# Liquid-like quark-gluon matter at RHIC

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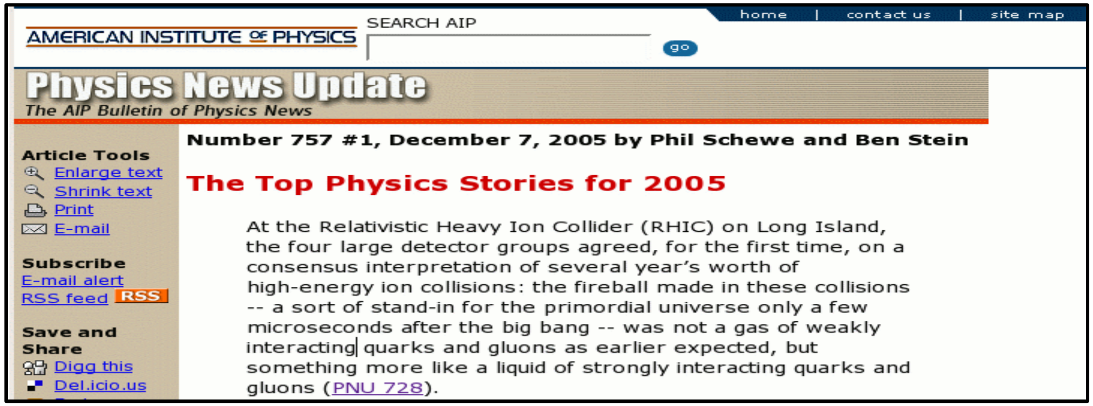
LBNL, 24 August 2009

# The quark-gluon liquid

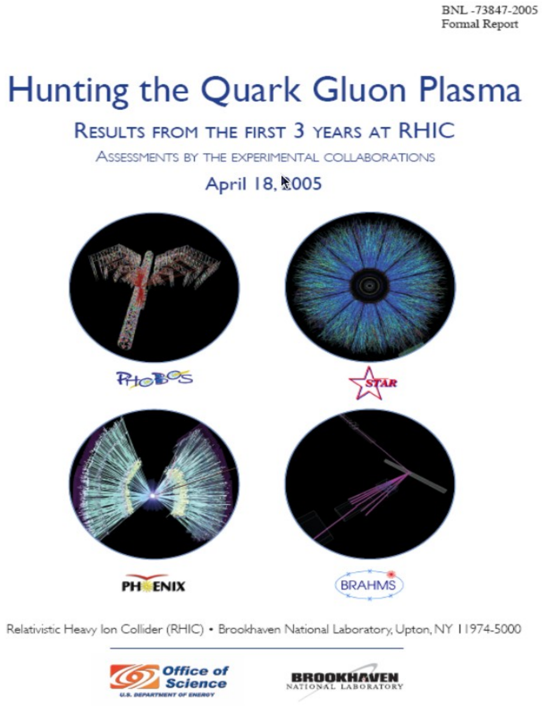
AIP Top Story 2005



**Number 757 #1, December 7, 2005 by Phil Schewe and Ben Stein**

**The Top Physics Stories for 2005**

At the Relativistic Heavy Ion Collider (RHIC) on Long Island, the four large detector groups agreed, for the first time, on a consensus interpretation of several year's worth of high-energy ion collisions: the fireball made in these collisions -- a sort of stand-in for the primordial universe only a few microseconds after the big bang -- was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons (PNU 728).



BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

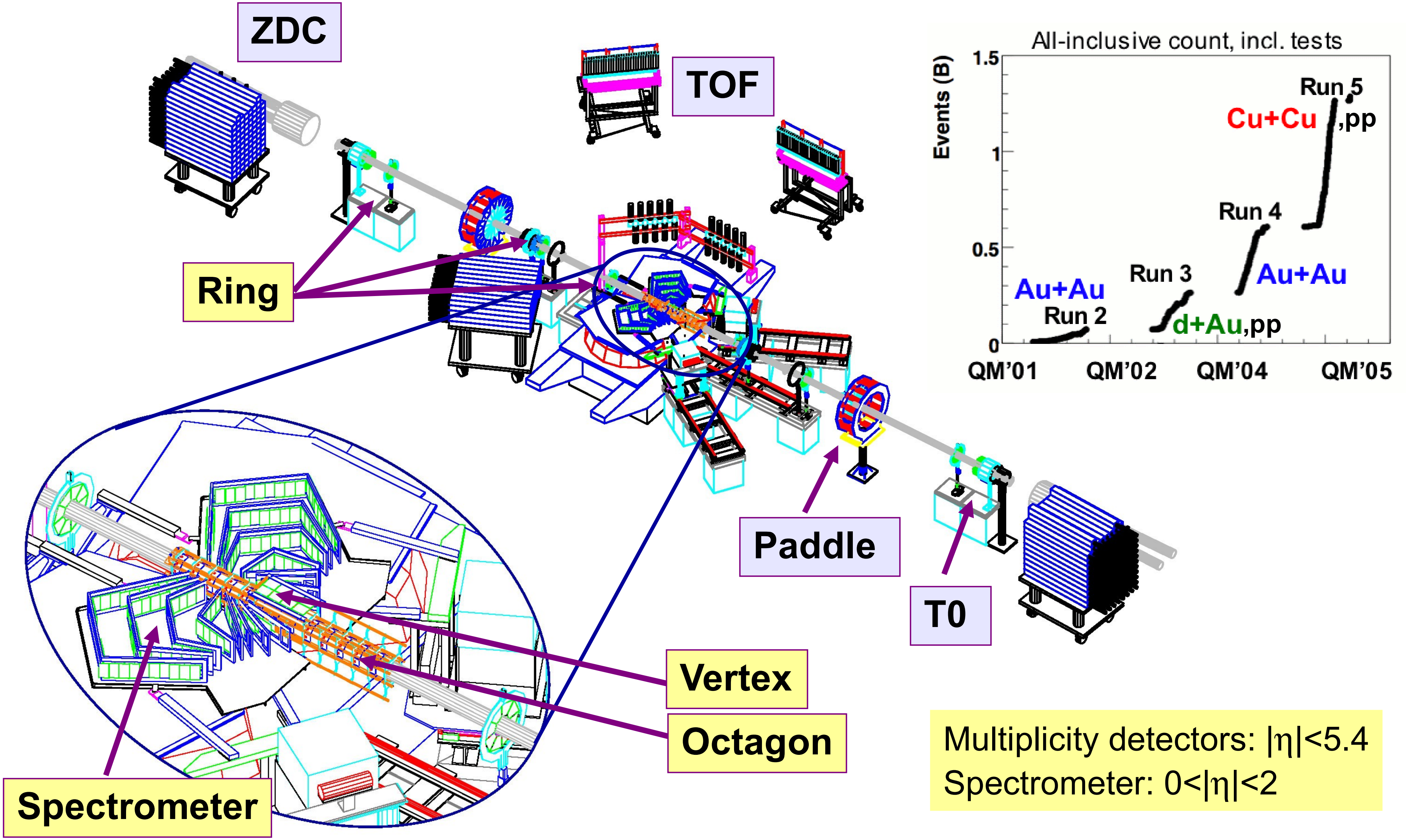
Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

"... the fireball made in these [heavy-ion] collisions ... was not a gas of weakly interacting quarks and gluons as earlier expected, but something more like a liquid of strongly interacting quarks and gluons"

(see http://www.aip.org/pnu/2005/split/757-1.html)

RHIC whitepapers:
NPA 757 1-283 (2005)

# PHOBOS experiment

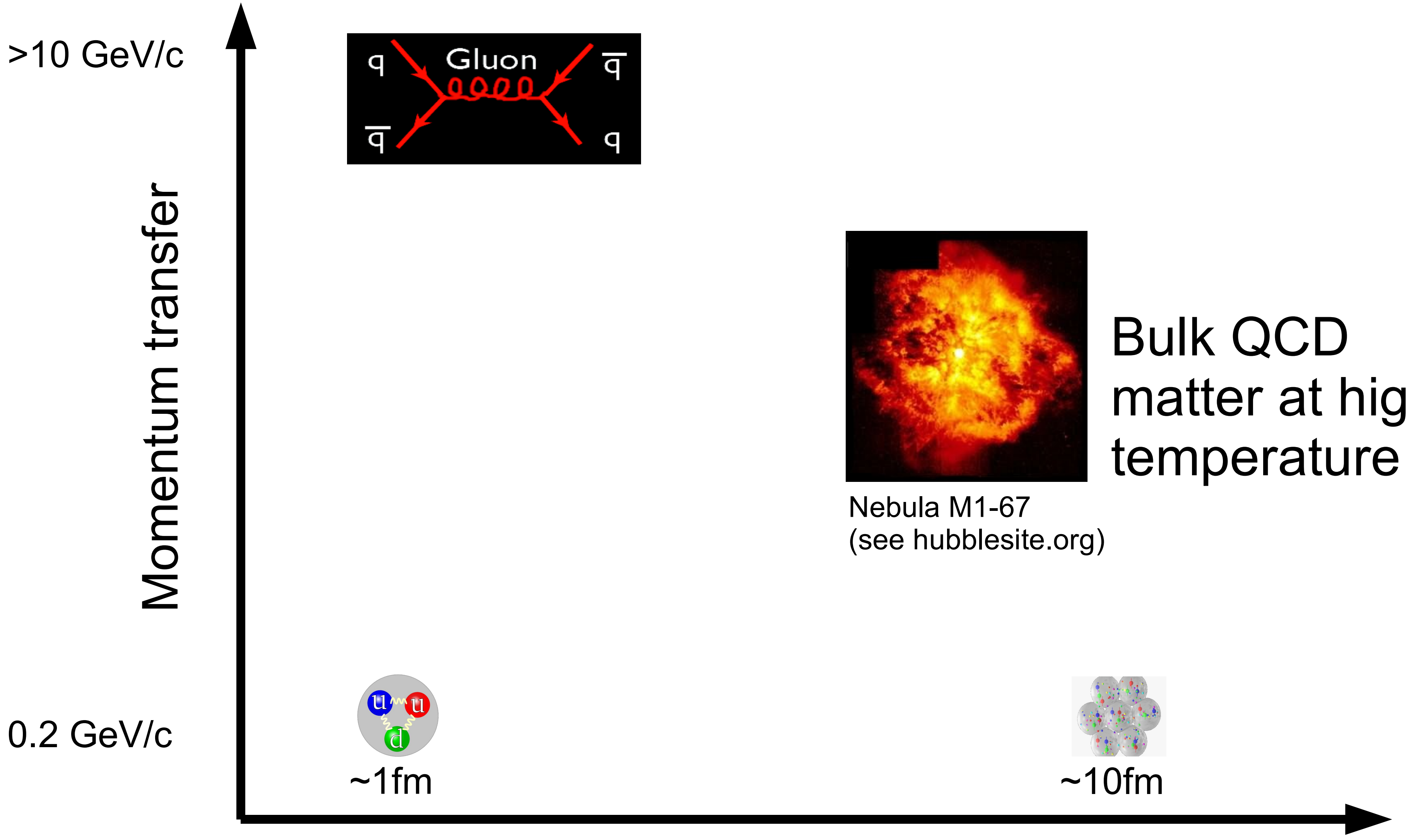


Multiplicity detectors: |η|<5.4
Spectrometer: 0<|η|<2

Small: 8M$, 50 people, 10 institutions

PHOBOS, NIM A499 603 (2003)

# QCD matter at high temperature



>10 GeV/c

0.2 GeV/c

Momentum transfer

Bulk QCD matter at high temperature

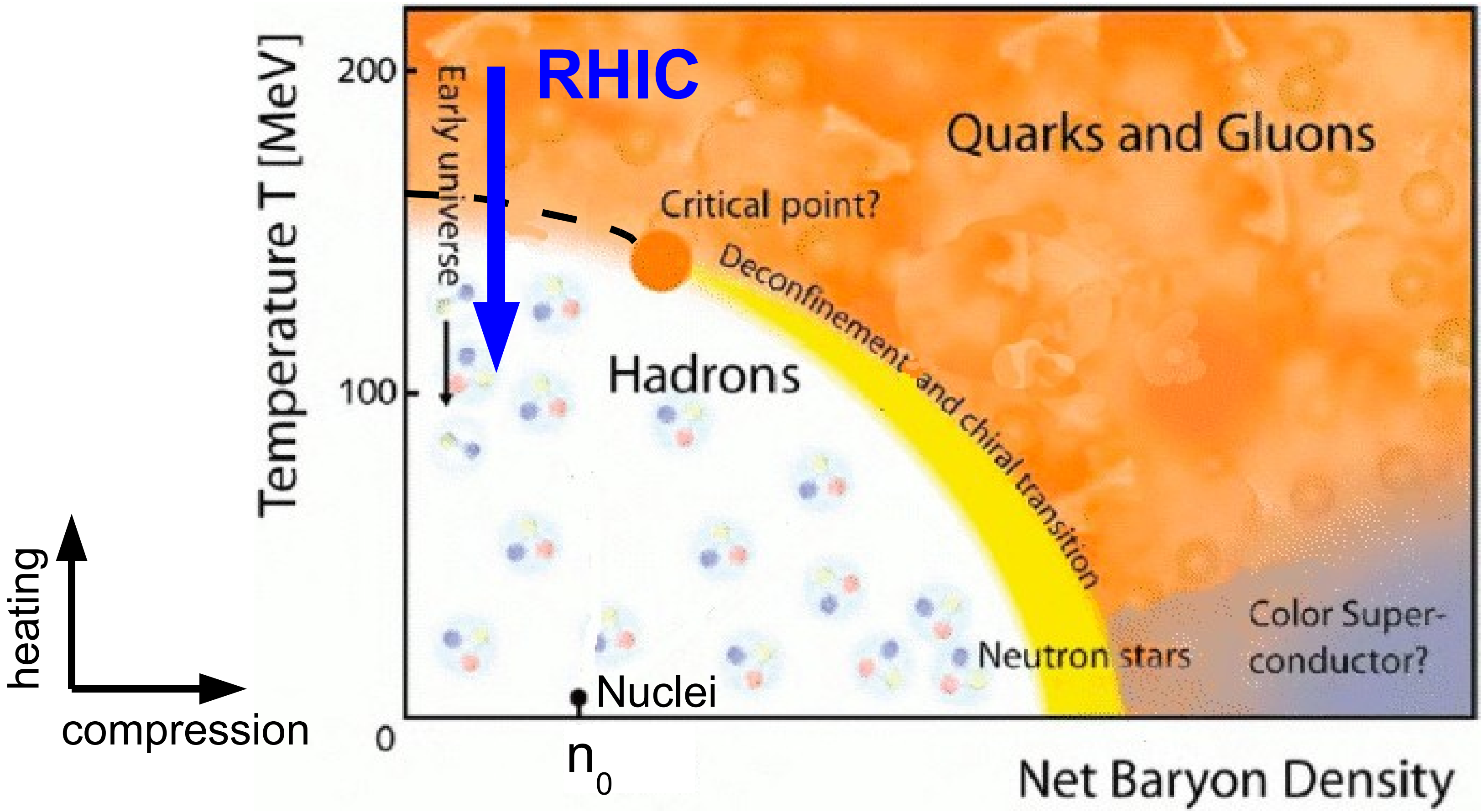
Nebula M1-67
(see hubblesite.org)

~1fm

~10fm

Transverse size of collision region

# QCD phase space diagram

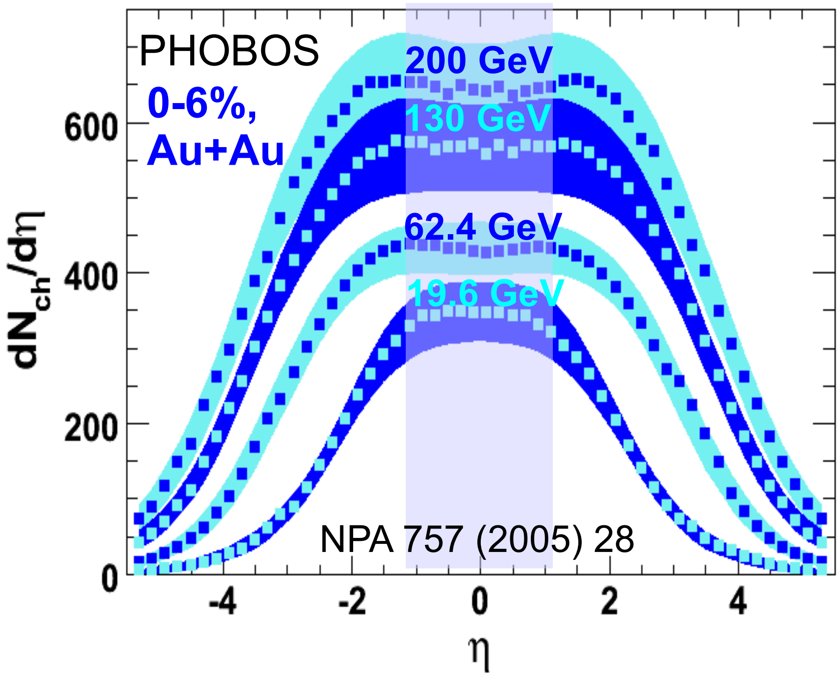


RHIC events (at mid-rapidity) are net-baryon free ($\bar{p}/p \approx 0.8$):
RHIC explores cross-over region of QCD phase diagram

# External parameters

Collision energy

## Charged particle density

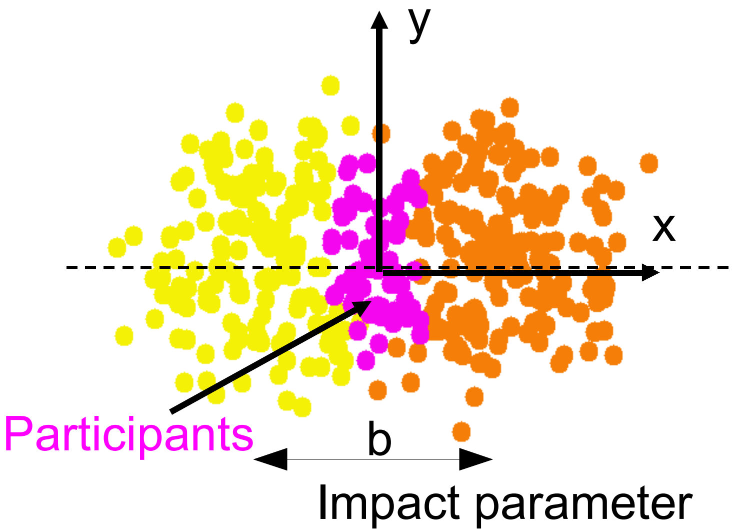


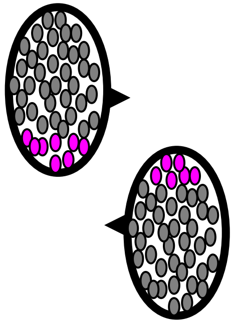
For 200 GeV at mid-rapidity,
the energy density exceeds 4x$\varepsilon_{crit}$

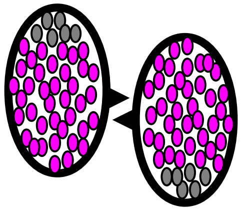
Collision centrality

# External parameters

- Centrality classes
  - Cross section percentile
  - Impact parameter (<b>)
  - #Participants (<$N_{part}$>~A)
    - Nucleons struck at least once
  - #NN-collisions (<$N_{coll}$>~$A^{4/3}$)
    - Total number of collisions
- Relate to data via Glauber MC based detector simulations





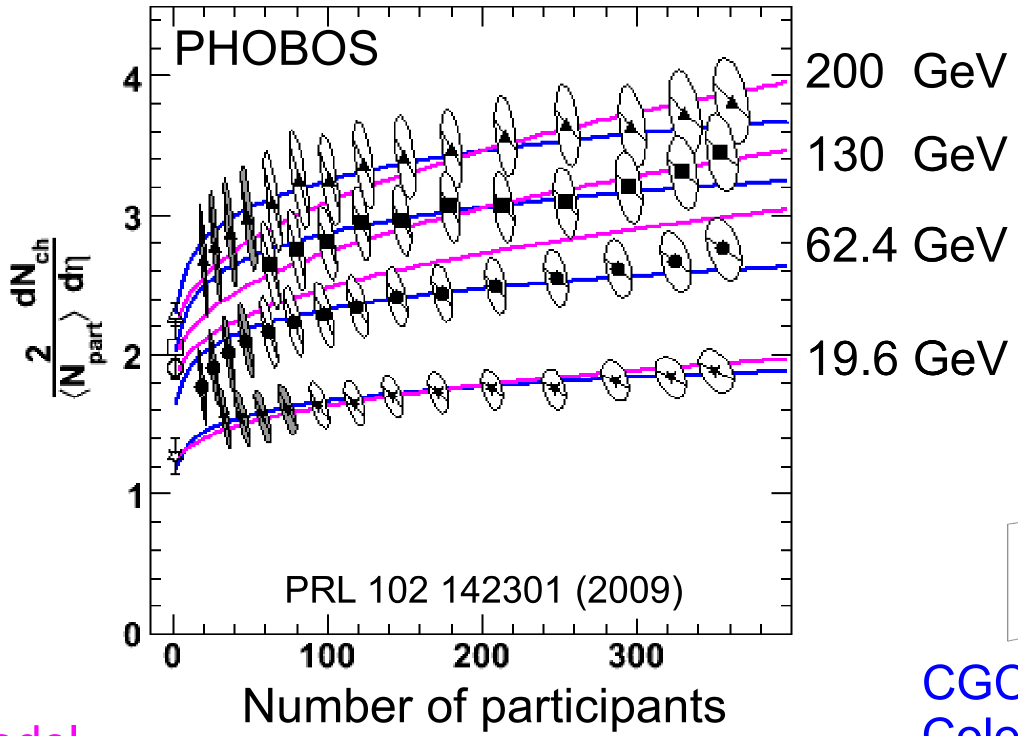


Collision energy

Collision centrality

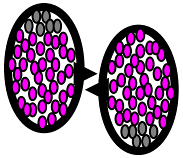
# Factorization of energy and centrality

Mid-rapidity density



PRL 102 142301 (2009)

Collision energy

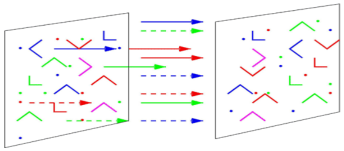


Glauber IC

Two-component model

$$\frac{dN}{d\eta}=\frac{dN}{d\eta^{pp}}((1-x)N_{coll}+x\,N_{part}/2)$$

PRC 70 021902 (2004)



CGC IC

Color glass condensate

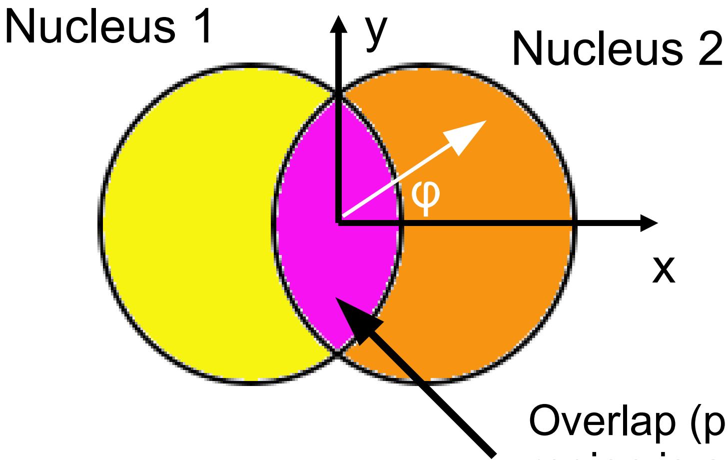
$$\frac{dN}{d\eta}\propto N_{part}^{\alpha}\sqrt{s}^{\lambda}$$

PRL 94 022002 (2005)

Collision centrality

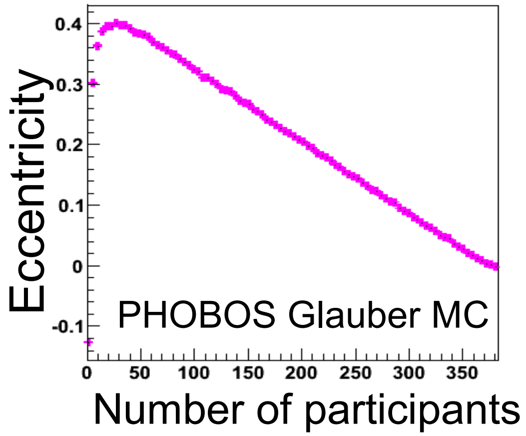
# External parameters

## Transverse geometry



Overlap (participant) region is asymmetric in azimuthal angle

$$\epsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$



Center of mass energy

Collision centrality

# Initial anisotropy and elliptic flow

Time

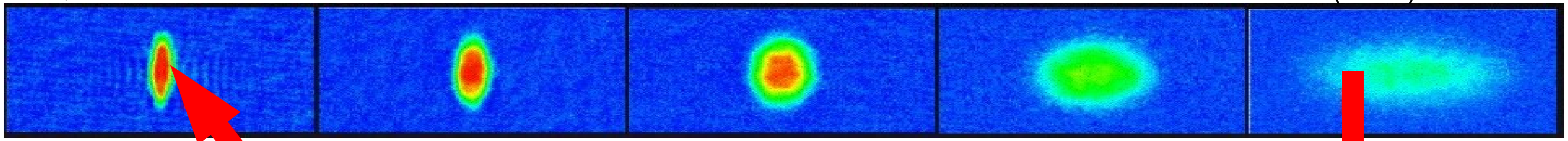
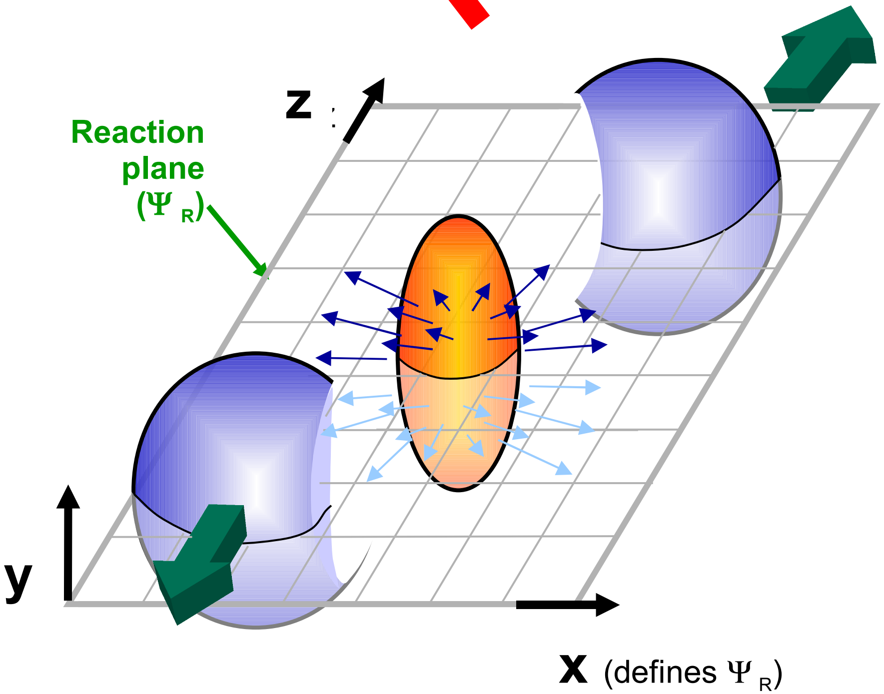
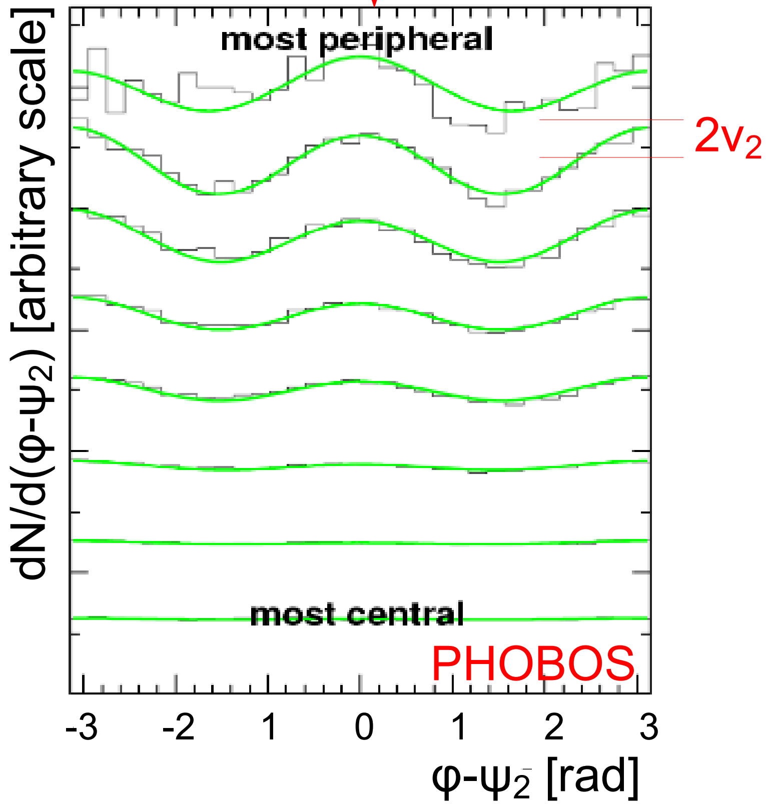


Illustration from Science 298 5601 (2002) 2179-2182





Initial spatial anisotropy eccentricity ε

Interactions present early

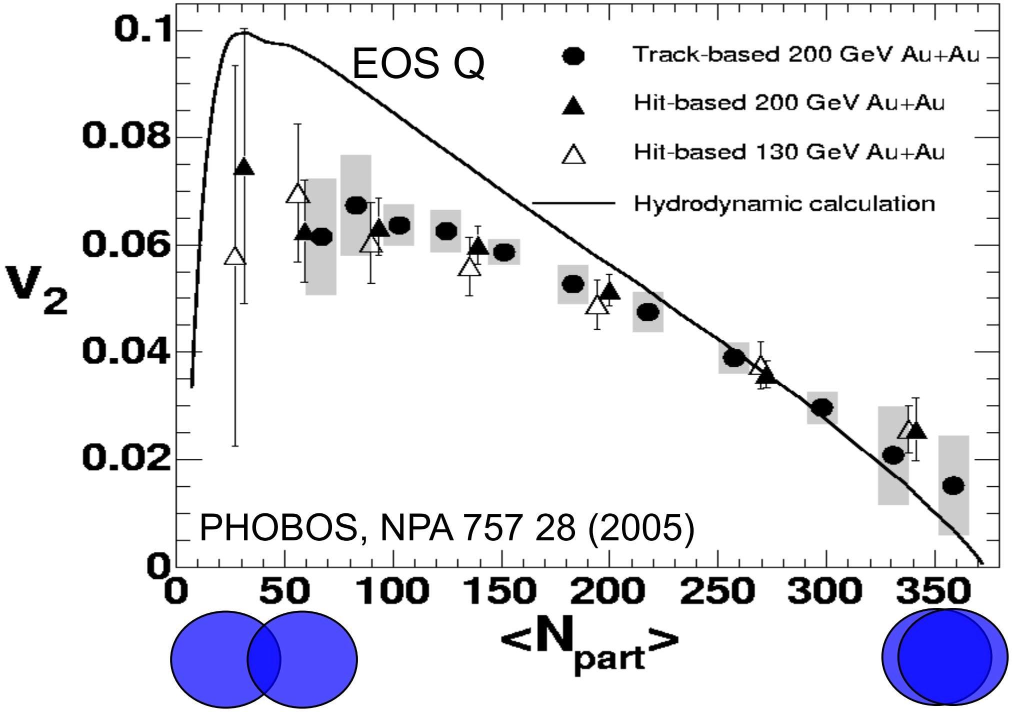
Momentum space anisotropy

$$v_2 = \langle \cos(2\phi - 2\Psi_R) \rangle$$

# Elliptic flow and ideal hydro

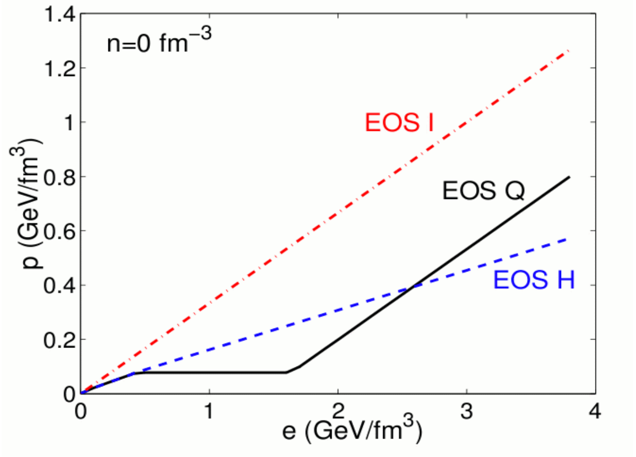
**Ideal relativistic hydrodynamics**

$$T^{\mu\nu}=(e+p)u^{\mu}u^{\nu}-p\,g^{\mu\nu}$$
$$\delta_{\mu}T^{\mu\nu}=0$$
$$\delta_{\mu}N_{i}^{\mu}=0,\ i=B,S,\ldots$$
$$p=p(e,n)$$ Closure with EoS



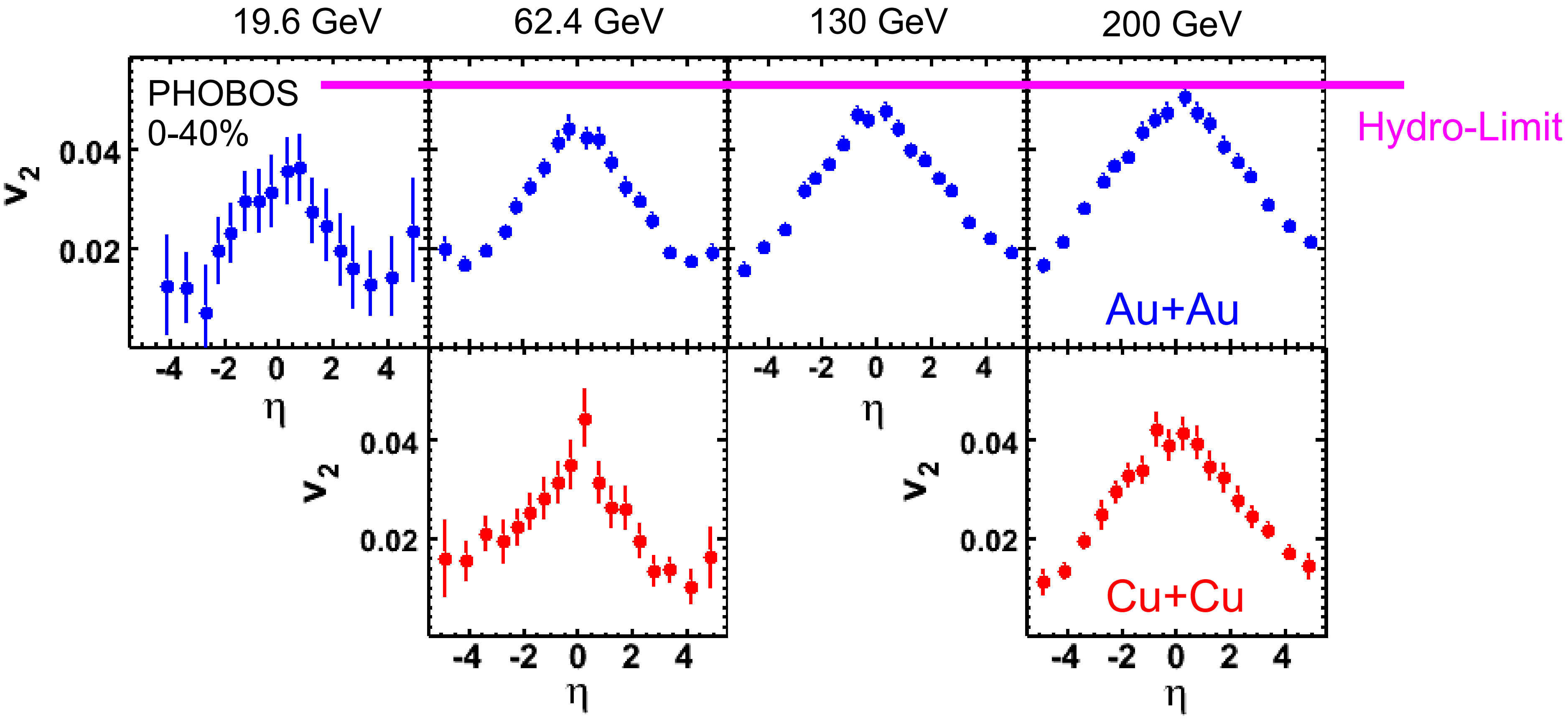
PHOBOS, NPA 757 28 (2005)

Assumption:
After a short thermalization time (≤1fm/c) a system in local equilibrium with zero mean free path and zero viscosity is created



Initial conditions (IC) →
Equation of state (EOS) → Hydro → Observables
Freeze-out cond. (FO) →

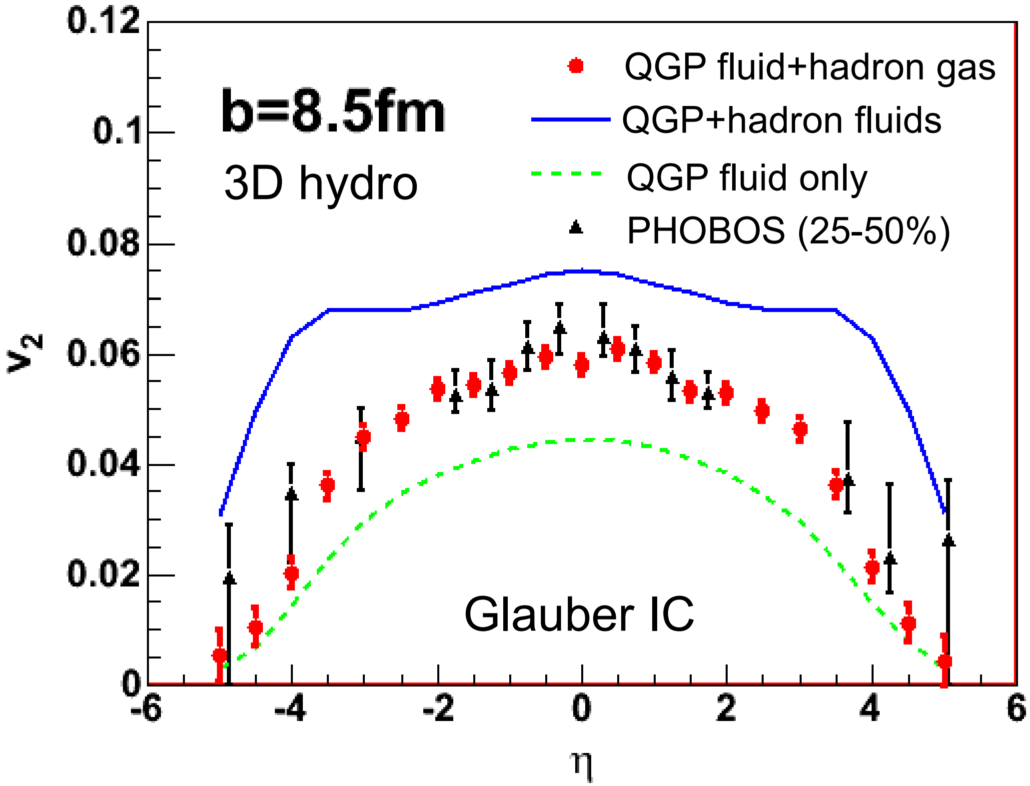
# Equilibrium only at mid-rapidity?



Hydro-limit reached at mid-rapidity for highest energies?

Au+Au: PRL 94 122303 (2005)
Cu+Cu: PRL 98 242302 (2007)

# Hydrodynamic model

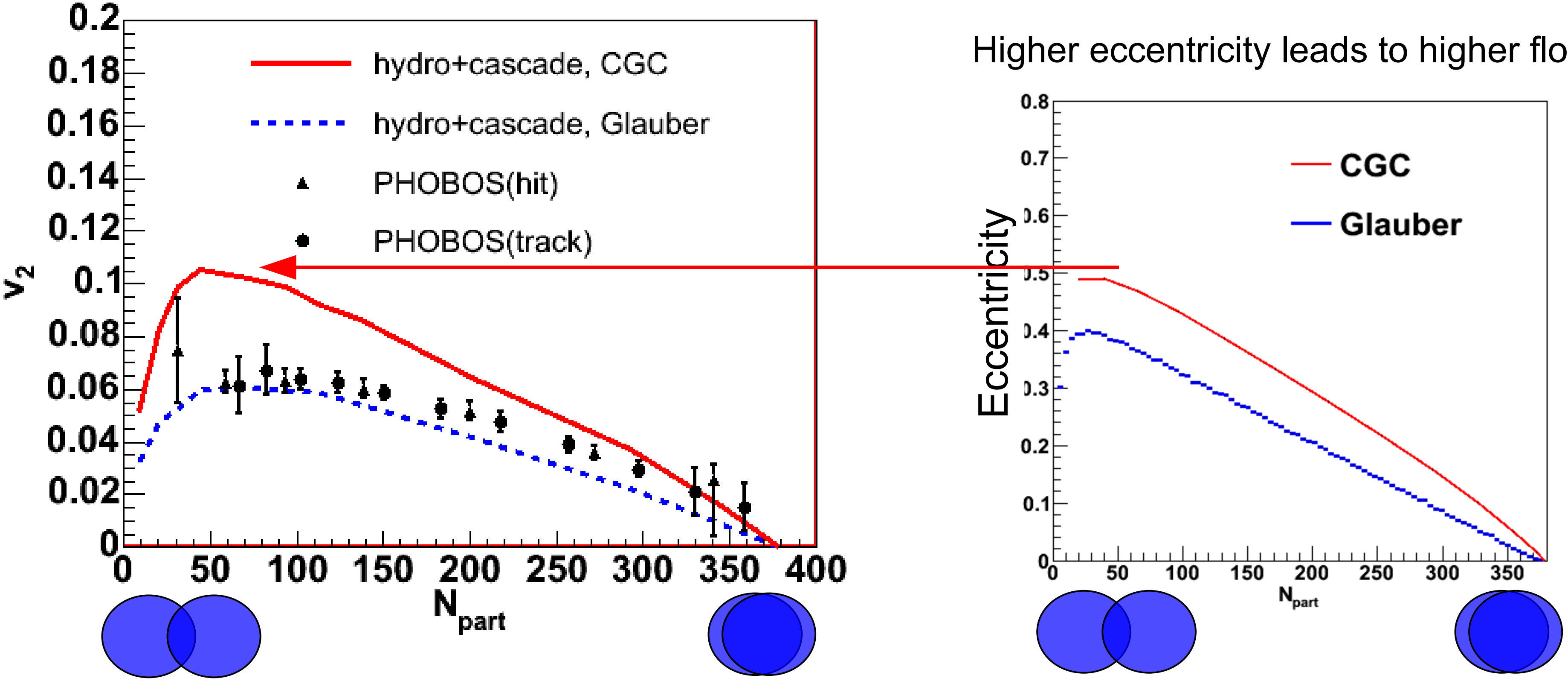


Hadronic corona is important

Remark: Hydrodynamic model ≠ ideal hydrodynamics (Boltzmann transport for hadrons includes effective viscosity through finite mean free path)

Hirano et al., PLB 636 299 (2006)

# Hydrodynamic model

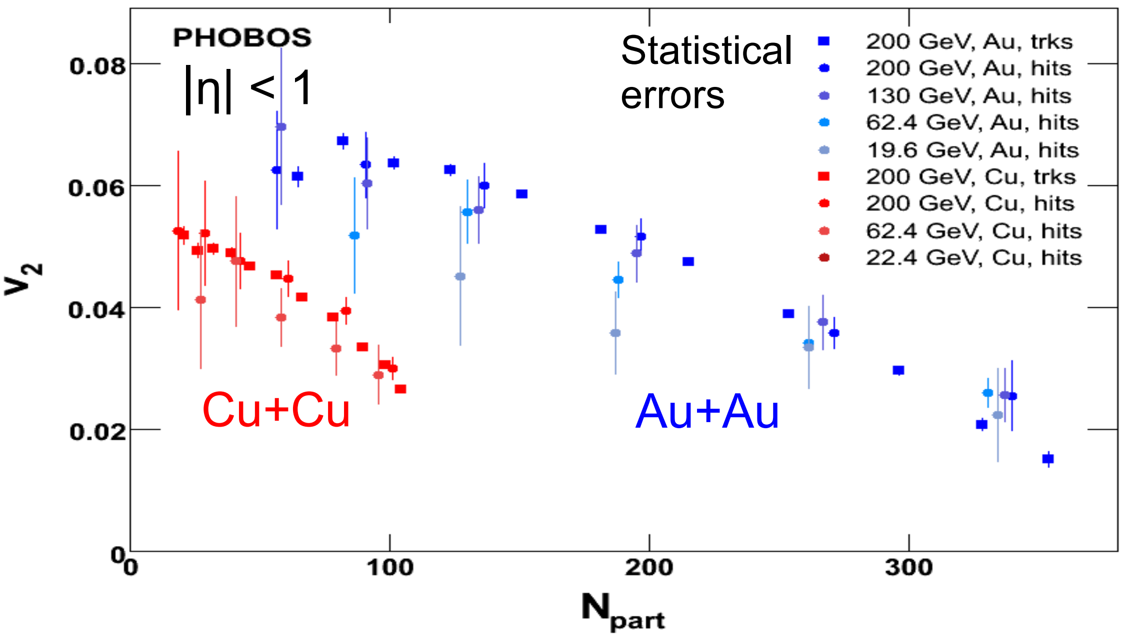


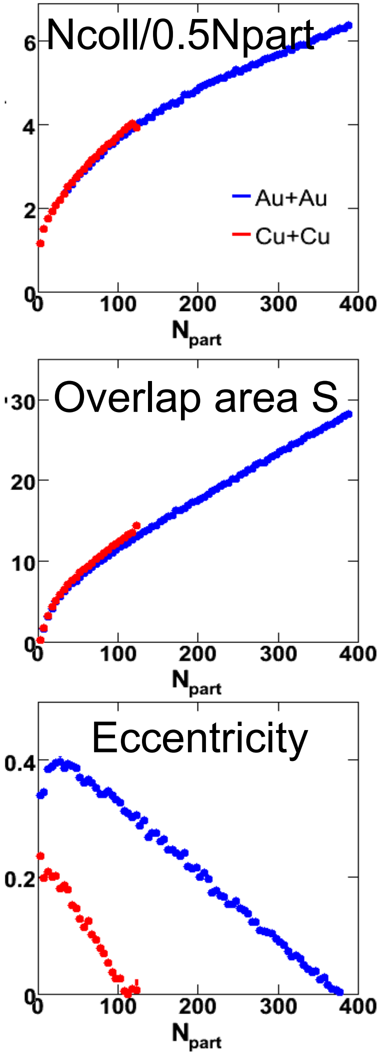
Higher eccentricity leads to higher flow

Ambiguity in description of initial state leads to ambiguity for model: viscous corrections and/or soft equation of state?

Hirano et al., PLB 636 299 (2006)

# Elliptic flow and collision geometry

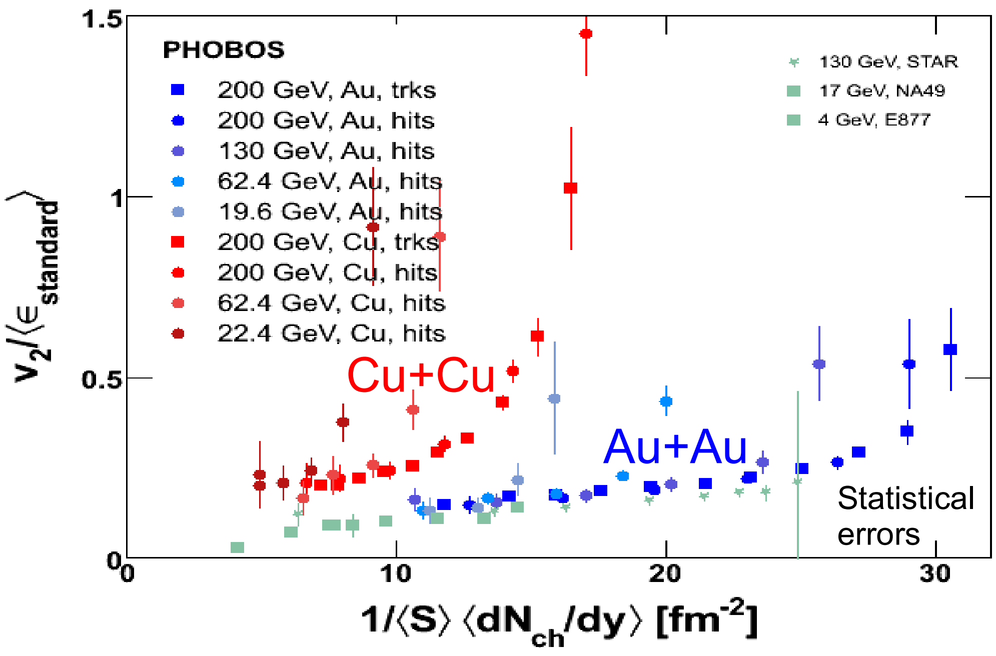


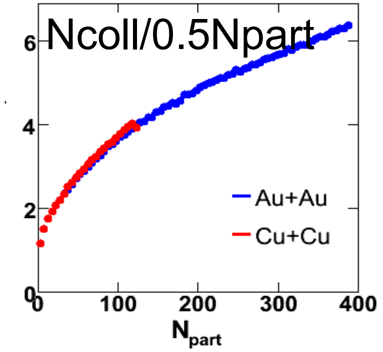


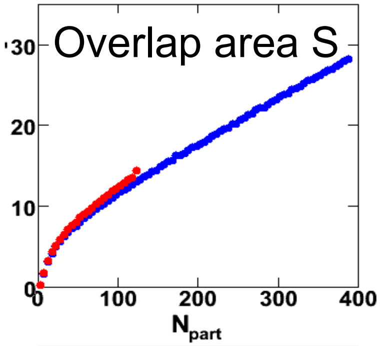
Geometry should cancel out in the $v_2/\varepsilon$ ratio

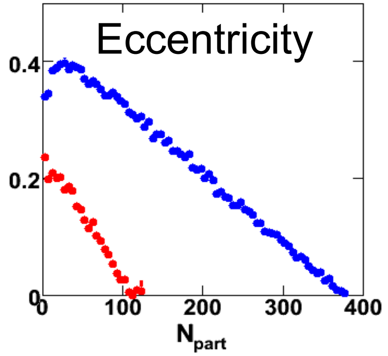
Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)
Cu+Cu, 22.4 GeV: prel. QM06

# Elliptic flow and collision geometry







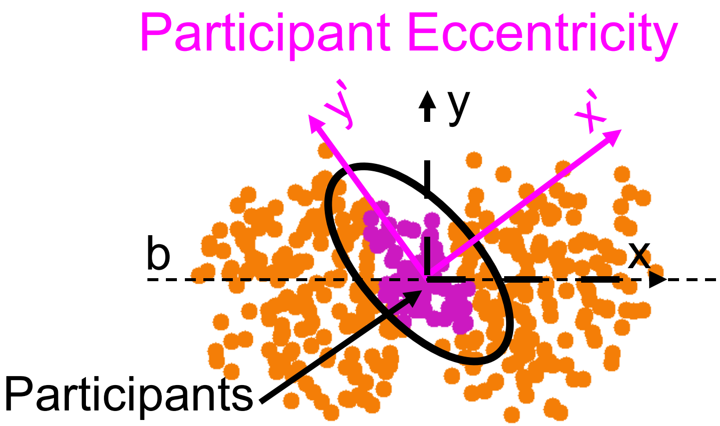


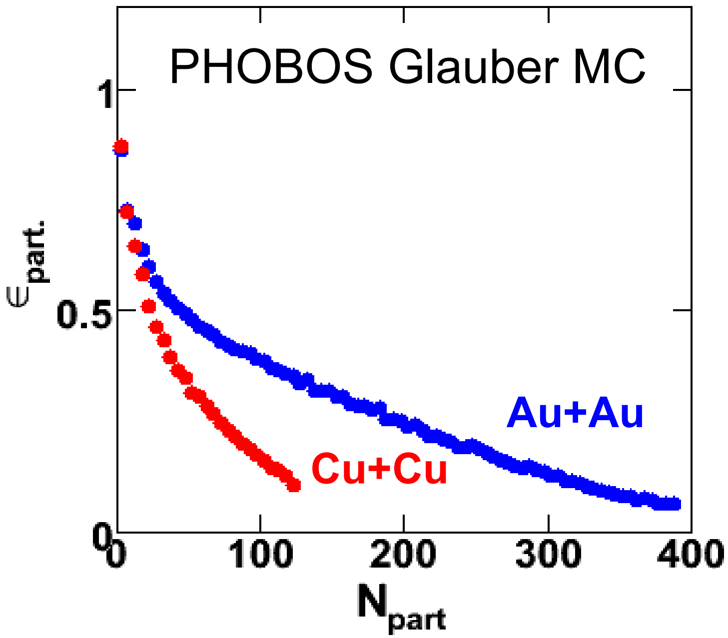
No scaling between Cu+Cu and Au+Au
using the standard eccentricity definition

Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)
Cu+Cu, 22.4 GeV: prel. QM06

STAR+NA49+E877, PRC 66 034904 (2002)
(data taken with no adjustments)

# Participant eccentricity





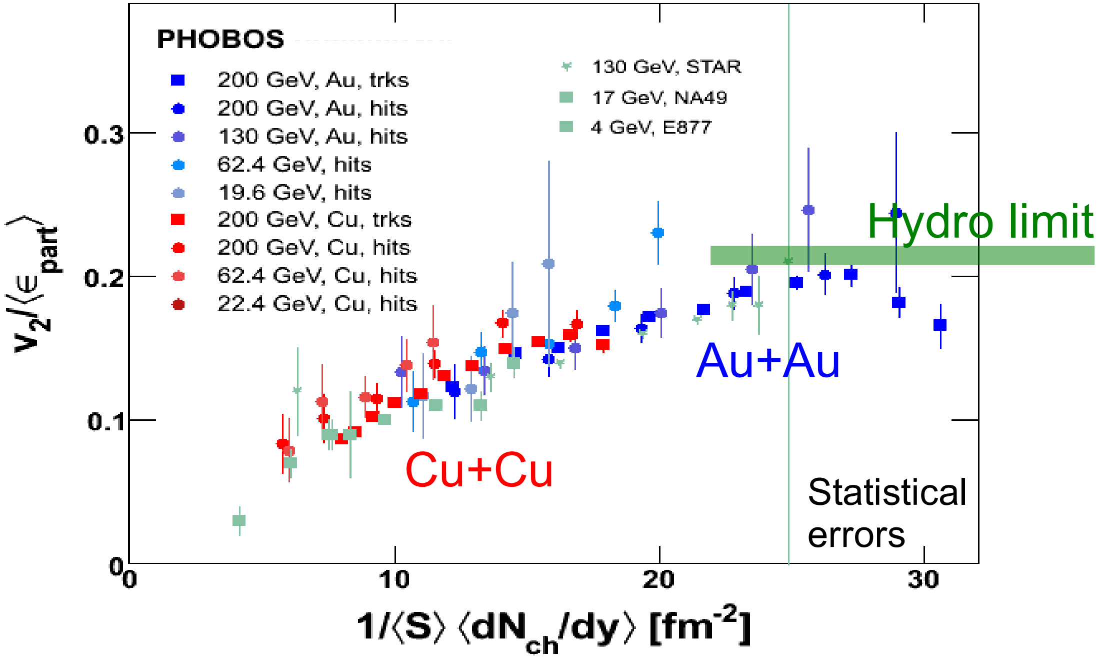
The spatial distribution of the interaction points of participating nucleons for the same b varies from event-to-event. Thus, event-by-event maximize

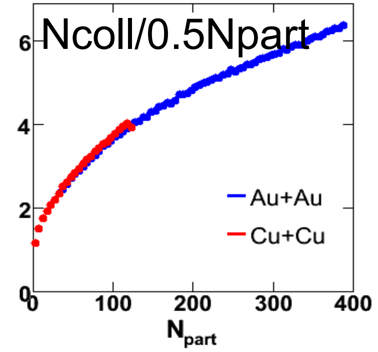
$$\epsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\boxed{\sigma_{xy}^2}}}{\sigma_y^2 + \sigma_x^2}$$

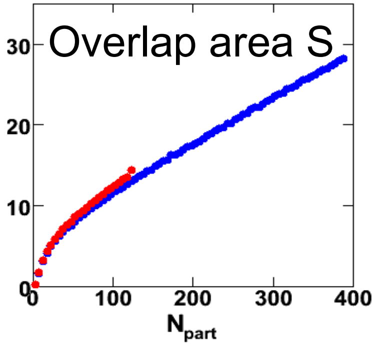
$$(0 < \epsilon_{\text{part}} \leq 1)$$

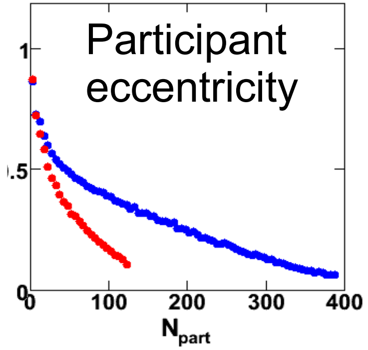
Introduced at QM05,
PHOBOS, PRL 98 242302 (2007)

# Elliptic flow and collision geometry







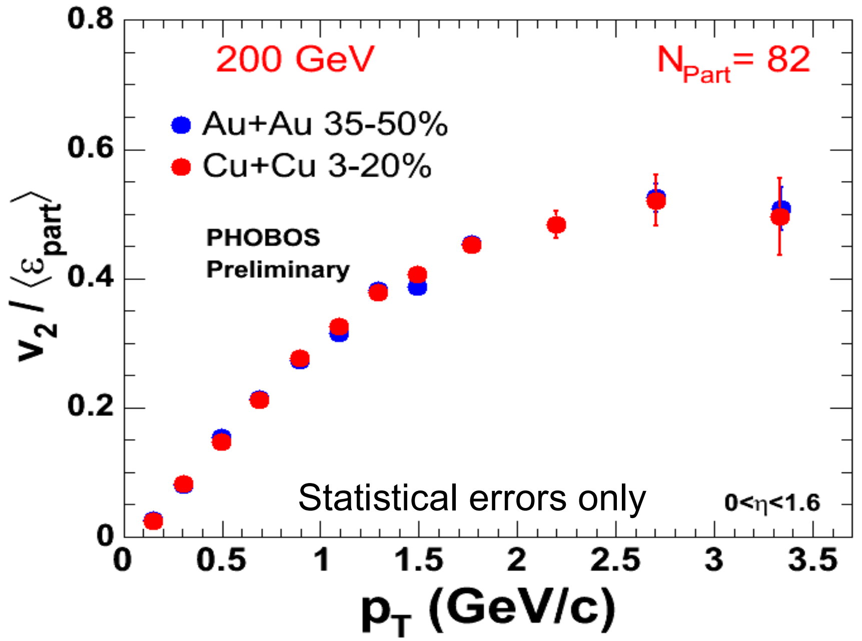


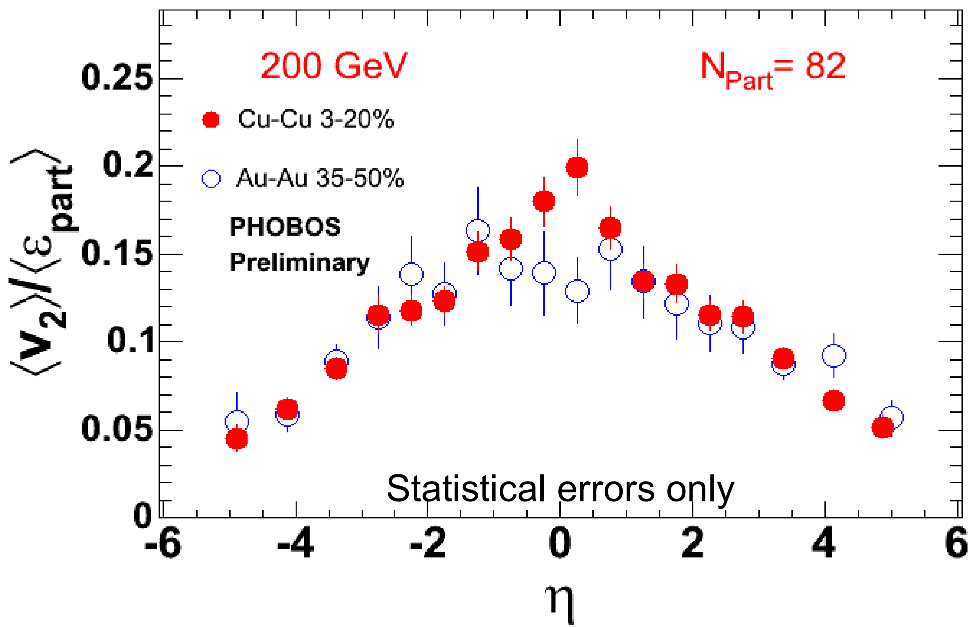
Scaling between Cu+Cu and Au+Au
using participant eccentricity definition

Au+Au, 200,130,62.4+19.6 GeV: PRL 94 122303 (2005)
Cu+Cu, 200+62.4 GeV: PRL 98 242302 (2007)
Cu+Cu, 22.4 GeV: prel. QM06

STAR+NA49+E877, PRC 66 034904 (2002)
(data taken with no adjustments)

# Eccentricity scaling is global



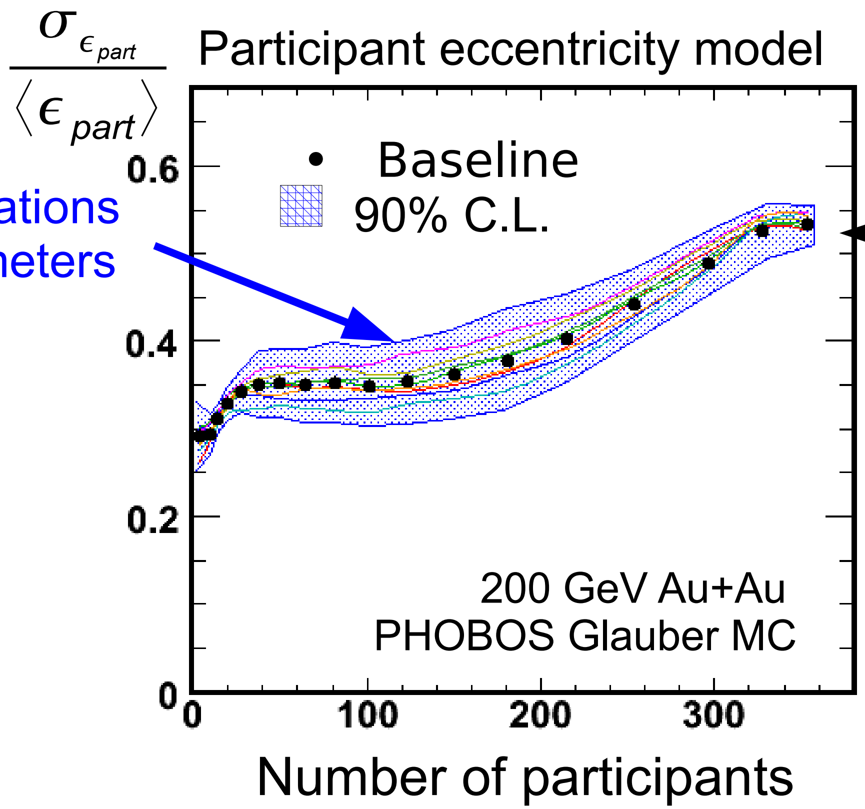


Unity of geometry, system, energy, transverse momentum and pseudorapidity for the same $N_{part}$ (~area density)

PHOBOS, JPG 34 887 (2007)

# Expected relative flow fluctuations

Uncertainty from variations of Glauber MC parameters



Analytic (b=0fm)

$$\sqrt{\frac{4}{\pi} - 1} \approx 0.52$$

Broniowski et al.,
PRC 76 054905 (2007)

Baseline parameters:

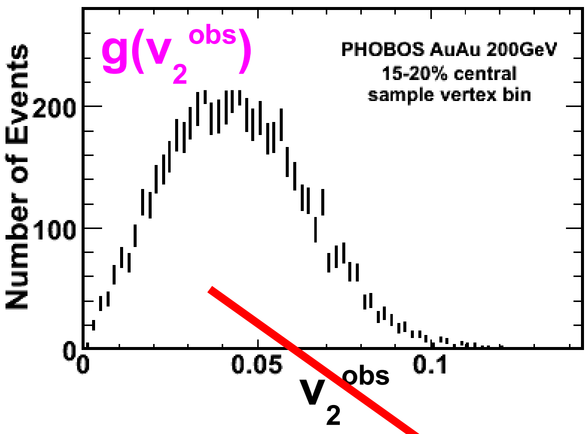
- Nucleon-nucleon cross section: $\sigma_{NN}$=42mb
- Skin depth: a=0.535fm
- Wood-saxon radius: $R_A$=6.38fm
- Inter-nucleon separation distance: d=0.4fm

If initial state fluctuations are present, expect large relative flow fluctuations: $\frac{\sigma_{v_2}}{\langle v_2 \rangle} \sim \frac{\sigma_{\epsilon_{part}}}{\langle \epsilon_{part} \rangle}$

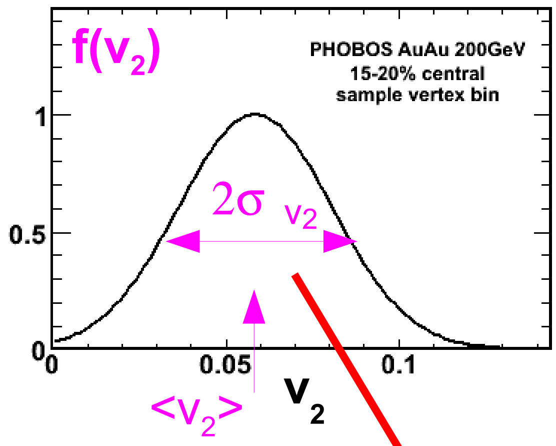
PHOBOS, nucl-ex/0608025

# Measuring elliptic flow fluctuations

Observed $v_2$ distribution



Parametrized $v_2$ distribution



Max-Likelihood fit to determine:

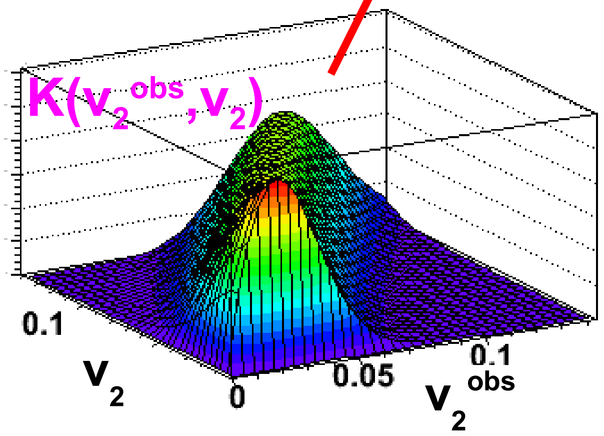
$\langle v_2 \rangle$ and $\sigma_{v2}$

Kernel

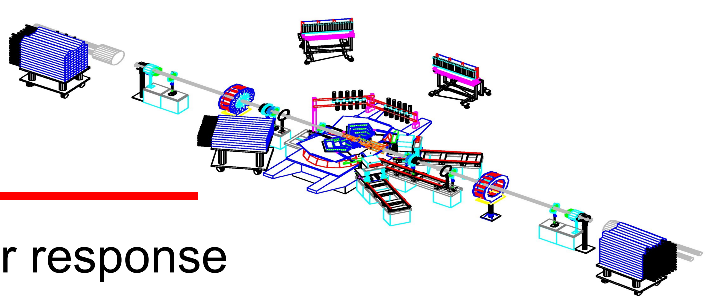
- Detector and acceptance effects
- Finite-number fluctuations
- Multiplicity fluctuations

$$g(v_2^{obs})=\int_0^1 K(v_2^{obs},v_2)\,f(v_2)\,dv_2$$

Kernel

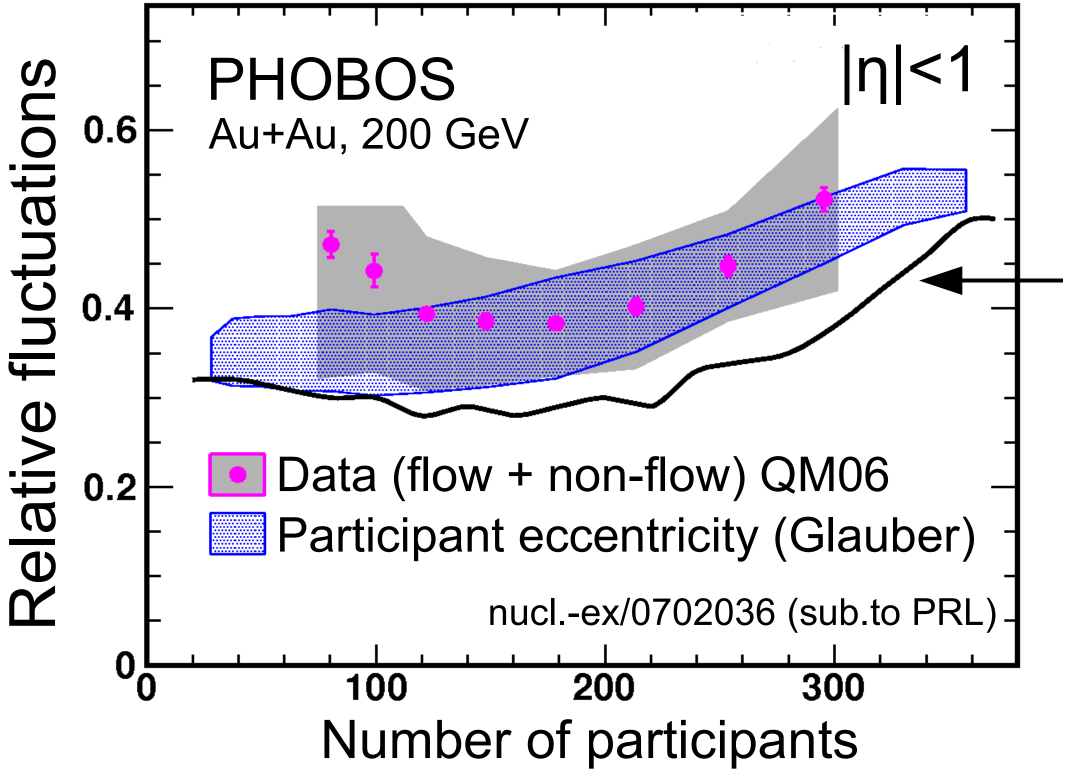


Detector response



PHOBOS, nucl.-ex/0702036 (sub.to PRL)

# Measured relative fluctuations



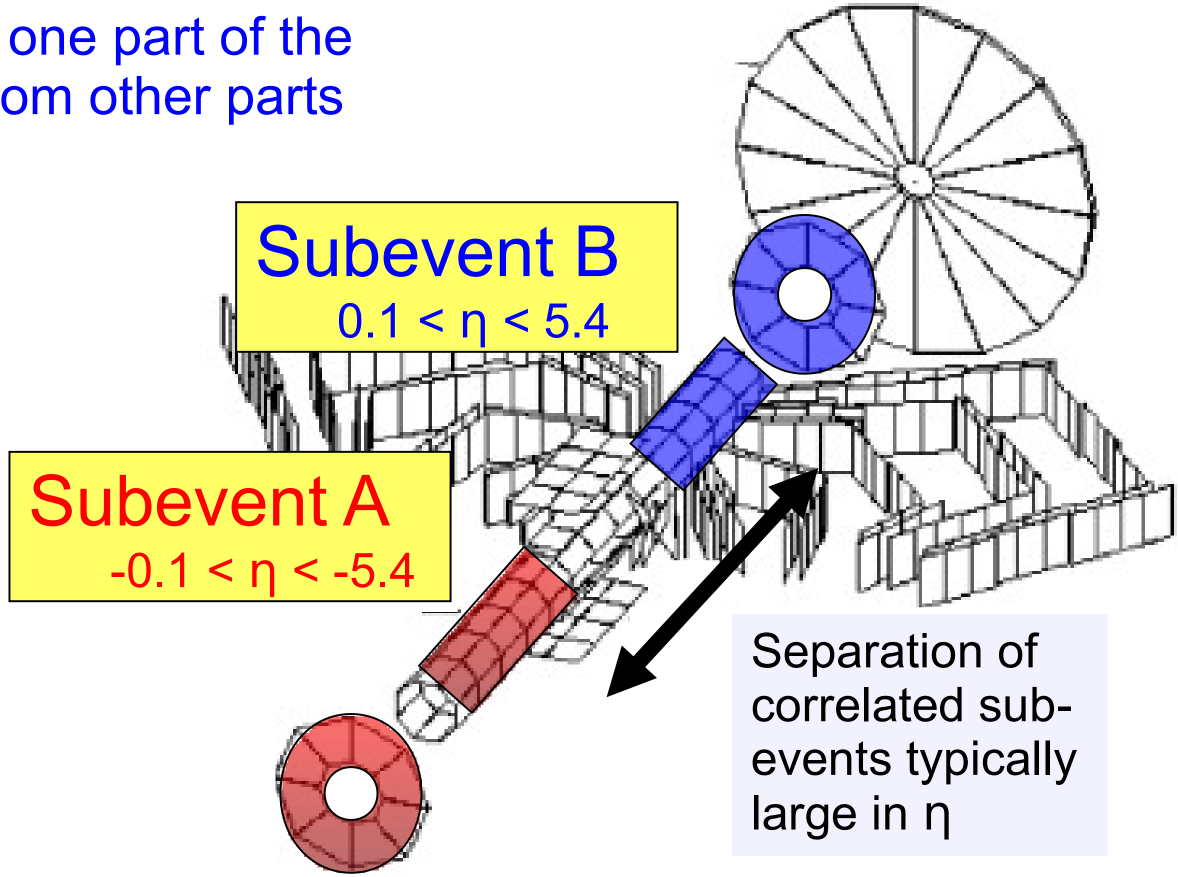
CGC-MC (fKLN)

Drescher, Nara,
PRC 76 (2007) 41903

Initial state fluctuations if indeed present seem not to be significantly enhanced in later stages of the collision

# Which moment of $v_2$ is measured?

- Reaction-plane / Sub-event technique
  - Correlate reaction plane determined from azimuthal pattern of hits in one part of the detector with information from other parts a of the detector



**Subevent B**

$0.1 < \eta < 5.4$

**Subevent A**

$-0.1 < \eta < -5.4$

Separation of correlated sub-events typically large in η

$$\tan(2\psi_A) = \frac{\langle \sin(2\phi) \rangle_A}{\langle \cos(2\phi) \rangle_A}$$

$$v_2^{obs} = \langle \cos(2\phi - 2\psi_A) \rangle_B$$

$$v_2 = \frac{\langle v_2^{obs} \rangle_{events}}{\sqrt{\underbrace{\langle \cos(2\psi_A - 2\psi_B) \rangle_{events}}_{\text{Resolution correction}}}}$$

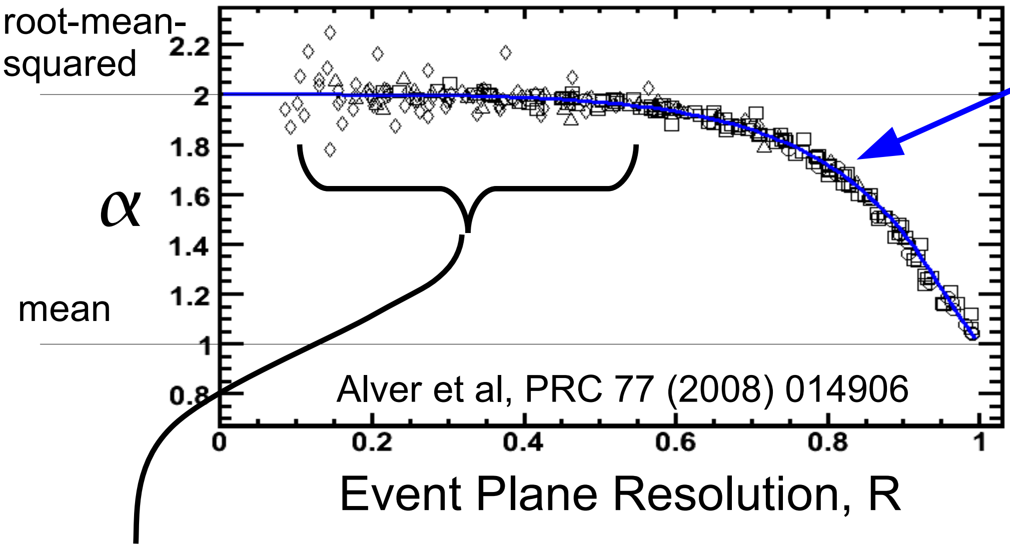
Poskanzer, Voloshin, nucl-ex/9805001

Resolution correction

# Which moment of $v_2$ is measured?

Define

$$v_2 \equiv \langle v_2^{\alpha} \rangle^{1/\alpha}$$



Alver et al, PRC 77 (2008) 014906

By now α is known:

$$\alpha = 2 - 4 i_1^2 / (i_0 + i_1)^2$$

Ollitrault et. al.,
PRC 80 80 014904 (2009)

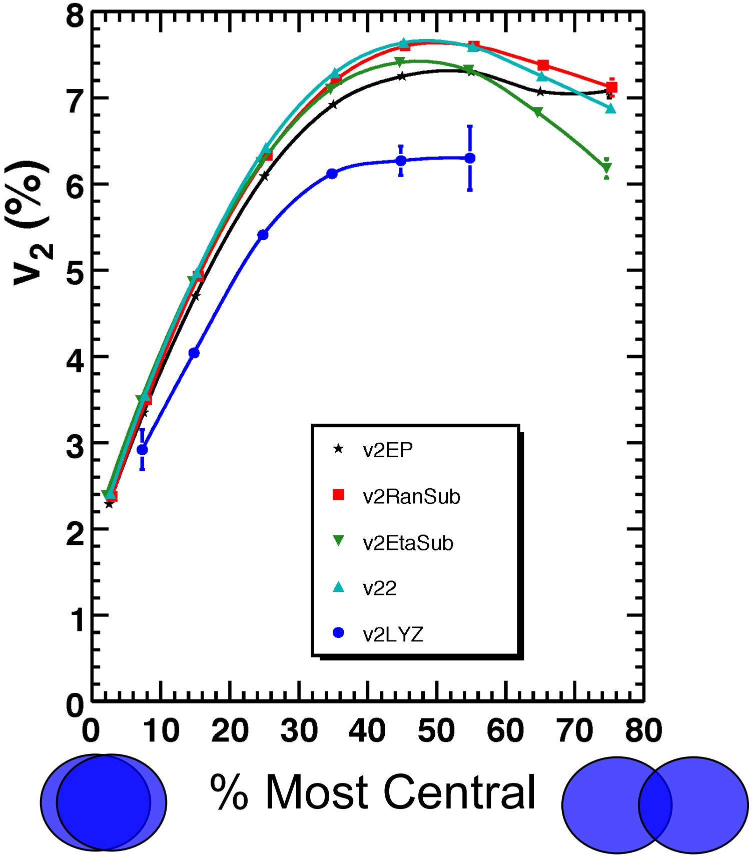
PHOBOS R:
0.13 – 0.55

For PHOBOS standard event-plane method $v_2\{EP\} = \sqrt{\langle v_2^2 \rangle}$

(For the observed fluctuations this implies about 10% difference)

# Correction for non-flow and fluctuations

Published STAR results



Derive analytic correction for non-flow and fluctuations in leading order of $\delta$ and $\sigma_{v_2}^2$

Eg, for 2-particle correlations:

$$\langle\cos(2\Delta\phi)\rangle = \langle v_2\rangle^2 + \sigma_{v_2}^2 + \delta$$

Non-flow term

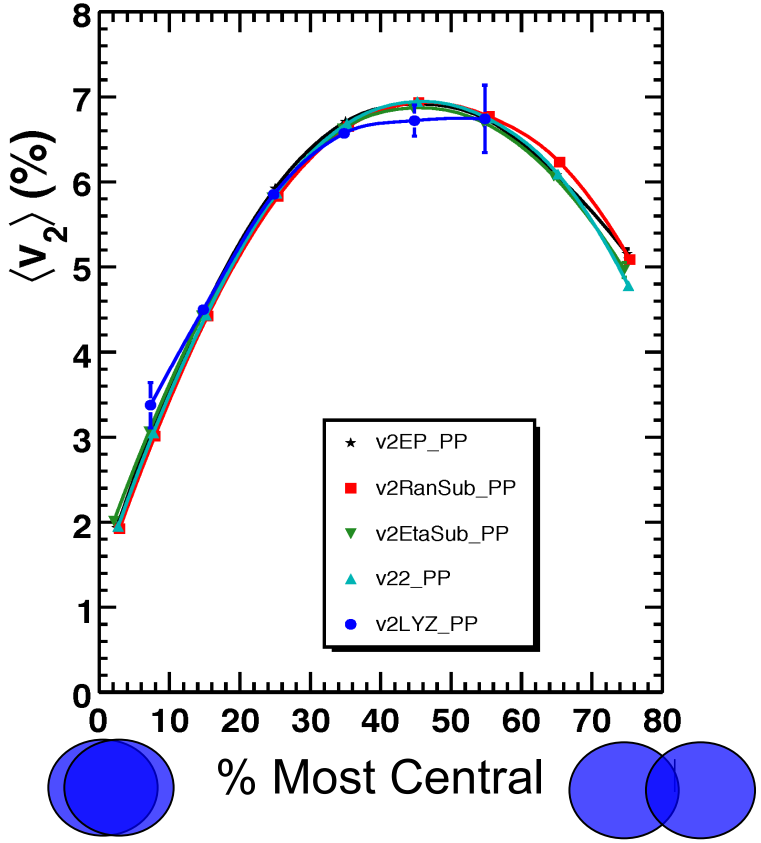
Differences between methods proportional to

$$\sigma_{tot} = \delta + 2\sigma_{v_2}^2$$

Need additional assumption or information to separate between non-flow and fluctuations

Ollitrault et. al.,
PRC 80 80 014904 (2009)

# Correction for non-flow and fluctuations



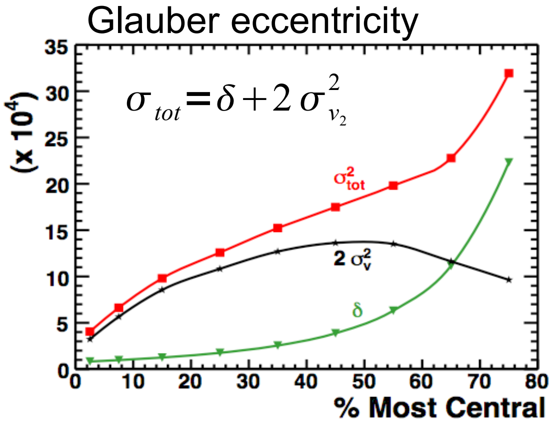
Corrected mean results

Model assuming:

$$\sigma_{v_2} = \frac{\sigma_{\epsilon_{\mathrm{part}}}}{\langle \epsilon_{\mathrm{part}} \rangle} \langle v_2 \rangle$$

$$\delta = \frac{2}{N_{\mathrm{part}}} \delta_{\mathrm{pp}}$$

with $\delta_{\mathrm{pp}} = 0.0145$



Glauber eccentricity

Corrected mean values agree in participant frame.
Reduces errors on $v_2$ measurements by about 20%.

Ollitrault et. al.,
PRC 80 80 014904 (2009)

# Contribution from non-flow correlations

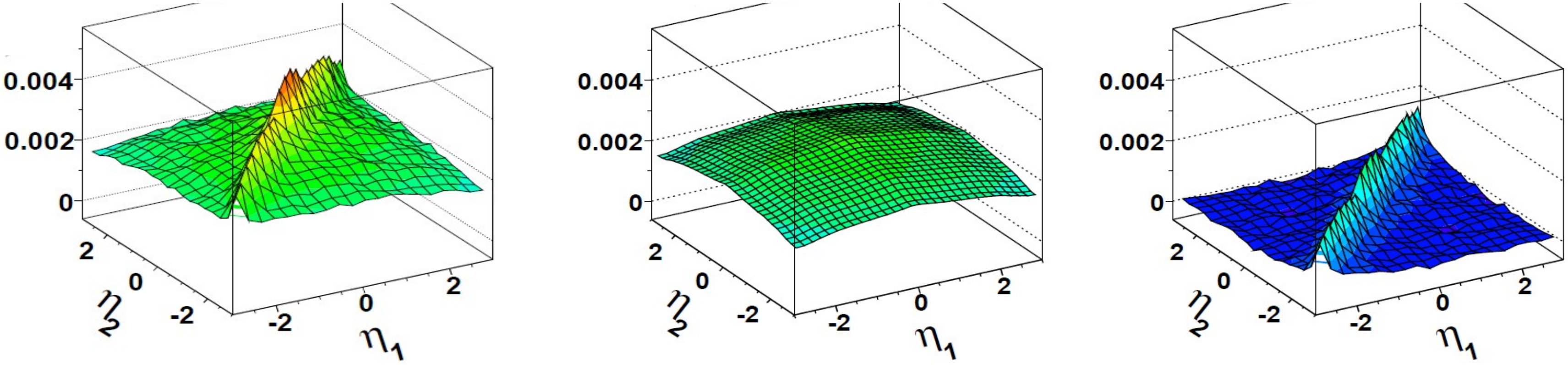
WORK IN PROGRESS

- PHOBOS has data driven analysis to measure the contribution of non-flow
  - Flow is a function of η and correlates particles at all Δη
  - Non-flow is dominated by short range correlations (small Δη)
  - Study correlations at different Δη

$$v_2^2(\eta_1,\eta_2) \equiv \langle \cos(2\Delta\phi) \rangle (\eta_1,\eta_2)$$
$$= v_2(\eta_1) * v_2(\eta_2) + \delta(\eta_1,\eta_2)$$

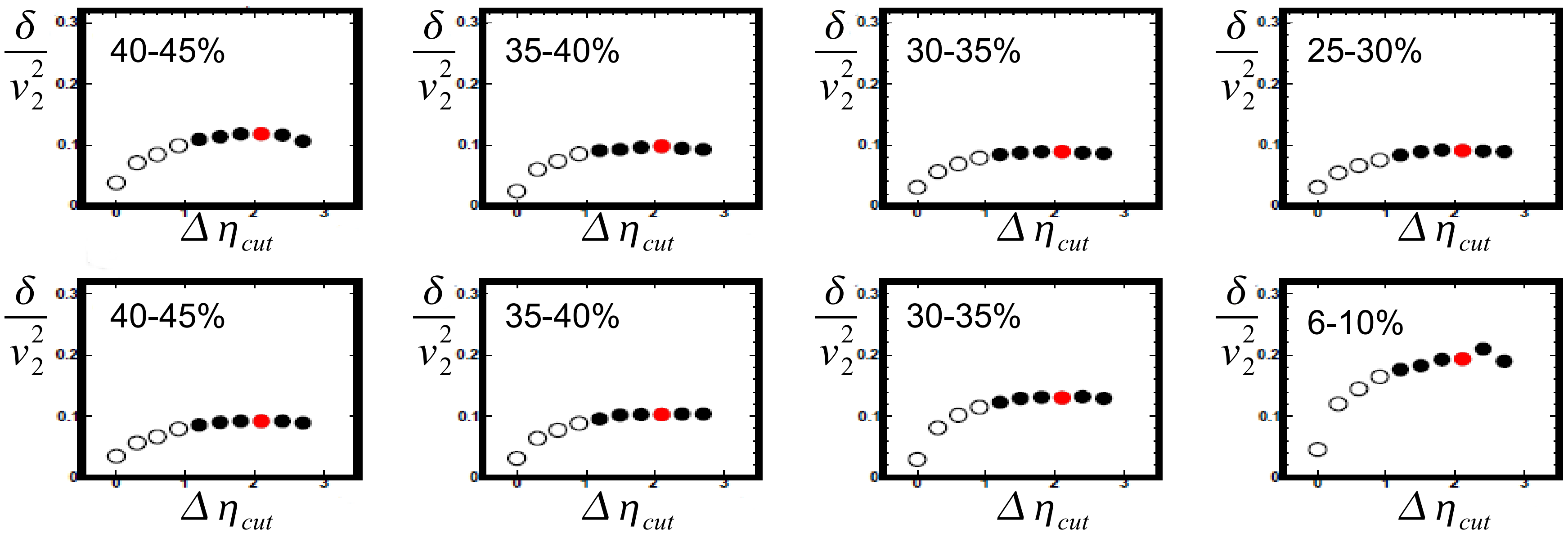
- Assume non-flow to be zero for Δη>2
- Fit $v_2^2(\eta_1,\eta_2) = v_2^{fit}(\eta_1) * v_2^{fit}(\eta_2), \ |\eta_2-\eta_1|>2$
- Subtract fit results at all $(\eta_1,\eta_2)$
- Integrate over particle pairs to obtain $\delta / v_2^2$
- Numerically relate $\delta / v_2^2$, $\sigma_{tot} / \langle v_2 \rangle$ and $\sigma_{flow} / \langle v_2 \rangle$

$$v_2^2(\eta_1,\eta_2) - v_2^{fit}(\eta_1) \times v_2^{fit}(\eta_2) = \delta(\eta_1,\eta_2)$$



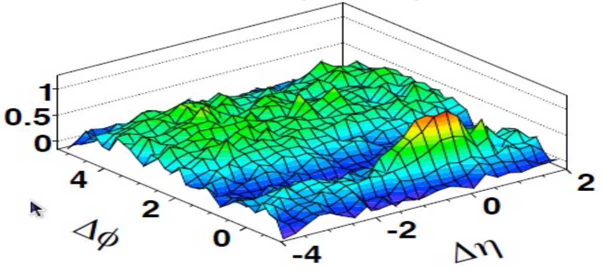
# Contribution from non-flow correlations

WORK IN PROGRESS



Non-flow ratio as a function of Δη cut used to obtain the fit.

Saturation is encouraging, although can not rule out contribution from flat long-ranged plateau

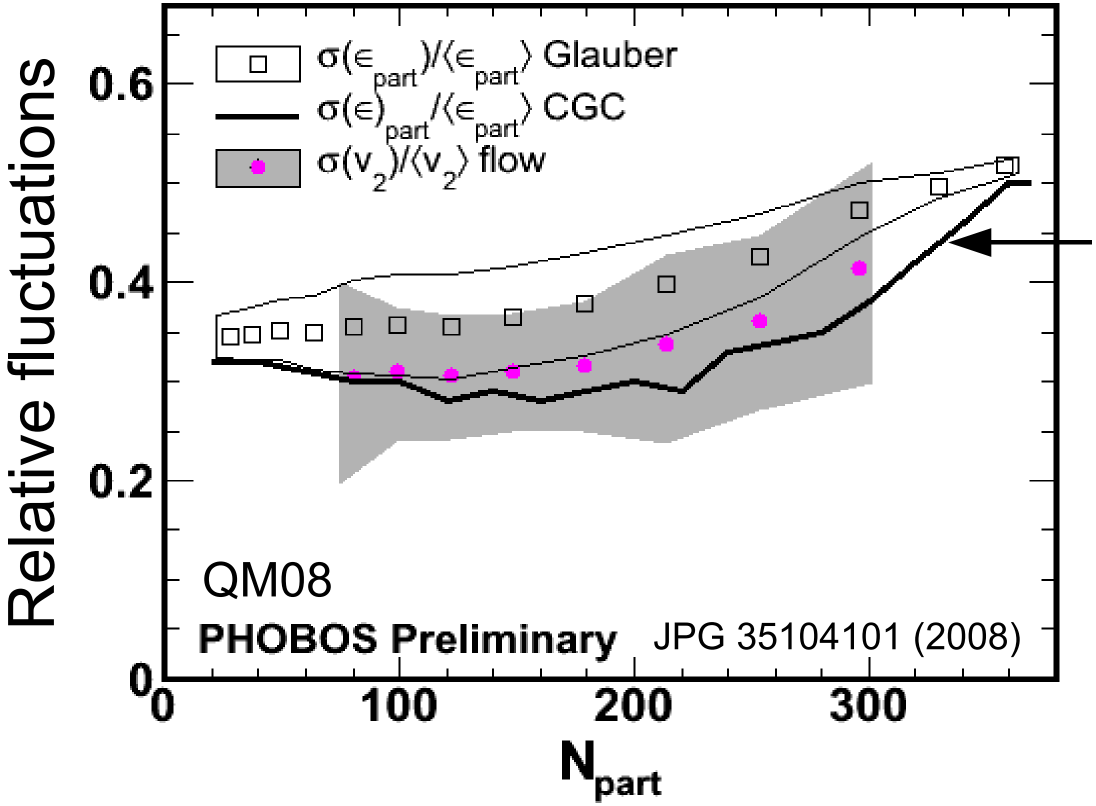


PHOBOS, arxiv:0903.2811 (sub. to PRL)

Red-point is baseline for analysis, while black points are used for systematic error

# Measured relative fluctuations

WORK IN PROGRESS



CGC-MC (fKLN)

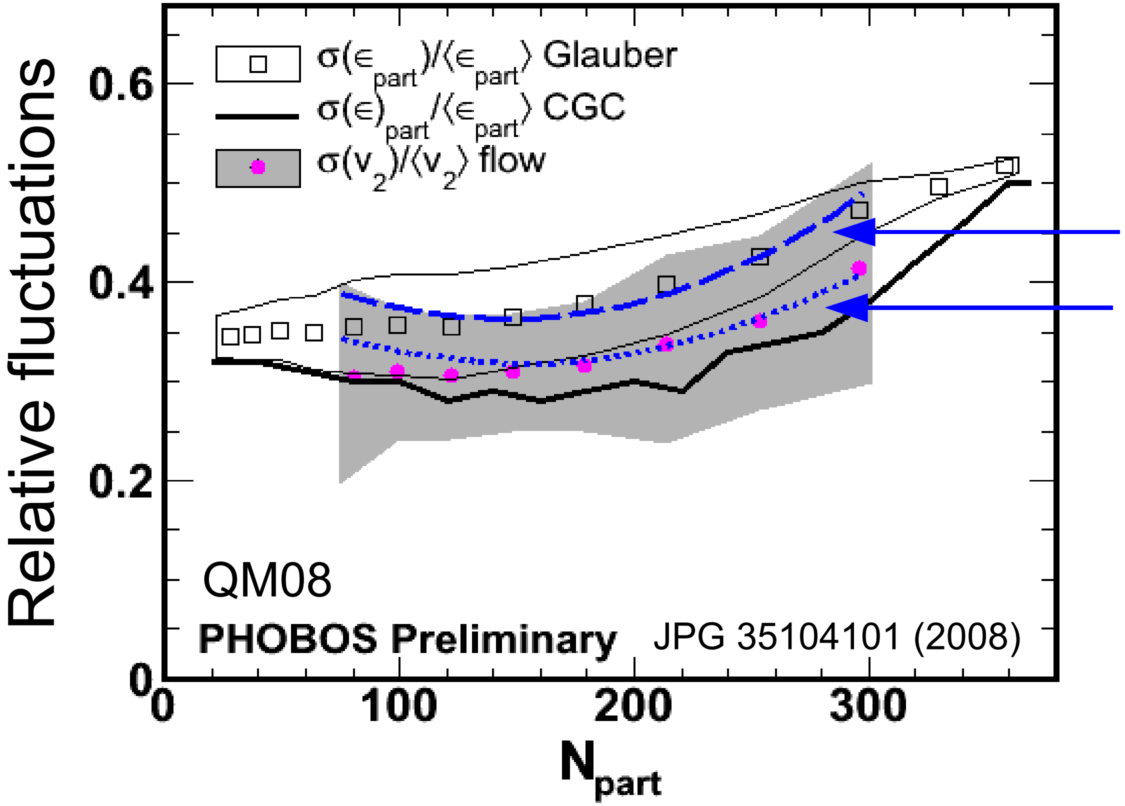
Drescher, Nara,
PRC 76 (2007) 41903

Initial state fluctuations if indeed present seem not to be significantly enhanced in later stages of the collision

Short-range non-flow contributions taken out

# Measured relative fluctuations

WORK IN PROGRESS



Analytic correction:

Glauber

CGC (30:70)

Ollitrault et. al.,
PRC 80 80 014904 (2009)

Initial state fluctuations if indeed present seem not to be significantly enhanced in later stages of the collision

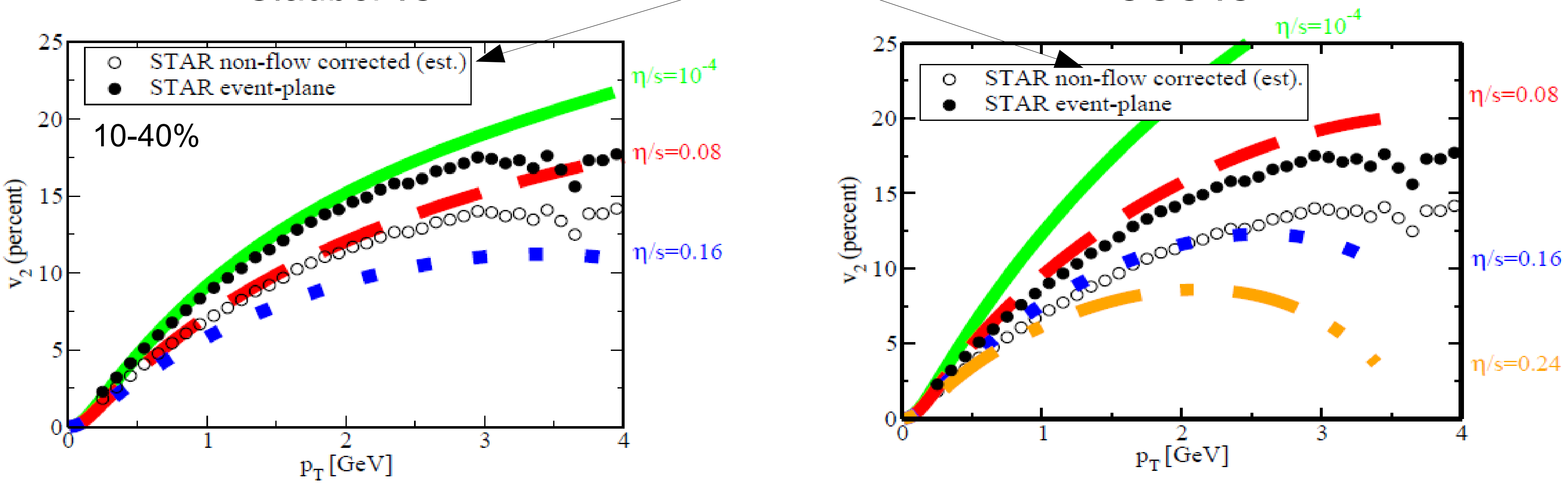
Results consistent with corrections based on the analytic correction model

# How viscous is the liquid?

Glauber IC

20% reduced

CGC IC



State-of-art results from second-order conformal hydro-dynamics (2+1D) yield a low shear viscosity to entropy ratio.

General consensus (from QM09) that: $\frac{\eta}{s} < 6 \times \frac{1}{4\pi}$

Reduced errors on $v_2$ data allows to study 20% effects.

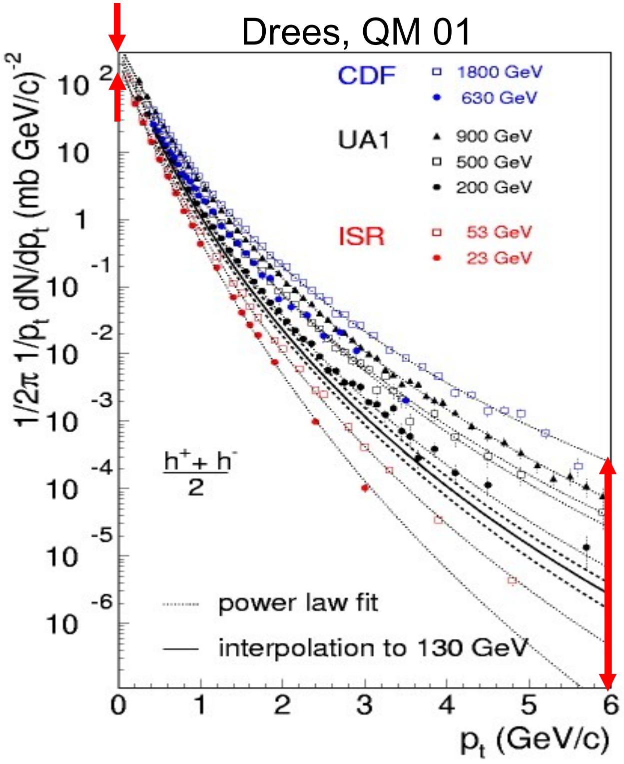
Luzum, Romatschke,
PRC 78 034915 (2008);
PRC 79 039903 (2009)

# External control parameters

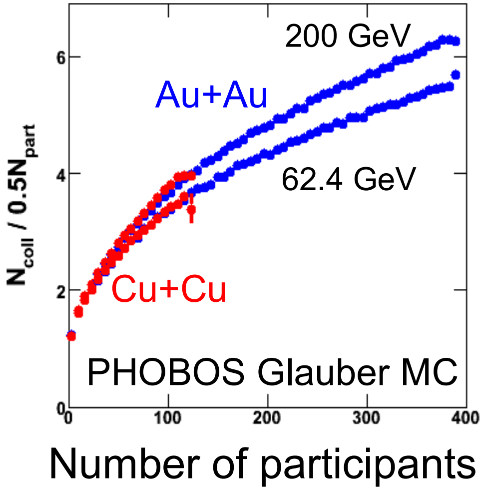
Center of mass energy

Ratio of “hard” to “soft” processes

Drees, QM 01



#Collisions / Part.Pairs



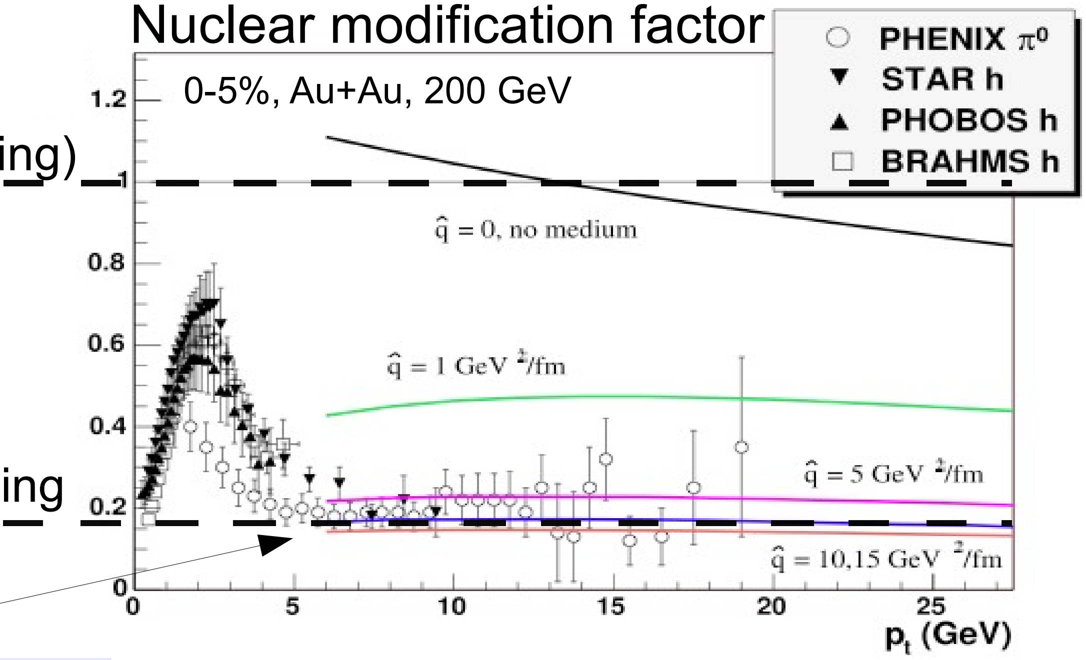
Collision centrality

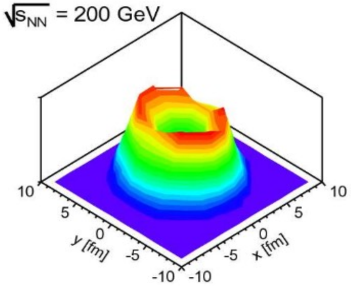
# How dense is the medium?

Nuclear modification factor

Expected yield
wrt pp ($N_{coll}$ scaling)

$N_{part}$ scaling





Origin of partons that yield >5GeV hadron in central Au+Au

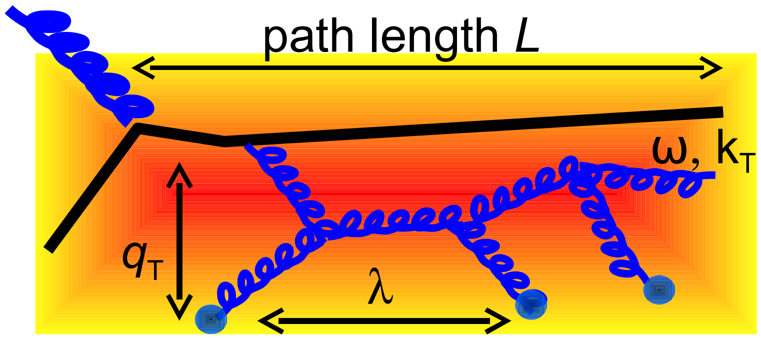
Maximal suppression?

$$N_{coll} \times \frac{S}{V} \approx N_{part}/2$$

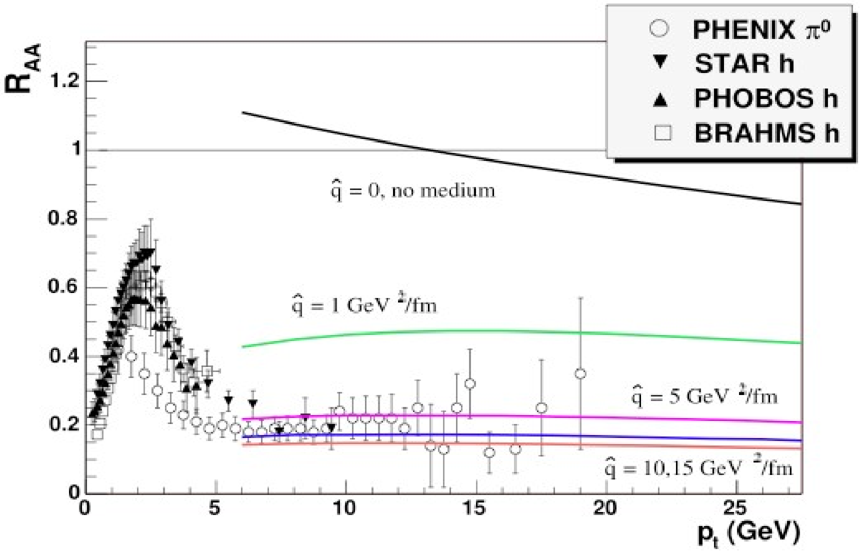
The medium is “black”: Leading spectra are suppressed by up to a factor of 5-6 wrt collision weighted pp reference

Escola et al., NPA 747 511 (2005)
Dainese et al., EPJC 38 461 (2005)

# Parton energy loss in BDMPS-Z-ASW



$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$$ encodes medium properties



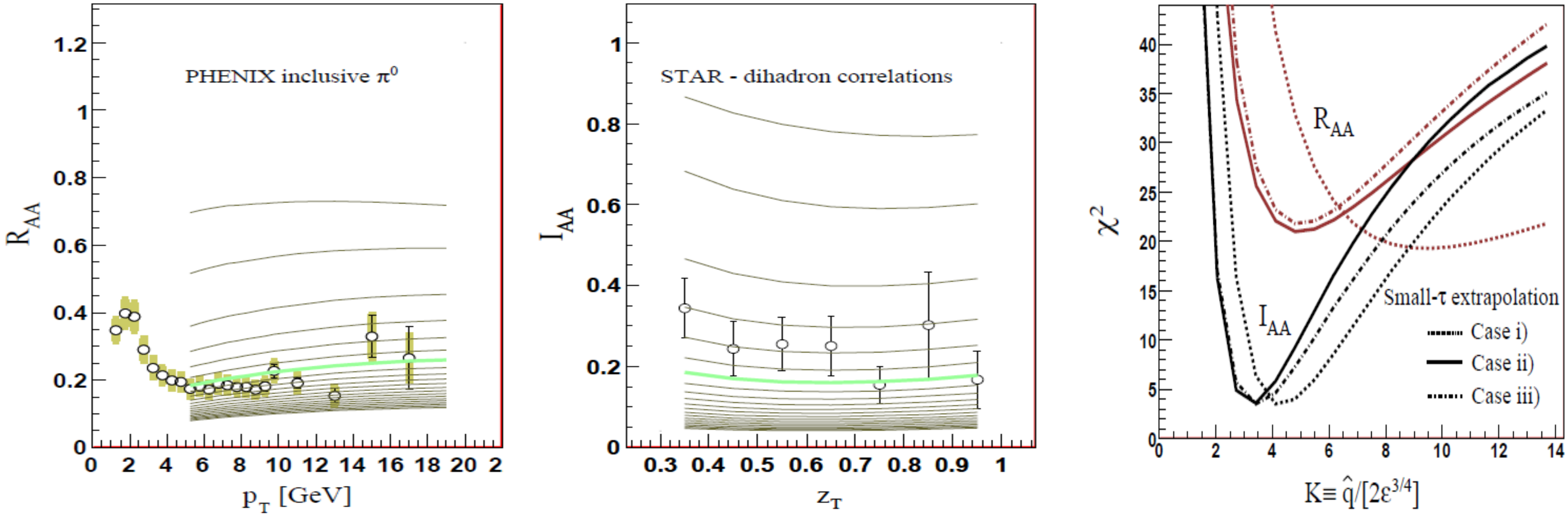
$$\left.\frac{d^2\sigma^{h}_{\text{quenched}}}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j}\int dF_{ab}\,d\Delta E_j\,dz_j\,dp^{\text{init}}_{T,j}\left.\frac{d^2\sigma^{ab\to jX}}{dp^{\text{init}}_{T,j}\,dy}\right|_{y\approx 0} \times$$

$$\delta(p^{\text{init}}_{T,j}-p_{T,j}-\Delta E_j)\,P(\Delta E_j;C_j,\hat{q}_j,L_j,p_{T,j})\,\frac{D_{h/j}(z_j)}{z_j^2}$$

Calculations lead to larger values of $\hat{q}$ than expected from pQCD arguments

Baier et al., NPB 483 291 (1997)
Zakharov, JTEPL 63 952 (1996)
Salgado, Wiedemann, PRD 68 014008 (2003)

# Results from constraint fits

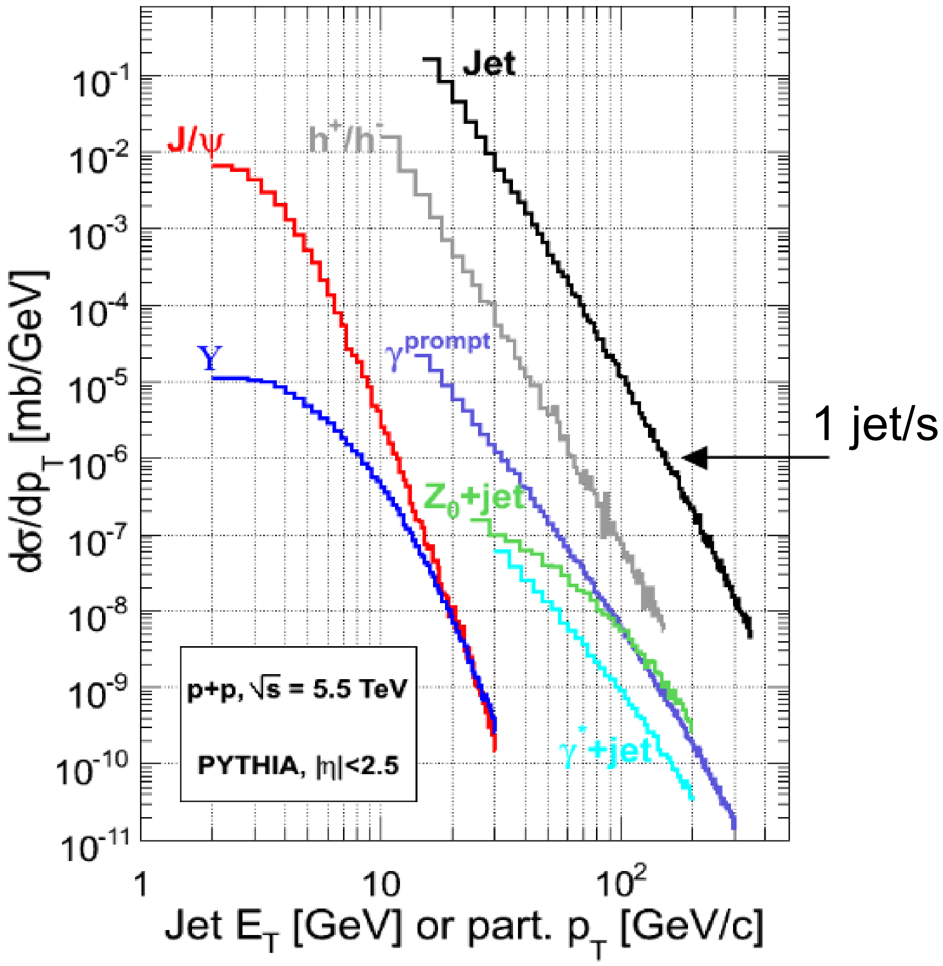


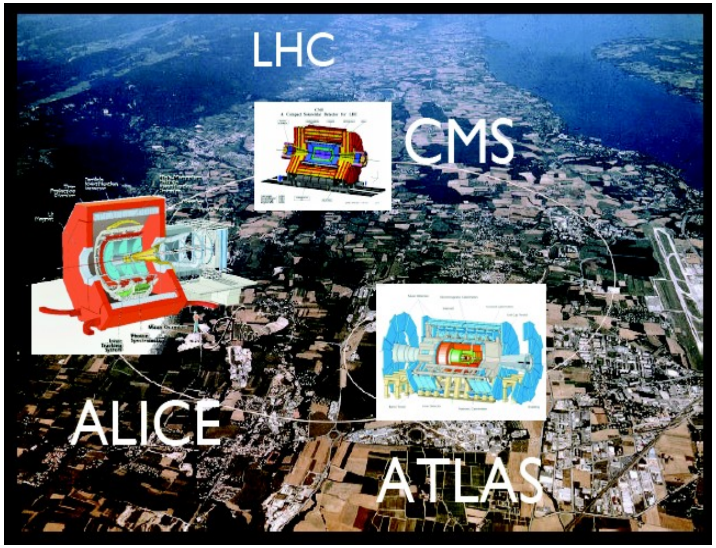
Jet quenching calculation using ASW quenching weights with a hydro description of the bulk finds $\hat{q} \approx 4\,\hat{q}_{pQCD}$

Armesto et.al, arXiv:0907.0667

# How can we learn more?

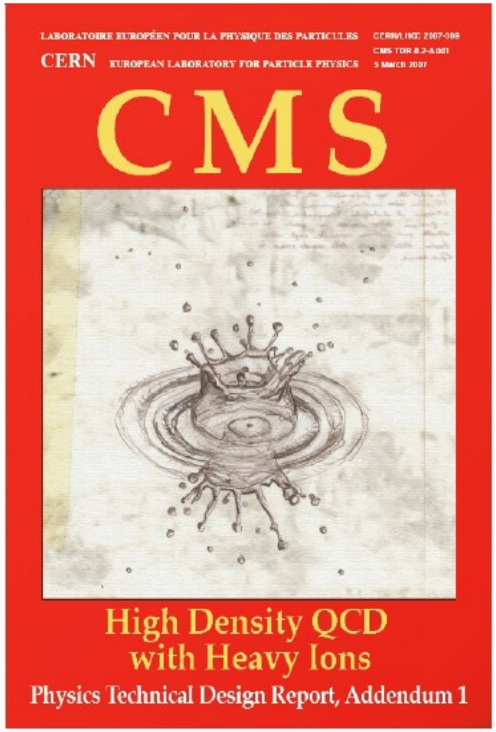
CMS, JPG 34 2307 (2007)





- At up to 5.5 TeV, high-$p_T$ probes abundant
- Qualitative new probes
  - $\gamma^*/Z_0$-jets
- Detailed study of hard scattering

# CMS as an HI experiment

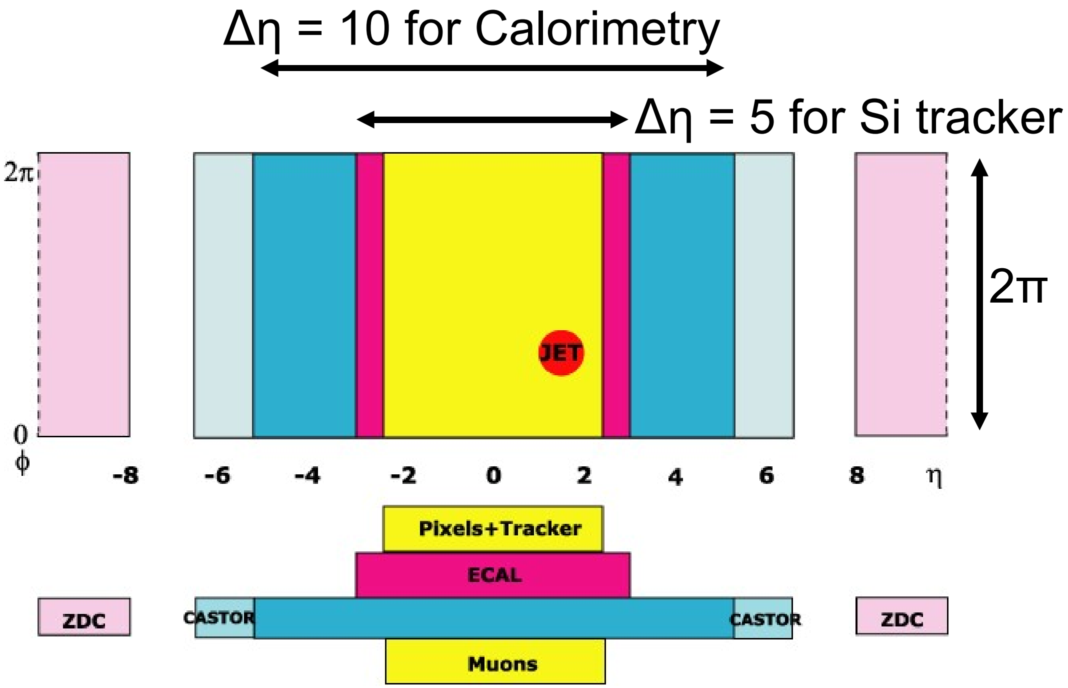


LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES CERN/LHCC 2007-009
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS CMS TDR 8.2-Add1
5 March 2007

CMS

High Density QCD
with Heavy Ions
Physics Technical Design Report, Addendum 1

JPG 34 2307 (2007)

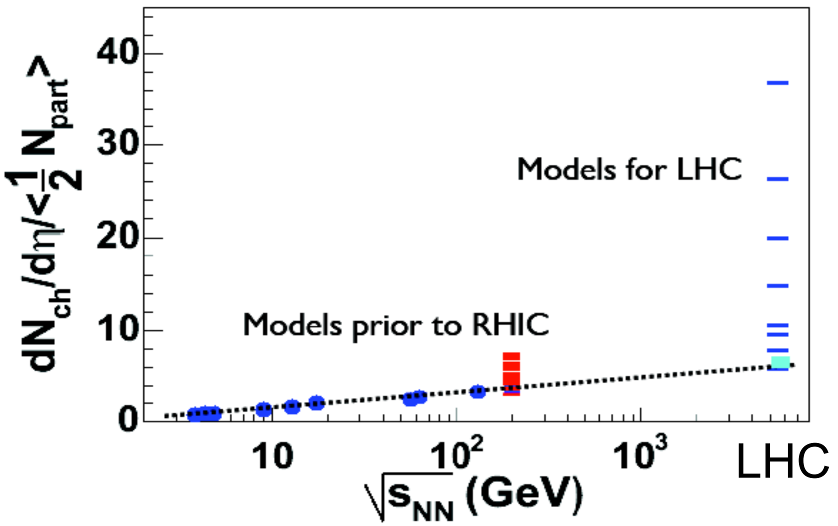


<u>Capabilities</u>

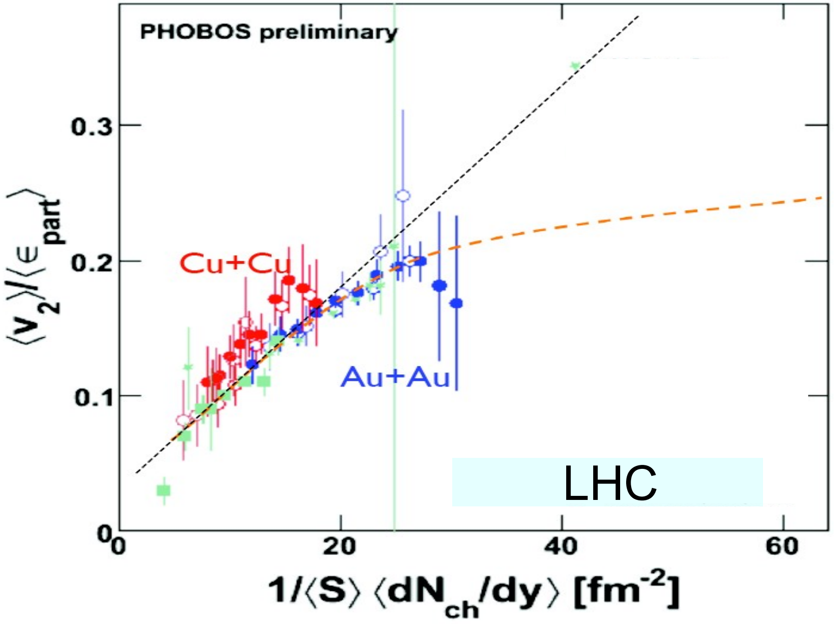
High-precision tracking over |η| < 2.5
Muon identification over |η| < 2.5
High resolution calorimetry over |η| < 5
Forward coverage
Large bandwidth: DAQ + Trigger

- Large (mid-rapidity) acceptance (tracker and calorimetry)
  - Also large forward coverage
- DAQ+HLT capable to inspect every single Pb+Pb event
  - Large statistics for rare probes

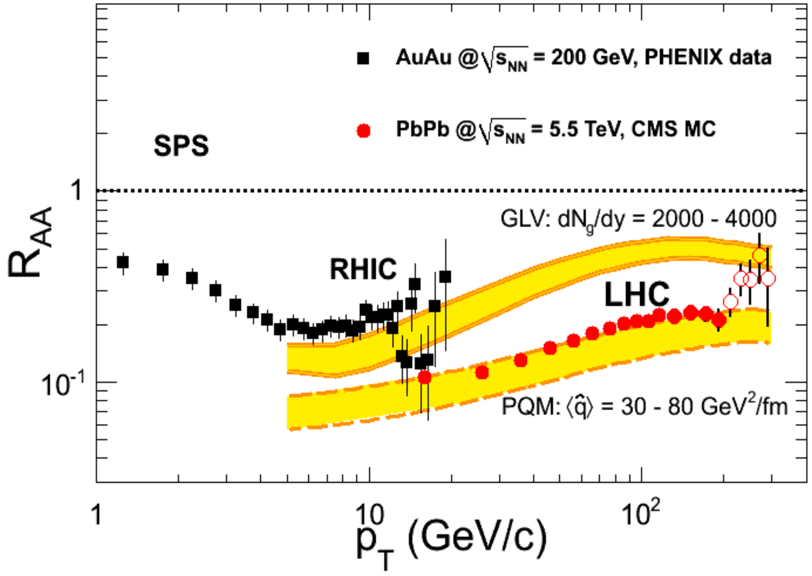
# Expected results from LHC in 2010



~1 day: Multiplicity → Initial density



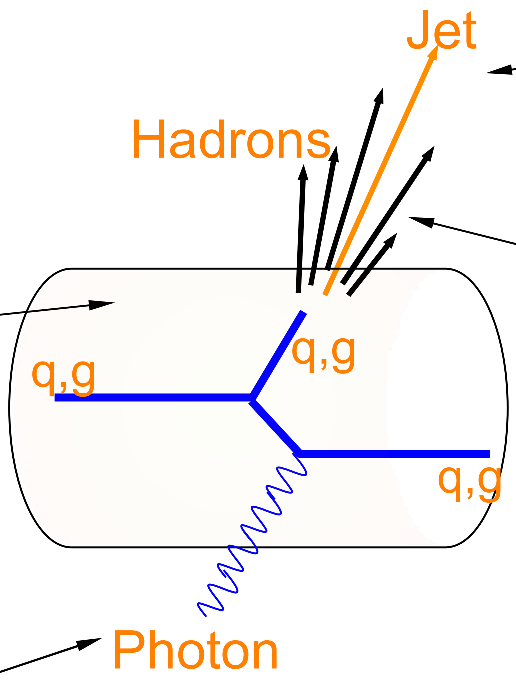
~1 week: Does $v_2$ saturate?



~1 month: Is the medium black?

Once we have these qualitative answers: Perform program of precision measurements of medium properties

# Photon-tagged jet FF



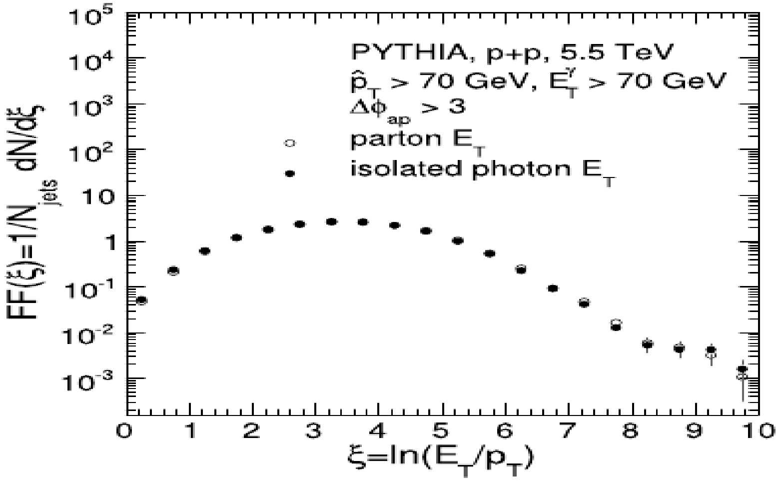
Jet axis provides parton direction

Multiplicity and flow measurements characterize density, path length

Charged hadron tracks used to calculate z = $p_T/E_T$

Photon energy tags parton energy $E_T$

Measure jet fragmentation function: $dN/d\xi$ with $\xi=-\log z = \log p_T/E_T$

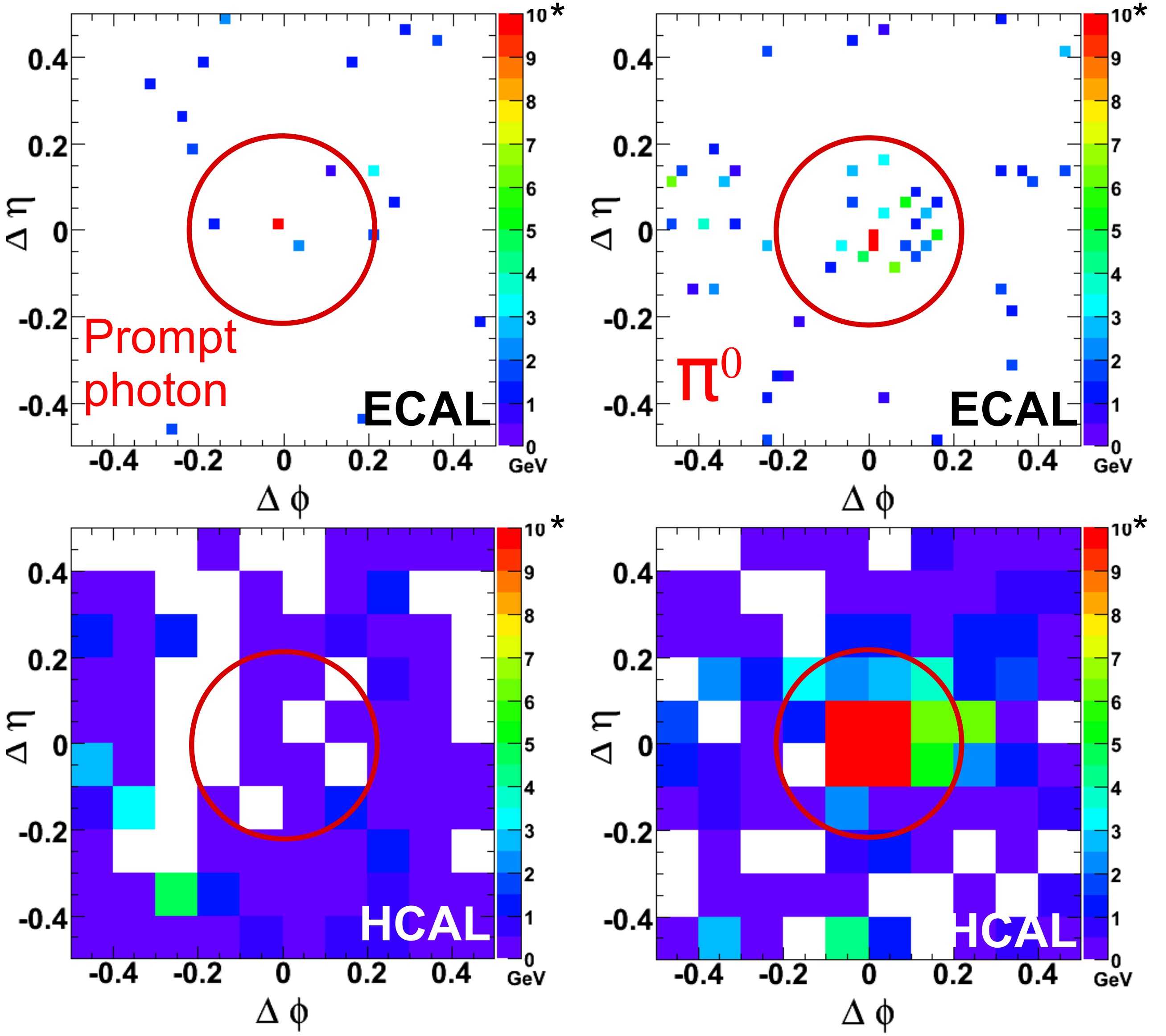


All results based on GEANT-4 simulations using full reco algorithms for one run-year statistics at design lumi and at 5.5 TeV

CMS, JPG 35 104166 (2008)

# Photon ID variables

- Selection variables
  - Cluster shape in ECAL
  - ECAL/HCAL energies in cones with R≤0.5
    - Background subtraction
  - Track isolation
- Total of 21 variables
  - Linear discriminant analysis (Fisher) and cut optimization using TMVA

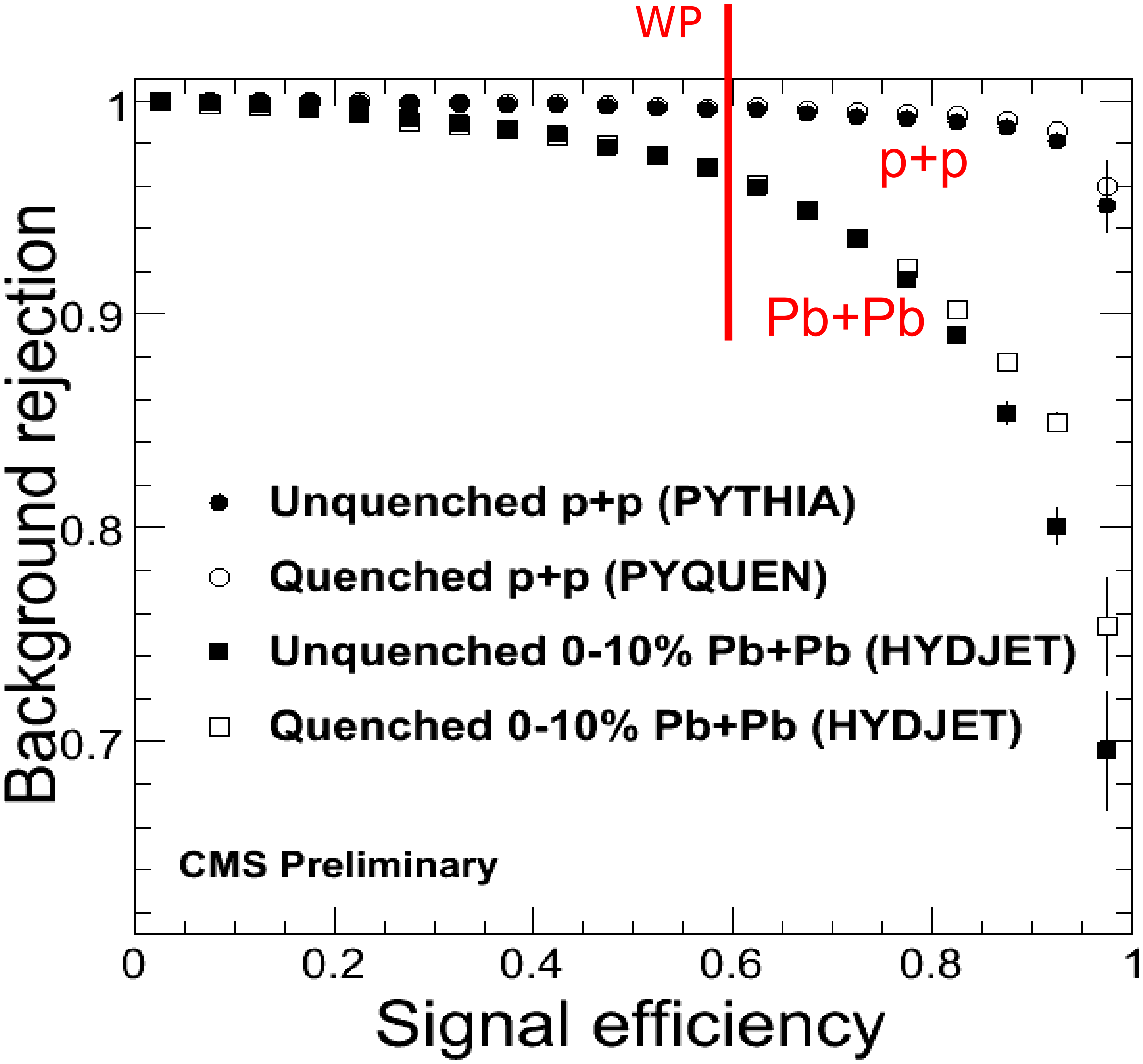


TMVA: http://tmva.sourceforge.net

*) Maximum set to 10 GeV

# Photon identification performance

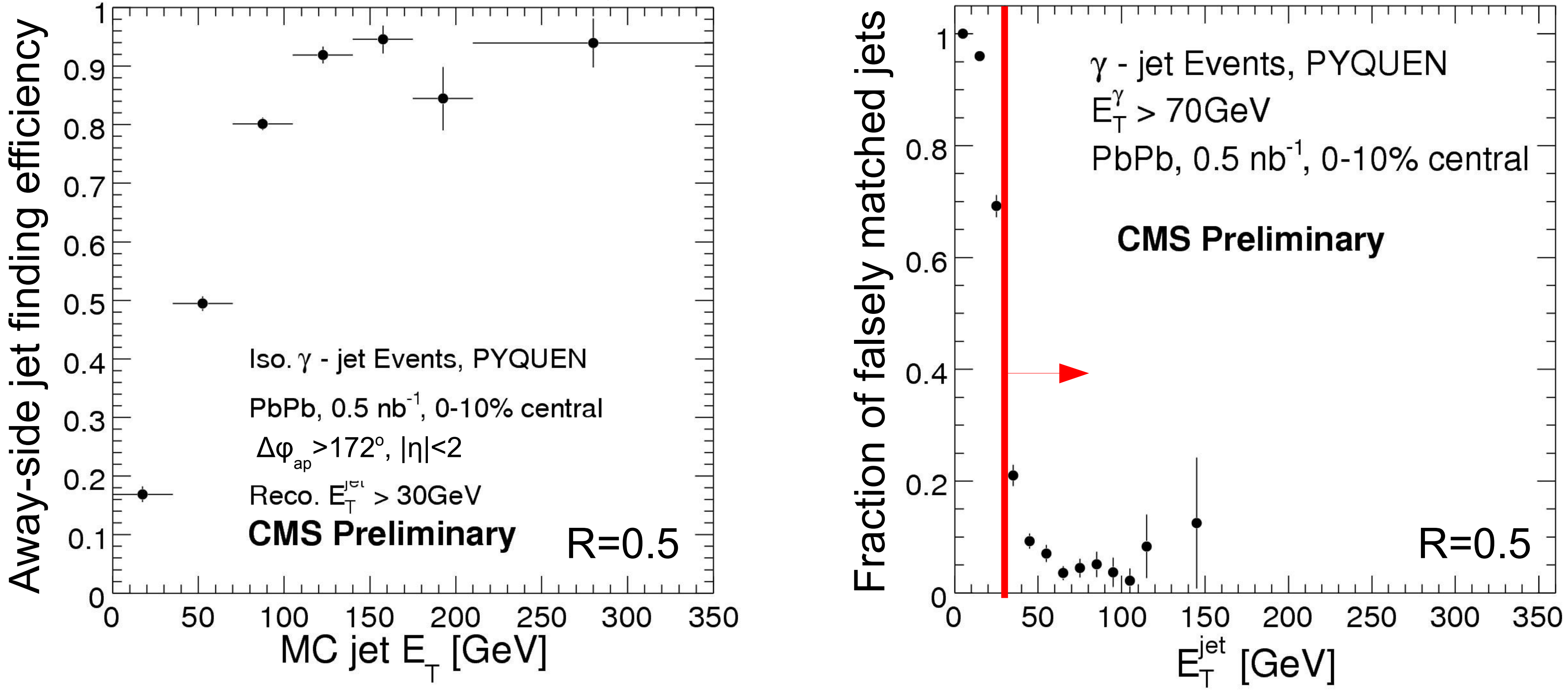
- Set working point to 60% signal efficiency
- Leads to 3.5% false acceptance (96.5% rejection)
- Training was done on unquenched samples only



For quenched Pb+Pb S/B improves from 0.3 to 4.5 after cuts

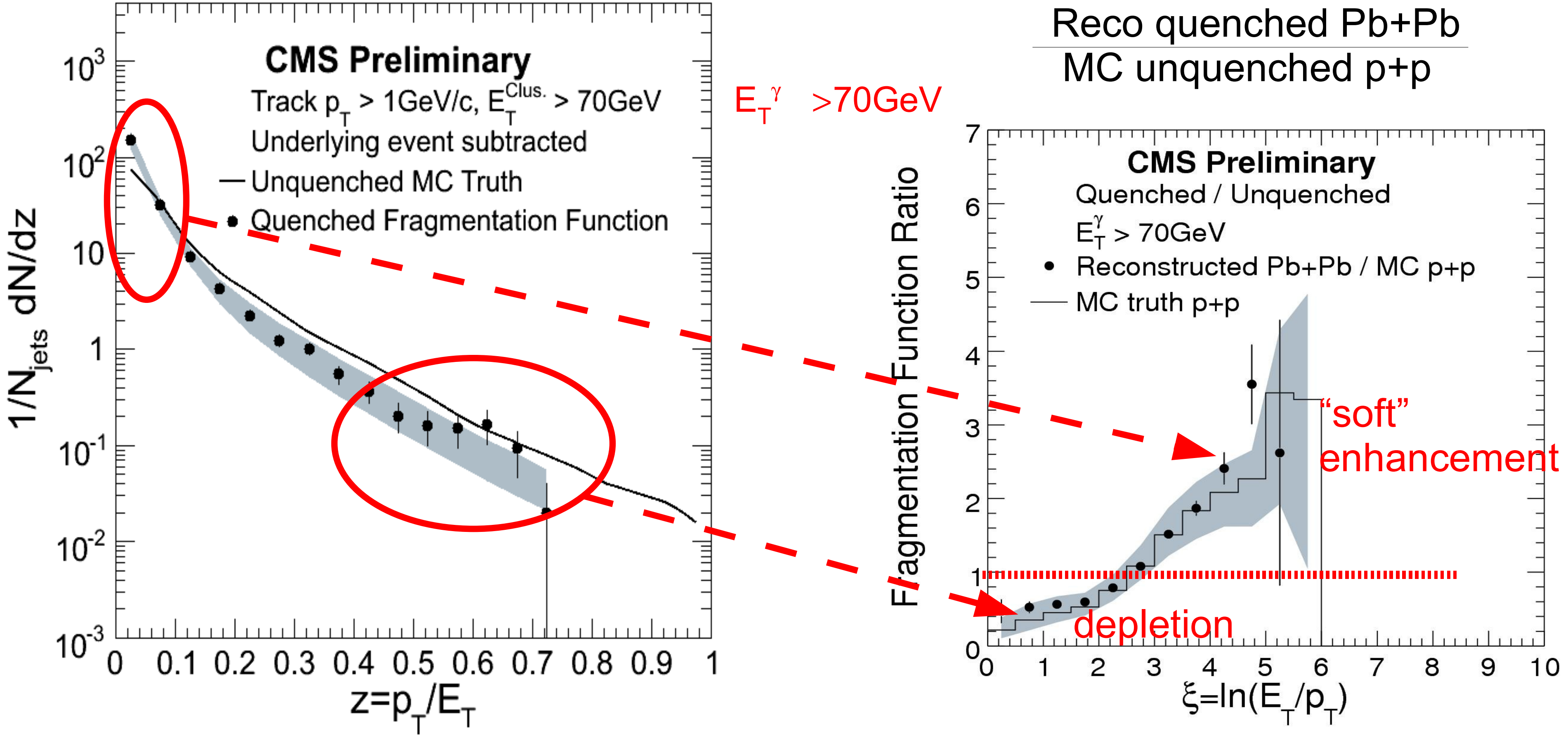
# Away-side jet finding (for tagged jets)

Quenched Pb+Pb



- Select away-side jet with $\Delta(\gamma,\text{jet}) > 172^0$, $|\eta| < 2$ and $E_T > 30$ GeV
  - The energy cut reduces the false rate to 10% level
    - Analysis does not use jet energy otherwise
  - Jet finding efficiency rises sharply
    - Main source (~30%) of systematic uncertainty in reconstructed FFs

# Final result: FF ratio



Medium modification of fragmentation functions can be measured with high significance for 0.35 < ξ < 5 (or z < 0.7)

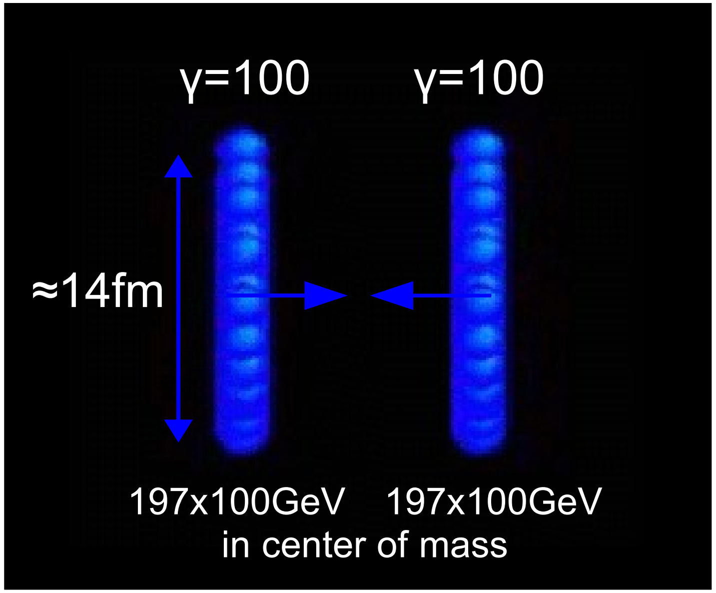
# Conclusions

- Significant progress in understanding and quantification of ”something more like a liquid”
  - Understanding of flow, non-flow correlations, flow- and eccentricity- fluctuations converges
  - Shear viscosity over entropy ratio small, probably smaller than 6 x theoretical minimum
  - Transport coefficient ~4x larger than expected from pQCD
  - Fruitful interaction between experimentalists and theoreticians
- Exiting times ahead with p+p and Pb+Pb @ LHC starting this year

I'd like to thank R.Stock, A.Dainese, A.Morsch, U.Wiedemann, C.Reed, B.Alver, E.Wenger, W.Li, G.Roland, W.Busza, G.Veres, M.Baker, P.Steinberger, U.Heinz, Y.Lee, Y.Yilmaz, A.Yoon and all members of the PHOBOS and CMS collaborations.

# Extra

# Au+Au collisions at RHIC

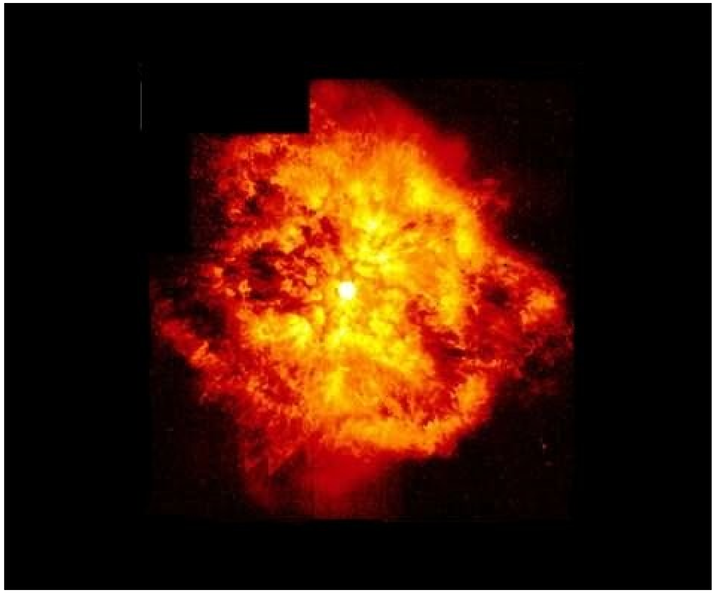


MIT heavy-ion collision evolution animation
Y.-J.Lee, S.Yoon, W.Busza
(c.f. PHOBOS homepage)

About 6 μJ of kinetic energy

1 GeV ≈ mass of proton
1 fm = $10^{-15}$m ≈ radius of proton

# Au+Au collisions at RHIC



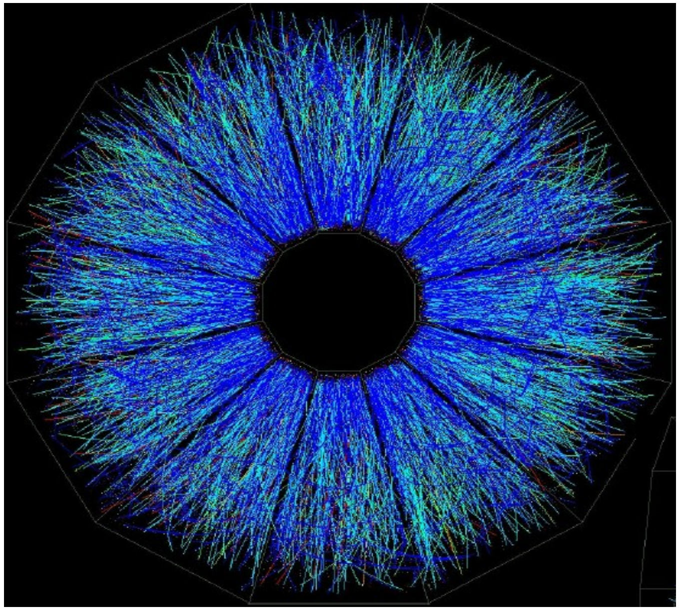
Nebula M1-67
(see hubblesite.org)

About 75% of the kinetic energy is converted into a short-lived 'fireball'

Proper life time
$\approx$ 10-15 fm/c = $10^{-23}$s

http://hubblesite.org/newscenter/archive/releases/1998/38/

# Au+Au collisions at RHIC



STAR event display

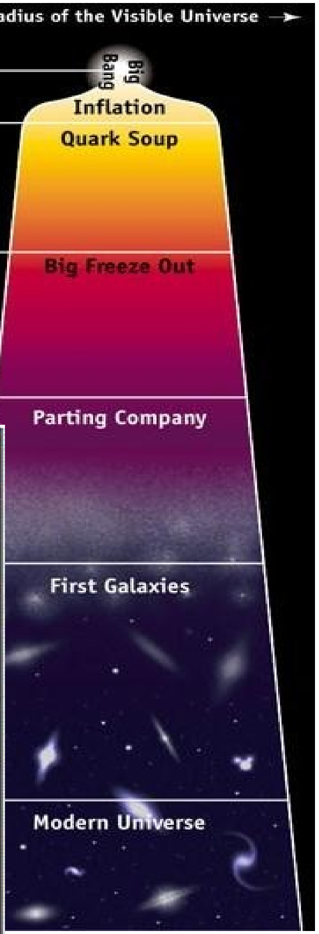
Out of the fireball,
thousands of particles emerge

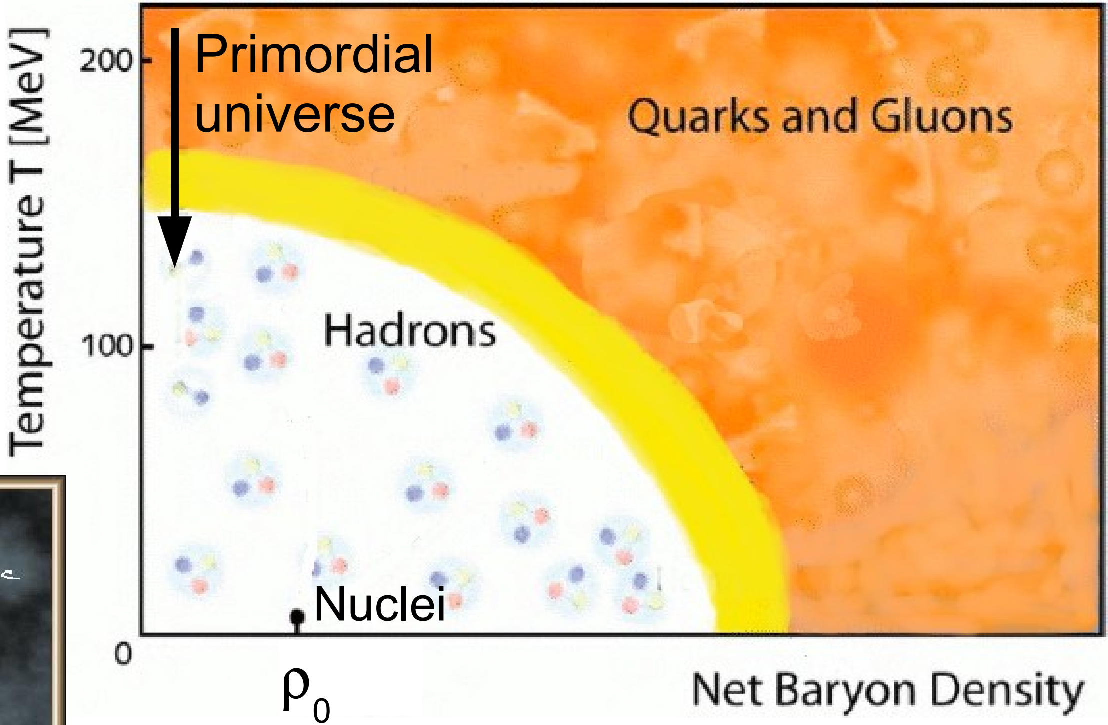
# Situation around 1975

In high energy physics we have concentrated on experiments, in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of “vacuum”, we must turn to a different direction; we should investigate some “bulk” phenomena by distributing high energy over a relatively large volume.

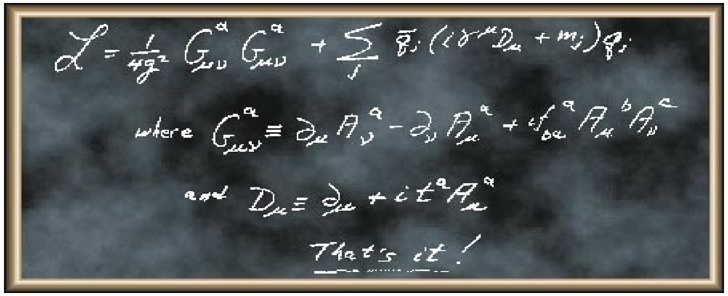
T.D.Lee,
Rev.Mod.Phys.47(1975)267

Quark-hadron phase transition in the primordial universe





Confinement +
chiral symmetry breaking (1973)



$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f_{abc} A^b_\mu A^c_\nu$

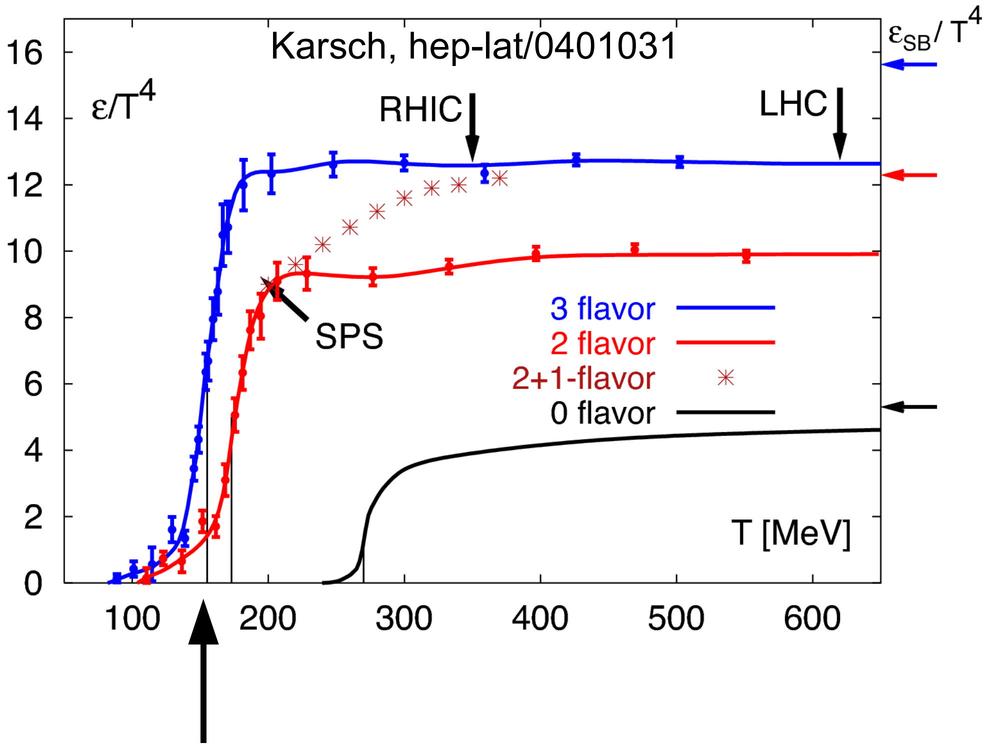
and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

# QCD matter at high temperature

TFLOPS super computer

$$Z=\int\prod dU\, e^{-S_G} \longrightarrow$$



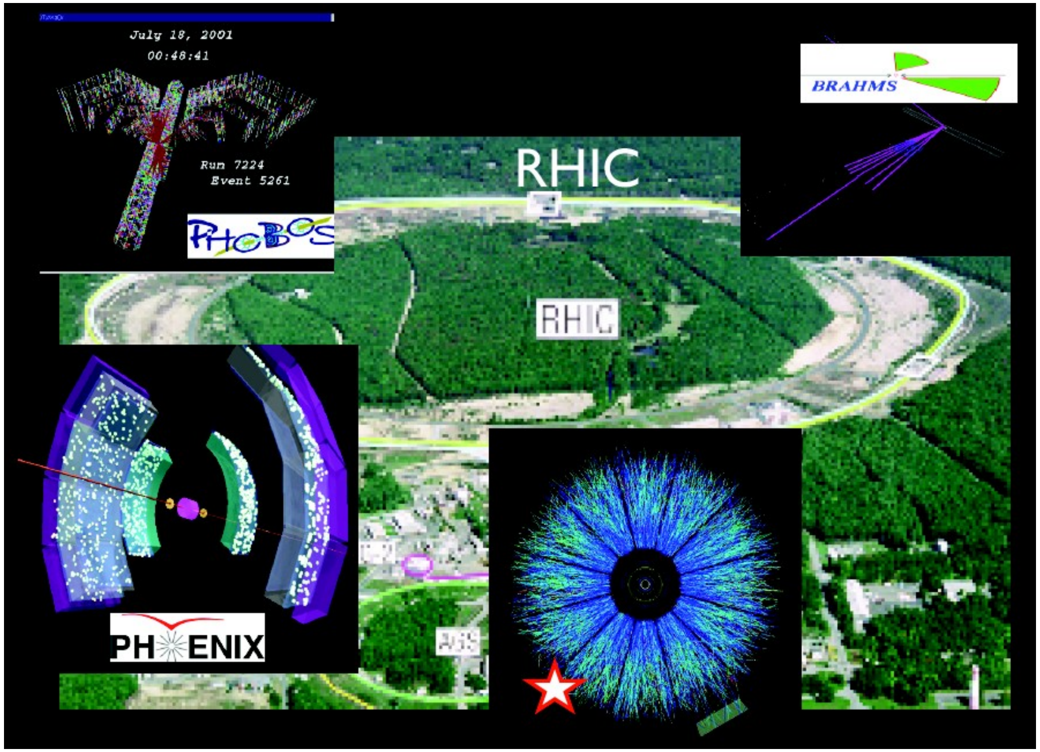
$T_{crit}$≈170MeV ~$2{\cdot}10^{12}$ K

$\varepsilon_{crit}$≈0.7GeV/fm$^3$ (~5 x $n_0$)

- Numerical calculations in LQCD:
  Phase transition at high T

- Cross-over / 1st order
  for finite densities
  (Details depend on lattice parameters and chiral + continuum limit extrapolations)

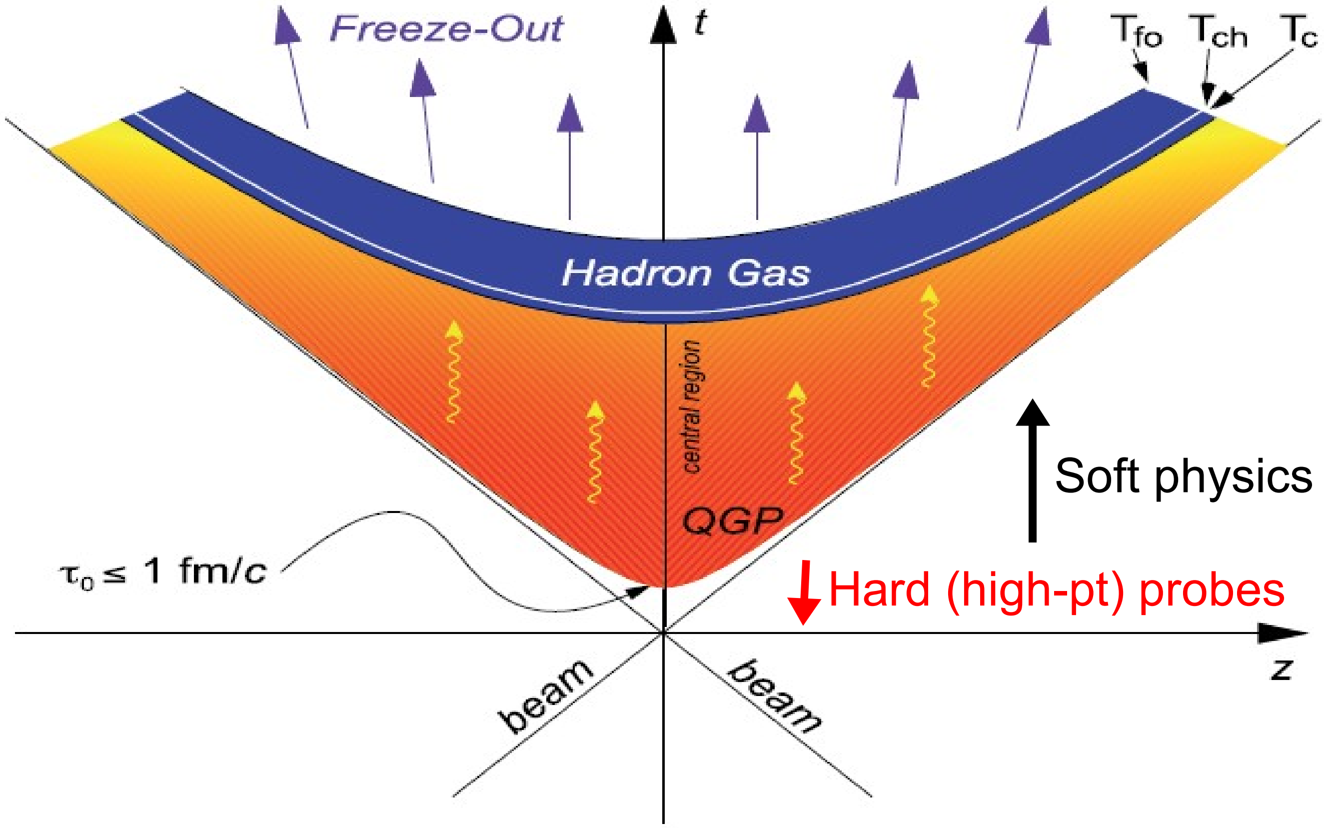
# Heavy ion experiments at RHIC



- Superconducting collider
  - 3.8 km circumference
- First beams in June 2000
  - p+p, d+Au, Cu+Cu, Au+Au
  - ~20, 62.4, 130, 200 AGeV
- 4 Experiments
  - PHENIX, STAR (big)
  - BRAHMS, PHOBOS (small)

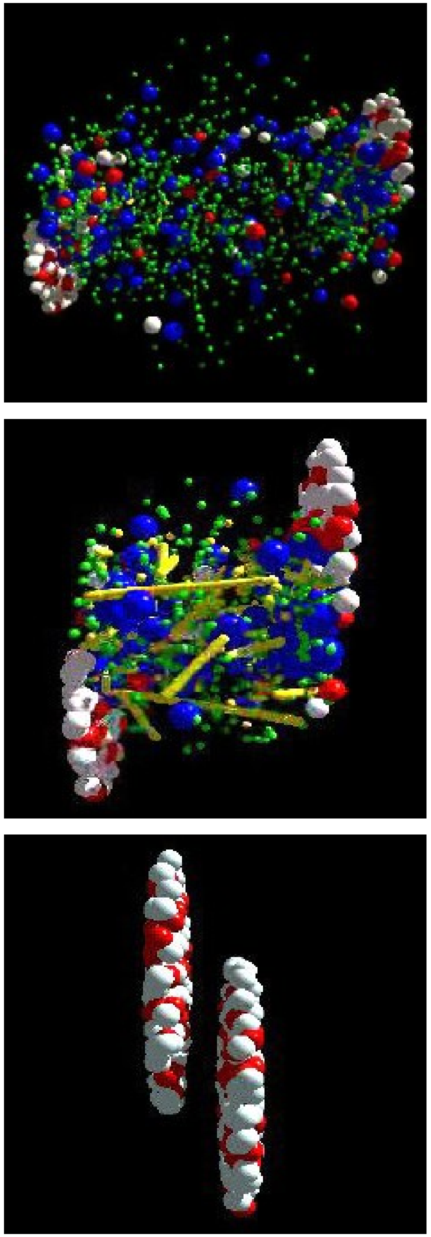
| | AGS | SPS | RHIC |
|---|---|---|---|
| $\sqrt{(s_{NN})}$ (GeV) | 5 | 17 | 200 |
| Beam rapidity | ±1.6 | ±3 | ±5.4 |

# Space-time collision evolution



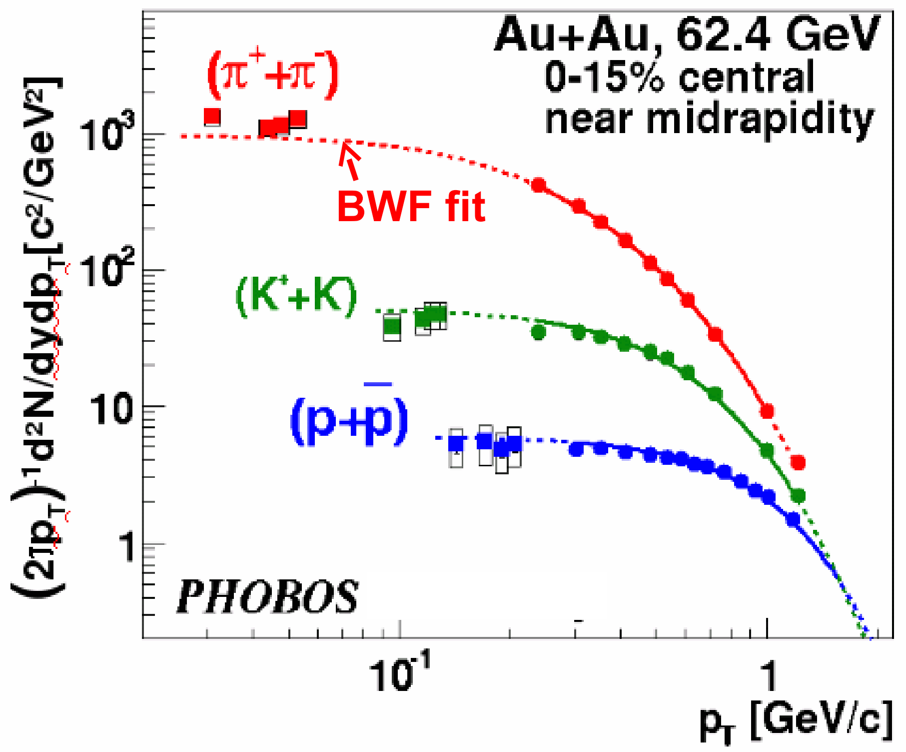
Soft physics regime

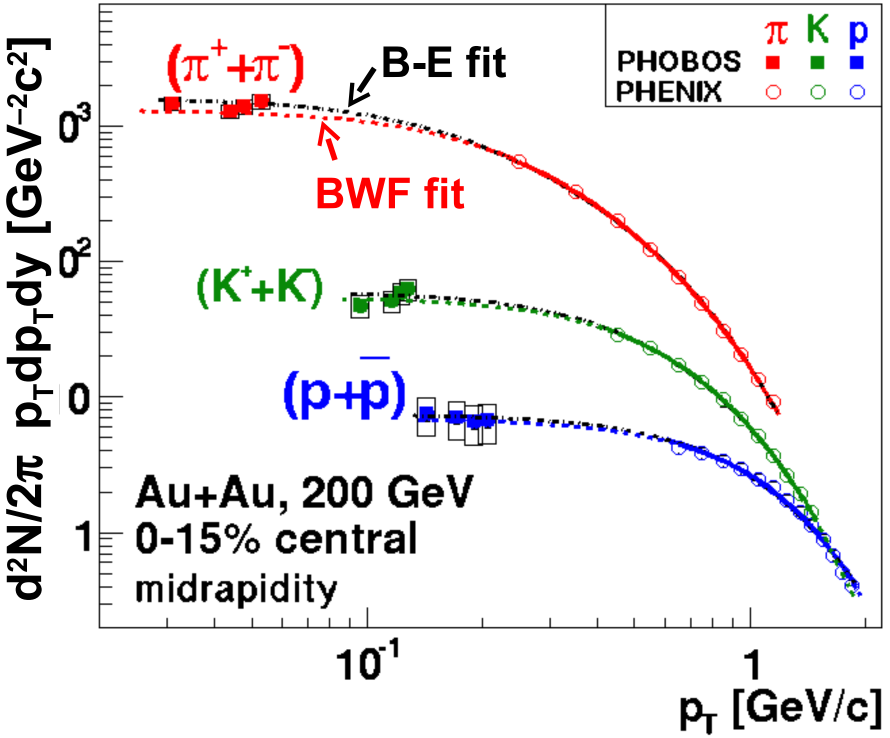
Hard (high-pt) probes



- Disentangle initial from final state effects (d+Au)
- Study density vs geometry effects (Au+Au, Cu+Cu)
- Need calibrated baseline (p+p)

# Properties of the medium





In a large volume + weakly interacting system, one expects the development of particles with long wavelengths.

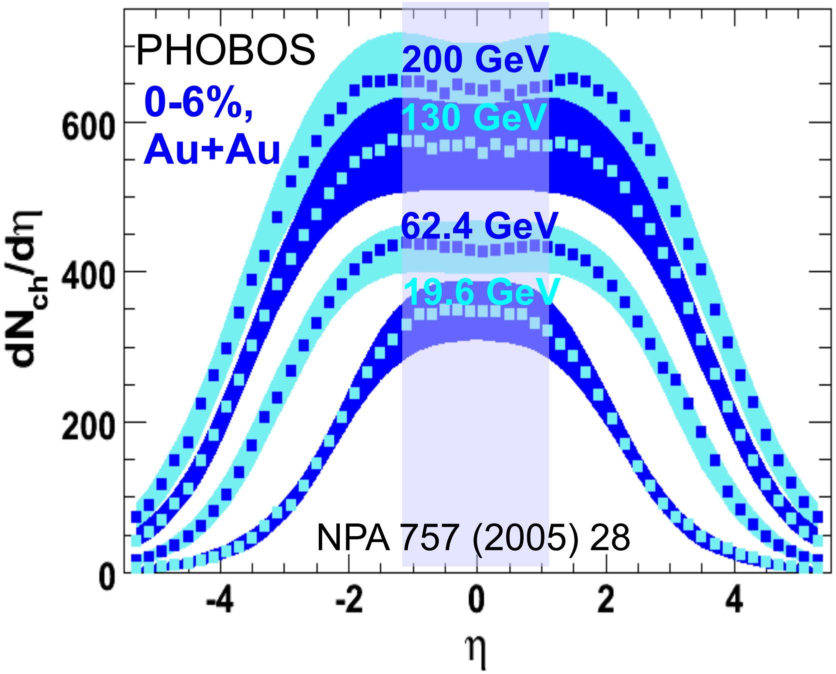
PHOBOS WhitePaper

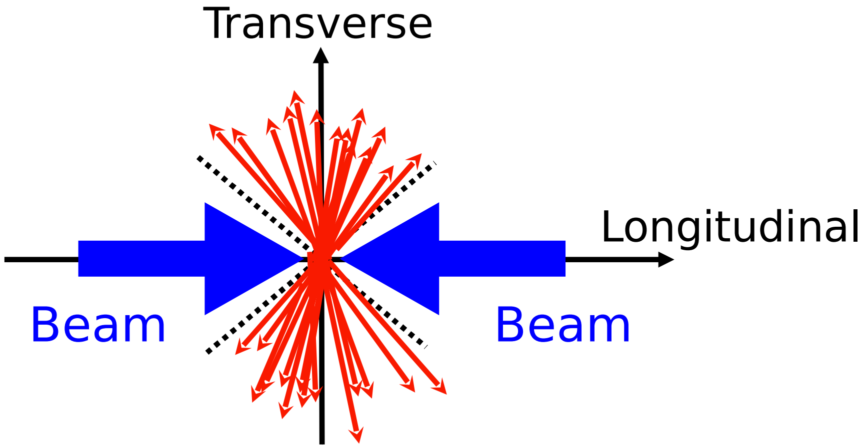
No evidence of enhanced particle production at very low $p_T$

constraints → <E>

200 GeV PHOBOS: PRC 70 051901 (R) (2004)
200 GeV PHENIX: PRC 69 034909 (2004)
62.4 GeV PHOBOS: PRC 75 024910 (2007)

# Energy density reached at RHIC





Use “energy flow” from longitudinal (=beam) to transverse direction for the estimate of energy/volume

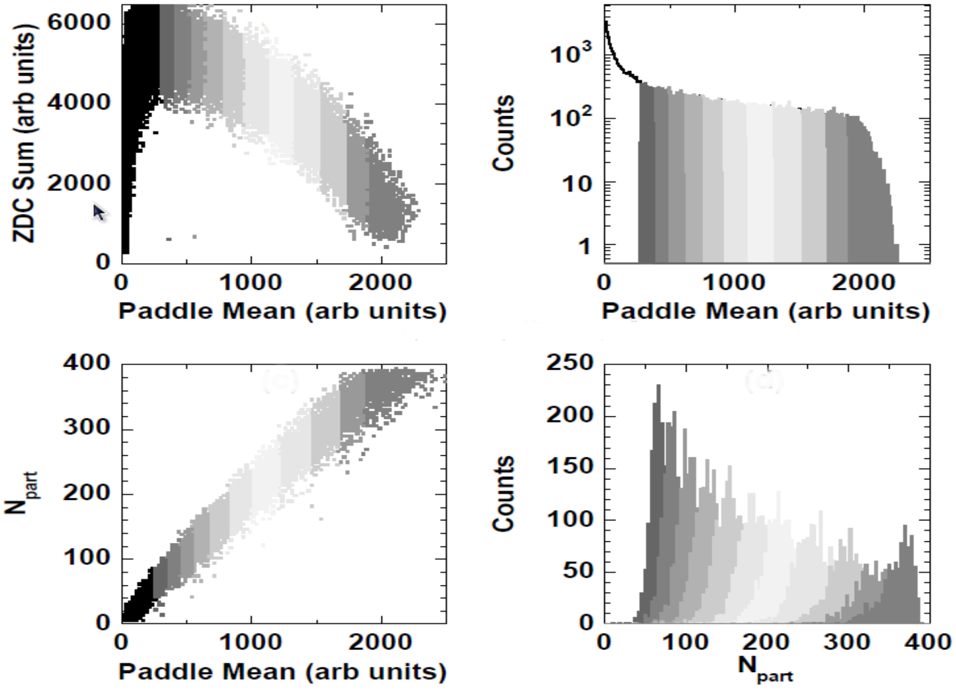
@200 GeV

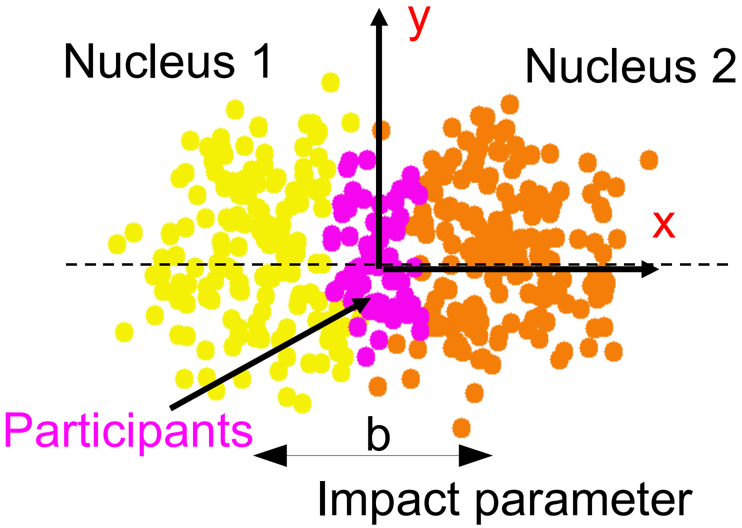
$$\frac{\text{1000 particles x 0.5 GeV/particle}}{\pi \text{ x } (7 \text{ fm})^2 * 1 \text{ fm}} \approx 3\text{GeV/fm}^3$$

(4x larger than $\varepsilon_{crit} \approx 0.7\text{GeV/fm}^3$)

# Centrality determination

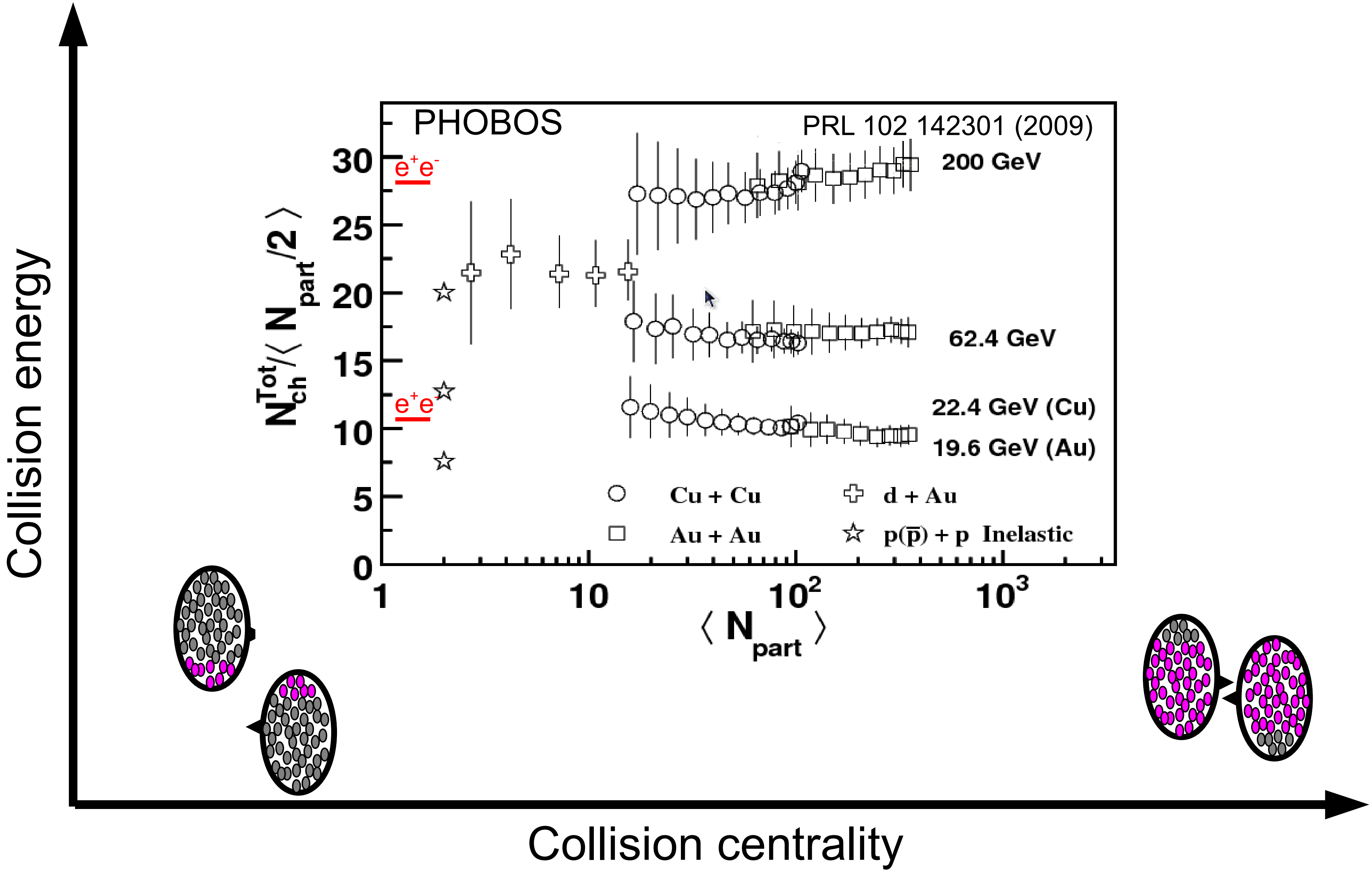
- Makeup of nuclei
  - Made up of nucleons drawn from Wood-Saxon distribution
  - Separate by b (with dN/db~b)
- Collision of nuclei
  - Assume: Nucleons travel along z on straight-line paths and interact when their centers are within $\sqrt{\sigma_{inel}^{NN}/\pi}$
  - #Participants is number of nucleons that interact at least once ($N_{part}$~A)
  - #NN-collisions is total number of collisions ($N_{coll}$~$A^{4/3}$)
- Relate to data via Glauber MC based detector simulations



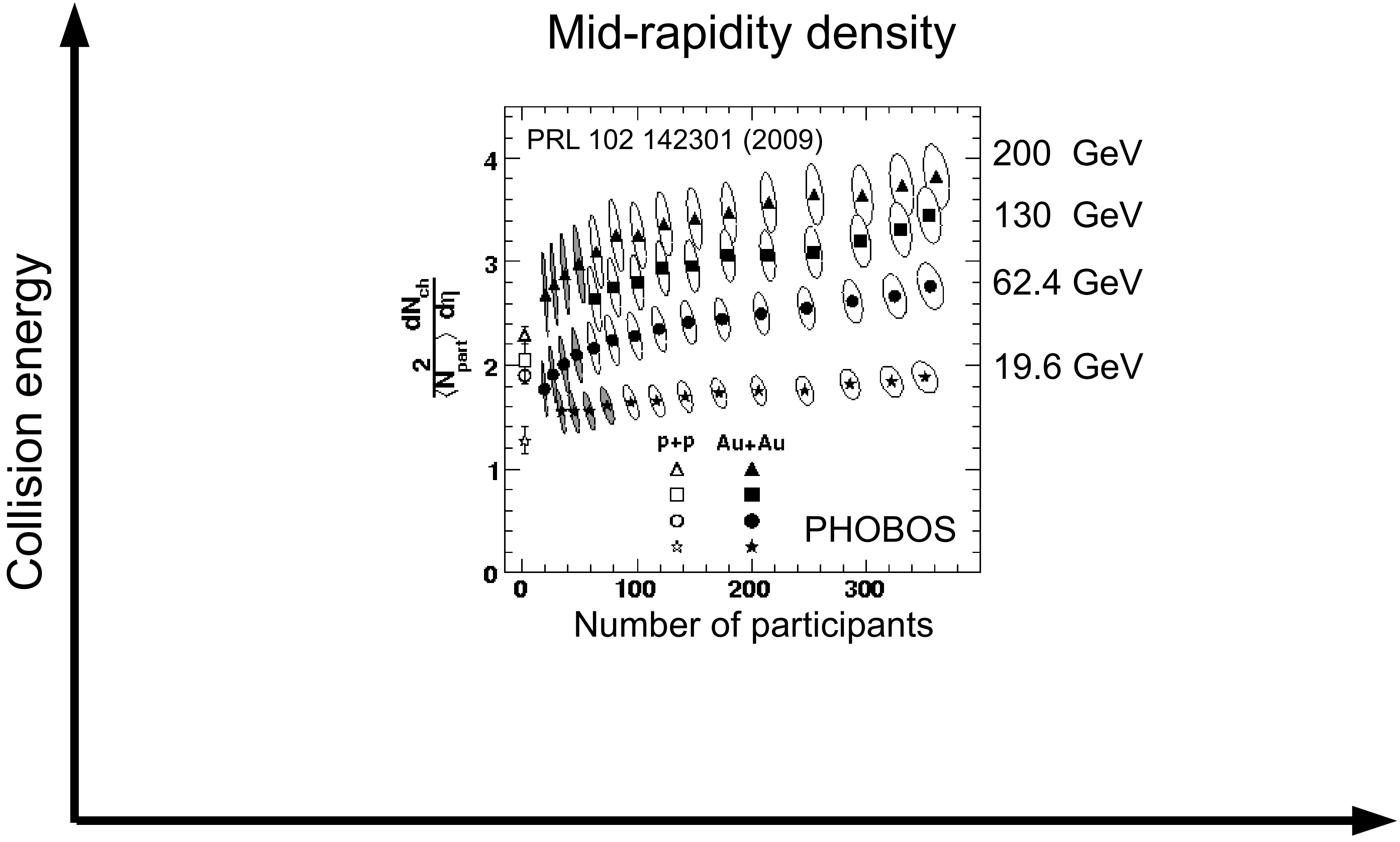


NPA 757 28 (2005)

# Total multiplicity vs centrality



# Factorization of energy and centrality



Mid-rapidity density

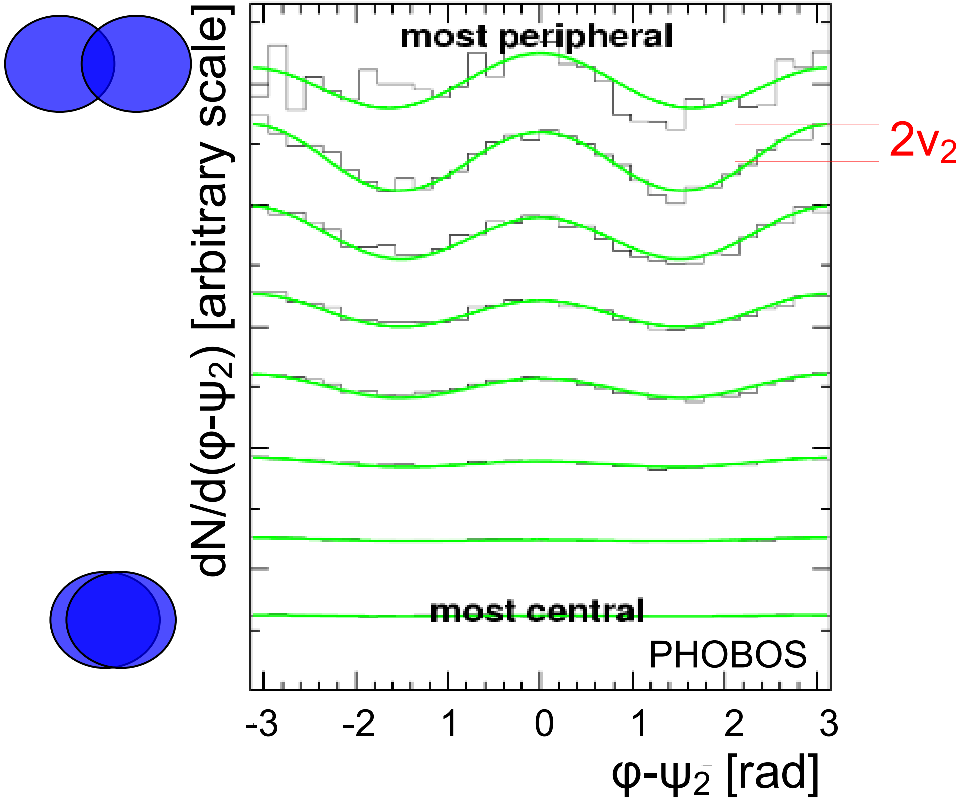
PRL 102 142301 (2009)

Collision energy

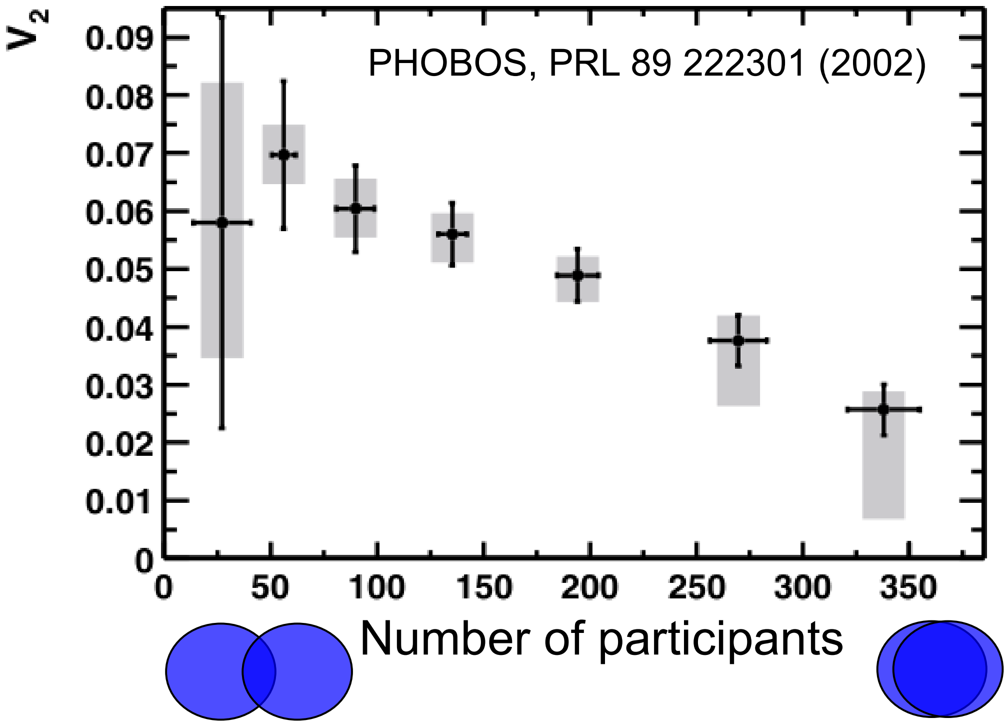
Collision centrality

# How do we prove that we make “matter”?

$$dN/d(\phi-\Psi_2) \propto 1 + v_2 \cos(2\phi - 2\Psi_2)$$

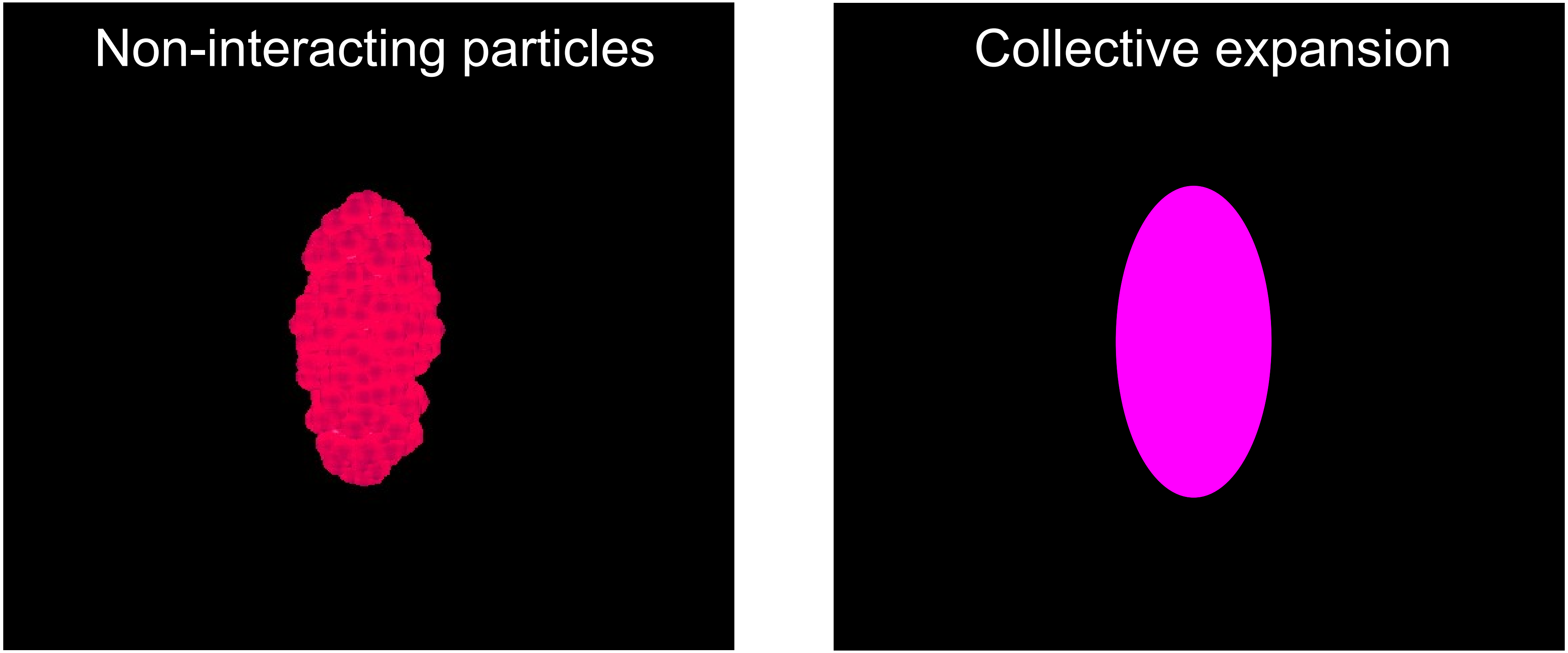


## Elliptic flow



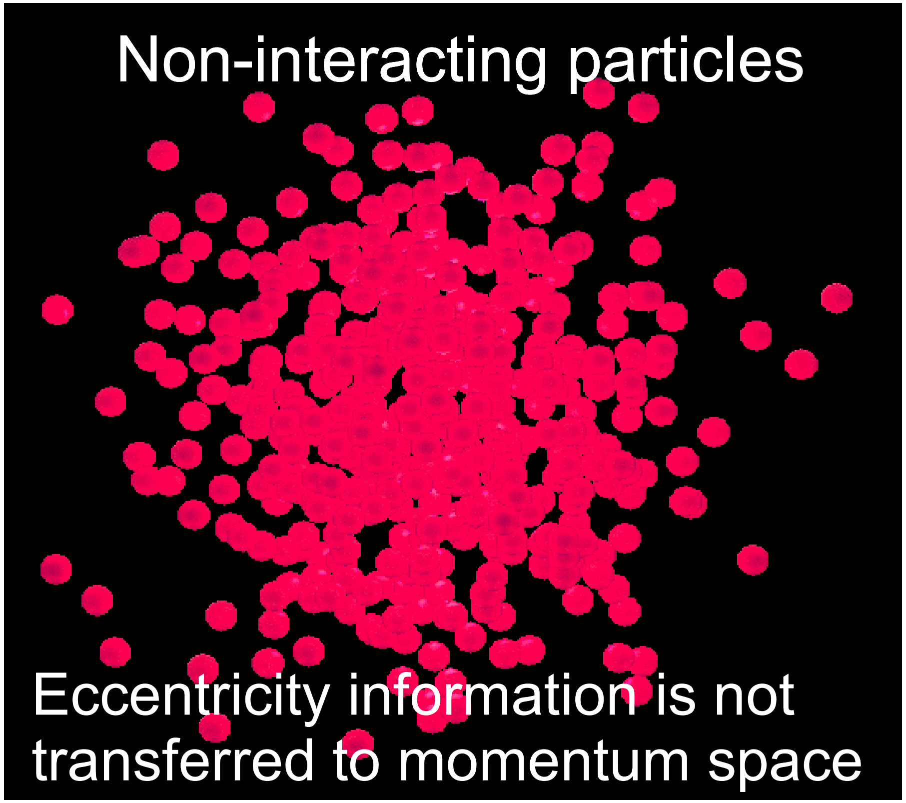
Initial anisotropy in coordinate space is translated into momentum space: Interactions are present!

# How do we prove that we make “matter”?



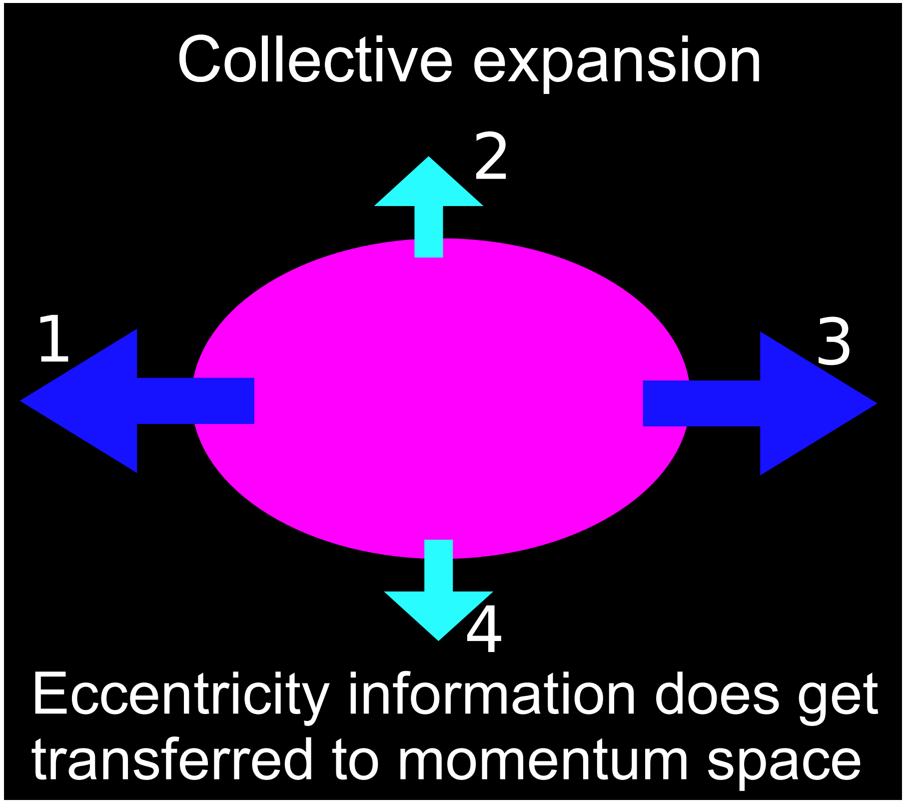
What happens to the shape (eccentricity) information during the expansion?

# How do we prove that we make “matter”?



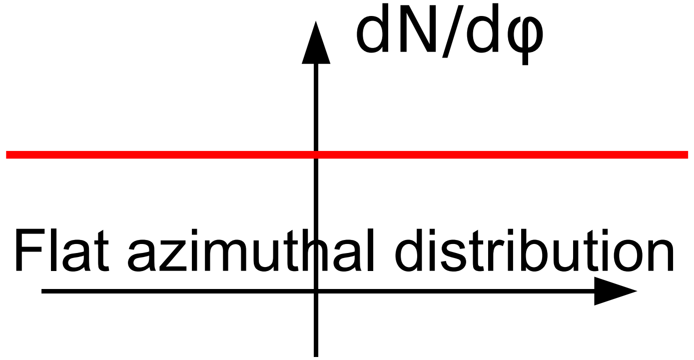
Non-interacting particles

Eccentricity information is not transferred to momentum space

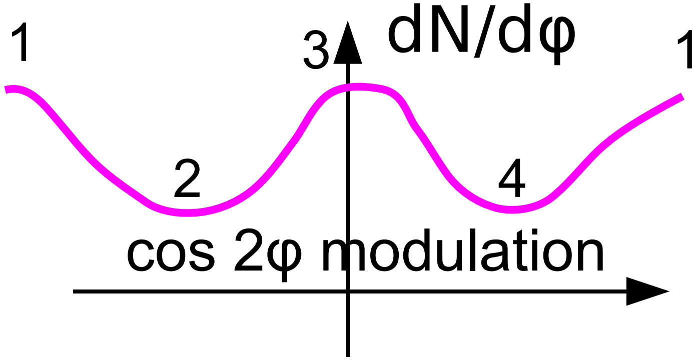


Collective expansion

Eccentricity information does get transferred to momentum space

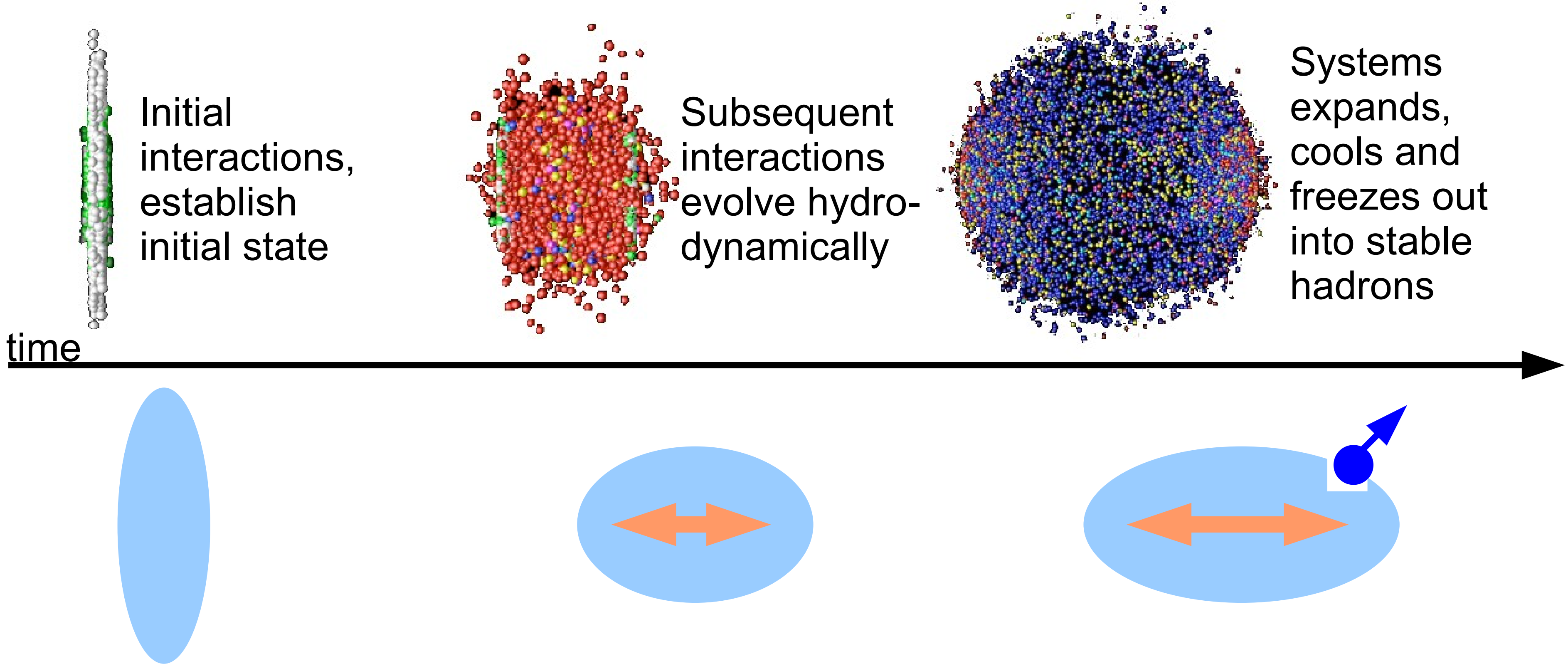


Flat azimuthal distribution



cos 2φ modulation

# Something more like a liquid



Initial interactions, establish initial state

Subsequent interactions evolve hydrodynamically

Systems expands, cools and freezes out into stable hadrons

Energy density thermalized in a volume, adjacent cells are in causal contact.

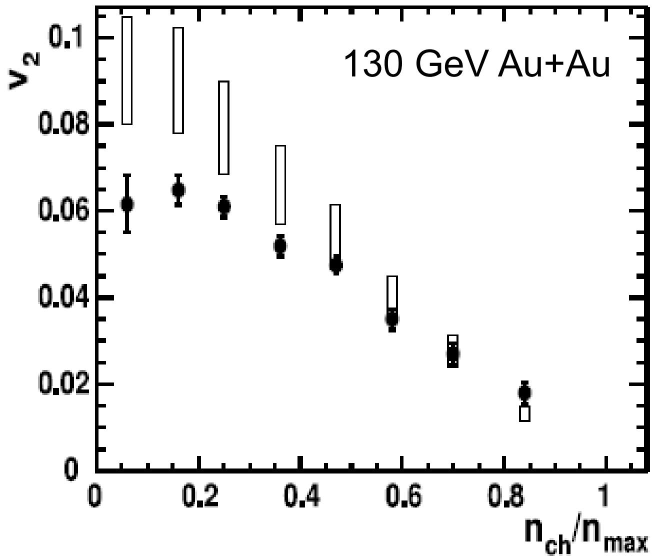
Pressure gradients develop via adiabatic expansion into vacuum

$$\boxed{\begin{array}{l}\delta_{\mu} T^{\mu\nu} = 0 \\ p = p(e, n)\end{array}}$$

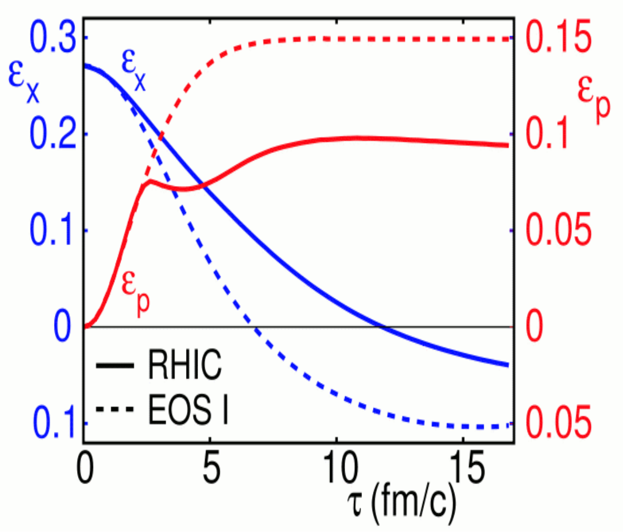
Fluid cells freeze out as isotropic fireballs when local temperature falls below $T_{fo}$

# Ideal hydrodynamics at RHIC

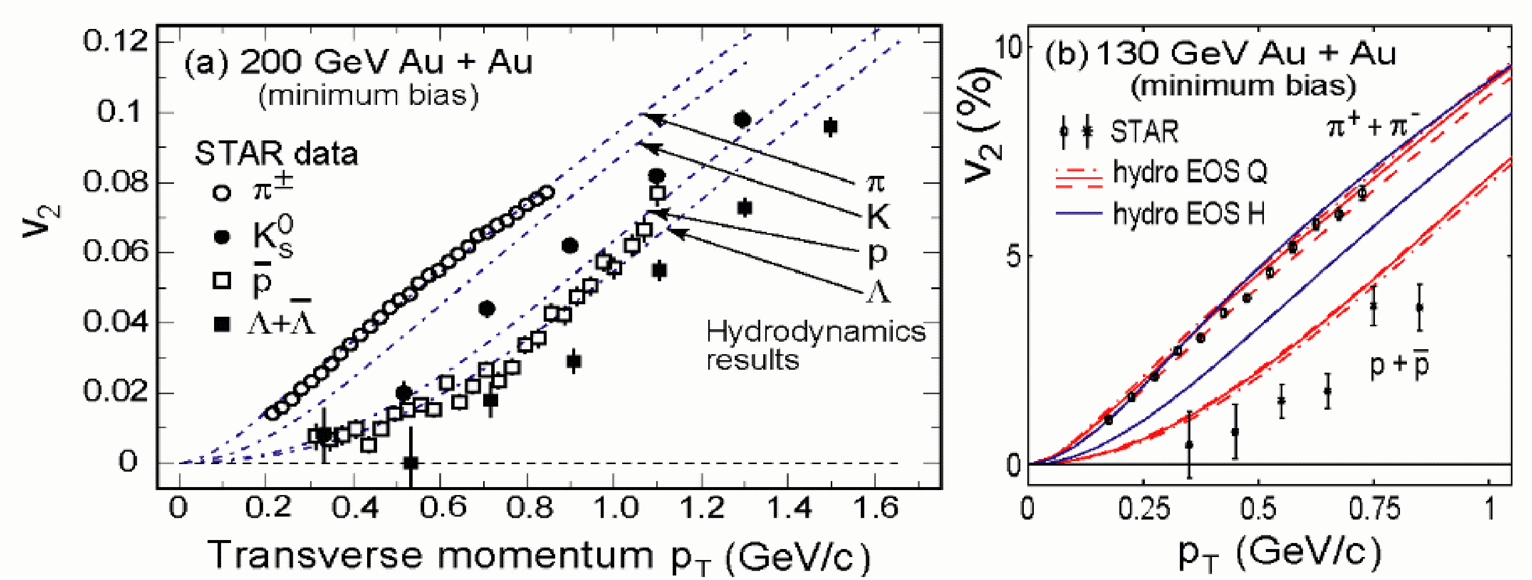
STAR, PRL 86 402 (2001)



Kolb, Heinz, nucl-th/0305084

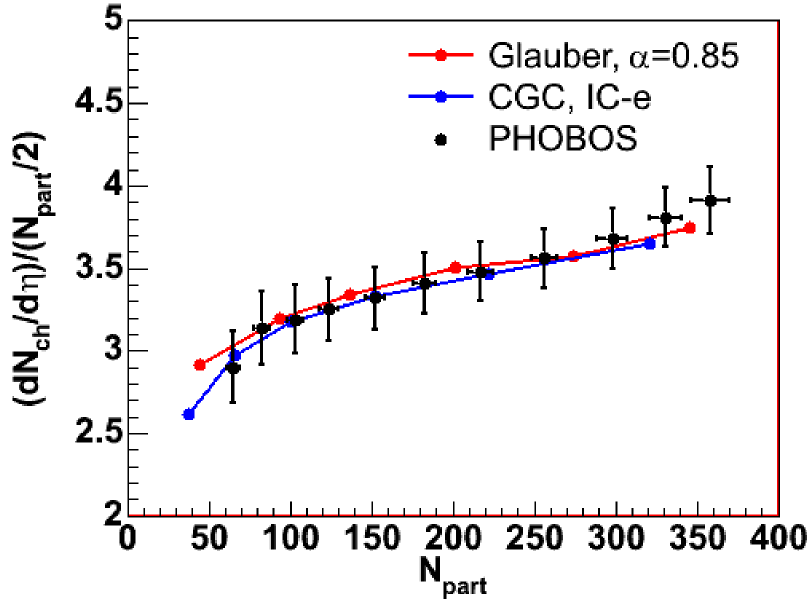


NPA 757 102-183 (2005)

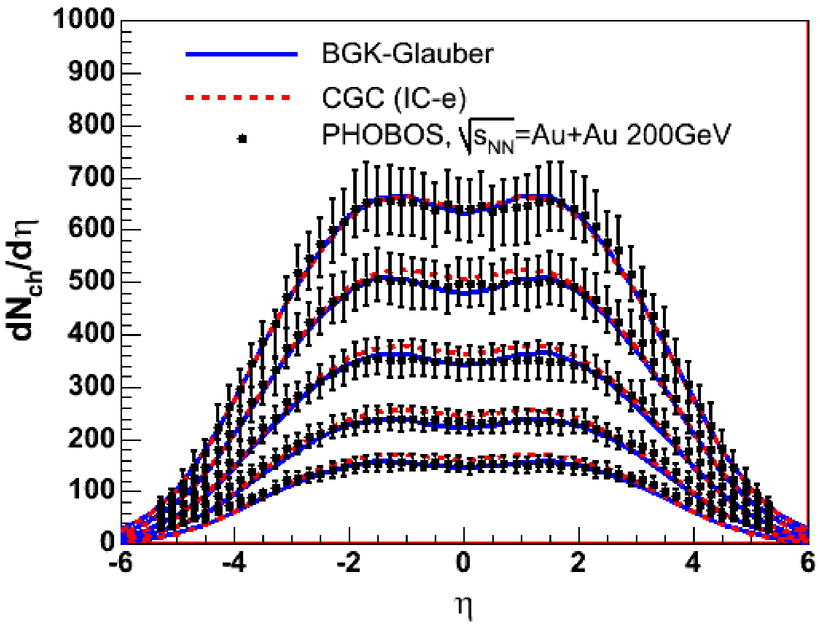


# Initial conditions for hydro model

Centrality dependence



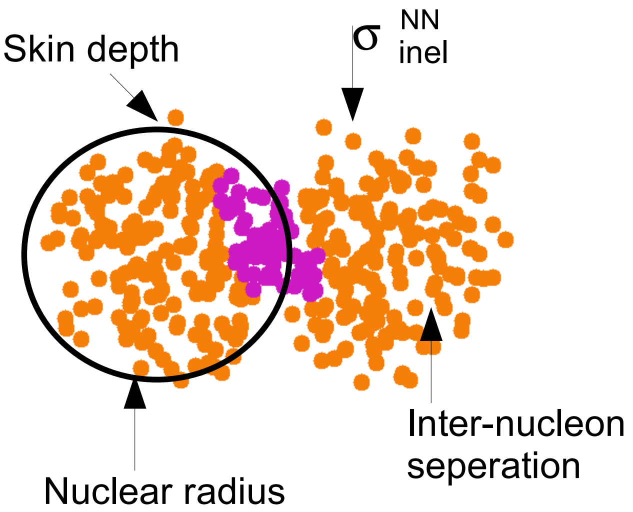
Rapidity dependence

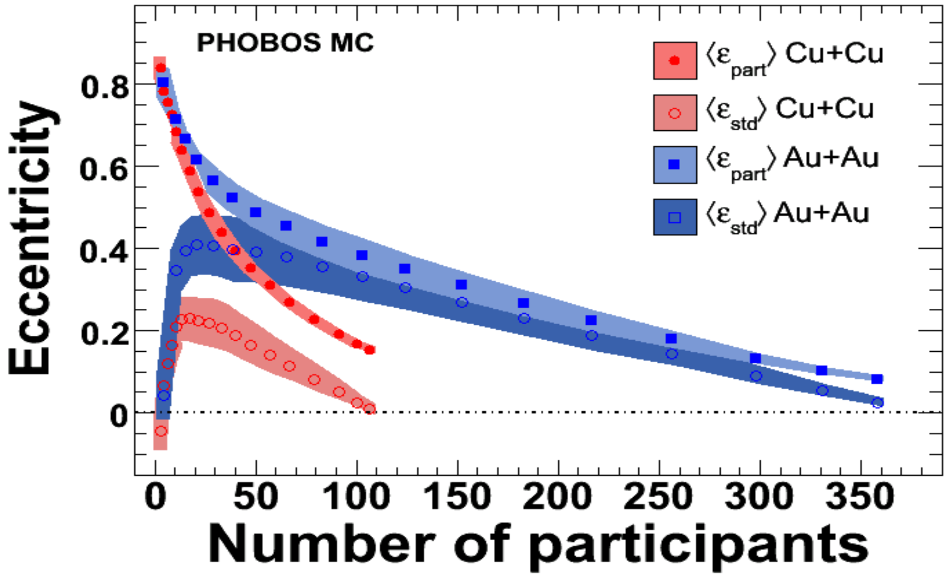


Two different initial conditions describe data

From Hirano's talk at
Hydrodynamics in Heavy Ion Collisions workshop, 2008 BNL

# Robustness of eccentricity definition





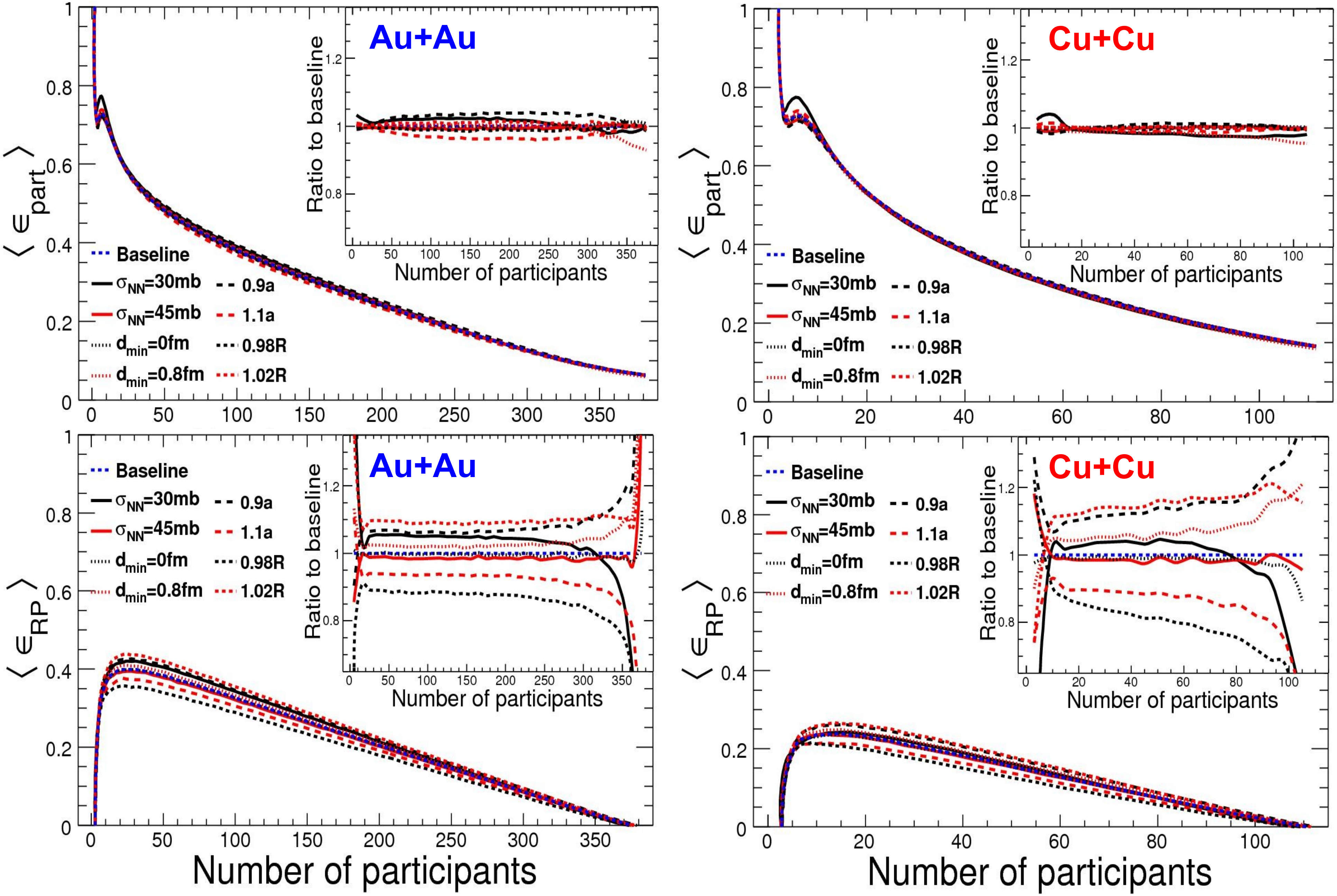
Baseline parameters:

- Nucleon-nucleon cross section: $\sigma_{NN}$=42mb
- Skin depth: a=0.535fm
- Wood-saxon radius: $R_A$=6.38fm
- Inter-nucleon separation distance: d=0.4fm

Robust definition wrt variation of Glauber parameters and to varying assumptions about matter production (not shown)

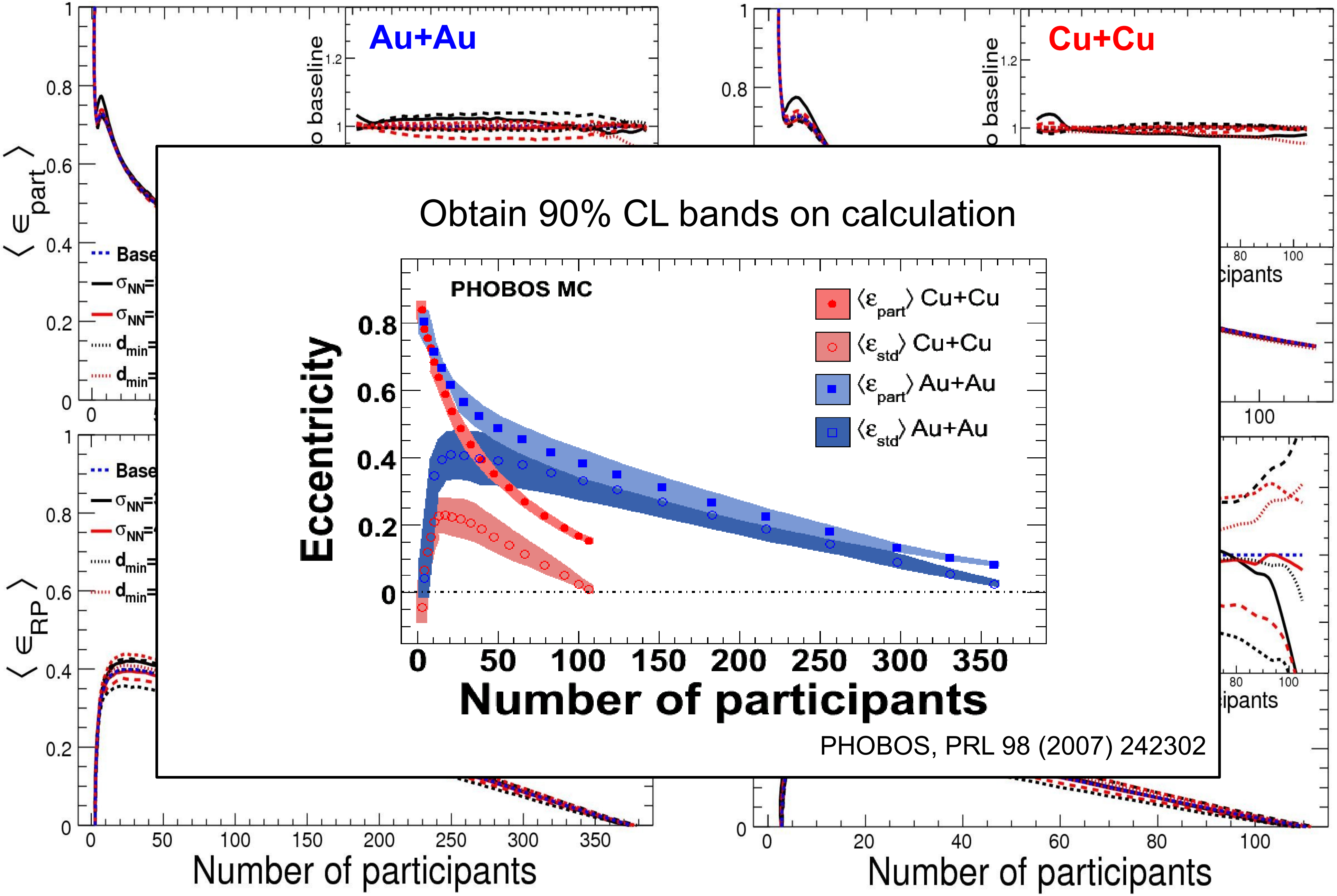
Alver et al., PRC 77 014906 (2008)

# Robustness of eccentricity definition



Alver et al., PRC 77 014906 (2008)

# Robustness of eccentricity definition



Obtain 90% CL bands on calculation

PHOBOS, PRL 98 (2007) 242302

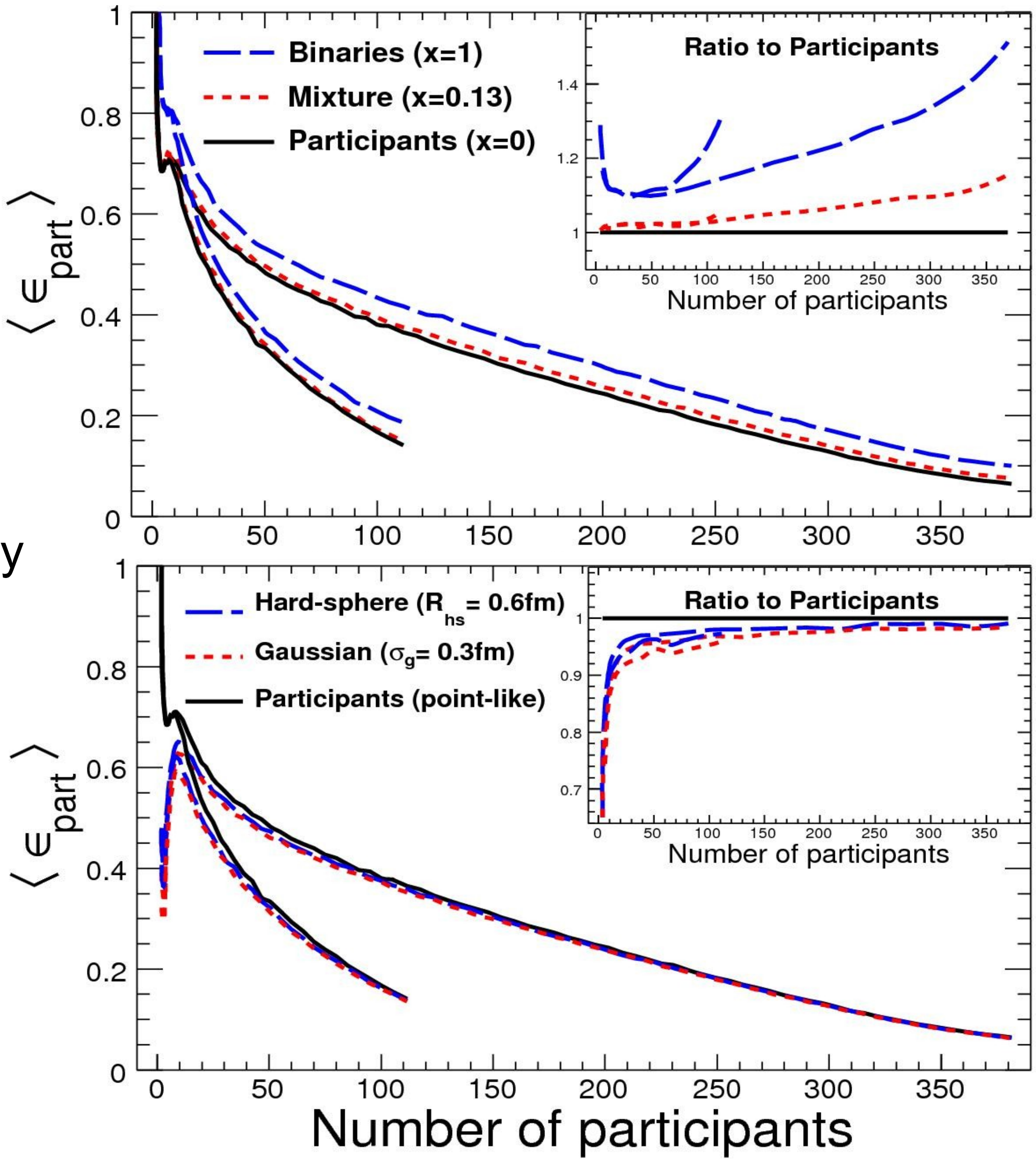
Alver et al., PRC 77 014906 (2008)

# Varying assumptions

- Model two component scenario
  - Matter production via participants and binary collisions

$$\frac{dN^{AA}}{d\eta}=\frac{dN^{pp}}{d\eta}\left(\frac{1-x}{2}N_{part}+x\,N_{coll}\right)$$

  - Mixture with x=0.13 describes mid-rapidity dN/dη quite well
    - 10% increase in eccentricity for central Au+Au
- Include thermalization time by smearing the matter around the original production point
  - Hard-sphere and Gaussian
    - For chosen set of parameters only a very small effect

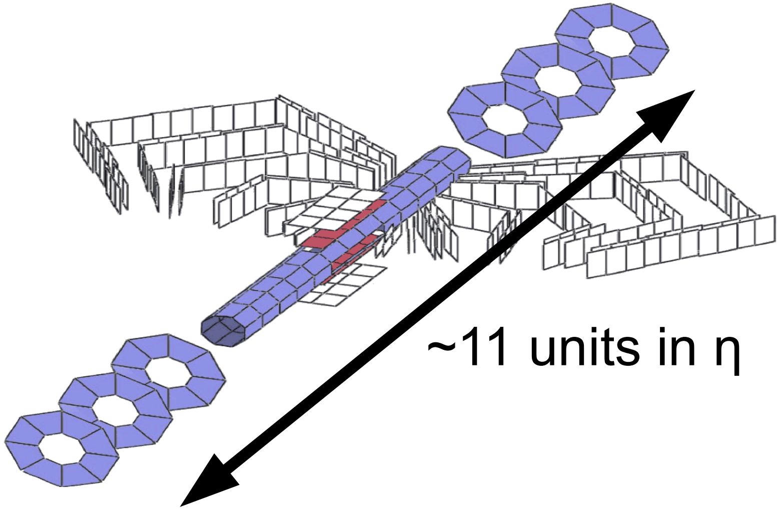


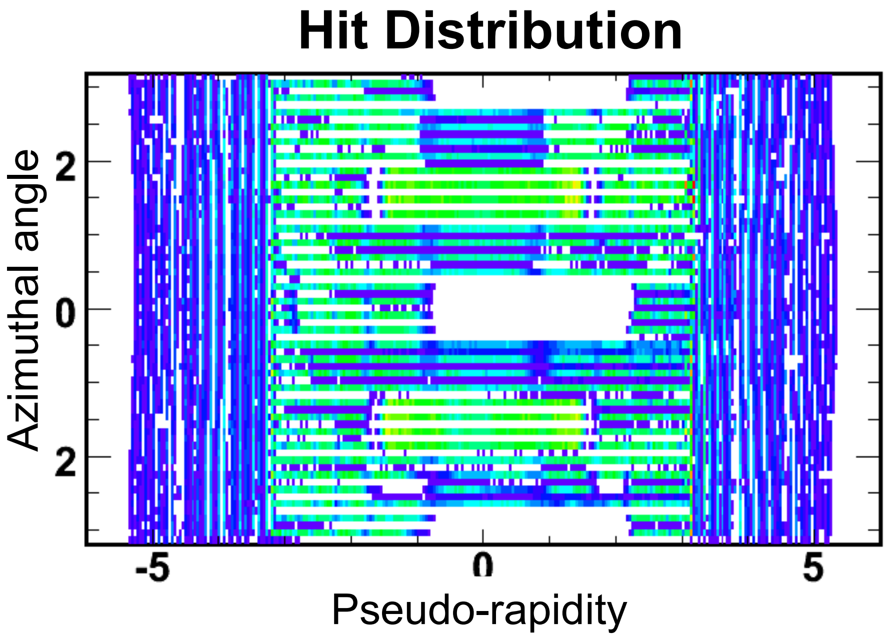
NB: More generalized studies also done, see Broniowski et al., PRC 76 (2007) 054905

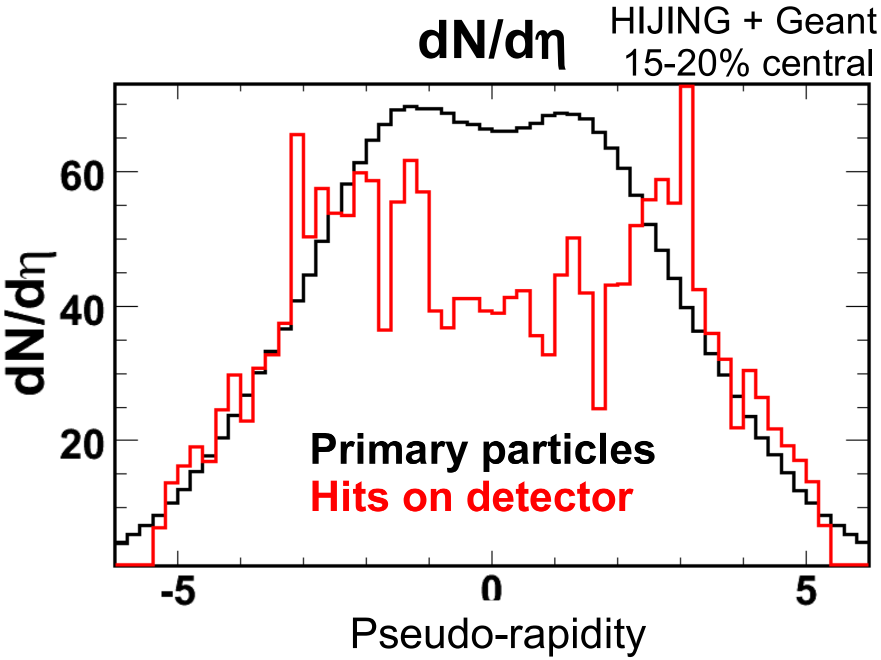
Alver et al., PRC 77 014906 (2008)

# Challenges of event-by-event $v_2^{obs}$

- PHOBOS Multiplicity Array
  - -5.4<η <5.4 coverage
  - Holes and granularity differences
- Usage of all available information in event to determine event-by-event a single value for $v_2^{obs}$







# Event-by-event measurement of $v_2^{obs}$

- Event-by-event measurement of $v_2^{obs}$
  - Deal with acceptance effects
  - Use all available hit information

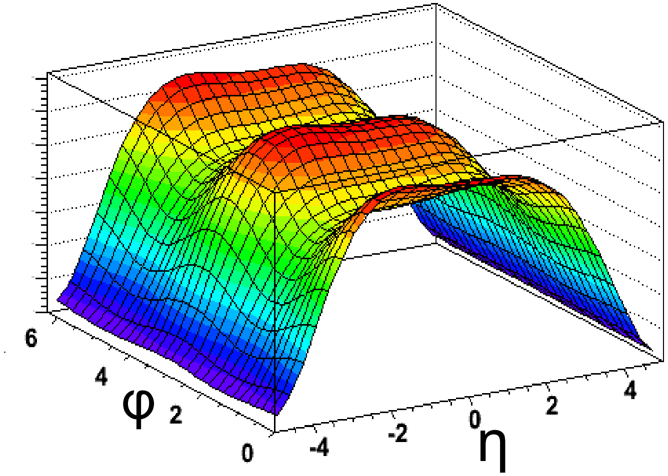
- Probability distribution function for hit positions:

$$P(\eta,\phi;\ v_2^{obs},\phi_0)=\underbrace{p(\eta)}_{\text{Normalization incl. acceptance}}\underbrace{[1+2v_2(\eta)\cos(2\phi-2\phi_0)]}_{\text{Probability of hit in }(\varphi,\eta)}$$

Normalization
incl. acceptance

**Probability of hit in (φ,η)**

**Probability distribution function**

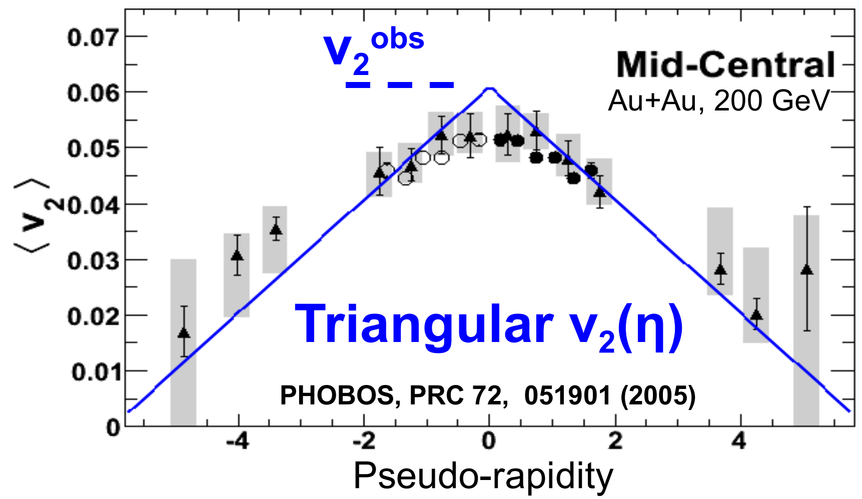


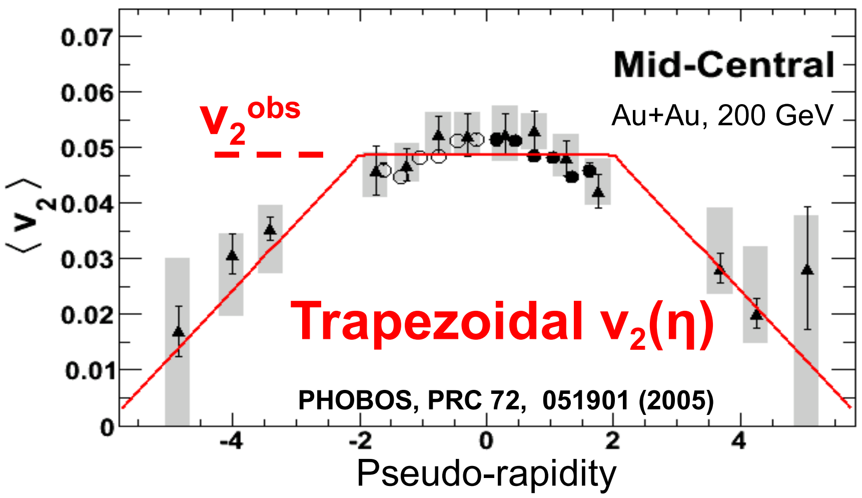
- Maximize the likelihood function to obtain $v_2^{obs}$ and $\varphi^0$ (event plane angle)

$$L(v_2^{obs},\ \phi_0)=\prod_{i=1}^{n}P(\eta_i,\phi_i;\ v_2^{obs},\phi_0)$$

nucl.-ex/0702036 (sub.to PRL),
nucl-ex/0608025 (Proceedings of Science)

# Event-by-event measurement of $v_2^{obs}$





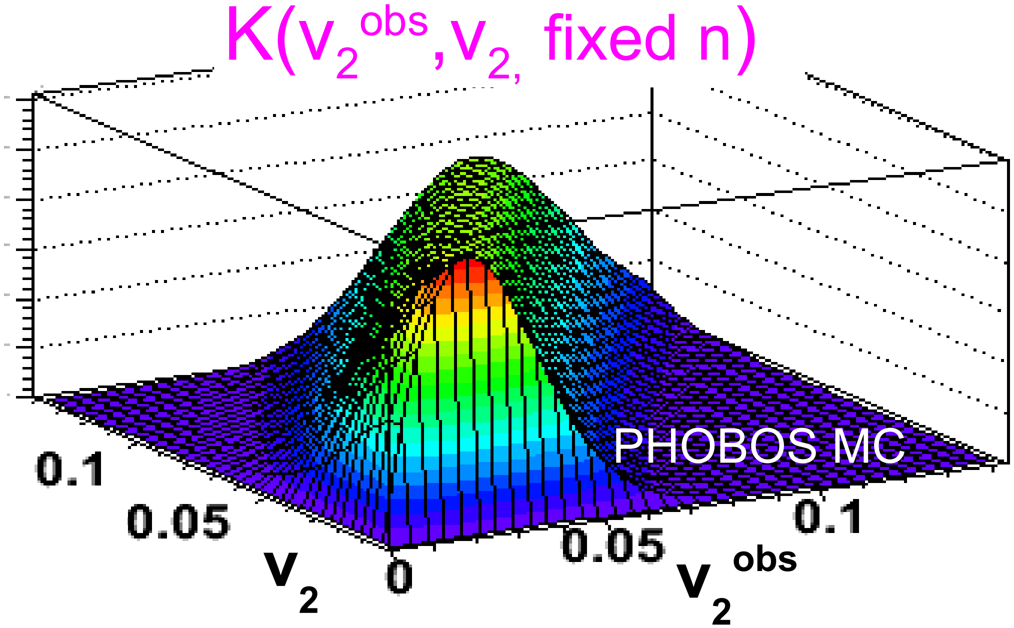
$$P(\eta,\phi;\, v_2^{obs},\phi_0)=p(\eta)[1+2\underbrace{v_2(\eta)}_{\text{Use known, measured shape}}\cos(2\phi-2\phi_0)]$$

Analysis is run on triangular and trapezoidal shape.
Results are averaged at the end.

nucl.-ex/0702036 (sub.to PRL),
nucl-ex/0608025 (Proceedings of Science)

# Determining the kernel

- "Measure" and record the $v_2^{obs}$ distribution in bins of $v_2$ and multiplicity (n) from large MC samples
  - $1.5 \cdot 10^6$ HIJING events
  - Modified φ to include triangular or trapezoidal flow



- Fit response function (ideal case)

$$K(v_2^{obs}, v_2, n) = \frac{v_2^{obs}}{\sigma^2} e^{-\left(\frac{v_2^{obs} + v_2^2}{2\sigma^2}\right)} I_0\left(\frac{v_2^{obs} v_2}{\sigma^2}\right)$$

(J.-Y.Ollitrault, PRD (1992) 46, 226)

- Changed to account for detector effects

$$v_2 \rightarrow (An + B) v_2 \qquad \sigma = \frac{C}{\sqrt{n}} + D$$

(suppression) (finite resolution)

nucl.-ex/0702036 (sub.to PRL),
nucl-ex/0608025 (Proceedings of Science)

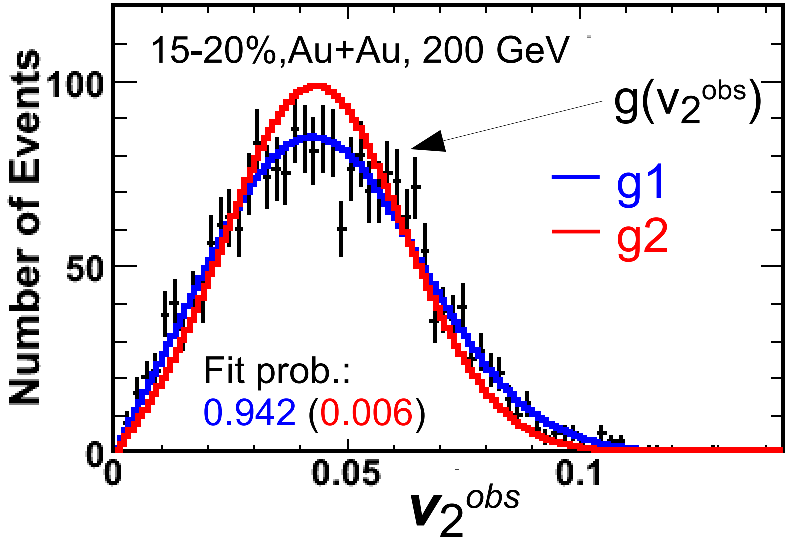
# Extracting dynamical fluctuations

$$\underbrace{g(v_2^{obs})}_{\text{Measured}} = \int_0^1 \underbrace{K(v_2^{obs}, v_2)}_{\text{Constructed from MC}} \underline{f(v_2)}\, dv_2$$

Gaussian Ansatz:

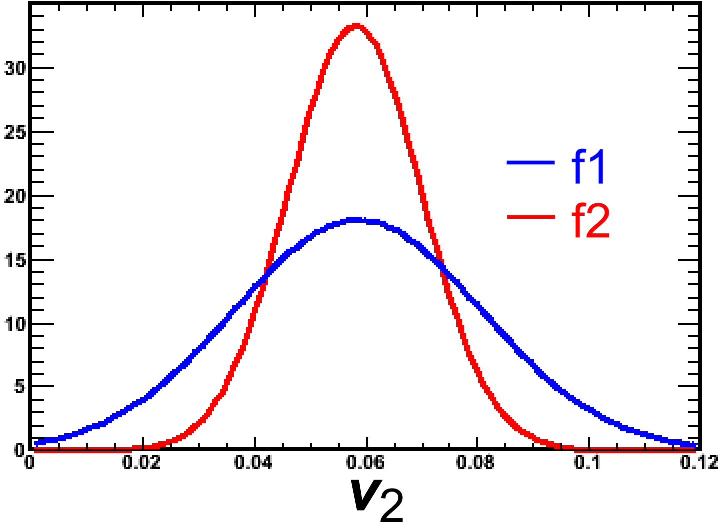
$$f(v_2) = \exp\left[\frac{-(v_2 - \langle v_2 \rangle)^2}{2\sigma_{v_2}^2}\right]$$

**Comparison with data $g(v_2^{obs})$**



Use kernel + integrate

**Different trials for Ansatz $f(v_2)$**



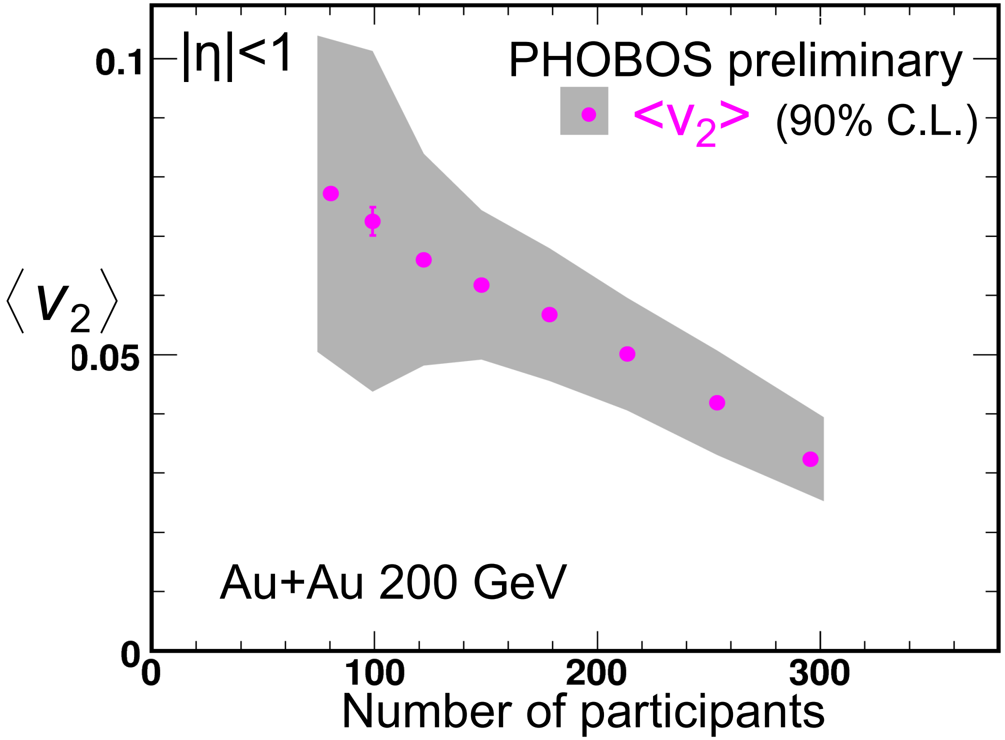
Compare expected $g(v_2^{obs})$ for trials with data:

Maximum-Likelihood fit → $\langle v_2 \rangle$ and $\sigma_{v_2}$

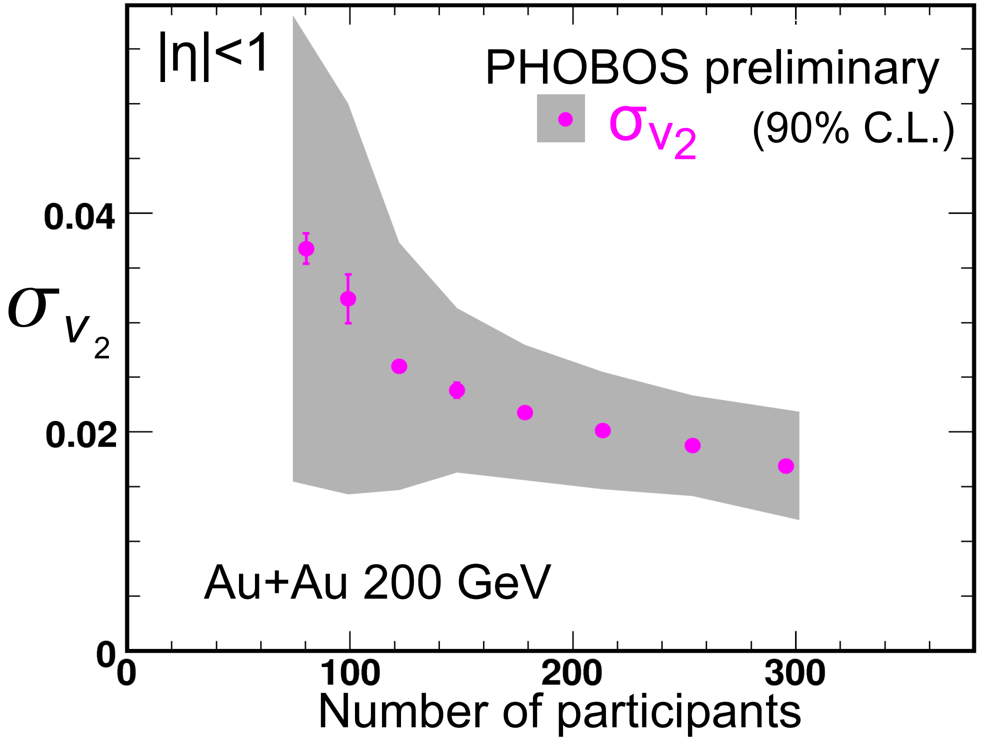
nucl.-ex/0702036 (sub.to PRL),
nucl-ex/0608025 (Proceedings of Science)

# Elliptic flow fluctuations: $<v_2>$ and $\sigma_{v_2}$

Mean elliptic flow



Dynamical flow fluctuations



Systematic errors:

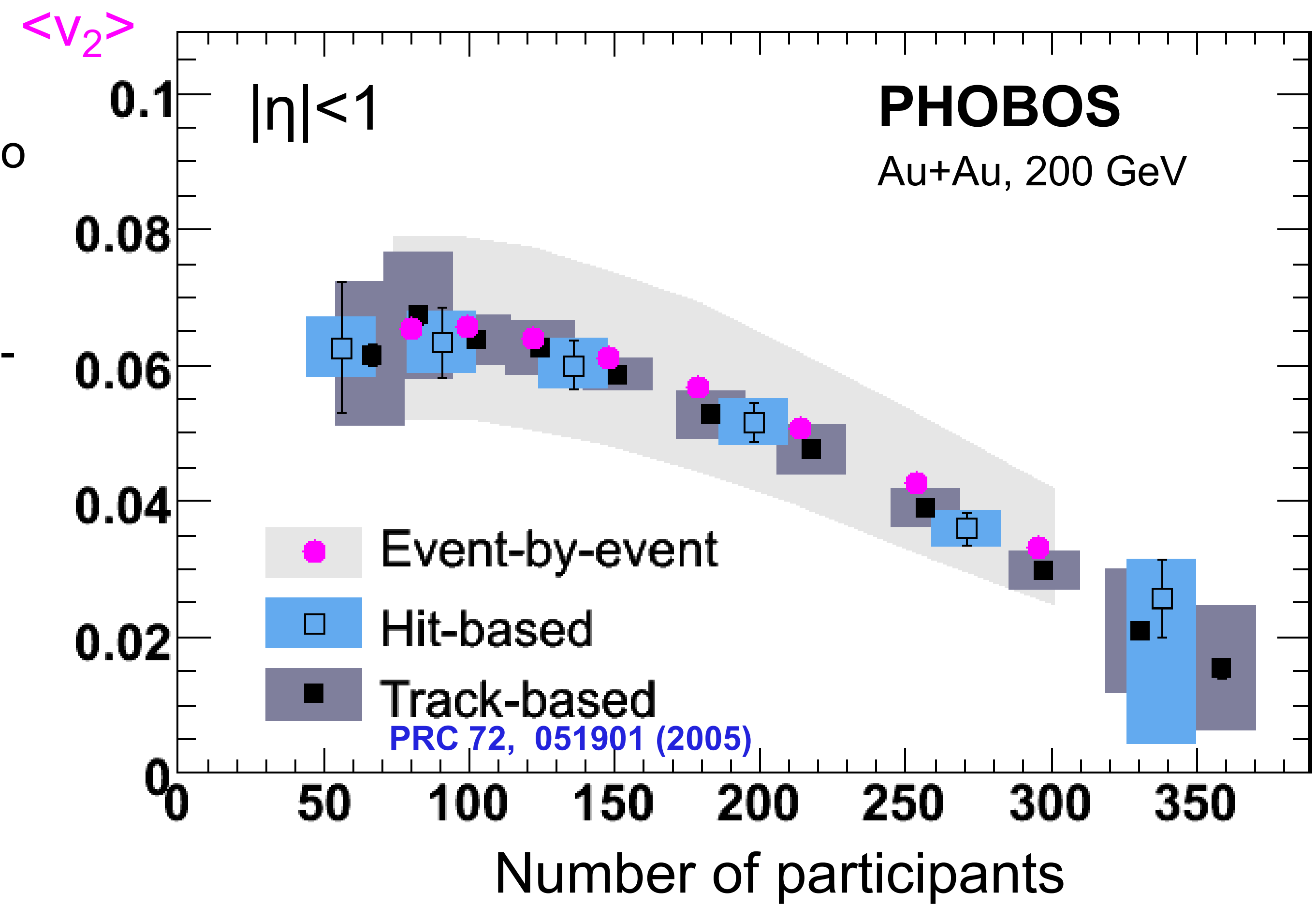
- Variation in η-shape
- Variation of $f(v_2)$
- MC response
- Vertex binning
- $\Phi_0$ binning

"Scaling" errors cancel in the ratio: relative fluctuations, $\sigma_{v_2}/<v_2>$

nucl.-ex/0702036 (sub.to PRL)

# Event-by-event $v_2$ vs published results

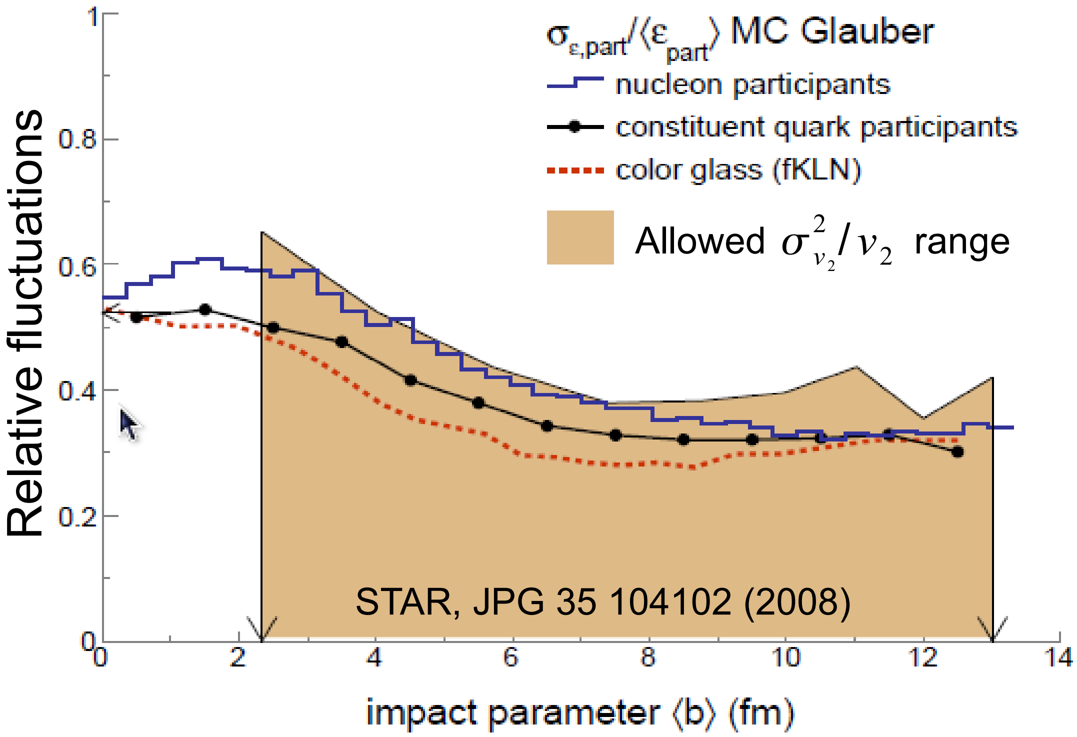
- Standard methods
  - Averaged over events to measure the mean
  - Hit- and track-based
  - Use reaction plane sub-event technique



Very good agreement of the event-by-event measured mean $v_2$ with the hit- and tracked-based, event averaged, published results

nucl.-ex/0702036 (sub.to PRL)

# Contribution from non-flow correlations



Non-flow correlations are few particle correlations not related to the reaction plane. They broaden the observed flow fluctuations non-trivially.

Upper limit on flow fluctuations

# Numerical subtraction

WORK IN PROGRESS

$$K(v_2^{obs}, v_2, n) = BG(v_2^{obs}, v_2, \sigma_n), \quad \sigma_n = 1/\sqrt{2n}$$

$$K_\delta(v_2^{obs}, v_2, n) = BG(v_2^{obs}, v_2, \sqrt{\sigma_n^2 + \sigma_\delta^2}), \quad \sigma_n = 1/\sqrt{2n}, \sigma_\delta = \sqrt{\delta/2}$$

$$g(v_2^{obs}) = \int K_\delta(v_2^{obs}, v_2, n) f_{flow}(v_2)\, \mathrm{d}v_2$$

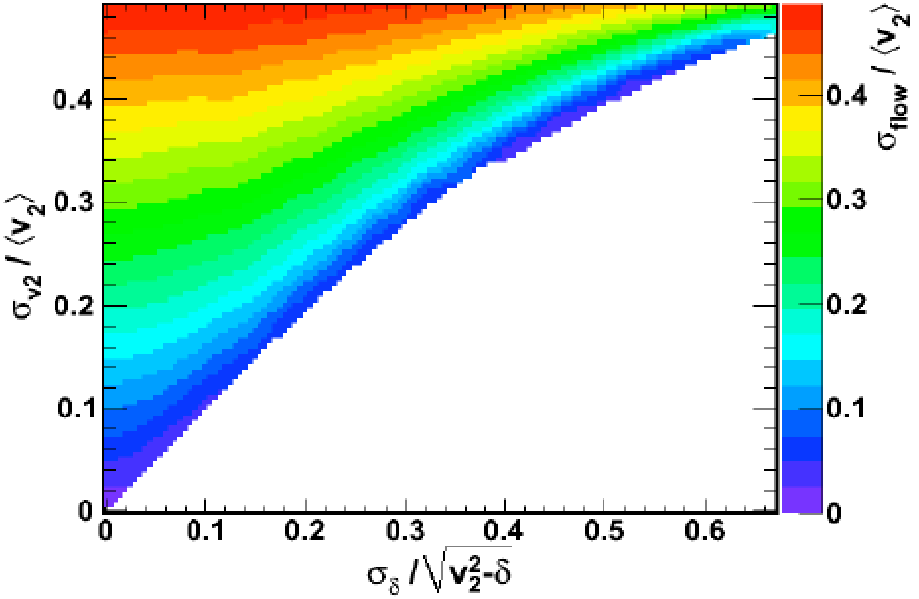
$$g(v_2^{obs}) = \int K(v_2^{obs}, v_2, n) f(v_2)\, \mathrm{d}v_2$$

Generate $g(v_2^{obs})$ using this

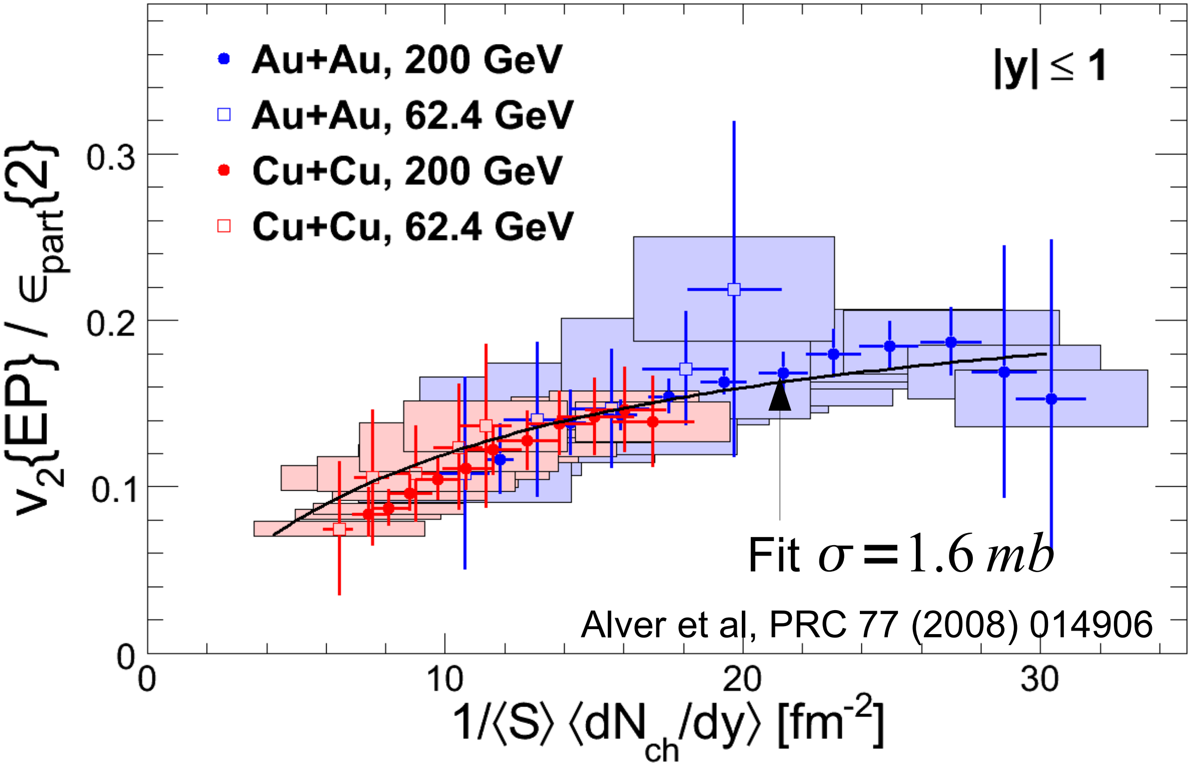
Do a fit using this

- Keep results as lookup table
- Results depend on $\sigma_n$
    - Use $\sigma_n$ = 0.4, 0.6 and 0.8

Lookup table



# How in-complete is the thermalization?

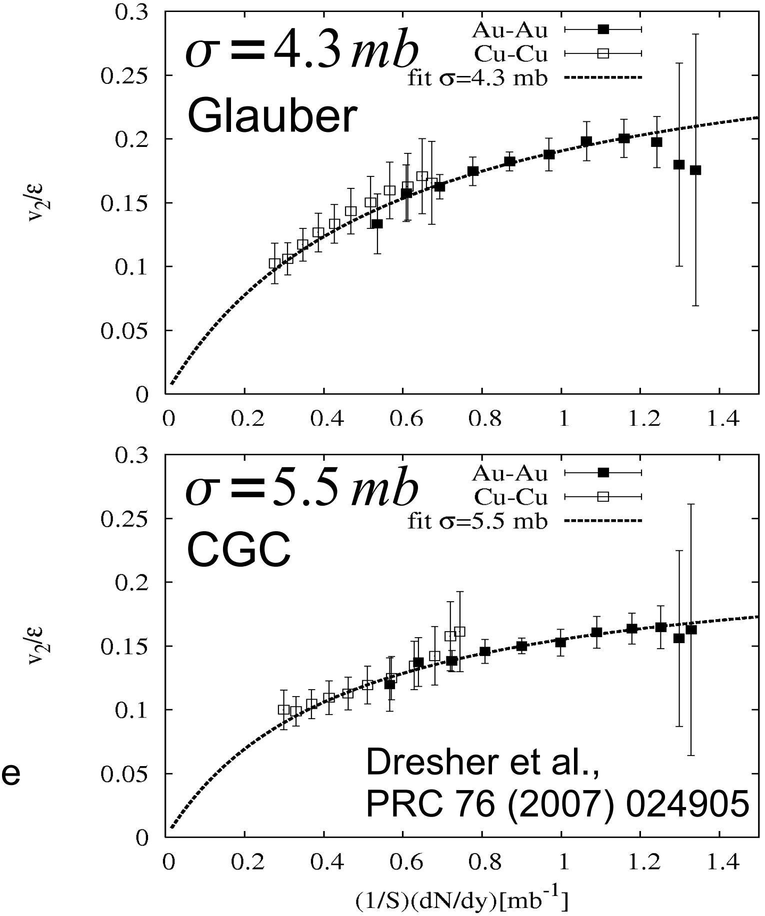


Alver et al, PRC 77 (2008) 014906

$$\frac{v_2}{\epsilon} = \frac{v_2^{hydro}}{\epsilon} \frac{1}{1+K/K_0} \qquad K_0 \approx 0.7$$

$$\frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} \frac{c_s}{c}$$

Bhalerao et al., PLB 627 (2005) 49-54



Dresher et al.,
PRC 76 (2007) 024905

Central Au+Au are about 20% away from ideal hydro limit

*) Assumed constant $c_s$, no phase transitions, 2d, boost invariance

**) Difference of factor 2 in horizontal scales

# Connection to Knudson and Reynolds?

Define rel. flow fluctuations:

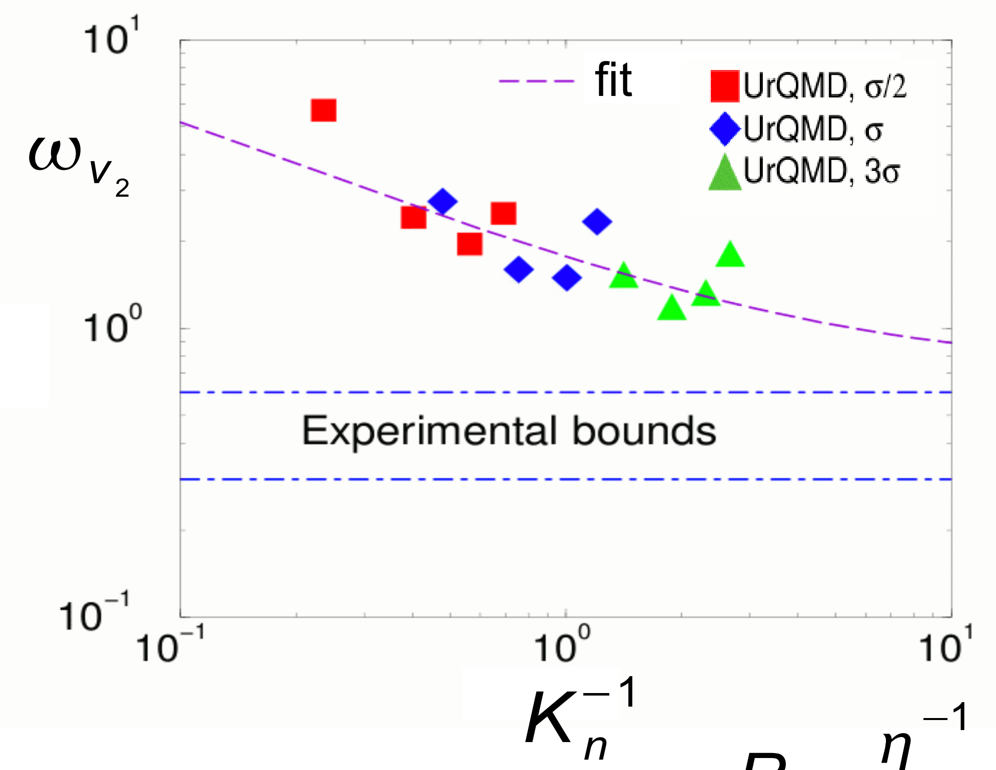
$$\omega_{v_2}^2 \equiv \frac{\sigma_{v_2}^2}{\langle v_2 \rangle^2} = \frac{\sigma_{\epsilon_{part}}^2}{\langle \epsilon_{part} \rangle^2} + \Delta_{dyn}^2$$

Define the inverse of the Knudson, the average number of collisions suffered by a dof in the system:

$$K_n^{-1} = L / \lambda$$

Assume Poissonian:

$$\Delta_{dyn} \sim \alpha \sqrt{K_n}$$

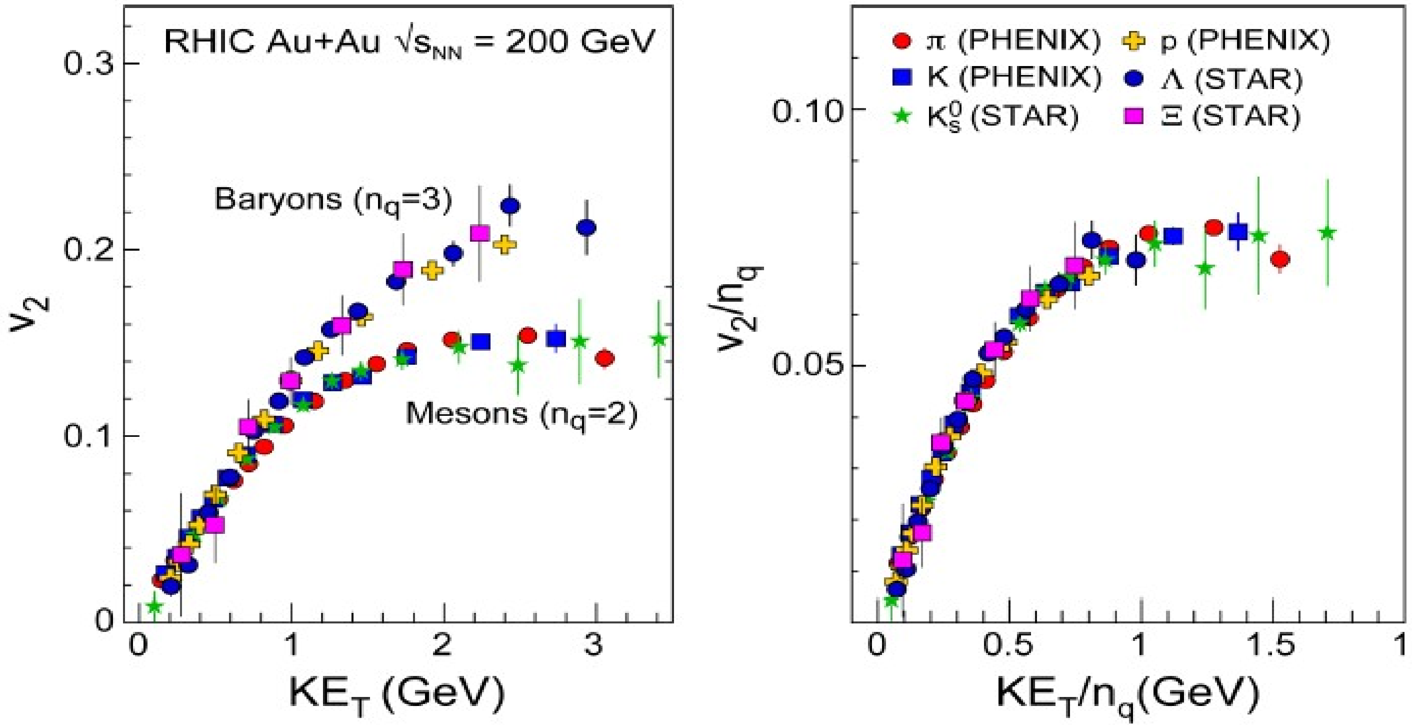


$\sim R_e \sim \frac{\eta}{s}^{-1}$

Viscosity must be large enough to avoid strong turbulence (that are not seen in the data)

S.Vogel, G.Torrieri, M.Bleicher, nucl-th/0703031

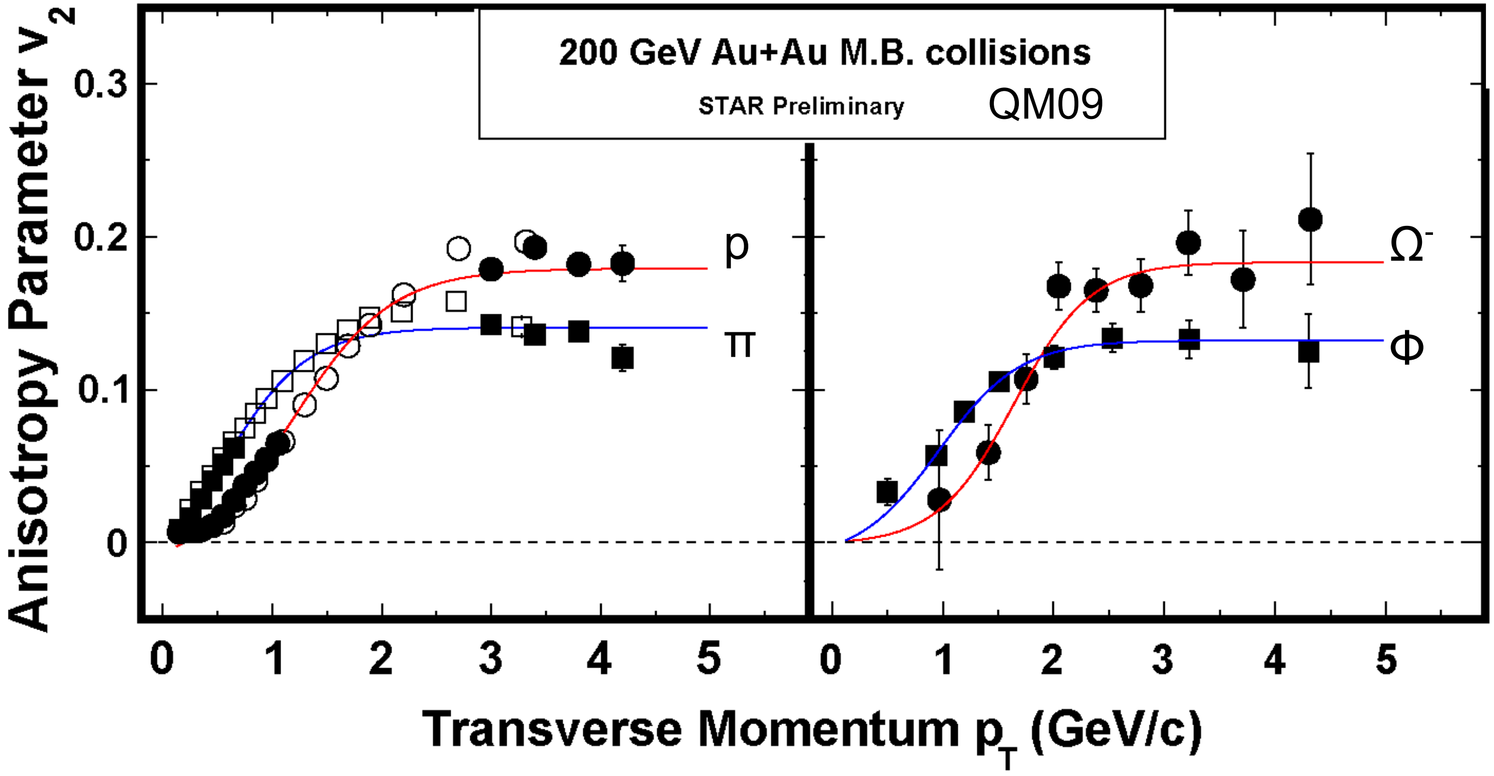
# What is the nature of the matter?



Flow mechanism “knows” about quarks,
however microscopic picture not understood.

PHENIX, PRL 98 162301 (2007)

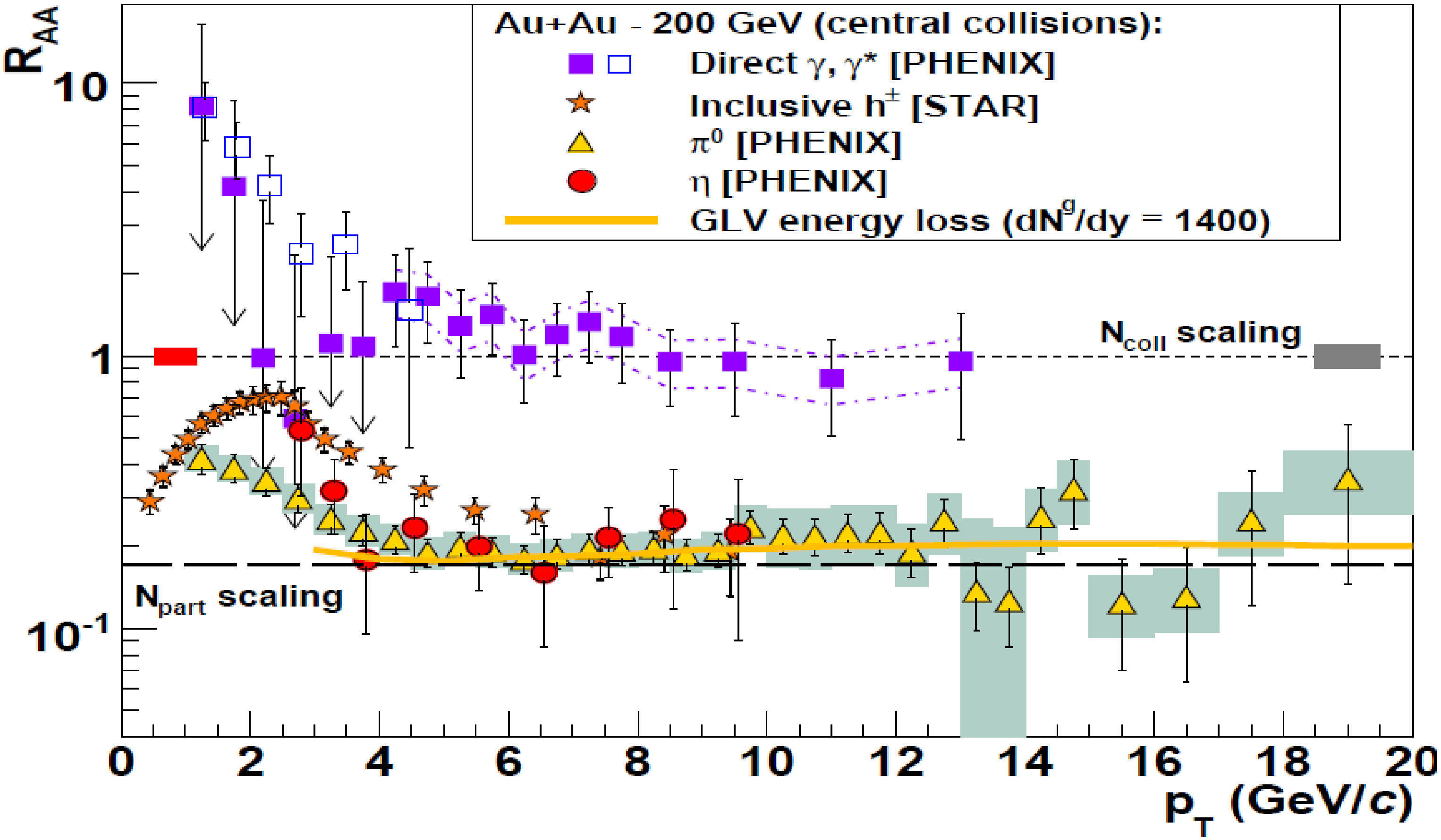
# What is the nature of the matter?



Partonic collectivity at RHIC: Heavy multi-strange particles flow as protons and pions

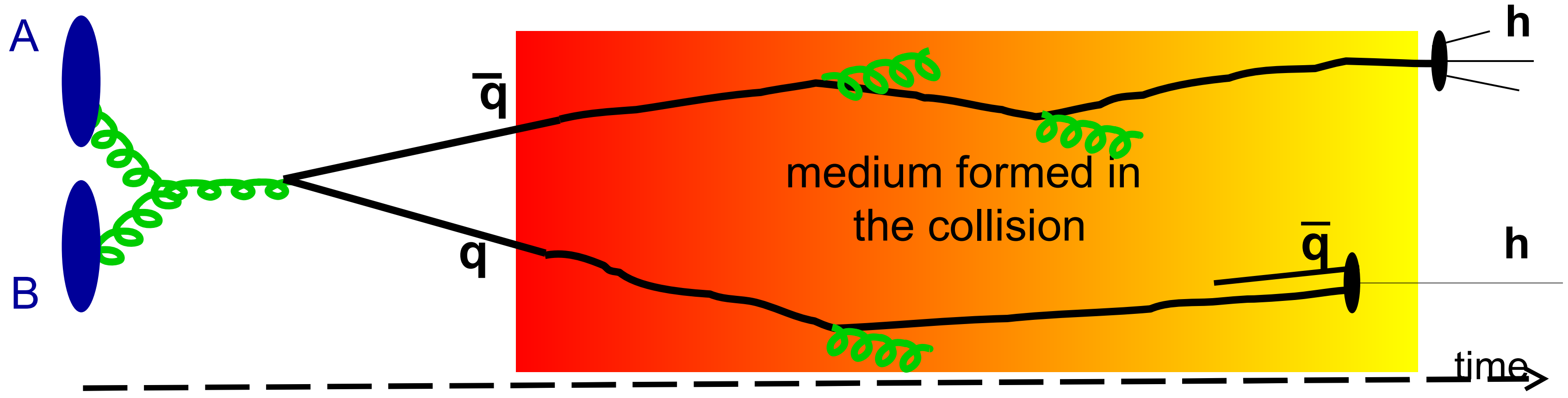
PHENIX π and p: nucl-ex/0604011v1
NQ inspired fit: X. Dong et al. PLB 597 328 (2004)

# Medium is black: Jet quenching

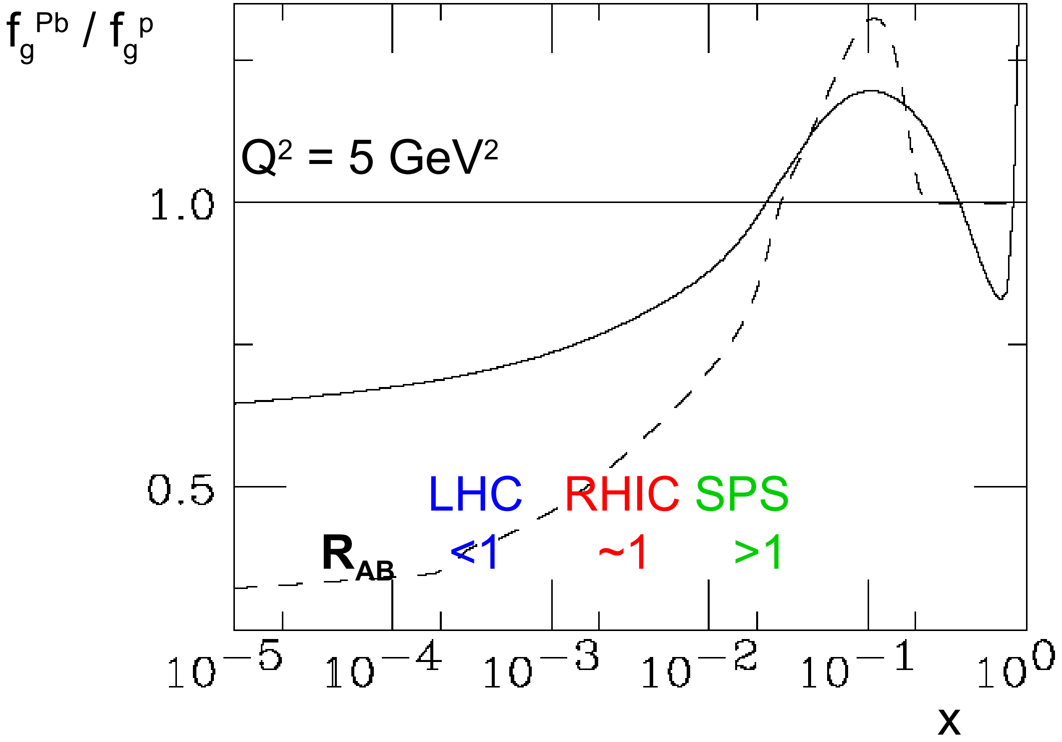


From 0902.2011, see references in there

# Hard probes in A+A collisions



- Proton-Proton baseline (pQCD)
- Initial-state effects
  - Nuclear PDF (anti-/shadowing)
  - $K_T$ broadening (Cronin)
- Final-state effects
  - Energy loss
  - In-medium hadronization / fragmentation

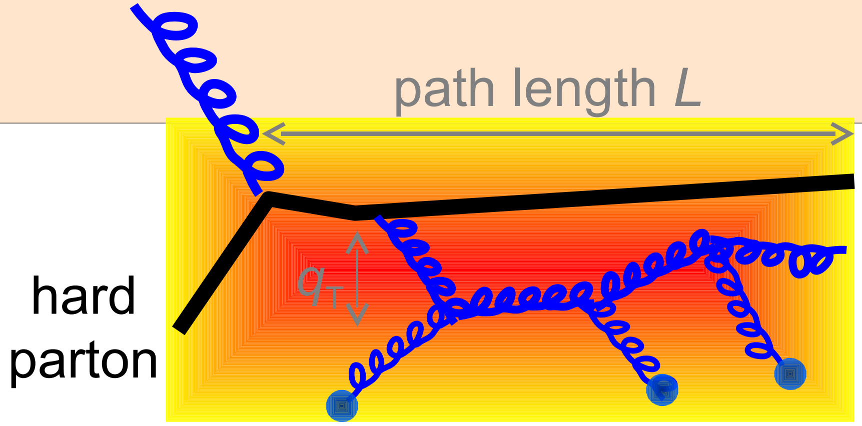


# Parton energy loss inspired by pQCD

- Partons travel a few (~4) fm in the high **color**-density medium
- Bjorken (`82): energy loss due to elastic (collisional) scattering
- Successive calculations (`92++) revealed(???) that medium-induced gluon radiation (QCD bremsstrahlung) dominates:

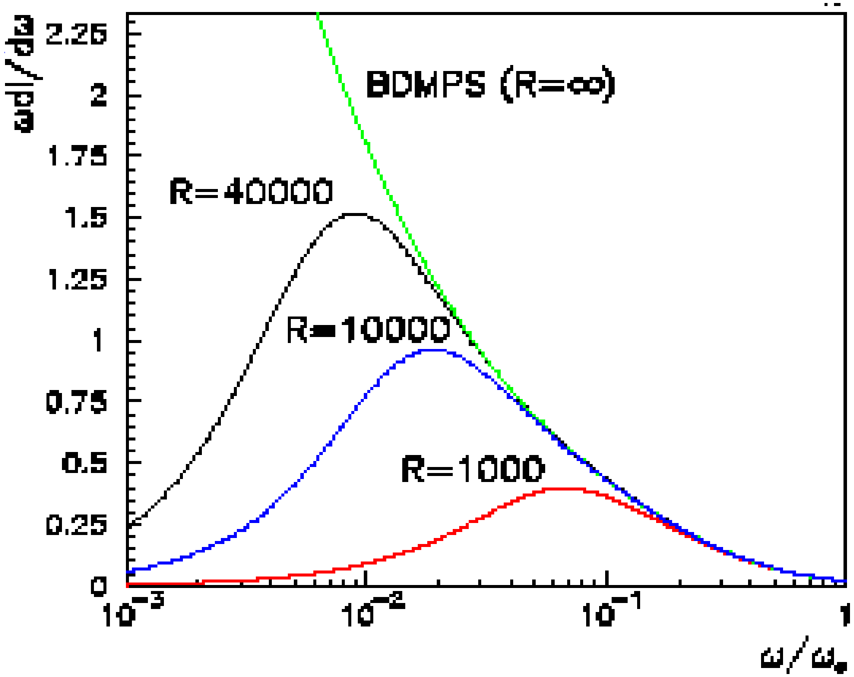
$$\omega \frac{dI}{d\omega dk} = \alpha_S C_R / \omega^2 \, F\left(\eta(\xi)\sigma(r)\right) \begin{cases} \nearrow \frac{1}{2}\hat{q}(\xi) r^2 & \text{(BDMPS)} \\ \searrow \left(n(\xi)\sigma(r)\right)^N & \text{(opacity expansion)} \end{cases}$$

- Coherent wave-function gluon acummulates $k_T$ due to multiple inelastic scatterings in the medium until decoheres and is radiated off the original hard parton



Bjorken, Gyulassy, Plümer, Thoma, Wang, Wang, Baier, Dokshitzer, Müller, Peigne’, Schiff, Levai, Vitev, Zhakarov, Salgado, Wiedemann, ...

# Parton energy loss in BDMPS-Z



**BDMPS-Z formalism**

$$\hat{q} = \frac{\langle q_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{dI}{d\omega} \propto \alpha_S C_R \begin{cases} \sqrt{\omega_c / \omega} & \text{for } \omega < \omega_c \\ (\omega_c / \omega)^2 & \text{for } \omega \geqslant \omega_c \end{cases}$$

| | |
|---|---|
| $C_R$ | Casimir coupling factor: 4/3 for q, 3 for g |
| $\omega_c = \hat{q} L^2 / 2$ | determines the scale of the radiated energy |
| $R = \omega_c L$ | related to constraint $k_T < \omega$ and<br>controls shape at $\omega \ll \omega_c$ |

Baier et.al, NPB 483 291 (1997)
Zakharov, JTEPL 63 952 (1996)
Salgado, Wiedemann, PRD 68 014008 (2003)

# Parton energy loss in BDMPS-Z

$$\langle \Delta E \rangle \approx \int_0^{\omega_c} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_S\, C_R\, \omega_C \propto \alpha_S\, C_R\, \hat{q}\, L^2$$

$$\langle \Delta E \rangle \propto \hat{q} \propto \rho \int dq_T^2\, q_T^2\, d\sigma / dq_T^2$$

(gluons volume-density and interaction cross section)

Probe the medium

## Finite parton energy (qualitatively)

- If E< $\omega_c$ (e.g. small $p_T$ with traversing large L) :

$$\langle \Delta E \rangle \approx \int_0^{E} d\omega\, \omega \frac{dI}{d\omega} \propto \alpha_S\, C_R\, \sqrt{E\, \omega} \propto \alpha_S\, C_R\, \sqrt{E}\, \sqrt{\hat{q}}\, L$$

  - Introduces dependence on parton energy
  - Reduces sensitivity to density
  - Leads to linear dependence on path length

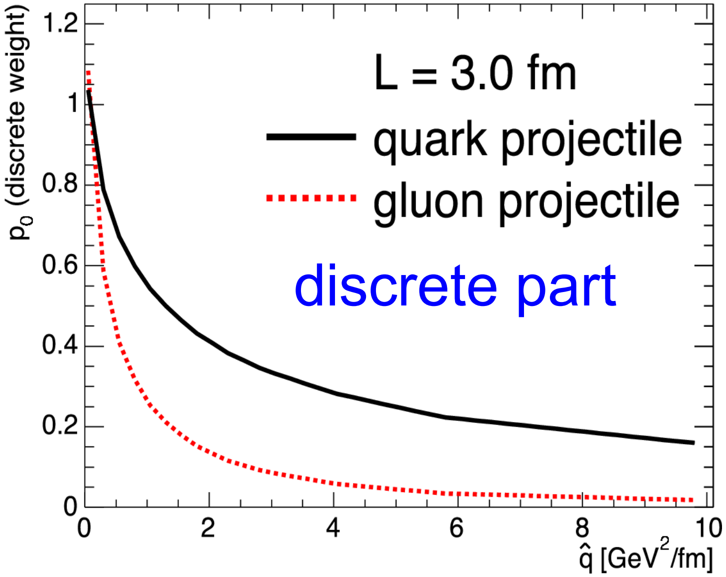
# Quenching weights

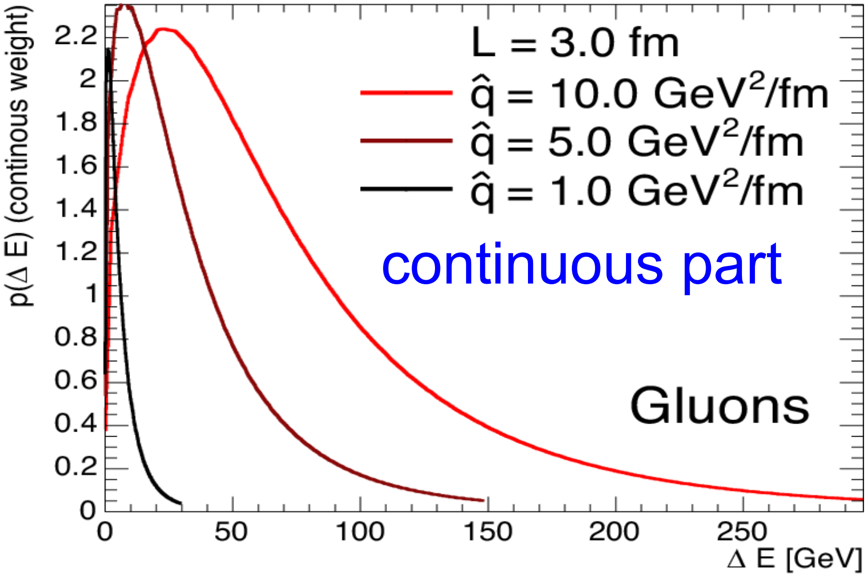
- Compute energy loss probability distributions

$$P(\Delta E) = \sum_{n=0}^{\infty}\left[\prod_{i=1}^{n}\int d\omega_i \frac{dI(\omega_i)}{d\omega}\right]\delta\left(\Delta E - \sum_{i=0}^{n}\omega_i\right)\exp\left[-\int d\omega \frac{dI}{d\omega}\right]$$

- Calculated from ω dI/dω in the $E \to \infty$ approximation (no E dep.)

$$P(\Delta E; C_R, \hat{q}, L) = p_0(C_R, \hat{q}, L) + p(\Delta E; C_R, \hat{q}, L) \qquad \left[\alpha_S = 1/3\right]$$





BDMS, JHEP 0109 033 (2001)
Salgado, Wiedemann, PRD 68 014008 (2003)

➡ Constrained weights

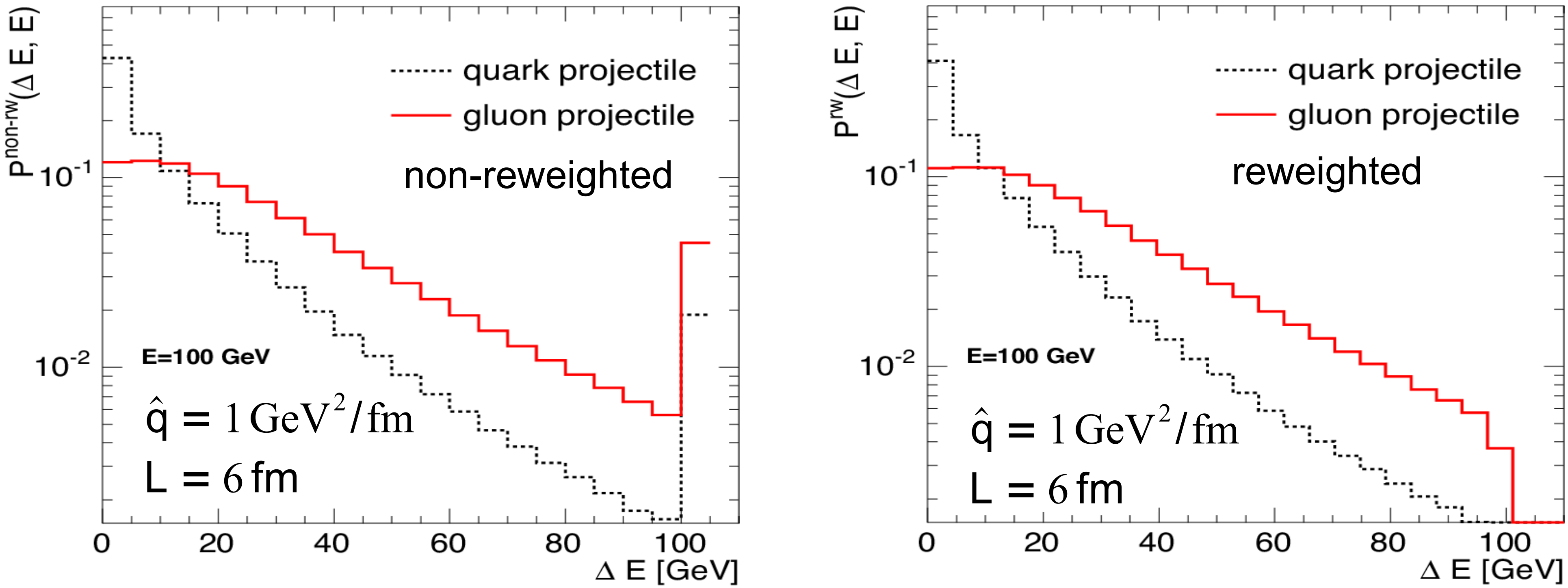
# Constrained quenching weights

Construct constrained weights from quenching weights

$$P(\Delta E; C_R, \hat{q}, L, E) \quad \text{with} \quad \Delta E \leq E$$

a) non-reweighted weight
(thermalize for Δ E>E)

b) reweighted weight
(truncate + renormalize at Δ E=E)



# PQM parton-by-parton approach

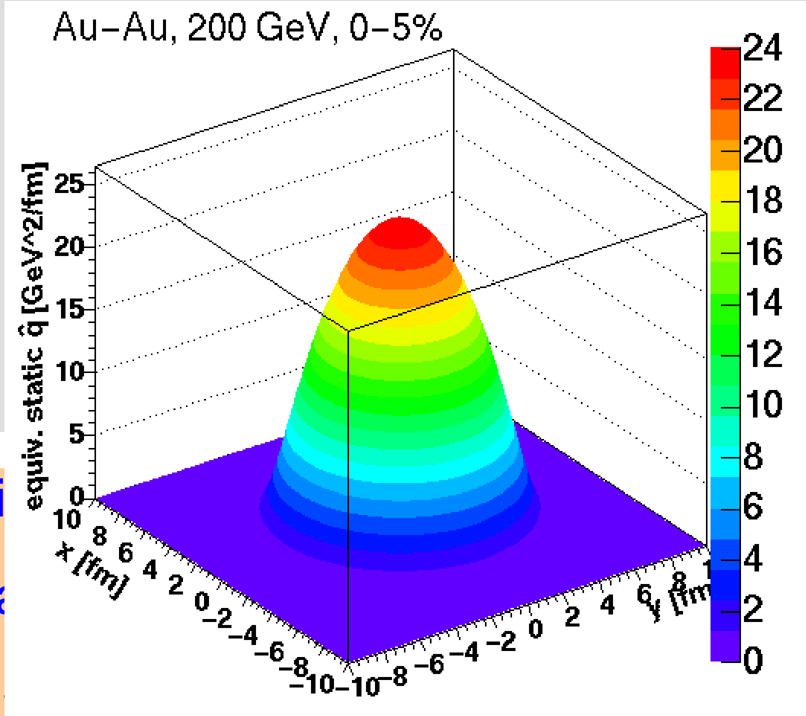
- Define “local” transport coefficient

$$\hat{q}\left(\xi ; x_0, y_0, \phi_0 ; b\right) = k \times T_A T_B\left(x_0 + \xi \cos\phi_0, y_0 + \xi \sin\phi_0 ; b\right)$$

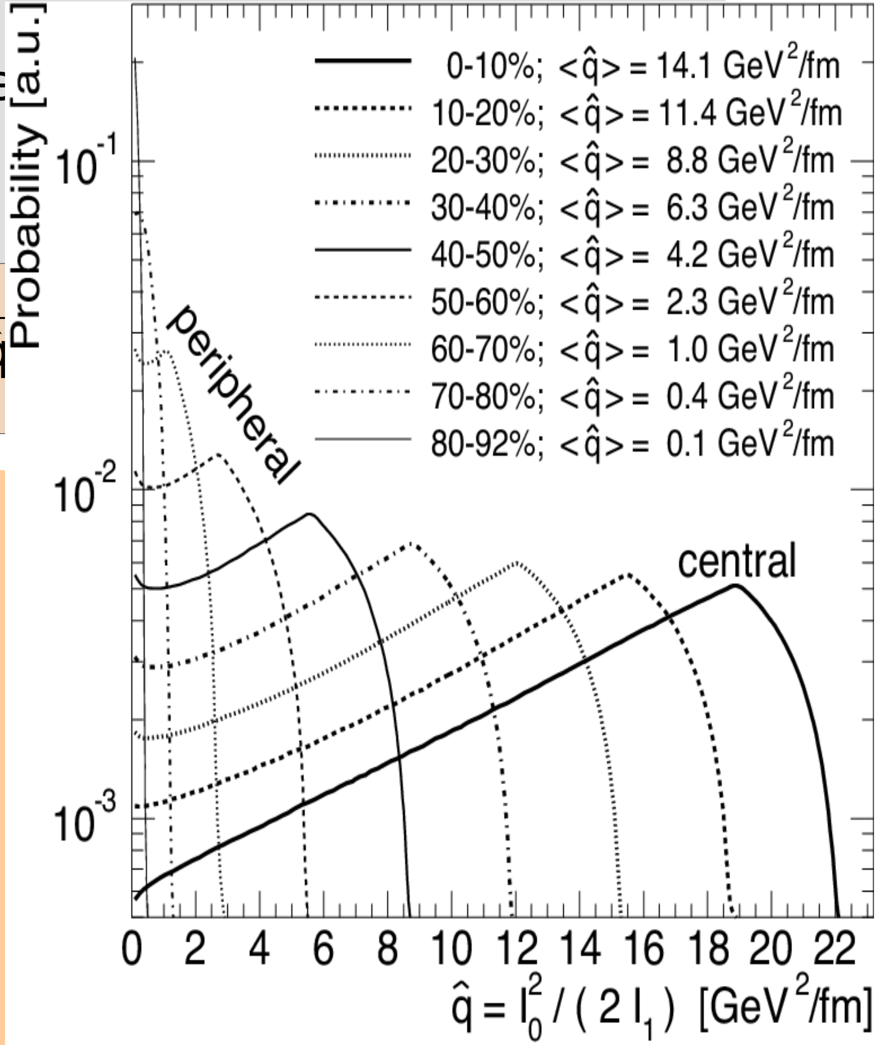
(note

ts

nt $\bar{\hat{q}}$



- Defi
- Para nce)
  - –
    - Implicitly depends on systems and energy (see later)
    - Use Glauber to scale to other centralities
    - Report $\langle\hat{q}\rangle \propto k$ for a given centrality range



Dainese et al., EPJC 461 (2005)

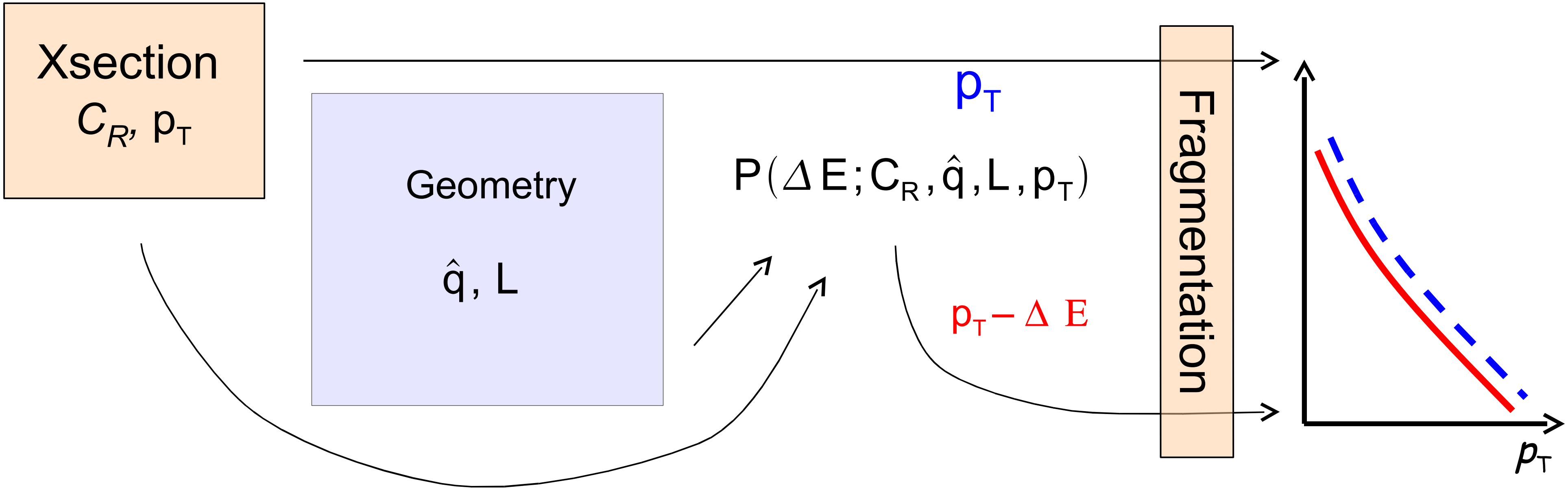
# Calculating quenched particle spectra

Factorized pQCD + final state quenching + vacuum fragmentation

$$\left.\frac{d^2\sigma^h_{\mathrm{quenched}}}{dp_T\,dy}\right|_{y\approx 0} = \sum_{a,b,j}\int dF_{ab}\,d\Delta E_j\,dz_j\,dp^{\mathrm{init}}_{T,j}\left.\frac{d^2\sigma^{ab\to jX}}{dp^{\mathrm{init}}_{T,j}\,dy}\right|_{y\approx 0}\times$$

$$\delta(p^{\mathrm{init}}_{T,j}-p_{T,j}-\Delta E_j)P(\Delta E_j;C_j,\hat{q}_j,L_j,p_{T,j})\frac{D_{h/j}(z_j)}{z_j^2}$$

Monte Carlo approach:



**Xsection**

$C_R$, $p_T$

Geometry

$\hat{q}$, L

$P(\Delta E;C_R,\hat{q},L,p_T)$

$p_T$

$p_T-\Delta E$

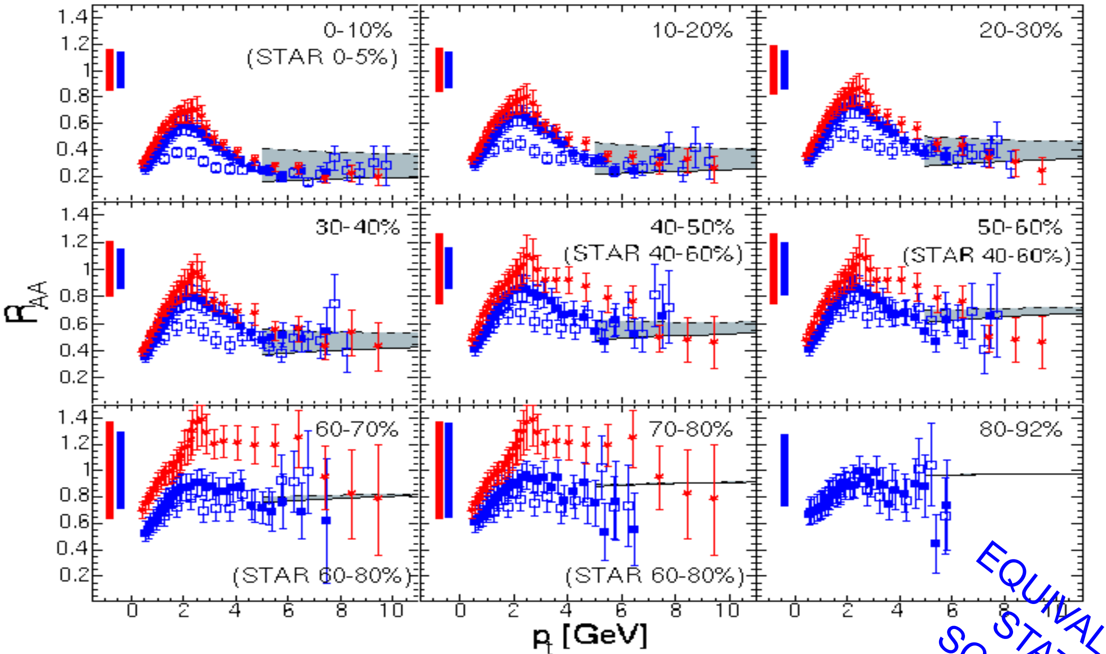
Fragmentation

# PQM for $R_{AA}$ in Au+Au at 200 GeV

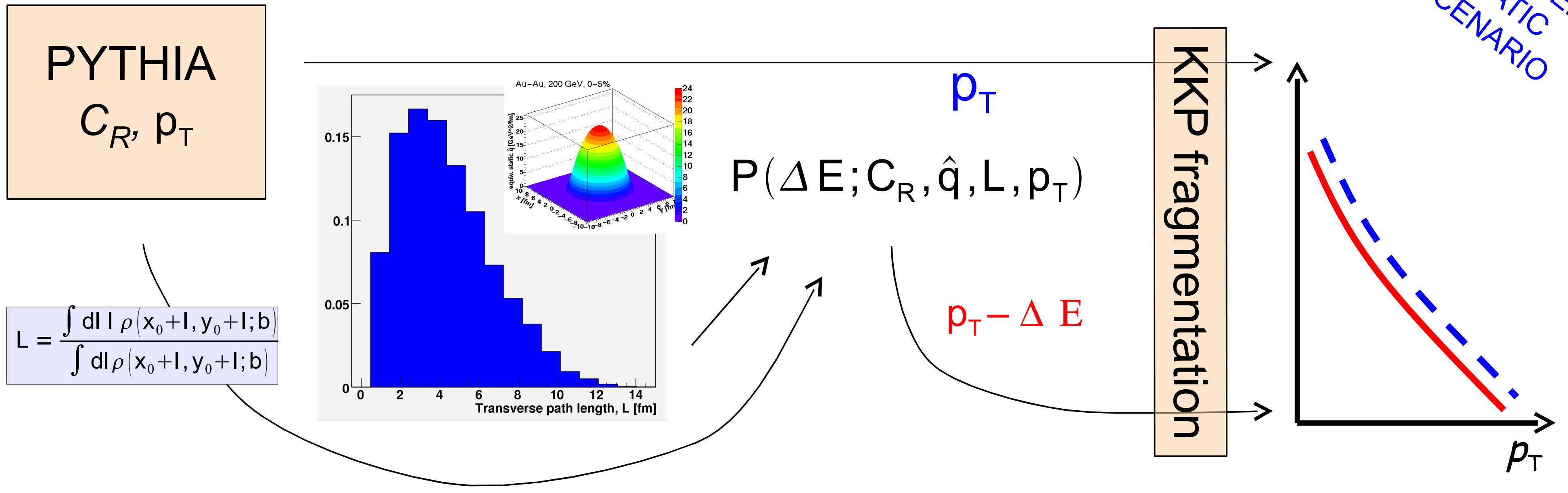
Need

$$\langle \hat{q} \rangle = 4 - 14\,\mathrm{GeV}^2/\mathrm{fm}$$

to describe the measured suppression in 0-10% Au+Au for Glauber-based length distribution



EQUIVALENT STATIC SCENARIO



**PYTHIA**

$C_R$, $p_T$

$$L = \frac{\int dl\, l\, \rho(x_0+l, y_0+l; b)}{\int dl\, \rho(x_0+l, y_0+l; b)}$$

$p_T$

$$P(\Delta E; C_R, \hat{q}, L, p_T)$$

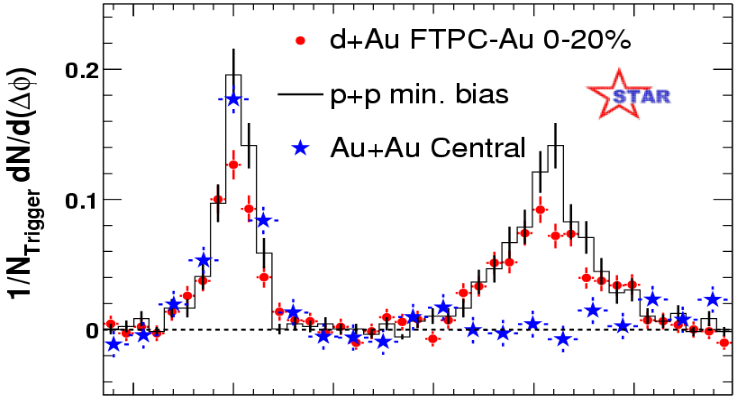
$p_T - \Delta E$

KKP fragmentation

# Correlations wrt trigger particle

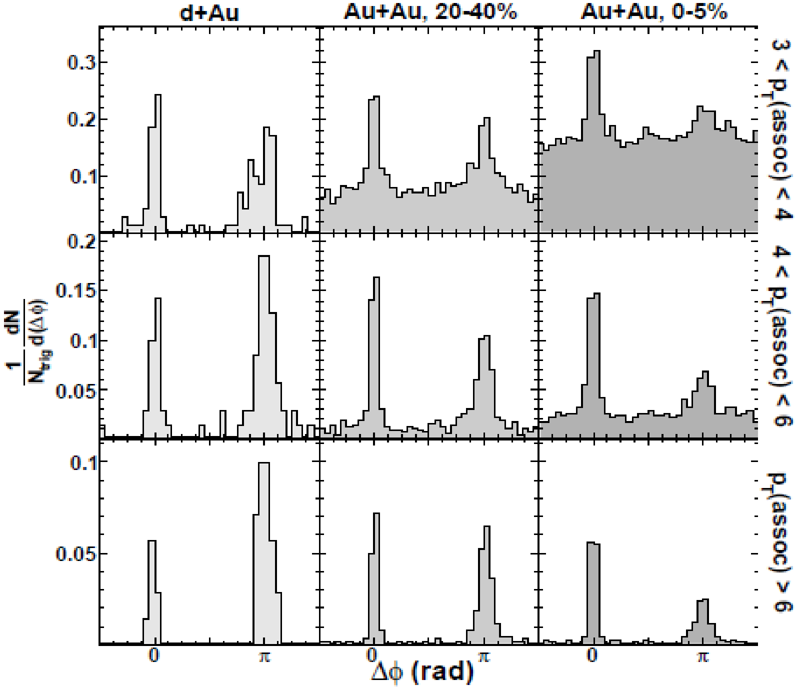
Trigger 4 < $p_T^{trigger}$ < 6 GeV

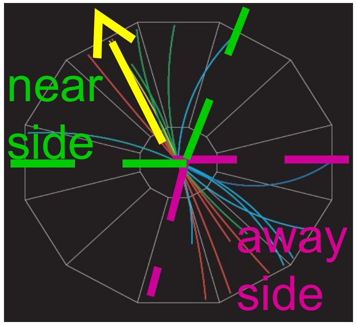
Assoc.: 2 GeV < $p_T$ < $p_T^{trigger}$

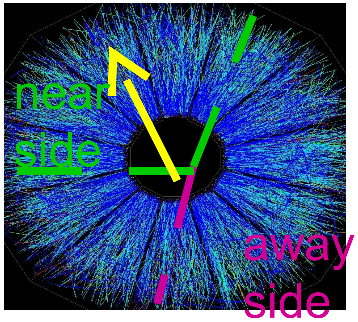


near-side away-side

Trigger 8 < $p_T^{trigger}$ < 15 GeV





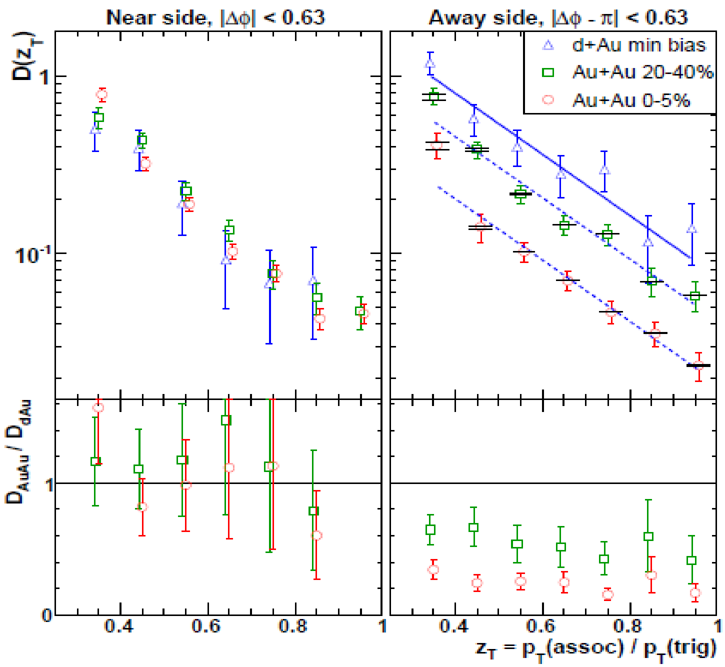


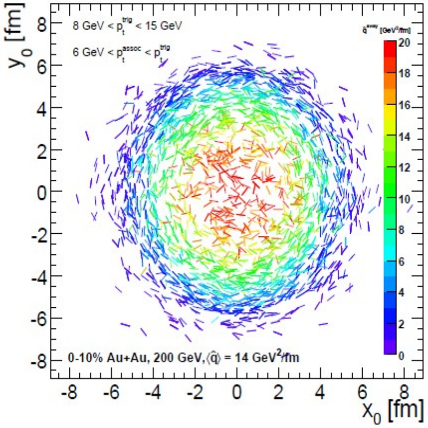
Dis-appearance and re-appearance of the away-side jet

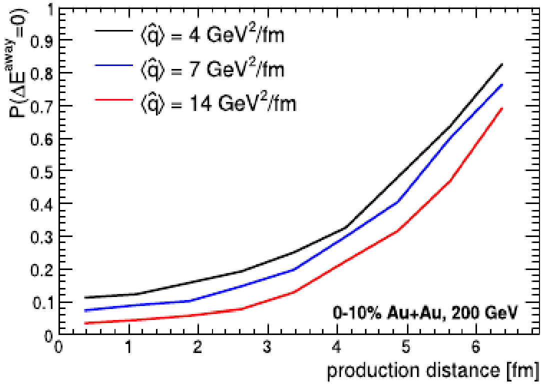
STAR, PRL 91 072304 (2003)
STAR, PRL 97 162301 (2006)

# PQM di-jet analysis

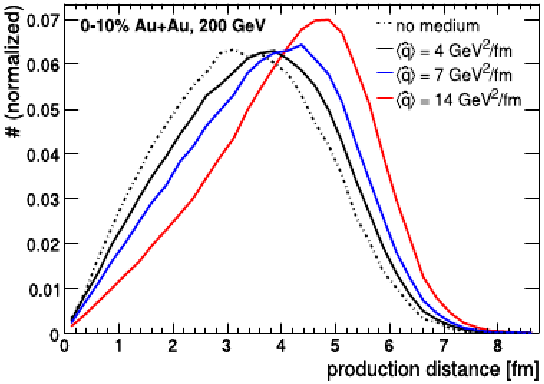
STAR, PRL 97 162301 (2006)



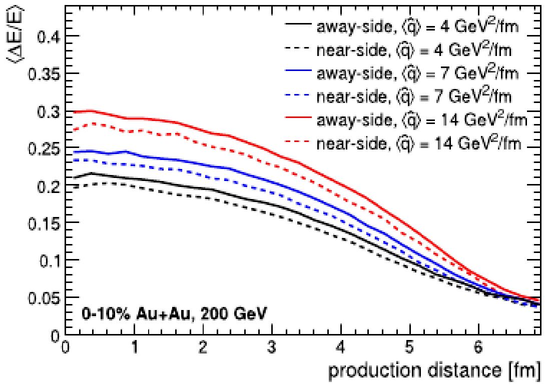




(a)



(b)

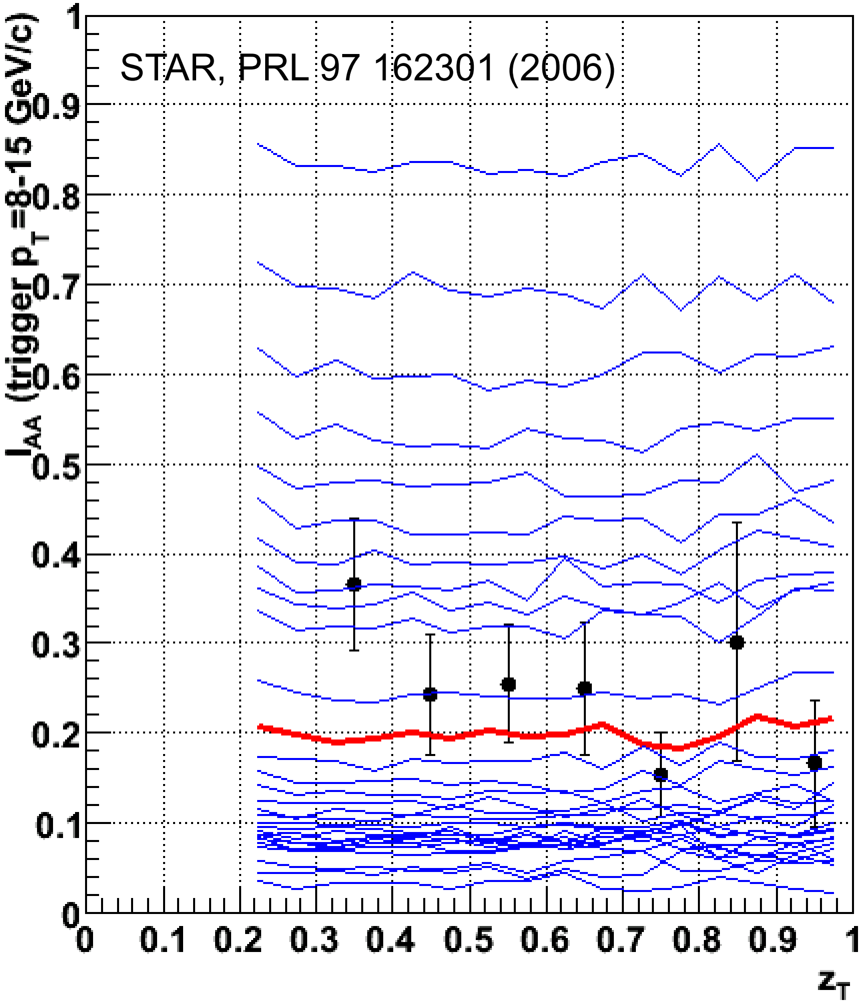


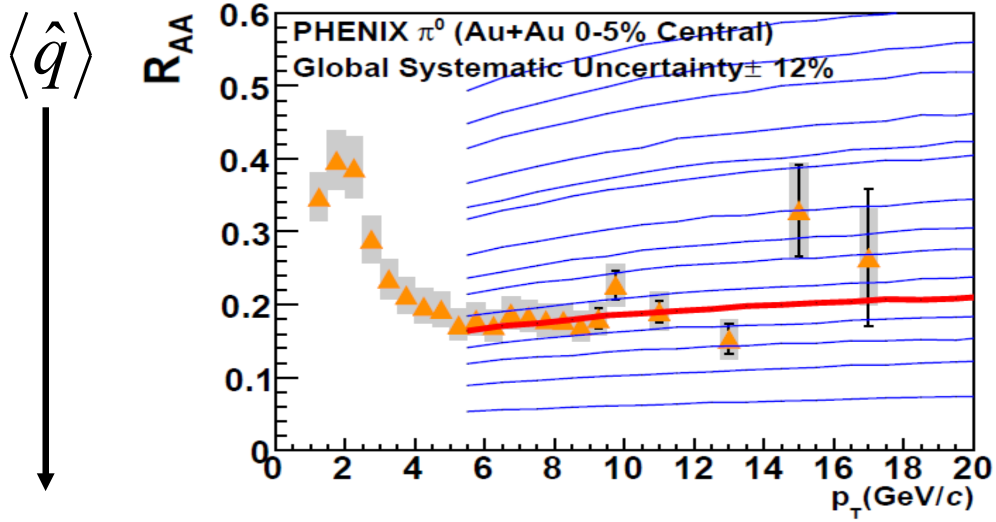
(c)

PQM results for highest sets of cuts suggests strong trigger/selection bias. The energy lost on the away side is very similar to that of the near side.

Loizides, EPJC 49 339 (2007)

# PQM calculations



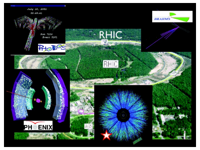


$$< \hat{q} >= 13.2 \ \pm^{2.1}_{3.2} \ (1\,\text{std.}) \ \pm^{6.3}_{5.2} \ (2\,\text{std.})$$

Value from $R_{AA}$(8 GeV) and $I_{AA}$(0.75) are not found to be compatible

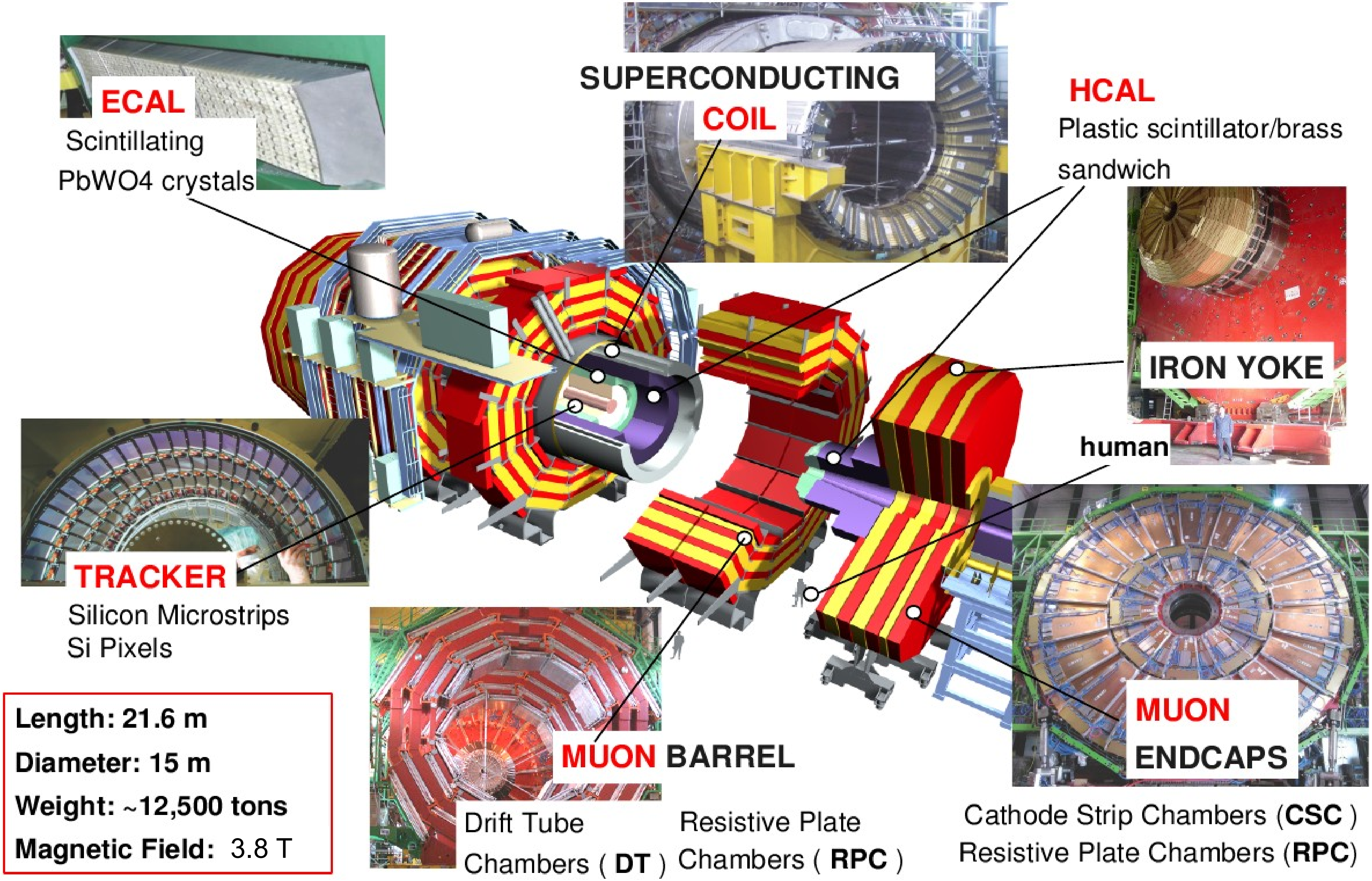
$$< \hat{q} >= 5.9 \ \pm^{1.3}_{0.9} \ (1\,\text{std.}) \ \pm^{3.2}_{1.7} \ (2\,\text{std.})$$

# Heavy ion experiments at LHC



| | AGS | SPS | RHIC | LHC |
|---|---|---|---|---|
| $\sqrt{(s_{NN})}$ (GeV) | 5 | 17 | 200 | 5500 |
| Beam rapidity | ±1.6 | ±3 | ±5.4 | ±8.6 |

# Compact Muon Solenoid



**ECAL**
Scintillating
PbWO4 crystals

**SUPERCONDUCTING COIL**

**HCAL**
Plastic scintillator/brass
sandwich

**IRON YOKE**

**human**

**TRACKER**
Silicon Microstrips
Si Pixels

**MUON BARREL**

Drift Tube
Chambers ( **DT** )

Resistive Plate
Chambers ( **RPC** )

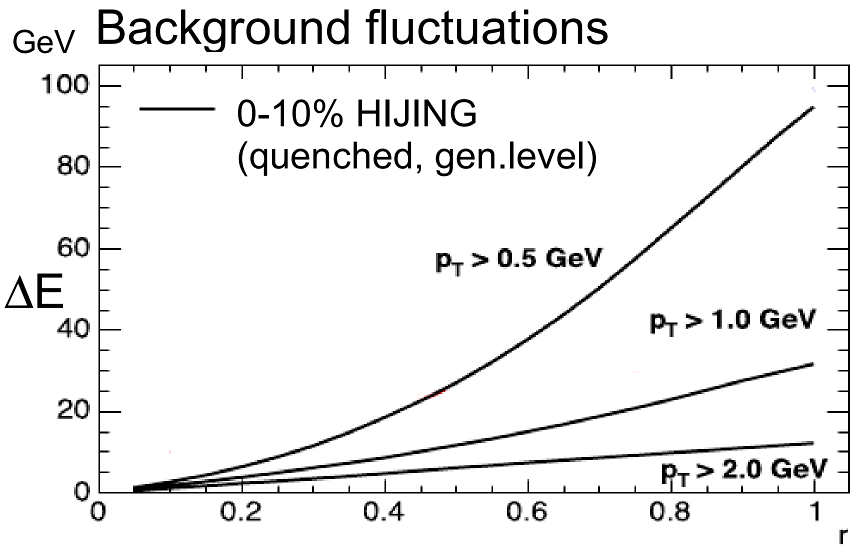
**MUON ENDCAPS**

Cathode Strip Chambers (**CSC** )
Resistive Plate Chambers (**RPC**)

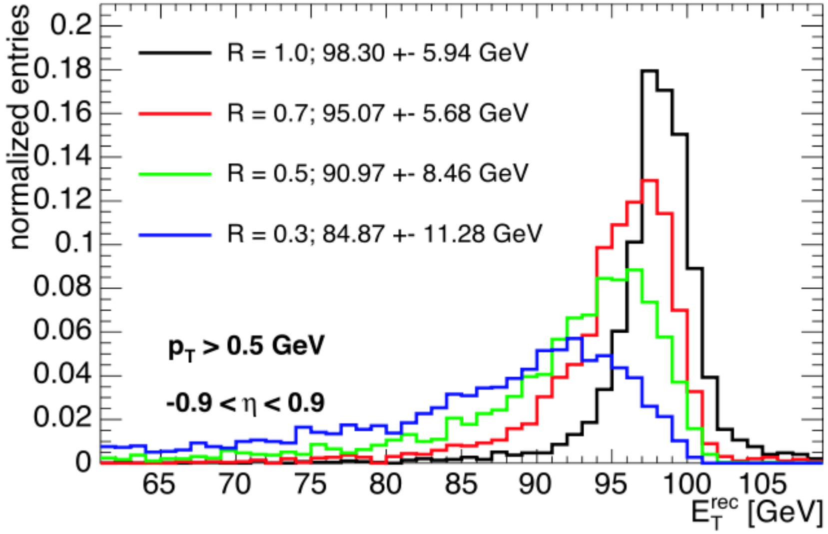
**Length: 21.6 m**
**Diameter: 15 m**
**Weight: ~12,500 tons**
**Magnetic Field:** 3.8 T

# Jet reconstruction in HI collisions

- Consequences of HI background
  - Mean energy in cone R
    $E_{bgk} = 0.5\mathrm{R}\, dE_T / d\eta$
  - For R=0.5,
    - 75 GeV in central Au+Au, RHIC
    - ~150 GeV in central Pb+Pb, LHC
- Furthermore, jet energy resolution degraded by
  - Background fluctuations
  - Out-of-cone fluctuations
  - Possible out-of-cone radiation
- Typically R=0.3 to 0.5 in HI



Out-of-cone fluctuations for 100 GeV jet (gen.level) PYTHIA

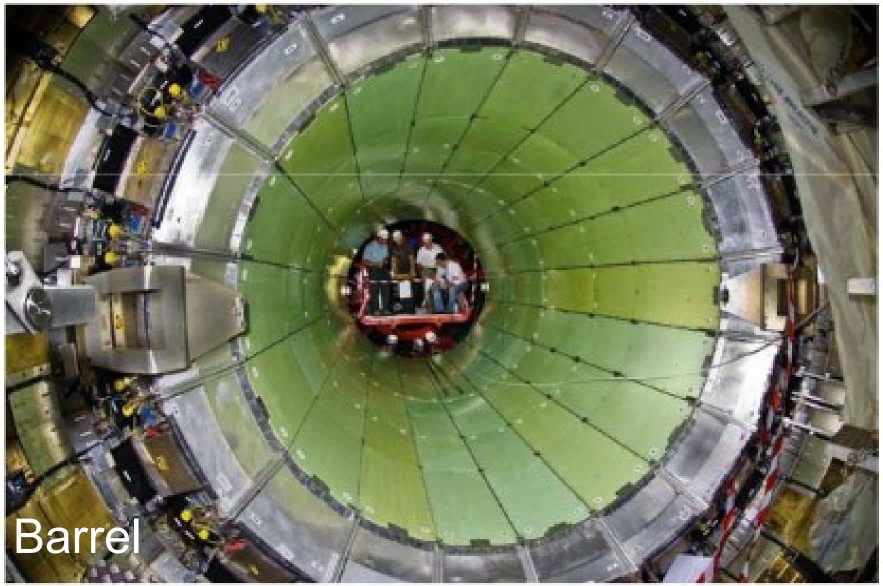


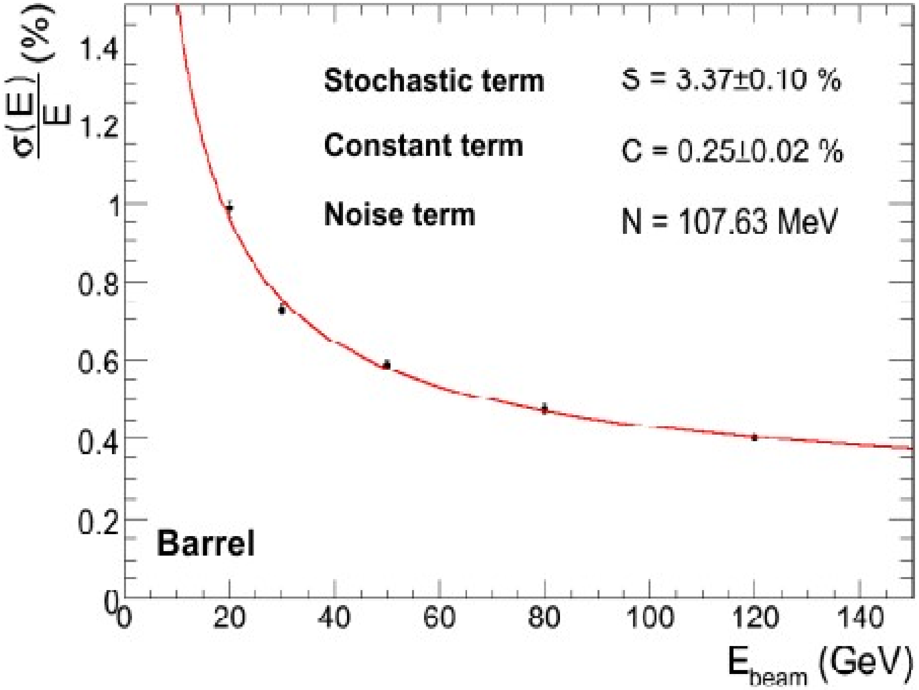
CL, thesis, nucl-ex/0501017

# Event selection summary

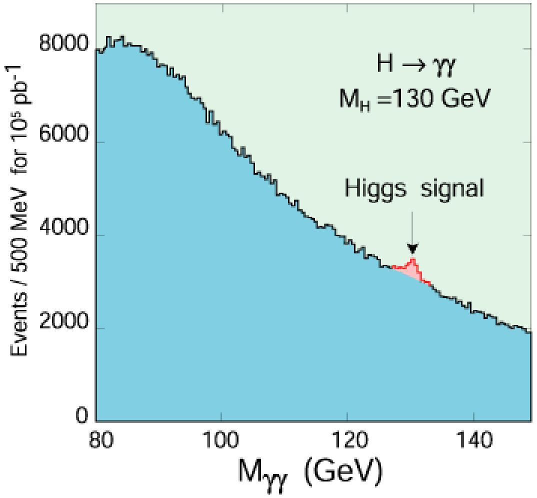
- Pb+Pb background events
  - 0-10% HYDJET v1.2, 1000 events, dN/dη ~ 2400
- PYTHIA (v6.411)/PYQUEN (v1.2) events
  - $E_T$ > 70 GeV potential trigger particle
  - $E_T$ > 60 GeV reconstructed supercluster
- Tracks
  - $p_T$ > 1 GeV/c, > 8 hits, prob > 0.01
- Reconstructed events
  - Isolated photon with $E_T$ > 70 (100) GeV, $|\eta|< 2$
  - Jet with $E_T$ > 30 GeV, $|\eta|< 2$, $\Delta(\gamma\ ,\text{jet}) > 3$
- Fragmentation function
  - Cone-size around jet axis: 0.5

# Electromagnetic calorimeter



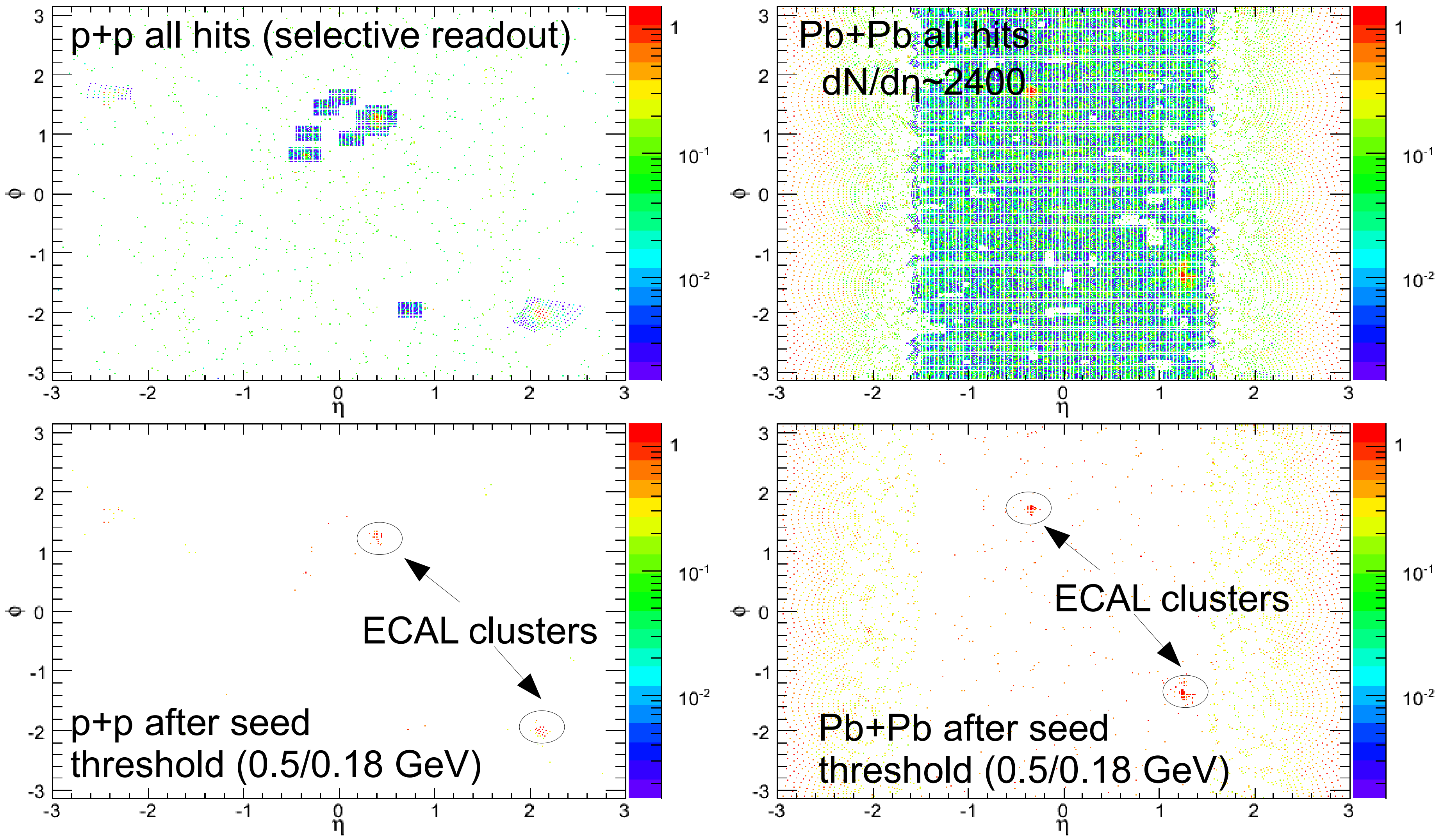


Benchmark:



- 75.000 lead tungstate crystals (+APD)
  - Granularity 0.017x0.017 to 0.05x0.05
  - Coverage up to |η|<3
- ΔE/E < 0.5% for E>100 GeV
  - Pre-shower detector since 2009, not yet exploited

# ECAL response in p+p and Pb+Pb

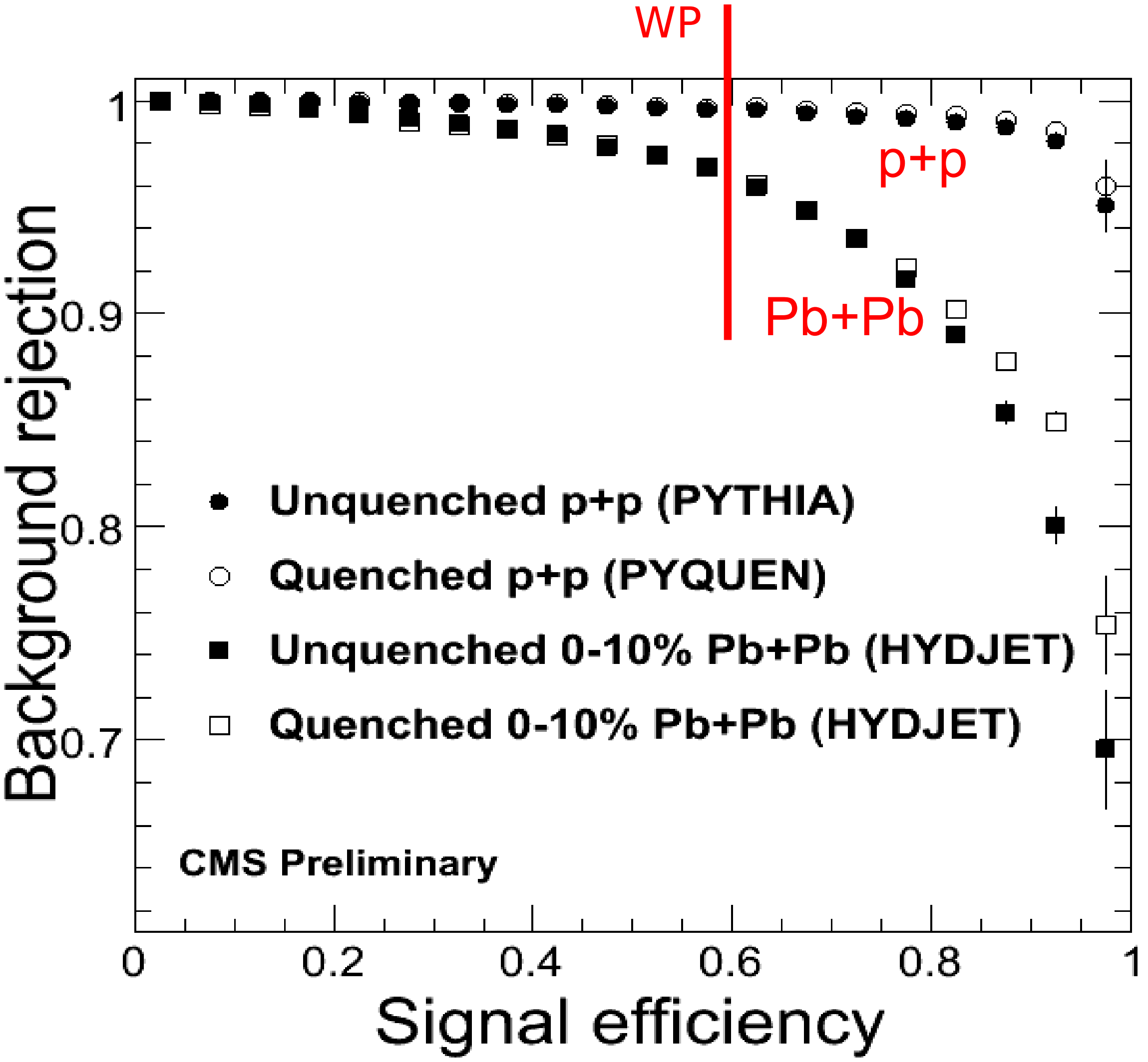


ECAL reconstruction chain used with standard p+p settings

NB: The two p+p (QCD) events are not the same.

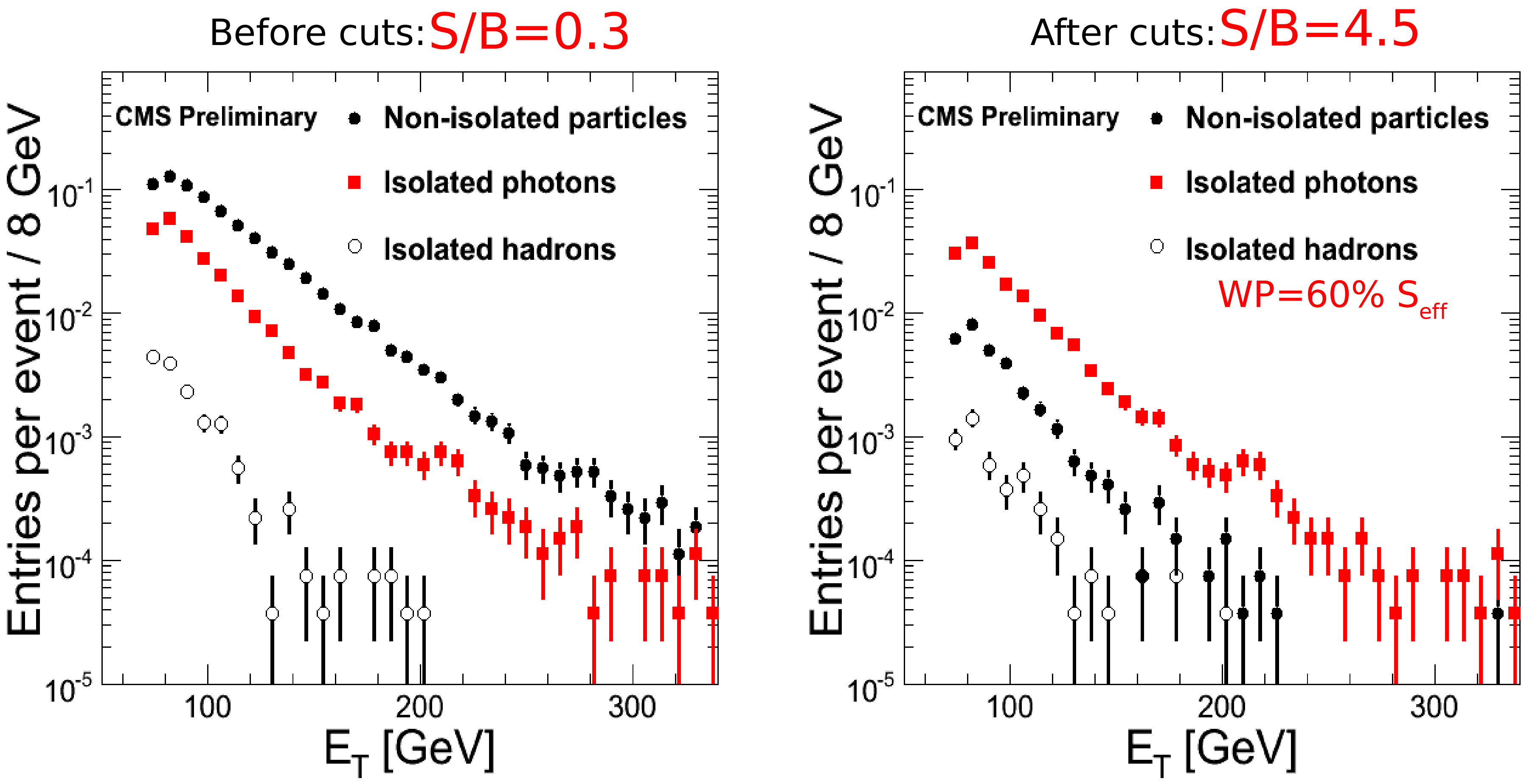
# Photon identification performance

- Set working point to 60% signal efficiency
- Leads to 3.5% false acceptance (96.5% rejection)
- Training was done on unquenched samples only



# Photon identification performance

Quenched Pb+Pb



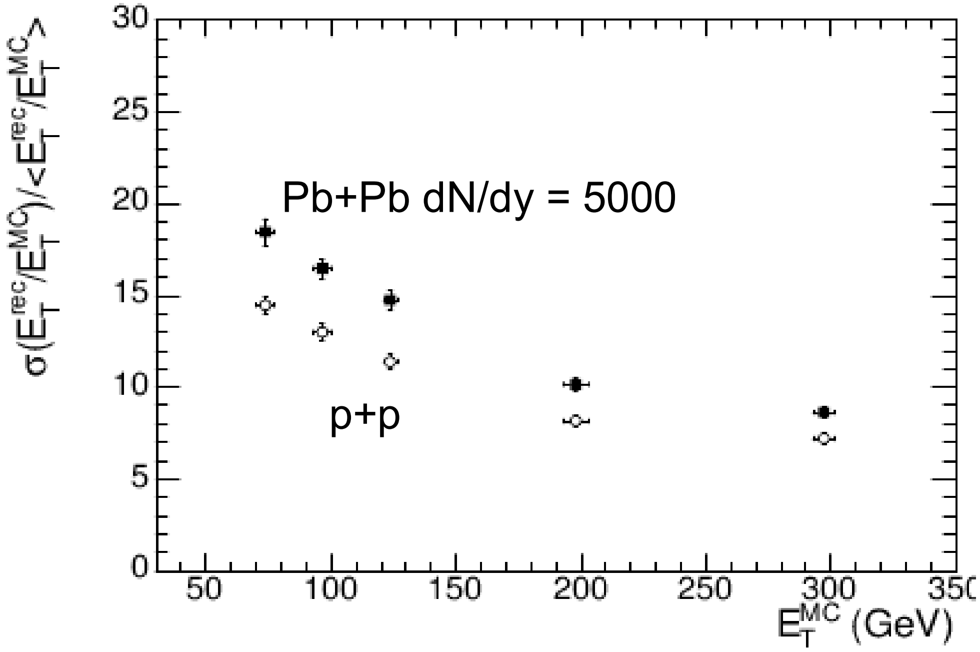
Before cuts: S/B=0.3

After cuts: S/B=4.5

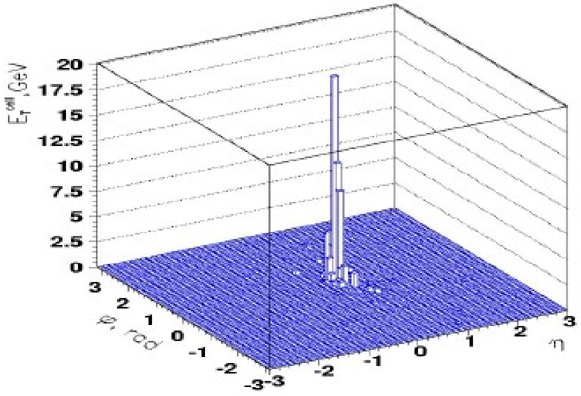
Photon isolation and shape cuts improve S/B by factor ~15

# Calorimetric jet reconstruction

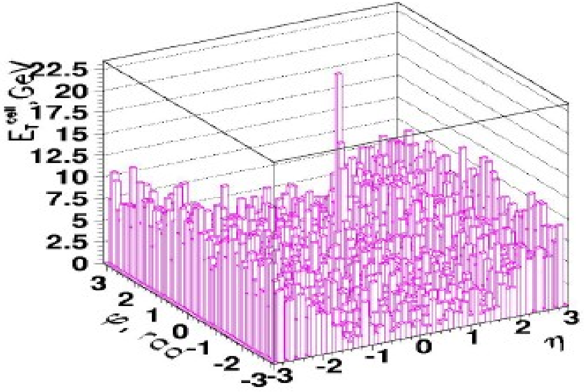
- Iterative cone jet finder with background (pileup) removal
    - R=0.5
- Spatial resolution in $\eta,\phi < 0.05$
- Jet energy correction non-trivial
    - $\gamma$-jet analysis does not use jet energy, except for a minimal cut on uncorrected jet $E_T$>30 GeV



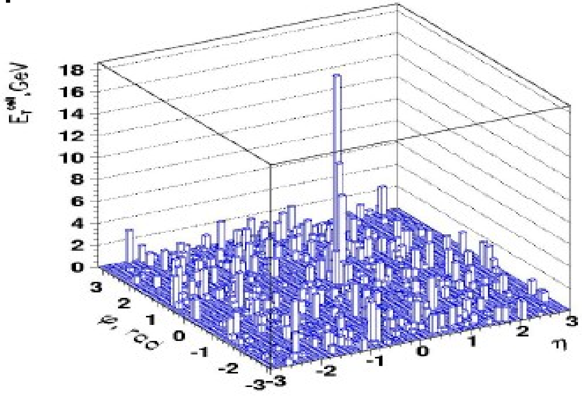
Jet in p+p



Same jet embedded in Pp+Pp



After pileup removal



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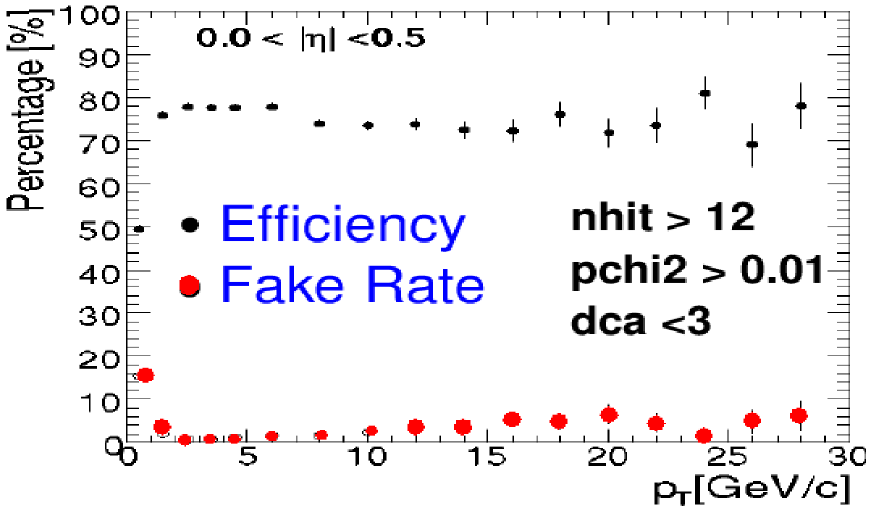
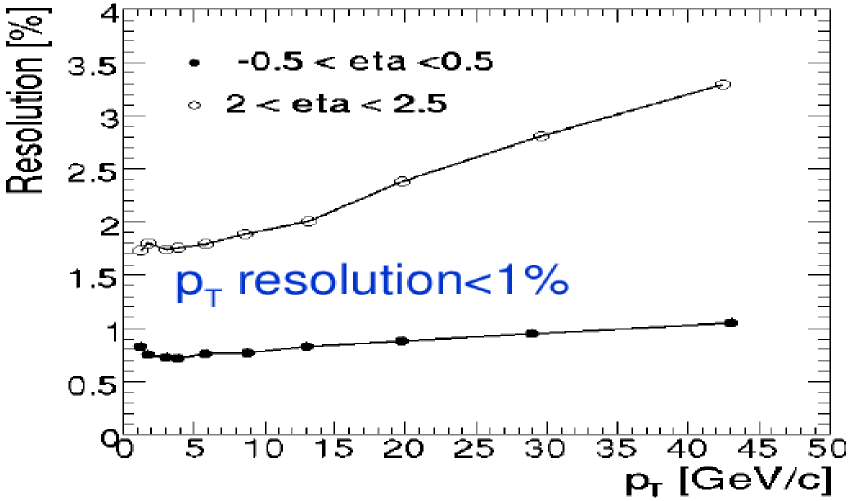
# Tracking in HI collisions

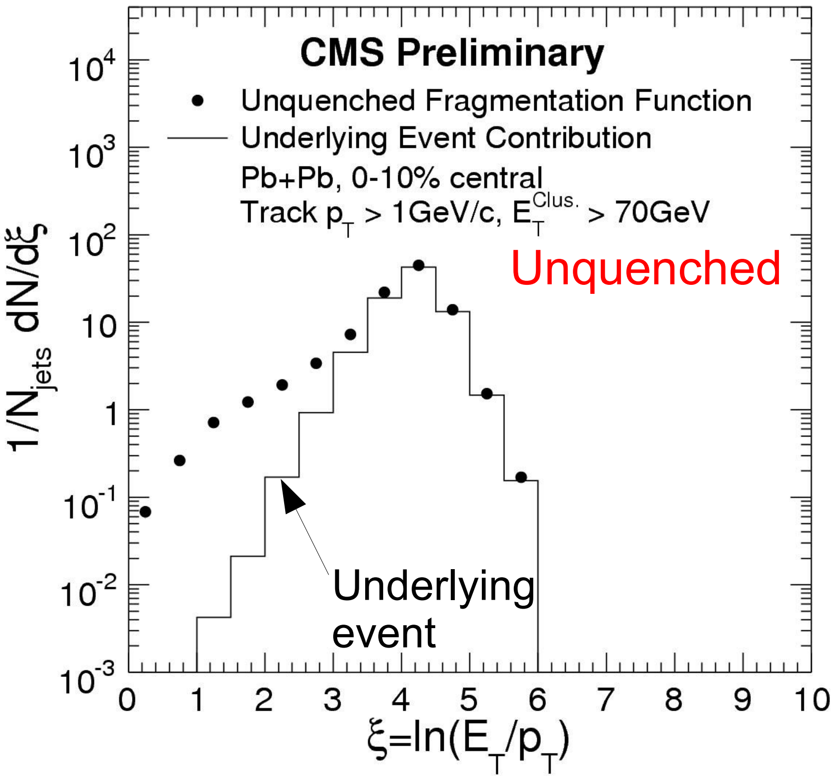
- Charged particle reconstruction using the silicon tracker
  - Algorithm is based on seeds from the silicon pixel detector
  - Extension of p+p with cuts optimized for Pb+Pb
  - Performance
    - Good efficiency
    - Low fake rate
    - Excellent momentum resolution

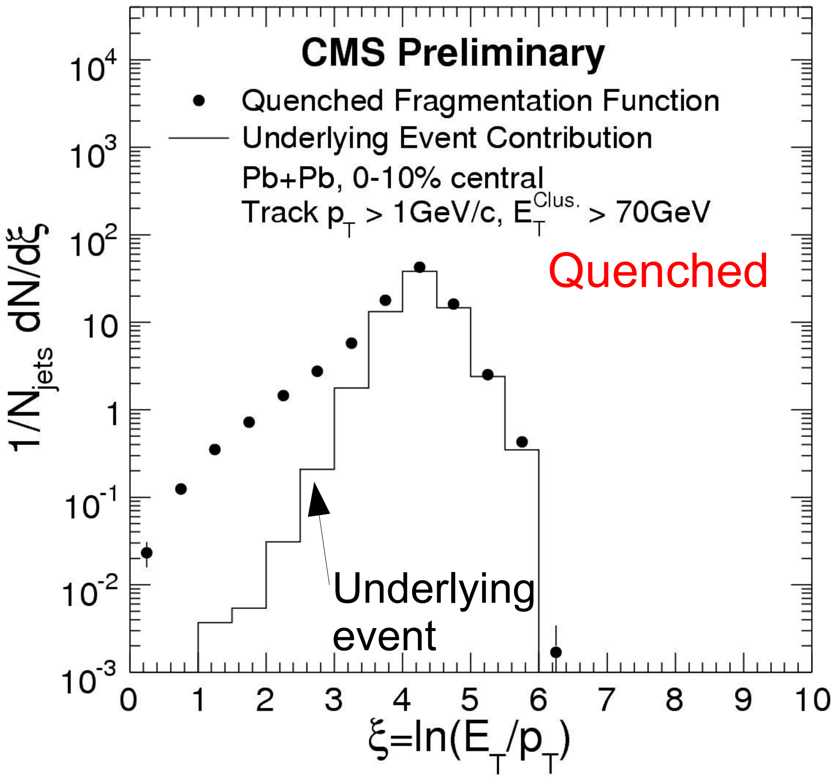




NIM A566 (2006) 123

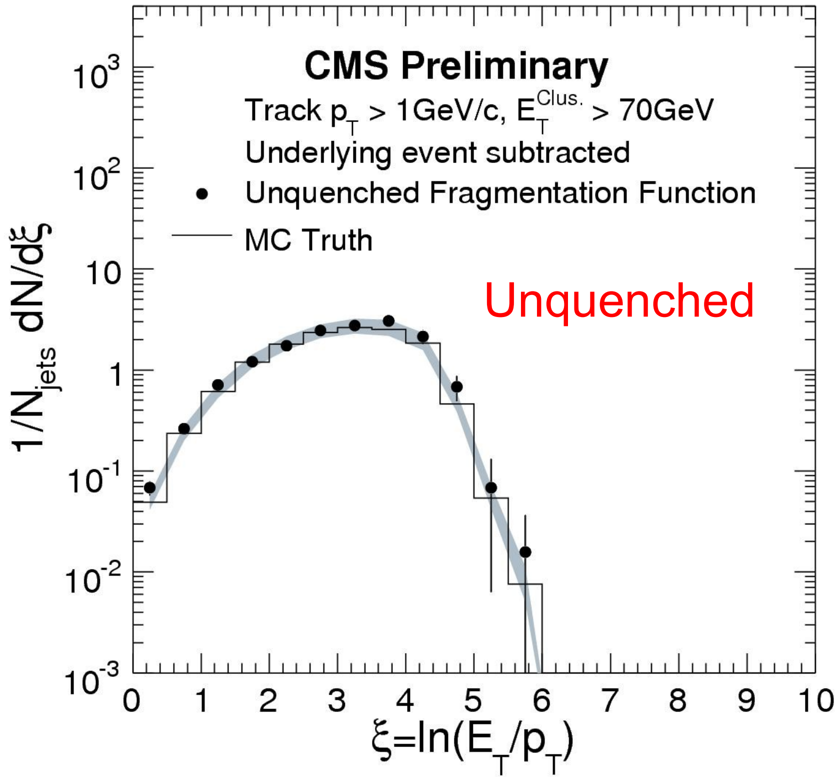
# Reconstructed FFs

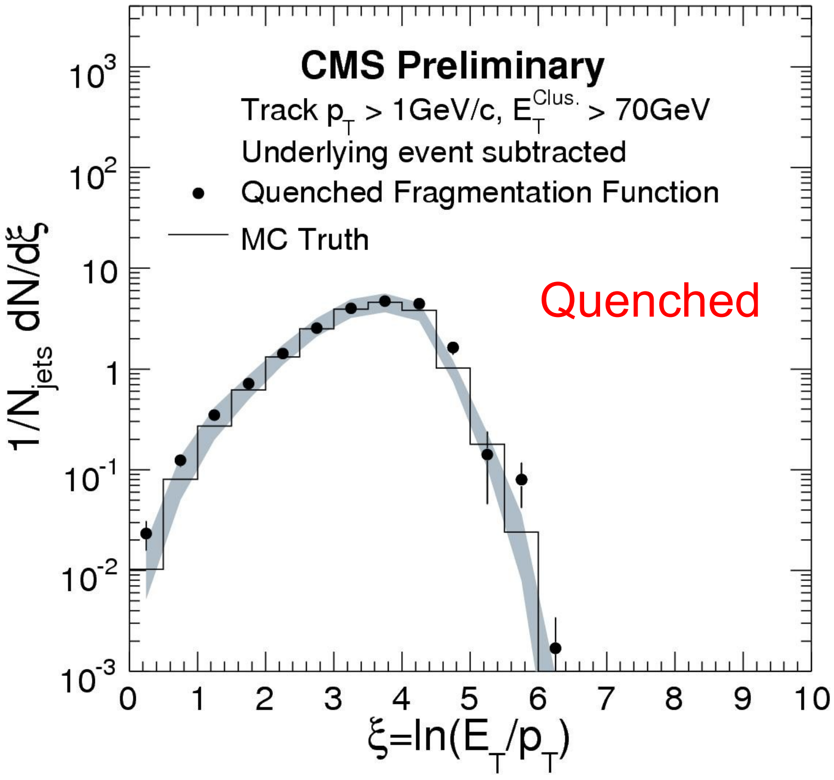




- Obtain dN/dξ using tracks in R=0.5 cone around jet axis
- For ξ>3 (~$p_T$<4GeV/c) dN/dξ dominated by underlying Pb+Pb event
  - Estimate background with R=0.5 cone rotated in φ by 90º rel. to jet
  - Sum event-by-event backgrounds and subtract
  - Correct for track finding efficiency

# Reconstructed FFs





- Major contributions to systematic uncertainty (added in quadrature)
  - Photon selection and background contamination (15%)
  - Track finding efficiency correction (10%)
  - Wrong/fake jet matches (10%)
  - Jet finder bias (up to 30% in quenched case)

} No or small ξ dependence

# Jet finder bias

- Jet finder bias leads to about 30% deviation in quenched case (10% in unquenched case)
- It has two contributions

  1) FFs and jet finding efficiency depend on parton $E_T$

  - Can be corrected with known turn-on curve (not done here)

  2) For a given parton $E_T$, jet finding probability depends on parton fragmentation pattern

  - The jet finder is more likely to find a jet with few high $p_T$ particles than jets with many soft particles
  - MC based correction might be possible (not done here)

- MC truth studies in narrow bins of parton $E_T$ suggest that 2) dominates

$$\frac{\text{MC truth for found reco jets}}{\text{MC truth for all jets}}$$