Probing the quark-gluon plasma using jets

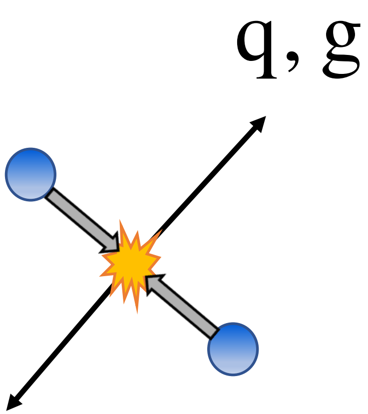
Jasmine Brewer

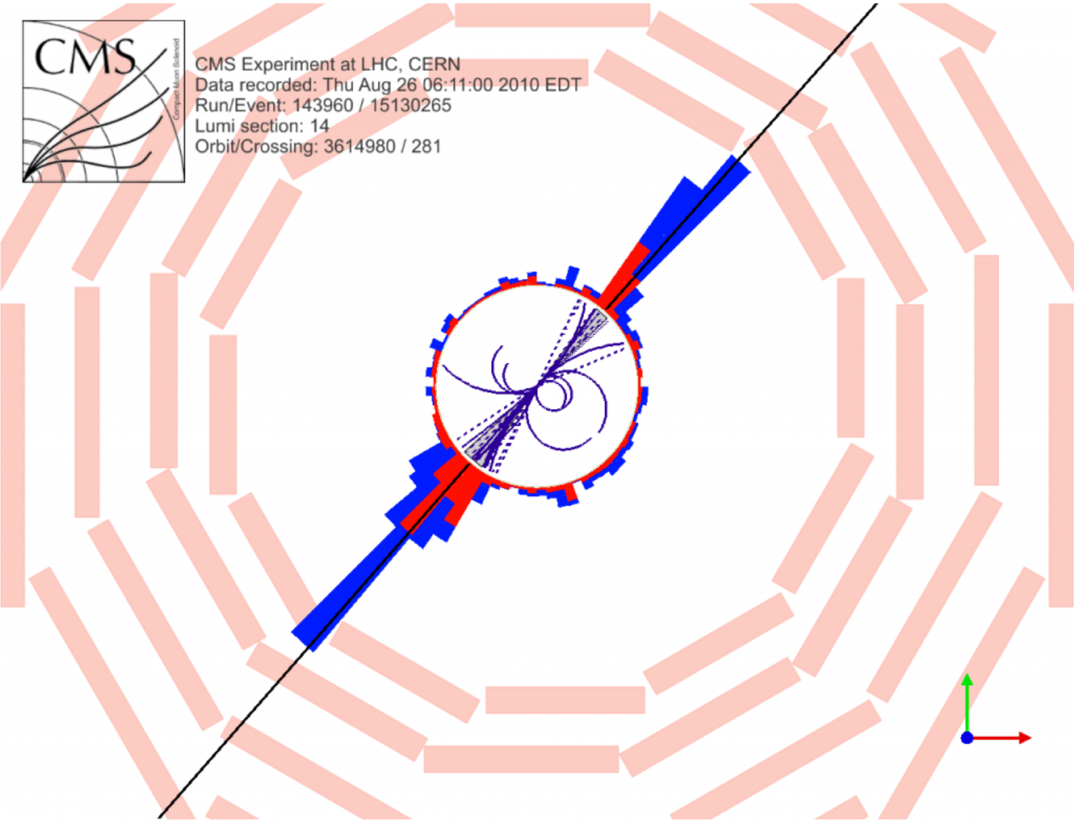
Current

Future

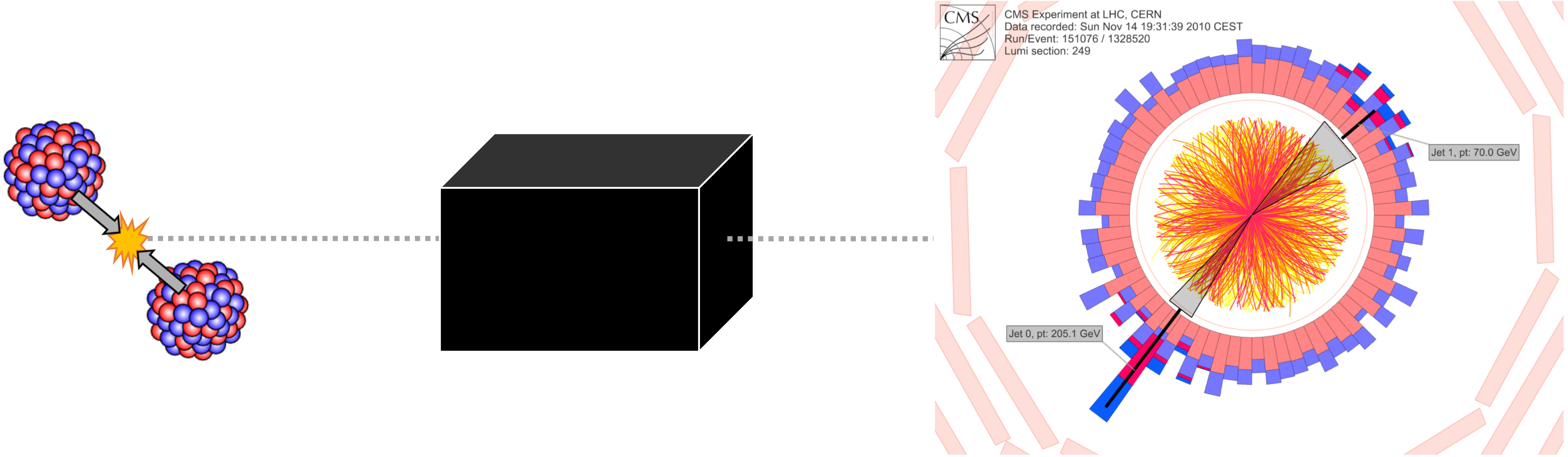
Hard Probes
June 3, 2020

Jets in proton-proton collisions….



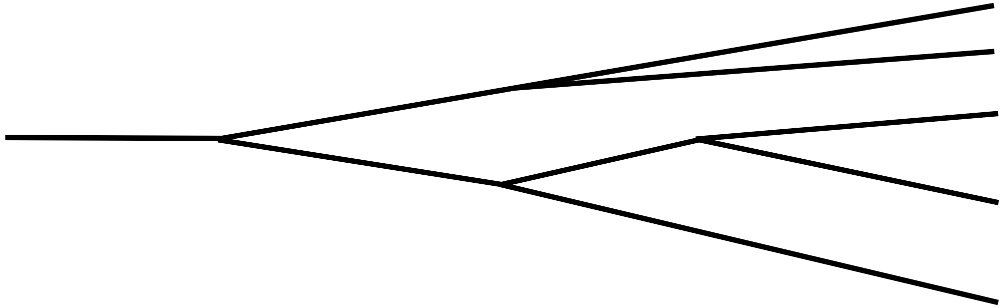


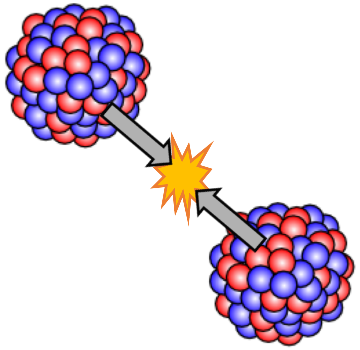
Jets in heavy-ion collisions….



What's in the box?

"Standard model" of jet modification



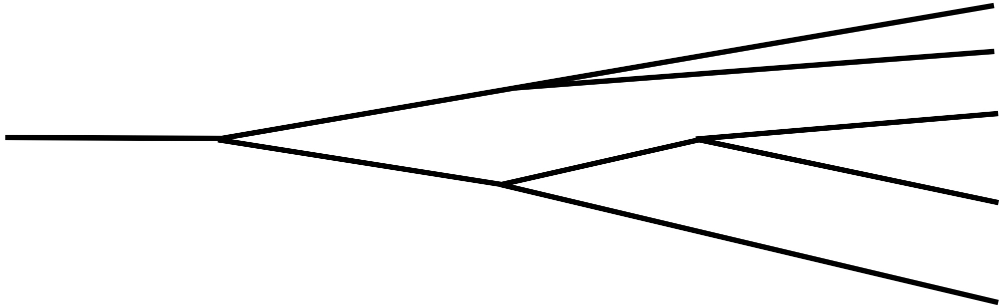


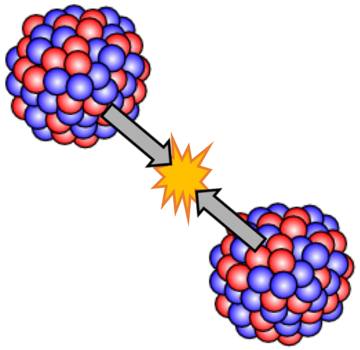
Shower evolution

Analytic methods; SCET

Monte Carlo

“Standard model” of jet modification





Shower evolution
Analytic methods; SCET
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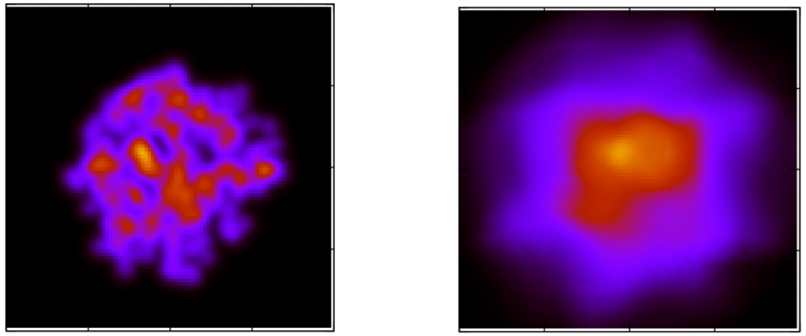
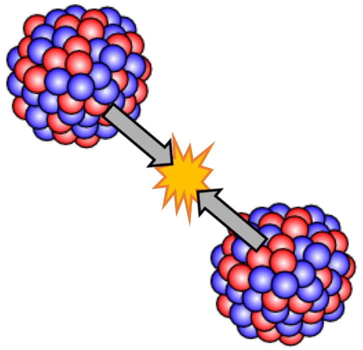
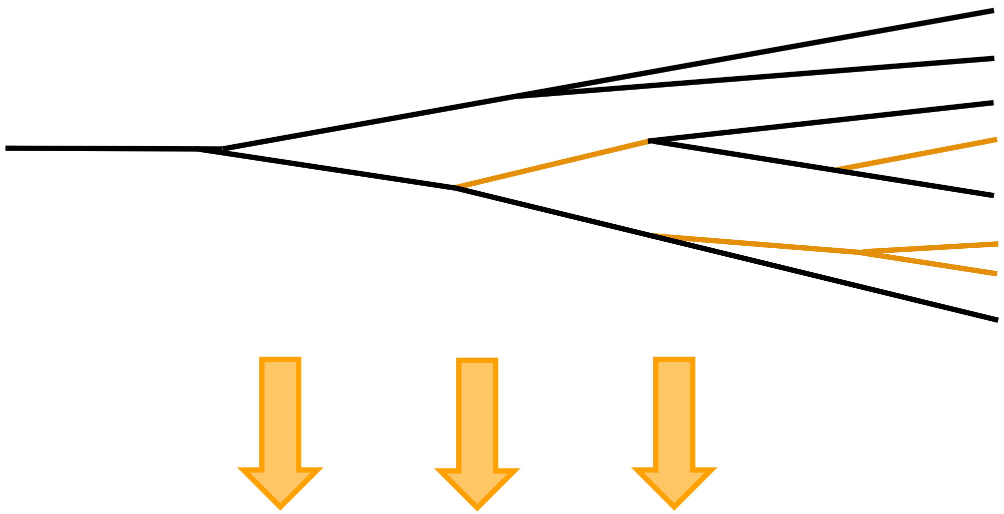


Medium evolution
Constant T; Bjorken flow
e-by-e viscous hydro

Fig: Schenke, Jeon, Gale [1009.3244]

“Standard model” of jet modification





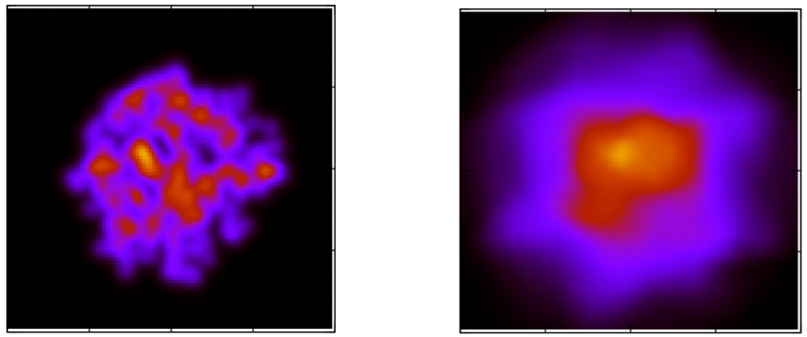


Fig: Schenke, Jeon, Gale [1009.3244]

Shower evolution

Analytic methods; SCET

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Shower modification

Medium-induced radiation

Drag; collisional energy loss

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Constant T; Bjorken flow

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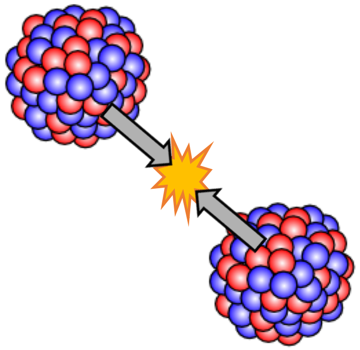

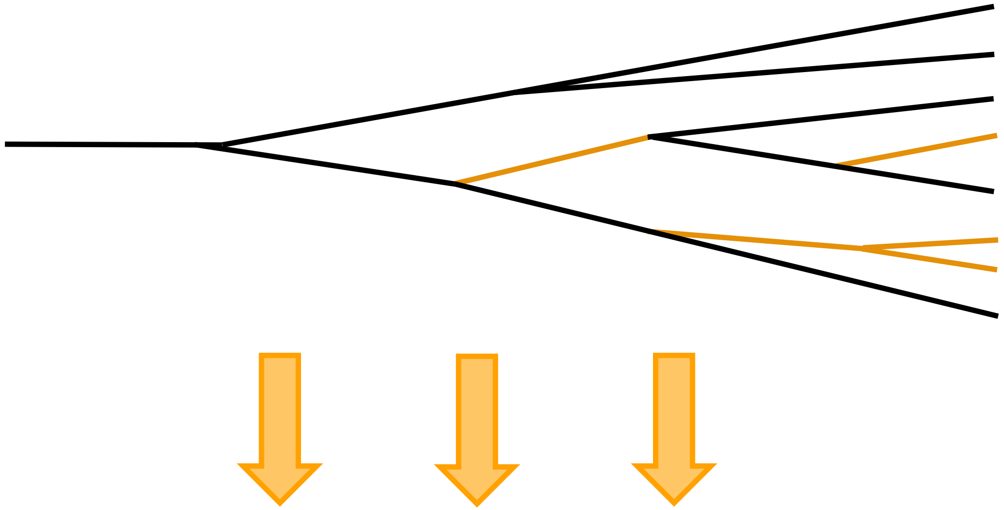

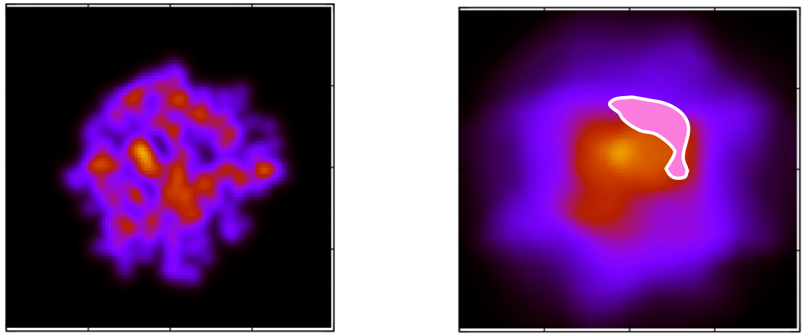

Fig: Schenke, Jeon, Gale [1009.3244]

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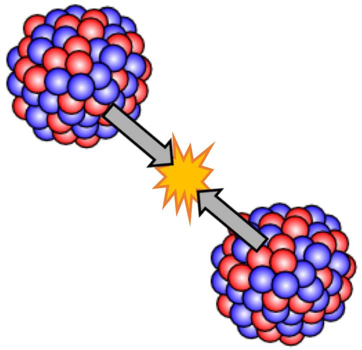
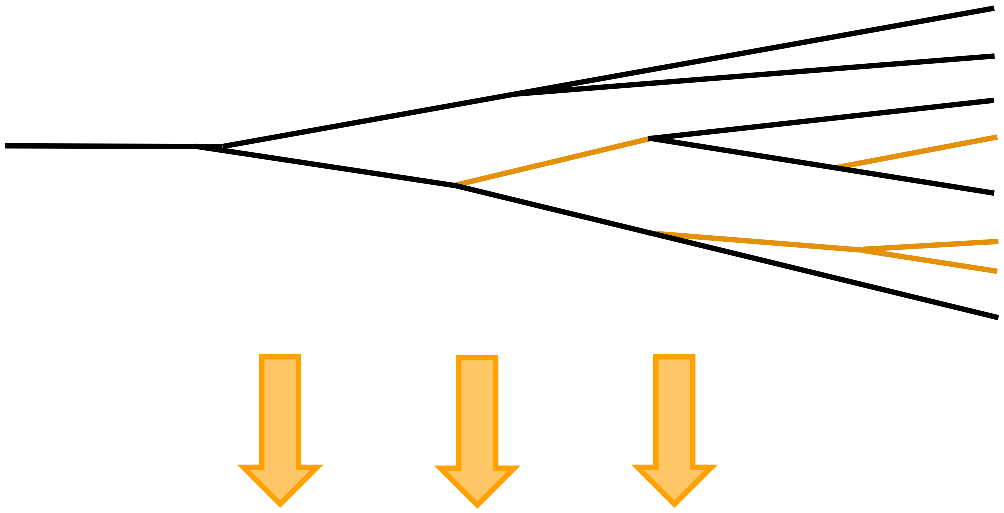
Medium response

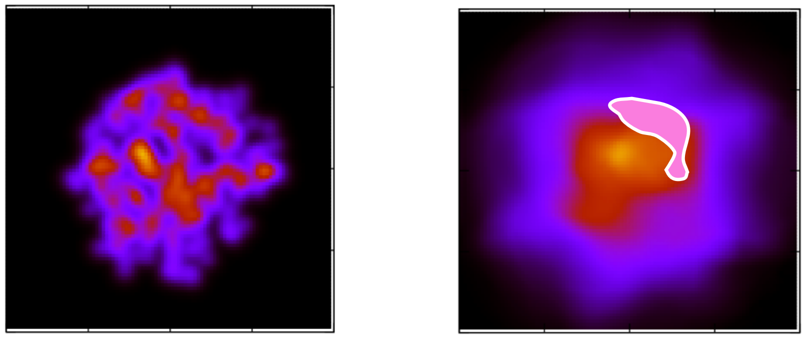
Energy deposited from jet

sources medium evolution

“Standard model” of jet modification







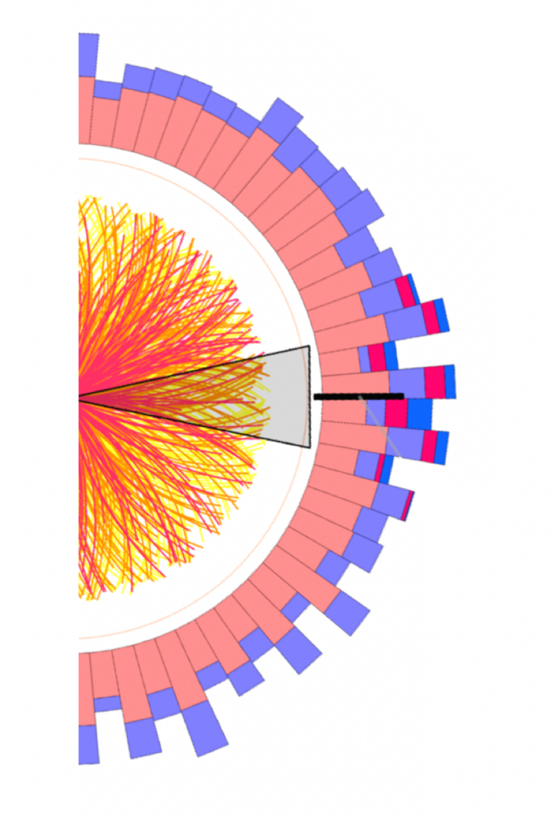


Fig: Schenke, Jeon, Gale [1009.3244]

Physics of the quark-gluon plasma suited to jets

Shower evolution

Analytic methods; SCET
Monte Carlo

Shower modification

Medium-induced radiation
Drag; collisional energy loss

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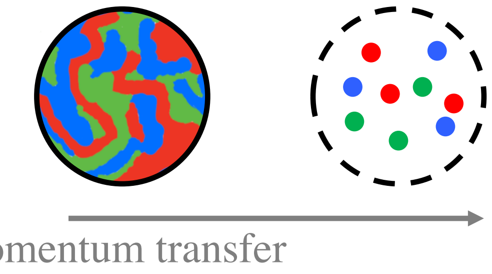
Microscopic structure of the QGP on different energy scales



Yang-Ting Chien: 8:20

Medium evolution

Constant T; Bjorken flow
e-by-e viscous hydro

Medium response

Energy deposited from jet sources medium evolution

Far-from-equilibrium response of the QGP

Yasuki Tachibana: 9:00

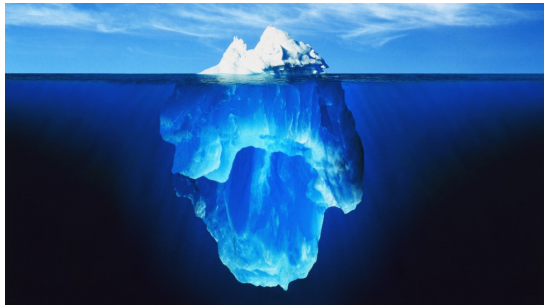
Jets as a probe of the quark-gluon plasma

- Models have more physics than the physics we are after
- Models all have some physics deficiencies (no first-principles solution)
- Models with very different physics of jet-medium interaction and medium response can agree with a variety of measurements

Crucial to have a way towards highlighting the physics we care about without requiring that models be perfect

Toward jets as a calibrated probe of the QGP

Things are (very often) not as they seem

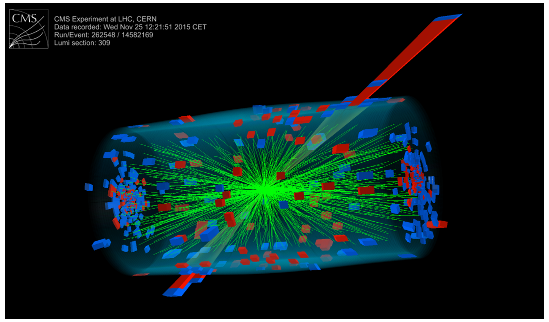


- Many effects obfuscate the interpretation of measurements

Opening the box

- Using models effectively as a tool to understand the physics behind data

Toward interpreting data without models



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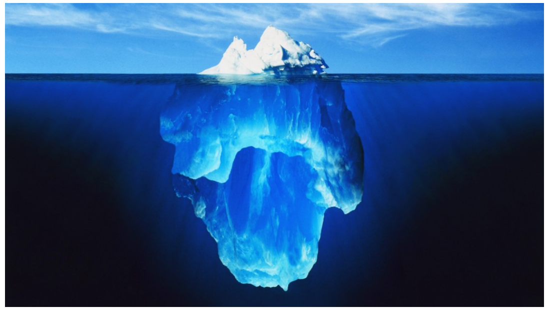

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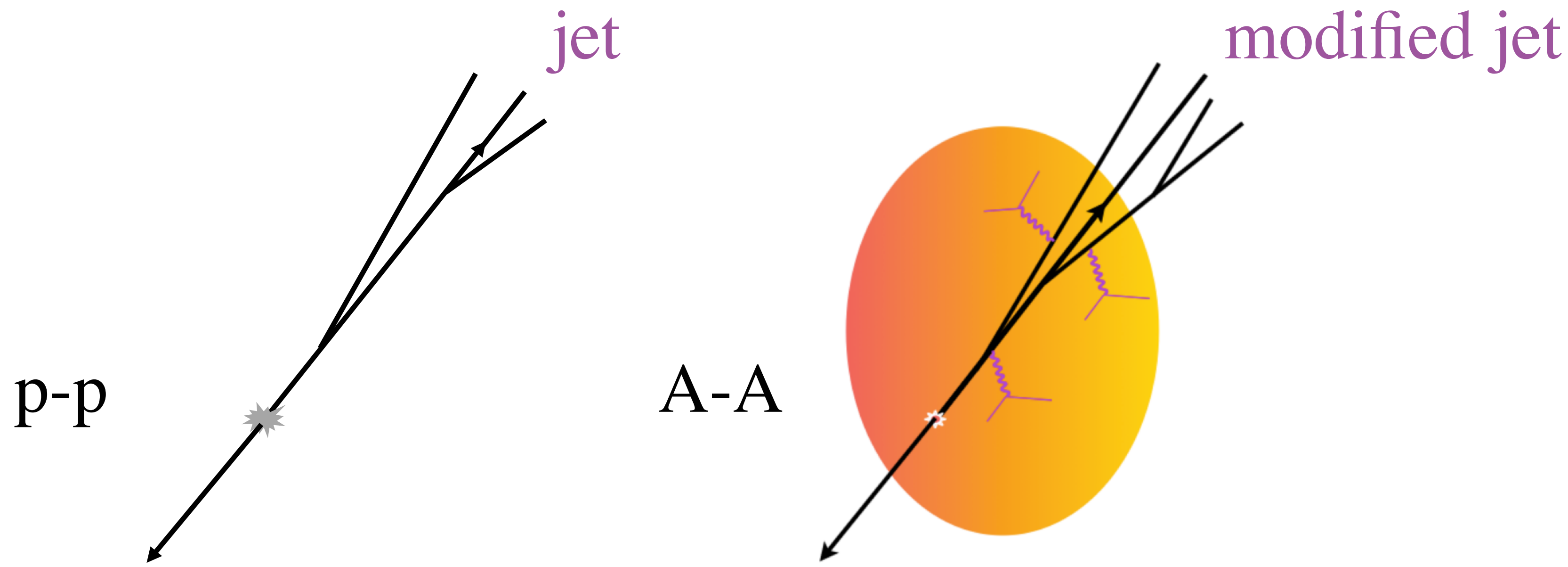
Toward interpreting data without models

How can jet modification be quantified?

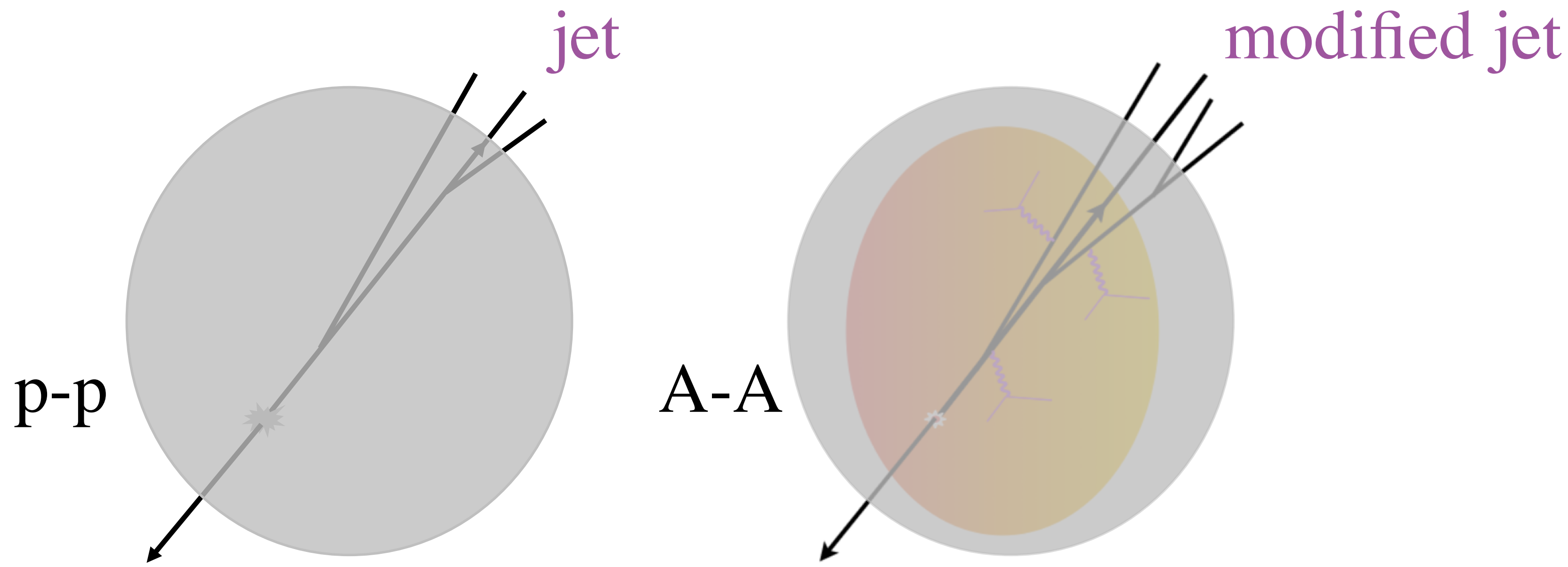
Ideally…



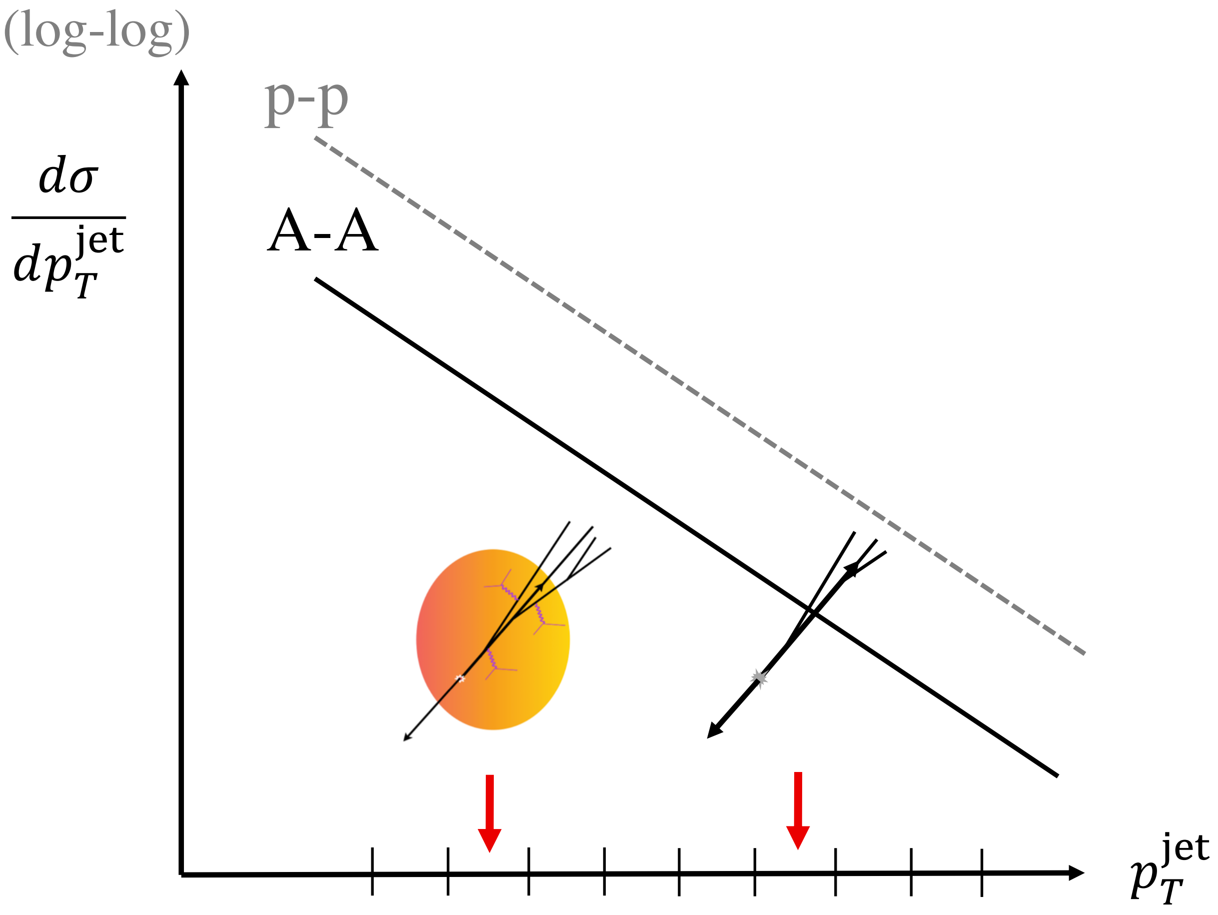
How do jets from an identical hard process differ in vacuum and in medium?

For inclusive jets, features of hard process cannot be observed

Reality…



“Jet modification” observables: part modification and part bias



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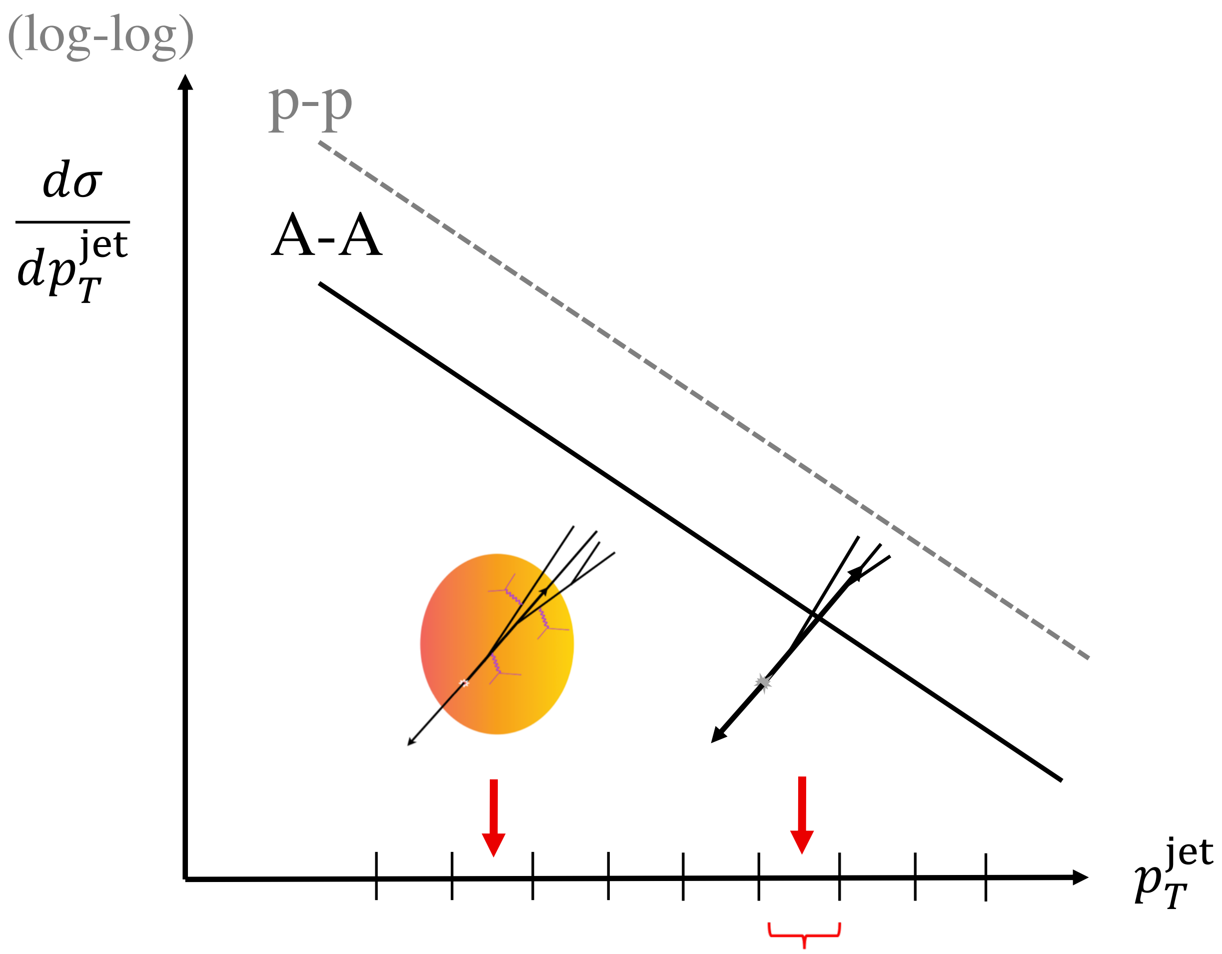
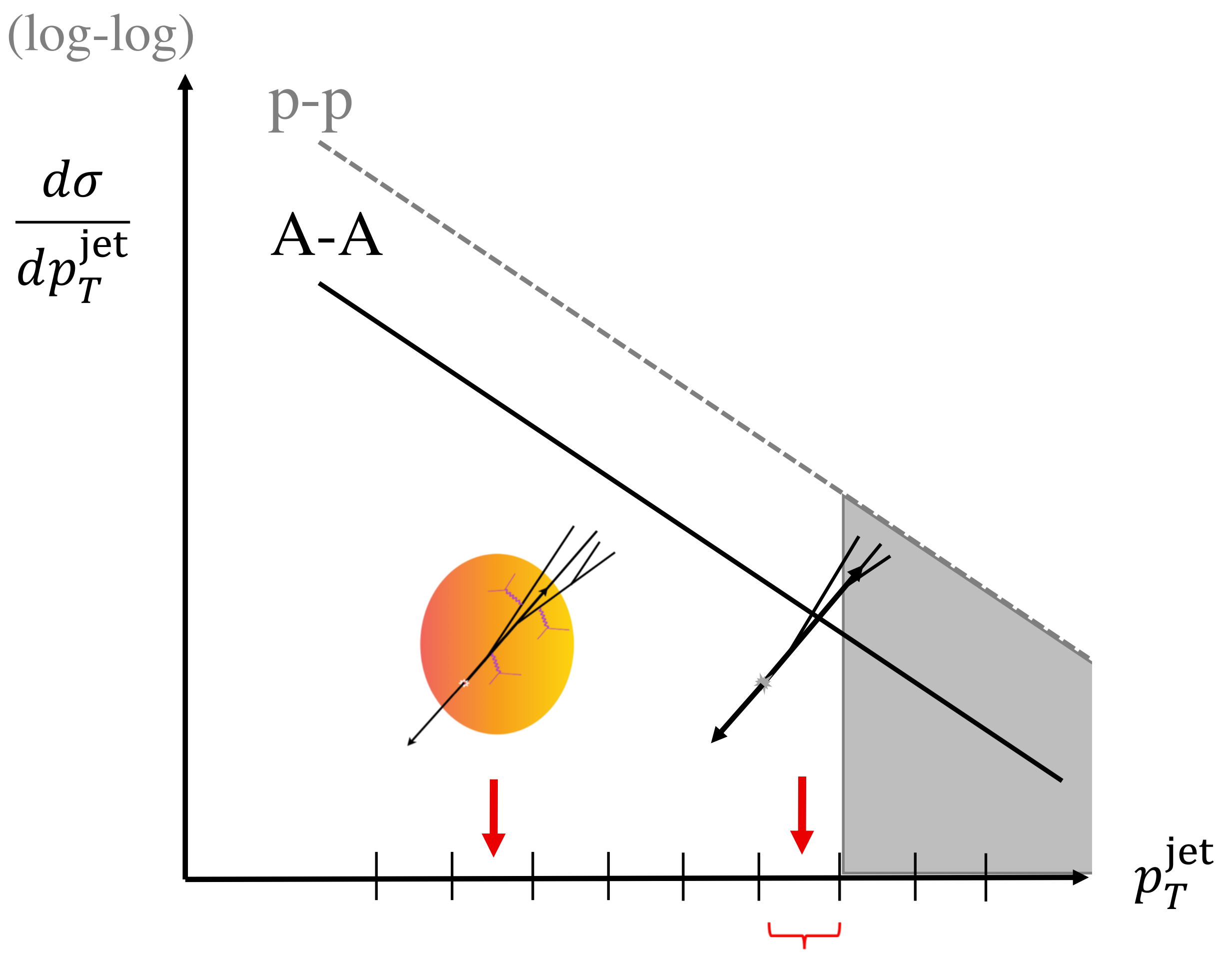


What are the A-A jets in this bin?

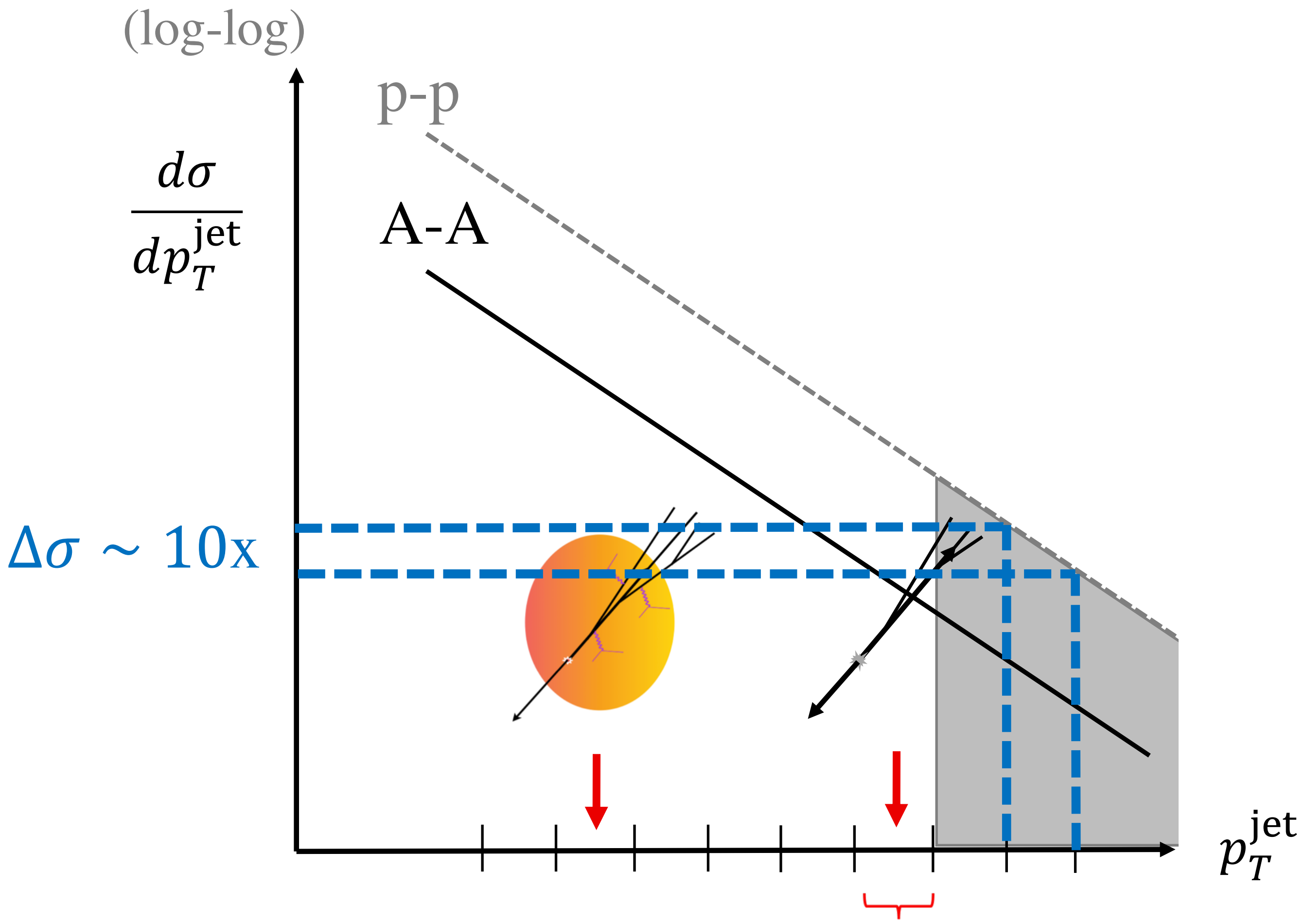
“Jet modification” observables: part modification and part bias



What are the A-A jets in this bin?

- Produced with higher p_T in vacuum

“Jet modification” observables: part modification and part bias



What are the A-A jets in this bin?

$\Delta p_T \sim 50$ GeV

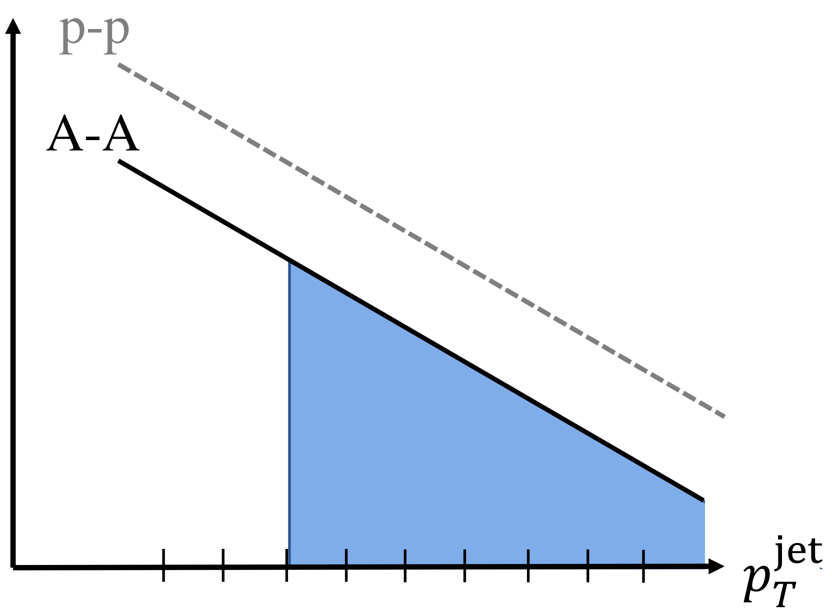
- Produced with higher p_T in vacuum
- Production cross-section falls by factor of ~10 between 100 and 150 GeV! CMS [1601.02001]

Most are relatively unmodified since those are produced in highest numbers!

Interpretation of modification depends crucially on jet selection

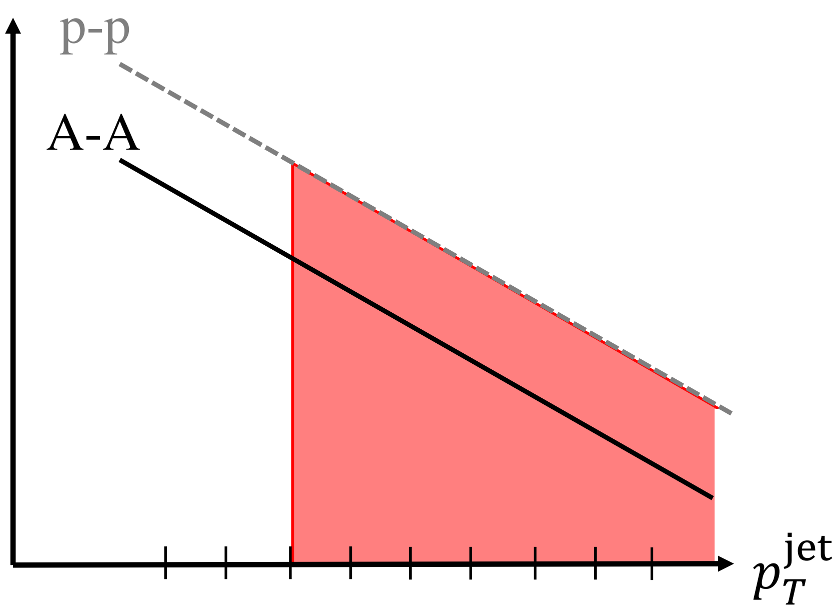
In hybrid model can look at the *same jet* before and after quenching

Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal [1405.3864]



Where did A-A jets come from?

Probed in inclusive jet



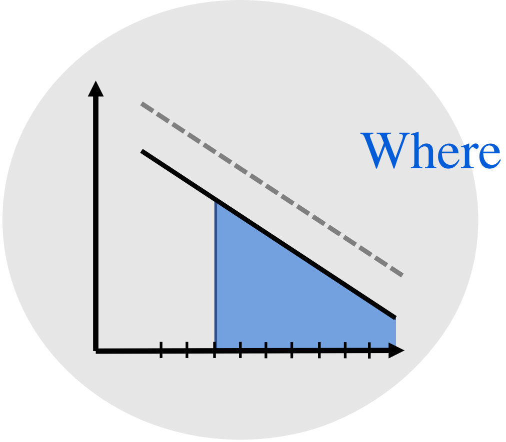
What do p-p jets become?

Probed in boson+jet

These questions have qualitatively different answers!

Brewer, Brodsky, Rajagopal; *in preparation*

Interpretation of modification depends crucially on jet selection



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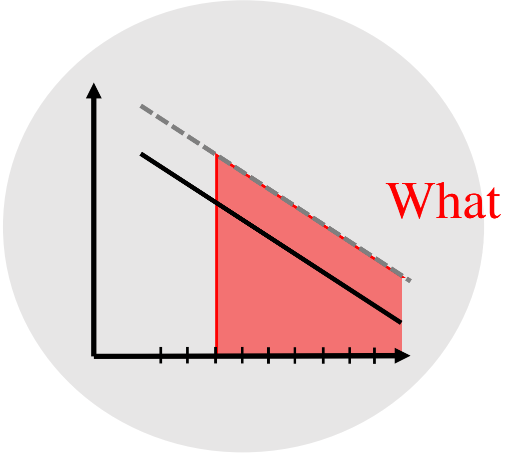
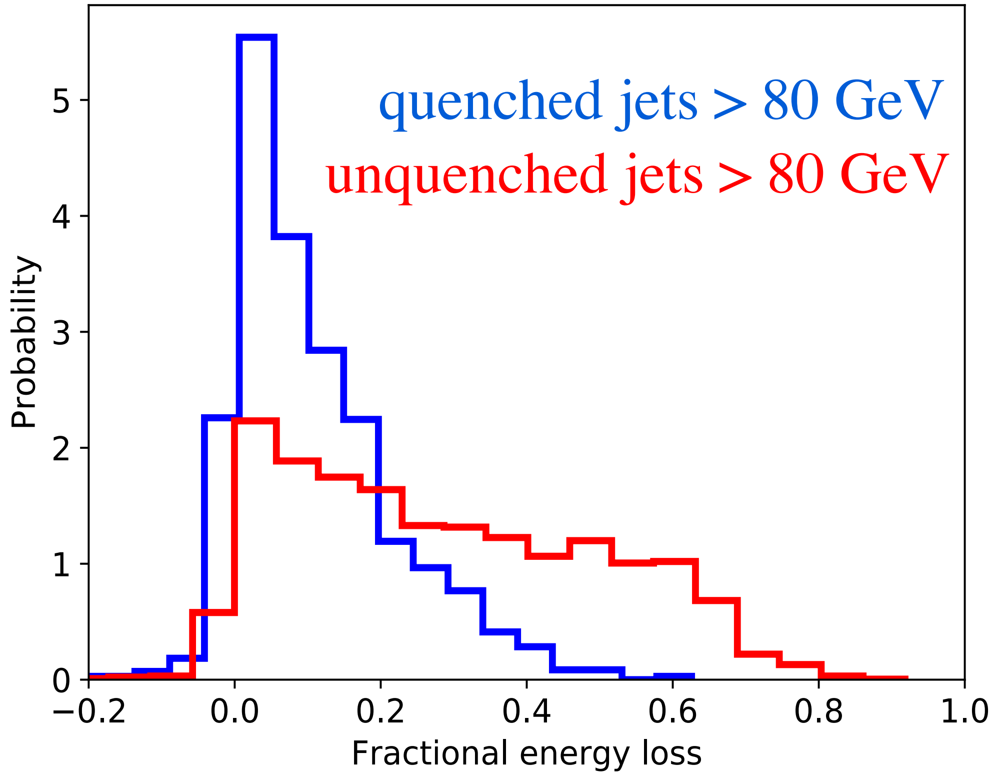


What do p-p jets become?

Fractional energy loss



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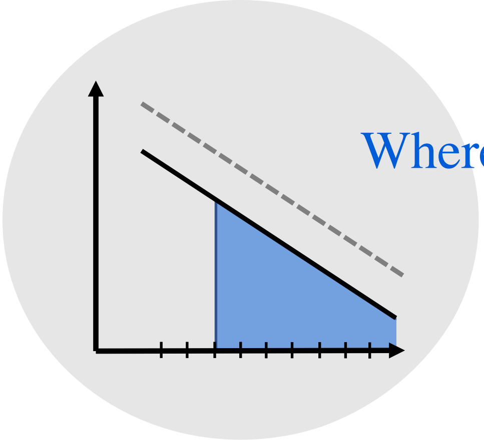

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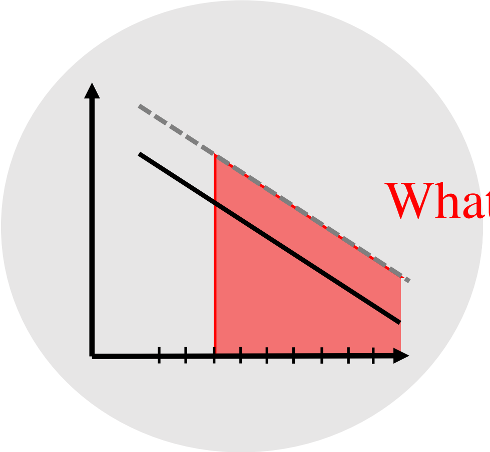

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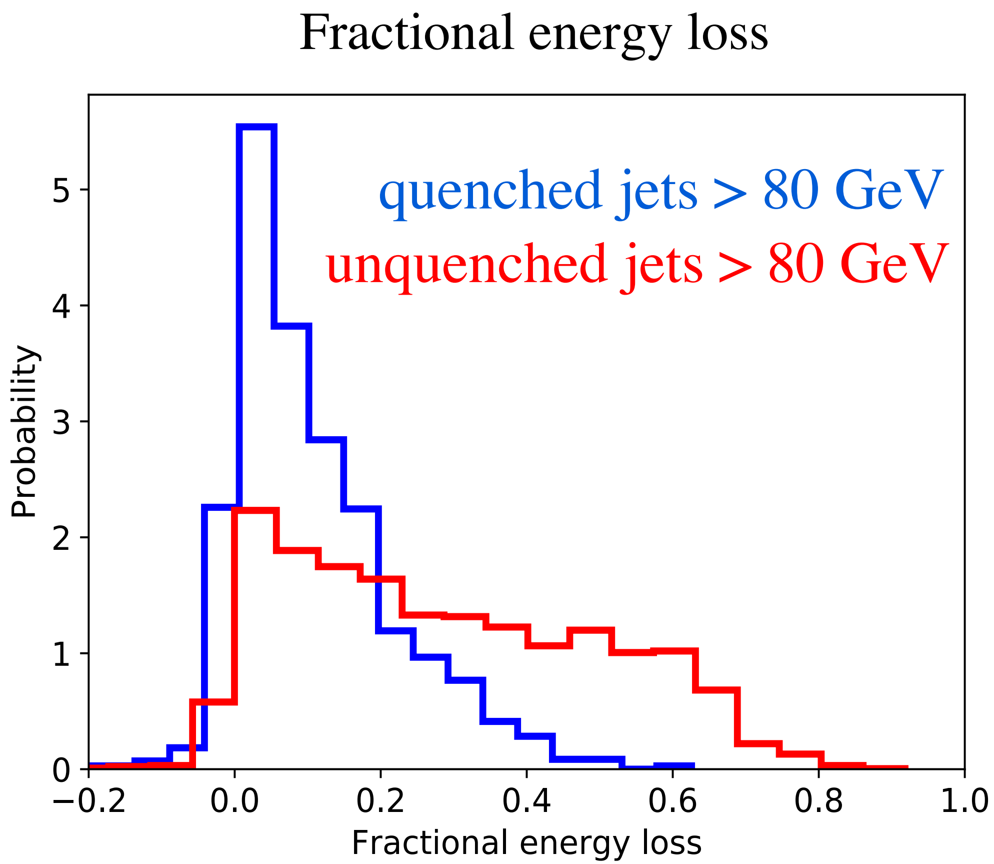
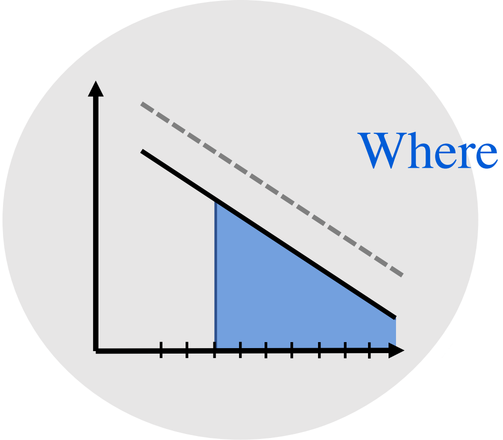


Sample of jets that lost little energy

Brewer, Brodsky, Rajagopal; *in preparation*

Interpretation of modification depends crucially on jet selection



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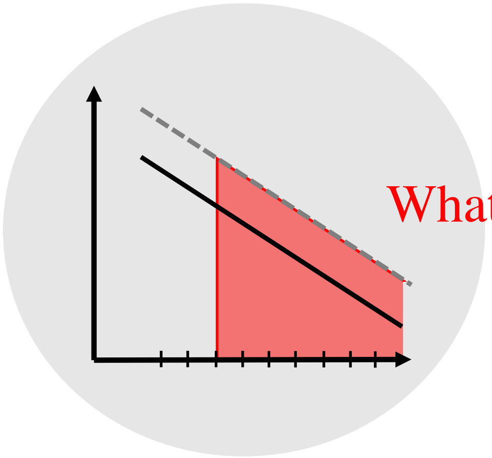
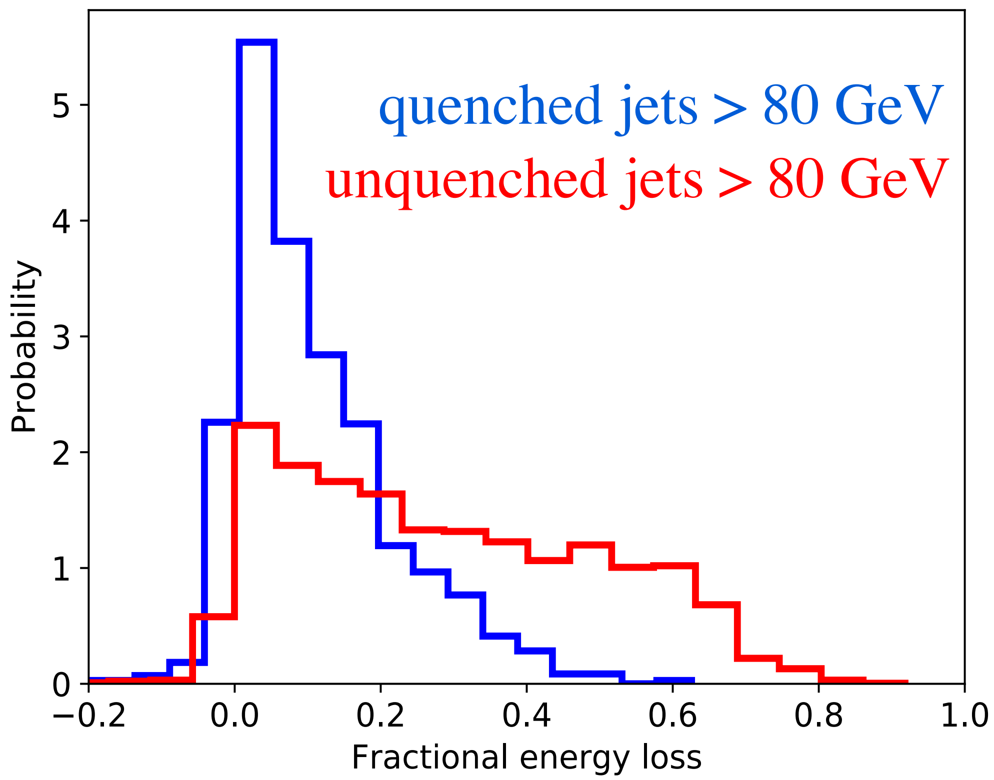


What do p-p jets become?

Fractional energy loss

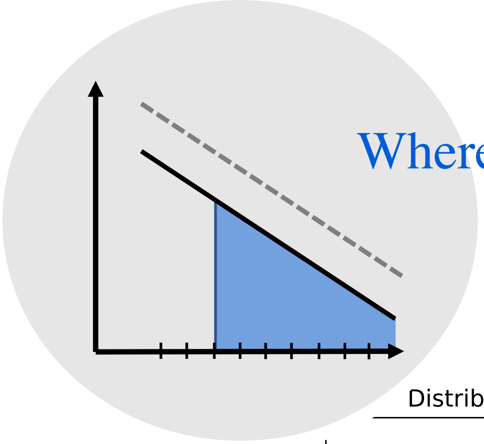


Sample of jets that lost little energy

Larger energy loss probed with γ/Z+jet

Brewer, Brodsky, Rajagopal; *in preparation*

Hybrid model study: interpretation depends crucially on jet selection



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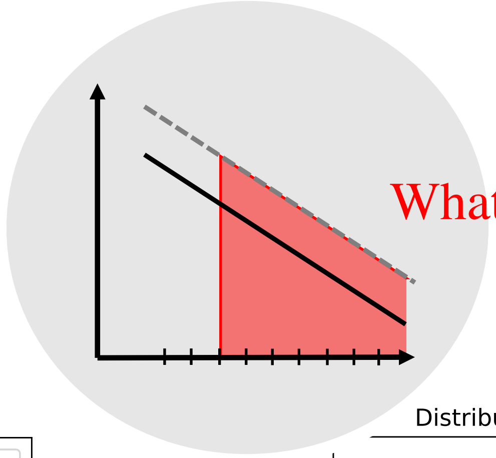

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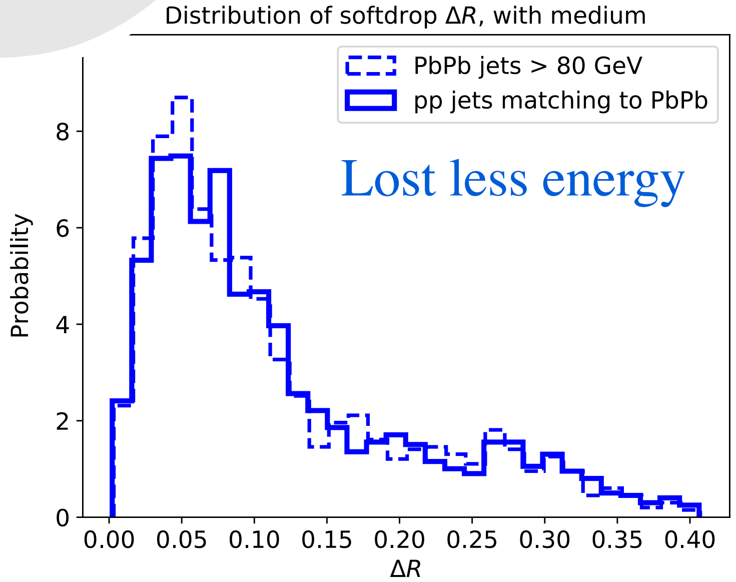
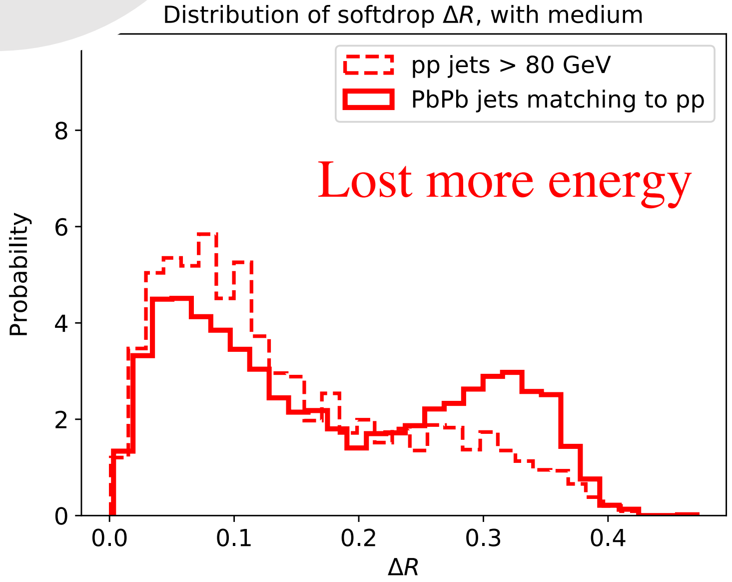


Lost less energy



Lost more energy

Quinn Brodsky
MIT undergraduate

Little ΔR modification

Casalderrey-Solana, Milhano, Pablos, Rajagopal [2002.09193]

Dramatic ΔR modification

Brewer, Brodsky, Rajagopal; *in preparation*

Toward jets as a calibrated probe of the QGP

Things are (very often) not as they seem

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Opening the box

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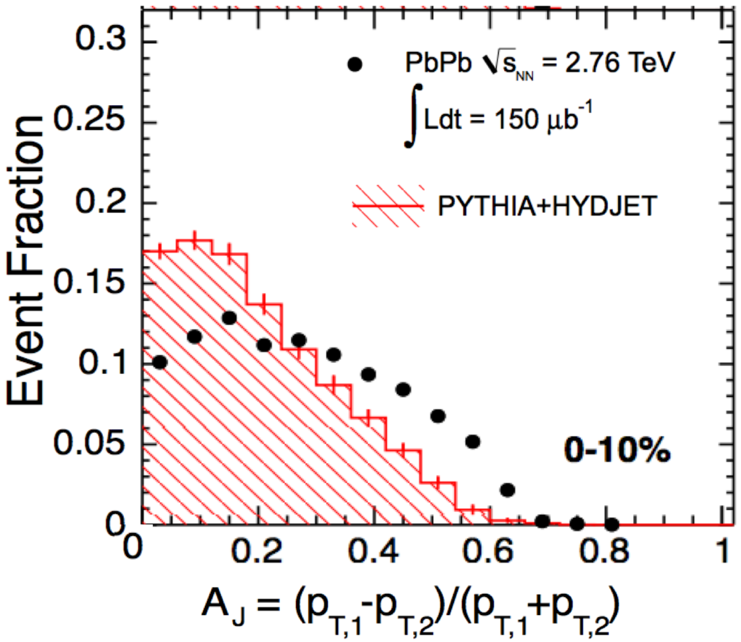
Toward interpreting data without models

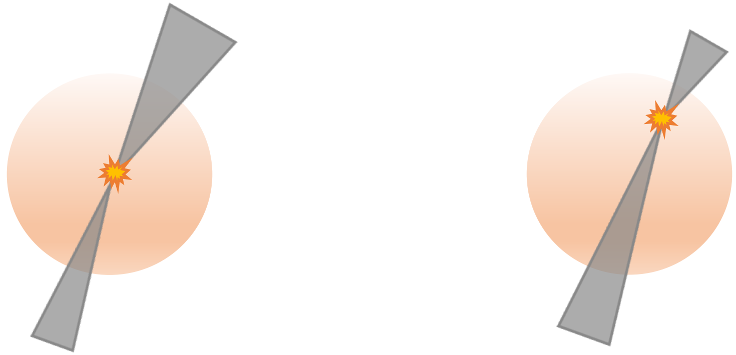
Models as a tool to understand data

What generates the higher energy asymmetry of dijets in A-A?



CMS [1202.5022]
(also measured by STAR and ATLAS)

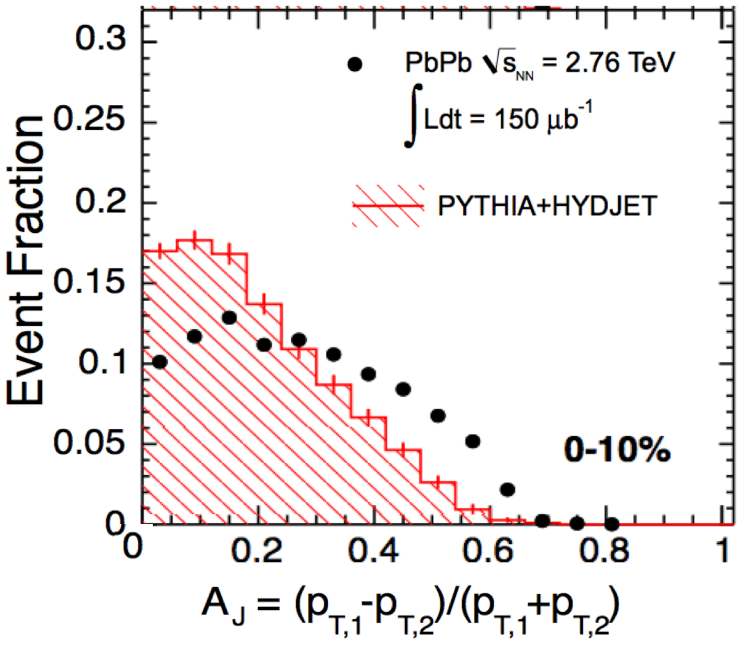
Standard intuition: path-length difference



Symmetric Asymmetric

Models as a tool to understand data

What generates the higher energy asymmetry of dijets in A-A?



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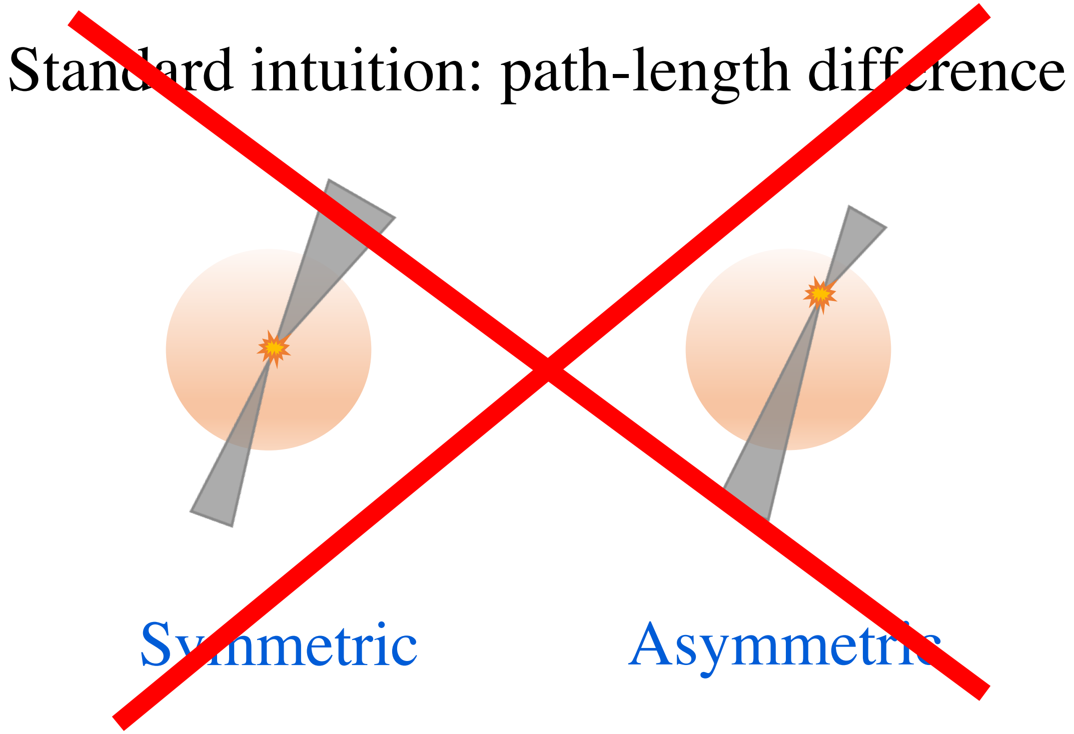
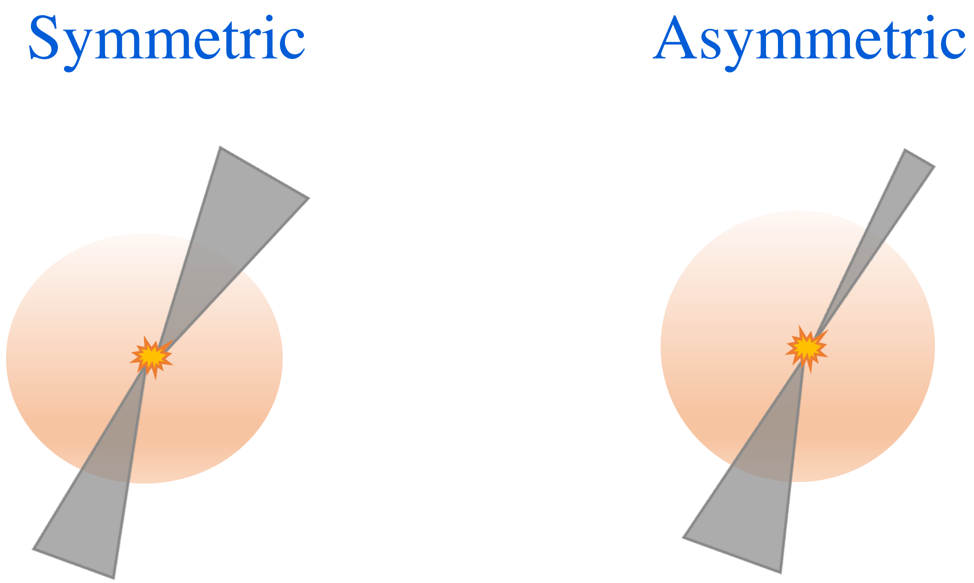


In several very different models, this intuition does *not* appear to be correct

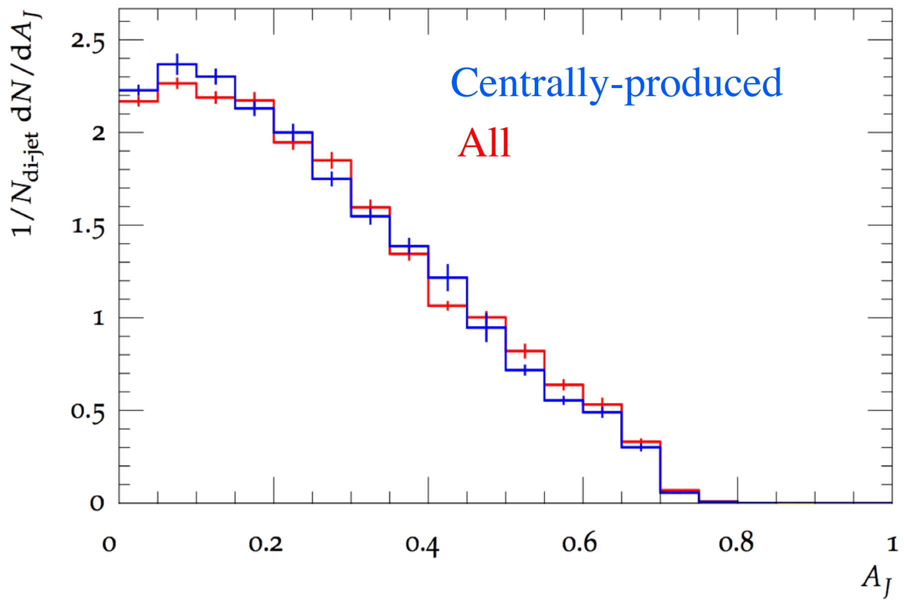
Another effect: fluctuations in jet structure cause asymmetric energy loss



Jets with same path length can lose different amounts of energy from their different structure

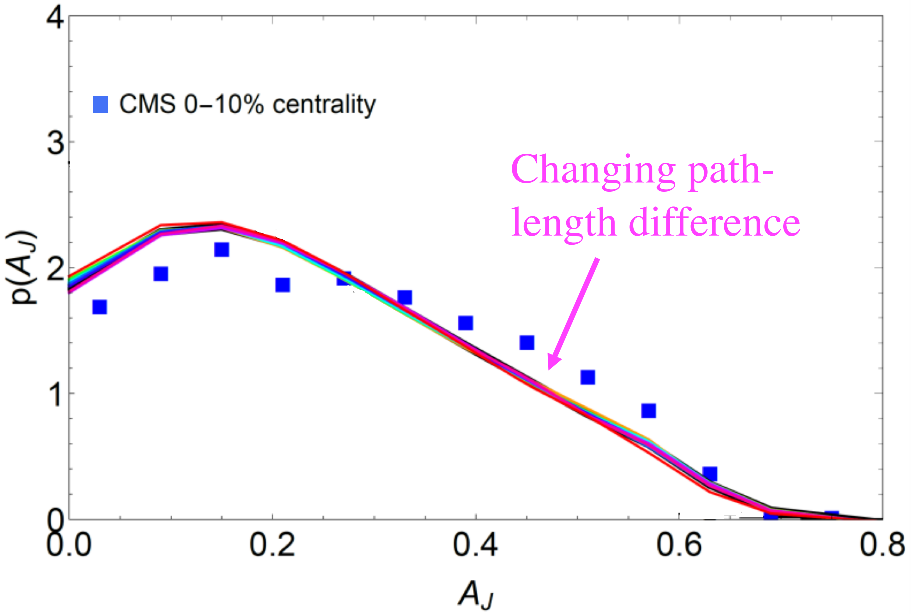
Dijet asymmetry can be generated with no path-length difference

JEWEL



Milhano, Zapp [1512.08107]

holographic model



Brewer, Sadofyev, van der Schee [1809.10695]

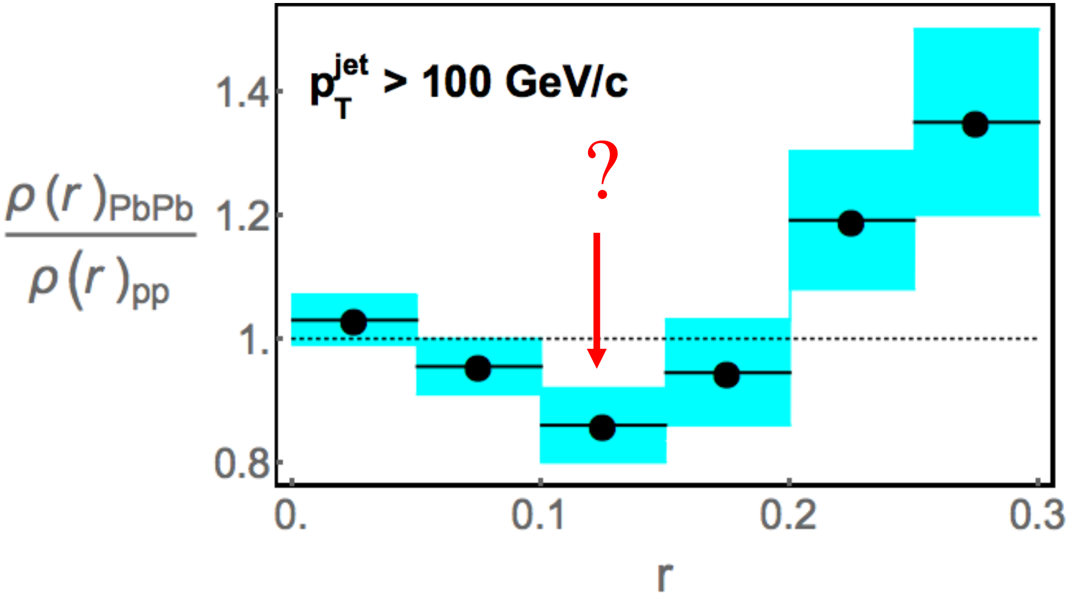
BDMPS-Z large energy loss fluctuations generate asymmetry for jets with same path length

Escobedo, Iancu [1601.03629]

In several models, path length difference not crucial for dijet asymmetry

Models as a tool to understand data

Does quenching cause jets to narrow?



CMS [1310.0878]

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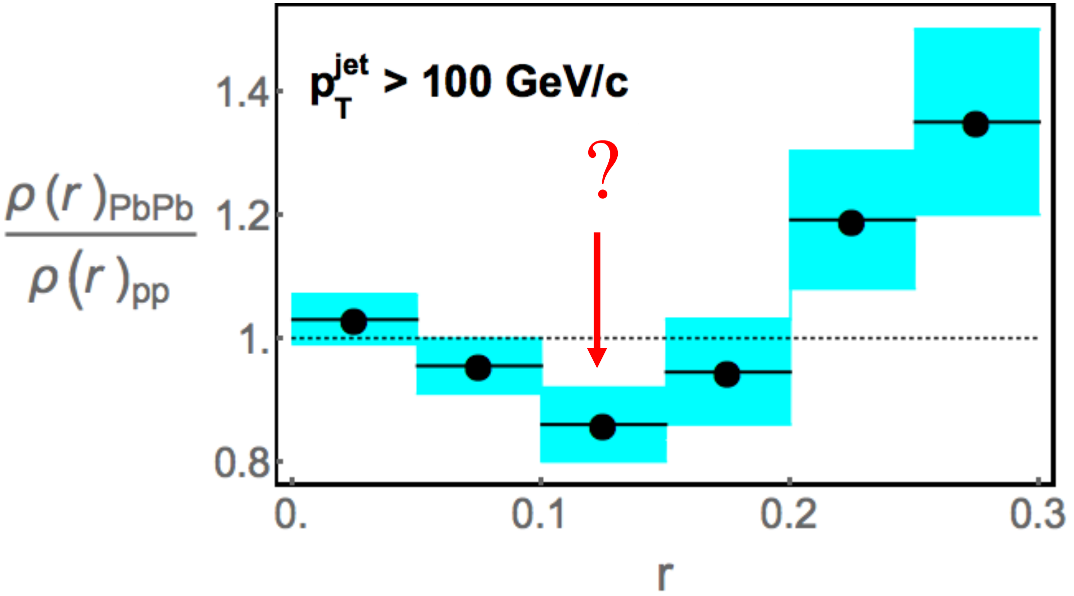
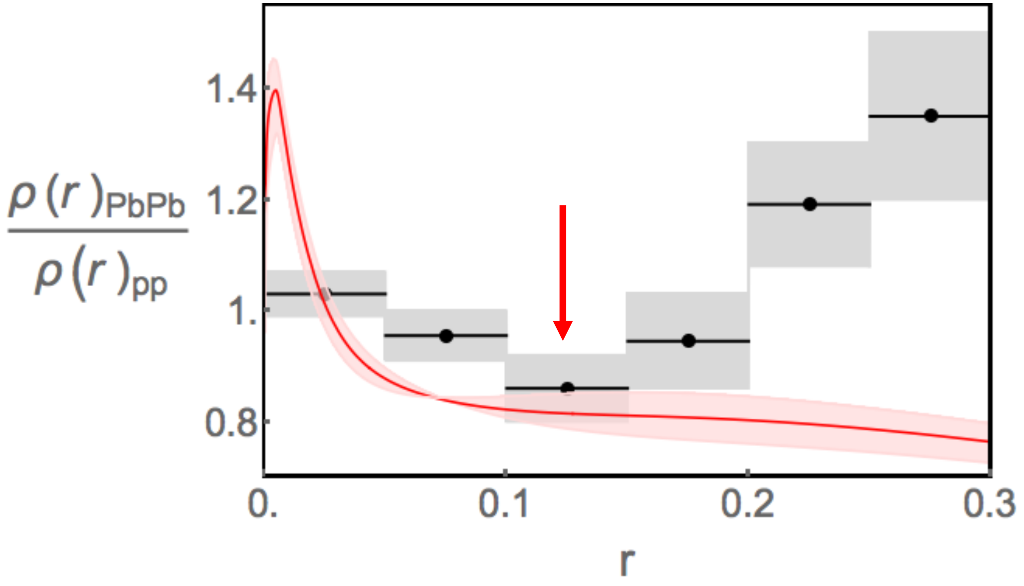
Does quenching cause jets to narrow?



CMS [1310.0878]

Holographic model where *every* jet widens



Rajagopal, Sadofyev, van der Schee [1602.04187]

Brewer, Rajagopal, Sadofyev, van der Schee [1710.03237]

Models as a tool to understand data

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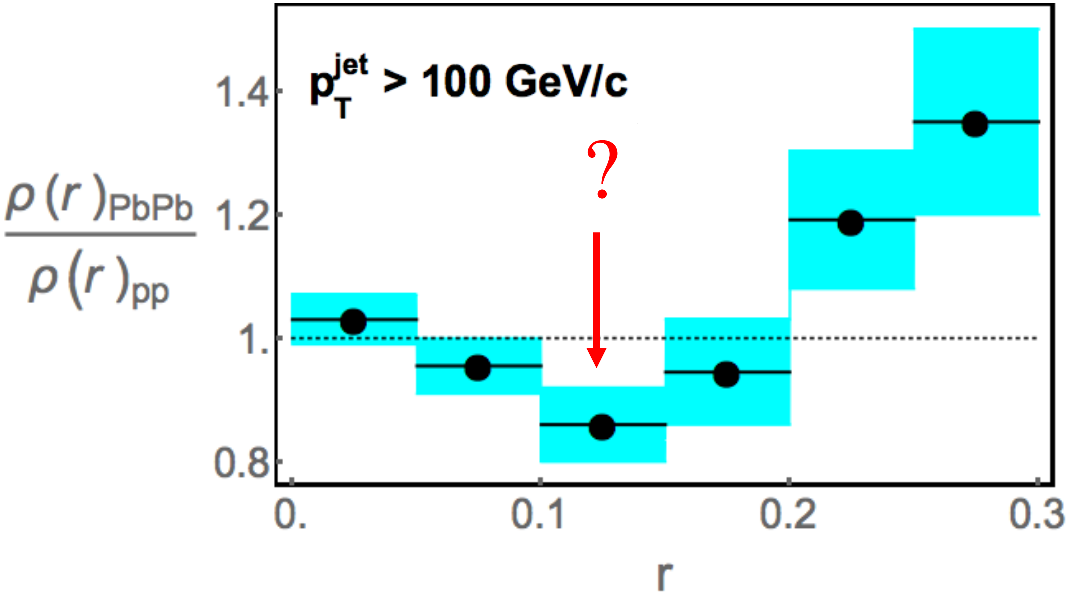

CMS [1310.0878]

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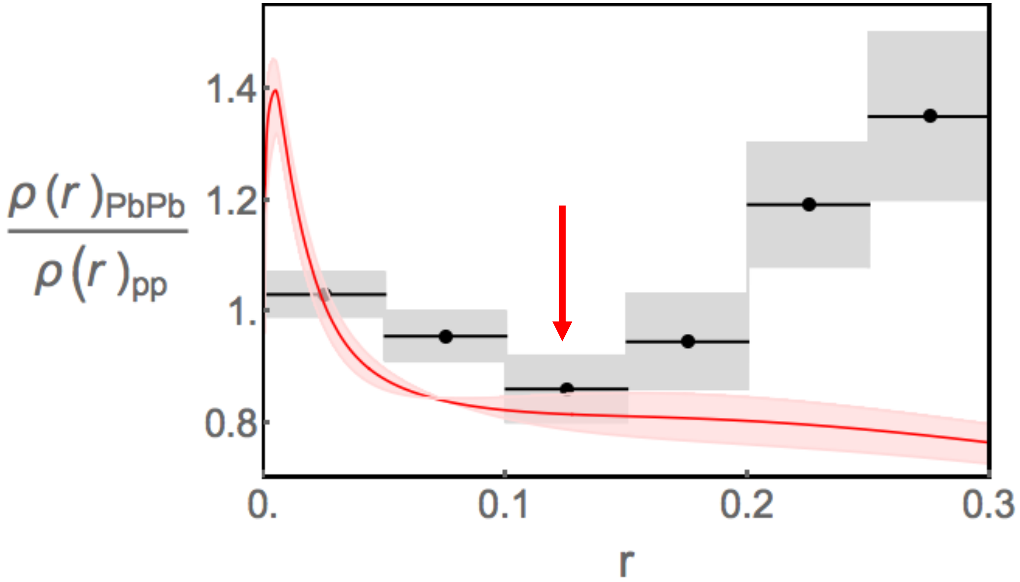


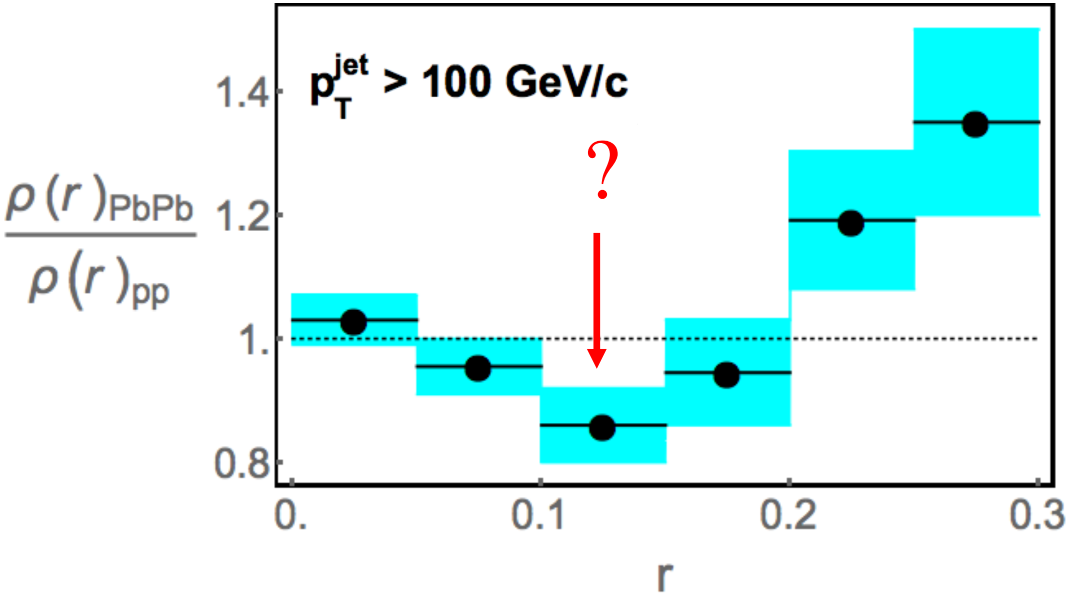
Rajagopal, Sadofyev, van der Schee [1602.04187]
Brewer, Rajagopal, Sadofyev, van der Schee [1710.03237]

Not necessarily; average jet width can narrow because selection favors (typically narrow) jets that lose least energy (increased quark jet fraction) Chien, Vitev [1509.07257]

also may impact fragmentation functions Caucal, Iancu, Mueller, Soyez [2005.05852]
Paul Caucal M 11:40

Models as a tool to understand data

Does quenching cause jets to narrow?



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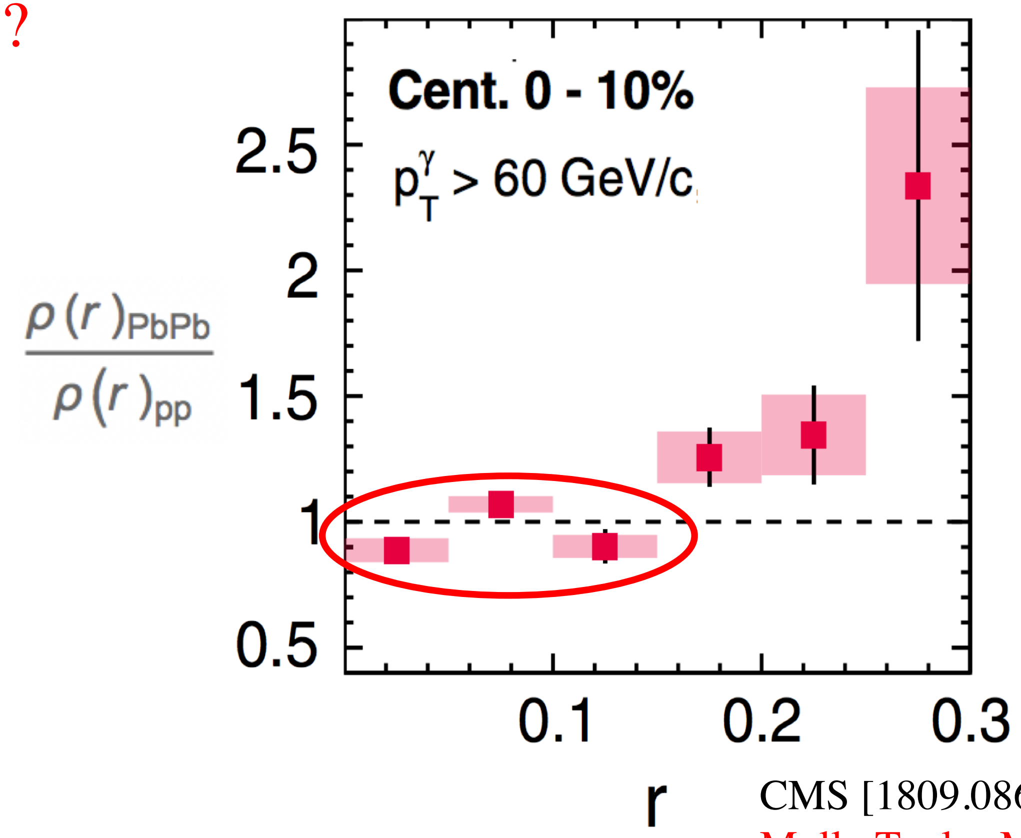

CMS [1809.08602]

Molly Taylor M 13:35

Narrowing is not apparent in γ-tagged jets where selection bias is removed

Exciting opportunities of boson-tagged jet measurements!

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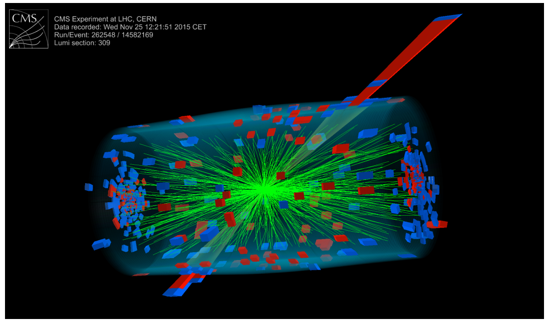
- Many effects obfuscate the interpretation of measurements

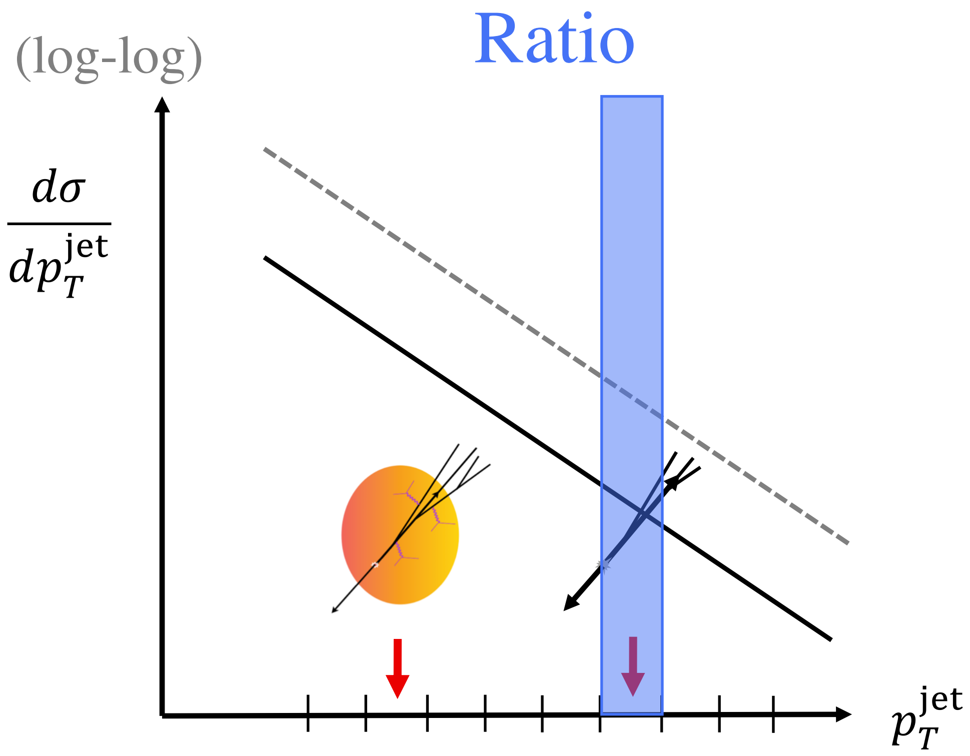
Opening the box

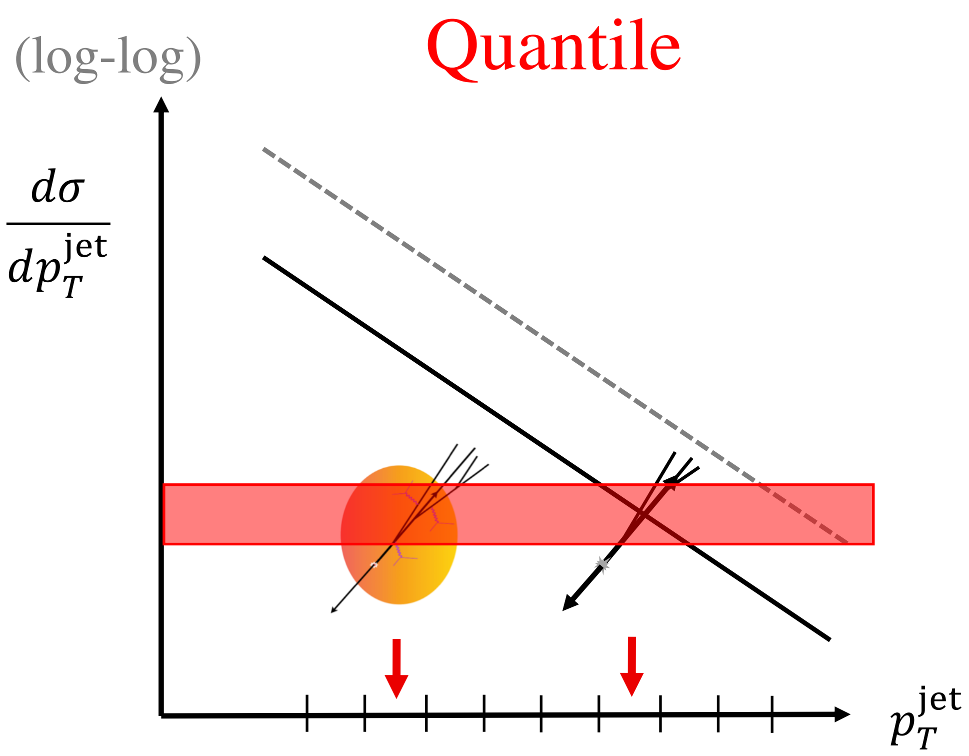
- Using models effectively as a tool to understand data

Toward interpreting data without models



Reducing the effect of p_T migration on jet observables



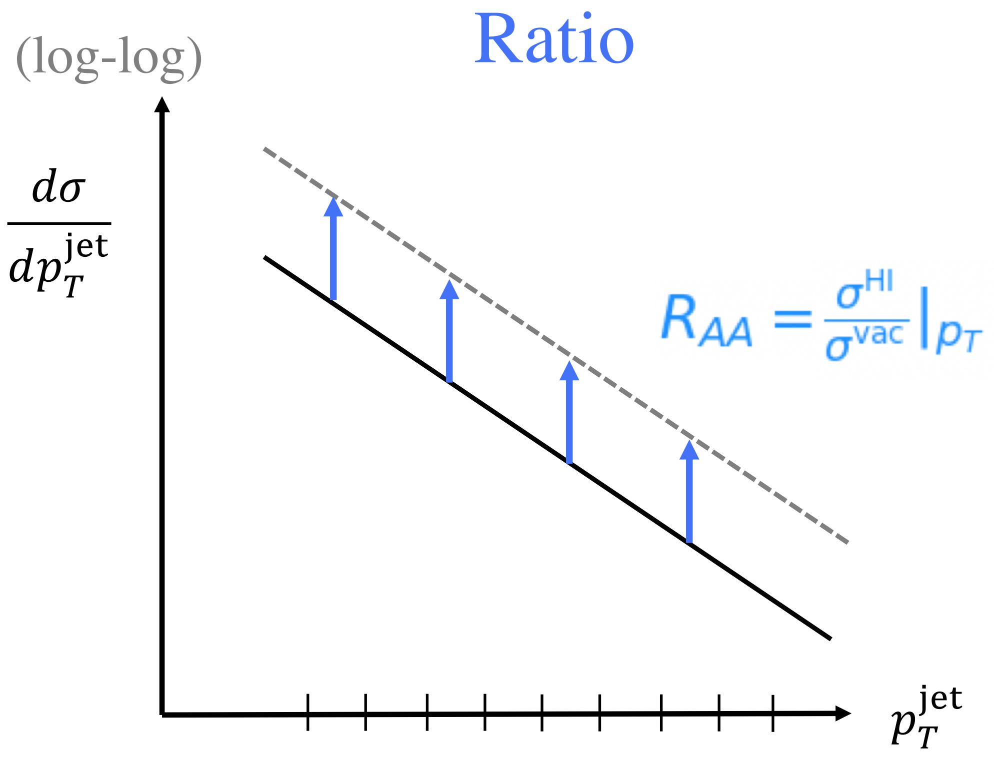


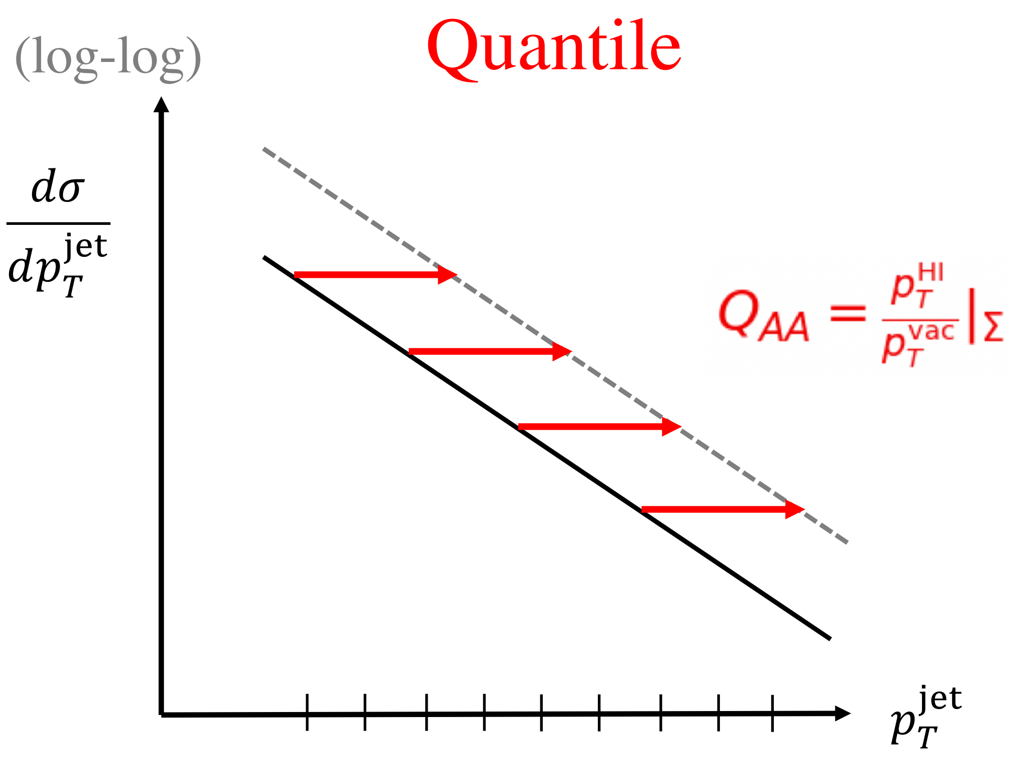
For hadrons: PHENIX [0611007, 1208.2254, 1509.06735]

Brewer, Milhano, Thaler [1812.05111]

Comparing jets horizontally corrects for biases due to average energy loss

Reducing the effect of p_T migration on jet observables





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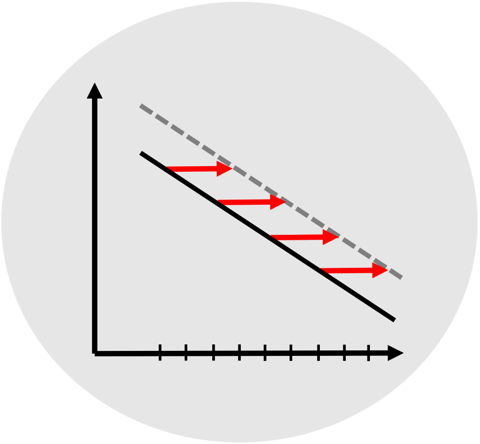
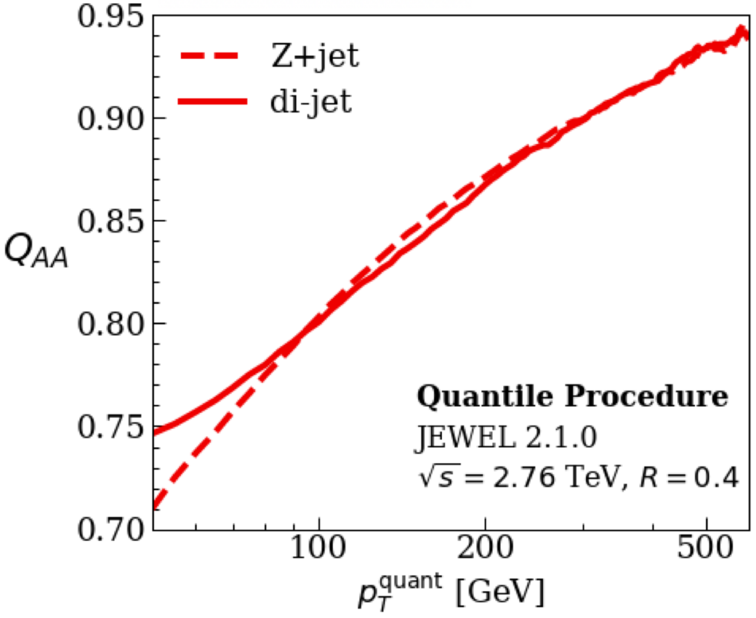
Comparing jets horizontally corrects for biases due to average energy loss

Toward measuring average fractional energy loss



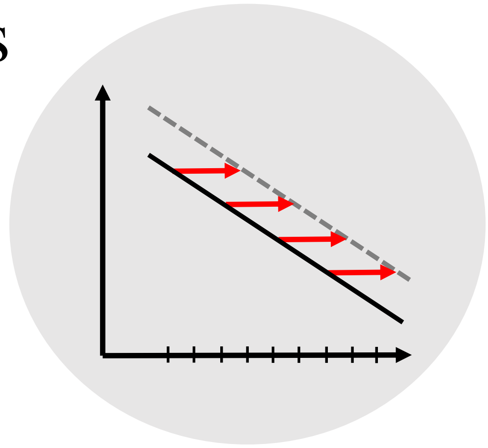
$$Q_{AA} = \frac{p_T^{\mathrm{HI}}}{p_T^{\mathrm{vac}}}\Big|_{\Sigma}$$



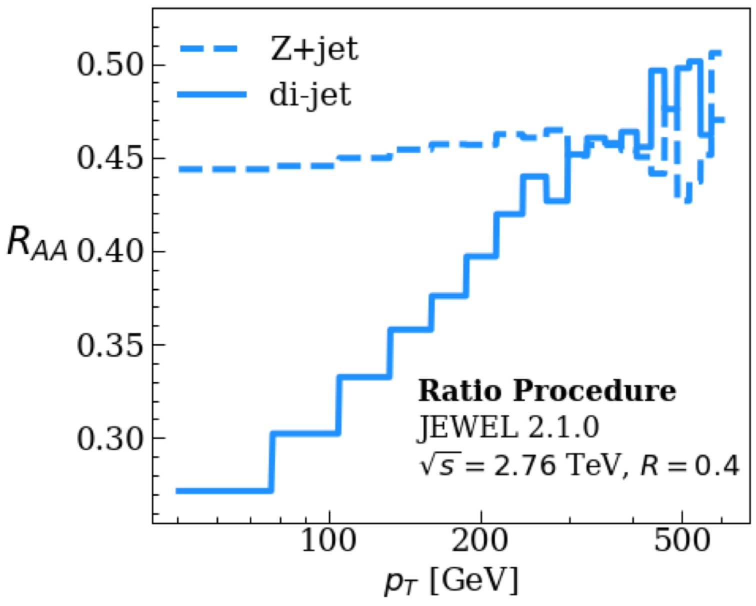
Average p_T loss per jet

Brewer, Milhano, Thaler [1812.05111]

Toward measuring average fractional energy loss

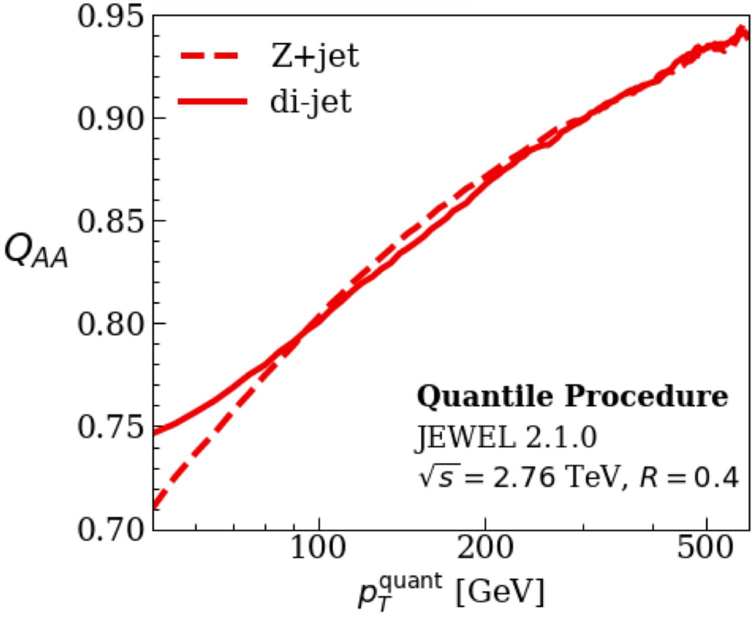


R_{AA}



Average # of jets lost per p_T

$Q_{AA} = \frac{p_T^{\mathrm{HI}}}{p_T^{\mathrm{vac}}}\Big|_\Sigma$



Average p_T loss per jet

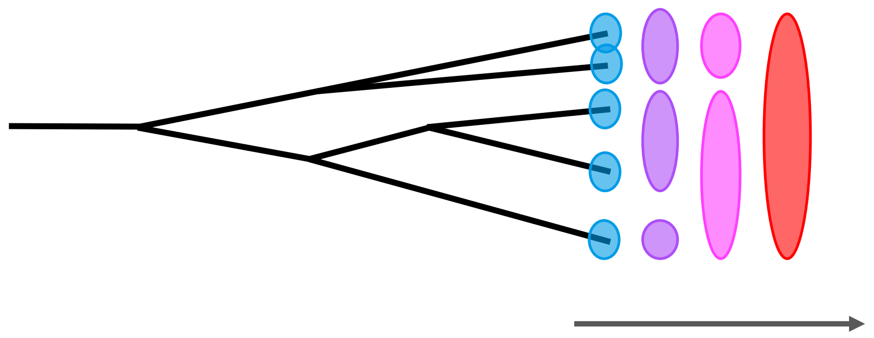
Brewer, Milhano, Thaler [1812.05111]

Q_{AA}

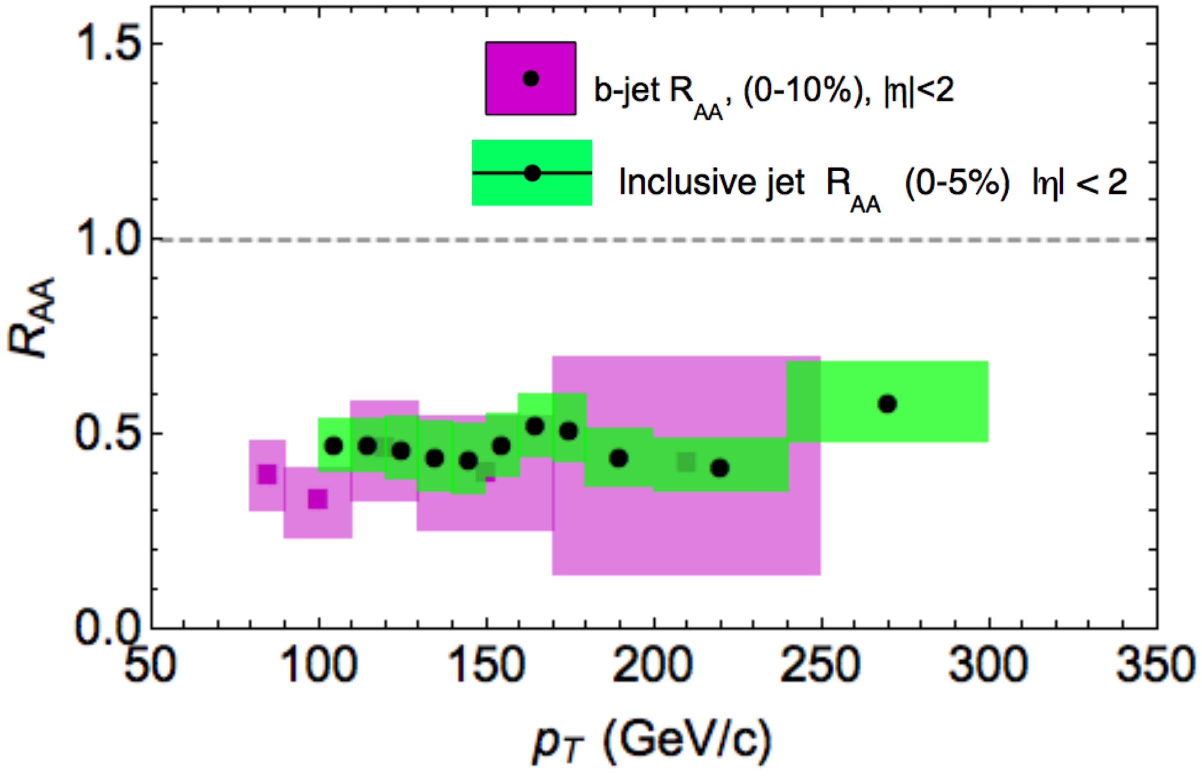
- is much less sensitive to vacuum spectra (crucial for RHIC ↔ LHC)
- tends to zero at high p_T even though R_{AA} is flat

Sample-dependence: are quark and gluon jets quenched differently?

On what scale does the QGP resolve the color (sub)structure of a jet?



Spousta, Cole [1504.05169]; Chien, Elayavalli [1803.03589];
Qui, Ringer, Sato, Zurita [1903.01993];
Casalderrey-Solana, Milhano, Pablos, Rajagopal [1907.11248];
Li, Vitev [1908.06979] ; Apolinario, Barata, Milhano [2003.02893]

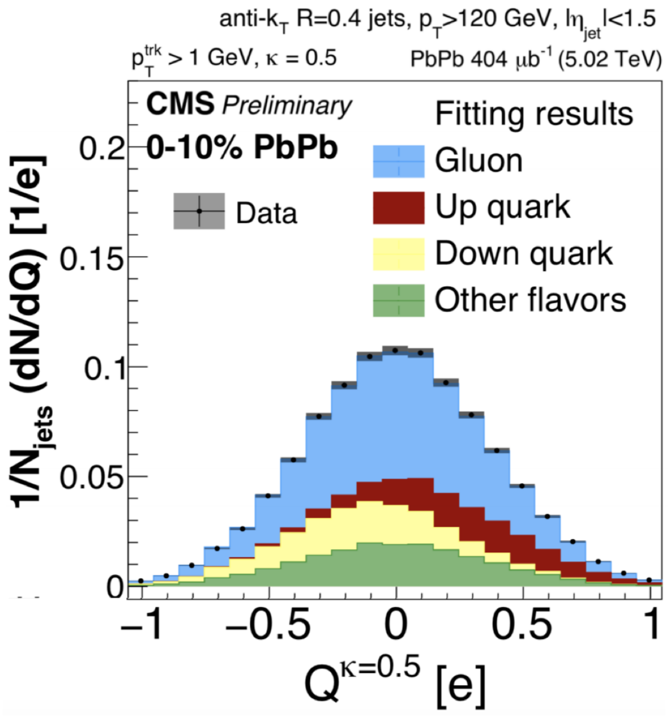


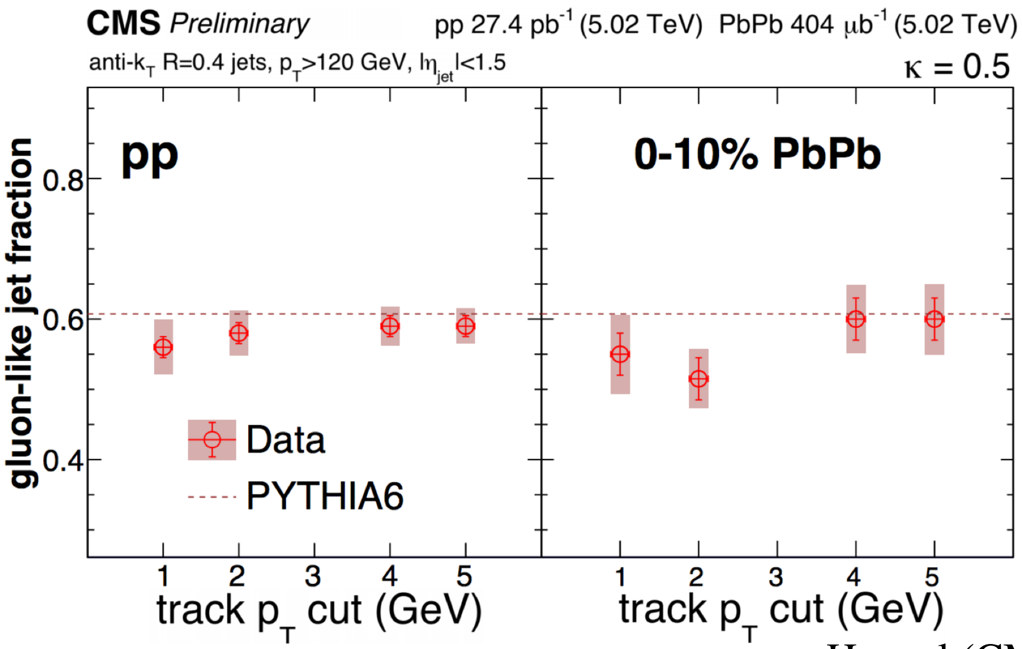
CMS [1312.4198], [1410.2576]
Xiao Wang W 13:35

Quantitatively: difficult because inclusive jets have large quark fraction, and maybe also different quark fraction in A-A and p-p

Quark- and gluon-dependence of jet quenching

CMS measurement of gluon fraction modification using jet charge found no modification





Hangal (CMS) [2004.14600]

Dhanush Hangal Th 13:10

Ivan Vitev W 12:25

Relies on template fitting with (assumed unmodified) PYTHIA jet charge distributions

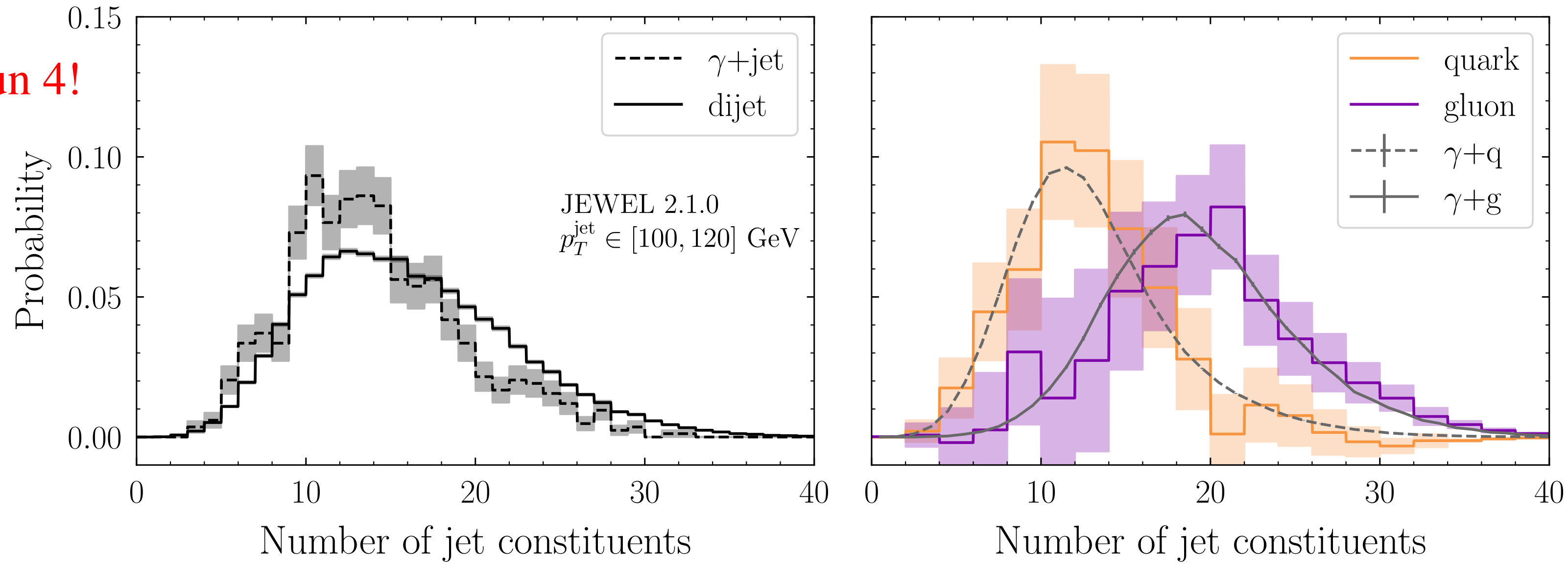
Going beyond templates

Two samples with different q/g fraction (e.g. dijet, γ+jet) can be used to extract q/g fractions and separate q/g distributions from data, without templates

Done in p-p: Metodiev, Thaler [1802.00008]
Komiske, Metodiev, Thaler [1809.01140]

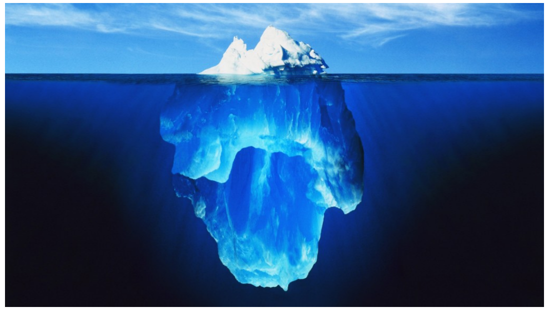
A-A

γ+jet statistics available in Run 4!



Brewer, Thaler, Turner; *in preparation*

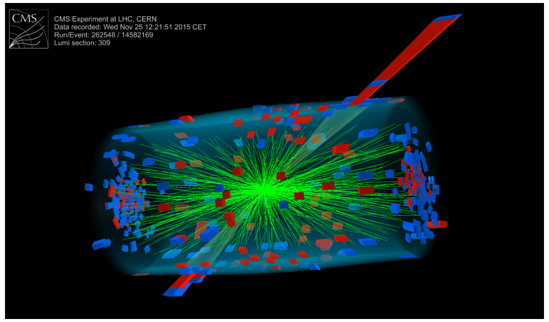
Possibility for data-driven measurement of quark and gluon jet modification and fraction modification



Inclusive samples have a lot of jets that lost little energy

Jet modification observables must be interpreted with care

- Models can help!



Toward interpreting data without models

- Enhancing sensitivity to more modified jets
- Separating modification of quark and gluon jets

Many thanks to

Quinn Brodsky, Yang-Ting Chien, Eliane Epple,
Raghav Kunnawalkam Elayavalli,
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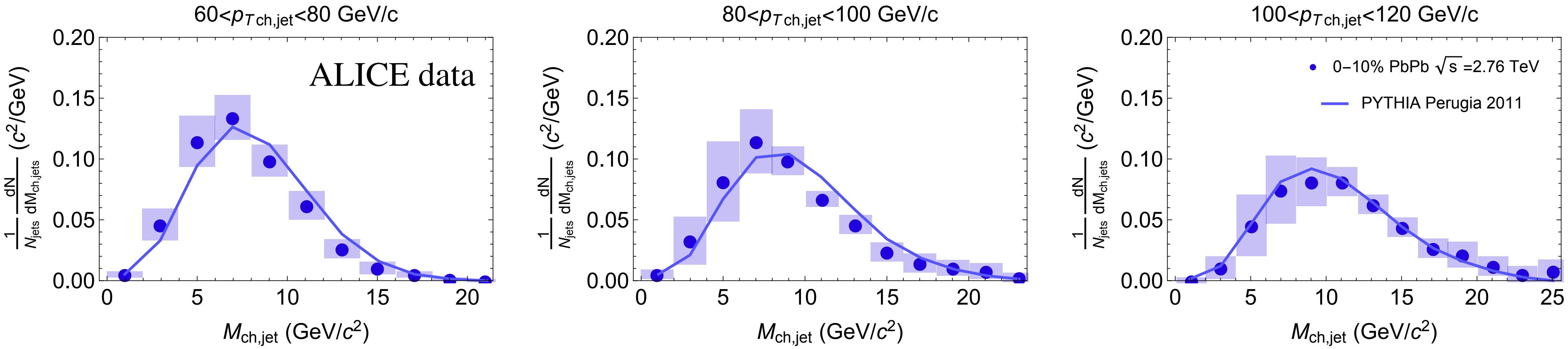
Krishna Rajagopal, Jesse Thaler,
Urs Wiedemann, Xiaojun Yao,
Yi Yin, and Nima Zardoshti

for valuable feedback and discussions!

Backup

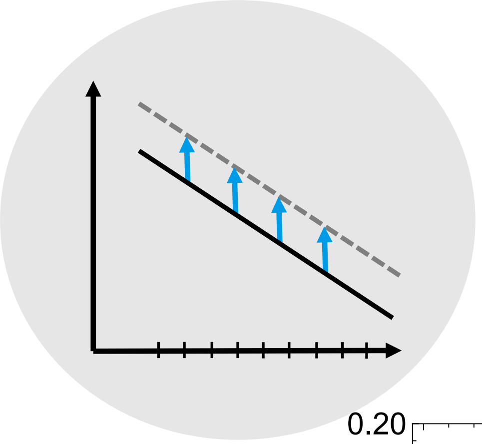
Distribution (un)modification does not imply jet (un)modification!

Apparent lack of modification of charged jet mass compared to PYTHIA expectation



ALICE [1702.00804]
(figure modified)

Comparing jets horizontally corrects for biases due to average energy loss



Ratio

compare p-p and A-A jets at same p_T

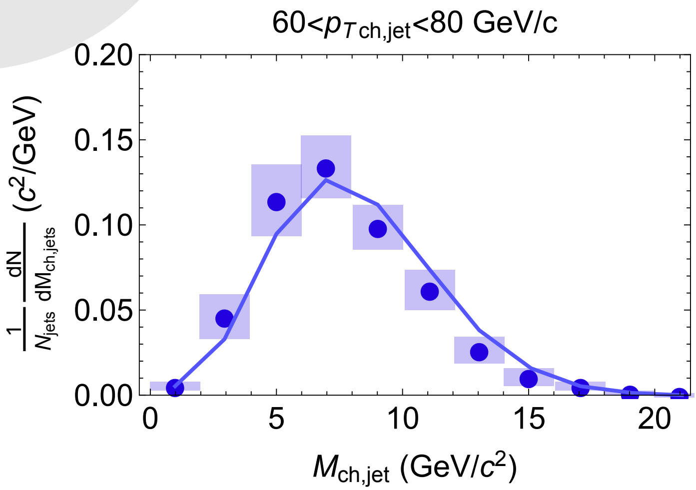
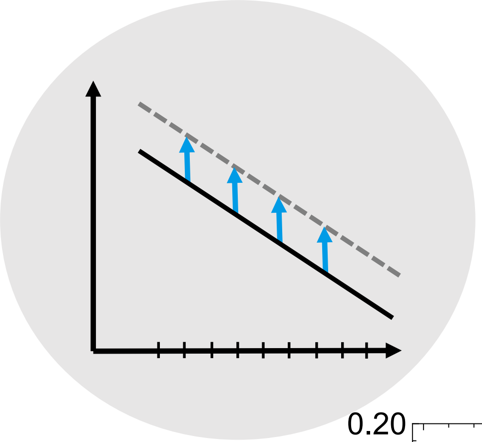


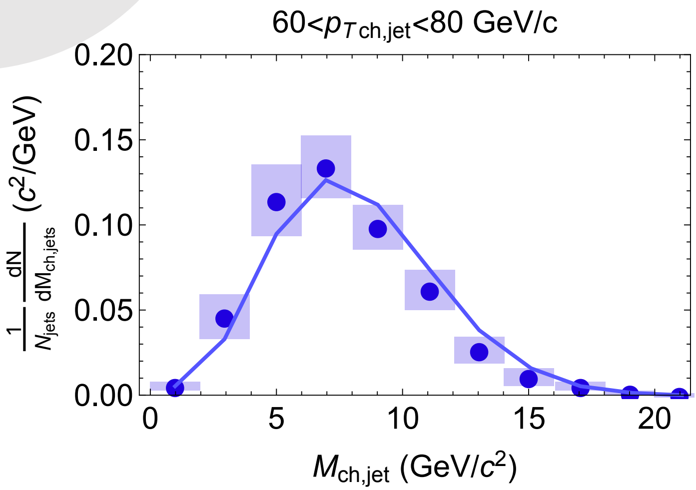
Fig: ALICE [1702.00804] (figure modified)

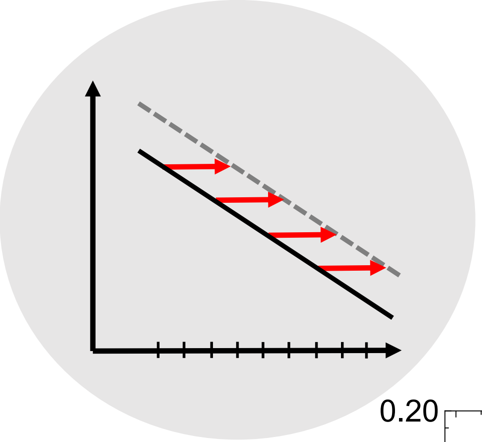
Comparing jets horizontally corrects for biases due to average energy loss



Ratio

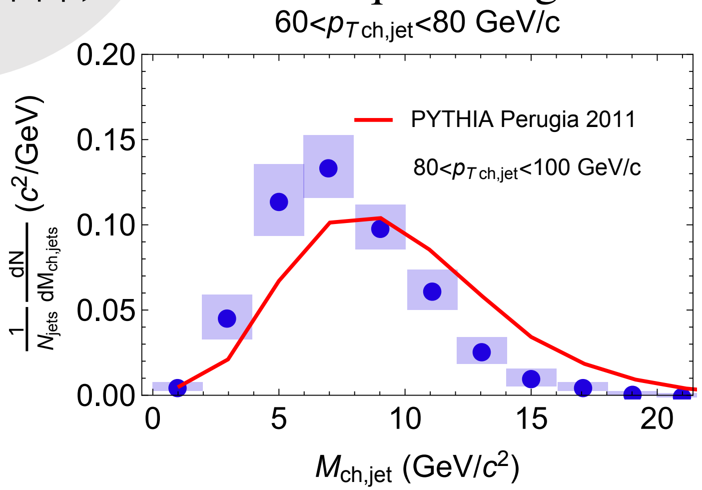
compare p-p and A-A jets at same p_T





Quantile

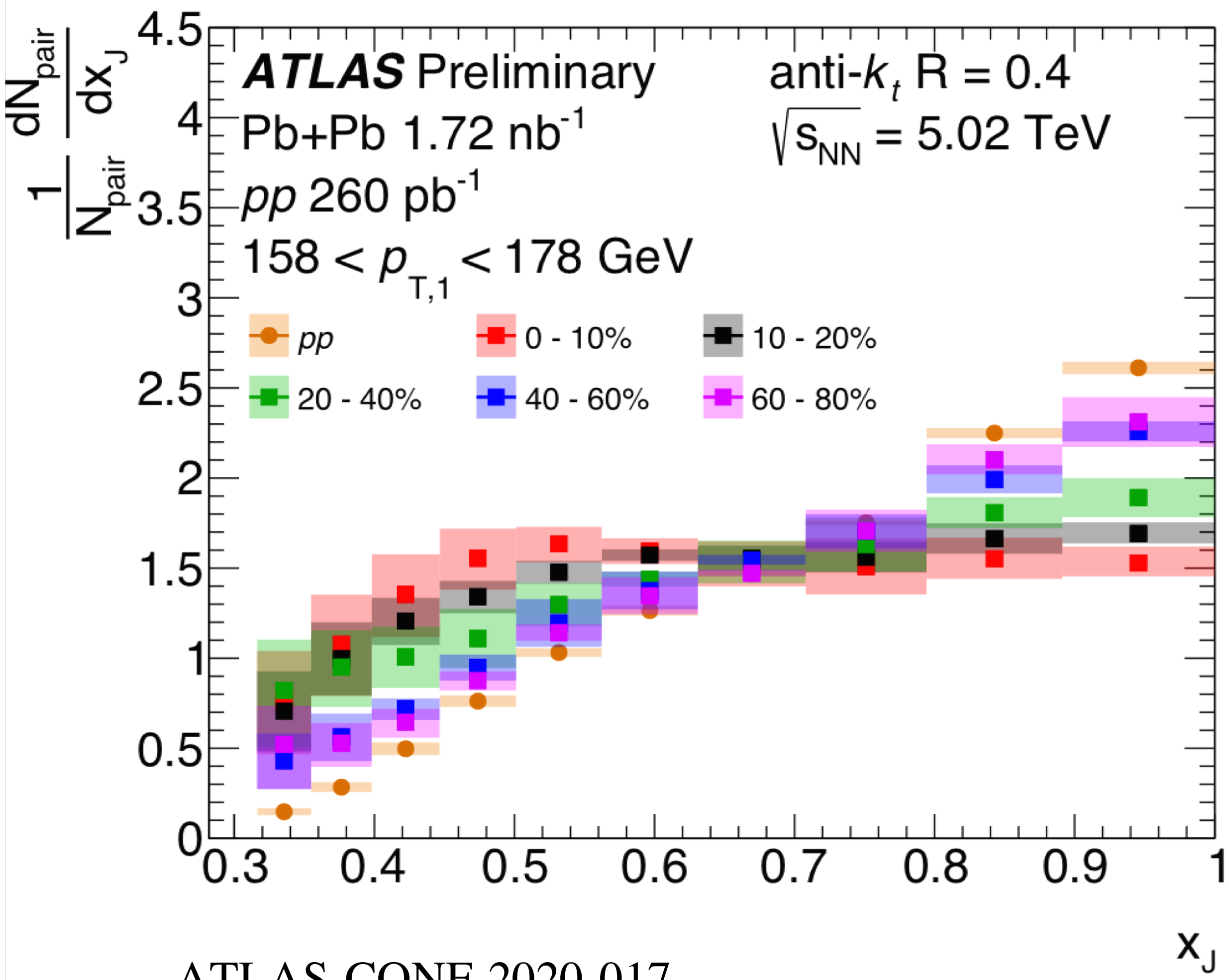
compare p-p and A-A jets with the same average p_T *before* quenching



Quantile procedure gives rigorous definition for what p_T ranges to compare between p-p and A-A

Fig: ALICE [1702.00804] (figure modified)

Going forward: centrality dependence of dijet asymmetry



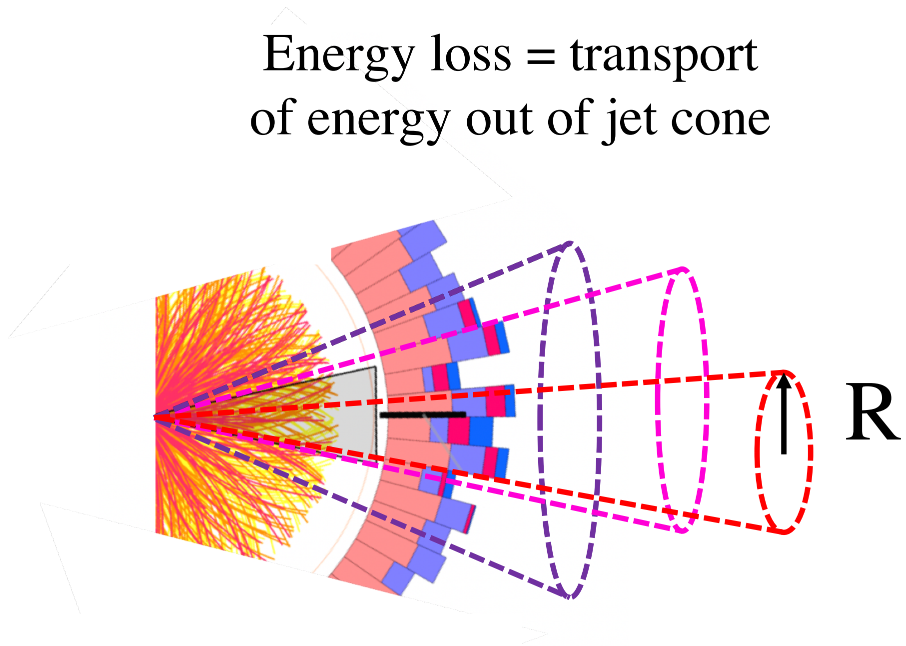
ATLAS-CONF-2020-017

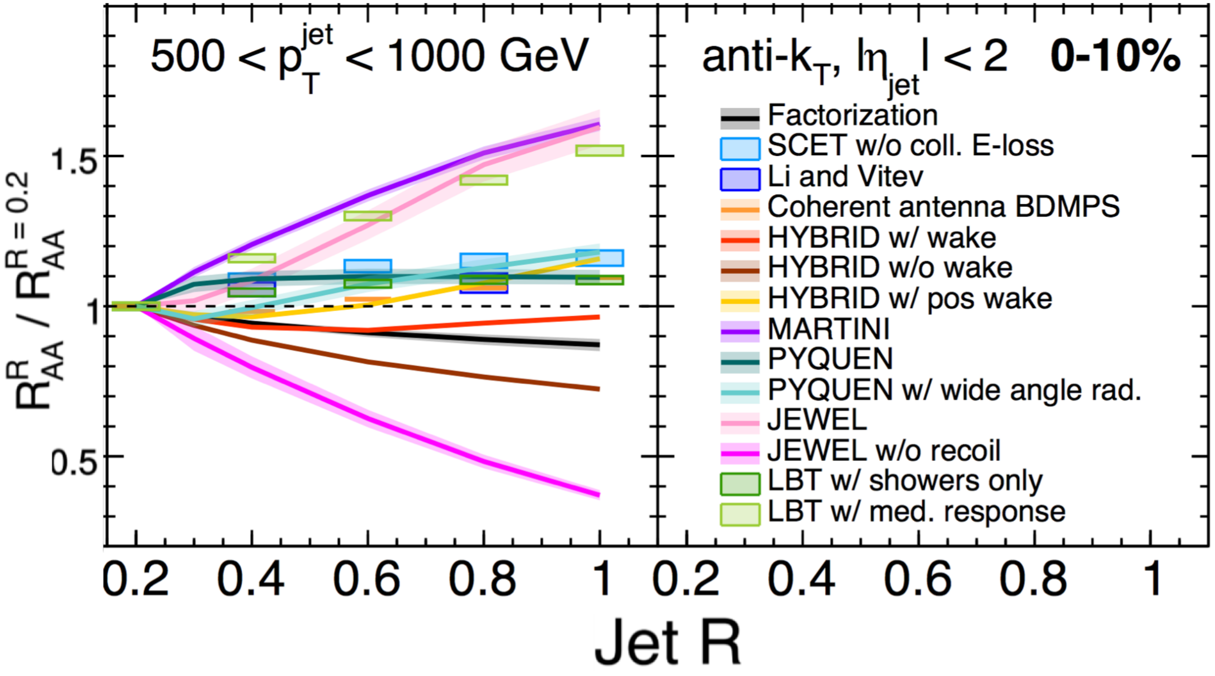
Virginia Bailey M 11:00

Using models to propose more sensitive measurements

Jet cone size dependence of energy loss

Energy loss = transport of energy out of jet cone





When is all energy recovered?

Taylor (CMS) QM '19

Sensitive to inclusion of medium response in many models

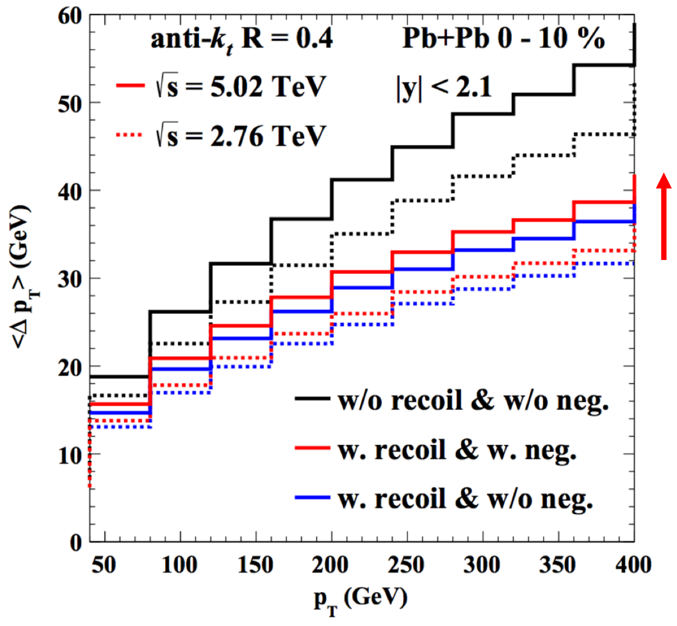
Going forward: want to discriminate between the different physics of medium response

R_{AA} is very sensitive to vacuum spectra

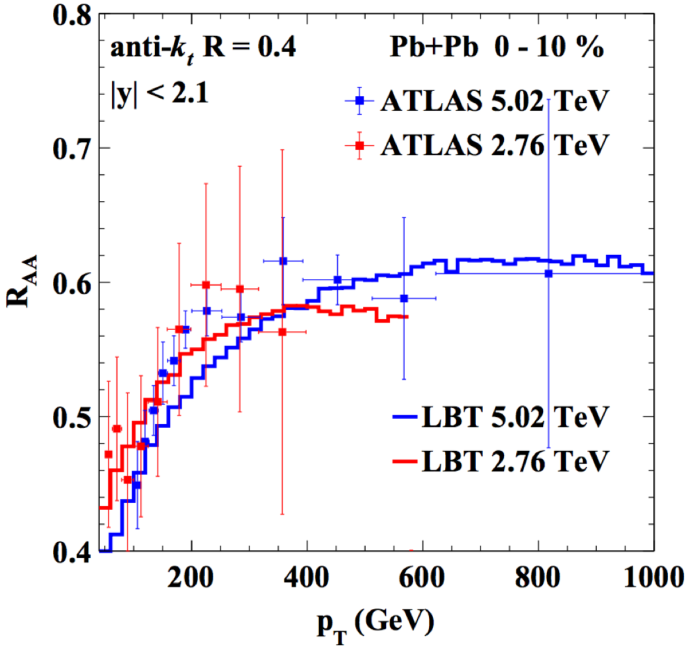
Ex: temperature-dependence of jet quenching between 2.76 and 5.02 TeV

LBT

Measured by ATLAS [1805.05635]



Increased energy loss at all p_T



Depending on p_T, R_{AA} increases or decreases due to spectra

He, Cao, Chen, Luo, Pang, Wang [1809.02525]

Much more dramatic difference in spectra between RHIC and LHC!

Q_{AA} crucial for quantitative comparisons