Heavy Flavored Jet Measurements using the CMS Detector

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Motivation for Flavored Jets

• **In Lead-Lead collisions:** Observation of flavor-dependent energy loss?
  – Differences in quark-plasma interactions based on quark mass differences?
  – Most pQCD models predict similar high-$p_T$ jet behavior for flavored and light jets [ Djordjevic (PRC 90:034910) & Vitev (PLB 726:251) ]
    • Some differences in flavored jet production, e.g. $q/g$ ratio + spectra slope

• **In Proton-Lead collisions:** Quantification of the cold nuclear matter effects for heavy-flavor objects at high-$p_T$
  – Allow for factorization of quenching effects in PbPb; theoretical predictions can be constrained by flavor-dependent energy-loss measurements
  – Observe flavor-dependence of CNM effects at high-$p_T$?
  – Observations of gluon nPDFs using jets?
Energy Loss Possibilities

- Different possibilities for in-medium energy loss mechanisms
  - Heavy quarks suffering **radiative energy loss** suppressed by dead-cone effect
  - **Collisional energy loss** affected by forced radiation from acceleration in collisions
  - **Mesonic energy loss** affected by modified meson dissociation probabilities (shorter meson formation time)
- These three energy loss mechanisms all depend on the quark masses *differently*
Current flavored jet measurements do not distinguish between different production mechanisms.

Herwig (NLO) predicts large contributions from all three production mechanisms in the measured $p_T$ range:
- Gluon can split anywhere from early to late in the collision evolution -> convolutes energy loss measurements!

These first LHC b-jet measurement are critical starting points for the future:
- di-b-jet and b-jet-hadron correlations can shed additional light
Identifying B-Jets

- Primary identification method is using a **Secondary Vertex**
  - Long lifetime of $b = \text{mm or cm}$ vertex displacement
- Flight distance ($L_{xy}$) of the secondary vertex used as a discriminating variable
- Also use displacement of jet tracks (impact parameters) as a cross-check

B-quark decays are heavily CKM-suppressed (violate CP conservation)

Algorithms described in: *JINST* 8 (2013) P04013
Calculating the b-jet Fraction

\[ \varepsilon_b = \frac{C_b f_b^{b\text{tag}} N_{b\text{tag}}}{f_b^{\text{untagged}} N_{\text{untagged}}} \quad [1] \]

\[ N_b^{\text{jets}} = N_{\text{total}}^{\text{jets}} \frac{f_b^{b\text{tag}}}{\varepsilon_b} \quad [2] \]

- Purity calculated via template fits to secondary vertex mass
- Efficiency calculated using template fittings both before and after flavor tagging [Eq. 1]
- Efficiency and purity are used to find the number of total b-jets in the sample [Eq. 2]

Data

PRL 113:132301 (2014)
• First measurement of heavy flavor jet $R_{AA}$
• Clear suppression of b-jets
  – $R_{AA}$ as a function of $p_T$ shows significant suppression to very high $p_T$
  – $R_{AA}$ shows clear trend as a function of centrality
• "Need pPb measurement to resolve degeneracy between $g_{\text{med}} = 2.0$ with Initial State and $g_{\text{med}} = 2.2$ without Initial State"
Comparisons to Inclusive Jets

- B-Jet suppression (0-10%) is consistent with inclusive jet (0-5%) suppression to within systematic error
- Systematics between inclusive and b-tagged jets are mostly uncorrelated
Proton-Lead Collisions

- Quantification of the initial-state effects for heavy-flavor objects at high-pT
  - Allow for future factorization of these effects in PbPb; theoretical predictions can be constrained by flavor-dependent energy-loss measurements
  - Are there flavor-dependences of CNM effects at high-pT?
- Additional possibilities to probe the nuclear PDFs
  - Strong correlation of b-jet production to gluon nPDFs
Still a good probe of **gluon** nPDFs

Inclusive jets (large quark component)

- Inclusive dijet measurement convoluted by **quark PDFs**, while b-jet measurements are dominated by **gluon PDFs**
B-Jet Spectra (pPb)

- Separation into pseudorapidity bins tests for nPDF effects
  - Bjorken-x correlates with jet rapidity

- Observe minimal effects w.r.t. $\eta$
  - No indications of nuclear-PDF effects
  - Dijet studies (future) can shed more light

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B-jet $R_{pA}$ & fraction

- Consistent with no enhancement ($< 1\sigma$ effect) for jets in pPb with respect to Pythia 6
  - Large reference uncertainty – no pp data @ 5 TeV
- B-jet fraction relatively consistent with PYTHIA 6 Z2 tune

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Comparison to Inclusive-Jets

- So far, the story is the same
  - B-jets show similar trends as do light jets across collision species and collision energy
Identifying Charm Jets

• Impose tight selections on secondary vertex decay to increase c-jet tagging efficiency
  – PbPb b jets use simple 2-prong Sec. Vtx. algorithm
  – C-Tagging uses 3-prong secondary vertex, displaced from Primary Vertex (< 65% of tracks shared with PV)
  – 3-prong vertices dominated by Heavy Flavored jets

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\[ p_{1,CM} = p_{v,CM} \]
\[ p_{1,lab} \sin \theta_1 = p_{v,lab} \sin \theta_2 = 0 \text{ (min)} \]
\[ M_{\text{corr}} = \sqrt{M_1^2 + p_1^2} + \sqrt{M_v^2 + p_v^2} \]
\[ M_{\text{corr}}(\text{min}) = \sqrt{M_1^2 + p_1^2 \sin^2 \theta_1 + p_1 \sin \theta_1} \]

- \( M_{\text{corr}} = \) Minimum secondary vertex mass consistent with vertex flight direction
- Attempts to restore \( p_{\text{perp}} \) balance w.r.t. flight direction from missing energy (e.g. \( \nu, \pi^0 \), etc.)
- B hadrons have higher \( p_{\text{perp}} \) components (on average) than do C hadrons
  - B’s have statistically larger values of \( M_{\text{corr}} \)
Charm-Jet Spectra

- First ever measurement of charm jets in a heavy-ion environment
  - One of the first ever in the high-energy field
- Find charm-jet spectra in pPb is consistent with PYTHIA prediction

CMS PAS HIN-15-012, CDS: 2055705
Summary

• In Lead-Lead collisions:
  – Flavor-dependent energy loss?
    • Not a dramatic effect
  – Differences in quark-plasma interactions based on quark mass differences?
    • Not at high-\(p_T\) - consistent with pQCD predictions

• In Proton-Lead collisions:
  – Observe flavor-dependence of CNM effects at high-\(p_T\)?
    • Results consistent with pQCD predictions of small CNM effects
    • Extends to both b-jets and c-jets (w.r.t. PYTHIA 6)
  – Observations of gluon nPDFs through jets?
    • Possibly with increased statistics and measurement of HF dijets
Charm-jet fraction also consistent with PYTHIA prediction

- Somewhat surprising – PYTHIA not known for reproducing jet flavor as well as NLO generators (HERWIG, POWHEG)

CMS Preliminary

pPb data, $-2 < \eta_{\text{lab}} < 2$

PYTHIA Z2 (5.02 TeV)

CMS Preliminary

pp data, $-2 < \eta < 2$

PYTHIA Z2 (2.76 TeV)
Global perspective of heavy-ion, heavy-flavored jet modification
- Parton mass-dependent effects are small at high-$p_T$
- C-jet systematic uncertainties reduced with addition of 5 TeV pp data (soon!)
AdS/CFT Models “Need More Work”

• Previous AdS/CFT predictions showed very different behavior for b/c jet RAA.
  – New addition of NLO effects limit applicability of these claims
**B-jet $R_{AA}$ (centrality)**

- $R_{AA}$ is smallest for most central collisions and moves toward unity for peripheral collisions.

- Most central b-jets show consistent suppression with inclusive jets (next slide).
Corrected Secondary Vertex Mass

- $M_{corr}$ provides additional discrimination power between light/charm/bottom jets than does pure secondary vertex mass.
- Shapes between bottom and charm different for $M_{corr}$

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Comparison to B-Mesons

- “Global” Heavy flavor results can show $p_T$-dependent effects
  - Somewhat obscured by fragmentation function widths
  - Extension of B-Meson result to PbPb may show mass-dependent suppression effects
Discriminators

In principle, many ways of tagging b-jets

- We use “SSV” = Simple secondary vertex
- “JP” = Jet Probability tagger used as cross-check (no SV)

\[ SSV = \ln(1 + \left| L_{xy} \right| / \sigma(L_{xy})) \]

\[ JP = \Pi \cdot \sum_{nTracks=0}^{N-1} \frac{(-\ln \Pi)^i}{i!} \]

\[ \Pi = \prod_{nTrack=1}^{N} \max(d_0, 0.005) \]