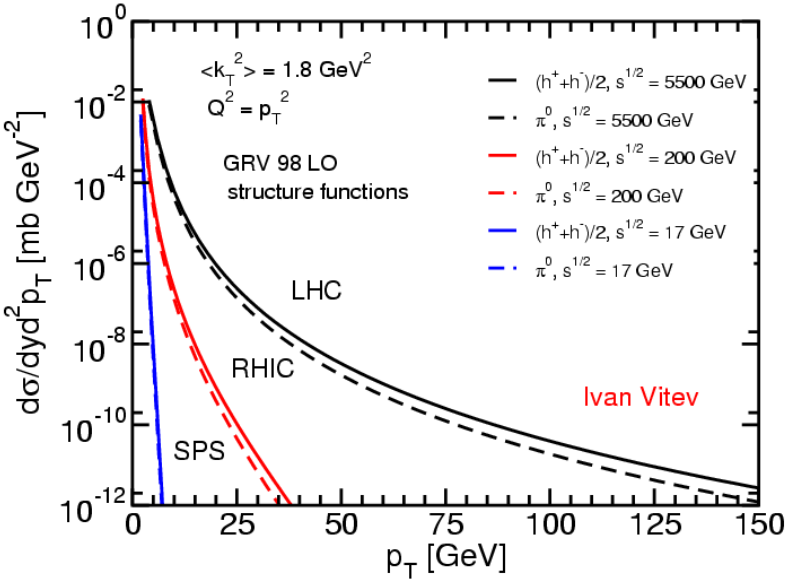
Measuring nuclear modification factors at high-p_T using jet triggers

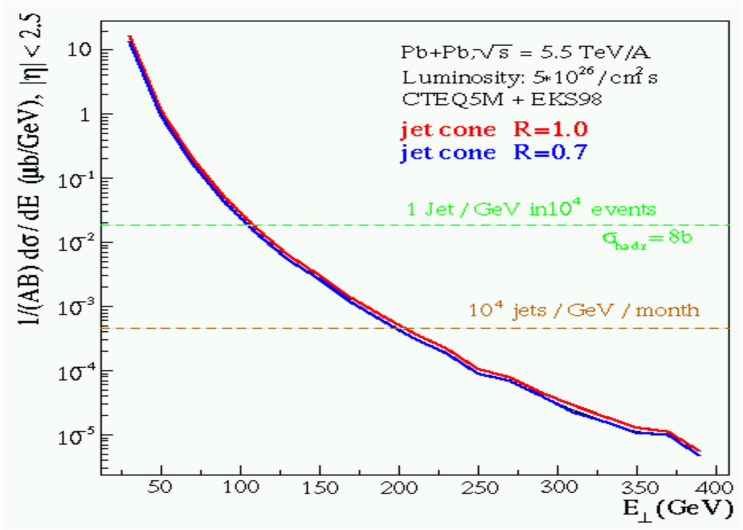
Krisztián Krajczár

High-p_T Physics at LHC

Tokaj, Hungary, 2008

Heavy Ion Physics at the LHC





Pb+Pb Collisions at $\sqrt{s_{NN}}$ ~ 5.5TeV

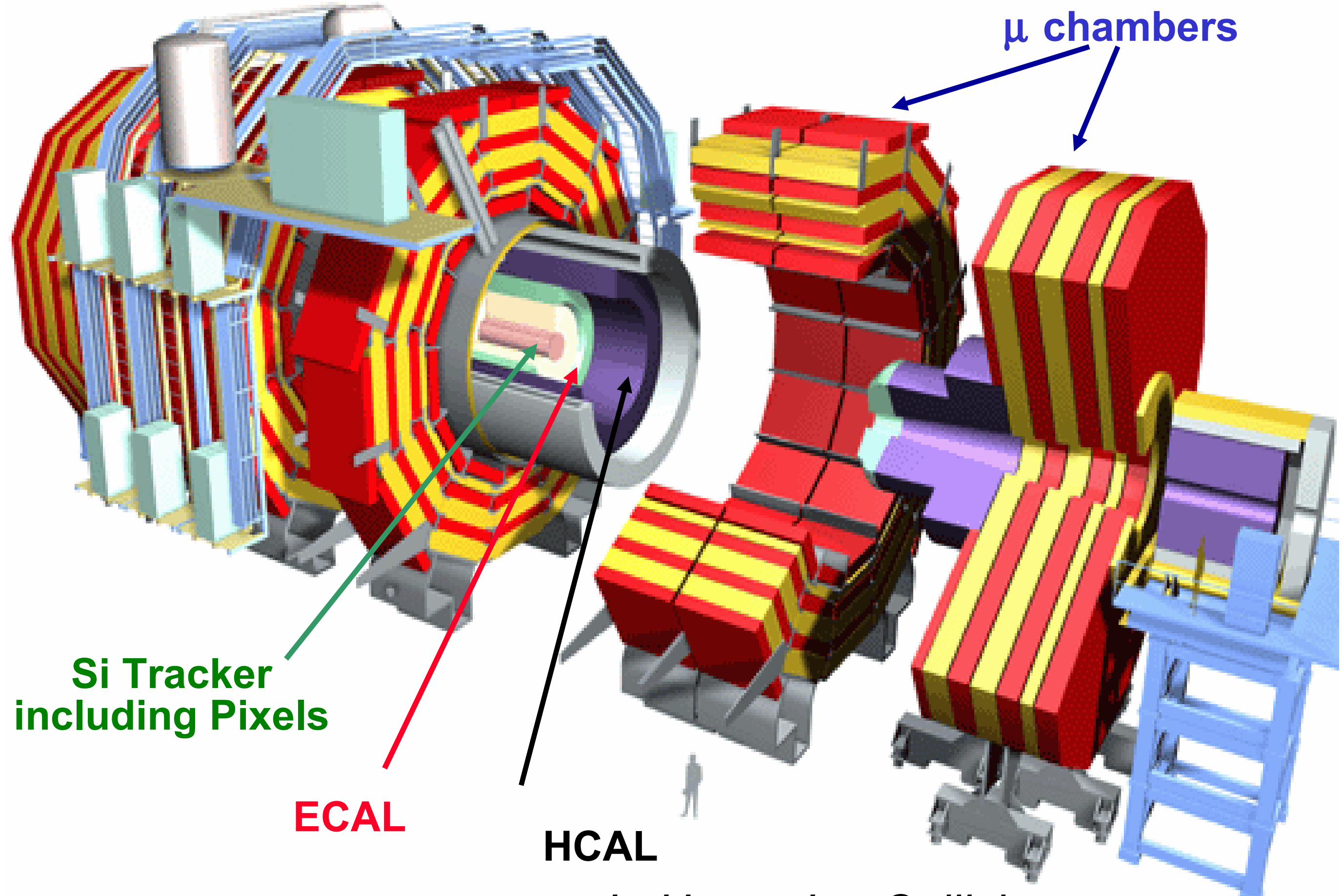
Large Cross section for Hard Probes

High luminosity: $10^{27}/cm^2s$

- Copious production of high p_T particles
  - Nuclear modification factors R_{AA} up to very high p_T
- Large cross section for J/ψ and ϒ family production
  - σ^{cc}_{LHC} ~ 10x σ^{cc}_{RHIC}
  - σ^{bb}_{LHC} ~ 100x σ^{bb}_{RHIC}
  - Different “melting” for members of ϒ family with temperature
- Large jet cross section
  - Jets directly identifiable
  - Study in-medium modifications

The Detectors

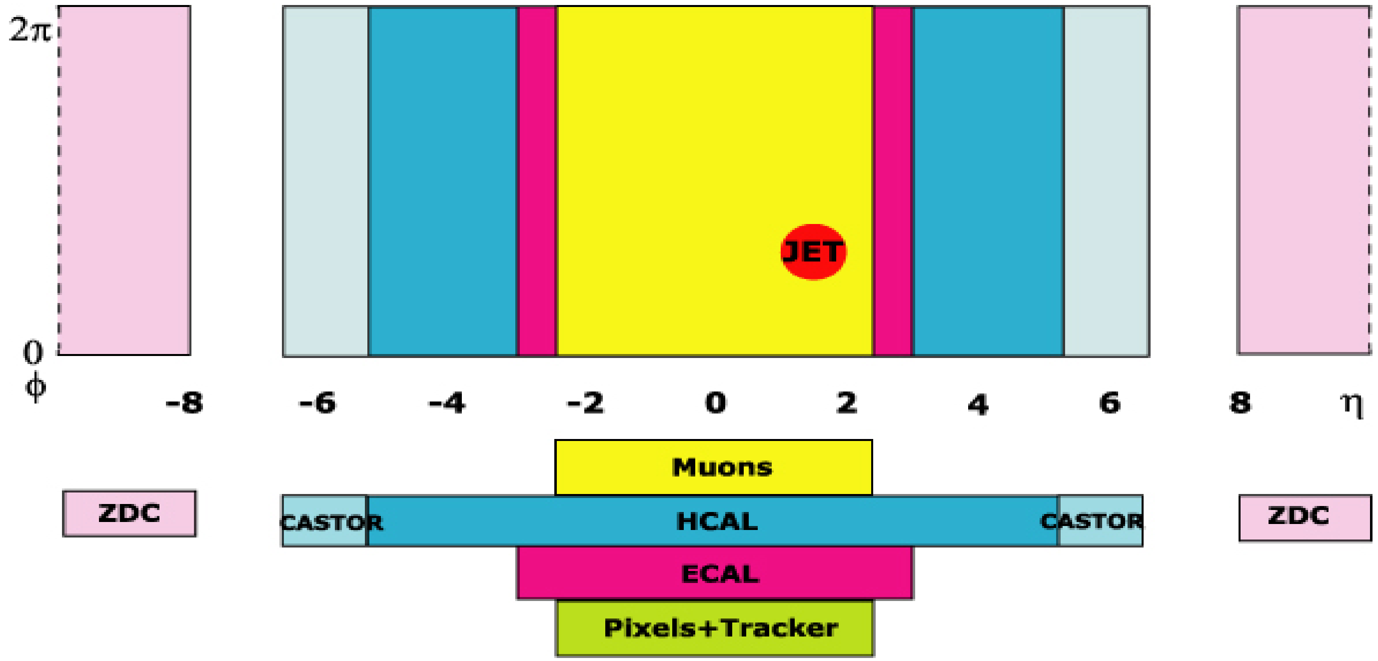
Designed for precision measurements in high luminosity p+p collisions



Hermetic Calorimetry
Large acceptance Tracker
Excellent Muon Spectrometer

In Heavy Ion Collisions:
Functional at the highest expected multiplicities
Detailed studies at ~$dN_{ch}/d\eta$ ~3000
cross-checks up to 7000-8000

CMS Detector Coverage



- Hermeticity, Resolution, Granularity
  - Central region $\Delta\eta$~5 equipped with tracker, electromagnetic and hadronic calorimeters and muon detector
- Forward coverage
  - Calorimetric coverage of $\Delta\eta$~10
  - CASTOR is dedicated for heavy-ion measurements, exotics: centauro
  - Zero Degree Calorimeter (ZDC), neutrons
- High data taking speed and trigger versatility

Jets in Heavy Ion Collisions

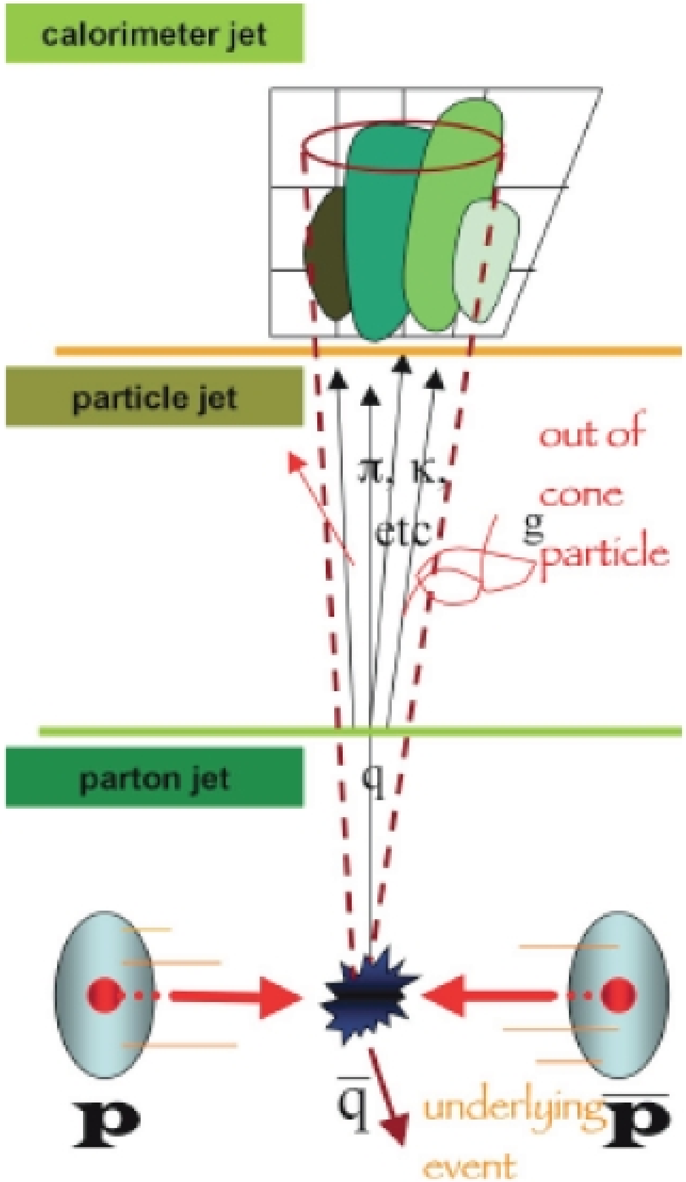
Hard partons and their energy loss: probe the medium

Partial list of observables:

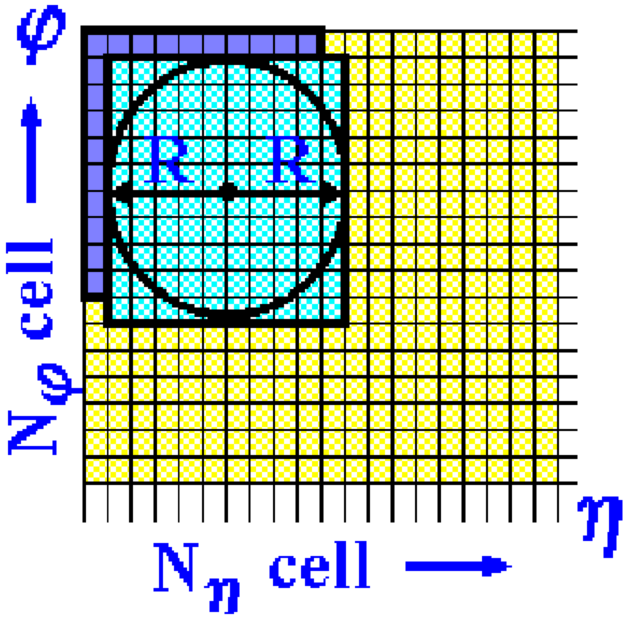
- High p_T particles and particle correlations
- Jet rates: single jets, multi-jets
- Jet fragmentation and shape
  - p_T of particles for $r < R$
  - Multiplicity of particles vs. r
  - Fragmentation function
- Additional information from
  - Jet+γ, Jet+Z correlations
  - Tagged heavy quark jets (b, c)

Jet Definitions

- **Parton jet**
  - This is what we can calculate
- **Final state particle jet**
  - Fragmentation/hadronization
  - MC generators rely on parametrizations of experimental data
- **Calorimeter Jet**
  - This is what we measure in the detector
- **Need to associate final state particles with initial parton**
  - No unique way of doing this!
  - Jet algorithms
  - => Jet Calibration



Iterative cone

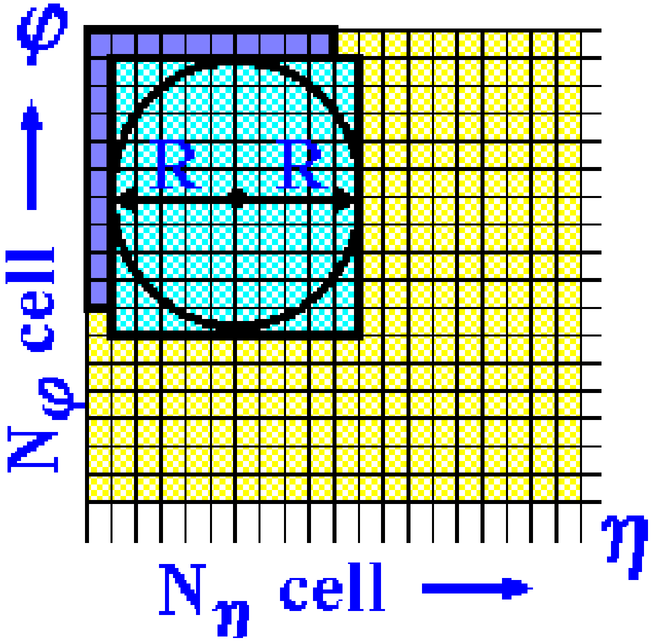


- Search for the particle with the highest E_T (seed)
- Use its η and φ to define the axis of the jet candidate
- Define a ring on the η-φ plane with a radius of R
- Collect final state particle with r < R
- Redefine the jet with the help of these particles:

$$E_{T,jet} = \sum_i E_T^i \qquad \eta_{jet} = \frac{1}{E_{T,jet}} \sum_i E_T^i \eta^i \qquad \phi_{jet} = \frac{1}{E_{T,jet}} \sum_i E_T^i \phi^i$$

- If Δη and Δφ < predefined value → quit

Background Subtraction Algorithm



Event-by-event background subtraction:

- Calculate $\langle E_T^{Tower}(\eta)\rangle$ and $D^{Tower}(\eta)$ for each η ring
- Recalculate all E_T^{Tower} tower energies:

$$E_T^{Tower} = E_T^{Tower} - E_t^{pile\text{-}up}$$

$$E_t^{pile\text{-}up} = \langle E_T^{Tower}(\eta)\rangle + D^{Tower}(\eta)$$

- Negative tower energies are replaced by 0

- Find Jets with $E_T^{jet} > E_t^{cut}$ using new tower energies
- Recalculate pile-up energy with towers outside of the jet cone
- Recalculate tower energy with new pile-up energy
- Final jets are found with the same iterative cone algorithm $E_T^{Jet} = E_T^{cone} - E_t^{pile\text{-}up\ new}$

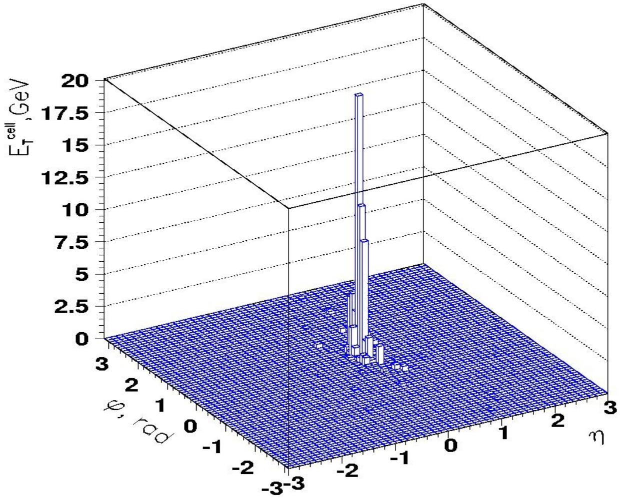
Jet Reconstruction

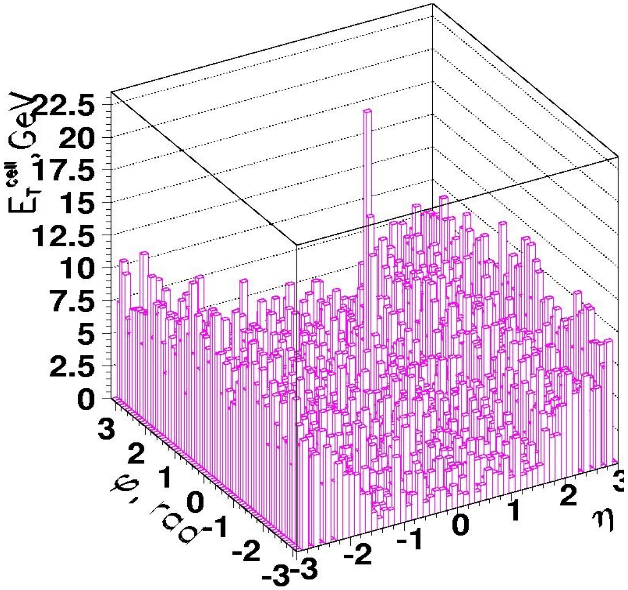
Jet E_T ~100GeV, Pb Pb background dN_{ch}/dy ~ 5000

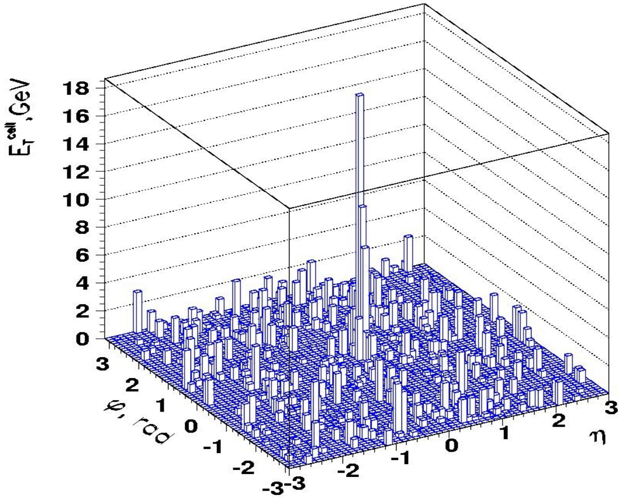
Jet in pp after pileup subtraction

Jet superimposed on Pb Pb background

Jet in Pb-Pb after pileup subtraction

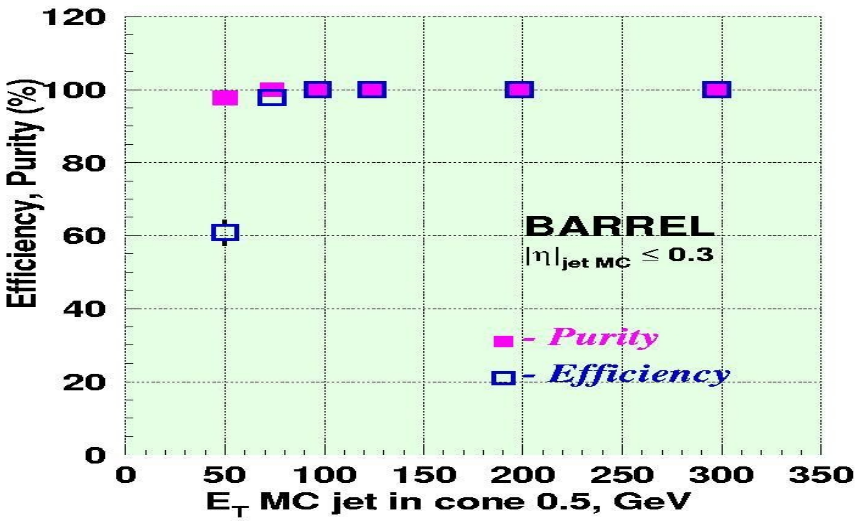


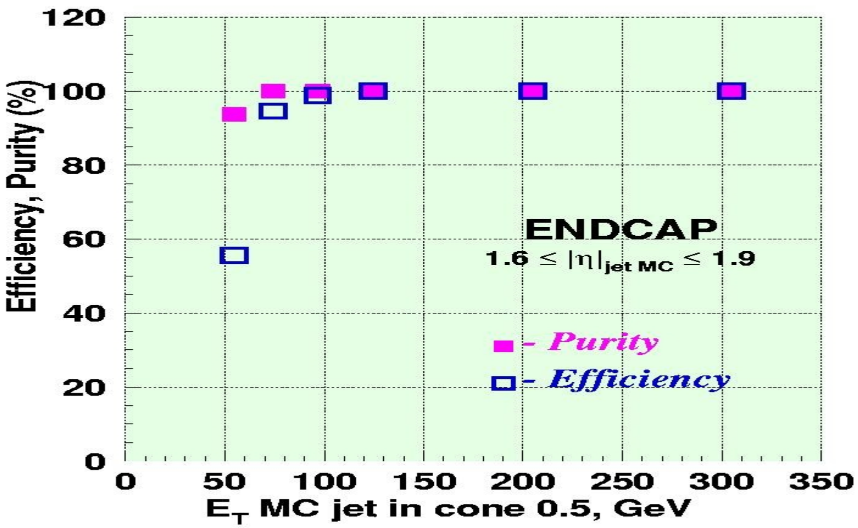




Efficiency, Purity vs. Jet Energy

Reconstructing 50-300 GeV Jets in Pb-Pb background

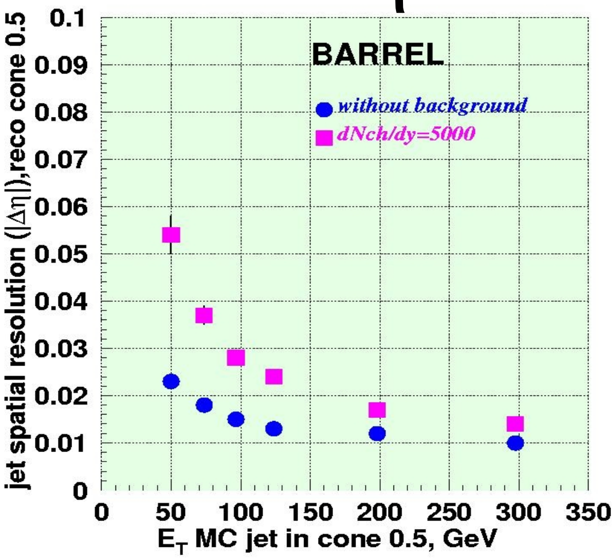




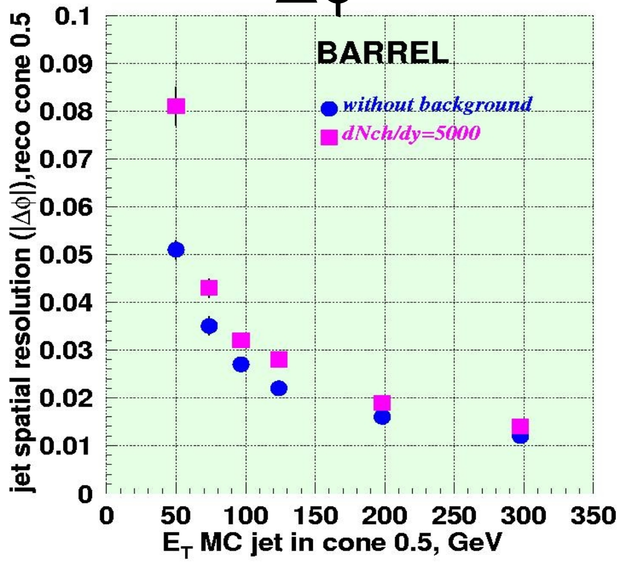
- **EFFICIENCY**
  - $\frac{\text{\# events with true reco. jets}}{\text{\# all jet events}}$
- **PURITY**
  - $\frac{\text{\# events with true reco. jets}}{\text{\# all reco. jet events (true+fake)}}$
- **Threshold of jet reco. E_T > 30 GeV.**
- **Above 75(100) GeV we achieve**
  - **100% efficiency and purity in the barrel (endcap)**

Jet Resolutions

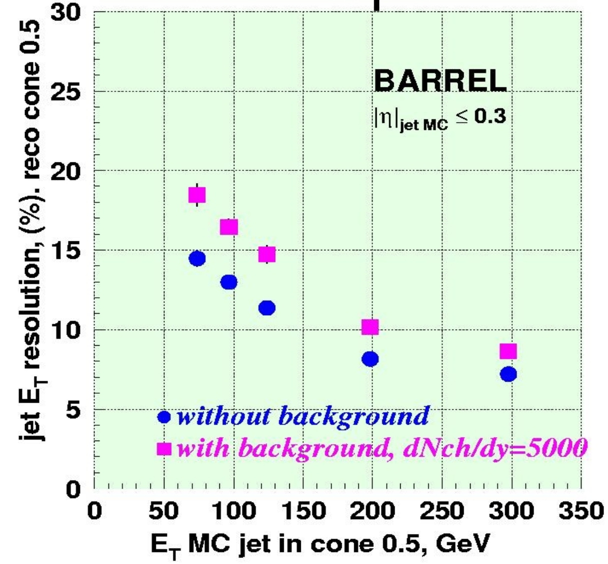
$\Delta\eta$



$\Delta\phi$

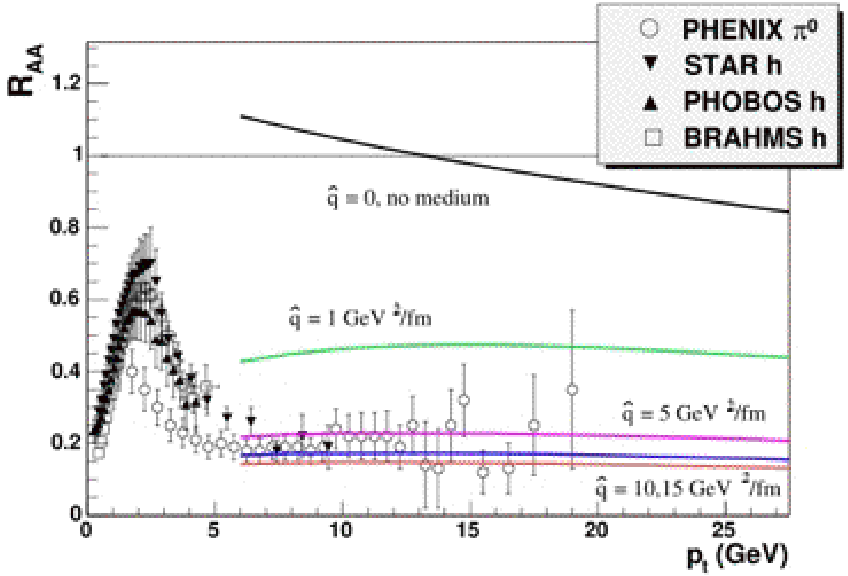


ΔE_T



- **The resolutions are degraded in Pb Pb collisions**
  - **η,ϕ better than size of calorimeter tower (0.087x0.087)**
  - **E_T resolution ~16% at 100GeV**
- **Expect further improvement by adding tracker information**
  - **p_T measurement of tracks is more precise than the response of the calorimeter**
  - **Recover charged tracks that are bent out of the jet cone by the magnetic field**

Jet Quenching @ RHIC



$$R_{AA} = \frac{\sigma_{pp}^{\mathrm{inel}}}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

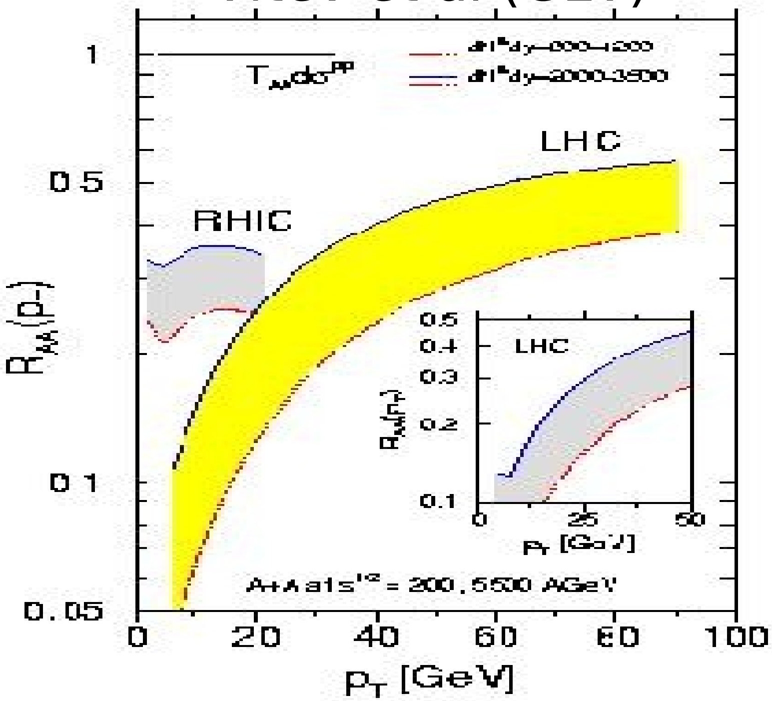
$$R_{CP} = \frac{\langle N_{\mathrm{coll}}^{\mathrm{periph}} \rangle}{\langle N_{\mathrm{coll}}^{\mathrm{central}} \rangle} \frac{d^2 N_{AA}^{\mathrm{central}}/dp_T d\eta}{d^2 N_{AA}^{\mathrm{periph}}/dp_T d\eta}$$

The nuclear modification factor R_{AA} or R_{CP}

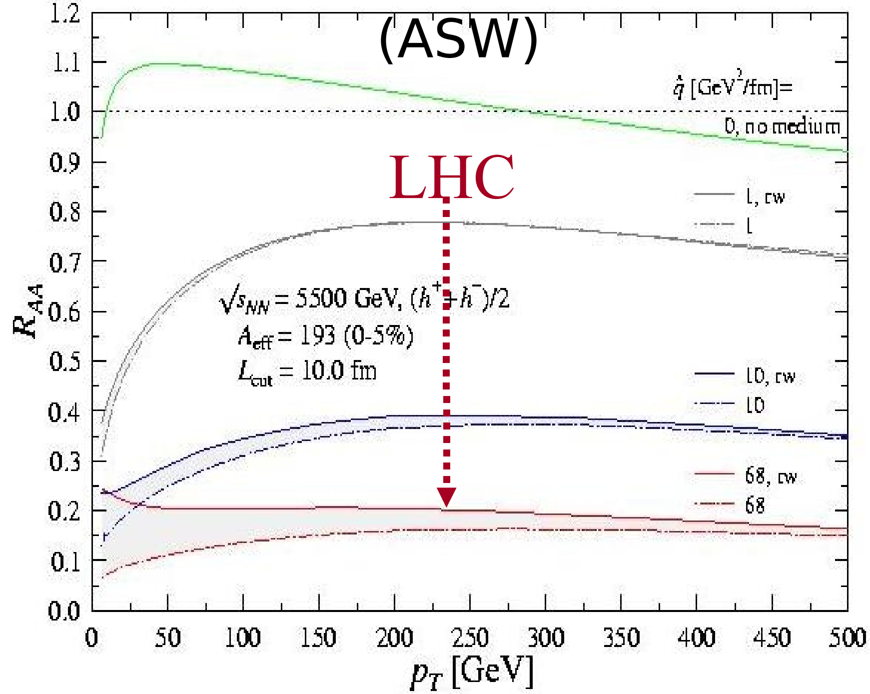
- **Compare charged hadron spectra in central PbPb collisions to a unquenched reference spectrum**
  - R_{AA}: central PbPb compared to pp scaled by the number of binary collisions
  - R_{CP} : central PbPb compared to very peripheral PbPb

Predictions for PbPb @ LHC

Vitev et al (GLV)

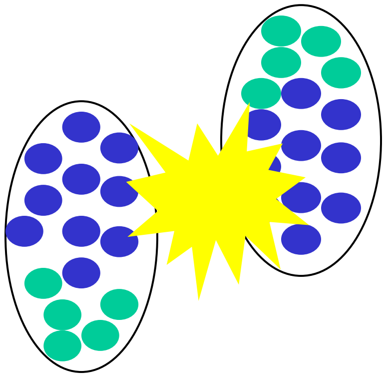


Armesto et al (ASW)



- **Predictions for R_{AA} at LHC energy vary widely**
  - **Significant differences at high p_T**
  - **Does the nuclear medium become transparent for high E_T partons**

The HYDJET Generator



- **Developed within the CMS HI Group**
  I.P. Lokhtin, A.M. Snigirev, Eur. Phys. J. C 46 (2006) 211
- **Soft particle production using Hydrodynamic model,**
  - includes bulk properties, flow etc…
- **Jets produced using PYQUEN**
  - PYTHIA with medium-induced quenching
- **Calculate the collision geometry (Glauber model)**
- **Assume energy in collisions below p_T^{min} just thermalizes and heats the medium**
  - Set p_T^{min} cutoff to define hard collisions, N_{hard}

- Soft Background
  - Bulk of the particles
  - Use HYDRO Generator

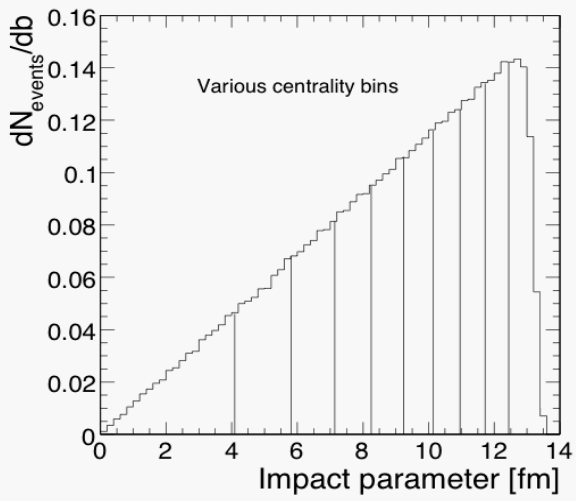
More details in Igor Lokhtin's talk

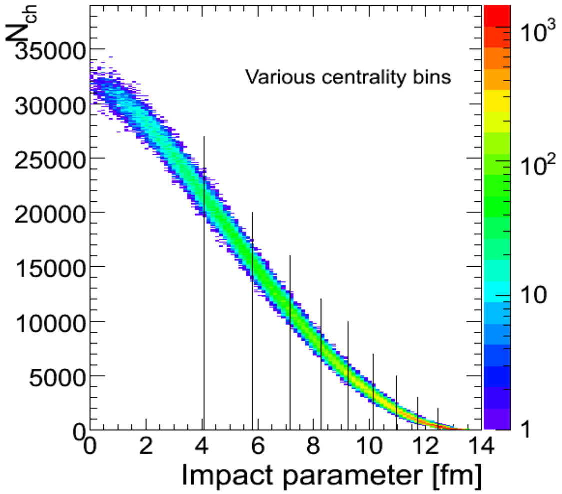
- Hard Signal
  - Generate N_{hard} signal collisions and add them to the background
    e.g. p_T^{min} = 7 GeV N_{hard} = 320
  - I.e run PYTHIA/PYQUEN with p_T^{min} N_{hard} times => Multijet events

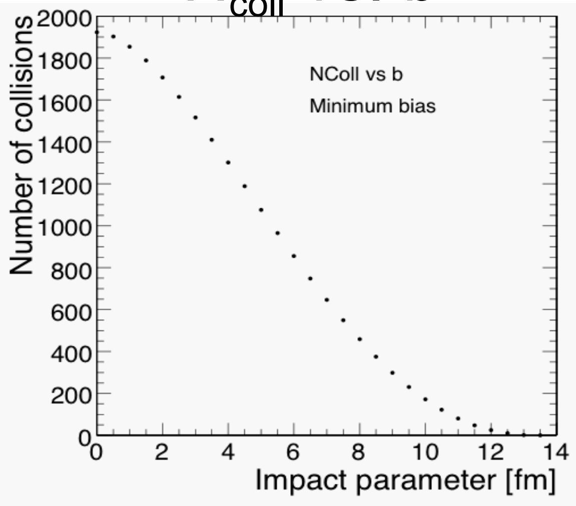
Collision Centrality

Multiplicity vs. b

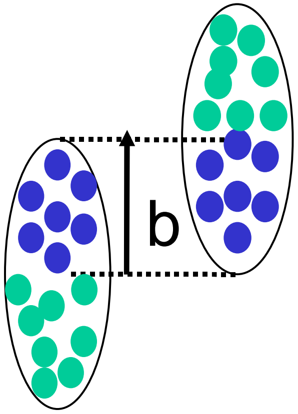
N_{coll} vs. b







Generator level plots!



- **The collision centrality determines the bulk properties of the events**
  - **Multiplicity increases with centrality**
    - Background to the Jet reconstruction
  - **Jet cross section proportional to N_{coll}**
  - **More parton energy loss in central collisions**
- **Data is analyzed as a function of centrality**
  - **Data sets are split in bins containing constant fractions of the total inelastic cross section**

HI HLT Bandwidth Allocation

Channel	E_T threshold	Bandwidth [MByte/s]	event size [MByte]	rate to tape [Hz]
min. bias	-	33.75 (15%)	2.5	13.50
jet	100 GeV	24.75 (11%)	5.8	4.27
jet	75 GeV	27 (12%)	5.7	4.74
jet	50 GeV	27 (12%)	5.4	5.00

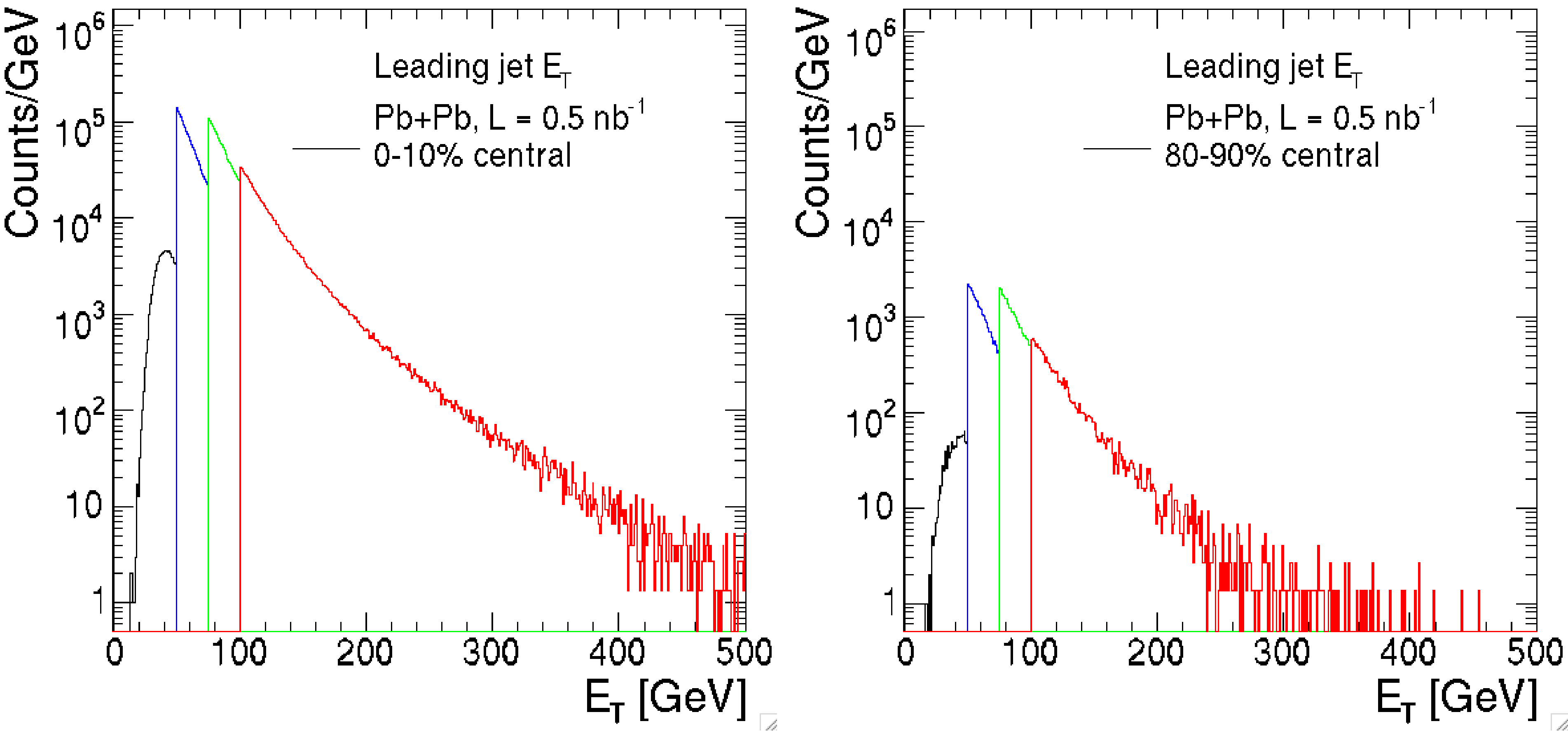
- **Statistics for one month of PbPb running**
  - **Assume an integrated luminosity of L = 0.5 nb^{-1}**
  - **Take bandwidth allocation from the HI-PTDR**
    J. Phys. G: Nucl. Part. Phys. 34 (2007) 2307-2455
  - **Calculate the rates of Calo Jets above the trigger thresholds that saturate the allocated bandwidth**
  - **Produce the full event statistics (on generator level) corresponding to one month of data taking**
  - **HLT: full offline jet algorithm with pile-up subtraction**

Jet Rates

Centrality bin	Data taking mode	Number of jets above: 50 GeV	75 GeV	100 GeV
0–10%	Infinite bandwidth	2.27×10^7	3.71×10^6	9.67×10^5
	Minimum bias	7.86×10^4	1.28×10^4	3.35×10^3
	Triggered	2.02×10^6	1.79×10^6	9.67×10^5
10–20%	Infinite bandwidth	1.40×10^7	2.51×10^6	6.74×10^5
	Minimum bias	4.85×10^4	8.69×10^3	2.33×10^3
	Triggered	1.23×10^6	1.21×10^6	6.74×10^5
20–30%	Infinite bandwidth	1.03×10^7	1.98×10^6	6.29×10^5
	Minimum bias	3.57×10^4	6.85×10^3	2.18×10^3
	Triggered	9.22×10^5	9.54×10^5	6.29×10^5
30–40%	Infinite bandwidth	7.06×10^6	1.25×10^6	3.17×10^5
	Minimum bias	2.44×10^4	4.33×10^3	1.10×10^3
	Triggered	6.33×10^5	6.01×10^5	3.17×10^5
40–50%	Infinite bandwidth	4.84×10^6	9.30×10^5	2.78×10^5
	Minimum bias	1.68×10^4	3.22×10^3	9.62×10^2
	Triggered	4.34×10^5	4.48×10^5	2.78×10^5
50–60%	Infinite bandwidth	3.28×10^6	5.89×10^5	1.72×10^5
	Minimum bias	1.14×10^4	2.04×10^3	5.95×10^2
	Triggered	2.94×10^5	2.84×10^5	1.72×10^5
60–70%	Infinite bandwidth	1.87×10^6	3.68×10^5	9.92×10^4
	Minimum bias	6.47×10^3	1.27×10^3	3.43×10^2
	Triggered	1.68×10^5	1.78×10^5	9.92×10^4
70–80%	Infinite bandwidth	9.23×10^5	1.80×10^5	4.98×10^4
	Minimum bias	3.12×10^3	6.23×10^2	1.72×10^2
	Triggered	8.26×10^4	8.67×10^4	4.98×10^4
80–90%	Infinite bandwidth	3.96×10^5	7.24×10^4	1.82×10^4
	Minimum bias	2.24×10^5	3.98×10^4	1.10×10^4
	Triggered	3.55×10^4	3.49×10^4	1.82×10^4
Total	Infinite bandwidth	6.54×10^7	1.16×10^7	3.20×10^6
	Minimum bias	2.26×10^5	4.02×10^4	1.11×10^4
	Triggered	5.82×10^6	5.59×10^6	3.20×10^6

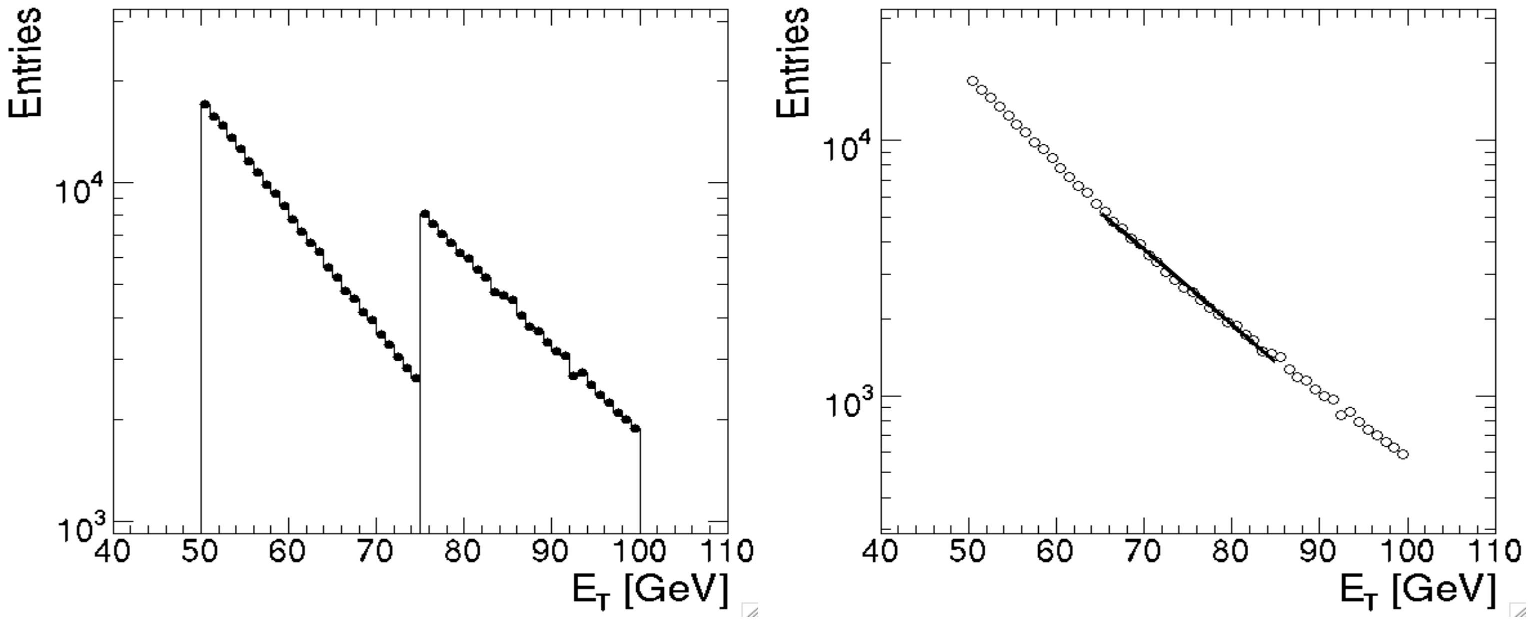
- **Events generated**
  - jet triggered events in centrality bins according to this table
  - 900k min. bias. Events per centrality bin

Leading Jet Distributions



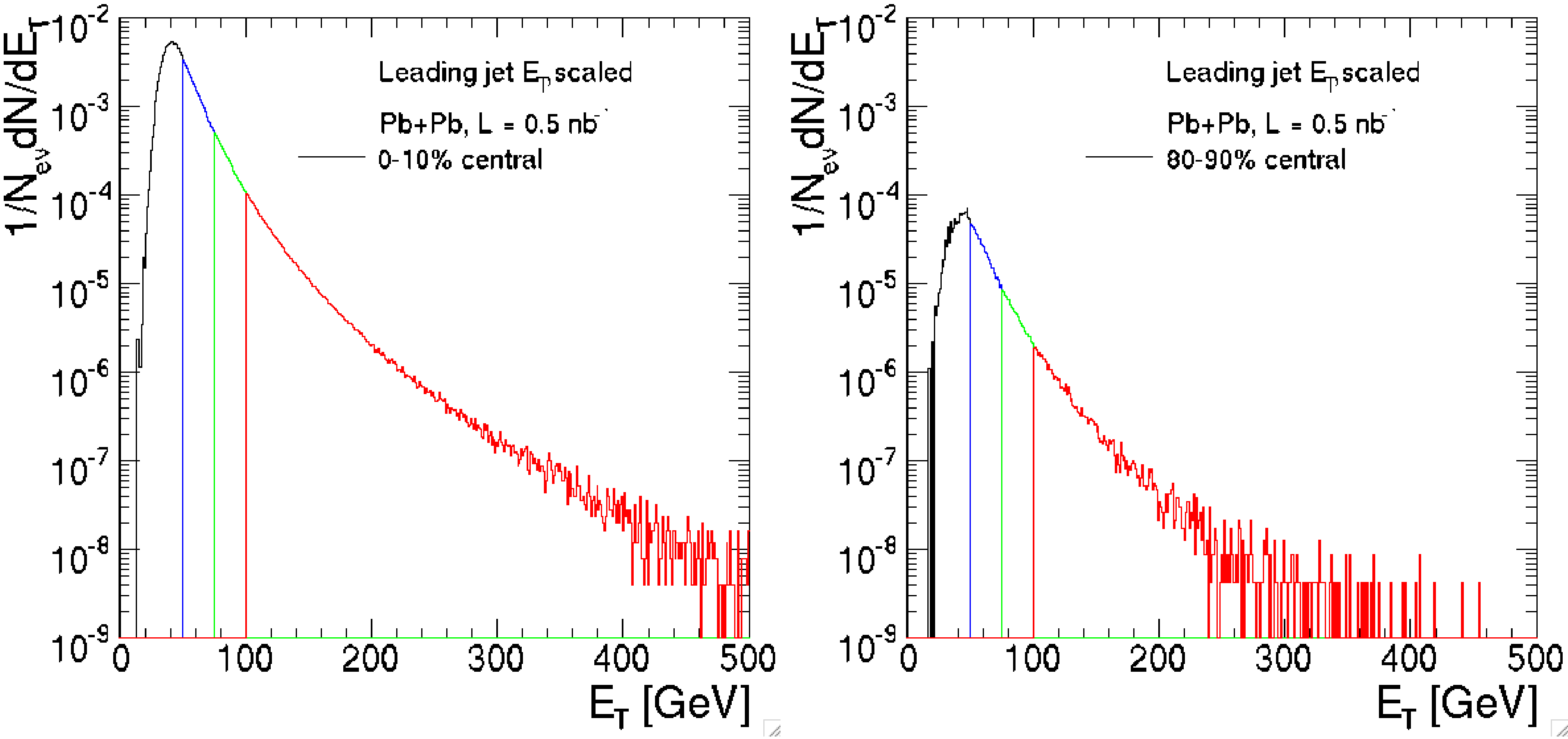
- **Statistics expected per month of PbPb running**
  - **Integrated luminosity: L = 0.5 nb^{-1}**
  - **Taking into account HLT bandwidth allocations**

Merging Datasets

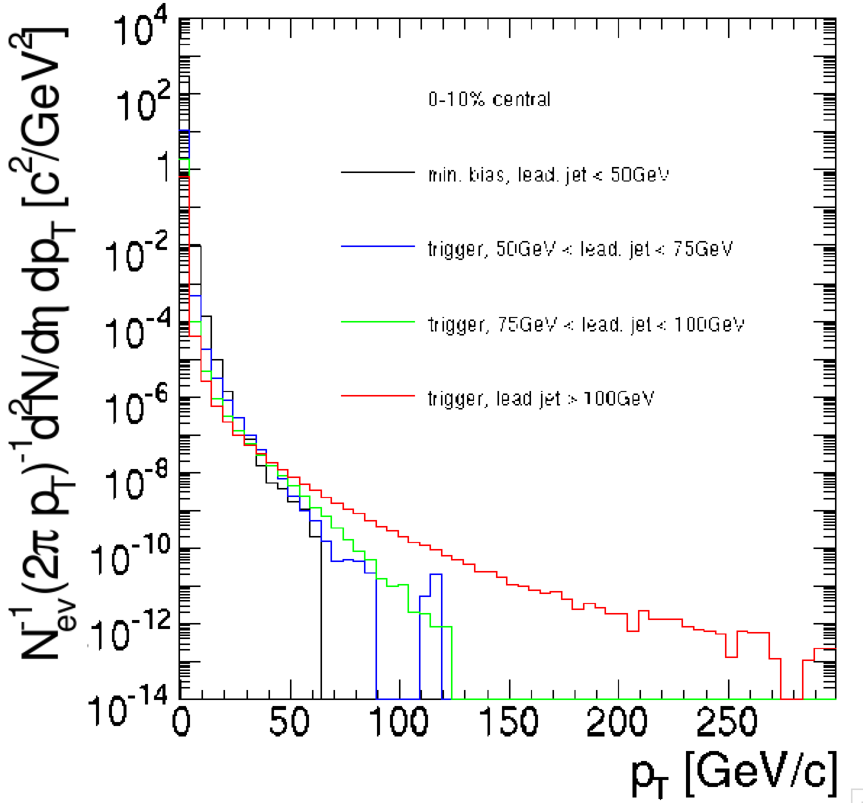


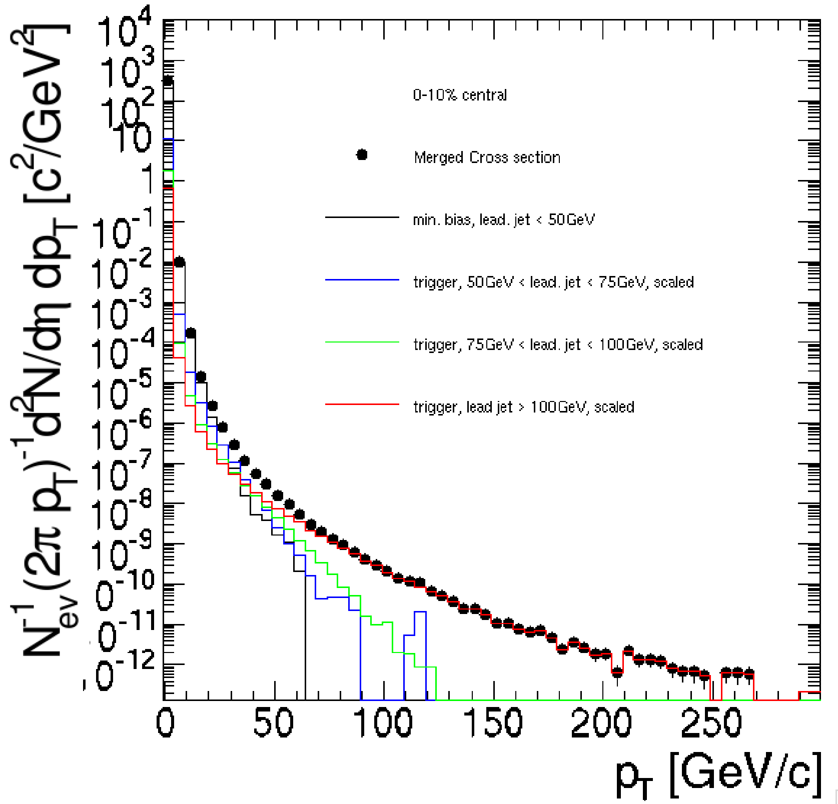
- **The prescale factor in the trigger is centrality independent**
  - **The relative scaledown in centrality bins depends on the quenching model and the change of the jet E_T resolution with centrality**
  - **Need a data driven determination of the scaledown factor**
    - Fit the joined spectrum with a power law
    - Vary the scaledown factor to minimize the χ^2 of the fit

Leading Jets (Scaled)



Merged Spectra

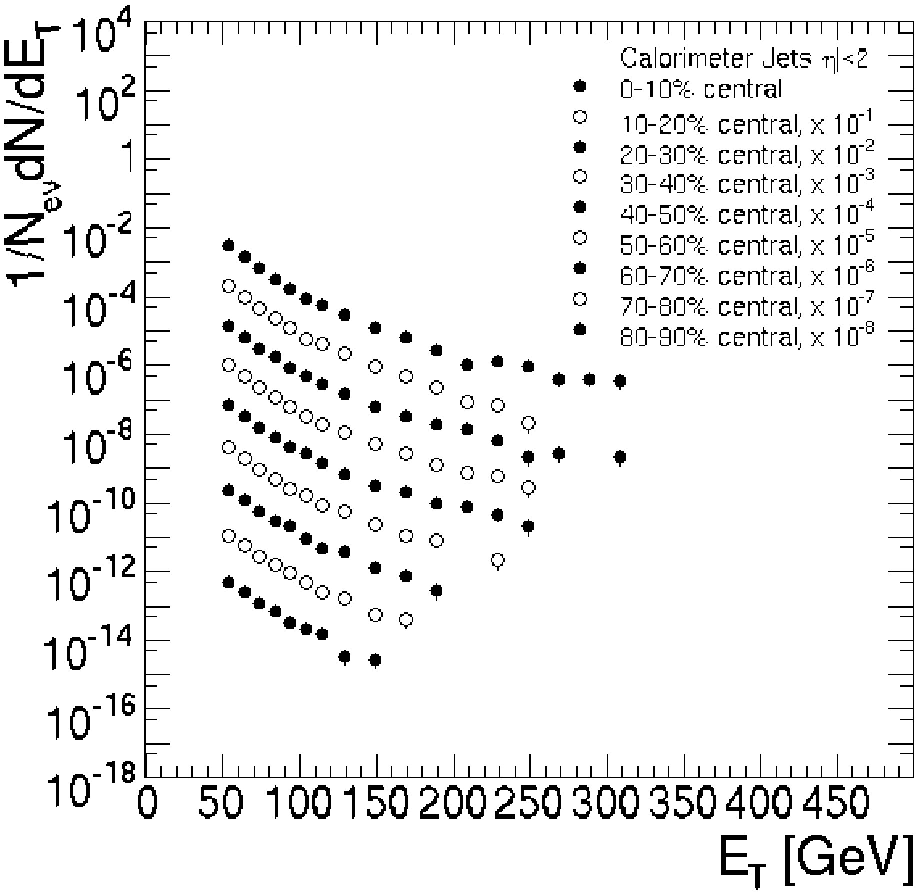


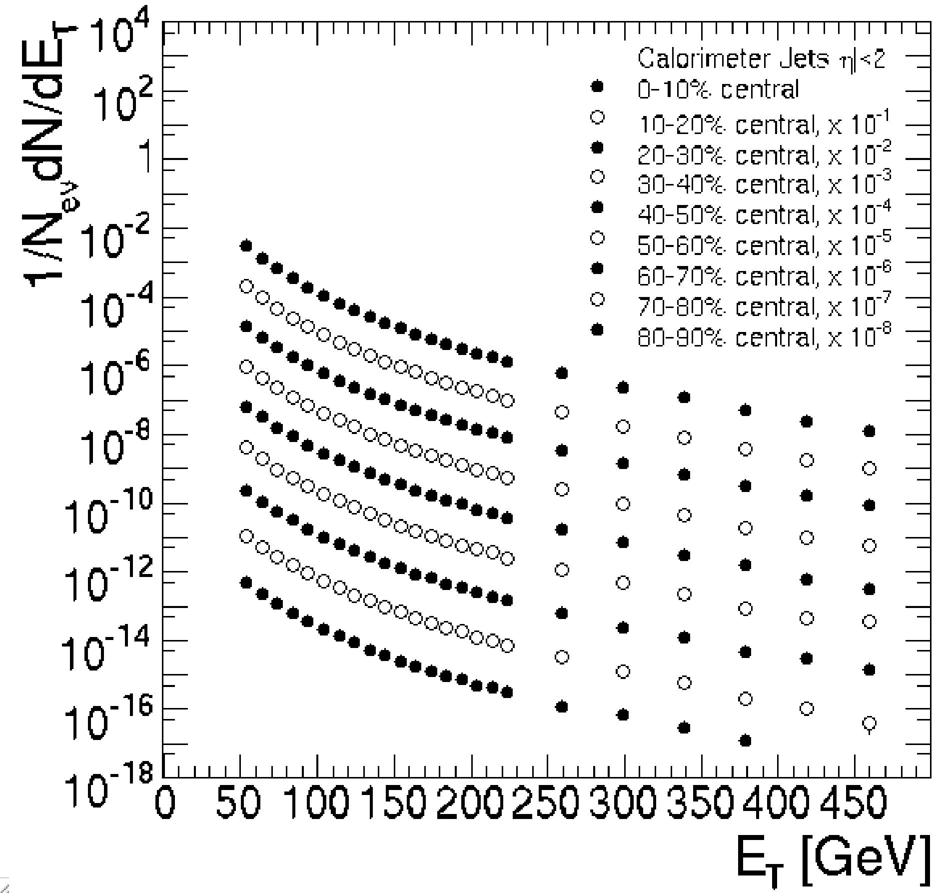


- **The scaledown factors between datasets can now be used to merge**
  - **Charged particle distributions**
  - **Inclusive jet spectra**

Inclusive Jet Distributions

Jets in |η| < 2

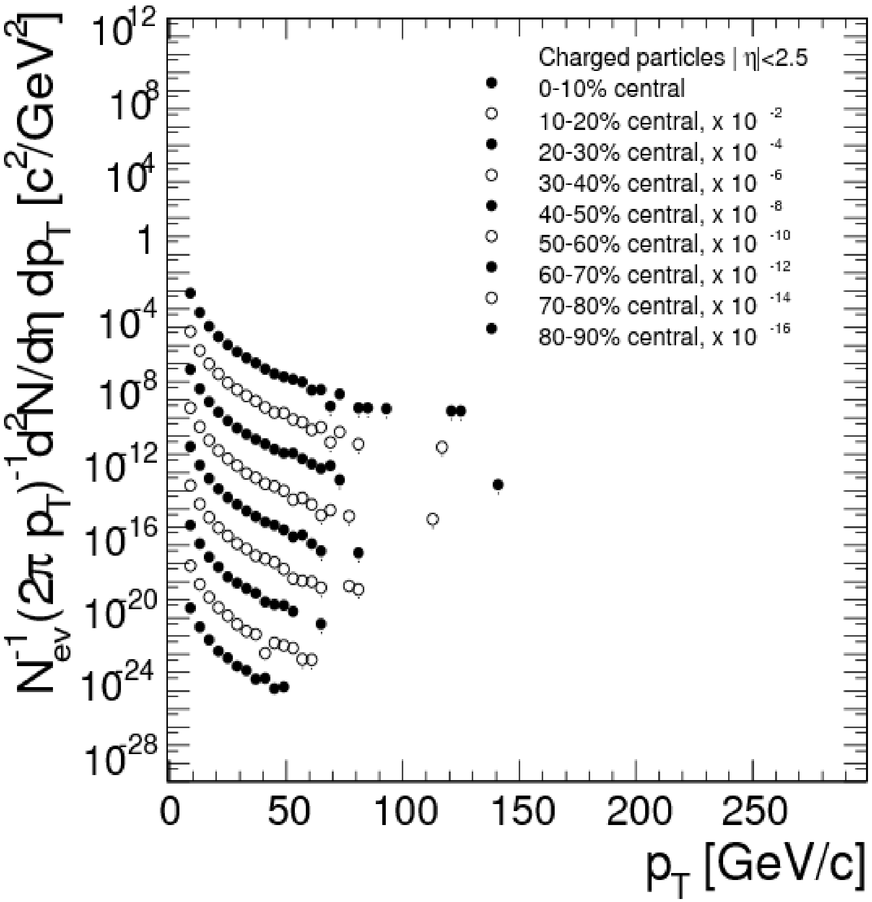


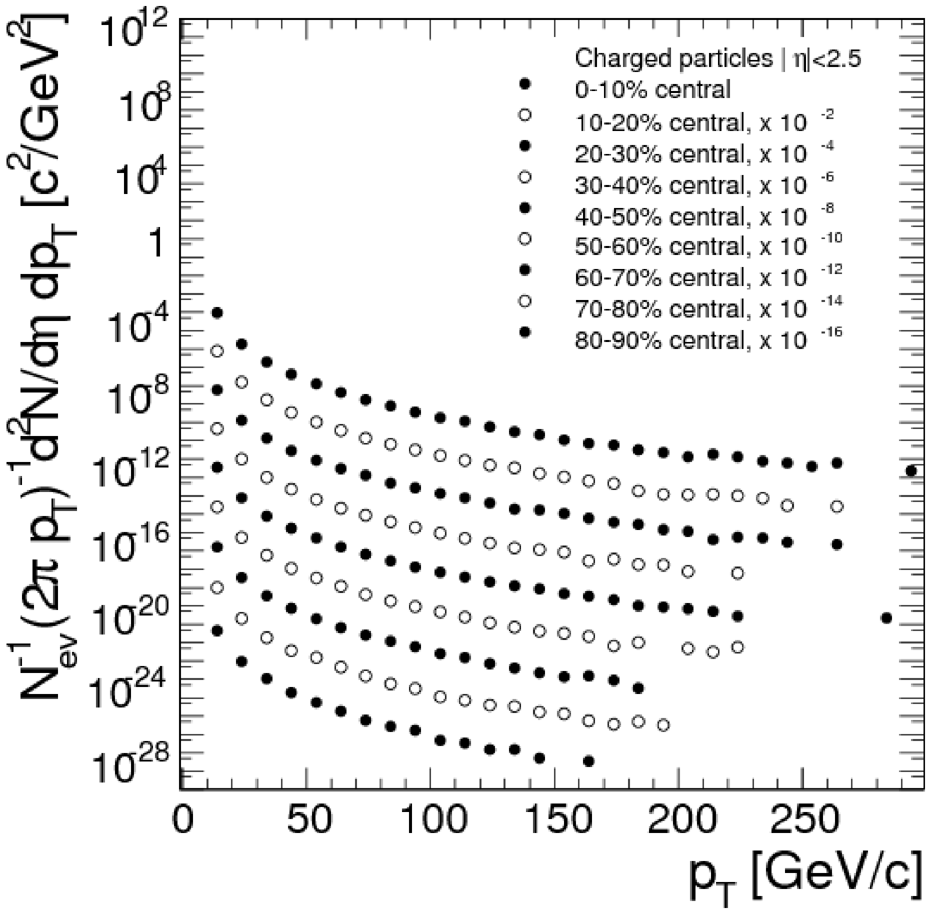


No E_T resolution correction was applied

Charged Particle Cross Sections

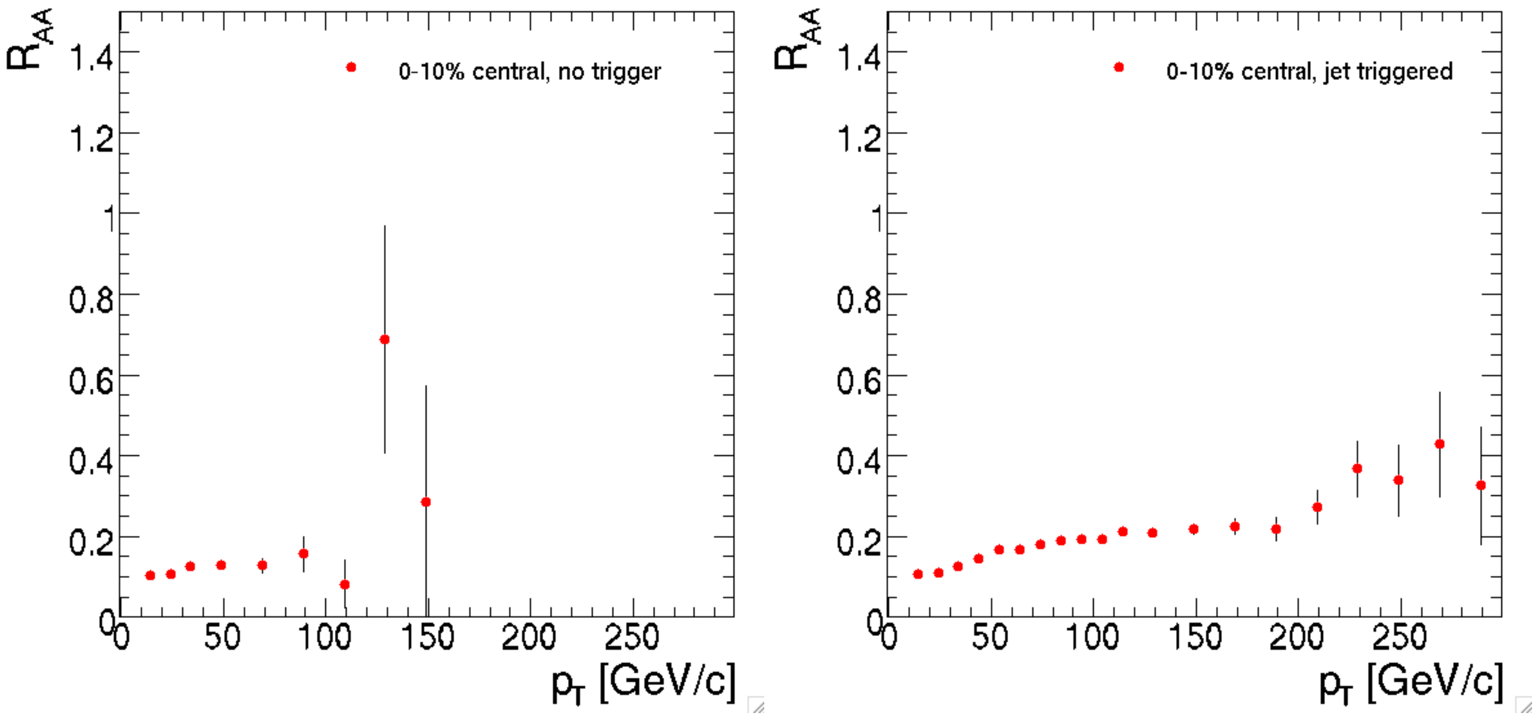
Charged particles in $|\eta| < 2.5$





Nuclear Modification Factor R_{AA}

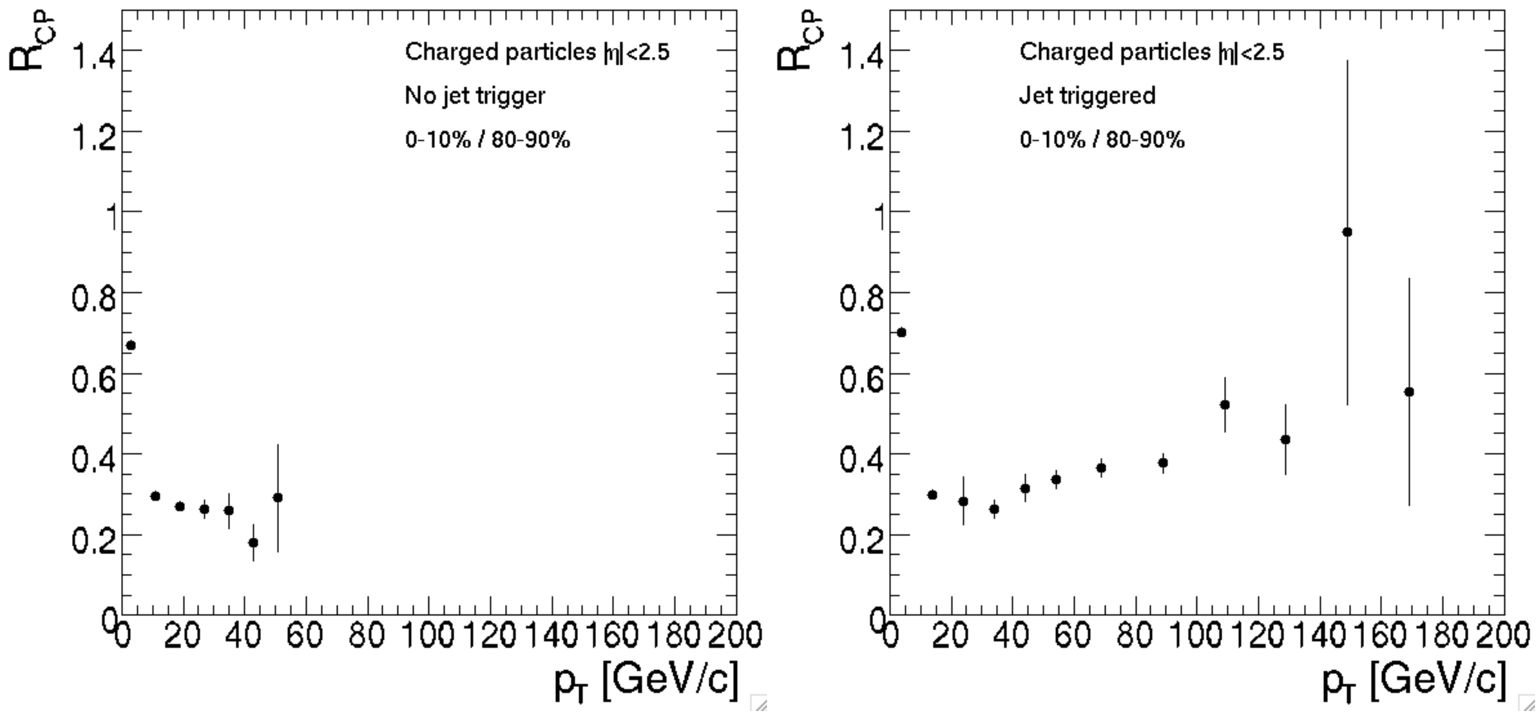
Charged particles in $|\eta| < 2.5$



- Note: R_{AA} needs a pp reference spectrum
  - pp @ 5.5 TeV will not be available initially
  - Reference spectrum needs to be interpolated between Tevatron and LHC @ 14TeV

Nuclear Modification Factor R_{CP}

Charged particles in $|\eta| < 2.5$



- R_{CP} does not need a reference spectrum
  - Limited by the reach of the peripheral spectrum
  - Includes nuclear effects in the reference spectrum

Summary

- **LHC energies are optimal for jet physics**
- **CMS is excellent for jet physics (calorimeters, tracker, coverage)**
- **HI HLT proposed to include jets, rates calculated**
- **R_{AA} p_T range much extended, using jet triggers**
- **Measurement not sensitive to details of jet resolution etc.**

Jet quenching and R_{AA} was exciting at RHIC and we can learn more at LHC at higher p_T

Backup Slides

What can we measure in Heavy Ions?

- **Some example Jets observables using calorimetry…**
  - **Jet cross sections**
  - **Jet - Jet correlations**
  - **Jet- γ/Z correlations**

  Probe energy loss of the leading parton

  … and particle reconstruction
  - **Jet fragmentation functions**
  - **Jet shape**
  - **Tagged heavy quark jets**
  - **Inclusive p_T spectra**
  - **Back-to-back particle correlations**

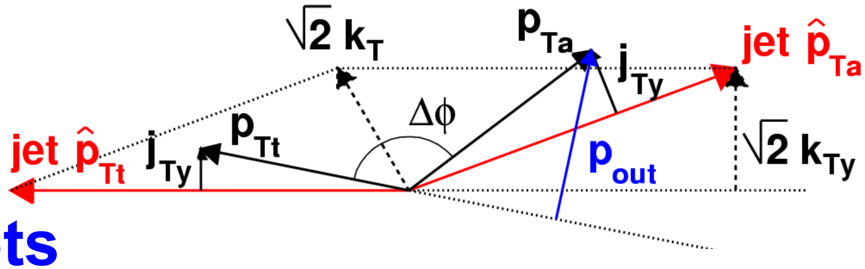
  Sensitive to the energy loss mechanism

- **Expected jet rates:**
  10^6s LHC run
  $L=5x10^{26}cm^{-2}s^{-1}$

Channel	Barrel	Barrel+Endcap
Jet+Jet, E_T >100GeV	$2.1x10^6$	$4.3x10^6$
γ+Jet, E_T >100GeV	$1.6x10^3$	$3.0x10^3$
Z(-> μ+μ-)+jet, E_T^{jet} ,p_T^Z >100GeV	30	45
Z(-> μ+μ-)+jet, E_T^{jet} ,p_T^Z >50GeV	180	300

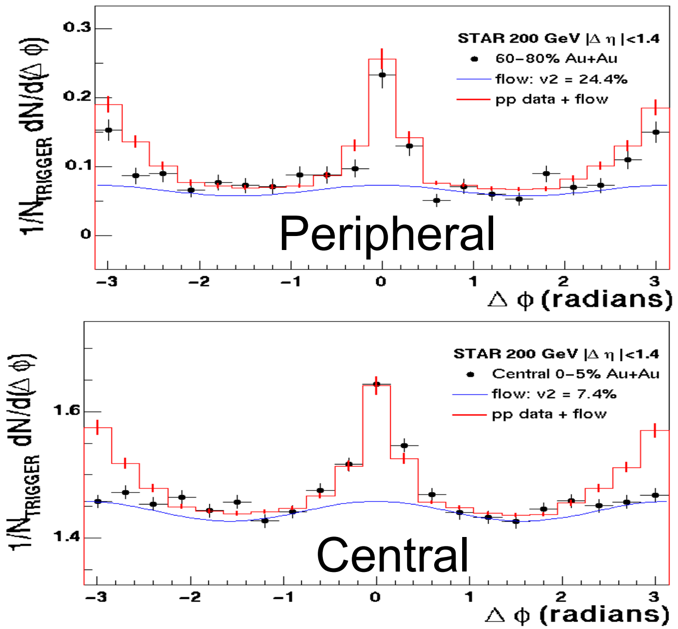
Jet Shapes: RHIC vs. LHC

- **RHIC: measure two particle correlations**
  - **This folds**
    - Intrinsic kT
    - Fragmentation
    - ….



- **LHC: study fully formed Jets**
  - **Directly reconstruct Jet axis and energy!**

RHIC: Particle-particle correlations:



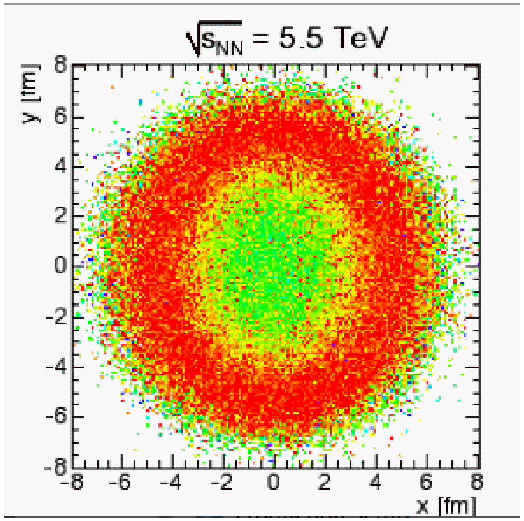
LHC: Jet-particle correlations

- $\Delta\phi$ correlations
- j_T, near and away side
- Fragmentation functions
  - $z = p_T/p_T^{Parton}$
  - Beware: parton p_T unknown!
  - Use final state jet energy?
- Jet E_T profiles

DiJets

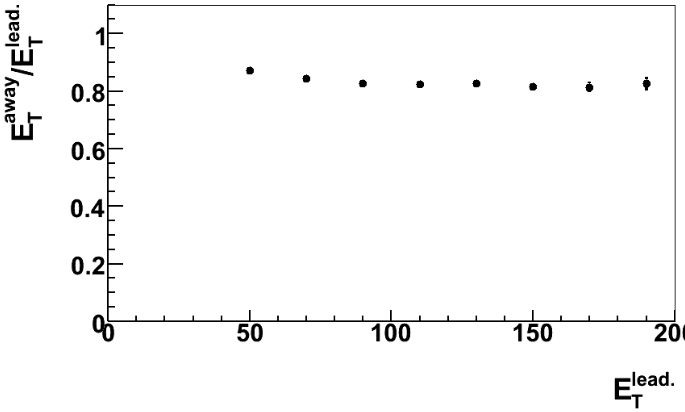
- **Make use of the surface bias**
  - **In a plane perpendicular to the beam of colliding ions high p_T hadron production is dominated by surface emission**
    - C. Loizides et al.
  - **Effect is strongly model dependent**

Production point of hadrons with p_T> 5GeV/c



- **Reconstruct dijets**
  - **Take the leading jet**
  - **Find the away side jet**
  - **Check the energy balance**
- **Experimental issues**
  - **Needs large η coverage**
  - **Uniform calorimeter response**
  - **Beware of initial state radiation**

Pure PYTHIA:
Away/Leading Jet E_T Balance:



Jet studies: new generators

- **Need better event generators at LHC: HYDJET**

  (*I.P. Lokhtin and A.M. Snigirev, hep-ph/0312204,hep-ph/0406038*)

  - **Developed within the CMS HI Group**
  - **Soft particle production using Hydrodynamic model,**
    - includes bulk properties, flow etc…
  - **Jets produced using PYQUEN**
    - PYTHIA with medium-induced quenching
  - **Full control of soft and hard physics assumptions**

- **Assumptions:**
  - **Particle production from soft physics and hard collisions factorizes**
  - **Soft particle production scales with interaction volume, i.e. participant pairs (N_{part})**
  - **Hard collisions scale with number of scattering centers, i.e. number of binary collisions (N_{coll})**

Soft + Hard Simulation Strategy

- **Assume energy in collisions below p_T^{min} just thermalizes and heats the medium**
  - **Set p_T^{min} cutoff to define hard collisions**
- **Calculate the collision geometry (Glauber model)**
- **Calculate N_{part} , N_{coll} and N_{hard} ($p_T > p_T^{min}$)**

Soft Background

- Bulk of the particles

Hard Signal

- Multijet events

- **Quenching by PYQUEN**
  - I.P. Lokhtin, A.M. Snigirev, Eur. Phys. J. C 46 (2006) 211
  - **Uses PYTHIA to calculate the initial parton configuration**
  - **Calculates hard parton rescattering and energy loss. Emitted gluons are added to the event record**
  - **Uses PYTHIA again for parton hadronization and final particle formation**