Recent jet correlation analysis at RHIC and LHC

ShinIchi Esumi
Inst. of Physics
Univ. of Tsukuba

jet/photon suppression(R_{AA}) / event anisotropy(v_2)
particle/jet correlation(I_{AA}) / geometrical dependence
mach-cone, ridge / soft-hard interplay
ridge in high mult. p+p events at LHC

Jet quenching

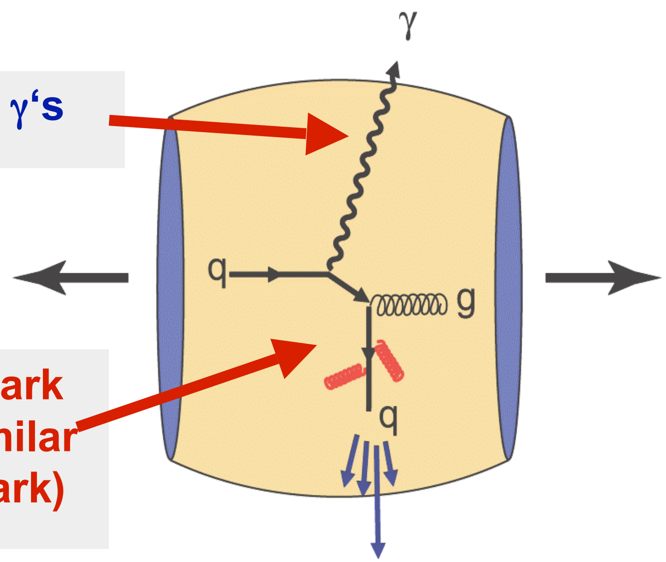
--- energy loss of parton in QGP ---

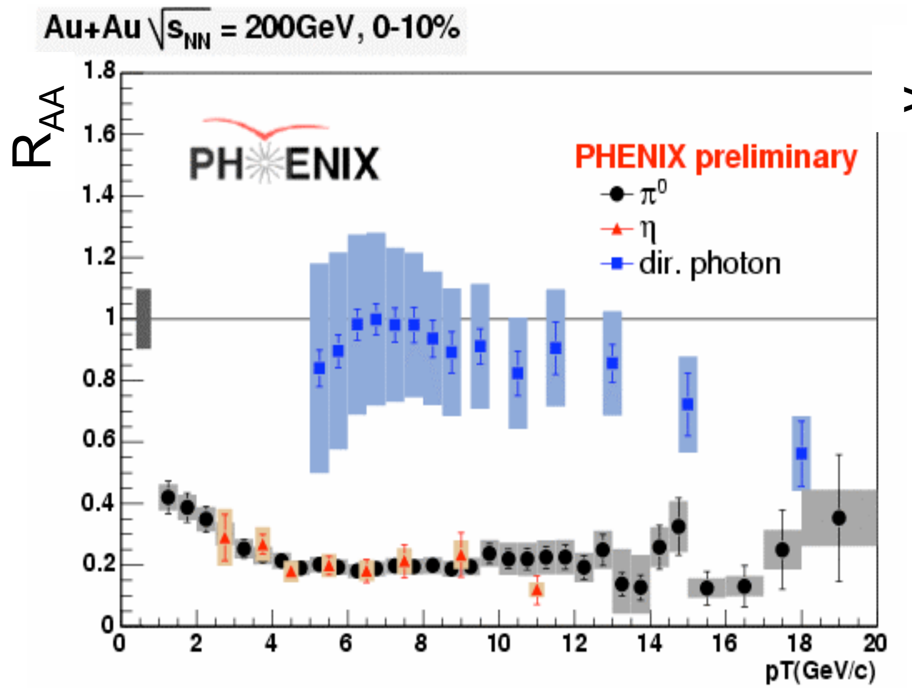
--- difference between hadron and direct photon ---

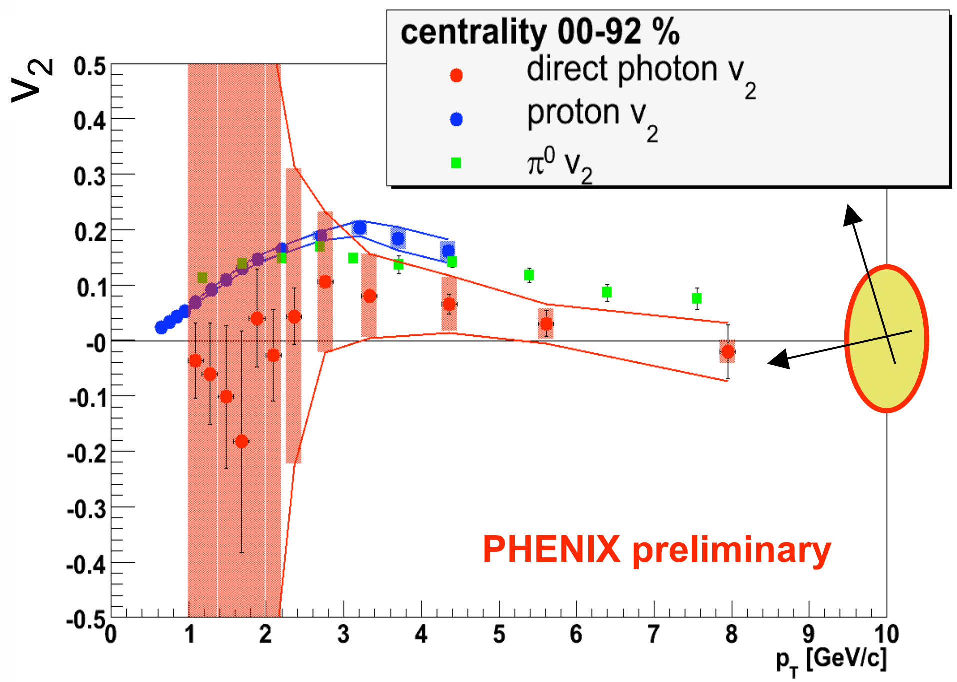
No energy loss for γ's

$$R_{AA} = \frac{\mathrm{Yield}_{AA} / \langle N_{binary} \rangle_{AA}}{\mathrm{Yield}_{pp}}$$

Energy loss for quark and gluon jets (similar even for heavy quark)



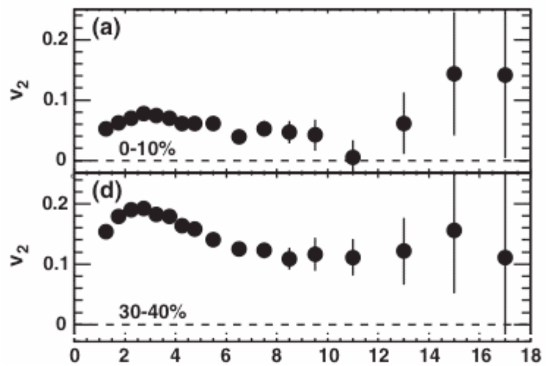


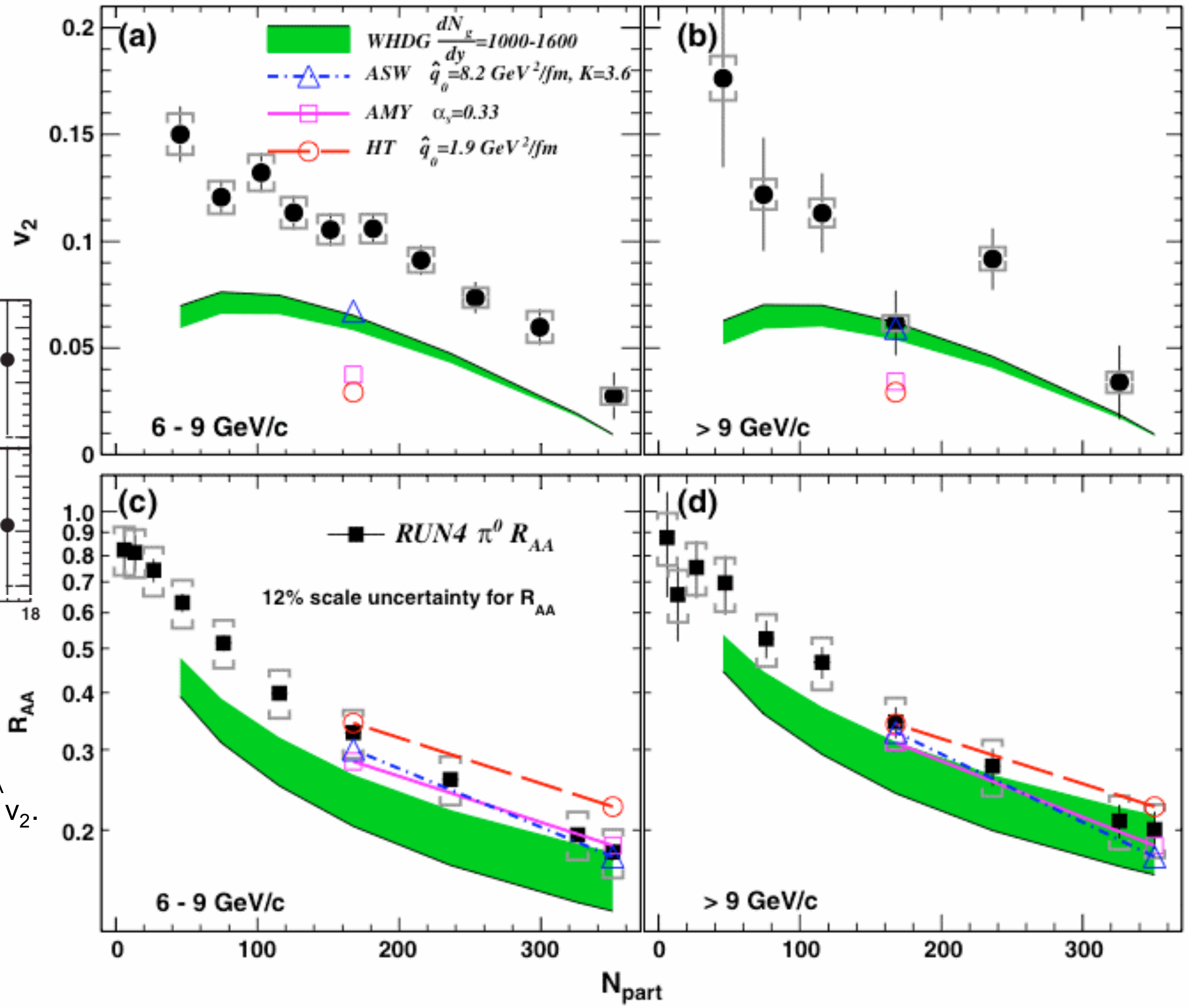


Understanding of high p_T π^0 v_2 and R_{AA} simultaneously

--- assumption of a common origin : energy loss ---

PRL105, 142301 (2010)

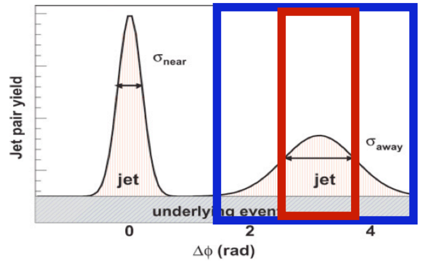




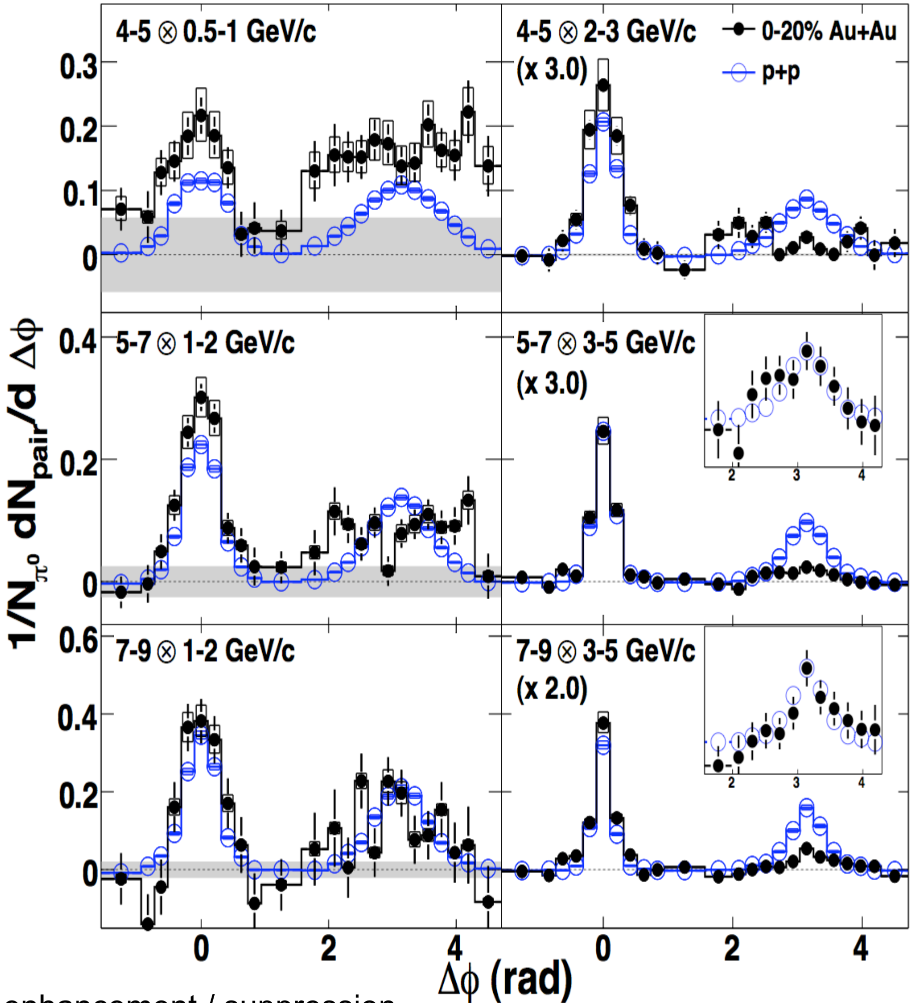
Models explaining measured R_{AA} do not usually explain measured v_2.

Two particle correlation (associate per trigger)

--- two different features at low/high p_T regions ---



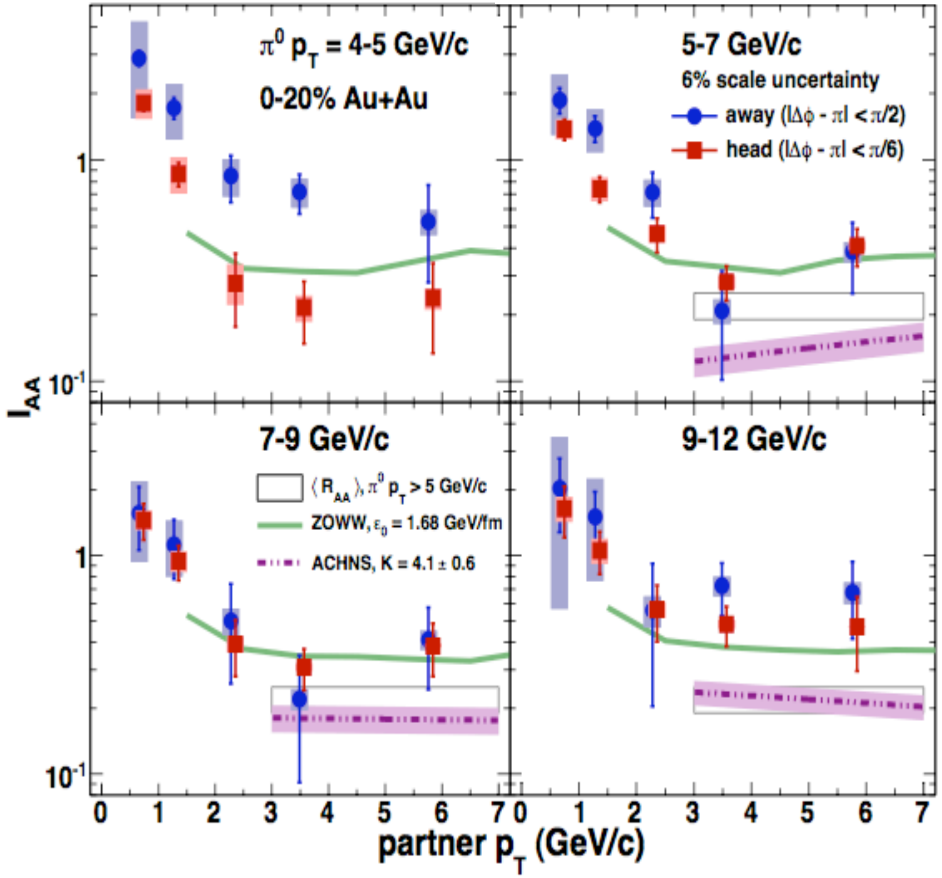
PRL104, 252301 (2010), arXiv:1002.1077



enhancement / suppression
broadening / un-modified shape

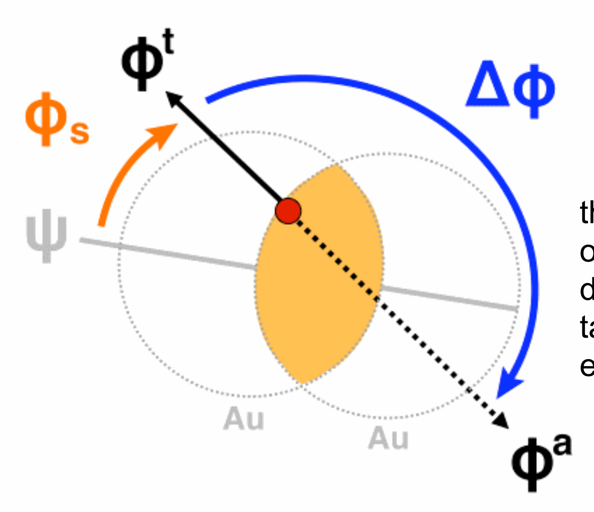
$$I_{AA} = \frac{(N^{ta}/N^{t})_{Au+Au}}{(N^{ta}/N^{t})_{p+p}}$$

I_{AA} is slightly higher than R_{AA}
less suppressed than singles
surface/tangential bias?

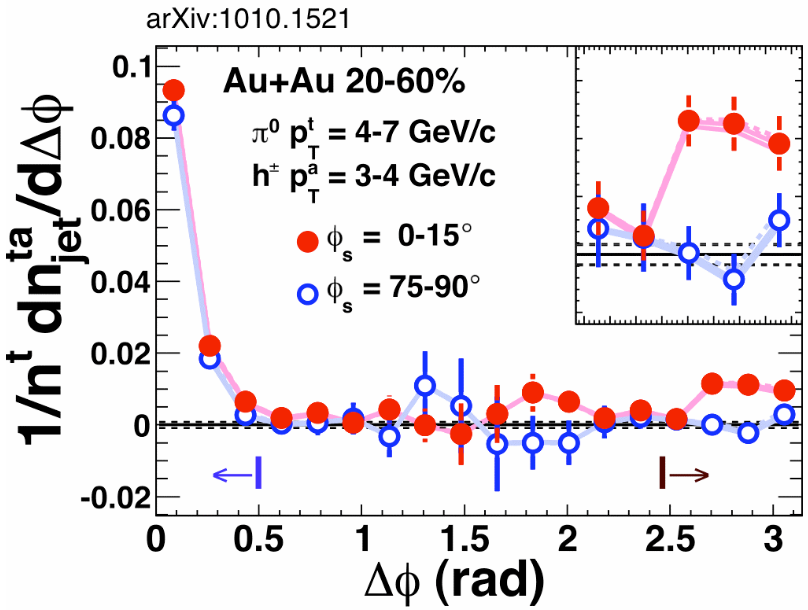


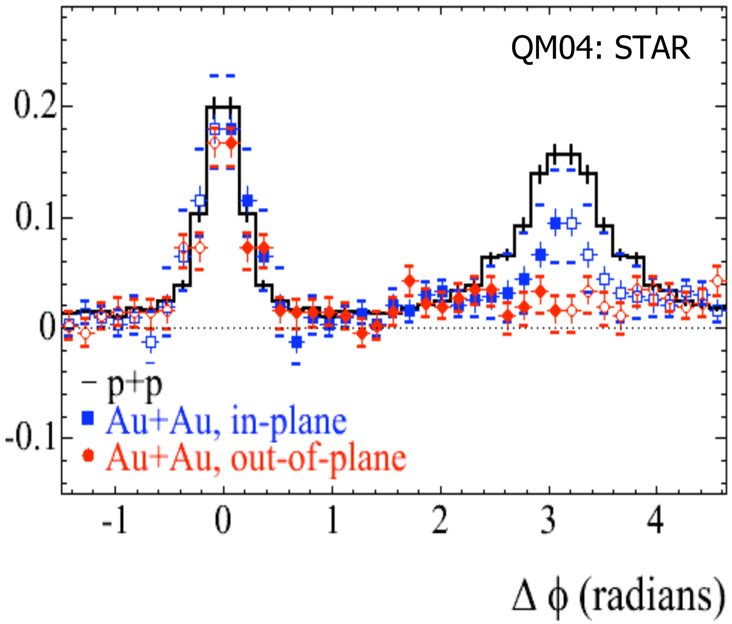
Reaction plane (path length) dependent energy loss

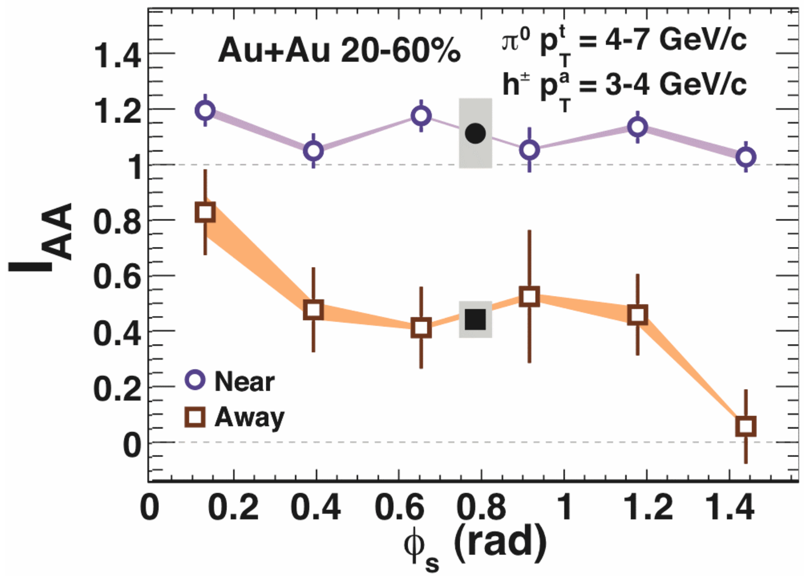
--- one of dominant sources of v_2 at high p_T ---



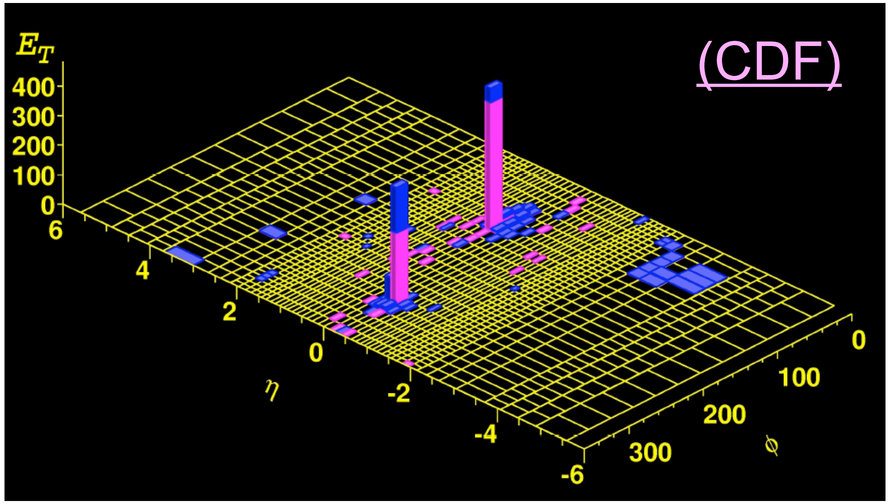
thickness dependence of penetration is more dominant than tangential surface emission.

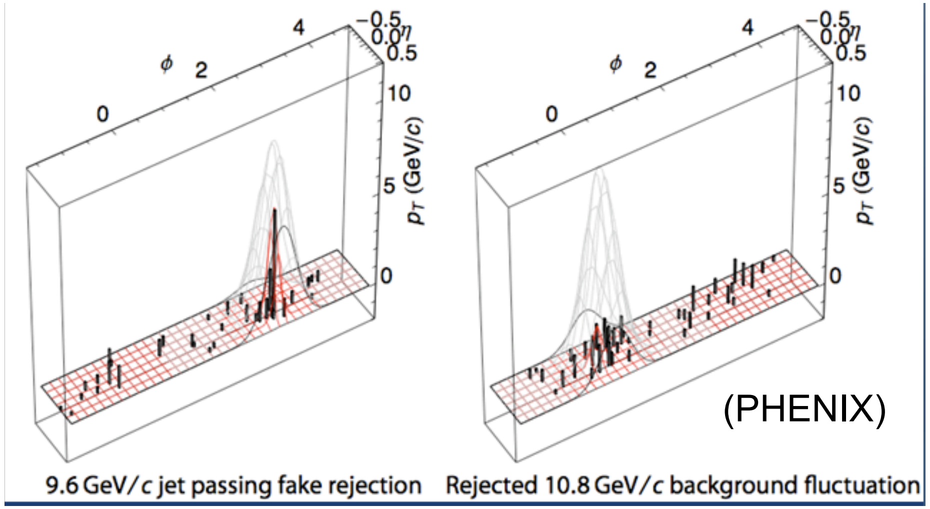






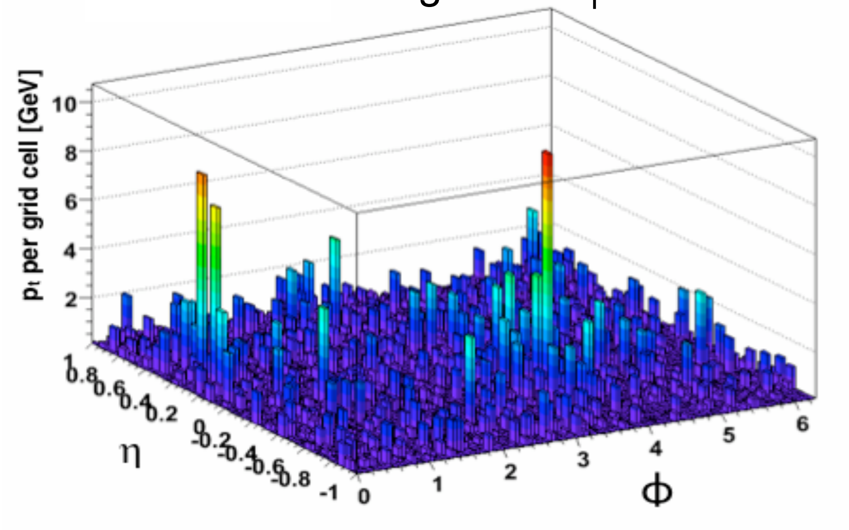
J. Harris, hard probe 2010





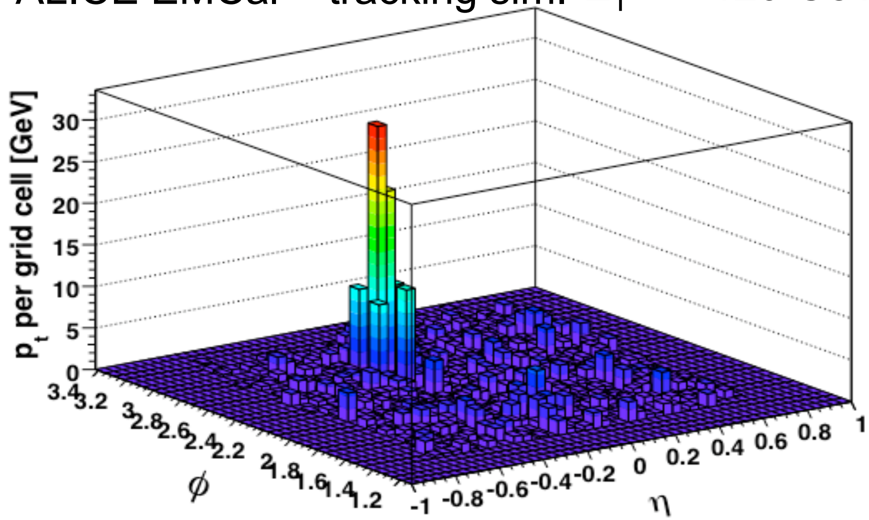
Central Au+Au $\sqrt{s_{NN}}$=200 GeV

STAR EMC + tracking data E_T^{jet} ~ 21 GeV



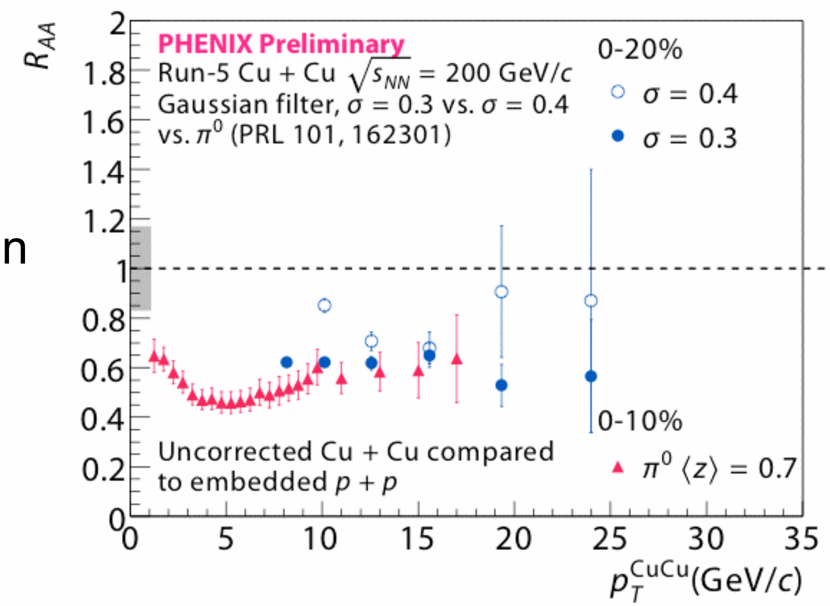
Central Pb+Pb $\sqrt{s_{NN}}$=5.5 TeV

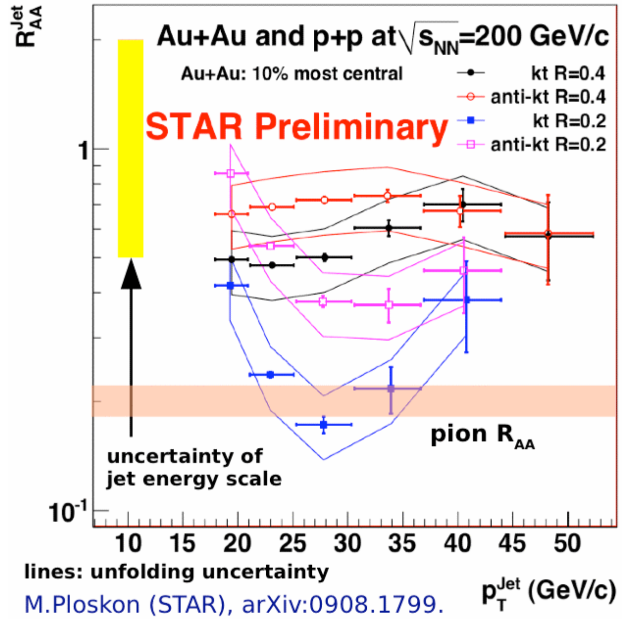
ALICE EMCal + tracking sim. E_T^{jet} ~ 120 GeV



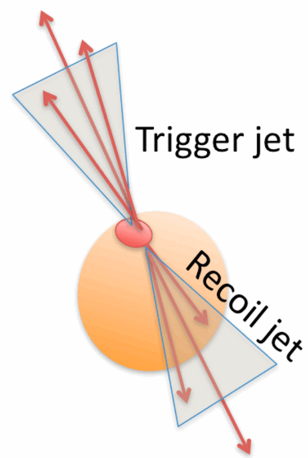
Hard Probe 2010, Yue Shi Lai

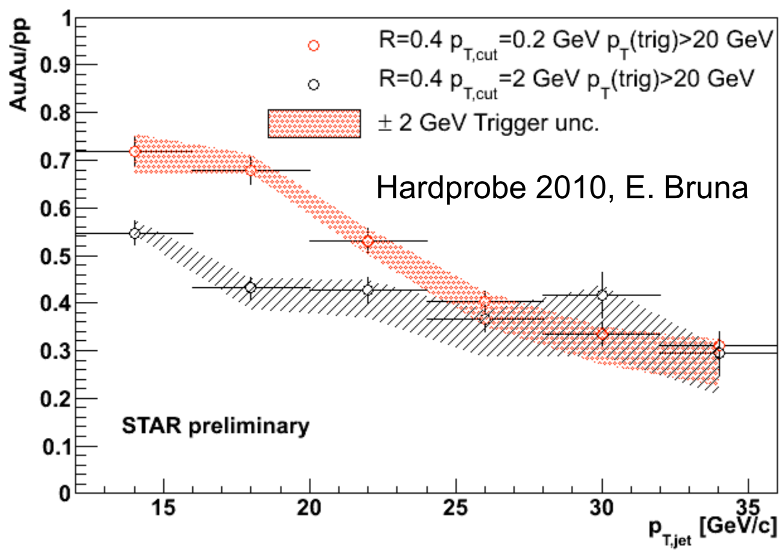
single-jet suppression





di-jet suppression





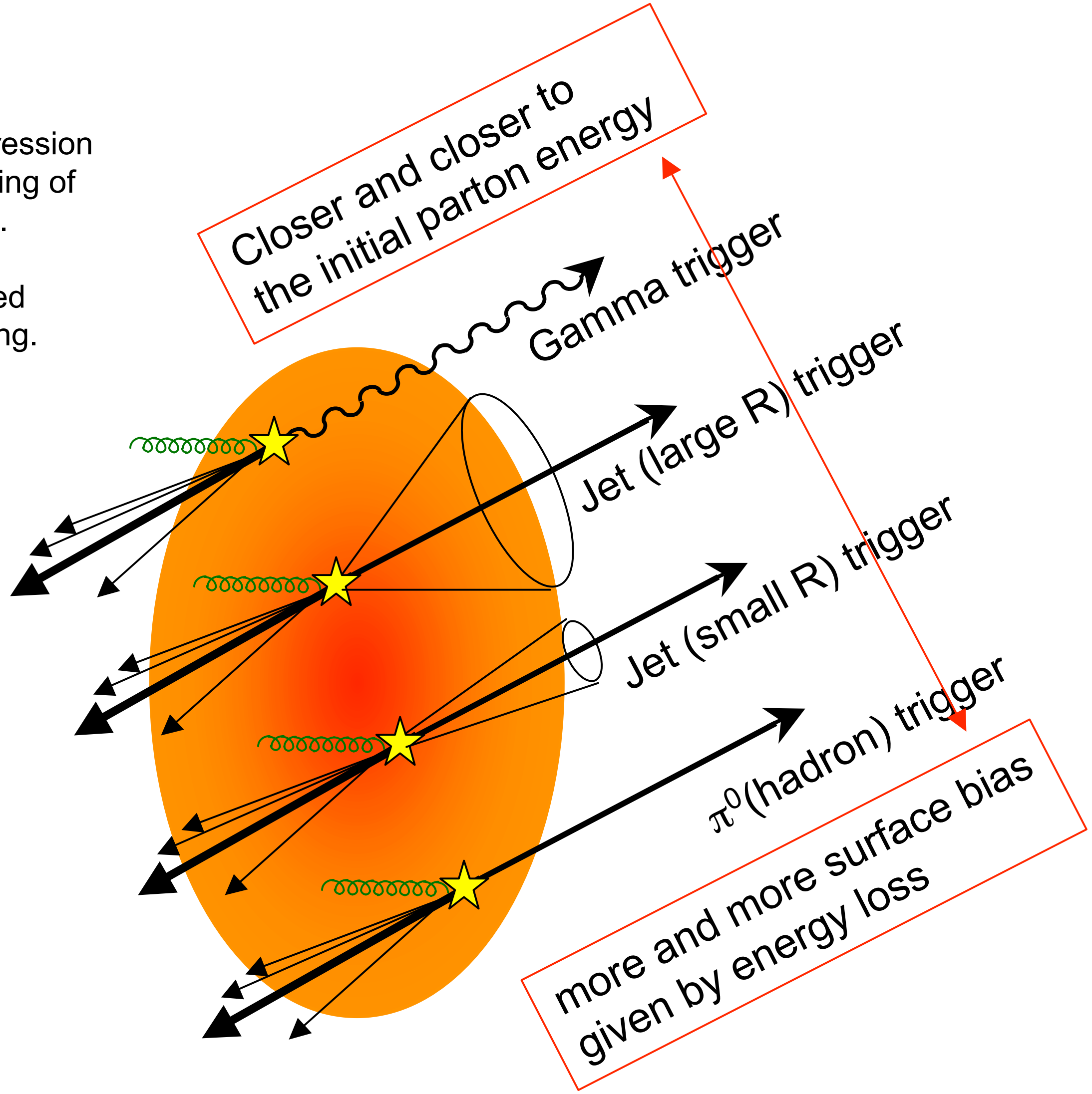
Recoil Jet: R=0.4, $p_{T,cut}$=2 GeV/c vs $p_{T,cut}$=0.2 GeV/c
Trigger Jet: $p_{T,cut}$=2 GeV/c, p_T(trig)>20 GeV/c

γ,Jet,π^0 - hadron correlation

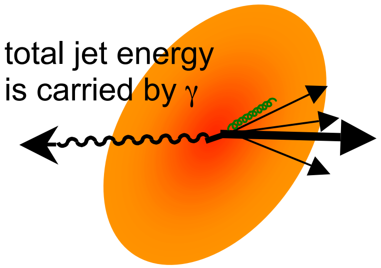
--- Comparisons are the most important! ---

cone size dependent jet suppression can be understood by recovering of energy loss with a larger cone.

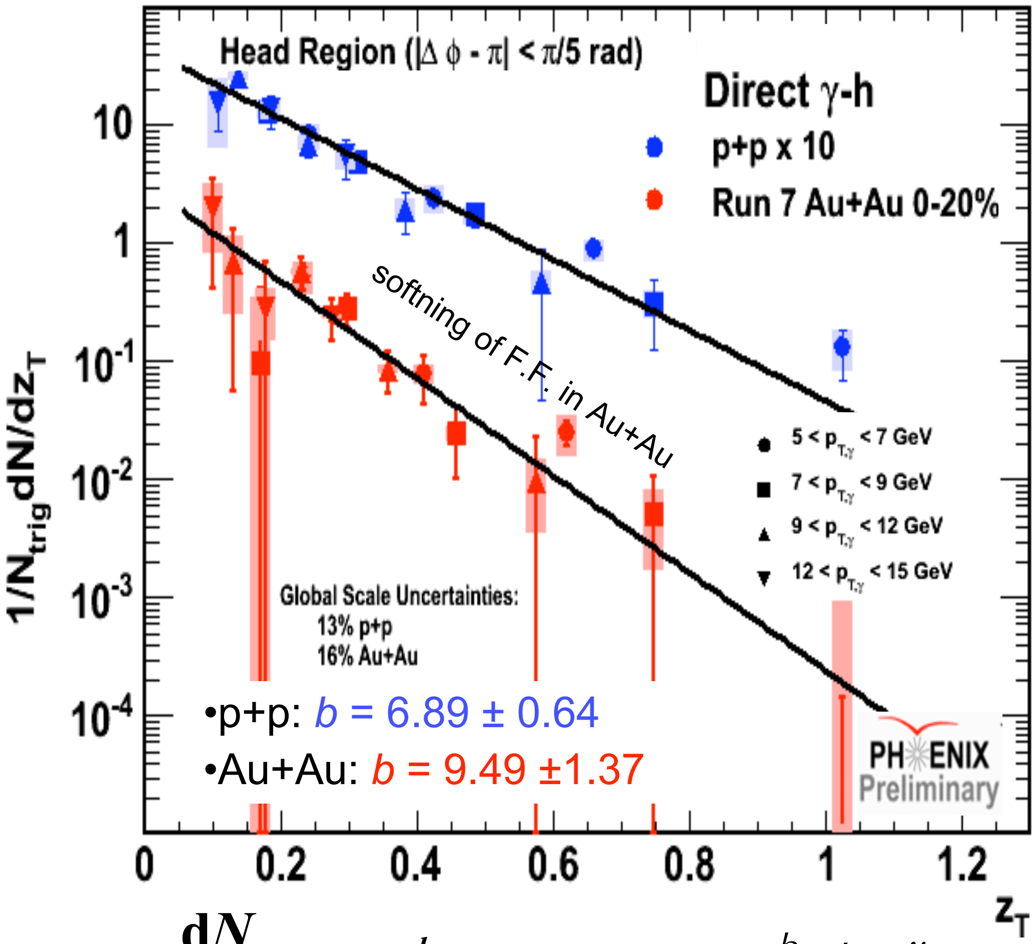
can be used to give a controlled bias in analysis and in triggering.



γ-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au



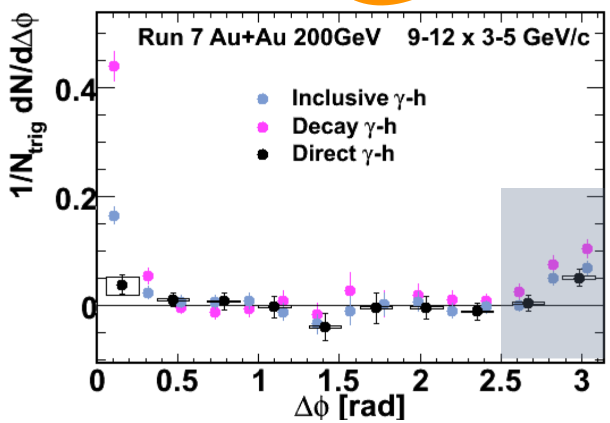
QM09 PHENIX

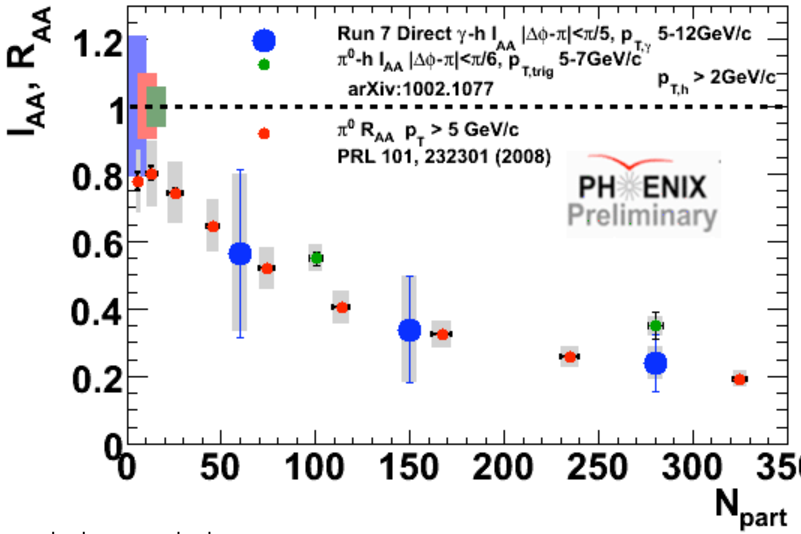


•p+p: b = 6.89 ± 0.64

•Au+Au: b = 9.49 ±1.37

$$\frac{dN}{dz_T} = Ne^{-bz_T} \qquad z_T = p_T^h / p_T^\gamma$$



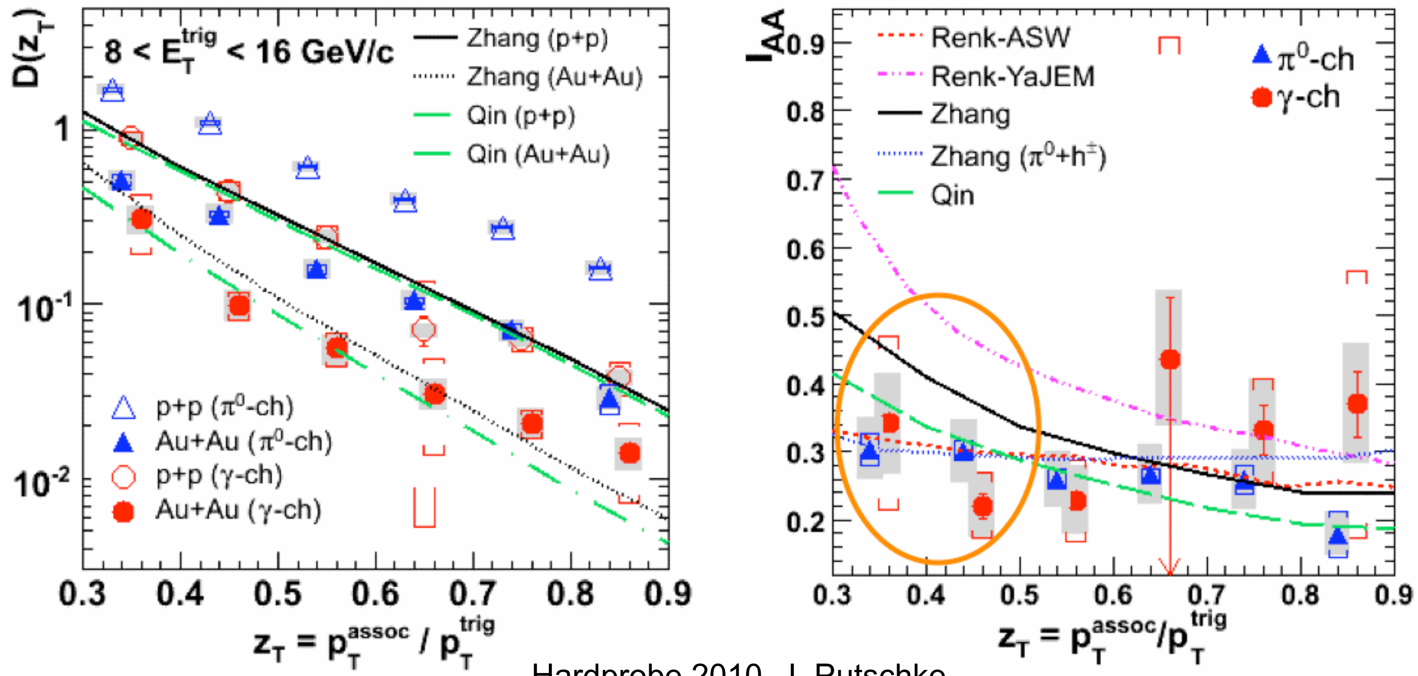


$I_{AA}^{\gamma\text{-had}} \sim R_{AA}^{had}$ is naively expected and confirmed.

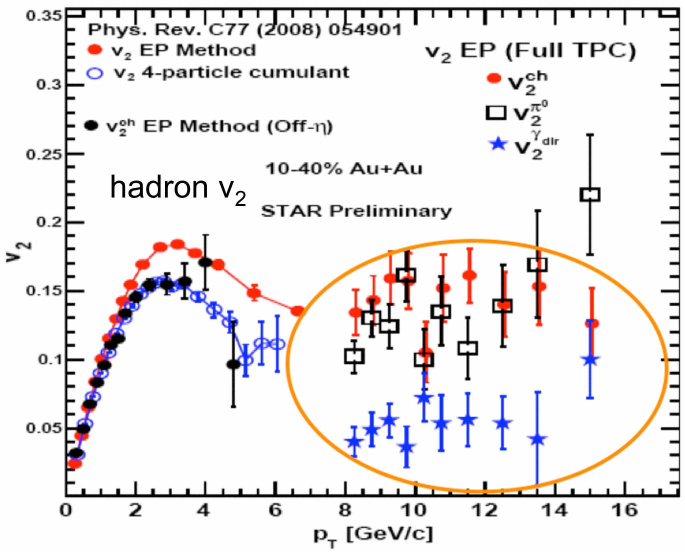
Slightly higher $I_{AA}^{\pi 0\text{-had}}$ from surface/tangential bias.

STAR, Phys. Rev. C 82 (2010) 34909

Direct photons from STAR experiment



Hardprobe 2010, J. Putschke

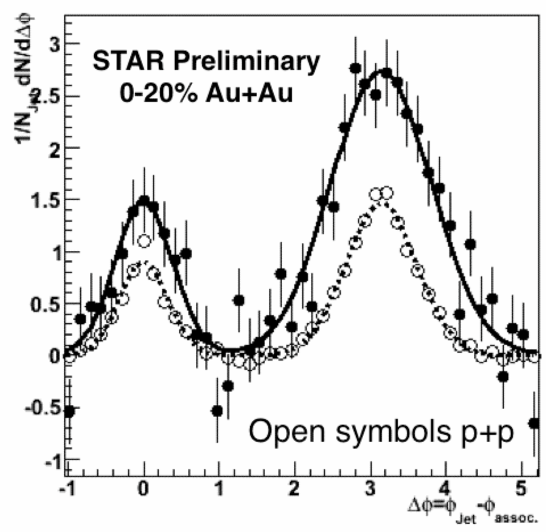


Jet - hadron correlation

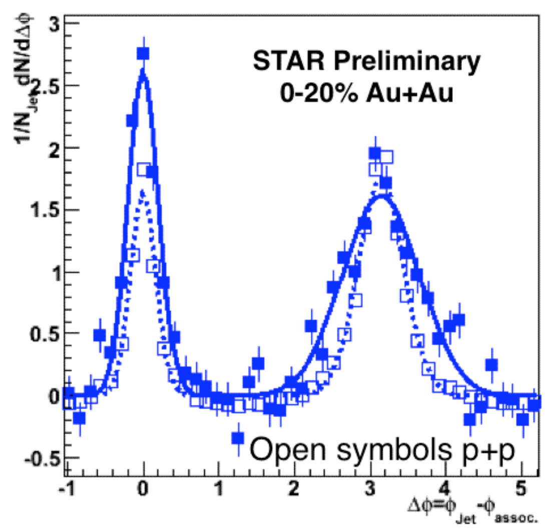
High Tower Trigger (HT) : $(\eta x \phi)=(0.05x0.05)$ $E_T>5.4GeV$

RHIC-AGS'09, J. Putschke

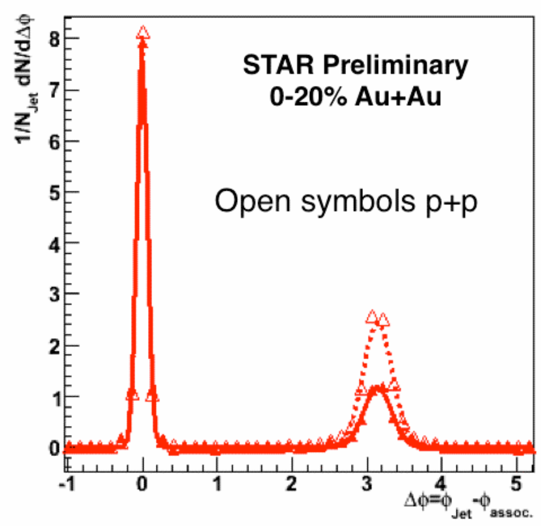
$0.2<p_{t,assoc}<1.0$ GeV

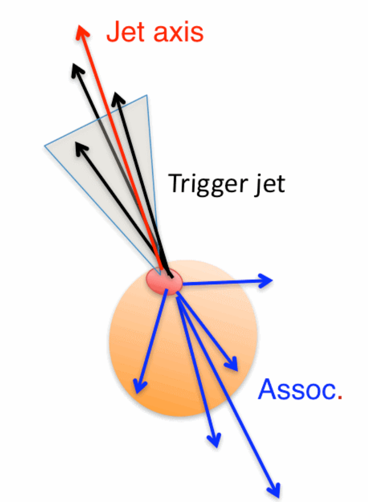


$1.0<p_{t,assoc}<2.5$ GeV

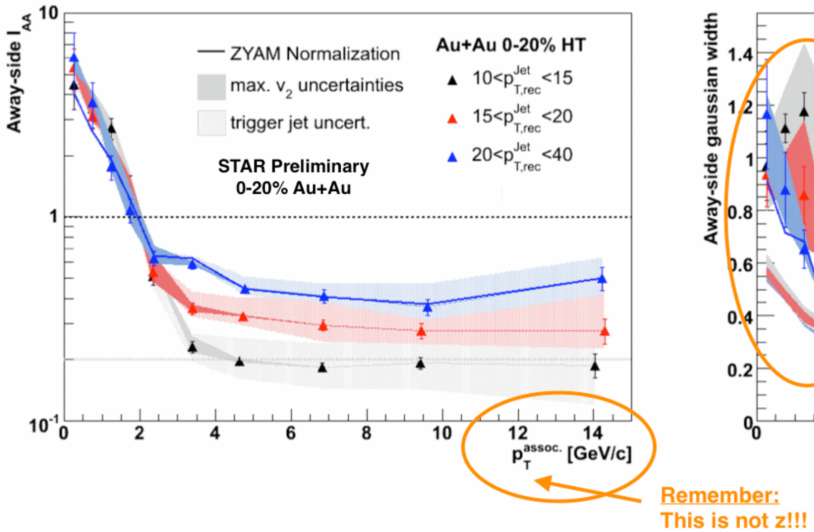


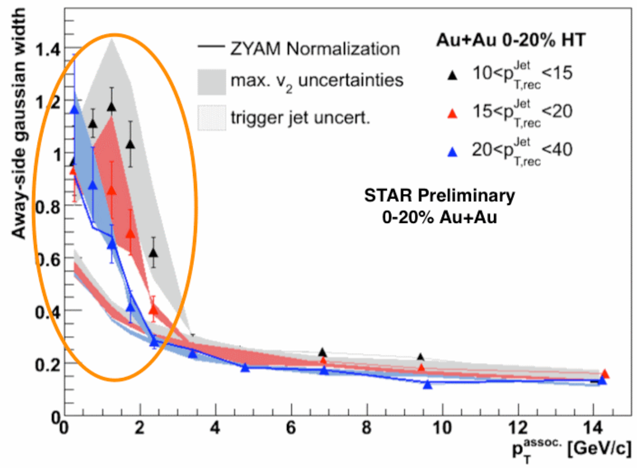
$p_{t,assoc}>2.5$ GeV



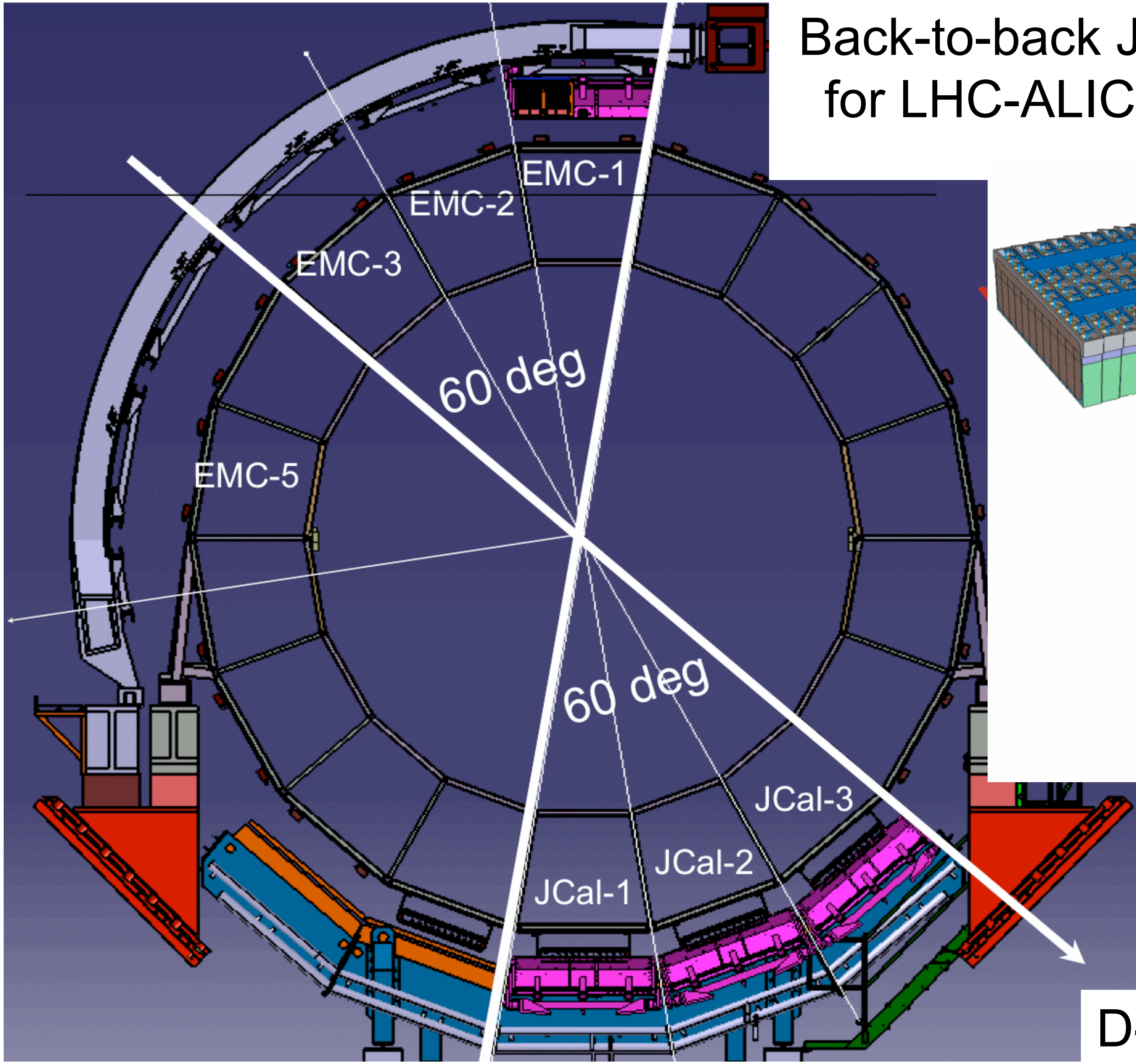


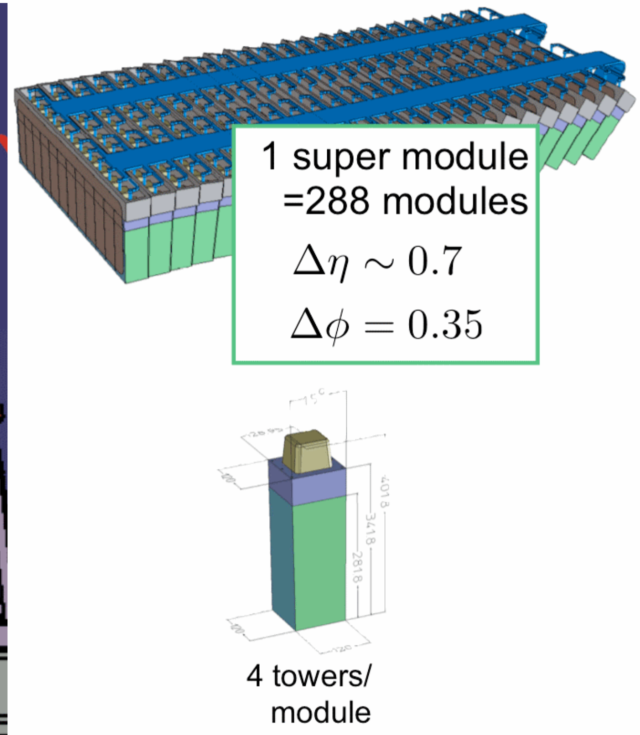
Hardprobe 2010, J. Putschke





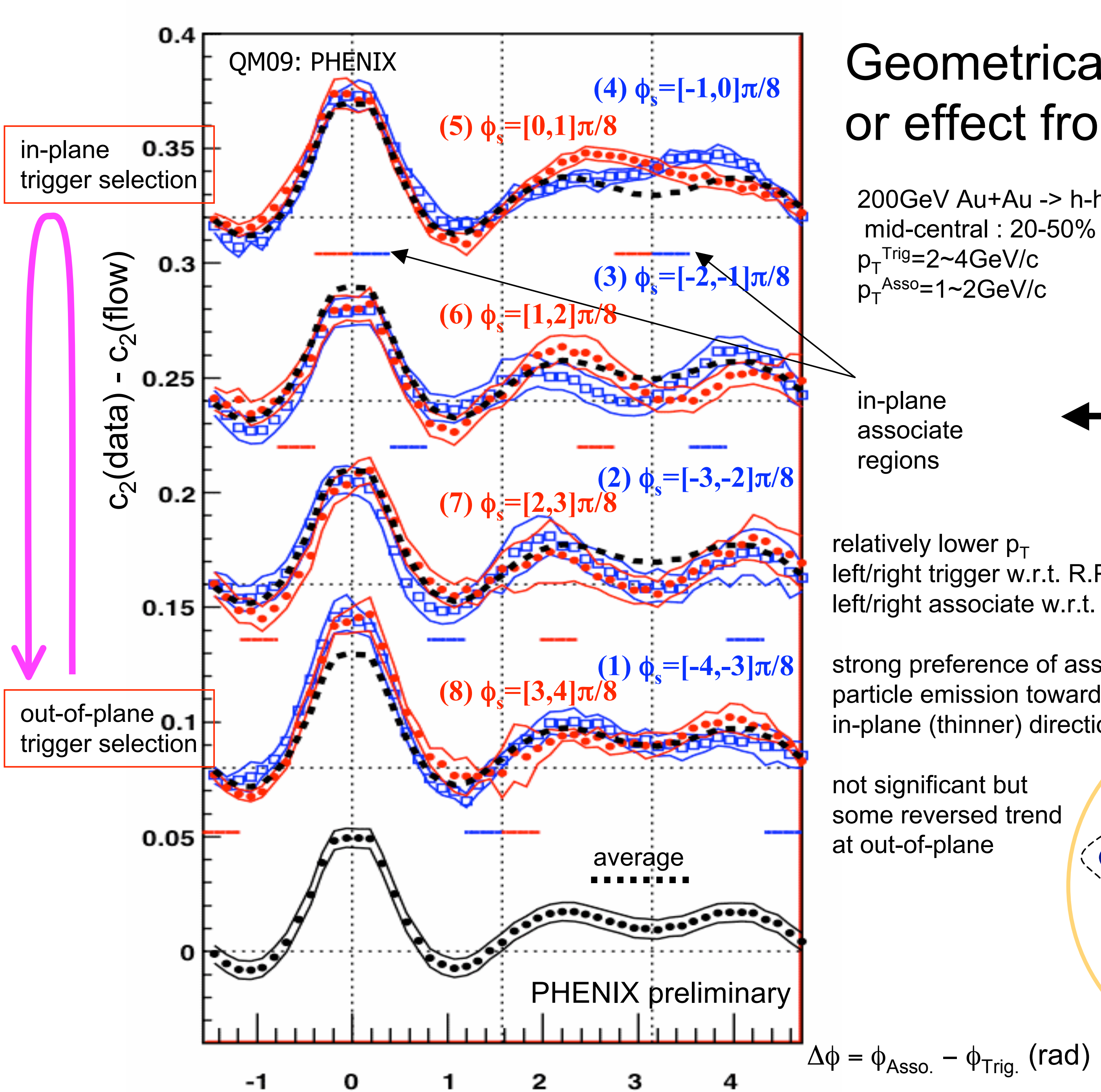
Back-to-back Jet Calorimeter for LHC-ALICE experiment





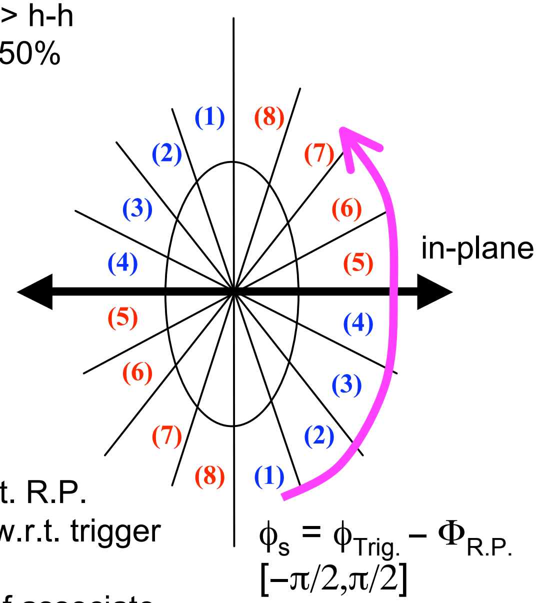
D-CAL upgrade

Geometrical dependence or effect from expansion?



200GeV Au+Au -> h-h
mid-central : 20-50%
p_T^{Trig}=2~4GeV/c
p_T^{Asso}=1~2GeV/c

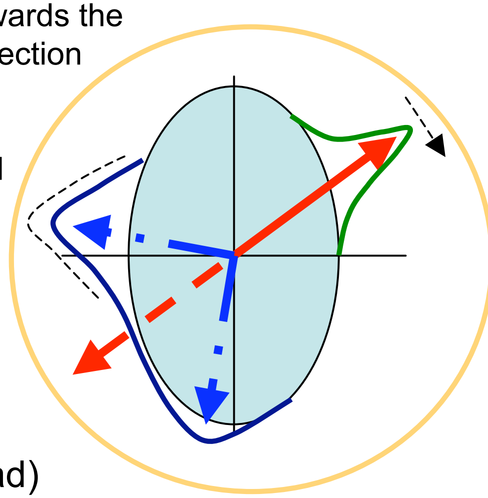
in-plane
associate
regions



relatively lower p_T
left/right trigger w.r.t. R.P.
left/right associate w.r.t. trigger

strong preference of associate particle emission towards the in-plane (thinner) direction

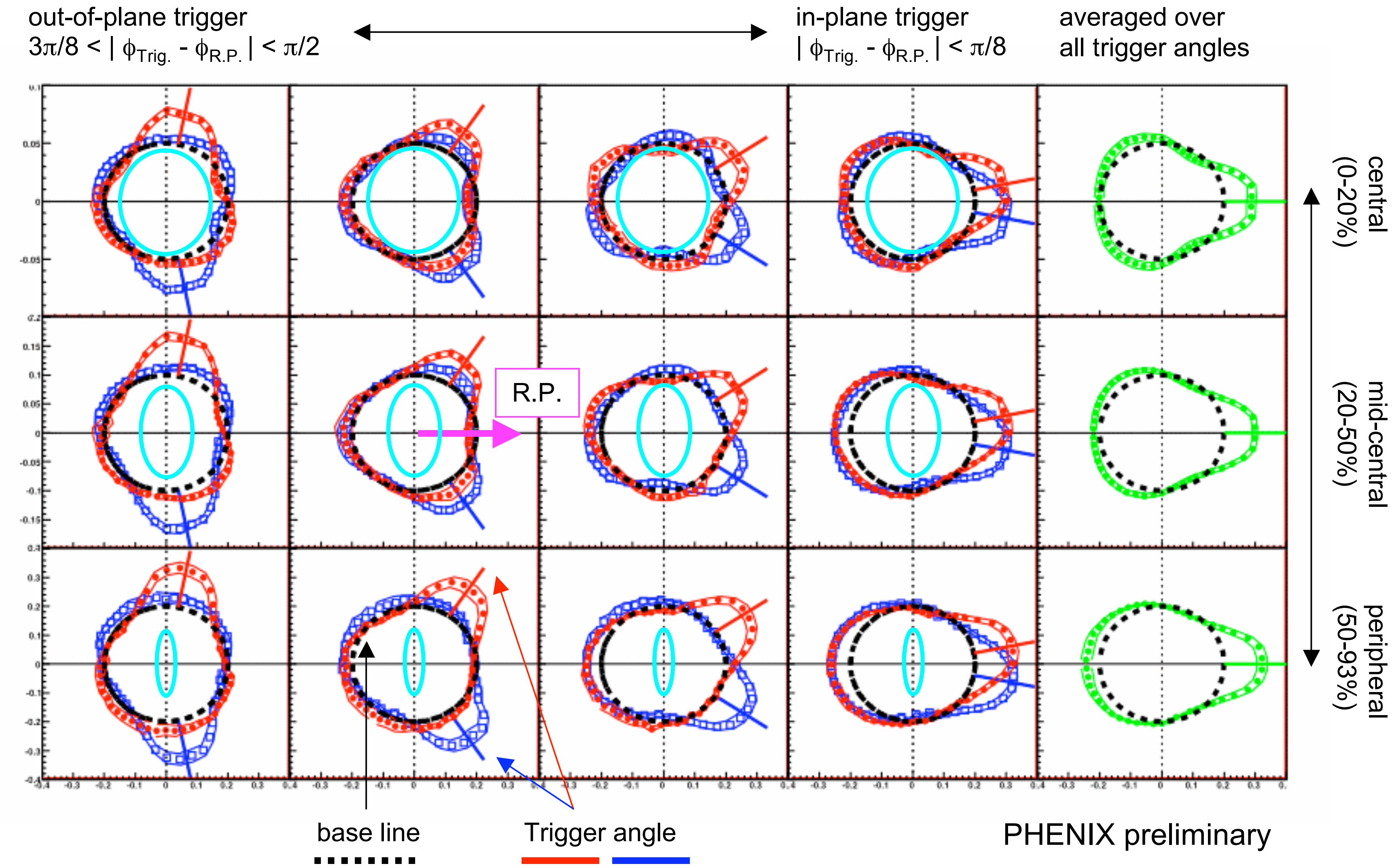
not significant but some reversed trend at out-of-plane



the same data in polar plots (R.P. is x axis)

--- associate distribution for a given trigger direction ---

200GeV Au+Au -> h-h
(p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)

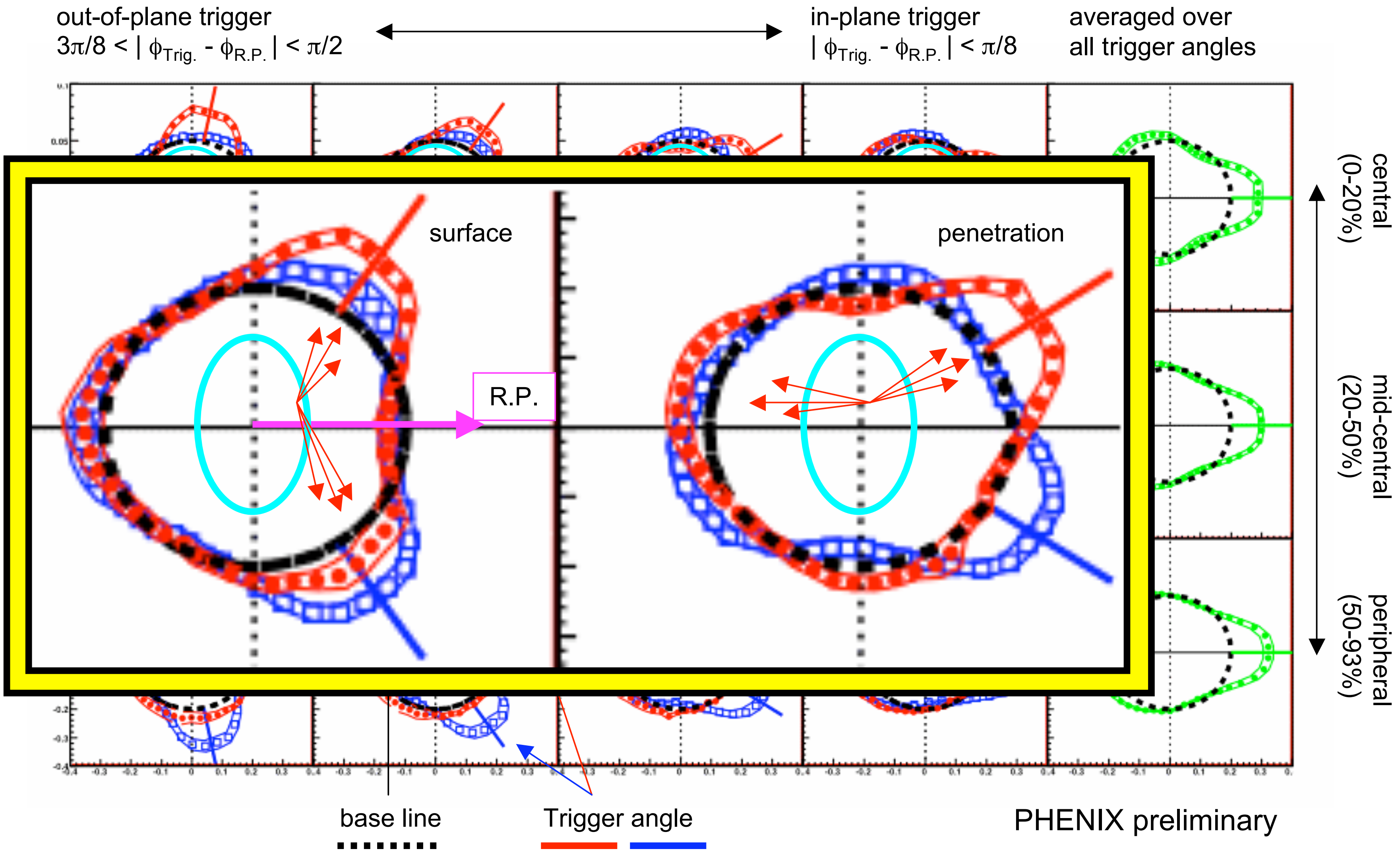


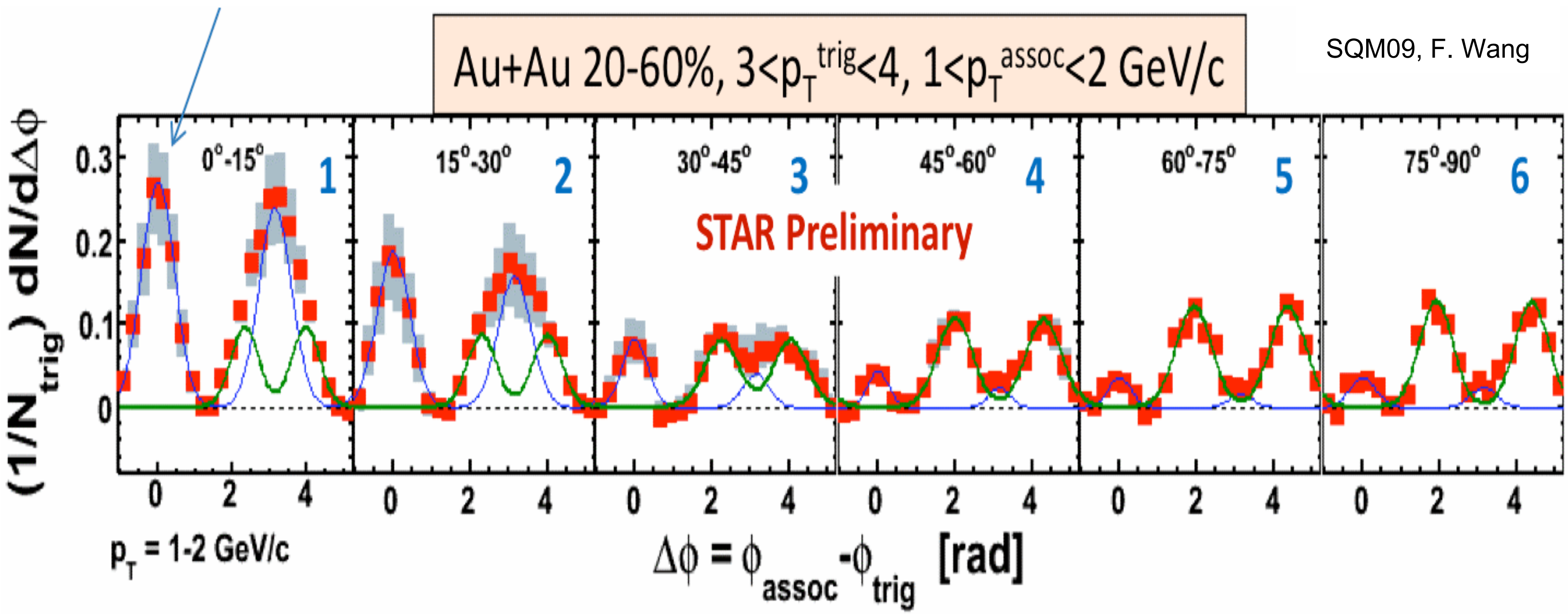
PHENIX preliminary

the same data in polar plots (R.P. is x axis)

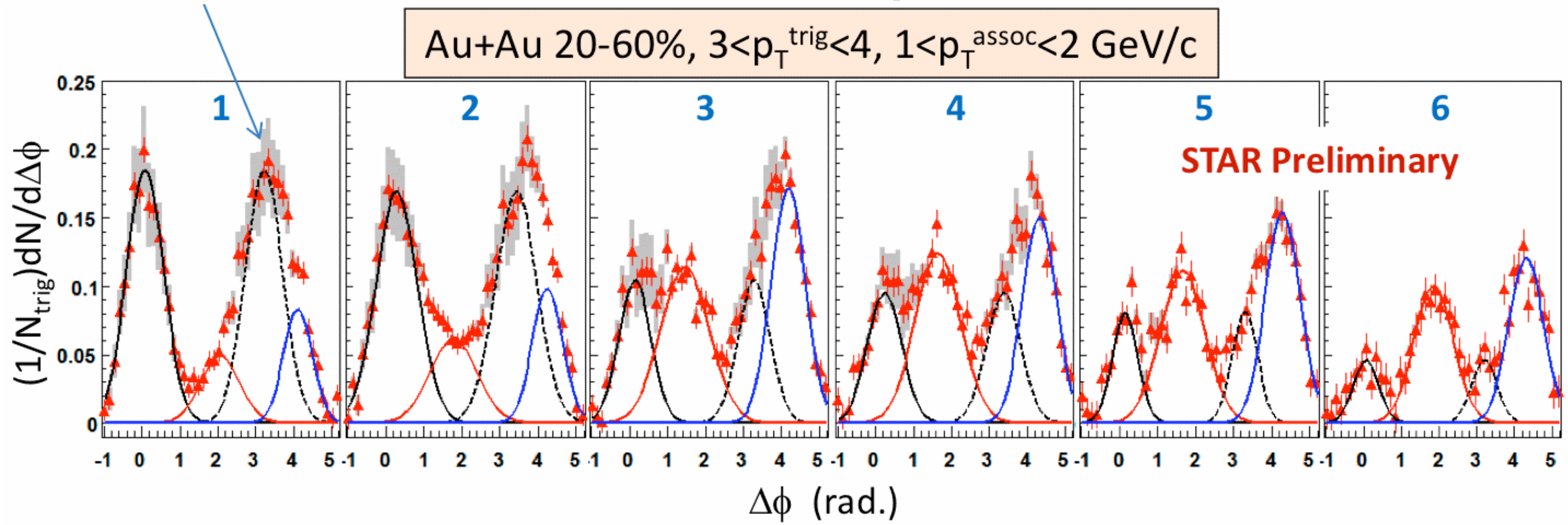
--- associate distribution for a given trigger direction ---

200GeV Au+Au -> h-h
(p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)





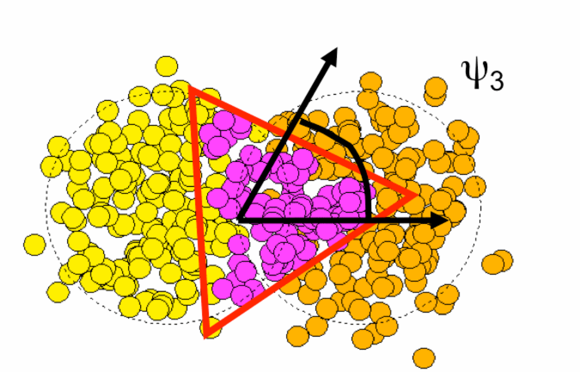
Au+Au 20-60%, 3<p_T^trig<4, 1<p_T^assoc<2 GeV/c
SQM09, F. Wang
0°-15° 1
15°-30° 2
30°-45° 3
45°-60° 4
60°-75° 5
75°-90° 6
STAR Preliminary
(1/N_trig) dN/dΔφ
p_T = 1-2 GeV/c
Δφ = φ_assoc - φ_trig [rad]



Au+Au 20-60%, 3<p_T^trig<4, 1<p_T^assoc<2 GeV/c
1
2
3
4
5
6
STAR Preliminary
(1/N_trig)dN/dΔφ
Δφ (rad.)

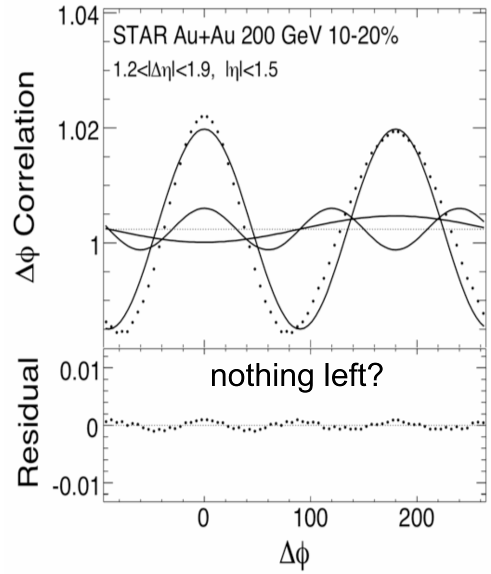
Burak Alver, GR, arXiv:1003.0194 (PRC 2010)

Participant Triangularity

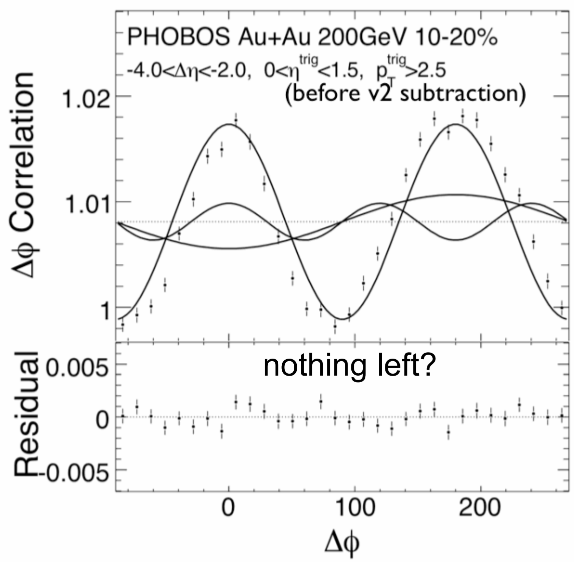


$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2\cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2\sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

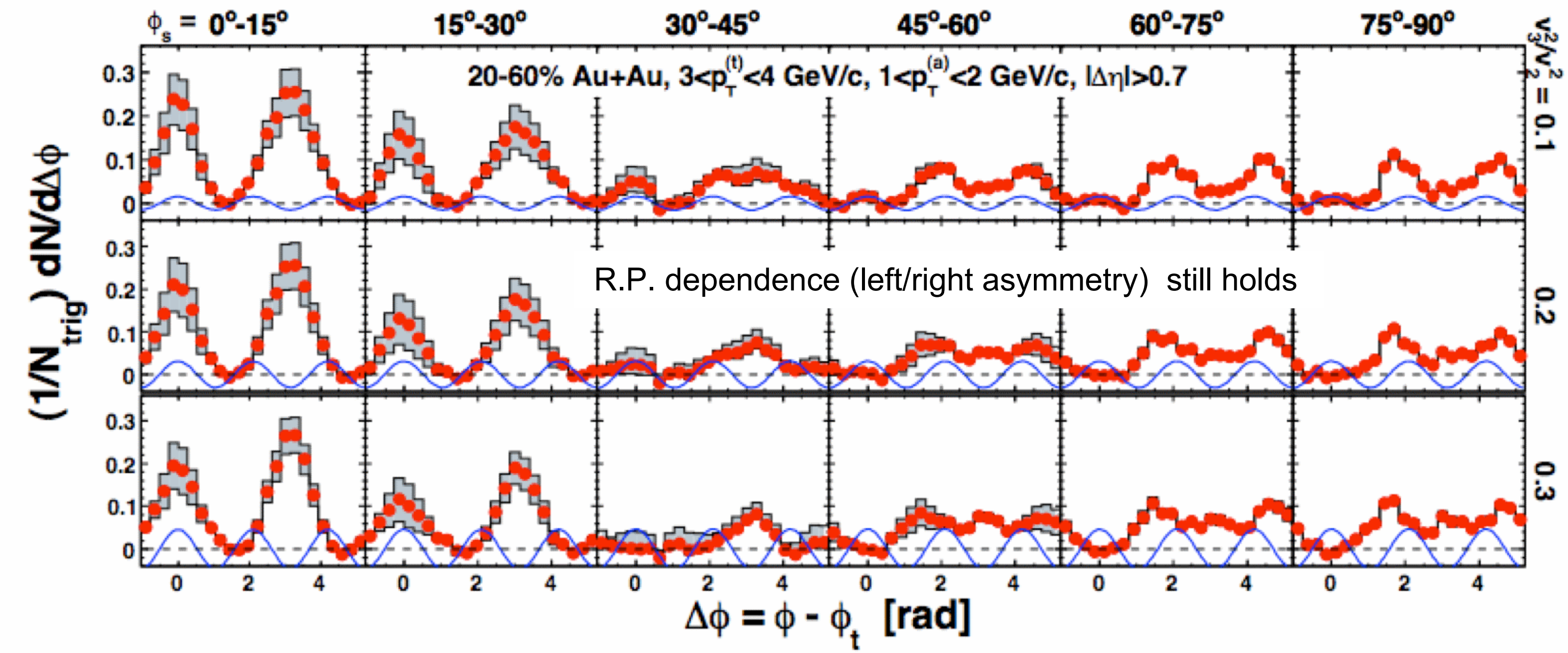
arXiv:0806.0513



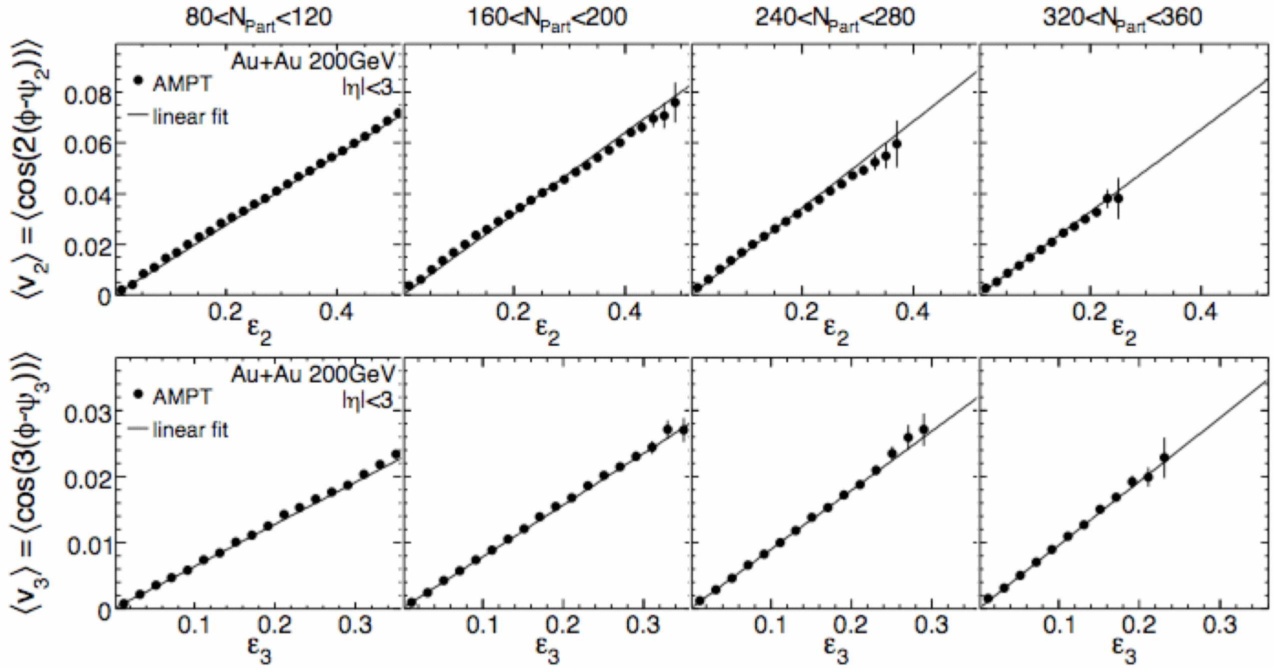
PRL 104, 06230 (2010)

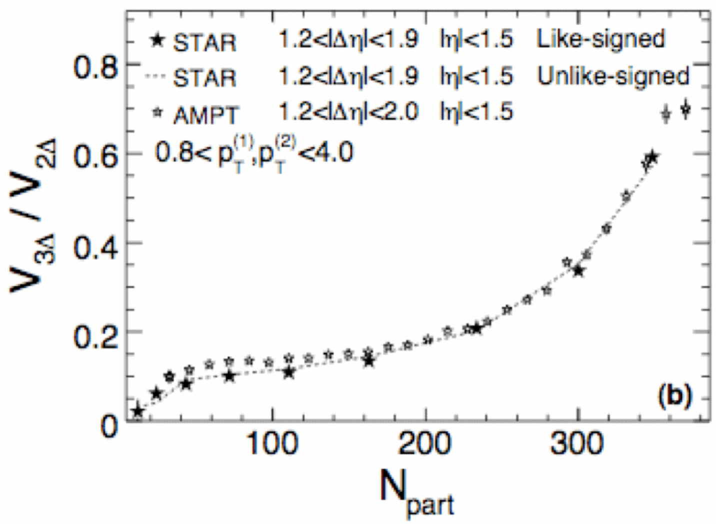


Hard Probe 2010, G. Roland



Burak Alver, GR, arXiv:1003.0194 (PRC 2010)



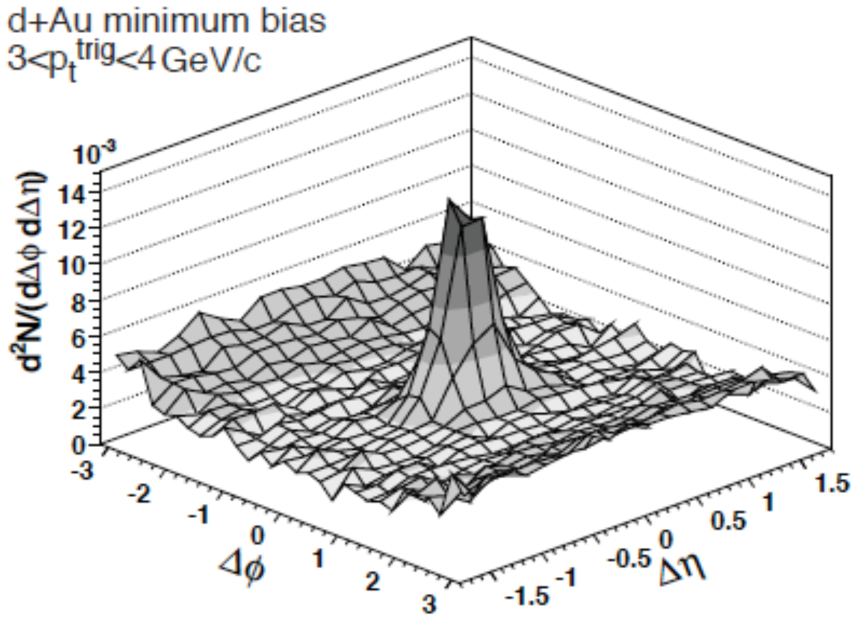


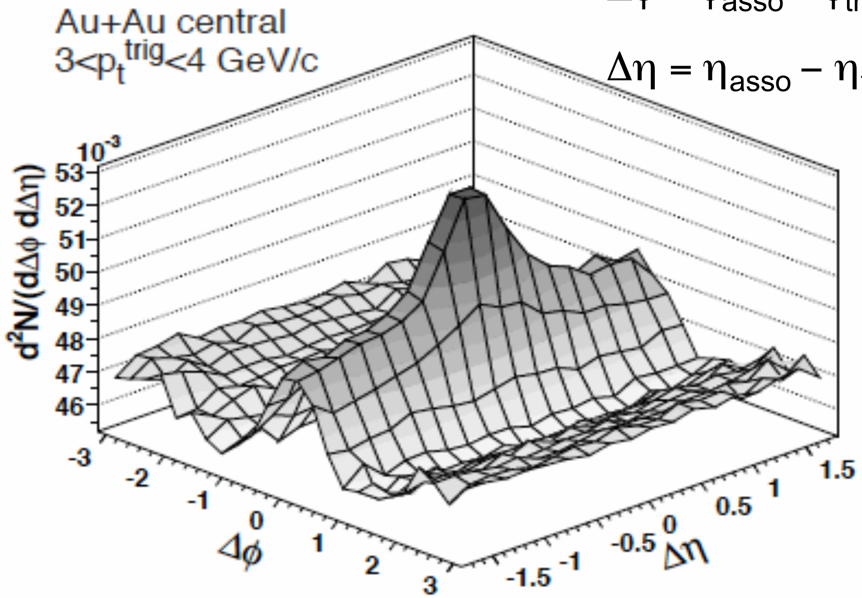
v_3 in AMPT reflects ε_3

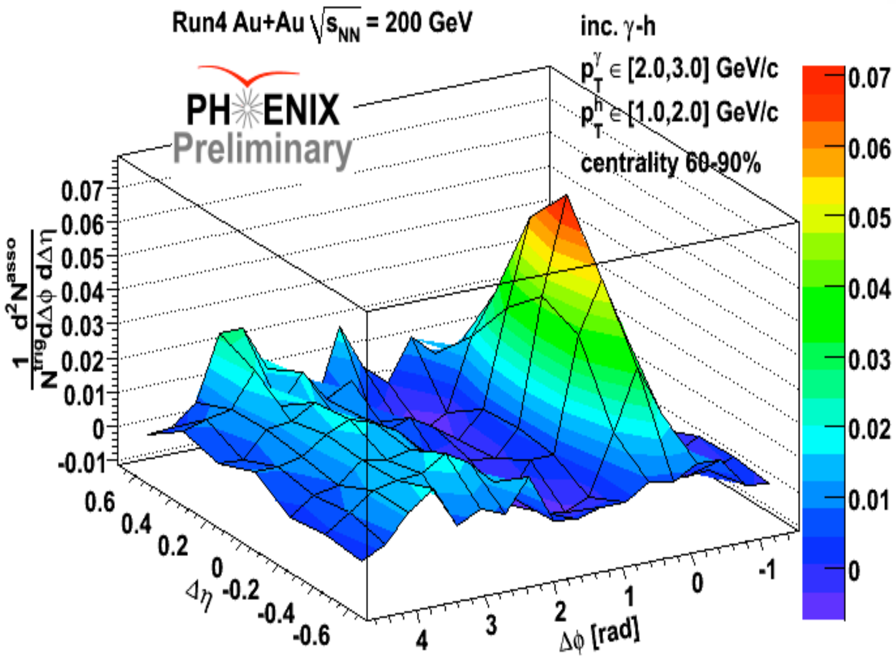
Provides extremely good description of v_3/v_2 vs centrality for p_T > 0.8 GeV data

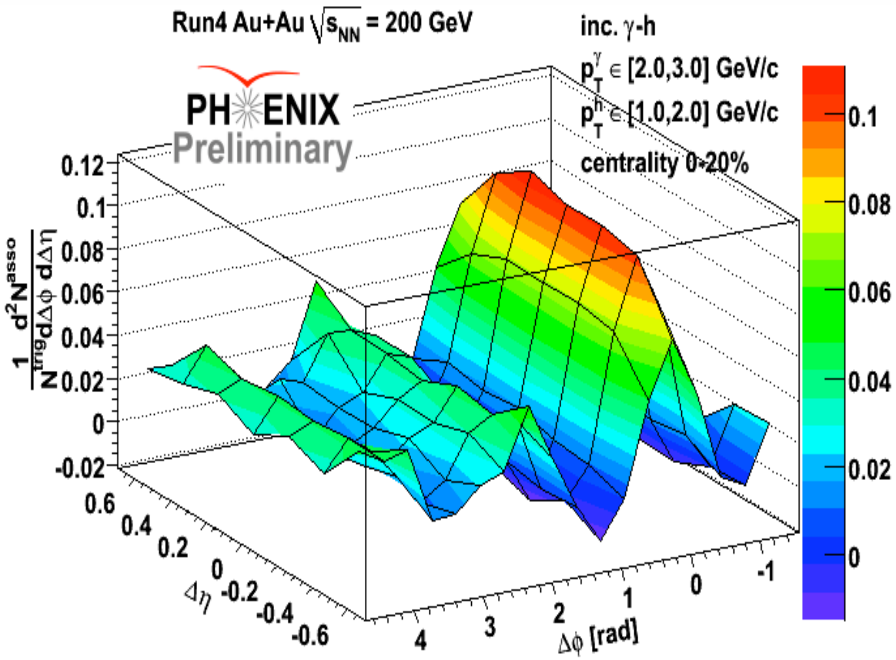
$$\Delta\phi = \phi_{asso} - \phi_{trig}$$

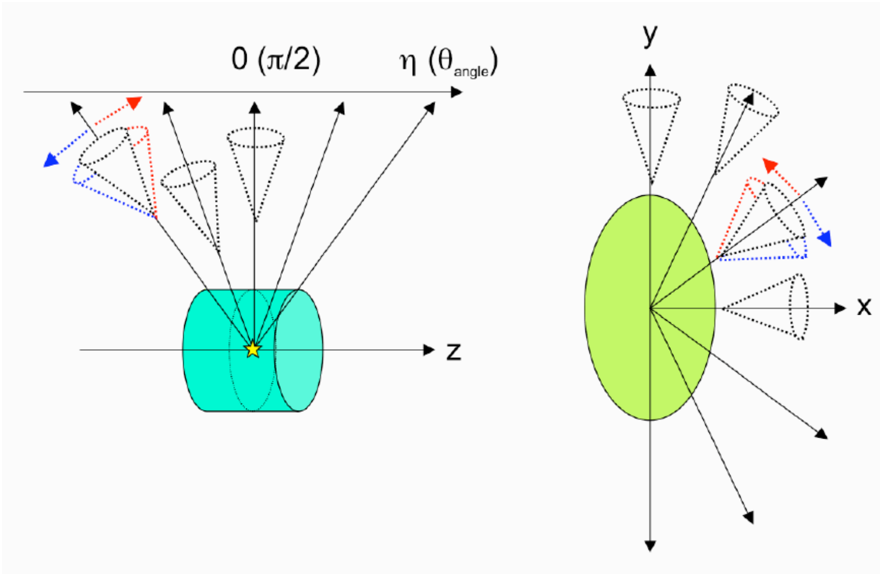
$$\Delta\eta = \eta_{asso} - \eta_{trig}$$





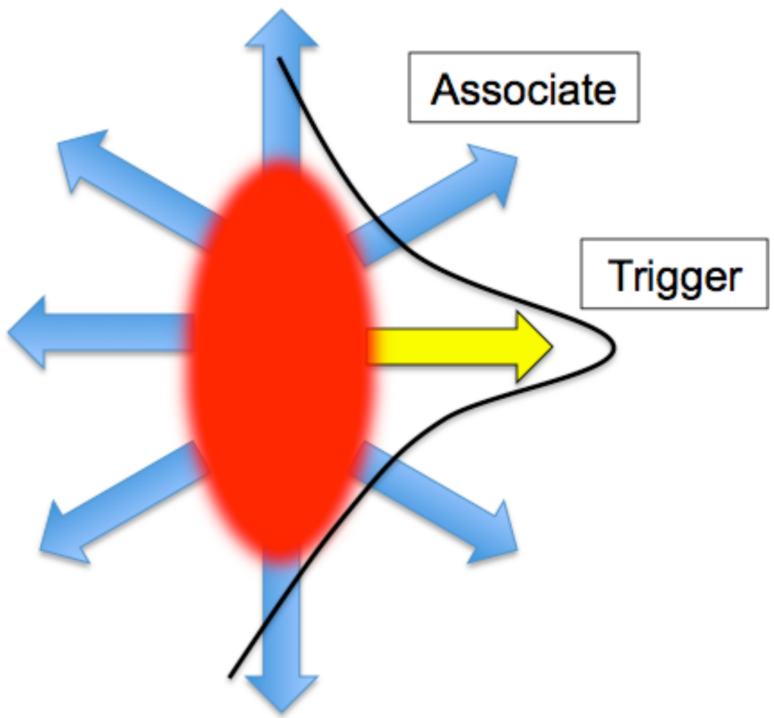




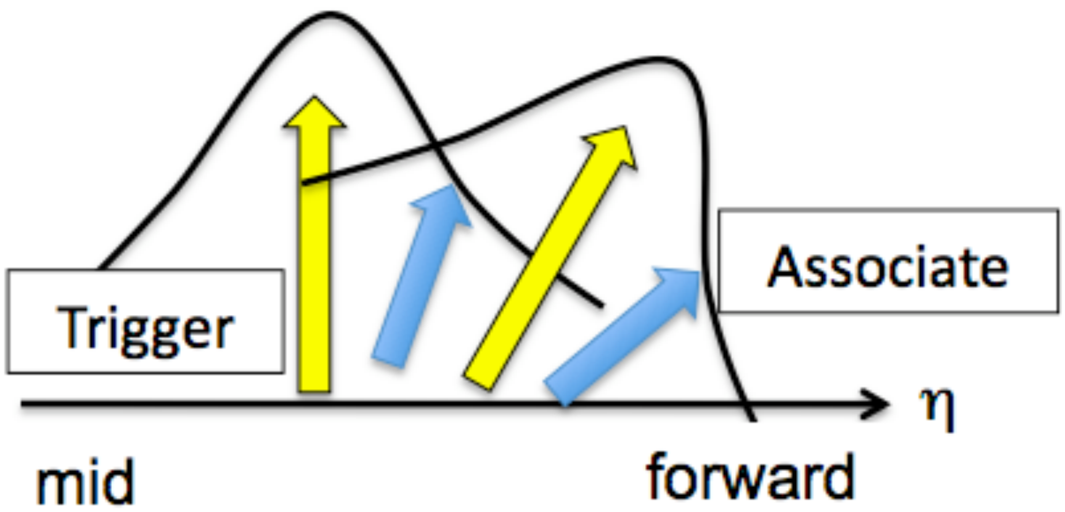


PHENIX data analysis is in progress by
Takahito Todoroki,
STAR data analysis is about to start…

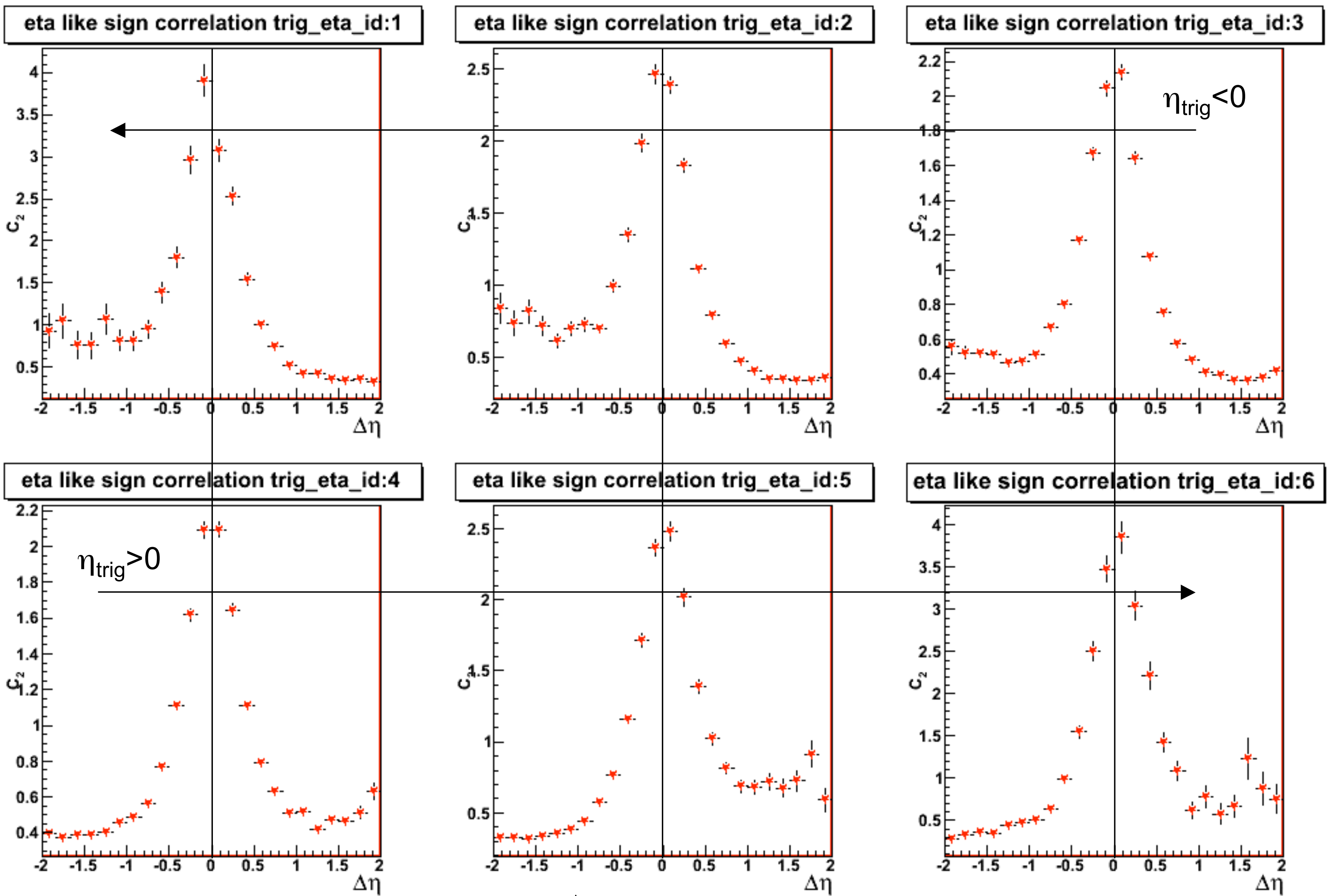
$$\Delta\phi = \phi_{asso} - \phi_{trig}$$



$$\Delta\eta = \eta_{asso} - \eta_{trig}$$

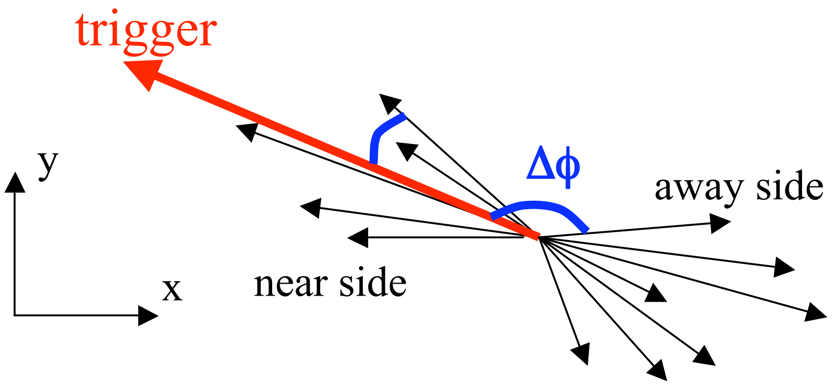


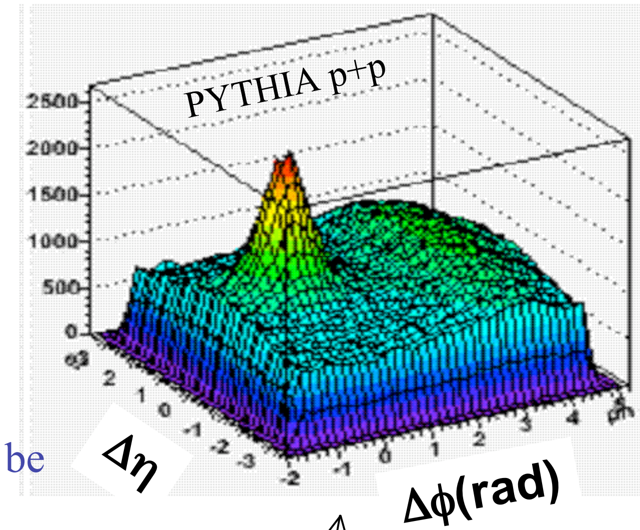
pythia8 : Ryo Funato



$\Delta\eta = \eta_{asso} - \eta_{trig}$

ATHIC2008
in Tsukuba,
S. Esumi





(1) away side of a back-to-back(b-t-b) jet is wider in η than in ϕ

(2) If there are two parallel b-t-b jets, away side of one b-t-b jet can be near side of the another b-t-b jet.

(3) Suppression as well as modification of b-t-b jet would depend on relative angle w.r.t. almond geometry, we know this from v_2 measurement and believe this is the major source of v_2 at high p_T .

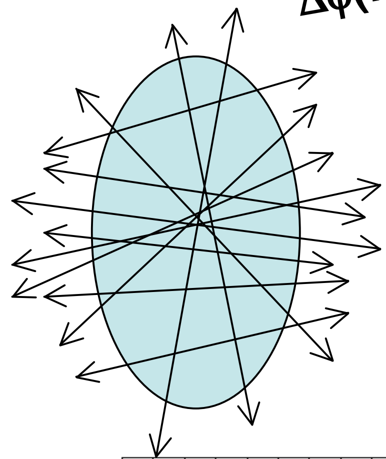
(4) Therefore, there should be inter b-t-b jets correlation give by the geometry from (3), this could make near side ridge like effect, especially if the effect (3) has shaper dependence than v_2(=cos2x).

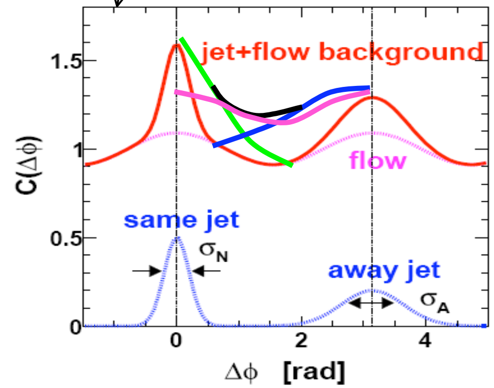
(5) We always measure inclusive v_2, which includes the effect (3). Therefore any modification which could generates the elliptic anisotropy would be included in the measured v_2 .

(6) We subtract BG contribution with this v_2 from (5) by maximizing BG contribution assuming zero jet yield at minimum at any dϕ.

(7) If near and away side jets overlap each other, this subtraction underestimates the jet yield and can change the extracted jet shape.

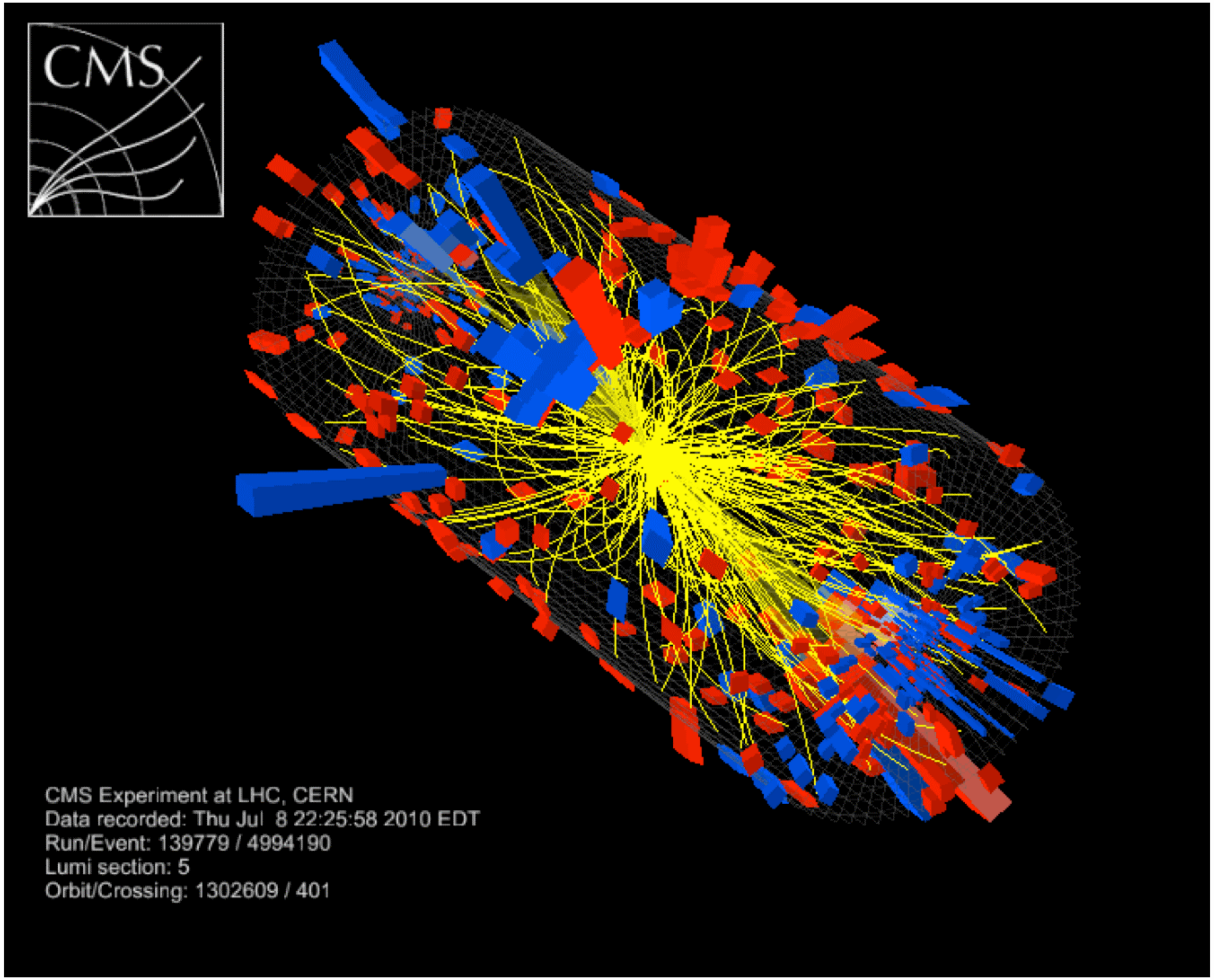
(8) If you extract angular dependence of jet w.r.t. R.P., the results will easily be affected by the choice of v_2 from (5).

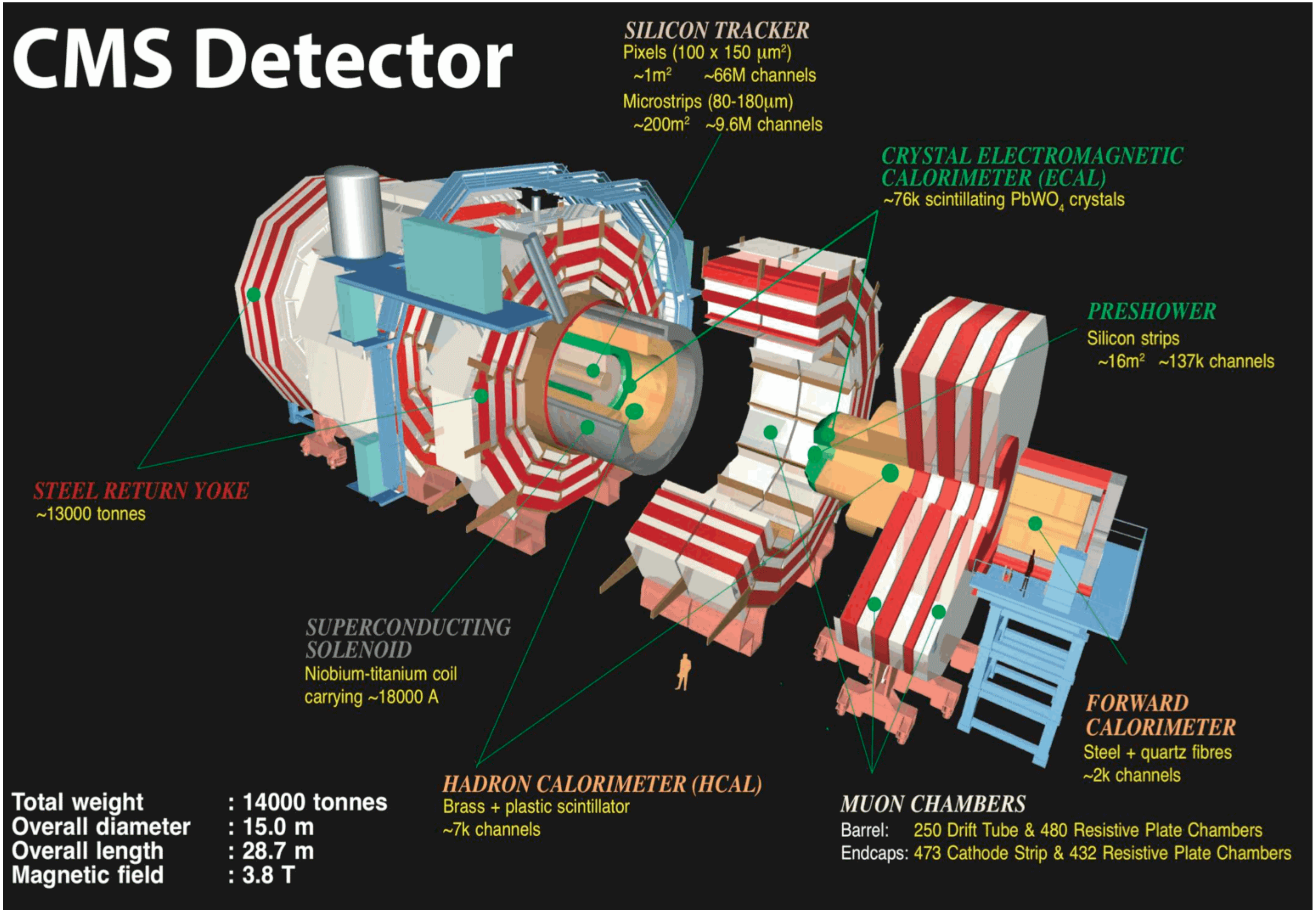


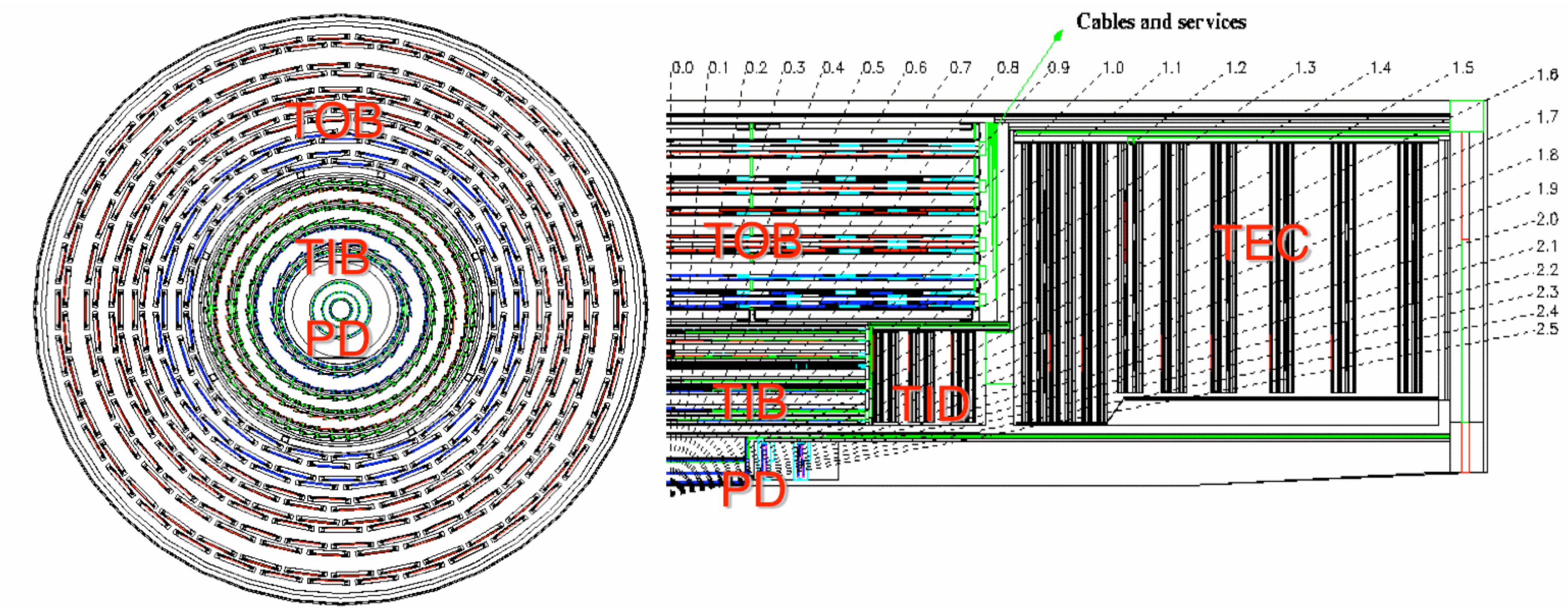


N_{ch} = 258 dNch/dη≈65

CMS, CERN Seminar, Sept. 21, 2010
CERN-PH-EP/2010-031
arXiv:1009.4122v1

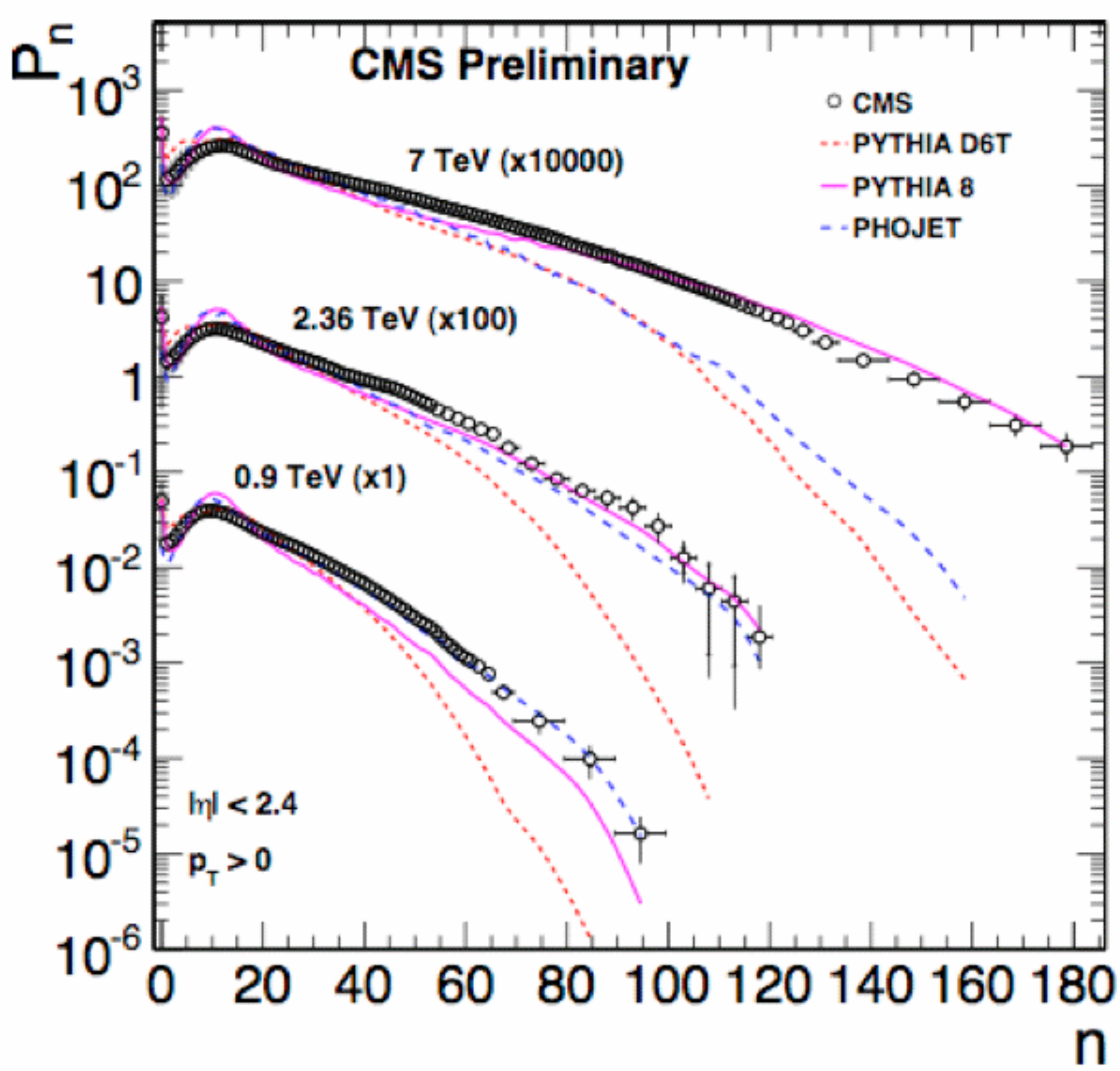


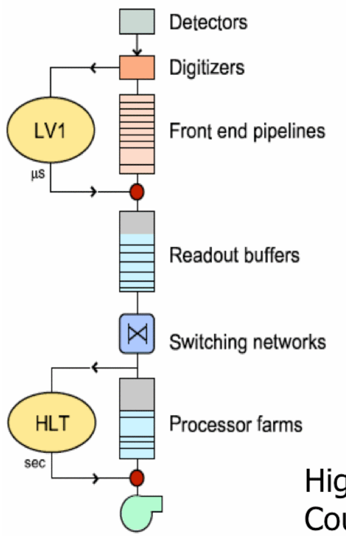

CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



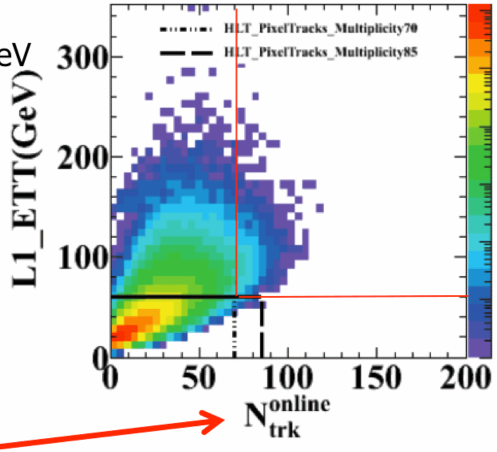
• Coverage up to **I I<2.5**; extremely high granularity, due to the small cell size and high longitudinal segmentation, to keep low occupancy (~ a few%) also at LHC nominal luminosity.

• It is the largest Silicon Tracker ever built: Strips: 9.3M channels; Pixels: 66M channels. **Operational fractions: strips 98.1%; pixel 98.3%**

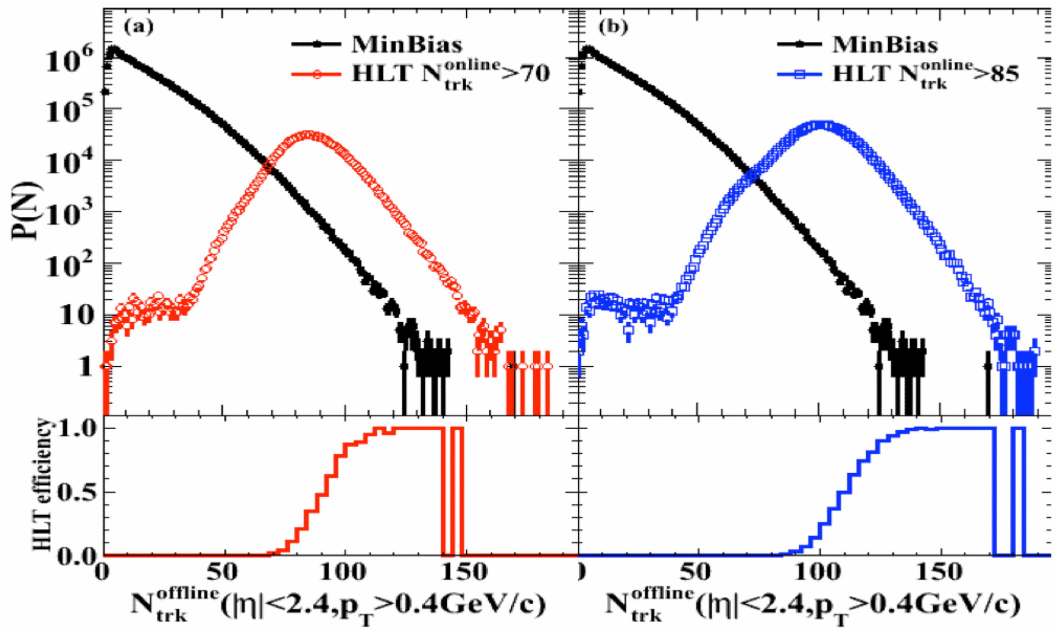

CMS Preliminary
P_n
7 TeV (x10000)
2.36 TeV (x100)
0.9 TeV (x1)
CMS
PYTHIA D6T
PYTHIA 8
PHOJET
|η| < 2.4
$p_T > 0$
n
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
20
40
60
80
100
120
140
160
180



Level-1:
Require E_T> 60 GeV
in calorimeters

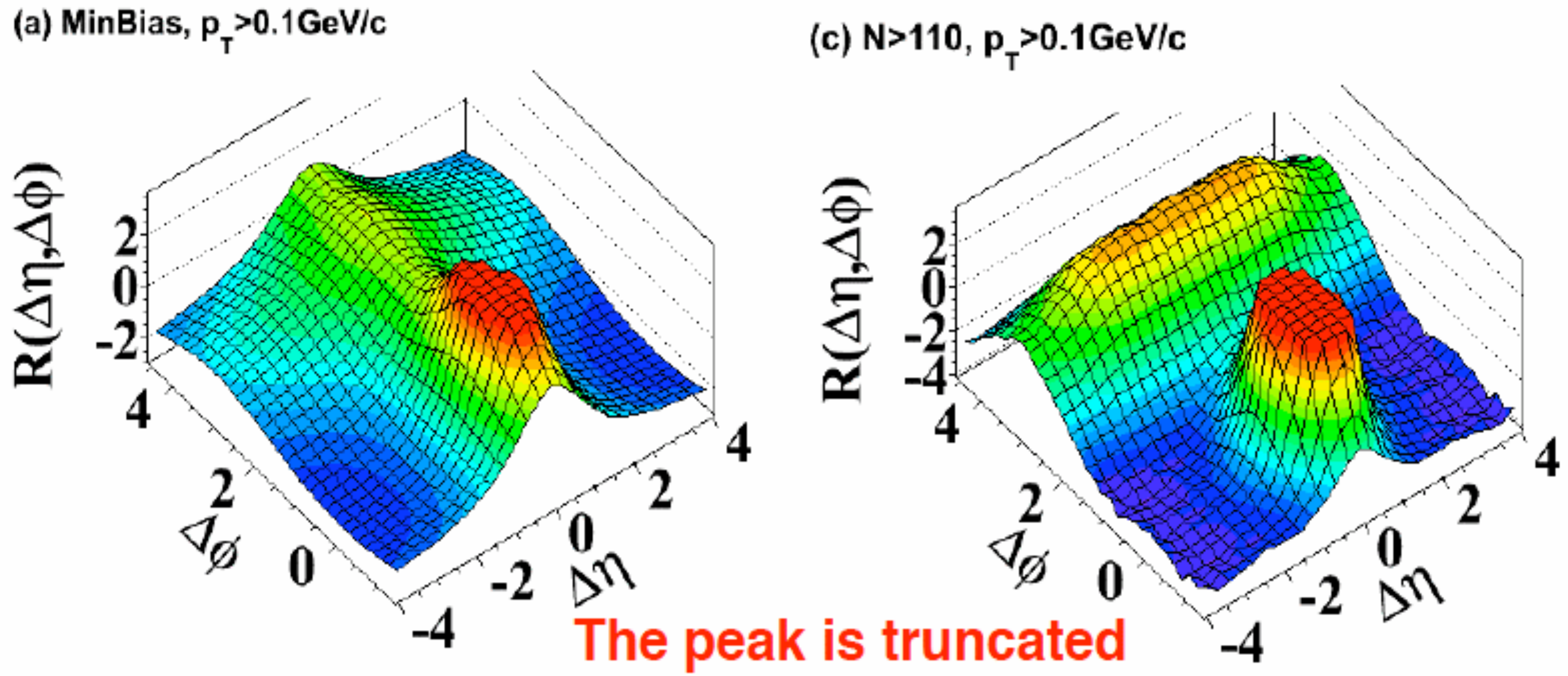


High-Level trigger:
Count number of tracks with p_T > 0.4 GeV/c, |η| < 2,
within dz < 0.12cm of a **single** vertex with z <10cm



Minimum Bias
no cut on multiplicity

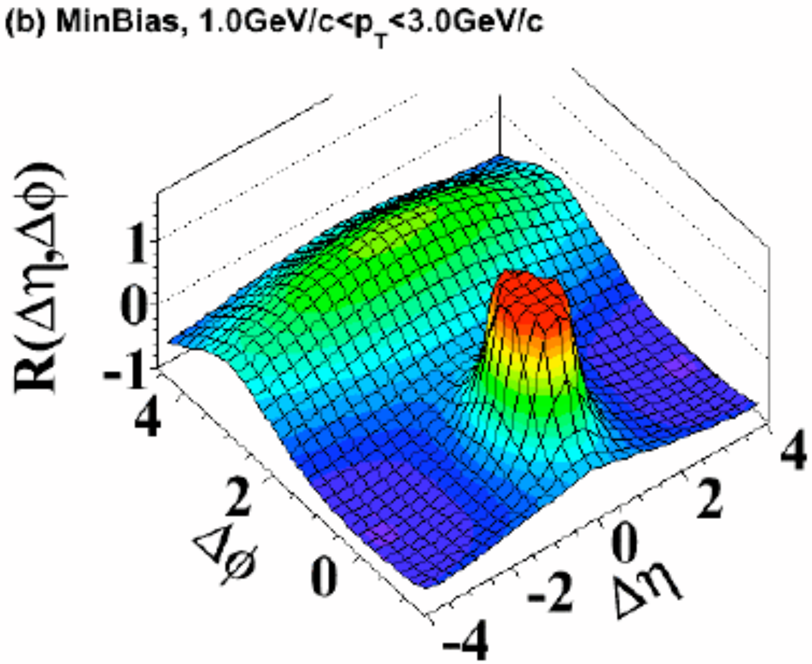
High multiplicity data set
and N > 110



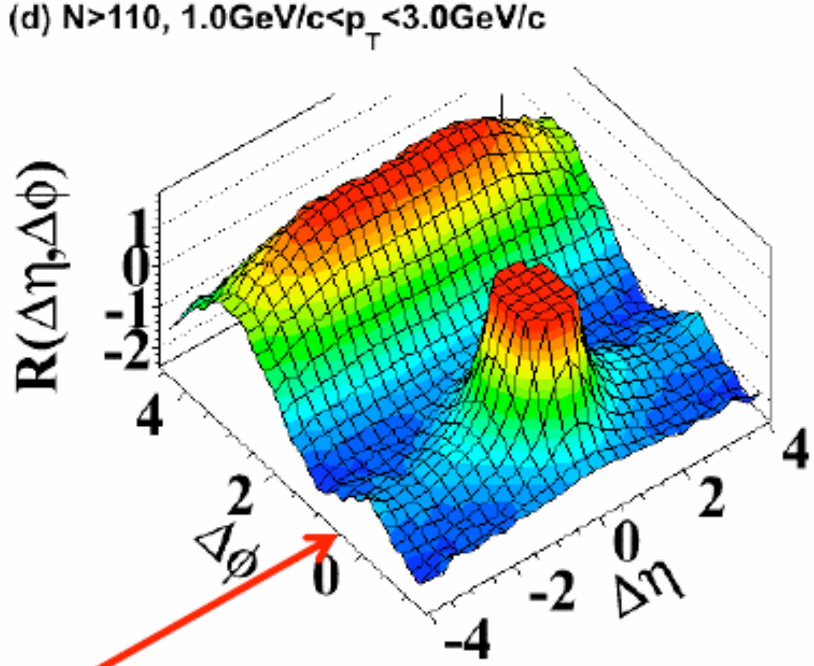
The peak is truncated
in both distributions

Back-to-back jet correlations enhanced in high multiplicity sample.

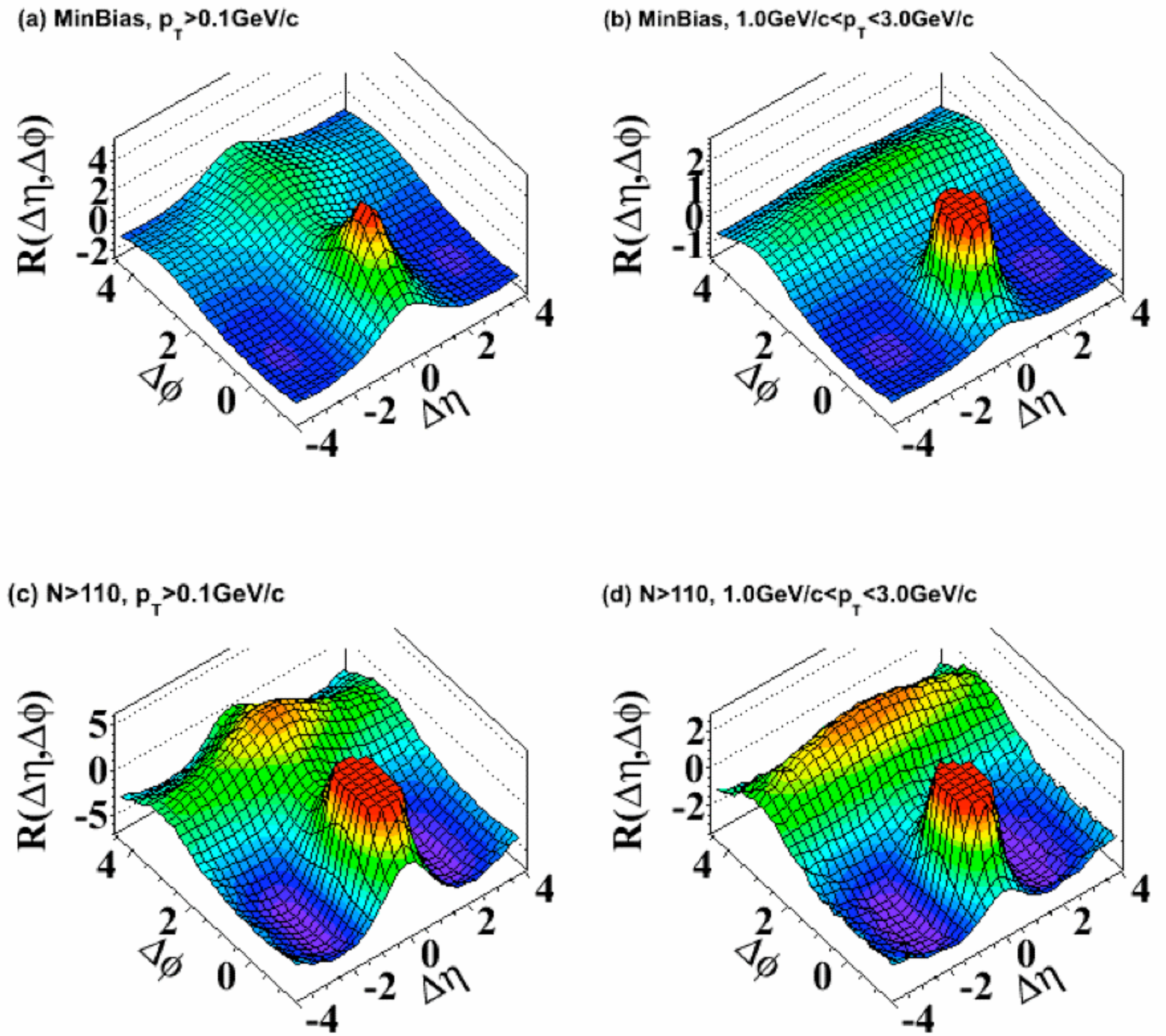
Minimum Bias
no cut on multiplicity



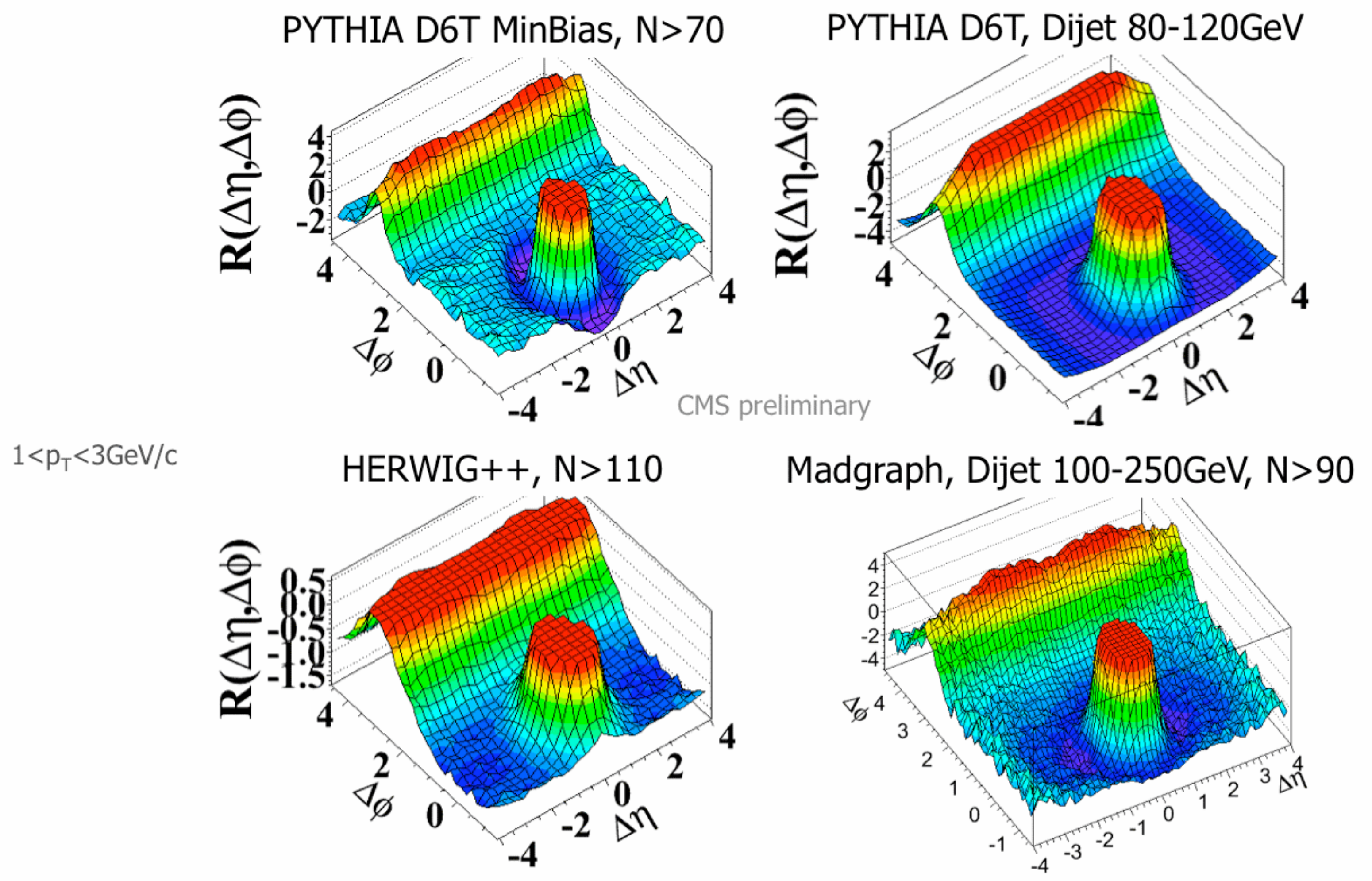
High multiplicity data set
and N>110



New "ridge-like" structure extending to large $\Delta\eta$ at $\Delta\phi \sim 0$



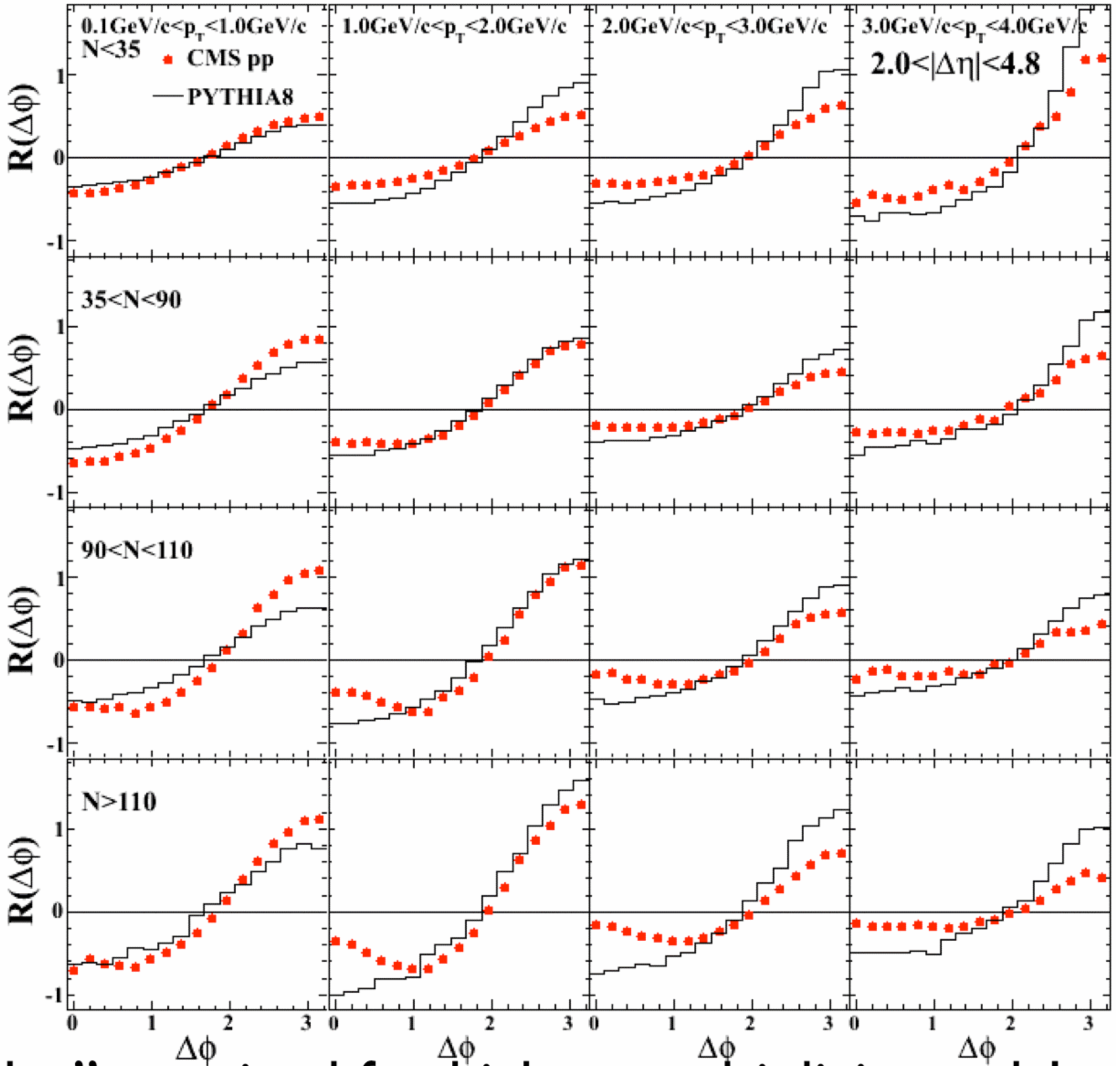
No $\delta\phi \sim 0$ structure in PYTHIA 8 at large $\delta\eta$
Same for Herwig++, madgraph, PYTHIA6

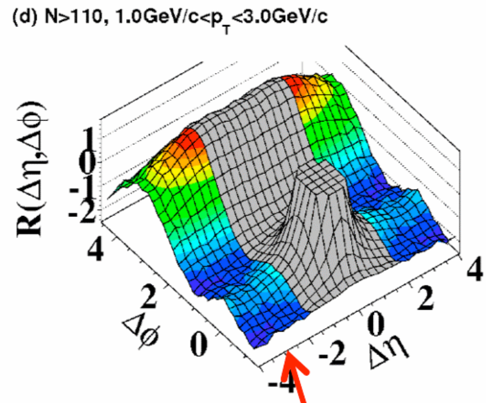


No ridge effect in these models (with the tunes used)

Increasing p_T

Increasing multiplicity



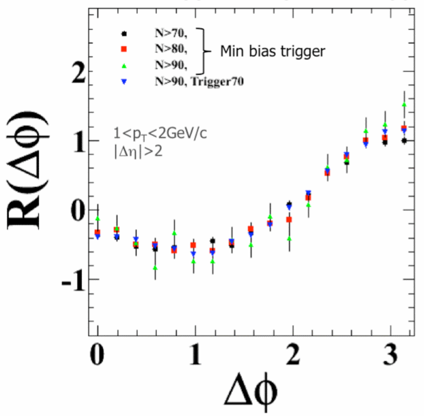


Project $|\Delta\eta| > 2$ onto $\Delta\phi$

"Ridge" maximal for highest multiplicity and $1 < p_T < 3$ GeV/c

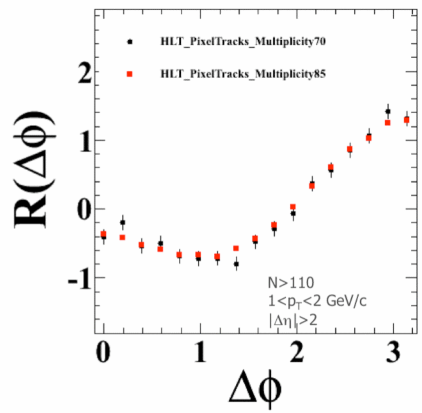
CMS arXiv:1009.4122

Min-bias trigger vs high mult trigger

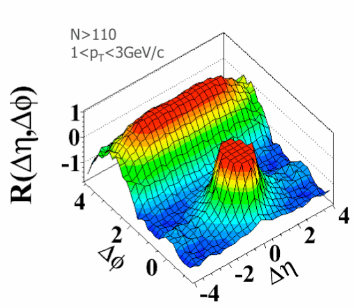


Ridge is seen using
min bias trigger + offline selection

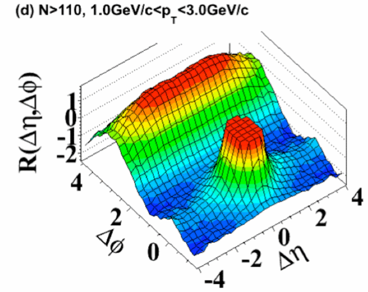
HLT 70 vs HLT 85 for N > 110



No trigger bias seen from
comparison of trigger paths



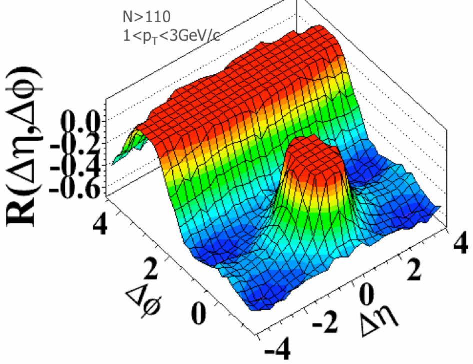
Pixel-only tracks
3 hits in pixel detector

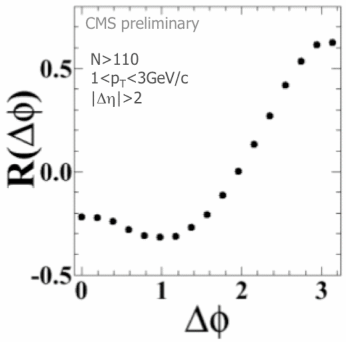


"HighPurity" tracks
Pixel + Silicon Strip tracker

(Largely) independent code
Independent detectors
Also: Variation of tracking +vertexing parameters

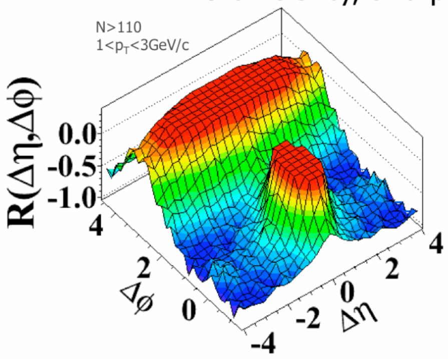
Use ECAL "photon" signal
Mostly single photons from π^0's
No efficiency, and p_T, ϕ smearing corrections

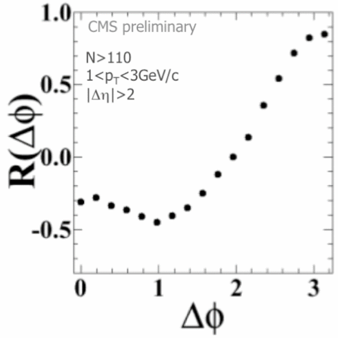




Track-photon correlations

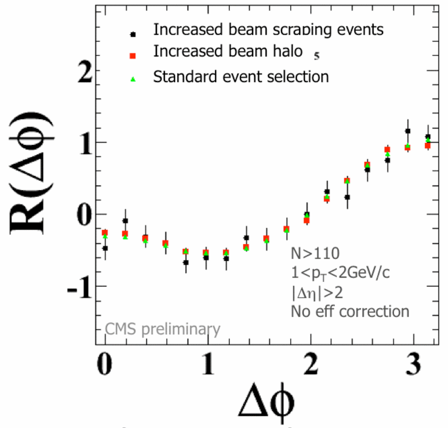
Use ECAL "photon" signal
Mostly single photons from π^0's
No efficiency, and p_T, ϕ smearing corrections



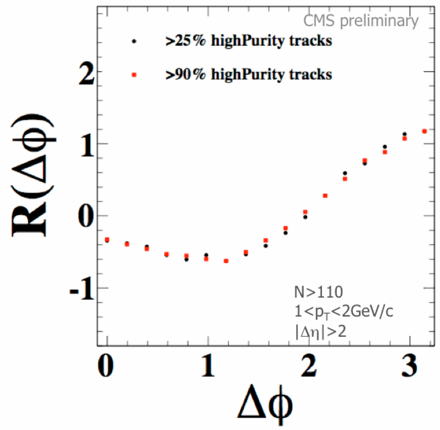


Photon-photon correlations
Qualitative confirmation
Independent detector, independent reconstruction

Select higher fraction of possible beam-gas or beam-scraping events



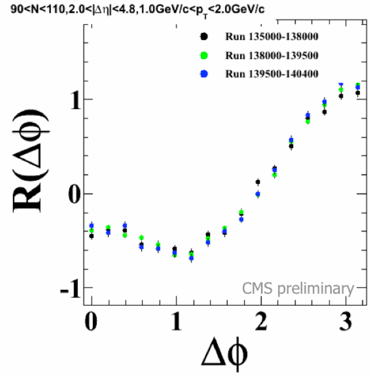
Reject beam background by veto on fraction of low quality tracks



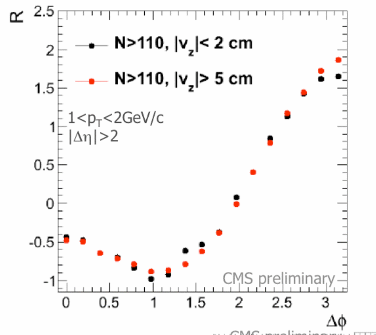
Ridge region shows no sensitivity to beam background

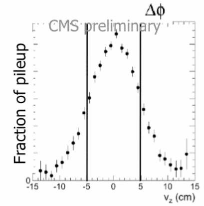
Note: Analysis is done on HighPurity tracks

Compare different run periods (fraction of pileup varies by x4-5)



Compare different vertex regions (fraction of pile-up ~ $dN/dvtx_z$)

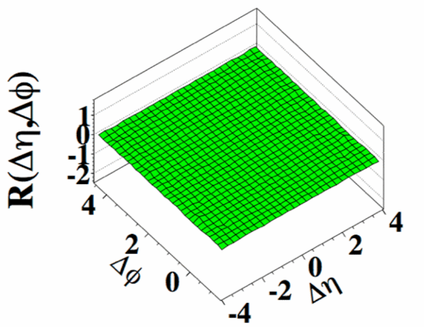


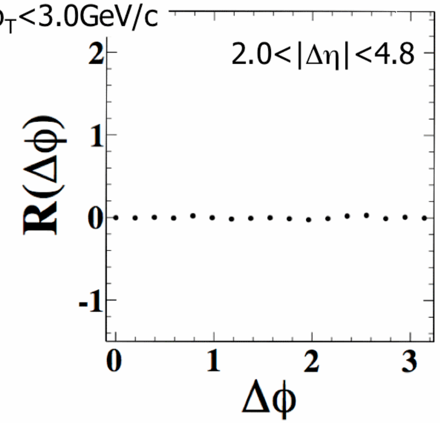


Change in pileup fraction by factor 2-4 has almost no effect on ridge signal

Correlate tracks from high multiplicity vertex with tracks from different collision (vertex) in same bunch crossing

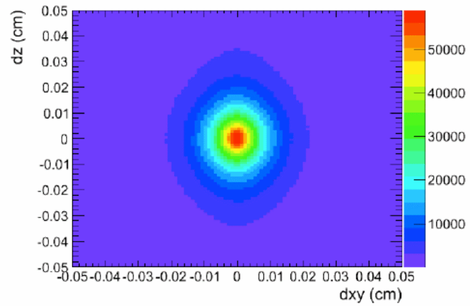
N>110
1.0GeV/c<p_T<3.0GeV/c



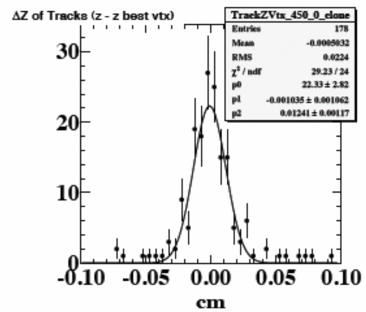


No background or noise effects seen in cross-collision correlations

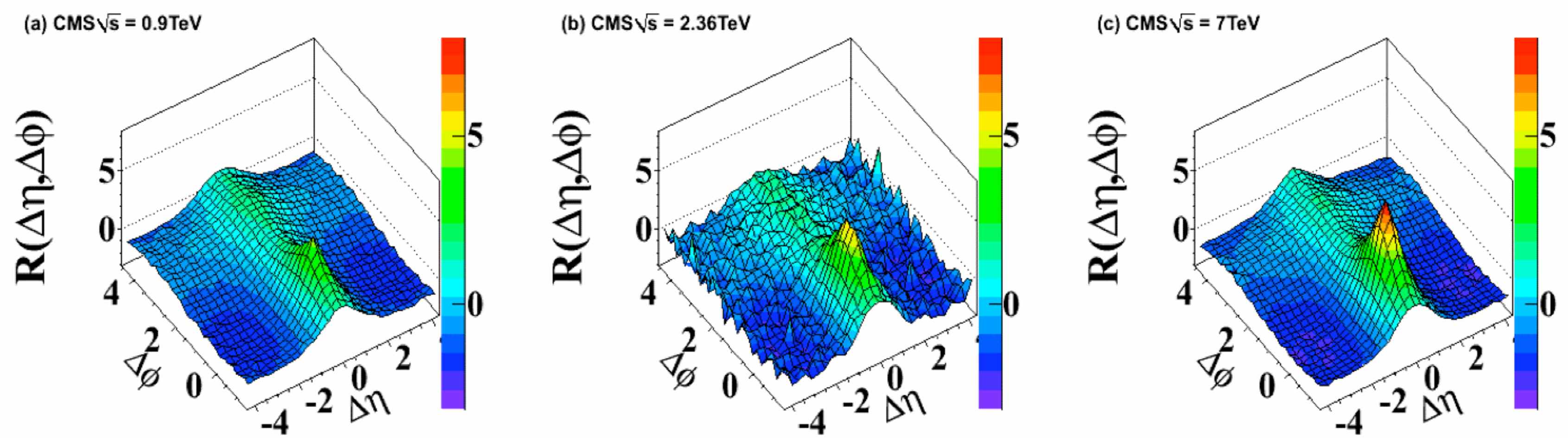
Track longitudinal and transverse impact parameter (p_T > 0.4 GeV/c)



Single-event track dz distribution

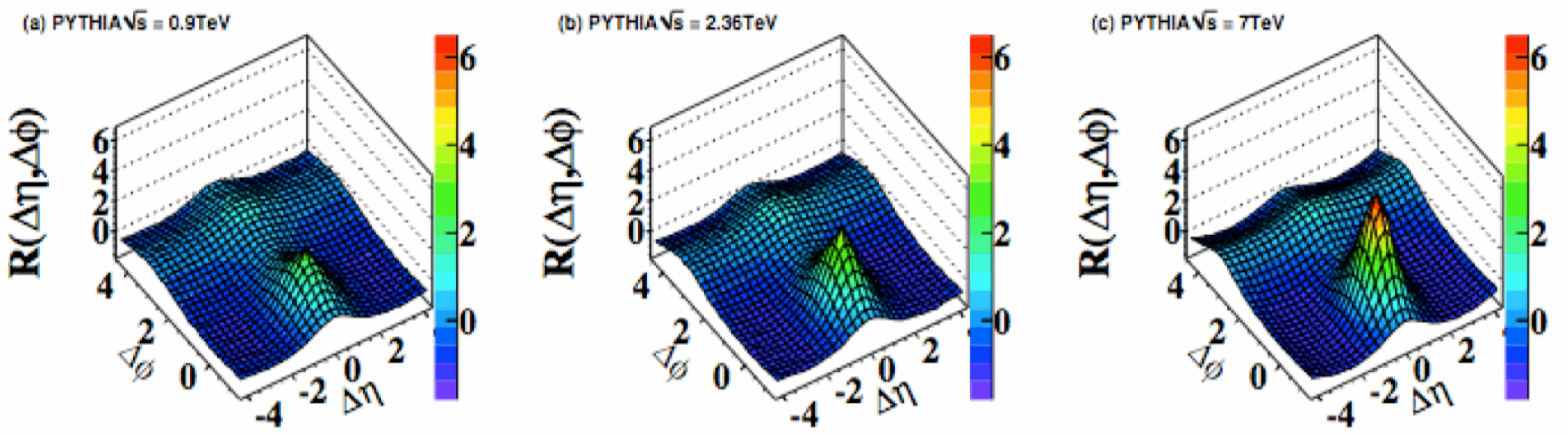


Pileup effects are suppressed due to excellent resolution
Track counting done with σ_{dz}, σ_{dxy} of O(100μm)



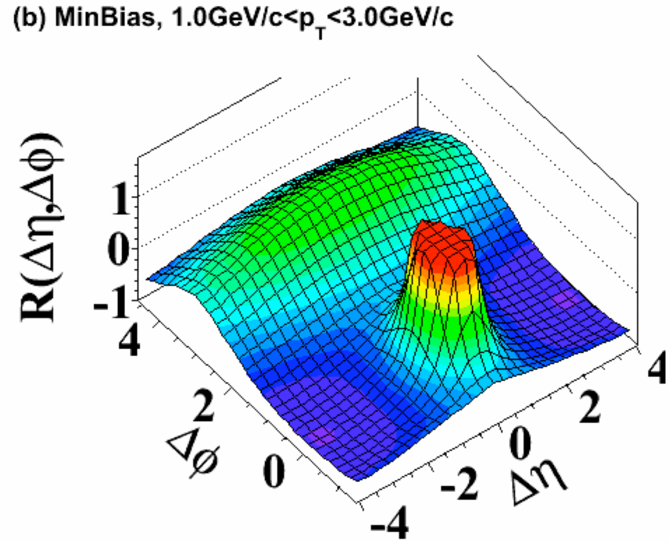
p_T-inclusive two-particle angular correlations in Minimum Bias collisions

Pythia D6T



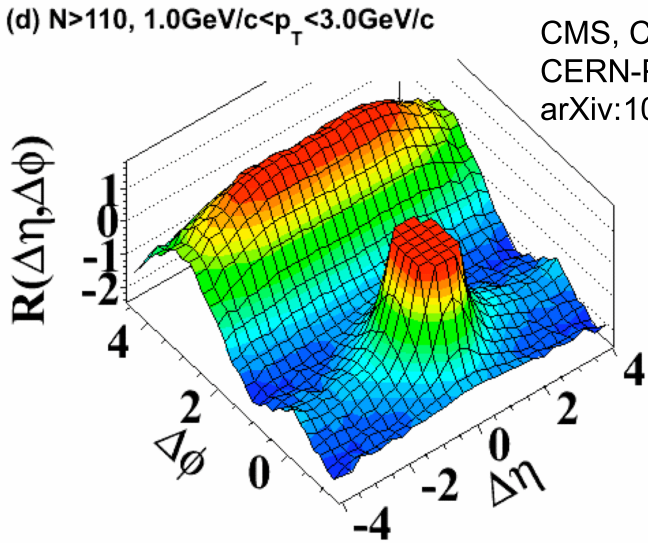
Ridge is seen at high multiplicity p+p(LHC)

MinBias



Charged hadron correlations in CMS tracker (|η| < 2.4)

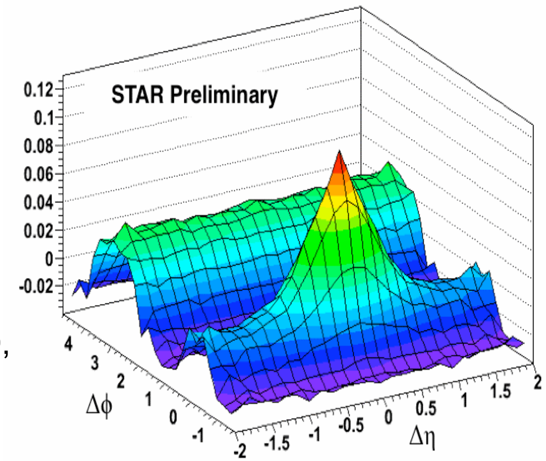
High multiplicity (N>110)



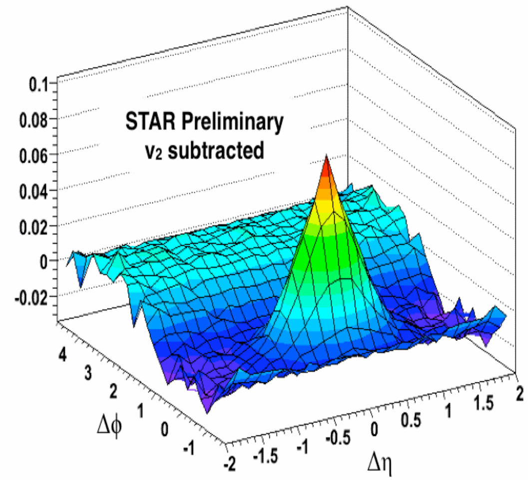
CMS, CERN Seminar, Sept. 21, 2010
CERN-PH-EP/2010-031
arXiv:1009.4122v1

long range correlation is also seen at ISR, SppS, Fermi lab.
consistent with CGC picture?
what if there is v2 in p+p?

Cu+Cu @ 200 GeV; 1<p$_T$<3 GeV/c
(multiplicity ~ CMS p+p)



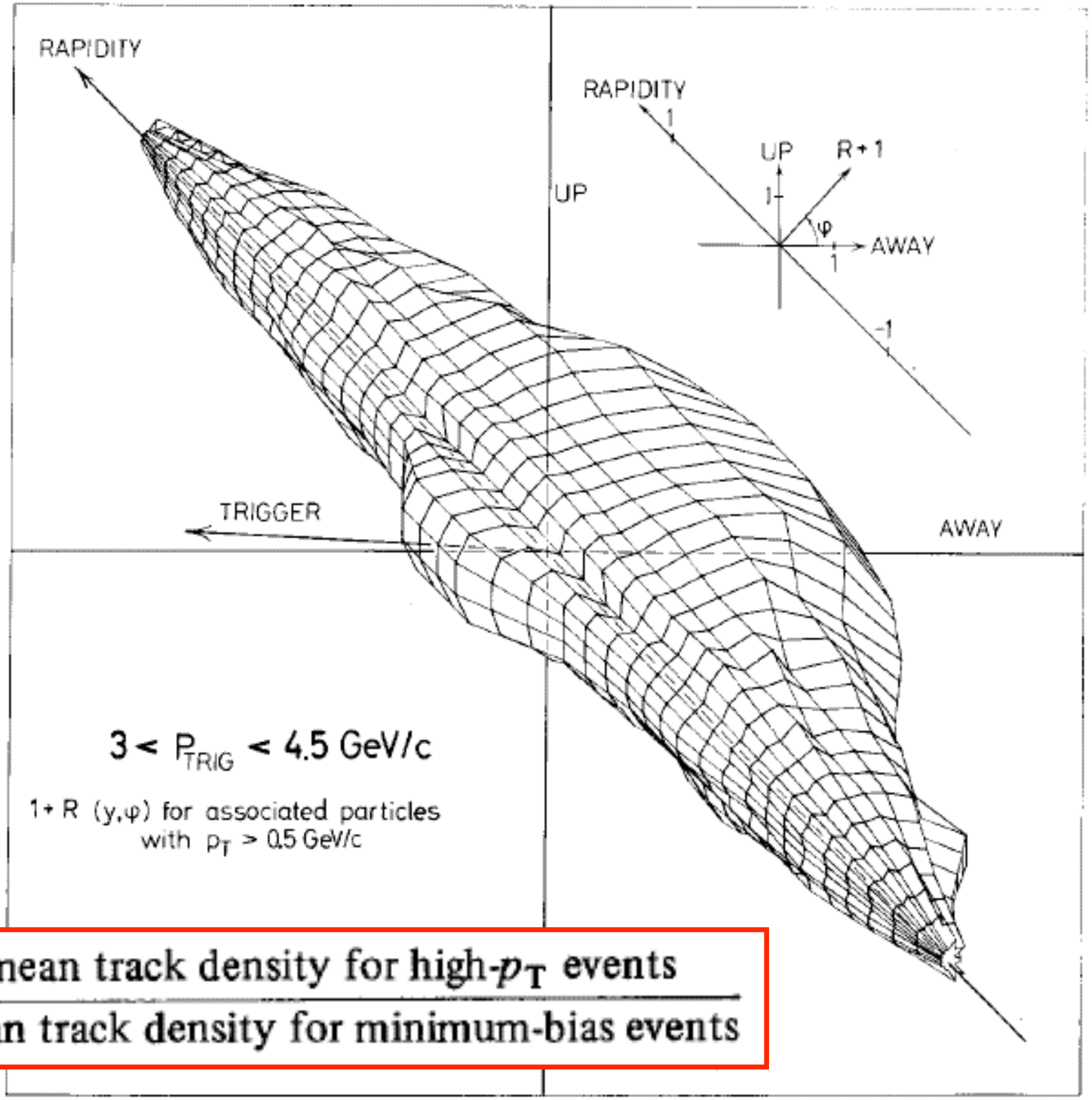
Cu+Cu @ 200 GeV; 1<p$_T$<3 GeV/c
(multiplicity ~ CMS p+p)



seen in Au+Au at RHIC, but not in Cu+Cu?
remember a large v_2 in Cu+Cu at RHIC
$\varepsilon_{STD} \sim \varepsilon_{part}$ (Au+Au)
$\varepsilon_{STD} << \varepsilon_{part}$ (Cu+Cu)

Hard Probe 2010,
J. Putschke

CERN-ISR
Nucl. Phys. B145 (1978) 305-348



$$R + 1 \approx \frac{\text{mean track density for high-}p_T\text{ events}}{\text{mean track density for minimum-bias events}}$$

Summary

jet/photon suppression(R_{AA}) / event anisotropy(v_2)
particle/jet correlation(I_{AA}) / geometrical dependence
mach-cone, ridge / soft-hard interplay
ridge in high mult. p+p events at LHC