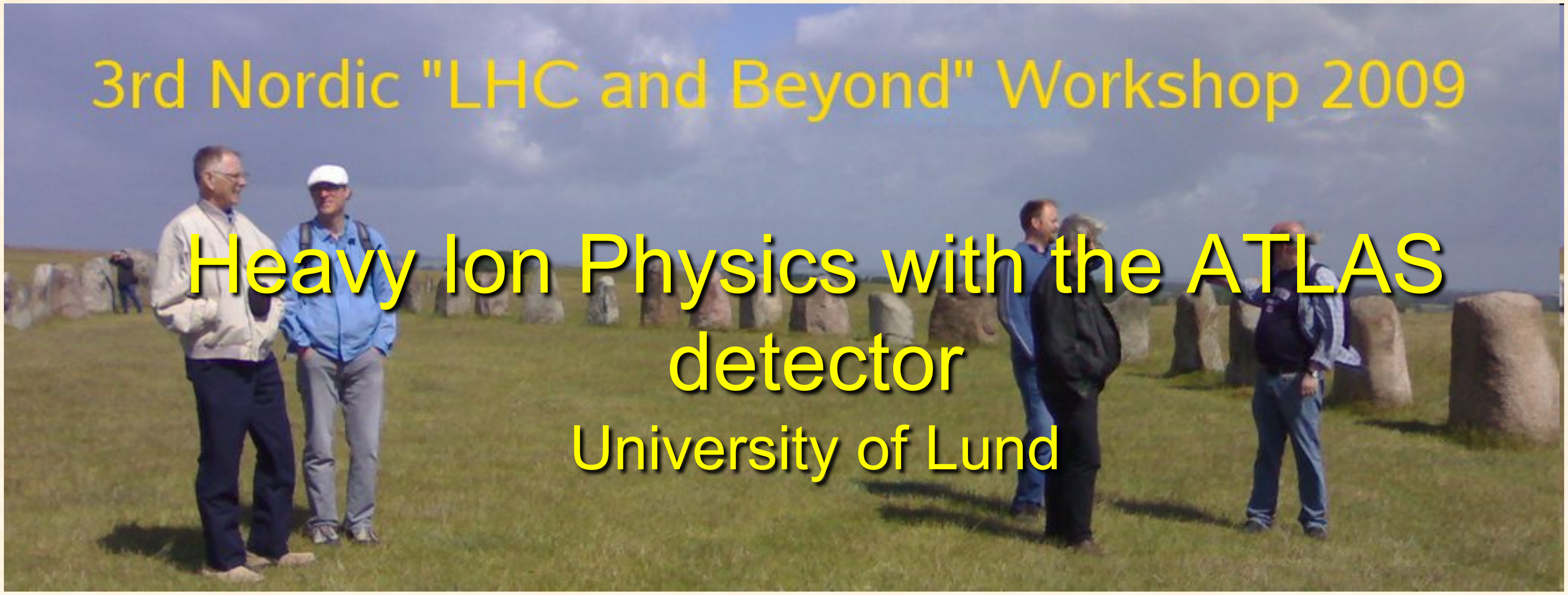


Heavy Ion Physics with the ATLAS detector

University of Lund

Flemming Videbaek

Brookhaven National Laboratory

For the ATLAS collaboration

ATLAS

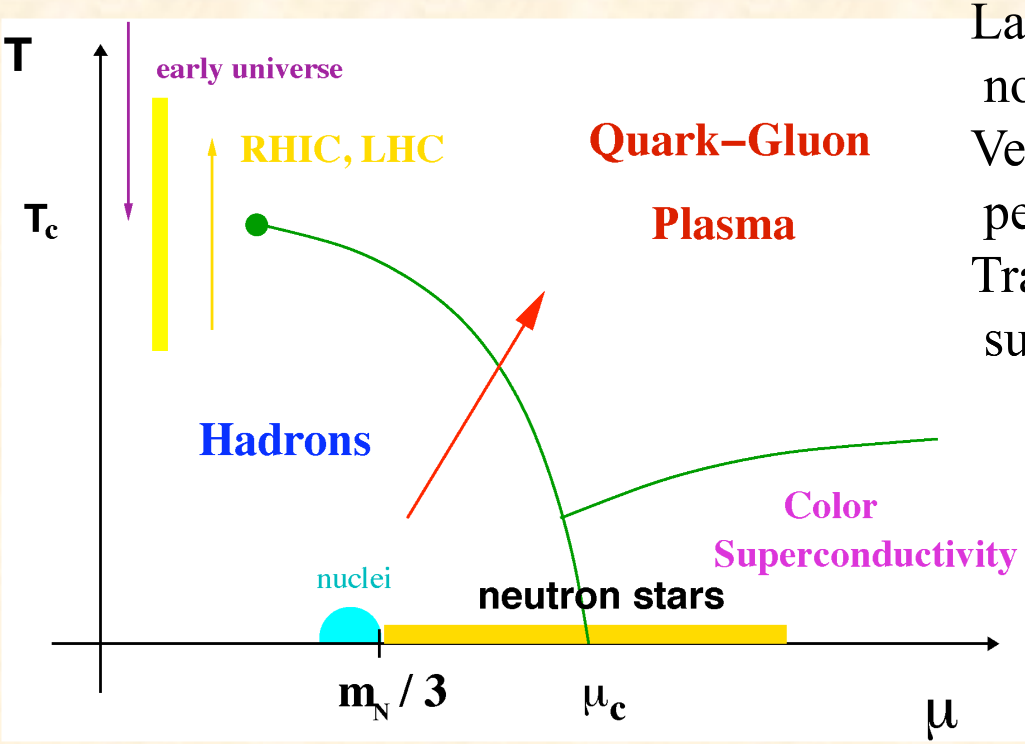
Office of Science

U.S. DEPARTMENT OF ENERGY

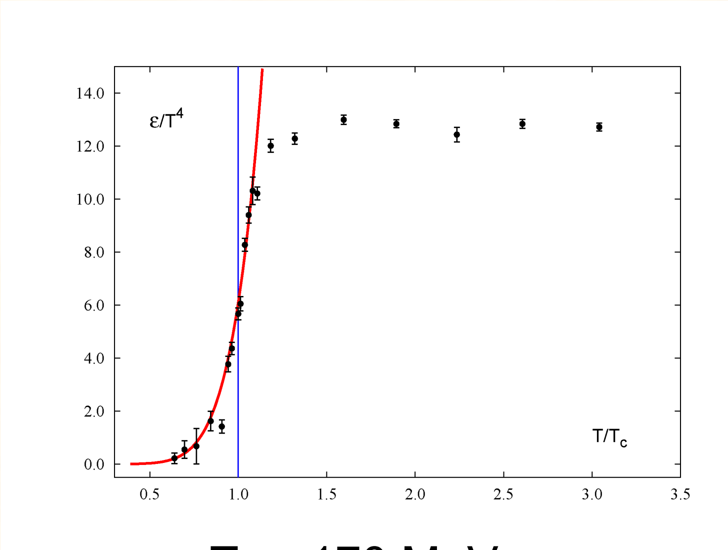
Overview of Lecture

- Introduction
  - Study of QCD and QCD matter.
  - Discoveries and lessons learned from RHIC and SPS
- The ATLAS HI program
  - The very first results –
    - bulk properties: multiplicity, collective flow, spectra
  - Jet measurements –quenching medium response
    - Jet reconstruction, jet shapes, di-jet,
  - Photon measurements = quenching medium response
    - Gamma, γ-jet, (tagged jets)
  - Charmonium measurements – probing Debye screening
  - Forward (low-x) physics with ZDC
- Summary

Study of QCD and QCD matter



Lattice QCD Low T:
 non-perturbative
Very high T:
 perturbative
Transition:
 surely non-pQCD!

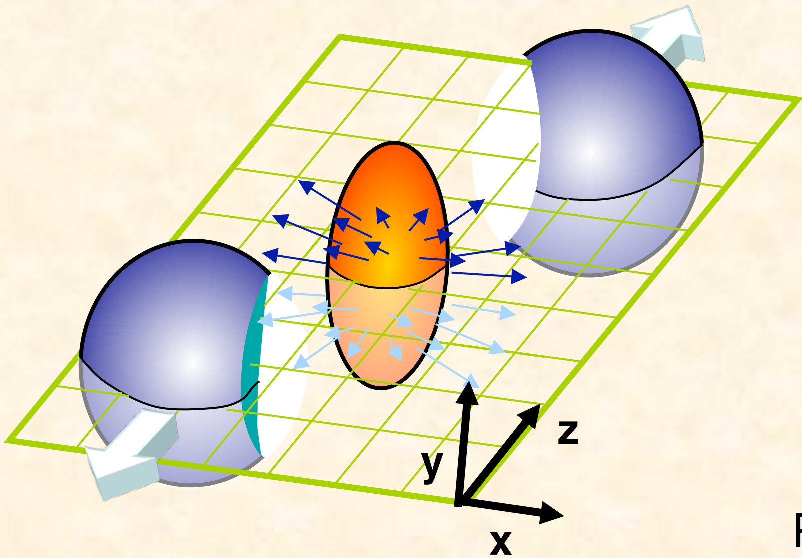


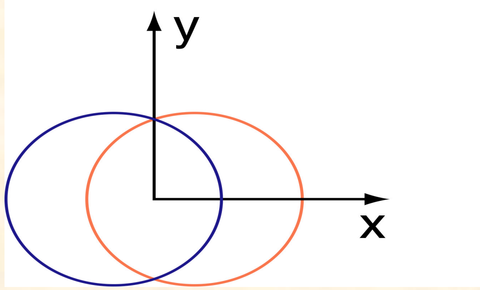
$T_c \sim 170$ MeV

Creating and Probing QCD matter

- Collide Heavy Ions (Au or Pb) at $\sqrt{s} > 17$ GeV
  - Last two decades at CERN, RHIC
  - Soon at LHC at 5.5 or 4 TeV at a factor of 20-30 increase in energy.
- Probes
  - Radiation, collective motion
  - Hard probes produced early in collision; partons interact with medium.

Collectivity: anisotropic (elliptic) flow

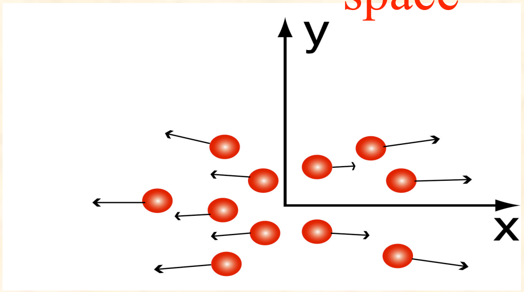




Almond shape overlap region in coordinate space

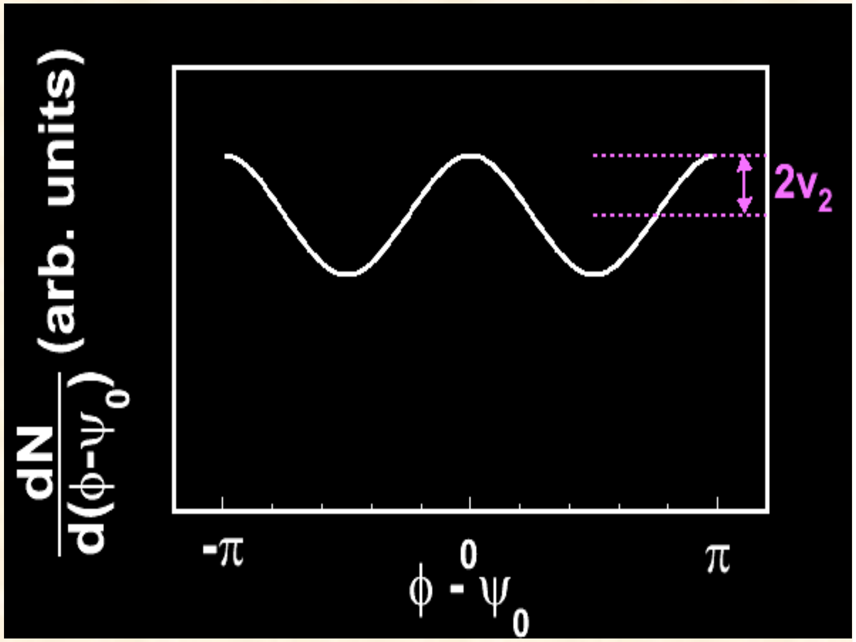
Pressure gradients lead to azimuthal anisotropy

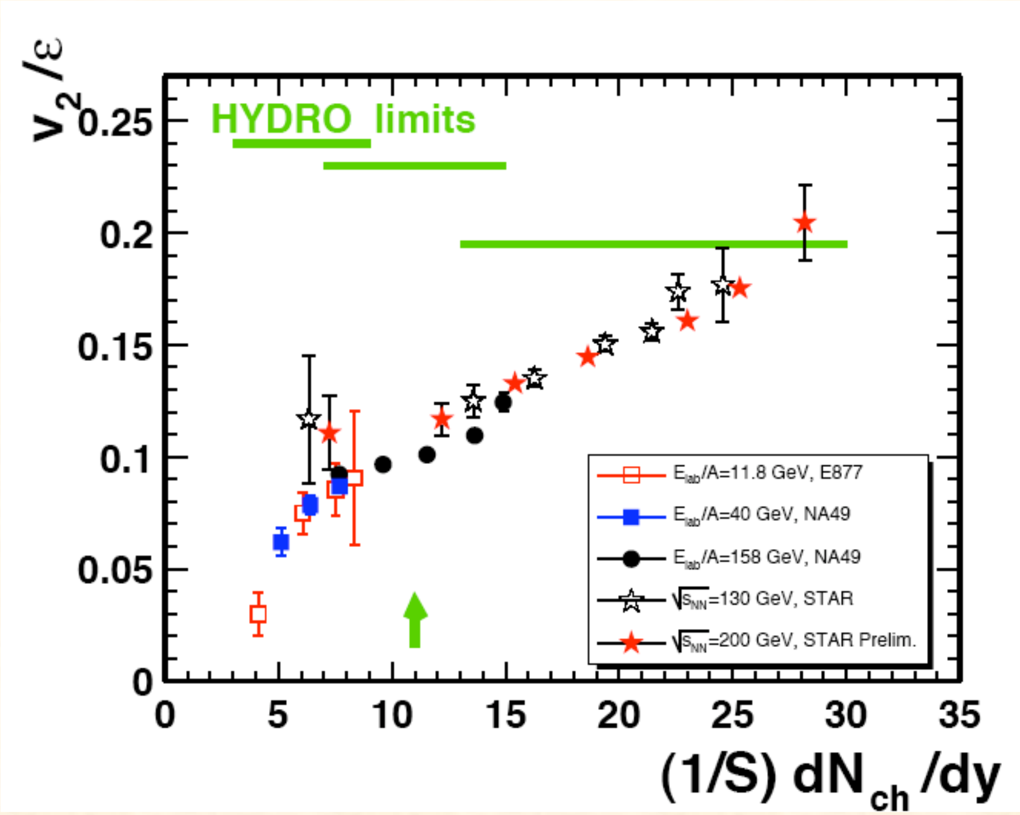
momentum space



$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow" Elliptic flow is the second harmonic in the Fourier expansion of azimuthal particle distribution.

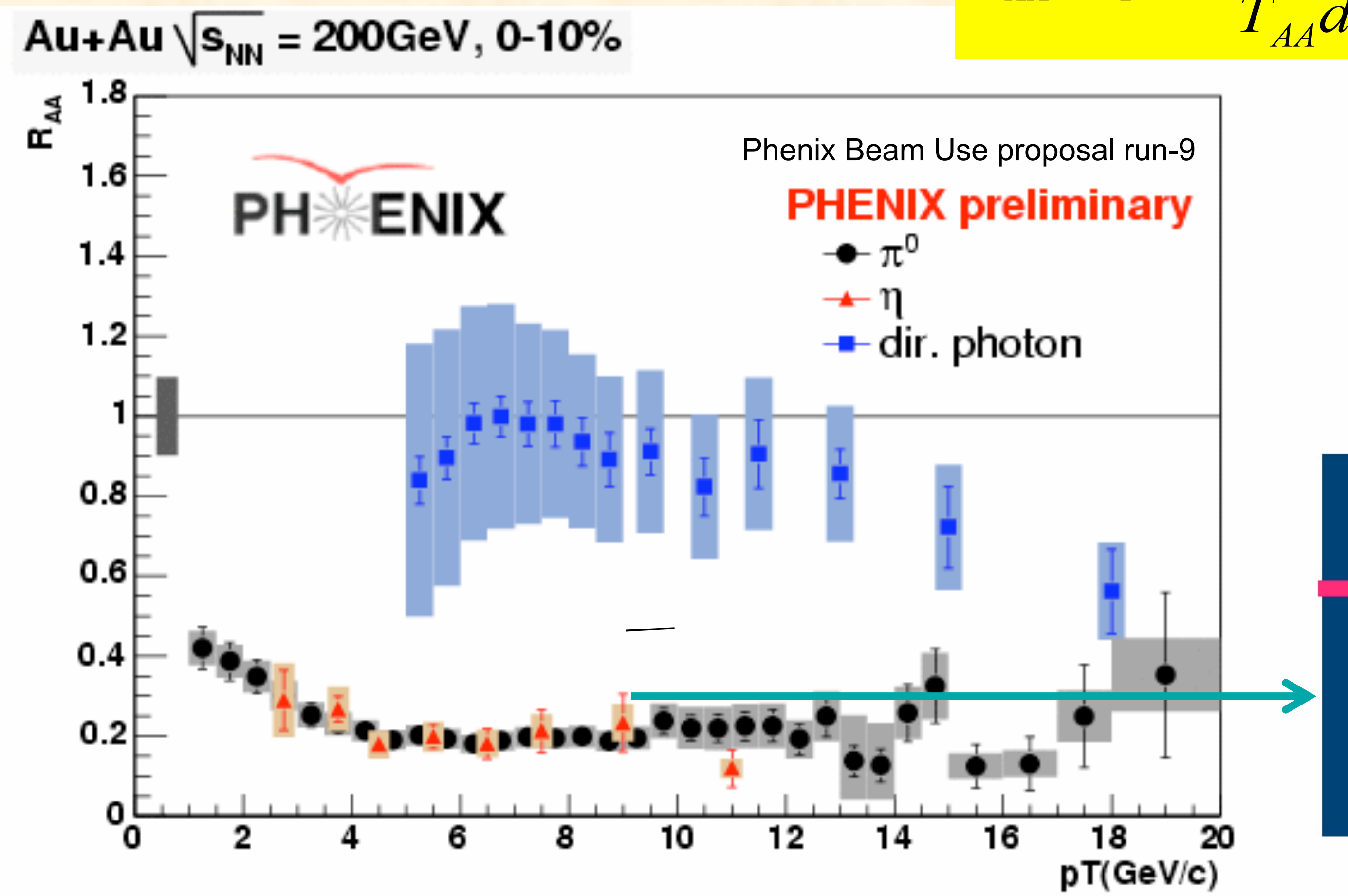


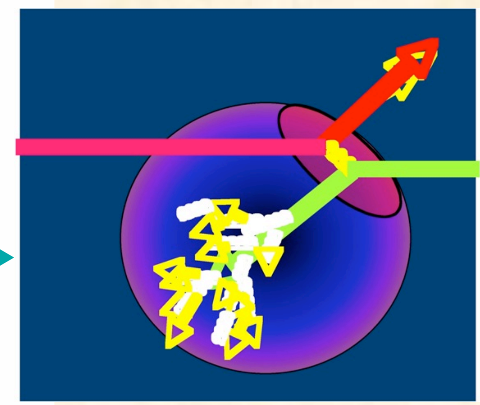


Matter flow collectively;
Only if the pressure has developed early (< 1 fm/c) is ideal hydro reached/maintained.
Calculations (newer) has shown that viscosity must be small

colored probes lose energy, photons don't

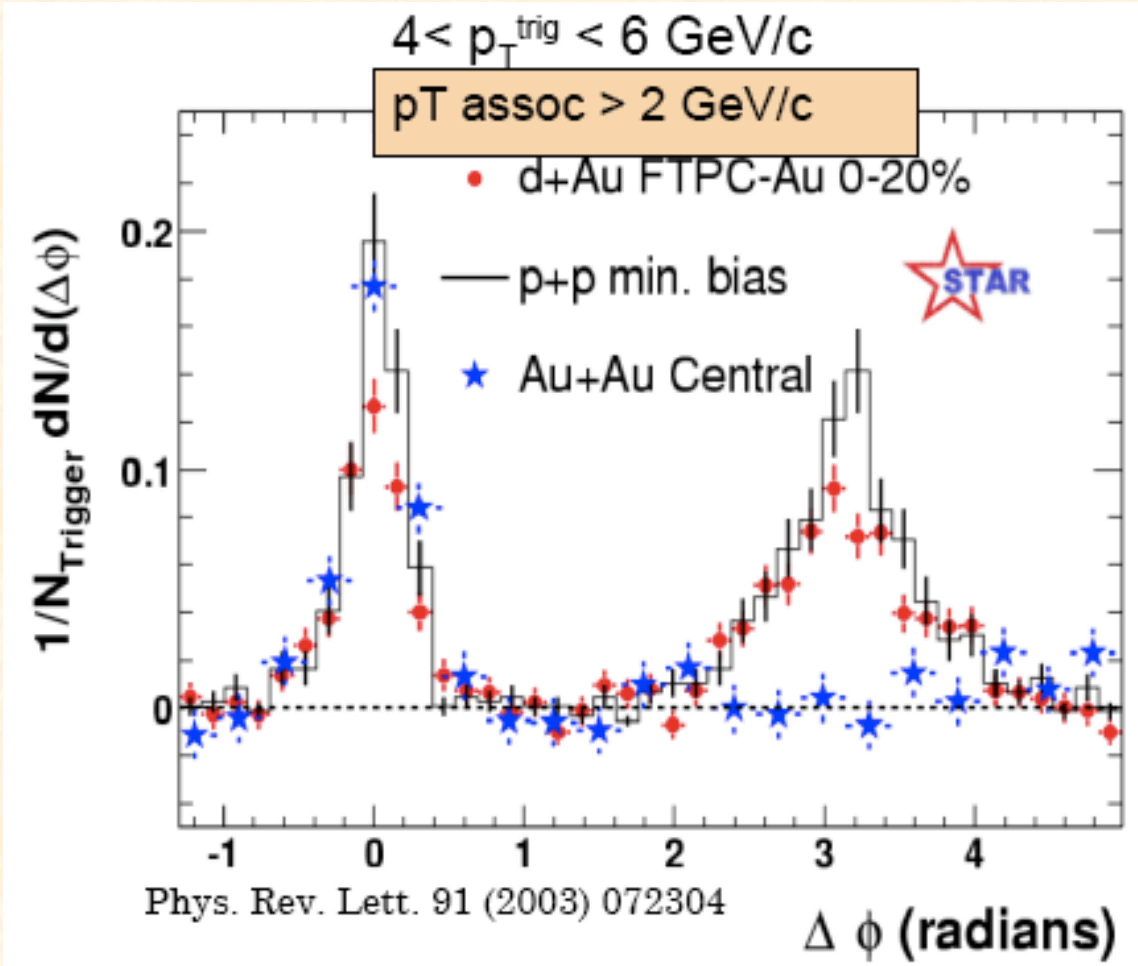
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$



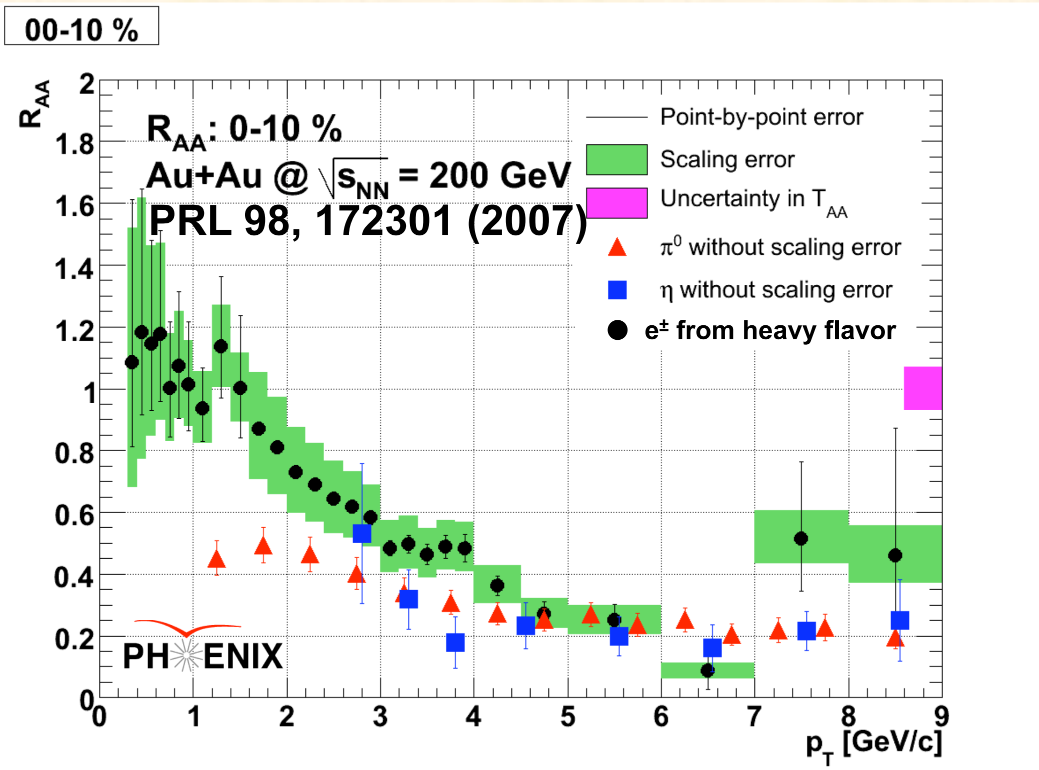


Surface emission

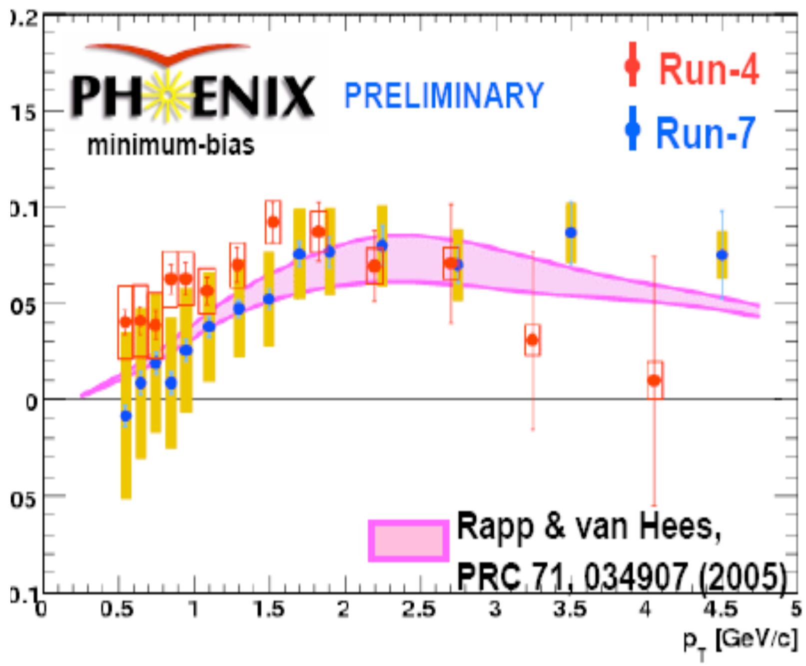
Di-jets are suppressed



opaque to heavy quarks*



Phenix Beam Use proposal run-9



Lose ~ as much energy
as light quarks & gluons!

Actually flow along with the bulk medium!

* Measured via c → e±, reconstructed D at low p_T

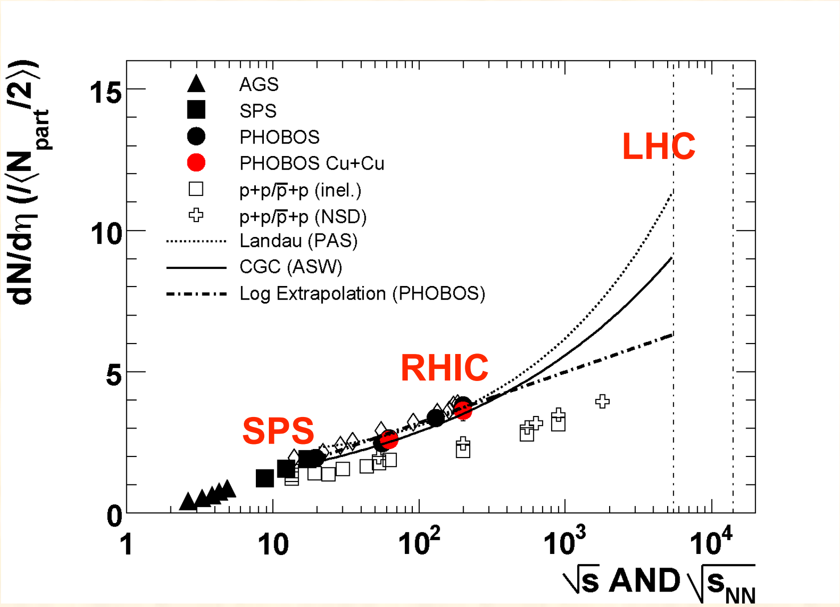
Expectations / Uncertainties for LHC

Bulk properties at LHC

$dN_{ch}/d\eta$ in Pb+Pb

N_{part} : # participating nucleon in collisions

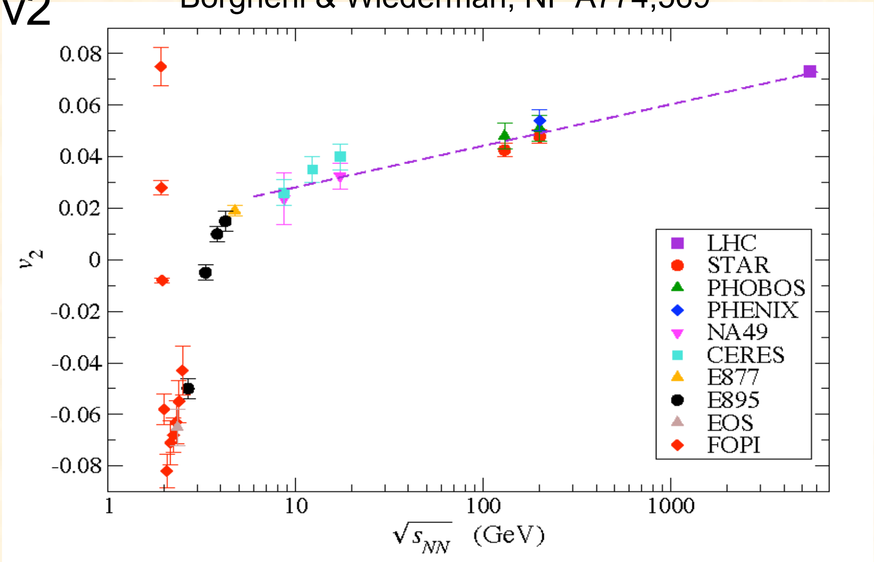
Large uncertainties



What happens to v_2 at high √s.
Is it saturated ?
Larger than ideal hydro?

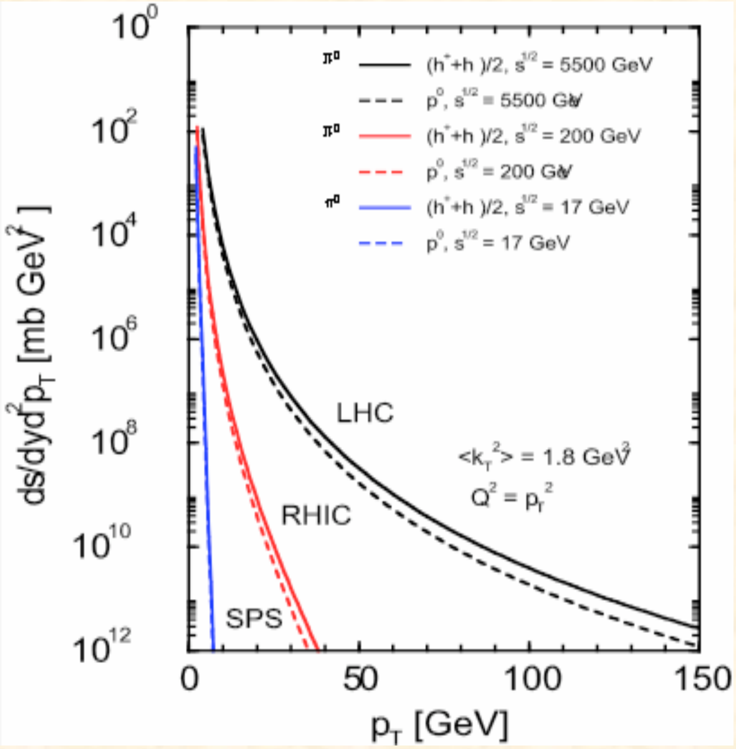
v2

Borgheni & Wiederman, NP A774,569



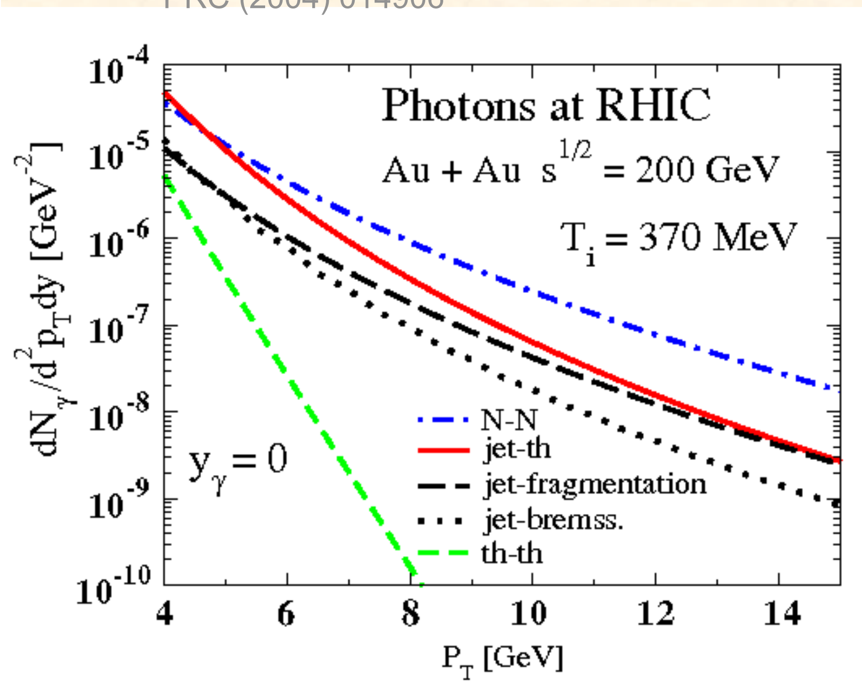
Jets at LHC

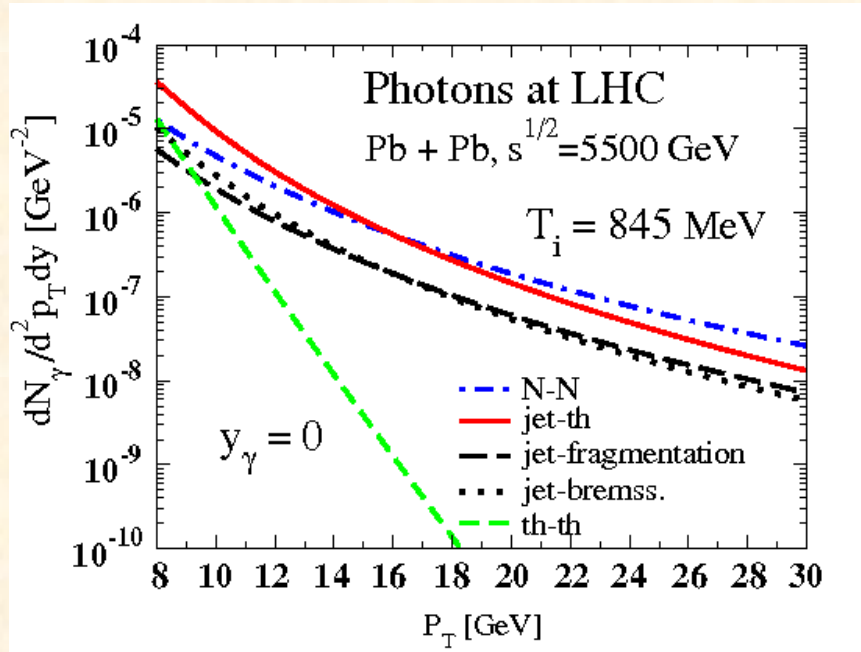
- At RHIC jet has primarily been studied through leading particle measurements.
- At LHC jets will be copiously produced per event.
- Will be ideal probe for study on effect of media on partons.



Medium Photons

Turbide, Gale, Jeon, and Moore
PRC (2004) 014906





Photons are abundantly produced at LHC

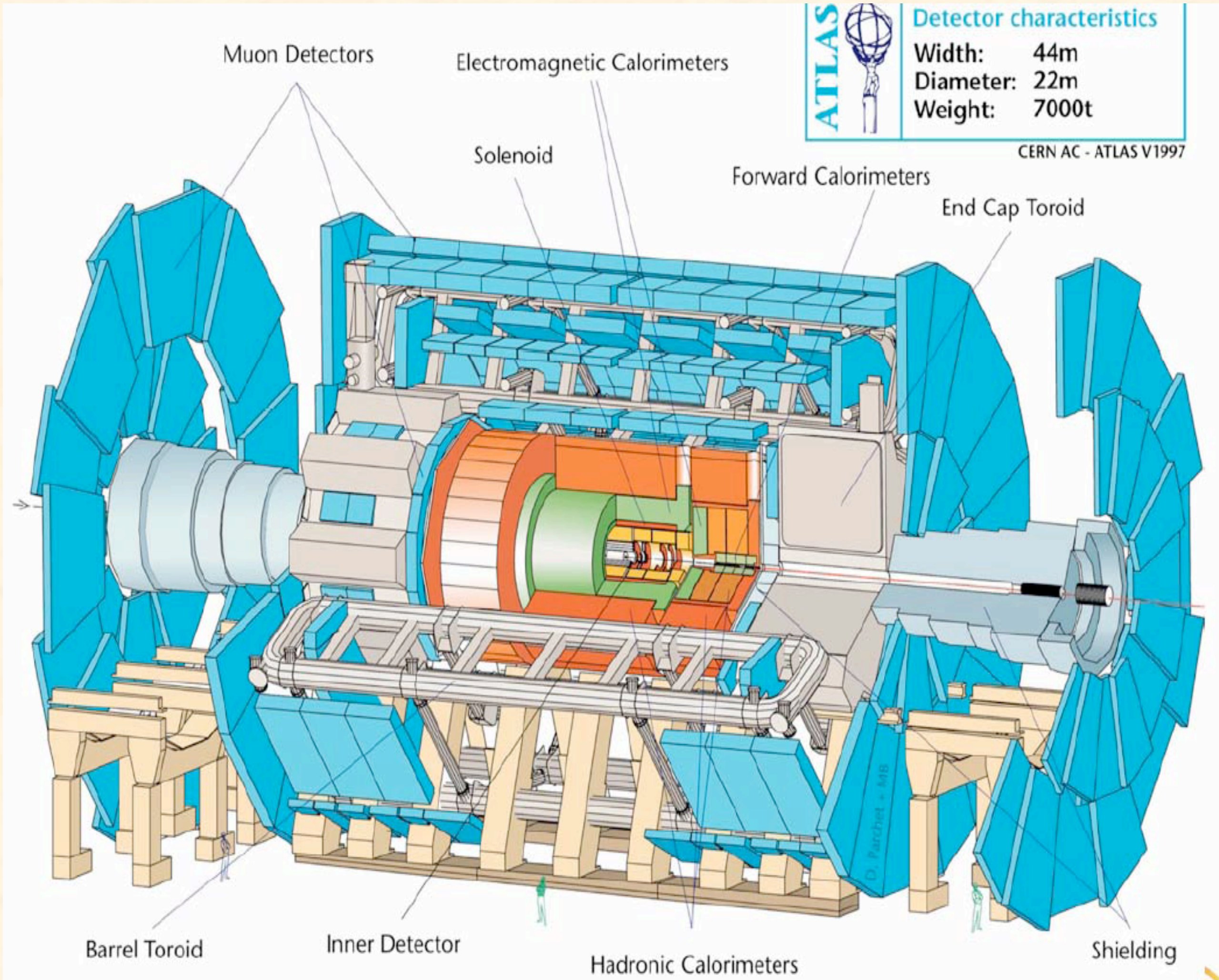
Jet-photon conversion in the plasma dominates $8<p_T<14$ GeV

Prompt hard NN scattering dominant for $p_T>20$GeV at LHC over and above thermal components.

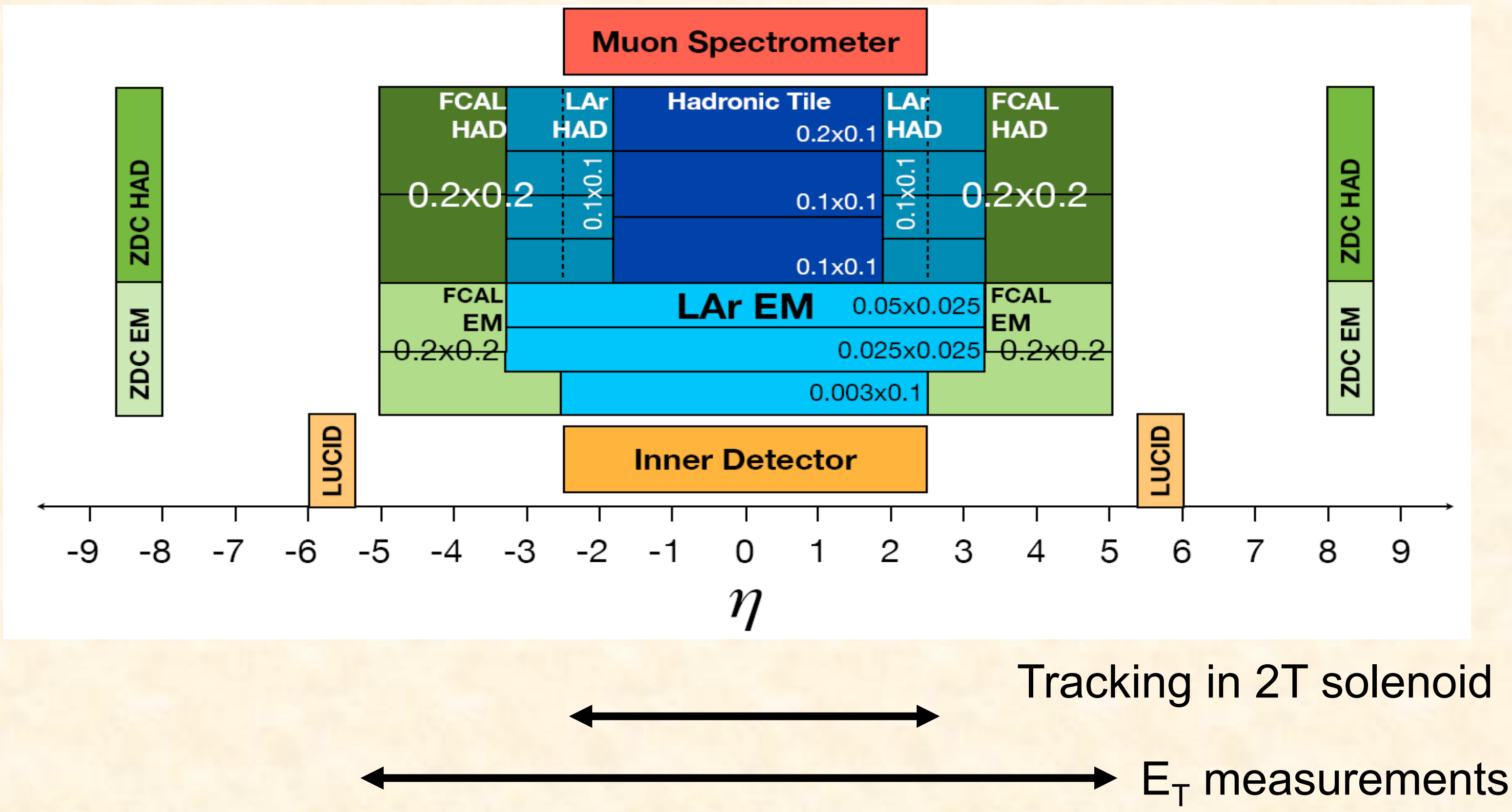
(taken from S.Bathe, RBRC, July 2008)

13

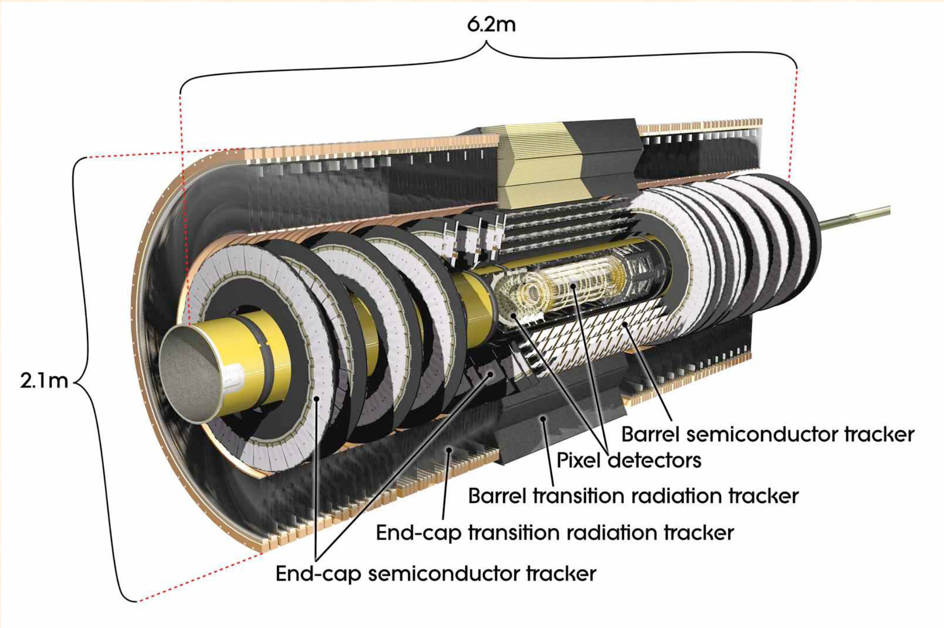
ATLAS detector



Phase space coverage
2π azimuthal coverage



Bulk Properties
Inner detector

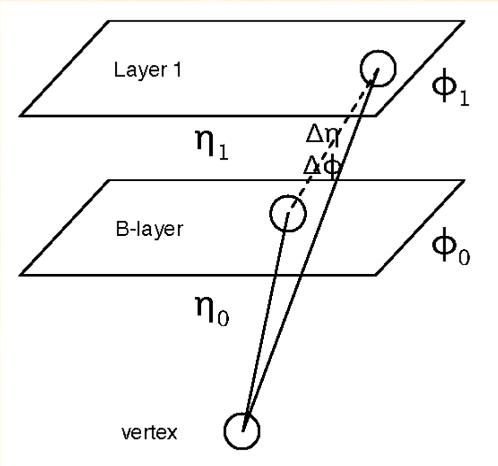


$dN_{ch/}d\eta$ – using hits in inner detectors

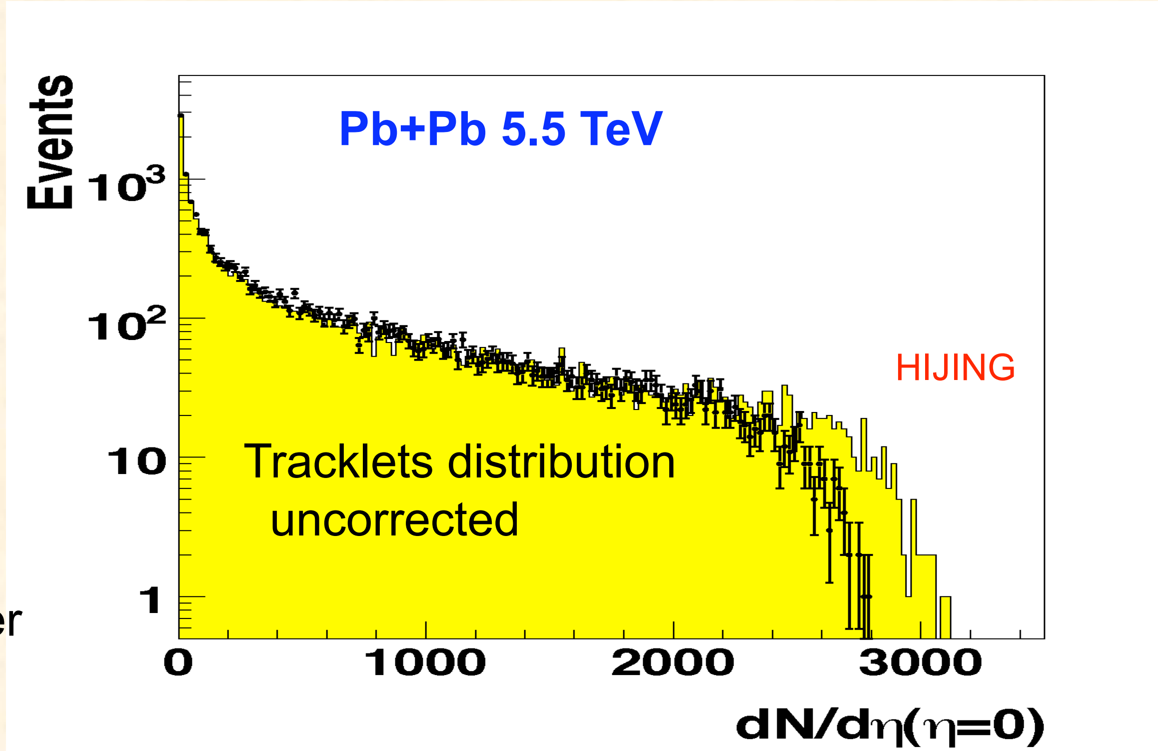
Occupancy in Central Pb+Pb at 5.5 TeV

Pixel < 2%; SCT < 20%

Multiplicities



Using vertex, B-layer and layer 1 hits to define tracklets.
(a la PHOBOS)
- clean; sensitive to low p_T tracks.



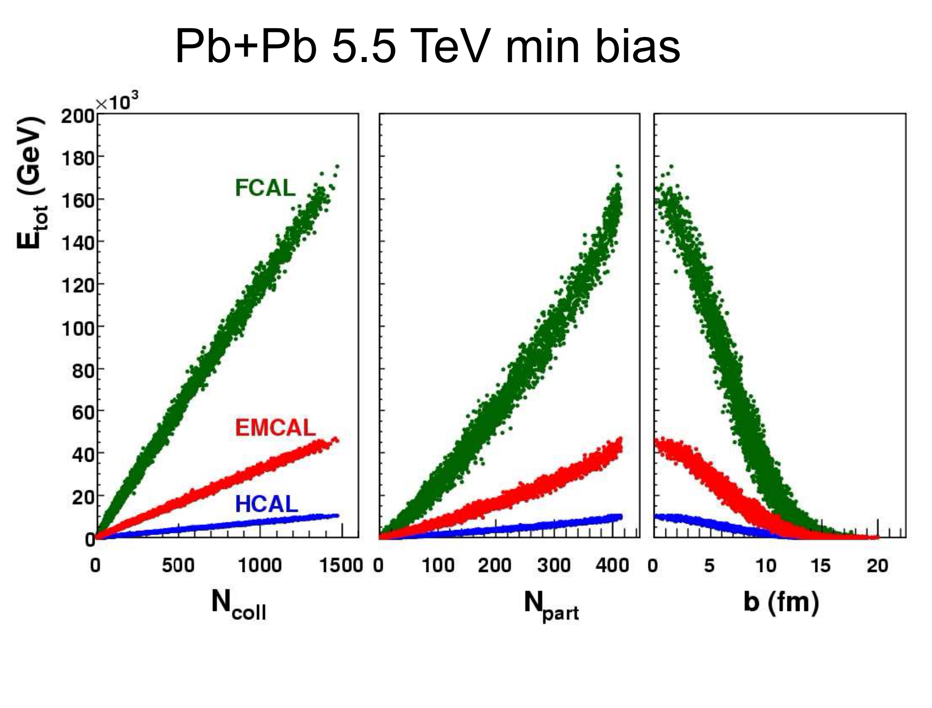
Tracklet method provides good estimate for initial Charged particle multiplicities.

E_T measurements

Collision centrality

Using Calorimeters

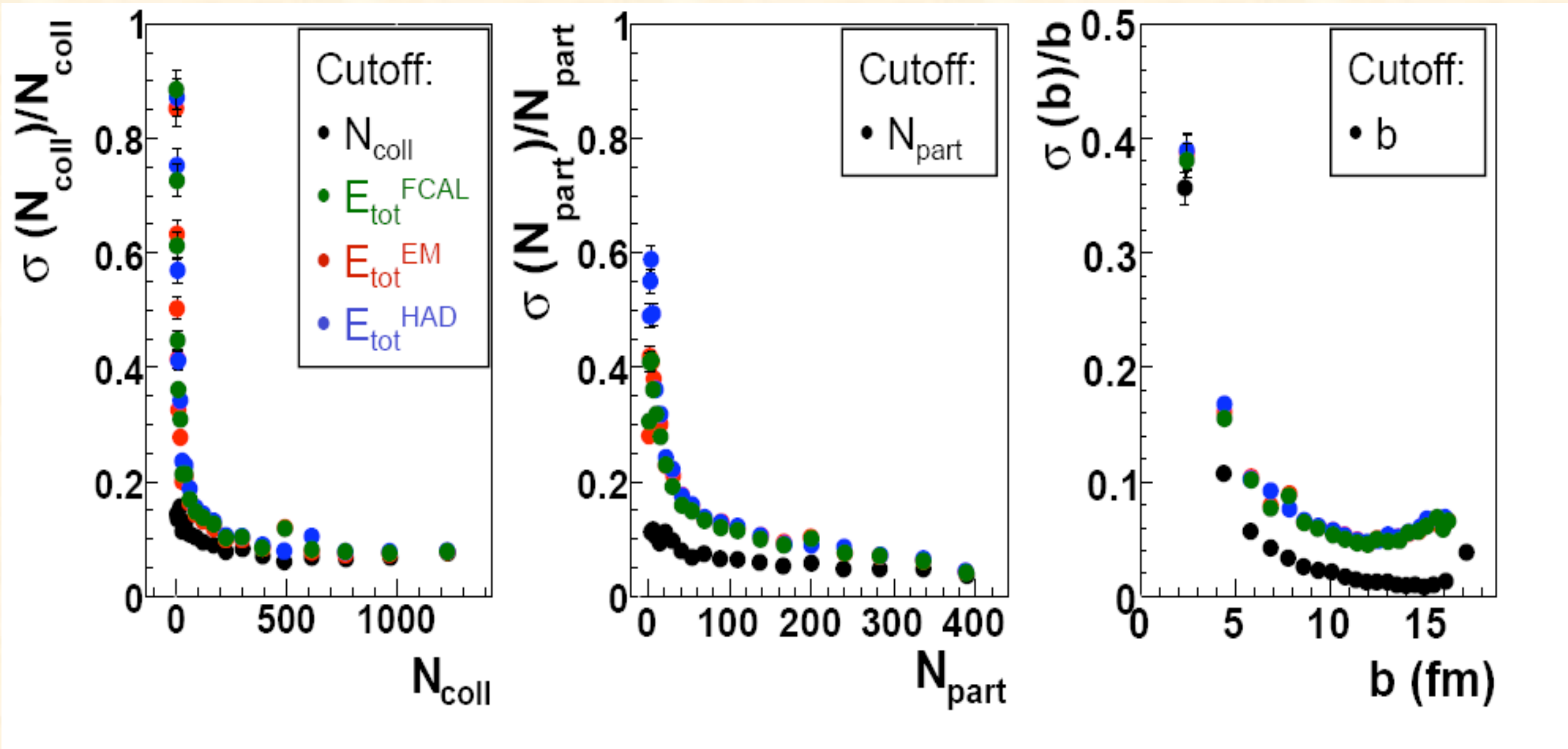
$Etot = \Sigma_{cells} E_{tot}$



E_{tot} is monotonically correlated with collision parameters (N_{coll} , N_{part},b). Energy depositions in different calorimeter system are well correlated.

Collision Centrality precision

HIJING – in 20 centrality bins; each 5% of inelastic cross section



Very good centrality determination in ATLAS with multiple methods.

E_T Measurements in Pb+Pb Collisions

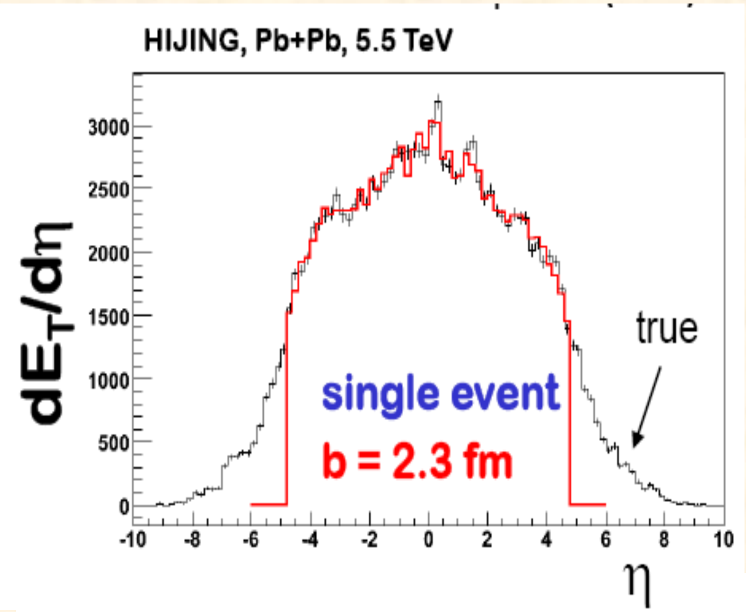
$dE_t/d\eta$ extracted from calibrated transverse energy deposited in Cells

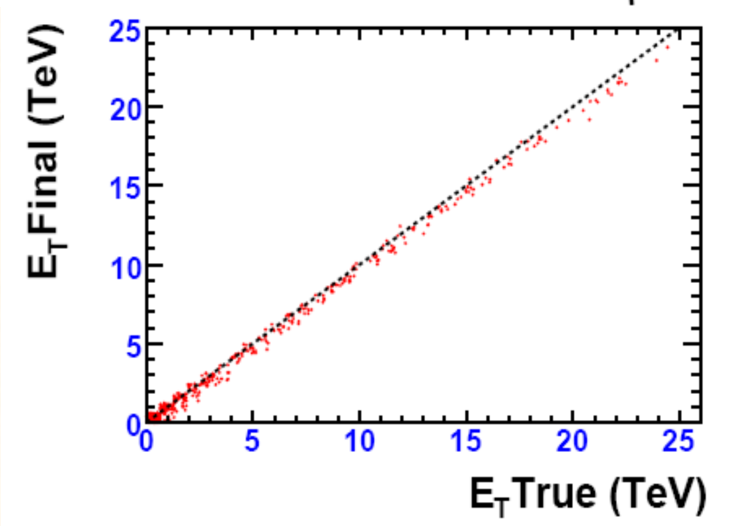
Evaluate correction from MC studies of $dE_{True\ (MC)}/dE_{T\ (cell)}$

Good agreement on cell base

Using missing $E_T$cluster based algorithm
-$E_T$cell) + E_T (muon)

-Accurate to ~5%.



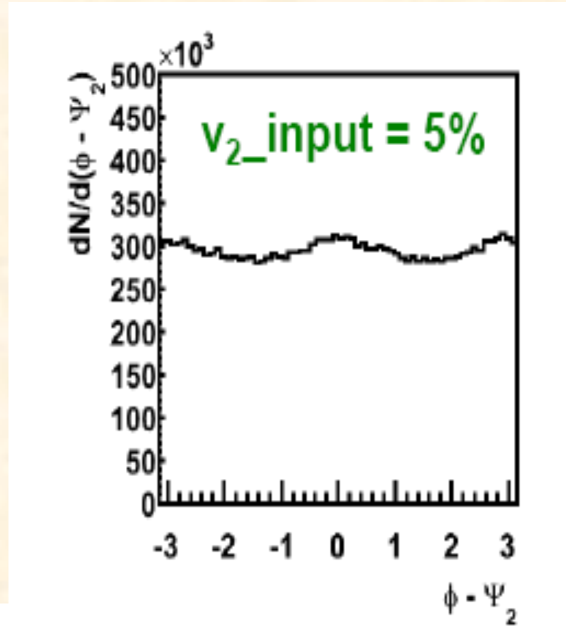


Elliptic flow

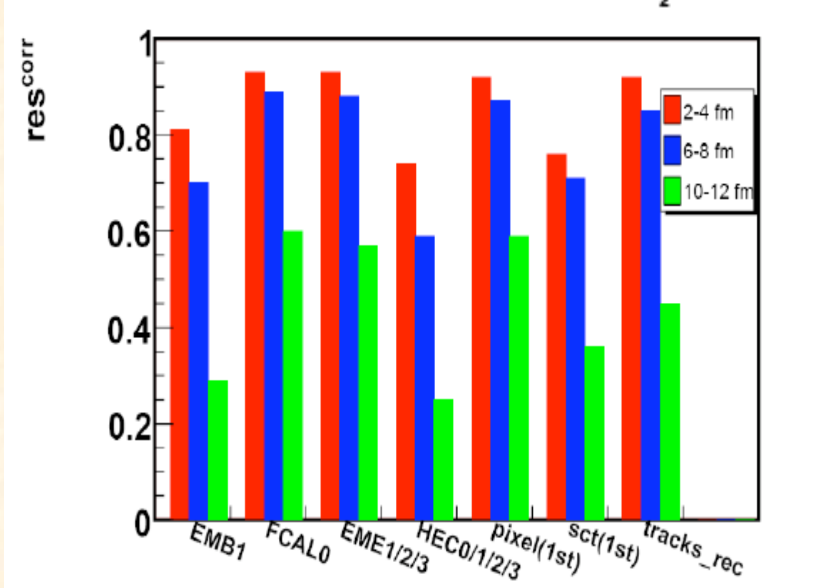
In ATLAS several methods can be deployed to extract the v_2 in the HI reactions.

Fourier decomposition with respect to estimated reaction plane (RP)

$$v_2 = \frac{v_2'}{\sqrt{\langle \cos[2(\Psi_2^N - \Psi_2^P)] \rangle}}.$$

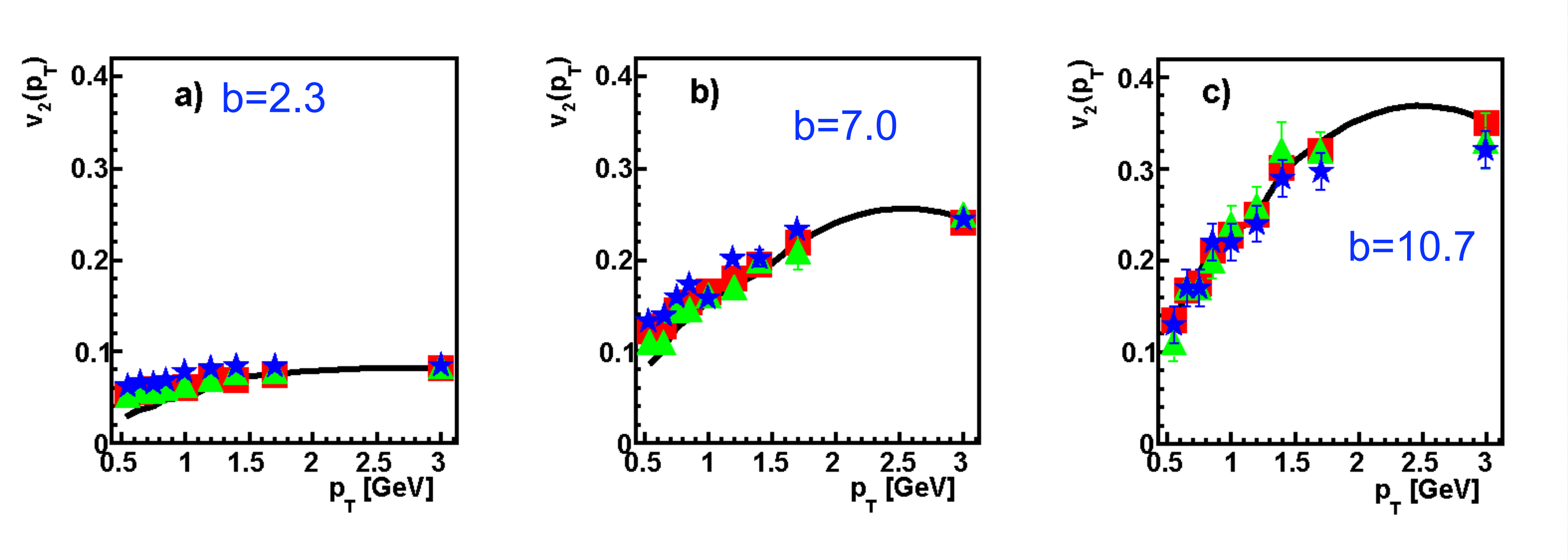


Resolution Correction for reaction plane estimated obtained with different sub systems.



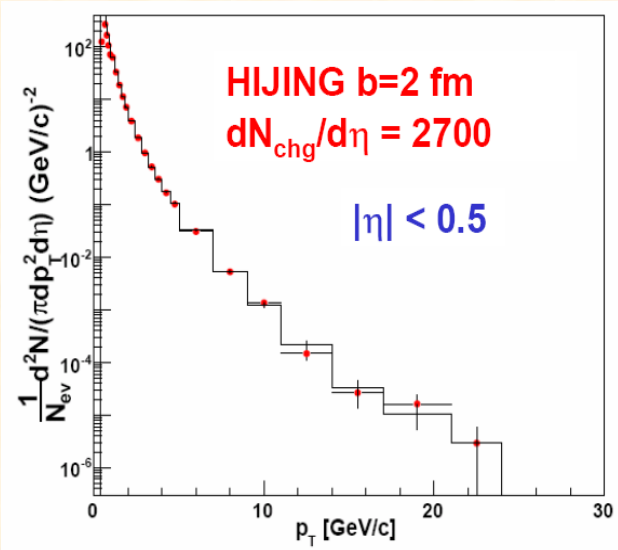
$v_2(p_T)$

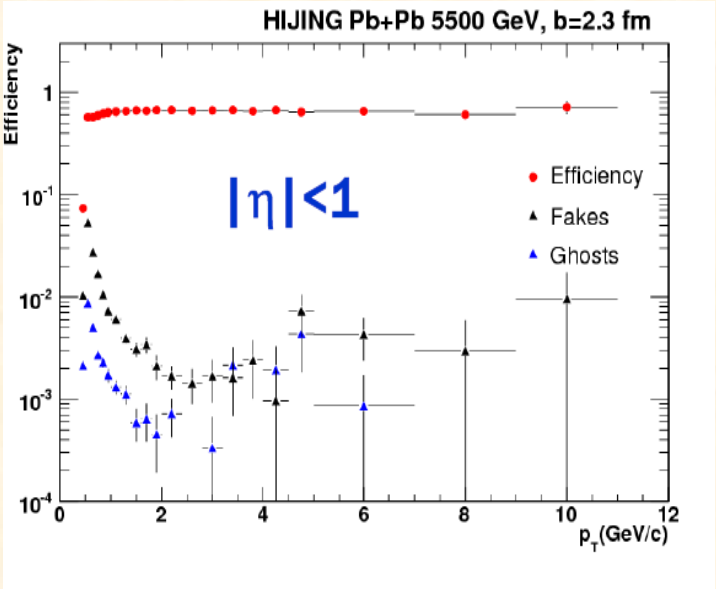
- Determine elliptic flow for charged hadrons
- RP (squares), two-particle correlations (stars), and Lee-Yang Zeros method (triangles)



Tracking

- Tracking uses pixel, SCT; The TRT has too high occupancies in HI collisions.
- Results are very good for $|\eta|<1$ but challenging for higher η.

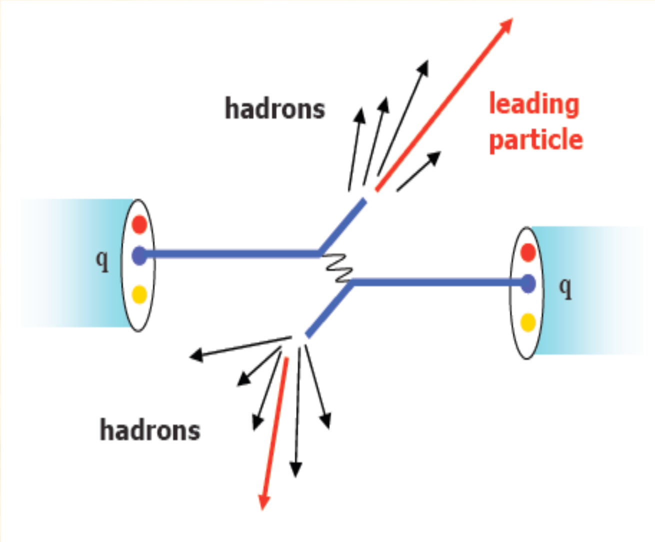


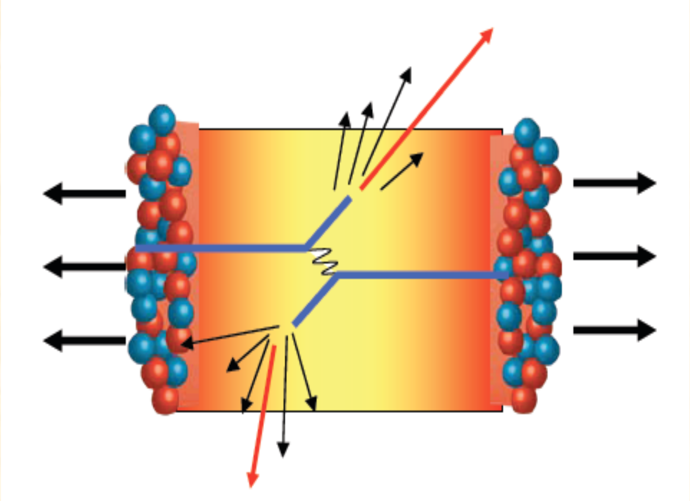


Summary - bulk

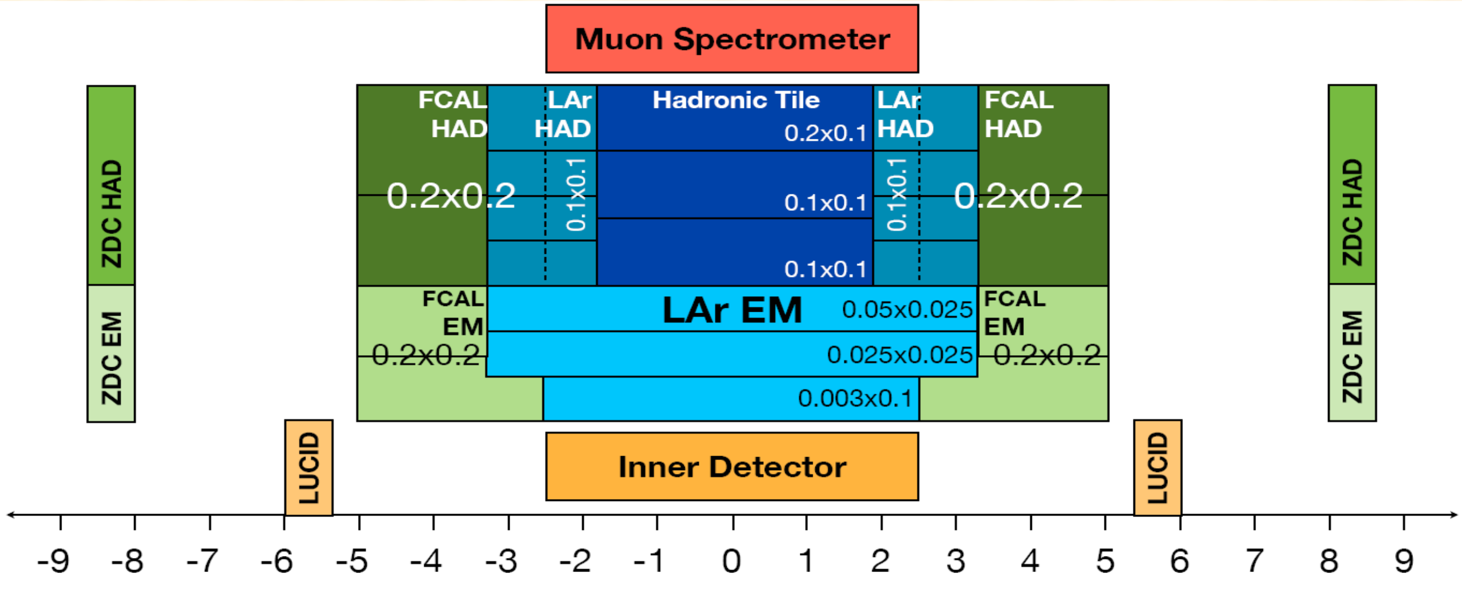
- The global measurement just discussed are also very relevant and easy to do for Min. Bias
- Centrality can be determined from calorimeters, charged particle distributions. The accuracy is ~ 10% on an events basis in $-2.5 < \eta < 2.5$
- Transverse energy $dE_T/d\eta$ can be determined on an event basis over broad η range.
- The elliptic flow can be determined over a large centrality range with good resolution (correction factors close to 1).

Probing the medium with initial scattered partons.





Phase space coverage
2π azimuthal coverage

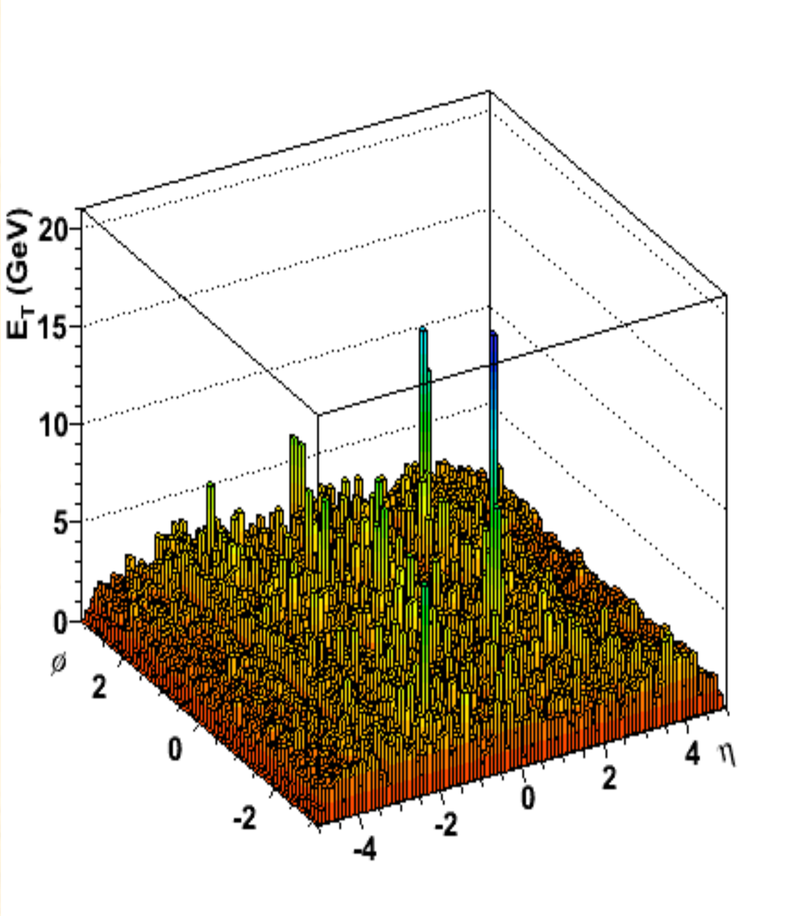


Calorimeters

- Longitudinal segmented (in EM and Hadronic)
- Fine eta strip in front of EMCal
    - Separate γ and π^0 below 70 GeV
- Ideal for jet and photon measurements
- Utilize tracking to study fragmentation properties.

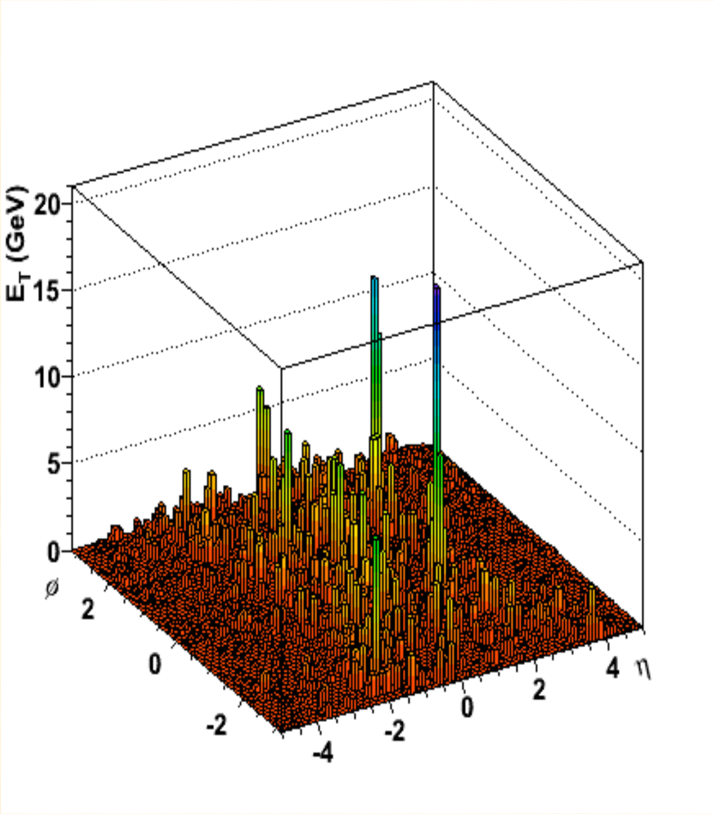
Jet Reconstruction

- Embed PYTHIA di-jet events in HIJING
  - Without quenching
  - Limit $Q^2 < 100$ GeV^2
    - i.e. no HIJING jets
  - 70 GeV jet
- Compare results to jet reconstruction on PYTHIA
  - Same approach as in 14 TeV p+p analysis



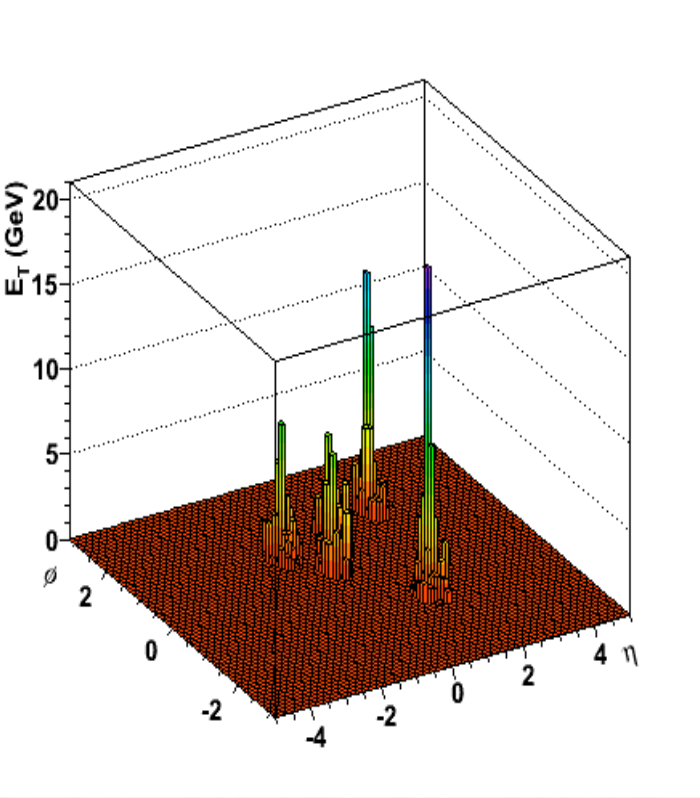
Jet Reconstruction

- In HI events subtract the underlying event by removing η-dependent average E_T

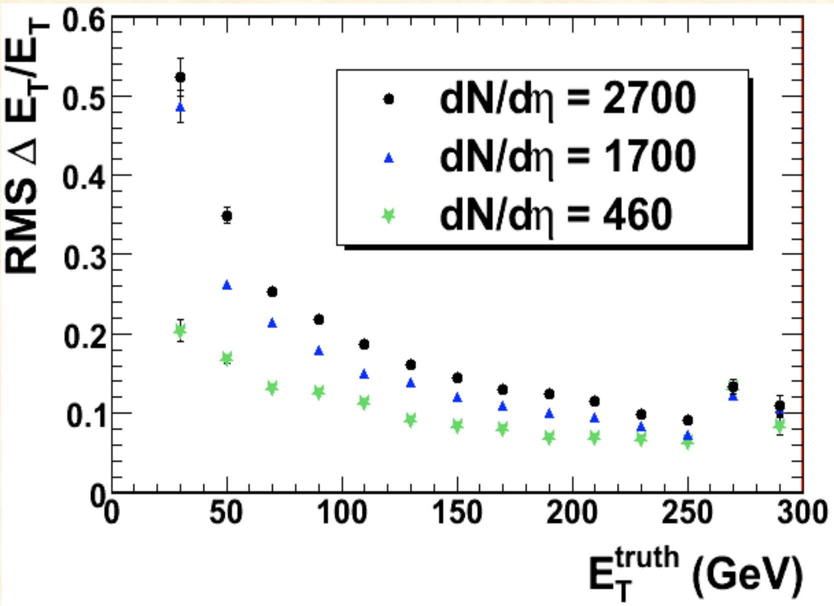


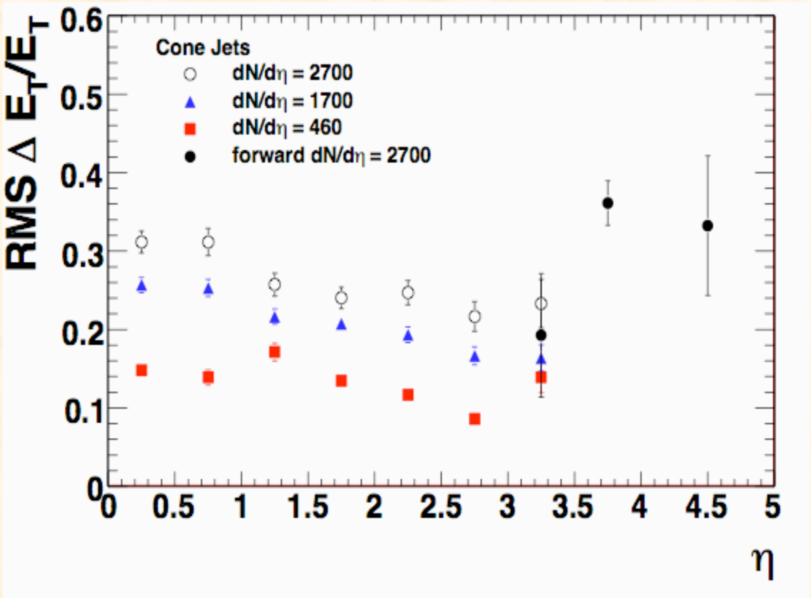
Jet Reconstruction

- Cone jet reconstruction
  - Cluster towers within a radius of R=0.4 around 5 GeV seed towers
  - Iterates on jet position until convergence or excluded



Jet performance, resolution

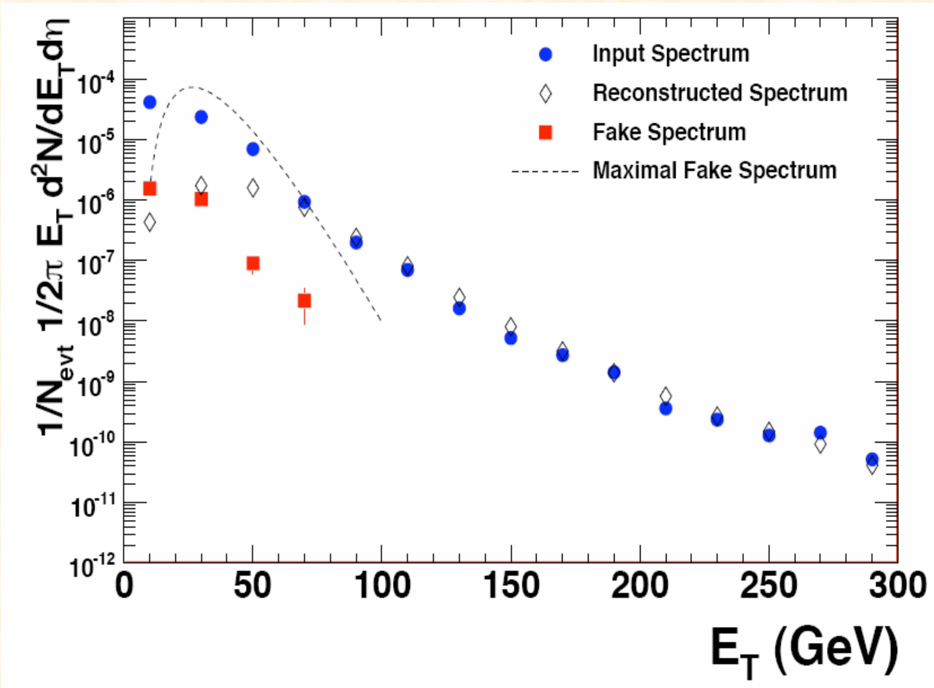


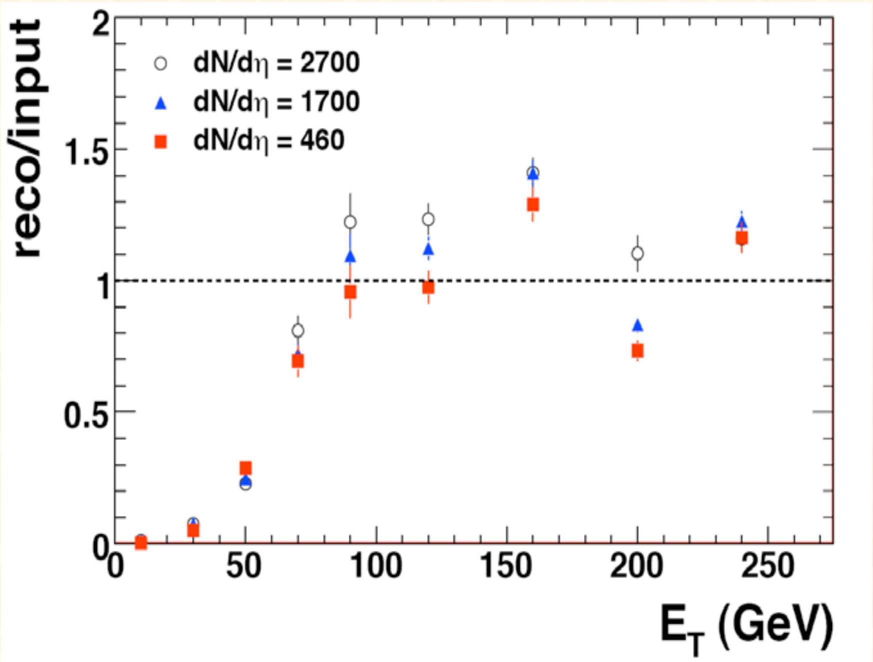


- Energy resolution gets somewhat worse with increasing multiplicity
- Resolution roughly constant with η.

Inclusive Jets in Pb+Pb

dN/dη ~2700



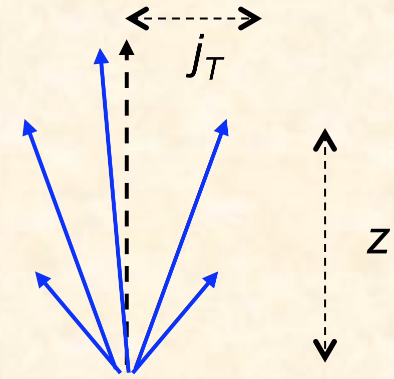


At 70 GeV

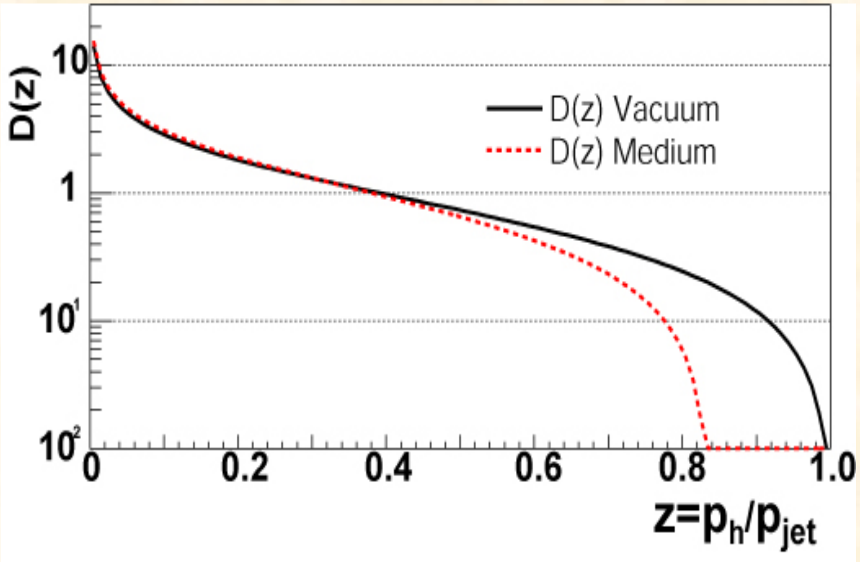
- Efficiency~ 70%
- B/(B+S) ~3%
- σ(E)/E ~25%

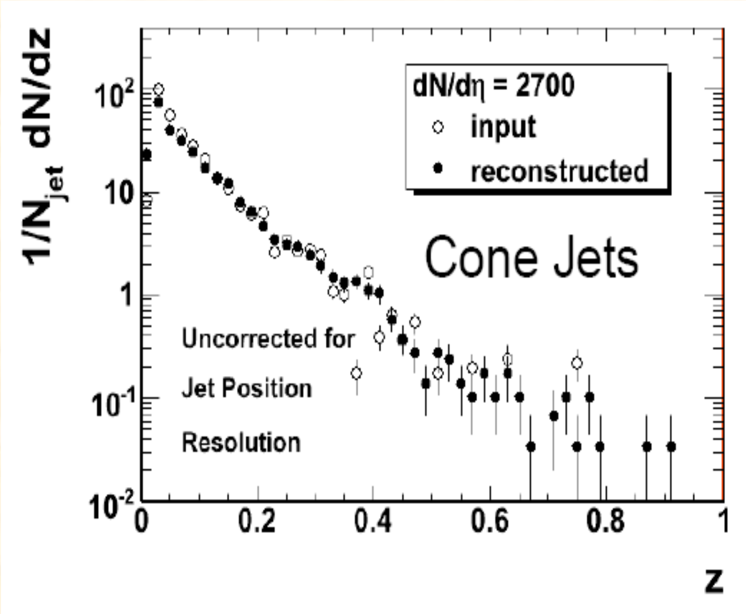
Example of jet reconstruction compared to input distribution.

Jet modification due to media



Fragmentation D(z) using leading charged hadrons.
Expectation this will reflect media properties.
Excellent reproduction in simulations.



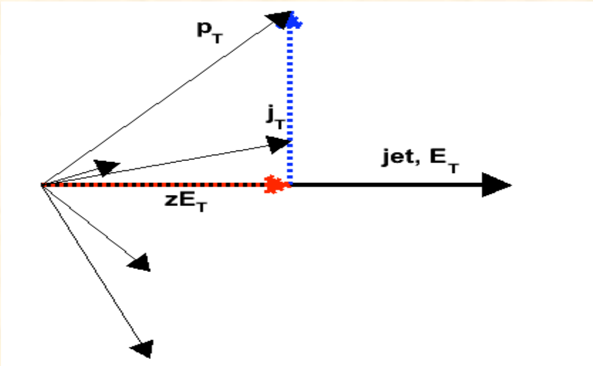


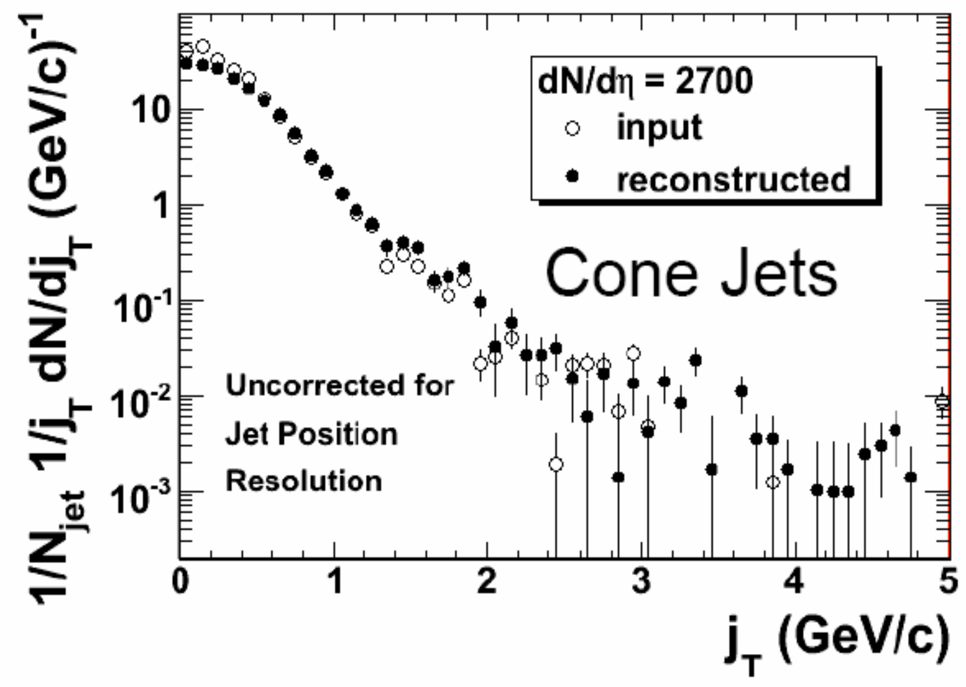
Jet modification due to media

Study j_T-distributions and modification

Track charged tracks to match jet in calorimeter

Enable us to investigate energy loss models





Di-jet reconstruction

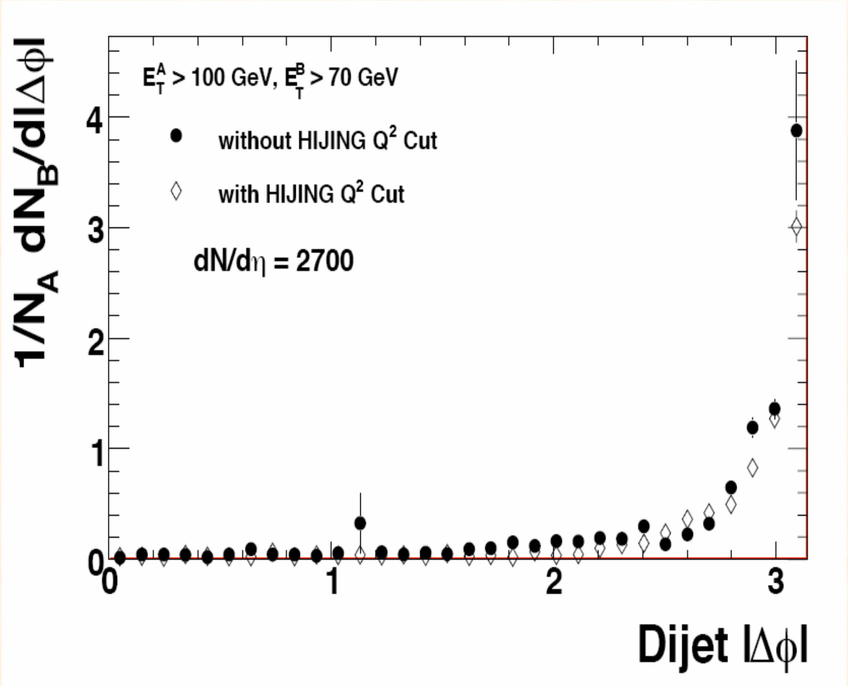
Angular correlation between back-to-back jet broader in Pb+Pb due to multiple scattering in medium

The large acceptance of ATLAS and good resolution allows for these studies.

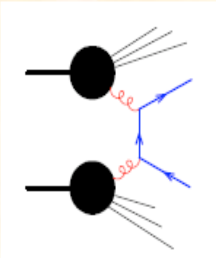
Large signal evident

Low background

• For a 100 GeV jet ~60% probability to detect associated jet (>70 GeV) from integrals of the conditional yields

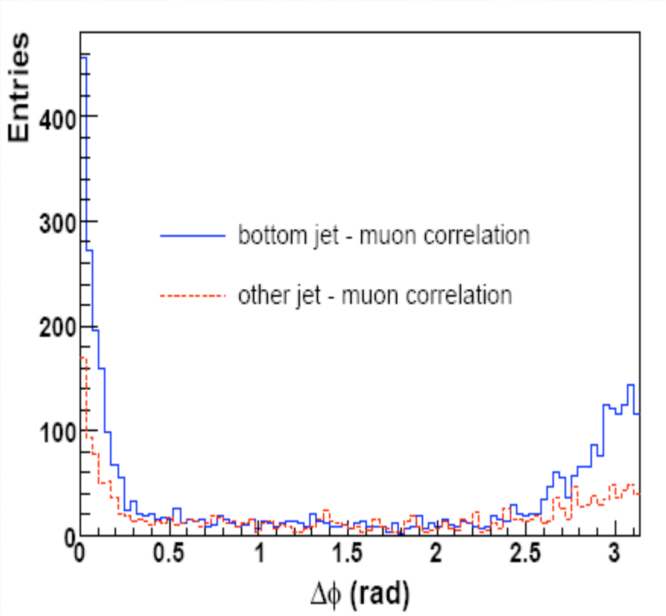


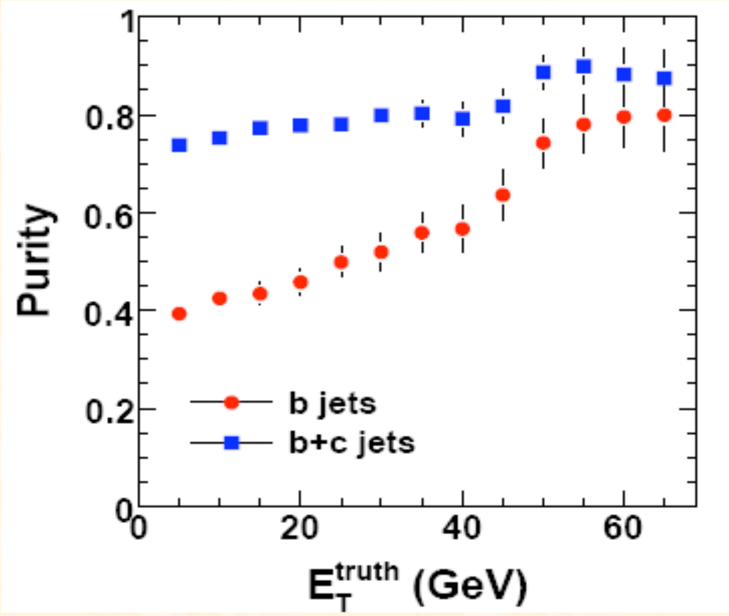
Heavy quark-jets Correlations



- Why are heavy flavors as suppressed as light flavors?
- **c,b→D,B + others →μ+ others**

- Tag heavy quark jet (c,b) by high p_T muons
- Require muon p_T>5 GeV and jet ET>35 GeV
  - Low p_T: 1/3 of away-side jet each from b/c, light quarks +gluons.
  - High p_T: dominated by bottom quark.





γ-jet Measurements

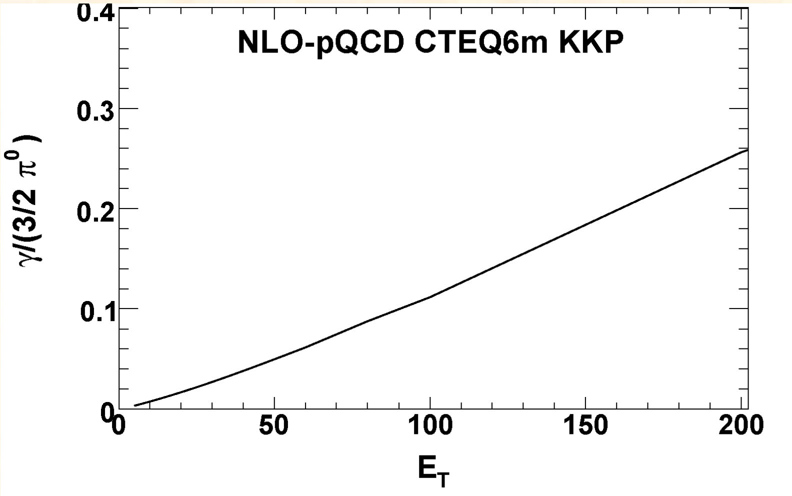
γ-jet gives better access to media modification studies.

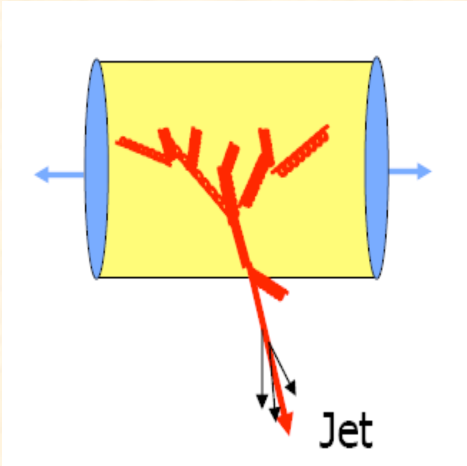
+Less surface bias.

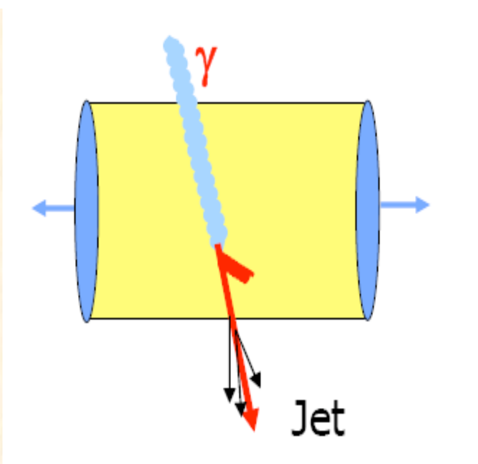
+Parton energy is precisely known.

-Large background from hadronic (π^0) decay

-Smaller yield



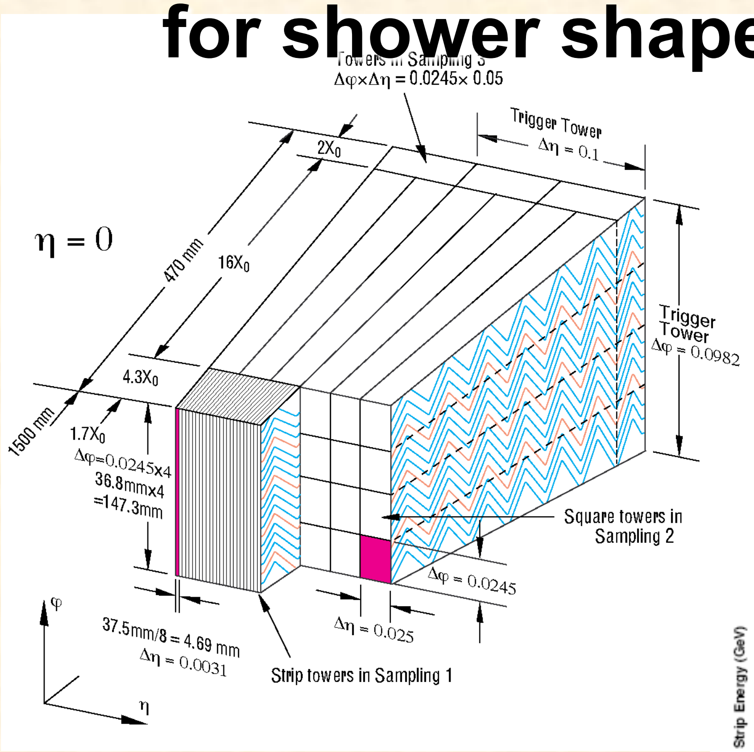




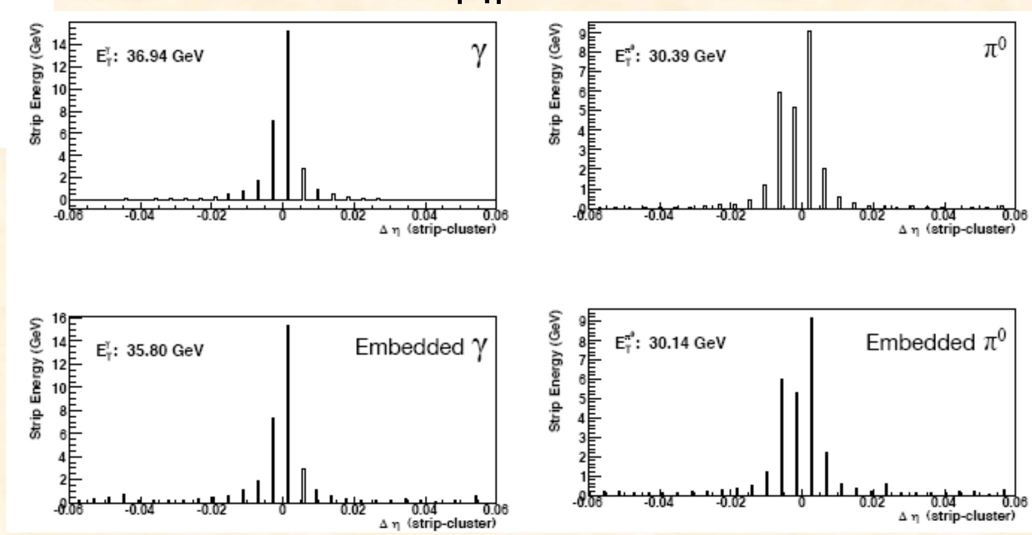
Photon-ID

- Two independent methods are possible in ATLAS
  - Shower shape analysis
  - Isolation Cuts.
- Will discuss these in the following slides

Strip layer of EMCAL provides for shower shape analysis



- Designed to measure and rejecting di-jets
- γ and π^0 separation for E_T<70 GeV
- Front layer
  - strips typically 0.003x0.1 in $\Delta\eta x\Delta\varphi$
  - Over $|\eta|$<2.5

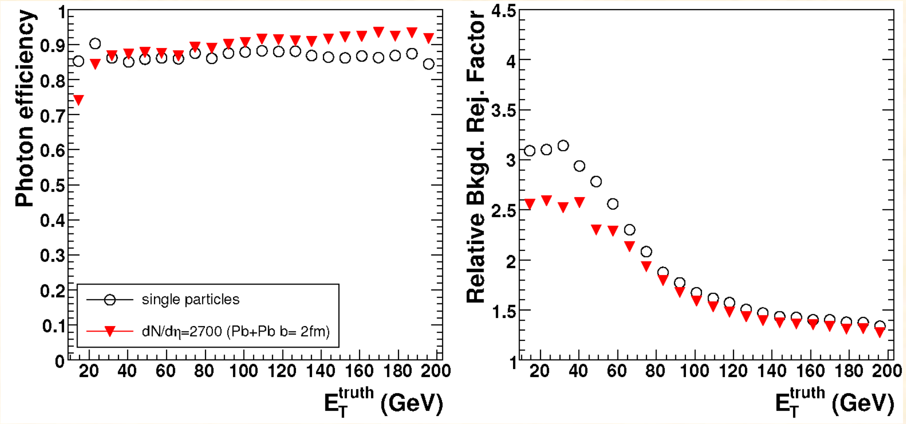


Photon identification

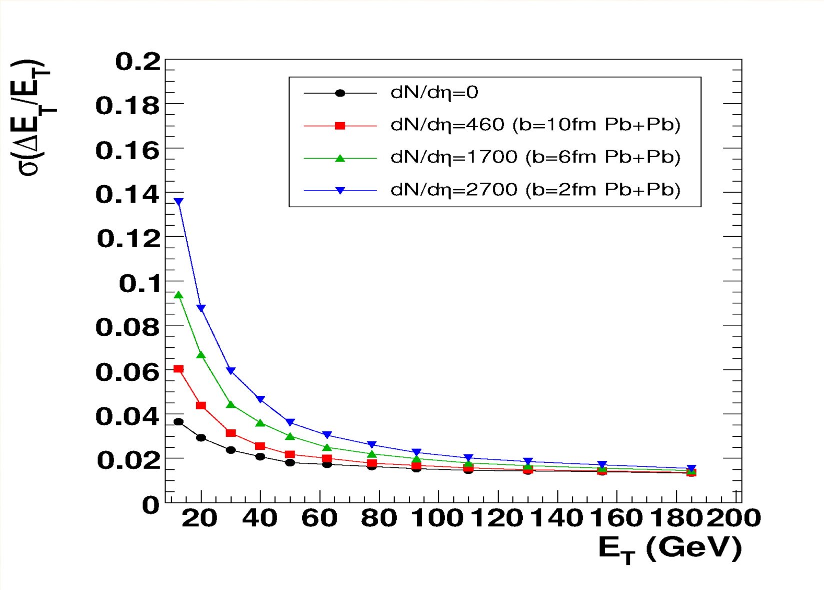
A number of different parameters have been developed based on information in the strip layer.

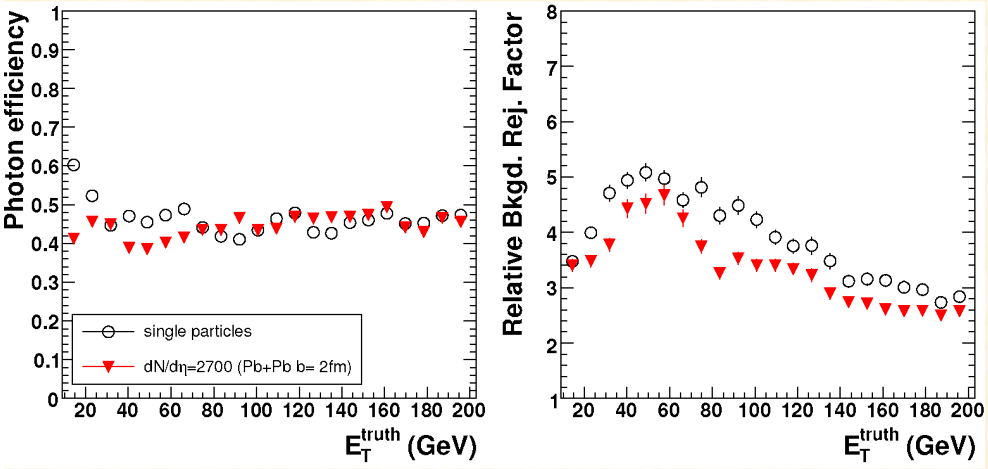
TMVA methods were used to optimize efficiency vs. background.

Good energy and angular resolution is achieved



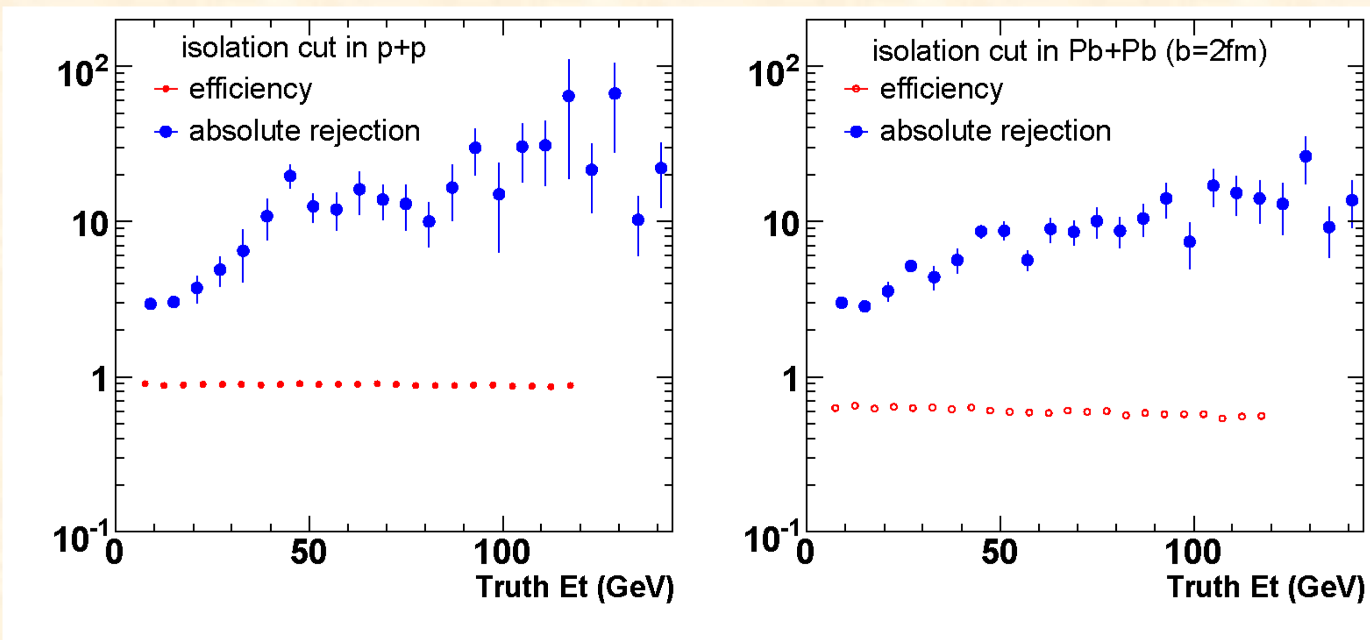
Rejection can be improved by tighter cuts



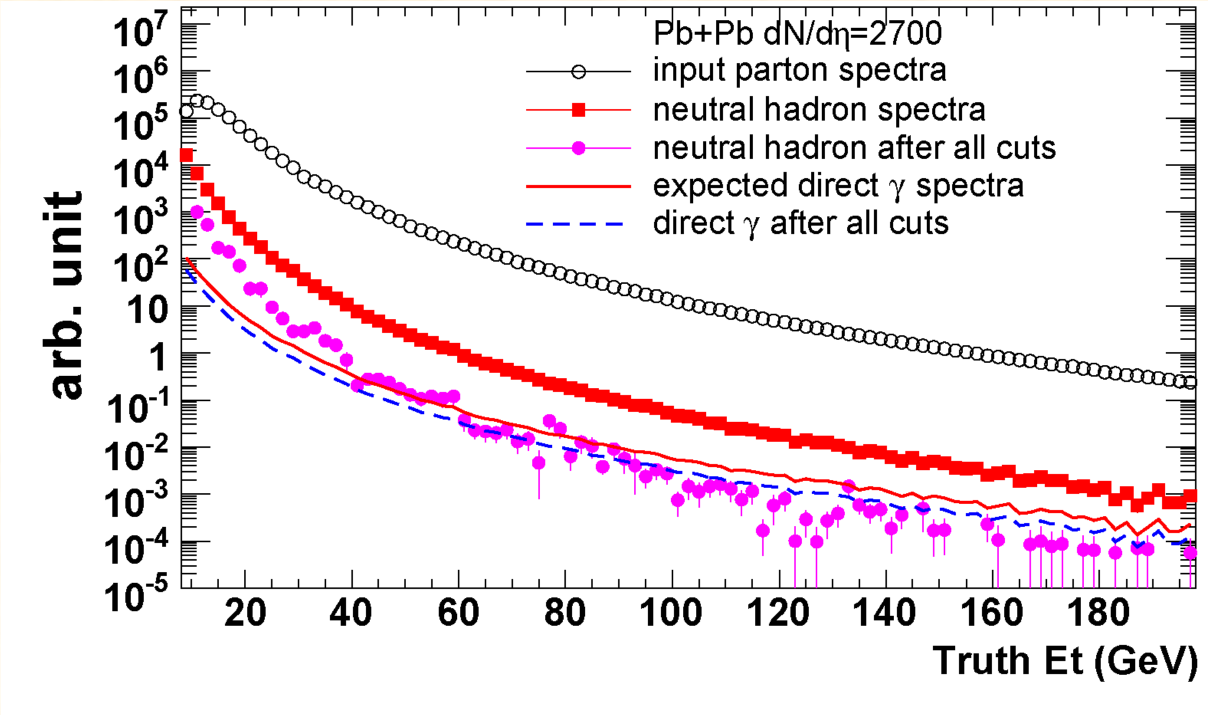


Isolation cuts

- Hight-p_t gammas from hadronic decays usually associated with jets. Ensure that no jet is nearby photon candidates.
- Isolation requirements
  - Only tracks with $p_t < 2.5$ within $0.02<R<0.2$ cone
  - Tower E_T <31 GeV (+ small fraction of photon)
- Cuts chosen to have high efficiency with good rejection

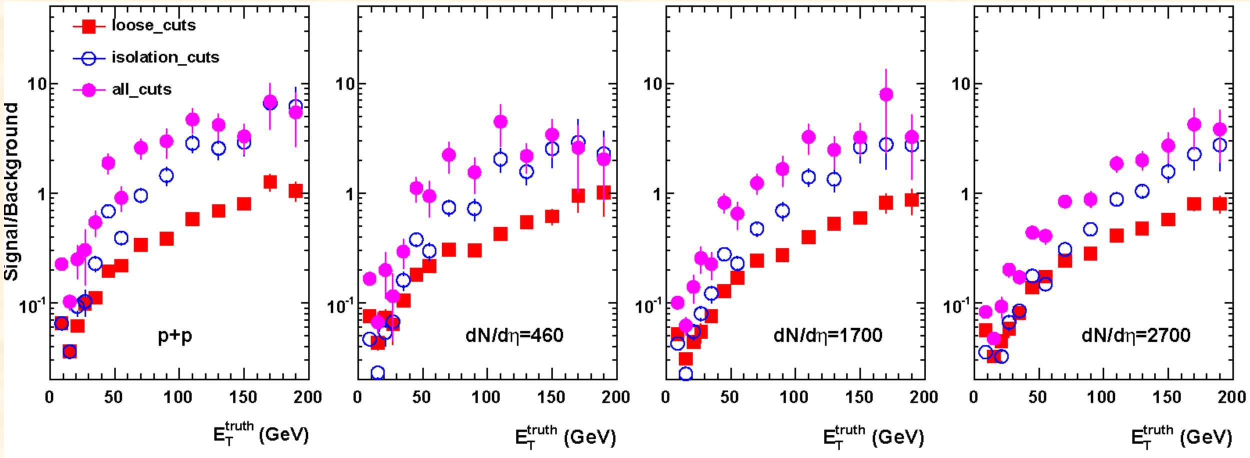


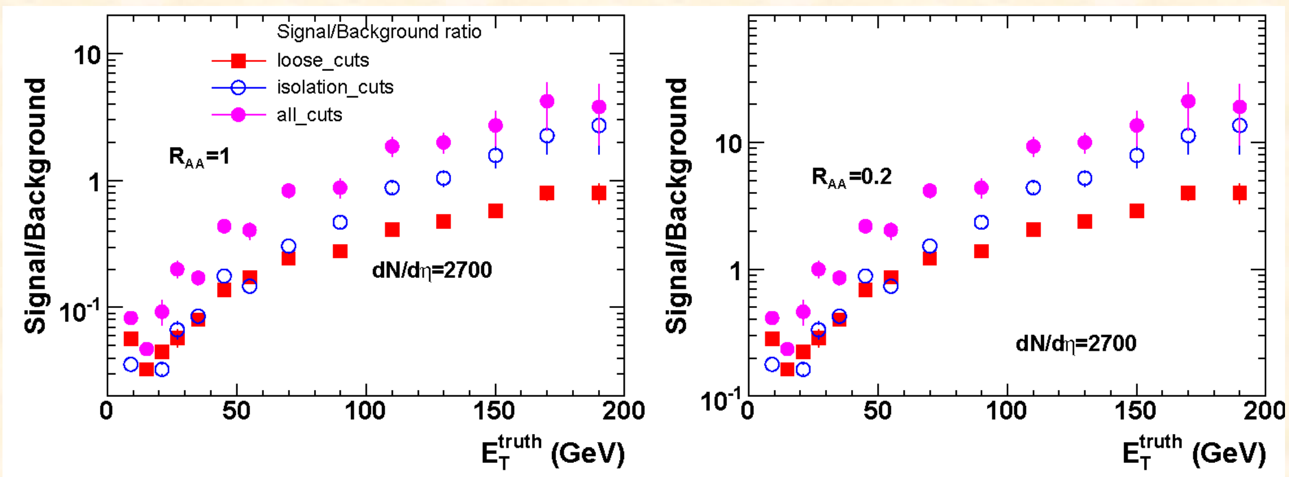
Combining cuts



- Performance of shower shape + isolation cuts for PYTHIA embedded di-jets in Central Pb+Pb events.
- Compared to direct photon spectrum.

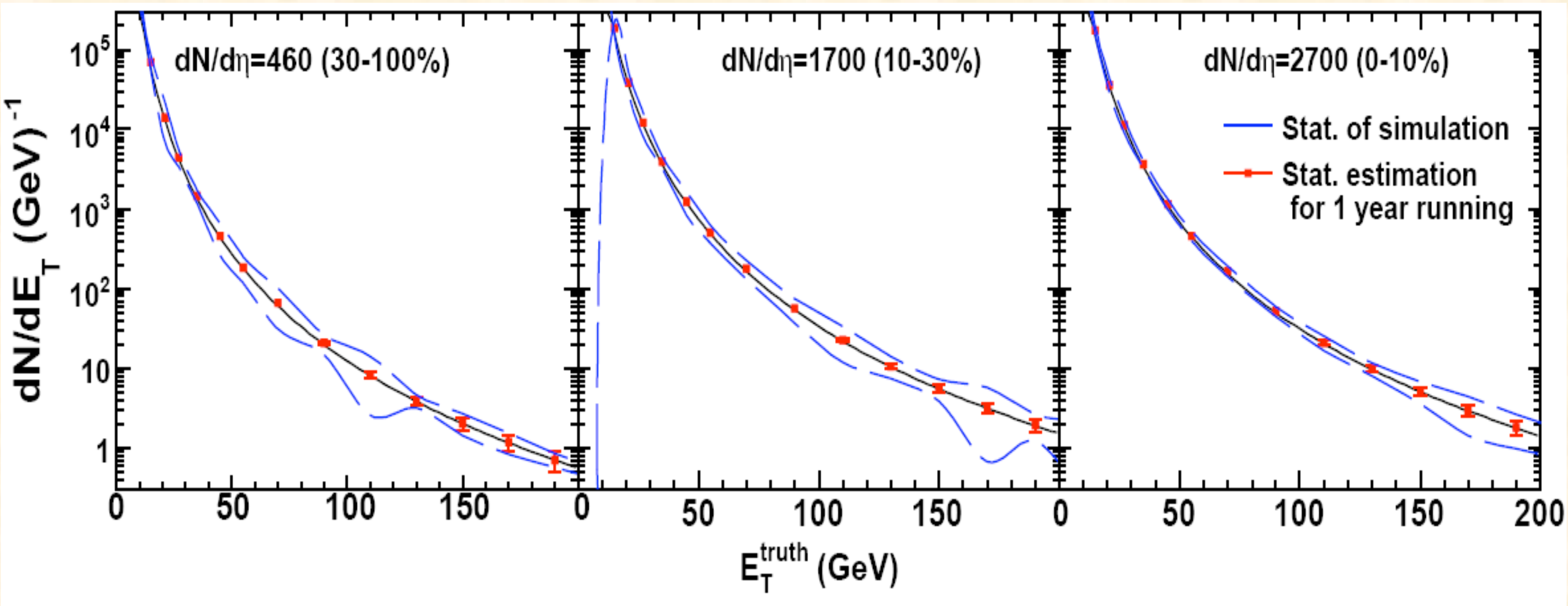
S/B vs. centrality and E_T





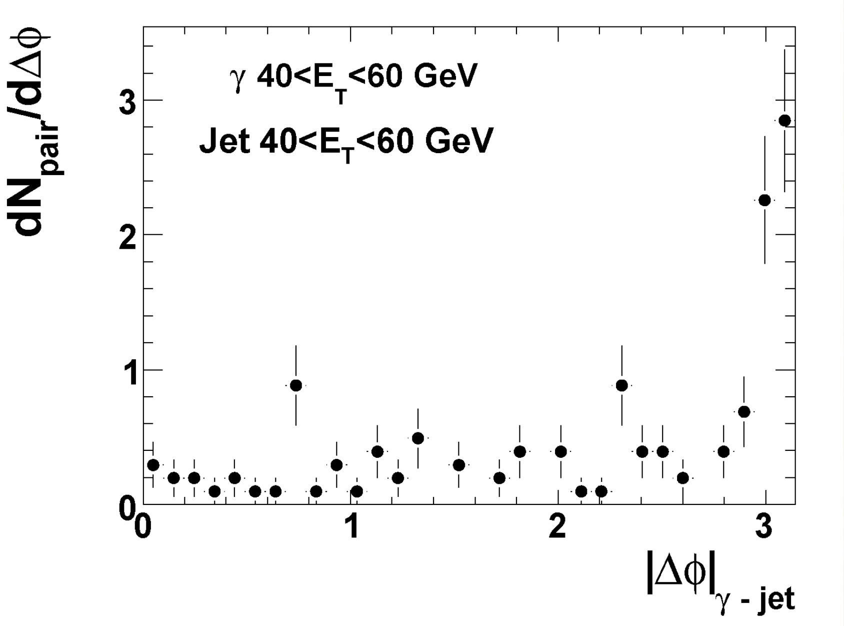
Estimated rates

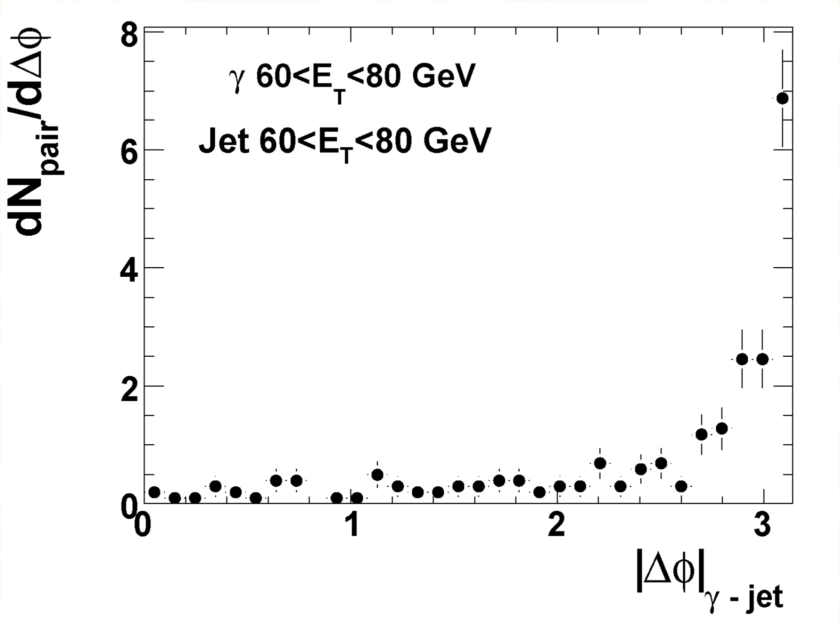
- Expected direct photon spectra for 1 month in $|\eta|<2.4$
- Assuming neutral hadron $R_{AA}=1$ (worst case).
- γ rate for 1 year LHC run of 0.5 nb^{-1}.
- 200k at E>30 GeV, 10 k at E>70 GeV
- Measurement γ-jet correlation and fragmentation function



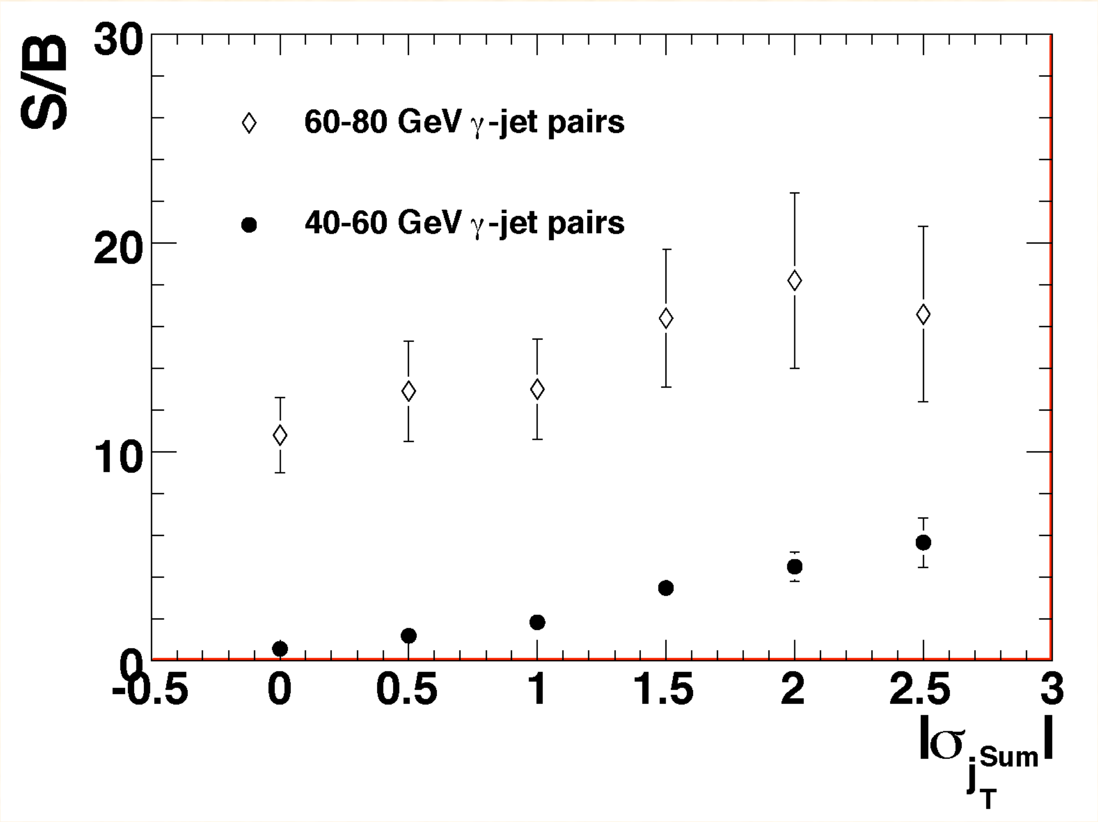
γ-jet Correlation

- Clean γ-jet dϕ distribution in central Pb+Pb.
- Measure in-medium jet-fragmentation function.
- May help jet analysis at low E_t by tuning algorithms, reject fake jets.





γ-jet S/B



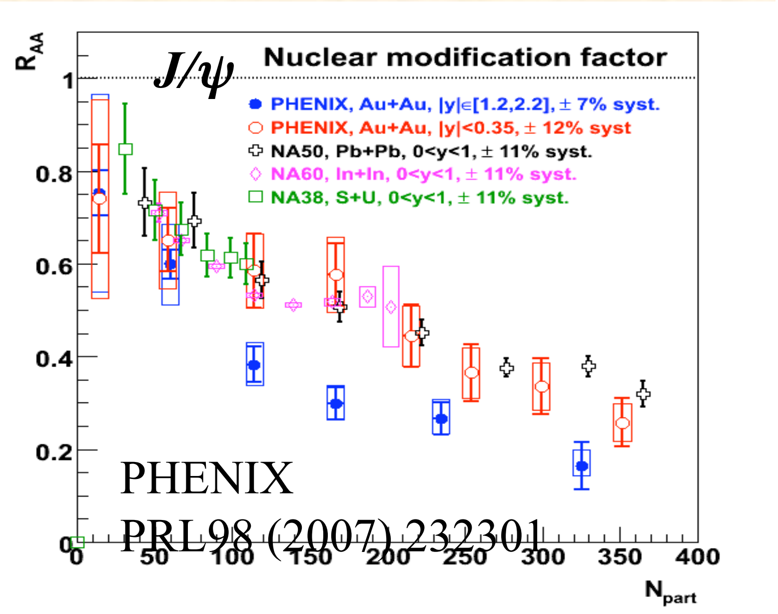
S/B
30
20
10
0
60-80 GeV γ-jet pairs
40-60 GeV γ-jet pairs
-0.5
0
0.5
1
1.5
2
2.5
3
|σ_{j_T^{Sum}}|

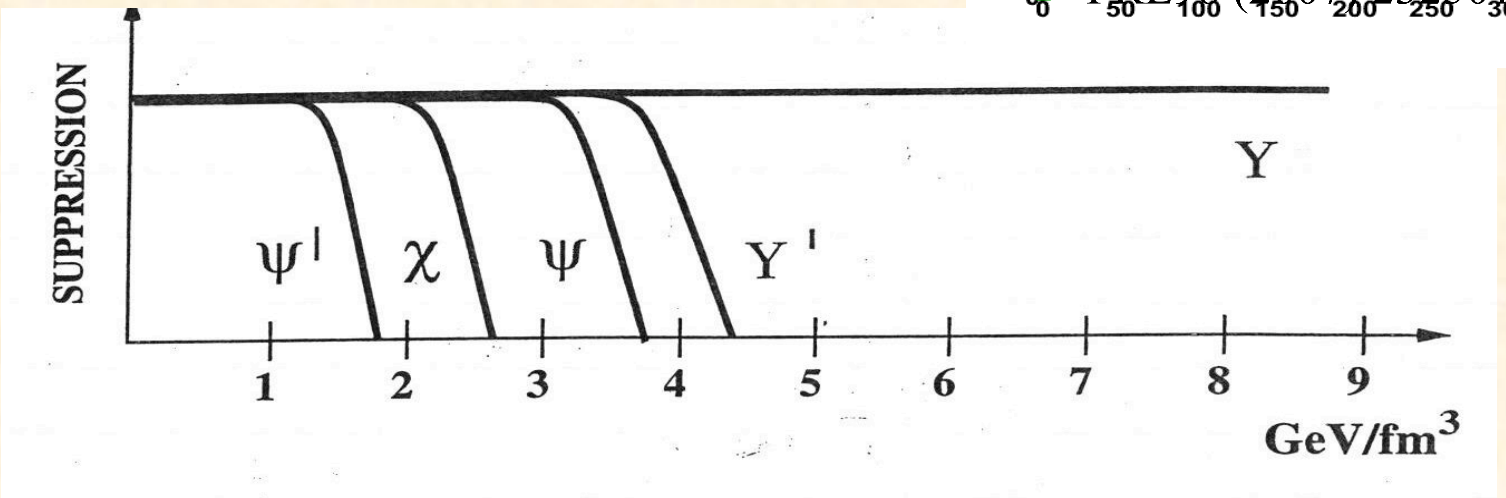
Summary γ, γ-jet

- The first EM-layer provides rejection factors against neutral hadrons of 1.5-6.
- Combination with isolation cuts provides a total relative rejection in central Pb+Pb of ~ 20.
- γ efficiency ~ 60% down to 20 GeV/c
- Tight shower cuts alone allow for studies of fragmentation photons, medium induced bremsstrahlung.
- Will provide 200k photons with S/B >1 for > 30 GeV/c; 10K > 70 GeV/c per HI run (1 month)

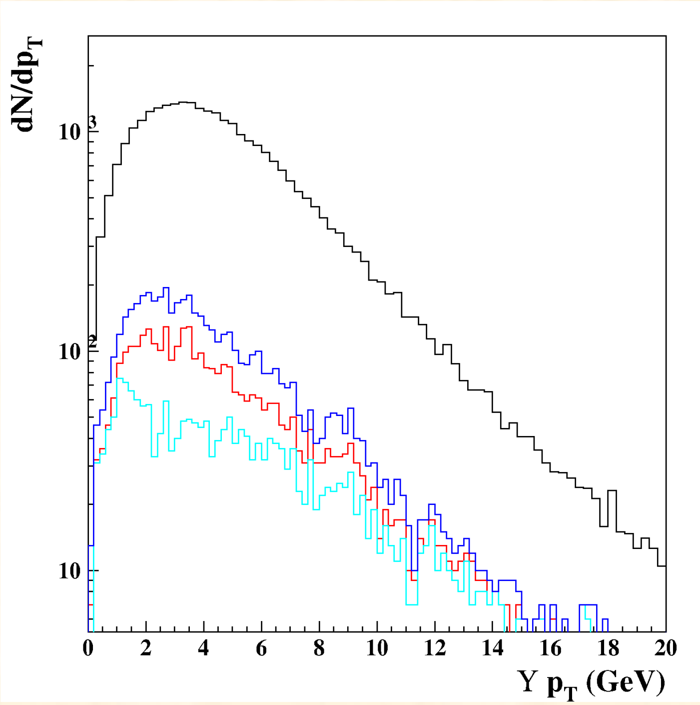
Quarkonia measurements.

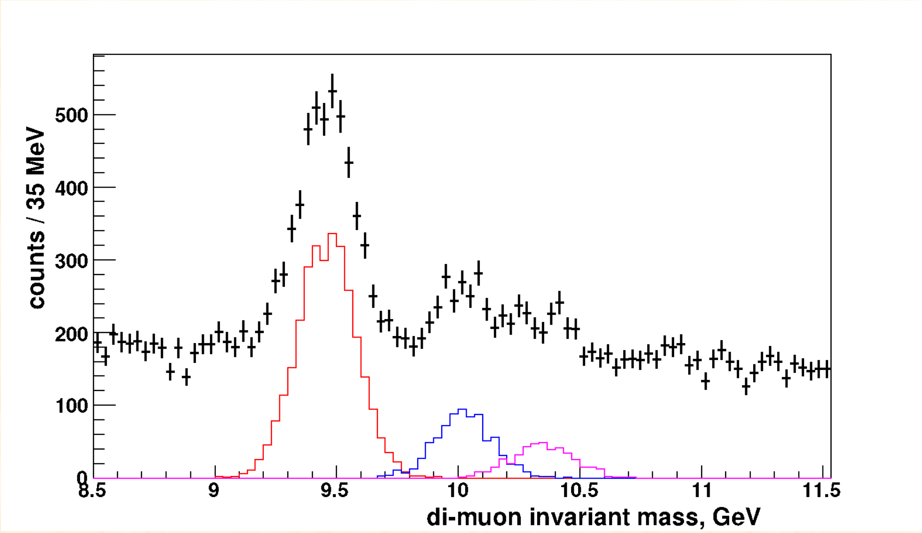
- Measurements of quarkonia has a long history from SPS, RHIC – but not conclusive.
- Will Upsilon states be more conclusive about color screening than J/Ψ states?
- Initial temperature higher at LHC.





Y measurements



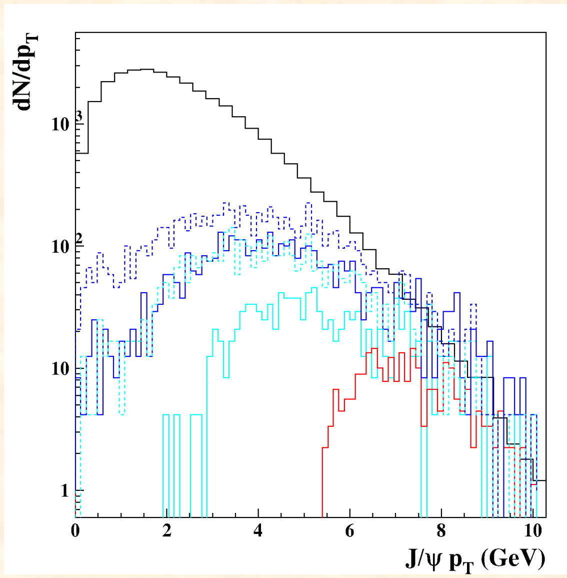


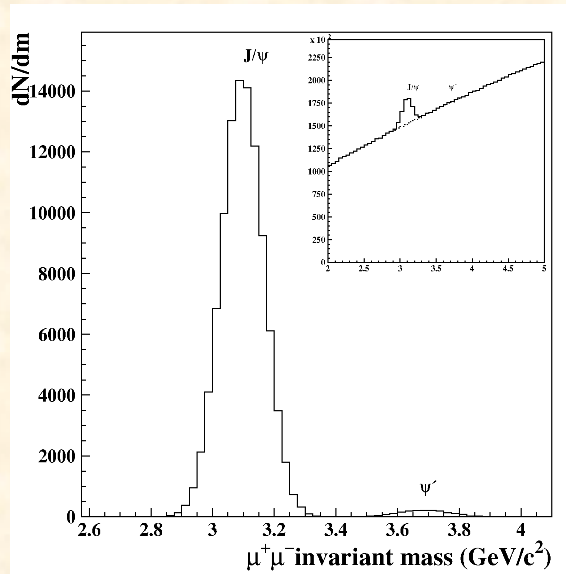
~ 1 month Pb+Pb with $|\eta|<1$.

Reconstructed Y – p_T spectrum.
Samples full p_T range in $|\eta| < 1$.

J/Ψ

J/Ψ provided connection to SPS/RHIC data.



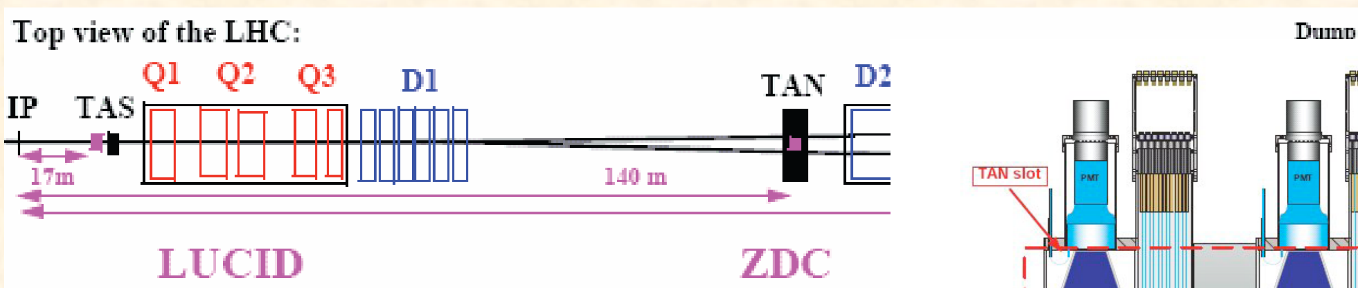


Reconstructed J/Ψ – p_T spectrum.
With nominal muon p_T cut samples high p_T region.
Possible with lower p_T cut to sample full p_T range, but at $|\eta|$ ~ 2.

~ 1 month Pb+Pb with $|\eta|<1$.
Muon p_T cut ~ 3 GeV/c

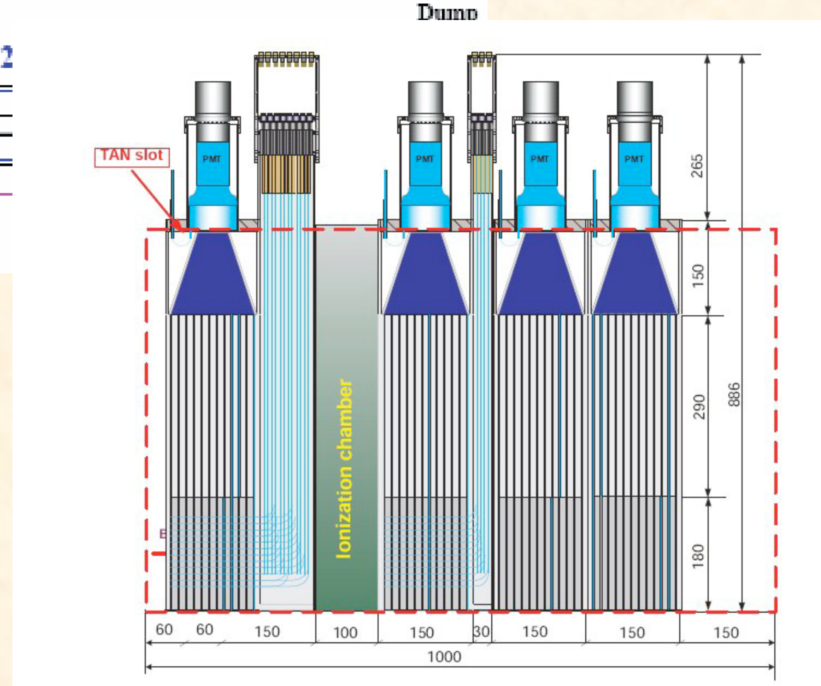
Forward Physics

- Design - triggering Pb+Pb , p+A and pp
- Located in TAN at 140 m – sensitive to spectator neutrons.



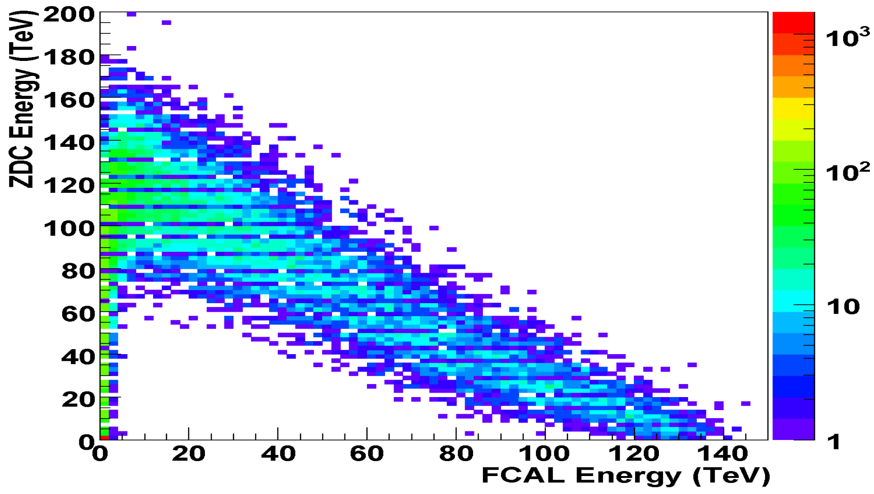
Front EM X-Y section (24*24)

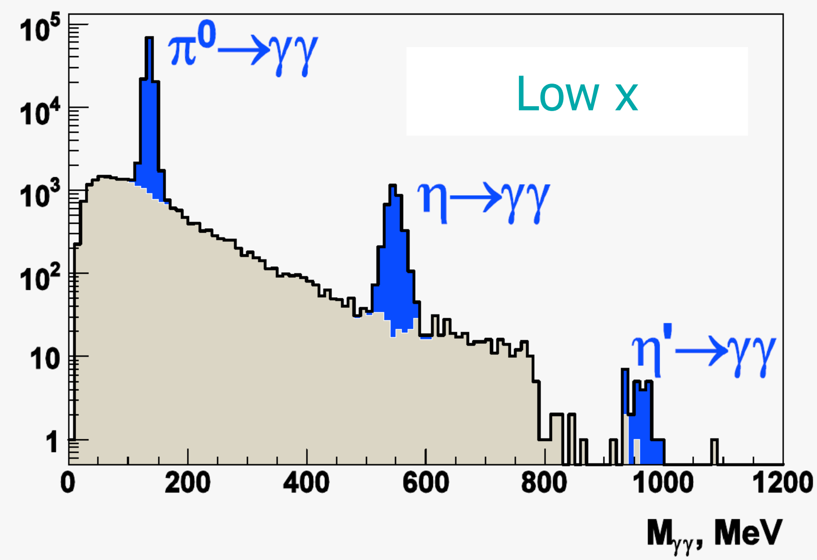
3 section hadronic calorimeter



Physics with ZDCs

Min Bias trigger for Pb+Pb. Fast and high efficiency.
Provide centrality determination together with central calorimeters
Provide access to low-x identified π^0, η in p+p and p+A





Summary
primary goals for ATLAS HI

- *day-1* measurements in p+p and Pb+Pb of global observables such as $dN/d\eta$, $dE_t/d\eta$, $v_2(p_t)$.
- Quantitative tomographic measurements of QGP using fully reconstructed jets, di-jet jet-fragmentation observables, photons, photon-jet.
- Probe Debye screening in the QGP via measurements of Υ decays.
- p+A for study of low-x semi-hard processes to study nuclear shadowing and test models of gluon saturation.

Thanks

- Thanks to my colleagues in the ATLAS HI working group.
- Material from

  ATLAS notes which are/will be in the conf proceedings:

  M. Spousta, ATL-PHYS-PROC-2009-022, ATL-PHYS-PROC-2009-002
  A. Trzupek, ATL-PHYS-PROC-2009-021
  J. Jia, ATL-PHYS-PROC-2008-047
  N. Grau, ATL-PHYS-PROC-2008-055
  L. Rosselet, P. Nevski, S. Timoshenko, ATL-PHYS-PUB-2008-003

  "Heavy Ion Physics Performance Report, in preparation"

We are looking forward to the first collisions and THANKS for your attention

Albert, did you do it ?

06/09 NERVEPIRRENDE. Forskere ved CERN i Schweiz eksperimenterer med at skabe et sort hul

Nerve wracking Researcher at CERN performs experiments to create black holes.

.*Tegning: Lars Andersen (Berlingske Tidende, 6 Septermber 2008)*