Inclusive charged jet spectra in pp and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

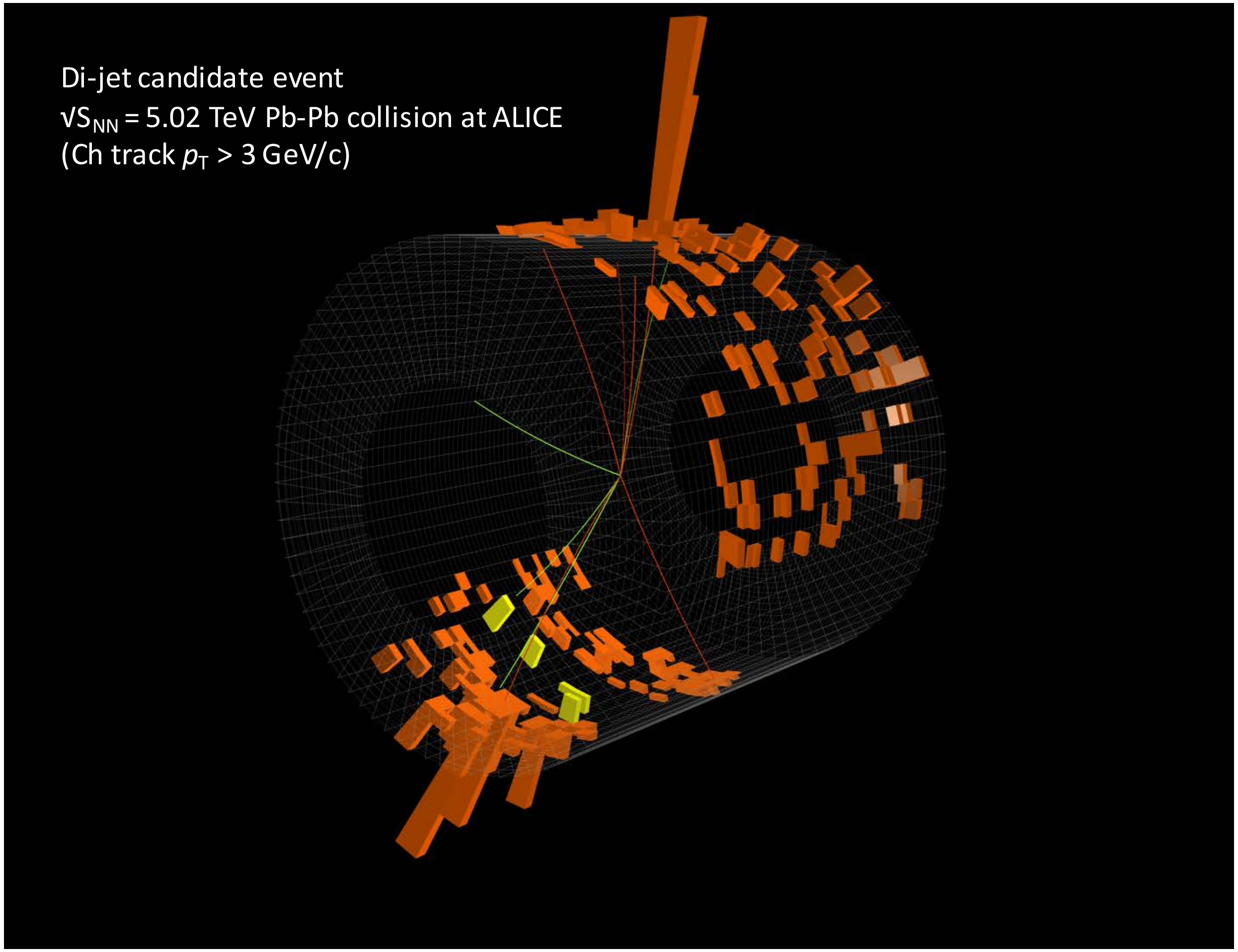
Ritsuya Hosokawa

University of Tsukuba, Japan
LPSC CNRS/IN2P3, Université Grenoble Alpes,France

Outline

- Introduction
  - Jet
  - Physics motivation
- ALICE experiment
- Results: Inclusive charged jet spectra measurements
- Summary and outlook

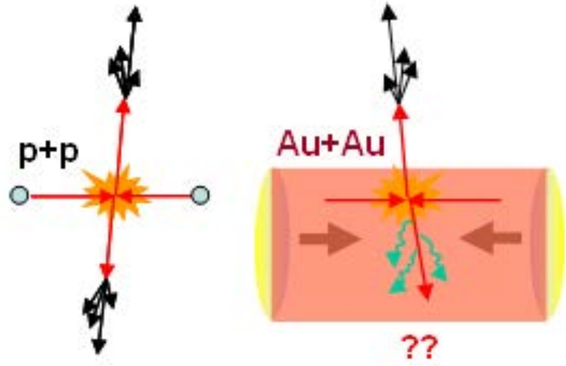
Jet



- Collimated spray of hadrons originated from hard scattered partons at the initial stage of collision

Physics motivations

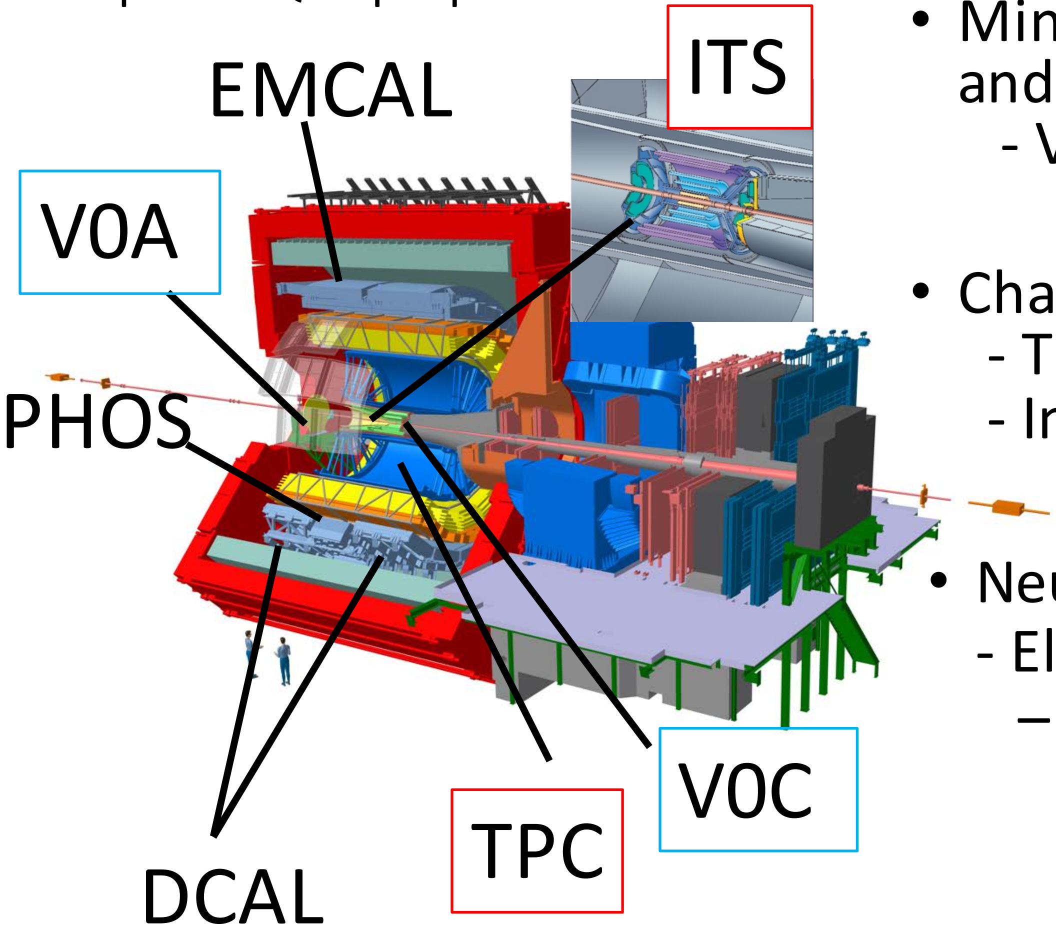
- pp collisions
  - Good test of pQCD calculations and MC generators for high energy physics
  - Reference for heavy ion collisions
- Pb-Pb collisions
  - Jets are well established probe for Quark-Gluon-Plasma (QGP) properties
    – QGP lifetime in heavy ion collisions is very short (~10^{-23})
      → Self produced probes, like jets, allows to access QGP properties
    – Jets are produced at an very early stage of collision
      → entire QGP evolution can be proved
  - Jets are modified while traversing the QGP
      → **Jet quenching effect**
        – QGP properties can be probed by evaluating the effect (Nuclear modification factor(R_{AA}), Jet shape…)



https://www.star.bnl.gov/

ALICE experiment

- Specialized for measurements of heavy ion collisions
- Explores QGP properties



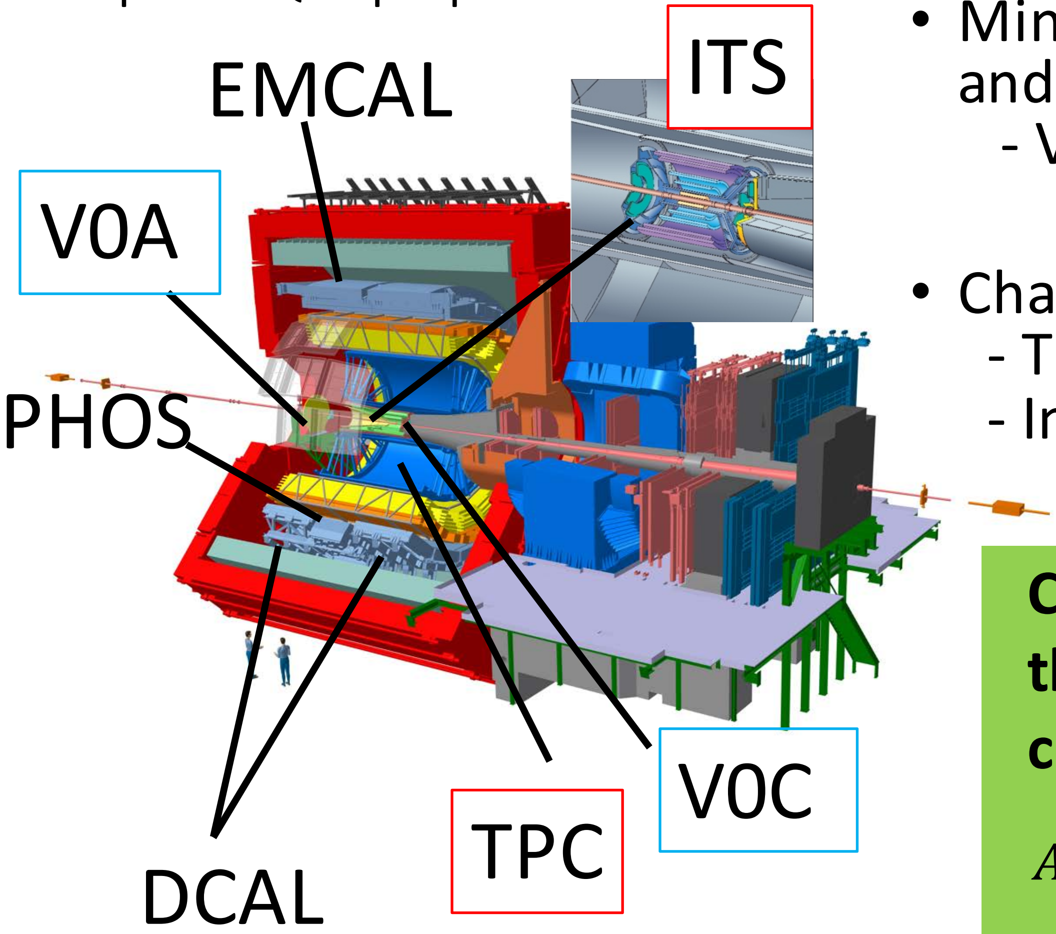
- Minimum bias event triggering and centrality determination
  - V0A,C

- Charged particle tracking
  - Time Projection Chamber (TPC)
  - Inner Tracking System (ITS)

- Neutral components measurement
  - Electro Magnetic Calorimeters
    – EMCAL, DCAL, (PHOS)

ALICE experiment

- Specialized for measurements of heavy ion collisions
- Explores QGP properties

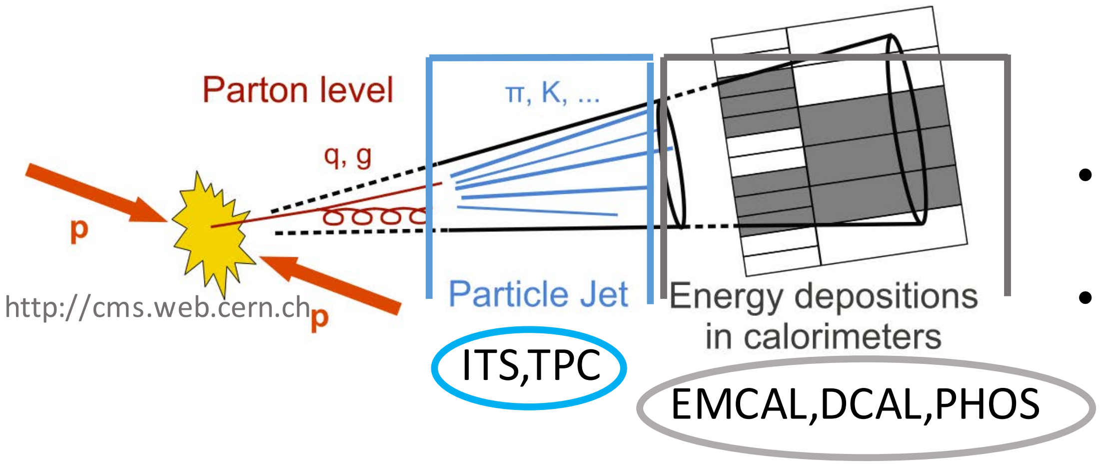


- Minimum bias event triggering and centrality determination
  - V0A,C
- Charged particle tracking
  - Time Projection Chamber (TPC)
  - Inner Tracking System (ITS)

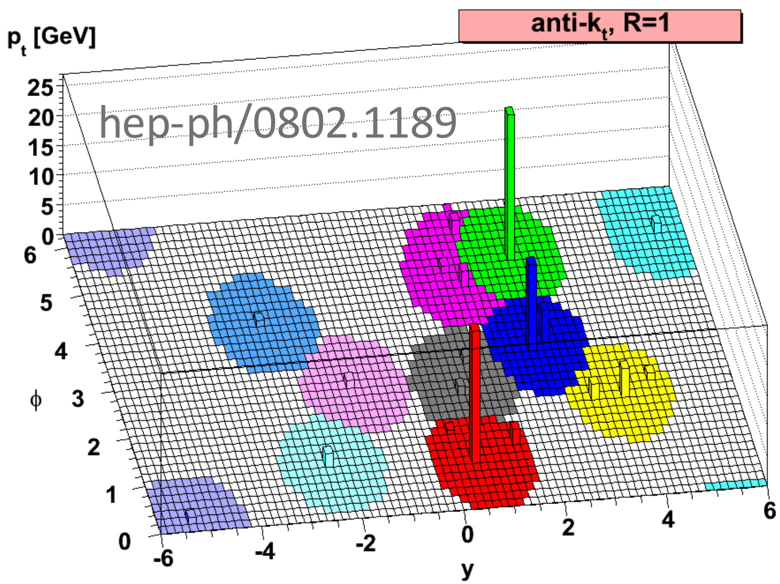
Charged jets were measured in this analysis with central barrel charged tracking detectors

$Acceptance: \; 0 < \varphi < 2\pi \, , \; |0.9| < \eta$

Jet reconstruction



- Signal jets were reconstructed by anti-k_t algorithm
- Background was estimated with jets reconstructed by k_t algorithm (p.12 in this slide)



1) Include all particles in the cluster list.

2) Calculate

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

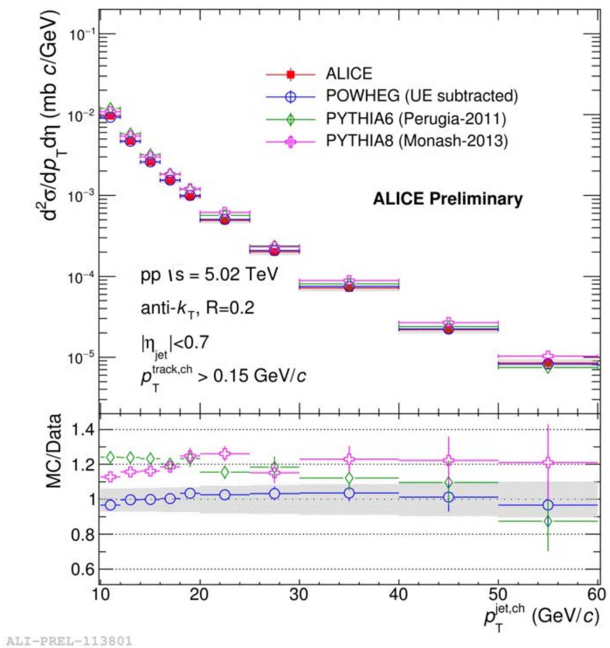
Where, p=-1,* $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, k_{ti}, y_i and ϕ_i are respectively the transverse momentum, rapidity and azimuth of particle i. R is radius parameter.

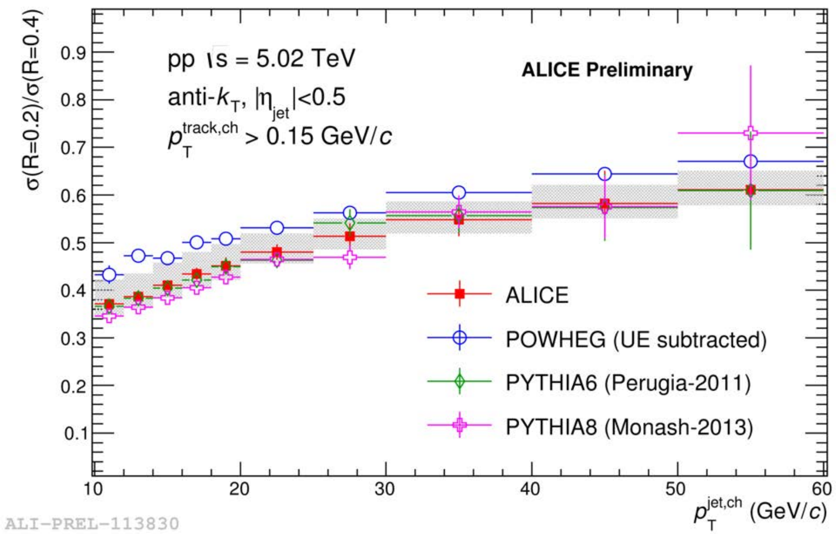
3) Set minimum value of d_{ij} and d_{iB} as $d_{\min}$. If $d_{ij} = d_{\min}$,calculate the sum of four-momentum of cluster i and j which is weighted by energy, then set the cluster i and j as one cluster. If $d_{\min} = d_{iB}$, consider d_{iB} a Jet and then remove d_{iB} from cluster list.

*(p=-1: anti-k_t algorithm, p=1: k_t algorithm)

Results: pp 5.02 TeV

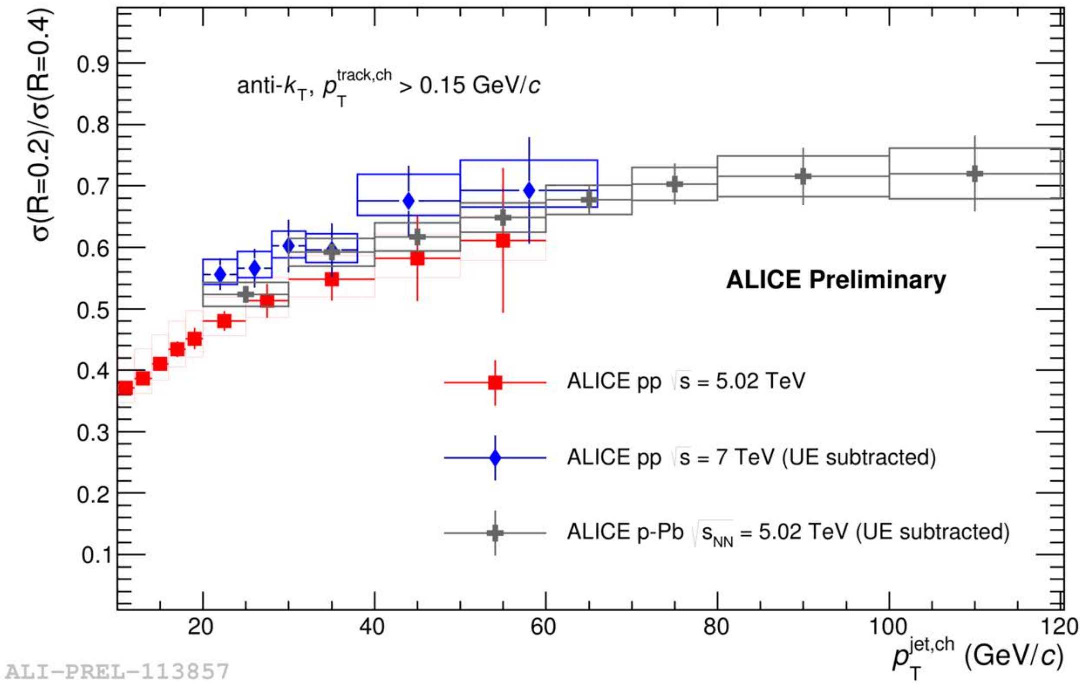
Inclusive charged jet cross section





- Differential charged jet cross section
  - Detector effects in real data were corrected by the SVD unfolding method with detector response extracted from MC simulation
  - Well described by POWHEG NLO calculation within systematic uncertainties
- Jet cross section ratio of R = 0.2 and R = 0.4 jets
  - Sensitive to the jet structure
  - Indicates stronger jet collimation at higher jet p_T
  - Well described by POWHEG and PYTHIA

Comparison with pp and p-Pb results



- No significant dependency on collision energy and collision system
  - Supports preceding study (Phys. Lett. B749 (2015) 68-81)

Results: Pb-Pb 5.02 TeV

Underlying event in Pb-Pb collisions

- Difficulty on heavy ion collisions
  - Large background (Underlying event, UE) to be subtracted

- Background density

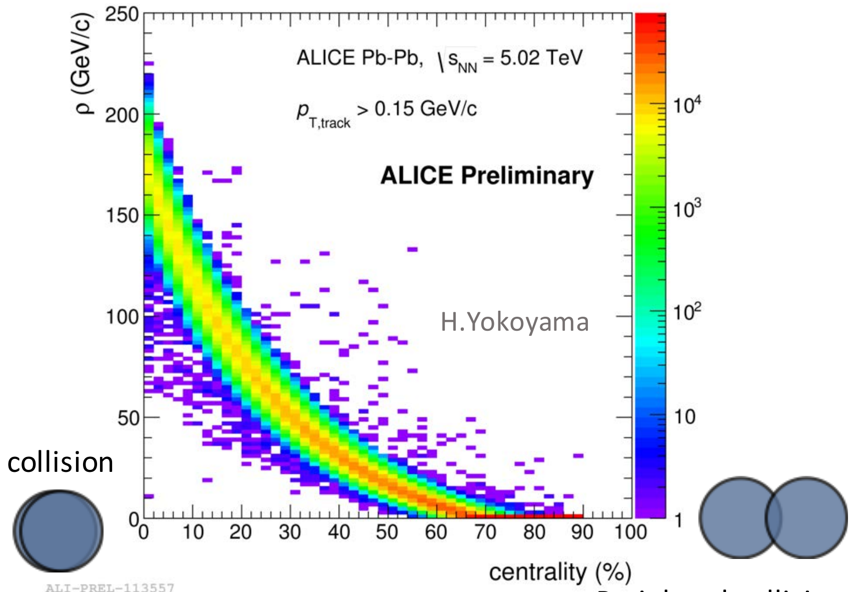
$$\rho = median\left\{\frac{p_{\mathrm{T,jet}}^{k_t}}{A_{i,\mathrm{jet}}}\right\}$$

  - here, $p_{\mathrm{T,jet}}^{k_t}$ are jets reconstructed by k_{t} algorithm
  - A_{jet}: jet area
  - excluding the highest p_{T} tow jets

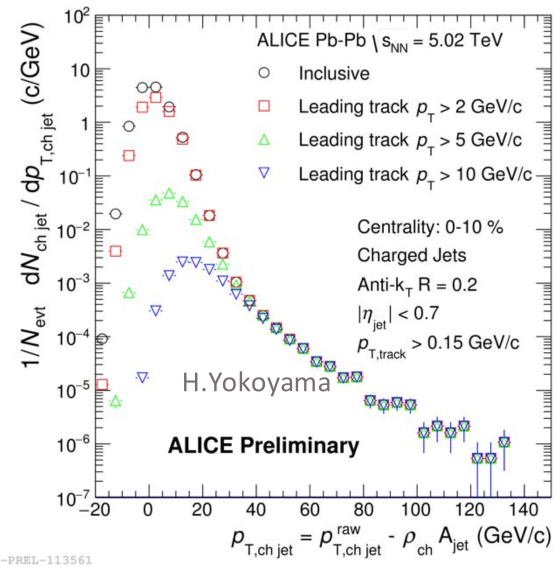
- Background subtraction

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

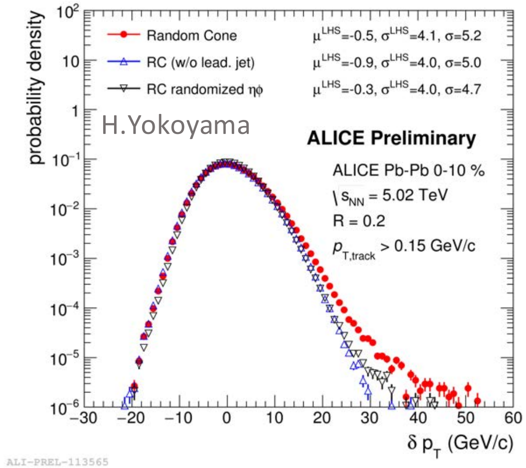
Central collision

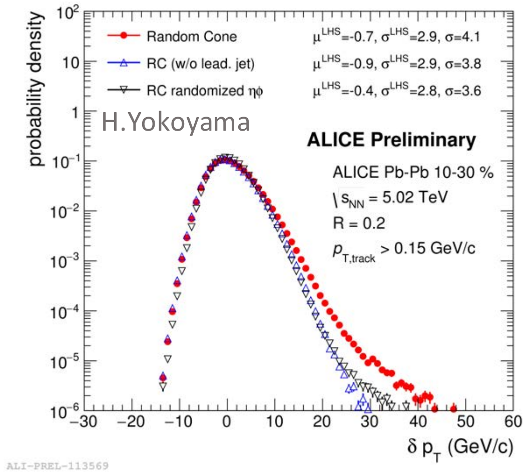


Peripheral collision



Underlying event in Pb-Pb collisions





- Underlying event fluctuation: δp_{T}

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

  RC: random cone

- 3 methods were tested
  1) Simply apply random cone without any limitations
  2) RC apart from leading jet ($\Delta r > 1.0$)
     - can be reduced contributions from signal jets component

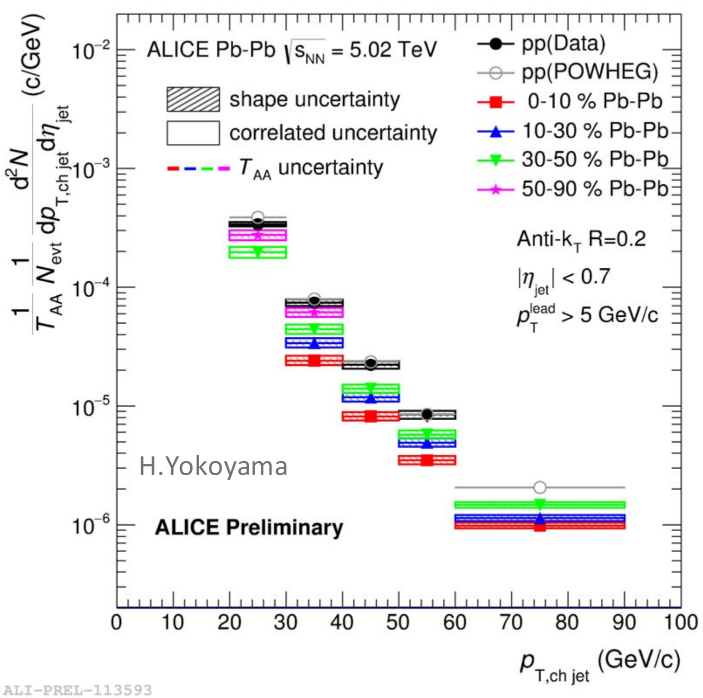
$$\Delta r = \sqrt{(\eta_{RC} - \eta_{jet})^2 + (\phi_{RC} - \phi_{jet})^2}$$

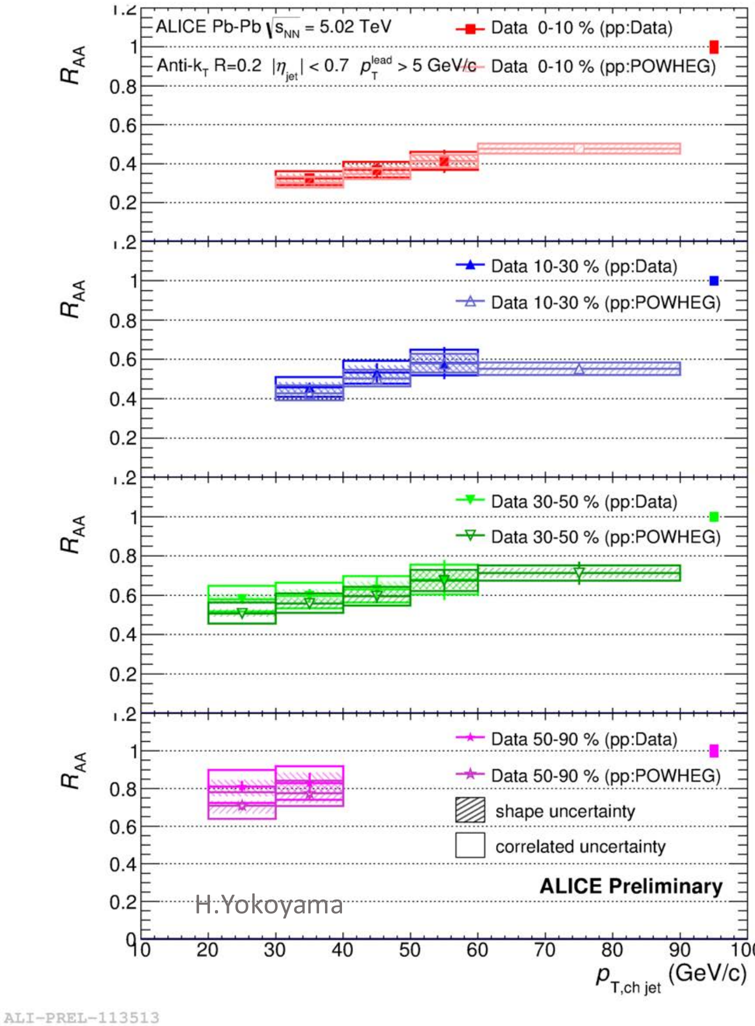
  3) randomized track(η,ϕ)
     - to exclude flow effect

In this analysis, 2) was selected as UE fluctuation

Charged jet nuclear modification factor: R_{AA}

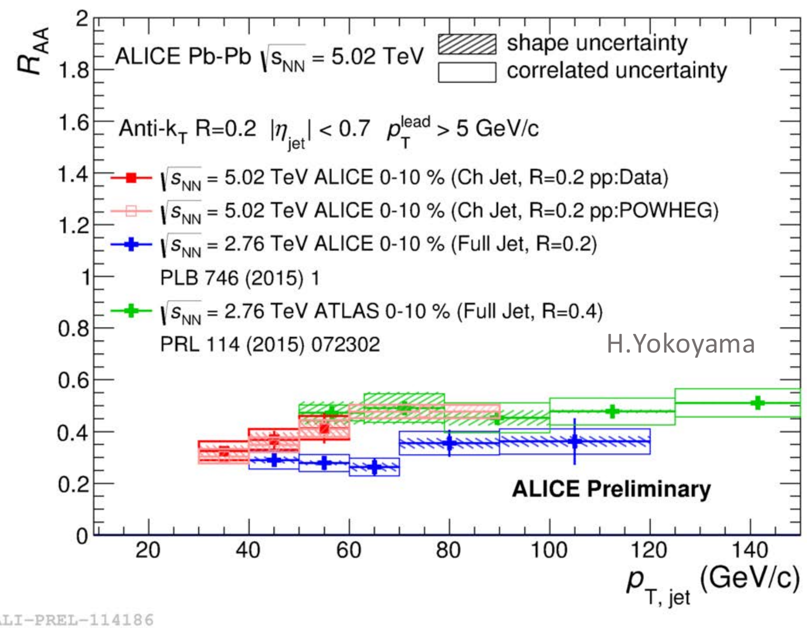
$$\frac{d^2\sigma}{dp_T d\eta} = \frac{\langle N_{coll}\rangle}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{dN^2_{ch\ jet}}{dp_T d\eta} \qquad R_{AA} = \frac{\frac{1}{\langle T_{AA}\rangle}\frac{1}{N_{evt}}\frac{dN_{ch\ jet}}{dp_T d\eta}}{\frac{d\sigma_{pp}}{dp_T d\eta}}$$

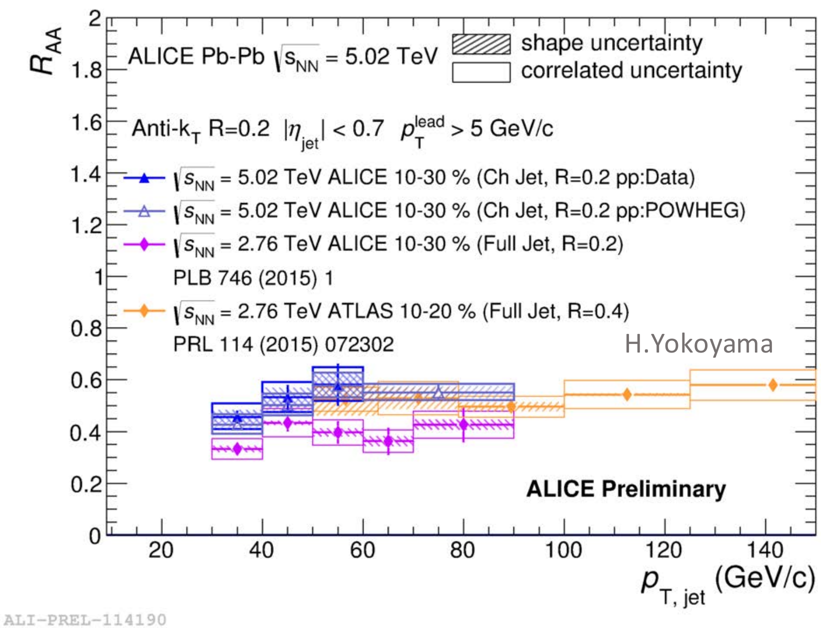




- Spectra in Pb-Pb collisions are corrected by SVD unfolding with detector(from MC) and background response(from data)
- Strong suppression at central collisions
  - Centrality dependence of the suppression
- Difference of pp reference (POWHEG or Real data)
  - Consistent within uncertainties

R_{AA} comparison with $\sqrt{S_{NN}}$ = 2.76 TeV





- Results at $\sqrt{S_{NN}}$ = 5.02 TeV are compared with…
  - Full jet R_{AA} in $\sqrt{S_{NN}}$ = 2.76 TeV collisions at ALICE (*R*=0.2)
  - Full jet R_{AA} in $\sqrt{S_{NN}}$ = 2.76 TeV collisions at ATLAS (*R*=0.4)

- Results at 5.02 TeV is comparable to the results at 2.76 TeV
  - Generally, more denser, hotter and ling time QGP formation is expected at higher $\sqrt{S_{NN}}$
  → Stronger suppression → decrease the R_{AA}

  - More harder (high p_T) jet generation is expected at higher $\sqrt{S_{NN}}$
  → flatter jet spectrum → increase the R_{AA}

→ effect of spectrum flattening is compensated by the stronger jet suppression

Summary

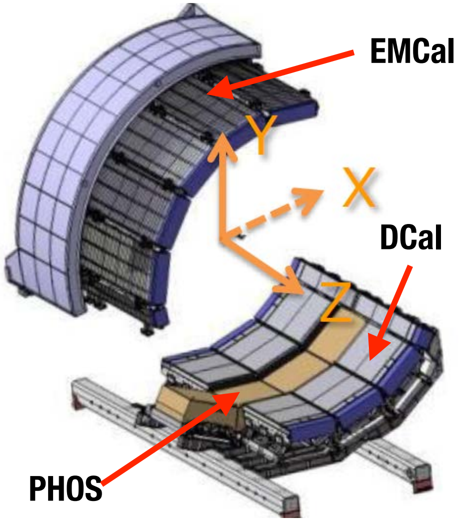
- First measurements of charged jet spectra and R_{AA} have been performed for LHC Run2 data at ALICE.

- pp collisions
  - Inclusive charged jet differential cross sections are well described by NLO calculation (POWHEG)
  - Jet cross section ratio is well described by POWHEG and PYTHIA
  - Reference for Pb-Pb collisions is established (~60 GeV/c)

- Pb-Pb collisions
  - Larger Underlying Event fluctuation is observed at most central collisions in comparison with peripheral collisions
  - Nuclear modification factor
    - Strong suppression is observed in central collisions
    - Comparable with the results in $\sqrt{S_{NN}}$ = 2.76 TeV collisions
    - effect of spectrum flattening is compensated by the stronger jet suppression

Outlook

- Extend jet p_T reach with more statistics
  (pp: ~25 % of full statistics, Pb-Pb: ~ few % of full statistics)
- Full jet measurement with calorimeters
  - Allows direct comparison with Run1(2.76 TeV) results



Back up

Data set and event selections: pp

- Data Set
  - Data: LHC15n pass2 lowIR(~25M events)
    MC: LHC15l1b2 (PYTHIA6, pp 5 TeV, Perugia-2011)
    MC: LHC15l1a2 (PYTHIA8, pp 5 TeV, Monash2013)
    MC: LHC16e1 (PYTHIA8, pp 5 TeV, Monash-2013, PtHard production)

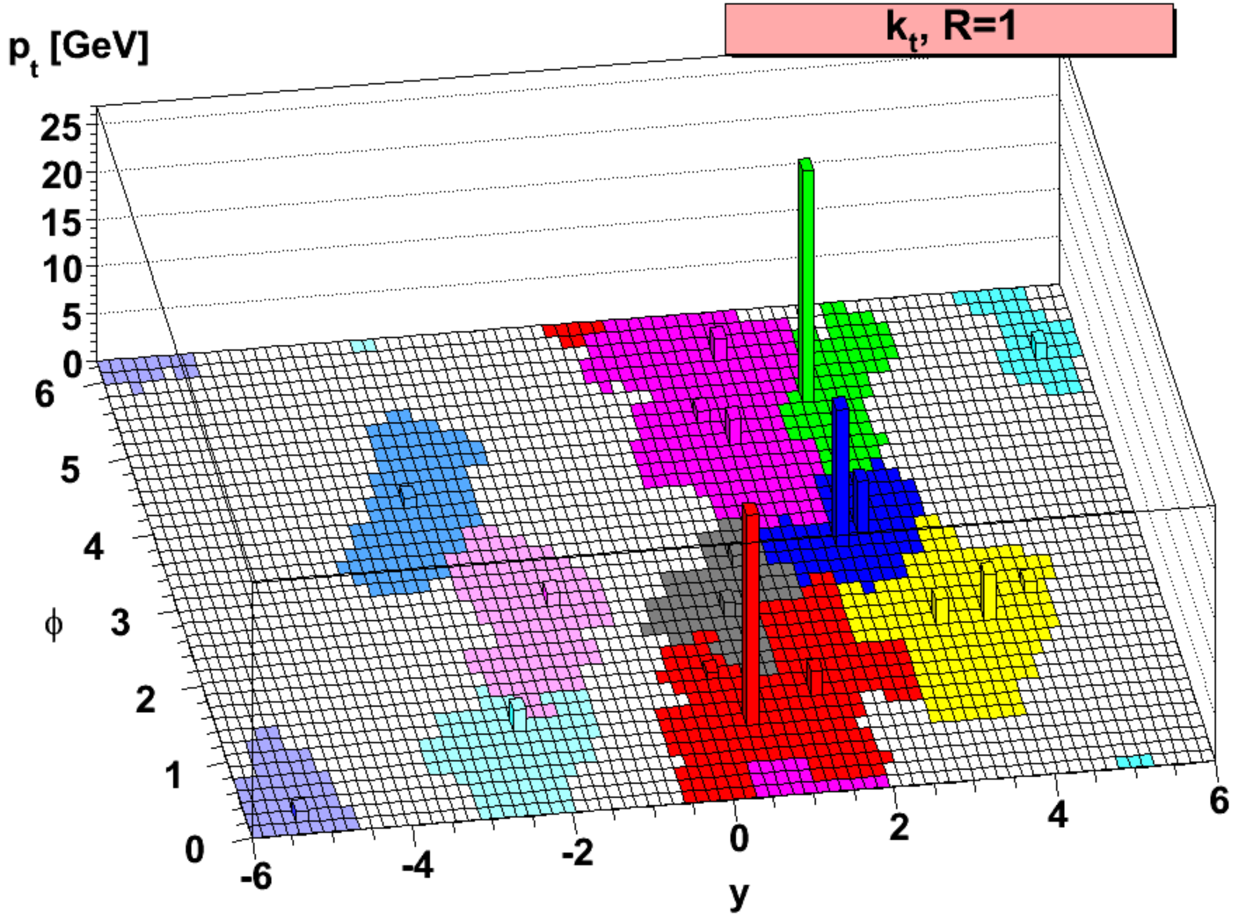
- Event selection
  - MB event selection (kINT7, V0A and V0C trigger)
  - $|VtxZ| < 10$ (cm)
  - Number of tracklets contributing to the primary vertex is at least **2**
  - Pileup event cut
  - $|VtxZ_{track} - VtxZ_{SPD}| < 0.5$ (cm)
  - $VtxZ_{SPD}$ reconstruction resolution is better than 0.25 (cm) and the dispersion is less than 0.04 *
- Jets
  - Charged tracks
  - Hybrid track (2011 version)
  - Utilized FastJet package
    FastJet v3.1.3
  - Anti-Kt algorithm
  - Cone radii R=0.2,0.4
  - Fiducial cut

Data set and event selections: Pb-Pb

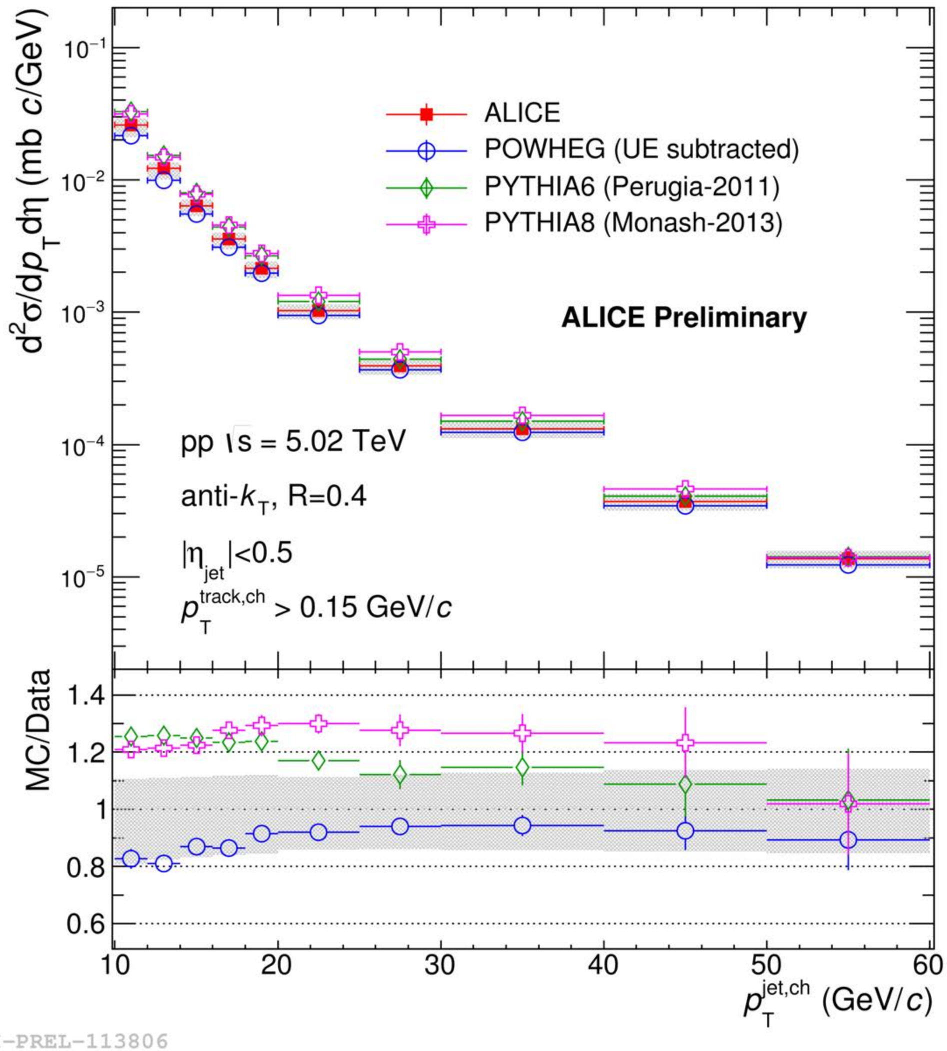
- **Data sets**
  - Pb-Pb data
    - LHC15o, $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb
    - pass2 low-IR, AOD (3.36M events)
  - MC simulation data
    - **PYTHIA**
      (tracking eff. Jet finding eff. detector RM)
      - LHC16e1
        (pthard-binned, jet production PYTHIA8),
        $\sqrt{s}$ = 5.02 TeV pp
      - LHC15l1b2
        (MB, PYTHIA6 Perugia-2011),
        $\sqrt{s}$ = 5.02 TeV pp
    - **HIJING** (tracking eff.)
      - LHC15k1a1, LHC15k1a2 , $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb

- **Event Selection**
  - kINT7
  - $| v_z^{SPD} - v_z^{PRI} | < 0.1$ cm
    (to avoid UE density mis-estimation)
  - $| v_z | < 10$ cm
- **Charged track selection**
  - Hybrid track selection in which same parameters used with LHC11h.
    - to compensate for inefficiency in SPD
  - $| \eta | < 0.9$, $p_T > 0.15$ GeV/c
- **Jet Reconstruction**
  - R=0.2 , anti-kt algorithm, pt-scheme
  - $| \eta | < 0.7$
  - Jet Area $> 0.6 \pi R^2$
    - to reduce fake jet contamination at low $p_{T, jet}$

k_t clusters



Charged jet cross section (R = 0.4)



Unfolding

The true distribution: $t(x)$
The observed distribution: $o(y)$

$$o(y) = \int dx A(x,y) t(x),$$

$A(x,y)$ is a response or detector matrix (is usually derived with MC).
Finding $A^{-1}(x,y)$ is ill-posed problem: very sensitive to small perturbations of the data.

Discrete formulation: $O[m] = A[m \times n] T[n]$
A_{ji} is the probability that given true input in i-th bin output will be measured in j-th bin
RooUnfold package *arXiv:1105.1160*
Regularization methods

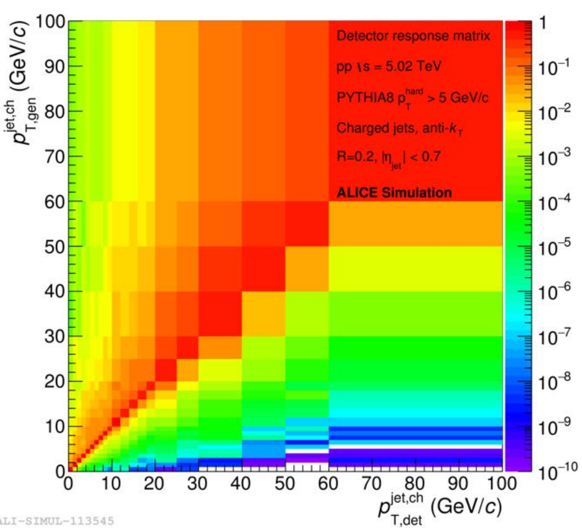
- iterative ("Bayesian"), *D'Agostini NIM A 362 (1995) 487*
- singular value decomposition (SVD), *H.Hoecker, V.Kartverlishvili, NIM(1996) 469*

Non-regularization method

- Bin-by-bin method (assumes no migration of events between bins, eg. resolution is much smaller than the bin size and no systematic shifts).

Response matrices

Inputs for unfolding by RooUnfold software package(arXiv:1105.1160)



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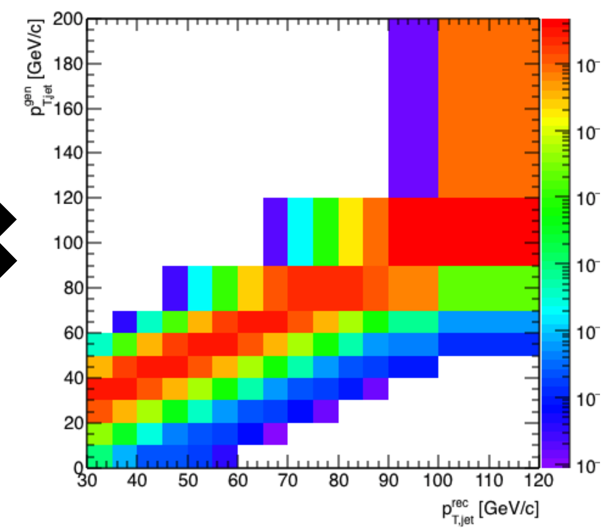
BKG RM for LHC15o data (0-10%)



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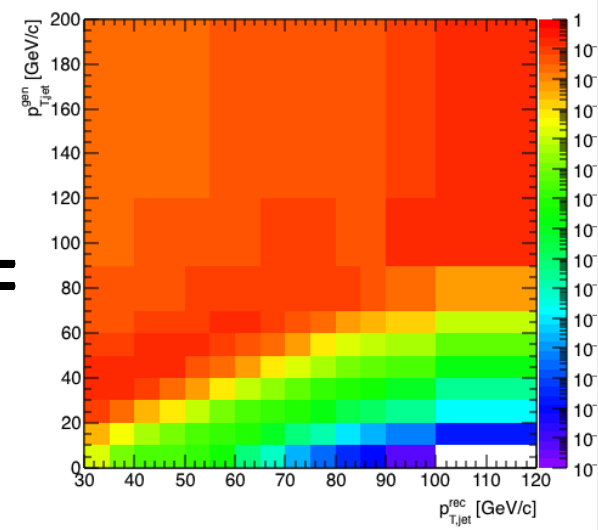
combined RM for 0-10% centrality



- Input for pp spectrum correction
- Input for Pb-Pb spectrum correction

Systematic uncertainties: pp

R=0.2	5-6 GeV	6-7 GeV	7-8 GeV	8-9 GeV	9-10 GeV	10-12 GeV	12-14 GeV	14-16 GeV	16-18 GeV	18-20 GeV	20-25 GeV	25-30 GeV	30-40 GeV	40-50 GeV	50-60 GeV
Efficiency	2	2.2	2.4	2.6	2.7	2.9	3.1	3.4	3.6	3.8	4.1	4.5	5.1	6	6.7
Resolution	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Secondary	2.3	2.3	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.2	2.2	2.3	2.3	2.3
UE subtraction(Minus only)	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	nglg.
Unfolding	2	2	2	2	2	2	2	2	2	2	3.2	3.2	3.2	3.2	3.2
Normalization	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Total (Minus, quadr. sum)	4.7	4.7	4.8	4.9	4.9	5.0	5.1	5.3	5.4	5.6	6.3	6.6	7.1	7.7	8.3
Total (Plus, quadr. sum)	4.6	4.7	4.8	4.9	4.9	5.0	5.1	5.3	5.4	5.6	6.3	6.6	7.1	7.7	8.3

R=0.4	5-6 GeV	6-7 GeV	7-8 GeV	8-9 GeV	9-10 GeV	10-12 GeV	12-14 GeV	14-16 GeV	16-18 GeV	18-20 GeV	20-25 GeV	25-30 GeV	30-40 GeV	40-50 GeV	50-60 GeV
Efficiency	2	2.4	2.7	3	3.3	3.6	4.1	4.5	5	5.3	5.8	6.5	7.2	7.9	8.3
Resolution	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Secondary	2.1	2.2	2.2	2.2	2.2	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.5
UE subtraction (Minus only)	1.1	1	1	0.9	0.8	0.8	0.7	0.6	0.6	0.5	0.5	0.4	0.3	0.3	0.2
Unfolding	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	5.8	5.8	5.8	5.8	5.8
Normalization	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Total (Minus,qurdr. sum)	6.6	6.7	6.8	6.9	7.1	7.2	7.5	7.7	8.0	8.2	9.2	9.7	10.1	10.7	11.0
Total (Plus, quadr. sum)	6.5	6.7	6.8	6.9	7.0	7.2	7.5	7.7	8.0	8.2	9.2	9.7	10.1	10.7	11.0

Systematic uncertainties: Pb-Pb

0-10 % centrality	30-40 [GeV/c]	50-60 [GeV/c]
Shape Uncertainties		
Unfolding Method	4.2	4.2
Regularisation Parameter	0.4	3.3
Measured p_T Range	+0.1 -3.2	+2.1 -1.2
Unfolded p_T Range	+0.1 -0.7	+0.5 -0.1
Generator	4.2	5.2
Shape Uncertainties : Total	+6.0 -6.8	+7.8 -7.6
Correlated Uncertainties		
δp_T selection	+5.1 -1.9	+3.8 -0.9
Flow Bias	6.4	4.6
TrackingEfficiency	1.5	5.9
Correlated Uncertainties : Total	+8.3 -6.8	+8.4 -7.5

10-30 % centrality	30-40 [GeV/c]	50-60 [GeV/c]
Shape Uncertainties		
Unfolding Method	2.2	2.2
Regularisation Parameter	1.3	3.9
Measured p_T Range	+1.4 -0.1	+1.1 -2.4
Unfolded p_T Range	+0.0 -1.2	+0.6 -0.1
Generator	4.2	5.2
Shape Uncertainties : Total	+5.1 -5.1	+7.0 -7.3
Correlated Uncertainties		
δp_T selection	+5.4 -1.9	+4.0 -1.5
Flow Bias	6.0	4.7
TrackingEfficiency	1.5	5.9
Correlated Uncertainties : Total	+8.2 -6.5	+8.5 -7.7