A Brief Summary of the Workshop and Path Forward

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Lehigh University

The Definition of Jets in a Large Background

RIKEN BNL Research Center Workshop
June 25-27, 2018 at Brookhaven National Laboratory

Fermi National Accelerator Laboratory

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

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December 1990

* To be published in the proceedings of the 1990 Summer Study on High Energy Physics, *Research Directions for the Decade*, Snowmass, Colorado, June 25 - July 13, 1990.

Snowmass Accord: Define Jets

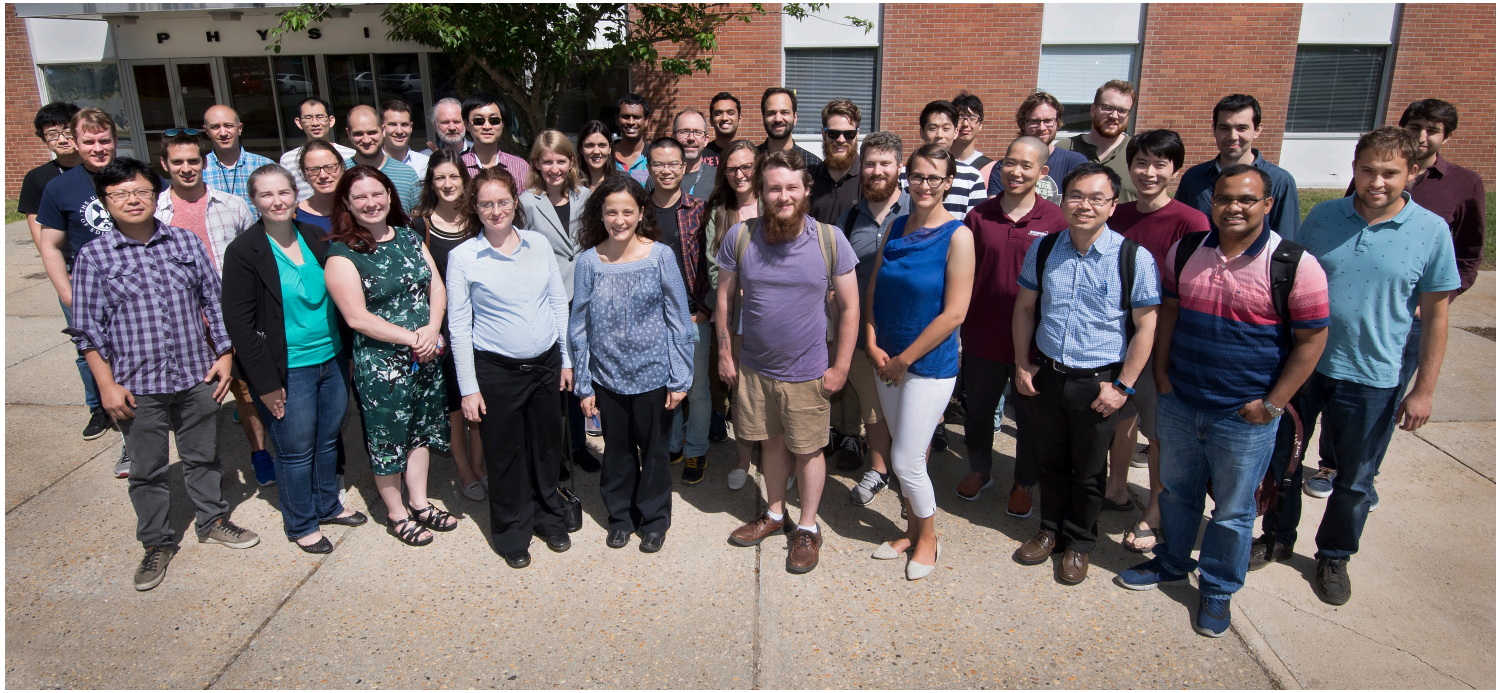
- **Experimental and theoretical definitions of jets must match!**
  - Underlying event is the most difficult
- Do we need an agreement for HI Jets?

Definition of Jets in a Large Background

- **Organizers:** M. Connors, G. Milhano, C. Nattrass, R. Reed, S. Salur
- **Spectra conveners:** R. Kunnawalkam Elayavalli, Y. Mehtar-Tani (R. Bertens)
- **Correlation conveners:** J. Noronha-Hostler, J. Huang
- **Substructure conveners:** Y. Lee, Y. Chien

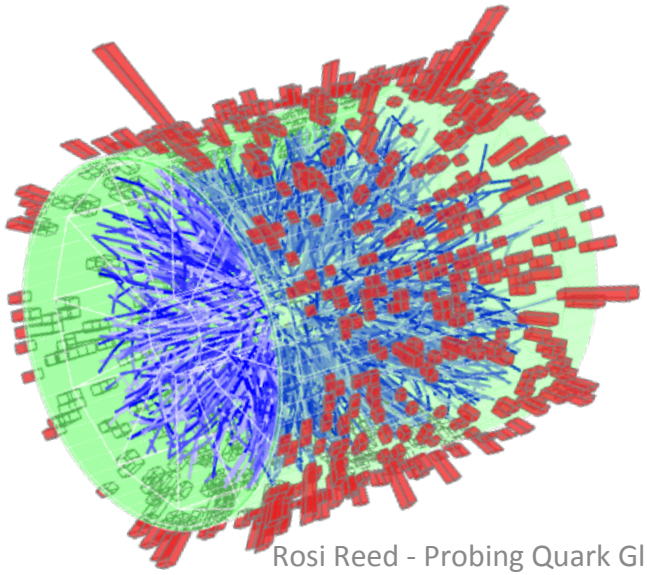
Thanks to RBRC for their support of our speakers and this workshop.

Many great talks and 30+ pages of meeting notes can be found at:
https://indico.bnl.gov/event/4312/

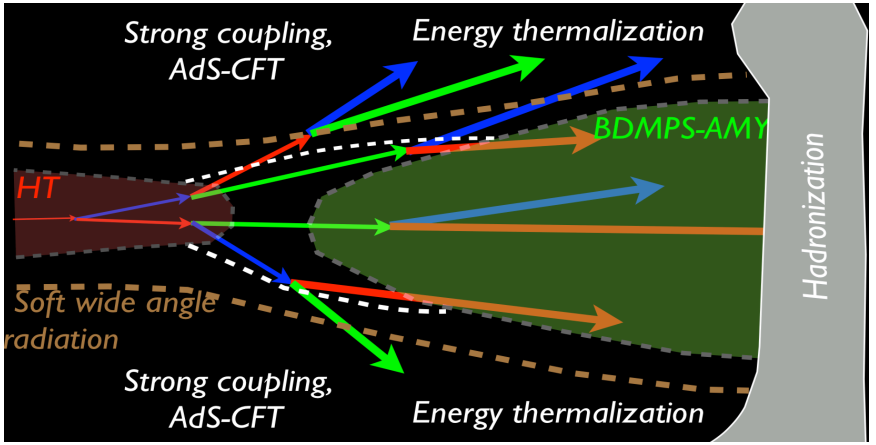


Goal

Discuss the **interplay** between **experimental** techniques and **theoretical** calculations with the aim of reaching an agreement on the way forward for **extracting jet measurements from large background** events such as those in heavy ion collisions and high luminosity p-p or electron-ion collisions.



Majumder, HP2015



Goal

Discuss the interplay between experimental techniques and theoretical calculations with the aim of reaching an **agreement*** on the way forward for extracting jet measurements from large background events such as those in heavy ion collisions and high luminosity p-p or electron-ion collisions.

*Work in Progress

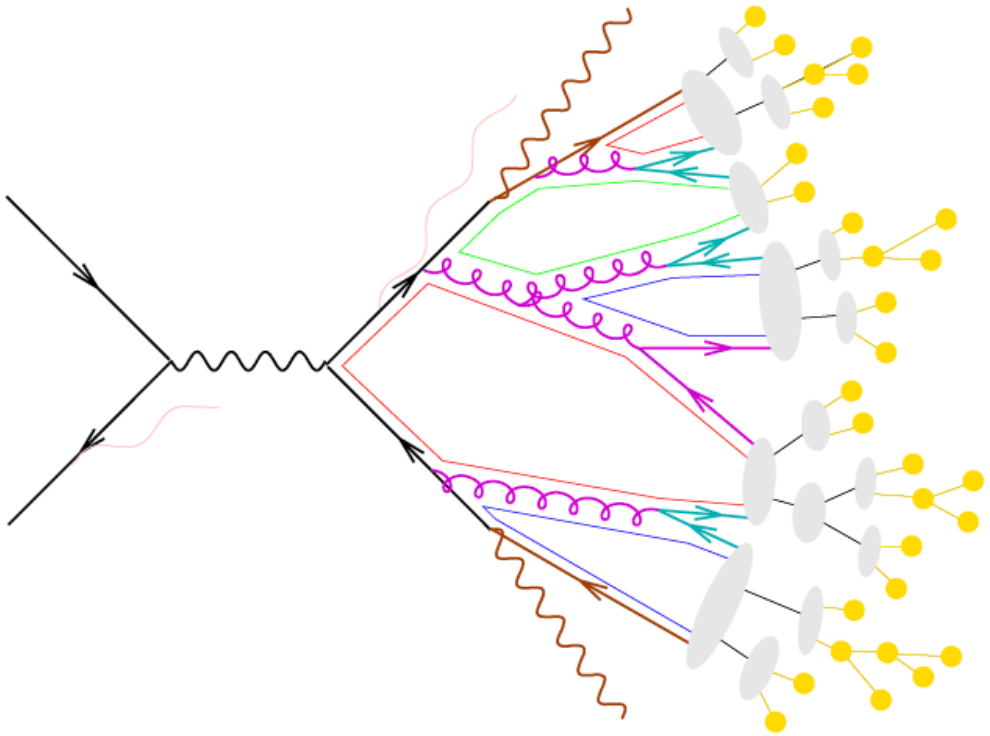
Questions Discussed

- Is an experimental jet equivalent to a theoretical jet?
- (How) can a given experimental technique be applied to a theoretical calculation?
- Can a bias imposed by an experimental technique be (easily/well) calculated theoretically?
- Can a given theoretical definition of background be distinguished from the signal in experiment?
- What is the sensitivity of techniques to interesting physics?
- How should background and background fluctuations be treated for full Monte Carlo models?
- How low in $p_{T,Jet}$ are jets still well defined? Do we need low p_T jets?

Jet Definition

- What is a jet?
  - Jets are not partons
  - Partons are not jets
  - There is not an unambiguous definition of a jet
- A jet is defined by the algorithm used to "find" it
  - Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable
  - Ideally a jet finding algorithm is:
    - Infrared safe
    - Colinear safe
    - Not dependent on the details of hadronization → Factorization

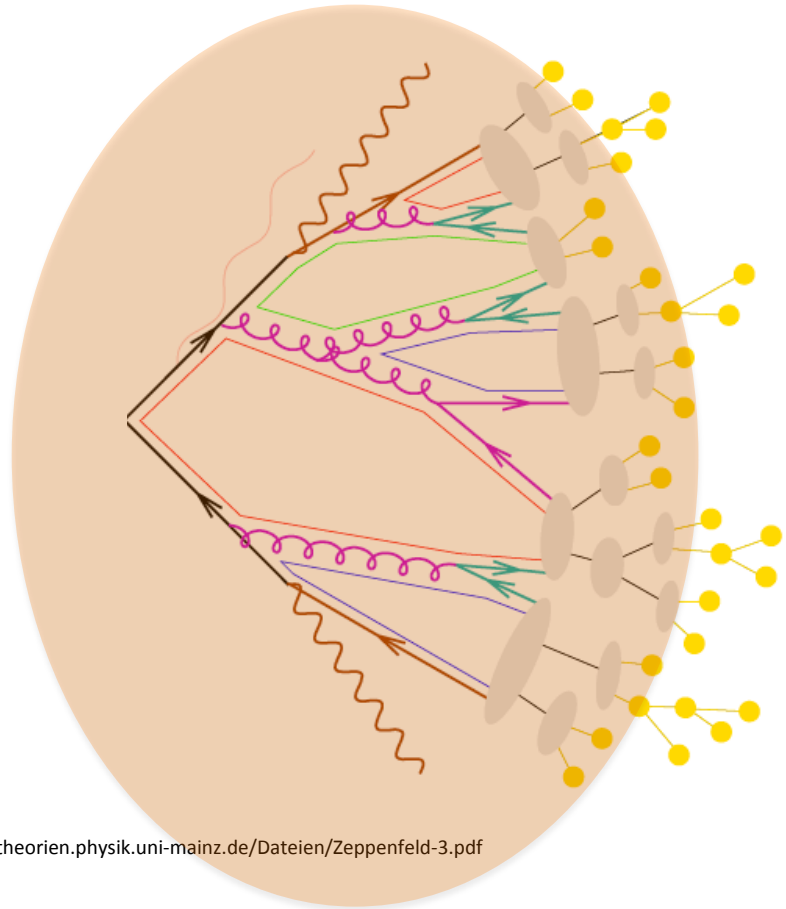
Jet Definition



https://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Even in proton-proton collisions, jets are very complicated objects
  - Multi-scale

Jet Definition



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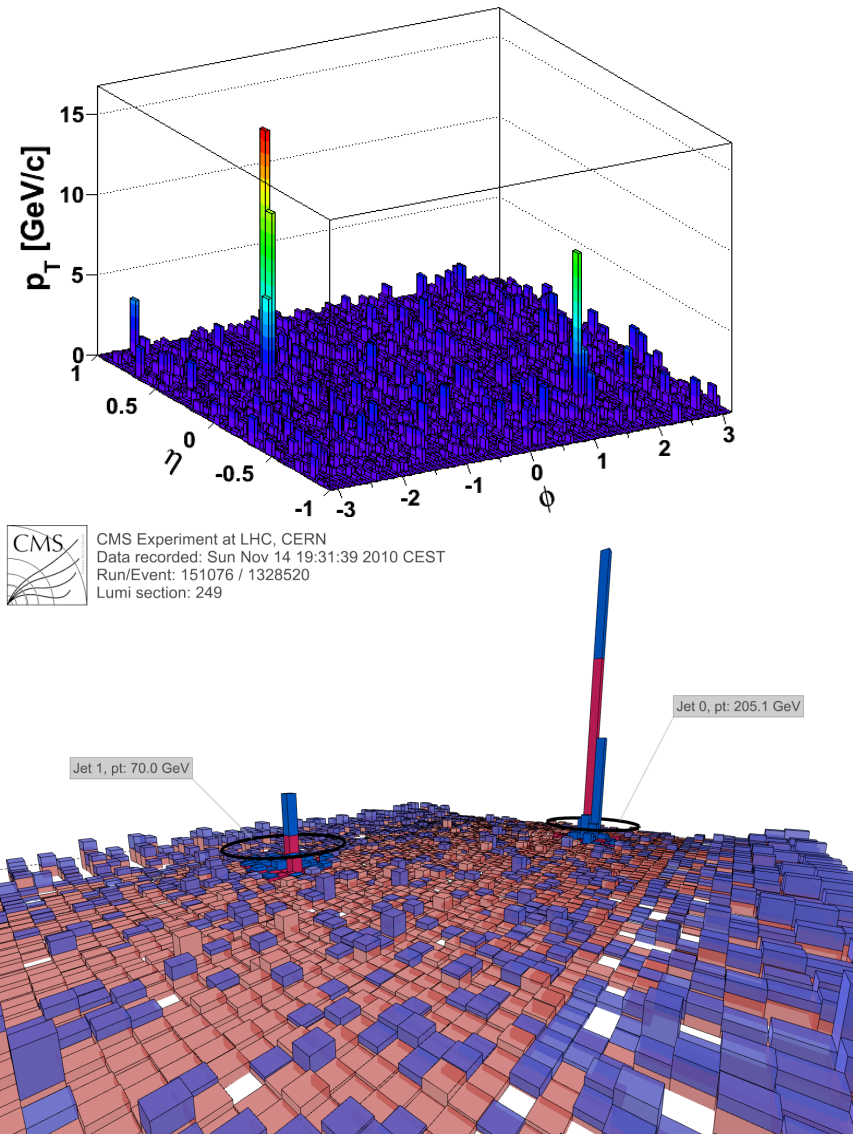
- Even in proton-proton collisions, jets are very complicated objects
  - Multi-scale
- Addition of the background
  - Smear measured kinematics
  - Create combinatorial "jets"
  - **Jet-medium interactions**

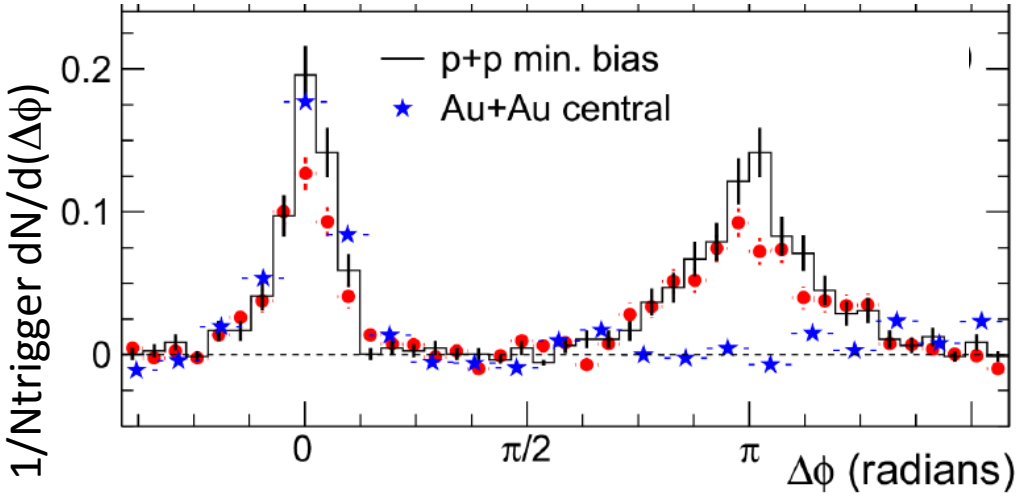
Then add the large background!

Jet Definition – Heavy Ions First Steps

Central Au+Au @ 200 GeV



- First measurements of jets were difficult!
  - Simplify the problem by looking only at the leading parton (hadron)
  - Iconic Dihadron plot

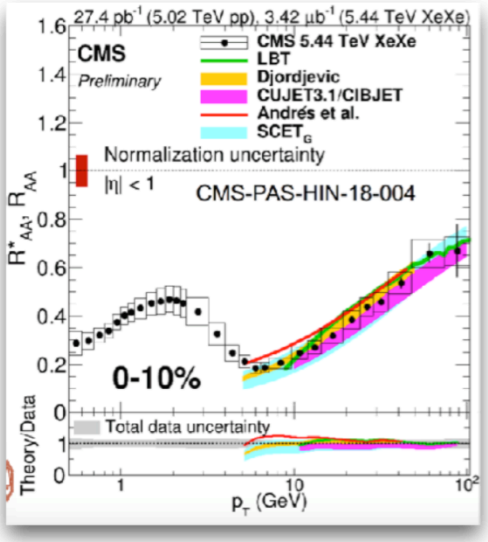


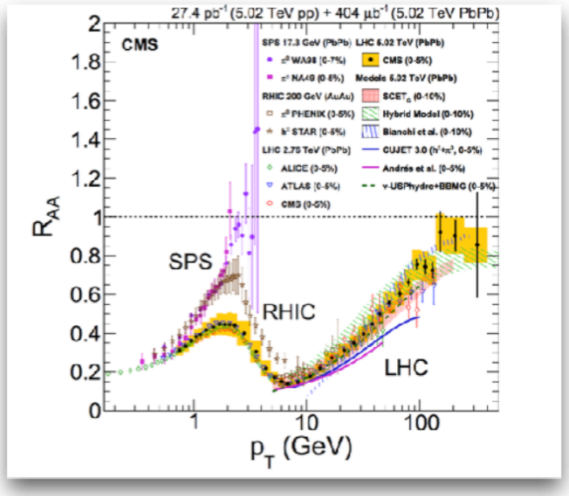
Jet Definition – Heavy Ions – Evolution

- Leading hadron measurements do not capture the entire process
  - Hadron R_{AA} is not particularly differential between models

Carlota Andres

R_{AA}





CMS Collaboration, JHEP 04 039 (2017)

"Everybody can describe R_{AA} "

Austin Baty, QM2018

Background removal in dihadron correlations is not as simple as first believed

- See talks by Eliane Epple and Joel Mazer

Jet Finding in AA Collisions

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm (JHEP 0804 (2008) 063)
  - Also creates combinatorial jet candidates
  - Jet kinematics smeared from background
- Resulting measurements are sensitive to methods used to suppress combinatorial jets and correct jet kinematics
  - Field initially focused on narrow/high energy jets
  - Method choice impacts different observables differently

Jet Finding in AA Collisions

- Jet finder: groups final state particles into jet ca
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  m
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  - Method choice impacts different observables differently

Can a **bias** imposed by an experimental technique be (easily/well) calculated theoretically?

Can a given theoretical **definition of background** be distinguished from the signal in experiment?

How should background and background fluctuations be treated for full Monte Carlo models?

Points of Consensus

- While there was not complete agreement from everyone, we did agree this task was important and necessary
  - And set out on the journey

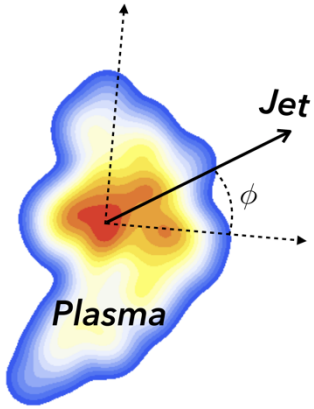
Points of Consensus

- Theory and experiment comparisons are valid when methods can be applied in both

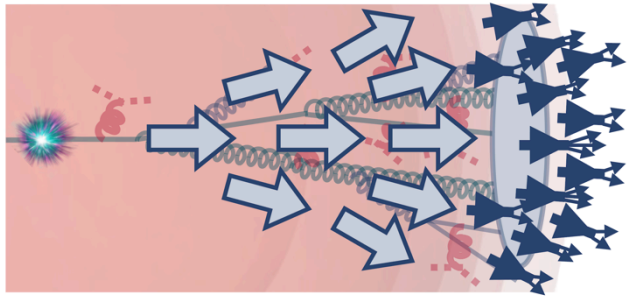
Points of Consensus

- Theory and experiment comparisons are valid when methods can be applied in both
  - **"Experimental and theoretical definitions of jets must match!"**
  - Background subtraction may be necessary
    - Poor understanding of the non-perturbative physics
    - Essential for HI physics to access low p_T kinematics

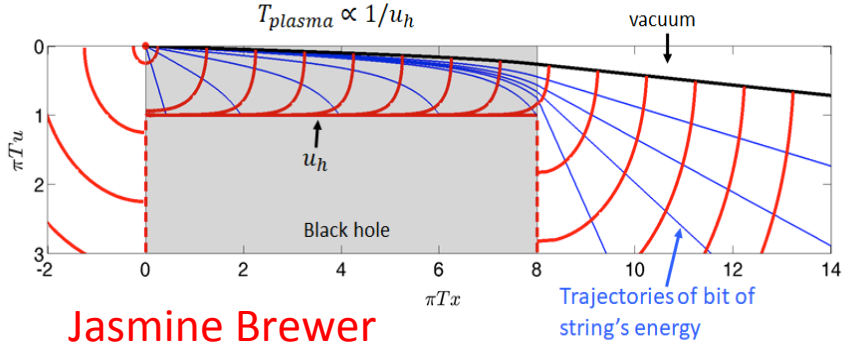
      Soft sector Phenomenological modeling lacks accuracy



Shuzhe Shi



Yasuki Tachibana



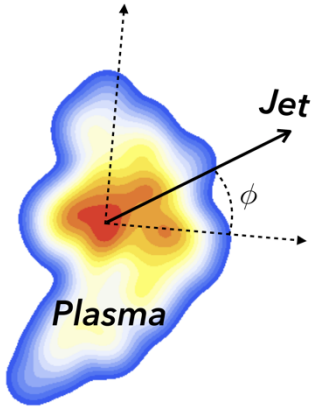
Jasmine Brewer

Points of Consensus

- Theory and experiment comparisons are valid when methods can be applied in both
  - **"Expe … ons of jets must …**
  - Backg … sary
    - Poc … ve physics
    - Ess … nematics

Allows comparisons using event generators, parton/ string models, NLO and holographic calculations…

Soft sector Phenomenological modeling lacks accuracy



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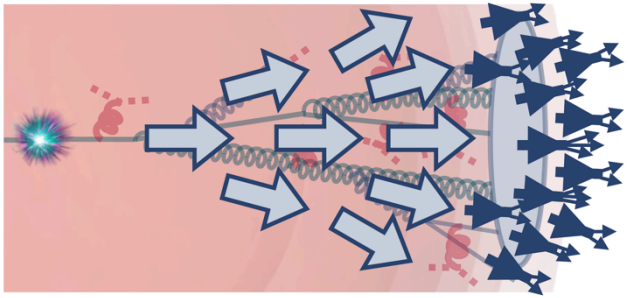

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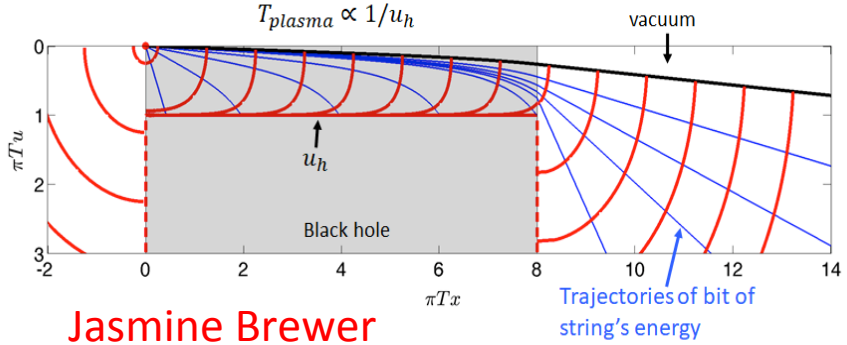

Jasmine Brewer

What are the necessary components of a background subtraction algorithm?

- Can be used in experimental measurements
- Can be used in theoretical calculations
- **Minimal assumption on the factorization of "soft" physics and "hard" physics**
- Classification should be theoretically sound and reproducible in calculations

Don't use background subtraction if it is not necessary – provide raw measurements along with corrected results & corrections.

Comparison of background methods

- Ensemble based or event-by-event/jet-by-jet?
- Methods
  - Mixed events
  - Constituent subtraction
  - Iterative removal of background (ATLAS and CMS)
  - η reflection as done by CMS
  - Random cone/calculate ave background (ALICE/STAR)

Correcting JES vs removing combintorial jets

- Are they all equal? Do they need to be?
- **Do these make sense theoretically? Can they be applied to theory?** Do we need to be collinear and infrared safe when estimating backgrounds?
- Do these methods make our measurements insensitive to interesting physics?

How to Evaluate Background Methods

Martin Spousta

- Jet energy scale $\left\langle \frac{p_{\mathrm{T,reco}} - p_{\mathrm{T,truth}}}{p_{\mathrm{T,truth}}} \right\rangle$
- Jet energy resolution $\sigma\left(\frac{p_{\mathrm{T,reco}} - p_{\mathrm{T,truth}}}{p_{\mathrm{T,truth}}} \right)$
- Jet position resolution $\sigma\left(\frac{\eta_{\mathrm{reco}} - \eta_{\mathrm{truth}}}{\eta_{\mathrm{truth}}} \right), \sigma\left(\frac{\phi_{\mathrm{reco}} - \phi_{\mathrm{truth}}}{\phi_{\mathrm{truth}}} \right)$
- Jet reconstruction efficiency $\frac{\#\text{ reco matching truth}}{\#\text{ truth}}$
- „Fake“ jet contribution $\#\text{ reco not matching truth}$

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- „Fake“ jet contribution

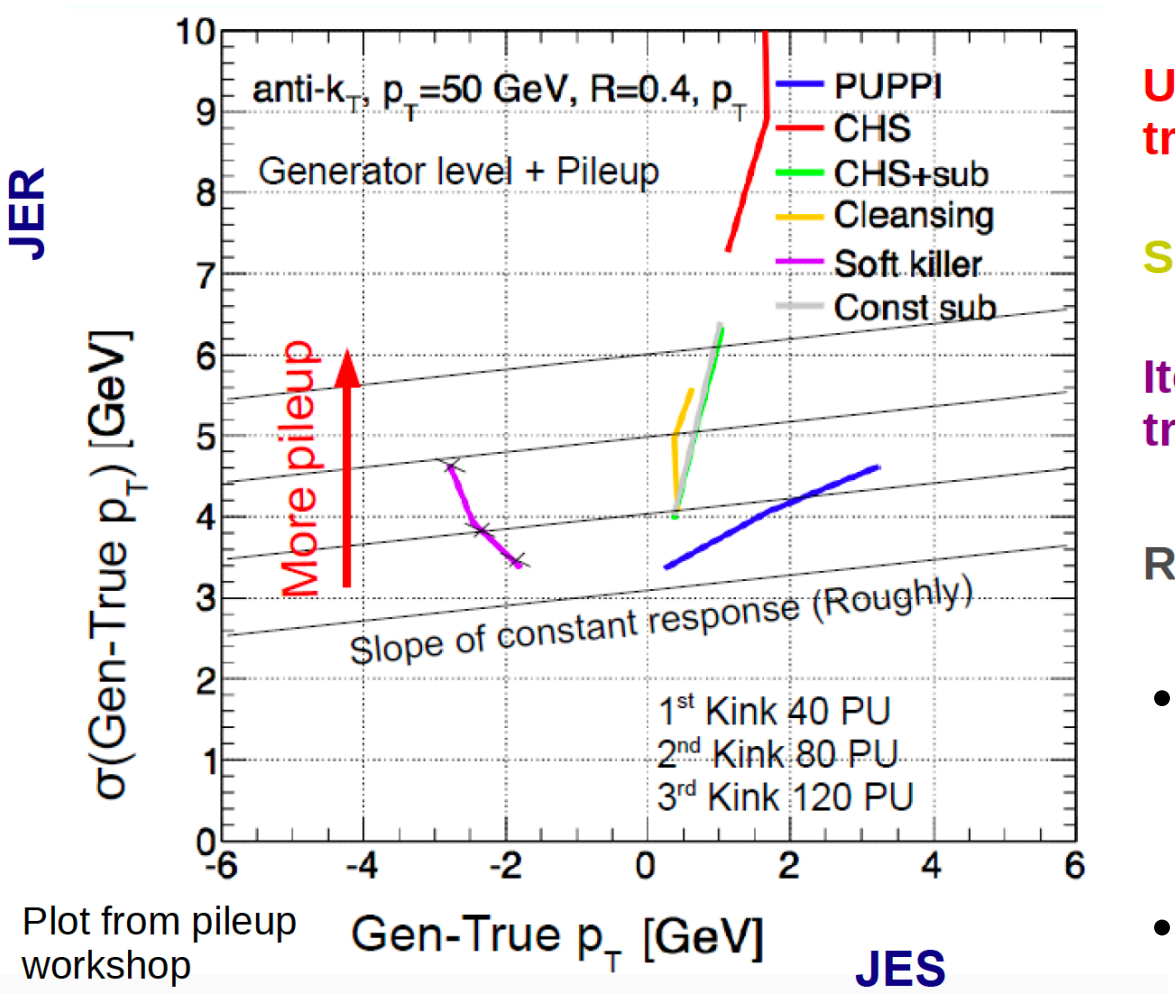
Or other observables:

$\langle X_{\mathrm{subtracted}} - X_{\mathrm{truth}} \rangle$ — Closure of subtraction, scale of X, linearity X

$\sigma(X_{\mathrm{subtracted}} - X_{\mathrm{truth}})$ — Resolution of X

How to evaluate the performance?

Marta Verweij



Plot from pileup workshop

New; based on HF/Voronoi

Uses vertexing to remove tracks + rho

Substructure + vertexing

Iterative removal of soft tracks

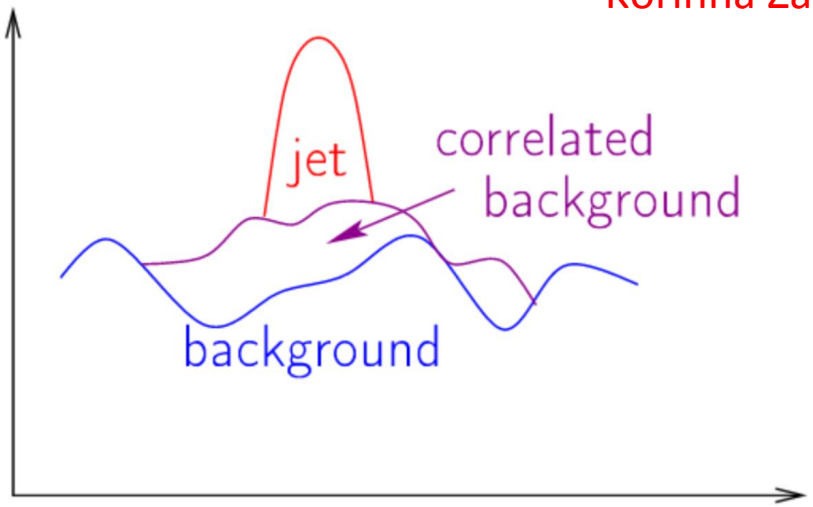
Rho per particle

- Performance as a function of pile-up differs
- Extensive study is done with pile-up for pp
- Learn from HEP!

Points of Consensus

- Theory and experiment comparisons are valid when methods can be applied in both
  - Jet signal includes **the correlated "background"**

Korinna Zapp



Experimental source of correlations can not be known, so must be included in definition of signal – **Jet-induced medium response**

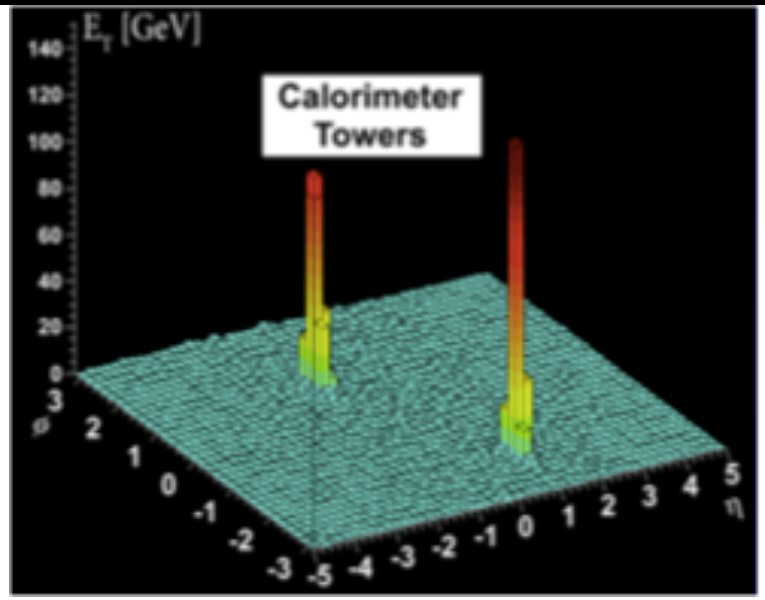
Initial hard scatter is uncorrelated with the rest of the event

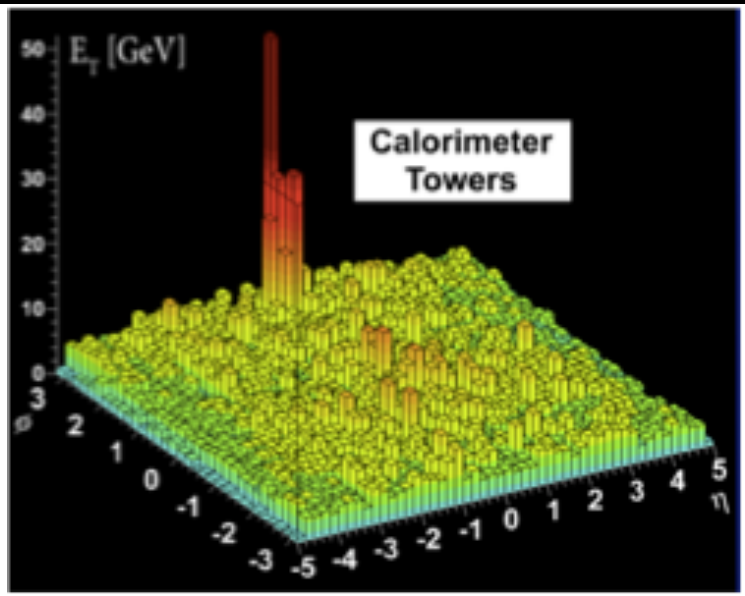
- QCD Factorization
- Interaction with the medium connects jet to the medium (and the background)

Further Consensus

Xin-Nian Wang
Mon. This Meeting

Jet energy and background subtraction





Jet energy as defined in the jet reconstruction algorithm

Uncorrelated background should be subtracted

Jet-induced medium response is correlated with jet: not background

Some of the energy lost by leading partons remain inside jet-cone

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  - For MC models: include effects other than detector effects such as p_T cuts

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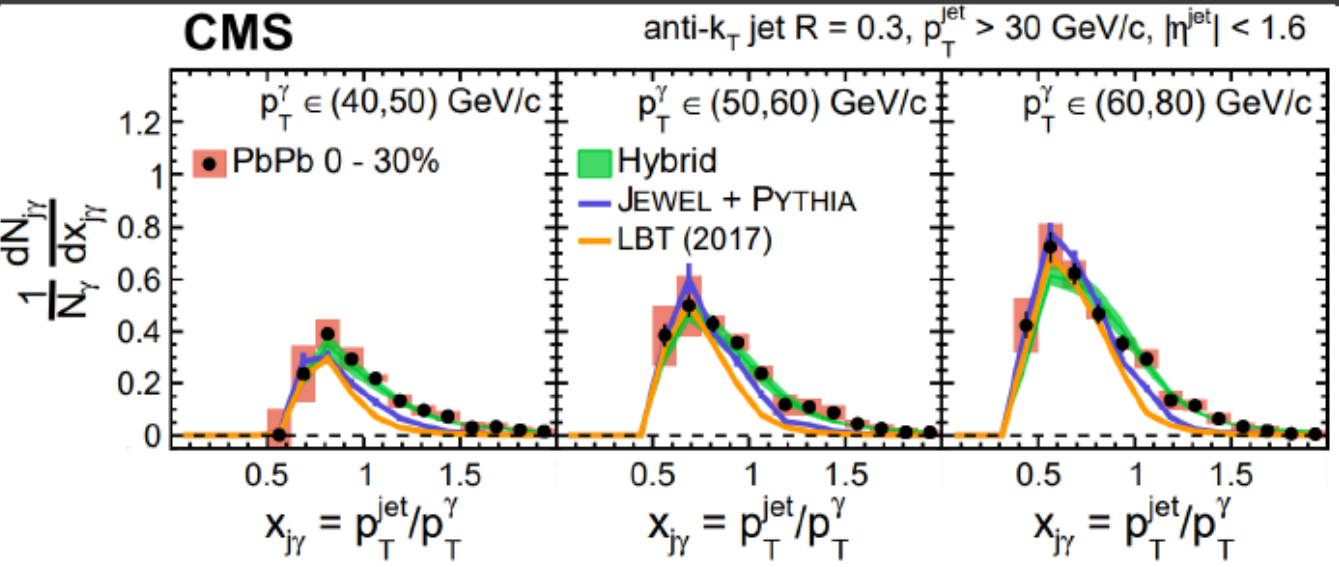
Kinematic cuts, background subtraction methods, and unfolding effects need to be evaluated carefully

Non-Apples-to-Apples Comparison

Photon-Jet Asymmetry

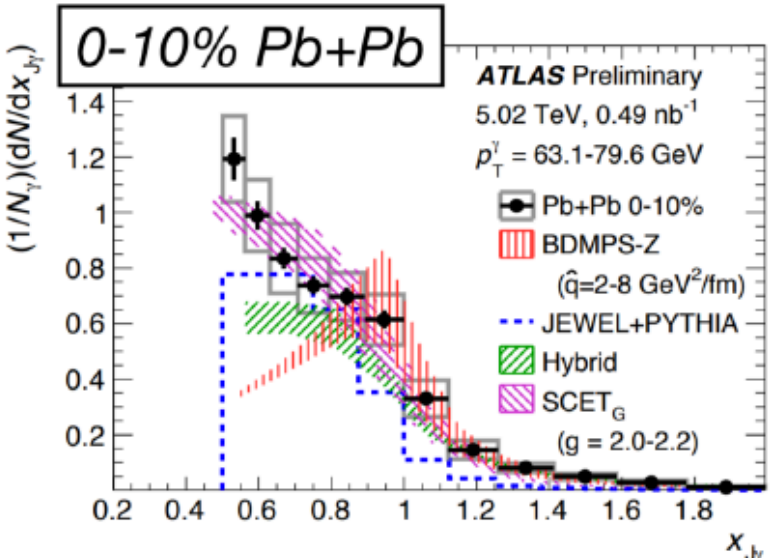
Yen-Jie Lee
Mon. This conference



Theory smeared

Data Unfolded

- Different conclusions on model comparisons between CMS and ATLAS at low $X_{j\gamma}$
- Example: HYBRID model describes CMS data almost perfectly; inconsistent with ATLAS data at low $X_{j\gamma}$
- Note the difference in the photon p_T and jet p_T selection



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  - Jet signal includes **the correlated "background"**
  - For MC models: include effects other than detector effects.
  - For analytical calculations: **regions of validity** should be assigned together with systematics due to underlying assumptions
- When possible, experiments publish their uncorrected data + Response Matrix

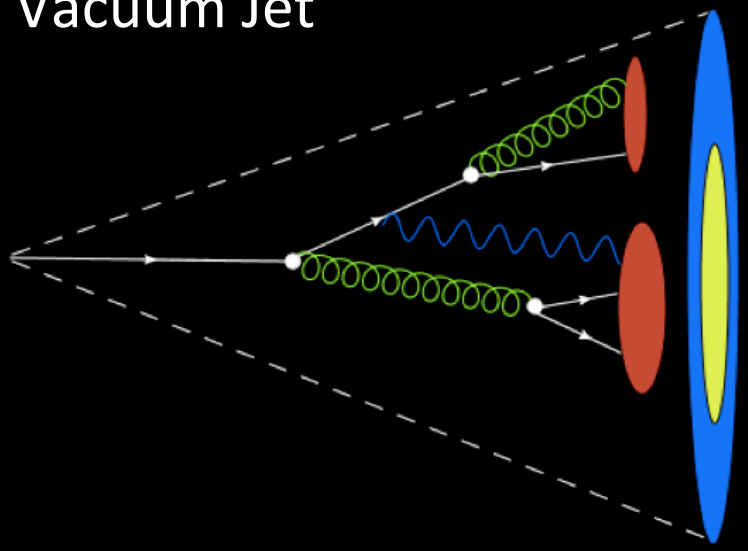
Enables later forward folding or alternate approaches to unfolding

“Raw” Data Example

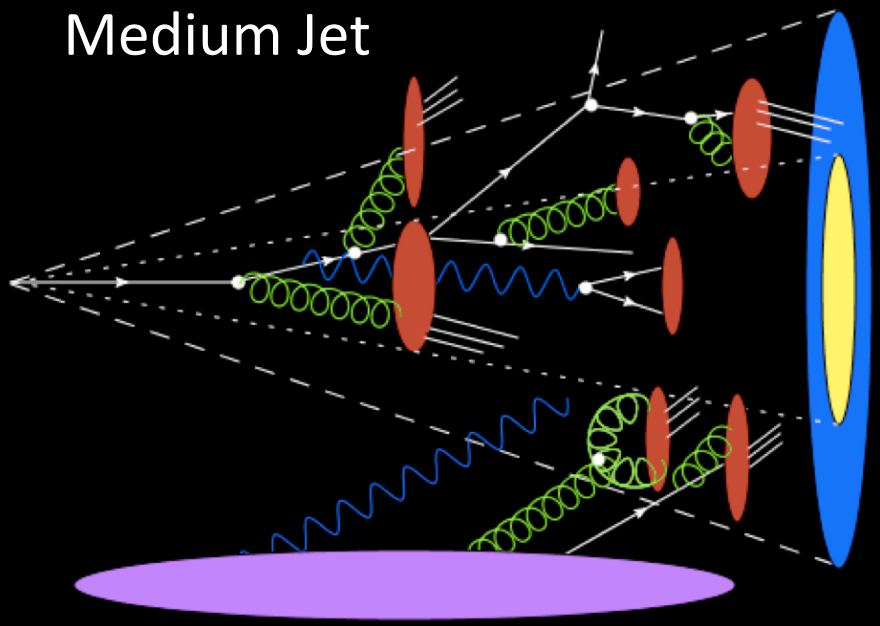
- Dihadron correlations missing v_3 term in background → 30-40 papers quantitatively wrong
- STAR paper with unsubtracted correlations → at least two reanalyses of data arxiv:1010.0690
  - Extract v_1 - Luzum & Ollitraut Phys.Rev.Lett. 106:102301,2011
  - Extract jet-like correlations - Nattrass, Sharma, Mazer, Stuart, Bejnood Phys. Rev. C 94, 011901(R) 2016

Changing View of Jets in HI Collisions

Vacuum Jet

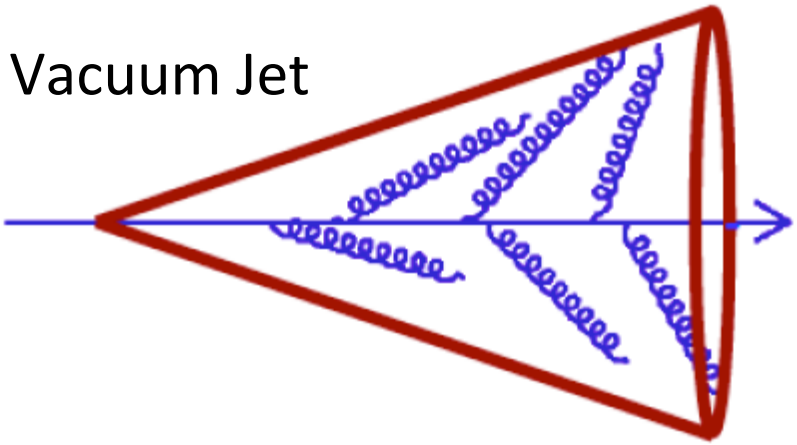


Medium Jet



Raghav Kunnawalkam Elayavalli

Vacuum Jet



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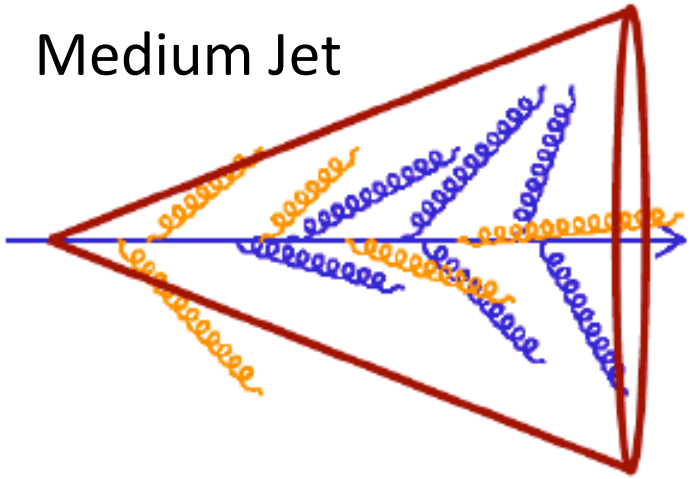
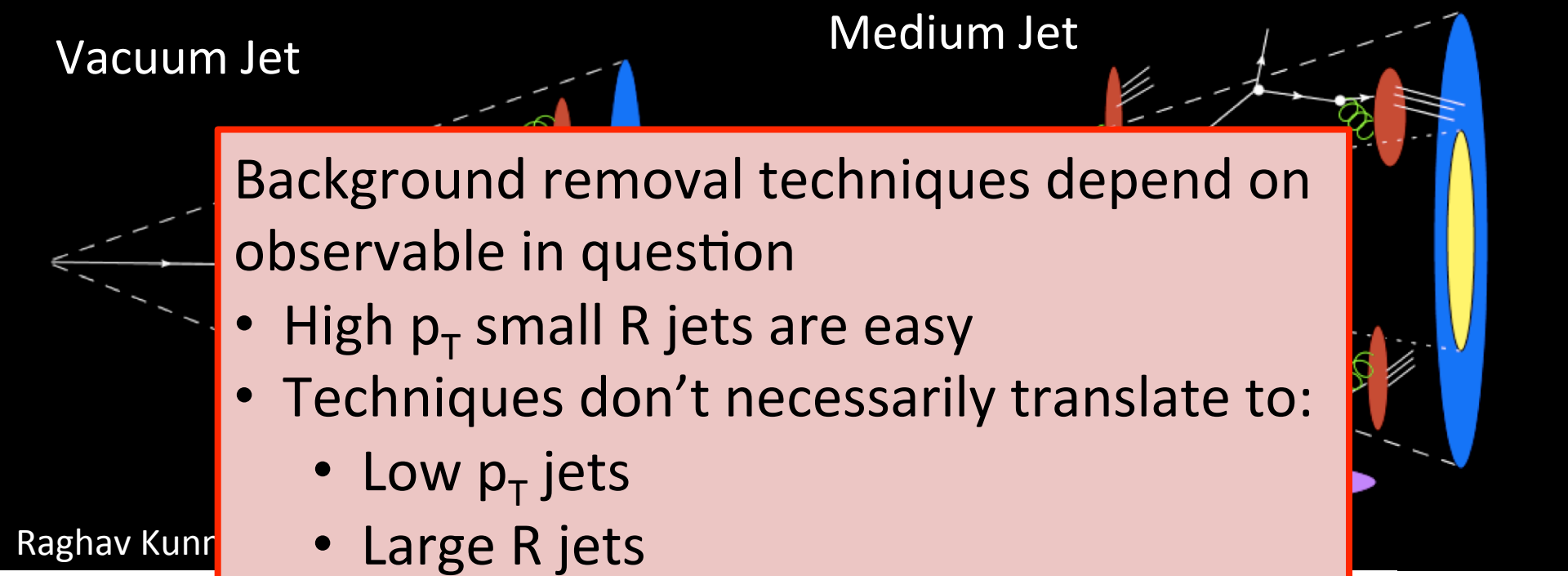
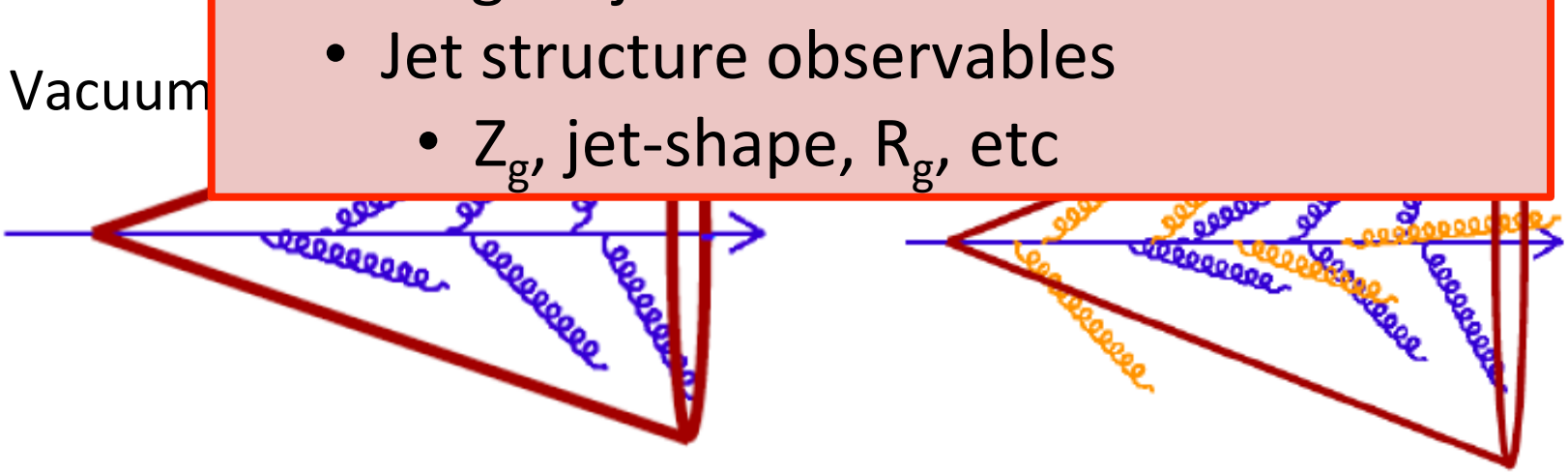


Changing View of Jets in HI Collisions



Background removal techniques depend on observable in question

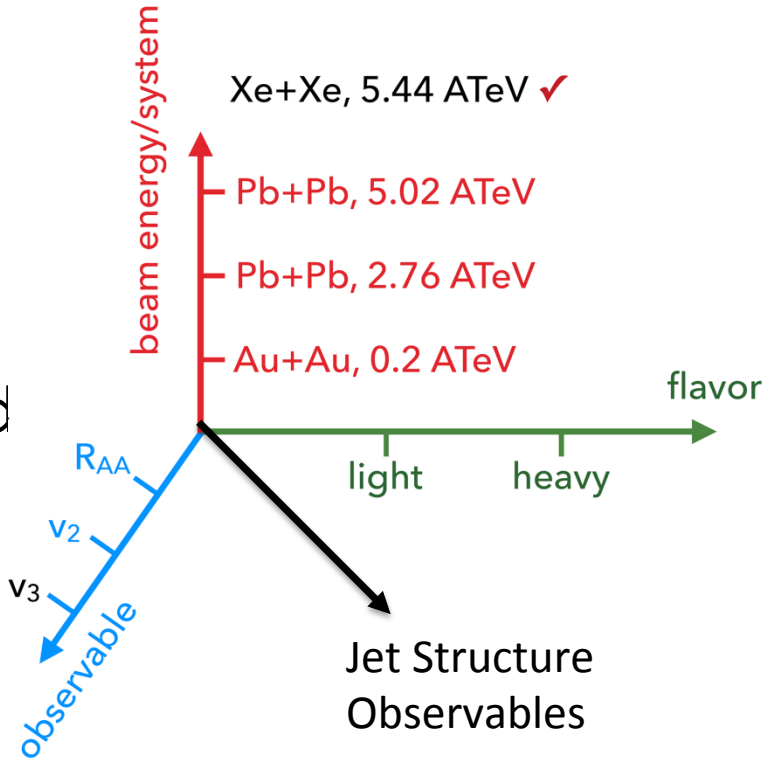
- High p_T small R jets are easy
- Techniques don't necessarily translate to:
  - Low p_T jets
  - Large R jets
  - Jet structure observables
    - Z_g, jet-shape, R_g, etc



Shuzhe Shi

Precision Studies: Power of global data analysis

- Global fitting leverages information+ differential power to extract optimal amount of information
- Require large efforts in simultaneously describing background and jetty probes
  - "Standard model(s)" of HI
  - Forward folding in experiments
  - Quantifying contribution from individual measurements
- Cautious models' validity and systematic bias on interpretation used in global fit



JETSCAPE

Conclusions

- Field has evolved since our days of leading hadron analyses
- Era of "precision heavy-ion physics" requires defining jets in a high background environment
  - Depends on observable, energy, jet R, p_T, and others
- Work is ongoing on reaching a consensus
  - Paper to that effect will come out of the workshop

Many thanks to all speakers

and participants!!