The ALICE experiment and its Electromagnetic Calorimeter EMCAL

Alessandra Fantoni

INFN, *Laboratori Nazionali Frascati*
ALICE Collaboration

I - The ALICE experiment:

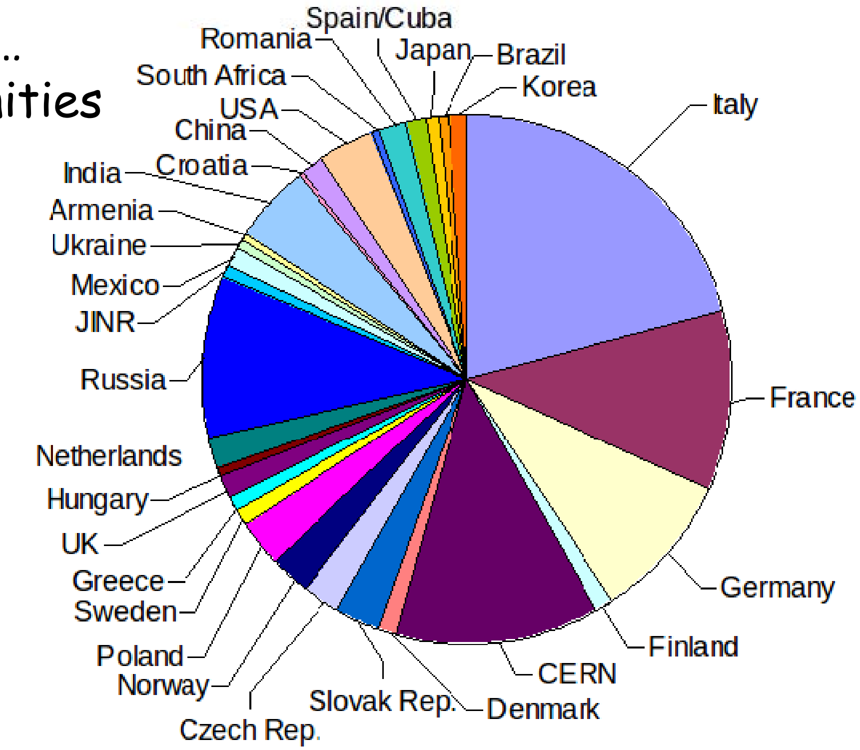
a) Some infos
b) Characteristiques, Constraints and Solutions
c) Obtained results

II - The Electromagnetic Calorimeter EMCAL:

a) Characteristiques
b) How it works
c) The Assembly
d) Results from test beams
e) The EMCAL status
f) The EMCAL upgrade: DCAL
g) Performance plots
h) Physics capabilities

I. The ALICE experiment

~ 1000 Members and growing…
from both NP and HEP communities
~30 Countries
~100 Institutes
~ 150 MCHF capital cost
(+ 'free' magnet)

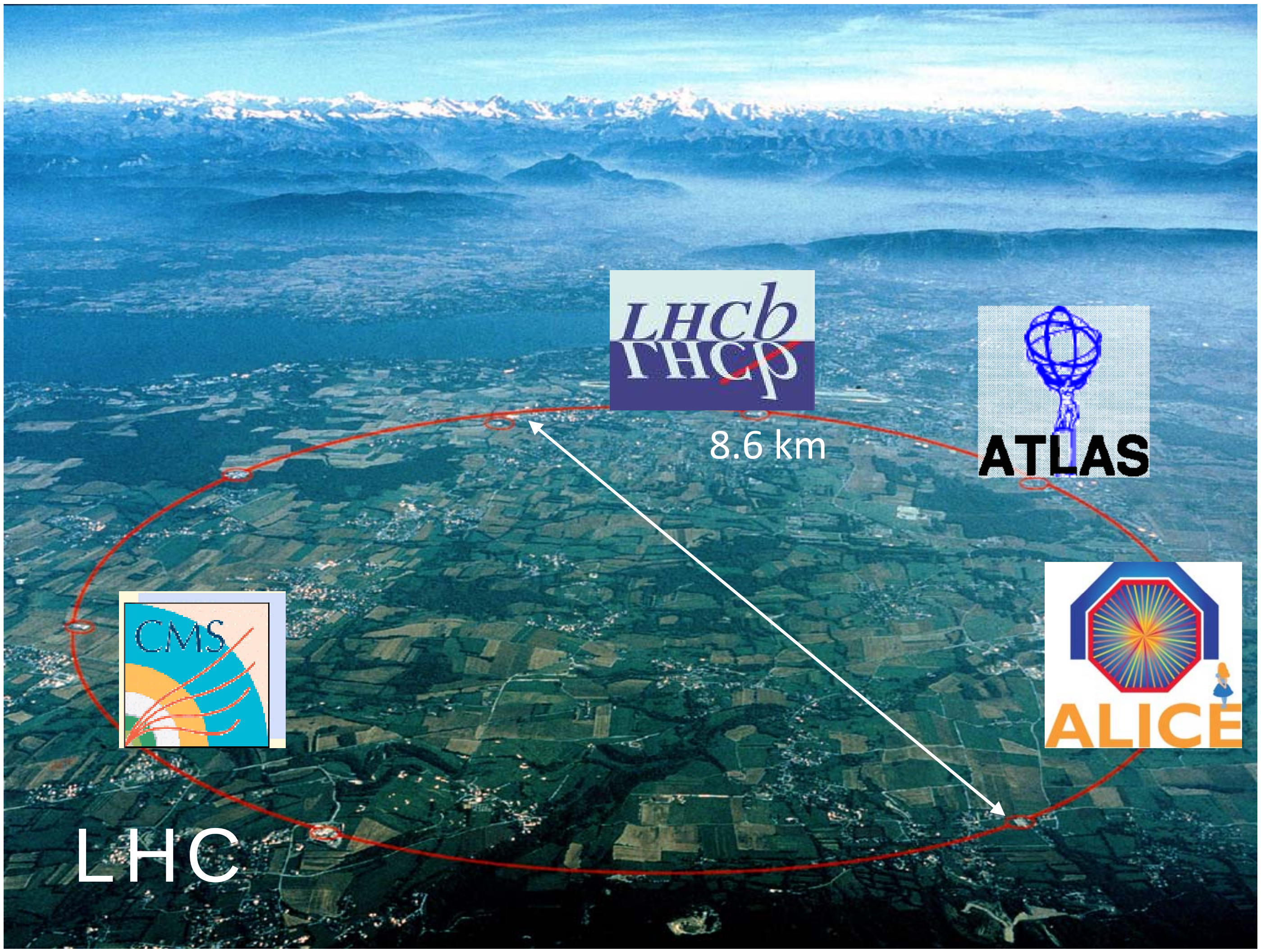


History: two decades …

1990-1996: Design
1992-2002: R&D
2000-2010: Construction
2002-2007: Installation
2008 -> : Commissioning

4 TP addenda along the way:
1996 : muon spectrometer
1999 : TRD
2006 : EMCAL
2010 : DCAL

I – a) Some infos



- 4 large experiments

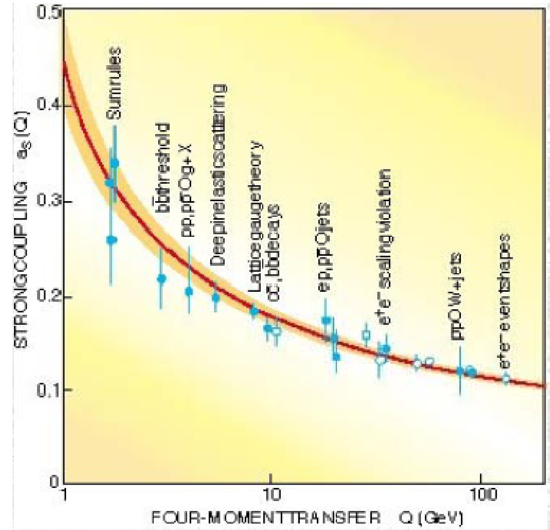
- ALICE

✓mainly dedicated to heavy-ion physics
✓p-p run for physics and reference

- Hard & Soft physics
- Excellent PID
-Tracking down to very low momenta

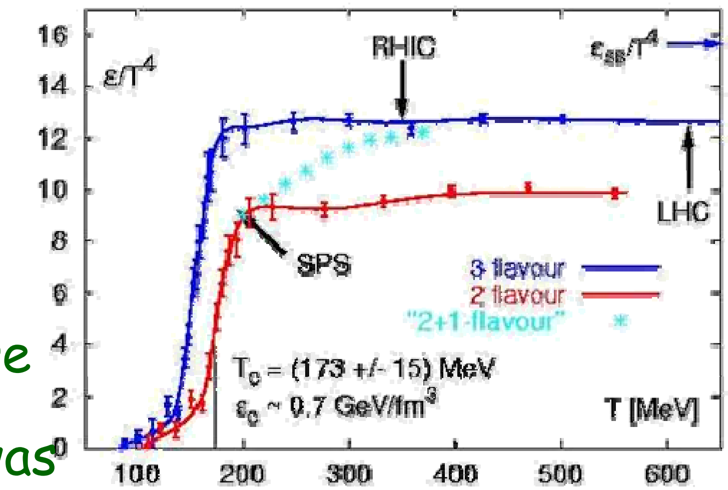
QCD expectations

Protons and neutrons are colorless objects made by confined colored quarks e gluoni: QCD



QCD aymptotic freedom (Nobel 2004 to Gross-Wilczek-Politzer) : at very high momentum transfer, the hadronic matter will melt in a plasma of deconfined and colored quarks and gluons.

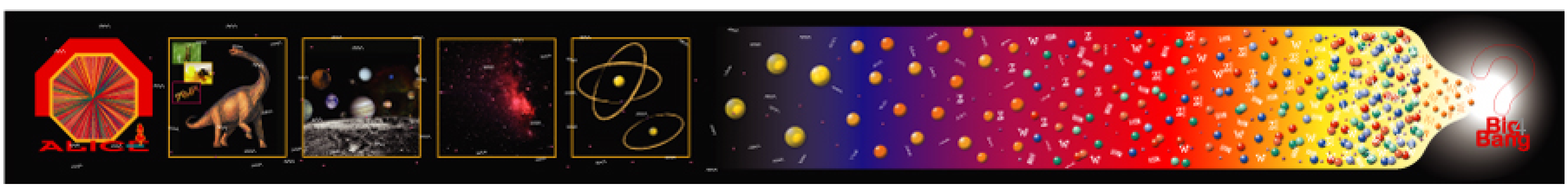
The critical temperature of 170 MeV has been reached by SPS and RHIC but evidence of residual interaction has been shown.



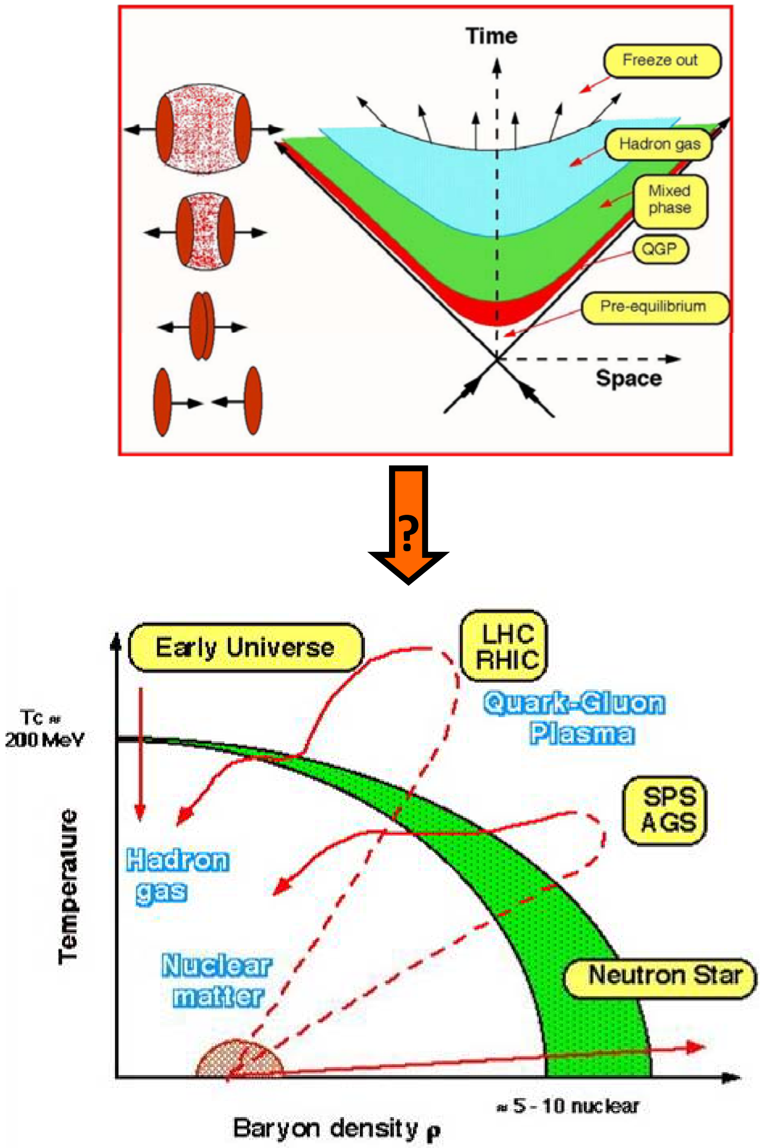
The matter created at RHIC behaves like a liquid and not like a gas!

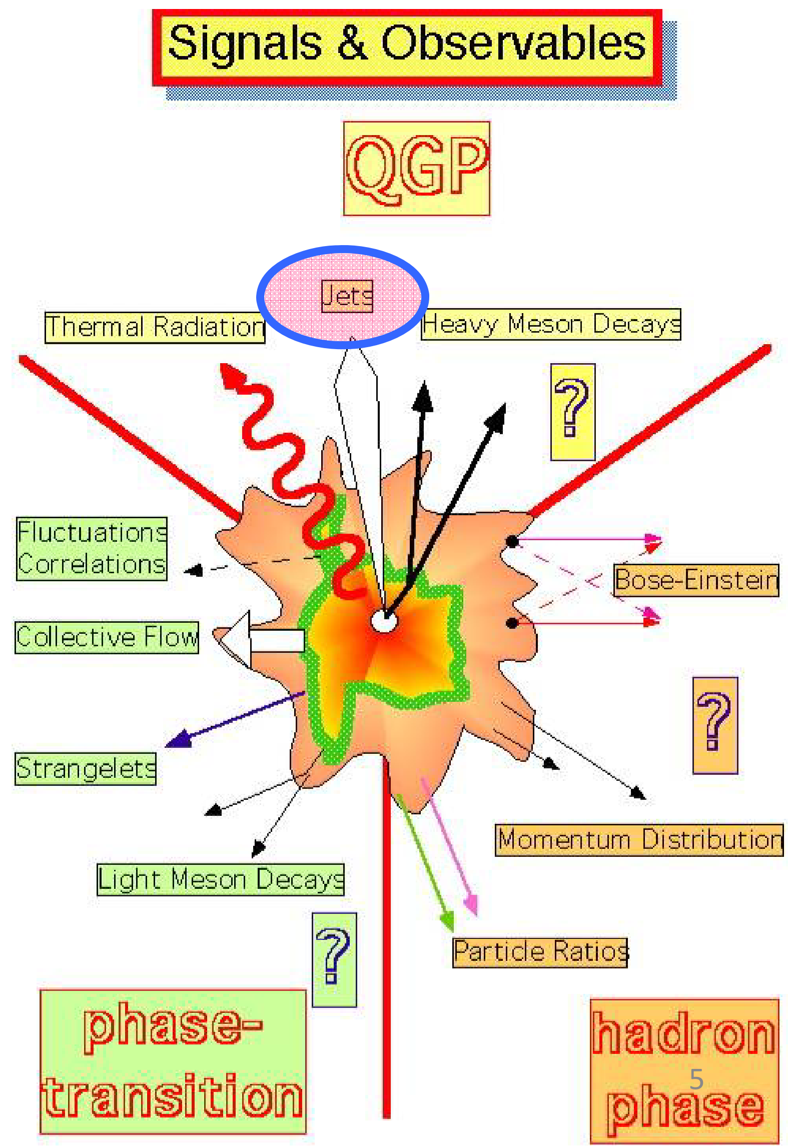
LHC will go well above the critical temperature

A Quark Gluon Plasma can be created, as it was in the early Universe just after the Big Bang



Dynamics and signals
(that will be studied by ALICE)





I – b) Characteristiques, Constrainsts and Solutions

- What makes ALICE different from ATLAS, CMS and LHCb?
  - Experiment designed for Heavy Ion collision
    - only dedicated experiment at LHC, must be comprehensive and be able to cover all relevant observables
    - VERY robust tracking
      - high-granularity detectors with many space points per track, very low material budget and moderate magnetic field
    - PID over a very large p_T range
    - Hadrons, leptons and photons
    - Very low p_T cutoff
    - Excellent vertexing
  - Price to be paid:
    - Slow detectors
    - Limited η and p_T coverage
- Complementary to the other experiments

Experimental Constraints (from the Heavy Ion running)

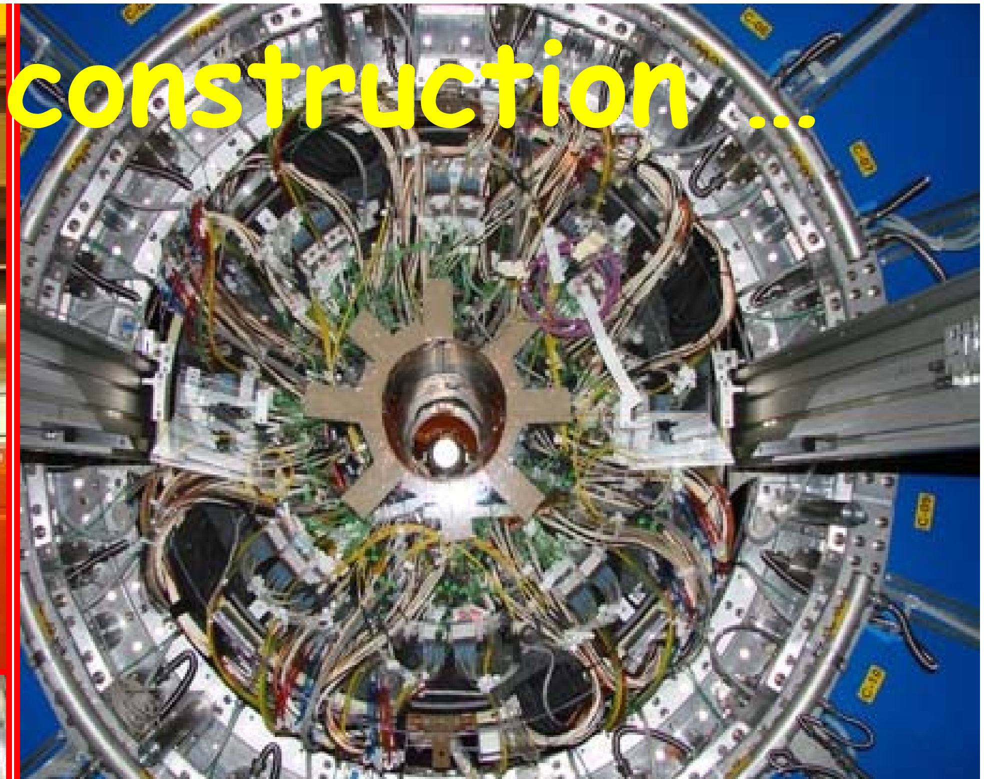
- extreme particle density ($dN_{ch}/d\eta \sim 2000 - 8000$)
  - x 500 compared to pp @ LHC
- large dynamic range in p_T:
  - from very soft (0.1 GeV/*c*) to fairly hard (100 GeV/*c*)
- lepton ID, hadron ID, photon detection
- secondary vertices
- modest Luminosity and interaction rates
  - 10 kHZ (Pb-Pb) to 300 kHZ (pp) (< 1/1000 of pp@10^{34})

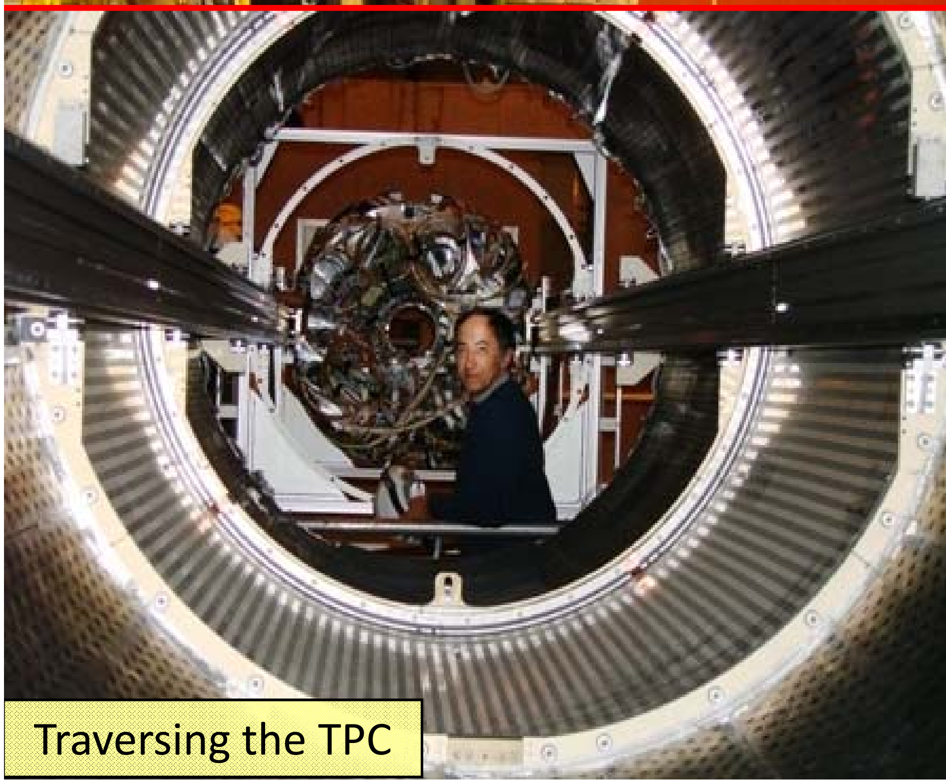
Experimental Solutions

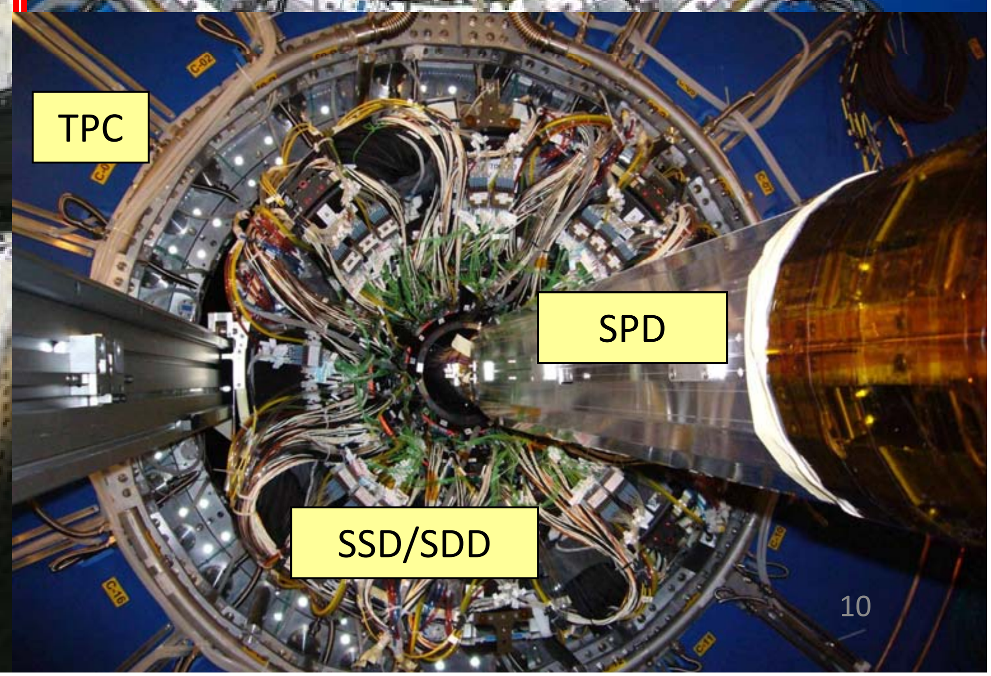
- **$dN_{ch}/d\eta$:** high **granularity**, 3D detectors (**560 million** pixels in the TPC alone, giving 180 space points/track, largest ever: $88m^3$), large **distance** to vertex (use a VERY large magnet)
  - EMCAL high-density crystals of $PbWO_4$ at **4.5 m** (typical is 1-2 m !)
- **p_t coverage**: **thin** det, moderate field (low p_t), large lever arm + resolution (large p_t)
  - ALICE: **< 10%X_0** in r < 2.5 m (typical is 50-100%X_0), **B= 0.5T**, **BL^2** ~ like CMS !
- **PID**: use of essentially all known technologies
  - dE/dx, Cherenkov & transition rad., TOF, calorimeters, muon filter, topological,
- **rate**: allows slow detectors (TPC, SDD), moderate radiation hardness

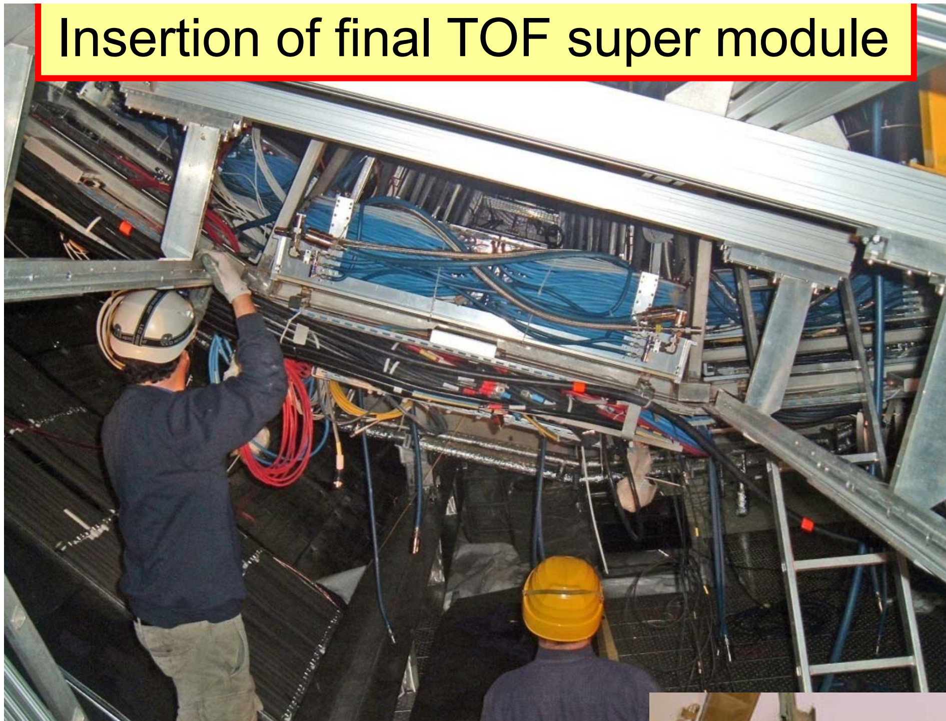

ALICE in 2001

… in construction …







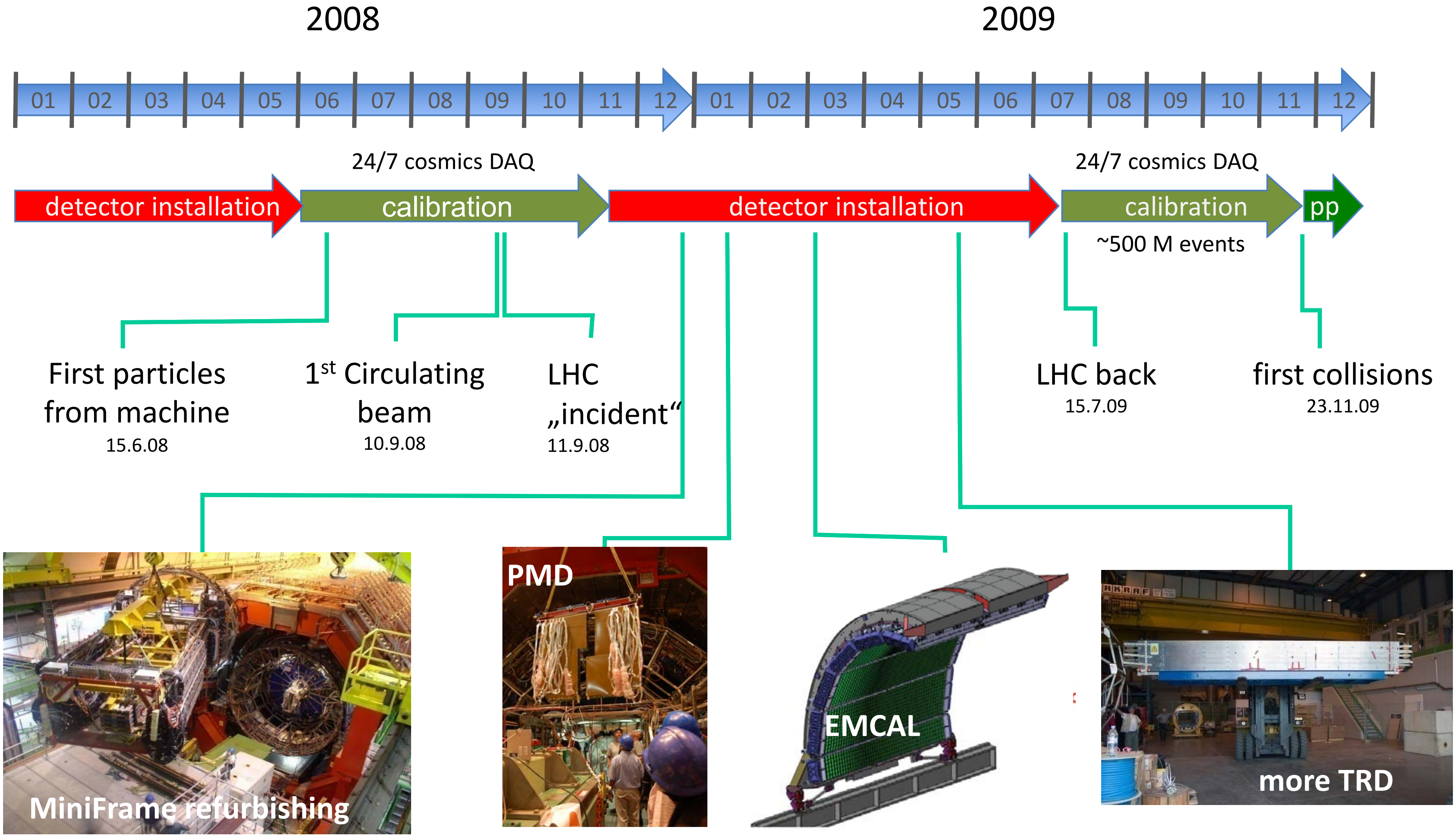

Insertion of final TOF super module


Installation of final muon chamber

ALICE in 2008

Formal end of ALICE installation July 2008

Commisioning and Calibration

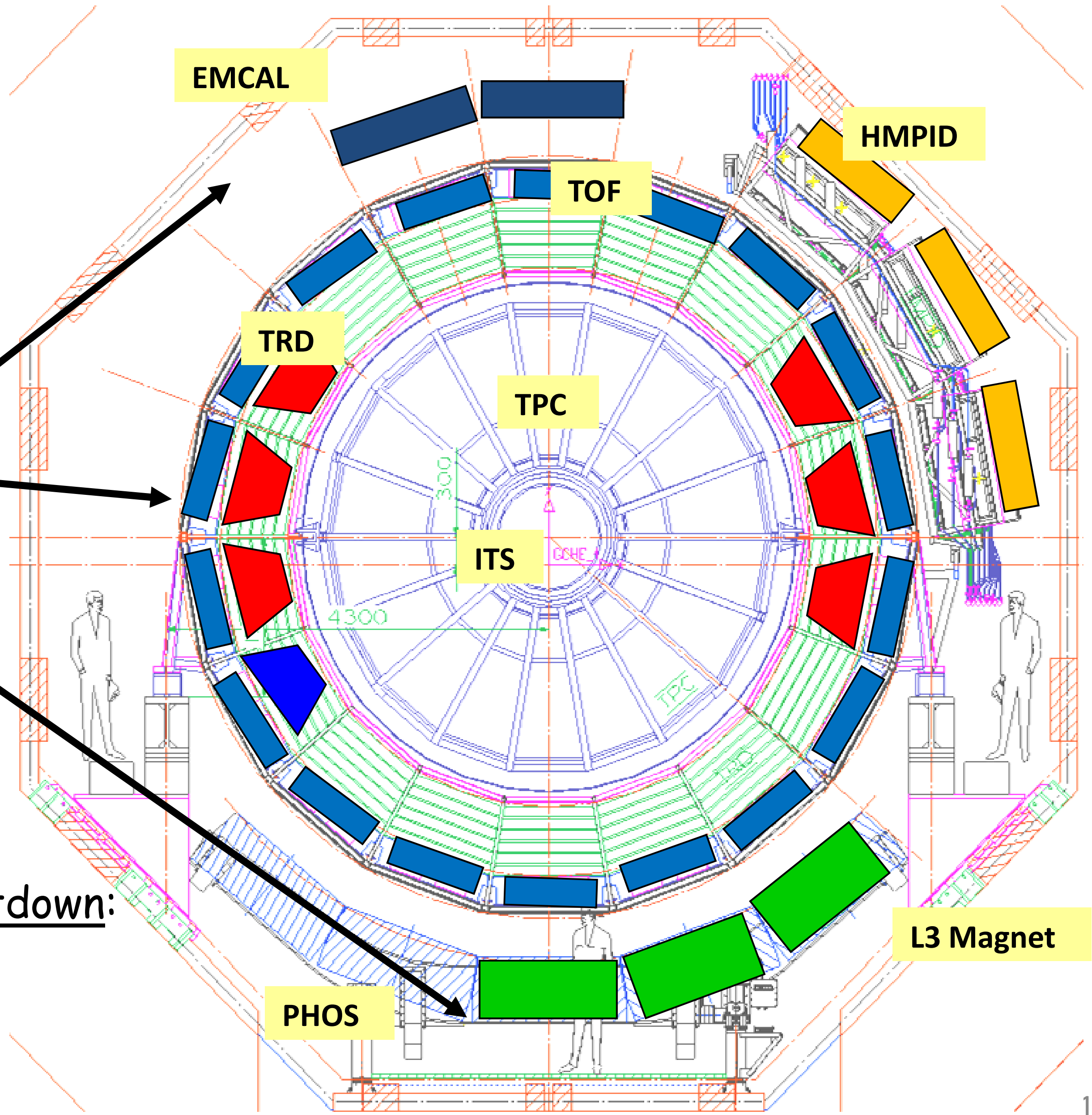


Detector Status in 2010 data taking

Completed since 2008:
ITS, TPC, TOF, HMPID,
FMD, T0, V0, ZDC,
Muon, Acorde
PMD , DAQ

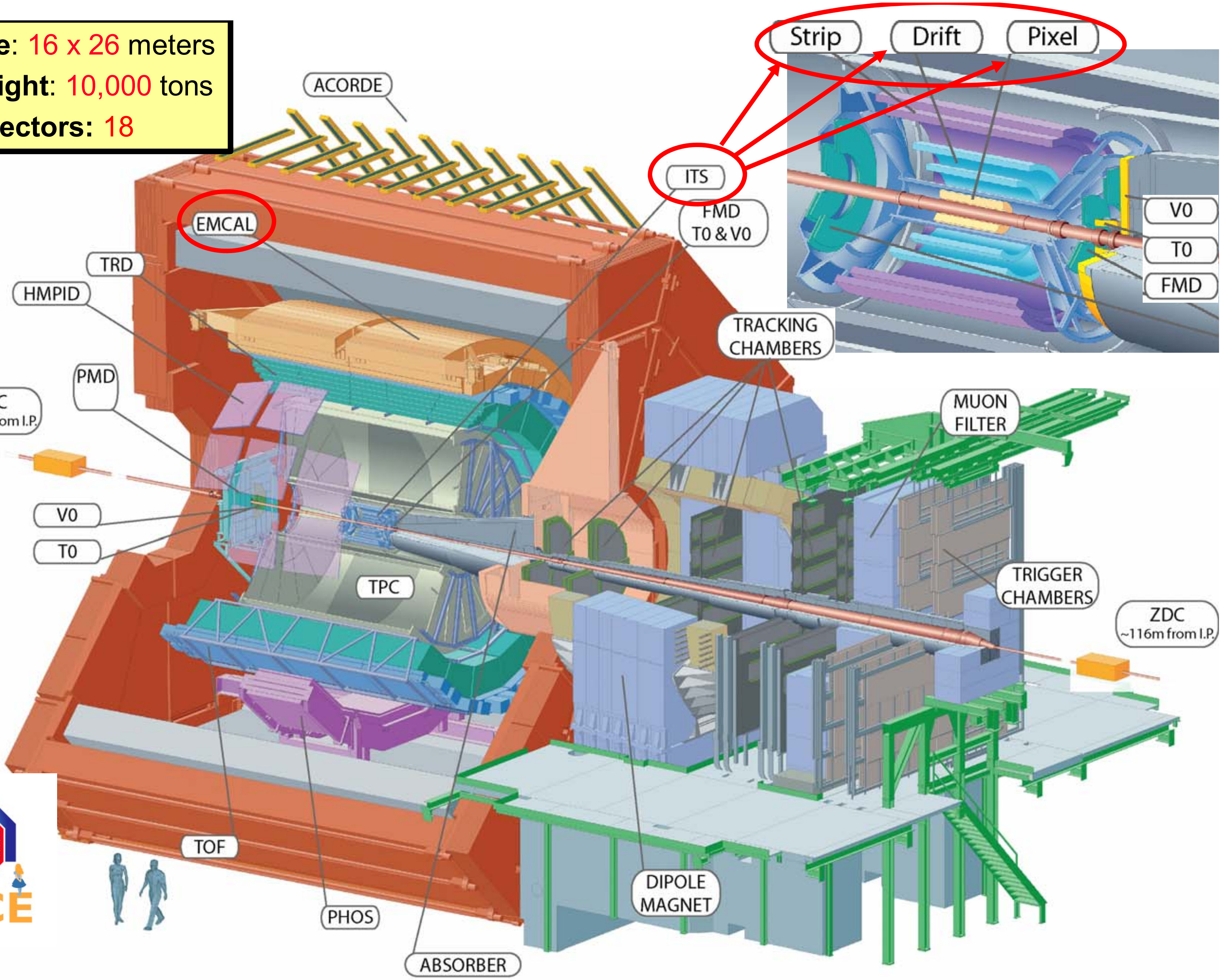
Partial installation:
4/10 **EMCAL** (approved 2008)
7/18 **TRD** (approved 2002)
3/5 **PHOS** (funding)

~ 60% HLT (High Level Trigger)



During the 2010 Winter shutdown:
6 EMCAL modules (-> 10/10)
3 TRD modules (-> 10/18)

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



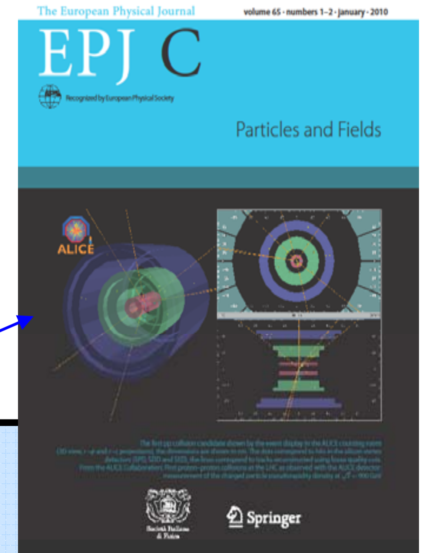
ALICE

I - c) Obtained results

Physics goals with pp :

- collect 'comparison data' for heavy-ion program
  - many signals measured 'relative' to pp
  - requires ~ 10^9 minimum-bias events
- comprehensive study of global 'Min Bias'

@LHC tuning of Monte Carlo



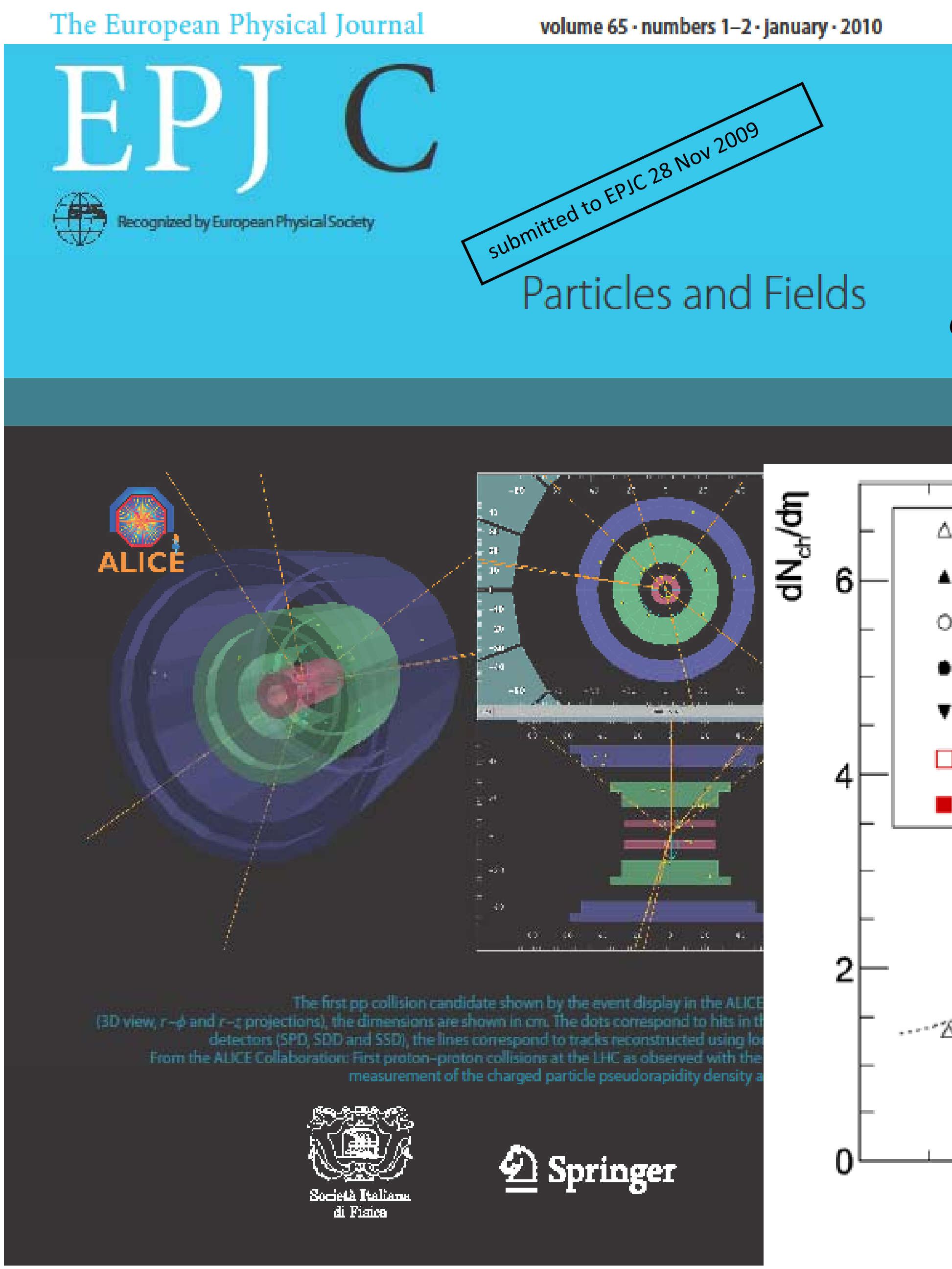
Final published results with pp:

– N_{ch} multiplicity & distributions

- 900 GeV: First LHC publication EPJC: Vol. 65 (2010) 111
- 900 GeV, 2.36 TeV: EPJC: Vol. 68 (2010) 89
- 7 TeV: EPJC: Vol. 68 (2010) 345

- pbar/p ratio (900 GeV & 7 TeV) PRL: Vol. 105 (2010) 072002
- momentum distributions (900 GeV) PLB: Vol. 693 (2010) 53
- Bose-Einstein correlations (900 GeV) PRD: Vol. 82 (2010) 052001
- Strangeness (K^0,Λ,X,W,f) production (900 GeV) EPJC: Vol. 71 (2011) 1594
- identified particles (p,K,p) spectra (900 GeV) PLB: Vol.696 (2011) 328

ALICE Collaboration, Eur.Phys.J.C65:111-125,2010



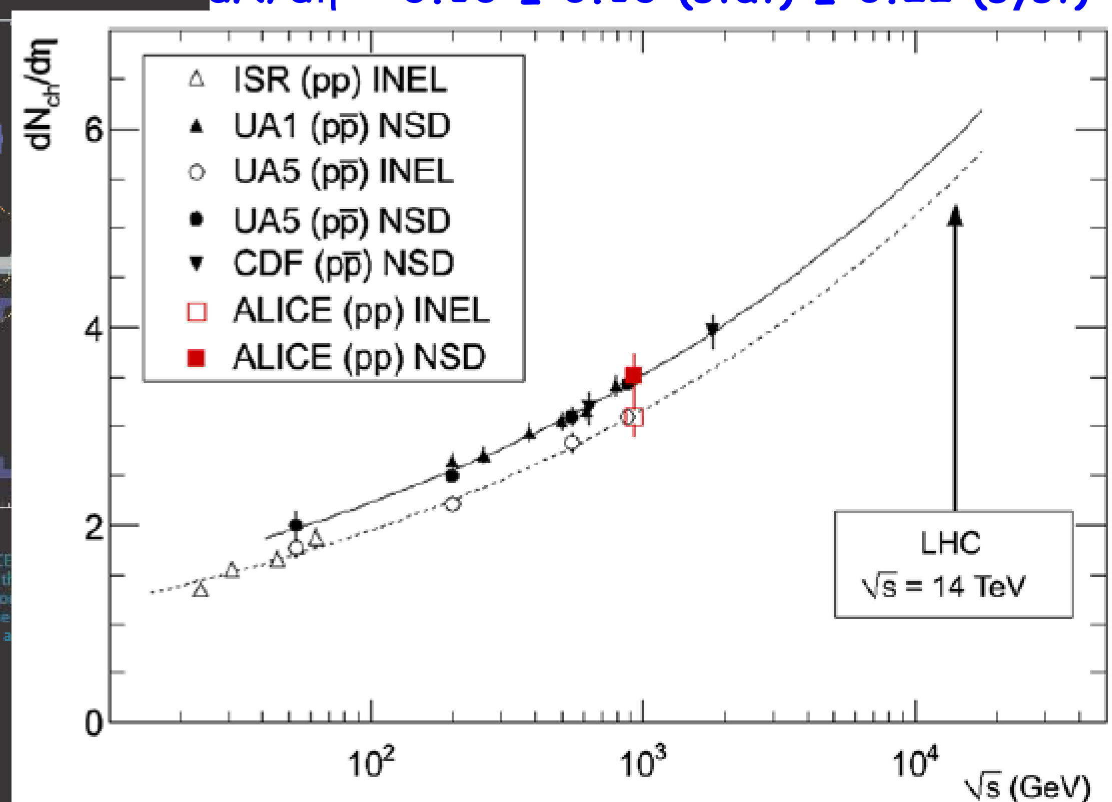
23 November 2009, Run 101498, 284 events

Preprint arXiv:0911.5430v1 [hep-ex] 28 Nov 2009

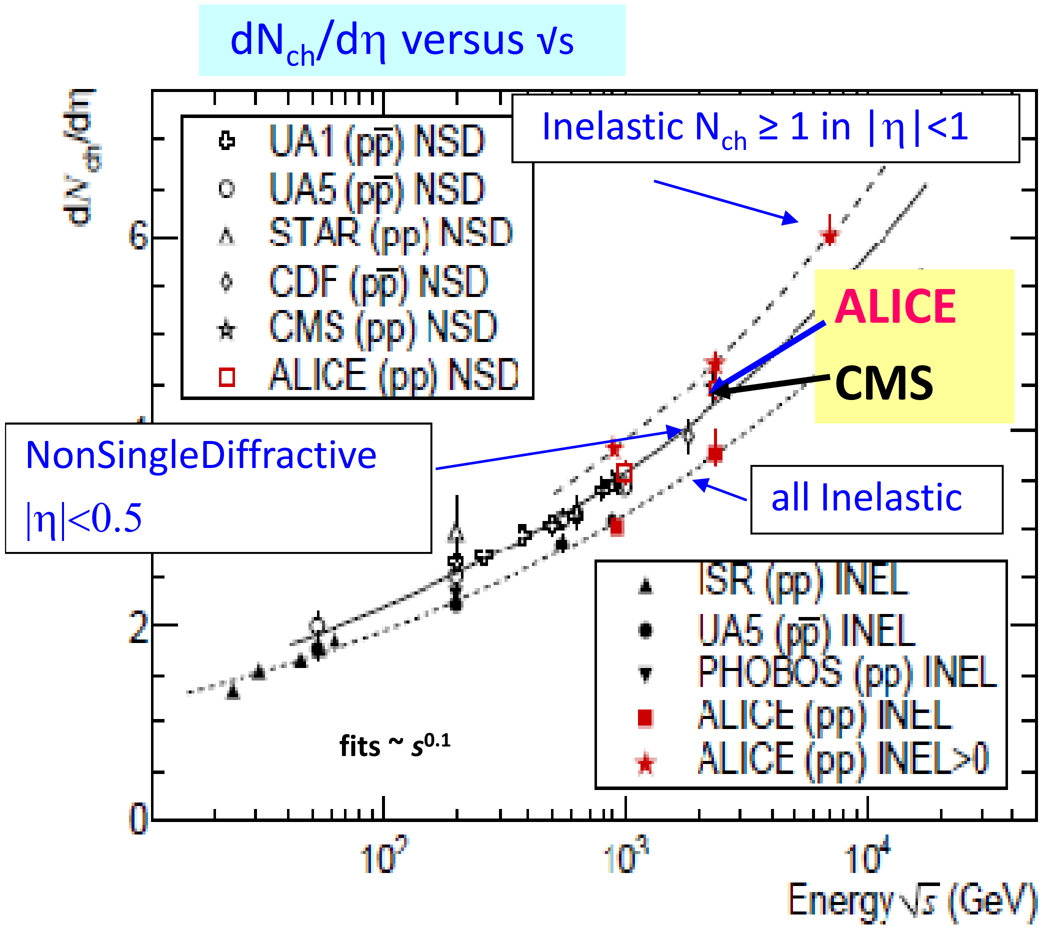
The FIRST LHC paper !!!!

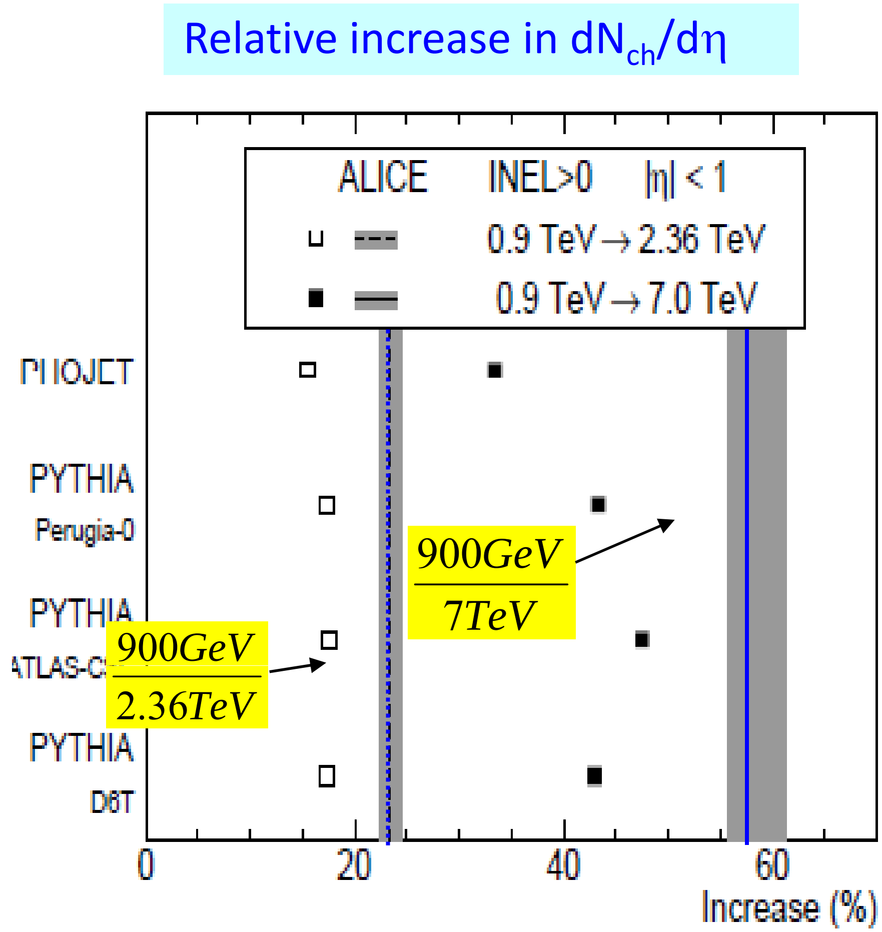
The average number of charged particles created (all Inelastic) in the range $|\eta| < 0.5$ in pp collisions at 900 GeV is:

$dN/d\eta = 3.10 \pm 0.13\ (stat) \pm 0.22\ (syst)$



$dN_{ch}/d\eta$ versus $\sqrt{s}$



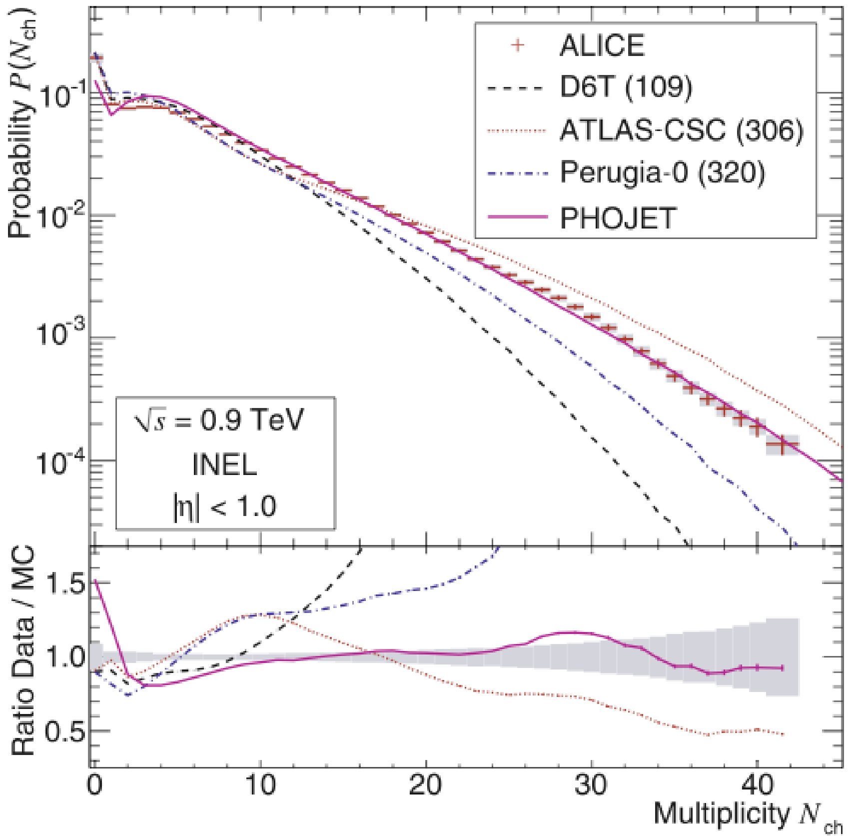


Results:

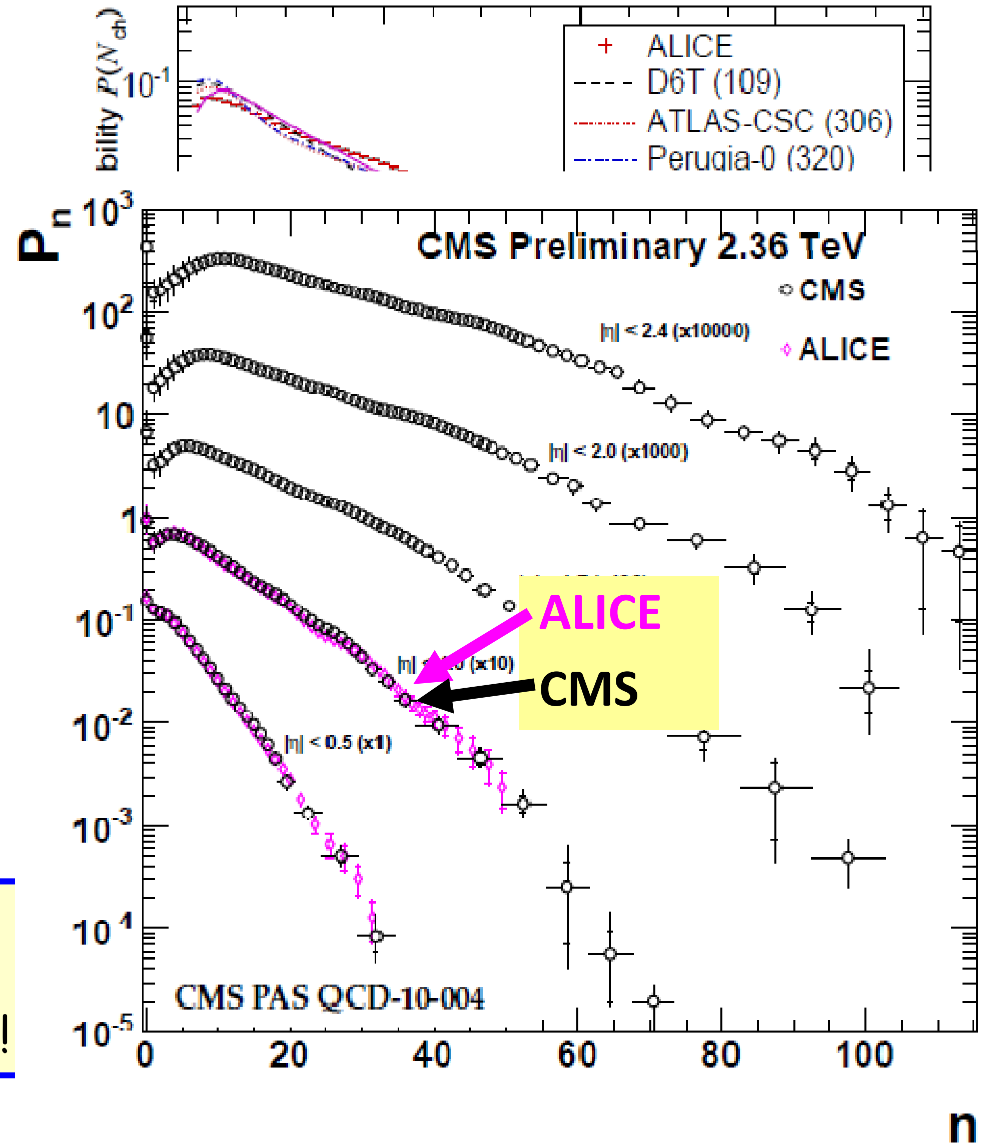
- $dN_{ch}/d\eta$ well described by power law $(\sqrt{s})^{0.2}$
- Alice & CMS agree to within 1 σ (< 3%)
- measured $dN_{ch}/d\eta$ increases with energy faster than in any models.

Multiplicity distributions

900 GeV



7 TeV



- The stronger increase in $dN_{ch}/d\eta$ is in high N_{ch} region.
- ALICE & CMS still agree perfectly !

Other physics results with pp

- Ongoing analyses
  - for 7 TeV pp multiplicity, spectra, HBT, identified particles, strangeness
    high multiplicity
  - π^0 and η transverse momentum spectra
  - Heavy flavour: charm (D^0,D^+, D^*), c,b -> μ, e^-
  - J/ψ -> $\mu\mu$, e^+e^-
  - pQCD: event topology, 2-particle correlations, jet fragmentation, …

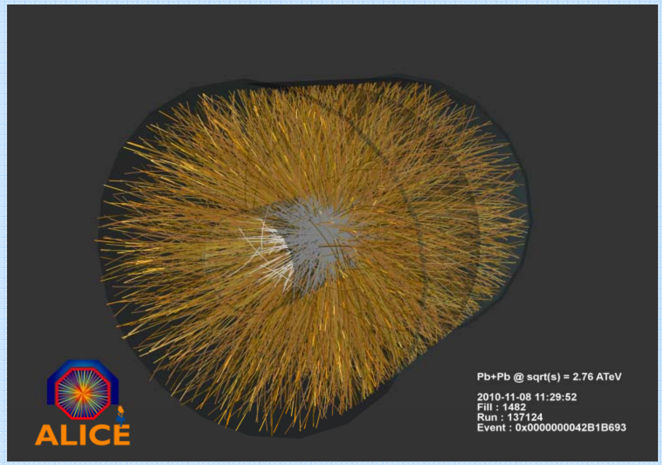
and some Physics results with Pb-Pb

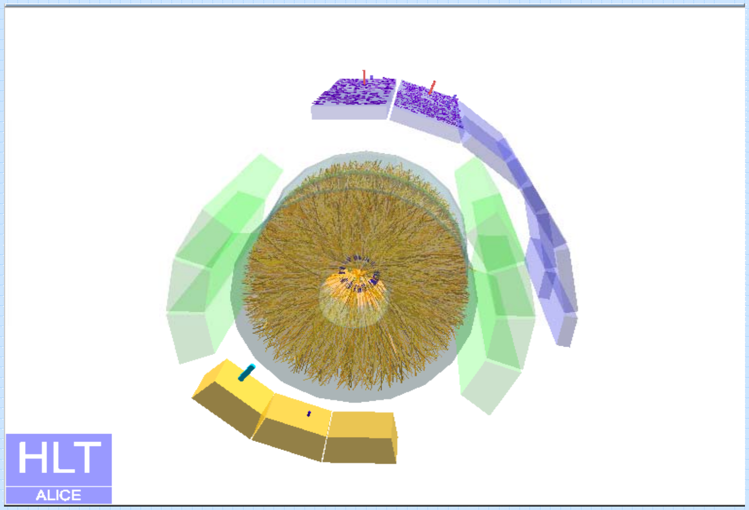
- Published results on Pb-Pb
  - multiplicity Pb-Pb collisions (2.7 TeV) PRL: Vol. 105(2010) 252301
  - Bose-Einstein correlations in Pb-Pb (2.7 TeV) PLB: Vol. 696 (2011) 328

Heavy Ion Physics with ALICE

- **first 10^5 events:** global event properties
  - multiplicity, rapidity density
  - elliptic flow
- **first 10^6 events:** source characteristics
  - particle spectra, resonances
  - differential flow analysis
  - interferometry
- **first 10^7 events:** high-p_T, heavy flavours
  - jet quenching, heavy-flavour energy loss
  - charmonium production
- yield bulk properties of created medium
  - energy density, temperature, pressure
  - heat capacity/entropy, viscosity, sound velocity, opacity
  - susceptibilities, order of phase transition

largest energy jump (×14) in the history of heavy-ion physics

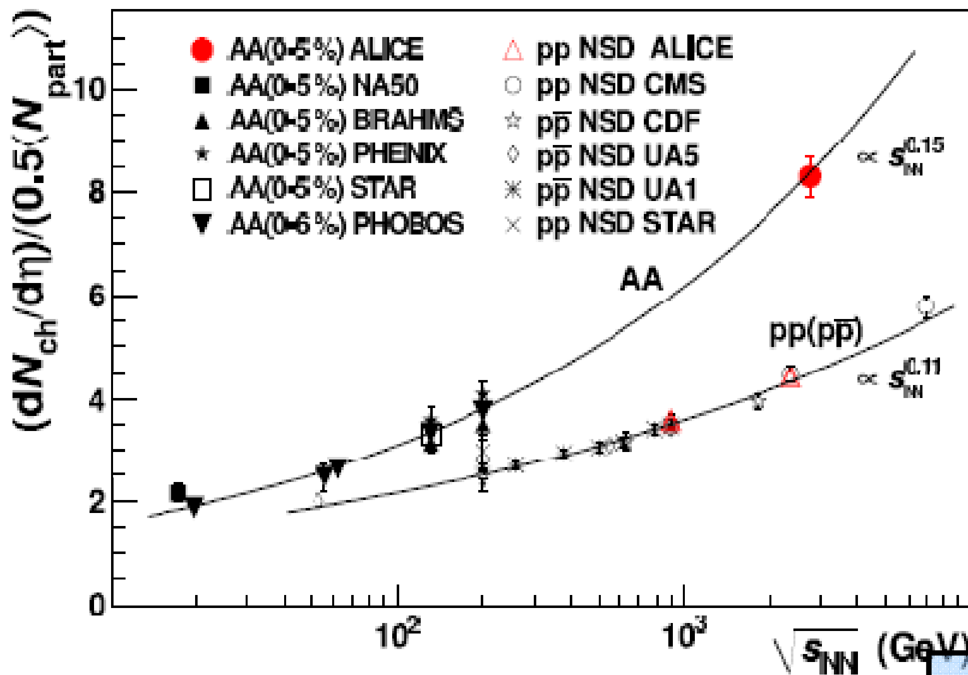




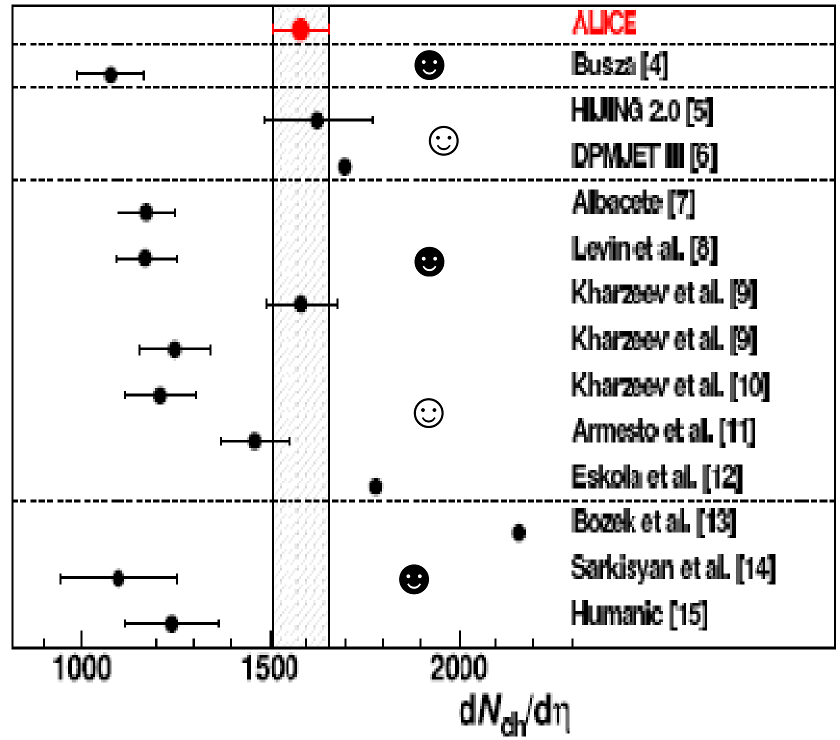
Charged particle $dN_{ch}/d\eta$ Pb-Pb 2.76 TeV

PRL 105 (2010) 252301

Data Sample: 50.000 M.B. collected on Nov. 9
Select the 5% most central collisions



$$dN_{ch}/d\eta = 1584 \pm 4\ (stat.) \pm 76\ (syst.)$$



- Increase by 1.9 wrt pp at same energy
- Increase by 2.2 wrt RHIC Au-Au 200GeV

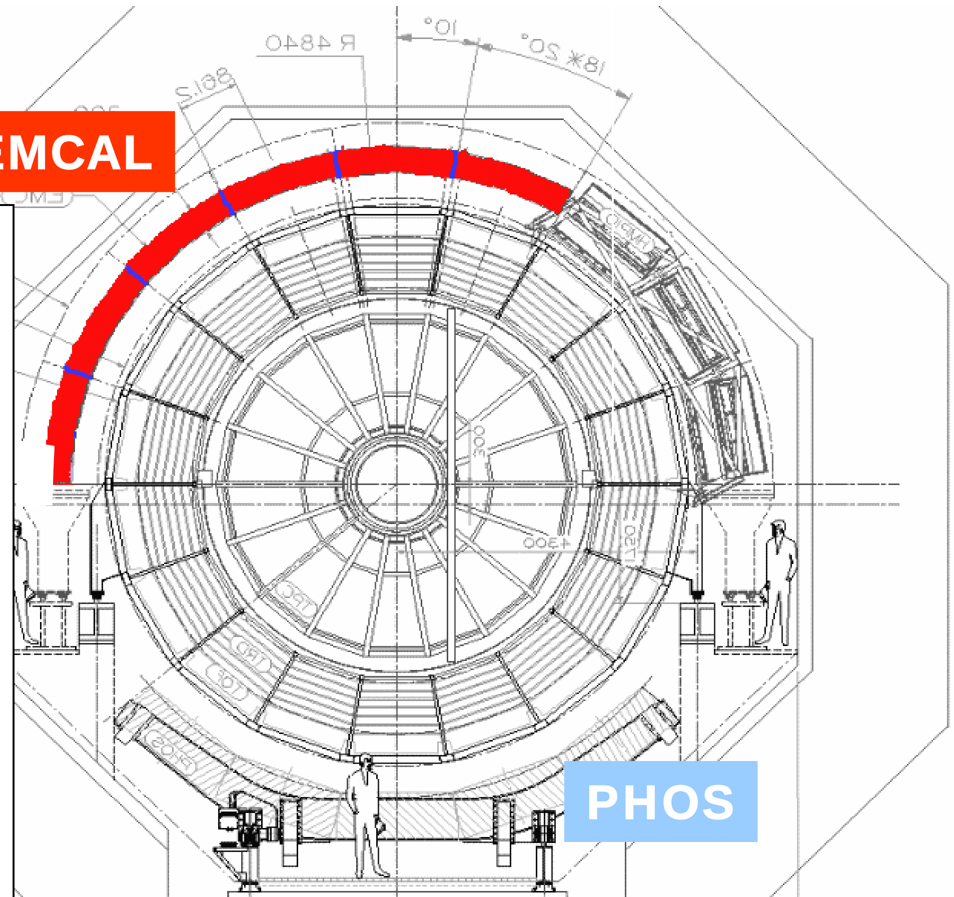
- ☻ Extrapolation based on RHIC
- ☺ pQCD MCs (Hijing, DPMJet)
- ☻ ☺ Initial State Gluon Density Saturation
- ☻ Hydrodynamic and hybrid models

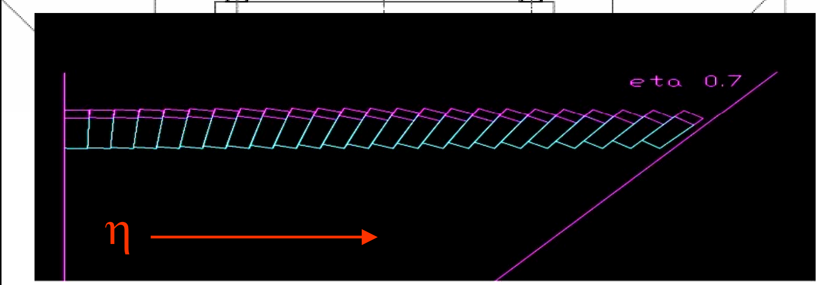
II - The electromagnetic calorimeter EMCAL: a) Characteristics

To do **jet** (quenching) **physics**:
- large coverage
- good granularity

EMCAL
— located **inside** the L3 solenoidal magnet
— **sampling** calorimeter: 20.1 X_0
— **sandwich**, 1.44 mm Pb/1.76 mm Scint
final geometry when installation completed
- $-0.7 < \eta < 0.7$
- $\Delta\Phi = 100°$
- small Φ gaps (~ 3 cm) aligned w/ TPC gaps

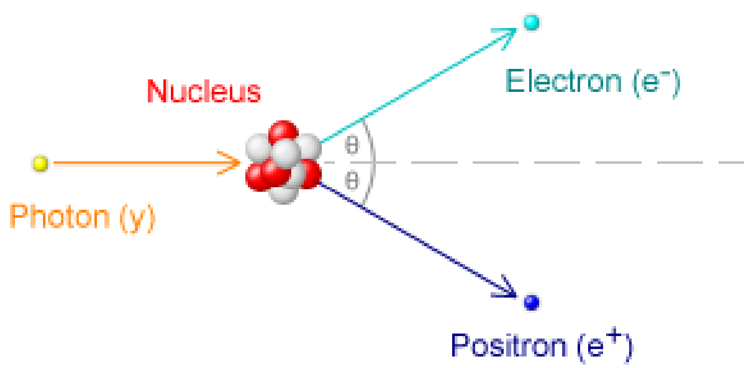
— sampling fraction 1/10.5
— density 5.86 g/cm^3
— R_M = 3.20 cm; X_0 = 12.3 mm
— Scintillator = Polystyrene (BASF143E + 1.5% pTP + 0.04% POPOP)
—10 super-modules in total
— granularity: **11520 towers**
tower size: $\Delta\eta\times\Delta\phi$ ~ 0.0143×0.0143
— σ_E/E ~ 10%
— installed back to back with PHOS

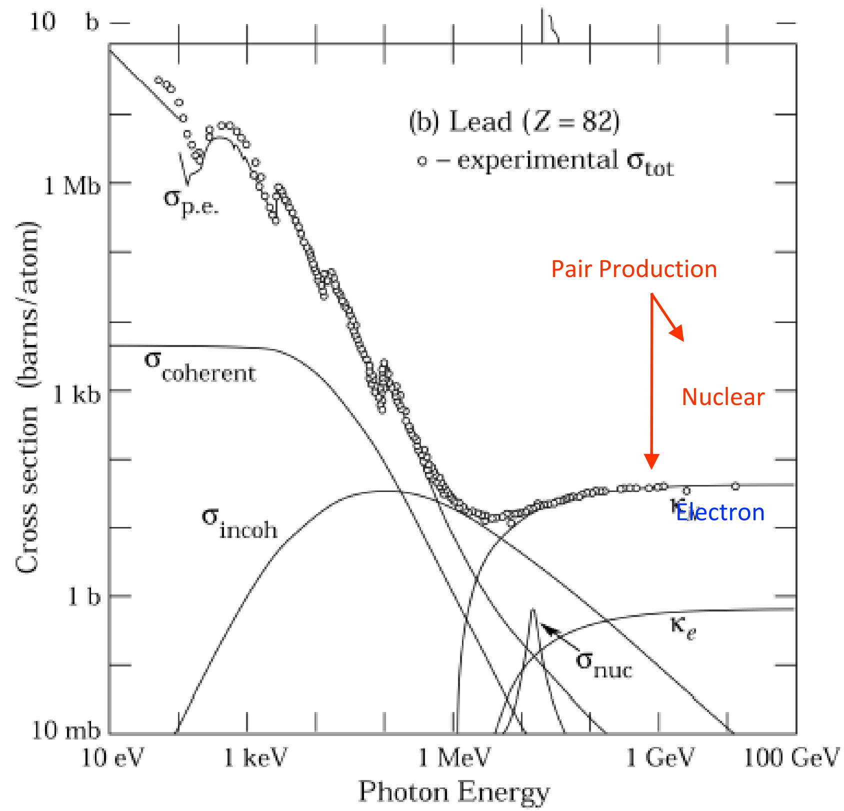




II - b) How it works

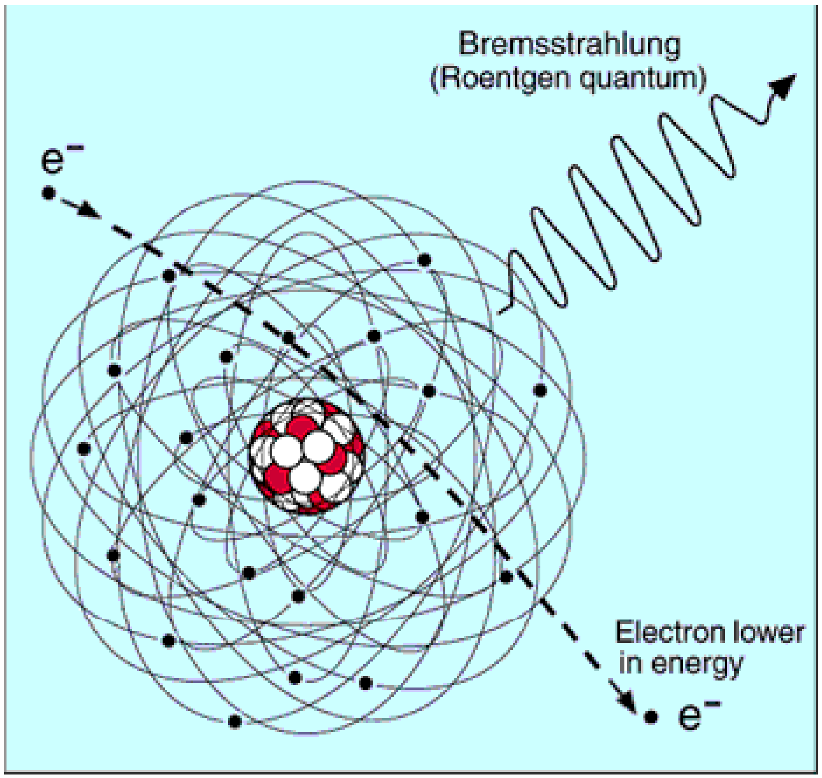
Photon Interactions with Matter



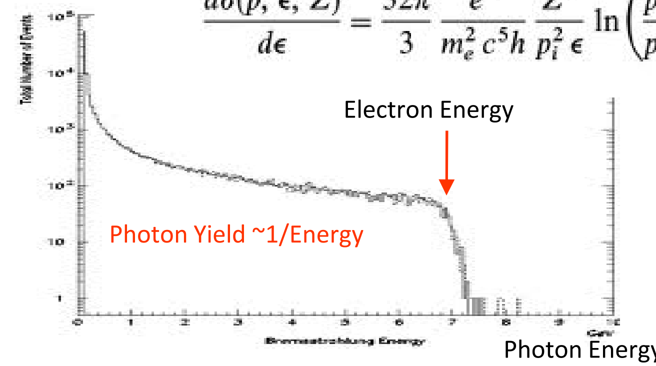


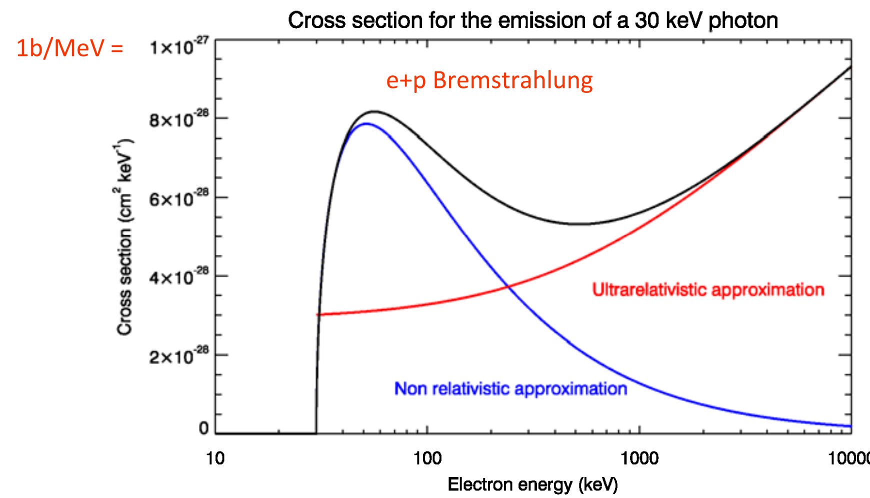
- At energies above ~1 MeV the dominant photon interaction is with the nuclear Coulomb field (κ_N) resulting in e^+e^- pair production
  - Each carries off ~1/2 photon momentum
  - (Small additional contribution of pair production for interaction with the electronic Coulomb field (κ_e))

Electron Interactions with Matter



$$\frac{d\sigma(p,\epsilon,Z)}{d\epsilon} = \frac{32\pi}{3}\frac{e^6}{m_e^2 c^5 h}\frac{Z^2}{p_i^2\,\epsilon}\ln\left(\frac{p_i+p_f}{p_i-p_f}\right),$$

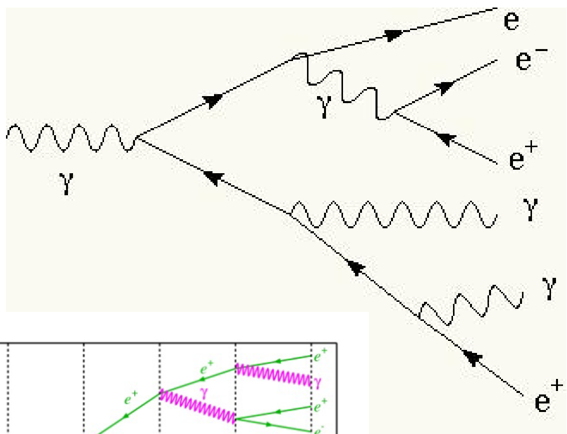




- At energies above few MeV the dominant process for electron interactions is with the nuclear Coulomb field (κ_N) resulting in radiation of a photon (Bremstrahlung)
  - Cross sections are much larger than for photon pair production, but typical small energy loss (small radiated photon energy)

Electromagnetic Showers

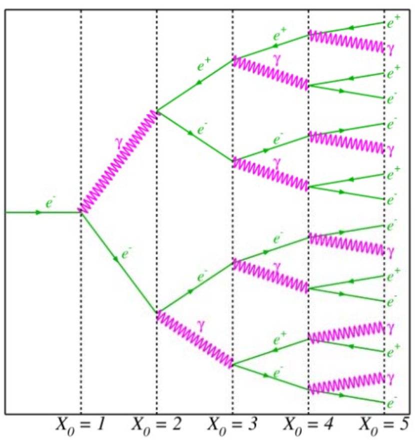
- An Electromagnetic Shower consists of a cascade of pair production from gammas and Bremstrahlung from electrons, until electron energies fall below the critical energy, E_{crit}, and photons are no longer radiated by electrons to sustain the shower.



Radiation Length (X_0) == Depth at which energy of electron (photon) is reduced by 1/e:

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$

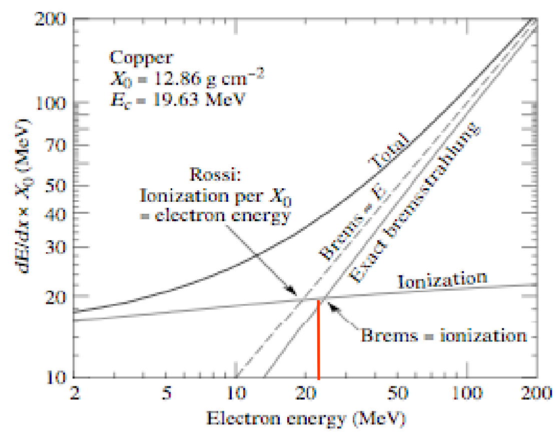
X_0 = 0.56cm (Pb); X_0 = 42cm (Scint.); X_0 = 1.2cm (EMCal)



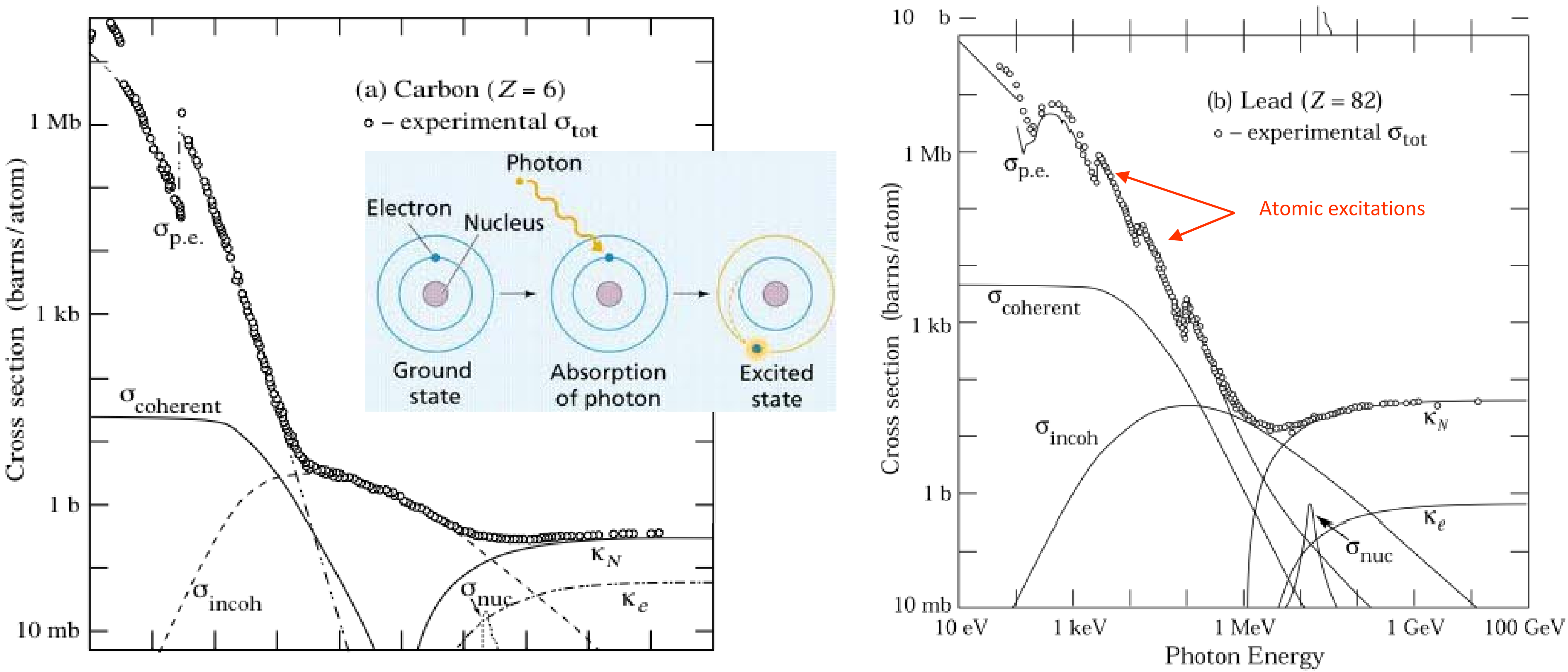
"Bad" schematic

Critical Energy == E where collisional energy loss equals radiative energy loss: E_{crit}(MeV) = 800/(Z+1.2)

E_{crit} = 8 MeV (EMCal)



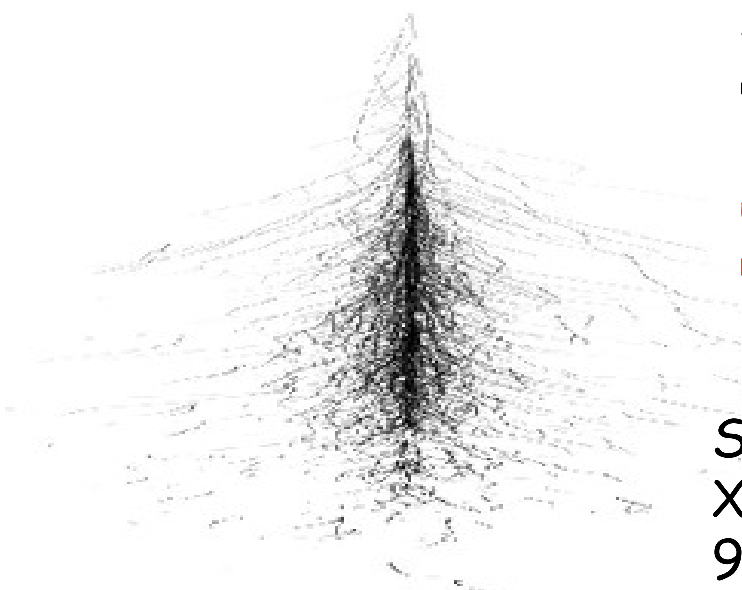
Electromagnetic Showers



- Low energy photons and electrons of shower induce atomic excitations by absorption or electron emission.
  - All of the shower energy is dissipated into atomic excitations, that finally end up as thermal motion (heat! ergo calorimeter!)

Electromagnetic Showers

- Due to the multiplicative growth in the number of electrons and photons in the shower, the shower maximum occurs when the energy of the leading particles falls below the critical energy.
  - Photon and electron showers are basically the same, except that the Bremstrahlung cross sections are larger and so electron showers develop ~1 X_0 earlier.



Gamma shower

Shower maximum depth:

$d = X_0 * (\ln (E/E_{crit}) + C_j)$

where C_j = -0.5 electrons; =+0.5 gammas

Example: depth = 7.5, 10.8, 14 X_0 for 1, 10, 100 GeV γ in EMCal (EMCal total depth = 20.1 X_0)

Shower width characterized by Moliere Radius:

$X_M = X_0 * (21.2/ E_{crit} (MeV))$

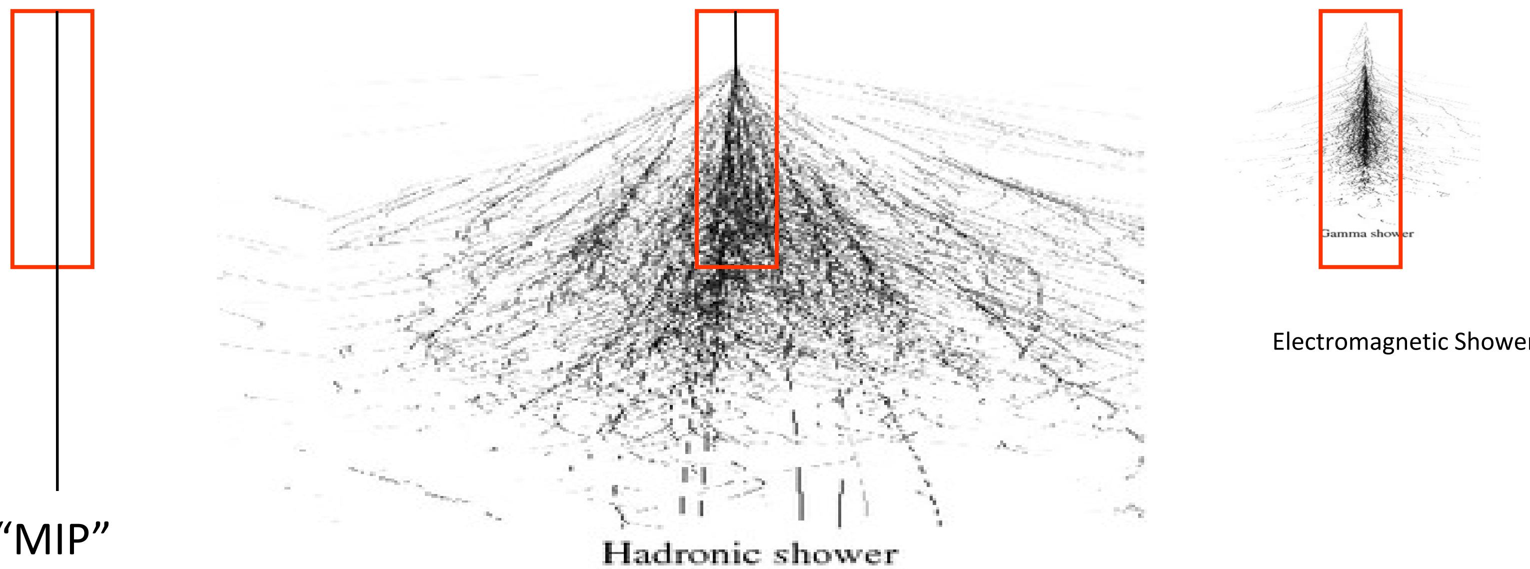
90% of Shower energy is contained within cylinder of radius X_M (99% within 3.5 X_M)

X_M = 3.2cm for EMCal

EMCal tower size = 6cm ~ shower size

Hadron interactions with Matter

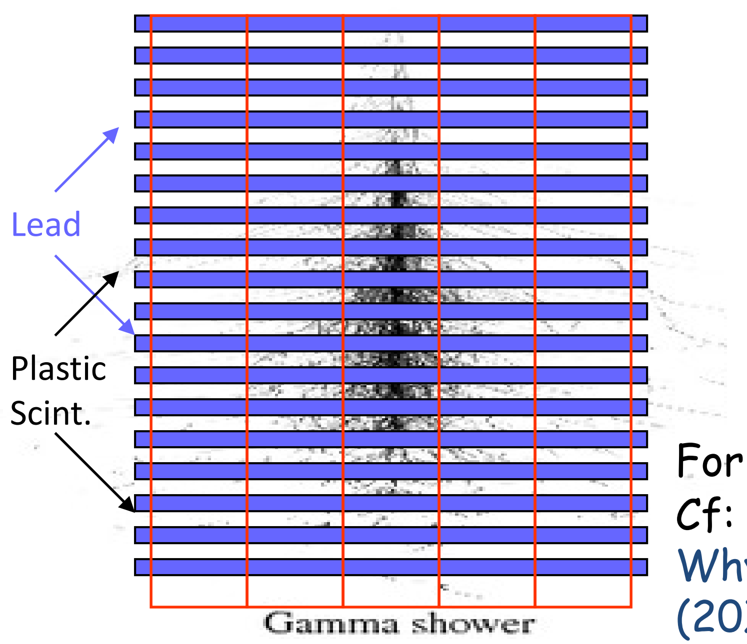
- Bremstrahlung radiation by heavy particles (hadrons and muons) is suppressed (by $1/m^2$). They lose energy at a "low constant rate" (dE/dx) by electromagnetic process of ionization and atomic excitation.
  - But if a hadron strikes a nucleus it will undergo a strong interaction - "hadron shower"
    - Large energy deposit (nucleus fragments, nucleon and pion emission…)
    - Nucleons and pion emitted to large angles; mostly doing dE/dx, but π^0's, γ's and electrons will create small electromagnetic showers within the hadronic shower



Nuclear interaction length (1/e energy loss): λ=17cm (Pb); (EMCal 11cm of Pb)

Energy Measurement

- The energy deposited in the calorimeter is "measured" by extracting "some signal" that is proportional to the energy deposit.
  - Examples: total ionization charge, or more typically scintillation light
- The "signal" then is obtained by "counting" the number of ionization charges or scintillation photons $N \sim E/E_{crit}$
  - The relative error (intrinsic resolution) on the energy measurement then goes like
    - $\delta E/E \sim const/sqrt(N) \sim \sigma_o/sqrt(E)$



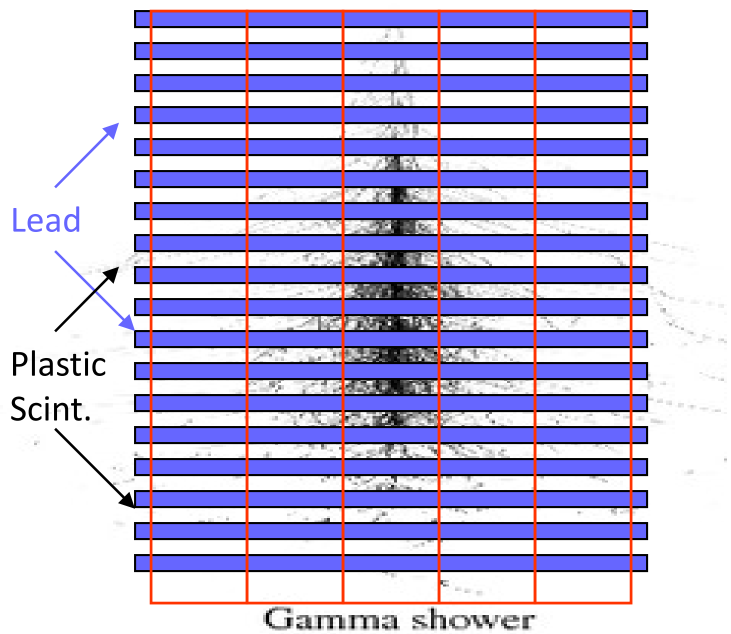
In a sampling calorimeter (like EMCal) the energy deposit is only "sampled" in the scintillator - it is "blind" to the energy deposited in the Lead. Energy resolution is worsened by the fraction 1/f of the energy sampled.

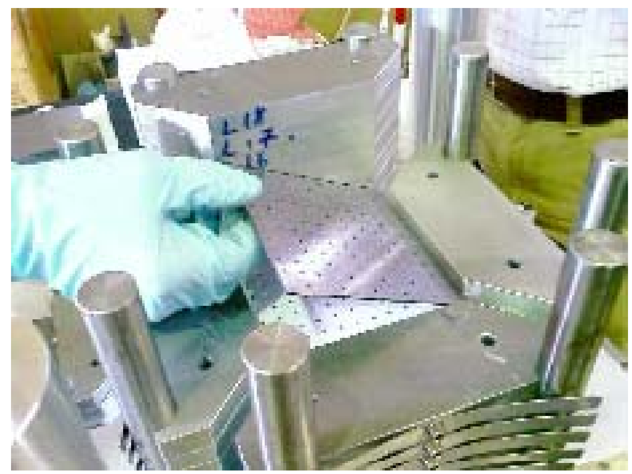
- $\delta E/E \sim \sigma_o/sqrt(E/f)$

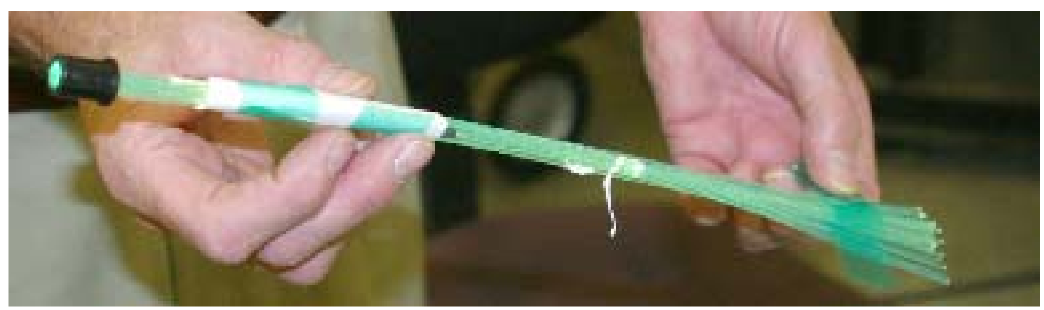
For EMCal: f=10.3: $\delta E/E$ is sqrt(f)~3x worse than scintillator
Cf: PHOS σ_o =3.5% ; EMCal σ_o =11%
Why sampling? It's cheap and compact
($20X_0$ of Plastic scintillator = 800cm!)

Sampling Calorimeter

- The deposited energy signal in a sampling calorimeter is the scintillation light in the scintillator, but it must be extracted -
  - Shashlik (Shish-Kebab) solution used for EMCal
    - Lead and Scintillator is "skewered" by Wave-Length Shifting (WLS) fibers on a grid of 1cm x 1cm spacing

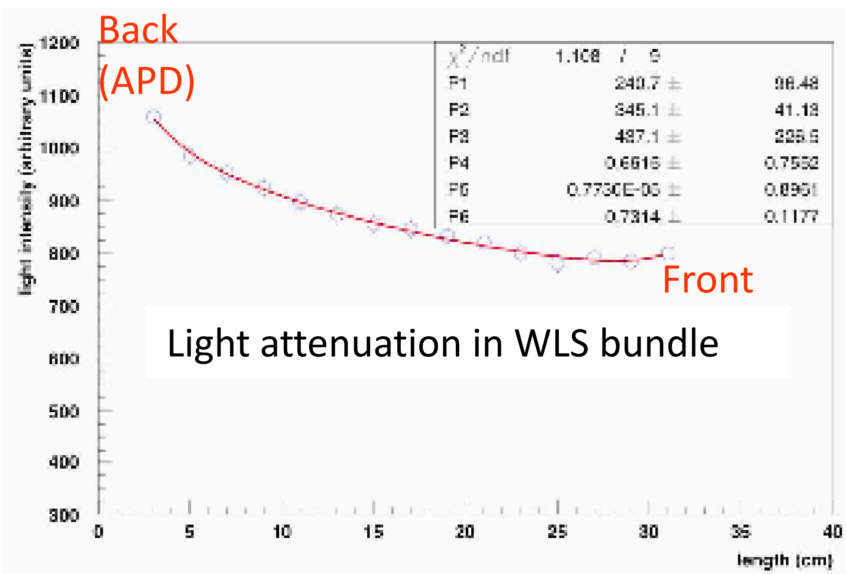


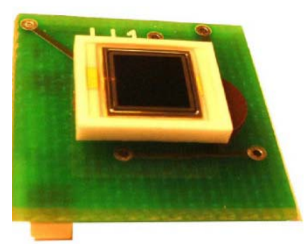


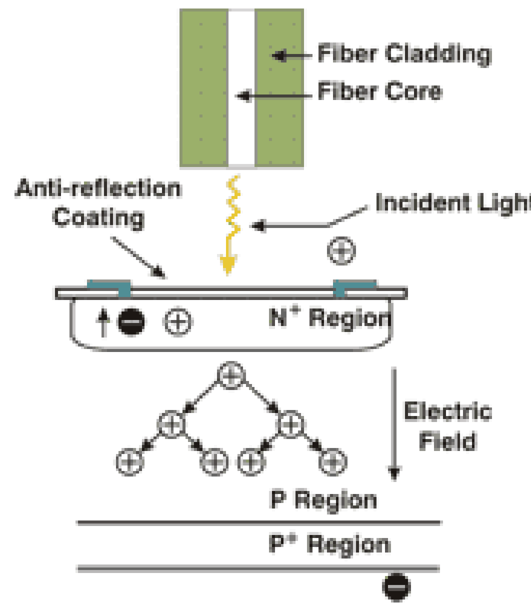


Sampling Calorimeter

- Transmission of the scintillator "signal" is "Lossy".
  - WLS intercepts only fraction of the scintillator light
  - Scintillator light must be absorbed, re-emitted, and captured by fiber
  - Attenuation of light in WLS
    - Small effect - but gives depth dependence of light yield per scintillator layer
  - WLS light is converted to charge Q (e-h) in Avalanche PhotoDiode (APD)
    - EMCal measurement gave ~4 photo-electrons per MeV of incident energy
      - Source of Poisson fluctuations ~sqrt(N_{pe})
        - » Example: for 1 GeV γ 's expect 1/sqrt(4000) = 1.5% contribution to the resolution.

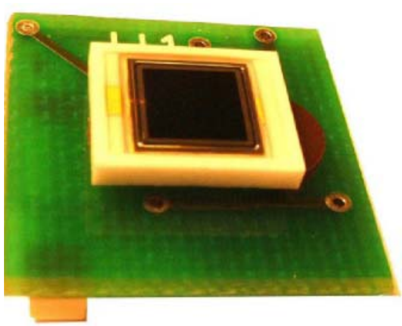




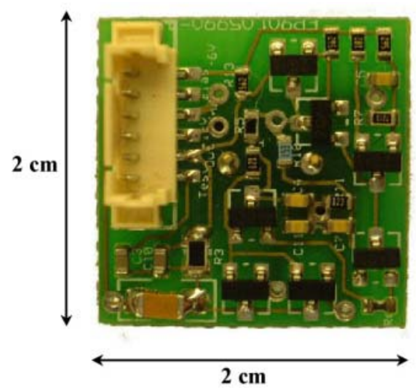


EMCal Readout

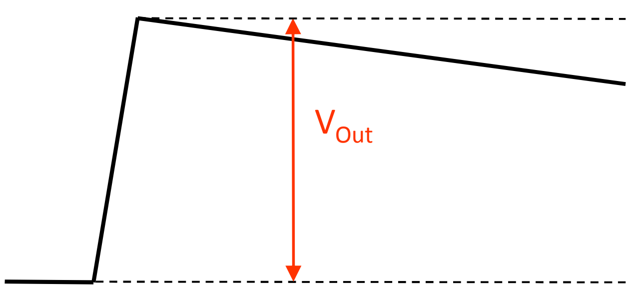
- In order to increase the signal (improve S/N) the charge signal is "boosted" in the APD by operating the APD at a gain of about M=30 (HV~350V)
  - 4 photo-electrons per MeV becomes 120 photo-electrons per MeV
    - However, the Poisson fluctuations are stil on the 4 photo-electrons per MeV
    - Also, the avalanche is a statistical process so it introduces additional fluctuations that will worsen the resolution.
  - The charge is integrated in the preamplifier to produce a voltage ($V_{Out} = Q/C$)
    - Charge conversion of 0.136 $\mu V/e^-$
      - Example: 1 GeV shower = 16.3mV voltage output from the preamplifier
    - Decay time of 100μsec (= a voltage step function on the time scale of relevance)



APD



Preamplifier



Signal

II - c) Assembly

Containment: 88 parts

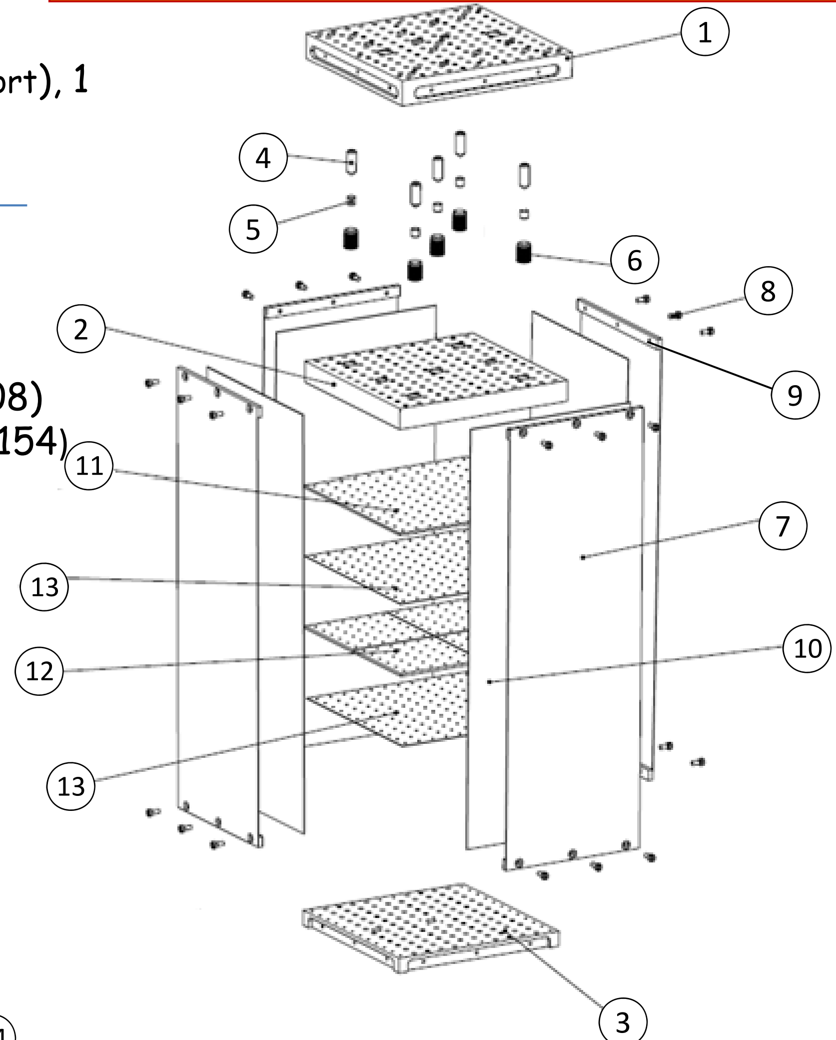
1) Back (holes: 144 thru for fibers + springs + mech. support), 1
2) Compression (holes: 144 thru for fibers + springs), 1
3) Front Plate (holes: 144 thru for fibers + springs + mech. support), 1
4) 5) Plungers (10)
6) Belleville washers (75)

Tensioning and Isolation: 40 parts

7) Stainless steel straps (4)
8) Screws (24)
9) Flanges (8)
10) Light tight stickers (4)

Sandwich: 538 parts

11) Lead tiles (76)
12) Scintillator tiles (308)
13) Bond paper sheets (154)



Readout : 165 parts

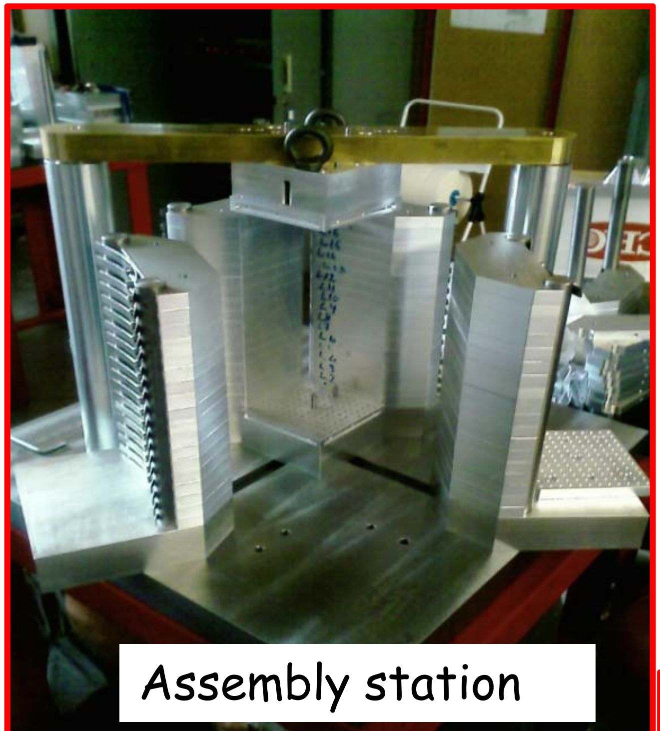
14) WLS fibers (144)
15) APD (4)
16) CSP (4)
17) Light guides (4)
18) Mount (4)
19) Collars (4)
20) Diffuser (1)

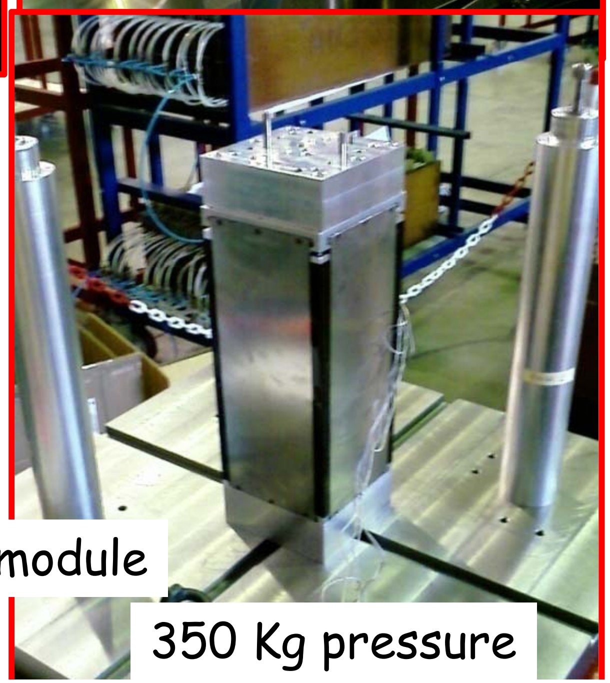
TOTAL components: 20

TOTAL parts: 831

Plus cabling, GMS and mech. supports

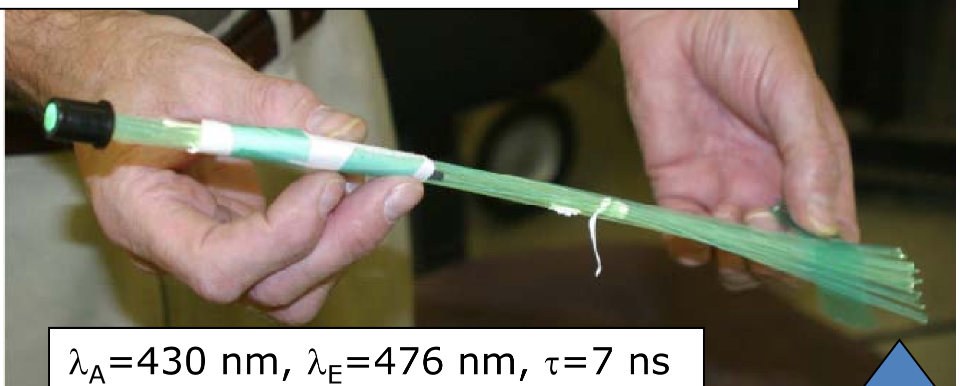
Module Production



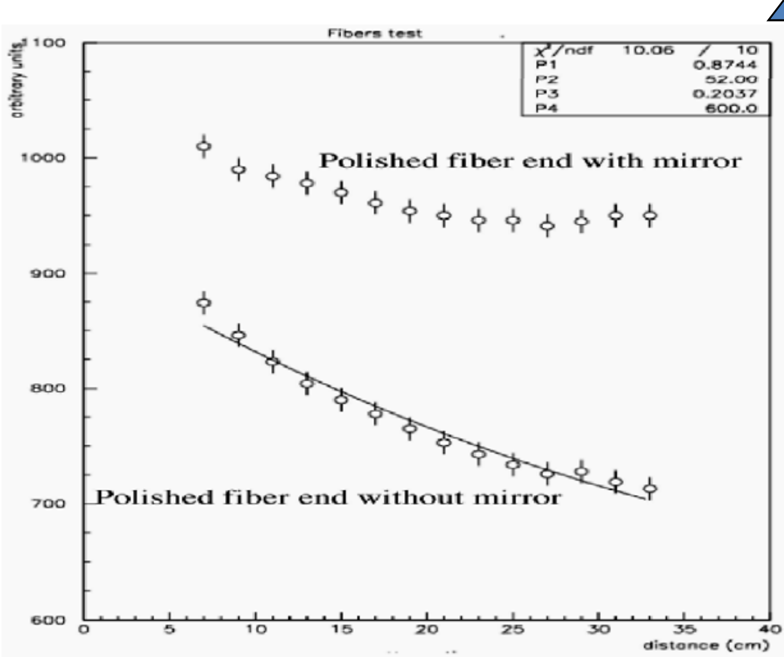


The EMCAL Readout

Y-11 (200) WLS double clad fibers

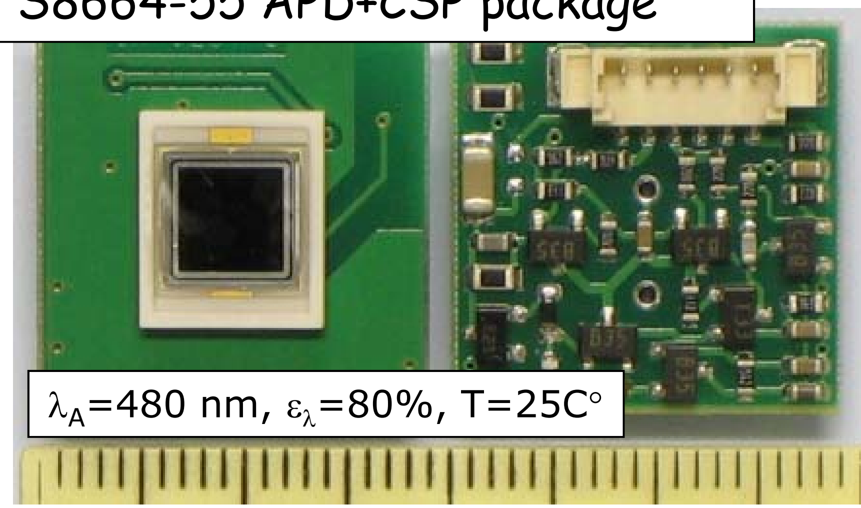


λ_A=430 nm, λ_E=476 nm, τ=7 ns



Aluminization

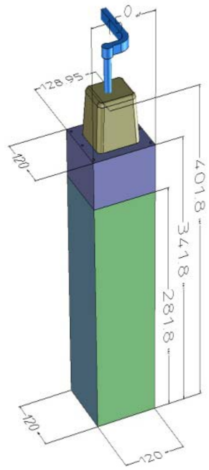
S8664-55 APD+CSP package



λ_A=480 nm, ε_λ=80%, T=25C°

fibers + light guide on package

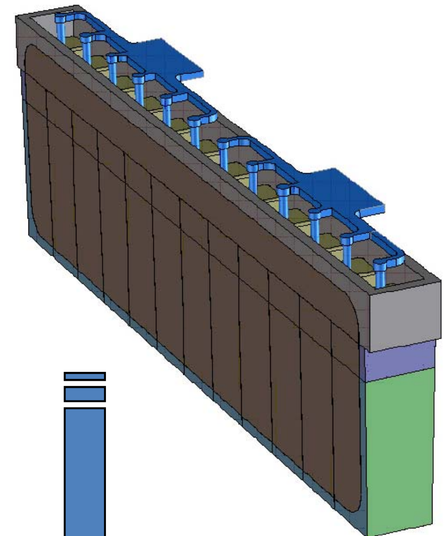
The EMCAL Modular Structure



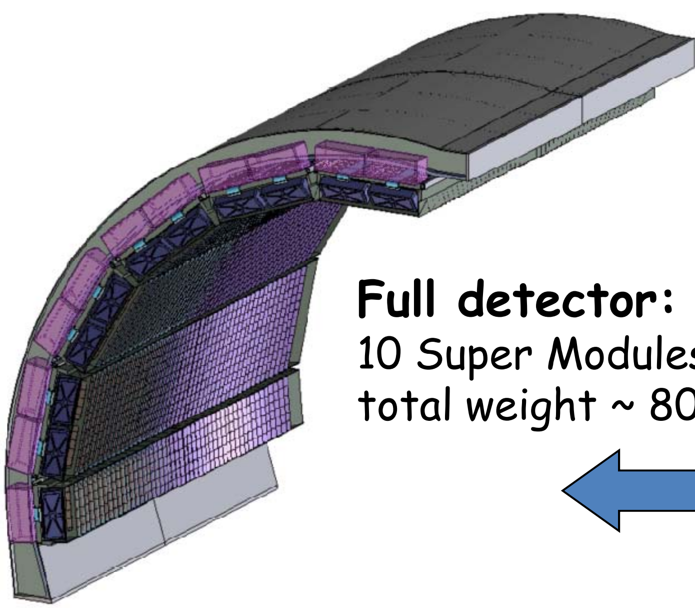
One Module

12 modules (4 for Prototypes)

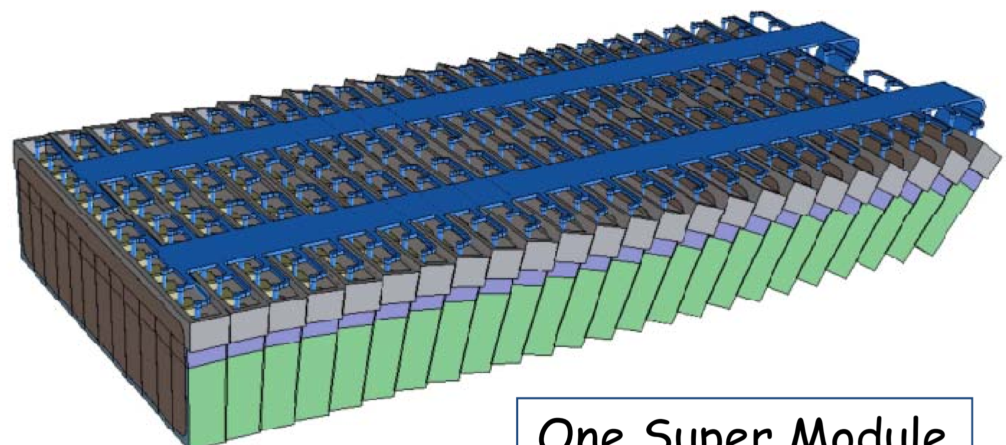
One FULL Strip Module



- 1 Module = 26.7 kg
- 1 Strip Module = 324 kg
- 1 Super-Module =288 modules ~ 7.7 tons

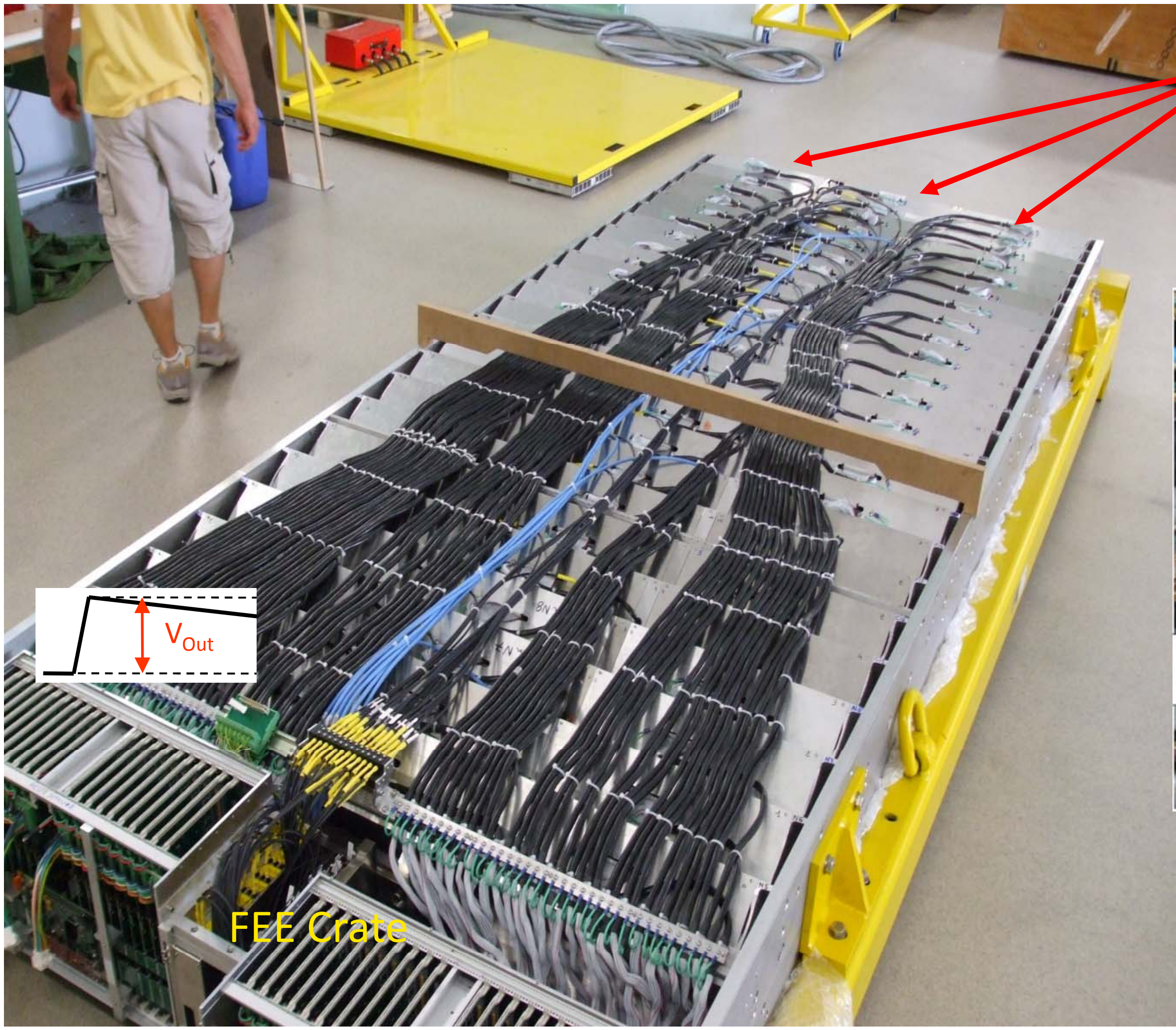


Full detector:
10 Super Modules,
total weight ~ 80 tons



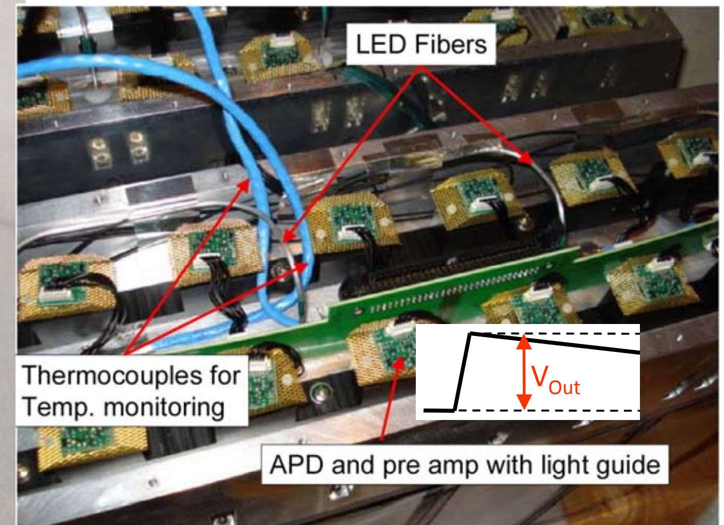
One Super Module

EMCal SM Readout



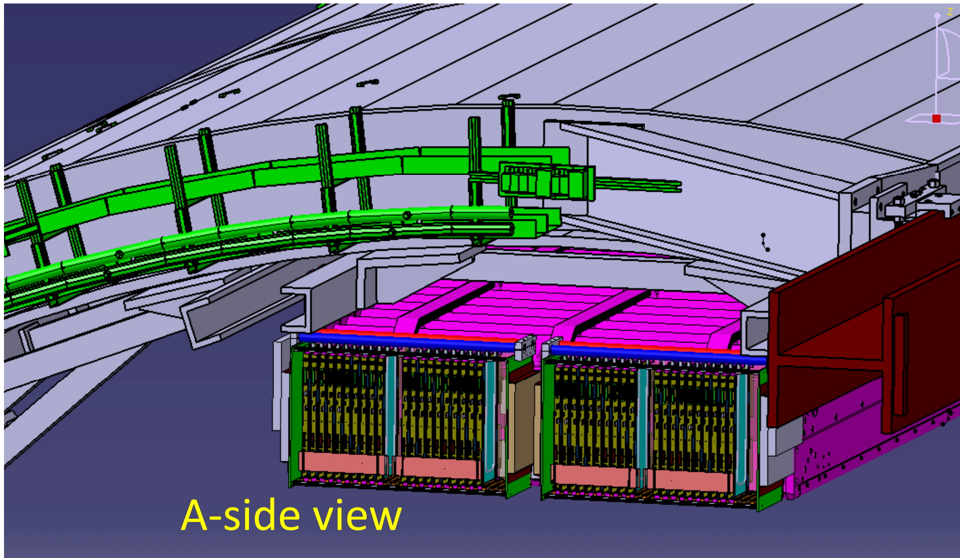
SM#2 @ Grenoble

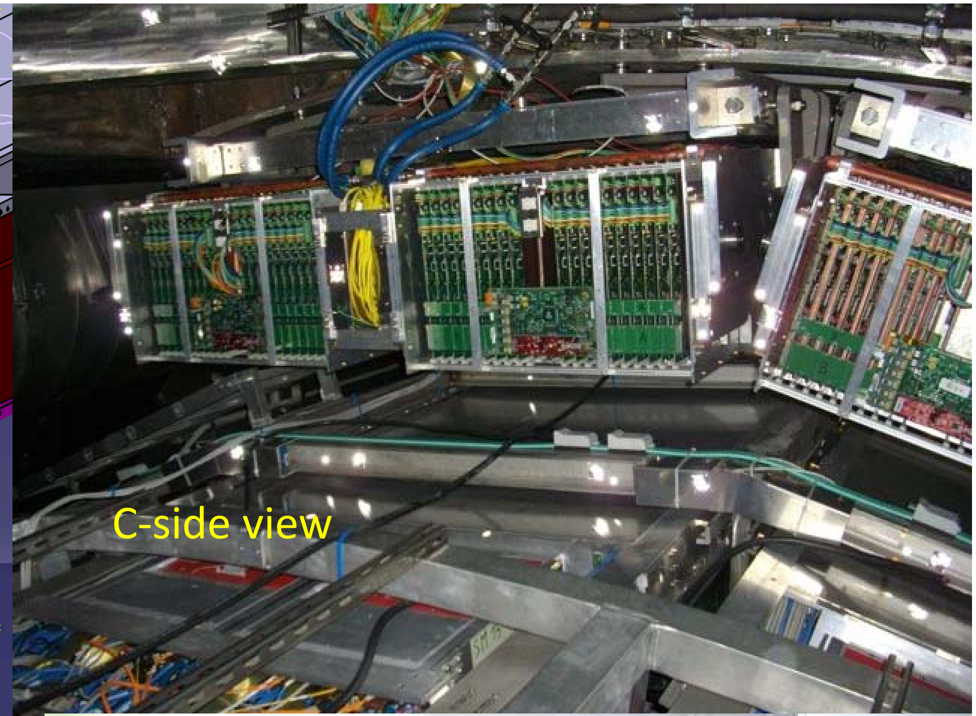
- 3 Shielded Ribbon Cables per Strip Module
  - 12 Modules (48 towers) per Strip

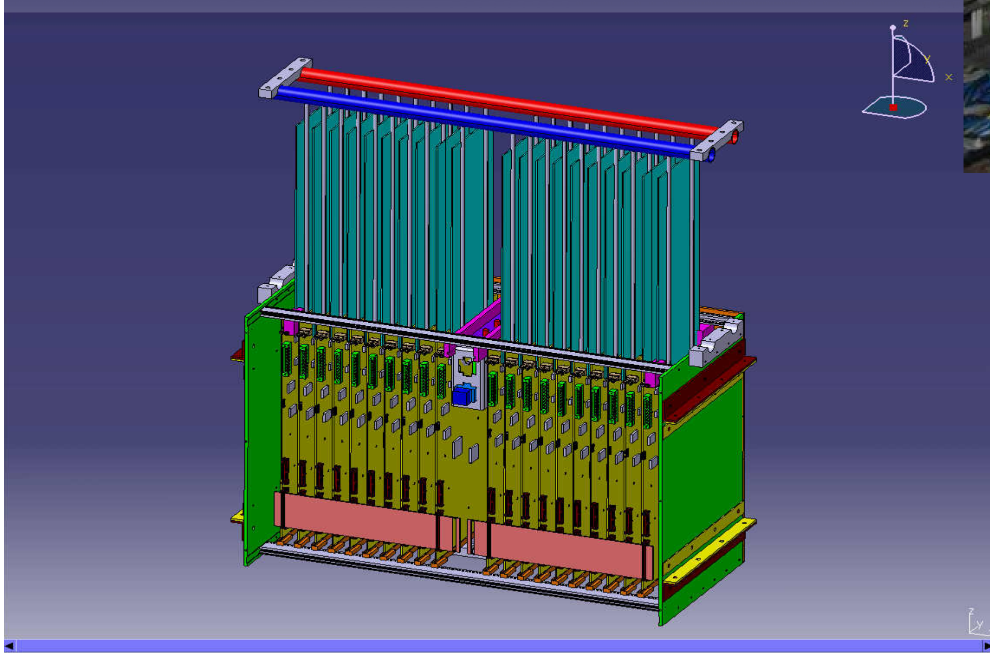


Signal from Preamp is transmitted over ribbon cable to Front End Electronics (FEE)

EMCal SMs Installed



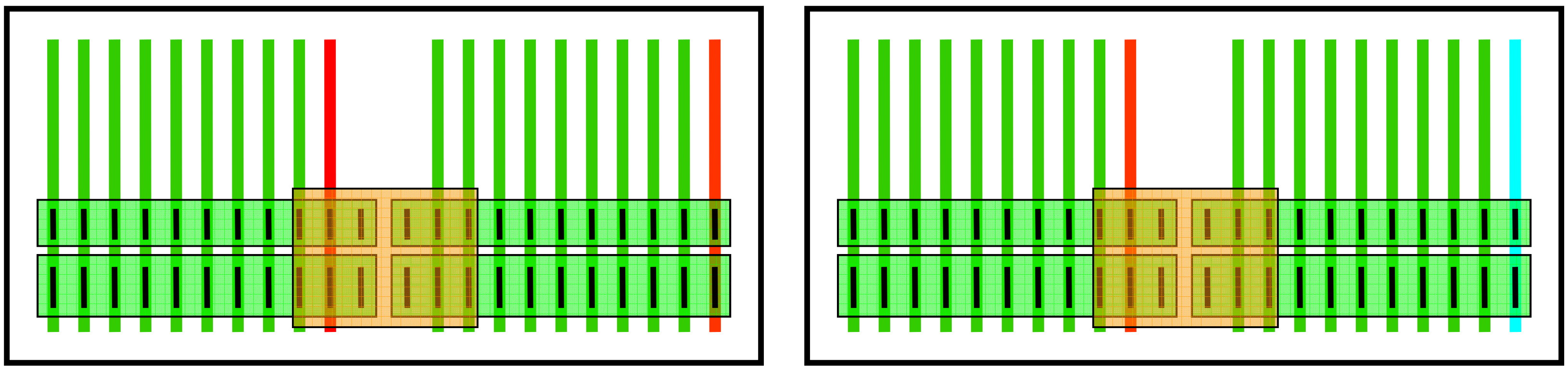




EMCal SM Readout

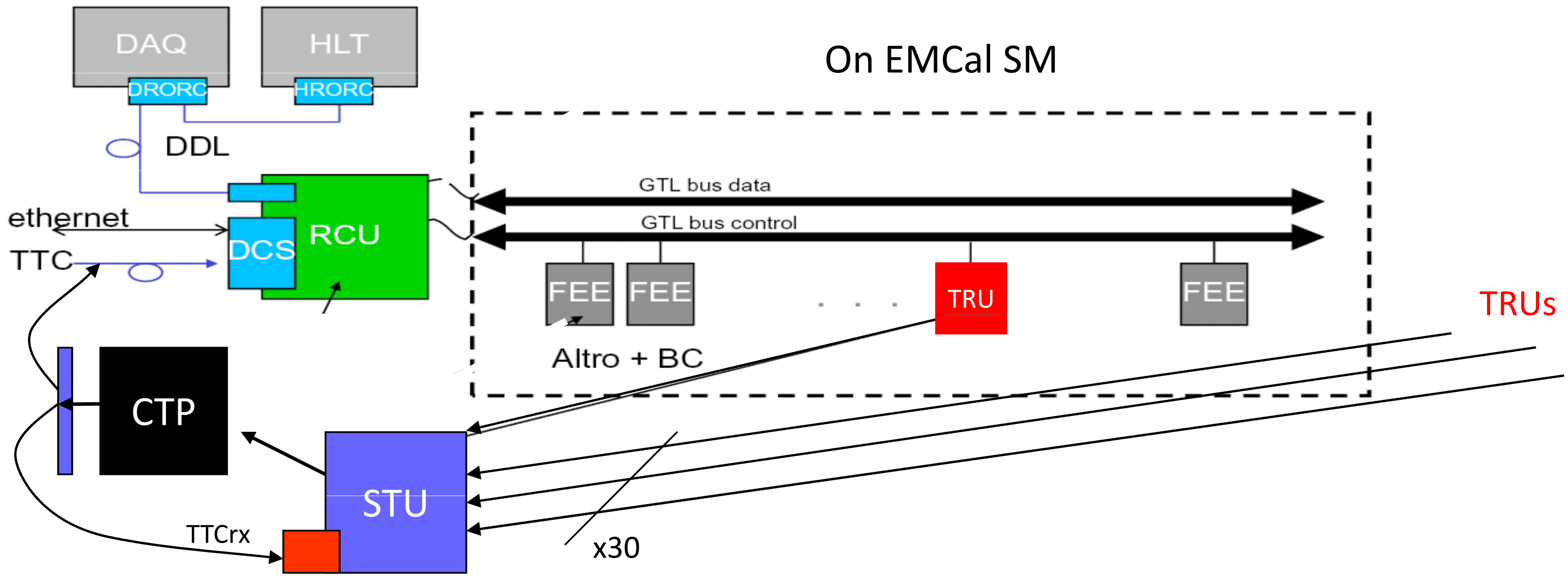
2 FEE Crates of SM

FEE
TRU
LEDRef



- Two FEE crates (2 RCUs) each with 2 GTL Buses with 9 FEE cards.
- A group of 12 FEE cards is connected to a Trigger Region Unit (TRU).
- An extra FEE card is installed at 4th TRU location to readout LED reference photodiodes.

EMCal Trigger

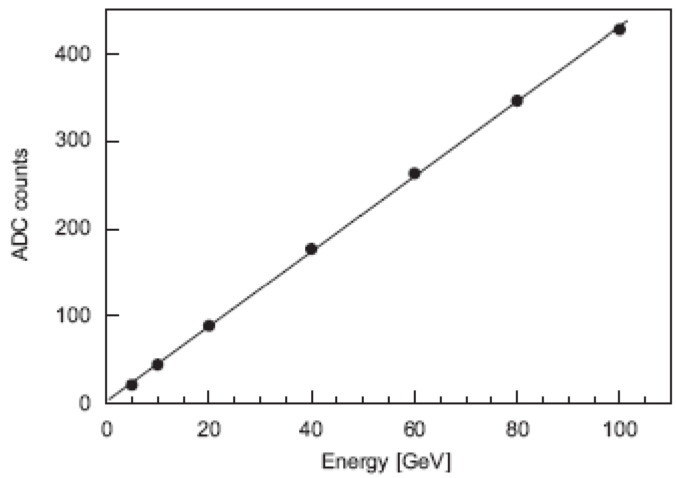


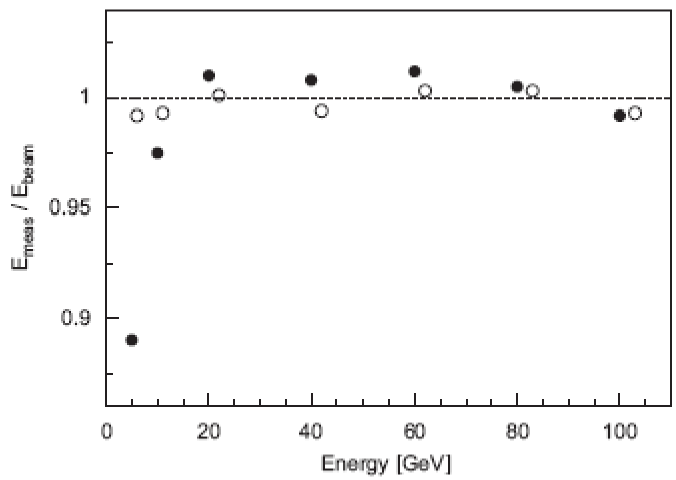
- Trigger Region Unit (TRU):
  - Flash digitizes analog energy sum of 2x2 towers (a module) input from 12 FEE cards
  - Zero subtraction, time-space sums, thresholds, peak detects, provides L0, and 2x2 time sum data shipped to STU
- Summary Trigger Unit (STU):
  - Performs "OR" of L0 signals from TRUs
  - Performs L1 single shower & jet trigger with multiplicity dependent (V0) threshold

II - d) Results from test beams

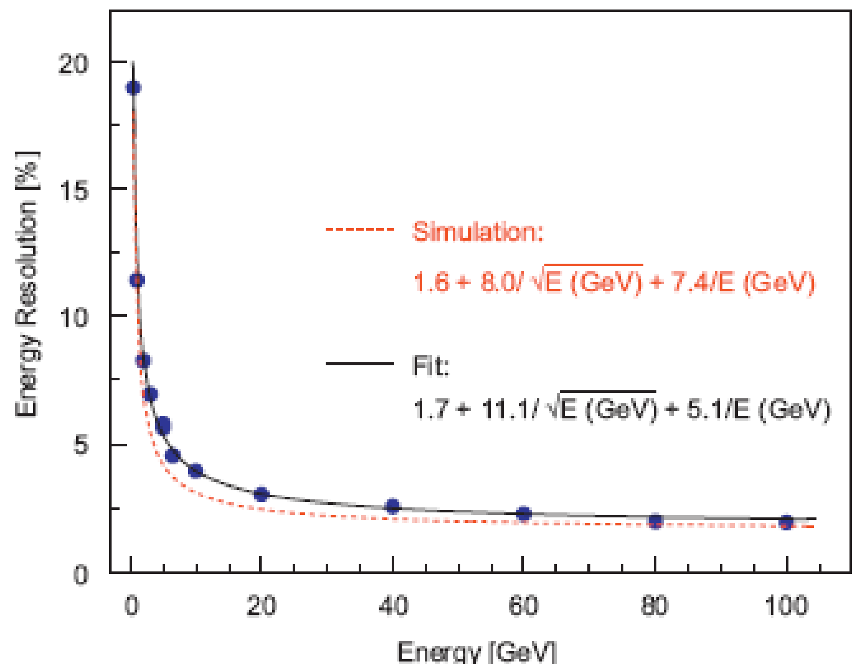
EMCAL prototypes (4 modules x 4 strips) under test beams:

FNAL, November 2005 & SPS + PS, September - October 2007





Linearity better than 1% above 20 GeV (3x3 tower cluster)

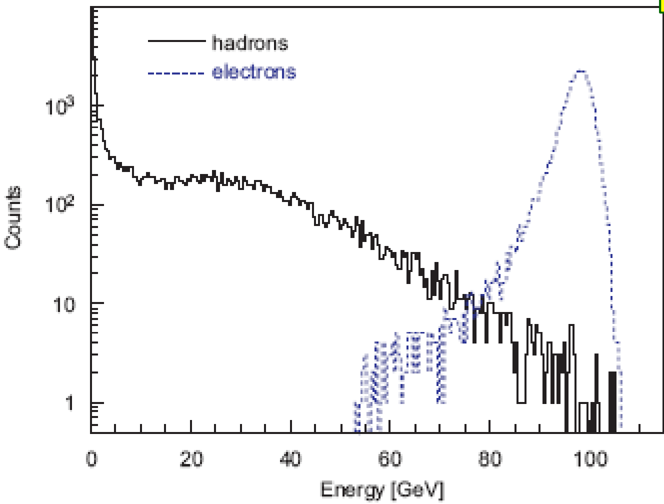


Energy resolution for electrons as a function of the incident beam momentum:

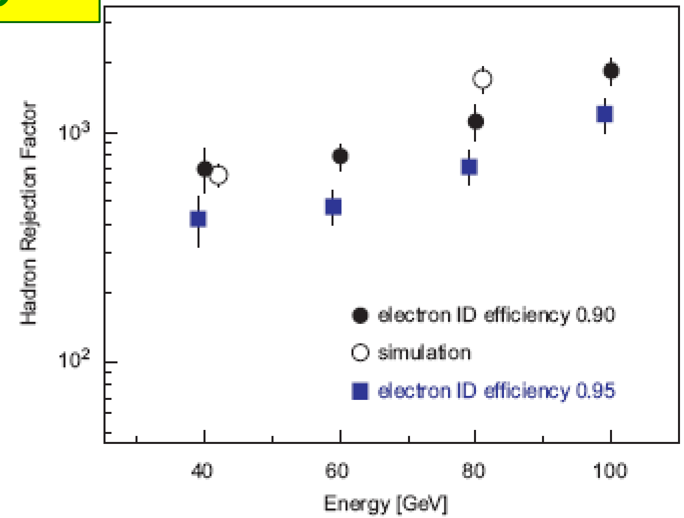
$$\sigma(E)/E = 1.7 + 11/\sqrt{E} + 5.1/E$$

NIM A 615 (2010) 6

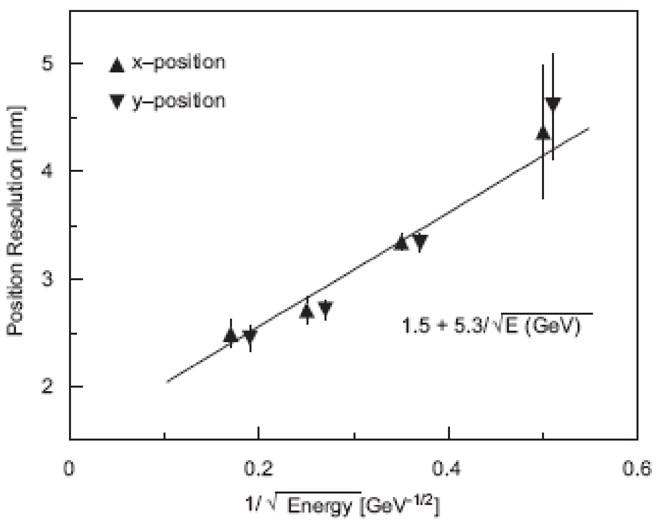
NIM A 615 (2010) 6



EMCAL response to *h* and *e*$^-$

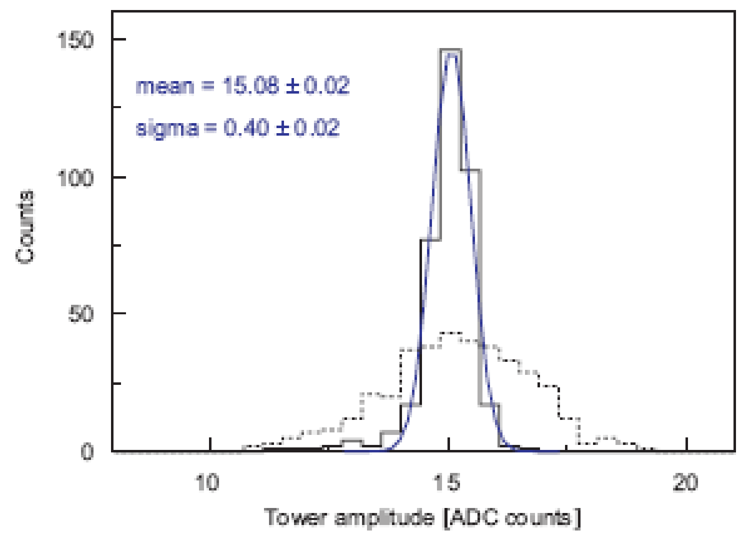


Hadron Rejection Factor 10^2-10^3



Position Resolution (mm):

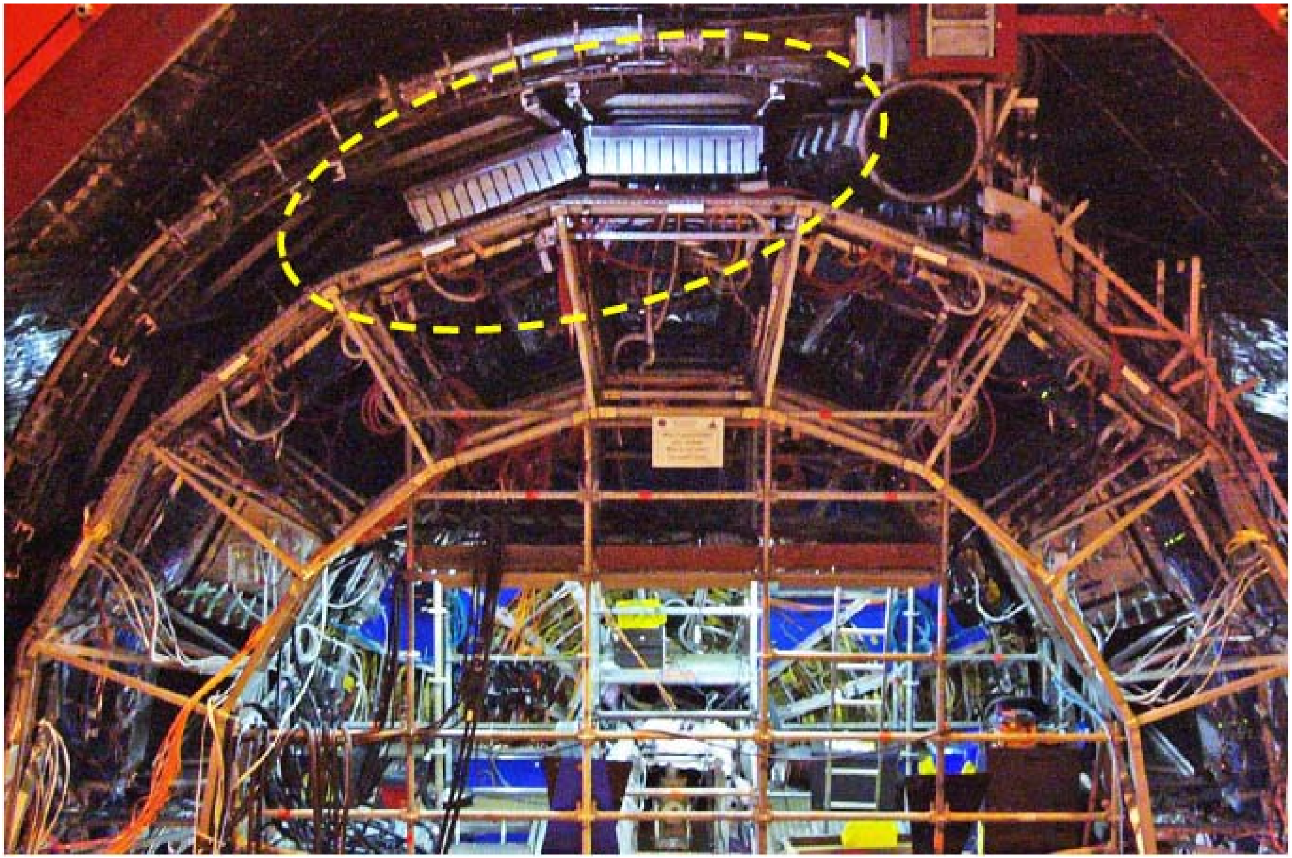
$$\Delta x = \Delta y = 1.5 + 5.3 / \sqrt{E}$$



Response of 384 towers before/after gain calibration

II - e) The EMCAL Status

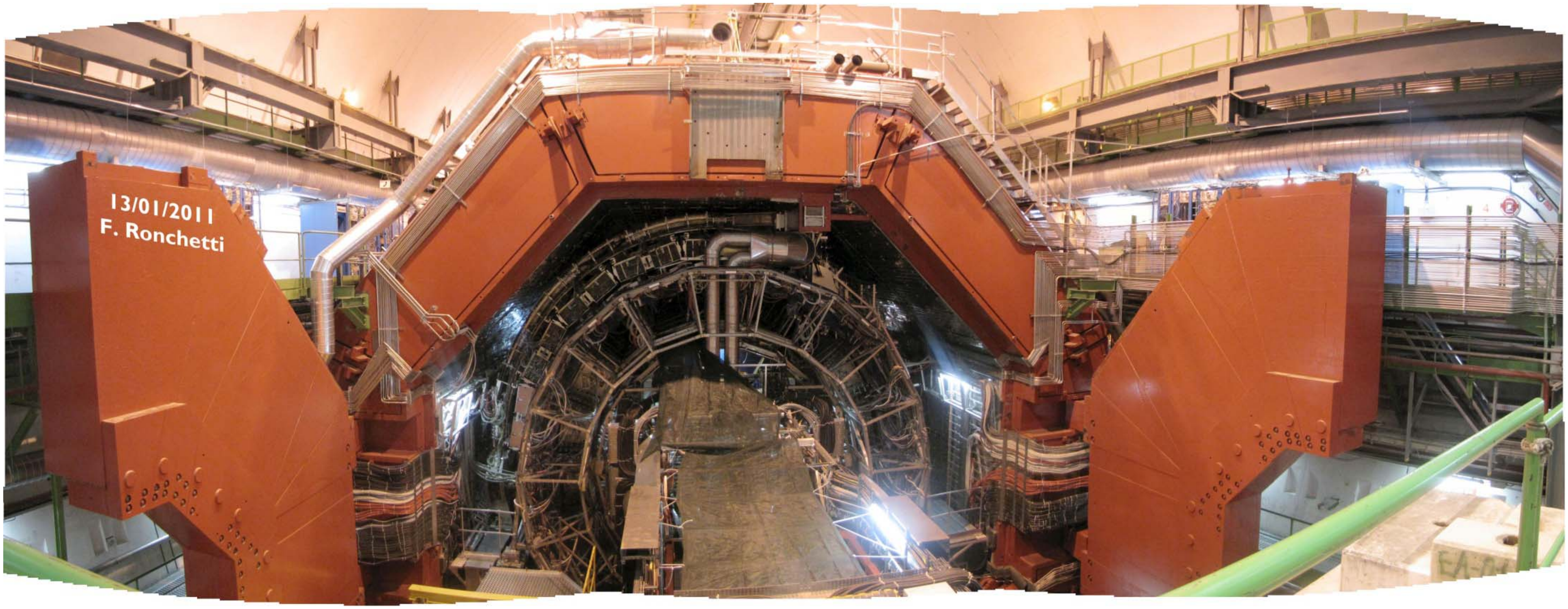
Installion of 2 SMs in ALICE in March 2009 and 2 SMs in July 2009 for 2010 data taking



EMCAL Collaboration
= USA + Europe
(France and Italy)

4 SMs installed in ALICE (2 in March and 2 in July 2009), operational and taking data in 2010

installed coverage: $\Delta\eta$ = 1.4 ; $\Delta\phi$ = 40°

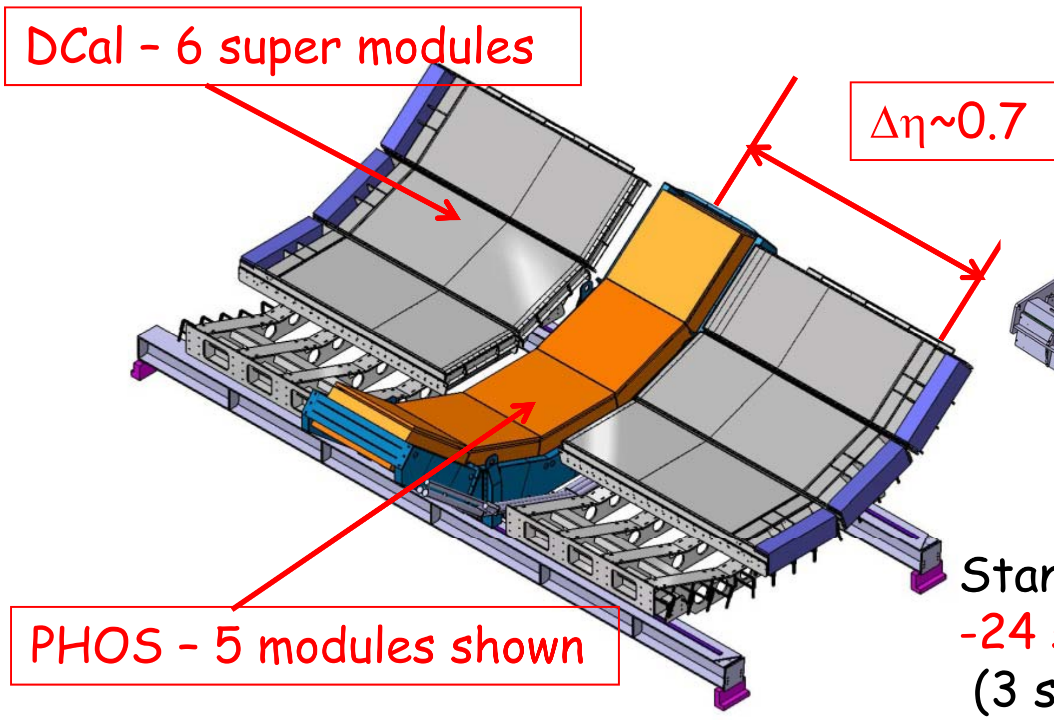


- Assembly of EMCAL modules completed in summer 2010
- strip-modules prepared & tested
- Supermodules assembled, tested & calibrated with LED and cosmics

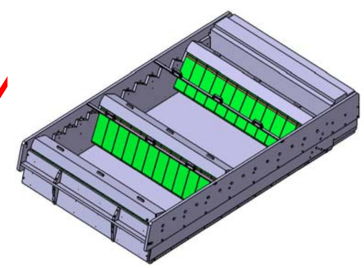
- 6 SMs installed in January 2011 during winter shutdown in 2 weeks
- All 10 EMCAL Supermodules installed in ALICE and operational ➔ EMCAL completed!!
- All 10 EMCAL Supermodules operational in 2011 data taking

II – f) EMCAL extension: DCAL

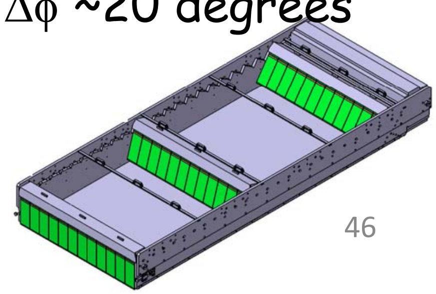
Despite EMCal being the last ALICE detector proposed, approved assembled, and (still partially) installed ....the first upgrade approved (by November 2009) by the ALICE collaboration is ..... an extension of EMCal → DCal back to back with EMCal for jet-jet and γ-jet physics



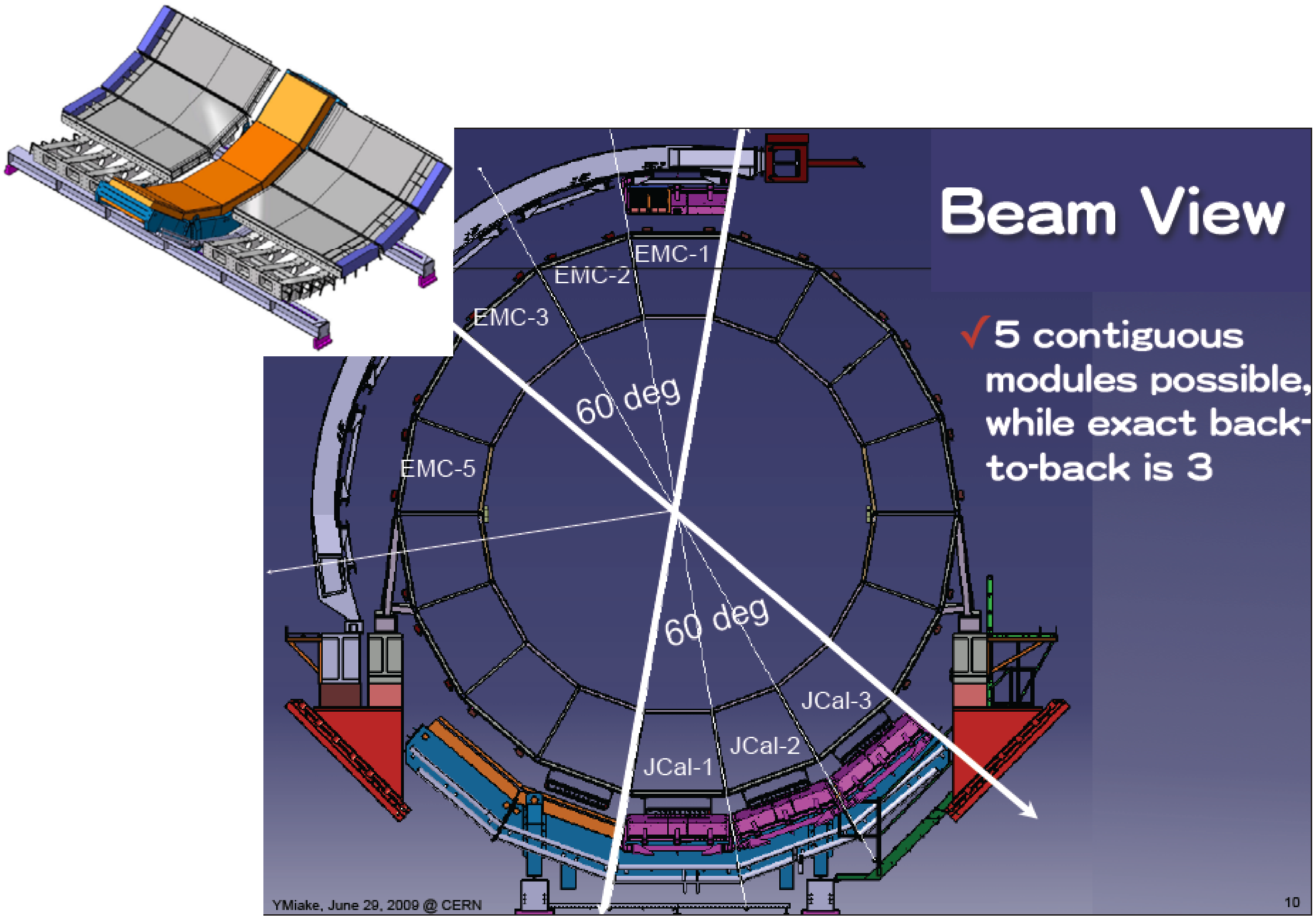
DCAL modules:
Same technology of EMCal
Shorter SM (2/3 of EMCal SM)



Shortened DCal SM
-16 strip modules
(2 shown)
- Installed η= 0 to ~0.7 (including PHOS)
- $\Delta\phi$ ~20 degrees



Standard EMCal SM
-24 strip modules
(3 shown)



DCAL Collaboration
= EMCAL Collab.
+ China (Wuhan)
+ Japan (Tsukuba)

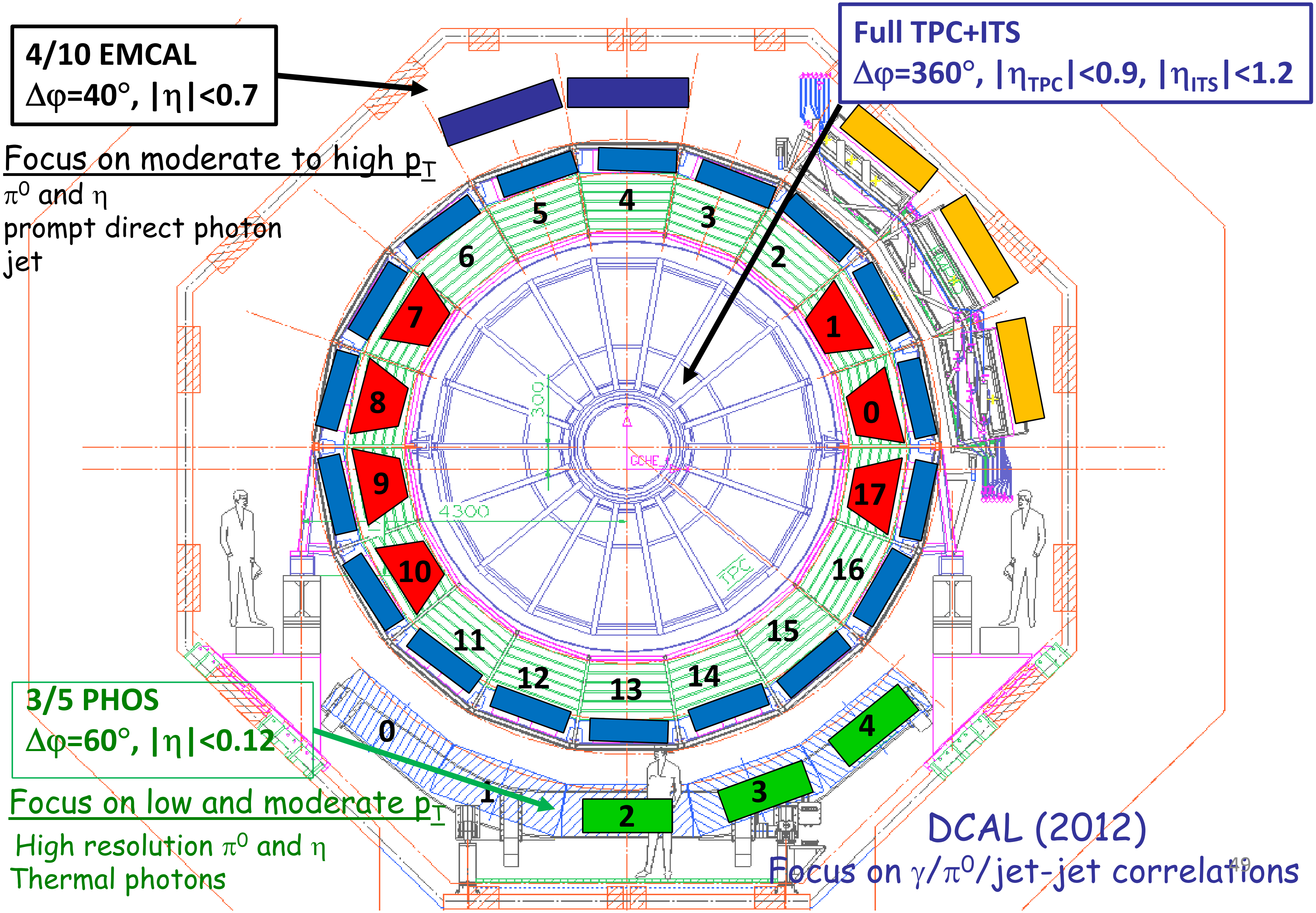
Focus on γ/π^0/jet-jet correlations

Assembly of DCAL modules started in summer 2010, all modules assembled, strips in preparation
Strips assembly and Supermodules assembly expected to be completed before autumn 2011, ready to be installed for 2012 runs (in case..)

II – g) EMCAL Performance plots

- Inclusive spectrum of π^0 production in pp collisions at 900 GeV and 7 TeV in mid-rapidity and p_T range from 0.3-0.5 to 20-30 GeV/c
- Measure inclusive spectrum of η and other neutral mesons production in pp collisions at 7 TeV in p_T range from 3-5 to 15-20 GeV/c
- Physics:
  - Constrain pQCD and non perturbative aspects of QCD
  - Provide reference spectrum for Pb-Pb collisions at 2.76 TeV

ALICE setup for 2010



Neutral meson measurement in ALICE

- ALICE provides 3 independent ways to identify π^0 and η mesons through invariant mass analysis of photon pairs and external conversion electrons:
  - h -> $\gamma\gamma$ (both on PHOS or EMCAL)
  - h -> $\gamma\gamma$
    └→ e^+e^- (CTS, PHOS or EMCAL)
  - h-> $\gamma\gamma$
    └→ e^+e^- └→ e^+e^- (CTS)

CTS = Central Tracking System

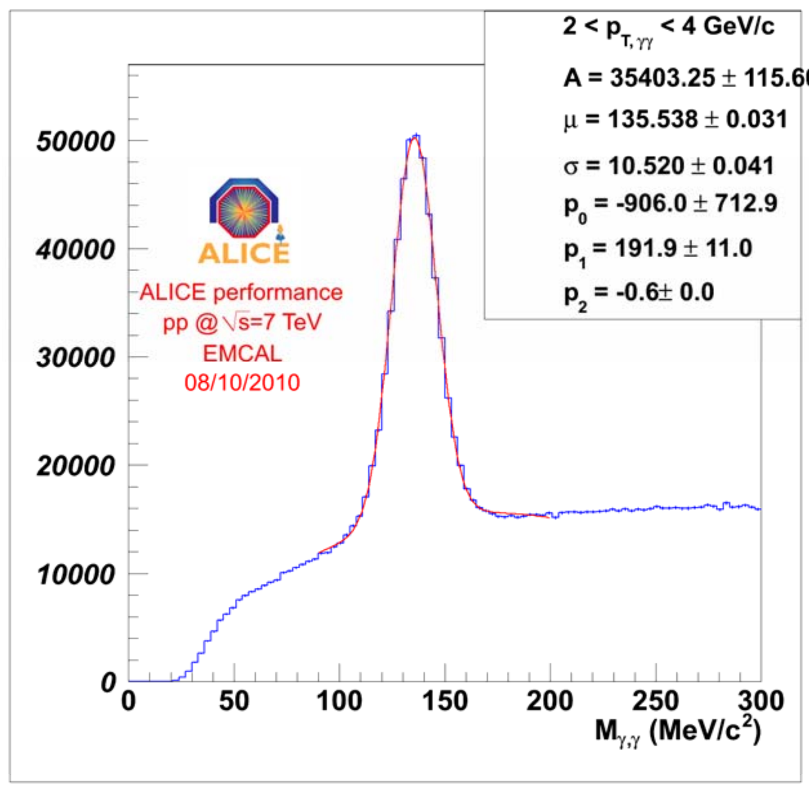
- Method of 2 γ invariant mass analysis works for γ registered in EMCAL up to p_T~15 GeV/c

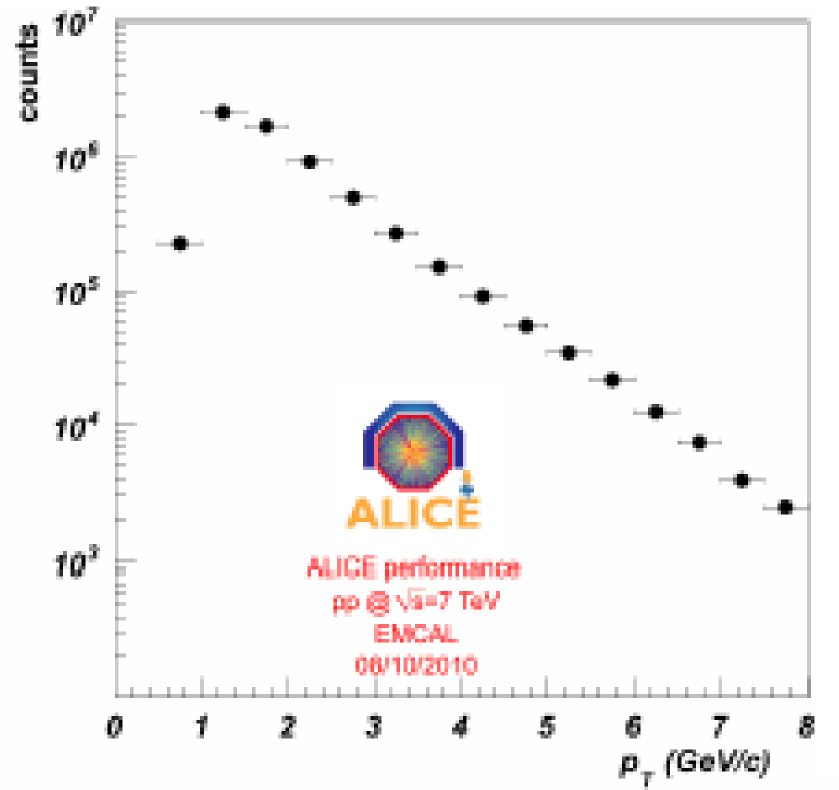
π^0, η direct photon spectra

$h \rightarrow \gamma + \gamma$

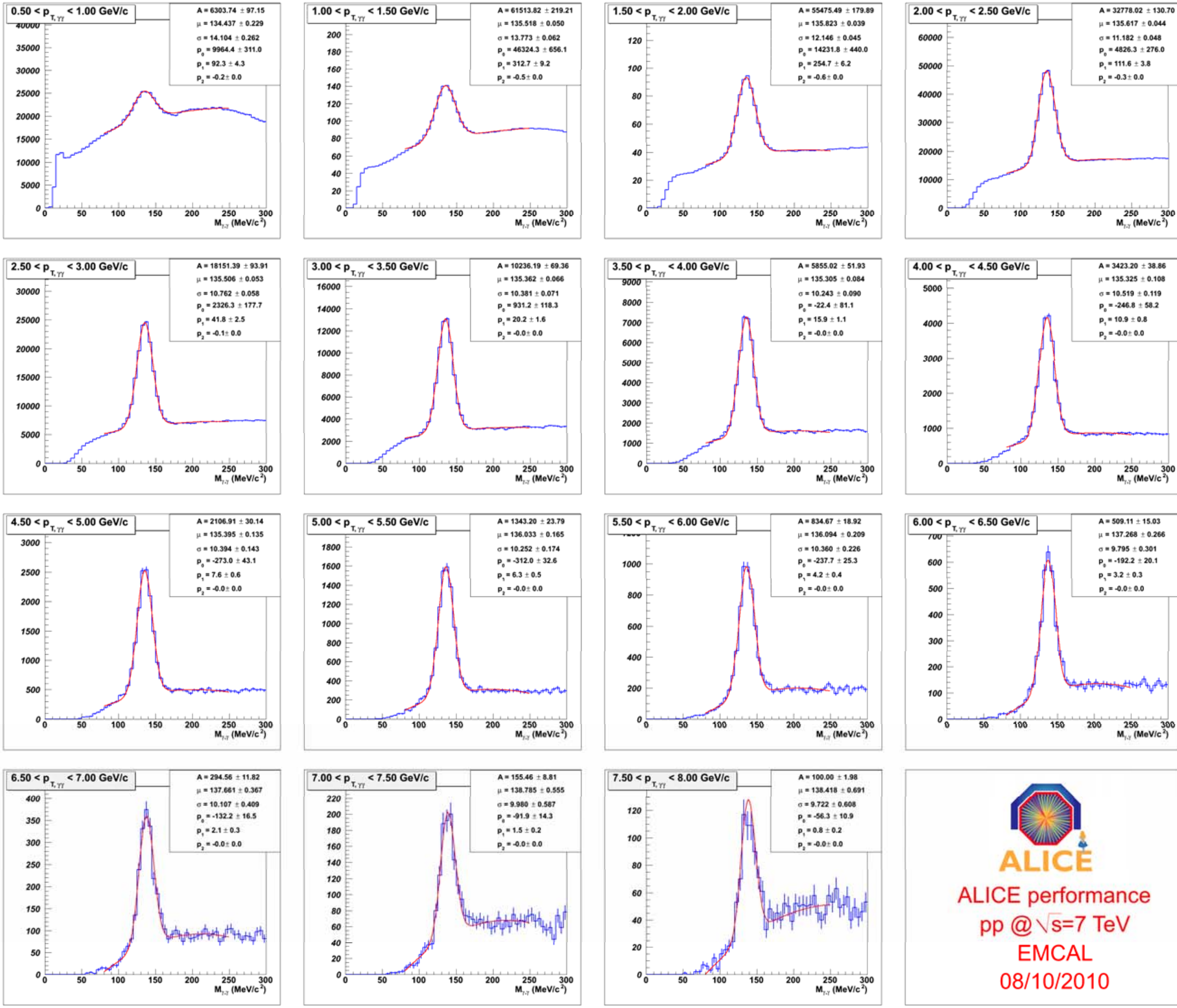
π^0

- pp @ 7 TeV, LHC10e pass, 180 Mevents
- cluster selection: N_{cell}=2, E_{cl}>0.5 GeV



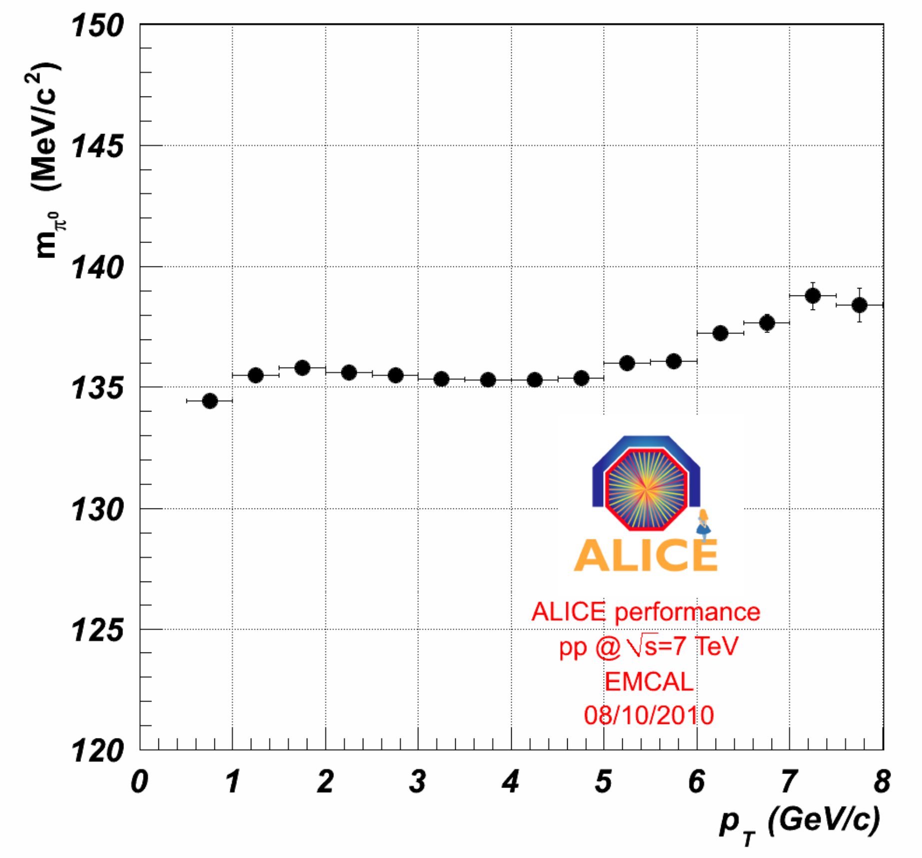


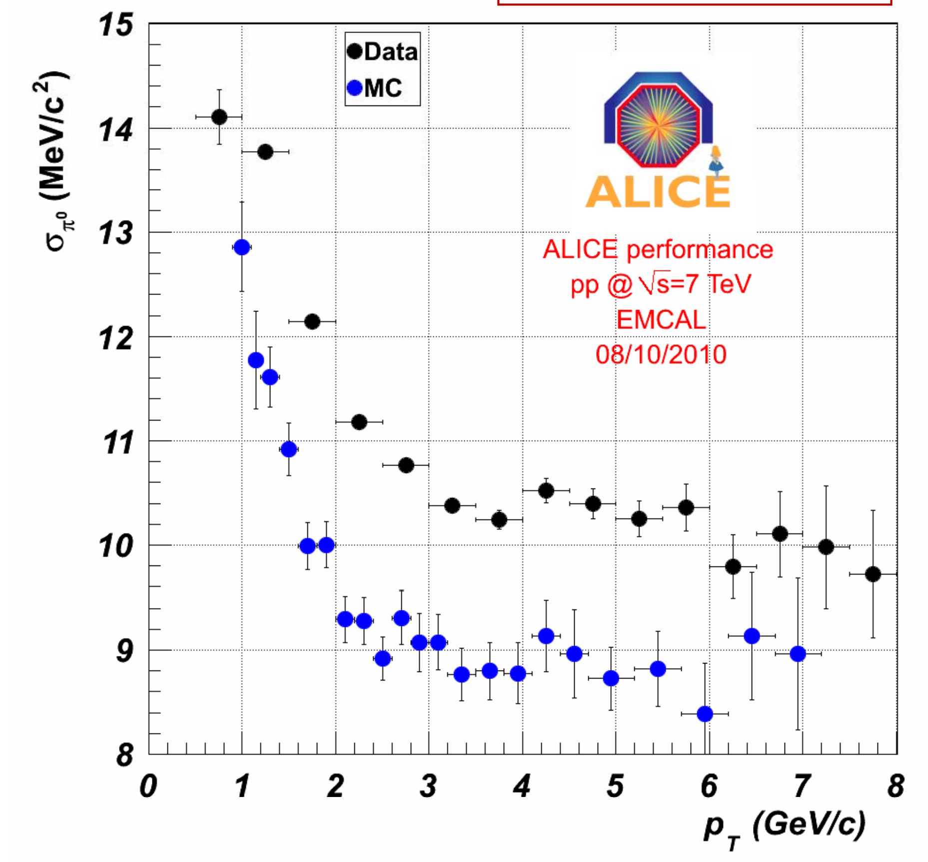
p_T reach ~10 GeV/c due to size of cells and clusterized used
Fit = Gauss + Polynomial 2nd order


0.50 < p_T,γγ < 1.00 GeV/c
A = 6303.74 ± 97.15
μ = 134.437 ± 0.229
σ = 14.104 ± 0.262
p0 = 9964.4 ± 311.0
p1 = 92.3 ± 4.3
p2 = -0.2± 0.0
1.00 < p_T,γγ < 1.50 GeV/c
A = 61513.82 ± 219.21
μ = 135.518 ± 0.050
σ = 13.773 ± 0.062
p0 = 46324.3 ± 656.1
p1 = 312.7 ± 9.2
p2 = -0.5± 0.0
1.50 < p_T,γγ < 2.00 GeV/c
A = 55475.49 ± 179.89
μ = 135.823 ± 0.039
σ = 12.146 ± 0.045
p0 = 14231.8 ± 440.0
p1 = 254.7 ± 6.2
p2 = -0.6± 0.0
2.00 < p_T,γγ < 2.50 GeV/c
A = 32778.02 ± 130.70
μ = 135.617 ± 0.044
σ = 11.182 ± 0.048
p0 = 4826.3 ± 276.0
p1 = 111.6 ± 3.8
p2 = -0.3± 0.0
2.50 < p_T,γγ < 3.00 GeV/c
A = 18151.39 ± 93.91
μ = 135.506 ± 0.053
σ = 10.762 ± 0.058
p0 = 2326.3 ± 177.7
p1 = 41.8 ± 2.5
p2 = -0.1± 0.0
3.00 < p_T,γγ < 3.50 GeV/c
A = 10236.19 ± 69.36
μ = 135.362 ± 0.066
σ = 10.381 ± 0.071
p0 = 931.2 ± 118.3
p1 = 20.2 ± 1.6
p2 = -0.0± 0.0
3.50 < p_T,γγ < 4.00 GeV/c
A = 5855.02 ± 51.93
μ = 135.305 ± 0.084
σ = 10.243 ± 0.090
p0 = -22.4 ± 81.1
p1 = 15.9 ± 1.1
p2 = -0.0± 0.0
4.00 < p_T,γγ < 4.50 GeV/c
A = 3423.20 ± 38.86
μ = 135.325 ± 0.108
σ = 10.519 ± 0.119
p0 = -246.8 ± 58.2
p1 = 10.9 ± 0.8
p2 = -0.0± 0.0
4.50 < p_T,γγ < 5.00 GeV/c
A = 2106.91 ± 30.14
μ = 135.395 ± 0.135
σ = 10.394 ± 0.143
p0 = -273.0 ± 43.1
p1 = 7.6 ± 0.6
p2 = -0.0± 0.0
5.00 < p_T,γγ < 5.50 GeV/c
A = 1343.20 ± 23.79
μ = 136.033 ± 0.165
σ = 10.252 ± 0.174
p0 = -312.0 ± 32.6
p1 = 6.3 ± 0.5
p2 = -0.0± 0.0
5.50 < p_T,γγ < 6.00 GeV/c
A = 834.67 ± 18.92
μ = 136.094 ± 0.209
σ = 10.360 ± 0.226
p0 = -237.7 ± 25.3
p1 = 4.2 ± 0.4
p2 = -0.0± 0.0
6.00 < p_T,γγ < 6.50 GeV/c
A = 509.11 ± 15.03
μ = 137.268 ± 0.266
σ = 9.795 ± 0.301
p0 = -192.2 ± 20.1
p1 = 3.2 ± 0.3
p2 = -0.0± 0.0
6.50 < p_T,γγ < 7.00 GeV/c
A = 294.56 ± 11.82
μ = 137.661 ± 0.367
σ = 10.107 ± 0.409
p0 = -132.2 ± 16.5
p1 = 2.1 ± 0.3
p2 = -0.0± 0.0
7.00 < p_T,γγ < 7.50 GeV/c
A = 155.46 ± 8.81
μ = 138.785 ± 0.555
σ = 9.980 ± 0.587
p0 = -91.9 ± 14.3
p1 = 1.5 ± 0.2
p2 = -0.0± 0.0
7.50 < p_T,γγ < 8.00 GeV/c
A = 100.00 ± 1.98
μ = 138.418 ± 0.691
σ = 9.722 ± 0.608
p0 = -56.3 ± 10.9
p1 = 0.8 ± 0.2
p2 = -0.0± 0.0
M_γγ (MeV/c²)
ALICE
ALICE performance
pp @ √s=7 TeV
EMCAL
08/10/2010

$h \rightarrow \gamma + \gamma$

π^0





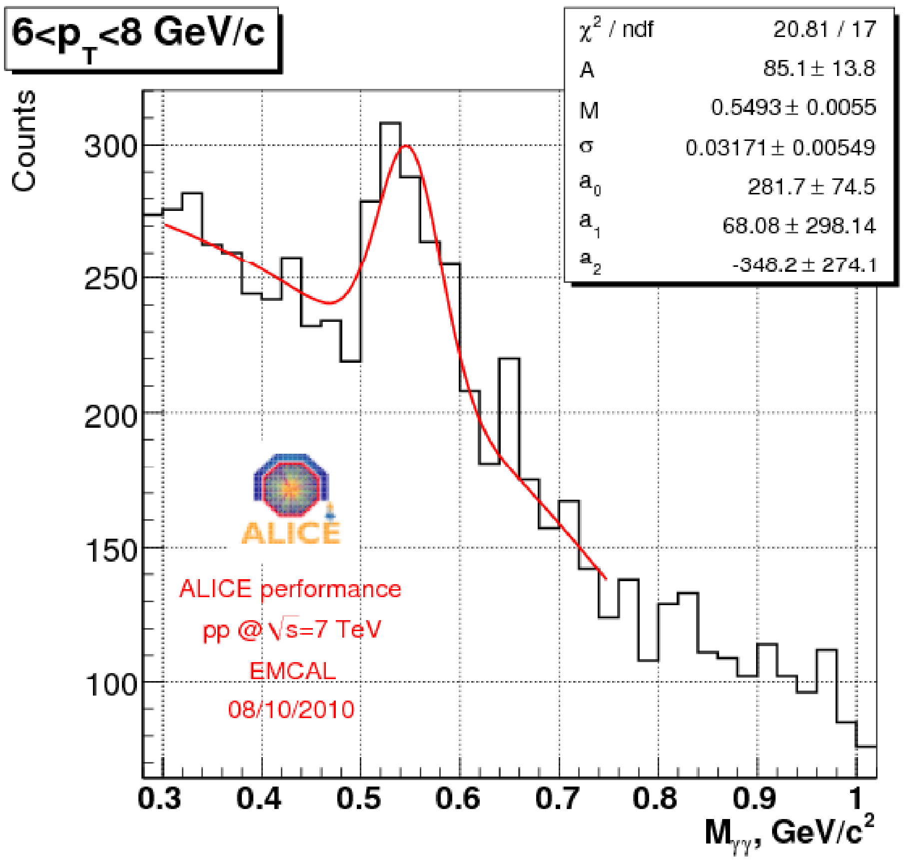
- Good linearity before clusters start to merge (~5GeV/c)
- Non final calibration results in non-optimal resolution

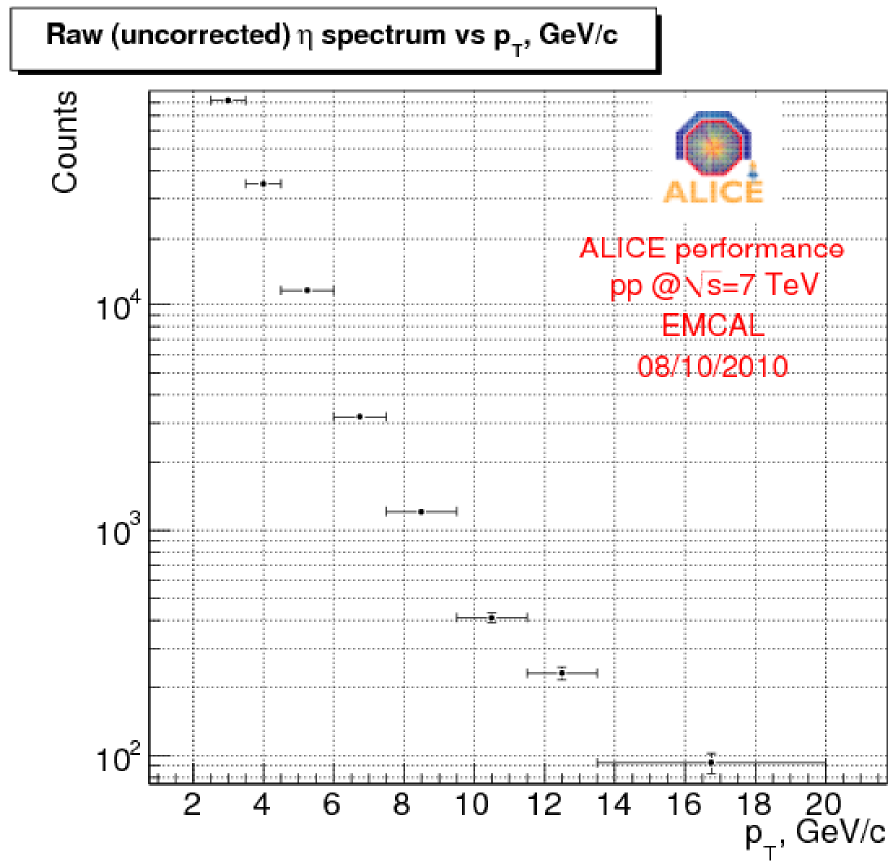
Working in progress for better tuning

$h \to \gamma + \gamma$

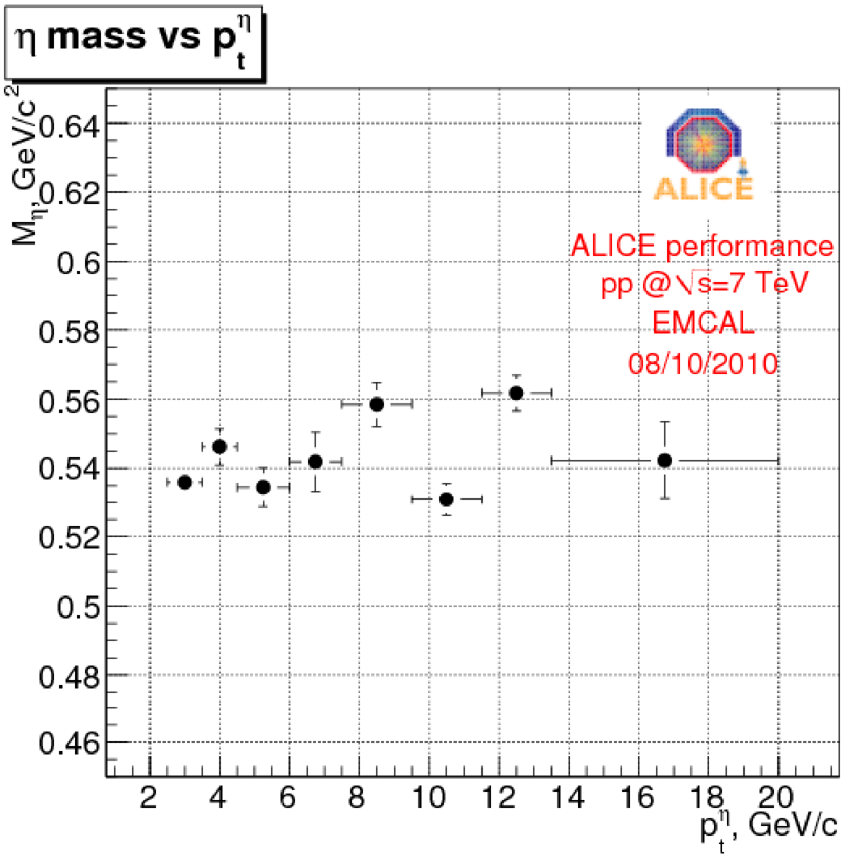
η

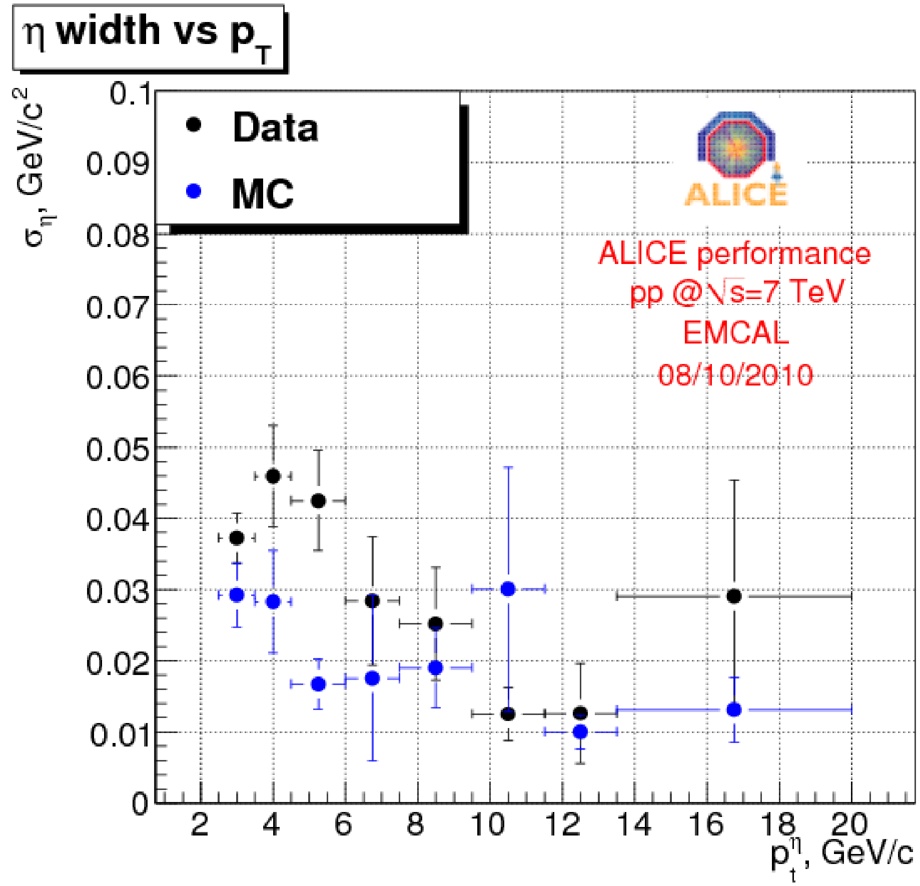
- pp @ 7 TeV, LHC10e pass, 180 Mevents
- cluster selection: $N_{cell}=2$, $E_{cl}>0.3$ GeV





h-> γ+γ
η





EMCAL able to measure η mesons in the range $2<p_T<20$ GeV/c

6. EMCAL Physics Capabilities

EMCal extends the scope of the ALICE experiment for jet quenching :

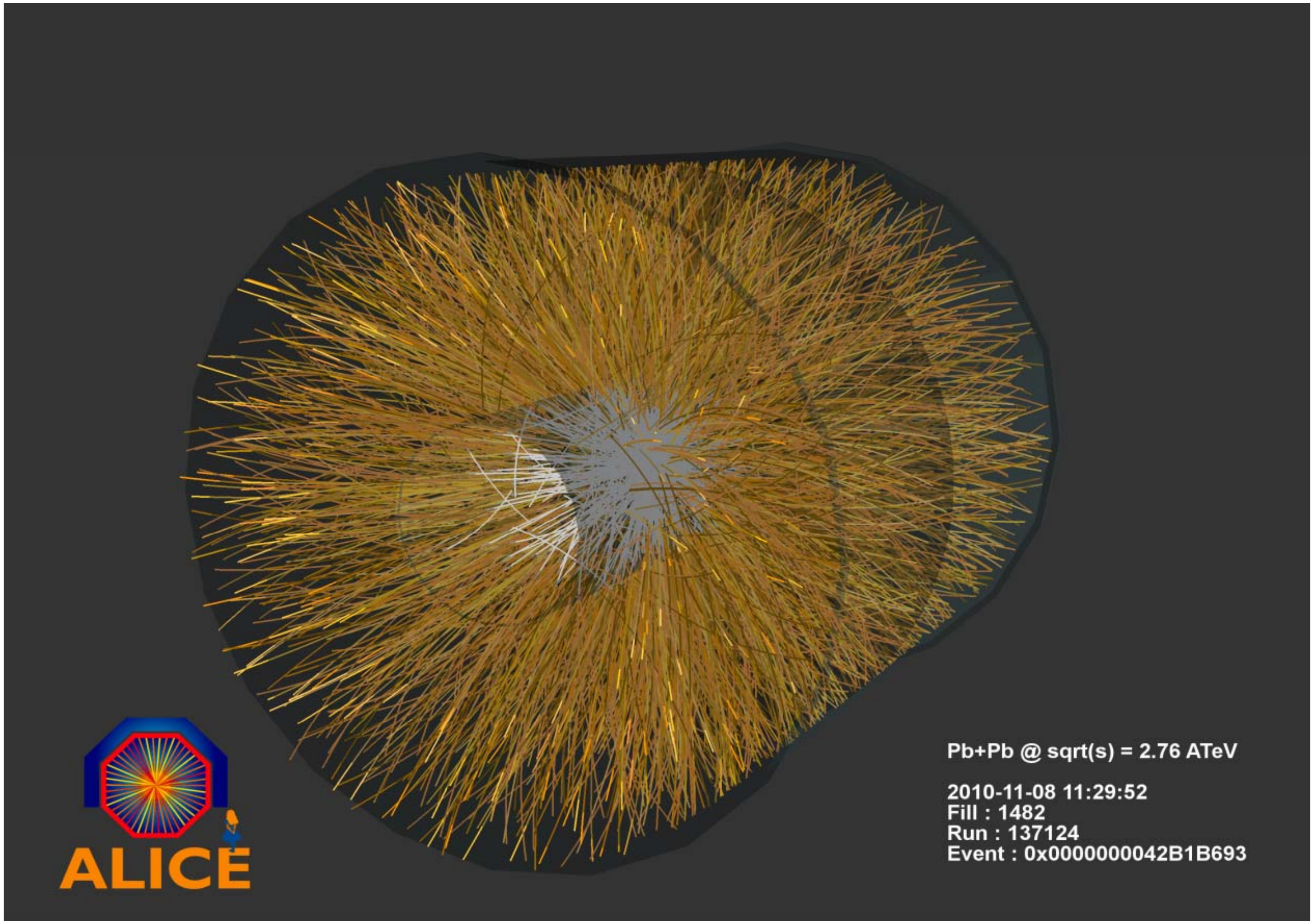
- EMCal provides a fast, efficient trigger for high p_T jets, γ (π^0), electrons
$\Rightarrow$ recorded yields enhanced by factor ~10-60

	L^{max} ($cm^{-2}s^{-1}$)	interaction rate	max rate to tape	EMCal enhancement	
				e,γ,π^0	jet
Pb+Pb	1.0×10^{27}	8 kHz	100 Hz	14	10
Ar+Ar	0.6×10^{29}	130 kHz	500 Hz	44	31
O+O	2.0×10^{29}	220 kHz	500 Hz	75	53
p+p	5.0×10^{30}	200 kHz	500 Hz	68	48

- EMCal markedly improves jet reconstruction through measurement of e.m. fraction of jet energy with less bias

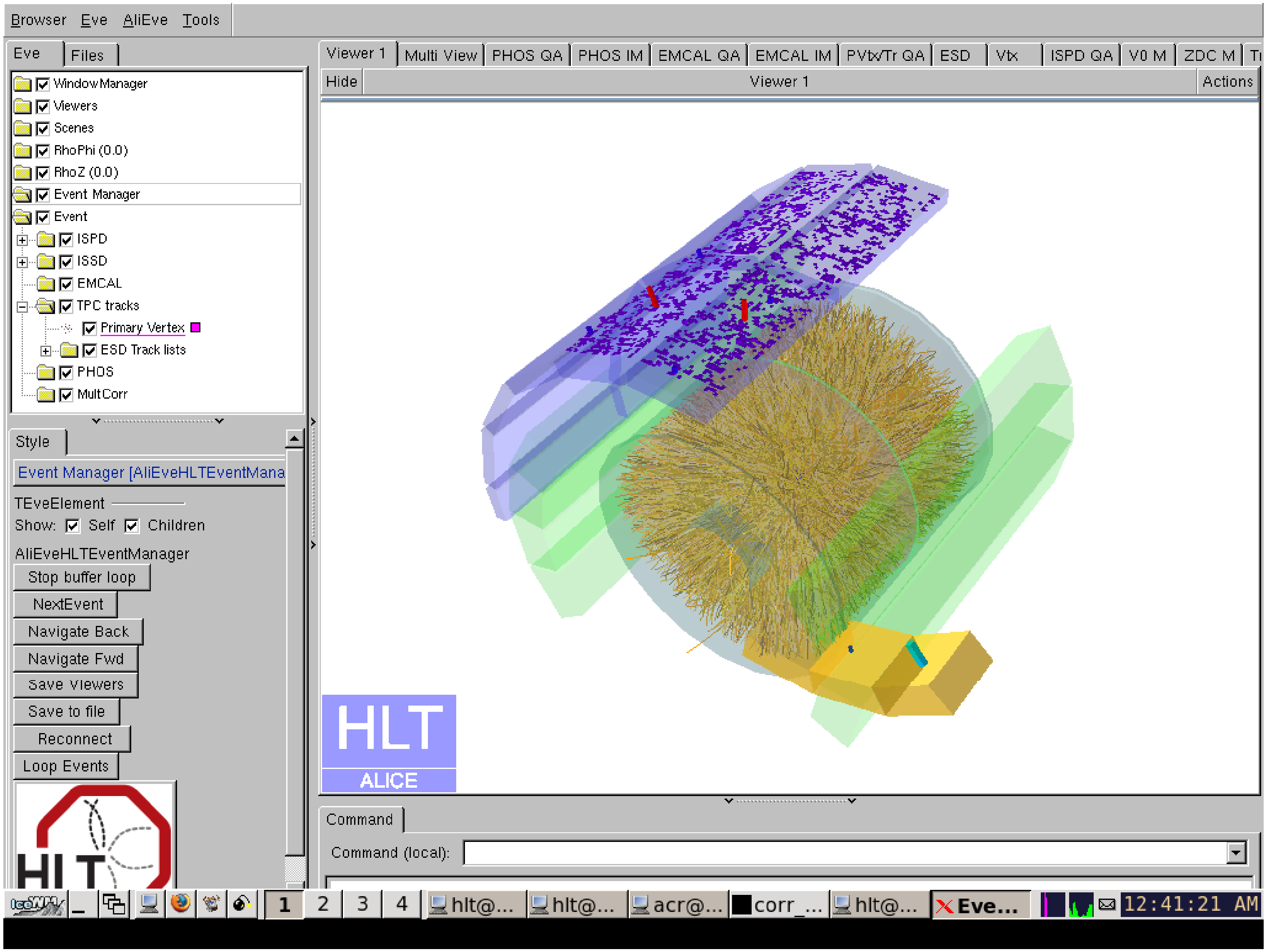
- EMCal provides good γ/π^0 discrimination, augmenting ALICE direct photon capabilities at high p_T

- EMCal provides good electron/hadron discrimination, augmenting and extending to high p_T the ALICE capabilities for heavy quark jet quenching measurements



Monday Nov. 18th @ 11:20 LHC declared
"Stable beam with ions" Pb-Pb @ 2.76 TeV

EMCAL ready .....



EMCAL HLT

One of the first Pb-Pb collisions @ 2.76 TeV from ALICE High Level Trigger display

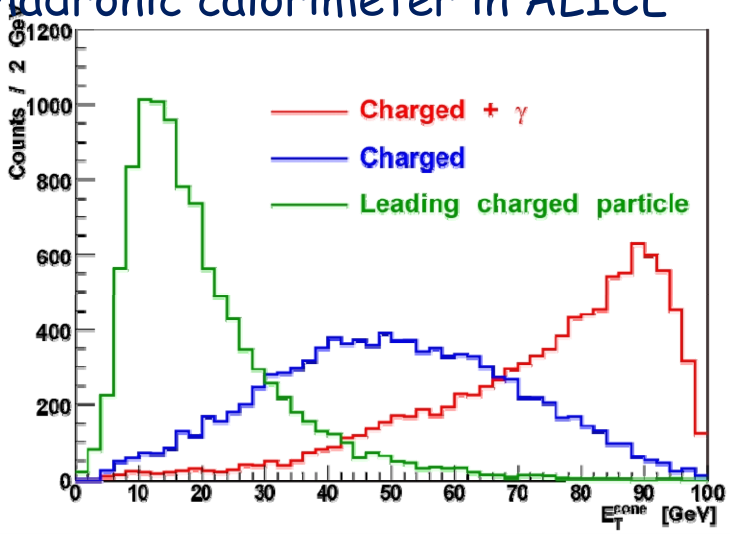
EMCAL able to run with the rest of ALICE

EMCAL: last detector installed, short time for developing HLT

➡ very good starting point!!!

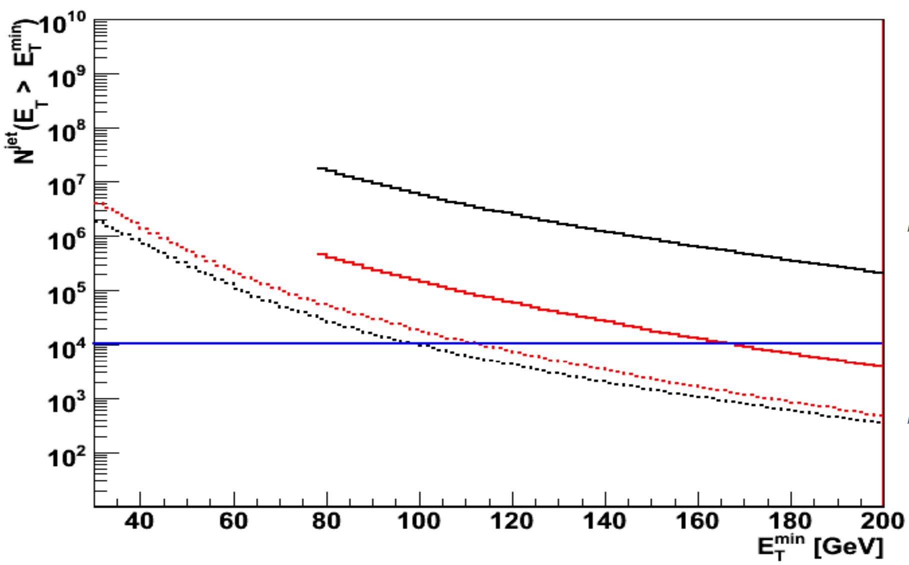
EMCAL for Jet reconstruction

Typical jet reconstruction : combination of e.m and hadronic calorimeters, but no hadronic calorimeter in ALICE



- Hadronic energy: charged tracks (TPC/ITS)
- Electromagnetic energy: EMCal
- Corrections:
  - unmeasured hadrons (n, K^0_L,...) (<10%)
  - hadronic energy (25%) in EMCal

Possibility to measure the neutral components of the jets

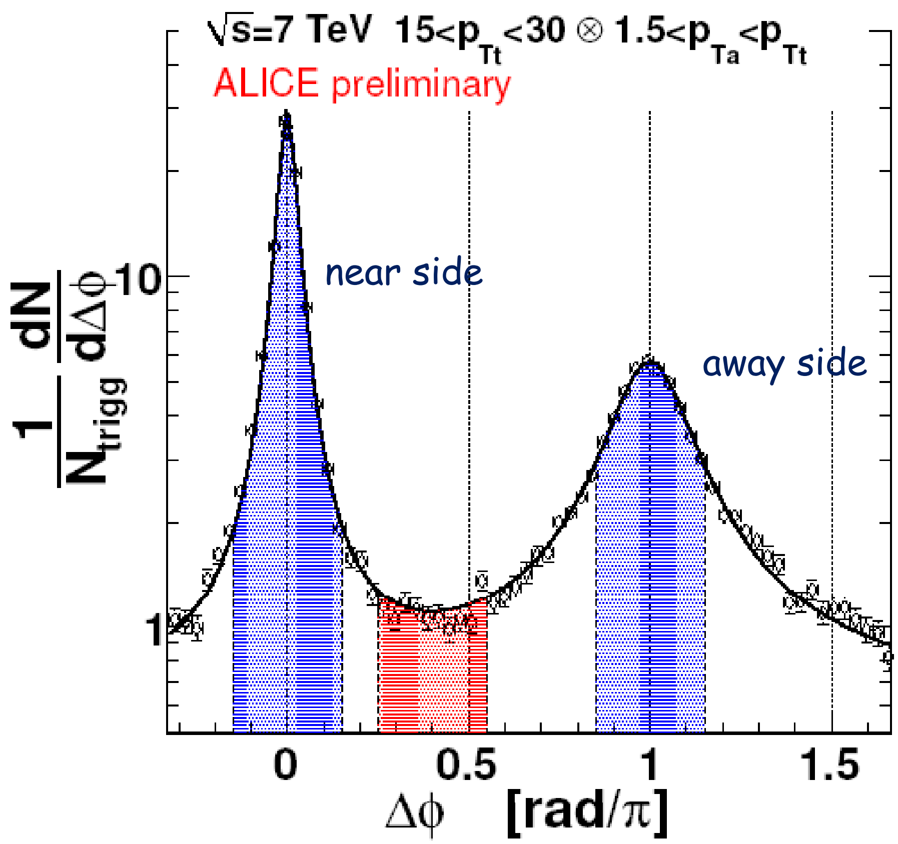


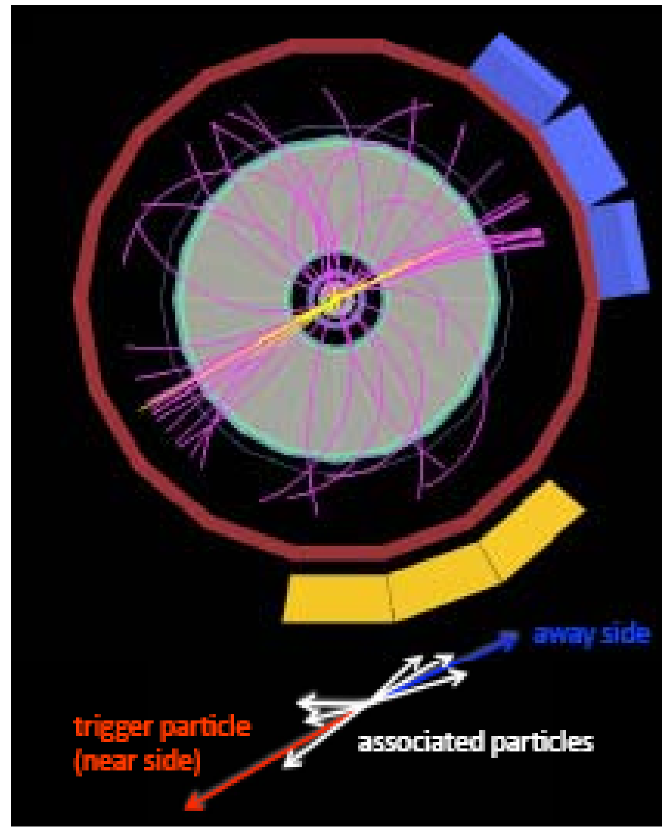
Track + Calo

Charged only

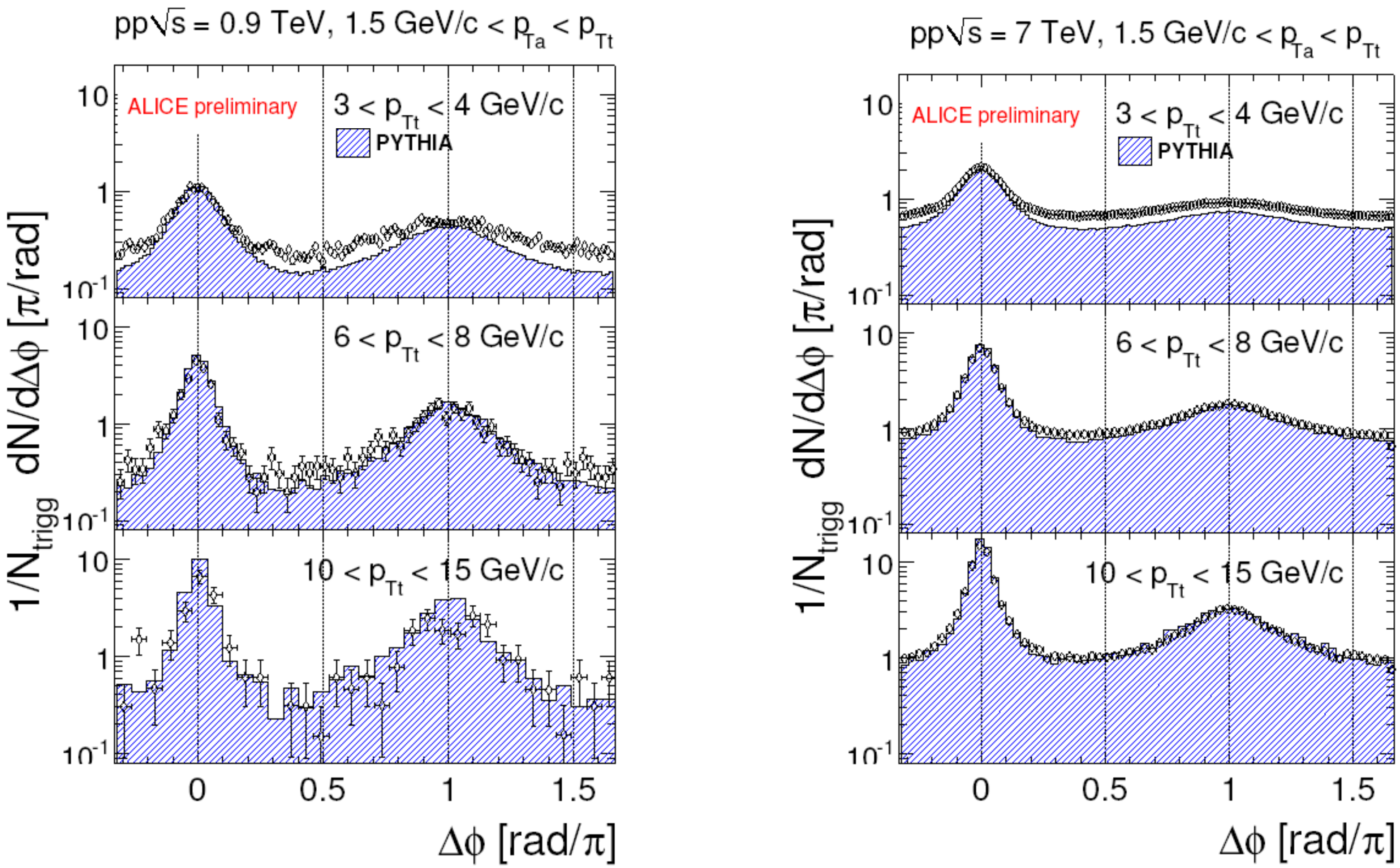
	Charged	Charged + neutral
RMS [GeV]	21	15
E_{cone}/E_T	0.50	0.77
Efficiency	67%	80%

Particle correlation ⟹ access to jet properties in kinematical regions where full jet recontruction is difficult

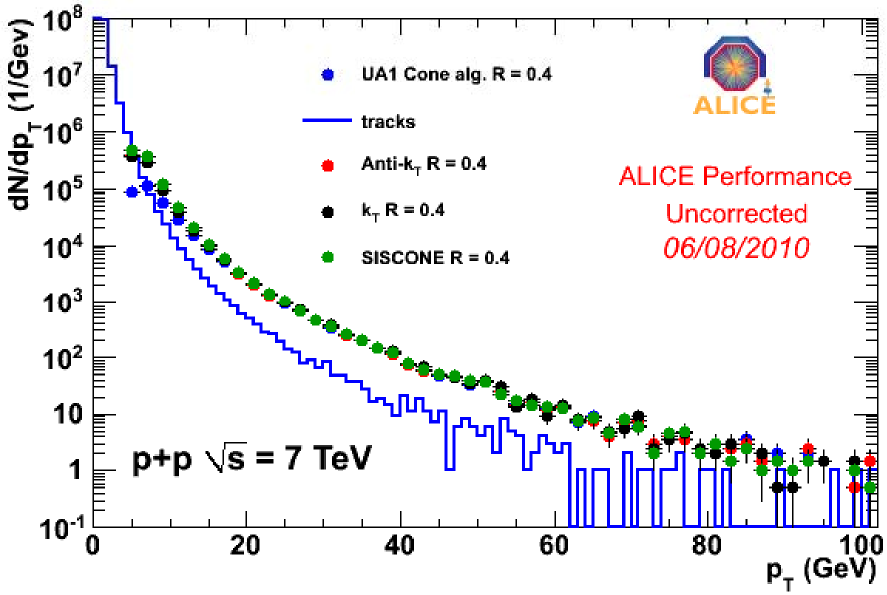




Angular Correlation Functions at 0.9 and 7 TeV



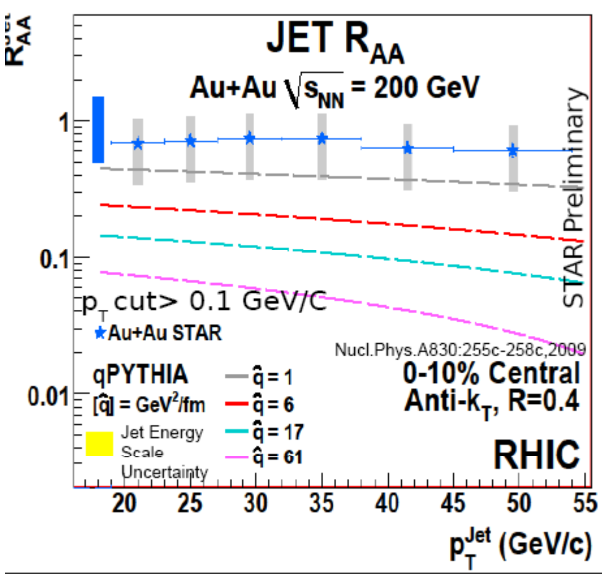
provide access to jet-like properties down to low p_T (mini-jets)

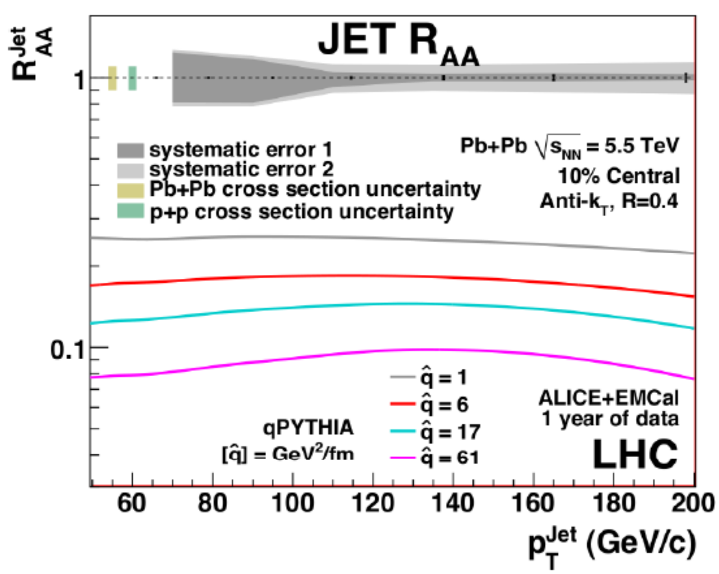


Jet reconstructed in ALICE with different algorithms (different sensitivity to background and different background subtraction scheme)

Good agreement for all jet finders

To test for Pb-Pb





Expected performance of ALICE jet measurement in 1 year Pb-Pb data taking with EMCAL

Comparison with RHIC Au-Au

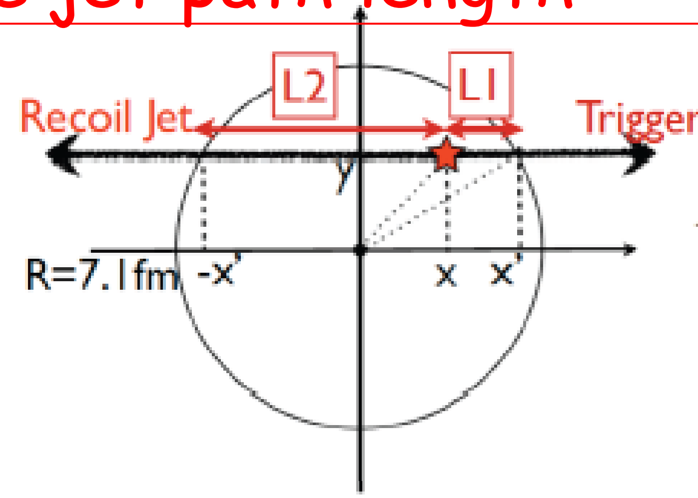
Much higher collision energy at LHC

Full EMCAL will enhance ALICE's capabilities for jet measurements

Jet quenching measurement with DCAL: controlled variation of the jet path length

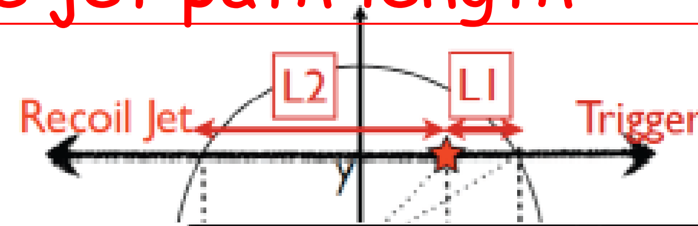
Triggering on high p_T hadron provides a unique bias of the jet recoiling azimuthally opposite:

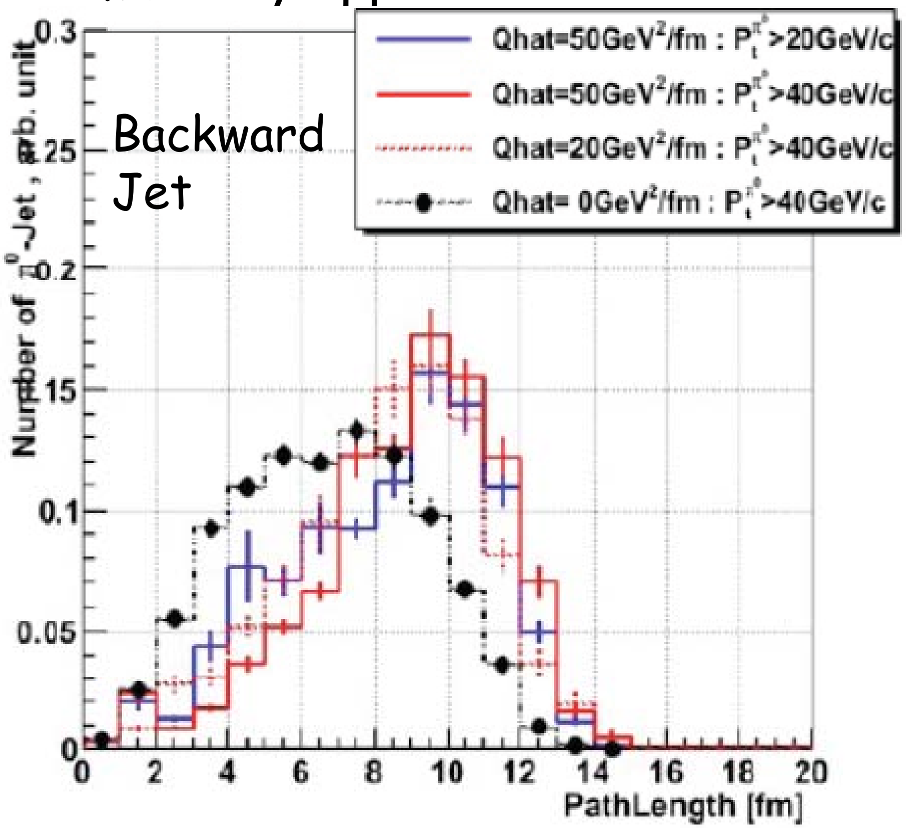
the hadron trigger arises from jet mainly generated near the surface (L1), thereby maximizing the path length of the recoiling jet in matter (L2).

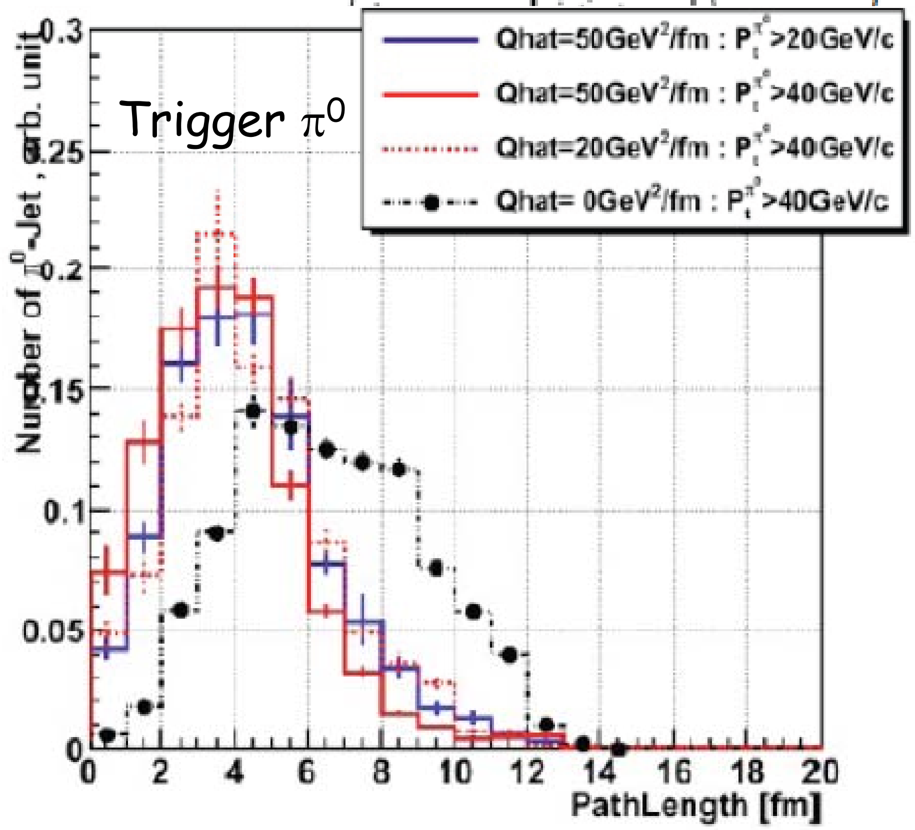


Jet quenching measurement with DCAL: controlled variation of the jet path length

Triggering on high p_T hadron provides a unique bias of the jet recoiling azimuthally opposite:







- Marked bias of several fm is seen for both jets.
- Triggering on high $P_T^{\pi 0}$ maximizes the path length of the recoiling jet in the matter
- Small dependence on Qhat and $P_T^{\pi 0}$ if these quantities are large enough→ geometric bias can be calculated reliably.

Summary

- ALICE experiment dedicated to HI
- ALICE installation done in 2008, other detectors installed in 2009-2010 (EMCAL)
- ALICE finally started its journey to Physics after 20 years of preparation

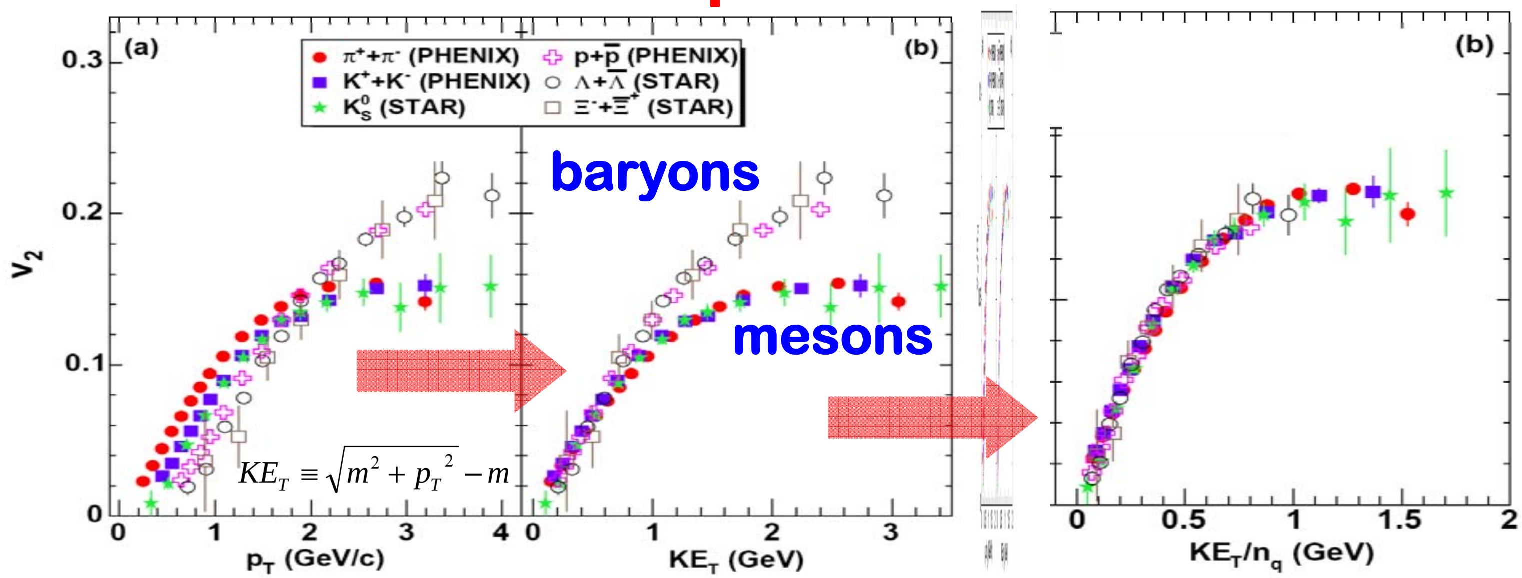
- EMCAL full installed in January 2011 and operational
- Great physics capabilities: possibility of full reconstruction of jets, measuring the neutral components
- DCAL installation for 2012 runs will allow back-to-back hadron-jet, jet-jet and γ-jet correlations

Travel in wonderland just started…

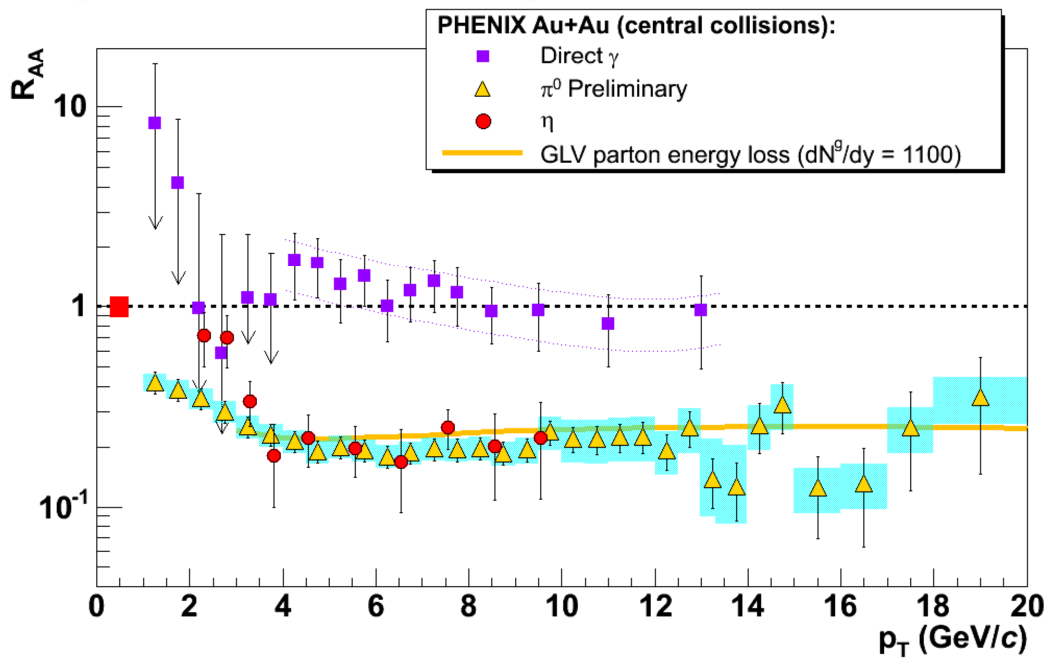
Back up

EXAMPLES FROM RHIC:
relevance of PID and photon detection…

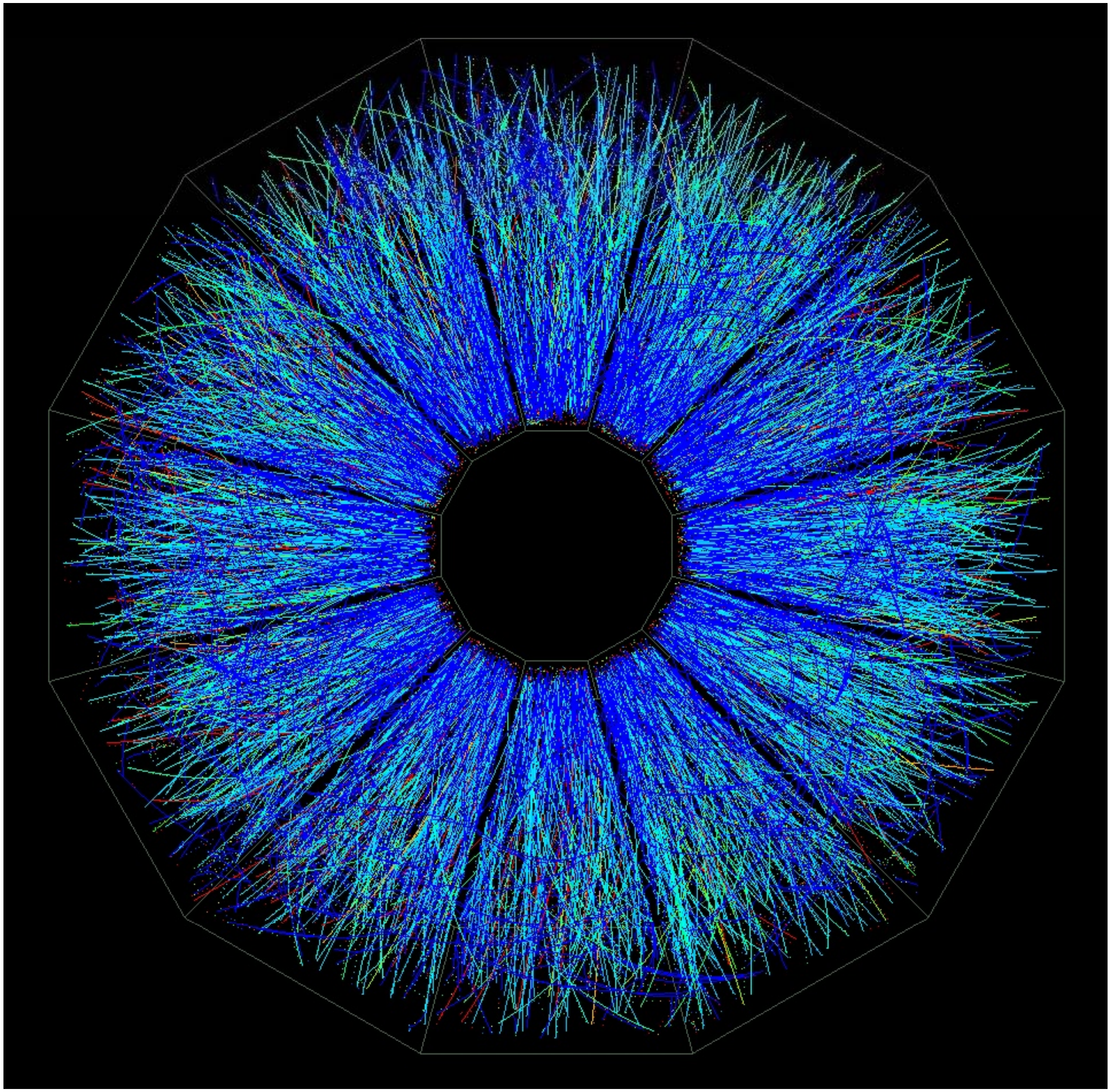
Flow



R_{AA}



and of robust tracking...



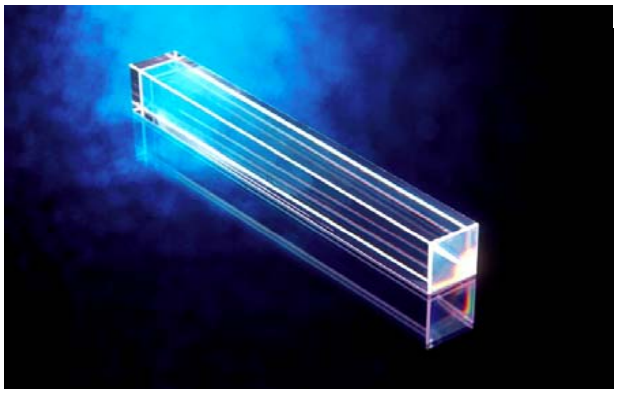
STAR

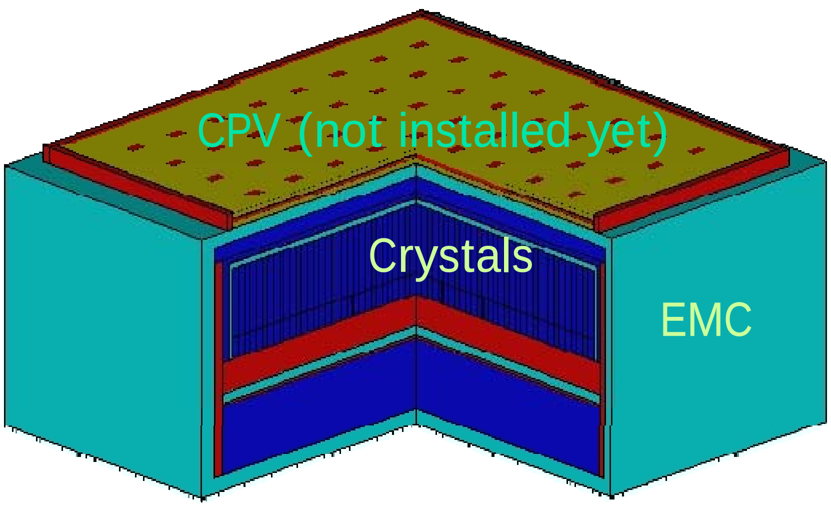
central Au-Au event

@ ~130 GeV/nucleon

CM energy

PHOton Spectrometer: PHOS





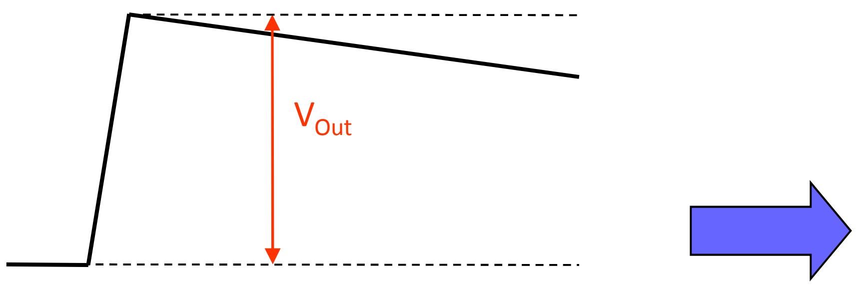
- High granularity and resolution spectrometer:
  - 10,752 (17,920) lead-tungstate crystals ($PbWO_4$), 3(5) modules (56x64 crystals per module)
  - crystal size: 22 x 22 x 180 mm^3
  - depth in radiation length: 20
  - Distance to IP: 4.4 m
  - Acceptance:
    - pseudo-rapidity [-0.12,0.12]
    - azimuthal angle 60°(100°)
  - For E > 10 GeV,

  $\Delta E/E < 1.5\%$ and σ_x = [0.5,2.5] mm

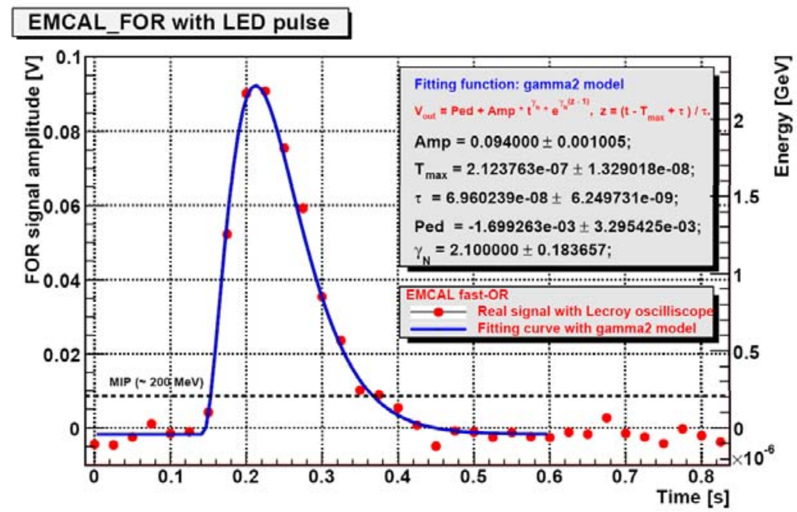
- Focus on low and moderate p_T
  - High resolution π^0 and γ
  - Thermal photons

EMCal Signal Processing

- The "voltage step" signal V_{Out} from the preamplifier is differentiated and integrated with a "2nd order Bessel integrator" (!) resulting in an output signal that has the shape of a $\Gamma(2)$ function.



Preamplifier Output

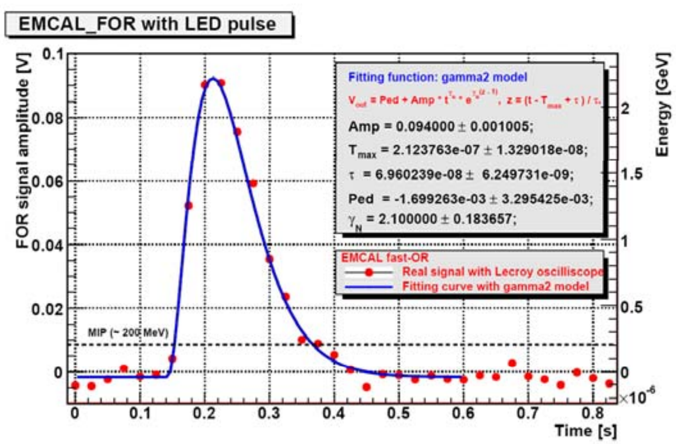


Shaper Output

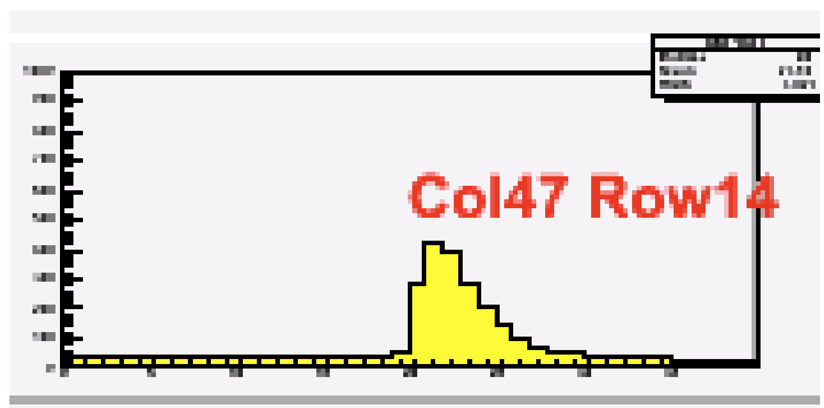
- The amplitude of the $\Gamma(2)$ is proportional to the preamplifier V_{Out} is proportional to the charge Q collected on the APD is proportional to the WLS light collected is proportional to the scintillation light produced is proportional to the energy deposited by the photon (electron) !

EMCal Signal Processing

- The shaper output is continuously being digitized every 100ns with 10-bits dynamic range by the ALTRO (ALICE TPC ReadOut) chip (i.e a 10-bit, 10MHz flash ADC).
  - (actually, each ALTRO has 16 Channels of FADC)
- When the ALTRO receives a L0 signal (issued by the ALICE Central Trigger Processor CTP) it stores a (user specified) number of post-L0 ADC samples as well as up to 15 (1.5μs) pre-L0 ADC samples in local buffer.
  - In ALICE, the L0 signal arrives at the detector FEE 1.2μs after the interaction
- When the ALTRO receives the L1 signal from the CTP it increments the data buffer pointer (data is saved for readout)
- When the ALTRO receives the L2 signal it decrements the pointer after reading the data (L2accept) or not (L2reject). The Readout Control Unit "packages" the data and sends it to the Local Data Collector (LDC) - so called ALTRO data, which sends it on to the Global Data Collector (GDC)



Shaper Output

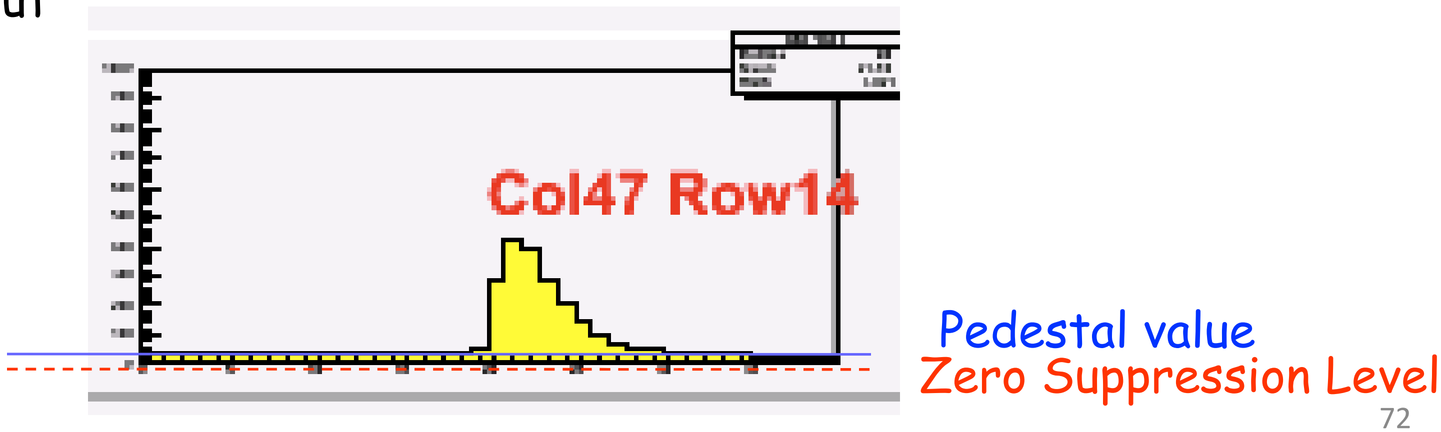


ALTRO Output

EMCal Signal Processing

More Precisely:

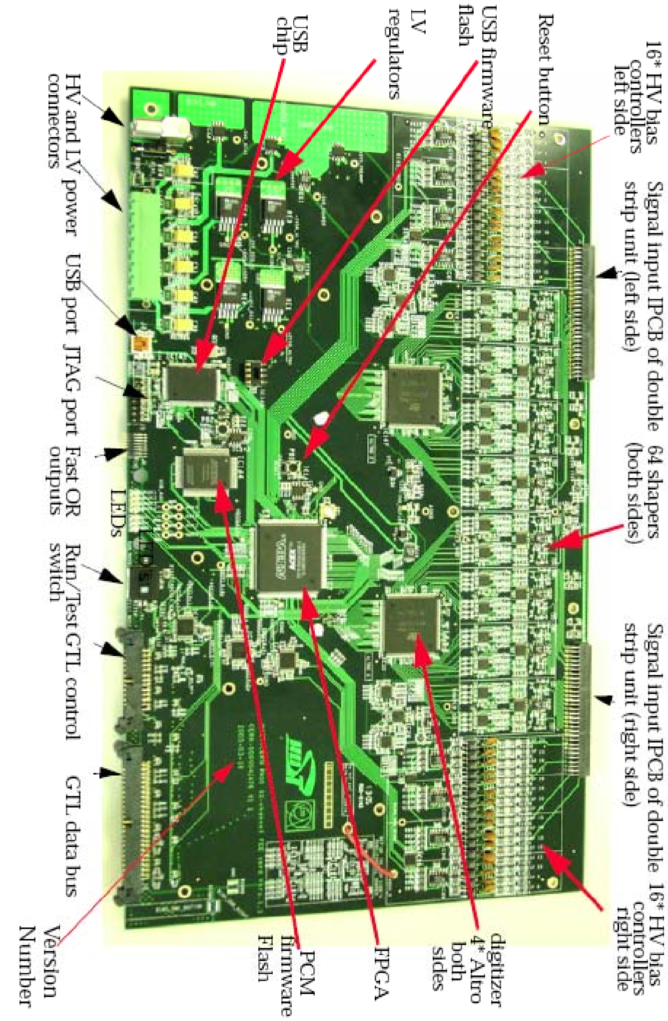
- The signal from each tower is split in the FEE into 3 parts:
  - A High Gain and Low Gain energy channel separated by a factor of 16 in gain
    - Full scale of low gain = 250 GeV; Least count of high gain = 16 MeV
  - A FastOr signal that is summed over the 2x2 towers of a EMCal module
    - The FastOr analog signal from each module is passed via cable to the EMCal Trigger Region Unit (TRU) where it is Flash Digitized at the LHC clock rate (40 MHz) @ 12 bits and used for the EMCal triggers (L0 generated in the TRU; L1 generated in the Summary Trigger Unit)
    - The FastOR data from the TRU can be rewritten into the data stream as if it was FEE ALTRO data (I.e. the TRU produces Fake ALTRO)
- To decrease the data volume, pedestal values can be subtracted from the data in the ALTRO and only time bins above a "Zero Suppression" threshold can be transmitted. Towers with no data can be dropped completely in "Sparse Data Readout"



ALTRO Output

EMCal FEE features

- 32 towers/FEE Card
- Individual APD Bias control (between 210 and 400V)
- Trigger capability with Analog sum of fast shaped (100ns) 2x2 adjacent towers, output to Trigger board to perform trigger logic. **Modified for EMCal.**
- Readout via GTL backplane (same as ALICE TPC), same Readout Control
- Dual shapers (CR-2RC) for each channel implemented with discrete components for increased dynamic range. E.g. x16 gain difference. **Modified for EMCal.**
  - EMCal uses 100ns shaping time
- Shaper output flash digitized with ALice Tpc ReadOut (ALTRO) chip. 10-bits, programmable sampling rate from 2-40MHz, use 10MHz.
- 14-bits effective dynamic range



EMCal version v1.1e

EMCal Trigger

The EMCal L0 high energy shower trigger:

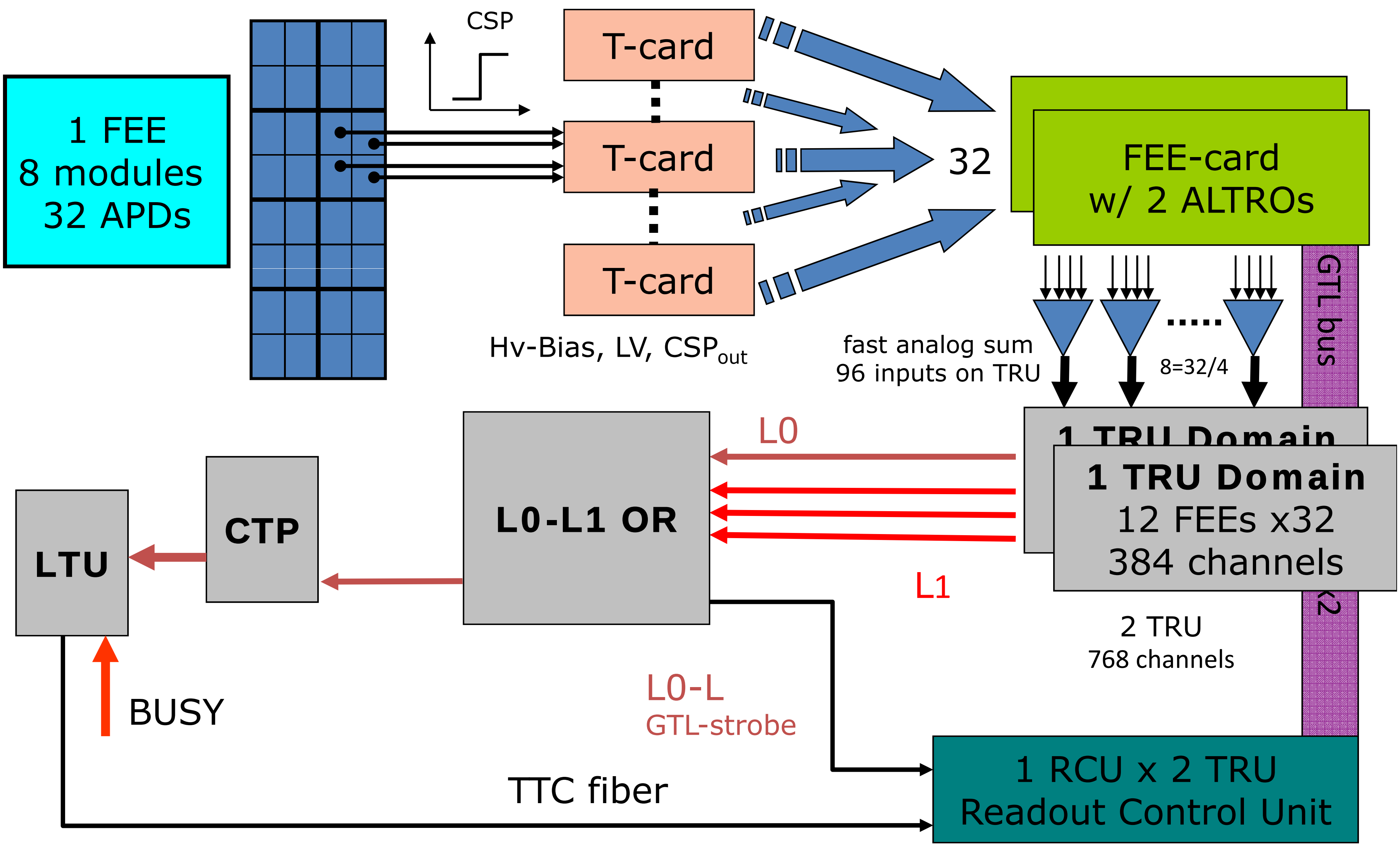
- Each TRU receives the analog sum energy from the 4x24 modules of 1/3 super module (input from 12 FEE FastOR outputs; 8 EMCal modules per FEE) via cables where it is Flash Digitized at the LHC clock rate (40 MHz) @ 12 bits.
- The TRU performs a digital pedestal subtraction and sums over several time bins and all combinations of adjacent 2x2 modules (4x4 towers).
- If a space-time sum is above the threshold that has been set, the L0 trigger is armed and the L0 decision is sent on the Beam Crossing when the time sum decreases after it has been increasing.
- The L0's within the TRU are OR'd together and the TRU sends the L0 decision each BC to the Summary Trigger Unit (STU).
- The Summary Trigger Unit OR's together the L0 results from all TRUs and sends the L0 decision each BC to the Central Trigger Processor, to arrive at the CTP within 800ns after the interaction.
- The CTP incorporates the EMCal L0 into the ALICE trigger decision and issues the ALICE L0 trigger, or not.

EMCal L1 Trigger

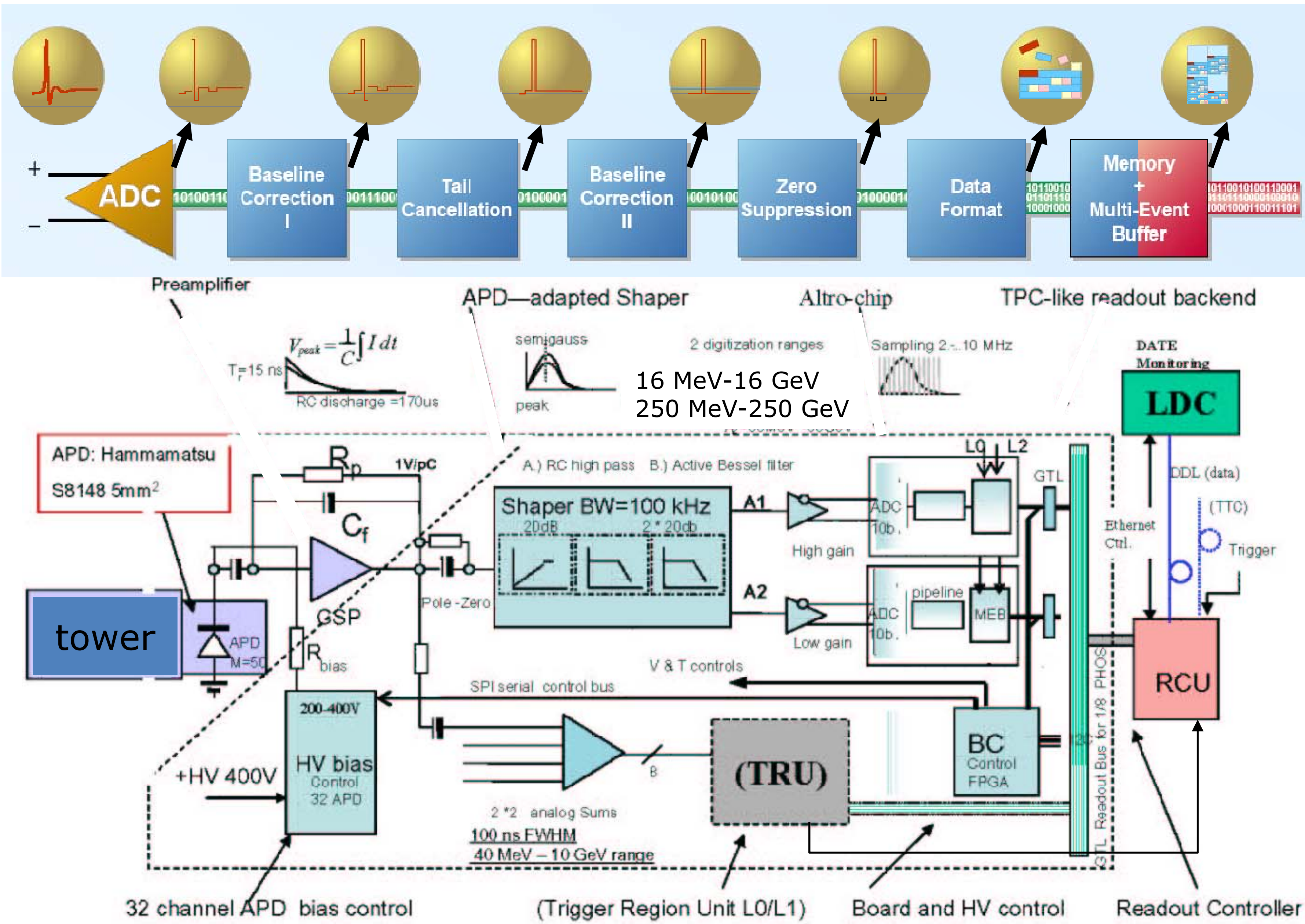
The EMCal L1 high energy shower and jet trigger:

- Upon receipt of the ALICE L0 trigger (or not), 1.2μs after the interaction, each TRU sends the digitized FastOr data for all EMCal modules (2x2 towers) for the BC corresponding to the L0 time, after pedestal subtraction and sum over several time bins, to the Summary Trigger Unit.
- The STU takes the module sum data from all TRUs and performs all adjacent 2x2 EMCal module sums (4x4) towers over the entire EMCal.
- If a 4x4 tower space-time sum is above the threshold that has been set, the L1 shower trigger is armed and the L1 EMCal shower trigger decision is sent to the CTP to arrive at the CTP at 5.6μs after the interaction.
- At the same time, the STU sums regions of 8x8 modules, and then sums all combinations of adjacent NxN regions of 8x8 module sums.
- If an NxN space-time sum is above the threshold that has been set, the L1 jet trigger is armed and the L1 EMCal jet trigger decision is sent to the CTP to arrive at the CTP at 5.6μs after the interaction.
- The CTP incorporates the EMCal L1 trigger information into the ALICE trigger decision and issues the ALICE L1 trigger, or not.

The EMCAL Electronic Chain

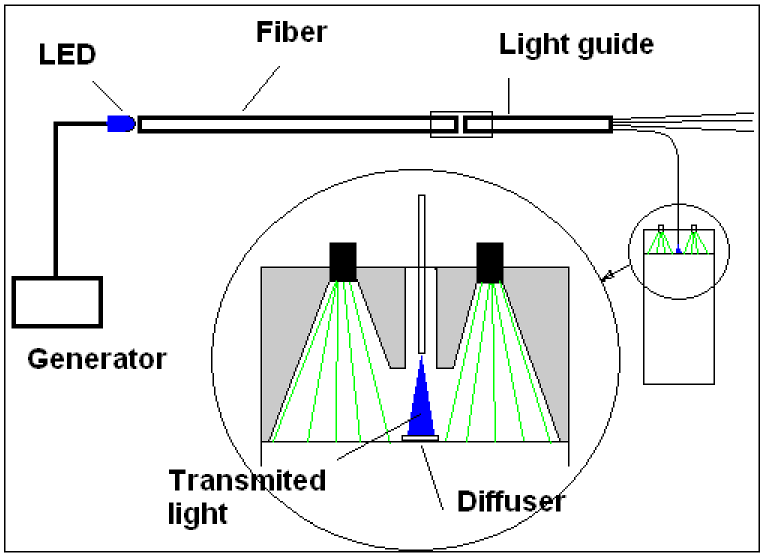


The EMCAL Readout and Electronics



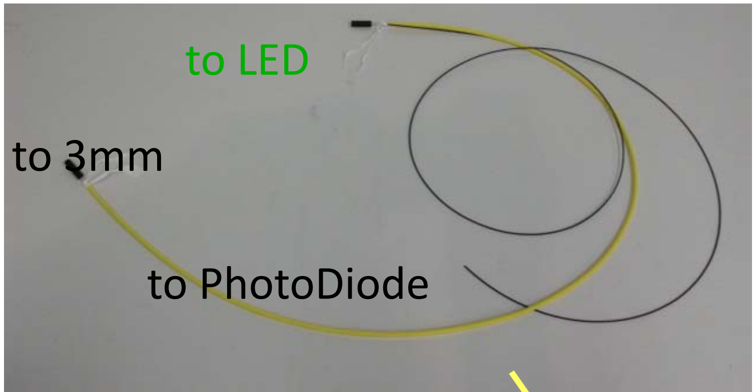
EMCal LED Gain Monitoring System

APD gain is temperature dependent 1/MdM/dT ~ 1.7%/C

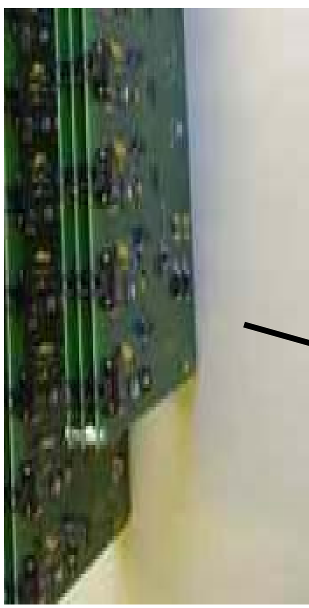


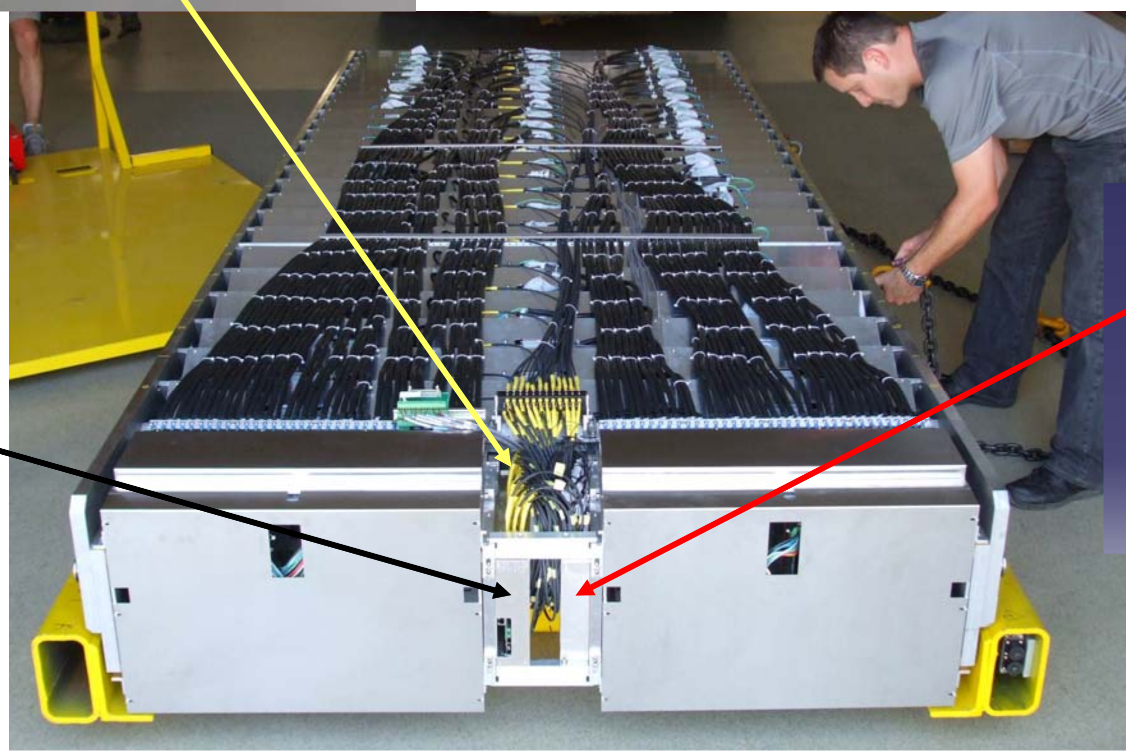
- LED system for gain monitoring and gain adjustment.
  - Calibration “calibrates” LED light/tower
  - Independently monitor LED light to normalize out light source
- One fiber per EMCalmodule (shown) excites WLS bundle - low efficiency.
- 12 modules (fibers) per strip module fed by one 3mm fiber from remote LED to strip module.

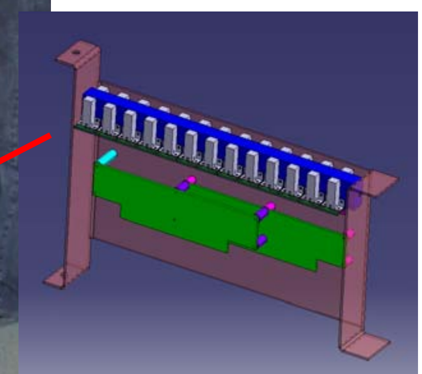
LED Light Monitoring System



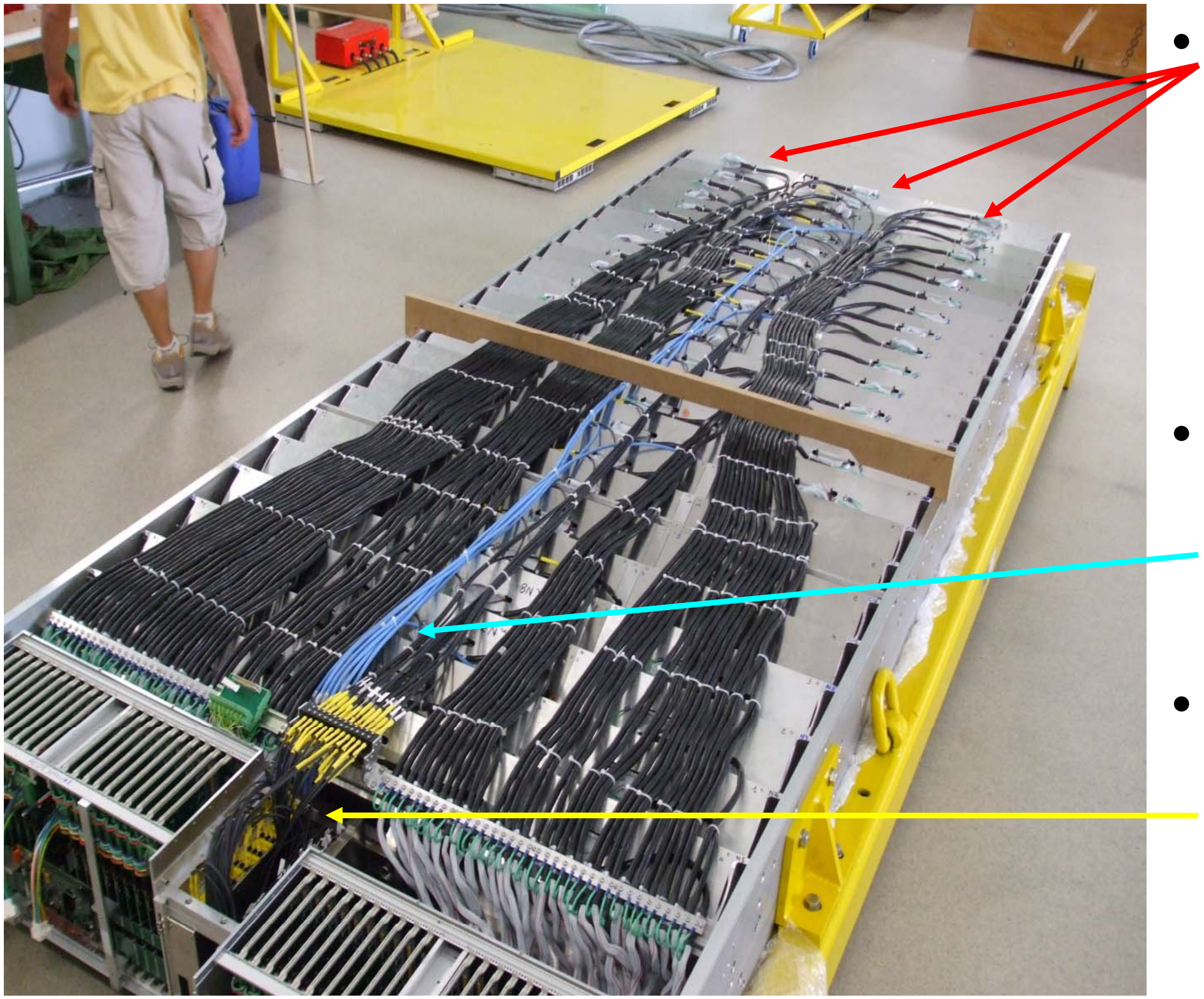
- LED Drivers and monitor located in space between FEE crates.
- LED system has been used to test SMs after arrival at CERN to insure that all channels are functional.





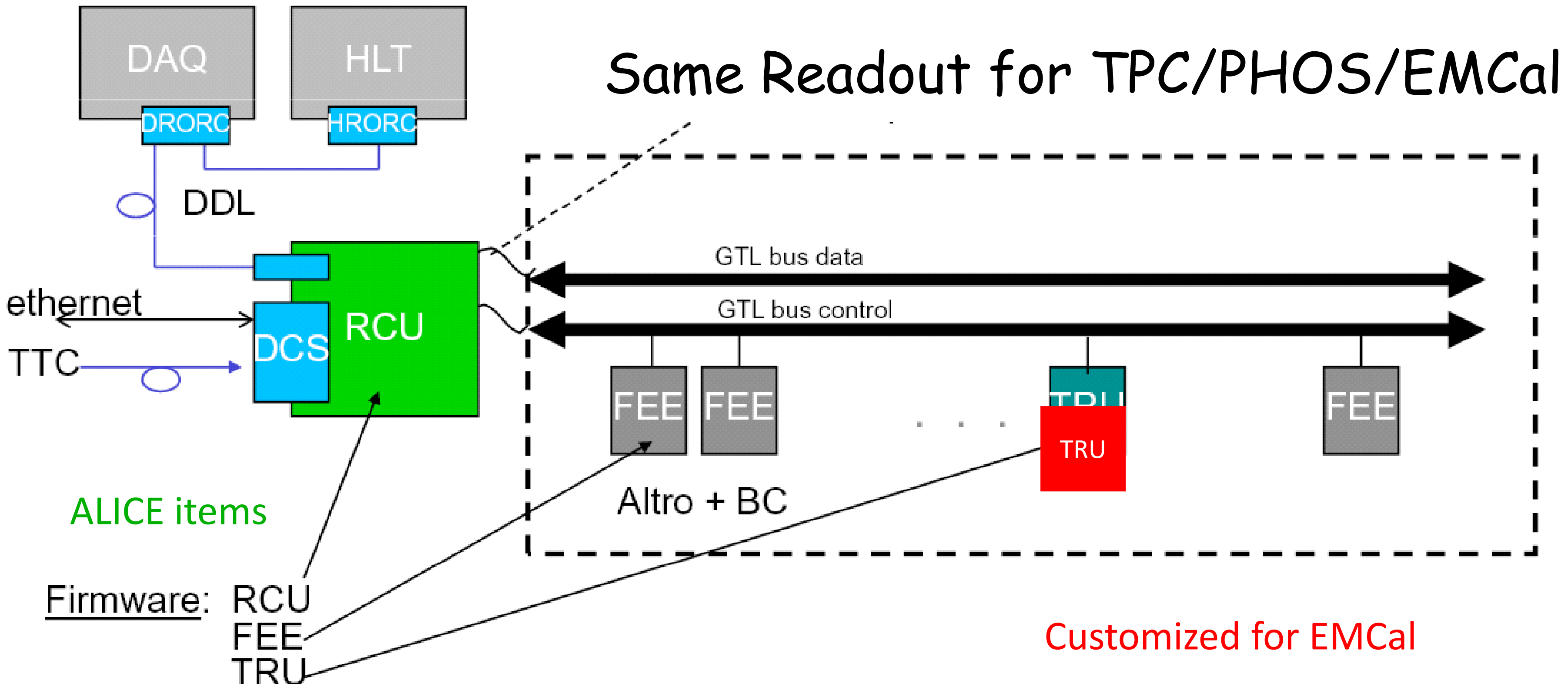


EMCal SM Readout



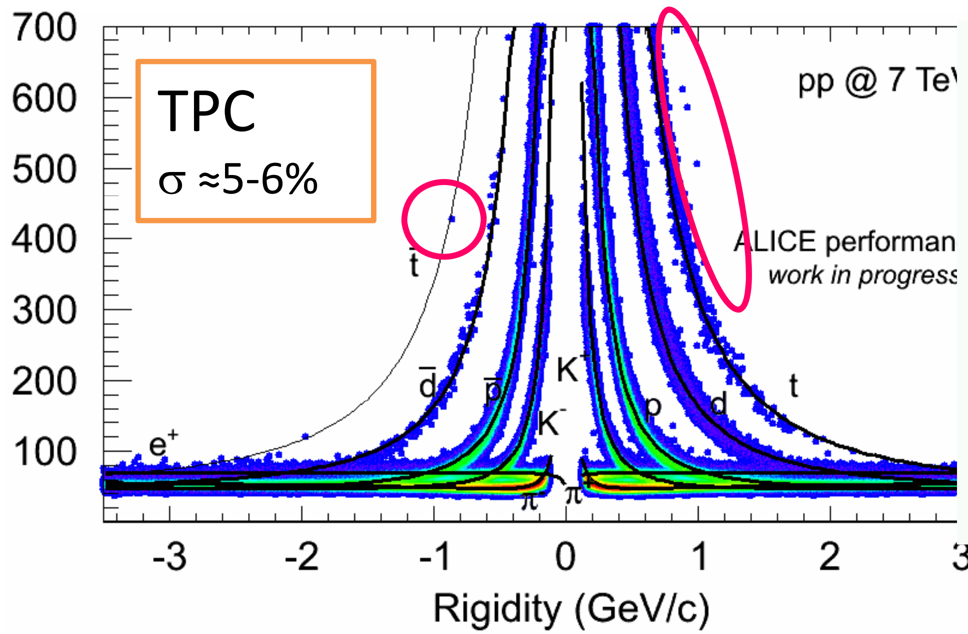
- 3 Shielded Ribbon Cables per Strip Module
  - APD bias, preamplifier LV, and signal
- 8 Temperature Sensors per SM
  - 2 sensors every 6th strip module
- LED monitoring
  - One 3mm Fiber (1 LED) per Strip
  - 24 LEDs per SM

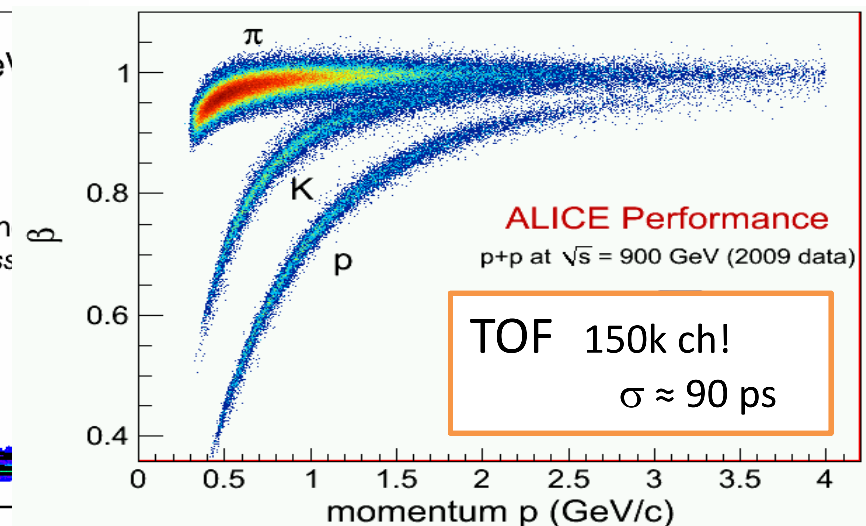
FEE / Trigger / DAQ Overview

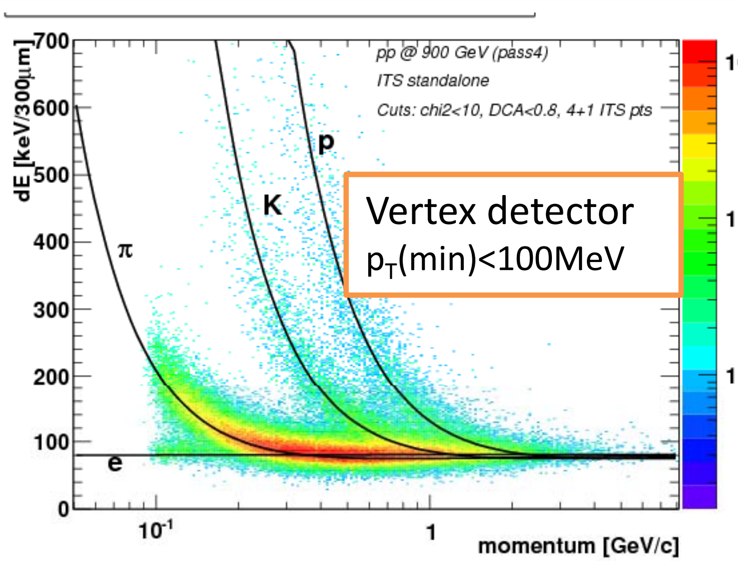


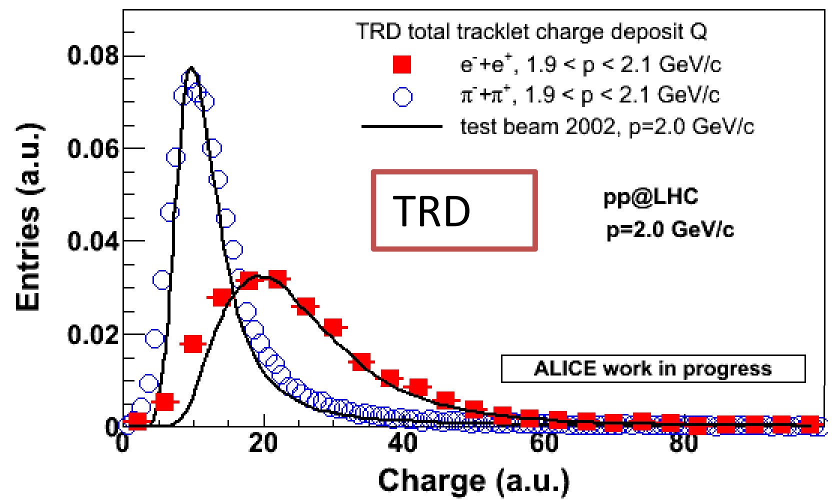
- 9 FEE + 1 Trigger Region Unit (TRU) setup/readout via GTL bus with 10 addresses.
- Readout Control Unit (RCU) controls FEE and TRU on up to 2 GTL bus branches.
- Detector Control System (DCS) RCU daughter card (simple LINUX processor) for FEE and TRU setup (e.g. APD bias)
- Data to DAQ via Detector Data Link on RCU - passed to High Level Trigger

Particle Identification



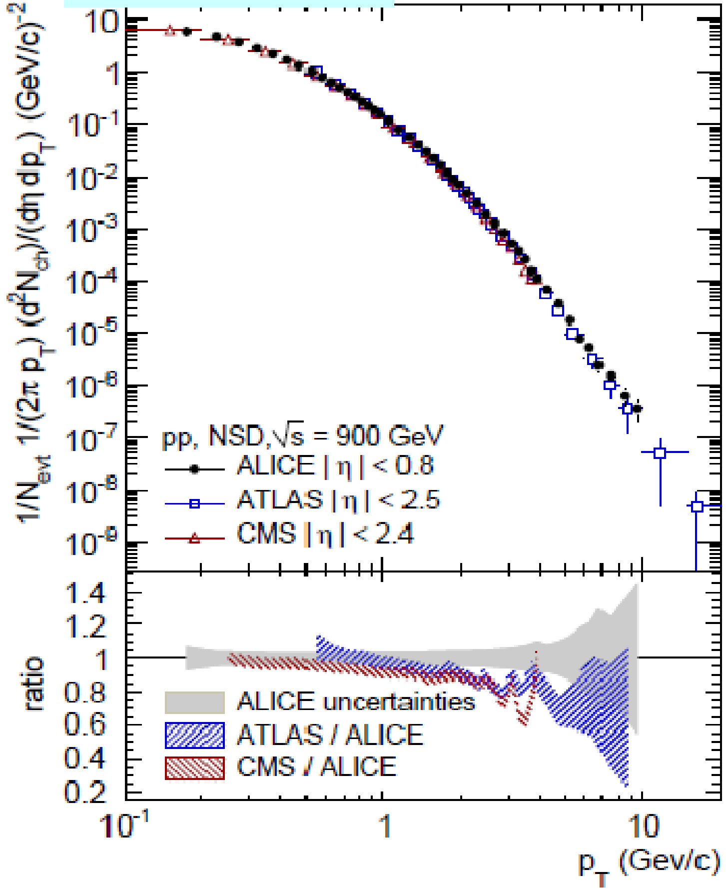




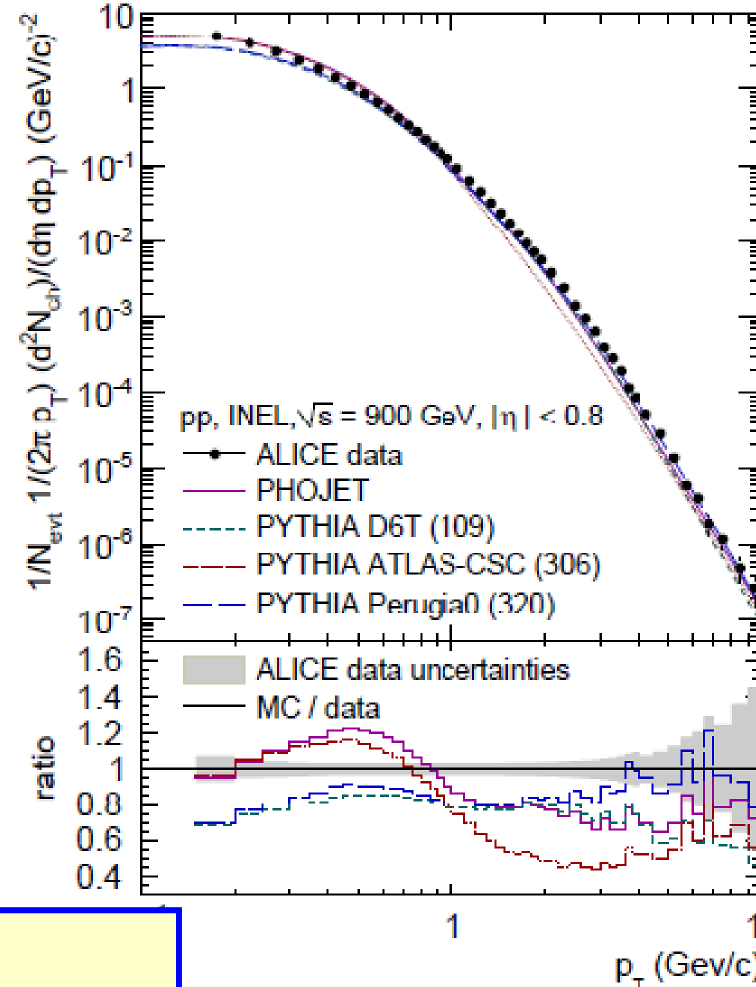


Momentum distribution 900 GeV

p_T distribution

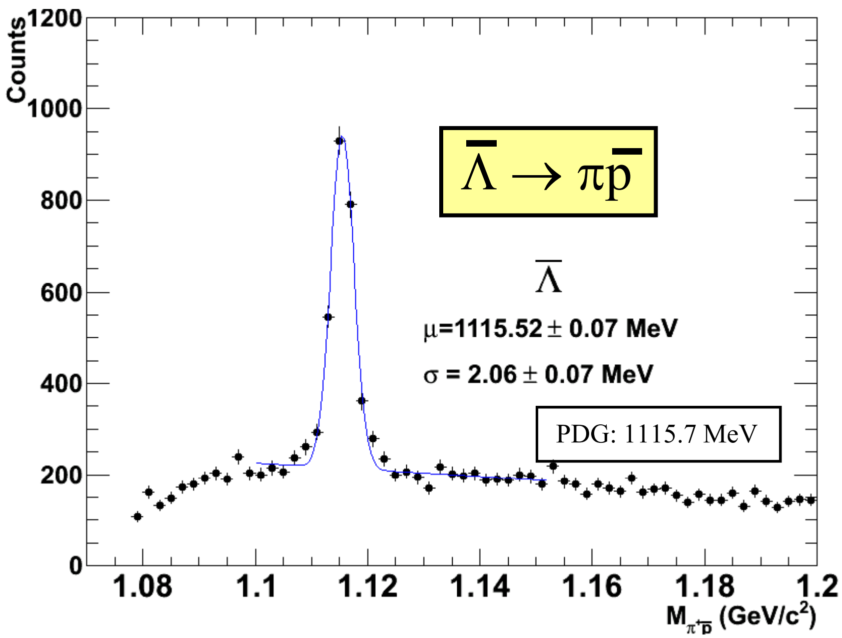


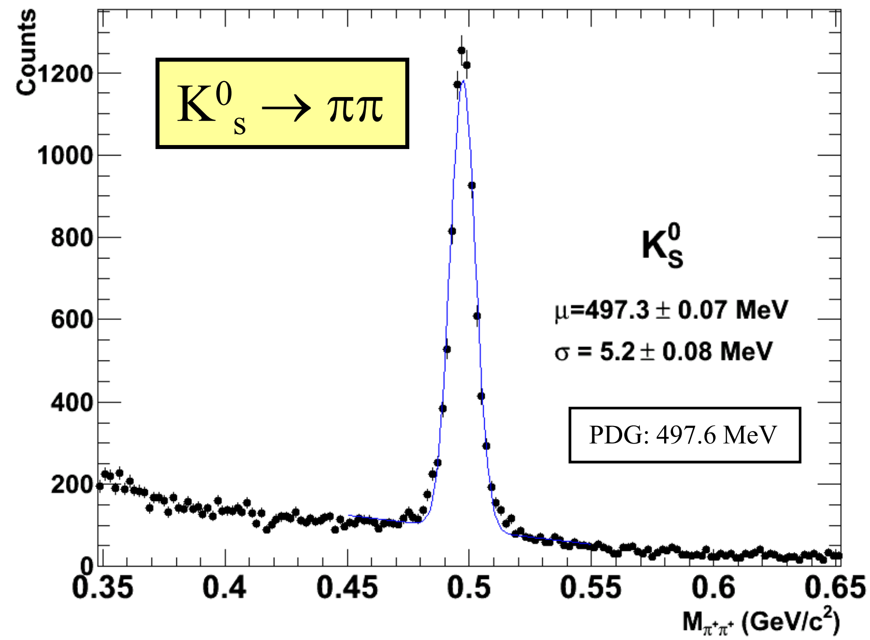
Comparison to MC's

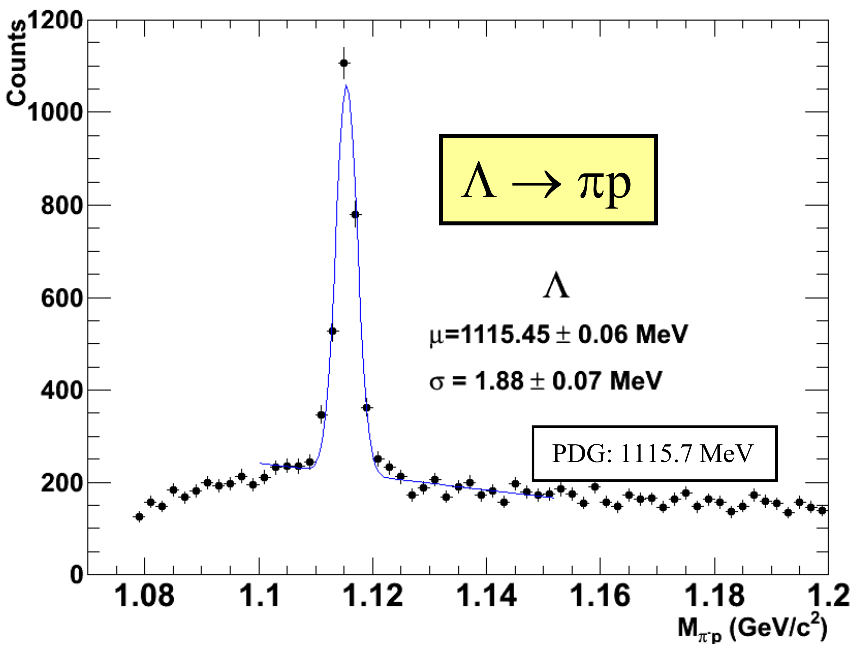


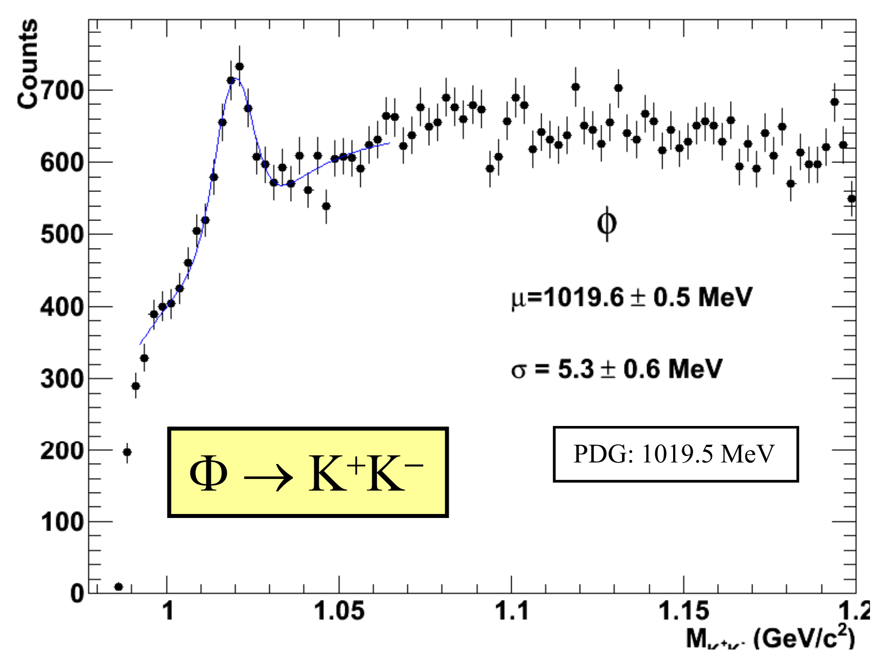
- At p_T>1 GeV/c data slightly above ATLAS and CMS
- Spectrum seems to get harder towards midrapidity
- None of the models and tunes investigated describe p_T

The Particle Zoo Revisited:

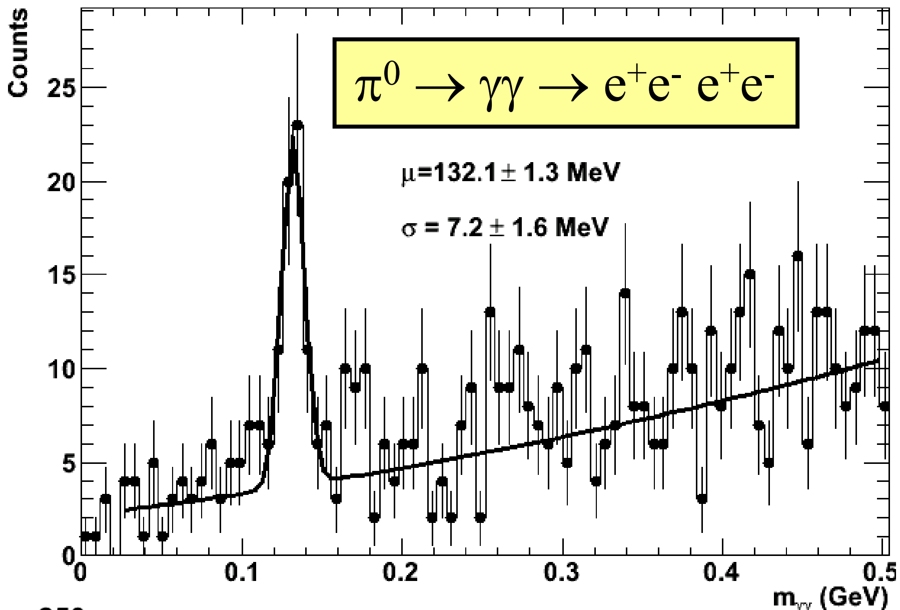


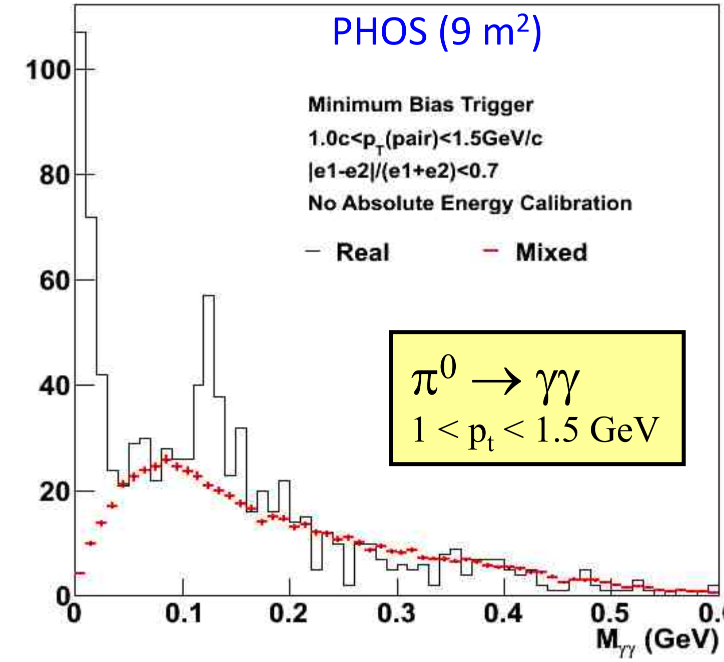


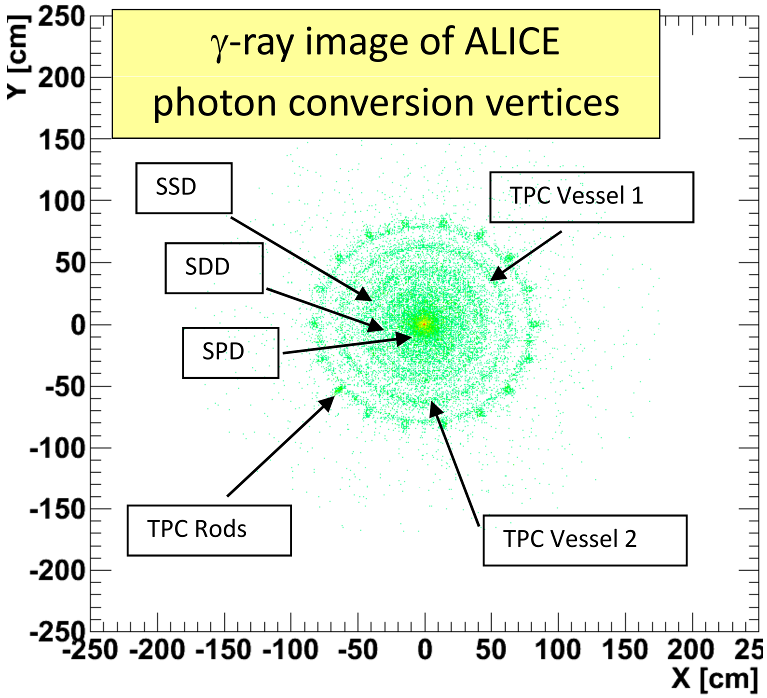


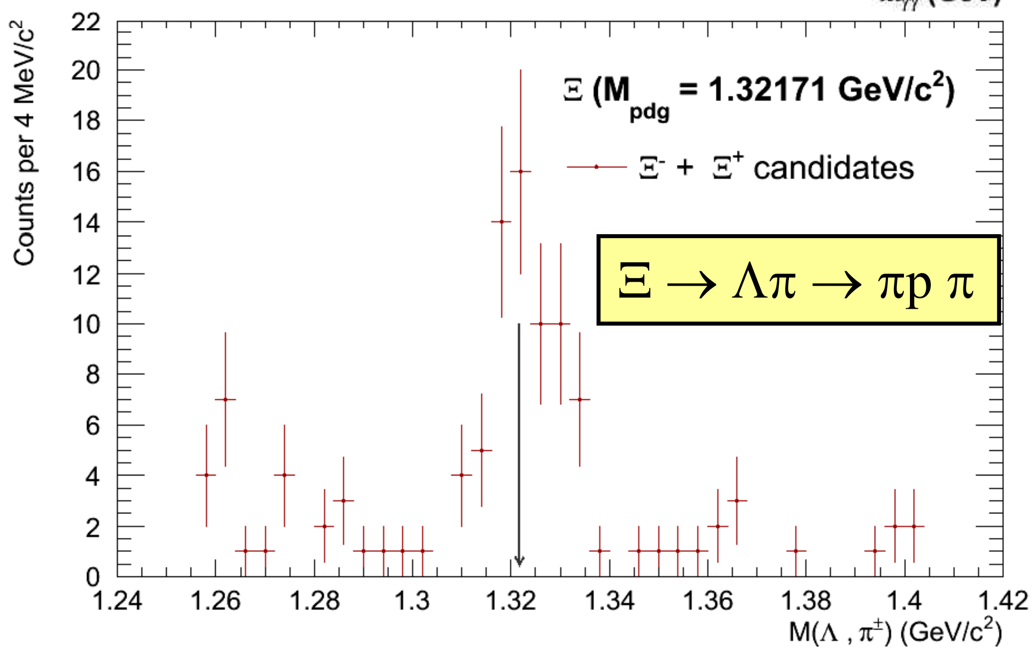


More Particles..



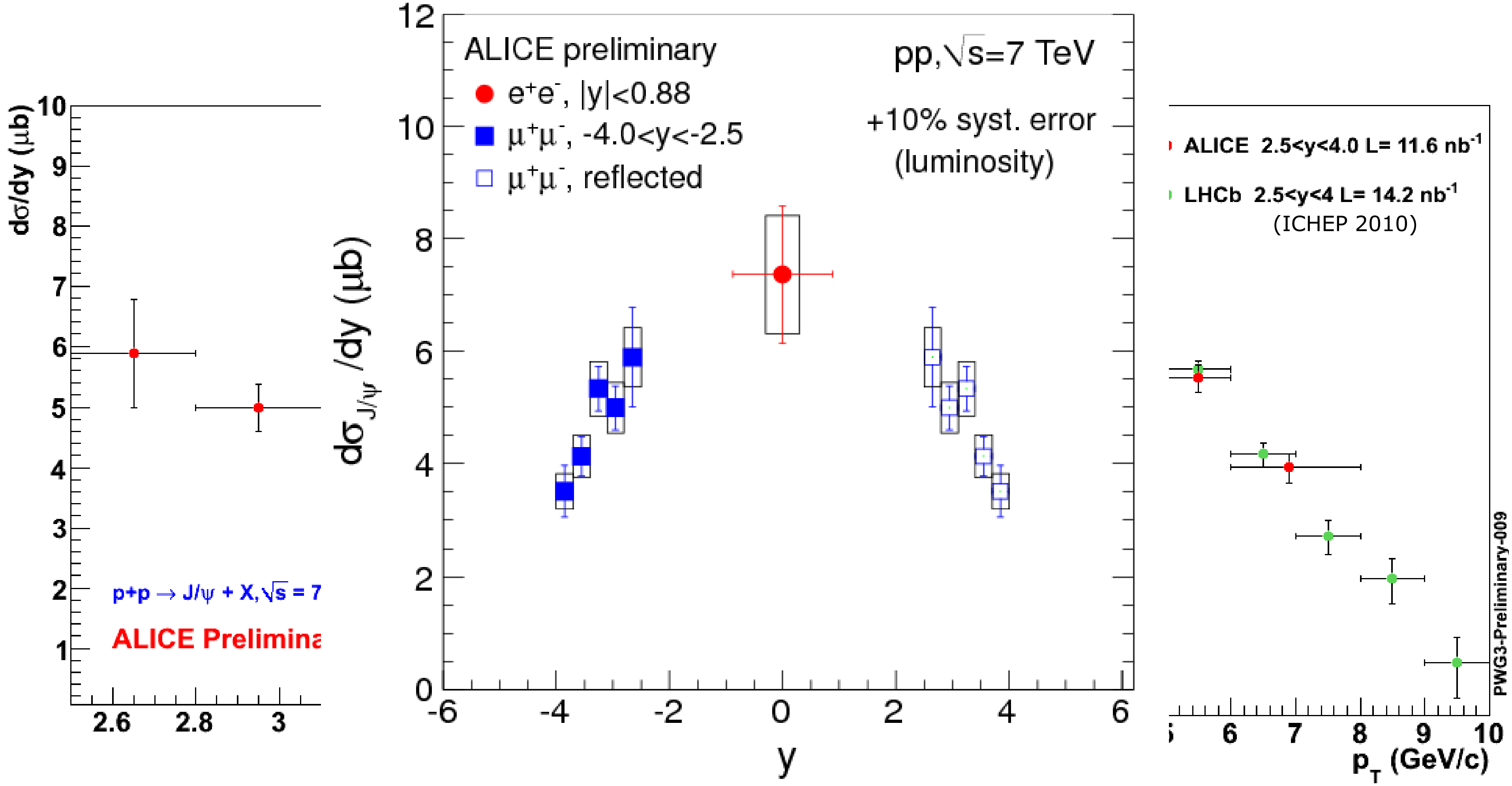






J/ψ cross section @ 7 TeV

very good agreement with LHCb pt spectra and cross section
cross-section measurement in central–forward regions match

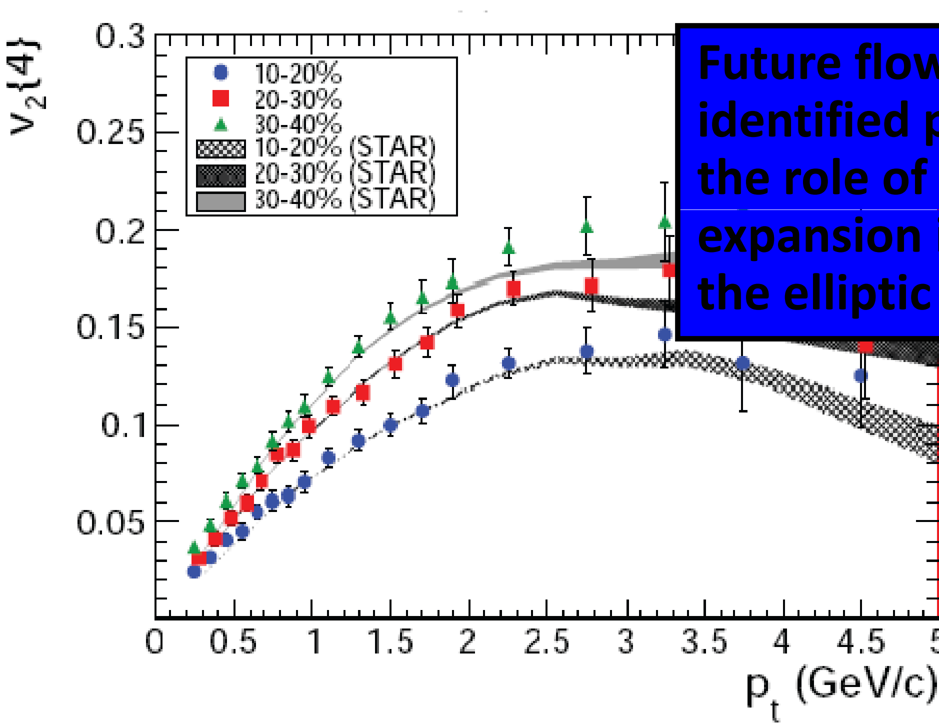


Elliptic flow (v_2) of charged particle

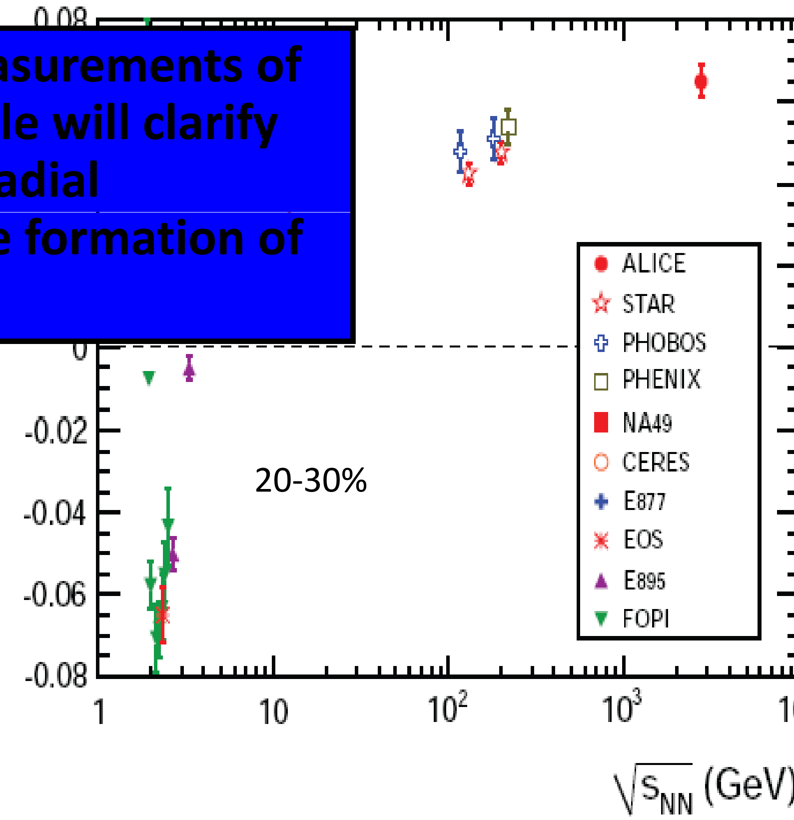
PRL 105 (2010) 252301

Data Sample: 50.000 Pb-Pb M.B. collisions collected on Nov. 9

Select 9 centrality classes in 0-80%



Future flow measurements of identified particle will clarify the role of the radial expansion in the formation of the elliptic flow



p_t dependence very similar for all three centrality bins

The p_t–integrated v_2 increases by 30% wrt RHIC → expected based on hydrodynamic models