Two-Dimensional D^0–Hadron Angular Correlations in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV}$

Alexander Jentsch – For the *STAR Collaboration*

RHIC/AGS Users' Meeting – Brookhaven National Laboratory – Long Island, NY

June 12th - 15th, 2018

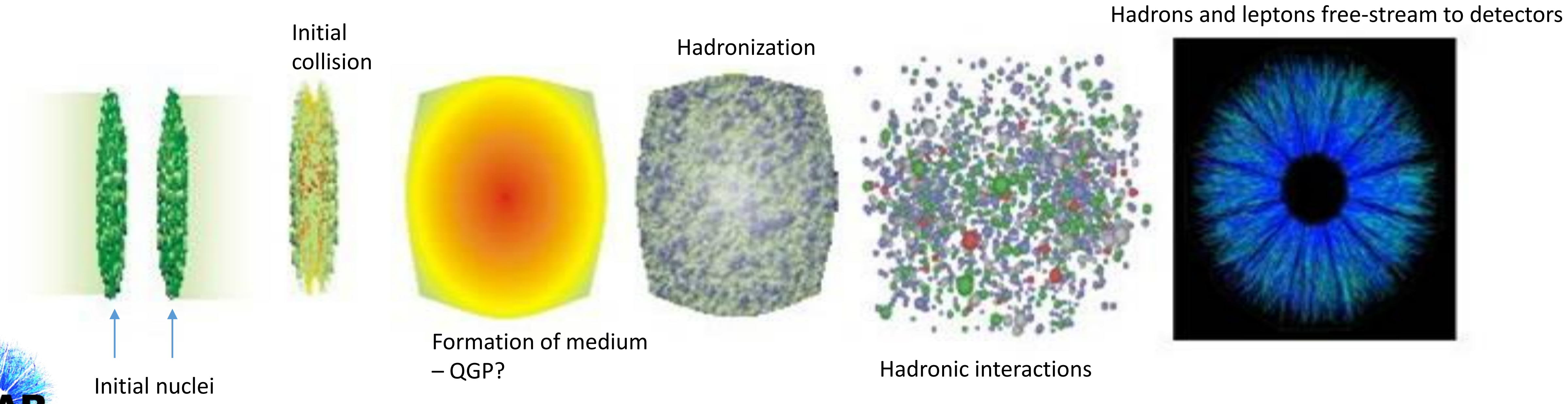
STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

TEXAS
The University of Texas at Austin

High Energy Nuclear Physics

- Enables the study of Quantum Chromodynamics (QCD) at high energy and density where QCD predicts the existence of a state of matter called the "Quark Gluon Plasma", characterized by deconfinement of quarks and gluons over nuclear distances.
- The QGP is studied experimentally in ultra-relativistic heavy-ion collisions.



Experimental Study of Heavy Ion Physics

- Lots of data have been studied from the heavy ion collisions at STAR.

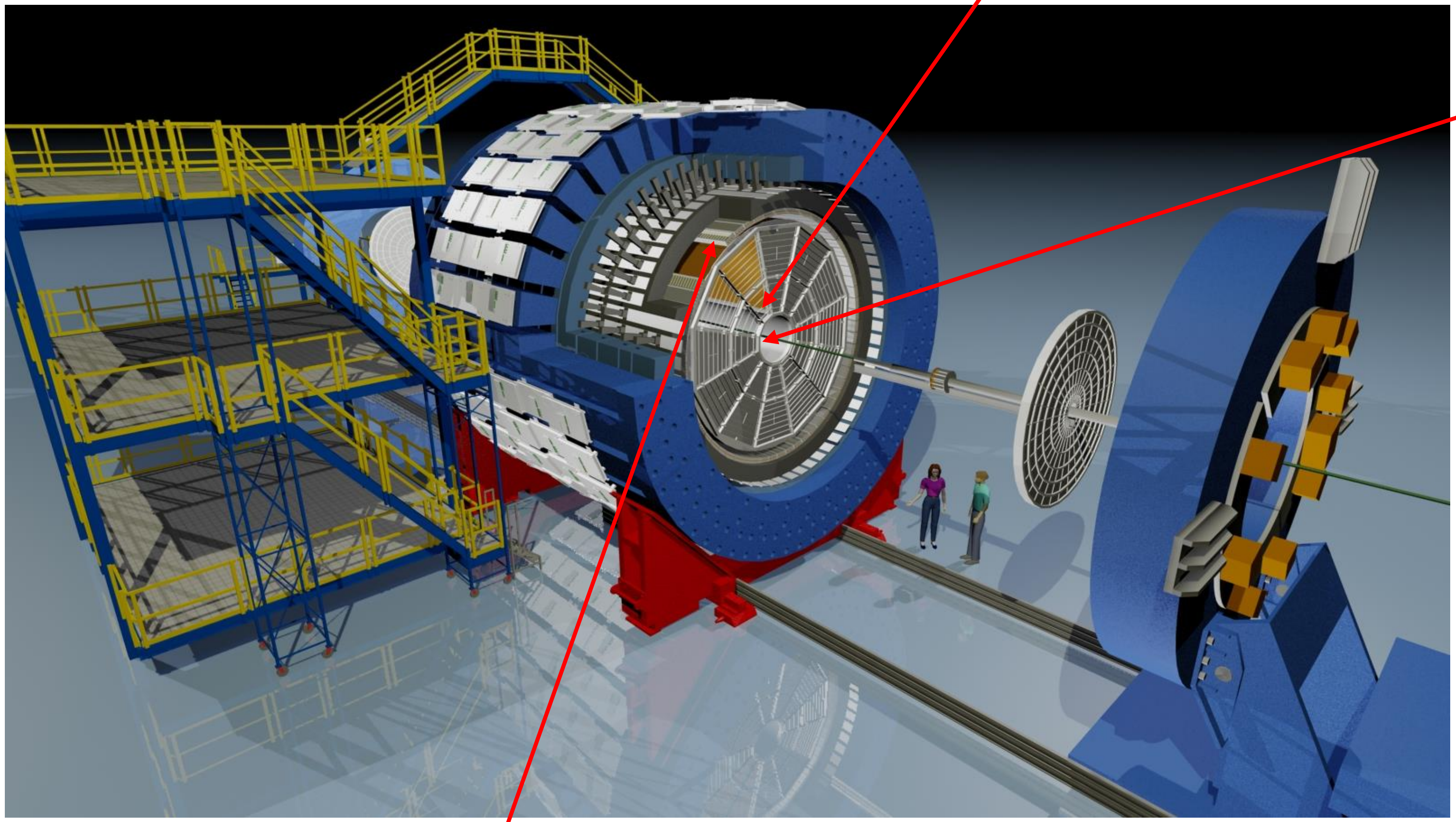
	Light Flavor (u,d,s)	Heavy Flavor (c,b)
Single-particle measurements (e.g. momentum distributions)	Measured for many particle species	Measured for many particles (D^0,$D^{+/-}$, D*, ϒ etc)
2-particle measurements (e.g. angular correlations)	Measured for mostly unidentified hadrons	Very few measurements (my analysis will add to this region)

- What is special about heavy-flavor quarks (c,b)?
  - Formed in initial stage of collisions by hard-scattering processes – sensitive to the entire evolution of the collision system.
  - May interact differently with the medium than (u,d,s) due to greater mass.

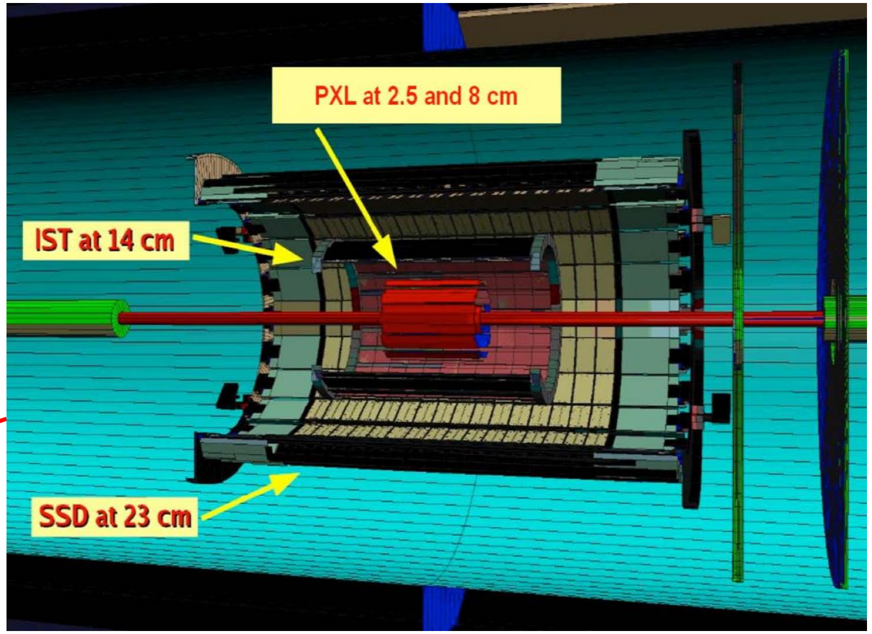
I am specifically studying the $\mathbf{D^0}(\mathbf{c\bar{u}})$ & $\overline{\mathbf{D^0}}(\bar{c}u)$ mesons in my analysis.

Schematic View of STAR

Time Projection Chamber (TPC)



Time of Flight (TOF)



Heavy Flavor Tracker (HFT)

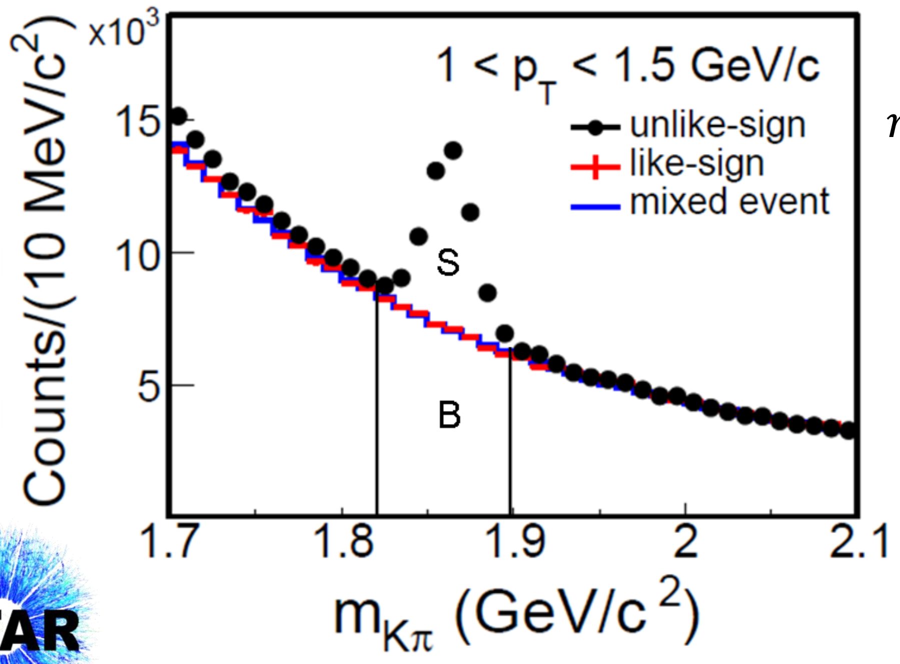
- Up to ~1500 tracks in the detector in a $\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au head-on (central) collision.
- Tracks are reconstructed from many different "hits" throughout the STAR detector.
- Many different species of particles are created in the collisions and detected by STAR.

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

- Reconstructed via the hadronic decay channel (D^0->K+π; BR ~4%).
- Challenging due to high combinatorial background.
- The HFT enables reduction of such background by allowing reconstruction of D^0 decay vertex.

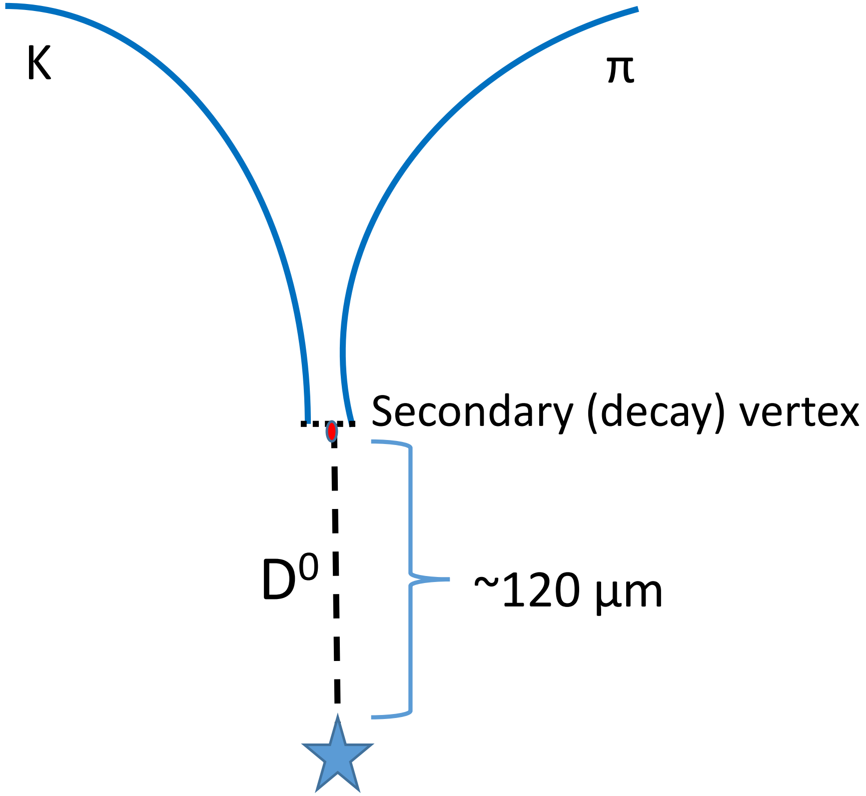
STAR Au+Au @ 200 GeV, 0-80%

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

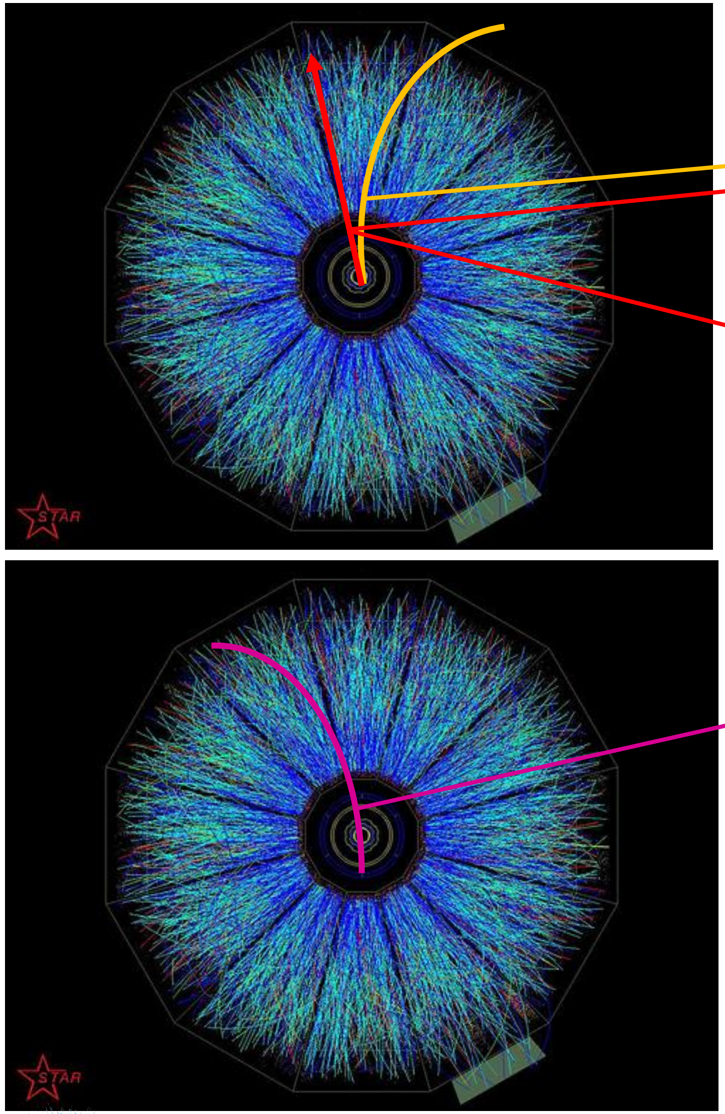


$$m_{D^0} = 1864.84 \pm 0.05 \text{ MeV}/c^2$$

(PDG)

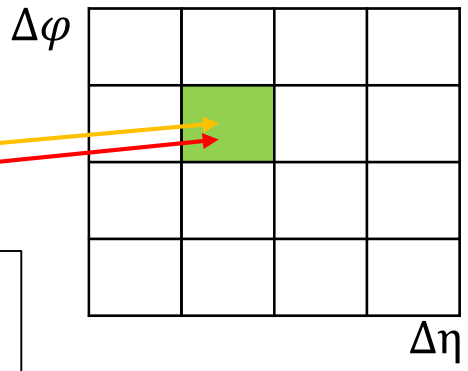


2D Angular Correlations

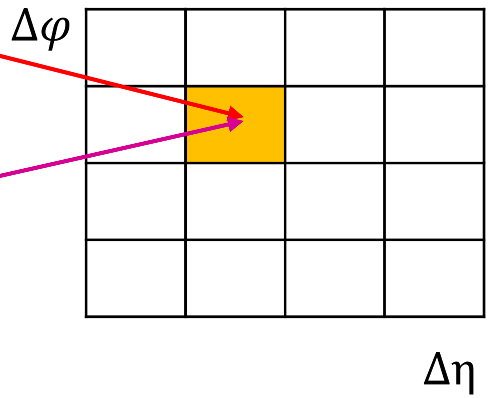


Trigger: D^0
Associated: $h^{\pm}$

Same event



Different event (mixed)



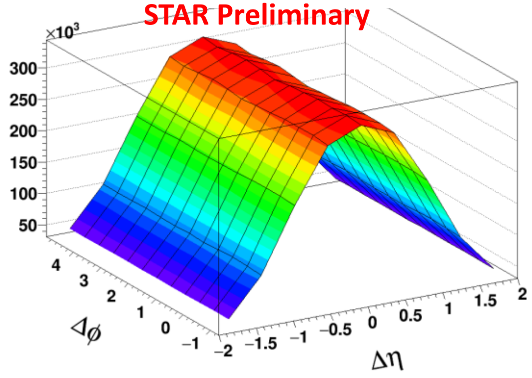
$$\rho_{same} = \frac{n_{same}}{\text{area of bin}}$$

$$\varphi_1 - \varphi_2 = \Delta\varphi$$

$$\eta_1 - \eta_2 = \Delta\eta$$

$$\rho_{mix} = \frac{n_{mix}\left(\frac{N_{same}}{N_{mix}}\right)}{\text{area of bin}}$$

$N = total\ entries\ in\ histogram$
$n = total\ entries\ in\ bin$
$\rho = two\ particle\ density$



Raw distributions are dominated by uncorrelated background and pair acceptance.

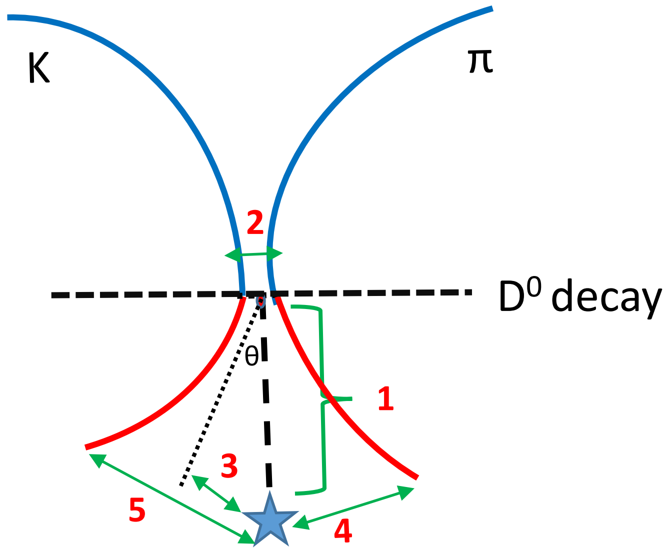
Correlation measure:

$$\frac{\Delta\rho}{\rho_{mix}} = \frac{\rho_{same} - \rho_{mix}}{\rho_{mix}} = \frac{\rho_{same}}{\rho_{mix}} - 1$$

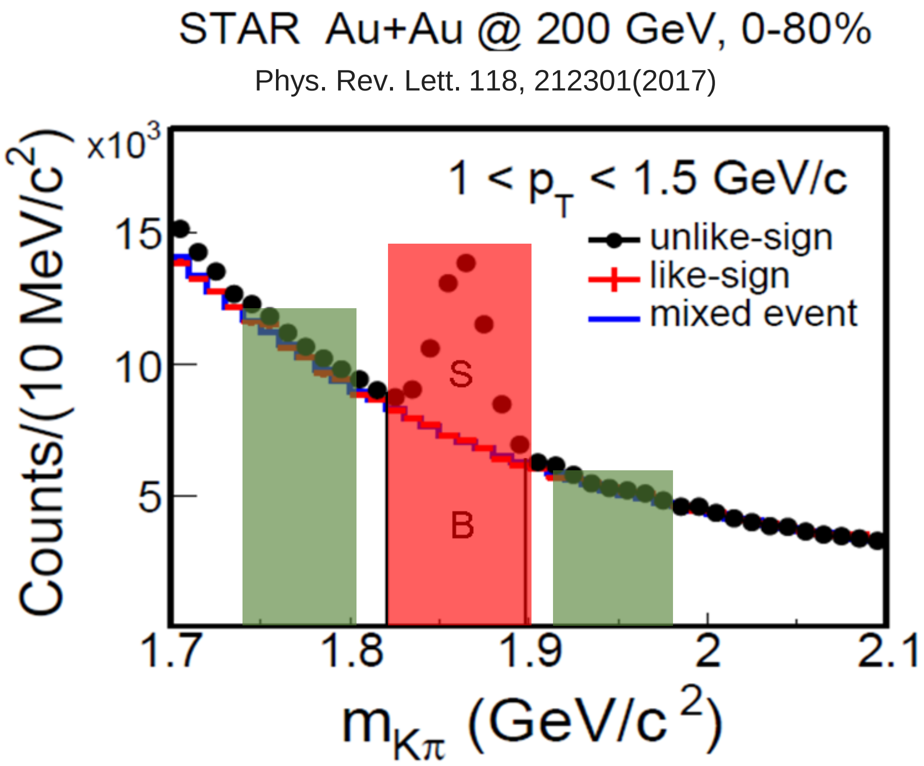
Event and Track Selection

- Event Selection
  - Minimum-bias events (~900M) from RHIC Run14.
  - Primary vertex $|V_Z| < 6cm$
  - $\left|V_Z - V_{Z,VPD}\right| < 3cm$
- Track Selection
  - Global tracks
  - All tracks must be "HFT" tracks
  - D^0 Reconstruction (trigger)
    - Wide p_T-bin (2-10 GeV/c) $\rightarrow$ cuts for the 2-3 GeV/c bin used.
    - K and π ID with TPC dE/dx
  - Associated hadron cuts (associated)
    - $|\Delta\eta| < 1.0, p_T > 0.15$ GeV/c

D^0 p_T (GeV/c)	0-1	1-2	2-3	3-5	5-10
1) Decay Length (μm) >	145	181	212	247	259
2) DCA Daughters (μm) <	84	66	57	50	60
3) DCA D^0 and PV (μm) <	61	49	38	38	40
4) DCA daughter π and PV (μm) >	110	111	86	81	62
5) DCA daughter K and PV (μm) >	103	91	95	79	58



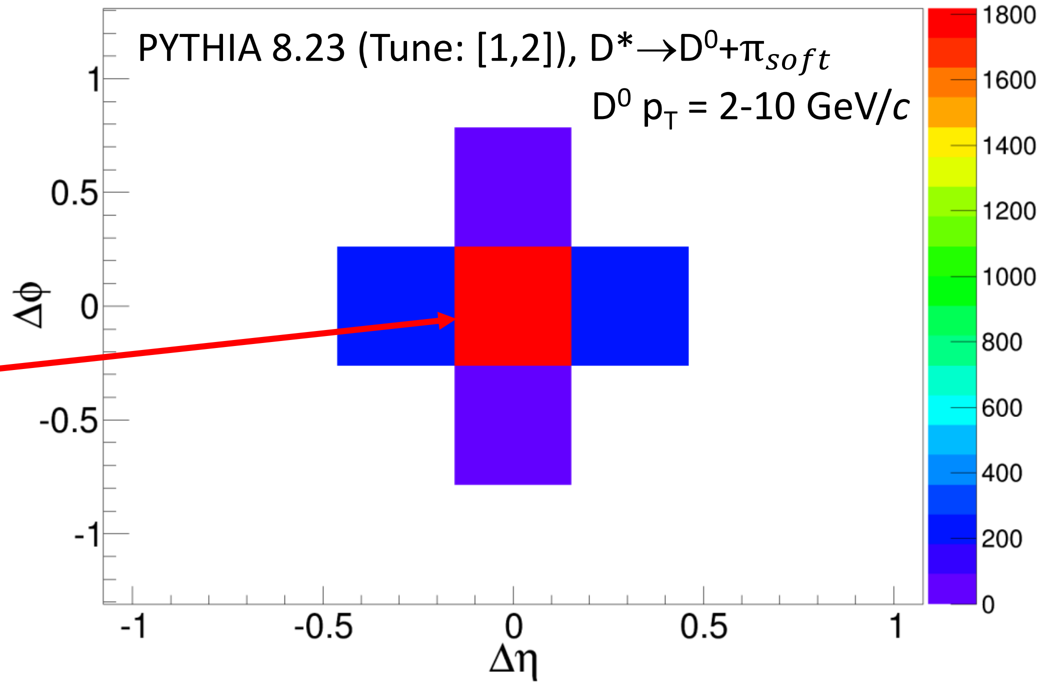
D^0 Invariant Mass Background Subtraction

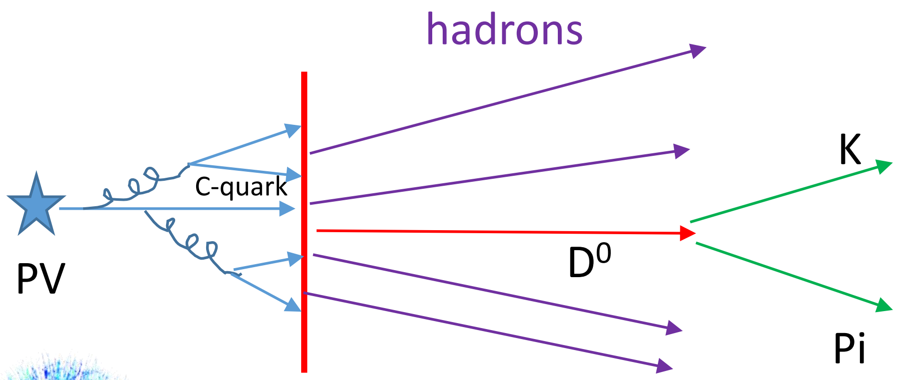


- The signal region (red band) of D^0 invariant mass distribution contains both real D^0s and random $K\pi$ pairs.
- Correlations are calculated using $K\pi$ pairs from sidebands in the invariant mass distribution (green bands).
- These normalized "sideband" correlations are then subtracted from those coming from the "signal region".

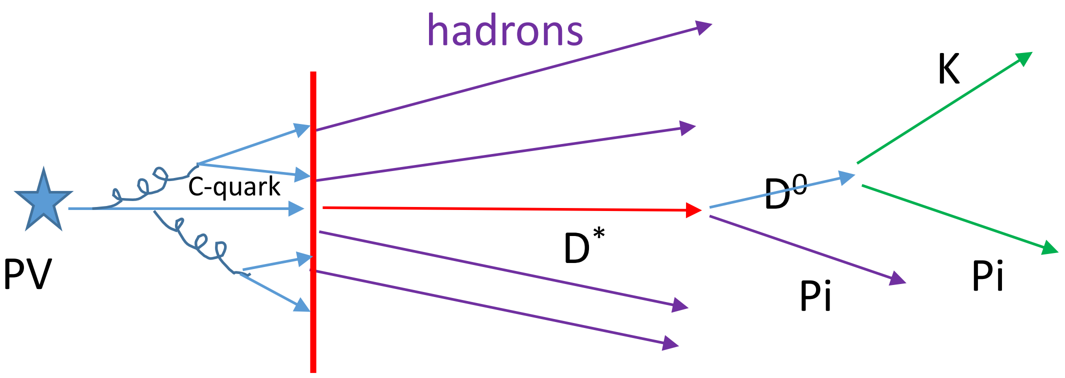
Additional Background from D* Decay

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





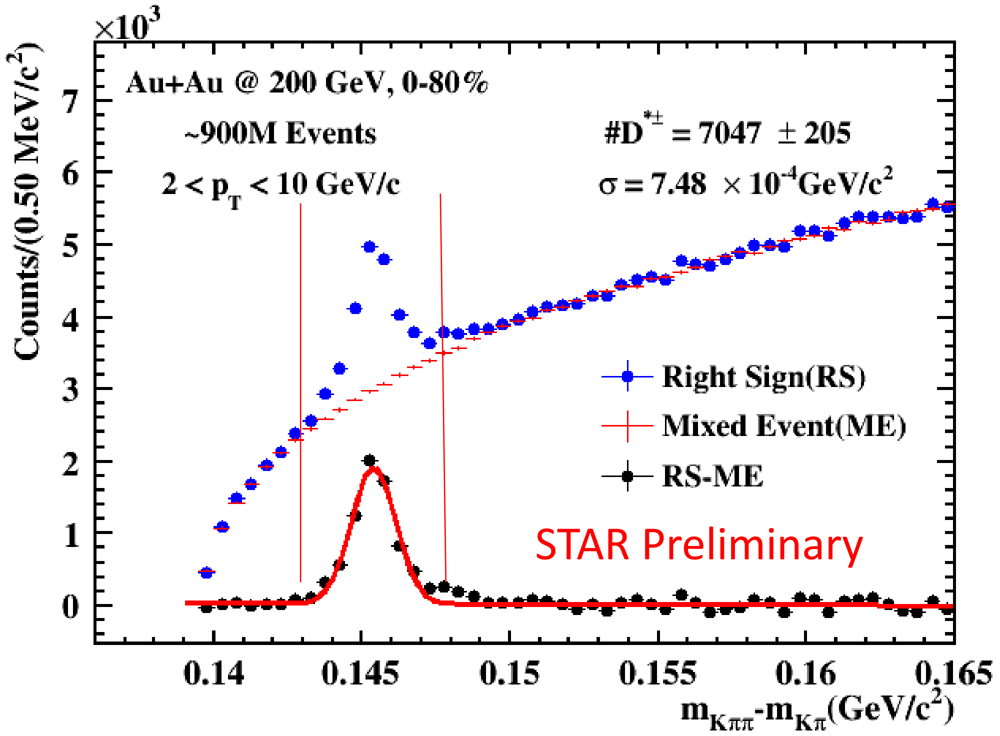
What we want.



What we DON'T want.

[1] arXiv:1507.00614 (2015)
[2] Phys. Rev. C **92**, 014910 *(2015)*

Removing D* Contamination

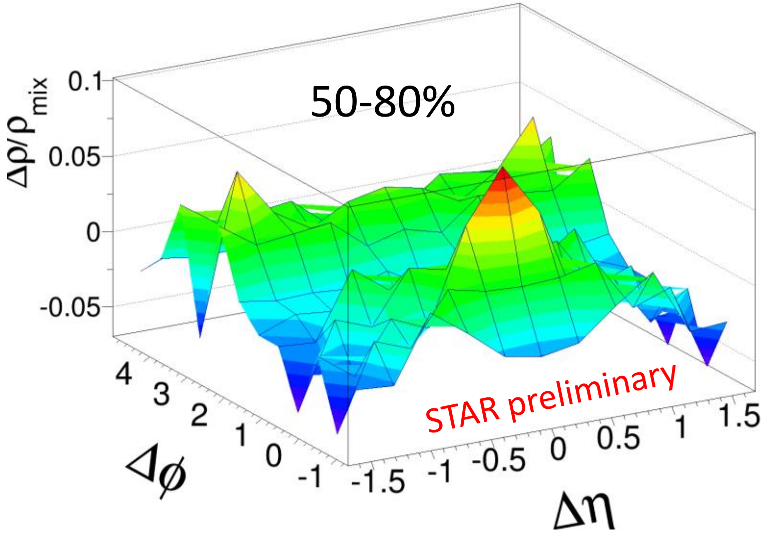


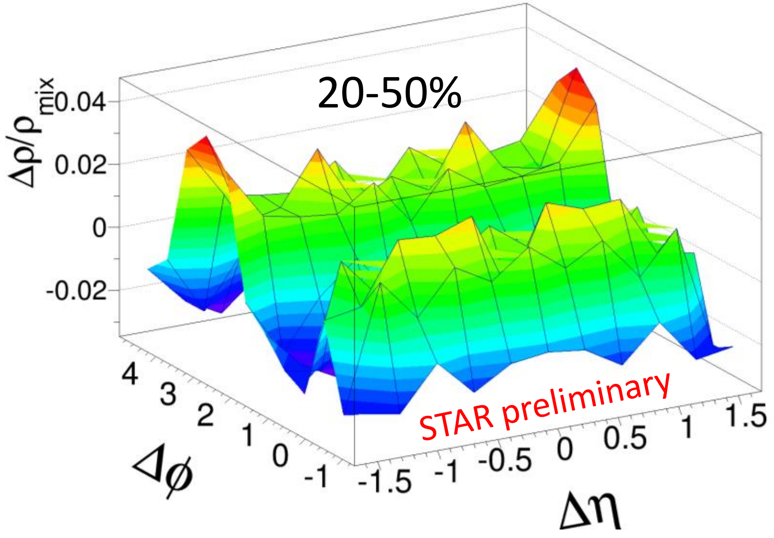
D+ production in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV measured by the STAR experiment*, Yuanjing Ji, Quark Matter 2018

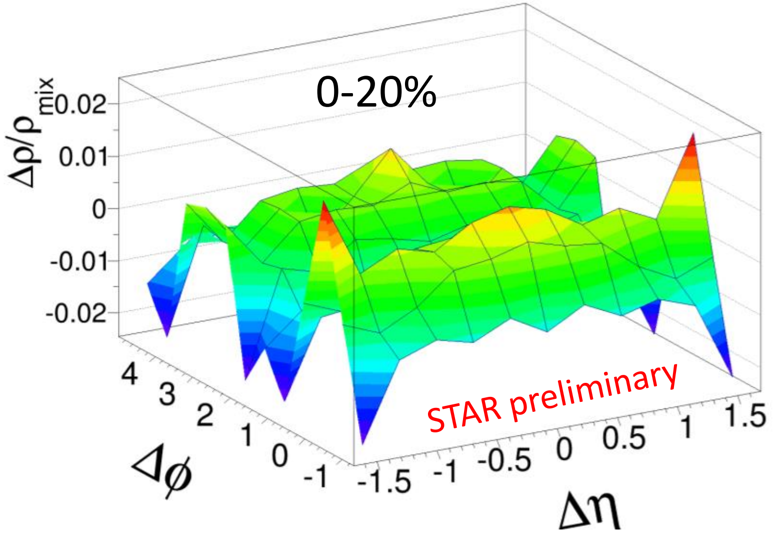
- We form an analogous correlation to our normal correlations.
  - The associated soft pion ($\pi^{\pm}_{soft}$):
    - .143 GeV< $M_{K\pi\pi\text{-soft}} - M_{K\pi}$ < .148 GeV (i.e. within the peak window for the D*).
    - Must be HFT-track (same as other associated cuts).
- This combination of same-event 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.

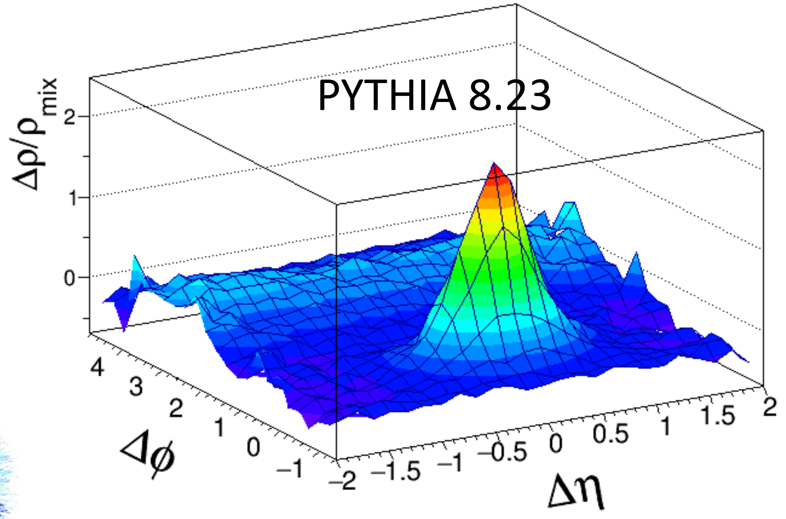
D^0-Hadron correlations in Au+Au $\sqrt{s_{NN}} = 200$ GeV
Symmetrized on ($\Delta\eta$,$\Delta\phi$), D^0 p_T = 2-10 GeV/c, $h^{\pm}$ p_T>.15 GeV/c

Increasing Centrality →









- Significant structure is seen on ($\Delta\eta$,$\Delta\phi$) that evolves with centrality.

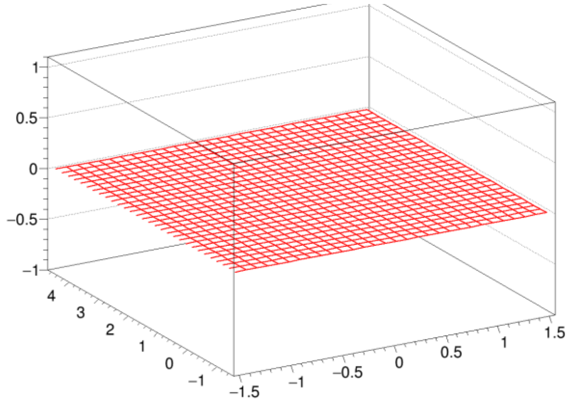
PYTHIA pp200 data sample (3M events) for D^0-Hadron correlations (D^0 p_T = 2-10 GeV/c, Tune: [1,2]).

[1] arXiv:1507.00614 (2015)
[2] Phys. Rev. C **92**, 014910 *(2015)*

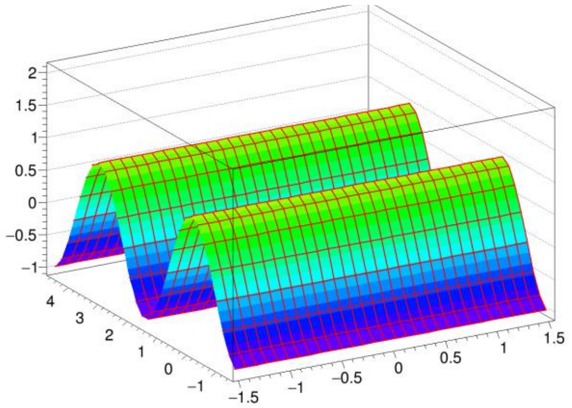
A Simple Mathematical Model to Fit the Data

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

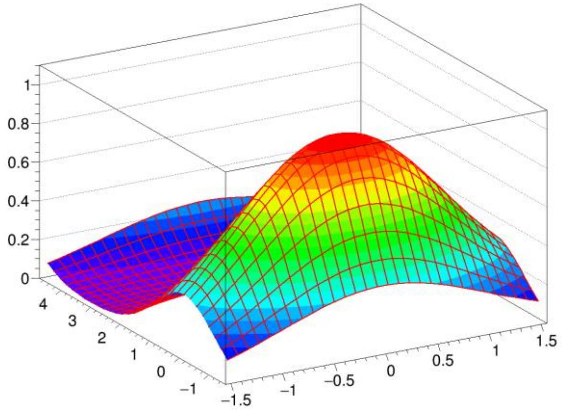
Constant-offset



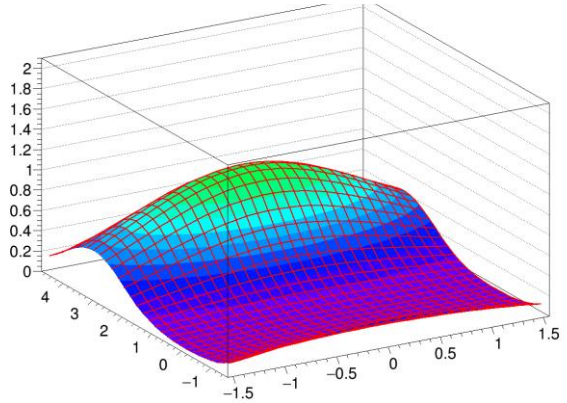
Quadrupole



Near-Side 2D Gaussian



Away-Side 2D Gaussian



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

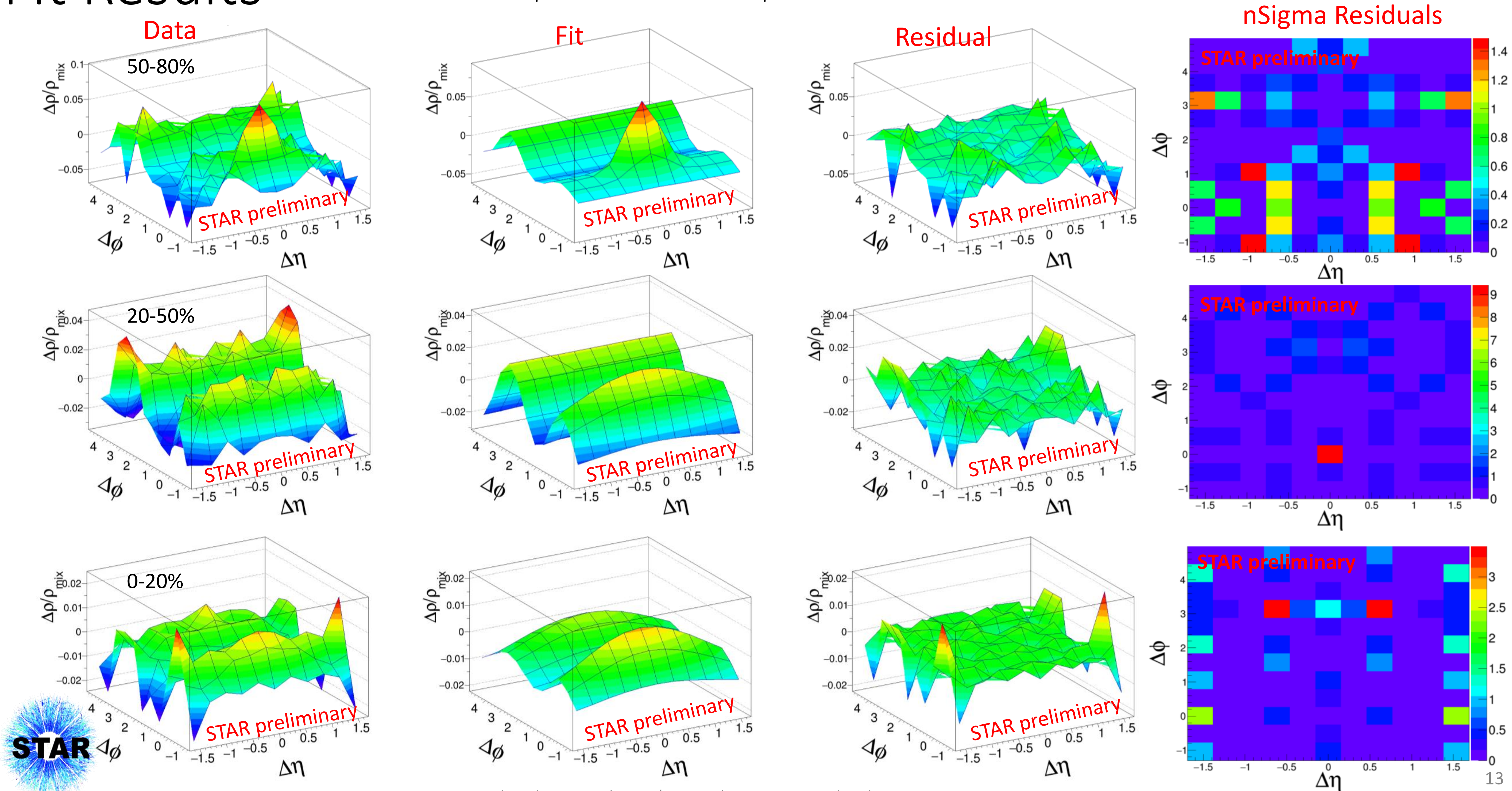
(details in backup)

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

STAR

Fit Results

D^0 p_T = 2-10 GeV/c, $h^{\pm}$ p_T>.15 GeV/c

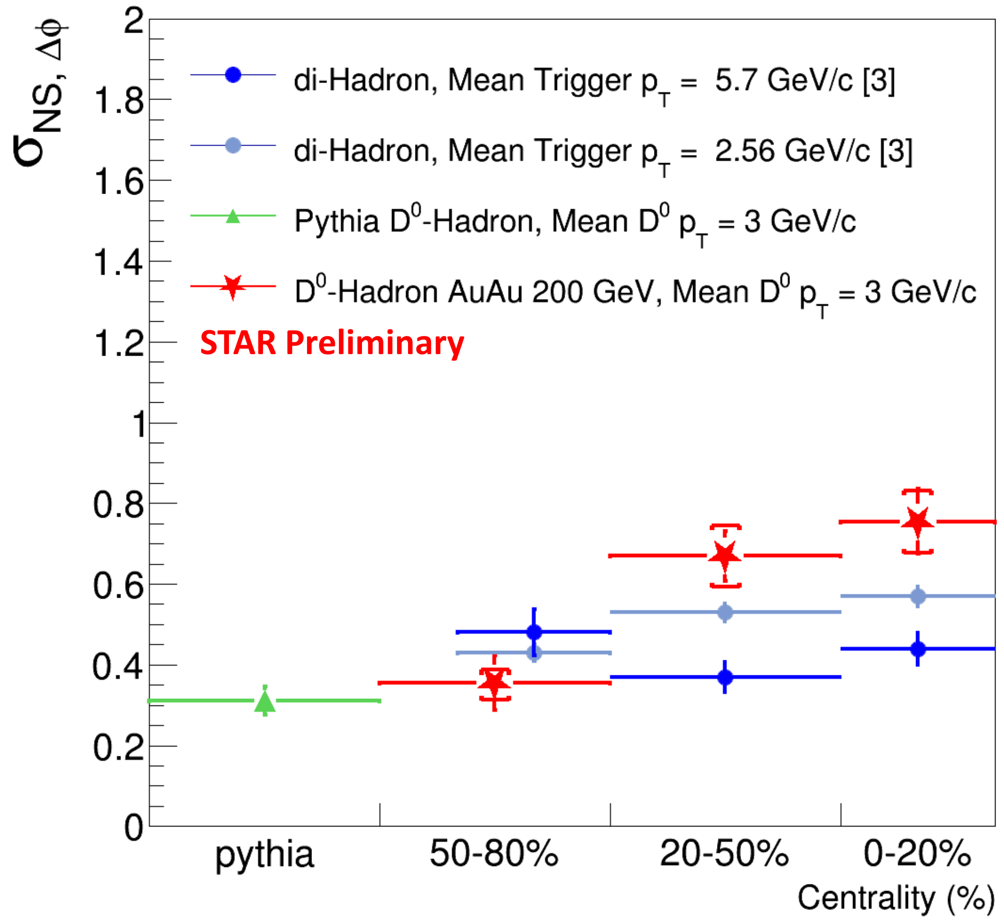


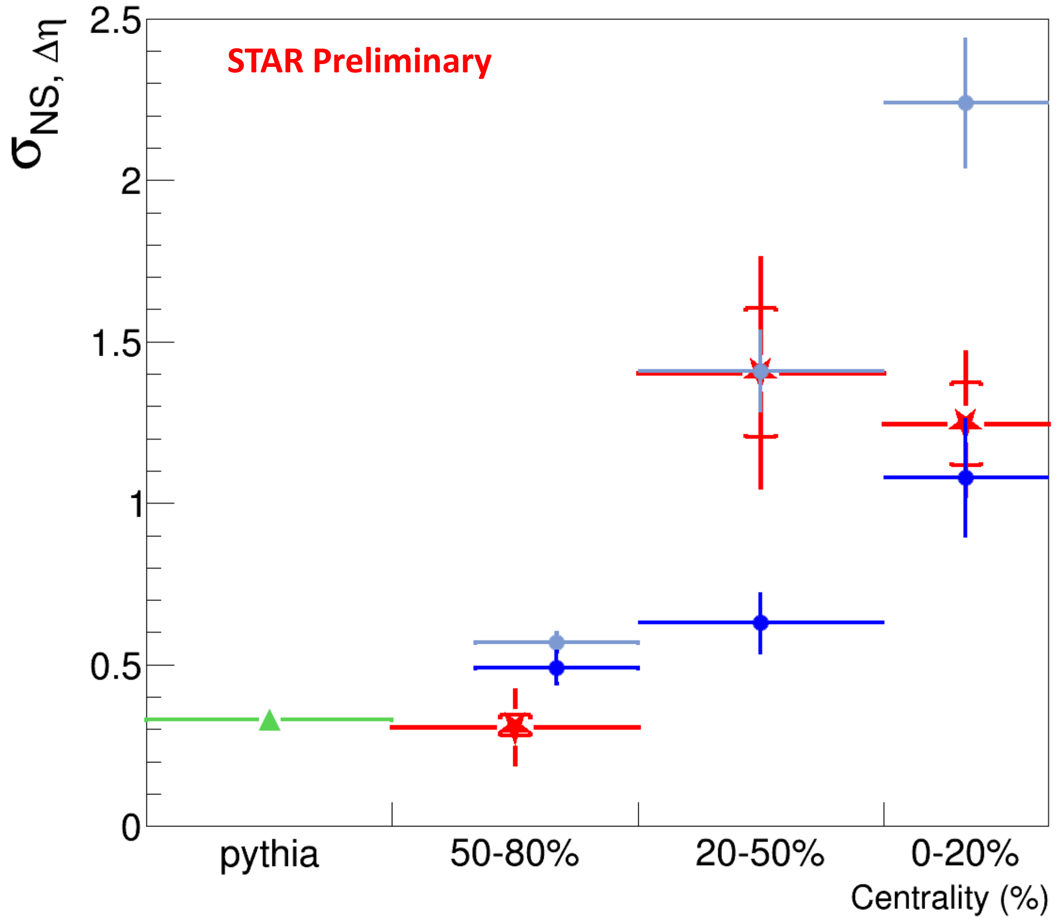
Sources of Systematic Uncertainties

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

STAR

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

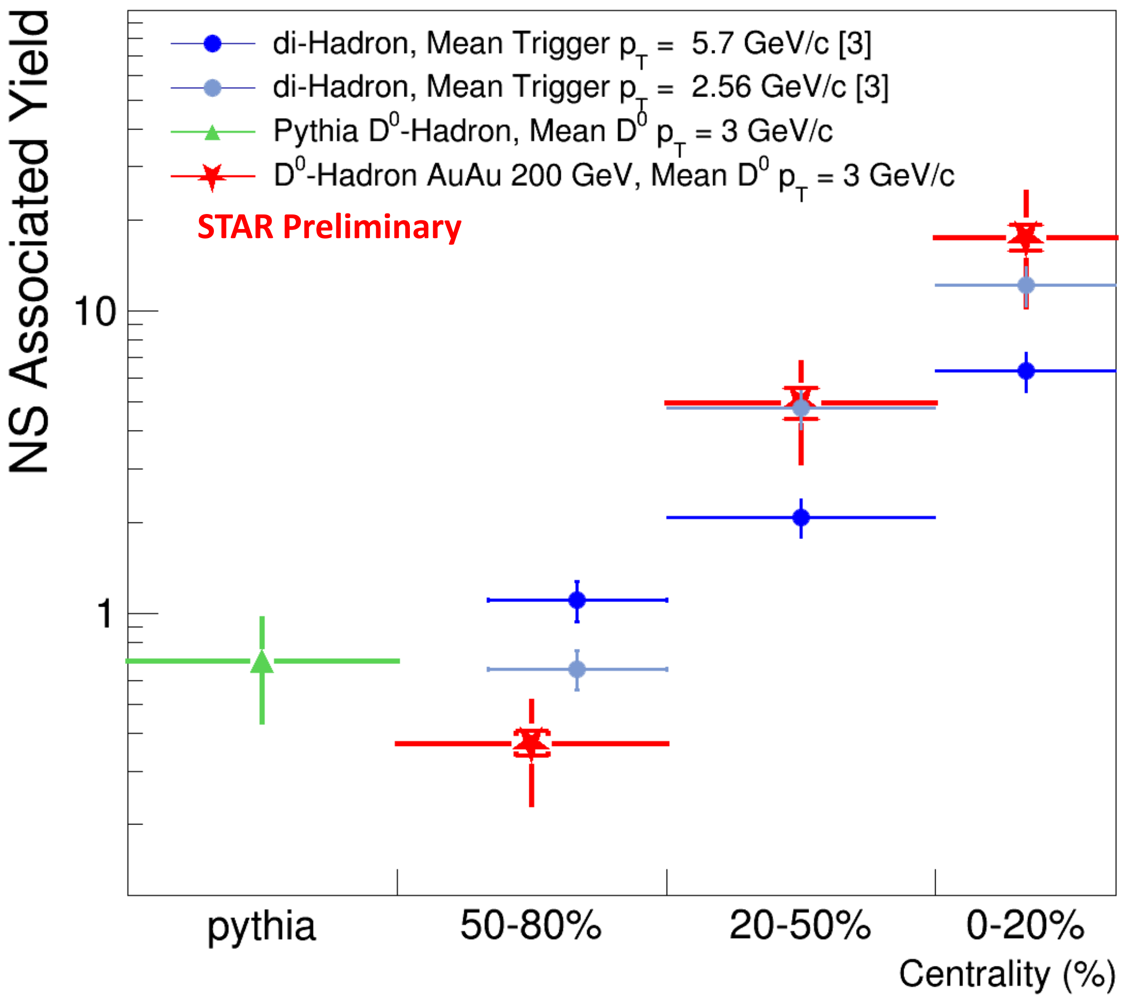




- First measurement containing Δη-dependence of D^0-hadron correlations.
- Broadening of near-side jet-like peak seen in both Δη and Δϕ from 50-80% to 20-50% in centrality, but stays constant within errors from 20-50% to 0-20%.
- The peripheral centrality bin (50-80%) matches closely with what is seen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

[1] arXiv:1507.00614 (2015)
[2] Phys. Rev. C **92**, 014910 *(2015)*
[3] PRC 91 064910 (2015)

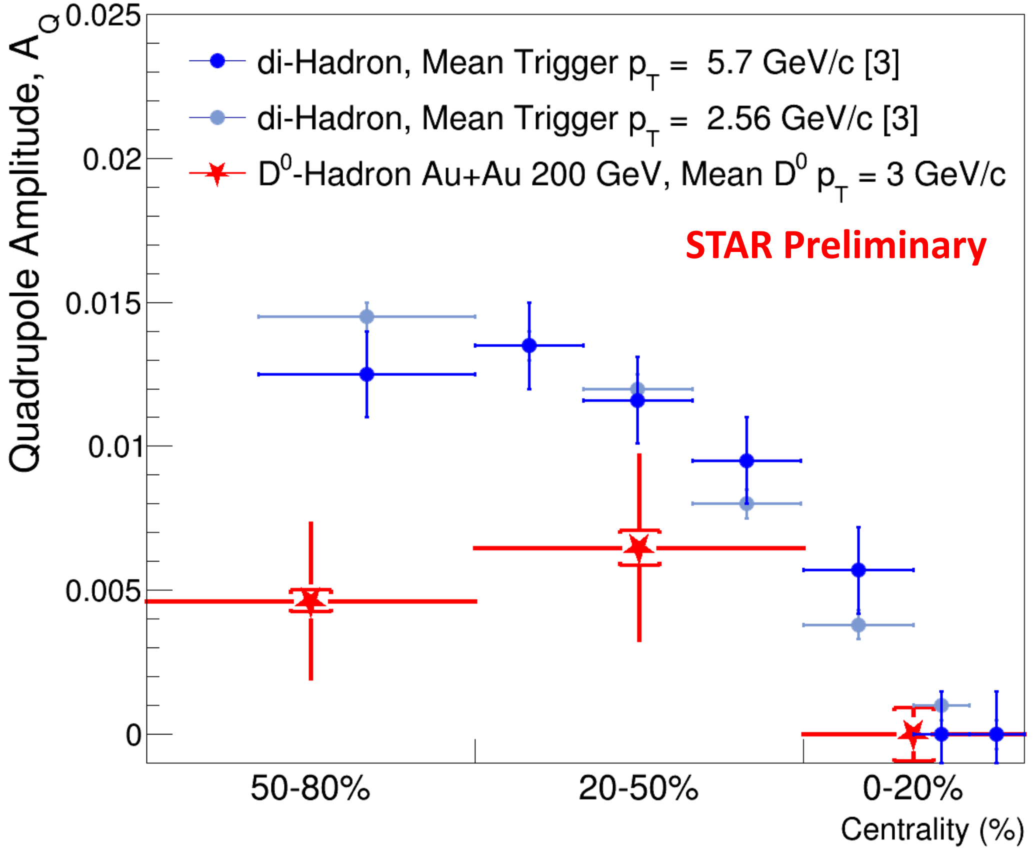
Near-Side Associated Yield Results

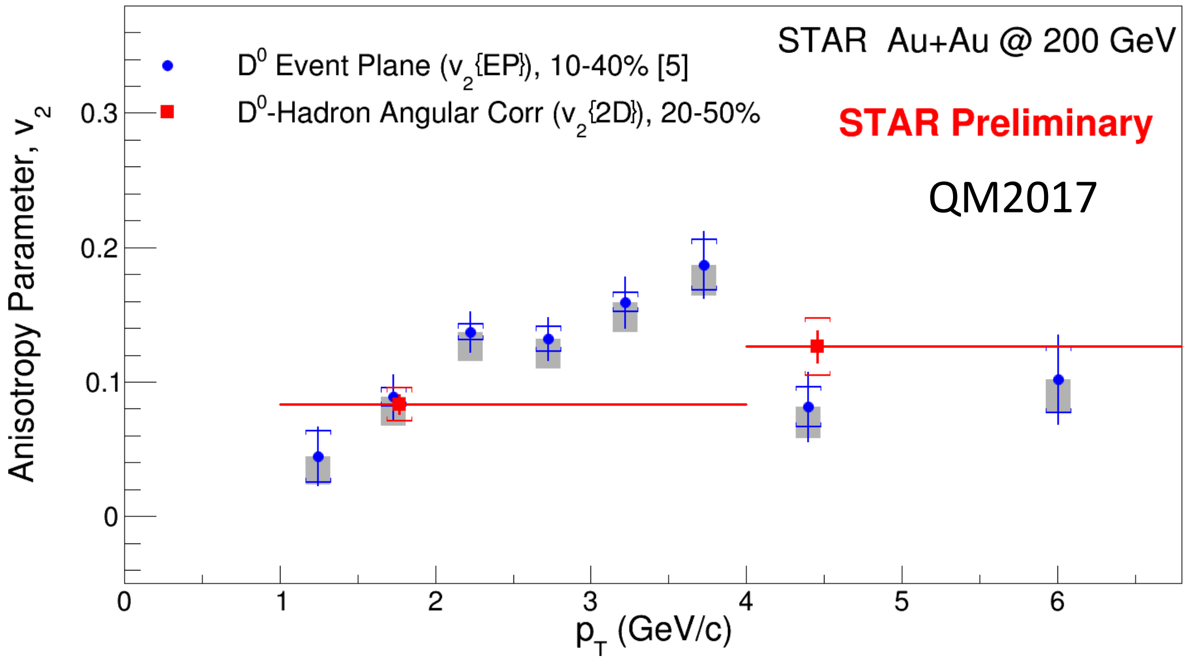


- NS associated yield increases with centrality.
- The trend with centrality is similar to the trends seen in light-flavor correlations at similar mean p_T.
- The NS associated yield in PYTHIA (Tune:[1,2]) is consistent with the yield in 50-80% Au+Au.
- Associated hadron averages ($\langle n_{h^{\pm}}(cent)\rangle$) obtained from [4].

[1] arXiv:1507.00614 (2015)
[2] Phys. Rev. C **92**, 014910 *(2015)*
[3] PRC 91 064910 (2015)
[4] PRC 86, 064902 (2012)

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 my newer binning is still consistent in this mid-central region.
- $v_2^{h^\pm}$ extracted from [4].

[3] PRC 91, 064910 (2015)
[4] PRC 86, 064902 (2012)
[5] PRL 118, 212301 (2017)

Conclusions

- First measurement of per-trigger yield and $\Delta\phi$-dependence of the near-side jet-like peak in D^0-hadron correlations in STAR.
- First measurement of the $\Delta\eta$-dependence of D^0-hadron correlations in heavy-ion collisions.
- Per-trigger yield increases with centrality similar to what is seen in light-flavor di-hadron correlations.
- The near-side widths on $\Delta\eta$ and $\Delta\phi$ in the 50-80% centrality agree with what is seen in PYTHIA, indicating minimal effects of the medium on the jet-like peak, coincident with a non-zero value of v_2.
- A large increase is seen in the near-side $\Delta\eta$-width from peripheral to mid-central collisions, which may indicate similar medium effects on both heavy and light-flavor quarks in heavy ion collisions.

Thank you!

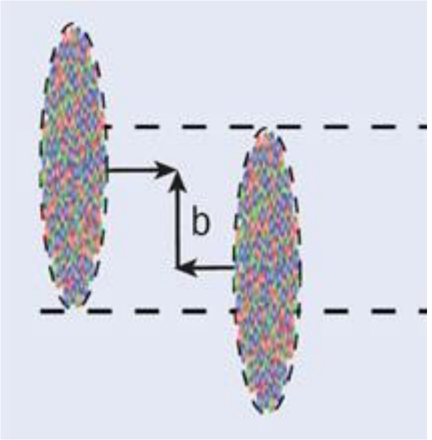
Backup

Relevant Kinematic Variables

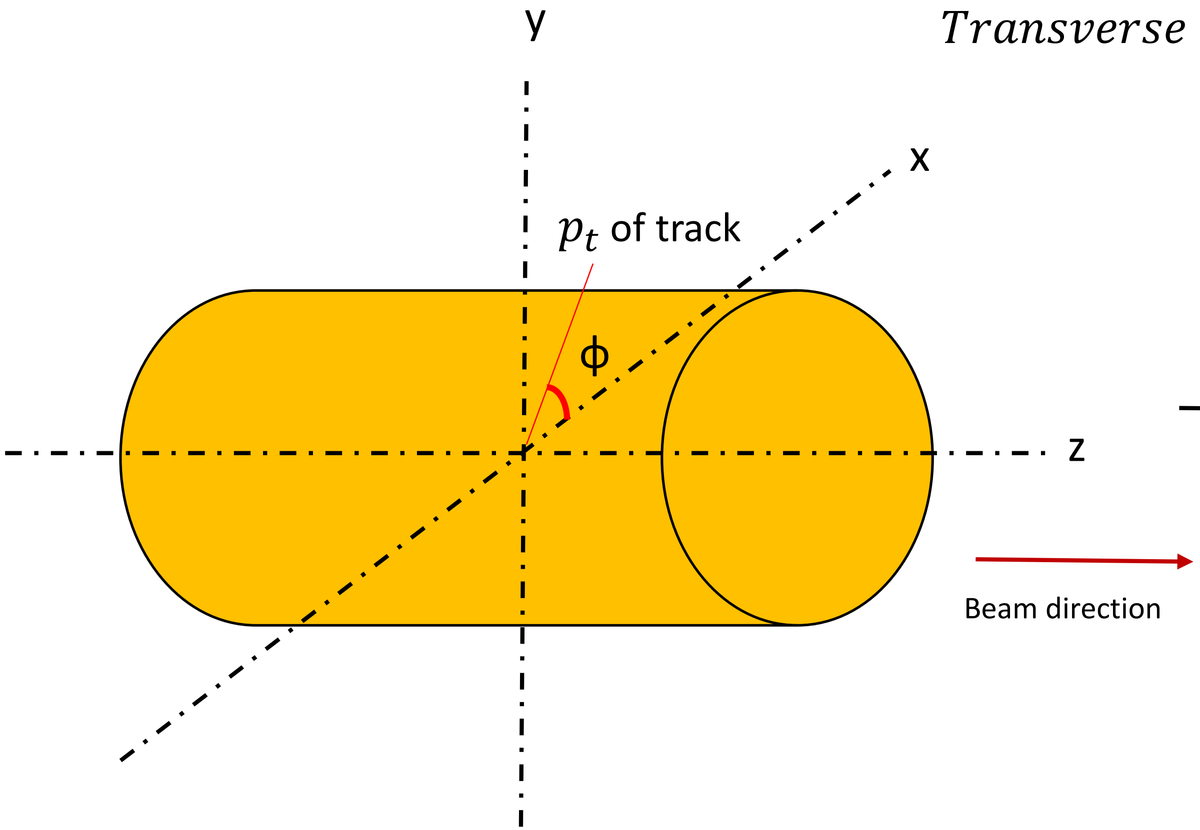
x-y plane: “transverse plane”

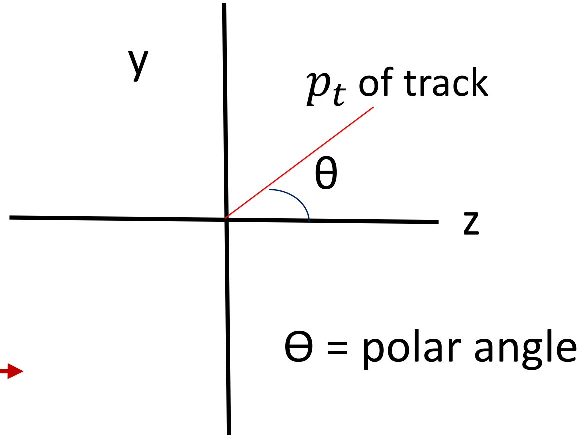
ϕ = azimuthal angle

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



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





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.

Getting the correlation coefficient in terms of observables in heavy ion collisions

$$corr. = \frac{Cov(x,y)}{\sigma_x \sigma_y} = \frac{\sigma_{xy}}{\sqrt{\sigma_x^2 \sigma_y^2}} = \frac{\frac{1}{N_{events}} \sum_i^{N_{events}} (n_{x,i} - \overline{n_x})(n_{y,i} - \overline{n_y})}{\sqrt{\overline{n_x} \cdot \overline{n_y}}} = \frac{\overline{n_x n_y} - \overline{n_x} \cdot \overline{n_y}}{\sqrt{\overline{n_x} \cdot \overline{n_y}}}$$

$$Poisson\ Stats:\ \sigma^2 = \overline{n}$$

$$\rho_{same} = \overline{n_x n_y}$$

$$\rho_{mix} = \overline{n_x} \cdot \overline{n_y}$$

$$\therefore \boxed{corr. = \frac{\Delta\rho}{\sqrt{\rho_{mix}}} = \frac{\rho_{same} - \rho_{mix}}{\sqrt{\rho_{mix}}}}$$

Our Correlation Measure: Pearson's Correlation Coefficient (PCC)

- PCC is a correlation measure defined in the following way:

$$corr. = \frac{Cov(x,y)}{\sigma_x \sigma_y}$$

- This general correlation measure can be related to *2-particle densities (ρ)* from the same event and from a suitable reference (mixed) event:

$$corr. = \frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{\rho_{same} - \rho_{ref}}{\sqrt{\rho_{ref}}} = \sqrt{\rho_{ref}}\,\frac{\Delta\rho}{\rho_{ref}}$$

- In practice, the ratio is measured directly from data, and multiplied by a "pre-factor" that is used to normalize the correlation (e.g. per-particle normalization).
- The "ref" refers to an uncorrelated reference, which is constructed using mixed events.

Deriving our D0-Hadron correlation measure

Consider:

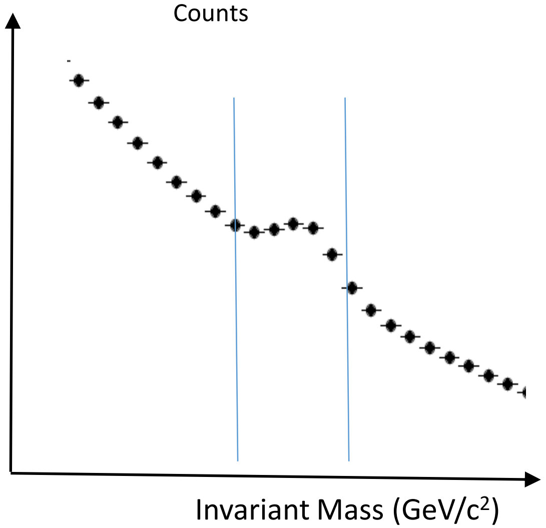
$$\Delta\rho^{signal} = \Delta\rho^{D0} + \Delta\rho^{[k\pi]} + \Delta\rho^{D^*\to\pi_{soft}}$$

Where $\Delta\rho^{signal}$ *represents the total correlated pair histogram in the* ***D⁰ mass window*** (signal region), which is the sum of the correlations with real D0s, the correlations with random $[k\pi]$ pairs and correlations coming from D* decay.

$$\Delta\rho^{signal} = \Delta\rho^{D0} + \rho_{ref}^{[k\pi]}\frac{\Delta\rho^{[k\pi]}}{\rho_{ref}^{[k\pi]}} + \rho_{ref}^{D^*\to\pi_{soft}}\frac{\Delta\rho^{D^*\to\pi_{soft}}}{\rho_{ref}^{D^*\to\pi_{soft}}}$$

$$\frac{\rho_{ref}^{signal}}{\rho_{ref}^{[k\pi]}}\frac{\Delta\rho^{signal}}{\rho_{ref}^{signal}} = \frac{\rho_{ref}^{D0}}{\rho_{ref}^{[k\pi]}}\frac{\Delta\rho^{D0}}{\rho_{ref}^{D0}} + \frac{\Delta\rho^{[k\pi]}}{\rho_{ref}^{[k\pi]}} + \frac{\rho_{ref}^{D^*\to\pi_{soft}}}{\rho_{ref}^{[k\pi]}}\frac{\Delta\rho^{D^*\to\pi_{soft}}}{\rho_{ref}^{D^*\to\pi_{soft}}}$$

$$\boxed{\frac{\Delta\rho^{D0}}{\rho_{ref}^{D0}} = \frac{\rho_{ref}^{signal}}{\rho_{ref}^{D0}}\left[\frac{\Delta\rho^{signal}}{\rho_{ref}^{signal}} - \frac{\rho_{ref}^{[k\pi]}}{\rho_{ref}^{signal}}\frac{\Delta\rho^{[k\pi]}}{\rho_{ref}^{[k\pi]}}\right] - \frac{\rho_{ref}^{D^*\to\pi_{soft}}}{\rho_{ref}^{D0}}\frac{\Delta\rho^{D^*\to\pi_{soft}}}{\rho_{ref}^{D^*\to\pi_{soft}}}}$$



A simple mathematical model to fit the data

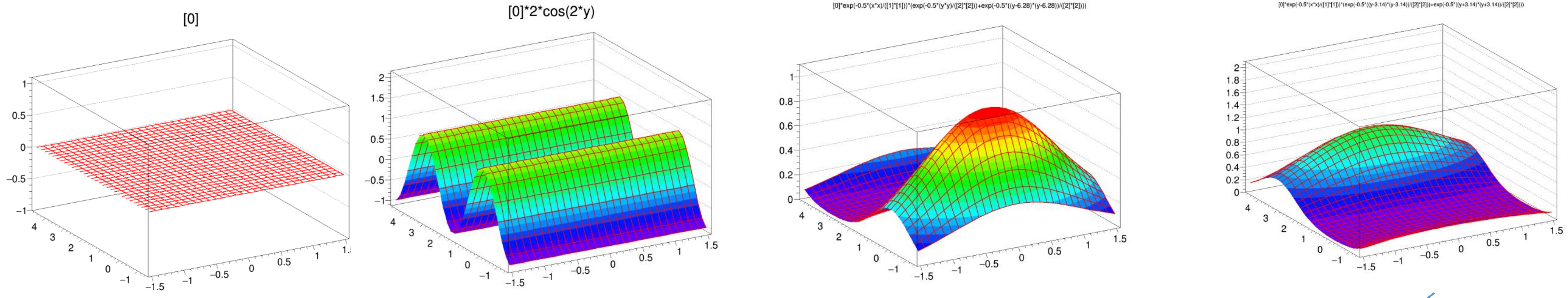
- We started with a simple fit-model with 8 parameters:
  - $A_0 + 2A_Q Cos(2\Delta\varphi) + A_{SS} e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{SS\Delta\eta}}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma^2_{SS\Delta\varphi}}} + A_{AS} e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma^2_{AS\Delta\eta}}}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

Constant-offset

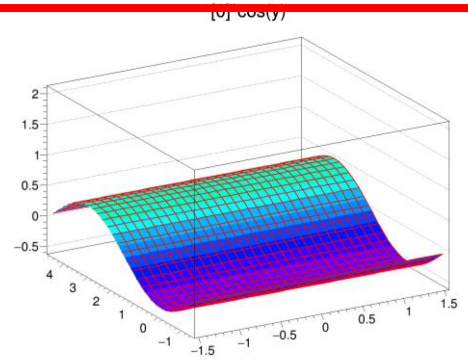
Quadrupole

near-side 2D Gaussian

Away-Side 2D Gaussian

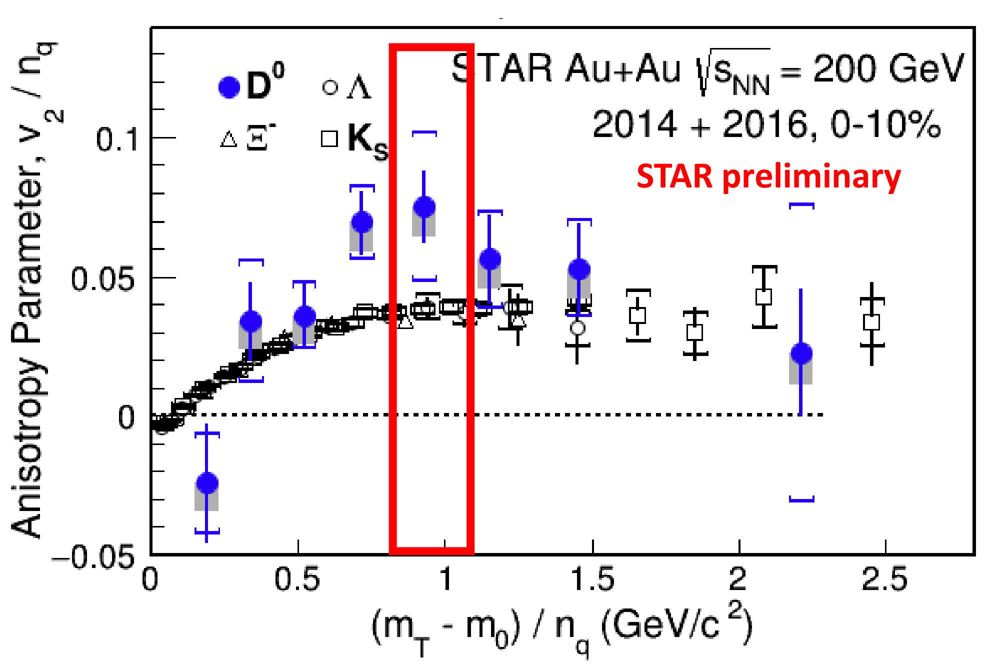


Note: if the away-side is very broad on $\Delta\varphi$ ($\sigma_{\Delta\varphi} \sim 1\ or\ more$), the Gaussian limits to a "dipole" (i.e. $A_D Cos(\Delta\varphi)$) due to its periodicity.

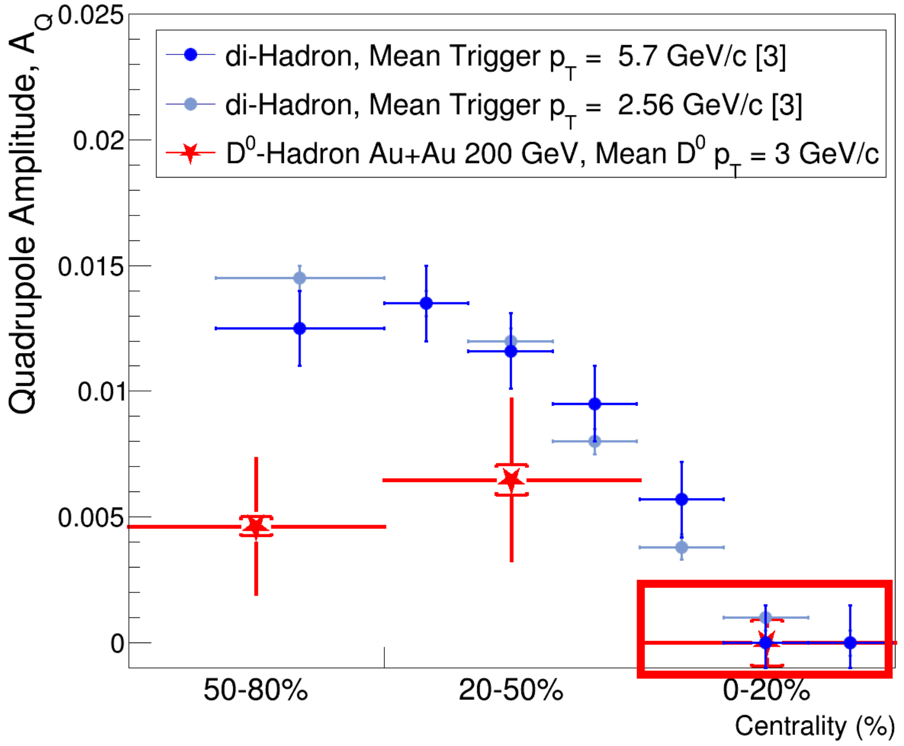


Dipole limit

What about the v_2 in the most-central bin?



D0-meson elliptic flow measurement in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV from STAR, Yue Liang, Quark Matter 2018



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

- At QM2018, a result was shown displaying a v_2 ~.1 for D^0-mesons with a mean p_T ~ 3 GeV/*c.*
  - My result shows a v_2 consistent with 0.
- This is likely due to different handling of “non-flow” contributions to the v_2 measurements.
  - Similar differences have been noted between light-flavor v_2 measurements from multi-particle cumulant methods and the event-plane method [6].

[3] PRC 91 064910 (2015)
[6] Phys. Rev. C **86** (2012) 14904 (arXiv:1111.5637v1)

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.

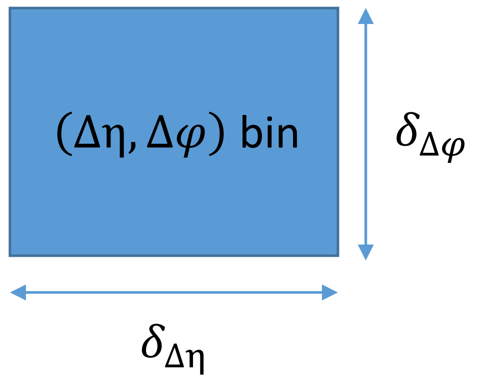
$$= 1 + 2\sum_{n=1}^{\infty} v_n^D v_n^h \cos(n(\varphi_D - \varphi_h)) \qquad \varphi_D - \varphi_h \equiv \Delta\varphi$$

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

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.

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

$\beta = mixed\ event\ norm.$

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

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

$f_{\eta,accep} = 2$
STAR acceptance

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

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

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