Recent QGP studies at LHC/RHIC and future plans at Fair/J-parc

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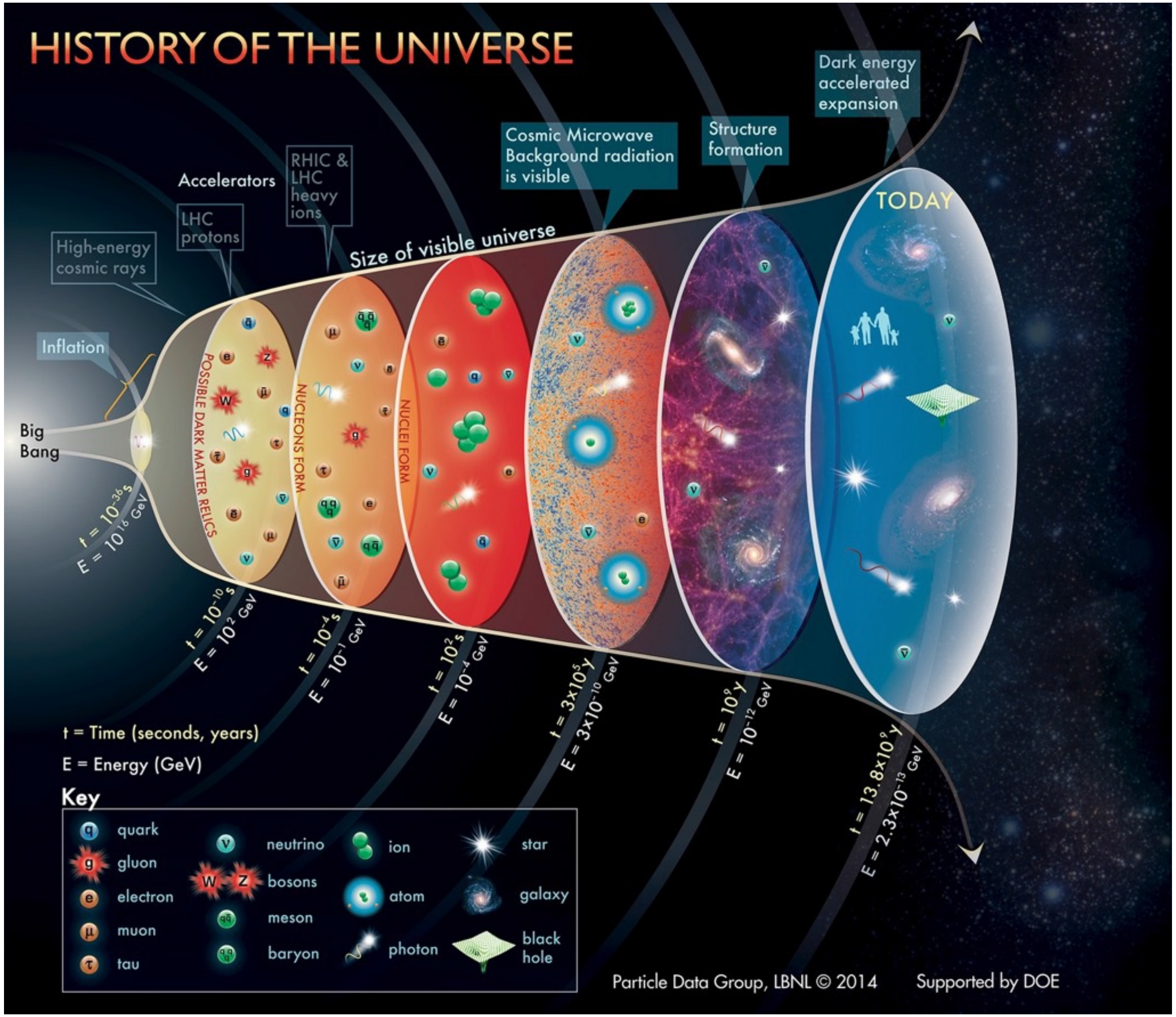


Contents

- Introduction
- Temperature
- Collective expansion
- Jet quenching
- Small system
- Beam energy scan
- Summary

(CiRfSE)
Center for Integrated Research in Fundamental Science and Engineering
「数理物質融合科学センター」

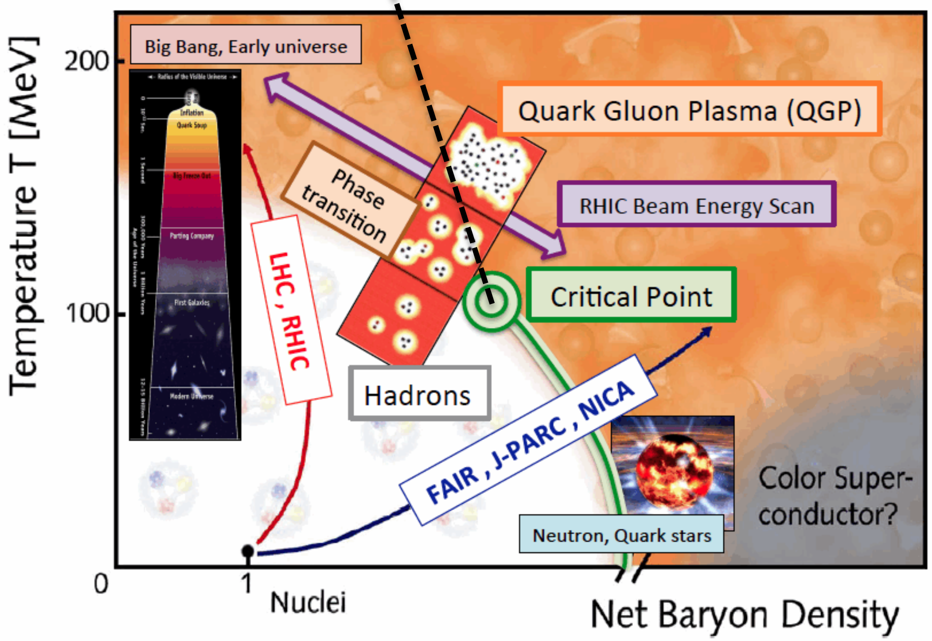
Research Core for the History of the Universe
「宇宙史国際研究拠点」

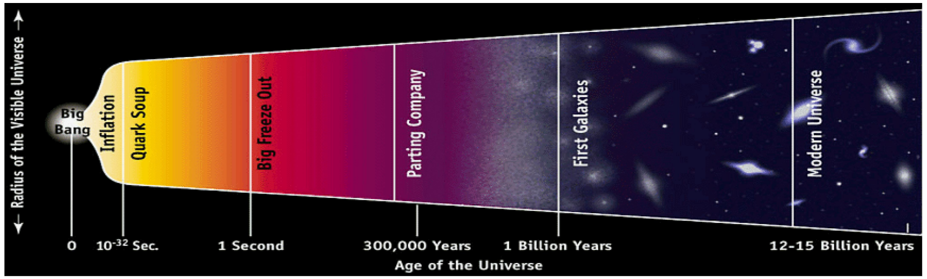
Division of Quark Nuclear Matters
「クォーク・核物質部門」

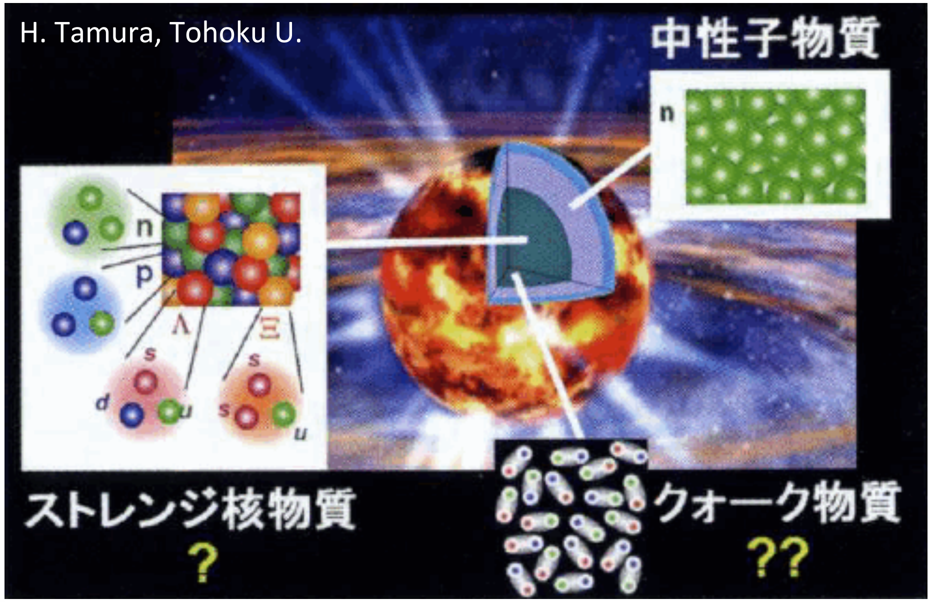
Quark Gluon Plasma (QGP)

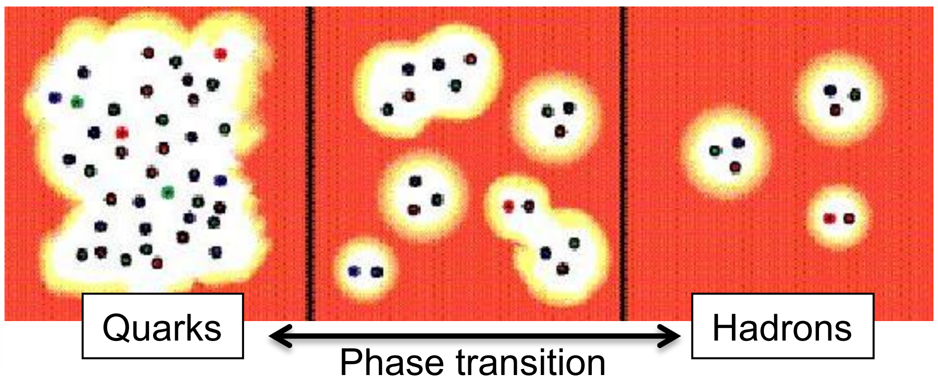
to search for a new state of matter
and to study property of matter

- Early universe, Neutron star
- Quark-hadron phase transition
- Non confined quark states
- Critical end point

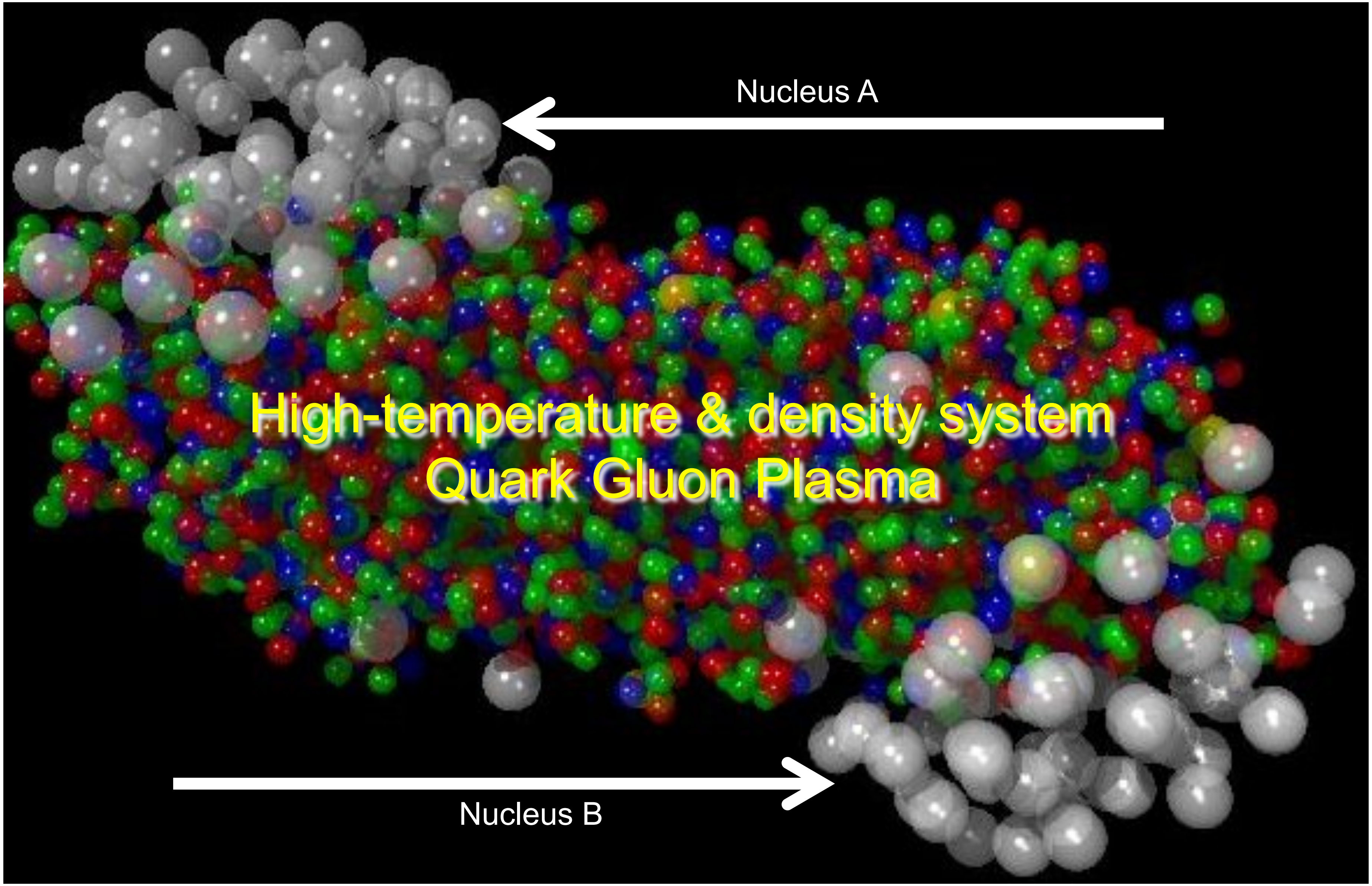






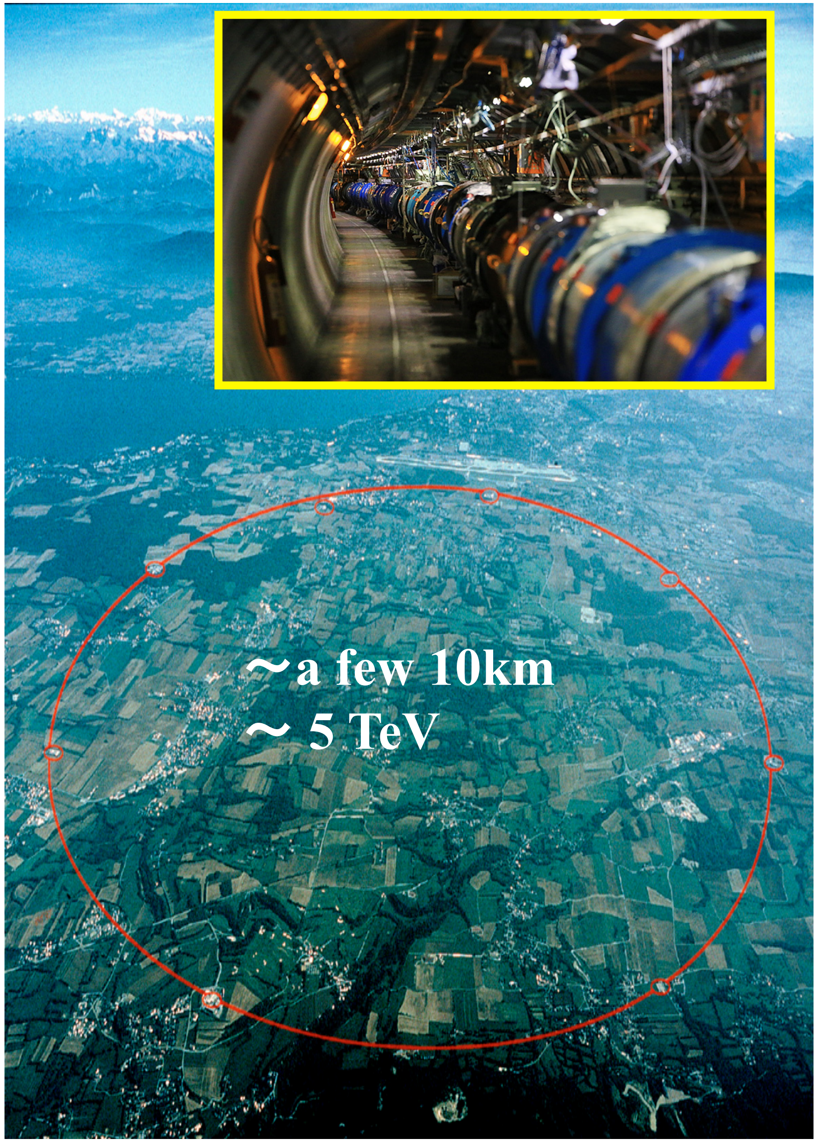


Heavy-Ion collision simulation



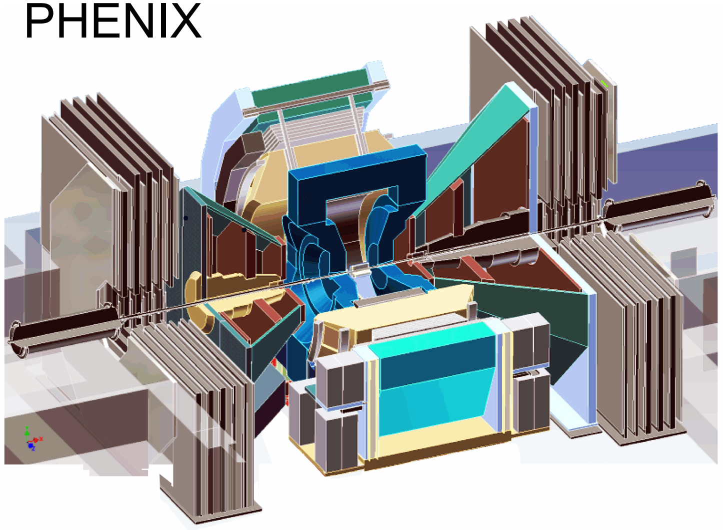
Relativistic Heavy-Ion Collider (RHIC)
Brookhaven National Lab. (BNL)
New York, USA

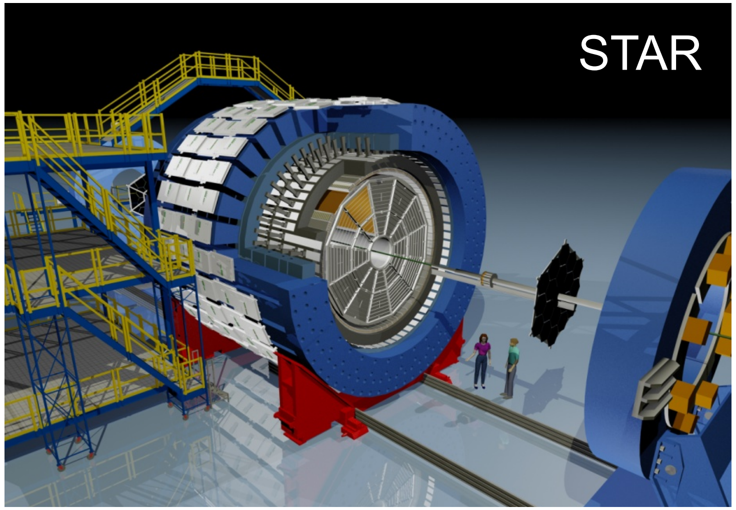
Large Hadron Collider (LHC)
European Organization for Nuclear Study (CERN), Geneva, Switzerland



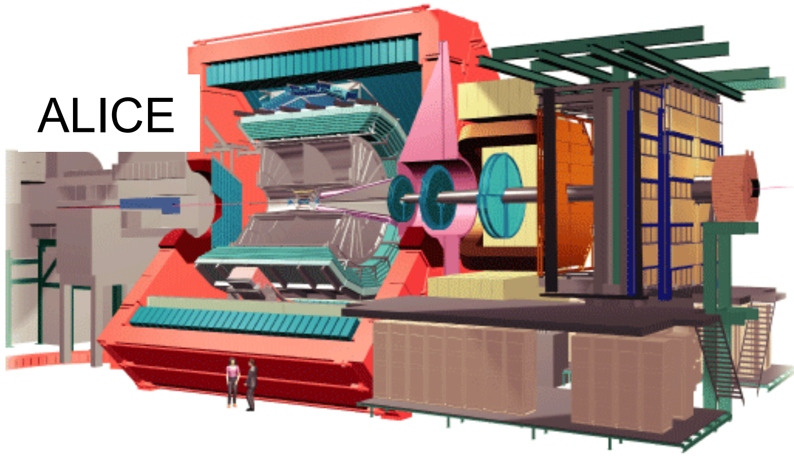
Experiments at RHIC and LHC

PHENIX

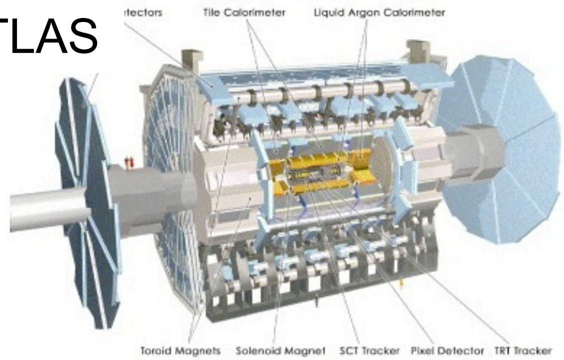




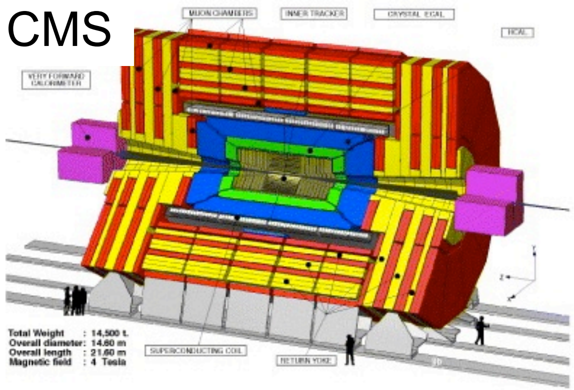
ALICE

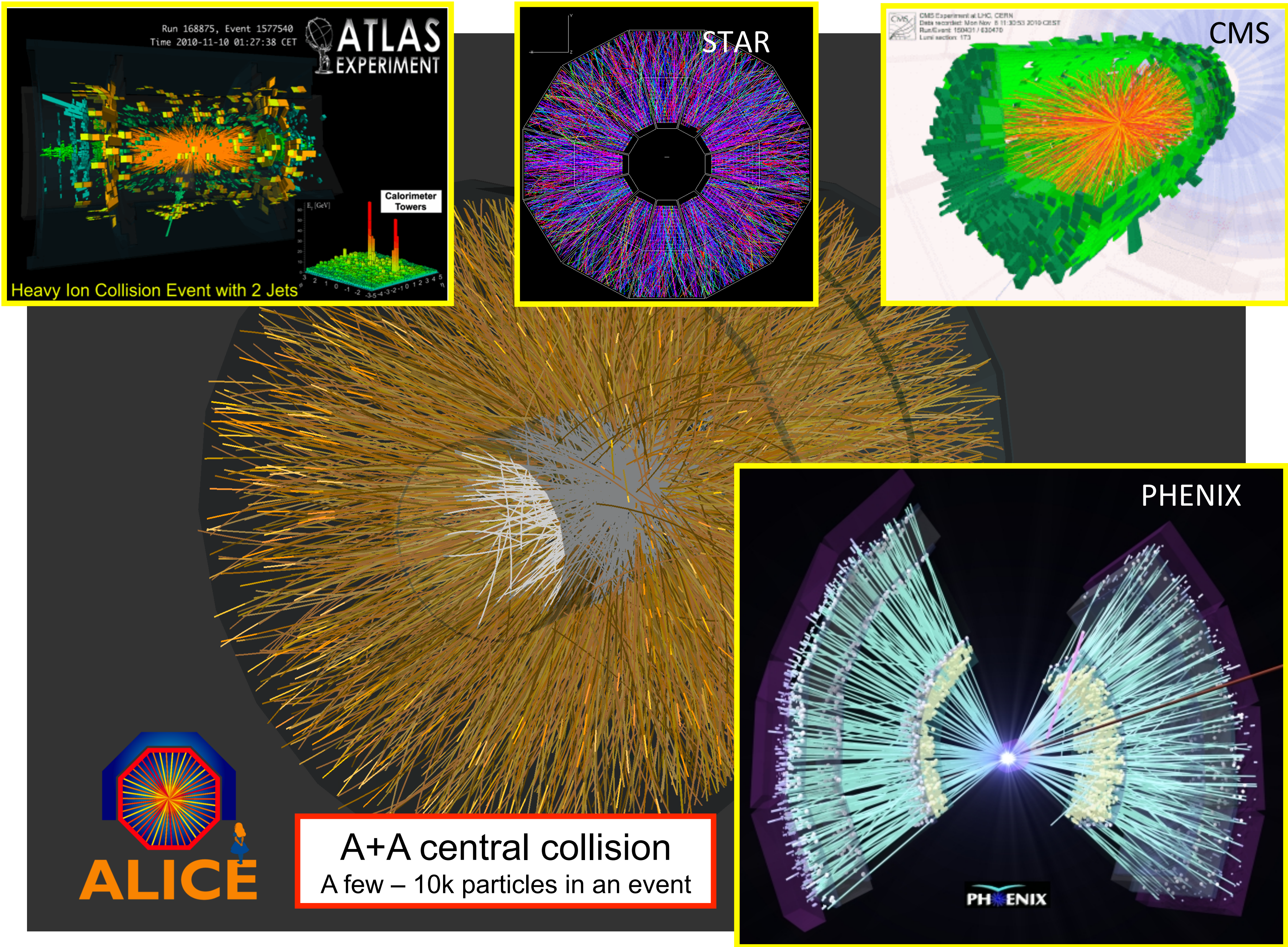


ATLAS



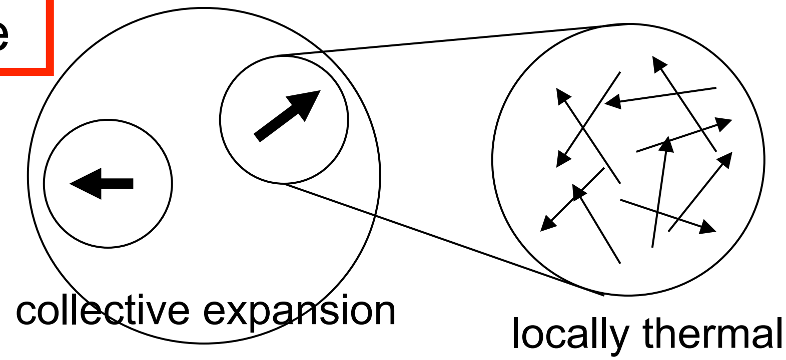
CMS



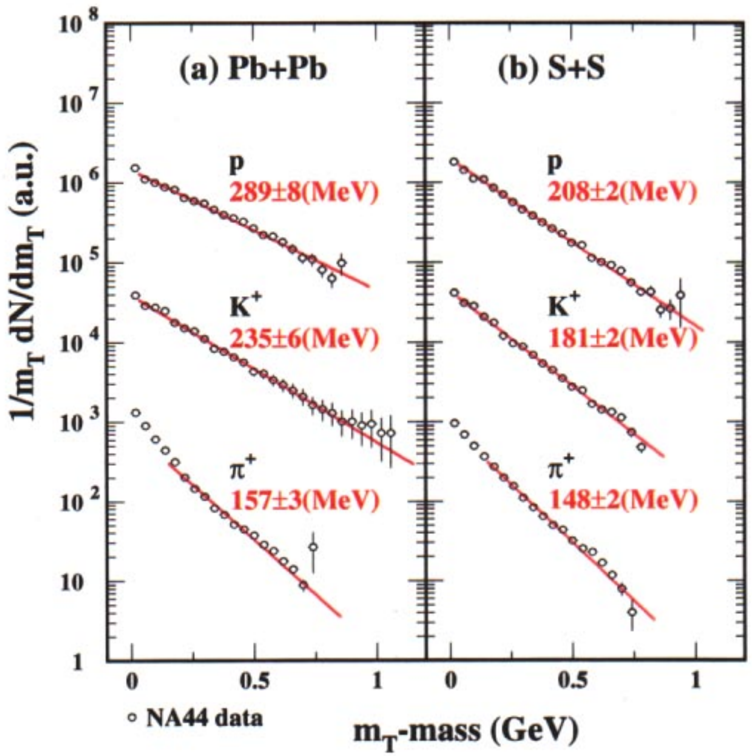

Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS EXPERIMENT
Calorimeter Towers
Heavy Ion Collision Event with 2 Jets
STAR
CMS
PHENIX
PHENIX
ALICE
A+A central collision
A few – 10k particles in an event

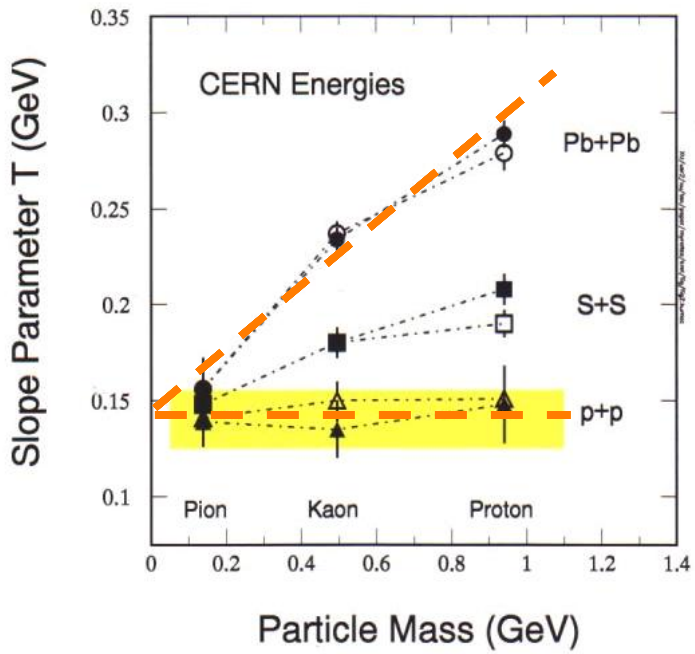
Thermal freeze-out from spectra shape

The end of elastic interactions,
where/when spectra are frozen.



m_T distributions of π,K,p





$E = E_{thermal} + E_{collective}$

$$T_{eff} = T_{fo} + 0.5\, m \langle v_\perp \rangle^2$$

~140 MeV

Chemical Freeze-out from particle yield

$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} {T_{ch}}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ {\lambda_q}^{Q_i}\ {\lambda_s}^{s_i}$$

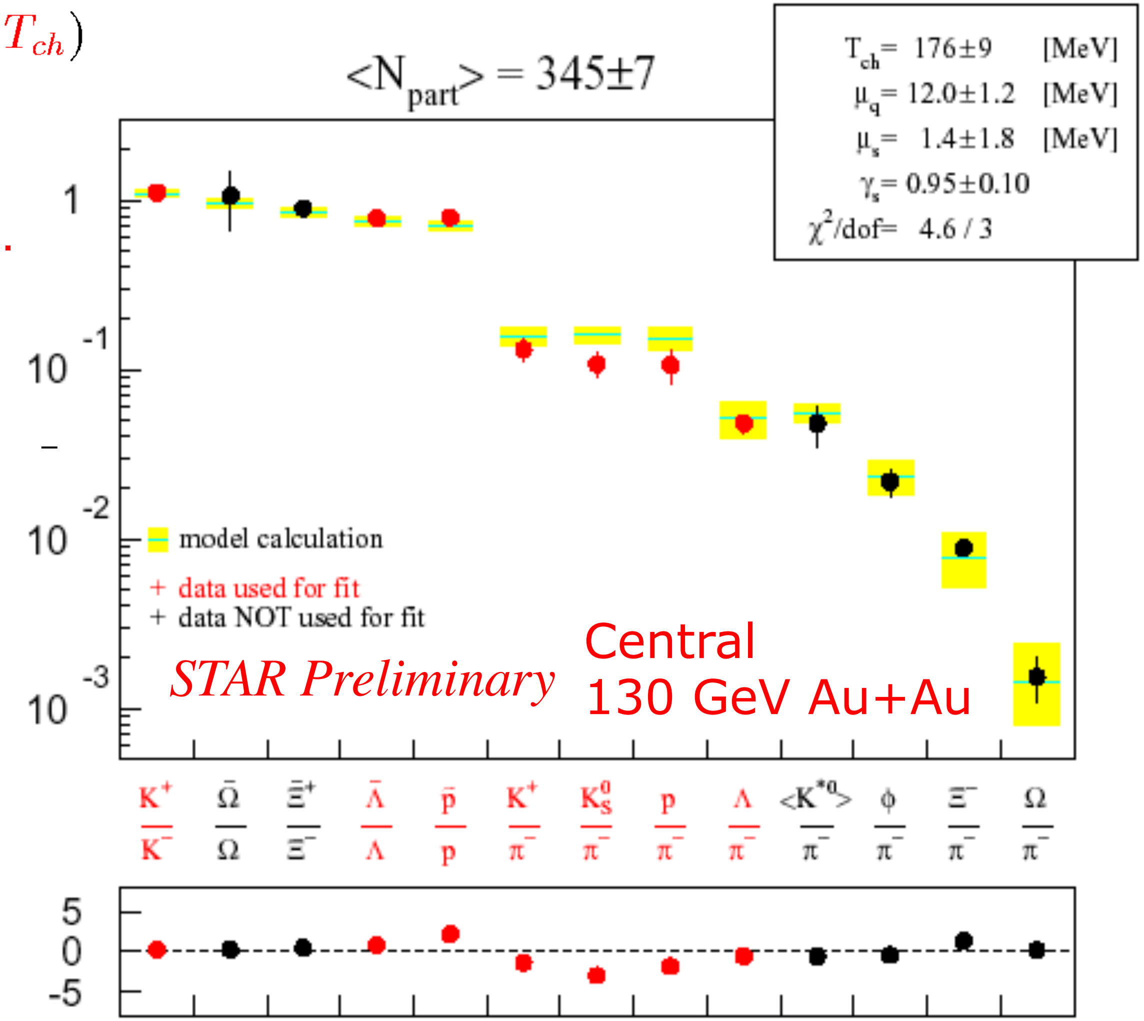
M. Kaneta and N. Xu,
J. Phys. G**27** (2001) 589

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

The end of inelastic interactions,
where/when yield/ratio are frozen.

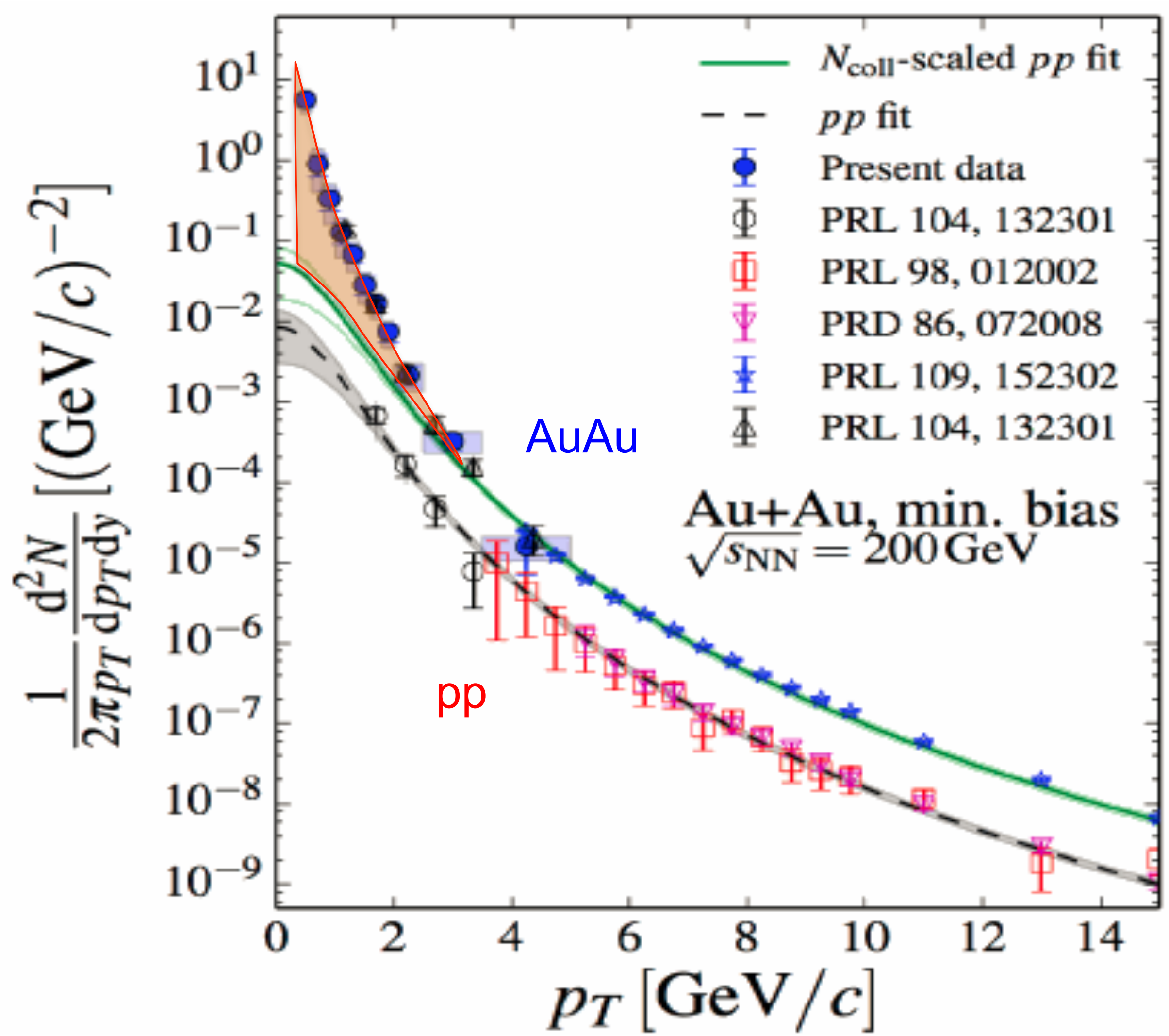
T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

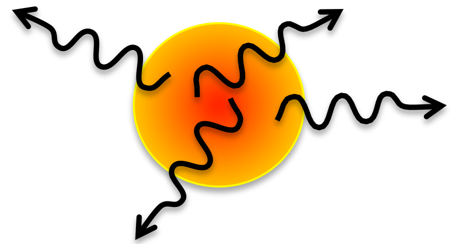
Q_i : 1 for u and d, -1 for u and d
s_i : 1 for s, -1 for s
g_i : spin-isospin freedom
m_i : particle mass
K2 : the second-order modified Bessel function



Simple chemical freeze-out model remarkably well agrees with data.

Thermal photon radiation from QGP





- Virtual and real photon measurements via internal and external conversion methods with electron pair measurements
- Real photon measurements with EMcal
- Initial temperature of 300-600MeV via measured slope of 220-240MeV

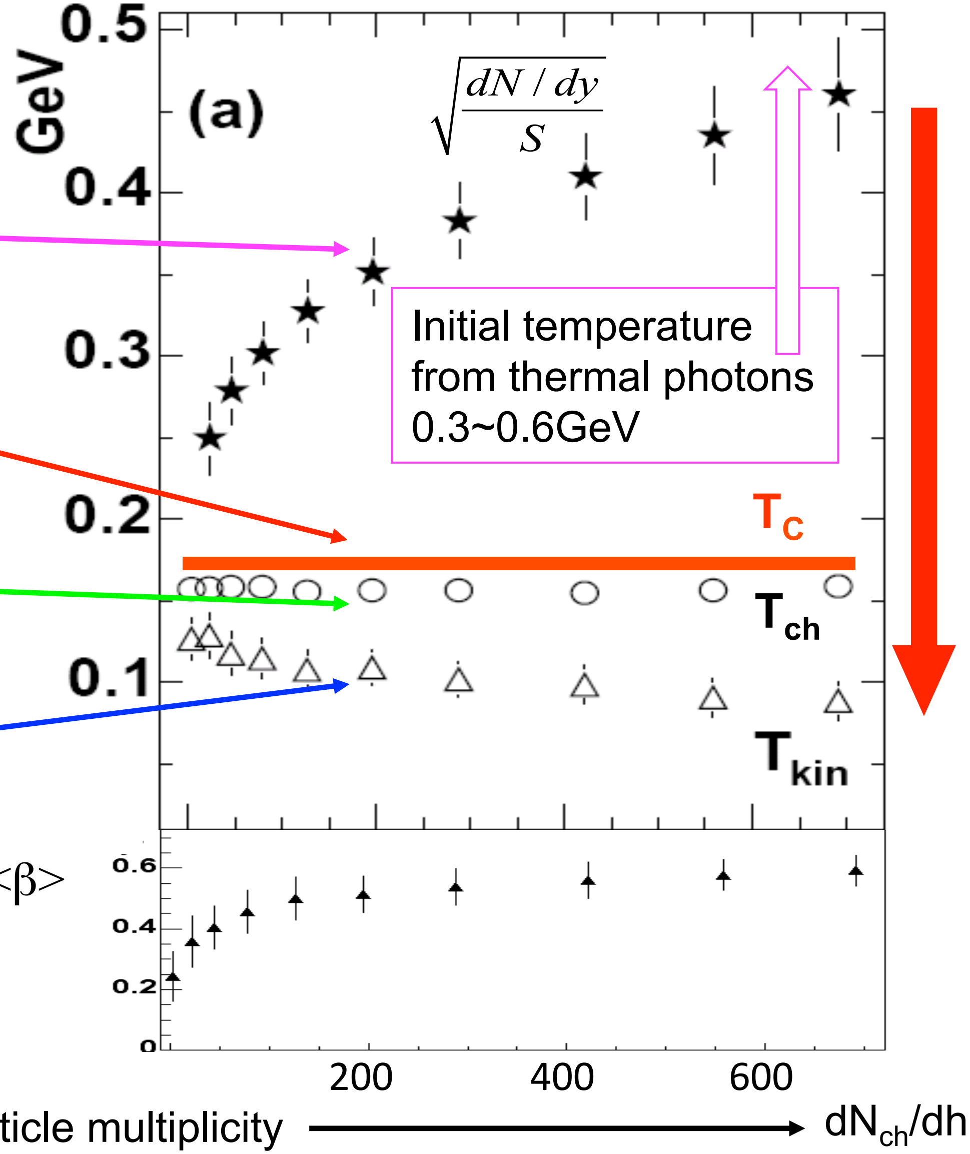
History of temperature

initial temperature
from the energy density

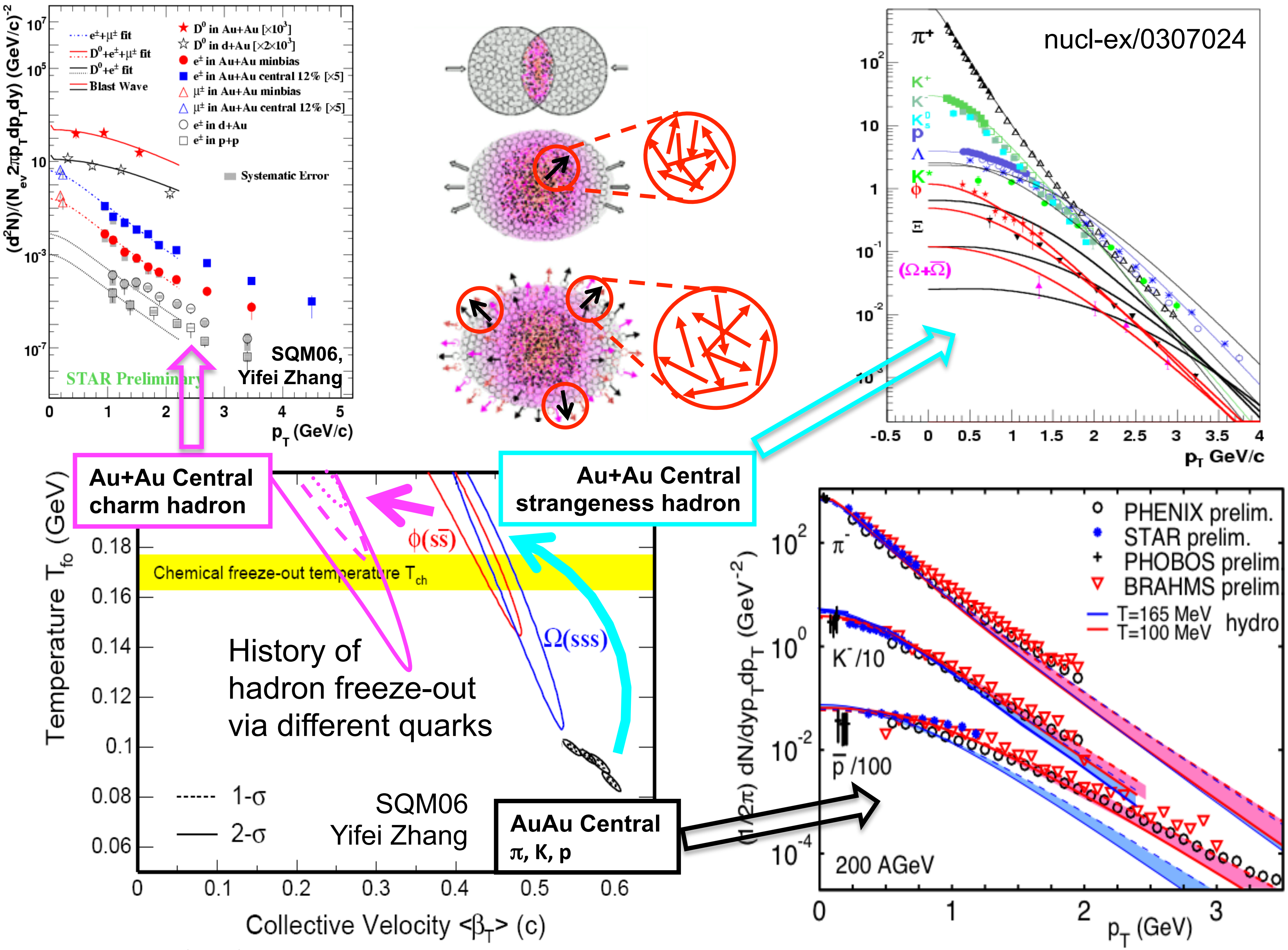
Phase transition at
critical temperature

Chemical freeze-out
temperature

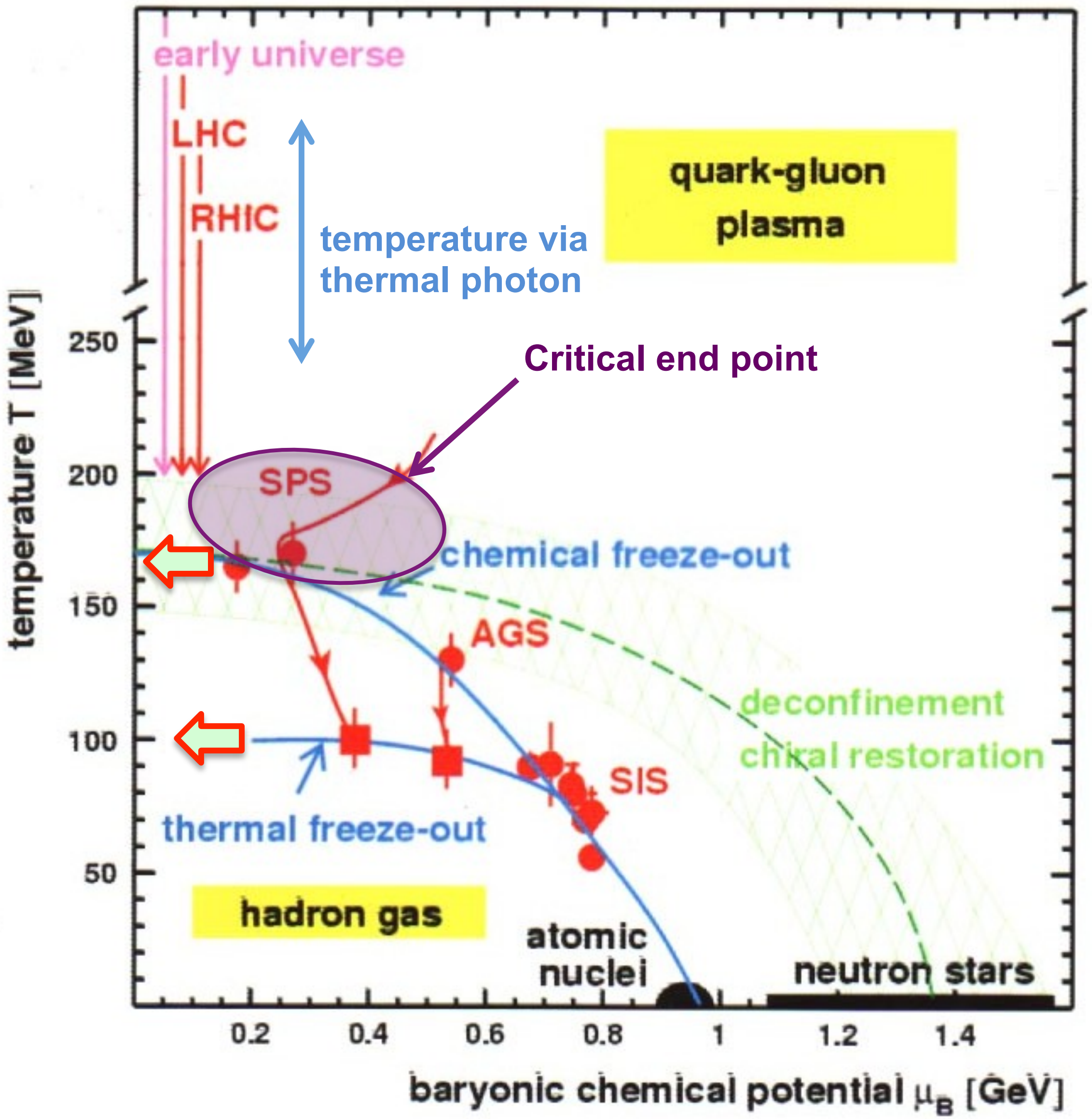
Thermal freeze-out
temperature

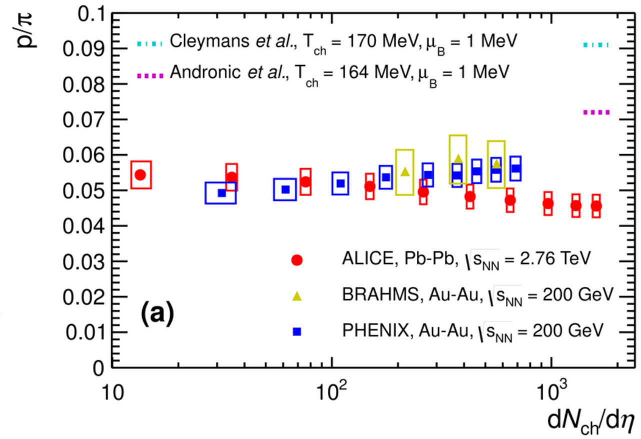


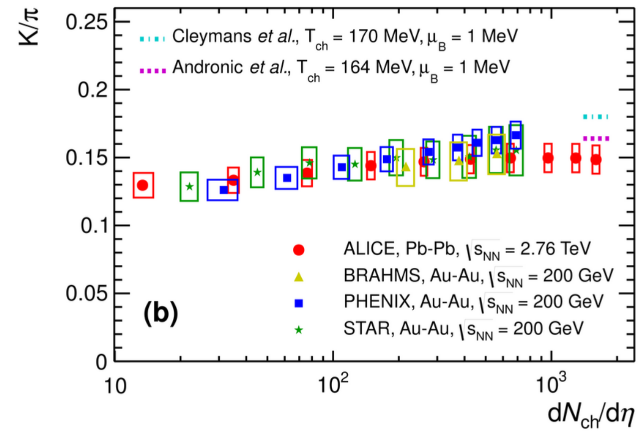
Blast Wave model fitting to various particle species

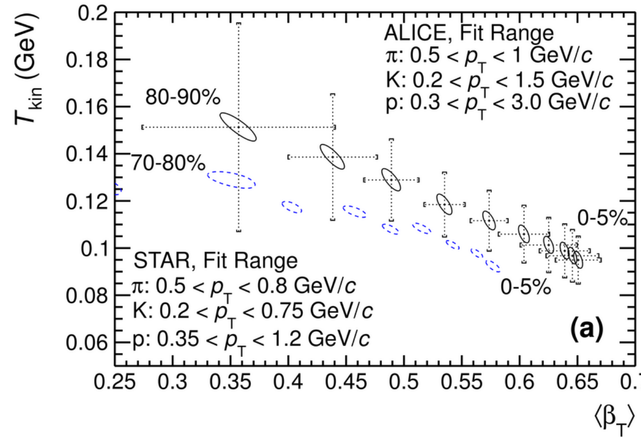


Comparison between beam energies



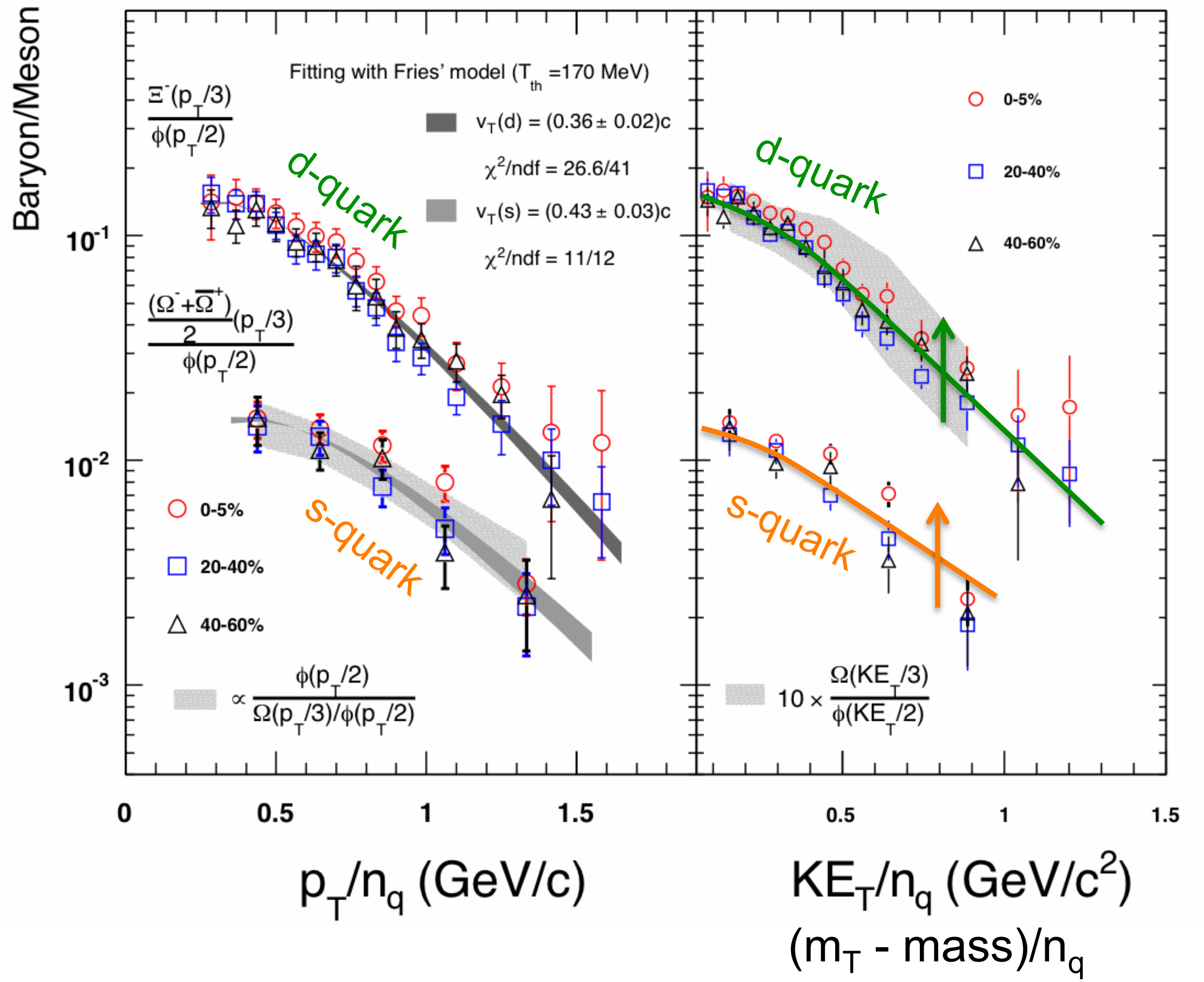


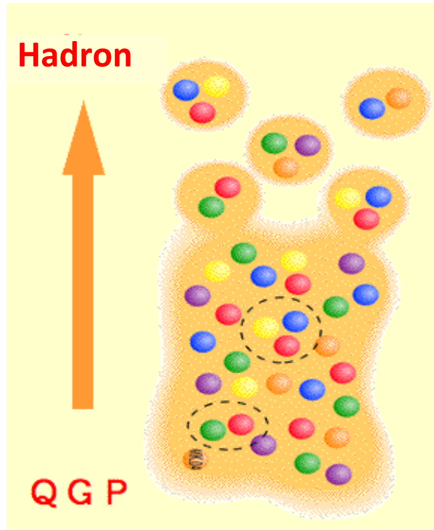




Quark momentum distribution
--- extracted from multi-strange hadron ratio ---

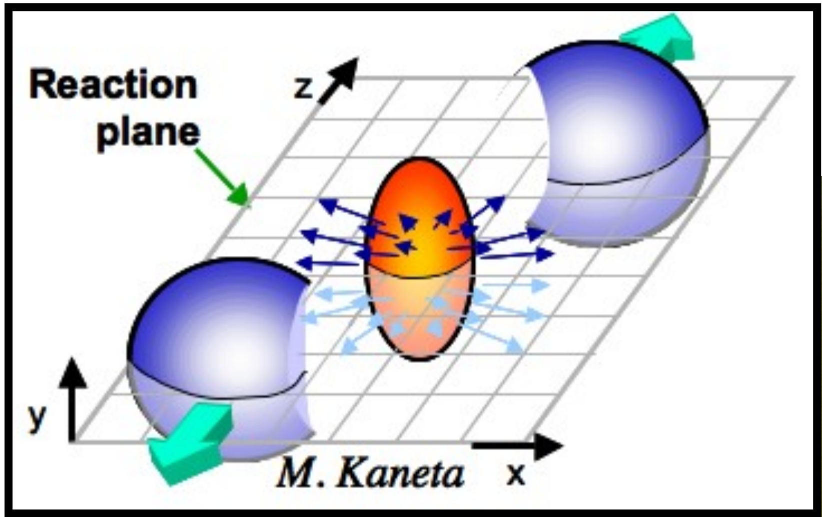
arXiv:0801.2265 [nucl-th]

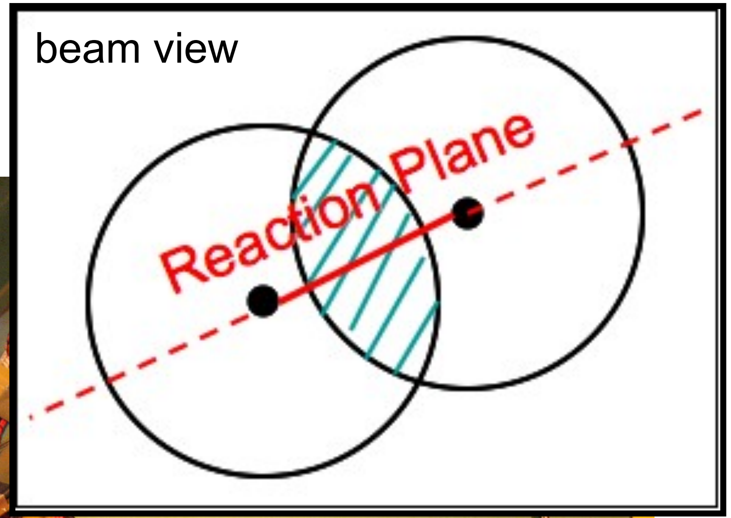


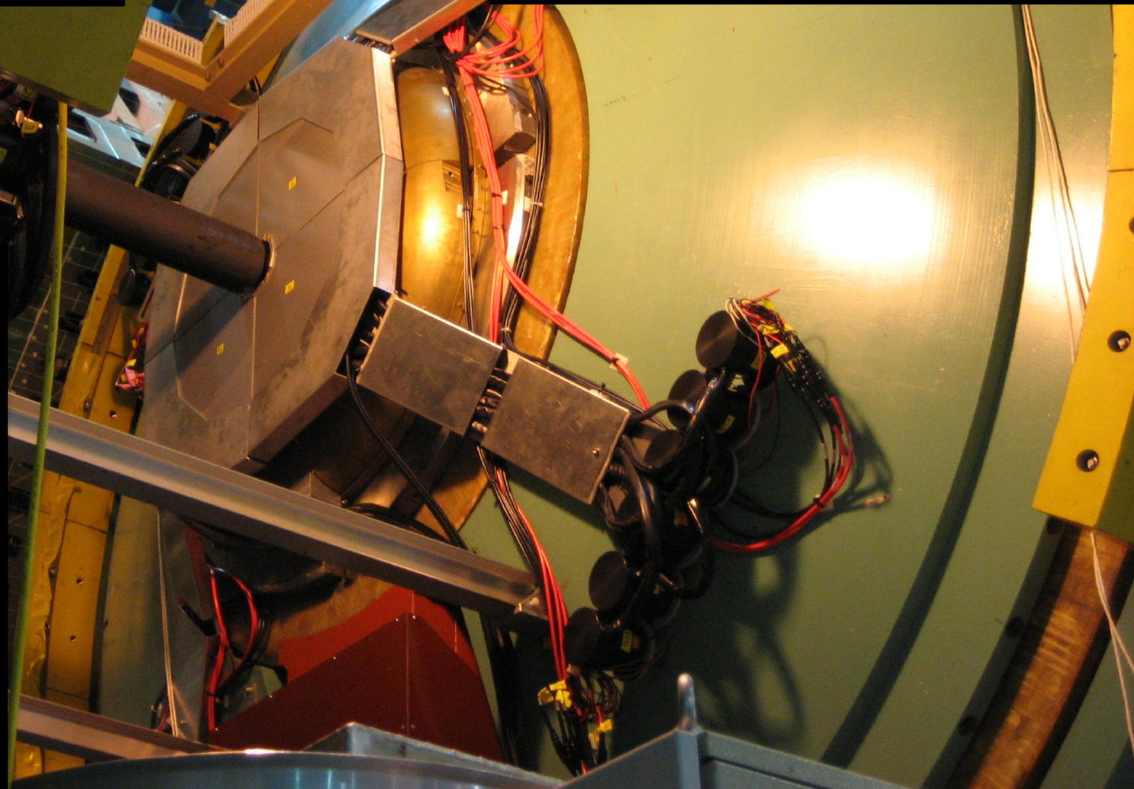


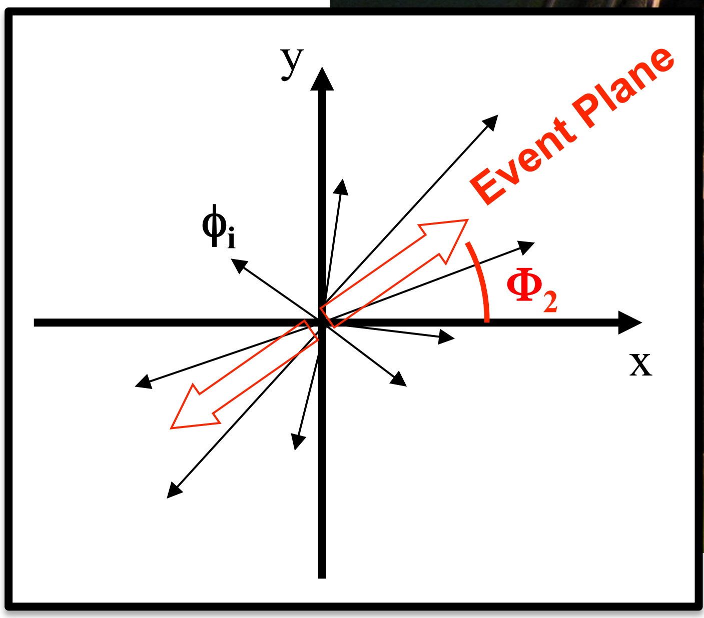
Collective radial expansion
-during the partonic phase
-before the hadronic phase

Quark coalescence or
recombination mechanism
for the hadronization

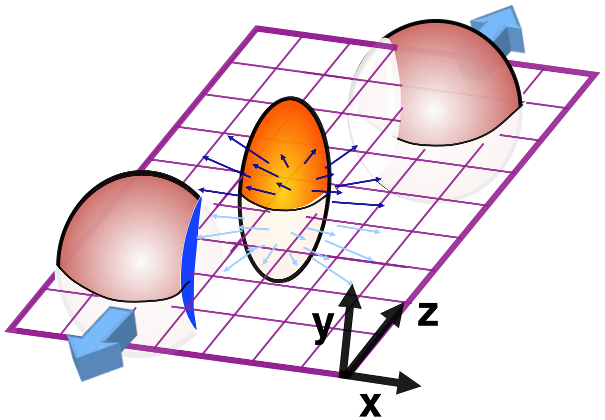

Reaction plane
z
y
x
M. Kaneta


beam view
Reaction Plane

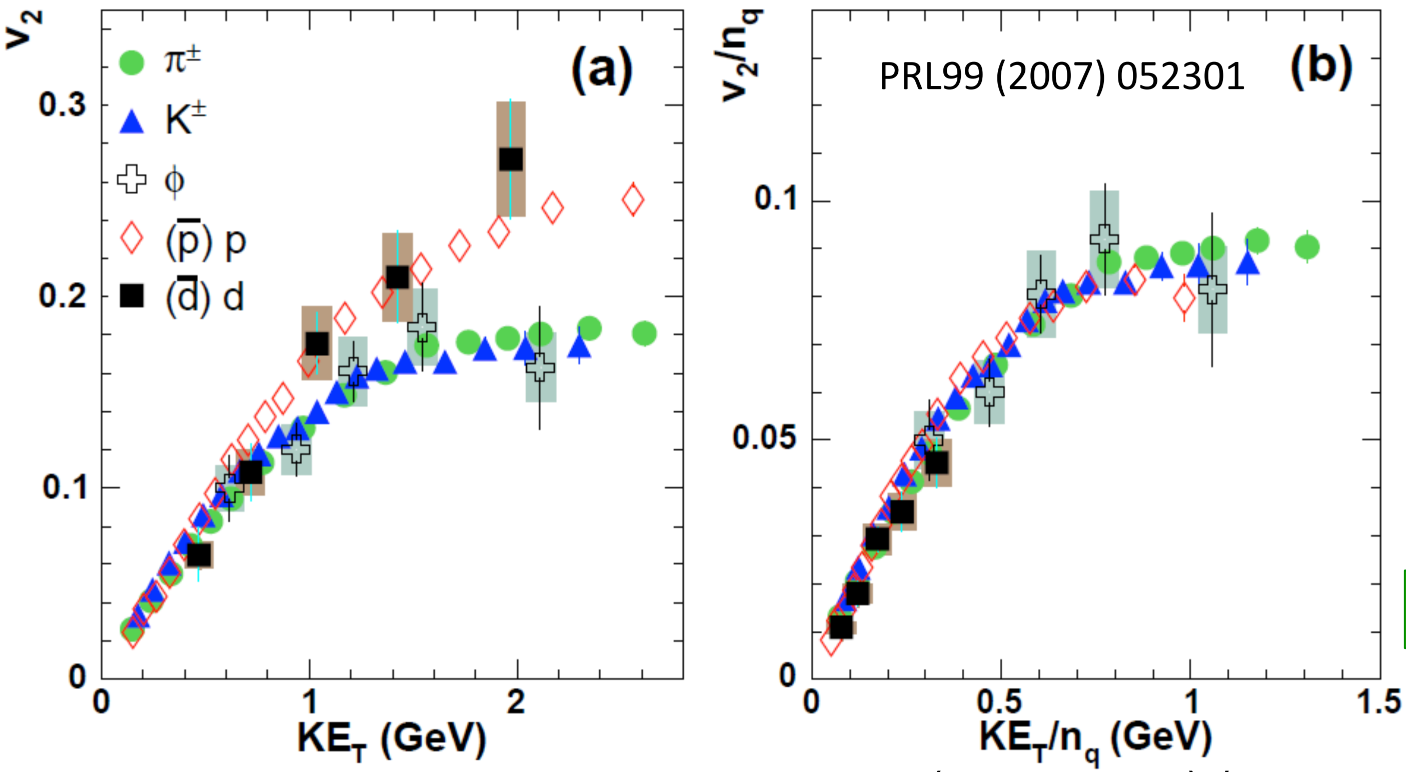



y
x
Event Plane
ϕ_i
Φ_2

Number of quark scaling in elliptic flow
--- quark coalescence feature ---

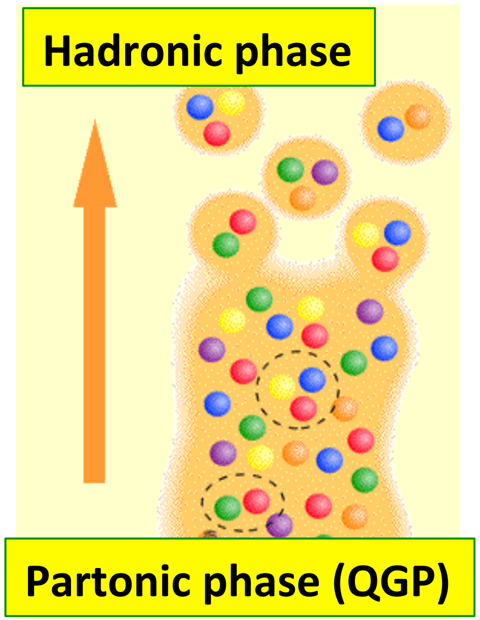


Indication of quark flow (in partonic phase)

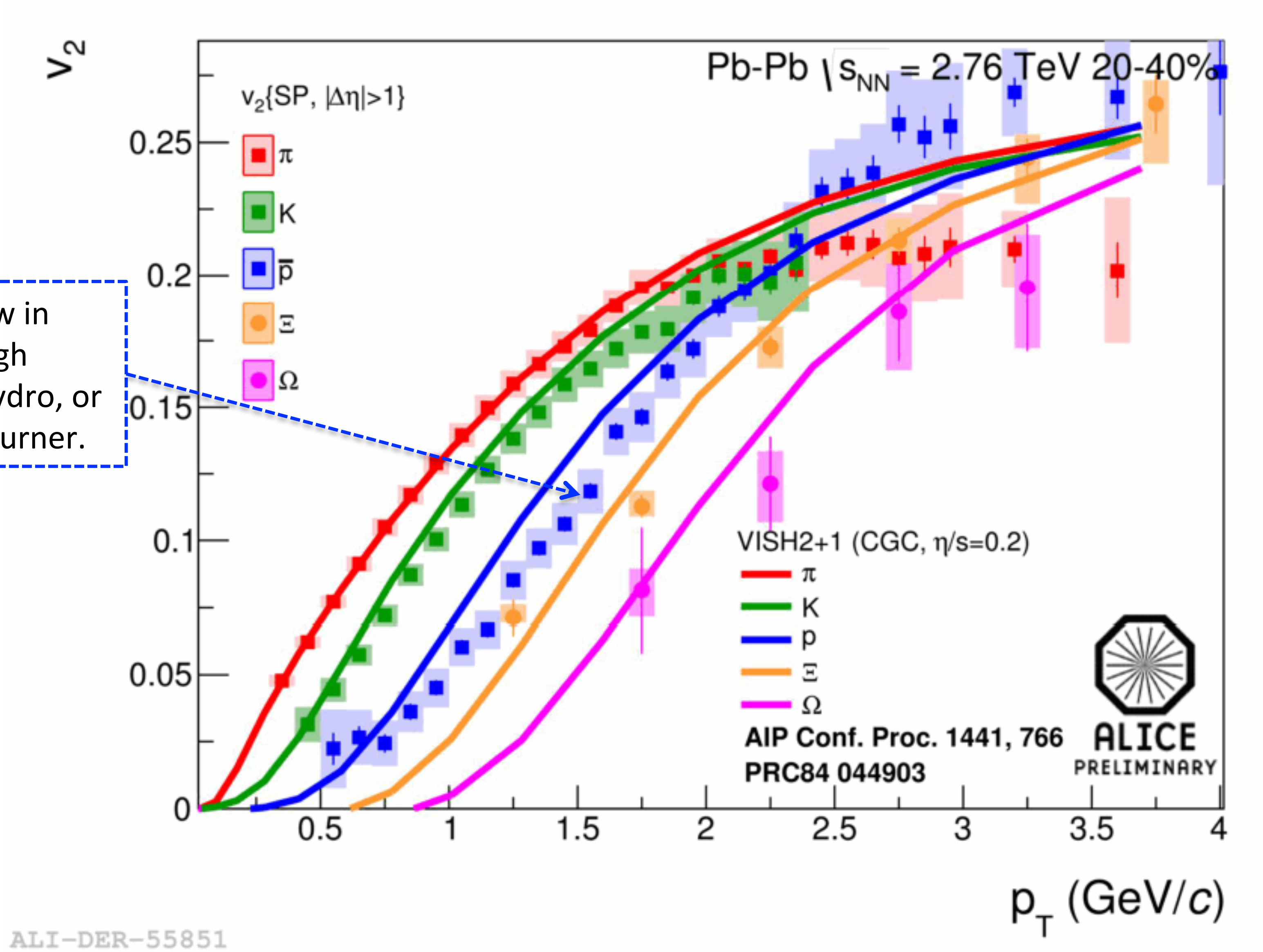


m_T - mass

(m_T - mass) / n_q

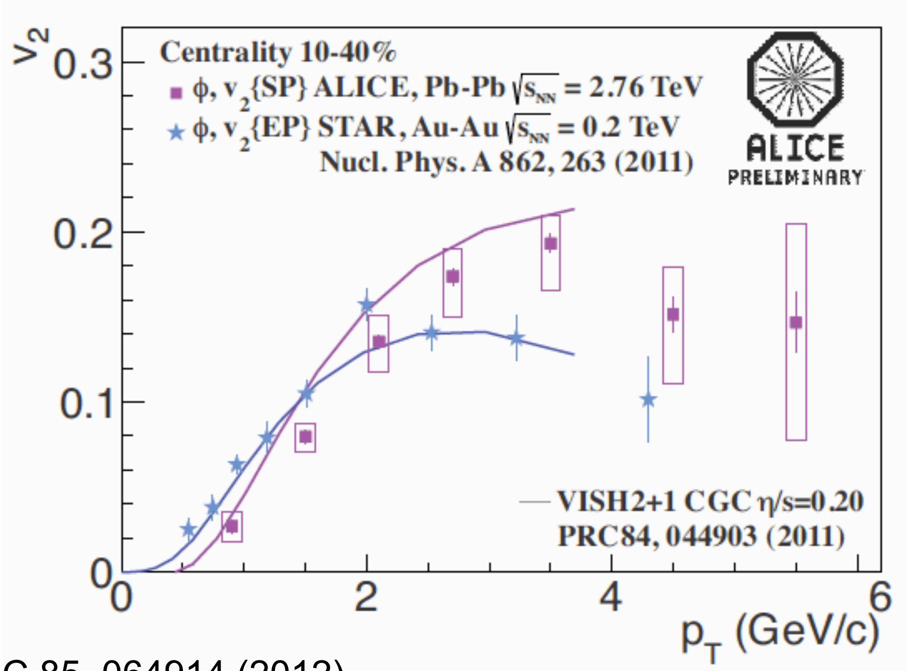


mass dependence of v_2 with hydro-model



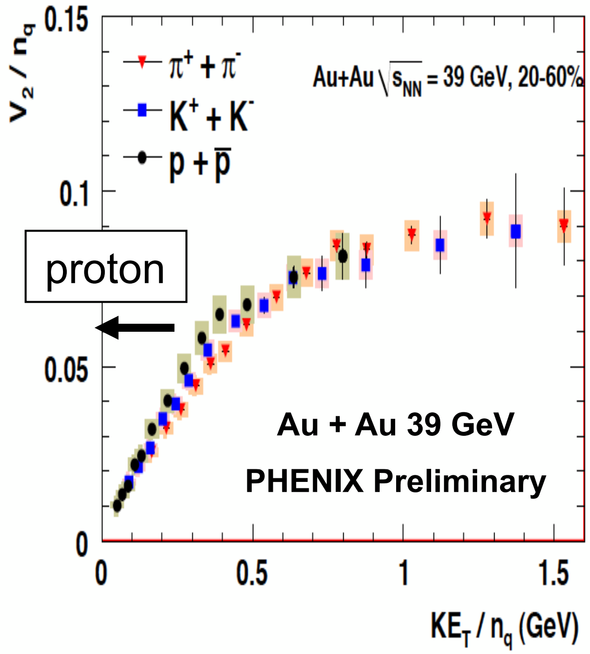
More radial flow in data. Not enough radial flow in hydro, or hadronic afterburner.

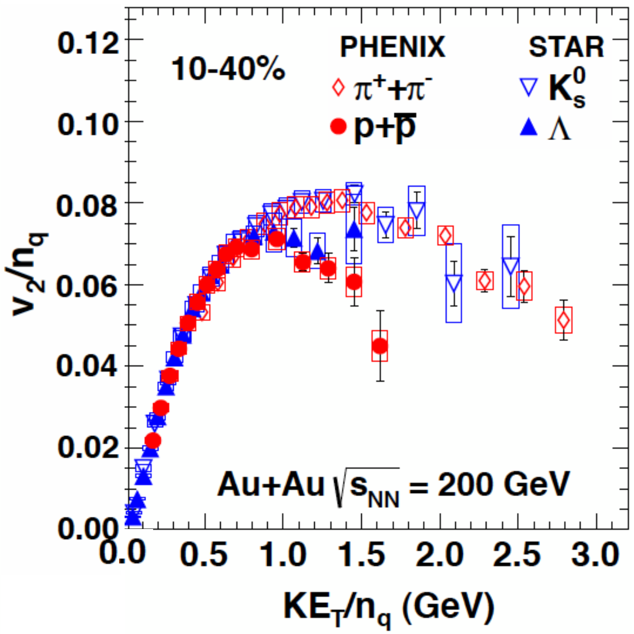
Beam energy dependence of v_2 (increased radial flow)

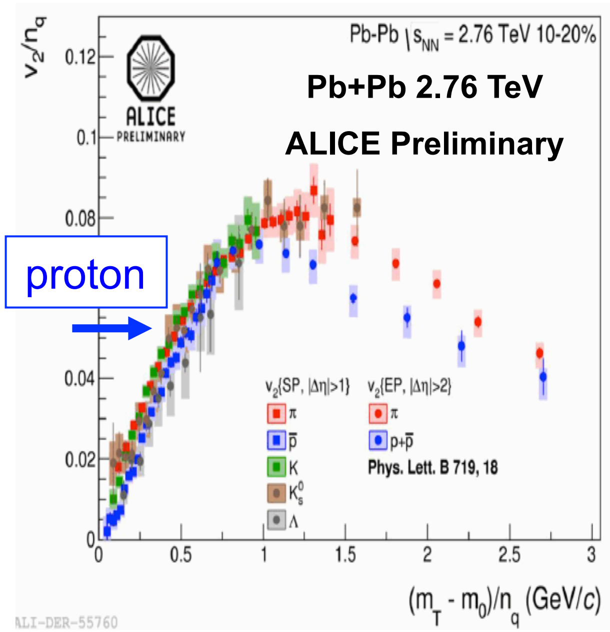


Relative momentum shift of heavier particles (protons) are larger than light hadrons (pions), which is consistent with an increased radial flow.

PRC 85, 064914 (2012)

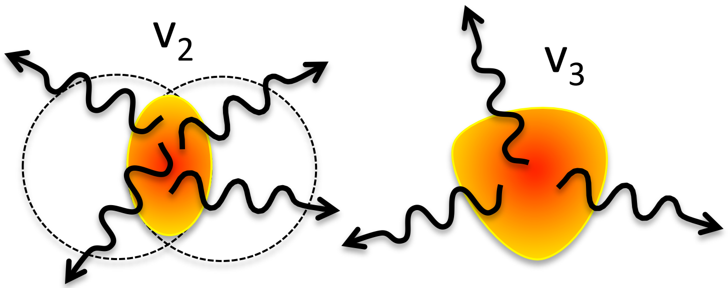


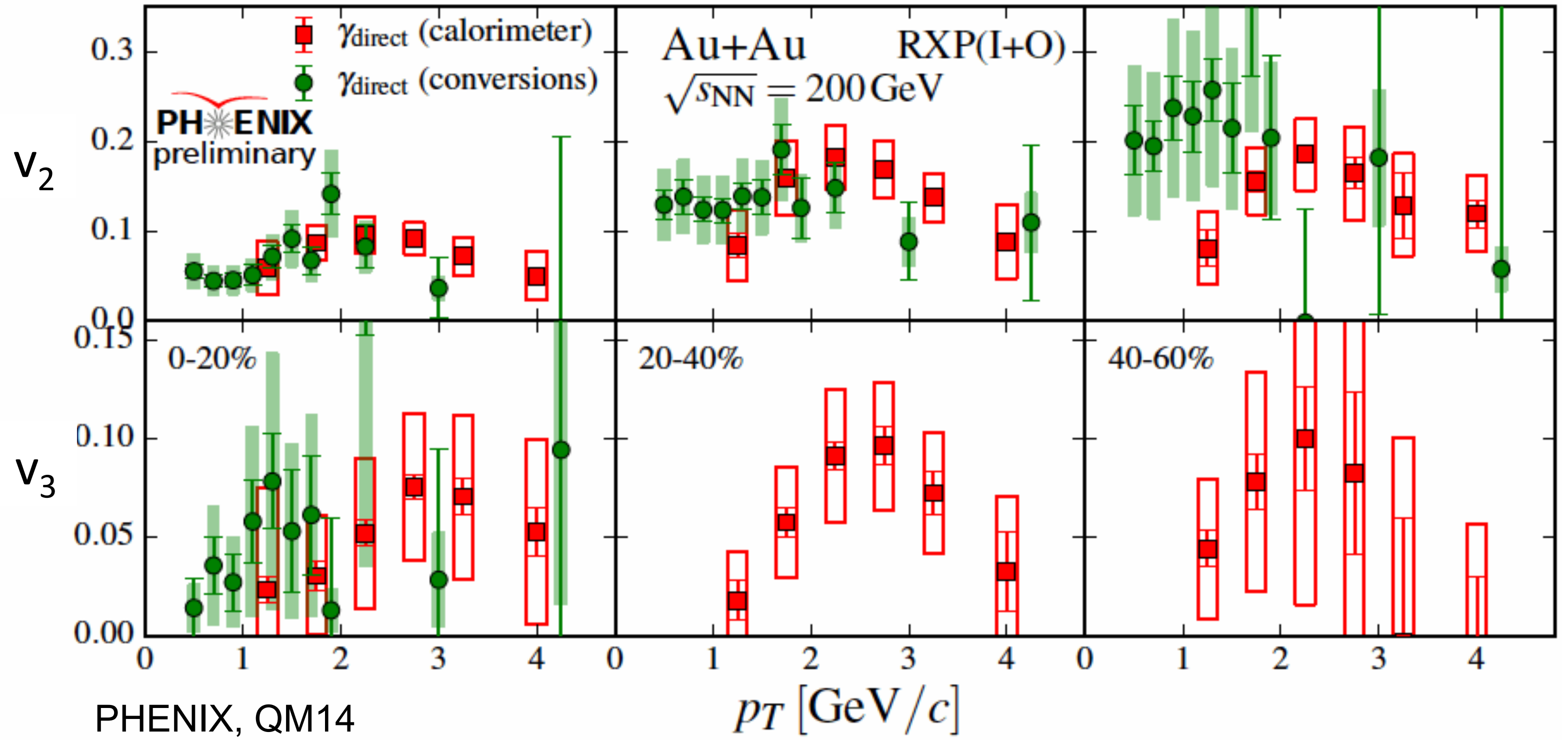




Direct (thermal) photon v_2 and v_3

$v_n = \langle \cos n(\phi^{particle} - \Phi_n^{plane}) \rangle$
(n=2 : elliptic flow), (n=3 : triangular flow)



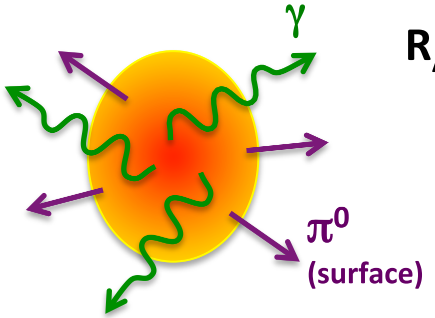


PHENIX, QM14

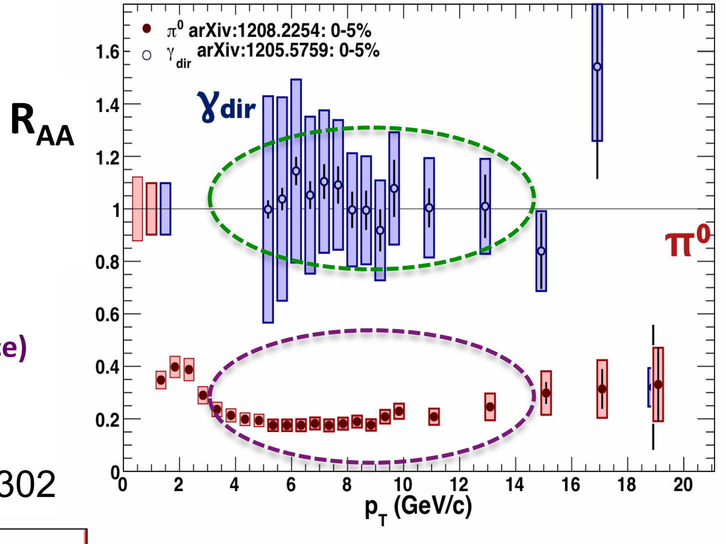
- comparable to hadron for both v_2 and v_3 at 2~3GeV/c
- significant contribution from photons from later stages (inconsistent with early photons from hotter period) --- direct photon puzzle
- flatter p_T dependence of v_2 at low p_T

High p_T direct photon as penetrating probe

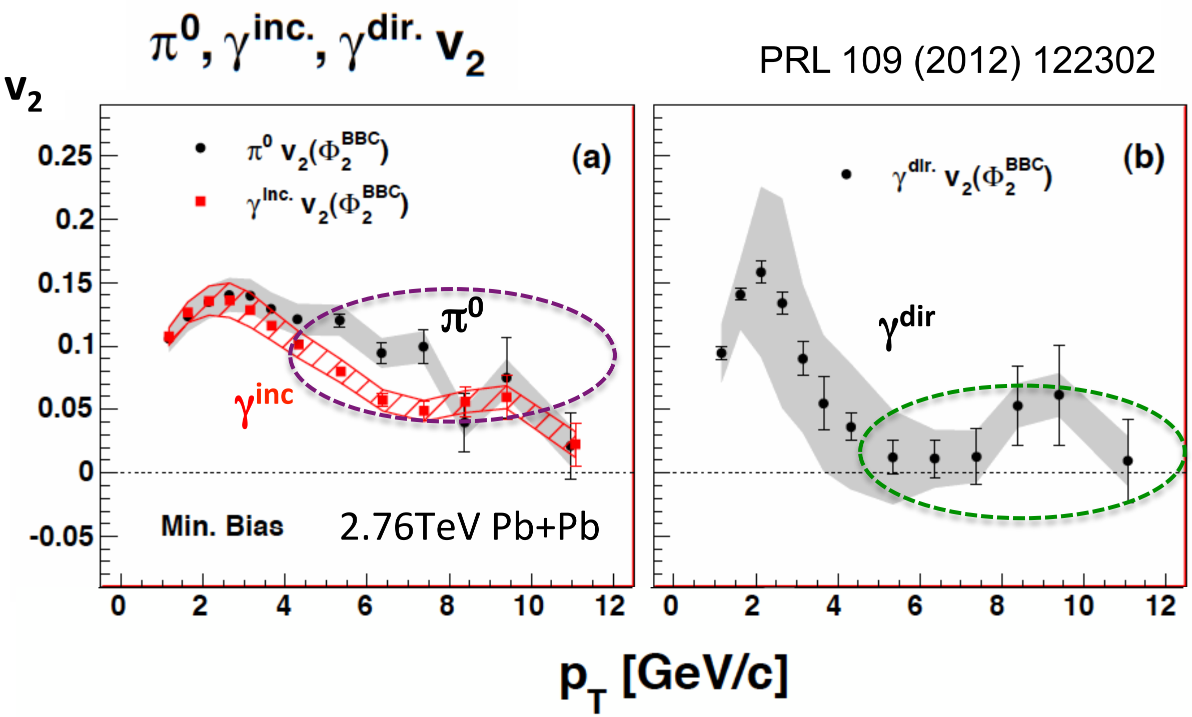
$p_T > 5$ GeV/c	hadron	γ^{dir}
R_{AA}	< 1	~ 1
v_2	> 0	~ 0



PRL 109 (2012) 152302



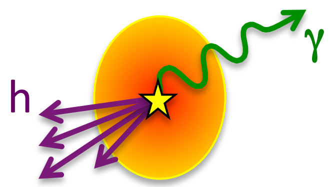
PRL 109 (2012) 122302

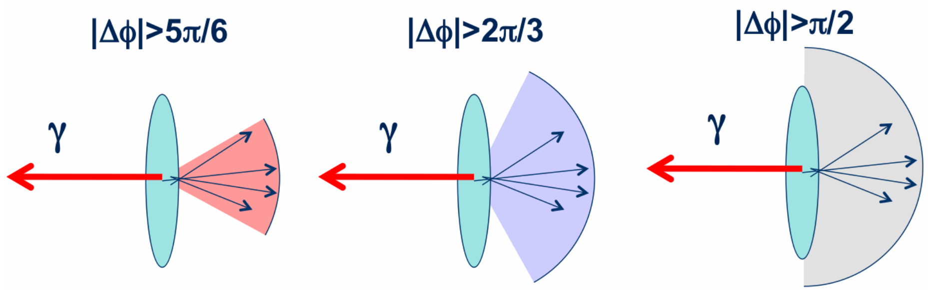


$$R_{AA} = \frac{N\,(A+A)}{N_{coll}\;N(p+p)}$$

relative yield with respect to a simple independent superposition of pp data

Energy loss at high p_T and re-distribution of the lost-energy at low p_T at RHIC





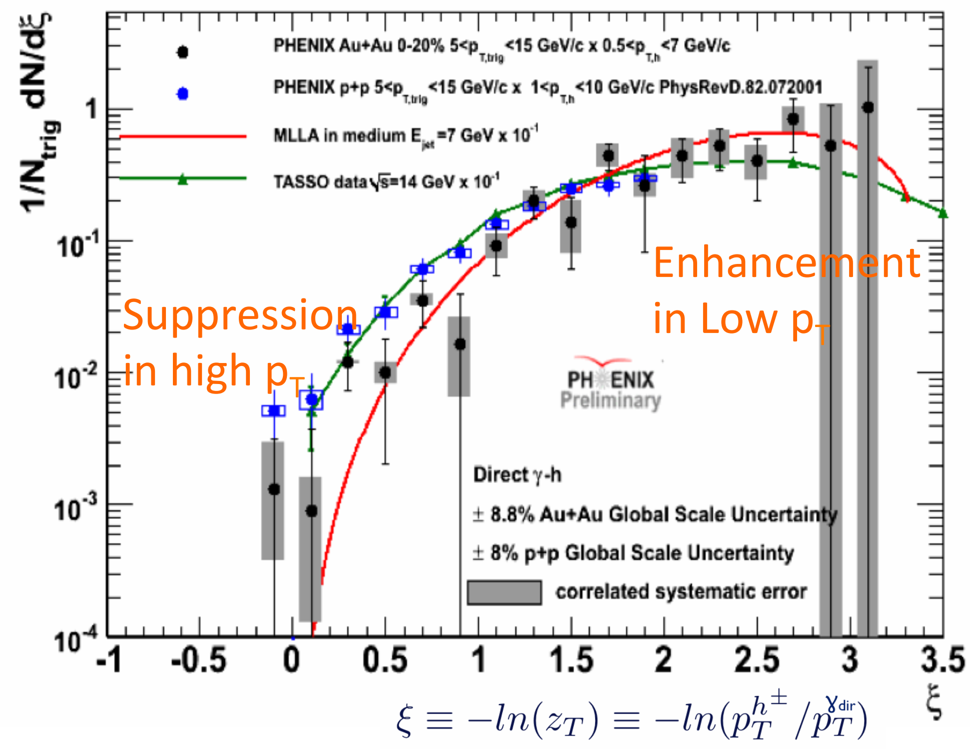
prompt photon - hadron correlation

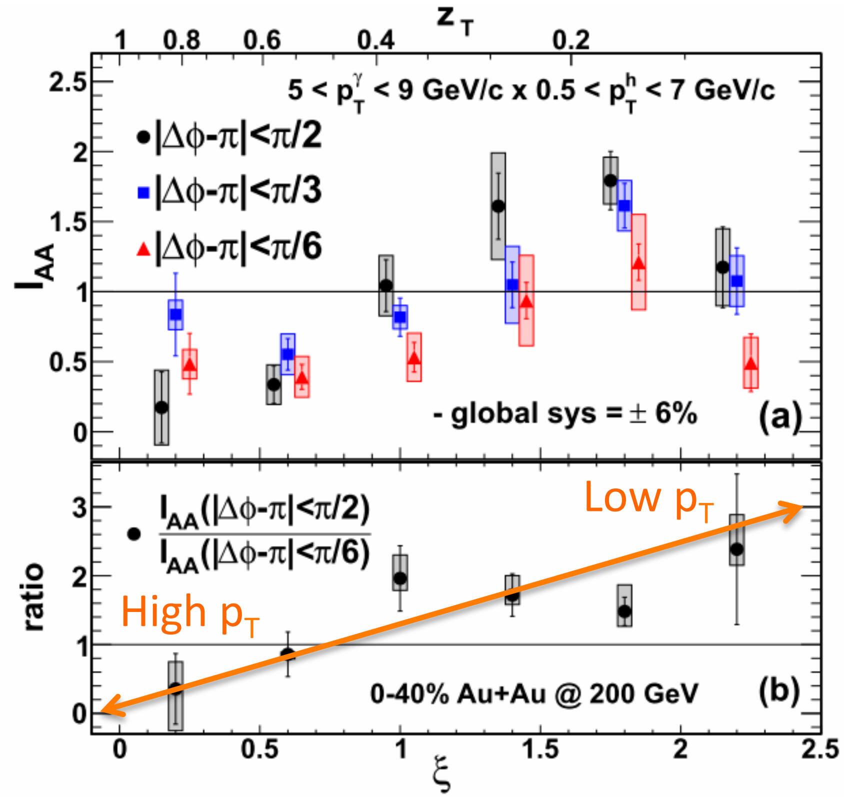
N_{PTY} = associate hadron yield per trigger γ

$I_{AA} = N_{PTY}(AA) / N_{PTY}(pp)$

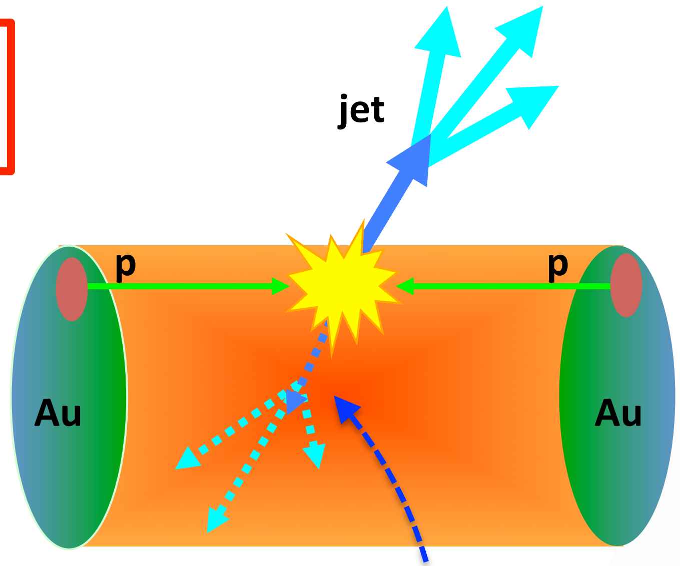
effect on bulk

PRL 111 (2013) 032301



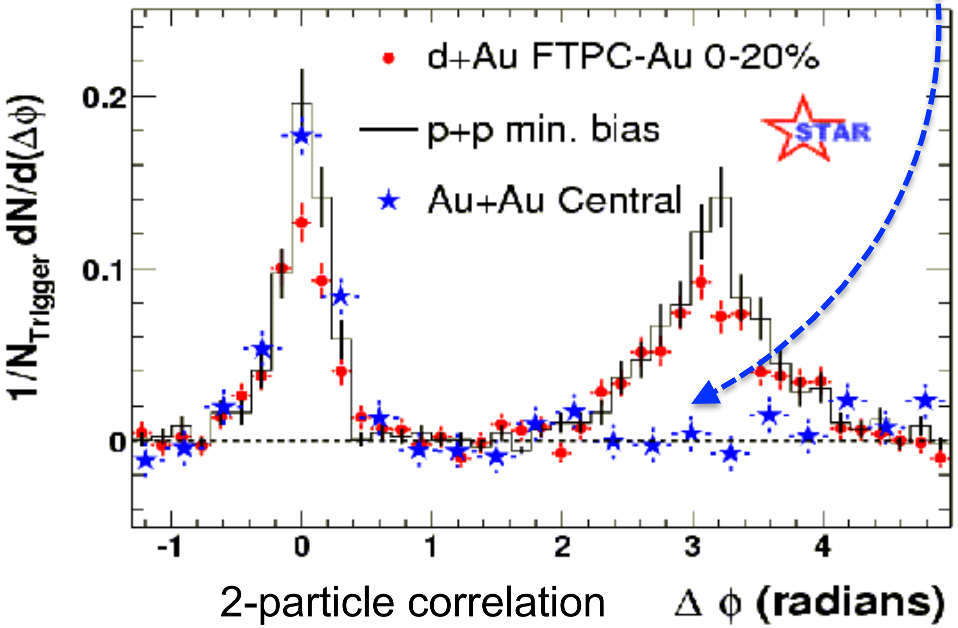


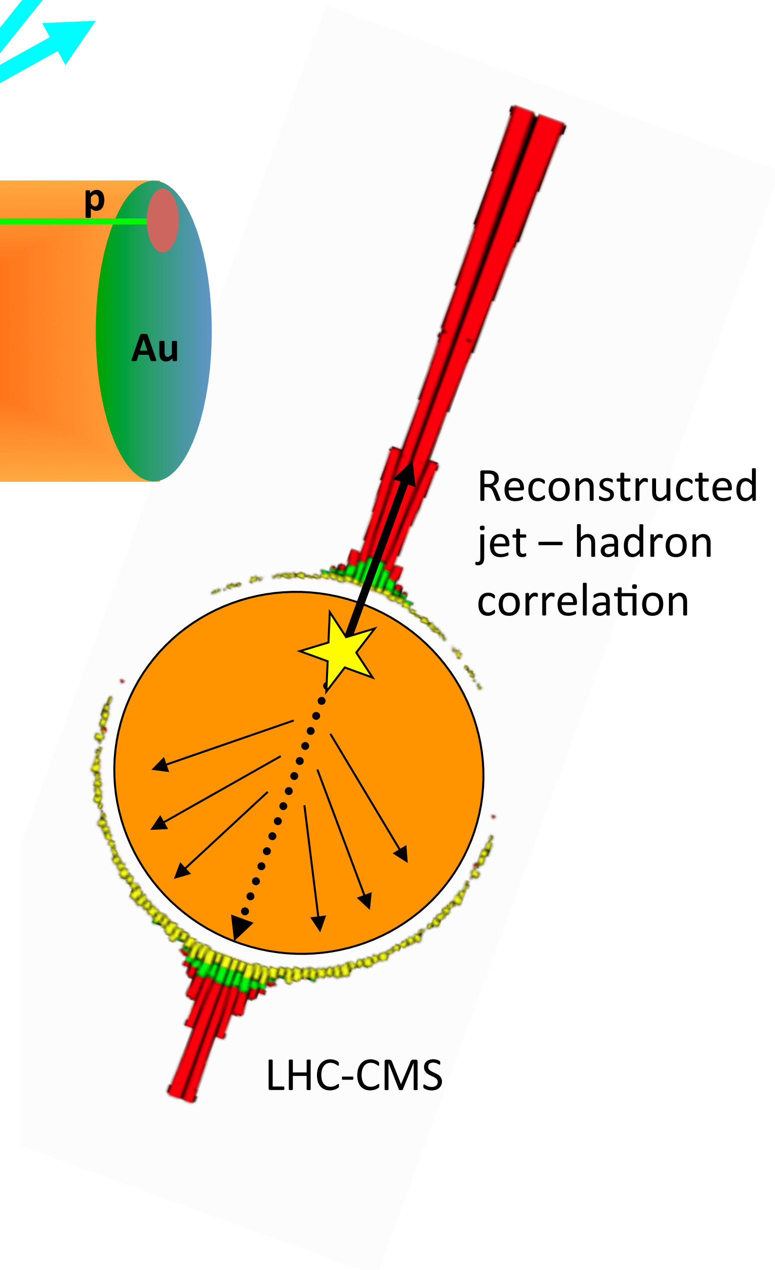
Partonic energy loss and Jet quenching



RHIC-STAR

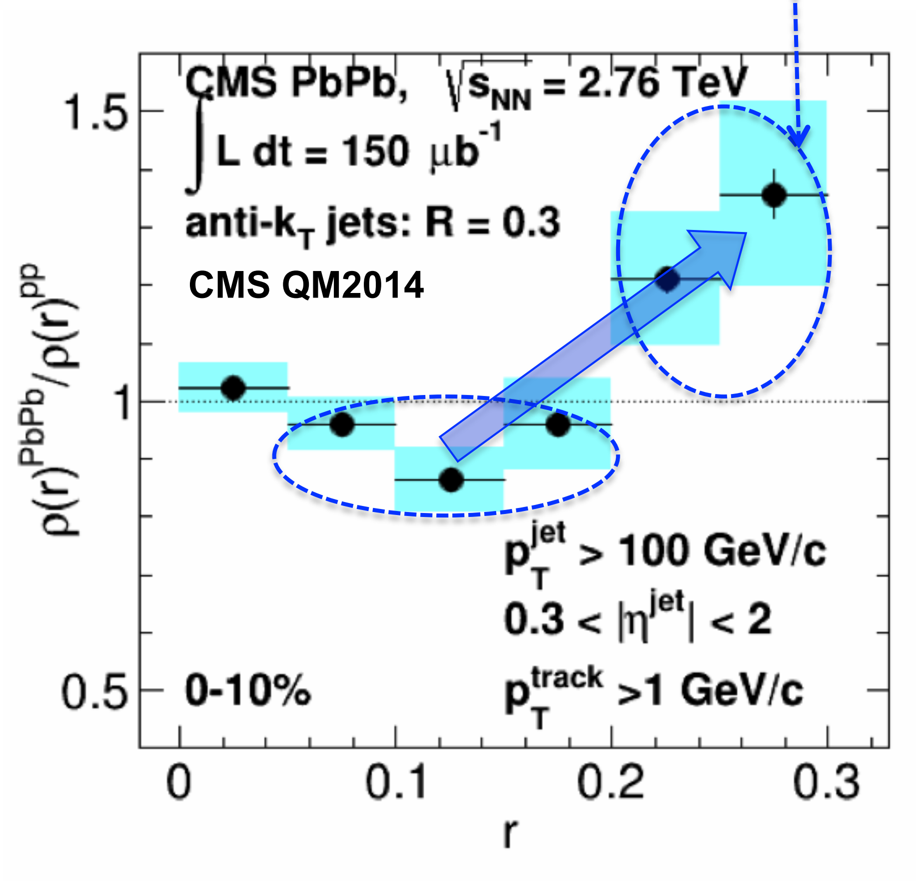
Phys. Rev. Lett. 91, 072304 (2003)

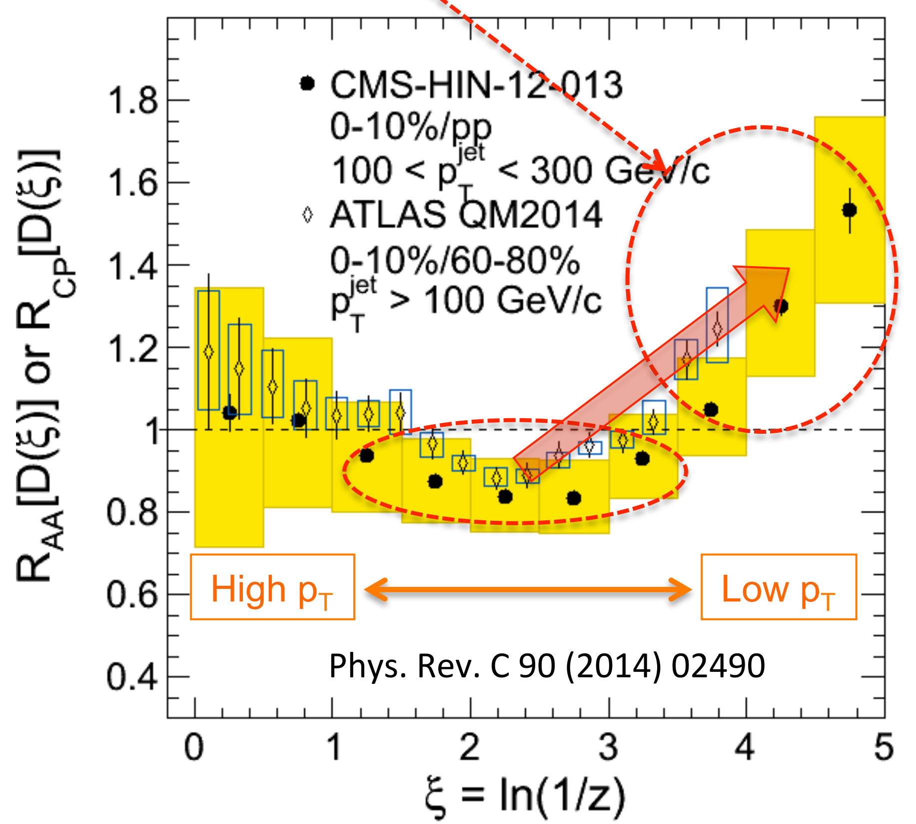


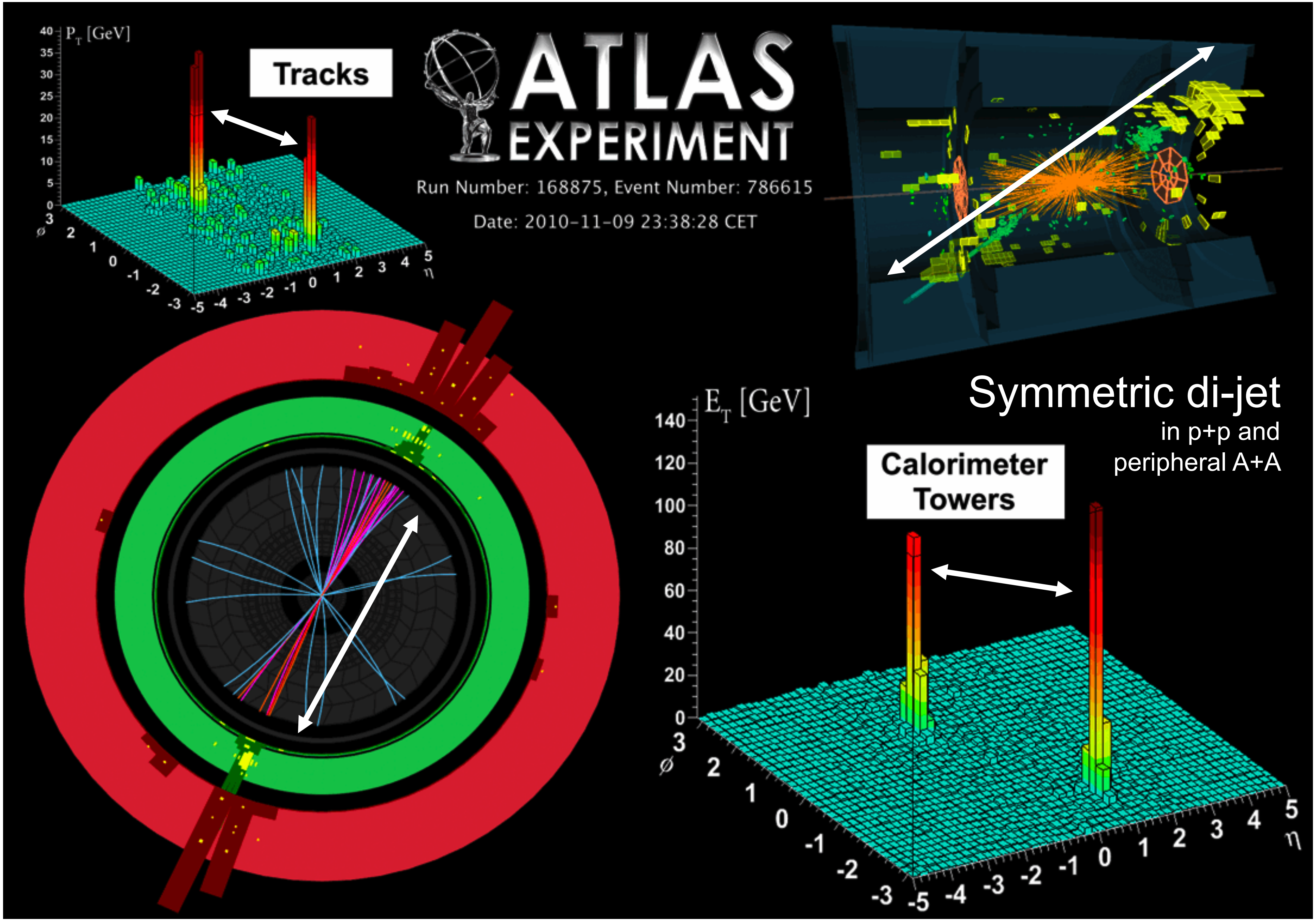


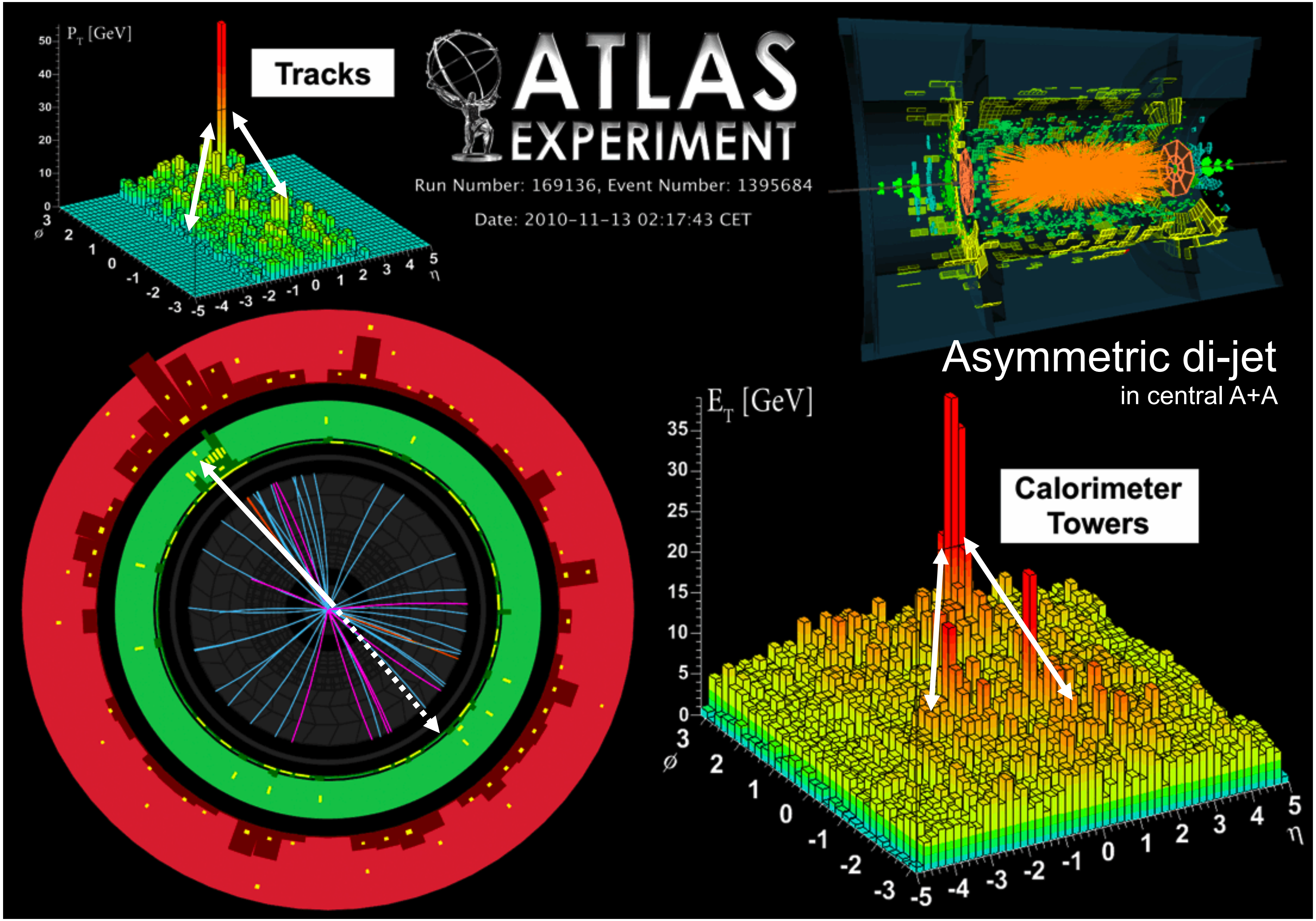
LHC CMS/ATLAS : Modification of Jet fragmentation

- re-distribution towards lower p_T particles
- re-distribution at larger angle






Tracks
ATLAS EXPERIMENT
Run Number: 168875, Event Number: 786615
Date: 2010-11-09 23:38:28 CET
Symmetric di-jet
in p+p and
peripheral A+A
Calorimeter Towers
P_T [GeV]
E_T [GeV]
ϕ
η

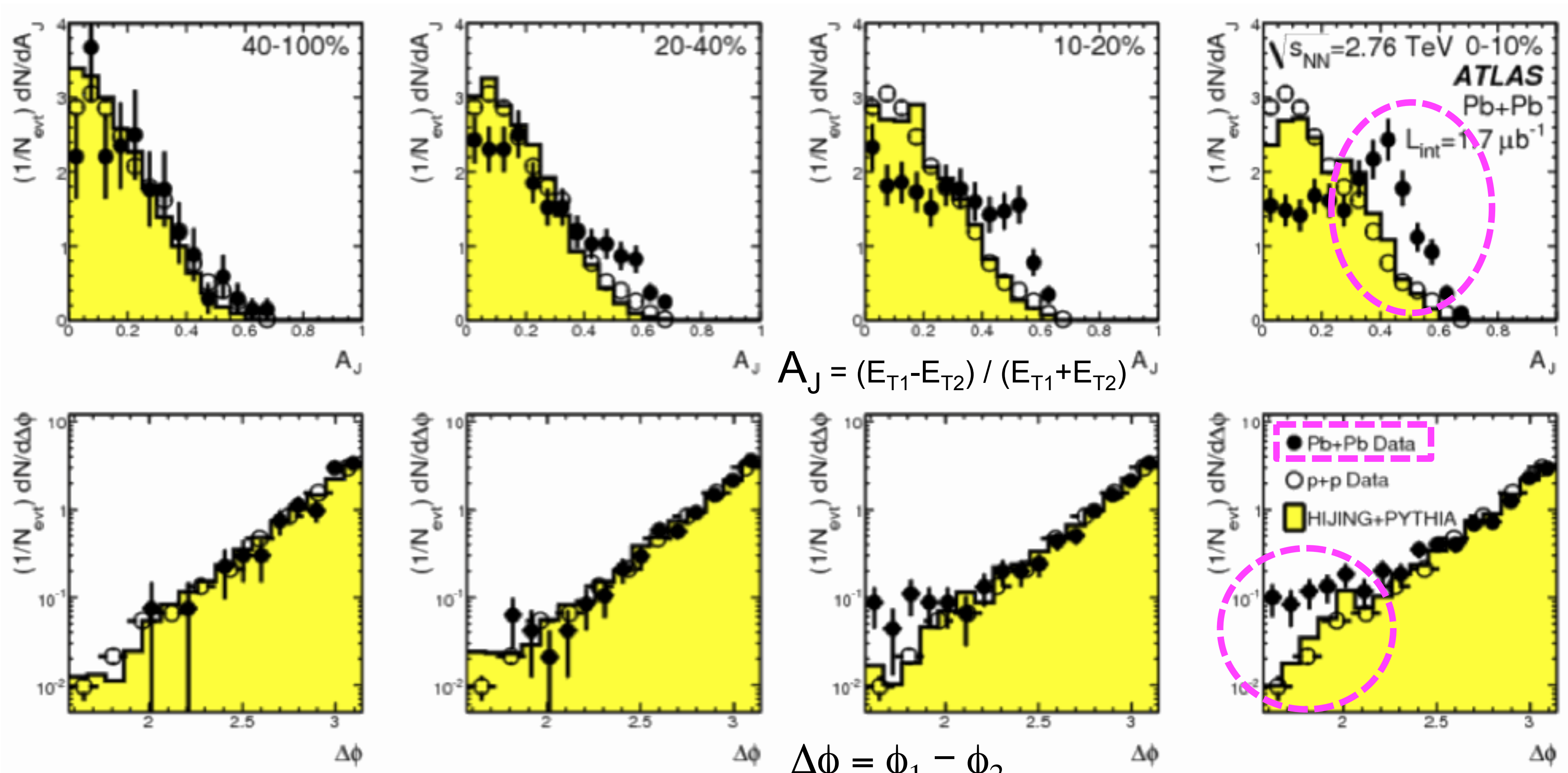

Tracks
ATLAS EXPERIMENT
Run Number: 169136, Event Number: 1395684
Date: 2010-11-13 02:17:43 CET
Asymmetric di-jet
in central A+A
Calorimeter Towers
P_T [GeV]
E_T [GeV]
ø
η

Jet asymmetry : A_J

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$E_{T1} > 100$ GeV
$E_{T2} > 25$ GeV

Peripheral Pb+Pb ⟷ Central Pb+Pb



$A_J = (E_{T1}\text{-}E_{T2}) / (E_{T1}+E_{T2})$

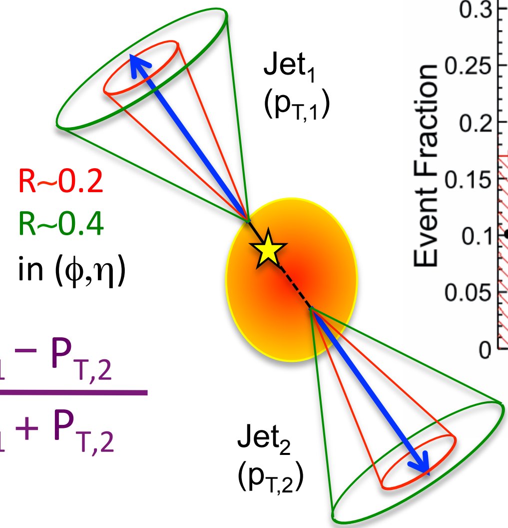
$\Delta\phi = \phi_1 - \phi_2$

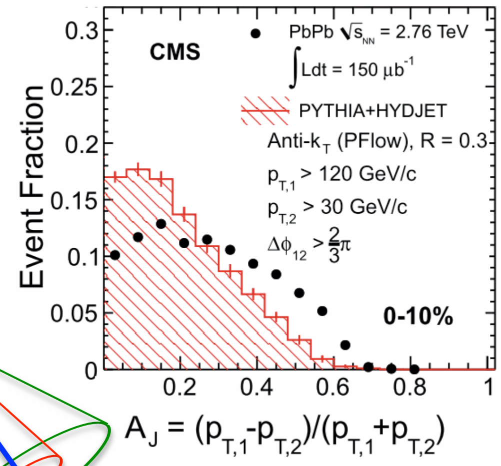
Phys.Rev.Lett.105:252303,2010

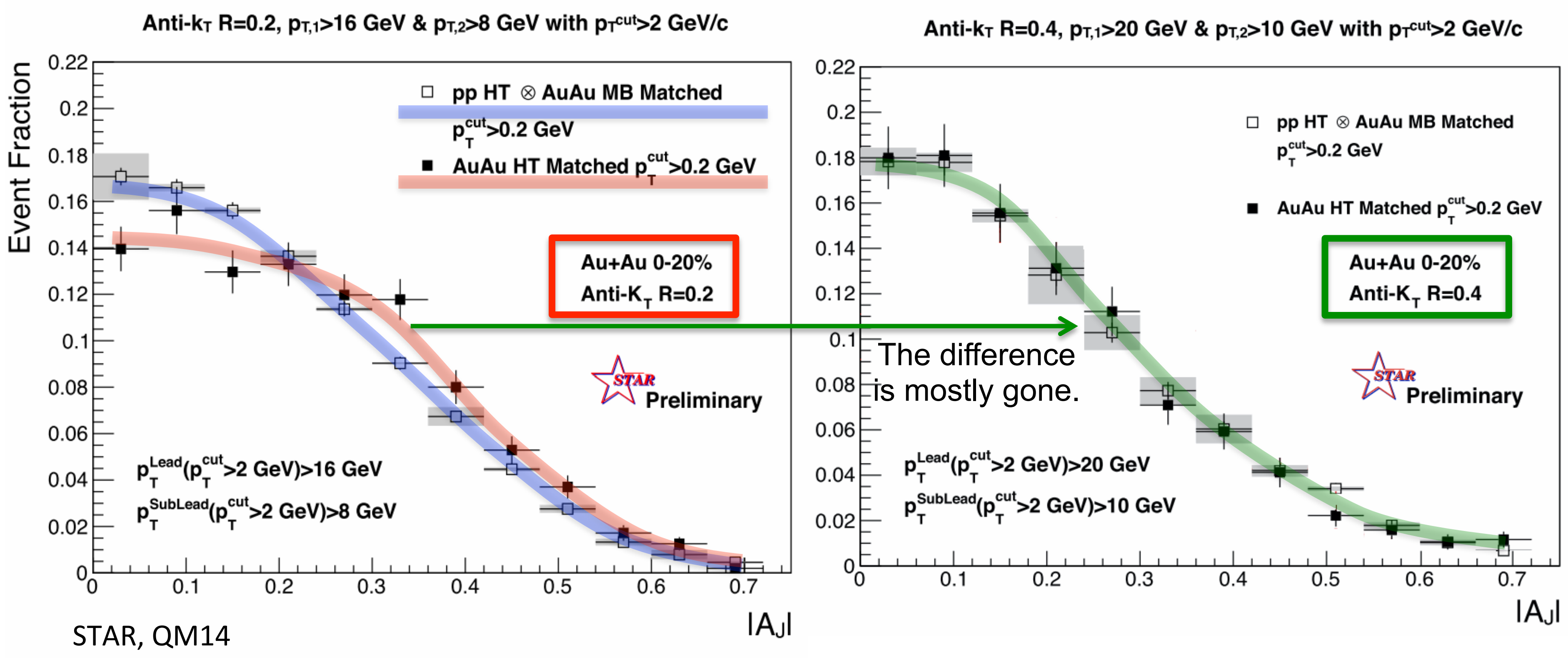
A_j measurement at RHIC-STAR

- similar effect with smaller jet cone R~0.2 at RHIC
- lower jet energy than LHC, smaller effect than LHC
- mostly recovered jet energy within larger jet cone R~0.4

$$A_J = \frac{P_{T,1} - P_{T,2}}{P_{T,1} + P_{T,2}}$$





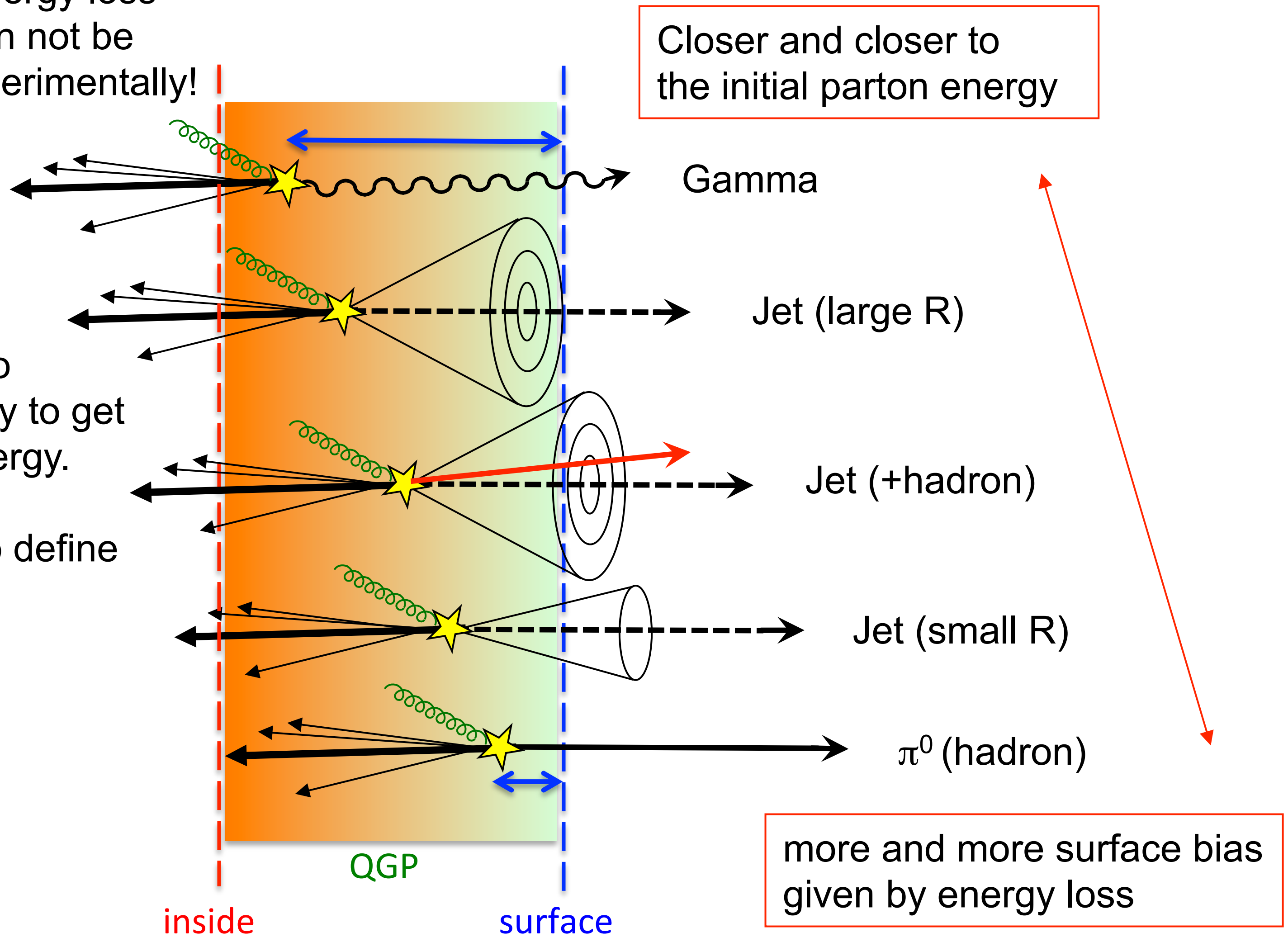


Systematic test of energy loss and redistribution with photons, jets and hadrons

These two effects (energy loss and redistribution) can not be clearly separated experimentally!

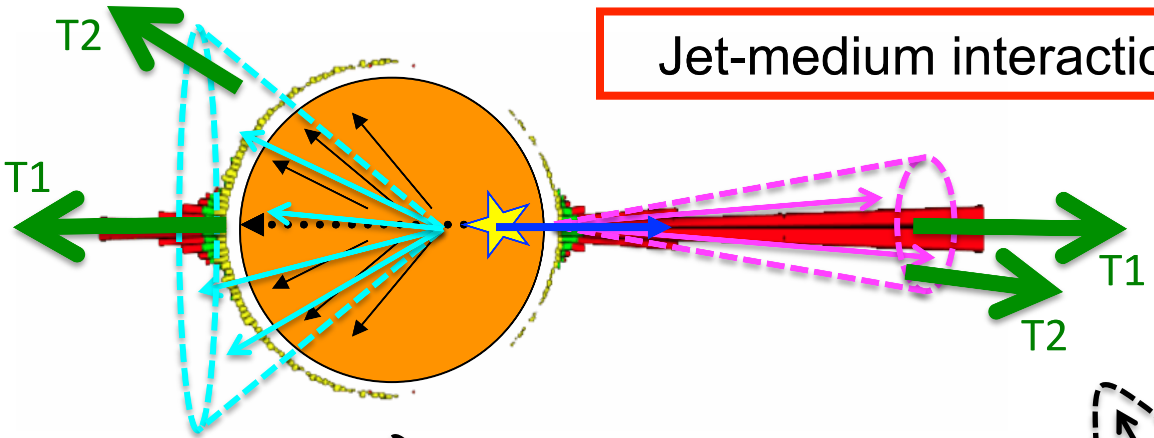
Jet reconstruction is to recover the lost energy to get the original parton energy.

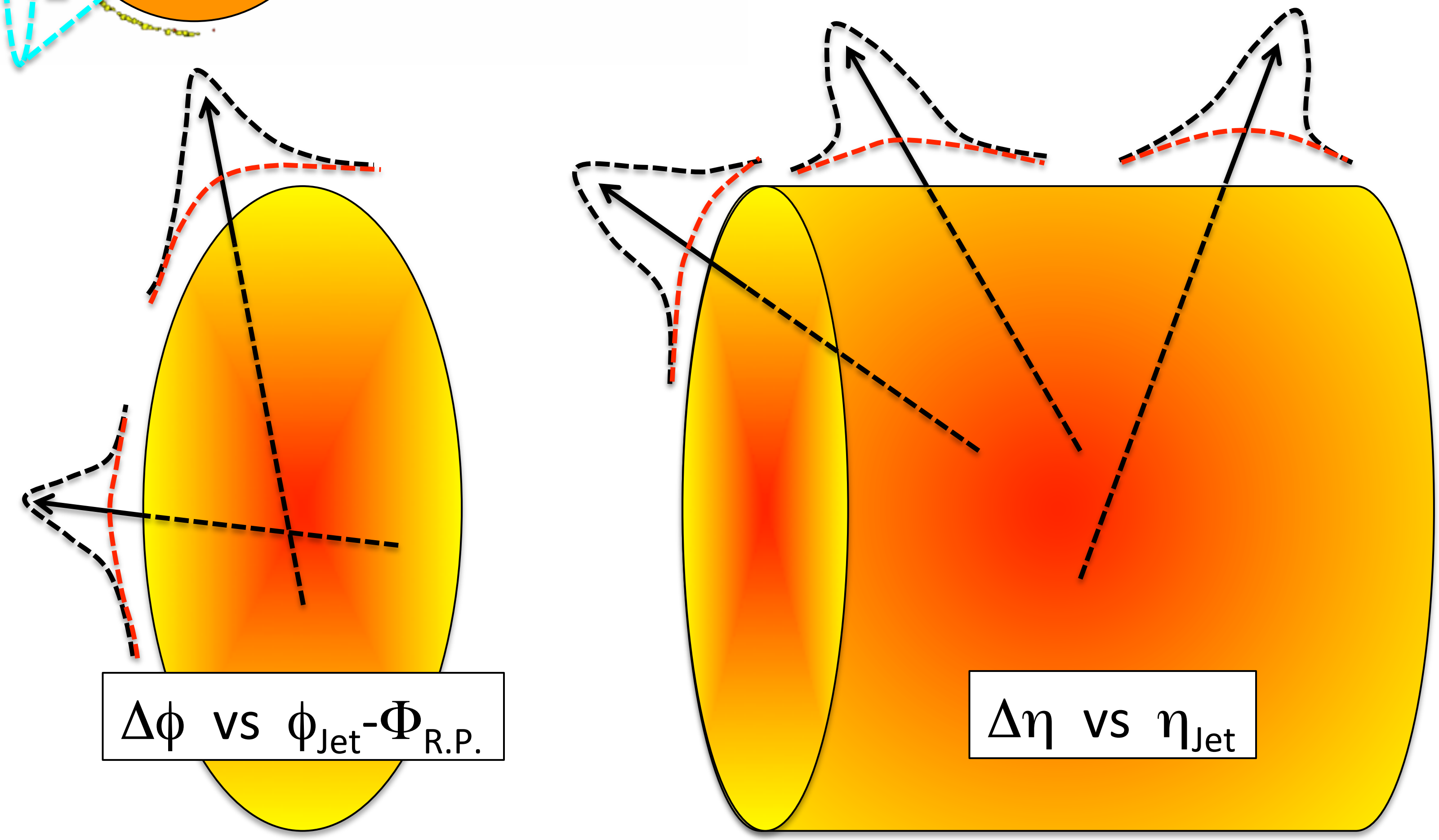
Jet as a control tool to define path length



Jet-medium interaction : hard-soft interplay

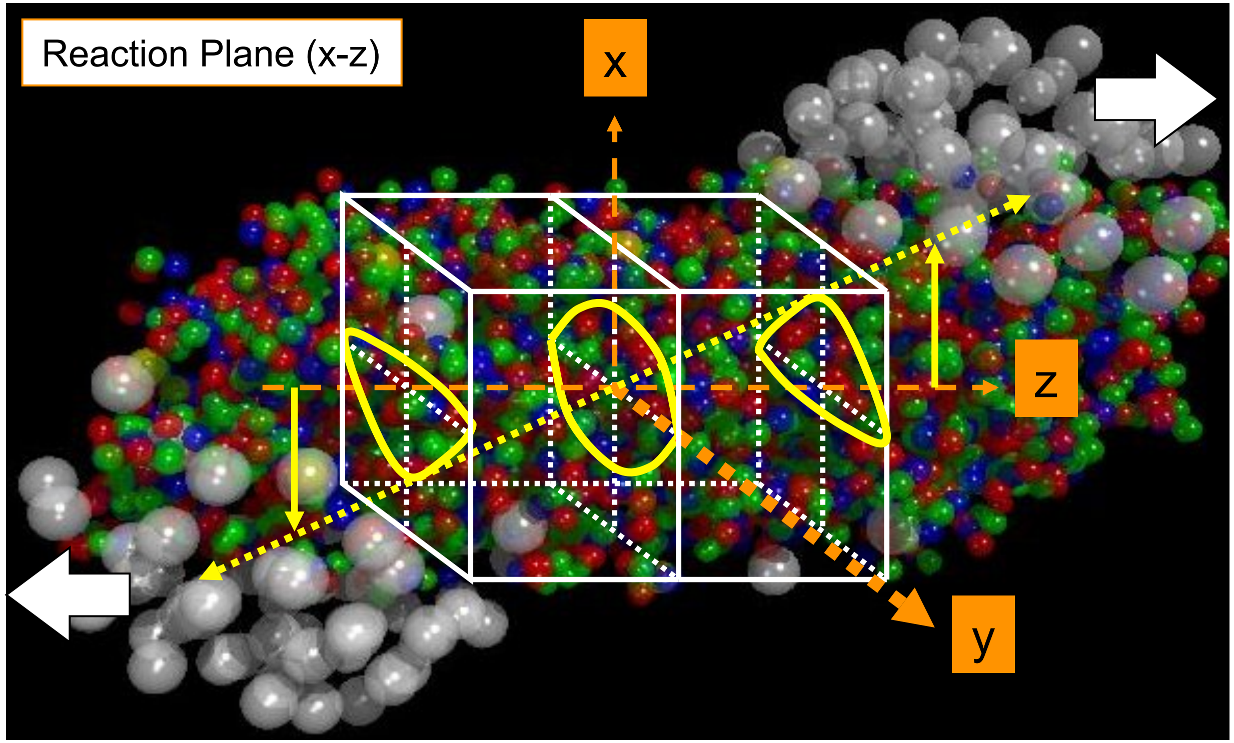
Jet axis dependence
with respect to geometry

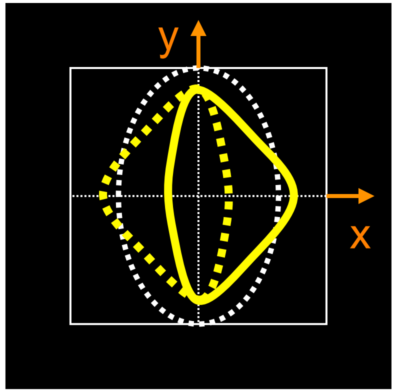




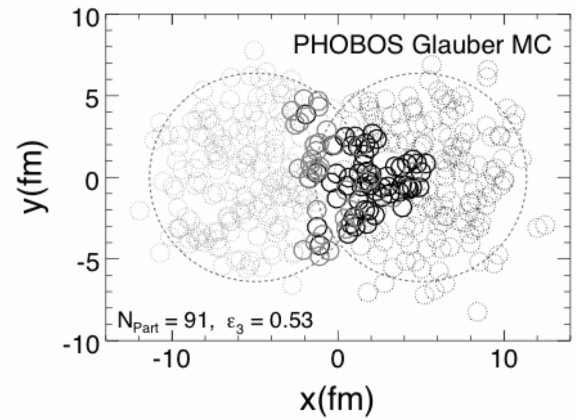
Higher order event anisotropy --- v_3 ---

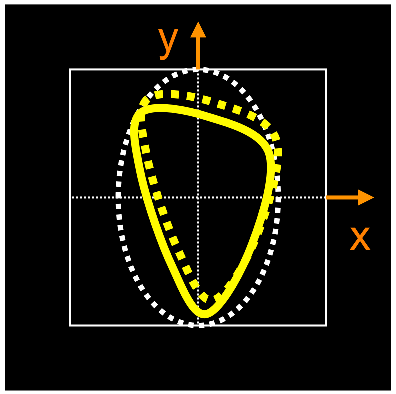
black-disk collision, sign-flipping v_3 like v_1
initial geometrical fluctuation, no-sign-flipping v_3



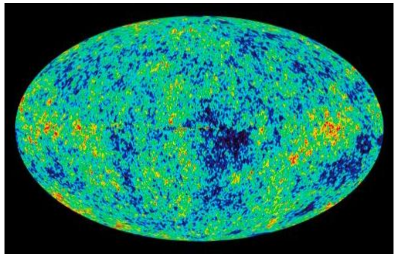


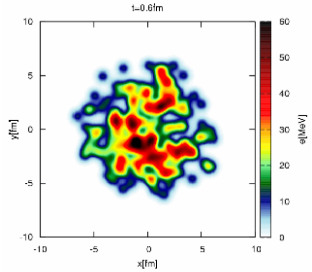
arXiv:1003.0194

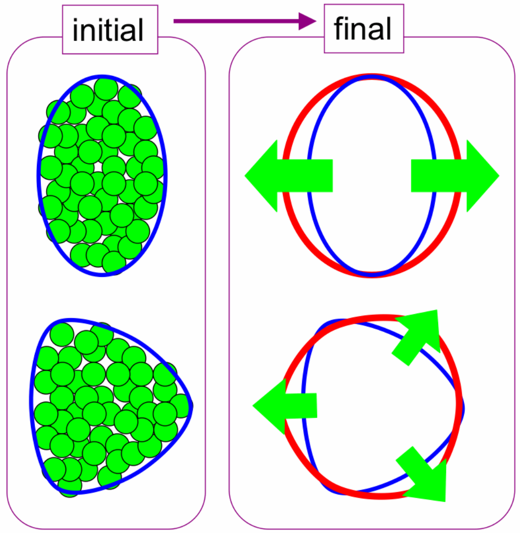




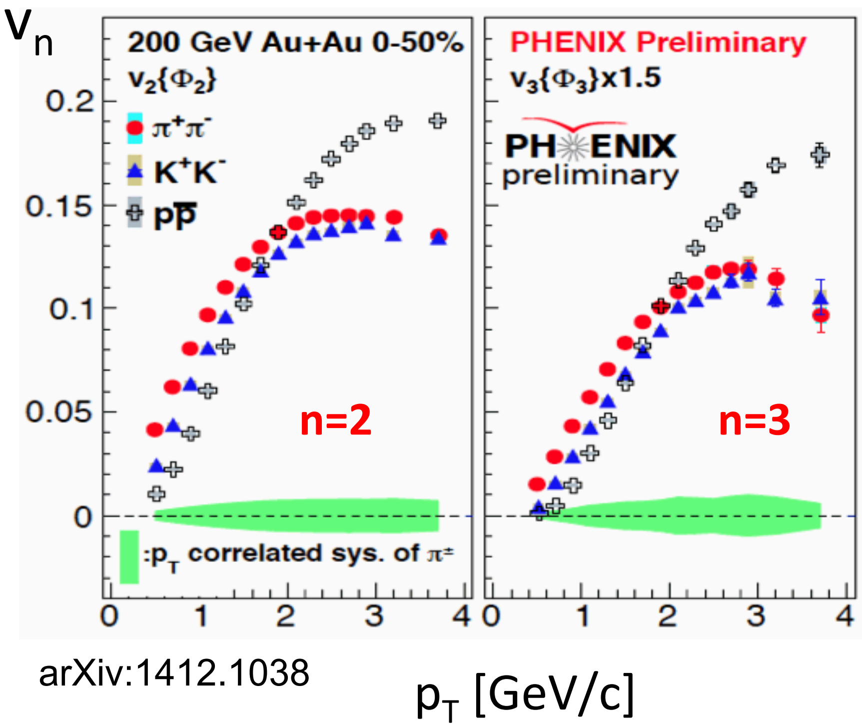
Elliptic and triangular expansion and freeze-out geometry





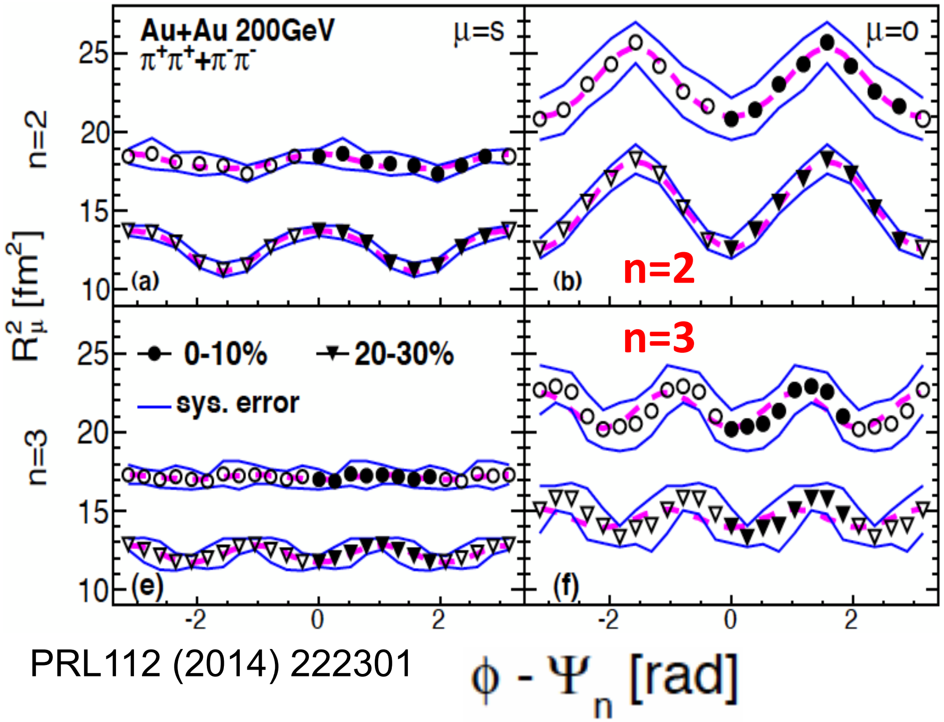


Elliptic and Triangular expansion : v_2, v_3



arXiv:1412.1038

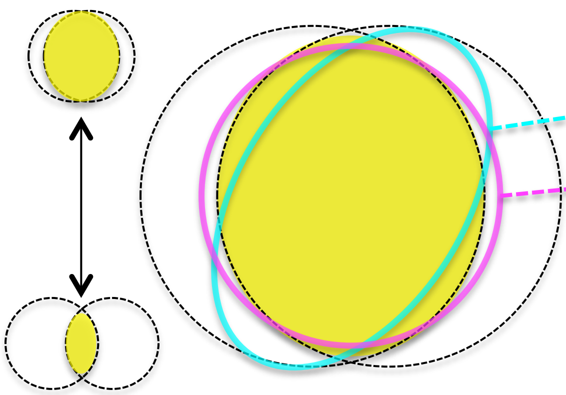
Elliptic and Triangular shape : $R^{HBT}{}_{\Phi 2}$, $R^{HBT}{}_{\Phi 3}$

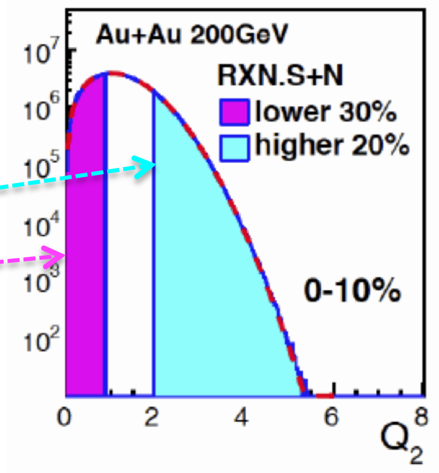


PRL112 (2014) 222301

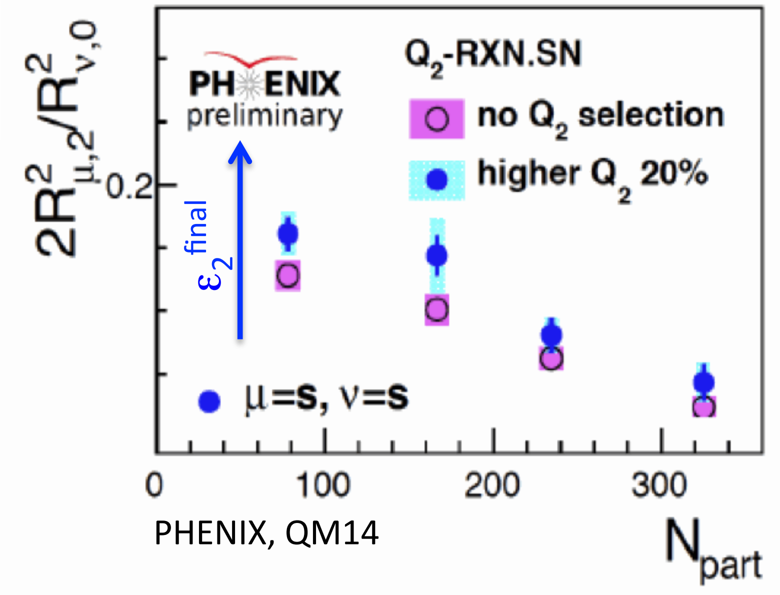
Event shape selection Q_2 (~v_2)

relation of $\varepsilon_2^{initial} - v_2 - \varepsilon_2^{final}$
for a given centrality



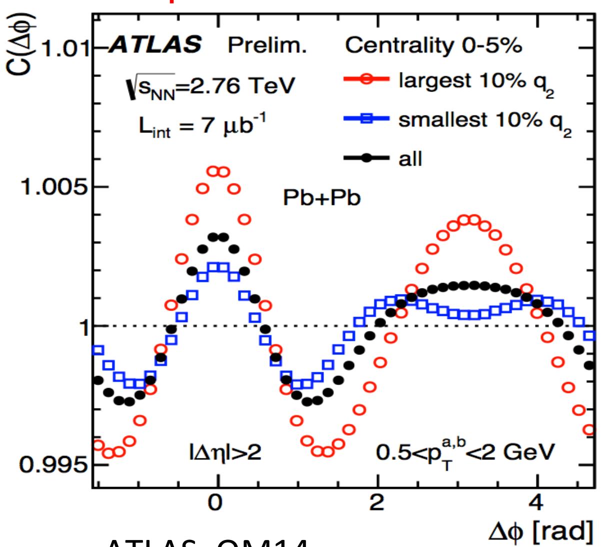


ε_{final} via HBT interferometry

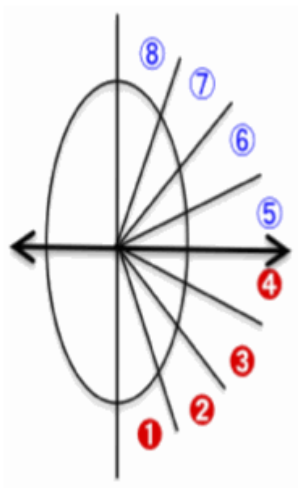


PHENIX, QM14

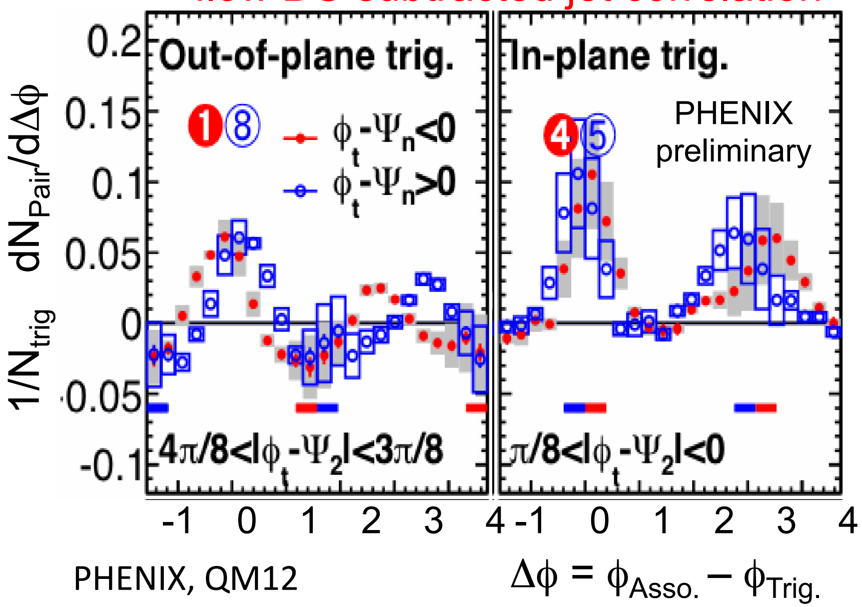
2-particle correlation



ATLAS, QM14



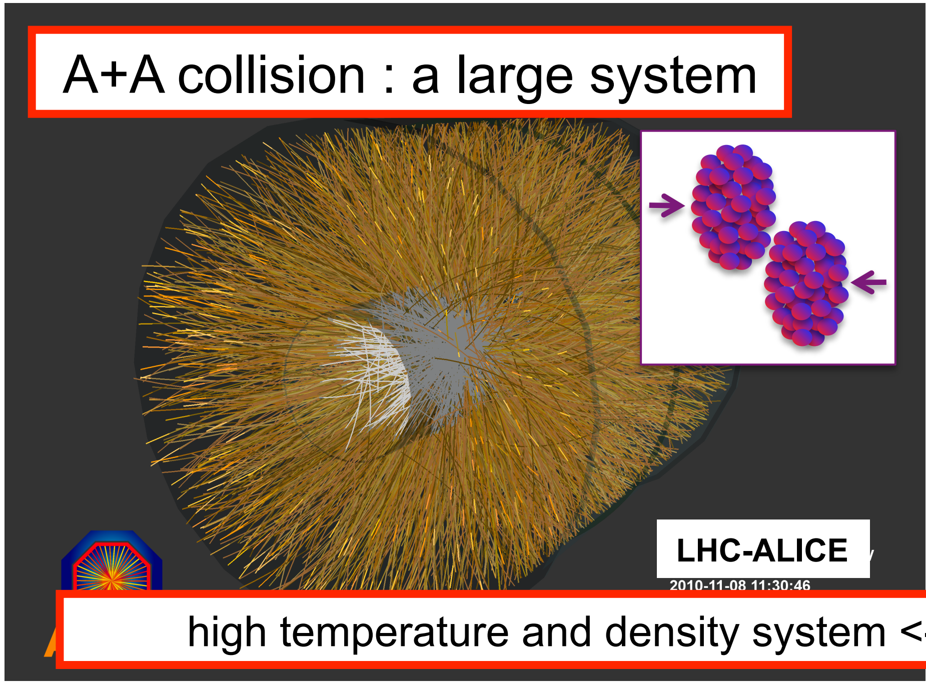
flow BG subtracted jet correlation



PHENIX, QM12

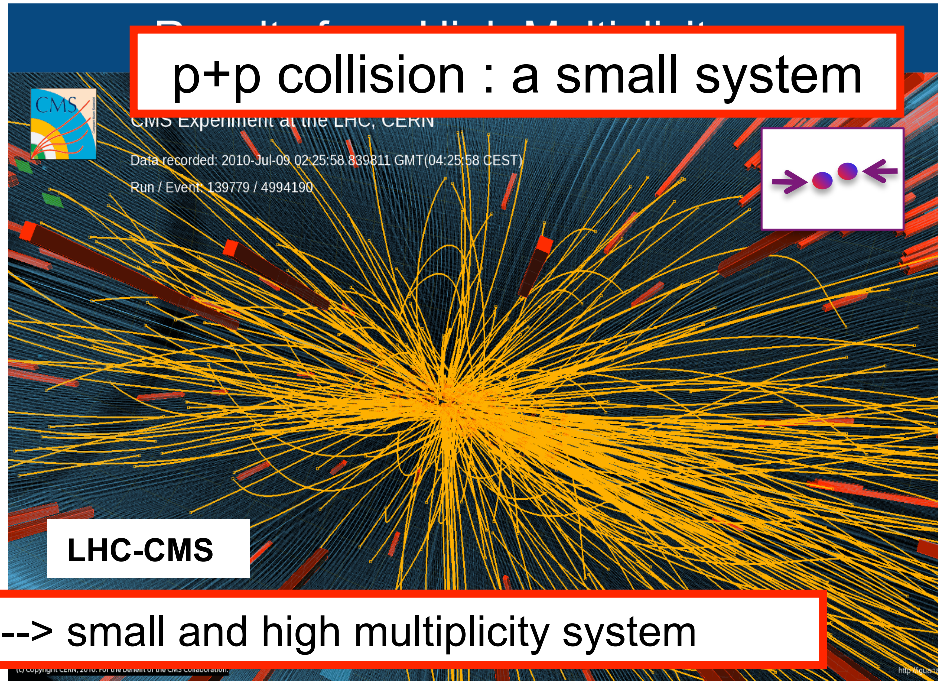
$\Delta\phi = \phi_{Asso.} - \phi_{Trig.}$

A+A collision : a large system



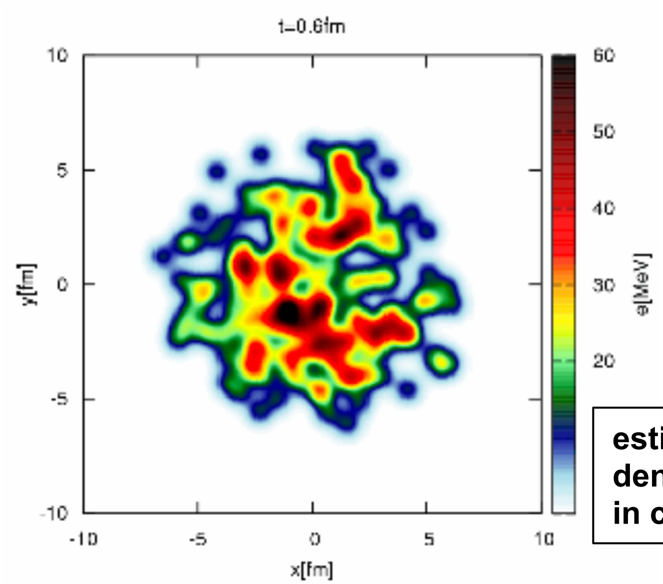
LHC-ALICE

p+p collision : a small system



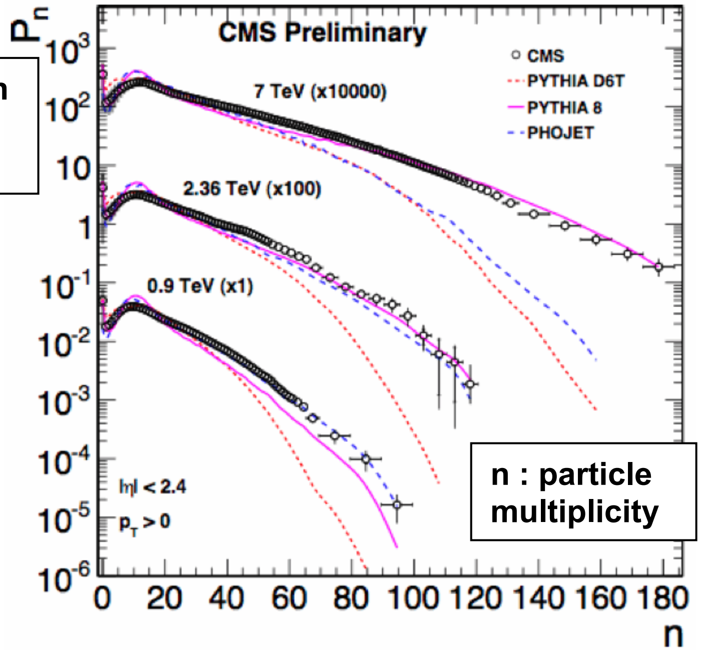
LHC-CMS

high temperature and density system <---> small and high multiplicity system



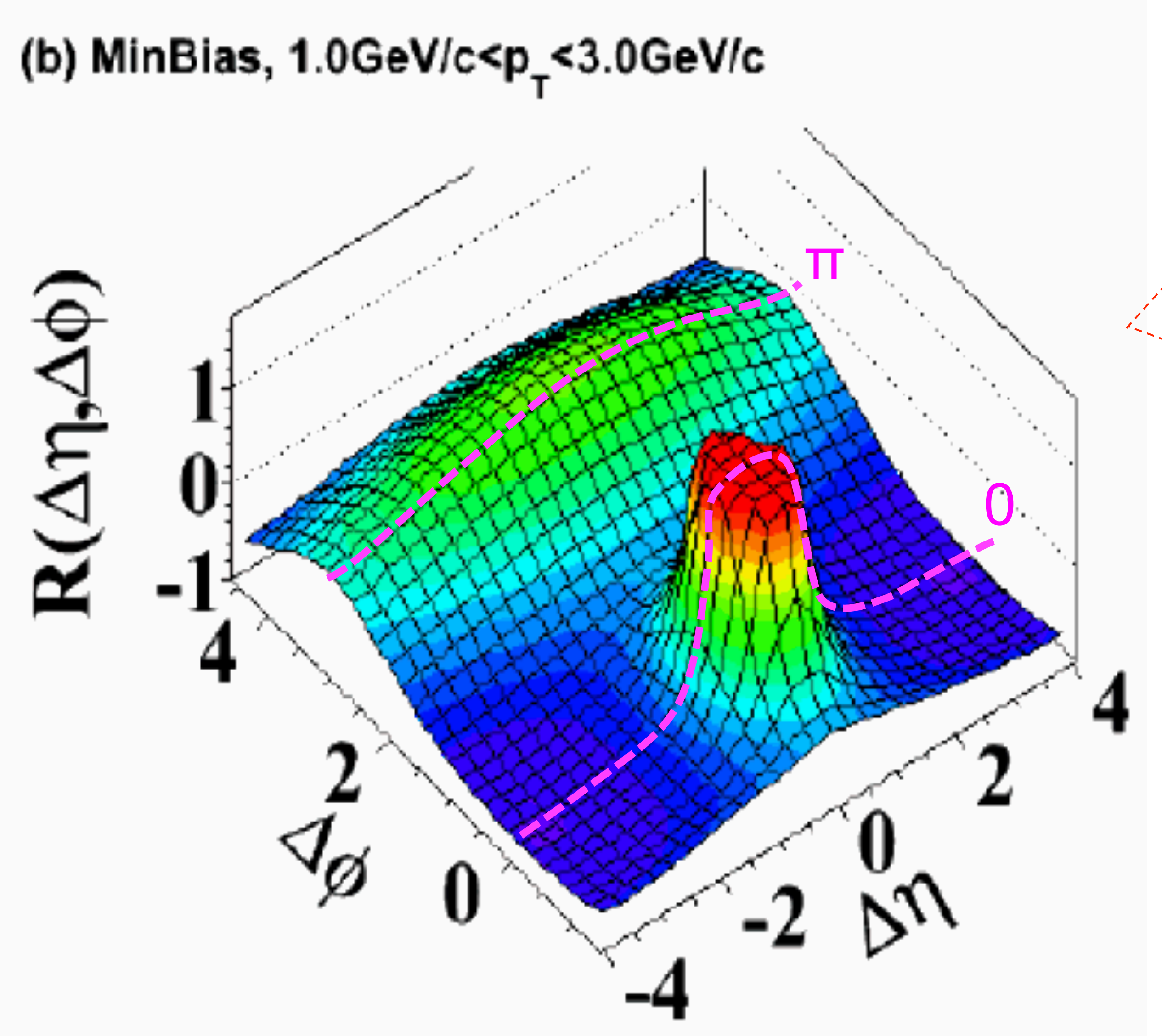
estimated initial energy density distribution in central A+A collision

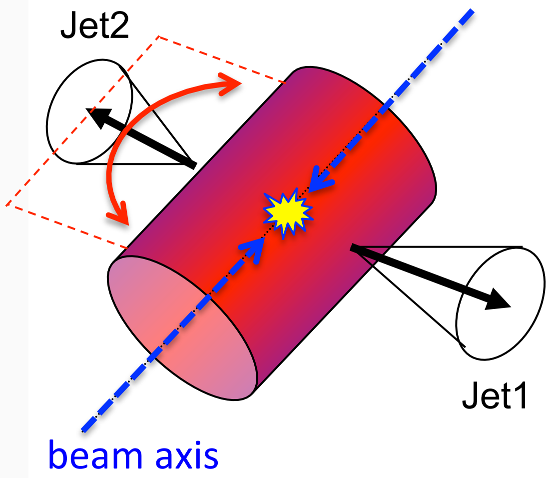
Probability distribution of event with "n" particles production



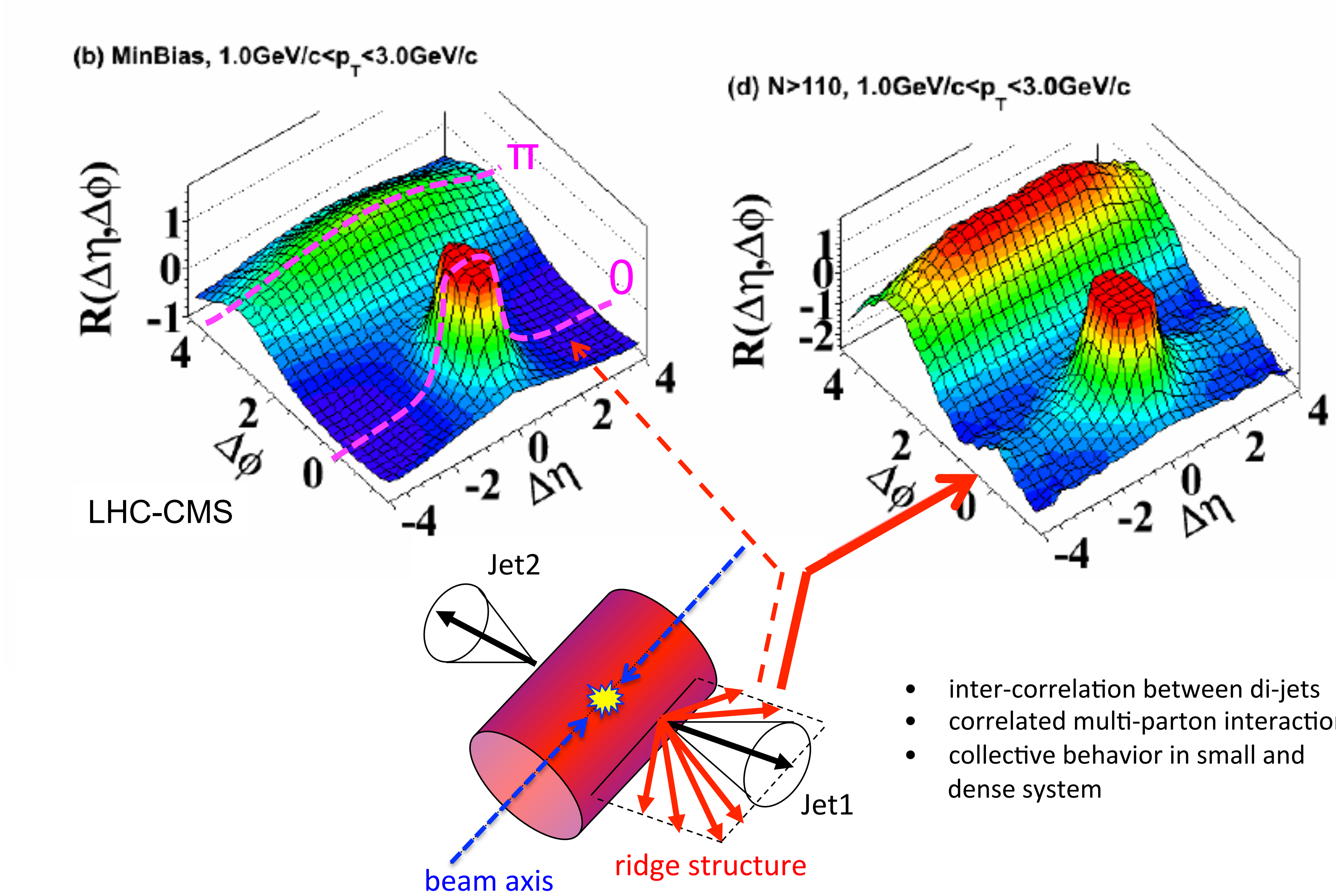
n : particle multiplicity

Two particle Δφ−Δη correlation



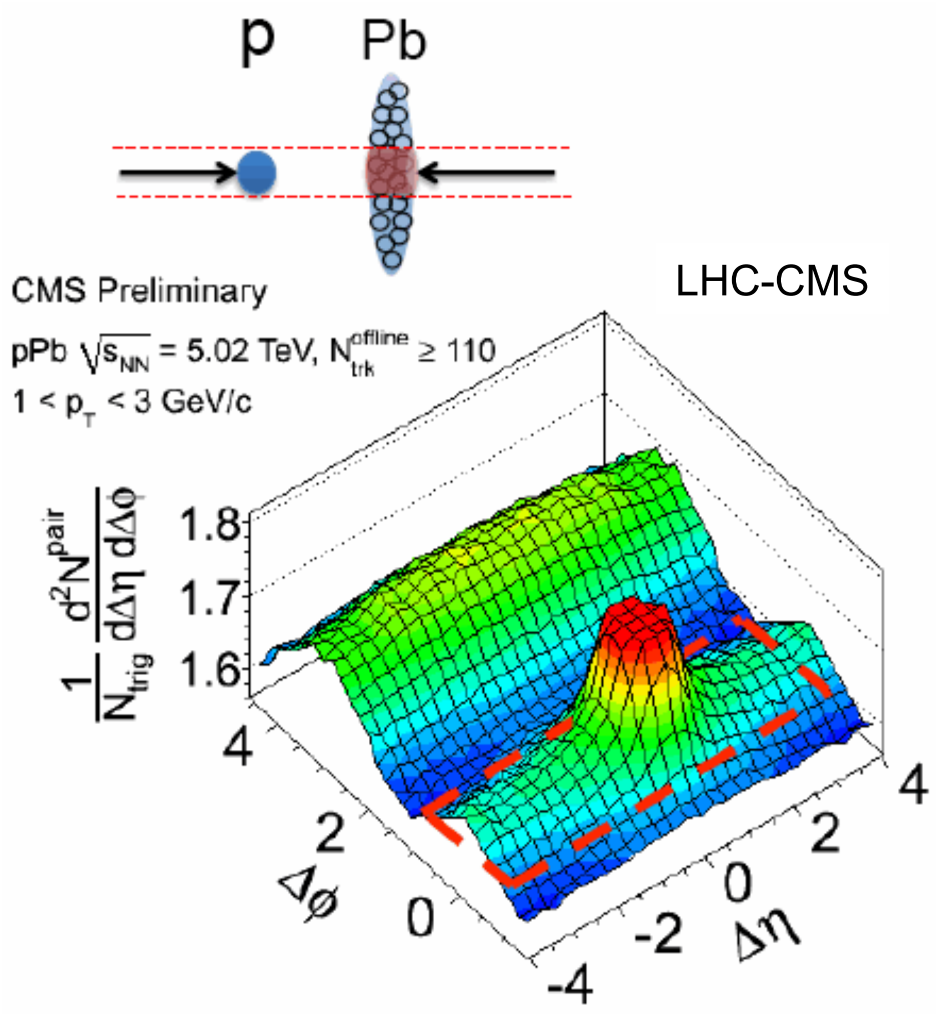


minimum bias p+p events ⟷ high multiplicity p+p events

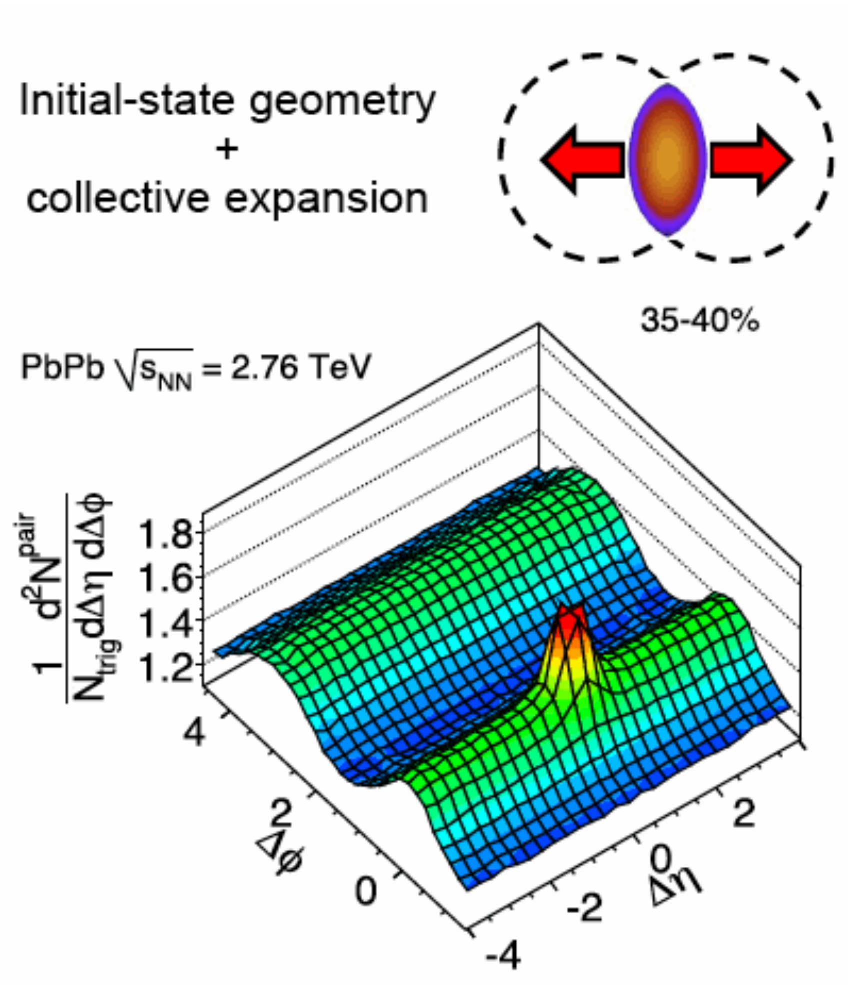


- inter-correlation between di-jets
- correlated multi-parton interactions
- collective behavior in small and dense system

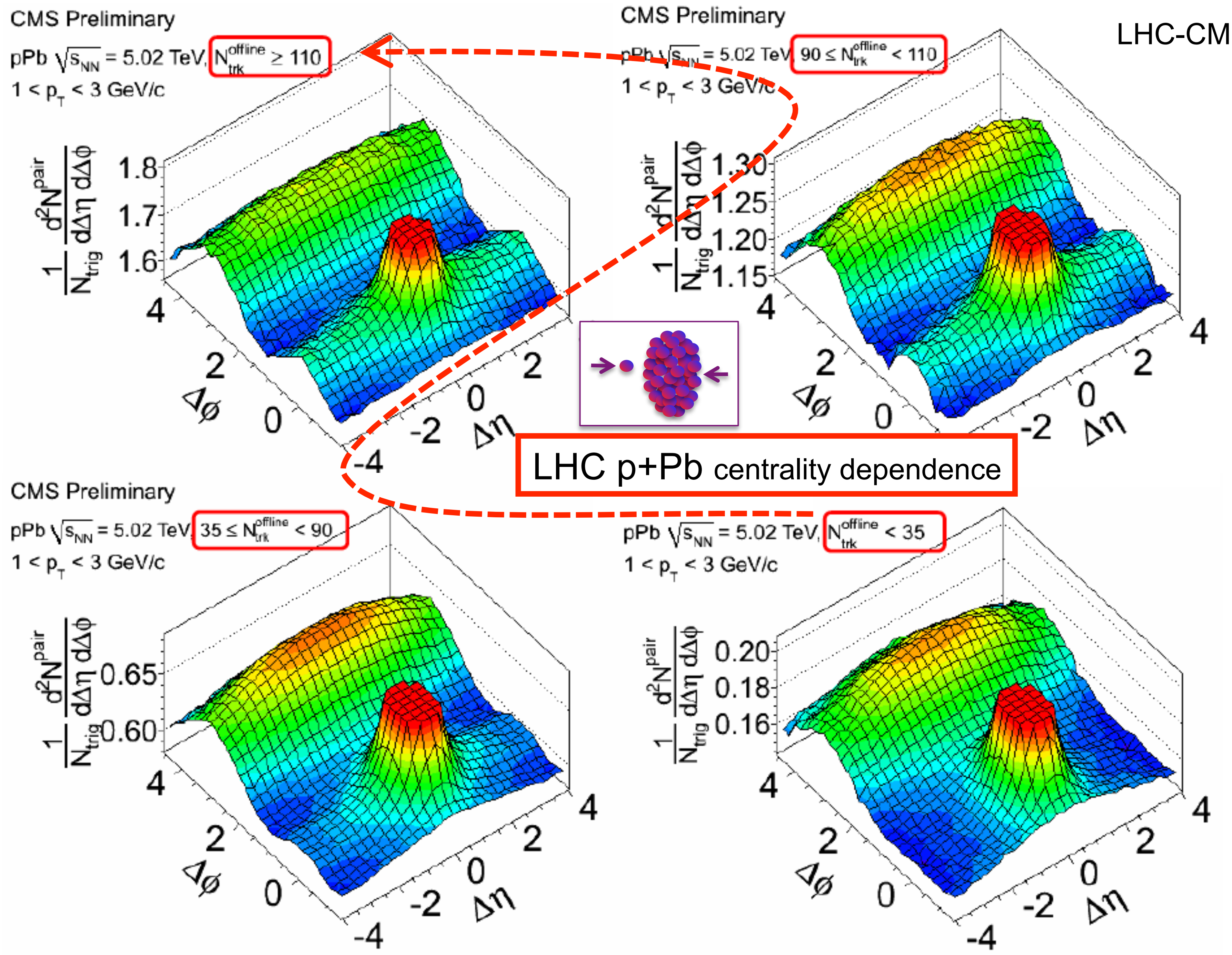
p+A collisions



A+A collisions



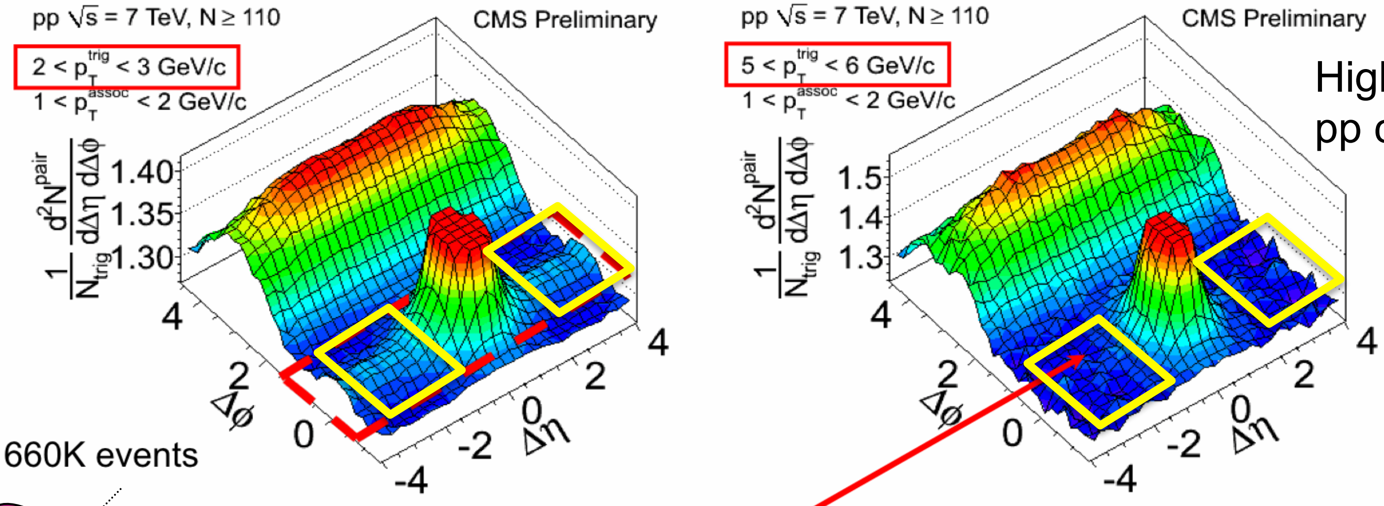
LHC-CMS


CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$
$1 < p_T < 3$ GeV/c
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $90 \leq N_{trk}^{offline} < 110$
$1 < p_T < 3$ GeV/c
CMS Preliminary
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $35 \leq N_{trk}^{offline} < 90$
$1 < p_T < 3$ GeV/c
pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} < 35$
$1 < p_T < 3$ GeV/c
$\frac{1}{N_{trig}} \frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
$\Delta\phi$
$\Delta\eta$
LHC p+Pb centrality dependence

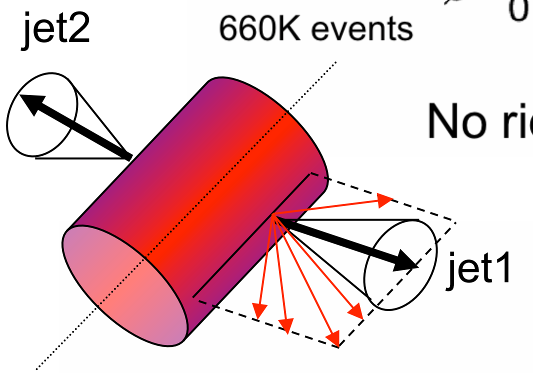
100 billion (1.78 pb^{-1}) sampled minimum bias events from high-multiplicity trigger

LHC-CMS

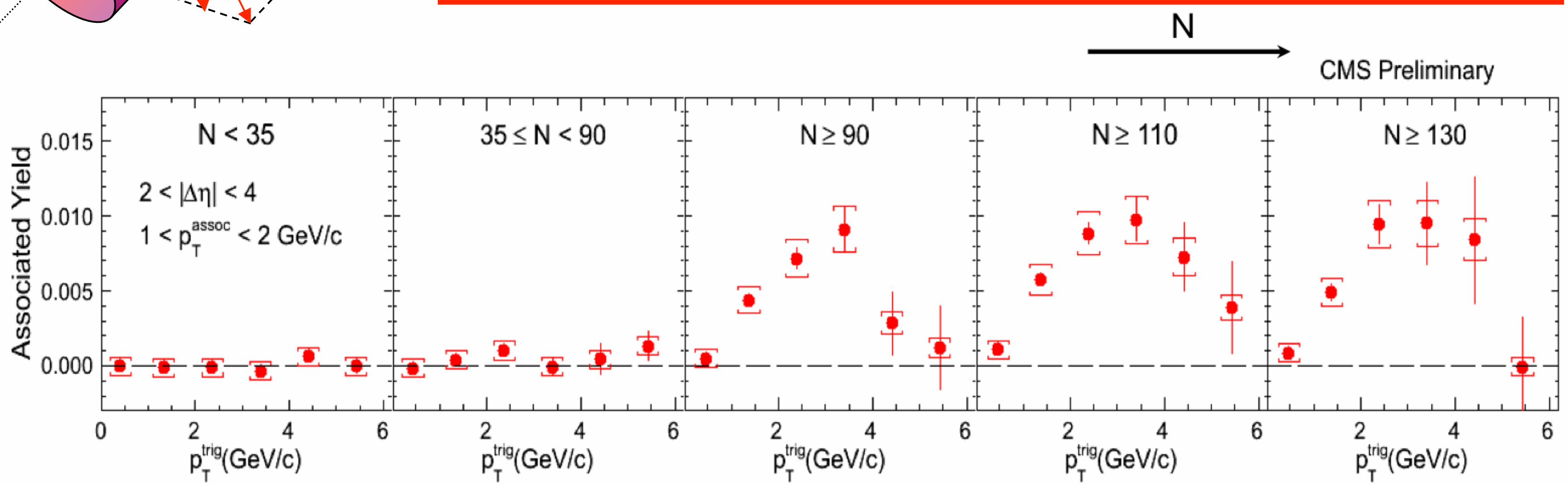
High multiplicity pp collisions



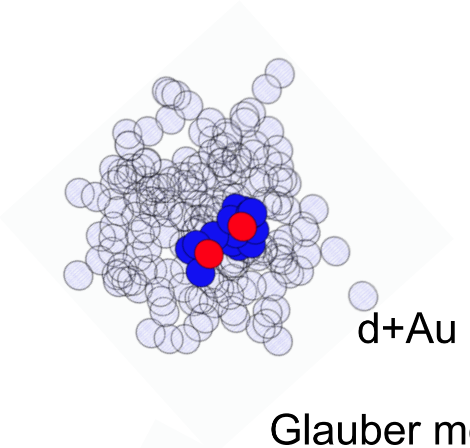
No ridge when correlating to high p_T particles!



peaked at p_T = 2~4GeV/c (ridge region |Δη| = 2~4)

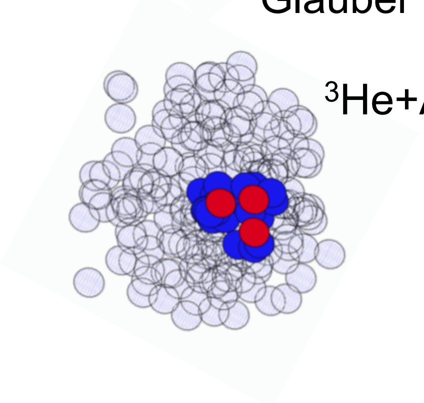


Elliptic flow in small system?

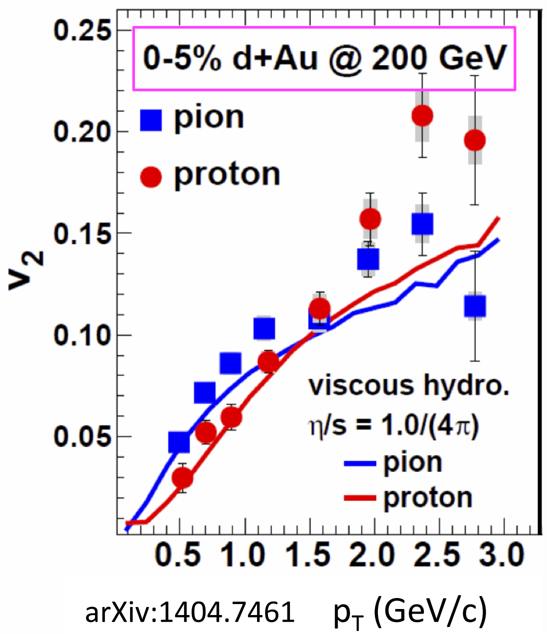


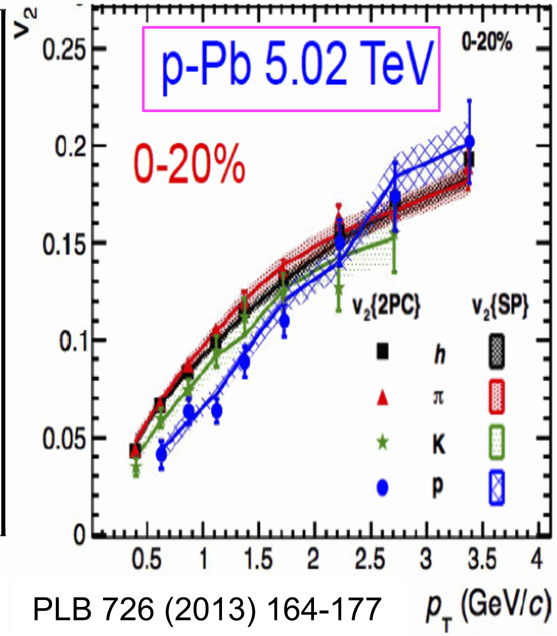
d+Au

Glauber model

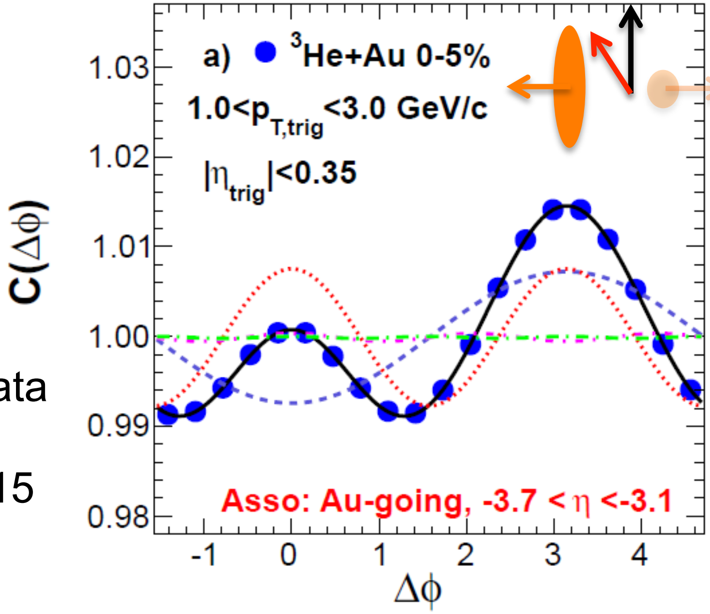


^{3}He+Au

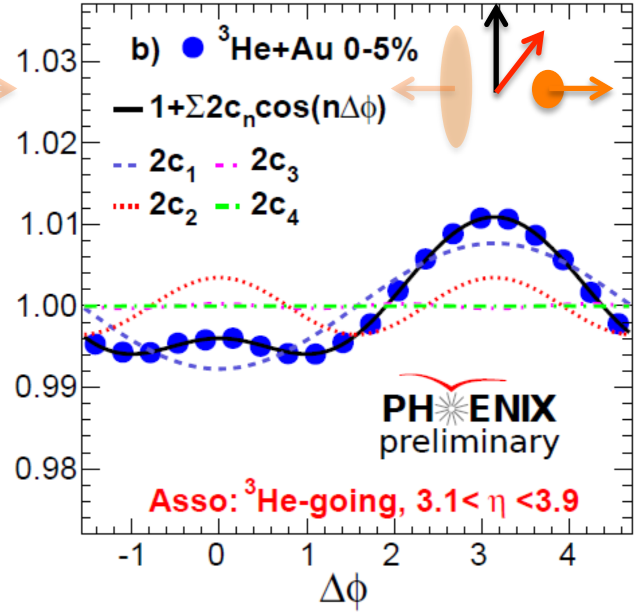




central - backward

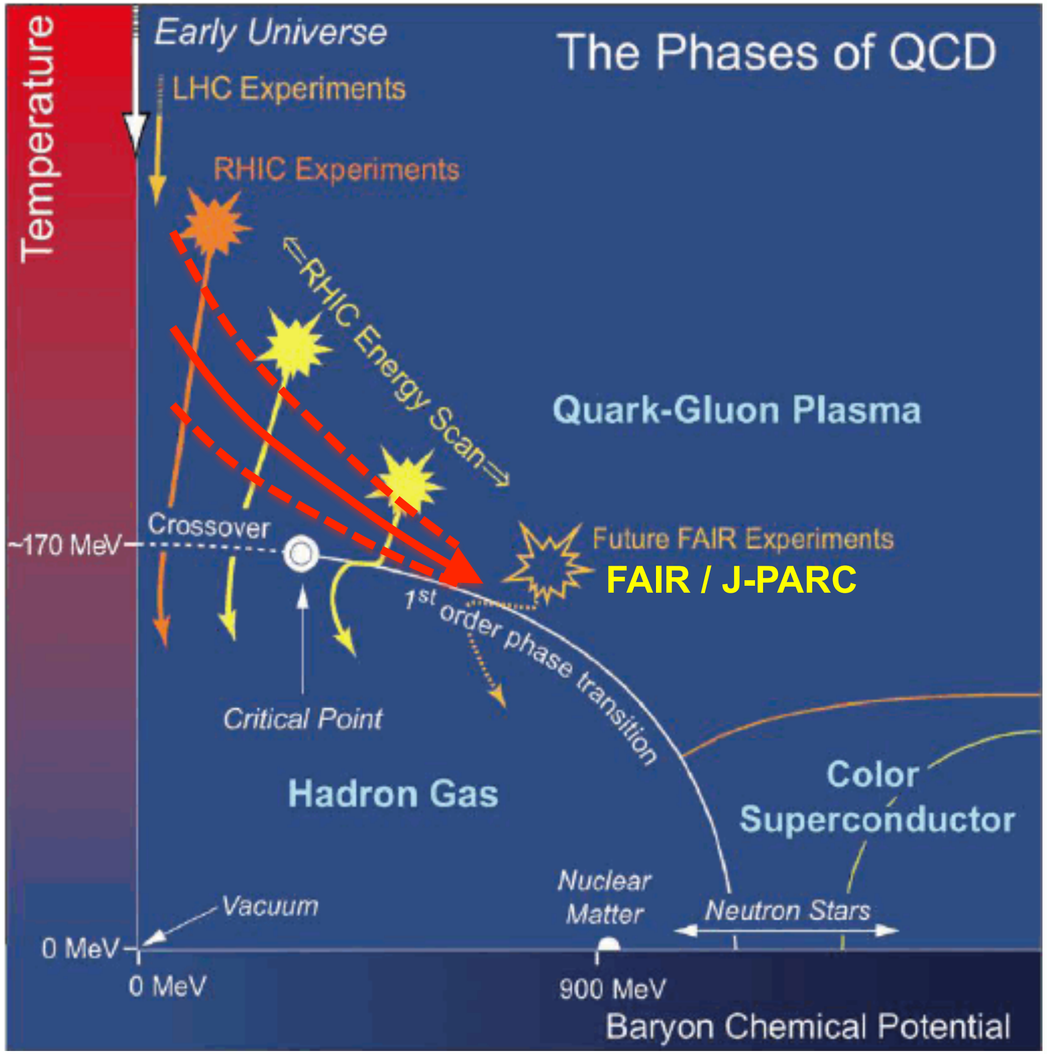


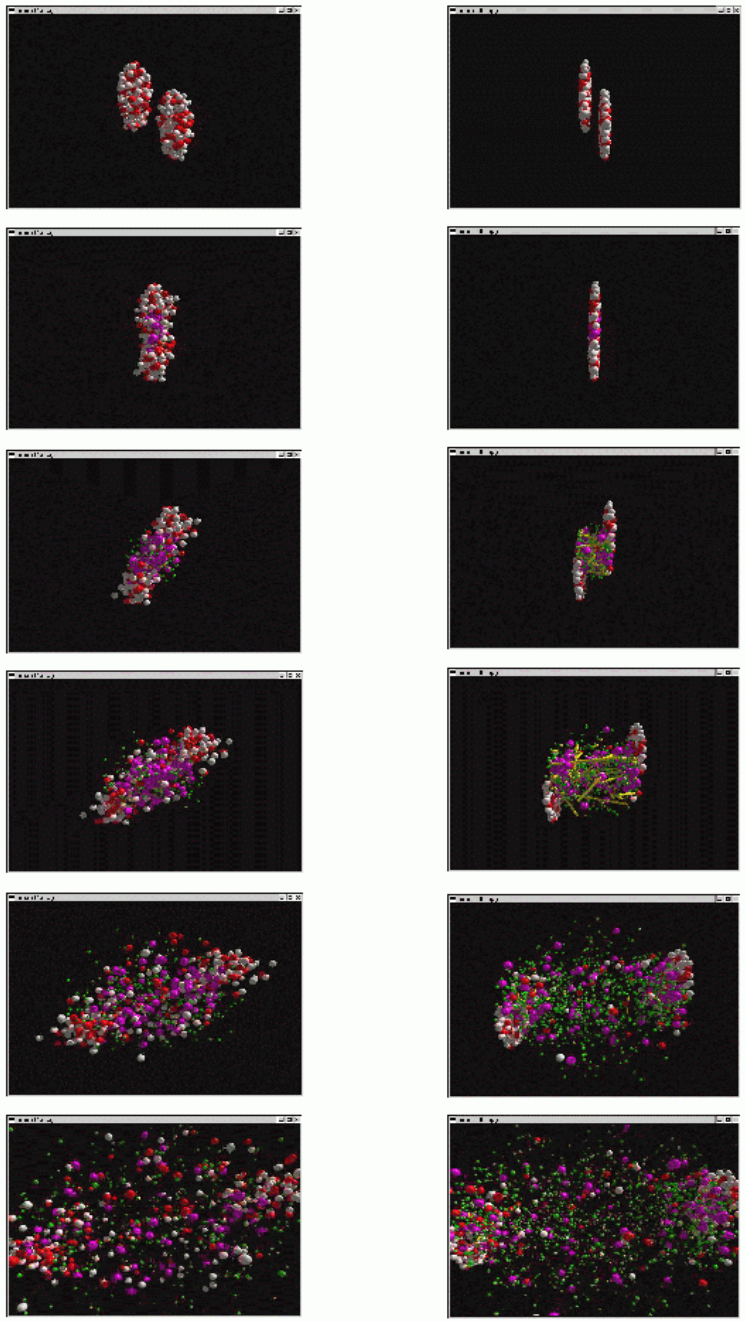
central - forward



* New ^{3}He+Au collision data from RHIC-RUN14
* p+p, p+Al, p+Pb in Run15 will come

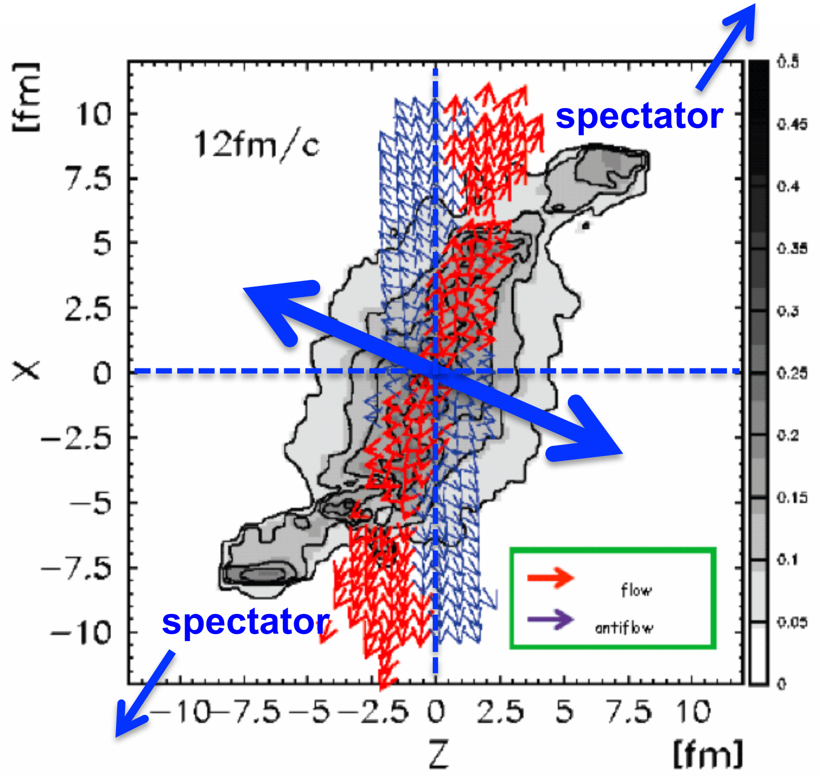
RHIC beam energy scan program
--- from high-temperature to high density ---





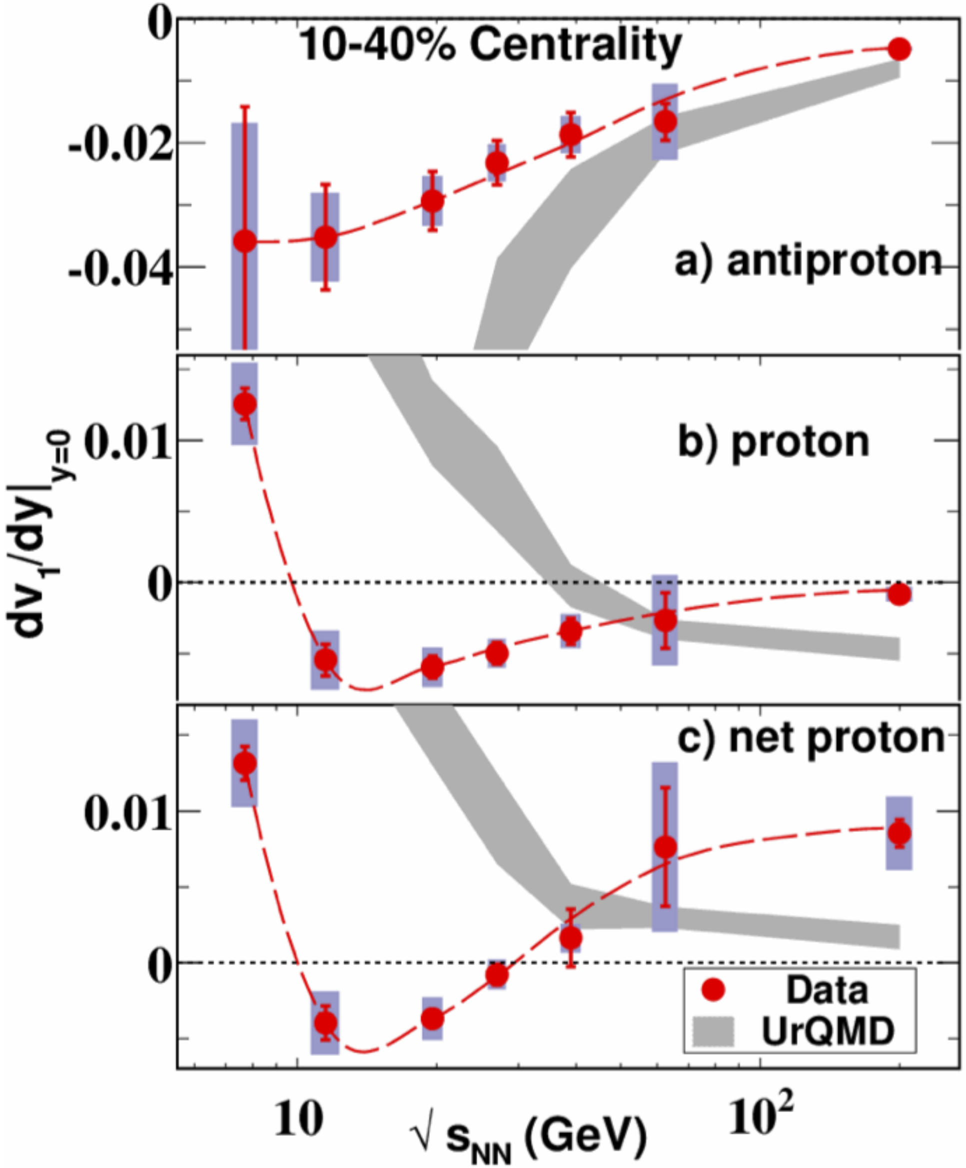
Directed flow v_1

- strong anti-flow of pion (and p-bar)
- small but significant anti-flow of proton
- sign change of v1 slope around 10GeV
- minimum around 10-20GeV

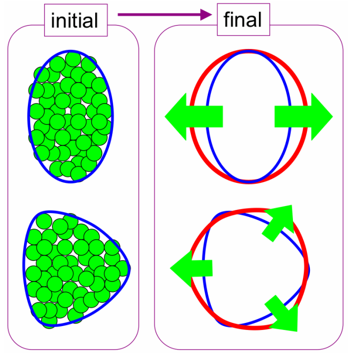


J. Brachmann et al., PRC 61, 24909 (2000).

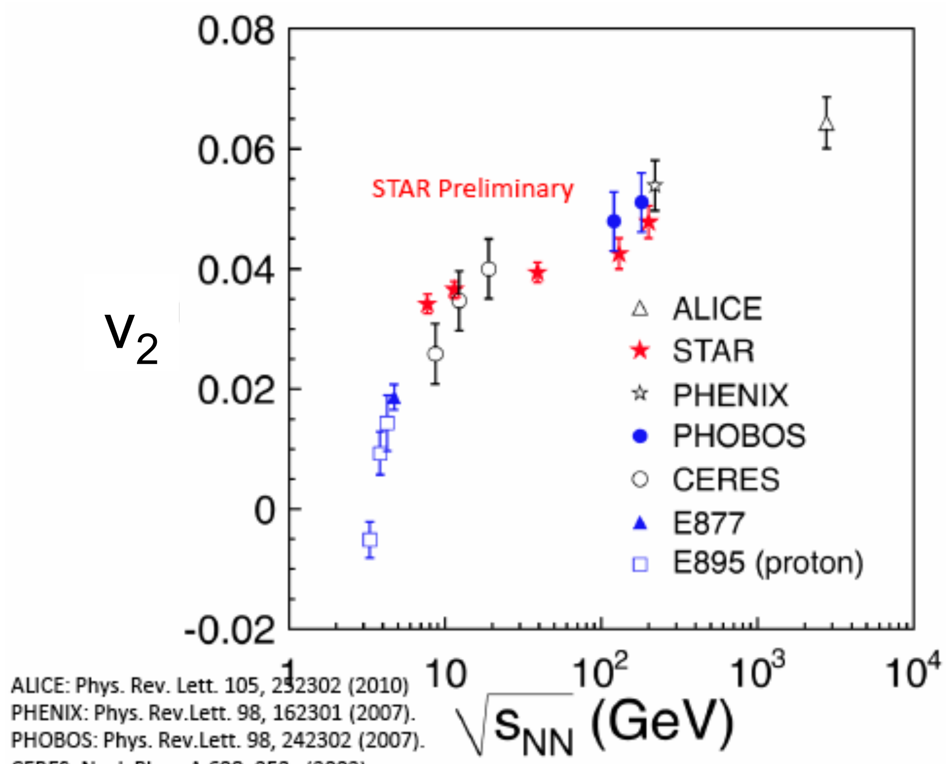
PRL112 (2014) 162301



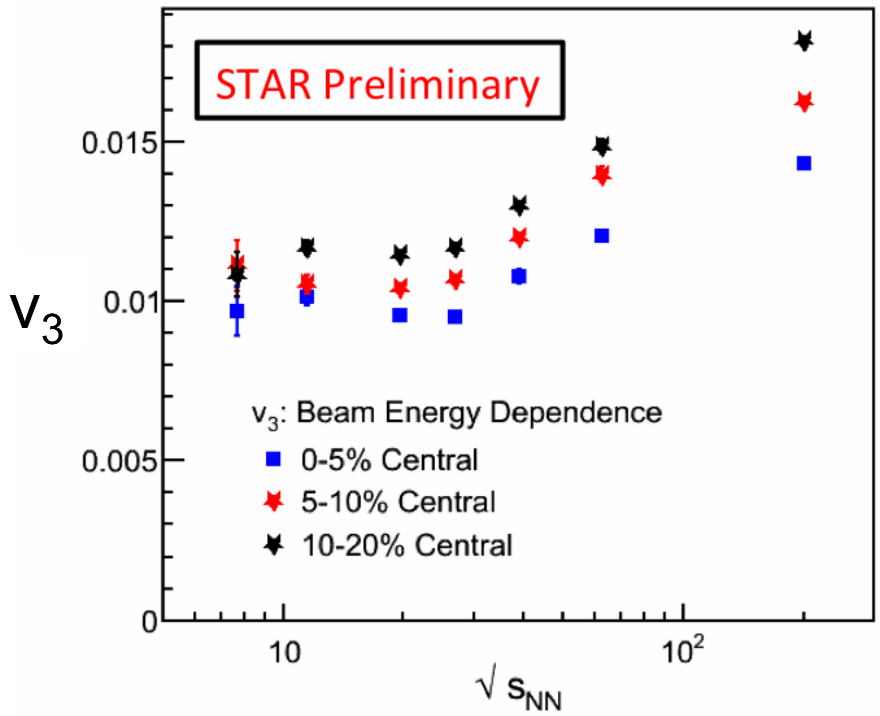
Beam energy dependence of v_2 and v_3



Smooth trend (not not?) of v_2 and v_3 with beam energy

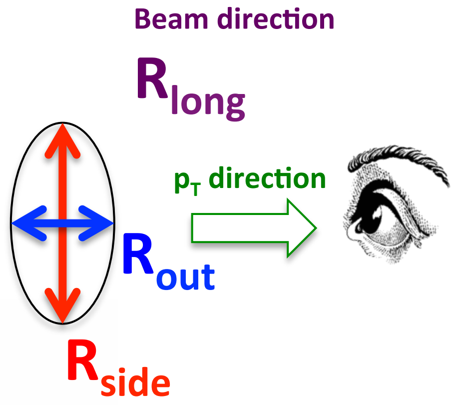


ALICE: Phys. Rev. Lett. 105, 252302 (2010)
PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007).
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005)

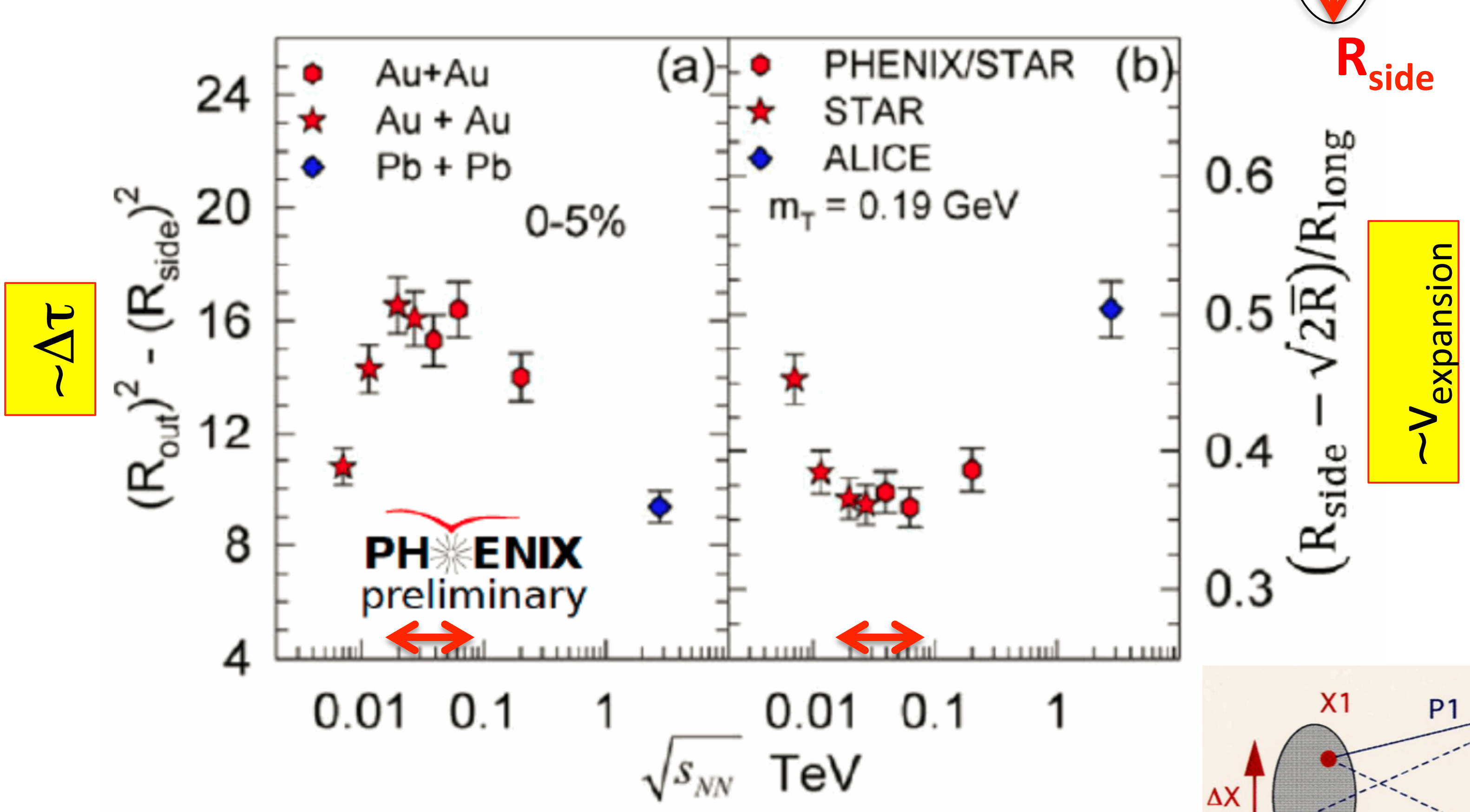


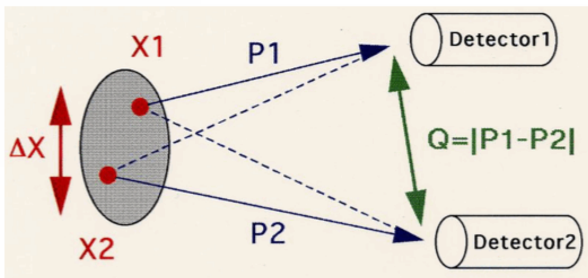
STAR Preliminary, QM12

Beam energy dependence of 2-particle interferometry measurement (HBT effect)

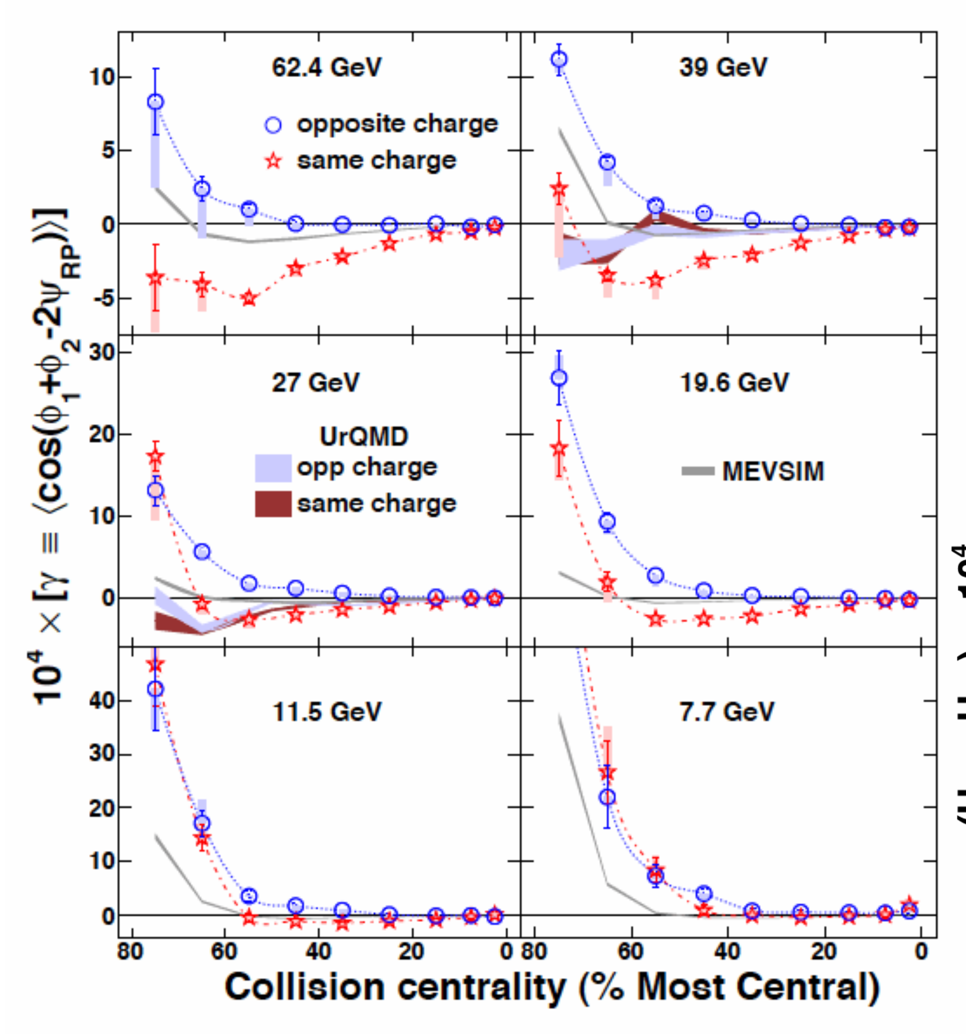


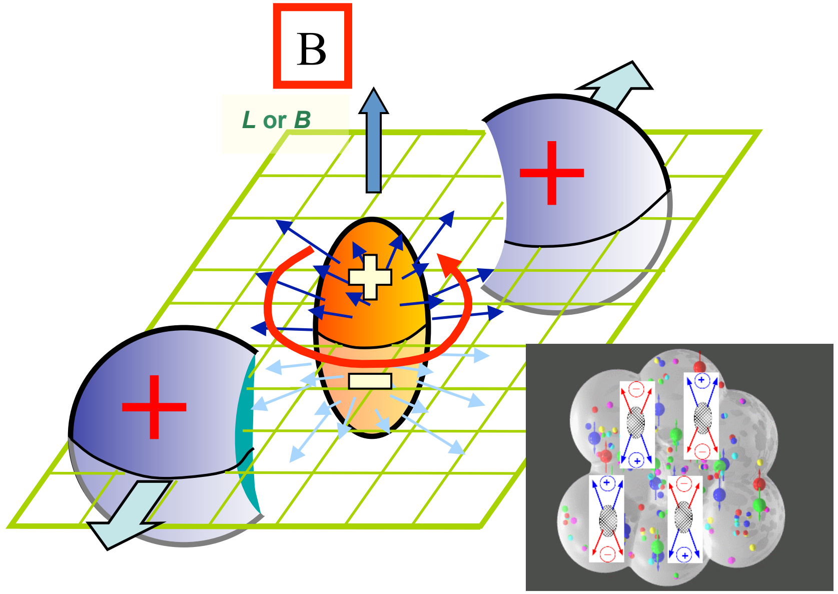
arXiv:1410.2559



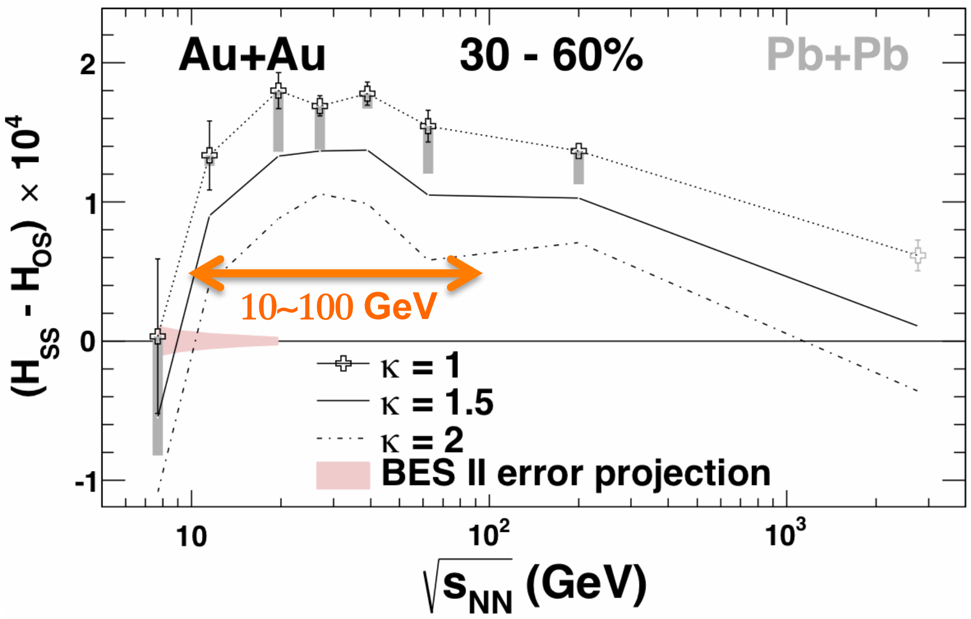


Local parity violation
in a strong magnetic field



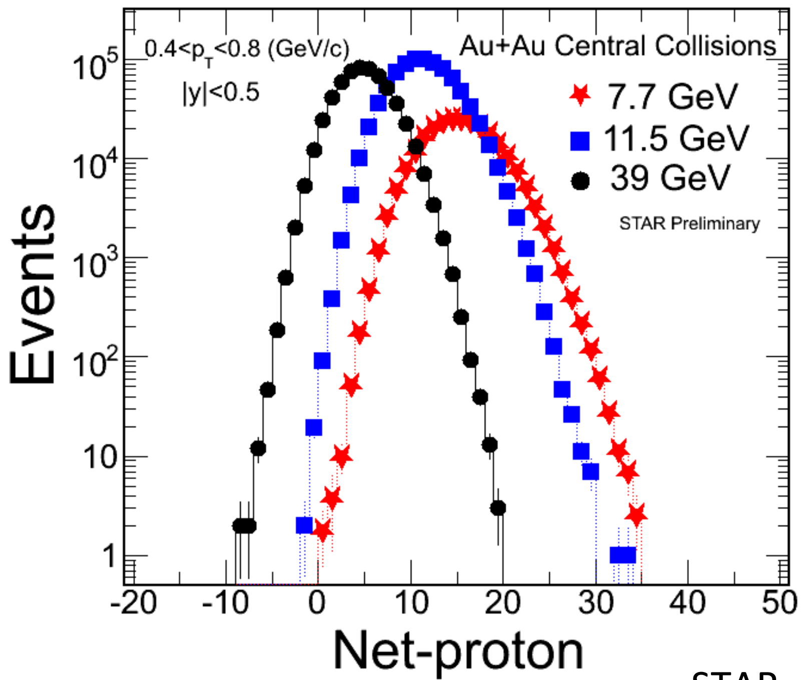


Phys. Rev. Lett. 113, 052302 (2014)

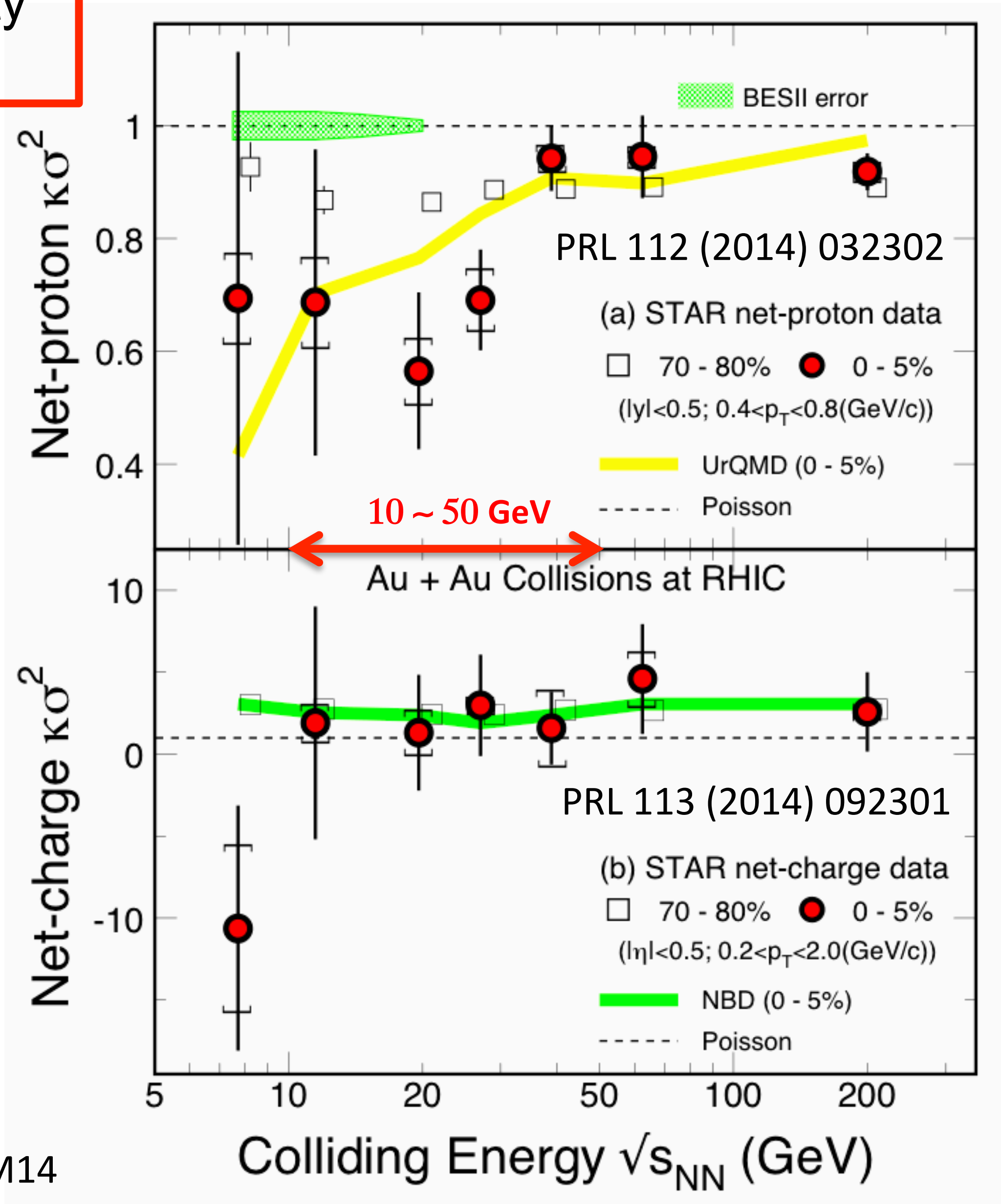


Fluctuation of conserved quantity vs beam energy

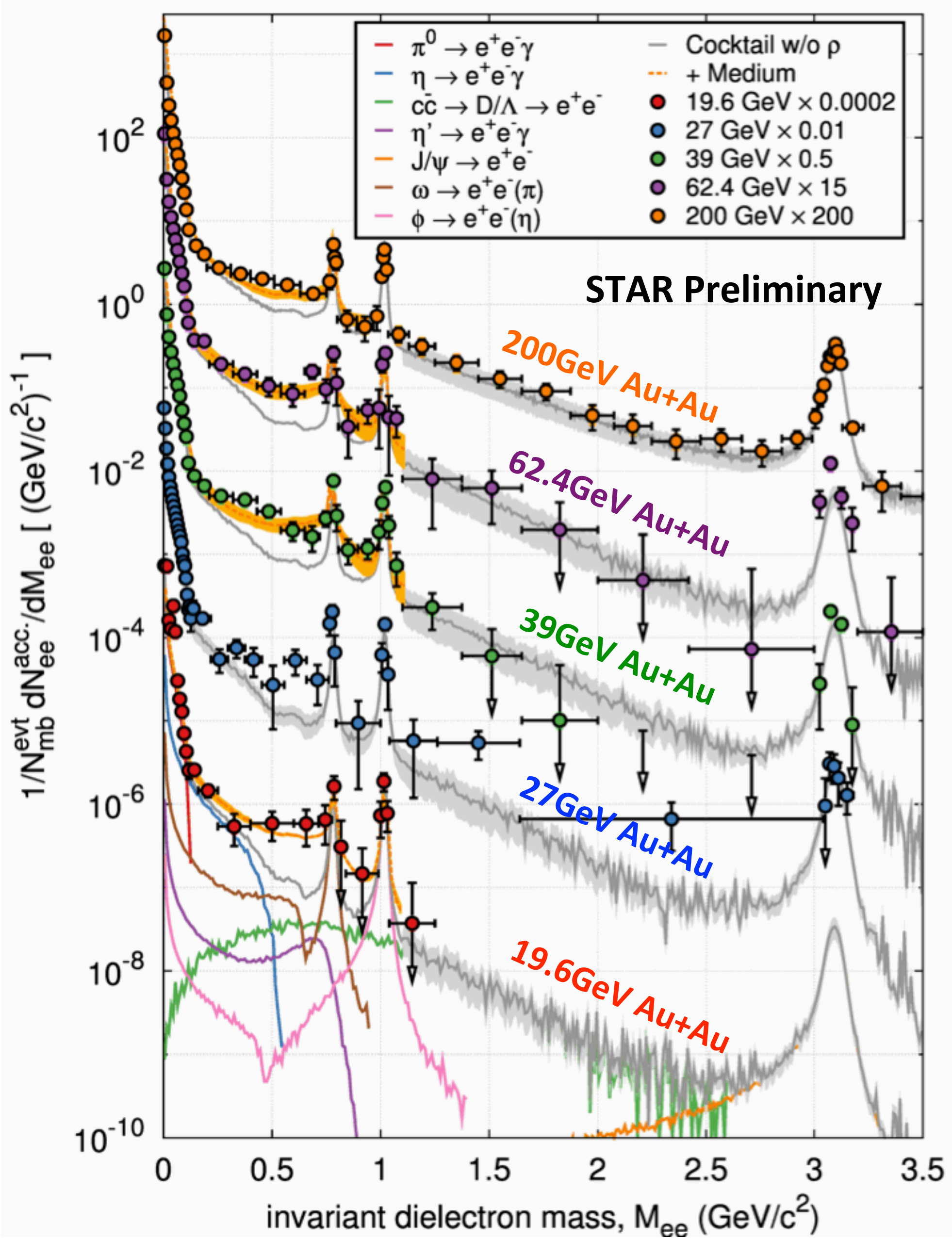
- Higher order moments (σ, S, κ) of net-baryon (net-proton) and net-charge distribution
- Non-monotonic behavior is expected around Critical Point.



STAR, QM14

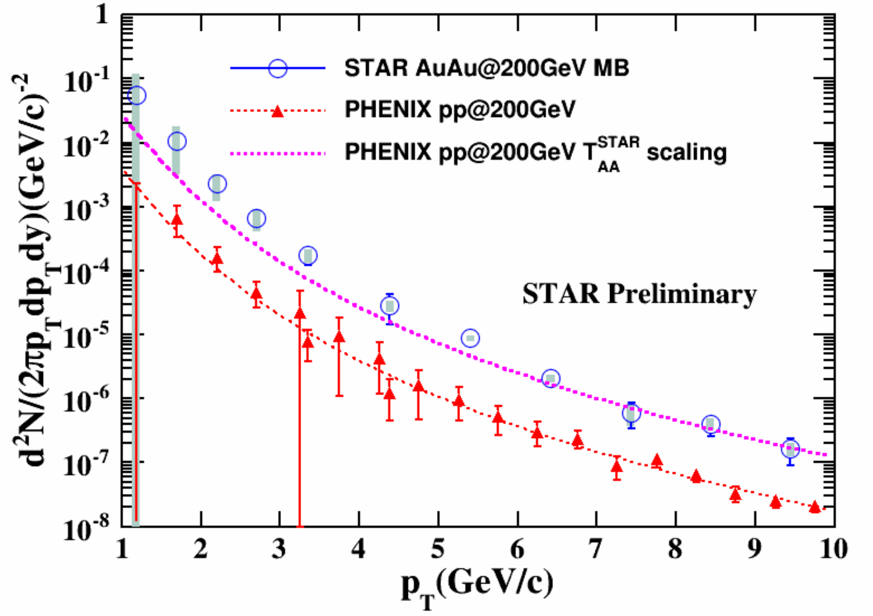


Patrick Huck, QM14



$M_{ee}^{inv.}$ spectra and direct $\gamma^{thermal}$ from STAR experiment

Chi Yang, QM14



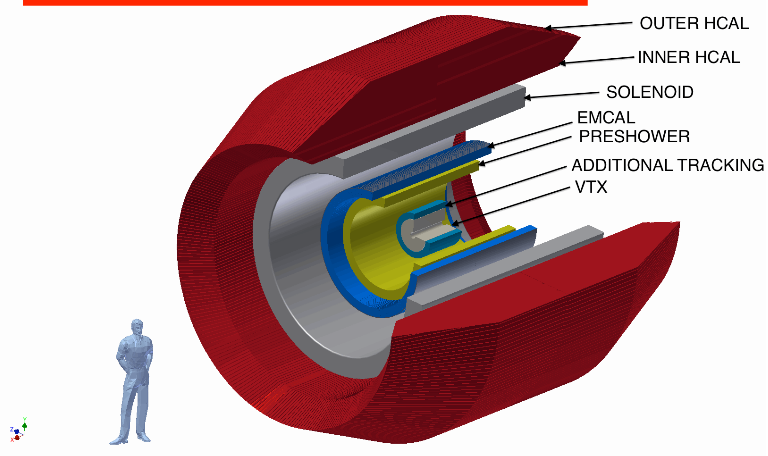
Low mass di-lepton yield :

almost consistent with CERES at ~20GeV

somewhat lower than PHENIX at ~200 GeV

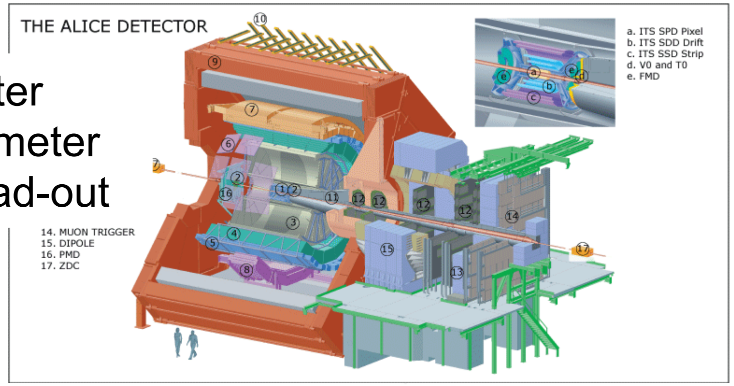
thermal photon spectra : consistent with PHENIX

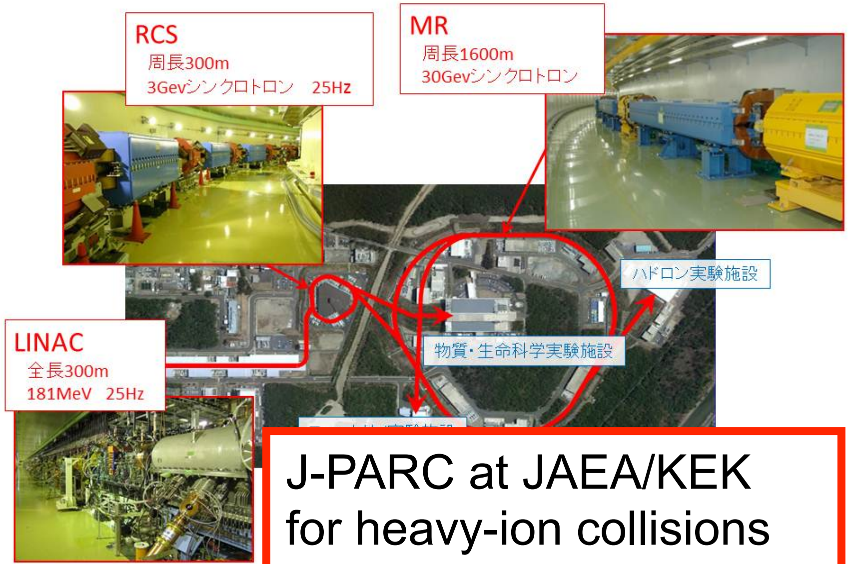
sPHENIX at RHIC-BNL
(New York, USA)



ALICE at LHC-CERN for Luminosity upgrade
(Geneva, Switzerland)

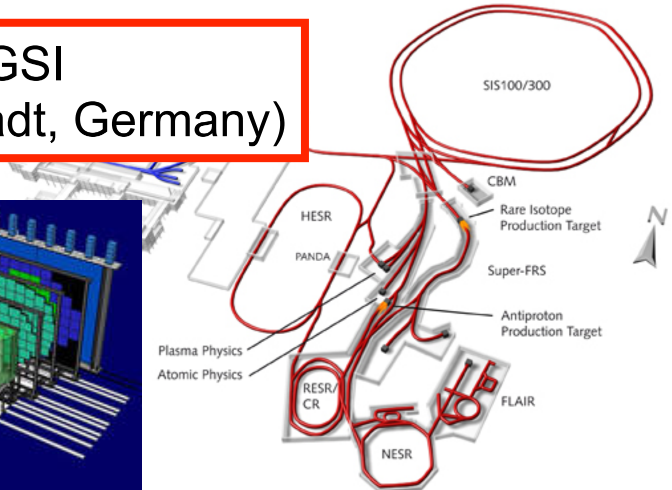
Di-jet calorimeter
Forward calorimeter
High-speed read-out

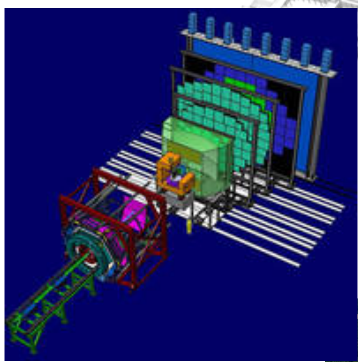


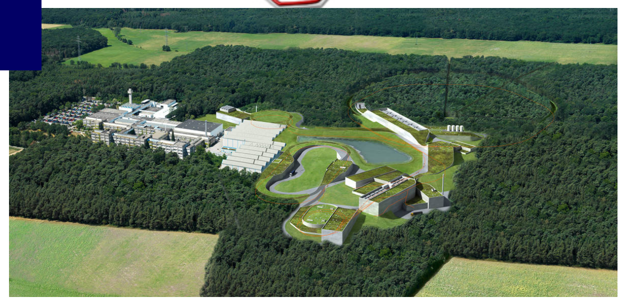


J-PARC at JAEA/KEK
for heavy-ion collisions
(Tokai, Japan)

FAIR at GSI
(Darmstadt, Germany)







Summary

slide from H. Sako, ATHIC14, Aug/2014, Osaka

from SPS to RHIC, LHC

- Temperature
- Collective expansion
- Jet quenching
- Small system
- Beam energy scan