying partons be deduced from properties of the jets they produce?

Generalized Angularity

- Jet angularity: a measurement of how spread out or concentrated the energy is
- Tunable to different aspects of jet fragmentation: $\kappa \geq 0$ and $\beta \geq 0$ control the momentum and angular contributions,
- Essential for understanding the internal structure and properties of jet, eg. q vs g

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta,$$

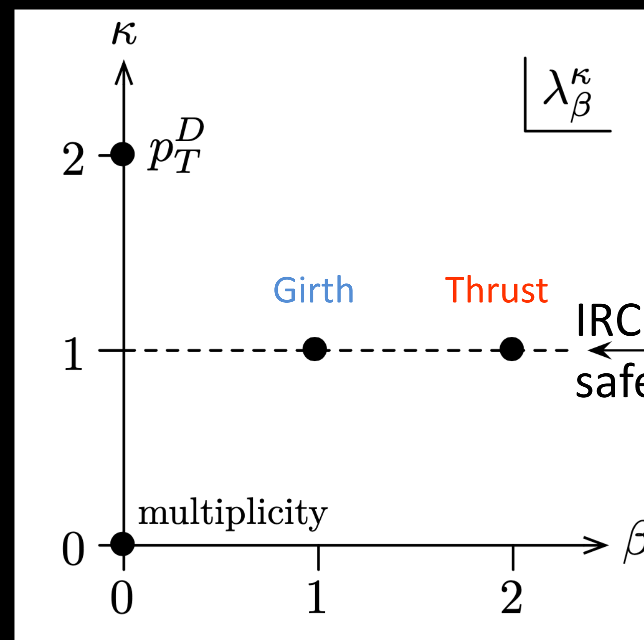
$$\Delta R_i = \sqrt{(\Delta y_i)^2 + (\Delta \phi_i)^2}$$

z_i: fractional p_T of ith jet constituent

Momentum dispersion p_T^D: (Energy Sharing)

$$p_T^D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

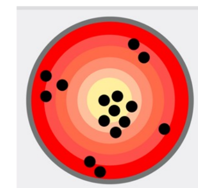
Measures 2nd moment of the constituent p_T distribution in the jet and is connected to how hard or soft the jet fragmentation is.



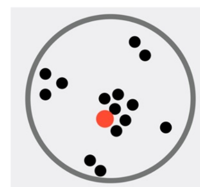
A. Larkoski, J. Thaler, W. J. Waalewijn JHEP11(2014)129

In fact, there are many jet substructure observables:

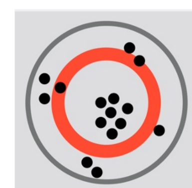
- Jet Mass: $M = \sqrt{E^2 - p_T^2 - p_z^2},$ Measures how spread out the constituents of the jet are.
- Jet Charge: $Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{i \in jet} q_i (p_T^i)^\kappa.$
- *Radial moment – girth (g):* $g = \sum_i \frac{p_{T,i}}{p_{T,jet}} |\Delta R_i|$ *Measures 1st radial moment or angularity and is sensitive to collimation / broadening of a jet*



- *LeSub:* $LeSub = p_{T,track}^{lead} - p_{T,track}^{sublead}$
- *Fragmentation*
- *function (FF):* $FF(z) = \frac{1}{N_{jet}} \frac{dN}{dz}$

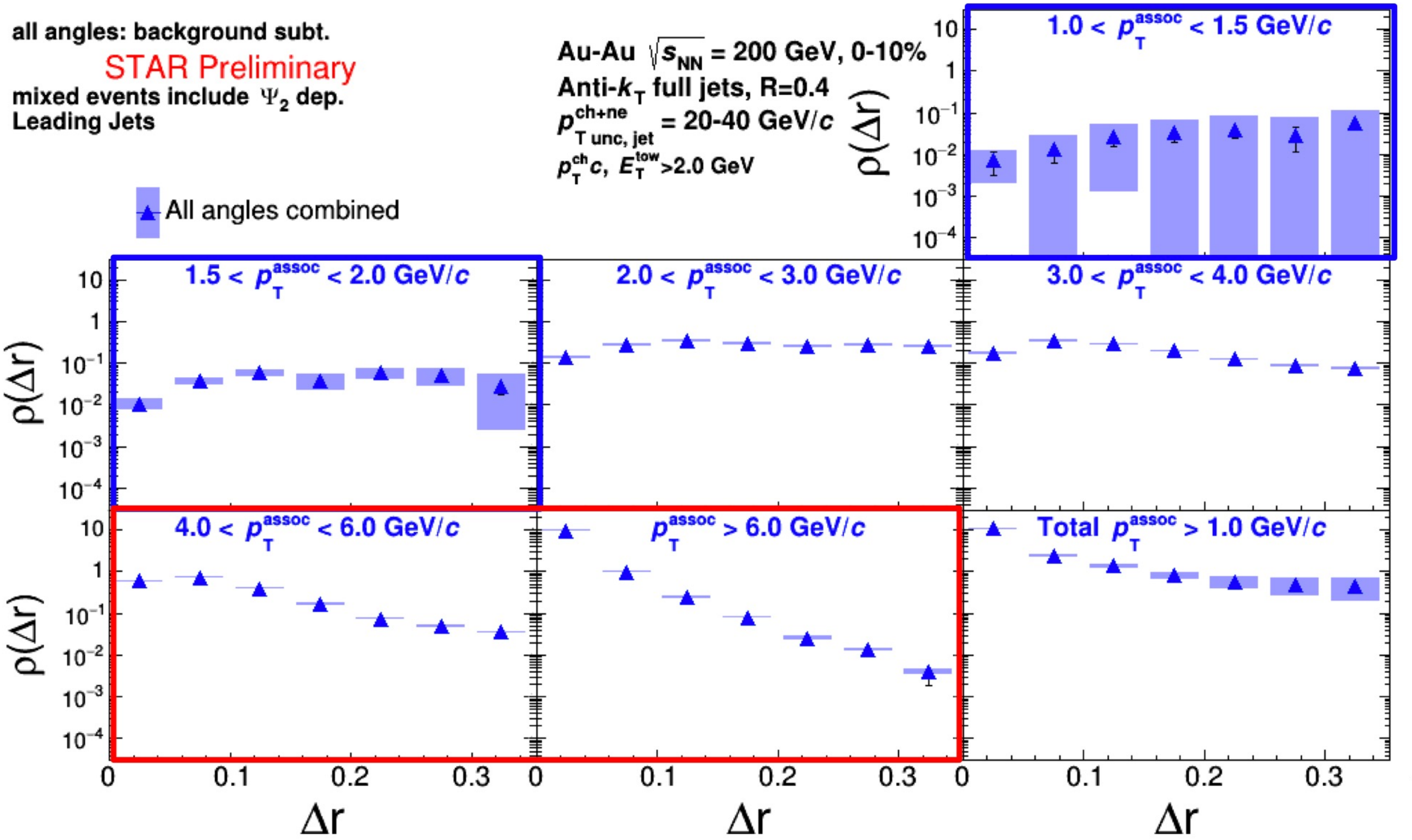


- *Differential jet shape:* $\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \Sigma_{\text{jets}} \frac{\Sigma_{\text{tracks} \in (r_a, r_b)} p_T^{\text{trk}}}{p_T^{\text{jets}}}$



Not an inclusive list but examples of jet substructure measurements that are currently being used as tools to disentangle different kinds of jets and study the effects of QGP.

Jet Shapes:



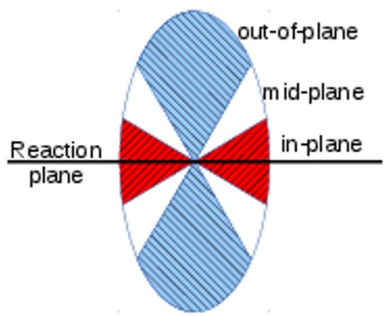
Low-p_T tracks dominated by background
High-p_T tracks located near jet core compared to low-p_T, as expected

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}\, p_{\text{T}}^{\text{trk}}}{p_{\text{T}}^{\text{jets}}}$$

Hadron yields relative to event plane

Control *path-length* of jet quenching with centrality and *event plane angle*

Fix trigger jet relative to the "2nd order" event plane: $\Psi_{EP,2}$



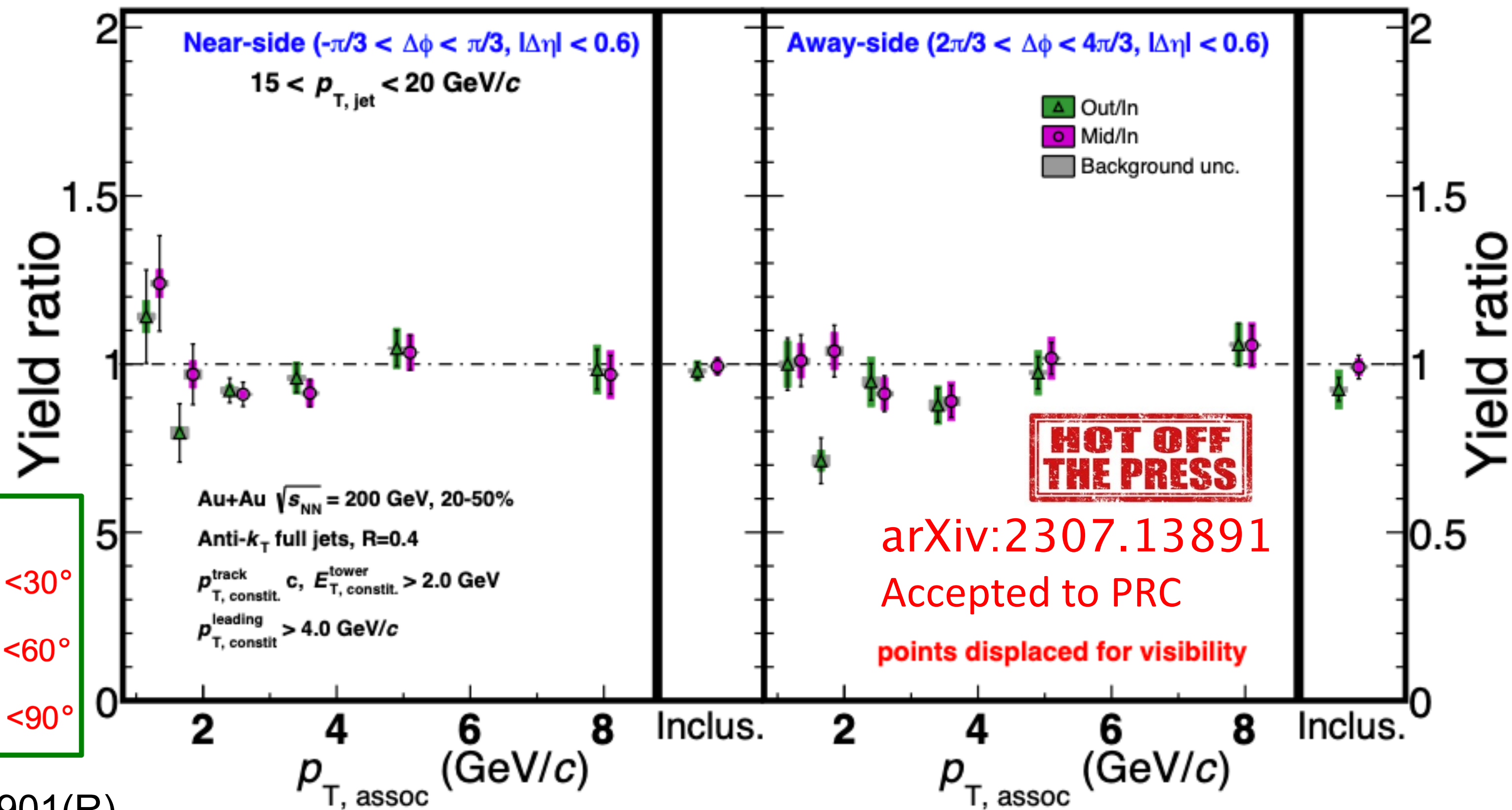
Event plane dependence

IN-plane: $0° < |\varphi_{jet} - \Psi_{EP,2}| < 30°$

MID-plane: $30° < |\varphi_{jet} - \Psi_{EP,2}| < 60°$

OUT-of-plane: $60° < |\varphi_{jet} - \Psi_{EP,2}| < 90°$

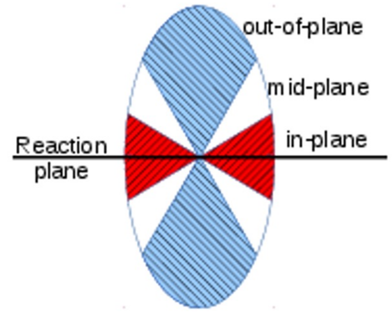
Phys. Rev. C89 (2014) 041901(R)

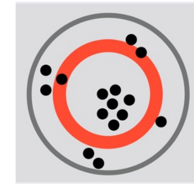


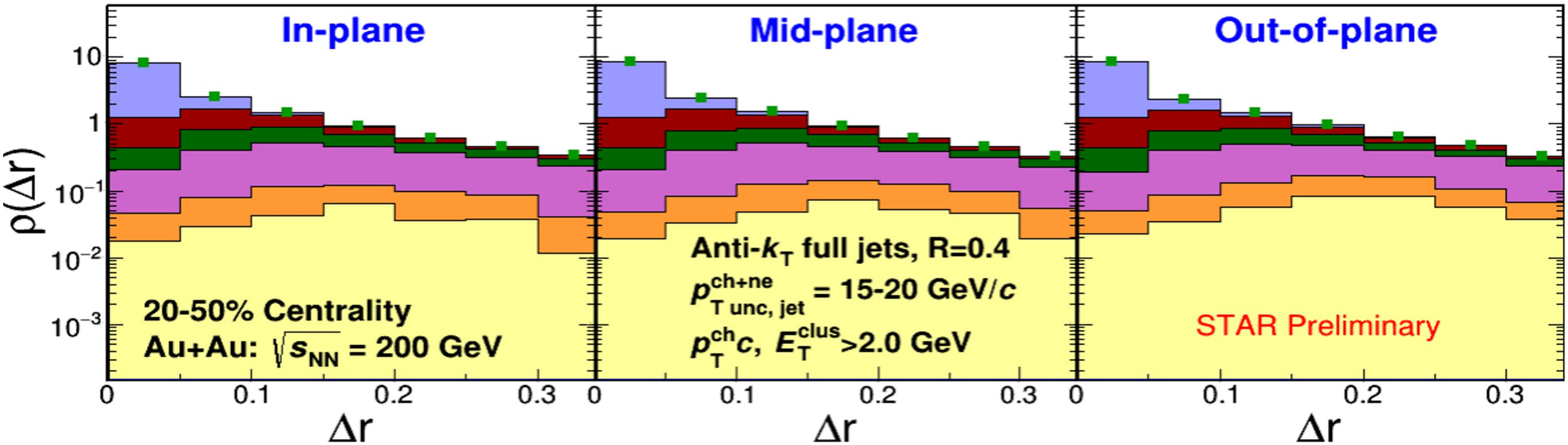
The associated yields show no dependence on the event plane.

Jet shapes relative to event plane

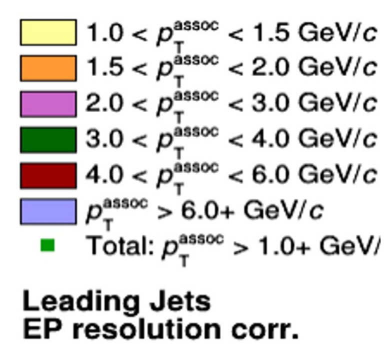
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\rm jets}}\Sigma_{\rm jets}\frac{\Sigma_{{\rm tracks}\in(r_a,r_b)}\, p_{\rm T}^{\rm trk}}{p_{\rm T}^{\rm jets}}$$







- Hints of low-p_T tracks pushed toward farther distances in out-of-plane relative to in-plane
- Above 2 GeV/*c*, results are consistent with each other
- Less steep than @ LHC Energies



CMS, Physics Letters B, Vol 730, (2014) p243-263

STAY TUNED: results for pp and finalized systematics are on their way!

Event Selection for Measurements of Angularities & D^0 Jets:

- Data:

Au+Au @ $\sqrt{s_{NN}}$ = 200GeV (2014)
Minimum Bias & High Tower (HT) triggered events tower with E_{tower} > 4 GeV
(for D0 jets) & (for Inclusive Jets)

- Simulations:

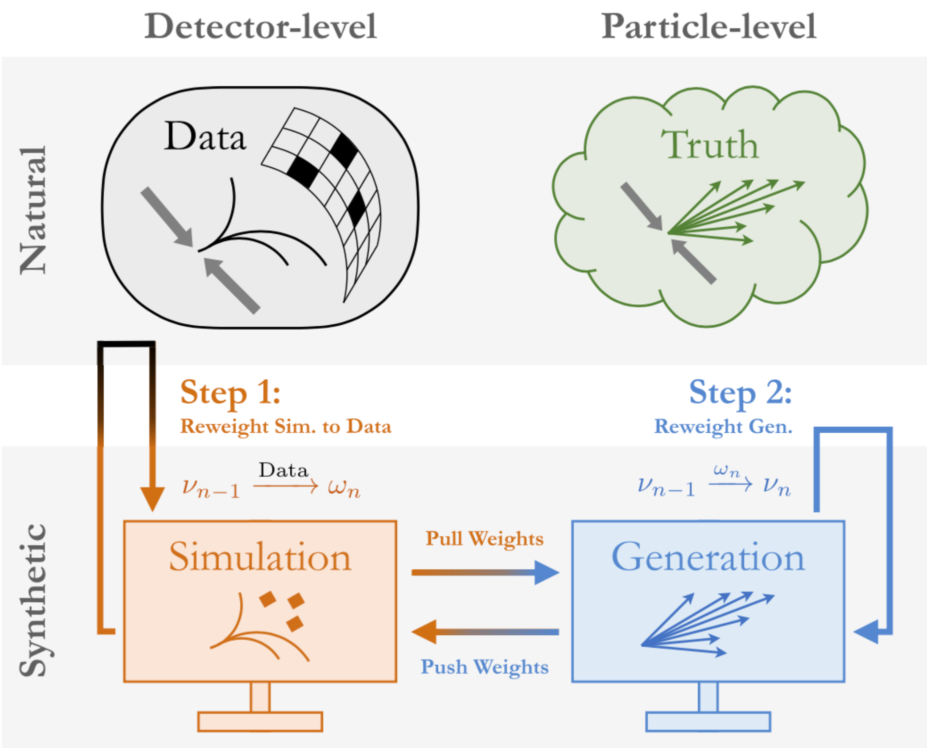
GEN: PYTHIA-6 Perugia-STAR dijet events
RECO: PYTHIA-6 Perugia-STAR + GEANT3 + STAR Au+Au Run14 MinBias

Jet Reconstruction:

M. Cacciari, G. Salam, G. Soyez, JHEP 04 (2008) 06

- TPC tracks & calorimeter energy depositions with the anti-k_T algorithm R = 0.4 (w/ FASTJET)
- Angularities: Hard-core jets i.e., constituents with $p_{T,trk}(E_{T,tower}/c) \geq 2$ GeV/c,
  D^0 jets: constituents with $p_{T,trk}(E_{T,tower}/c) \geq 0.2$ GeV/c
- Jet area > 0.4 to suppress fake jets
- $N_{con,charged} \geq 2$ for non-trivial values of observables

Corrections to experimental data:
(Background and detector effects)



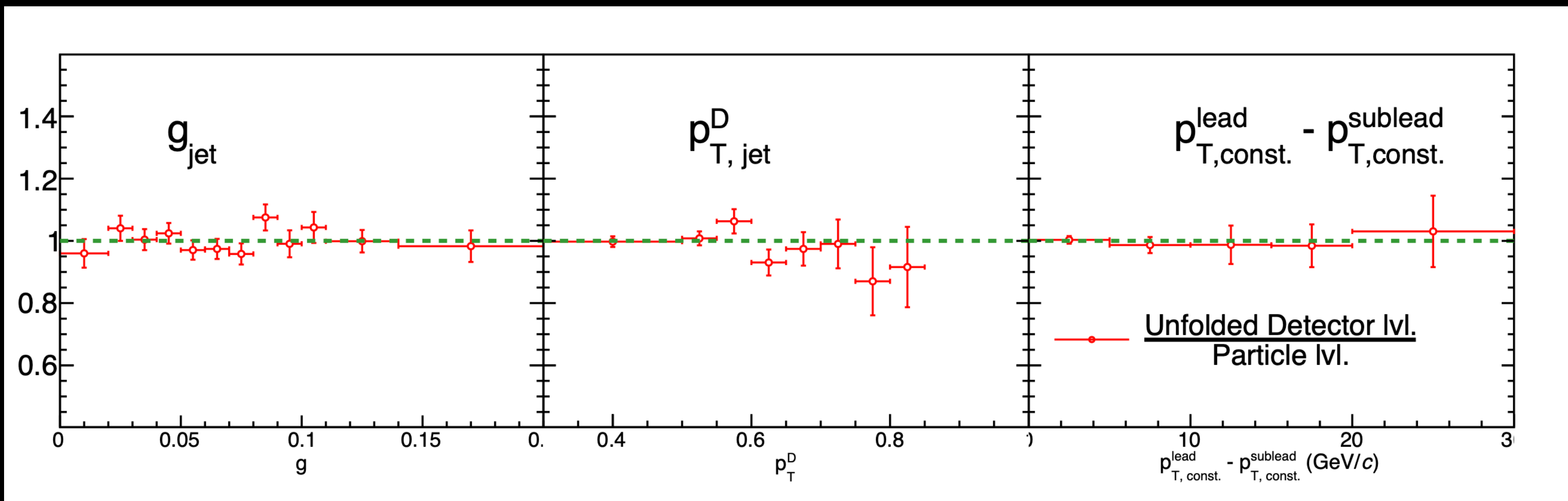
- MultiFold: An unfolding method that iteratively reweights a simulated dataset, using ML.
- Unbinned: Use of arbitrarily high-dimensional data to incorporate information from the full phase space.
- Simultaneously unfolding of $p_{T,jet}$,η_{jet}, ϕ_{jet}, $N_{con,charged}$, p_{TD} , LeSub and Girth

- Multifolding uses Dense Neural Networks (DNNs) trained on full embedding sample at the detector level and the generator level
- DNNs were implemented using Energyflow package

A. Andreassen , P. T. Komiske , E. M. Metodiev , B. Nachman, and J. Thaler, PRL 124, 182001 (2020)

(JHEP 04 (2018) 013)

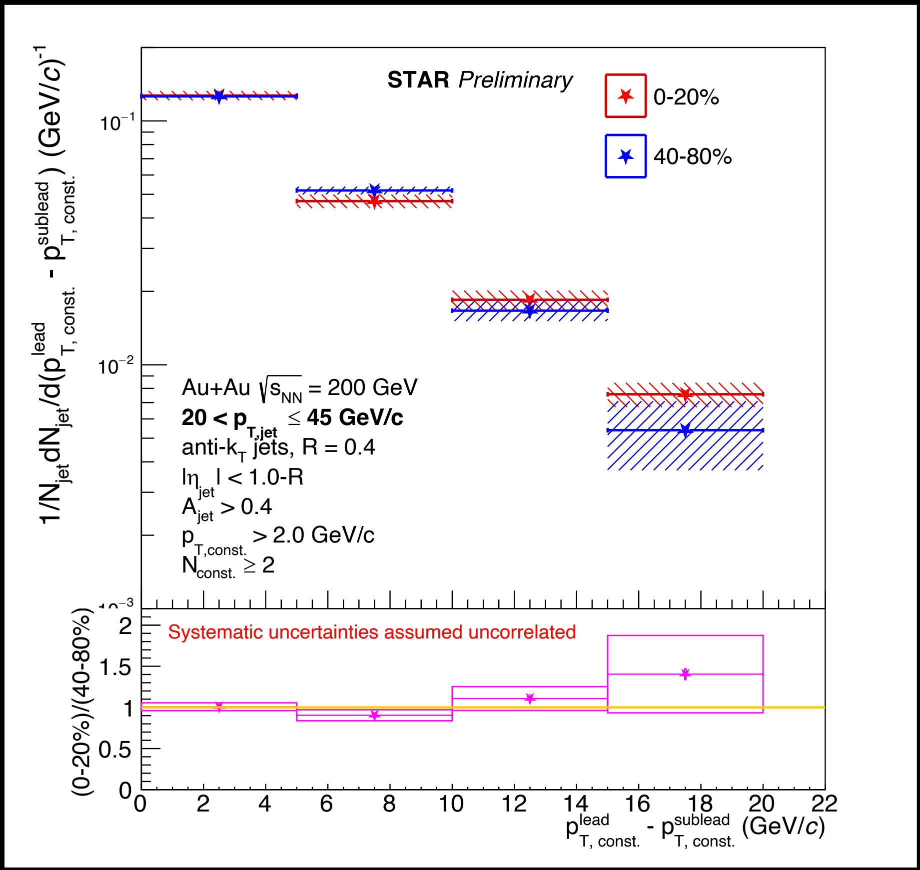
Ex: Performance of Multi-Fold



+ 4 more observables for a net 7D unfolding

Good closure is observed for inputted jet observables in central and peripheral collisions.

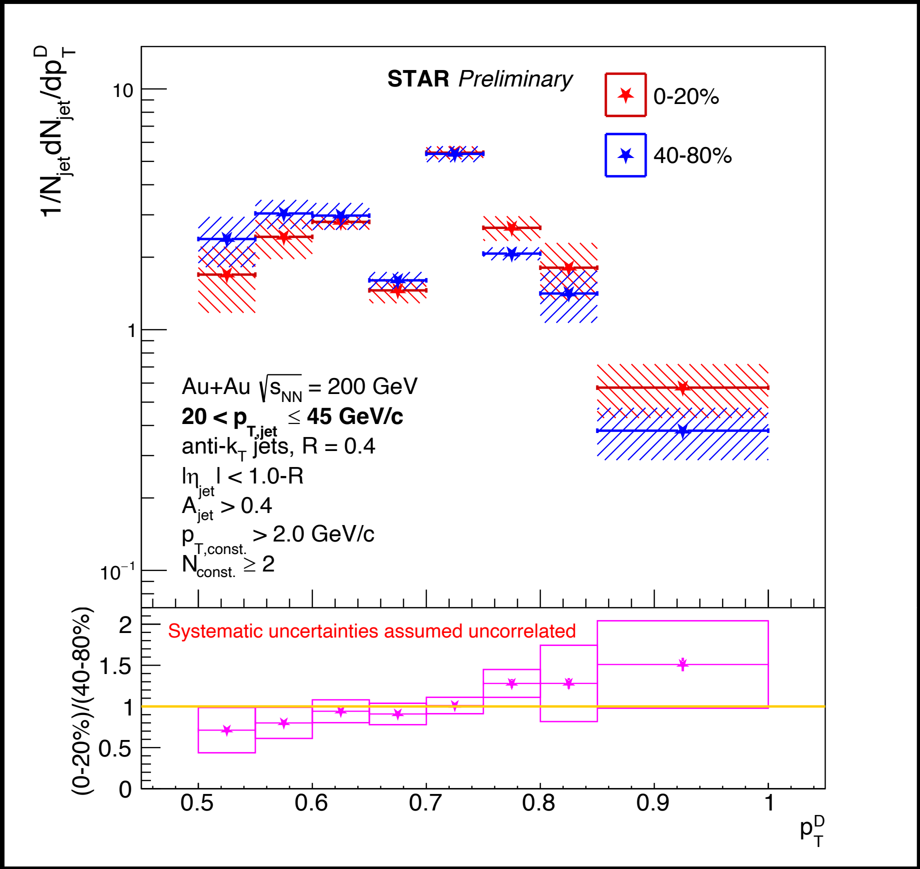
LeSub



$$LeSub = p^{lead}_{T,track} - p^{sublead}_{T,track}$$

Consistent within conservative systematic conservative uncertainties between central, peripheral collisions .

Dispersion

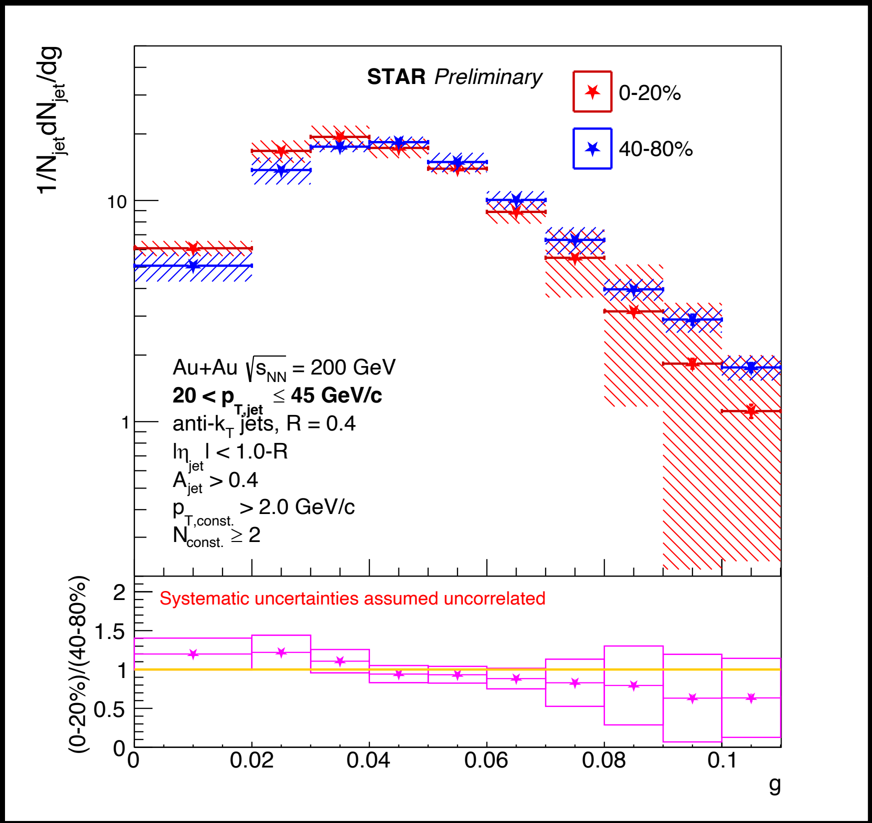


$$p_T^D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

The kink at 0.7 due to strong dependence on number of constituents in jet .

Consistent within conservative systematic conservative uncertainties between central, peripheral collisions .

Girth

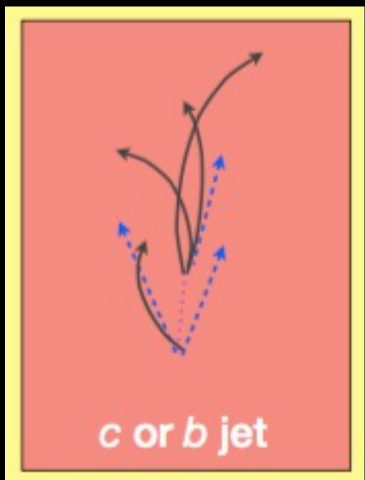


$$g = \sum_i \frac{p_{T,i}}{p_{T,jet}} |\Delta R_i|$$

Consistent within conservative systematic conservative uncertainties between central, peripheral collisions .

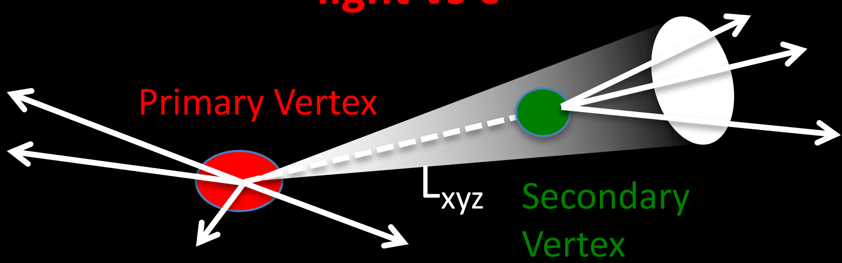
Studies ongoing to improve systematic uncertainties.

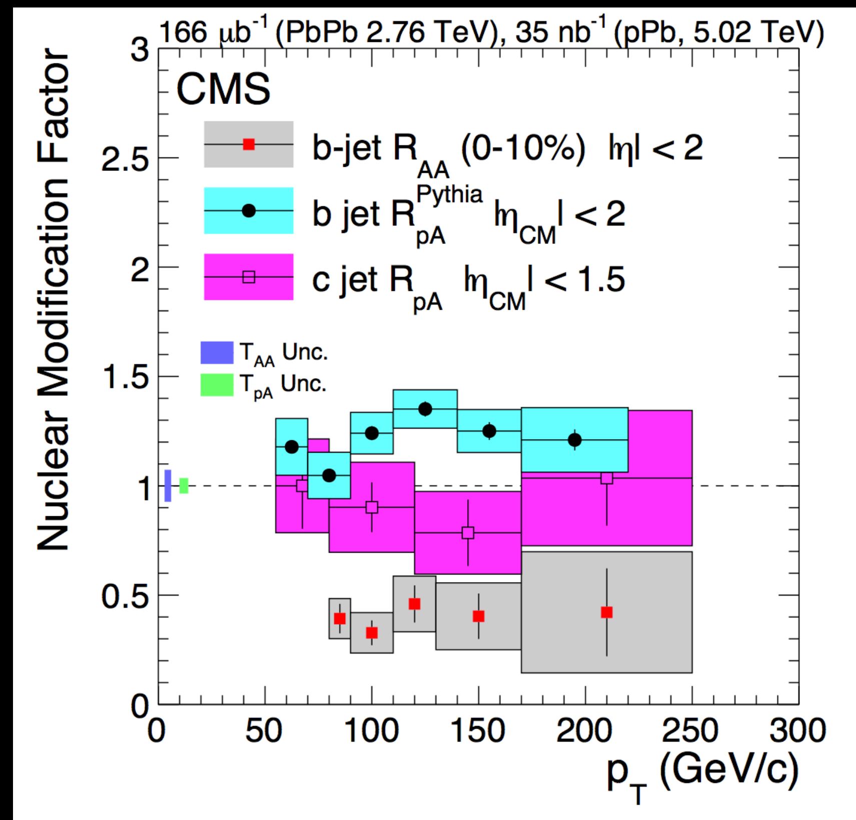
Heavy Flavor Dependence



Heavy flavor tagged jets can be selected on displaced vertices.

3+ Body Secondary Vertex Tagging: light vs c

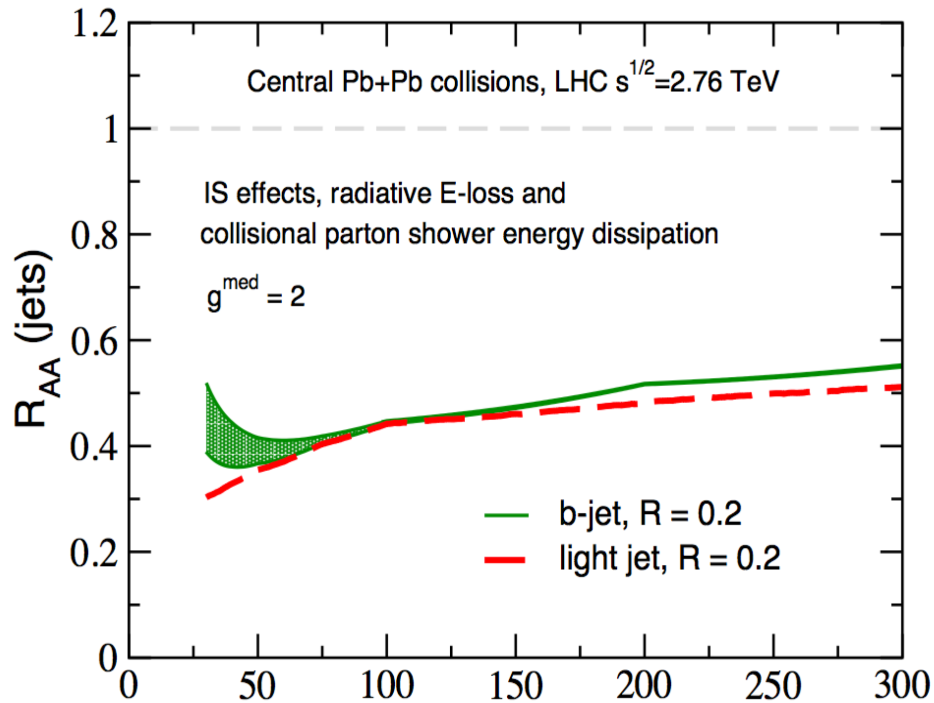




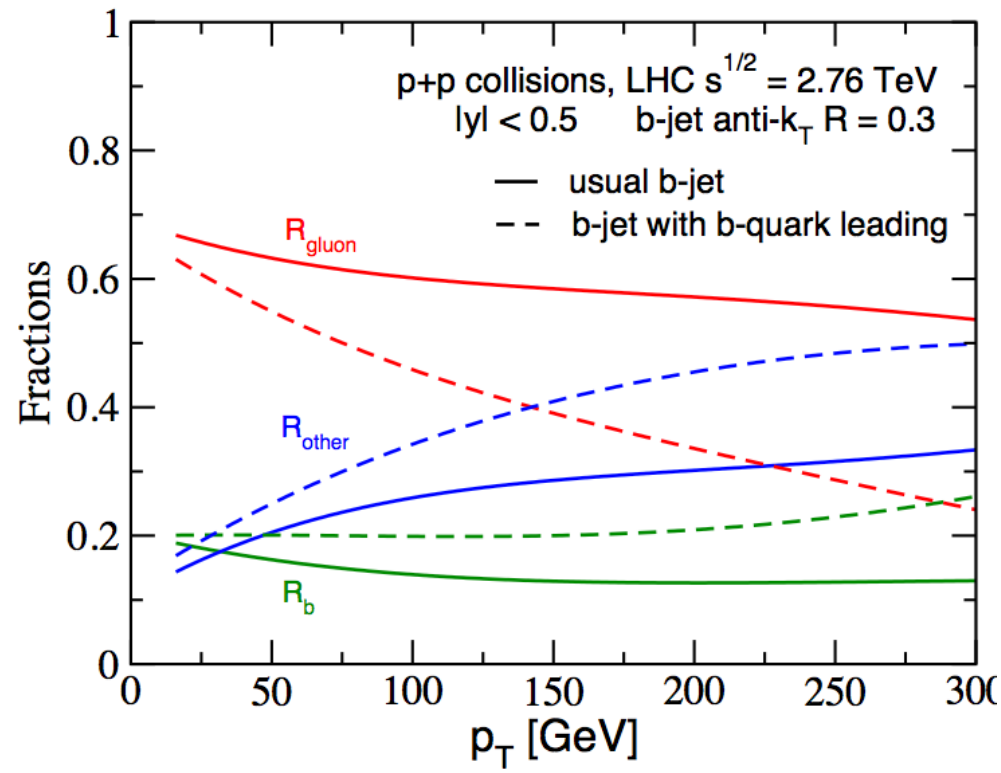
Suppression of b quarks in PbPb, while no suppression in pPb collisions

CMS, Phys. Rev. Lett. 113, no. 13, 132301 (2014)
CMS, Phys. Lett. B 754, 59 (2016)
CMS, arXiv:1612.08972 (2016)

Caveat: b/c jet might not be original!



Huang, Kang, Vitev



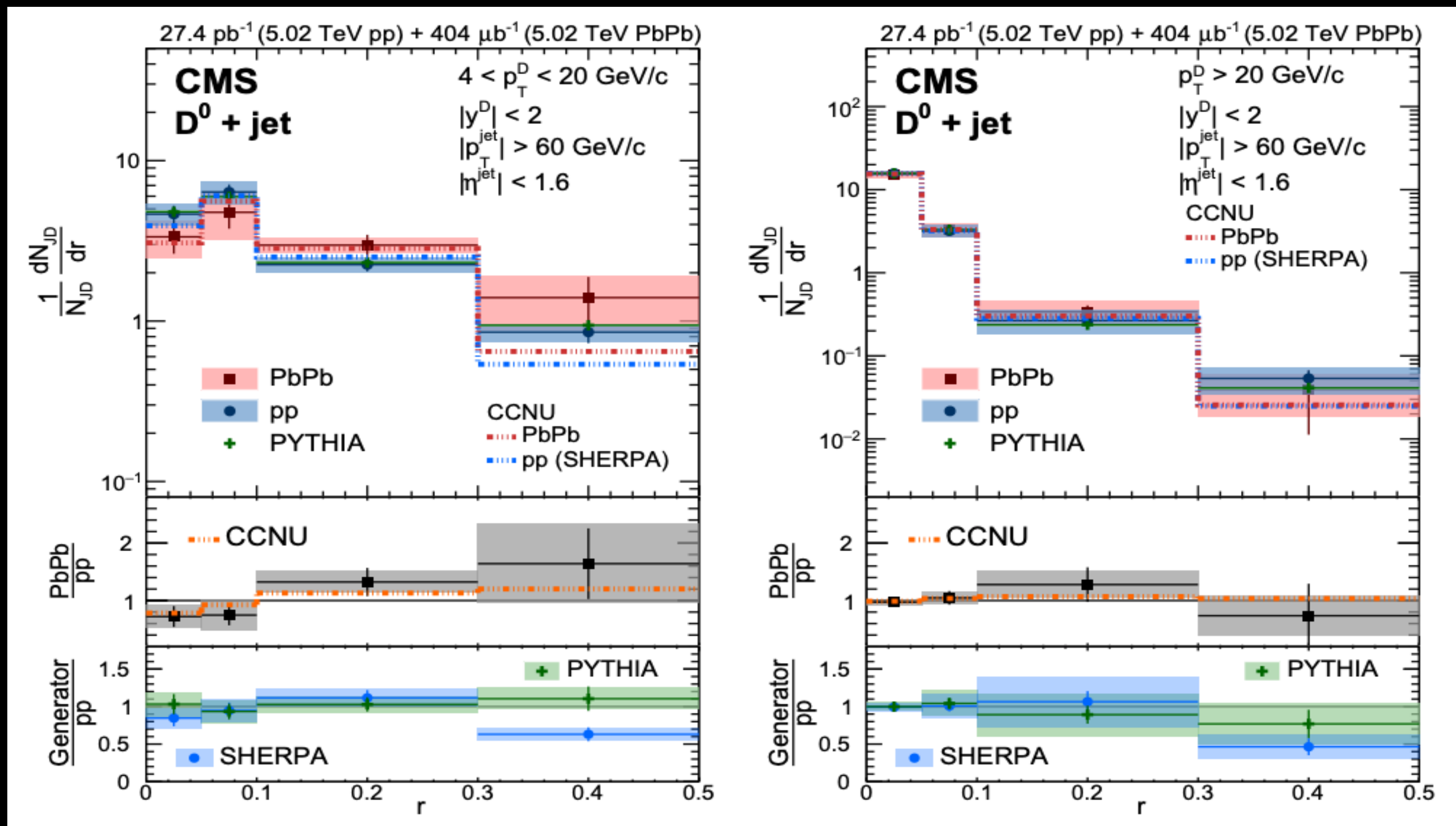
At high pt region, mass effect can be neglected. Study at RHIC is necessary.

R_{gluon}:fraction of g->b
R_b :fraction of b->b
R_{other}:fraction of q->b

Explore multi tags such as c/b jet with D/B and γ.

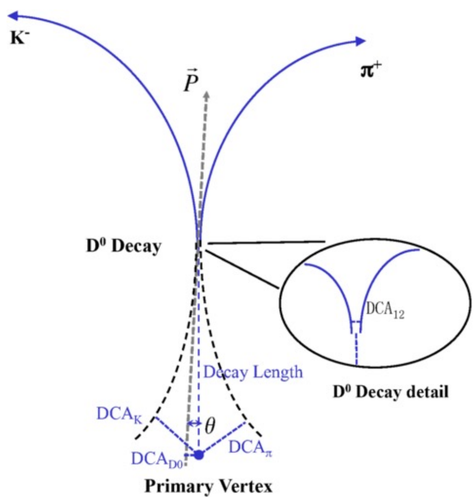
Explore with jets with D^0 mesons at LHC

CMS, Phys. Rev. Lett. 125 (2020) 102001

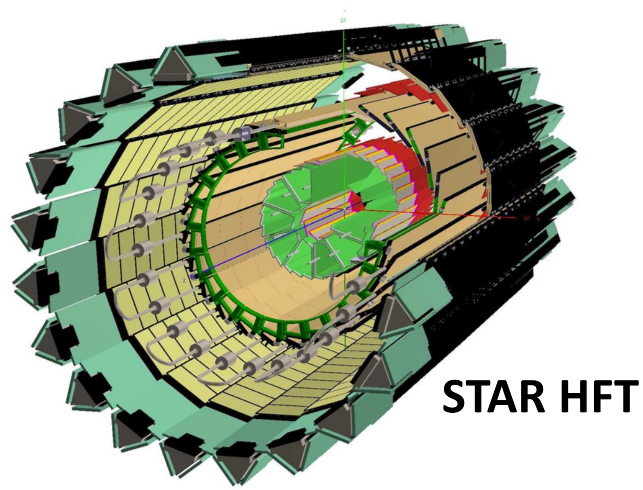


of the data. In PbPb collisions, compared to the pp results, the D^0 meson distribution for $4 < p_T^D < 20\,GeV/c$ hints at a larger distance on average with respect to the jet axis, reflecting a diffusion of charm quarks in the medium created in heavy ion collisions. At higher p_T^D, the PbPb and pp radial distributions are found to be similar.

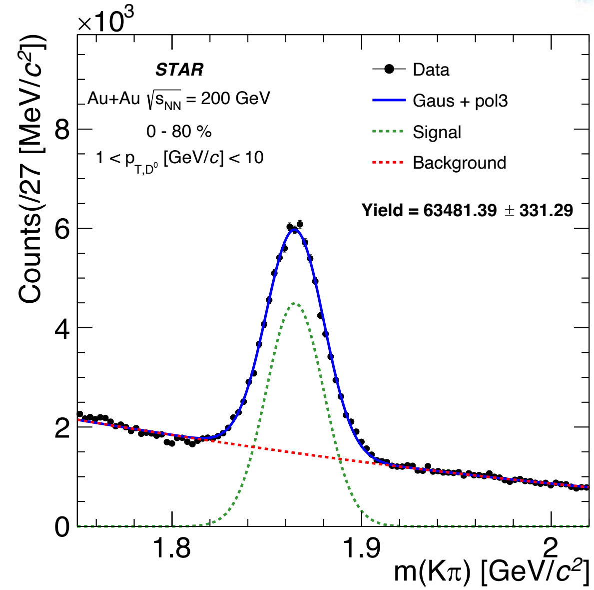
D^0 Reconstruction with STAR



K and π identified using TPC and TOF



Excellent track pointing resolution to improve signal to background ratio in HF hadron reconstruction.



Topological cuts utilizing HFT on the D^0 candidates improve signal significance

$_s\mathcal{P}lot$

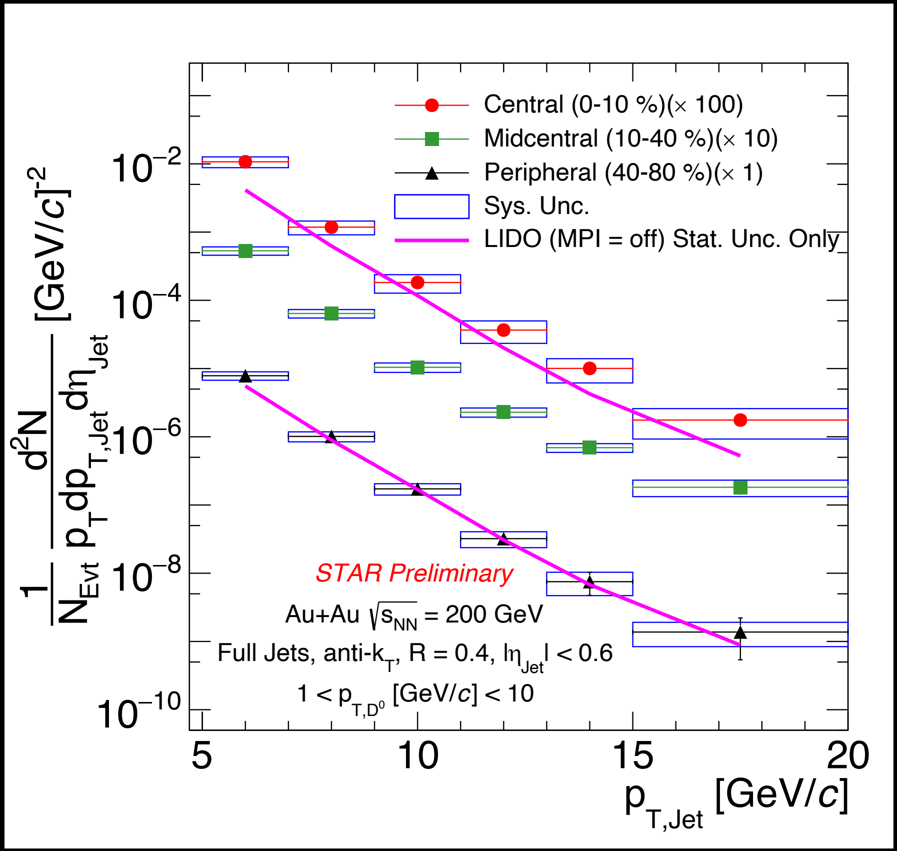
- Native class in RooStats, and widely used in HEP

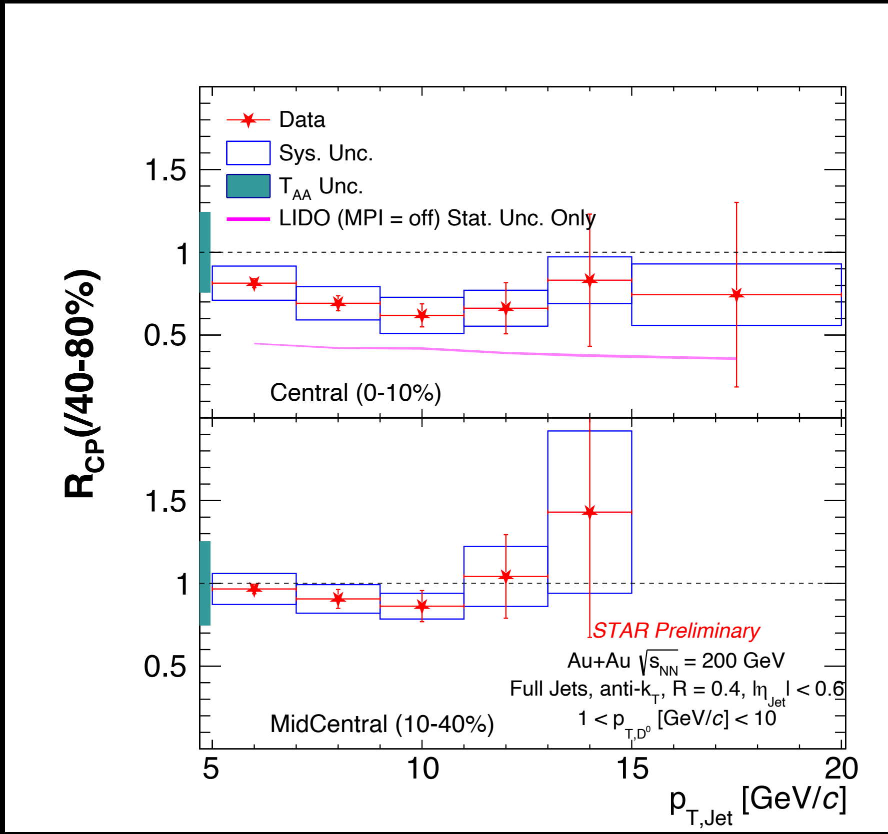
STAR, Phys. Rev. C 99 (2021) 034908

- Unbinned maximum likelihood fit to invariant mass integrated over all kinematics
- $p_{\mathrm{T,jet}}$ and radial distributions with all D^0-tagged jet candidates using sWeights
- Easy to include reconstruction efficiencies versus D^0 kinematics

Nucl. Instrum. Methods Phys. Res., A (2005) 555

Transverse momentum spectra of D^0 Jets



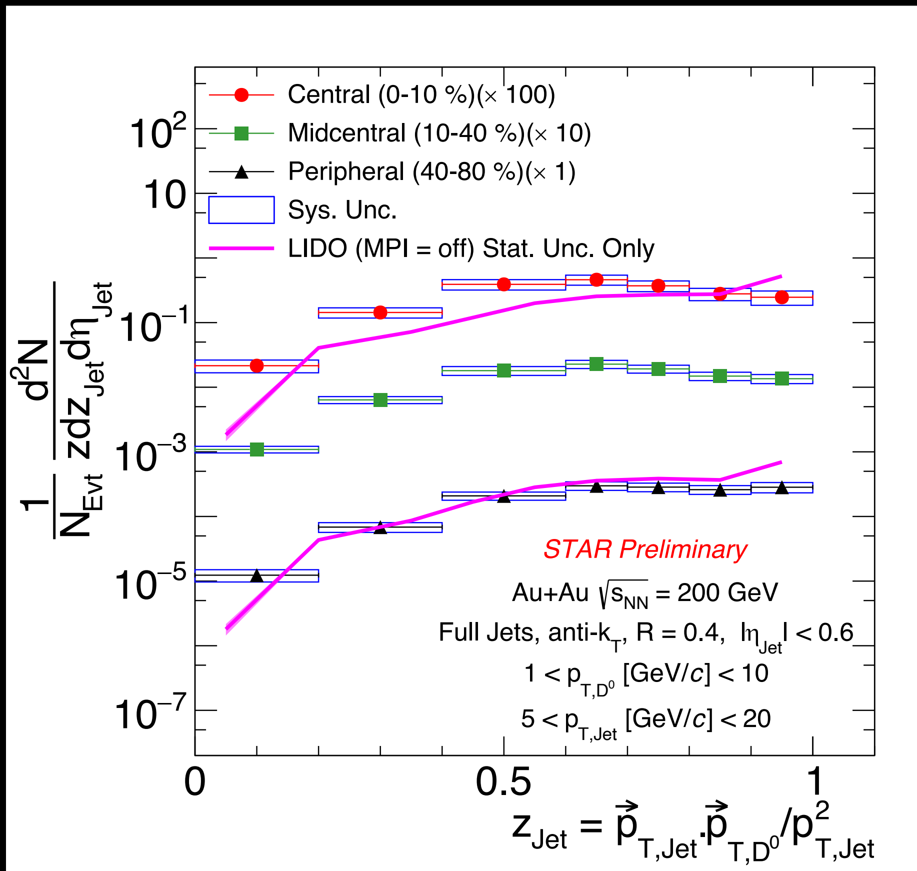


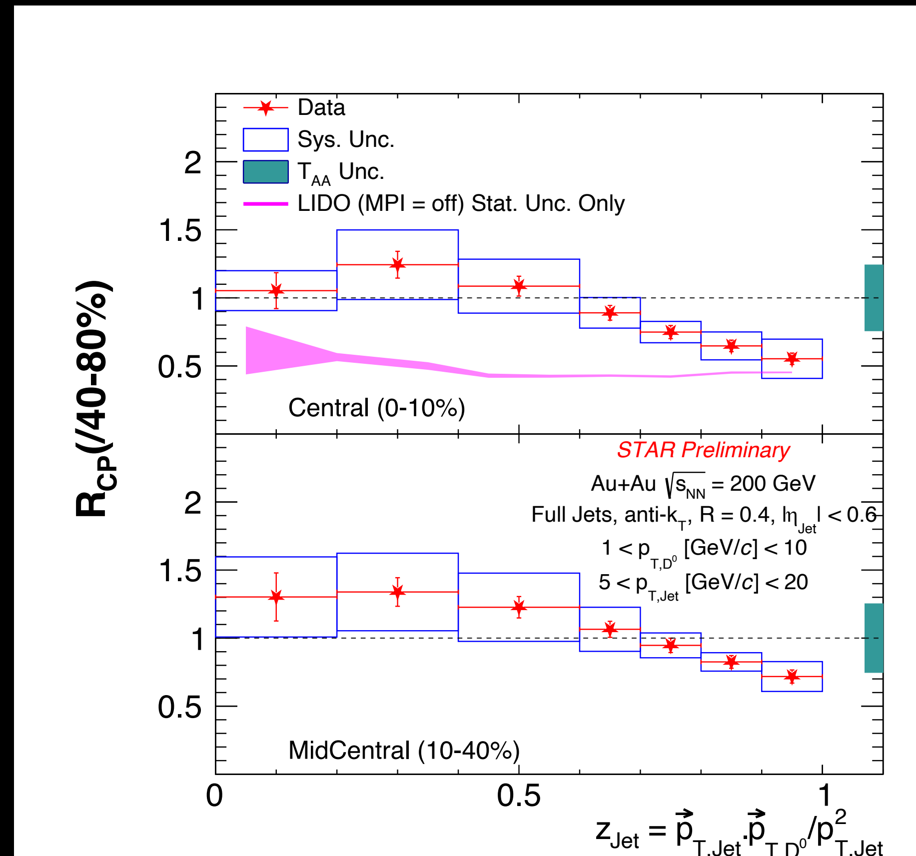
LIDO **agrees well** with yield in peripheral events, **slightly underpredicts** yield in central events.

Hint of suppression for central.
Rcp midcentral events **consistent with 1**

W. Ke, Y. Xu, S. Bass, Phys. Rev. C 98, 064901 (2018)

Fragmentation Function of D^0 Jets



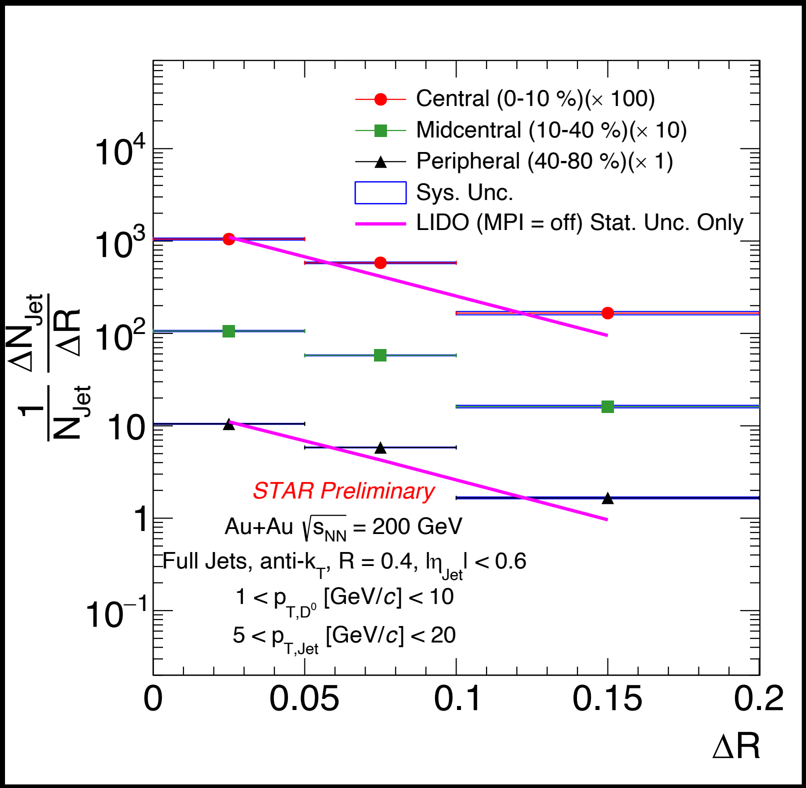


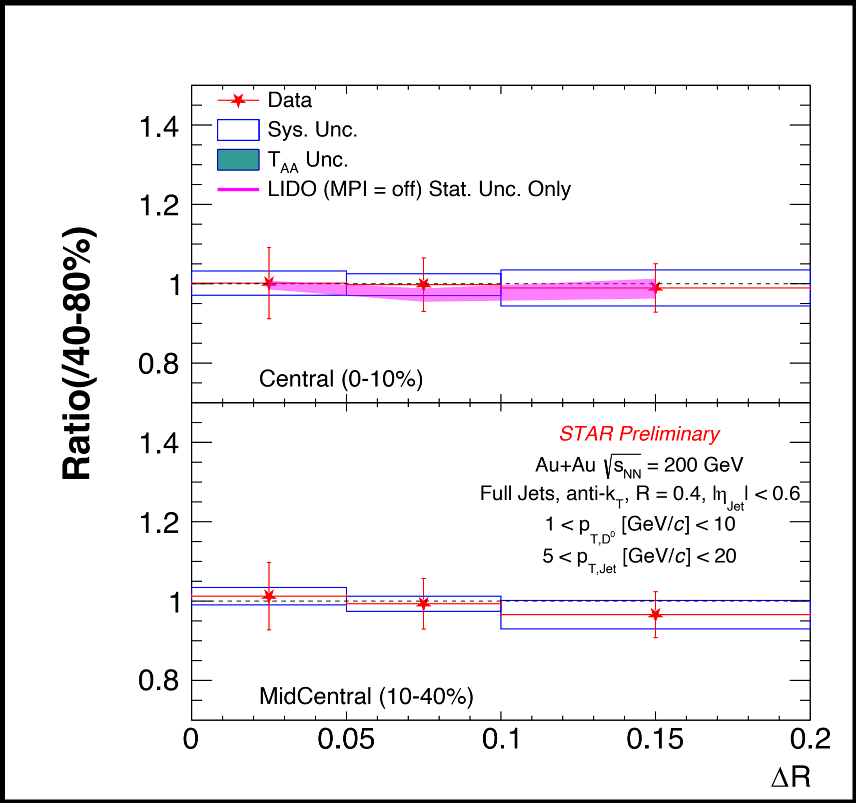
W. Ke, Y. Xu, S. Bass, Phys. Rev. C 98, 064901 (2018)

Hard fragmented D^0 jet yield **suppressed** in central & midcentral events

Soft fragmented D^0 jet yield **ratio consistent with 1** in central & midcentral events

Radial Profile of D^0 Jets





$$\Delta R = \sqrt{(\eta_{Jet} - \eta_{D^0})^2 + (\phi_{Jet} - \phi_{D^0})^2}$$

LIDO **agrees with** radial profile

W. Ke, Y. Xu, S. Bass, Phys. Rev. C 98, 064901 (2018)

Ratio of radial profiles consistent with 1

No hint of diffusion at RHIC energies.

Conclusions

First fully corrected observations of p_T^D, Girth and LeSub from hard-core jets in AA collisions at RHIC energies

- First heavy-ion results using Multifold to remove detector effects and residual background fluctuations.
- Central and Peripheral events results look alike within current uncertainty estimates.

First D^0-tagged jet measurement at RHIC energies

- A shift in transverse momentum is observed towards a suppression in the nuclear modification factors.
- Hard fragmented jets are suppressed in central collisions.
- No diffusion is observed.

STAY TUNED: Results for pp and finalized systematics are on their way!