Measurement of inclusive jet p_{T} spectra in $\mathrm{p+p}$ collisions at ALICE

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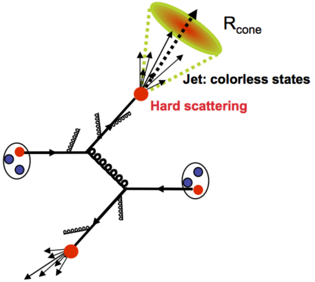
Goals

1. To get familiar with the basics of QCD, hard processes and jets
2. To analyse inclusive p_{T} pspectra of charged jets in $\mathrm{p+p}$ collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ measured by ALICE
3. To study the underlying event accompanying the production of jets
4. To determine the jet reconstruction response matrix
5. To unfold jet p_{T} spectra

Hard scatteing



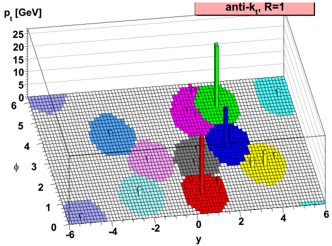
- A jet is a shower of particles originating from a fragmenting parton after a hard scattering
- Hadron production cross-section

$$\sigma_{A+B\to h+X} = \sum_{a,b,c,d} \int dx_1\, dx_2\, F_{a/A} \cdot F_{b/B} \cdot \sigma^{QCD}_{a+b\to c+d} * D_{h/c}$$

- $\sigma^{QCD}_{a+b\to c+d}$ calculated from QCD

Jets

- Sequential recombination jet algorithms: anti-k_T and k_T
- Implemented in *FastJet* [1]



metrics:

$$d_{ij} = \min(p_{\mathrm{T},i}^{2p}, p_{\mathrm{T},j}^{2p})\frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = p_{\mathrm{T},i}^{-2}$$

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

R – jet resolution parameter ("radius")

$\mathrm{anti}-k_\mathrm{T} : p = -1$

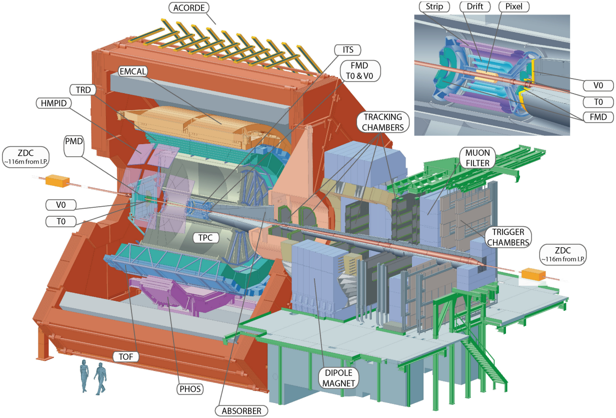
$k_\mathrm{T} : p = 1$

- Collinear and infrared safety

[1] Matteo Cacciari, Gavin P. Salam, Gregory Soyez, CERN-PH-TH/2011-297

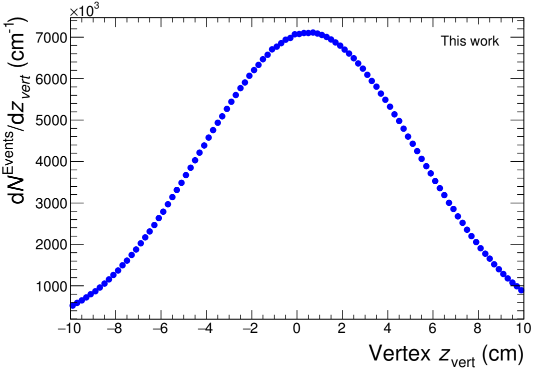
ALICE detector

- ITS and TPC used for charged track reconstruction
- V0 used for triggering



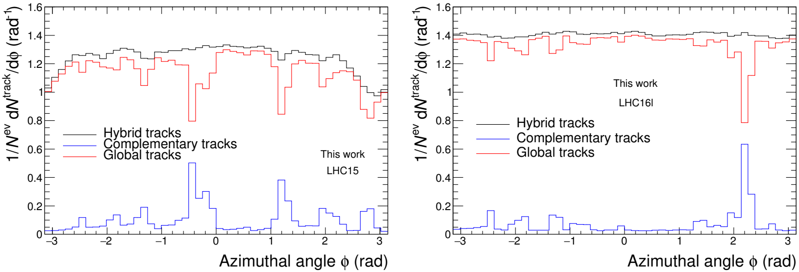
Event selection in analysis

- Charged jets in $\mathrm{p+p}$ collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ measured by ALICE
- Two datasets: *LHC15f* and *LHC16l*
- Trigger: coincidence of $V0A$ and $V0C$ signals
- $z-$vertex cut: $|z_{\mathrm{vert}}| < 10\ \mathrm{cm}$
- Events that passed the cuts: *2015f:* 6.6×10^7, *2016l:* 4.02×10^7



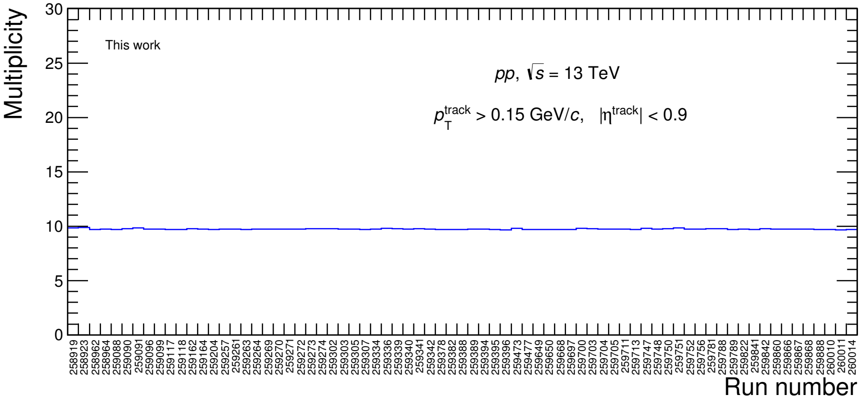
Track selection

- $p_{\mathrm{T}}^{\mathrm{track}} > 150\ \mathrm{MeV}/c$, $|\eta^{\mathrm{track}}| < 0.9$ for uniform track reconstruction efficiency and acceptance
- Hybrid tracks consisting of good quality (global) and worse quality (complementary tracks)
- Global tracks: TPC refit and an SPD hit required



- *LHC15f* hole in ϕ $\rightarrow$not applicable for jet reconstruction $\rightarrow$ only *2016l* analysed further

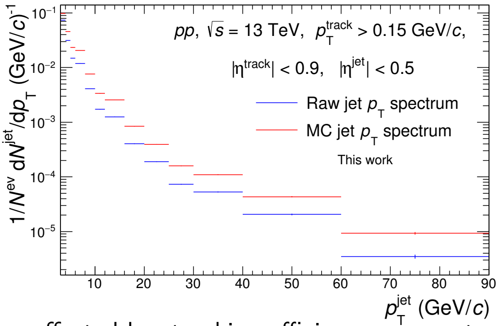
Mean track multiplicity in event in given run (**2016l**)



- All runs from *2016l* have been accepted

Jet reconstruction

- Charged, anti-k_t, $R = 0.4$ jets with $|\eta_{\mathrm{jet}}| < 0.5$ reconstructed by *FastJet*
- *2016l* compared with PYTHIA Perugia 11, MC
- $p_{\mathrm{T}}^{\mathrm{bins}} = \{3, 4, 5, 6, 8, 10, 12, 16, 20, 25, 30, 40, 60, 90\}\ (\mathrm{GeV}/c)$



- Jet spectra affected by: tracking efficiency, momentum smearing and underlying event

Underlying event

- Underlying event (UE): background from soft physics
- Event-by-event correction: $p_{\mathrm{T,corr}}^{\mathrm{jet}} = p_{\mathrm{T}}^{\mathrm{jet}} - \rho \cdot A^{\mathrm{jet}}$
- Background energy density ρ estimated as

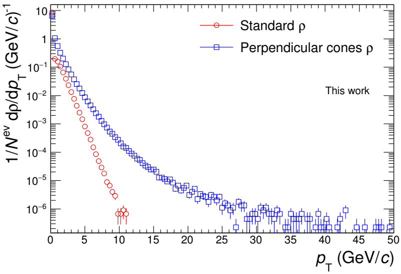
$$\rho^{\mathrm{std}} = \underset{\text{all } k_{\mathrm{T}} \text{ jets}}{\mathrm{median}} \left\{ \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{A^{\mathrm{jet}}} \right\} \qquad [1]$$

$$\rho^{\mathrm{cone}} = \frac{p_{\mathrm{T}}^{\mathrm{track}}}{2\pi R^2}, \text{ in two } \perp \text{ cones to the leading jet in azimuth}$$

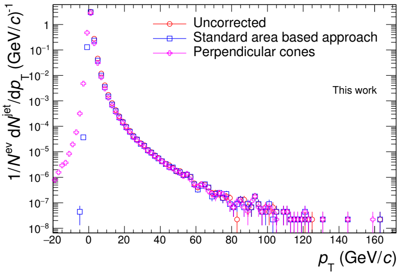
$$\rho^{\mathrm{CMS}} = \underset{\text{physical } k_{\mathrm{T}} \text{ jets}}{\mathrm{median}} \left\{ \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{A^{\mathrm{jet}}} \right\} \cdot \frac{A^{\text{phys jets}}}{A^{\text{all jets}}} \qquad [2]$$

[1] M. Cacciari, G. P. Salam, Phys. Lett. B659 (2008) 119–126
[2] CMS Collaboration, CERN-PH-EP-2012-152

UE corrected spectra



ρ^{std} and ρ^{cone}



Raw jet spectra, p_{T} corrected by $A^{\mathrm{jet}}\rho$

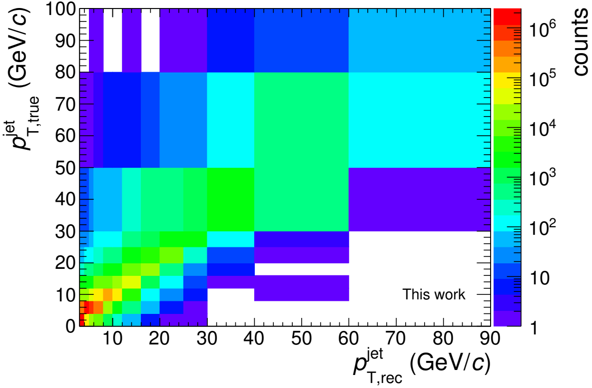
Corrections of measured raw spectra on detector effects

- Bin-by-bin correction: $\mathrm{Corrected} = \frac{\mathrm{d}N^{jet}/\mathrm{d}p_\mathrm{T}\big|_{\text{true,MC}}}{\mathrm{d}N_{jet}/\mathrm{d}p_\mathrm{T}\big|_{\text{rec,MC}}} \cdot \mathrm{d}N_{jet}/\mathrm{d}p_\mathrm{T}\big|_{\text{rec,data}}$
- Unfolding: $\mathbb{A}\vec{b}^{true} = \vec{b}^{rec} \quad \Rightarrow \quad \vec{b}^{true} = \mathbb{A}^{-1}\vec{b}^{rec}$
- $\mathbb{A}$ - Response matrix, often singular $\Rightarrow$ regularisation and inversion of $\mathbb{A}$ and finding a solution close to the prior spectrum
- Prior spectrum $\leftrightarrow$ Ansatz of the solution
- Singular Value Decomposition [1]: $\mathbb{A} = \mathbb{USV}^T$, where $\mathbb{U}$,$\mathbb{V}$ - orthogonal matrices, $\mathbb{S}$ - diagonal matrix, regularisation parameter k

[1] A. Hoecker, V. Kartvelishvili, Nucl.Instrum.Meth.A372:469-481,1996

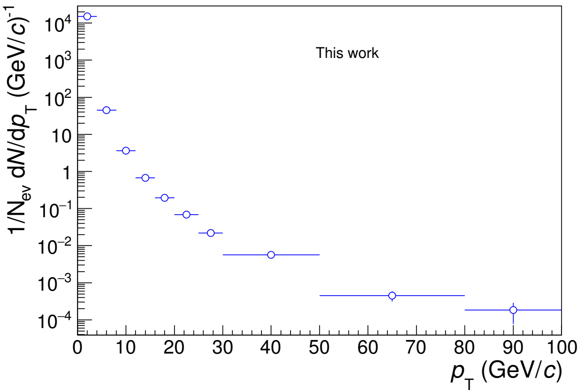
Response matrix

- Obtained from minimum bias production PYTHIA Perugia 11 + GEANT anchored to *2016l*
- Jet matching: minimising $\left(\varphi^{\text{jet}}_{\text{true}} - \varphi^{\text{jet}}_{\text{rec}}\right)^2 + \left(\eta^{\text{jet}}_{\text{true}} - \eta^{\text{jet}}_{\text{rec}}\right)^2$

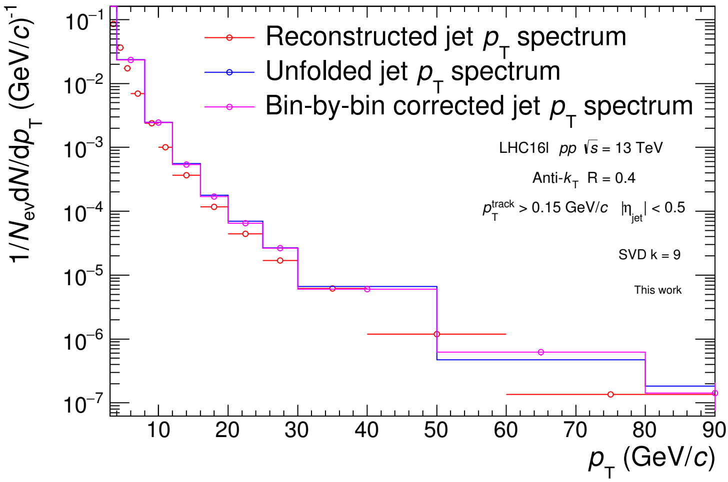


Prior jet spectrum

- Minimum bias PYTHIA 8, tune $4C$, $\mathrm{p+p}$ at $\sqrt{s} = 13$ TeV used as prior

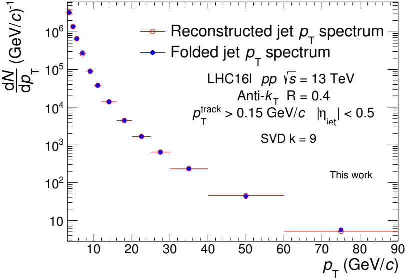


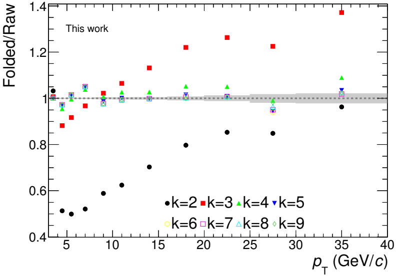
Unfolded spectrum



Consistency check

- Unfolded spectrum folded with the response matrix and compared with the raw spectrum





- Grey bars represent the relative statistical errors of the reconstructed spectrum

Summary and outlook

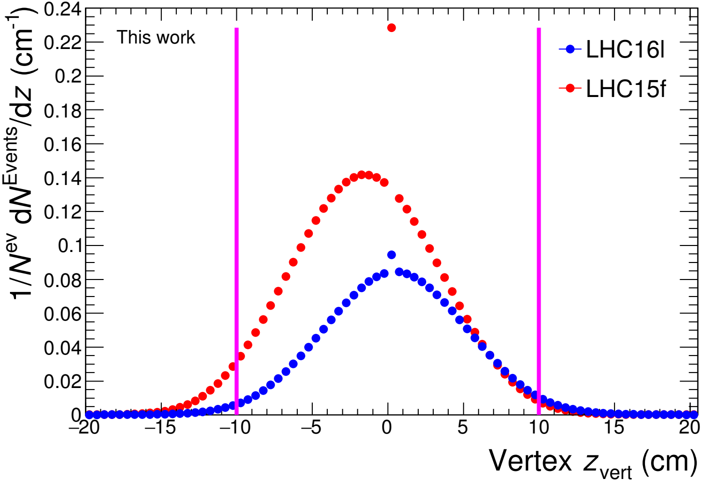
- Analysed charged jets from $\mathrm{p+p}$, $\sqrt{s} = 13\ \mathrm{TeV}$ measured by ALICE
- Determined the detector response matrix
- Unfolded uncorrected jet p_{T} spectra
- **Outlook:**
- Increase the statistics of the response matrix
- Unfold spectra corrected for the underlying effect
- Estimate systematic uncertainties
- Comparison with Monte Carlo event generators

Backup

2015f:	226085, 226170, 226175, 226176, 226177, 226183, 226208, 226210, 226212, 226217, 226220, 226225, 226444, 226445, 226452, 226466, 226468, 226472, 226476, 226483, 226495, 226500, 226532, 226543, 226551, 226554, 226569, 226573, 226591, 226593, 226596, 226600, 226602, 226603, 226605, 226606
2016l:	259389, 259394, 259395, 259396, 259473, 259477, 259649, 259650, 259668, 259697, 259700, 259703, 259704, 259705, 259711, 259713, 259747, 259748, 259750, 259751, 259752, 259756, 259781, 259788, 259789, 259822, 259841, 259842, 259860, 259866, 259867, 259868, 259888, 260010, 260011, 260014

Analysed run numbers.

Vertex cut


This work
LHC16l
LHC15f
$1/N^{ev}\, dN^{Events}/dz\ (cm^{-1})$
Vertex z_{vert} (cm)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−20
−15
−10
−5
0
5
10
15
20

SVD

- SVD theorem:
  $(\forall \mathbb{A} \in \mathbb{C}^{m,n}) (\exists \mathbb{U} \in \mathbb{C}^{m,m}, \mathbb{V} \in \mathbb{C}^{n,n}, \mathbb{S} = \mathrm{diag}(\sigma_1, ..., \sigma_r)) \left(\mathbb{A} = \mathbb{U}\mathbb{S}\mathbb{V}^T\right)$
  where $\mathbb{U}, \mathbb{V}$ are orthogonal, $(\forall k \in \hat{r}) (\sigma_k \in \mathbb{C})$ and $r = \mathrm{rank}\,(\mathbb{A})$
- Solving $\mathbb{A}\vec{x} = \vec{b} \Leftrightarrow$ minimizing $\left(\mathbb{A}\vec{x} - \vec{b}\right)\left(\mathbb{A}\vec{x} - \vec{b}\right)^T$
- Regularization of the ill-posed problem: minimizing the form $\left(\mathbb{A}\vec{x} - \vec{b}\right)\left(\mathbb{A}\vec{x} - \vec{b}\right)^T + \tau\,(\mathbb{C}\vec{x})^T\,(\mathbb{C}\vec{x}) \Rightarrow$
- Over-determined set of eqs.

$$\begin{pmatrix} \mathbb{A} \\ \sqrt{\tau}\mathbb{C} \end{pmatrix} \vec{x} = \begin{pmatrix} \vec{b} \\ \vec{0} \end{pmatrix} \Leftrightarrow \begin{pmatrix} \mathbb{A}\mathbb{C}^{-1} \\ \sqrt{\tau}\mathbb{I} \end{pmatrix} \mathbb{C}\vec{x} = \begin{pmatrix} \vec{b} \\ \vec{0} \end{pmatrix}$$

SVD II

- $\mathbb{A}\mathbb{C}^{-1} = \mathbb{U}\mathbb{S}\mathbb{V}^T$ therefore $\mathbb{U}\mathbb{S}\mathbb{V}^T\mathbb{C}\vec{x} = \vec{b} \Leftrightarrow \mathbb{S}\mathbb{V}^T\mathbb{C}\vec{x} = \mathbb{U}^T\vec{b}$
- $\vec{d} := \mathbb{U}^T\vec{b},\ \vec{z} := \mathbb{V}^T\mathbb{C}\vec{x} \Rightarrow \mathbb{S}\vec{z} = \vec{d}$
- $z_i = \frac{d_i\,\mathbb{S}_{ii}}{\mathbb{S}_{ii}^2+\tau}$

1. Invert $\mathbb{C}$
2. Decompose $\mathbb{A}\mathbb{C}^{-1}$ as $\mathbb{A}\mathbb{C}^{-1} = \mathbb{U}\mathbb{S}\mathbb{V}^T$
3. Calculate $\vec{d}$ and $\vec{z}$
4. $\vec{x} = \mathbb{V}\mathbb{C}^{-1}\vec{z}$