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Parton interactions in medium
Experiment

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June 13, 2024

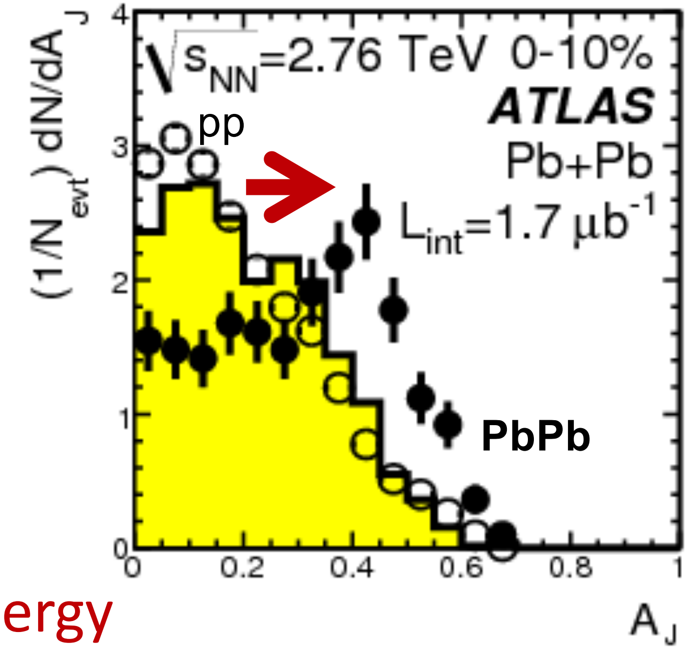
Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)

Jet energy asymmetry
$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$

In pp: used to calibrate jets

In PbPb: physics signal



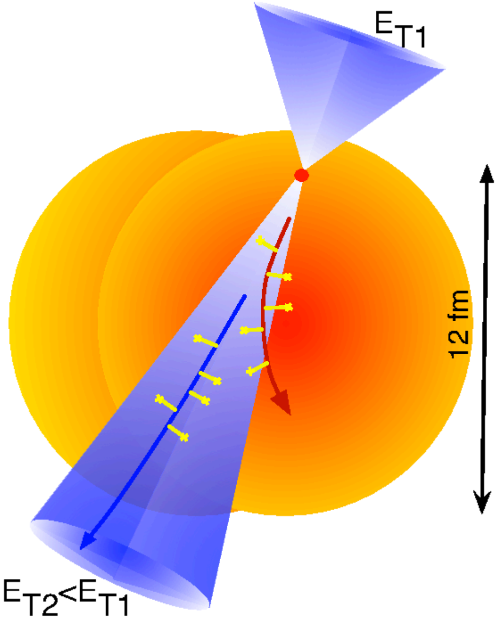
Phys.Rev.Lett.105:252303,2010

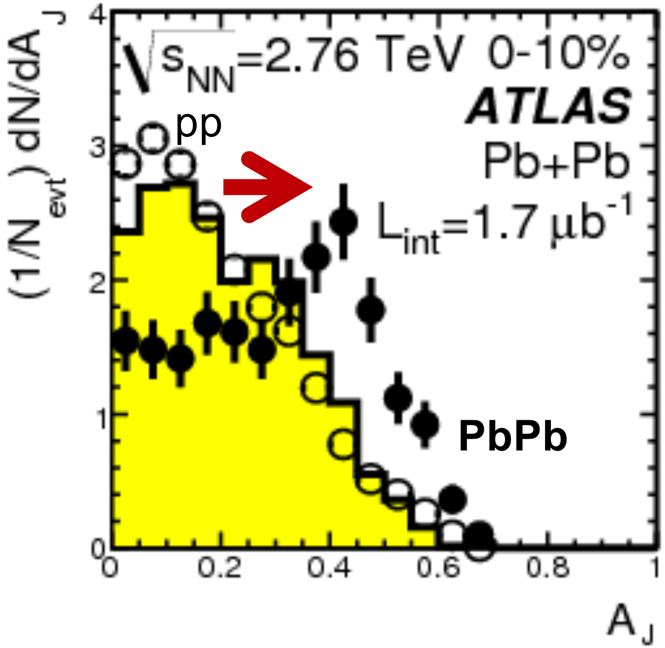
balanced *unbalanced*

Dijets in PbPb are less balanced in energy

Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)





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Dijets in PbPb

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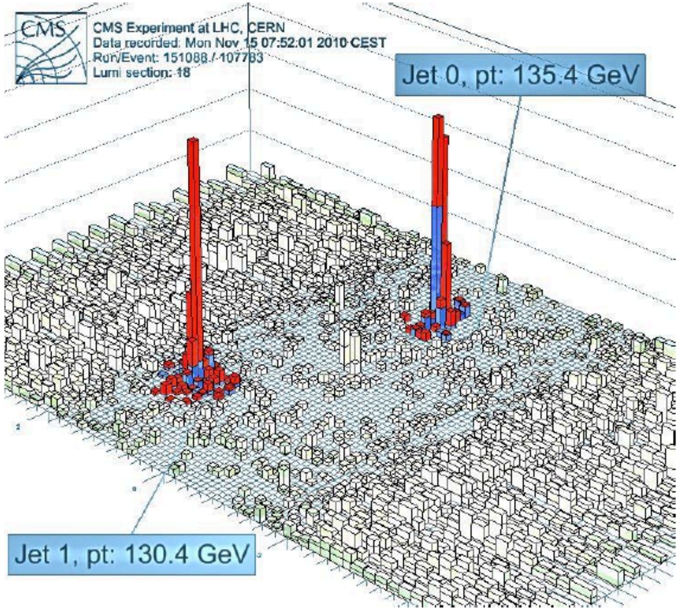
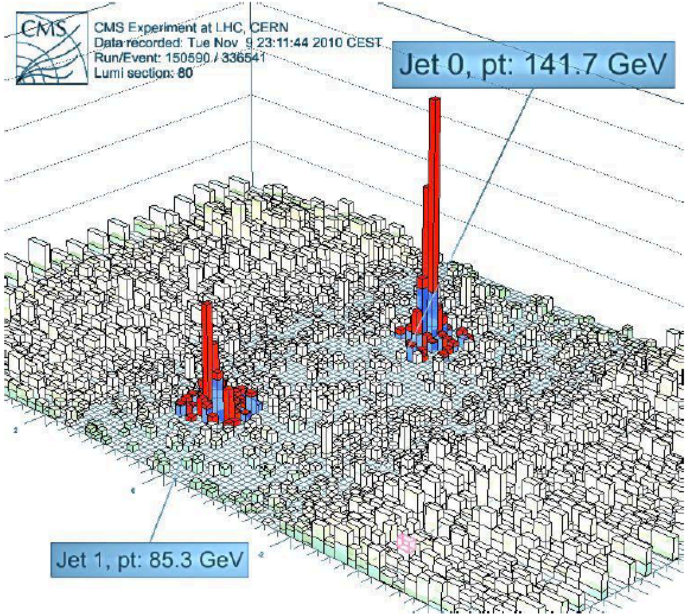


Balanced
Energy

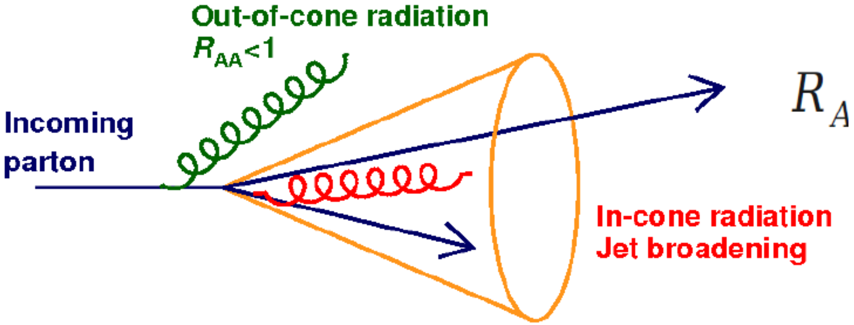


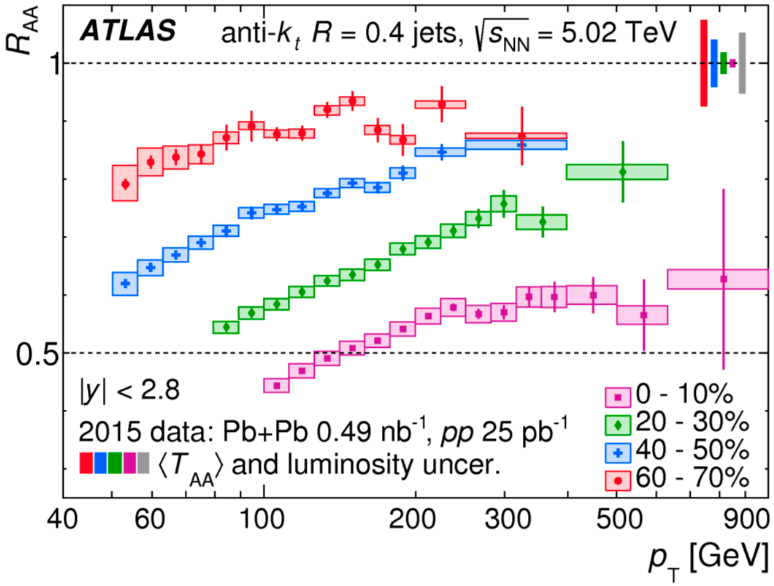
Unbalanced
Energy

Jet R_{AA}

Jets don’t recover all expected energy

→out of the cone



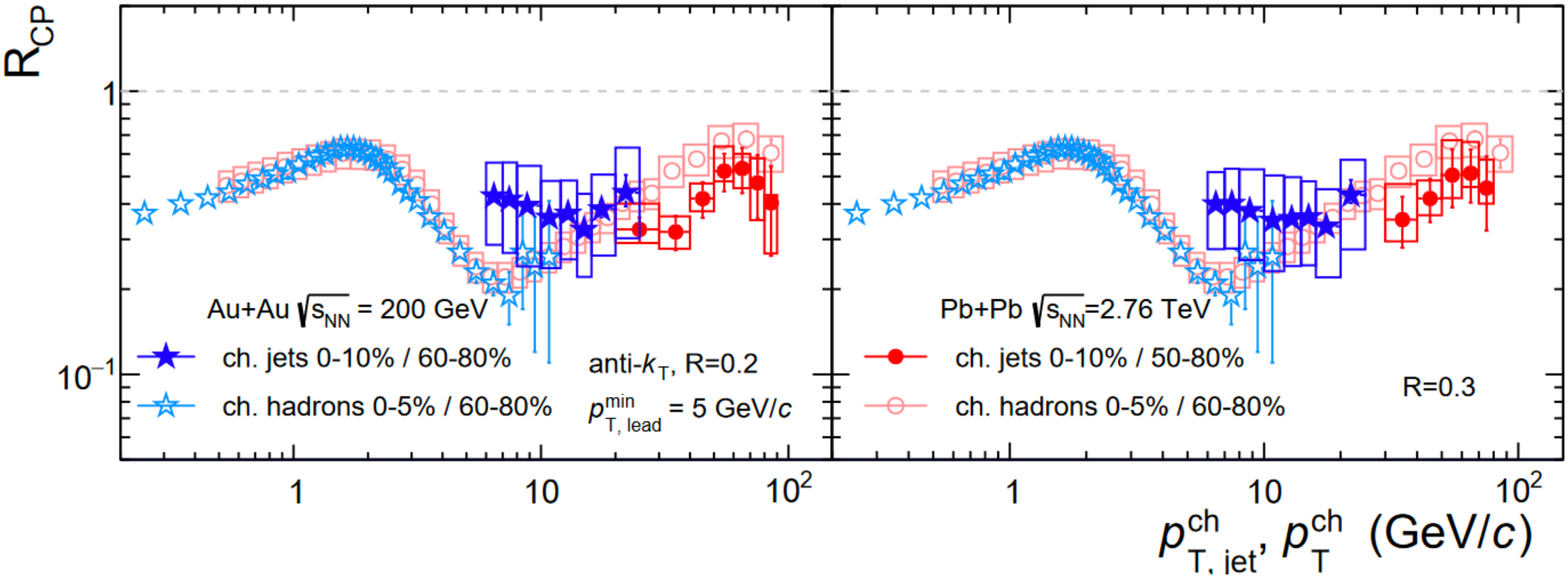


ATLAS, PLB 790 (2019) 108

Hadron vs Jet R_{AA}

Similar suppression for single hadrons and jets.

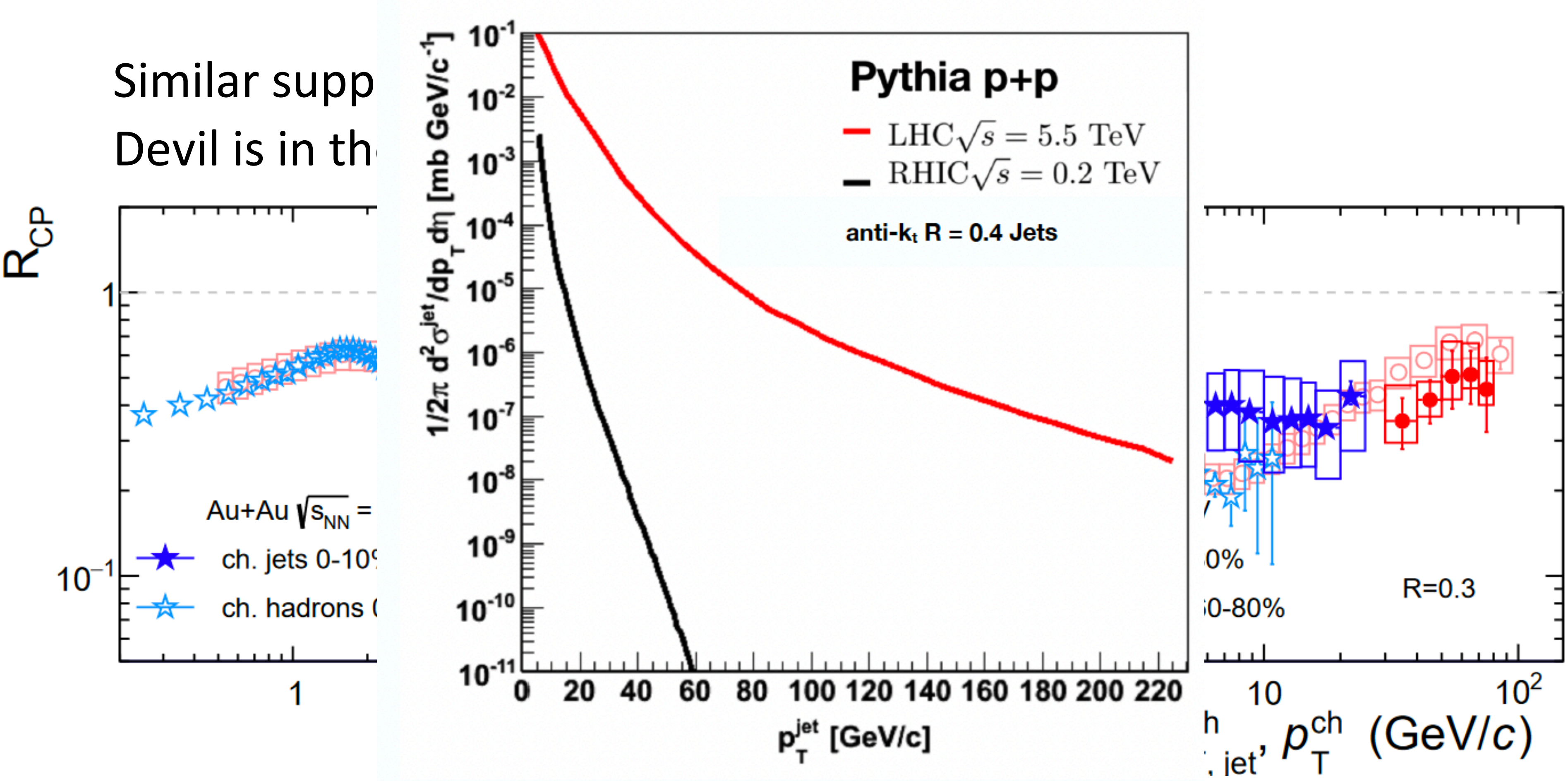
Devil is in the details.

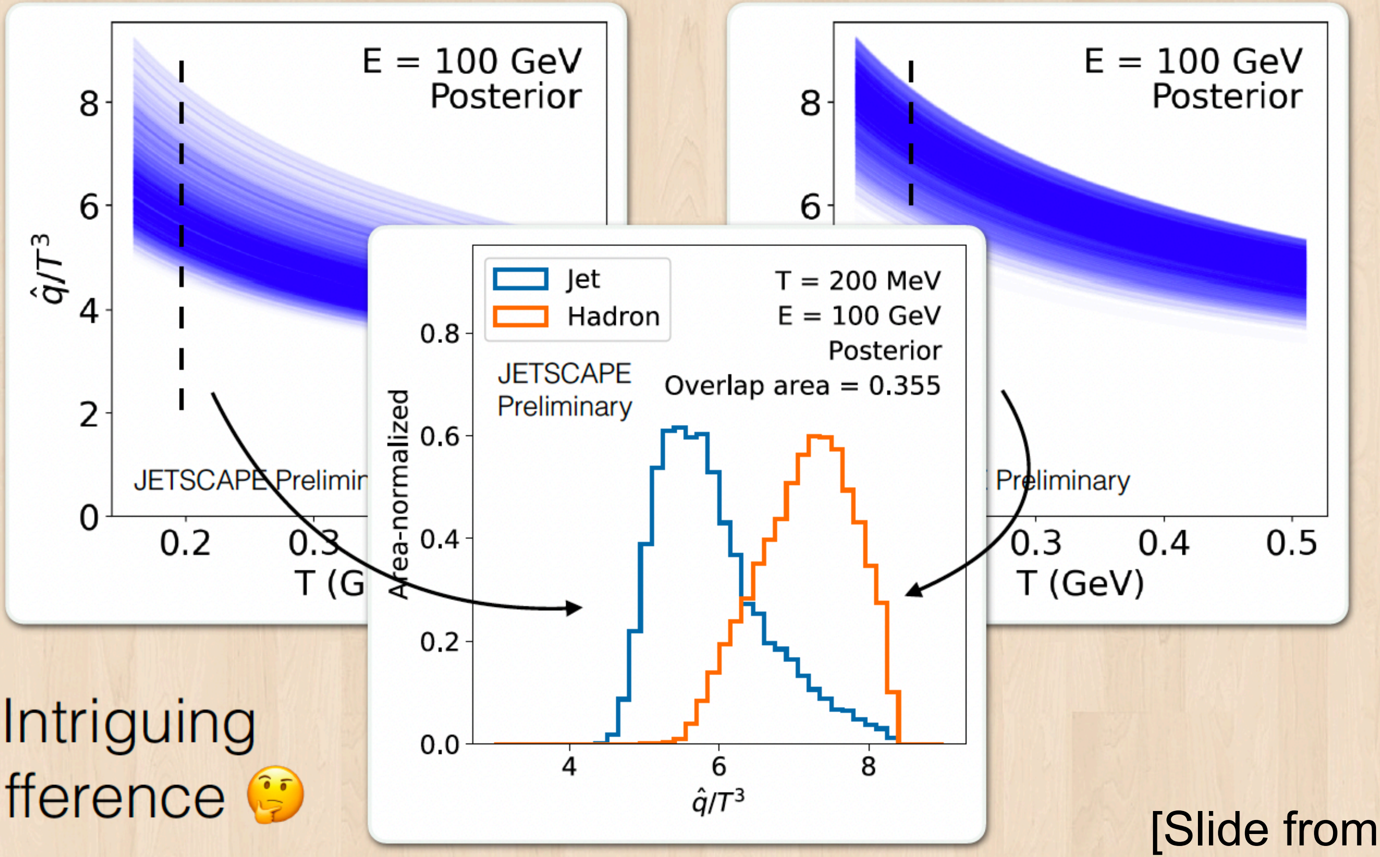


Hadron vs Jet R

Similar supp

Devil is in th

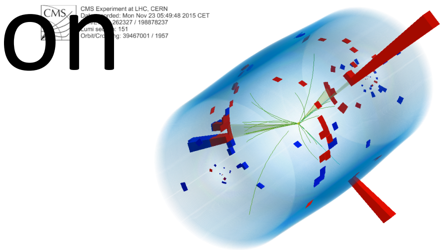




Intriguing difference 🤔

[Slide from Yi Chen]

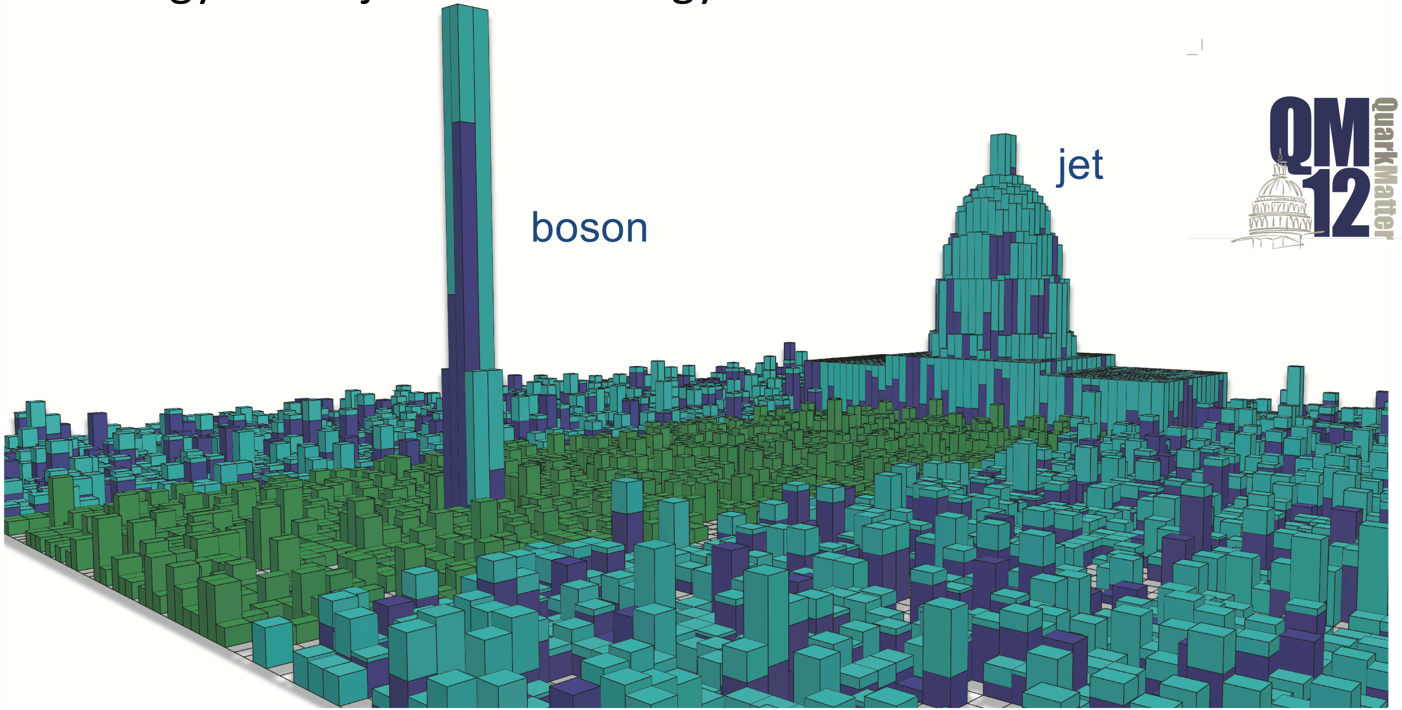
Boson-jet correlation



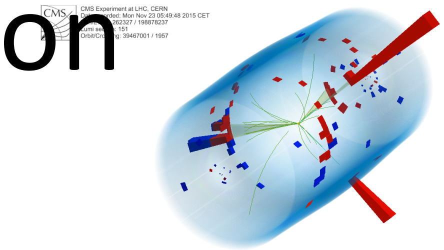
Advantage of boson-jet correlations:

Z bosons and photons aren’t affected by medium

You know the energy of the jet before energy loss



Boson-jet correlation



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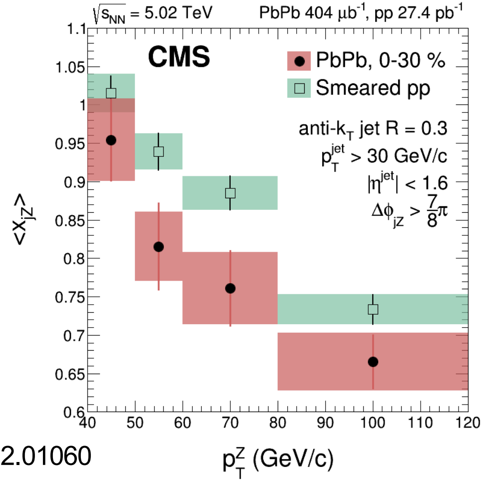
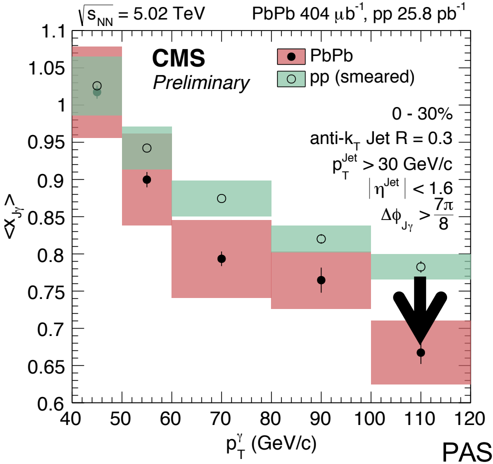
Z-jet



arXiv: 1702.01060

photon-jet



PAS-HIN-16-002

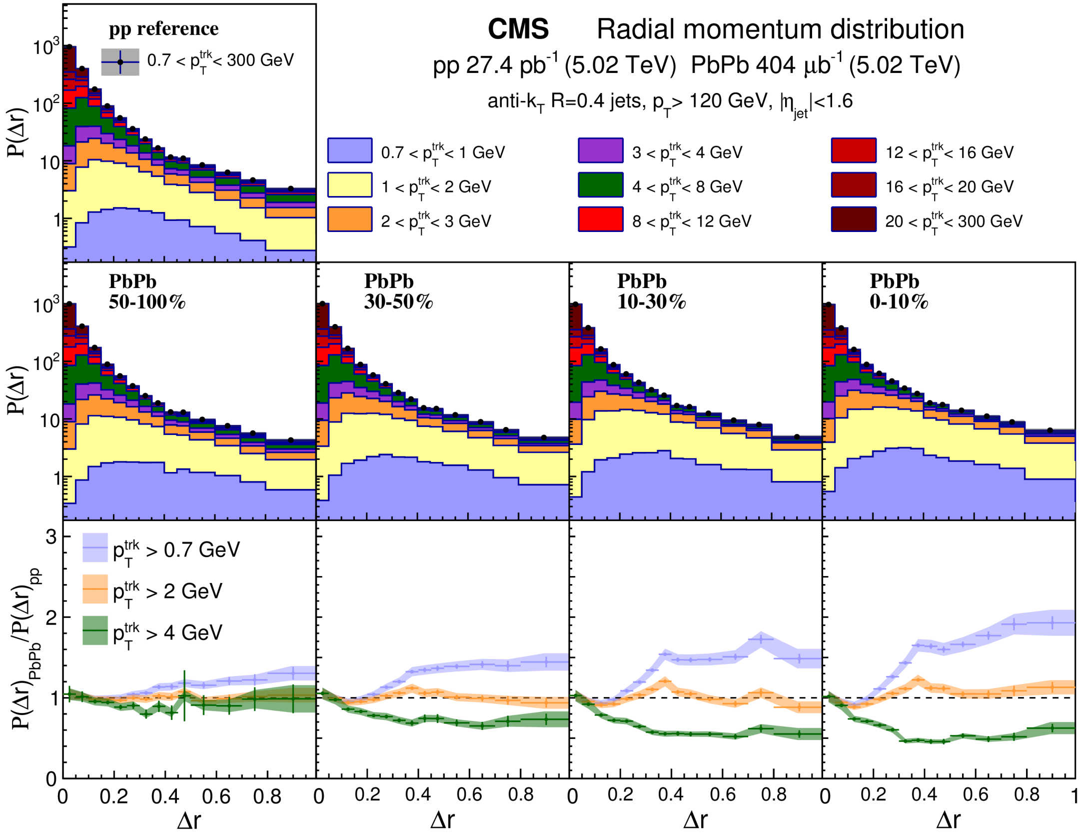
$$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

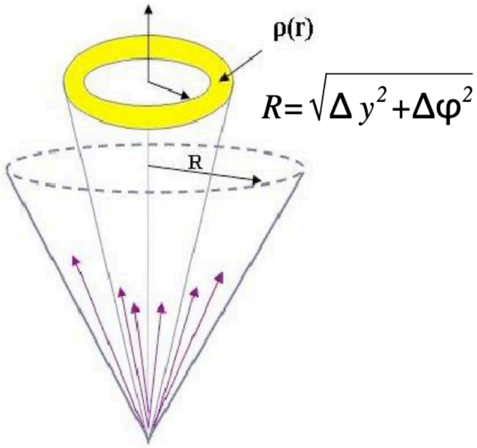
pp

PbPb

Jets loose ~15% energy due to medium interaction

Where did the energy go?



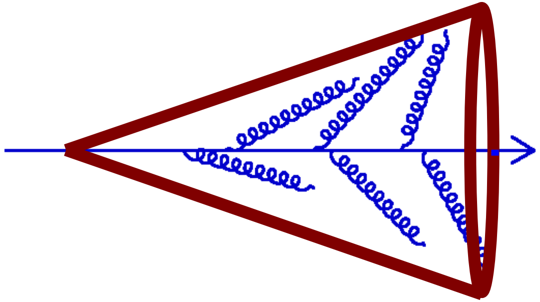


JHEP 05 (2018) 006

What is jet substructure?

Dynamics of particles inside the jet

Two scales: angular + momentum space



Fragmentation Functions

Single hadron

Classic Jet Shapes

All hadrons

Groomed Observables

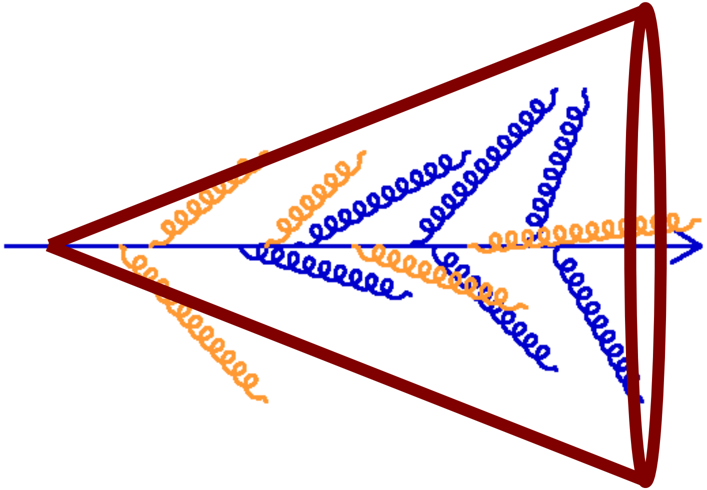
Subset of hadrons

Sketches by J. Thaler

Why jet substructure?

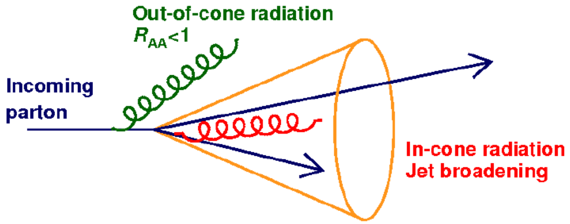
Structure of quenched jet different from unquenched?

- How is the parton shower modified?
- What is the exact mechanism modifying the shower?
- Can we relate shower modifications to medium properties?

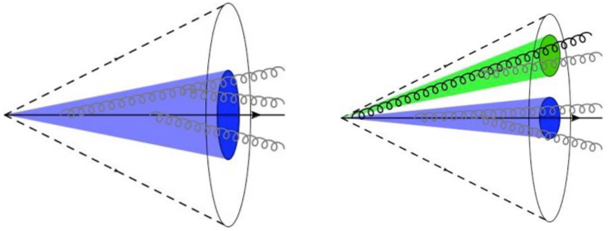


Jet modification in hot QCD medium

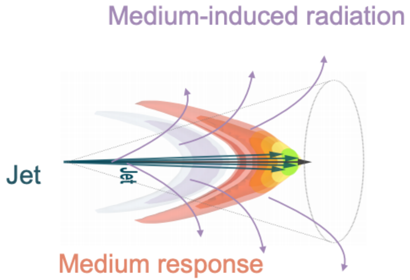
Medium-induced energy loss



Coherence effects



Medium recoil

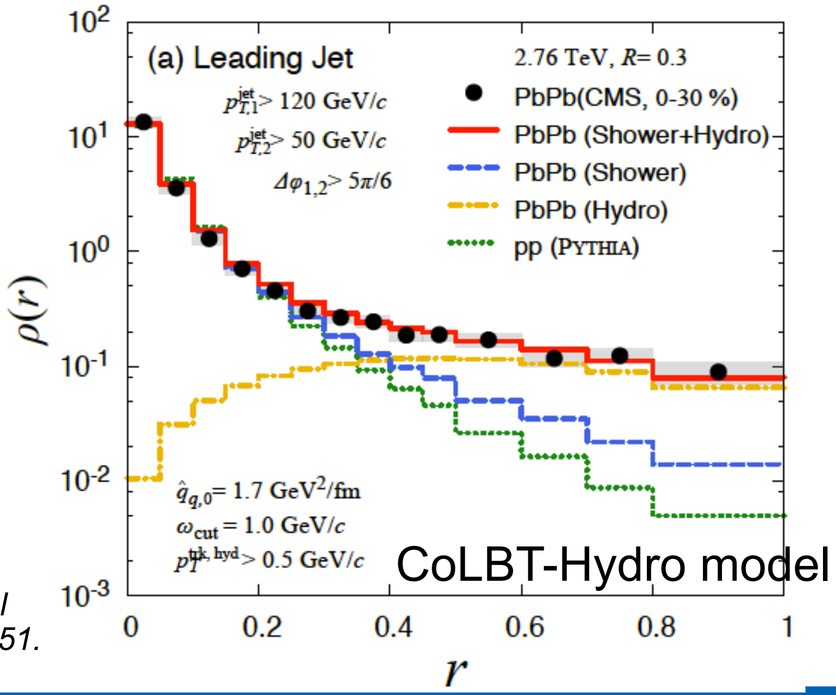


Medium response

Medium excitation | wake | jet-correlated medium

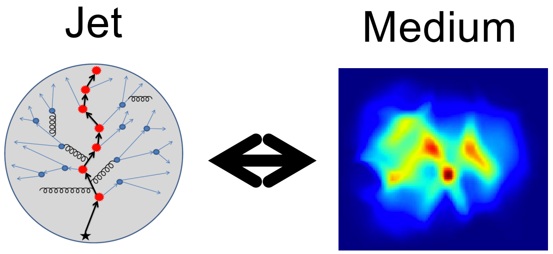
== a bit of the medium becomes part of the jet

→ Causing excess of soft particles at large angle



CoLBT-Hydro model

Tachibana et. al
arXiv:1701.07951.



Quenched parton shower
+ medium excitation

Quenched parton shower

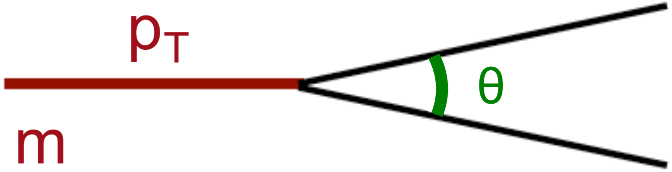
Vacuum parton shower

Medium response
needed to explain large
angle measurements

Hard splitting as probe of medium

Idea: let a high p_T parton that splits into two other partons (antenna) propagate through the medium

Then study the influence of the medium on the antenna



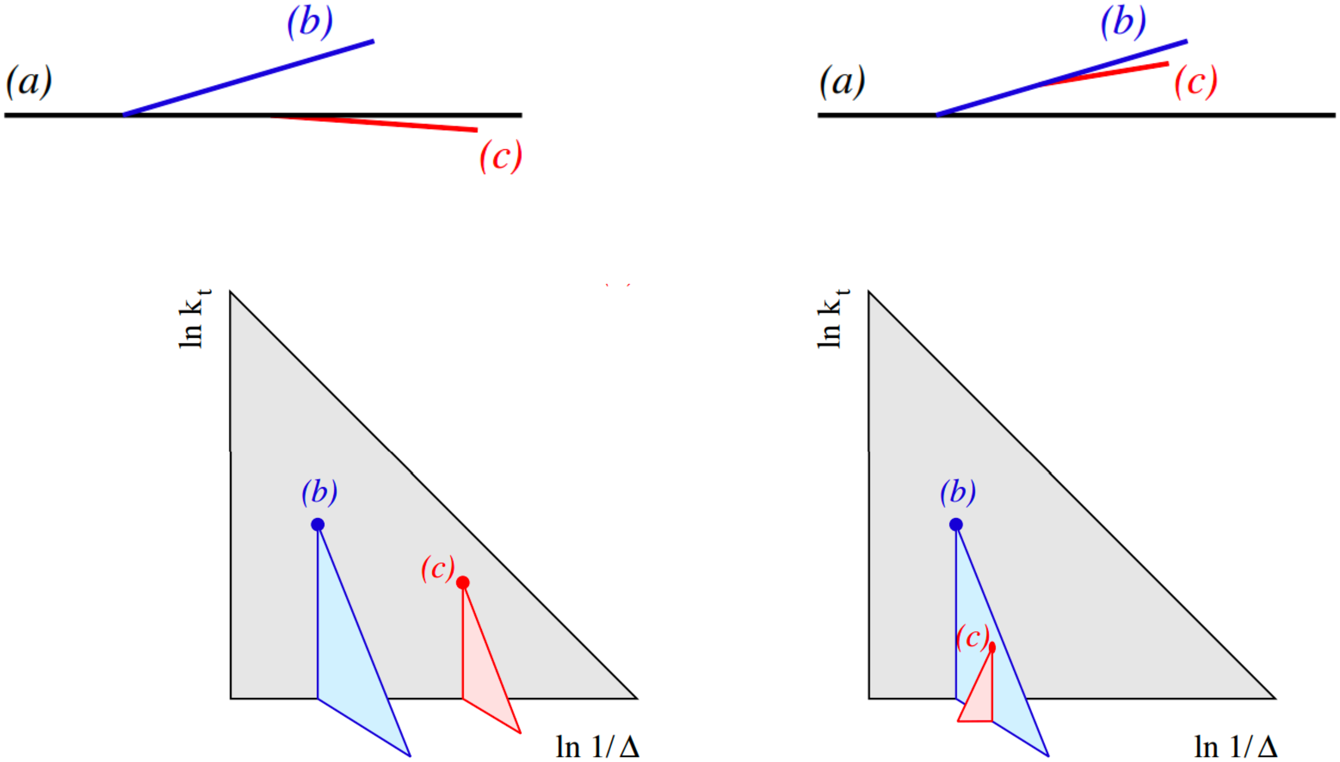
$p_{T,1} = (1\text{-}z_{\text{split}})p_T$

$p_{T,2} = z_{\text{split}}\, p_T$

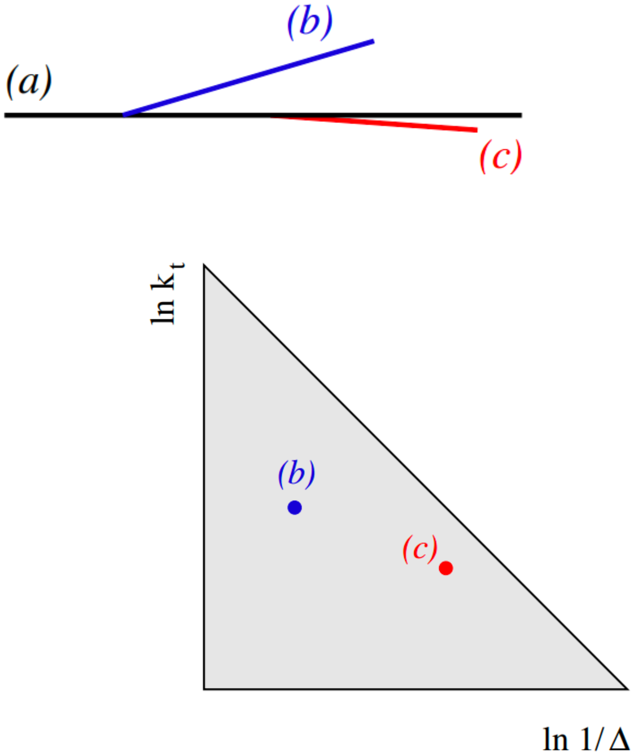
Splitting probability in vacuum:

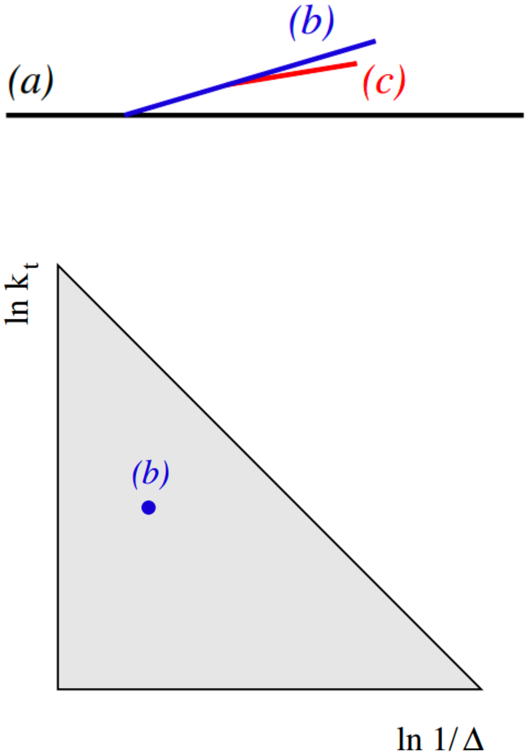
$$\mathrm{d}\mathcal{P}_{\mathrm{vac}} = 2\frac{\alpha_s C_R}{\pi}\,\mathrm{d}\log z\theta\,\mathrm{d}\log\frac{1}{\theta}$$

Jet Lund Plane



Primary Jet Lund Plane

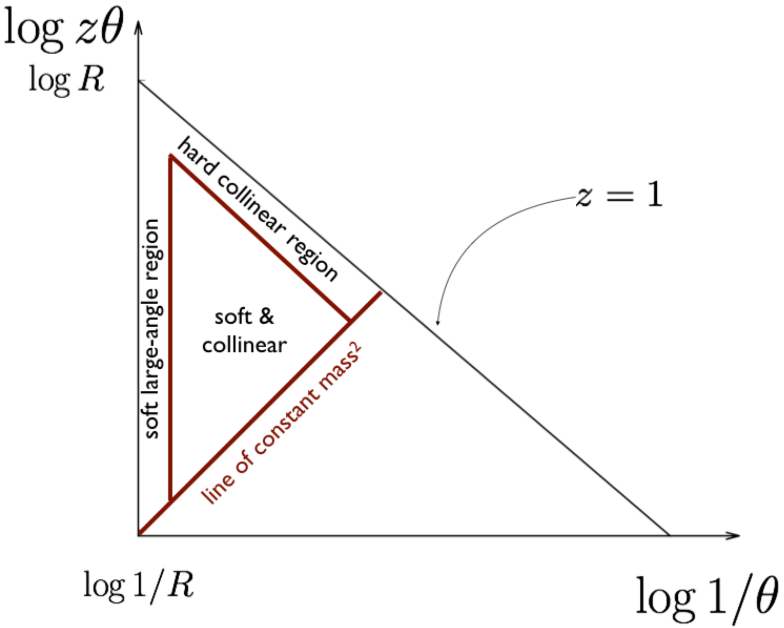




The Lund diagram

Just a plane to depict parton splittings

$$k_\perp/E \sim z\theta$$



$$\rho(\Delta, k_t) = \frac{1}{N_{\text{jets}}} \frac{d^2 n_{\text{emissions}}}{d\ln\frac{1}{\Delta}\, d\ln k_t}$$

$$\rho^{\text{LO},i}_{\text{soft-coll.}}(\Delta, k_t) = \frac{2\alpha_s C_i}{\pi}$$

Triangle uniformly filled for a vacuum parton shower at LO

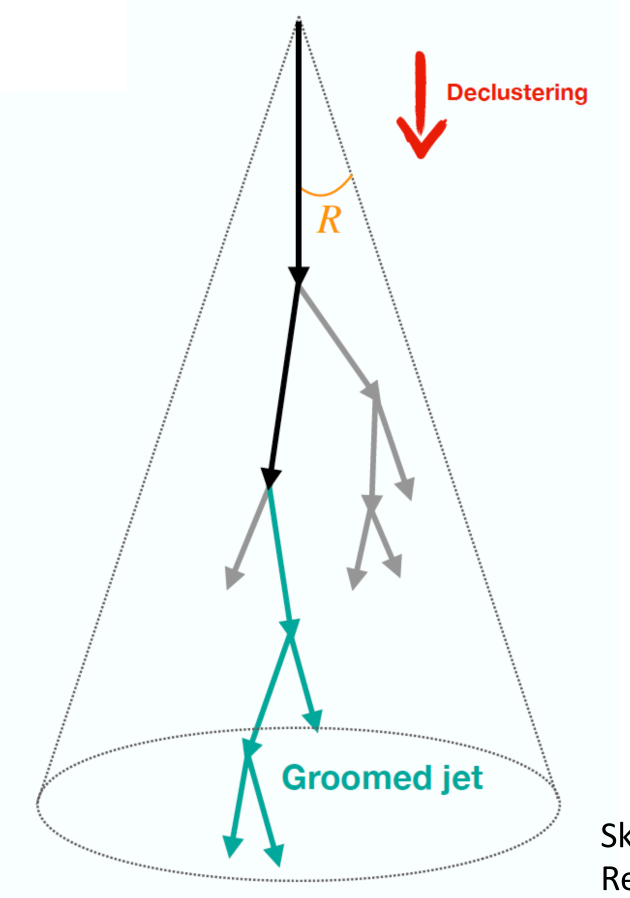
B. Andersson, G. Gustafson, L. Lönnblad and U. Pettersson, Z. Phys. C 43 (1989) 625

F. Dreyer, G. Salam, G. Soyez arXiv:1807.04758

Access to splittings in experiment

Order constituents in the jet

Walk back in history to identify splittings of interest



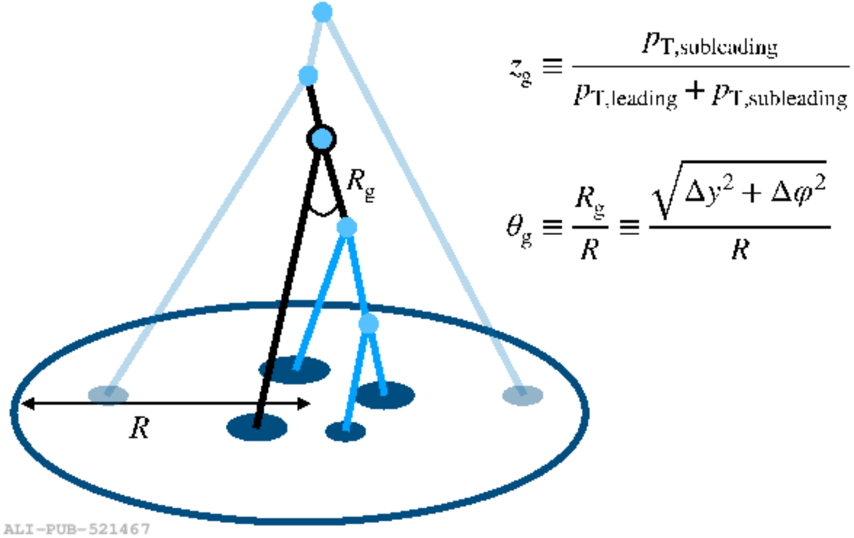
Sketch by Rey Torres

Access to splittings in experiment

Order constituents in the jet

Walk back in history to identify
splittings of interest

Define your observable
- can be one specific splitting;
- but also multiple in one jet;

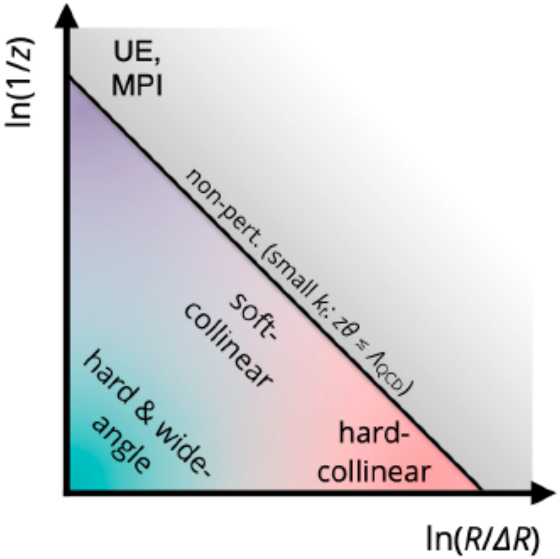


$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

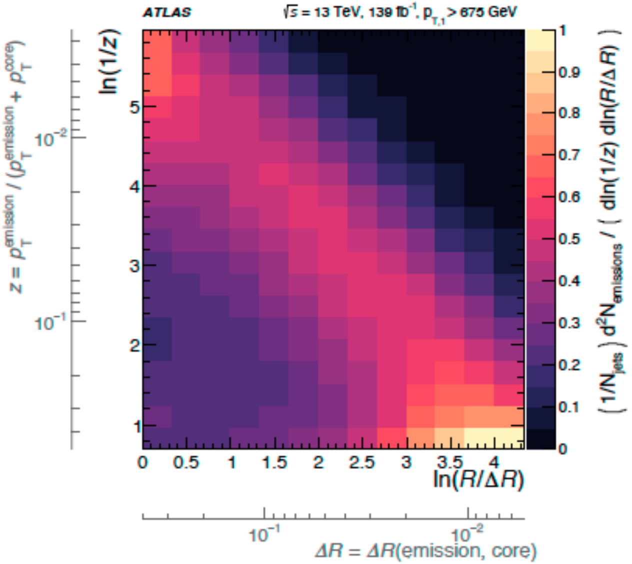
$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

ALI-PUB-521467

Vacuum Lund Plane



ATLAS, PRL 124 (2020) 22, 222002



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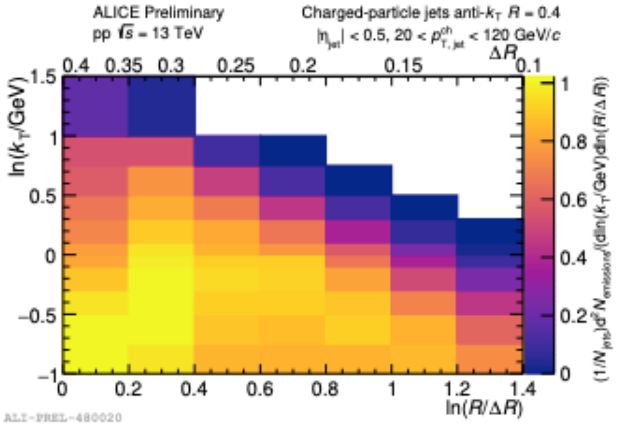
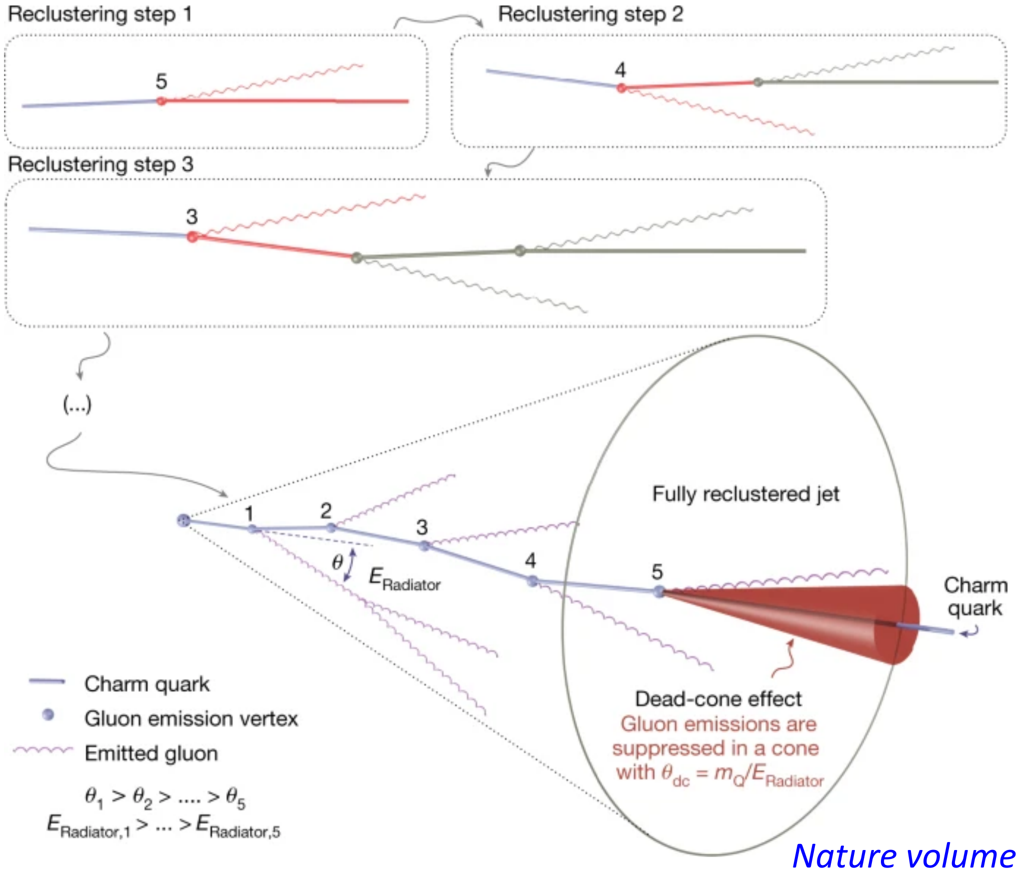


Running of α_s sculpts the plane

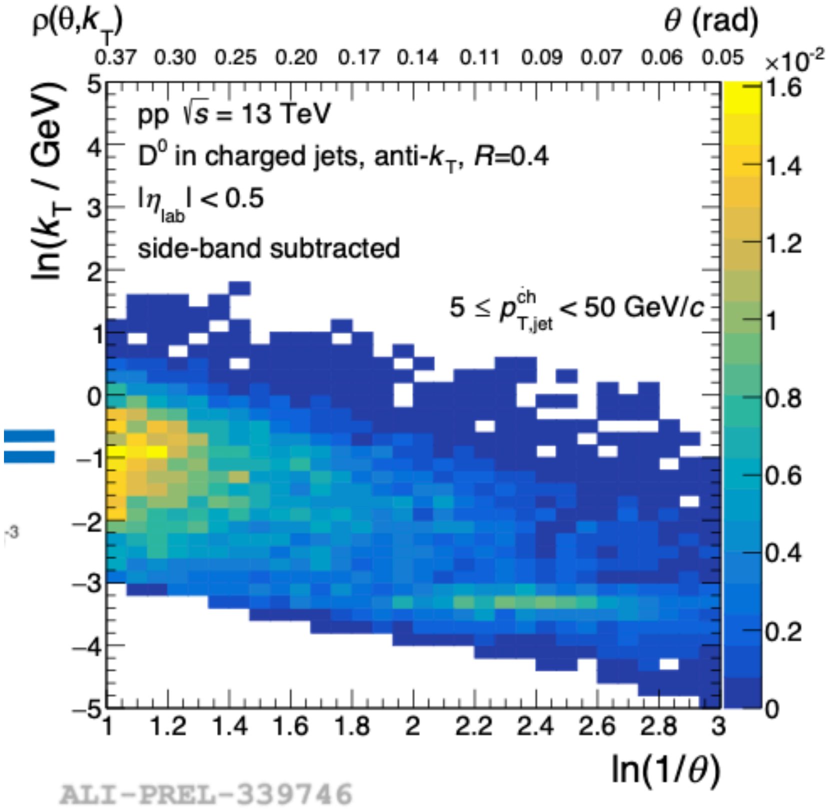
Dead Cone

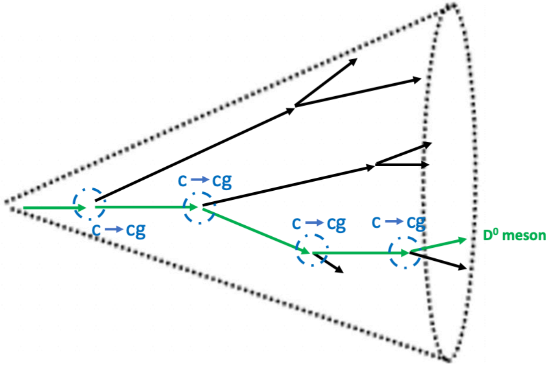


Nature volume 605, pages440–446 (2022)

Dead Cone

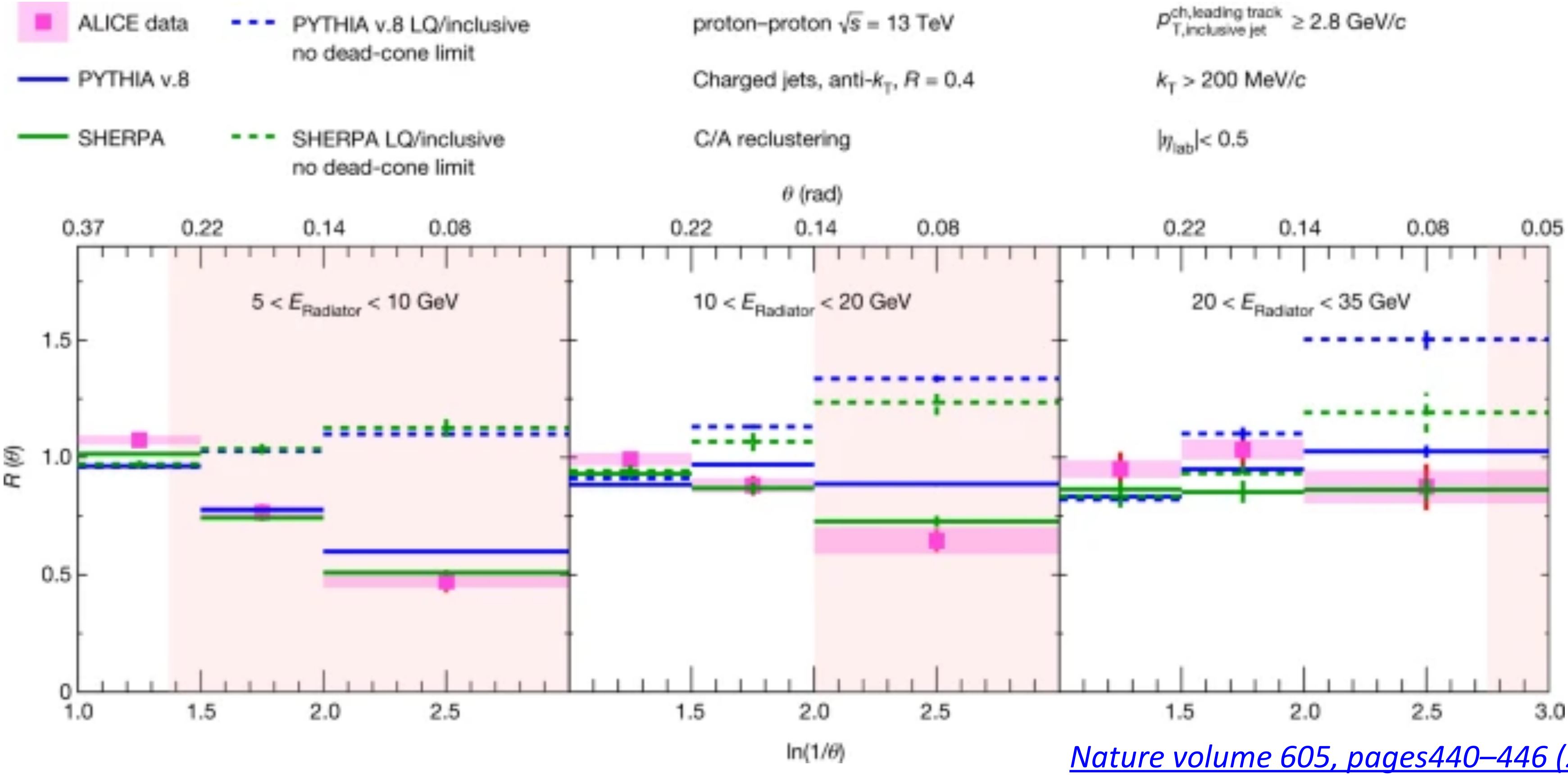
=





[Nature volume 605, pages440–446 (2022)](#)

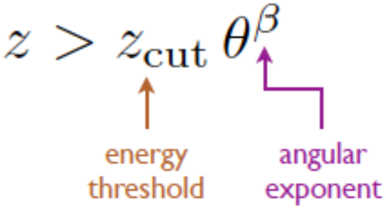
Dead Cone



[Nature volume 605, pages440–446 (2022)](https://www.nature.com/articles/s41586-022-04572-w)

Lund plane and grooming

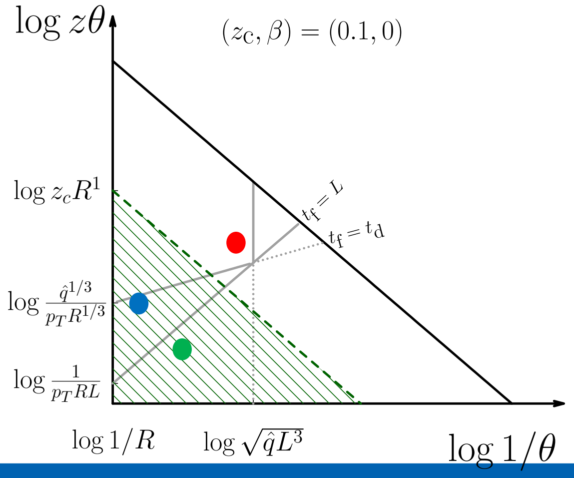
Grooming selects on momentum fraction and angle of branches in angular ordered tree

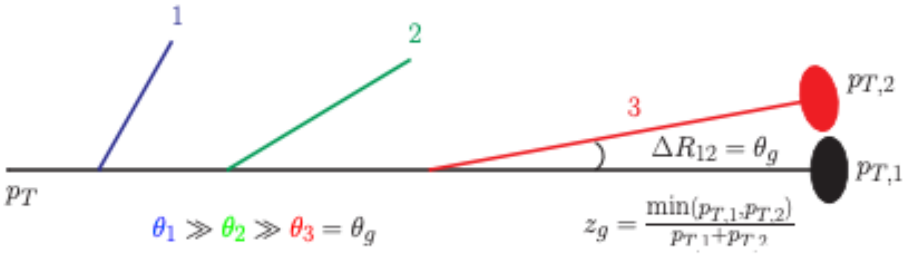

$$z > z_{\rm cut}\,\theta^{\beta}$$

energy threshold

angular exponent

$z_{\rm cut}$ = 0.1 and β = 0





Lund and grooming

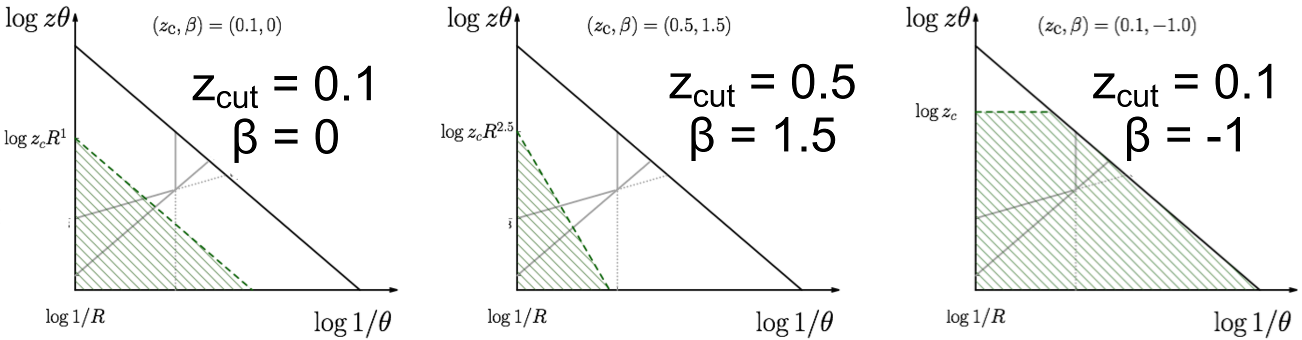
Grooming selects on momentum fraction and angle of branches in angular ordered tree

$$z > z_{\text{cut}}\,\theta^{\beta}$$

energy threshold

angular exponent

[Shaded region is excluded.]



$z_{\text{cut}} = 0.1$, $\beta = 0$

cuts only on the energy sharing fraction

$z_{\text{cut}} = 0.5$, $\beta = 1.5$

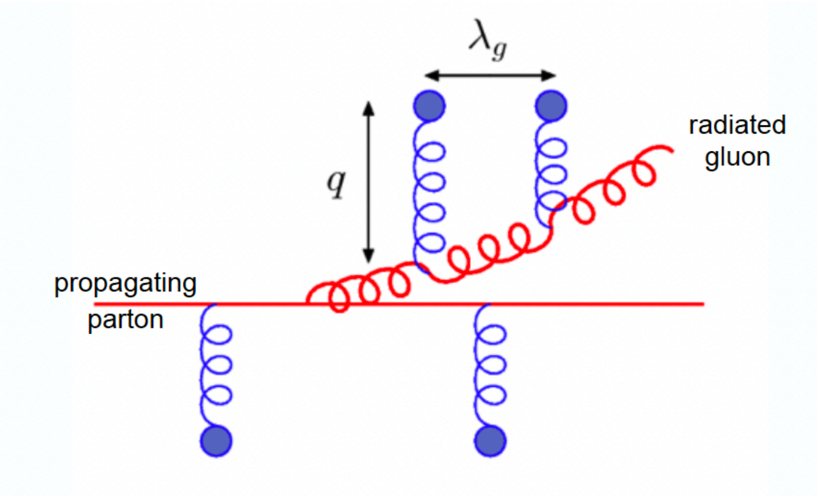
stronger grooming at large angle

$z_{\text{cut}} = 0.1$, $\beta = -1$

only hard radiation remains

Varying the grooming condition allows to select different regions of radiation phase space

Transport Coefficent



$$\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$$

Mean transverse kick per unit path length
Depends on density through mean free path λ:

$$\lambda \propto \frac{1}{\rho}$$

Energy loss depends on $\hat{q}$ and medium length (L)

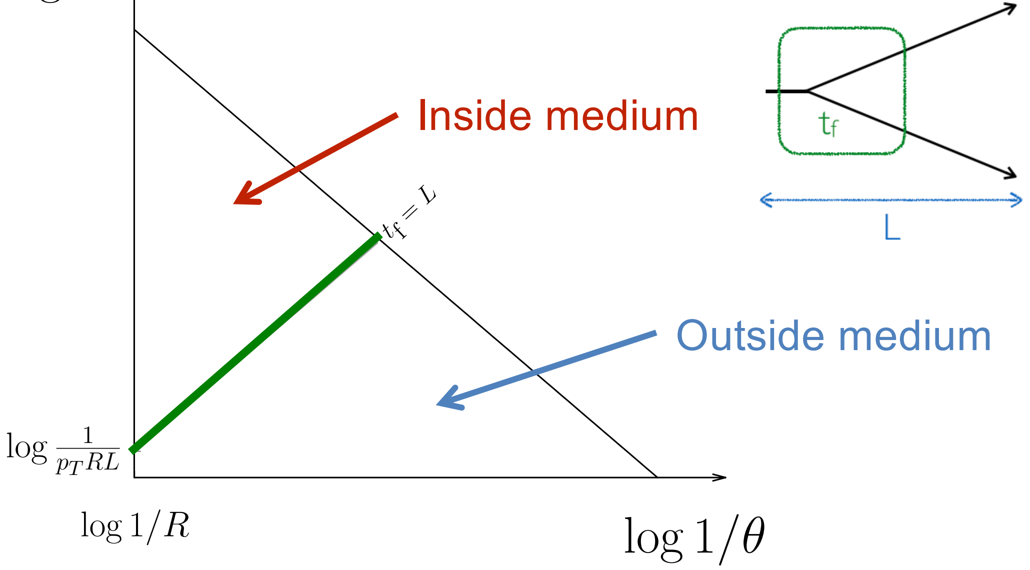
$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

In or outside the medium

A splitting can either occur inside or outside the medium

→ depends on the formation time of the splitting

$$t_\mathrm{f} \sim \frac{1}{z p_\mathrm{T} \theta^2} \quad \Rightarrow \quad \log z\theta = \log\frac{1}{\theta} + \log\frac{1}{p_\mathrm{T} L}$$

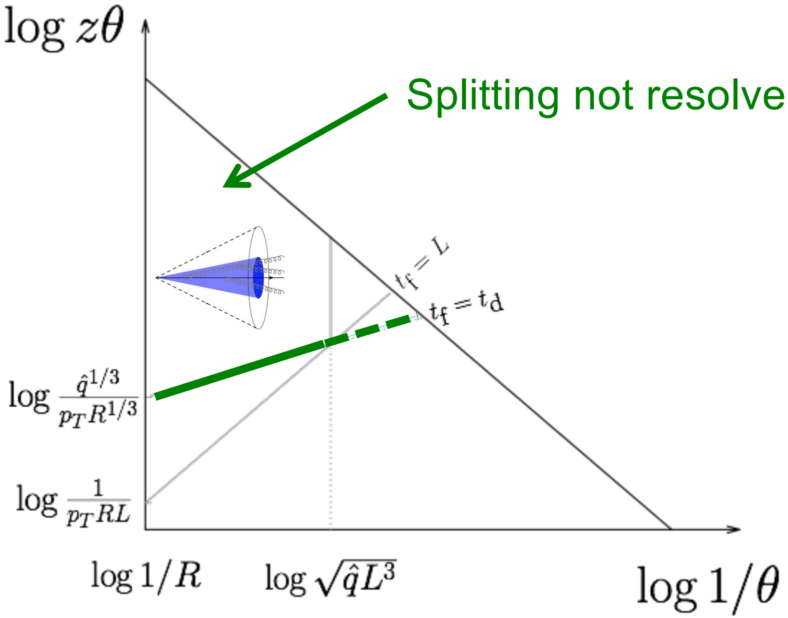


Inside medium

Outside medium

arXiv:1808.03689

Coherent or incoherent splitting



Splitting not resolved by medium

Formation time: $t_f \sim \frac{1}{z p_T \theta^2}$

Decoherence time: $t_d \sim \frac{1}{(\hat{q}\theta^2)^{1/3}}$

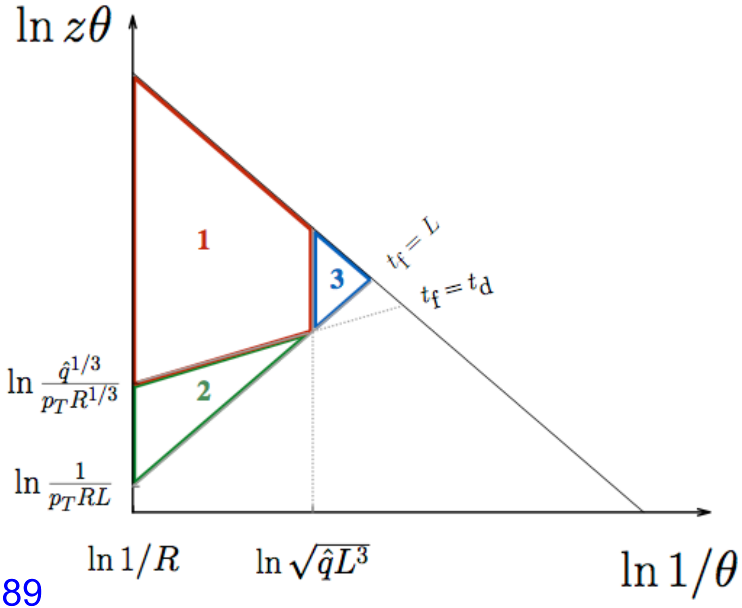
$$\log z\theta = \frac{1}{3}\log\frac{1}{\theta} + \log\frac{\hat{q}^{1/3}}{p_T},$$

arXiv:1808.03689

Phase space in medium

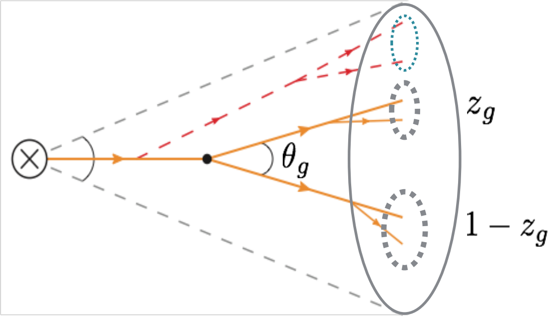
3 regions for a splitting happening in medium

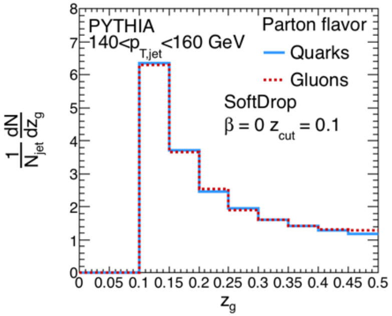
1) vacuum-like splitting inside medium that will be quenched
2) medium-induced splitting → not uniform in Lund plane
3) unresolved splitting

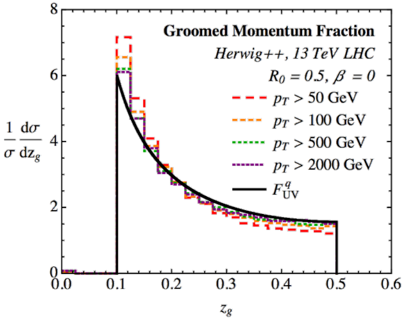


arXiv:1808.03689

Shared momentum fraction







JHEP 1405 (2014) 146

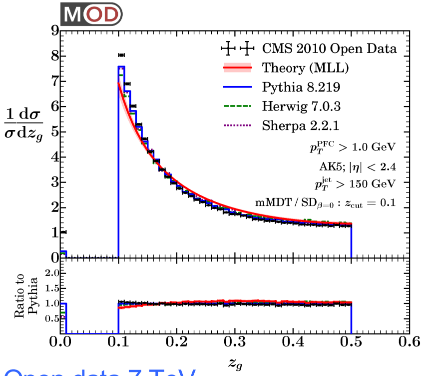
No flavor dependence
Weak jet p_T dependence
In vacuum: Altarelli-Parisi splitting function

Observable:
Momentum balance between the two subjets as defined by grooming procedure

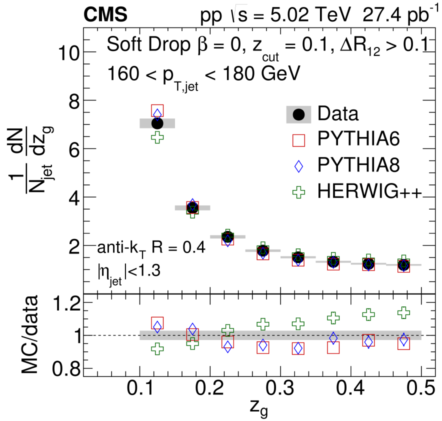
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$

Momentum fraction carried by the subleading branch

Jet splitting function

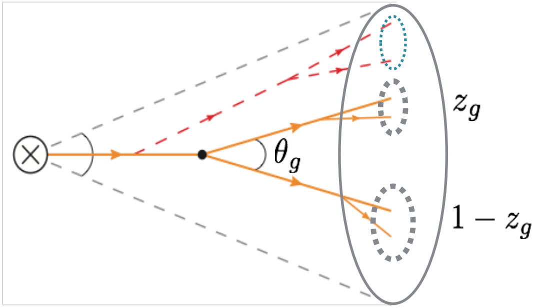


CMS Open data 7 TeV
Larkoski, Marzani, Thaler, Tripathee, Xue
PRL 119 (2017), 132003
Phys.Rev. D96 (2017), 074003



CMS 5 TeV, PRL 120 (2018), 142302

Robust observable: Momentum fraction carried by the subleading branch of first hard splitting



$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}},$$

With groomed jets: soft large angle radiation removed to define the hardest splitting

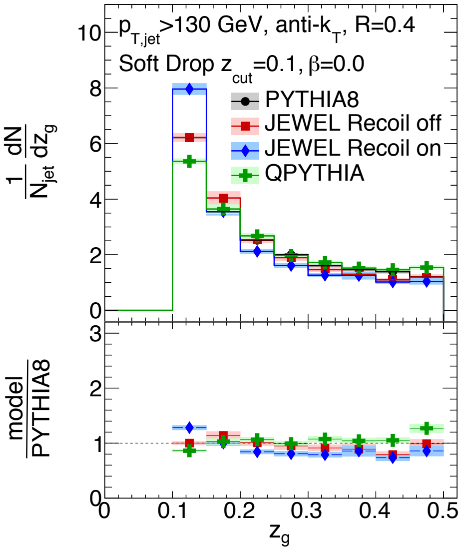
$$\frac{1}{N_{\rm jets}}\frac{dN_i}{dz_g} \propto \overbrace{\bar{P}_i(z_g)}^{\text{measure splitting function !}} \sim \frac{1}{z_g}$$

- Weak dependence on α_s
- Weak dependence on jet p_T
- In vacuum: Altarelli-Parisi Splitting Function

Grooming settings and z_g

Comparison of jet quenching MCs (JEWEL,QPYTHIA) with vacuum model (PYTHIA)

$z_{cut} = 0.1$ and $\beta = 0$



In presence of hot QCD medium:

- Grooming condition triggered by **vacuum-like** or **medium–induced** emission
- Both branches of hardest split lose energy independently if $\theta_g > \theta_C = 2/\sqrt{\hat{q}L^3}$

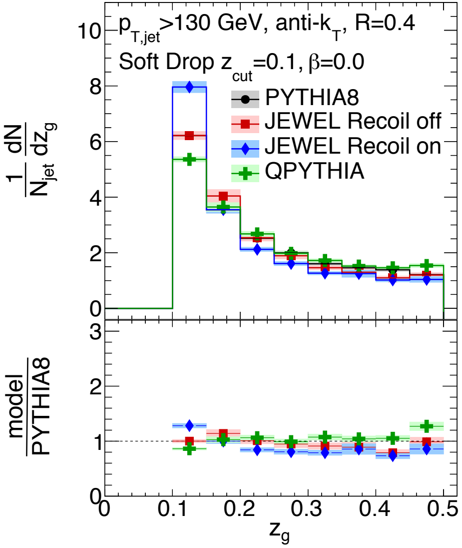
Transport coefficient
of medium

Length of
medium

Grooming settings and z_g

Comparison of jet quenching MCs (JEWEL,QPYTHIA) with vacuum model (PYTHIA)

z_{cut} = 0.1 and β = 0



In presence of hot QCD medium:

- Grooming condition triggered by **vacuum-like** or **medium–induced** emission
- ~~Both branches of hardest split lose energy independently if $\theta_g > \theta_C = \frac{2}{\sqrt{\hat{q}L^3}}$~~

not implemented in these models

Grooming settings and z_g

Comparison of jet quenching MCs (JEWEL,QPYTHIA) with vacuum model (PYTHIA)

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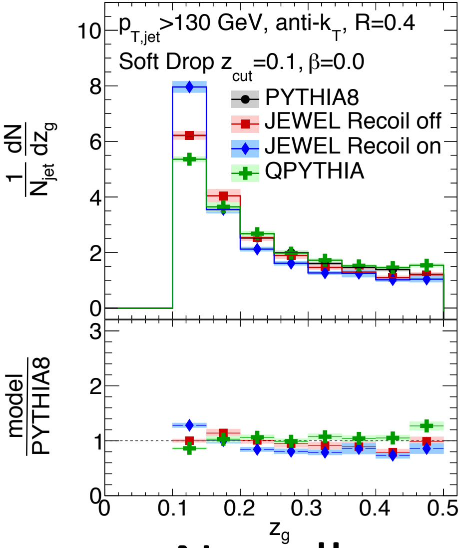
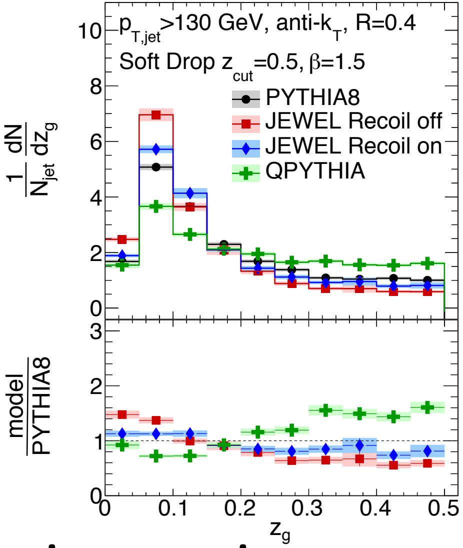
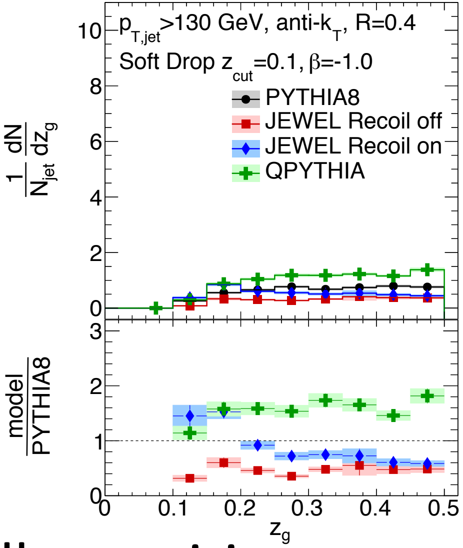


z_{cut} = 0.5 and β = 1.5



z_{cut} = 0.1 and β = -1



Not all grooming settings equally sensitive to different physics assumptions

Splitting fraction

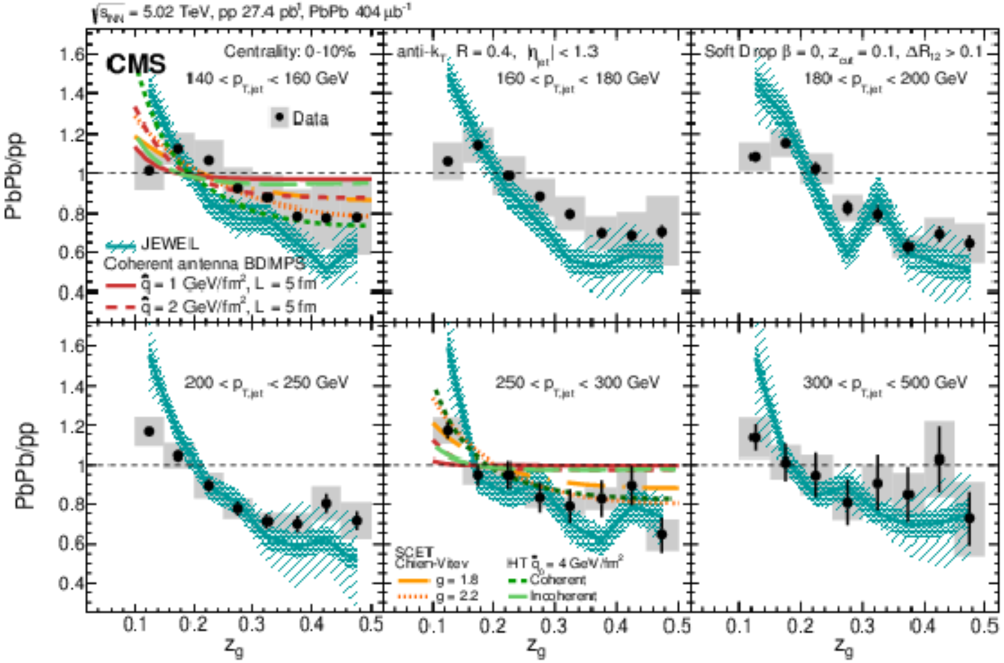
For first measurements, pp reference was smeared.

Distributions were self-normalized

Data suggested:

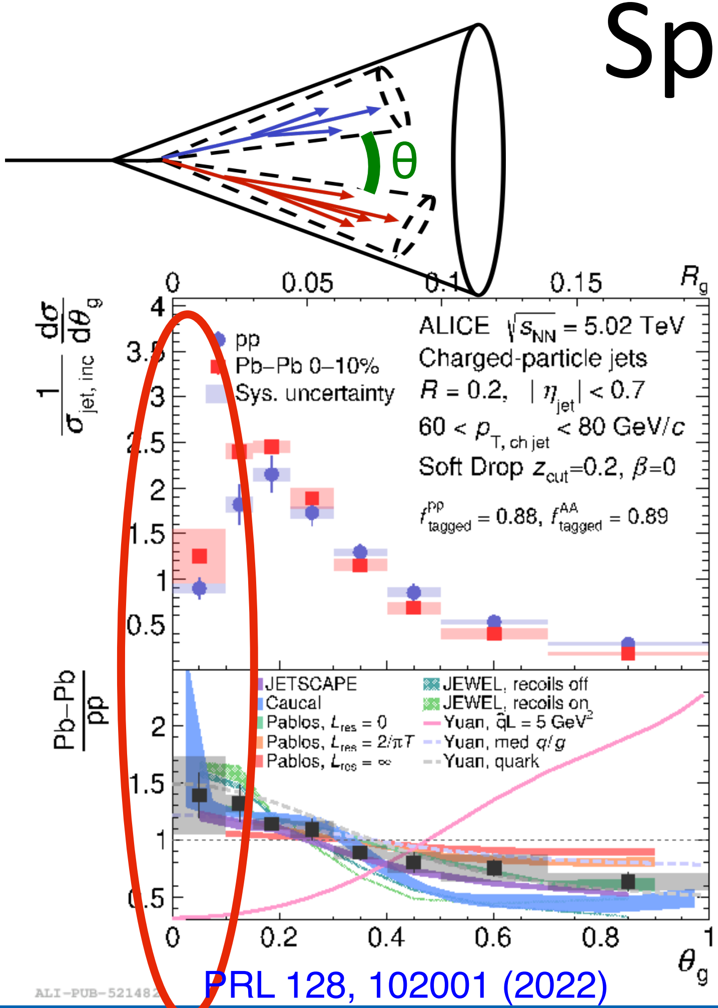
Splittings in quenched jets are a bit less balanced

Models capture the trend but different physics mechanisms responsible



Phys. Rev. Lett. 120 (2018) 142302

Splitting angle

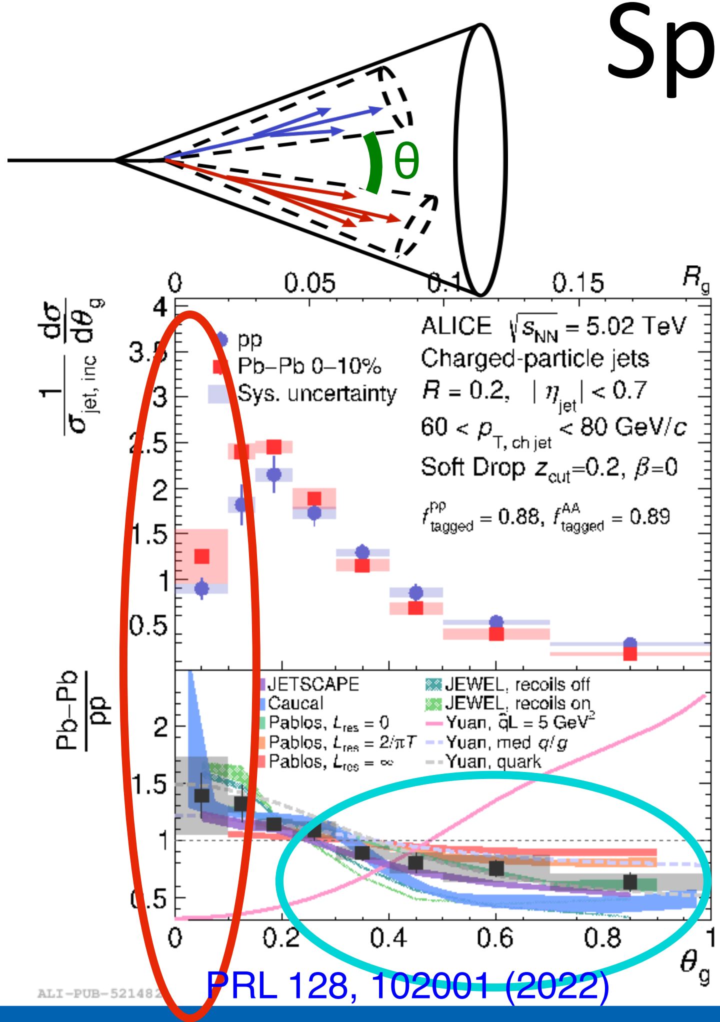


PRL 128, 102001 (2022)

Small θ_g: less vacuum-like emitters from which energy can be radiated

→less suppression observed in data

Splitting angle

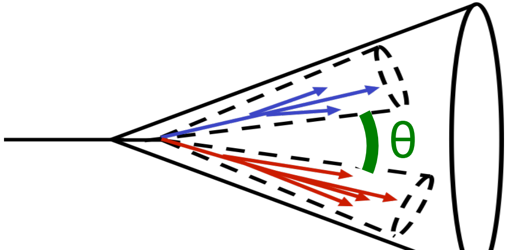


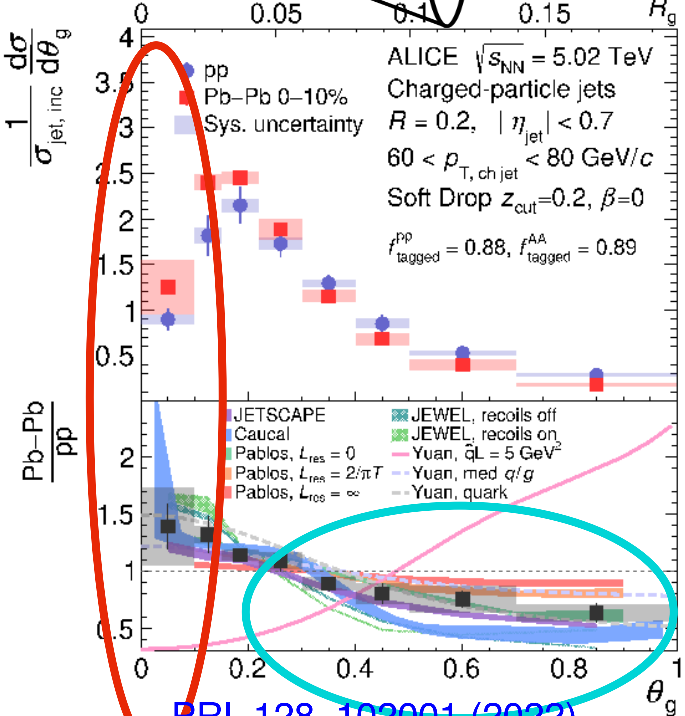
PRL 128, 102001 (2022)

Small θ_g: less vacuum-like emitters from which energy can be radiated
→less suppression observed in data

Large θ_g : more suppressed

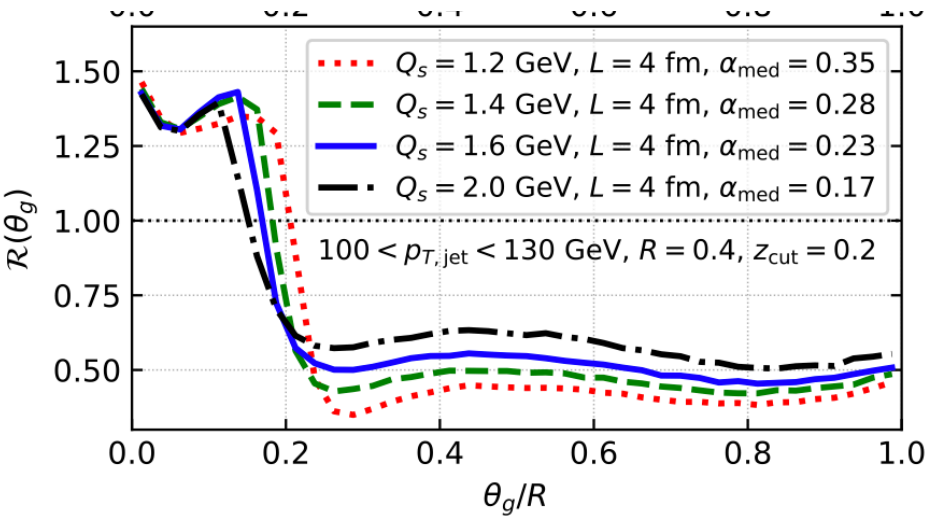
Splitting angle





PRL 128, 102001 (2022)

Caucal, Iancu, Soyez, 1907.04866 & 2012.01457



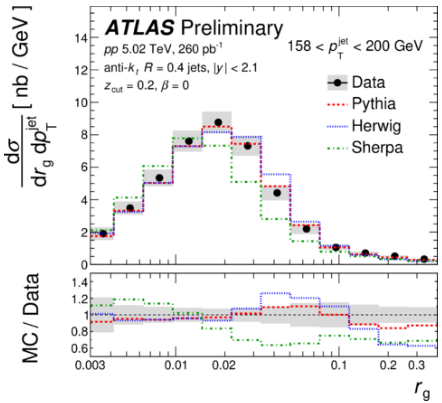
Jets with $\theta_g \geq \theta_c$ are suppressed while jets with $\theta_g \leq \theta_c$ are relatively enhanced.

Is ALICE seeing color coherence effect?
Or is this due to the number of emitters?
Or a selection bias?

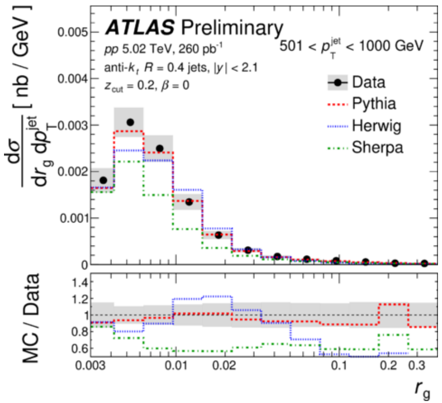
Suppression vs splitting angle

r_g decreases with p_T in vacuum

Low p_T

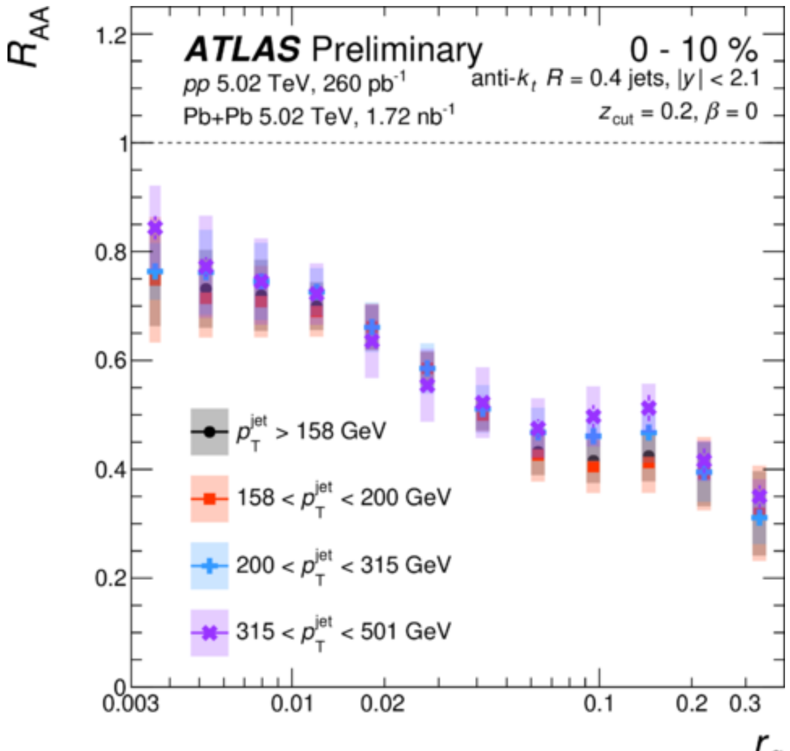


High p_T



Jet p_T selection + energy loss results in observed r_g dependence

How much room remains for decoherent energy loss within the cone picture?

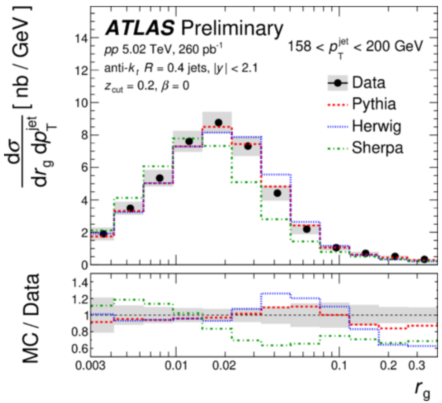


ATLAS-CONF-2022-026

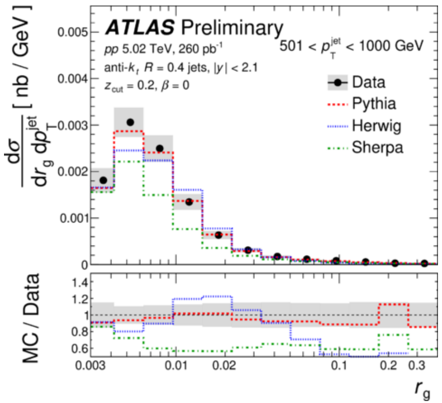
Suppression vs splitting angle

r_g decreases with p_T in vacuum

Low p_T



High p_T



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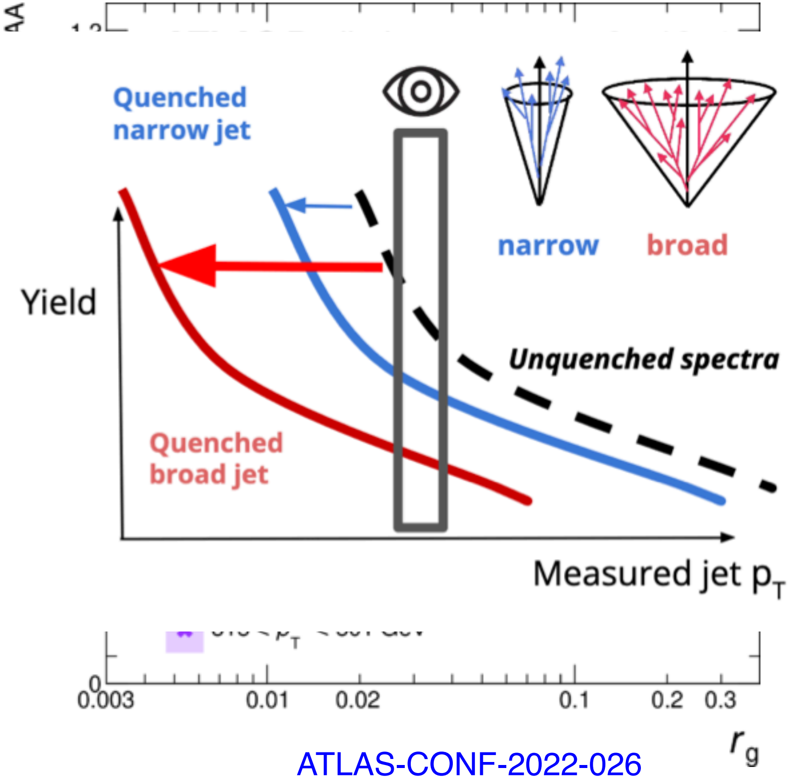

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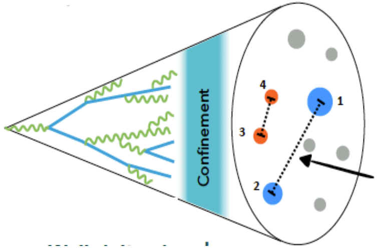
Energy-energy correlators



$$\frac{d\sigma}{dR_L^2} = \text{constant}$$

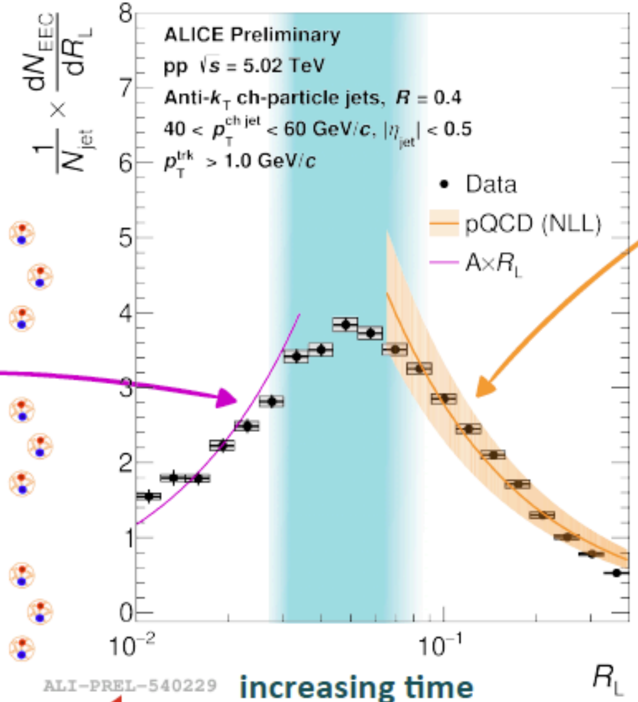
$$\rightarrow \frac{d\sigma}{dR_L} \propto R_L$$

Free hadron scaling (hadronic degree of freedom)

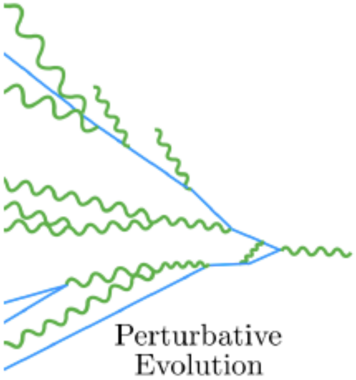
Energy weight

$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \boxed{\frac{p_{T,i}\, p_{T,j}}{p_{T,\mathrm{jet}}^2}} \delta(R'_L - R_{L,ij})$$

Confinement



pQCD scaling (partonic degree of freedom)

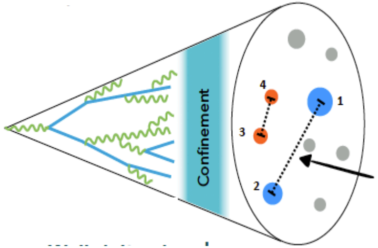


increasing time

Small angle ← **Large angle**

decreasing energy scale

Energy-energy correlators



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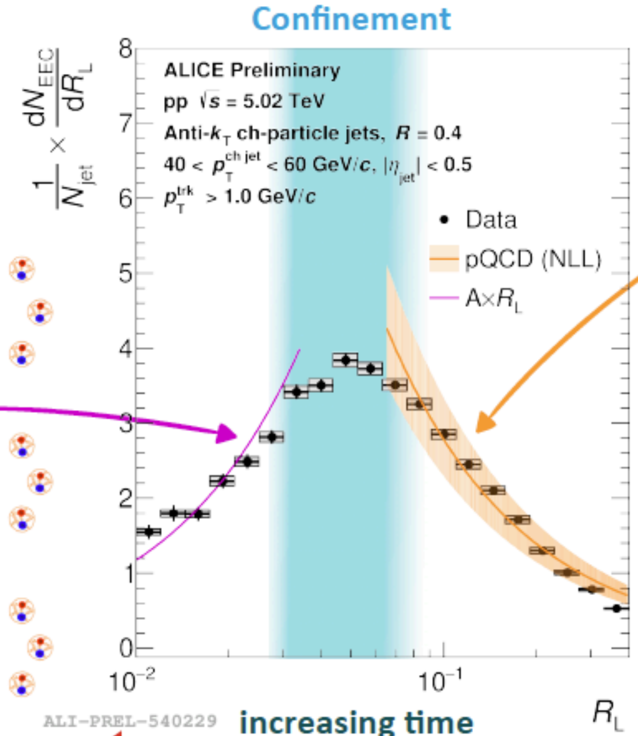
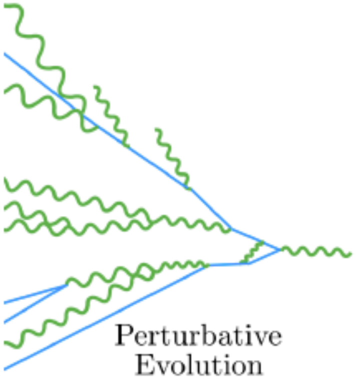
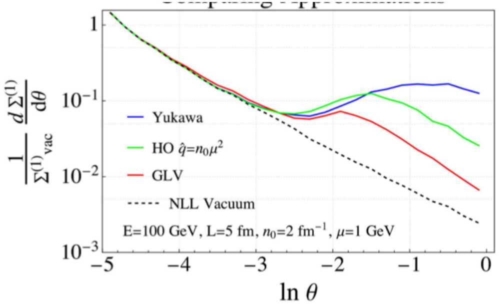


pQCD scaling (partonic degree of freedom)

Free hadron scaling (hadronic degree of freedom)



[arXiv:2303.03413](https://arxiv.org/abs/2303.03413)



increasing time

Small angle **Large angle**

decreasing energy scale

In experiment we see the end of the parton shower.
A convolution of many effects. Multi-scale problem

Decorrelation of radiated gluons

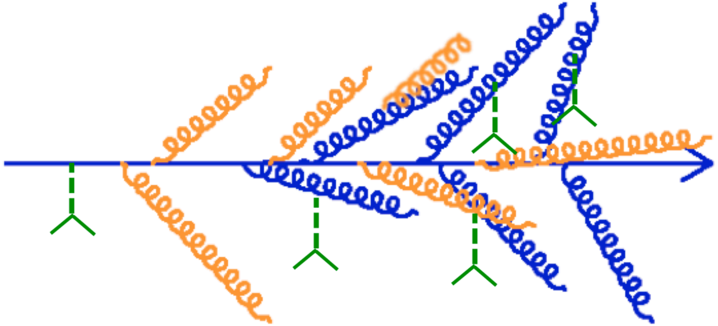
All partons in shower ‘see’ medium

Role of coherence

Medium response

…

…



Each jet observable has different sensitivity

Summary

Jets are never simple.

And even more complicated when traversing a quark-gluon plasma.

Making progress on understanding in-medium parton shower

→ This leads to more accurate extraction of QGP properties (transport coefficient $\hat{q}$, (de)coherence angle θ_c, …)

But there are open questions

- Role of medium response? Resolution scale of QGP? Quasi-particles?

Exciting times ahead with new data runs at RHIC and LHC

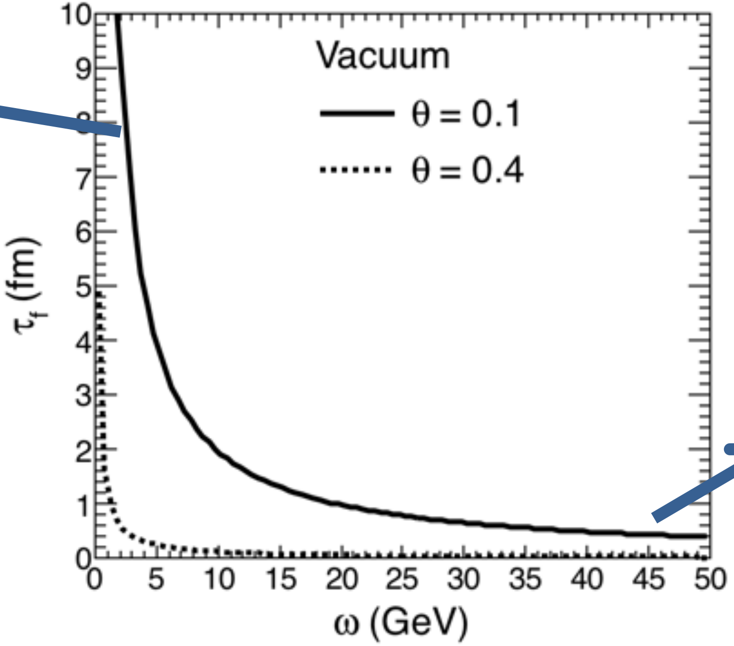
Thank you

z_g – formation times

Vacuum formation time of gluons with certain energy

Low energy gluons are emitted late

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$



High energy gluons are emitted early

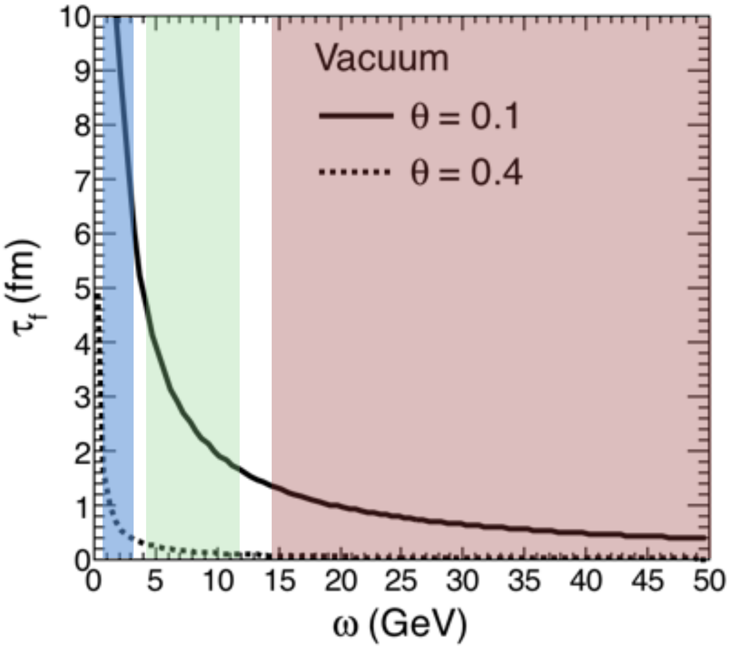
Large angle radiation first, small angle later

→ A lot of the vacuum radiation is created too late to see the medium

z_g – RHIC vs LHC

Vacuum formation time of gluons with certain energy

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$



Phase space covered for z_g=0.1

STAR

ALICE

CMS

Different experiments probing very different formation times. No overlap

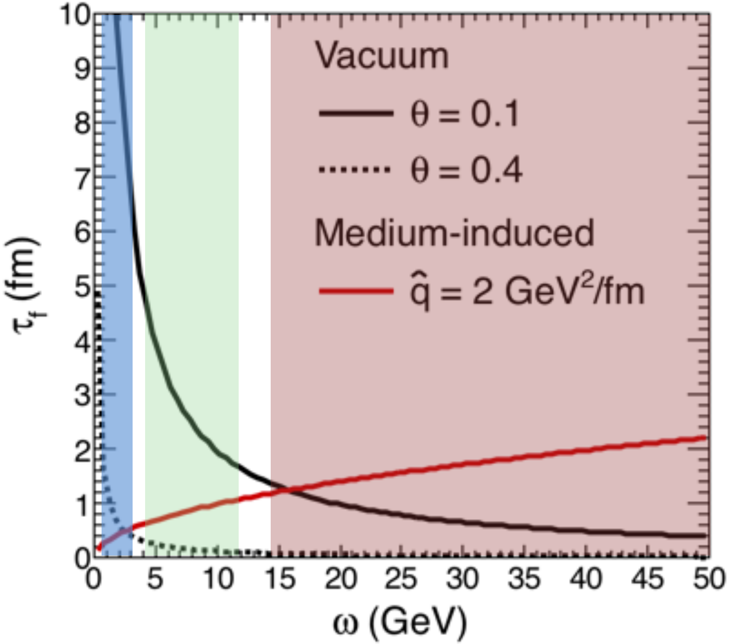
z_g – RHIC vs LHC

Vacuum and medium formation times

Hard medium-induced radiation happens late in the shower

$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

$$\tau_f^{med} \cong \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}$$

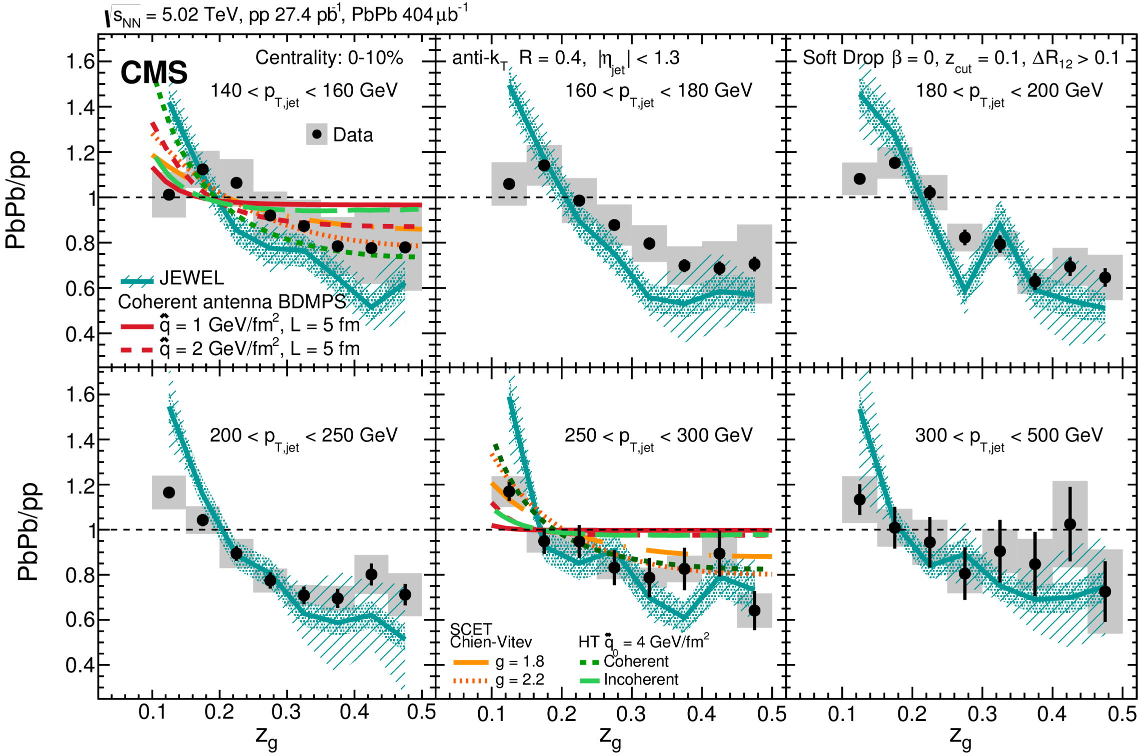


Phase space covered for z_g=0.1

- STAR
- ALICE
- CMS

Jet p_T dependence

Modification gets slightly weaker when increasing jet p_T



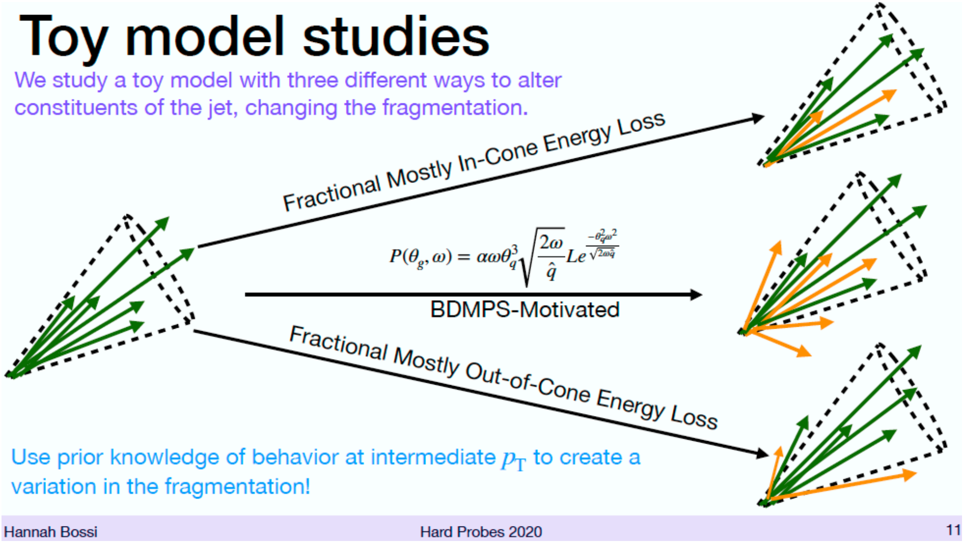
PRL 120 (2018) 142302

Due to normalization, cannot distinguish between increase at low z_g or suppression at high z_g

Machine Learning Biases

Machine learning used to improve p_T resolution

But how sensitive is the training to the fragmentation model?



Toy model studies

We study a toy model with three different ways to alter constituents of the jet, changing the fragmentation.

Fractional Mostly In-Cone Energy Loss

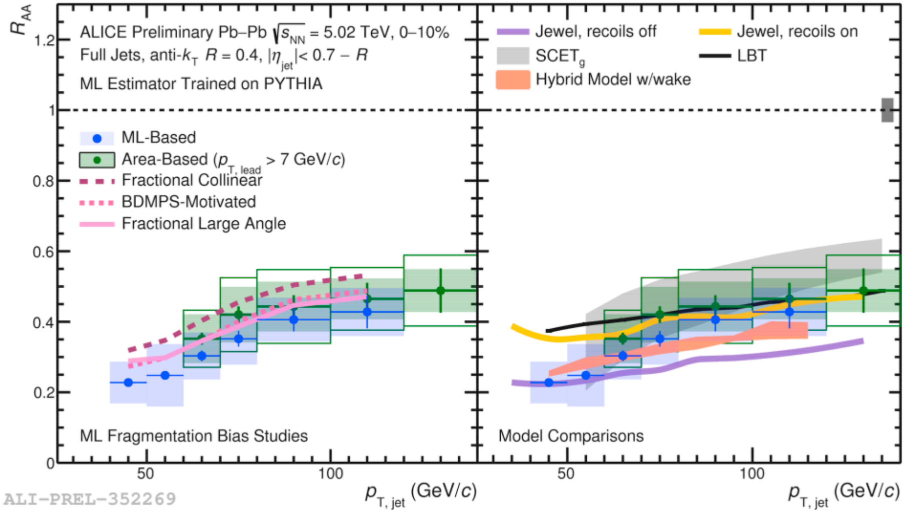
$$P(\theta_g, \omega) = \alpha\omega\theta_q^3\sqrt{\frac{2\omega}{\hat{q}}}Le^{\frac{-\theta_q^2\omega^2}{\sqrt{2\omega\hat{q}}}}$$

BDMPS-Motivated

Fractional Mostly Out-of-Cone Energy Loss

Use prior knowledge of behavior at intermediate p_T to create a variation in the fragmentation!

Hannah Bossi Hard Probes 2020 11



Effects of up to 40% are observed

Future: need method less dependent on model and/or constrain FF