Studies of Heavy-Flavor Jets Using D^0-hadron Correlations in Azimuth and Pseudorapidity in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV}$ at the STAR Experiment

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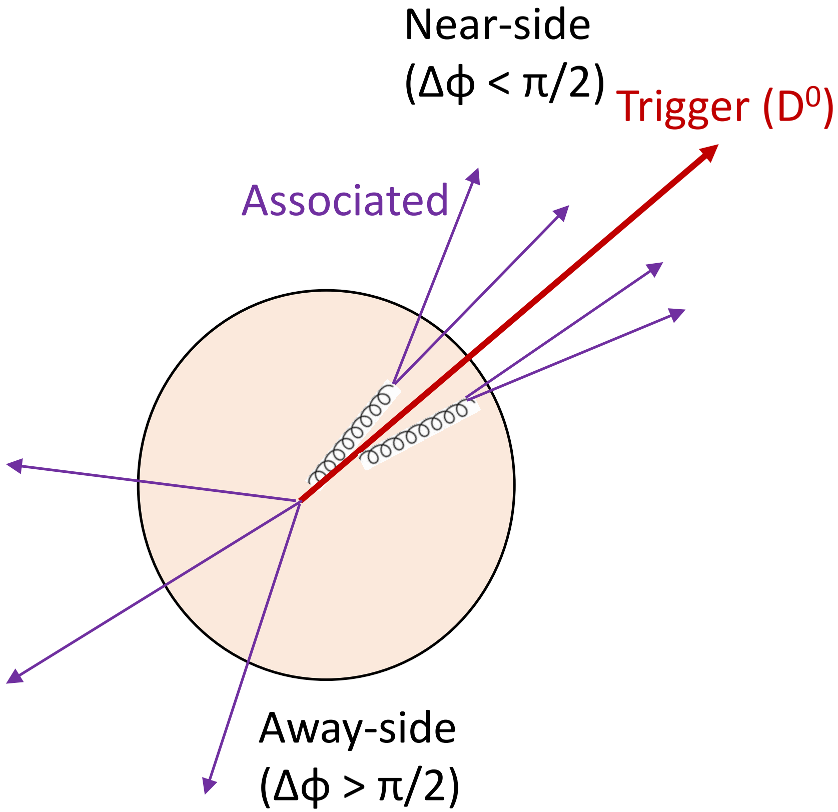
Motivation

- Why heavy flavor quarks?
    - Heavy flavor (HF) quarks and hadrons provide unique insight into the QGP because of their early formation time, and their decay outside the medium - sensitive to the evolution of the entire medium.



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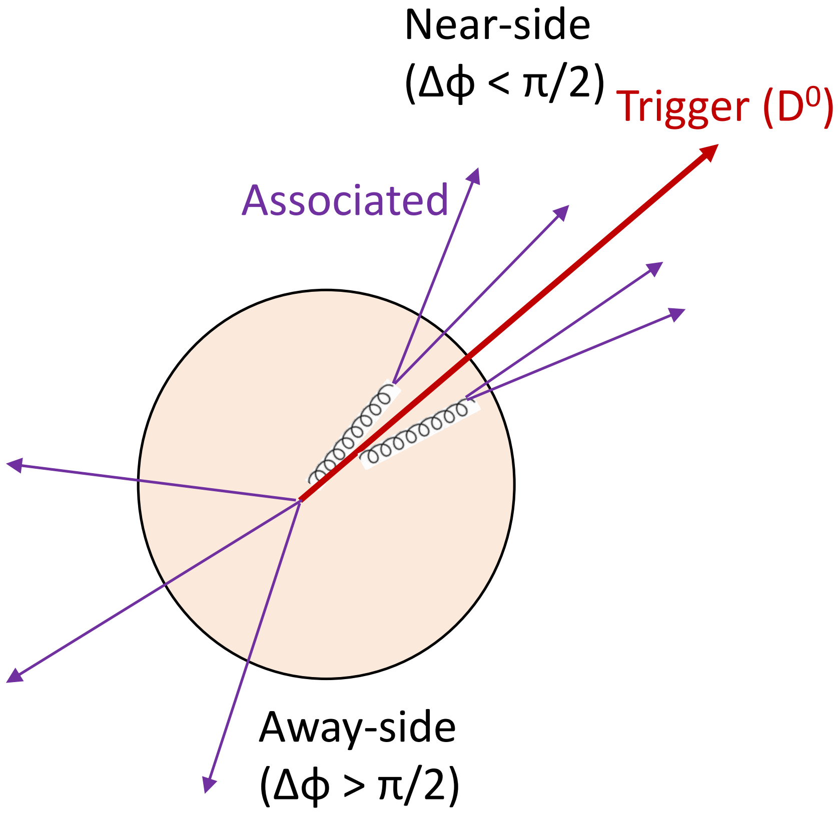
- Why correlations?
  - Correlations allow for the study of the shape and per-trigger yields of jet-like structures.
    - Allows for the analysis of effects of radiative and collisional energy loss.
  - 2D correlations on $(\Delta\eta,\Delta\phi)$ allow for separation of jet-like structures and flow-harmonics directly.



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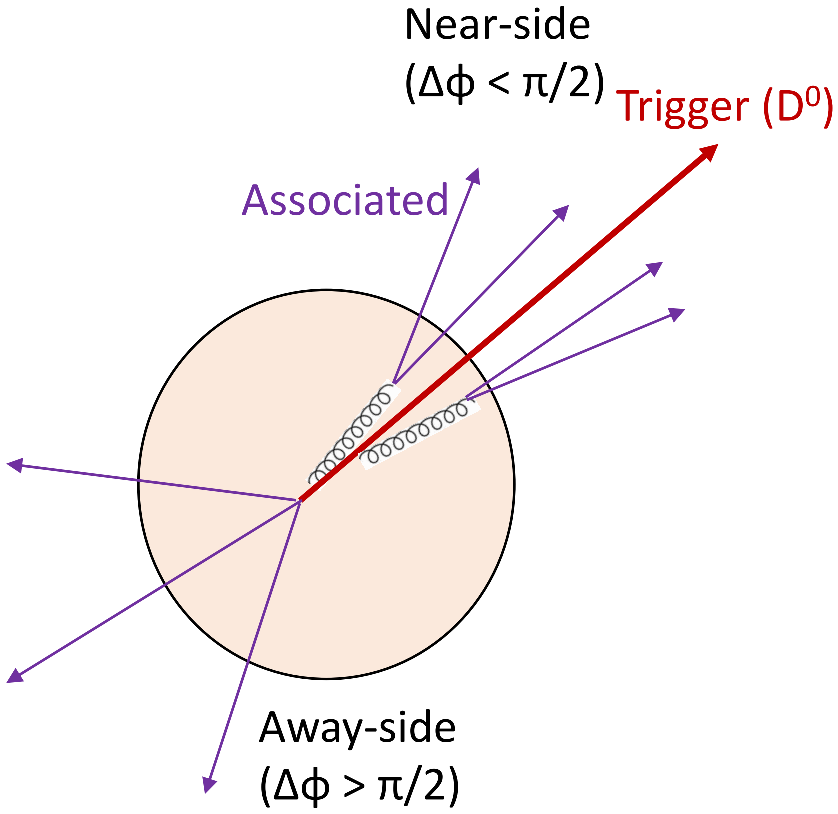
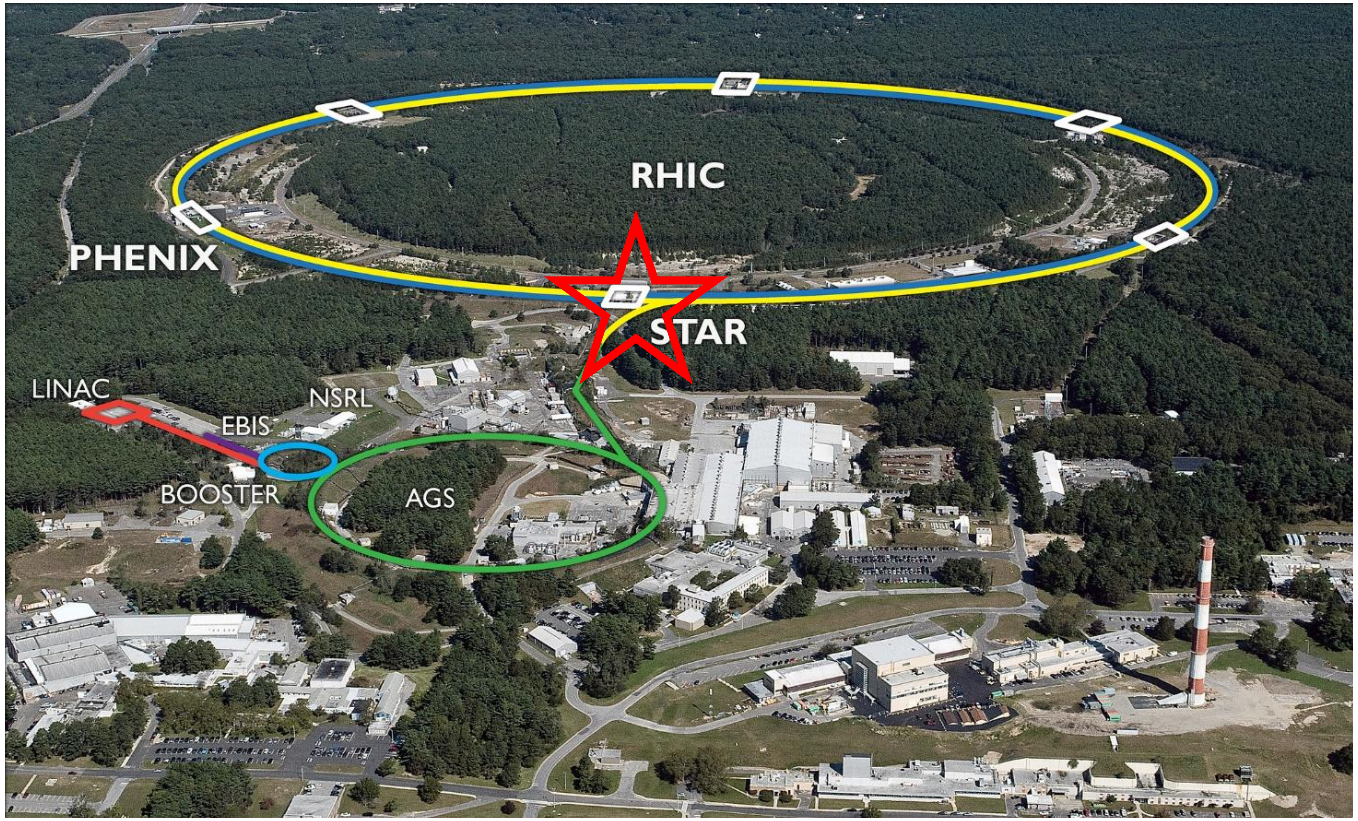


Theory originally predicted HF quarks would lose less energy than LF quarks in a QGP [1-3].
Comparison of the correlations from HF quarks and LF quarks provide insight into this prediction.

[1] Yu.L. Dokshitzer, D.E. Kharzeev Phys. Lett. B 519, 199 - 206 (2001).
[2] S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy Nucl. Phys. A 784, 426 (2007)
[3] S. Cao, Guang-You Qin, and Xin-Nian Wang Phys. Rev. C 93, 024912 (2016)

Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Laboratory in Upton, NY (Long Island).

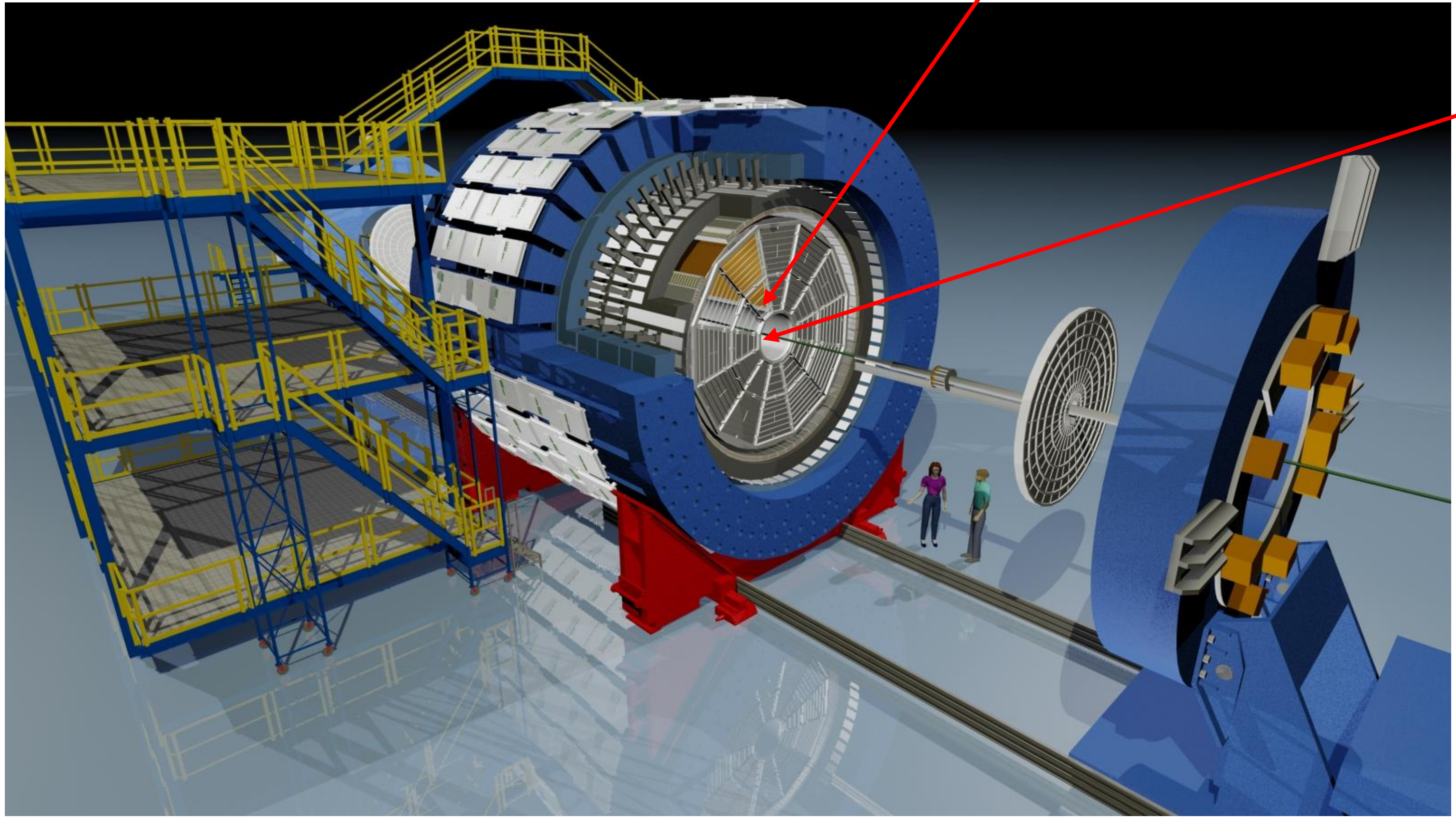


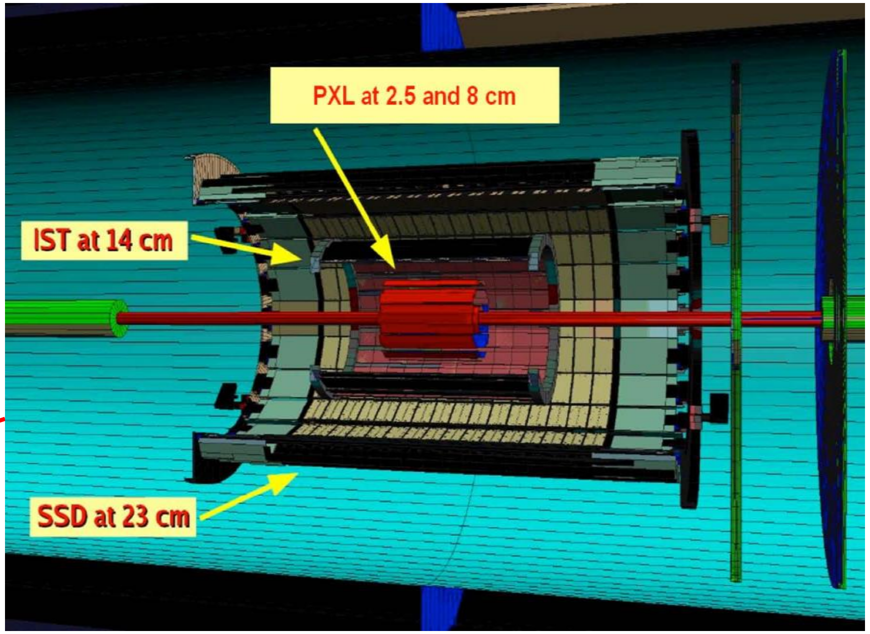
https://www.bnl.gov/rhic/images.asp

- Various energies and species
  - Au, Cu, U, He-3, deuteron, etc.
- **Au-Au:** $\sqrt{s_{NN}} = \mathbf{200\ GeV}$, $62\ \mathrm{GeV} - 3\ \mathrm{GeV}$.
- **p-p:** $\sqrt{s} = 200\ \mathrm{GeV}$, $\sqrt{s} = 510\ \mathrm{GeV}$, etc.
  - Proton spin studies
  - Baseline measurements for heavy-ion collisions

Schematic View of STAR

Time Projection Chamber (TPC)





Heavy Flavor Tracker (HFT)

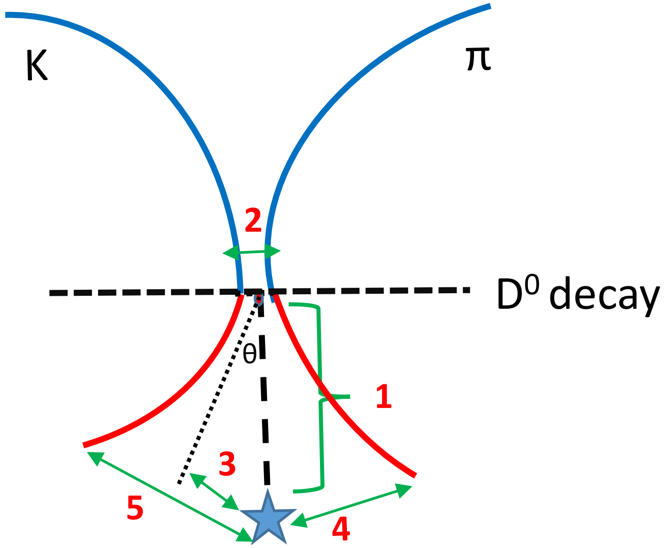
- TPC acceptance
  - 2π in azimuth
  - $|\eta| < 1$
  - Reconstructed track $p_T > 0.15$ GeV/*c*
- HFT acceptance
  - 2π in azimuth
  - $|\eta| < 1$
  - DCA resolution in both rφ and z directions ~30 μm at $p_T \gtrsim 1$ GeV/*c*

Event and Track Selection

- Event Selection
  - Minimum-bias events (~900M) recorded in 2014.
  - Primary vertex $|V_Z| < 6$ cm (HFT acceptance)

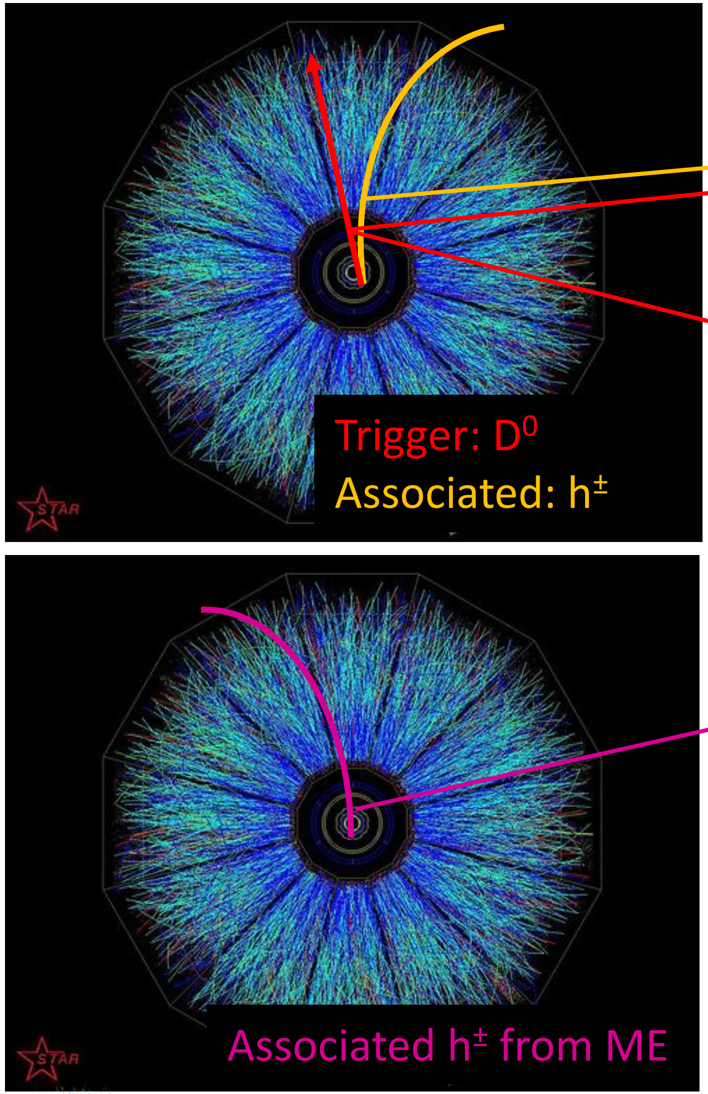
- Track Selection
  - All tracks must be "HFT" tracks
  - D^0 Reconstruction (trigger)
    - Wide p_T-bin: 2-10 GeV/c
    - K and π ID with TPC dE/dx
  - Associated hadron cuts (associated)
    - $|\eta| < 1.0, p_T > 0.15$ GeV$/c$

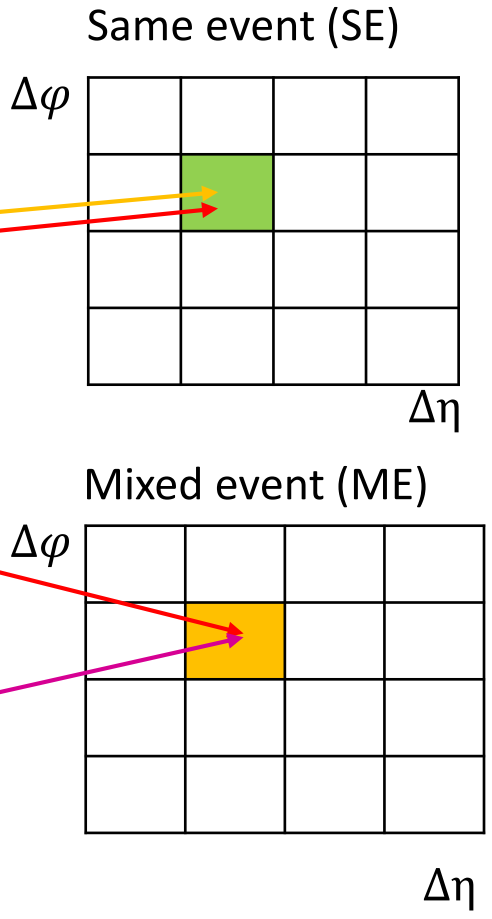
Topological Cuts	D^0 p_T = 2-10 GeV/c
1) Decay Length (μm) >	212
2) DCA Daughters (μm) <	57
3) DCA D^0 and PV (μm) <	38
4) DCA daughter π and PV (μm) >	86
5) DCA daughter K and PV (μm) >	95



[1] L. Adamczyk et al. (STAR Collaboration) PRL 118, 212301 (2017)

2D Angular Correlations

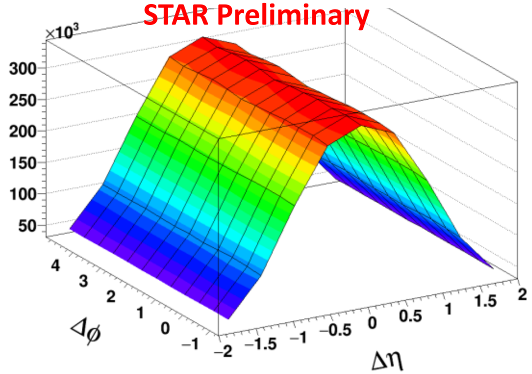




$$\Delta\varphi = \varphi_{D^0} - \varphi_{h^\pm}$$

$$\Delta\eta = \eta_{D^0} - \eta_{h^\pm}$$

$$\alpha = \frac{\sum_{\Delta\eta,\Delta\varphi\ bins} SE}{\sum_{\Delta\eta,\Delta\varphi\ bins} ME} \cong \frac{1}{N_{ME}}$$

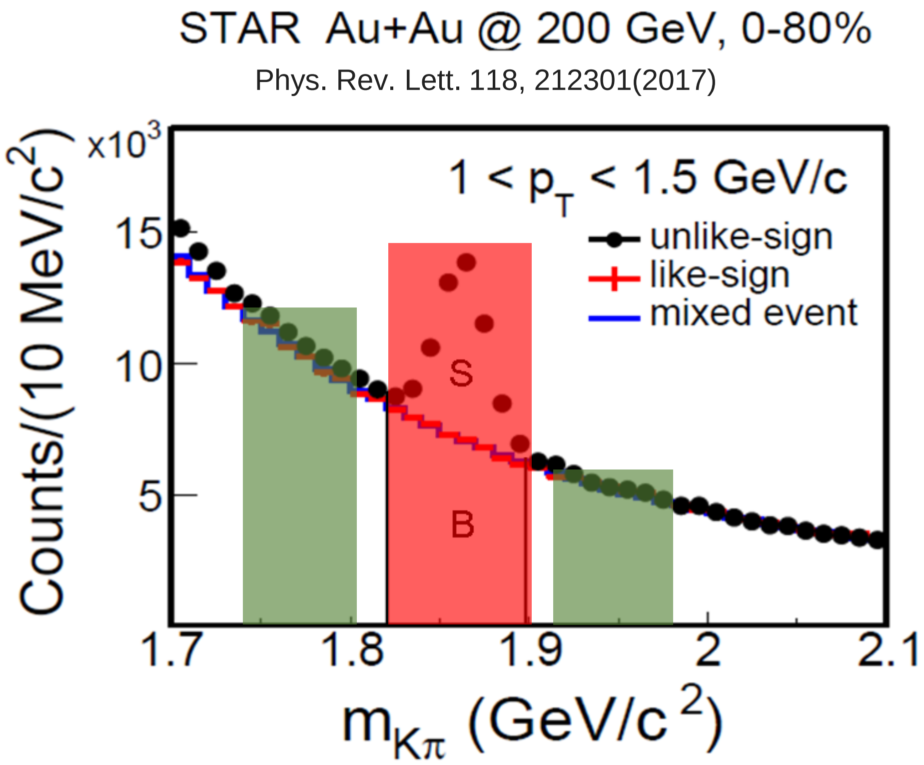


Raw distributions are dominated by uncorrelated background and pair acceptance.

Correlation measure:

$$corr. = \frac{SE - \alpha ME}{\alpha ME} = \frac{SE}{\alpha ME} - 1$$

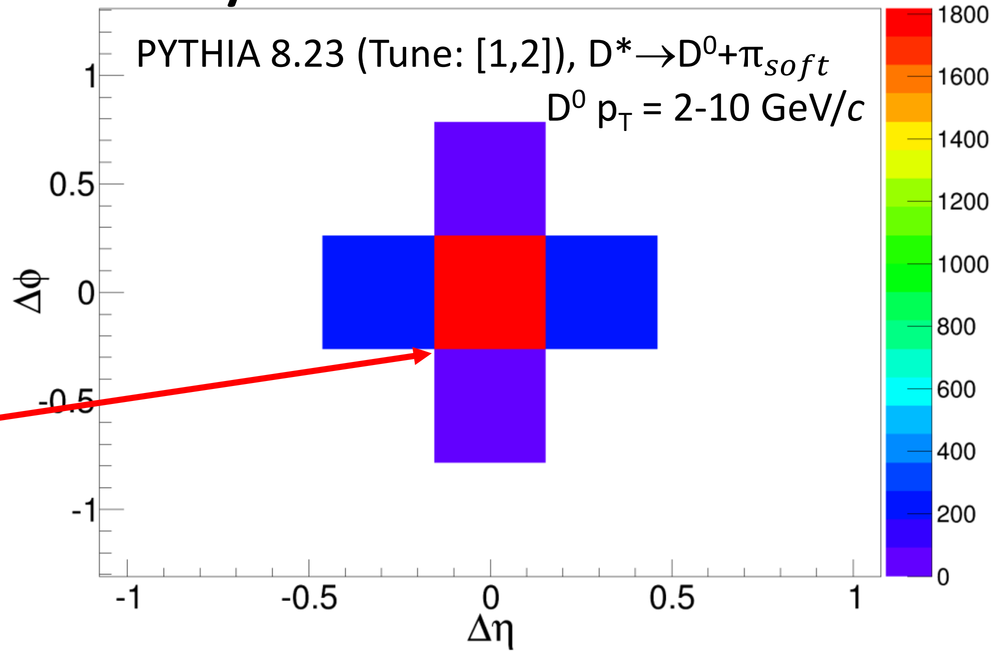
D^0 Invariant Mass Background Subtraction

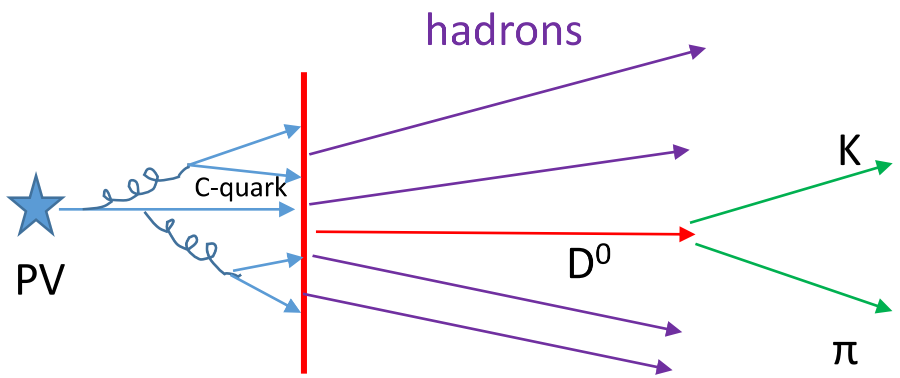


- The **signal region** contains both real D^0s and background Kπ pairs.
- Correlations from background Kπ pairs are estimated from **sidebands.**
- These normalized **sideband** correlations are then subtracted from those coming from the **signal region**.

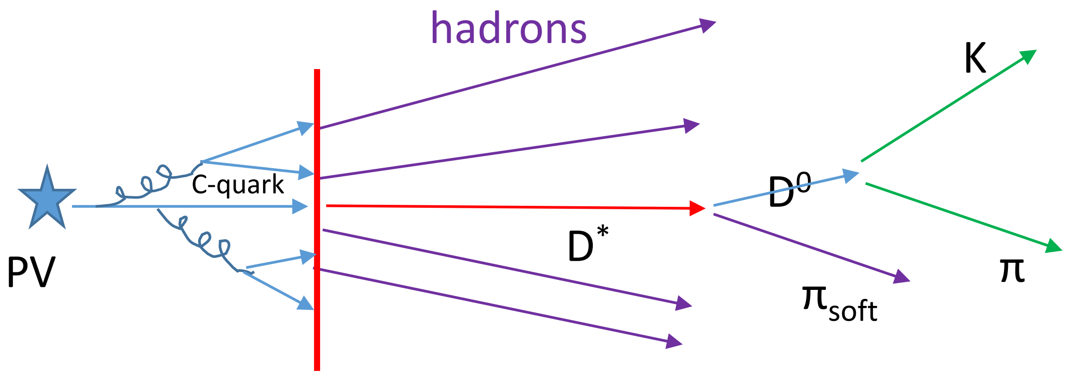
Additional Background from D* Decay

- $\mathrm{D}^{*\pm} \rightarrow \mathrm{D}^0 + \pi^{\pm}$ (BR ~67%).
  - Accounts for ~20% of our D^0 sample.
- Happens at predominantly small angles between the D^0 and $\pi^{\pm}$, which means we get an increase of D^0-hadron pairs only in the (Δη,Δϕ) = (0,0) bin from the $\mathrm{D}^0 + \pi^{\pm}$ pair.





What we want.

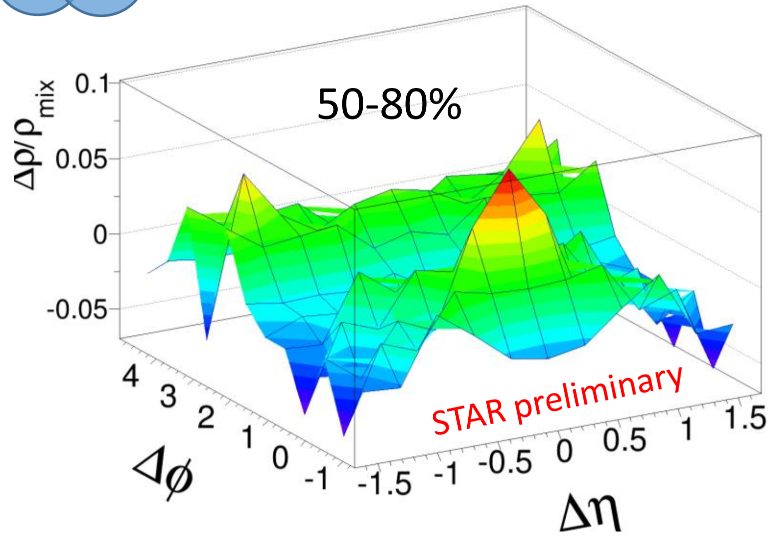


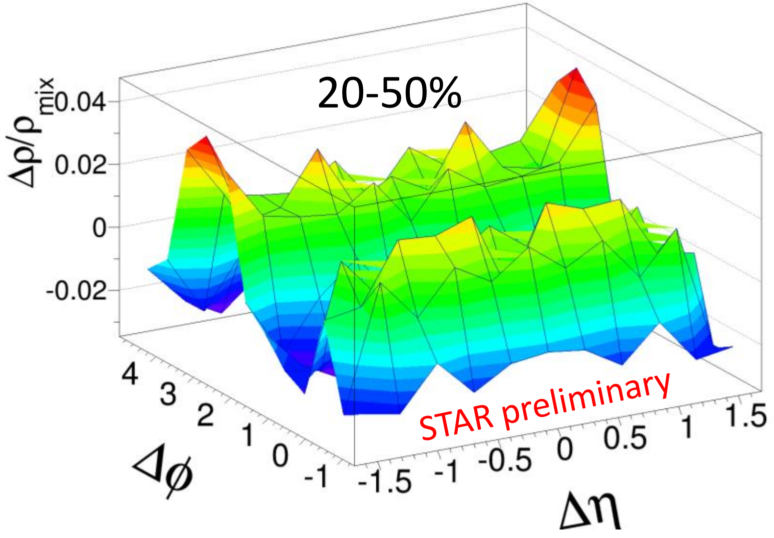
What we DON'T want.

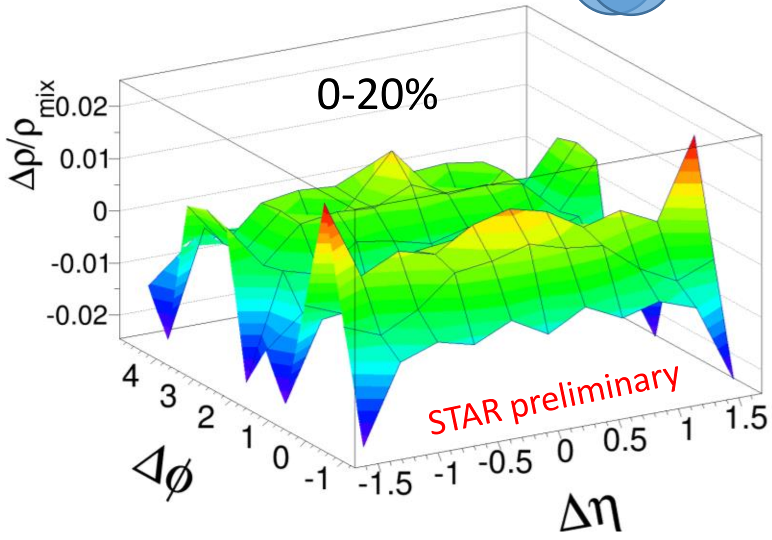
[1] S. Shi, X. Dong, M. Mustafa arXiv:1507.00614 (2015)
[2] L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. D 86, 072013 (2012)

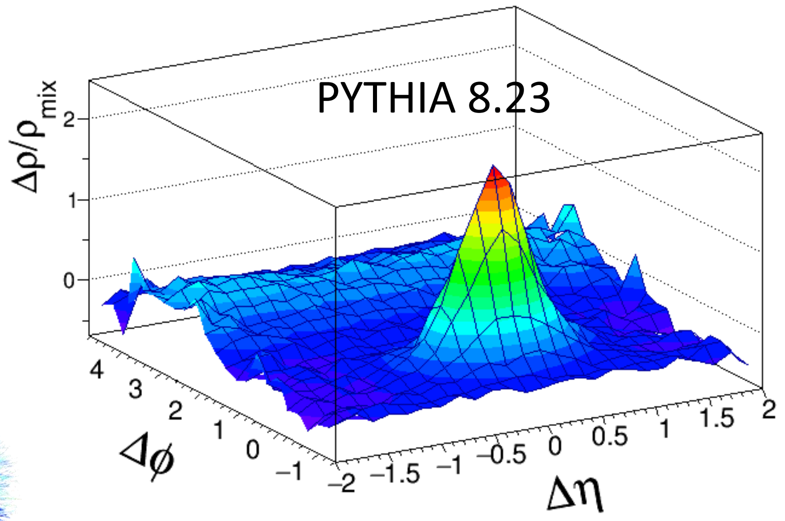
D^0-hadron Correlations in Au+Au $\sqrt{s_{NN}} = 200$ GeV
Symmetrized on (Δη,Δϕ), D^0 p_T = 2-10 GeV/*c*, $h^{\pm}$ p_T>0.15 GeV/*c*


Increasing Centrality









- Significant structure is seen on (Δη,Δϕ) that evolves with centrality.

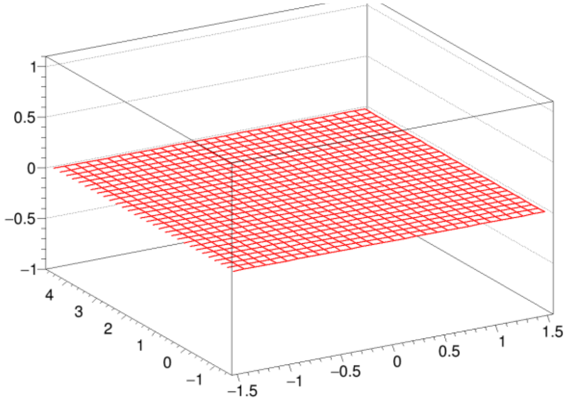
PYTHIA pp200 data sample (3M events) for D^0-Hadron correlations (D^0 p_T = 2-10 GeV/c, Tune: [1,2]).

[1] S. Shi, X. Dong, M. Mustafa arXiv:1507.00614 (2015)
[2] L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. D 86, 072013 (2012)

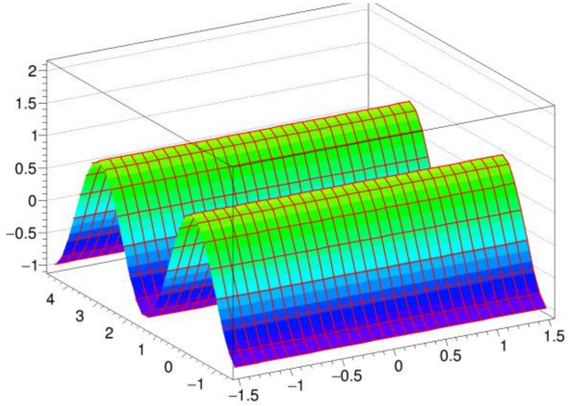
A Simple Mathematical Model to Fit the Data

- Fitting is done with a simple model with 8 parameters:
  - $A_0 + 2A_Q\{2D\}Cos(2\Delta\varphi) + A_{NS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{NS,\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{NS,\Delta\varphi}}} + A_{AS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{AS,\Delta\eta}}} * e^{-\frac{1}{2}\frac{(\Delta\varphi-\pi)^2}{\sigma^2_{AS,\Delta\varphi}}} + periodicity\ for\ \Delta\varphi\ Gaussian$

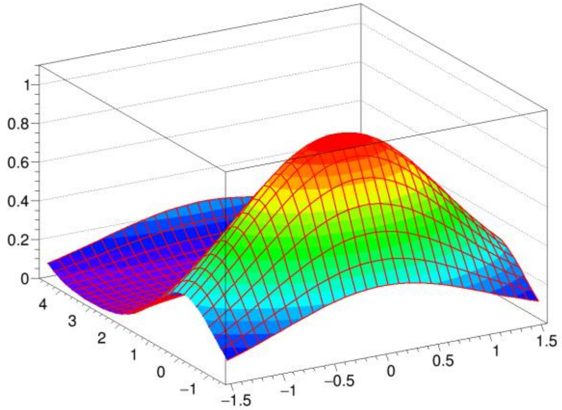
Constant-offset



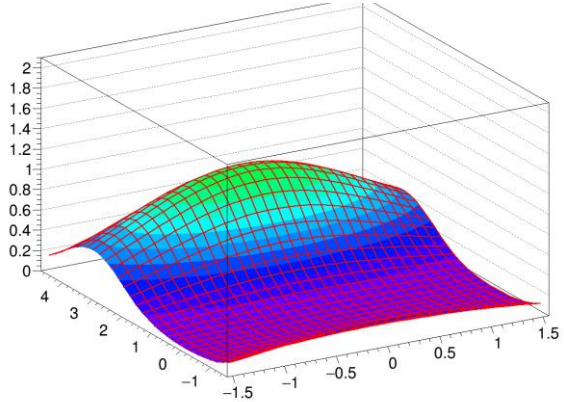
Quadrupole



Near-Side 2D Gaussian



Away-Side 2D Gaussian



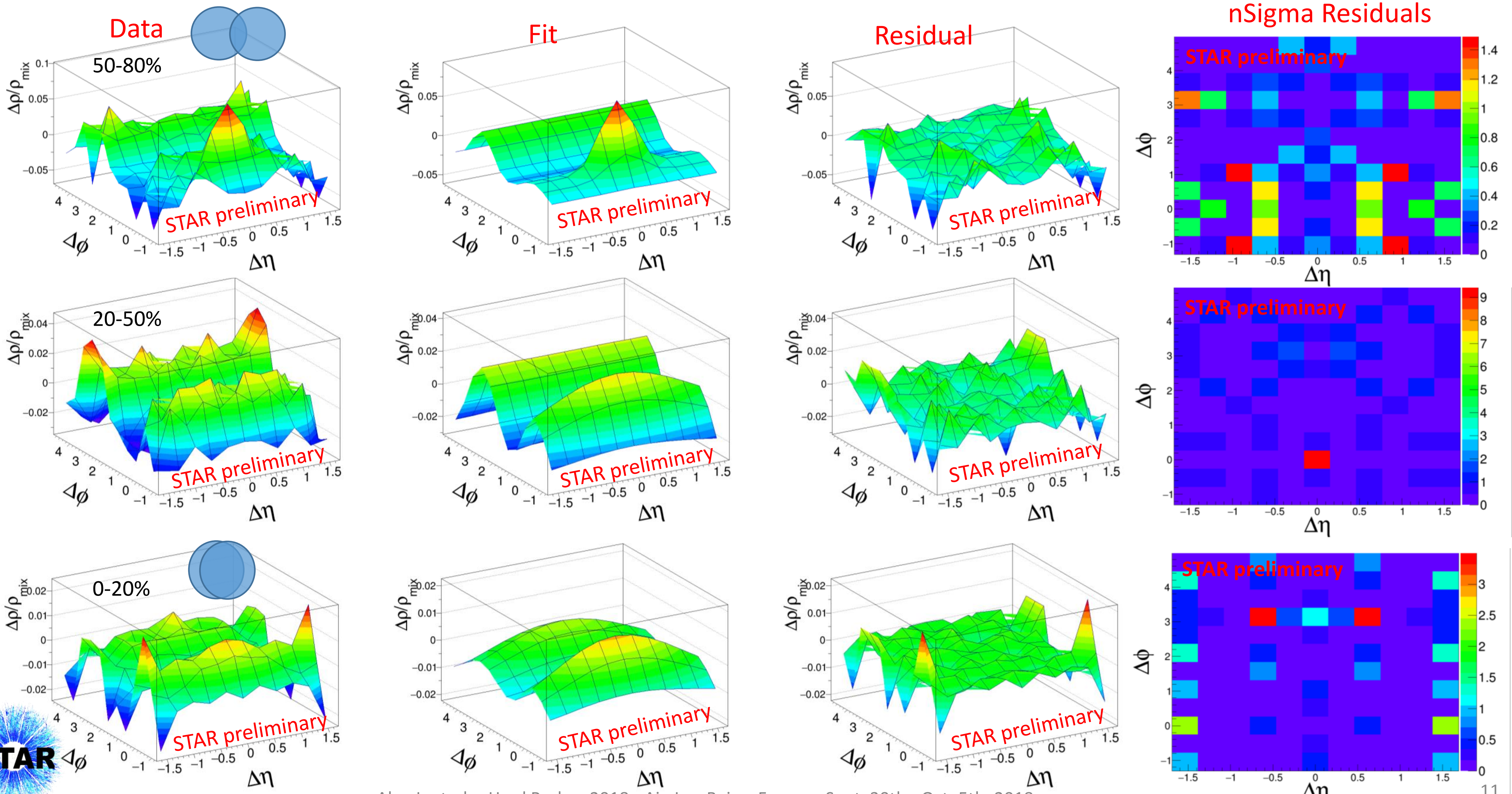
$A_Q\{2D\} = v_2^{h^\pm}\{2D\}v_2^{D^0}\{2D\}$

(details in backup)

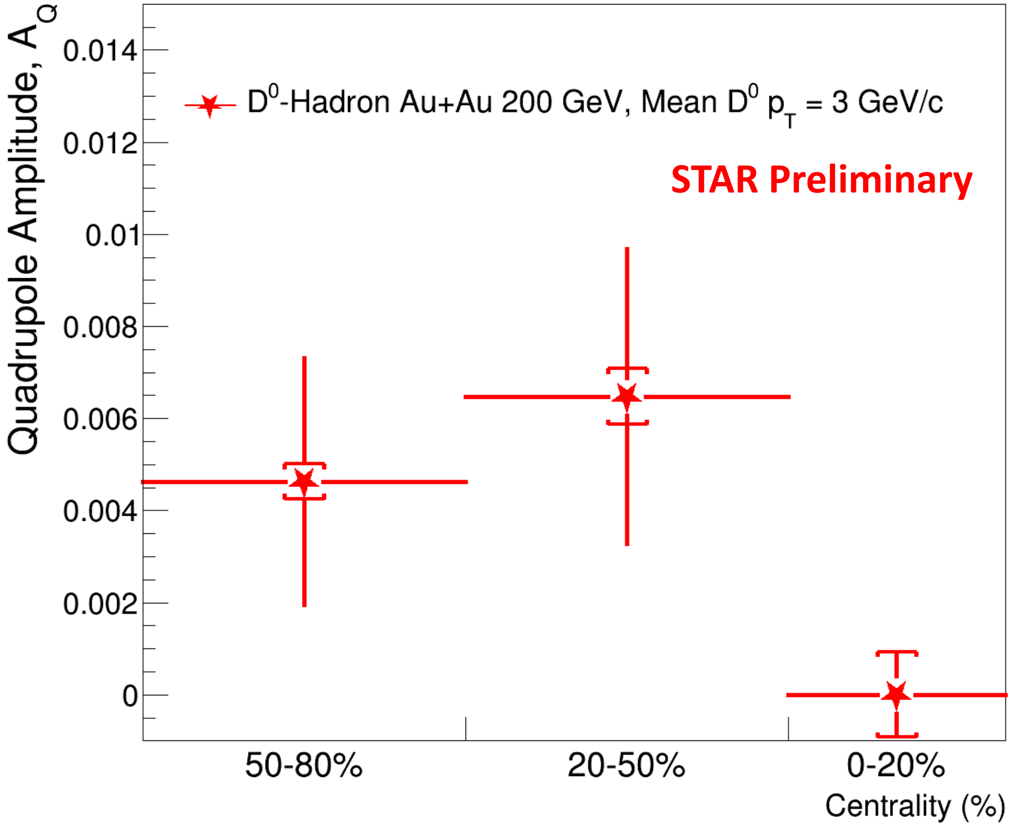
$$\text{NS Associated Yield} = \frac{\langle n_{h^\pm}(cent)\rangle}{4\pi} * \iint \Delta\eta\Delta\varphi A_{NS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{NS,\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{NS,\Delta\varphi}}}$$

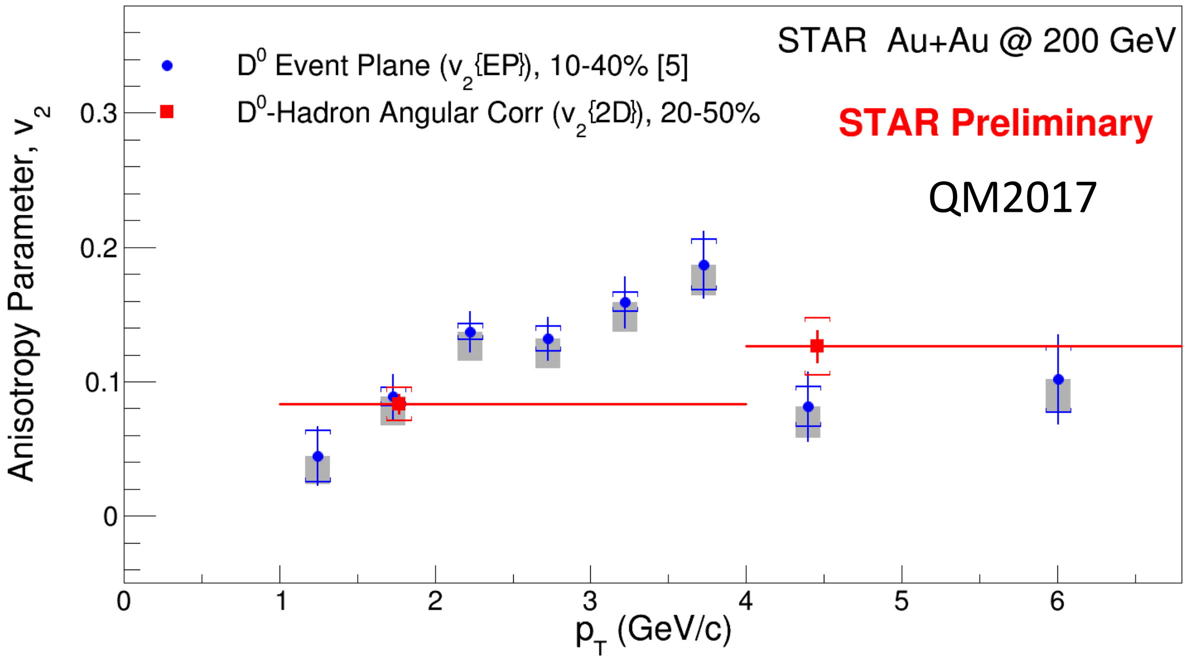
Fit Results

D^0 p_T = 2-10 GeV/c, $h^{\pm}$ p_T > 0.15 GeV/c



D^0 v_2 Consistency Check with Published Data



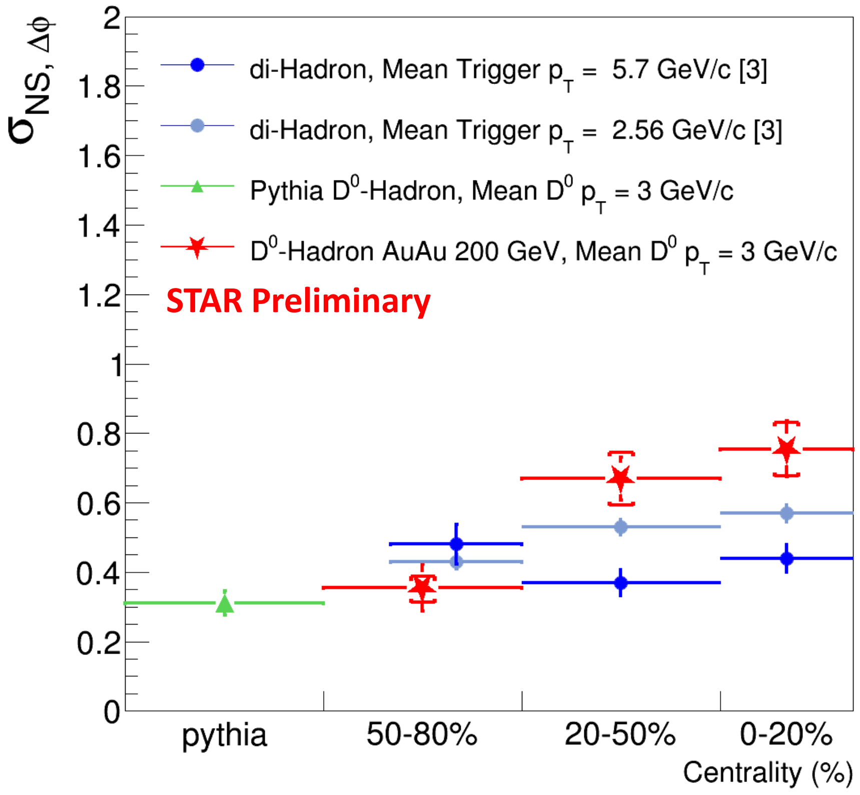


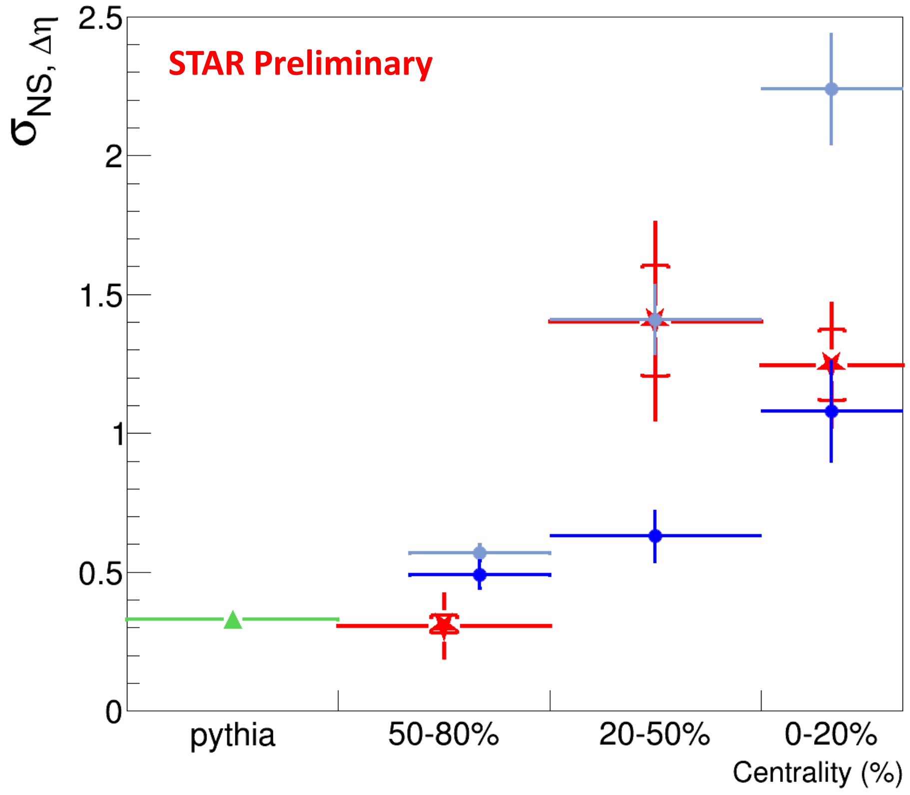
$$A_Q\{2D\} = v_2^{h^\pm}\{2D\} v_2^{D^0}\{2D\}$$

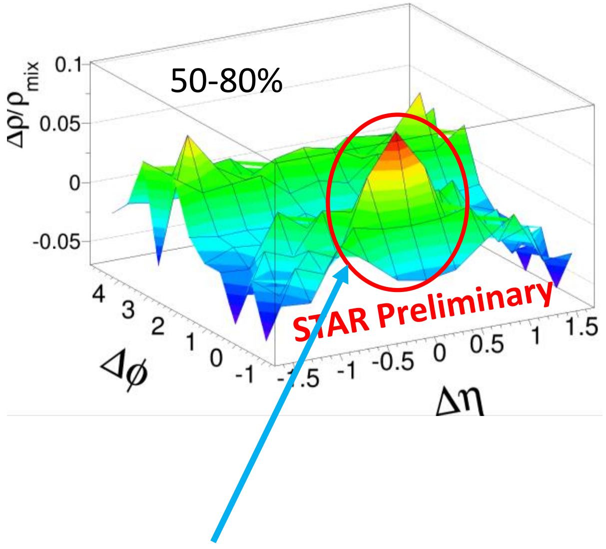
- Extracted v_2 of the D^0 from this analysis agrees with previous measurement in the overlapping, mid-central bin [5].
- The results (red) on the right-hand plot are from QM2017, when different p_T bins were used. The result from the newer p_T binning is consistent in this mid-central region.
- $v_2^{h^\pm}$ extracted from [4].

[3] D. Kettler, D. Prindle, and T. Trainor PRC 91, 064910 (2015)
[4] G. Agakishiev *et al.* (STAR Collaboration) PRC 86, 064902 (2012)
[5] L. Adamczyk et al. (STAR Collaboration) PRL 118, 212301 (2017)

Fit-Parameter Results (for the Near-Side Peak)







Near-side peak

- First measurement containing $\Delta\eta$-dependence of D^0-hadron correlations.
- Broadening of near-side jet-like peak seen in both $\Delta\eta$ and $\Delta\phi$ from 50-80% to 20-50% in centrality, but stays constant within errors from 20-50% to 0-20%.
- The peripheral centrality bin (50-80%) matches closely with what is seen in PYTHIA (tune parameters from [1,2]).

[1] S. Shi, X. Dong, M. Mustafa arXiv:1507.00614 (2015)
[2] L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. D 86, 072013 (2012)
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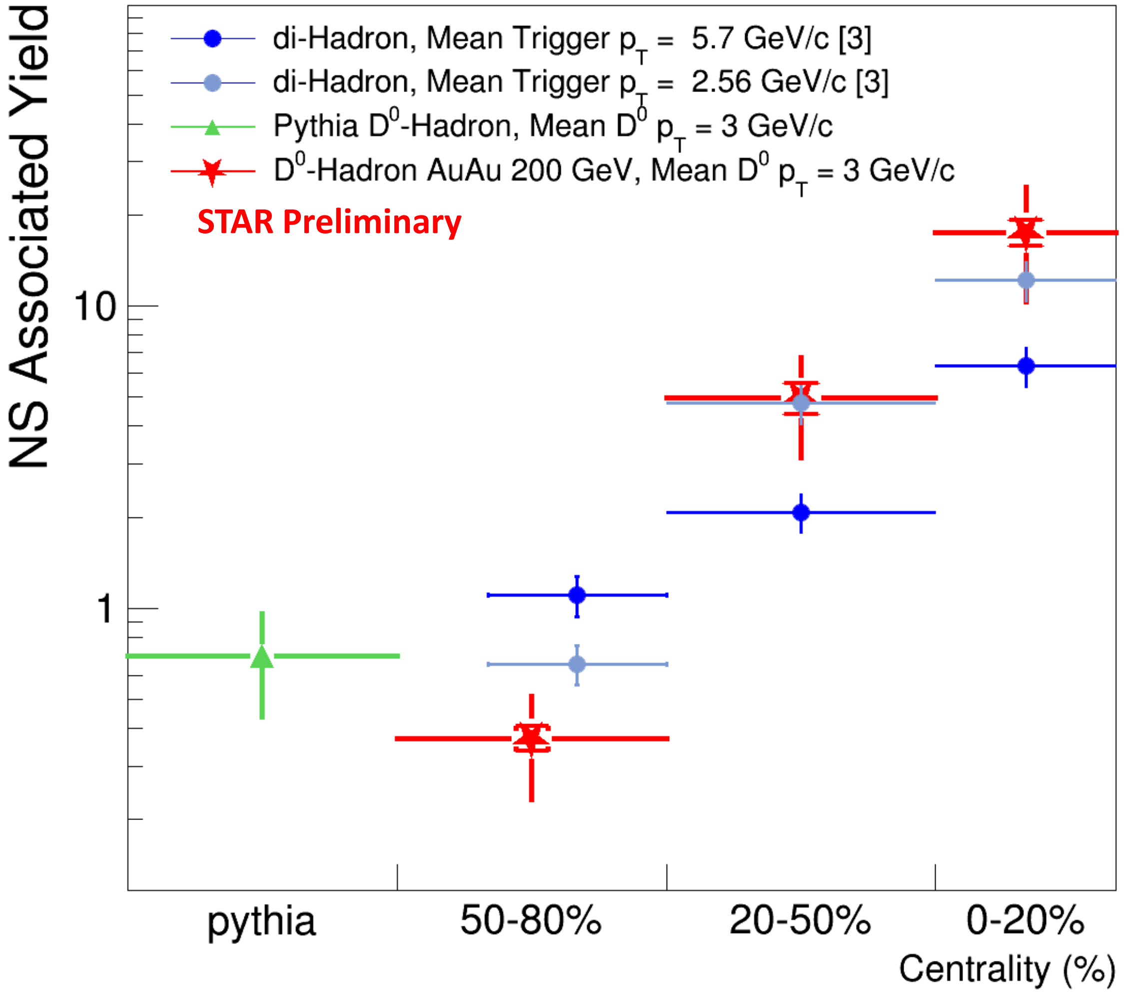
Near-Side Associated Yield Results



- NS associated yield increases with centrality.
- The trend with centrality is similar to the trends seen in light-flavor correlations at similar mean p_T.
- The NS associated yield in PYTHIA (Tune:[1,2]) is consistent with the yield in 50-80% Au+Au.

[1] S. Shi, X. Dong, M. Mustafa arXiv:1507.00614 (2015)
[2] L. Adamczyk *et al.* (STAR Collaboration) Phys. Rev. D 86, 072013 (2012)
[3] D. Kettler, D. Prindle, and T. Trainor PRC 91, 064910 (2015)
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- First measurement of 2D D^0-hadron angular correlations in heavy-ion collisions.
- Comparison of near-side widths and yields to light-flavor correlations at similar trigger mean-p_T indicate similar behavior of correlations with a light-flavor or heavy-flavor (charm) trigger.
- Near-side widths and yields in the 50-80% centrality agree with PYTHIA, indicating minimal effects of the medium on the jet-like peak, coincident with a non-zero value of v_2.

Thank you!

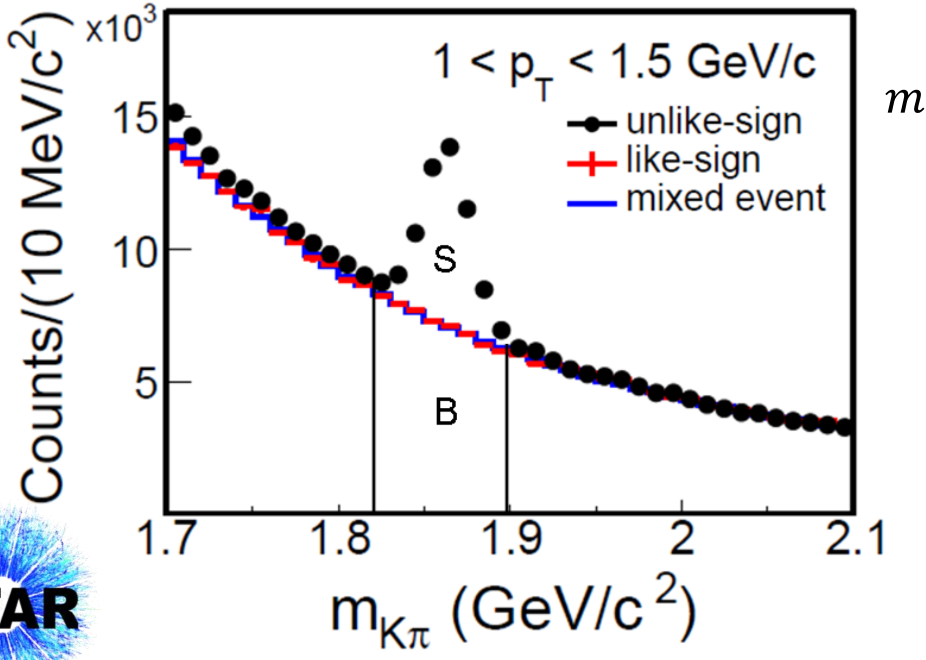
Backup

D^0 Reconstruction with the Heavy Flavor Tracker (HFT)

- Reconstructed via the hadronic decay channel ($D^0 (and\ \overline{D}^0) \rightarrow K + \pi$; BR ~4%).
- Challenging due to high combinatorial background.
- The HFT enables high-precision reconstruction of the D^0 decay vertex, which allows for rejection of background.

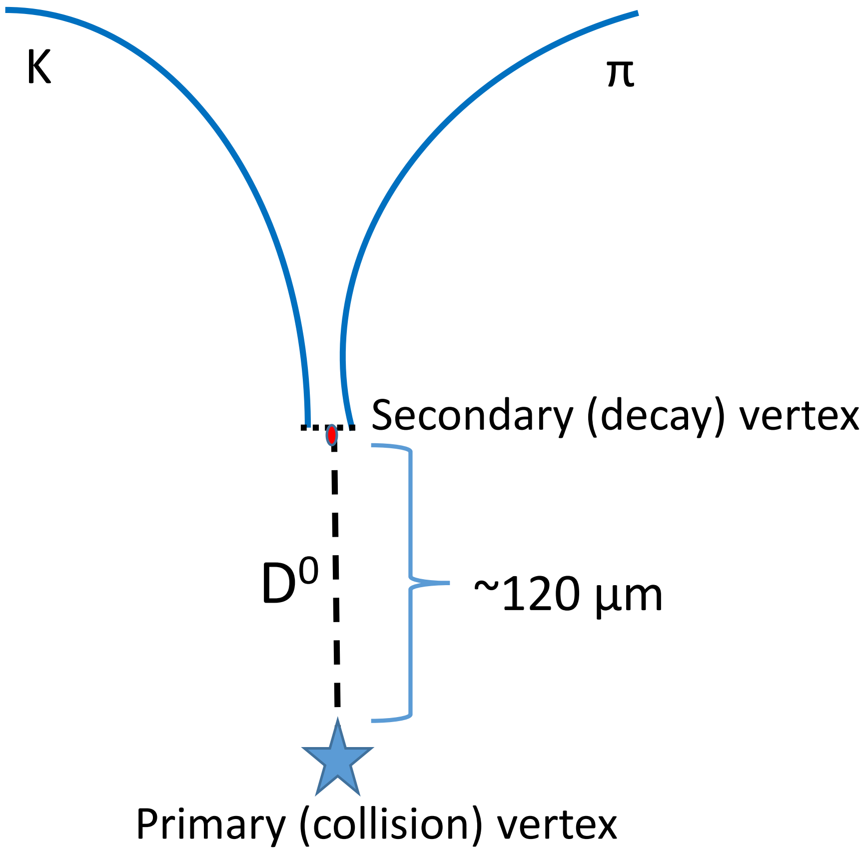
STAR Au+Au @ 200 GeV, 0-80%

Phys. Rev. Lett. 118, 212301(2017)



$$m_{D^0} = 1864.84\ \pm 0.05\ \mathrm{MeV}/c^2$$

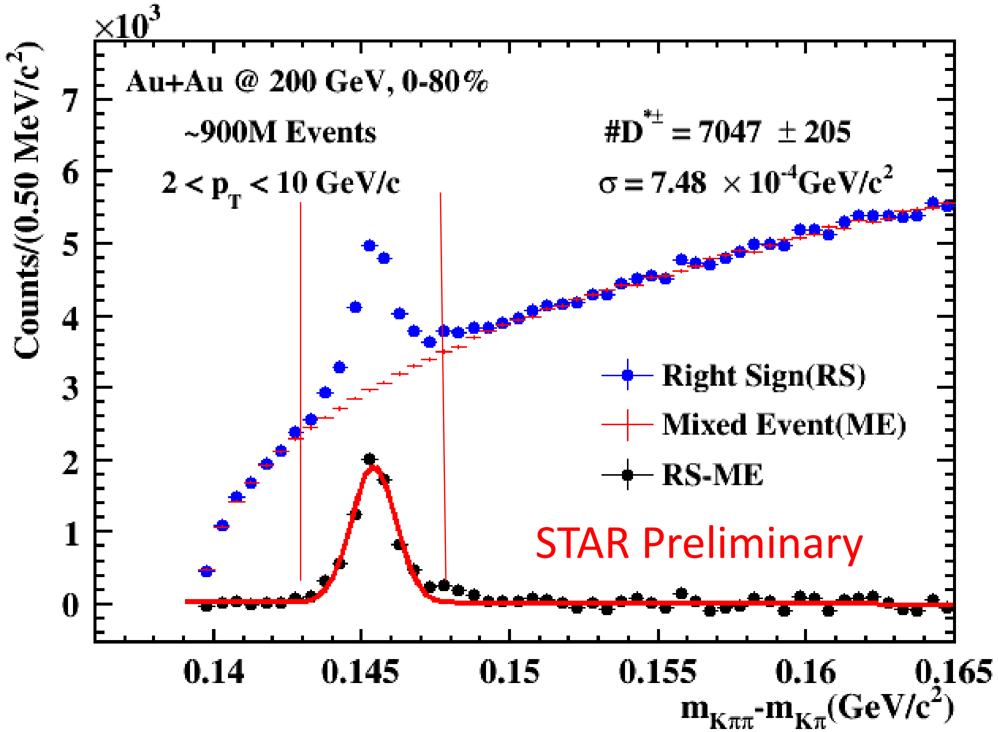
(PDG)



Sources of Systematic Uncertainties

- D^0 Reconstruction
  - B-meson feed down
  - Varying D^0 reconstruction topological cuts (e.g. decay length)
  - Extraction of D^0 signal and background yields
  - Varying position and width of sidebands for background
- Fitting
  - Varying model elements in fit
  - Best fits from various binning options on $(\Delta\eta, \Delta\phi)$
- Other important contributions
  - D* Correction
  - Secondary hadrons
  - Pileup (estimated from di-hadron correlations)

Removing D* Contamination



D+ production in Au+Au collisions at* $\sqrt{s_{\mathrm{NN}}}$*= 200 GeV measured by the STAR experiment*, Yuanjing Ji, Quark Matter 2018

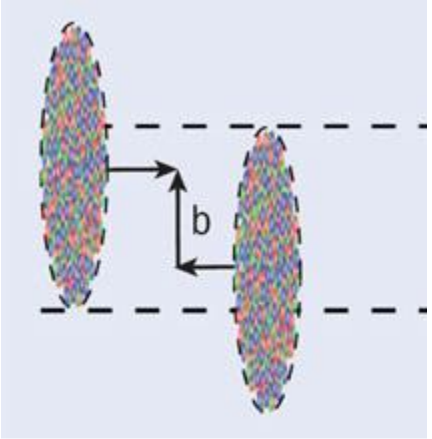
- We form an analogous correlation to our normal correlations.
  - The associated soft pion ($\pi^{\pm}_{soft}$):
    - .143 GeV< $M_{K\pi\pi\text{-soft}} - M_{K\pi}$ < .148 GeV (i.e. within the peak window for the D*).
    - Must be HFT-track (same as other associated cuts).
- This combination of same-event and mixed-event D^0-candidate+$\pi^{\pm}_{soft}$pairs are normalized and acceptance-corrected in the same way as the normal correlations, and the D* invariant mass background is removed.
- This correlation is subtracted from the D^0 “signal region” correlations.

Relevant Kinematic Variables

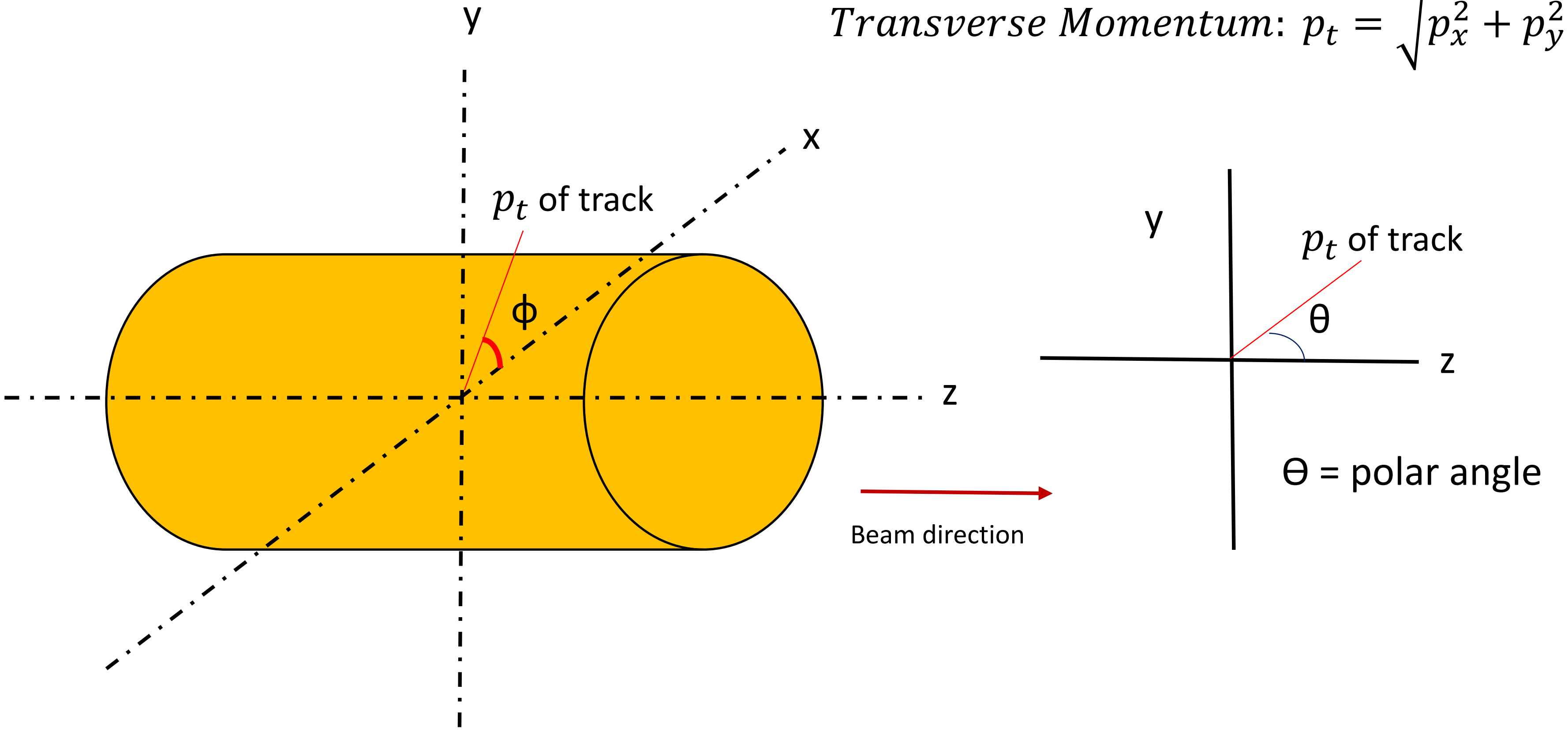
x-y plane: “transverse plane”

ϕ = azimuthal angle

$Transverse\ Momentum\!: p_t = \sqrt{p_x^2 + p_y^2}$



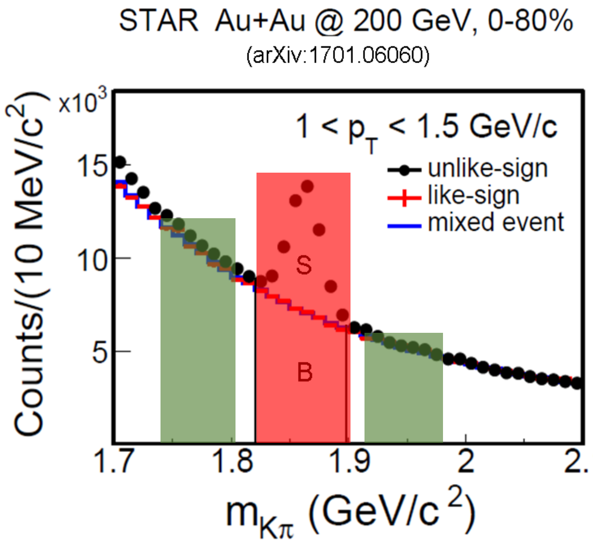
Centrality: a measure of the overlap of the colliding nuclei via track multiplicity or deposited energy. We cannot directly measure the impact parameter, b.



Θ = polar angle

Instead of the polar angle, which is not Lorentz-invariant, we use the $Pseudorapidity\!: \eta = -\ln\left[tan\left(\frac{\theta}{2}\right)\right]$, which is the rapidity in the high-energy limit, and is dependent on the polar angle.

Deriving our D^0-Hadron correlation measure


STAR Au+Au @ 200 GeV, 0-80%
(arXiv:1701.06060)

$$C_{signal} = C_{D^0+h} + C_{BG+h} + C_{D^*\to D^0+\pi_{soft}}$$

Where "C" refers to the number of true correlated pairs (e.g. $C = SE - \alpha ME$), and "signal" refers to pairs with triggers from the red-band, BG refers to BG triggers from the invariant mass spectrum and the D* term refers to the D^0 + π_{soft} pair from a D* decay.

$$corr. = \frac{C_{D^0+h}}{ME_{D^0+h}} = \frac{C_{signal}}{ME_{D^0+h}} - \frac{C_{BG+h}}{ME_{D^0+h}} - \frac{C_{D^*\to D^0+\pi_{soft}}}{ME_{D^0+h}}$$

$$\frac{C_{signal}}{ME_{D^0+h}} = \frac{\alpha_{signal}ME_{signal}}{ME_{D^0+h}}\frac{C_{signal}}{\alpha_{signal}ME_{signal}} \cong \frac{S+B}{S}\frac{C_{signal}}{\alpha_{signal}ME_{signal}}$$

$$\frac{C_{BG+h}}{ME_{D^0+h}} = \frac{\alpha_{BG+h}ME_{BG+h}}{ME_{D^0+h}}\frac{C_{BG+h}}{\alpha_{BG+h}ME_{BG+h}} \cong \frac{B}{S}\frac{C_{BG+h}}{\alpha_{BG+h}ME_{BG+h}} \cong \frac{B}{S}\frac{C_{SB+h}}{\alpha_{SB+h}ME_{SB+h}}$$

$$\frac{C_{D^*\to D^0+\pi_{soft}}}{ME_{D^0+h}} = \frac{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}}{ME_{D^0+h}}\frac{C_{D^*\to D^0+\pi_{soft}}}{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}} \cong \frac{S+B}{B}\frac{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}}{\alpha_{signal}ME_{signal}}\frac{C_{D^*\to D^0+\pi_{soft}}}{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}}$$

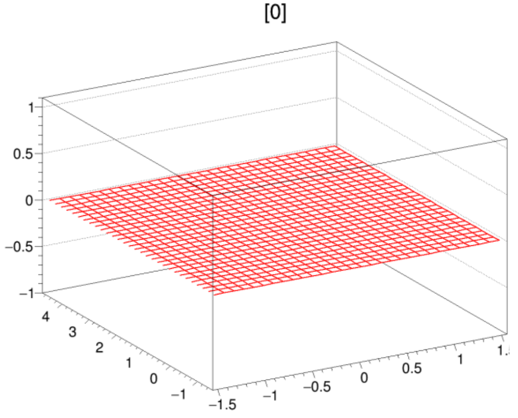
$$\boxed{\frac{C_{signal}}{ME_{D^0+h}} = \frac{S+B}{S}\frac{C_{signal}}{\alpha_{signal}ME_{signal}} - \frac{B}{S}\frac{C_{SB+h}}{\alpha_{SB+h}ME_{SB+h}} - \frac{S+B}{B}\frac{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}}{\alpha_{signal}ME_{signal}}\frac{C_{D^*\to D^0+\pi_{soft}}}{\alpha_{D^*\to D^0+\pi_{soft}}ME_{D^*\to D^0+\pi_{soft}}}}$$

STAR

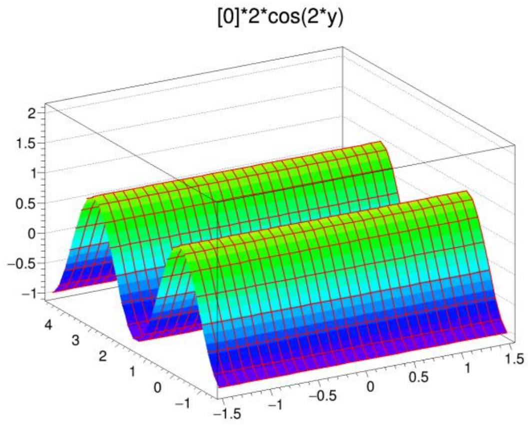
A simple mathematical model to fit the data

- We started with a simple fit-model with 8 parameters:
  - $A_0 + 2A_Q Cos(2\Delta\varphi) + A_{SS} e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{ss\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{ss\Delta\varphi}}} + A_{AS} e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{AS\Delta\eta}}} * e^{-\frac{1}{2}\frac{(\Delta\varphi-\pi)^2}{\sigma^2_{AS\Delta\varphi}}} + periodicity\ for\ \Delta\varphi\ Gaussian$

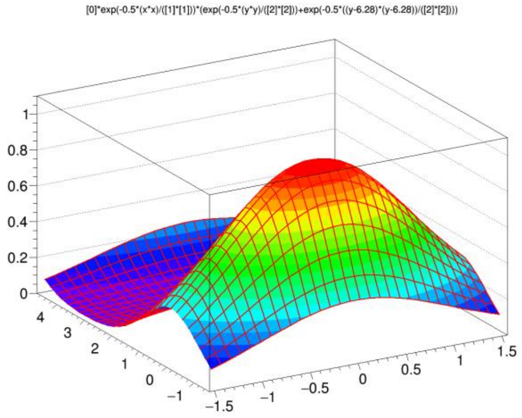
Constant-offset



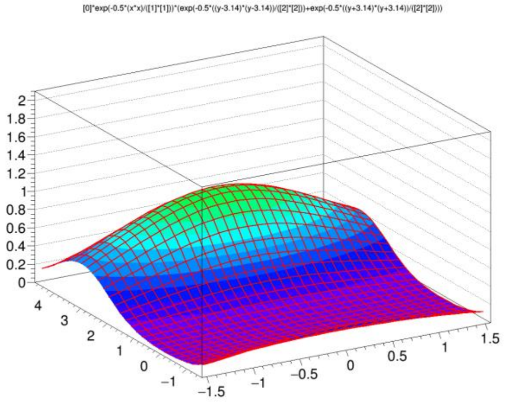
Quadrupole



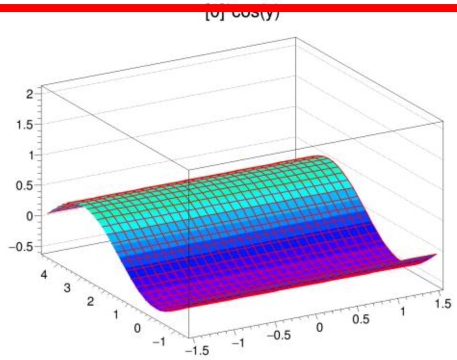
near-side 2D Gaussian



Away-Side 2D Gaussian



Note: if the away-side is very broad on $\Delta\varphi$ ($\sigma_{\Delta\varphi}\sim 1\ or\ more$), the Gaussian limits to a "dipole" (i.e. $A_D Cos(\Delta\varphi)$) due to its periodicity.



Dipole limit

Relating the Quadrupole Amplitude (A_Q) to v_2

$$\frac{dN}{d\varphi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_R))$$ Fourier decomposition of single-particle distribution on φ.

$$\left\langle \frac{dN_D}{d\varphi}\frac{dN_h}{d\varphi} \right\rangle_{\Psi} = \left\langle \left(1 + 2\sum_{n=1}^{\infty} v_n^D \cos(n(\varphi_D - \Psi_R))\right)\left(1 + 2\sum_{n=1}^{\infty} v_n^h \cos(n(\varphi_h - \Psi_R))\right) \right\rangle$$

Average of the product of the single-particle distributions over all the reaction-plane angles in all events.

This is an azimuthal, two-particle correlation.

$$= 1 + 2\sum_{n=1}^{\infty} v_n^D v_n^h \cos(n(\varphi_D - \varphi_h))$$

$$\varphi_D - \varphi_h \equiv \Delta\varphi$$

$$= 1 + \boxed{2 v_2^D v_2^h \cos(2\Delta\varphi\ )} + \cdots$$

This n=2 term is exactly the quadrupole term used in the multi-parameter fit.

Calculating NS Associated Yield from Fit Parameters

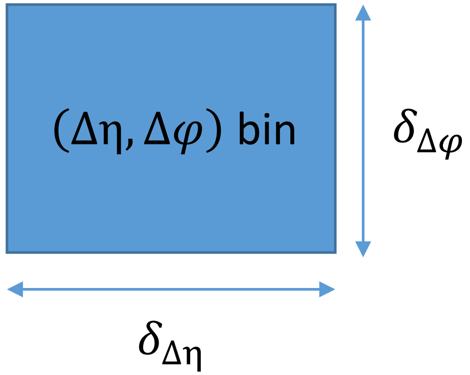
$$\frac{\Delta\rho^{D0}}{\rho^{D0}_{ref}} = \frac{\sum_{N_{events}}\left(n_{pairs,same}(\Delta\eta,\Delta\varphi) - \beta n_{pairs,mix}(\Delta\eta,\Delta\varphi)\right)}{\frac{2N_{events}\langle n_{D0}\rangle\langle n_{hadrons}\rangle}{N_{\Delta\varphi}N_{\Delta\eta}}\left(1-\frac{|\Delta\eta|}{f_{\eta,accep}}\right)}$$

To get the NS associated yield, we want to integrate the NS peak.

$$= \frac{N_{\Delta\varphi}N_{\Delta\eta}}{2N_{events}\langle n_{D0}\rangle\langle n_{hadrons}\rangle} \underbrace{\sum_{\Delta\eta\Delta\varphi:NS\ Peak}\left[\frac{\sum_{N_{events}}\left(n_{pairs,same}(\Delta\eta,\Delta\varphi) - \beta n_{pairs,mix}(\Delta\eta,\Delta\varphi)\right)}{\left(1-\frac{|\Delta\eta|}{f_{\eta,accep}}\right)}\right]}_{N_{pairs,NS\ peak}}$$

$$\underbrace{\frac{N_{pairs,NS\ peak}}{N_{events}\langle n_{D0}\rangle}}_{\text{NS Associated yield}} \cong \frac{2\langle n_{hadrons}\rangle}{N_{\Delta\varphi}N_{\Delta\eta}} \sum_{\Delta\eta\Delta\varphi:NS\ Peak}\left[\frac{\Delta\rho^{D0}}{\rho^{D0}_{ref}}\right]_{NS\ Peak}$$

$$\boxed{Y_{NS,Assoc.} \cong \frac{2\langle n_{hadrons}\rangle}{N_{\Delta\varphi}N_{\Delta\eta}}\frac{1}{\delta_{\Delta\varphi}\delta_{\Delta\eta}}\iint d\Delta\eta\, d\Delta\varphi\, A_{NS}\, e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{ss\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{ss\Delta\varphi}}}}$$



$$\boxed{\beta = mixed\ event\ norm.}$$

$$\boxed{N_{\Delta\varphi}, N_{\Delta\eta} = number\ of\ \Delta\varphi\ and \Delta\eta\ bins}$$

$$\boxed{\begin{array}{c} f_{\eta,accep} = 2 \\ \text{STAR acceptance} \end{array}}$$

$$\boxed{N_{events}\langle n_{D0}\rangle = total\ D^0s}$$

$$\boxed{\frac{\Delta\rho^{D0}}{\left(1-\frac{|\Delta\eta|}{f_{\eta,accep}}\right)} = \begin{array}{c} acceptance\ corrected \\ \#\ of\ correlated\ pairs \end{array}}$$