Measurement of Jet Quenching in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in the ALICE Experiment at the LHC

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Outline

- **Quark-Gluon Plasma and Jet Quenching**
  - Quark-Gluon Plasma
  - Jets in Heavy Ion Collisions
- **The ALICE Experiment at the LHC**
- **Development and commissioning of the ALICE Calorimeter L1 Trigger system**
  - L1-Jet Trigger Algorithm
  - background subtraction method
  - Trigger Performance
- **Inclusive jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions**
  - Jet Reconstruction
  - Underlying Event
  - Unfolding Technique
- **Summary**

Quark-Gluon Plasma (QGP) and Jet Quenching

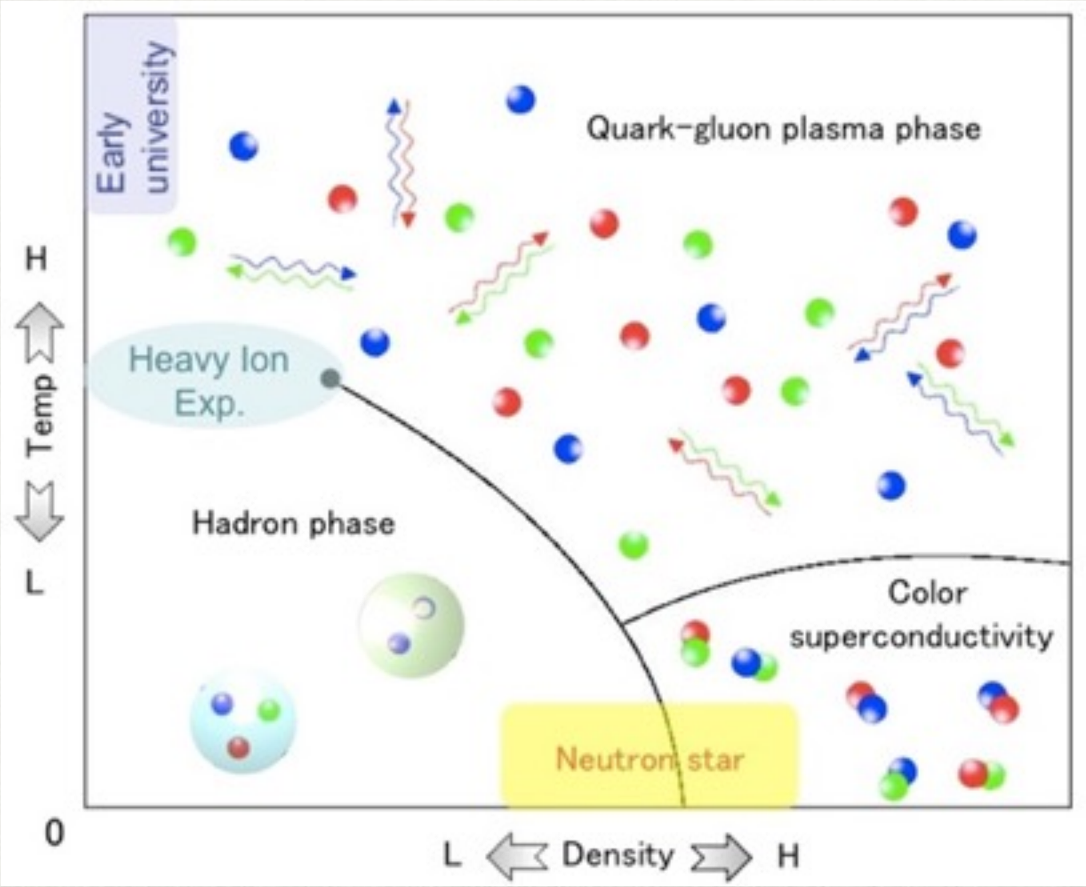
A brief journey to the beginning of the Universe

What is QGP ?

- **Quark-Gluon Plasma (QGP)**
  - Hot & dense color thermalized QCD matter prevailing at the early Universe ~1μs after big bang
  - Deconfined state of quarks and gluons
  - Theoretically inferred through lattice gauge simulations of QCD

How to create ?

- **‘Little Bang’**
  - high-energy head-on nucleus-nucleus collisions at particle accelerators
  - Recreate QGP droplets for a brief period of time to quantitatively map out the QCD phase diagram



Jets in HI Collisions (Hard Probes of the QGP)

What's a Jet ?

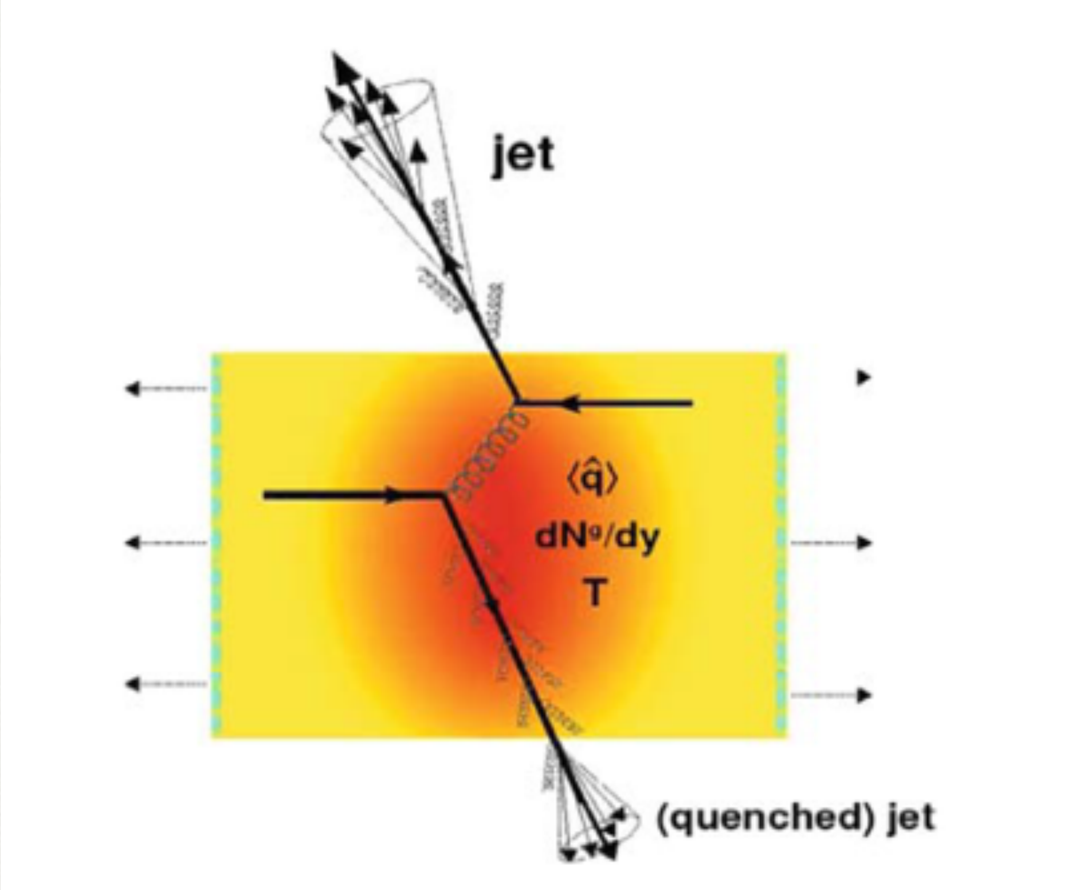
- Collimated spray of hadrons produced by the hard scattering of partons at the initial stage of the collision
- high-Q^2 process, $p_T \gtrsim 20$ GeV

Why Jets ?

- The QGP lifetime is so short (~10^{-23}s) that characterization by external probes is ruled out
  - **self-produced probe**
- Occur at early stage ~1/Q
  - **probe the entire medium evolution**
- Production rate calculable within pQCD
  - **well calibrated probe**
- Large cross-section at the LHC
  - **copious production**
- Reconstructed Jet enables to access
  - **4-momentum of original parton**
  - **jet structure (energy re-distribution)**

Jet Quenching

- Attenuation or disappearance of observed Jets in Pb-Pb
  - due to partons' energy loss in the QGP
  - **evaluation of the degree of the attenuation gives us QGP properties**

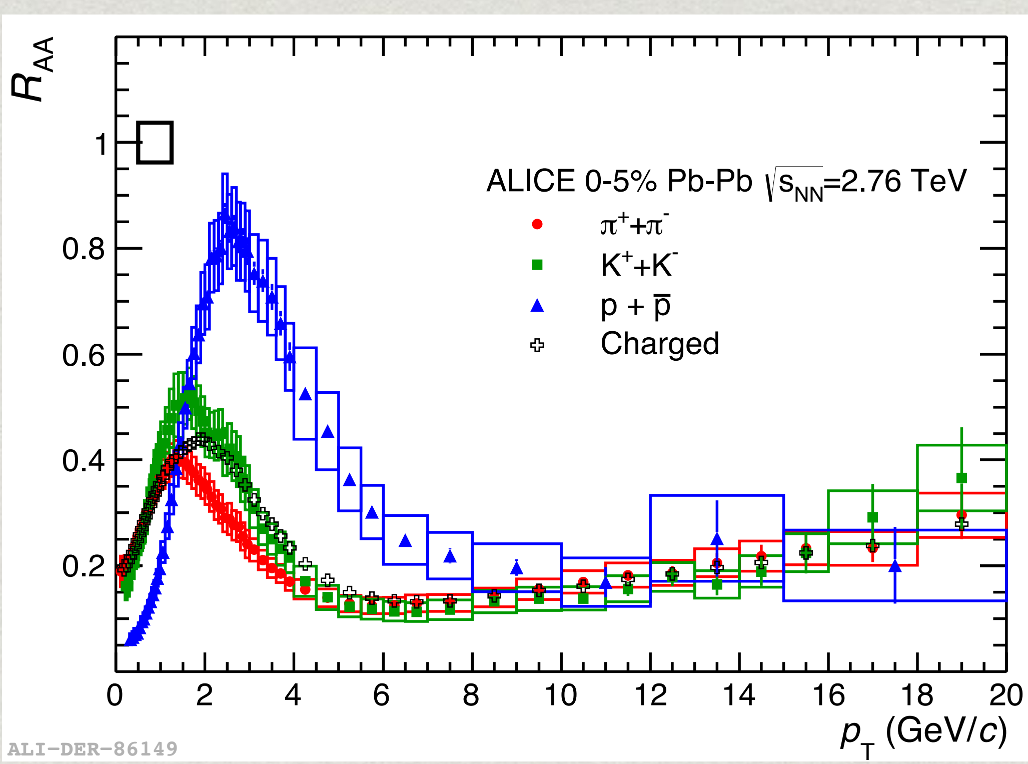


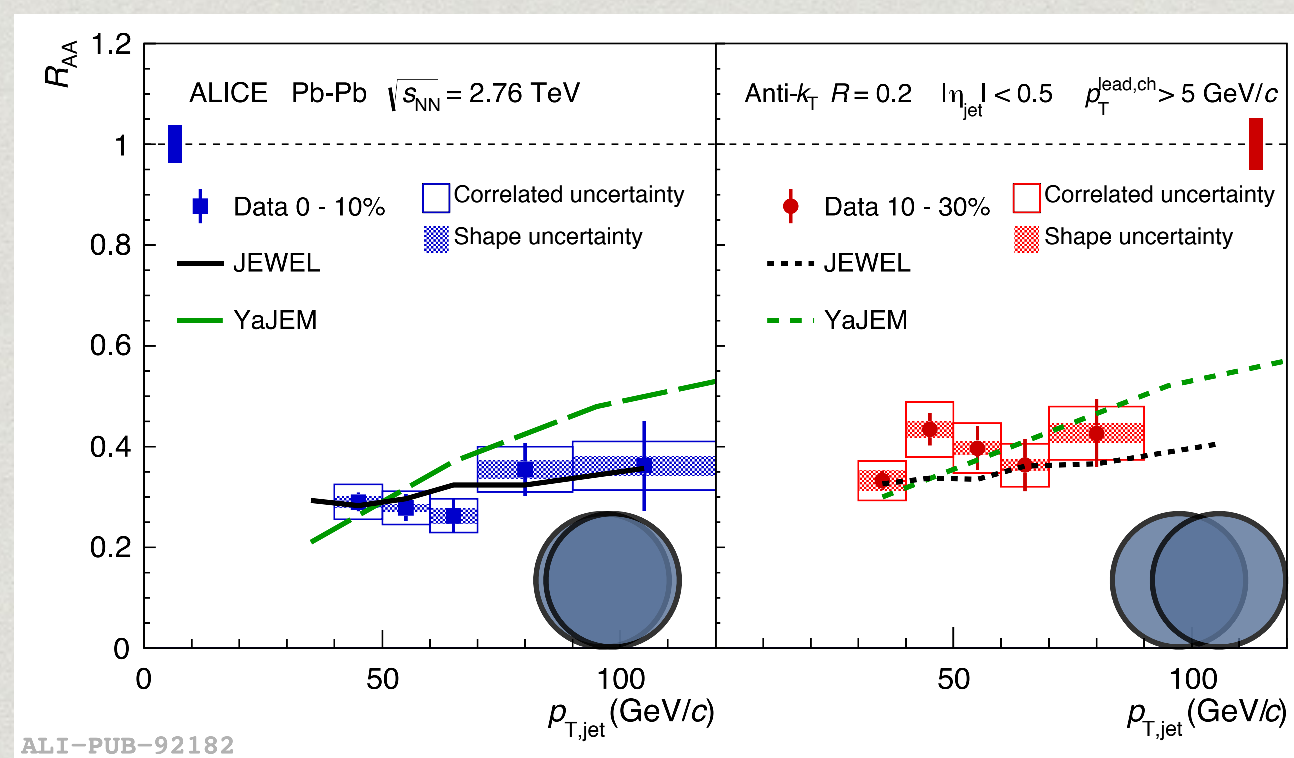
ALICE Jet Quenching Measurements in Pb-Pb

- Nuclear modification factor : R_{AA}
  - if $R_{AA} = 1$, NO modification of the matter

$$R_{AA} = \frac{1}{< N_{coll} >} \cdot \frac{\#\text{of particles(jets) in PbPb}}{\#\text{of particles(jets) in pp}}$$

- **high-p_T hadrons**
  - strong suppression : R_{AA}~0.2
  - proxy for Jet (parton) : p_T >10 GeV/c
  - fragmentation pattern changed
- **Jets**
  - strong suppression : R_{AA}~0.4
  - Jet shape broadens? where is the lost energy?





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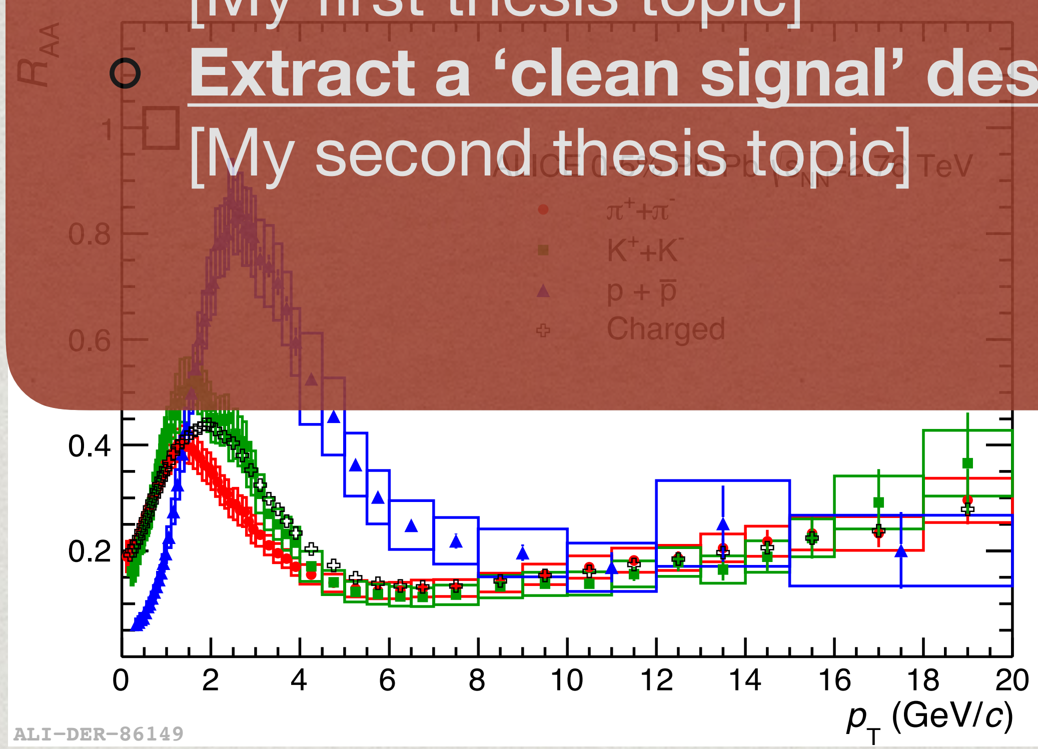
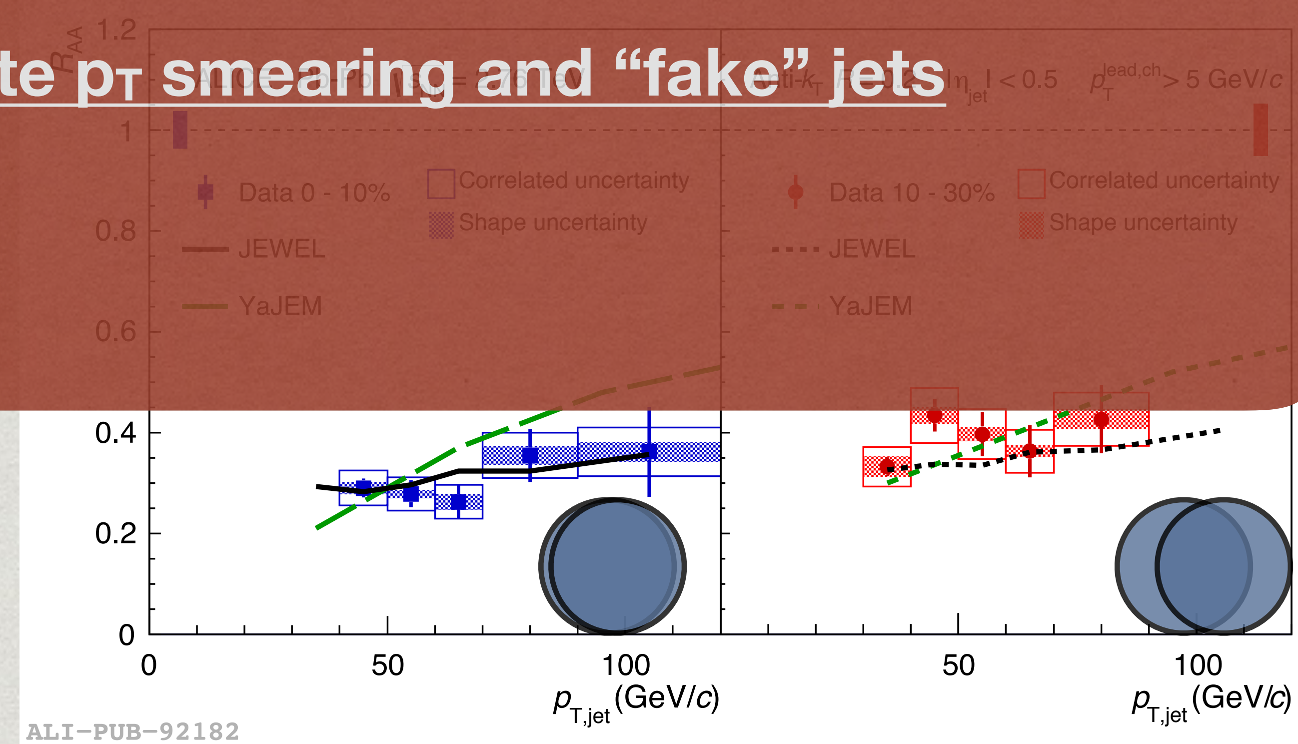
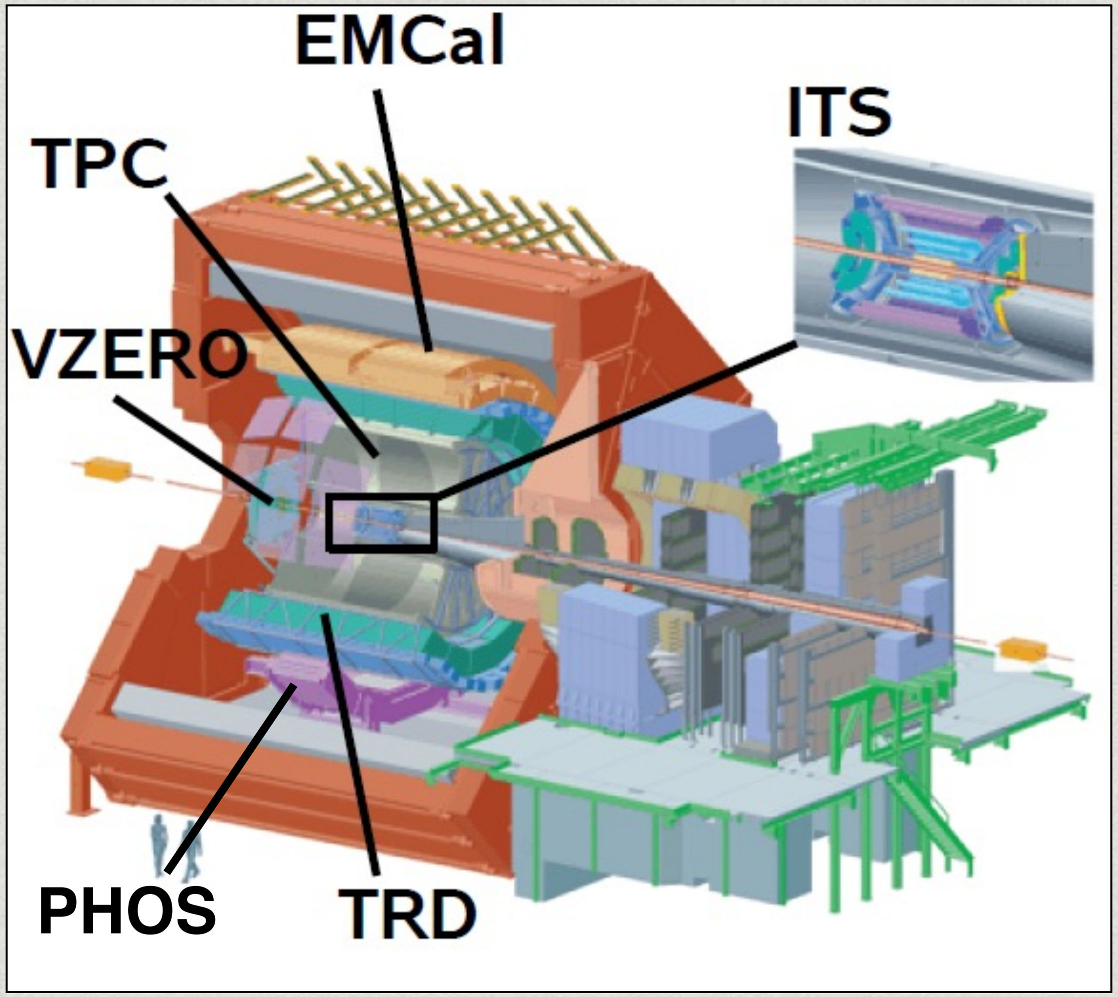
- Jet measurement in Pb-Pb collisions is challenging because of very large fluctuating background.
  - **<u>Need a dedicated trigger algorithm to select events containing jets</u>** [My first thesis topic]
  - **<u>Extract a ‘clean signal’ despite p_T smearing and “fake” jets</u>** [My second thesis topic]





Jet Measurement in LHC-ALICE



- ALICE detector focus on Heavy Ion Experiment
  - LHC Run2 period started from 2015
    - $\sqrt{s}$ = 13 TeV p-p
    - $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb

Charged Particles : $|\eta| < 0.9$, $0<\phi<2\pi$

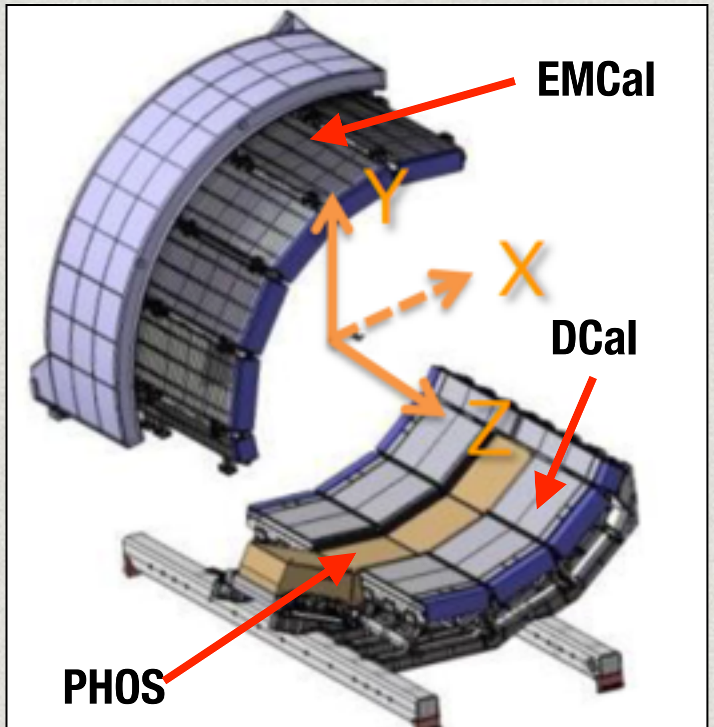
- ITS : silicon tracking detector
- TPC : gas detector
- **Charged constituents**

Full Jet

Charged Jet

Neutral particles : $|\eta| < 0.7$

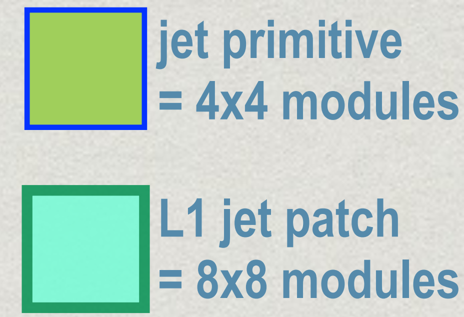
- EMCal, (DCal : Run2 from 2015-)
  - Pb-Scintillator sampling calorimeter
- PHOS
  - lead-tungsten crystal (PWO) based calorimeter
- **Neutral constituents**



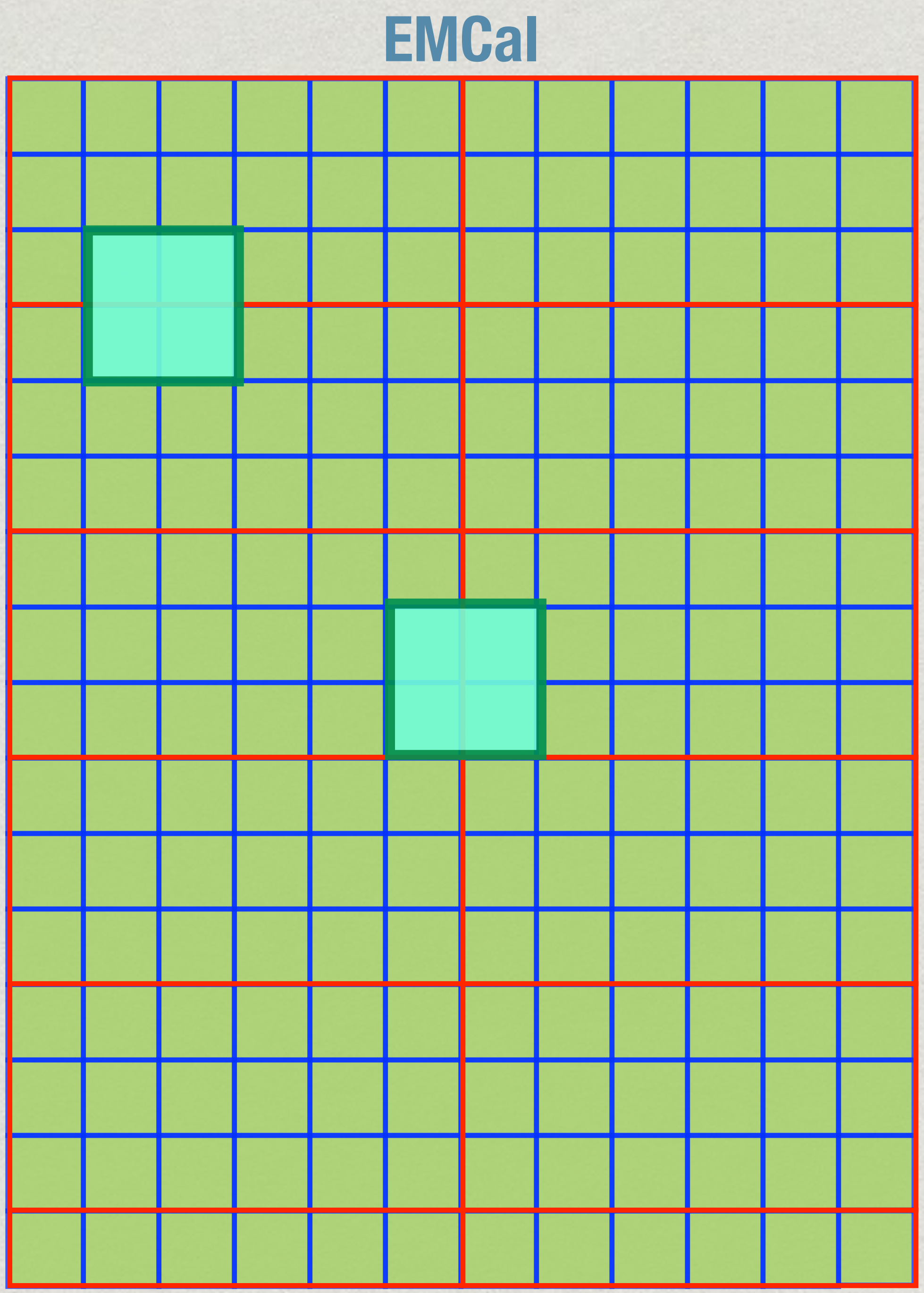
- Calorimeters trigger Jet events & high-p_T photon event
- **L1 trigger implementation**

Development of the L1-Jet/photon Trigger System by Calorimeters

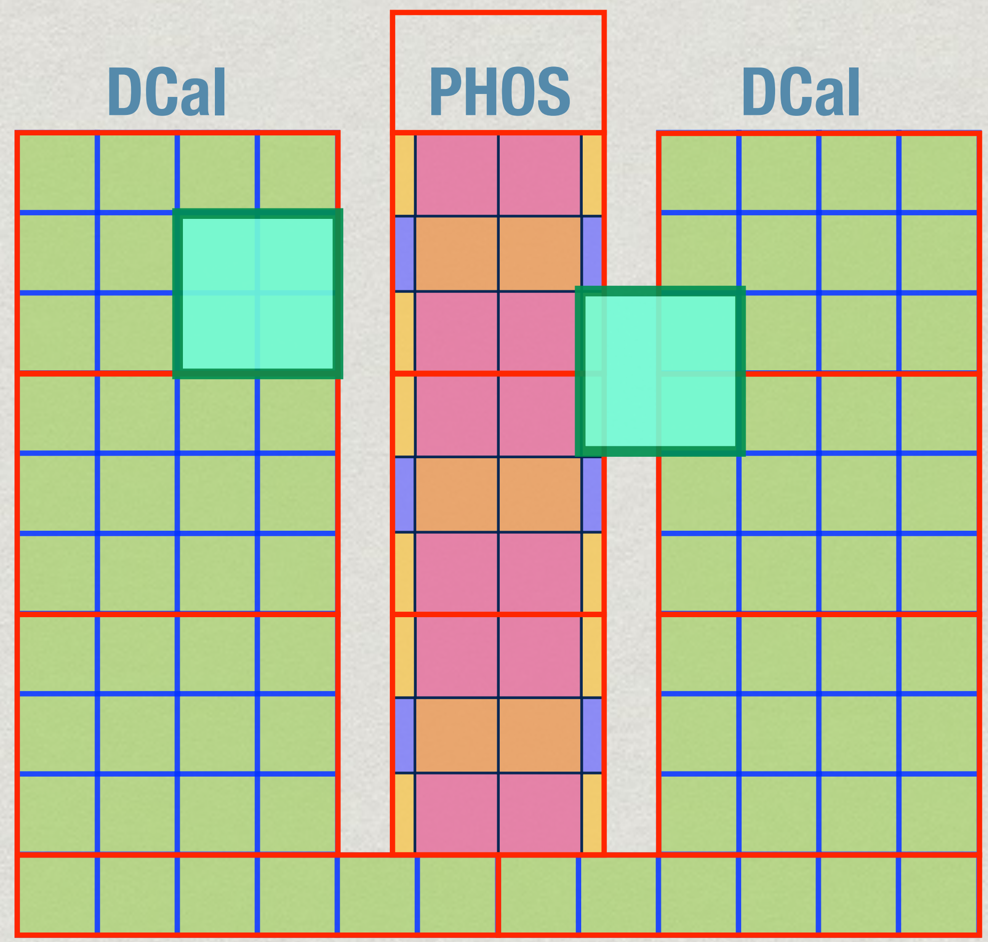
L1-Jet Trigger Algorithm

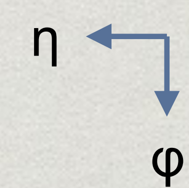


- Search events with energy deposit larger than threshold in certain area
- L1 Jet patch (= 8x8 EMCal modules)
    - Amplitude calculation by sliding window algorithm



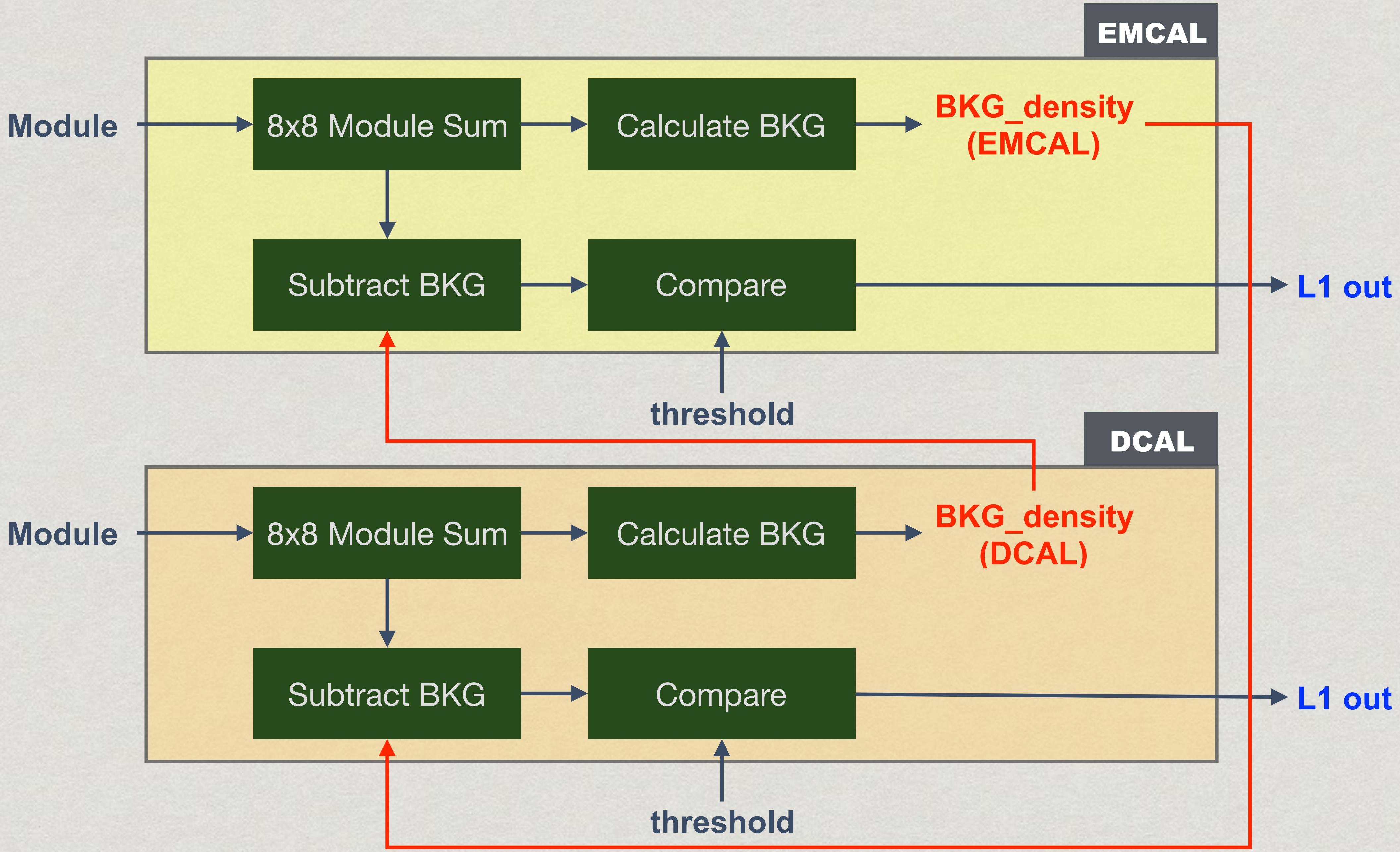
- Amplitudes of PHOS jet primitive are scaled
    - complicated geometry of DCal+PHOS side



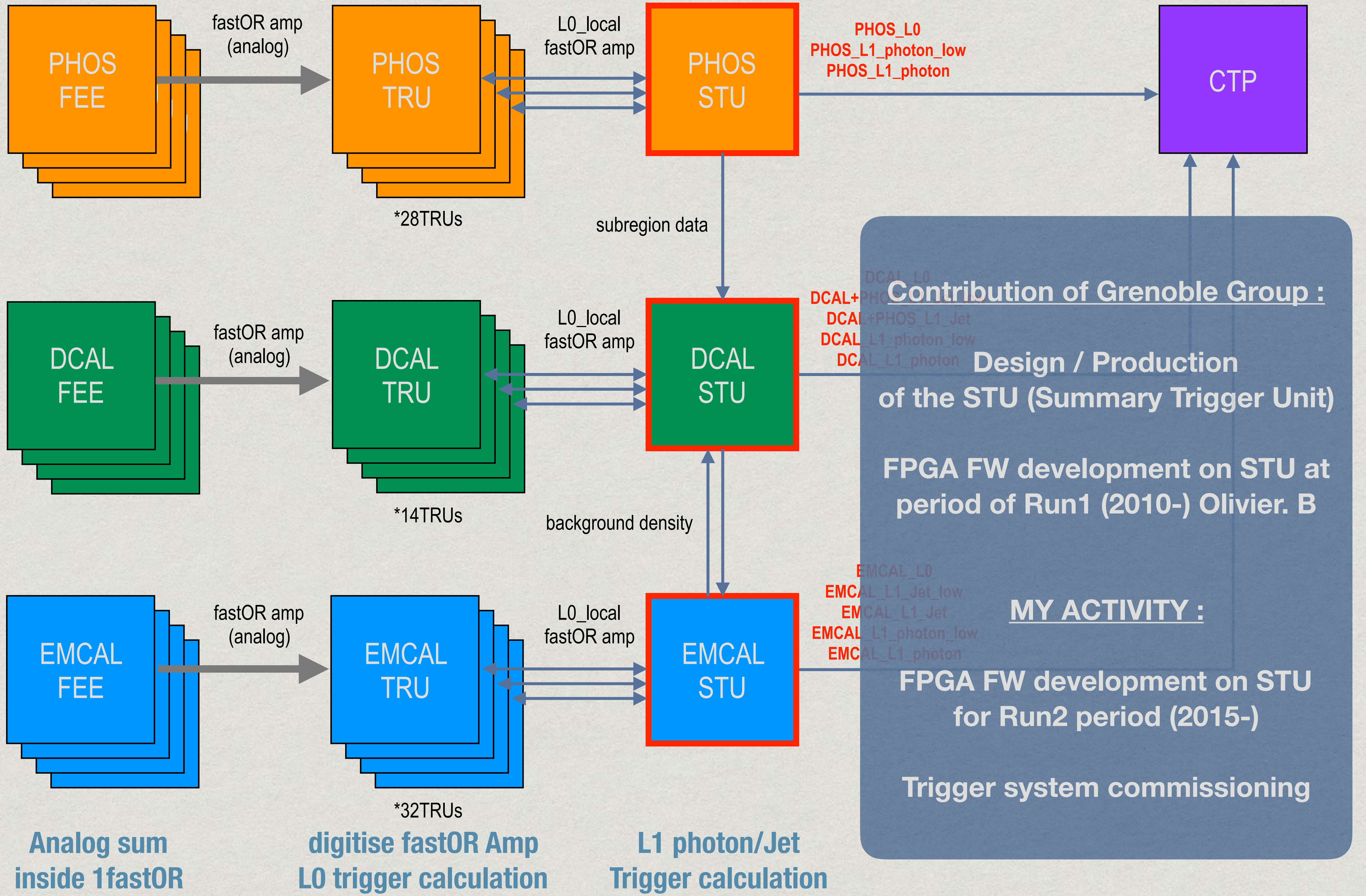


L1-Jet Background Subtraction Method in Pb-Pb

- Large background energy deposit superimposed to the jet energy
- event-by-event correction using the background measured on the opposite side
  - To avoid jet bias on background estimate
  - To obtain a reliable event-by-event background



L1 System of ALICE Calorimeters



Contribution of Grenoble Group :

Design / Production of the STU (Summary Trigger Unit)

FPGA FW development on STU at period of Run1 (2010-) Olivier. B

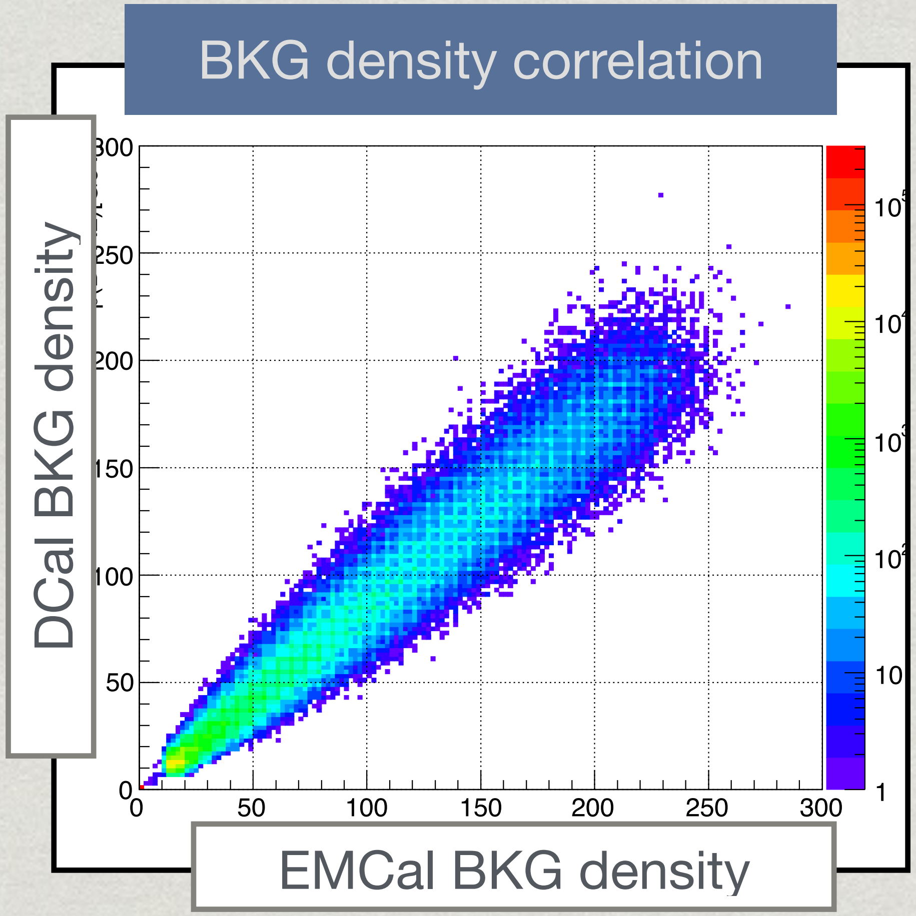
MY ACTIVITY :

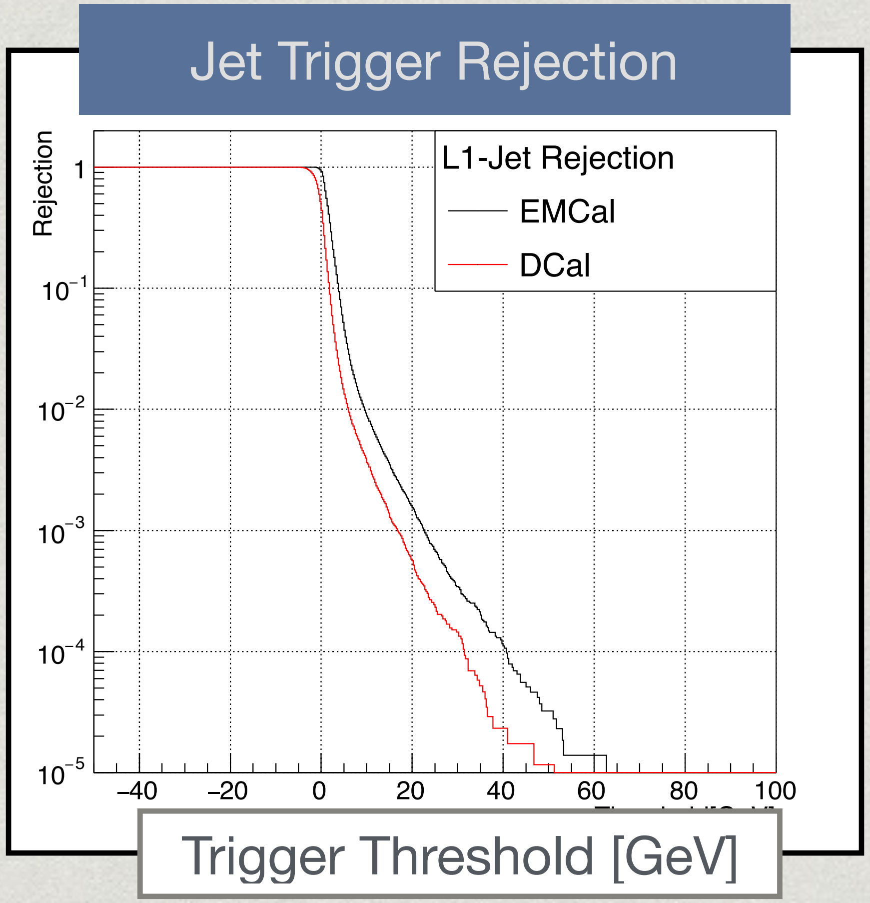
FPGA FW development on STU for Run2 period (2015-)

Trigger system commissioning

Trigger Performance

- Data produced by Pb-Pb run in 2015
  - PHOS didn't join in whole Jet Trigger calculation due to insufficient tune of TRUs
- **BKG density correlation between EMCal and DCal**
  - Reasonable positive correlation
- **Trigger rejection**
  - To define threshold which satisfy the BandWidth restriction of the data taking
  - ~1000 for L1-Jet @20GeV threshold





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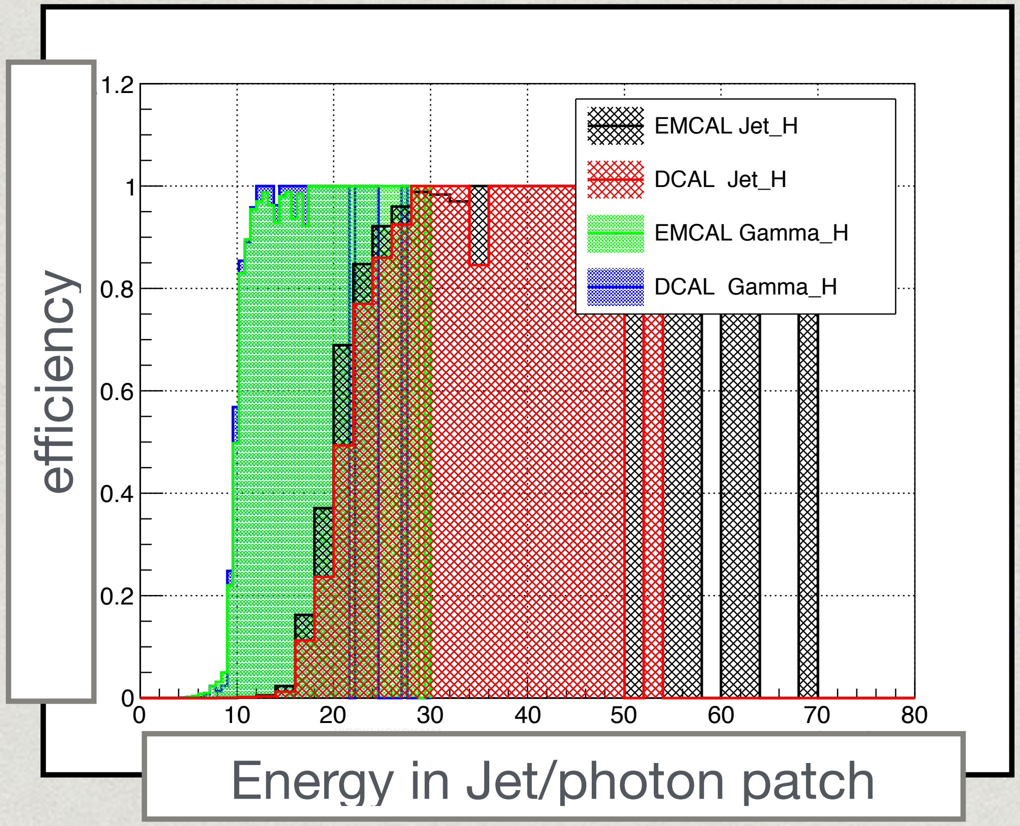
- **Trigger rejection**
  - To define threshold which satisfy the BandWidth restriction of the data taking
  - ~1000 for L1-Jet @20GeV threshold
- **Trigger efficiency**
  - clear turn-on at set values of 10 GeV (L1-photon) and 20 GeV (L1_Jet)

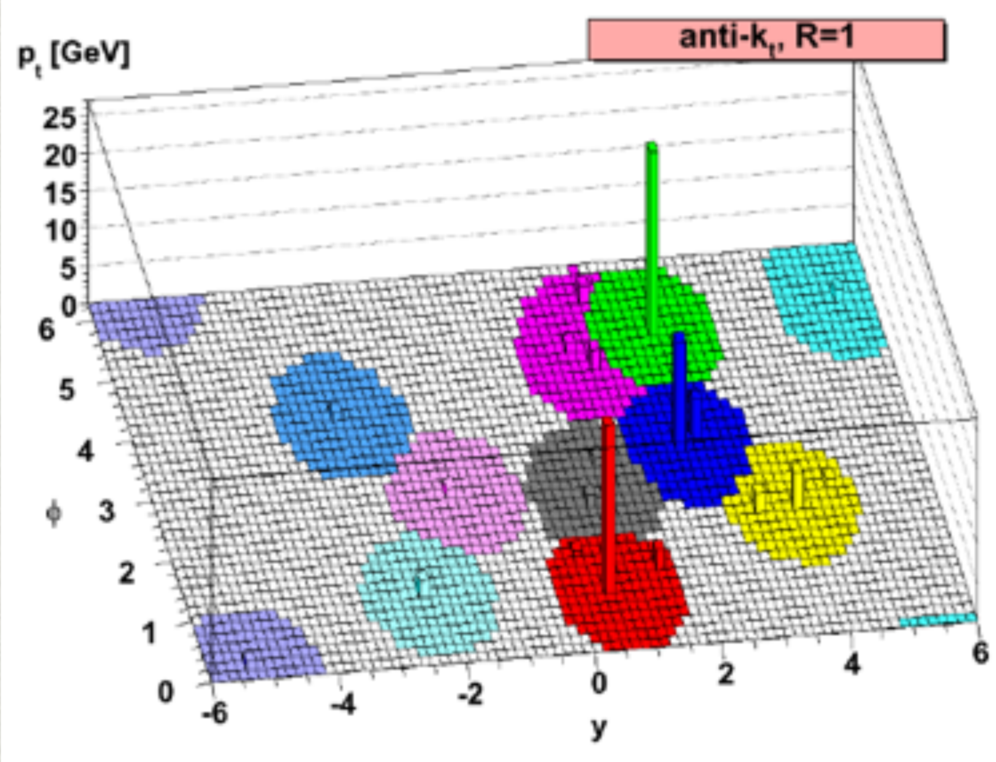


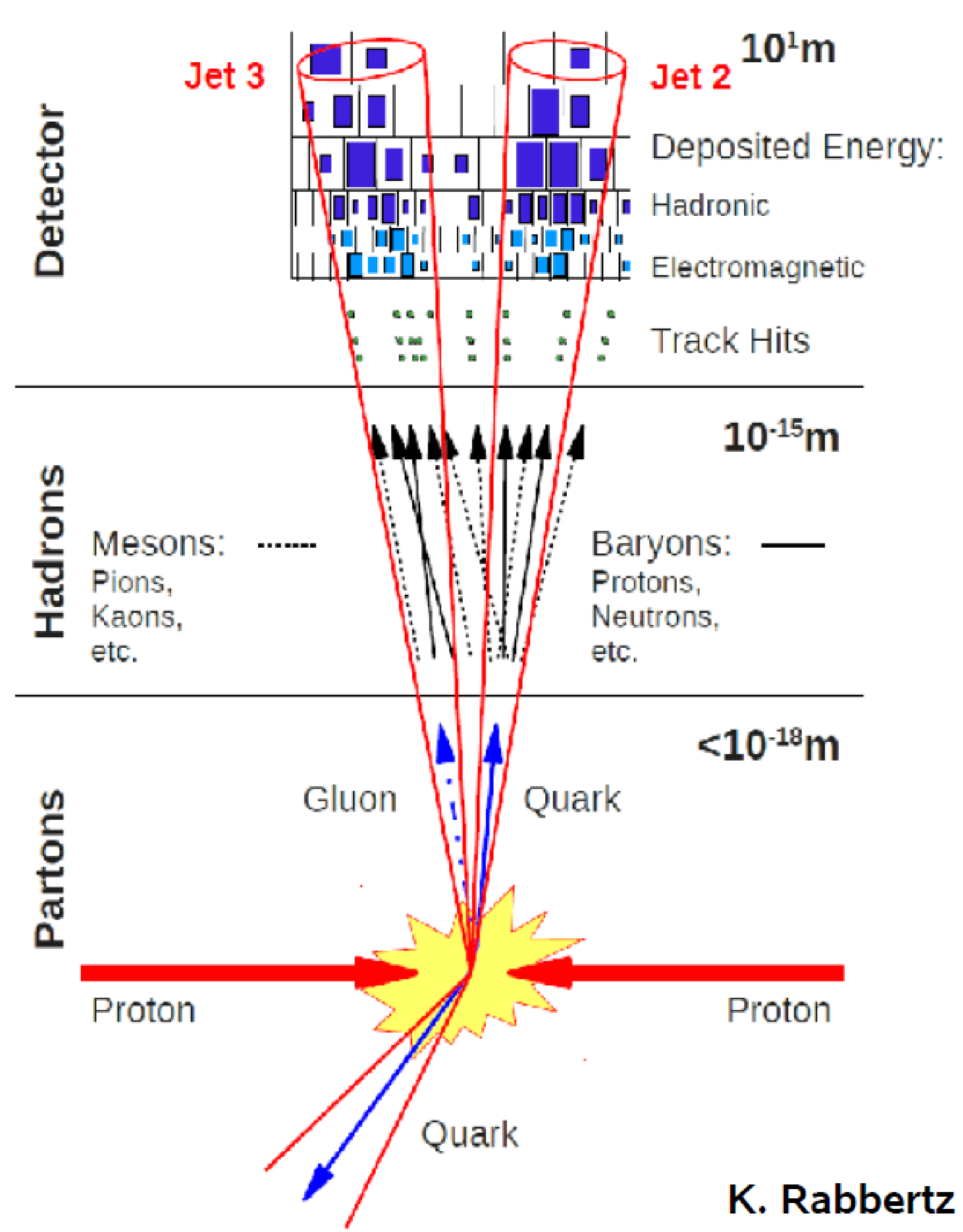
All L1-Jet/photon Triggers by Calorimeters Worked Well in 2015 Pb-Pb Runs!

Measurement of the Inclusive Jet with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb Collisions

(1) Jet Reconstruction

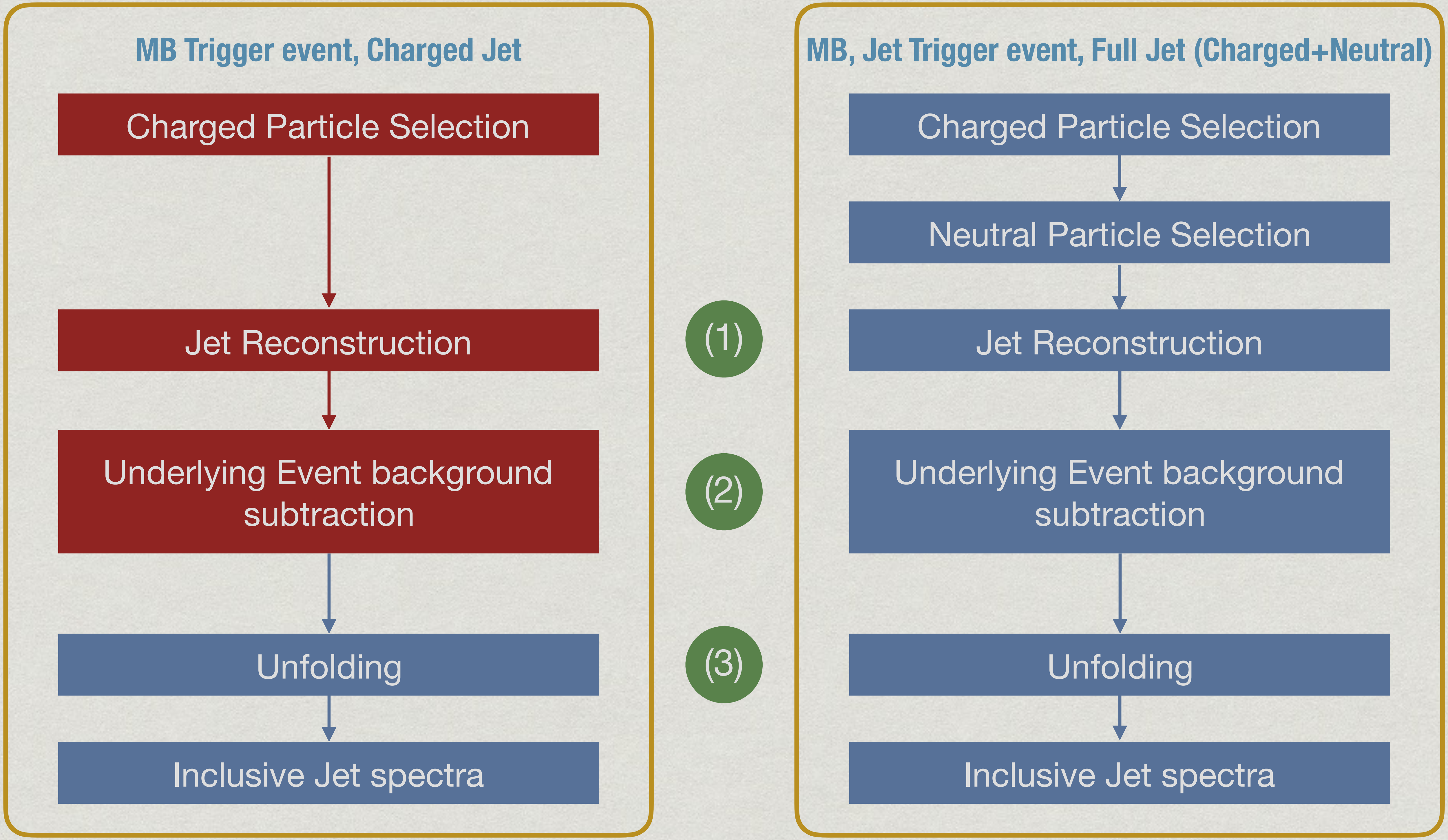
- Correspondence between detector level, hadron level and parton level.
- Jet Reconstruction
  - using observable particles
  - **sequentially combine or classify these particles into clusters (Jet candidates)**
- Some types of algorithms



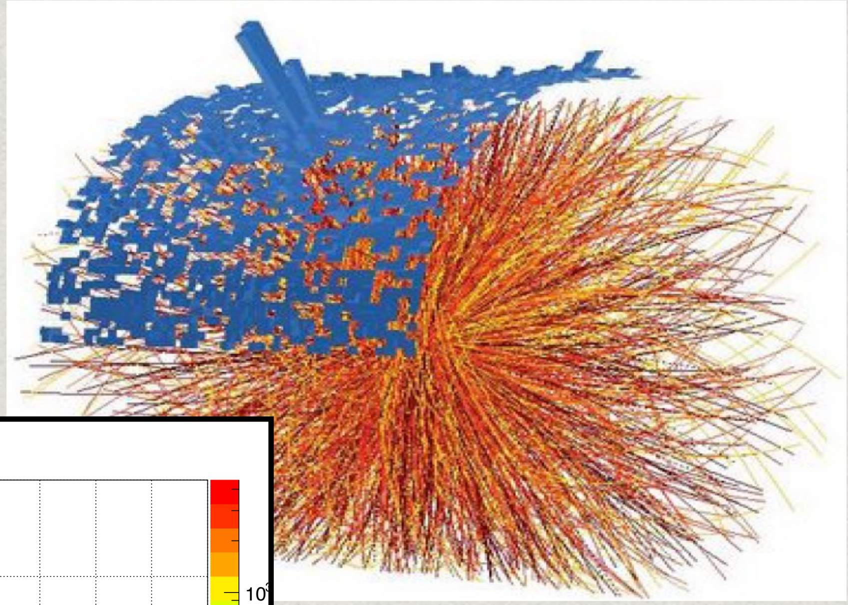


Analysis Strategies

Data : Pb-Pb ($\sqrt{s_{NN}}$ = 5.02 TeV) taken in 2015 Nov. and Dec.

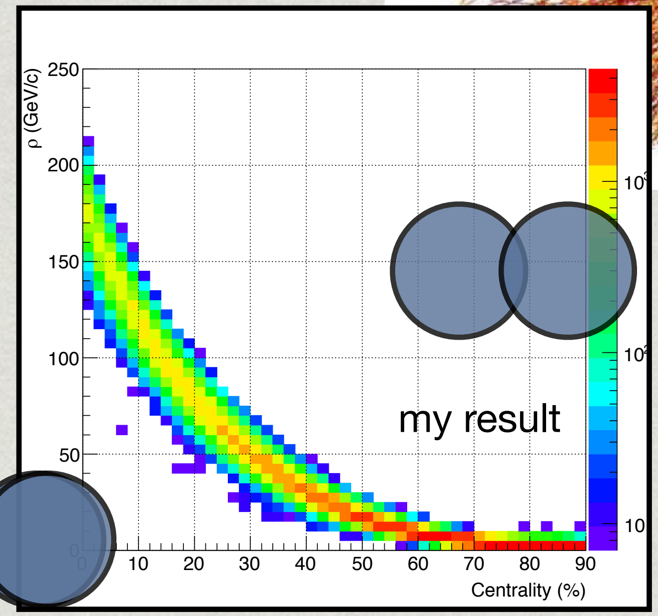


(2) Underlying Event



Difficulties in Heavy Ion Collision

- large background superimposed to the Jets
  - $dN_{ch}/d\eta$ ~ 2000 in most central collisions



← charged jet BKG density vs. centrality

↓ Jet p_T spectra before/after BKG subtraction (R=0.4)

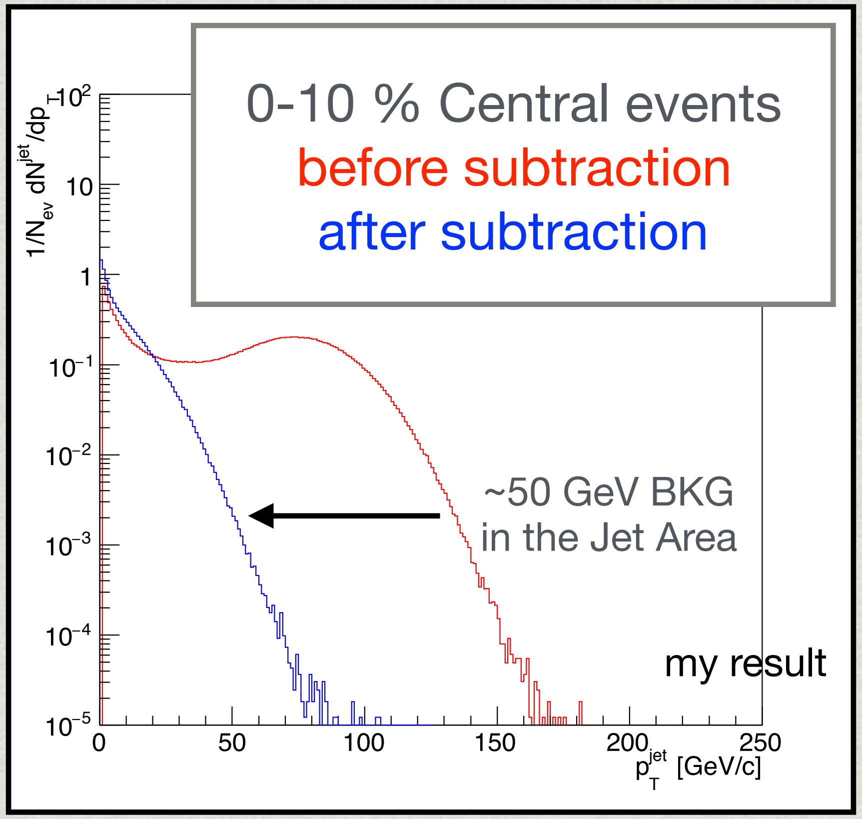
Jet Background Subtraction

- background density : ρ
  - median of k_T clusters except largest two:

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$

Estimated BKG is subtracted from each Jet event-by-event basis via

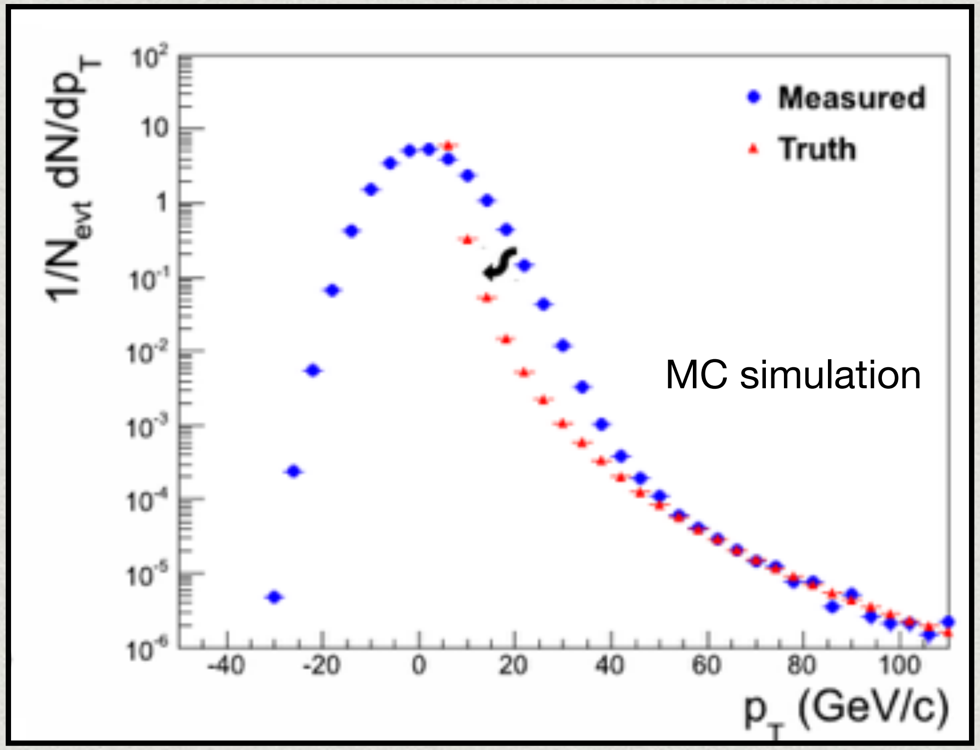
$$p_{T,j}^{sub} = p_{T,j} - \rho A_j$$



(3) Unfolding

More correction NEEDED!

- **Detector effect (e.g. smearing)**
- **background fluctuation**



Unfolding technique

- **Background Fluctuations**

$$M_m = G_{m,d} \cdot D_d$$

Measured jet spectrum (M_m); Response matrix ($G_{m,d}$); spectrum corrected for BKG fluctuation (D_d)

- **Detector Effects**

$$D_d = G_{d,t} \cdot T_t$$

spectrum corrected for BKG fluctuation (D_d); Response matrix ($G_{d,t}$); "unknown" true jet spectrum (T_t)

Inverted Response matrix gives "TRUE" jet spectrum via

$$M_m = G_{m,d} \cdot G_{d,t} \cdot T_t = G_{m,t} \cdot T_t$$

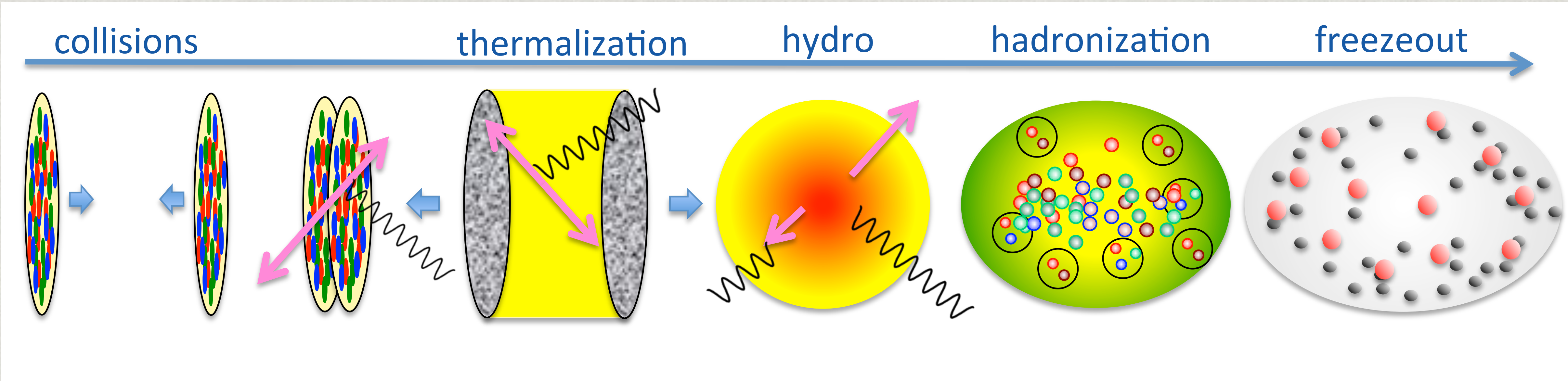
Summary

- **Quark-Gluon Plasma (QGP)**
  - Deconfined state of quarks and gluons
  - Created in “Little Bang” (Heavy Ion Collisions)
- **Jet quenching**
  - Attenuation of the energy of hard scattered parton
  - Best equivalent to quarks/gluons
- **Development of L1-Jet/photon trigger system by ALICE Calorimeters**
  - Background subtraction method was implemented on STU.
  - All work was achieved.
- **Measurement of Inclusive Jets in HI collisions**
  - Need some experimental technique

    (jet reconstruction, underlying event subtraction and unfolding)
  - work in progress
    - Charged Jet Spectra and nuclear modification factor : until Sep. 2016
    - Full Jet Analysis : depend on the EMCal calibration status

BACKUP

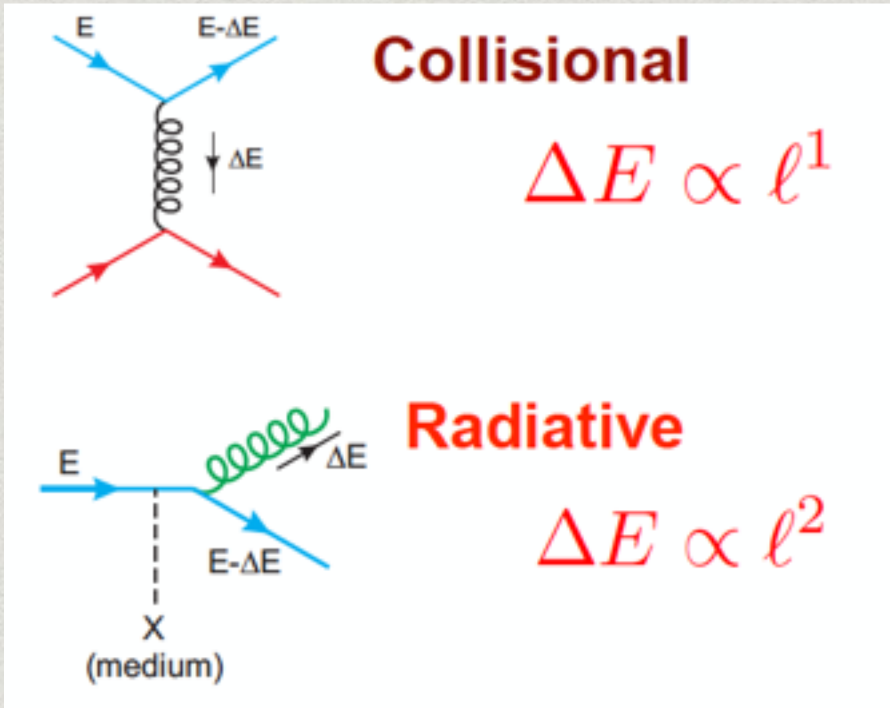
Relativistic Heavy Ion Collision

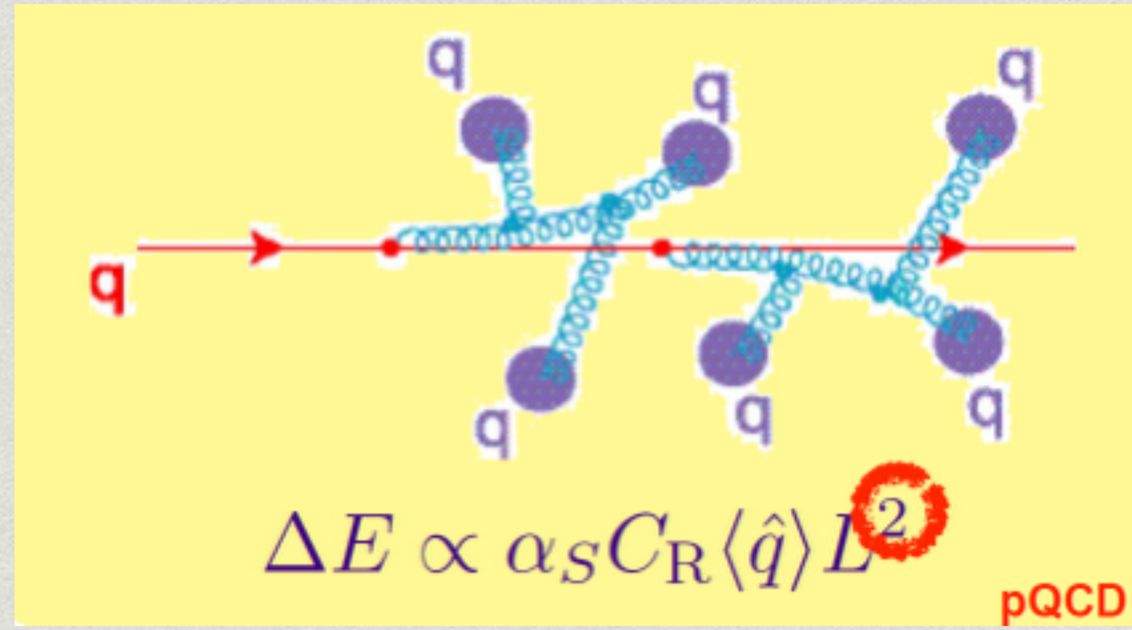


- Hard parton scattering
  - high momentum parton production
- Creation of a Quark-Gluon Plasma
  - thermalisation of strongly interacting partons
  - collective / thermodynamical properties
- Phase transition
  - from parton phase to hadron phase
  - $T_c \approx 155$MeV, $\varepsilon_c \approx 0.5$GeV/fm^3
- Hadronic phase
  - fix species, number and momentum of hadrons

- **Final particles (hadrons, leptons) are detected by particle detector**

Modelling of the Jet Quenching



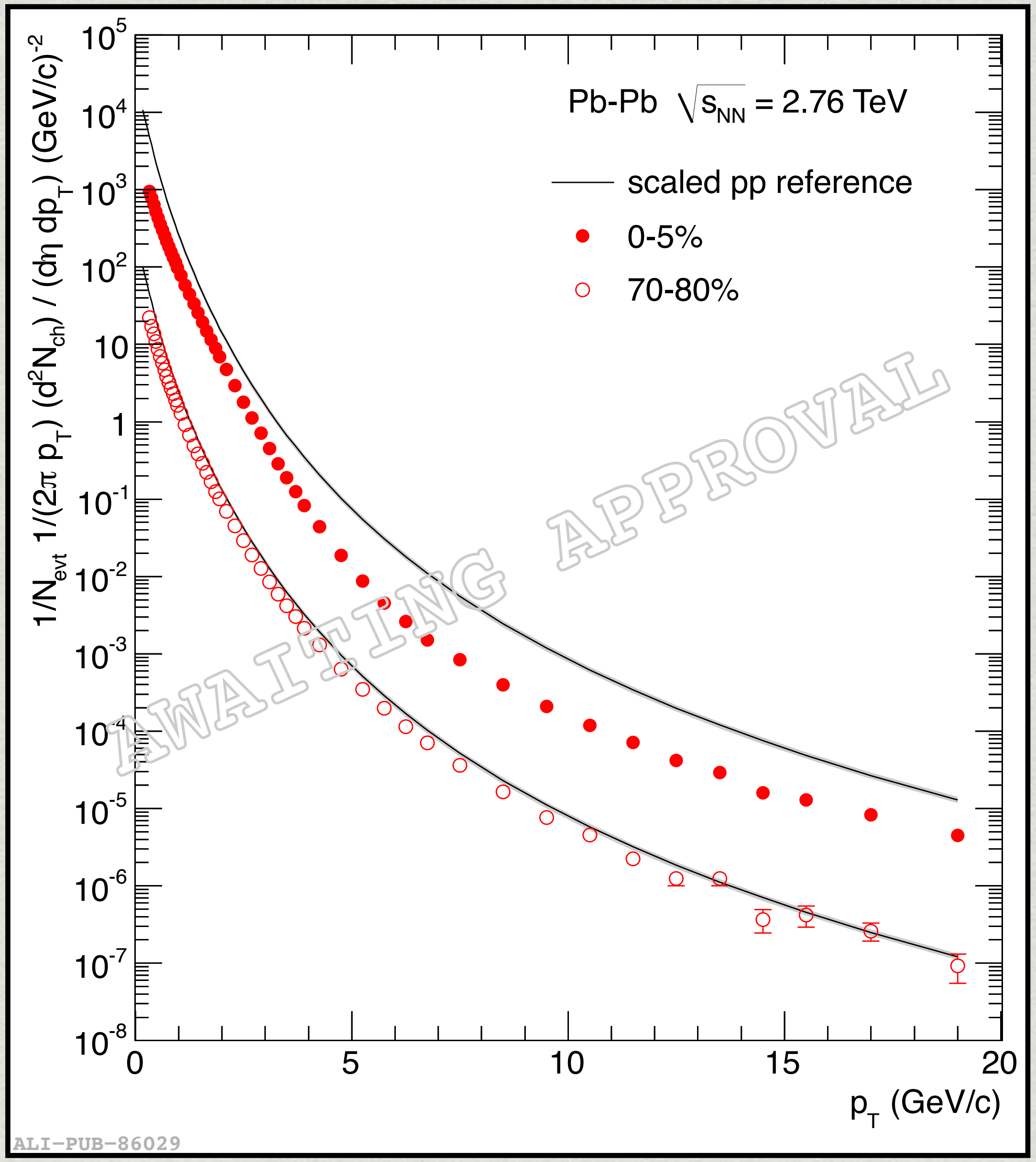


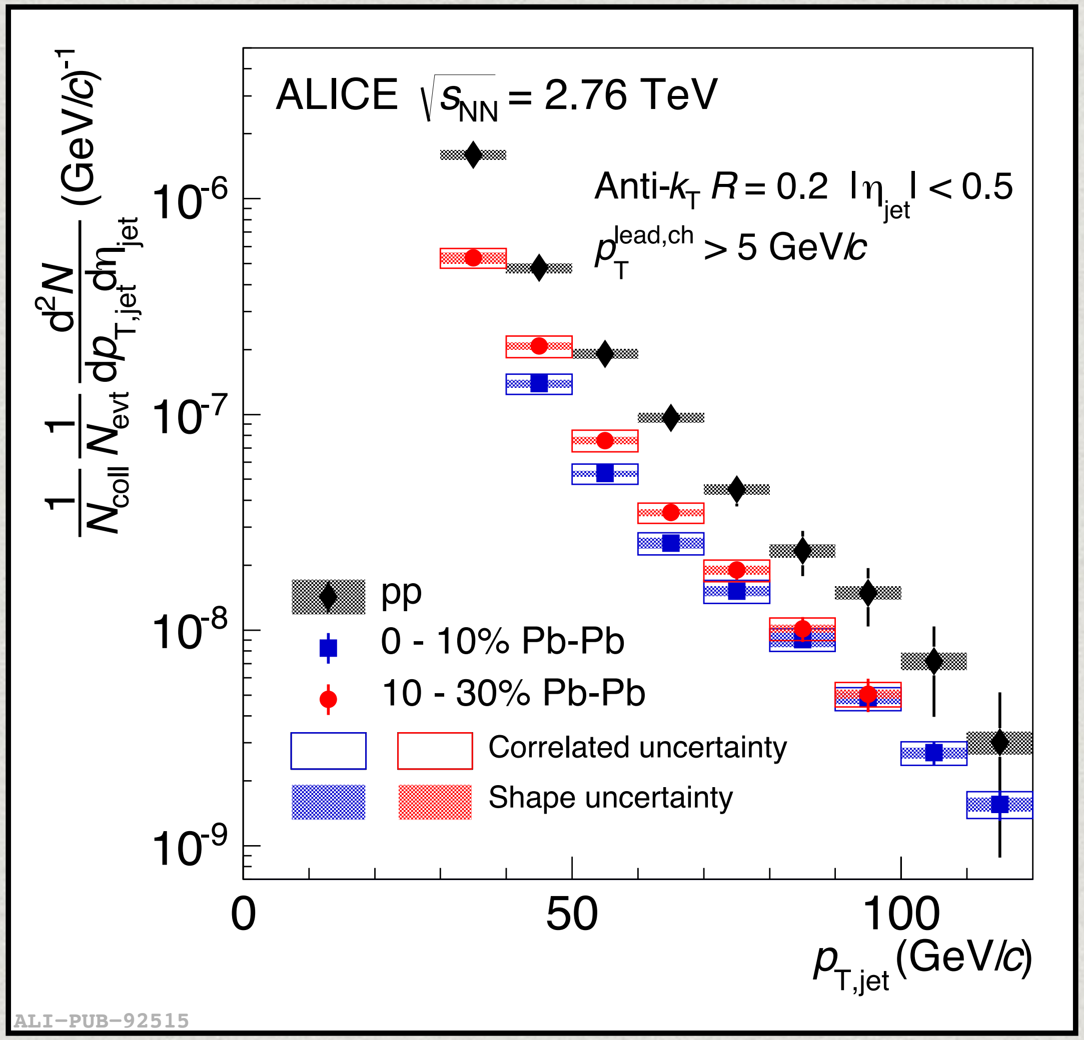
$$\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho\sigma$$

- Radiative energy loss (gluon bremsstrahlung) is dominant
- Relative strength is controlled by Casimir factor C_R
  - $\alpha_s C_F$: q→qg
  - $\alpha_s C_A$: g→gg
  - $\alpha_s T_F$: g→qqbar

- **ΔE measurement provides information on matter properties (Jet tomography)**

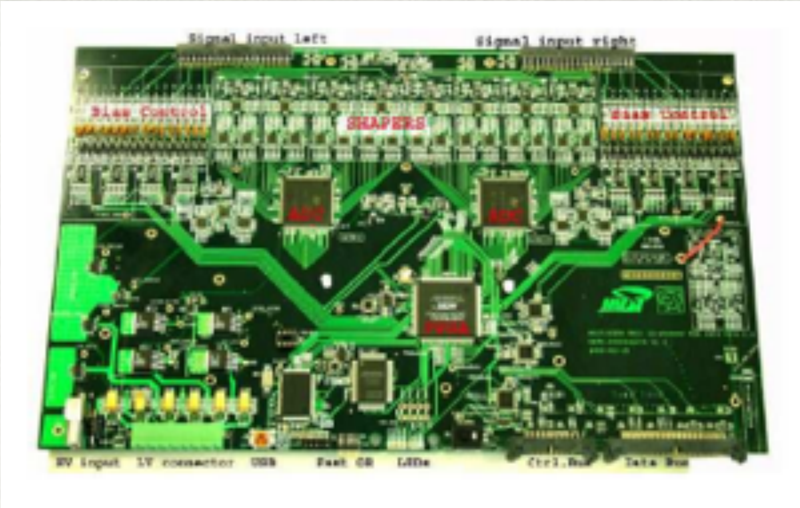
Jet / charged particle spectra in Pb-Pb and p-p collisions





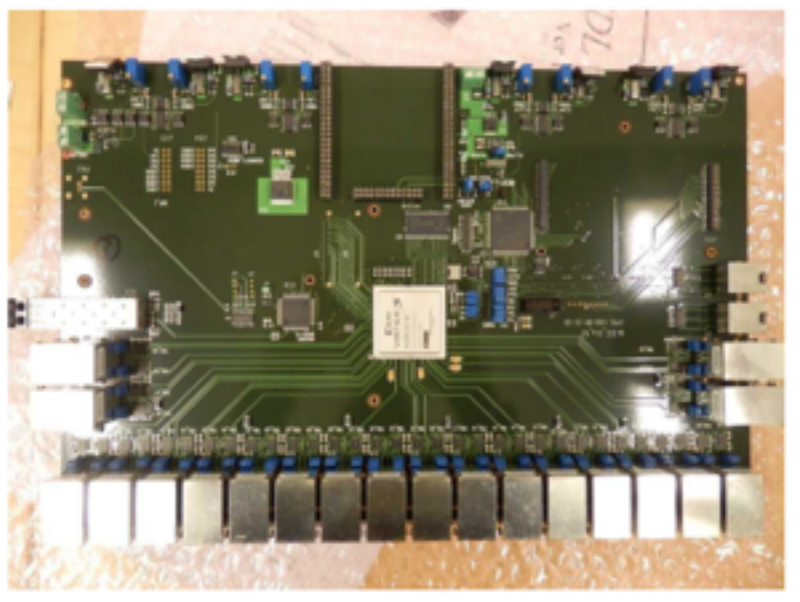
FEE, TRU and STU

- FEE (Front-End Electronics card)
  - mainly, calculate analog sum of 2x2 towers amplitude
  - fastOR (module) = 2x2 towers area
- TRU (Trigger Region Unit)
  - digitise analog fastOR amplitude
  - L0 calculation
- STU (Summary Trigger Unit)
  - L1-Jet/Photon calculation



FEE

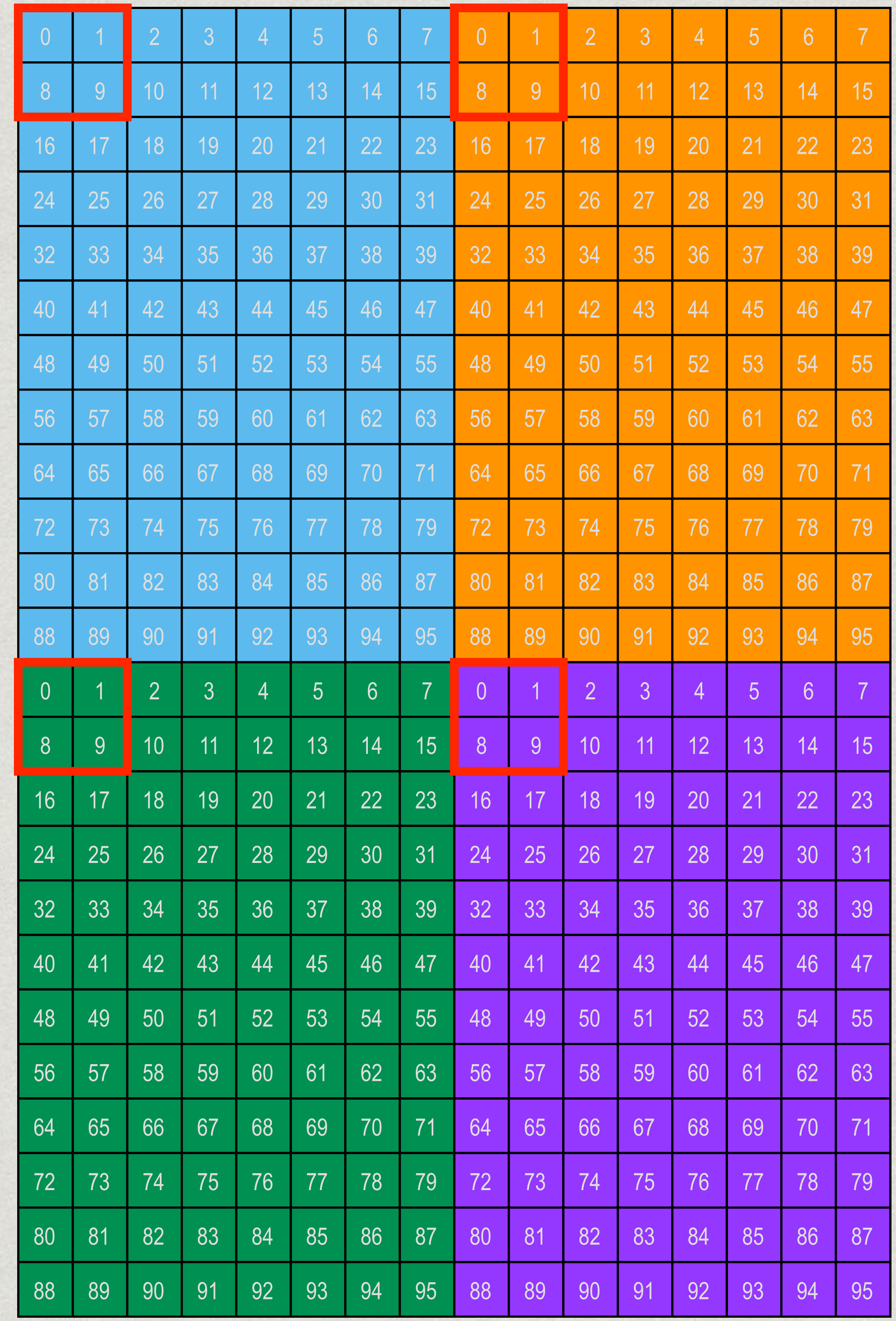
TRU



STU

L1 photon/Jet algorithm in Run2

- L1-photon patch
  - 2x2 [modules] (EMCAL, DCAL)
  - 2x2 [2x2 crystals] (PHOS)
  - on-the-fly sliding window algorithm



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- L1-photon patch
  - 2x2 [modules] (EMCAL, DCAL)
  - 2x2 [2x2 crystals] (PHOS)
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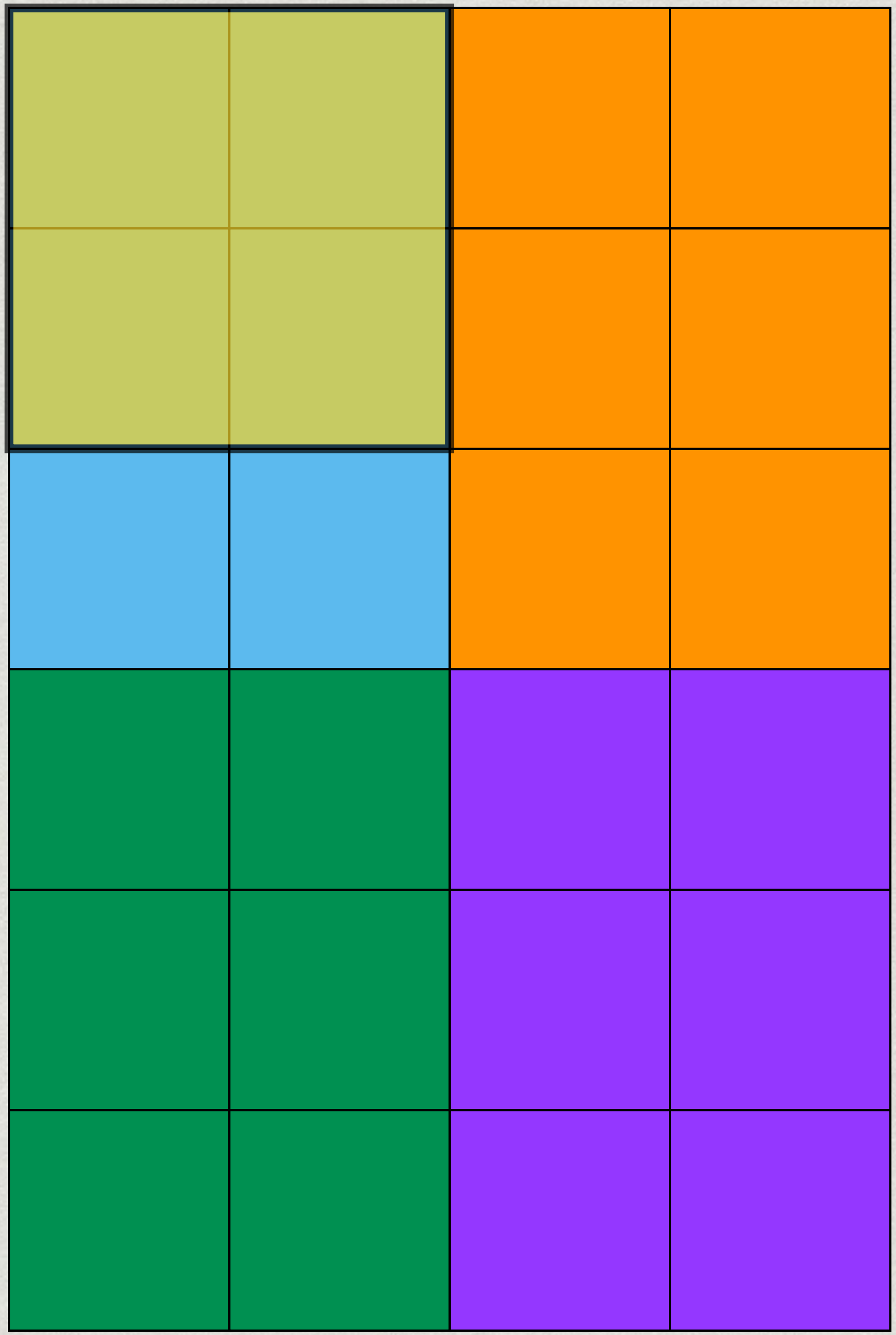
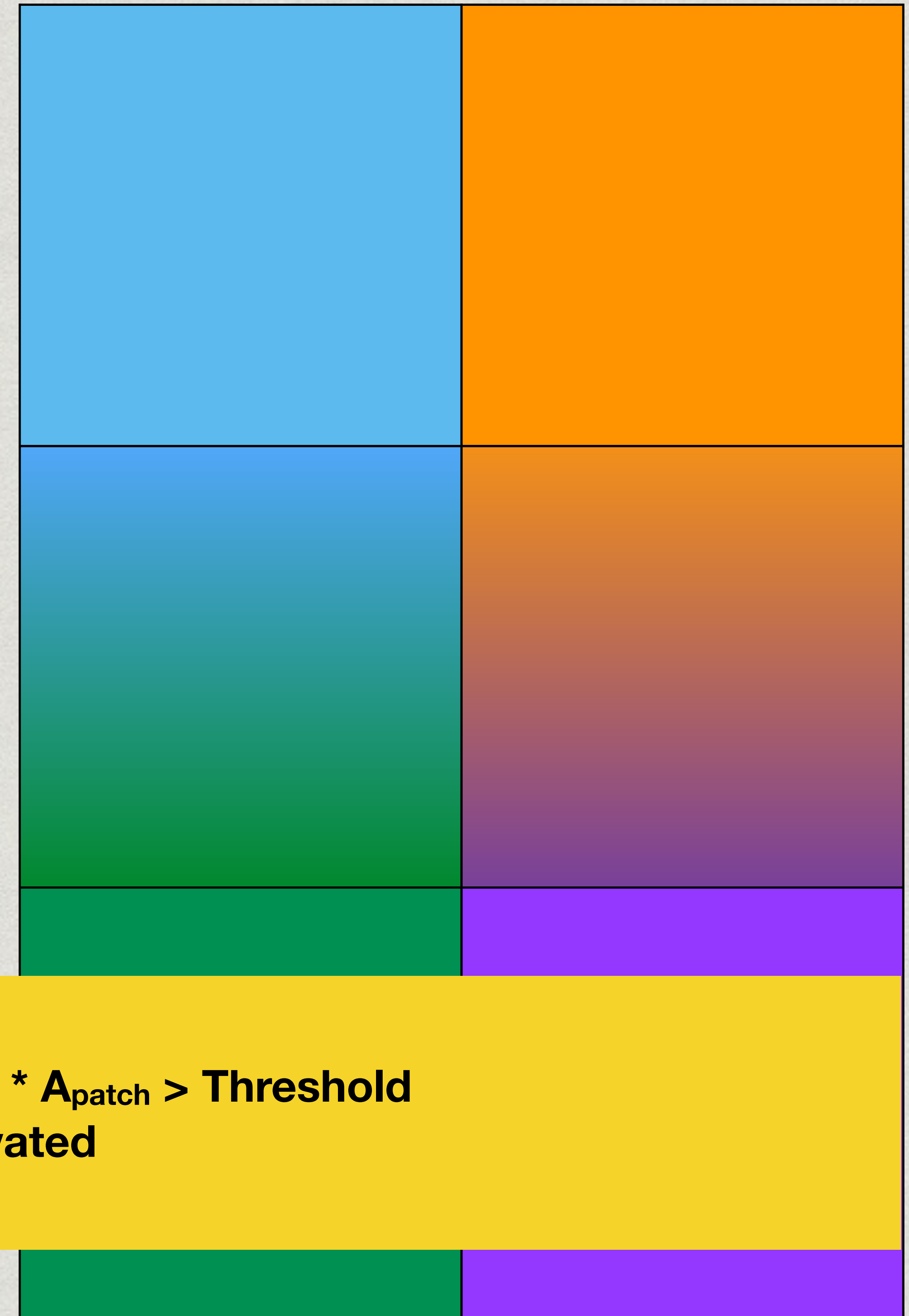
- L1-Jet patch
  - (jet-primitive = 4x4 modules)
  - 2x2 jet-primitives
  - sliding window algorithm



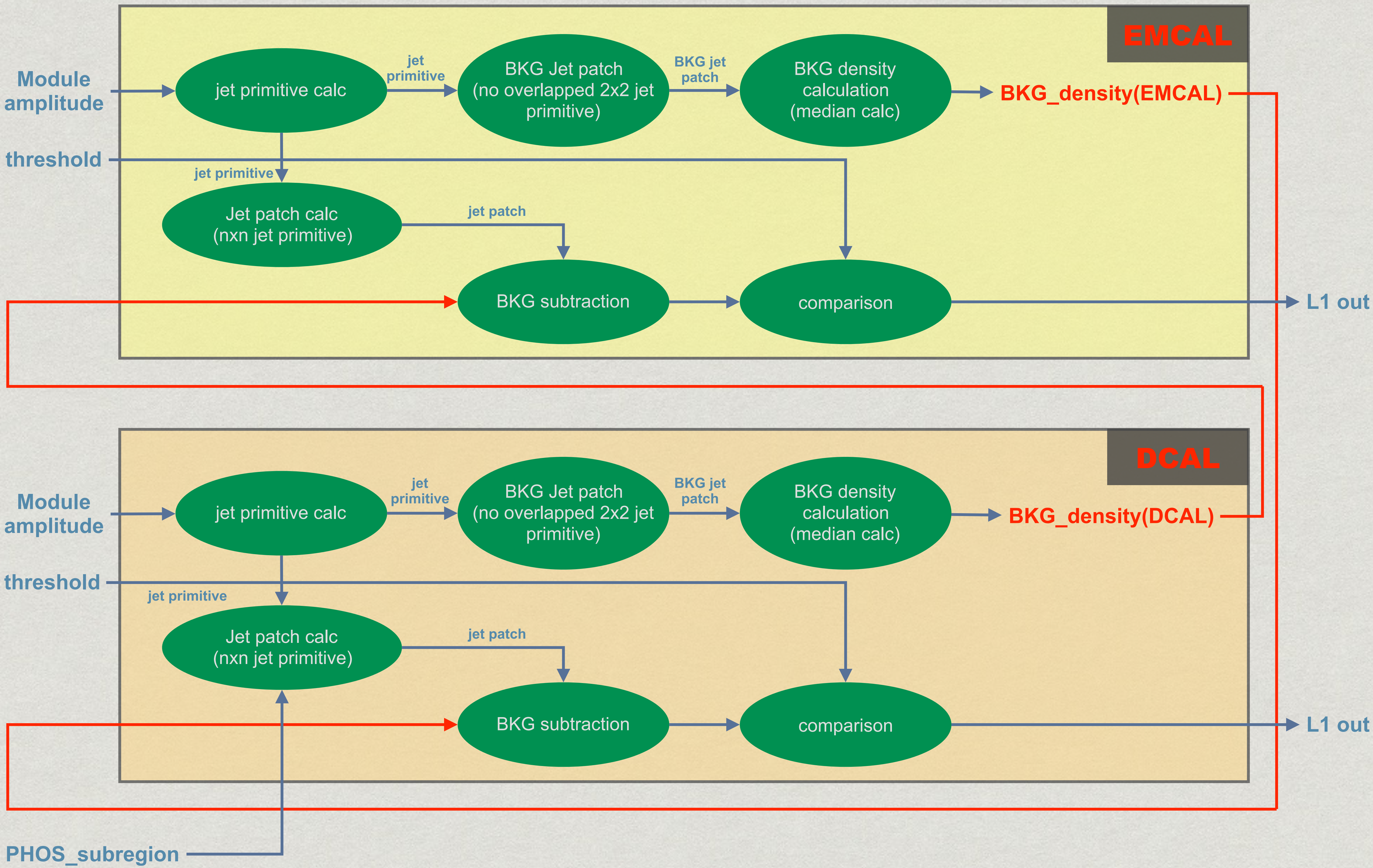
L1 photon/Jet algorithm in Run2

- L1-photon patch
  - 2x2 [modules] (EMCAL, DCAL)
  - 2x2 [2x2 crystals] (PHOS)
  - on-the-fly sliding window algorithm
- L1-Jet patch
  - (jet-primitive = 4x4 modules)
  - 2x2 jet-primitives
  - sliding window algorithm
- L1-Jet background
  - BKG patch = 2x2 jet-primitives
  - no overlap
  - BKG = median of BKG patch amp



E_{patch} - median$\{E_{BKG}/A_{BKG}\}$ * A_{patch} > Threshold
=> L1 activated

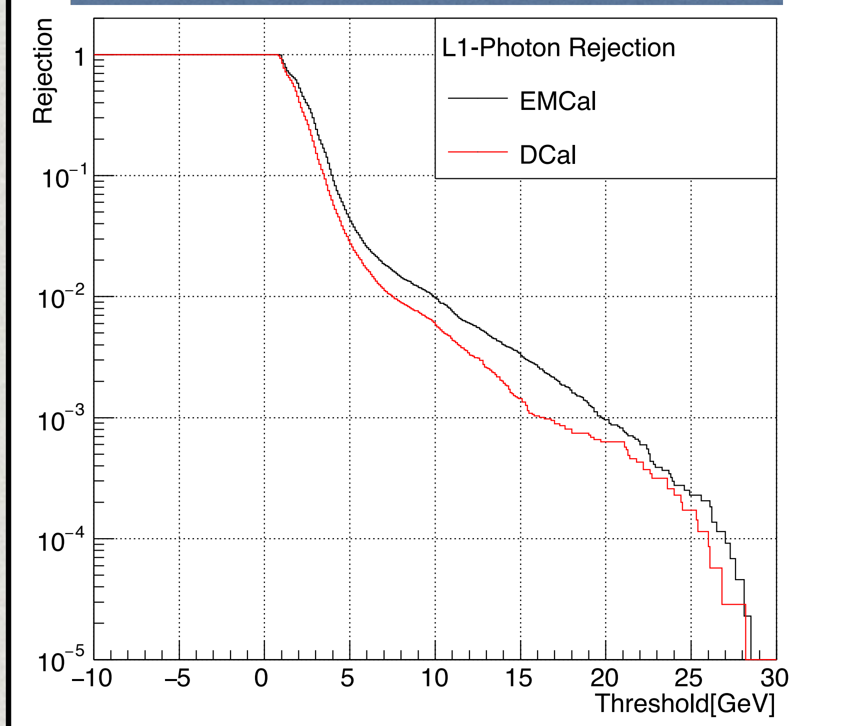
L1-Jet Background Subtraction Method



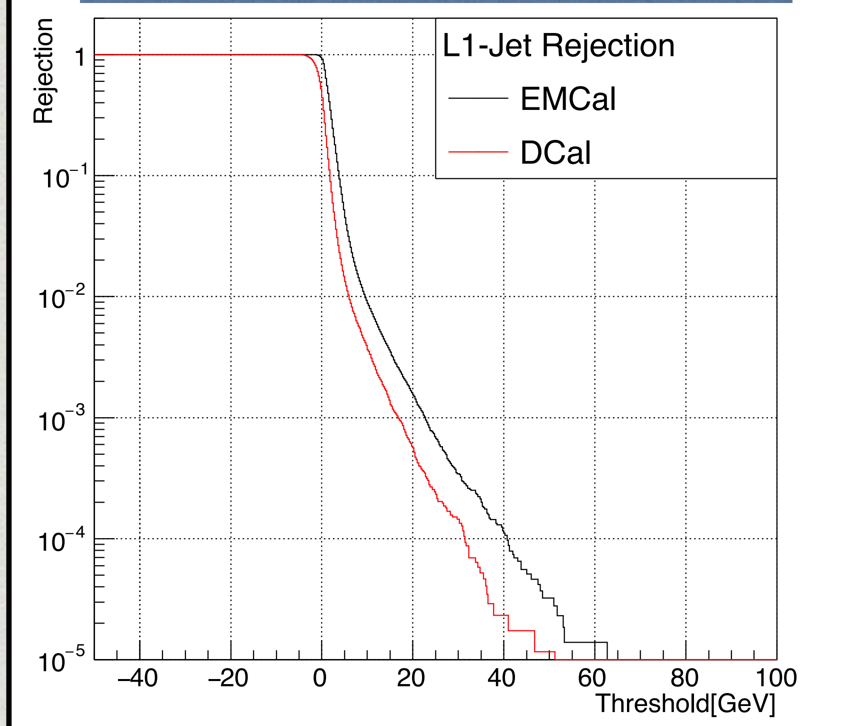
Trigger Rejection, Trigger Efficiency

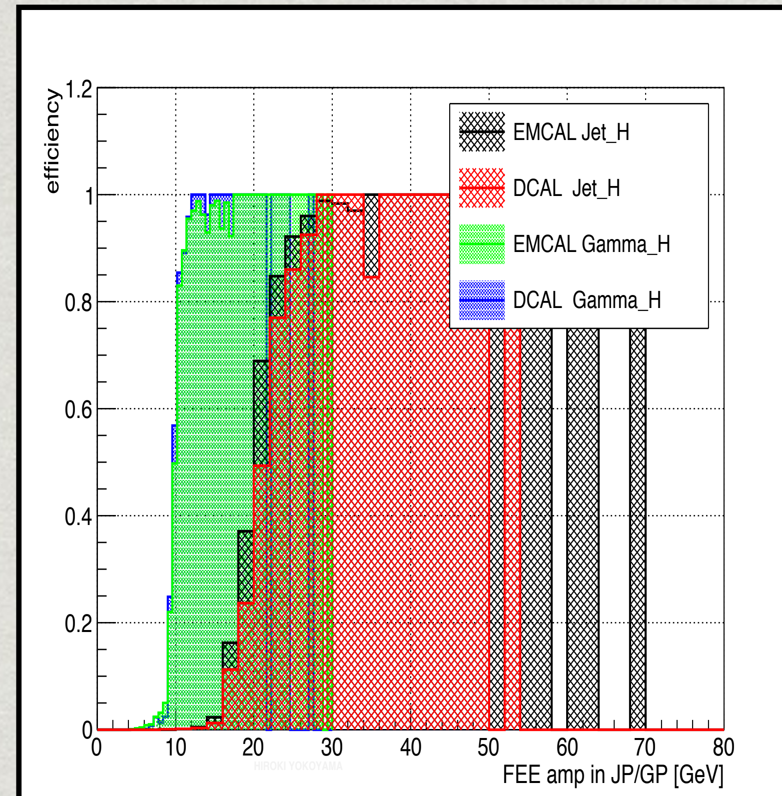
$$\textbf{Trigger Efficiency} = \frac{\textbf{Number of Jet Patch in Triggered Events}}{\textbf{Number of Jet Patch in MB Events}}$$

Photon Trigger



Jet Trigger



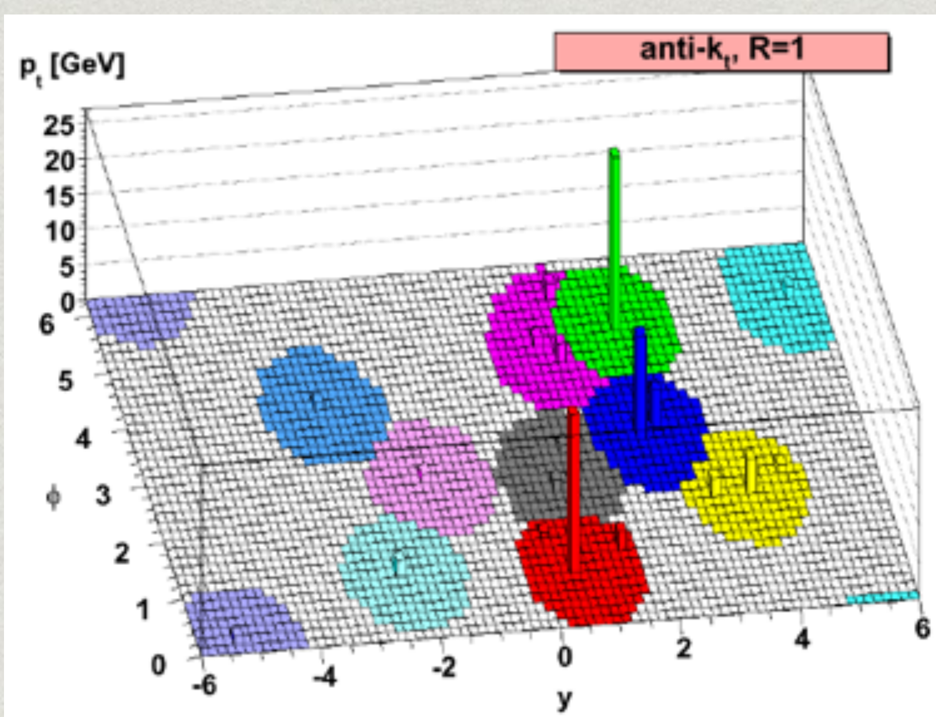


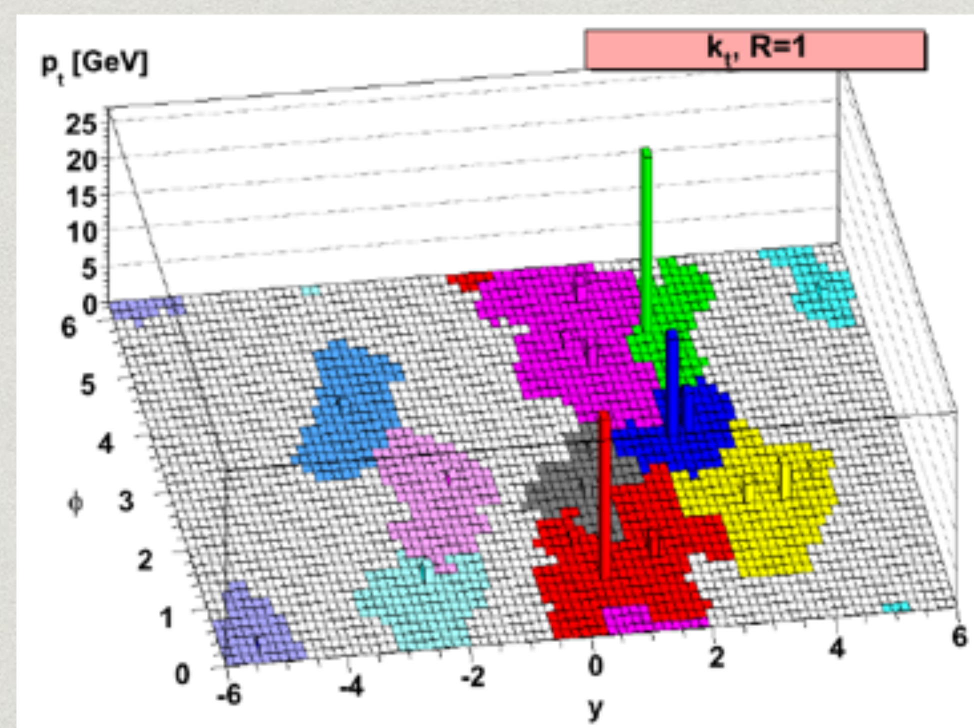
Jet Reconstruction Algorithm

- FastJet anti-k_T algorithm (p=-1, p=1 for k_T algorithm)
  - calculate d_{ij} and d_{iB} by all particles combination
    - when minimum “d” among them is part of d_{ij}
      - merge particle “i” and “j”
    - when minimum “d” among them is part of d_{iB}
      - that cluster defined as jet
  - repeat until no particle are left

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \,,$$
$$d_{iB} = k_{ti}^{2p} \,,$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$





Definition of the Underlying Energy Density

1. Output of k_T algorithm : the list of the k_T clusters (p_i, A_i)
   - k_T algorithm is better than anti-k_T algorithm for background estimation because low-p_T particles are apt to be the cluster constituents.
2. Remove largest two clusters from the list
   - because (2nd) largest cluster is the real Jet candidate.
3. Calculate median of "p_{Ti} / A_i"
   - "median" is better than "average" because the average calculation tend to be affected by seeped real-jet signal

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$

Underlying Event @ other centrality

- at the peripheral collision, background subtraction don’t have impact due to the small background