Recap from the EPIC workshop- Early Physics with Heavy Ions at LHC

Sebastian White

presented at Galileo Galilei Institute
Arcetri, Florence
21 September 2011

THE ROCKEFELLER UNIVERSITY
Science for the benefit of humanity
CENTER FOR STUDIES IN PHYSICS AND BIOLOGY

Outline

- Historical Factoids and interesting dates
- selected results of the 3 LHC HI experiments from the 2010 Pb-Pb run (borrowing from synthesis of Safarik's workshop summary), experimental tools
- some comments and opportunities

“the fly in the cathedral”

E. Rutherford, **The scattering of alpha and beta particles by matter and the structure of the atom**, *Philosophical Magazine*, volume **21** (1911),

[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. Rutherford, *F.R.S., University of Manchester**.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which

- Moseley, R & Chadwick, Oppenheimer
- “region of anomalous interaction”-> Hostadter
- R to Royal Society, Nov. 1927->*time to go industrial*
- 10^{-8} --> $<10^{-16}$ cm

1974- an interesting year

- Fritzsch, Gell-Mann,Leutwyler, Phys. Lett. B 47, 365 (**1973**)
- bag model(1974)
  - Chodos, Jaffe et al. (MIT) and Bardeen, Chanowitz et al. (SLAC)
- Lederman sent me to CERN for thesis
- “November Revolution”
- T.D.Lee and G.C.Wick,PRD 9 (1974),2291- “we.. inquire whether it is experimentally possible in a limited domain in space to ‘excite’ the ordinary vacuum to an abnormal state”
- “Bear Mountain Meeting” organized by Lederman, TD Lee, Ruderman, Baym
  - Cocconi discussed heavy nuclei in ISR, etc.
  - this meeting rated by Baym as significant milestone in launching HI physics

implementation

- 1983- Aurora NSAC meeting coincided with the termination of Isabelle (CBA)
- 1986 (this is 25th anniversary!)-1st heavy nuclei in the SPS
- 2000->present - RHIC
- 2010- start of LHC heavy ion program

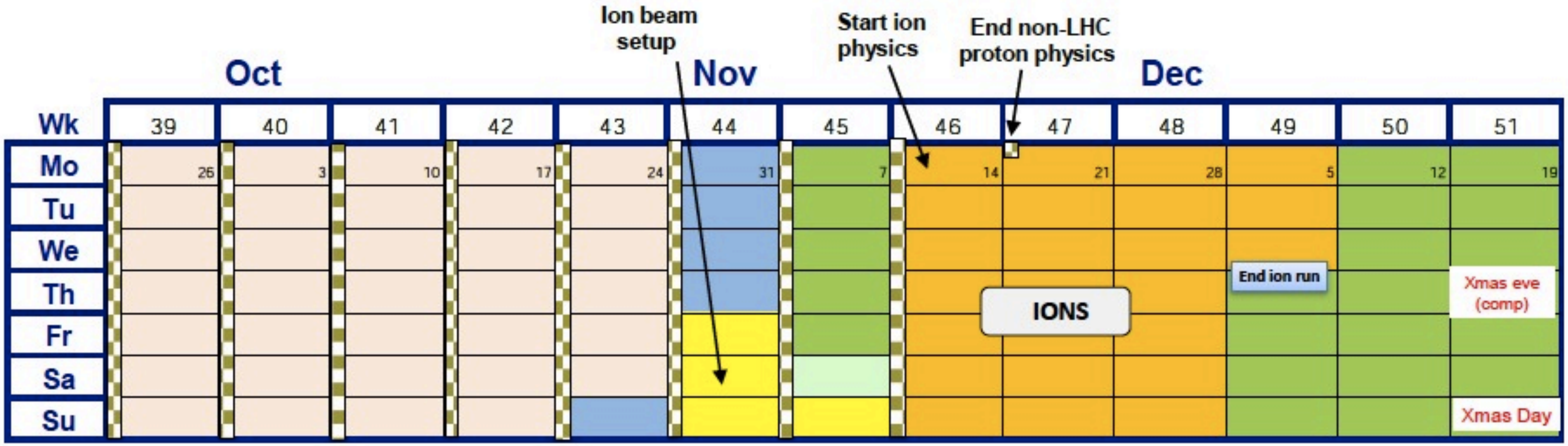
slide from Safarik

FIRST NUCLEAR EVENT AT LHC – November 7th 2010

… celebrating 93rd anniversary of the …

Great October Socialist Revolution (November 7th, 1917)

going forward-rest of 2011



<u>notes</u>

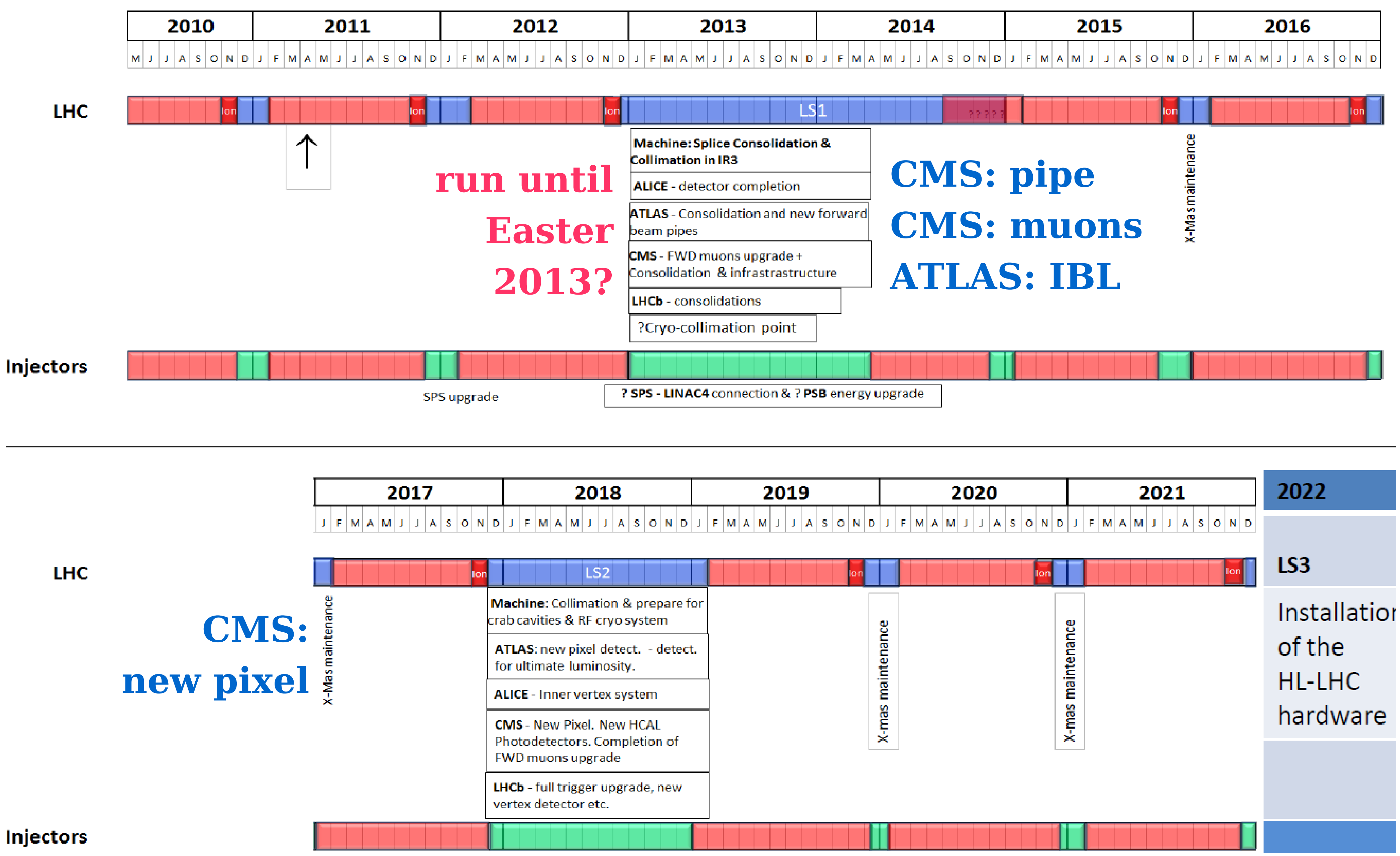
pp:this week LHC achieved 3.3 x10^{33} L_{peak}
recorded integrated L now 3 fb^{-1}

PbPb:expect 3 weeks data at ~5x 2010 Lum.

pPb: test run planned, probabbly at beginning of HI period.
deliver “some” collisions to experiments (~1-2M events?)

HI runs out to 2021

an LHC 10 year plan as of June 2011



LHC HI physics:challenge of communicating to HEP

- It is sometimes said that QCD is a solved theory.The rest is details. "QCD is a solved theory"=>biology is "just" physics and chemistry.
- Strong interaction of 2 partons is fundamentally different from QED, which HEP physicists know and love.
- Pomeron physics is more complex than the equivalent photon approximation, which inspired this picture
- QCD vacuum confines lines of force. In order to shed light on QCD we must "melt" the vacuum (TD Lee).
  - This led to quest to create a *"Feuersturm"* (firestorm)* that melts the vacuum.
  - Attempt to analyze this picture introduced many concepts unfamiliar to HEP –ie entropy, enthalpy, shear, viscosity, chemical potential,etc-which refer to created particles rather than vacuum(Bjorken, Shuryak, et al.)
  - Quest for higher temperature starting from Bevalac, AGS/SpS-> colliders (W.J.Willis). Strong evidence that new medium created in 2000->now era at RHIC($T>T_{Hagedorn}$). First evidence that ~3 times increase in energy density at LHC.

*a conflagration which attains such intensity that it creates and sustains its own wind system

Convergence

- LHC brings together many topics originally the province of dedicated accelerators
  - Machines for new particle searches (SppS, Tevatron)
  - HI accelerators
  - HERA physics (crucial for elucidating shadowing effects using hard photoproduction in Pb-Pb collisions).[1]
- New experimental issues associated with characterizing initial configuration of composite particles, which make up Pb and p beams. Tools developed in HI world for this could impact pp analyses.[2]

[1] Phys Rev Lett. 2006 Mar 3;96(8):082001. "Probing small parton densities in ultraperipheral A A and pA collisions at the CERN large Hadron Collider."Strikman M, Vogt R, White S.

[2] Phys Rev Lett. 2008 Apr 18;100(15):152002 "How to probe high gluon densities in pp collisions at the Large Hadron Collider"Drescher HJ, Strikman M.

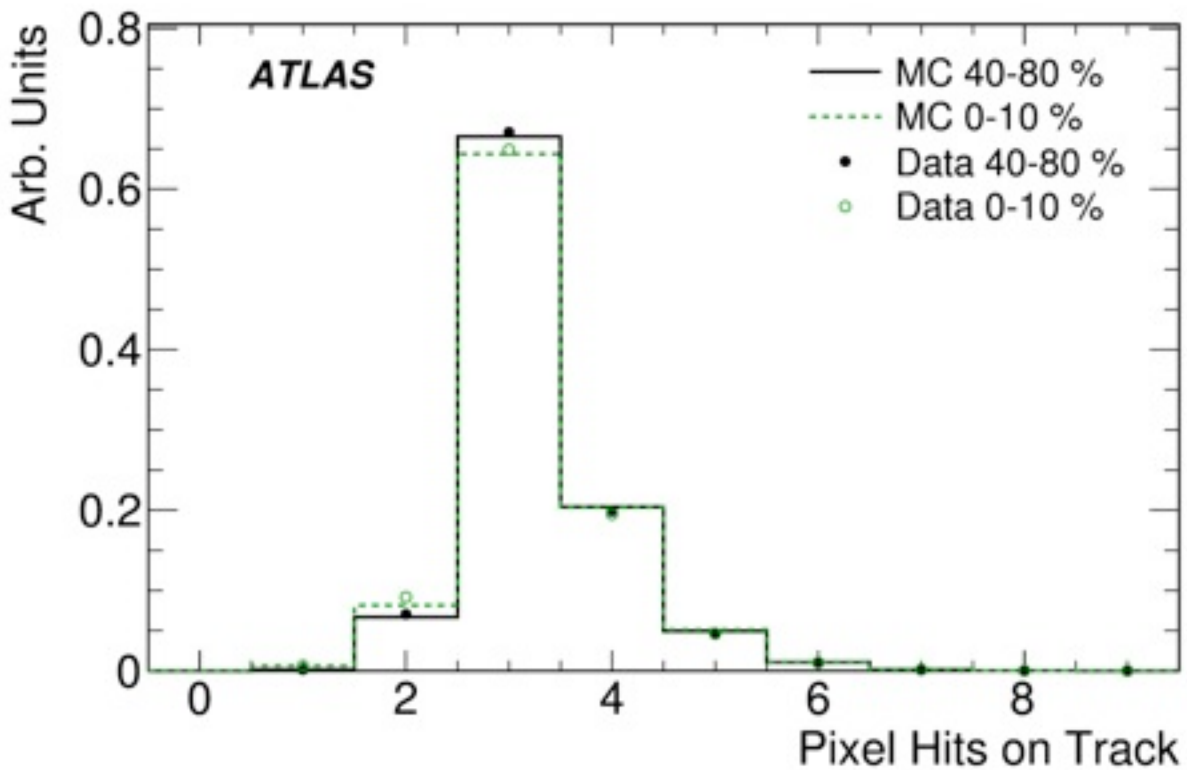
bullets from 3 expts

(following slides primarily from Karel Safarik's workshop summary)

- jet suppression by ~same magnitude as identified hadron suppression at RHIC. Due to fact that fragmentation unchanged.
- for most central collisions this may be surprising. How does q lose so much energy without affecting fragmentation pattern? How is diffuse energy radiated?
- non-isotropic flow measured in great detail. How to model it? Relation to earlier features-ie ridge- at RHIC.
- quarkonium suppression measured and initial baseline from W,Z.

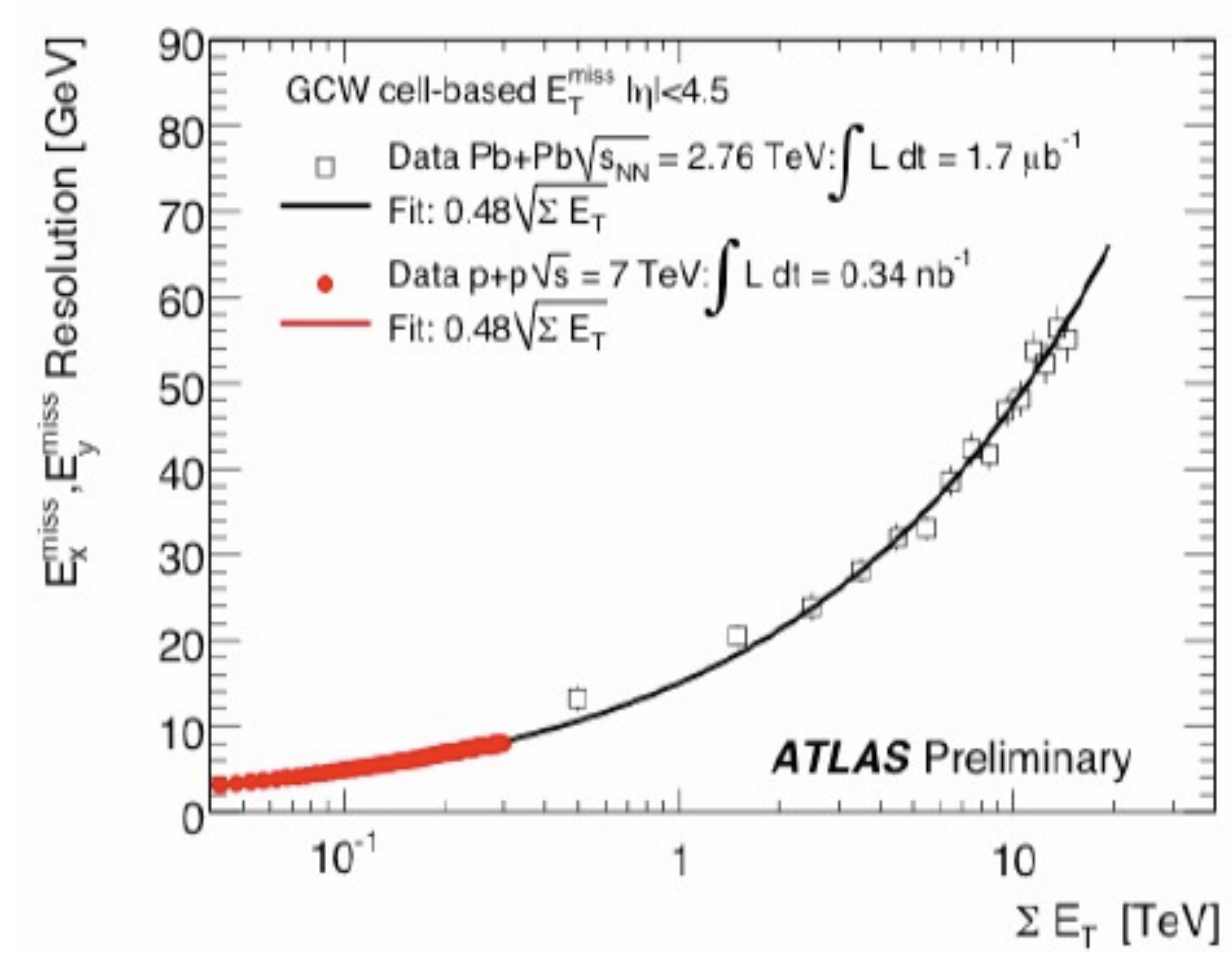
Detectors have been Robust in HI also: eg ATLAS

- Most of the μ efficiency dependence on centrality is coming from ID
  - occupancy effects causing good tracks to fail our track selection cuts
- Estimate systematics by comparing differences between data and MC on the selection threshold
  - Studied as a function of centrality
  - maximum deviation of 3% found in the most central bins
  - 2 muons → 6% maximum total systematics

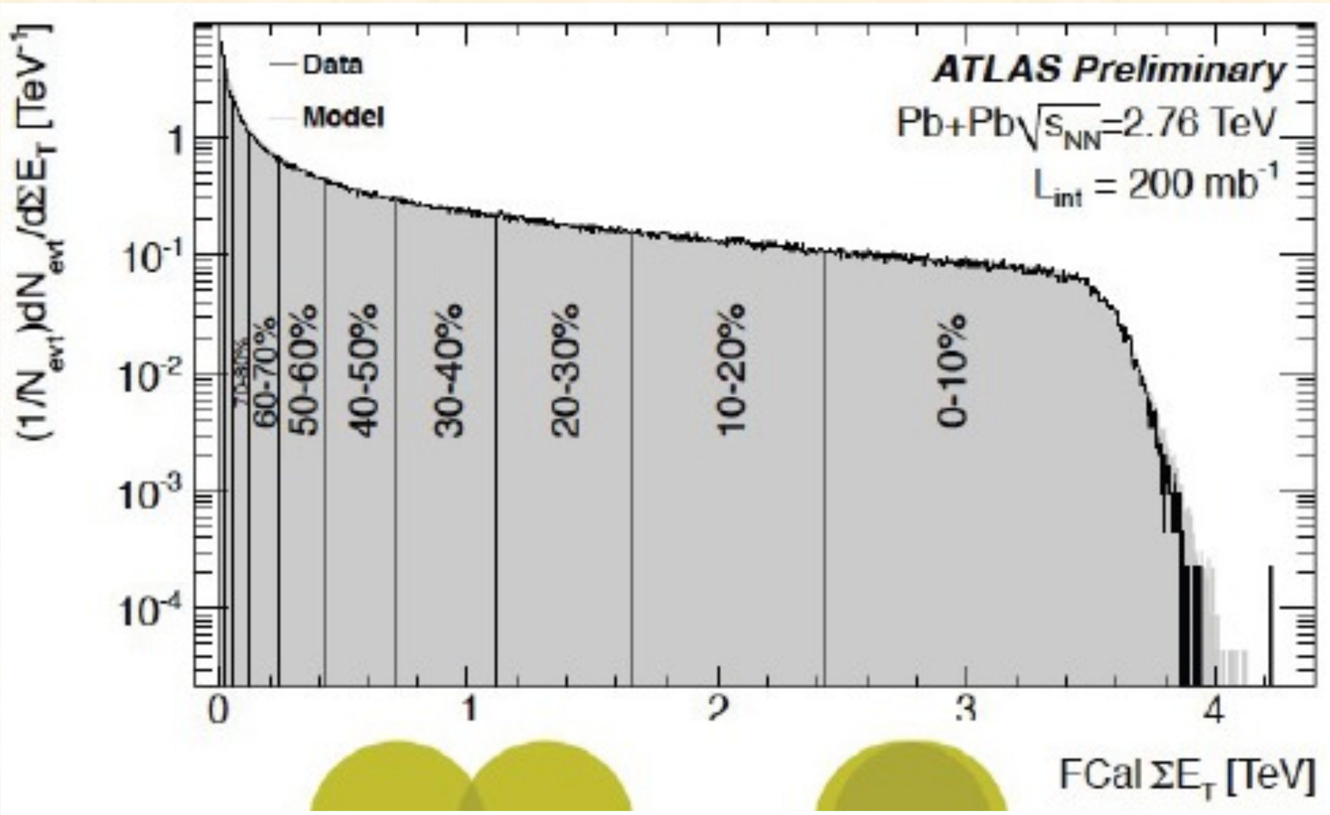


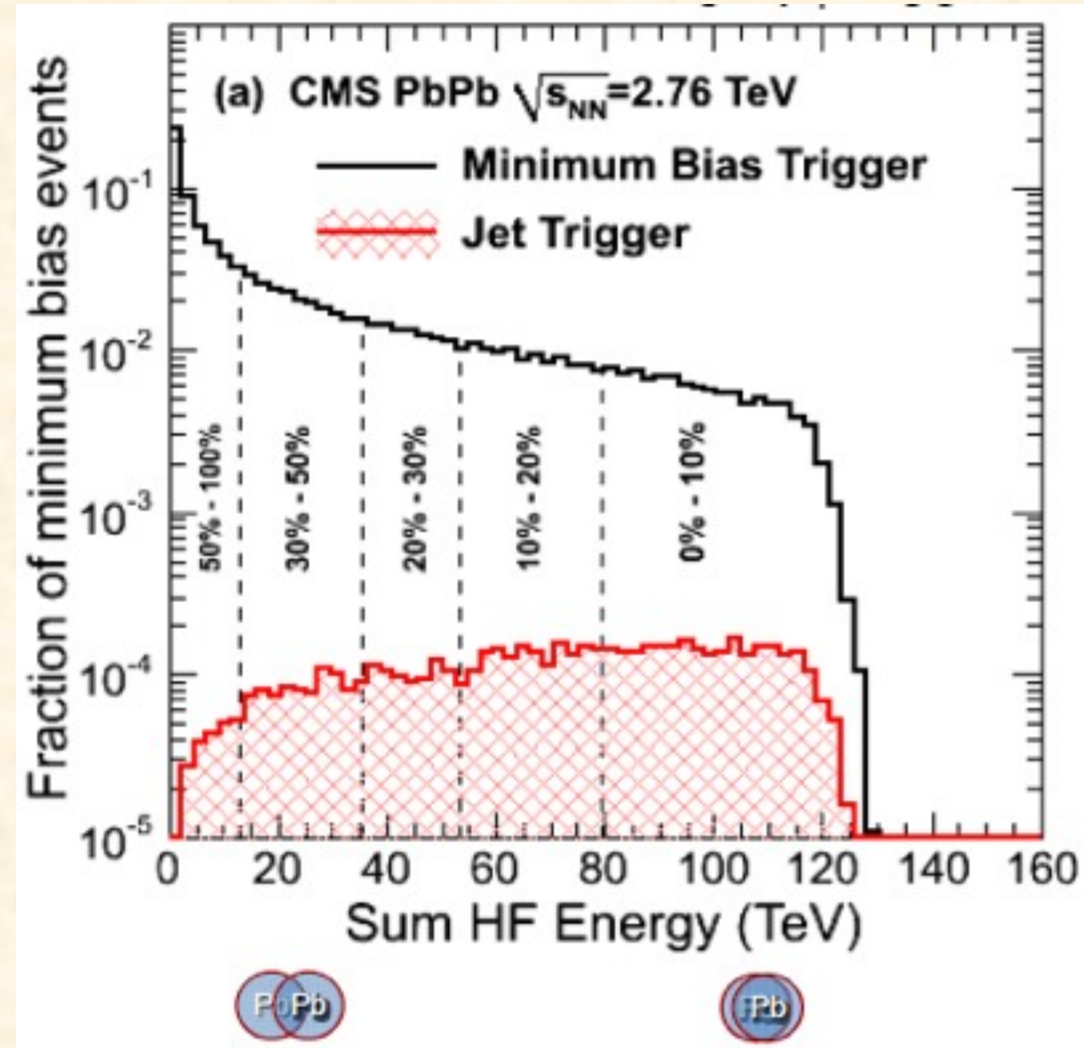
E_T Reconstruction

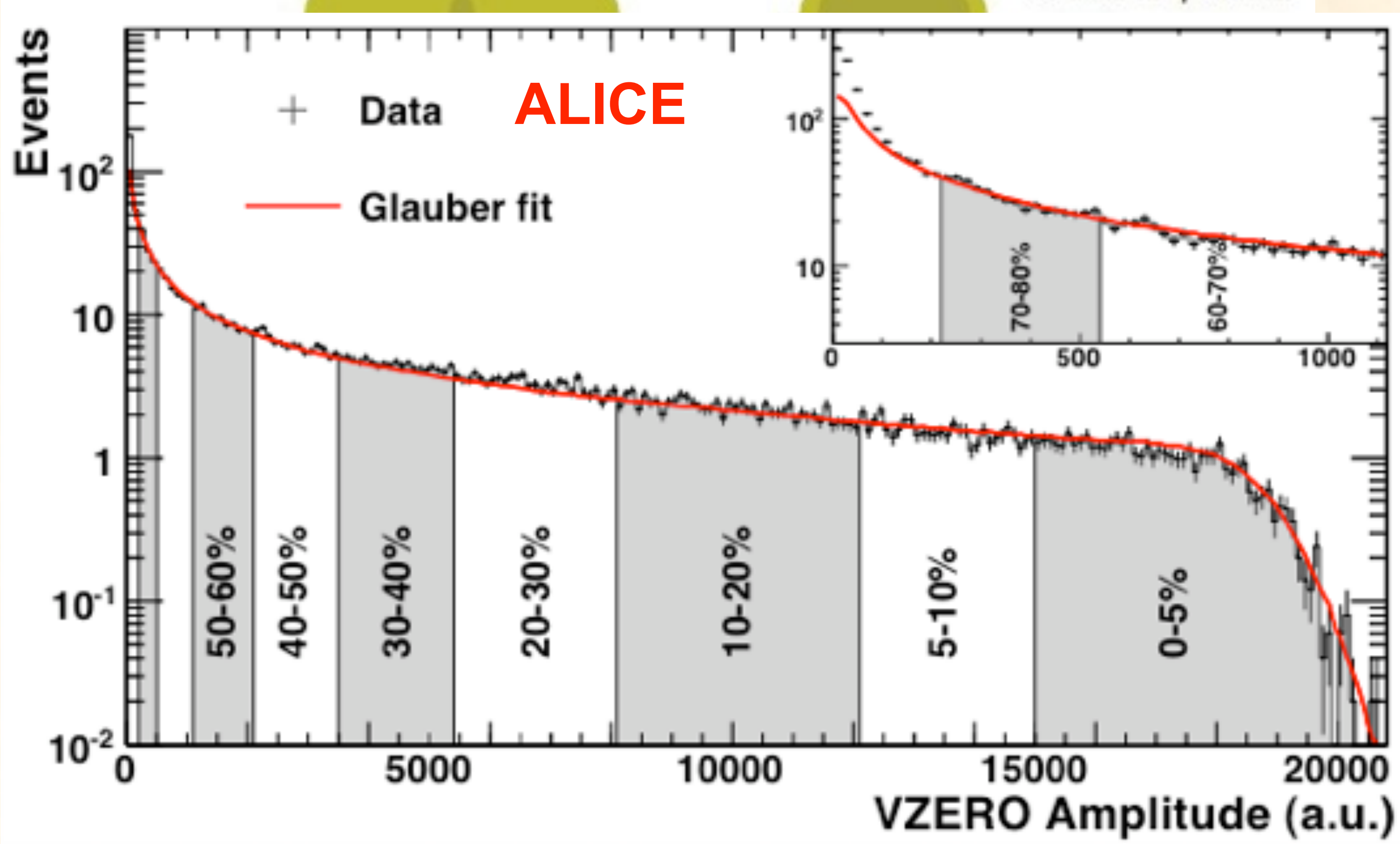
- Missing E_T Resolution(rms in case of PbPb) follows same trend as in pp data.



Centrality selection





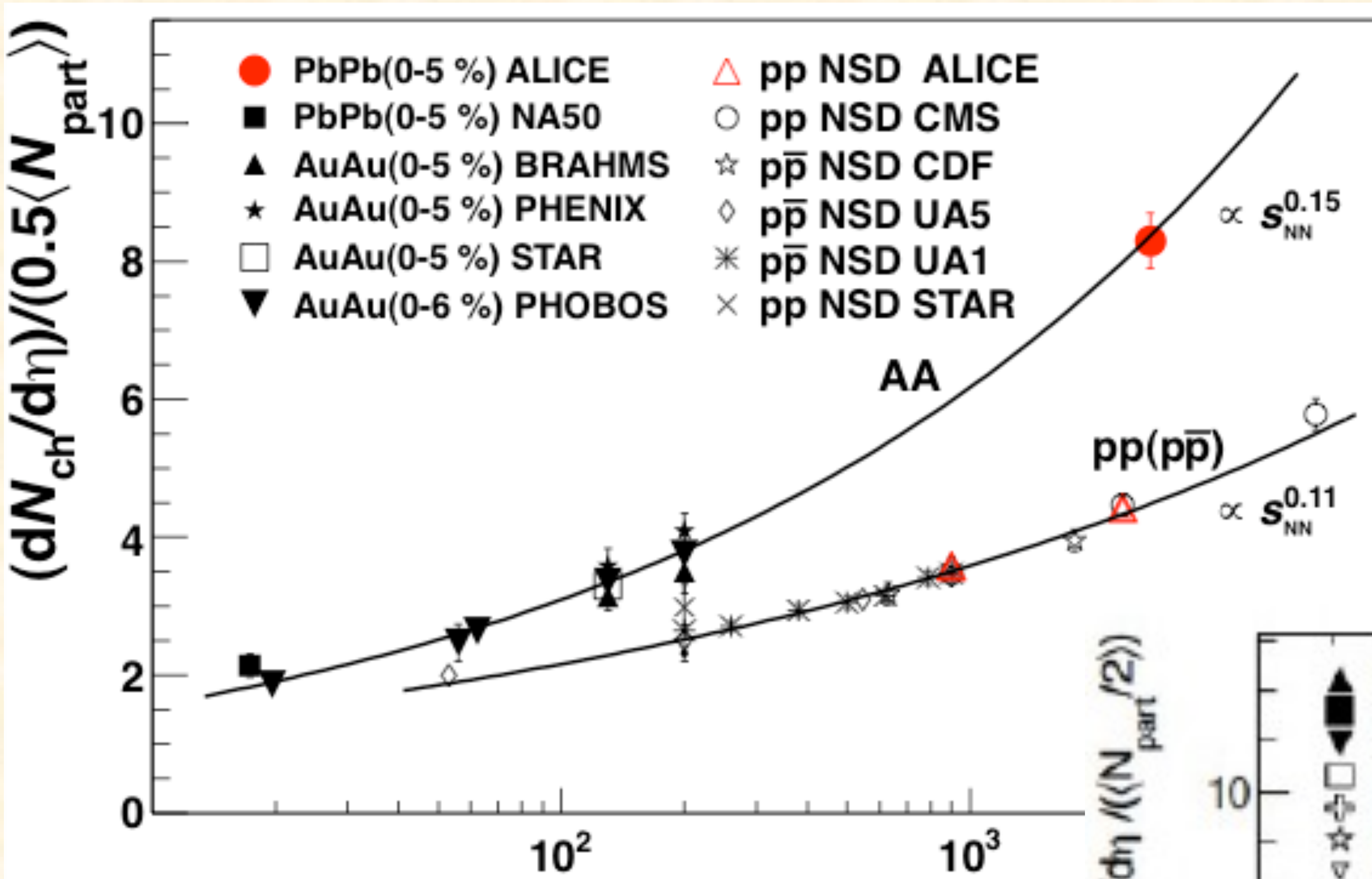


S.White, ATLAS

B.Wyslouch, CMS

M.Nicassio, ALICE

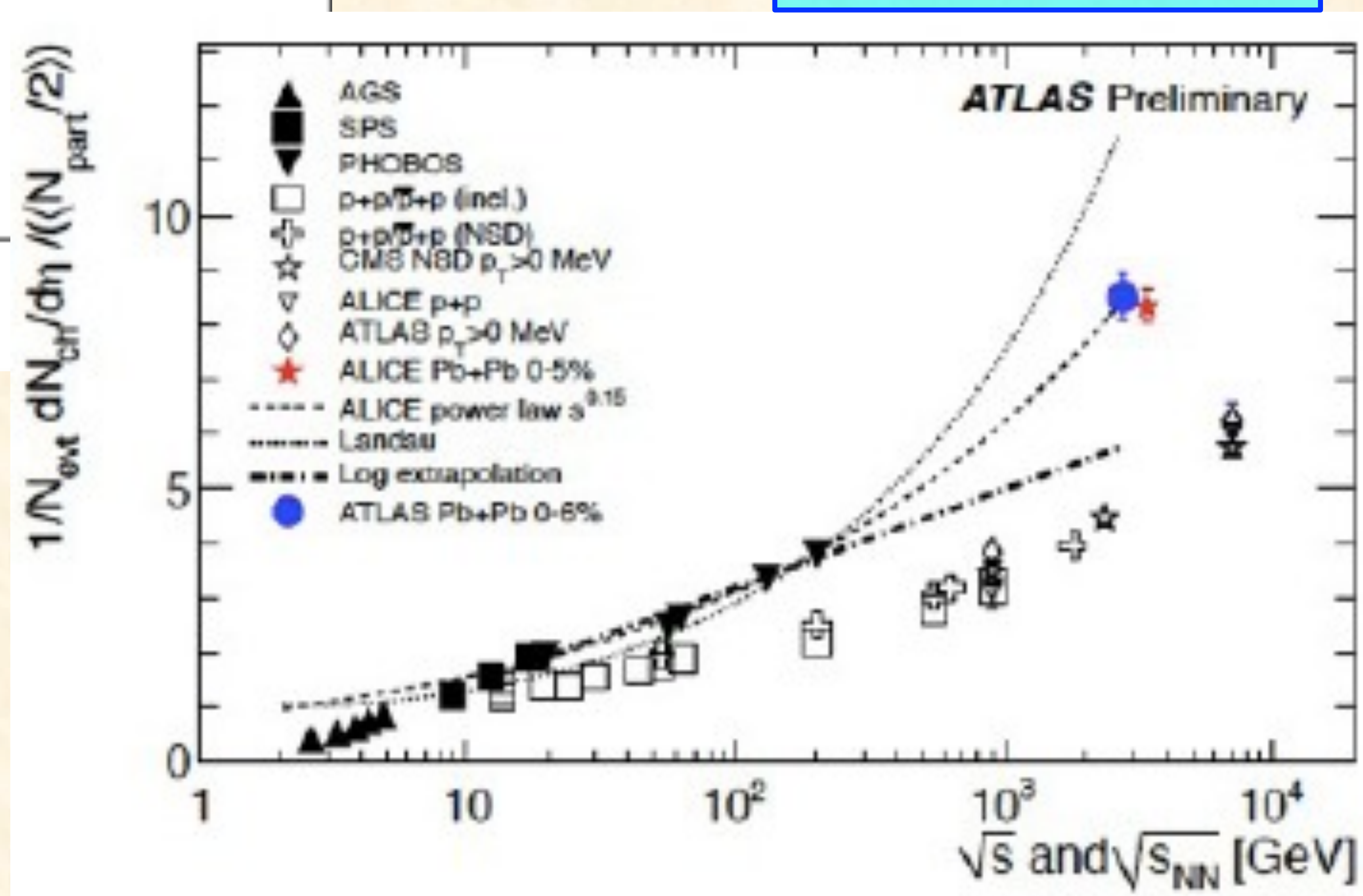
Energy dependence of multiplicity



- growing faster then pp
- increase by factor
-2.2 compared to RHIC
-1.9 compared to pp

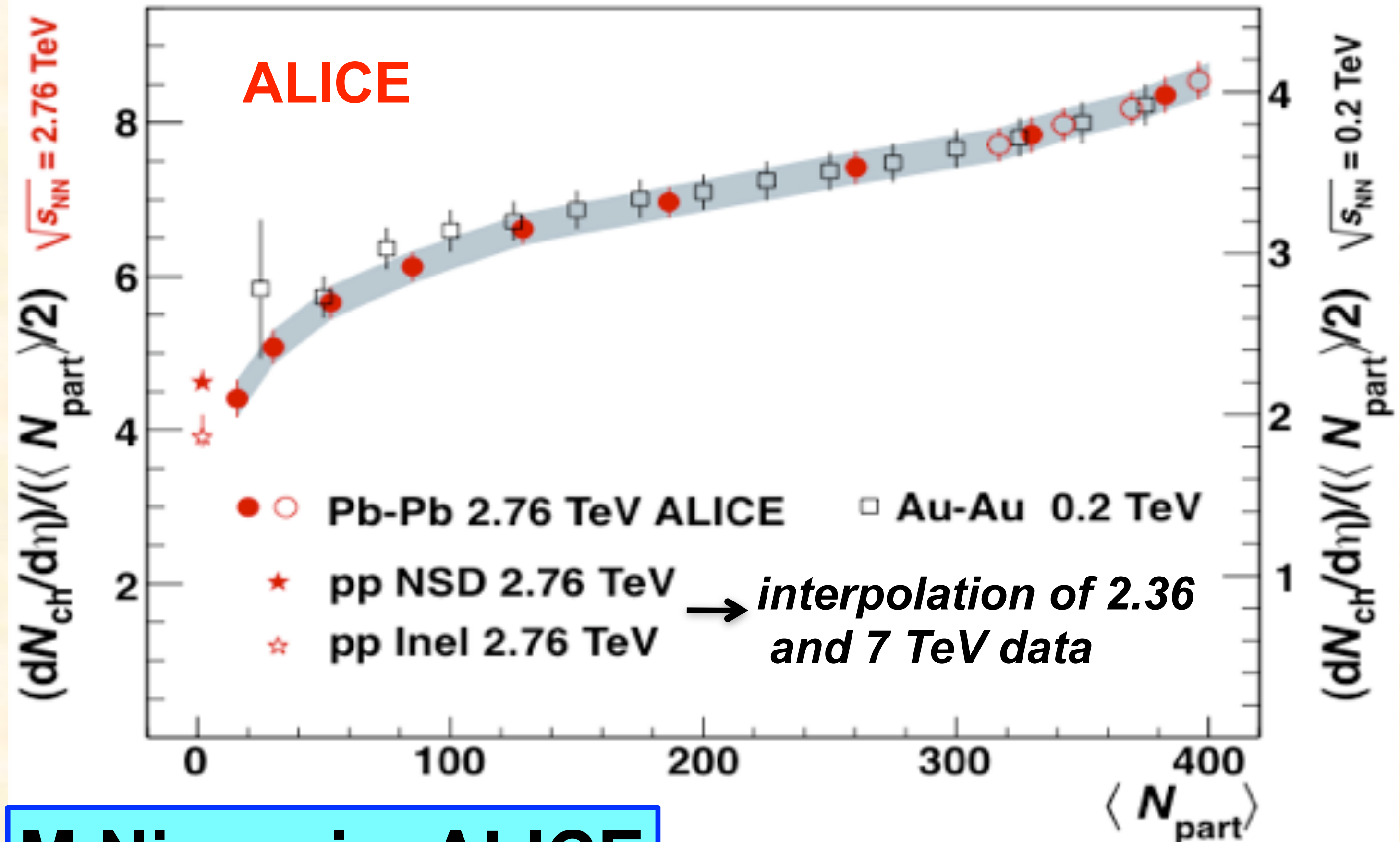
S.White, ATLAS

M.Nicassio, ALICE



agreement among experiments

Centrality dependence of multiplicity



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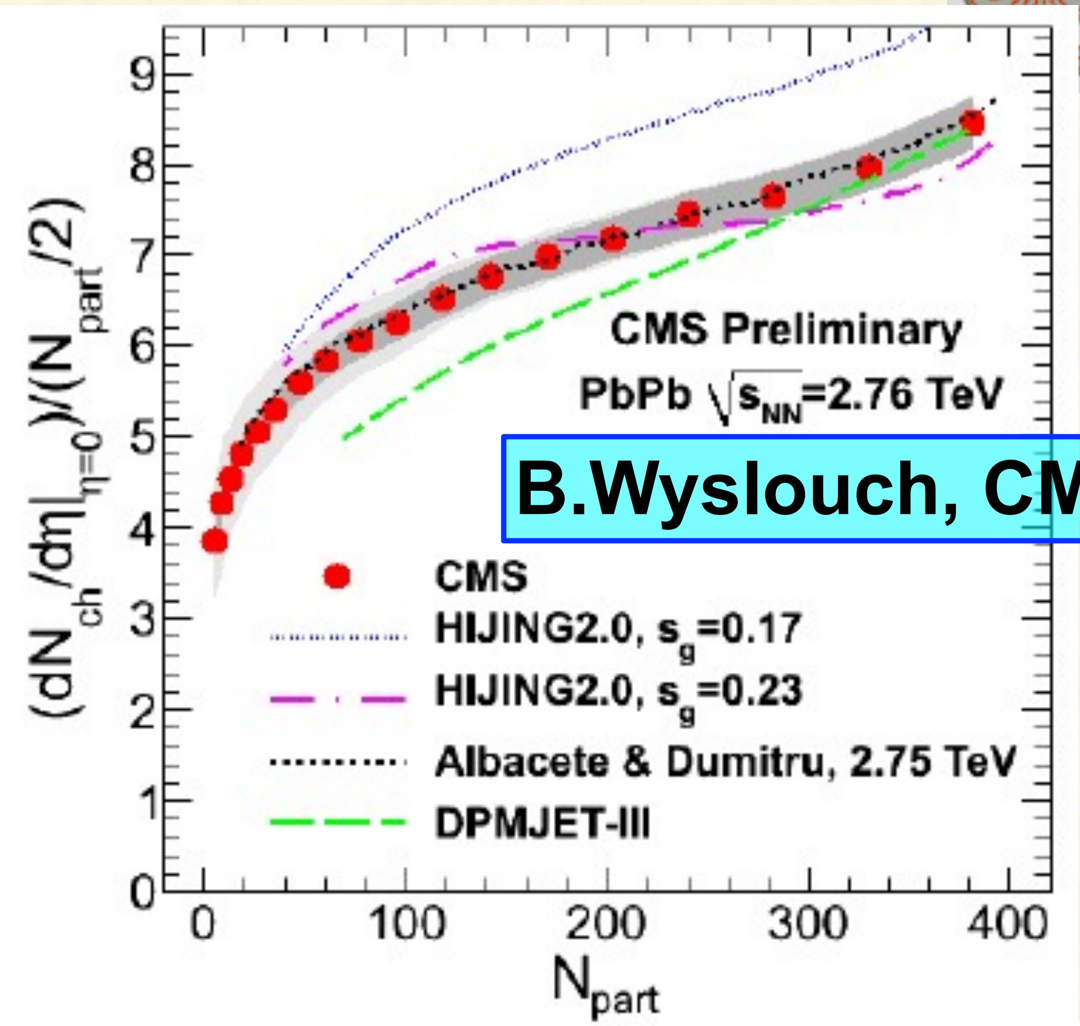
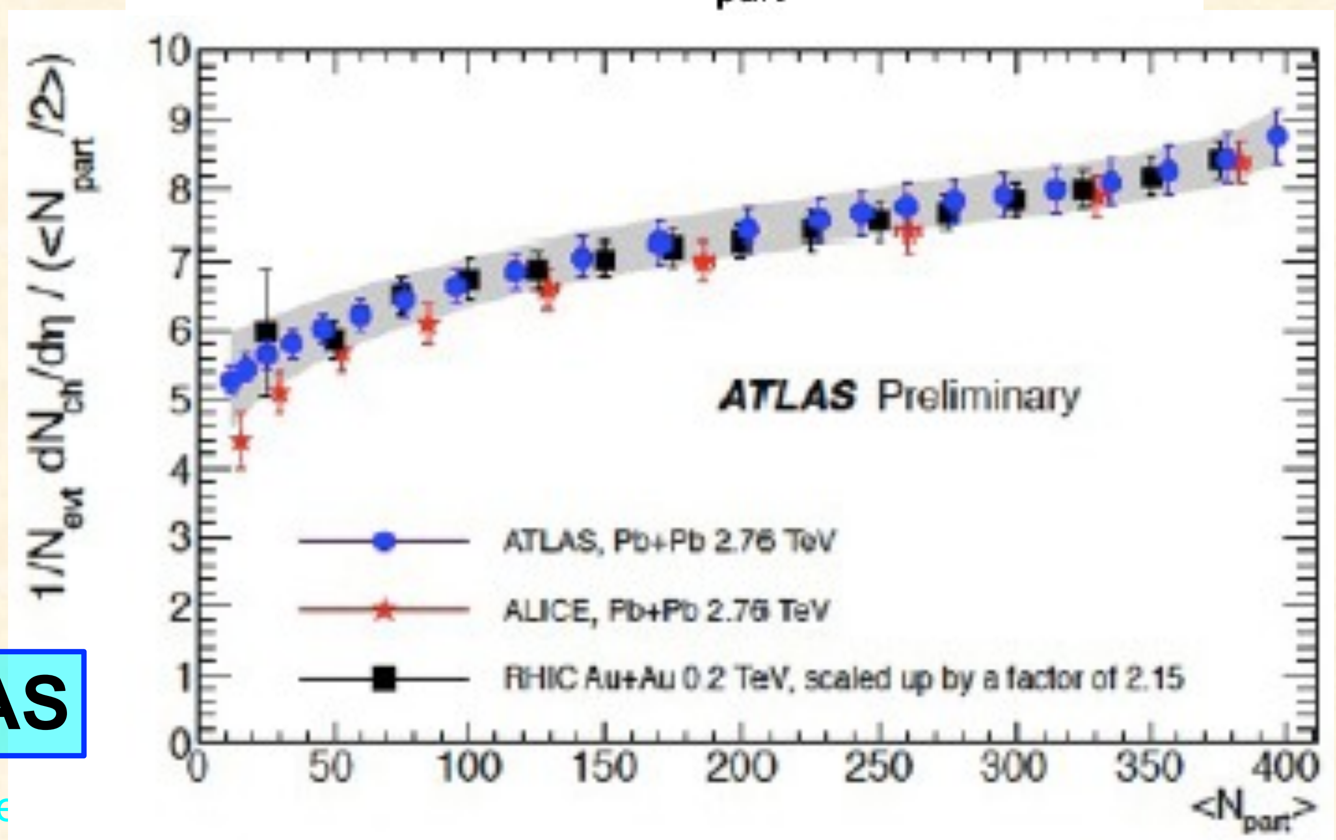


B.Wyslouch, CMS



S.White, ATLAS

Measurement of Flow and Correlations(ATLAS)

Event Plane method:

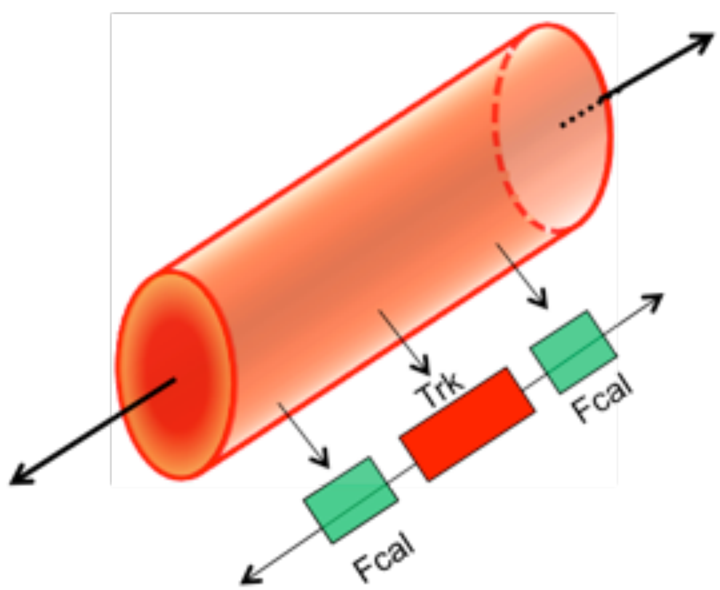
- Correlate tracks at |η|<2.5 with EP from full FCal in 3.3<|η|<4.8 full FCal method
- Correlate tracks at η>0 with EP from FCal at η<0 and vice versa $FCal_{P(N)}$ method

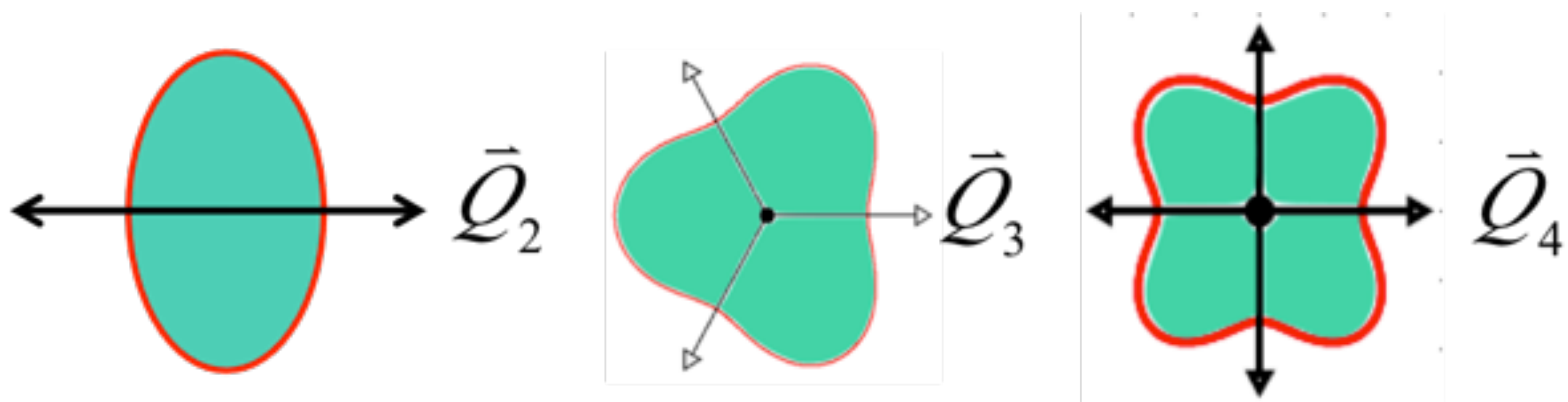
The latter significantly increase the η gap between track and FCal: <Δη> =3 to 5

Two-particle correlation method:

- Charged particle pairs with a large rapidity gap, e.g. |Δη|>2.

8 μb^{-1} Pb+Pb data from fall 2010 (48 M events)





- v_n^{obs} measured by correlation of tracks with n^{th} flow vector Q_n at FCal
- Followed by a resolution correction

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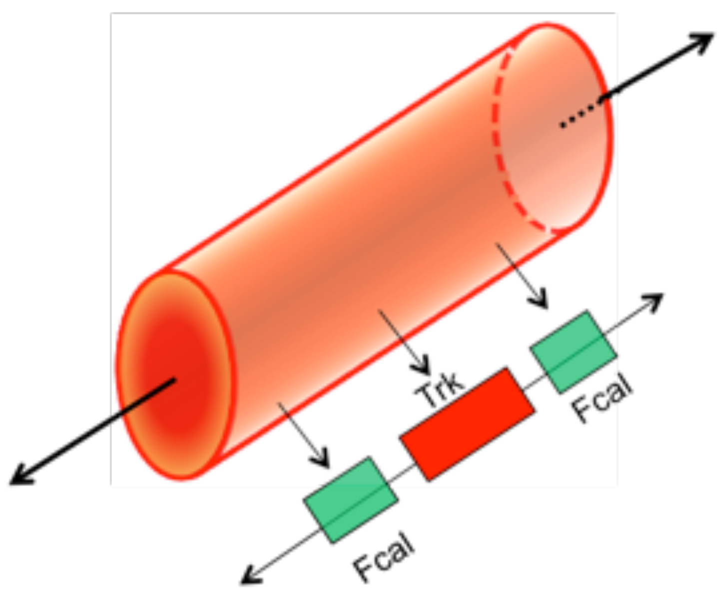

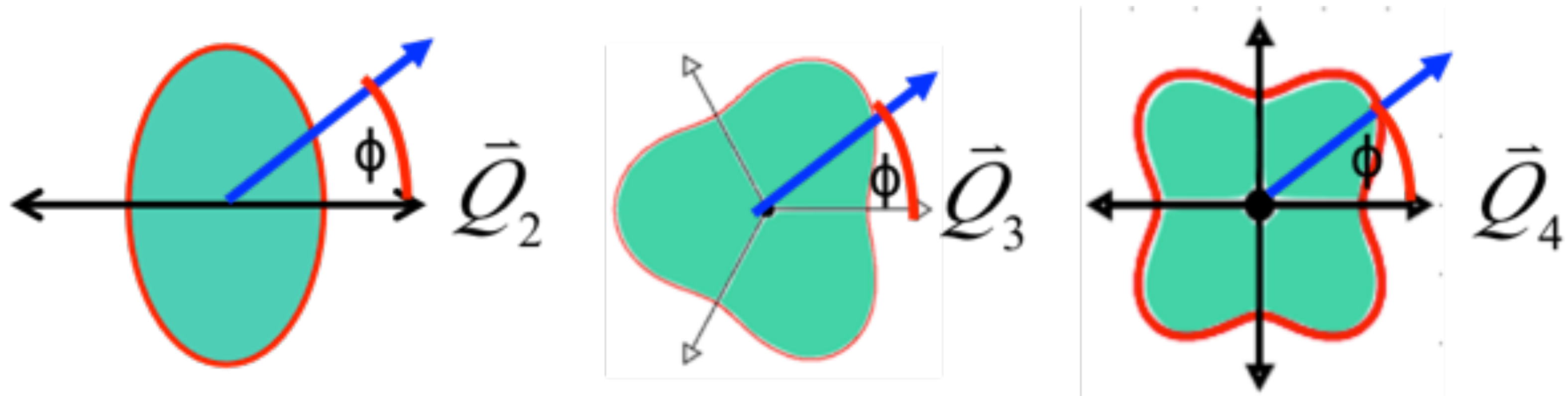

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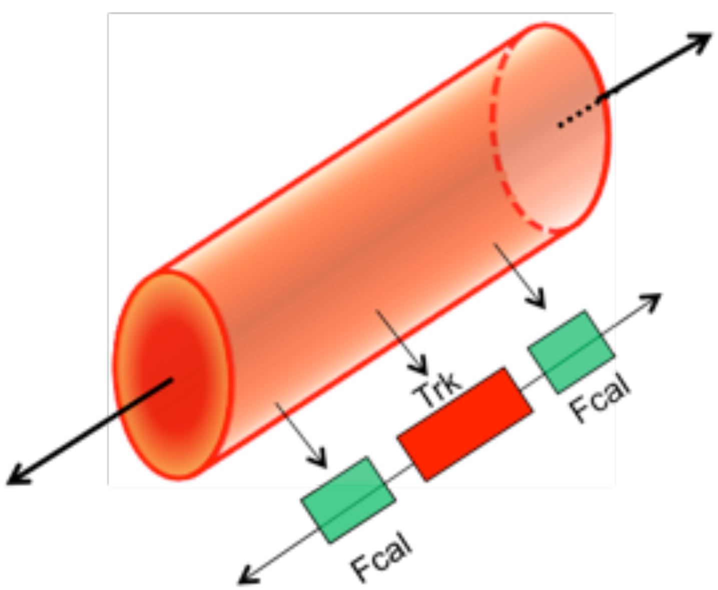
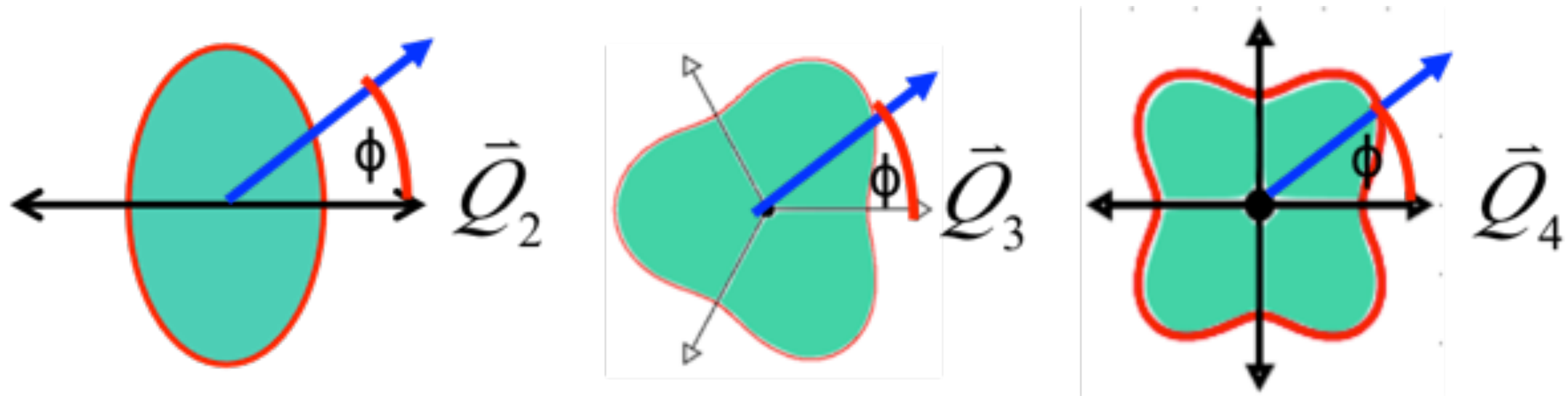
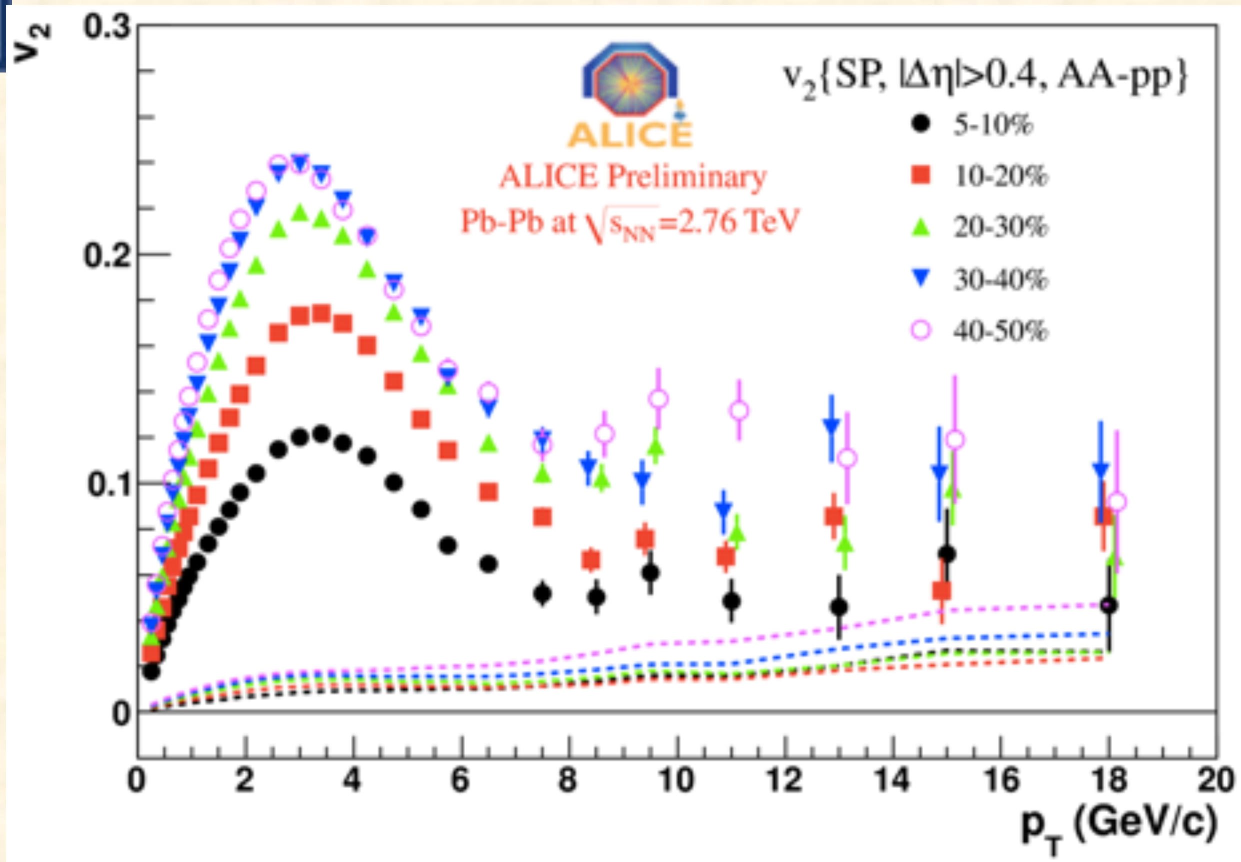




$$v_n = \frac{v_n^{\mathrm{obs}}}{\mathrm{Res}\{\Psi_n\}} = \frac{\langle \cos n(\phi - \Psi_n)\rangle}{\langle \cos n(\Psi_n - \Psi_{\mathrm{RP},n})\rangle}$$

- v_n^{obs} measured by correlation of tracks with n^{th} flow vector Q_n at FCal
- Followed by a resolution correction

v_2 at high p_t



J.Harris, ALICE

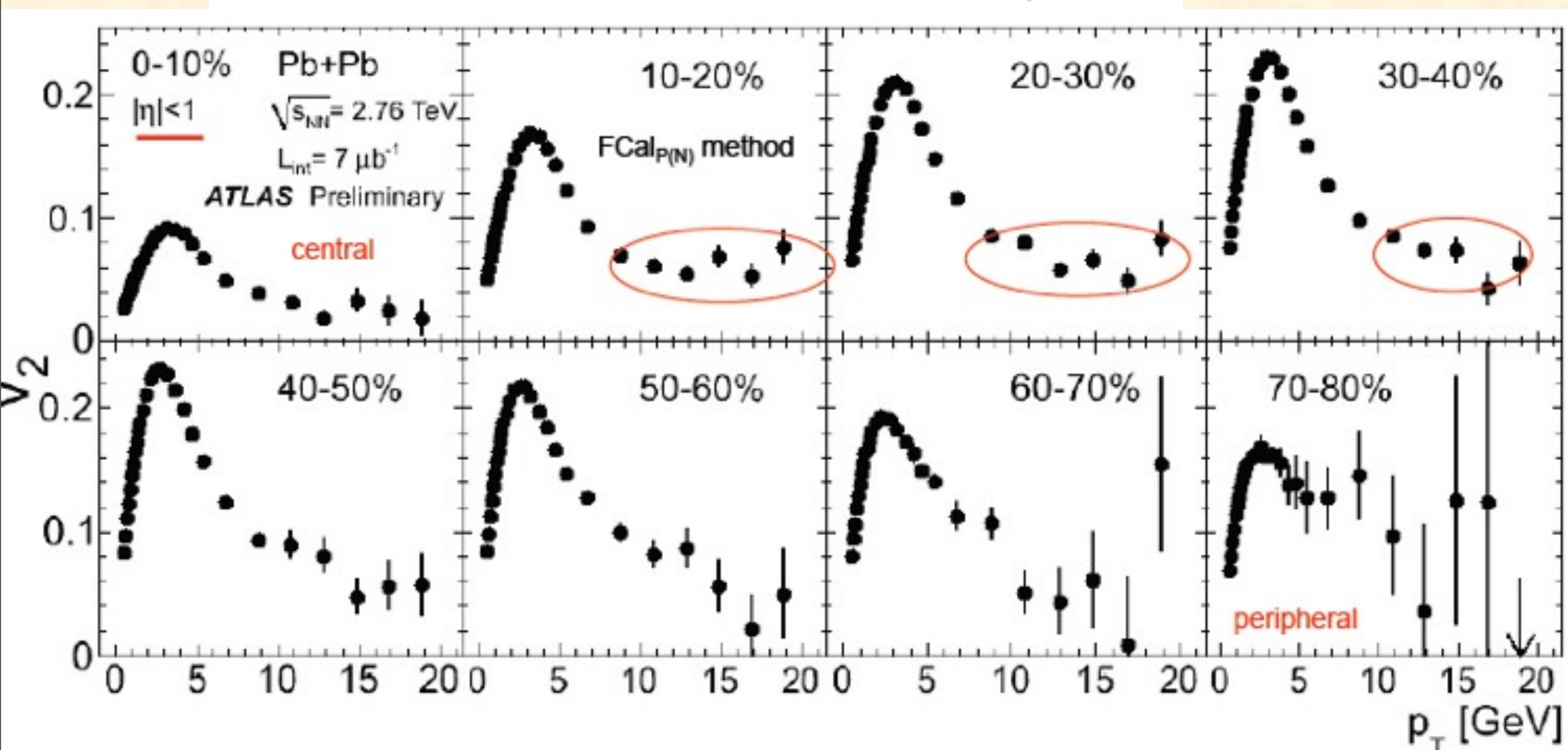
Characteristics:

v_2 inceases (up to ~ 3 GeV/c)

v_2 decreases (3 – 8 GeV/c)

v_2 ~ flat beyond

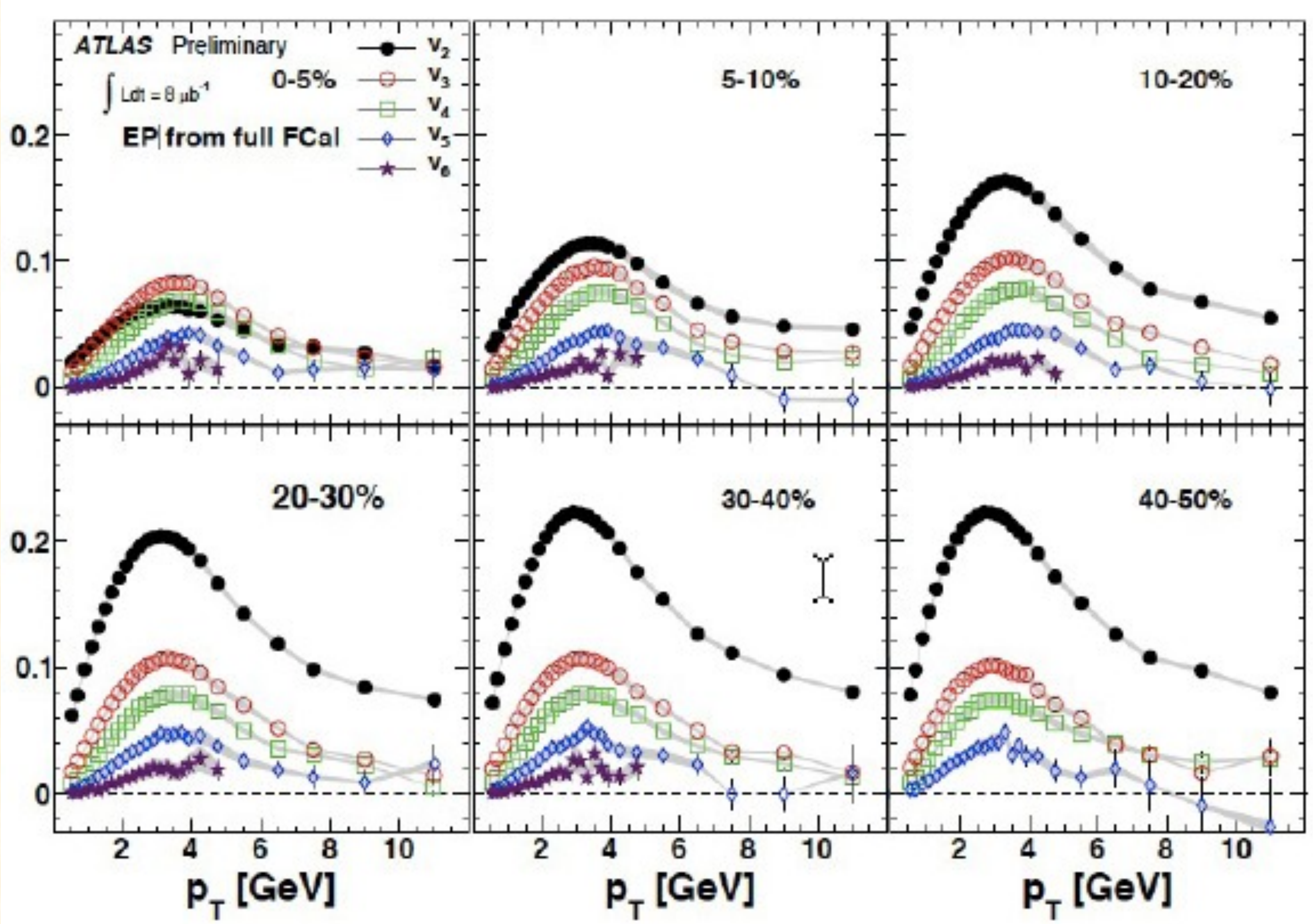
Expected centrality dependence



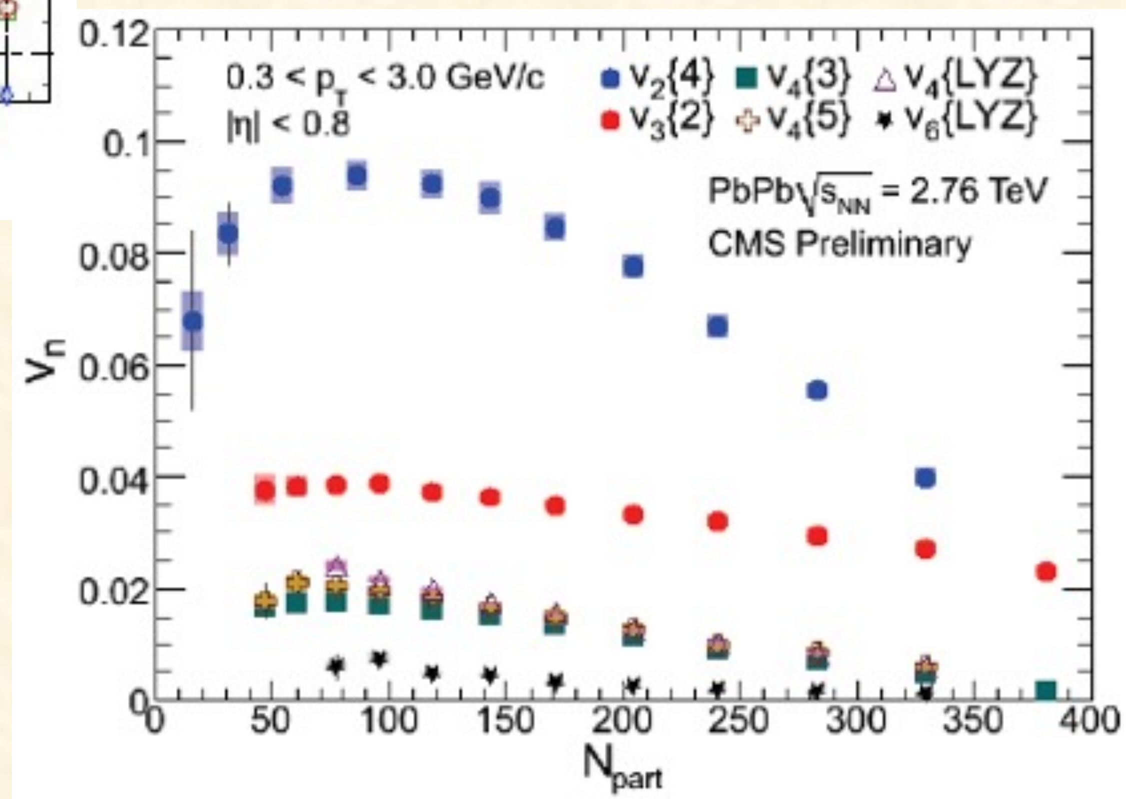
S.White, ATLAS

Higher harmonics

S.White, ATLAS



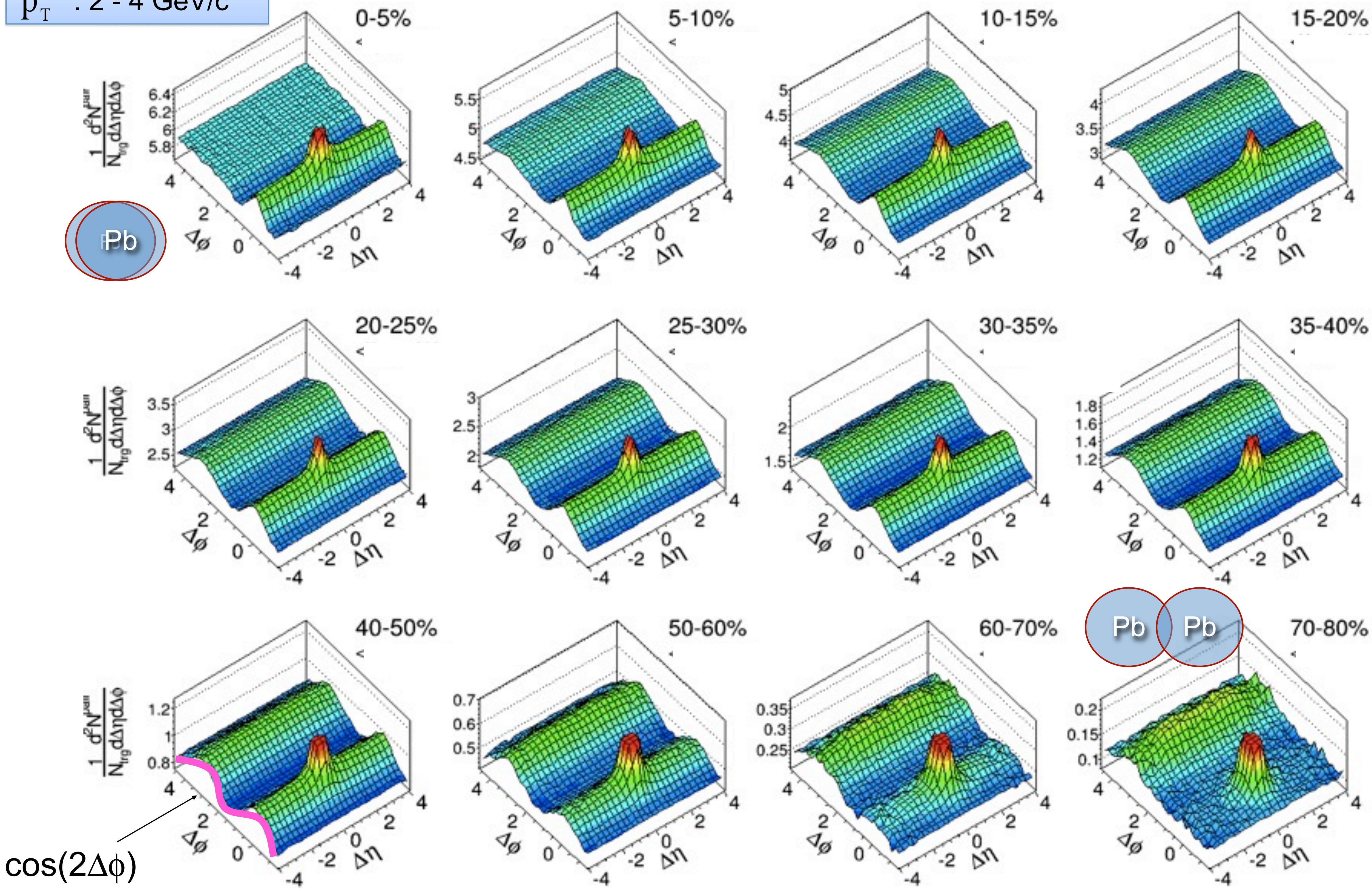
M.Issah, CMS



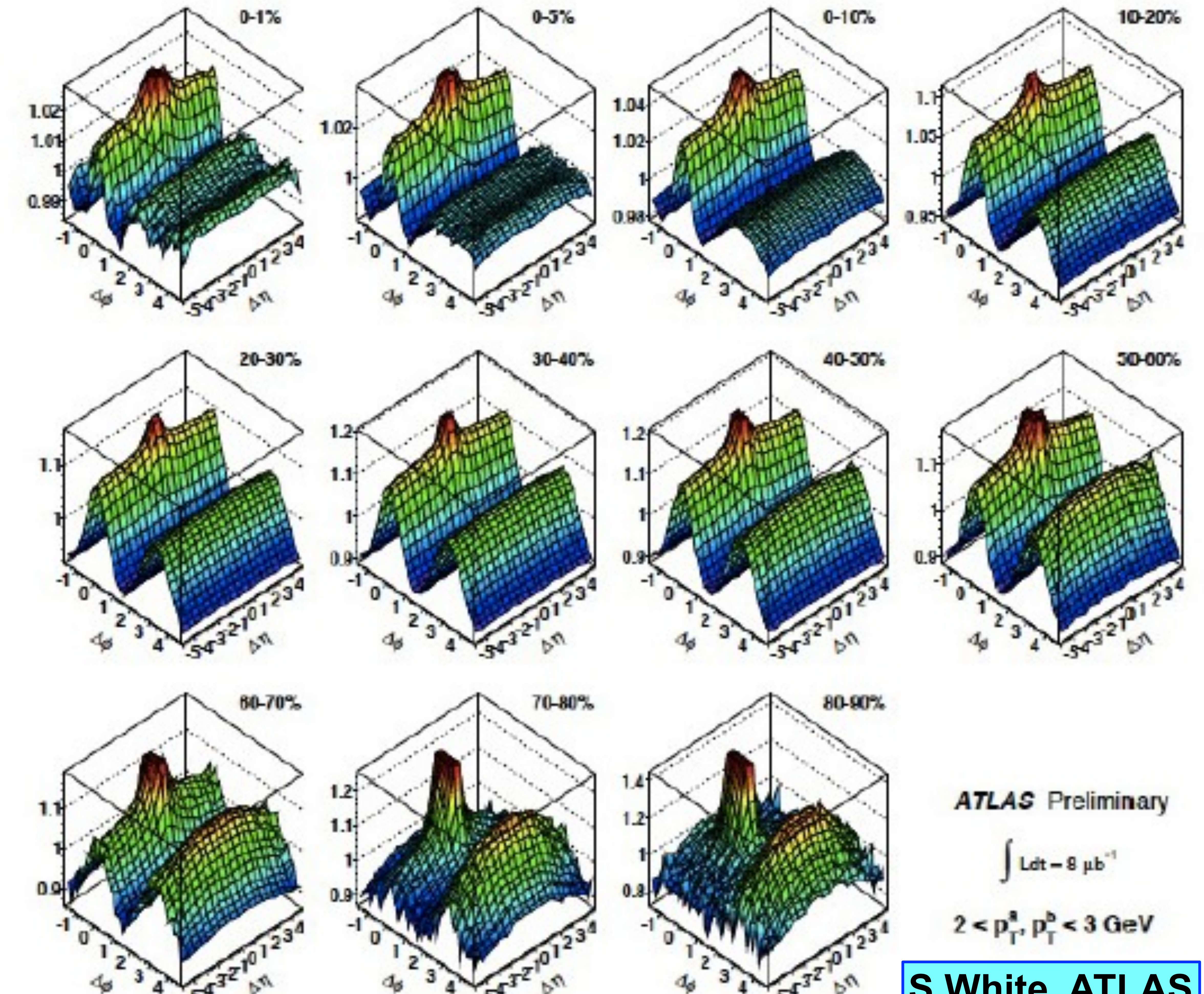
Triggered dihadron correlations in PbPb

p_T^{trig} : 4 - 6 GeV/c
p_T^{assoc} : 2 - 4 GeV/c

PbPb 2.76 TeV



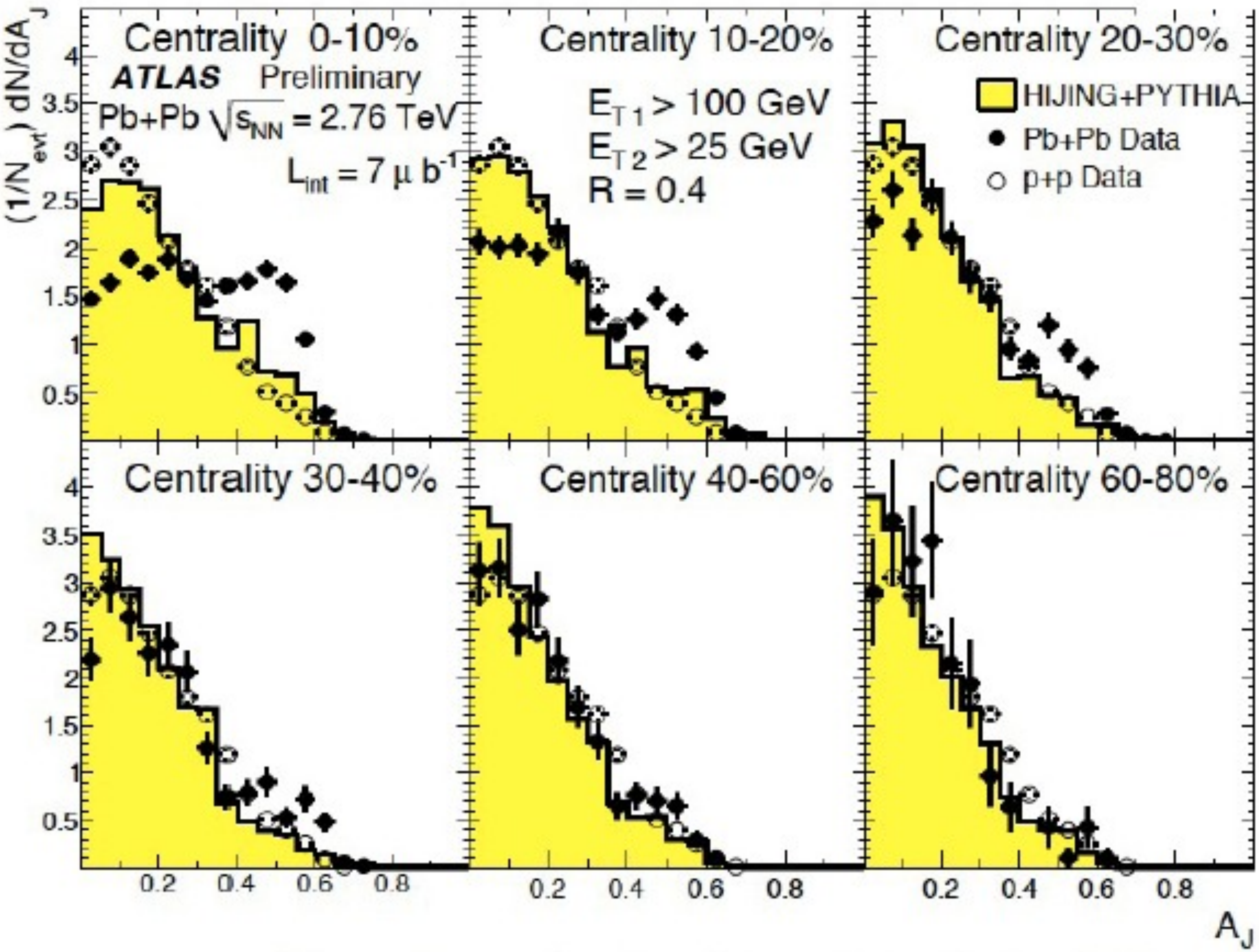
J.Callner, CMS



S.White, ATLAS

Dijet Asymmetry (R=0.4)

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

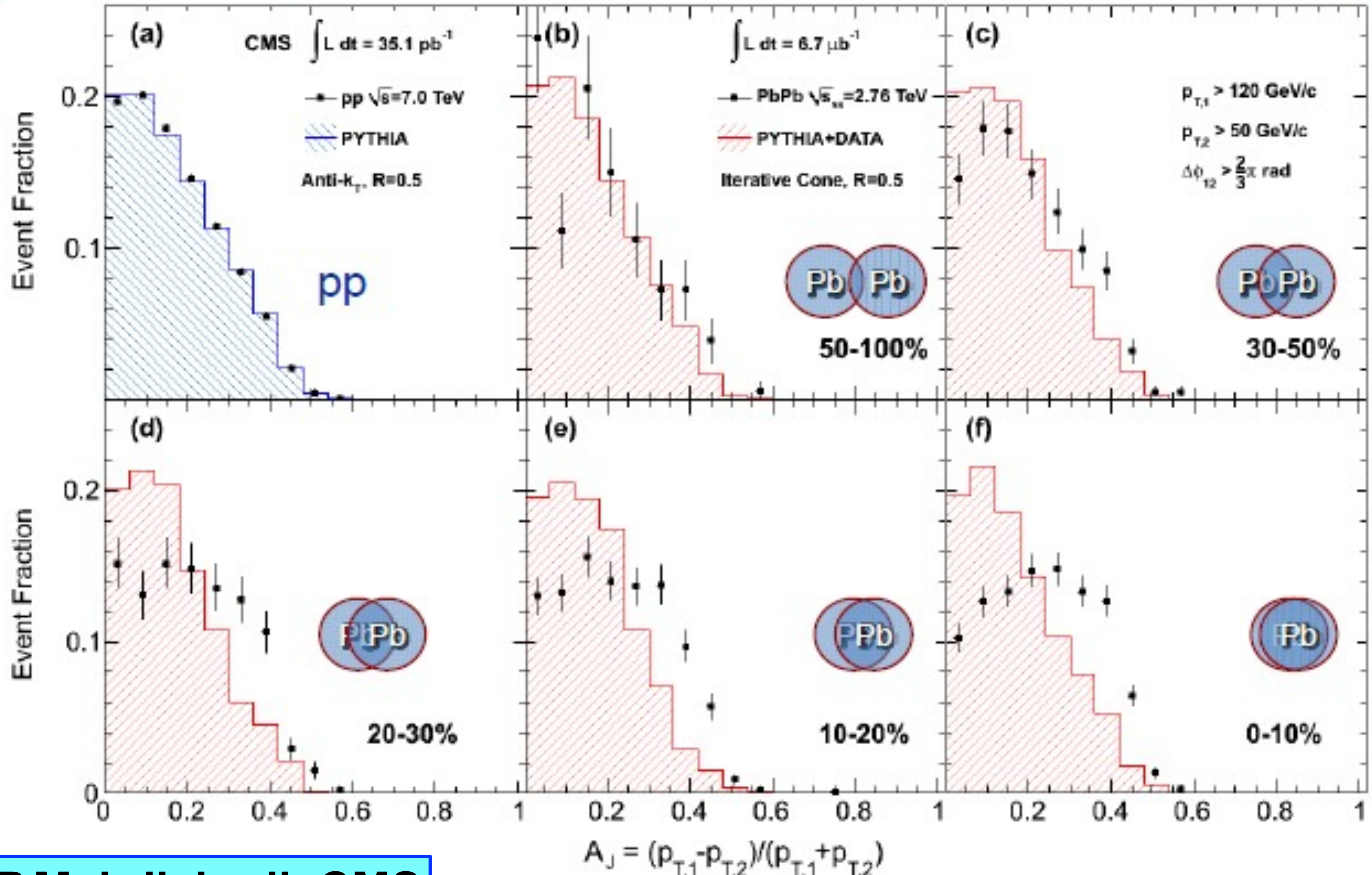


ET1> 100GeV

Phys. Rev. Lett. 105, 252303 (2010)

S.White, ATLAS

Dijet energy imbalance: CMS



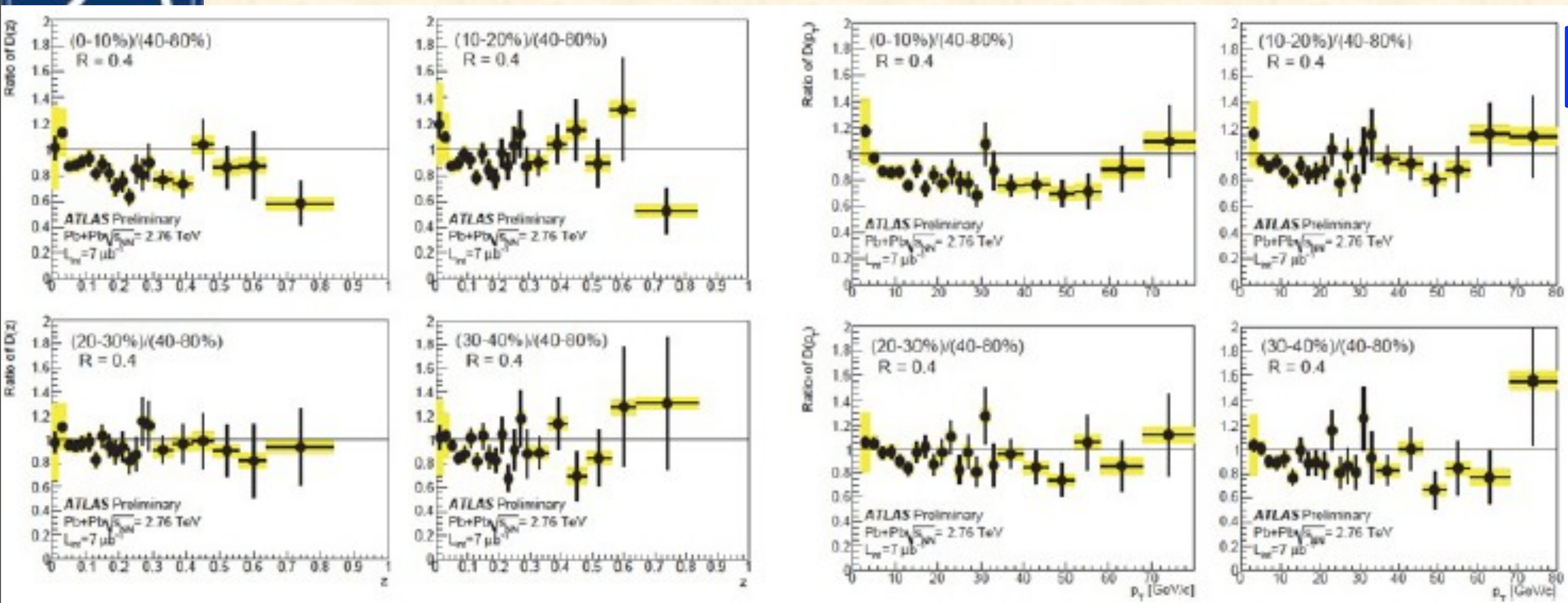
S.P.Mehdiabadi, CMS

Parton energy loss is observed as a pronounced energy imbalance in central PbPb

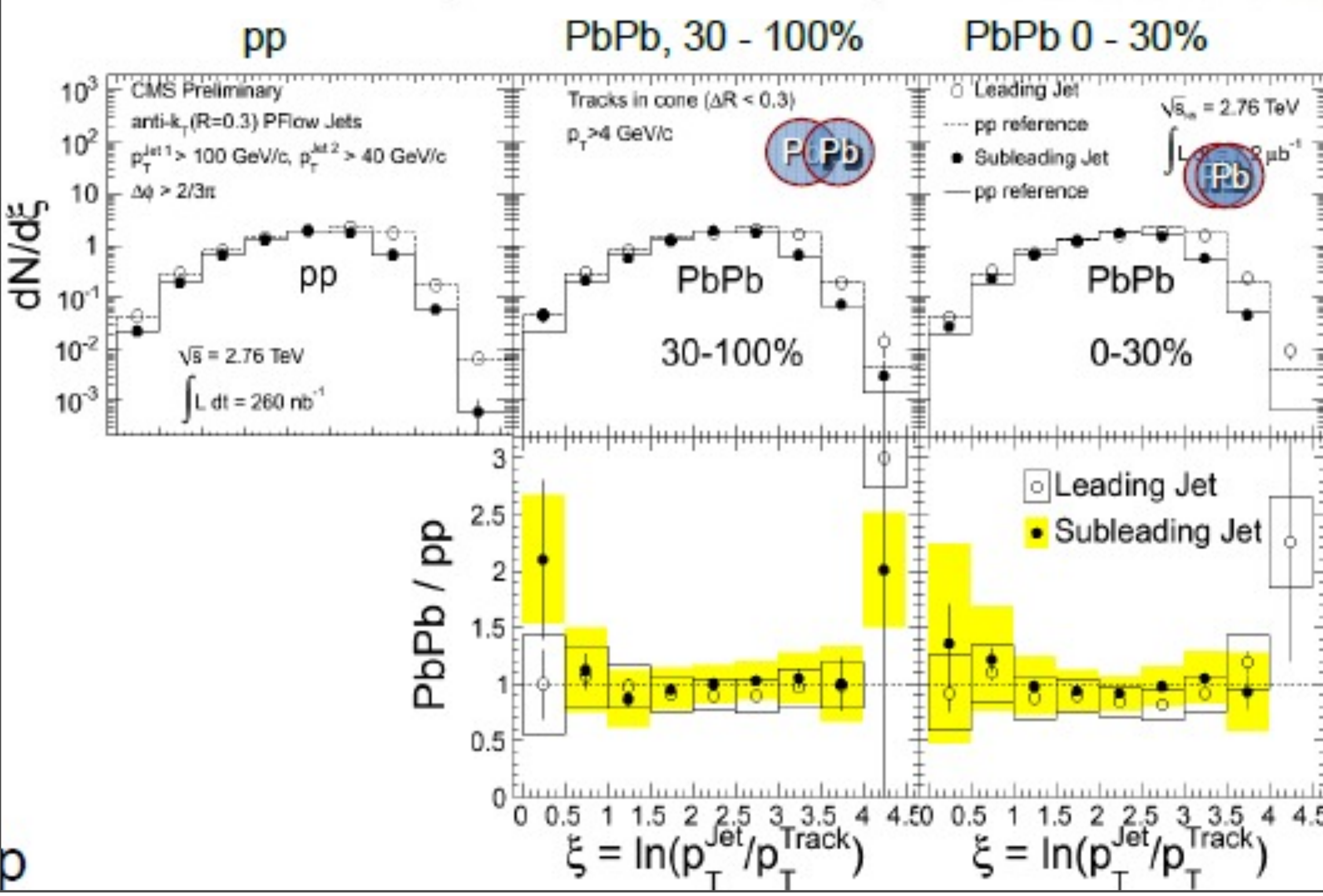
arXiv:1102.1957 Submitted to PRC

B.Wyslouch, CMS

Jet fragmentation functions



S.White, ATLAS

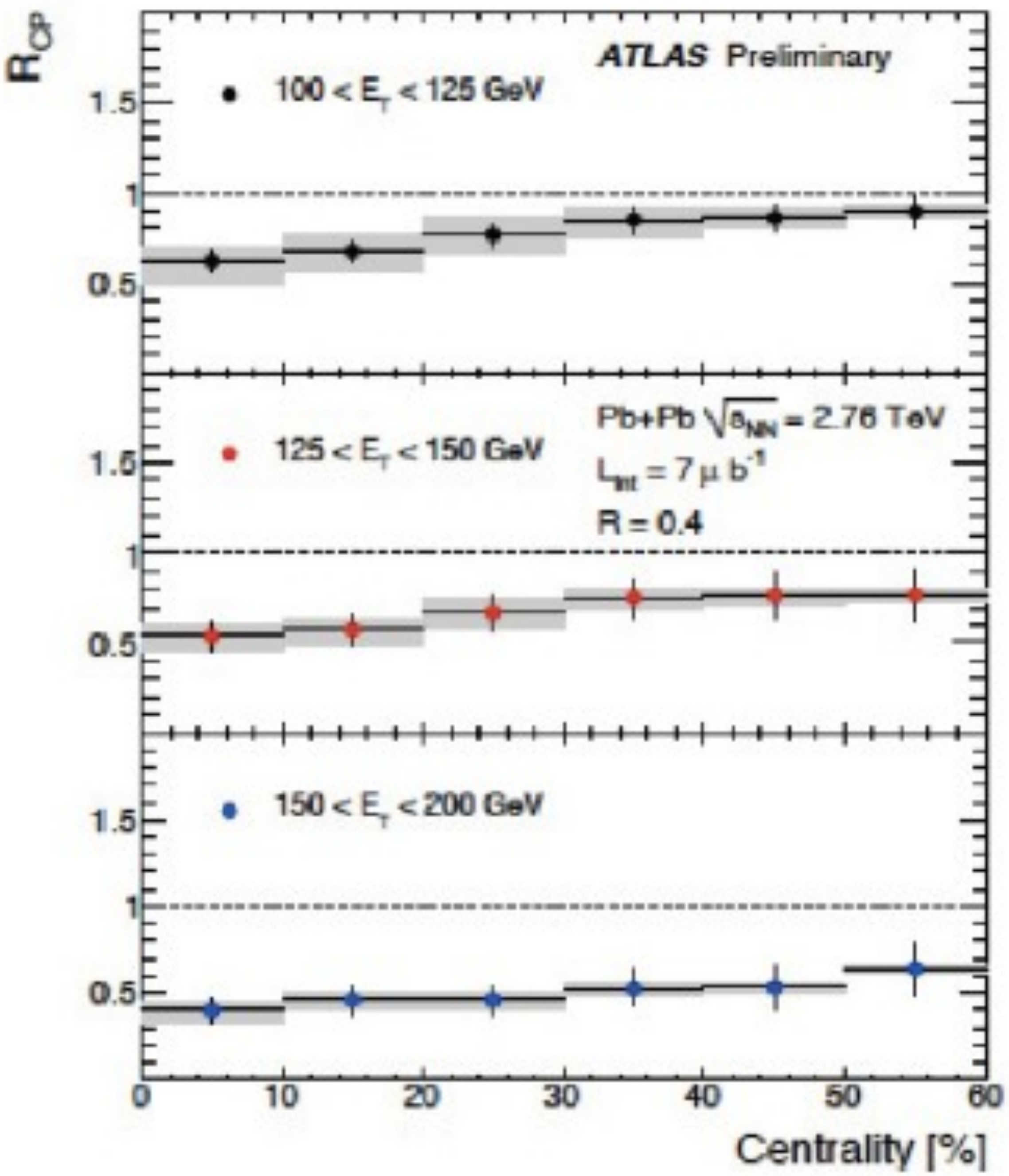


Fragmentation functions for pp and PbPb (CMS) or for different centralities (ATLAS) – very similar fragmentation in vacuum

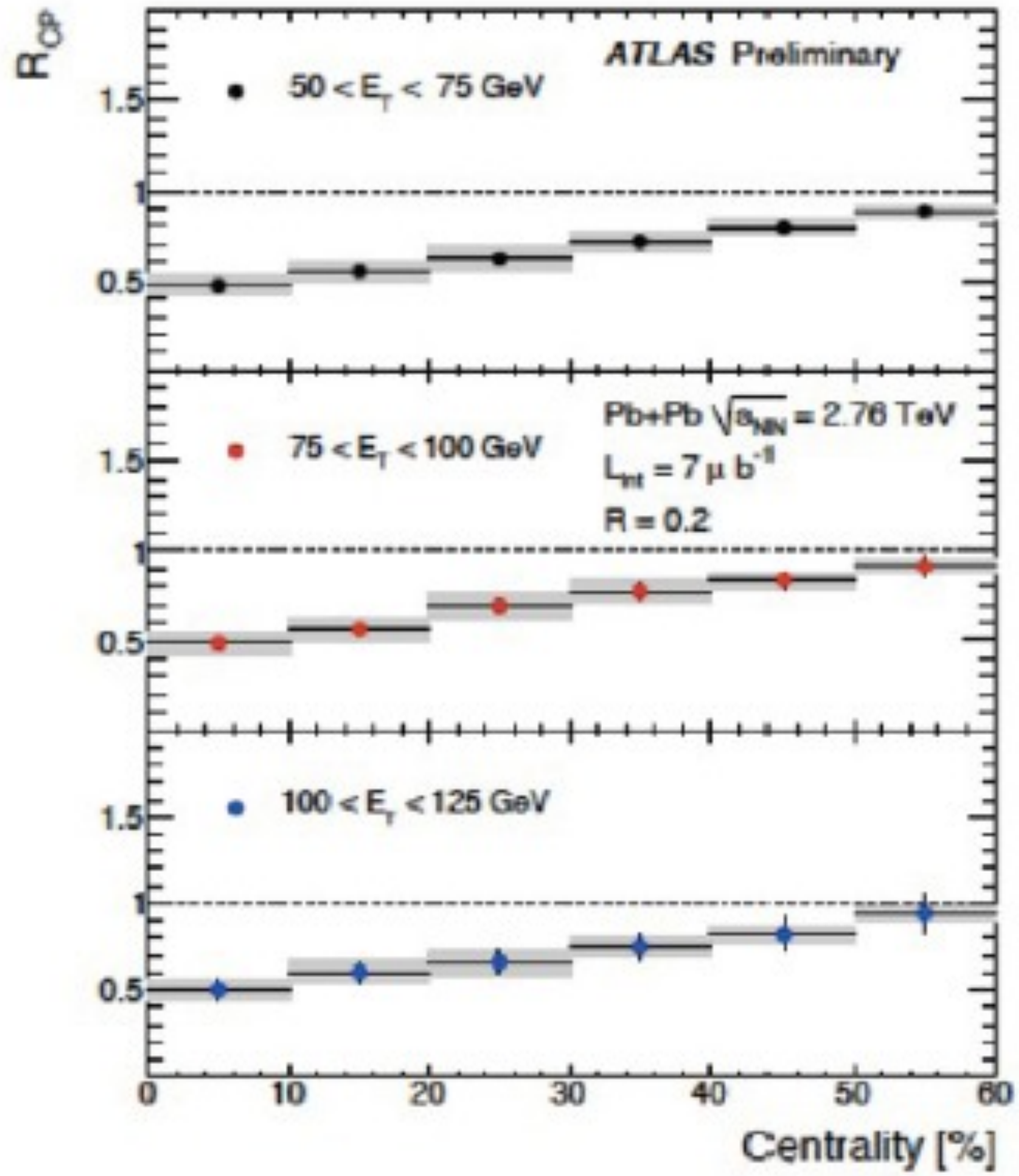
Modification happened "outside the jet"

S.P.Mehdiabadi, CMS

Inclusive Jet Yields



cone size, R=0.4



cone size, R=0.2

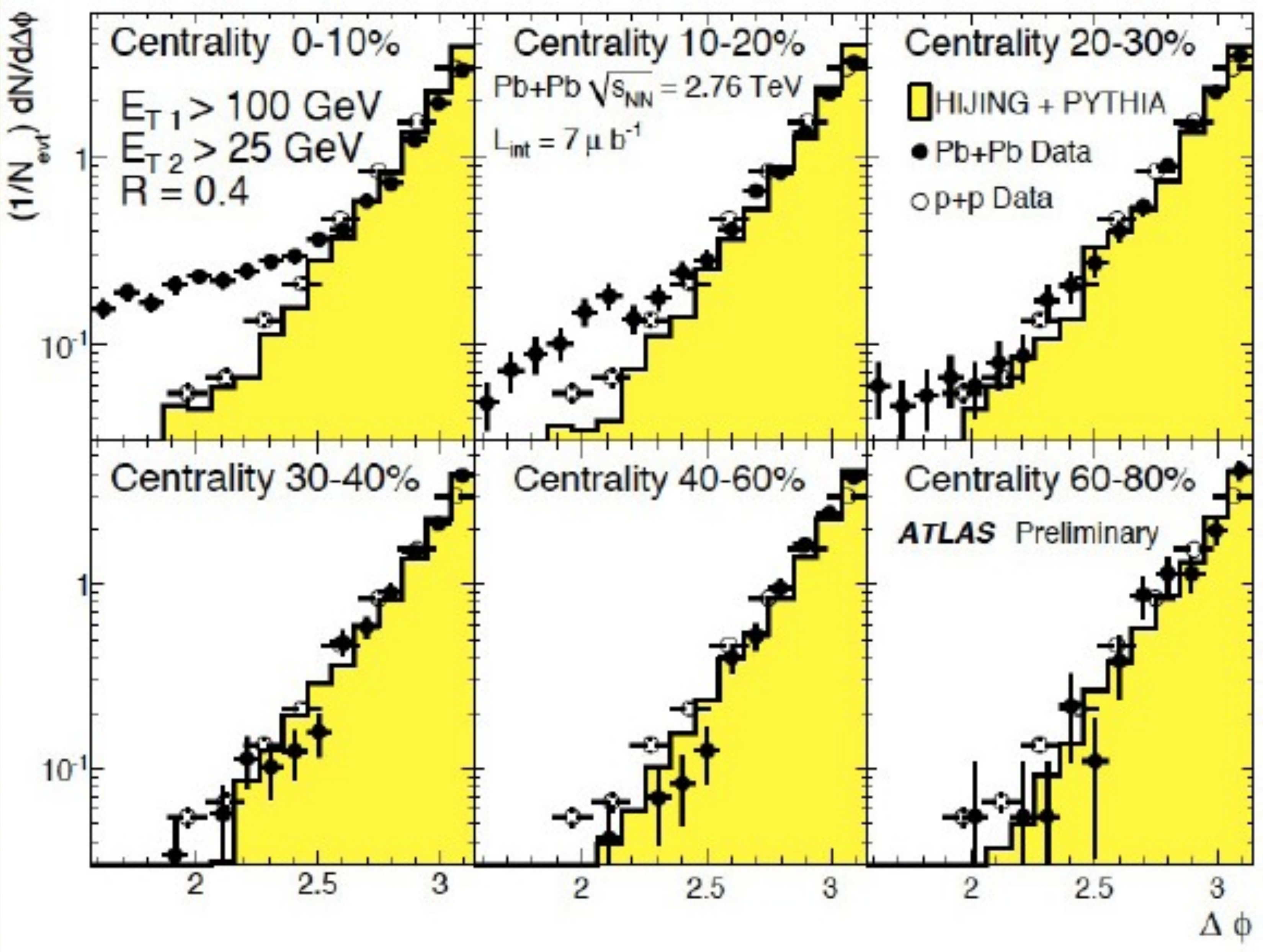
- Suppression by factor ~2 of entire jet. Not just leading hadron.
- Doesn't depend strongly on cone size.

$$R_{CP} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

S.White, ATLAS

Jet angular correlations

S.White, ATLAS

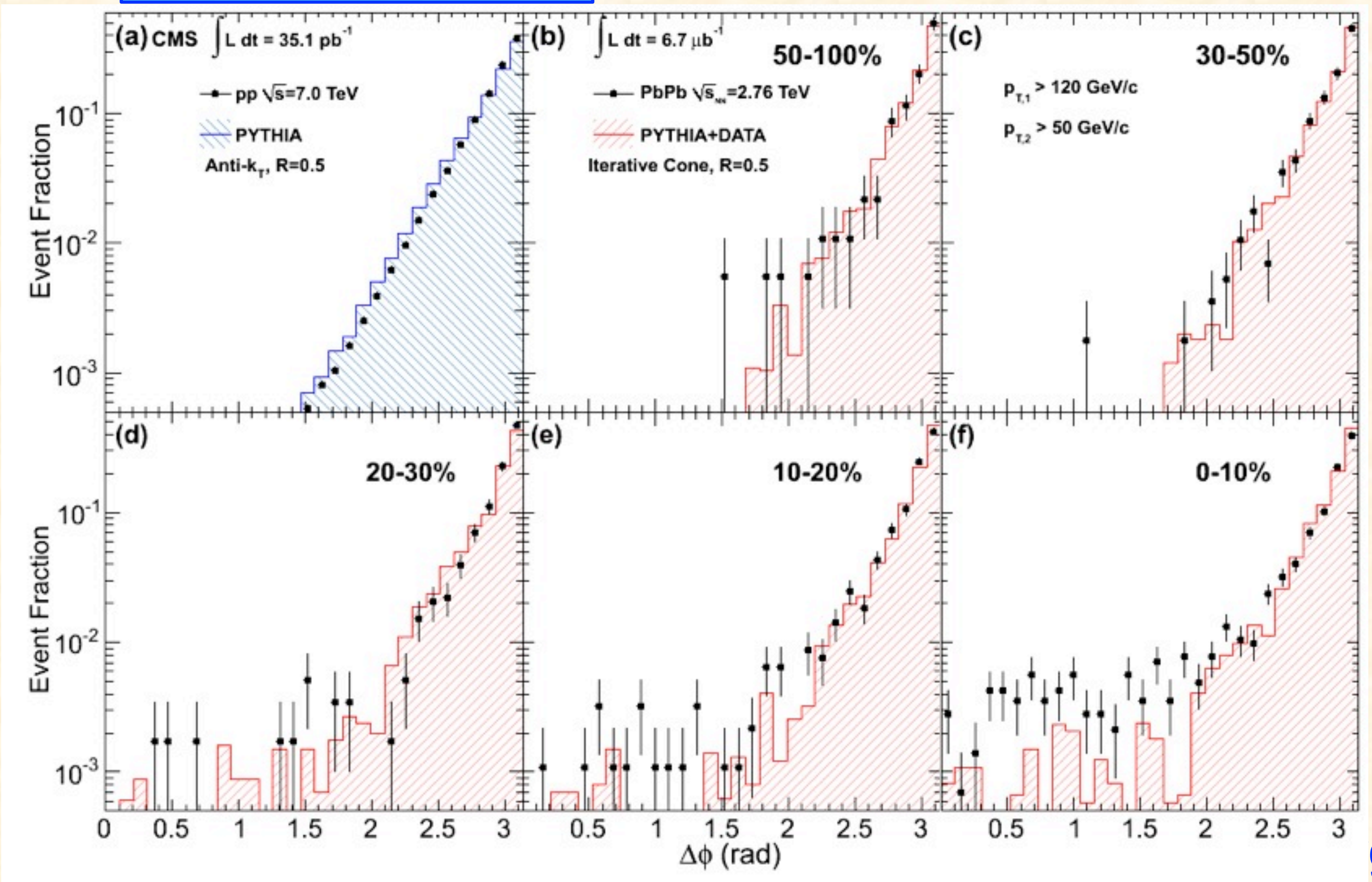


In most central events ~ 50% of jets are suppressed, still most of those which lost large fraction of energy are well aligned in φ! Shown also by CMS at QM

Jet angular correlations

S.P.Mehdiabadi, CMS

S.White, ATLAS



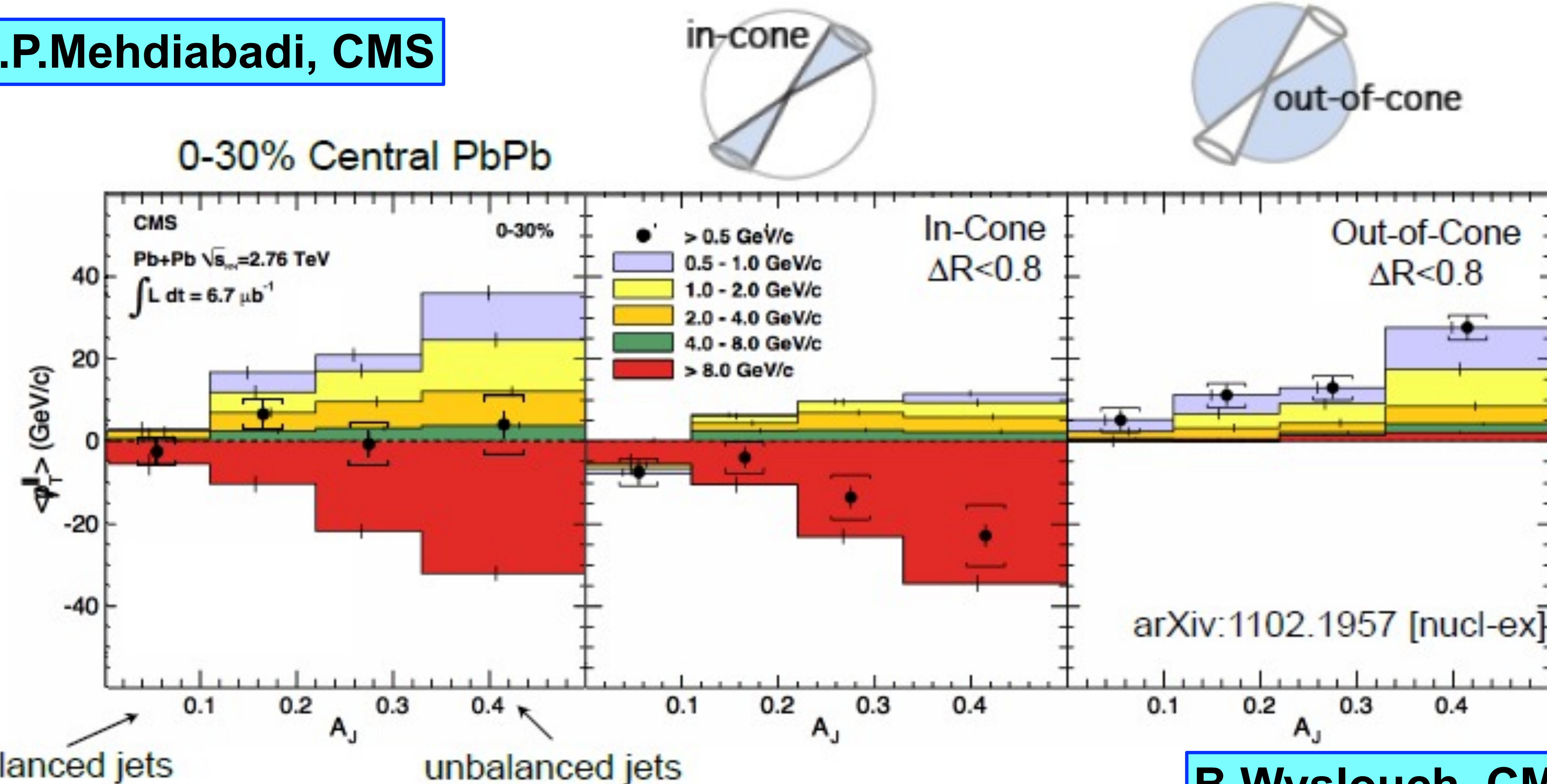
d,

gy

are well aligned in ϕ! Shown also by CMS at QM

Missing-$p_T^{||}$

S.P.Mehdiabadi, CMS

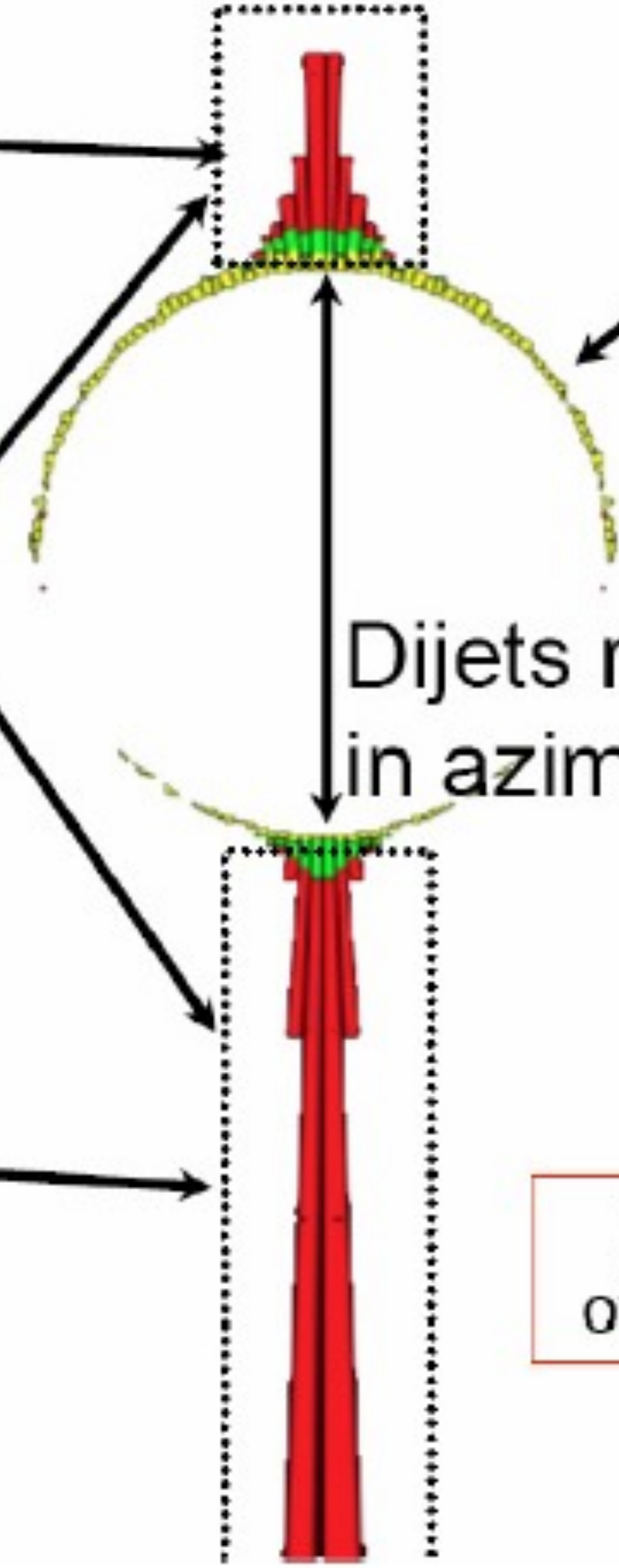


B.Wyslouch, CMS

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

The momentum difference in the dijet is balanced by low p_T particles at large angles to the jet axis

Jet “quenching”: what have we learned so far?



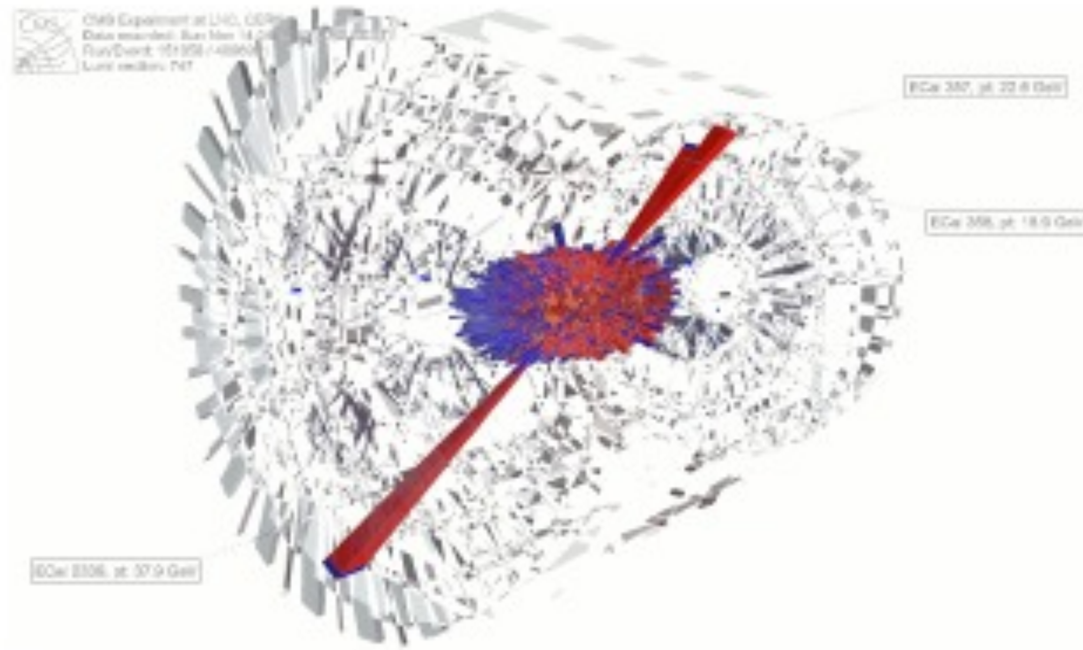
Experimental characterization of energy flow in dijet final states

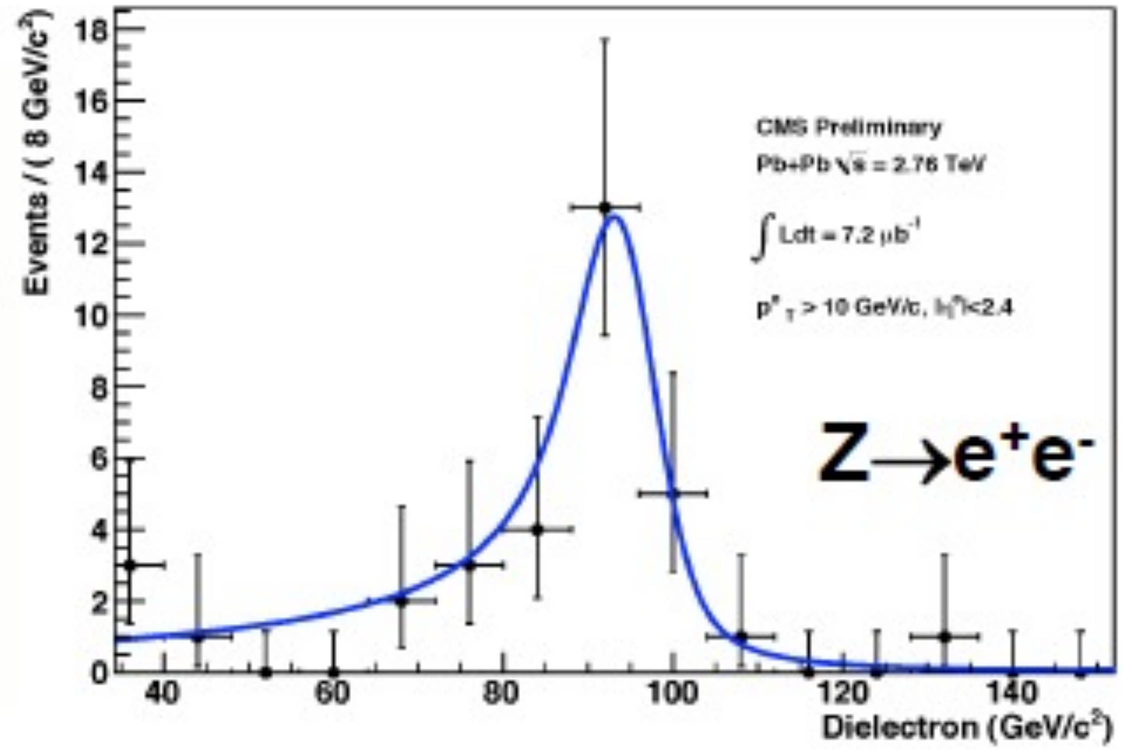
B.Wyslouch, CMS

S. Mehdiabadi

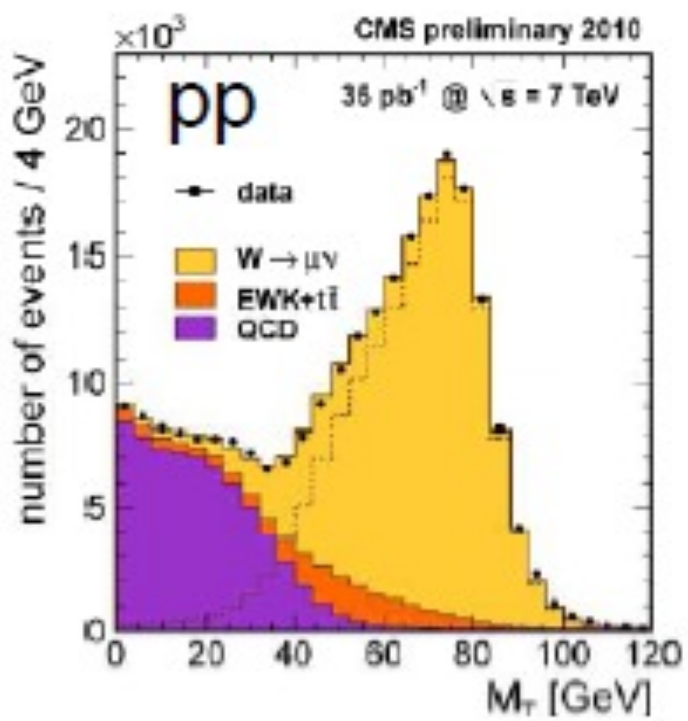
$Z^0 \to e^+e^-$ and $W \to \mu\nu$

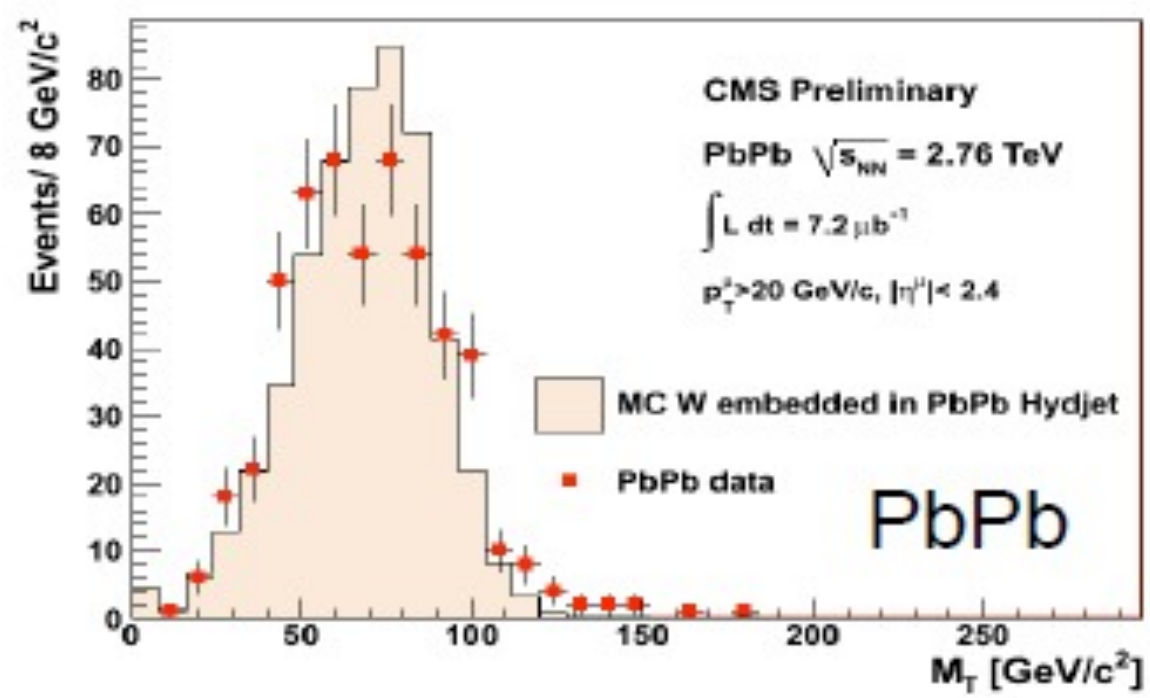
Z^0





Hint of W±

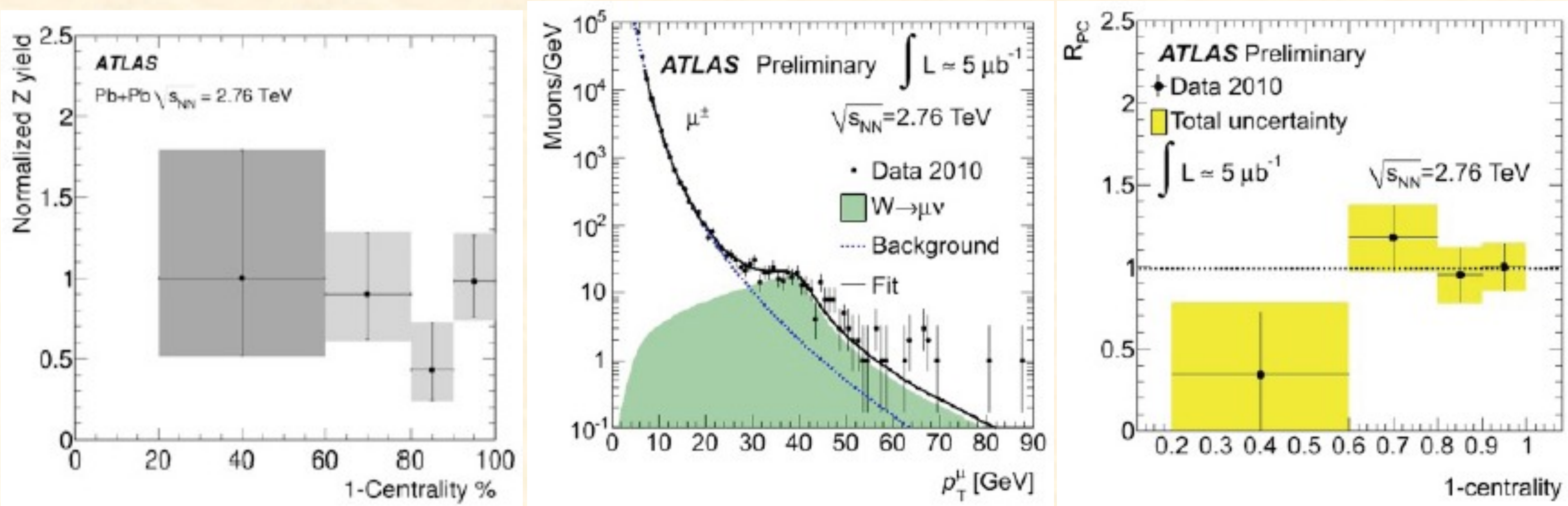




$$M_T = \sqrt{2 p_{T\mu} p_{T\nu} (1 - \cos\phi_{\mu\nu})}$$

B.Wyslouch, CMS

Z and W from ATLAS



S.White, ATLAS

Z and W yields consistent with binary collision scaling

Conclusions

General

- experimentally clear picture emerging of energy loss in medium. Interpretation remains challenging. Tools within the experiments to address critiques of analysis. Additional data from pPb and hard photoproduction will be useful.

Global observables

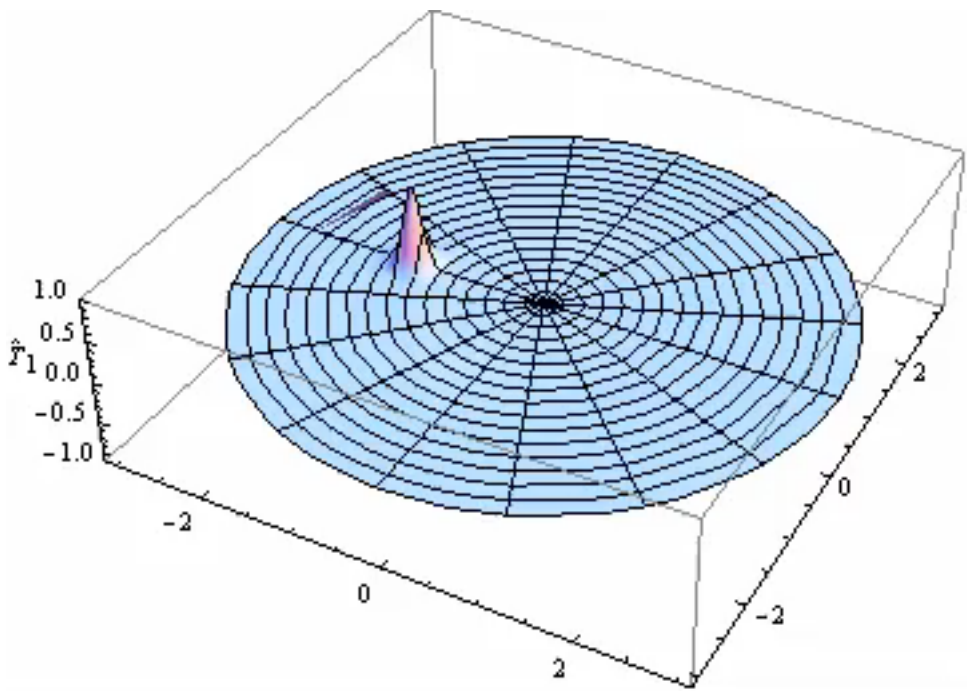
- Centrality dependence of inclusive multiplicity scales with beam energy
- Transverse momentum dependence of v_2 scales out to highest p_T (modulo large errors at RHIC)
- η dependencies of flow and multiplicity very weak within $|\eta|<2.5$
- Detailed study of higher order flow coefficients challenges ridge & cone interpretation. New information to help constrain viscous hydro models.

High p_T observables

- $W^{\pm}$ production consistent with simple scaling with N_{coll}
- Jet production systematic suppressed by a factor of ~2 relative to peripheral collision.
- Charged hadron R_{CP} measured out to 30 GeV: centrality dependence of suppression similar to jets

Thank You LHC!!

a derivation of anisotropic flow features from initial perturbations:Staig and Shuryak



Comparison to preliminary ATLAS data
Staig and Shuryak "The second act of hydro:small perturbations" arxiv: 1106.3242v2[hep-ph]. Data from J.Jia's talk at QM 2011.

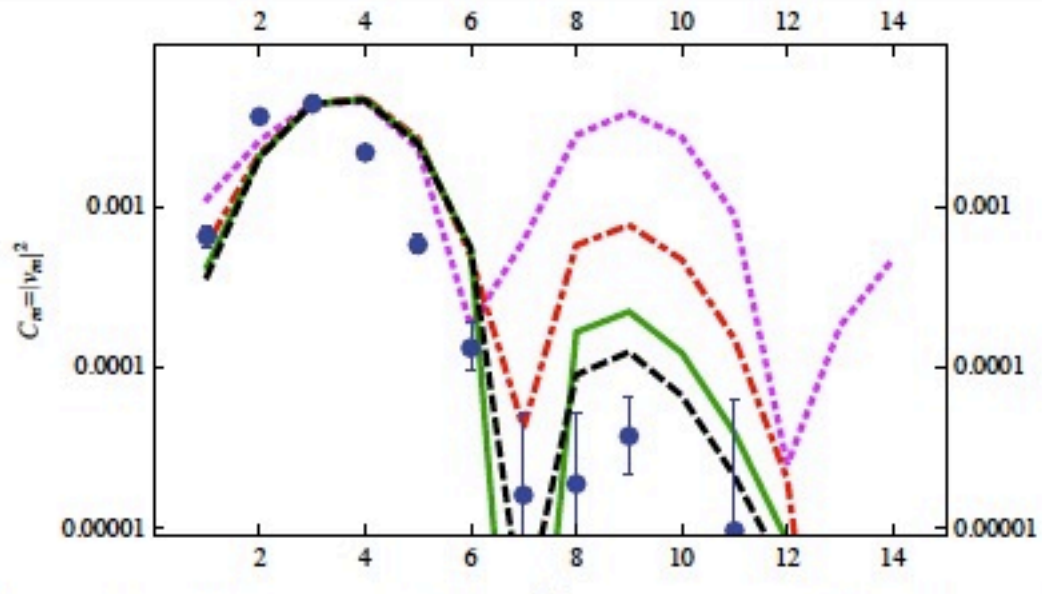


Figure 1. (Color online) The power spectrum of flow harmonics, $|v_m|^2$ versus m. The data points are preliminary ATLAS data [8]. Four curves top-to-bottom (dashed magenta,dash-dotted red, solid green and dashed blue) are our calculations for viscosity-to-entropy ratios $4\pi\eta/s = 0, 1, 1.68, 2$, respectively. All curves are normalized to the m=3 harmonics.

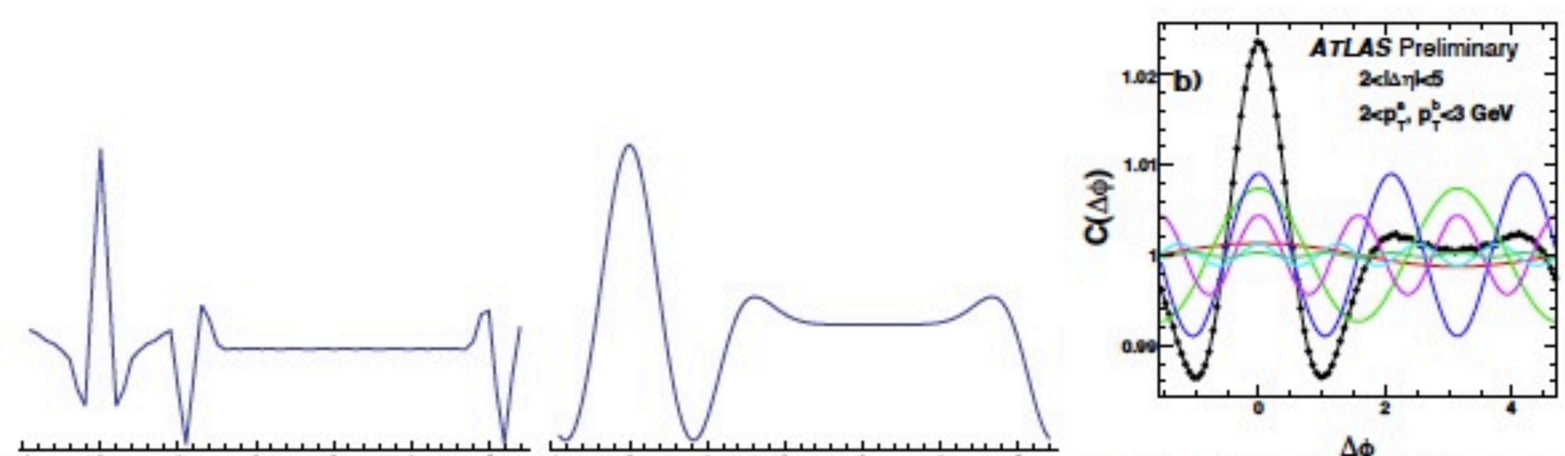
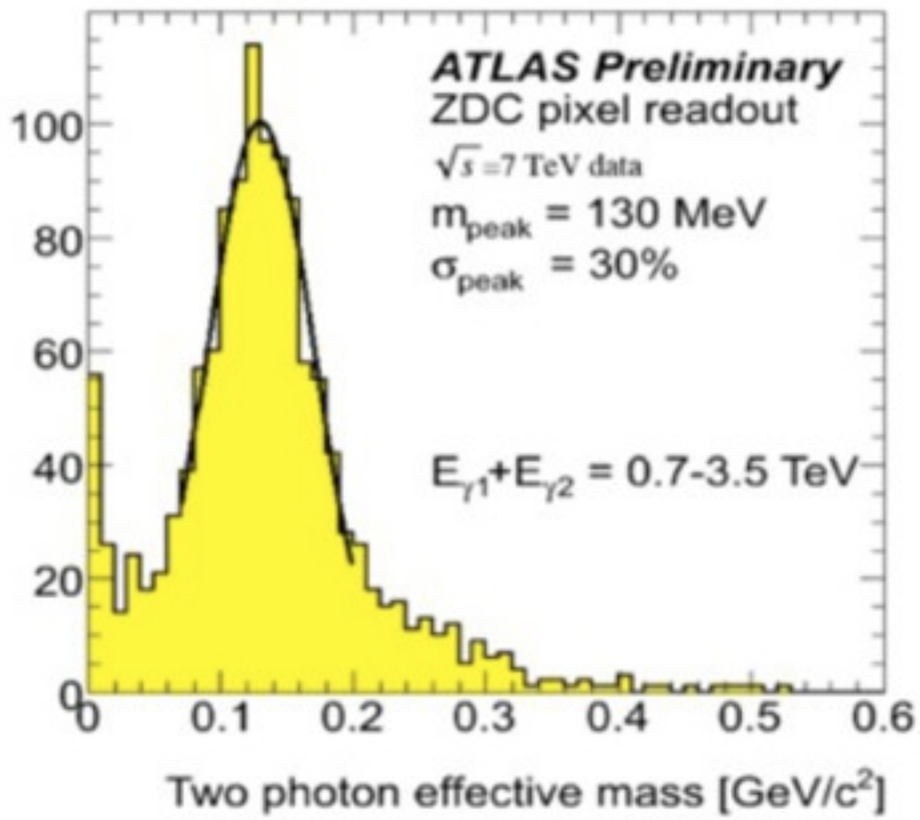


Figure 2. The two-pion distribution as a function of azimuthal angle difference $\Delta\phi$, our calculation [4]. Two left plots are for viscosity-to-entropy ratios $\eta/s = 0, 0.134$, respectively, while the right one is from ATLAS report [8]. Similar data have been reported at this meeting by all RHIC/LHC collaborations.

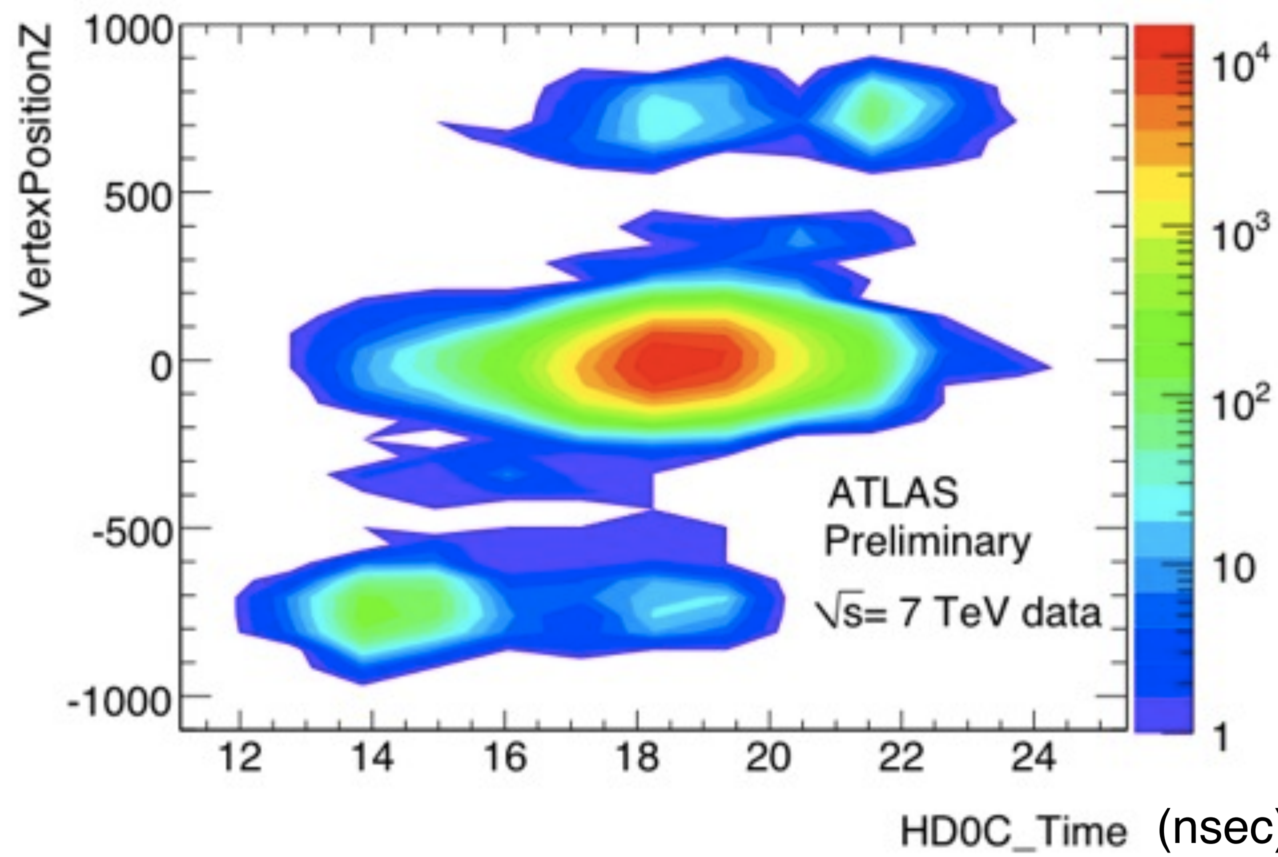
additional material

Prospects for Forward Physics

- ATLAS ZDC is a unique 3d imaging forward EM/Hadron calorimeter with good timing resolution but all 3 HI experiments have Zero Degree Calorimeters.
- Performance using early energy calibration(pp performance plots below) adequate to extend LHCf physics to not only π^0 but also n,Λ,K_S adding analysis of central event also.
- Enabled many papers in PHENIX- eg. reaction plane HI,J/Psi Photoproduction, DAu Diffraction Dissociation, etc.



early calibration,
data taken using low resolution module
respectable π^0 peak!



(nsec)

reconstruction of complex beamspot structure
in a store with significant 400 Mhz rf component.
Using Silicon tracker vertex reconstruction (within +/-1 m)
and ZDC time of arrival relative to LHC clock.

Challenges

- characterize energy loss of heavy quarks also in the medium
- can we explore similar phenomena by selecting very central pp collisions in which gluon density expected to be similar to AuAu at rts=200GeV/u? (Bjorken, Strikman, et al.)
- inadequacies of HI and pp modelling have limited interest in exploring opportunities in forward physics (HIJING lacks, eg initial configurations, fermi motion, coalescence. uRQMD=Fermi step distribution). Similar issues with pp models.

New data

- potential for new triggers to capture hard photoproduction physics in next PbPb run. Crucial role in understanding effects of shadowing.
- other beam species- ie p-Pb?
- extend capabilities of detectors (ie ZDC) to contend with rapid increases in pp luminosity now reached by LHC. What role can technology from HI physics continue to play at $>10^{33}$?

Appendix:are there any simple problems in QCD?

- ρ=Re(A)/Im(A). (really more fundamental than QCD. Tests QFT.)
- "the Pomeron is simple". Vacuum quantum numbers. Experimentally (eg Central Exclusive Production of MSSM Higgs) very clean. Theoretically fiendishly difficult (Durham).
- fundamental quark scattering through jets and leading particles (BBK and late ISR physics).
- parton energy loss in new dense, high temperature medium.
- lattice QCD: mass spectrum, phase transition....

Bibliography

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- A classic from Fermilab:"Highly relativistic nucleus-nucleus collisions: The central rapidity region", J. D. Bjorken, FNAL, Phys. Rev. D 27, 140–151 (1983)
- Stan Brodsky's lectures: http://www.slac.stanford.edu/grp/th/recentlectures.html#Stan_Brodsky
- student lecture on diffraction: "Diffraction at the LHC: a non-technical Introduction", S.White http://adsabs.harvard.edu/abs/2010arXiv1003.4252W
- a non-conventional analysis framework:"Mathematica with ROOT" http://root.cern.ch/drupal/content/mathematica-importer-root-data-files
- LHC beam spot animations: http://library.wolfram.com/infocenter/Articles/7716/