Physics with DCal in ALICE

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(for the ALICE DCal Project)

筑波大学
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ALICE

由于ALICE DCal 的喷射物理的研究

中條 達也

筑波大学

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ALICE

Before my talk…

A short history; Relationship between Hangzhou and Japan

南宋2代皇帝 孝宗
Emperor Xiaozong
(1127-1194)

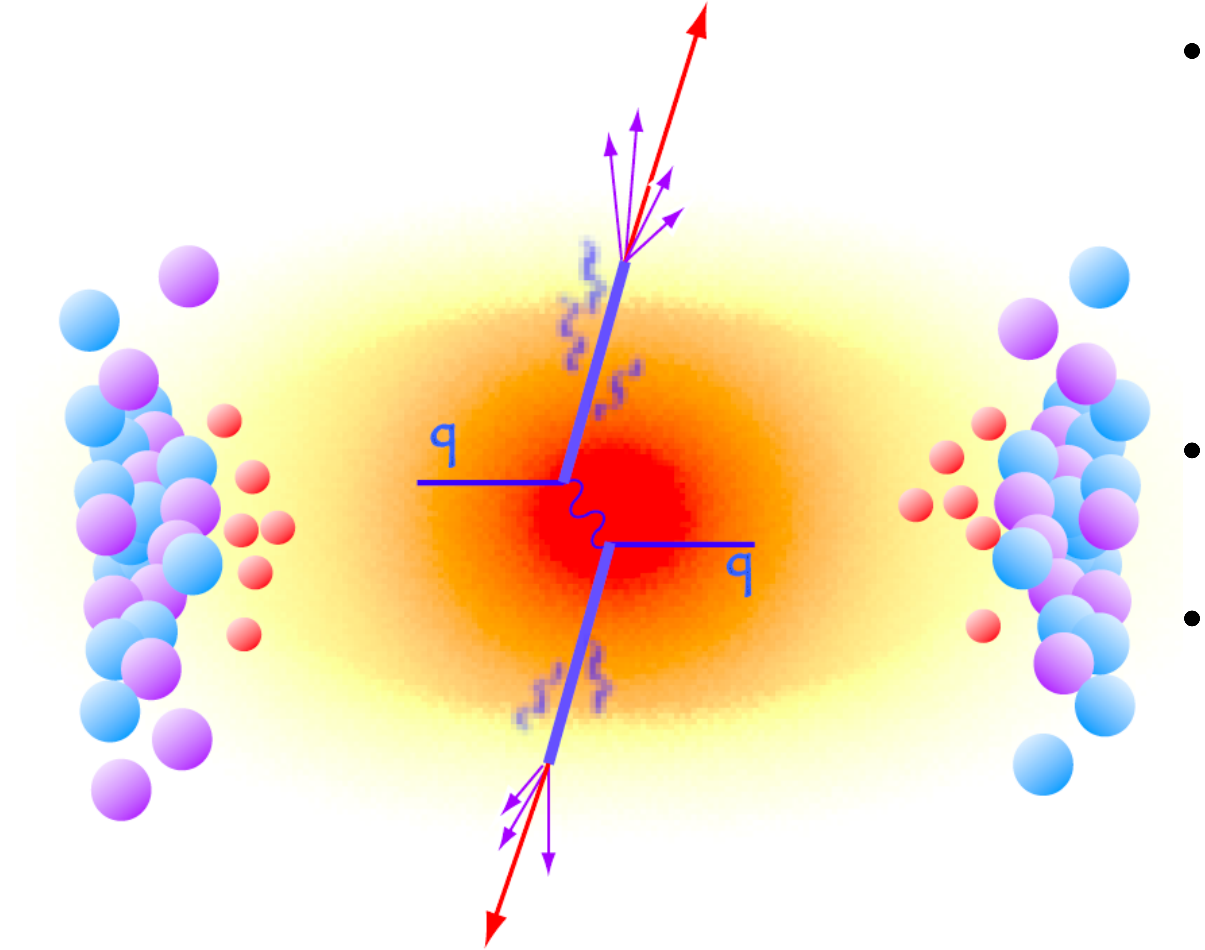
平清盛
General Taira no Kiyomori
(1118-1181)

- Hangzhou 杭州：Capital of Song dynasty (Southern Song 1127-1279).
- There is a trade between Song Dy. and Japan (Hakata) in 10-13 cent, 日宋貿易
- From Song: Cupper Coin, Silk, Chinaware, Book, Canon of Buddhism, etc.
- From Japan: Gold, Silver, Sulfur, Pearl, Handcrafts, etc.
- **Big impact on development of Japanese economy at that time!**

Outline

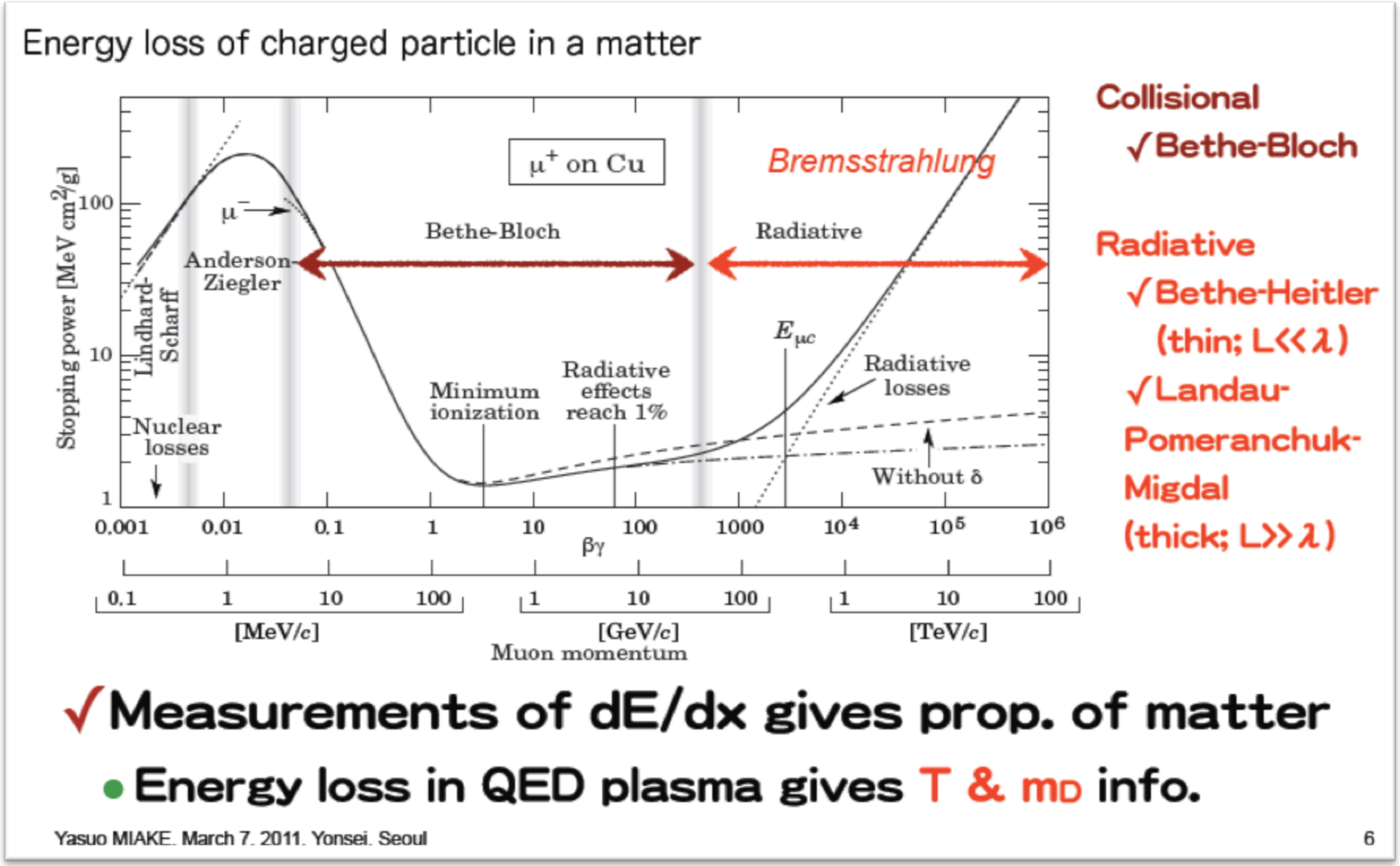
1. Introduction
   - Parton energy loss & jet quenching
   - First results on jet quenching at LHC
2. Dijet Calorimeter (=DCal) in LHC-ALICE
3. Physics cases for DCal
4. Current stats and plan
5. Summary

1. Introduction: Parton Energy Loss



- After the discovery of QGP at RHIC, we are now interested in the properties of QGP in detail.
- From discoveries to precision measurements.
- Energy loss of parton (ΔE) in hot and dense medium has a rich and key contents to identify the QGP properties.

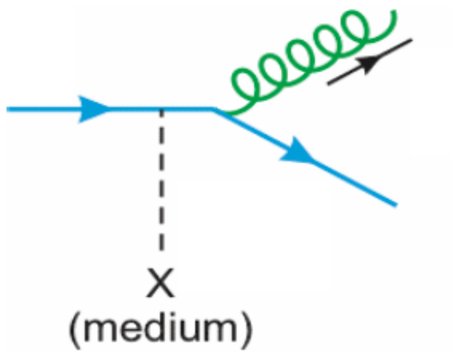
Analogy: dE/dx in QED

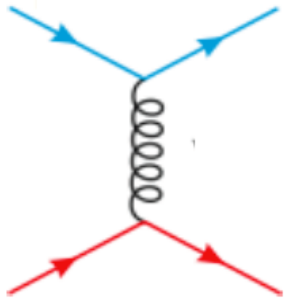


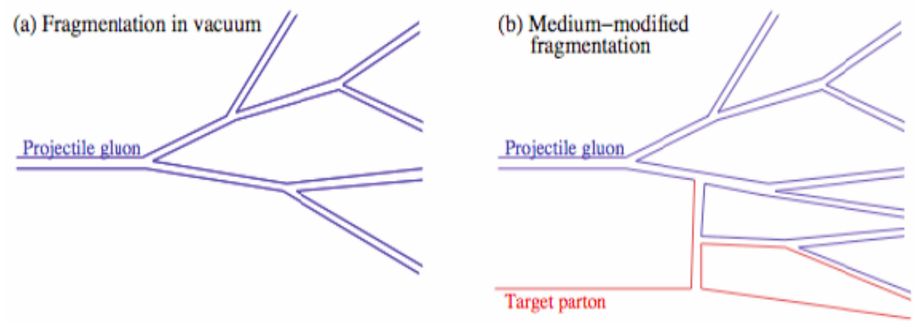
Can we understand dE/dx of parton in QGP like this?

Ingredients of parton energy loss in hot/dense matter

Figures taken from Christof Roland's talk (QM11)







(a) Radiative energy loss in medium

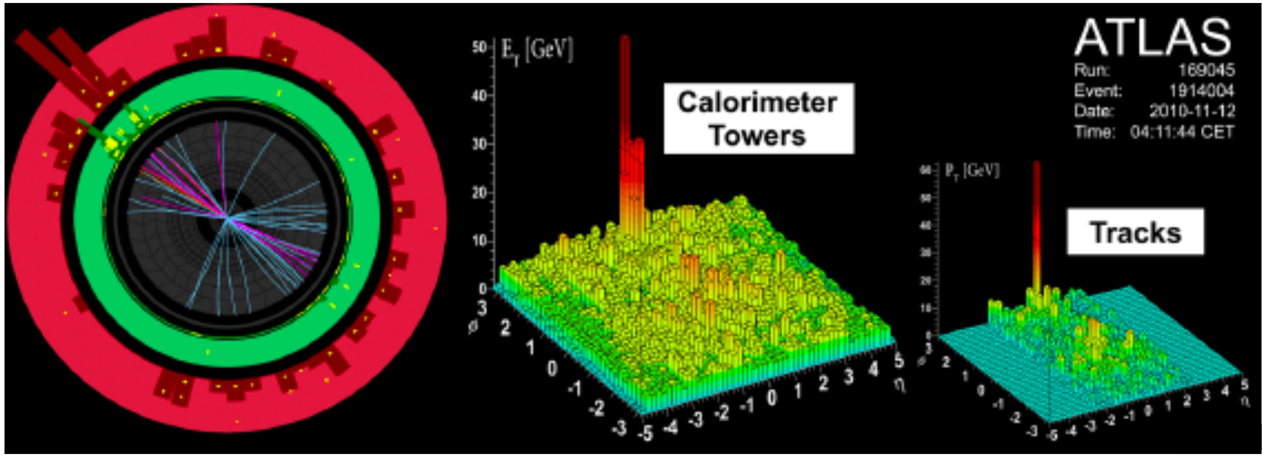
(b) Collisional energy loss in medium

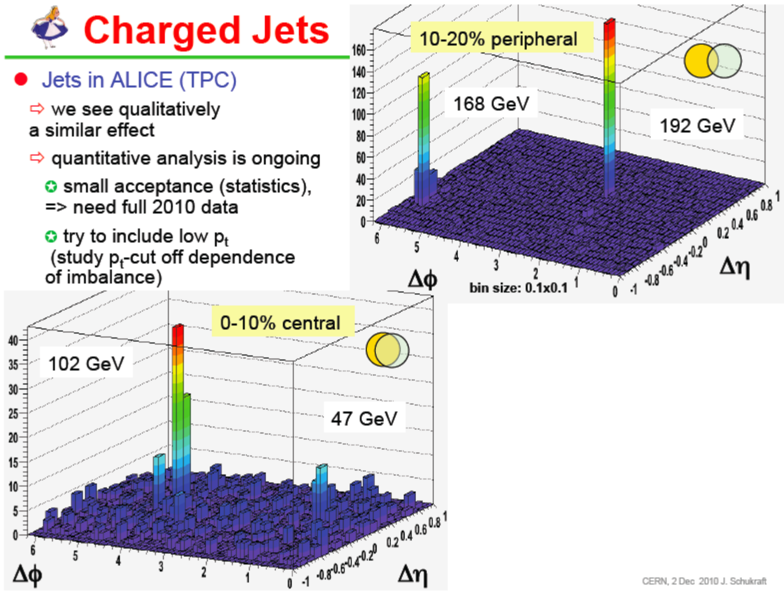
(c) Fragmentation (in vacuum, or medium modified), and jets.

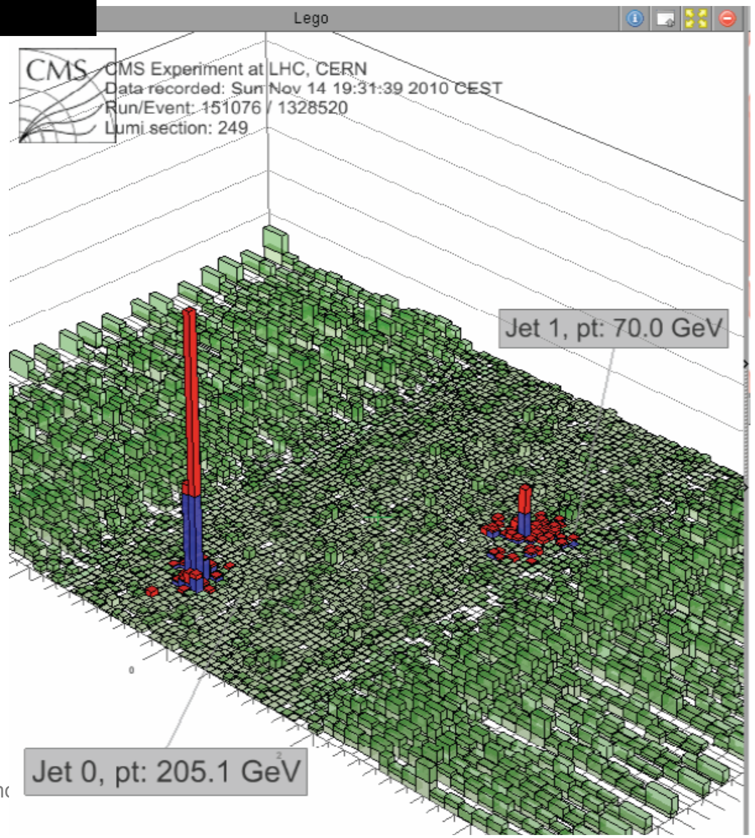
$$\frac{dE_{\rm rad}}{dx} = \frac{\alpha_s N_c}{4}\hat{q}_R L; \qquad \hat{q}_R = \rho \int dq_T^2 \frac{d\sigma_R}{dq_T^2} q_T^2,$$

- These ingredients are sensitive to medium properties, and location and time of the process happens.
- **Direct jet reconstruction → a crucial role to determine the medium properties.**

Direct jet quenching is seen at LHC!

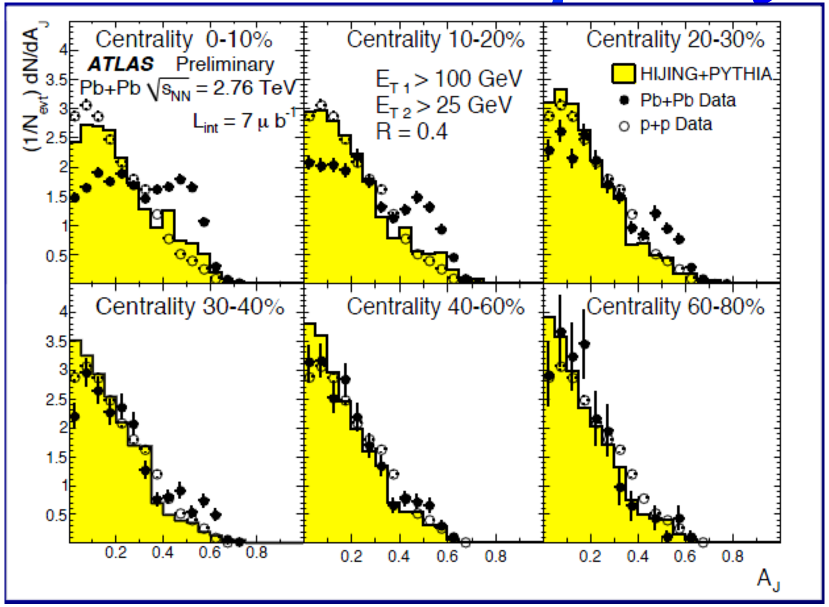




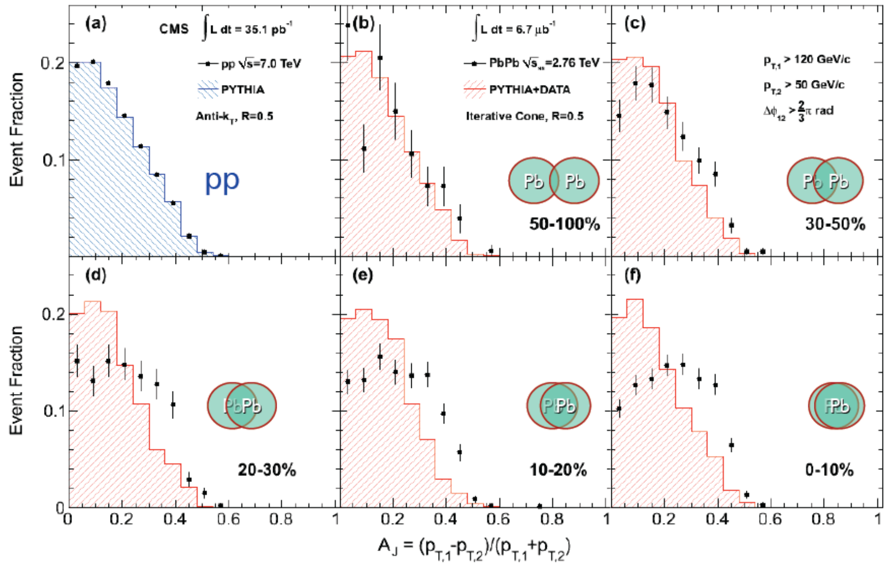


cs at RHIC and LHC, Hangzho
21, 2011 (T. Chujo)

A_J: di-jet asymmetry



ATLAS R=0.4



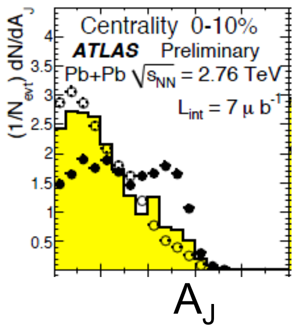
CMS R=0.5

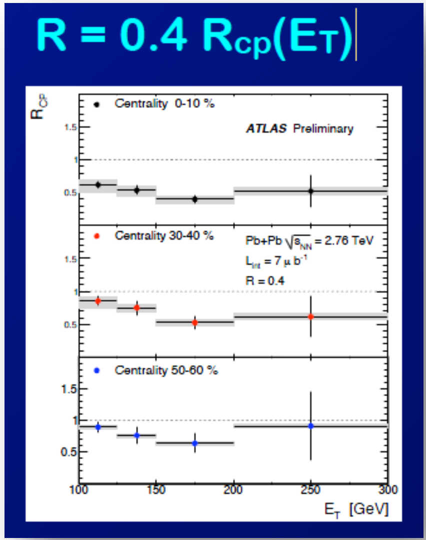
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Quantify jet energy imbalance by the asymmetry ratio.
- Large asymmetry is seen in energy imbalance.

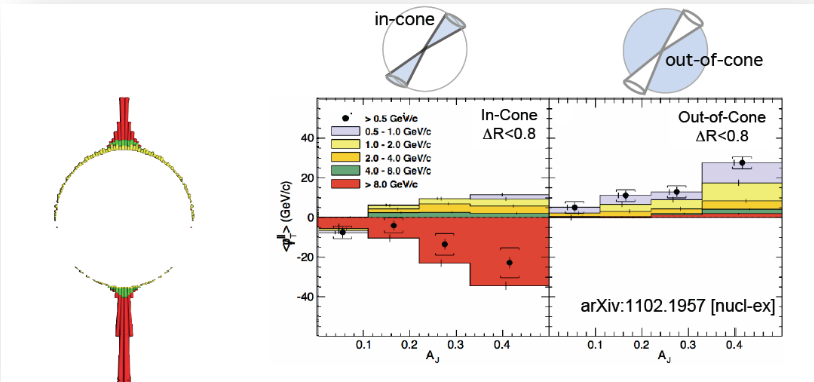
Highlights on jets at LHC (QM2011)

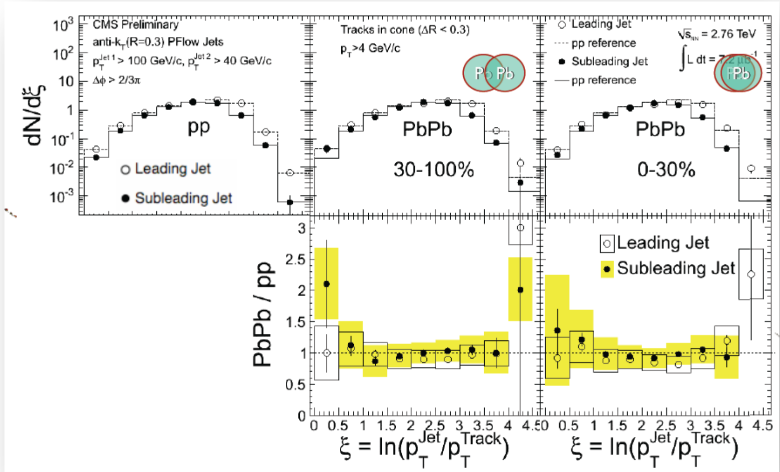
1. Extremely large energy loss on the away side jets.
   - Large energy asymmetry in central Pb+Pb.
   - Jet R_{cp} ~ 0.5.
2. Little modification of jet shape
   - both near and away side.
   - Both transverse (j_T) and longitudinal (FF).
   - No broadening of jets.





3. Lost energy is used for the low p_T bulk particle production at large angle!





What's next?

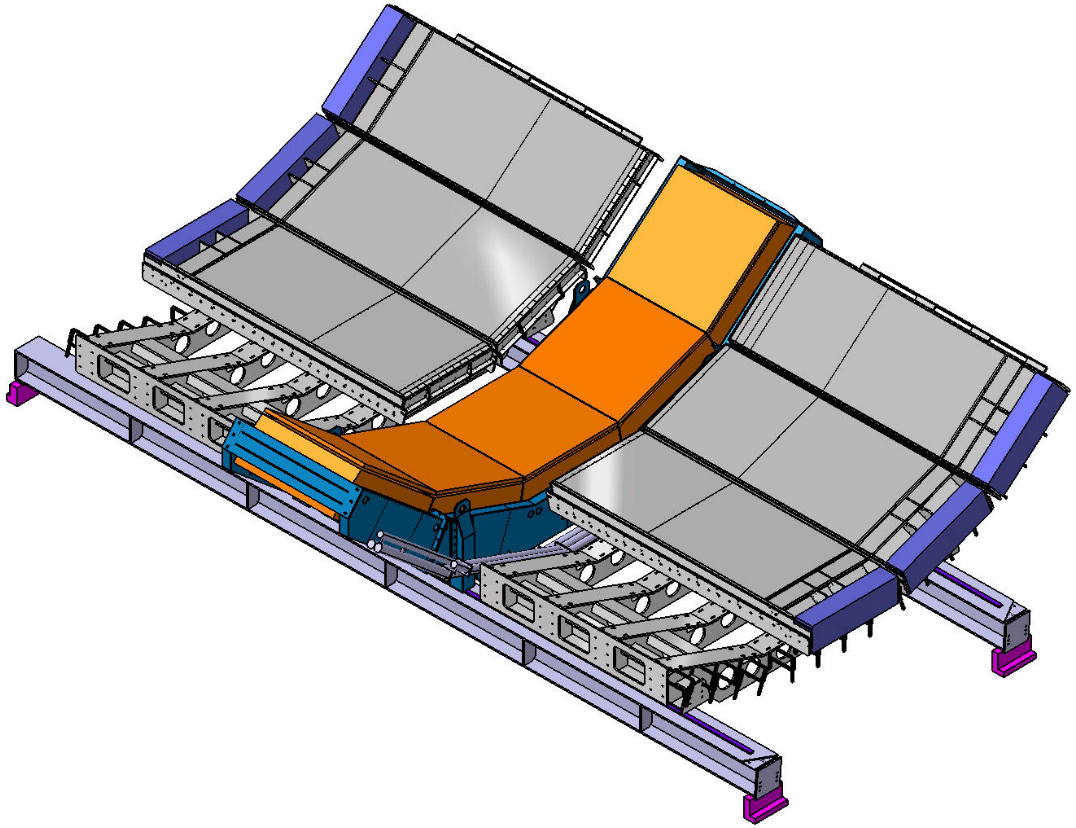
- One has to study this very interesting phenomena in great detail from many aspects.
- (personally) Interested in the medium response (soft particle production) by the passage of energetic parton and its energy loss.
  - Re-heated matter?
  - If so, what the mechanism of re-heating?
  - …

In order to answer this question:

"Jet axis" is one of the key parameters. Then, measure the other observables surrounding the jet jet axis, including soft particles.

- Particle composition of bulk soft particles produced by jets.
- Reaction plane dependence of jet properties (path length effect).

- **ALICE has an advantage of this kind of analysis.**

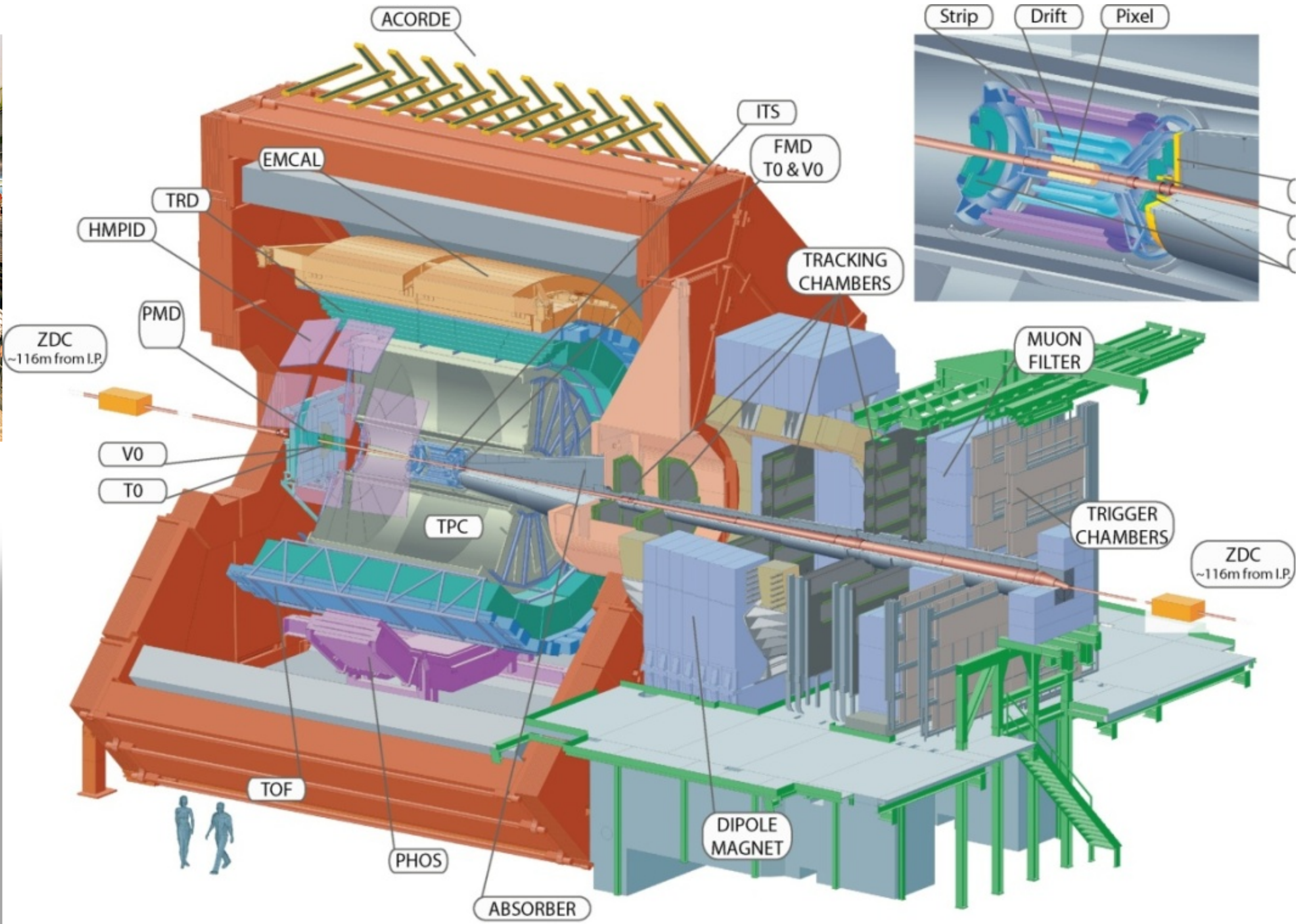


2. DIJET CALORIMETER (=DCAL) IN LHC-ALICE

ALICE experiment

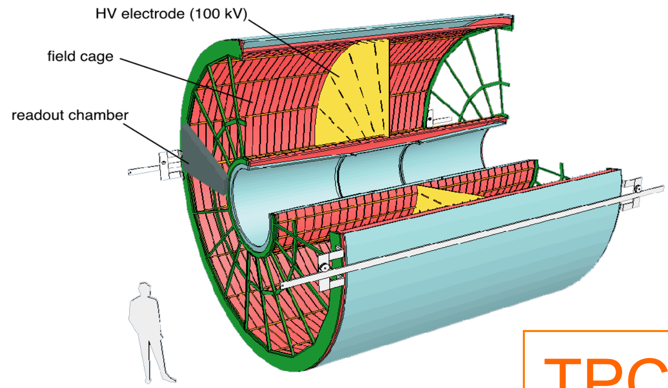
ALICE = *A* *L*arge *I*on *C*ollider *E*xperiment

- Dedicated heavy ion experiment at LHC:

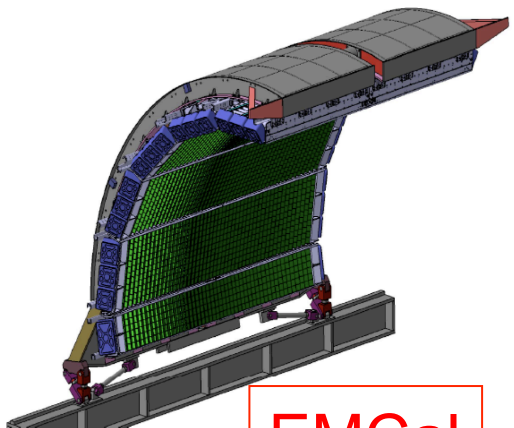


Key detectors for jet measurement in ALICE

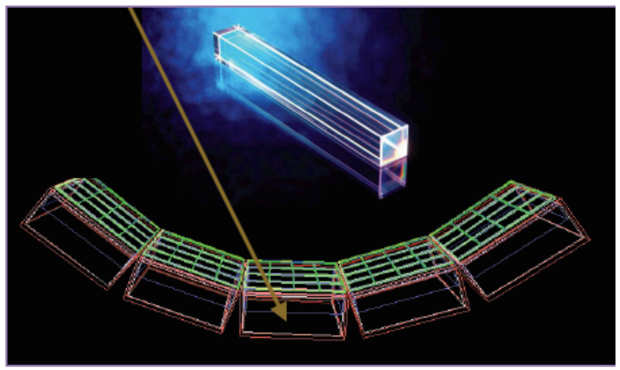
- **TPC (+ITS)**
  - **Charged particles $\Delta\eta$ = 1.8.**
  - Excellent momentum resolution.
  - Excellent PID and heavy flavor tagging.
- **EMCal**
  - Pb-Scint sampling EMC.
  - $\Delta\phi$ = 107°, $\Delta\eta$ = 1.4
  - **Energy resolution ~10%/√E_γ**
  - Jet and γ trigger
- **PHOS**
  - PWO crystal EMC.
  - 220° < ϕ < 320°, $\Delta\eta$ = 0.24
  - **Energy resolution ~3%//√Eγ**
  - γ trigger.



TPC

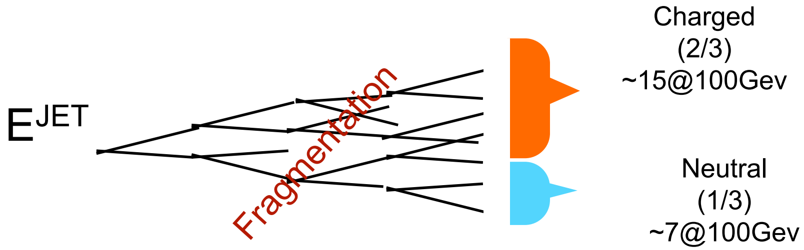


EMCal



PHOS

Fluctuation by neutral

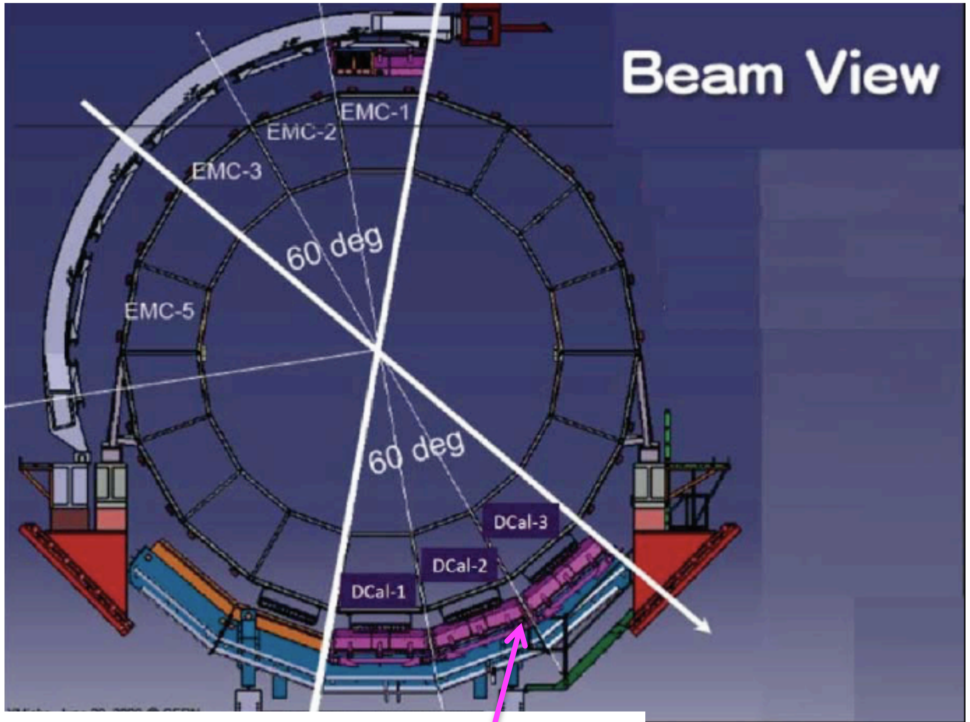


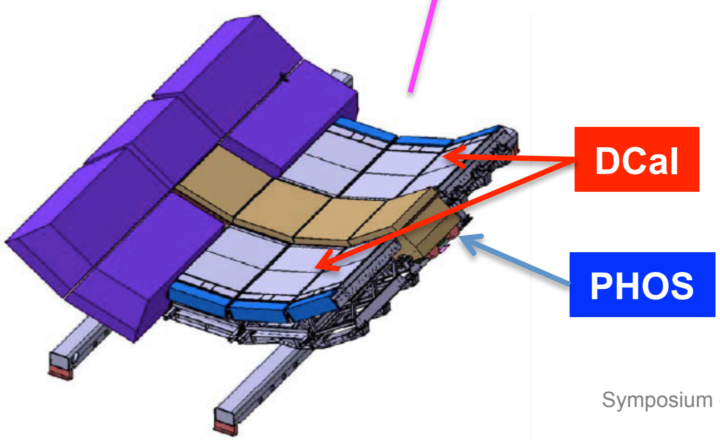
$$E^{JET}=E^{CHARGED}+E^{NEUTRAL}$$

$$dE^{CHARGED} = -dE^{NEUTRAL}$$

- **Current jet identification in ALICE is limited, due to the limited acceptance of EMCal; neutral component does matter.**
- **Statistical fluctuation with total energy limitation.**
  - **Total jet energy is fixed.**
    - **fluctuation of neutral play significant role**
    - **Need larger acceptance EMC on opposite side of EMCal in ALICE.**

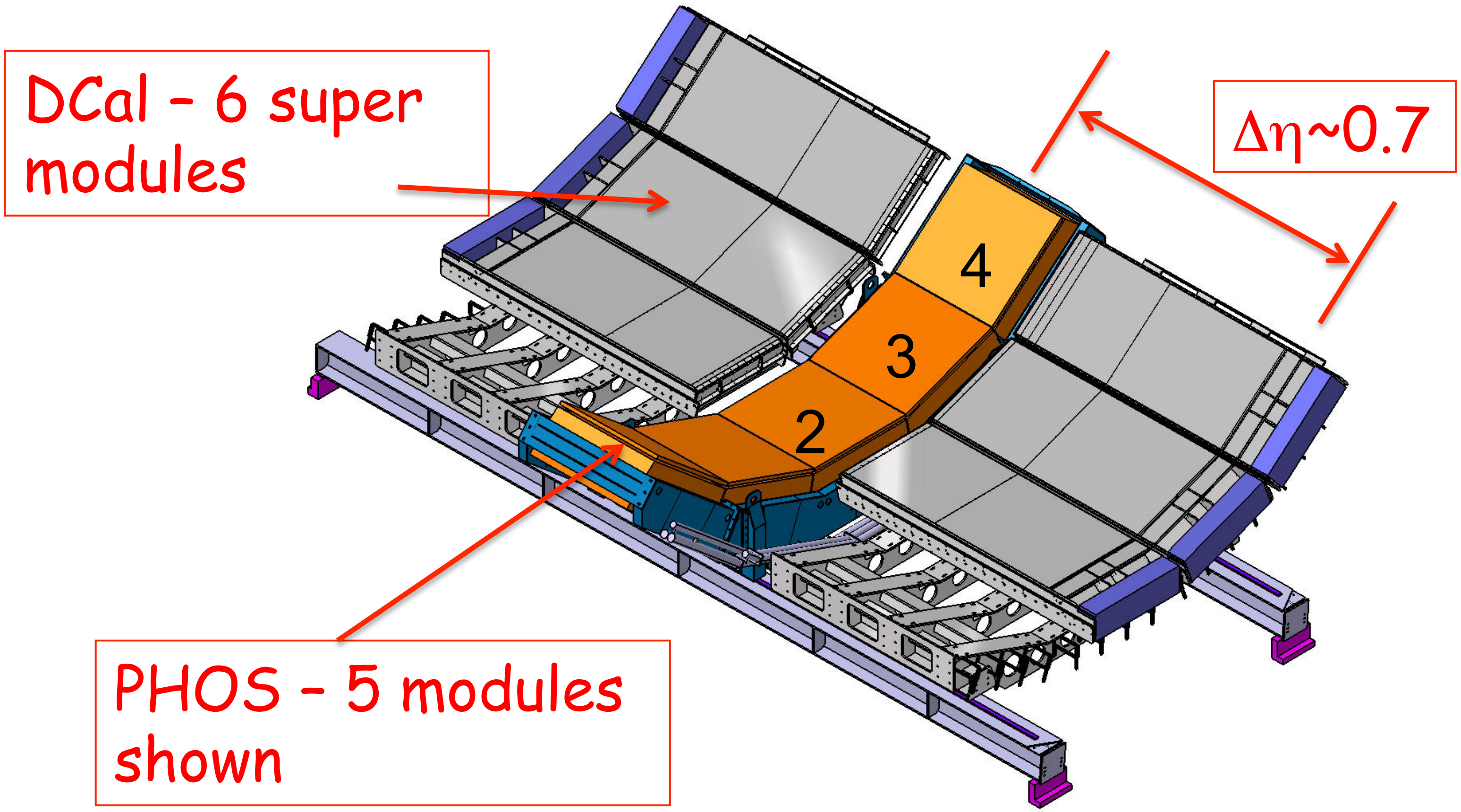
ALICE Dijet Calorimeter (DCal)





- ***Extension of the acceptance of EMCal .***
- ***Lead-scintillator sampling type EMC with APD readout.***
  - ***EMCal: $\Delta\phi$ = 110°***
  - ***DCal: $\Delta\phi$ = 60° (on opposite side of EMCal)***
  - ***$\Delta\eta$ = 0.7 for both EMCal and DCal + PHOS***
  - ***~10%/√E***
- ***Allow back-to-back hadron-jet, di-jet measurements in ALICE, with R = 0.4, up to p_T ~ 150 GeV/c.***
- ***Enhance jet, γ trigger capability.***

D-Cal Design



6 Super Module configuration was chosen to have a largest possible jet radii in DCal, together with PHOS, i.e. R=0.4

ALICE-DCal Collaboration

China
Huazhong Normal University (CCNU), Wuhan

Finland
University of Jyvaskyla

France
LPSC Grenoble, Subatech Nantes, IPHC Strasbourg

Italy
INFN Catania, LNF Frascati,

Japan
Hiroshima University, University of Tokyo, University of Tsukuba,

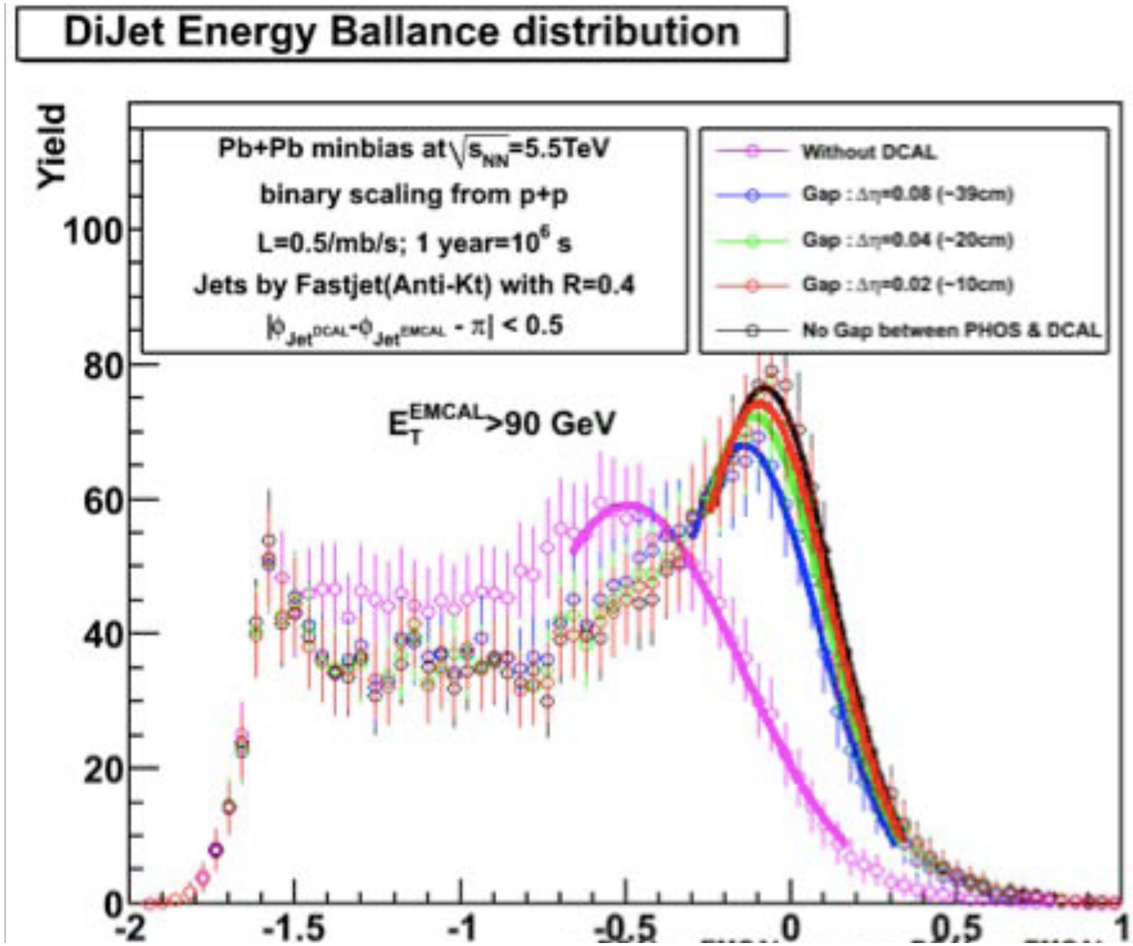
Switzerland
CERN

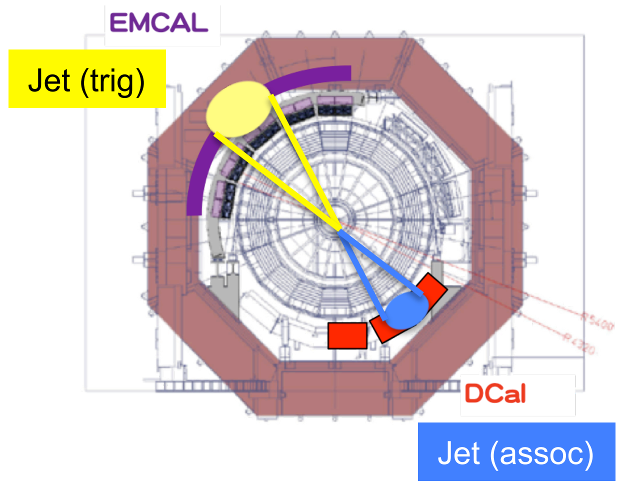
USA
Lawrence Berkeley National Laboratory, Wayne State University, University of Houston, University of Tennessee, Lawrence Livermore National Laboratory, Yale University, Oak Ridge National Laboratory, Creighton University, Cal Poly San Luis Obispo, Purdue University

3.Physics case of DCal

- **Case1: Jet-Jet in p+p**
- **Case2: Jet-Jet in Pb+Pb (quenching effect)**
- **Case3: π^0-Jet in Pb+Pb**
  - Notes:
    - MC simulation study using qPYTHIA.
    - "DCal" means including PHOS acceptance, i.e. DCal+PHOS.
    - Uncertainty on data points: Pb+Pb (central 0-10%) @ 5.5 TeV one year running statistical uncertainty (= 0.5 nb^{-1}).
    - Jet reconstruction: FAST jet anti-kT algorithm, R=0.4.

Case1: Dijet in p+p

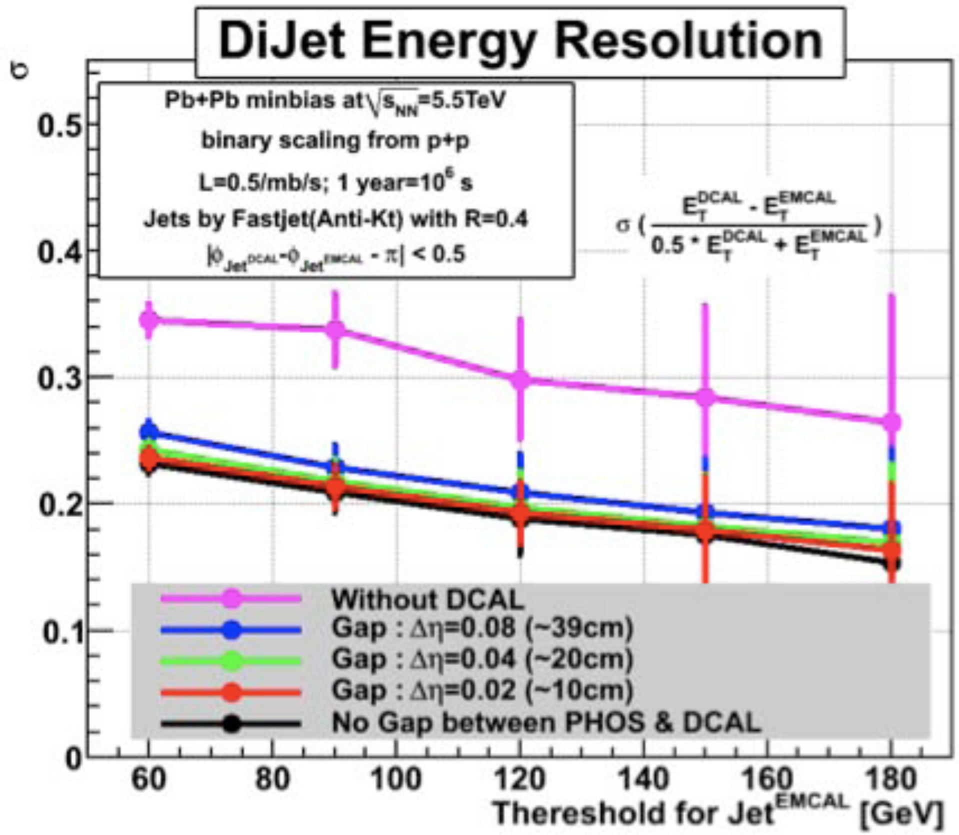


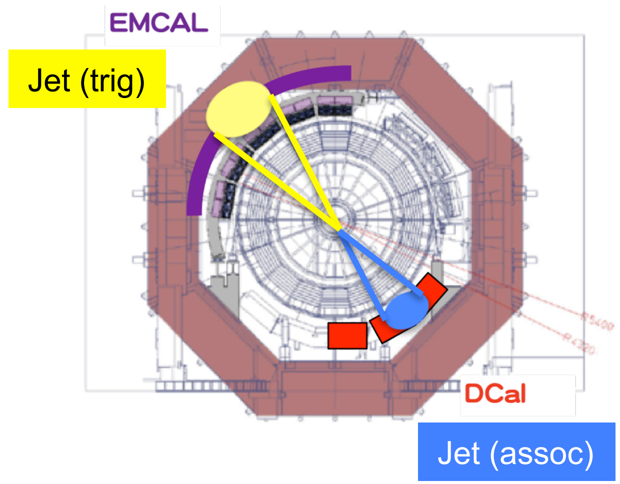


$$\Delta = \frac{(E_T^{DCal} - E_T^{EMCal})}{(E_T^{DCal} + E_T^{EMCal})/2}$$

- Dijet energy balance, Δ.
- No quenching (p+p)
- **True dijet peak Δ~0, except without DCal.**
- **No clear peak EMC-TPC (no DCal).**
- Asymmetric shape due to recoil jet escape the acceptance of DCal, and jet from BG.
- **DCal is essential for better Δ resolution.**

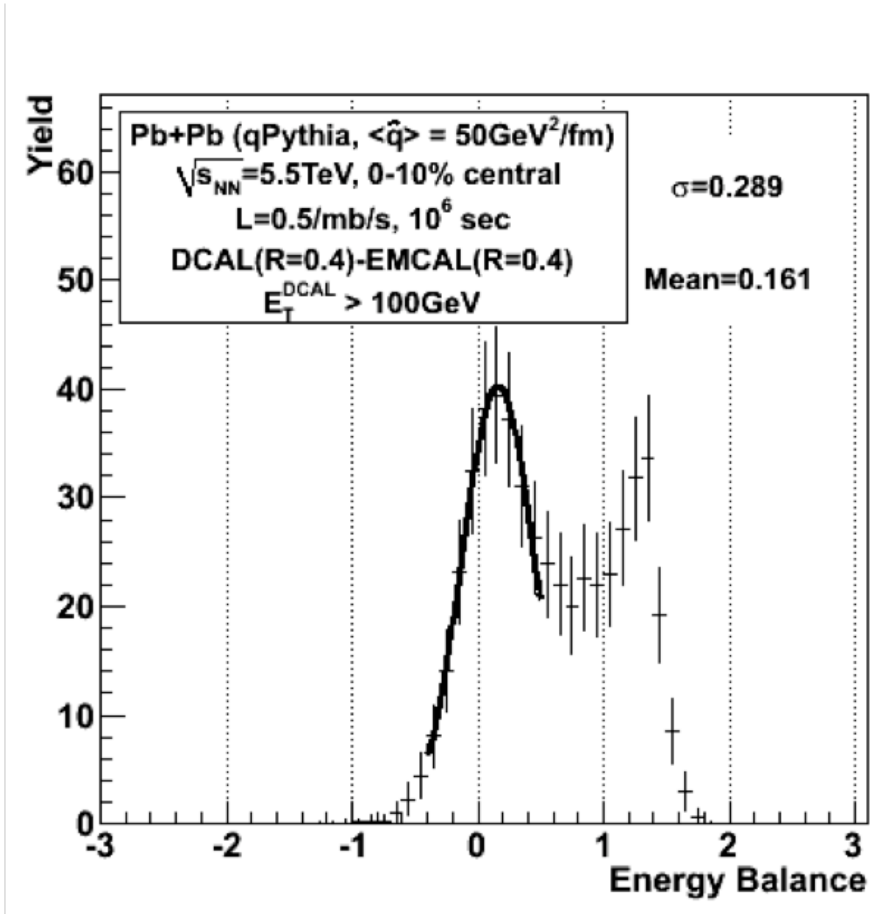
Case1: Dijet in p+p



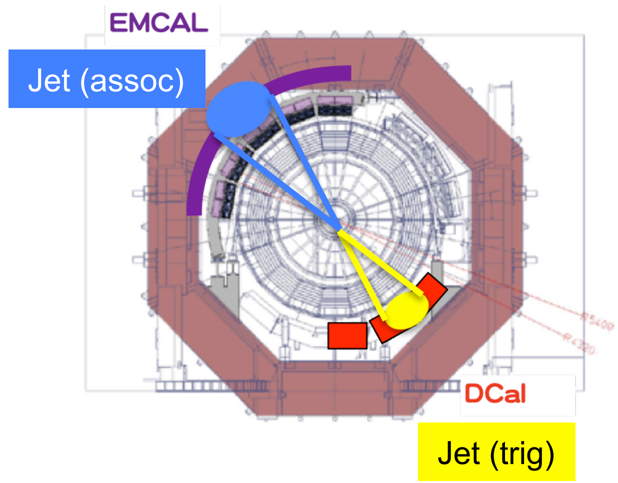


- DCal improves the energy balance resolution from ~35% to ~25% @ E_T^{EMCal} = 60 GeV, down to <20% for higher E_T^{EMCal}.
- Small effect by gap between PHOS and DCal.

Case2: Dijet in Pb+Pb, quenched jet



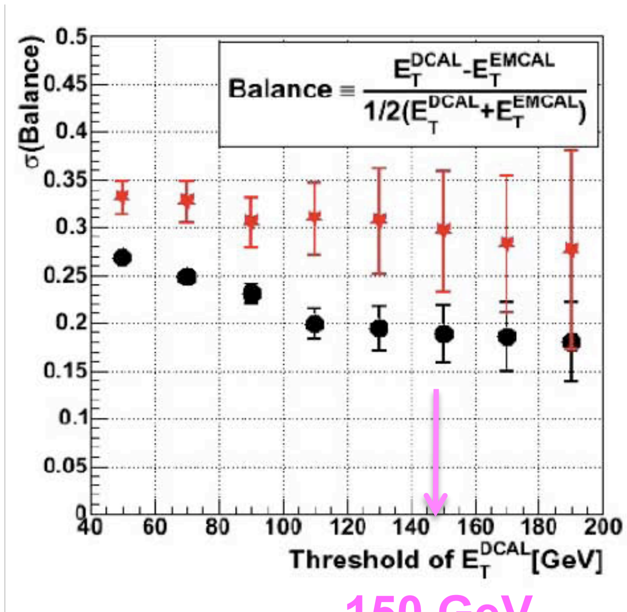
$$\Delta = \frac{(E_T^{DCal} - E_T^{EMCal})}{(E_T^{DCal} + E_T^{EMCal})/2}$$



- Same as “Case1” but, **required trigger jet in DCal side** instead.
- “Tail” on positive side due to trigger for DCal.
- In this case, <qhat> = 50 GeV^2/fm, and DCal jet energy threshold of 100 GeV.
- Peak: true dijet with quencing.
  - look at sigma, and centroid to quantify the jet quenching effect (see next slide).
- Tail: recoil jet out of acceptance, BG.

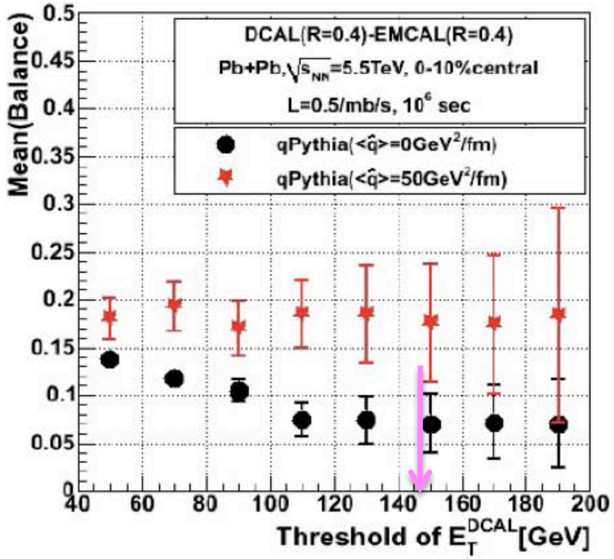
Case2: Dijet in Pb+Pb, quenched jet

Width

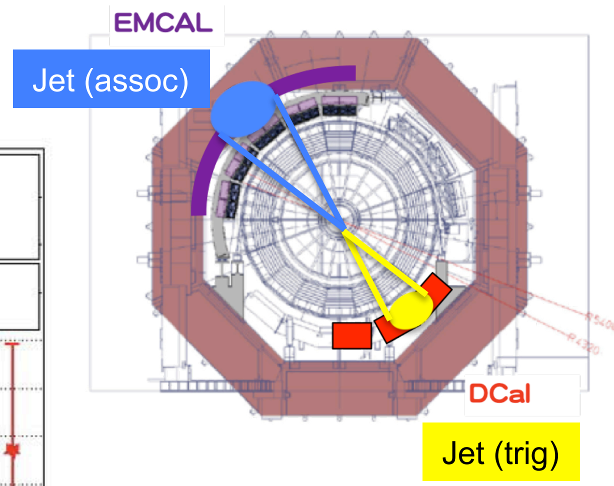


150 GeV

Centroid



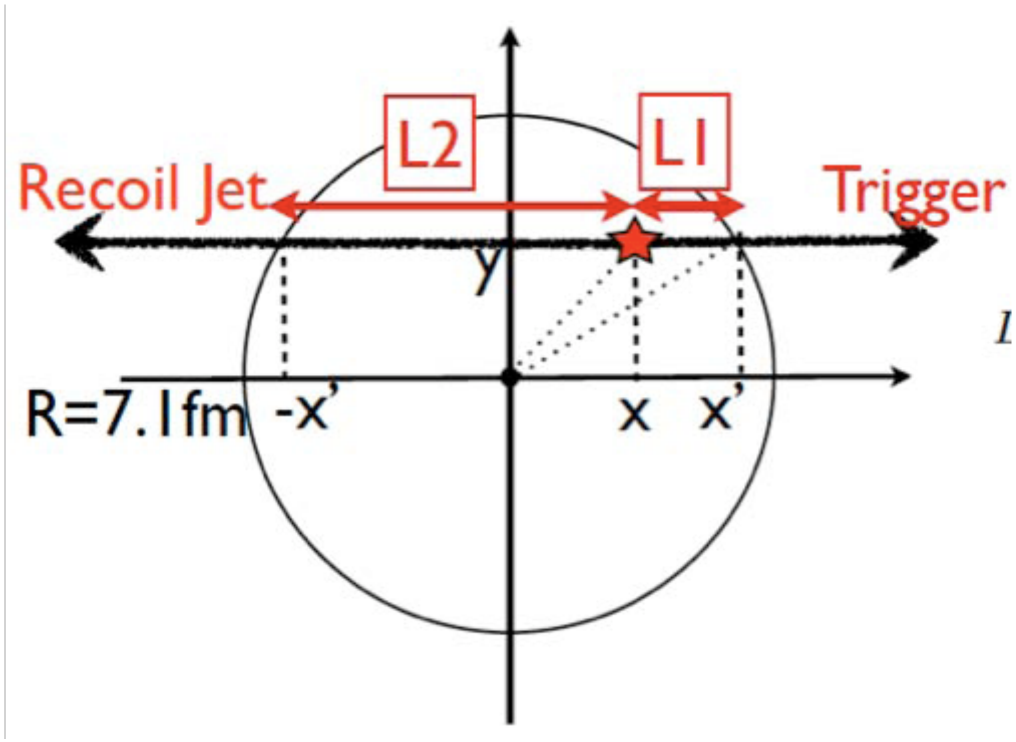
150 GeV

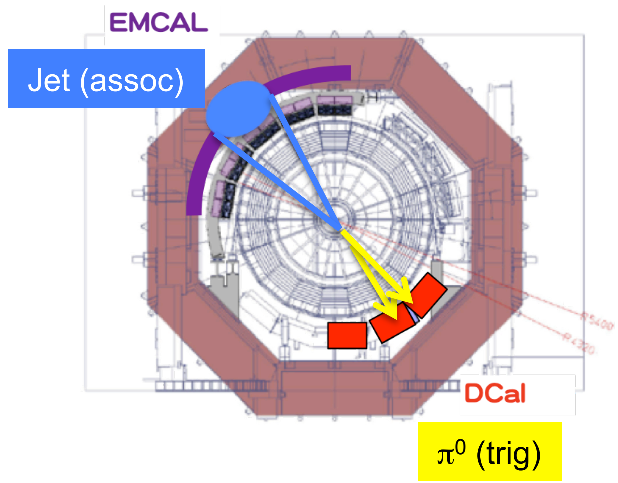


- **Red: <qhat> = 50 GeV²/fm**, **Black: <qhat> = 0 GeV²/fm.**
- Broadening of peak is seen for jet quenching.
- Shift of centroid -> energy loss.
- Using one year Pb+Pb running (in this model & parameter set), possible to study jet quenching effect up to E_T^{DCal} ~ 150 GeV.

Case 3: π^0-jet, control path length

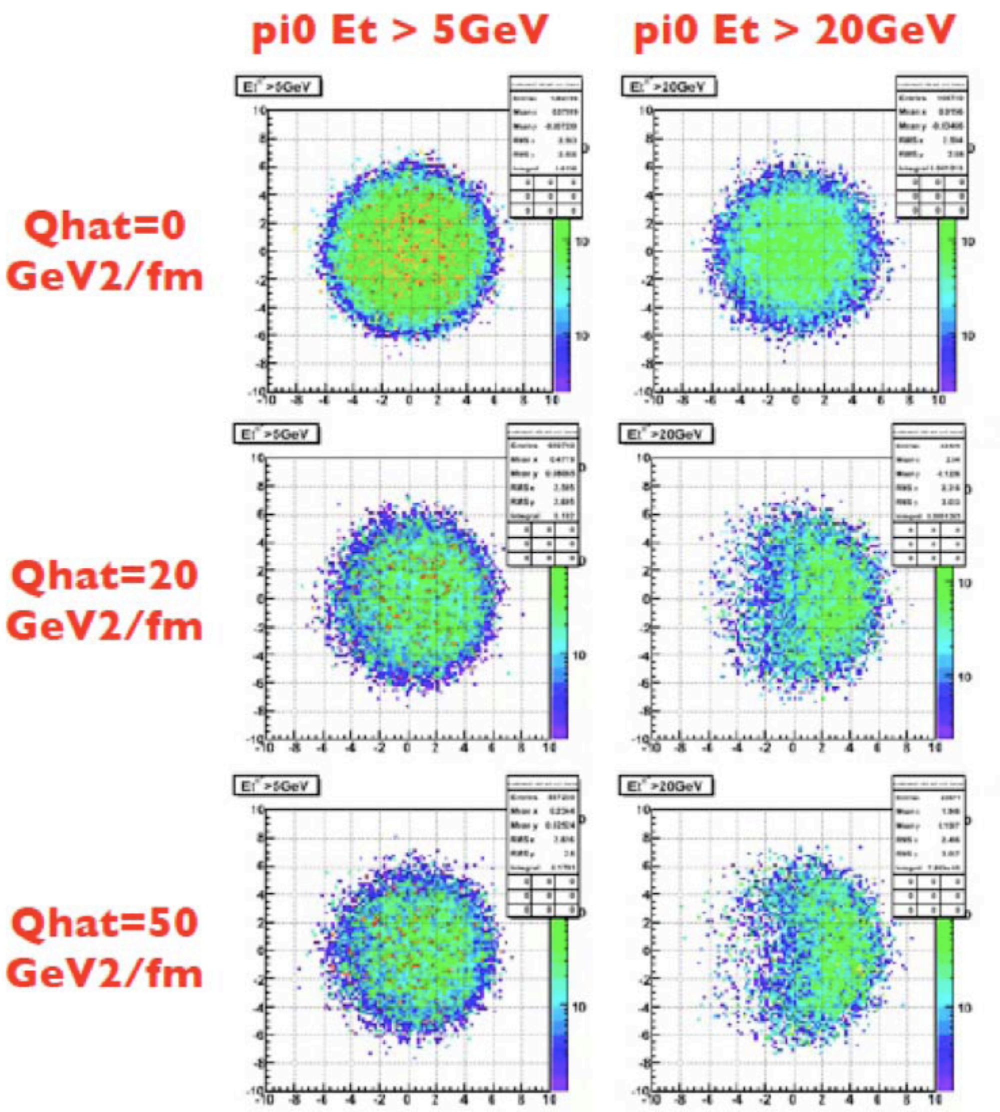
Geometry of π^0 trigger and associated recoil jet

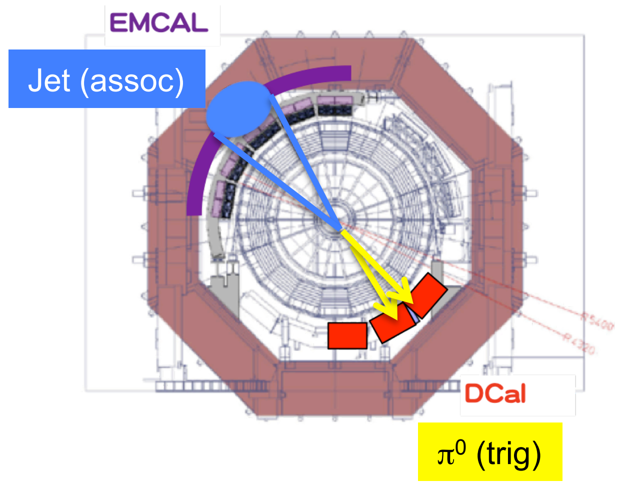




- Trigger π^0 in DCal, requiring jet in EMCal.
- Producing strong geometry bias by hand, i.e. "control" the path length of jet.

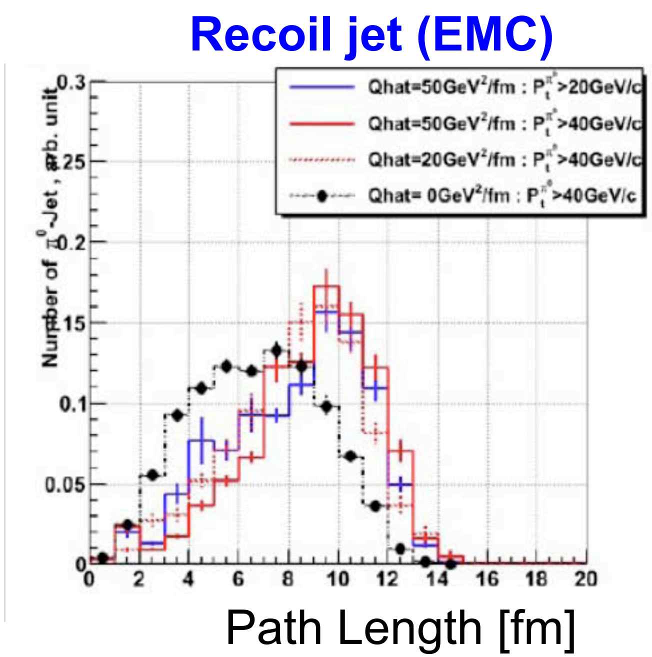
Case 3: π^0-jet, control path length

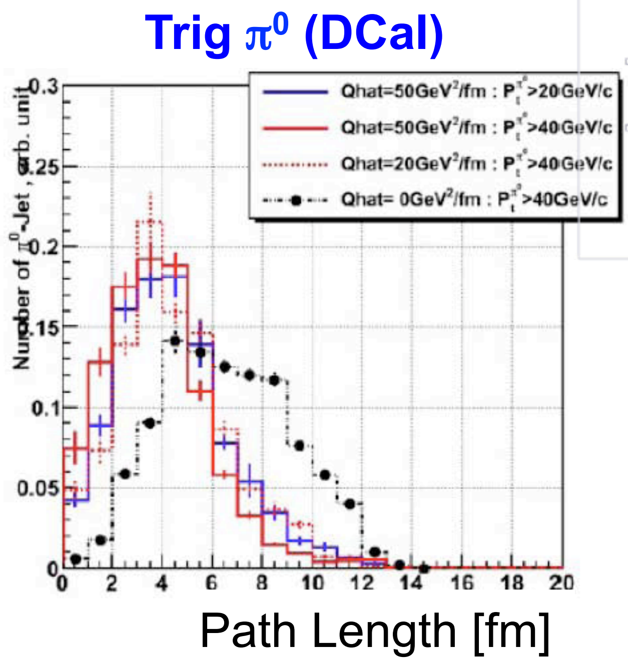


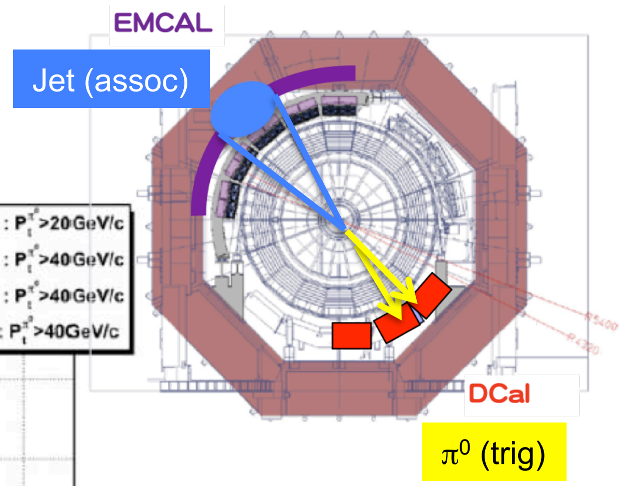


- Hard scattering point (in x-y plane) of trigger π^0 with associate recoil jet.
- **The higher E_T π^0, the stronger surface bias.**
- <qhat> = 20 & 50 GeV^2/fm
  - small difference.
    → can be used as geometry measure of emission point, without knowing the quench parameters.

Case 3: π^0-jet, control path length

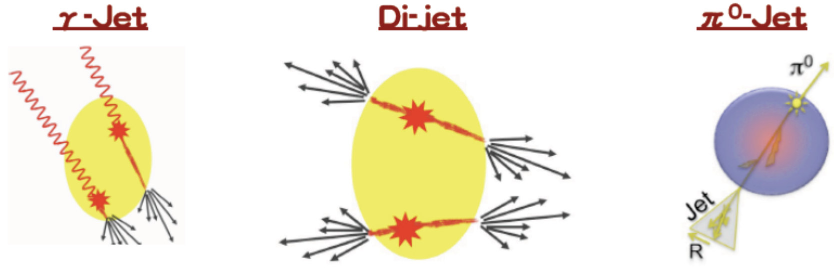




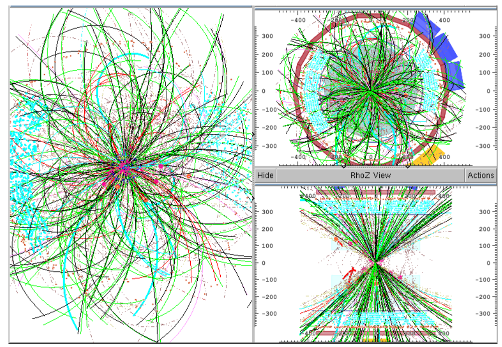


- **Trigger π^0 (right): Minimizing path length.**
- **Recoil jet (left): Maximizing path length.**
- **Path length of jet medium, "control" experiment.**
- Efficient trigger of π^0 (Level 1) is the key, and it is capable by utilizing existing level 1 readout for EMC.

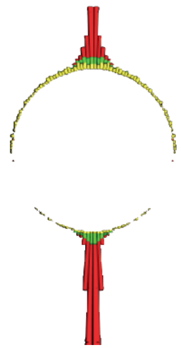
Other interesting measurements with DCal

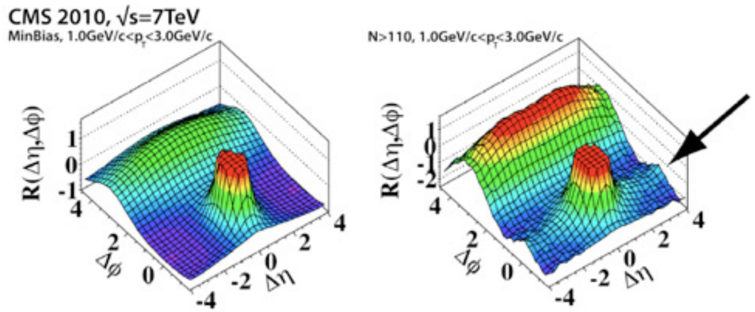


- **γ-jet:**
  - Golden channel.
  - Complementally to h (π^0) -jet, jet-jet.
- **Medium responses with jet axis**
- **Ridge study with di-jet & π^0 - jet**
- **Reaction plane dependence of:**
  - di-jet energy balance
  - π^0-jet
- **Discrimination of quark jet, gluon jet**
  - Study of energy loss mechanism.
  - Multiplicity, γ-jet (mostly quark jet) can be used.
- **Heavy flavor tagged jets**
  - Energy loss for c, b quarks.
- **Multi-jet events**
- **Jet quenching in High multiplicity p+p events?**



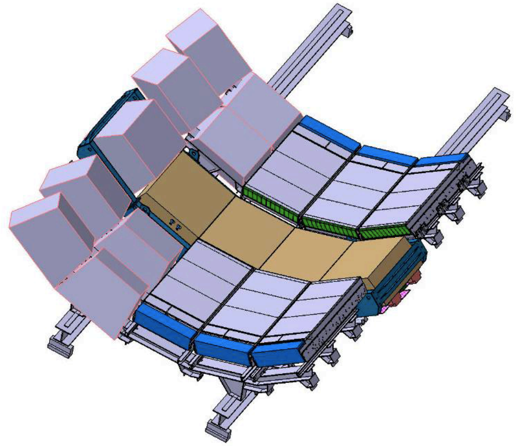
High multiplicity p+p event @ 7 TeV (ALICE)





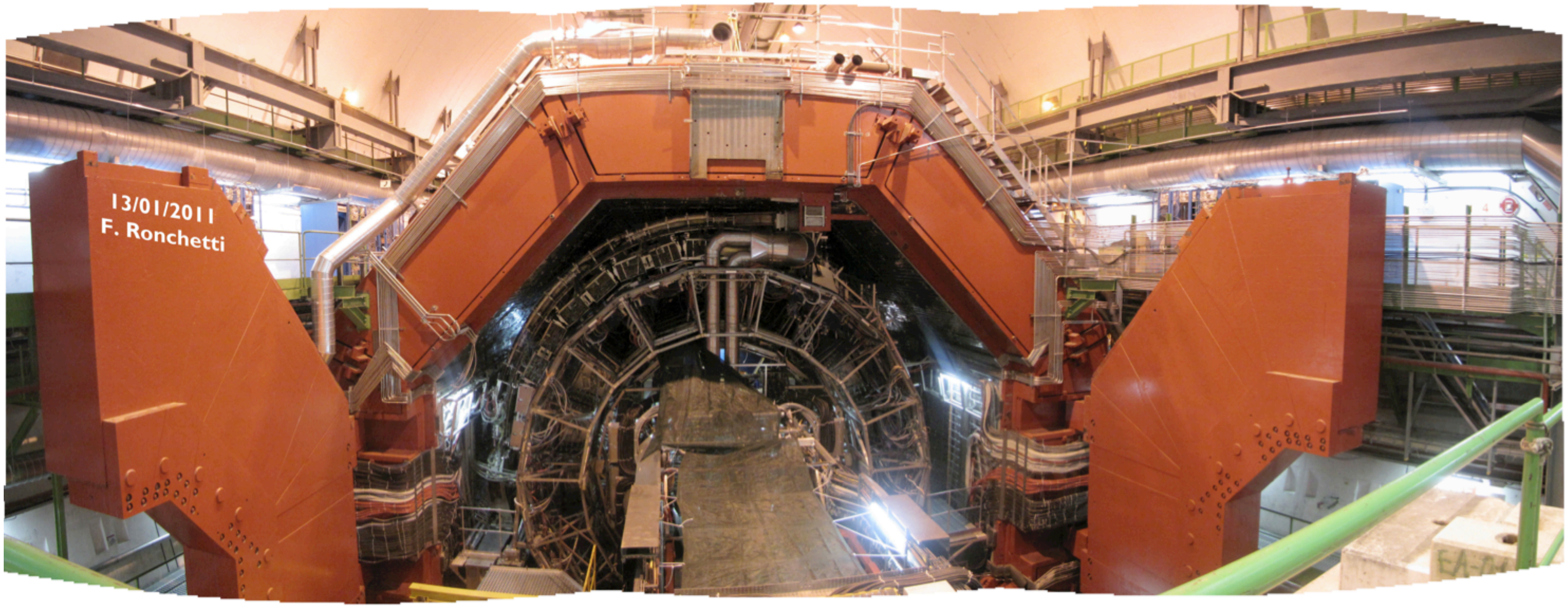
4. Current status and schedule

- DCal has been approved by the ALICE collaboration, Oct. 2009.
- Module production in France, Japan and China has been basically completed.
  - 3.0 SM from Wayne State Univ. (USA)
  - **1.5 SM from Tsukuba (Japan)**
  - **1.0 SM from Wuhan (China)**
  - 0.5 SM from Nantes (France)
    - Total: 6 SM (192 x 6 = 1152 modules) for DCal.



- Integrated SM in Nantes, Grenoble.
- **Installed in the ALICE experimental area during the long LHC shutdown in 2012-2013.**

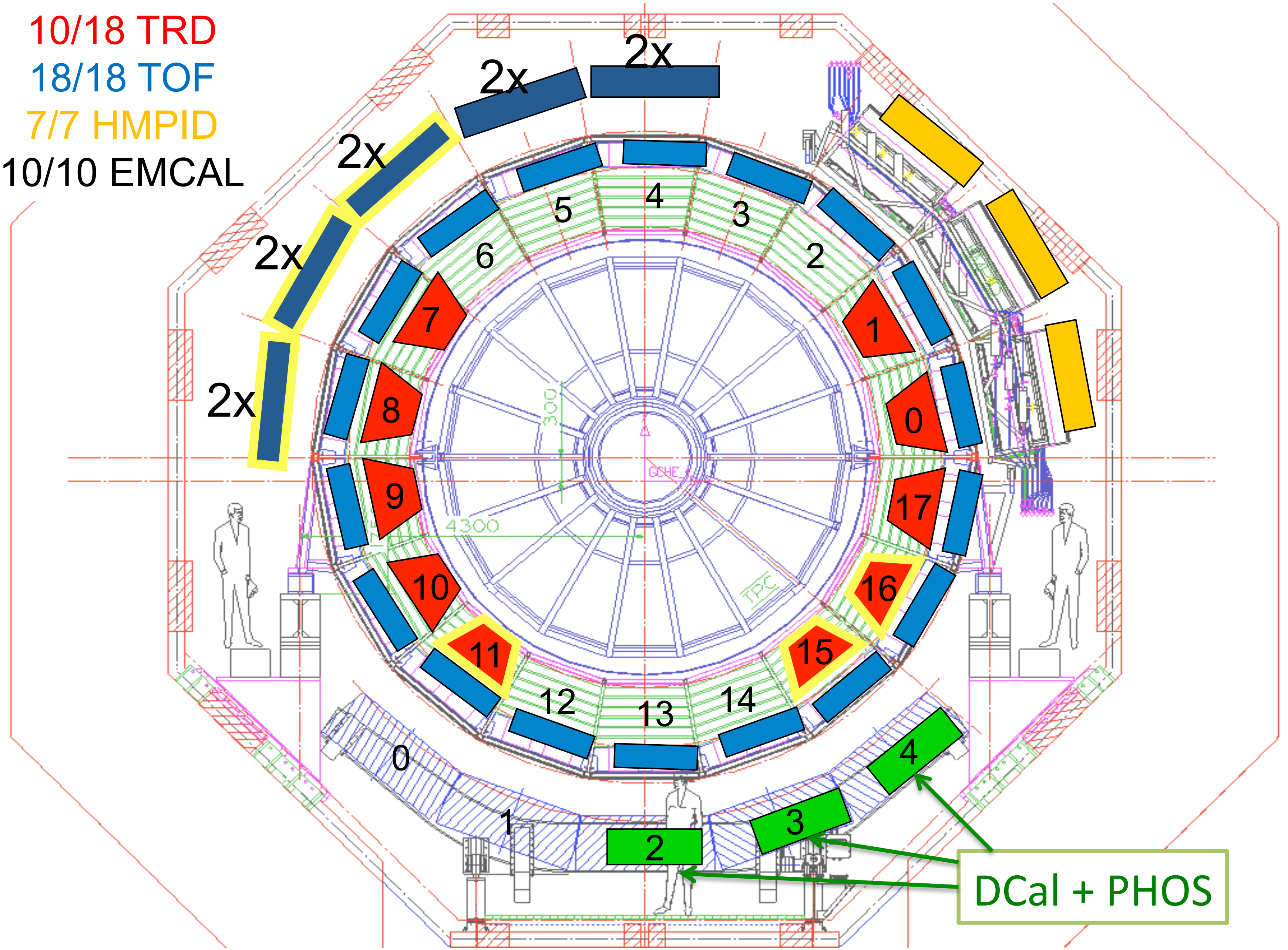
EMCal status in 2011



- On Jan. 2011, EMCal installation has been completed.
  - 2880 modules installed in 10 super modules.
  - Principal construction sites: USA, France, Italy.
- Started data taking with the full EMCal coverage from LHC11.

Next, DCal

3/5 PHOS
10/18 TRD
18/18 TOF
7/7 HMPID
10/10 EMCAL



At Tsukuba (Japan)

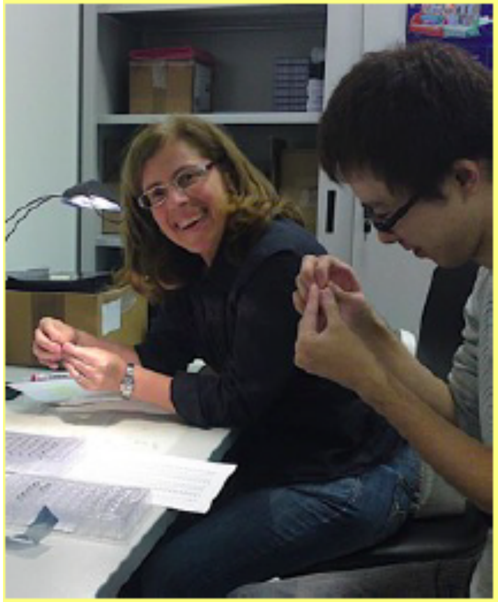
All module production has been completed (July 2011).

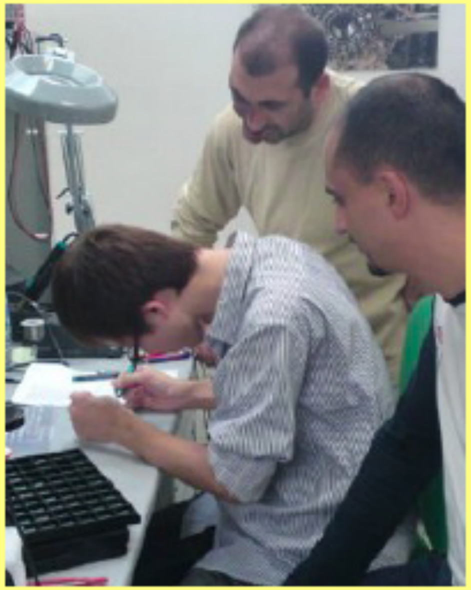
At Nantes (France)

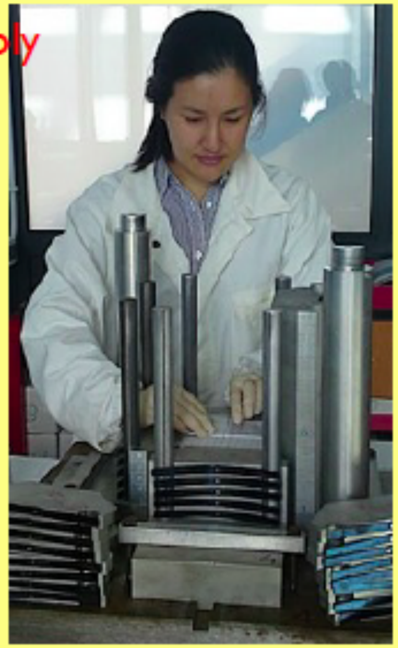
All module production has been (or to be) sent to Nantes.

At Catania (Italy)

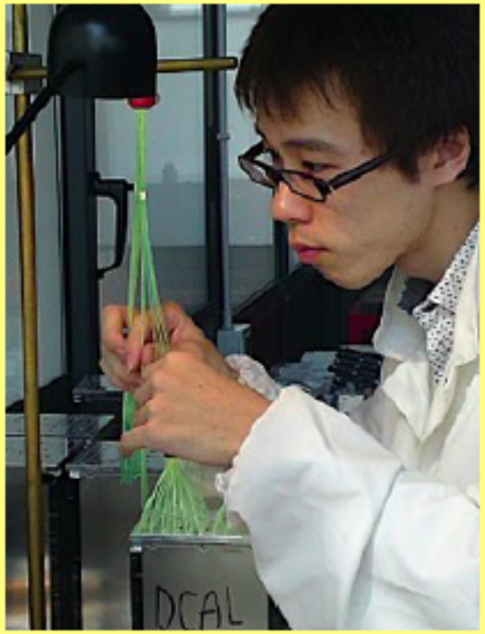
Hiroki & Maya at Catania fir APD & module assembly







Maya Shimura

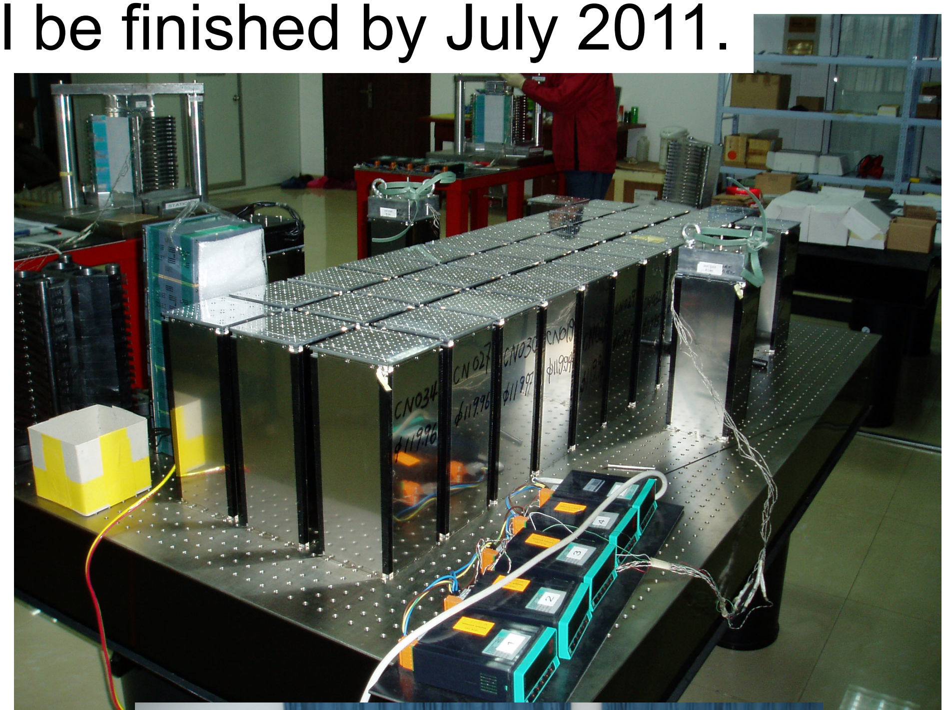


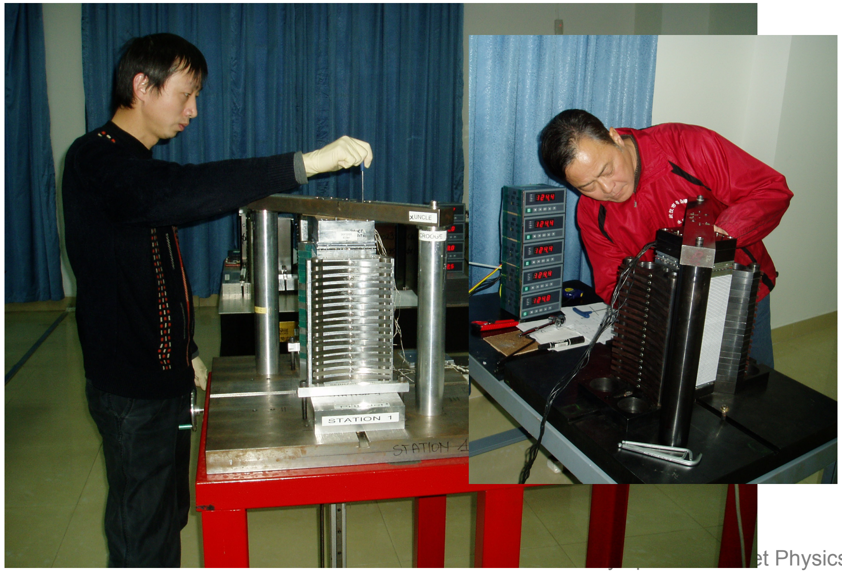
Hiroki Yokoyama

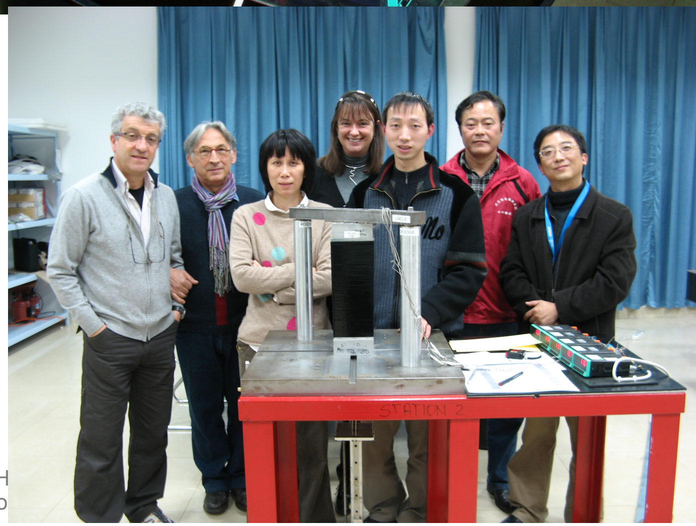
Module Assembly & APD assembly/calibration at Catania

At Wuhan, CCNU (China)

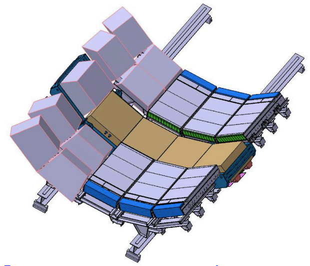
All module production will be finished by July 2011.







5. Summary



- Dijet Electromagnetic Calorimeter (DCal) in ALICE experiment provide a powerful & crucial tool to investigate hot and dense matter in HI collisions at LHC, through dijet and π^0-jet using jet axis:

  1. Di-Jet correlations:
     - Energy balance of jet.
  2. π^0-Jet correlations:
     - Control path length of jet.

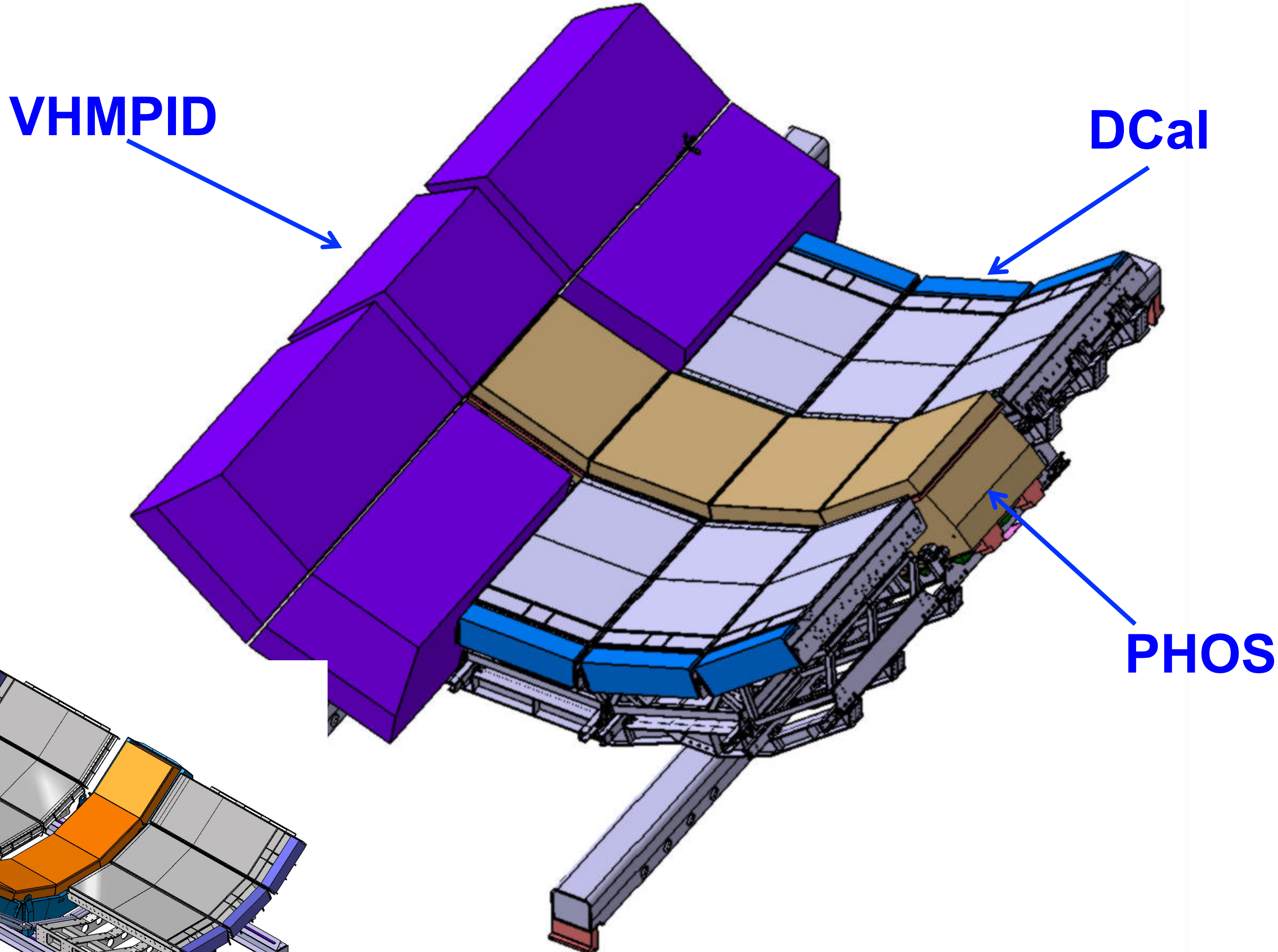
- Together with other measurements (e.g. γ-jet, reaction plane dep., medium response), one may get a complete understanding of jet quenching mechanism at LHC energy, i.e. "jet tomography", and the nature of QGP.

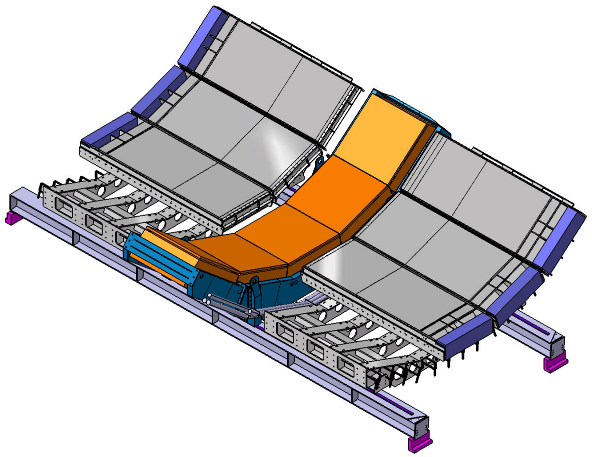
- DCal will be installed in the next LHC long shutdown (2012-2013), and will be ready to take 5.5 TeV Pb+Pb data in the following year.

謝謝！

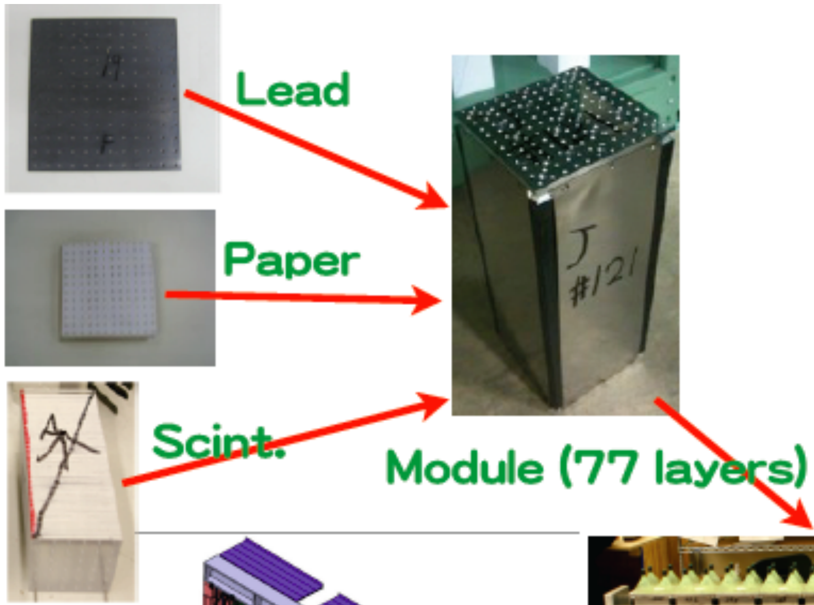
BACKUP SLIDES

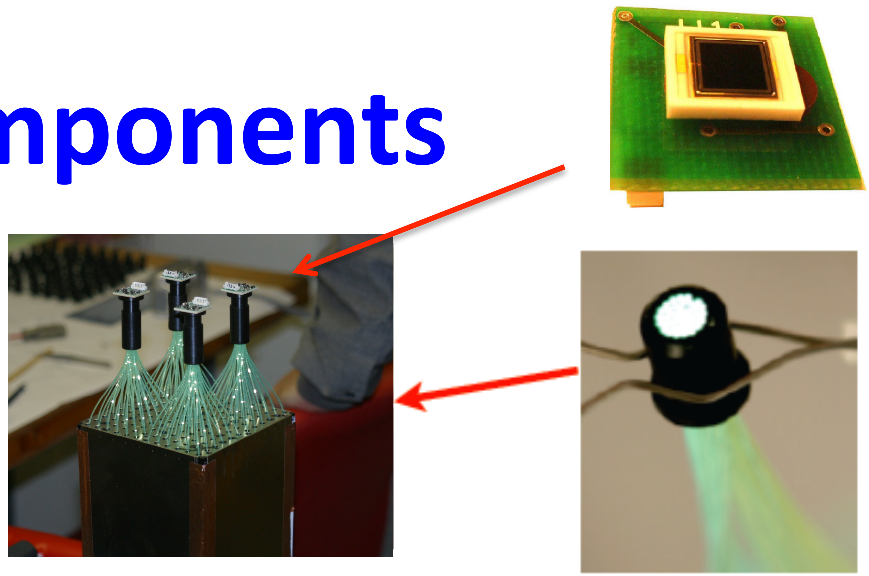
DCal Integration



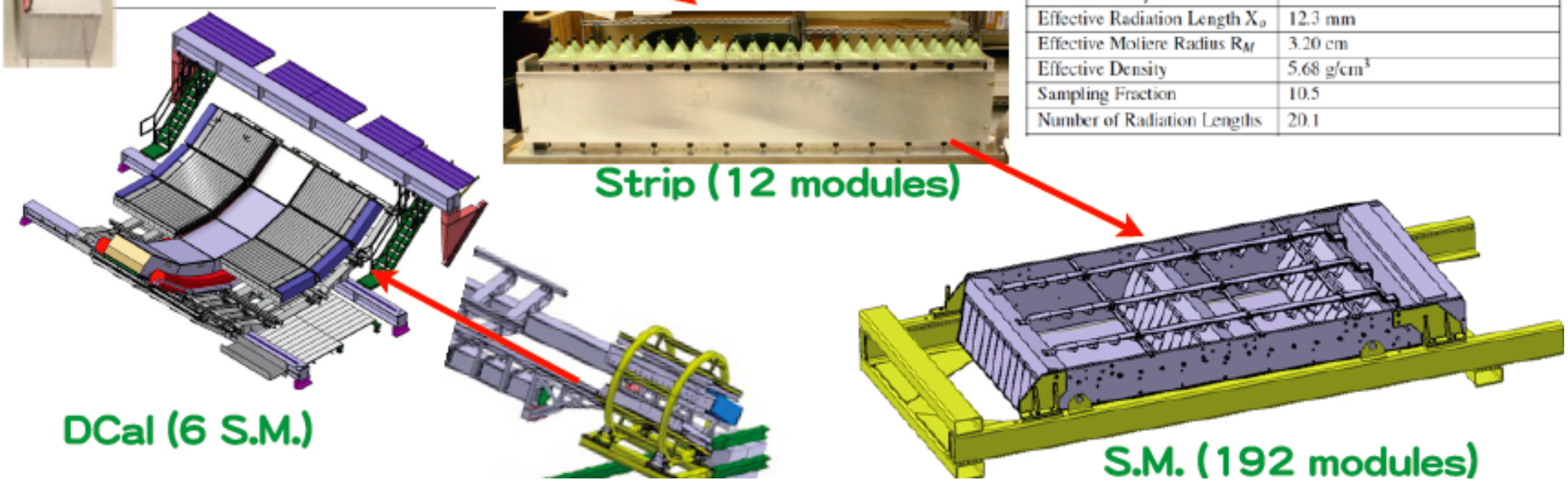


DCal components

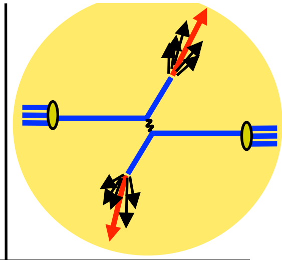




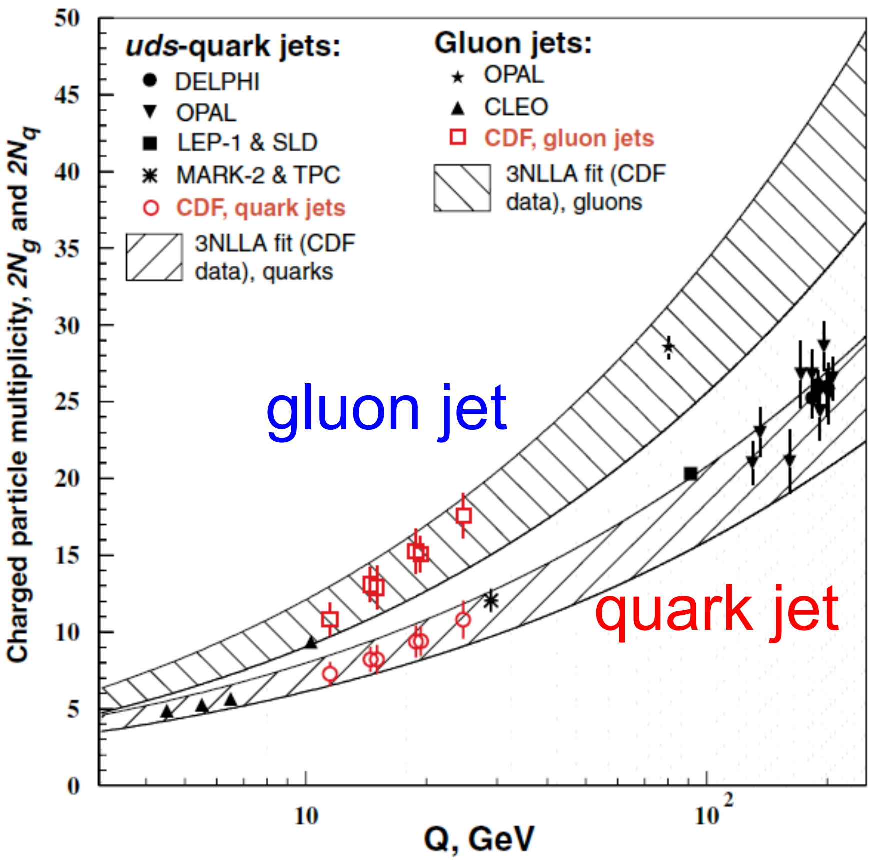
Quantity	Value
Tower Size (at η=0)	~6.0 × ~6.0 × 24.6 cm^3 (active)
Tower Size	$\Delta\phi$ x $\Delta\eta$ = 0.0143 x 0.0143
Sampling Ratio	1.44 mm Pb / 1.76 mm Scintillator
Number of Layers	77
Effective Radiation Length X_0	12.3 mm
Effective Moliere Radius R_M	3.20 cm
Effective Density	5.68 g/cm^3
Sampling Fraction	10.5
Number of Radiation Lengths	20.1



Possibility of Parton ID



CDF, PRL94(2005)171802



- As a new generation exp., from Particle ID to Parton ID !
  - According to CDF exp., charged/neutral works
- Might be very difficult in heavy ion environment
- Nevertheless, challenge!
- It becomes feasible for higher p_t jet

Jet trigger in Pb+Pb

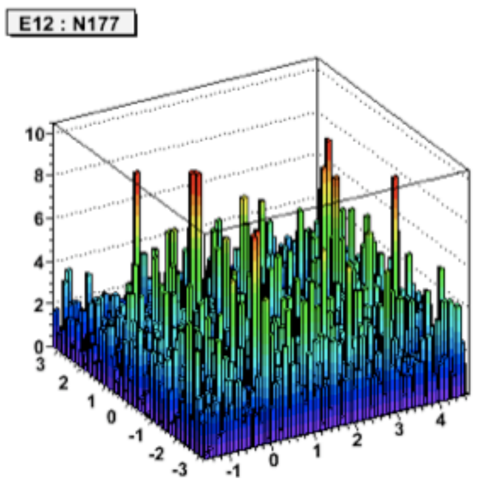
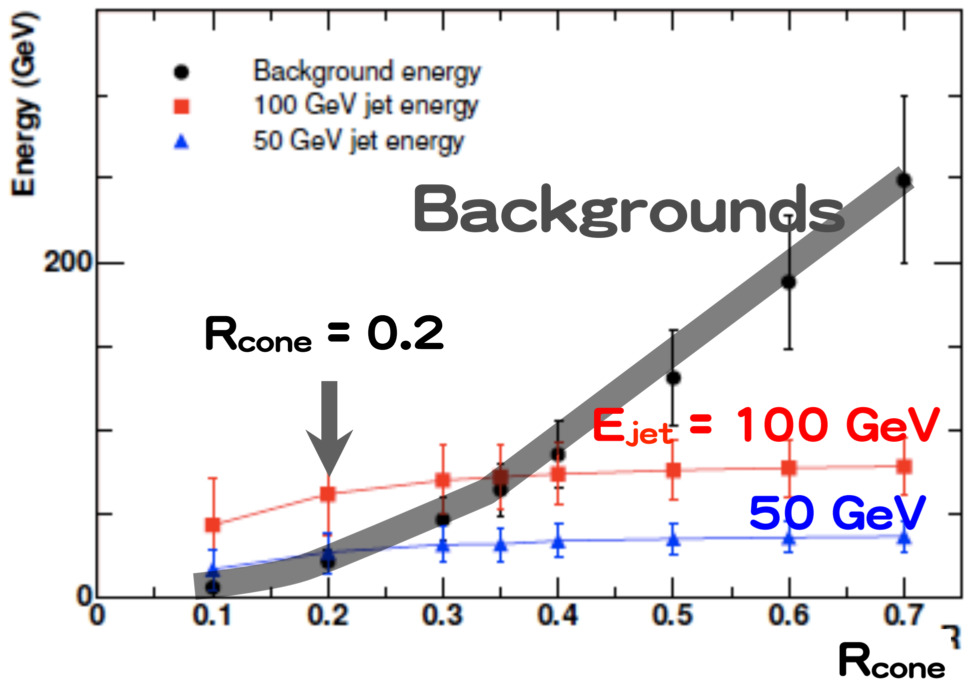
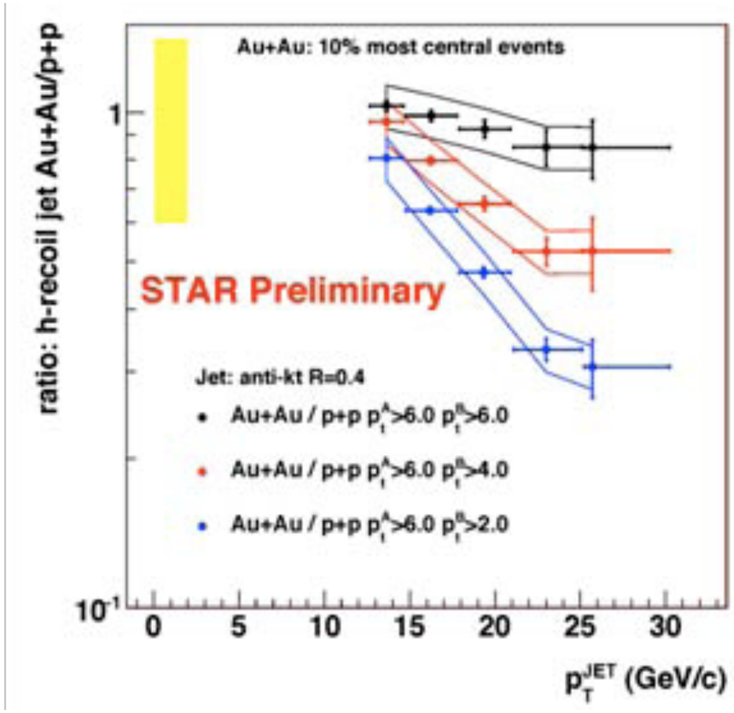


Fig.8.4 of TDR

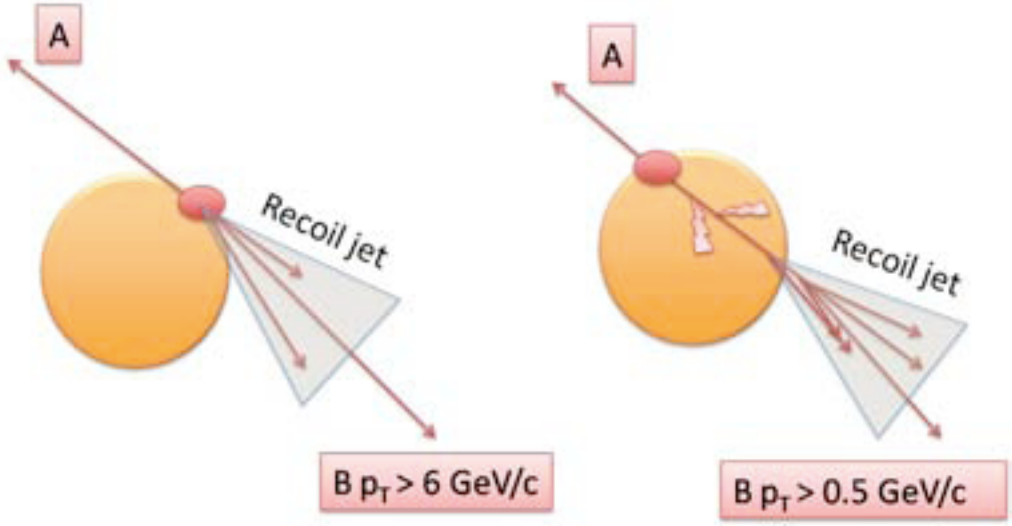


- With R_{cone} = 0.2, triggering jet of < 50 GeV becomes difficult.
- Back-to back

Full jet reconstruction, and h-jet correlations at RHIC

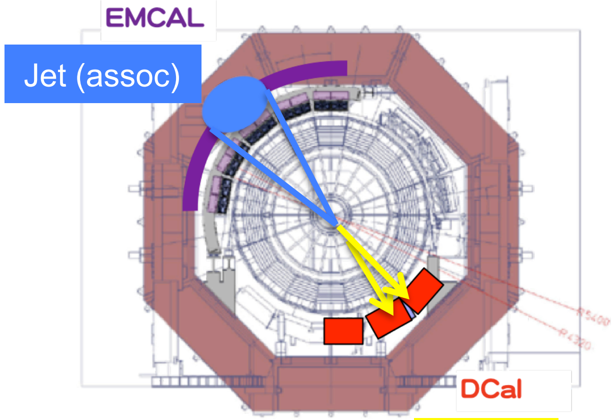


Key to understand jet in HI collisions:
(1) correlations, (2) fully reconstructed jet.



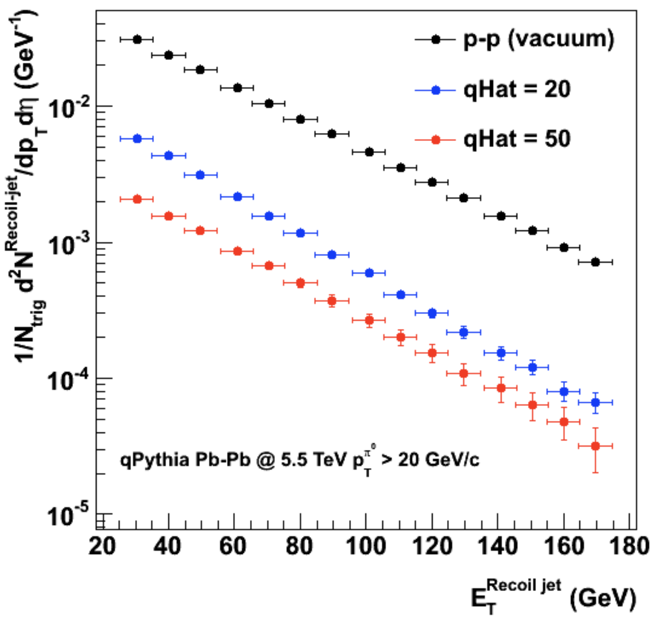
- Used fully reconstructed jet (by STAR TPC & EMC).
- Trigger high p_T hadron, and look at **recoil jet** in away side, measure conditional yield in (Au+Au / p+p).
- **Stronger suppression for lower recoil jet energy.**
  - indicating broadening of recoil jet cone size.
- **"Controlled" surface bias.**

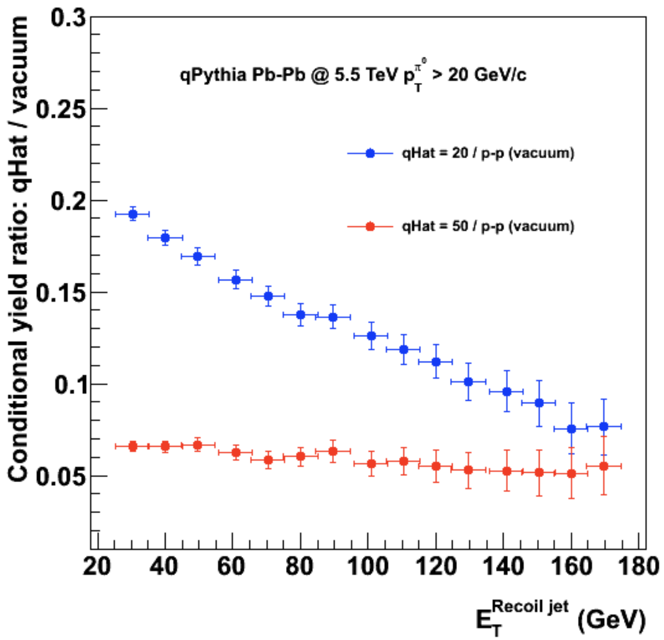
Case 3: π^0-jet, control path length

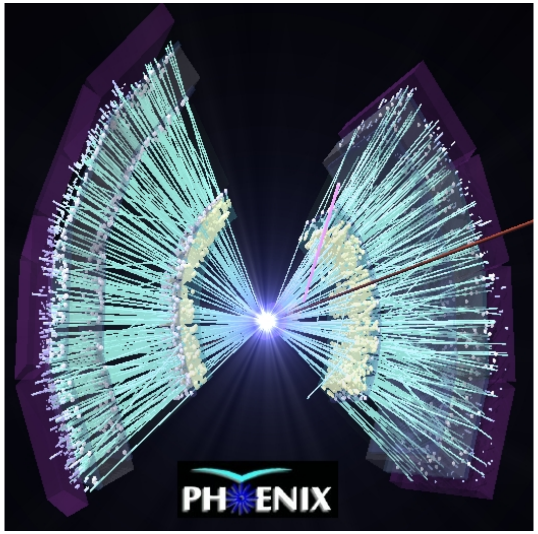


semi-inclusive jet spectrum (π^0-jet)

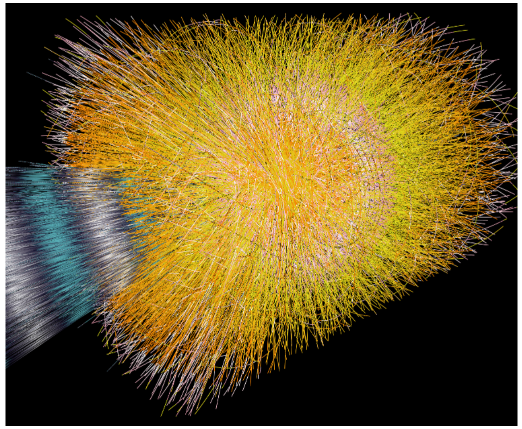
Au+Au/p+p





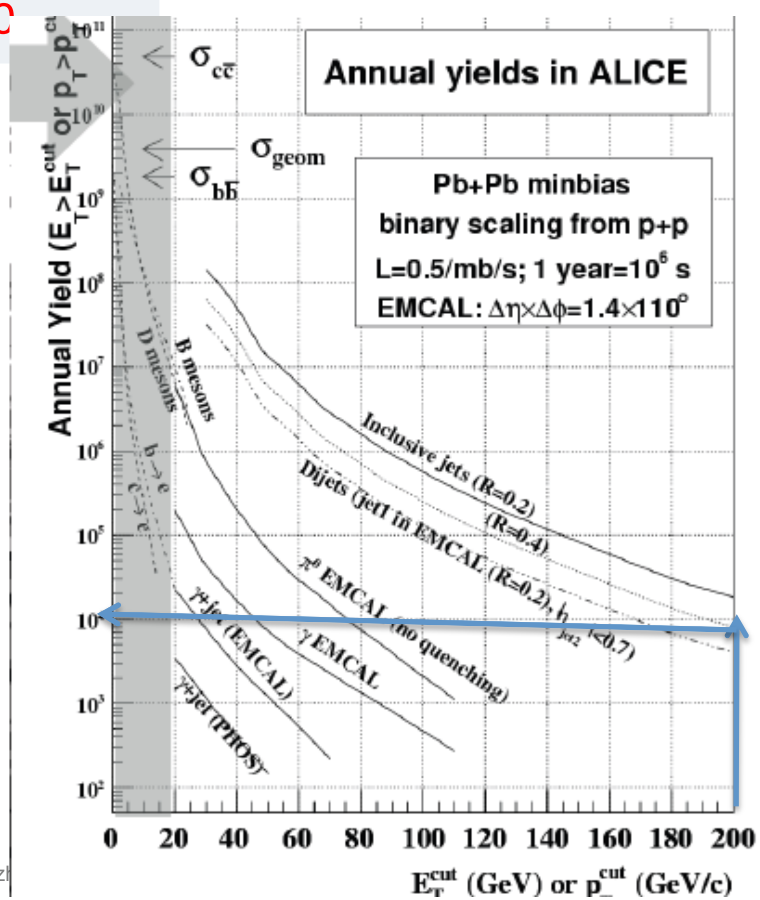


RHIC vs. LHC



	RHIC	LHC
$\sqrt{s_{NN}}$ (GeV)	200	5500
T/T_c	1.9	3.5-4.0
ε (GeV/fm³)	5	15-60
τ_{QGP} (fm/c)	2-4	> 10

RHIC

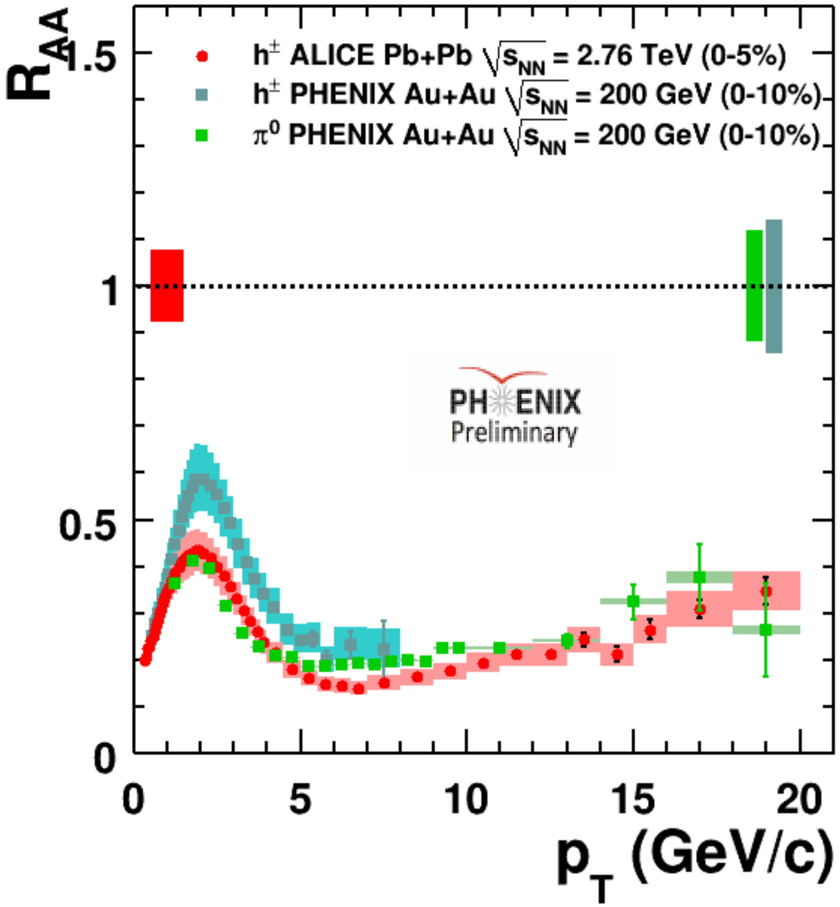


- **LHC: Jet production dominant.**
  - **Study the matter by clean many hard probes, and look at response of bulk matter in HI collisions.**

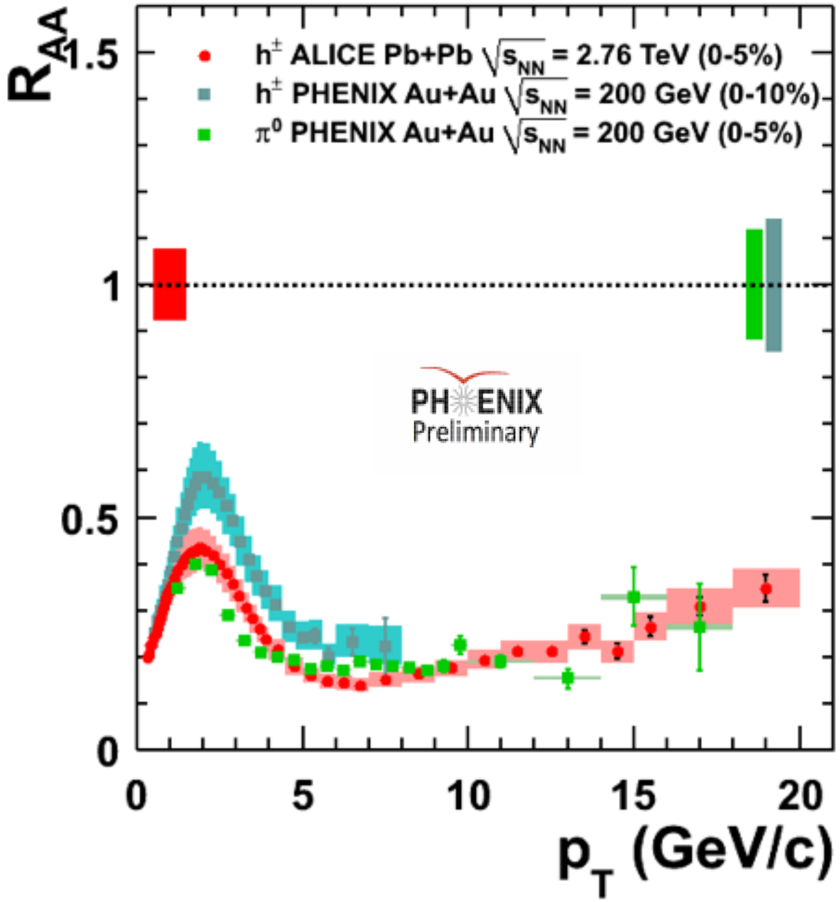
LHC:
Inclusive jets (R=0.4), annual yield; 10^4 @ p_T = 200 GeV/c (5.5 TeV, Year-1)

R_{AA}: RHIC vs. LHC, Similar R_{AA}!

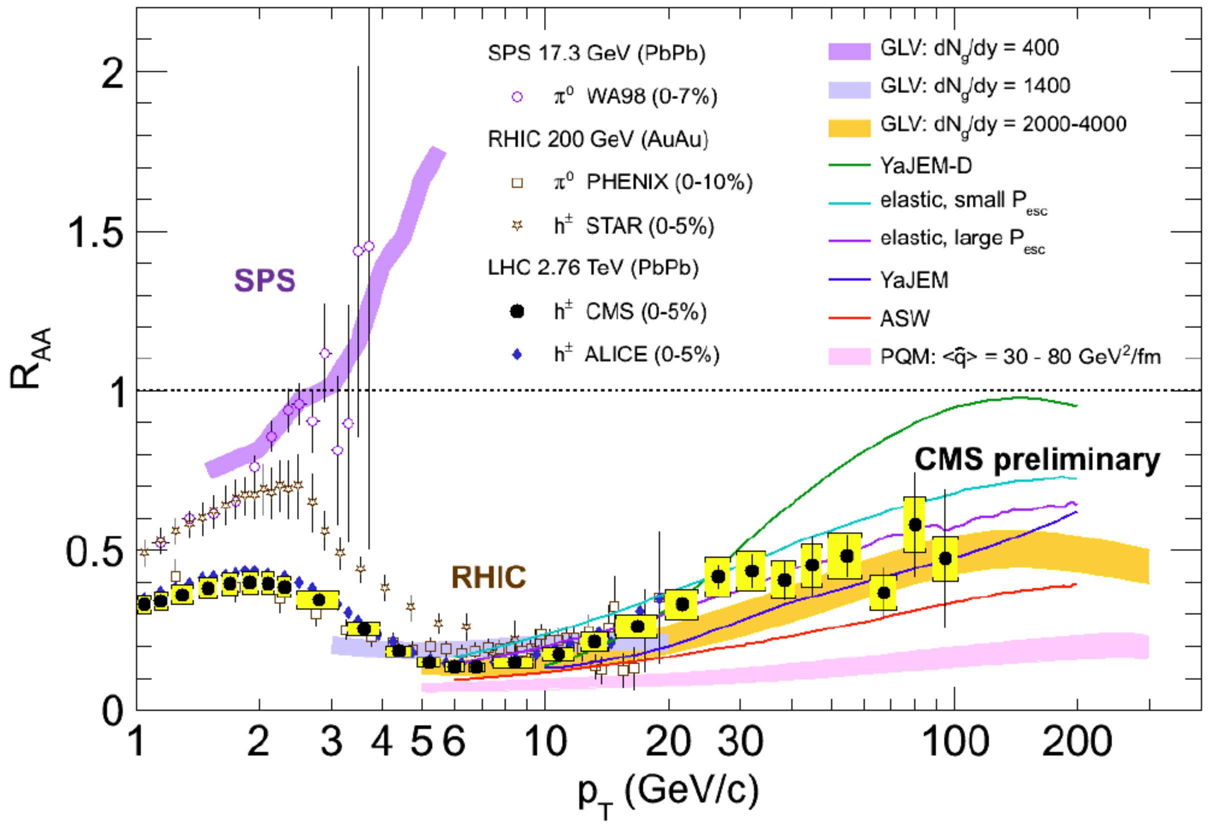
0-5% ALICE with 0-10% PHENIX Centrality



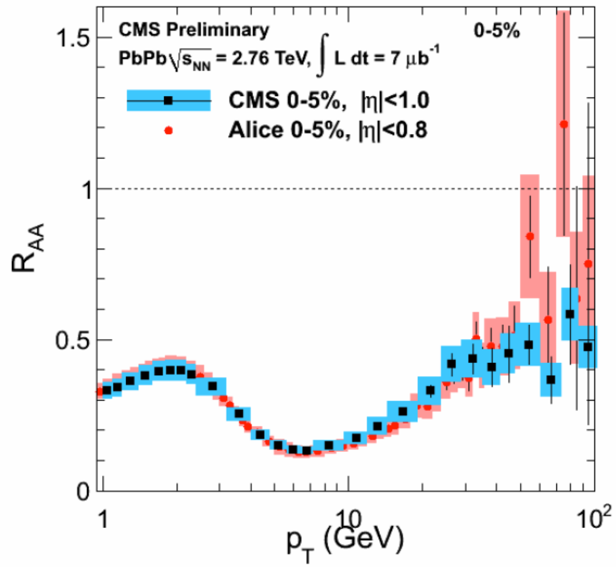
0-5% ALICE with 0-5% PHENIX Centrality



R_{AA}: Rise for p_T>10 GeV/c



Strong constraint on the parton energy loss models



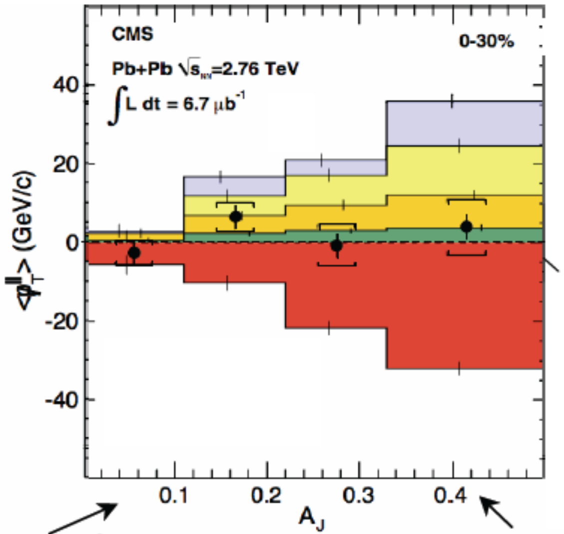
Minimum R_{AA} is ~0.1 at p_T~6 GeV/c; stronger suppression than RHIC (R_{AA}~0.2)
Rise to R_{AA} ~ 0.5 at p_T~30-40 GeV/c and stay constant (?)

Where energy/momentum goes (CMS) (1)

Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb



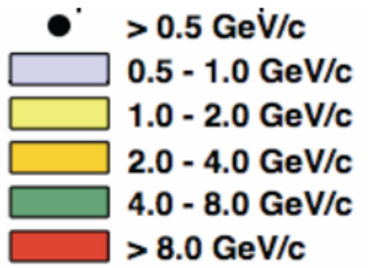
excess away from leading jet

excess towards leading jet

balanced jets

unbalanced jets

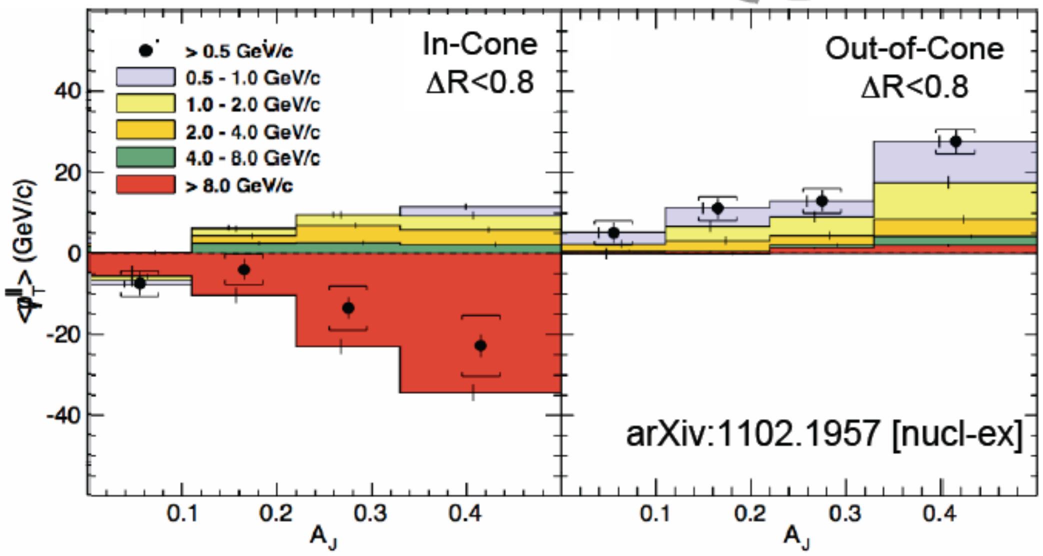
Calculate missing p_T in ranges of track p_T:



The momentum difference in the dijet is balanced by low p_T particles

Where energy/momentum goes (2)

Missing-$p_T^{||}$



3rd lesson learned:

The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis