Heavy-Flavor Jets & Correlations in Heavy-Ion Collisions

Alexander Jentsch *for the STAR Collaboration*

November 14th, 2019

Brookhaven National Laboratory
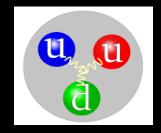
STAR

BROOKHAVEN
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

Why does Heavy-Ion Physics matter?

Protons, neutrons, etc.

Quarks and gluons (partons)

Quantum Chromodynamics (QCD) – the theory of the strong nuclear force

Proton

Quarks and gluons are normally "confined" inside of hadrons – not seen alone in nature!

Why does Heavy-Ion Physics matter?

Protons, neutrons, etc.
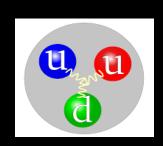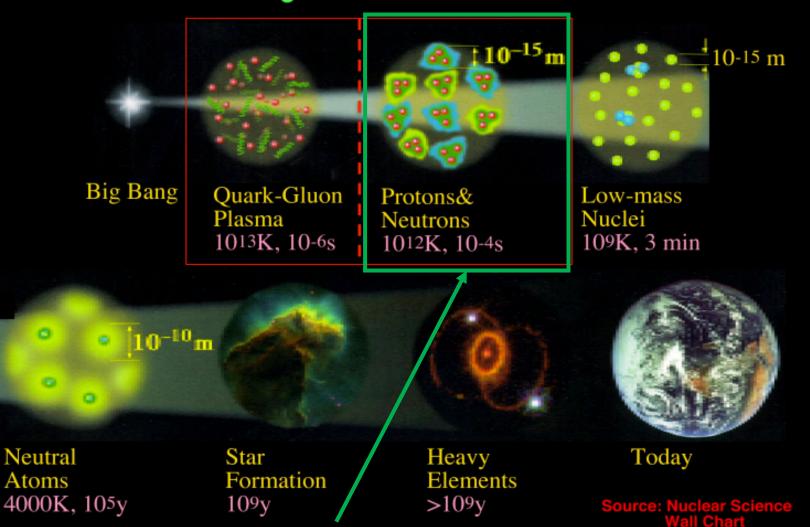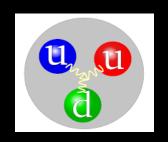
Quarks and gluons (partons)

Quantum Chromodynamics (QCD) – the theory of the strong nuclear force

Proton

History of the Universe

10^{-15} m

$10\text{-}15$ m

Big Bang

Quark-Gluon Plasma
10^{13}K, 10^{-6}s

Protons & Neutrons
10^{12}K, 10^{-4}s

Low-mass Nuclei
10^9K, 3 min

10^{-10} m

Neutral Atoms
4000K, 10^5y

Star Formation
10^9y

Heavy Elements
$>10^9$y

Today

Source: Nuclear Science Wall Chart

Quarks and gluons are normally "confined" inside of hadrons – not seen alone in nature!

3

Why does Heavy-Ion Physics matter?

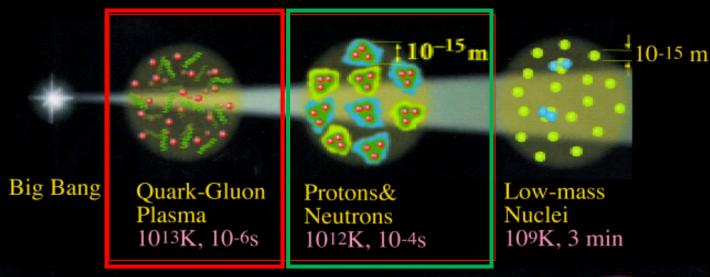**Protons, neutrons, etc.**

↓

Quarks and gluons (partons)

↓

Quantum Chromodynamics (QCD) – the theory of the strong nuclear force

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History of the Universe

10^{-15} m $10\text{-}15$ m

Big Bang

Quark-Gluon Plasma
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Protons & Neutrons
10^{12}K, $10\text{-}4$s

Low-mass Nuclei
10^{9}K, 3 min

Neutral Atoms
4000K,

Going further back in time, the universe was hot enough for quarks and gluons to be deconfined!
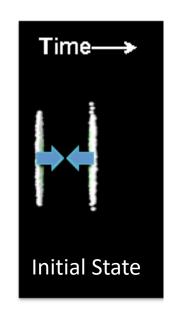
A state of matter called a Quark-Gluon Plasma!

Heavy-Ion Physics

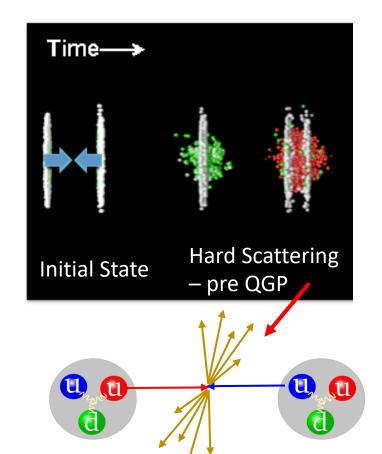- Heavy-Ion Physics provides a laboratory environment to study the Quark-Gluon Plasma (QGP) – where quarks are deconfined over nuclear distances.

Heavy-Ion Physics

- Heavy-Ion Physics provides a laboratory environment to study the Quark-Gluon Plasma (QGP) – where quarks are deconfined over nuclear distances.

Time ⟶

Initial State

Hard Scattering – pre QGP

Lots of overlapping proton + proton (or neutrons) collisions!

Heavy-Ion Physics

- Heavy-Ion Physics provides a laboratory environment to study the Quark-Gluon Plasma (QGP) – where quarks are deconfined over nuclear distances.
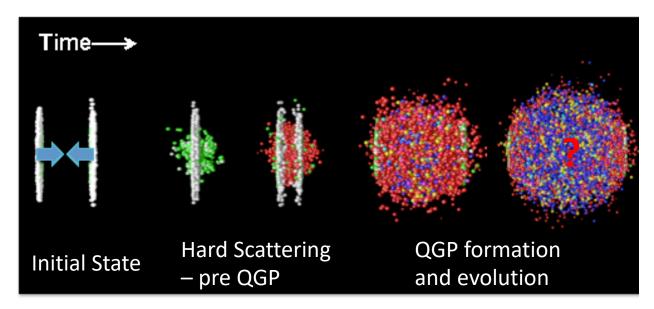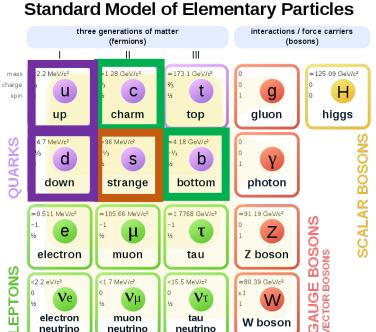

Lot's of overlapping interactions taking place – deconfined quarks and gluons!
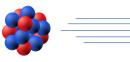**Only lives for 10^{-23} seconds!**

Heavy-Ion Physics

- Heavy-Ion Physics provides a laboratory environment to study the Quark-Gluon Plasma (QGP) – where quarks are deconfined over nuclear distances.
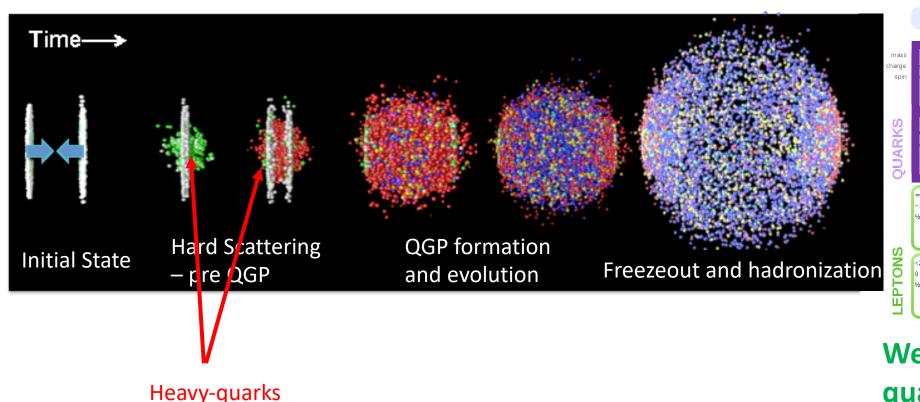

Time ⟶

Initial State

Hard Scattering – pre QGP

QGP formation and evolution

Freezeout and hadronization

Heavy-quarks formed before QGP!

Standard Model of Elementary Particles

We will focus on the charm quark, and a hadron it forms, the D^0 ($c\overline{u}$)!

Heavy-Ion Physics

- Heavy-Ion Physics provides a laboratory environment to study the Quark-Gluon Plasma (QGP) – where quarks are deconfined over nuclear distances.

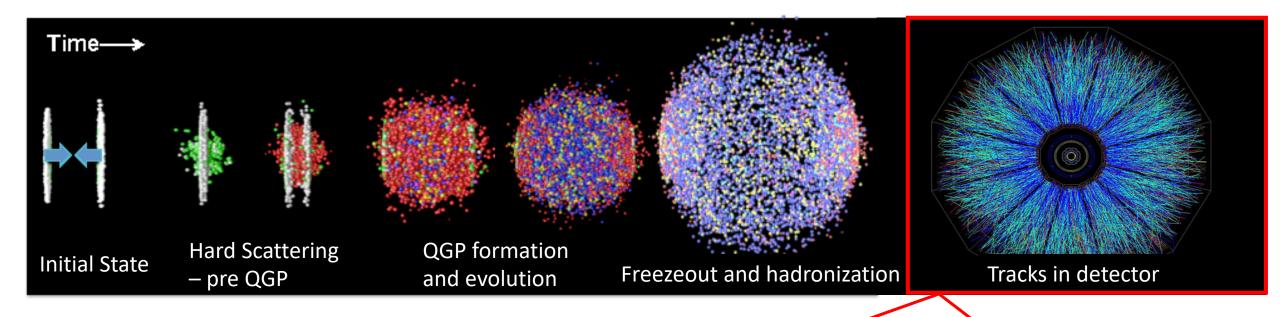Time ⟶

Initial State | Hard Scattering – pre QGP | QGP formation and evolution | Freezeout and hadronization | Tracks in detector
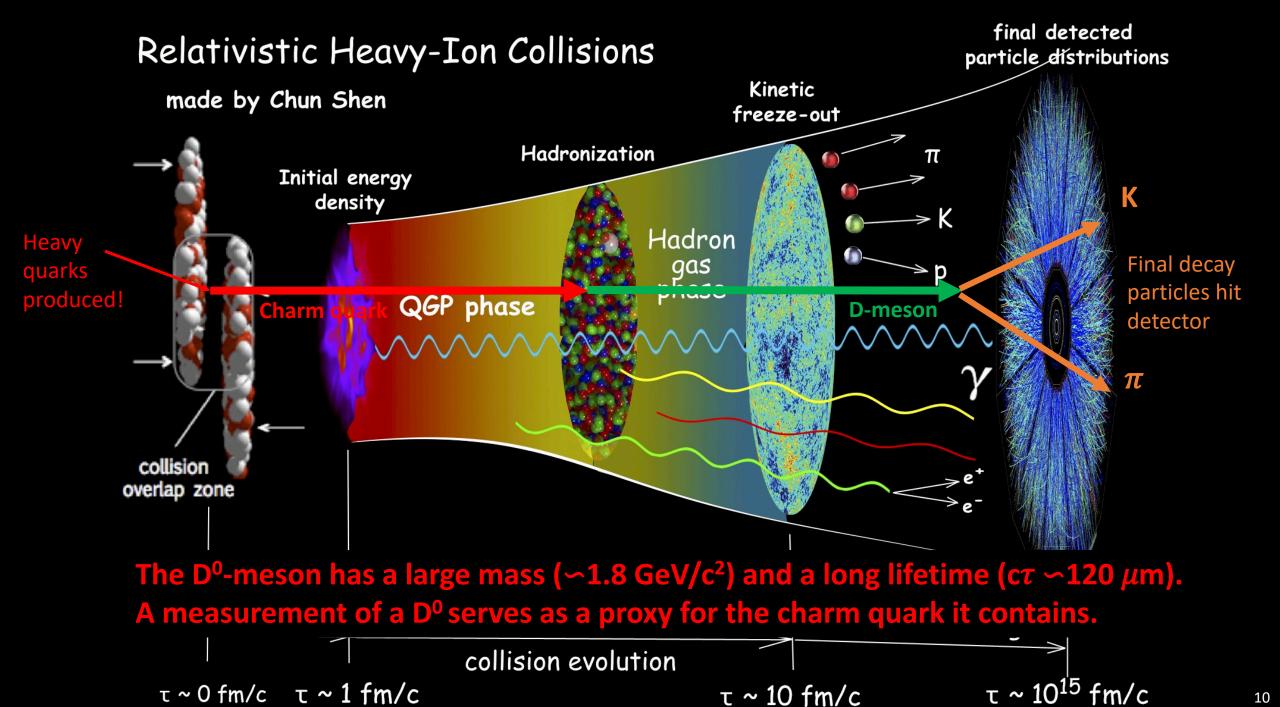
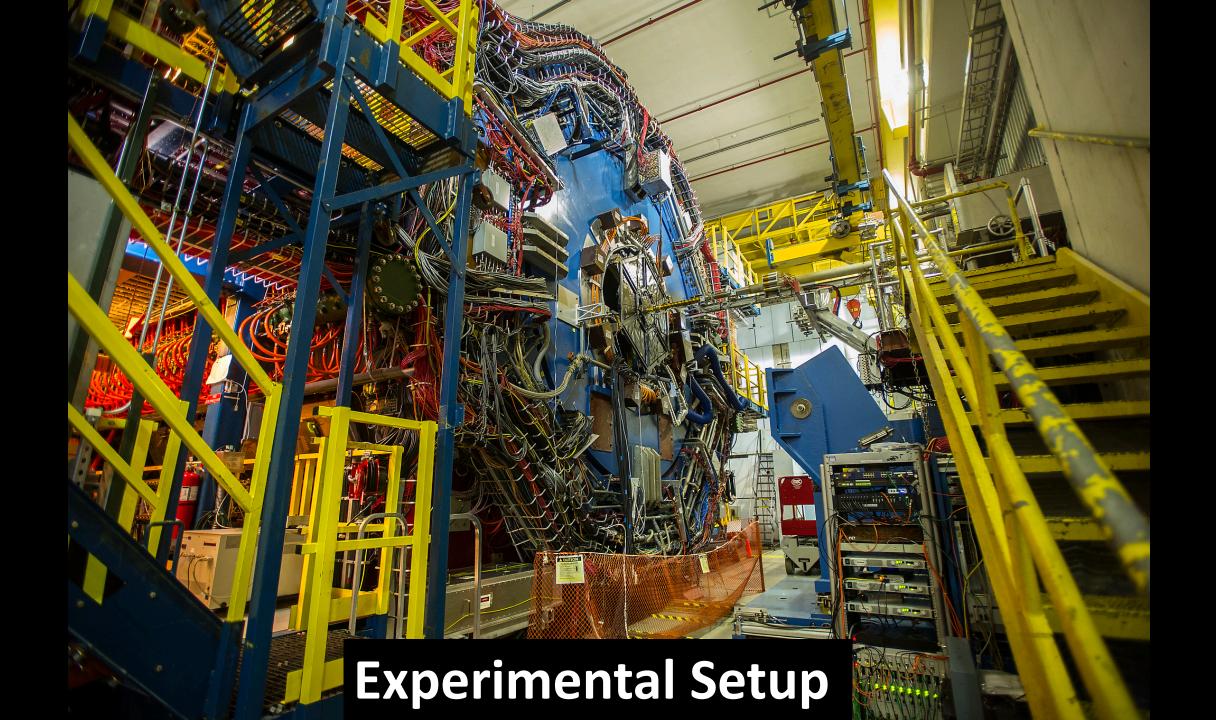What we actually see in the lab! Only the very end of the collision!
A single heavy-ion collision can potentially produce ~1000 particle tracks in the detector!

- Pions ~ 80% (light quarks)
- Kaons ~ 15% (light + strange quarks)
- Protons (light quarks)
- Electrons, photons, and muons

Relativistic Heavy-Ion Collisions

made by Chun Shen

Kinetic
freeze-out

Hadronization

Initial energy
density

Heavy
quarks
produced!

Charm quark **QGP phase**

Hadron
gas
phase

D-meson

π

K

p

γ

e^+

e^-

K

Final decay
particles hit
detector

π

collision
overlap zone

**The D^0-meson has a large mass (∿1.8 GeV/c^2) and a long lifetime (cτ ∿120 μm).
A measurement of a D^0 serves as a proxy for the charm quark it contains.**

collision evolution

$\tau \sim 0$ fm/c $\tau \sim 1$ fm/c $\tau \sim 10$ fm/c $\tau \sim 10^{15}$ fm/c

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How do we study something that only lives for 10^{-23} seconds and produces thousands of particles?!

Experimental Setup

Relativistic Heavy Ion Collider (RHIC)

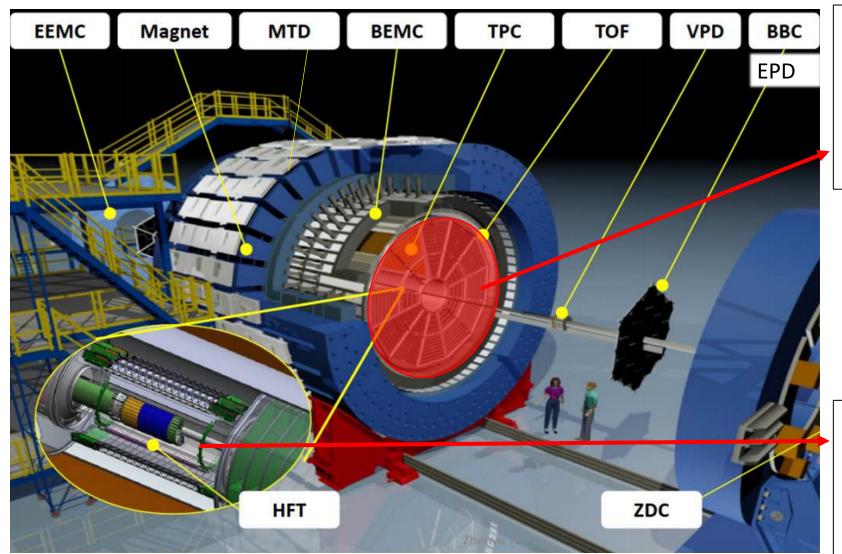**2.38 miles in circumference!**
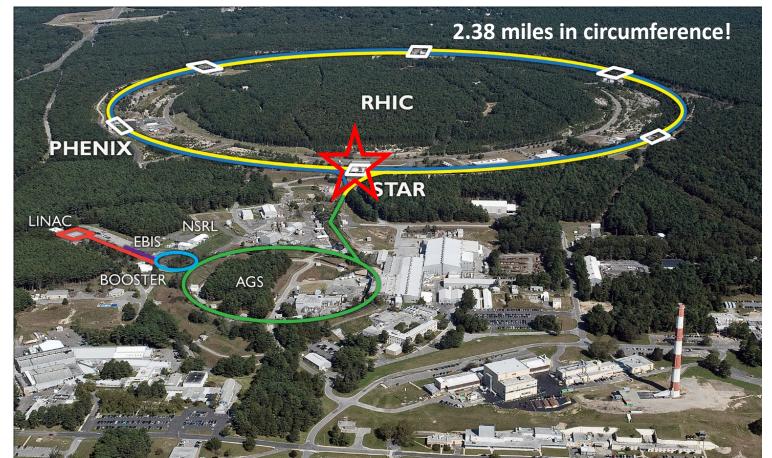
https://www.bnl.gov/rhic/images.asp

- Various energies and species
  - Au, p, Cu, U, He^3, deuteron, etc.
- **Au+Au:** $\sqrt{s_{NN}} = 200$ **GeV**
  - $\sqrt{s_{NN}} = 62$ GeV $-$ 3 GeV.
  - Can run in fixed-target mode to get to lower energies.
- **p+p:** $\sqrt{s} = 200$ GeV, $\sqrt{s} = 510$ GeV, etc.
  - Baseline measurements for heavy-ion collisions.
  - Polarized proton beams.
  - Hadronic structure.

RHIC is the world's most versatile high-energy collider and has been colliding particles for 20 years!
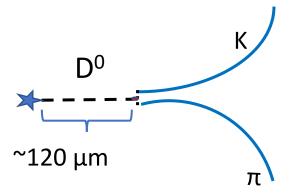
Solenoidal Tracker at RHIC (STAR)

Time Projection Chamber (TPC)
- Main detector for "tracking" particles.
- Gives particle momentum (with a 0.5 T magnetic field parallel to the beam).
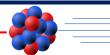- Identifies particles using energy loss in the TPC gas.

Heavy Flavor Tracker (HFT)
- Used for rejecting background in reconstructing heavy-flavor mesons.
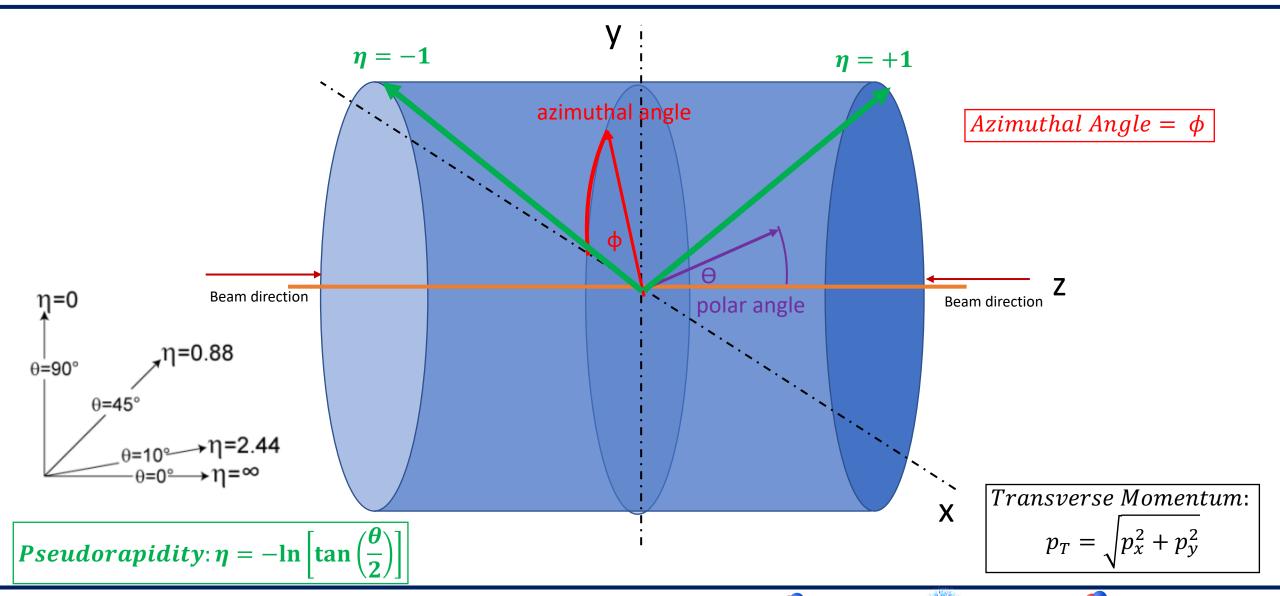- The D-meson travels about 120 μm before decaying into a K and a π.

Relevant kinematic variables

azimuthal angle

ϕ

$\eta = -1$

$\eta = +1$

y

z

Beam direction

Beam direction

Θ

polar angle

x

$\eta=0$

$\theta=90°$

$\eta=0.88$

$\theta=45°$

$\theta=10°$ $\eta=2.44$

$\theta=0°$ $\eta=\infty$

$Azimuthal\ Angle = \phi$

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

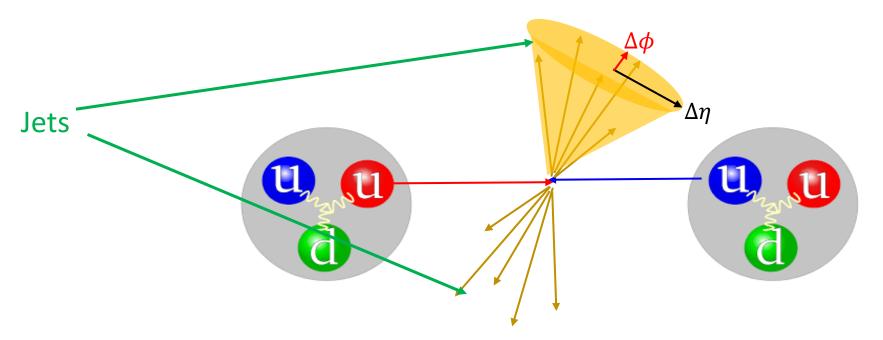$Pseudorapidity: \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$

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What about an observable?

Jets

When partons interact at high energy, they can annihilate and form back-to-back sprays of particles called "jets".
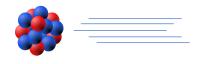

Jet properties we can measure:
- **Number of particles in jet.**
- **Total energy.**
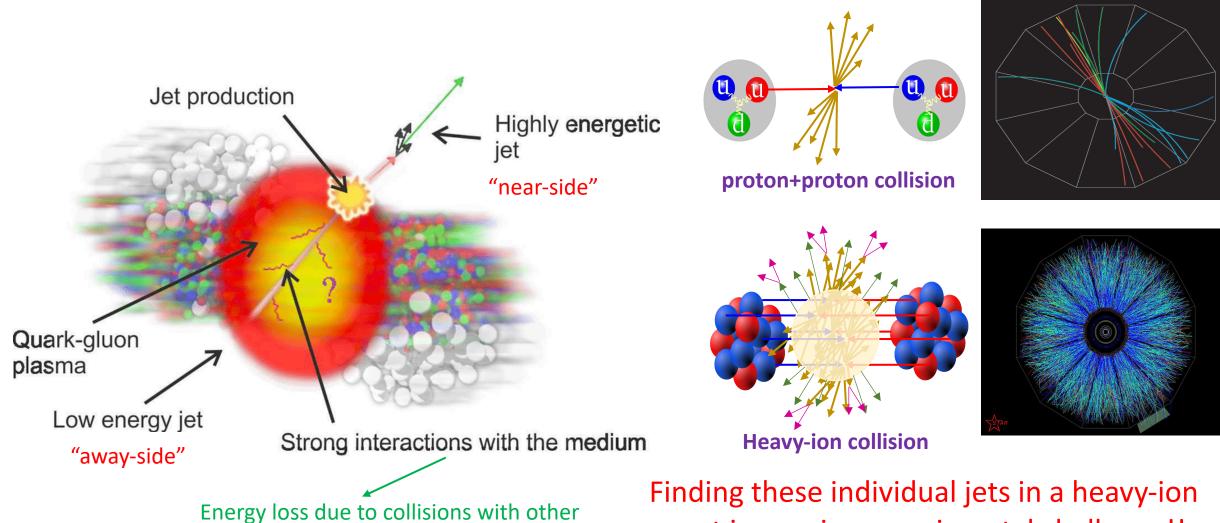- **Angular distribution (shape).**
- **And many others!**

➢ We can also study particular types of quarks (i.e. charm) by studying the jets containing those quarks.

Jets

Jet production

Highly **energetic** jet

"near-side"

Quark-gluon plasma

Low energy jet

"away-side"

Strong interactions with the **medium**

Energy loss due to collisions with other partons, or radiation of gluons.

proton+proton collision

Heavy-ion collision

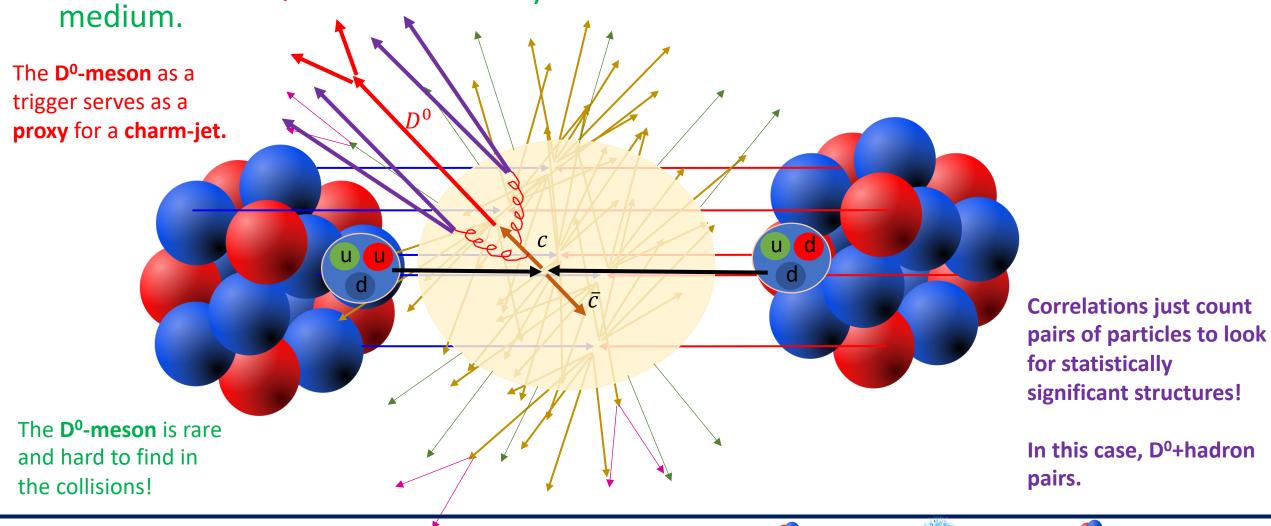Finding these individual jets in a heavy-ion event is a major experimental challenge!!

Studying heavy-flavor jets using correlations!

- Heavy flavor quarks are produced early, evolve into hadrons which then decay outside of the QGP medium – they are sensitive to the evolution of the entire medium.
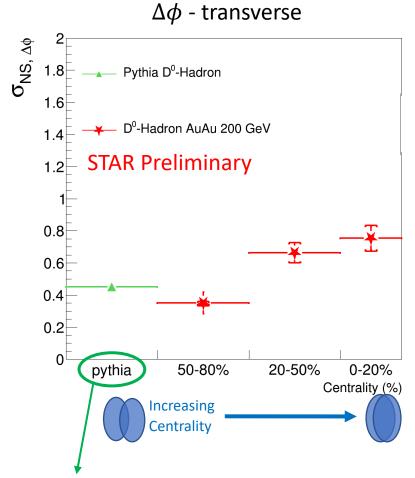
The **D⁰-meson** as a trigger serves as a **proxy** for a **charm-jet**.

D^0

c

$\bar{c}$

u
u
d

u
d
d

The **D⁰-meson** is rare and hard to find in the collisions!

Correlations just count pairs of particles to look for statistically significant structures!

In this case, D⁰+hadron pairs.

Analysis Results

Jet-Shape Results

$\Delta\phi$ - transverse

- Pythia D^0-Hadron
- D^0-Hadron AuAu 200 GeV

STAR Preliminary

Increasing Centrality
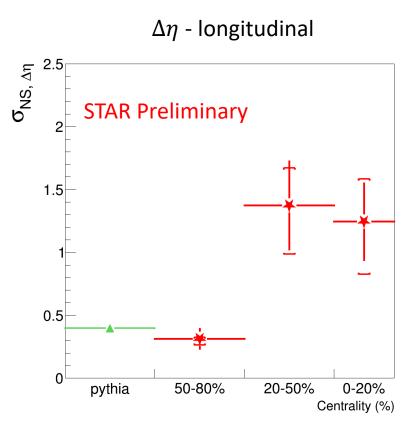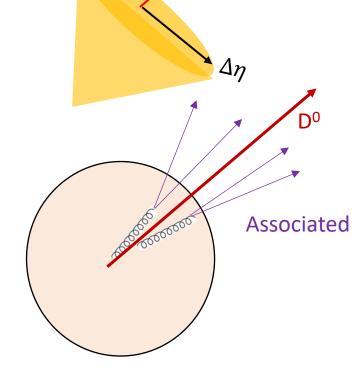
"PYTHIA" simulates proton + proton collisions.

$\Delta\eta$ - longitudinal

STAR Preliminary

$\Delta\phi$

$\Delta\eta$
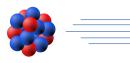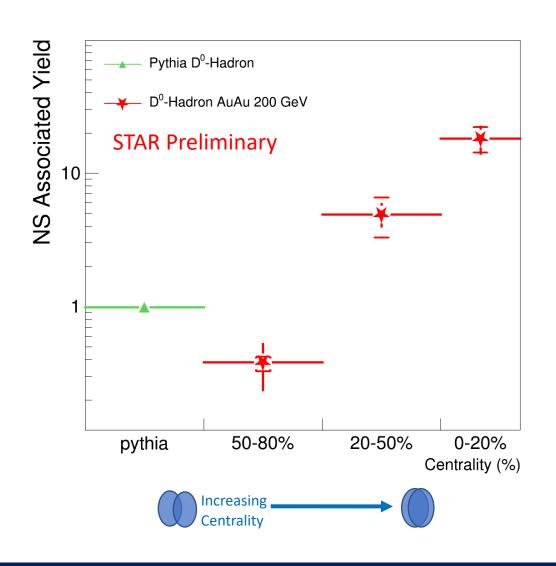
D^0

Associated

The jet containing the charm-quark gets **broader** as the system-size (overlap) gets larger!

Number of associated particles?

Number of associated particles increases with system size! → More interactions!
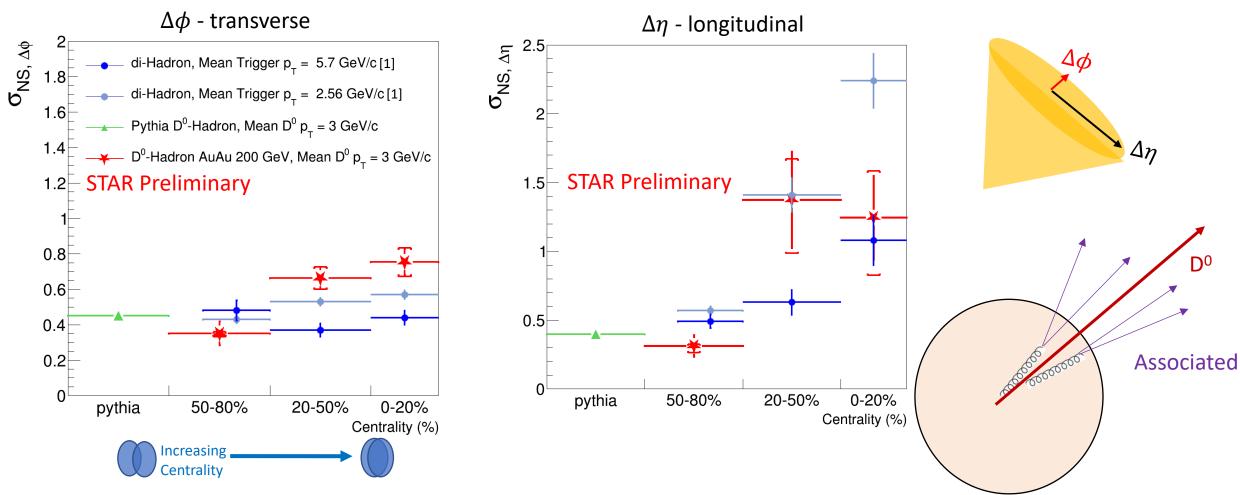
Near-side
$(\Delta\phi < \pi/2)$

D^0

Associated

Comparison with light-flavor quark correlations

$$m_{u,d,s} < m_c$$
$$\Delta E_{u,d,s} > \Delta E_c$$

Jet-Shape Comparison

$\Delta\phi$ - transverse

di-Hadron, Mean Trigger p_T = 5.7 GeV/c [1]
di-Hadron, Mean Trigger p_T = 2.56 GeV/c [1]
Pythia D^0-Hadron, Mean D^0 p_T = 3 GeV/c
D^0-Hadron AuAu 200 GeV, Mean D^0 p_T = 3 GeV/c

STAR Preliminary

$\sigma_{NS, \Delta\phi}$

Centrality (%)

Increasing Centrality

$\Delta\eta$ - longitudinal

STAR Preliminary

$\sigma_{NS, \Delta\eta}$

Centrality (%)

$\Delta\phi$

$\Delta\eta$

D^0

Associated

Similar change in shape for jets containing light- and charm quarks!

[1] PRC 91 064910 (2015)

NS Associated Yield

- di-Hadron, Mean Trigger p_T = 5.7 GeV/c [1]
- di-Hadron, Mean Trigger p_T = 2.56 GeV/c [1]
- Pythia D^0-Hadron, Mean D^0 p_T = 3 GeV/c
- D^0-Hadron AuAu 200 GeV, Mean D^0 p_T = 3 GeV/c
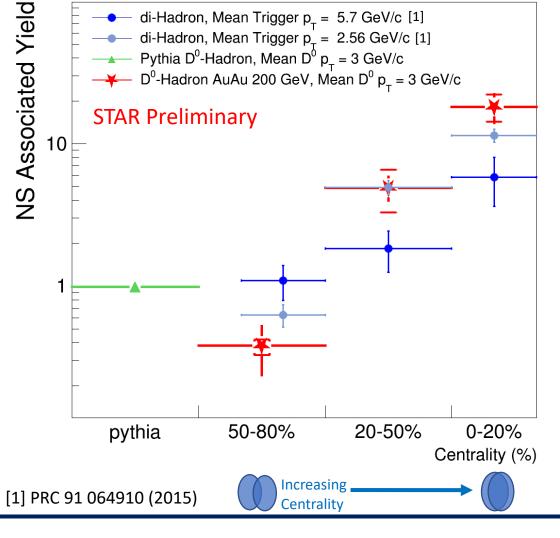
STAR Preliminary

pythia   50-80%   20-50%   0-20%
Centrality (%)

Increasing Centrality

[1] PRC 91 064910 (2015)
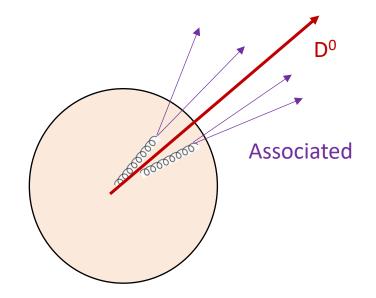
For a **similar momentum particle**, the light-flavor and charm evolve the same way with collision system size!!

D^0

Associated

Conclusions

Increasing Centrality

Peripheral → Central

- Charm-quark correlations from peripheral Au+Au collisions look similar to what is predicted by PYTHIA.
  - Peripheral collisions "look" like individual proton + proton collisions → less likelihood of QGP formation.

- The charm-containing jet is strongly modified by the QGP medium in both shape and yield.
  - Evidence of jet broadening with charm quarks previously seen in light-flavor correlations.
  - Observation of a substantial increase in the jet yield as a function of centrality → indication of partonic interactions.

- Comparisons to light-flavor correlations indicate that charm-quarks at similar momentum experience similar net interactions in the medium!
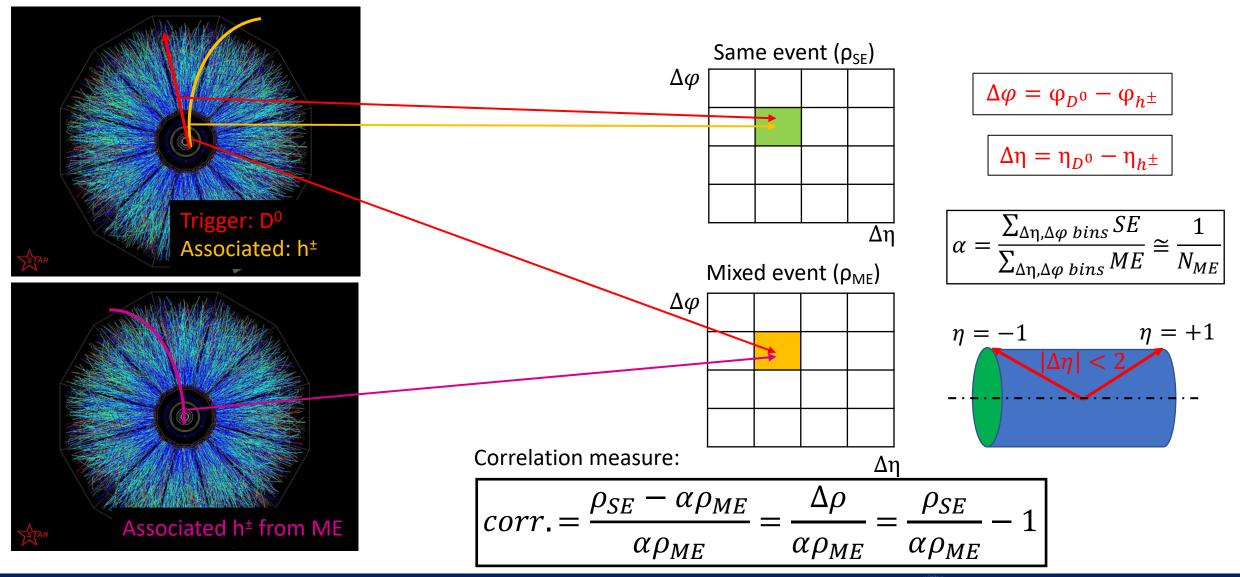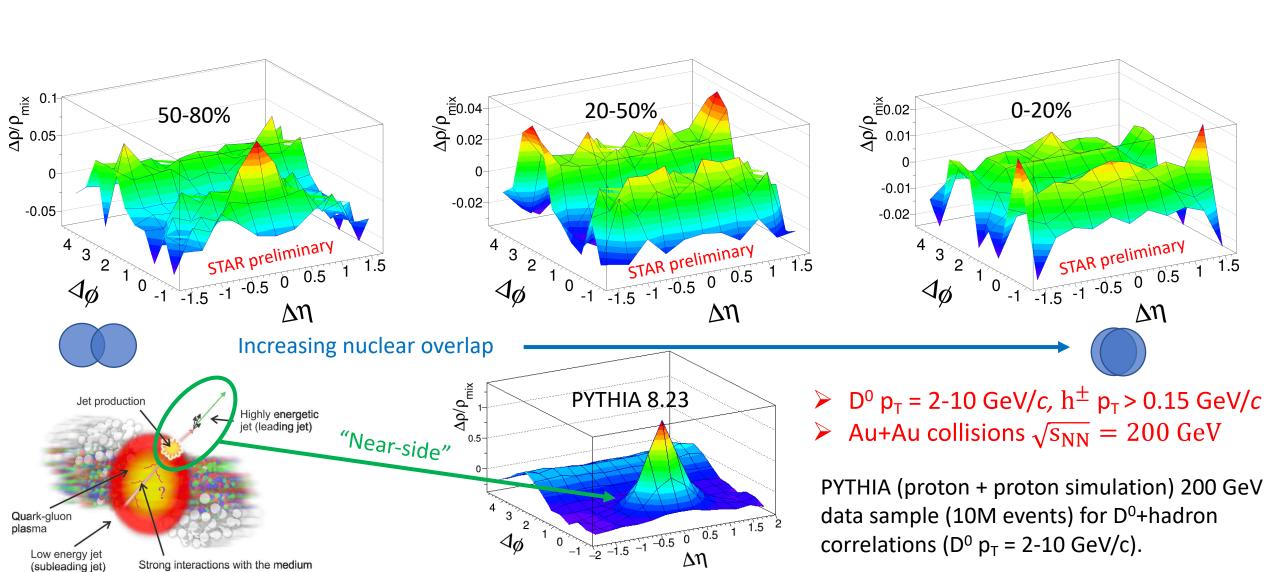
Thank you!

Backup

2D Angular Correlations

Trigger: D^0
Associated: $h^\pm$
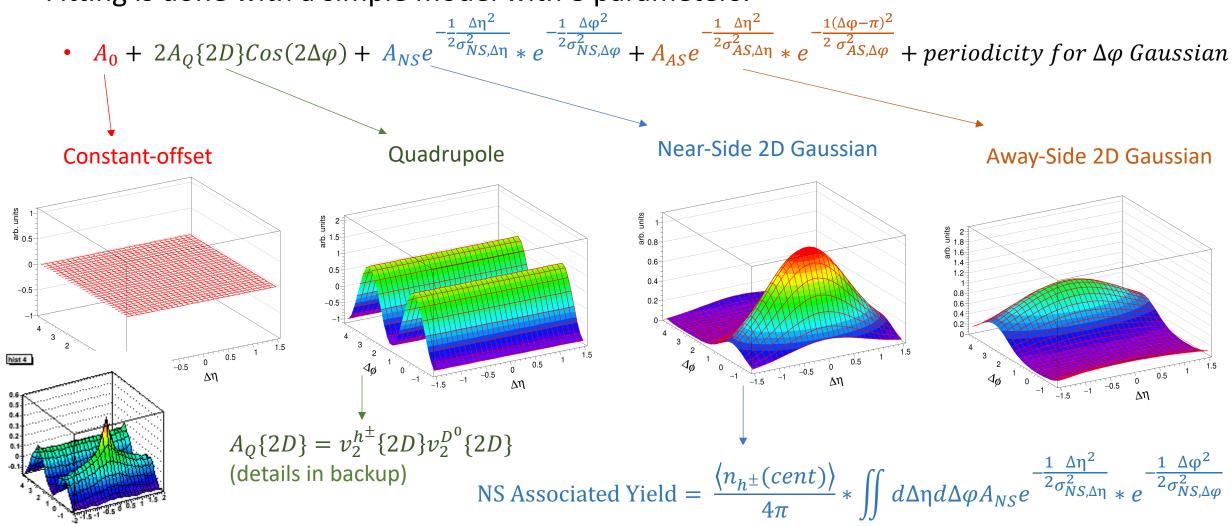
Associated $h^\pm$ from ME

Same event (ρ_{SE})

$\Delta\varphi$

$\Delta\eta$

Mixed event (ρ_{ME})

$\Delta\varphi$

$\Delta\eta$

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

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

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

$\eta = -1$ $\qquad$ $\eta = +1$

$|\Delta\eta| < 2$

Correlation measure:

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

D⁰ + hadron correlations

50-80% $\Delta\rho/\rho_{mix}$ STAR preliminary

20-50% $\Delta\rho/\rho_{mix}$ STAR preliminary

0-20% $\Delta\rho/\rho_{mix}$ STAR preliminary

Increasing nuclear overlap

Jet production

Highly **energetic** jet (leading jet)

Quark-gluon plasma

Low energy jet (subleading jet)

Strong interactions with the medium

"Near-side"

PYTHIA 8.23

➤ D⁰ p_T = 2-10 GeV/c, h$^\pm$ p_T > 0.15 GeV/c
➤ Au+Au collisions $\sqrt{s_{NN}}$ = 200 GeV

PYTHIA (proton + proton simulation) 200 GeV data sample (10M events) for D⁰+hadron correlations (D⁰ p_T = 2-10 GeV/c).

A simple model to fit the data
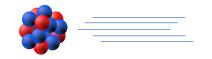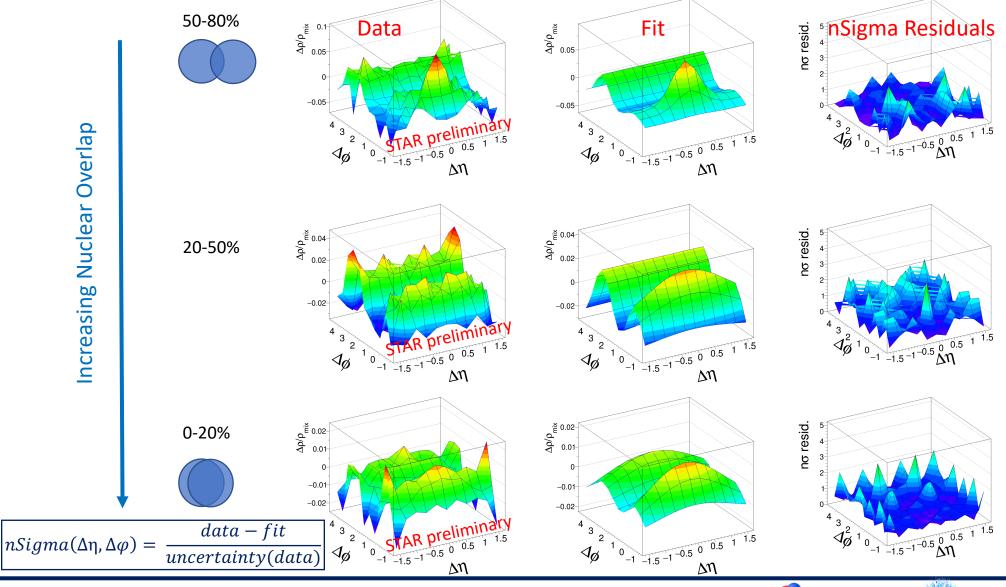
- Fitting is done with a simple model with 8 parameters:

$$A_0 + 2A_Q\{2D\}Cos(2\Delta\varphi) + A_{NS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma_{NS,\Delta\eta}^2}} * e^{-\frac{1}{2}\frac{\Delta\varphi^2}{\sigma_{NS,\Delta\varphi}^2}} + A_{AS}e^{-\frac{1}{2}\frac{\Delta\eta^2}{\sigma_{AS,\Delta\eta}^2}} * e^{-\frac{1(\Delta\varphi-\pi)^2}{2\ \sigma_{AS,\Delta\varphi}^2}} + periodicity\ for\ \Delta\varphi\ Gaussian$$

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)

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

Fit results

Increasing Nuclear Overlap

50-80%

20-50%

0-20%

Data

Fit

nSigma Residuals

STAR preliminary

$$nSigma(\Delta\eta, \Delta\varphi) = \frac{data - fit}{uncertainty(data)}$$

Deriving our D^0-Hadron correlation measure

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

$1 < p_T < 1.5$ GeV/c

- unlike-sign
+ like-sign
— mixed event

$$\Delta\rho_{signal} = \Delta\rho_{D^0+h} + \Delta\rho_{BG+h} + \Delta\rho_{D^*}$$

Where "$\Delta\rho$" refers to the number of true correlated pairs (e.g. $\Delta\rho = \rho_{SE} - \frac{N_{SE}}{N_{ME}}\rho_{ME}$), and $\alpha = \frac{N_{SE}}{N_{ME}}$, "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 $D^0 + \pi_{soft}$ pair from a D* decay.

$$corr. = \frac{\Delta\rho_{D^0+h}}{\rho_{ME,D^0+h}} = \frac{\Delta\rho_{signal}}{\rho_{ME,D^0+h}} - \frac{\Delta\rho_{BG+h}}{\rho_{ME,D^0+h}} - \frac{\Delta\rho_{D^*}}{\rho_{ME,D^0+h}}$$

$$\frac{\Delta\rho_{signal}}{\rho_{ME,D^0+h}} = \frac{\alpha_{signal}\rho_{ME,signal}}{\rho_{ME,D^0+h}} \frac{\Delta\rho_{signal}}{\alpha_{signal}\rho_{ME,signal}} \cong \frac{S+B}{S} \frac{\Delta\rho_{signal}}{\alpha_{signal}\rho_{ME,signal}}$$

$$\frac{\Delta\rho_{BG+h}}{\rho_{ME,D^0+h}} = \frac{\alpha_{BG+h}ME_{BG+h}}{\rho_{ME,D^0+h}} \frac{\Delta\rho_{BG+h}}{\alpha_{BG+h}\rho_{ME,BG+h}} \cong \frac{B}{S} \frac{\Delta\rho_{BG+h}}{\alpha_{BG+h}\rho_{ME,BG+h}} \cong \frac{B}{S} \frac{\Delta\rho_{SB+h}}{\alpha_{SB+h}\rho_{ME,SB+h}}$$

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

$$\boxed{\frac{\Delta\rho_{signal}}{\rho_{ME,D^0+h}} = \frac{S+B}{S} \frac{\Delta\rho_{signal}}{\alpha_{signal}\rho_{ME,signal}} - \frac{B}{S} \frac{\Delta\rho_{SB+h}}{\alpha_{SB+h}ME_{SB+h}} - \frac{S+B}{S} \frac{\alpha_{D^*}\rho_{ME,D^*}}{\alpha_{signal}\rho_{ME,signal}} \frac{\Delta\rho_{D^*}}{\alpha_{D^*}\rho_{ME,D^*}}}$$

Derivation of pseudorapidity

Pseudorapidity is the longitudinal rapidity in the high energy limit $(E \gg m, E \approx p)$.

$$y_z = \frac{1}{2} log \left(\frac{E + p_z}{E - p_z} \right) \rightarrow \frac{1}{2} log \left(\frac{p + p_z}{p - p_z} \right) \qquad and \ p_z = pCos(\theta)$$

longitudinal rapidity

$$= \frac{1}{2} log \left(\frac{p + pCos(\theta)}{p - pCos(\theta)} \right) \rightarrow \frac{1}{2} log \left(\frac{1 + Cos(\theta)}{1 - Cos(\theta)} \right) \qquad and \ tan \left(\frac{\theta}{2} \right) = \sqrt{\frac{1 - \cos(\theta)}{1 + \cos(\theta)}}$$

$$= -\frac{1}{2} log \left(\frac{1 - Cos(\theta)}{1 + Cos(\theta)} \right) \rightarrow -log \left(\sqrt{\frac{1 - \cos(\theta)}{1 + \cos(\theta)}} \right)$$

$$= -log \left(tan \left(\frac{\theta}{2} \right) \right) \rightarrow \boxed{\eta \equiv -log \left(tan \left(\frac{\theta}{2} \right) \right)}$$

Calculating NS Associated Yield from Fit Parameters

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

$(\Delta\eta, \Delta\varphi)$ bin $\quad\delta_{\Delta\varphi}$

$\delta_{\Delta\eta}$
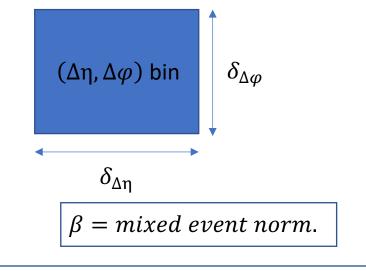
To get the NS associated yield, we want to integrate the NS peak.

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

$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{N_{pairs,NS\ peak}}$

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

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

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

$\boxed{\begin{array}{c} f_{\eta,accep} = 2 \\ STAR\ acceptance \end{array}}$
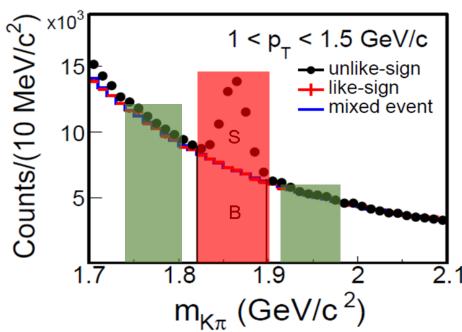
$\boxed{N_{events}\langle n_{D0}\rangle = total\ D^0s}$

NS Associated yield

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

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

D⁰ Invariant Mass Background Subtraction

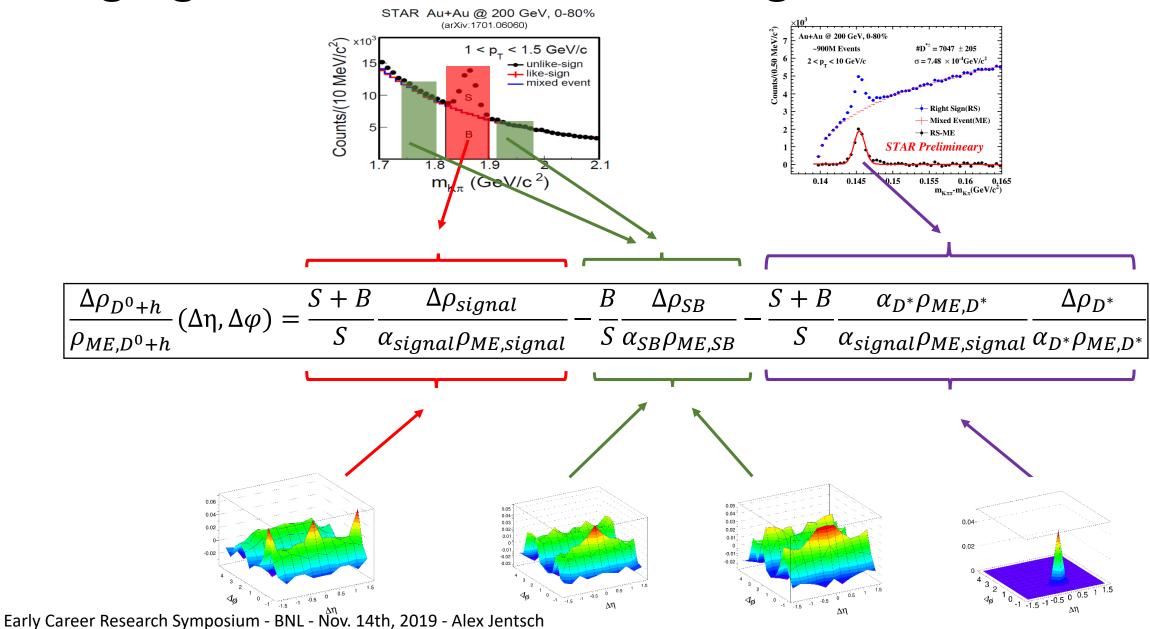STAR Au+Au @ 200 GeV, 0-80%
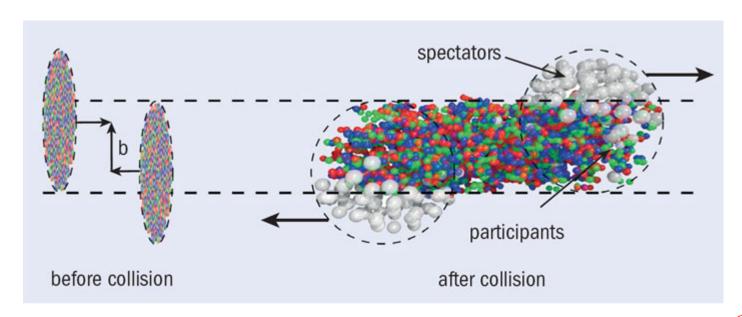Phys. Rev. Lett. 118, 212301(2017)

- The **signal region:**
  - contains both real D^0s and background $K\pi$ pairs.

- Background correlations:
  - estimated using $K\pi$ pairs from **sidebands** in the invariant mass distribution.

These normalized **sideband** correlations are then subtracted from those coming from the **signal region**.
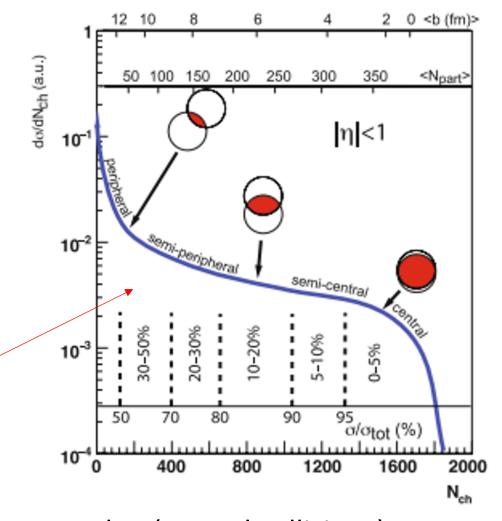
Bringing All the Contributions Together

$$\frac{\Delta\rho_{D^0+h}}{\rho_{ME,D^0+h}}(\Delta\eta, \Delta\varphi) = \frac{S+B}{S}\frac{\Delta\rho_{signal}}{\alpha_{signal}\rho_{ME,signal}} - \frac{B}{S}\frac{\Delta\rho_{SB}}{\alpha_{SB}\rho_{ME,SB}} - \frac{S+B}{S}\frac{\alpha_{D^*}\rho_{ME,D^*}}{\alpha_{signal}\rho_{ME,signal}}\frac{\Delta\rho_{D^*}}{\alpha_{D^*}\rho_{ME,D^*}}$$
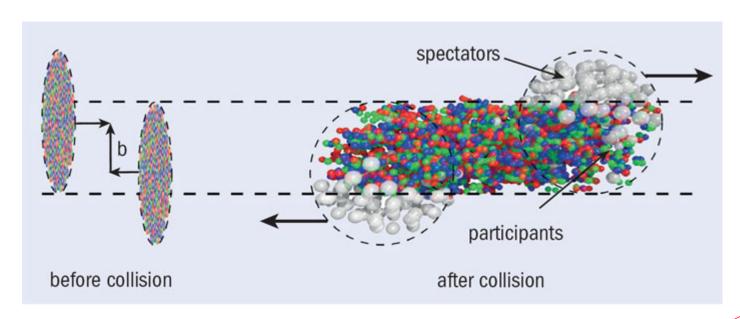
Digression: Centrality

Centrality: a measure of the overlap of the colliding nuclei via track multiplicity or deposited energy. We cannot directly measure the impact parameter, b.
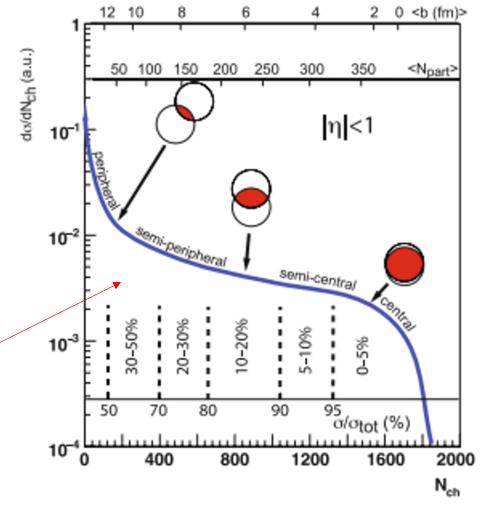
Lower percent fractions (e.g. 0-20%) → more nuclear overlap (central collisions).
Higher percentages (e.g. 50-80%) → less overlap (peripheral).

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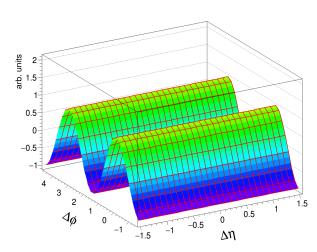
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Lower percent fractions (e.g. 0-20%) → more nuclear overlap (central collisions).
Higher percentages (e.g. 50-80%) → less overlap (peripheral).

Centrality is related to both system-size and the initial geometry of the collision!

What do the correlation structures mean?

Quadrupole

Near-Side 2D Gaussian

Away-Side 2D Gaussian

Related to initial geometry (is maximum in *mid-central* collisions, which have an elliptical overlap).

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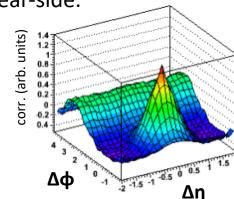

Near-Side 2D Gaussian
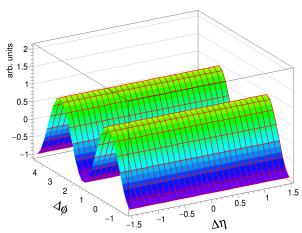

Related to the jet containing the charm-quark.

Away-Side 2D Gaussian

Related to the recoil jet containing the charm-quark – experiences more of the medium than the near-side.
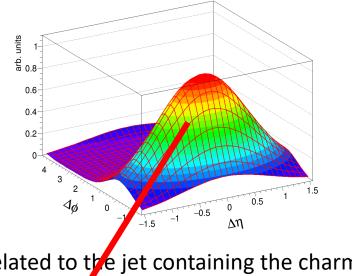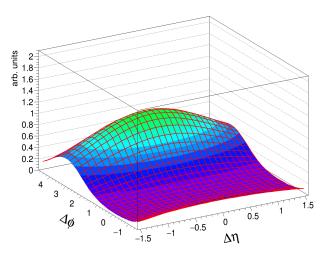
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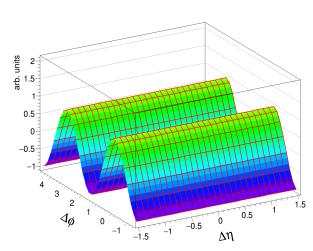Related to the jet containing the charm-quark.

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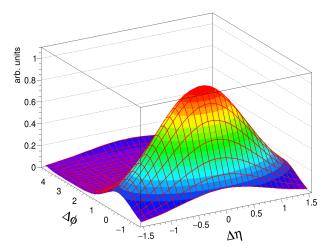**The integral of NS Gaussian → average number of particles correlated with the D^0!**

Related to fragmentation and interactions in the medium!

What do the correlation structures mean?

Quadrupole
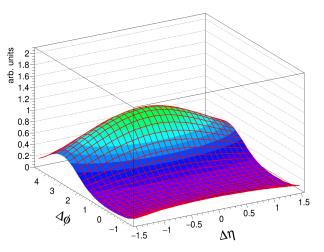

Related to initial geometry (is maximum in *mid-central* collisions, which have an elliptical overlap)

Near-Side 2D Gaussian

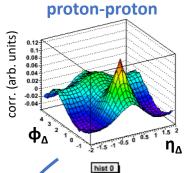Related to the jet containing the charm-quark.

Away-Side 2D Gaussian

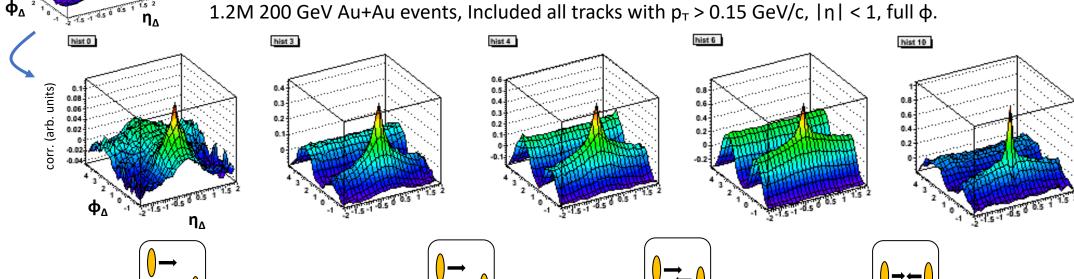Related to the recoil jet containing the charm-quark – experiences more of the medium than the near-side.

The evolution of these structures with system-size (centrality) can indicate how the charm-correlations are affected by the presence of more medium.

Correlations in Heavy-Ion Collisions

proton-proton

- In heavy-ion collisions, new structure is observed, and the correlations can be studied as a function of collision system size.

1.2M 200 GeV Au+Au events, Included all tracks with $p_T > 0.15$ GeV/c, $|\eta| < 1$, full ϕ.

- **The correlations change as a function of the size of the nuclear overlap -> size of the QGP medium!**

The STAR Collaboration, Phys. Rev. C **86**, 064902 (2012)