The CMS Barrel Calorimeter Response to Particle Beams from 2 to 350 GeV/c

Efe Yazgan (Texas Tech University)
on behalf of CMS HCAL Collaboration

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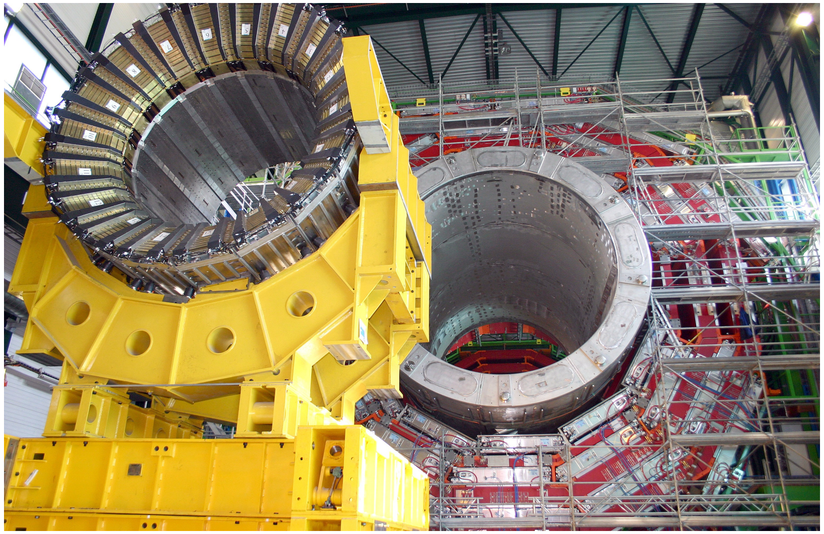


Outline

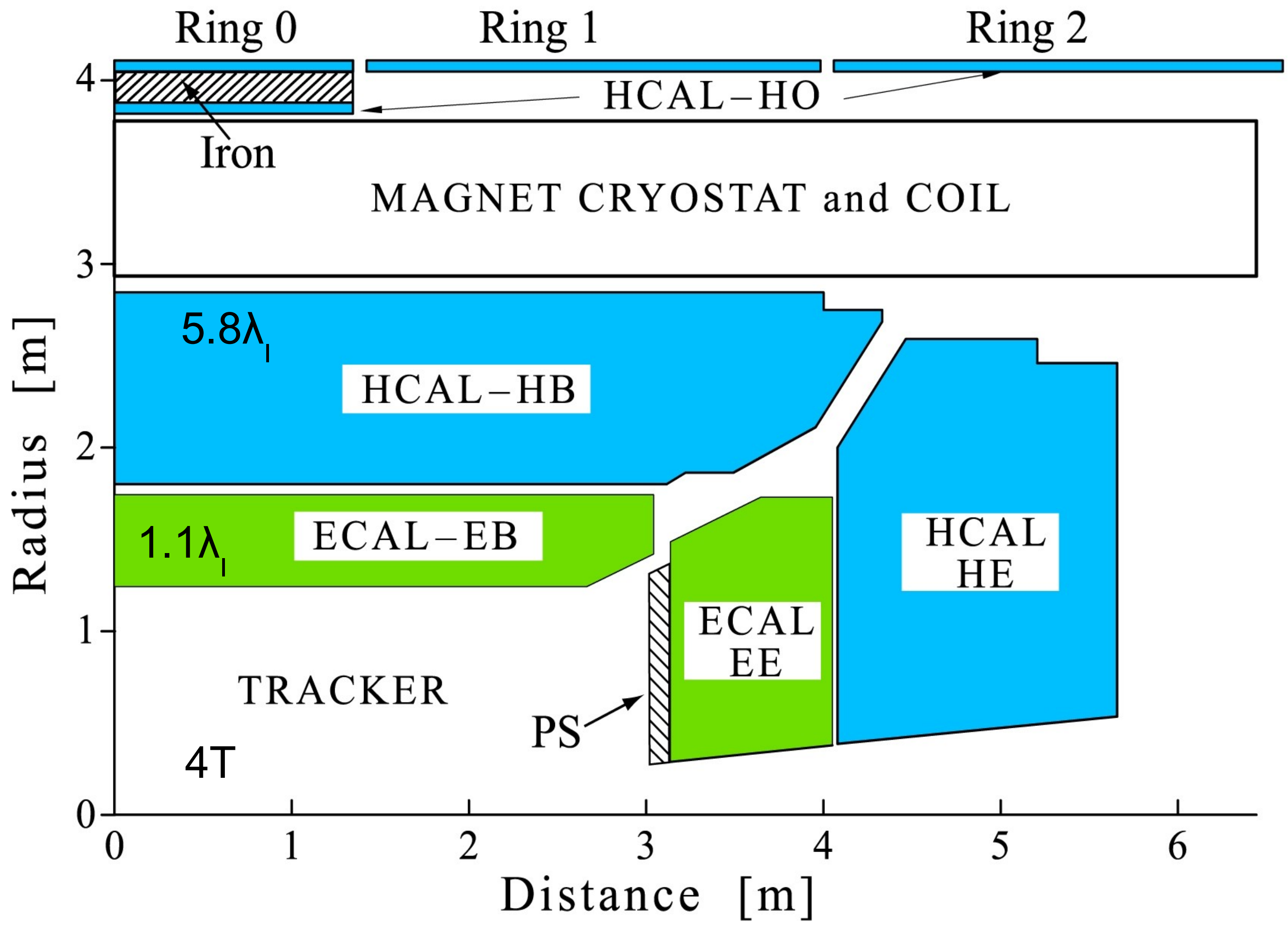
- Description of barrel calorimeters(EB,HB,HO) and test beam 2006 setup
- H2 beam line, beam clean-up, particle identification and beam composition
- EB+HB Combined calorimeter response
  - $\pi^{+/-}$,$K^{+/-}$,p,$\bar{p}$,μ
- Response parametrization and correction
- Summary

Calorimeters

HB/HO: measure timing, angular direction, hadronic shower energy – calorimetric triggers, jet/met reconstruction.

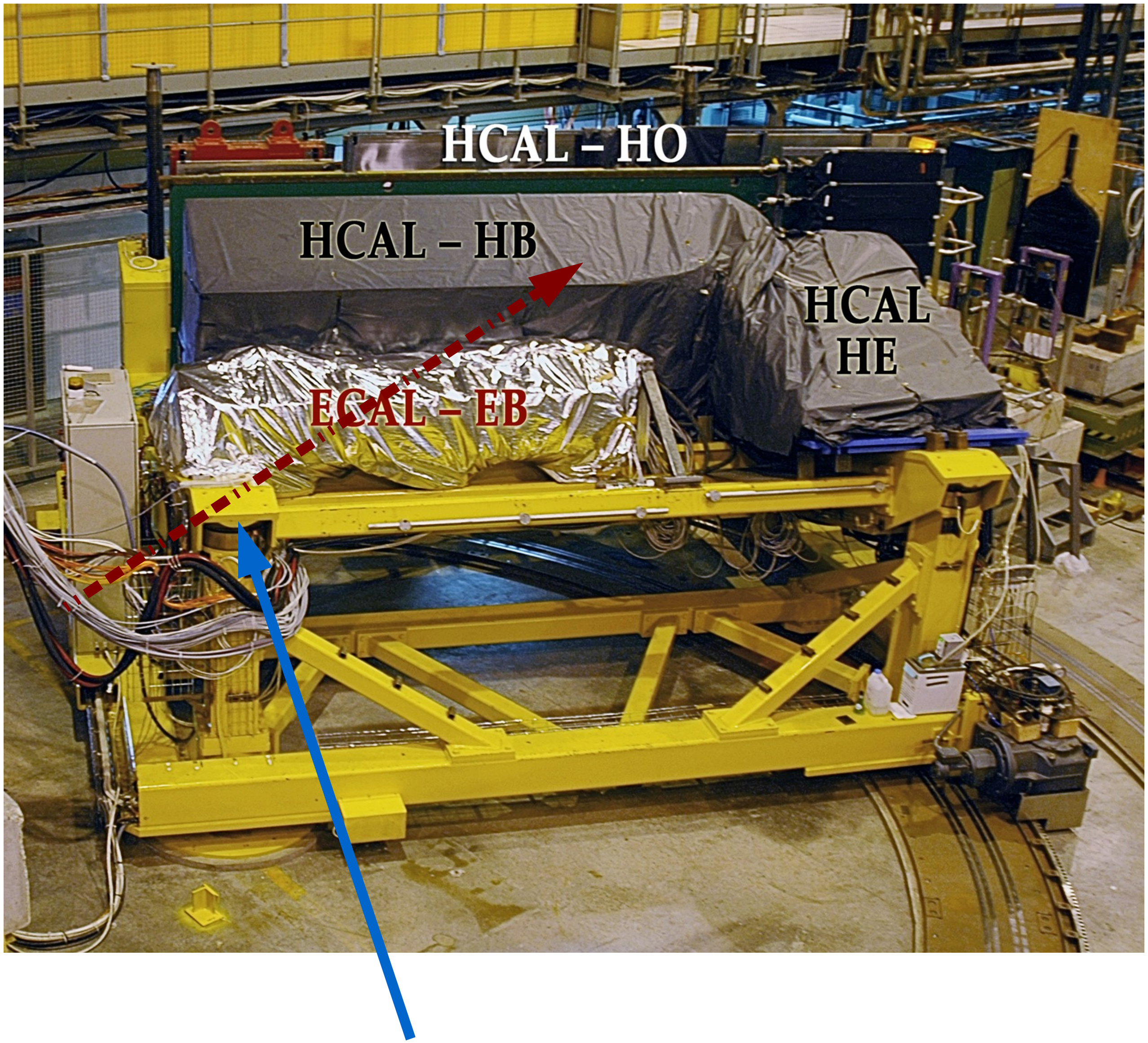
Scintillator tiles are read out with embedded wavelength shifting fibers.

brass(non-magnetic absorber) & scintillator tiles.



1 complete EB supermodule (1700 $PbWO_4$ crystals) of width $\Delta\Phi$=20°.
Crystal length = 25.8X_0.
Light conversion to signal by 2 APDs / crystal.

Test Beam 2006 Setup

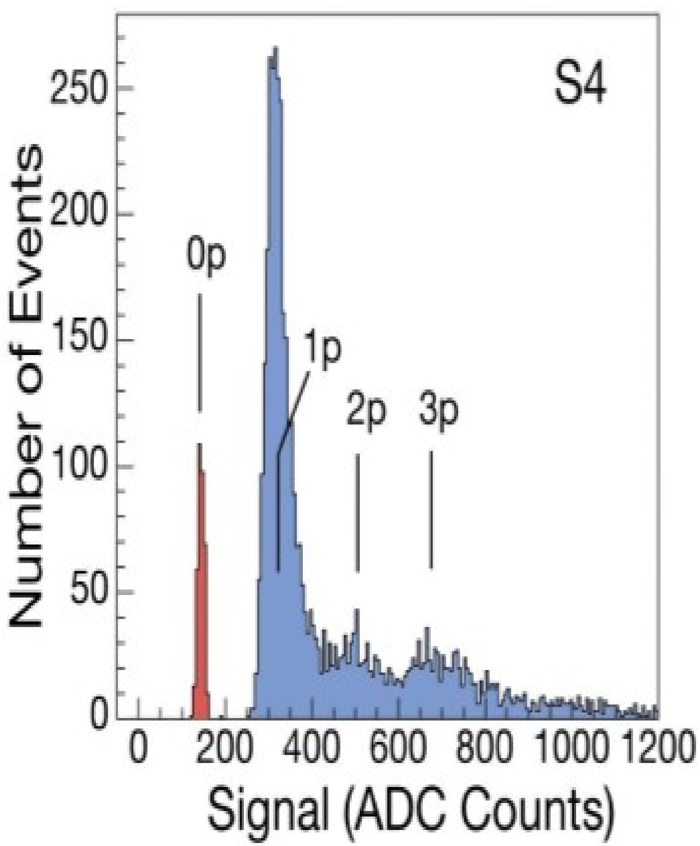


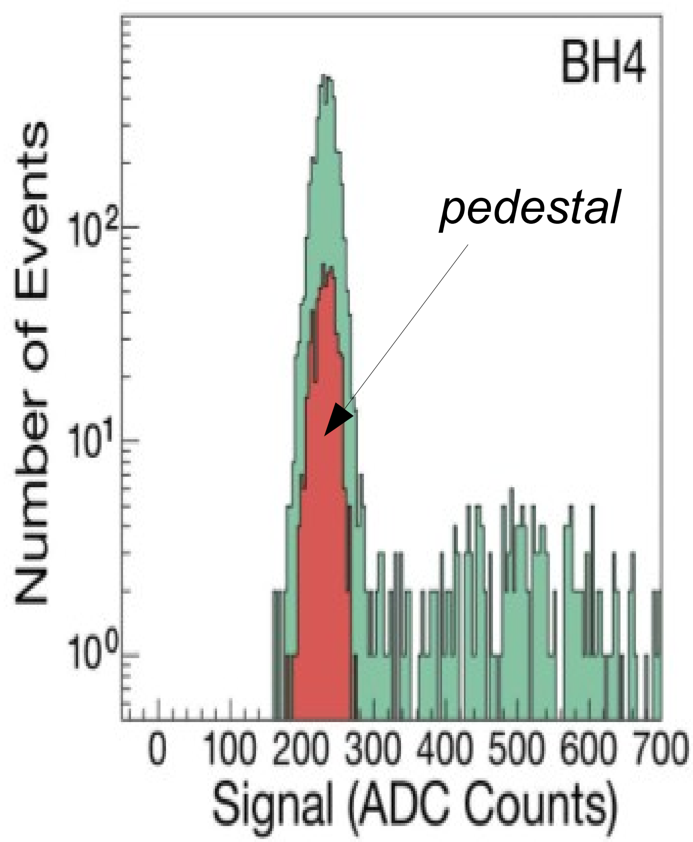
Pivot ~ interaction point

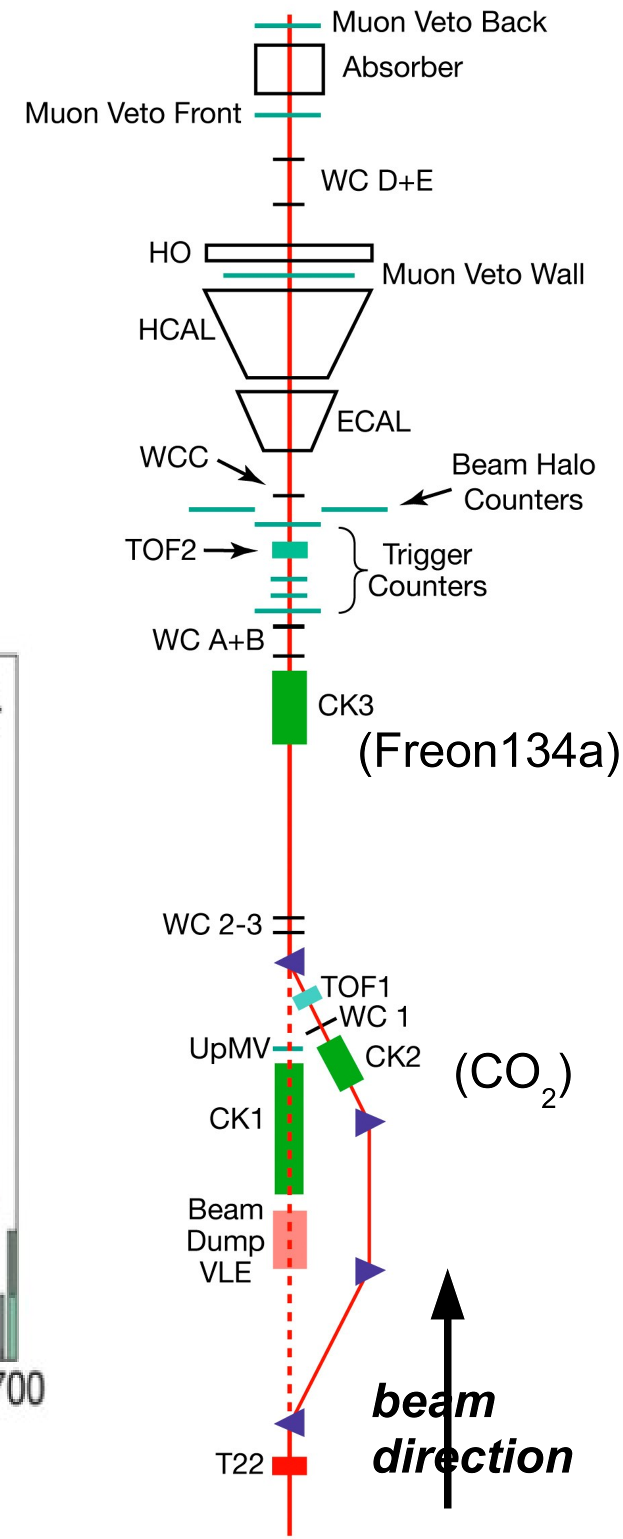
- HB: 40 deg in Φ
- HE: 20 deg Φ
- HO: Ring 0,1,2
- ECAL(SM9): 20 deg in Φ
- +final CMS electronics

H2 Beam Line at the SPS

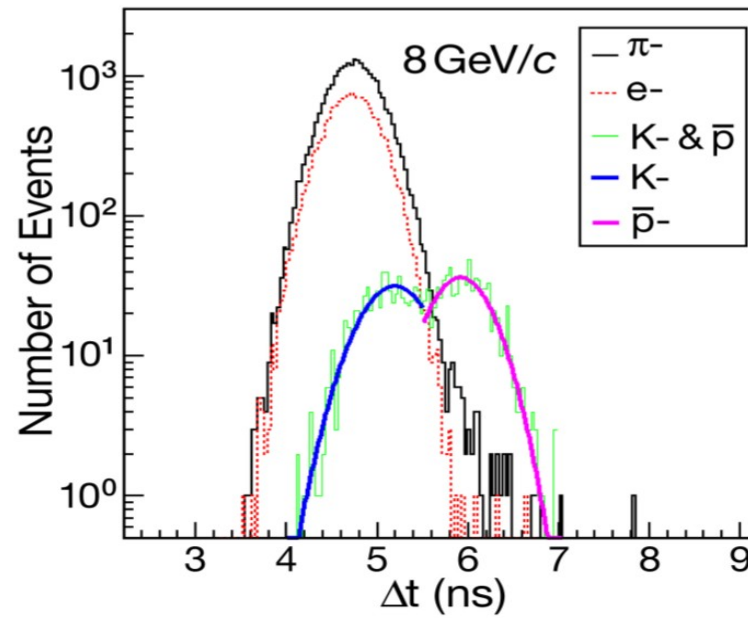
- Beam cleaning:
  - Single hit in S1, S2 and S4 trigger counters (S1*S2*S4 define 4x4 cm^2 area on the front face of the calorimeter).
  - Remove wide angle secondaries: Beam Halo counters (BH1-4) 7x7 cm^2 hole.





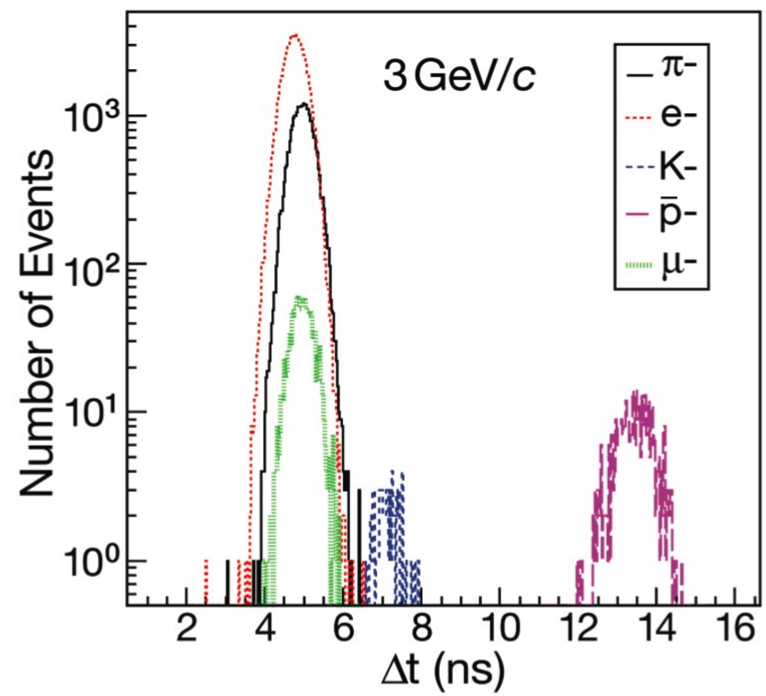


- Particle ID in the Very Low Energy Mode:
  - Muons: Muon Counters
  - Electrons: CK2 and CK3
  - Protons: CK3 and Time-of-flight counters (TOF)
  - Kaons: TOF and CK3
  - Pions: All the remaining particles.



-- CK3 pressure set depending on the desired discrimination
between electrons, pions, and kaons.

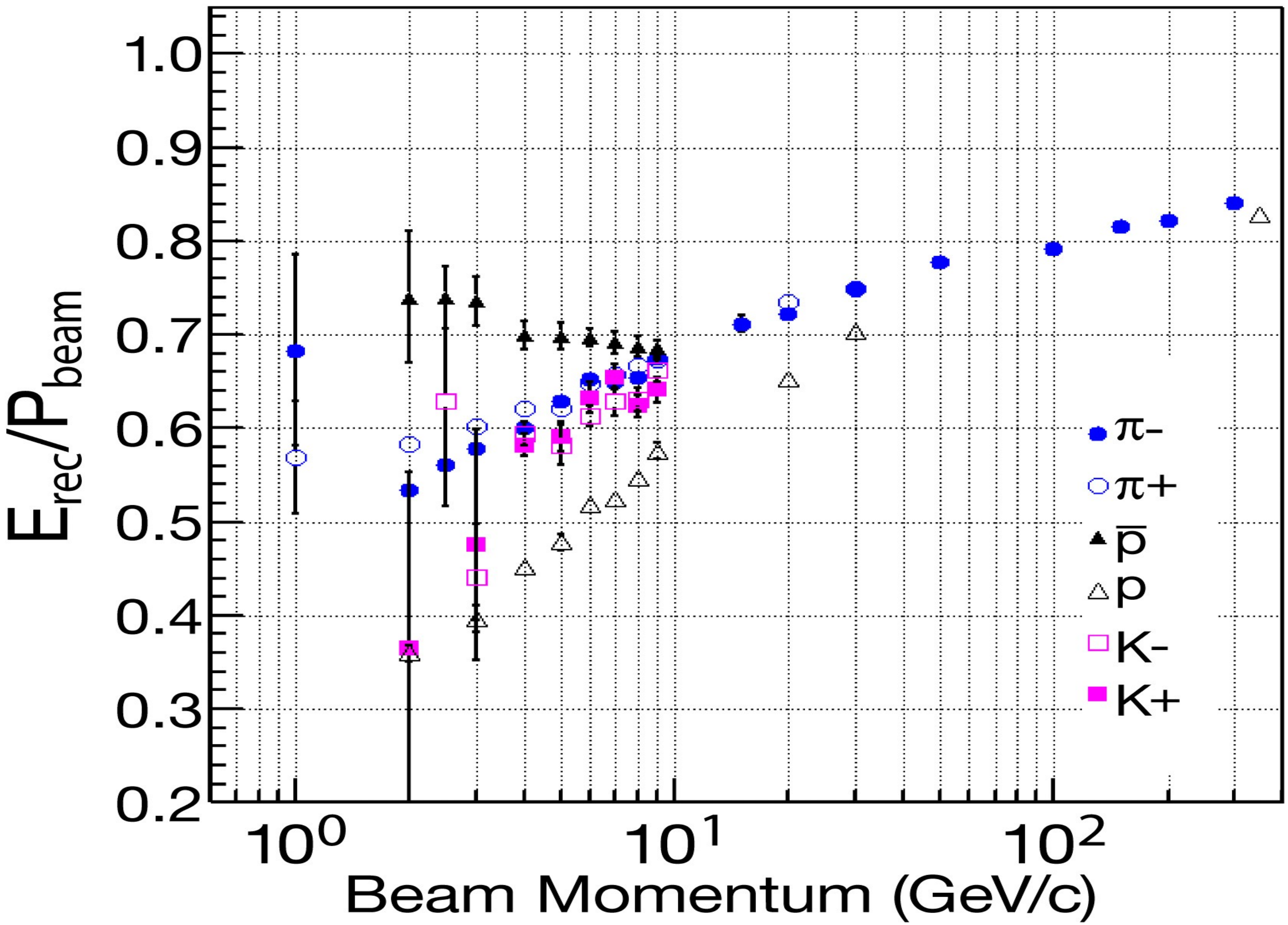
-- TOF1 & TOF2 separation ~55 m. Δt ~ 300 ps.
Protons and pions(& kaons) are well separated up to 7 GeV/c w/ TOF system alone.



Beam Composition

- High energy mode
  - no anti-proton contamination in negative beams.
  - Beam almost all protons at 350 GeV/c in positive beams.
- The beam content depends strongly on the momentum.
  - At higher momenta the beam is largely pions.
  - At lower momenta electrons dominate.

Combined Calorimeter (EB+HB+HO) Response



HB: 3x3 towers
EB: 7x7 crystals
HO: 3x2 towers

Energy Scale:
EB: 50 GeV electron
HB: 50 GeV electron

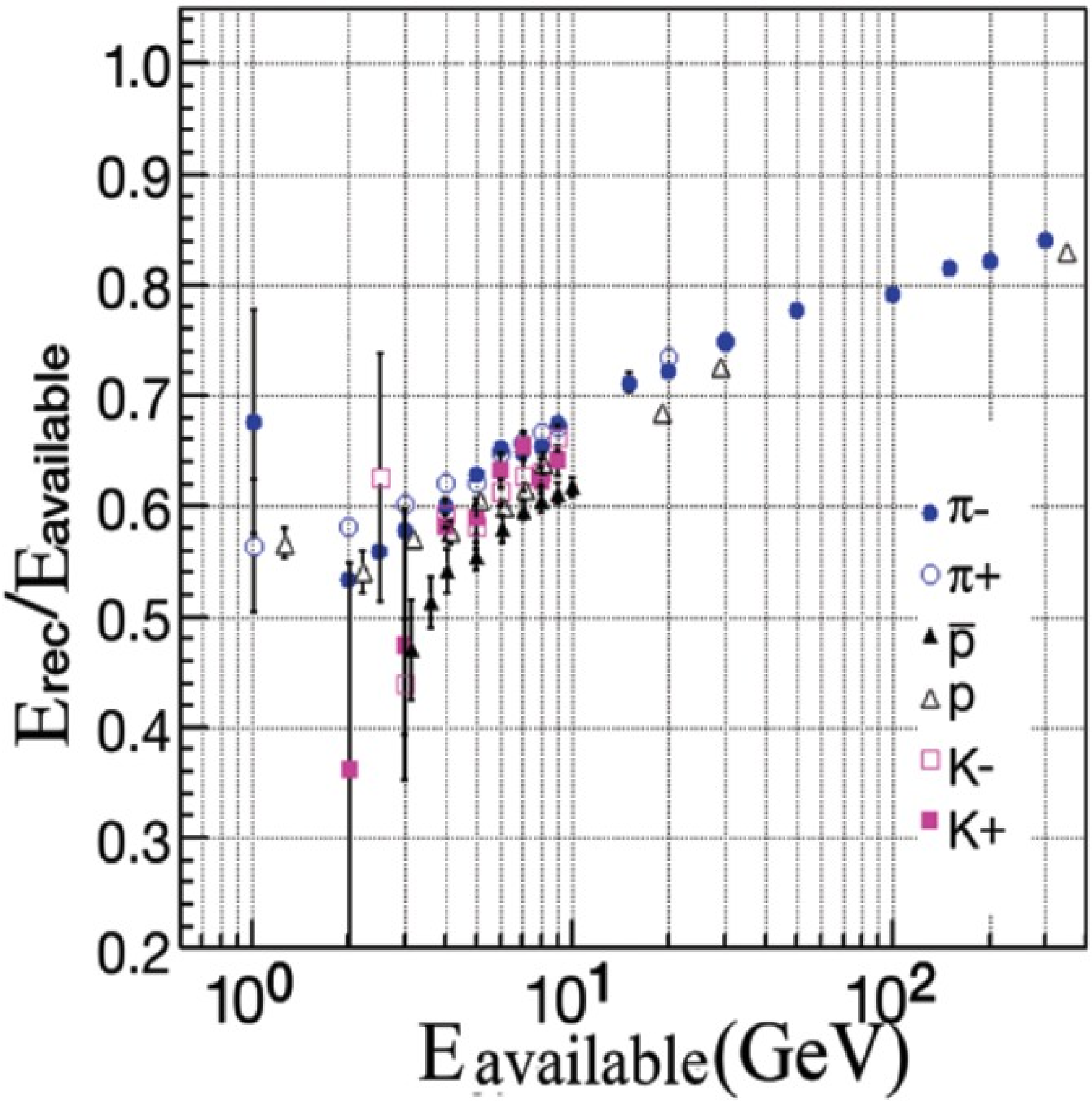
At 5 GeV:
pion resp. ~62 %
proton resp. ~47%
antiproton resp. ~70%

Available Energy

$E_{available}$(pions,kaons) ~ KE + m

$E_{available}$(P) ~ KE

$E_{available}(\overline{P})$ ~ KE + $2m_p$



π+/π- Response Ratio

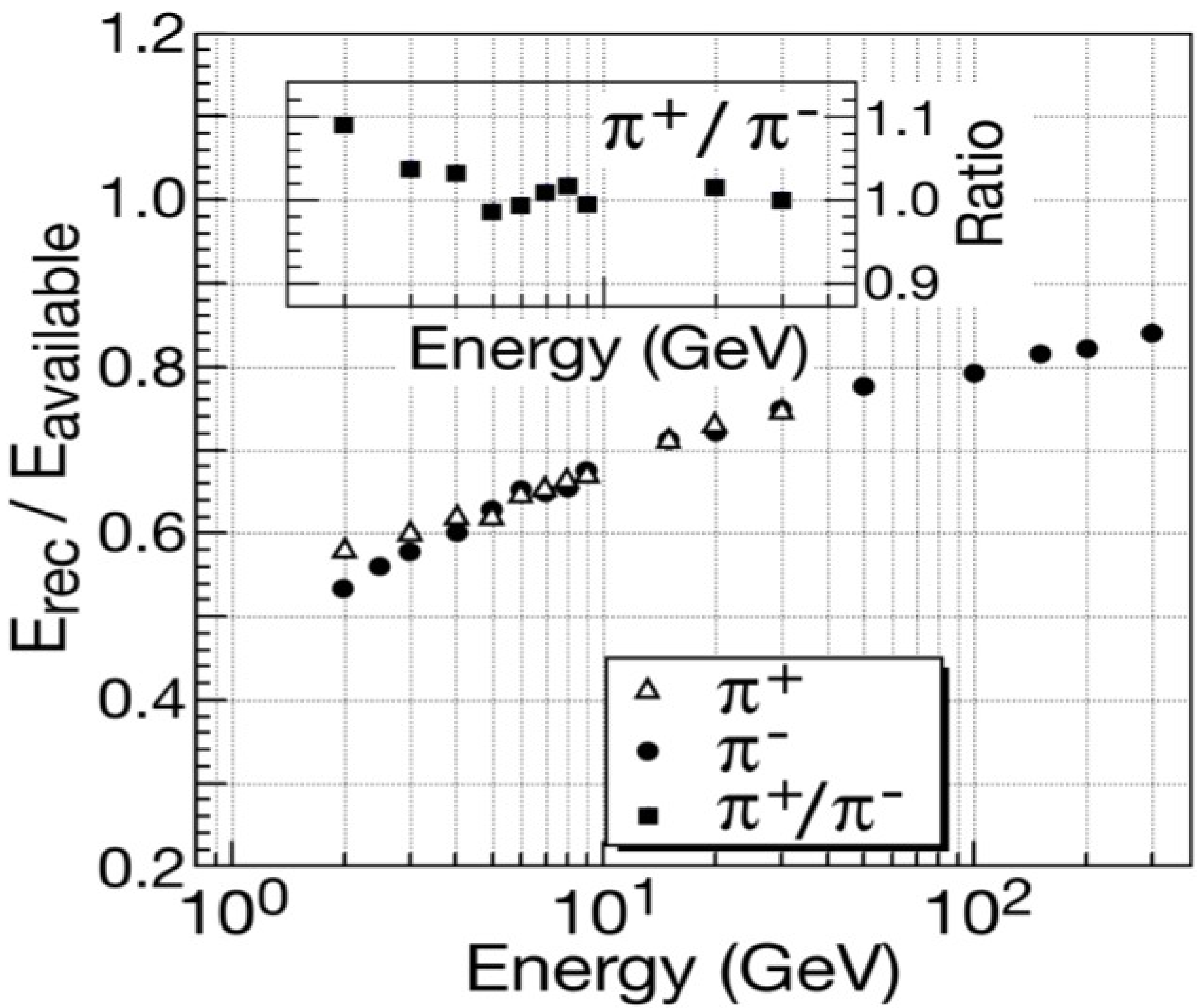
- Response to π^+ > response to π^- increasing with decreasing energy → at 2 GeV π^+ is 10% greater than π^-

Charge exchange reactions:

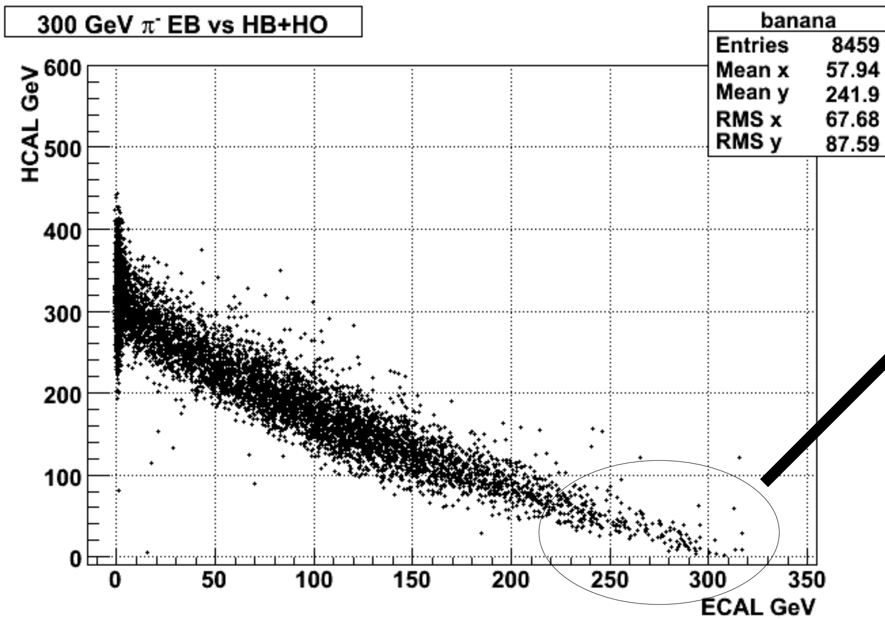
$\pi^+ + n \rightarrow \pi^0 + p$ (1)

$\pi^- + p \rightarrow \pi^0 + n$ (2)

The heavy nuclei in the calorimeter material has 50% more neutrons than protons -- the effect of reaction 1 is larger than 2.



π⁻/p Response Ratio



Charge exchange reaction:

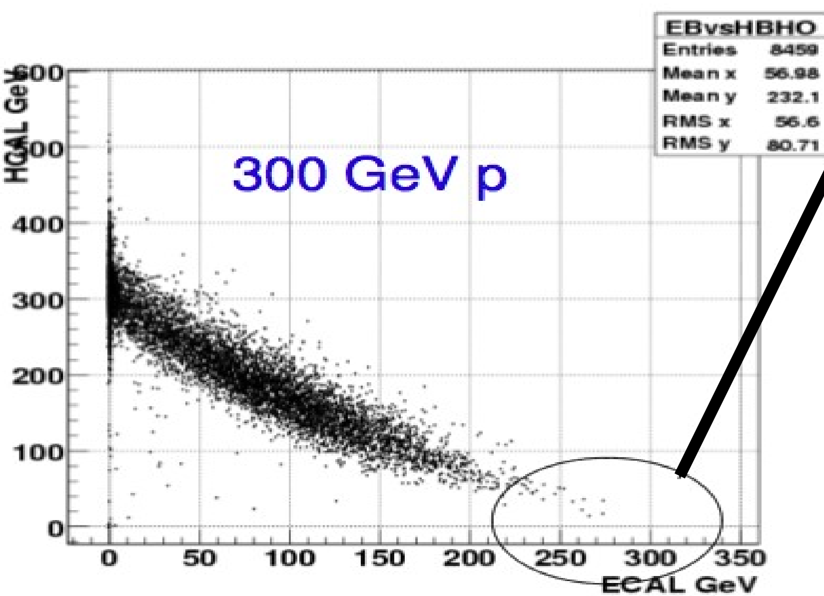
$\pi^-(\bar{u}d) + p(uud) \rightarrow \pi^0(u\bar{u}) + n(udd)$.

But baryon number conservation prevents π^0 creation when the showers are initiated by protons.

$p(uud)+n(udd) \rightarrow p(uud)+n(udd)$

$p(uud)+p(uud) \rightarrow p(uud)+n(uud)$

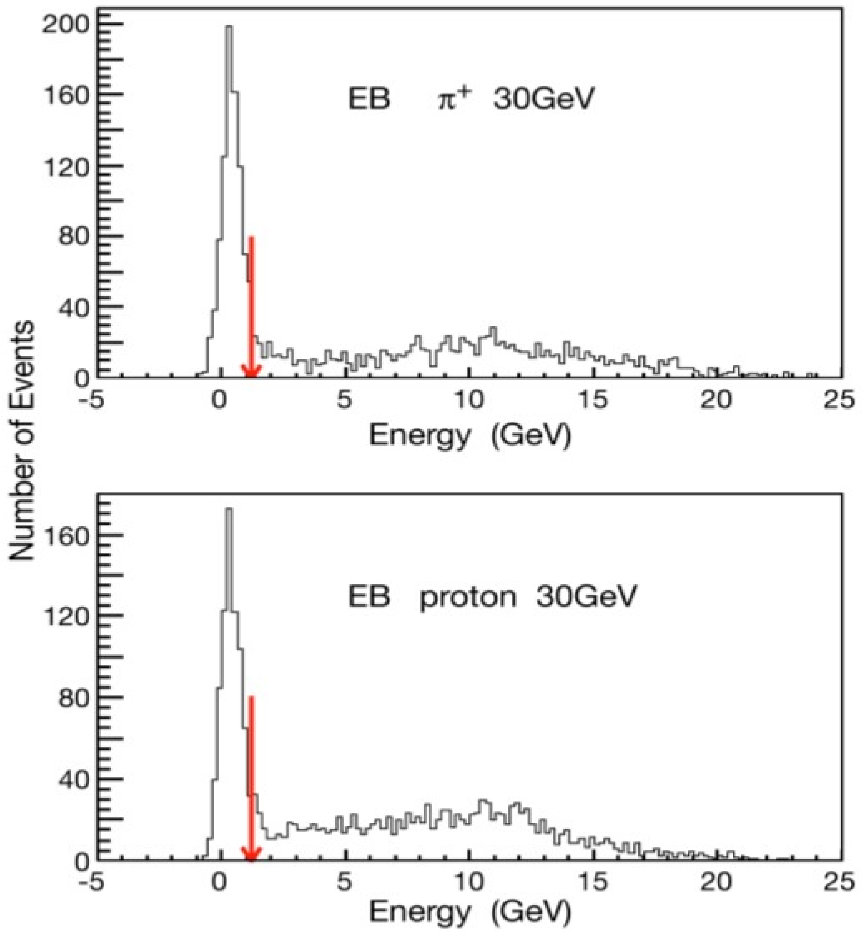
---> production of π^0 is not favored.



- Response to protons is systematically are smaller than that of π⁻

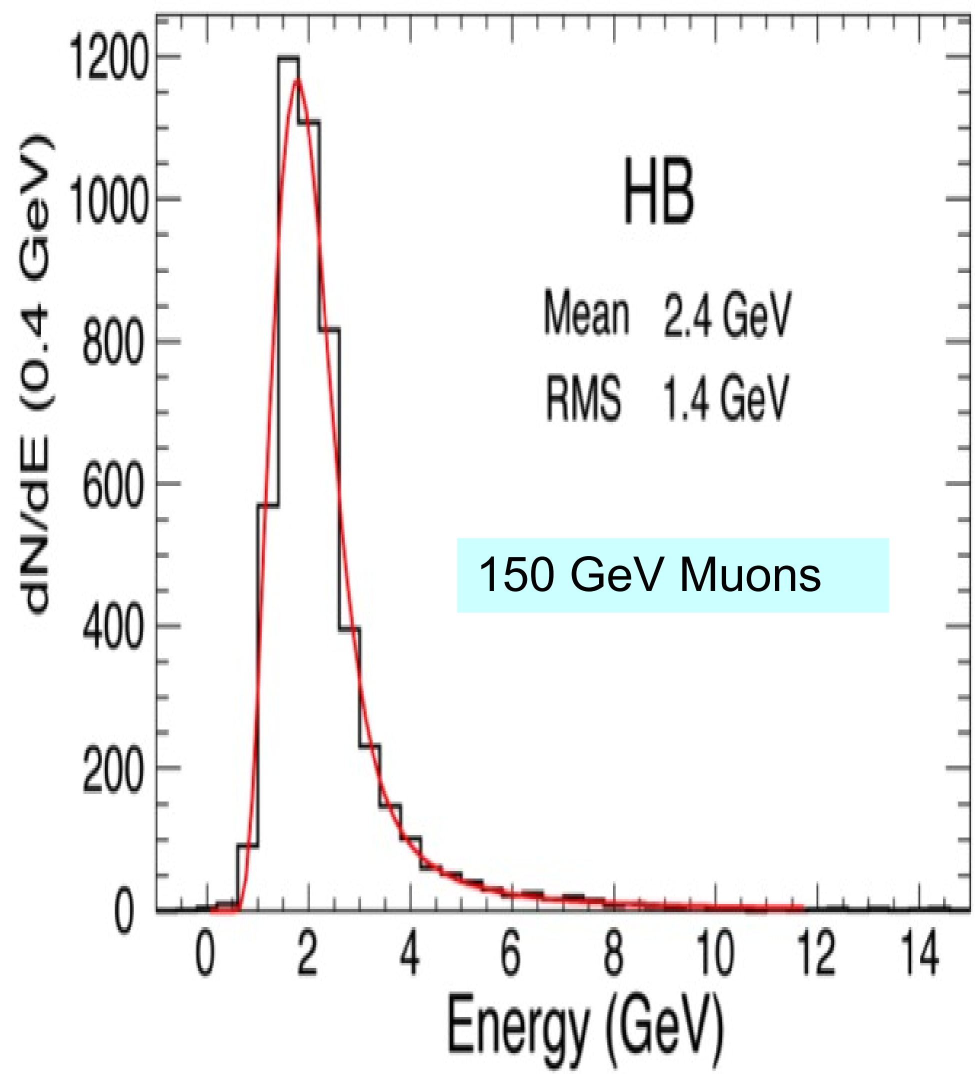
π/p Response Ratio

- Larger fraction of baryons start showering in EB since the total cross section for p > π^-.
- fraction of particles passing through EB without interacting
  - pions: 41%
    - produce more π^0. Even though fewer π^- interact, those that interact have larger signal
  - protons: 35%
- The effective thickness of EB
  - pions: $0.89\lambda_I$
  - protons: $1.05\lambda_I$



μ Response

- Noise in a single tower of HB ~200 MeV
  - Very good isolated muon identification.
  - HB trigger electronics is designed to generate an isolated muon trigger.

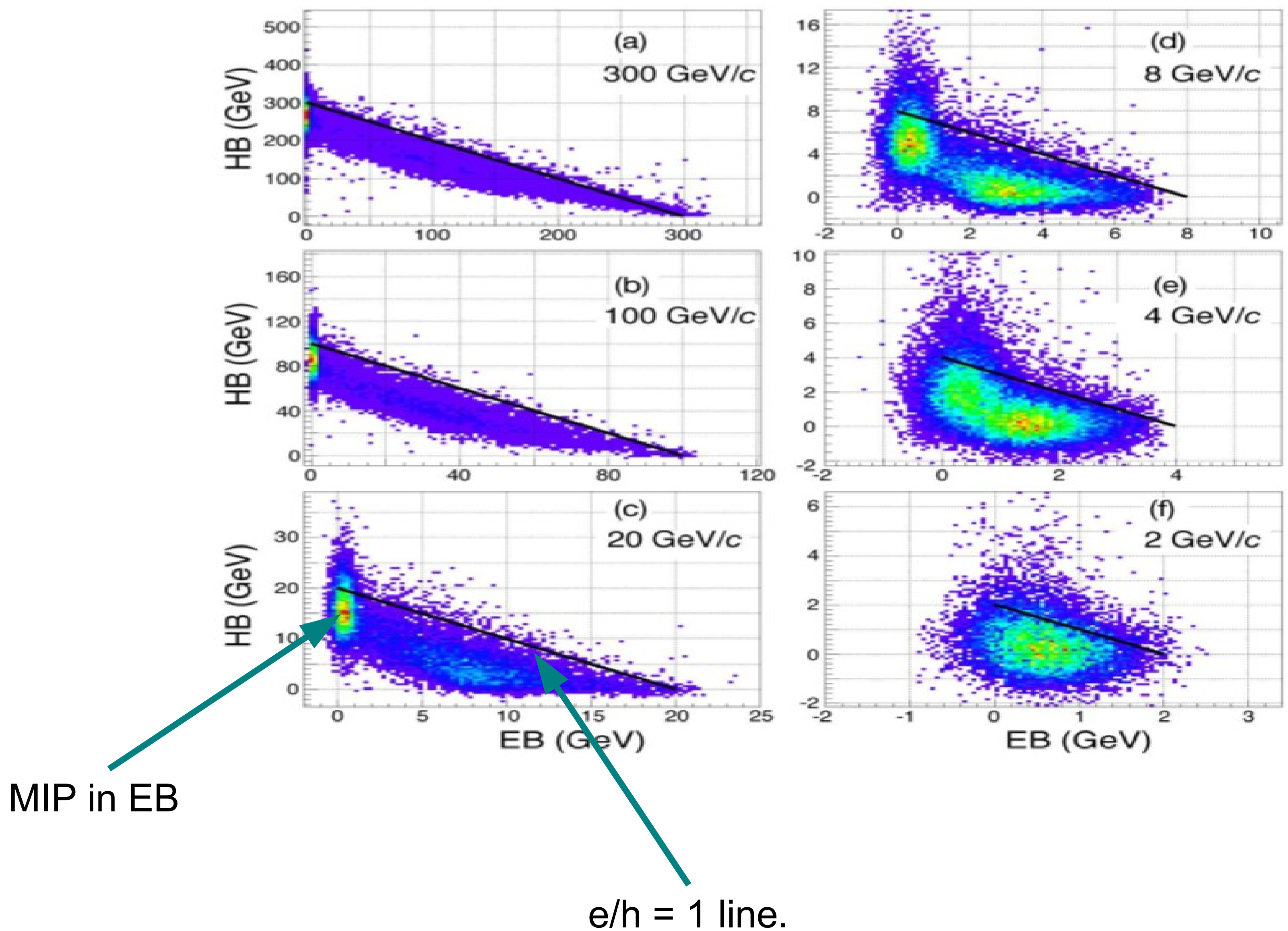


Optimization of Energy Reconstruction

- The response for charged hadrons is not a linear function of energy for non-compensating calorimeters, e/h≠1.
- Moreover, EB and HB have very different values of e/h.
- Therefore, corrections are needed to obtain the correct mean particle energy.

reminder: e/h is the conversion efficiency of em and had energy to an observable signal.

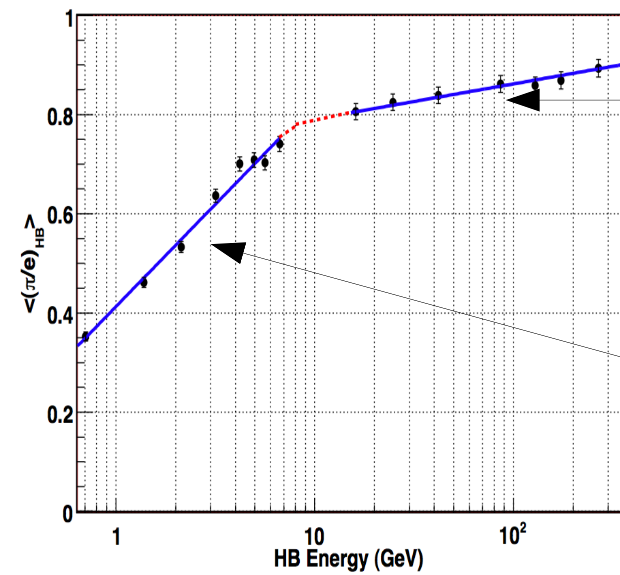
“Bananas” for π Beams



Response Optimization

- Apply thresholds:
  - 7x7 EB crystals < 0.8 GeV
  - 3x3 HB towers < 1.0 GeV
  - 3x2 HO towers < 2.0 GeV
- $\langle\pi/e\rangle$ for HB as a function of $\langle E_{HB}\rangle$ using MIP in EB events.
- Correct HB energy using π/e function
- Determine $\langle\pi/e\rangle$ for EB as a function of $\langle E_{EB}\rangle$ using the corrected HB energies and the beam energy constraint.
- Correct EB energy using π/e function
- Correct the remaining non-linearity as a function of EB energy fraction.

HB Response to π's

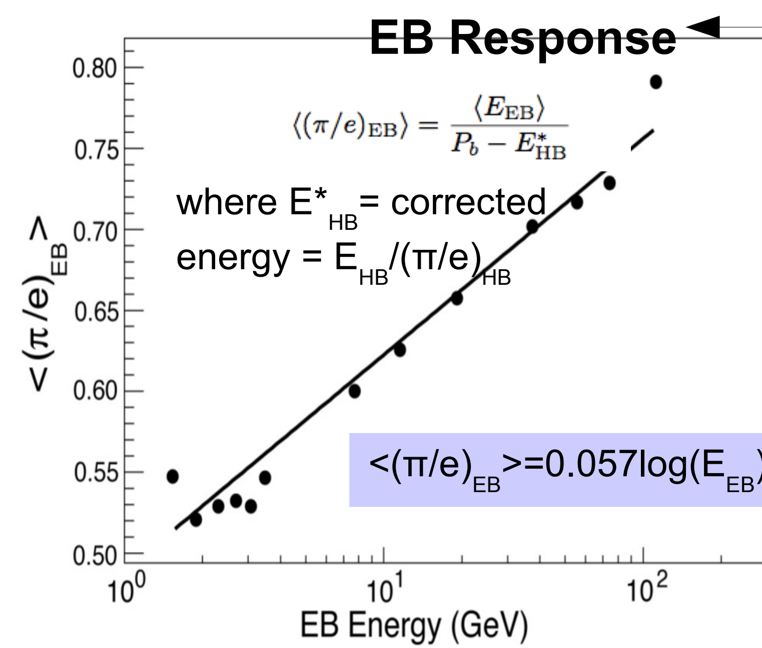


E(HB) > 8 GeV:

$\pi/e=[1+(e/h-1)f_0]/(e/h)$

$f_0=0.11\log E_{HB}$ (Wigmans) ---> e/h=1.4

E(HB) < 8 GeV: $0.18\log(E_{HB})+0.14$



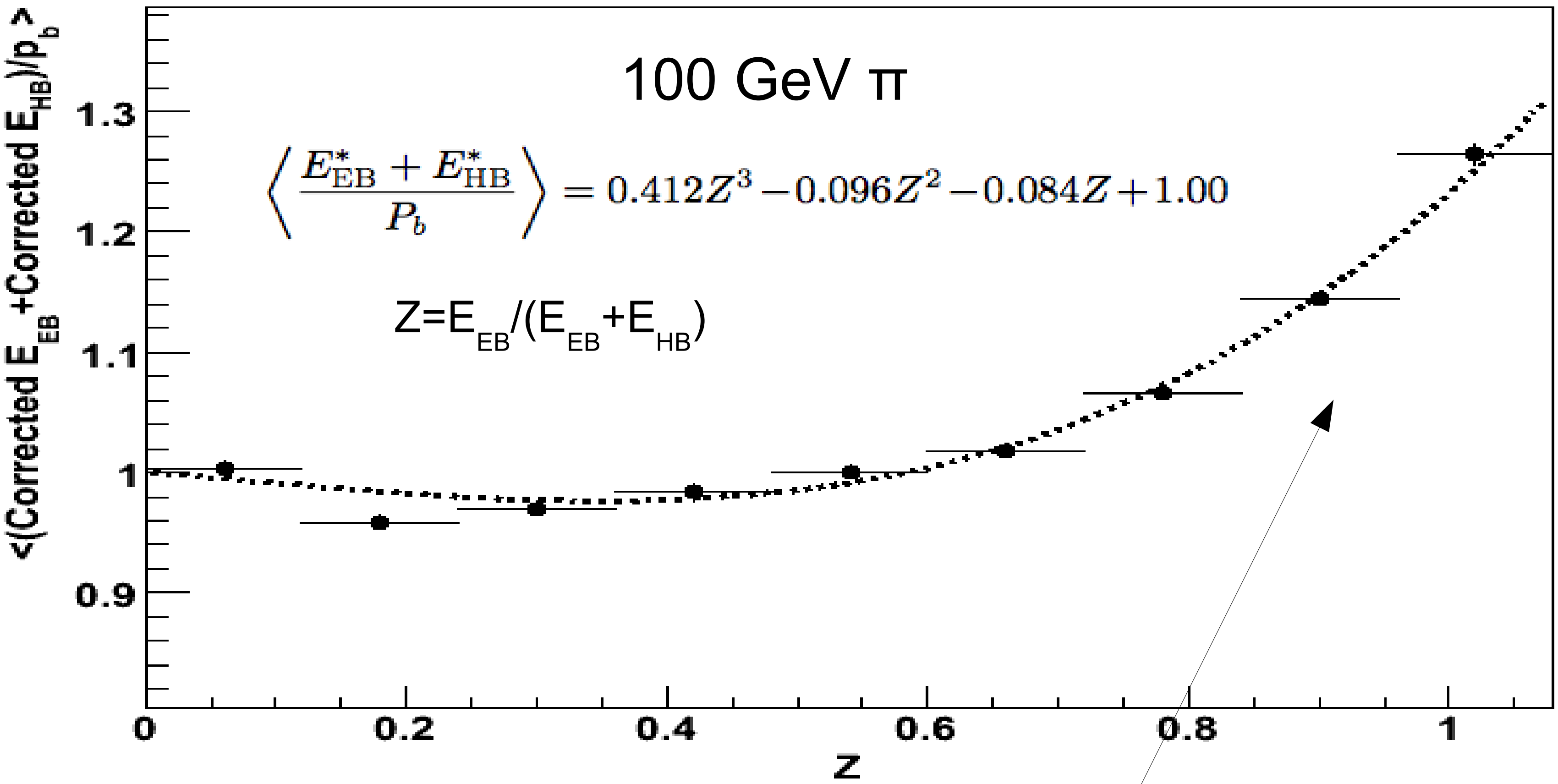
$$\langle(\pi/e)_{EB}\rangle = \frac{\langle E_{EB}\rangle}{P_b - E^*_{HB}}$$

where E^*_{HB} = corrected energy = $E_{HB}/(\pi/e)_{HB}$

$\langle(\pi/e)_{EB}\rangle=0.057\log(E_{EB})+0.490$

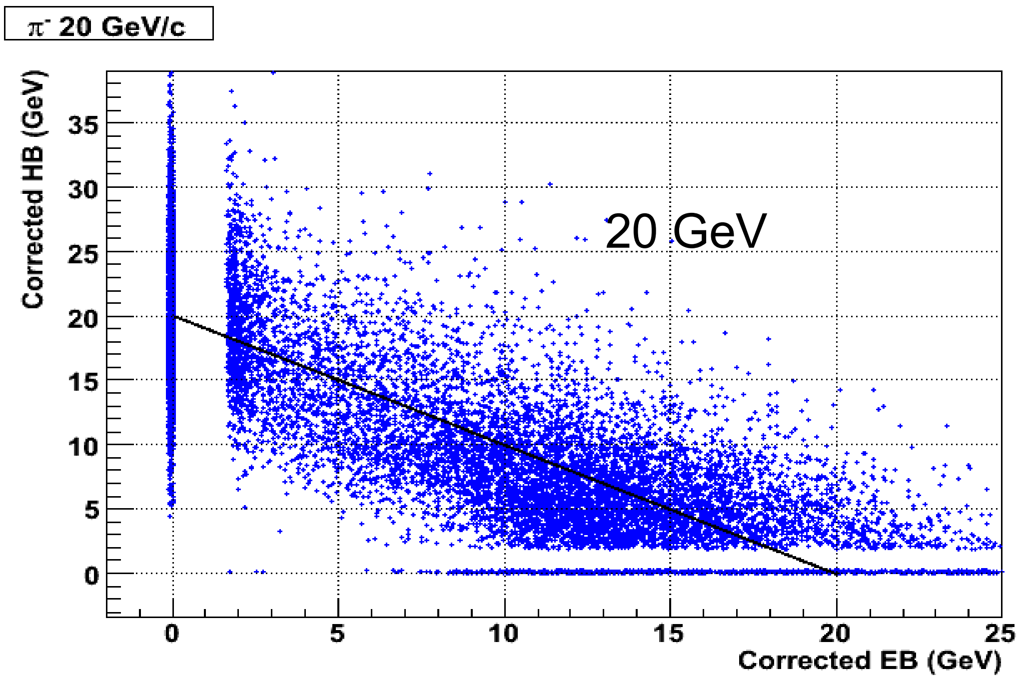
w/ events that have significant energy *both* in EB & HB.

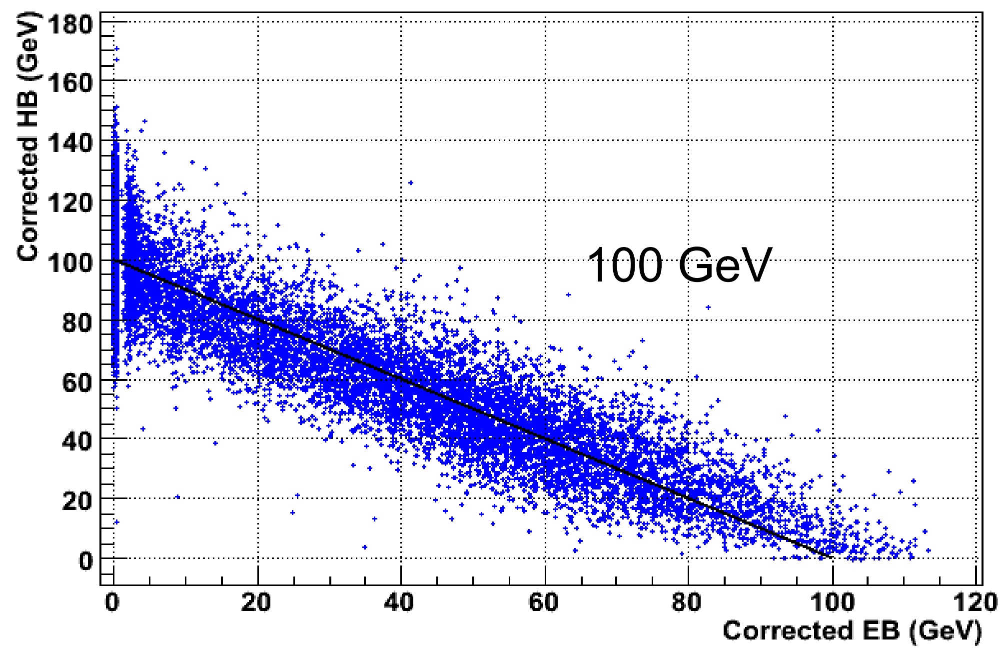
Total Response vs EB Fraction



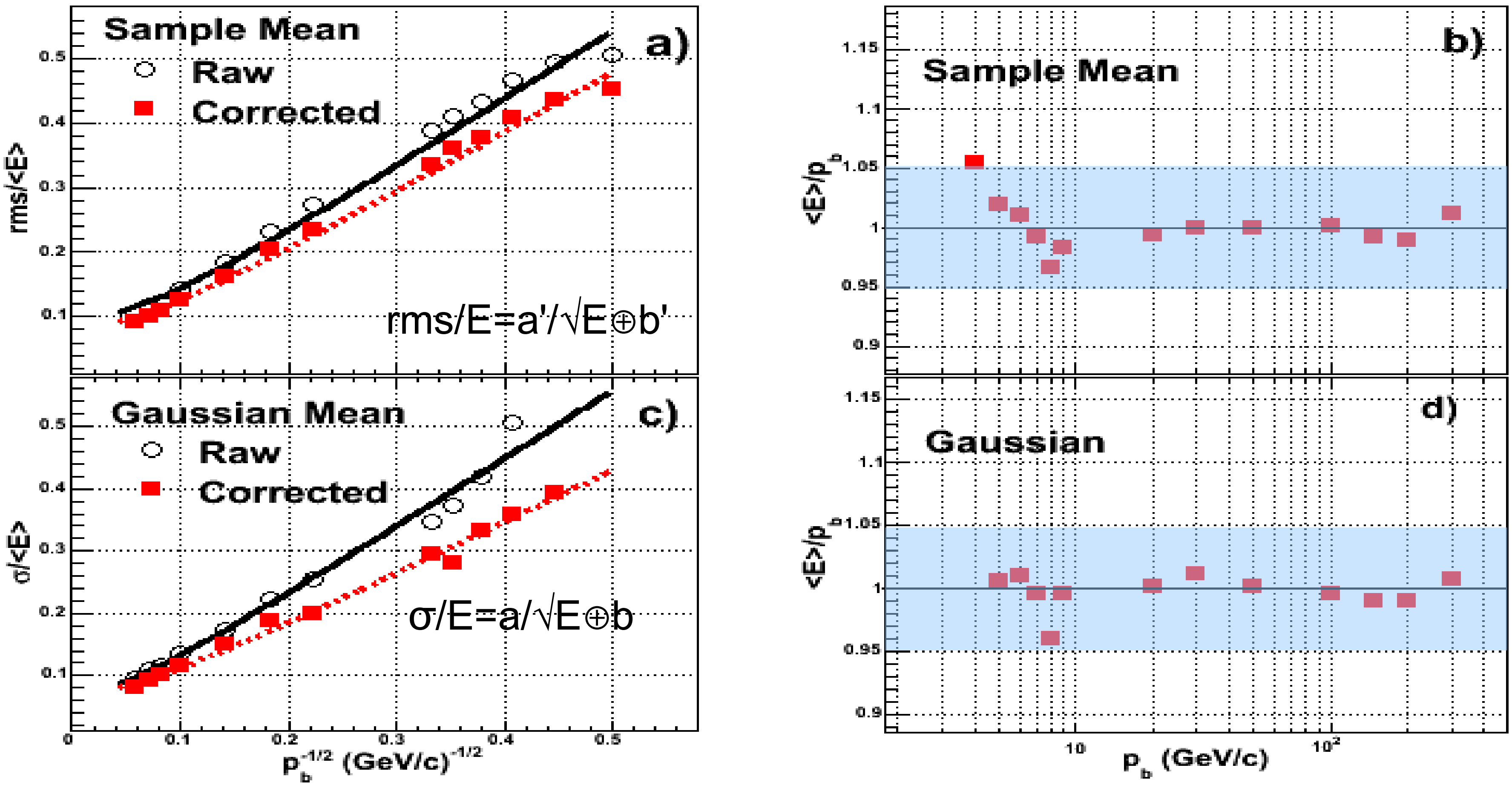
hadronic shower in EB fluctuates largely to neutrals. So we do the final step of correction as a function of Z.

“Bananas” of the Corrected Barrel System





Corrected Resolution and Response



- Linearity restored within 5% for p≥5 GeV and 2-3% for p≥9 GeV.

$\sigma/E = a/\sqrt{E} \oplus b = 84\%/\sqrt{E} \oplus 7\%$ in P = 5-300 GeV/c

Summary & Conclusions 1

- The CMS barrel calorimeter has been exposed to particle beams with momenta 2-350 GeV/c.
- The particle identification detectors separated electrons, muons, pions, kaons, and protons over a substantial energy range.
- HO was used to reduce the effects of leakage at high energies.

Summary & Conclusions 2

- The response to different hadrons is studied.
  - Simple interesting regularities are observed.
    - π^-/π^+ response, π^-/p response, $\pi/\bar{p}$ response
- Linearity for negative pions was optimized
  - TB06 explored the low energy response where previously used parametrizations no longer fit the data well. Important to understand and apply corrections to data.
  - The corrected data: Linearity restored within 5% for $p \geq 5$ GeV and 2-3% for $p \geq 9$ GeV.
  - The stochastic and constant term for energy resolution of the combined system are 84% and 7% respectively.

Summary & Conclusions 3

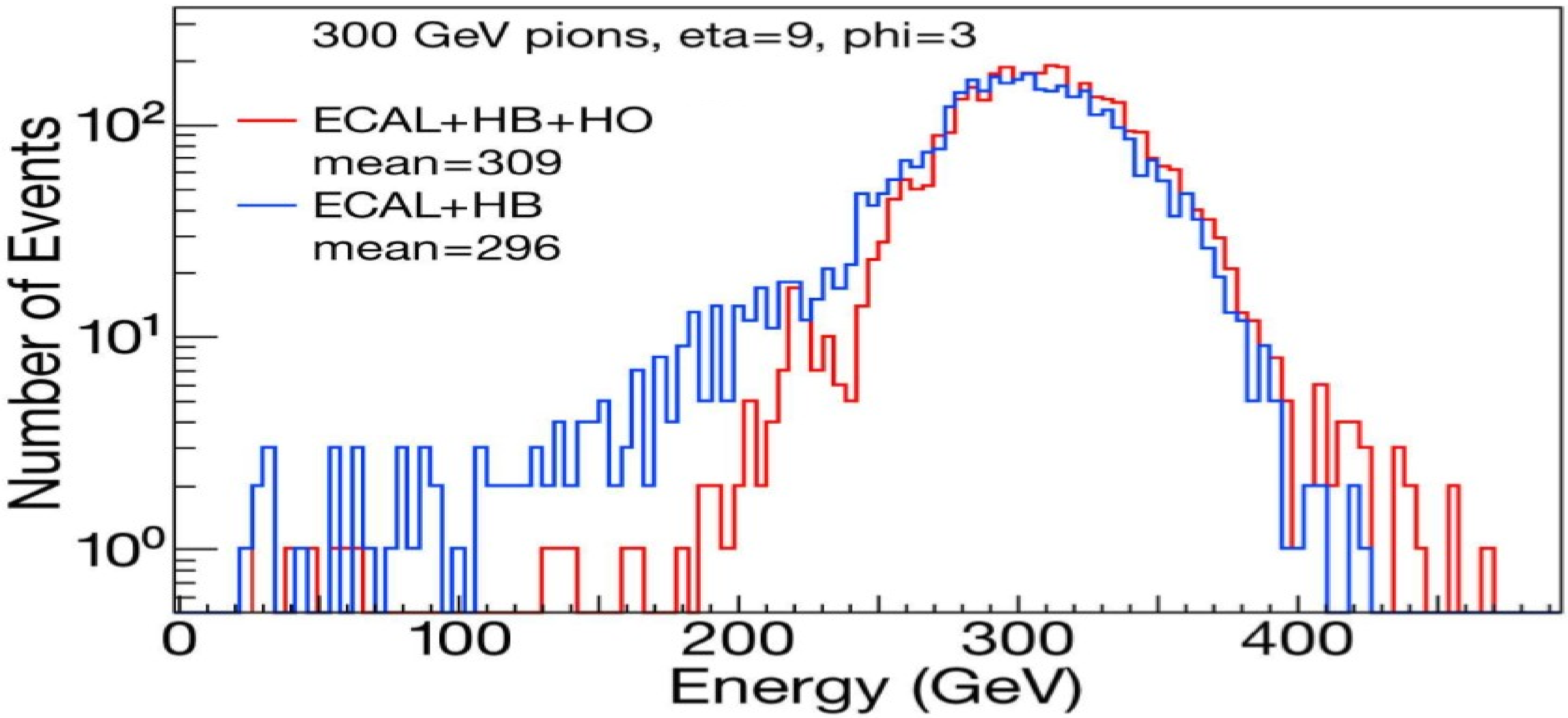
- Correction method works for single isolated particles and the test beam environment.
- Direct application of the method to jets is not possible since jets are formed both from isolated as well as non-isolated objects.
  - If the photons from π^0s in a jet can be separated from the charged hadrons, then the corrections could be applied on the charged hadrons and then the jet may be better reconstructed.

References

- **CMS Physical Technical Design Report, Volume I, Detector Performance and Software, CERN/LHCC 2006-001.**
- **'Calibration of the CMS Calorimeters', D. Green, FERMILAB-FN-0704 (2001)**
- R. Wigmans, Nucl. Inst. and Meth. A408 (1998) 380

BACKUP

Hadron Outer Calorimeter for High Energy Particles



- Note the reduced low energy leakage tail.

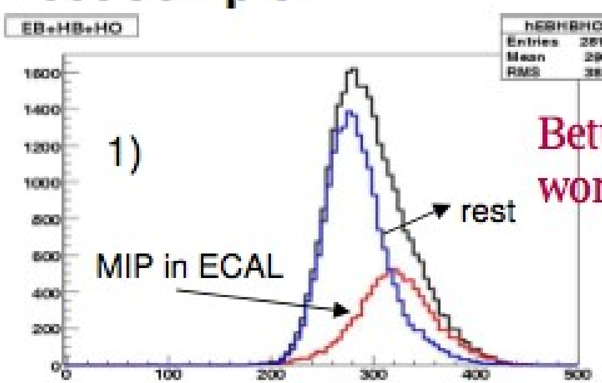
Energy Scale Calibration for HCAL (Electrons ; Pions)

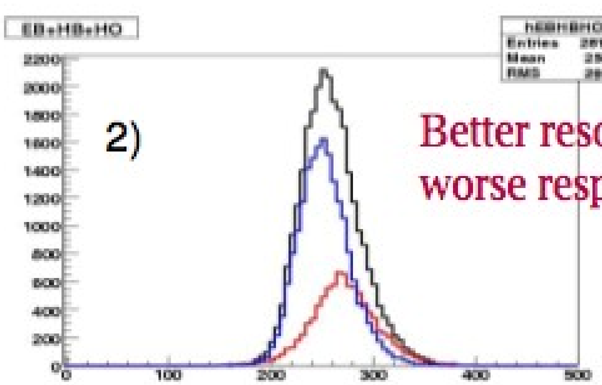
$E = a \times EC + b \times HC$

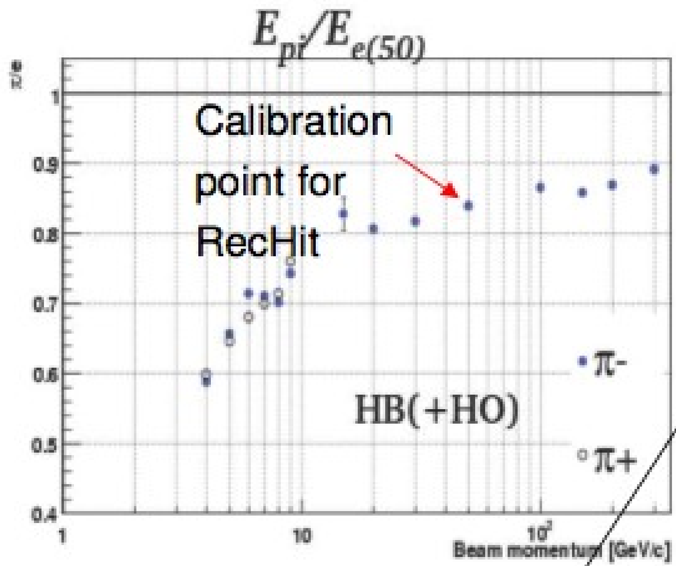
Two calibration scheme

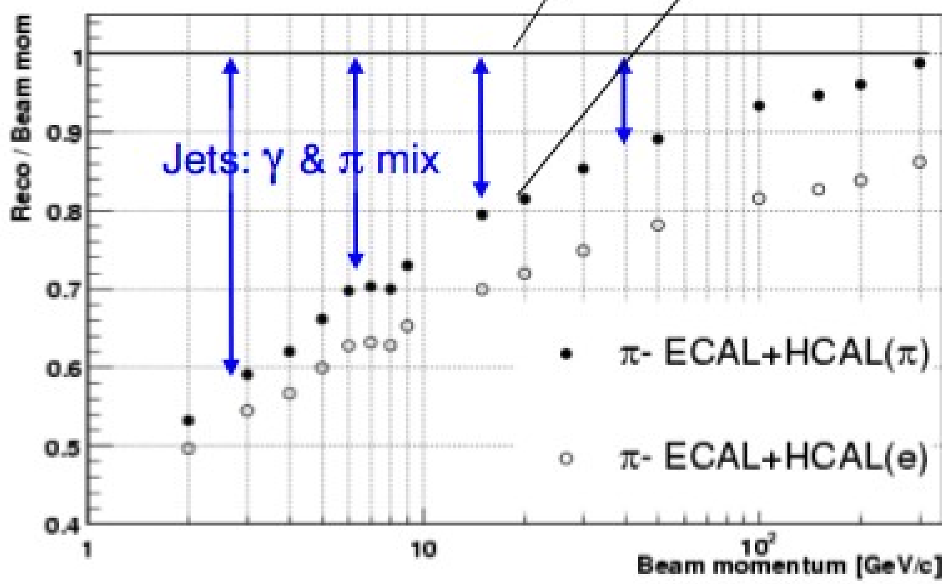
- EC: calibrated with electrons
- 1) HC: calibrated with pion (50GeV)
- 2) HC: calibrated with electrons

300GeV pion









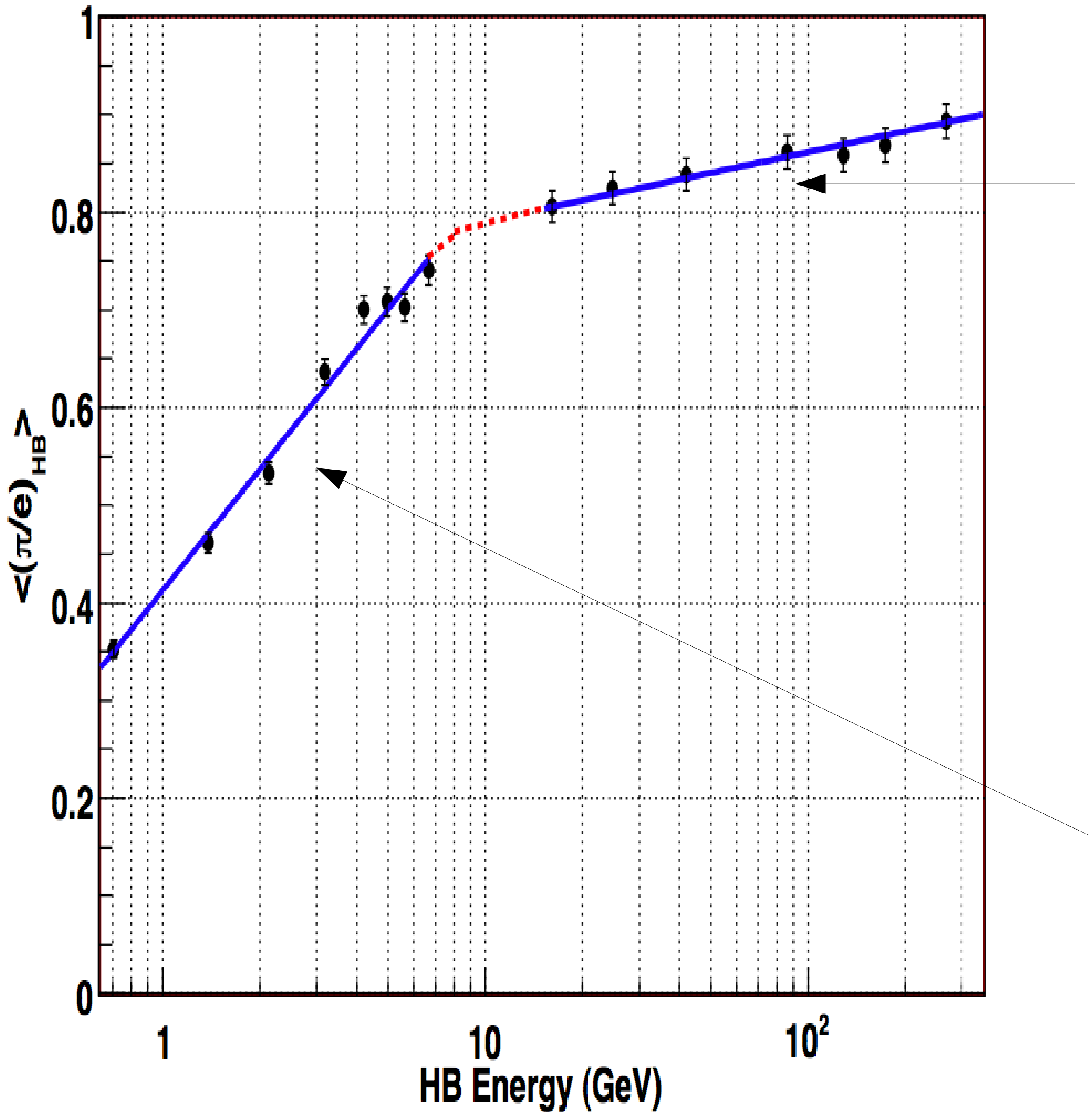
If jet fragments all into π^0's.

If jet fragments all into charged particles.

pi/e=1 ideal for jet reco.

Default for CaloTower

HCAL Response



E(HB) > 8 GeV:

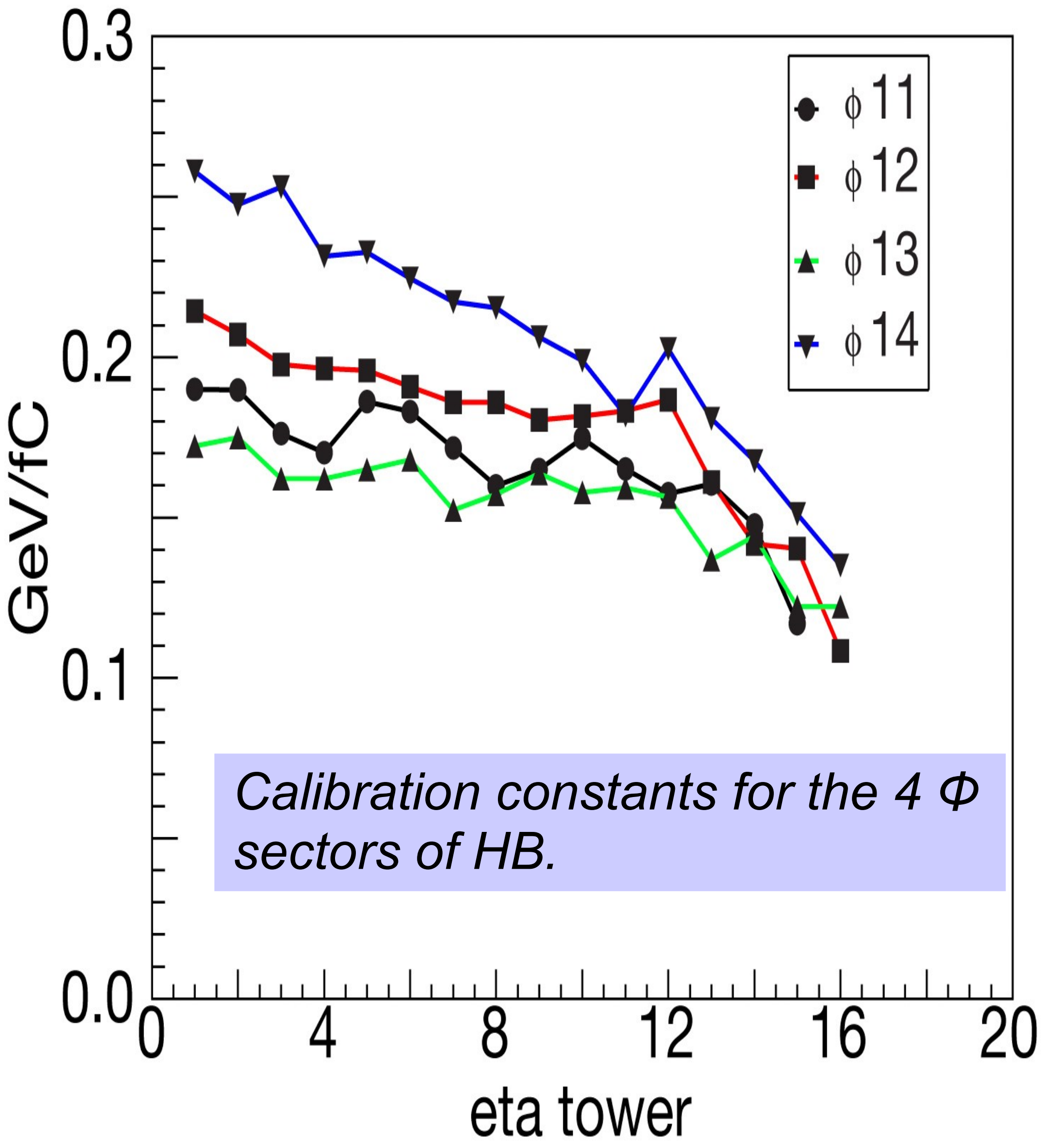
$\pi/e=[1+(e/h-1)f_0]/(e/h)$

$f_0=0.11\log E_{HB}$
(Wigmans)
--->e/h=1.4
Only valid down to 8 GeV!

We use a diferent log function for:
E(HB) < 8 GeV:
$0.18\log(E_{HB})+0.14$

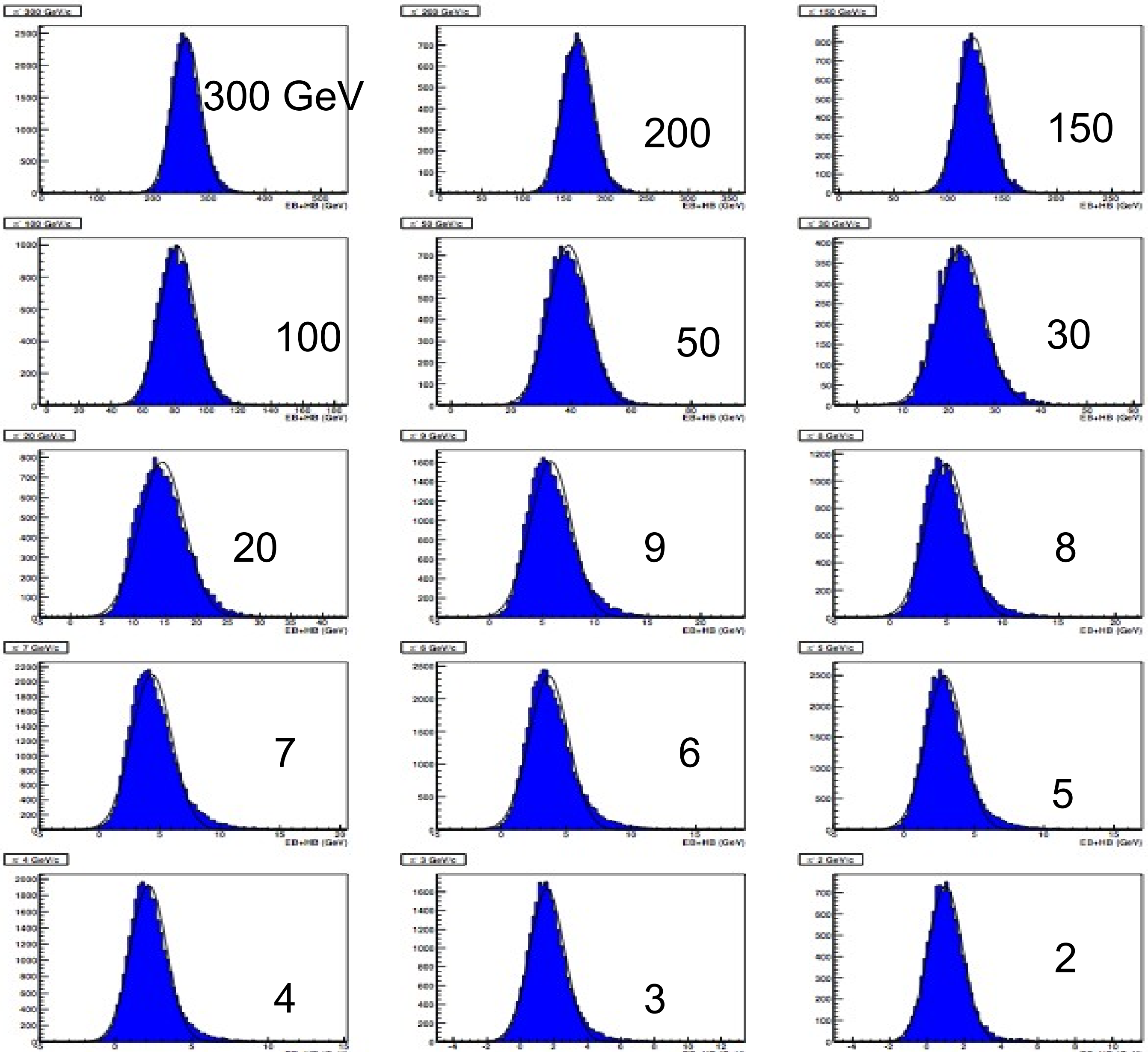
Wire Source Calibration

- The response of each HB scintillator tile of each layer measured: 5-mCi Co^{60} moving wire radioactive source.
- Light attenuation in the optical fibers, loss in fiber connectors, and the HPD gain differences.
- fiber length increases with η
- tower-to-tower calibration precision: 2% --> derived by comparing the consistency of the relative source and beam data.



Calibration constants for the 4 Φ sectors of HB.

Raw EB+HB without Noise Cuts



Without the noise cuts, the distributions are gaussian down to 2 GeV/c.