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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Introduction

LHC-ALICE experiment

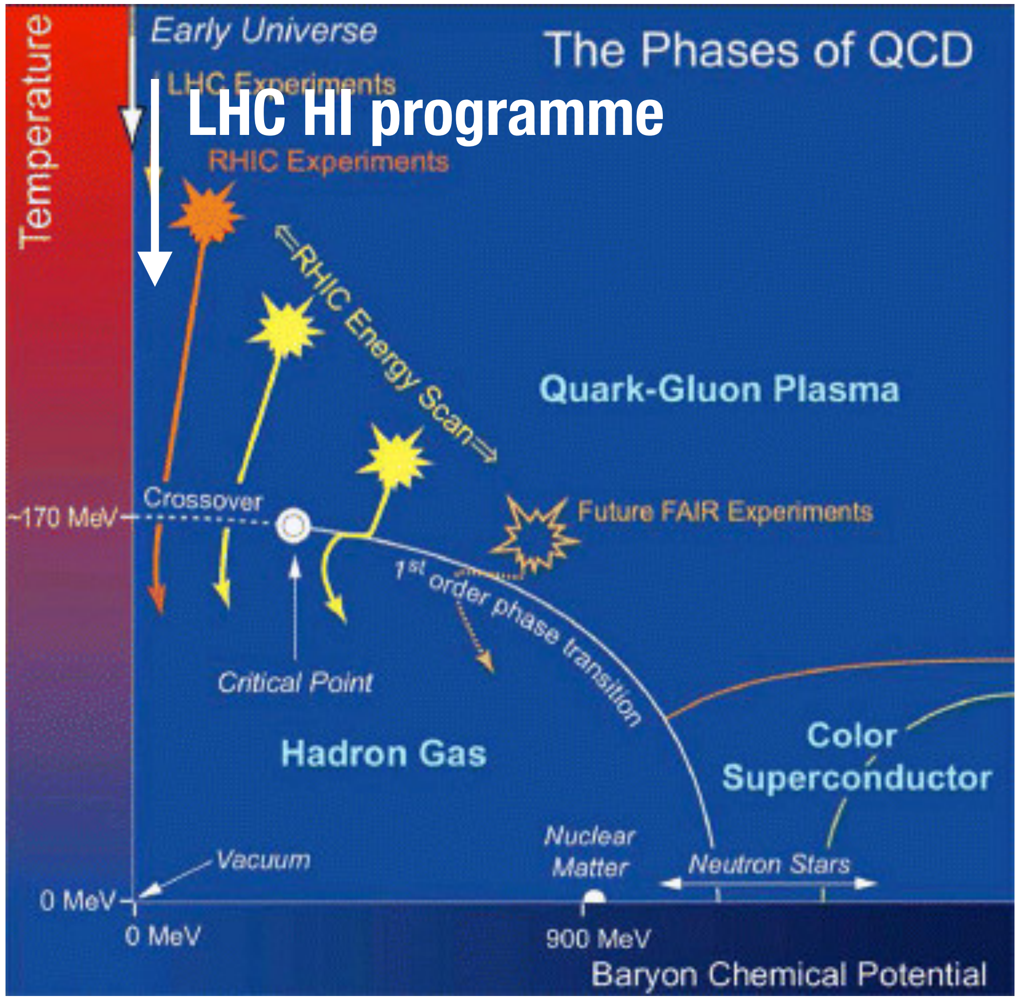
EMCAL L1 trigger development

Jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions

Results

Quark Gluon Plasma (QGP)

- ☑ Hot & dense colour thermalised QCD matter
- ☑ Deconfined state of quarks and gluons
  - prevailing at the early Universe ~1μs after big bang
- ☑ Theoretically inferred through lattice gauge simulations of QCD
  - T_c~154(9) MeV , ε_c~0.18-0.5 GeV/fm^3



Pramana. 84. 773-786

How to Create QGP?

☑ **Ultra-Relativistic Heavy Ion Collision**

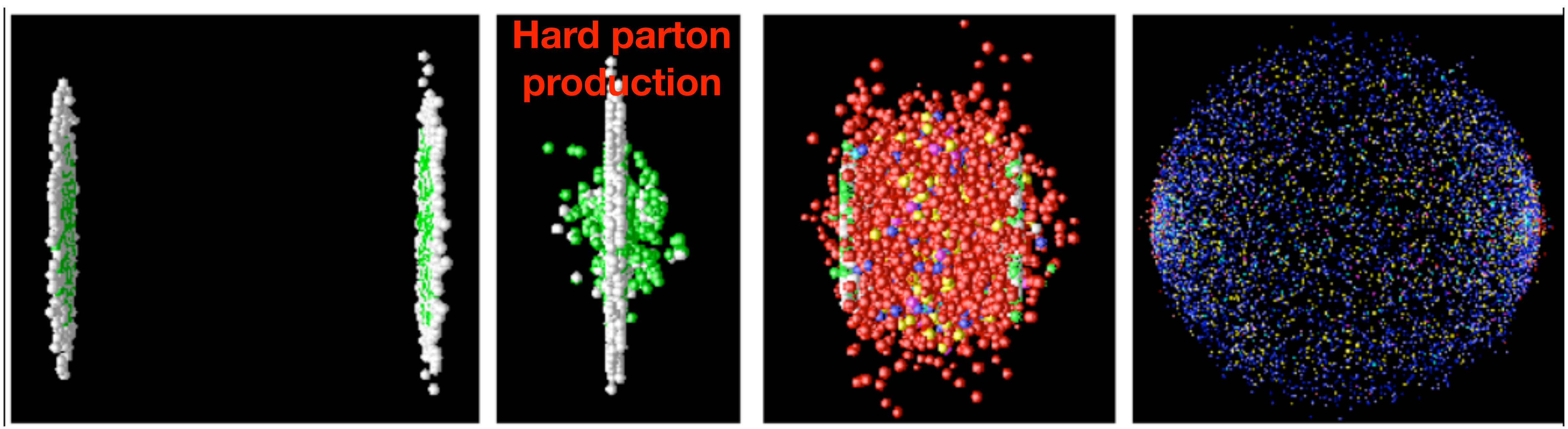
- high-energy nucleus-nucleus collisions at particle accelerators (RHIC, LHC)
- create QGP for a finite time to quantitatively map out the QCD phase diagram

☑ **Hard Probes**

- produced by high-p_T QCD process
- initial hard parton scattering
- "Jets"

☑ **Soft Probes**

- bulk of created particles
- dominant at low-p_T



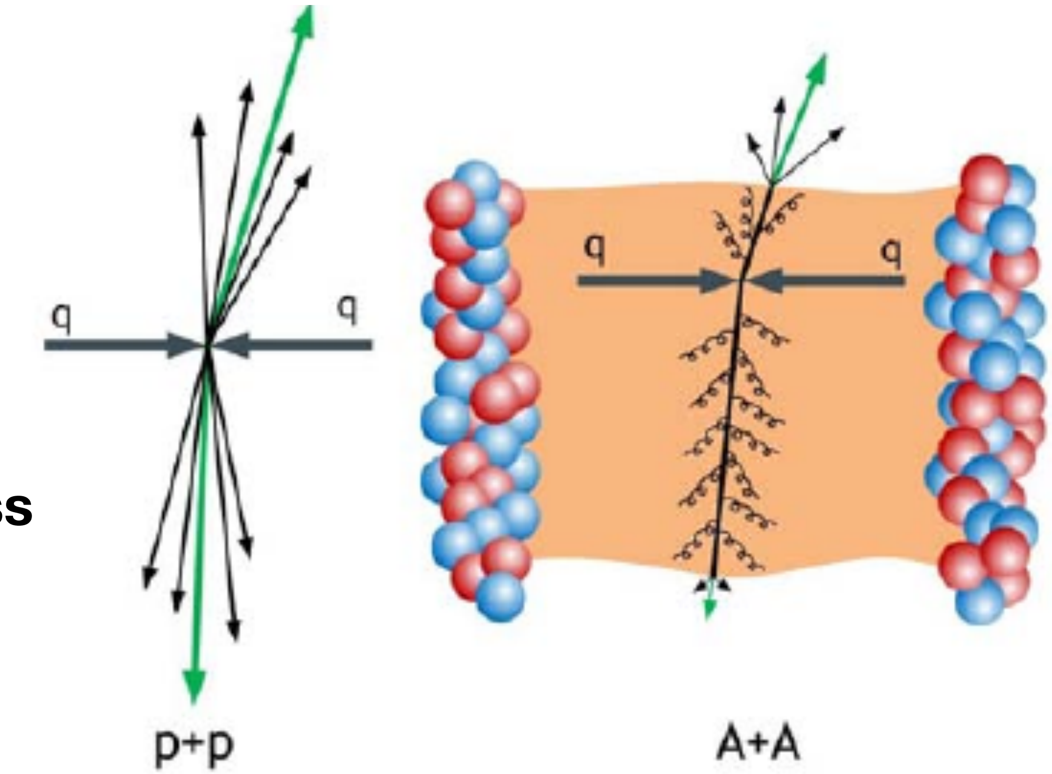
before Collision | QGP Phase | Hadron Phase

Hard Probes of the QGP : Jets

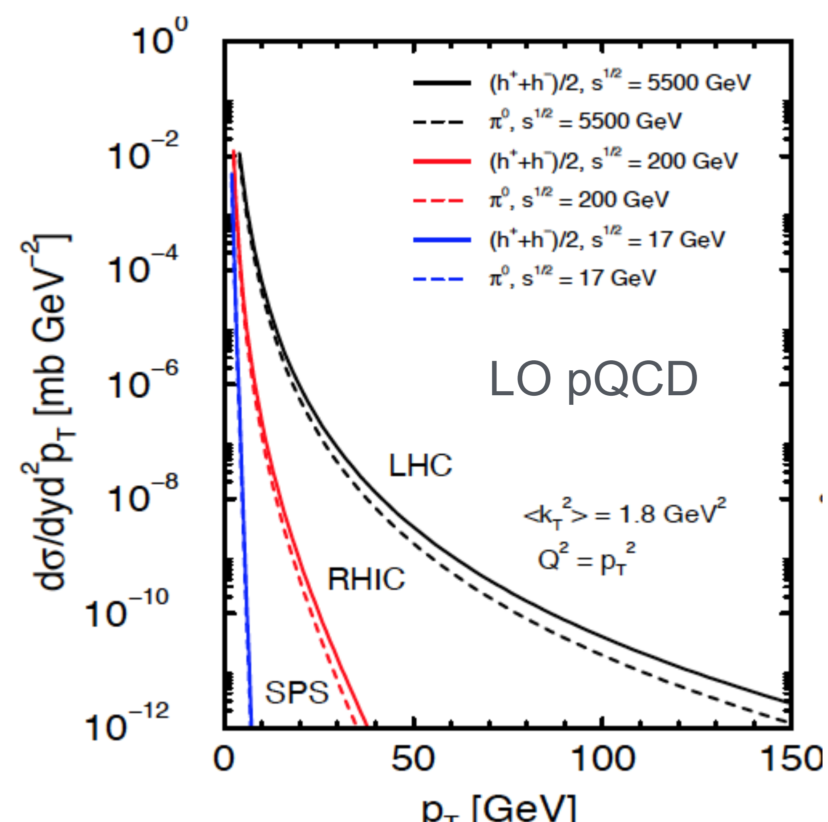
Jet Quenching

☑ partons' energy loss in the QGP

- Energy attenuation/disappearance or shape modification of observed Jets
- **evaluation of these modifications allows to assess QGP properties**



1. **Self-produced probes**
   - short QGP lifetime (~10^{-23} s)
2. **Probe the small system**
   - high-Q^2 process
3. **Probe the entire medium evolution**
   - occur at early stage : $\tau \sim 1/Q$
4. **Well calibrated probes**
   - production rate calculable within pQCD
5. **Copious production at the LHC**
6. **Access to initial parton kinematics**
   - via jet reconstruction

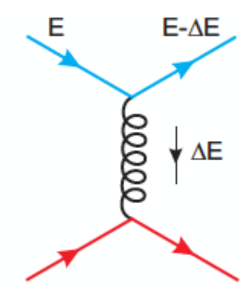


hep-ph/0212109

Parton Energy Loss in QGP

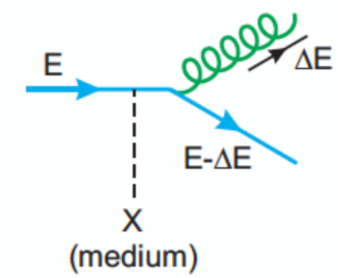
- ☑ Jet-medium interaction
  - Collisional energy loss
  - Radiative energy loss
  - Which is dominant for energy loss in QGP ?

- ☑ parton energy loss depends on
  - parton specie
  - parton momentum
  - path length
  - collision geometry
  - beam energy



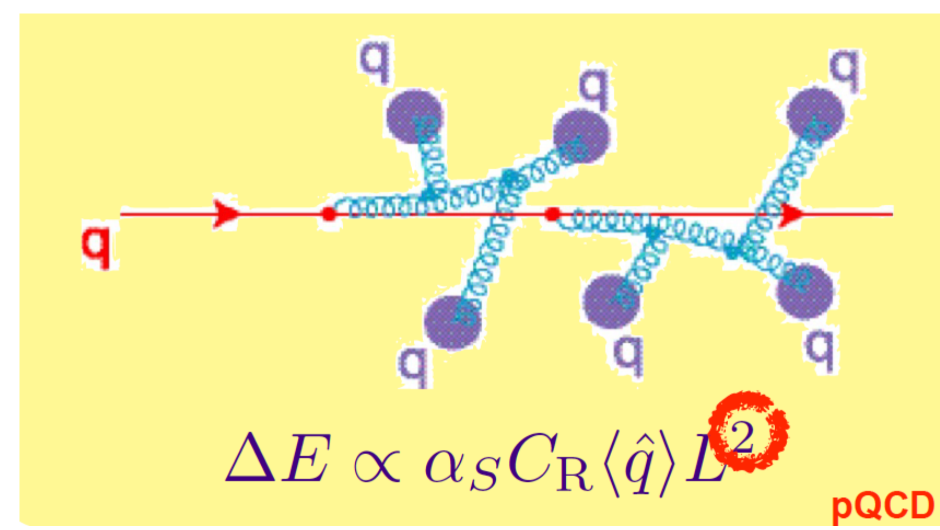
Collisional

$$\Delta E \propto \ell^1$$



Radiative

$$\Delta E \propto \ell^2$$

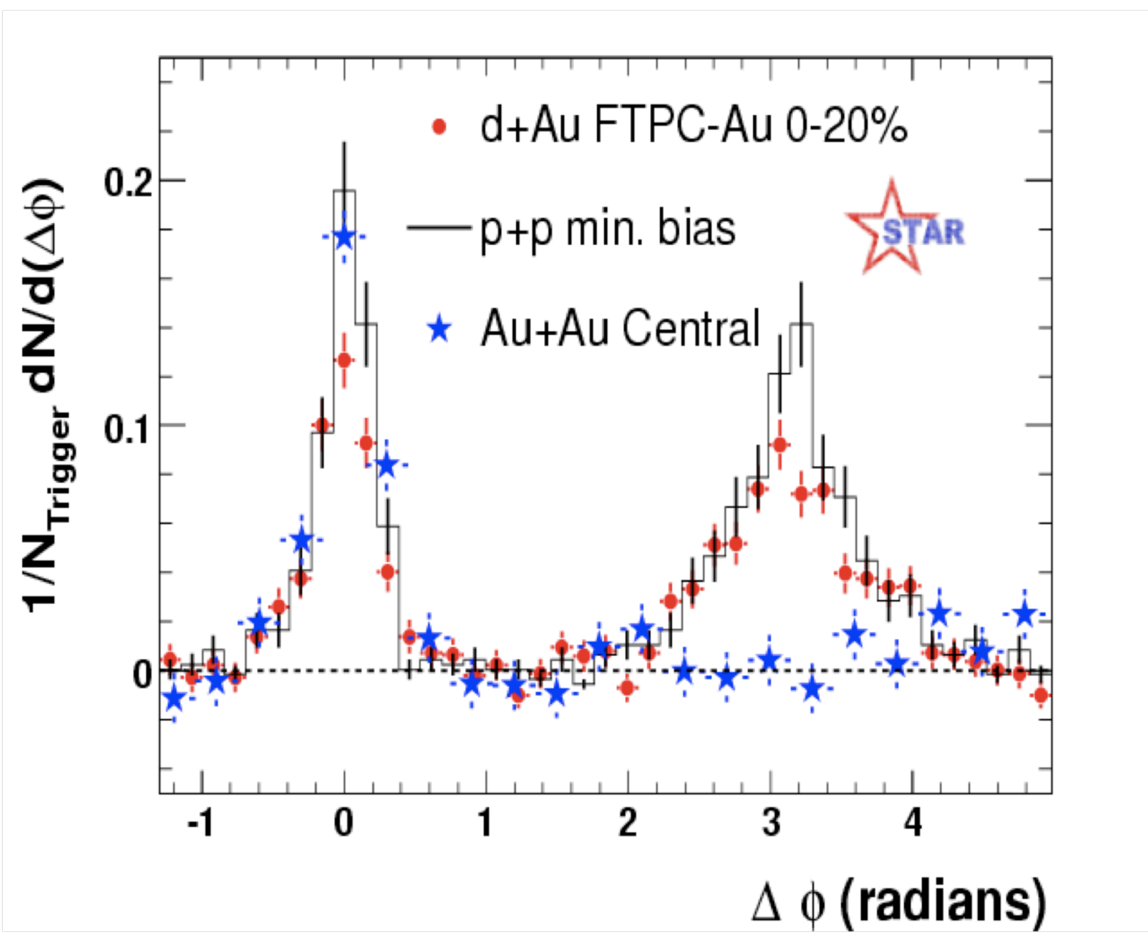


ΔE measurement provides information on QGP properties
(medium temperature, gluon density, parton-medium coupling strength…)

Experimental Results of Jet Quenching

☑ **Angular correlation of high-p_T hadrons**

- disappearance of away side peak in central Heavy-Ion collisions (Au-Au , $\sqrt{s_{NN}}$ = 200 GeV)
- fragmentation of quenched partons



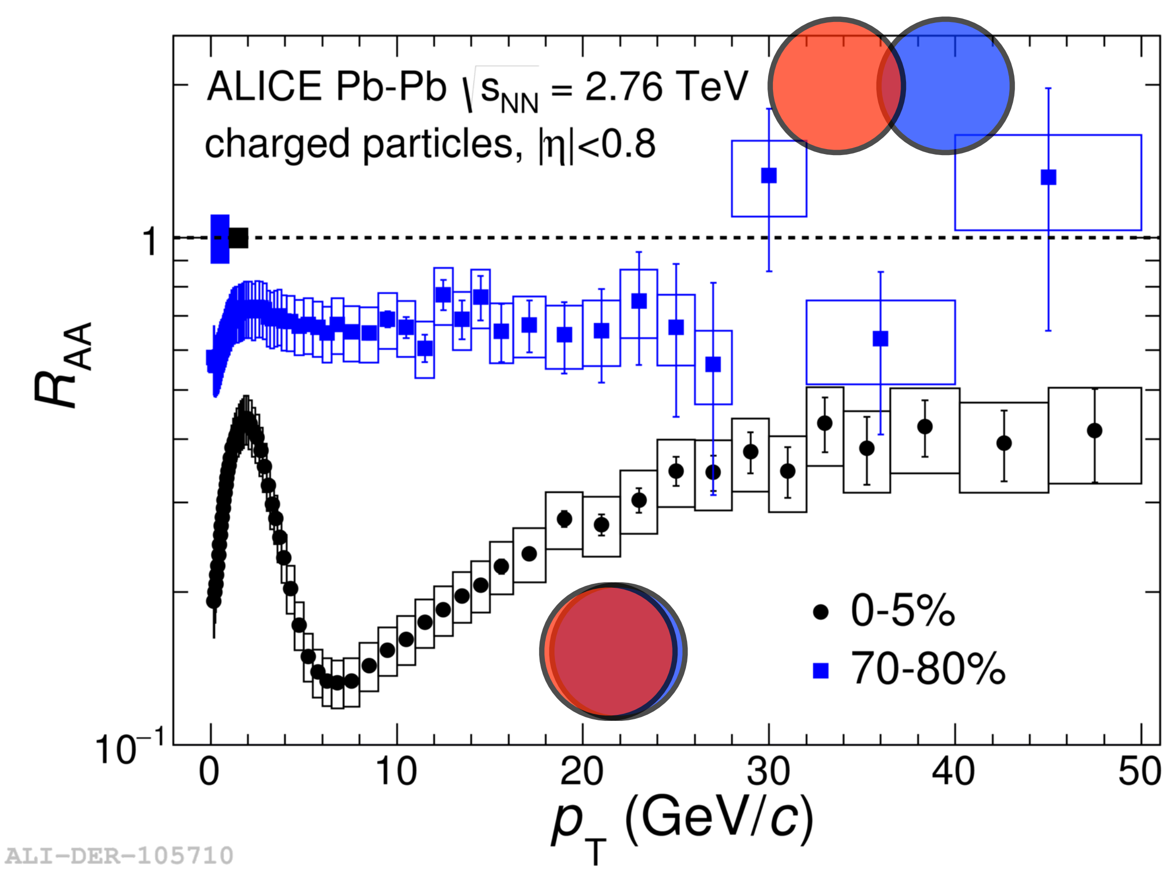
$4 < p_T^{trig}$ [GeV/c] < 6
$2 < p_T^{asso}$ [GeV/c] $< p_T^{trig}$

PRL 91, 072304 (2003)

☑ **Nuclear modification factor : R_{AA}**

$$R_{AA} = \frac{\text{particle/jet yield in AA}}{\text{particle/jet yield in pp}}$$

- high-p_T hadrons = leading constituent of jet
- strong suppression : R_{AA} ~ 0.1 to 0.4



PLB 720 (2013) 52

Motivation

- ☑ Jet Quenching
  - Parton energy loss through parton-medium interaction
    - Particle-medium coupling strength, medium temperature, medium density
- ☑ Jet Measurement
  - Reconstructed jet is powerful probe for QGP study
    - Smaller surface bias than single particle measurement
    - Direct comparison to theory due to recovering initial parton kinematics
  - Jet-by-Jet measurement is enabled in LHC energy
    - Development of jet reconstruction technique
    - Copious production of high-momentum jets
- ☑ **Jet measurement at $\sqrt{s_{NN}}$ = 5.02 TeV in LHC-ALICE**
  - First fully reconstructed jet measurement at highest centre of mass energy
    - Extreme condition of the medium in the world
  - Complementary measurement at low jet p_T region lower than 100 GeV/c.
  - Centre-of-mass energy dependence, path length dependence of jet energy loss

Introduction

LHC-ALICE experiment

EMCAL L1 trigger development

Jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions

Results

Large Hadron Collider

- Largest and most powerful particle collider built by CERN

Run1 (2009 ~ 2013)

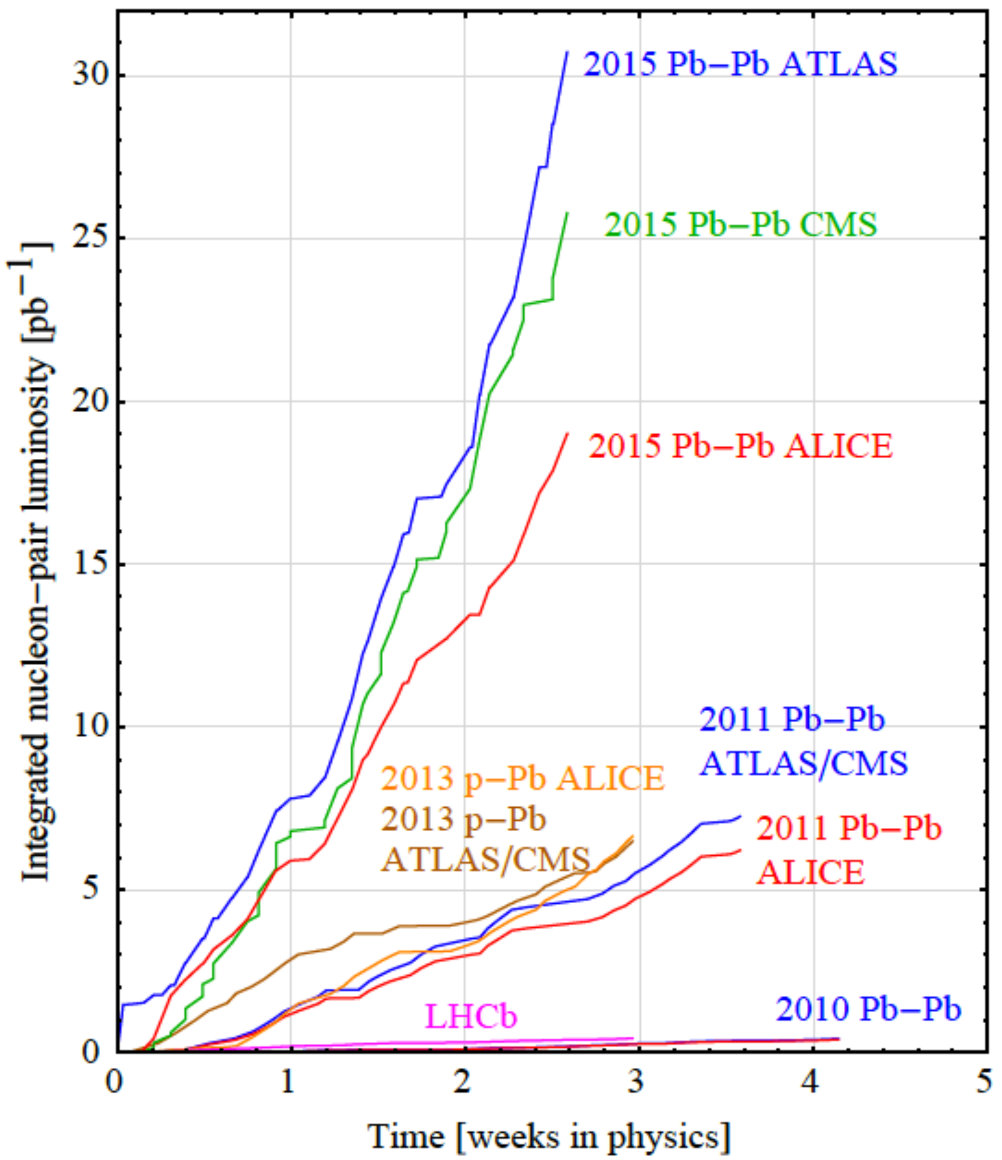
- pp : $\sqrt{s}$ = 2.76, 7, 8 TeV
- Pb-Pb : $\sqrt{s_{NN}}$ = 2.76 TeV
- p-Pb : $\sqrt{s_{NN}}$ = 5.02 TeV

Long Shutdown 1

upgrade on beam energy and luminosity

Run2 (2015 ~ 2018)

- pp : $\sqrt{s}$ = 5.02 TeV, 13 TeV
- Pb-Pb : $\sqrt{s_{NN}}$ = 5.02 TeV
- p-Pb : $\sqrt{s_{NN}}$ = 8 TeV



Jet Measurement in LHC-ALICE

Charged Particles : |η| < 0.9, 0<φ<2π

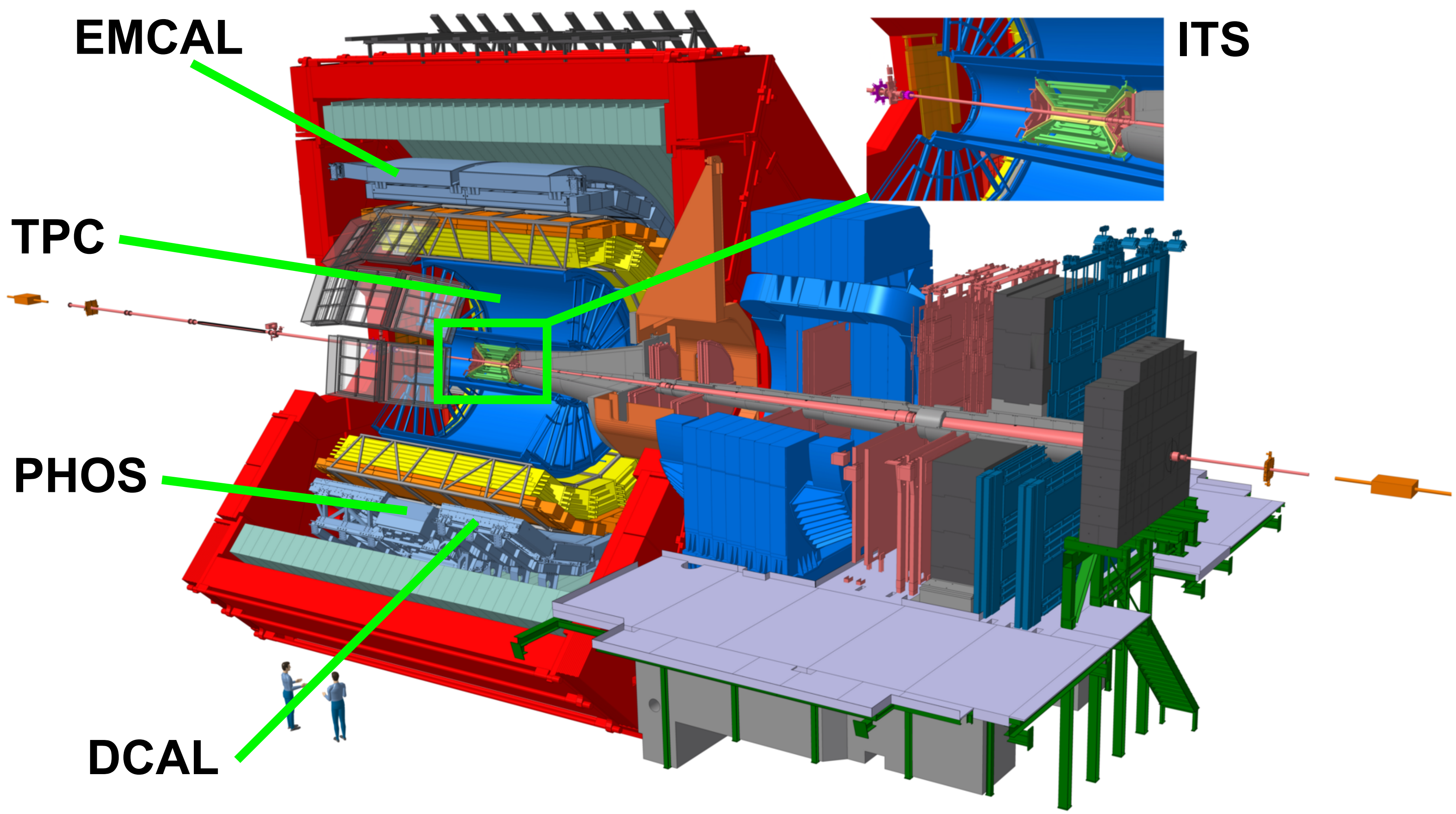
- ☑ **ITS** : silicon tracking detector
- ☑ **TPC** : time projection chamber

⇒ Charged Jet

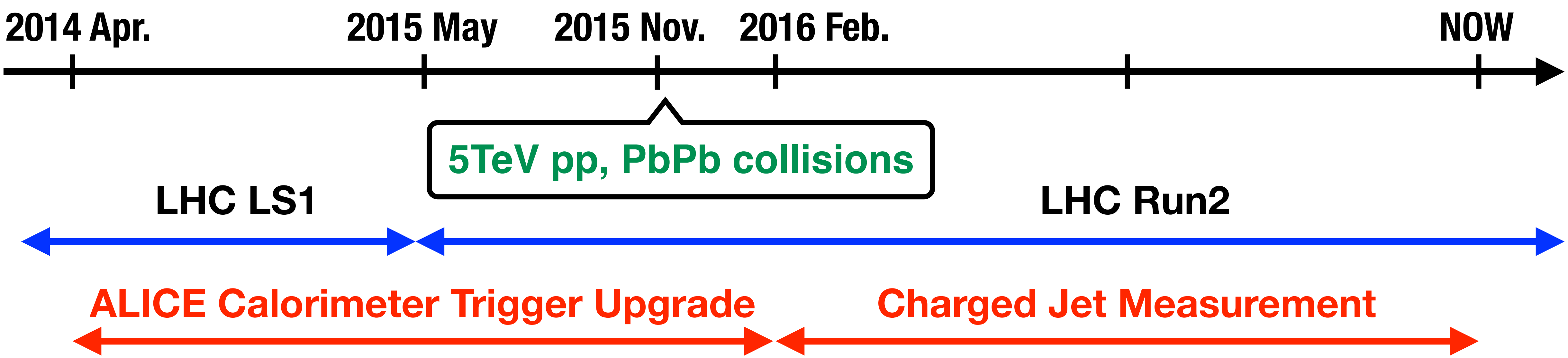
Neutral particles : |η| < 0.7

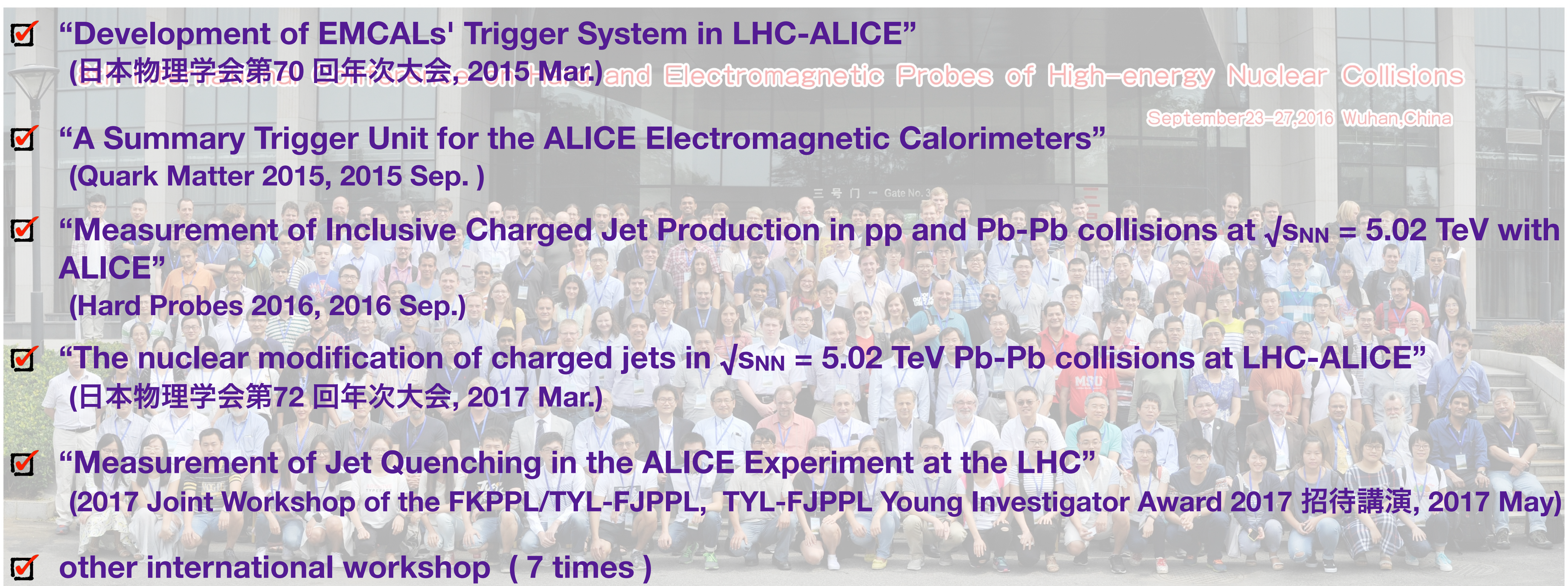
- ☑ **EMCAL, (DCAL** : Run2 from 2015-)
  - Pb-Scintillator sampling calorimeter
- ☑ **PHOS**
  - lead-tungsten crystal (PWO) based calorimeter

⇒ Charged+Neutral = Full Jet



My PhD Activity





- ☑ "Development of EMCALs' Trigger System in LHC-ALICE"
  (日本物理学会第70 回年次大会, 2015 Mar.)
- ☑ "A Summary Trigger Unit for the ALICE Electromagnetic Calorimeters"
  (Quark Matter 2015, 2015 Sep.)
- ☑ "Measurement of Inclusive Charged Jet Production in pp and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE"
  (Hard Probes 2016, 2016 Sep.)
- ☑ "The nuclear modification of charged jets in $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions at LHC-ALICE"
  (日本物理学会第72 回年次大会, 2017 Mar.)
- ☑ "Measurement of Jet Quenching in the ALICE Experiment at the LHC"
  (2017 Joint Workshop of the FKPPL/TYL-FJPPL, TYL-FJPPL Young Investigator Award 2017 招待講演, 2017 May)
- ☑ other international workshop (7 times)

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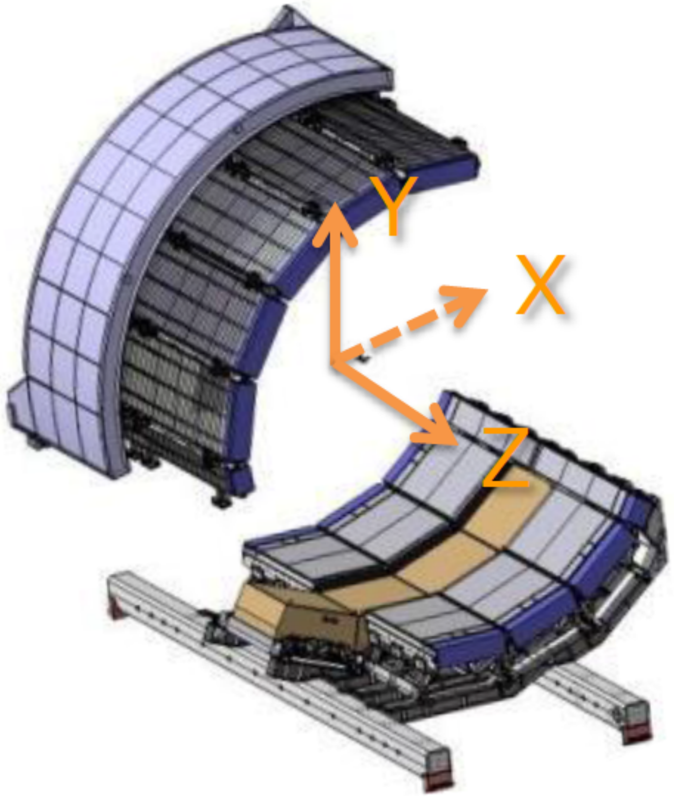
Results

ALICE electromagnetic calorimeters

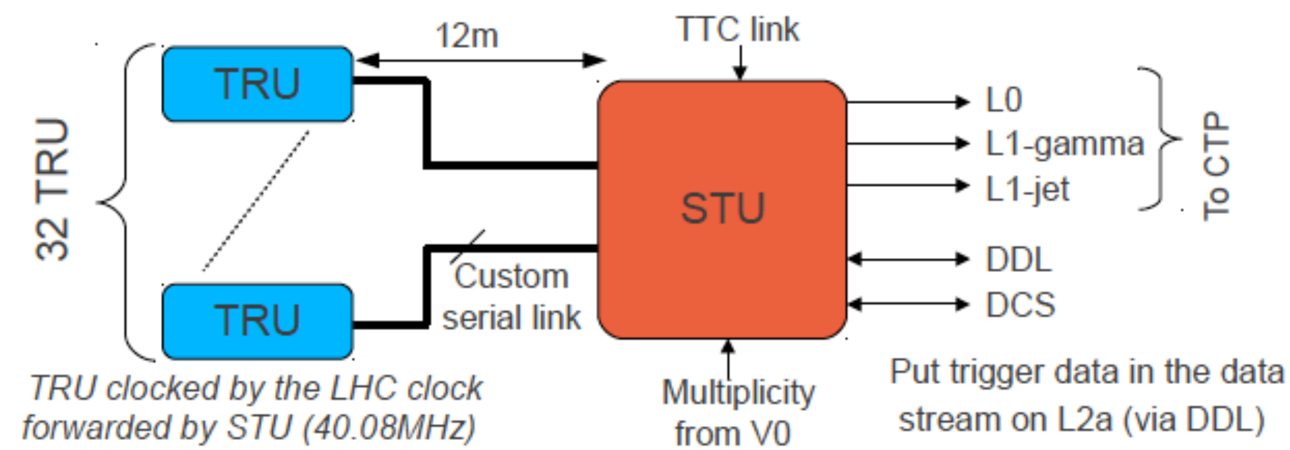
- EMCAL and DCAL
  - large acceptance coverage
    - to improve jet energy resolution by adding neutral constituents
  - DCAL is installed at the opposite side of EMCAL in azimuth
    - for the correlation study of back-to-back jets
- PHOS
  - high granularity and high energy resolution
  - focus on direct photon and π^0 measurement with very high energy

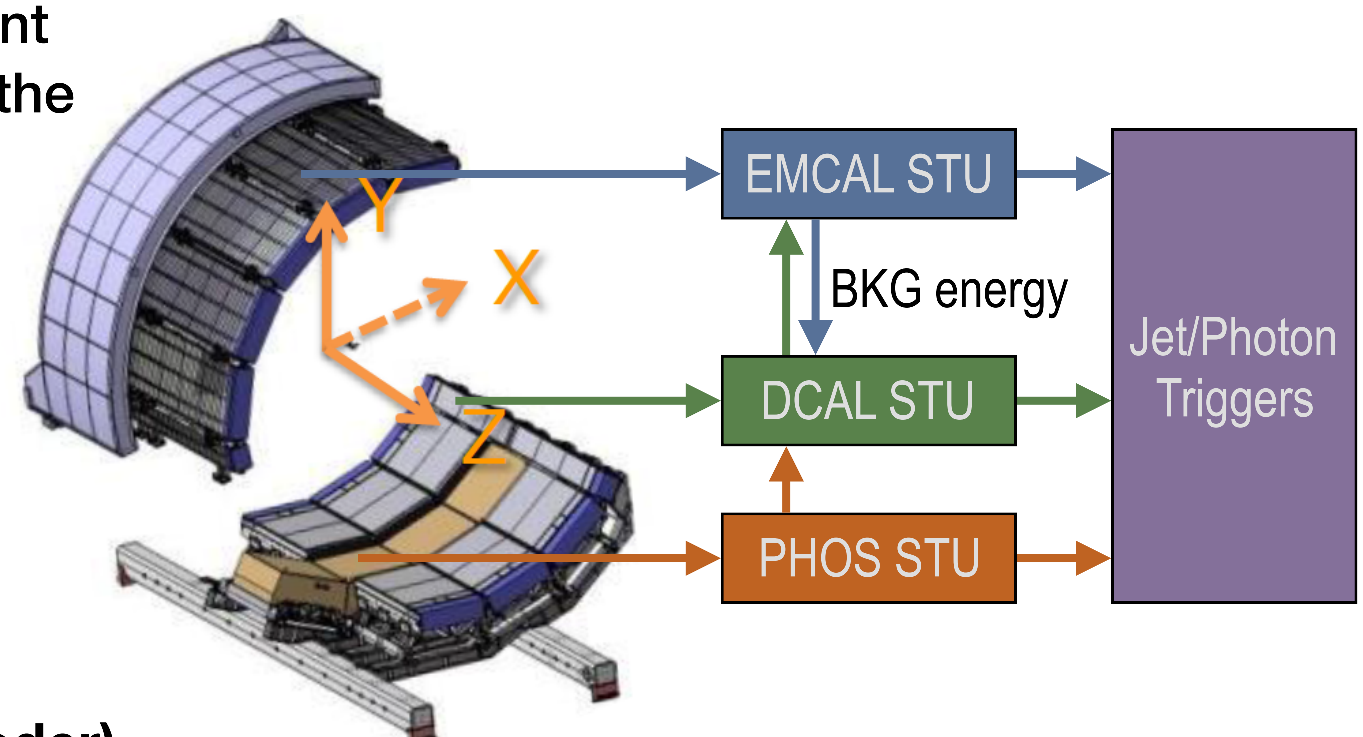
- As a trigger detector
  - Level-0 (fast but simple, low threshold) and Level-1
  - EMCAL and DCAL : high energy jets and photons
  - PHOS : high energy photon



ALICE Calorimeter Trigger Upgrade

- **Level-1 trigger upgrade during LS1**
  - to select events with large energy deposit within these calorimeters
  - produced by Summary Trigger Unit (STU)
- **Firmware development of STU**
  - new firmware : DCAL and PHOS
  - NEW trigger algorithm
    - pp, p-Pb : constant threshold
    - Pb-Pb : soft background event-by-event subtraction in EMCAL estimated from the median of jet patch energies in DCAL (and vice versa)
  - implementation of STU busy signal
  - fit for new data format
- **Commissioning & QA**
- **DCS software upgrade**
- **Offline code development (mapping, decoder)**

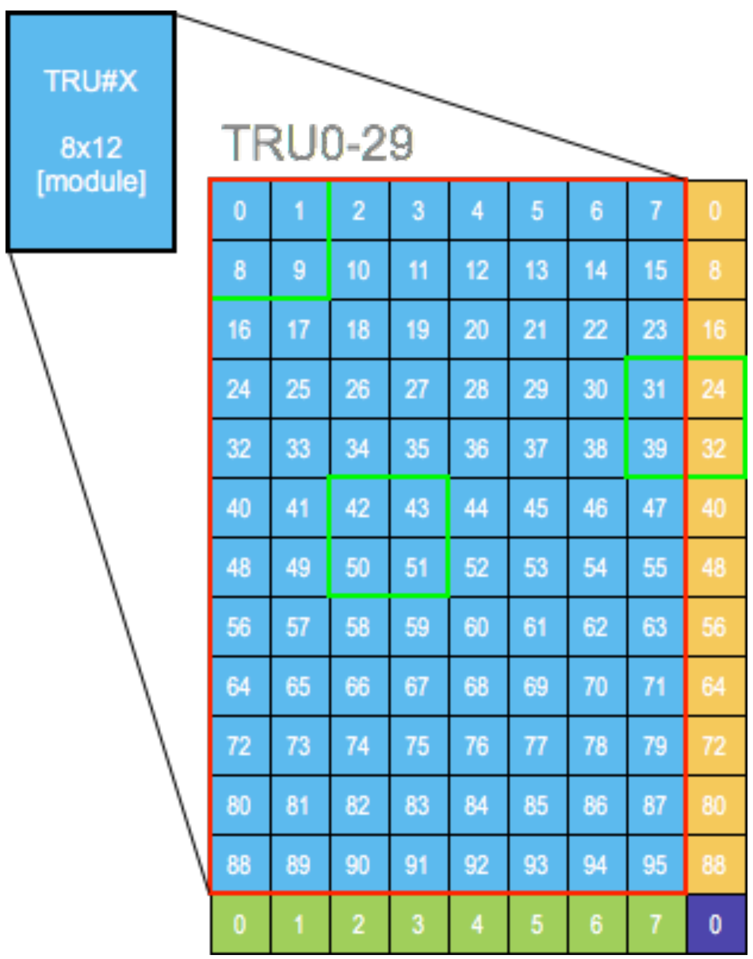




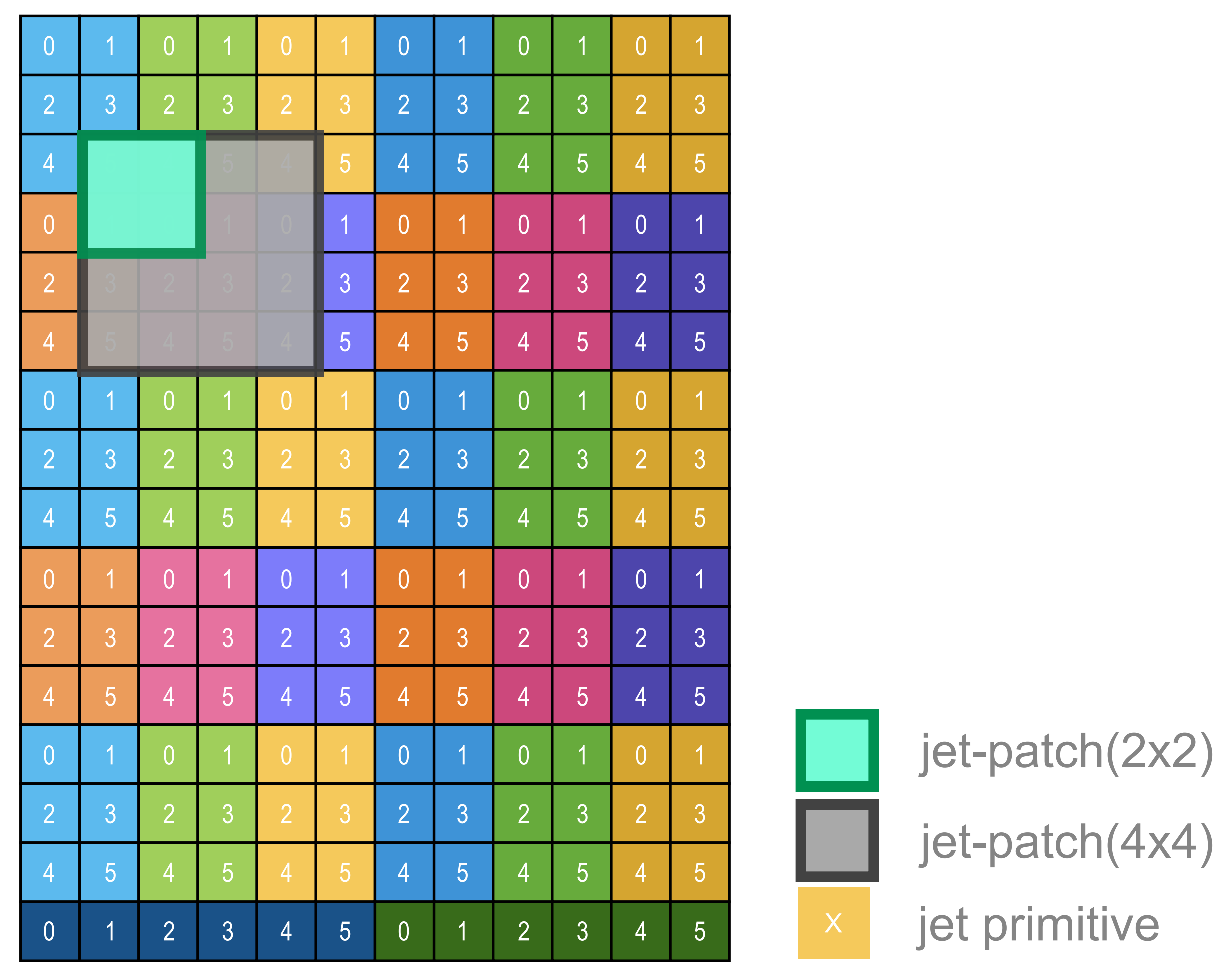
L1-photon and L1-Jet Algorithm

- Minimum unit for trigger calculation : “FastOR”

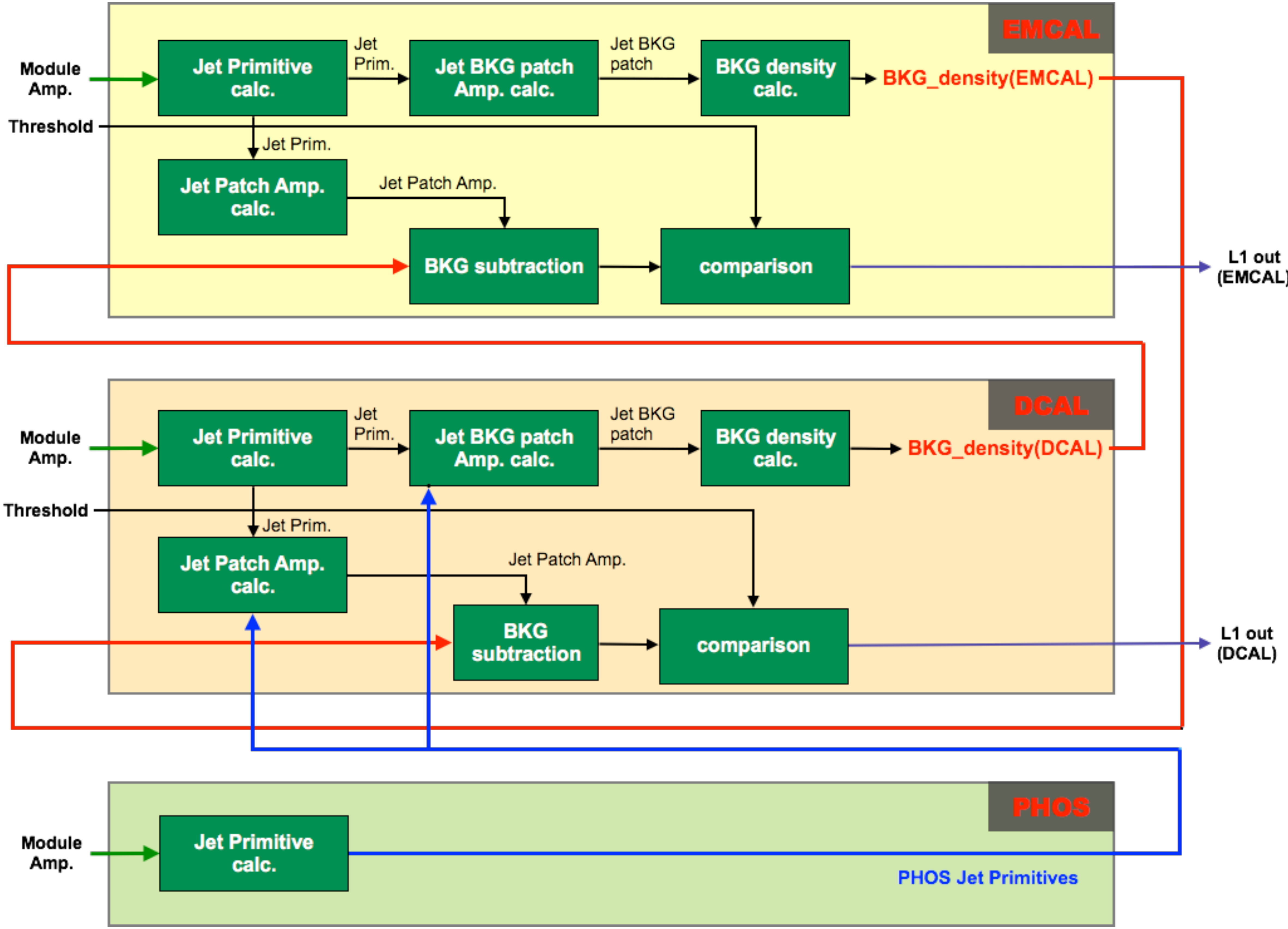
- L1-photon
  - 2x2 FastOR/patch
  - FastOR basis sliding window



- L1-Jet
  - 8x8 (or 16x16) FastOR/patch
  - Jet primitive (=4x4 FastOR) basis sliding window
  - DCAL+PHOS combined

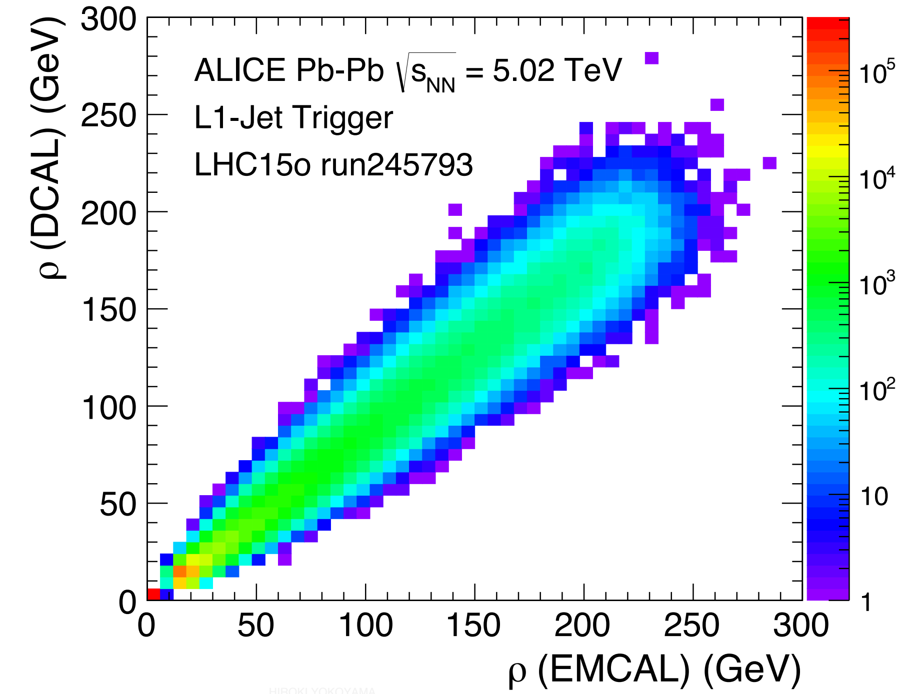


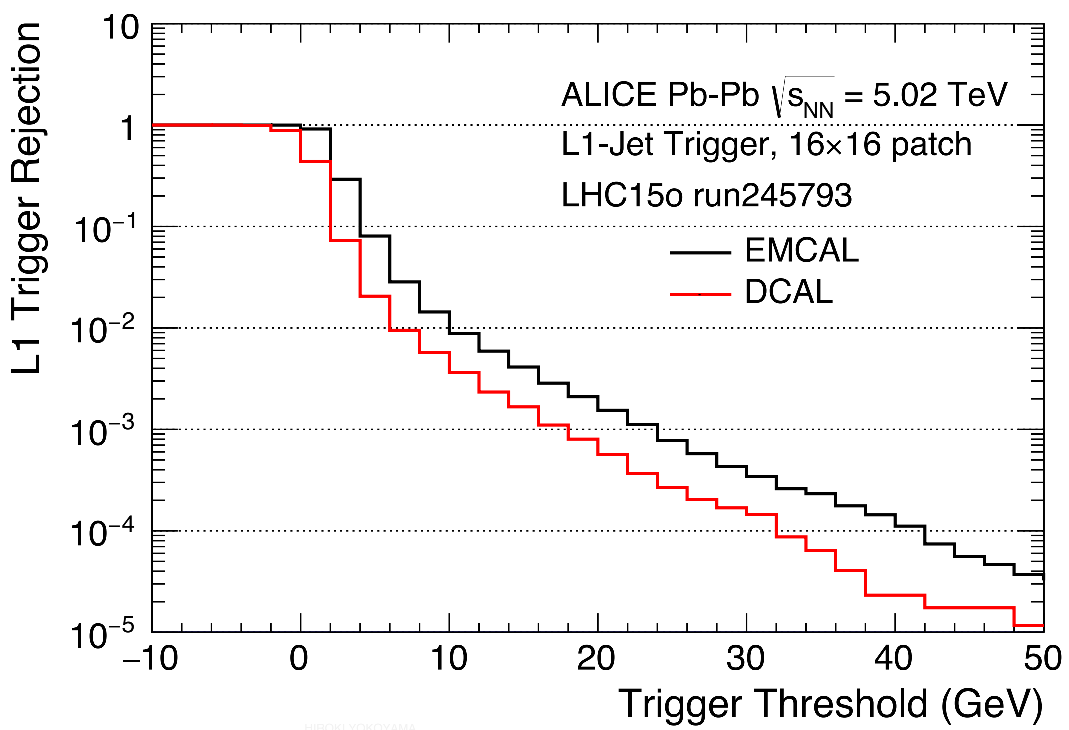
Soft Background Subtraction

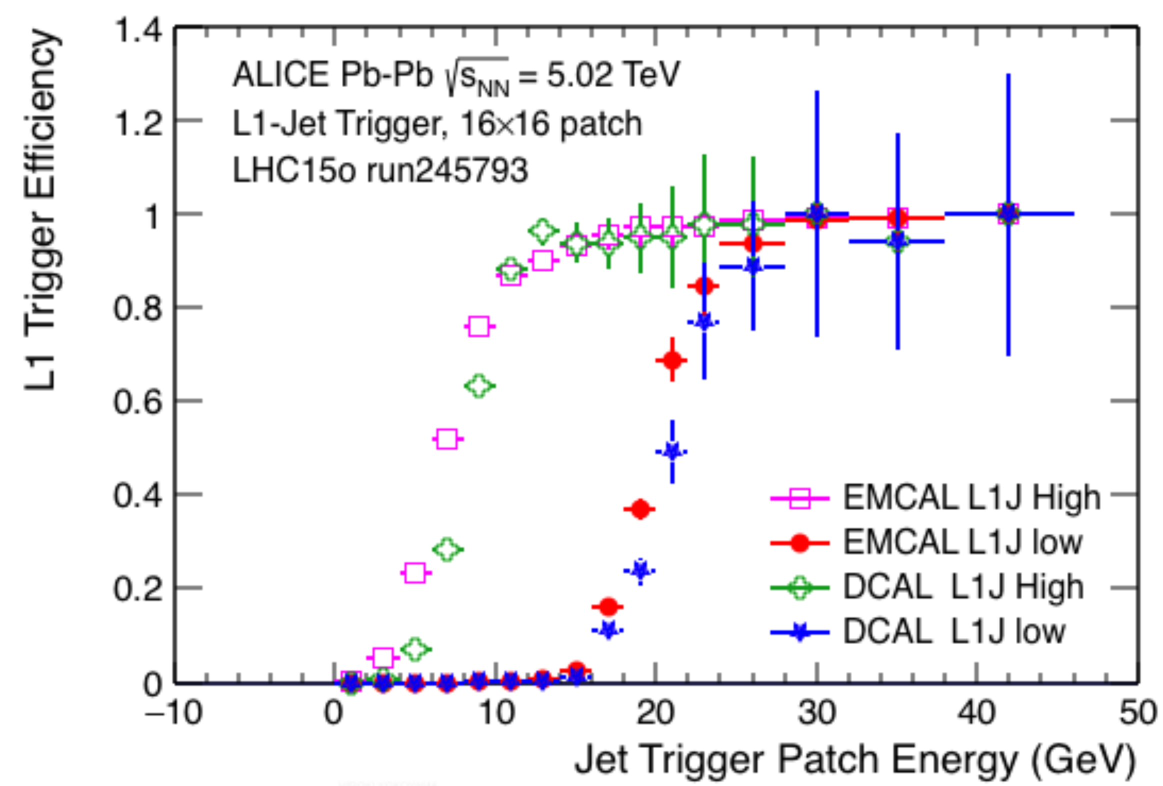


Trigger Performance

- ☑ In operation since 2015 Pb-Pb runs
- ☑ Correlation of estimated BKG densities
  - new BKG communication working
- ☑ Threshold is decided by trigger rejection
- ☑ Trigger turn-on efficiently with different threshold







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Jet measurement with $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions

Results

Analysis Flow

1. Event/Track Selection

Event
- $\sqrt{s_{NN}}$ = 5.02 *TeV*, Pb-Pb
- Min. Bias trigger (3.36M events)
- $|v_Z| < 10$ cm

Charged Particle
- $|\eta| < 0.9$
- $p_T > 0.15$ *GeV/c*
- hybrid track selection

2. Jet Reconstruction
- anti-k_T algorithm
- $R = 0.2$
- $|\eta^{jet}| < 0.7$
- $p_T^{lead} > 5$ *GeV/c*

3. Soft BKG subtraction
- subtract average BKG event-by-event

Average Background Density
- k_T algorithm
- median calculation

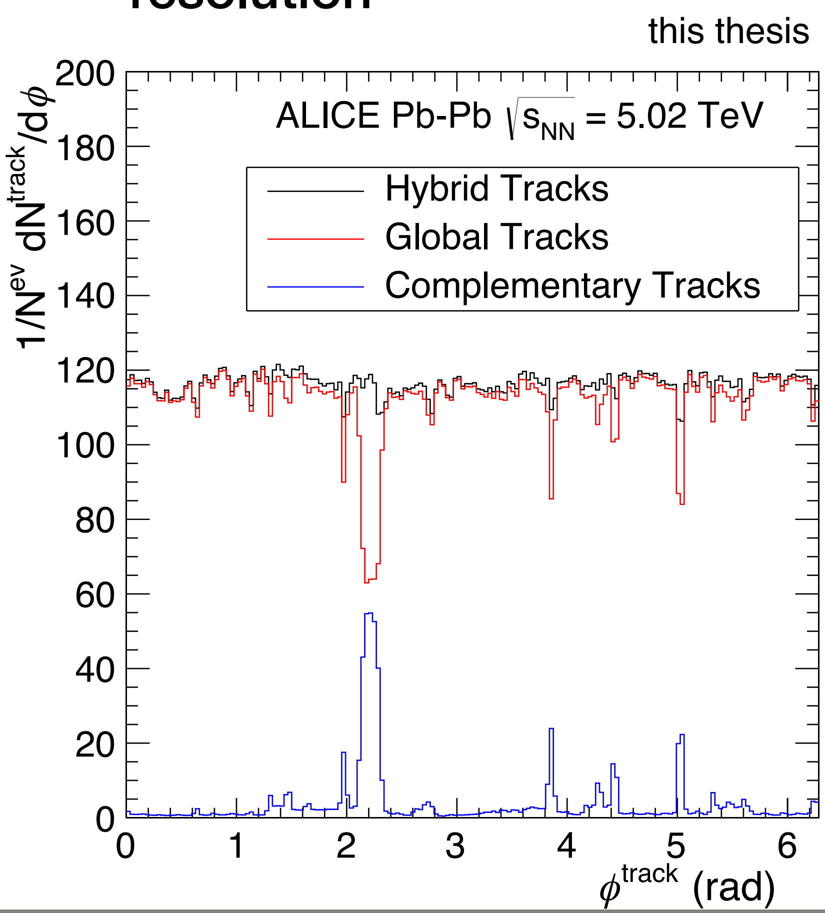
4. Unfolding
- correct detector effects
- correct BKG fluctuation

- SVD unfolding method
- input response of detector effects and BKG fluctuation

5. Inclusive Jet spectrum

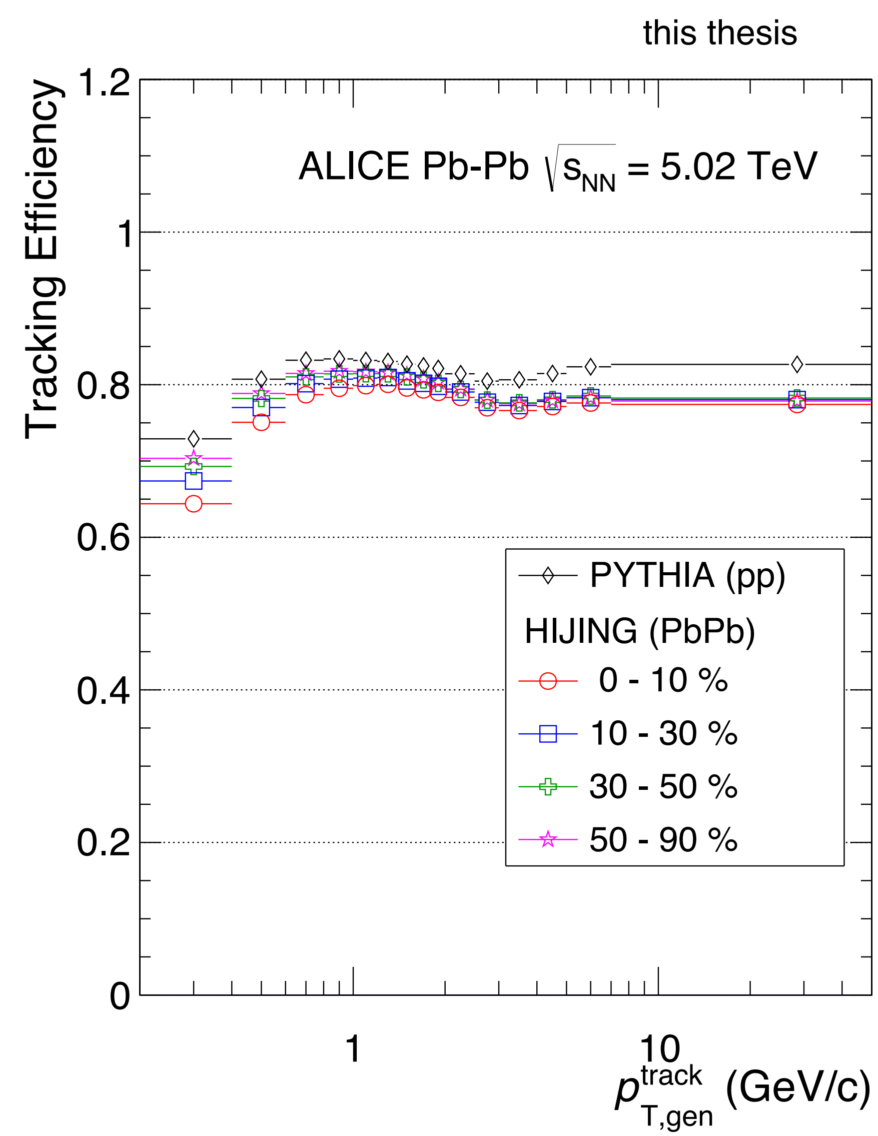
Track Selection

- Hybrid Tracks = Global + Complementary Tracks
  - Global Tracks
    - ITS+TPC with track matching
    - large inefficient region in SPD (inner-most ITS layer)
    - -> non-uniformity of track distribution in ηφ
  - Complementary Tracks
    - without SPD hits
    - primary vertex constraint to improve tracking p_T resolution



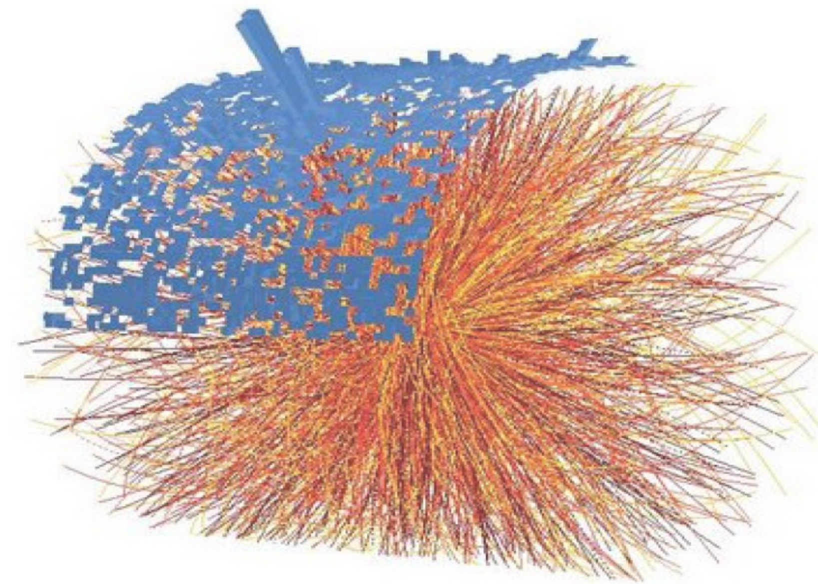
- Tracking Efficiency
  - HIJING+GEANT simulation
  - smaller in the most central collisions due to large multiplicity

$$\varepsilon\left(p_{\mathrm{T}}^{\mathrm{gen}}\right) = \frac{\mathrm{d}N^{\mathrm{rec,matched}}\left(|\eta| < 0.9\right)/\mathrm{d}p_{\mathrm{T}}^{\mathrm{gen}}}{\mathrm{d}N^{\mathrm{gen}}\left(|\eta| < 0.8\right)/\mathrm{d}p_{\mathrm{T}}^{\mathrm{gen}}}$$



Challenge in Heavy-Ion Collisions

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

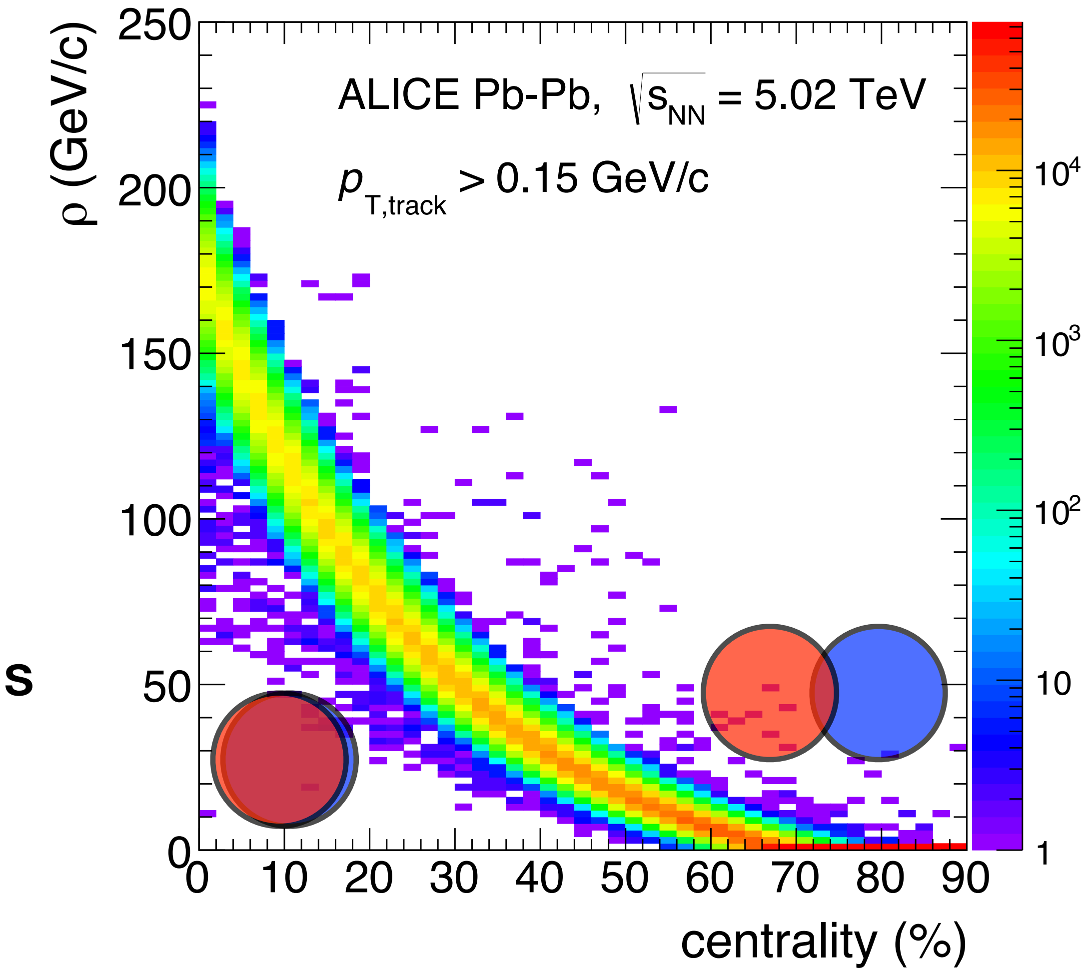


- **Average Background Density : ρ**
  - k_T clusters excluding two leading clusters

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

  - event-by-event calculation
  - ρ ~ 145 *GeV/c* for 0-10%
  - (~18 *GeV/c* for *R*=0.2 jets)

- **Combinatorial Jets Removal**
  - random combination of BKG particles
  - minimum leading constituent p_T^{lead} > 5 *GeV/c* is required

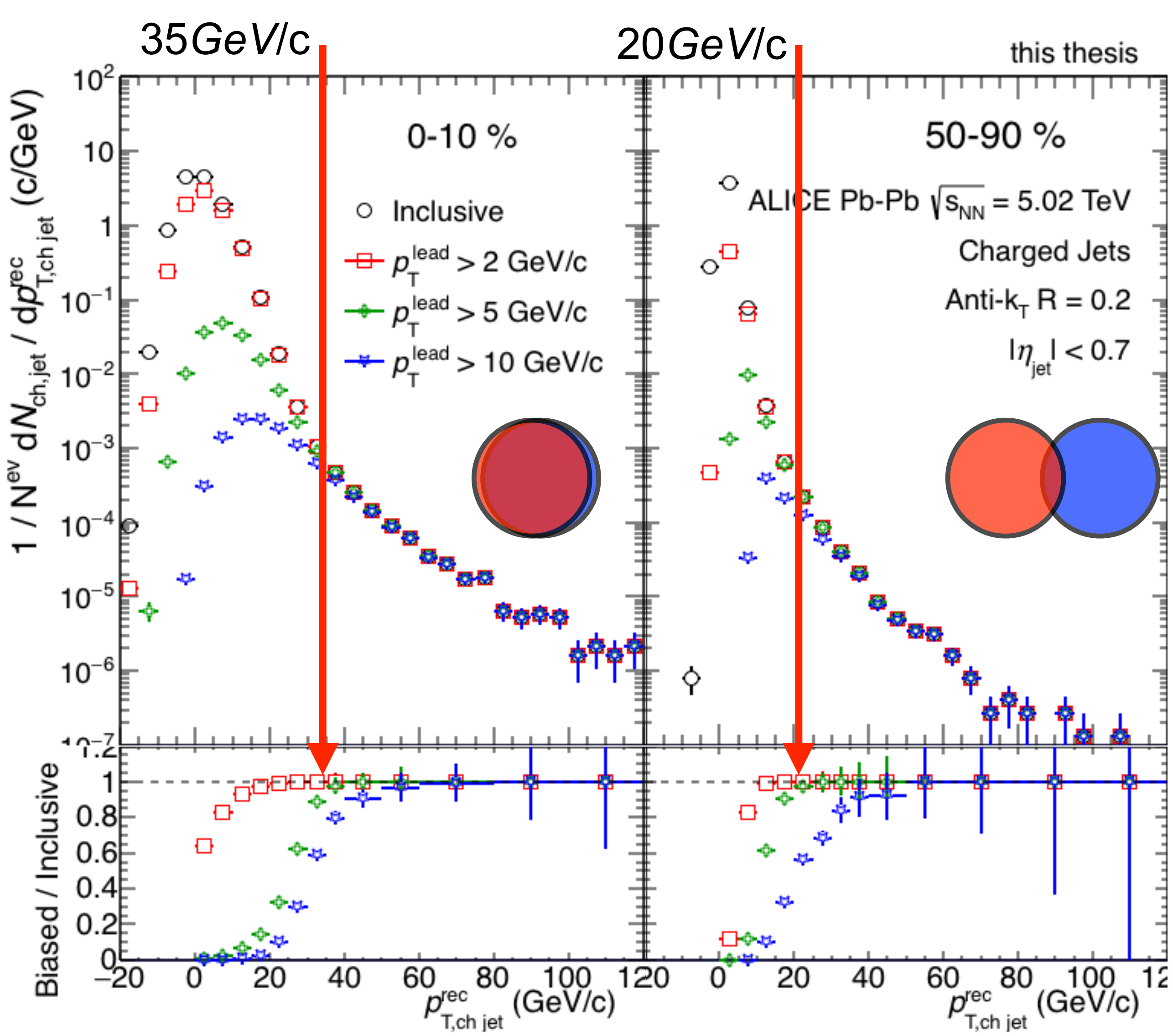


Soft Background Subtraction

- ☑ Average background is subtracted from jet momentum

$$p_{\mathrm{T,jet}}^{\mathrm{rec}} = p_{\mathrm{T,jet}}^{\mathrm{raw}} - \rho\, A_{\mathrm{jet}}$$

- ☑ **Leading track p_T bias**
  - up to 35 *GeV/c* for p_T^{lead} > 5 *GeV/c* (0-10%)
  - smaller in peripheral
    - softer fragmentation in central collisions
    - and/or larger combinatorial Jet

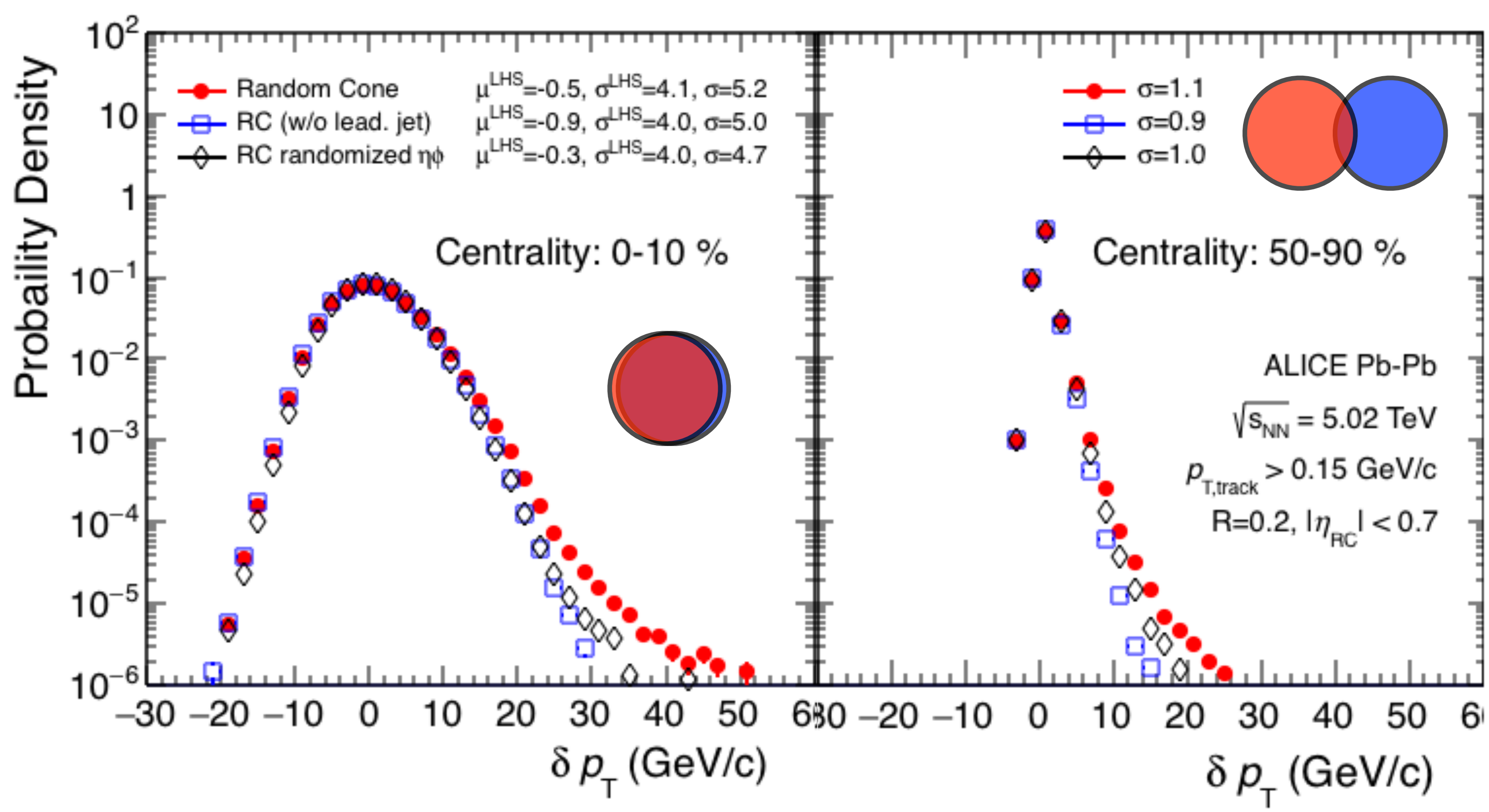


Underlying Event Fluctuation

- **Background fluctuation : δp_T**
  - from region to region around average background
  - **Random Cone method**
  - (exclude leading jet neighbour : $\Delta r > 1.0$)

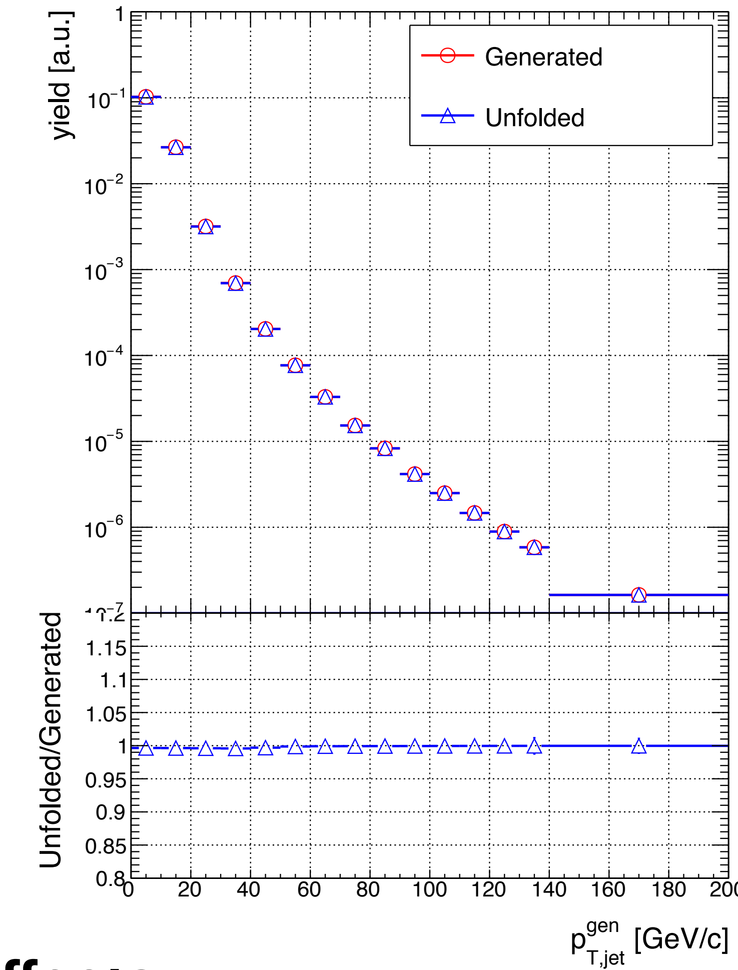
$$\delta p_{\rm T} = \sum_{i}^{RC} p_{{\rm T},i}^{\rm track} - \rho\,\pi R^2$$

- **δp_T width (magnitude of fluctuation)**
  - ~ 5 GeV/c (0-10%)
  - smaller in peripheral



Unfolding

- Measured jet spectrum is distorted by
  - <u>Detector effect</u> (tracking efficiency and p_T resolution)
  - <u>Background fluctuations</u>
  - ⇒ **<u>Unfold measured spectrum to get true spectrum</u>**



<u>Background Fluctuations</u>

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

- M_m: Measured jet spectrum
- $G_{m,d}$: **RM given by δp_T distribution**
- D_d: spectrum corrected for BKG fluctuation

<u>Detector Effects</u>

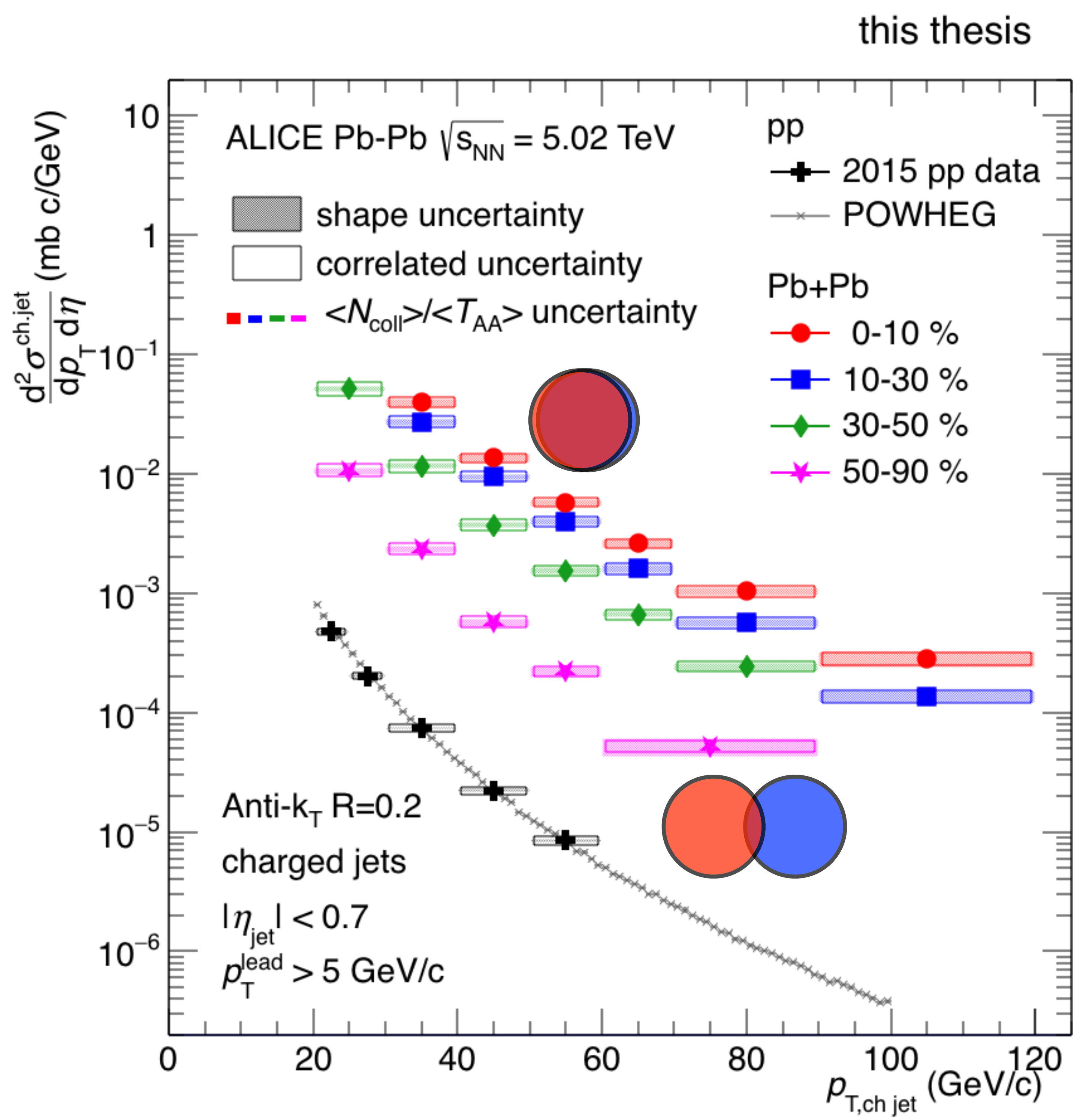
$$D_d = G_{d,t} \cdot T_t$$

- D_d: spectrum corrected for BKG fluctuation
- $G_{d,t}$: **RM given by Detector Simulation**
- T_t: "unknown" true jet spectrum

Inverted Response matrix gives "TRUE" jet spectrum via

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

Charged Jet Cross Section



☑ **Systematic Uncertainties**

- Unfolding Procedure (shape unc.)
- δpT distribution (correlated unc.)
- UE density due to elliptic flow (correlated unc.)
- Tracking efficiency and resolution (correlated unc.)

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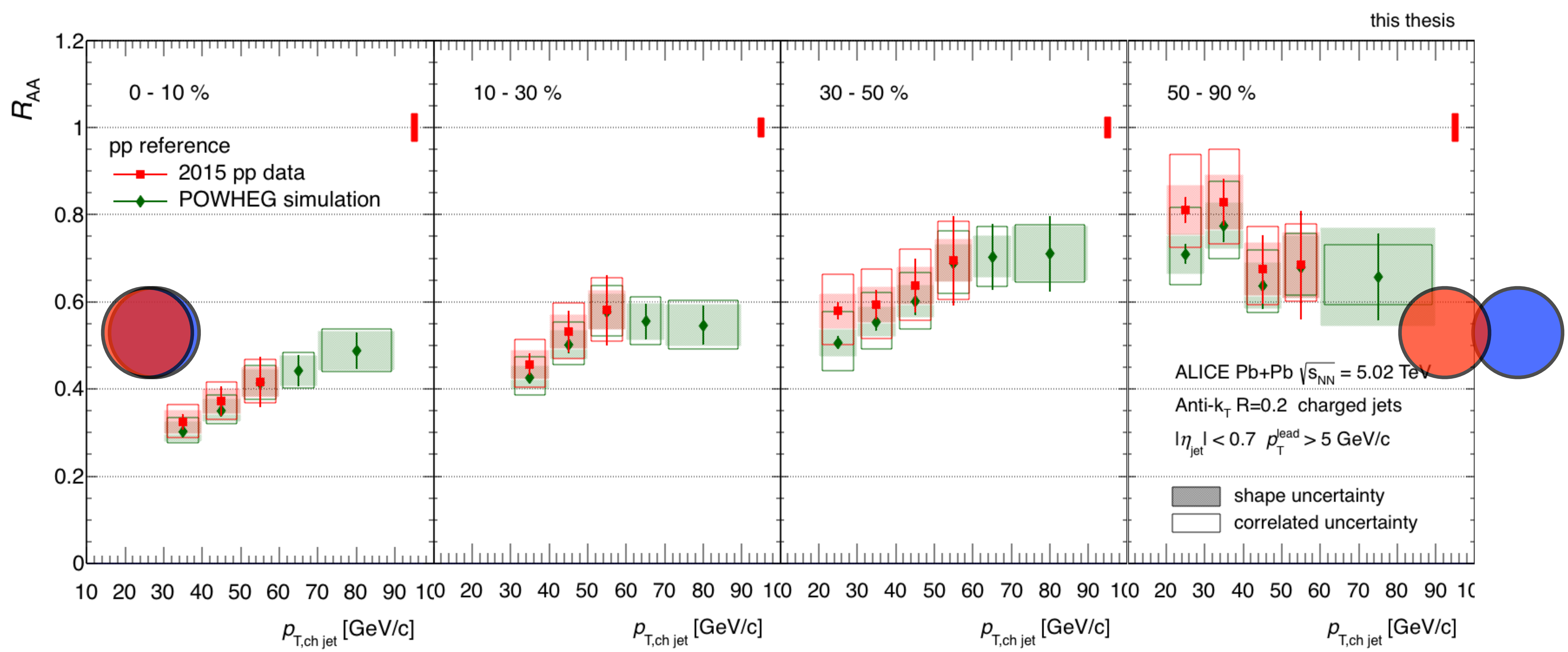
Jet Suppression

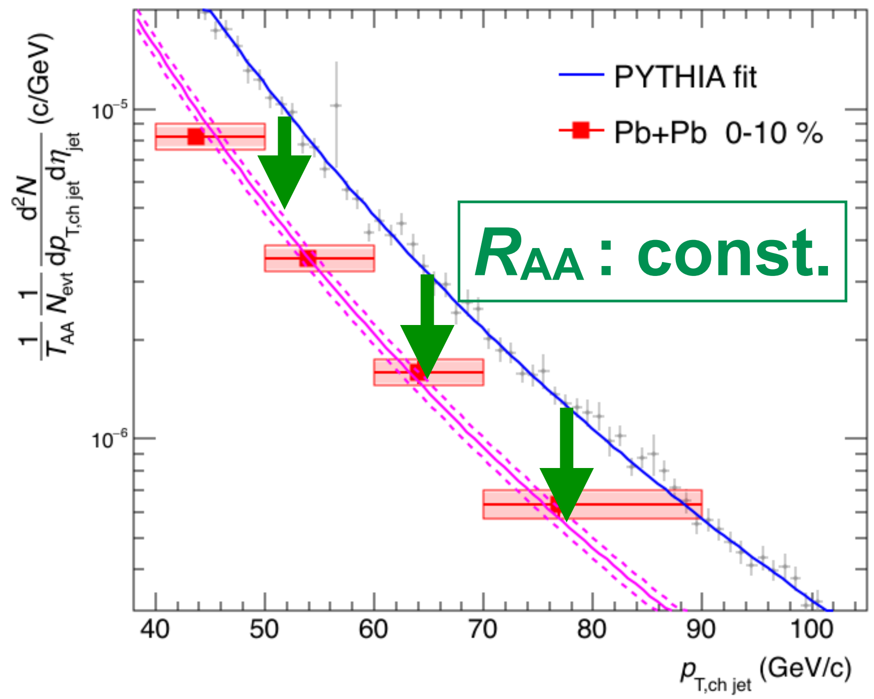
- ☑ **Nuclear modification factor : R_{AA}**
  - $R_{AA} > 1$: enhancement of jet yield
  - $R_{AA} < 1$: suppression

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2\sigma^{\mathrm{AA}}/dp_{\mathrm{T}}d\eta}{d^2\sigma^{\mathrm{pp}}/dp_{\mathrm{T}}d\eta}$$

- ☑ **Strong jet suppression is observed in the most central collisions**
  - smaller in peripheral (= closer to pp)
  - (POWHEG : NLO pQCD calculation with MC)

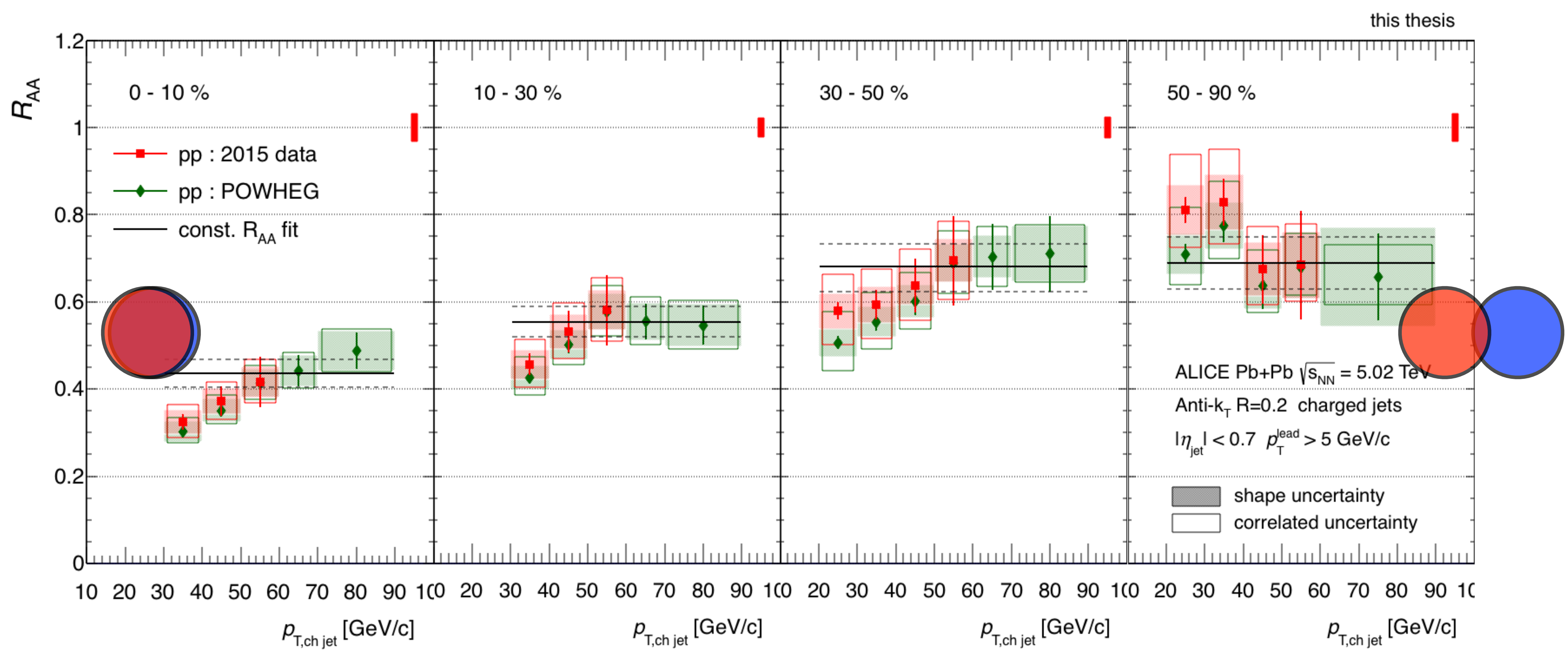


Simplified Energy Loss Model (1)



☑ **Assumption** : fractional jet disappearance :

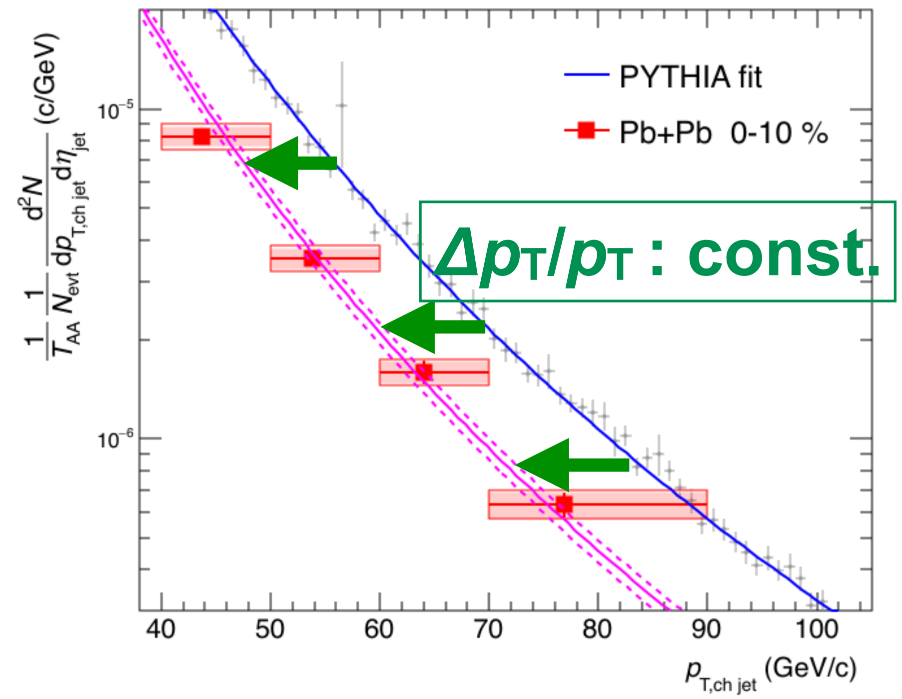
- R_{AA} is constant
- ⇒ same shape with pp except yield reduction
- spectrum fitting with one free parameter
- $\chi2$ = 4.3E-1 (0-10%)

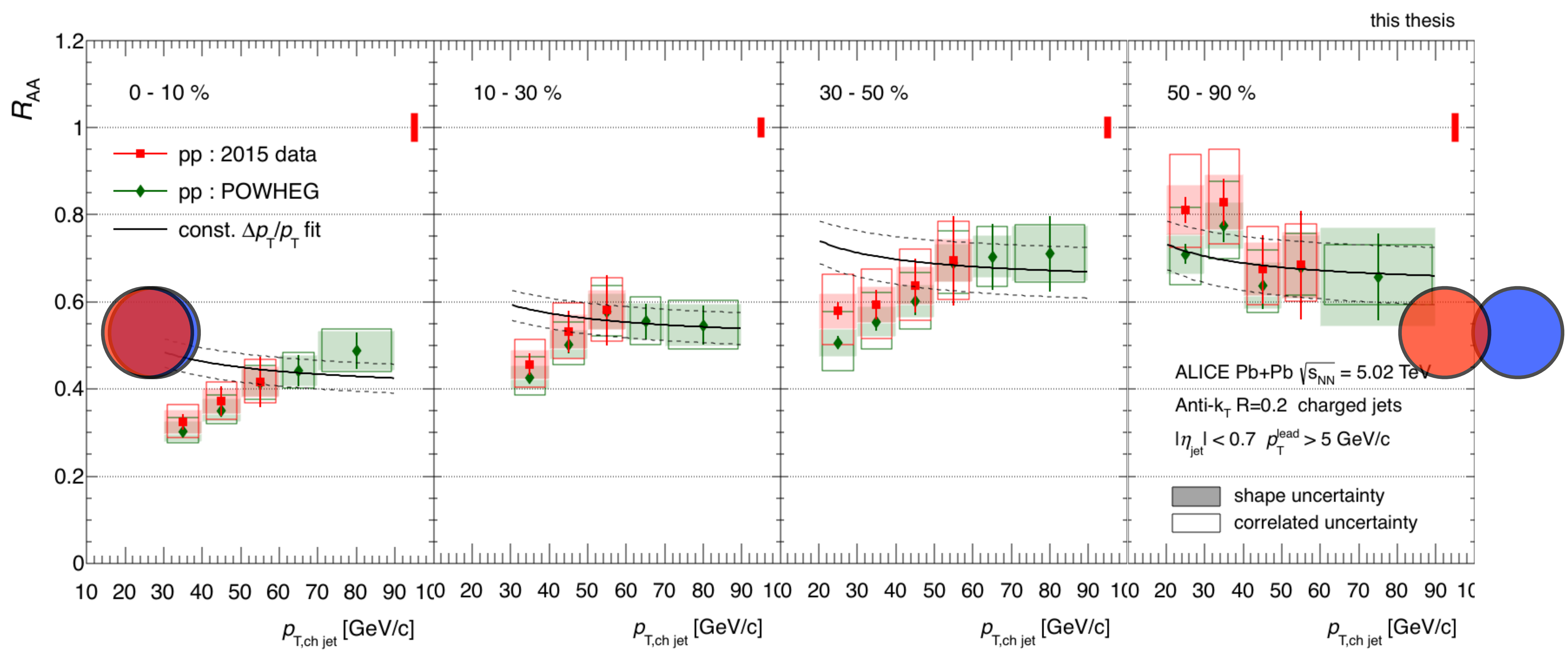


Simplified Energy Loss Model (2)

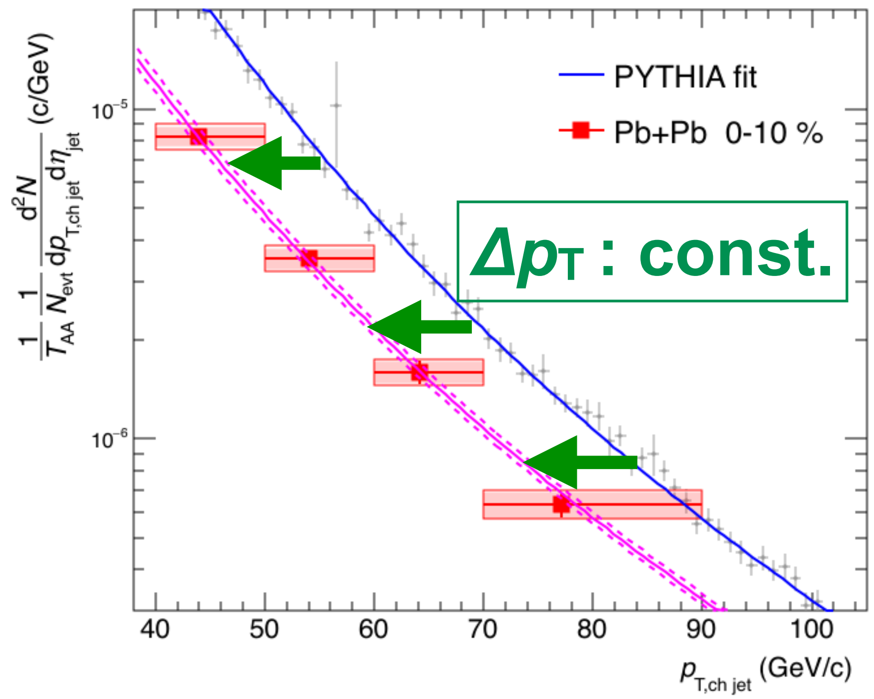
☑ **Assumption : fractional energy loss :**

- Δp_T is proportional to p_T
- ⇒ same shape with pp except p_T shift
- spectrum fitting with one free parameter
- $\chi 2$ = 5.8E-1 (0-10%)

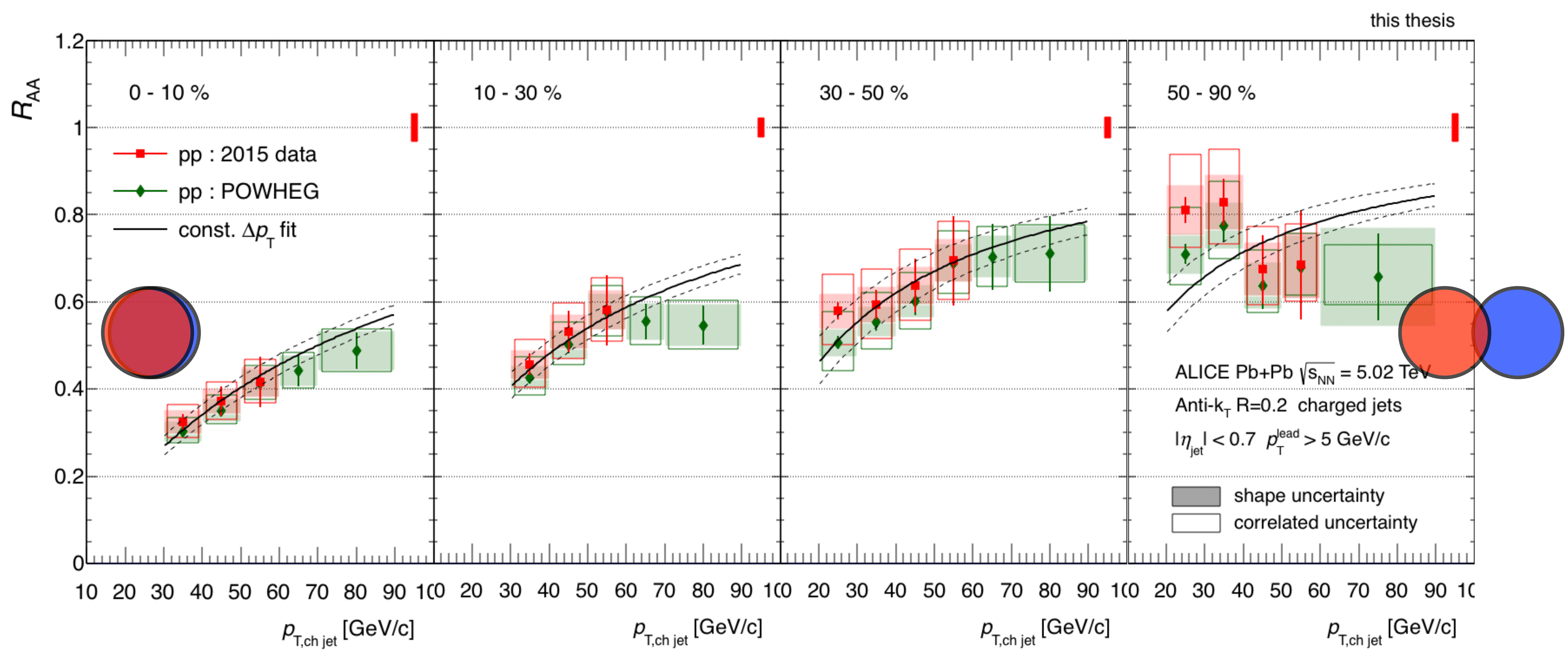




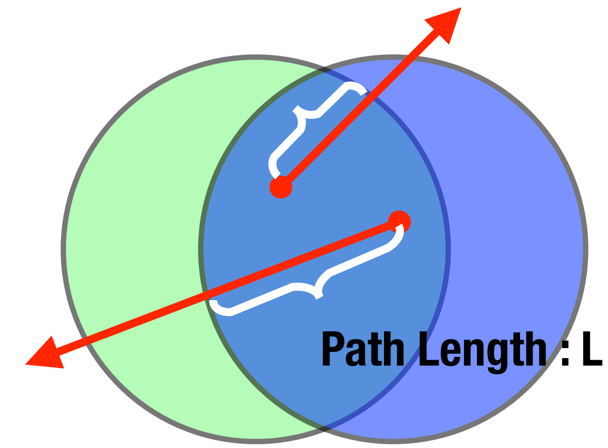
Simplified Energy Loss Model (3)



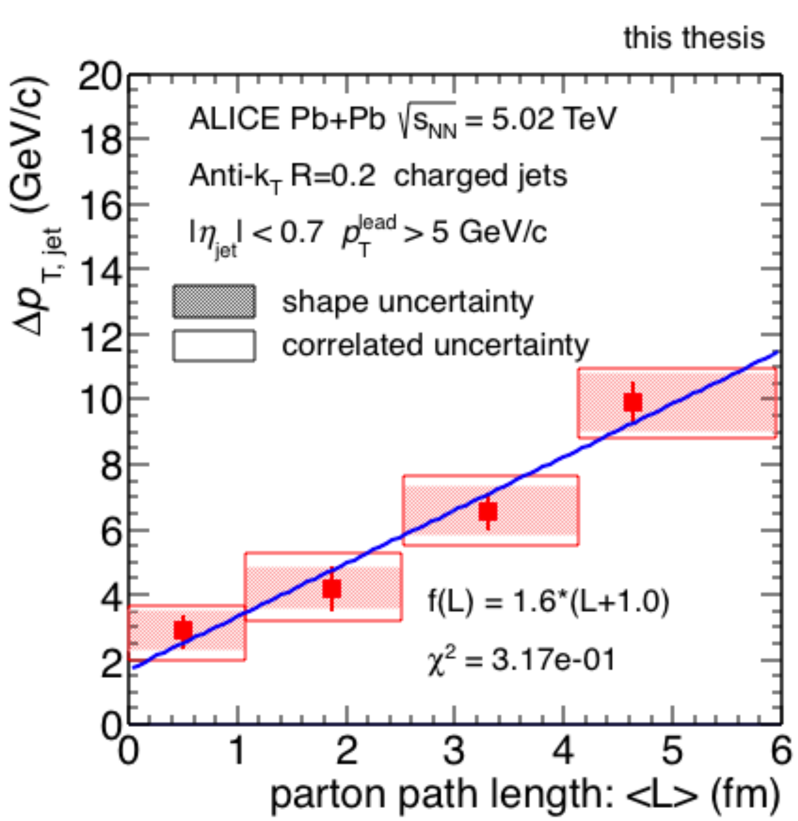
- ☑ **Assumption** : constant energy loss
  - Δp_T is constant (NO p_T dependence)
  - ⇒ same shape with pp except p_T shift
  - spectrum fitting with one free parameter
- ☑ $\boldsymbol{R_{AA}}$ **distribution well described** (up to ~90 *GeV/c*)
  - $\chi 2$ = 4.1E-2 (0-10%)

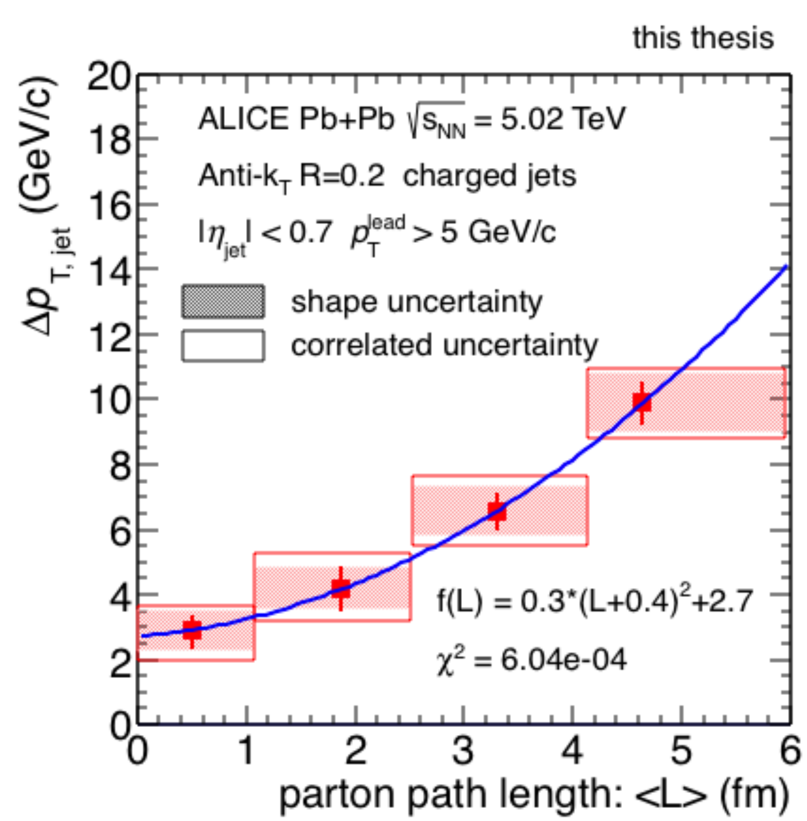


Energy Loss v.s. Path Length



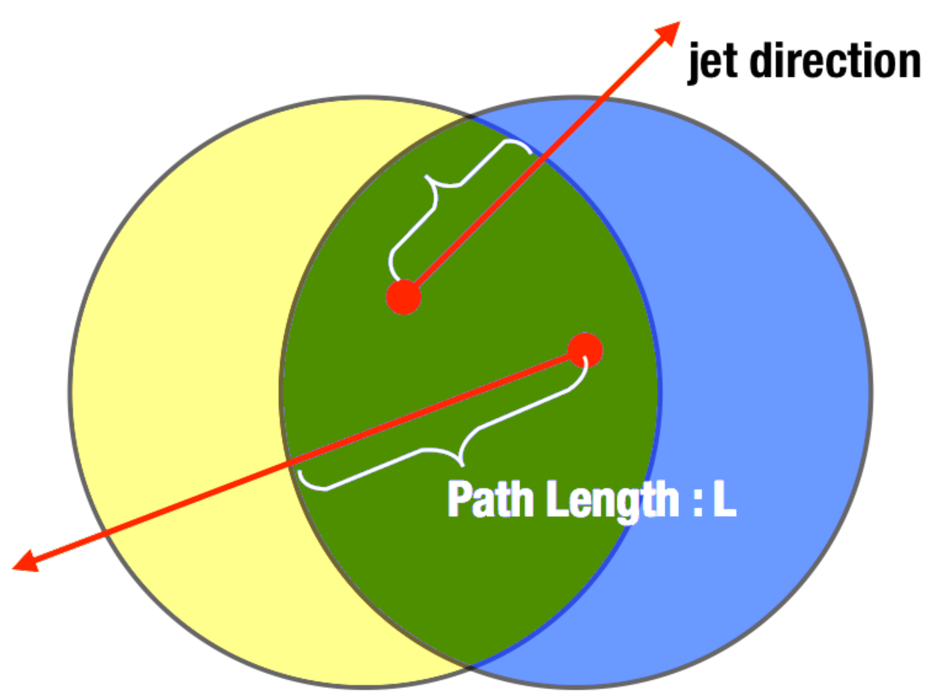
- Parton path length is estimated by Toy Model
  - average path length in transverse overlapped area
- **Energy loss increases with parton path length**
  - ~10 *GeV/c* at most central collisions (for *R*=0.2 charged jets)
  - quadratic function fit gives better agreement than linear fit
  - not ruled out collisional energy loss due to large uncertainty

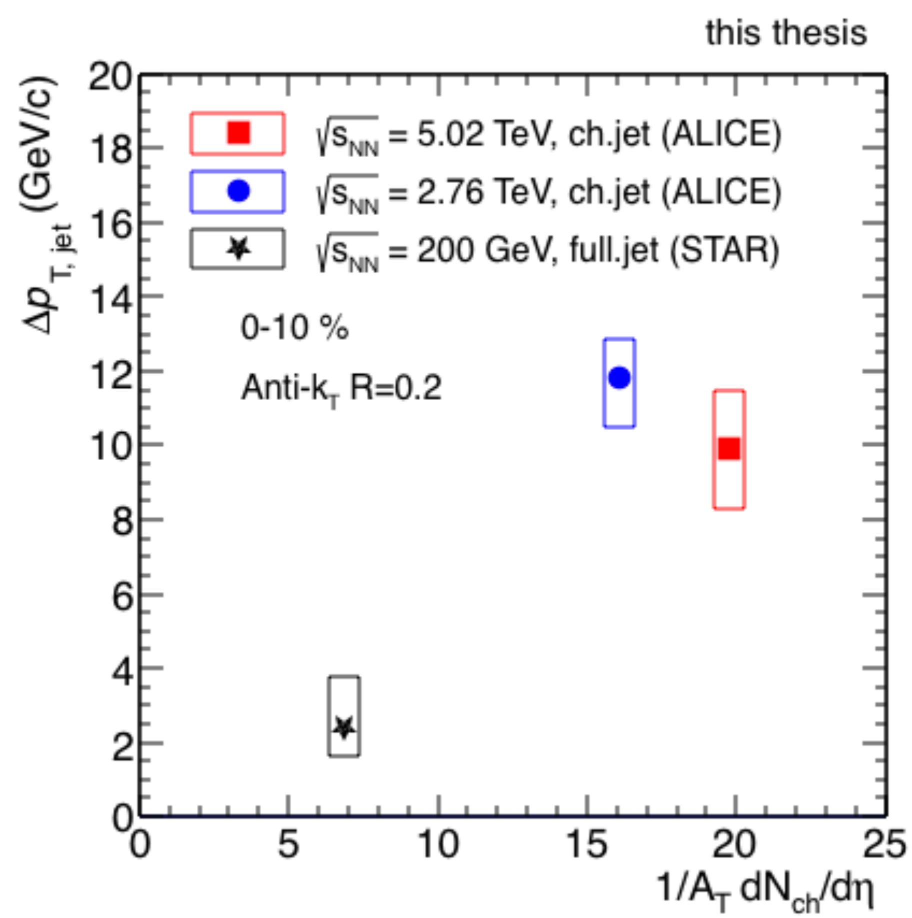




Centre-of-mass energy dependence

- ☑ $dN_{ch}/d\eta \propto dN_g/d\eta$
  - charged multiplicity density per unit transverse area
- ☑ <u>larger energy loss in LHC than RHIC</u>
  - due to higher gluon density in QGP





Summary

- **Jet Quenching**
  - parton energy loss in QGP
  - jet is great probe to assess QGP properties
- **ALICE EMCAL Trigger Upgrade during LS1**
  - L1-photon/Jet triggers production by STU
  - New detector, New triggering algorithm
  - In operation since first Pb-Pb runs in RUN2
- **Inclusive Jet Measurement in $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb collisions**
  - strong jet suppression is observed in the most central collision
  - constant energy loss model well describes observed R_{AA}
  - jet energy loss increases with parton's path length
  - larger in LHC energy than RHIC due to higher gluon density

Backup

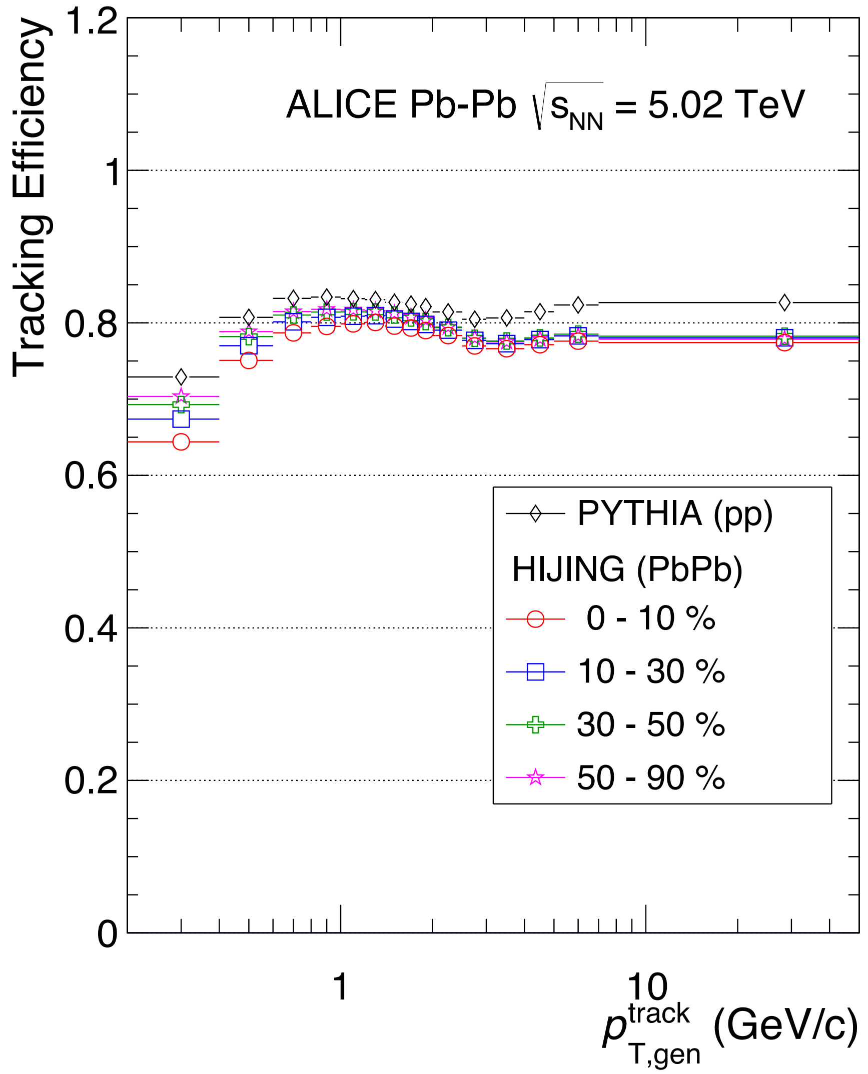
Q&A

- ☑ 18 GeV/c for R=0.2 の根拠、意味は？
- ☑ Delta pT の分布がガウス分布ではない点について、pure な thermal 分布する粒子を eta, phi で降った場合、ガウス分布になるか？
- ☑ “excluding leading jet neighbor” とあるが、sub leading の寄与は無視できるのか？
- ☑ Flow Bias +- 4 GeV/c は rho に対してか？
- Delta_pT, jet vs. L について、radiative なのか、collisional なのか、議論して欲しい
- Delta_pT, jet の sqrt(s) 依存性、特に RHIC との比較、横軸 dN/deta (~gluon deisty, energy density)にした場合の議論も加えて欲しい。energy loss が radiative なのかどうかを議論。
- ☑ single track efficiency (centrality, pT　依存性)を示して欲しい
- 論文について：プロットと本文での結論を結びつけて書いて欲しい
- (1), (2) の Simplify energy loss model に加えて、Yield が減る方向（↓）のモデルも入れて、　それではデータを説明できないことを示して欲しい。

Assurance of tracking quality

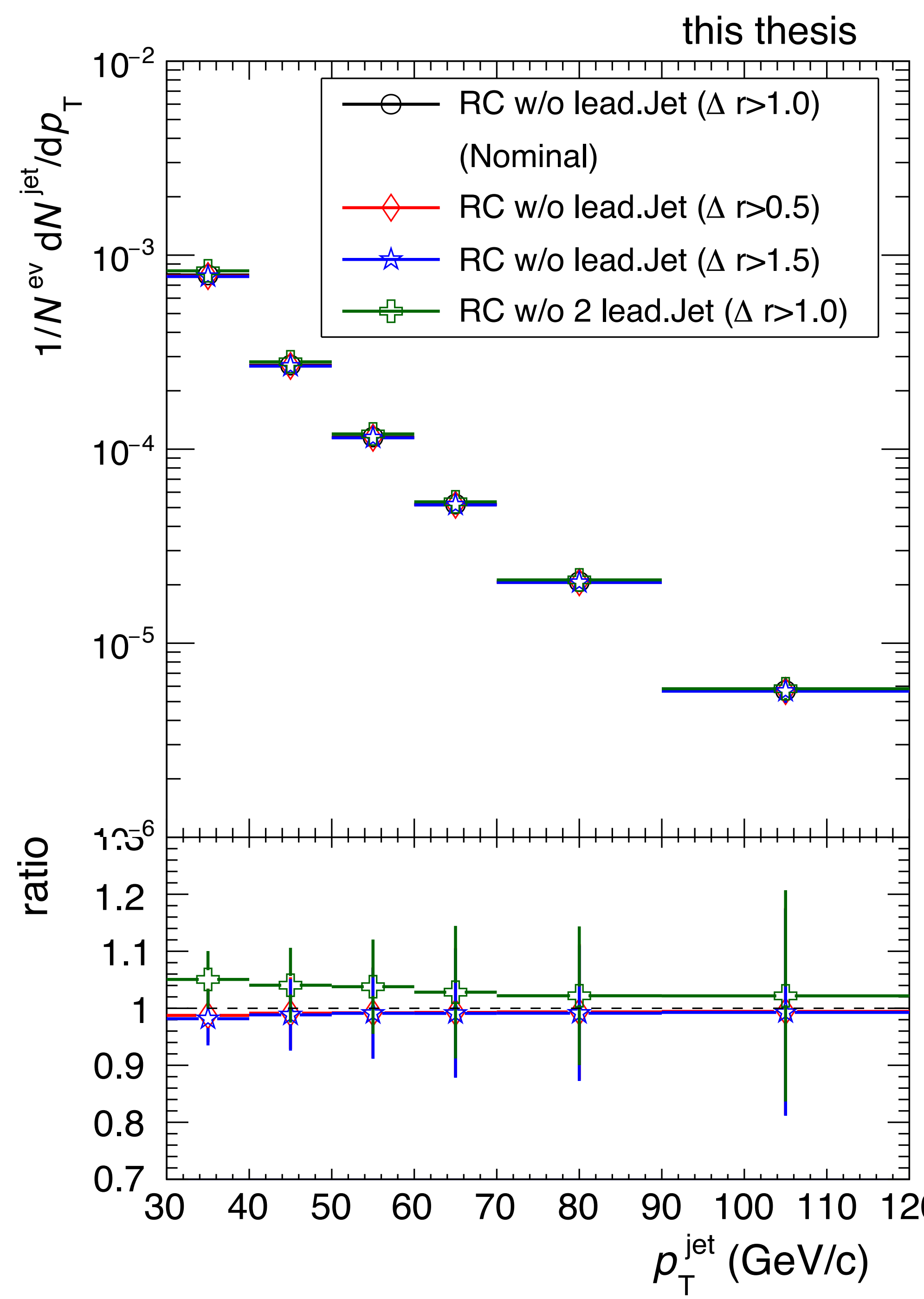
- single track efficiency
  - HIJING+GEANT simulation
  - tracking inefficiency due to high multiplicity is less than few % down to ~0.3 GeV/c
  - bit larger at lower p_T

this thesis



Effect from sub-leading jet to δp_T evaluation

- ☑ The nominal selection of RC is “RC excluding leading jet neighbor”
  - NOT usual to catch back-to-back jets in detector acceptance
  - due to the limitation of $|\eta_{track}| < 0.9$
- ☑ “RC away from sub leading”
  - -> variation of systematic uncertainty
  - ~5% at low jet p_T
- ☑ 3rd leading jets are much rare
  - NOT included as systematic variation
  - RC selection with too many jet excluded, results in too much bias

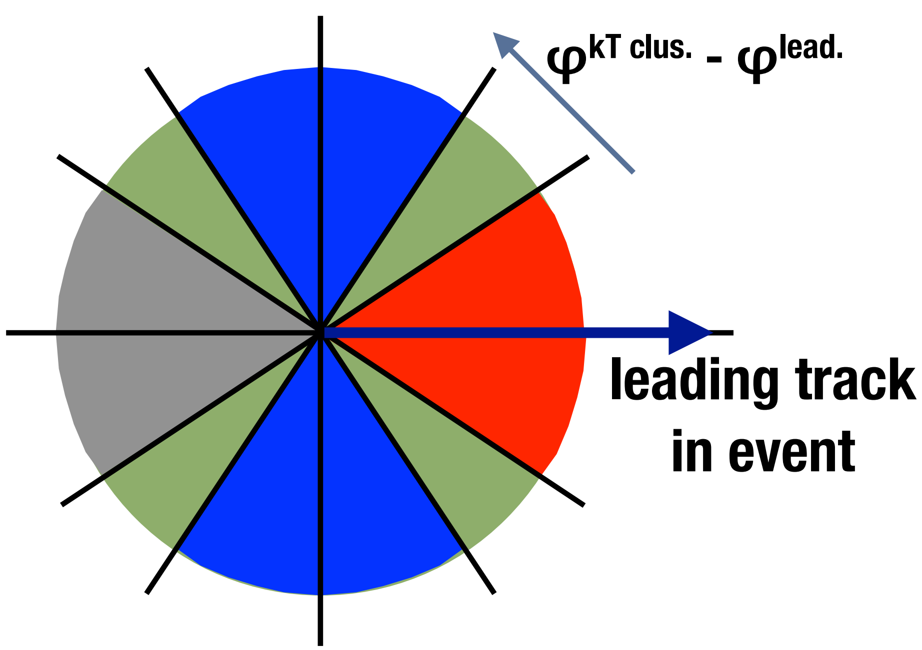


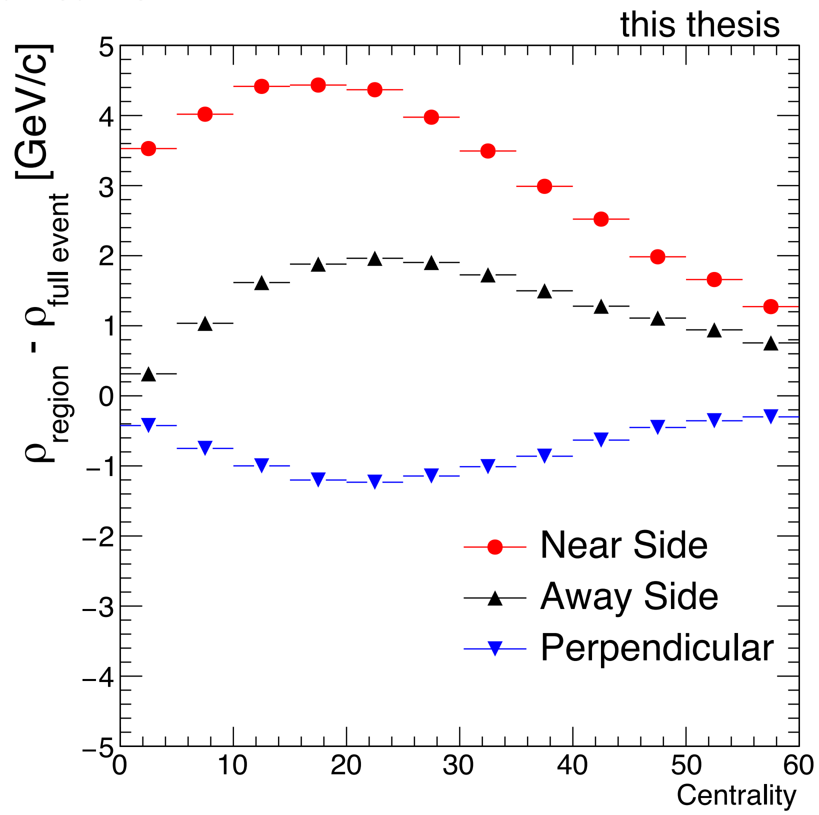
S/B energy ratio in reconstructed jet

- ρ(0-10%) = 145 GeV/c for R=0.2 jets.
  - average underlying event energy for R=0.2 jet is ~18 GeV/c in 0-10%
    - ρ(0-10%) * πR^2 = 18 GeV/c
  - S/B = ~1.7 for 30 GeV/c jet
  - S/B = ~2.7 for 50 GeV/c jet

How to determine Flow Bias

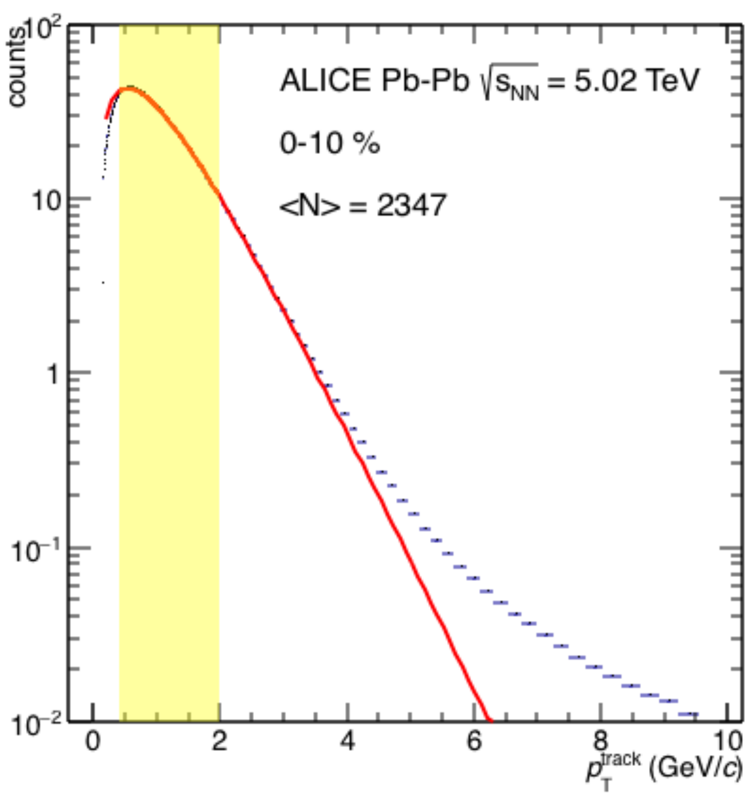
- k_T cluster selection on median calculation
  - according to direction of event leading track
  - event leading track p_T > 5 GeV/c
  - -> effect of particles fragment outside of jet
  - -> effect of elliptic flow (leading track tends to be found in-plane)
- The bias for ρ calculation : ±4 GeV/c
  - ±4 (GeV/c) * πR^2 = ±0.5 GeV/c, for RC with R=0.2
  - δp_T distribution shift of ±0.5 GeV/c as variation

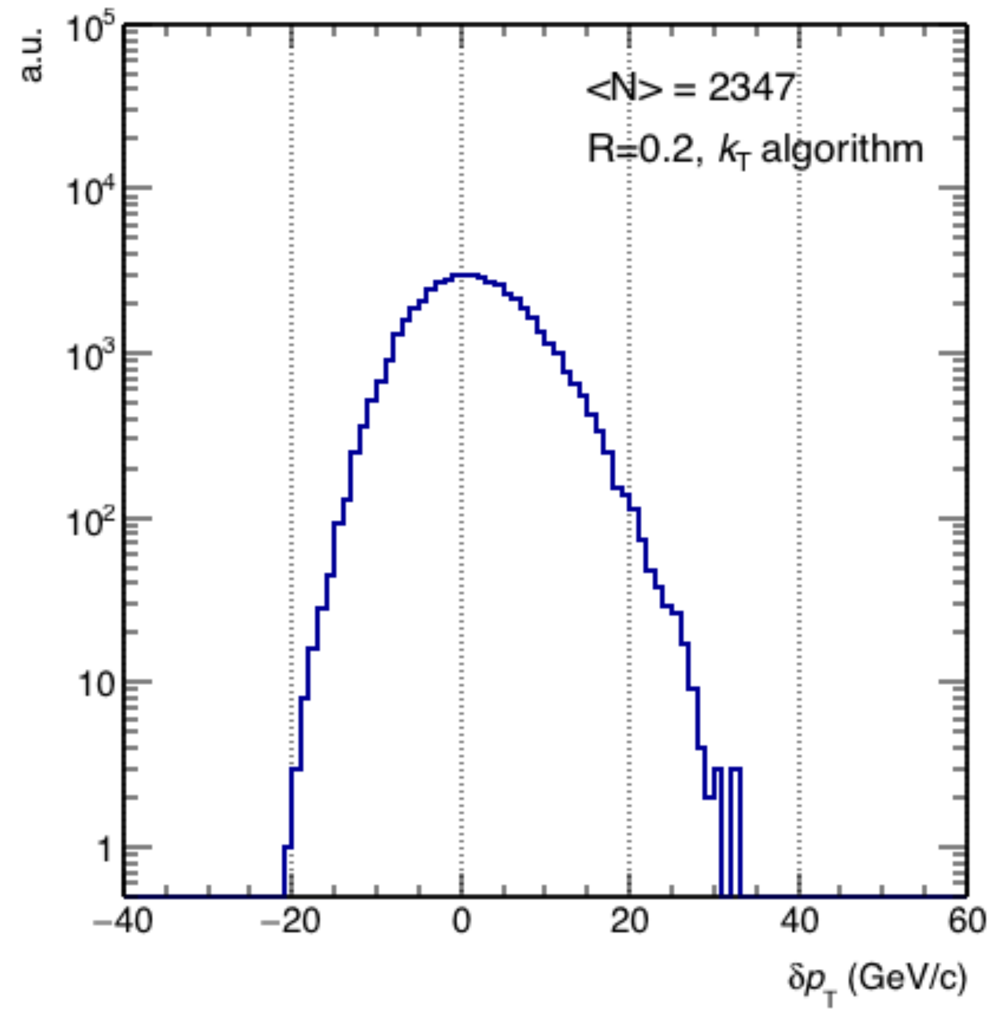




δp_T distribution for thermal track p_T distribution

- asymmetry shape of δp_T distribution even in ηϕ-randomised track
  - when track p_T distribution follows pure thermal distribution, does it becomes gaussian?
- Generate N=2350 (assuming 0-10%), ηΦ-randomised tracks according to charged track spectrum fit at low-p_T.
  - -> asymmetry δp_T distribution





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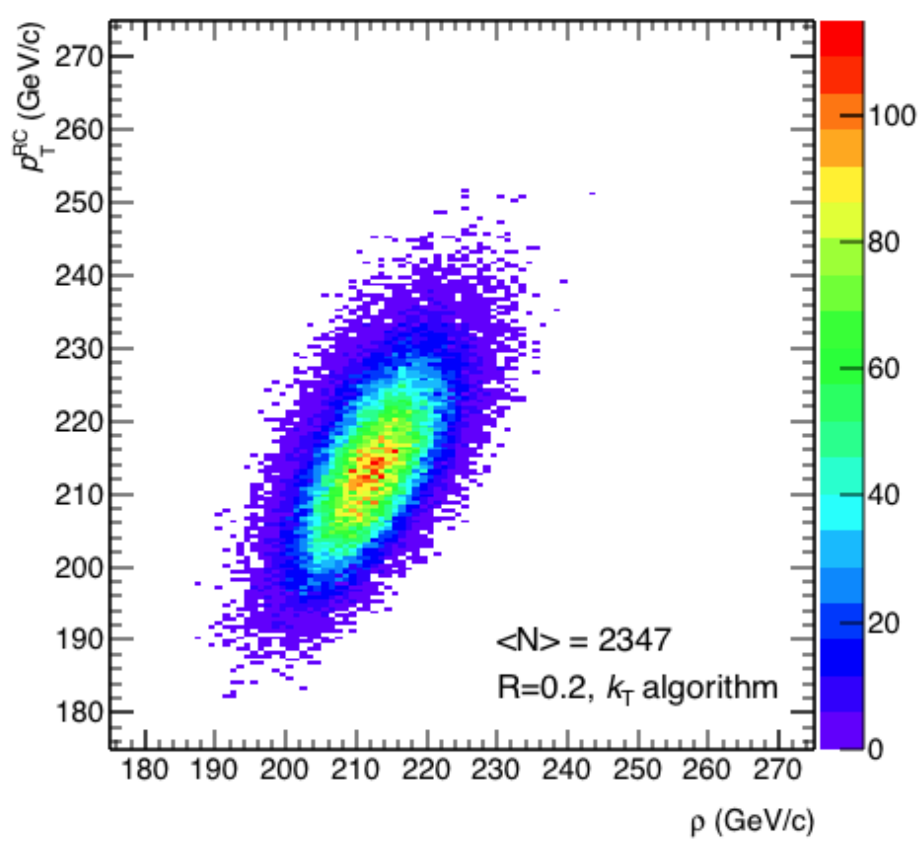
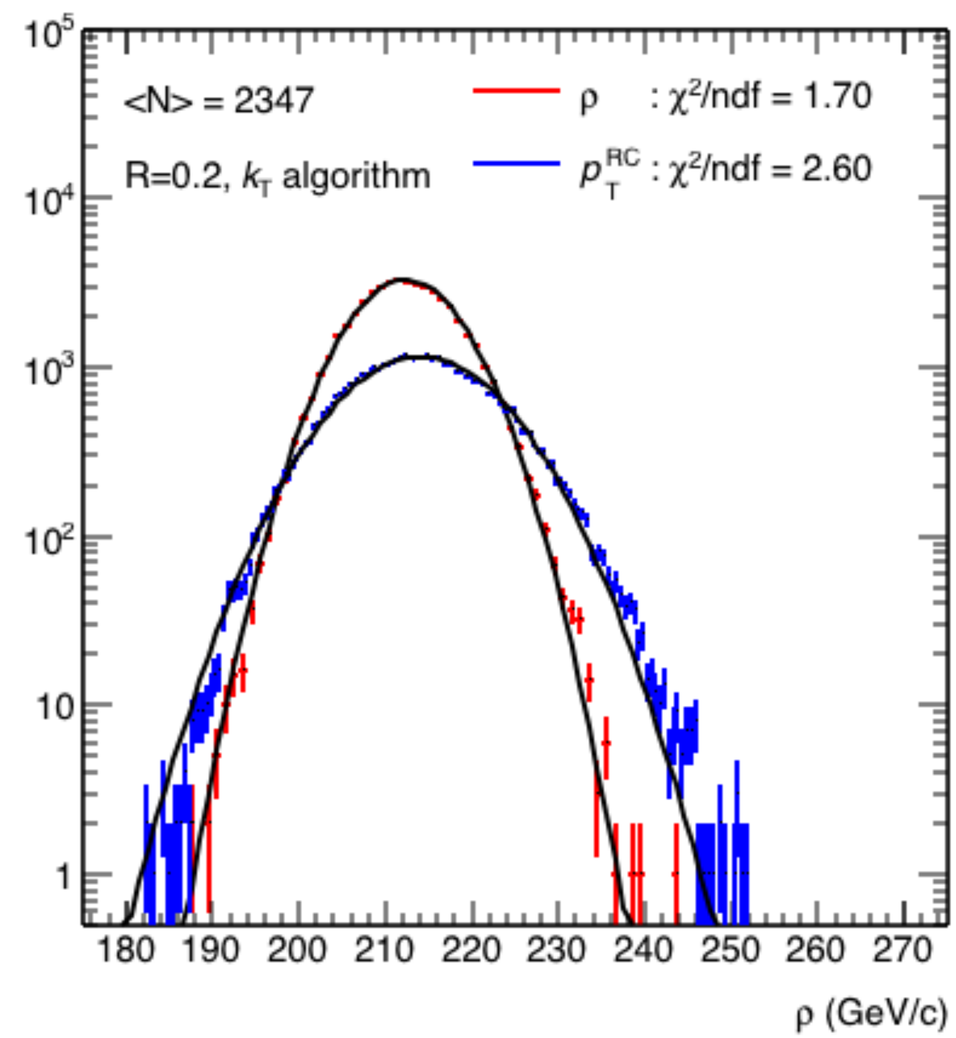
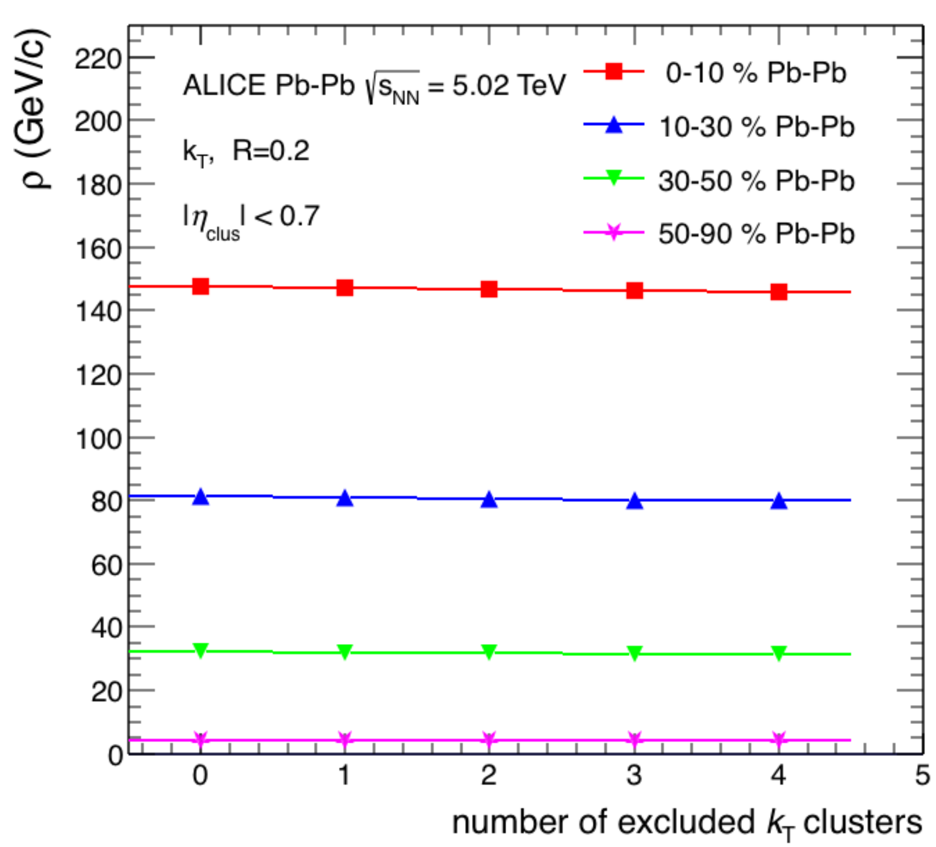


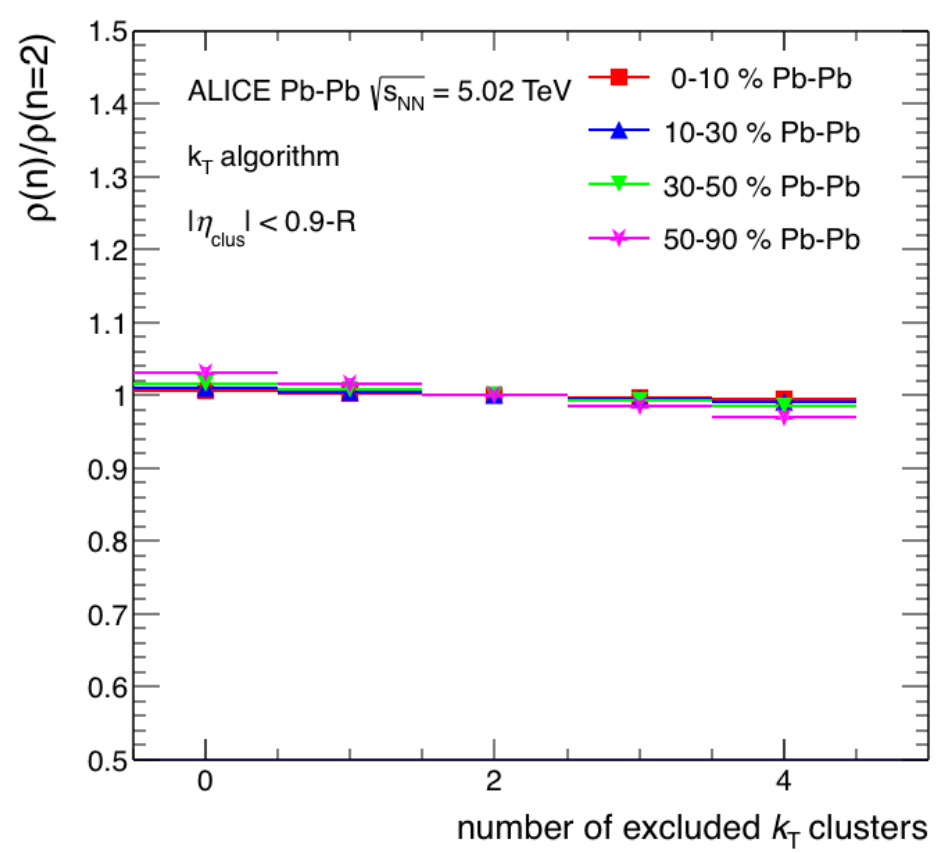


Average underlying event stability (1)

☑ **number of excluded k_T clusters for median calculation**

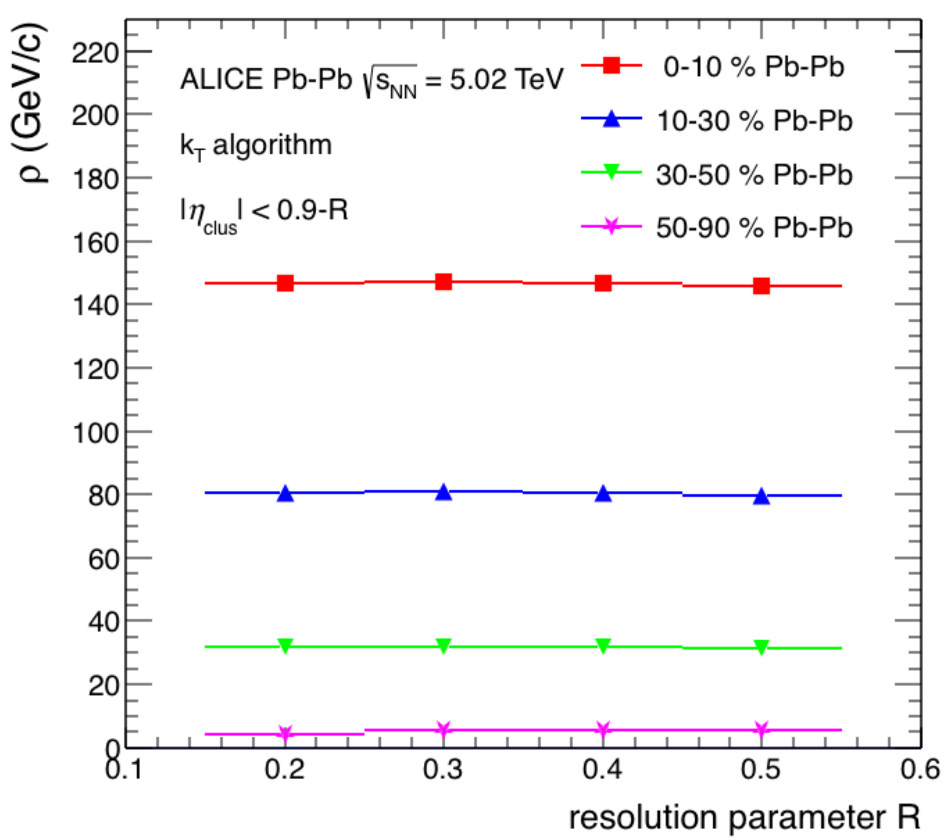
- 0 (no exclusion) to 4, R=0.2
- < 1% for 0-10%, 10-30% and 30-50%
  - $\Delta\rho < 1.5$ GeV/c ($\Delta(\rho\pi R^2) < 180$MeV/c)
- < 3% for 50-90%
  - $\Delta\rho < 110$ MeV/c ($\Delta(\rho\pi R^2) < 20$MeV/c)

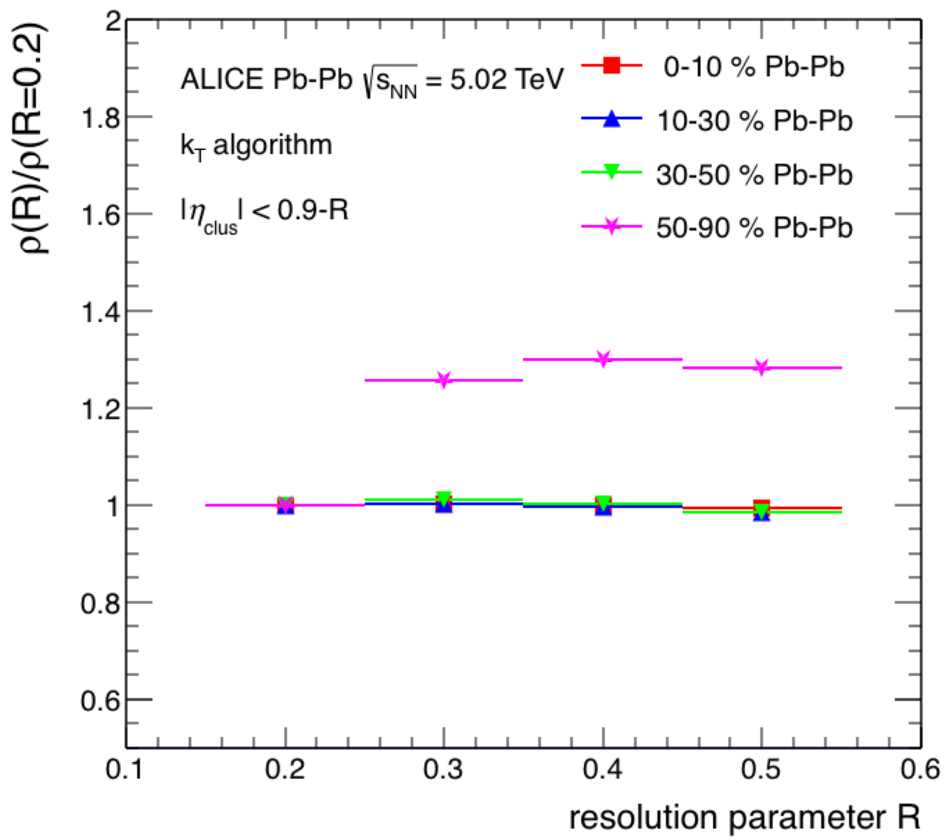




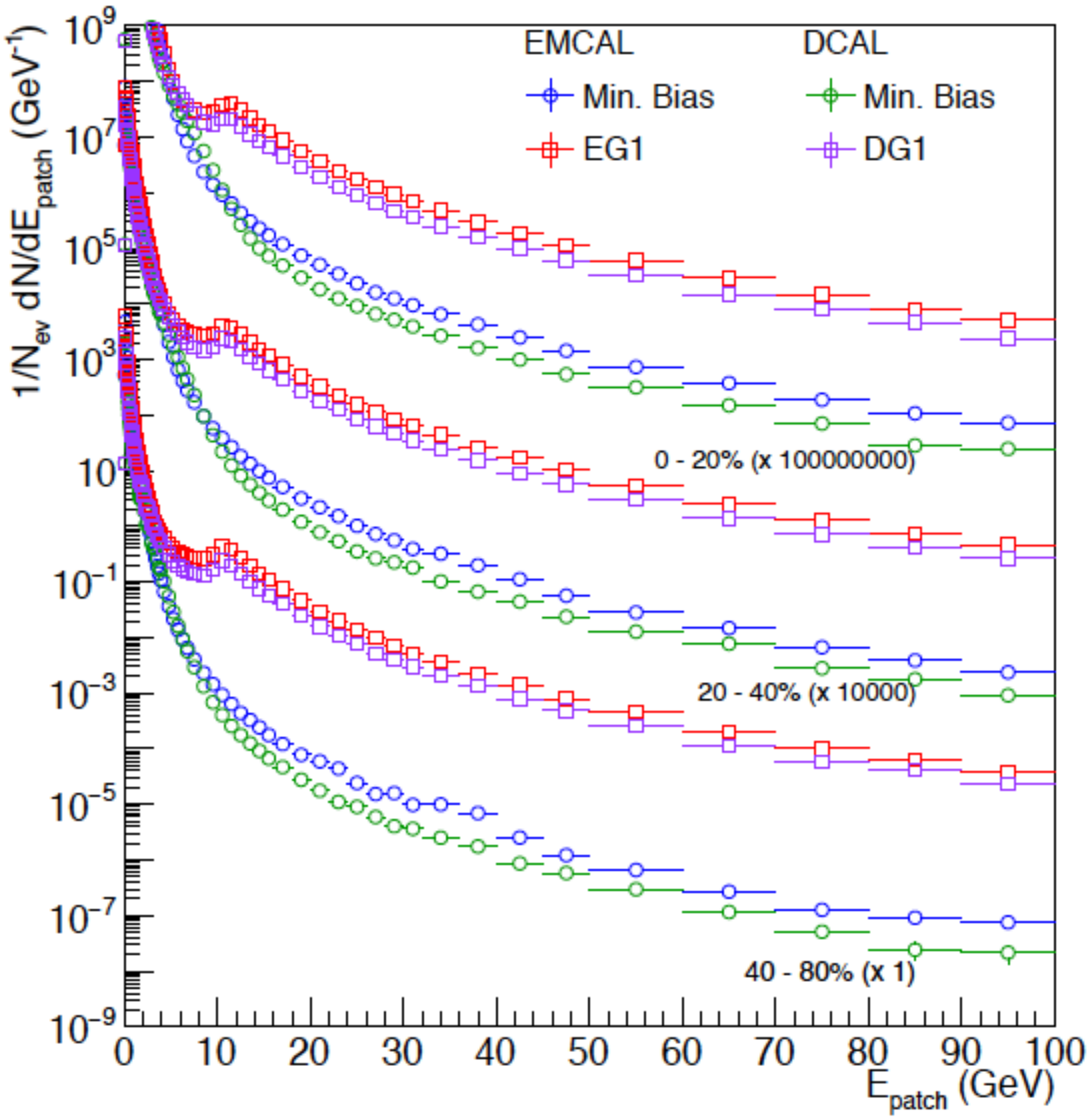
Average underlying event stability (2)

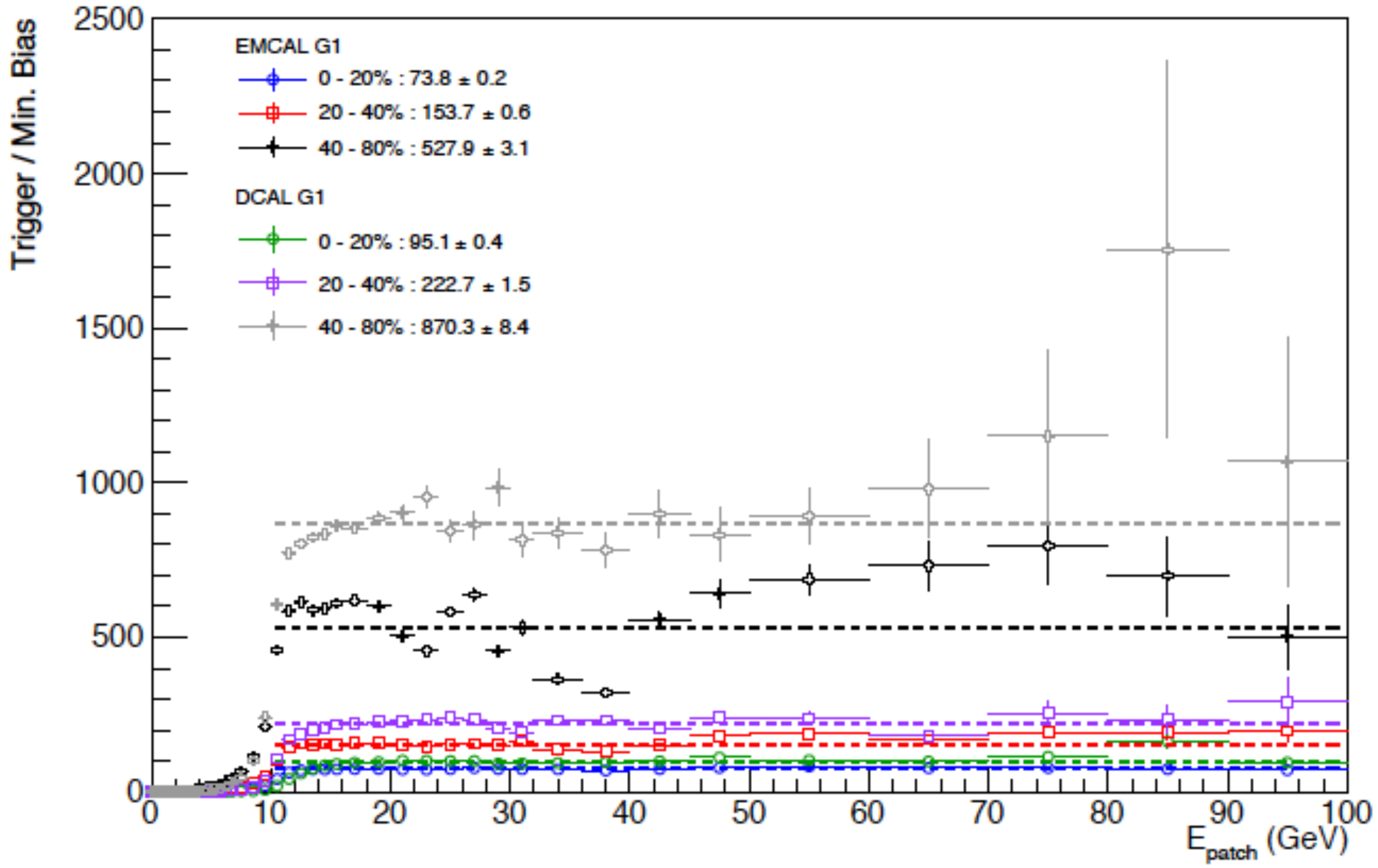
- **resolution parameter of k_T algorithm**
  - from R=0.2 to 0.5 (number of excluded clusters : 2)
  - < 2% for 0-10%, 10-30% and 30-50%
    - $\Delta\rho$ < 3 GeV/c ($\Delta(\rho\pi R^2)$ < 370MeV/c)
  - < 30% for 50-90%
    - $\Delta\rho$ < 110 MeV/c ($\Delta(\rho\pi R^2)$ < 140MeV/c)





Spectra and turnon curves for the Gamma triggers

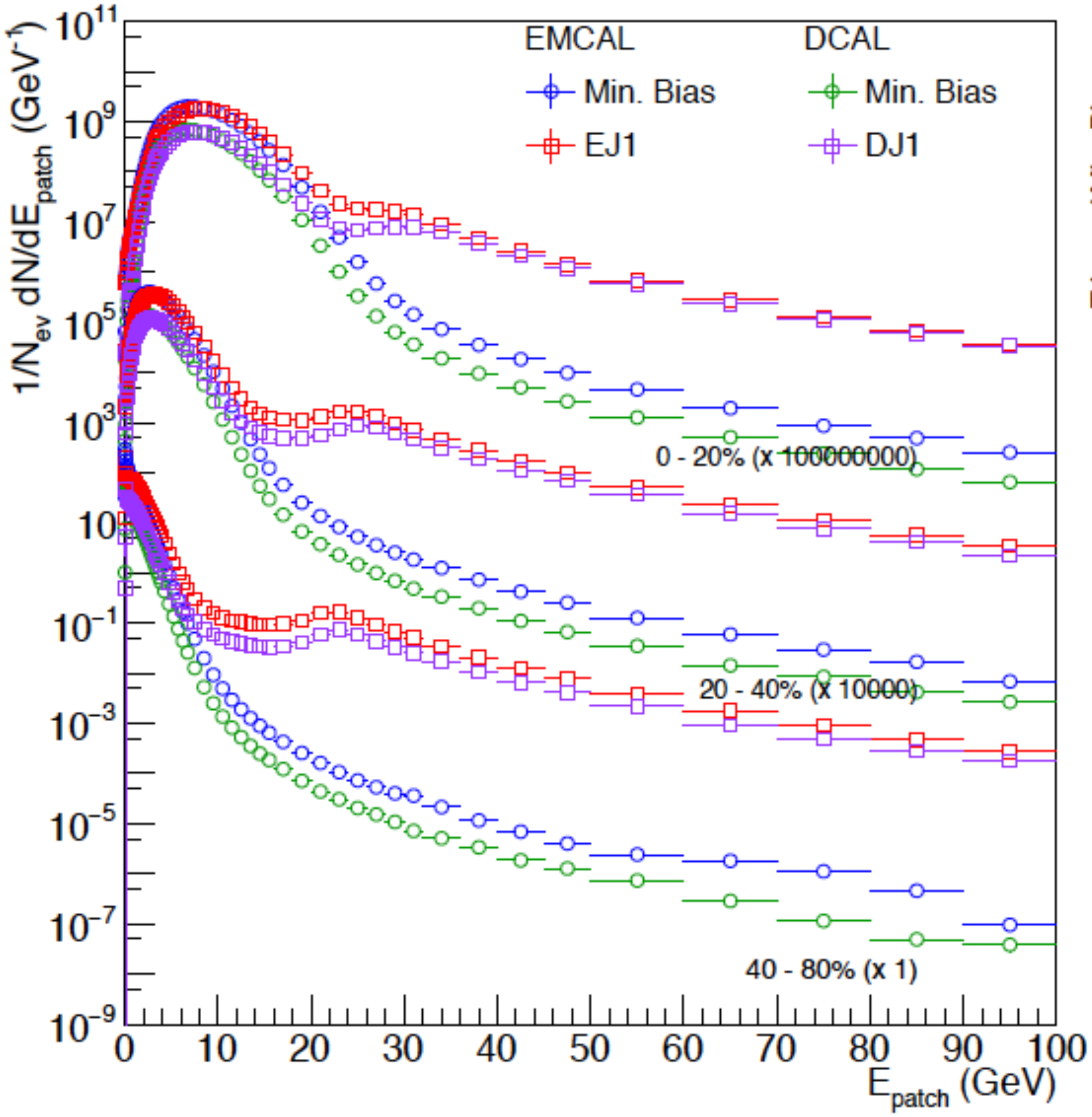


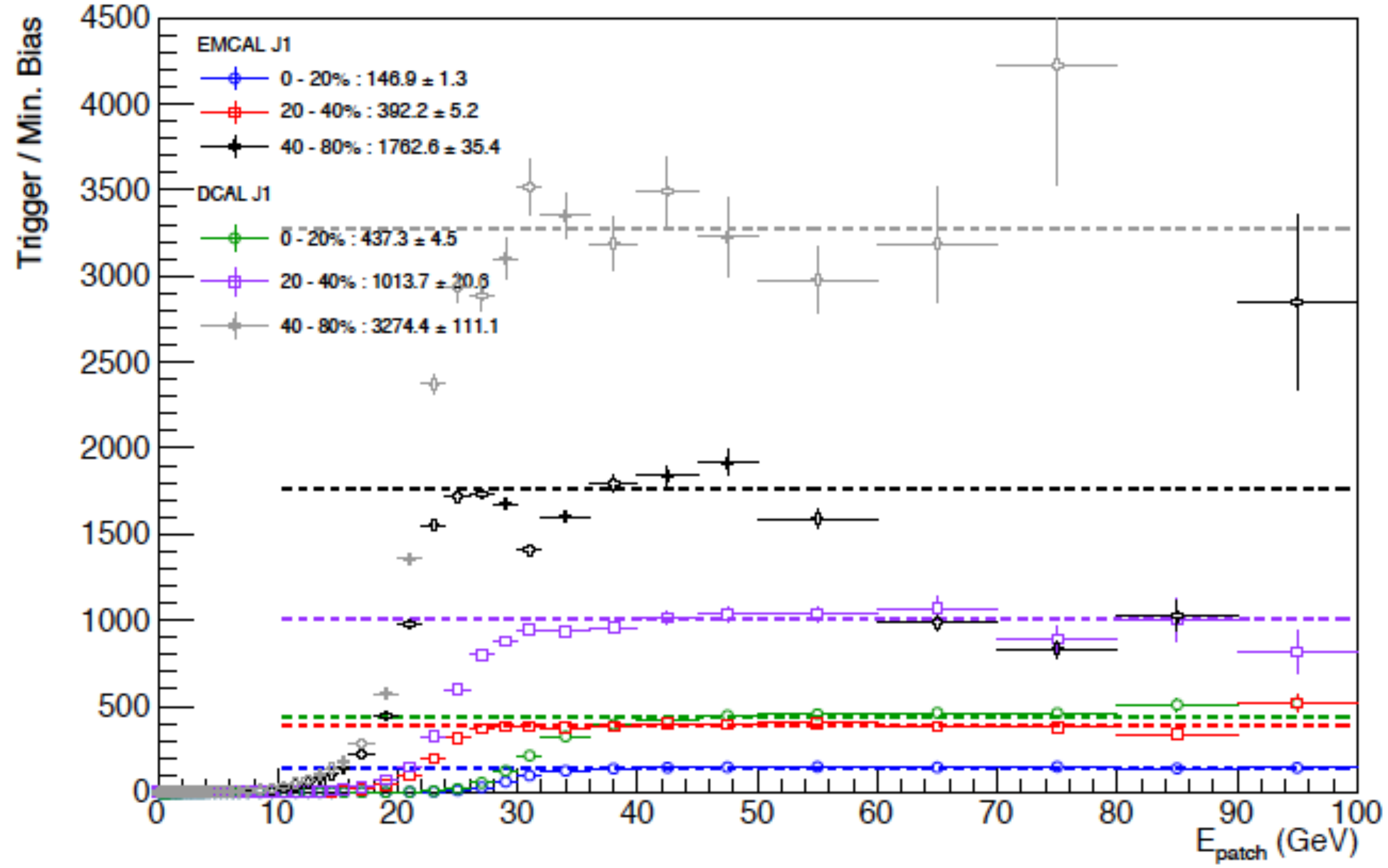


Sharp turnon at 10 GeV patch energy

Centrality dependence of the Gamma triggers visible

Spectra and turnon curves for the jet trigger





Turnon centrality-dependent:

~ 40 GeV for 0-20%, ~20 GeV for 40-80%

Influence of dijets

- Dijets in acceptance could bias background estimate
- Scanning bias as function of dijet kinematics

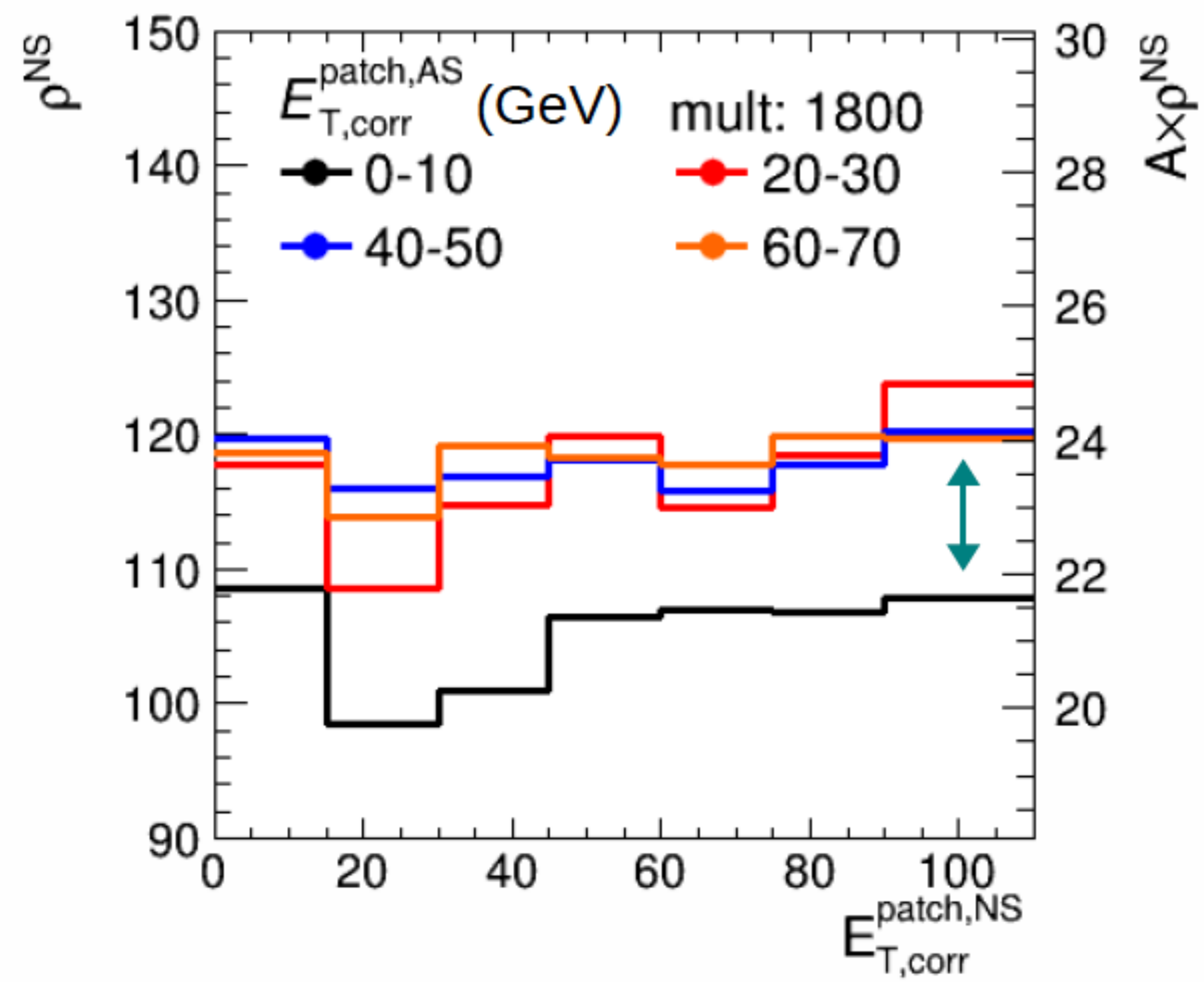
Figure shows influence of dijets as function of p_T of leading patch (proxy for jet) in EMCal and DCal

NS: near-side. In this figure EMCal
AS: away-side. In this figure DCal

ρ^{NS}: background estimate for EMCal patches estimated from patches in DCal

$A\times\rho^{NS}$: subtracted energy

Black points: no hard jet at away-side
All other colors: more or less balanced dijets in acceptance

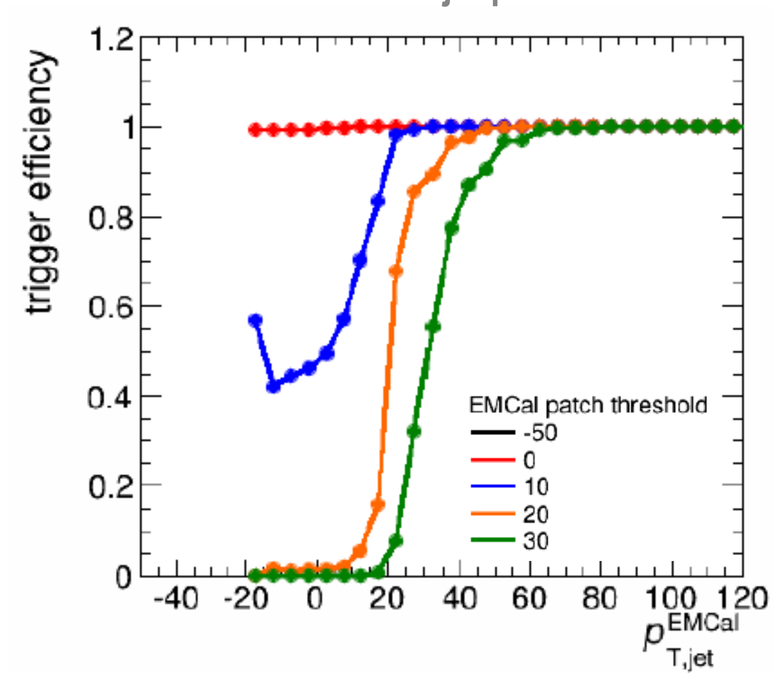


Dijet bias ~2 GeV for 32x32 patch (A~0.23).
Unbiased (di)jet sample can be selected by requiring the trigger jet to be a few GeV larger than the trigger threshold.
Larger bias if jets are quenched?

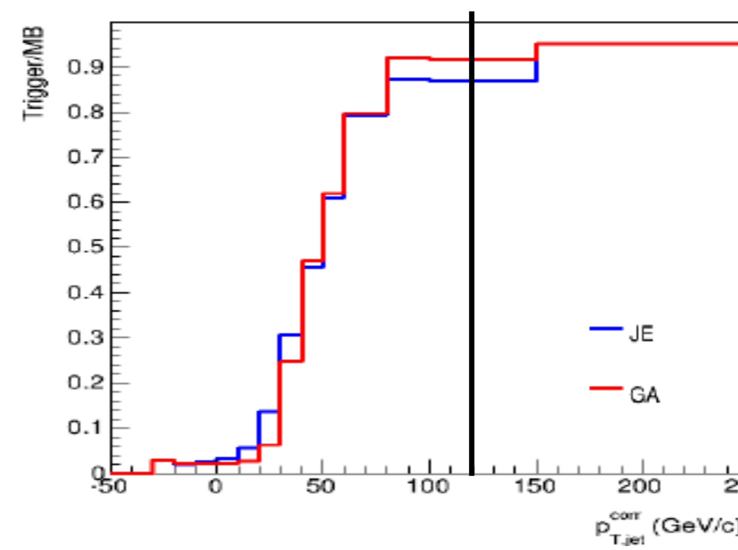
Expected Trigger Performance

Trigger efficiency
BKG density subtraction
turn on steeply

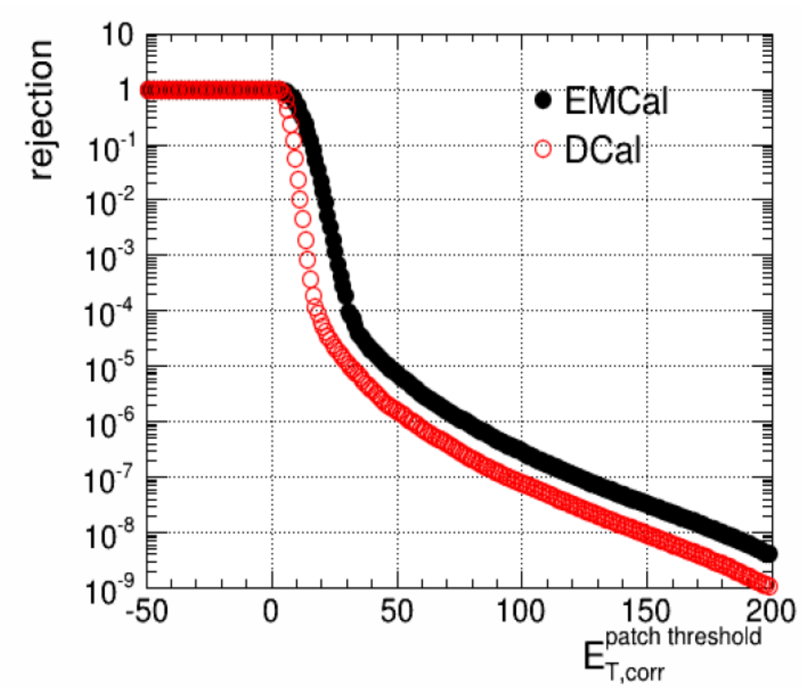
DCAL-BKG-density subtraction
from EMCAL jet patch

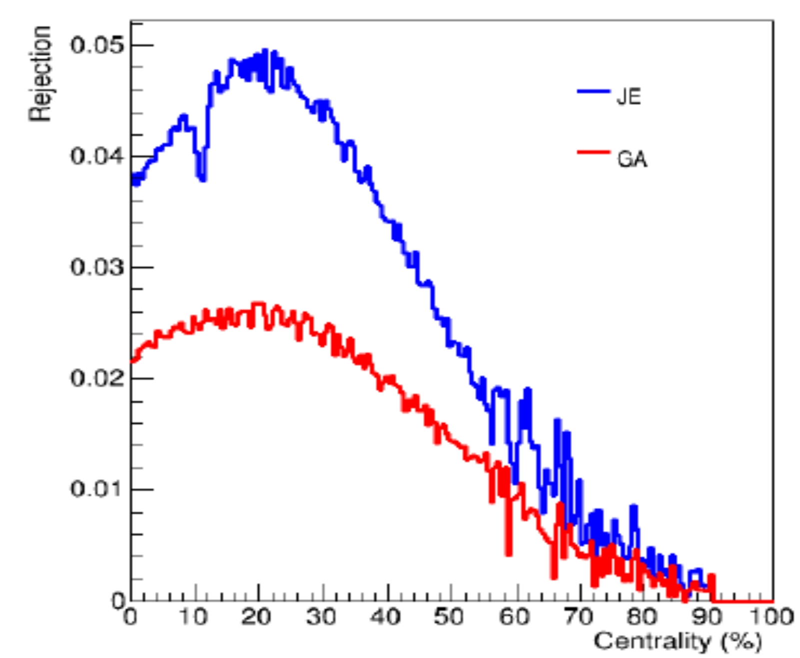


LHC11h data,
central , V0-dep threshold



Rejection factor
BKG density subtraction
larger rejection power

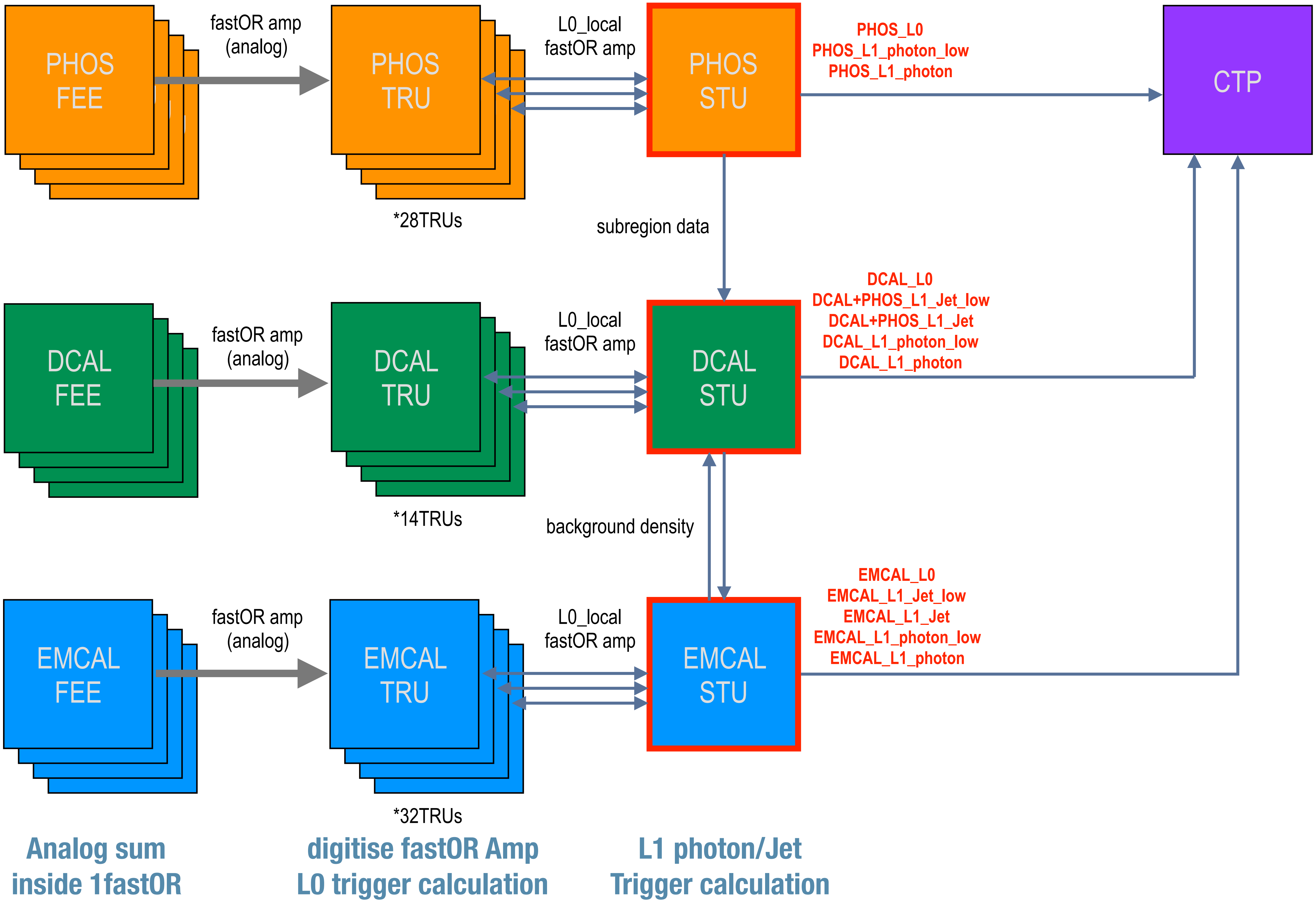




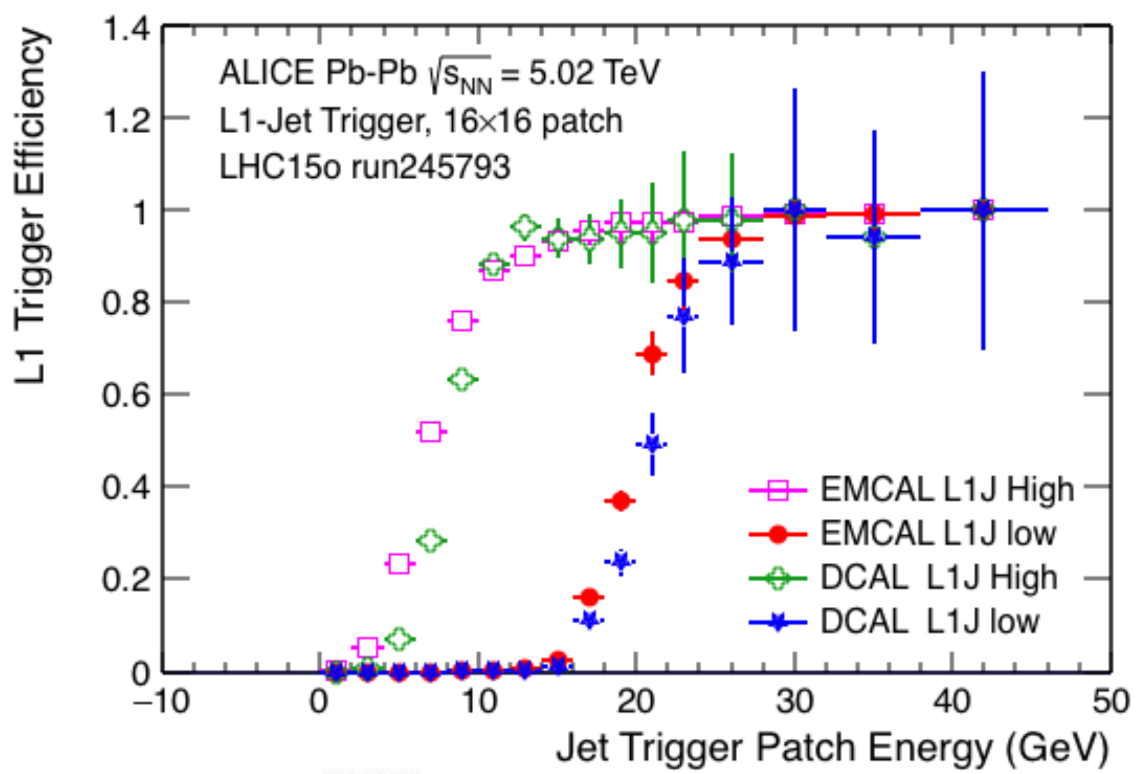
central event

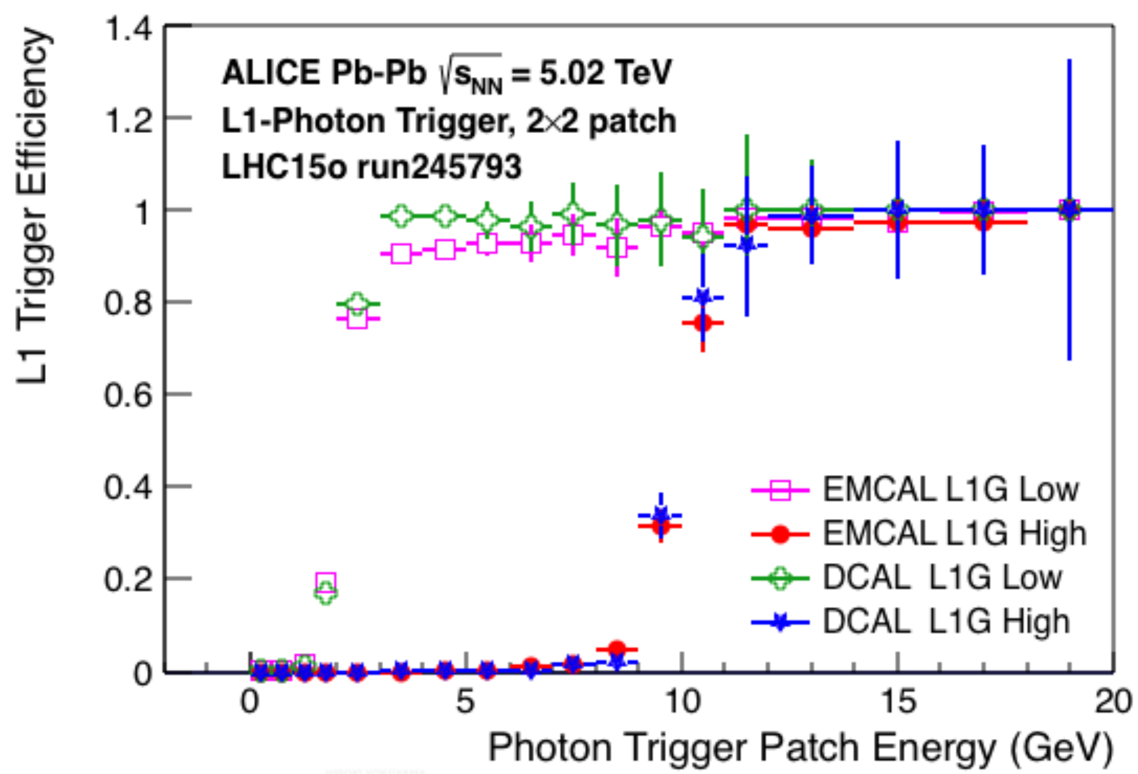
figures by Rosi, and Marta

Trigger System of ALICE Calorimeters



L1-Jet/photon trigger efficiency





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

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

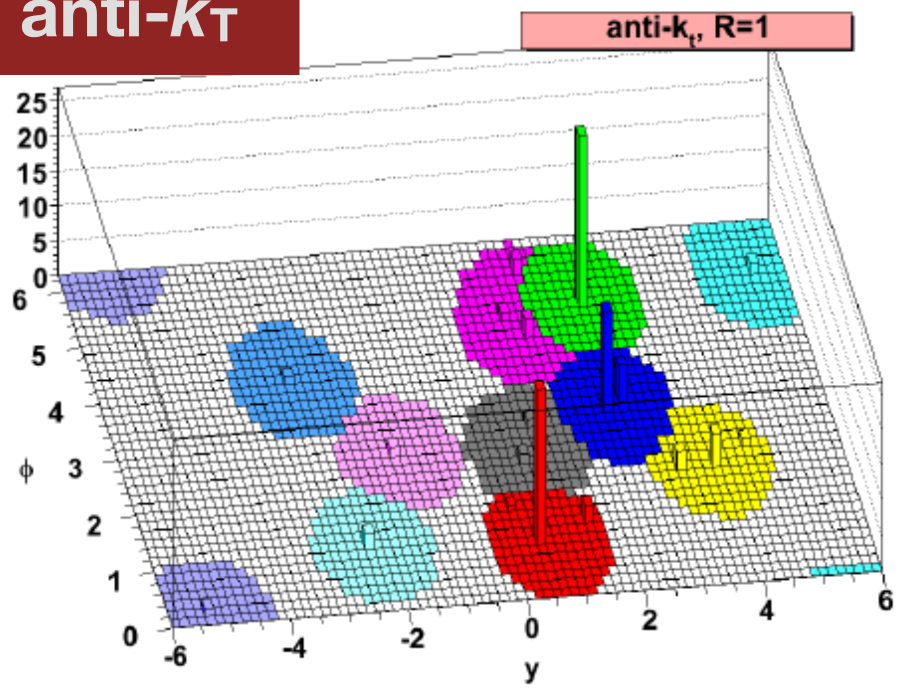
$$d_{iB} = k_{ti}^{2p} ,$$

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

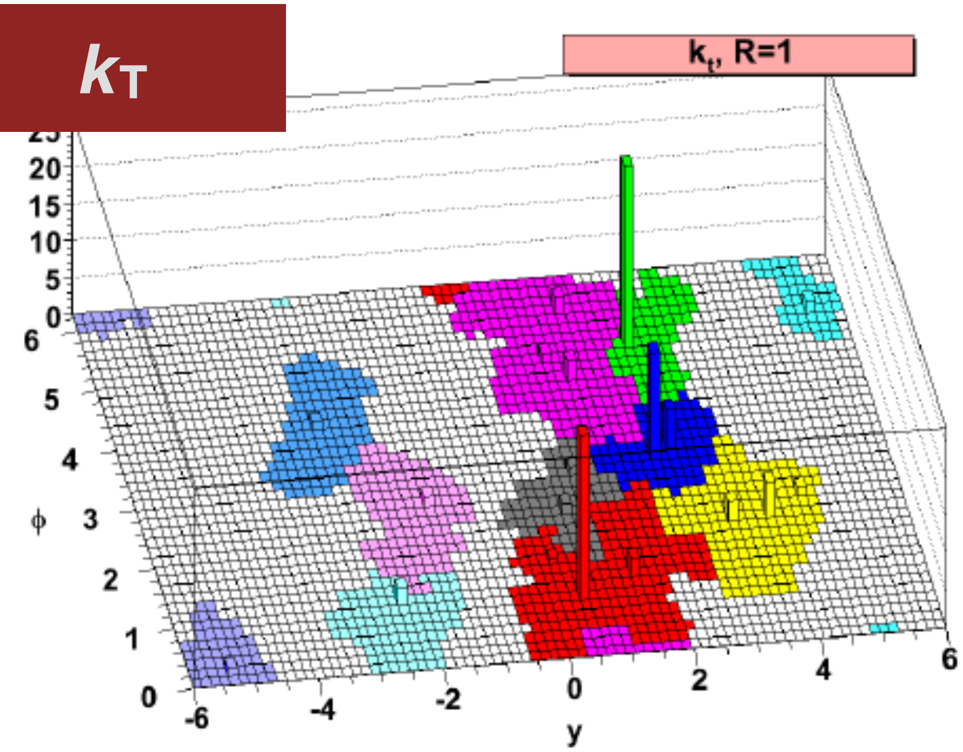
Jet Reconstruction

- **Combine/classify particles into clusters sequentially**
  - based on p_T weighted distance
  - (correspondence between parton level and detector level).
- **Anti-k_T algorithm**
  - start clustering from high-p_T particles ⇒ **Signal Jet** in Heavy Ion collisions
  - Circular and centred around harder energy deposit (with radius ~R)
- **k_T algorithm**
  - start clustering from low-p_T particles ⇒ **Estimation of Soft BKG**

anti-k_T



k_T



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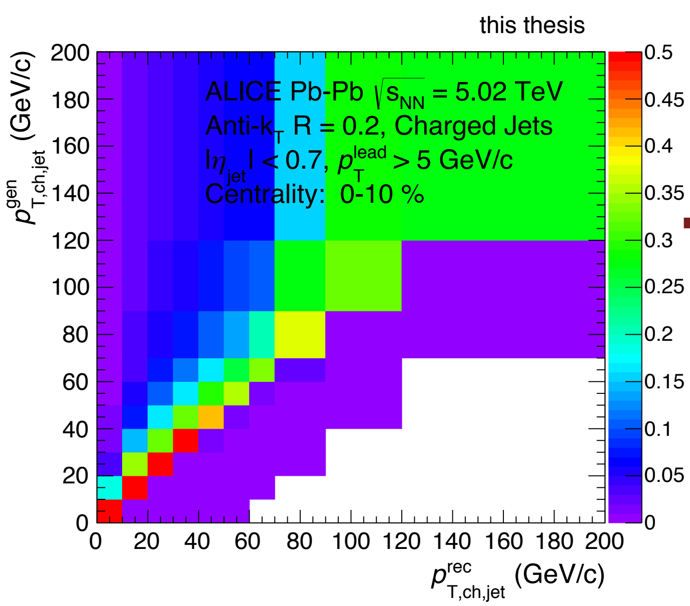
Unfolding

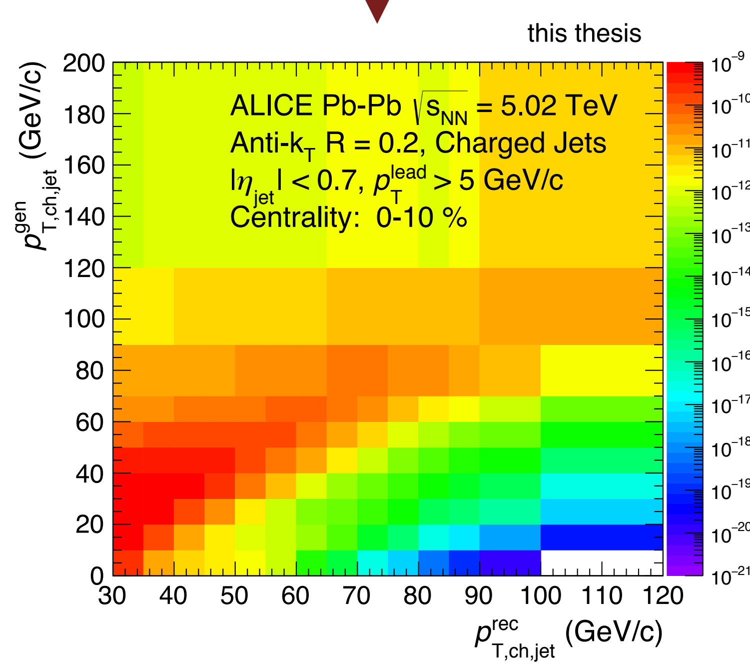
☑detector RM

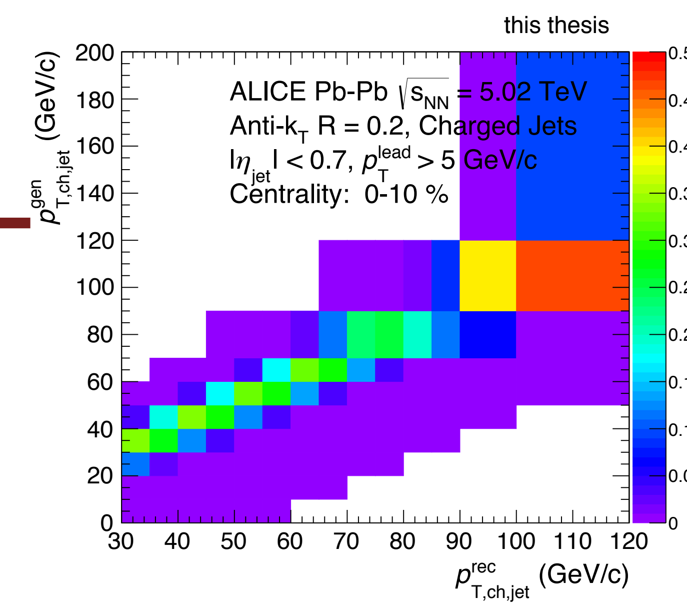
- given by PYTHIA
- track reduction according to tracking inefficiency in Pb-Pb collisions

☑background RM

- created by δp_T distribution (w/o lead. jet)







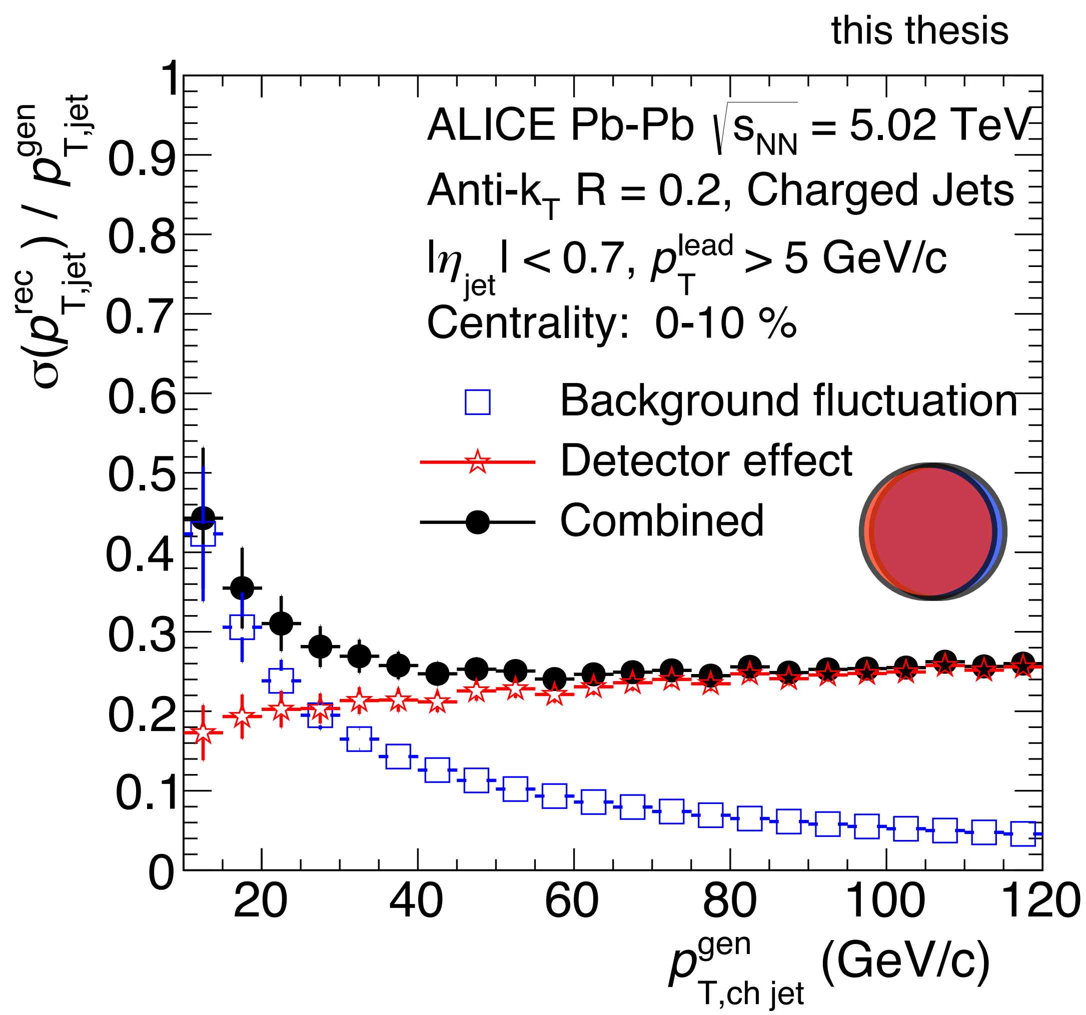
unfold spectrum with combined RM

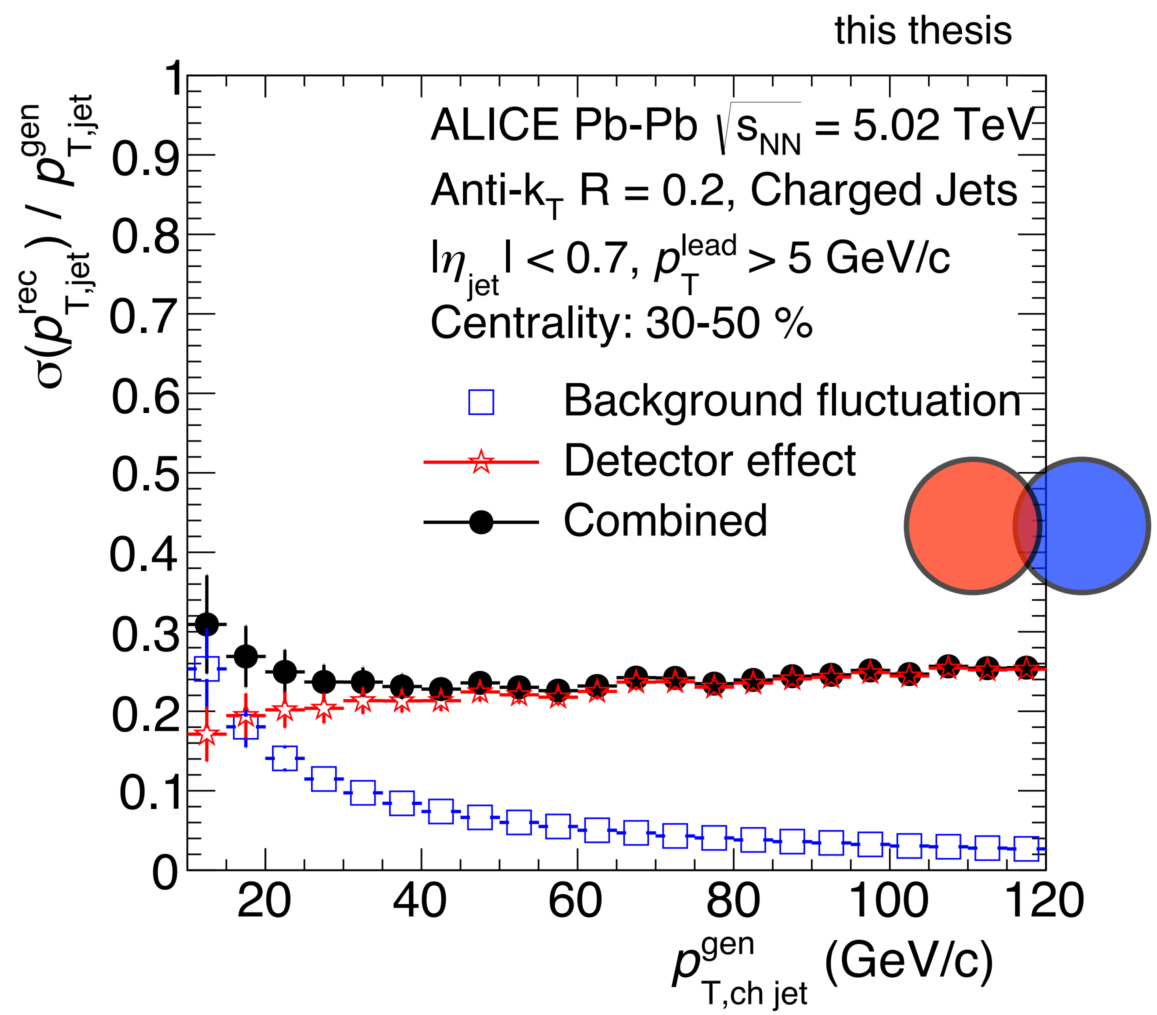
☑Jet finding efficiency

- given by PYTHIA
- same track reduction and p_T^{lead} selection with detector RM.

Jet Energy Resolution

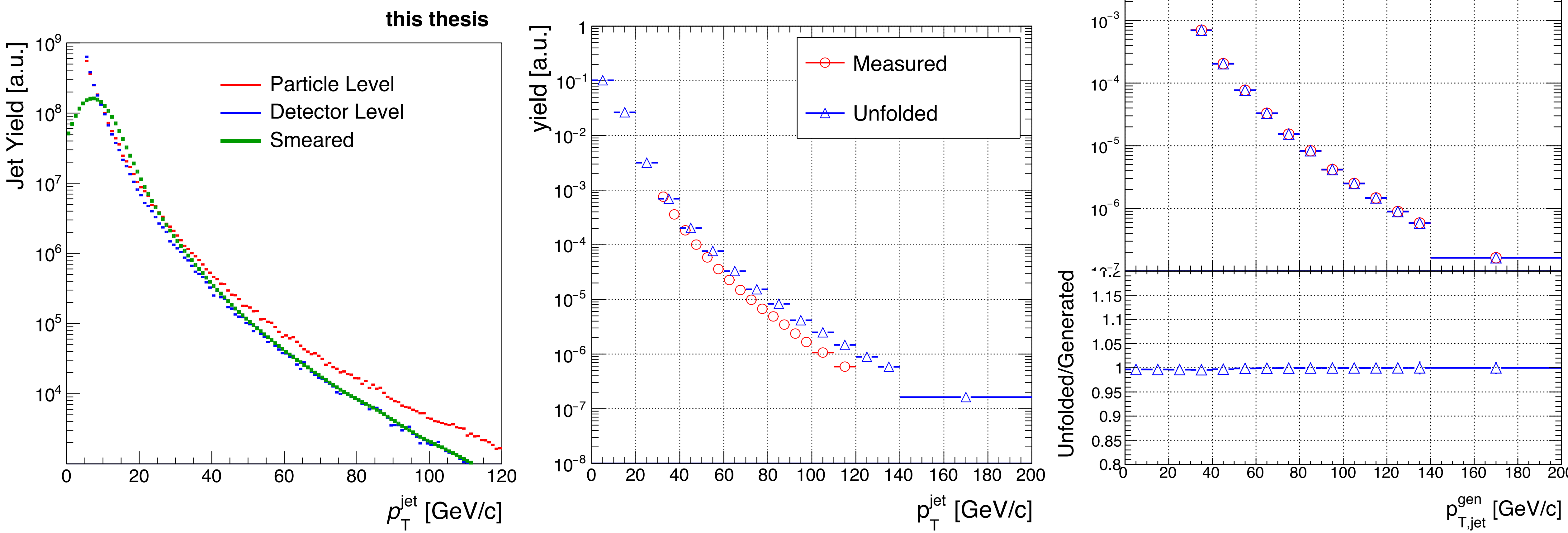
- Jet energy resolution is derived by the Response Matrixes
- Effect from Underlying Event Fluctuation
  - dominant in lower jet pT
- Detector Effect
  - dominant at higher jet pT





Unfolding QA

- particle level : PYTHIA8
- detector level : PYTHIA8 + GEANT
- measured spectrum
  - smeared detector level jet spectrum
  - BKG fluctuation σ = 4 GeV/c assumed
- Unfolded and Generated match within 1~2%accuracy



Systematic Uncertainty

☑ **Unfolding Procedure (shape unc.)**

1. **unfolded p_T range**
2. **measured p_T range**
3. **Unfolding method** (SVD)
   - Bayesian unfolding
4. **Regularisation parameter**
5. **Generator selection**

☑ **δpT distribution (correlated unc.)**

6. **RC selection** (without lead. jet Δr < 1.0)
   - Δr < 0.5 and 1.5
   - apart from 1st and 2nd lead. jets

☑ **UE density due to elliptic flow (correlated unc.)**

7. **Flow Bias**
   - ± 4 *GeV*/c for background density

☑ **Tracking efficiency and resolution (correlated unc.)**

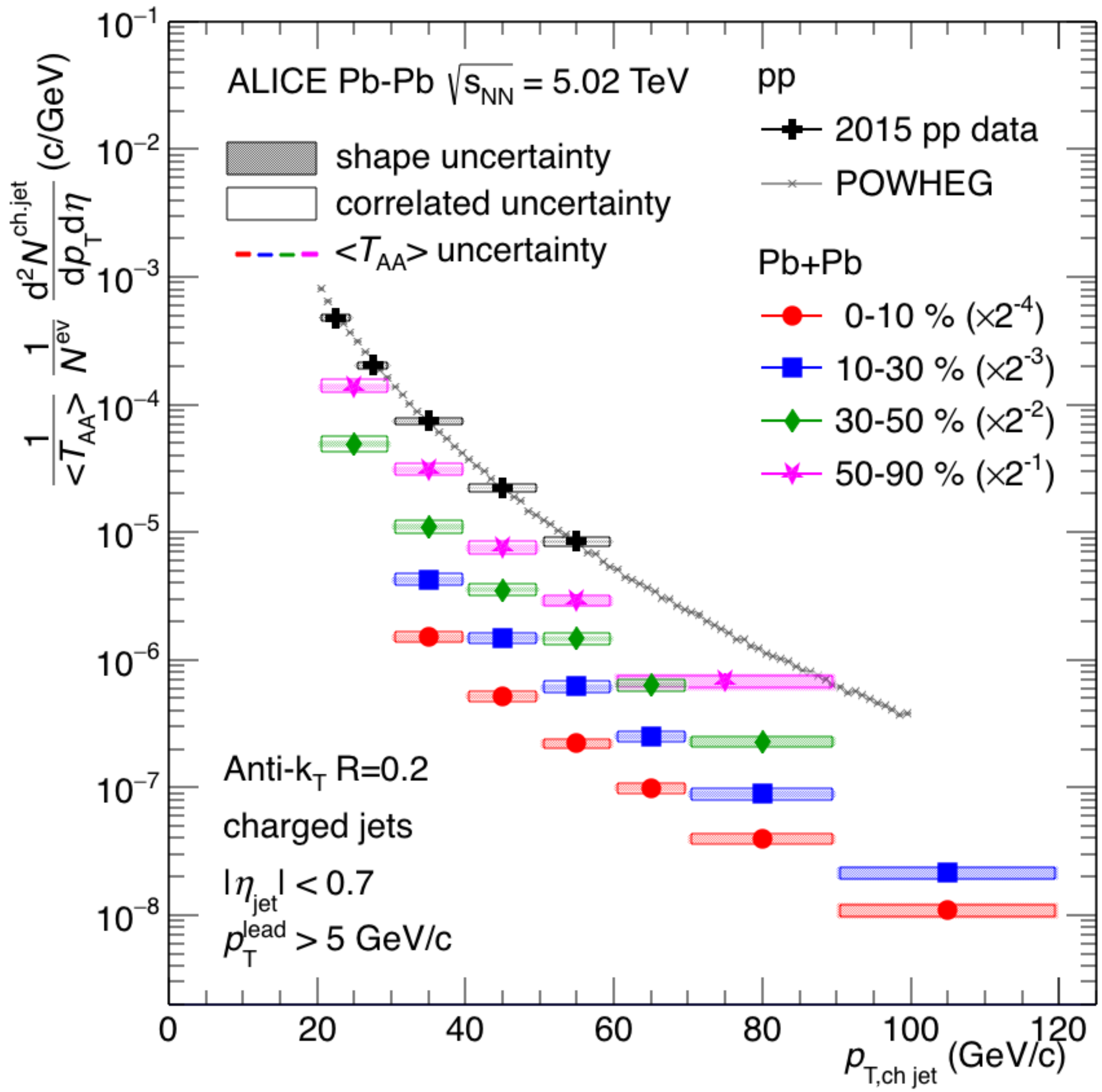
8. **Tracking Efficiency**
   - ± 4% from nominal value
9. **Tracking Efficiency**
   - ± 20% from nominal value

$p_{\mathrm{T,ch\,jet}}$	50 - 60 GeV/c
p_{T} range unfolded	± 1.0
p_{T} range measured	± 1.2
Unfolding method	± 4.4
Regularisation	± 2.4
Generator/Prior	± 5.7
Total shape uncertainty	± 7.7
δp_{T}	$^{+3.8}_{-0.9}$
Flow bias	$^{+4.7}_{-4.4}$
Tracking efficiency	± 6.8
Tracking resolution	± 3.4
Total correlated uncertainty	$^{+9.7}_{-8.8}$

0-10 % centrality

<N_{coll}> scaled Charged Jet Cross Section

this thesis



pp Inclusive Jet Cross Section

Jet cross section at $\sqrt{s}$ = 5.02 TeV pp collisions in 2015

- POWHEG NLO calculations well describes measured spectrum within systematic uncertainties

Ritsuya Hosokawa

Dataset

- $\sqrt{s}$ = 5.02 TeV, pp collisions
- MB triggered events (25.5M events)

Charged track selection

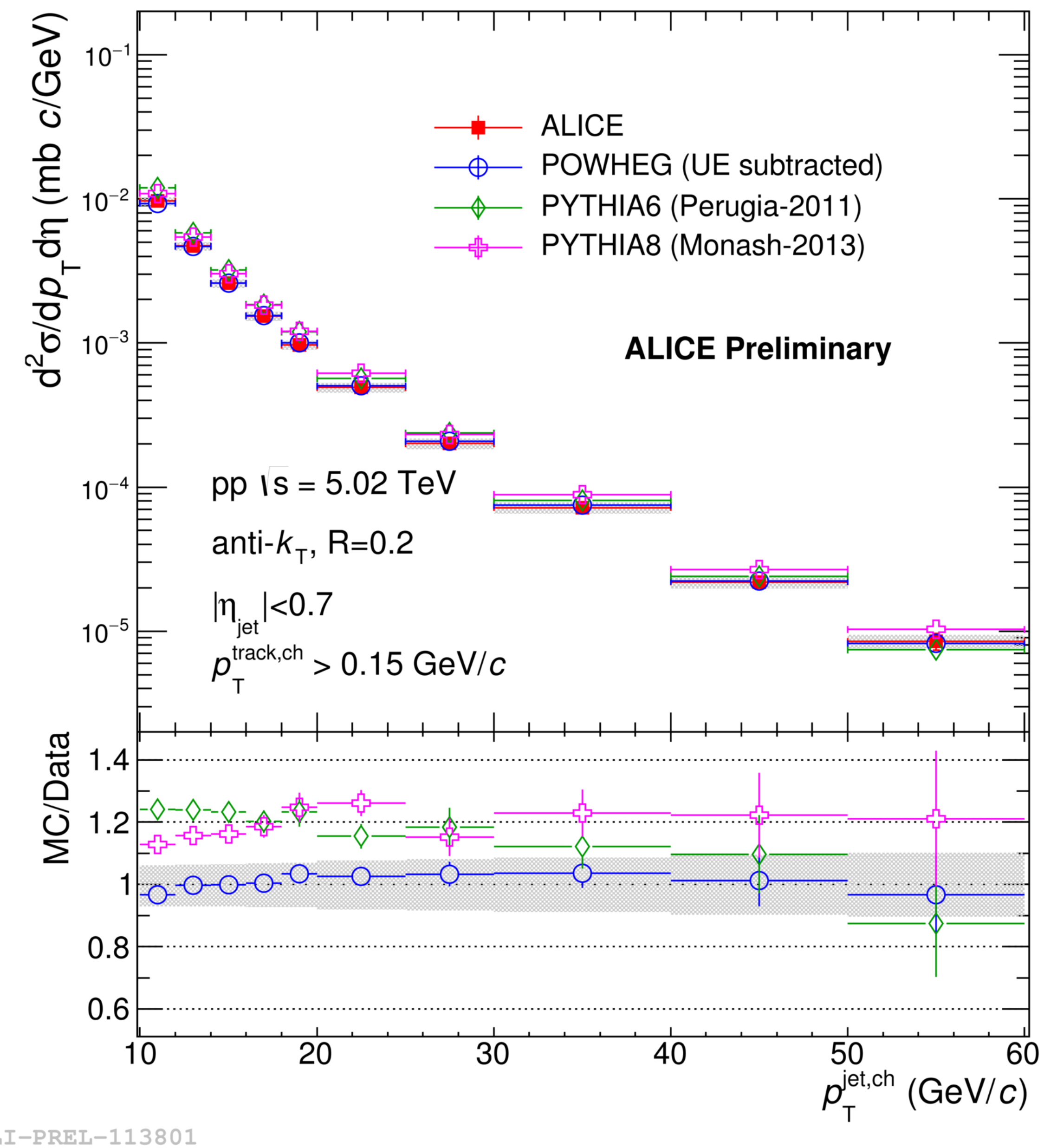
- $|\eta| < 0.9$, $p_T^{track} > 0.15$ GeV/c

Jet reconstruction

- anti-kt jet reconstruction algorithm
- R = 0.2
- $|\eta| < 0.7$, ($p_T^{lead} > 5$ GeV/c for R_{AA} ref.)

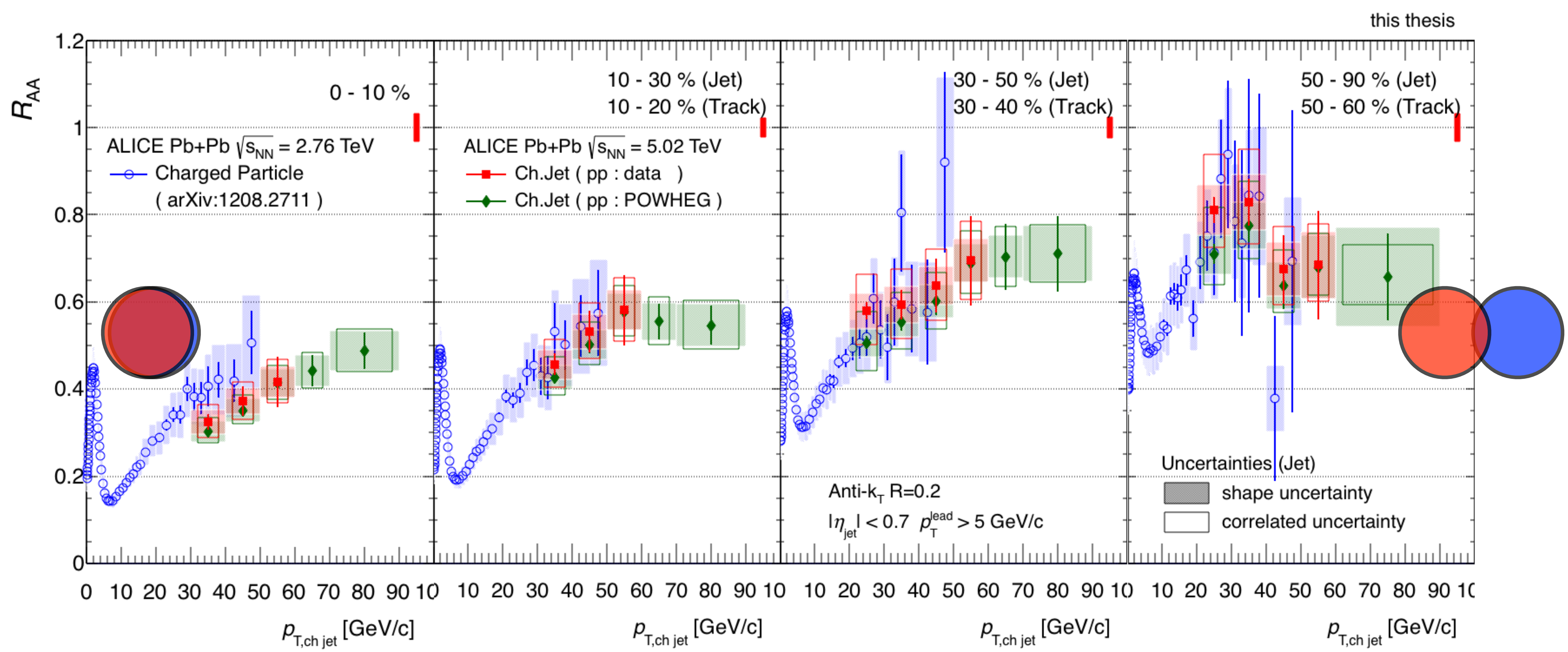
Unfolding

- to correct for detector effects



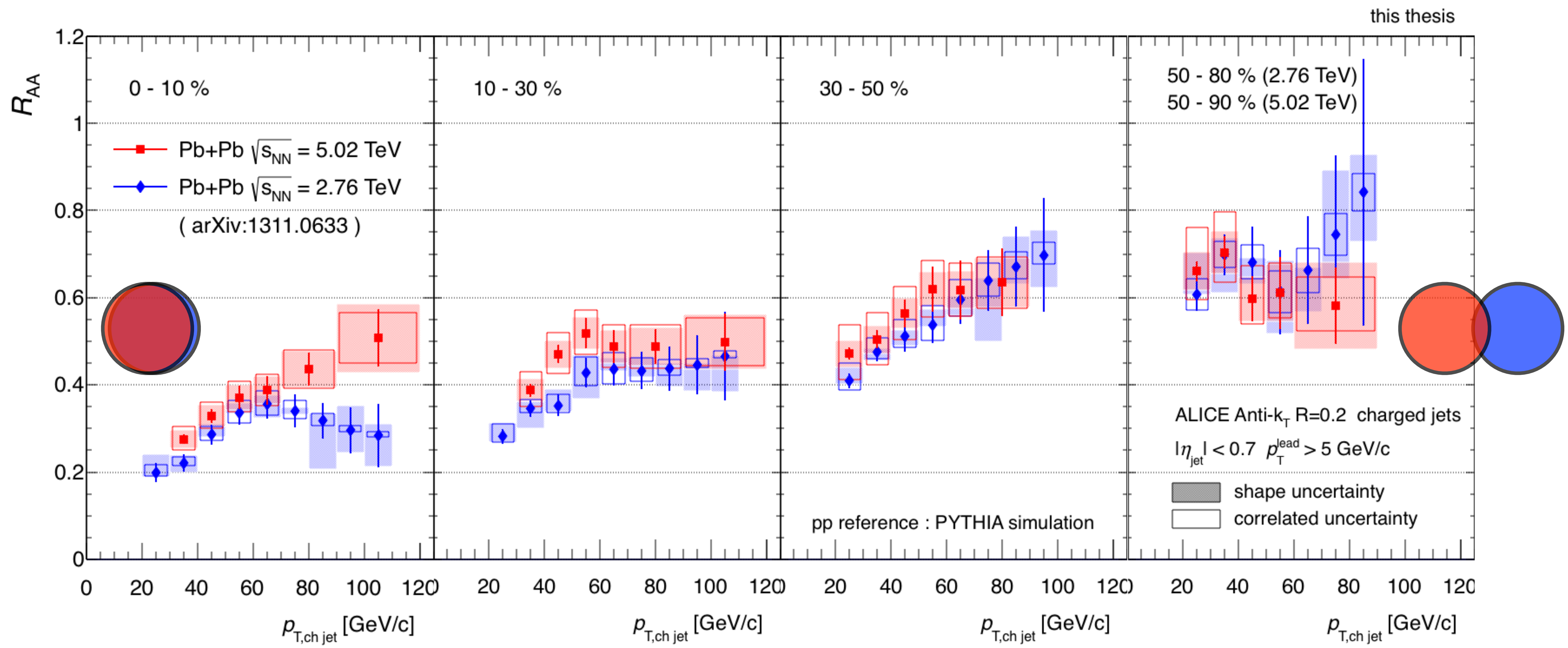
Comparison with Charged Particle ($\sqrt{s_{NN}}$ = 2.76 TeV)

- ☑ Energy scale is different
  - momentum fraction of leading track : ~0.5 (in pp collisions)
- ☑ Roughly consistent with jet RAA
  - after energy scaling

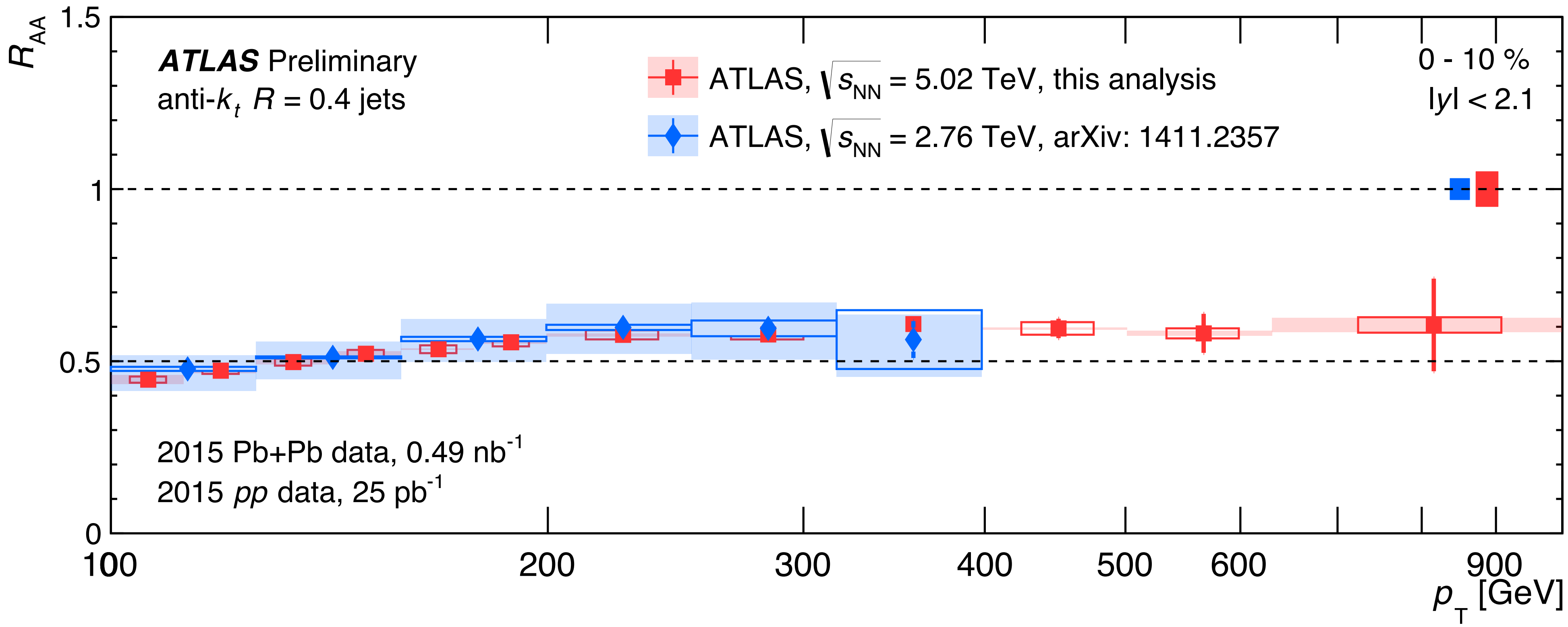


Comparison with $\sqrt{s_{NN}}$ = 2.76 TeV

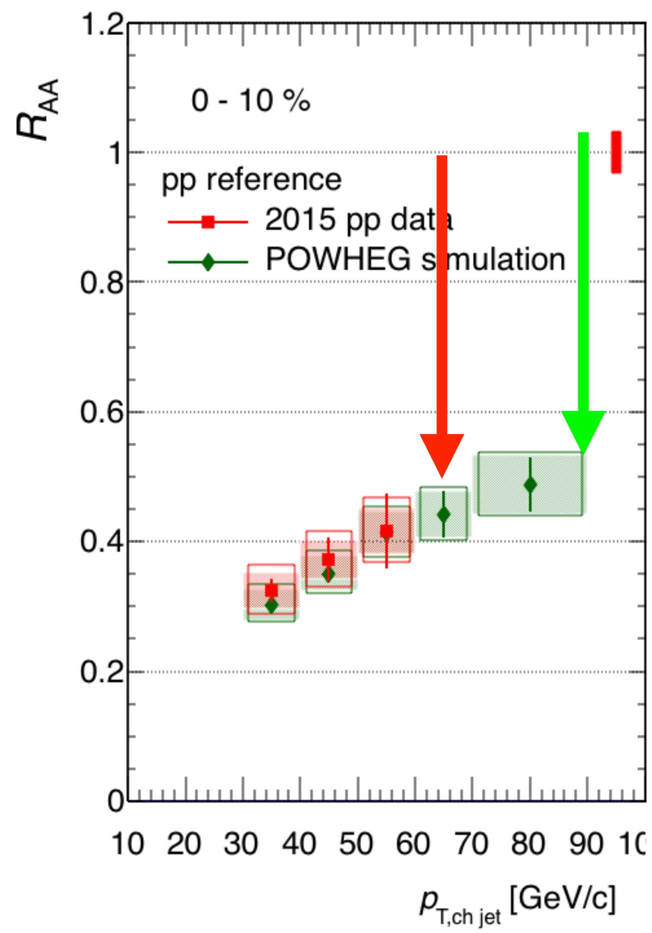
- ☑ **ALICE, Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV, R=0.2 charged jet**
  - pp reference : PYTHIA MC
- ☑ **Equivalent R_{AA}**
  - hotter/denser medium ⇒ stronger jet suppression ⇒ smaller R_{AA}
  - harder collision ⇒ flatter jet spectrum ⇒ larger R_{AA}

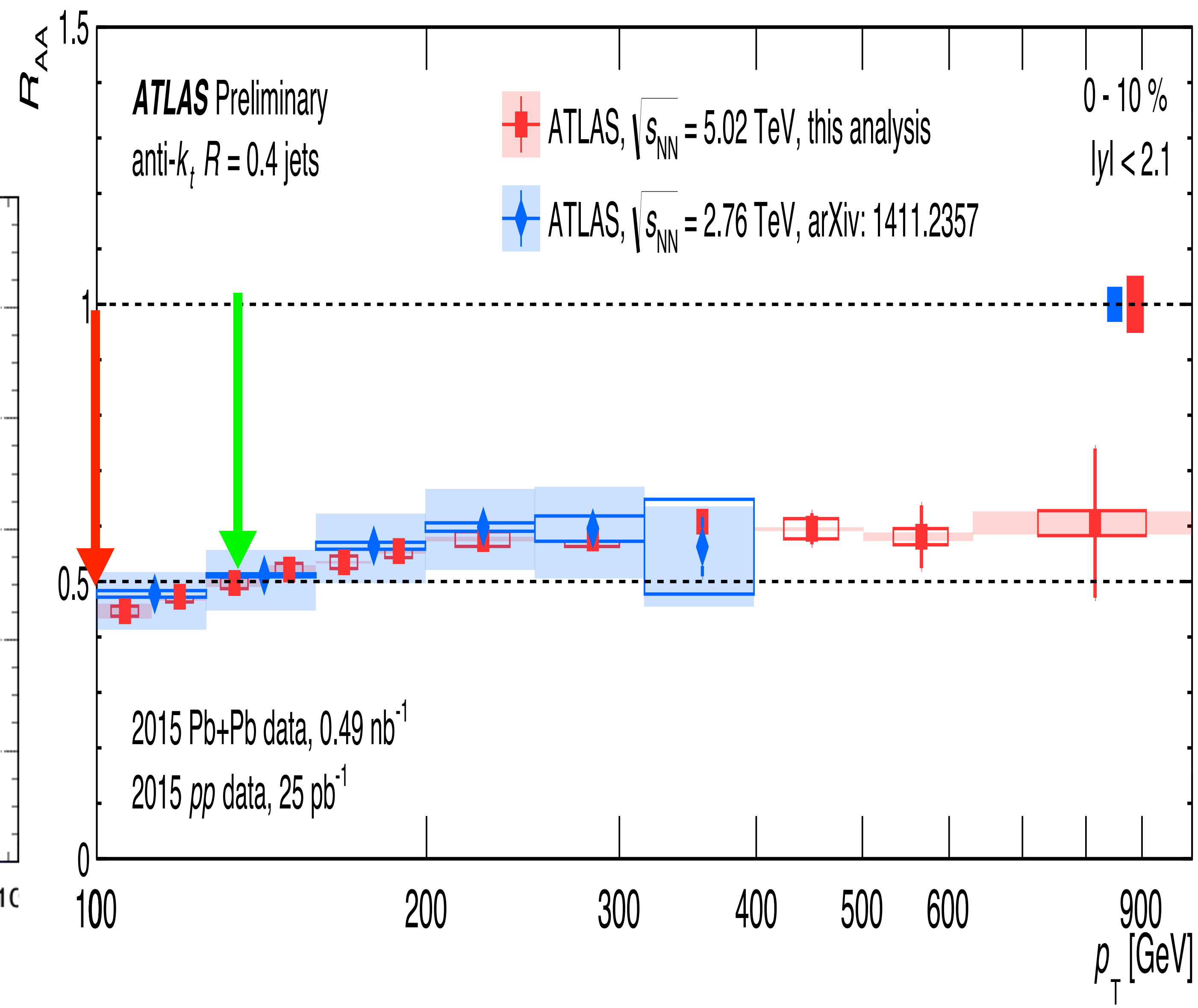


ATLAS jet RAA : 5.02 TeV vs. 2.76 TeV

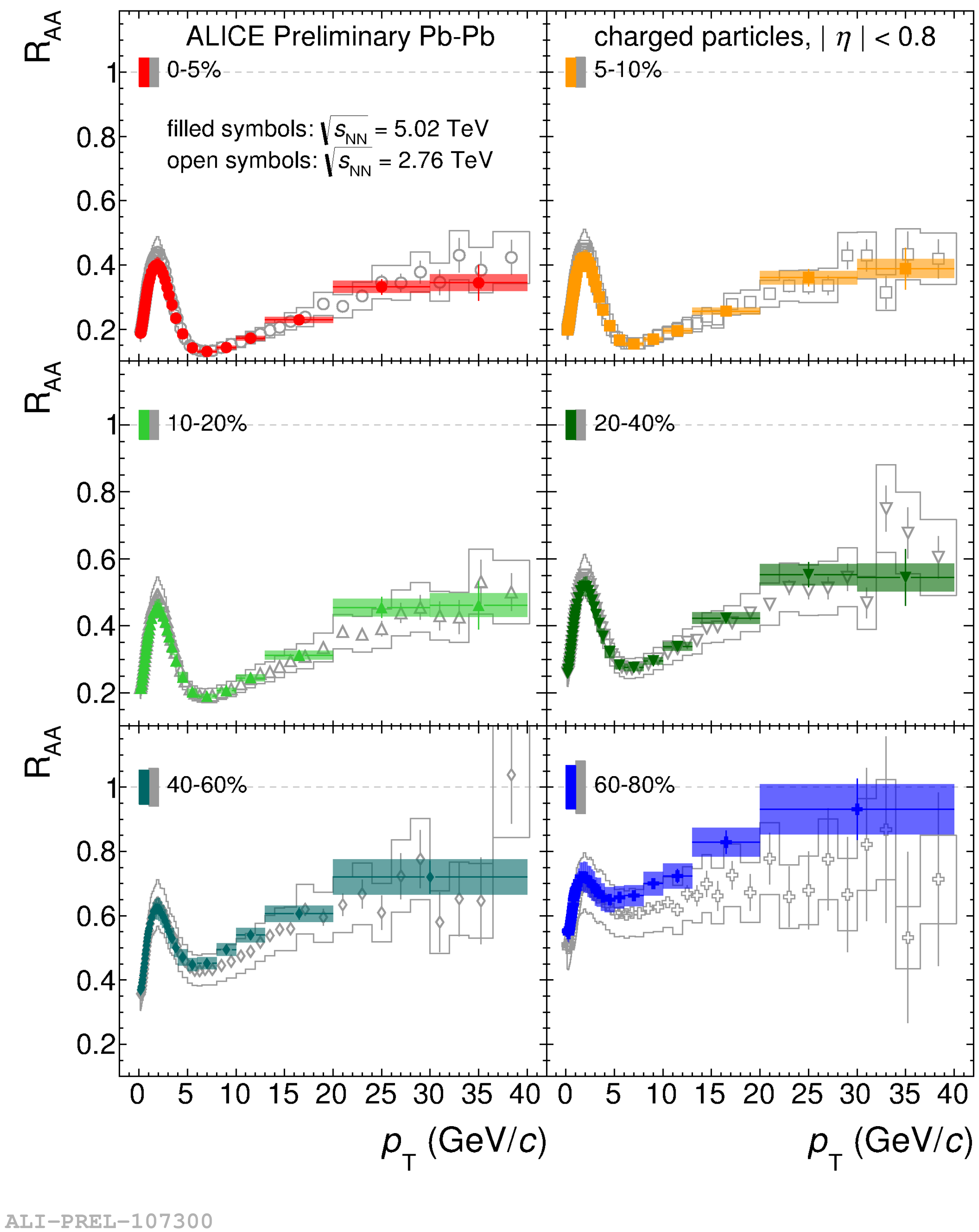


Comparison to ATLAS jet RAA





ALICE ch. particle RAA : 5.02 TeV vs. 2.76 TeV



RAA : cone size dependence @ CMS

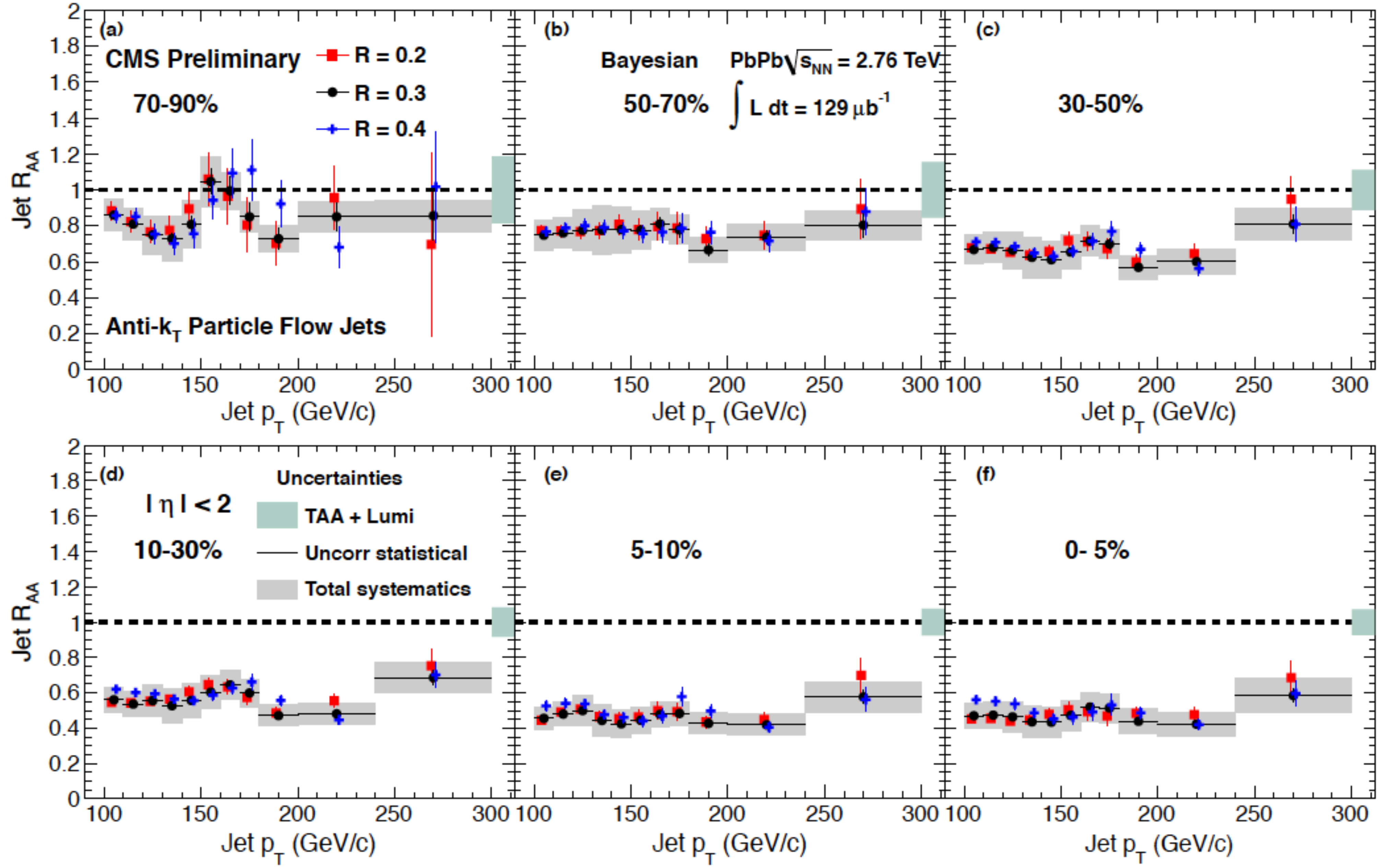


Figure 7: Jet R_{AA} in different effective cone sizes for anti-k_T jets using the Bayesian unfolding method for the given centrality bins. The vertical lines indicate uncorrelated statistical uncertainty, and the wide band the systematic uncertainty for Bayesian unfolding R=0.3. The green box above 300 GeV/c represents the overall combined uncertainty from T_{AA} and luminosities.