Measurement of Inclusive Charged Jet Production in pp and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

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Hard Probes 2016 24/09/2016

Outline

- Introduction
  - Jet quenching
- ALICE experiment
- Measurement of inclusive charged jets in $\sqrt{s_{NN}}$ = 5.02 TeV pp and Pb-Pb collisions
  - Jet cross section in pp
  - Underlying event density
  - Underlying event fluctuation
  - Jet cross section in Pb-Pb
  - Nuclear modification Factor
  - Comparison with previous results
- Summary and Outlook

Jets in HI Collisions (Hard Probes of the QGP)

What's a Jet ?

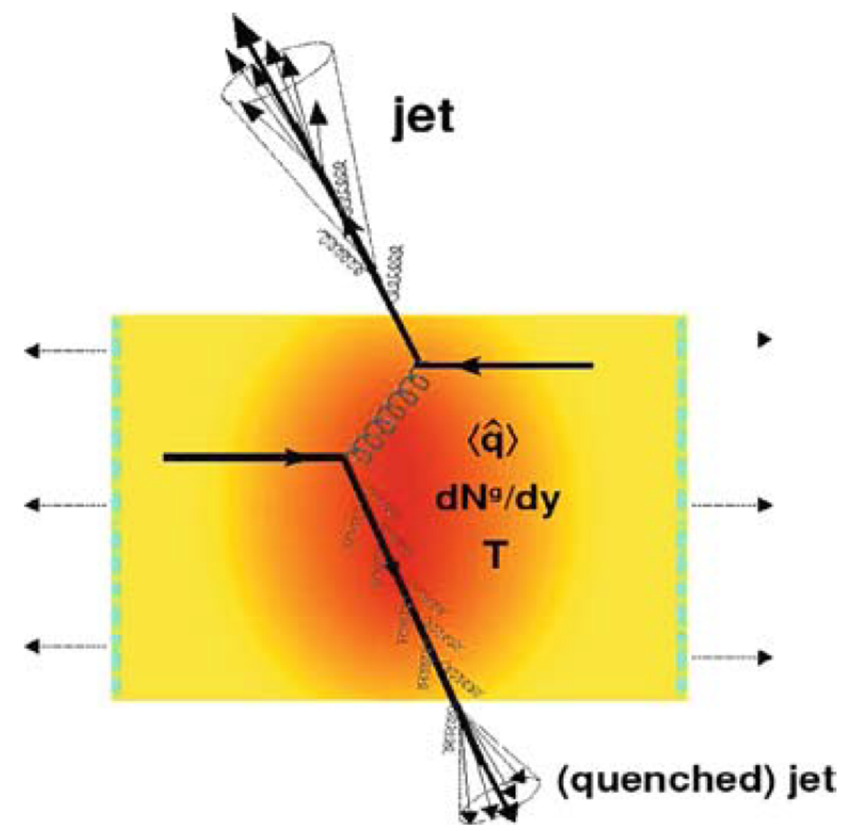
- Collimated spray of hadrons produced by the hard scattering of partons at the initial stage of the collision
- high-Q^2 process, $p_T \gtrsim 20$ GeV

Why Jets ?

- The QGP lifetime is so short ($\sim 10^{-23}$ 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**



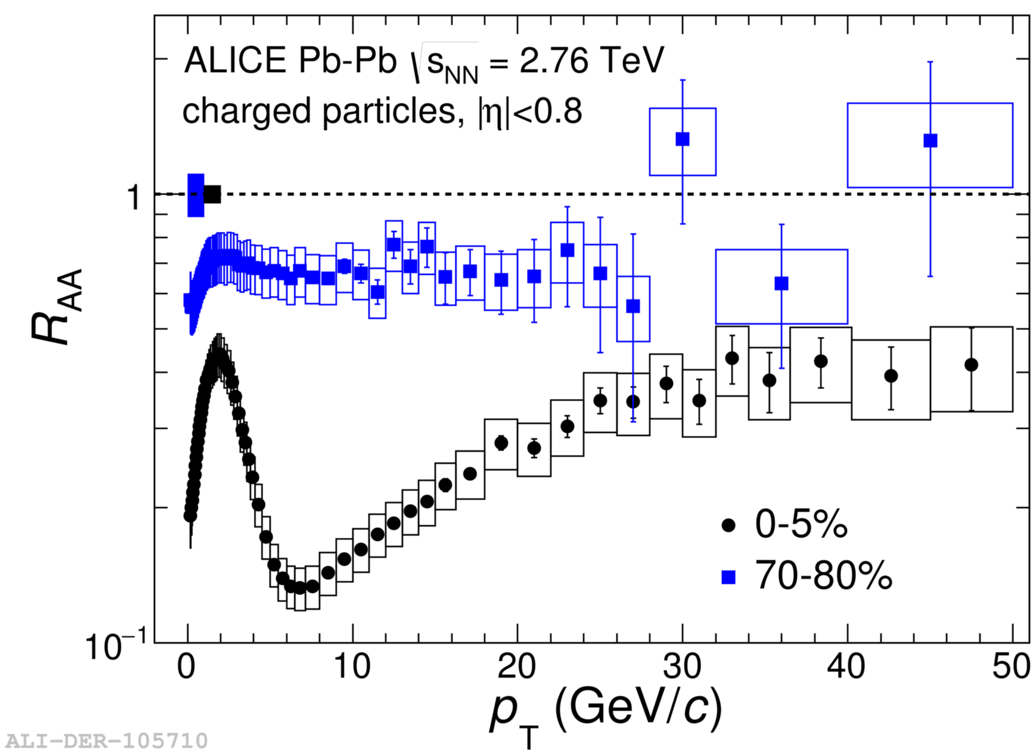
ALICE Jet Quenching Measurements in Pb-Pb

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

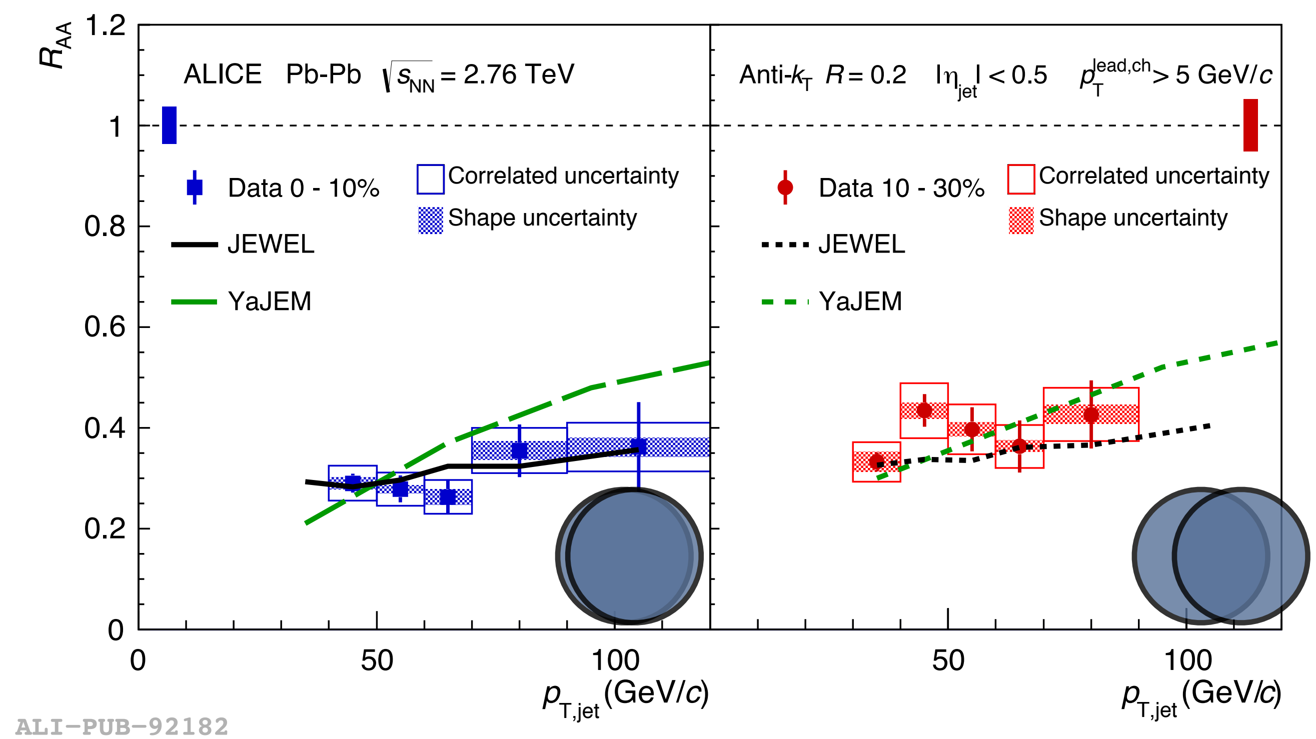
$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{dN_{ch\ jet}}{dp_T d\eta}}{\frac{d\sigma_{pp}}{dp_T d\eta}}$$

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

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



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



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

ALICE Jet Quenching Measurements in Pb-Pb

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

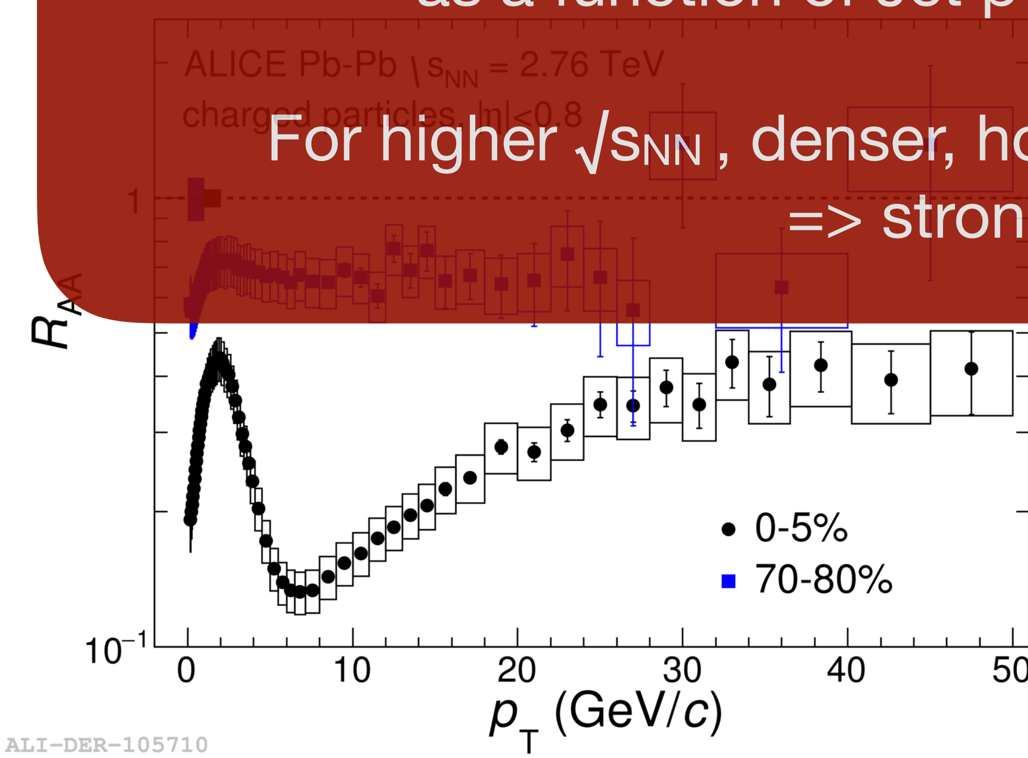
$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{dN_{ch\ jet}}{dp_T d\eta}}{\frac{d\sigma_{pp}}{dp_T d\eta}}$$

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

- **Jets**
  - strong suppression : $R_{AA} \sim 0.4$
  - Jet shape broadens?

We are interested in quantifying the jet suppression (parton energy loss) as a function of Jet p_T , collision energy and centrality

For higher $\sqrt{s_{NN}}$, denser, hotter and longer-lived QGP is created.
=> stronger jet suppression



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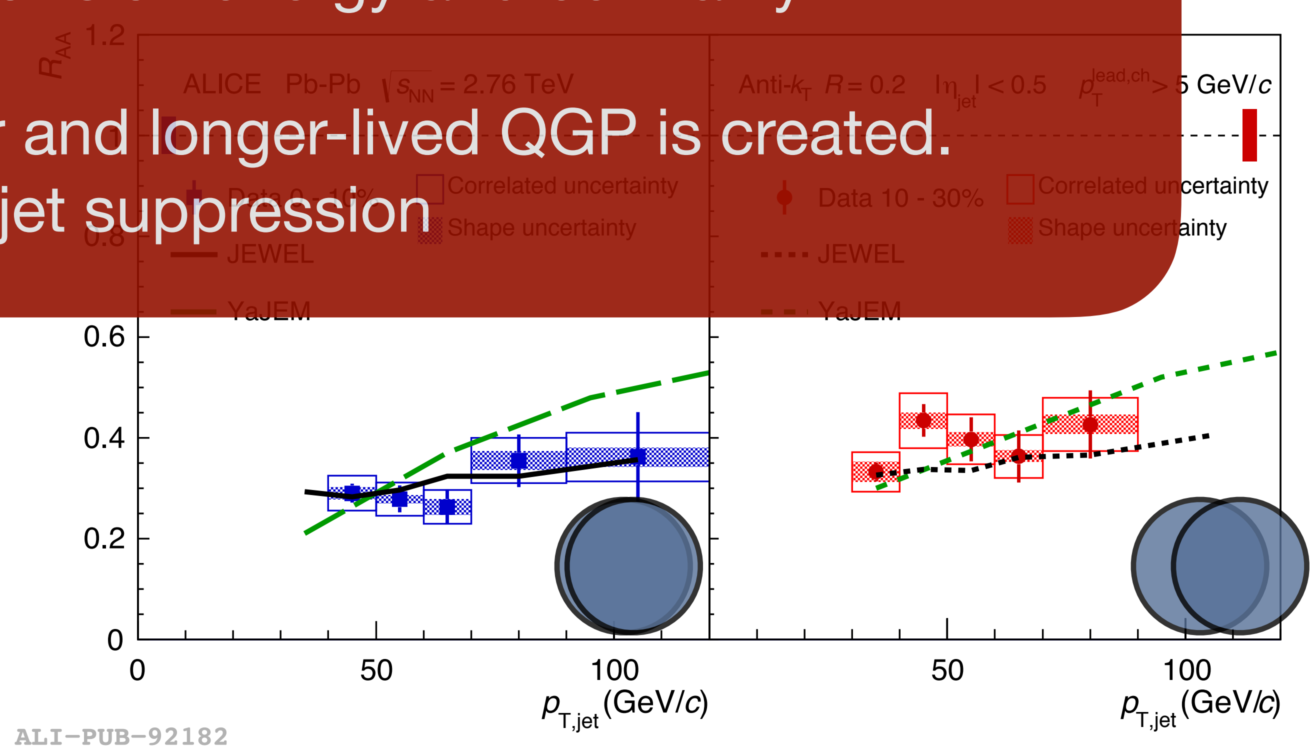
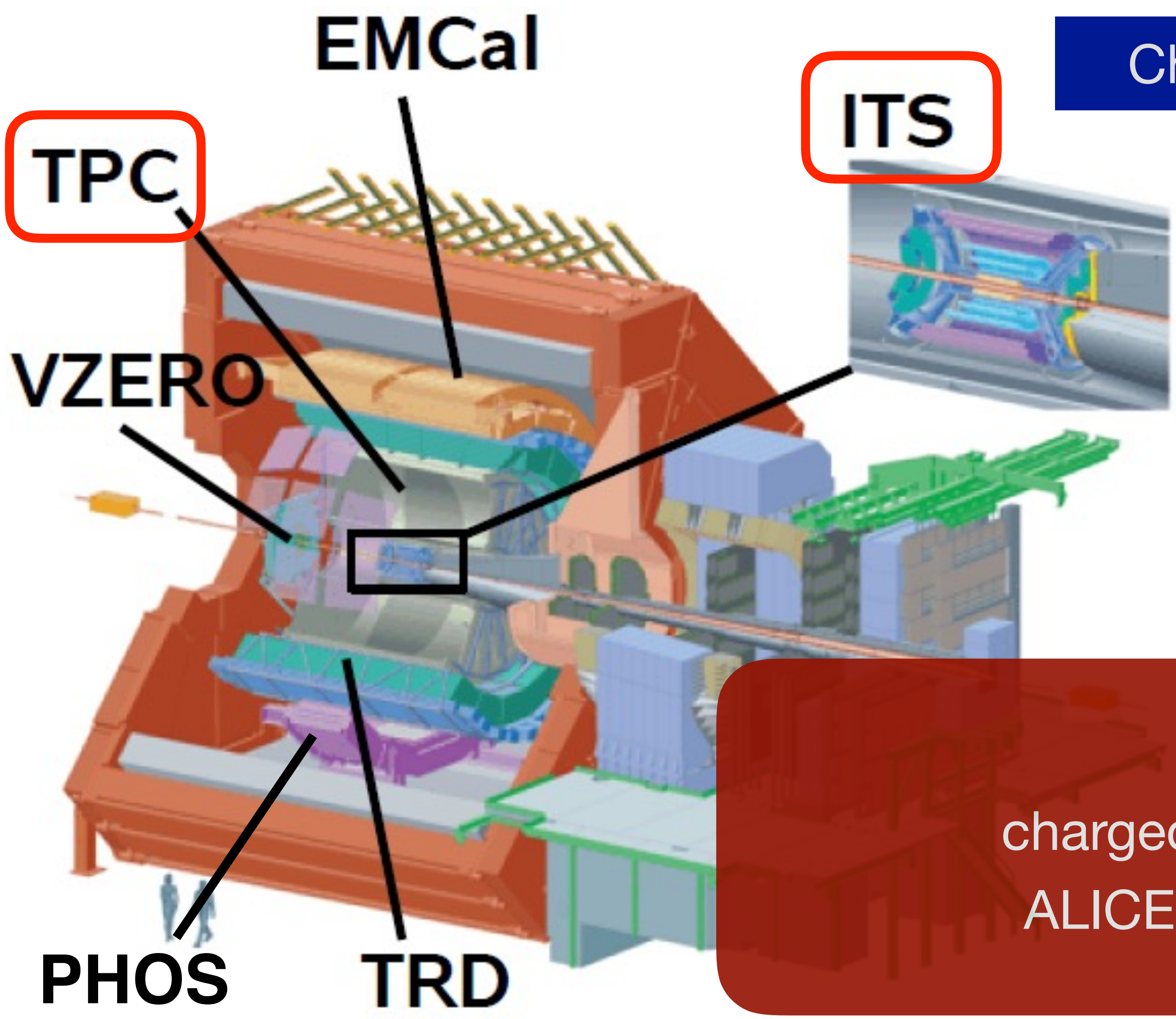


Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV , PLB 746 (2015) 1

Jet Measurement in LHC-ALICE

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



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

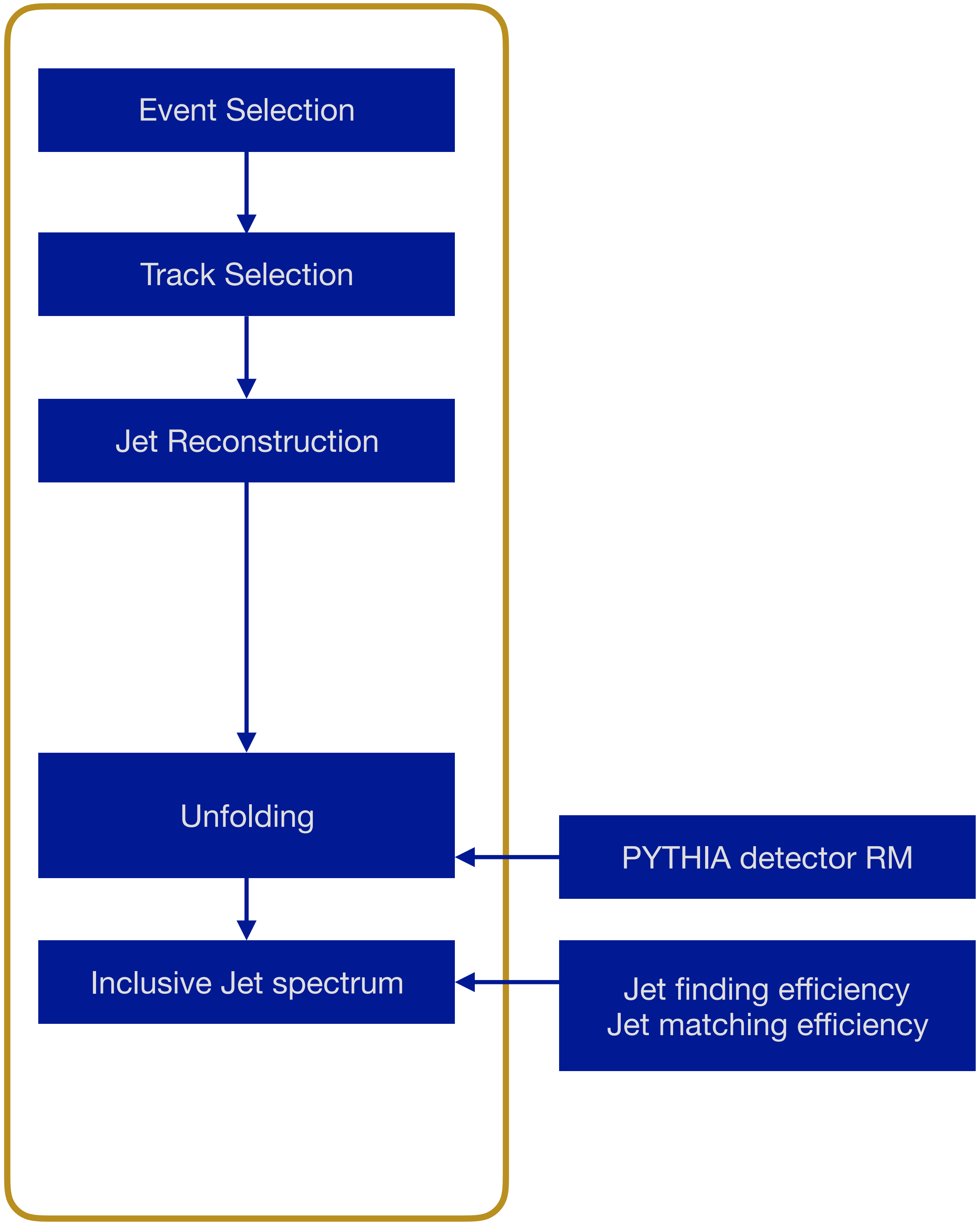
- ITS : silicon tracking detector
- TPC : Time Projection Chamber

Charged Jet

In this analysis,
charged jets are measured using
ALICE central barrel detectors.

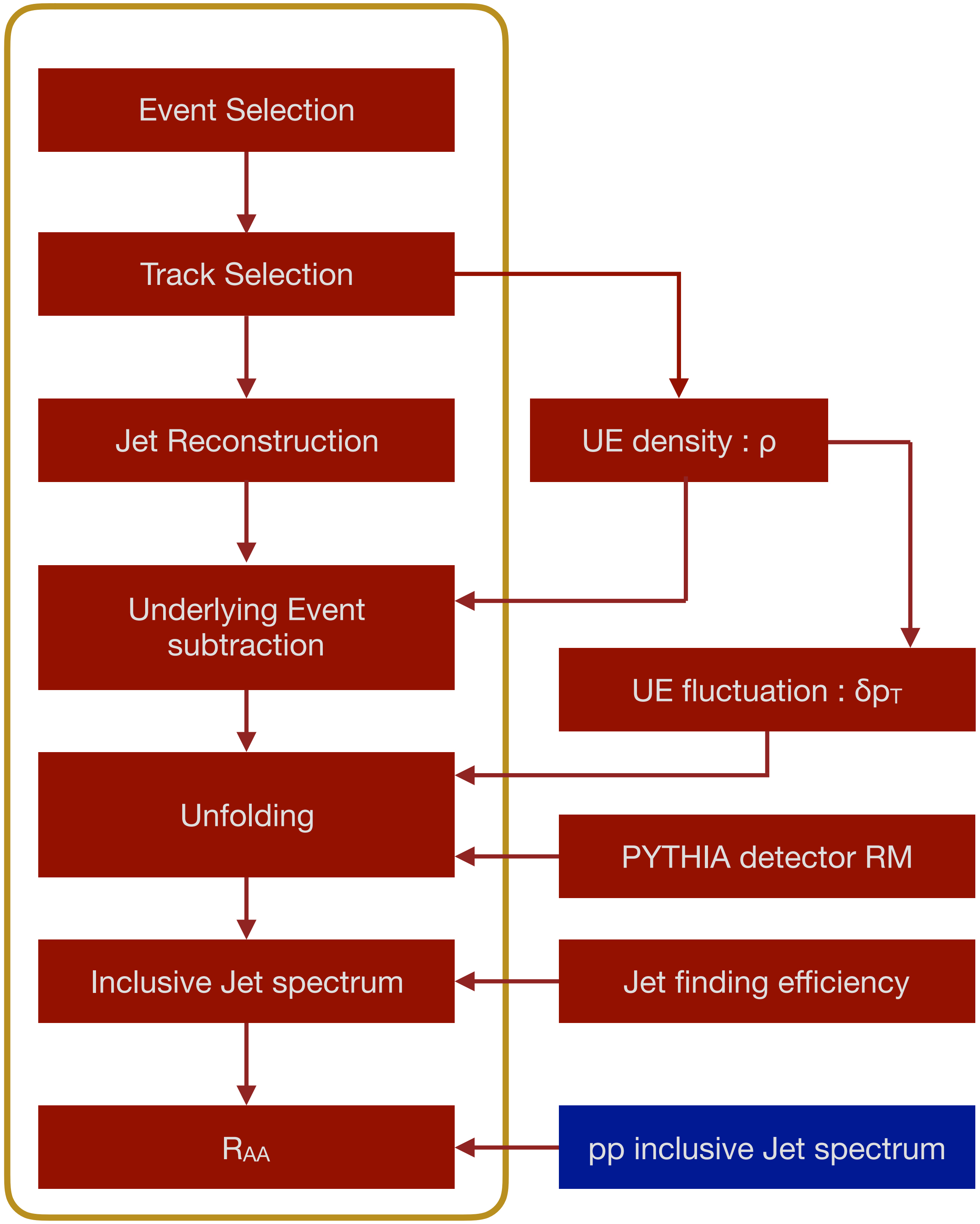
Analysis Flow (pp collisions)

- **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, 0.4
  - $|\eta| < 0.7$, ($p_T^{lead} > 5$ GeV/c for R_{AA} ref.)
- **Unfolding**
  - to correct for detector effects
- **Inclusive jet spectrum**
  - fully corrected to charged particle level



Analysis Flow (Pb-Pb collisions)

- **Dataset**
  - $\sqrt{s_{NN}}$ = 5.02 TeV, Pb-Pb collisions
  - MB triggered events (3.36M events, ~3% of full statistics)
- **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
- **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

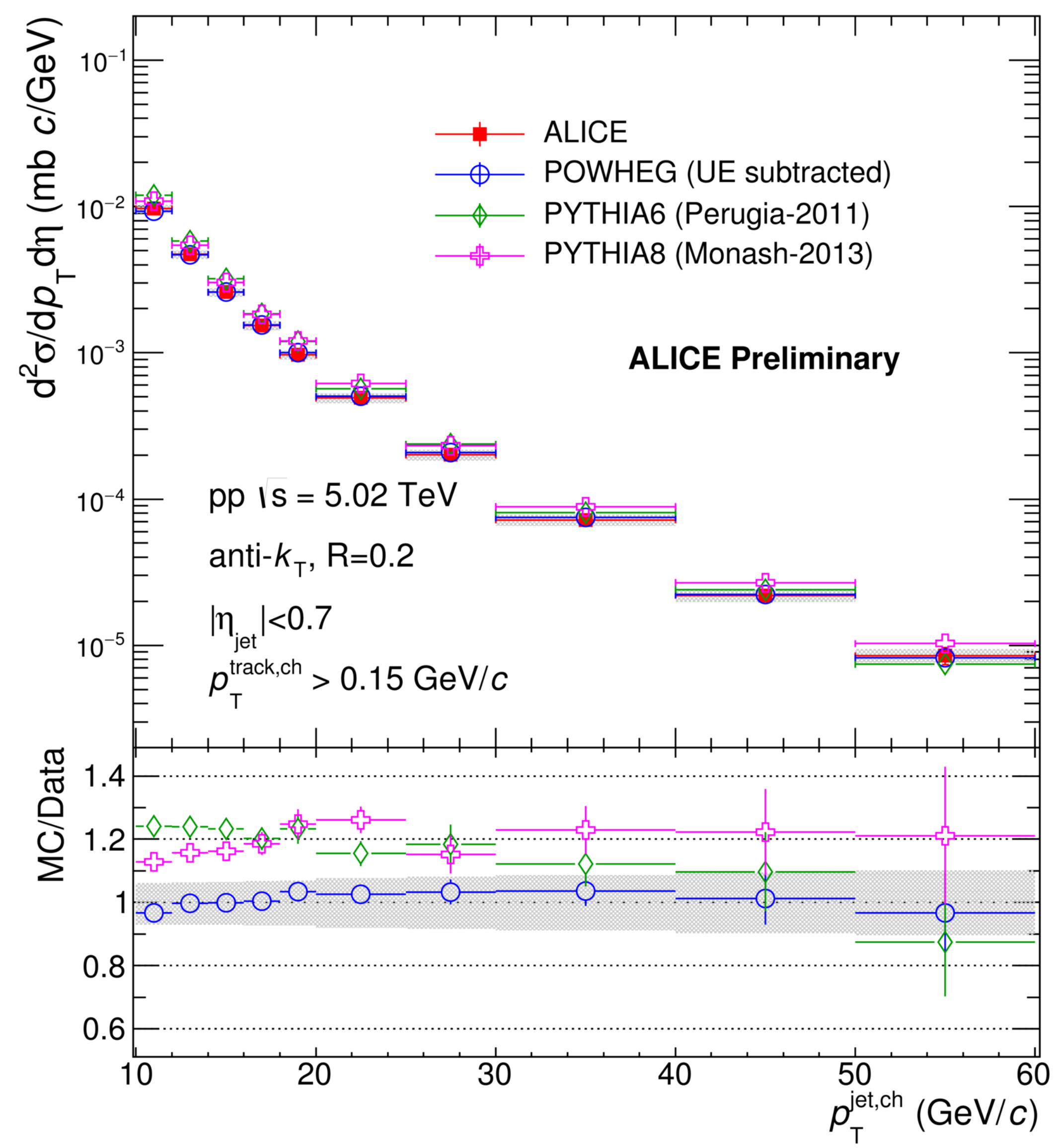


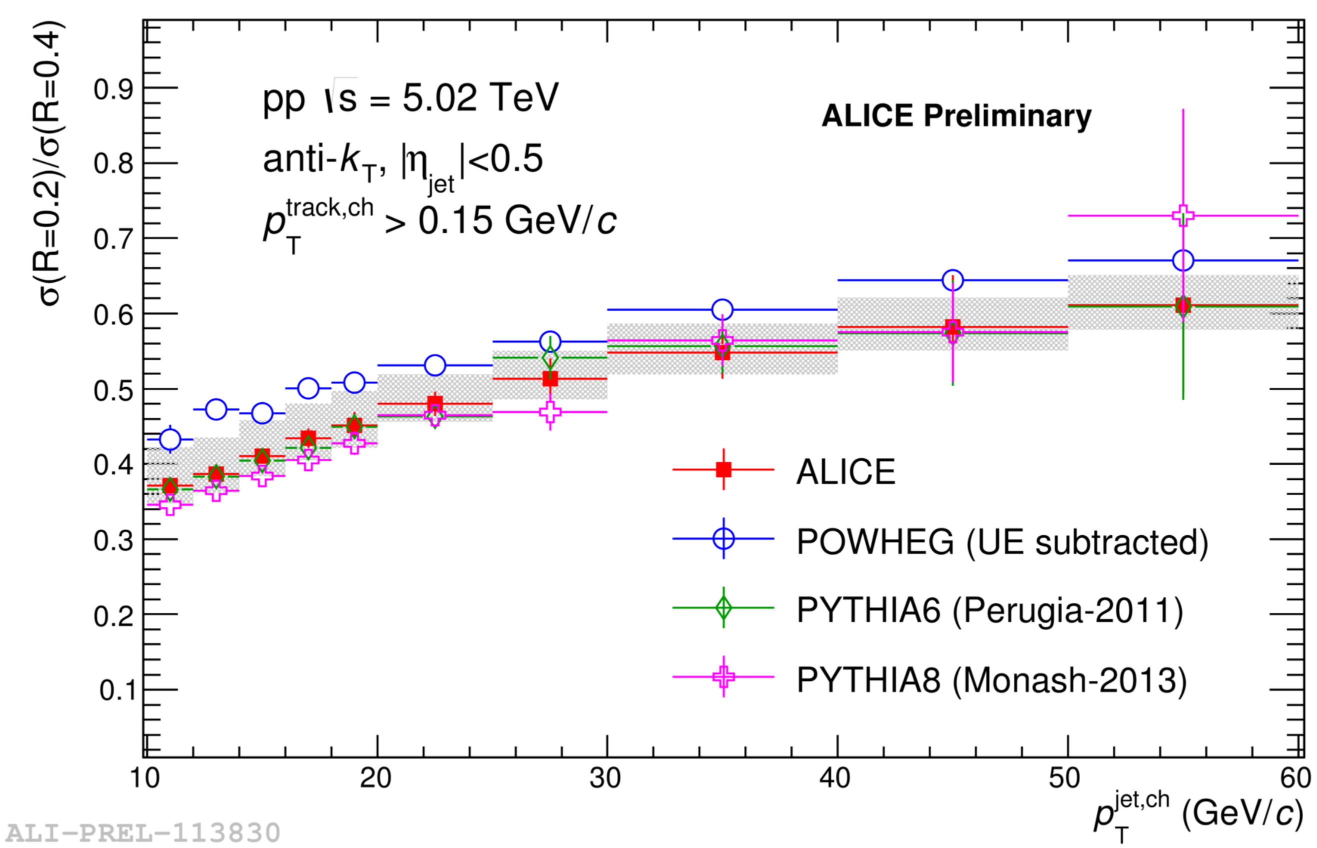
pp Inclusive Jet Cross Section

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

- poster : Measurement of inclusive charged jet cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV with ALICE at the LHC

- **Ratio of cross sections**
  - σ(R=0.2) / σ(R=0.4)
  - sensitive to the jet structure
  - stronger collimation at high p_T
  - well described by PYTHIA6, PYTHIA8 and POWHEG





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

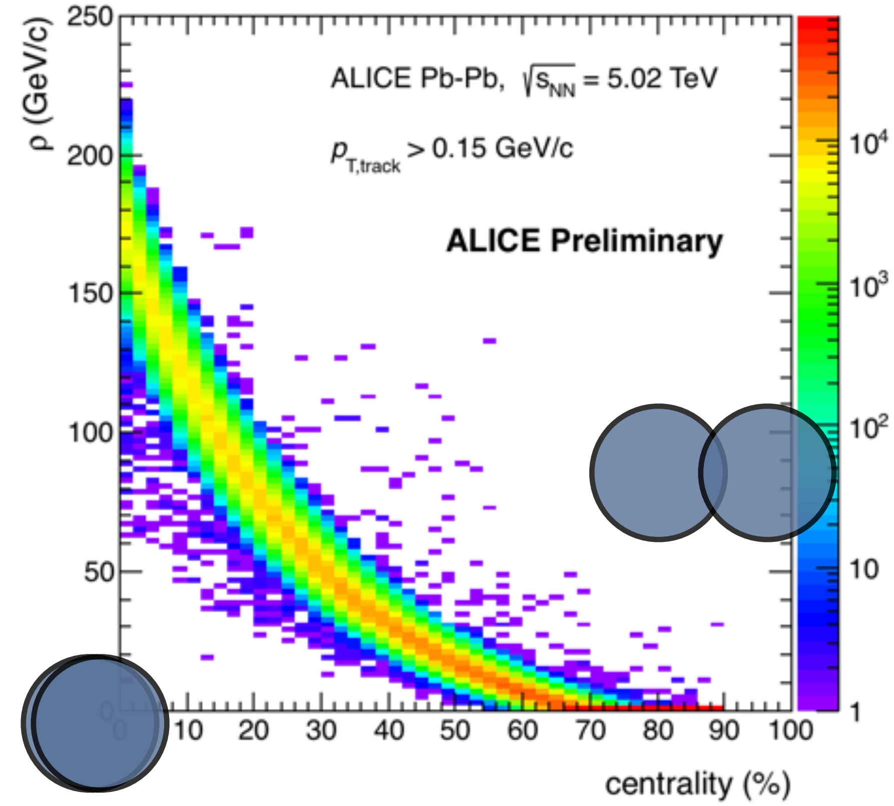
- **background density : ρ**
  - median k_T excluding the highest two clusters

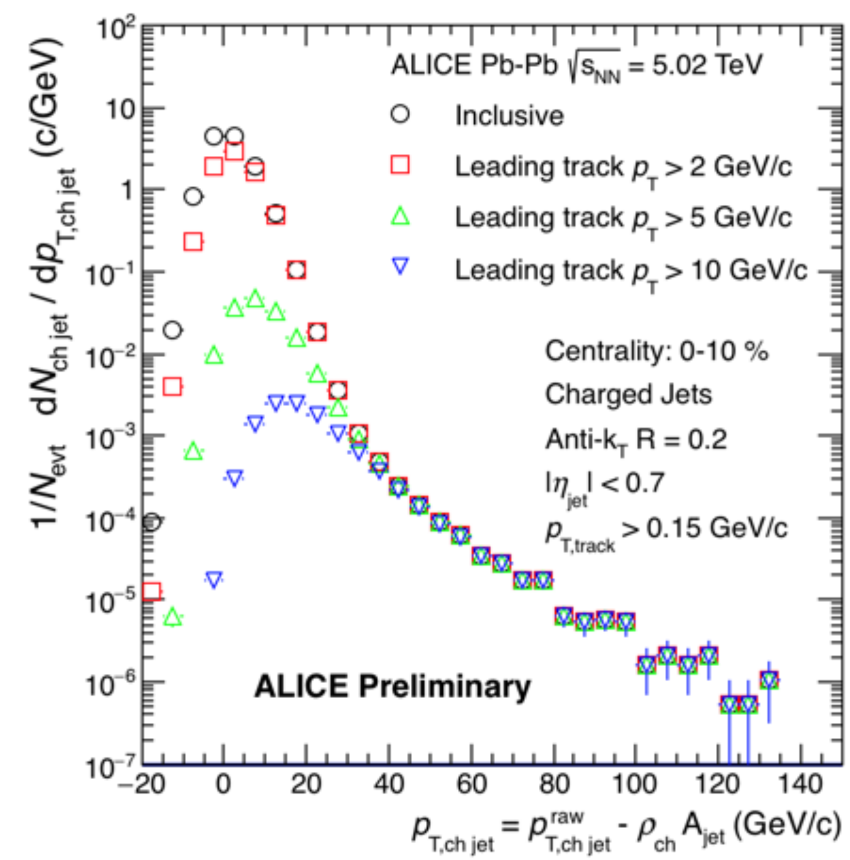
$$\rho = median\left\{\frac{p_{\mathrm{T,i}}}{A_{\mathrm{i}}}\right\}$$

  - 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

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

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





Underlying Event Fluctuation

UE fluctuation : δp_T

- δp_T is used as a measure for background fluctuations

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

- **Random Cone Method**

  1) random selection

  2) RC apart from leading jet ($\Delta r > 1.0$)

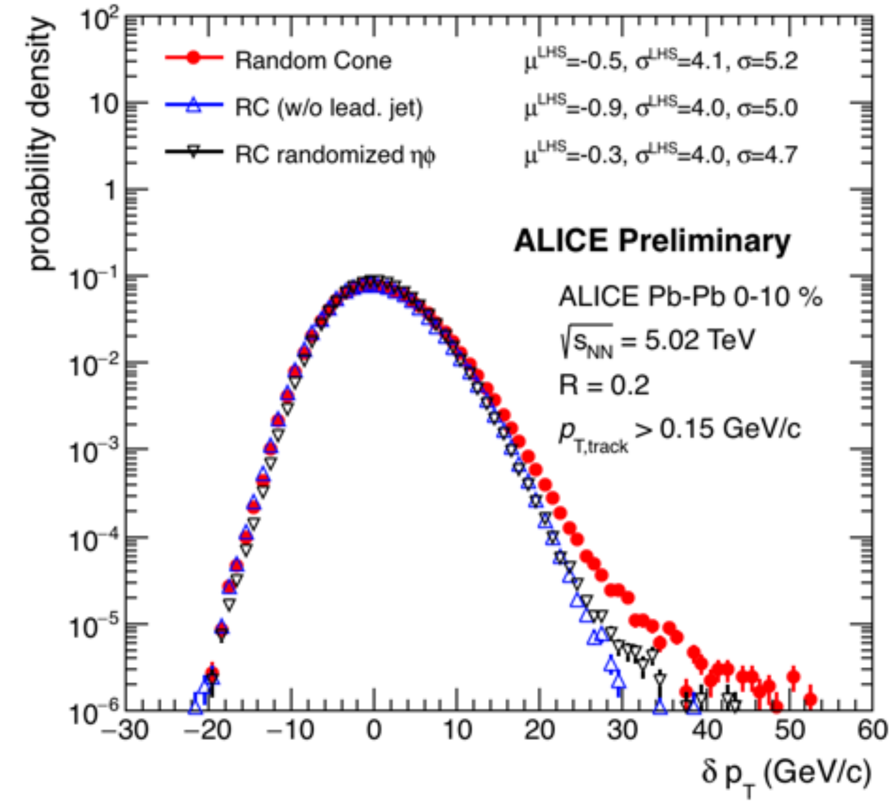
     - to reduce jet component.
     - $\Delta r = \sqrt{(\eta_{RC} - \eta_{jet})^2 + (\phi_{RC} - \phi_{jet})^2}$

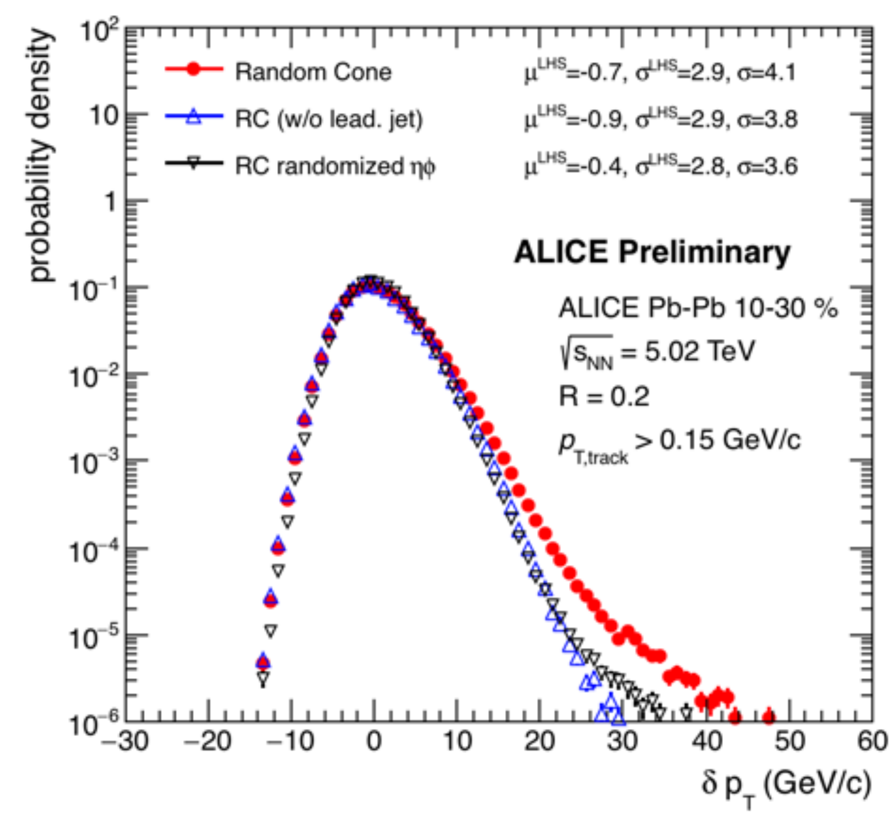
  3) use $\eta\phi$ randomised tracks

     - to exclude flow effect

- **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

- **2) RC with $\Delta r > 1.0$ is selected as UE fluctuation**

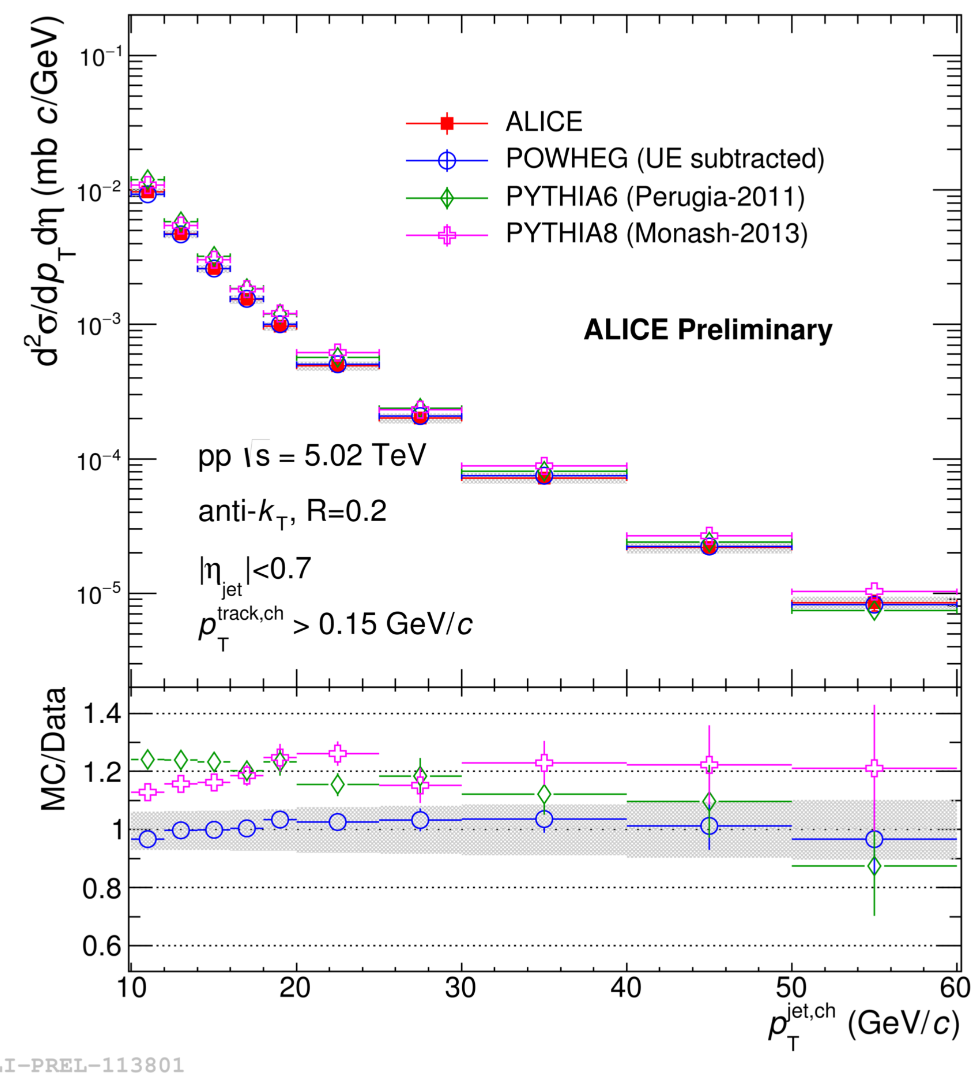




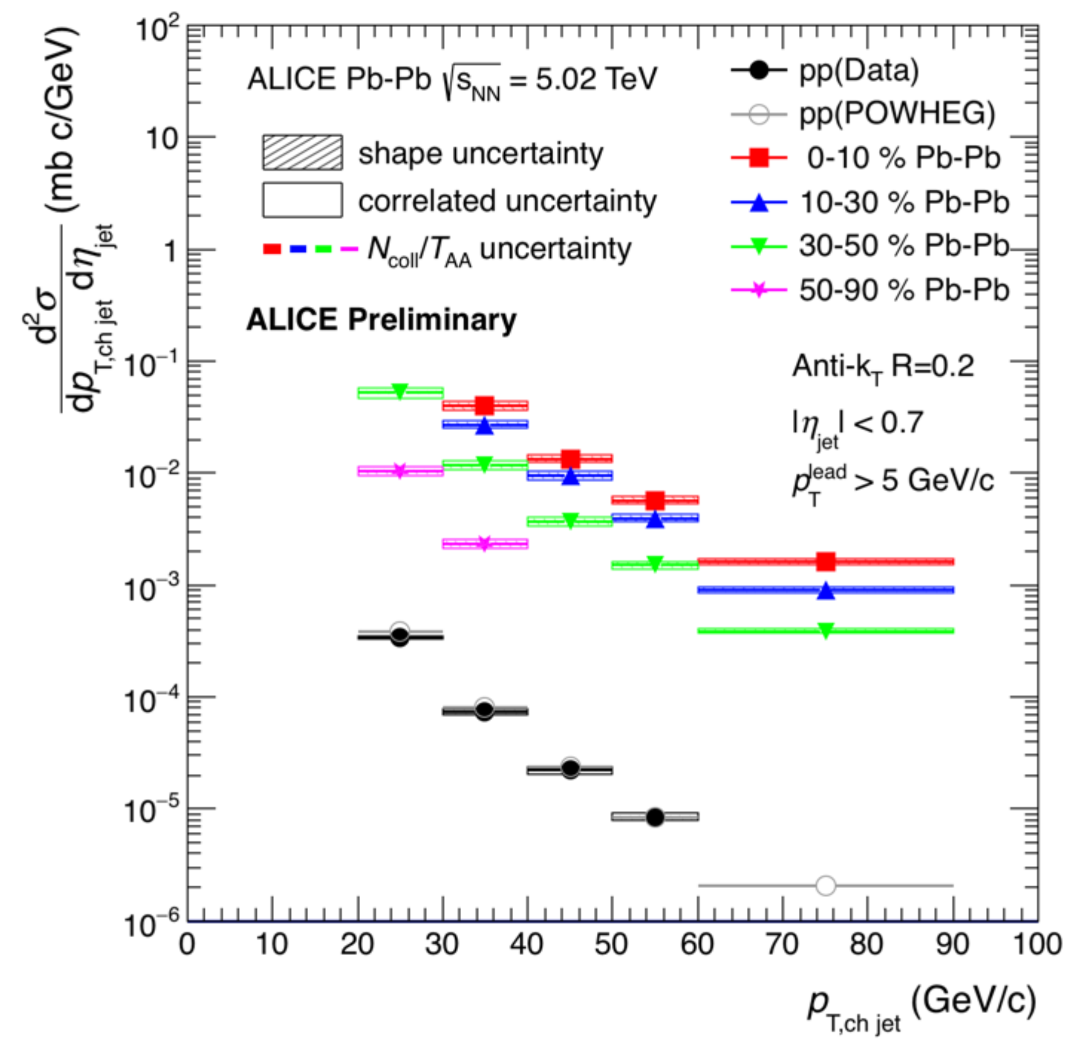
Inclusive Jet Cross Section

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

- **pp Jet cross section (reference for R_{AA})**
  - pp reference run ($\sqrt{s_{NN}}$ = 5.02 TeV)
  - POWHEG simulation
    - to compensate for the limited statistics of data (extend kinematic reach)



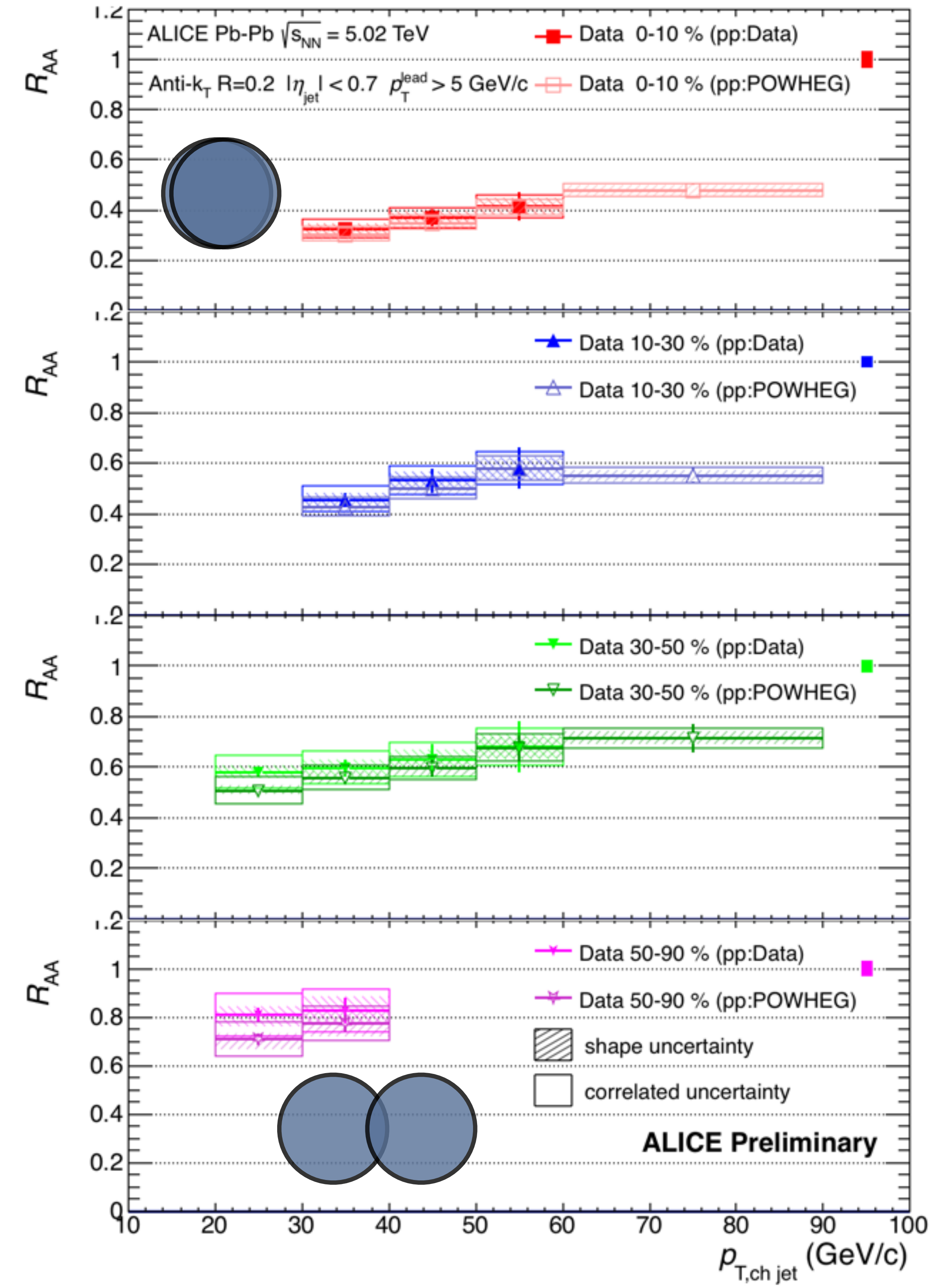
- **Pb-Pb Jet cross section**
  - 4 centrality bins (0-10, 10-30, 40-50, 50-90%)
  - correlated uncertainty
    - correlated among p_T bins
  - shape (uncorrelated) uncertainty
    - related to the shape of spectrum



Nuclear Modification Factor : R_{AA}

- **R_{AA} in each centrality bin**
  - Increased suppression from peripheral ~0.8 to central ~0.4
- **difference of pp reference**
  - pp data / POWHEG simulation
  - consistent within uncertainties

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



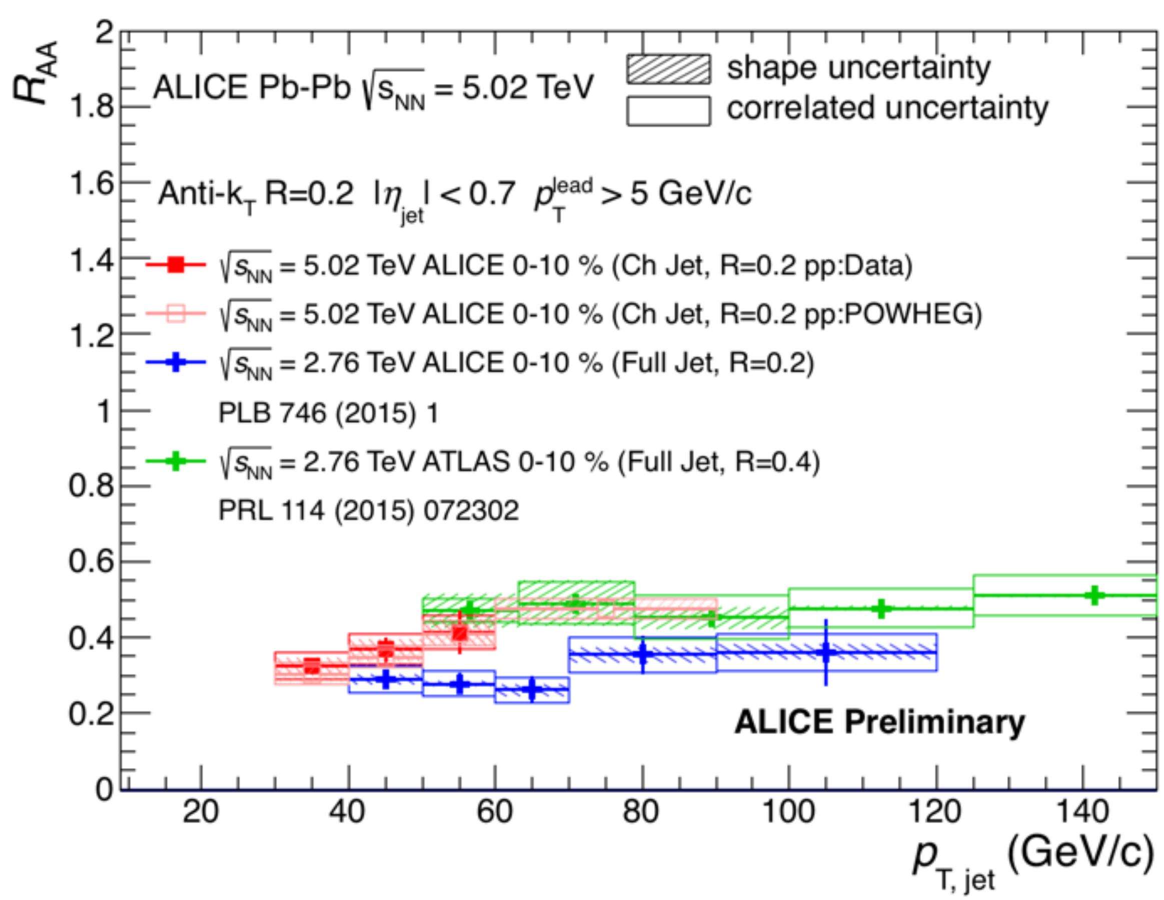
Comparison of R_{AA} with $\sqrt{s_{NN}}$ = 2.76 TeV

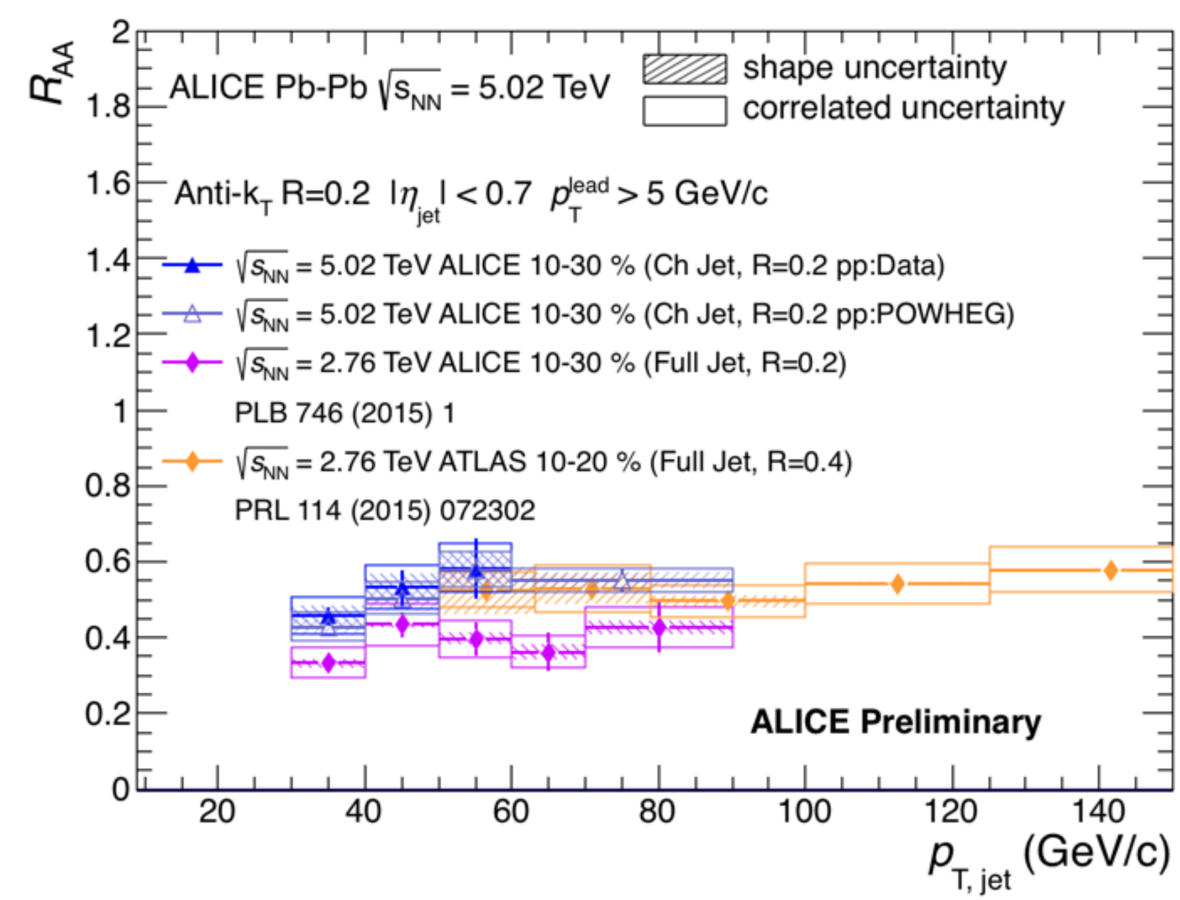
- Charged Jet R_{AA} in $\sqrt{s_{NN}}$ = 5.02 TeV (R=0.2) is compared with
  1. Full Jet R_{AA} in $\sqrt{s_{NN}}$ = 2.76 TeV (R=0.2 , ALICE)
  2. Jet R_{AA} in $\sqrt{s_{NN}}$ = 2.76 TeV (R=0.4 , ATLAS)

  ☑ ***Jet energy scale is different,***
  (resolution parameter R is different in ATLAS)

- **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***

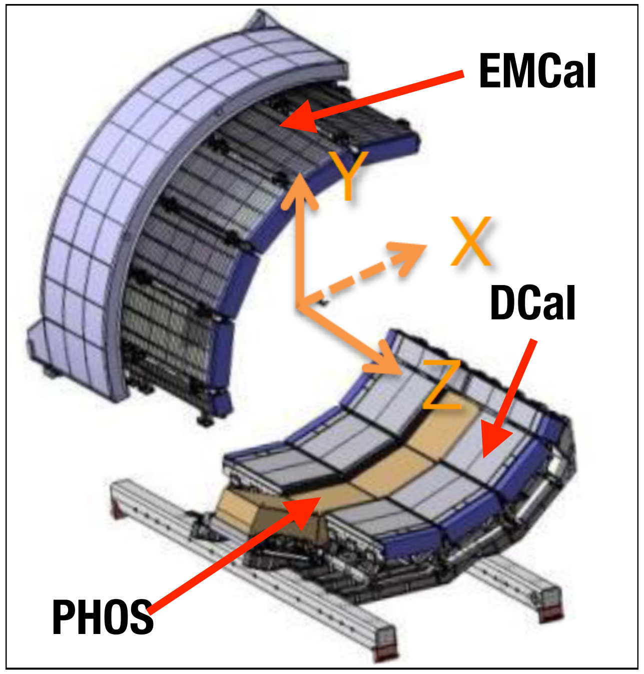




Summary

- **First measurement of jet R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV**
  - Charged jet, R=0.2, p_T^{lead} > 5 GeV/c
  - pp cross section , σ(R=0.2) / σ(R=0.4)
    - well described by POWHEG NLO simulation
  - Evaluation of Underlying Event density / fluctuation
    - large fluctuating underlying event in most central collisions
  - Nuclear Modification Factor : R_{AA}
    - strong suppression in most central collisions
    - R_{AA} value is comparable to $\sqrt{s_{NN}}$ = 2.76 TeV
      - effect of flattening of the spectrum compensated by stronger jet suppression

- **Outlook**
  - More statistics to extend kinematic reach
    (Few percent of full statistics is used in this analysis.)
  - Full-jet measurement
    - enable direct comparison with Run1 results
    - three electromagnetic calorimeters in ALICE



BACKUP

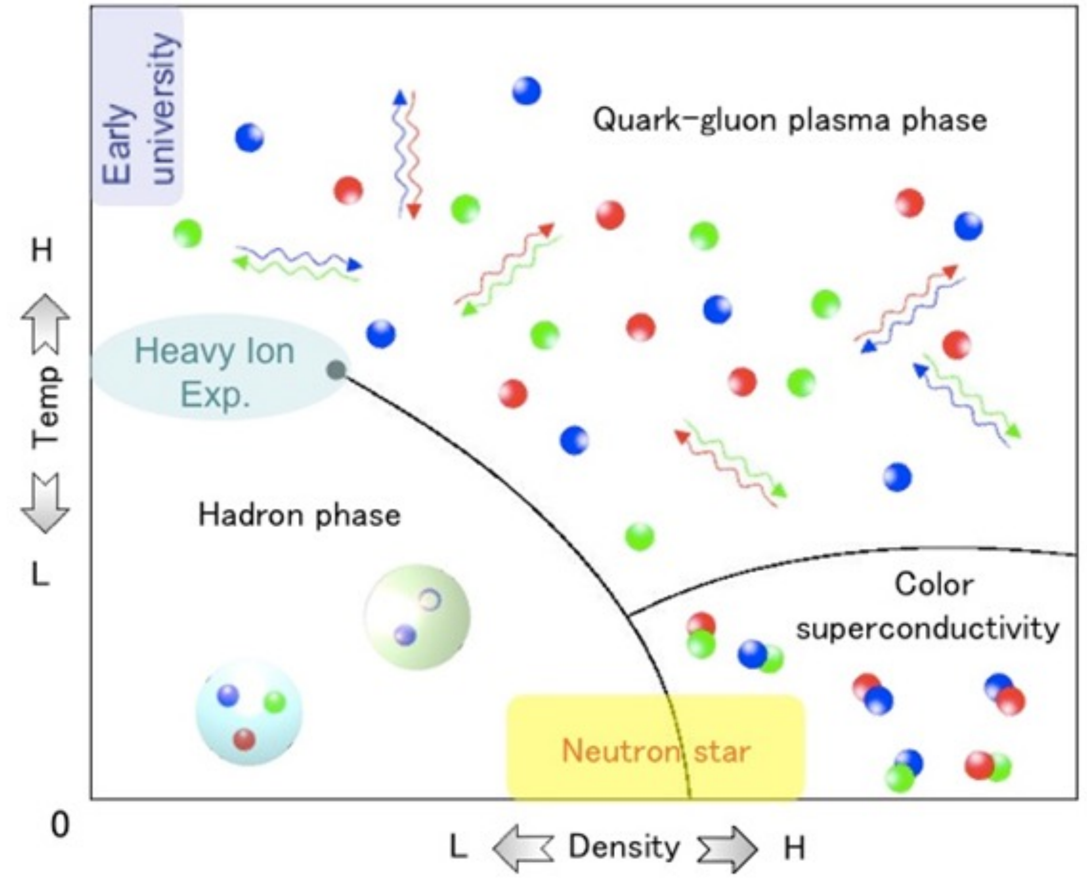
Quark-Gluon Plasma

What is QGP ?

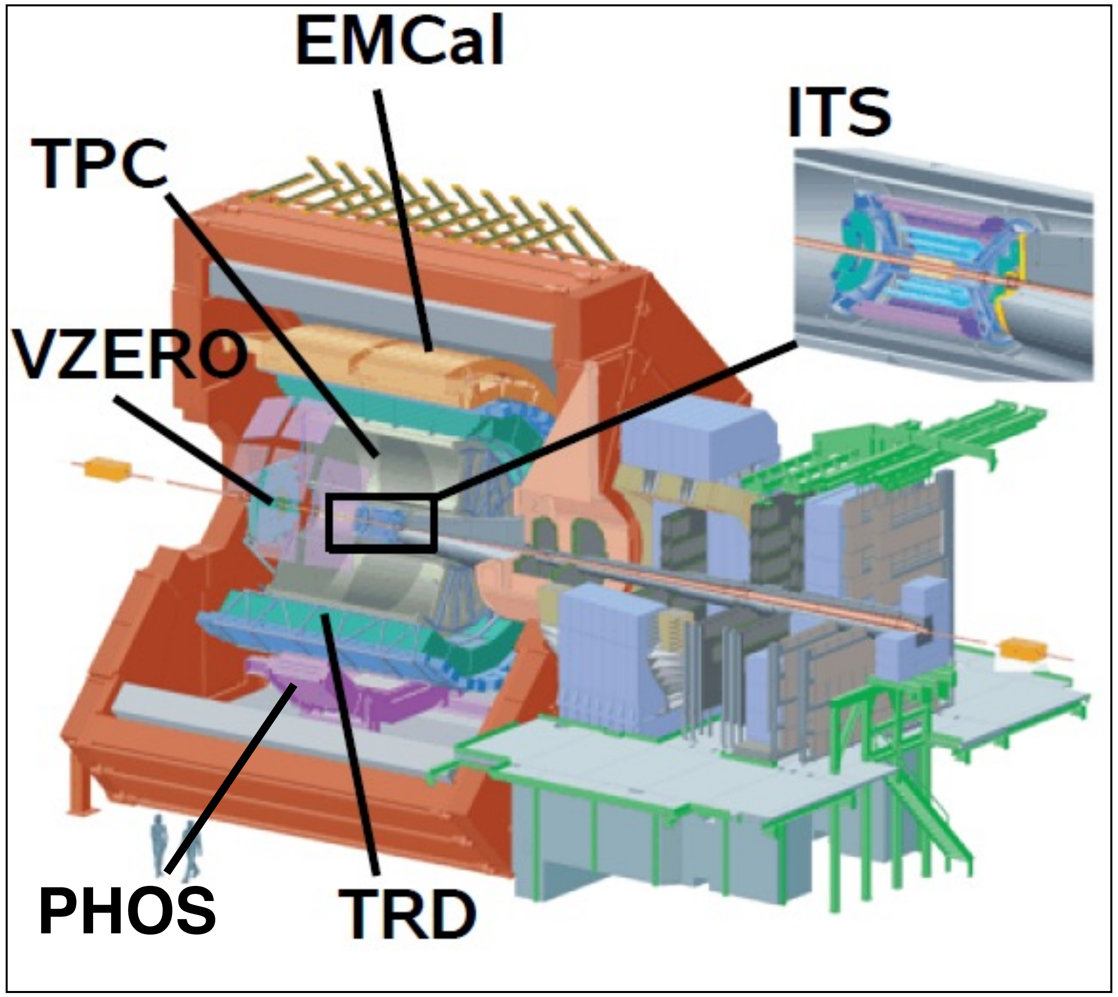
- **Quark-Gluon Plasma (QGP)**
  - Hot & dense color thermalized QCD matter prevailing at the early Universe ~1μs after big bang
  - Deconfined state of quarks and gluons
  - Theoretically inferred through lattice gauge simulations of QCD

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



Jet Measurement in LHC-ALICE



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

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

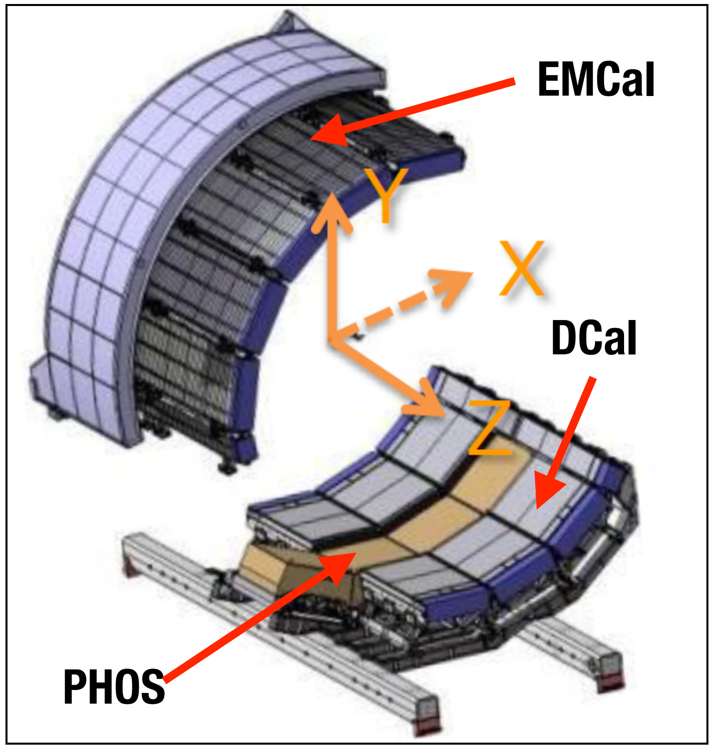
- ITS : silicon tracking detector
- TPC : Time Projection Chamber
- **Charged constituents**

Full Jet

Charged Jet

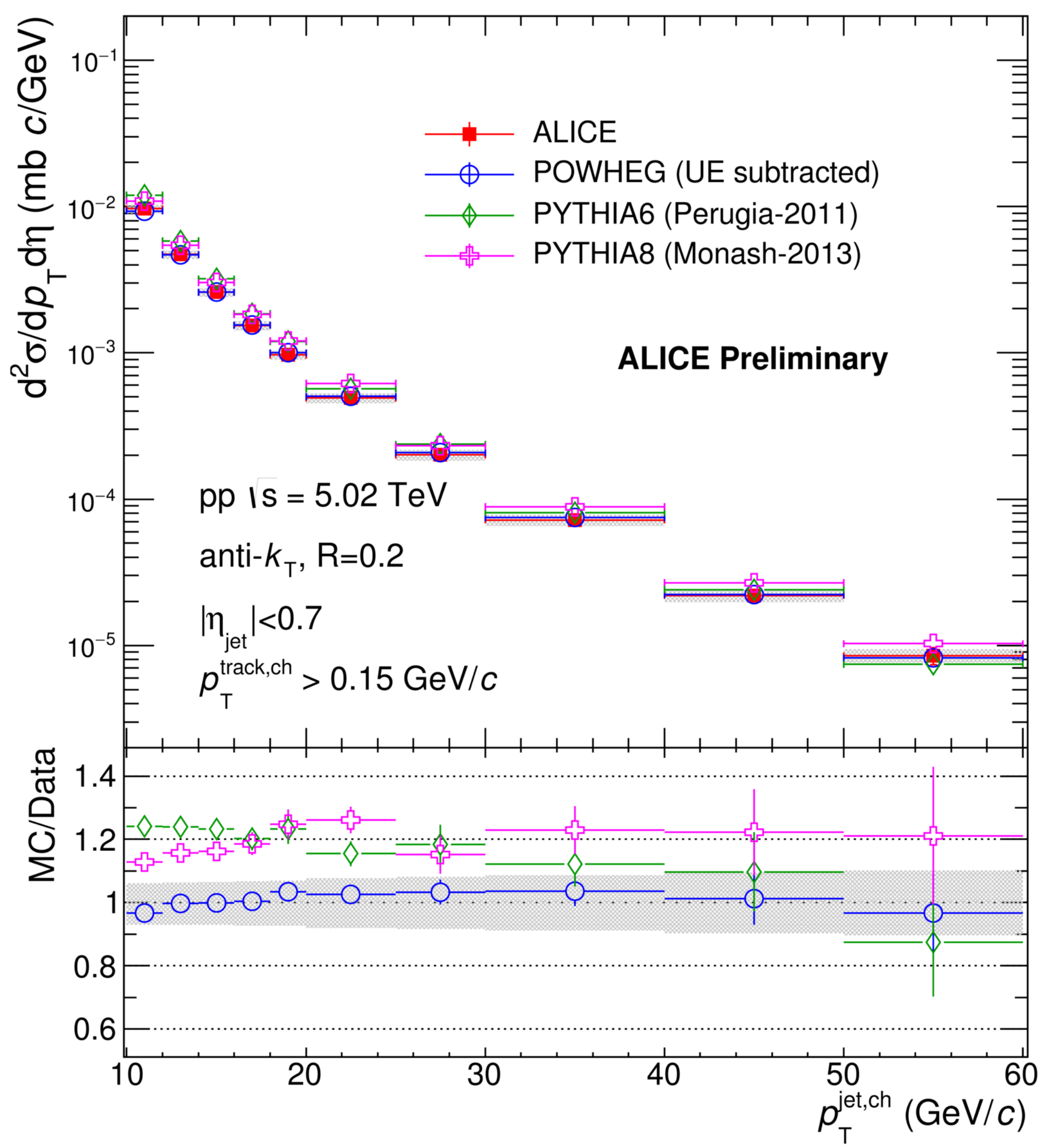
Neutral particles : $|\eta| < 0.7$

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



pp Inclusive Jet Cross Section

R=0.2



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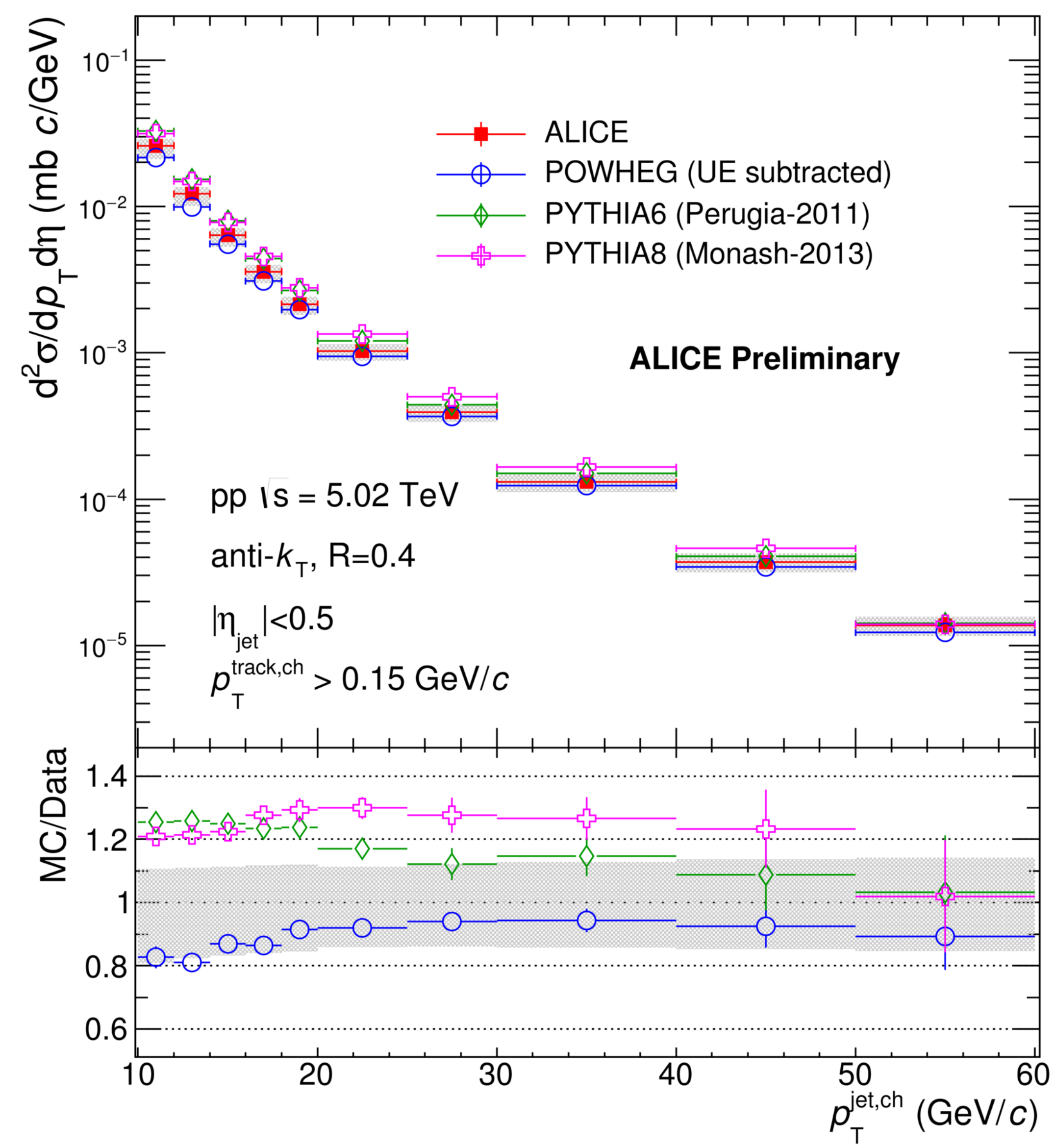
R=0.4



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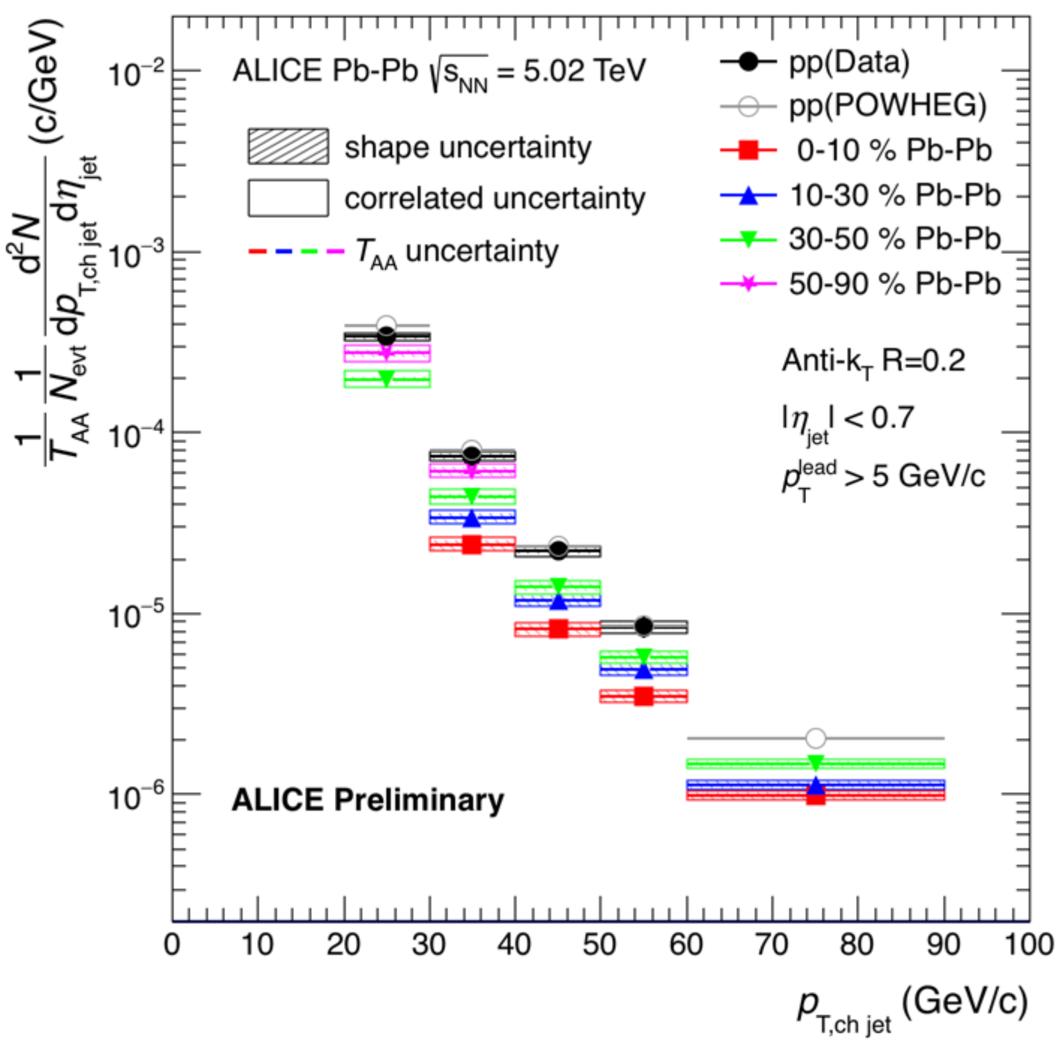
Data selection

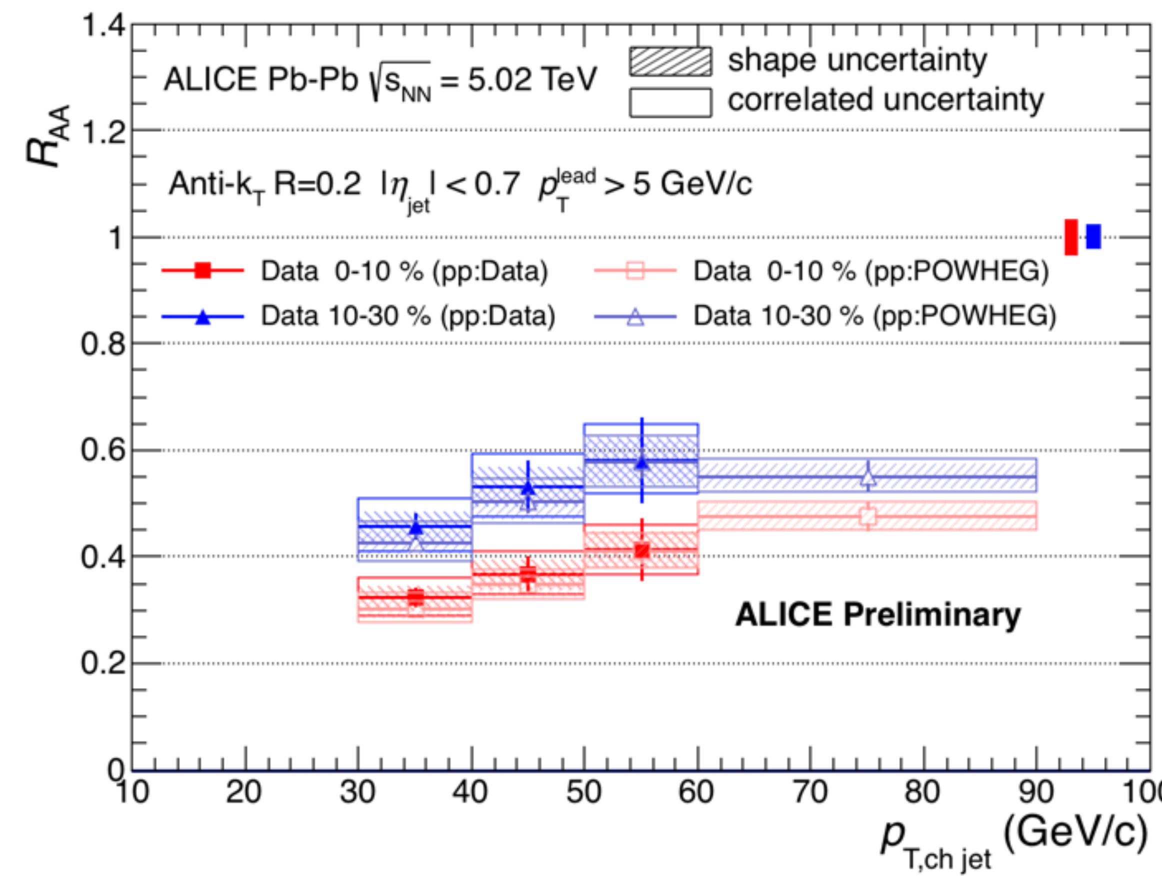
- **Data sets**
  - **Pb-Pb data**
    - LHC15o, $\sqrt{s_{NN}}$ = 5.02 TeV Pb-Pb
    - pass2 low-IR, AOD (3.36M events)
  - **MC simulation data**
    - **PYTHIA**
      (tracking eff. Jet finding eff. detector RM)
      - LHC16e1
        (pthard-binned, jet production PYTHIA8),
        $\sqrt{s}$ =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

Inclusive Jet Spectrum, R_{AA}

- **Inclusive Jet Spectrum**
  - scaled by nuclear overlap function : T_{AA}
- **R_{AA} in each centrality bin**
  - strong suppression in 0-10% than 10-30% centrality





Underlying Event Density

Charged Track Multiplicity

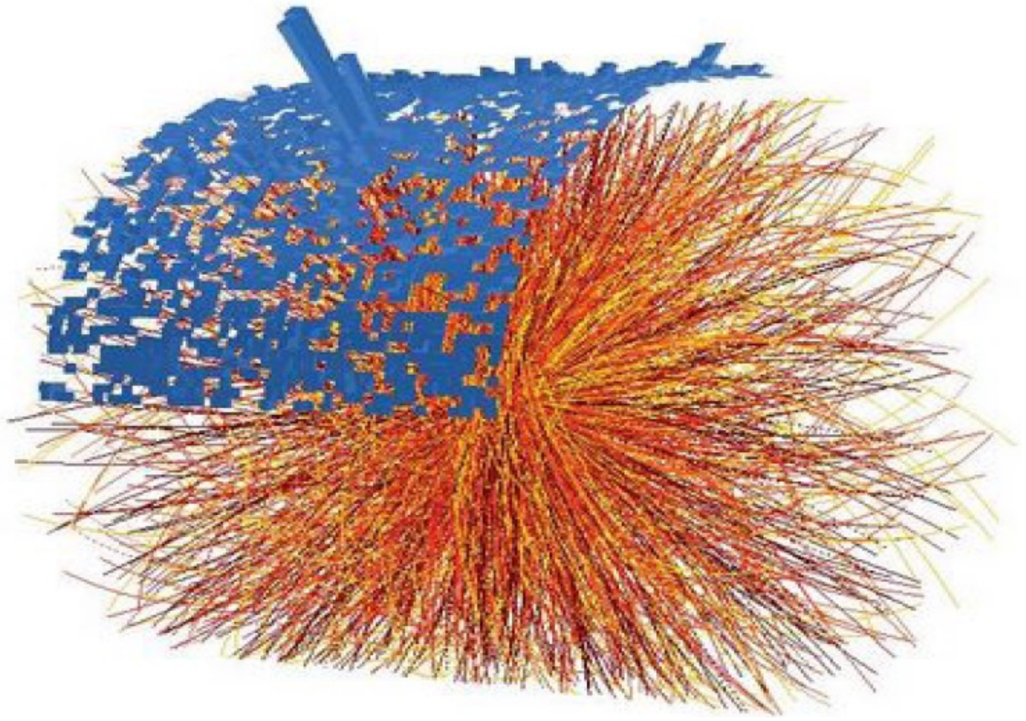
- large background superimposed to the Jets
  - $dN_{ch}/d\eta$ ~ 1300 (0-10% centrality)

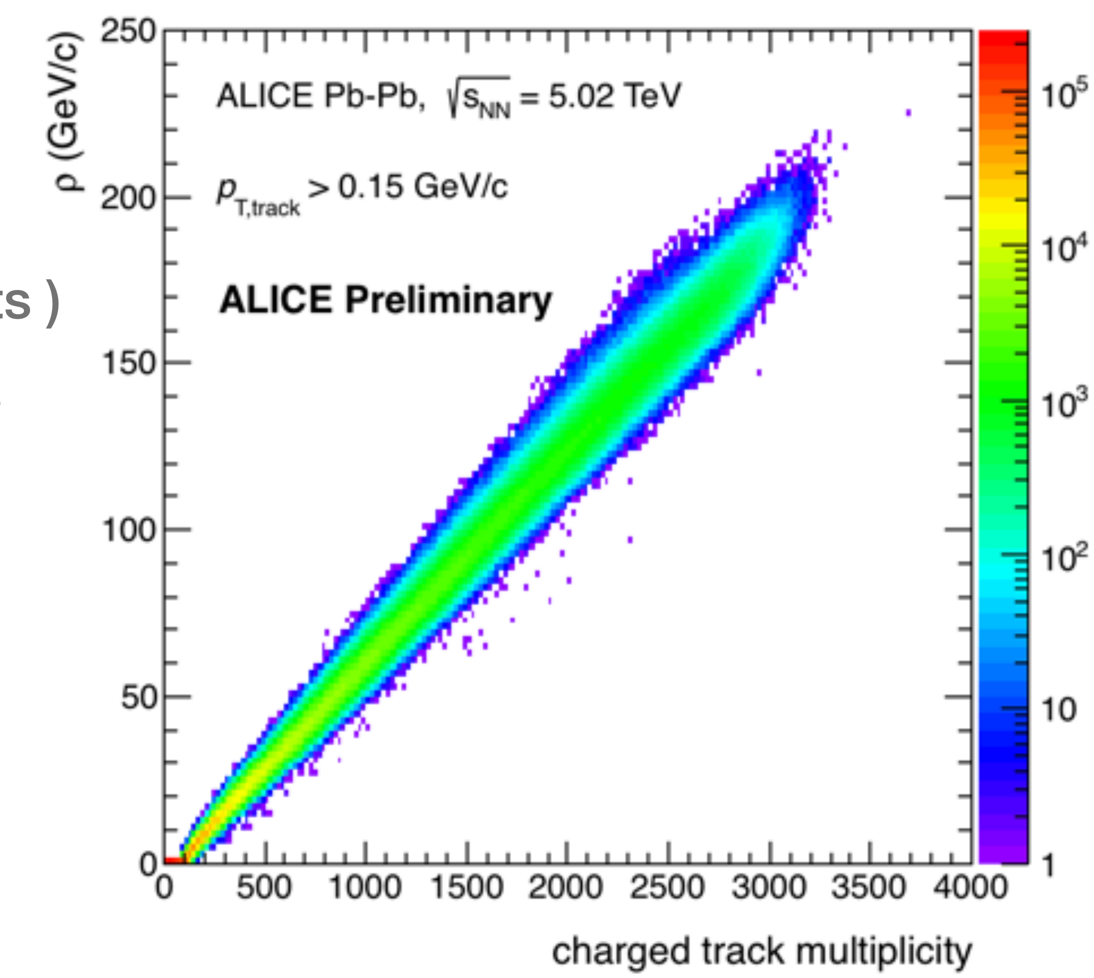
Underlying Event Density

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

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

  - ρ ~ 145 GeV/c for 0-10% (~18 GeV/c for R=0.2 jets)
  - The average background energy density ρ scales linearly with track multiplicity.





Systematic Uncertainty

- source of systematic uncertainties
  - RC selection (exclude RC w/ dr < 1.0)
    - exclude RC w/ dr < 0.5, 1.5
    - w/o 1st, 2nd lead. jets
  - Unfolding method (SVD)
    - Bayesian unfolding
  - measured p_T range (30 - 120 GeV/c for 0-10% centrality)
    - ± 5 GeV/c for lower limit
    - ± 10 GeV/c for upper limit
  - unfolded p_T range (0 - 200 GeV/c for 0-10% centrality)
    - +10 GeV/c for lower limit
    - ± 25 GeV/c for upper limit
  - Regularisation parameter (k = 5)
    - k = 4, 6
  - Flow Bias
    - ± 4 GeV/c for background density
  - Generator selection (Pythia8)
    - PYTHIA6: Perugia0, HERWIG
  - Tracking Efficiency
    - ± 4 % from nominal value
    - evaluated by fast simulation

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