Measurement of jet spectra reconstructed with charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV with the ALICE detector at the LHC

(LHC-ALICE実験 $\sqrt{s_{NN}}$=5.02 TeV 鉛鉛衝突実験における荷電粒子ジェットの測定)

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Outline

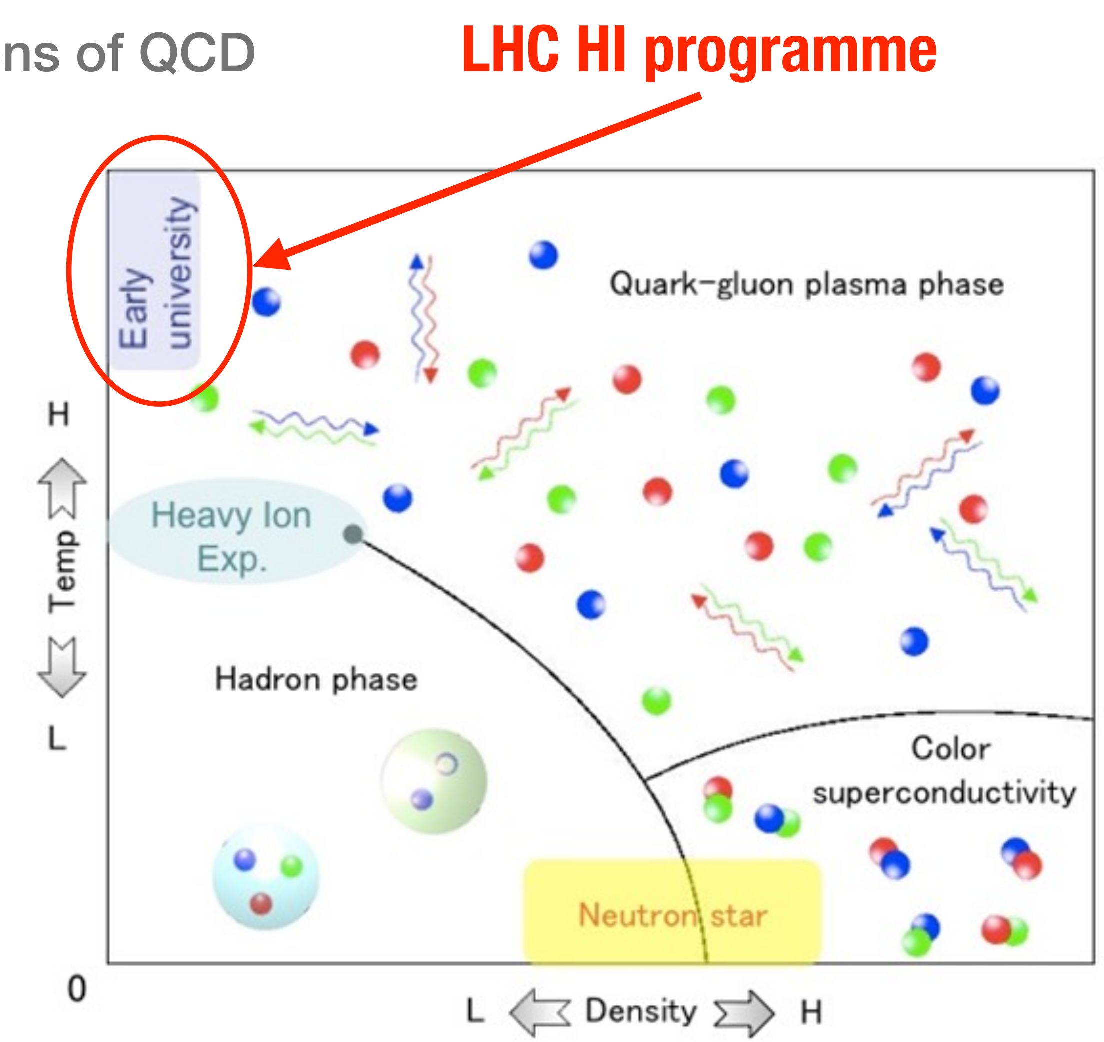
- **Introduction**
  - Quark-Gluon Plasma and Jet Quenching
  - LHC-ALICE Experiment
- **Development and commissioning of the ALICE Calorimeter L1 Trigger system**
- **Inclusive Charged jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions**
- **Summary**

- **Introduction**
- **Development and commissioning of the ALICE Calorimeter L1 Trigger system**
- **Inclusive Charged jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions**

Quark Gluon Plasma

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



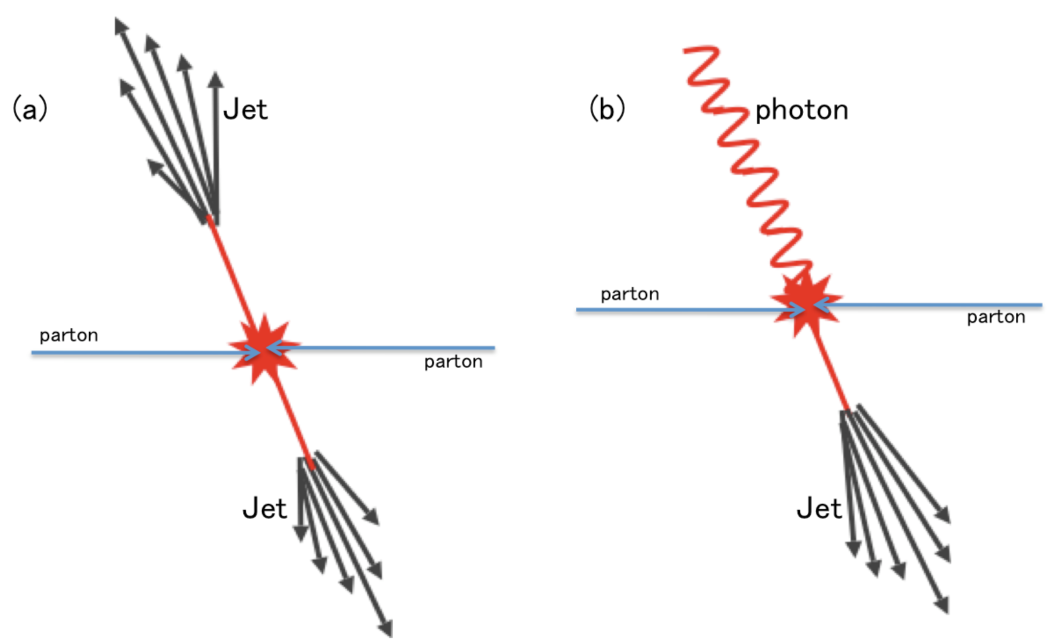
How to create ?

- '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)

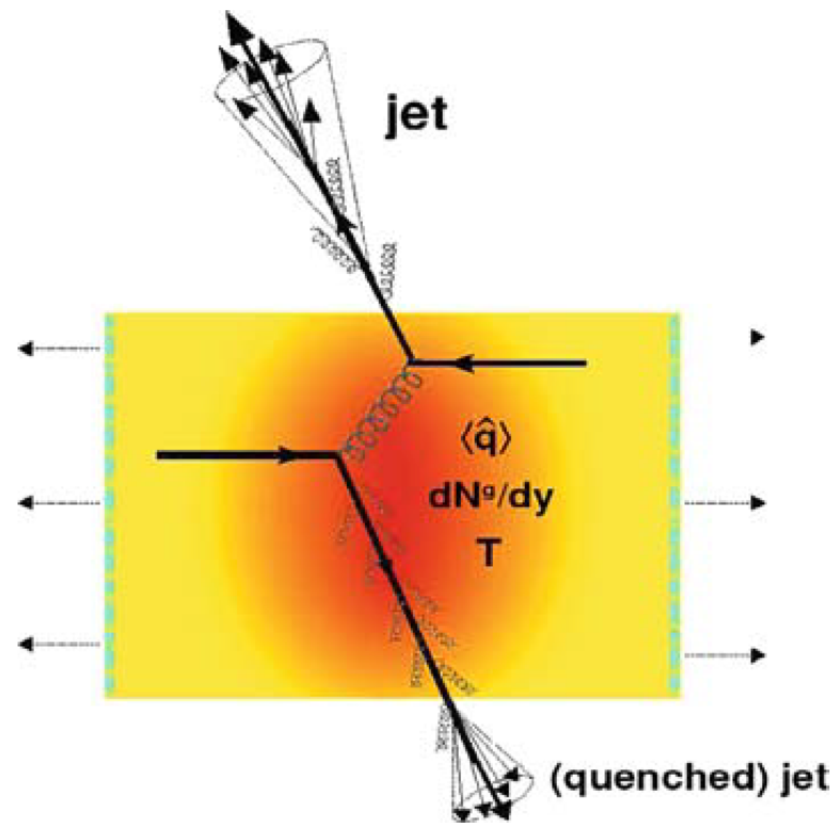
What's a Jet ?

- 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



Jet Quenching

- Attenuation or disappearance of observed Jets in Pb-Pb
  - due to partons' energy loss in the QGP
  - jet shape broadening
  - **evaluation of the degree of the attenuation allows to assess QGP properties**



Jets in HI Collisions (Hard Probes of the QGP)

What's a Jet ?

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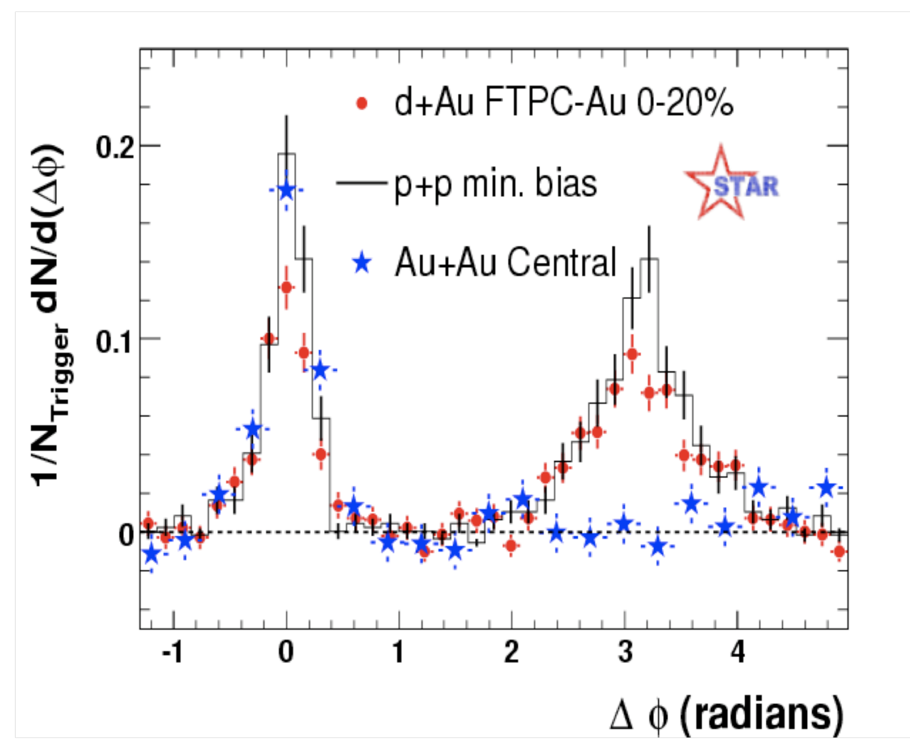
Why Jets ?

- The QGP lifetime is so short (~10^{-23} s) that characterisation by external probes is ruled out
  - **self-produced probes**
- Occur at early stage : $\tau \sim 1/Q$
  - **probe the entire medium evolution**
- Production rate calculable within pQCD
  - **well calibrated probes**
- 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
  - jet shape broadening
  - **evaluation of the degree of the attenuation allows to assess QGP properties (e.g. dE/dx)**



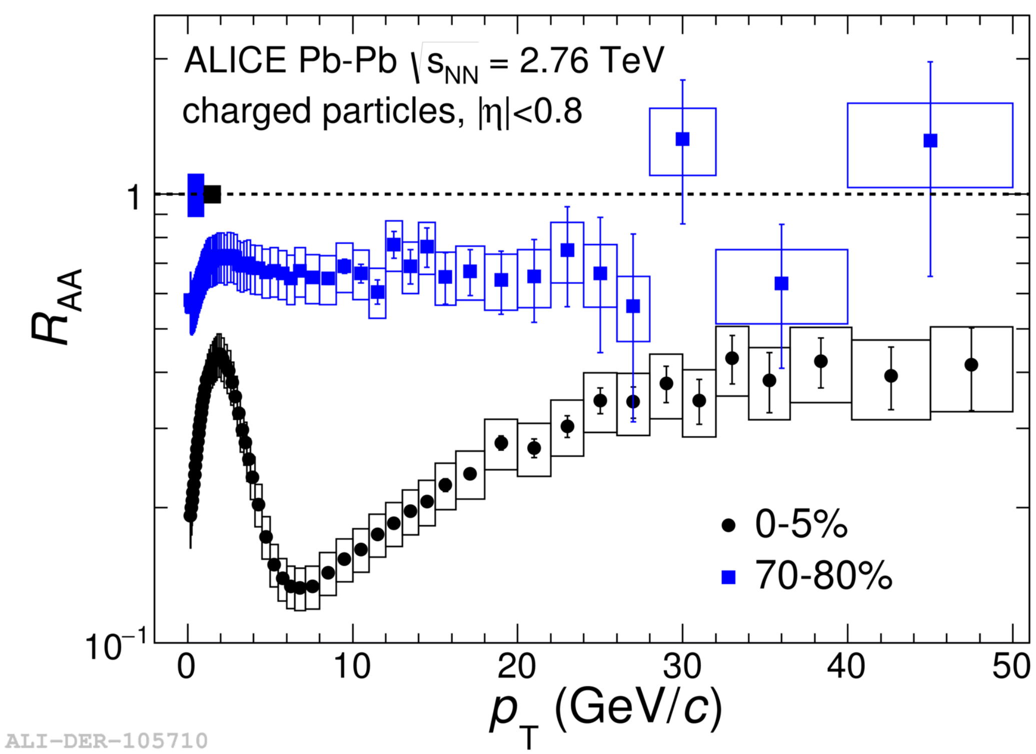
two-particle angular correlations
$4 < p_T^{trig}$ [GeV/c] < 6, $2 < p_T^{asso}$ [GeV/c] $< p_T^{trig}$
Phys. Rev. Lett. 91, 072304 (2003)

ALICE Jet Quenching Measurements in Pb-Pb

- **Nuclear modification factor : R_{AA}**
  - if $R_{AA} = 1$, NO modification

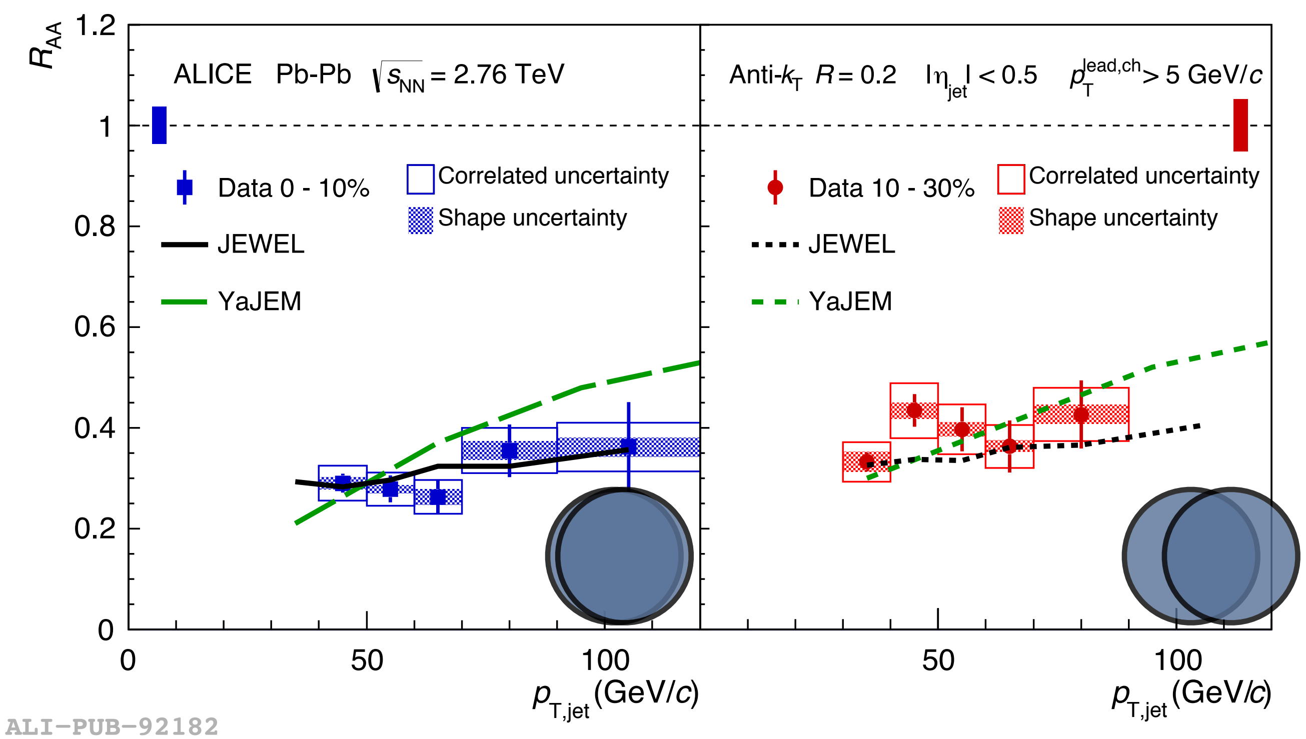
$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{dN_{ch\ jet}}{dp_T d\eta}}{\frac{d\sigma_{pp}}{dp_T d\eta}}$$

- **High-p_T Hadrons**
  - strong suppression : R_{AA}~0.2
  - proxy for Jet (parton) : p_T >10 GeV/c
  - fragmentation of quenched partons



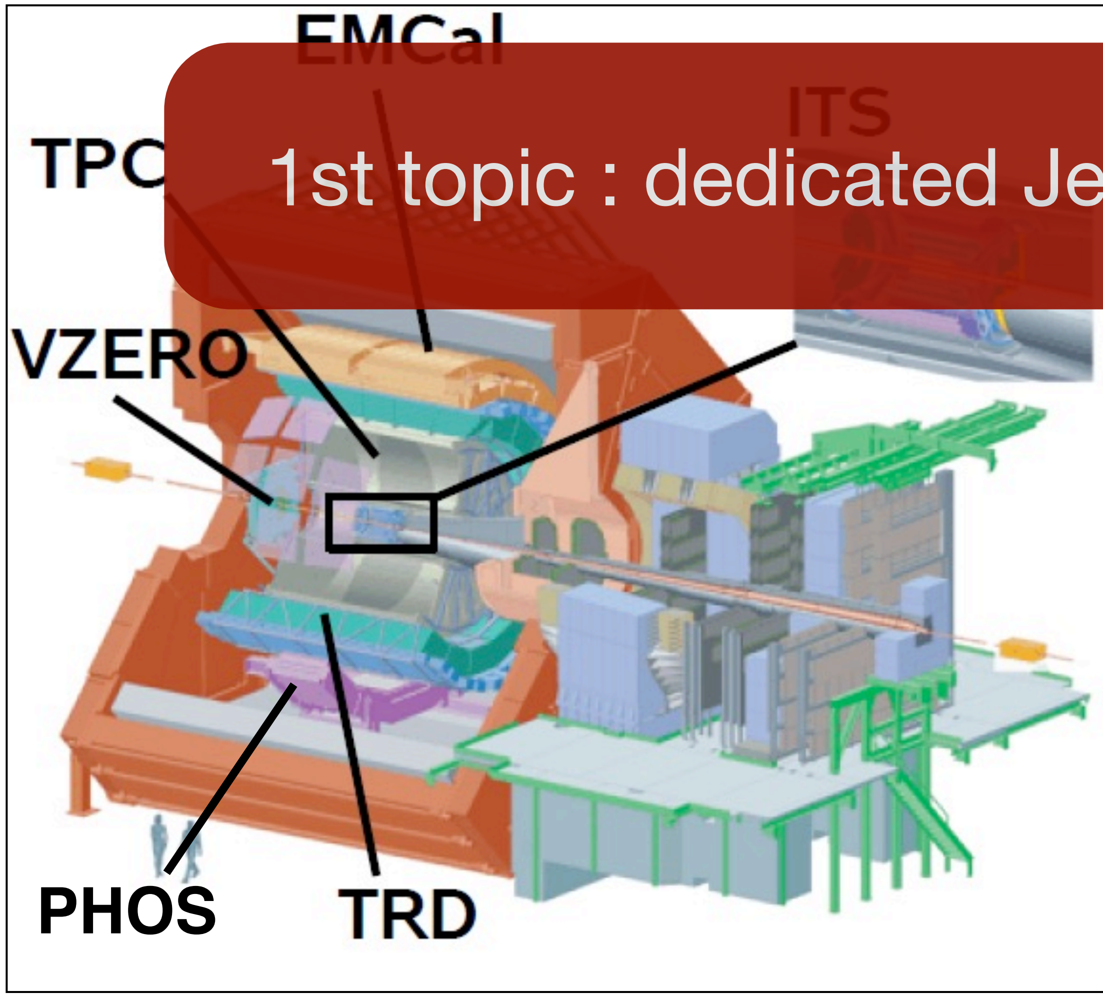
Centrality Dependence of Charged Particle Production at Large Transverse Momentum in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV , PLB 720 (2013) 52

- **Jets**
  - strong suppression : R_{AA}~0.4
  - Jet shape broadens?
    where is the lost energy?



Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV , PLB 746 (2015) 1

Jet Measurement in LHC-ALICE



- ALICE detector focus on Heavy Ion Experiment
  - LHC Run2 period started from 2015
    - $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb, pp
    - $\sqrt{s_{NN}}$ = 8 TeV p-Pb

1st topic : dedicated Jet/photon trigger implementation

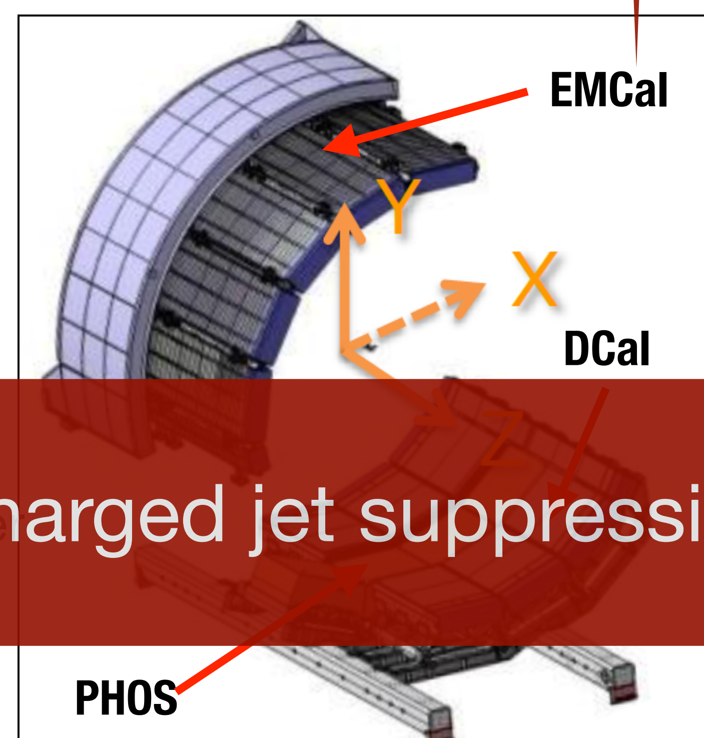
Charged Particles : |η| < 0.9, 0<ϕ<2π

- ITS : silicon tracking detector
- TPC : Time Projection Chamber
- **Charged constituents**

Charged Jet

Neutral particles : |η| < 0.7

- EMCal, (DCal : Run2 from 2015-)
  - Pb-Scintillator sampling calorimeter
- PHOS
  - lea...
- **Neutral constituents**



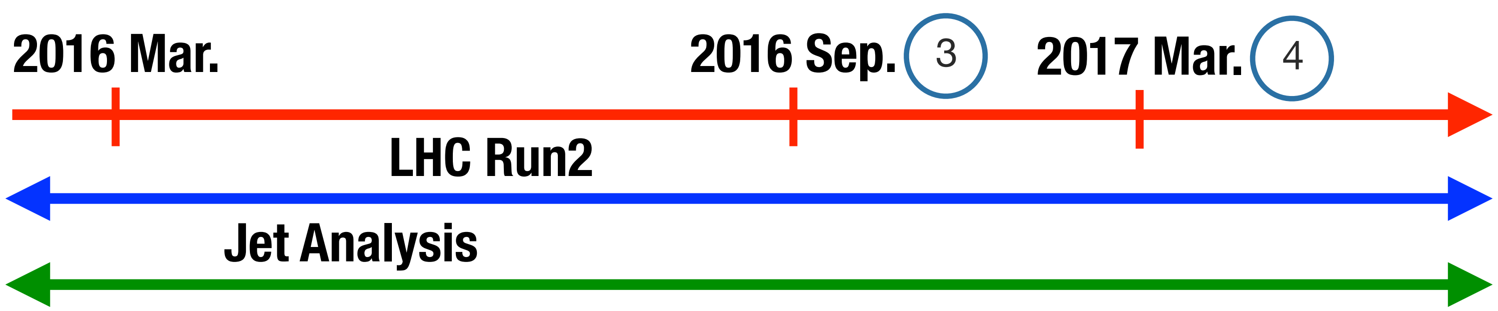
2nd topic : evaluation of charged jet suppression in Pb-Pb

My Activity

(1) 2015 Mar. 日本物理学会第70 回年次大会 : “Development of EMCALs' Trigger System in LHC-ALICE”

(2) 2015 Sep. Quark Matter 2015 : [poster] “A Summary Trigger Unit for the ALICE Electromagnetic Calorimeters”

- 国際ワークショップでの口頭発表（4回）



Stay in
CERN : ~15 months
Grenoble LPSC : ~5 months

(3) 2016 Sep. Hard Probes 2016 : [oral] “Measurement of Inclusive Charged Jet Production in pp and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE”

(4) 2017 Mar. 日本物理学会第72 回年次大会 : “The nuclear modification of charged jets in $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions at LHC-ALICE”

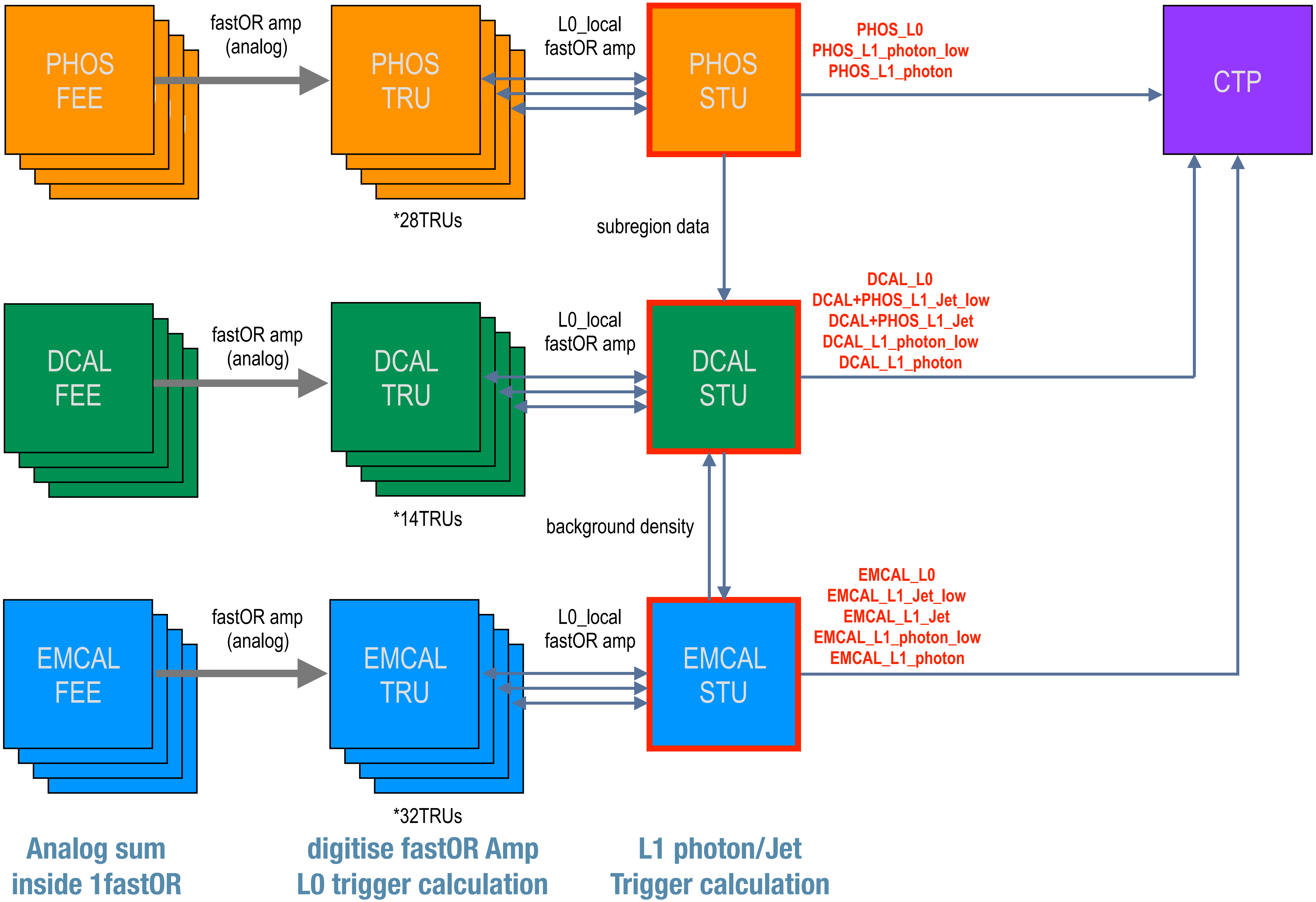
- 国際ワークショップでの口頭発表（3回）

- Introduction
- Development and commissioning of the ALICE Calorimeter L1 Trigger system
- Inclusive Charged jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions

Motivation

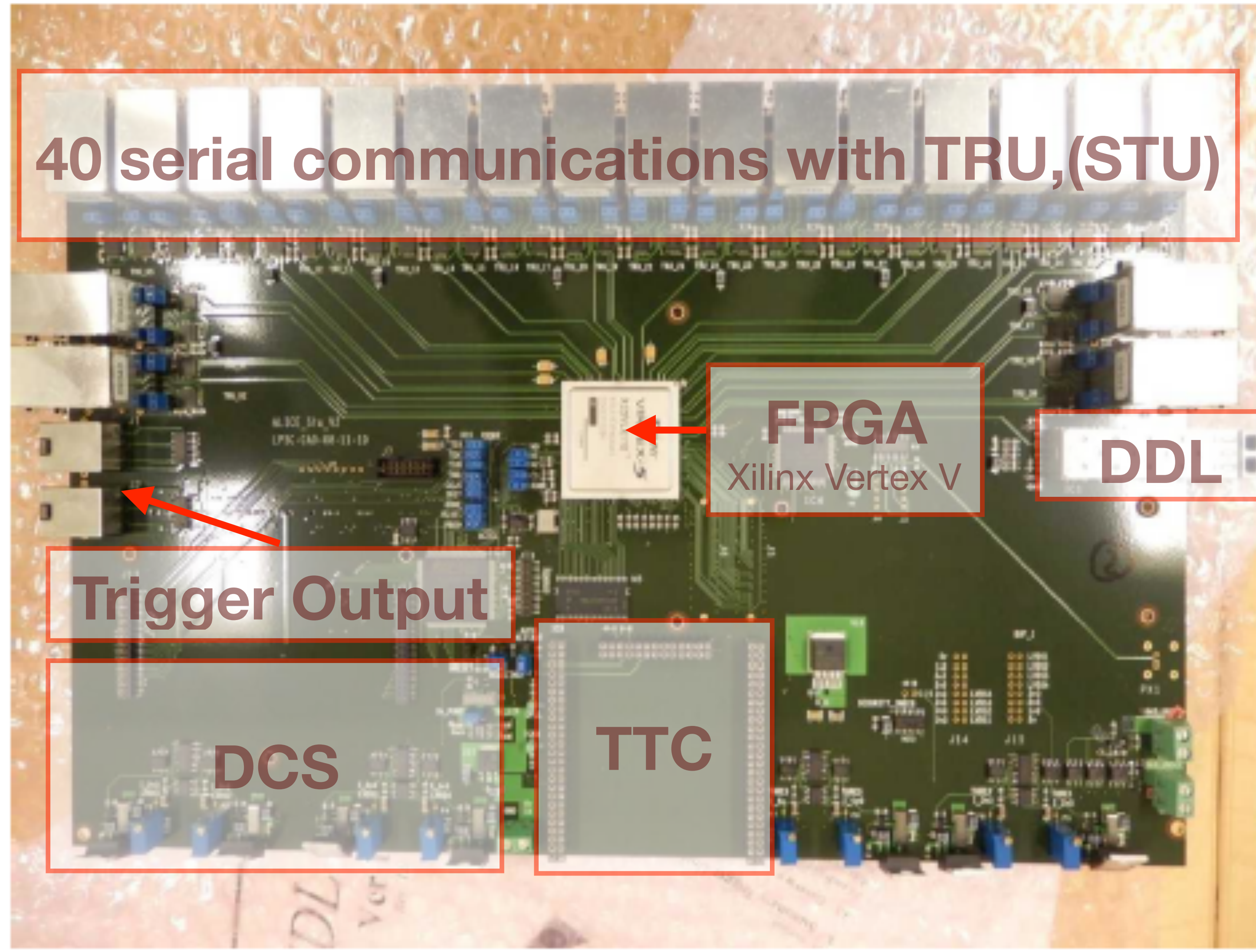
- ALICE calorimeter upgrade for Run2
  - new calorimeter : DCAL
  - trigger hardware retrofitness on PHOS
  - trigger algorithm
  - et al…
- new Jet/photon trigger implementation is required

Trigger System of ALICE Calorimeters



Summary Trigger Unit

- TTC (Trigger Trigger Clock)
  - clock management (40 MHz)
  - new L1/L2 Class message
- DDL (Detector data Link)
  - DAQ for trigger
  - new data header (CDH v3)
  - Trigger Information
    - trigger setting
    - raw data etc…
- DCS
  - Control Command
  - new command
- Trigger Busy Signal

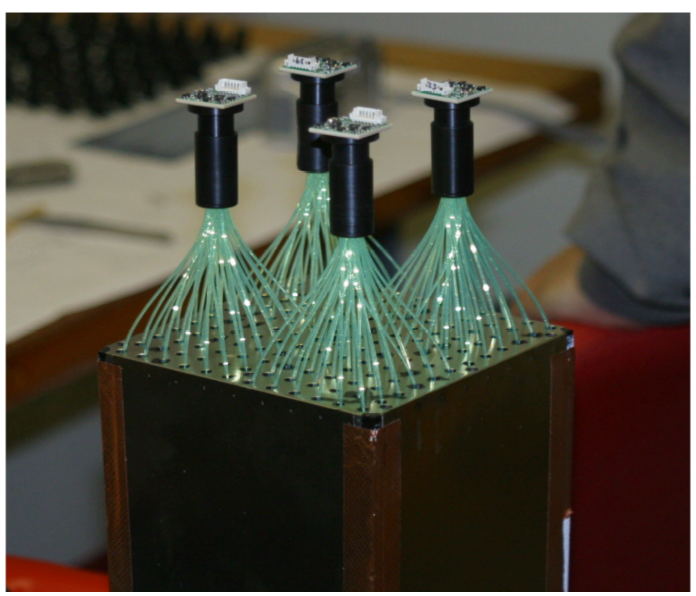


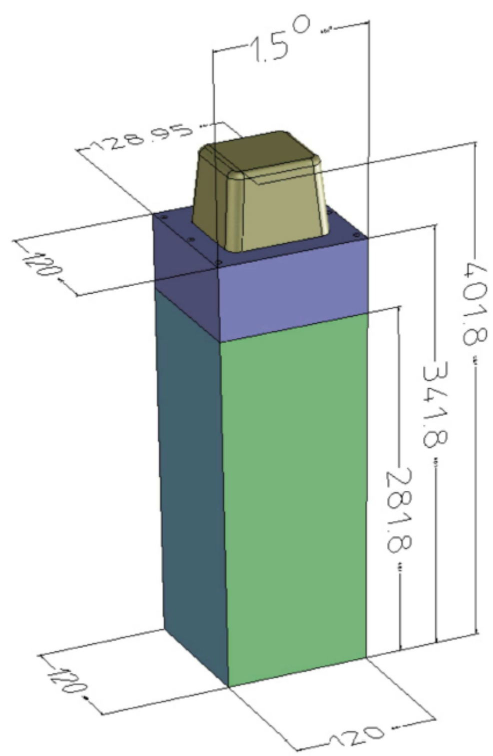
- Trigger Output
- FastOR Amplitude
- L0 local
- Mean BKG signal, Jet Primitive signal

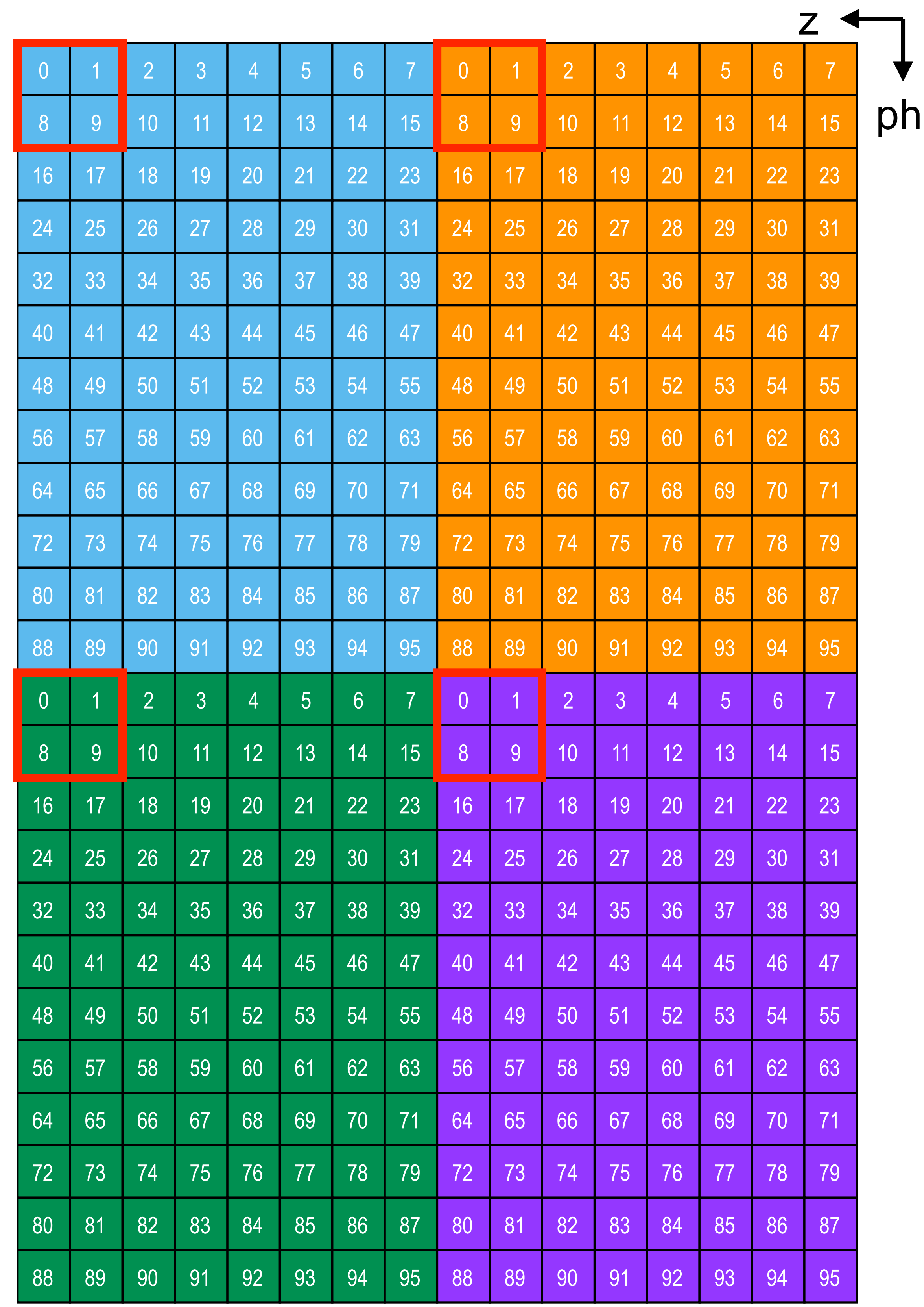
most of all modules(functions) are controlled by FPGA on STU

Level 1 Trigger Algorithm

- L1 Photon patch
  - 2x2 FastOR
  - sliding window algorithm based on FastOR
- On-the-Fly calculations
  - to reduce HW resource

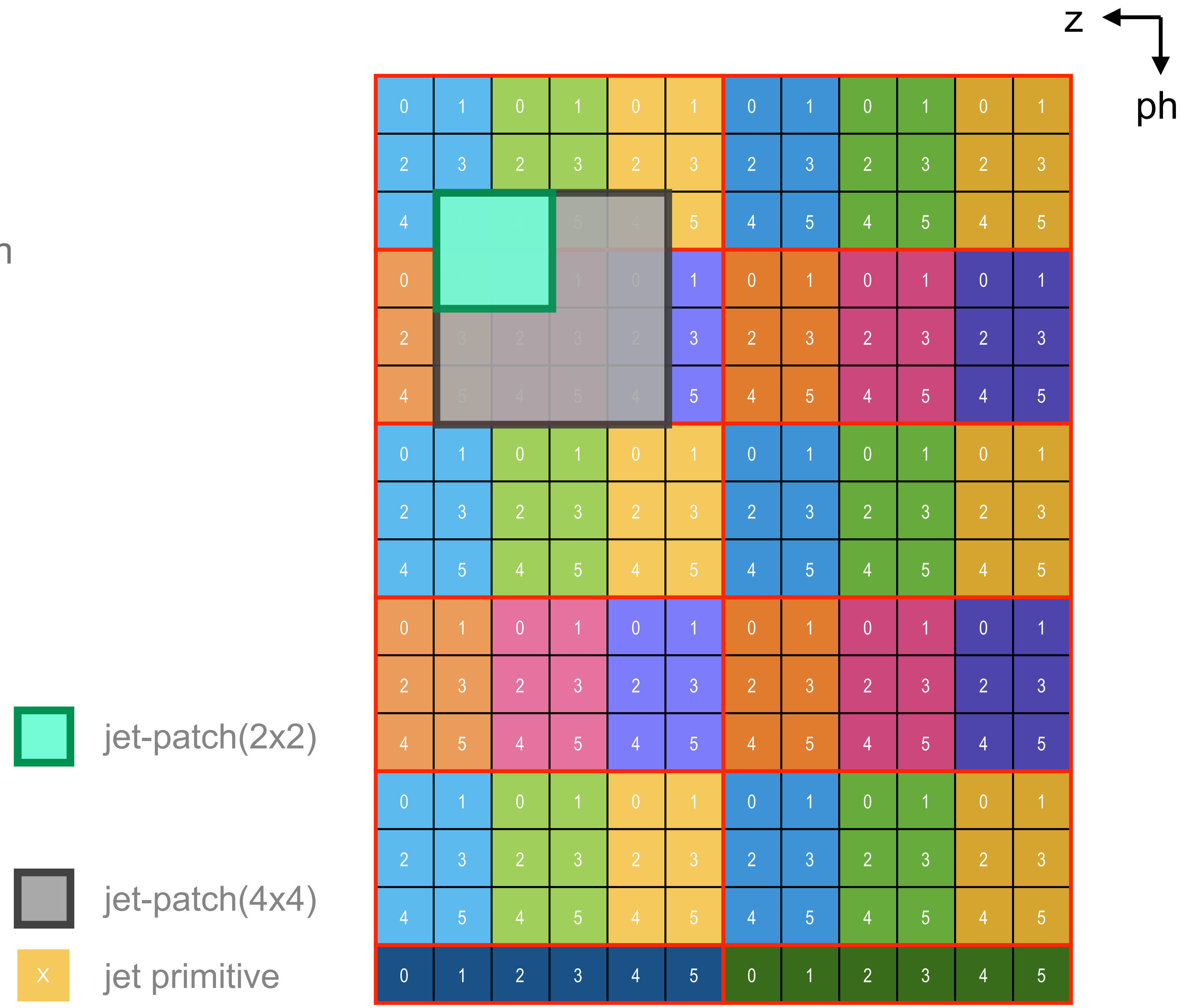




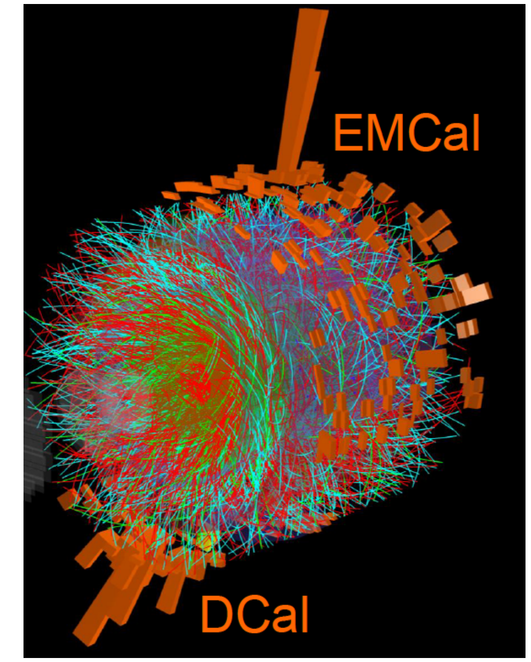


Level 1 Trigger Algorithm

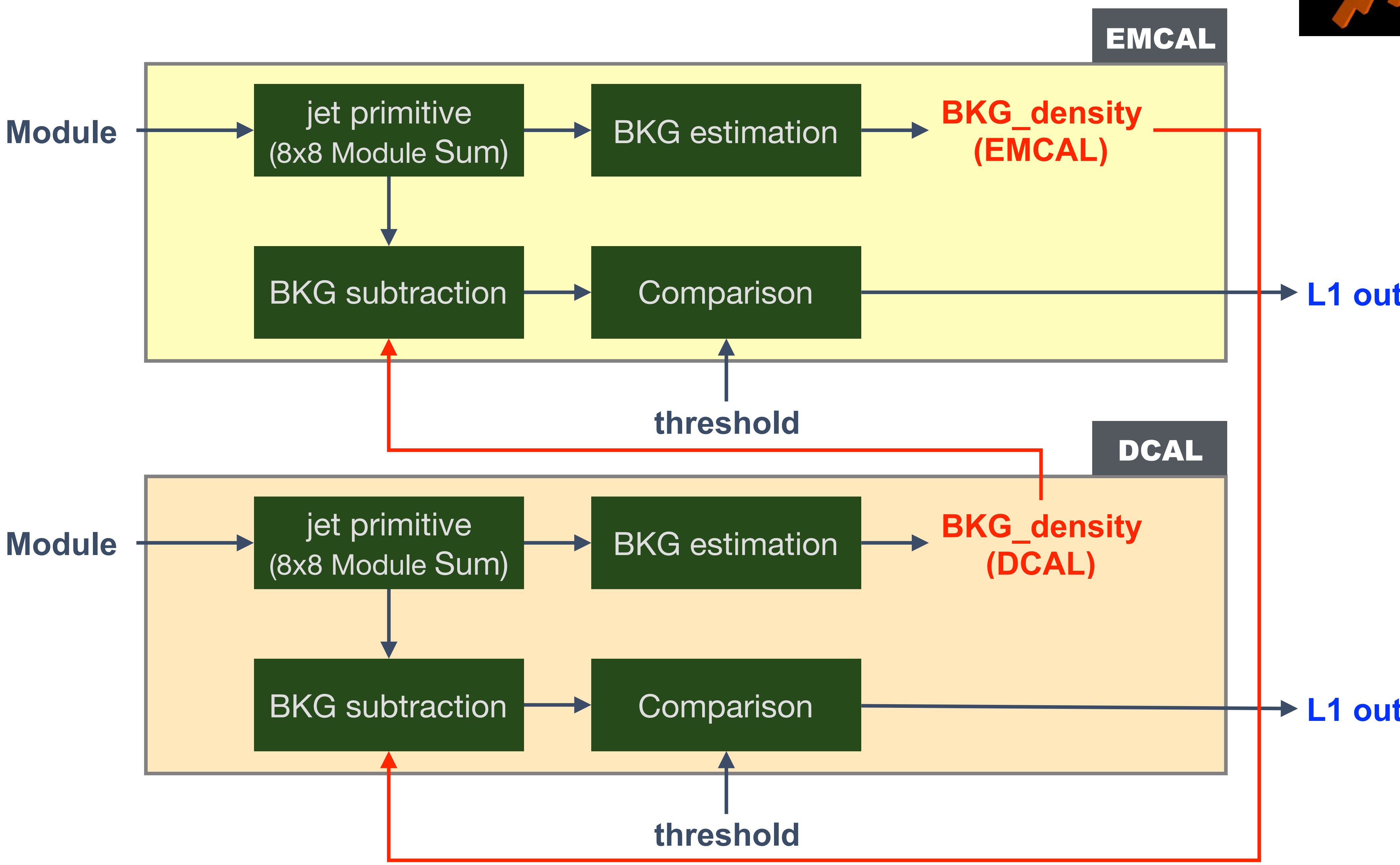
- L1 Jet patch
  - 2x2 or 4x4 jet primitives
  - sliding window algorithm based on jet primitive (4x4 FastOR)



Level 1 Trigger Algorithm



- 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

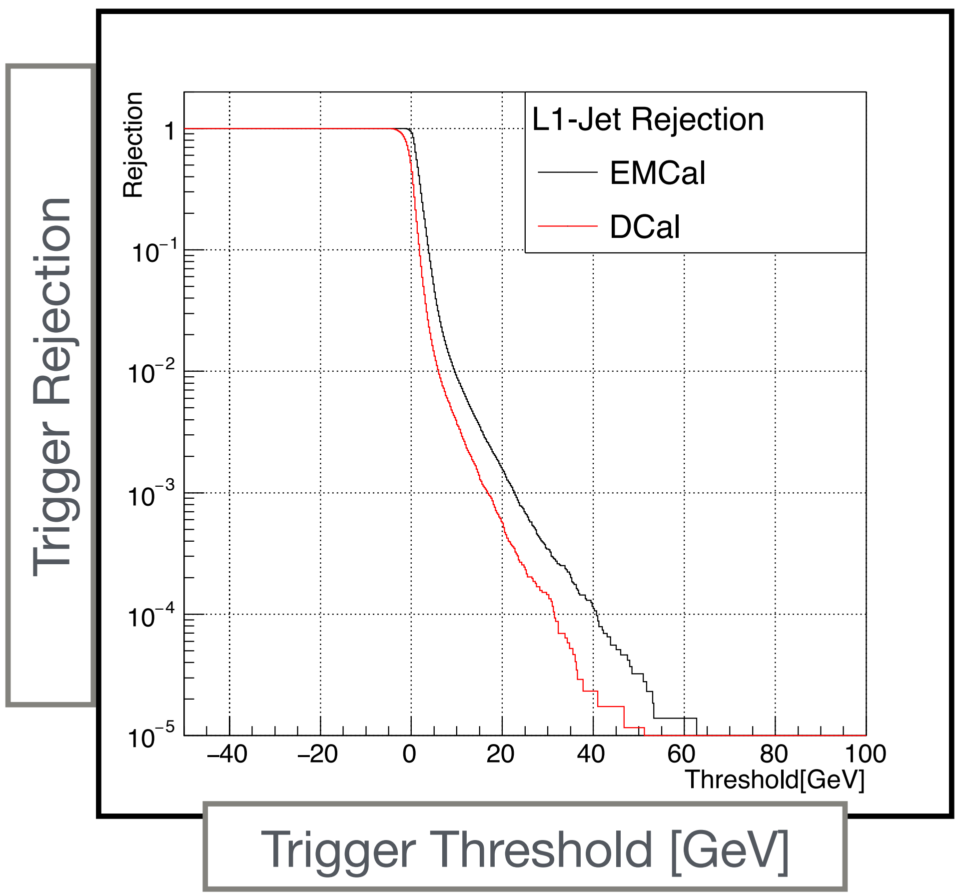


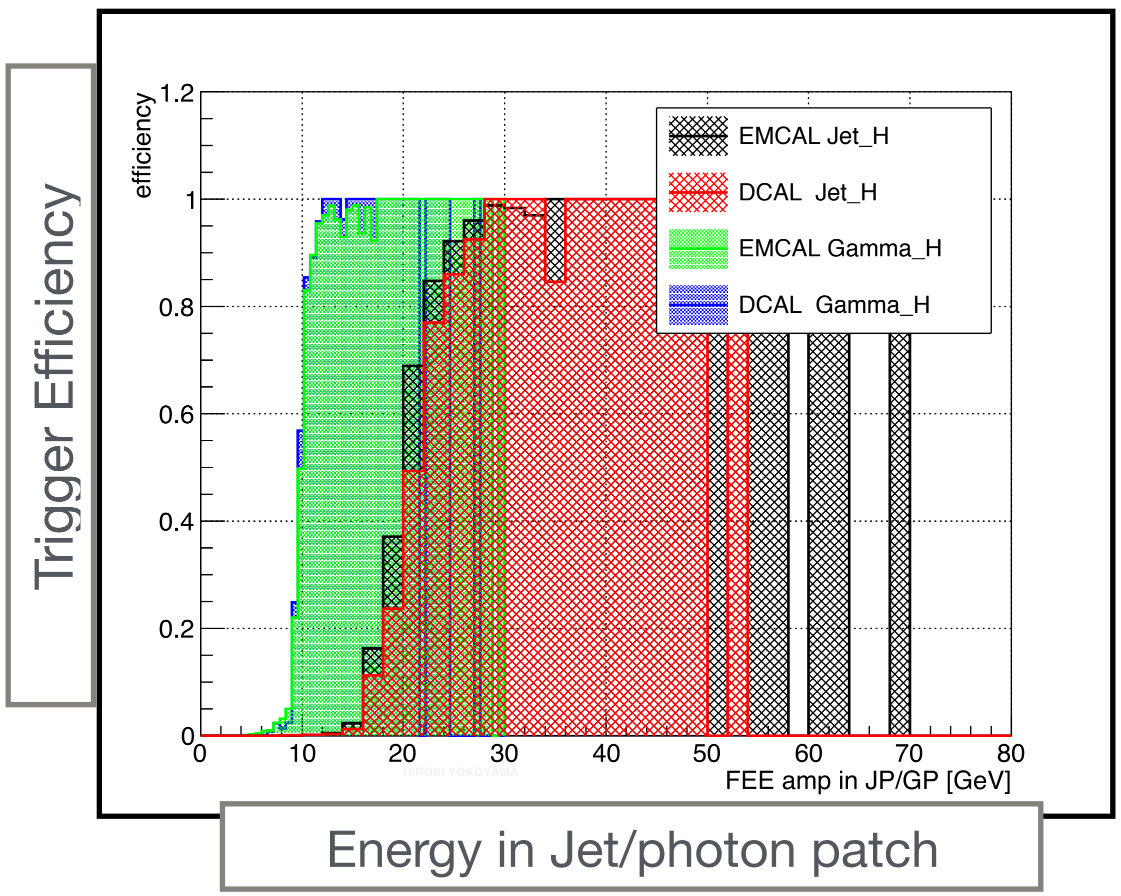
Trigger Performance

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

- **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!

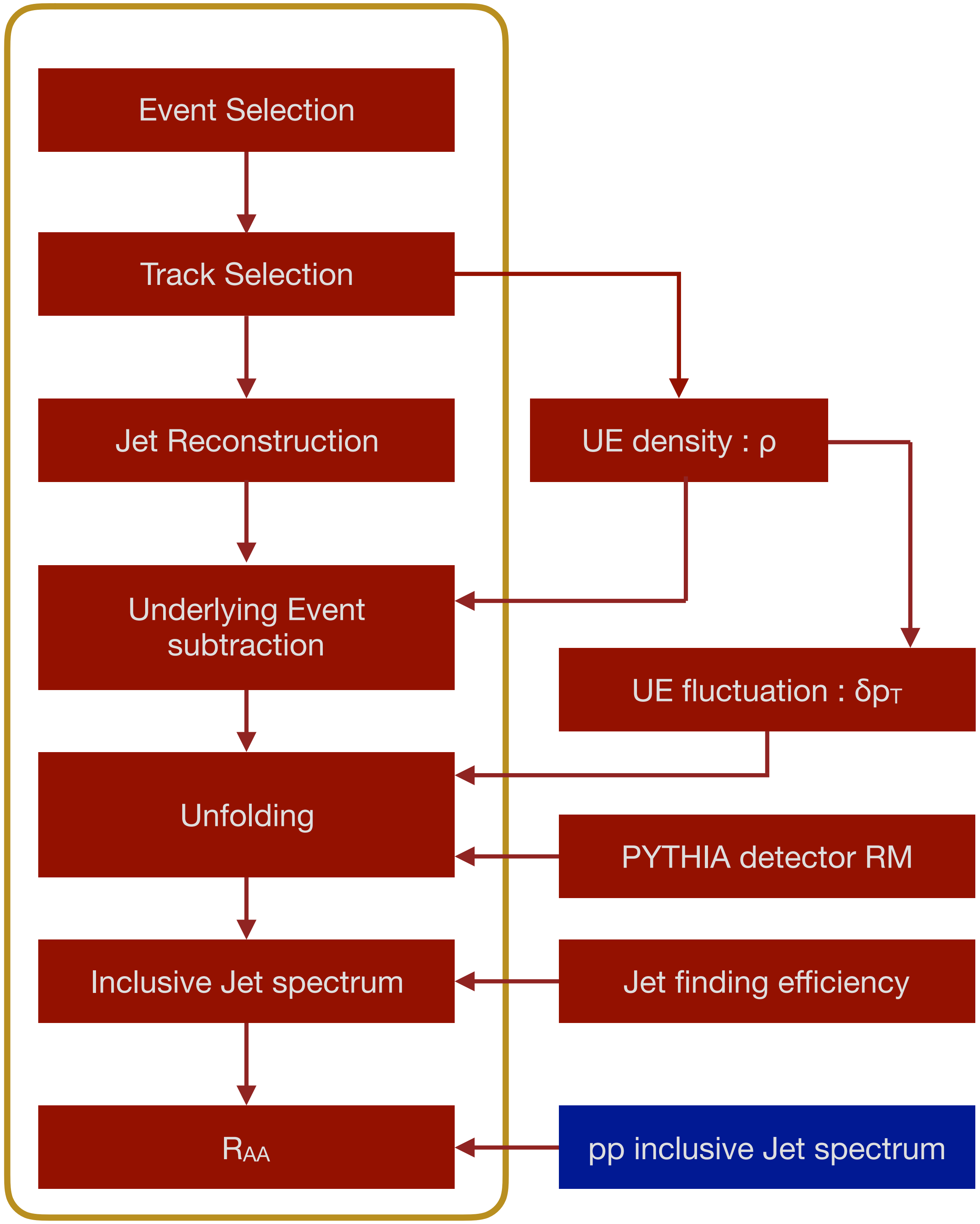
- Introduction
- Development and commissioning of the ALICE Calorimeter L1 Trigger system
- Inclusive Charged jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions

Motivation

- Jets
  - closer probes to the partons than handons
  - powerful tools for study of QGP properties
- strong suppression observed at central Pb+Pb collisions
  - Nuclear modification factor R_{AA}
  - extreme condition (highest energy in the world : $\sqrt{s_{NN}}$ = 5.02 TeV)
  - -> systematic understanding of parton energy loss in QGP

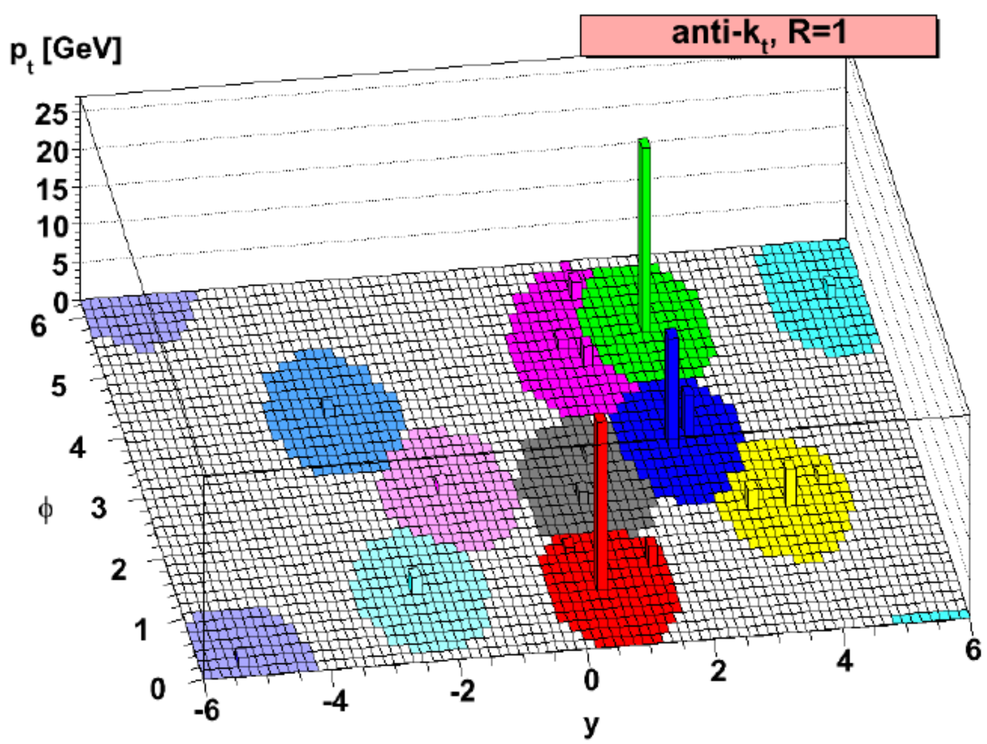
Analysis Flow (Pb-Pb collisions)

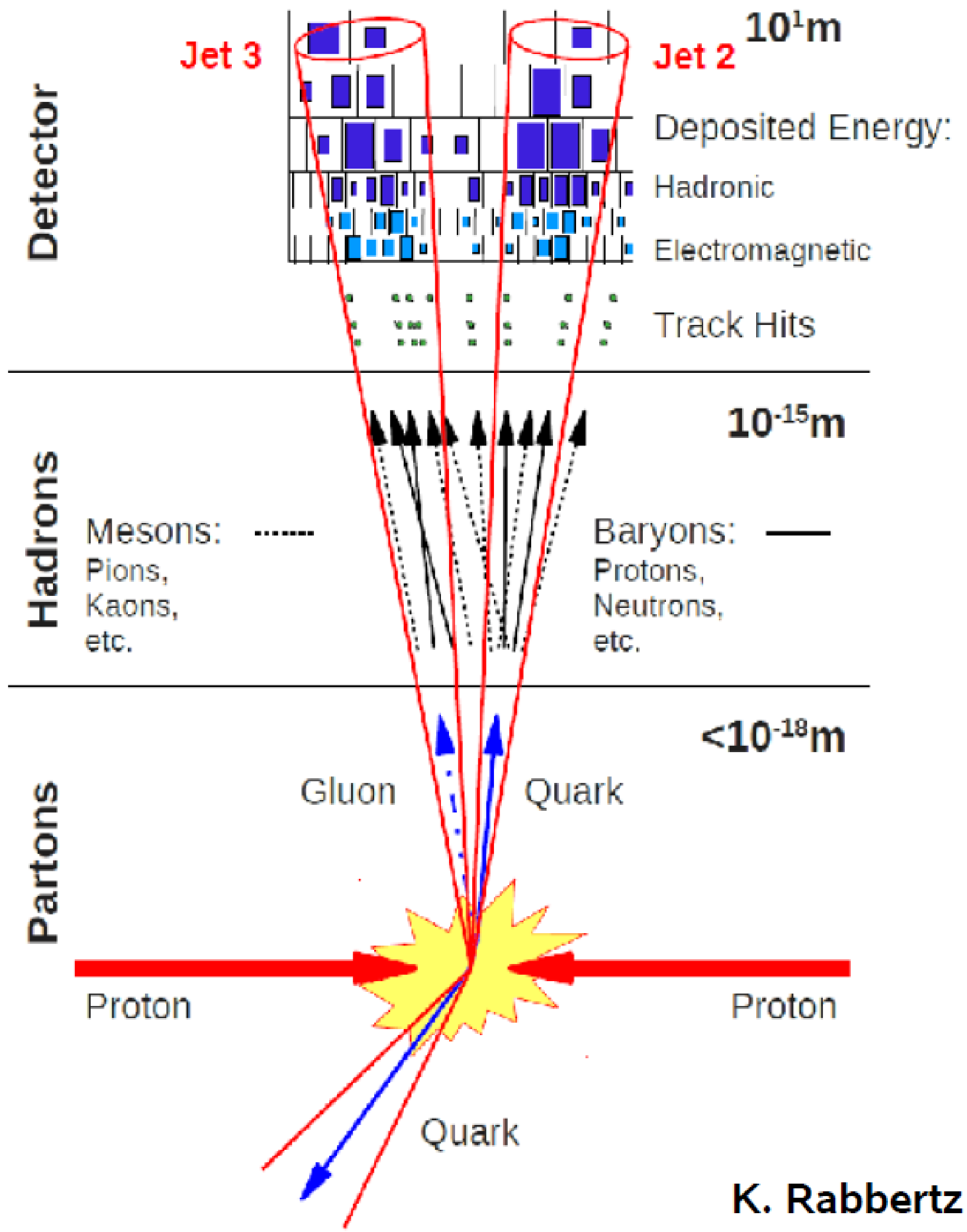
- **Dataset**
  - $\sqrt{s_{NN}}$ = 5.02 TeV, Pb-Pb collisions
  - MB triggered events
    (3.36M events, ~5% of full statistics)
- **Charged track selection**
  - | η | < 0.9, p_T^{track} > 0.15 GeV/c
- **Jet reconstruction**
  - anti-k_T jet reconstruction algorithm
  - R = 0.2
  - | η | < 0.7, p_T^{lead} > 5 GeV/c
- **Underlying Event subtraction**
  - background is subtracted from reconstructed jet
- **Unfolding**
  - to correct for detector effects and background fluctuations
- **Inclusive jet spectrum, R_{AA}**
  - fully corrected to charged particle level, assess nuclear modification



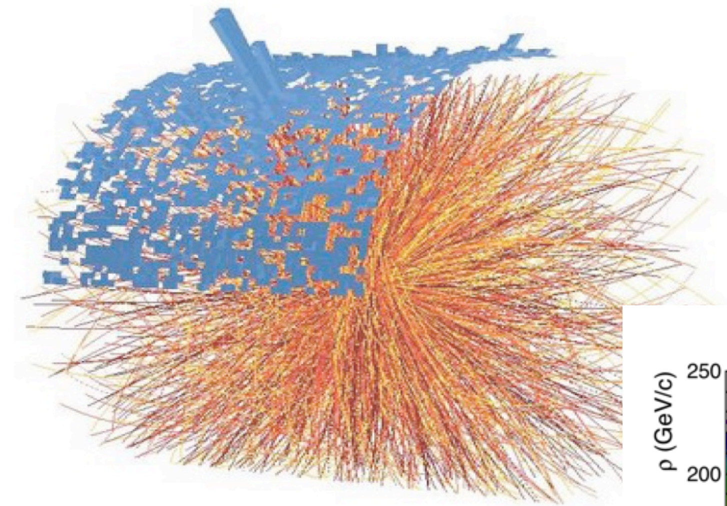
Jet Reconstruction

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





Underlying Event Density



Challenge in Heavy-Ion Collisions

- large background contribution to jet energy
    - $dN_{ch}/d\eta$ ~ 1300 (0-10% centrality)

Jet Background Subtraction

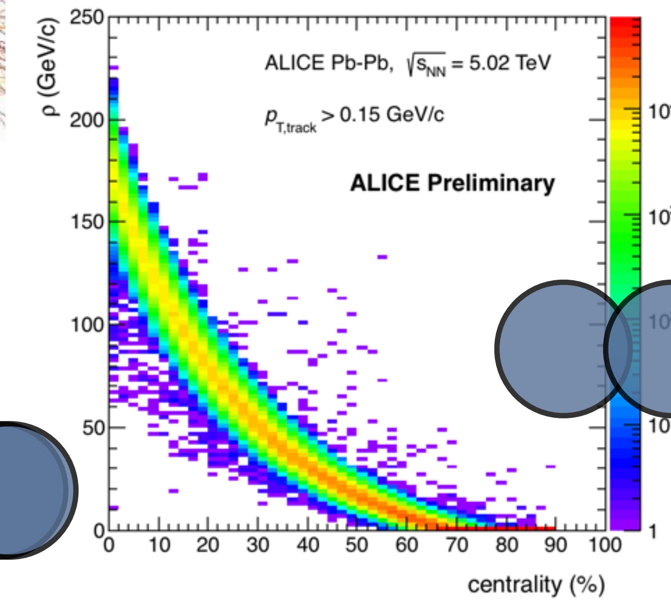
- **background density : ρ**
    - median k_T excluding the highest two clusters

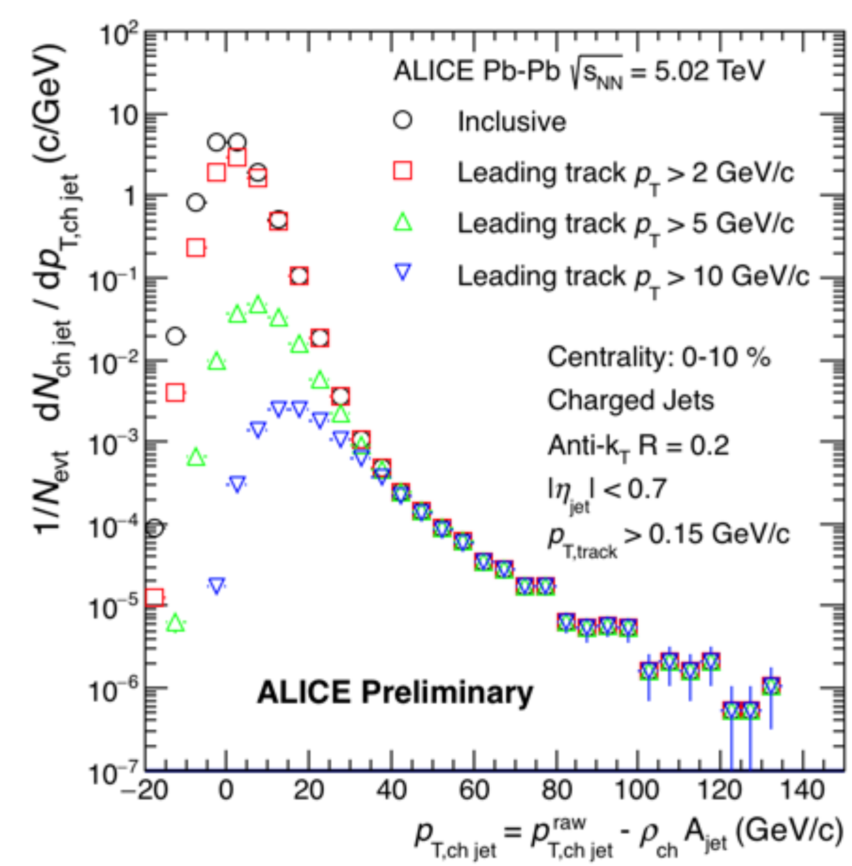
$$\rho = median\left\{\frac{p_{T,i}}{A_i}\right\}$$

    - ρ ~ 145 GeV/c for 0-10% (~18 GeV/c for R=0.2 jets)
- **background subtraction**
    - background is estimated event-by-event and subtracted from each jet

$$p^{rec}_{T,ch\ jet} = p^{raw}_{T,ch\ jet} - \rho \cdot A^{rec}_{jet}$$

    - minimum leading constituent p_T > 5 GeV/c requirement <u>suppresses combinatorial jets in low momentum</u>





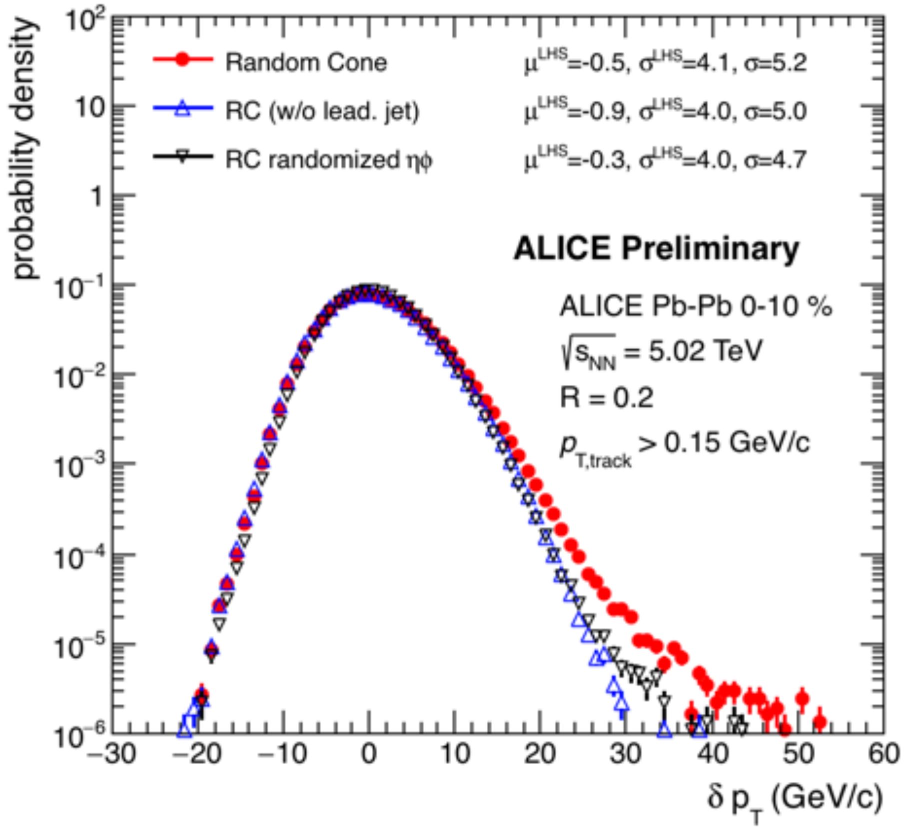
Underlying Event Fluctuation

UE fluctuation : δp_T

- δp_T is used as a measure for background fluctuation
  - for the correction of measured spectrum

$$\delta p_T = \sum_{i}^{RC} p_{T,i}^{track} - A \cdot \rho$$

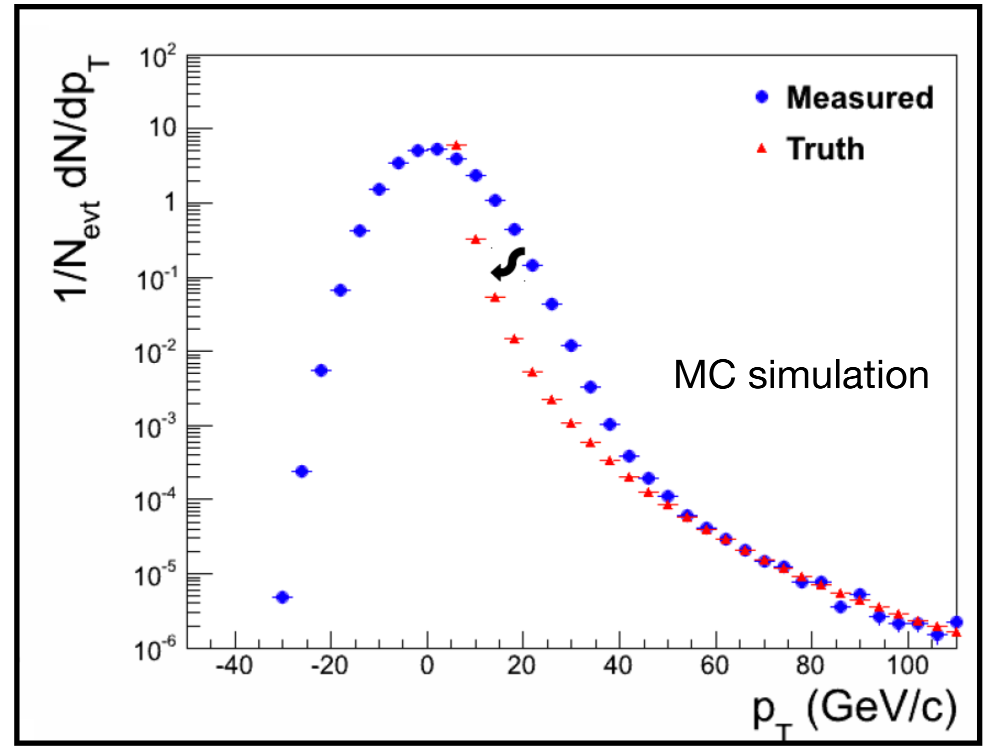
- **δp_T width (magnitude of UE fluctuation)**
  - fluctuations larger in central than in peripheral collisions
  - ~5 GeV/c for R=0.2, 0-10% centrality



Unfolding

More correction NEEDED!

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



Unfolding technique

- **Background Fluctuations**

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

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

- **Detector Effects**

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

$G_{d,t}$: Response matrix; T_t: "unknown" true jet spectrum

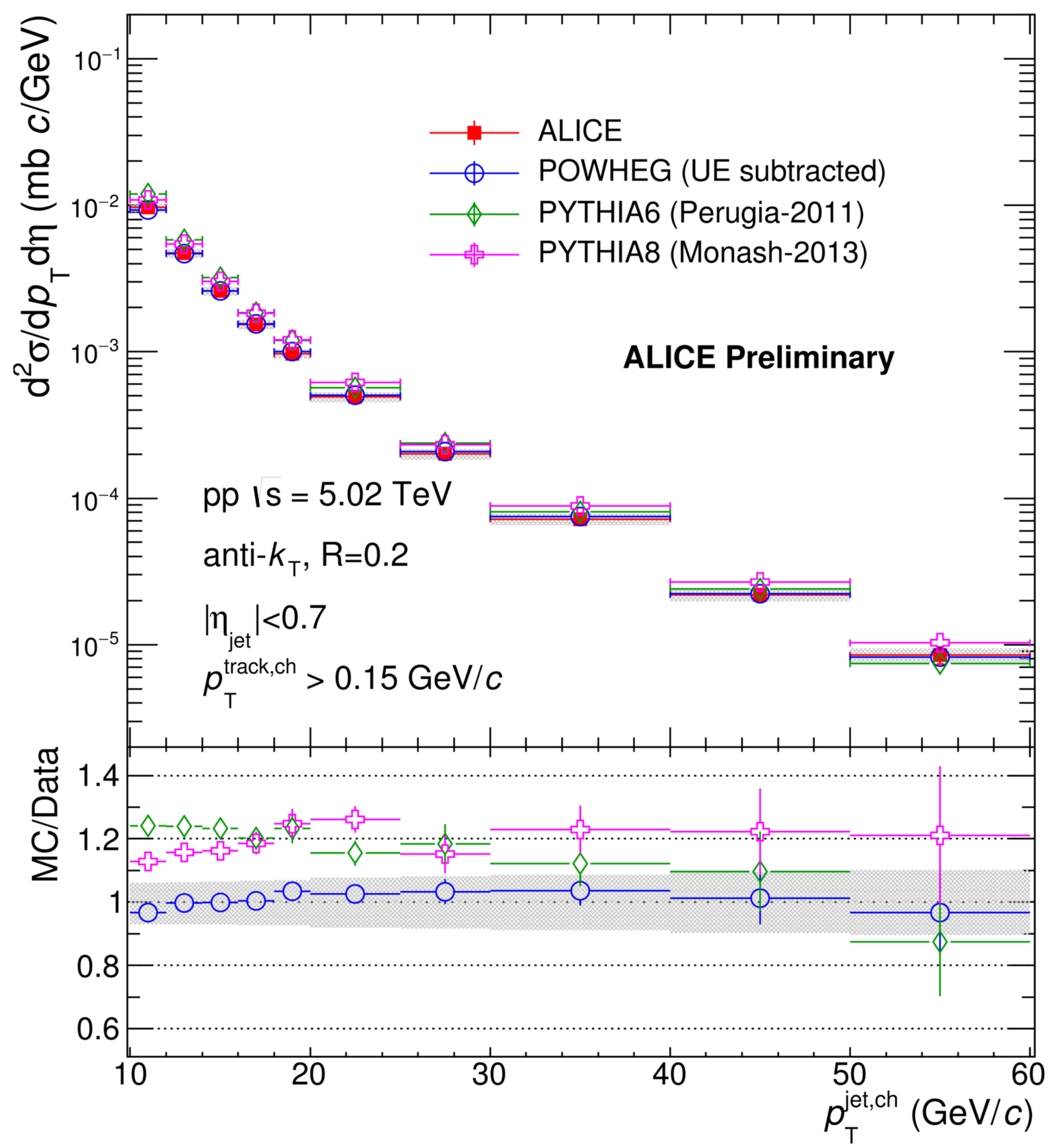
Inverted Response matrix gives "TRUE" jet spectrum via

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

pp Inclusive Jet Cross Section

- **Jet cross section**
  - well described by POWHEG NLO calculations within systematic uncertainties

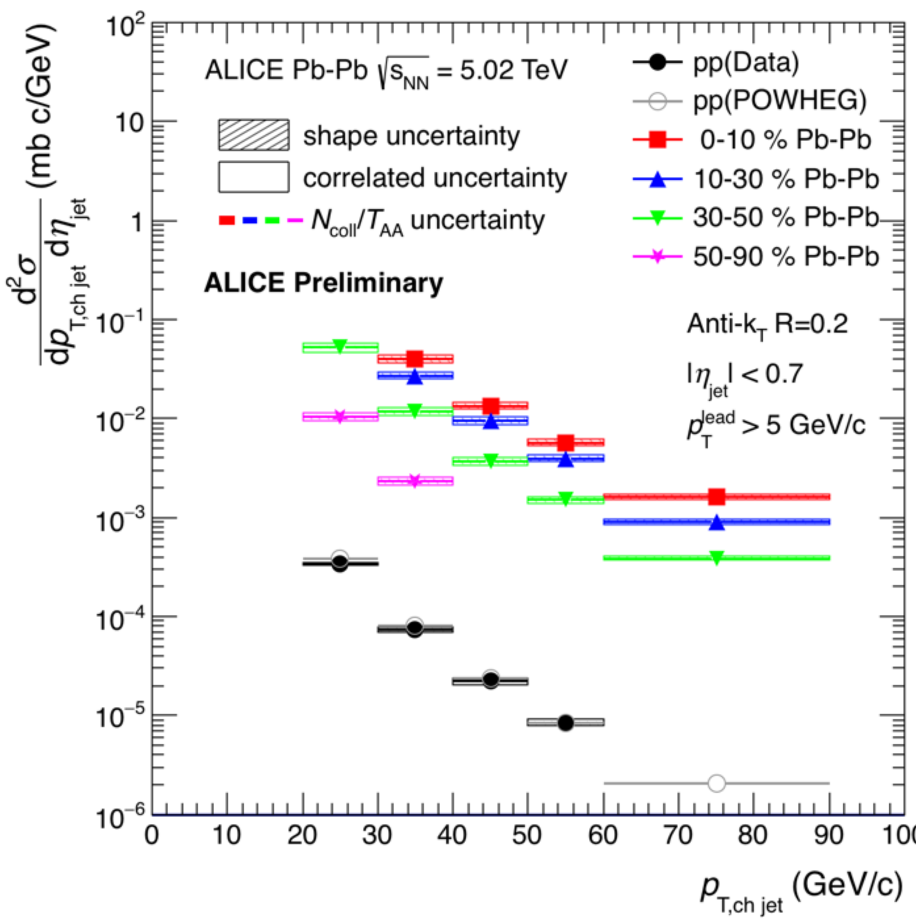
Ritsuya Hosokawa

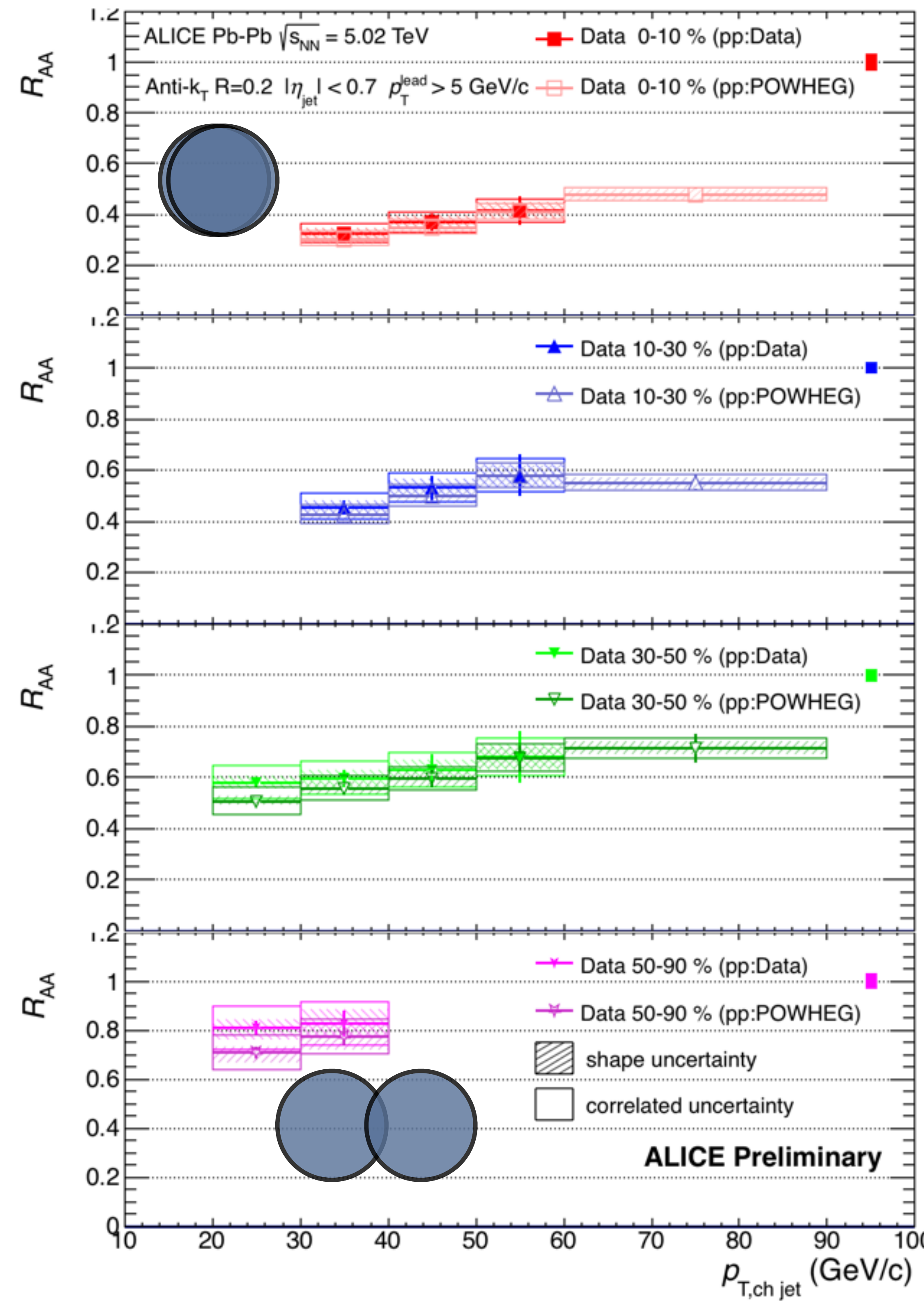


Nuclear Modification Factor : R_{AA}

$$R_{AA} = \frac{\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{dN_{ch\ jet}}{dp_T d\eta}}{\frac{d\sigma_{pp}}{dp_T d\eta}}$$

- **Nuclear modification factor : R_{AA}**
  - $R_{AA} > 1$, enhancement of yield
  - $R_{AA} < 1$, suppression
- **R_{AA} in each centrality bin**
- Increased suppression from peripheral ~0.8 to central ~0.4

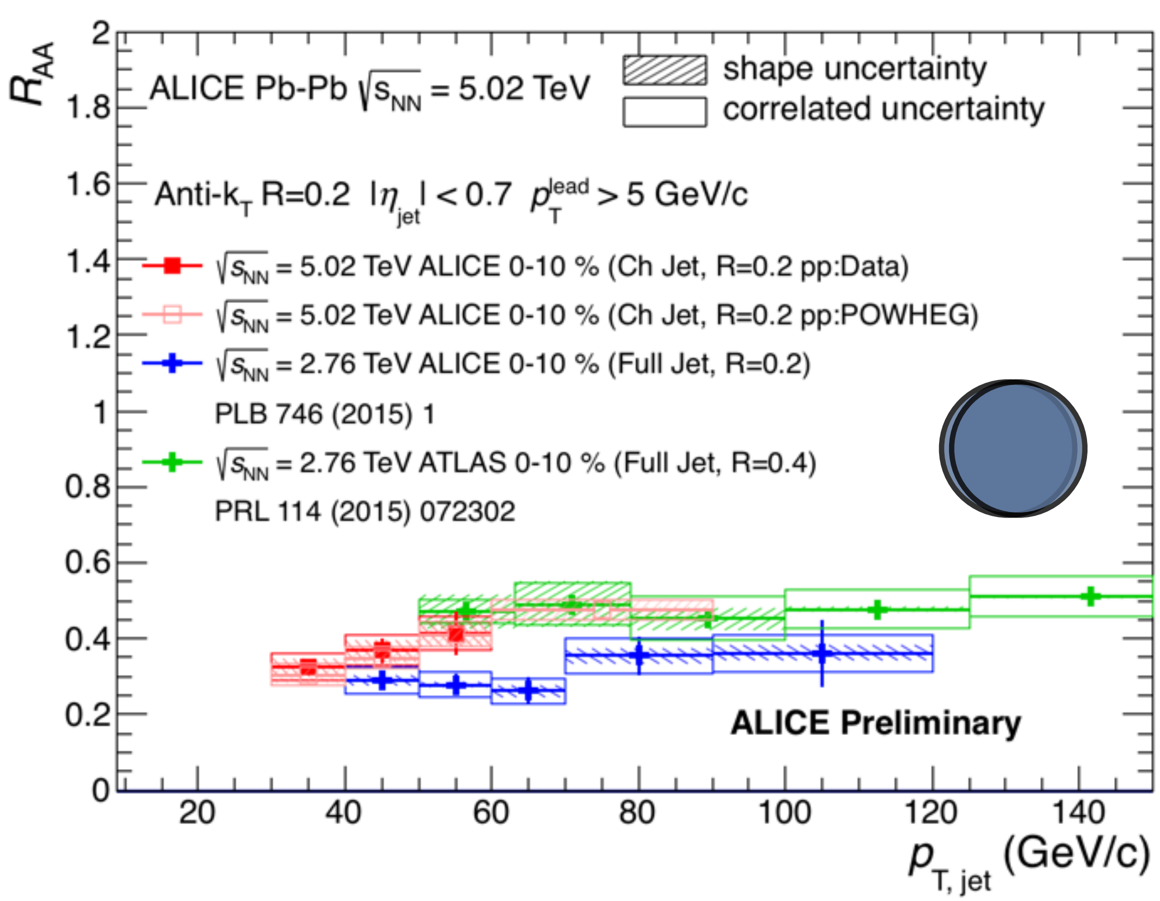


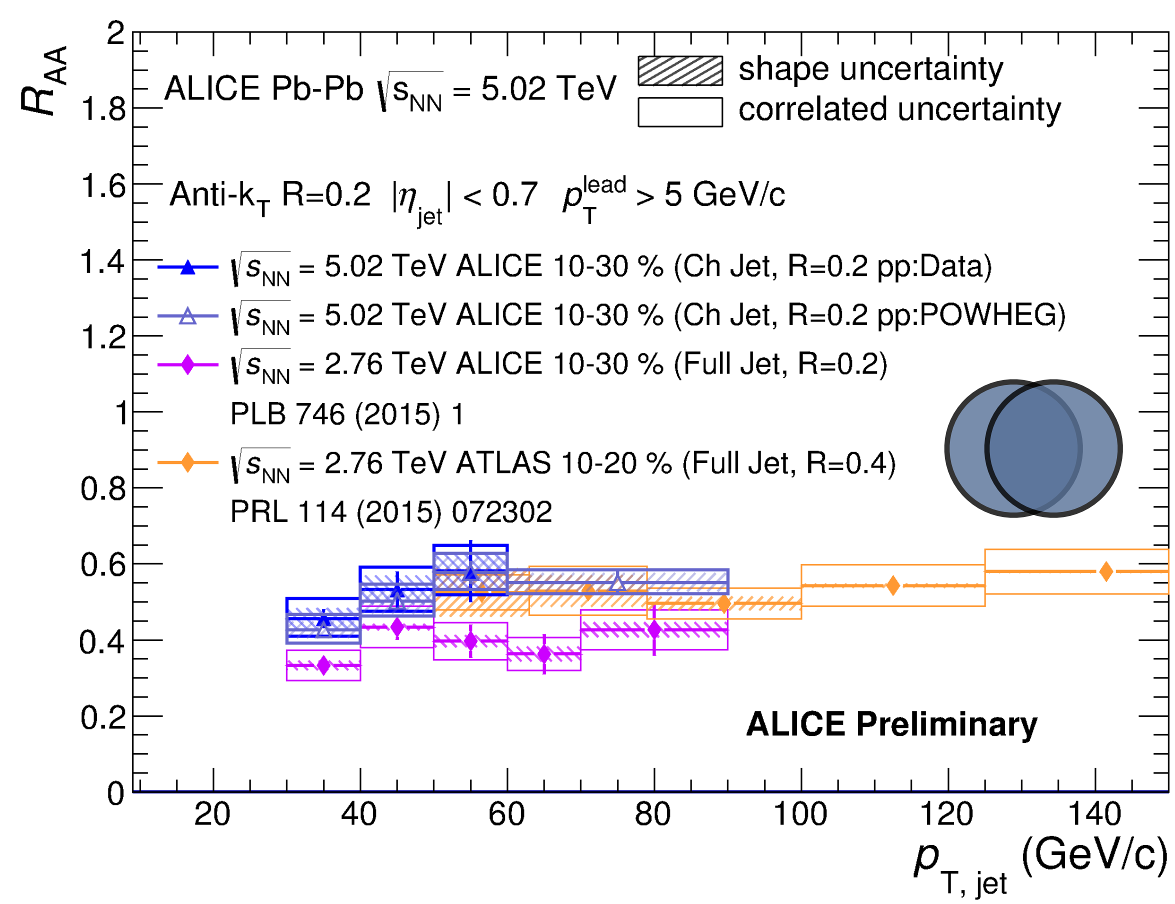


Nuclear Modification Factor : R_{AA}

- R_{AA} (5.02TeV) is comparable to R_{AA} (2.76TeV)
  - denser medium⇒stronger jet suppression ⇒smaller R_{AA}
  - harder collision⇒flatter jet spectrum ⇒larger R_{AA}

☑ effect of flattening of the spectrum compensated by stronger jet suppression ?





ALI-PREL-114190

Summary

- Jet Quenching
  - Attenuation of jets in central Heavy-Ion collisions
  - -> jets are good probe to access QGP property
- **development & commissioning of ALICE-EMCals' L1 trigger system**
  - Jet/photon triggers working well in Run2
  - achieves expected performance
- **Inclusive charged jets R_{AA} in $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb Collisions**
  - Jet measurement at highest energy in the world.
  - strong suppression at central collisions (~0.4 at 0-10 centrality)
  - suppression weaken at peripheral collisions (~0.8 at 50-90% centrality)
  - comparable to R_{AA} in $\sqrt{s_{NN}}$ = 2.76 TeV
  - -> balance b/w spectrum flattering and stronger suppression?

Outlook

- using ~5% of full statistics
- analysis with full statistics
  - kinematic reach : 90 GeV/c -> 130 GeV/c at 0-10% centrality
- evaluate jet radius dependence
  - jet shape (broadning)