Jet measurements with ALICE: substructure, dead cone, charm jets

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This talk: a selection of pp results

- Groomed jet substructure
- Measurement of the dead-cone
- D-mesons in jets: production
- D-meson and $\Lambda_c$-baryon: fragmentation

→ Test of pQCD and hadronization models
→ Flavor-dependent production and fragmentation
→ Baseline for measurements in heavy-ions

Not covered: Jets in heavy ion collisions

- Modification of substructures by jet-medium interactions
- Flavor-dependent energy loss mechanisms
Jet measurements with ALICE

- **central barrel**: $|\eta| < 0.9$

**Time Projection Chamber:**
- *gas detector*
- charged-particle tracking and identification

**Inner Tracking System**
- *silicon detectors*
- charged-particle tracking, secondary vertex

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**Charged-particle jets**
- Full azimuth coverage
- Experimentally easier

**ElectroMagnetic Calorimeter**
- sampling scintillator
- full jet reconstruction
  - $|\eta| < 0.7$, $1.4 < \phi < \pi$
Jet measurements with ALICE

**Charged-particle jets**
- Full azimuth coverage
- Experimentally easier

**Full jets**
- Direct theory comparison
- Limited acceptance, technically more challenging

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  \[ |\eta| < 0.7, \ 1.4 < \varphi < \pi \]

Heavy-flavor identification:
- Lifetime of heavy flavor:
  - \[ c\tau (D) \approx 100-300 \mu m \]
  - \[ c\tau (B) \approx 400-500 \mu m \]
- Secondary vertex resolution:
  - < 100 \mu m

Secondary vertex resolution:
- Impact parameter
- Decay length
- Jet axis
- Primary vertex
- Secondary vertex
Groomed jet substructure

- Access to the hard parton structure of a jet
  - Mitigate influence from underlying event, hadronization
  - Direct interface with QCD calculations

- Soft-drop grooming: Remove large-angle soft radiation
  - Recluster a jet with Cambridge-Aachen algorithm (angular ordered)
  - Iteratively remove soft branches not fulfilling

\[ z > z_{\text{cut}} \theta^\beta \]

\[ z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \]

\[ \theta = \frac{\Delta R_{12}}{R} \]

Larkoski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146
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- Substructure variables
  - Groomed momentum fraction
    \[ z_g = \frac{p_{T,\text{sublead}}}{p_{T,\text{lead}} + p_{T,\text{sublead}}} \]
  - Groomed radius
    \[ \theta_g \equiv \frac{R_g}{R} \]
  - Number of soft drop splittings
    \[ n_{SD} \]
Soft Drop grooming: $z_g$ vs. jet $R$

- **Full-jet groomed momentum fraction in pp collisions at $\sqrt{s}=13$ TeV**
  - $z_{\text{cut}}=0.1$, $\beta=0$, absolute normalized, no background subtraction
- **At low $p_T$:**
  - small radii jets tend to split more symmetrically
  - larger radii: higher sensitivity to non-perturbative effects
- **Slight $p_T$-dependence for small radii**
- **Trends reproduced well by PYTHIA**
Soft Drop grooming: $z_g$ vs. $\beta$

- Charged-particle jet groomed momentum fraction in pp collisions at $\sqrt{s}=13$ TeV
  - $z_{\text{cut}}=0.1$, $R=0.4$, absolute normalized
  - A weak $p_T$-dependence is present
  - Trends reproduced relatively well by PYTHIA
Soft Drop grooming: $\theta_g$ vs. $\beta$

- Charged-particle jet groomed radius in pp collisions at $\sqrt{s}=13$ TeV
  $z_{\text{cut}}=0.1$, $R=0.4$, absolute normalized

- Smaller $\beta$ grooms soft splittings away $\rightarrow$ more collimated jets

- Trends reproduced relatively well by PYTHIA

  $\rightarrow$ possibility to explore contributions from partonic and hadronic stages
Dead cone: Forward emissions from radiators with large mass are suppressed

\[ \theta < \frac{m_q}{E_q} \]

Measurements at LEP:
- Flavor-dependence of angles between jet fragments
  - Low-background $e^+e^-$ environment
  - Indirect measurements w.r.t. jet axis
Dead cone: the Lund plane

- $D^0$ as well as inclusive jets: Reclustering with C/A
  
  L. Cunqueiro, M. Ploskon, PRD 99, 074027

- Lund plane populated with all splittings of the radiator’s prong
  
  - $D^0$: depletion expected at low angles (~higher $\ln(1/\theta)$ values)
  
  Note: 10 to 15% feed-down contribution in $D^0$ from $b$
Dead cone: the Lund plane

- $D^0$ as well as inclusive jets: Reclustering with C/A
  - L. Cunqueiro, M. Ploskon, PRD 99, 074027
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- $k_T$-cut to remove contamination from hadronization, decay and the underlying event
Dead cone effect in ALICE

D-tagged to inclusive ratios vs. $\ln(1/\theta)$ at $\sqrt{s}=13$ TeV

- Significant suppression of radiation in D-tagged jets towards low angles
  - effect decreases towards higher energy of the radiator ($\rightarrow \theta > m_q/E_q$)
  - effect decreases towards lower $k_T$ cut ($\rightarrow$ more contamination)

First direct measurement of the dead cone effect in pp collisions
Dead cone: model comparison

- **D-tagged to inclusive ratios** vs. $\ln(1/\theta)$ at $\sqrt{s}=13$ TeV
- Simulations with PYTHIA6 describe ALICE data qualitatively
Charm production: D⁰-jet cross sections

- **Analysis technique**
  - Identify D⁰ mesons via hadronic decays
  - Replace decay products with D⁰ in jet

- **Comparison with models**
  - NLO POWHEG+PYTHIA (hvq) calculations consistent with data (only marginally at low-\( p_T \))
  - Neither LO PYTHIA 6 and 8, nor NLO HERWIG 7 describe the cross-section
Charm fragmentation: D-jet $z_{||}$

- **Parallel momentum fraction**, pp $\sqrt{s}=13$ TeV
  - Characteristic to heavy-flavor fragmentation
- **D-meson fragmentation** is softer at high $p_T$ than at lower $p_T$
  - POWHEG+PYTHIA6 predicts a stronger change towards low $p_T$
Charm fragmentation: $\Lambda_c$-jet and D-jet $z_{||}$

- **Parallel momentum fraction**, pp $\sqrt{s}=13$ TeV
  - Characteristic to heavy-flavor fragmentation
- **D-meson fragmentation** is softer at high $p_T$ than at lower $p_T$
  - POWHEG+PYTHIA6 predicts a stronger change towards low $p_T$
- **$\Lambda_c$ fragmentation**: similar trends (different $p_T$ range!)
  - PYTHIA8 with SoftQCD settings performs well with $\Lambda_c$
  - Opportunity to compare baryon to meson fragmentation
D-jet substructure: $z_g$, $R_g$, $n_{SD}$

- **D⁰-tagged charged-jet groomed substructure**
  
  pp $\sqrt{s}=13$ TeV, $z_{cut}=0.1$, $\beta=0$

- **$n_{SD}$**: charm jets typically have less hard splitting than light jets

  → **Consistent with harder heavy-flavor fragmentation** (mass and color charge effects)
Jet substructures with soft-drop grooming in pp collisions
- Full jets vs. $R$, charged jets vs. $\beta$ in a broad $p_T$ range
  - Opportunity to explore contributions of pQCD and hadronization
  - Baseline for measurements in heavy-ions

Charm-jet measurements in pp collisions
- Clear indication of the dead cone effect in first direct measurement
- D-tagged jet cross sections, D and $\Lambda_c$ parallel momentum fraction
- $D^0$-jet substructure indicates harder fragmentation than light flavor
  - Test of pQCD models and flavor-dependent fragmentation

Summary and outlook
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- **Jet substructures with soft-drop grooming in pp collisions**
  - Full jets vs. $R$, charged jets vs. $\beta$ in a broad $p_T$ range
    - Opportunity to explore contributions of pQCD and hadronization
    - Baseline for measurements in heavy-ions

- **Charm-jet measurements in pp collisions**
  - Clear indication of the dead cone effect in first direct measurement
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Stay tuned for new results soon
Thank You!
Jet suppression in Pb-Pb

- Measurement down to $p_T = 40 \text{ GeV}/c$ => redistribution of energy
- Only weak dependence seen in data on jet resolution $R$
- Challenge to some models: stronger $R$ dependence predicted than in data
Jet-medium interactions

- **Low $p_T$:** Azimuthal h-h correlations, per-trigger normalized
  - **Broadening** of central angular correlation peaks in the $\Delta \eta$ direction
  - Understanding: rescattering with radial flow (AMPT)

- **Higher $p_T$:** Azimuthal h-h correlations, $I_{AA} = Y_{AA}/Y_{pp}$
  - **Narrowing** of the peak in central events in the $\Delta \eta$ direction
  - Jet structure modifications? No proper understanding by models.
Jet Substructure in Pb-Pb

- **First intra-jet splitting $z_g$**
  - At small angles ($\Delta R < 0.1$): consistent $z_g$ distributions in Pb-Pb and vacuum
  - At large angles ($\Delta R > 0.2$): $z_g$ distributions are steeper in medium than in vacuum

- **Early jet development influenced by medium**
Charm fragmentation: D-jet $z_{||}$ vs. $p_T$

- **parallel momentum fraction**
  - Characteristic to heavy-flavor fragmentation

- D-meson fragmentation is softer at high $p_T$ than at lower $p_T$

- POWHEG+PYTHIA6 predicts a stronger change towards low $p_T$

$pp \sqrt{s} = 13$ TeV

$5 < p_{T,\text{ch,jet}} < 7$ GeV/c

$7 < p_{T,\text{ch,jet}} < 10$ GeV/c

$10 < p_{T,\text{ch,jet}} < 15$ GeV/c

$15 < p_{T,\text{ch,jet}} < 50$ GeV/c
Baryon-to-meson ratio: $\Lambda_c^+/D^0$, $\Xi_c^0/D^0$

- $\Xi_c^0/D^0$ as well as $\Lambda_c^+/D^0$ are underestimated by models based on $ee$ collisions: Does charm hadronization depend on collision system?
  - PYTHIA8 with string formation beyond leading colour approximation? Christiansen, Skands, JHEP 1508 (2015) 003
  - Feed-down from augmented set of charm-baryon states? He, Rapp, 1902.08889
- Detailed measurements of charm baryons provide valuable input for theoretical understanding of HF fragmentation
Heavy flavor jets in p-Pb

- Heavy-flavor jets measured down to $p_T = 10$ GeV/c
- No mid-rapidity nuclear modification of HFE jets visible
  - Regardless of chosen jet resolution parameter
- Cross section of beauty jets tagged with displaced vertices also described by POWHEG HVQ x A (pp) within uncertainty
ALICE Upgrade for Run-3 and Run-4

- Up to 50 kHz Pb-Pb interaction rate
- Requested Pb-Pb luminosity: 13 nb$^{-1}$ (50-100x Run2 Pb-Pb)
- Improved tracking efficiency and resolution at low pT
- Detector upgrades: ITS, TPC, MFT, FIT
- Faster, continuous readout