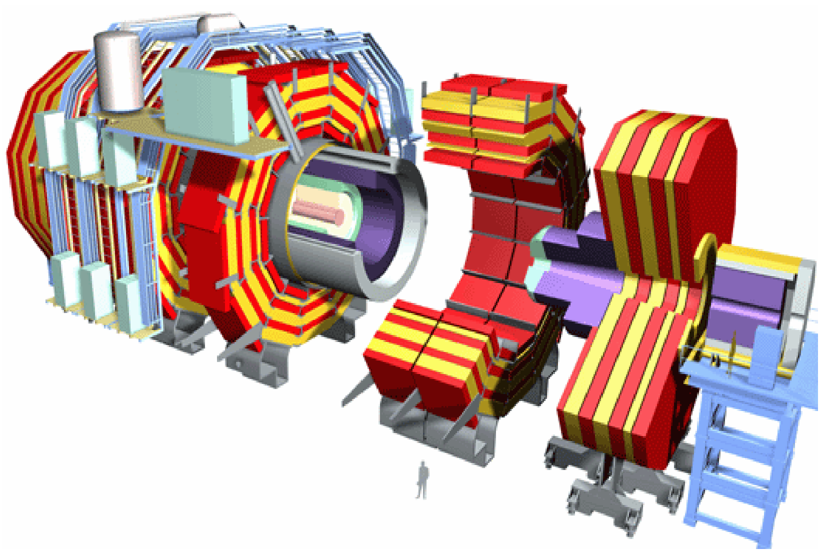
Jet Finding in the CMS Heavy Ion Programs



APCTP Workshop
POSTECH, Pohang, Feb. 27, 2006

Inkyu PARK
Dept. of Physics, University of Seoul

Athens, Auckland, Budapest, CERN, **Chonbuk Univ.**, Colorado, Cukurova, Iowa, Kansas, **Korea Univ.**, Los Alamos, Lyon, Maryland, Minnesota, MIT, Moscow, Mumbai, Rice, **Univ. of Seoul**, Vanderbilt, UC Davis, UI Chicago, **Yonsei Univ.** , Zagreb

Contents

total of 55 pages → So let's move fast…

LHC
as a new tool
for HI Physics

LHC as a new tool for HIP

- **Once again a big energy jump! LHC will accelerate and collide heavy ions at energies far exceeding the range of existing accelerators. It means**
  - Extended kinematic reach for pp, pA, AA
  - New properties of the initial state, possible gluon saturation at mid-rapidity
  - A hotter and longer lived partonic phase
  - Increased cross sections and availability of new hard probes

	AGS	SPS	RHIC	LHC
$\sqrt{s_{NN}}$[GeV]	5	20	200	5500
E increase		x4	x10	x28
y range	±1.6	±3.0	±6	±8.6

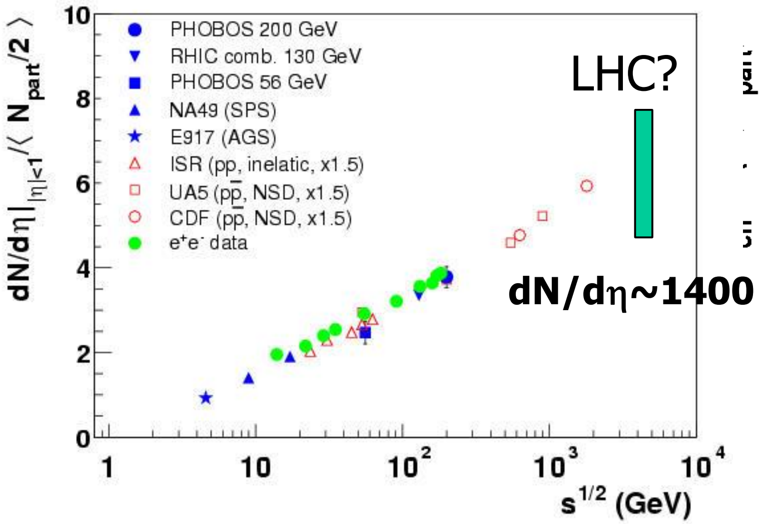
Quark Gluon Plasma

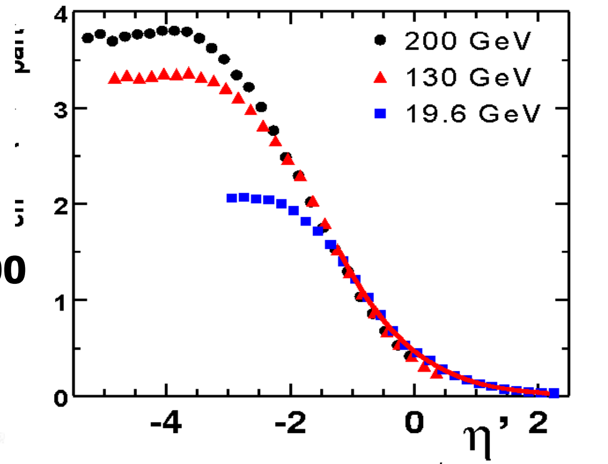
- Data from SPS & RHIC show new and unexpected properties of hot nuclear matter
  - Jet quenching, strong elliptical flow, d+Au- control data indicate that we have produced strongly interacting color liquid
- LHC will significantly increase energy density
  - new properties of the QGP
    - Continuation of strong coupling regime?
    - Weakly interacting Plasma?
  - New discoveries guaranteed!

Soft observables: RHIC → LHC

RHIC shows a simple energy dependence. How about at the LHC ?

Charged particle multiplicity, limited fragmentation

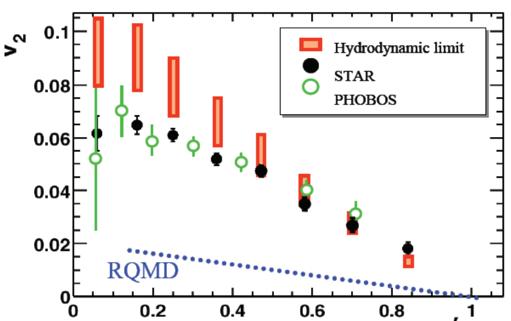




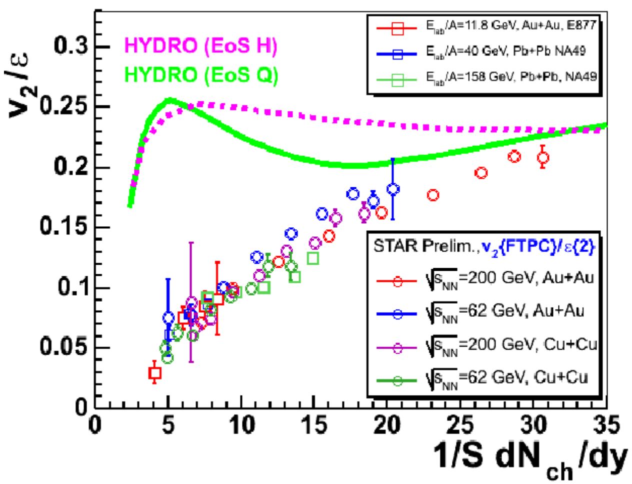
$$\eta' \equiv \eta - y_{beam}$$

- **RHIC prefers Hydrodynamic limit. How about at the LHC?**

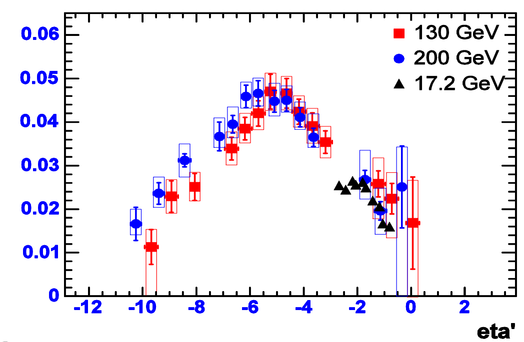
PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)
STAR: Phys. Rev. Lett. **86**, 402 (2001)



Compilation and Figure from M. Kaneta

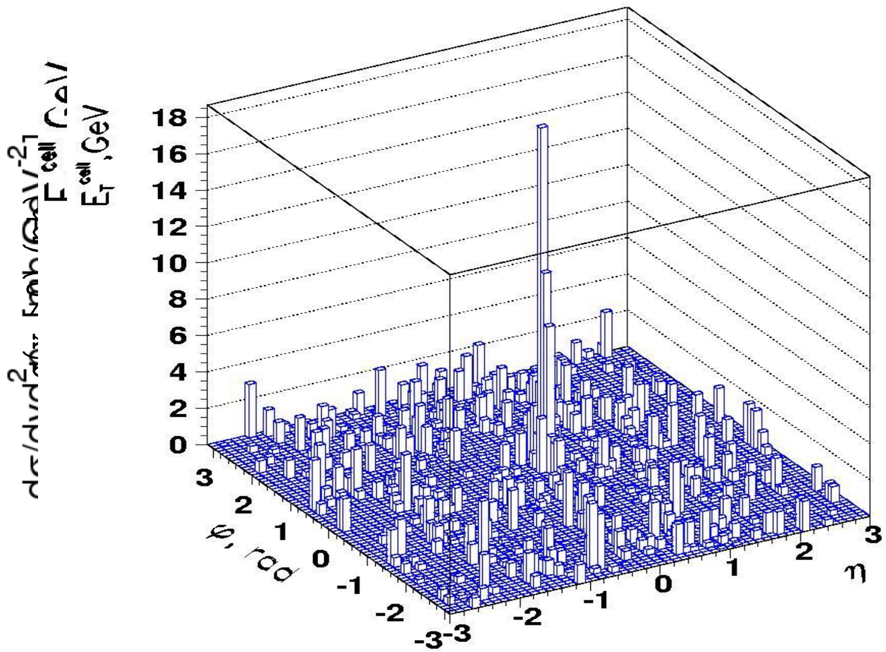


Flow



Hard observables: RHIC → LHC

- Copious production of high p_T, high-mass particles
- Large production cross section for the J/ψ and · family
- Jets are fully reconstructed for the first time in heavy ion collisions.



After background subtraction

LHC accelerator schedule

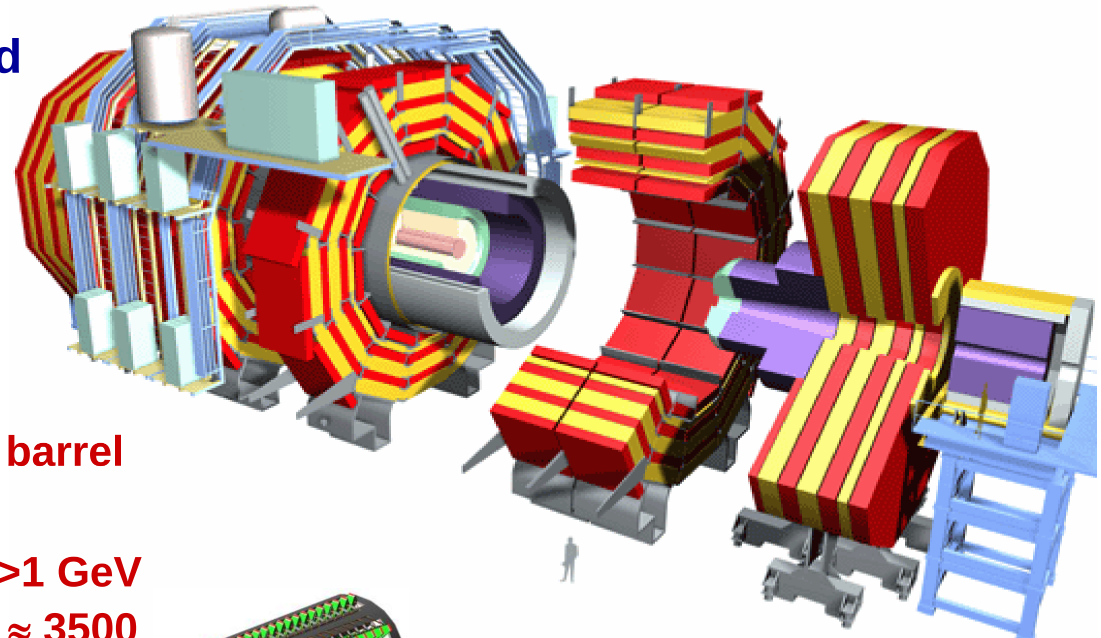
Calendar Year	p+p	Heavy Ions
2007	450+450 GeV, $5 \cdot 10^{30}$ Short engineering run	none
2008	14 TeV, $0.5 \cdot 10^{33}$	5.5 TeV, $5 \cdot 10^{25}$ Pb+Pb
2009	14 TeV, $1 \cdot 10^{33}$	5.5 TeV, $1 \cdot 10^{27}$ Pb+Pb
2010	14 TeV, $1 \cdot 10^{34}$	5.5 TeV, $1 \cdot 10^{27}$ Pb+Pb
2011	14 TeV, $1 \cdot 10^{34}$	5.5 TeV, $1 \cdot 10^{27}$ Pb+Pb, other ions

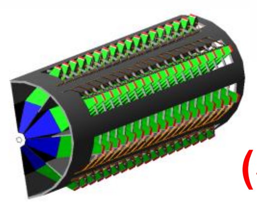
- Heavy Ion runs always follow p+p runs, at the end of calendar year
- Nominal data taking time:
  - p+p: 10^7 seconds/year
  - Heavy ions: 10^6 seconds/year: 0.5 nb^{-1}
- Heavy Ion nominal luminosity is likely to be reached earlier than for p+p

CMS as detectors for HI Physics

CMS, as a heavy ion experiment

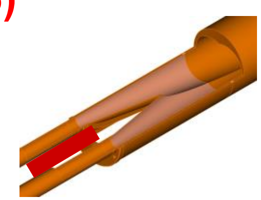
- **Calorimeters: high resolution and segmentation**
  - **Hermetic coverage up to $|\eta|<5$**
  - **$|\eta|<6.6$ with CASTOR**
  - **Zero Degree Calorimeter**
- **Muon tracking: μ from Z^0, J/ψ, Υ**
  - **Wide rapidity coverage: $|\eta|<2.4$**
  - **$\sigma_m \approx 50$ MeV at the Υ mass in the barrel**
- **Silicon Tracker**
  - **Good efficiency and purity for $p_T>1$ GeV**
  - **Pixel occupancy: <2% at $dN_{ch}/d\eta \approx 3500$**
  - **$\Delta p/p \approx$ 1-2% for p_T <100 GeV**
  - **Good low p_T reach using pixels**
- **DAQ and Trigger**
  - **High rate capability for A+A, p+A, p+p**
  - **High Level Trigger: real time HI event reconstruction**





CASTOR

(5.2 < $|\eta|$ < 6.6)

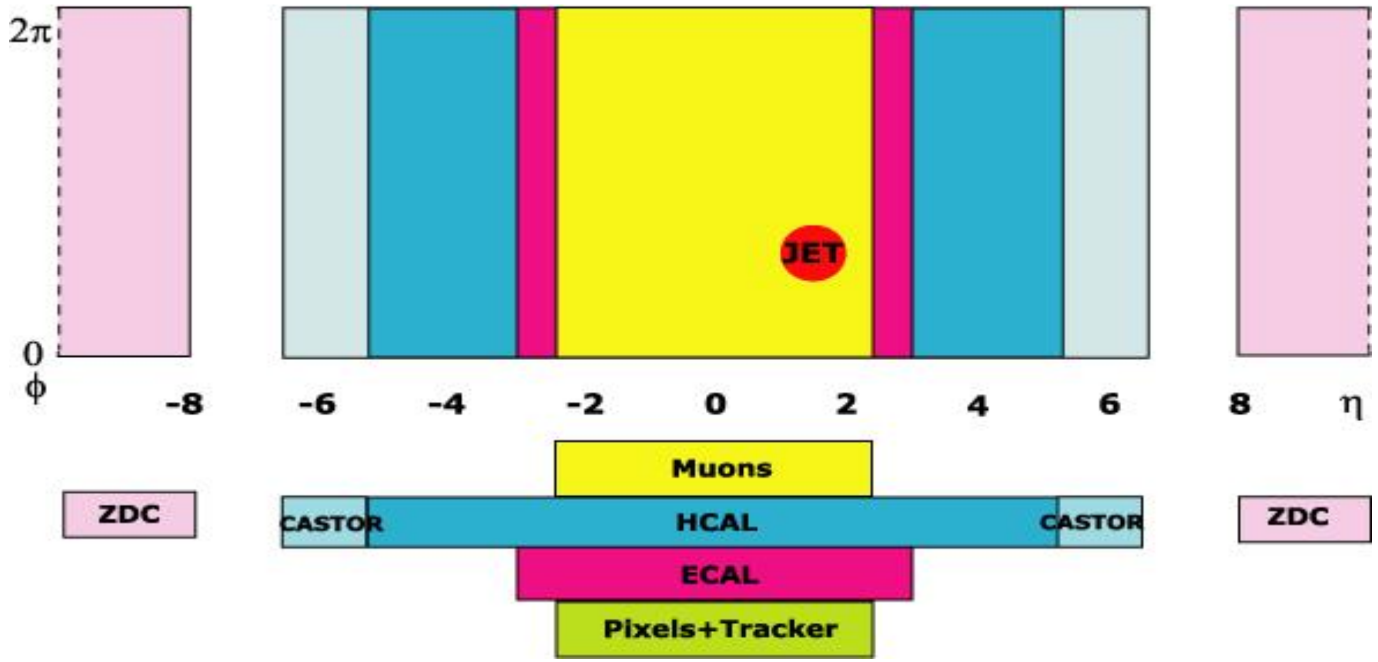


ZDC

(z = $\pm$140 m, $|\eta|$ > 8.2 neutrals)

Functional at the highest expected multiplicities:
studied in detail at $dN_{ch}/d\eta \approx$3000-5000 and cross-checked at 7000-8000

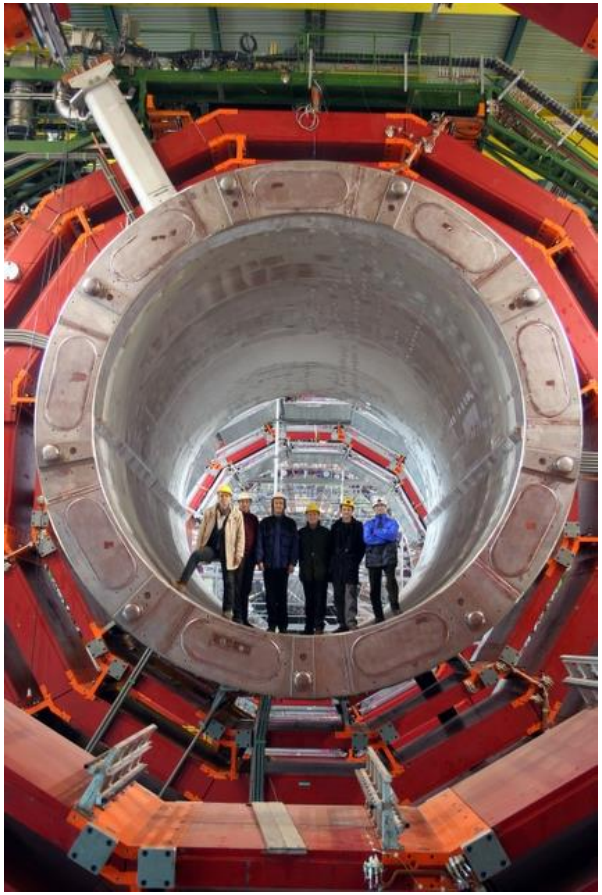
CMS Detector Coverage

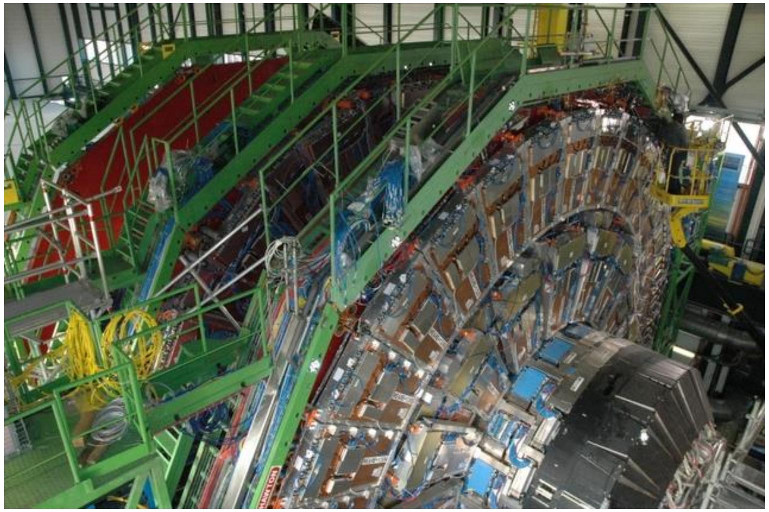


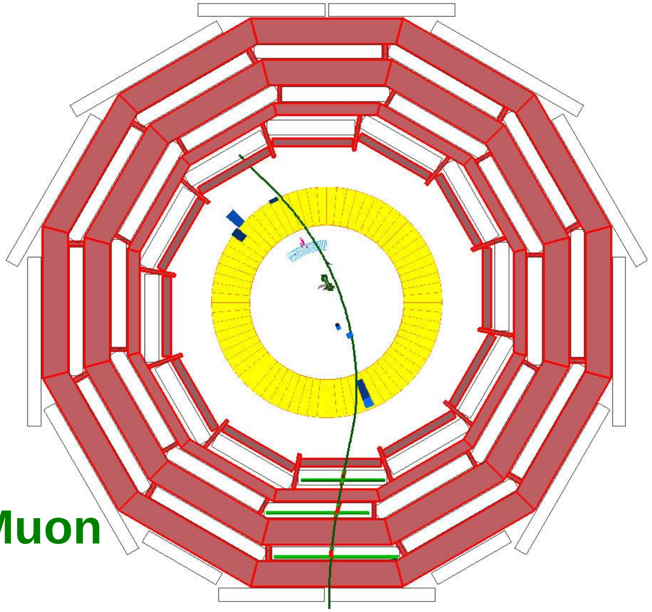
- Hermeticity, Resolution, Granularity
  - Central region $\Delta\eta \sim 5$ equipped with tracker, electromagnetic and hadronic calorimeters and muon detector
- Forward coverage
  - Calorimetric coverage of $\Delta\eta \sim 10$
  - Additional calorimeters proposed to extend the coverage: CASTOR $\Delta\eta \sim 14$
  - Zero Degree Calorimeter (ZDC)
- High data taking speed and trigger versatility

Sub detector	Coverage
Tracker, muons	$\mid \eta \mid < 2.4$
ECAL + HCAL	$\mid \eta \mid < 3.0$
Forward HCAL	$3.0 < \mid \eta \mid < 5.2$
CASTOR	$5.2 < \mid \eta \mid < 6.6$
ZDC (neutrals)	$8.2 < \mid \eta \mid$

CMS getting ready for beam



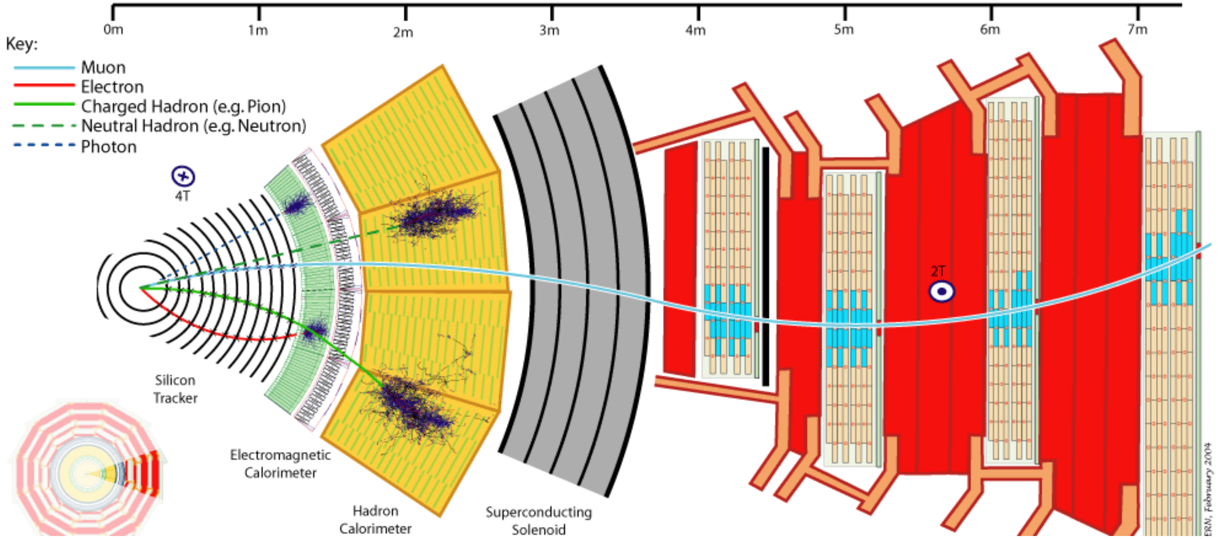


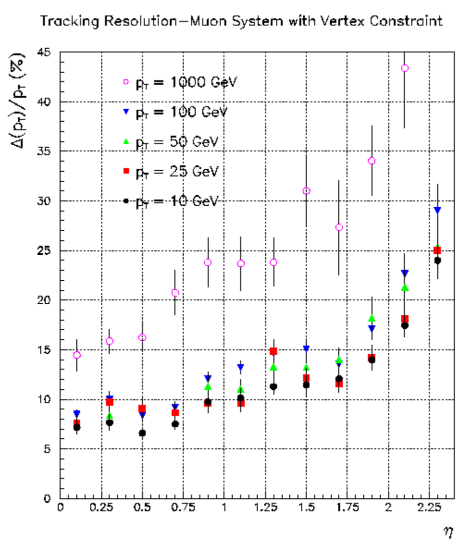


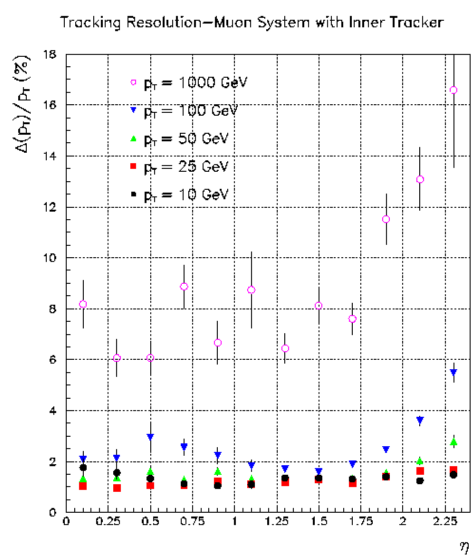
2006 Magnet operation, CMS Magnet operated at 4T, the nominal field!

Cosmic Muon

Measuring Muons







Resolution Standalone

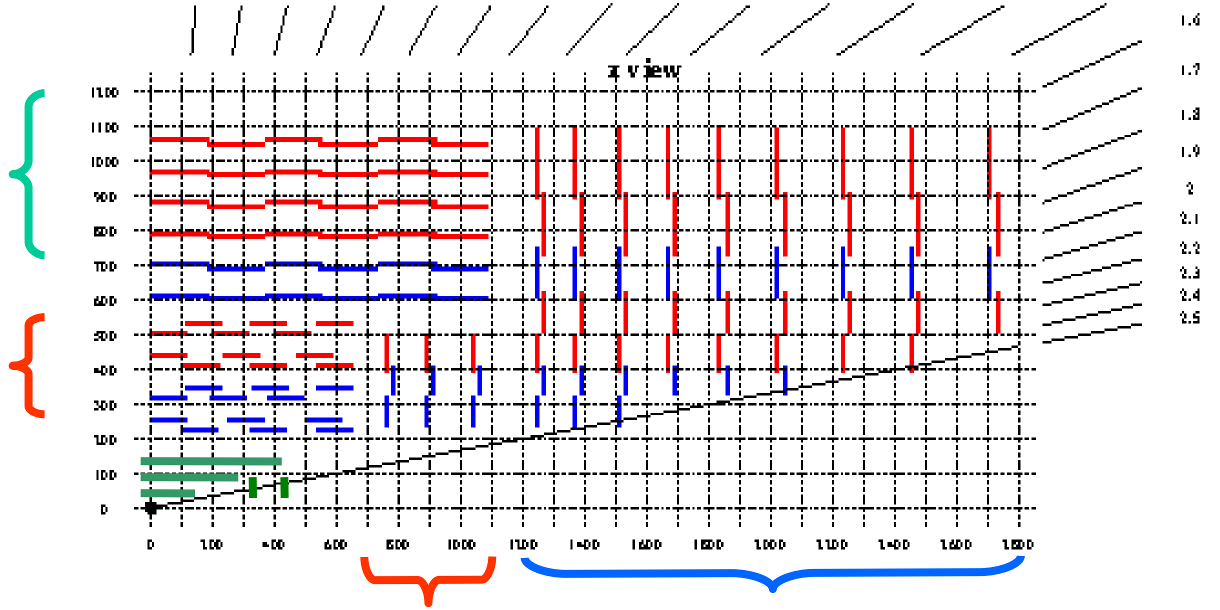
Resolution with tracker

Tracker layout

6 layers
Outer
Barrel

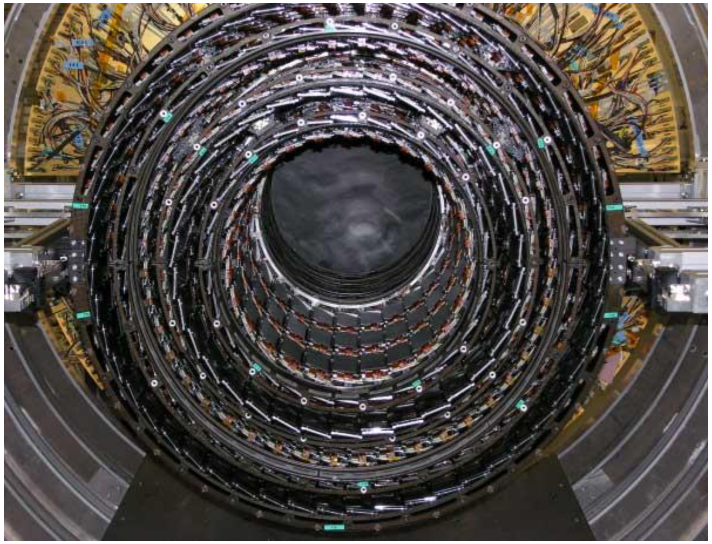
4 layers
Inner
Barrel

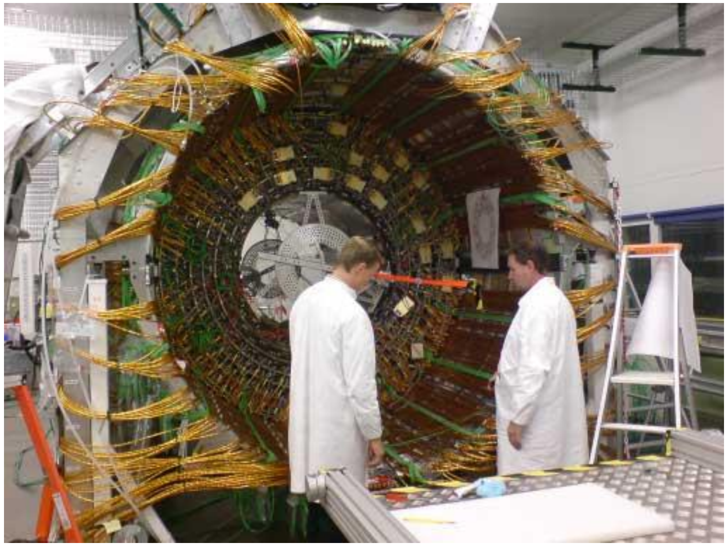
3 Pixel Layers



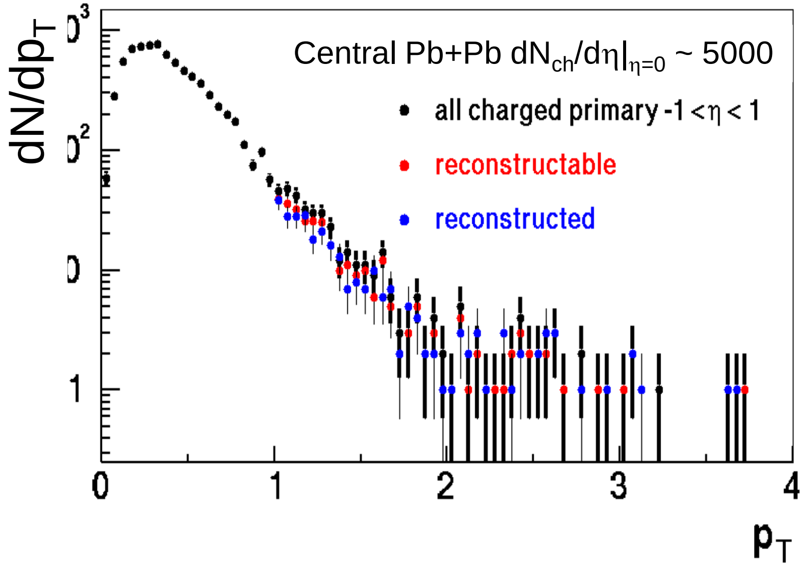
3 disks

9 disks

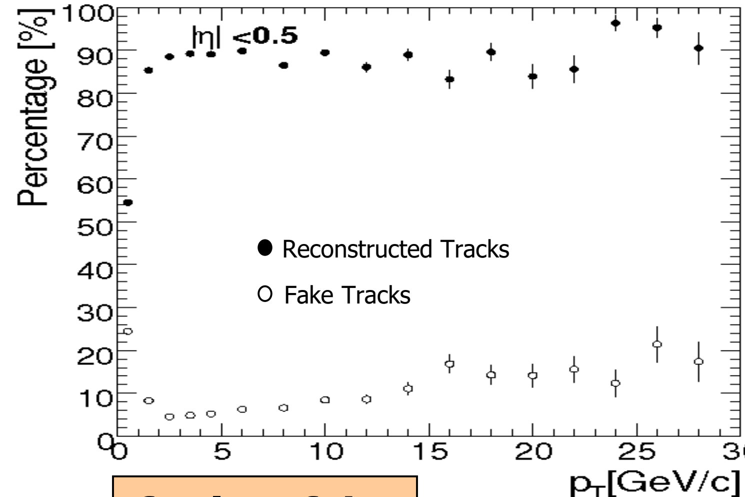


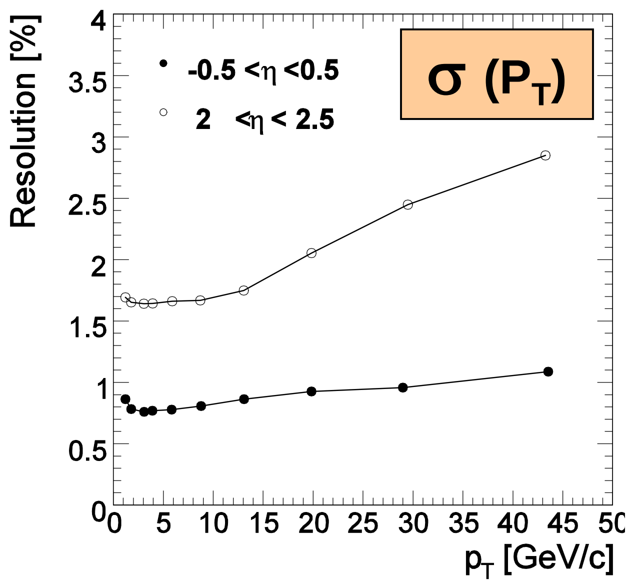


Tracking Performance for HI

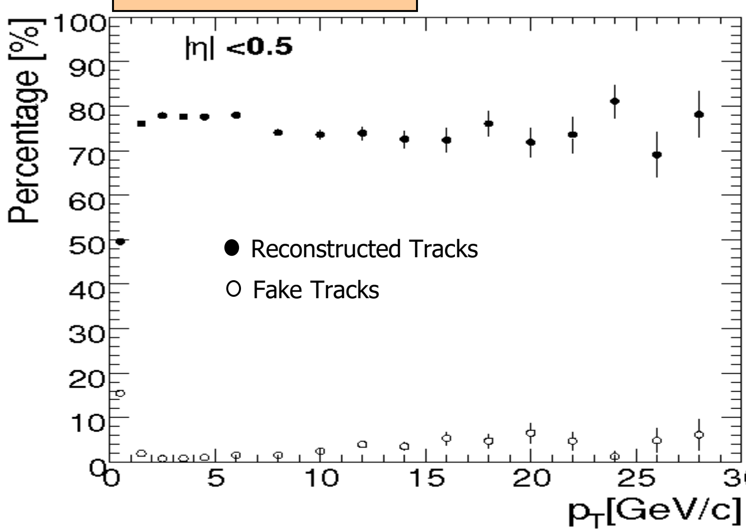


for high efficiency

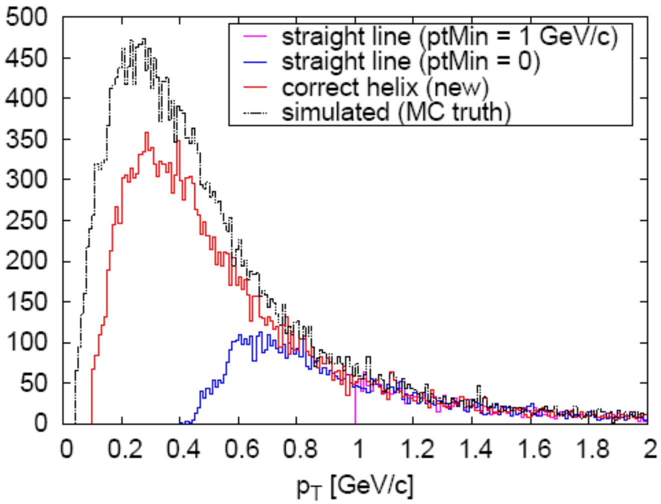




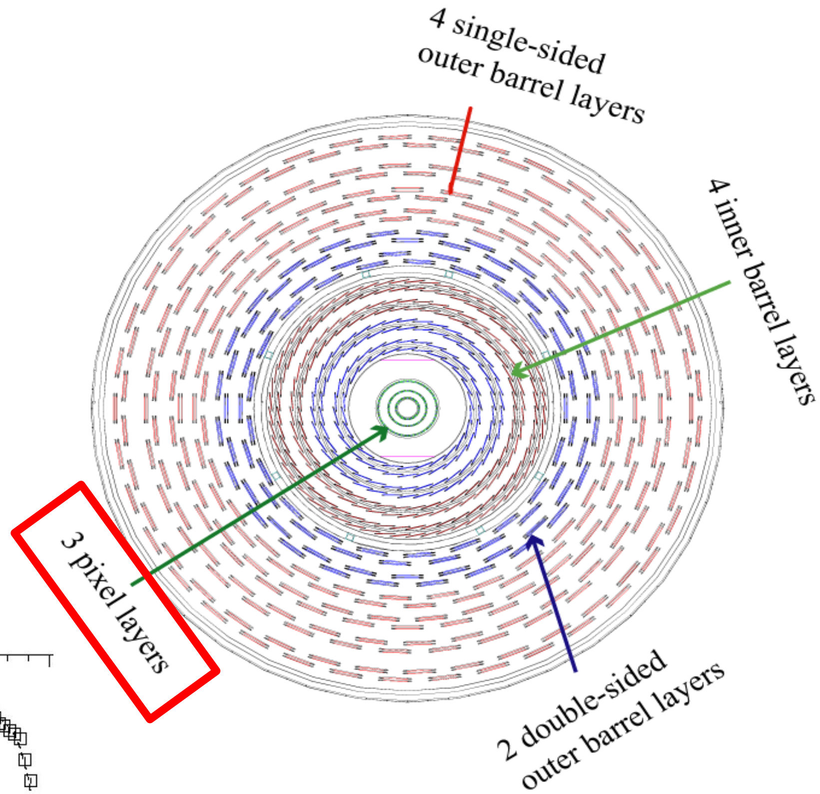
for low fake

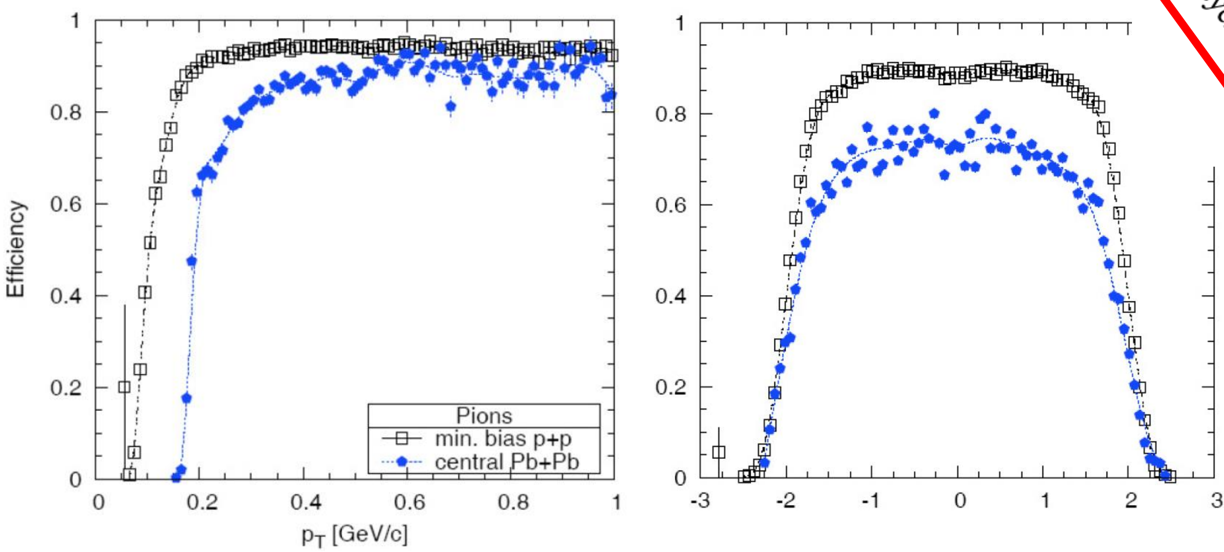


Low p_T tracking using three layers of pixels

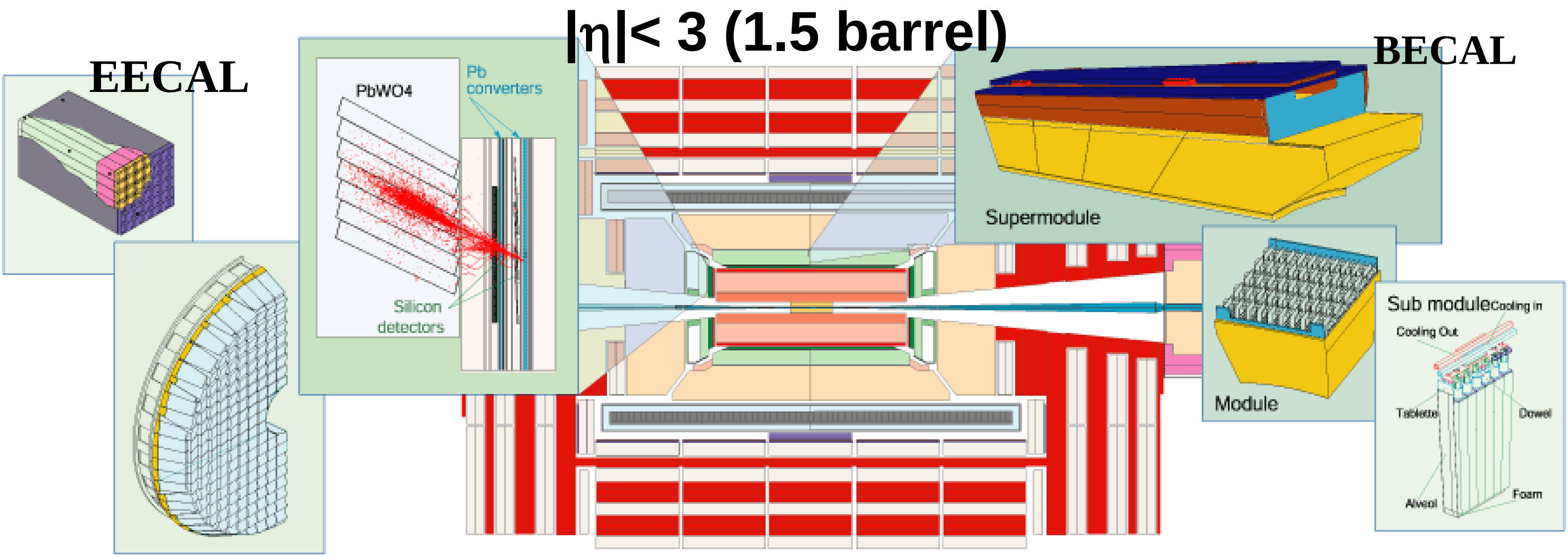


Pixel tracking

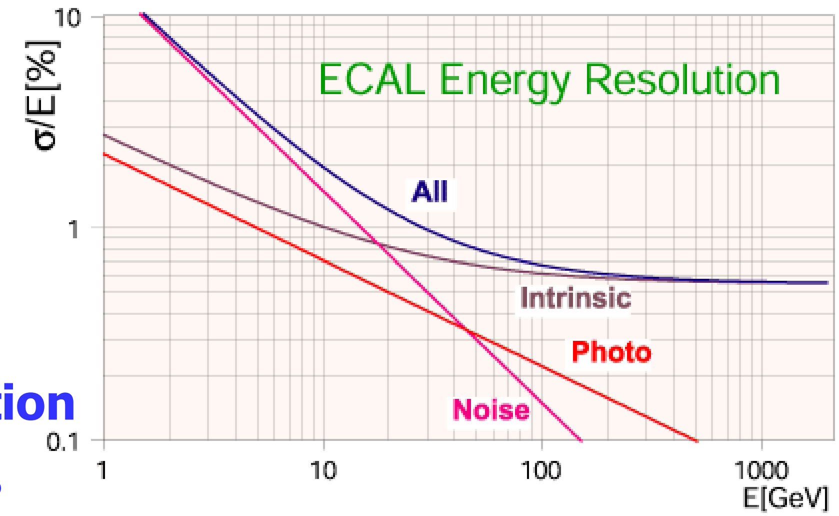




Electromagnetic Calorimeter

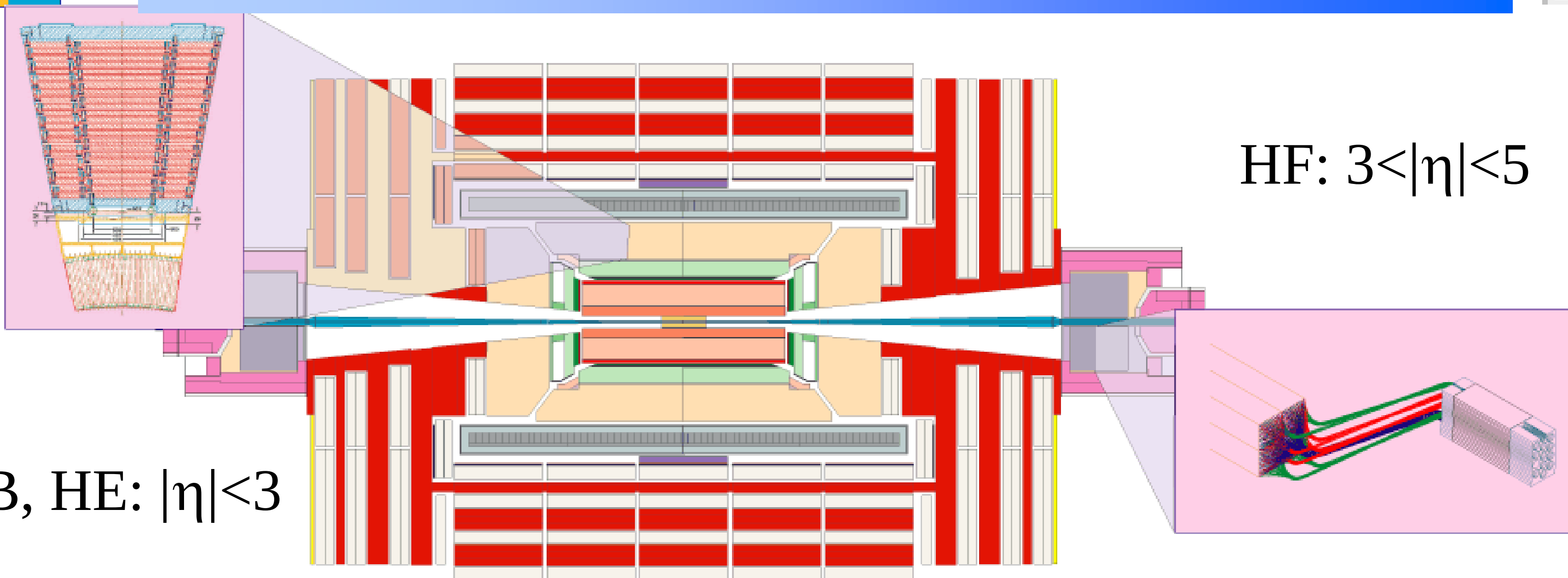


- **76000 PbWO4 crystals**
  - **Granularity in $\Delta\eta \times \Delta\phi$:**
  - **0.0174 x 0.0174 (Barrel) and**
  - **0.0174 x 0.0174 to 0.05x0.05 (Endcap)**
- **Endcap with preshower for γ/p0 separation**
- **Details in CMS Technical Design Reports**



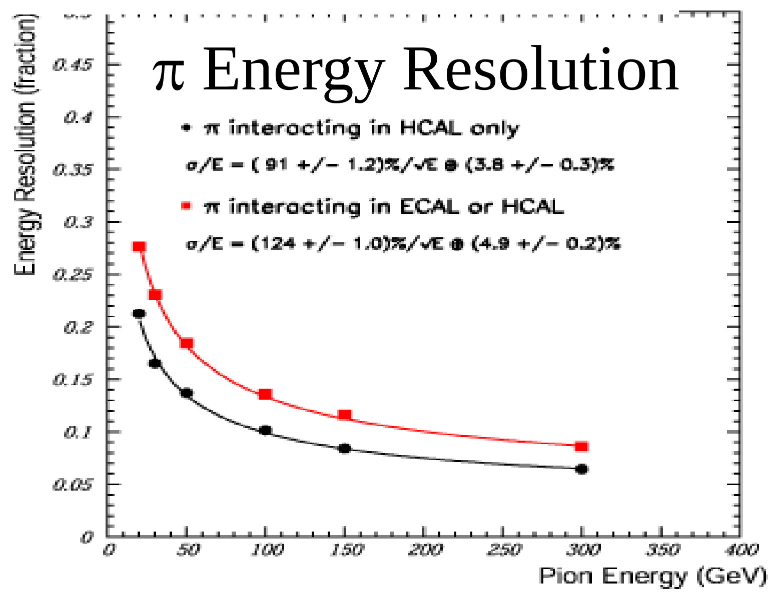
HCAL

HF: 3<|η|<5



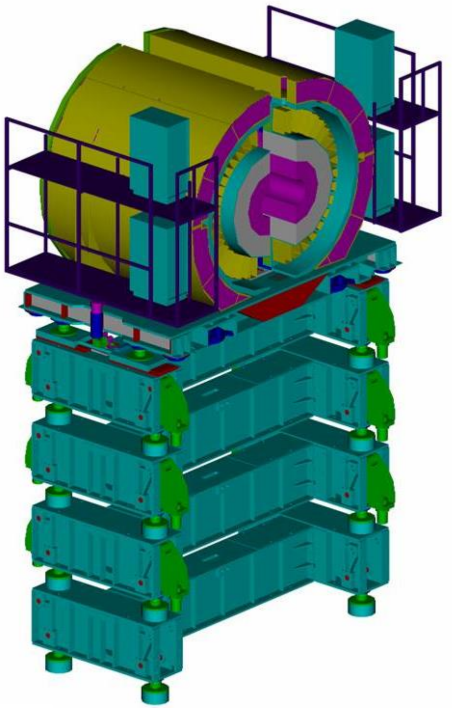
HB, HE: |η|<3

- Barrel (HB) and Endcap (HE): Cu/Scintillator
- Forward (HF): Fe/Cerenkov(fiber)
- High granularity: Δη x Δφ
  - 0.087 x 0.087 (barrel)
  - 0.087 - 0.35 x 0.087 - 0.175 (endcap)
  - 0.152 - 0.3 x 0.175 (HF)
- 5.15 interaction lengths at η=0
- Dynamic range: 5 MeV-3 TeV

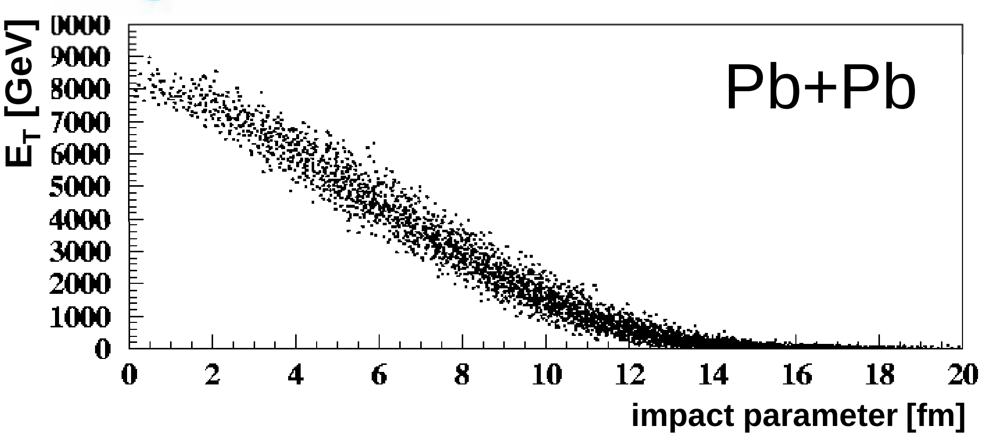


Centrality and forward detectors

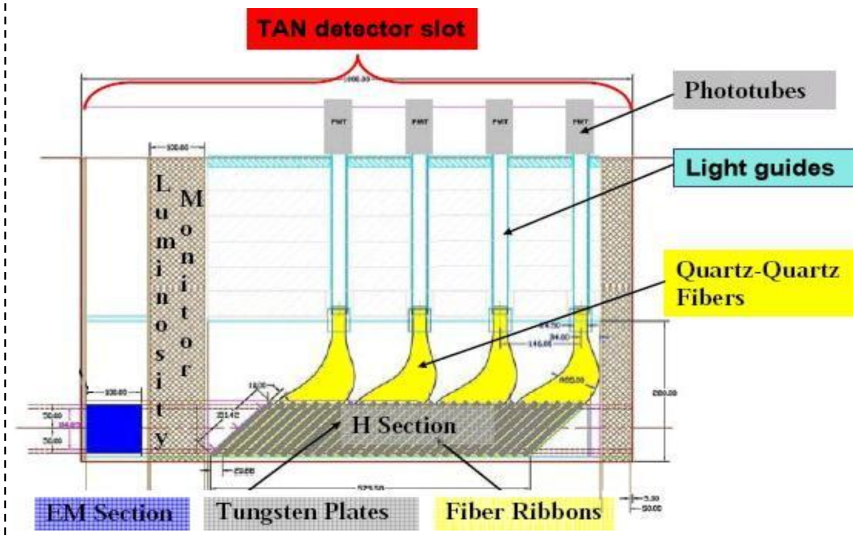
Centrality (impact parameter) determination is needed for physics analysis



Energy in the forward hadronic calorimeter



Zero Degree Calorimeter

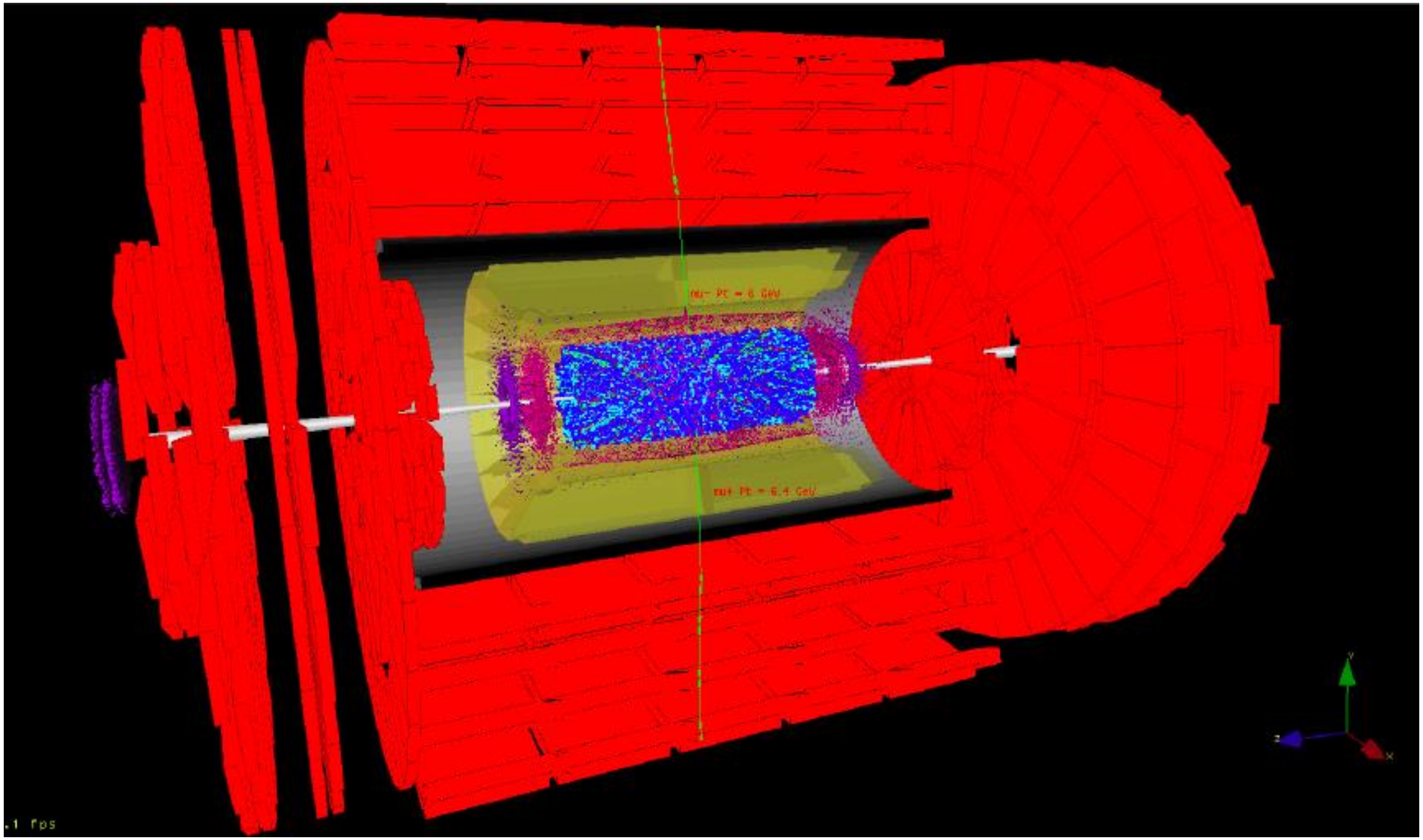


- Tungsten-quartz fibre structure
- electromagnetic section: $19X_0$
- hadronic section $5.6\lambda_0$
- Rad. hard to ≈20 Grad (AA, pp low lum.)
- Energy resolution: ≈10% at 2.75 TeV
- Position resolution: ≈2 mm (EM sect.)

CMS-HI
Physics capability

Heavy Ion MC Event in CMS

Pb+Pb event (dN/dy = 3500) with $\Upsilon \rightarrow \mu^+\mu^-$



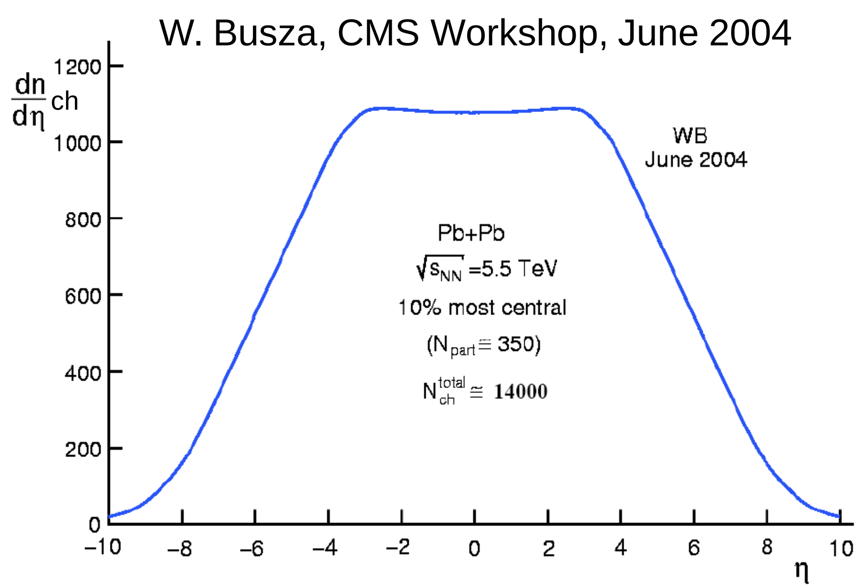
Pb+Pb event display: Produced in pp software framework (simulation, data structures, visualization)

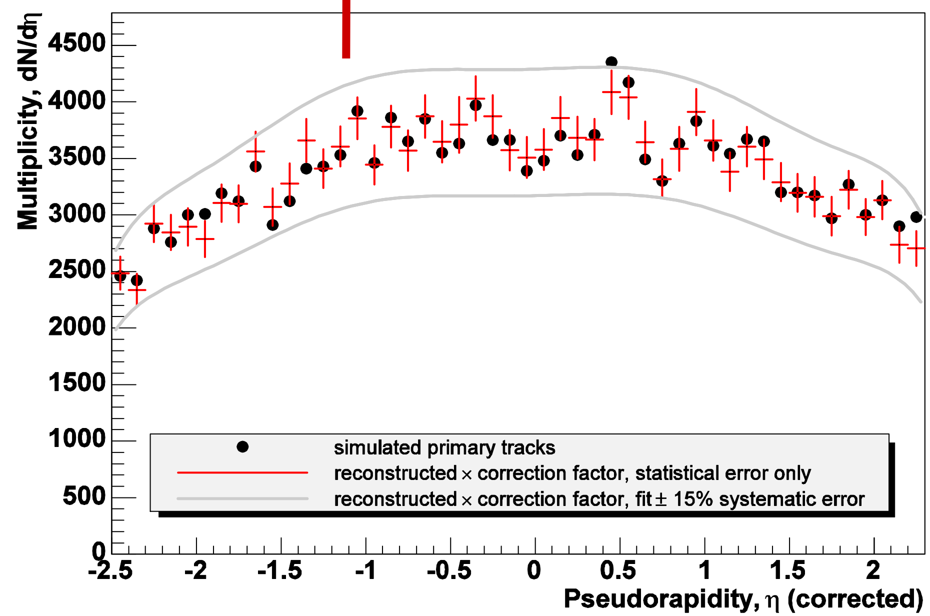
Charged particle multiplicity

Will be one of the first results, important for initial energy density, saturation, detector performance etc.

- high granularity pixel detectors
- pulse height measurement in each pixel reduces background
- Very low p_T reach, p_T>26 MeV (counting hits)

Simple extrapolation from RHIC data

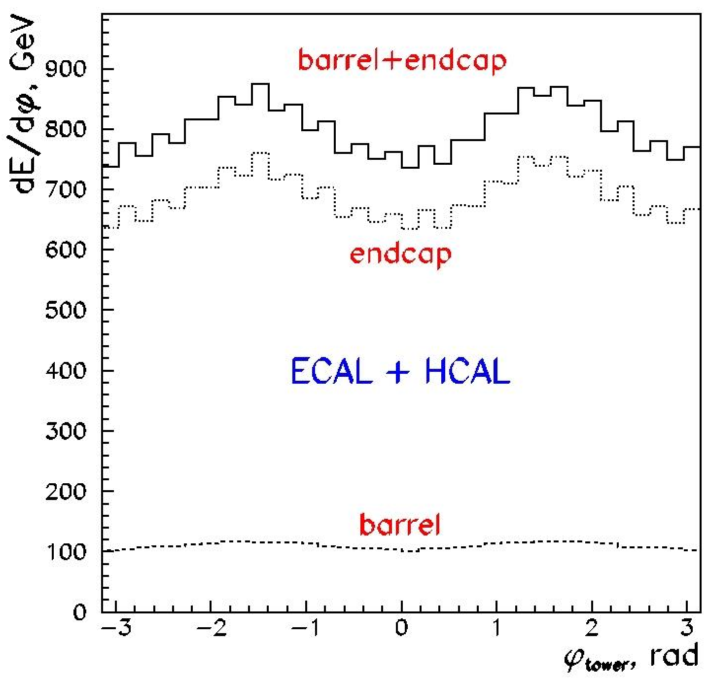




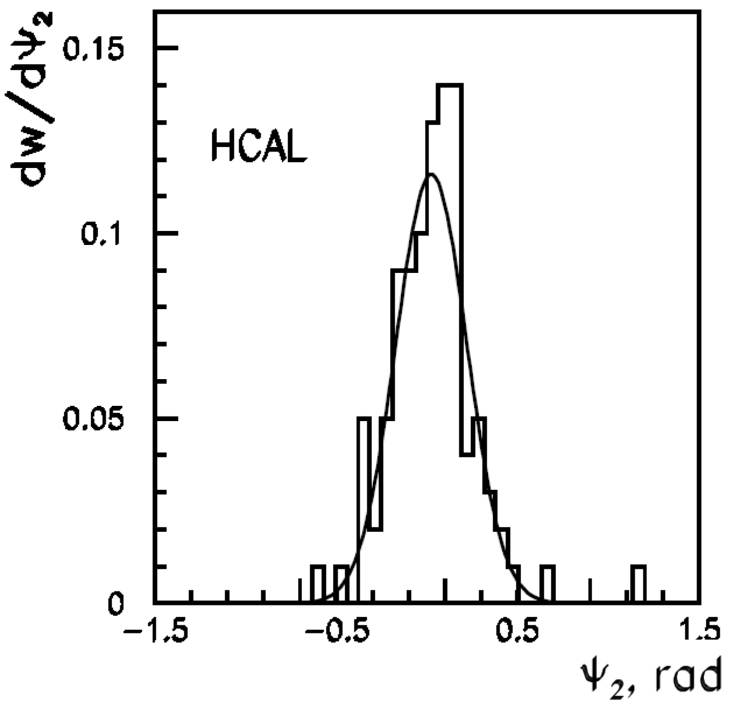
Muon detection, tracking, jet finding performance checked up to $dN_{ch}/d\eta$=5000

C. Smith, 2003

Elliptic Flow measurements in CMS



CMS Note 2003-019

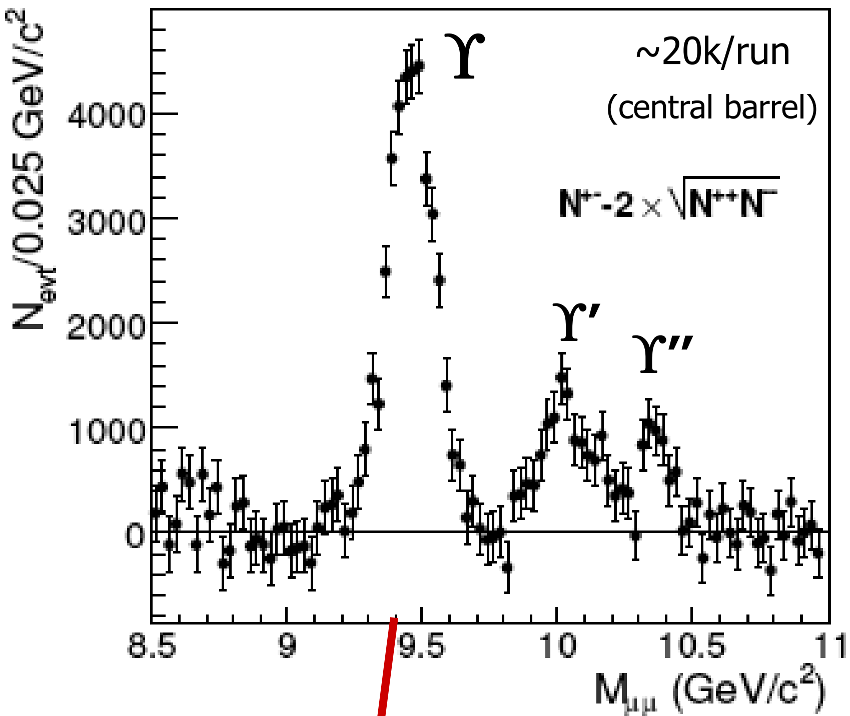


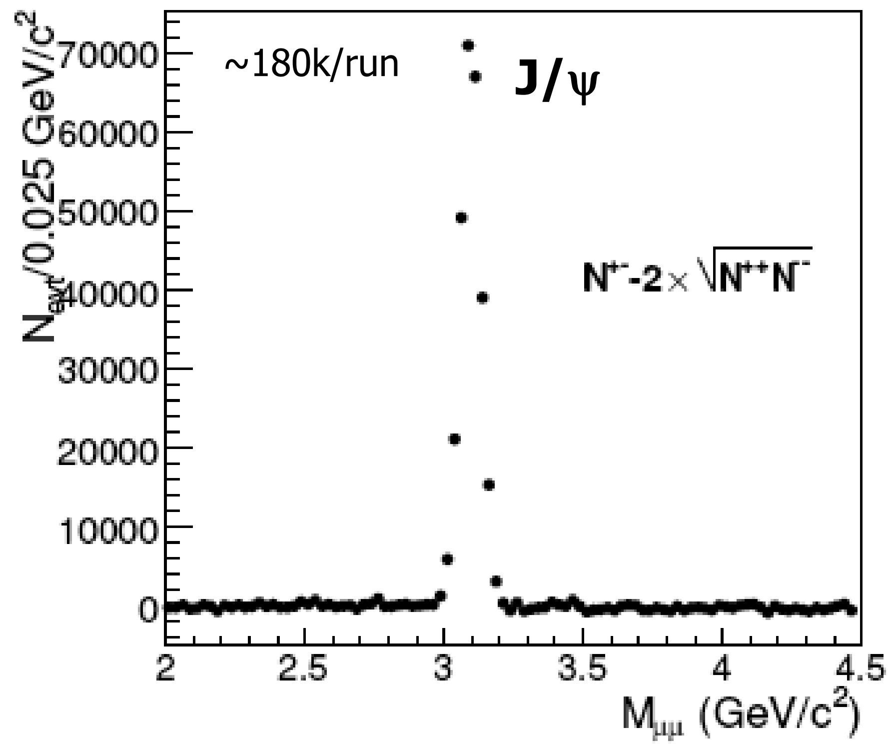
CMS Note 2003-019

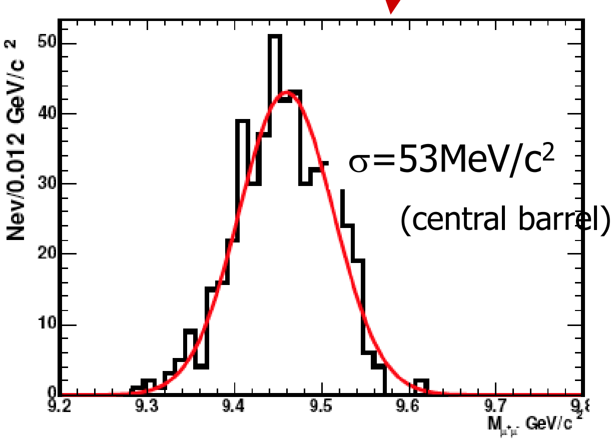
- **Reaction plane reconstructed via energy deposited in ECAL+HCAL: σ=0.12 rad**
- **Left: reconstructed energy deposition in the barrel and endcap regions for electromagnetic and hadronic calorimeters as function of the azimuthal angle for b = 6 fm**
- **Right: difference between generated and reconstructed reaction plane angle for Pb+ Pb collisions b = 6 fm**

S. Petrushanko, 2003

Quarkonia: Υ and J/ψ



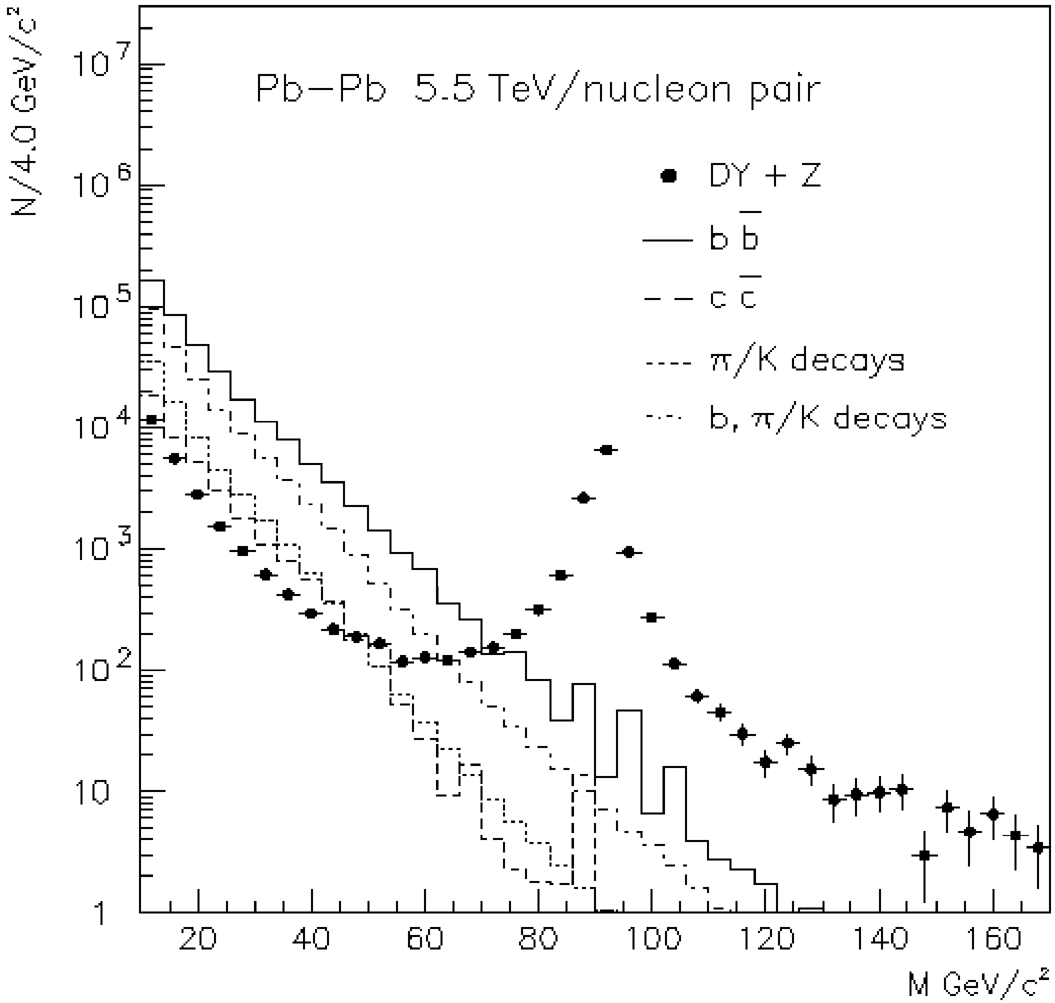




- **Best J/ψ, Υ mass resolution at LHC.**
- **Unique separation of Υ(1S), (2S), (3S) at $|\eta|<2.5$**

Kodolova, Bedjidian, 2006

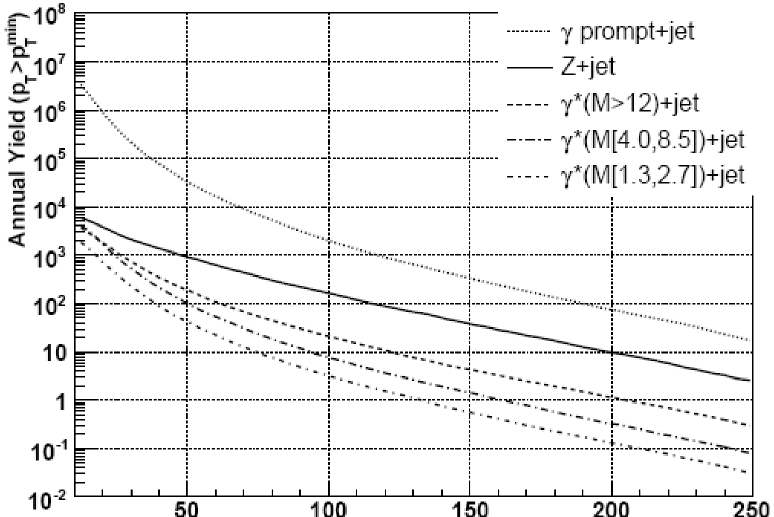
High Mass Dimuon, Z Production



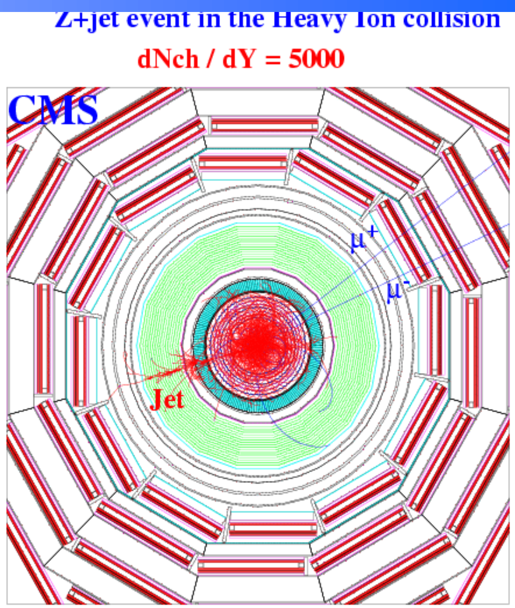
Kvatadze, 1999

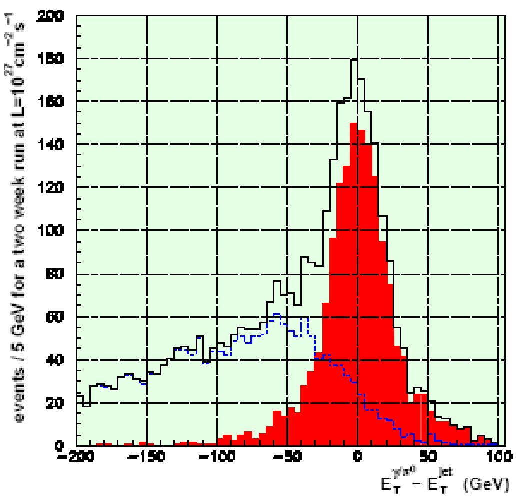
- **Z->μμ reconstructed with high efficiency by design**
  - **A probe to study nuclear shadowing**
  - **Unaffected reference for jet-tagging studies**
- **Dimuon continuum dominated by b decays**
  - **Heavy quark energy loss**
- **High statistics**
  - **O(10^4) Z per nominal HI run**

Tagged jets: jet+γ, $Z/\gamma^*\to\mu\mu$

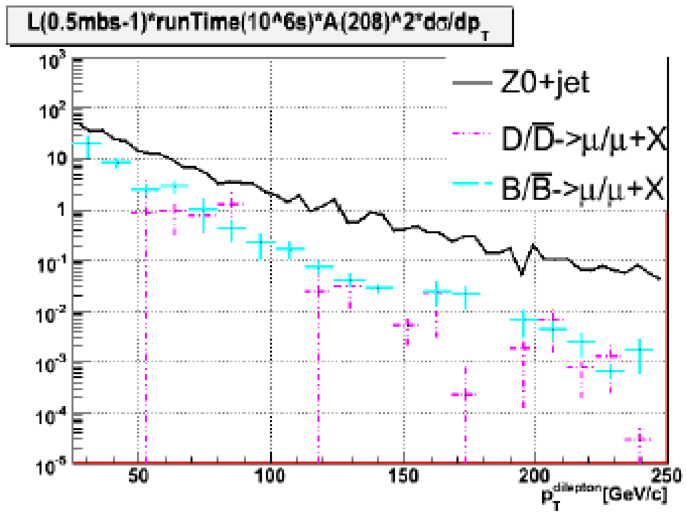


Annual yield of tagged jets, CMS acceptance





Jet+γ E_{Tjet}>120 GeV/c^2



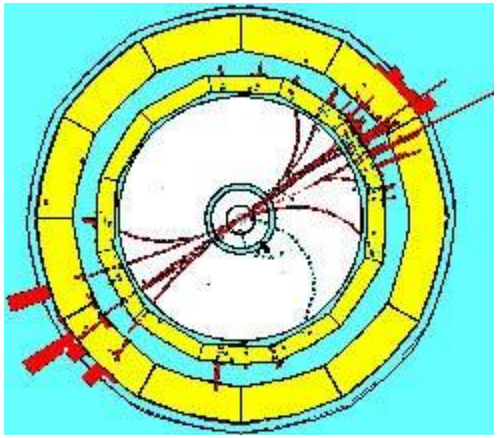
Jet+$\mu^+\mu^-$ 81 GeV/c^2<$M_{\mu\mu}$<101 GeV/c^2

C. Mironov, 2006

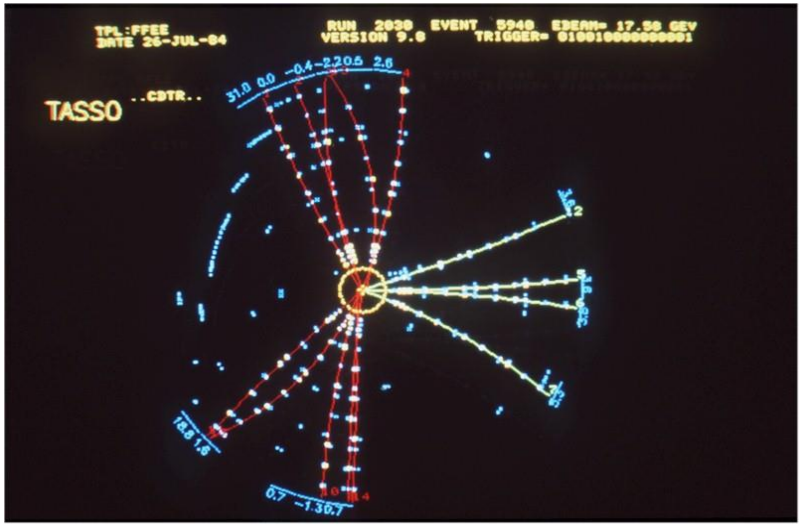
Introduction to Jet and Jet finders

Jet?

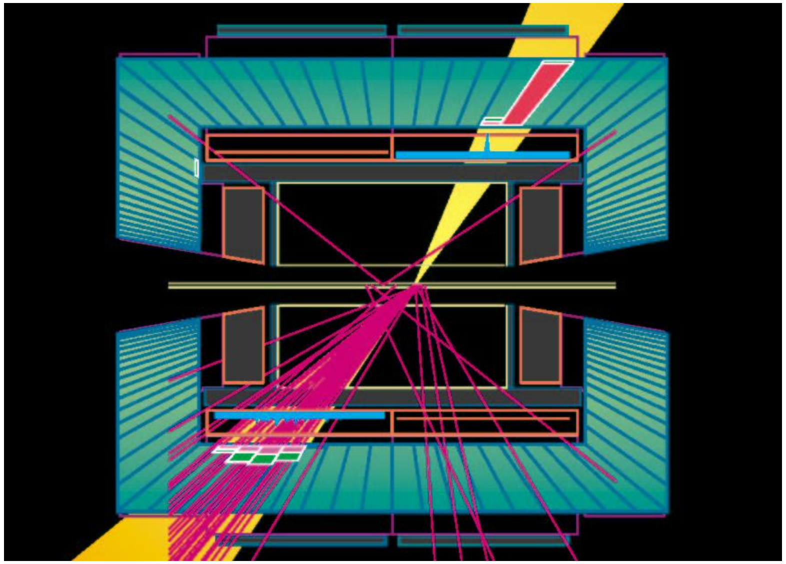
- Collimation of final state particles in a certain direction in collision events
- Particle in a jet has little transverse momentum along with the jet direction.



LEP/ALEPH



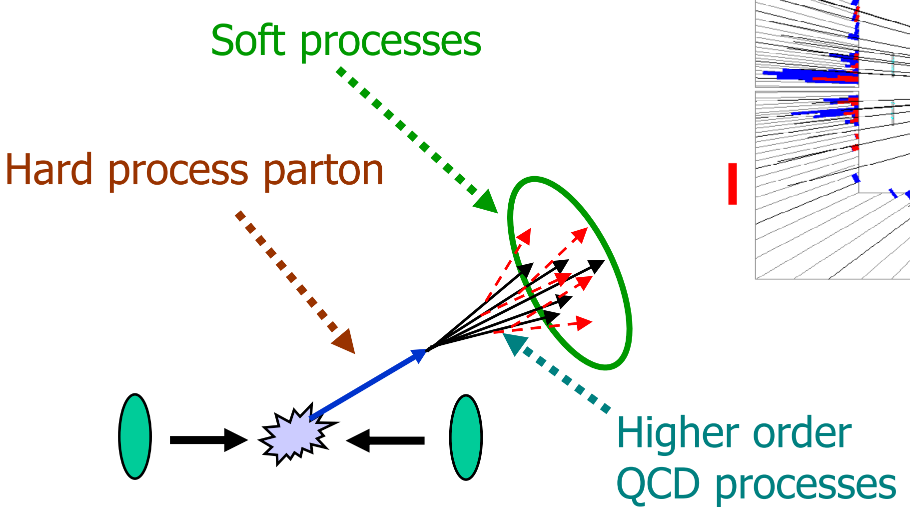
PETRA/TASSO

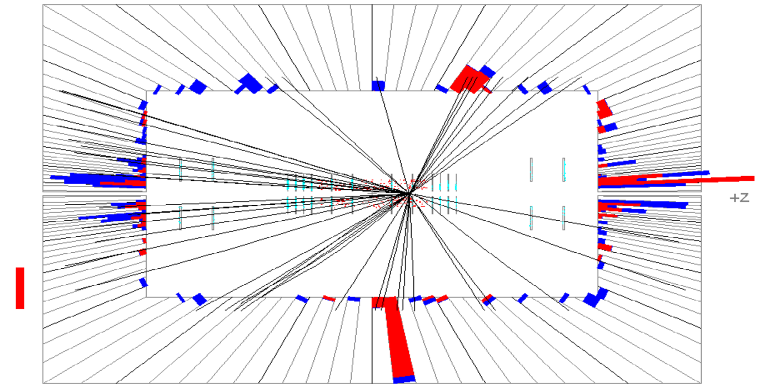


Tevatron/CDF

Jet: from parton to detector signal

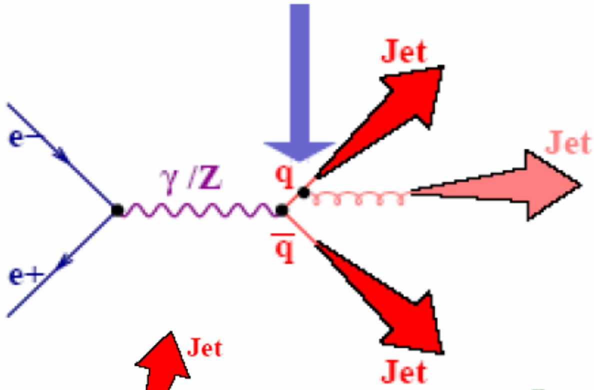
- **Parton → fragmentation / hadronization**
- **Charged particles → Trackers**
- **Charged and Neutrals → ECAL & HCAL**

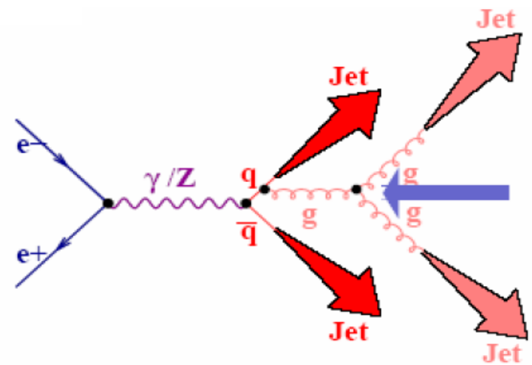


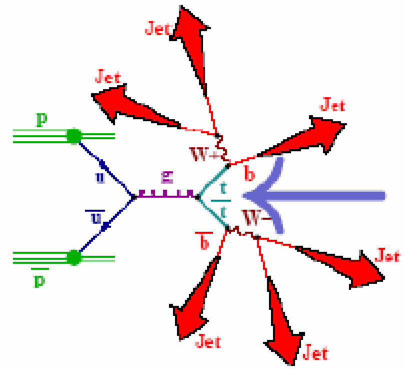


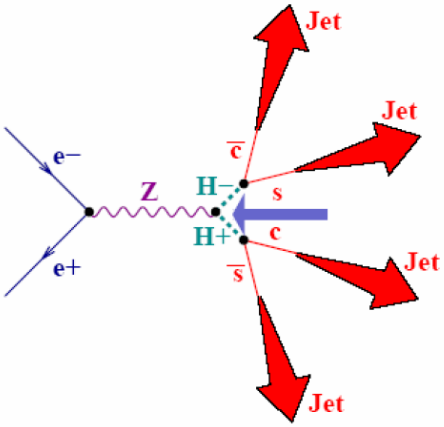
QCD partons → jets of hadrons → detector signals

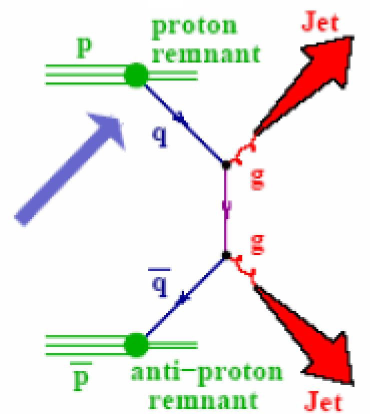
Why Jets are important?

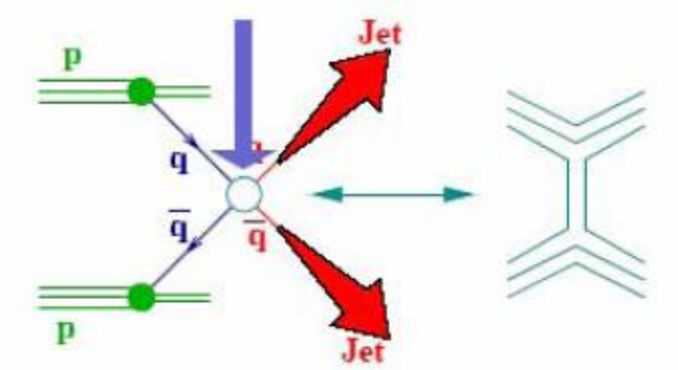












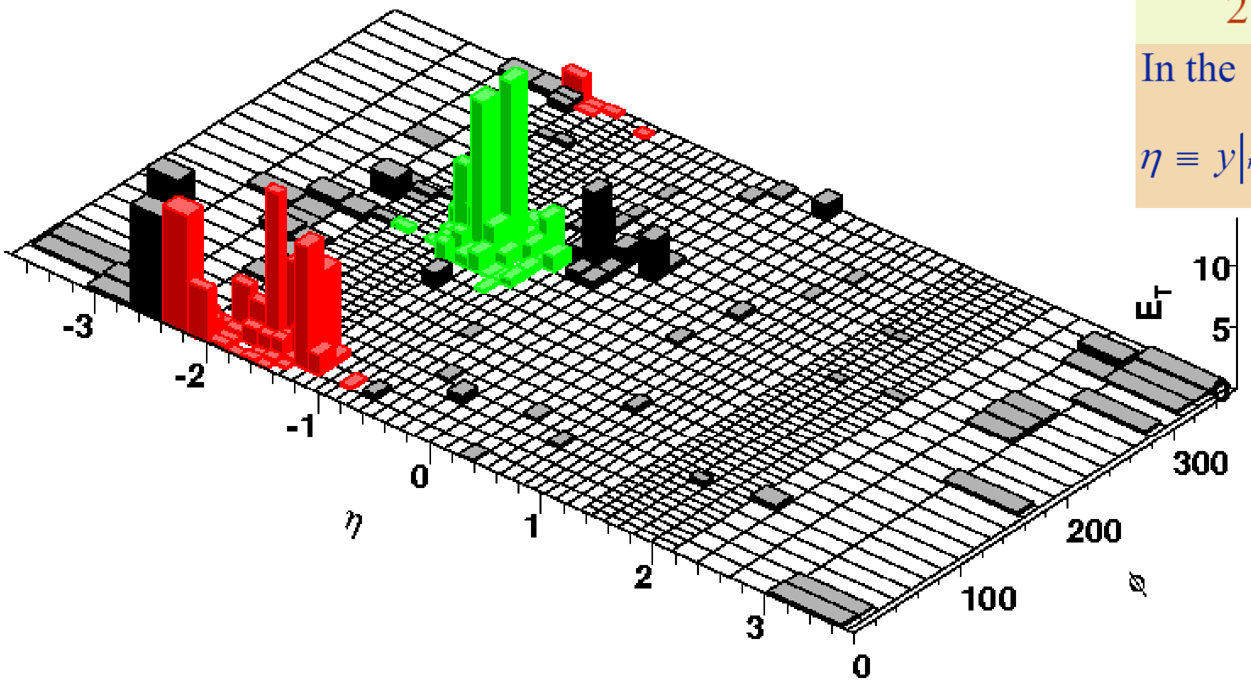
- Measurement of α_s .
- Fragmentation functions
- PDF
- Understanding QCD
- Quark-Gluon Plazma
- Heavy quark study
- Search for Higgs
- SUSY, new Physics

Typical shape of E_T $\eta-\phi$ map

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

In the limit $\beta \to 1$ (or $m << p_T$) then

$$\eta \equiv y\big|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$



- **The best jet finder is human eyes**
- **Computational approach is natural and mandatory**

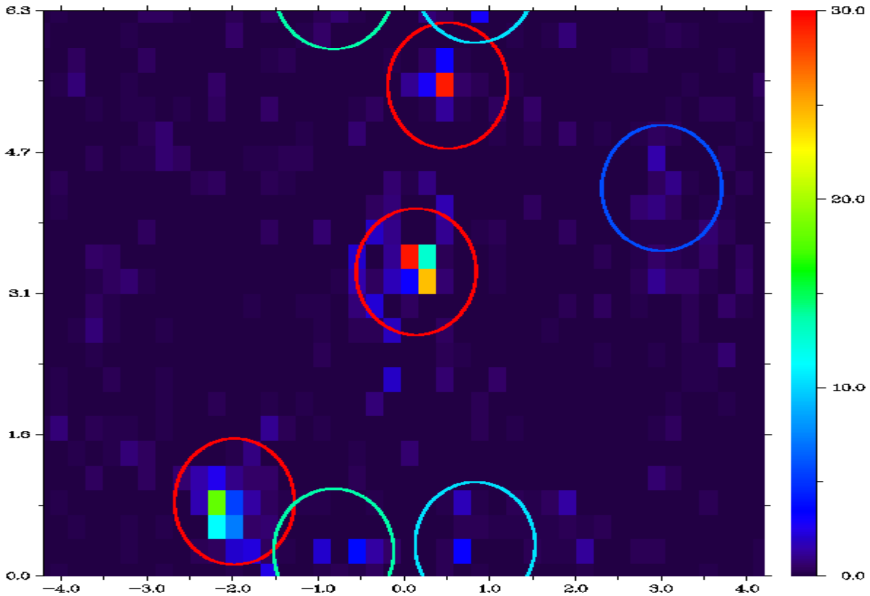
Various jet finding algorithms

- **Cone algorithm**
- **Iterative cone algorithm**
- **Sliding window algorithm**
- **Mid-point cone algorithm**
- **K_T algorithm**
- **FastJet algorithm (K_T with CGAL)**
- **Mulguisin algorithm (ATLAS JetFinder Library)**
  - **proposed and by the man you are looking at**

→ Systematic study on various jet-finders at the LHC energy is important

Cone algorithm and its variants

- **Simple and intuitive.**
- **Cone seed starts with the maximum E_T cell**
- **consider all cells within R**



- **Cone center → (η^C, ϕ^C)**
- **Cell i is**

$$\sqrt{(\eta^i - \eta^C)^2 + (\varphi^i - \varphi^C)^2} \le R$$

- **Energy of cone**

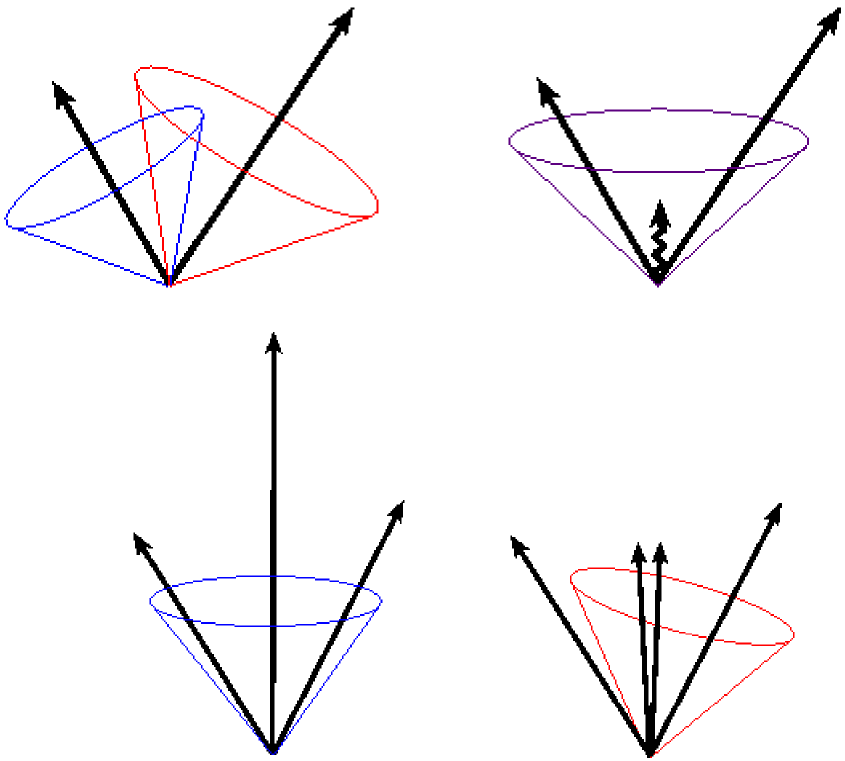
$$E_T^C = \sum_{i \subset C} E_T^i$$

- **Energy weighted center of jet**

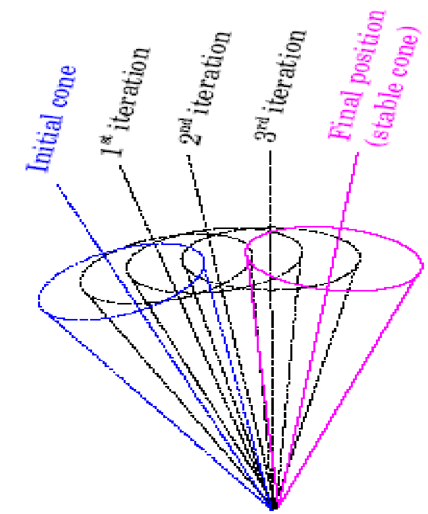
$$\bar{\eta}^C = \sum_{i \subset C} E_T^i * \eta^i / E_T^C \;\; ; \;\; \bar{\varphi}^C = \sum_{i \subset C} E_T^i * \varphi^i / E_T^C$$

- **overlapping jet, sharing, etc.**

Cone algorithm variants



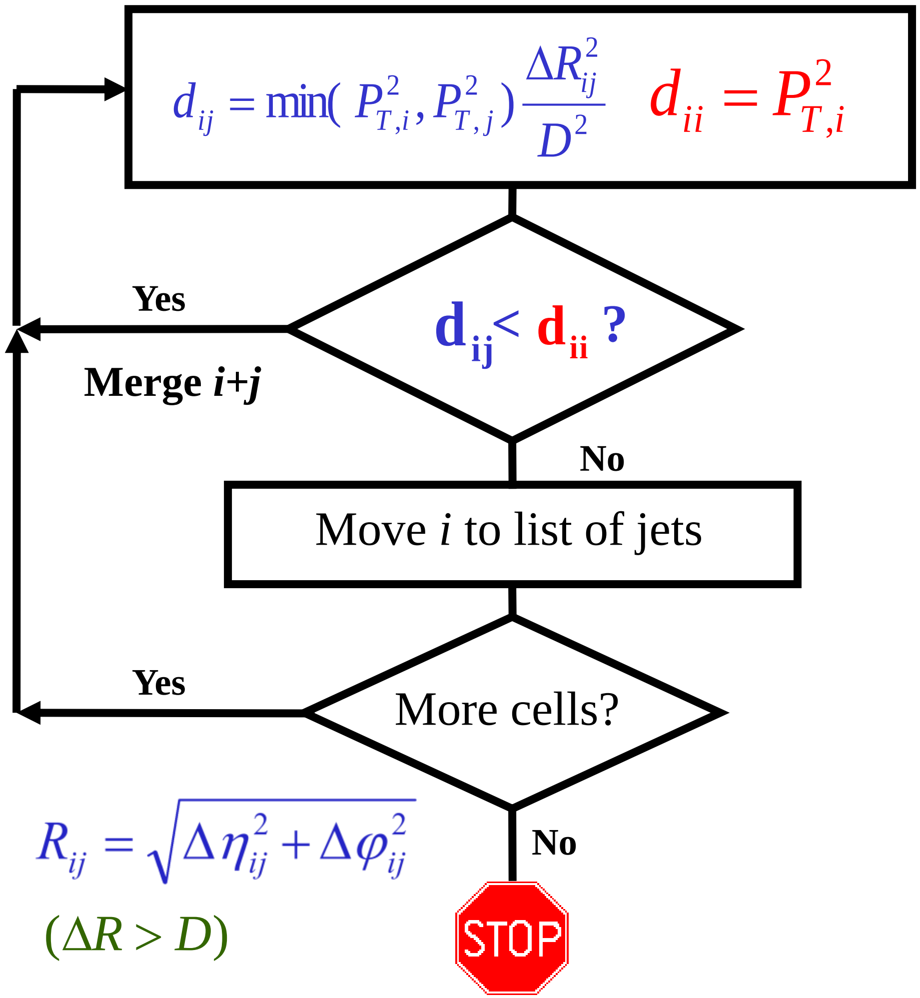
- Cone algorithm → infrared unsafe, collinear unsafe
- Most of time cone center is not jet center (E_T weighted) → Re-center cone, and update cell list
- CPU ~ $O(N^2)$



- Cone merge, separation, recalculating the jet center, etc. are necessary → various cone variants, such as Mid-point, Iterative, Double cone, etc..

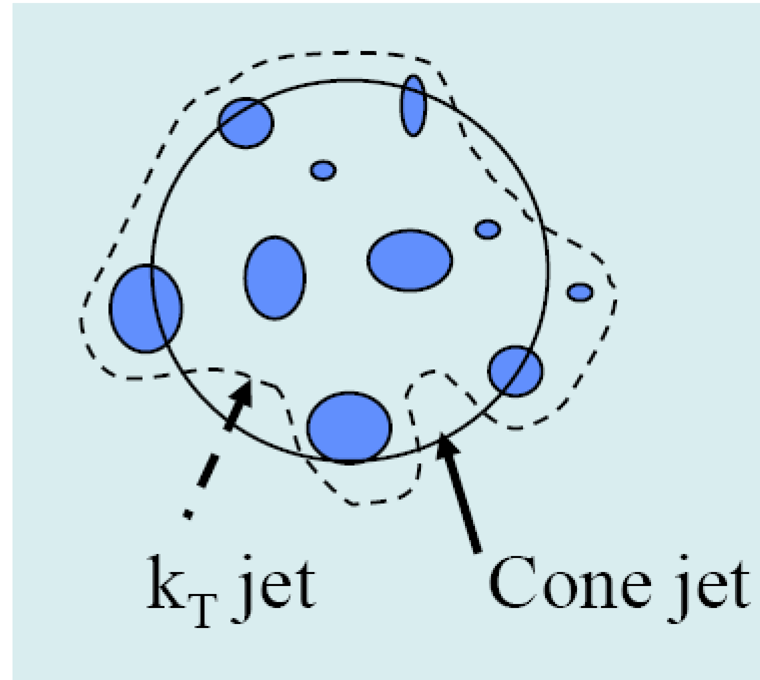
K_T Jet finder (Durham algorithm)

- **Minimize Invariant mass → Looks like to have theoretical basis, but not really.**
- **No overlapped jets, every parton, particle, or detector cell is assigned to a jet**



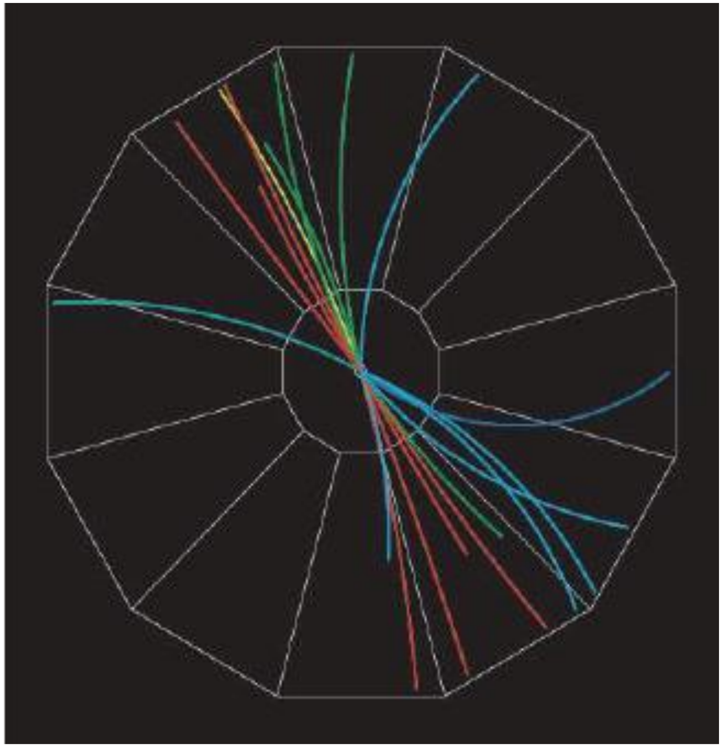
K_T algorithm continued

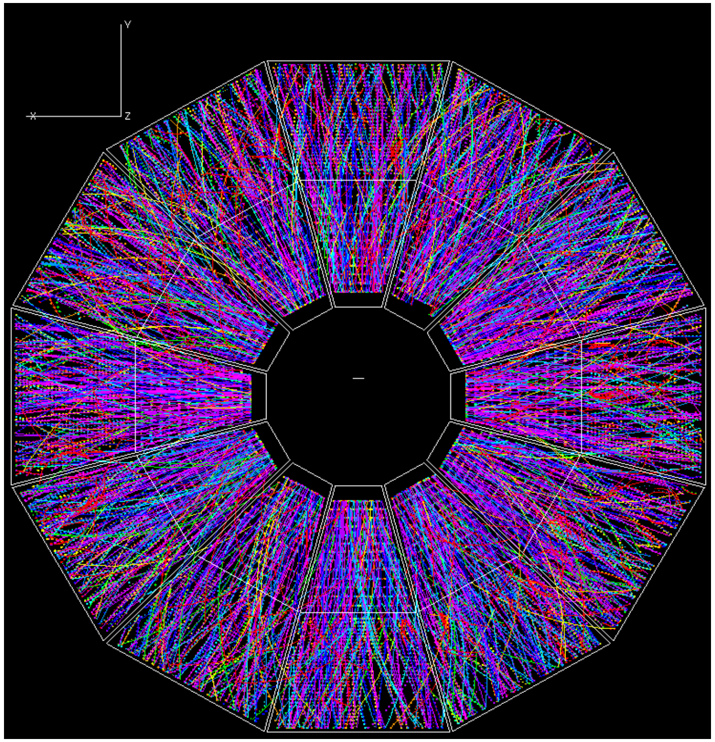
- **Infrared, Collinear safe!**
- **Less sensitive to hadronization effects**
- **Not easy to calibrate jet energy compared with Cone jet**
- **Big CPU consumption**
- **CPU ~ $O(N^3)$**
- **No way in the case of trackers with LHC HI program**



Jets in pp & Jets in NN

p+p @ $\sqrt{s}$ = 200 GeV **STAR Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV**



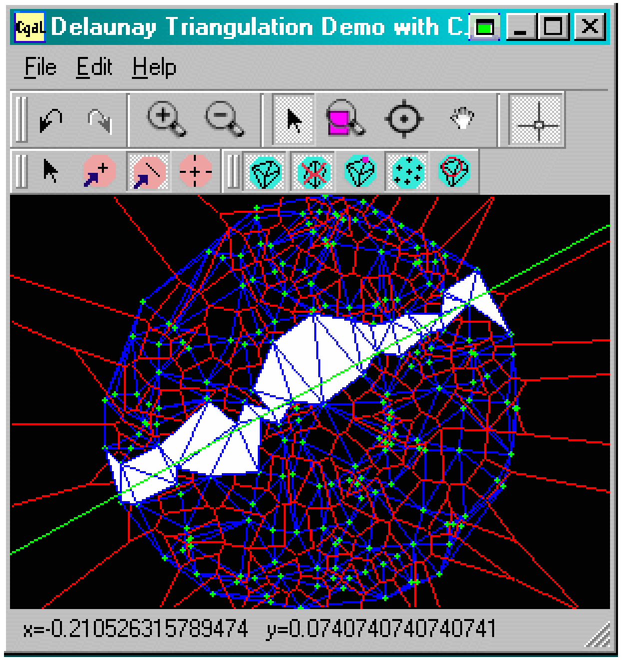


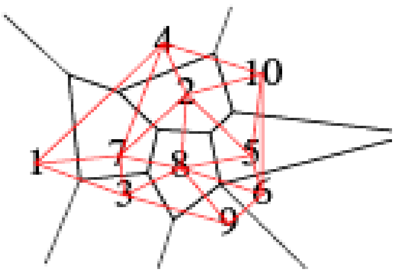
Special care is needed to find jet in HI program

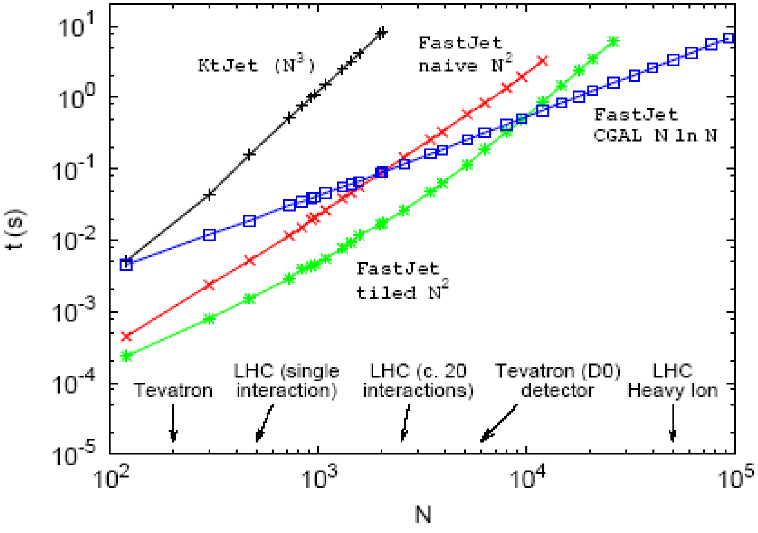
Leading particle was considered as the Jet signal at RHIC

FastJet

- M. Cacciari, G. Salaam hep-ph/0512210
- CGAL geometry package is used
- Extracting 3D model from point clouds using Delaunay triangulation algorithm

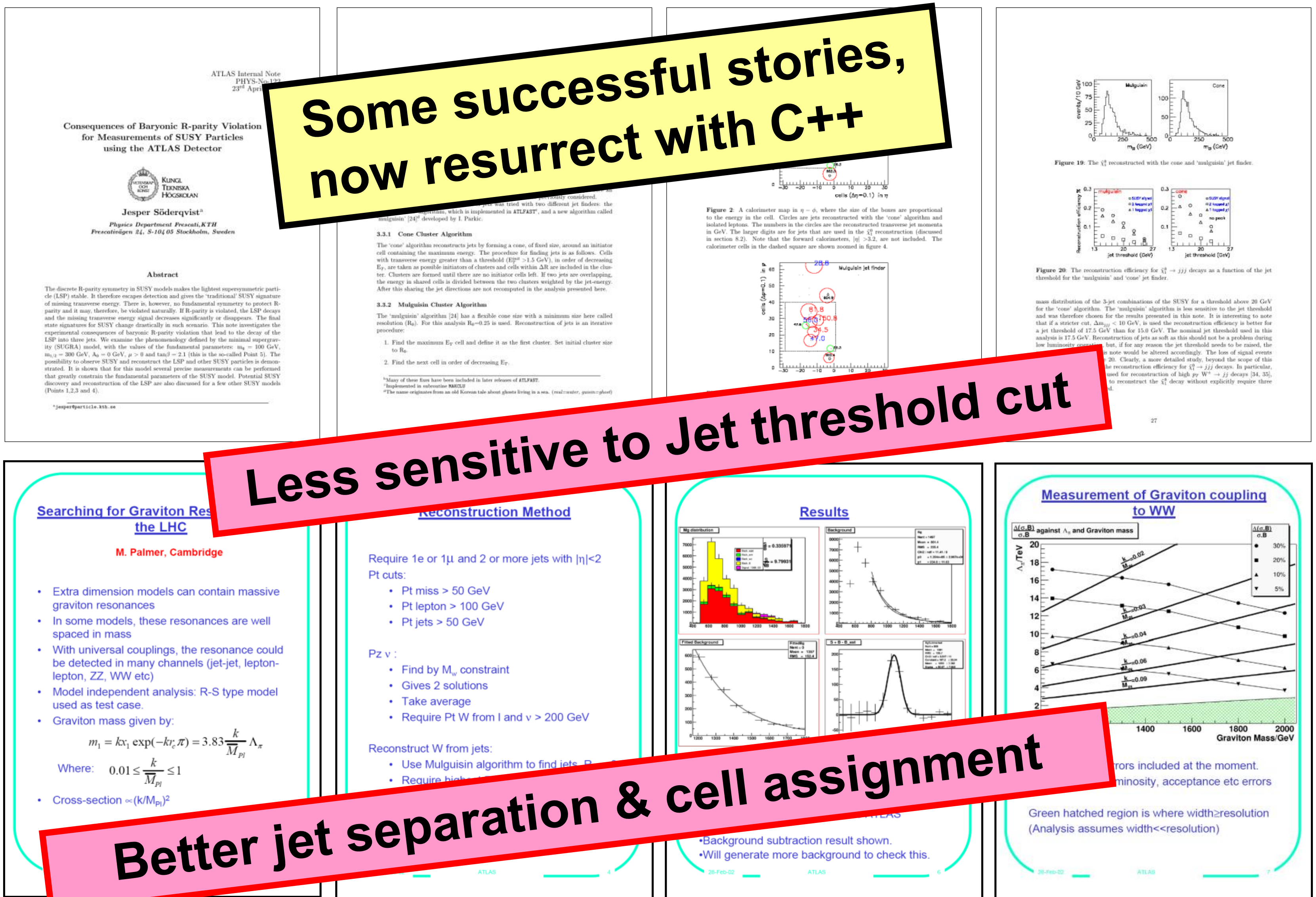






The only solution for LHC Heavy Ion ?

Mulguisin algorithm



Some successful stories, now resurrect with C++

Less sensitive to Jet threshold cut

Better jet separation & cell assignment

CMS-HI Korean Physicists lead the jet finder activity

Brief history and now

- **2006 summer: We have visited CERN and started implementation of Jet Finding Library in HIROOT.**
- **FastJet (M. Cacciari et al), a promising Kt substitute, was needed to be implemented.**
- **2006 fall: CMS-KR Heavy-Ion team was formed. ~5 PhDs and ~10 graduate students from 4 institutions**
  - **Univ of Seoul, Chonbuk Nat'l Univ, Korea Univ. Yonsei Univ.**
- **CMS-HI convener made a visit to Korea to promote CMS-KR.**
- **2007 now: 6 graduate students are working with HIROOT/CMSSW**
  - **2 are writing their theses for Master degree with Jet finding**
  - **2 are working with MC/muon for their PhD degree**
  - **2 are doing more computing/grid elaborated work**

What has been done so far

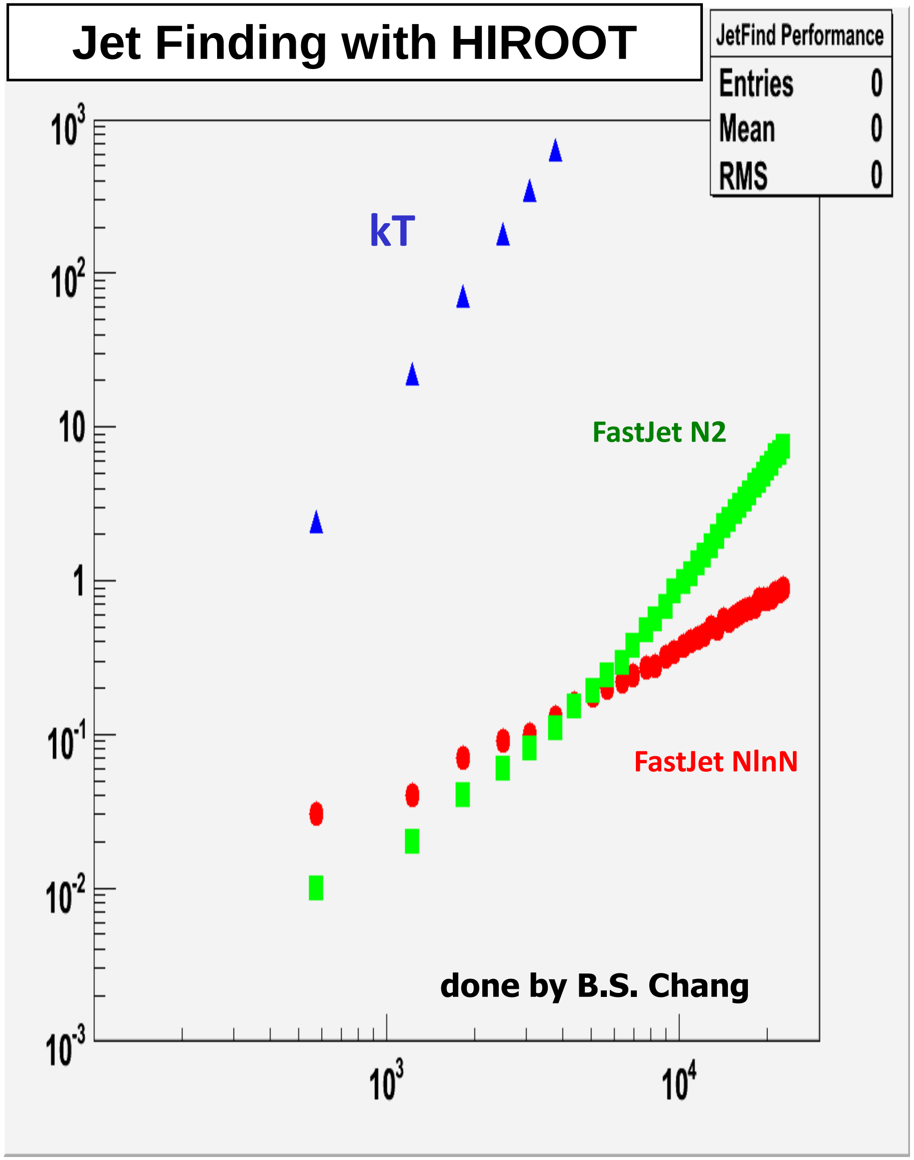
- 3 Jet algorithms were implemented and tested
- THISimpleKtJetFinder → from a historical FORTRAN version
- THIFastJetFinder → from M. Cacciari's release
- THIMulguisinJetFinder → MGS algorithm from ATLAS Jet library
- Job assignment:
  - Inkyu → hiroot coding, library implementation
  - BS Chang, KS Kim → Jet study, benchmark
  - DH Moon, JH Kim → MC generation (HIJING, HYDJET)
  - JW Park → Heavy-Ion Data Grid preparation

Benchmark test with HIROOT

- **Use CMS-HI Tier2 of UoS**
- ***HIROOT + CGAL 3.2.1 patch, fastjet 2.0.0***
- ***DATA : generated with* HYDJET/HIROOT**
  - **Multiplicity ~ E^n where n=1,2,3,4**
  - **4 Hydjet Type(THIHydjet::EydjetSel)**
  - **25 Energy Level (100~14000)**
  - **400 runs each 100 events**
- ***Jet Finders for benchmark : 6 finders (JetTh=30GeV)***
  - **IterativeCone with/without Seed Threshold**
  - **SimpleKt**
  - **FastJet(N2), FastJet(NlnN)**
  - **Mulguisin**

Reproduced what FastJet claimed

Jet Finding with HIROOT



M. Cacciari's publication

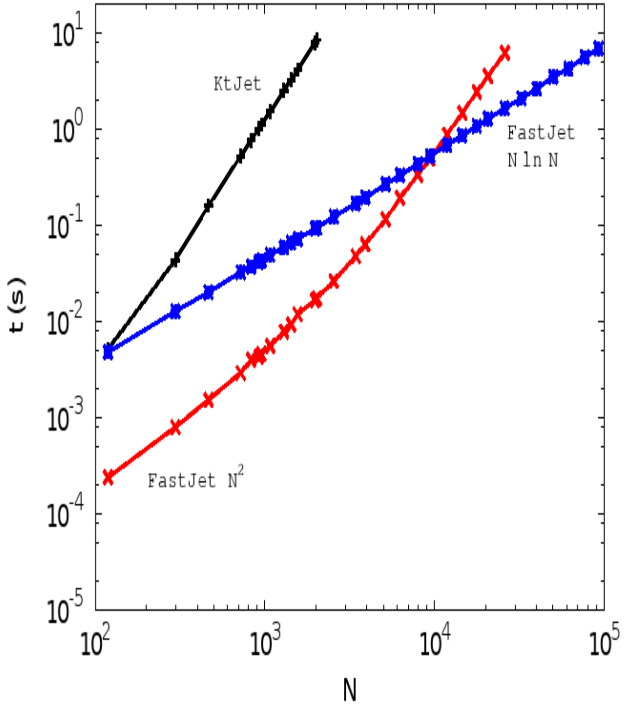
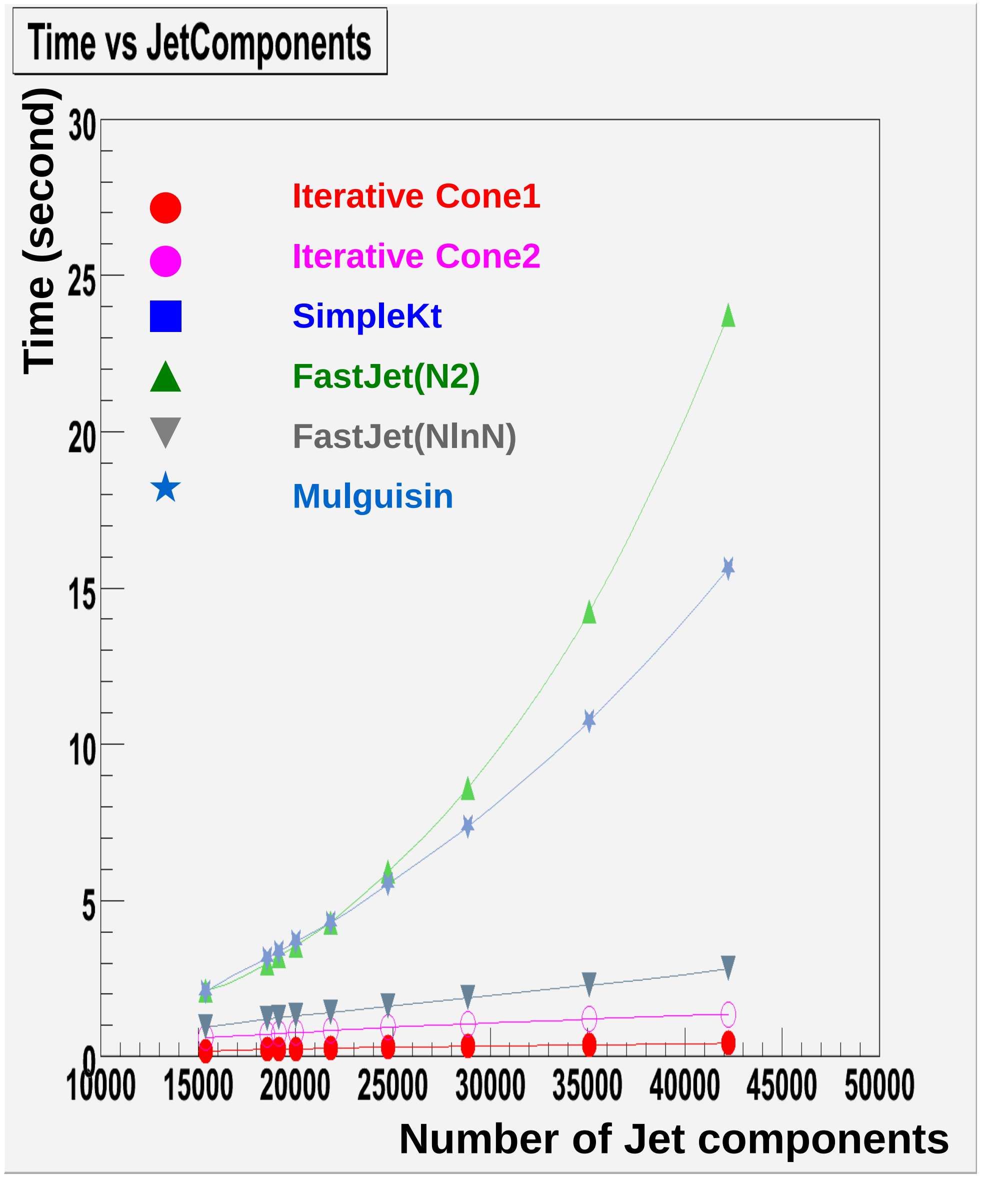


Figure 2: The running times (on a 3 GHz Pentium 4 processor with 1 GB of memory, 512 kB of cache, and version 3.4 of the GNU g++ compiler) of the KtJet [22] and FastJet implementations of the k_t-clustering jet-finder versus the number of initial particles. Different values of N have been obtained by taking a LHC dijet event with $p_t \simeq 60$ GeV and adding on variable numbers of minimum bias events. Both kinds of events have been simulated with Pythia 6.3 [28].

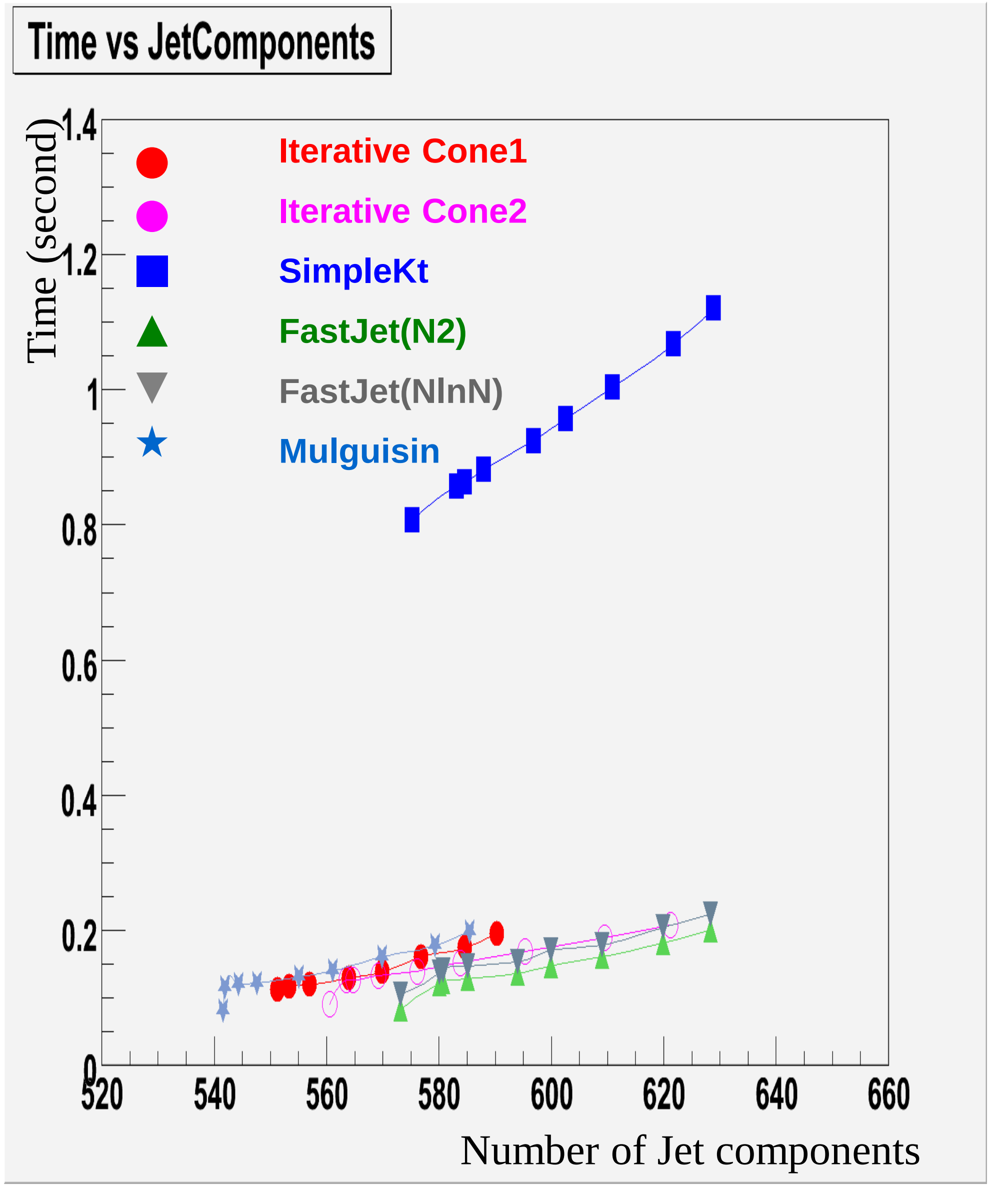
Benchmark: Particle level study



- KT algorithm fails with high multiplicity
- Cone is faster than FastJet
- FastJet (N2) and MGS show O(N2) behaviour
- FastJet (NlnN), i.e. with CGAL, show fast result, thus can be a substitution of KT
- Not a real case!!

done by B.S. Chang

Benchmark: Calorimeter level study



- Calorimeters are applied
- # of cells (or towers) are limited (<2000)
- KT works but still slow → O(N3)
- FastJet, Cone, MGS show all very similar speed
- Now it's matter of performance & resolution.

Jet Finding at CMS-HI

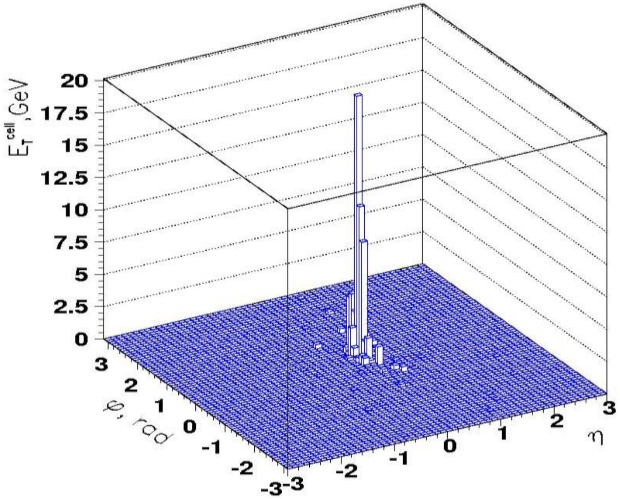
Jet Reconstruction

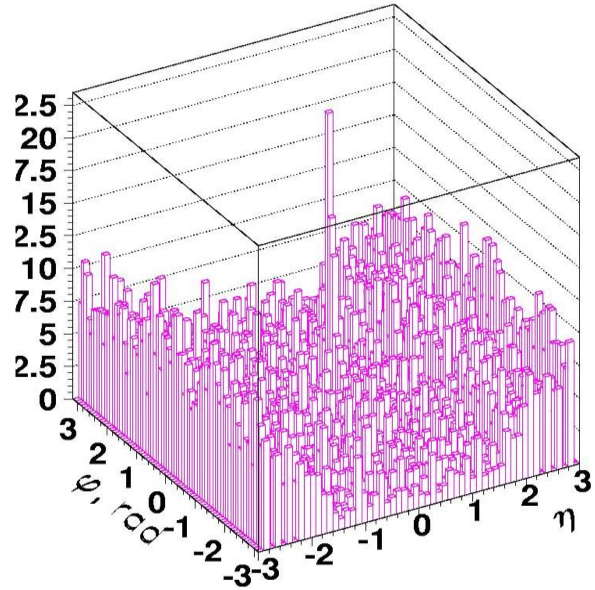
Jet E_T ~100GeV, Pb Pb background dN_{ch}/dy ~ 5000

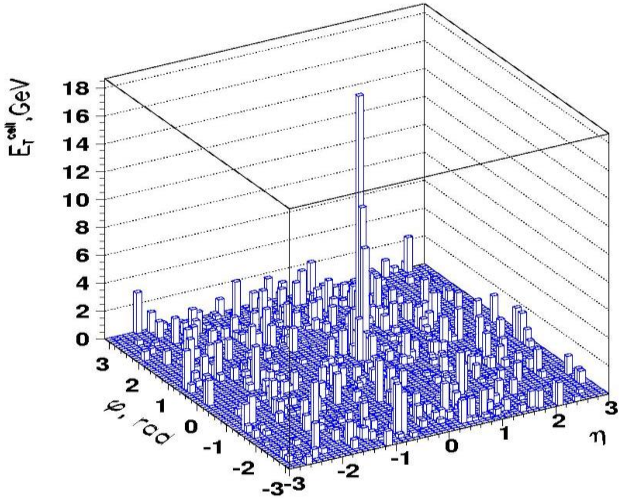
Jet in pp after pileup subtraction

Jet superimposed on Pb Pb background

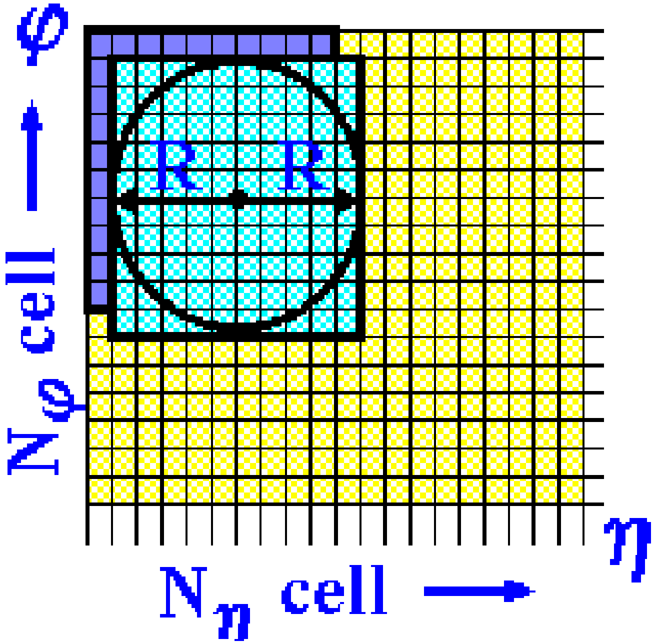
Jet in Pb-Pb after pileup subtraction







Background Subtraction Algorithm



Event-by-event background subtraction:

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

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

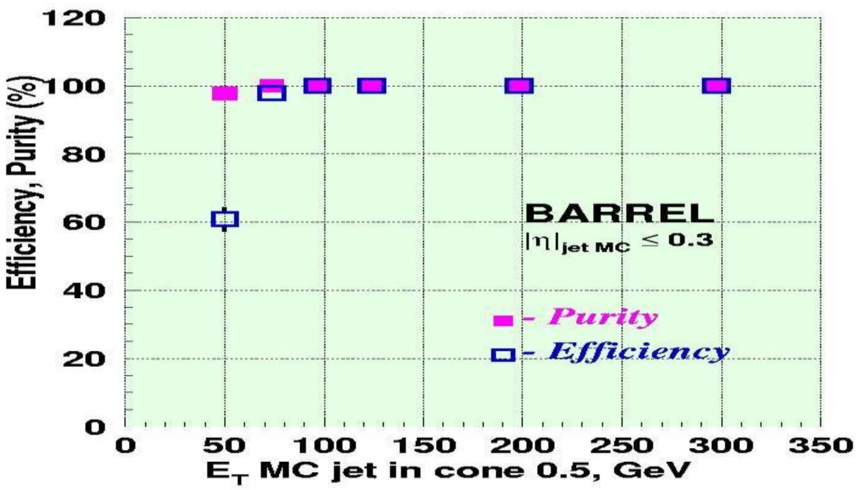
$$E_t^{pile\text{-}up} = <E_T^{Tower}(\eta)> + D^{Tower}(\eta)$$

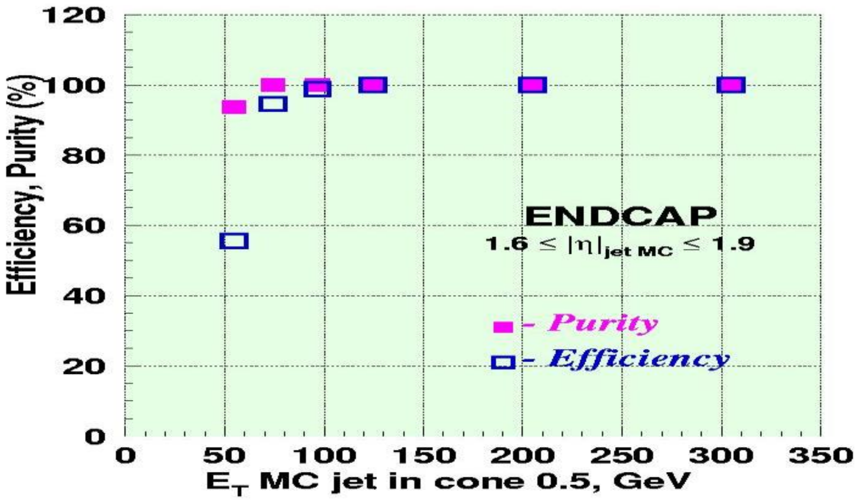
- Negative tower energies are replaced by zero

- Find Jets with $E_T^{jet} > E_t^{cut}$ using standard iterative cone algorithm 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 $E_T^{Jet} = E_T^{cone} - E_t^{pile\text{-}up\ new}$

Efficiency, Purity vs. Jet Energy

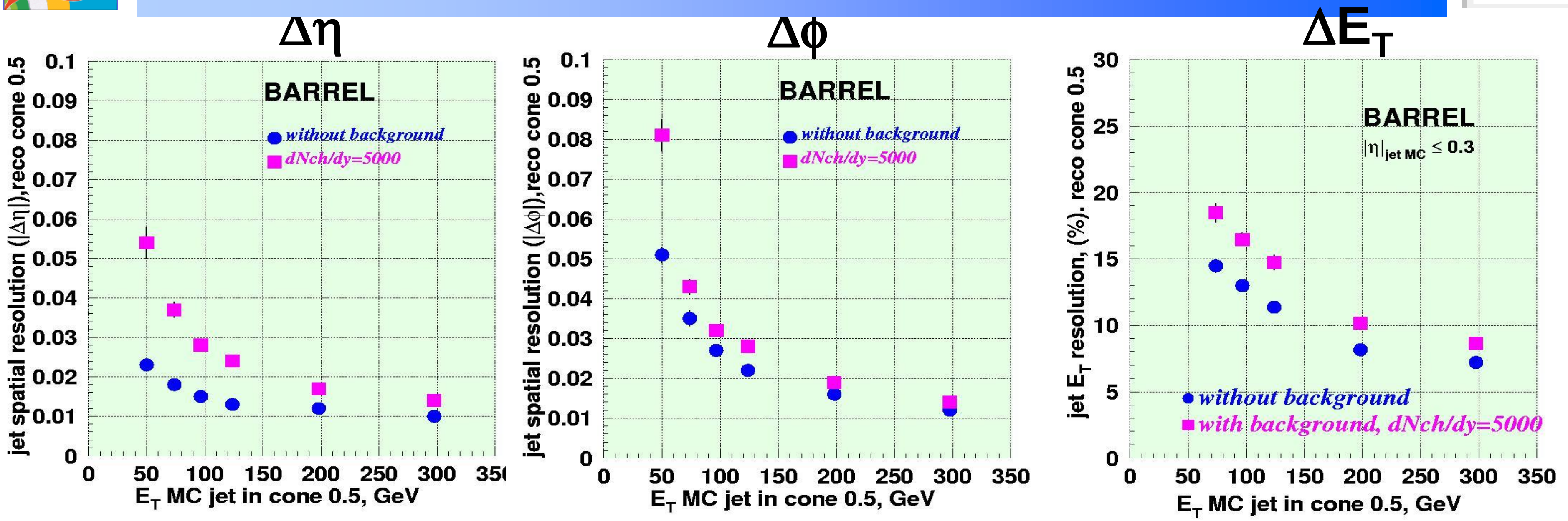
Reconstructing 50-300 GeV Jets in Pb-Pb background





- EFFICIENCY
  - Number of events with true reco. Jets/Number of all generated events
- PURITY
  - Number of events with true reco. QCD Jets/ Number of all reco. Jet events (true+fake).
- Threshold of jet reco. ET >30 GeV.
- Above 75(100) GeV we achieve
  - 100% efficiency and purity in the barrel (endcap)
  - Unbiased

Jet Resolutions



- 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

Remarks & Summary

Heavy Ion Data generation and Grid

- KU are working with HYDJET, HIJING with HIROOT / CMSSW + Muon package work
  - Study HYDJET and CMS MC generation with CMSSW
- E.J.Kim et al. have visited MIT in early Feb., and are setting now CMS-HI Tier2/3.
  - Learn MIT Tier 2 & d-Cache, operation, etc.
- Univ. of Seoul will invest $0.2M for computing upgrade (2007 budget plan)
  - 256 machines → Data storage configuration
  - 64TB (mid 2007) → 128 TB (end 2007) → 256TB (goal)
- New CPU 64bit dual core machines are to come
  - total of 128 Xeon cluster (TIER2)

Pure Koreans contributions to CMS

- Full contribution! KT Jet and FastJet implementations in HIROOT / CMSSW.
  - Kt, FastJet, Mulguisin
- CMS-HI Tier2 (both Data grid & CPU grid) will be added as a Korean contribution
  - both LCG and OSG are available. MC contribution too.
- Muon package contribution will be added
- We move forward toward CMS JetFinder Library.
- Visible contribution to CMS/LHC world.
- Strongly hope to do real physics with our jetfinder library.

Remarks & Summary

- Understanding jet is crucial in LHC experiments.
- The CMS Detector will allow precision jet study
  - The combination of large acceptance Calorimeters high precision charged particle tracking and flexible Trigger/DAQ system will allow us to address a wide range of Jet Physics observables
- Jet Physics in Heavy Ion Collisions will be an exciting new field of study with jets
  - Need to develop many new experimental techniques
- New algorithms should be considered due to unprecedented CPU time and better precision
  - FastJet, Mulguisin, and hybrid algorithms
- KR CMS-HI group will do real contributions and will make real physics outputs