ÉCOLE DE PHYSIQUE
LES HOUCHES

RHIC:
From colliding ions to physics results

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QCD School, Les Houches
Mar 25 - Apr 4, 2008

RHIC

Part III: (Latest) Results

Focus: Hard Probes

The Meta Talk Slide

At RHIC we see the

hottest T=200-400 MeV ~ $3.5 \cdot 10^{12}$ K

densest ε=30-60 $\varepsilon_{\text{nuclear matter}}$

matter

ever studied in the laboratory

that

flows large "elliptic" flow

as a (nearly) perfect fluid

with systematic patterns consistent with

quark degrees of freedom valence quark scaling

and a viscosity to entropy density ratio

lower

than any other known fluid

All hints towards a ***strongly coupled*** system

What's the problem here ?

There are no hard numbers in these statements

Why is that?

- We still do not have a "Standard Model" for HI collisions that describes the various phases and their dynamic in a coherent way.
  - Only a model that describes what we observe *consistently* can be used to extract hard numbers:
    - EOS, initial conditions, transport coefficients, ...
- We need more precise data beyond what we have right now

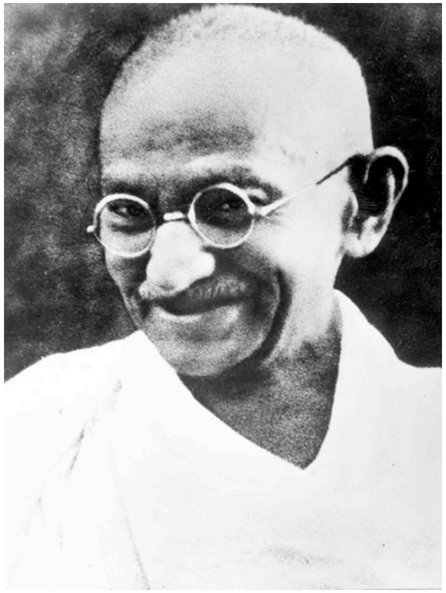
Qualitative → Quantitative

Requires (from experimental side):

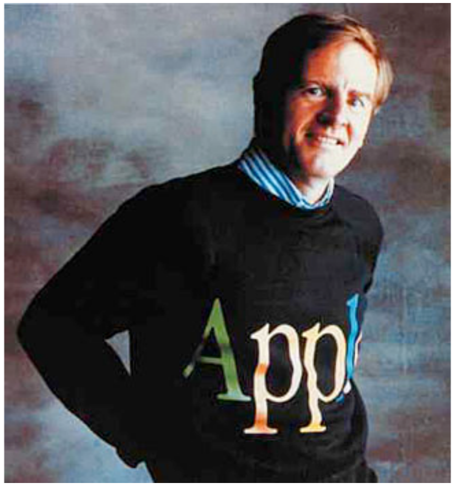
- higher precision = detector upgrades, more statistics (RHIC-II)
- new techniques, new probes (see above), new ideas ...

What others say

"It is the quality of our work which will please God and not the quantity."
Mahatma Gandhi



"No great marketing decision have ever been made on quantitative data"
John Sculley (CEO Pepsi & Apple)



Exploring the Phases of Nuclear Matter

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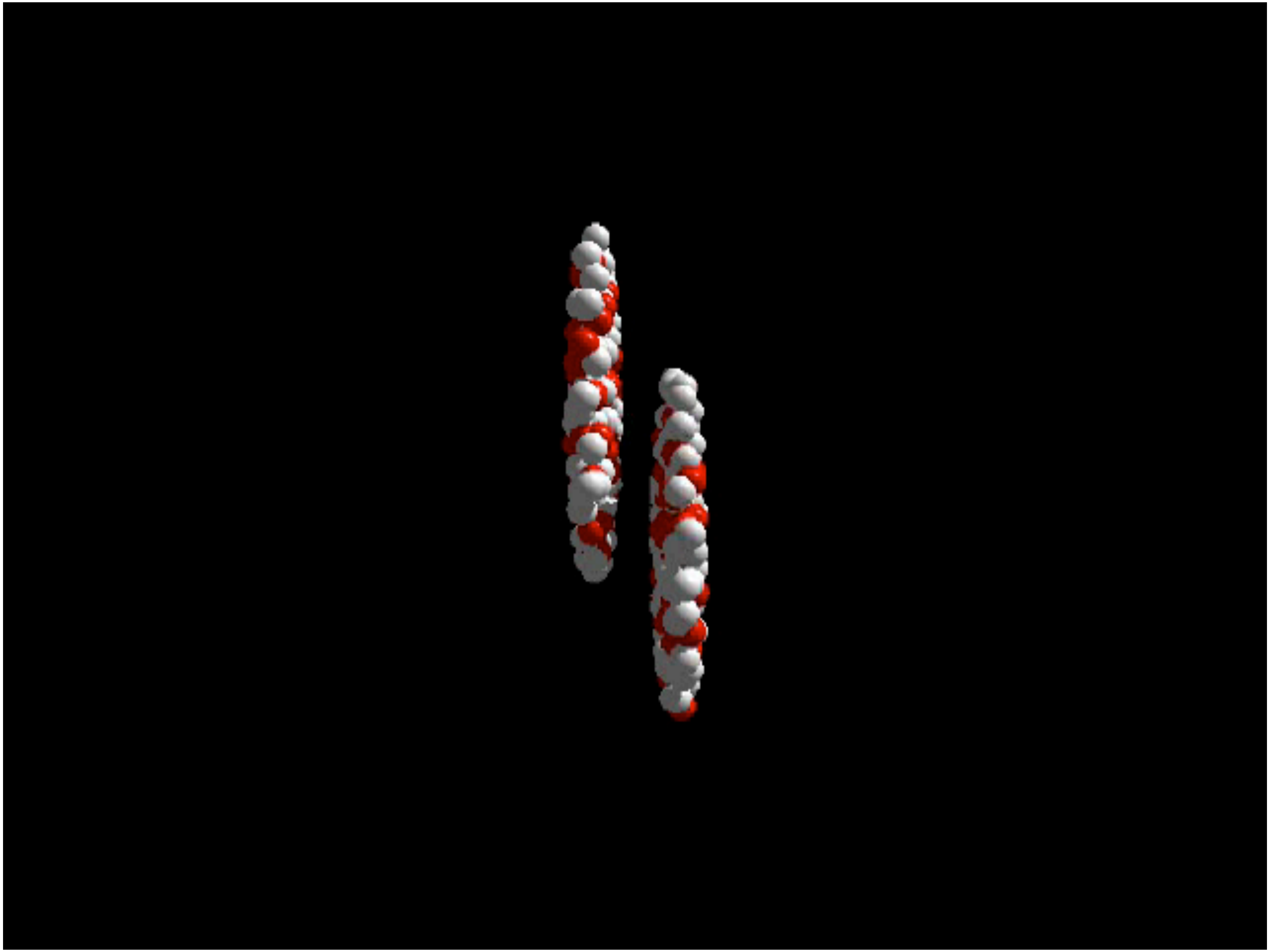
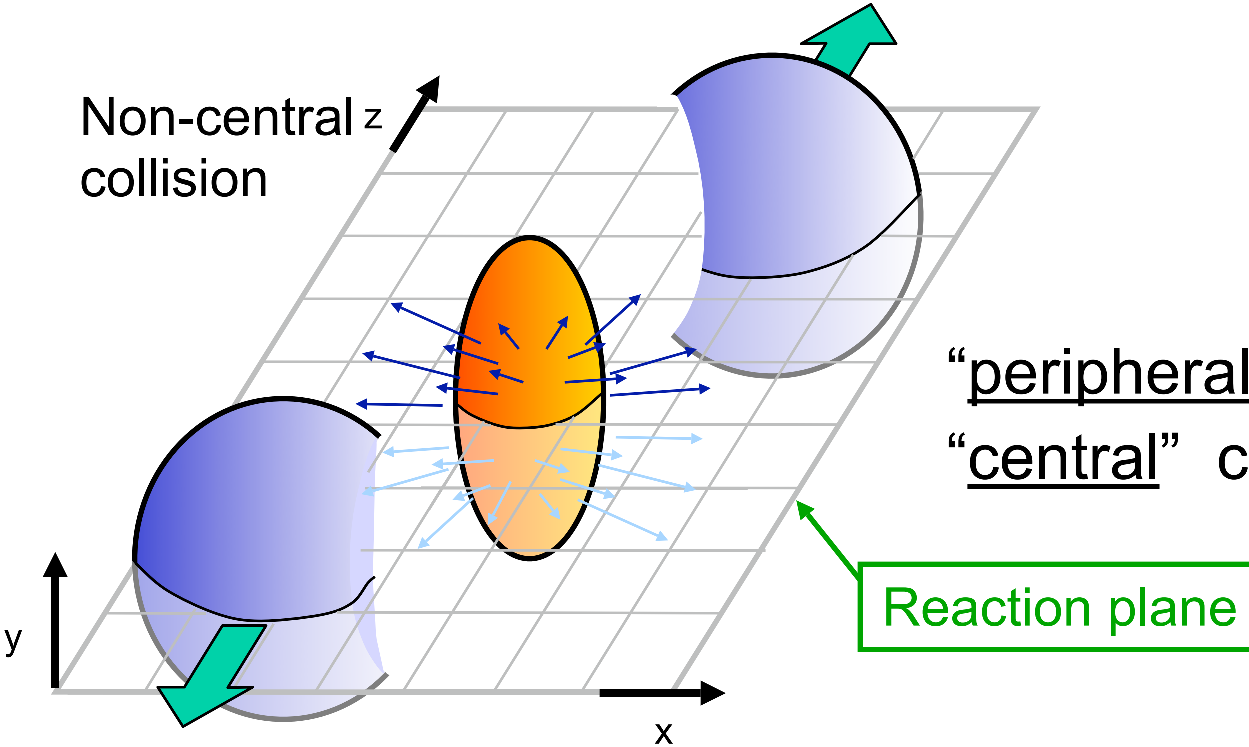


Geometry of a Heavy-Ion Collision



"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<u>central</u>" collision ($b \sim 0$)

Number of participants (N_{part}): number of incoming nucleons (participants) in the overlap region

Number of binary collisions (N_{bin} or N_{coll}): number of equivalent inelastic nucleon-nucleon collisions

$N_{bin} \geq N_{part}$

Quantifying geometry

p+p: 2 Participants, 1 Binary Collision

Participants: those nucleons that have interacted at least once

Binary collisions: the number of 1+1 collisions

Quantifying geometry

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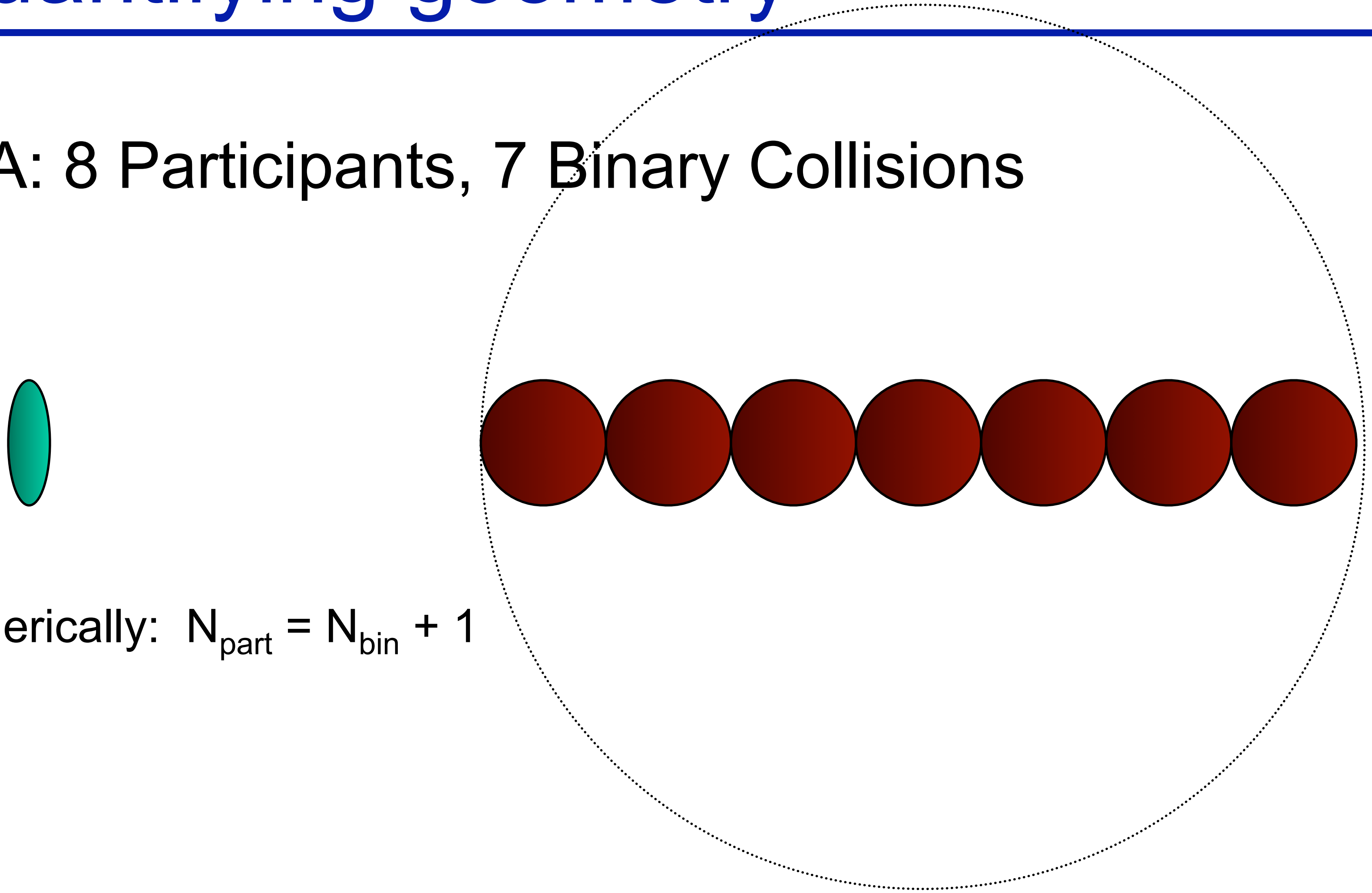
Quantifying geometry

p+A: 8 Participants, 7 Binary Collisions



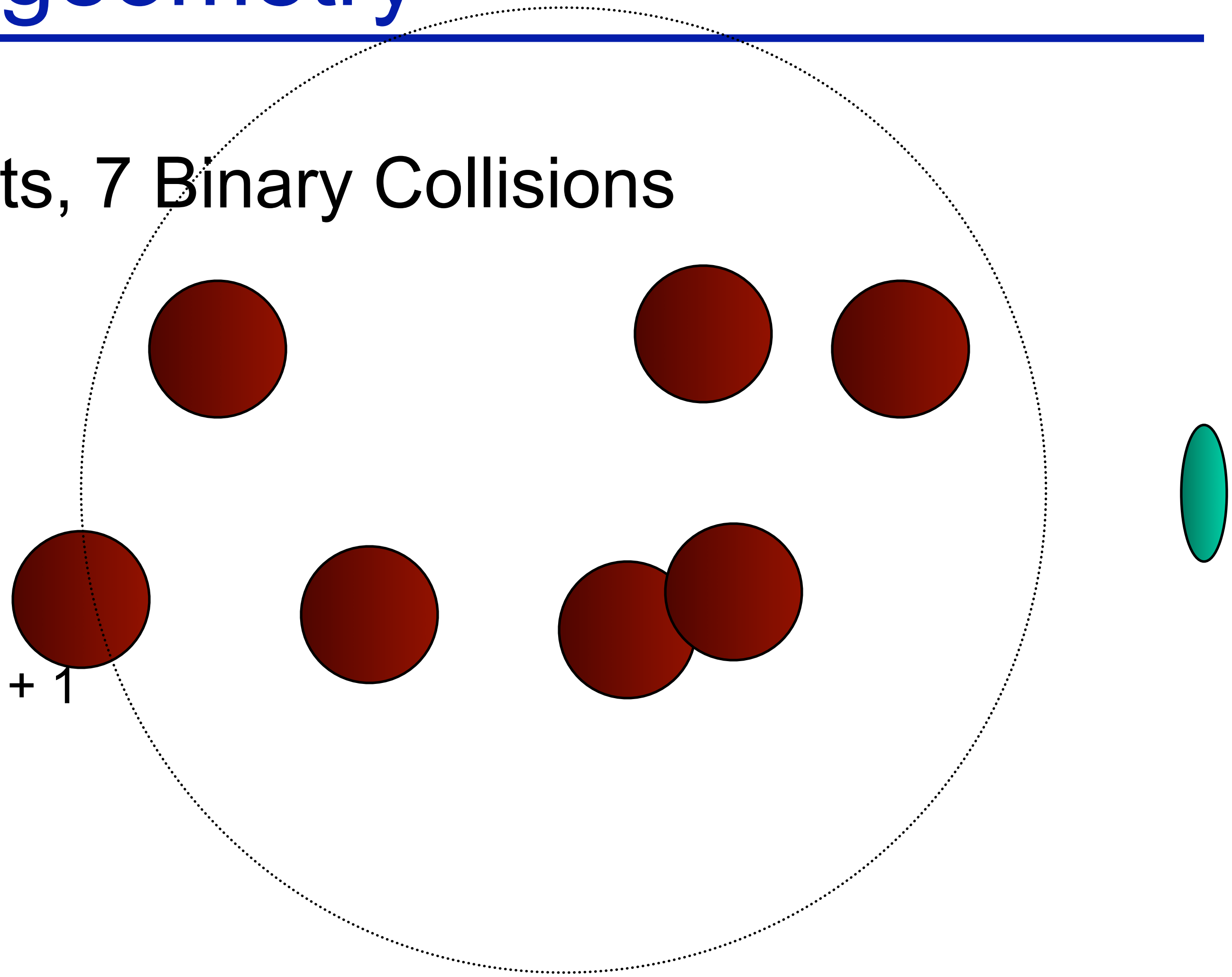
Generically: $N_{part} = N_{bin} + 1$

Participants: those nucleons that have interacted at least once

Binary collisions: the number of 1+1 collisions

Quantifying geometry

p+A: 8 Participants, 7 Binary Collisions



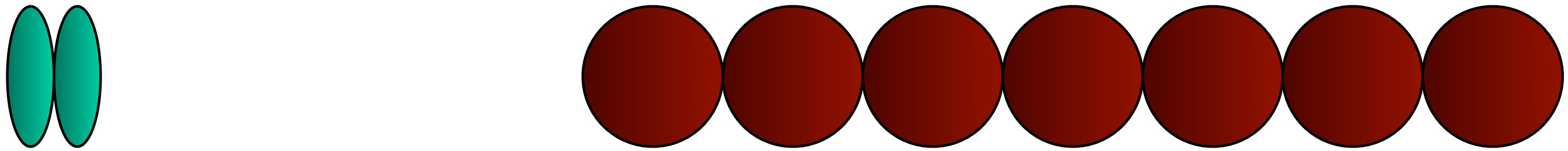
Generically: $N_{part} = N_{bin} + 1$

Participants: those nucleons that have interacted at least once

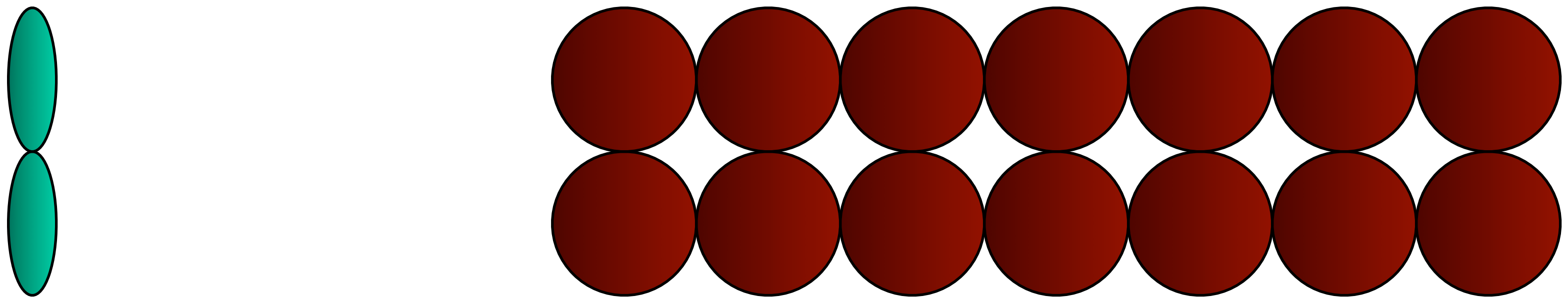
Binary collisions: the number of 1+1 collisions

Quantifying geometry

A+A: 9 Participants, 14 Binary Collisions



A+A: 16 Participants, 14 Binary Collisions



Quantifying geometry

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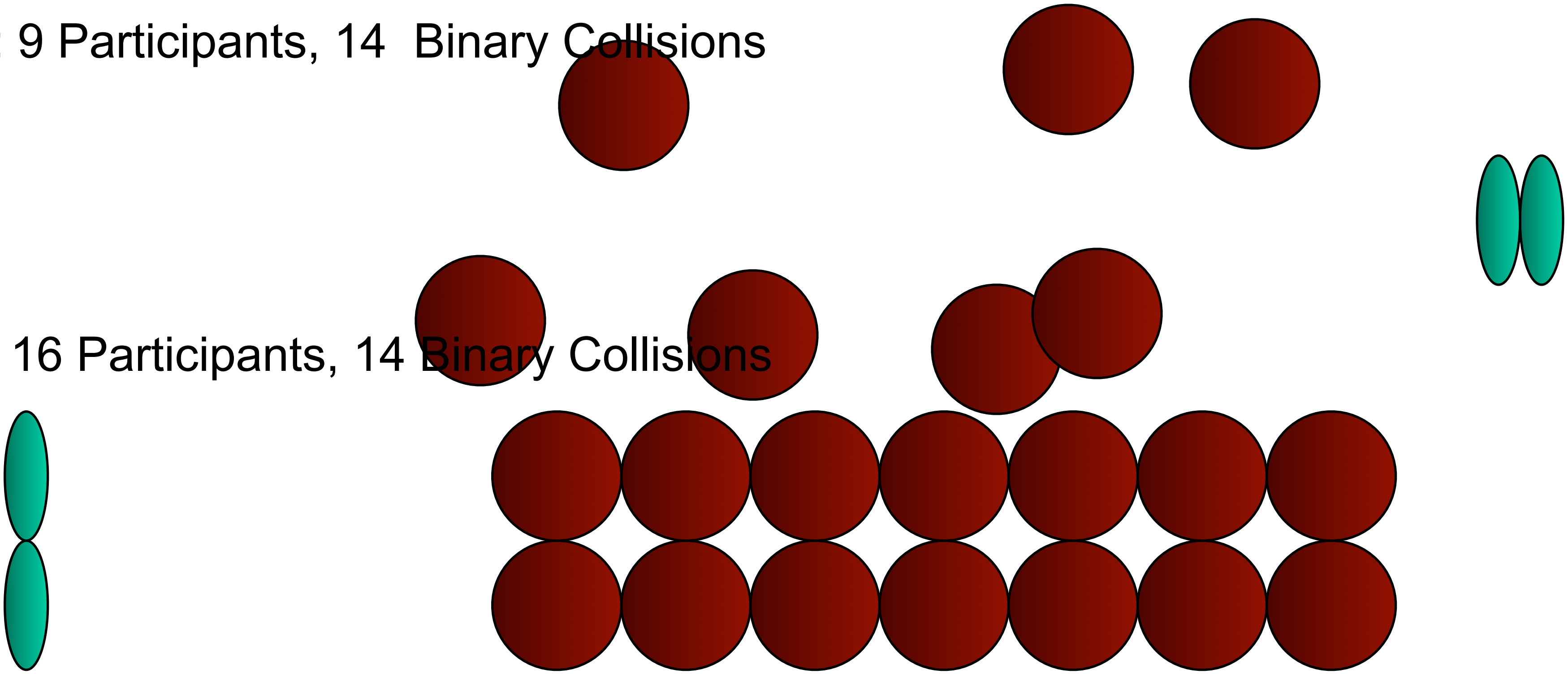

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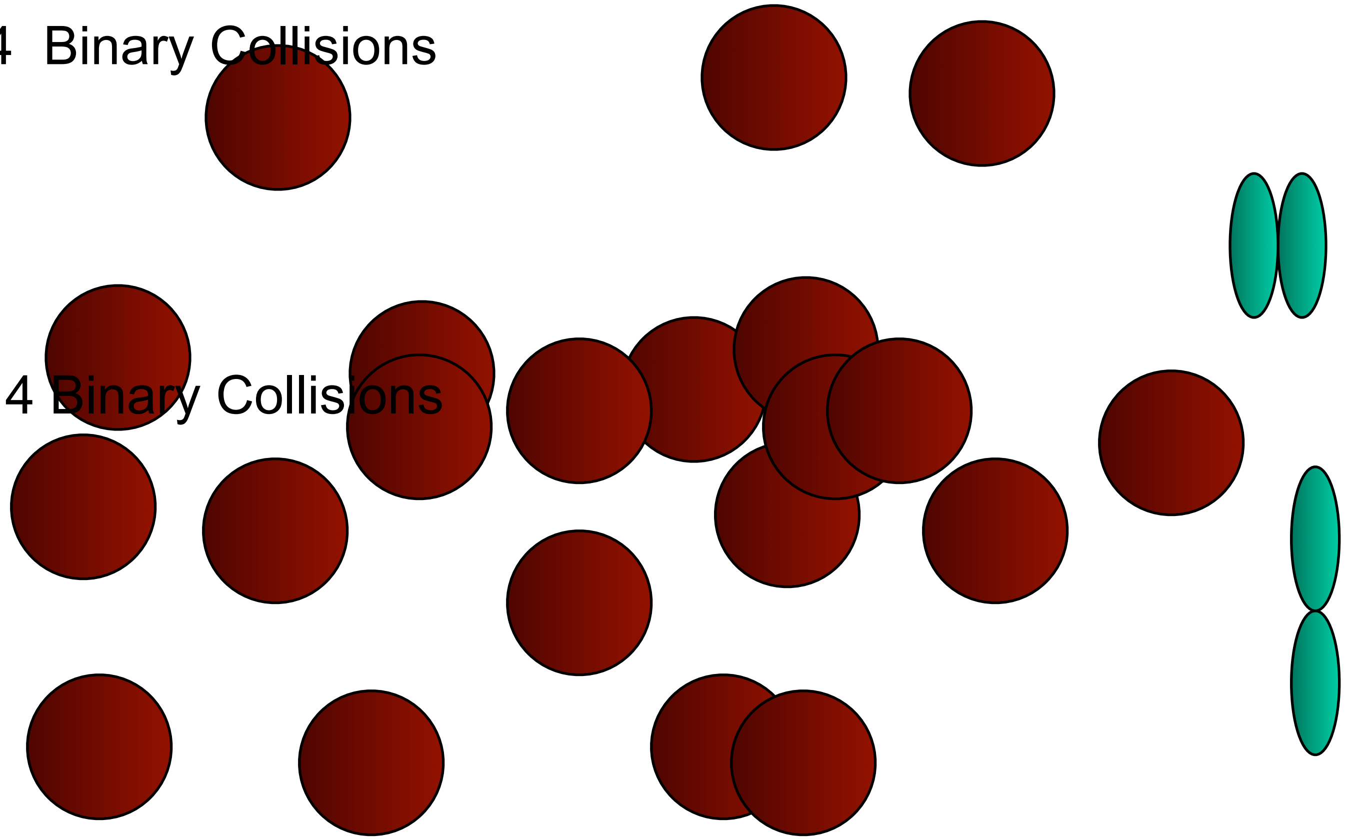

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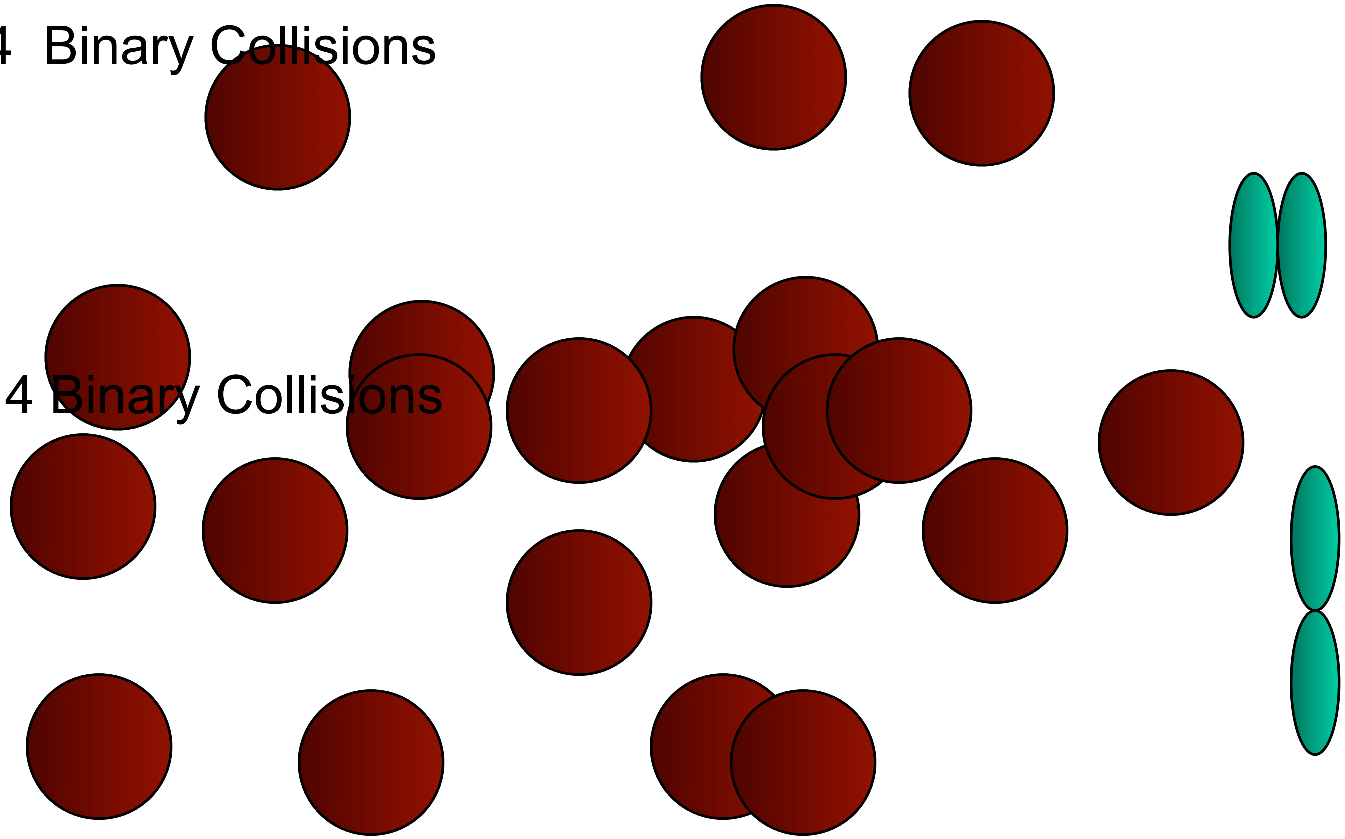


Note: How N_{part} and N_{bin} are extracted takes a lecture alone

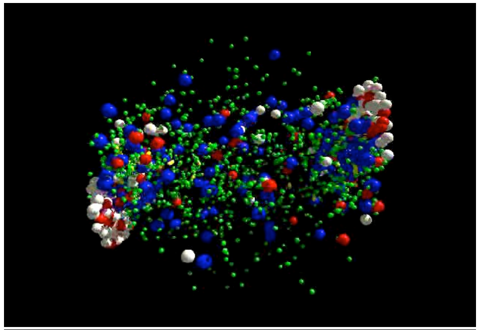
Brief: Info from ZDC & BBC and a simple version of Glauber theory is used to derive N_{part} and N_{bin}. Assumptions:

- Eikonal: constituents of nuclei proceed in straight-line trajectories
- Interactions determined by initial-state shape of overlapping nuclei

Where we can look?

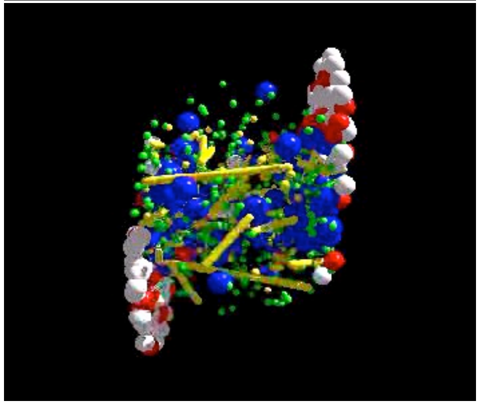
1. Final State

Yields of produced particles: Thermalization, Hadrochemistry



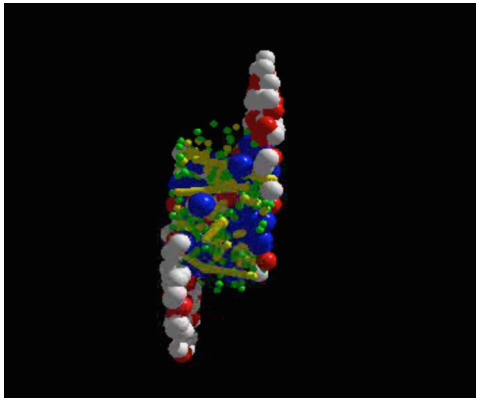
2. Probes of dense matter

Tomography: jets traversing the hot and dense matter



3. Early State

Hydrodynamic flow from initial spatial asymmetries



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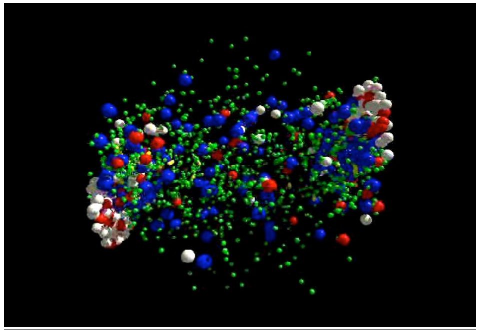

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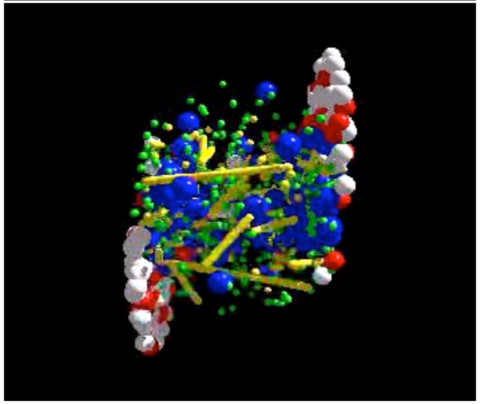

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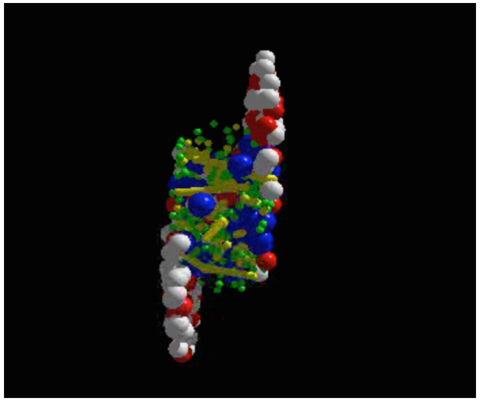
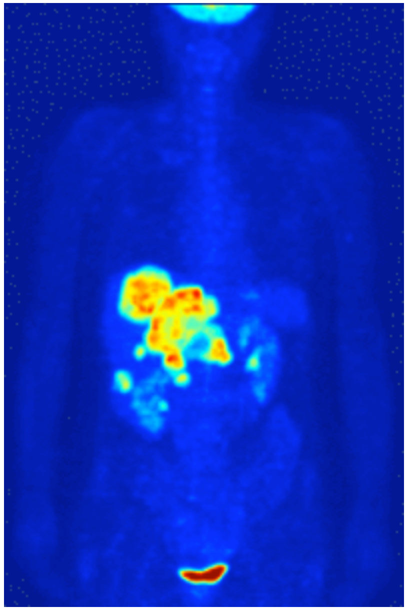


Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)



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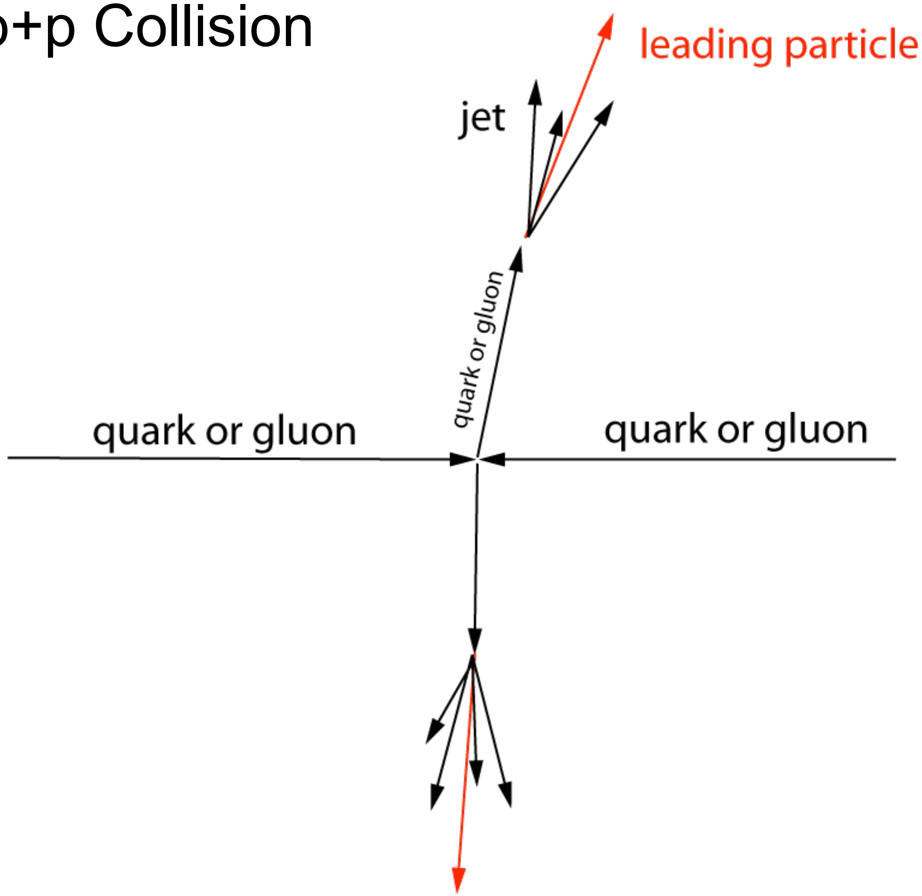
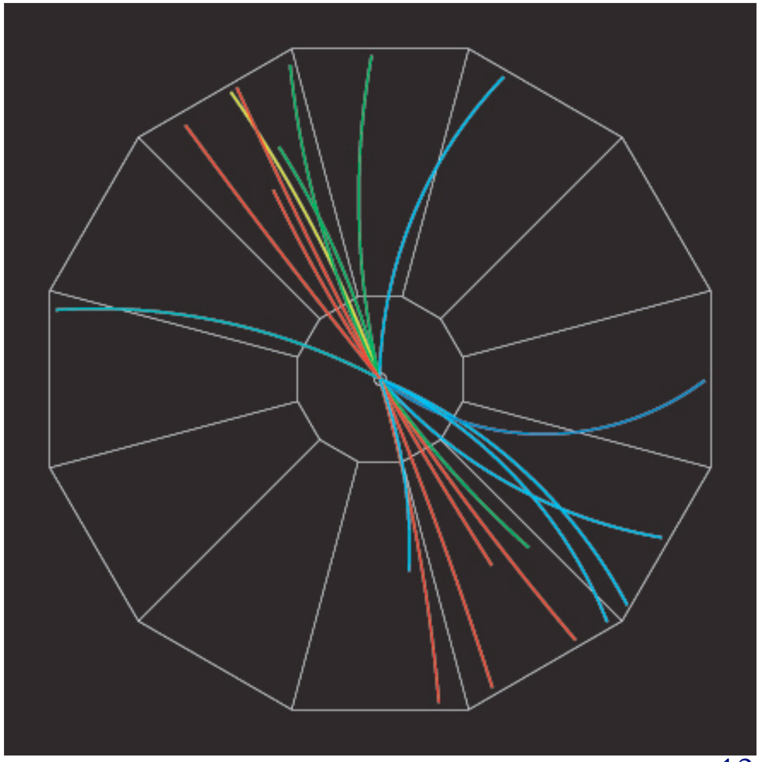
p+p Collision



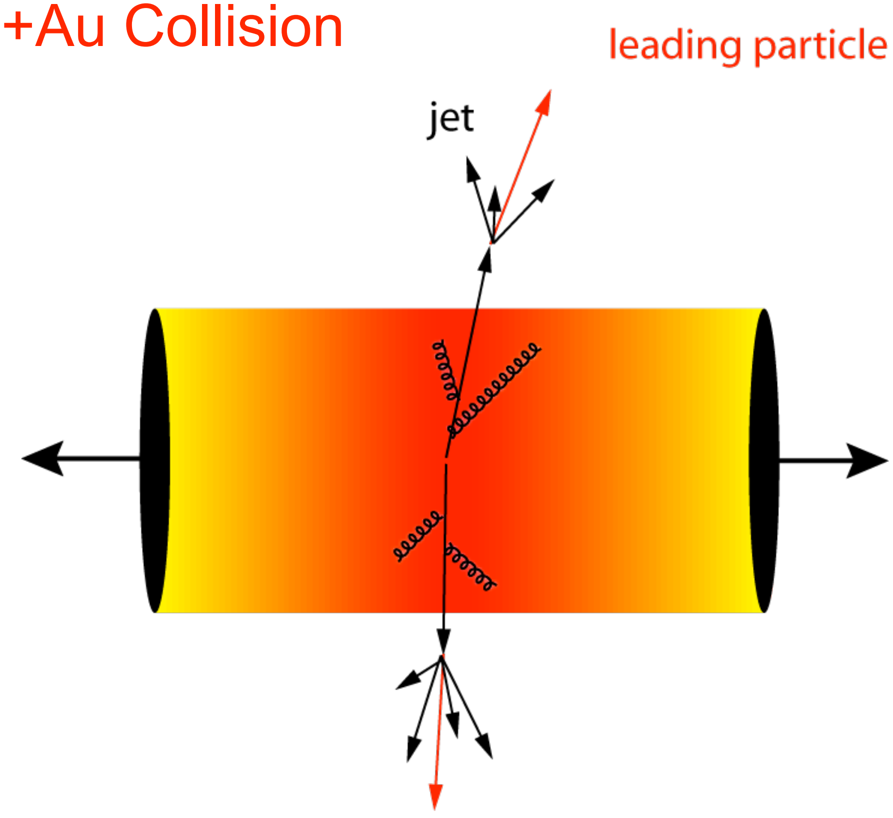


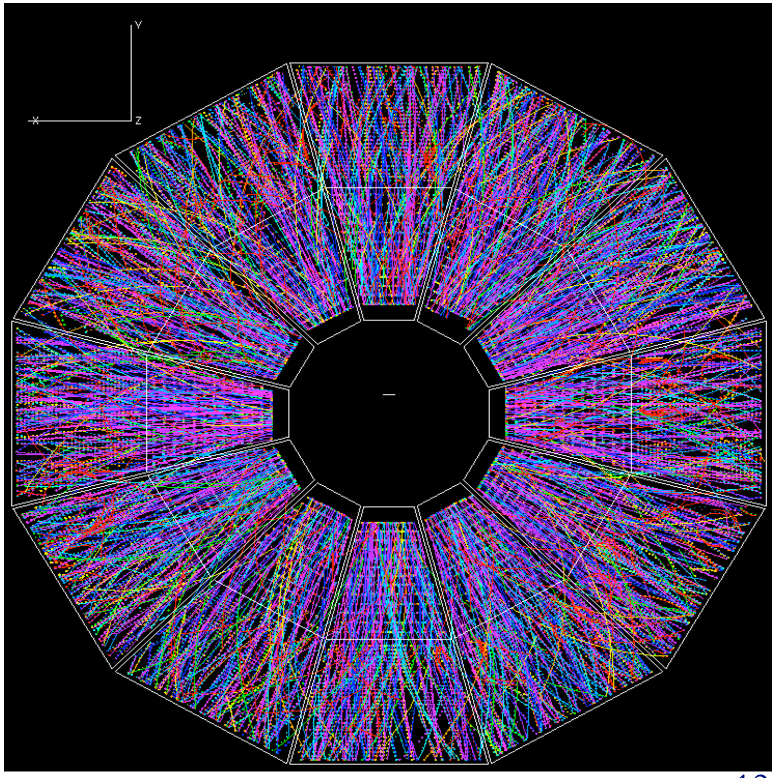
Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)
- Calibrated interaction (beam of known energy and direction)
- Suppression pattern tells about density profile

Au+Au Collision





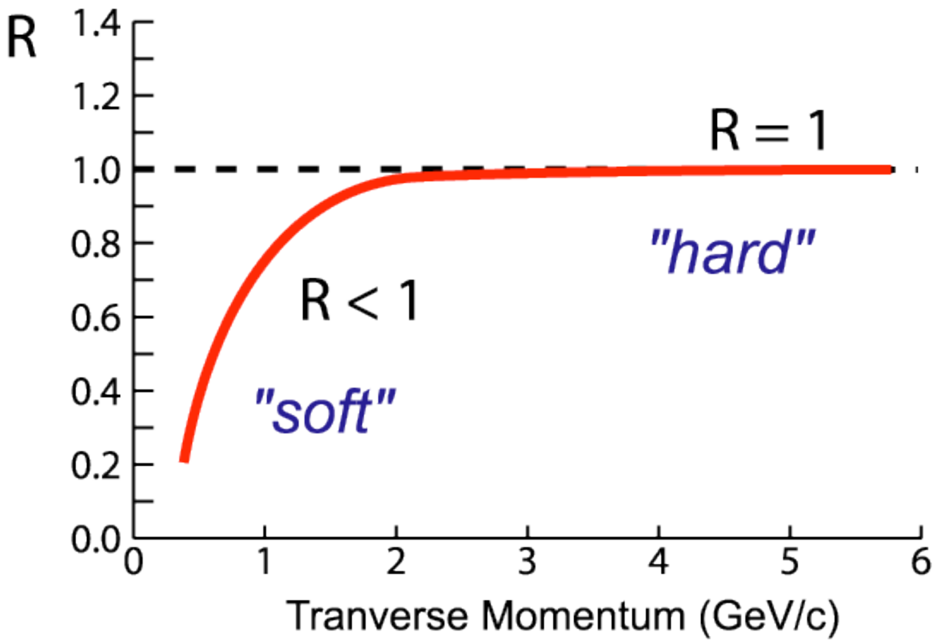
How to Measure ?

Compare Au+Au with p+p Collisions ⇒ R_{AA}

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

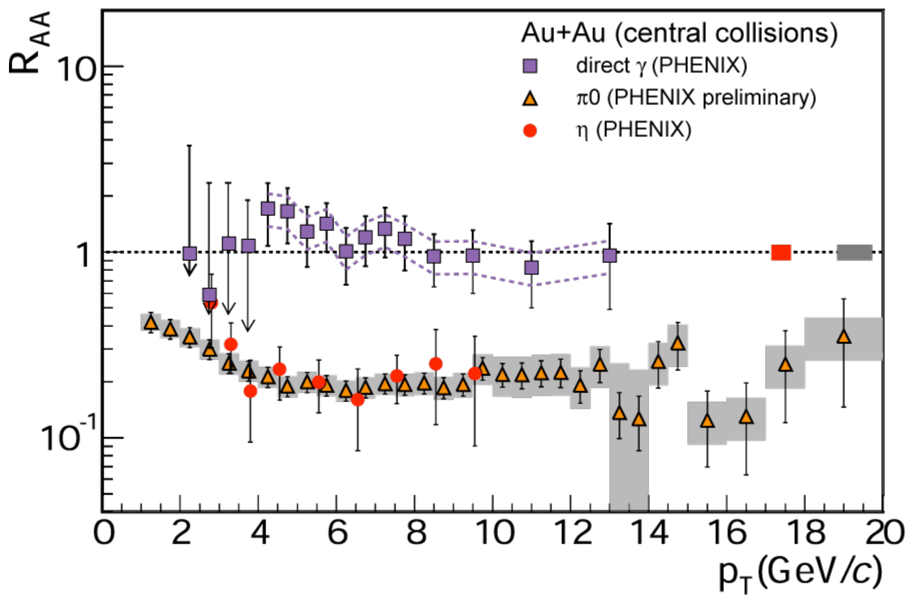
Average number of NN collision in an AA collision



No "Effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate

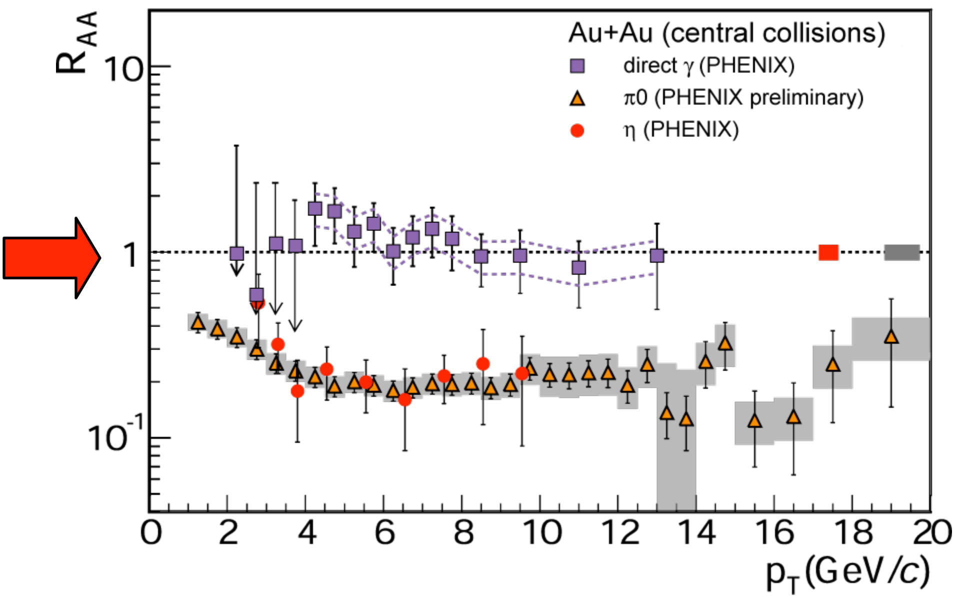
Suppression: R < 1

High-p_T Suppression – Matter is Opaque



Observations at RHIC:

High-p_T Suppression – Matter is Opaque



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1. Photons are not suppressed
   - Good! γ don't interact with medium
   - N_{coll} scaling works

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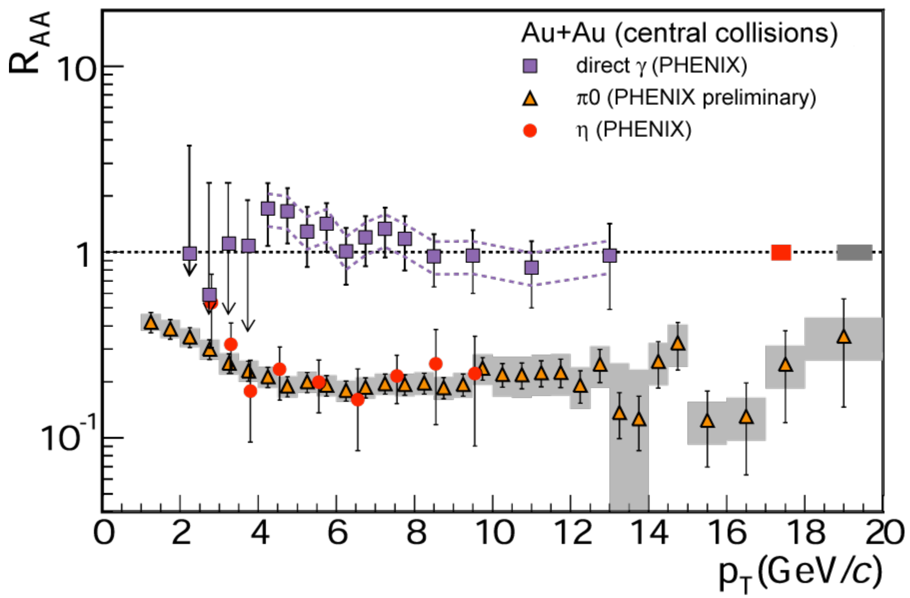

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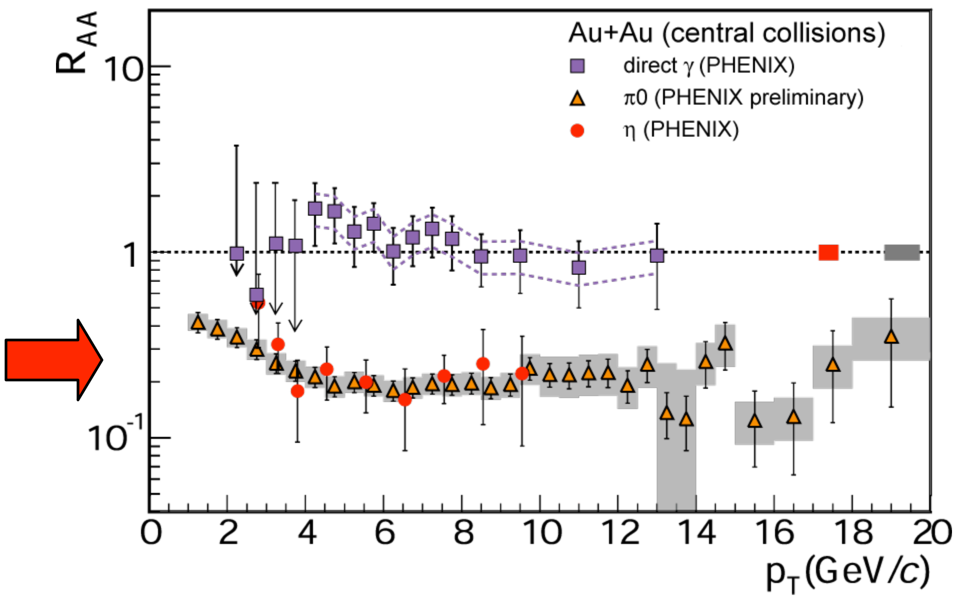

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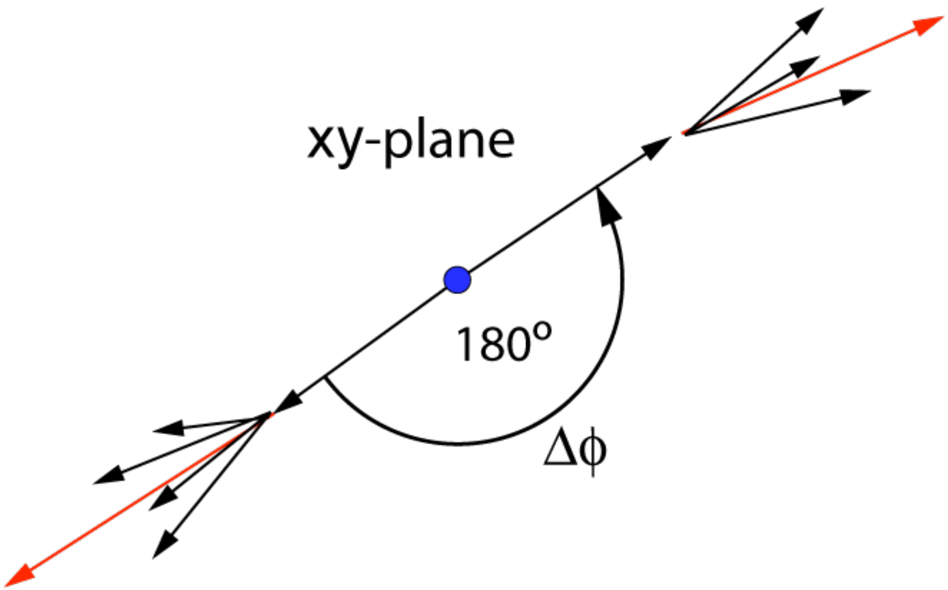

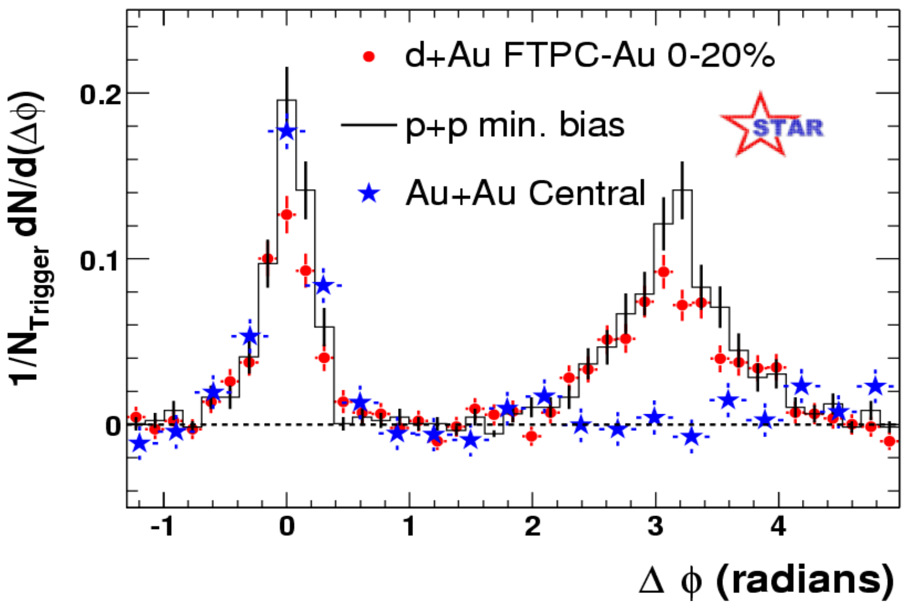

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   - Partner in hard scatter is absorbed in the dense medium

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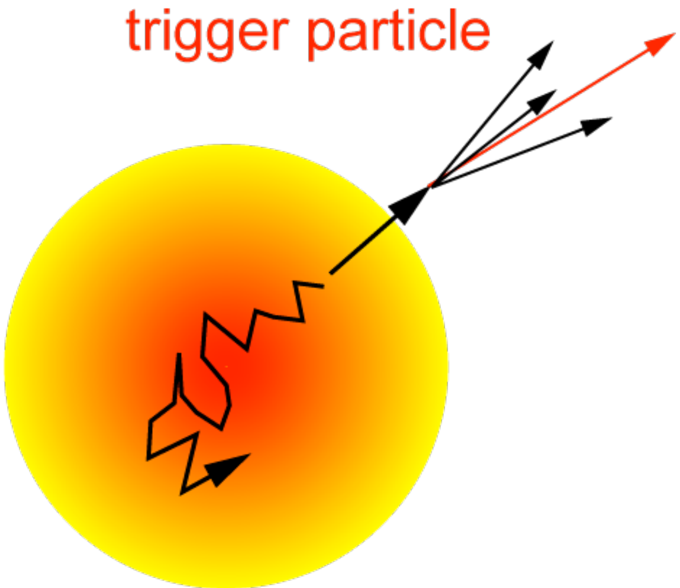

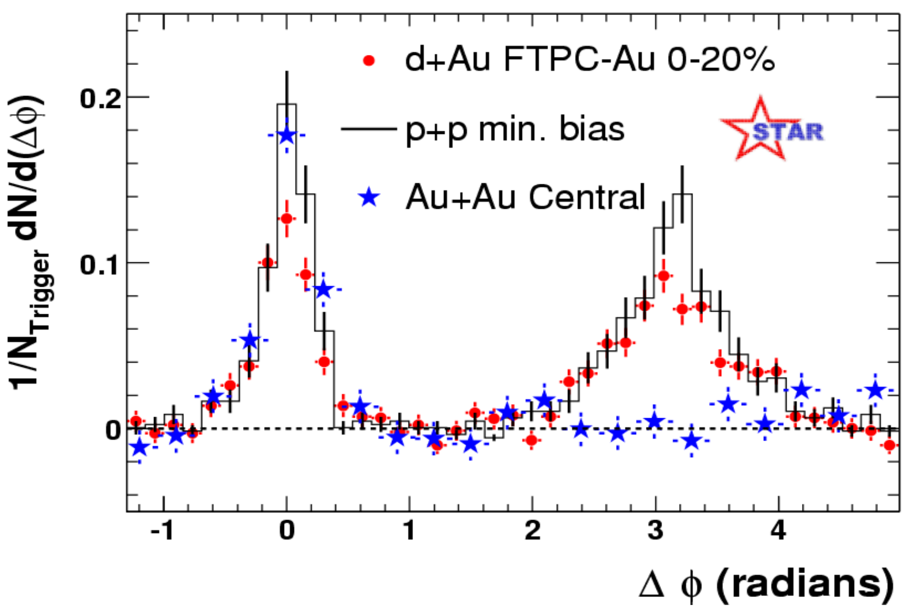

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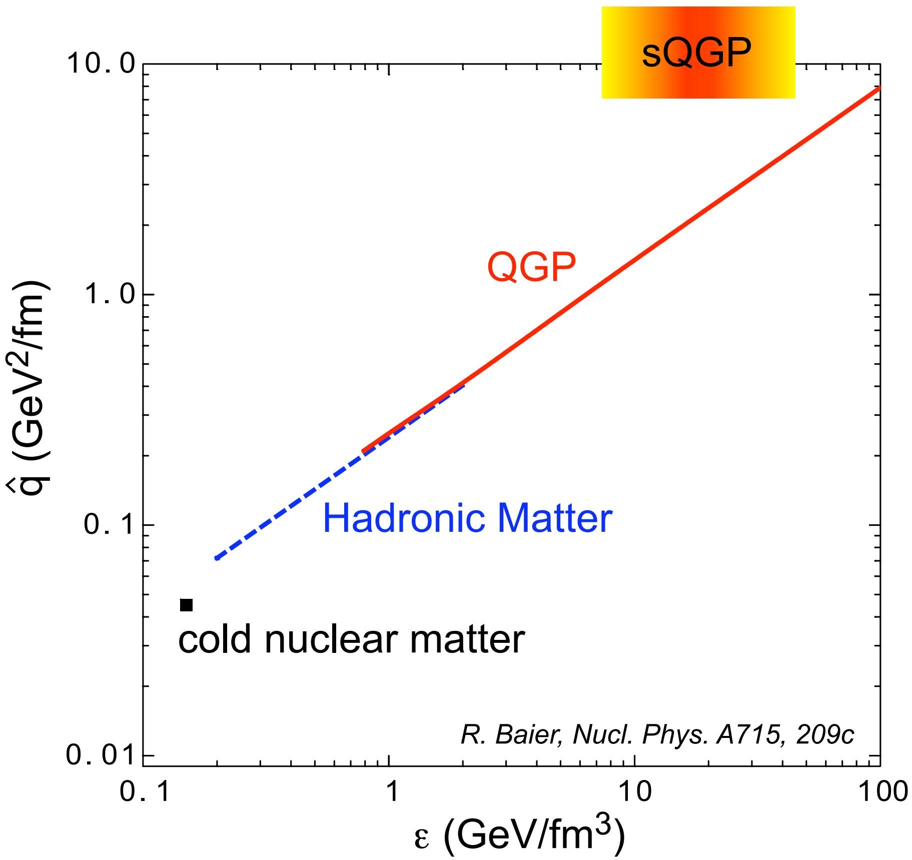
Interpretation

- Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium



- Mean parton energy loss ∝ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim L^2$ (medium length)
    $\Rightarrow \sim L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$

$$\Delta E \approx \frac{C_R \alpha_s}{4} \hat{q} L^2$$

$$\hat{q} \approx \underbrace{\rho\sigma}_{\text{Scattering Density}} \cdot \overbrace{\langle k_T^2 \rangle}^{\text{Color Force Range}} \approx c\,\varepsilon^{3/4}$$

or: the $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length

  - gluon density dN_g/dy

Constraining $\hat{q}$

Model	Opacity Parameter	One Standard Deviation Uncertainty
PQM	$\langle \hat{q} \rangle = 13.2\ \mathrm{GeV}^2/\mathrm{fm}$	$^{+2.1}_{-3.2}$
GLV	$dN^g/dy = 1400$	$^{+270}_{-150}$
WHDG	$dN^g/dy = 1400$	$^{+200}_{-375}$
ZOWW	$\epsilon_0 = 1.9$	$^{+0.2}_{-0.5}$

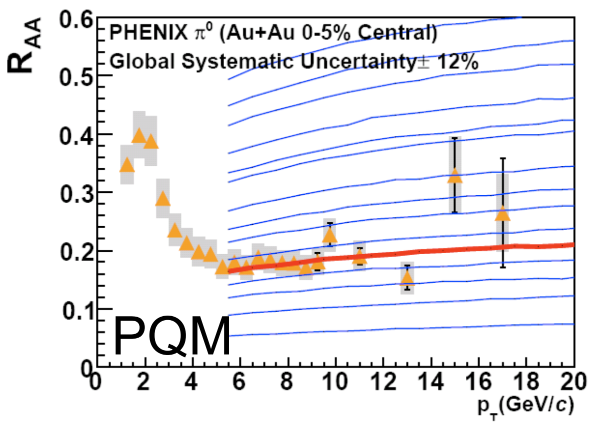
PHENIX: http://arxiv.org/abs/0801.1665

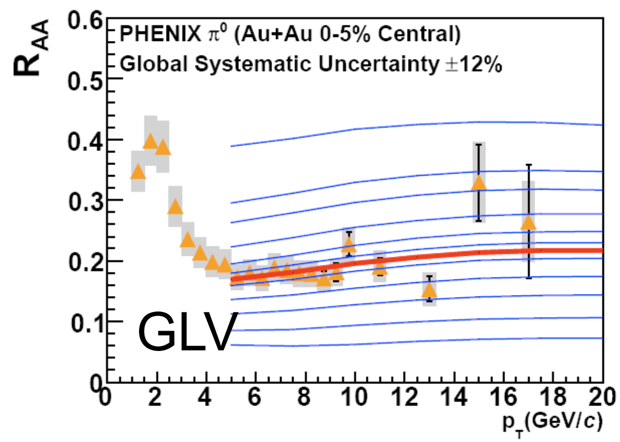
PQM: A. Dainese, C. Loizides, G. Paic, Eur. Phys. J C38: 461 (2005). C. Loizides, Eur. Phys. J.C49, 339 (2007) [hep-ph/0608133].

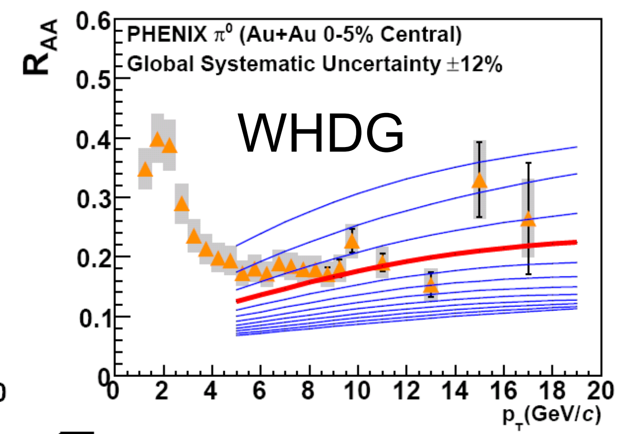
GLV: I. Vitev, Phys. Lett. B639, 38 (2006) [hep-ph/0603010]. M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. B571, 197 (2000) [hep-ph/9907461].

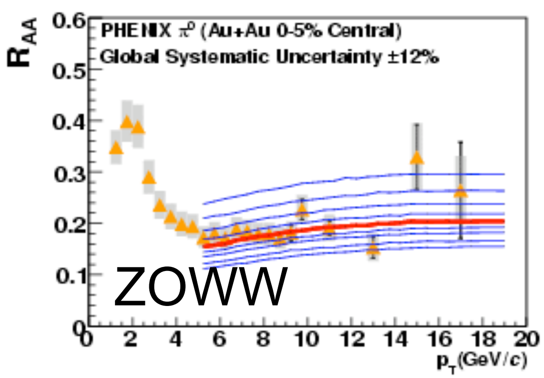
WHDG: W.A. Horowitz, S. Wicks, M. Djordjevic, M. Gyulassy,in preparation; S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 783, 493 (2007) [nucl-th/0701063]; S. Wicks, W. Horowitz, M. Djordjevic,M. Gyulassy, Nucl. Phys. A 784, 426 (2007) [nucl-th/0512076].

ZOWW: H. Zhang, J.F. Owens, E. Wang, X-N Wang, Phys Rev. Lett. 98: 212301 (2007) [nucl-th/0701045].





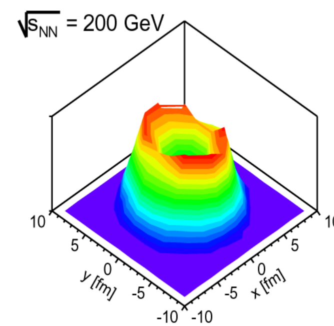




Problems

- Surface bias effectively leads to saturation of R_{AA} with density
- Expanding medium

$$\hat{q} = \hat{q}(\vec{r}, \tau)$$



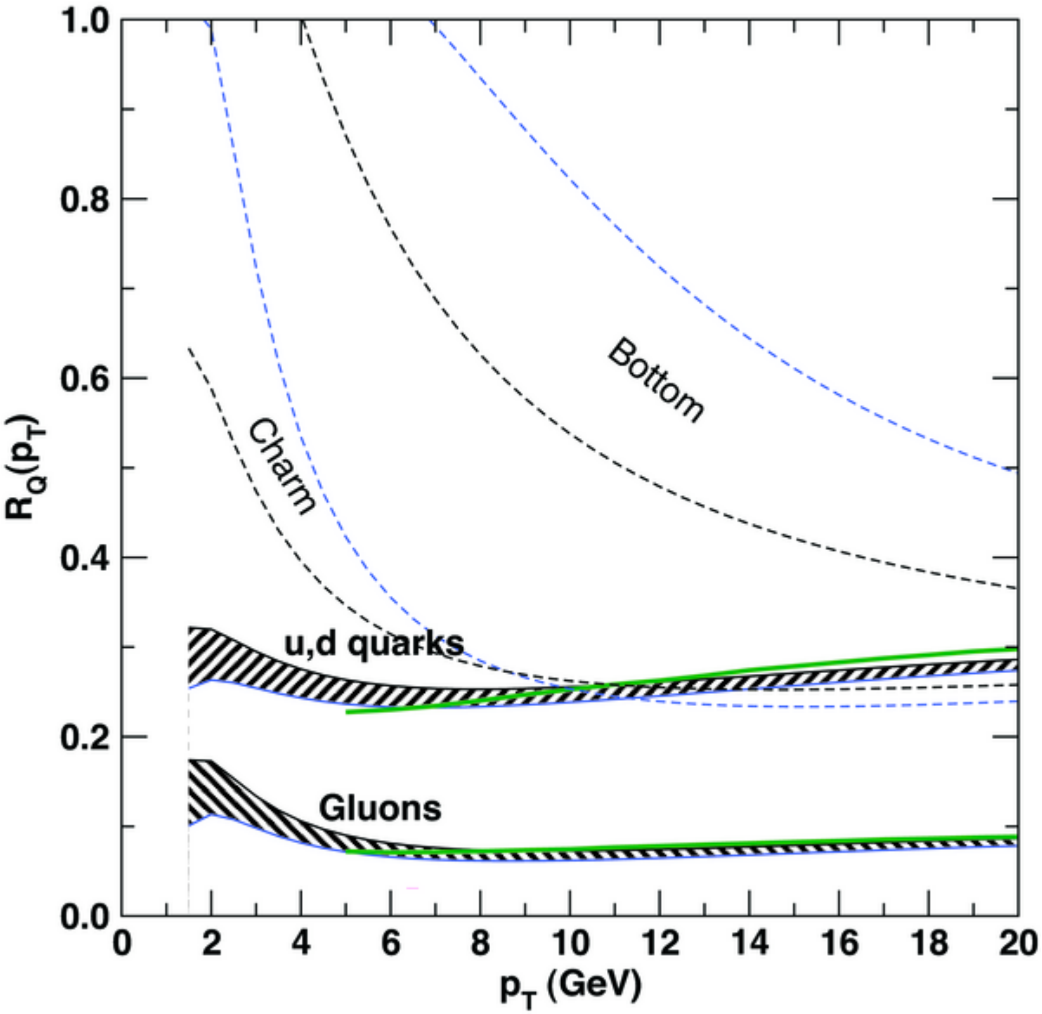
Distributions of parton production points in the transverse plane

A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. C38(2005) 461

Calibrated Interaction? Gray Probes

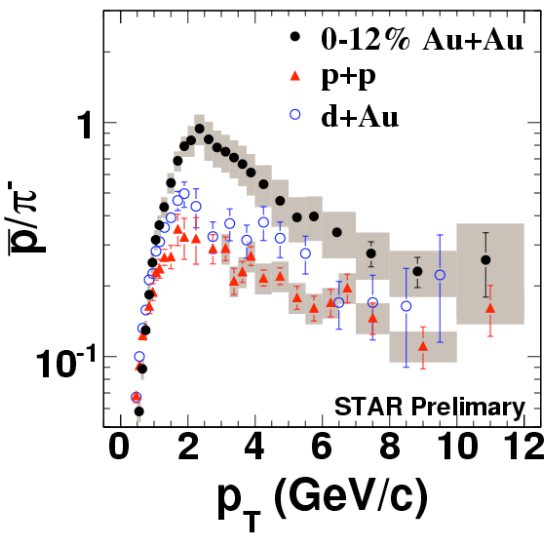
- Problem: interaction with the medium so strong that information lost: “Black”
- Significant differences between predicted R_{AA}, depending on the probe
- Experimental possibility:
  - recover sensitivity to the properties of the medium by varying the probe
  - studying 2 or even 3 high-p_T particle correlations

Wicks et al, Nucl. Phys. A784 (2007) 426

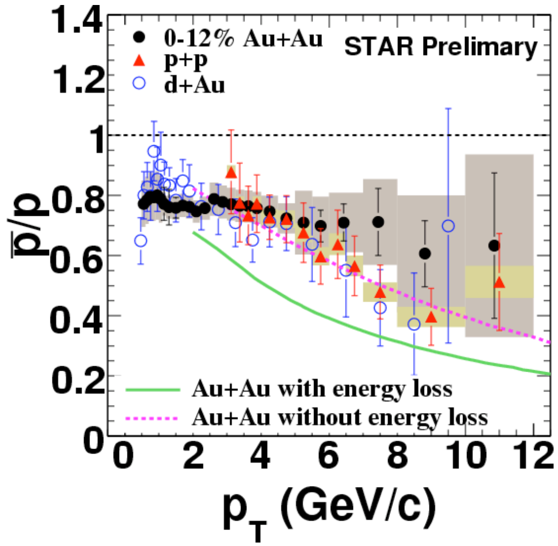


Color Factors: No shade of gray?

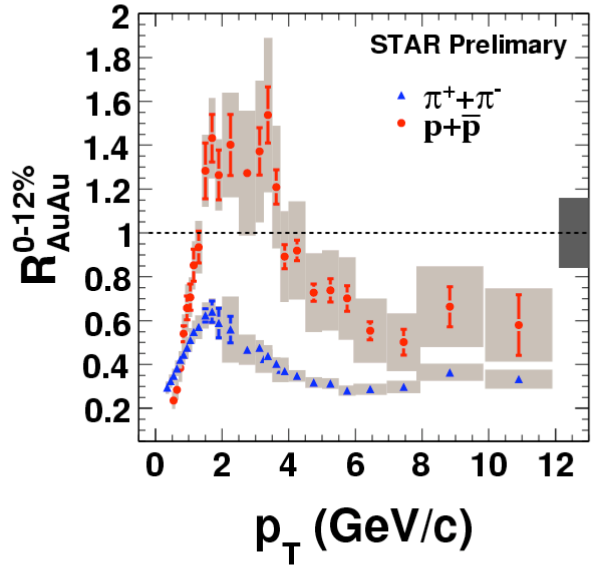
Anti-Baryon/meson



Anti-particle/particle



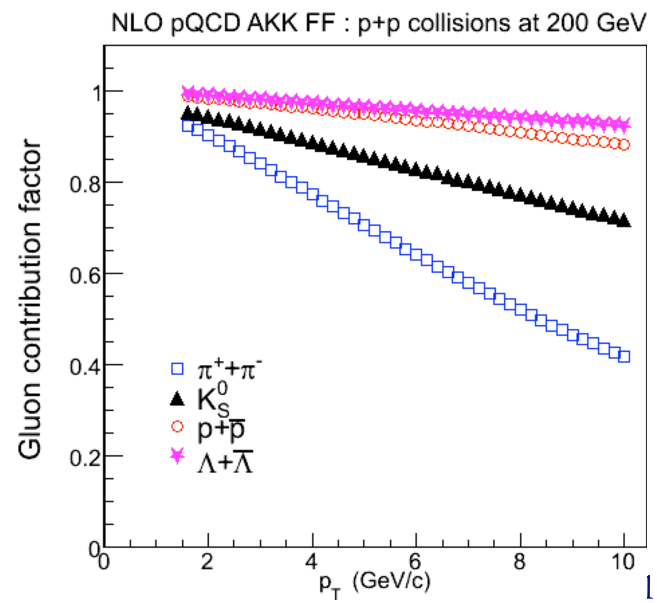
Baryon & meson NMF



STAR : PLB 637 (2006) 161, PRL 97 (2006) 152301, PLB 655 (2007) 104

$$\langle \Delta E \rangle \propto \alpha_s C \langle \hat{q} \rangle L^2$$

The Color Factor Effect $\dfrac{\Delta E_g}{\Delta E_q} = 9/4$

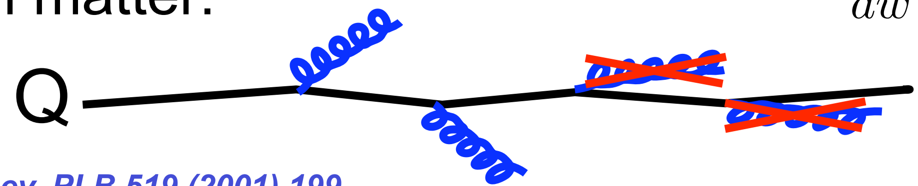


- Higher precision p+p reference:
  - Higher suppression of gluons than quarks should lead to higher suppression of protons and especially antiprotons
  - **Still** no sign of this, in fact appears to go the wrong way
  - Are FF correct? Baryon production?

High-p_T Heavy Quarks are Gray Probes

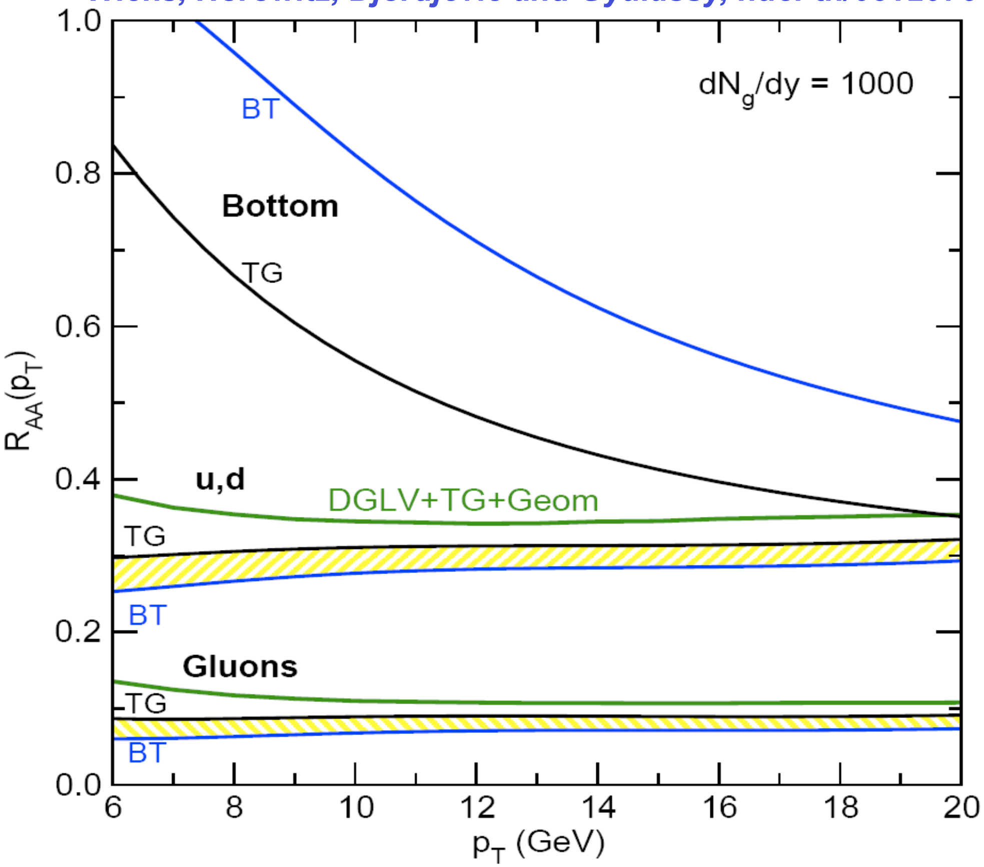
Dead cone effect implies lower heavy quark energy loss in matter:

$$\omega \frac{dI}{dw}\bigg|_{\mathrm{HEAVY}} = \frac{\omega \frac{dI}{dw}\big|_{\mathrm{LIGHT}}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

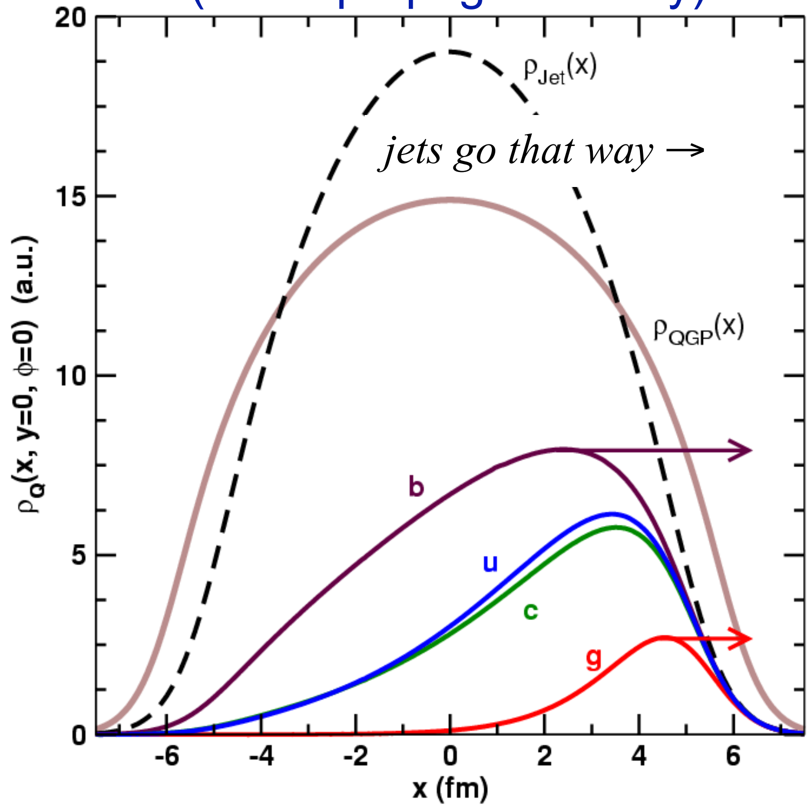


Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Wicks, Horowitz, Djordjevic and Gyulassy, nucl-th/0512076



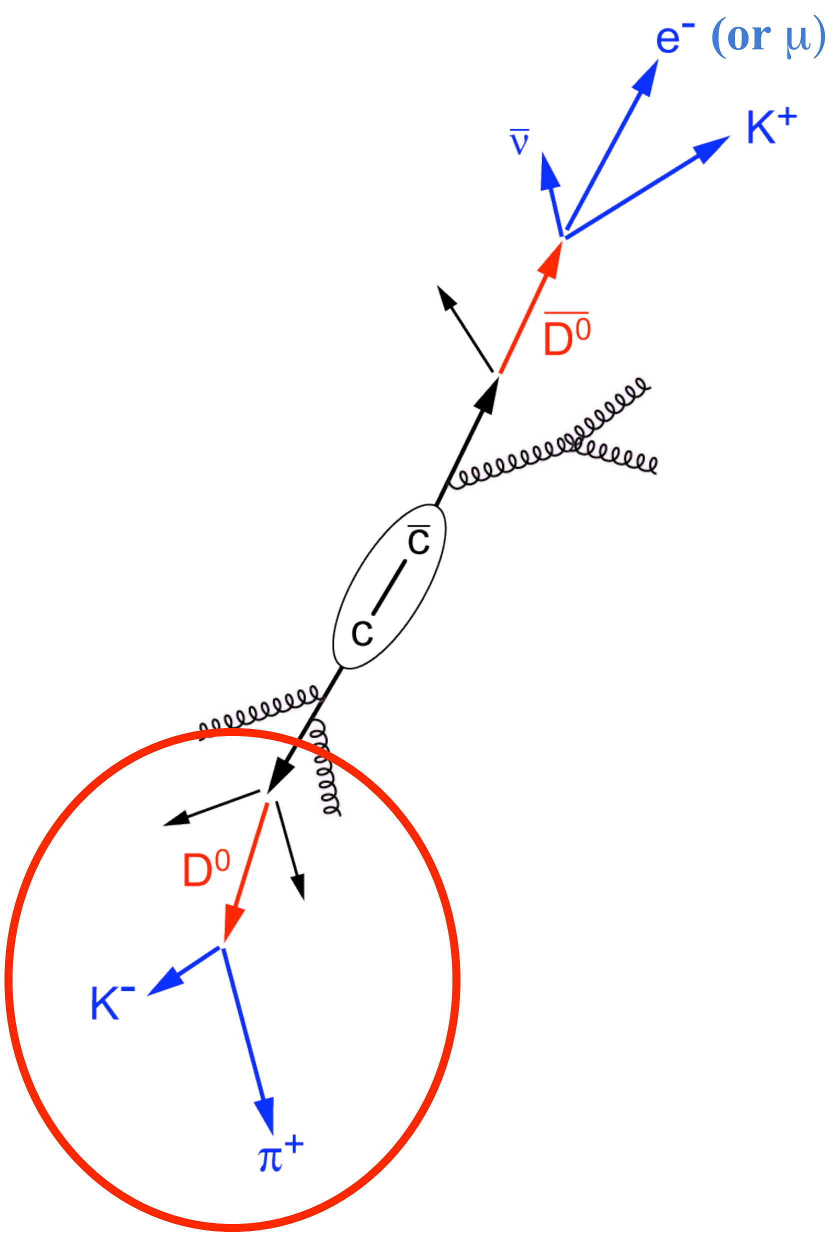
Origin of surviving jets p_T= 15 GeV (radial propagation only)



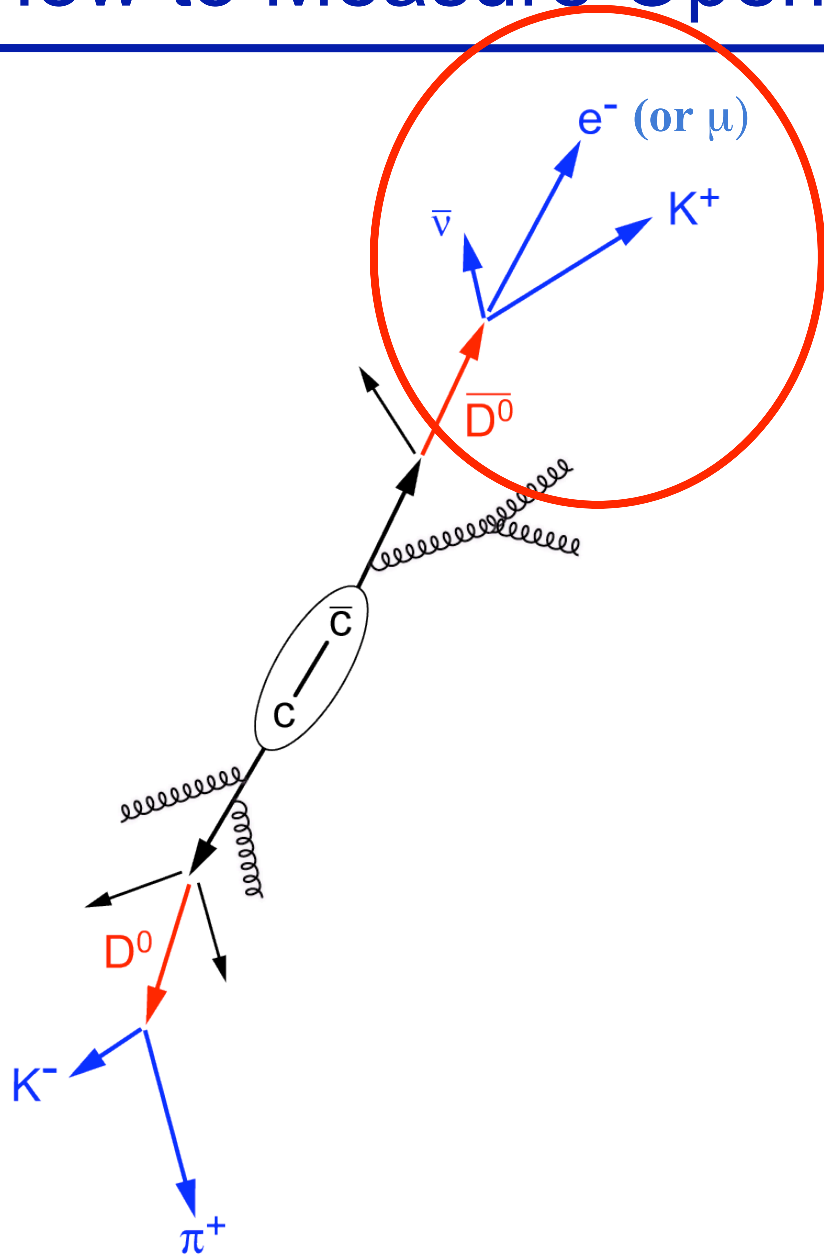
How to Measure Open Heavy Flavor ?

- <u>Hadronic decay channels</u>
  - $D^0 \rightarrow K\pi$ (B.R.: 3.8%)
  - $D^{\pm} \rightarrow K\pi p$ (B.R.: 9.1%)
  - $D^{*\pm} \rightarrow D^0\pi$ (B.R.: 68% × 3.8% ($D^0 \rightarrow K\pi$) = 2.6%)
  - $\Lambda_c \rightarrow p K \pi$ (B.R.: 5%)

- Pro:
  - Direct clean identification (*peak*)
- Cons:
  - No trigger
  - Large combinatorial background
  - Need handle on decay vertex
    - charm cτ~100-200 μm
    - bottom cτ~400-500 μm
  - ⇒ requires high resolution silicon vertex detectors



How to Measure Open Heavy Flavor ?



Semileptonic decay channels

- $c \rightarrow \ell^+ + \text{anything}$ (B.R.: 9.6%)
  - $D^0 \rightarrow \ell^+ + \text{anything}$ (B.R.: 6.87%)
  - $D^\pm \rightarrow \ell^\pm + \text{anything}$ (B.R.: 17.2%)
- $b \rightarrow \ell^+ + \text{anything}$ (B.R.: 10.9%)
  - $B^\pm \rightarrow \ell^\pm + \text{anything}$ (B.R.: 10.2%)

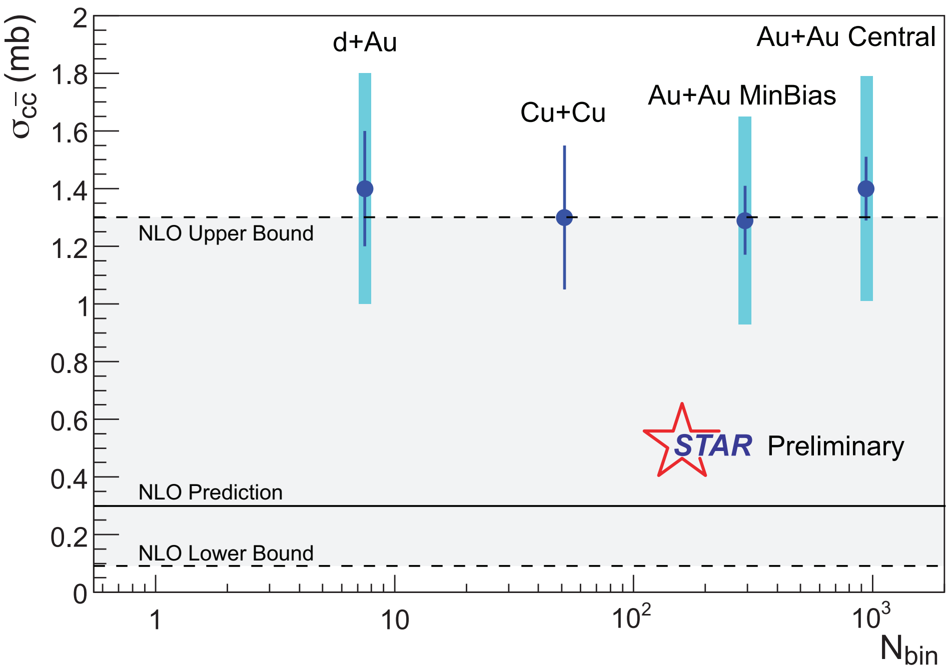
Pro:

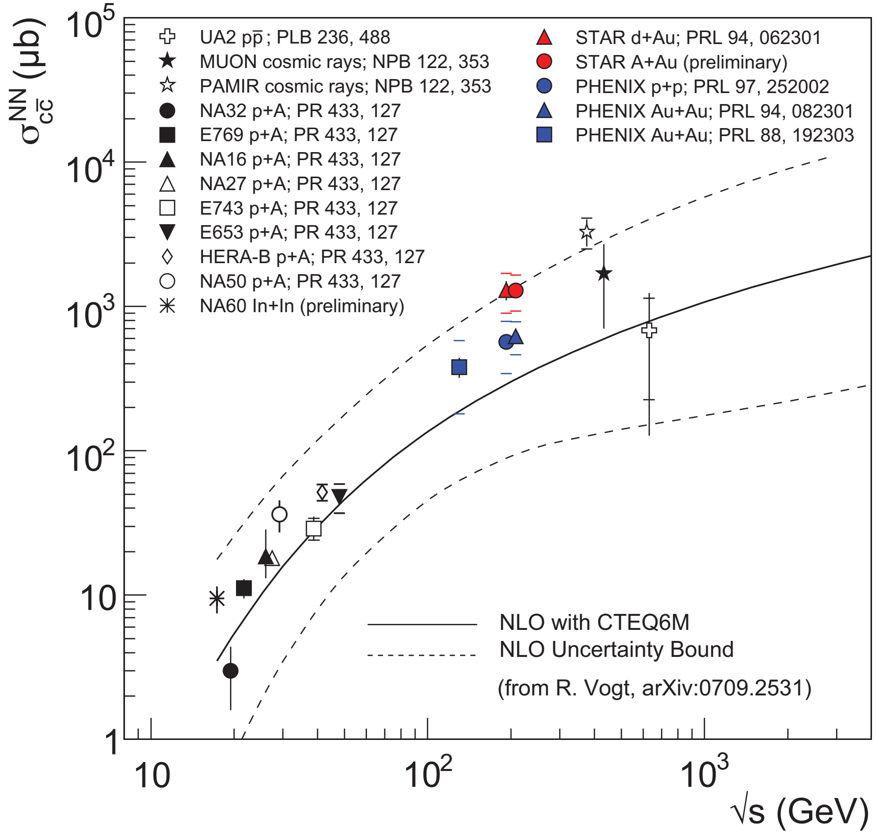
- Can deploy (simple) trigger

Cons:

- *Continuum*: cannot disentangle bottom and charm contributions?
- "*Photonic*" Electron Background:
  - γ conversions ($\pi^0 \rightarrow \gamma\gamma$)
  - π^0, η, η' Dalitz decays
  - ρ, ϕ, … decays (small)
  - Ke3 decays (small)

Total charm cross-section via D→Kπ





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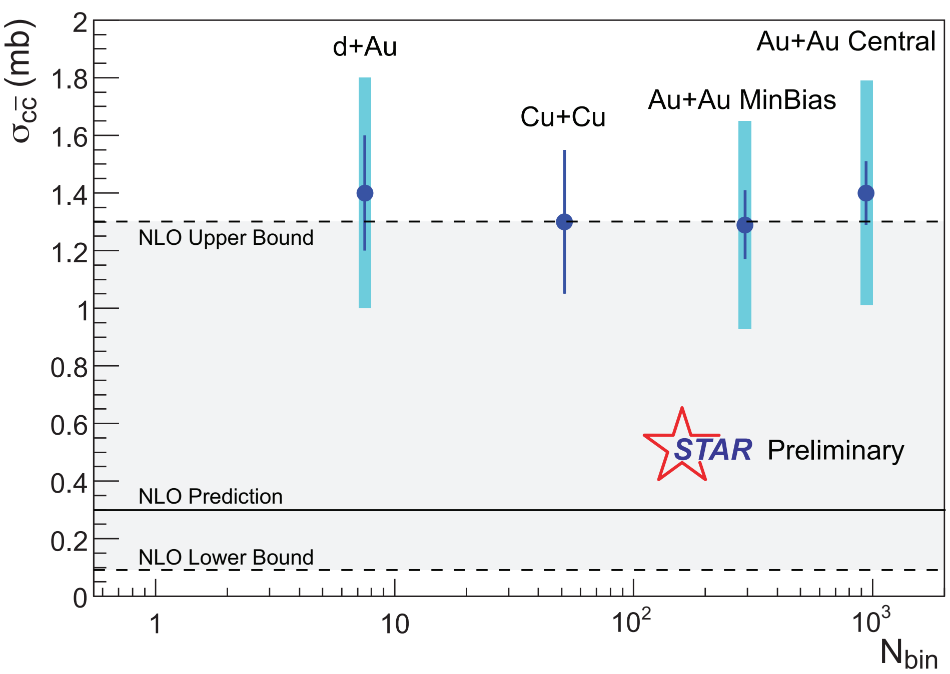
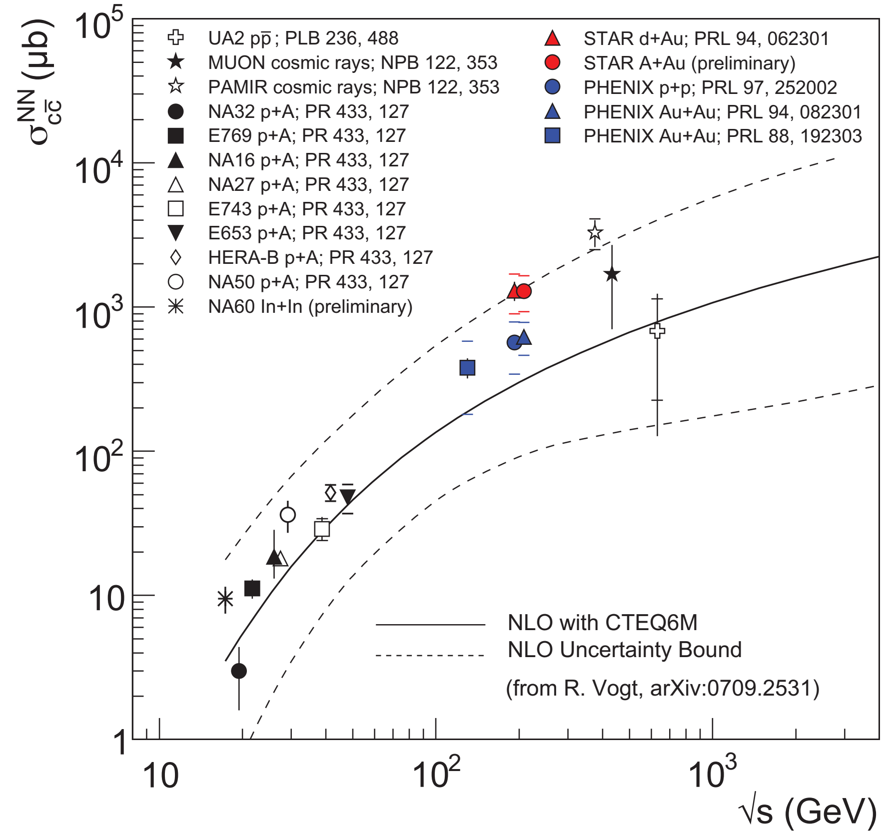
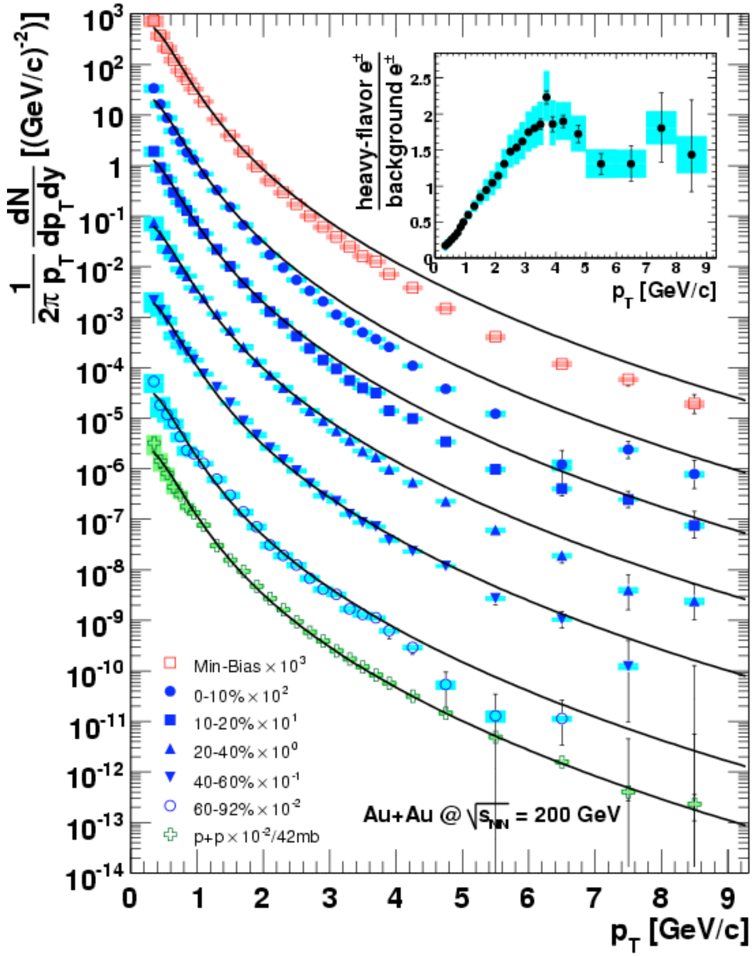


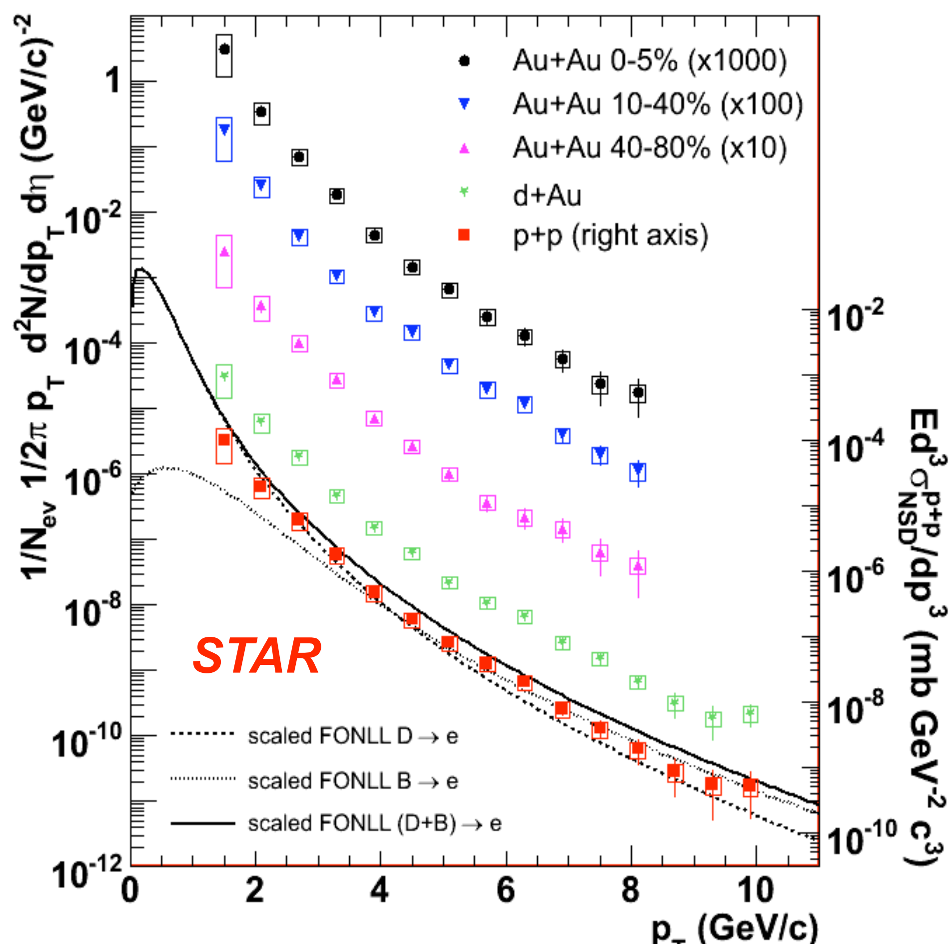


- Charm cross section scale with N_{bin} collisions (expected)
- Multiple measurements in different channels all give the same result (expected)
- Charm cross-section is higher than NLO calculations but within errors (unexpected?)
- STAR and PHENIX differ on this one by a factor of 2 (unexpected)

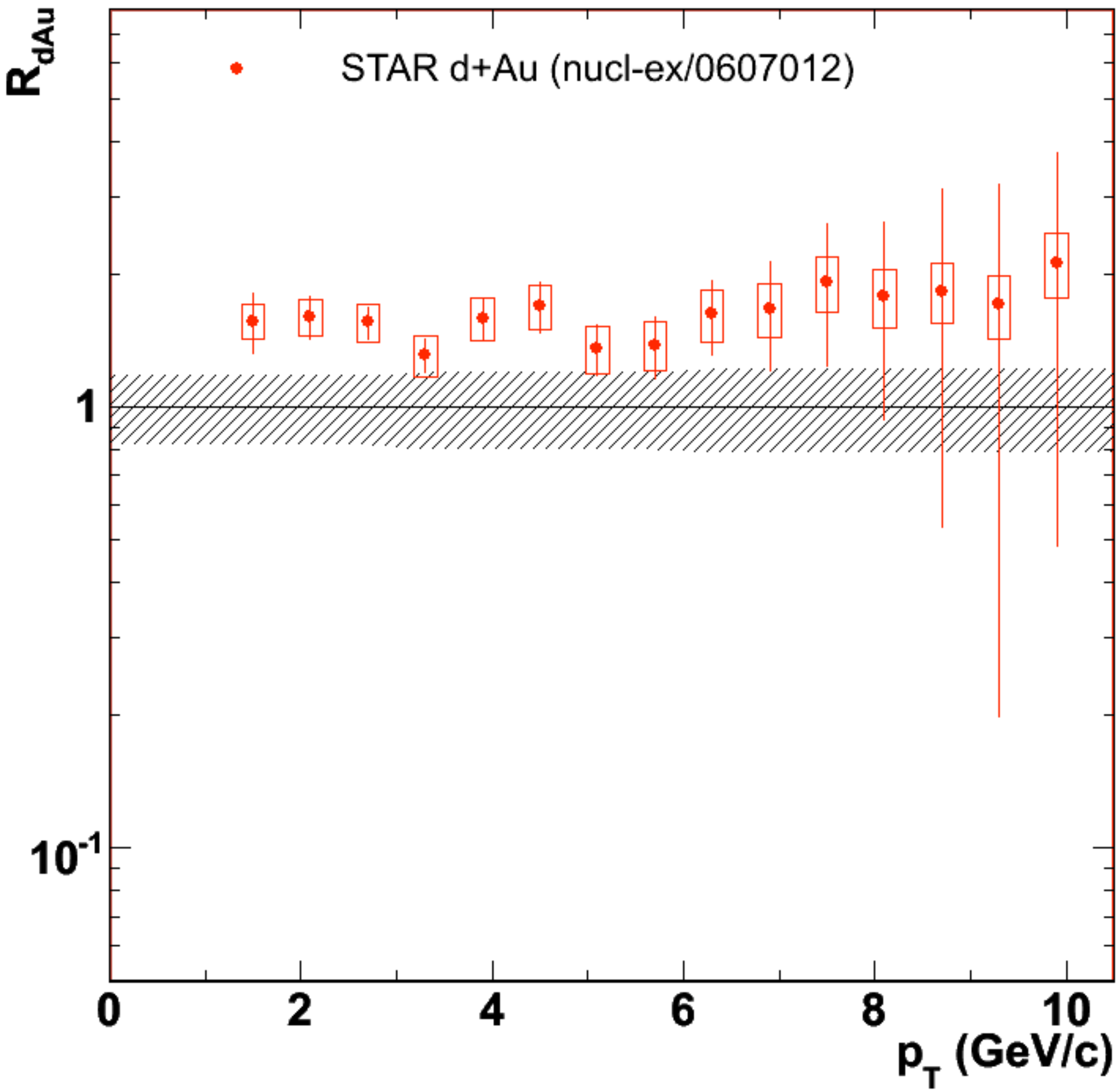
Electrons from semileptonic charm decays

- $c \rightarrow \ell^+ + \text{anything}$ (BR ~ 10%)
- A very complex analysis
- STAR and PHENIX in pp and Au+Au (STAR also d+Au)



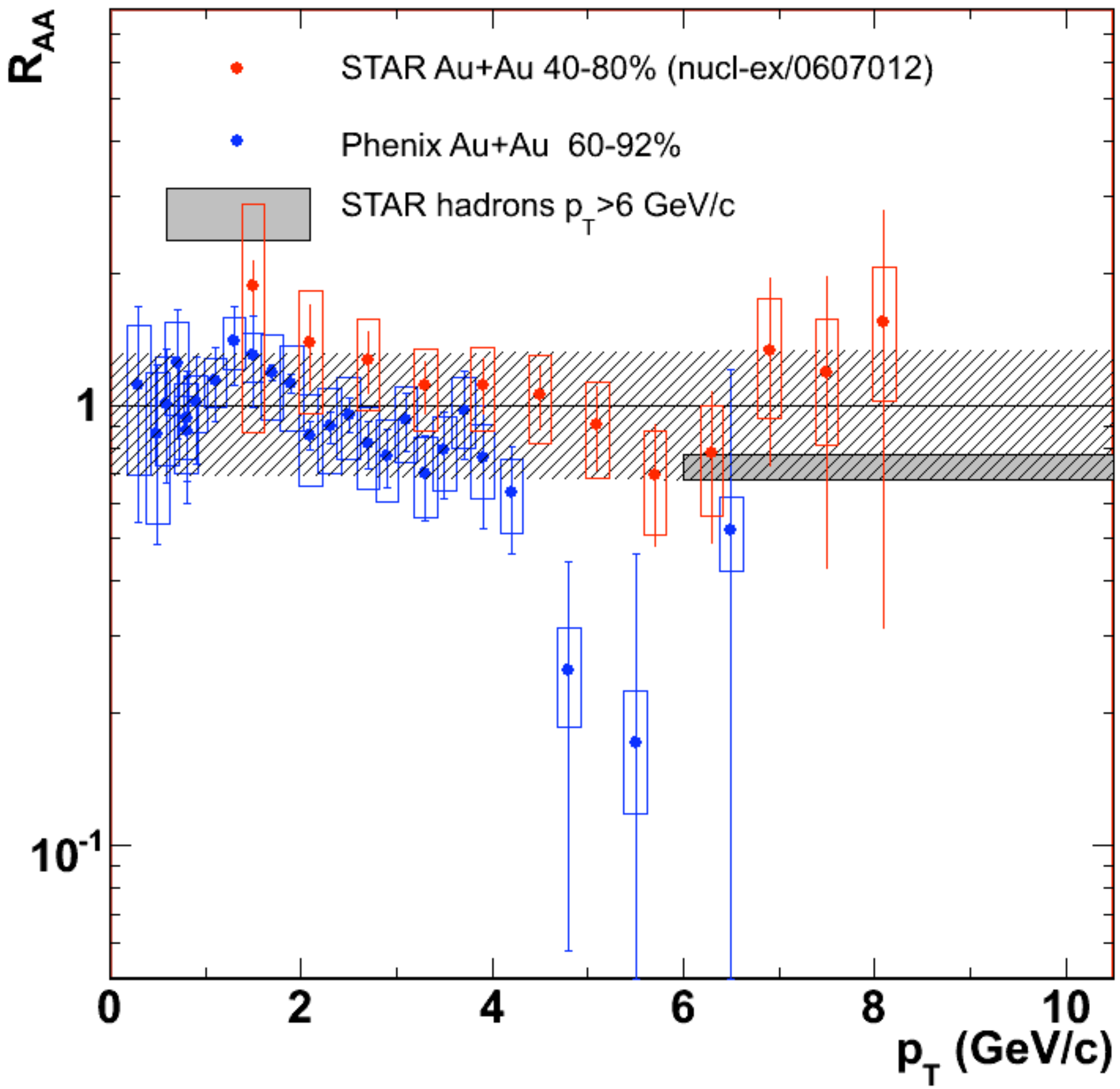


Big Surprise R_{AA}: from d+Au to Central Au+Au



d+Au:
no suppression expected
slight enhancement
expected (Cronin effect)

Big Surprise R_{AA}: from d+Au to Central Au+Au



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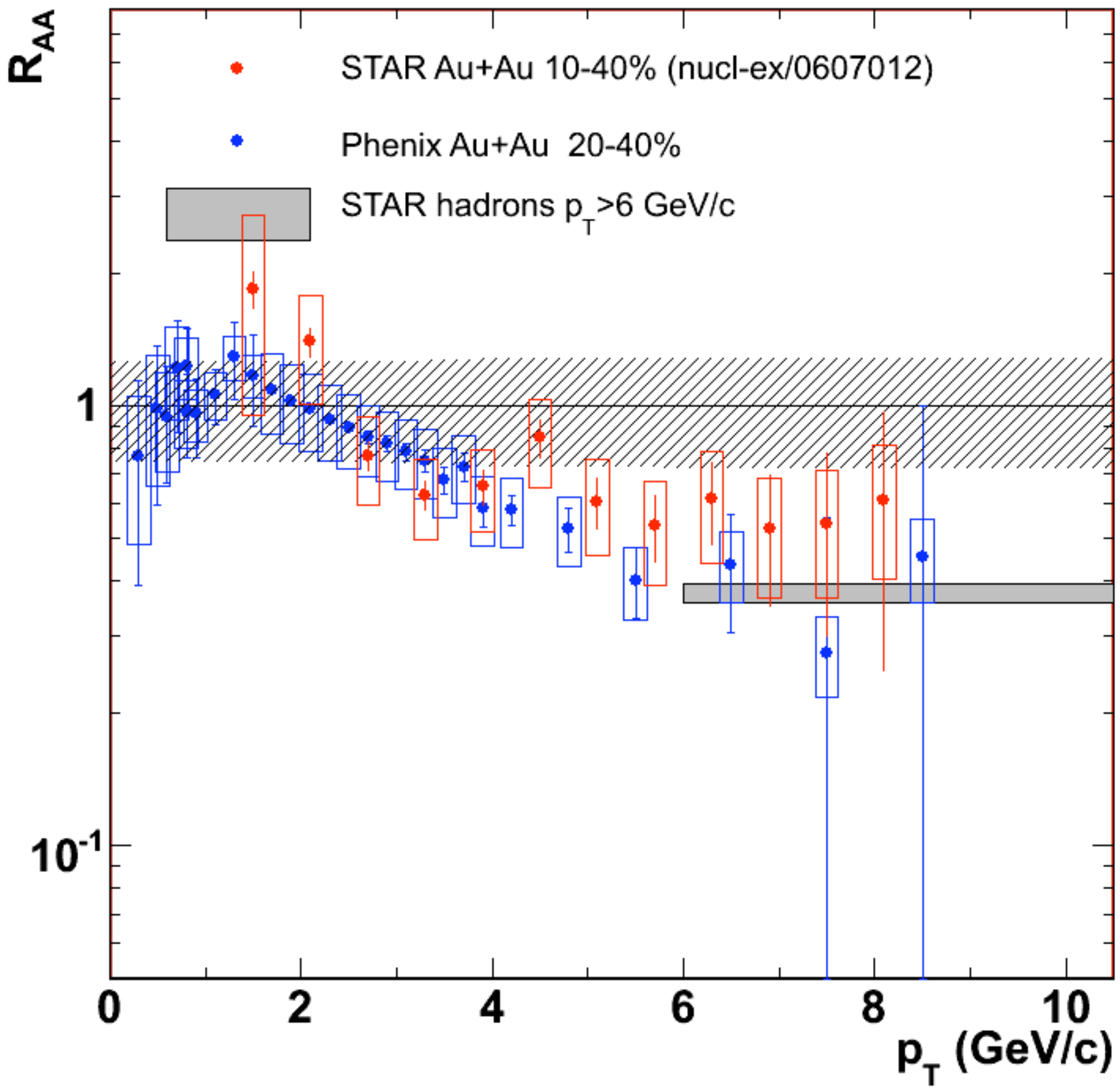
slight enhancement expected (Cronin effect)

Peripheral Au+Au:
no suppression expected

Big Surprise R_{AA}: from d+Au to Central Au+Au



d+Au:
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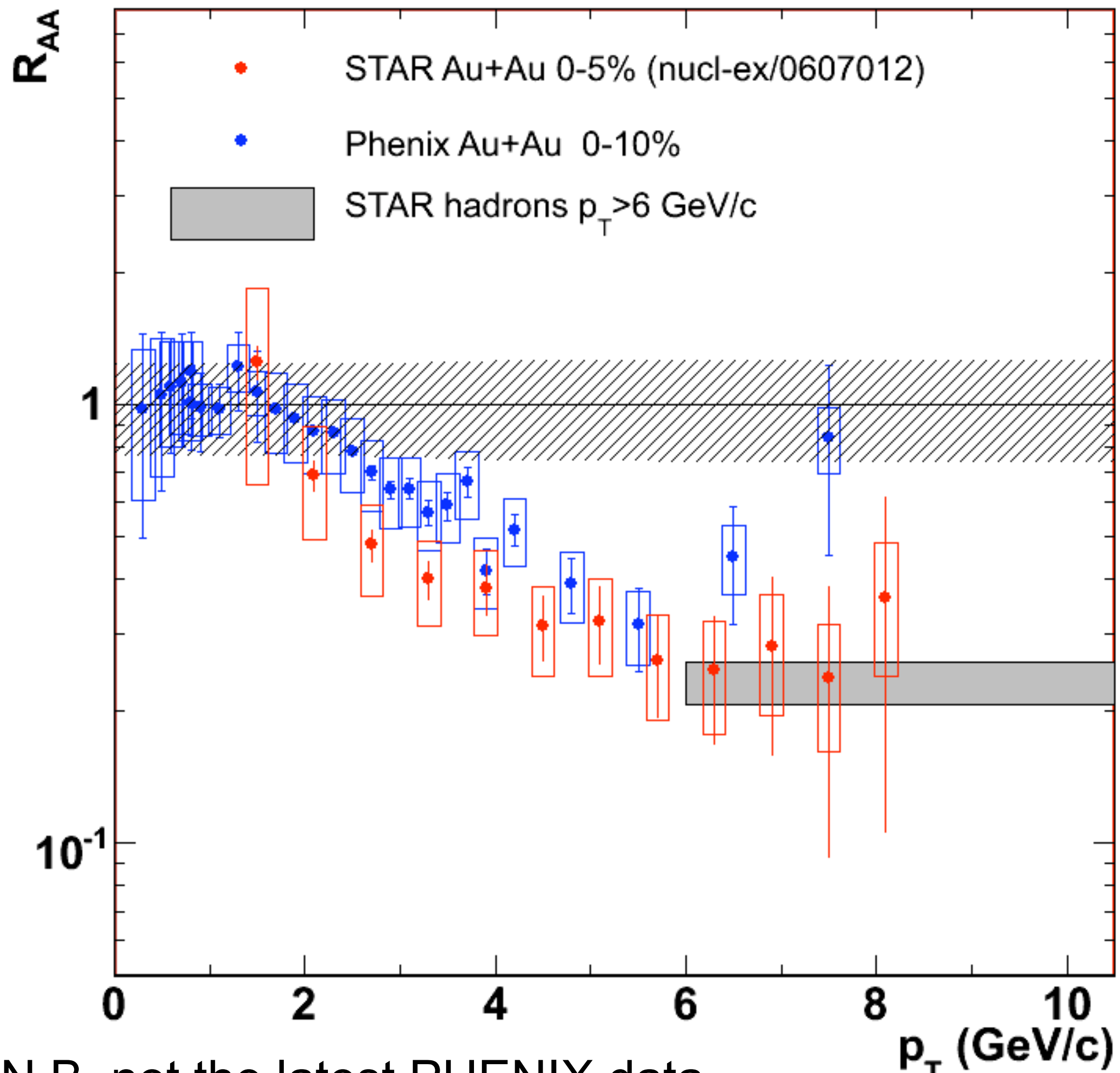
Peripheral Au+Au:
no suppression expected

Semi-Central Au+Au:
very little suppression expected

Big Surprise R_{AA}: from d+Au to Central Au+Au



N.B. not the latest PHENIX data

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Central Au+Au:
little suppression expected ?!

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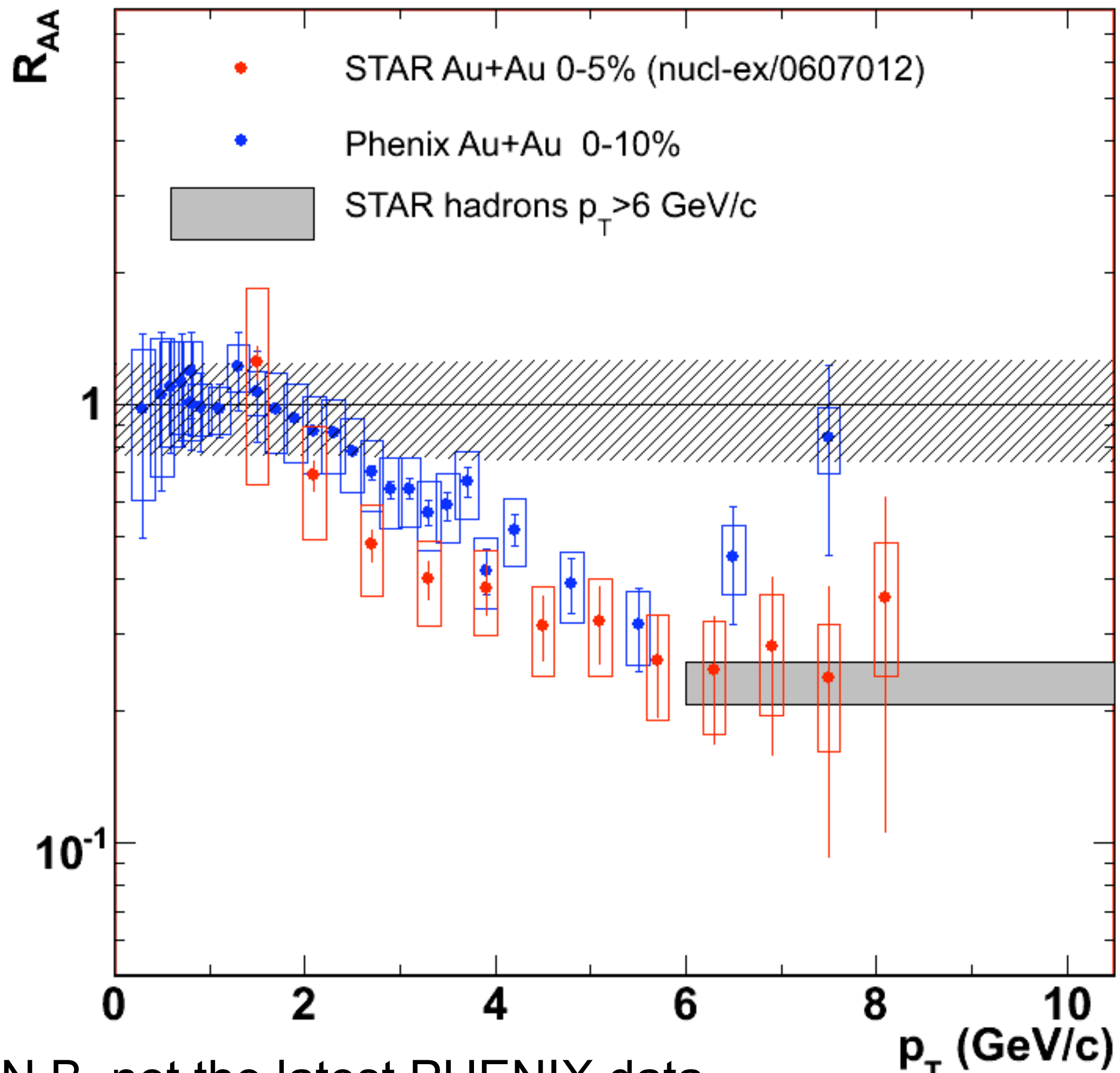

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very little suppression expected

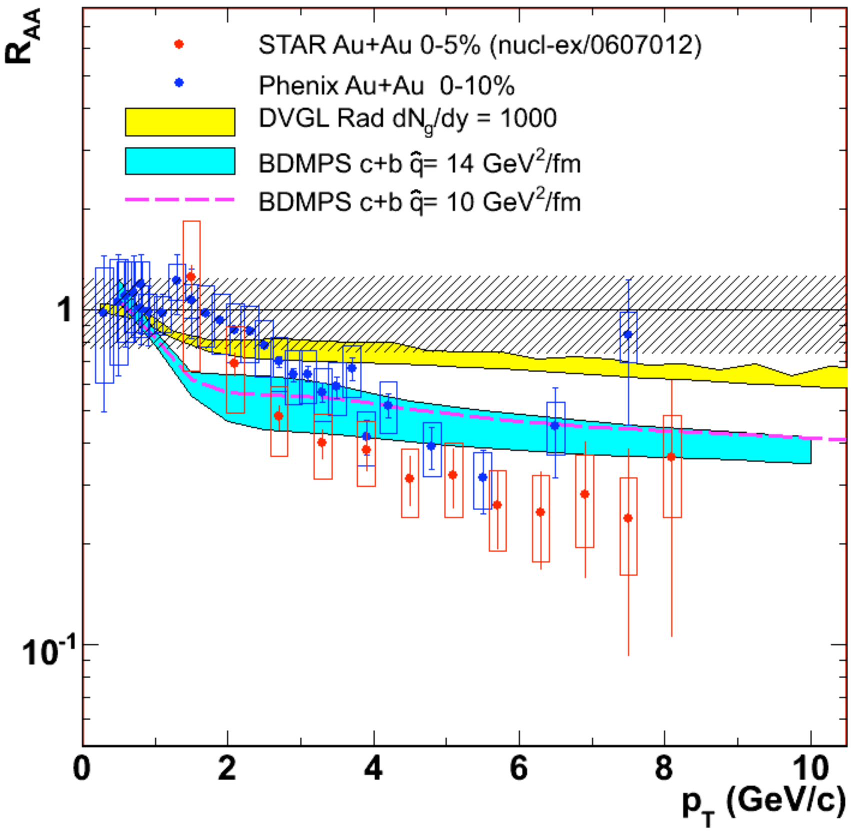
Central Au+Au:
little suppression expected ?!

Measurement of non-photonic electrons from semileptonic D decays show substantial suppression in central Au+Au collisions comparable to that from light mesons

Theory Behind R_{AA} of Heavy Flavor ?!

Describing the suppression is difficult for models

(especially when describing the Eloss of light hadrons simultaneously)



➡ radiative energy loss with typical gluon densities is not enough
(Djordjevic et al., PLB 632(2006)81)

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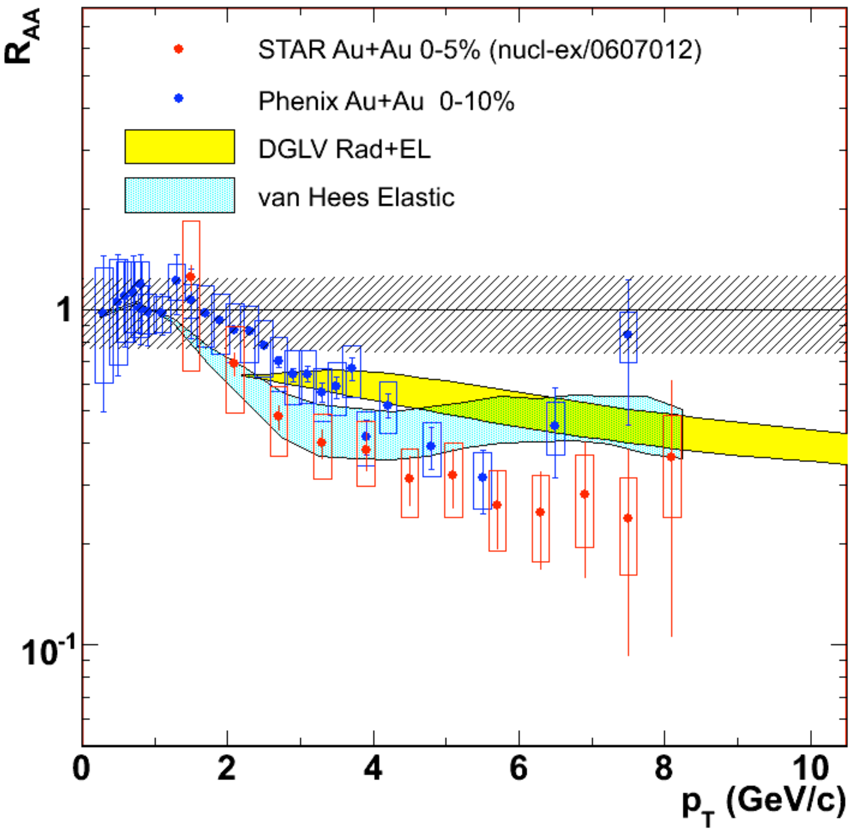

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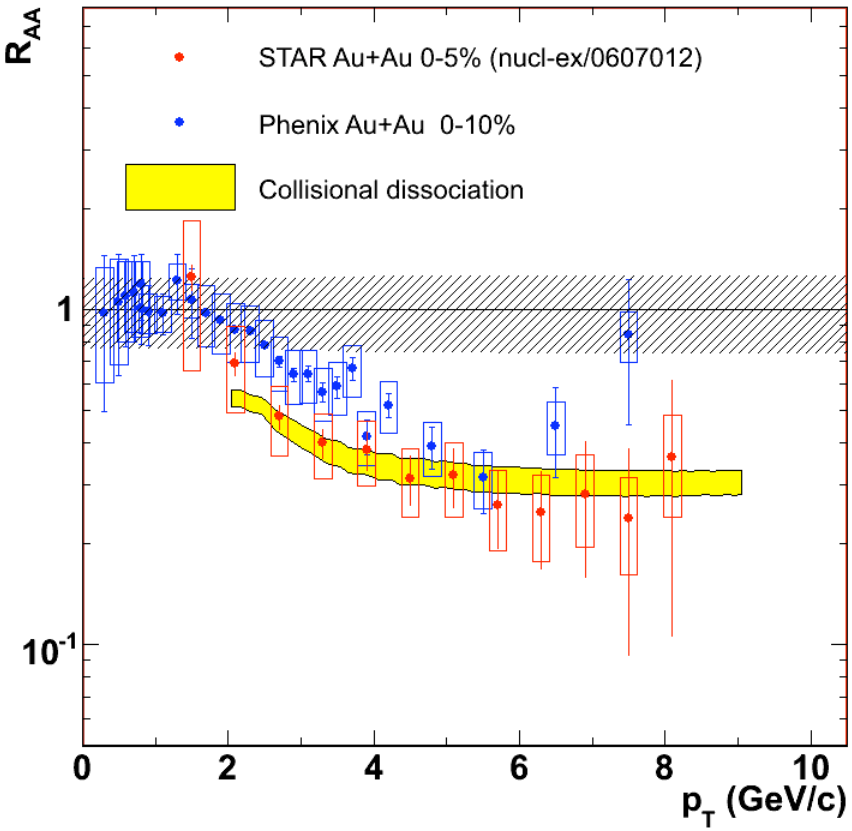

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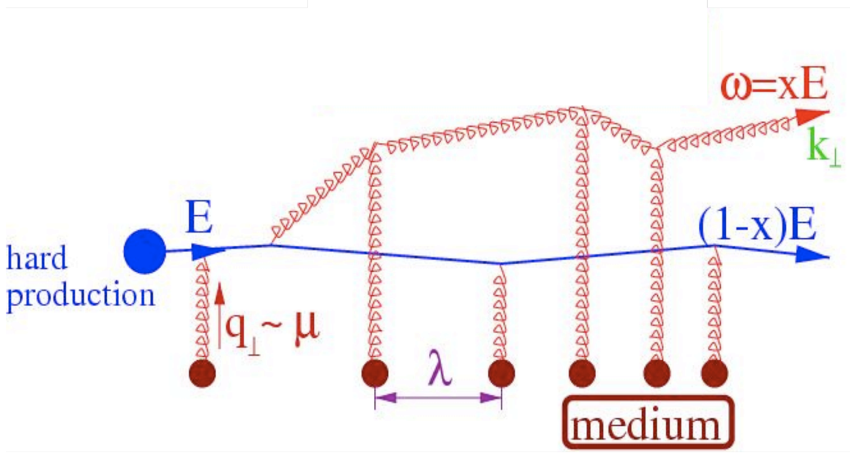

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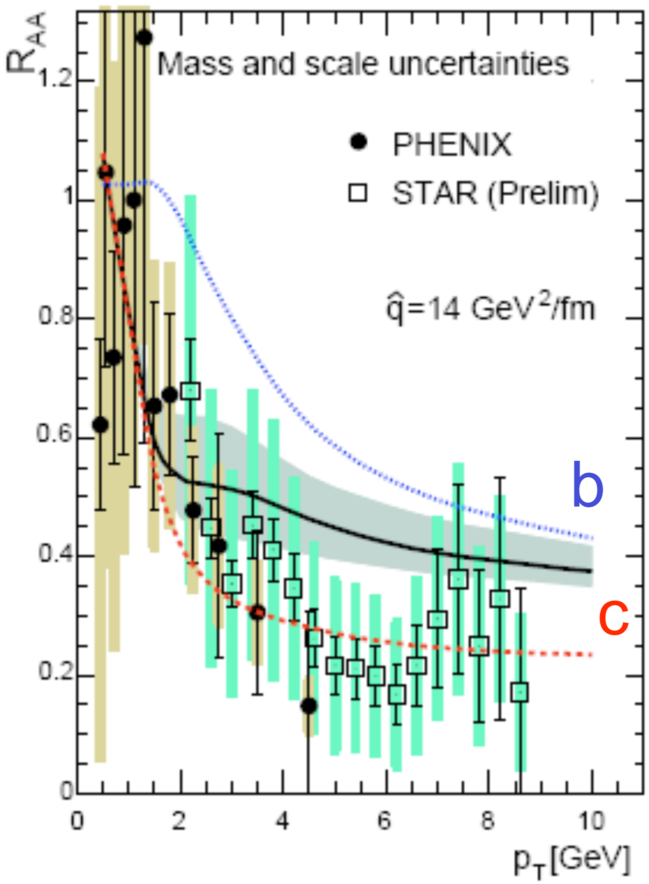
- ➡ Radiative energy loss in a finite dynamical QCD medium

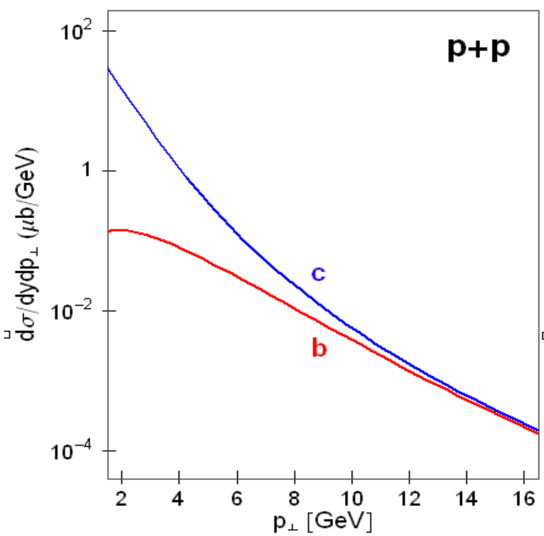
  Djordjevic & Heinz, arXiv:0802.1230v1 (2008)

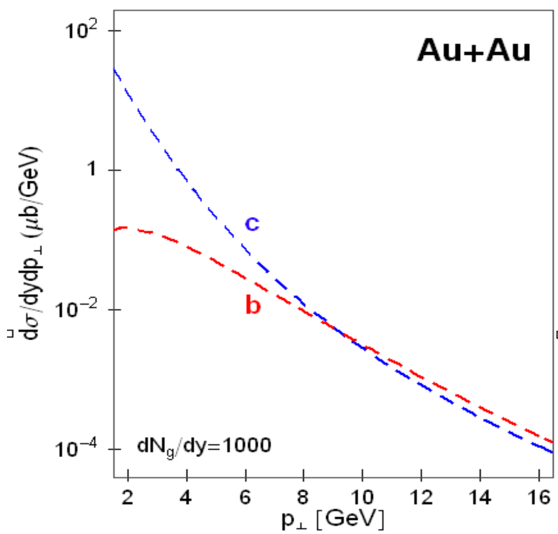
But wait ... it gets even more complicated

N. Armesto et al, nucl-ex/0511257



- Charm/bottom composition in **all** E-loss calculations based on FONLL with 'average' parameter set



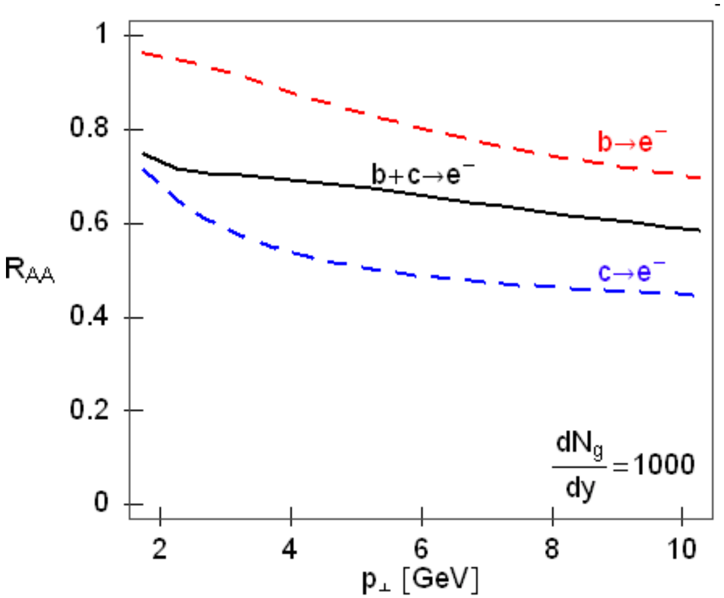


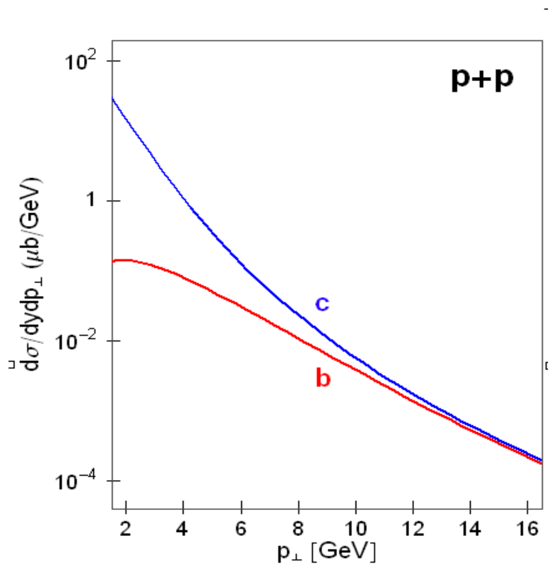
Before quenching

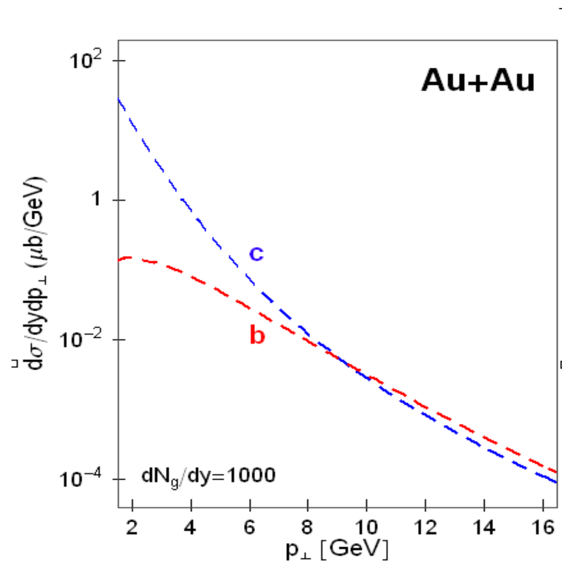
After quenching

But wait ... it gets even more complicated

- Charm/bottom composition in **all** E-loss calculations based on FONLL with ‘average’ parameter set







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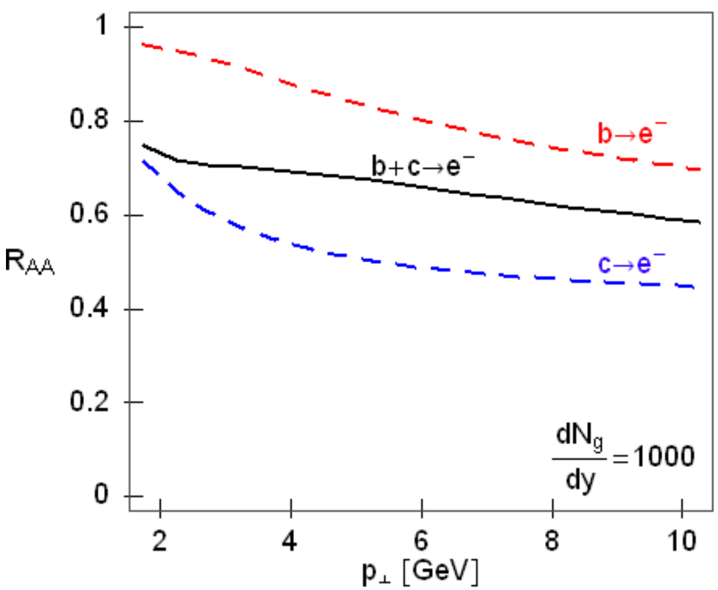

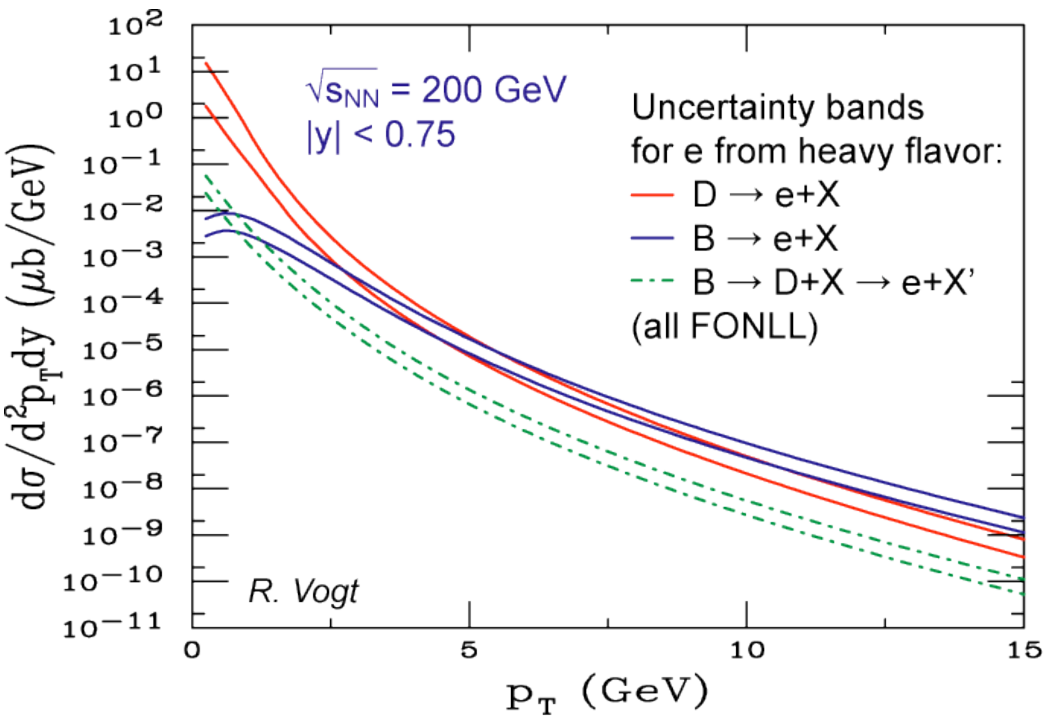

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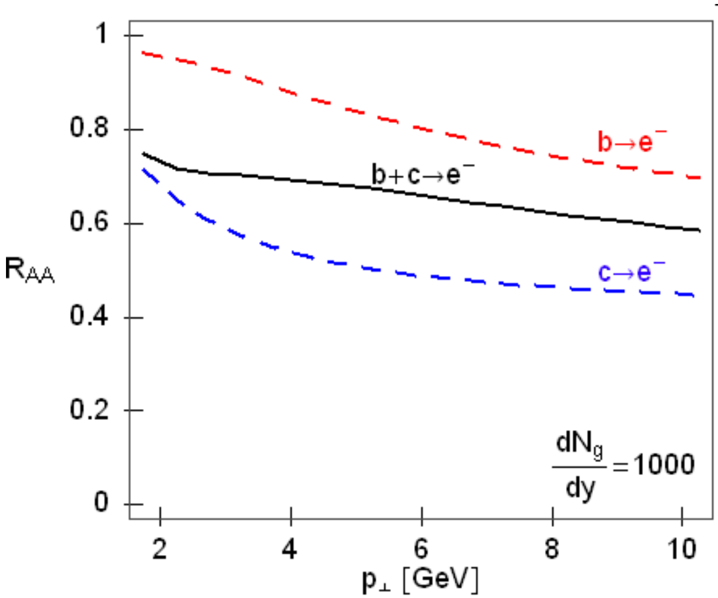
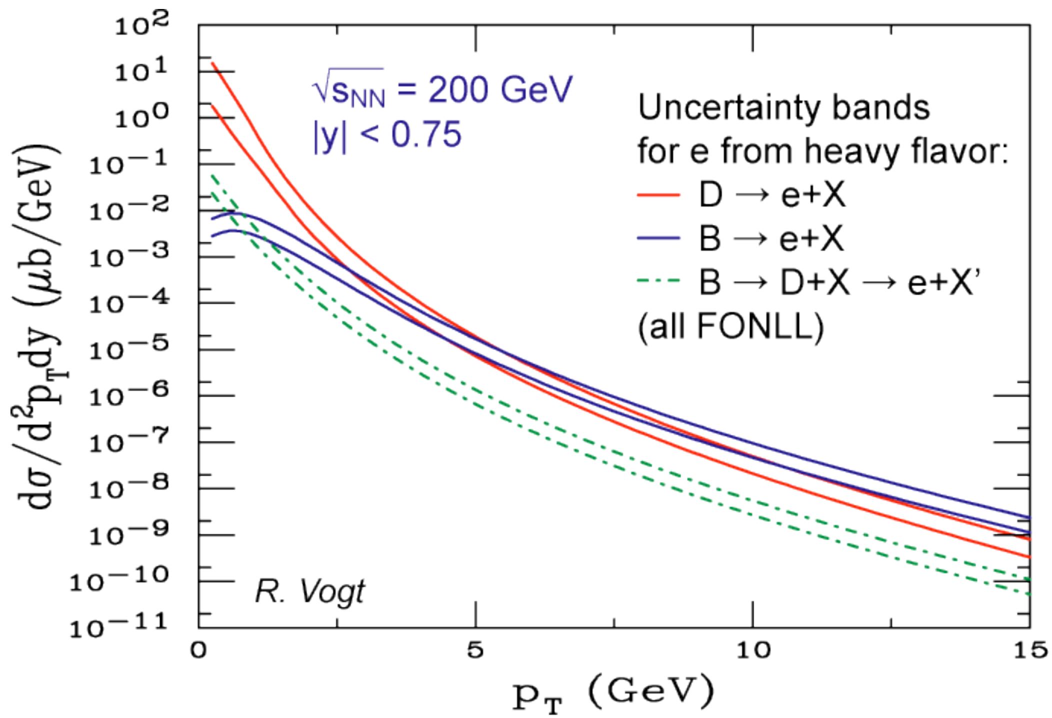
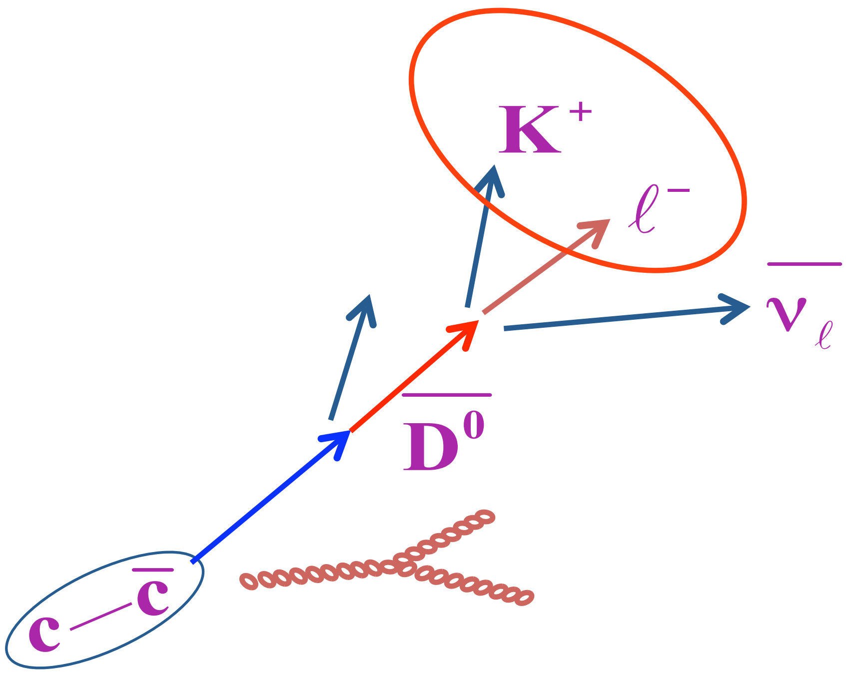




- Charm/bottom composition is an assumption …
- Even NLO/FONLL leaves lots of room
- Shifting bottom dominance to higher or lower p_T could change the picture !

Finding c/b: Method 1 by PHENIX

PHENIX separates c→e component using the charge correlation of K and e from D-meson decay.



If D-meson decays into charged kaon and electron, their charges are opposite:

$$\overline{D} \rightarrow K^+ e^- X$$

$$D \rightarrow K^- e^+ X$$

Thus one can determine the fraction of c→e component by measuring the fraction associated with opposite sign kaon, or opposite sign charged hadron

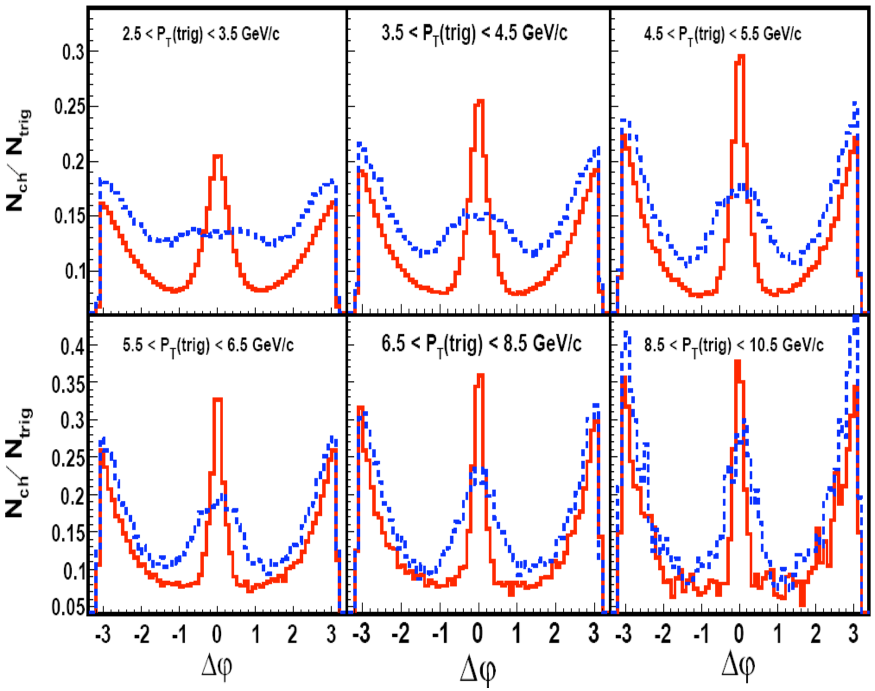
Note that e K pairs from B decays are mostly like sign with a small contamination from unlike (1/6)

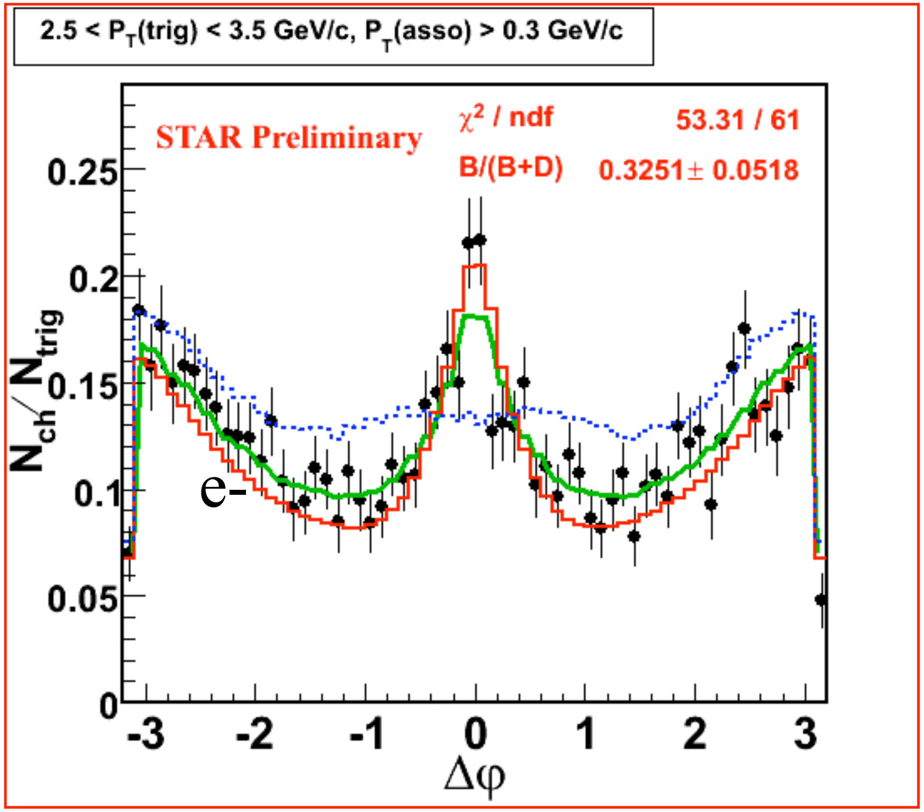
Actual analysis is done as e-h charge correlation (i.e. no kaon PID) for higher statistic

Finding c/b: Method 2 by STAR

STAR studies the small azimuthal angular correlation of eh pairs from c or b decays (small angle ⇒ from same decay as e)

PYTHIA: blue=bottom, red=charm



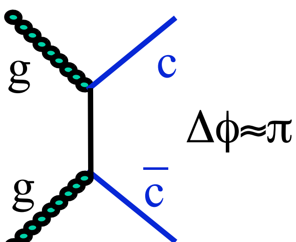


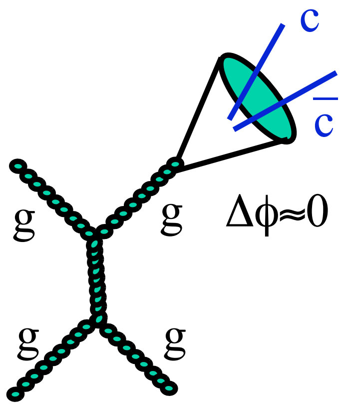
- c, b: significant difference in the near-side correlations.
- Width of near-side correlations largely due to decay kinematics.
  - B decay has larger Q value

Finding c/b: Method 3 by STAR

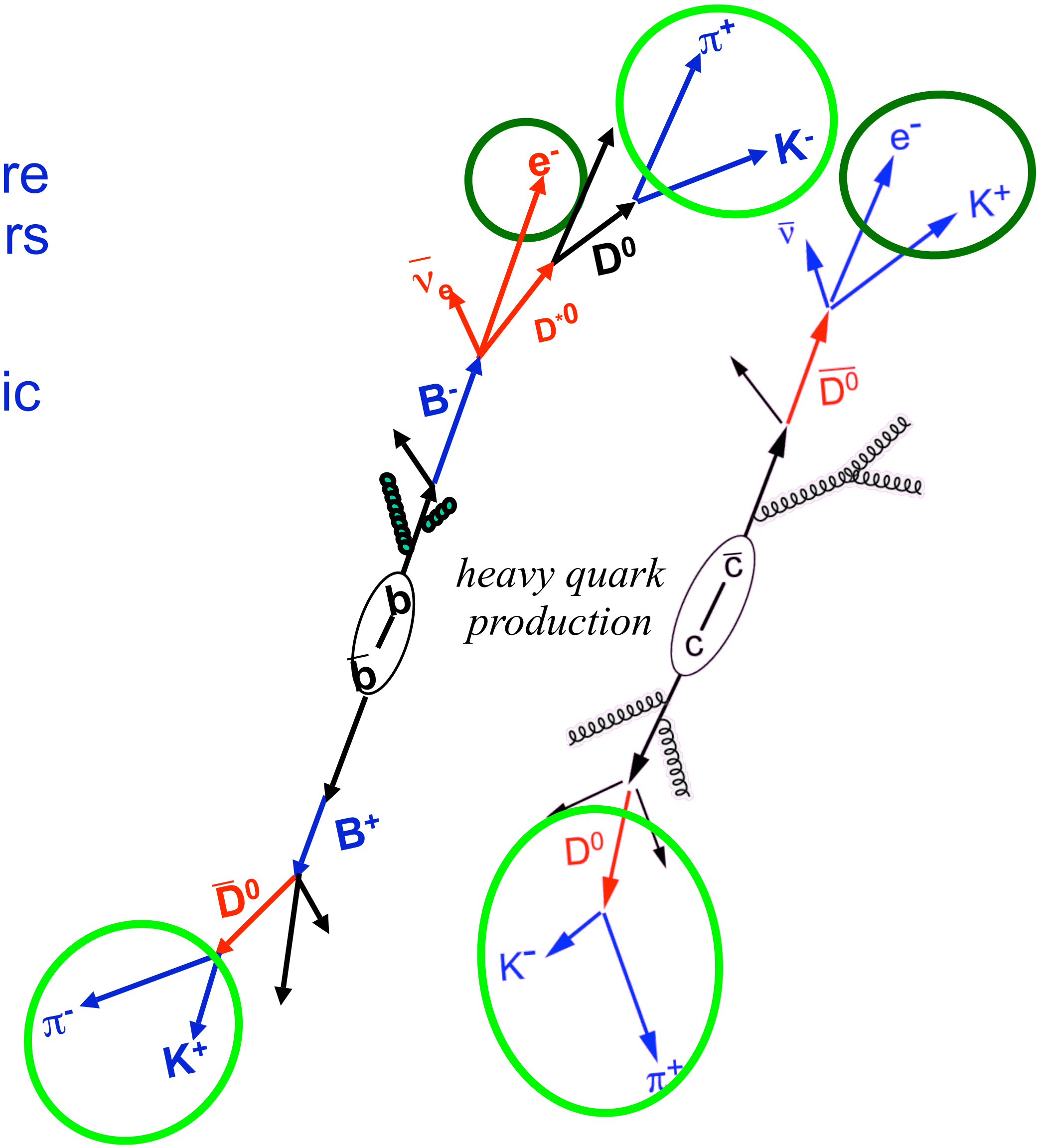
Approach: e-D^0 correlations

- non-photonic electrons from semi-leptonic charm decays are used to trigger on c-$\bar{c}$, b-$\bar{b}$ pairs
- back-2-back D^0 mesons are reconstructed via their hadronic decay channel (probe)
- Underlying production mechanism can be identified using second charm particle





flavor creation gluon splitting/fragmentation



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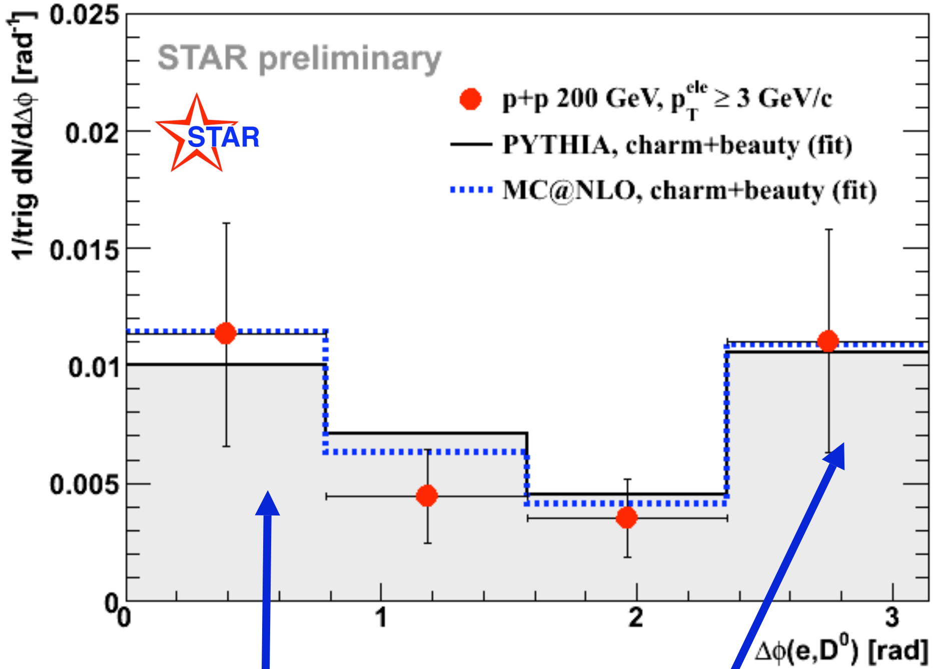
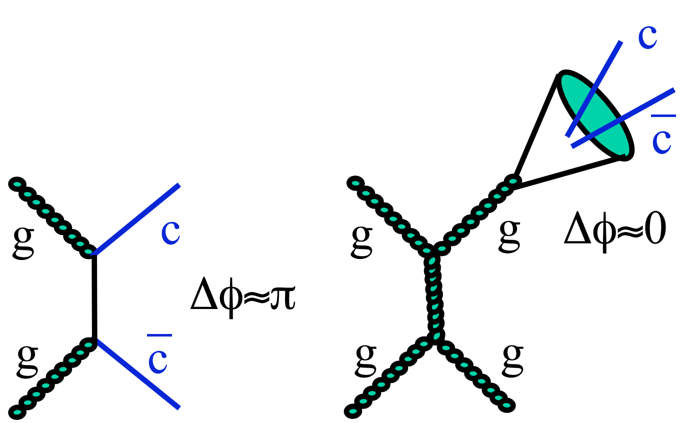


essentially from B decays only

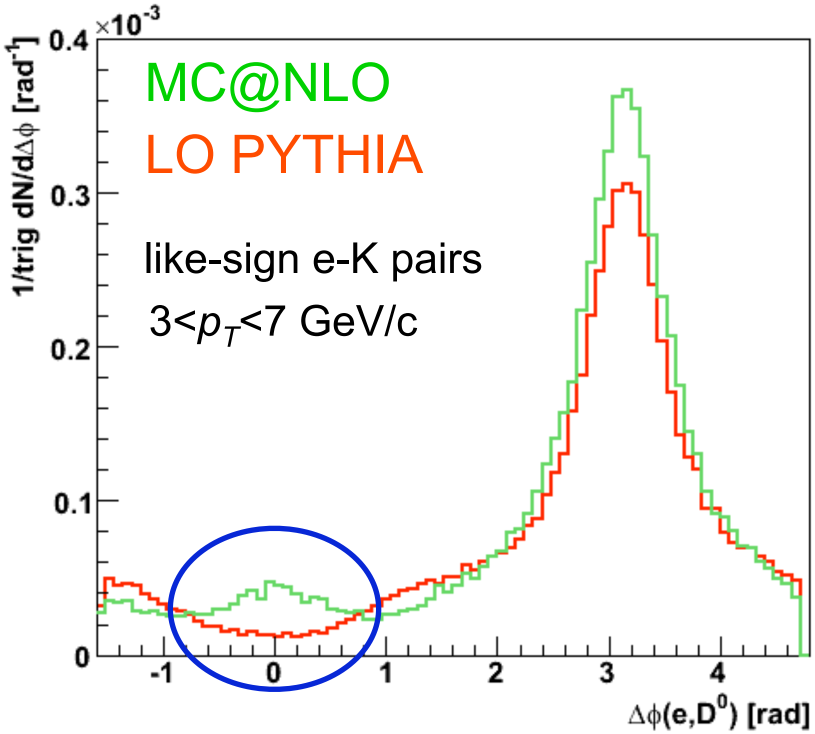
≈75% from charm
≈25% from beauty



flavor creation gluon splitting/fragmentation

And what's about gluon splitting?

MC@NLO predictions for charm production



• NLO QCD computations with a realistic parton shower model

• Away-side peak shape: remarkable agreement between LO PYTHIA and MC@NLO

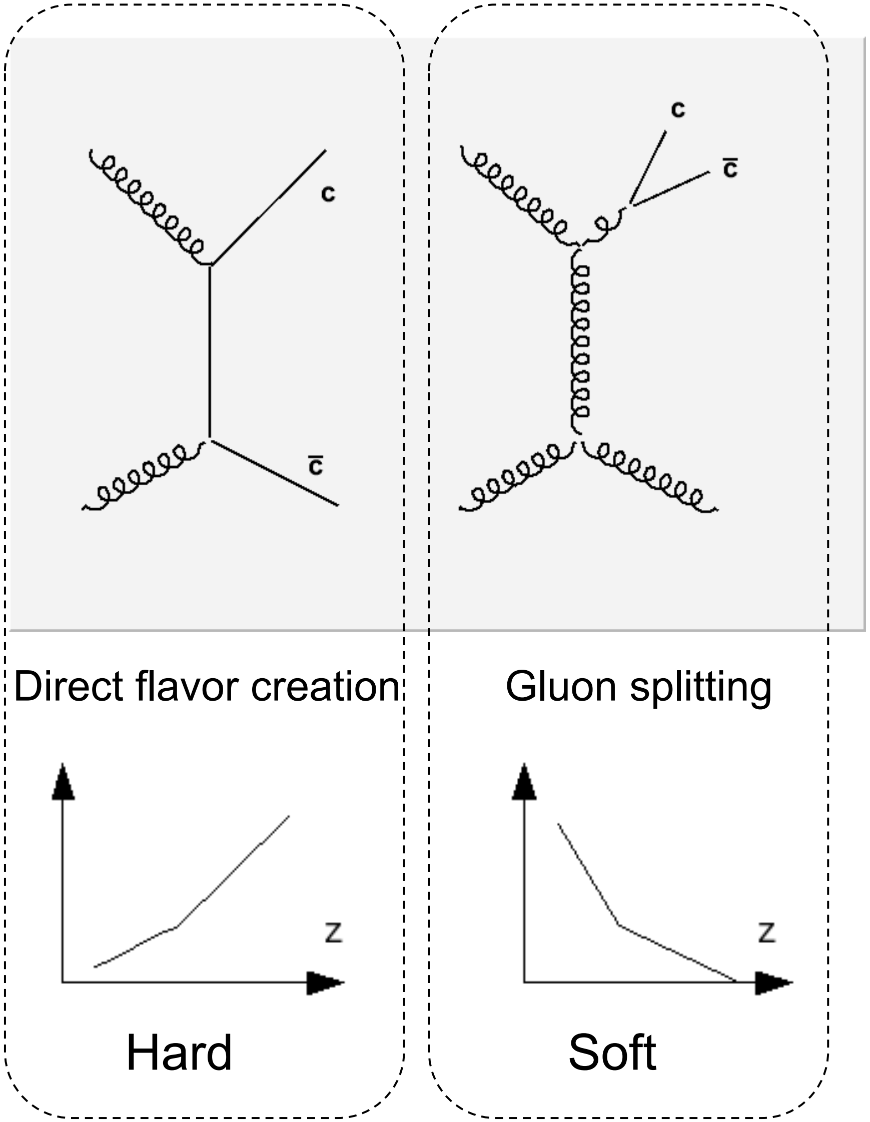
• Near-side: GS/FC ≈ 5%
→ small gluon splitting contribution
→ in agreement with STAR measurement (next slide)

- S. Frixione, B.R. Webber, JHEP 0206 (2002) 029
- S. Frixione, P. Nason, and B.R. Webber, JHEP 0308 (2003) 007
- private code version for charm production

And what's about gluon splitting?

Here's how it works

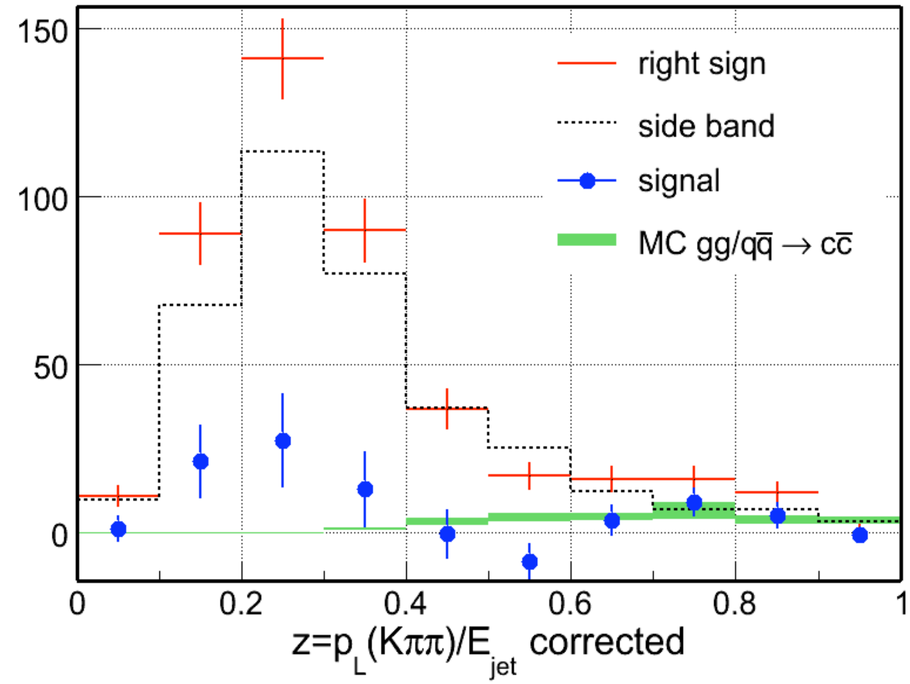
- Check what QCD says



And what's about gluon splitting?

Here's how it works

- Check what QCD says
- Determine STARs jet trigger sensitivity on z



$p_L(K)$: momentum projection of K on jet axis

And what's about gluon splitting?

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- Check what QCD says
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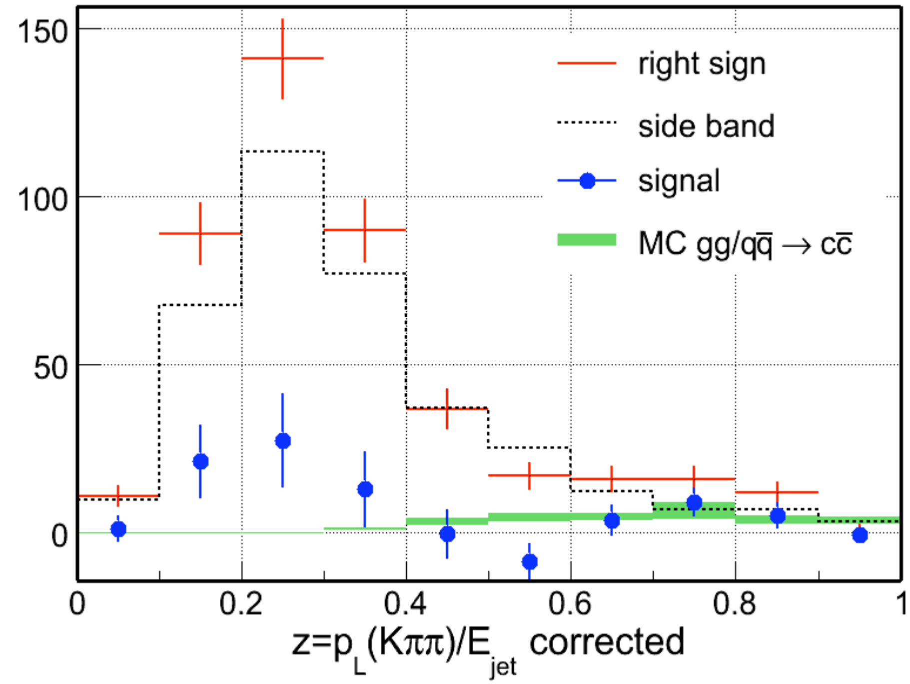
- Find jets (easily said)



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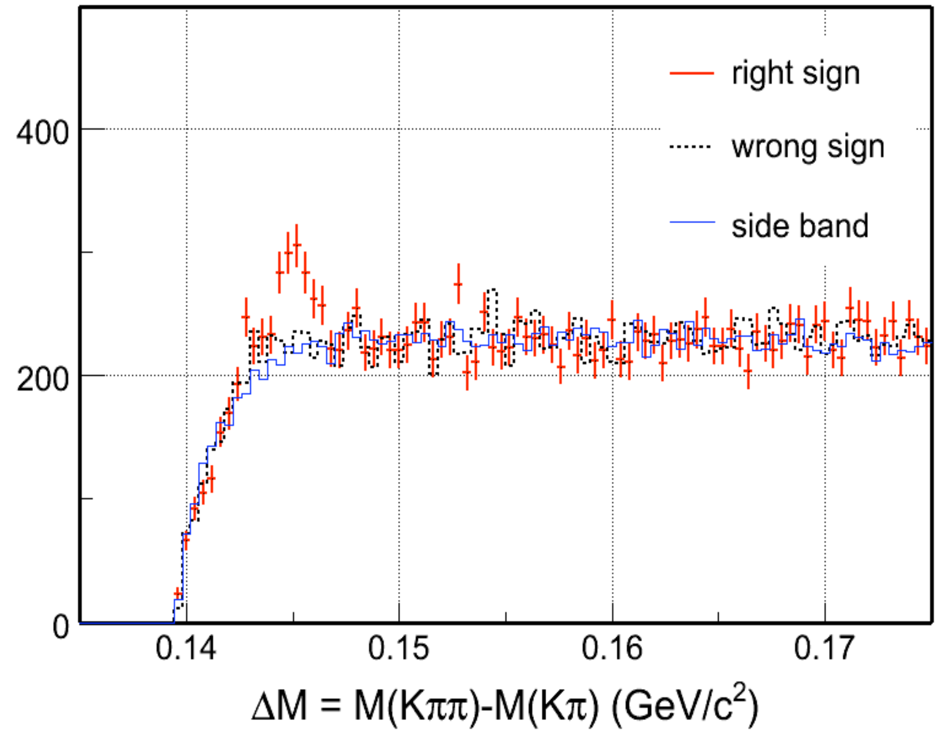
And what's about gluon splitting?

Here's how it works

- Check what QCD says
- Determine STARs jet trigger sensitivity on z
- Find jets (easily said)
- Look for D* in the cone

$$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$$

$$m_{D^{*+}} - m_{D^0} = 145.421 \pm 0.010\,MeV$$



right sign: $K^-\pi^+\pi^+$
wrong sign: $K^-\pi^-\pi^+$

And what's about gluon splitting?

Here's how it works

- Check what QCD says
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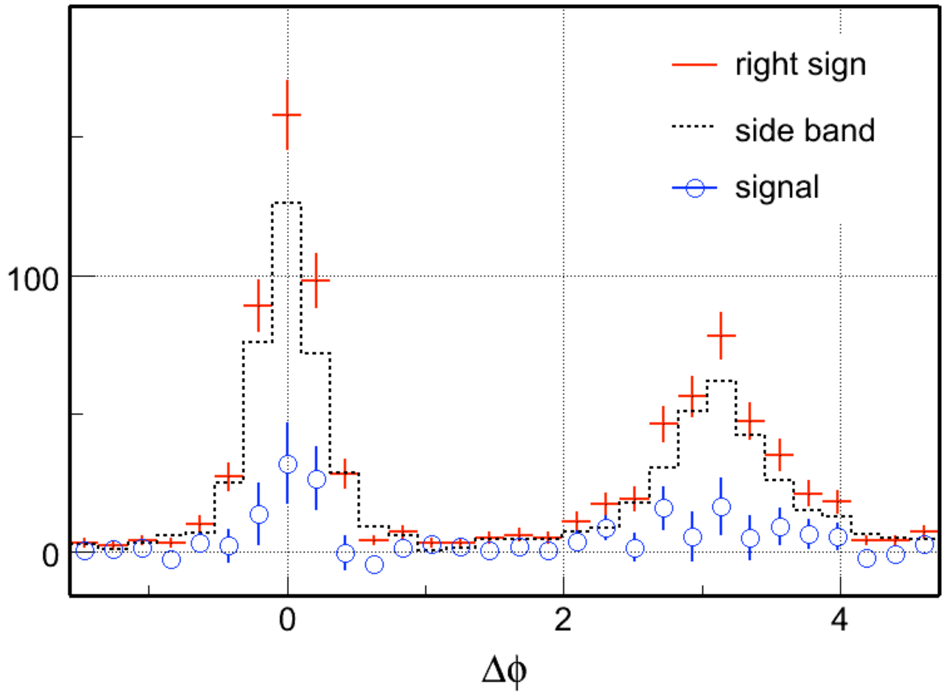
- Find jets (easily said)
- Look for D* in the cone
- D*-jet azimuthal correlations

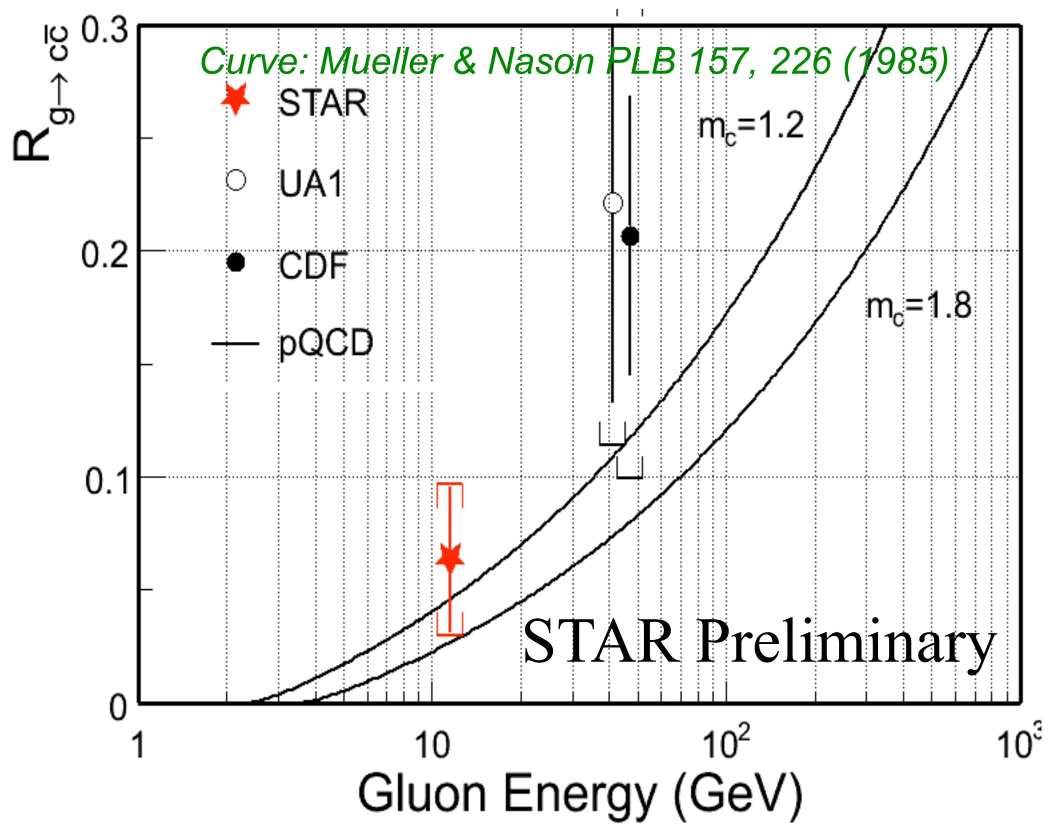
D* - jet correlation



And what's about gluon splitting?

Here's how it works

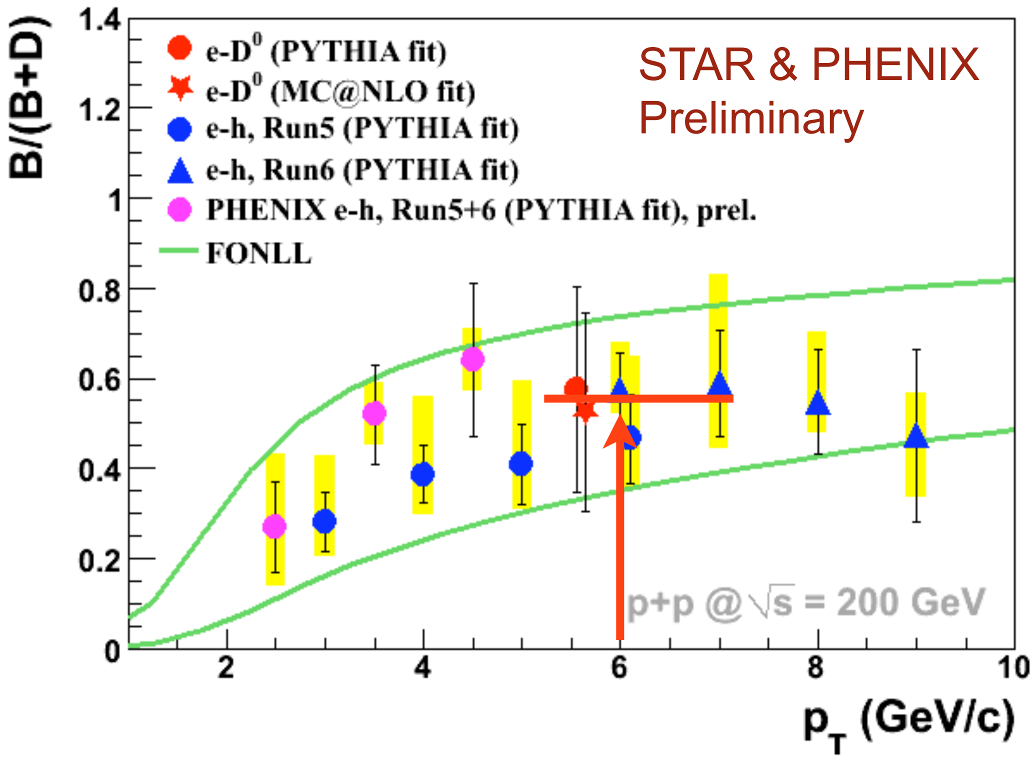
- Check what QCD says
- Determine STARs jet trigger sensitivity on z
- Find jets (easily said)
- Look for D* in the cone
- D*-jet azimuthal correlations
- Et voila: it's indeed small

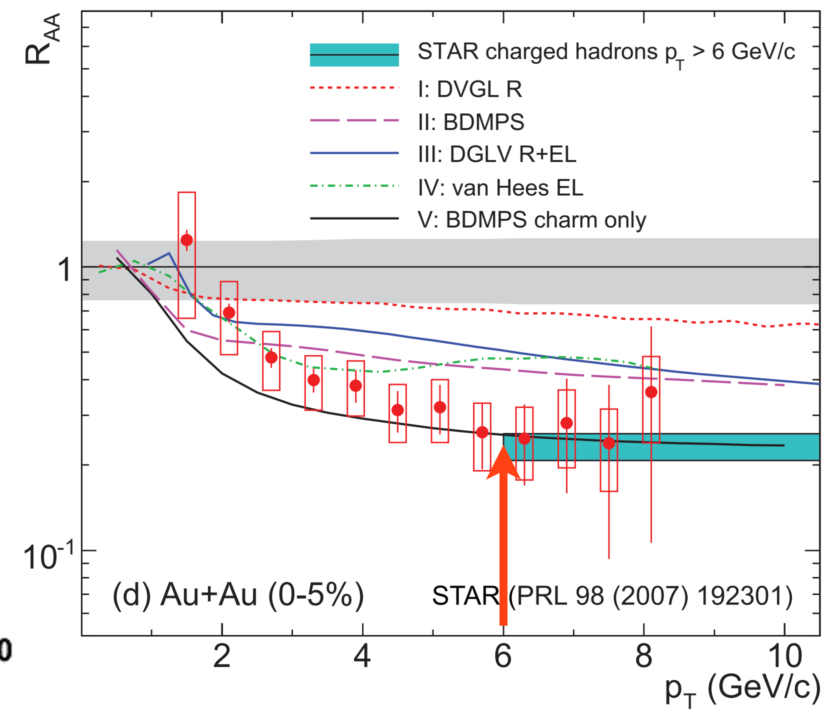


$$N(D^{*+}+D^{*-})/N(\mathrm{jets}) = (1.5 \pm 0.8 \pm 0.5) \times 10^{-2}$$

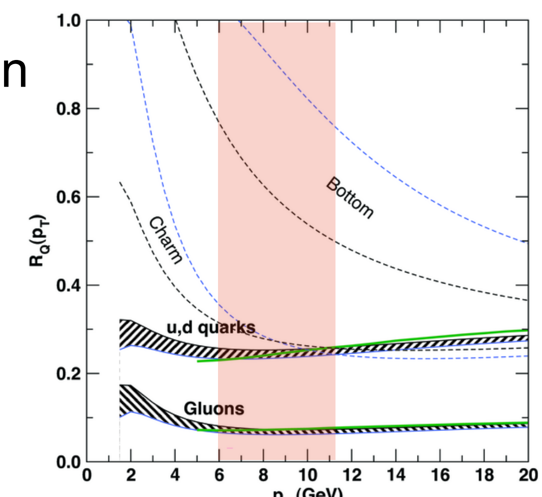
$0.2<z<0.5$, $\langle E_T \rangle \sim 11$ GeV

And now the verdict ...





- Correlation measurements in STAR and PHENIX constrain beauty contribution to non-photonic electrons in p+p collisions
- ~55% bottom at p_T^e = 6 GeV/c
- Beauty appears to be suppressed by more than predicted
- Detector upgrades still sorely needed to measure b and c R_{AA} separately



No gray probes at RHIC ?

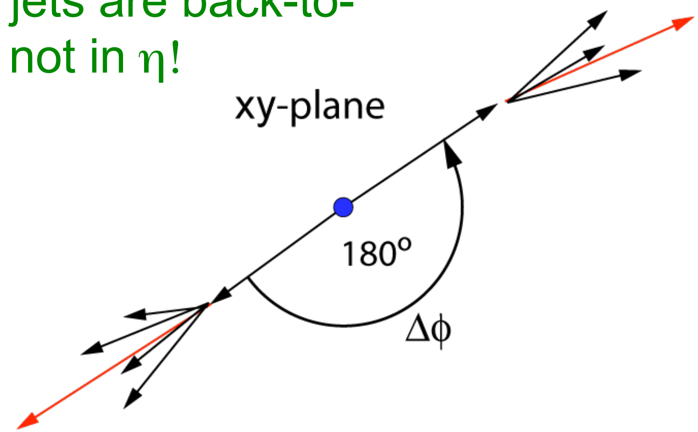
- Glue is quenched
- Light Quarks are quenched
- Charm is quenched
- ... and now even Bottom appears to be quenched

Do we really understand energy loss in the medium?

Looking closer: Dihadron correlations

Terminology:

Keep in mind: jets are back-to-back in ϕ only not in η!



Trigger particle:

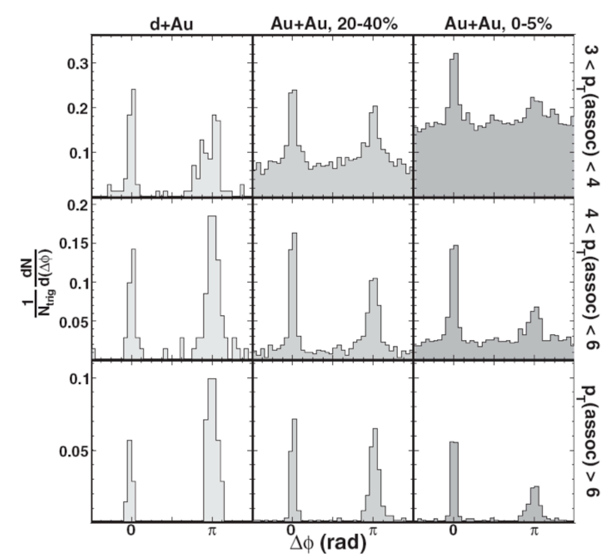
- Is the hadron that “triggered” the event, typically the hadron with the highest p_T. In most case that’s the leading hadron of the jet, i.e. the one with the highest z ($z=E_h/E_{jet}$)
- It’s p_T is labelled p_T^{trig}

Associated particle:

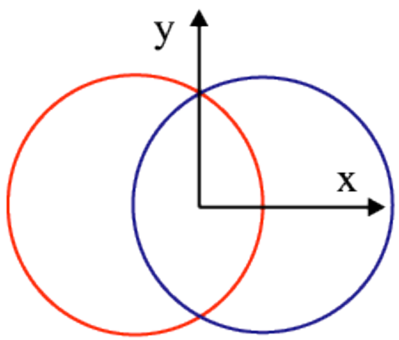
- Is the hadron that you correlate the trigger particle with. It can be any hadron, either from the same jet as the trigger particle (near side correlations) or the opposite side jet (away-side correlations) or from the underlying event.
- It’s p_T is labelled p_T^{assoc}
- usually $p_T^{assoc} \leq p_T^{trig}$

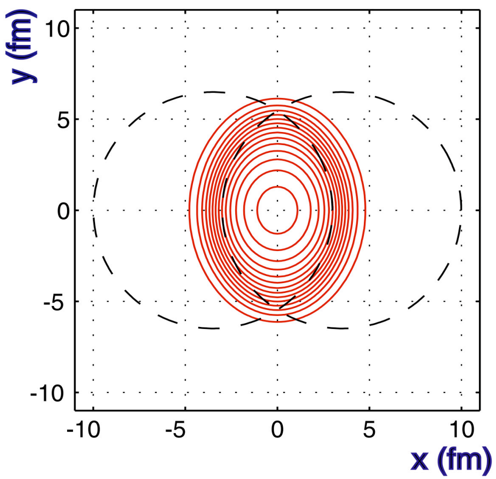
Per trigger correlated yield:

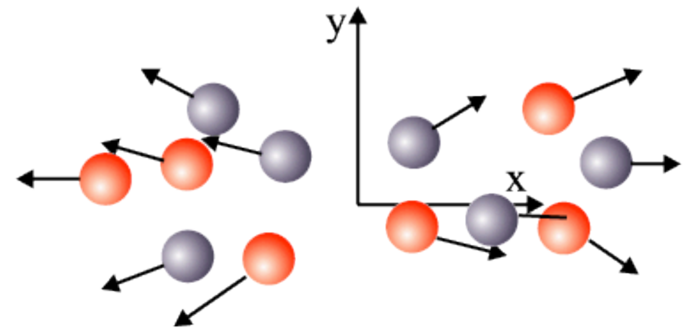
$$C(\Delta\phi) = \frac{1}{N_{trigger}} \frac{1}{\epsilon} \int d\Delta\eta N(\Delta\phi, \Delta\eta)$$



N.B.: Azimuthal Anisotropy of Emission - Elliptic Flow



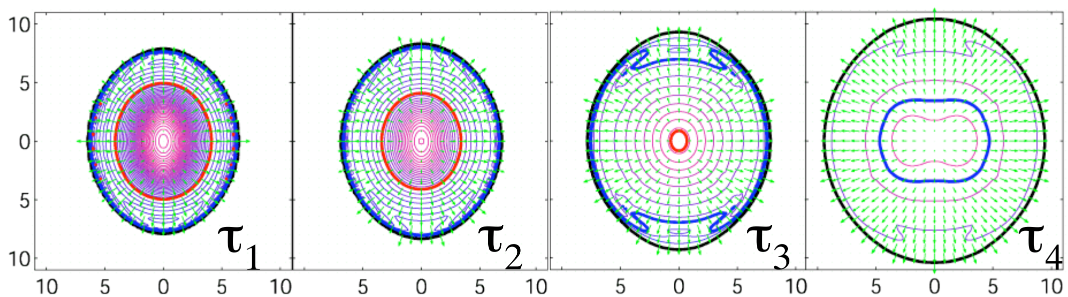




Almond shape overlap region in coordinate space → Interactions/ Rescattering → Anisotropy in momentum space

Au+Au at b=7 fm

P. Kolb, J. Sollfrank, and U. Heinz



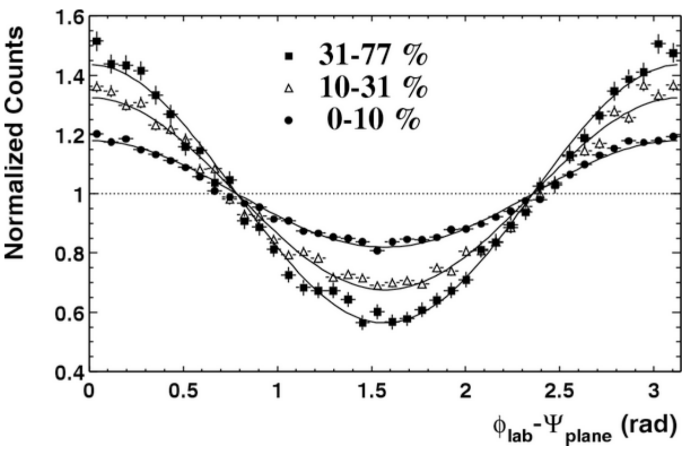
Use a Fourier expansion to describe the angular dependence of the particle density

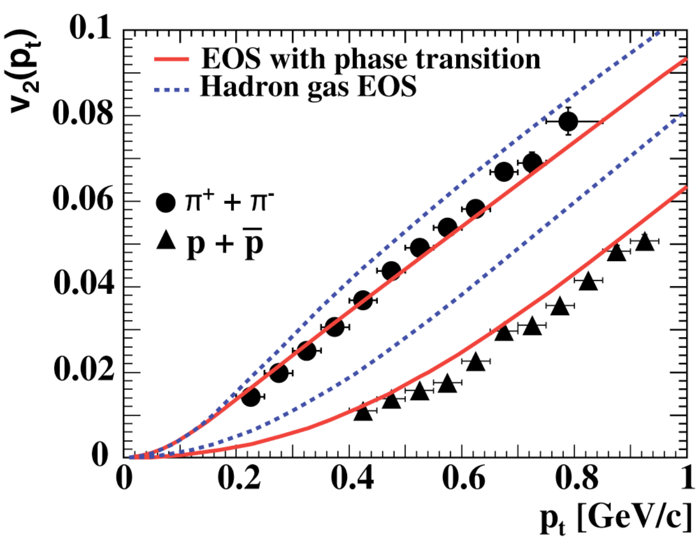
$$dN/d\phi \propto 1 + 2v_2\cos(2\phi) + 2v_4\cos(4\phi) + \ldots$$

v_2: 2nd harmonic Fourier coefficient in $dN/d\varphi$ with respect to the reaction plane

Elliptic Flow – Indicator for Early Thermalization

- Elliptic flow observable sensitive to early evolution of system
- Mechanism is self-quenching
- Large v_2 is an indication of ***early*** thermalization





- Huge asymmetry found at RHIC
  - massive effect in azimuthal distribution w.r.t reaction plane
  - Factor 3:1 peak to valley from 25% v_2
- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal (zero viscosity) hydrodynamics

⇒ "perfect liquid"

Dihadron background

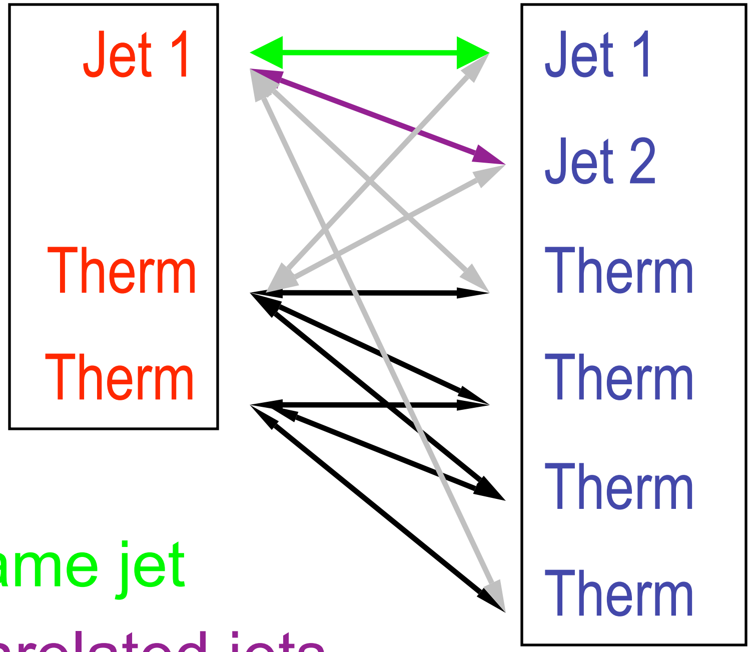
The two-source model:

We *assume* that all hadrons come from one of two sources: jet fragmentation (prompt) or thermal/flow (multicollisional).

Goal: to count same-jet pairs and look at their distribution in relative angle.

Particles A from high-p_T "trigger" bin

Particles B from low-p_T "partner" bin



The good stuff — Same jet

"Background" — Unrelated jets, Jet-thermal, Thermal-thermal

Background expectations

To see the same-jet pairs, all we have to do is subtract away the background, ie all the other kinds of pairs. It sounds so simple! What can we expect?

- Background pairs distribution should have quadrupole *shape*

$$\text{If } \frac{dn^A}{d\phi^A} \propto \left[1 + 2\left\langle v_2^A \right\rangle \cos\left(2\left(\phi^A - \Phi^{\mathrm{RP}}\right)\right)\right] \text{ and } \frac{dn^B}{d\phi^B} \propto \left[1 + 2\left\langle v_2^B \right\rangle \cos\left(2\left(\phi^B - \Phi^{\mathrm{RP}}\right)\right)\right]$$

$$\text{then } \frac{dn^{AB}}{d(\Delta\phi)} \propto \left[1 + 2\left\langle v_2^A v_2^B \right\rangle \cos(2\Delta\phi)\right]$$

$$\text{Questions: Is } \left\langle v_2^A v_2^B \right\rangle = \left\langle v_2^A \right\rangle \left\langle v_2^B \right\rangle \text{ ?}$$

$$\frac{dN^{AB}_{\mathrm{Background}}}{d(\Delta\phi)} = b_0\left[1 + 2\left\langle v_2^A v_2^B \right\rangle \cos(2\Delta\phi)\right]$$

Describing the distribution of background pairs boils down to getting two numbers: the average background rate, and the quadrupole modulation strength.

There are many, many methods on the market and there are continuous discussion about which method is the best. Each has distinct advantages and drawbacks….

Dihadron background subtraction

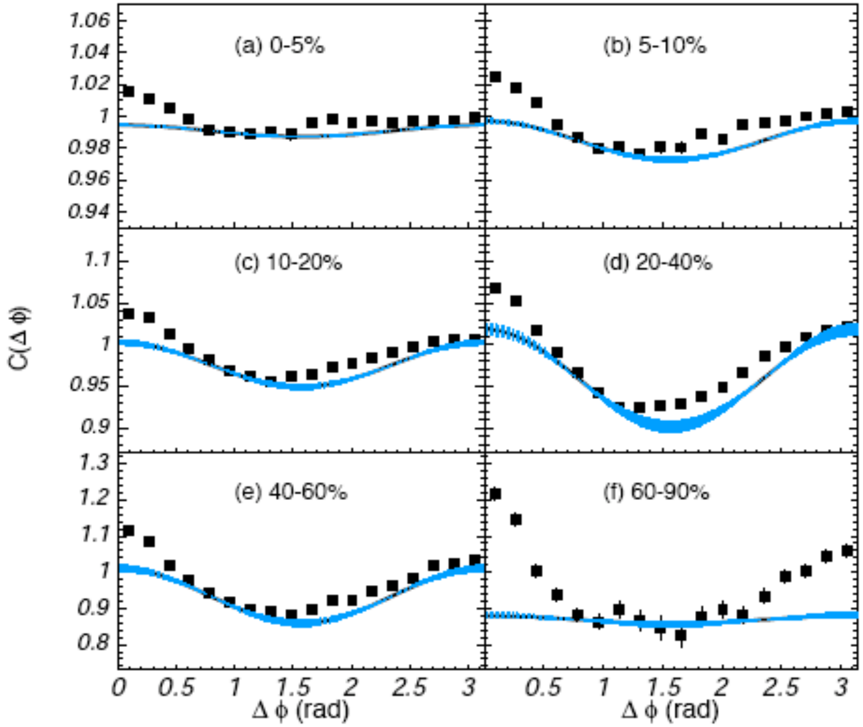
One method will do here:

1. Fix quadrupole moment using existing flow (v_2) measurement for the given centrality, species, p_T
2. Use the ZYAM method (Zero Yield At Minimum)

In the ZYAM approach we raise the background b_0 level until the background meets the data at one point; the remaining jet pairs distribution then have zero yield at minimum. We thus make no assumption about the shape of the jet pairs.

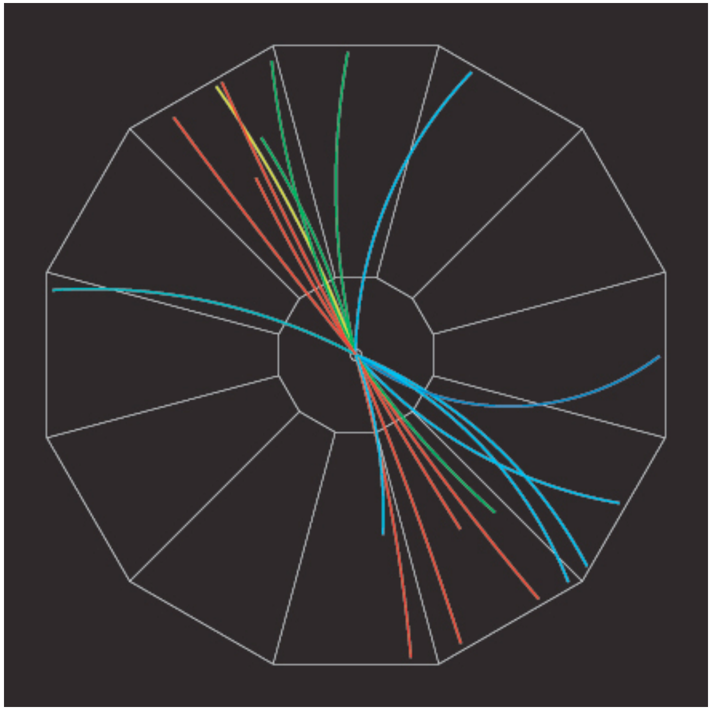
$$\frac{dN^{AB}_{\text{Background}}}{d(\Delta\phi)} = b_0\left[1 + 2\left\langle v_2^A v_2^B \right\rangle \cos(2\Delta\phi)\right]$$

PHENIX dihadron distributions

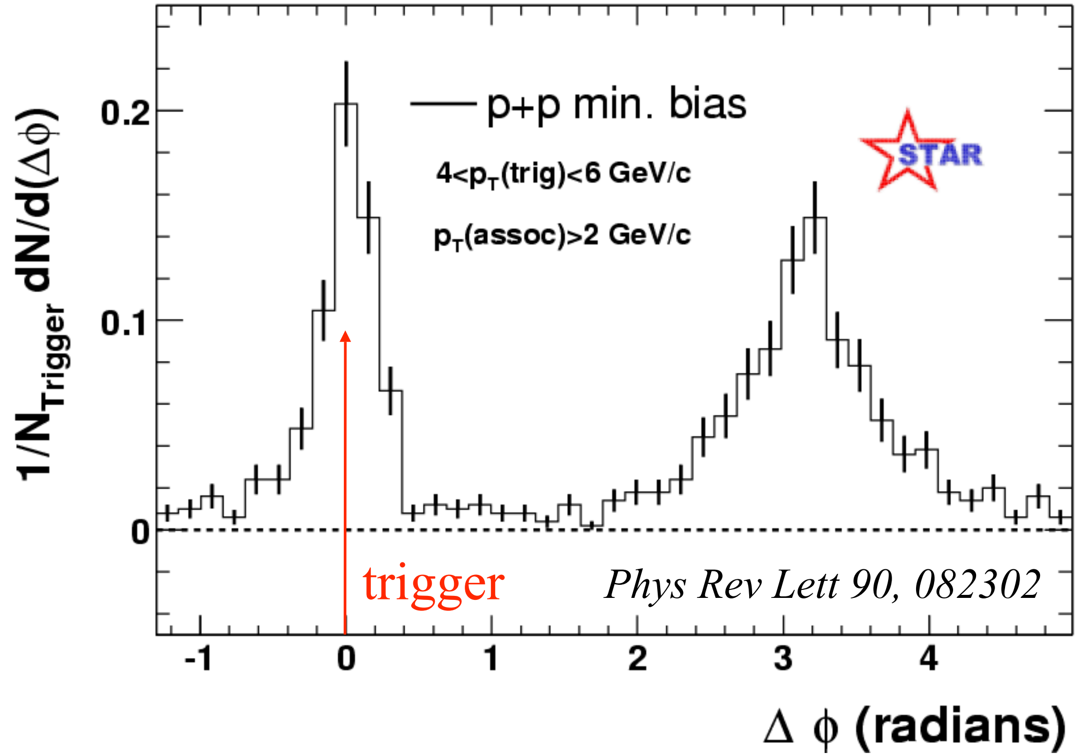


The study that started it all ...

p+p → dijet



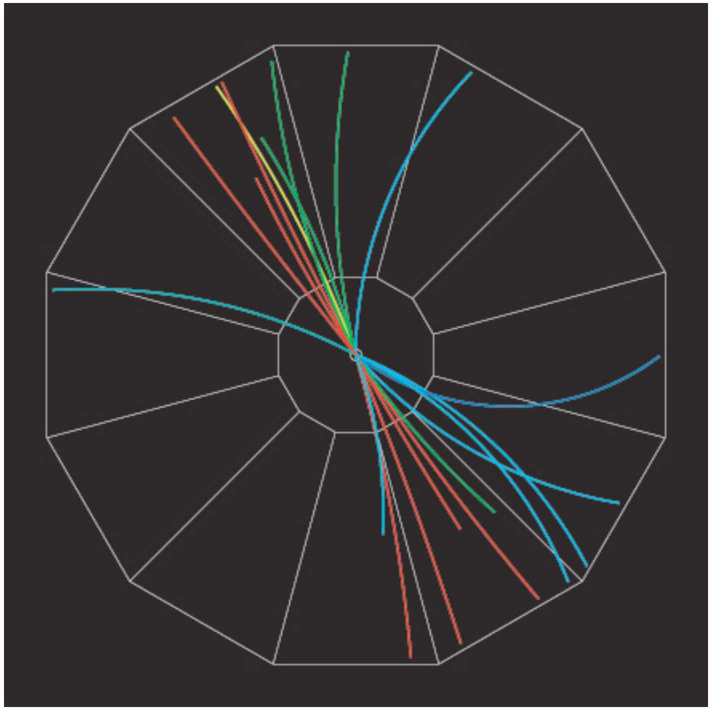
min. bias p+p collisions



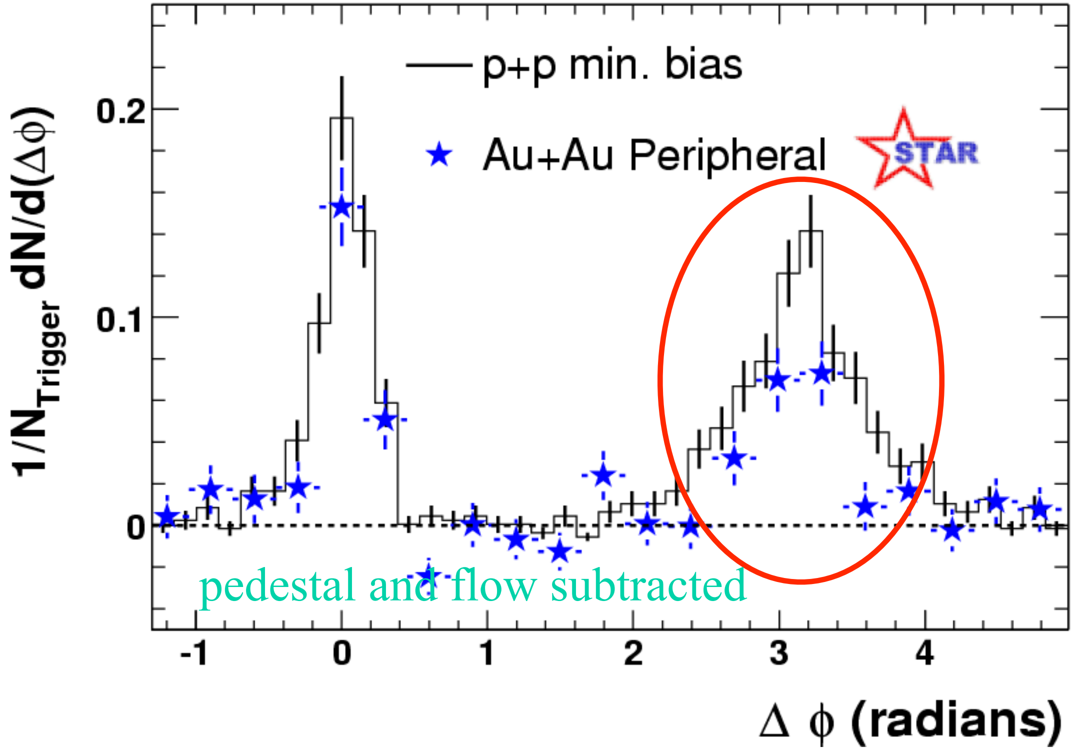
- Trigger: highest p_T track, p_T>4 GeV/c
- Δφ distribution: 2 GeV/c < p_T < $p_T^{trigger}$
- normalize to number of triggers

The study that started it all ...

p+p → dijet



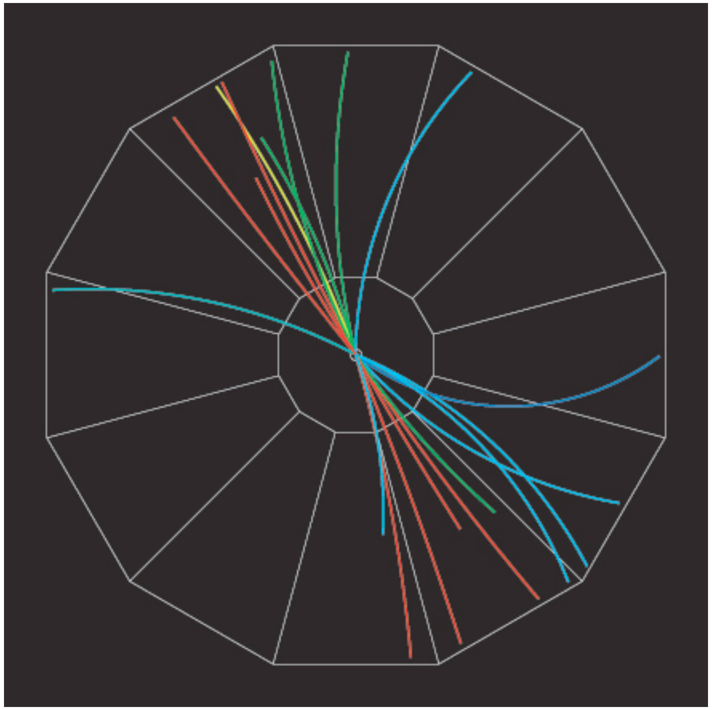
peripheral Au+Au collisions



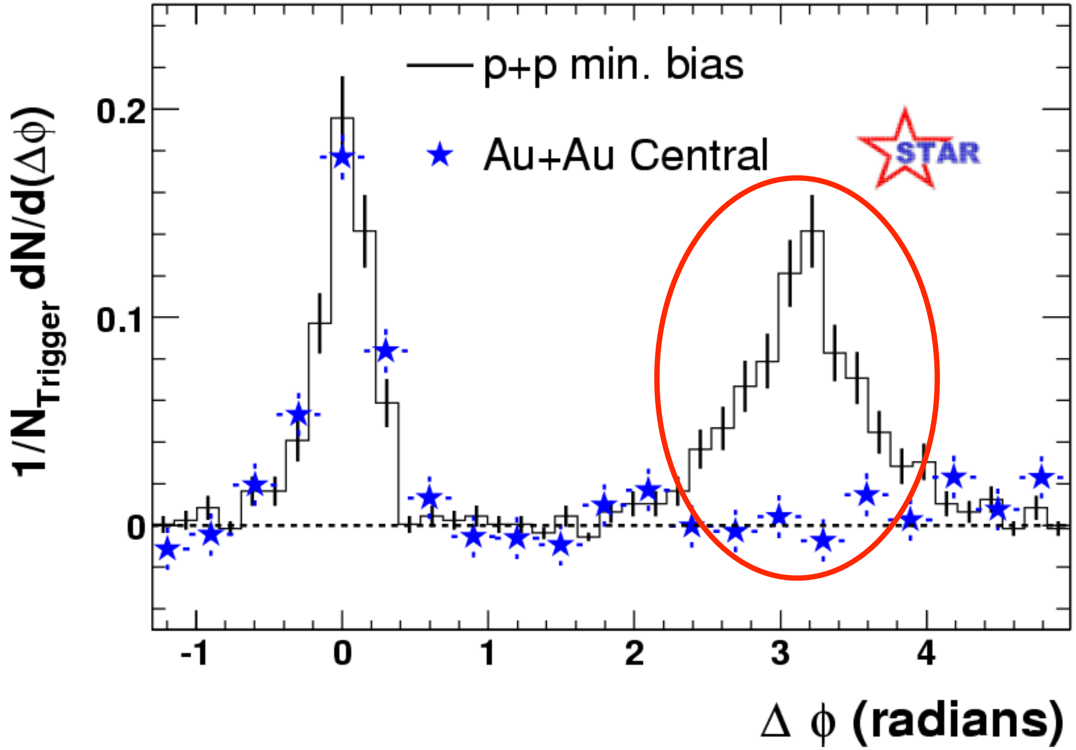
- Trigger: highest p_T track, p_T>4 GeV/c
- Δφ distribution: 2 GeV/c < p_T < $p_T^{trigger}$
- normalize to number of triggers

The study that started it all ...

p+p → dijet



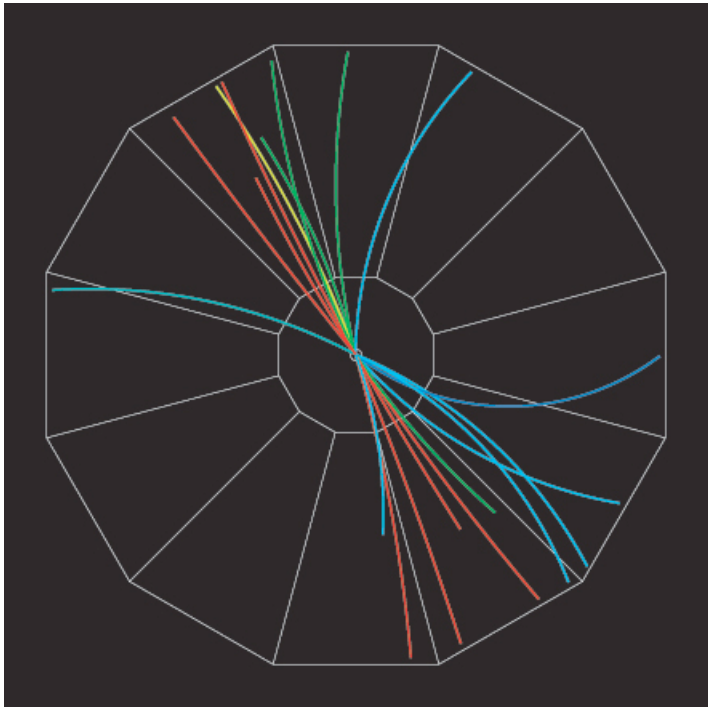
central Au+Au collisions



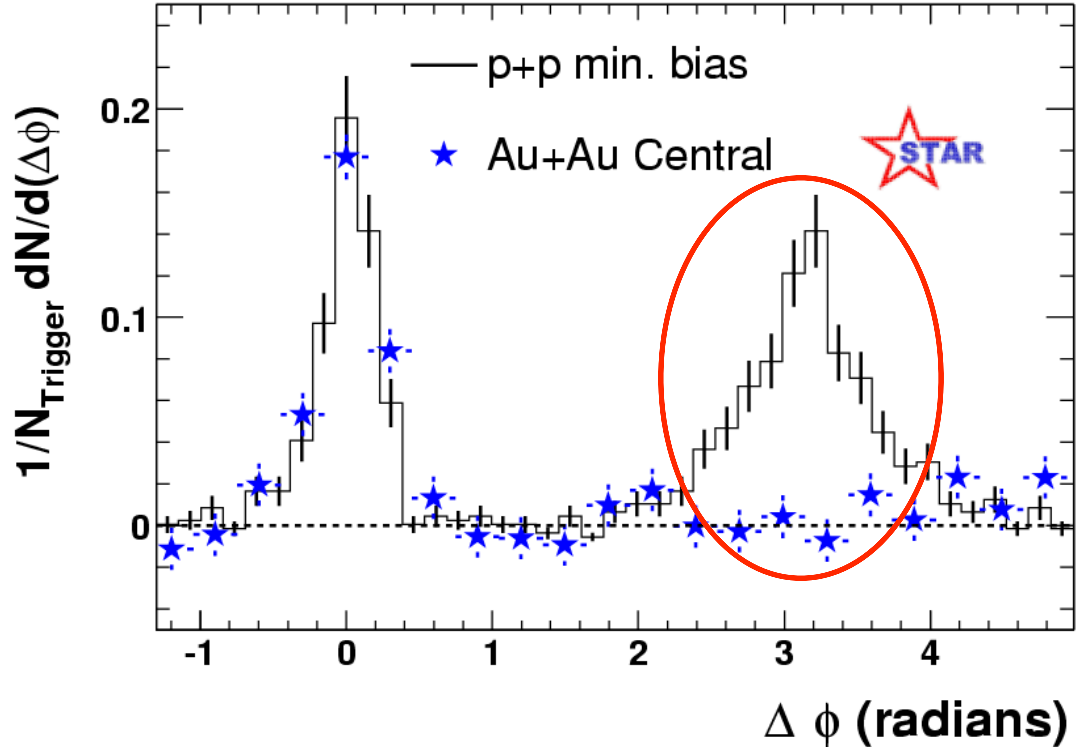
- Trigger: highest p_T track, p_T>4 GeV/c
- $\Delta\varphi$ distribution: 2 GeV/c < p_T < $p_T^{trigger}$
- normalize to number of triggers

The study that started it all ...

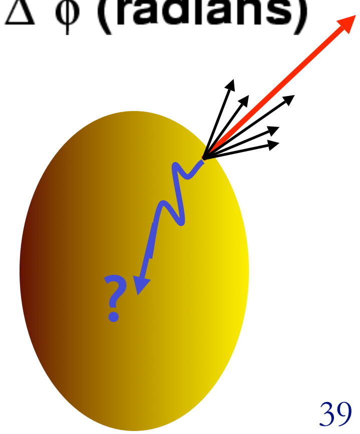
p+p → dijet



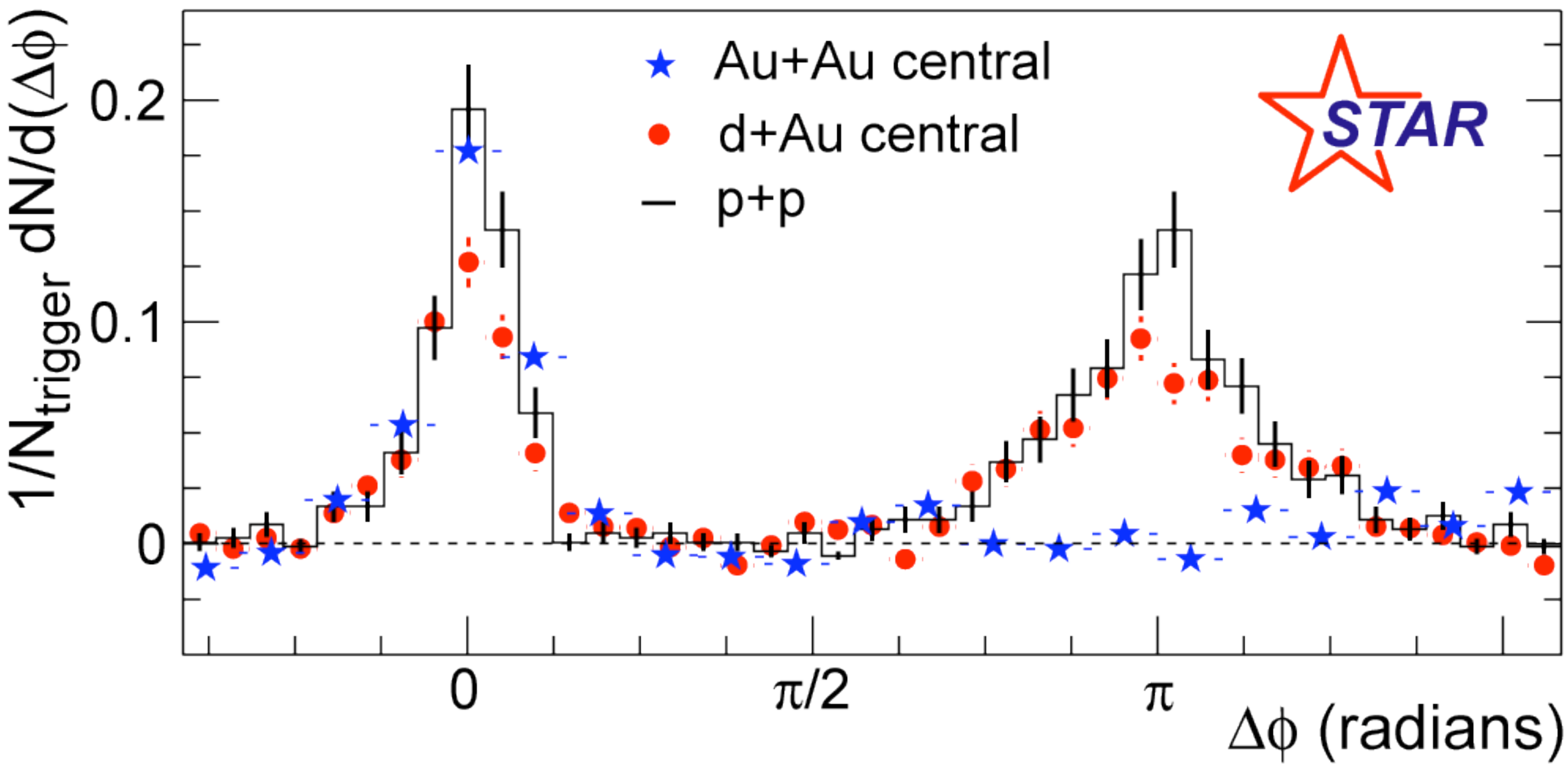
central Au+Au collisions



Δφ ≈ 0: peripheral and central Au+Au similar to p+p
Δφ ≈ π: strong suppression of back-to-back correlations in central Au+Au

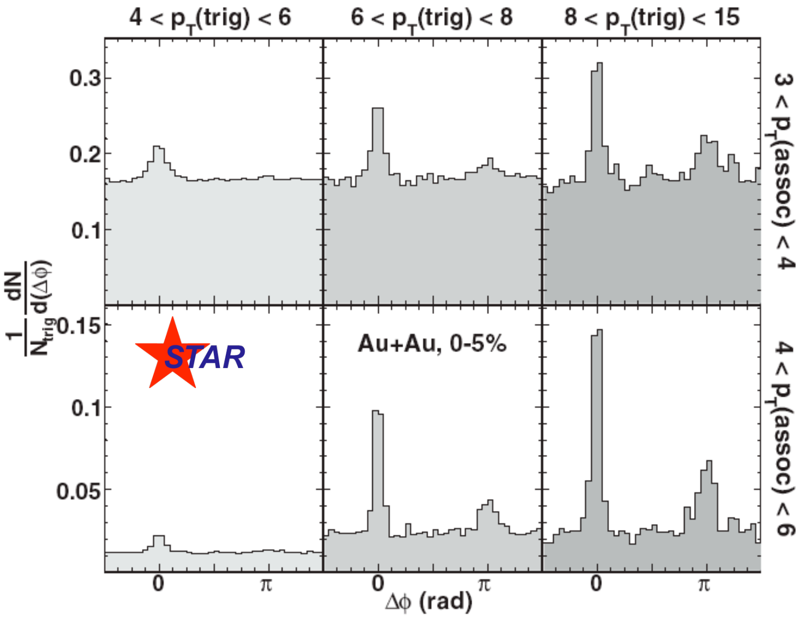


All together: p+p, d+Au, Au+Au



- Near side $\Delta\varphi \approx 0$: p+p, d+Au, Au+Au similar
- Back-to-back $\Delta\varphi \approx \pi$: Au+Au suppressed relative to p+p **and** d+Au
- Suppression of back-to-back correlations in central Au+Au is a final-state effect

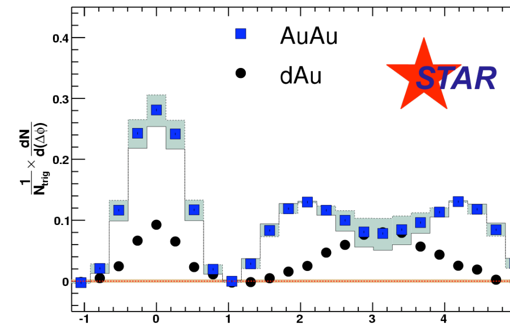
One exciting finding after the other ...



STAR (PRL 97, 162301):

At high p_T di-jets re-emerge in Au+Au

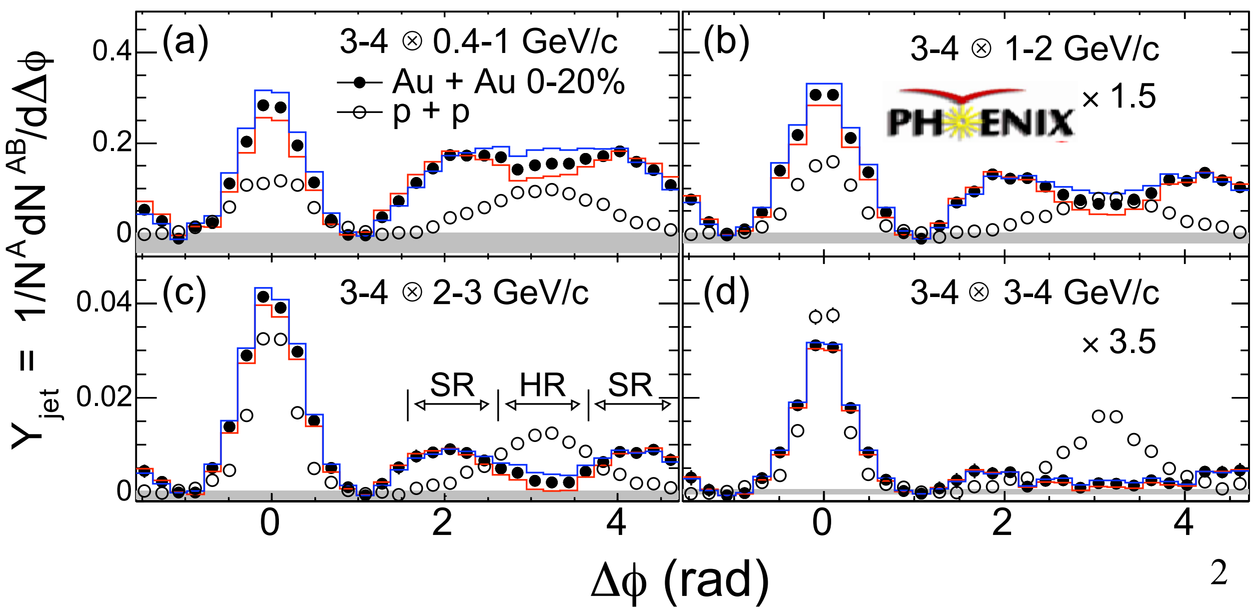
- punch through ?
- tangential jets ?



PHENIX (PRC77, 011901):

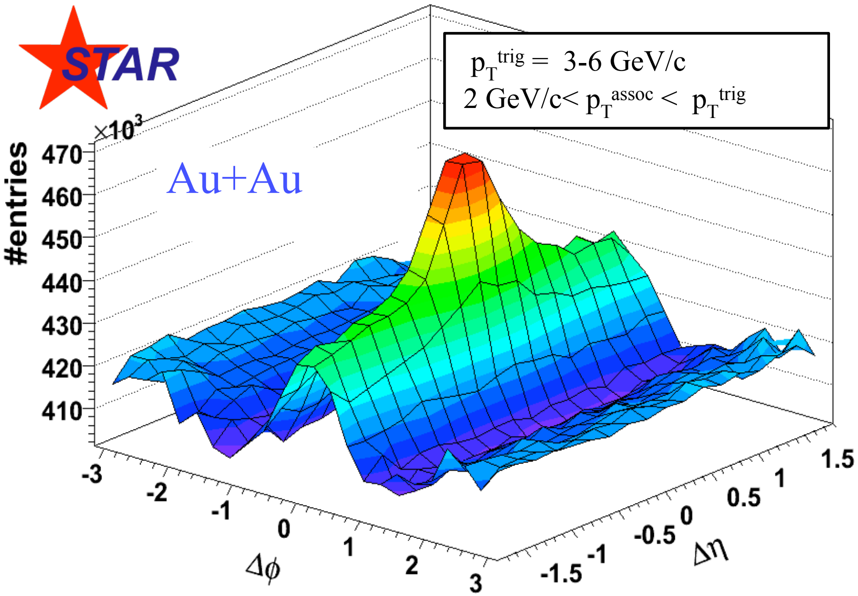
Double hump structure on the away side

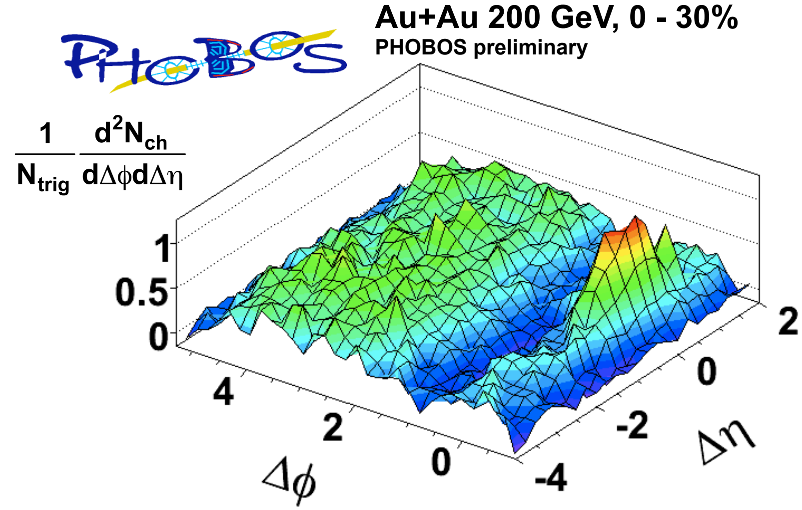
- medium response to jet
- conical emission ?
- mach cone ?
- deflected jets ?



An embarrassment of ridges ...

Long range Δη correlations on the near-side - The “Ridge”

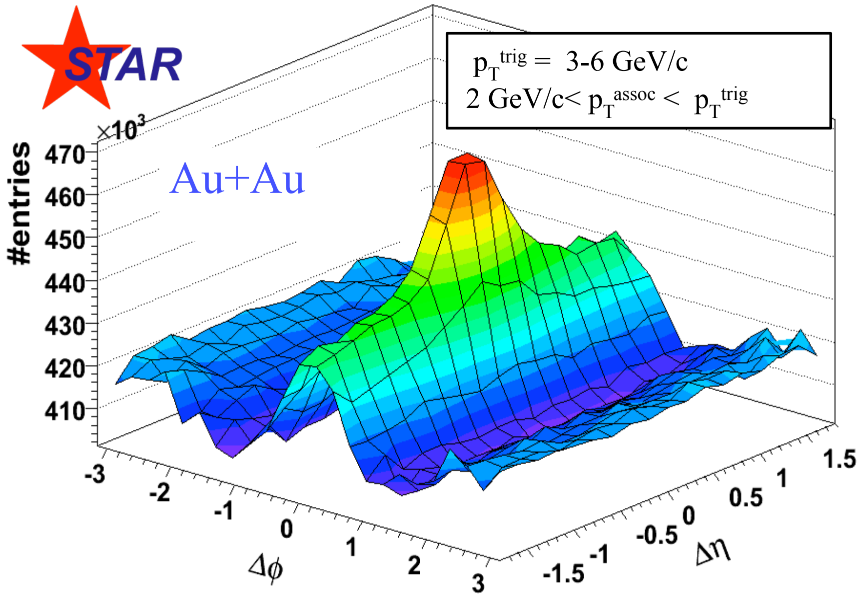


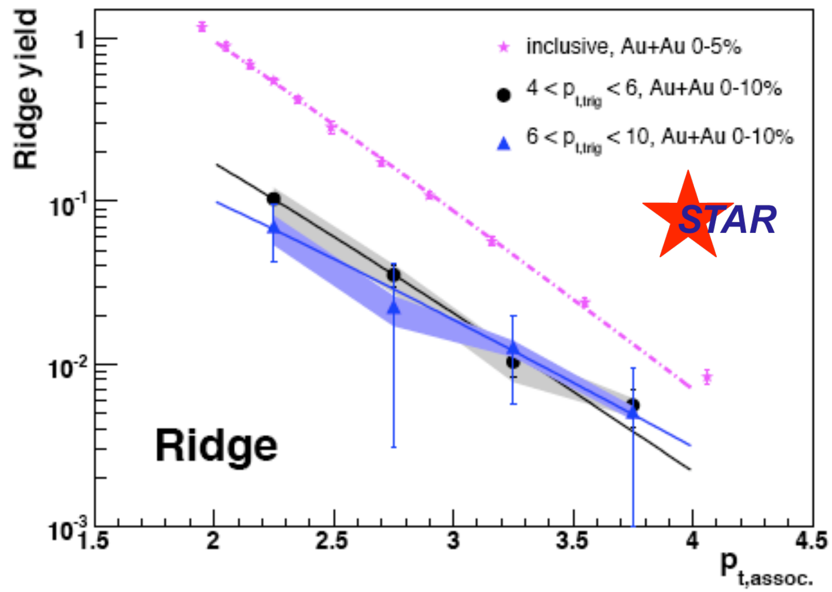


- medium response to jet ?
- the ridge extends to very high rapidity

An embarrassment of ridges ...

Long range Δη correlations on the near-side - The “Ridge”

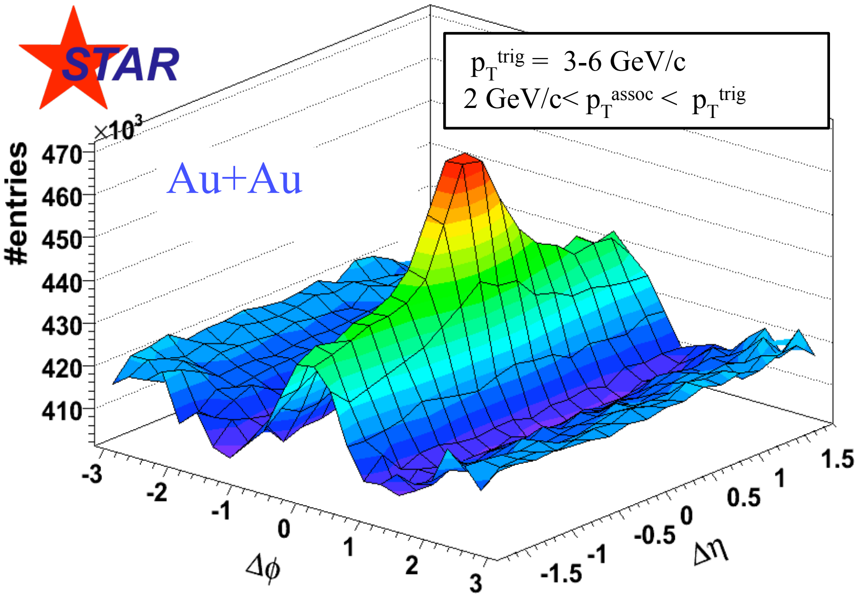


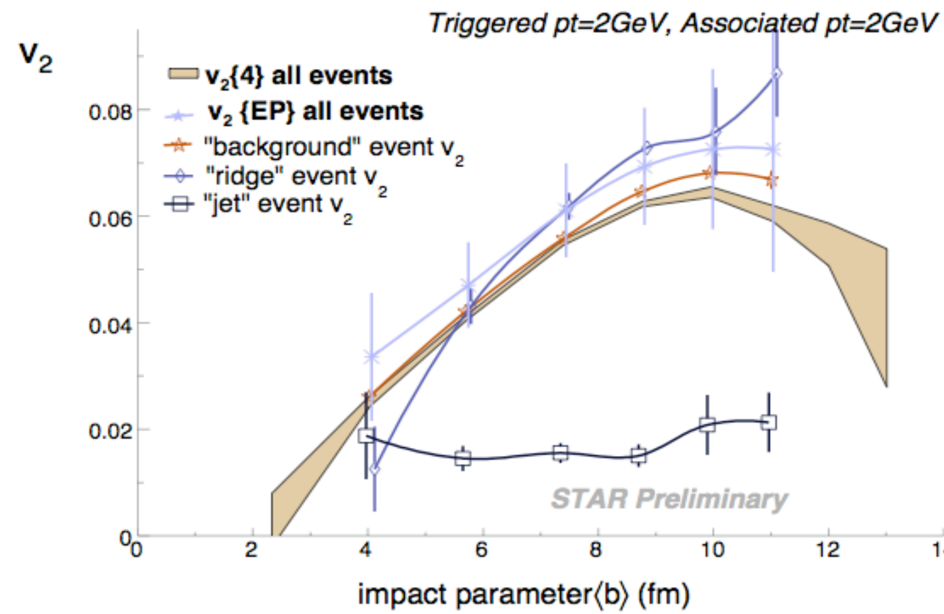


- medium response to jet ?
- the ridge extends to very high rapidity
- the p_T distribution is close to that of the underlying medium

An embarrassment of ridges ...

Long range Δη correlations on the near-side - The "Ridge"

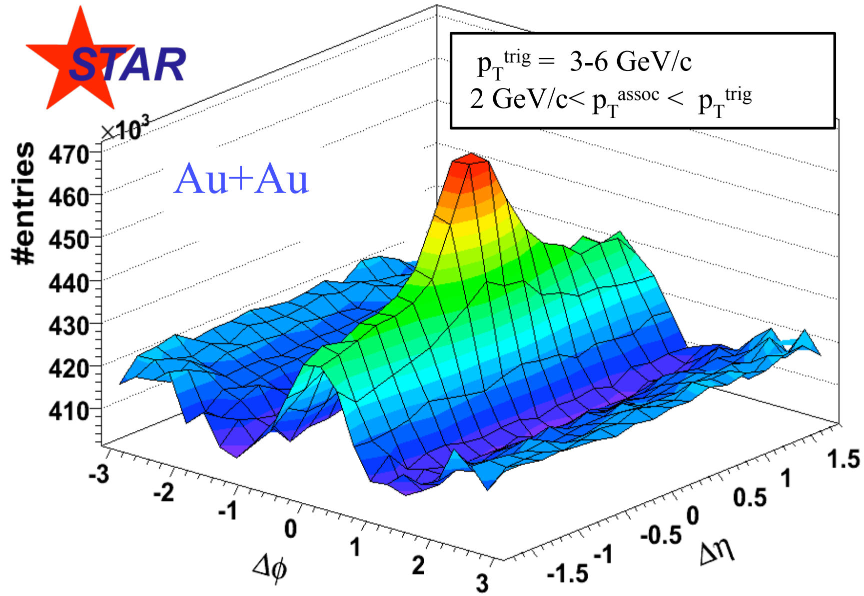


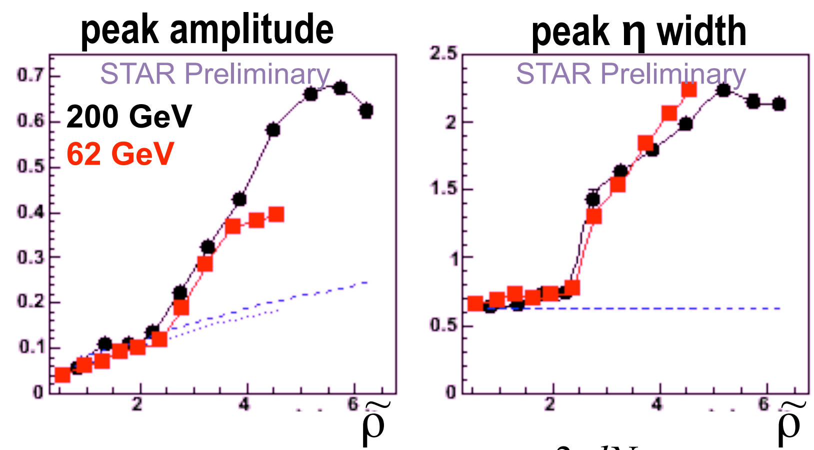


- medium response to jet ?
- the ridge extends to very high rapidity
- the p_T distribution is close to that of the underlying medium
- v_2 of the ridge is close to that of the underlying medium

An embarrassment of ridges ...

Long range Δη correlations on the near-side - The “Ridge”





Transverse particle density $\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta} / S$

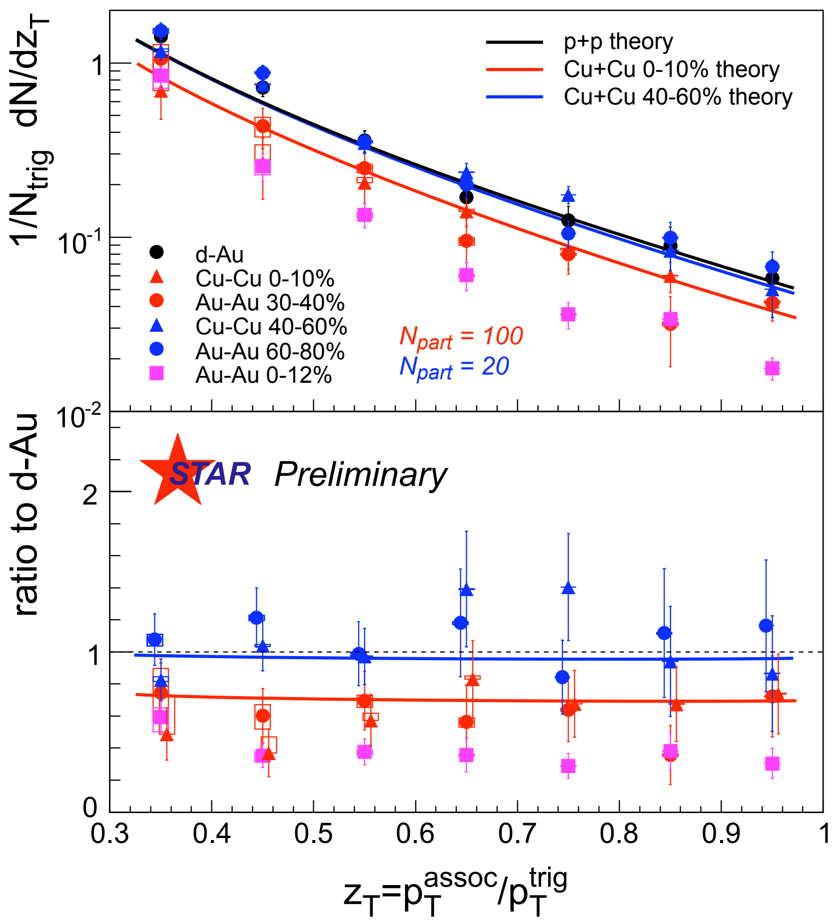
- medium response to jet ?
- the ridge extends to very high rapidity
- the p_T distribution is close to that of the underlying medium
- v_2 of the ridge is close to that of the underlying medium
- At low p_T (untriggered), extension in Δη turns on abruptly
- Note: Ridge yield needs to be subtracted to find “true” jet correlation

Some possible ridge explanations

- QCD bremsstrahlung radiation boosted by transverse flow
  - S.A.Voloshin, Phys.Lett.B. 632(2007)490, E.Shuryak, hep-ph:0706.3531
- Broadening of quenched jets in turbulent color fields
  - A.Majumder et.al Phys. Rev. Lett.99(2004)042301
- Momentum Kick Model
  - C.Y. Wong hep-ph:0712.3282
- In medium radiation and longitudinal flow push
  - N.Armesto et.al Phys.Rev.Lett. 93(2007) 242301
- Recombination between thermal and shower partons at intermediate p_T
  - R.C. Hwa & C.B. Chiu, Phys. Rev. C 72 (2005) 034903

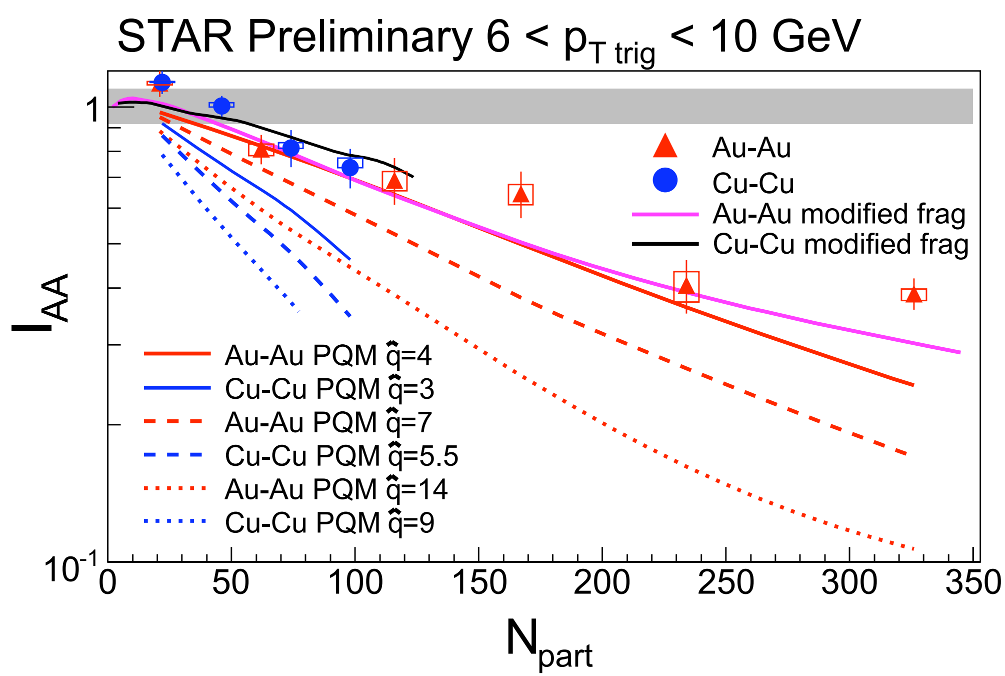
All qualitatively consistent with the features of ridge

Closer Look: *What* is actually loosing energy?



H. Zhong et al., PRL 97 (2006) 252001
C. Loizides, Eur. Phys. J. C 49, 339-345 (2007)

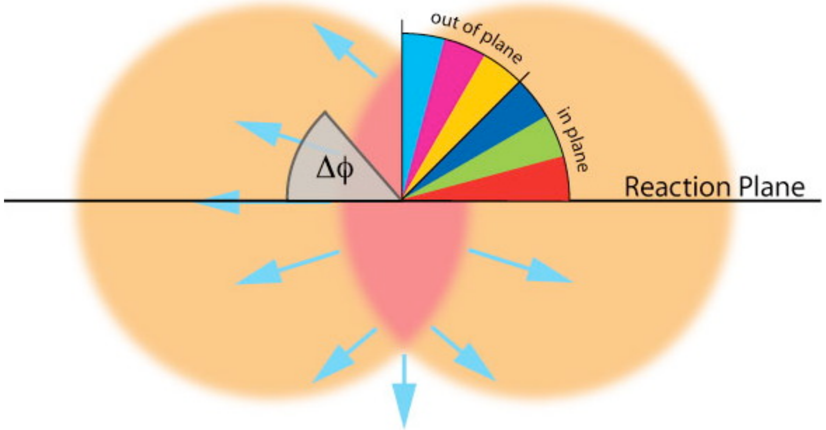
$$I_{AA} = \frac{C_{Au+Au}}{C_{p+p}}$$



- Denser medium in central Au+Au than central Cu+Cu
- Similar medium for similar N_{part}
- Vacuum fragmentation after parton E_{loss} in the medium

- Inconsistent with Parton Quenching Model calculation
- Modified fragmentation model better

Dihadrons: L dependence of E-loss

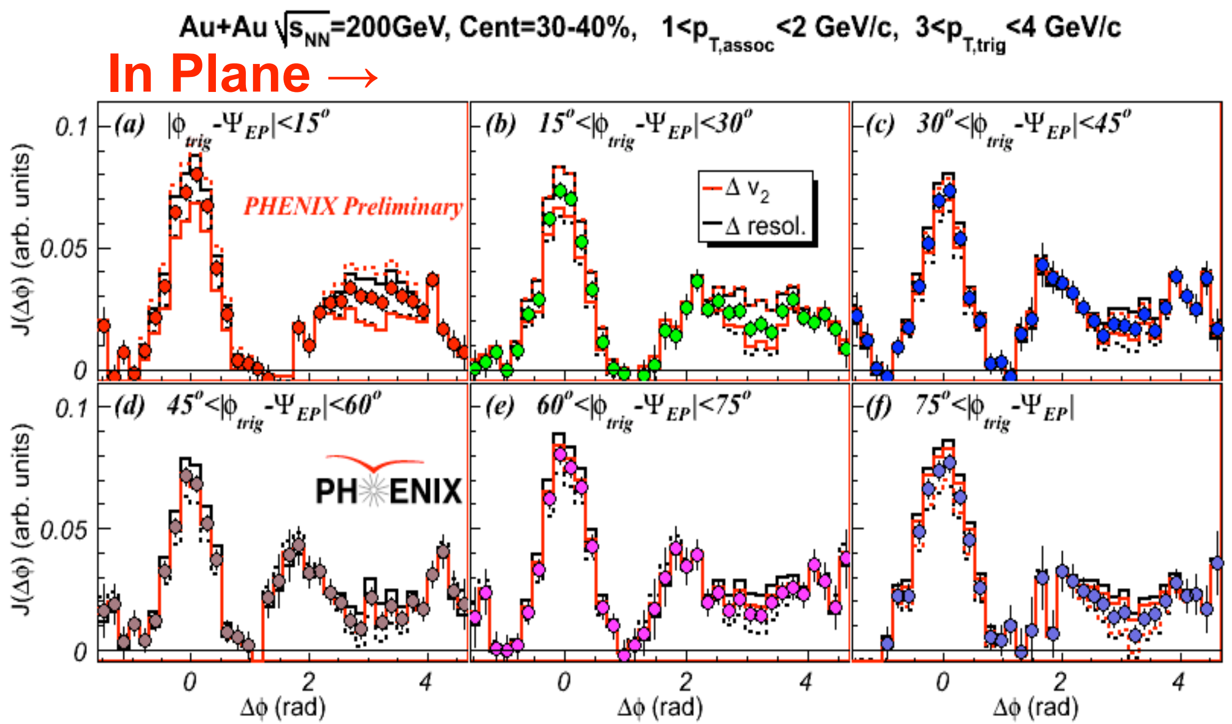


- To gain more insights into the away-side modification and near-side ridge, we study Reaction Plane dependence.
- Non-central collision (20-60%):
- Select trigger particle direction relative to reaction plane.

PHENIX and STAR: away side shape changes w/ angle of trigger with respect to reaction plane

The position of the cone (?) does not change with angle of trigger hadron *w.r.t* reaction plane.

In Plane →

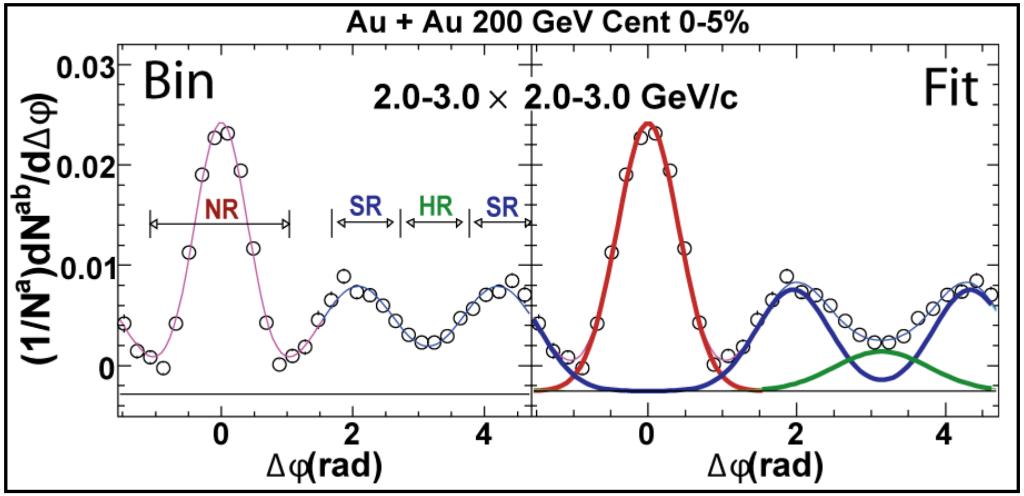


Out of Plane

What's with this "cone"?

Possible Explanations

One thing seems clear:
It's the reaction of the medium to a high-p_T parton traversing it

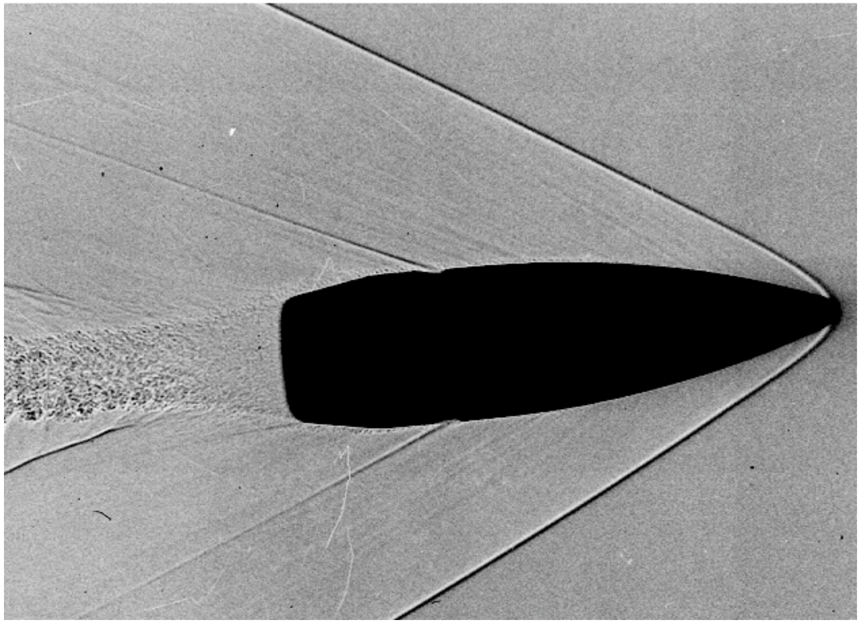


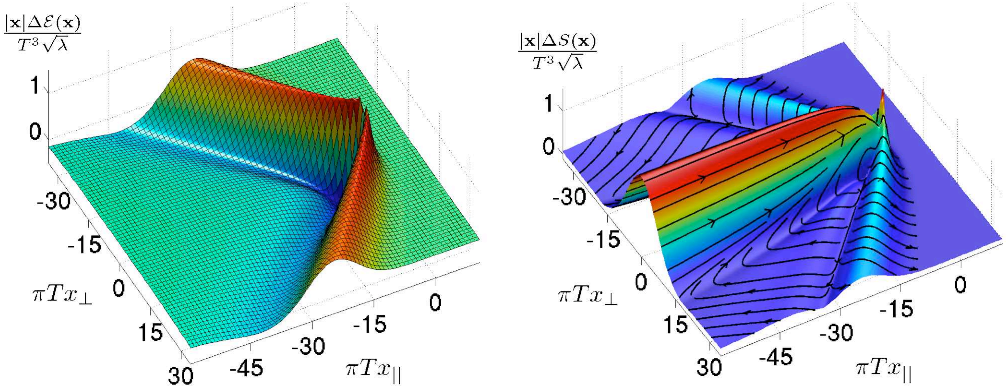
- Deflected jets
- Cherenkov cone
  - I.M. Dremin (Nucl. Phys. A750: 233, 2006)
  - V. Koch et. al. (Phys. ReV. Lett. 96, 172302, 2006)
- Mach cone
  - Hydrodynamics
    - H. Stöcker et al. (Nucl.Phys.A750:121,2005)
    - J. Casalderra-Solana et. al. (Nucl.Phys.A774:577,2006)
    - T. Renk & J. Ruppert (Phys.Rev.C73:011901,(2006))
  - Colored plasma
    - J. Ruppert & B. Müller (Phys.Lett.B618:123,2005)
  - AdS/CFT
    - S. Gubser, S. Pufu, A. Yarom. (arXiv:0706.4307v1, 2007)

The Mach Cone

- Is a Mach cone created when a supersonic parton propagates through the quark gluon plasma?

- A Mach cone is formed when an object moves faster than the speed of sound in the medium.



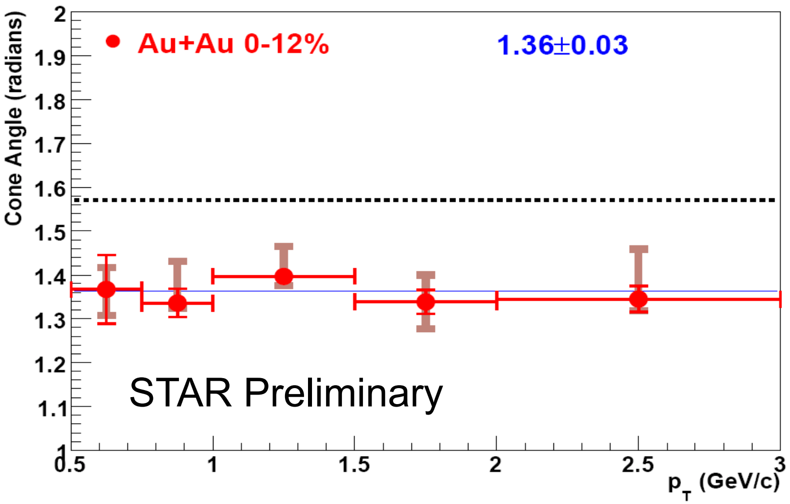


Chesler & Yaffe
arXiv:0712.0050

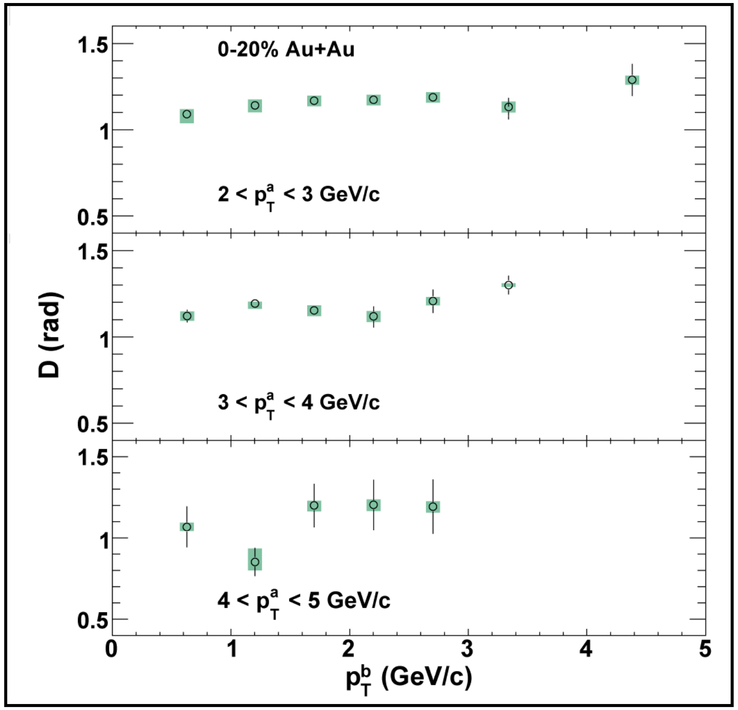
What if it's a cone ?

STAR and PHENIX find:

- Cone angle does not change appreciably as a function of p_T of trigger or associated hadron ...
- ... or centrality, or angle wrt reaction plane



PHENIX Preliminary



STAR from 3-particle correlations,
PHENIX from 2-particle correlations

Naive calculation of time averaged velocity of sound in medium:

Cone angle ~ 1.36 radians $\Rightarrow c_s = 0.2c$ (oops a bit too small)

Conclusions on High-p_T RHIC Physics

- Exciting data on medium response, but still
  - need to understand the surface bias (and ways out e.g. γ-h/jet)
  - need to improve 3-particle correlation techniques (not covered here)
  - full jet reconstruction (in progress)
- Our understanding of energy loss is incomplete
  - Can we describe heavy flavor and light quark Eloss simultaneously?
    - latest news: bottom appears to be quenched too
  - We must determine whether energy loss is perturbative e.g. determine whether quenching depends on color factors (don't see this in data)
- We need more coherent theory+expt. efforts
  - It's too early to be trying to determine things to 10, 20, 30%
    - When there are much larger theoretical uncertainties.
    - We at RHIC need be using (and refining our) data to help resolve those theoretical uncertainties. Detector upgrades underway!