Basic requirements of background subtraction for jet physics in HI collisions

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Definition of Jets in a Large Background
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Why do we do background subtraction?

• In principle, experimentalist could publish jet data without background subtraction (and probably the right choice too.)

• The issue is the poor understanding of the non-perturbative physics:
  • Important for a large part of the accessible kinematics phase space in HI collisions
  • Phenomenological models for soft physics are still not accurate enough

• Naively, one try to make the maxima use of the data-driven method to remove “soft physics” component, but also introduce dependence on the underlying assumption

• Hope to reveal the underlying physics message
Physics Goal in Heavy Ion Collisions with Jets

- Nuclear PDFs
- Role of pre-hydrodynamization phase, starting and ending point of QGP
- QGP properties
  - Mechanism of parton-medium interaction
  - Extract the scattering power
  - Color screening length
  - Sound waves / wakes
  - ...
- Hadronization of QGP
- ...

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Definition of Jets in a Large Background
Would like to study the jets from hard scattering as a proxy of the partons.

Ideally, we don’t want to include the underlying events from multi-parton interaction.

In reality, they can not be separated in a well defined way.

Jets used in pp collisions does include the UE.
Jet Spectra in pp(bar) collisions

Jet spectra with large R parameter from proton-(anti-)proton collisions are well understood. Consistent with NLO calculations.
Inclusive hadron pseudorapidity density in pPb collisions at LHC energies is like ~ 4-5x larger than pp collisions at similar collision energy.

UE effect of 100 GeV jet in pp with R=0.7 is roughly the same as UE effect of 70 GeV jet in pPb MB with R=0.3 (100 GeV x 4 x 0.3² / 0.7² ~ 70 GeV)
Dijet pseudorapidity in the LAB Frame

Idea: Angular distributions of high $p_T$ dijets

CMS pPb $35 \text{ nb}^{-1}$
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ p_{T,1} > 120 \text{ GeV/c} \]
\[ p_{T,2} > 30 \text{ GeV/c} \]
\[ \Delta\phi_{1,2} > 2\pi/3 \]
\[ \text{All } E_T^{4<|\eta|<5.2} \]

\[ \eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2} \]
\[ \propto 0.5 \log \left( \frac{x_p}{x_{Pb}} \right) + \eta_{CM} \]

\[ \frac{dN_{\text{dijet}}}{d\eta_{\text{dijet}}} \]

\[ x_p < x_{Pb} \]

Sensitive to EMC effect

\[ x_p \sim x_{Pb} \]

Sensitive to anti-shadowing

\[ x_p > x_{Pb} \]

Sensitive to shadowing

EPJC 74 (2014) 2951
Observation of gluon EMC effect

CMS

pPb (35 nb⁻¹), pp (27.4 pb⁻¹)

\( \sqrt{s_{NN}} = 5.02 \) TeV

- anti-\( k_T \) \( R = 0.3 \) jets
- \( p_T^{j_1} > 90 \) GeV, \( p_T^{j_2} > 20 \) GeV
- \( \Delta \phi_{1,2} > 2\pi/3 \)
- \( \eta_{dijet} \)
- Data
- Syst. uncert.
- EPS09
- DSSZ
- pp NLO pQCD: CT14

- **EPS09**: hint of **anti-shadowing** and EMC effect of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing
- UE effect small / negligible in inclusive MB events for normalized distributions
CMS use PYTHIA6 + HIJING and PYTHIA6 to validate most of the pPb collision analysis.
  - PYTHIA6: Jets in NN collisions + NN UE
  - HIJING: pPb UE
  - PYTHIA6+HIJING: assuming no correlation between UE and hard process (which is not true)

Experimental procedure in short:
  - Make sure the jet spectra extracted from PYTHIA6 + HIJING are consistent with PYTHIA6 after corrections
  - The corrected result INCLUDES UE from NN

NLO calculation: without UE
  - Make sure the hadronization effects are small by comparing parton level and hadron level in PYTHIA and HERWIG

To be safe: only rely on data at high jet $p_T$ for nPDF fit
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- …

- Hadronization of QGP
- …
• Signal jet probably should include the jet from hard scattered parton and “correlated background” (medium recoil)

From Korinna Zapp (CERN)
1. Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2. Run anti $k_T$ algorithm on background subtracted towers

3. Exclude reconstructed jets $> p_T^{\text{cut}}$ Recalculate the background energy

4. Run anti $k_T$ algorithm on background subtracted towers to get final jets
Let the “ghost” remove the underlying event

- Correction derived from PYTHIA NN scattering (with UE)
- Problem: Both algorithms remove the NN UE first and put it back by PYTHIA based jet energy correction
  - Is that what we want? Probably not.

See Chris McGinn’s talk On the CMS algorithms and his new development
• Experimental issues: some background subtraction techniques could remove part of the signal (such as $\eta$ reflected cone and $\eta$ ring subtraction). **Amount of signal removal is not accessible to the theorists.**

• **Idea: mixed event subtraction**
Tracks from the underlying event are uncorrelated with the photon
- Estimate contribution of underlying event by embedding the photon into minimum bias (MB) events
- Select MB events with similar event characteristics
  - Centrality, primary vertex position, event plane angle

Ran Bi (MIT)
Background Subtraction for Photon-Tagged Jets

- Contributions from background tracks (UE) and background jets (fake jets) must be subtracted.
Background Subtraction for Photon-Tagged Jets

- Contributions from background tracks (UE) and background jets (fake jets) must be subtracted.
Define Jets in a Large Background

- Decrease the population of gluon jets: >70% of the tagged jets are quark jets
- Observation of modified jet fragmentation function in PbPb with respect to pp
  - No significant high \(z\) (or small \(\xi = \ln(1/z)\)) enhancement observed
  - CMS only measured down to \(\xi \geq 0.5\) (or \(z \leq 0.7\))
  - It would be good to have high \(p_T\) associated jet version of this analysis
Inclusive Jet Shape

Photon-tagged Jet shape  \( \text{PbPb} / \text{pp} \)

- \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)
- \( p_T^\gamma > 60 \text{ GeV/c} \)
- \( \text{PbPb} 404 \mu\text{b}^{-1} \)
- \( \text{anti-}k_T \) jet \( R = 0.3 \)
- \( \text{pp} 27.4 \text{ pb}^{-1} \)
  - \( p_T^{\text{jet}} > 30 \text{ GeV/c}, \Delta\phi_{j\gamma} > \frac{7\pi}{8} \)

CMS Preliminary

\[ \rho(r)_{\text{PbPb}} / \rho(r)_{\text{pp}} \]

- Data
- \( \text{SCET}_G \) Chien-Vitev
- LBT

\[ \rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (r_a, r_b)} p_T^{\text{trk}}}{\sum_{\text{tracks}} p_T^{\text{trk}}} \]

Inclusive Jet shape  \( \text{PbPb} / \text{pp} \)

- CMS PbPb, \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)
- \( L \text{ dt} = 150 \mu\text{b}^{-1} \)
- \( \text{anti-}k_T \) jets: \( R = 0.3 \)

- \( p_T^{\text{jet}} > 100 \text{ GeV/c} \)
- \( 0.3 < |\eta^{\text{jet}}| < 2 \)
- \( p_T^{\text{track}} > 1 \text{ GeV/c} \)

Varying the jet flavor
- Due to the lower jet \( p_T \) in photon-tagged jet and changed quark vs. gluon ratio
- Would be nice to measure high \( p_T \) tagged jet

Yen-Jie Lee
Definition of Jets in a Large Background
**D-Jet correlation**

**Enhancement of low $p_T$ light hadrons at large angles about jets**
- Light hadron jet shape analysis
- How to explain
  - medium-induced gluon radiation?
  - medium response? $m_c \gg T_{QGP}$
  - multiple scatterings?
  - .......
- Vary mass of the associated hadrons
  - Heavy flavor!

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**Jing Wang (MIT)**

**Definition of Jets in a Large Background**

*Yen-Jie Lee*
D-Jet Correlation

Low D $p_T$: $4 < p_T^D < 20$ GeV/c

- The ratio of PbPb over pp:
- Low D $p_T$: increases as a function of $r$
  - Hint that $D^0$ are further from jet axis in PbPb than pp
- High D $p_T$: consistent with unity

High D $p_T$: $p_T^D > 20$ GeV/c

Jing Wang (MIT)
Experimental issues in large system

- Event mixing is probably currently the most promising tool to gain statistical accuracy (in jet-by-jet level or in event level)

- The estimated imperfection of the subtraction using the signal definition shown before (signal + correlated medium response) is quoted as systematics

- Issues related to correction of resolution effects:
  - Introduce model dependence (ex: unfolding or correction with PYTHIA) which is not reversible
  - In addition, we don’t have yet full theoretical understanding of the signal part
Theoretical Interpretation of the Excess

Modification of the shower inconsistent between models

Different explanation of the large angle enhancement in jet shape measurement

- **SCET\(_G\)**: Splitting function (large angle radiation)
- **JEWEL & JETSCAPE**: medium recoil parton
- **CCNU**: recoil parton + hydro dynamical evolution
- **HYBRID**: fully thermalized medium response
- **McGill**: medium response + shower

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Observables with Minimal Background Subtraction

- Quenched energy distribution depends on the R parameter used in the Anti-k_T algorithm
- Background subtraction only in jet reco level
- Hint of narrower leading jet (or wider subleading jet) in PbPb collisions.
- **Soft particles extends to larger Δ in dijet events reconstructed with larger R parameter**
Zg vs. ΔR Phase Space

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

ΔR

Ideal world, different phase space correspond to different physics
Zg vs. ΔR Phase Space

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

- The reality may be much more complicated than that
- The excitement: One could construct different observables which are sensitive to different part of the phase space and provide stress test on models
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Modification of W mass in Top event

Negligible interaction between Top / W and the QGP

- Longer total delay time of the W ($\tau_{\text{tot}}$) leads to smaller modification of W mass in heavy ion collisions
- Probe the “start” and “end” time of the QGP!!

$\tau_{\text{m}}$: quenching end time

Liliana Apolinário (LIP) et al.

“A Yoctosecond Chronometer.” (Gavin Salam)
Sensitivity to the Medium End Time

- Sensitivity to medium end time ($\tau_m$):
  - HL-LHC PbPb Program (10 nb$^{-1}$): 1.4 fm/c
  - 1 month KrKr (30 nb$^{-1}$): 1.8 fm/c

Full exploitation of this probe only at FCC energies
Highly Boosted Top or Boson Jets in HE-LHC or FCC

• At very large $p_T$, a better strategy is probably to avoid UE subtraction.

• Suppression of UE effect and soft radiation with grooming procedure

• Grooming setting could be optimized to achieve the best mass resolution

• Could be communicated with theorists

Liliana Apolinário (LIP)
Issues Related to Resolution Correction

• Correction of resolution effect is model dependent
  • In CMS, we use PYTHIA, which doesn’t describe quenched jet substructure
  • Effects related to modification of quenched jet are estimated by reweighting the PYTHIA quark and gluon fraction
  • It is corrected to NN scattering level (include UE from NN, which is coming from PYTHIA (!) ).

• Limitation of resolution smearing:
  • Hard to compare results from exp directly
  • Hard to parameterize the resolution function for more complicated observables such as groomed jet mass and subjet momentum sharing

• Issue of both treatments: we assume factorization of signal and background:
  • Which is ambiguous and artificial, probably not necessary in the long run

• To which level do we correct to?
  • Correct only detector effects (keep the UE fluctuation untouched)
  • Correct also UE fluctuation?
Moving beyond the current measurements

- Exciting new future direction: fluctuation of jet quenching
  - “Parton shower shape dependence of jet quenching”

- We need to study the interplay between “hard” and “soft” physics:
  - Medium response, sound wave and wake
  - Medium recoil
  - Thermalization of jet
  - To move away from the “perfect fluid” paradigm and to study the inner workings of QGP

- Can those be achieved using the current strategy?
Inputs to the Basic Requirements

• Basic Requirement for background subtraction:
  • Can be used to achieve our physics goal
  • Can be used in experimental measurements
  • Can be used in theoretical calculations

• Minimal assumption on the factorization of “soft” physics and “hard” physics.
  • If needed, classification should be theoretically sound and reproducible in calculations.

• Don’t do background subtraction if it is not necessary

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