Heavy-Ion Collisions
-
examining the Quark Gluon Plasma

Physics in Collisions

Kobe - Japan

Helen Caines - Yale University

September 2nd 2009

Outline:
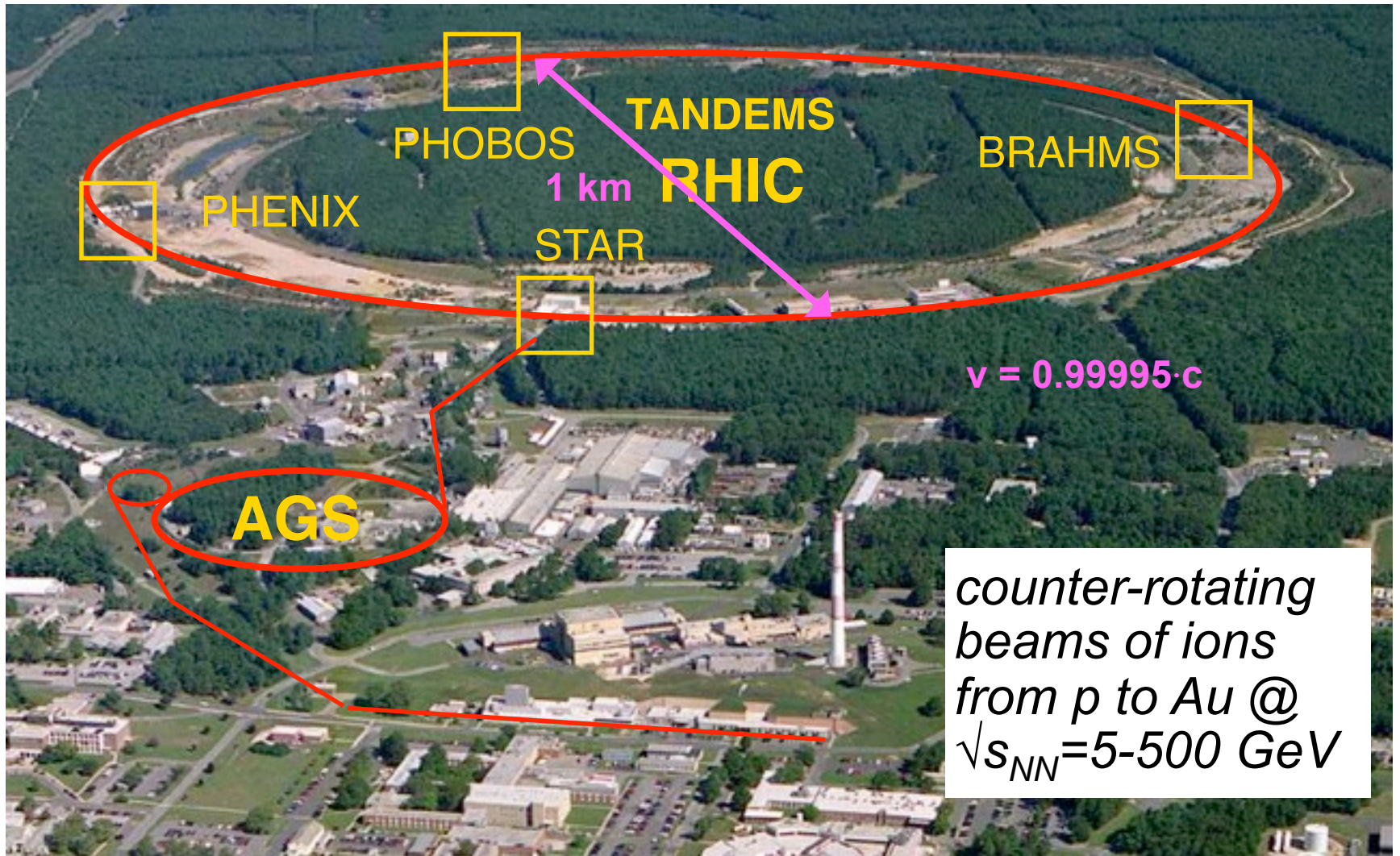 *Studying sQGP via jets*
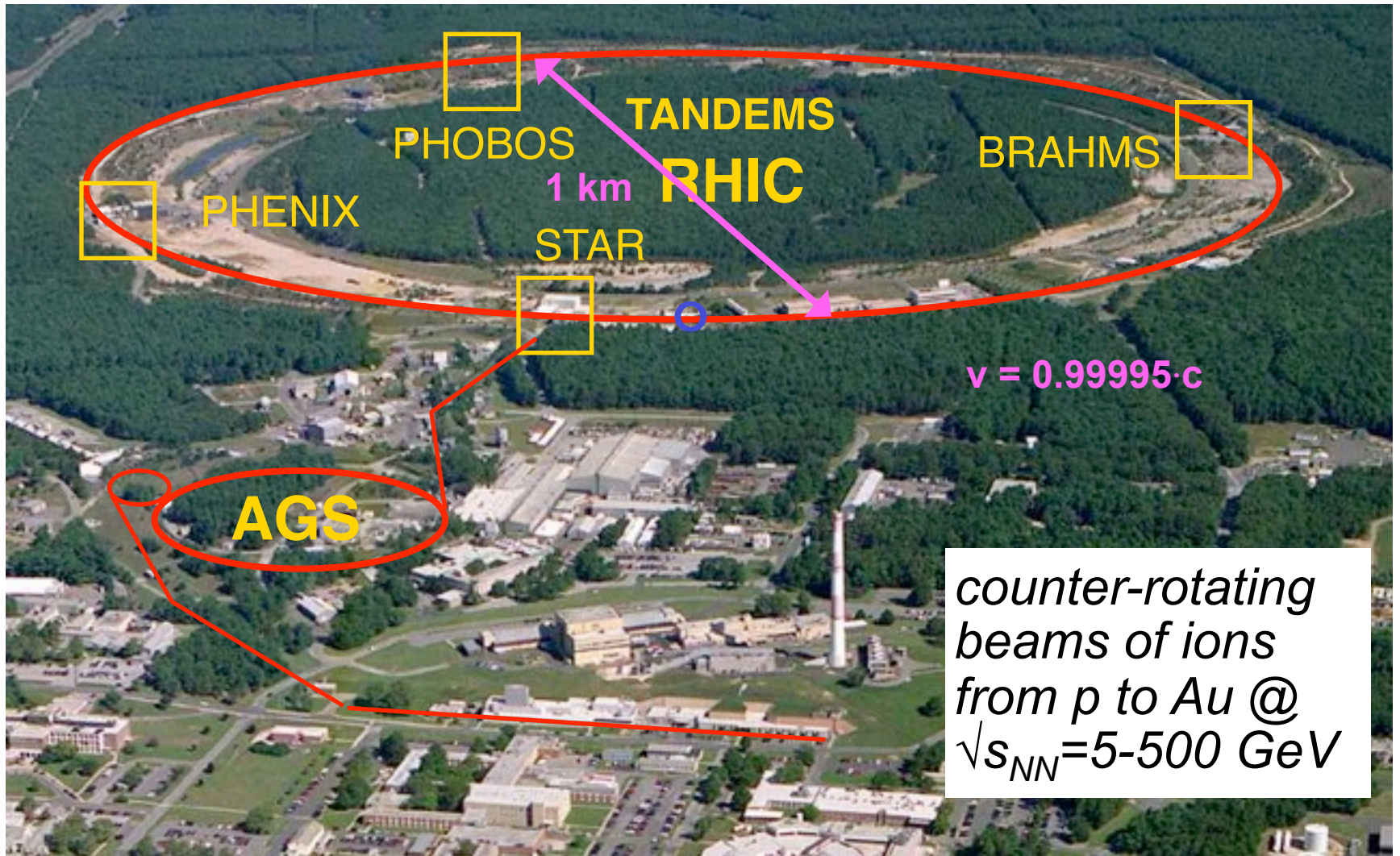 *Using sQGP to observe local strong*
  parity violation effects
 Outlook

LUX ET VERITAS

RHIC - Relativistic Heavy Ion Collider

TANDEMS

1 km

RHIC

PHOBOS

PHENIX

BRAHMS

STAR

v = 0.99995·c

AGS

counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

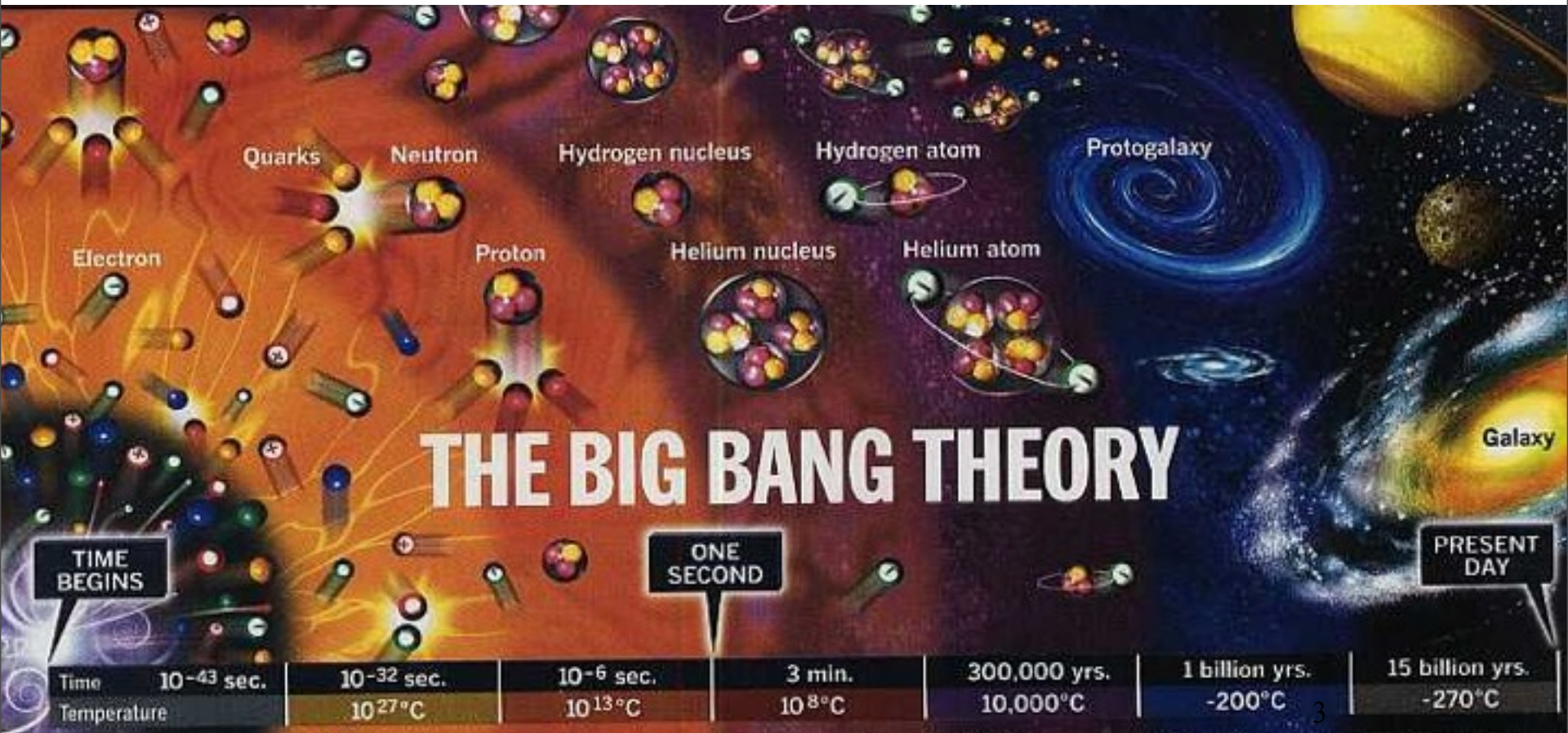PHENIX and STAR - multi purpose experiments still running

RHIC - Relativistic Heavy Ion Collider

PHENIX and STAR - multi purpose experiments still running

Creating a Quark Gluon Plasma

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario."   Ed Witten, Phys. Rev. D (1984)

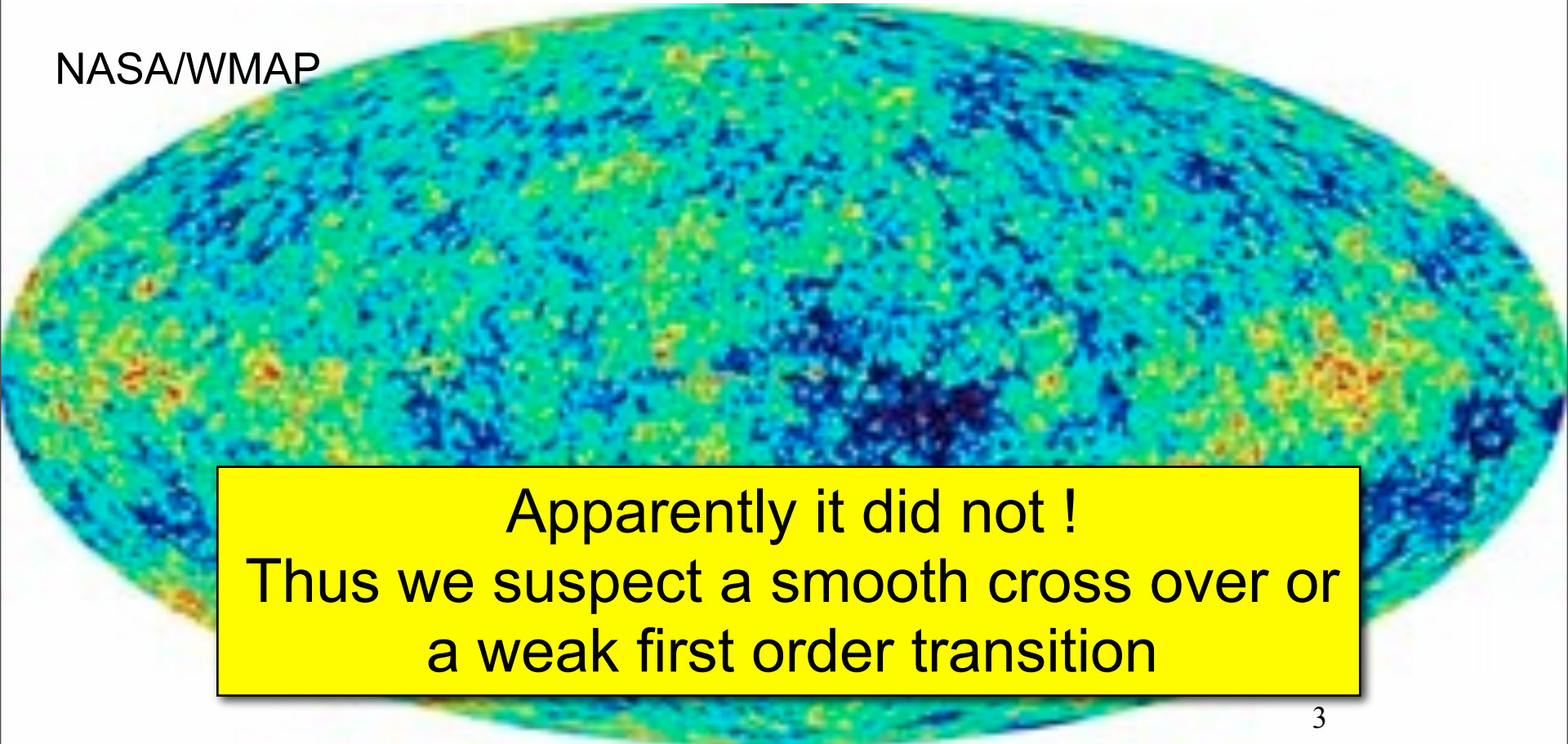# Creating a Quark Gluon Plasma

"A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario."   Ed Witten, Phys. Rev. D (1984)

NASA/WMAP

Apparently it did not !
Thus we suspect a smooth cross over or a weak first order transition

At RHIC we create a new state of matter

- Energy density in the collision region is way above that where hadrons can exist

- The initial temperature in the collision region is way above that where hadrons can exist

- The medium has quark and gluon degrees of freedom in initial stages

> We have created a new state of matter at RHIC
> - the sQGP

- A sQGP: flows like an almost "perfect" liquid
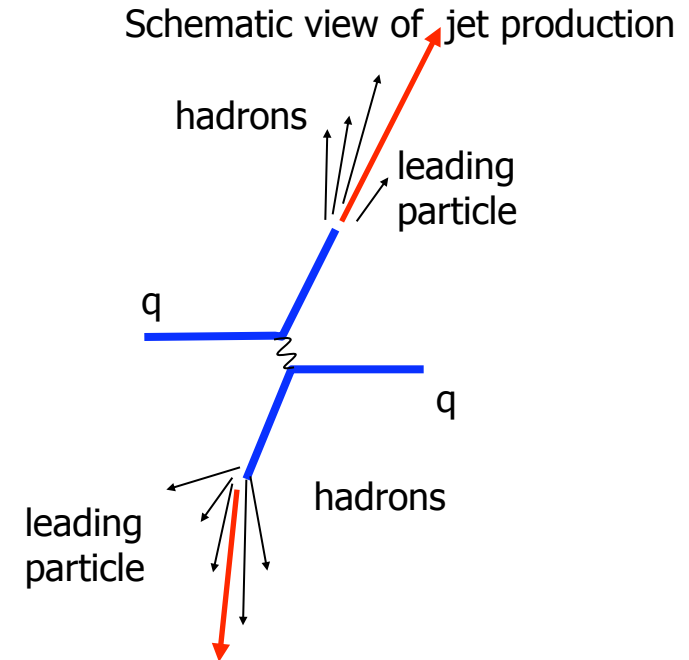 interacts strongly with partons passing through it

Studying sQGP properties

Early production in parton-parton scatterings with large Q^2

Must **pass through the medium** to escape

Direct interaction with partonic phases of the reaction

Schematic view of jet production

hadrons

leading particle

q

q

leading particle

hadrons
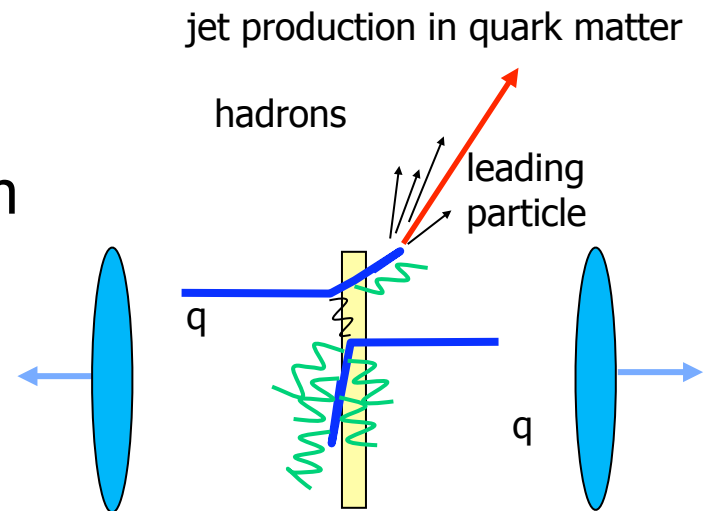
Studying sQGP properties

Early production in parton-parton scatterings with large Q^2

Must pass through the medium to escape

Direct interaction with partonic phases of the reaction

Use jets to probes sQGP

- interaction of partons with medium
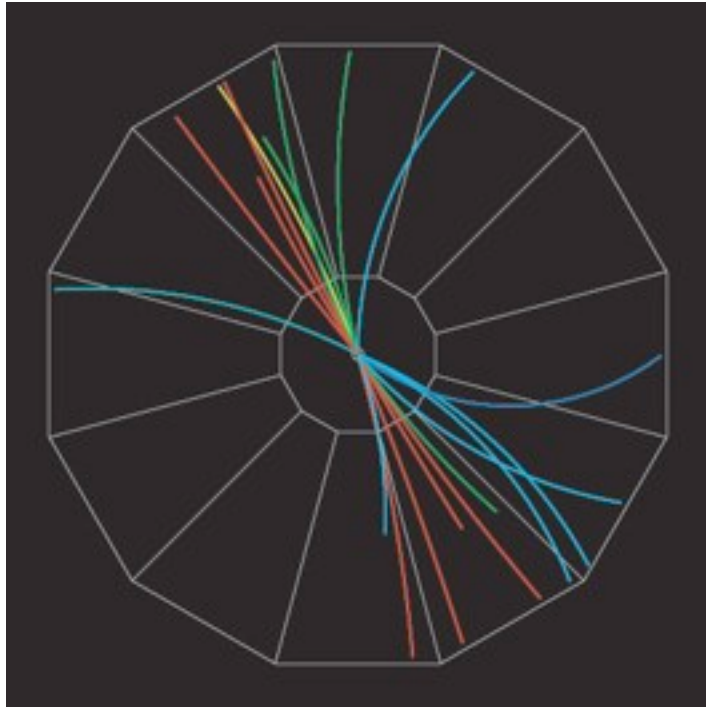 → attenuation/absorption of jets

- compare Au-Au to p-p

jet production in quark matter

hadrons

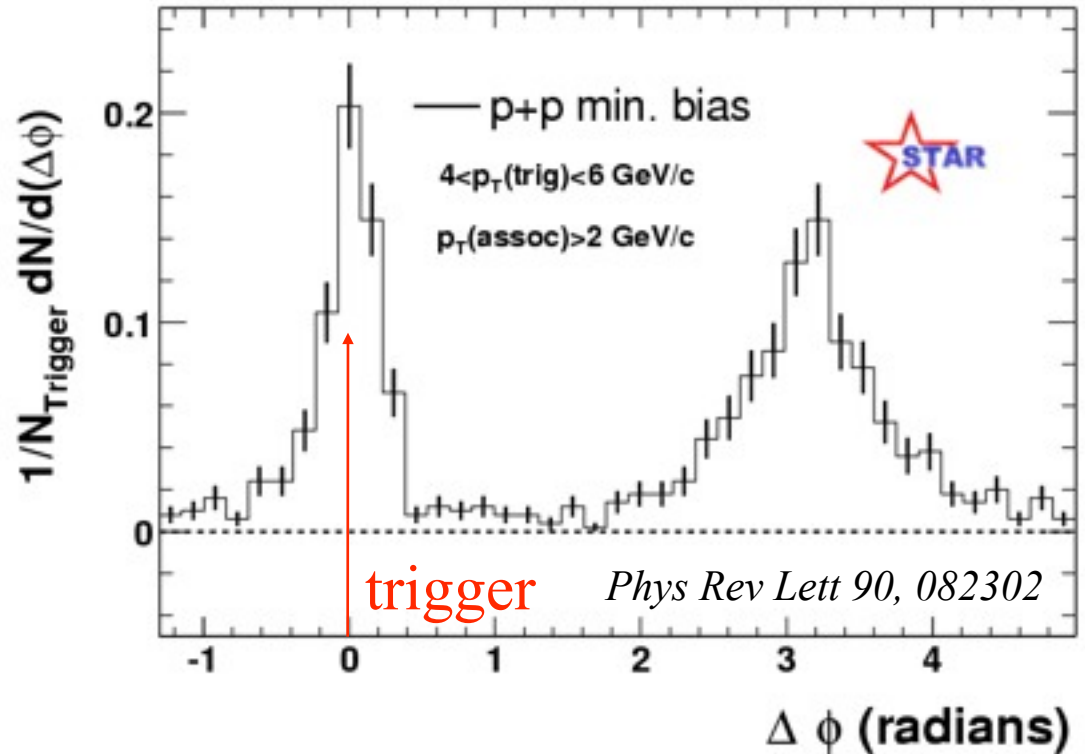leading particle

q

q

High p$_T$ particles - proxy for jet

p-p → dijet
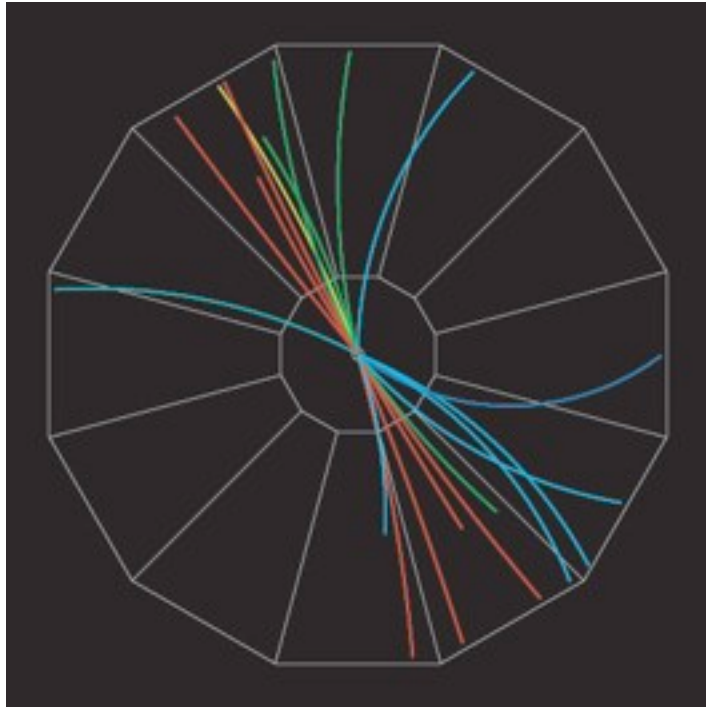

- Trigger: highest p$_T$ track

- Δφ distribution:

High p$_T$ particles - proxy for jet

p-p → dijet

min. bias p-p collisions

Phys Rev Lett 90, 082302

trigger

High p$_T$ particles - proxy for jet

p-p → dijet

central Au-Au collisions
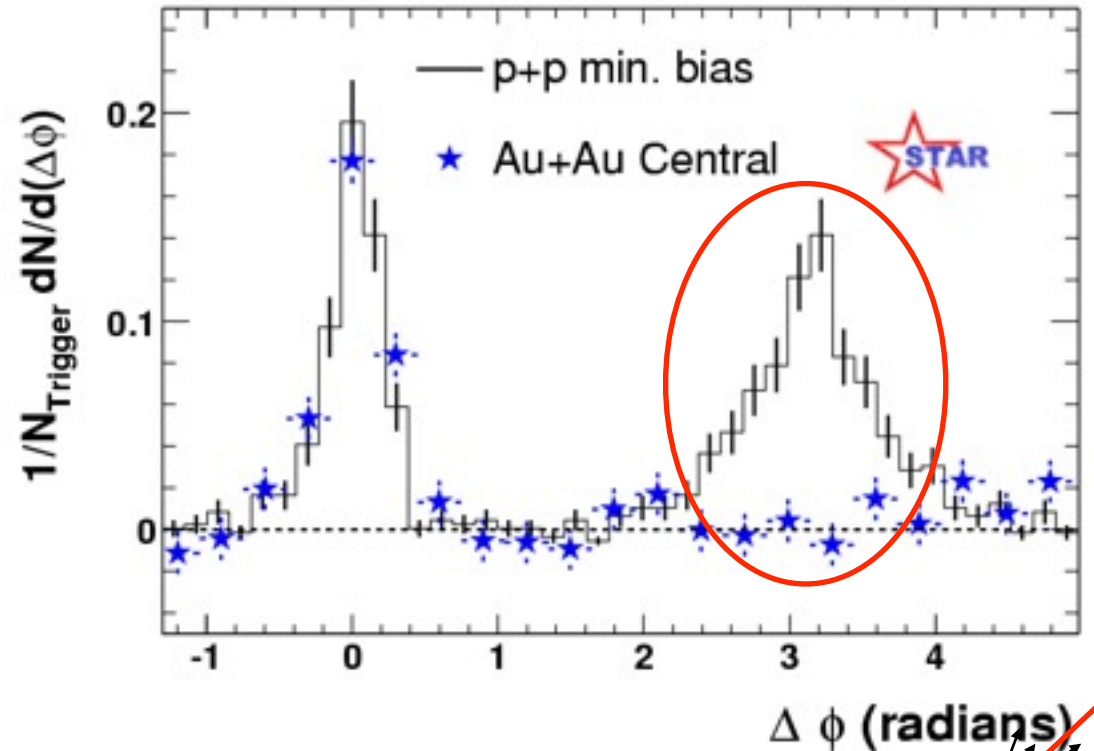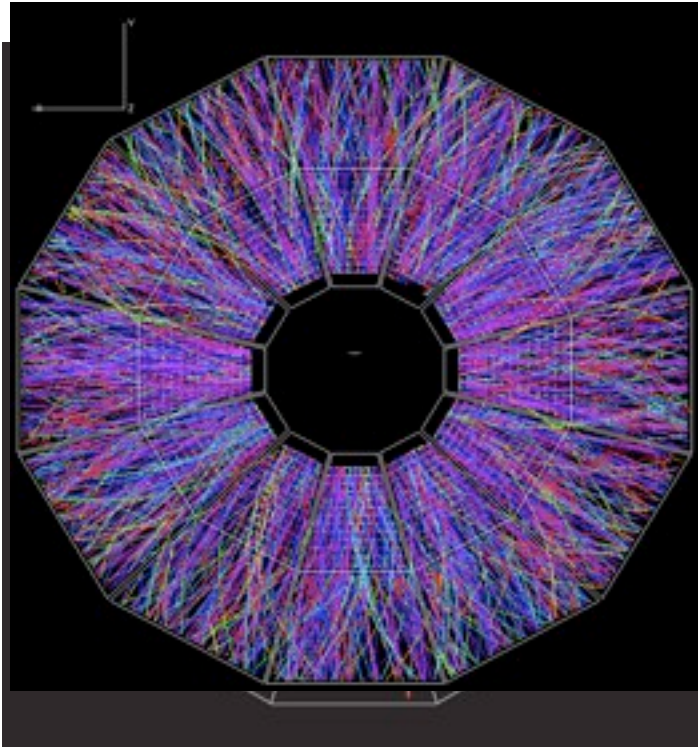
Δφ ≈ 0: central Au-Au similar to p-p

Δφ ≈ π: strong suppression of back-to-back correlations in central Au-Au
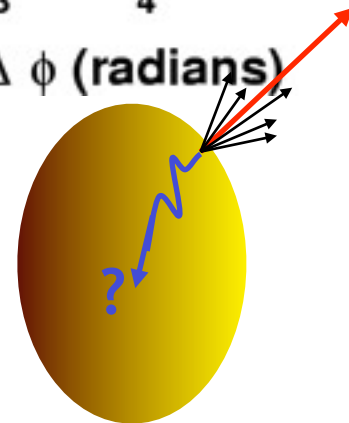
Interpretation

Gluon radiation: Multiple final-state gluons radiate off from produced hard parton - induced by the traversed dense colored medium
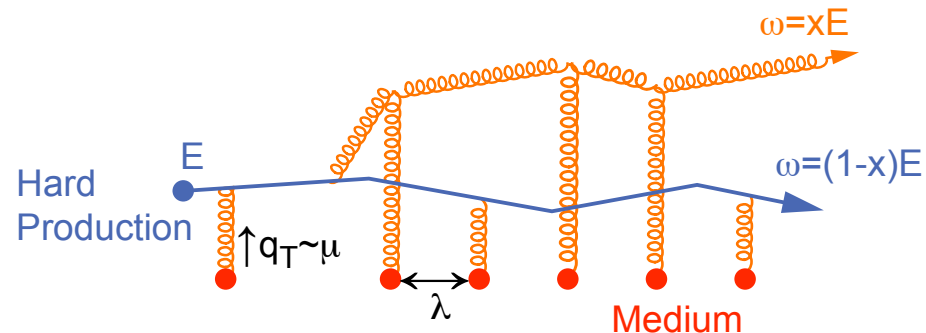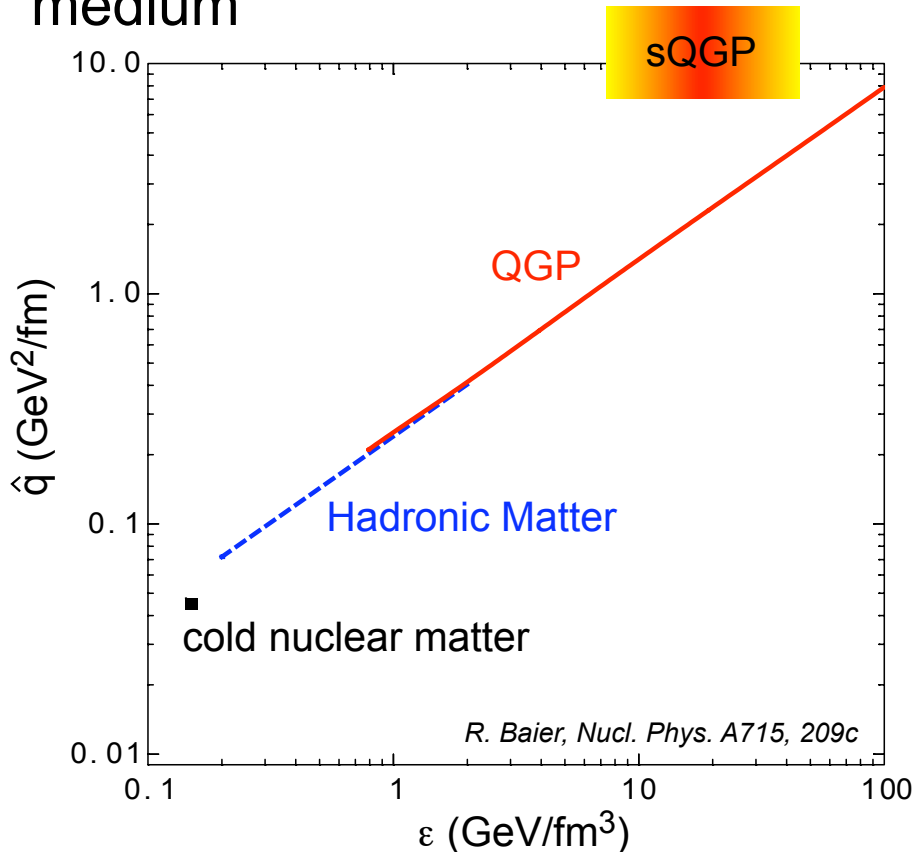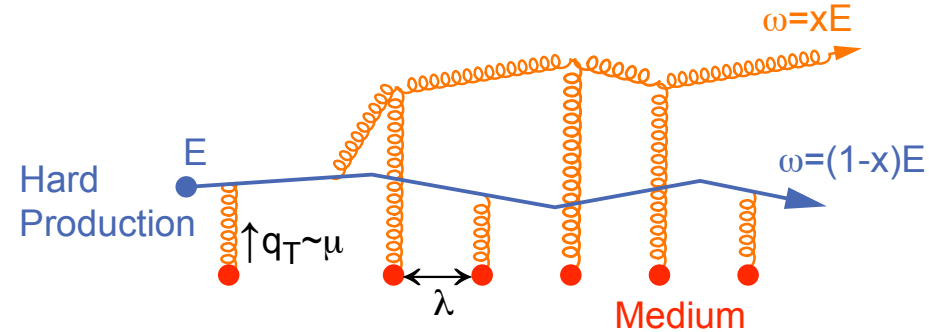
Interpretation

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

- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E_{loss} \sim \rho_{gluon}$ (gluon density)
  - $\Delta E_{loss} \sim \Delta L^2$ (medium length)
    $\Rightarrow \sim \Delta L$ with expansion
- Characterization of medium
  - transport coefficient $\hat{q}$
- is $\langle p_T^2 \rangle$ transferred from the medium to a hard gluon per unit path length
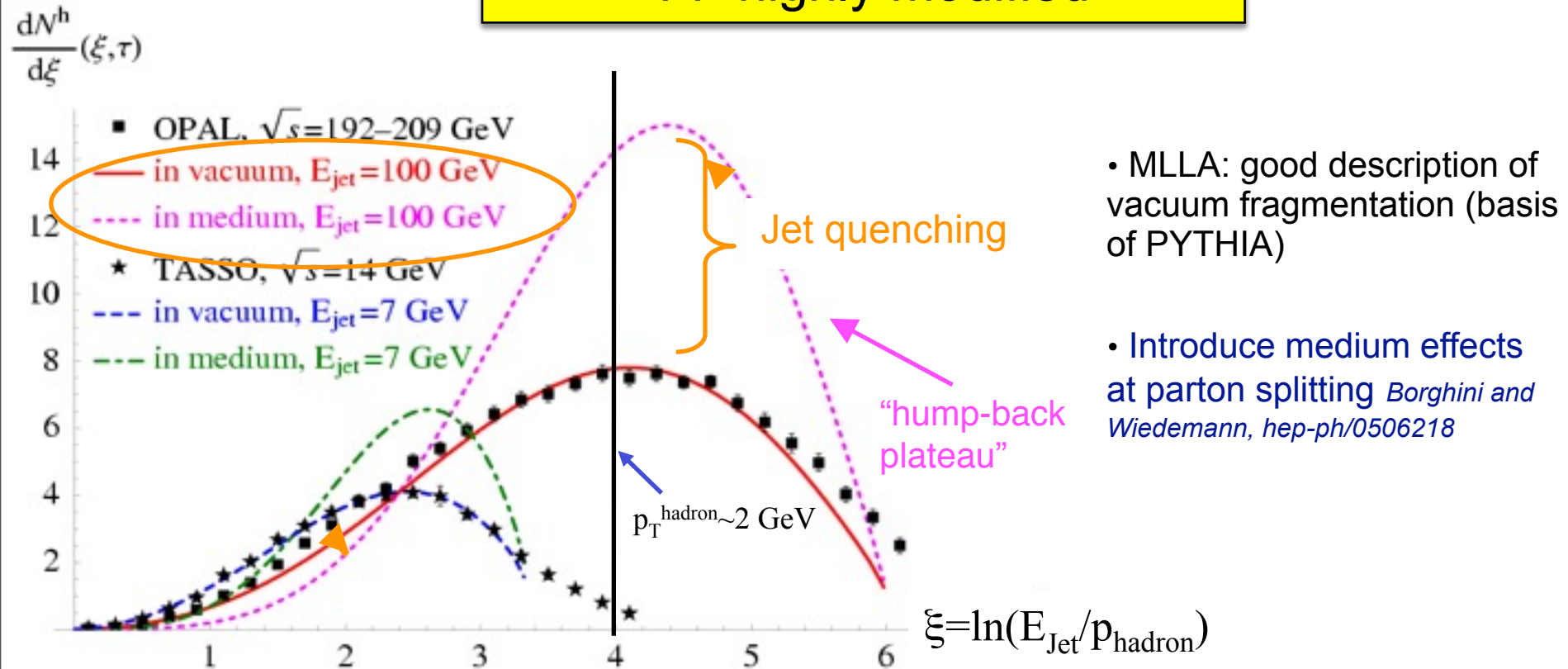
$$\hat{q} \sim 5\text{-}10 \text{ GeV/fm}$$

R. Baier, Nucl. Phys. A715, 209c
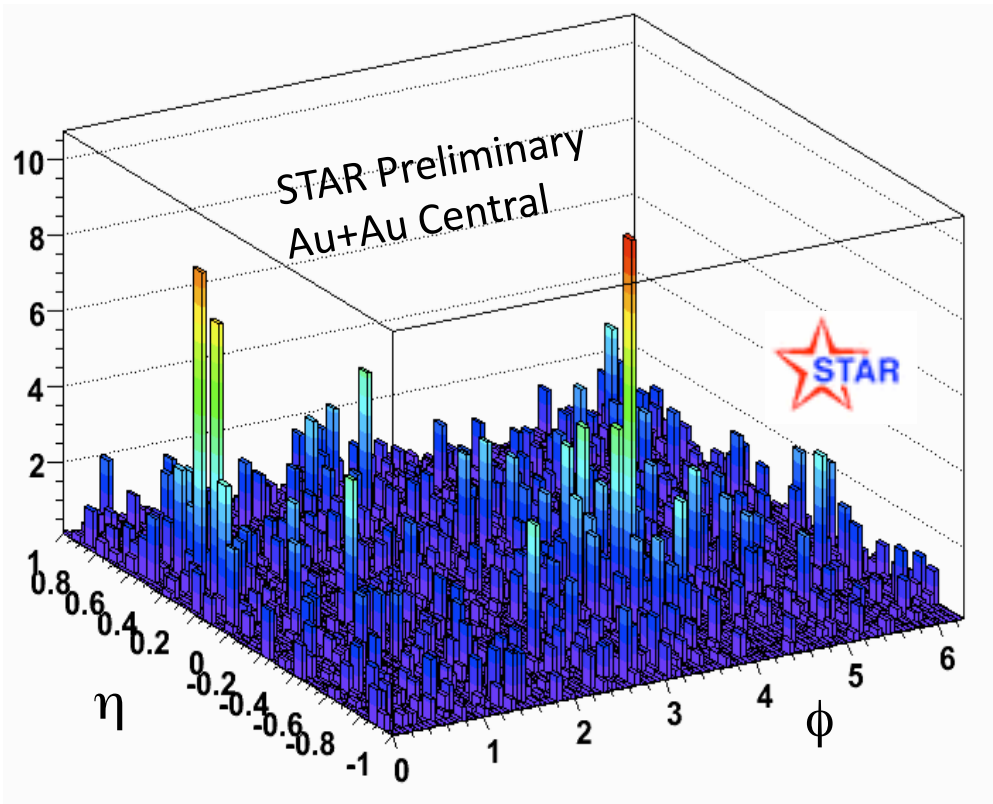
Towards a complete study of jet-quenching

Di-hadrons *indirect* measurements of jet quenching !

Needed to develop techniques to allow full jet reconstruction:

> **"full" partonic energy recovered**
> **FF highly modified**

$\frac{dN^h}{d\xi}(\xi,\tau)$

- OPAL, $\sqrt{s}$=192–209 GeV
- in vacuum, E_{jet}=100 GeV
- in medium, E_{jet}=100 GeV
- TASSO, $\sqrt{s}$=14 GeV
- in vacuum, E_{jet}=7 GeV
- in medium, E_{jet}=7 GeV

Jet quenching

"hump-back plateau"

$p_T^{hadron} \sim 2$ GeV

$\xi = \ln(E_{Jet}/p_{hadron})$

- MLLA: good description of vacuum fragmentation (basis of PYTHIA)

- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

Helen Caines

Can you "see" jets a RHIC?

STAR Preliminary Au+Au Central

PHENIX Preliminary Cu+Cu

Run-5 Cu + Cu at $\sqrt{s_{NN}}$ = 200 GeV
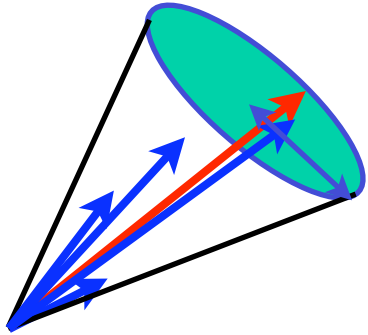Run 150513, event 277518, 19-20% cent.

Joern Putschke HP2008

Yue Shi Lai QM2009

Clearly visible above background in both experiments

Jet reconstruction - algorithms

Seedless Cone - SISCone:

Fastjet package - [Cacciari, Soyez, arXiv: 0704.0292]

- $R_{cone} = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)}$
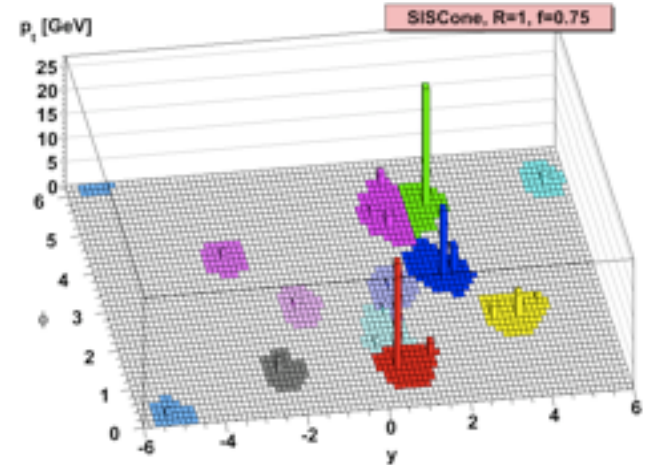- all particles used.
- Splitting/Merging destroys cone shape.

Jet reconstruction - algorithms

Seedless Cone - SISCone:

Fastjet package - [Cacciari, Soyez, arXiv: 0704.0292]

- $R_{cone}=\sqrt{(\Delta\varphi^2+\Delta\eta^2)}$
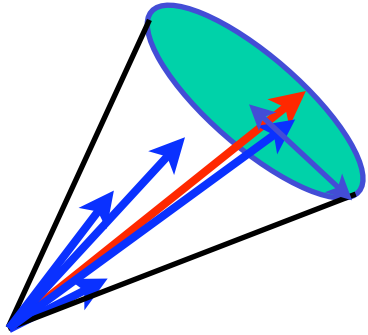- all particles used.
- Splitting/Merging destroys cone shape.

Recombination k_T /Anti-k_T:

- starts from low (high) p_T.
- merges weighted by $1/p_T$ (p_T) i.e. high (low) p_T is dis-favored.

[Cacciari, Salam, Soyez, arXiv:0802.1189]

Jet reconstruction - algorithms

Seedless Cone - SISCone:

Fastjet package - [Cacciari, Soyez, arXiv: 0704.0292]

- $R_{cone} = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)}$
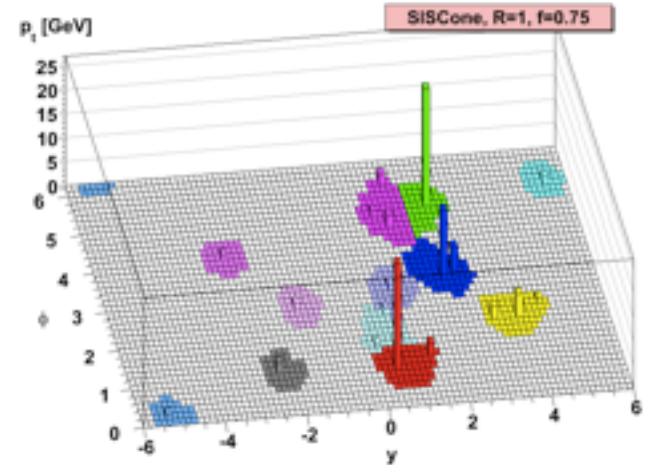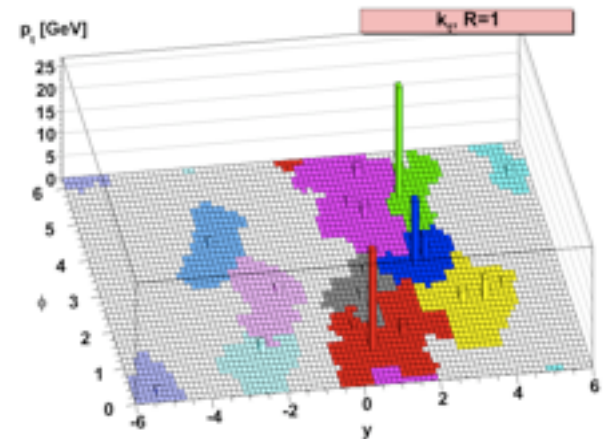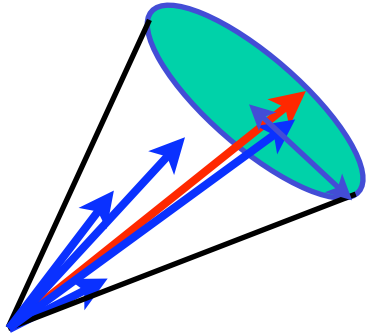- all particles used.
- Splitting/Merging destroys cone shape.
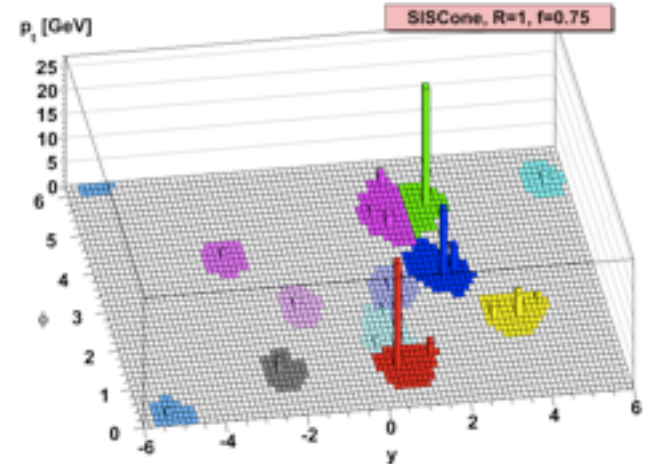
Recombination k_T /Anti-k_T:

- starts from low (high) p_T.
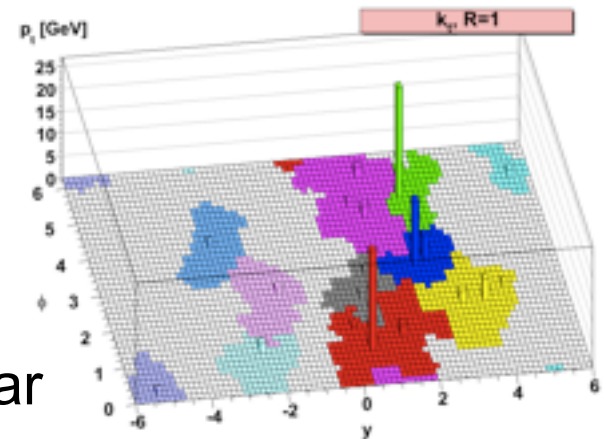- merges weighted by $1/p_T$ (p_T) i.e. high (low) p_T is dis-favored.

Gaussian Filter:

- cone like but no infrared/collinear issues.
- focusses on core

[Cacciari, Salam, Soyez, arXiv:0802.1189]

Jets at RHIC – a calibrated probe?
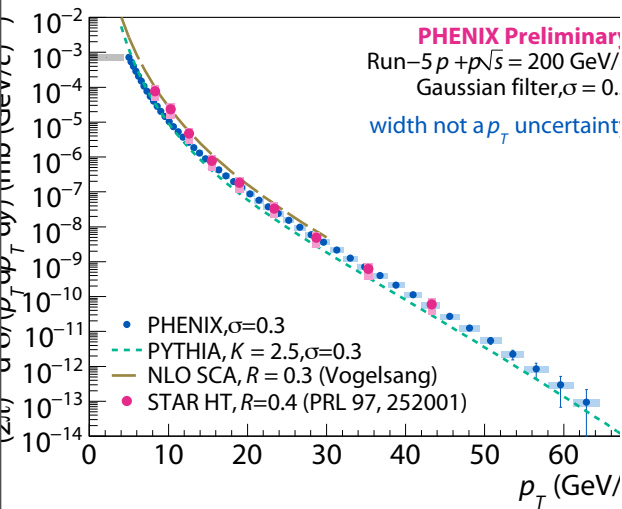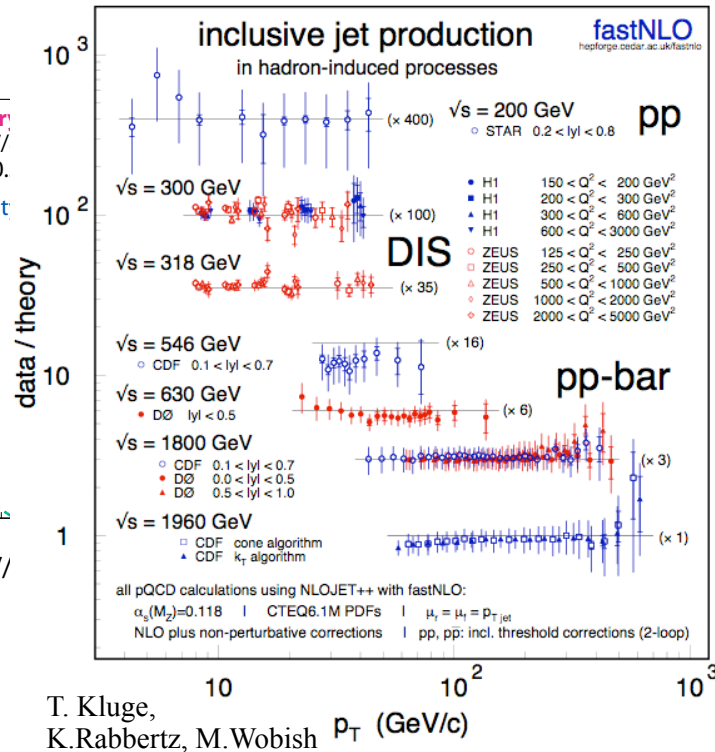
PHENIX Preliminary
Run−5 p +$p\sqrt{s}$ = 200 GeV/
Gaussian filter,σ = 0.

width not a p_T uncertaint

- PHENIX,σ=0.3
- - - PYTHIA, K = 2.5,σ=0.3
— NLO SCA, R = 0.3 (Vogelsang)
● STAR HT, R=0.4 (PRL 97, 252001)

STAR : PRL 97 (2006) 252001
PHENIX: Y.Lai QM2009

T. Kluge,
K.Rabbertz, M.Wobish

- Jet cross-section in p-p is well described by NLO pQCD calculations over 7 orders of magnitude.
- Excellent description when included in world data

Jets at RHIC – a calibrated probe?
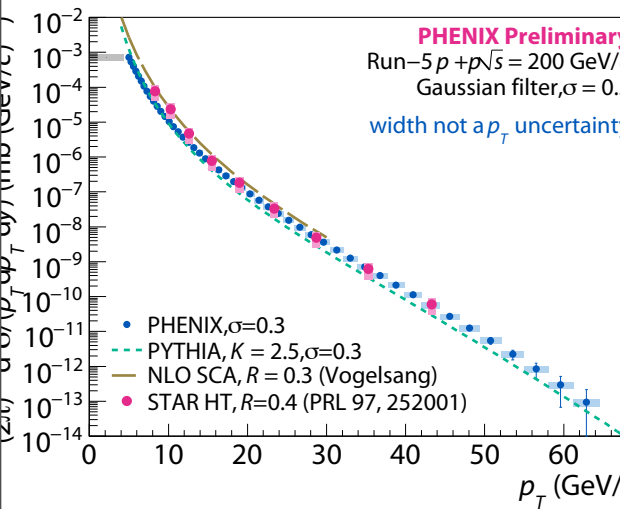
STAR : PRL 97 (2006) 252001
PHENIX: Y.Lai QM2009

T. Kluge,
K.Rabbertz, M.Wobish

STAR : PLB 637 (2006) 161
S. Albino et al, NPB 725 (2005) 181

- Jet cross-section in p-p is well described by NLO pQCD calculations over 7 orders of magnitude.
- Excellent description when included in world data
- Minimum bias particle production in p-p also well modeled.

Jets at RHIC – a calibrated probe?
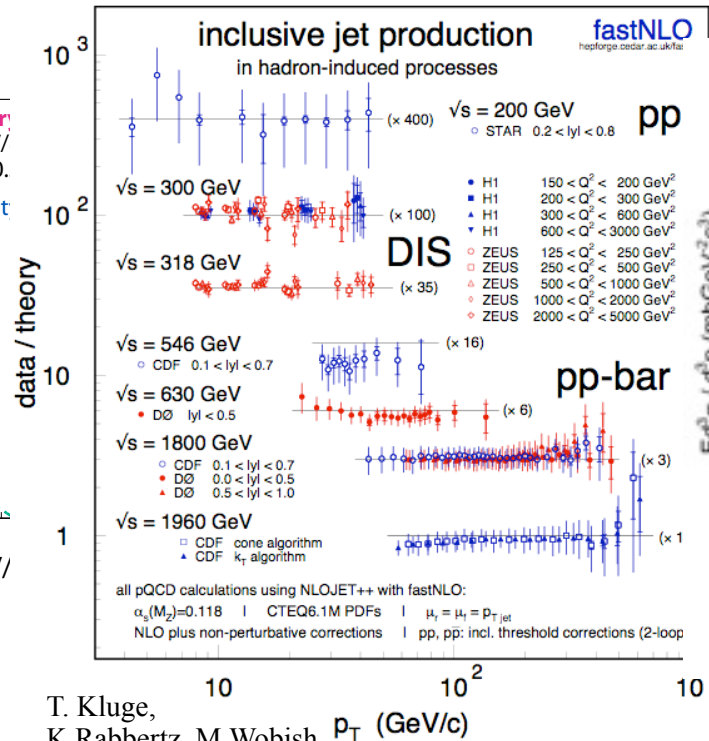
STAR : PRL 97 (2006) 252001
PHENIX: Y.Lai QM2009

T. Kluge,
K.Rabbertz, M.Wobish
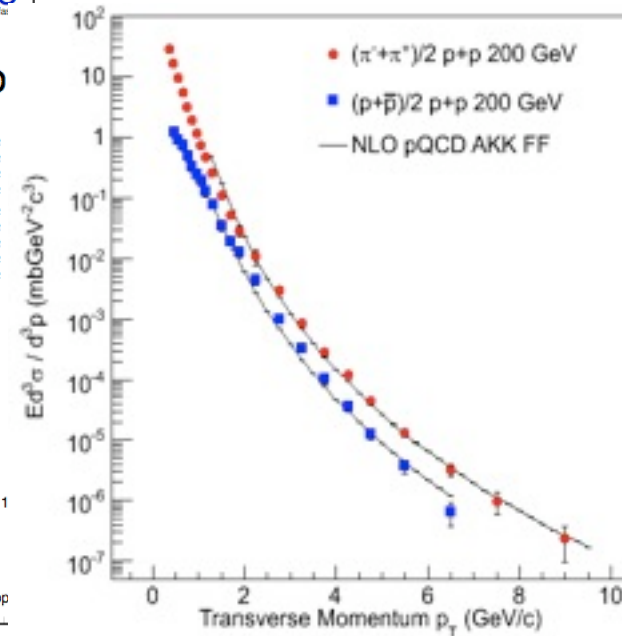
STAR : PLB 637 (2006) 161
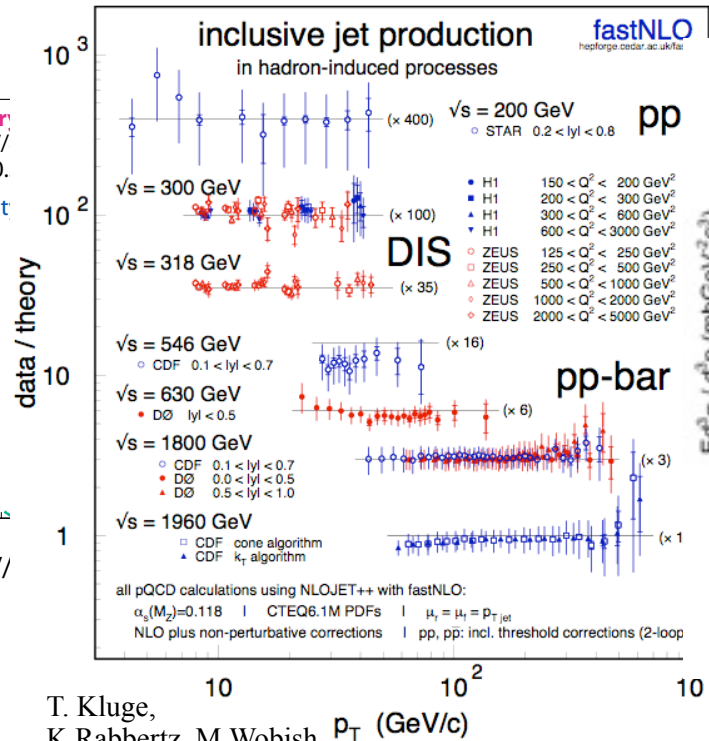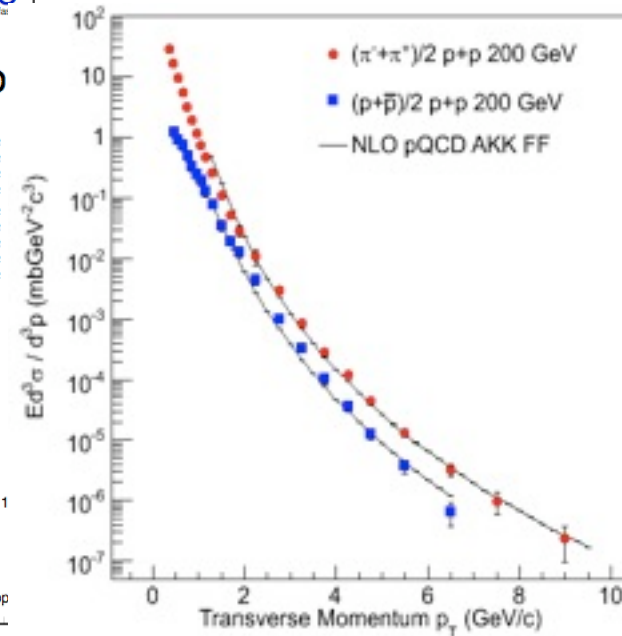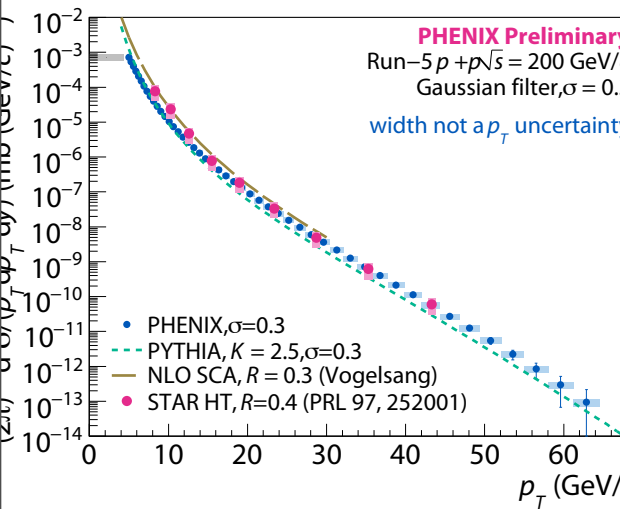S. Albino et al, NPB 725 (2005) 181

- Jet cross-section in p-p is well described by NLO pQCD calculations over 7 orders of magnitude.
- Excellent description when included in world data
- Minimum bias particle production in p-p also well modeled.

What about fragmentation?

Charged hadrons fragmentation Fns
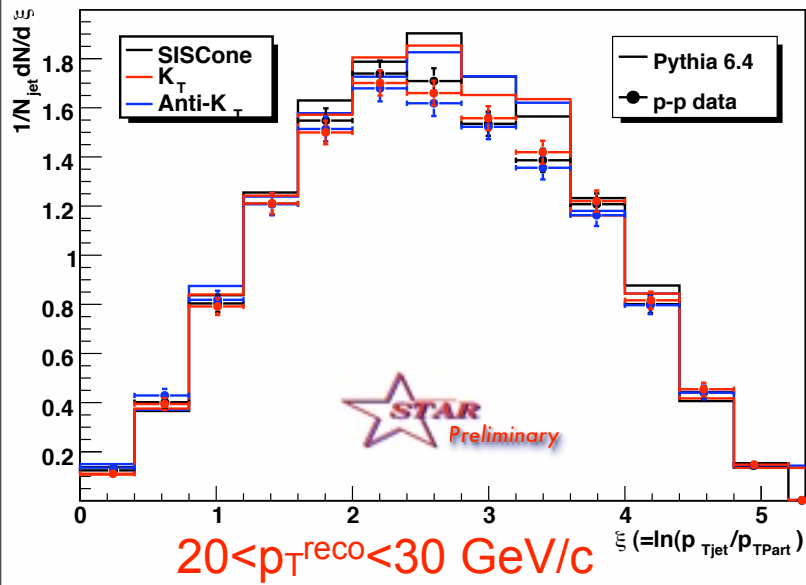
R=0.4

$|\eta_{jet}|<1-R$
$p_{Ttrack}>0.2$ GeV/c

Data not corrected to particle level.

"PYTHIA" = PYTHIA+ GEANT

R=0.7

20<p_T^{reco}<30 GeV/c

30<p_T^{reco}<40 GeV/c
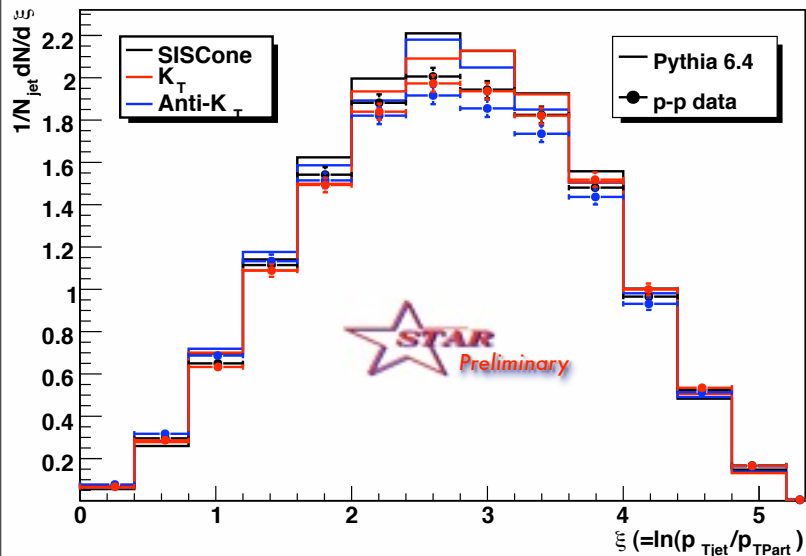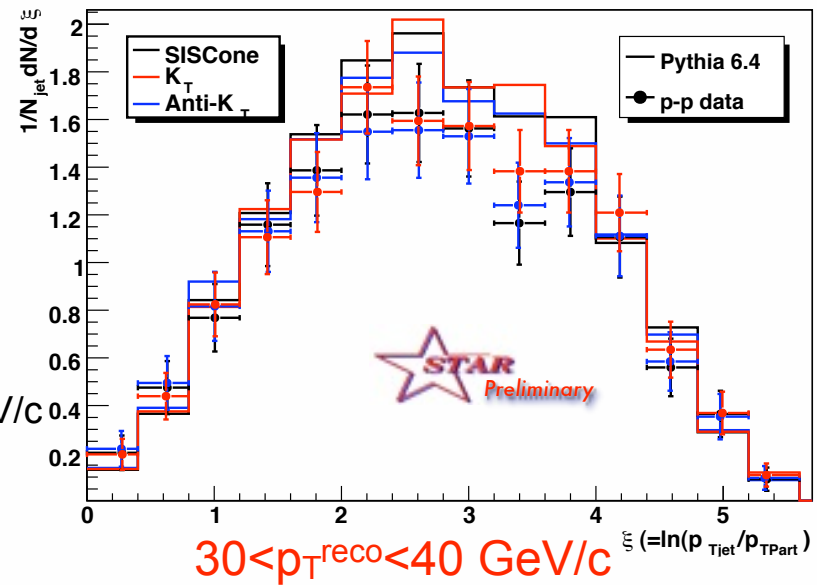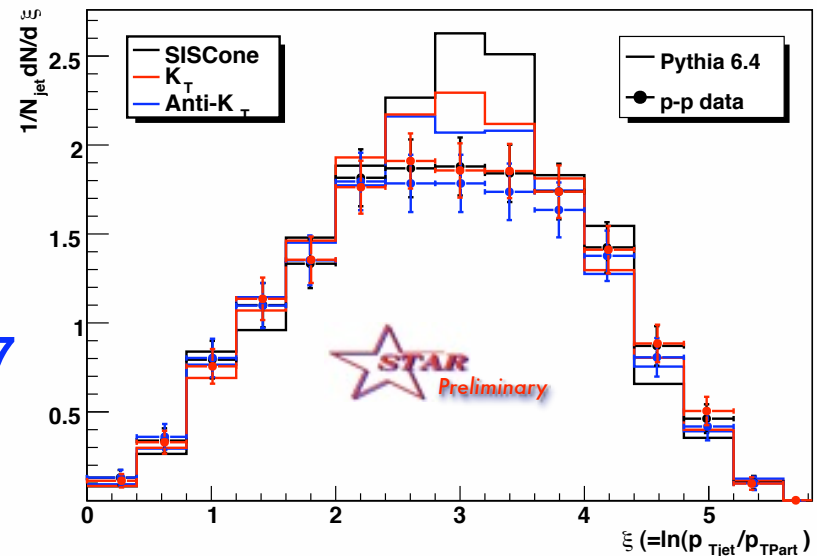
Reasonable agreement between PYTHIA and data

The underlying event in p-p collisions
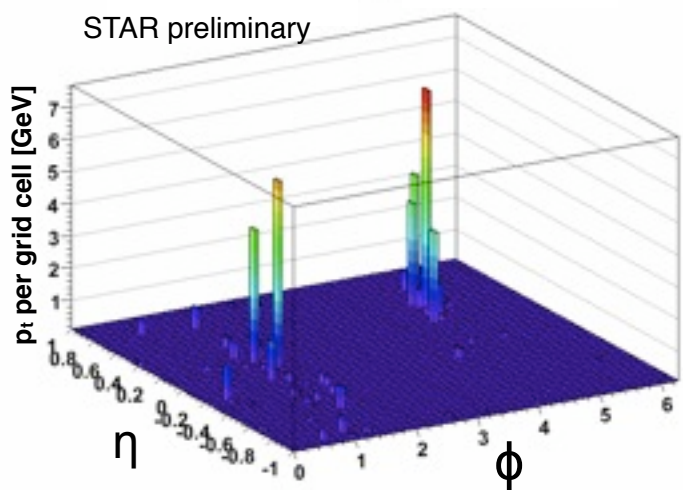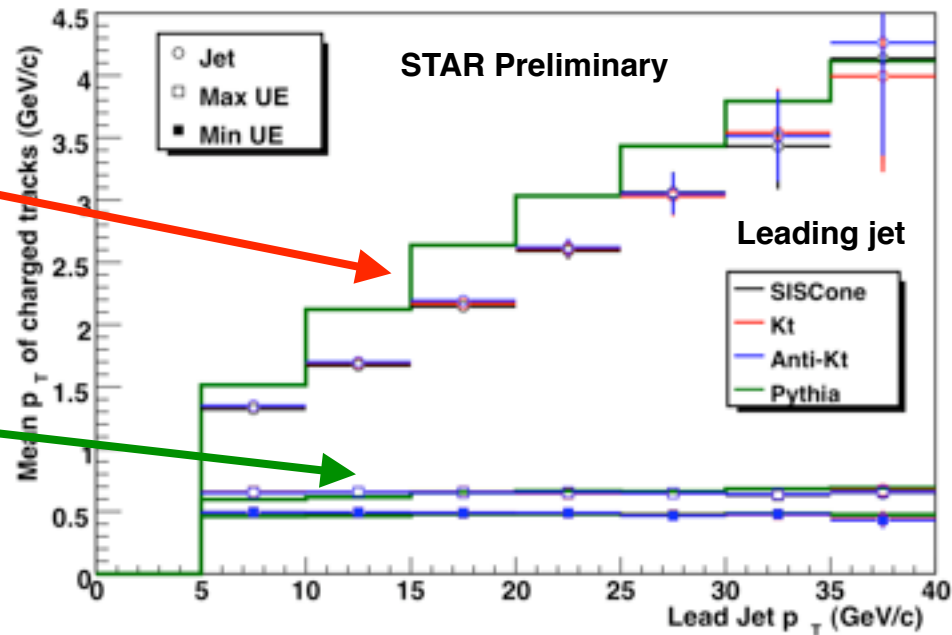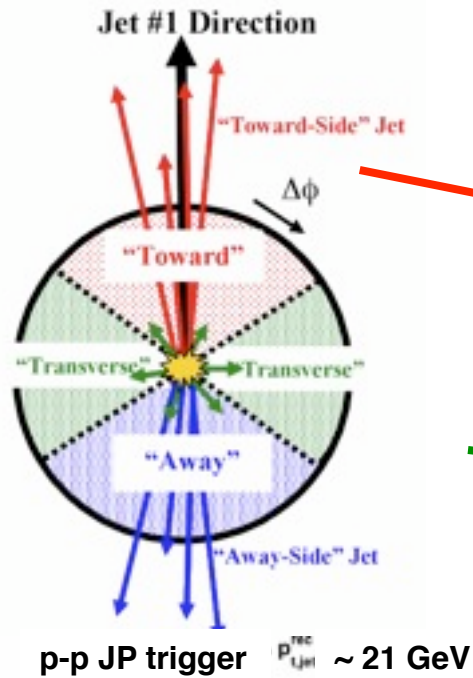

Jet #1 Direction

"Toward-Side" Jet

$\Delta\phi$

"Toward"

"Transverse" "Transverse"

"Away"

"Away-Side" Jet

p-p JP trigger $p_{Ljet}^{rec} \sim 21$ GeV

STAR preliminary

p_t per grid cell [GeV]

η ϕ

STAR Preliminary

○ Jet
□ Max UE
■ Min UE

Leading jet

— SISCone
— Kt
— Anti-Kt
— Pythia

Mean p_T of charged tracks (GeV/c)

Lead Jet p_T (GeV/c)

- RHIC data support smaller UE activity from MPI at LHC than standard "ATLAS" tunes predict. PYTHIA "tune-A" closer to data

The underlying event in p-p collisions
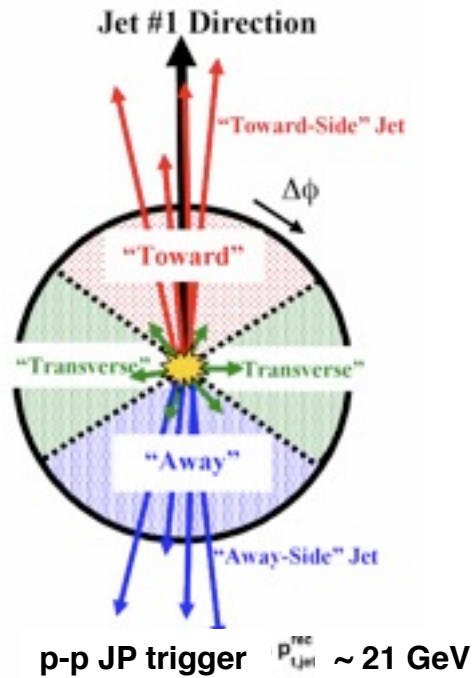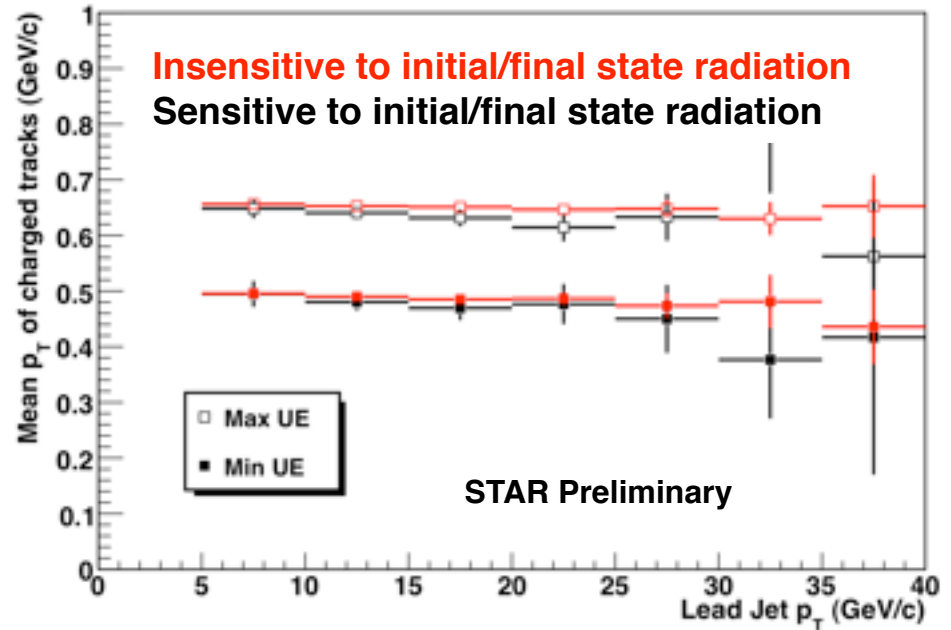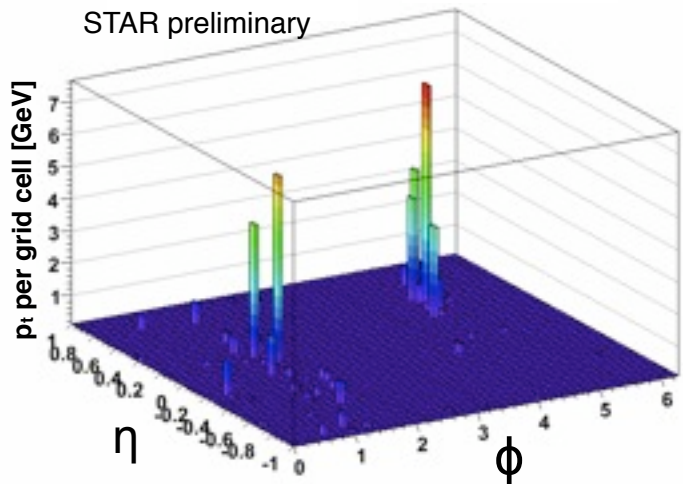
Jet #1 Direction

"Toward-Side" Jet

$\Delta\phi$

"Toward"

"Transverse" "Transverse"

"Away"

"Away-Side" Jet

p-p JP trigger $p_{t,jet}^{rec} \sim 21$ GeV

STAR preliminary

p_t per grid cell [GeV]

η ϕ

Mean p_T of charged tracks (GeV/c)

Insensitive to initial/final state radiation
Sensitive to initial/final state radiation

□ Max UE
■ Min UE

STAR Preliminary

Lead Jet p_T (GeV/c)

- RHIC data support smaller UE activity from MPI at LHC than standard "ATLAS" tunes predict. PYTHIA "tune-A" closer to data

Very little initial/final state radiation at large angles at RHIC energies

Cold nuclear matter effects on k_T

Before looking at scattering effects in Au-Au we want to again investigate what happens in d-Au (where we expect no QGP).

Already showed that the away-side di-hadron correlation is not suppressed.

- Intrinsic k_T - scattering of parton in matter before fragmentation

- Results in non back-to-back jets even in $\Delta\phi$

- $k_{T,raw} = p_{T1}*\sin(\Delta\phi)$

Trigger Jet

k_T

Recoil Jet

Cold nuclear matter effects on k_T

Before looking at scattering effects in Au-Au we want to again investigate what happens in d-Au (where we expect no QGP).

Already showed that the away-side di-hadron correlation is not suppressed.

- Intrinsic k_T - scattering of parton in matter before fragmentation

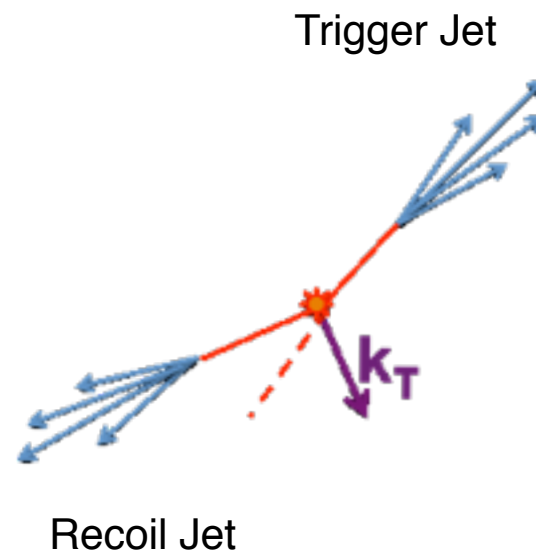- Results in non back-to-back jets even in $\Delta\phi$

- $k_{T,raw} = p_{T1}*\sin(\Delta\phi)$

No significant CNM effects seen

p+p anti-kt   **d+Au** anti-kt

p+p, $p_{T,2}$: 10 - 20 GeV/c
$\sigma_{kT,raw}$ = 2.83 ± 0.05 GeV/c

d+Au, $p_{T,2}$: 10 - 20 GeV/c
$\sigma_{kT,raw}$ = 2.98 ± 0.08 GeV/c

p+p, $p_{T,2}$: 20 - 30 GeV/c
$\sigma_{kT,raw}$ = 2.39 ± 0.21 GeV/c

d+Au, $p_{T,2}$: 20 - 30 GeV/c
$\sigma_{kT,raw}$ = 2.76 ± 0.24 GeV/c

STAR Preliminary
200 GeV

$p_{T,1}*\sin(\Delta\phi)$

Full-jet reconstruction in HI collisions

Underlying event background a significant challenge - magnitude and fluctuations

Tools have been developed (i.e. FastJet package) and methods (unfolding) to correct via data driven approach

Need to avoid (as far as possible) reliance on theory

Full-jet reconstruction in HI collisions

p+p JP trigger $p_{t,jet}^{rec}$ ~ 21 GeV

Au+Au 0-20% $p_{t,jet}^{rec}$ ~ 21 GeV

STAR preliminary
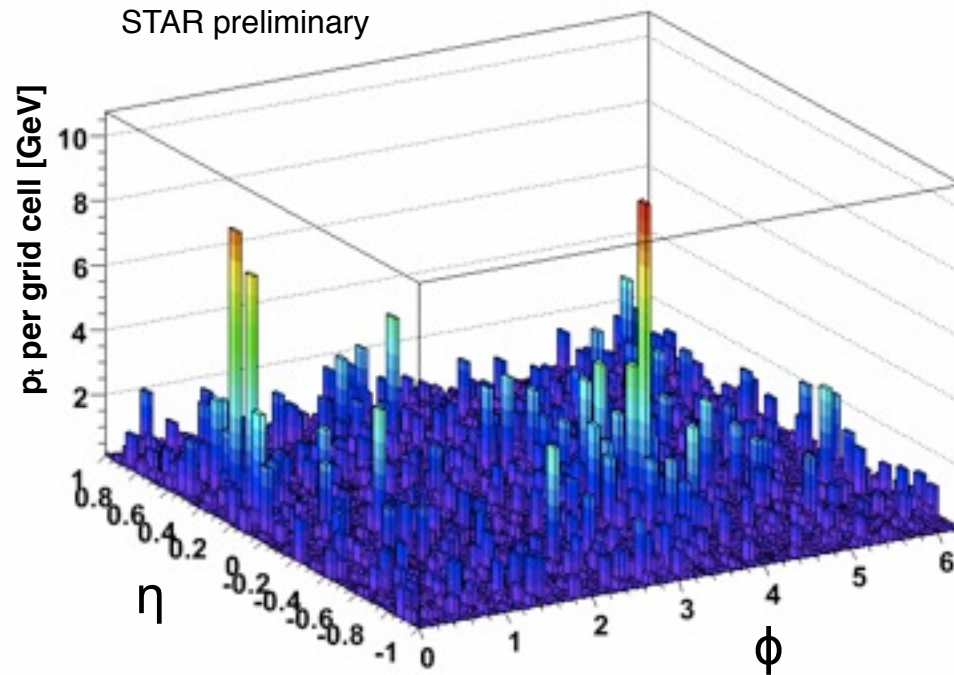
STAR preliminary

Underlying event background a significant challenge - magnitude and fluctuations

Tools have been developed (i.e. FastJet package) and methods (unfolding) to correct via data driven approach

Need to avoid (as far as possible) reliance on theory
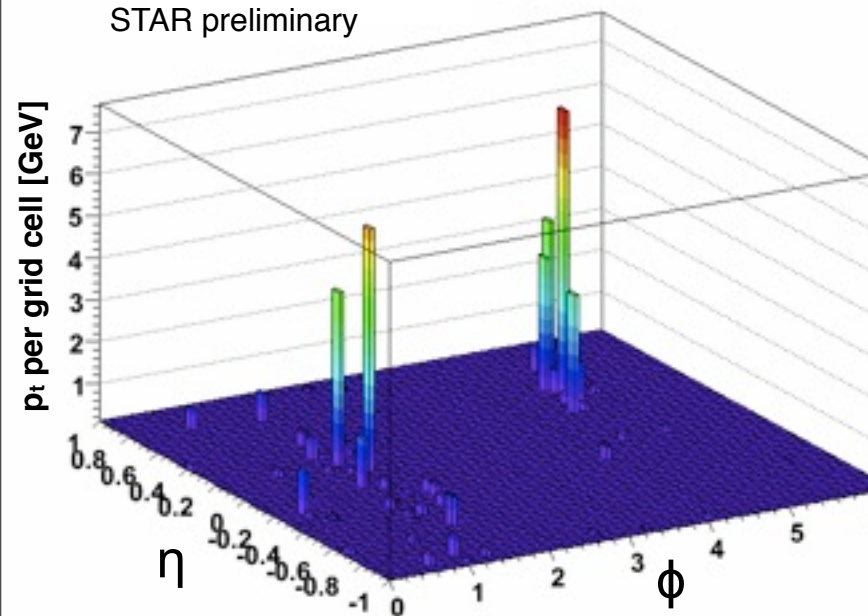
Background - central Au-Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + ρ A ± σ √A

ρ - background energy per unit area
A - jet area

E_{bg} ~ 45 GeV for R_C=0.4
(S/B ~0.5 for 20 GeV jet)

Background - central Au-Au collisions

Event-by-event basis:

p_T (Jet Measured) ~ p_T (Jet) + $\rho A \pm \sigma \sqrt{A}$

ρ - background energy per unit area
A - jet area

E_{bg}~ 45 GeV for R_C=0.4
(S/B ~0.5 for 20 GeV jet)
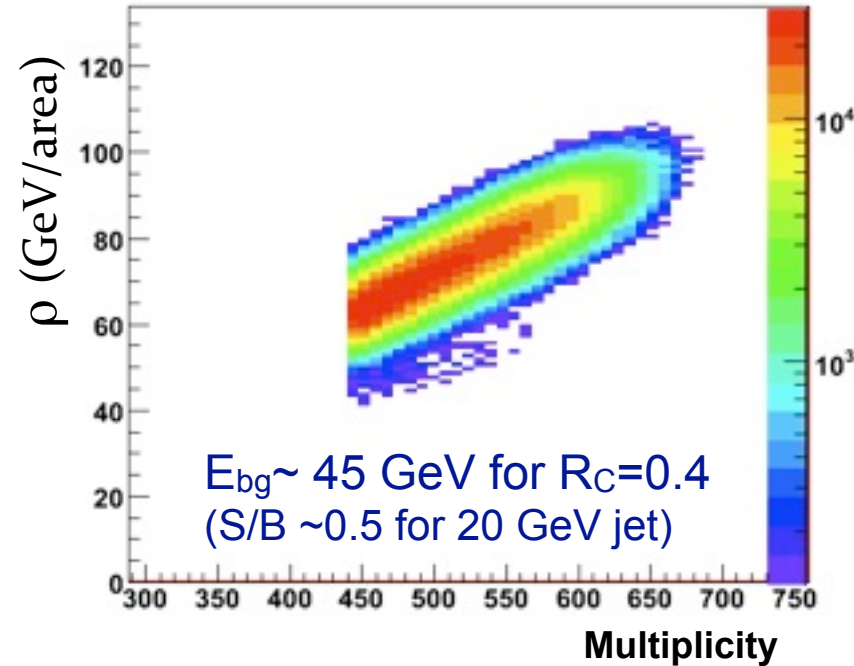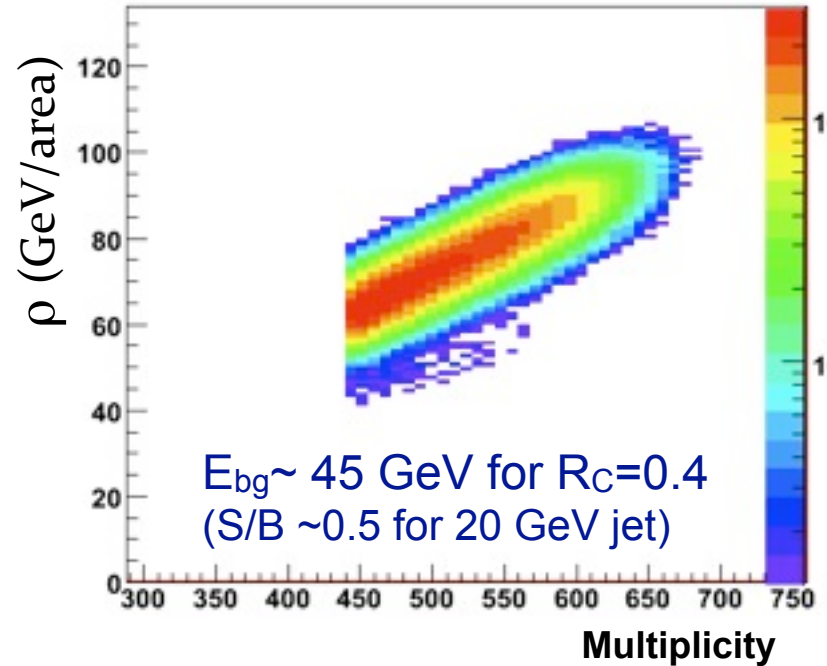
Substantial region-to-region
background fluctuations

σ - comparable magnitude from
FastJet and naïve random cones

**Both reduced significantly
by increasing p_T^{cut}**
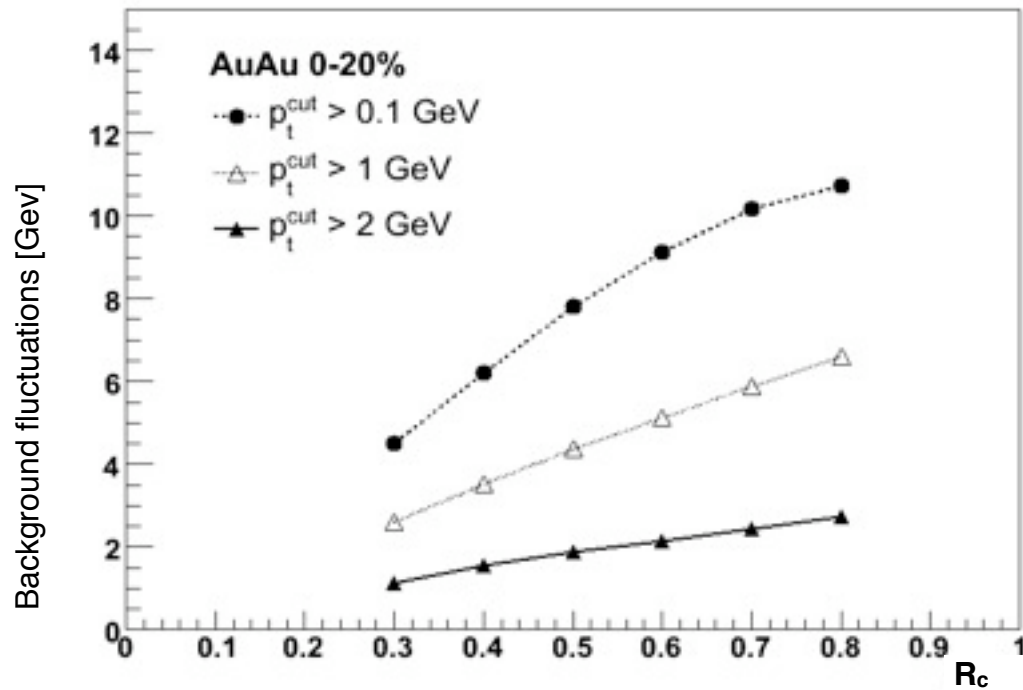
What's expected from Au-Au jet spectrum

p and E MUST be conserved even with quenched jets

- Study nuclear modification factor (R_{AA}) of jets

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

Average number of p-p collision in A-A collision

- If jet reconstruction complete and unbiased $R_{AA}==1$

What's expected from Au-Au jet spectrum

p and E **MUST** be conserved even with quenched jets

- Study nuclear modification factor (R_{AA}) of jets

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

Average number of p-p collision in A-A collision

- If jet reconstruction complete and unbiased $R_{AA}==1$

- If some jets absorbed and/or not all energy recovered $R_{AA}<1$
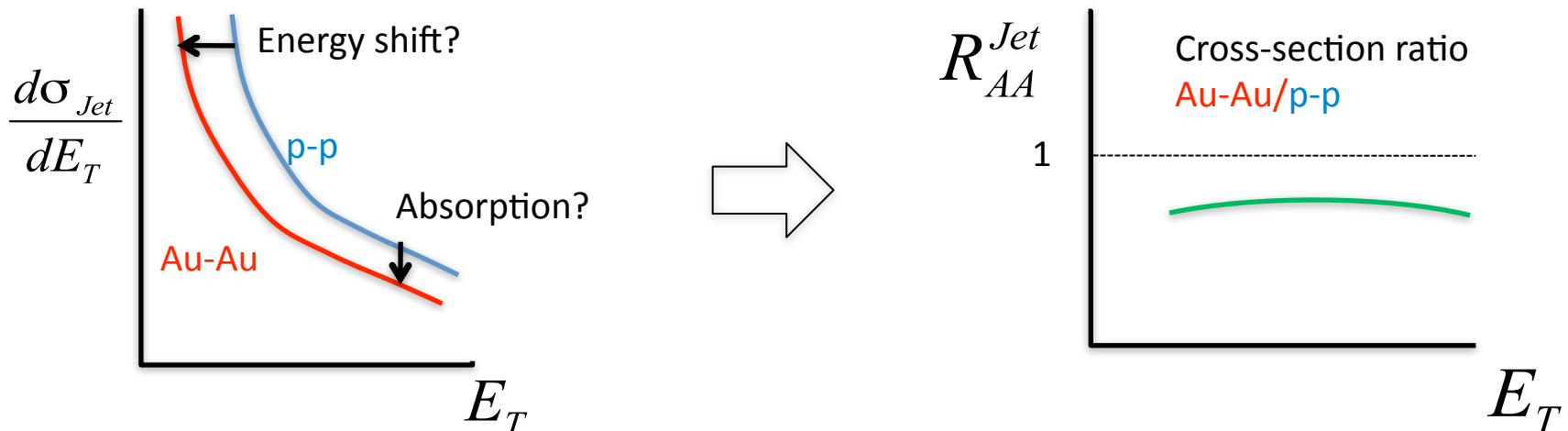
Inclusive jet x-section in Au-Au and Cu-Cu

Au-Au collisions 0-10%

M.Ploskon QM2009

Y. Lai QM2009
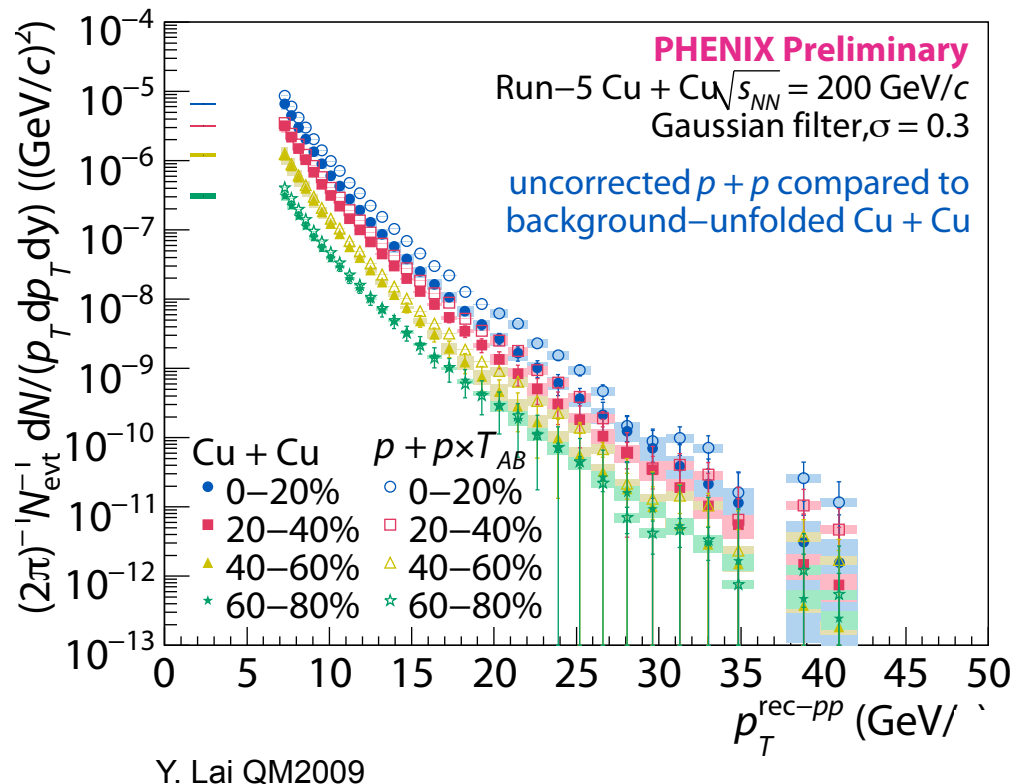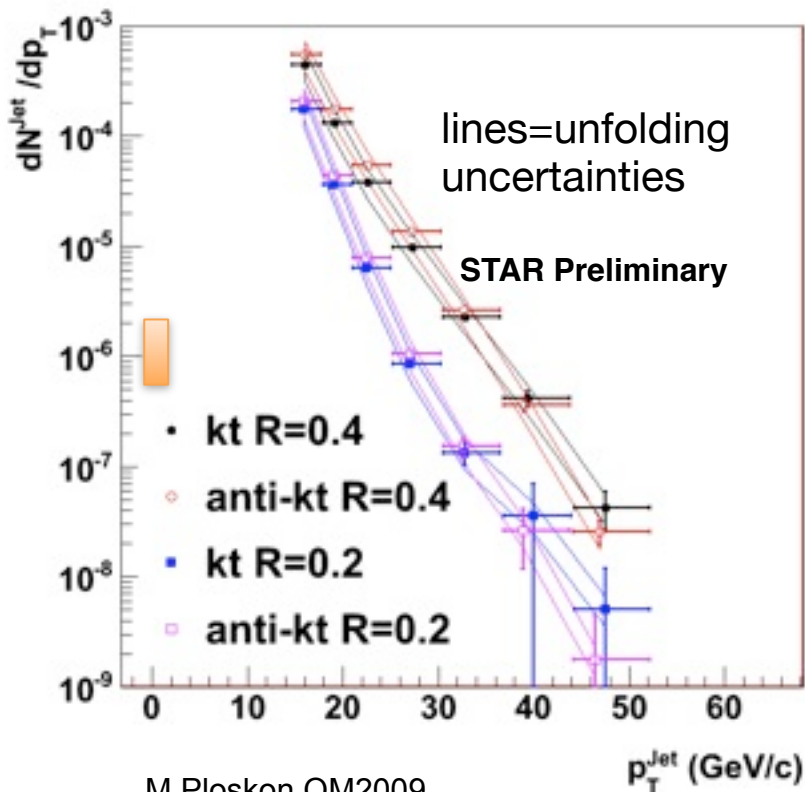
Inclusive jet spectrum measured in A-A collisions for first time

Extends reach of jet quenching studies to p_T > 40 GeV

Jet R_{AA} in Cu-Cu using Gaussian Filter
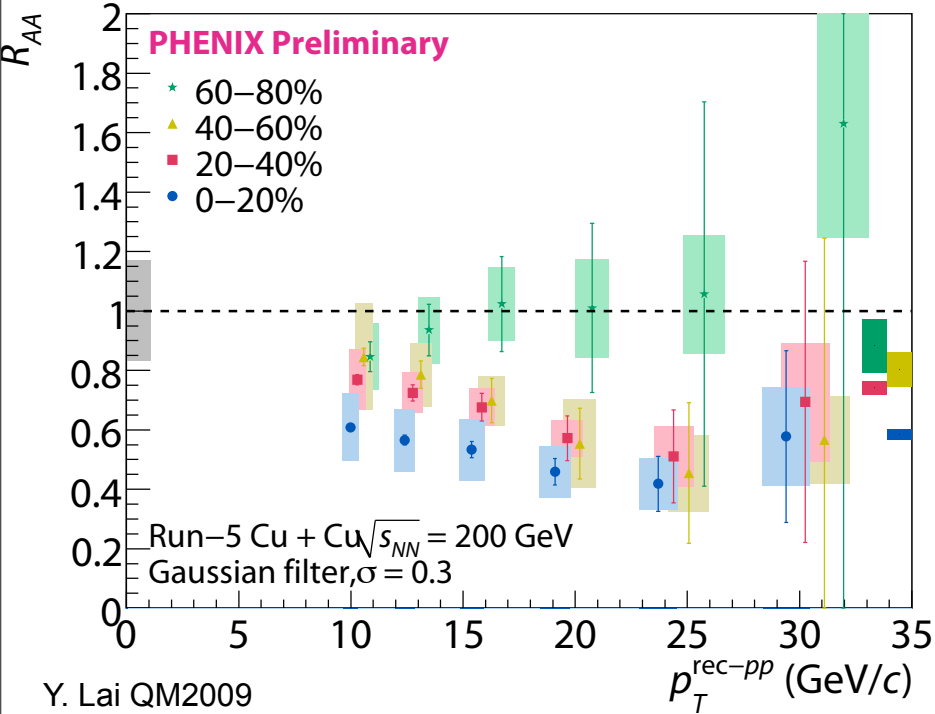
Y. Lai QM2009

Gaussian Filter: designed to find vacuum like fragmentation

- Reconstructed jets highly suppressed in central collisions

Jet R_{AA} in Cu-Cu using Gaussian Filter
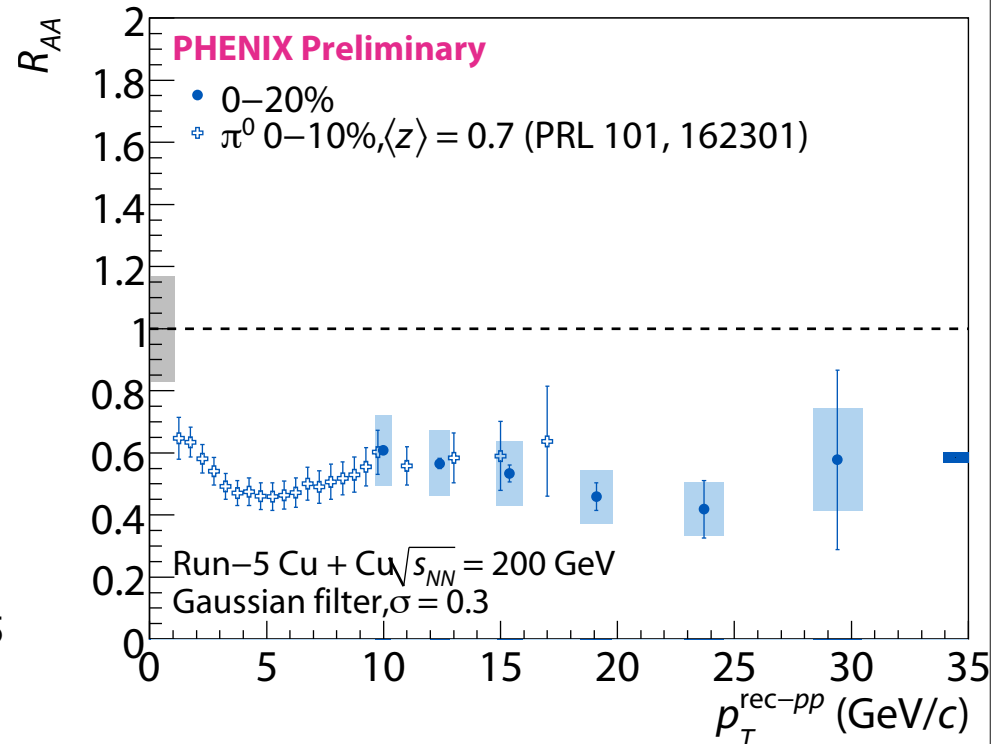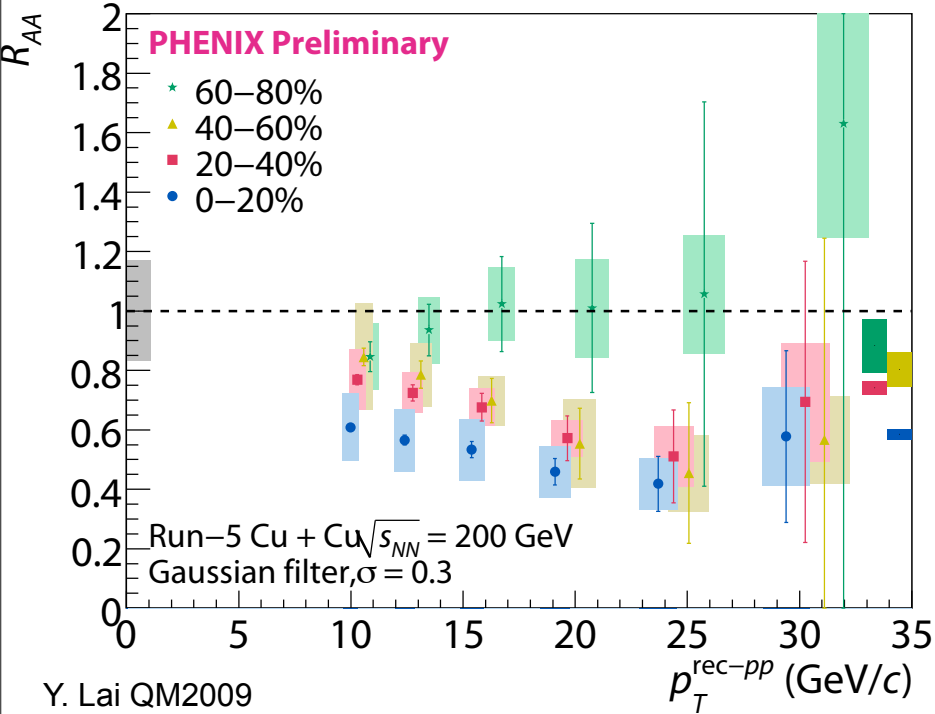
Y. Lai QM2009

Gaussian Filter: designed to find vacuum like fragmentation

- Reconstructed jets highly suppressed in central collisions

- Jets as suppressed as single particles

Jet R$_{AA}$ in Cu-Cu using Gaussian Filter
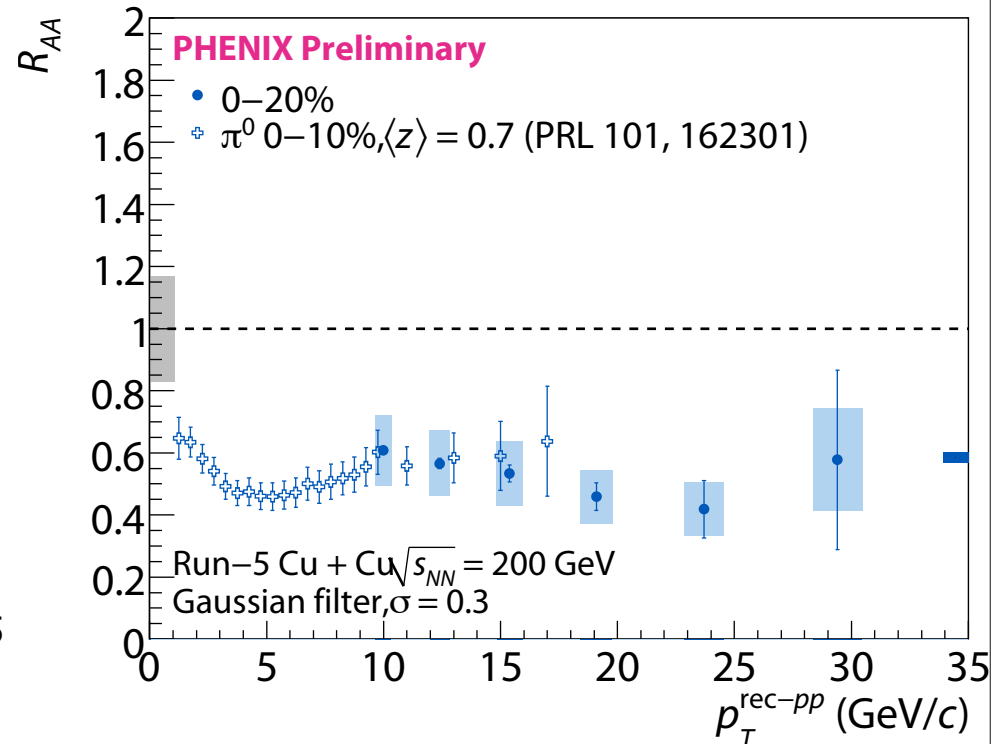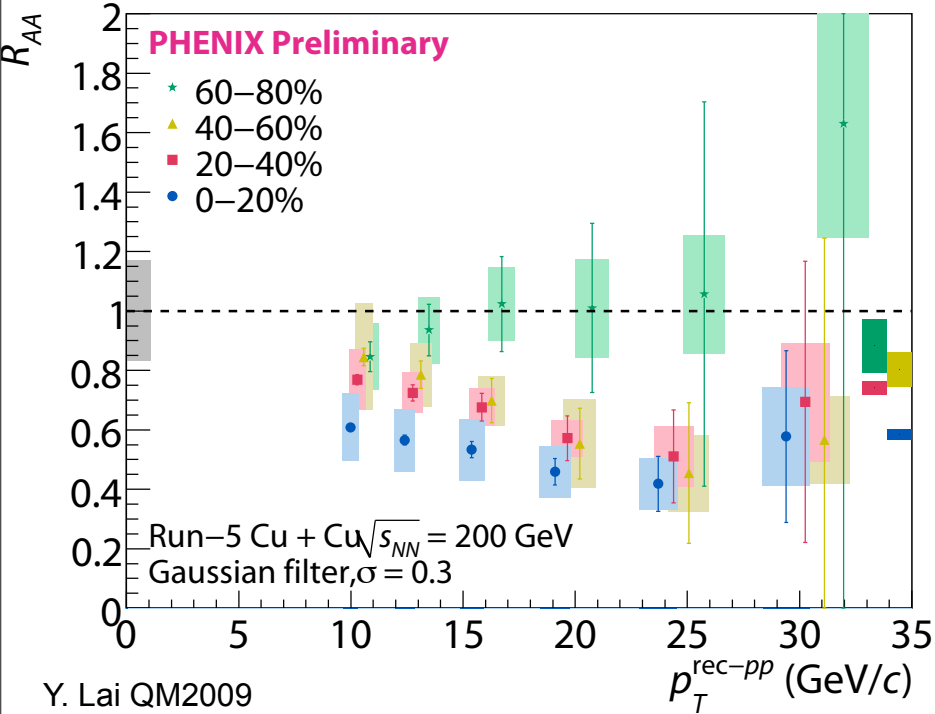
Y. Lai QM2009

Gaussian Filter: designed to find vacuum like fragmentation

- Reconstructed jets highly suppressed in central collisions

- Jets as suppressed as single particles

Energy shift or jet not reconstructed?

Look at the jet energy profile

M. Ploskon QM2009
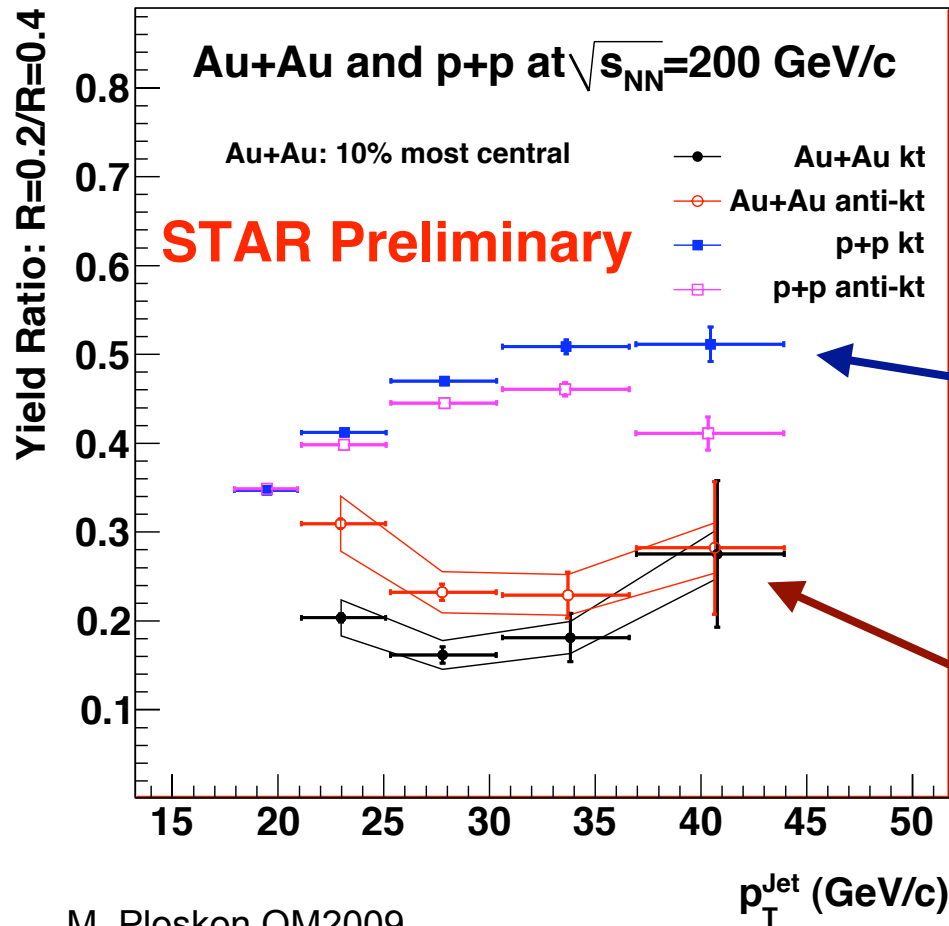
p-p:
"Focussing" of jet fragmentation with increasing jet energy

Au-Au:
"Broadening" of jet fragmentation with increasing jet energy

De-focussing of energy profile when jet passes through sQGP

Jet-hadron correlations Au-Au vs. p-p
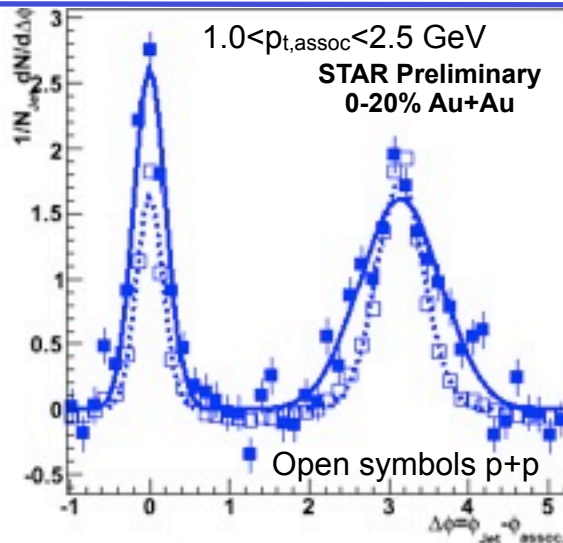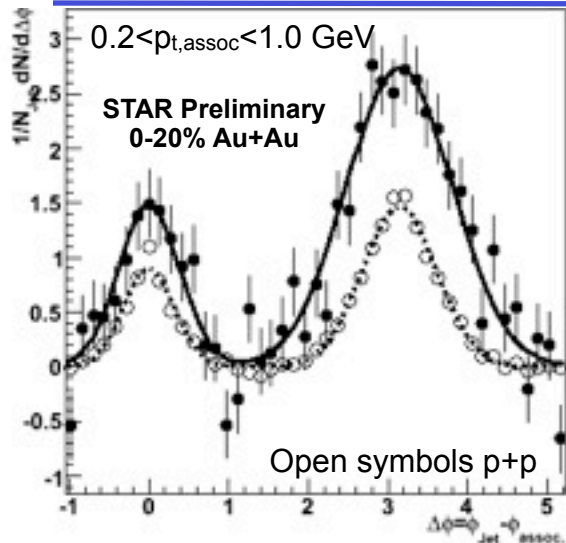
$0.2 < p_{t,assoc} < 1.0$ GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

$1.0 < p_{t,assoc} < 2.5$ GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

High Tower Trigger (HT):
tower 0.05x0.05 (ηxϕ)
with $E_t > 5.4$ GeV

$\Delta\phi = \phi_{Jet} - \phi_{Assoc.}$

ϕ_{Jet} = jet-axis found by Anti-k_T, R=0.4, $p_{t,cut} > 2$ GeV and $p_{t,rec}$(jet)>20 GeV

J.Putschke RHIC/AGS 2009

$p_{t,assoc} > 2.5$ GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

$\Delta\phi_1$

Trigger jet

$\Delta\phi_2$

Recoil jet

Jet-hadron correlations Au-Au vs. p-p

0.2<$p_{t,assoc}$<1.0 GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

J.Putschke RHIC/AGS 2009

1.0<$p_{t,assoc}$<2.5 GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

$p_{t,assoc}$>2.5 GeV

STAR Preliminary
0-20% Au+Au

Open symbols p+p

High Tower Trigger (HT):
tower 0.05x0.05 (ηxφ)
with E_t> 5.4 GeV

$\Delta\phi=\phi_{Jet} - \phi_{Assoc.}$
ϕ_{Jet} = jet-axis found
by Anti-k_T, R=0.4,
$p_{t,cut}$>2 GeV and
$p_{t,rec}$(jet)>20 GeV

- Broadening of recoil-side

- Softening of recoil-side

First direct measurement of Modified Fragmentation due to presence of sQGP

Summary of Jet Studies

- p-p jet reference measurements are well understood - we have a calibrated probe

- The UE at RHIC is small and suggests MPI at LHC will be smaller than initially predicted

- Cold nuclear matter effects on jets are small (d-Au compared to p-p)

- The large background under jets in A-A can be accounted for
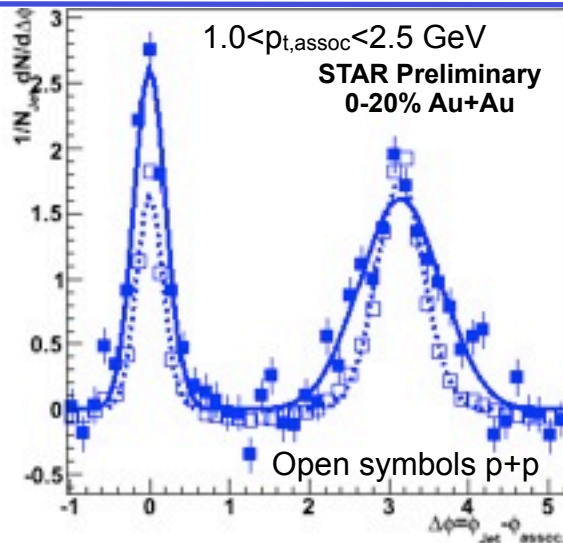
- Jets reconstructed in A-A assuming vacuum frag. show same suppression as for single hadrons (Gaussian filter studies)

- Strong evidence of broadening and softening of the jet energy profile (R=0.2/R=0.4, jet-hadron)

Results can be explained as due to significant partonic energy loss in the sQGP before fragmentation

Local Strong Parity Violation

In QCD, chiral symmetry breaking is fundamental and due to nontrivial topological solutions; among the best evidence for this physics would be *event-by-event local strong parity violation*

• Topological charge density illustration of QCD vacuum structure of gluon-field configurations in 4-D (movie available) from lattice-based simulations

Box volume = 2.4 X 2.4 X 3.6 fm^3.
Animation/Picture by *Derek Leinweber*

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

Energy of gluon field

N_{CS} =   -2   -1   0   1   2
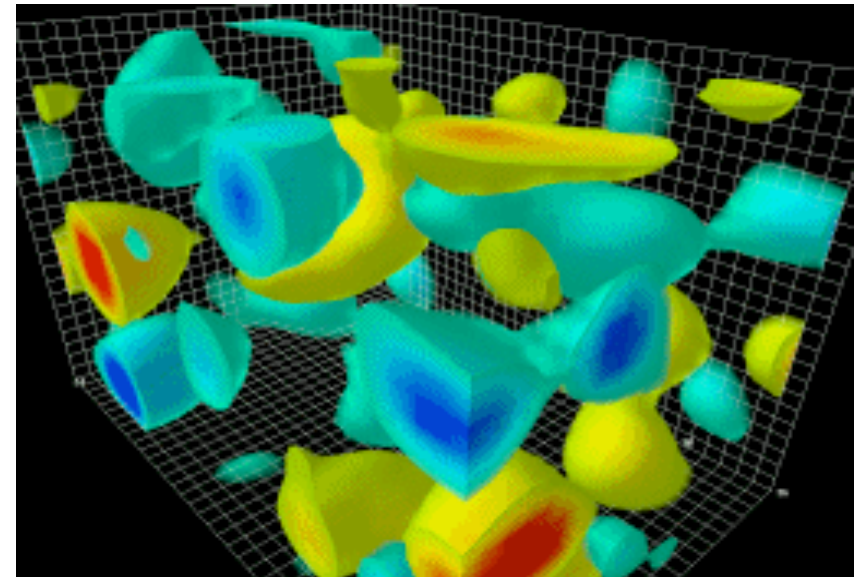
instanton

sphaleron

Local Strong Parity Violation

In QCD, chiral symmetry breaking is fundamental and due to nontrivial topological solutions; among the best evidence for this physics would be *event-by-event local strong parity violation*

● Topological charge density illustration of QCD vacuum structure of gluon-field configurations in 4-D (movie available) from lattice-based simulations
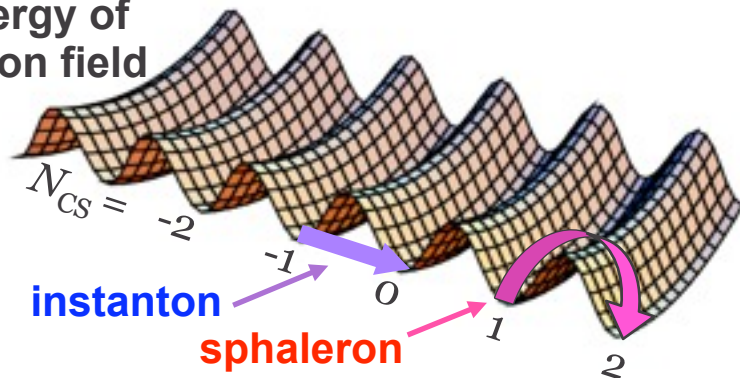
Box volume = 2.4 X 2.4 X 3.6 fm^3.
Animation/Picture by *Derek Leinweber*

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

Energy of gluon field

N_{CS} = -2   -1   0   1   2

instanton

sphaleron

All non-Abelian gauge theories admit such non-trivial vacuum fluctuations – e.g., B- and CP-violating sphalerons frozen in at EW phase transition are (one) speculated origin of Baryon Asymmetry of the Universe!

LSPV and sQGP

Usually this effect is confined within a nucleon and averages to zero over space and time

Heavy-Ion collision: deconfined partons over large volume + chiral symmetry restoration

Attempt to see this effect at RHIC in non-central collisions:

L or *B*

LSPV and sQGP

Usually this effect is confined within a nucleon and averages to zero over space and time

Heavy-Ion collision: deconfined partons over large volume + chiral symmetry restoration

Attempt to see this effect at RHIC in non-central collisions:

L or *B*

large orbital angular momentum perp. to RP + large localized B fields
+ deconfined phase
⇒ strong P violating domains with diff. no. of left & right handed quarks

Kharzeev et al. PRL 81 (1998) 512, and PRD 61 (2000) 111901
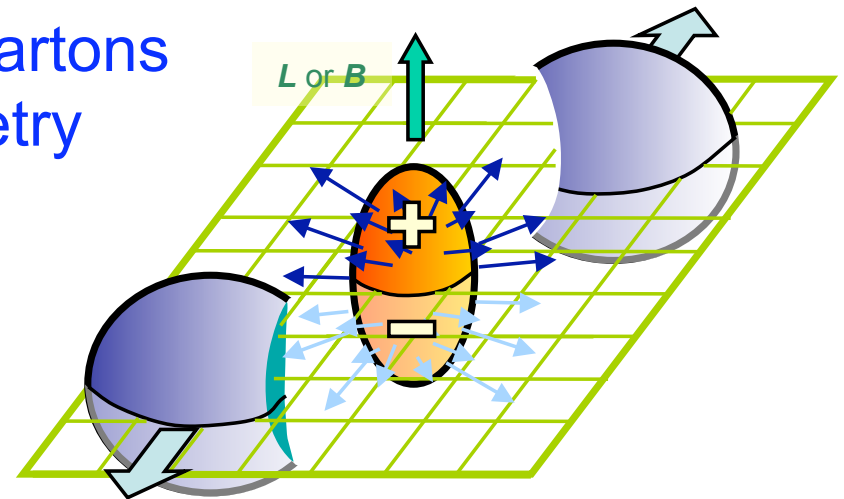
LSPV and sQGP

Usually this effect is confined within a nucleon and averages to zero over space and time

Heavy-Ion collision: deconfined partons over large volume + chiral symmetry restoration

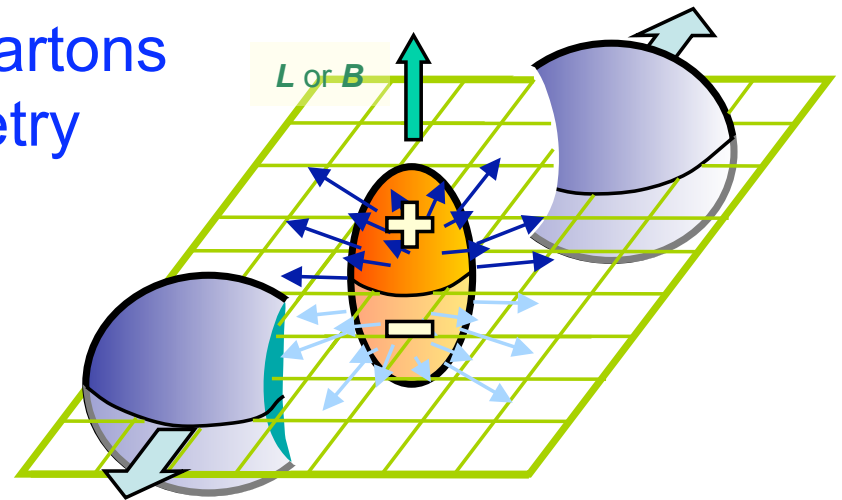Attempt to see this effect at RHIC in non-central collisions:
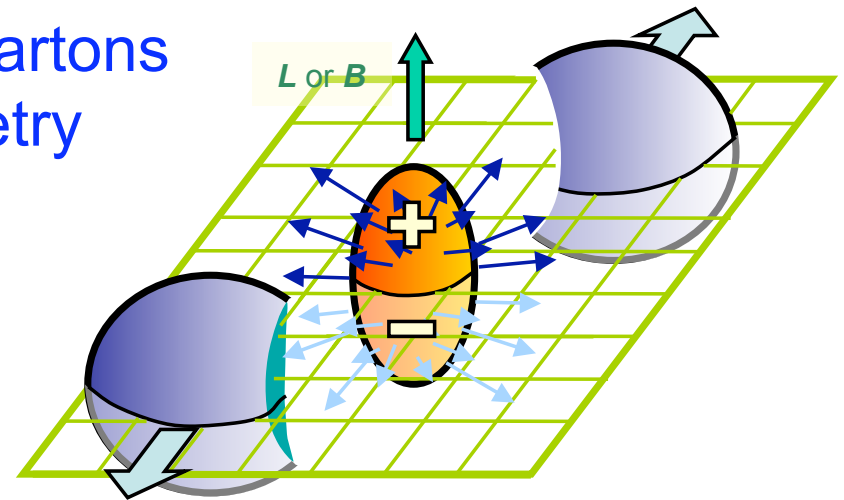
large orbital angular momentum perp. to RP + large localized B fields
+ deconfined phase

⇒ strong P violating domains with diff. no. of left & right handed quarks

Kharzeev et al. PRL 81 (1998) 512, and PRD 61 (2000) 111901

⇒ Preferential emission of like sign particles in the direction of the

angular momentum i.e. opposite sides of the reaction plane

(Voloshin PRC 70 (2004) 057901)

LSPV - making the measurement

$$\frac{dN_\pm}{d\phi} \sim 1 + 2a_\pm sin(\phi - \Psi_{RP}) + ..$$

the asymmetry

Averages to zero due to random
domains

instead measure

$$\langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx$$
$$(v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$

Doesn't average to zero

LSPV - making the measurement

$$\frac{dN_\pm}{d\phi} \sim 1 + 2a_\pm sin(\phi - \Psi_{RP}) + ..$$

the asymmetry

Averages to zero due to random domains

instead measure

$$\langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx$$
$$(v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$

Doesn't average to zero

- Measurement follows expected trends

STAR AuAu 200 GeV
- same charge, TPC
- opp charge, TPC
- same charge, FTPC
- opp charge, FTPC

S. Voloshin, QM09

STAR Preliminary

Opposite side

Same side

- Excellent statistical significance for Au-Au and Cu-Cu at top RHIC energies

LSPV - making the measurement

$$\frac{dN_\pm}{d\phi} \sim 1 + 2a_\pm sin(\phi - \Psi_{RP}) + ..$$

the asymmetry

Averages to zero due to random domains

instead measure

$$\langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \approx$$
$$(v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$

Doesn't average to zero

- P-even so may contain other effects: several investigated (resonances, jets) none result in observed magnitude and centrality dependence of signal

- Measurement follows expected trends

- Excellent statistical significance for Au-Au and Cu-Cu at top RHIC energies

LSPV - making the measurement

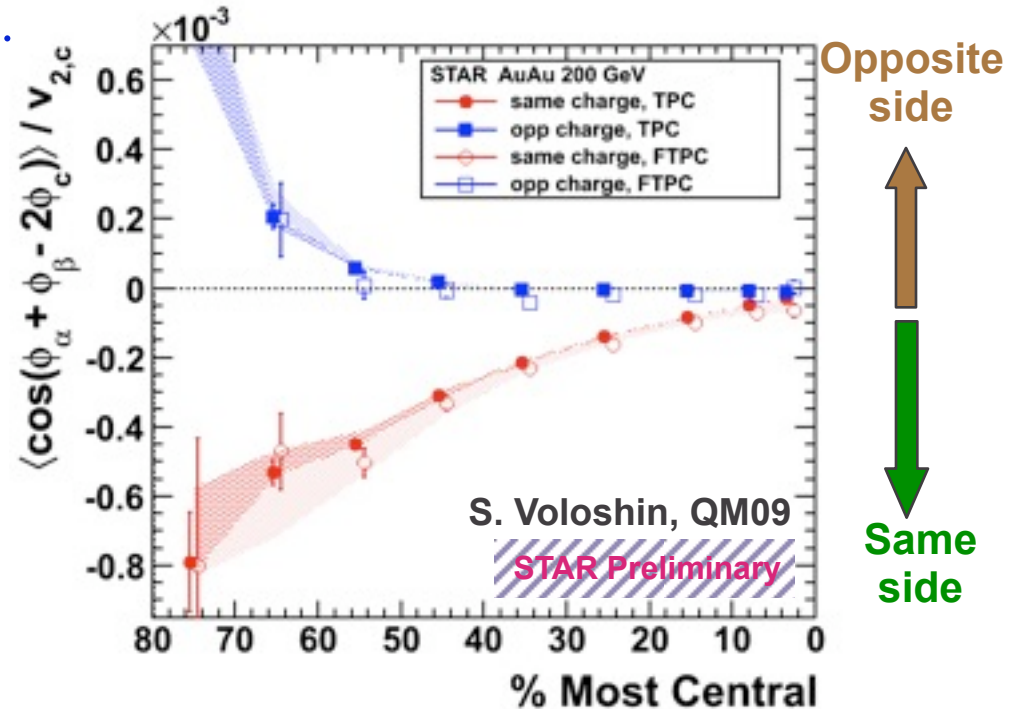$$\frac{dN_\pm}{d\phi} \sim 1 + 2a_\pm sin(\phi - \Psi_{RP}) + ..$$

the asymmetry
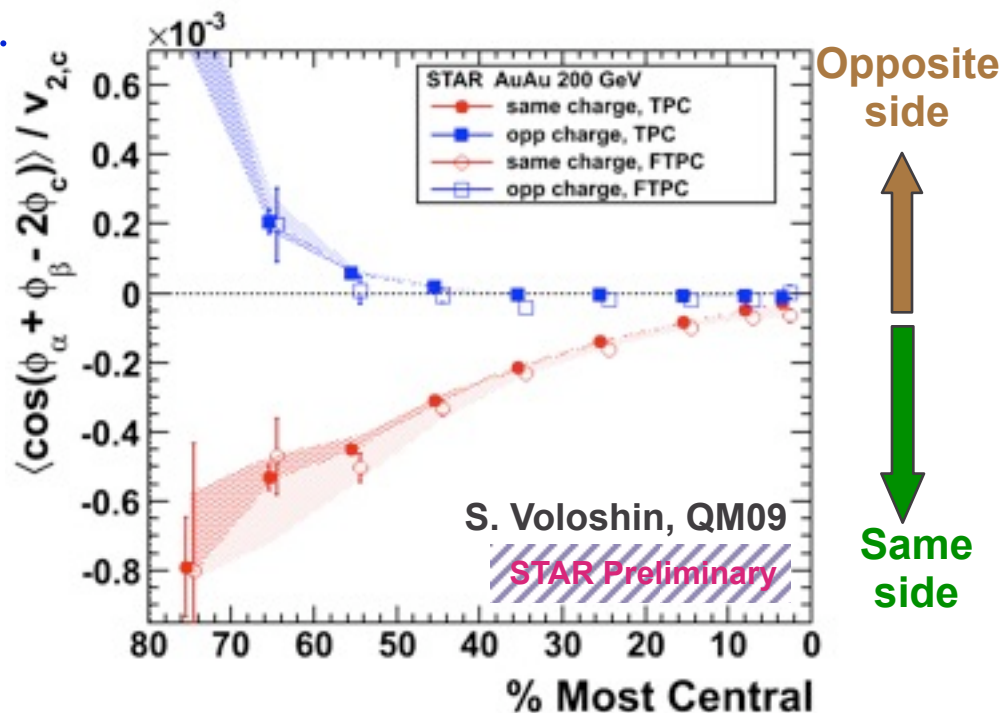
Averages to zero due to random domains

instead measure

$$\langle cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle \approx$$
$$(v_{1,\alpha}, v_{1,\beta} - a_\alpha a_\beta)$$

Doesn't average to zero

- P-even so may contain other effects: several investigated (resonances, jets) none result in observed magnitude and centrality dependence of signal

- Measurement follows expected trends

Opposite side

Same side

S. Voloshin, QM09

STAR Preliminary
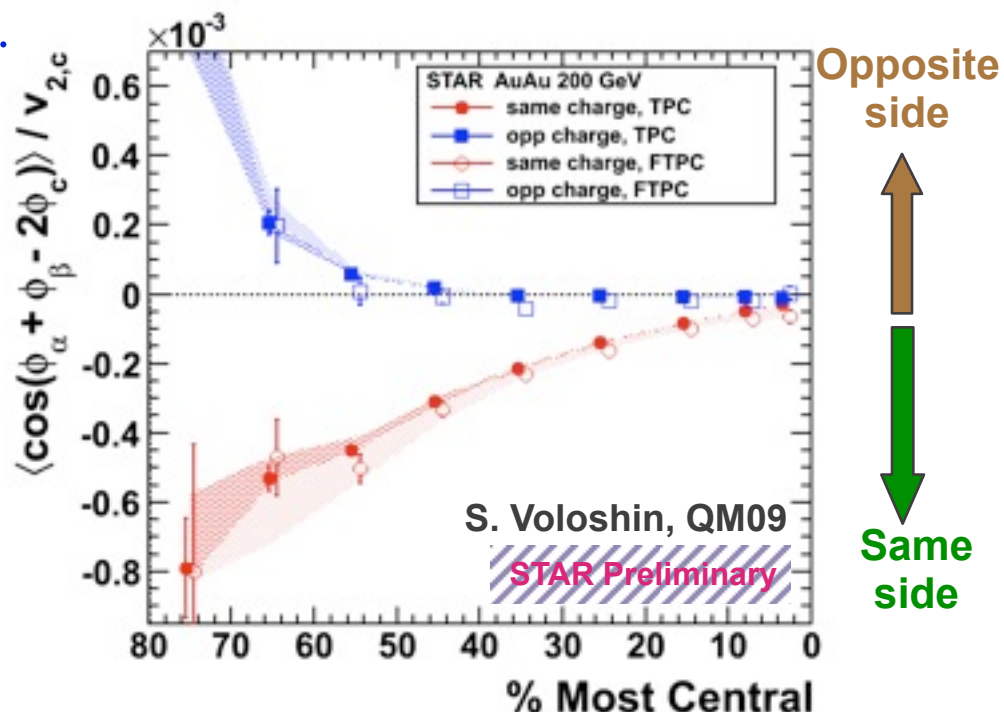
- Excellent statistical significance for Au-Au and Cu-Cu at top RHIC energies

B-field+deconfinement +chiral restoration→ strong threshold effect

What's next - RHIC: Beam Energy Scan
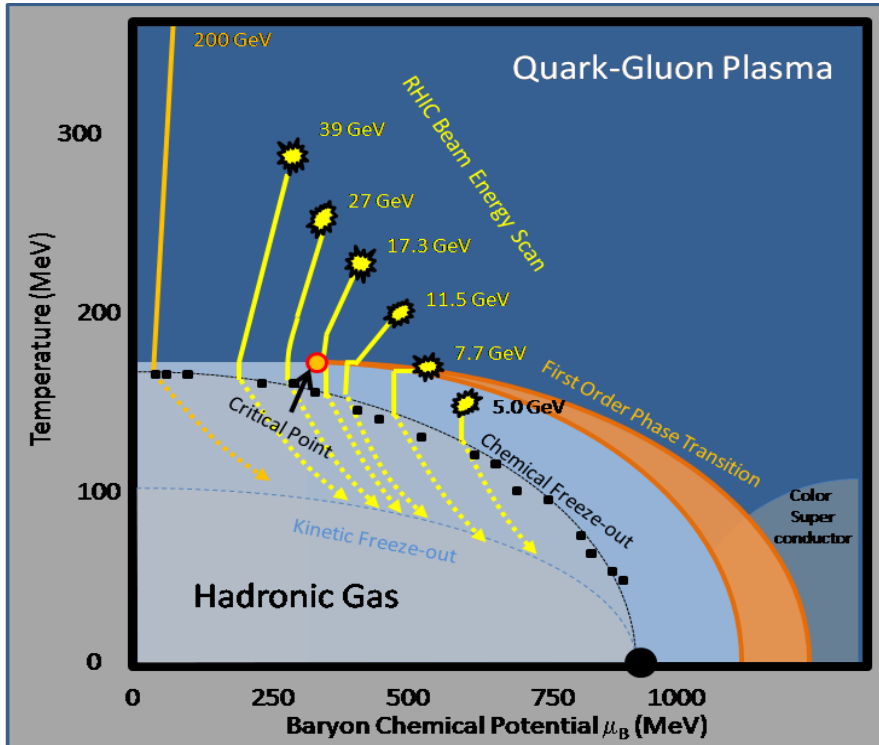
At RHIC we transition to a new state of matter - the sQGP

Lattice QCD predicts:
- High T & Low μ_B
  Cross-over
- High μ_B & Low T -
  1st order transition
- Mid μ_B & Mid T -
  Critical Point

What's next - RHIC: Beam Energy Scan

At RHIC we transition to a new state of matter - the sQGP

Lattice QCD predicts:
- High T & Low μ_B

  Cross-over
- High μ_B & Low T -

  1st order transition
- Mid μ_B & Mid T -

  Critical Point

Location of CP not known - experimental search needed

Scan from √s=5-40 GeV starts 2010
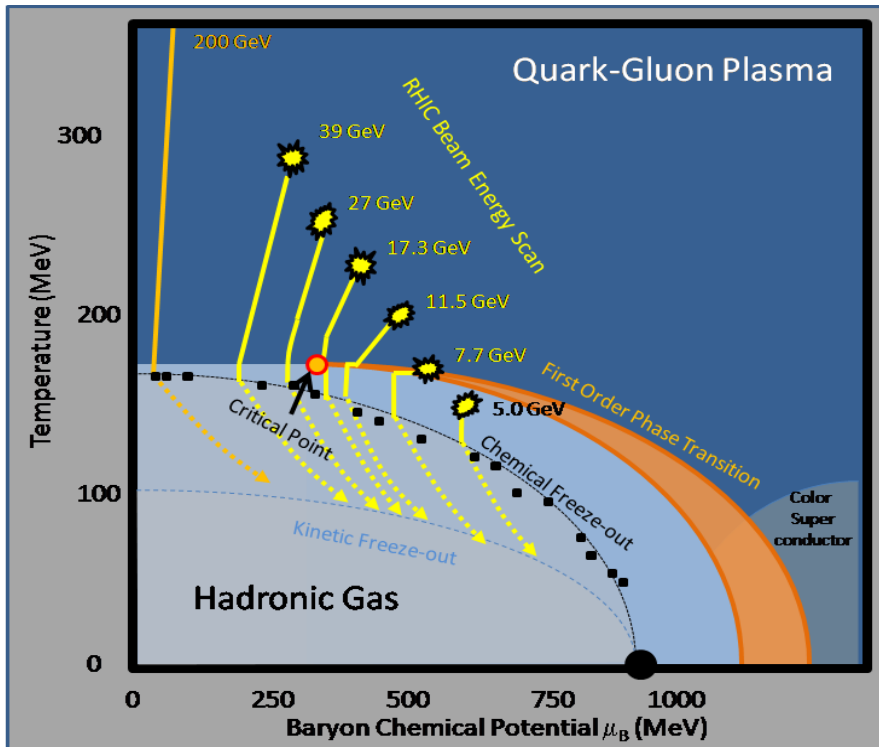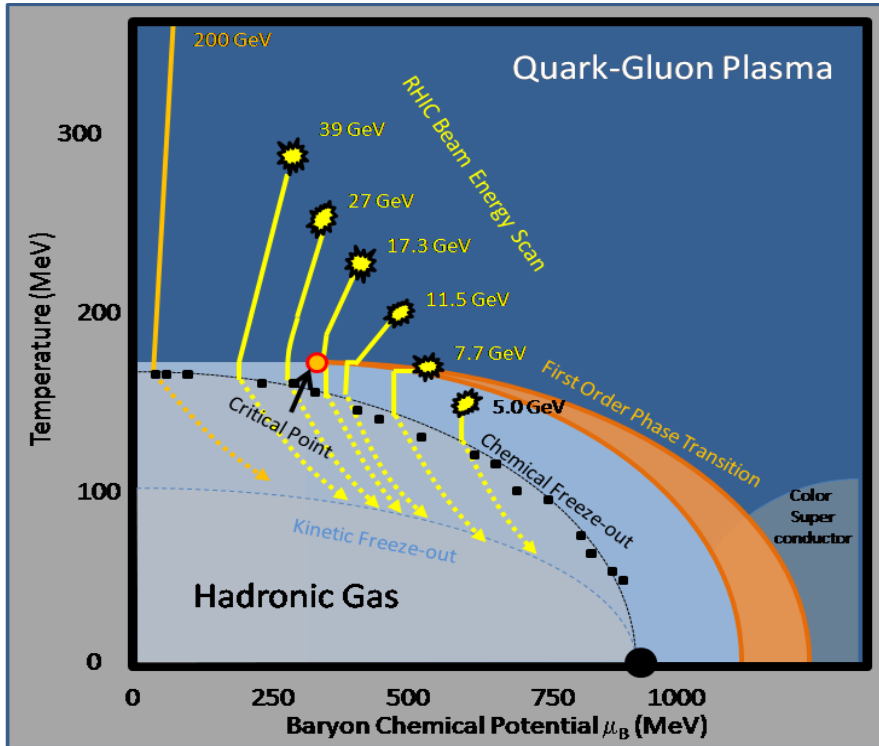(BES also at FAIR and SPS)

What's next - RHIC: Beam Energy Scan

At RHIC we transition to a new state of matter - the sQGP

Lattice QCD predicts:
- High T & Low μ_B

  Cross-over
- High μ_B & Low T -

  1st order transition
- Mid μ_B & Mid T -

  Critical Point

Location of CP not known - experimental search needed

Scan from √s=5-40 GeV starts 2010
(BES also at FAIR and SPS)

Evidence of a critical point and/or 1st order phase transition?

Does LSPV signal persist?

What √s does sQGP "turn off"?

What's next - LHC: The new energy frontier

LHC starting in couple of months. Pb-Pb collisions in 2010
Over an order of magnitude higher energy than at RHIC

Jet and heavy flavour frontiers to be fully explored

ALICE, ATLAS, CMS
All have heavy-ion programs

LQCD, Z. Fodor, Lattice 2007
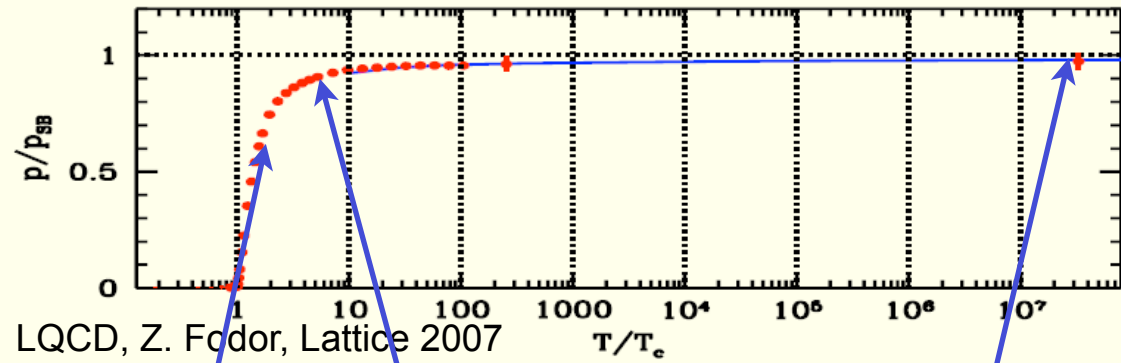
RHIC   LHC   Ideal Gas

sQGP: hotter, bigger, longer lived more detailed measurements

Does matter at LHC still behave as near "perfect" liquid?

Summary

- RHIC and LHC have exciting new programs that start during 2010.

- Many results still to be fully understood and predictions left to test. Key questions being asked:
    - How do partons interact with the sQGP and what are the mechanisms of their energy loss?
    - What are the properties of the medium produced and how do they change at different energies?
    - What/where are the landmarks on the QCD phase diagram?

- Evidence of local strong parity violation - fundamental prediction of QCD
    - continue to test with BES

If you understand everything, you must be misinformed - Japanese Proverb

Geometry of a heavy-ion collision

Non-central collision

Reaction plane

Picture: © UrQMD

XZ – the reaction plane
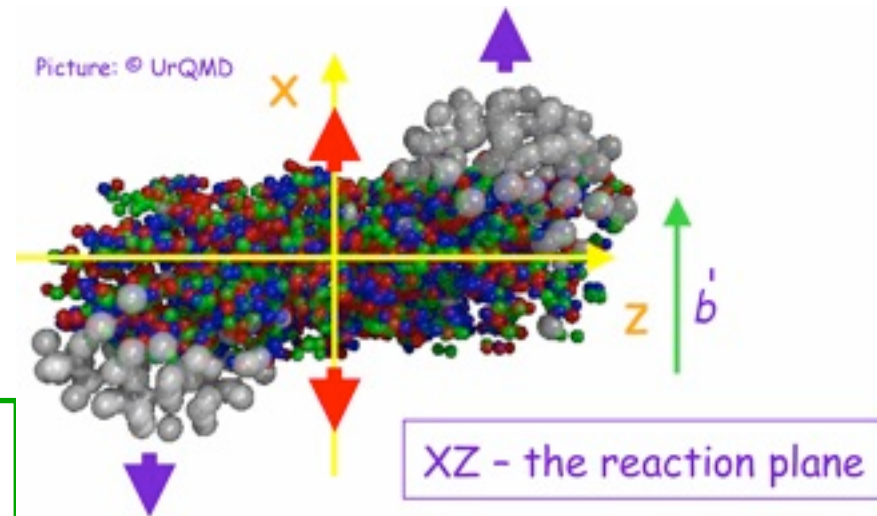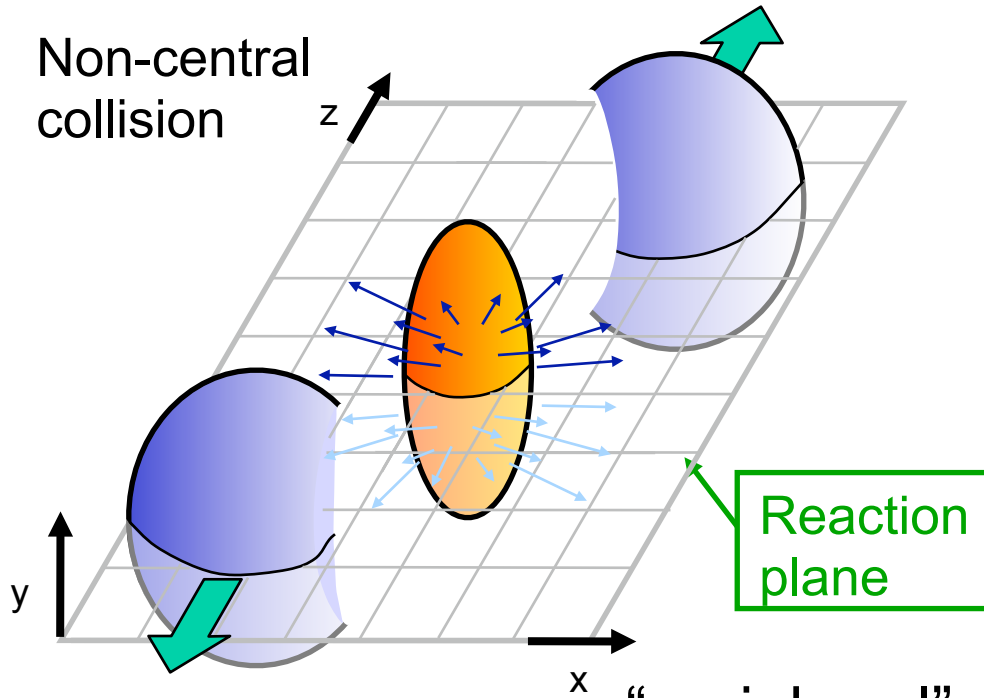
"<u>peripheral</u>" collision ($b \sim b_{max}$)

"<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}): number of equivalent inelastic nucleon-nucleon collisions

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

Effect of hard scattering cut-off scaling
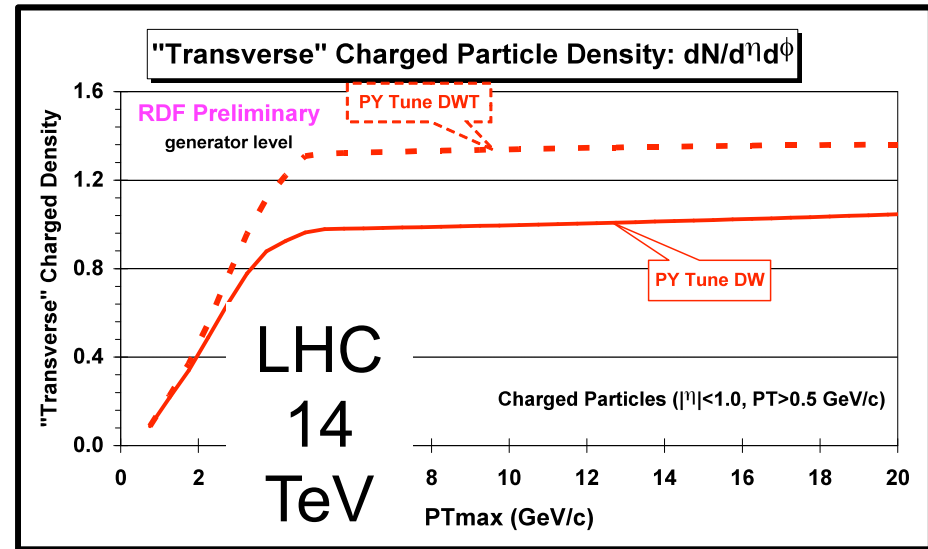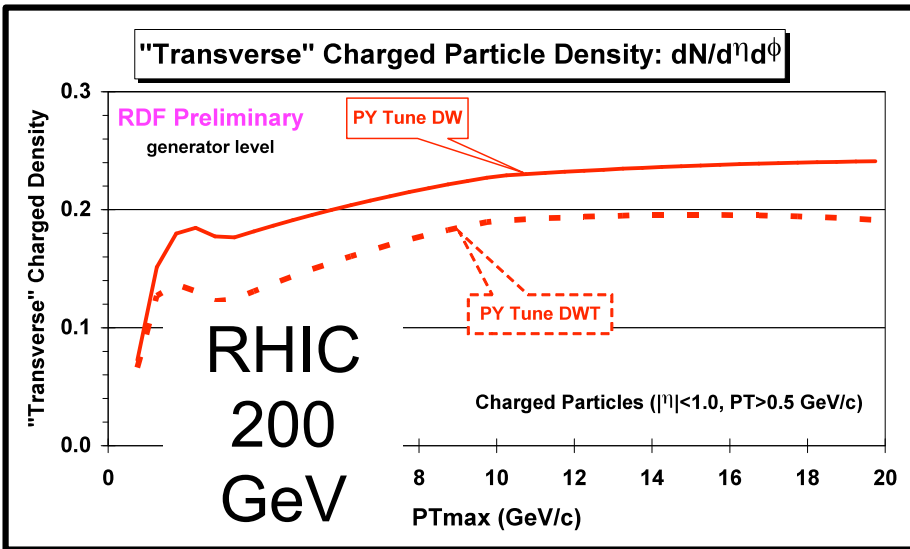

Hard-Scattering Cut-Off PT0

PYTHIA 6.206

ε = 0.25 (Set A))

ε = 0.16 (default)
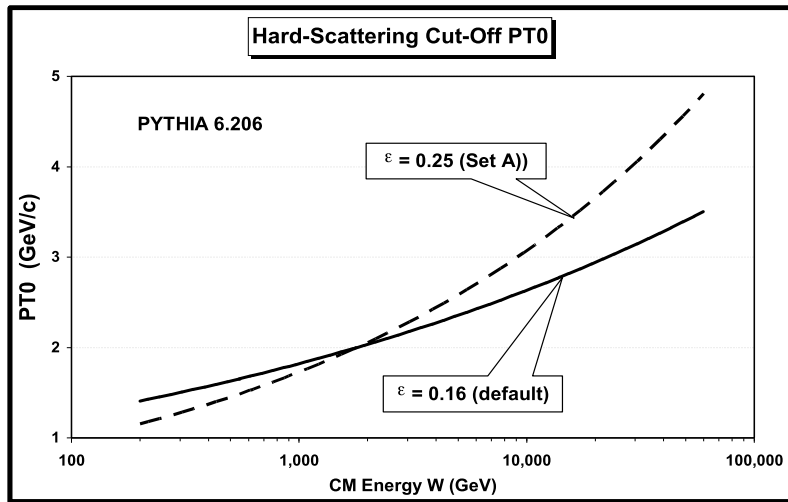
ε = 0.16 (DWT) $\rightarrow$ 0.25 (DW)

Increasing ε creates smaller energy dependence for UE

$\rightarrow$ 35% more RHIC
$\rightarrow$ 26% less LHC

"Transverse" Charged Particle Density: dN/dηdϕ

RDF Preliminary
generator level

PY Tune DW

PY Tune DWT

RHIC 200 GeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

"Transverse" Charged Particle Density: dN/dηdϕ

RDF Preliminary
generator level

PY Tune DWT

PY Tune DW

LHC 14 TeV

Charged Particles (|η|<1.0, PT>0.5 GeV/c)

Measurable effect at RHIC

From Rick Field

"Fake-Jet" contribution

"Fake" jets: signal in excess of background model from random association of uncorrelated soft particles (i.e. not due to hard scattering)
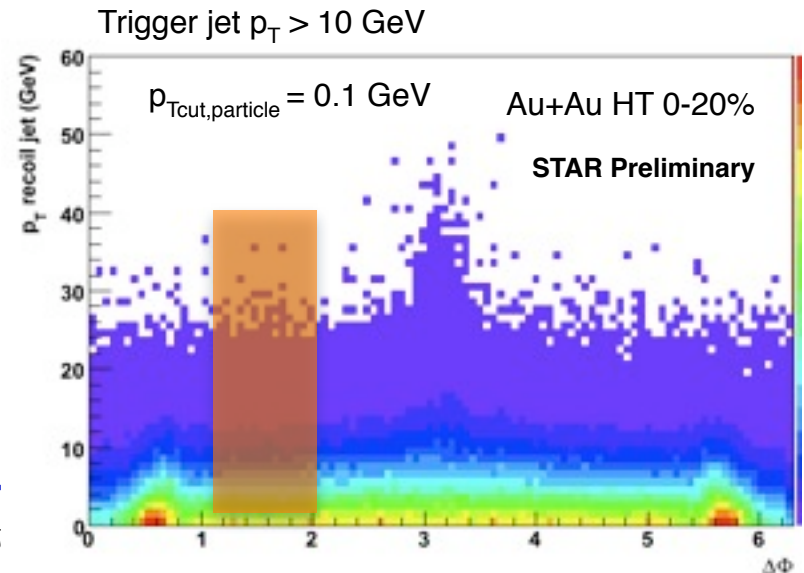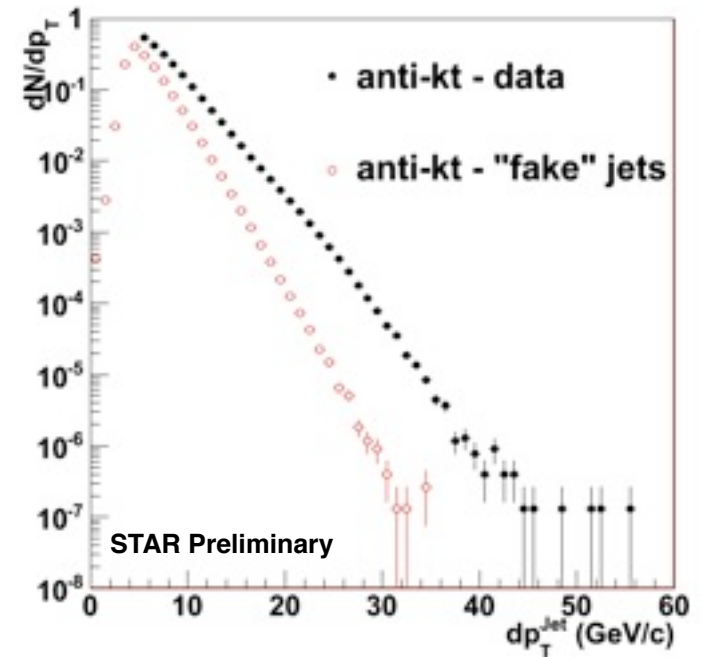
• **Inclusive jet spectrum**:
Spectrum of "jets" after randomizing HI event in φ and removing leading jet particle

• **Di-Jet / Fragmentation function:**
Background di-jet rate
= "Fake" + Additional Hard Scattering

Estimated using "jet" spectrum at 90 deg.

dN/dp_T

• anti-kt - data

○ anti-kt - "fake" jets

STAR Preliminary

dp_T^{jet} (GeV/c)

Trigger jet p_T > 10 GeV

$p_{Tcut,particle}$ = 0.1 GeV

Au+Au HT 0-20%

STAR Preliminary

p_T recoil jet (GeV)

ΔΦ

Spectrum Unfolding

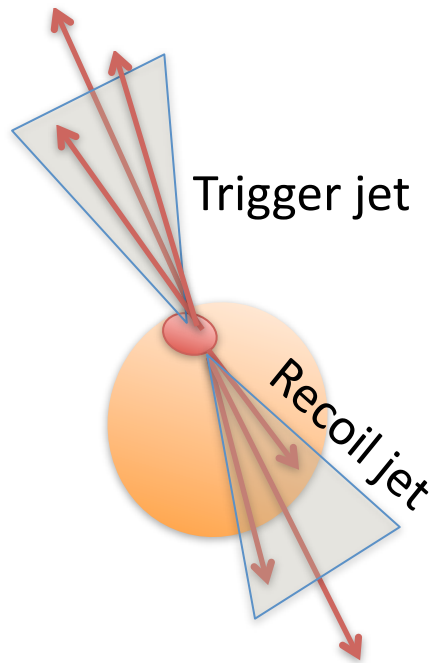**Corrections for smearing of jet p_t due to HI bkg. nonuniformities:**

1) raw spectrum

2) removal of "fake"-correlations

3) unfolding (bayesian) of HI bkg. fluctuations

4) correction for p_T resolution
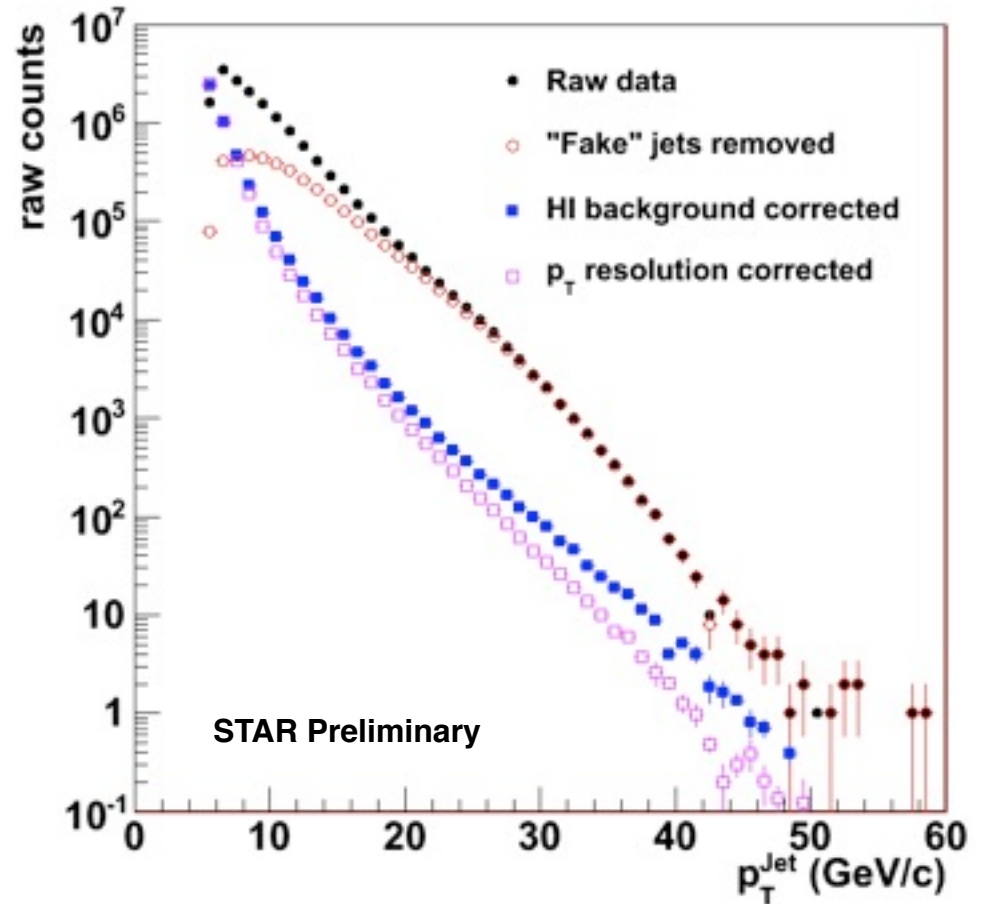
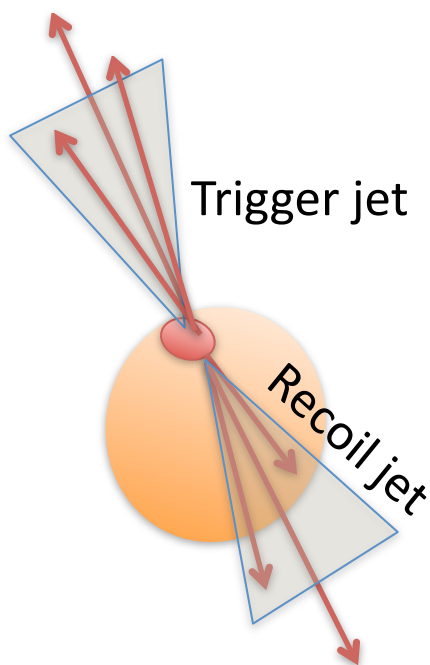# Recoil jet R_{AA} in Au-Au

Trigger jet

Recoil jet

- Select unmodified trigger jet
- comes from surface

- Maximizes path-length for the back-to-back jets

Recoil jet R$_{AA}$ in Au-Au

Trigger jet

Recoil jet

Plot:
- ▼ AntiKt R=0.4, p_t^{trig}>10 GeV/c
- — Background uncertainty $\sigma_{bkg} \pm 1$ GeV
- --- Trigger jet energy uncertainity

AuAu(0-20%)/pp

p+p 200 GeV
Au+Au (0-20%) 200 GeV
STAR Preliminary

E.Bruna QM2009

$p_{t,rec}$(recoil) [GeV/c]

- • Select unmodified trigger jet - comes from surface
- • Maximizes path-length for the back-to-back jets
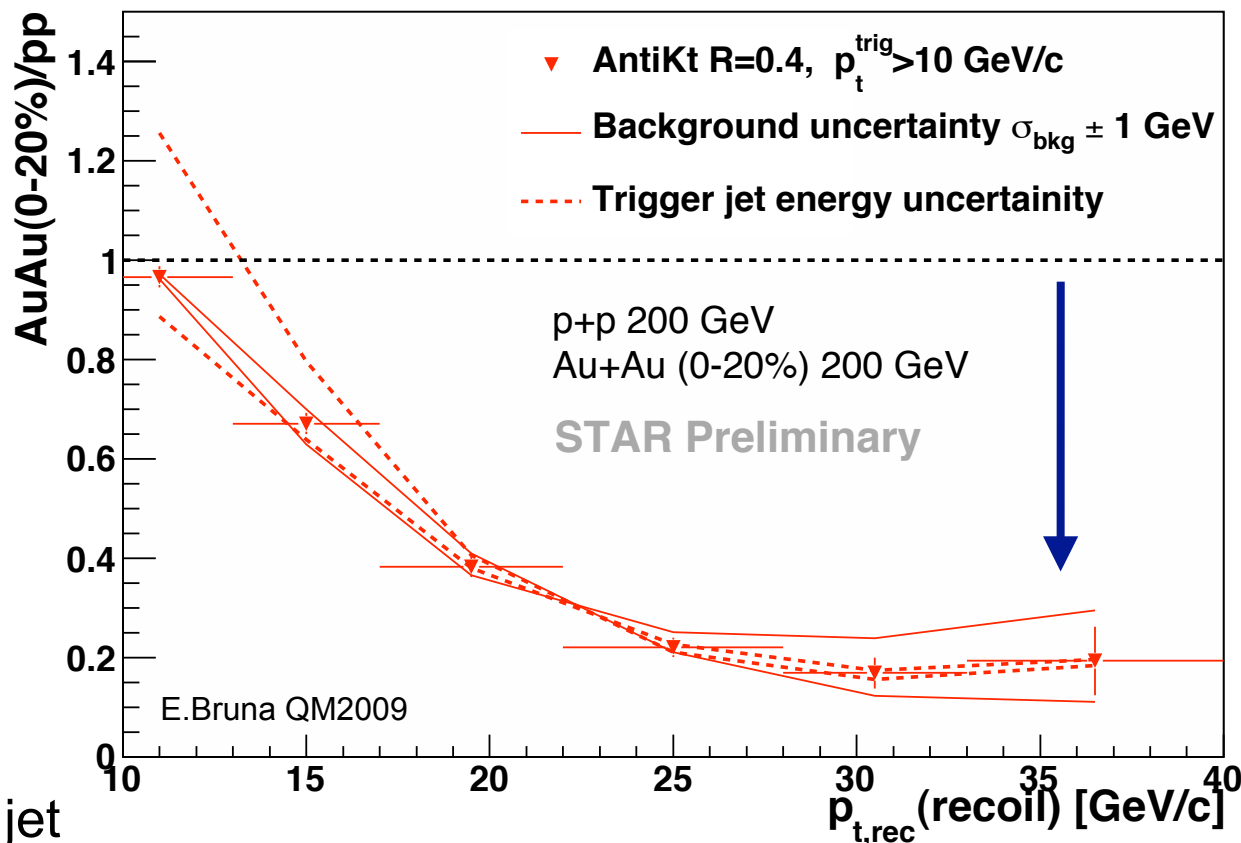
yield now also strongly suppressed for R=0.4

Jets no longer found due to extreme modification?