Studying the jet core with jet substructure

Laura Havener, Yale University
ECT* Workshop, Jet quenching in the QGP
Thursday, June 16th, 2022

Wright Laboratory

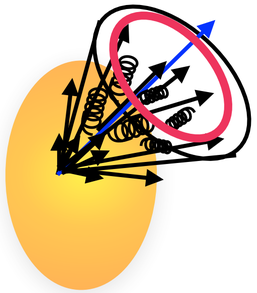
Yale

Jet internal structure

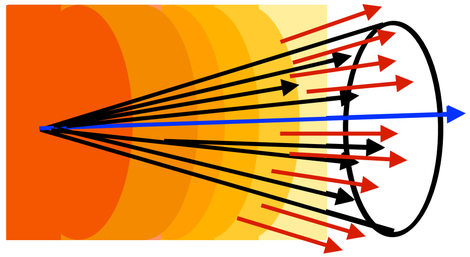
- Different variables probe a different aspect of jet structure modification

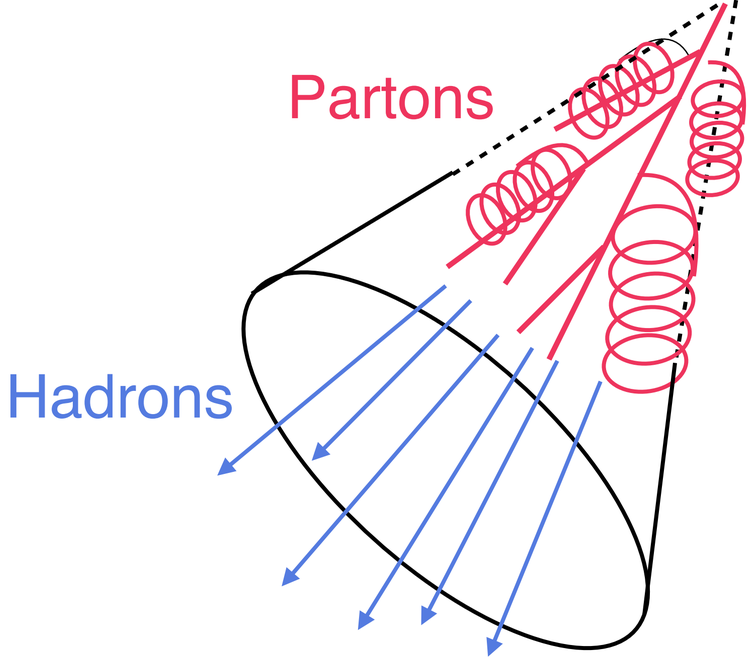
➡ Distribution of charged hadrons inside the jet

Momentum broadening



Medium response





See talks by Rey Cruz-Torres and Martin Rybar

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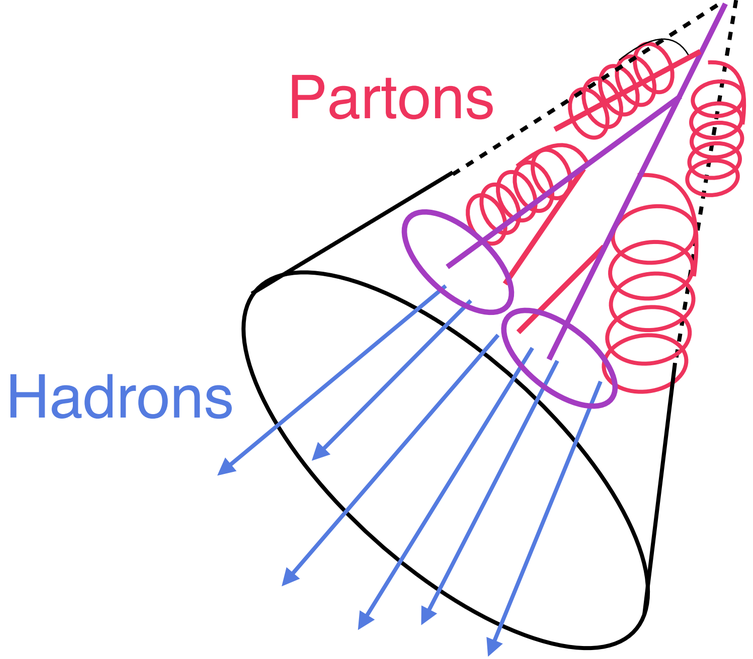

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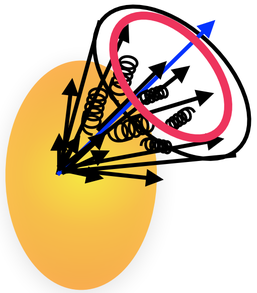

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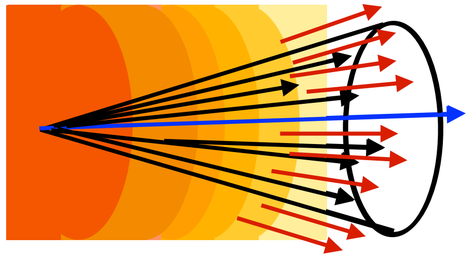

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➡ Subjets from hard parton splittings

Separate out hard signal from softening of constituents and medium response to focus on modification of hard core

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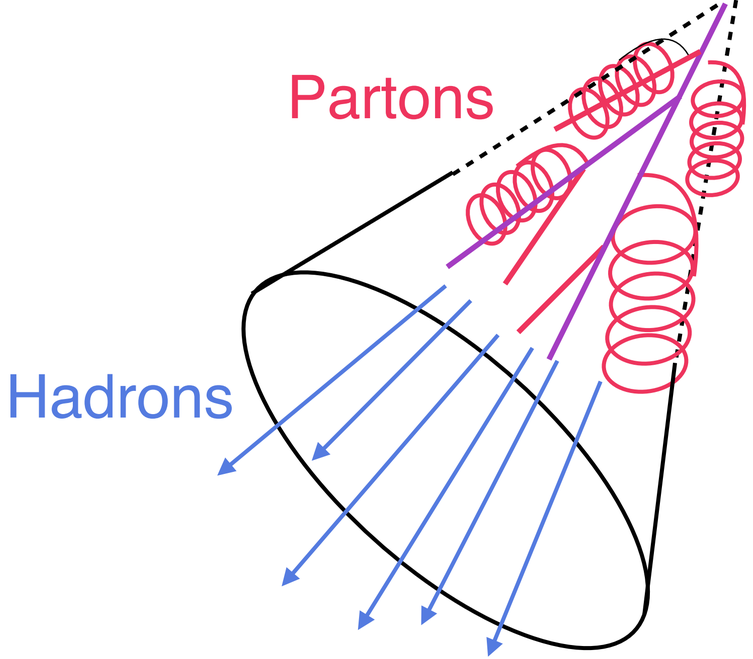

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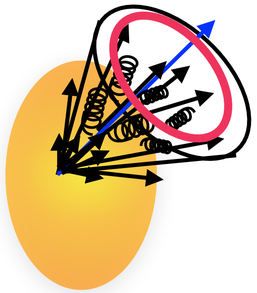

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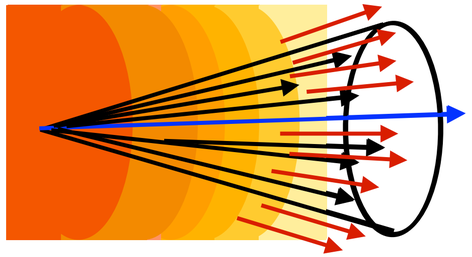

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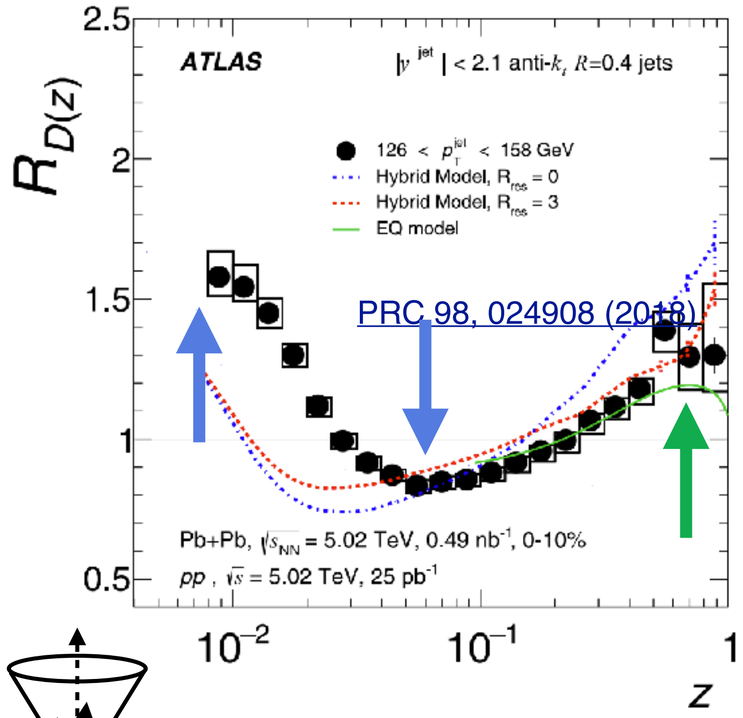
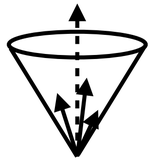
Jet shapes and fragmentation

- Jet fragmentation:

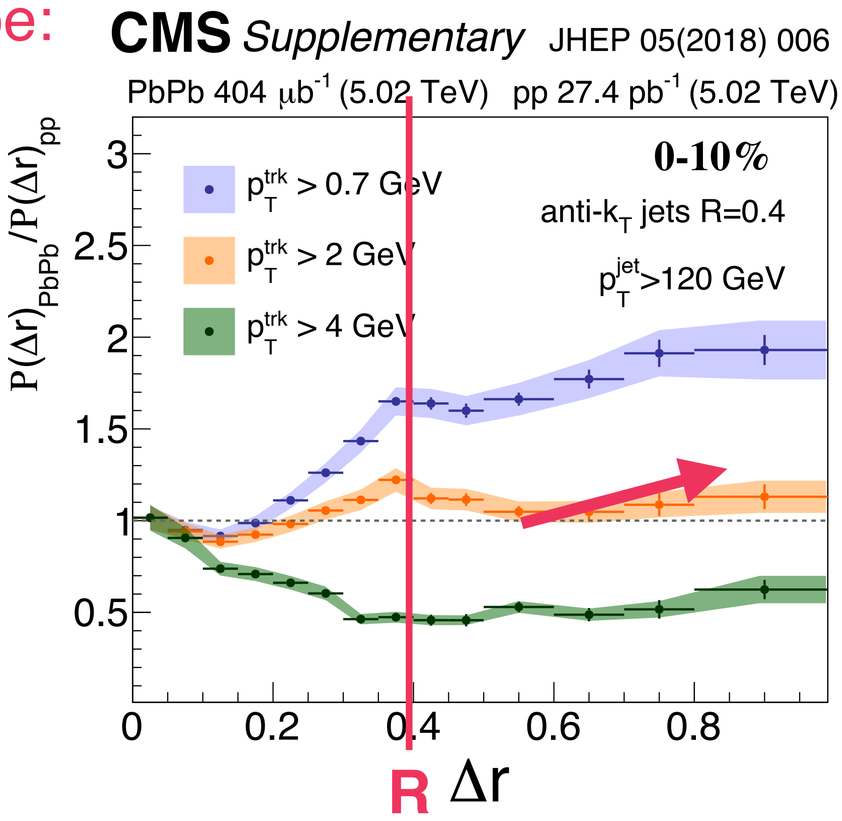


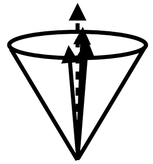
PRC 98, 024908 (2018)



Energy transferred to soft particles inside the jet

- Jet shape:

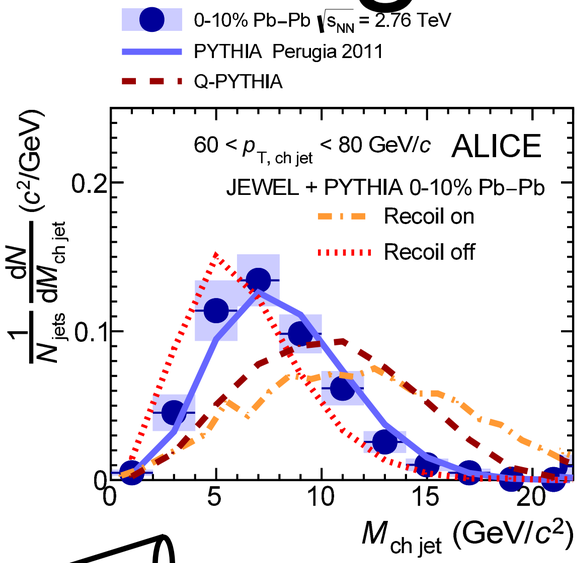




Hardening of core: high z enhancement from quark vs. gluons?

Soft particles are at large angles from jet axis

Jet angularities



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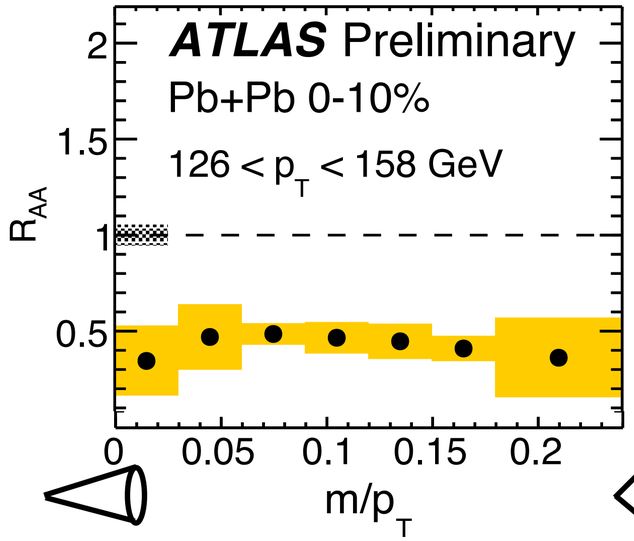
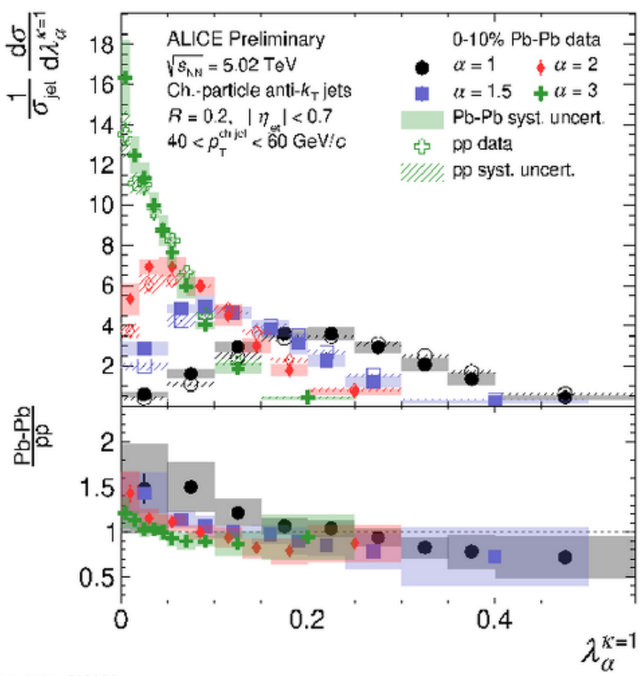
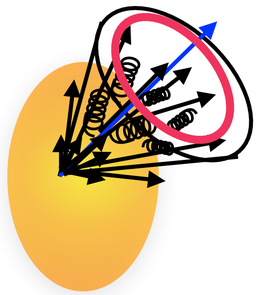
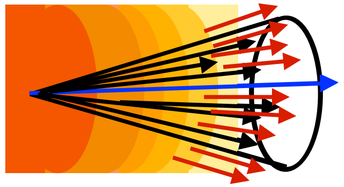




- Little to no significant modification of jet *mass (~α =2)* or *width (α =1)*



- Insensitive to medium effects or cancellation of effects?
  - Softening and broadening of constituents
    - Inside cone->larger mass
    - Outside cone->smaller mass
  - Medium recoil->larger mass
  - Larger jets more modified-> smaller mass



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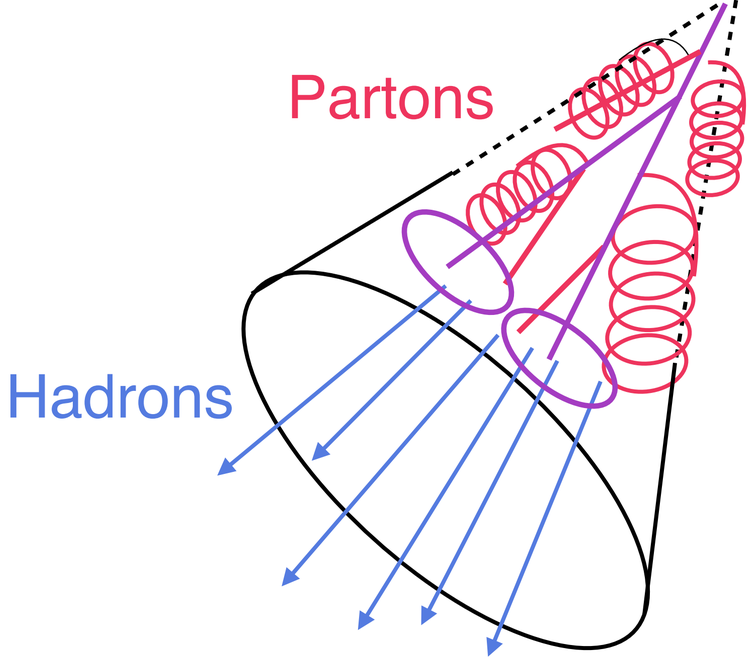

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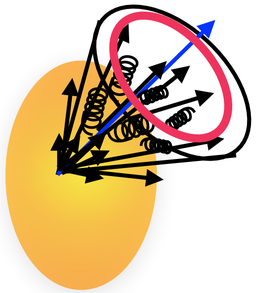

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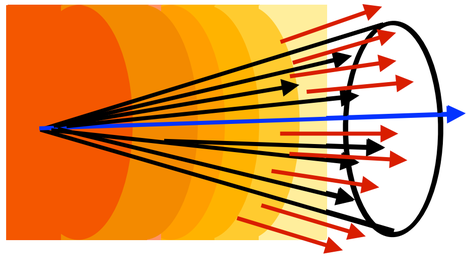
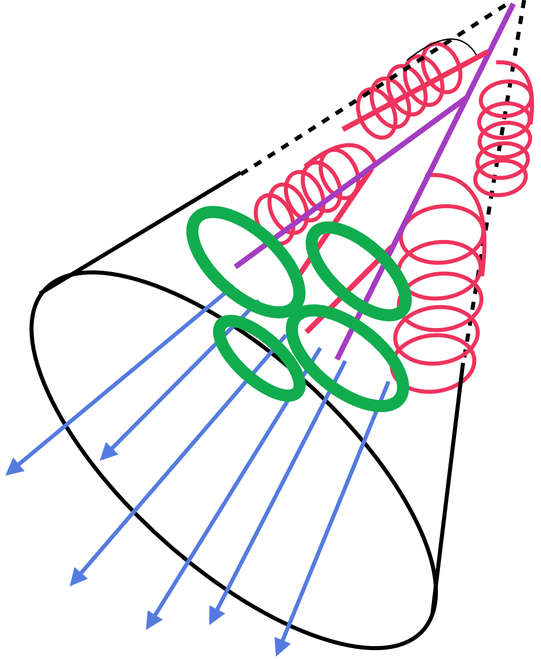


➡ **Subjets from hard parton splittings**

Separate out soft signal from softening of constituents and medium response to focus on modification of hard core

Subjets as a probe of the jet core



➡ Subjets from hard parton splittings

Separate out soft signal from softening of constituents and medium response to focus on modification of hard core

- Utilize methods from pp:

Removes non-perturbative effects

Perturbative regime under better theoretical control

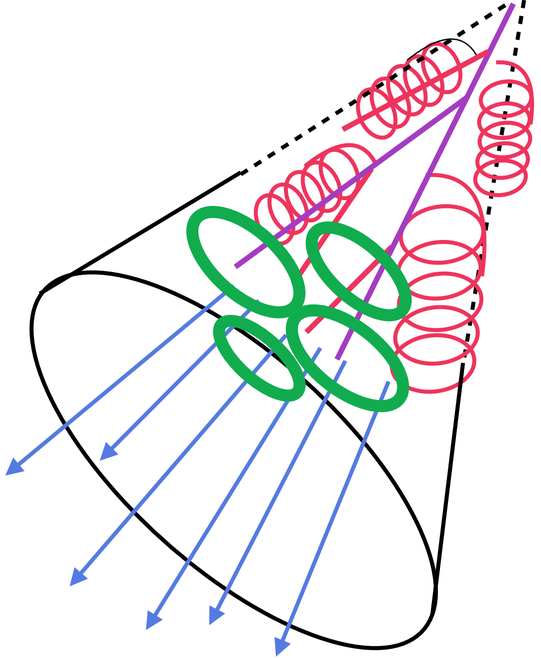
Advantage: less sensitive to HI background

Access hard jet splittings to focus on modification of hard core of jet

Grooming Trimming

Reclustered subjets within a jet: access parton level fragmentation

Subjets as a probe of the jet core



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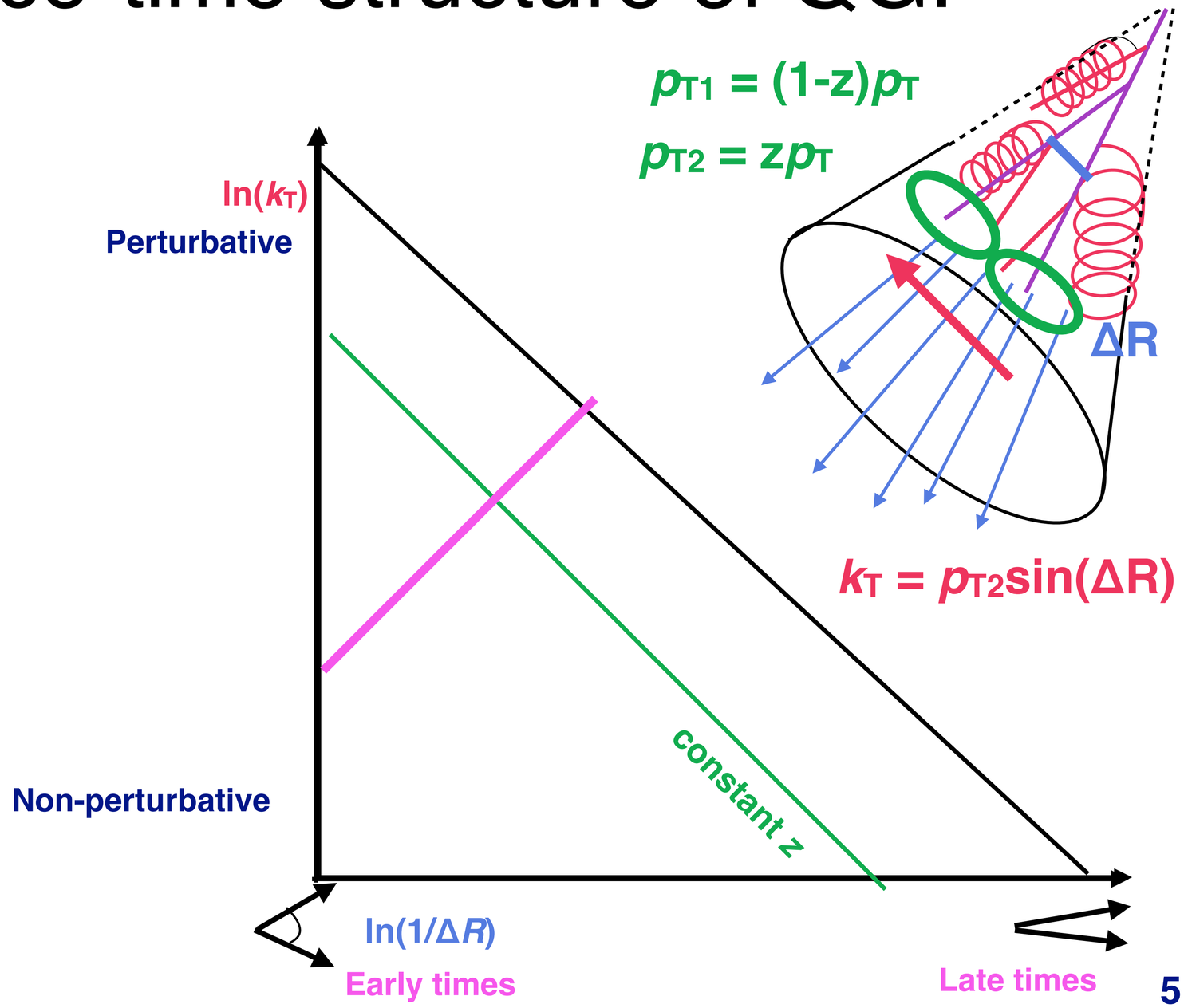
Lund Plane: space-time structure of QGP



- Formation time:

$$t_f = \frac{1}{(1-z)k_T \Delta R}$$

Y. L. Dokshitzer, et.al.

Lund Plane: space-time structure of QGP

1: Outside of medium

- Formation time: wider jets formed earlier experience more medium

See Liliana's talk today

Y. L. Dokshitzer, et.al.

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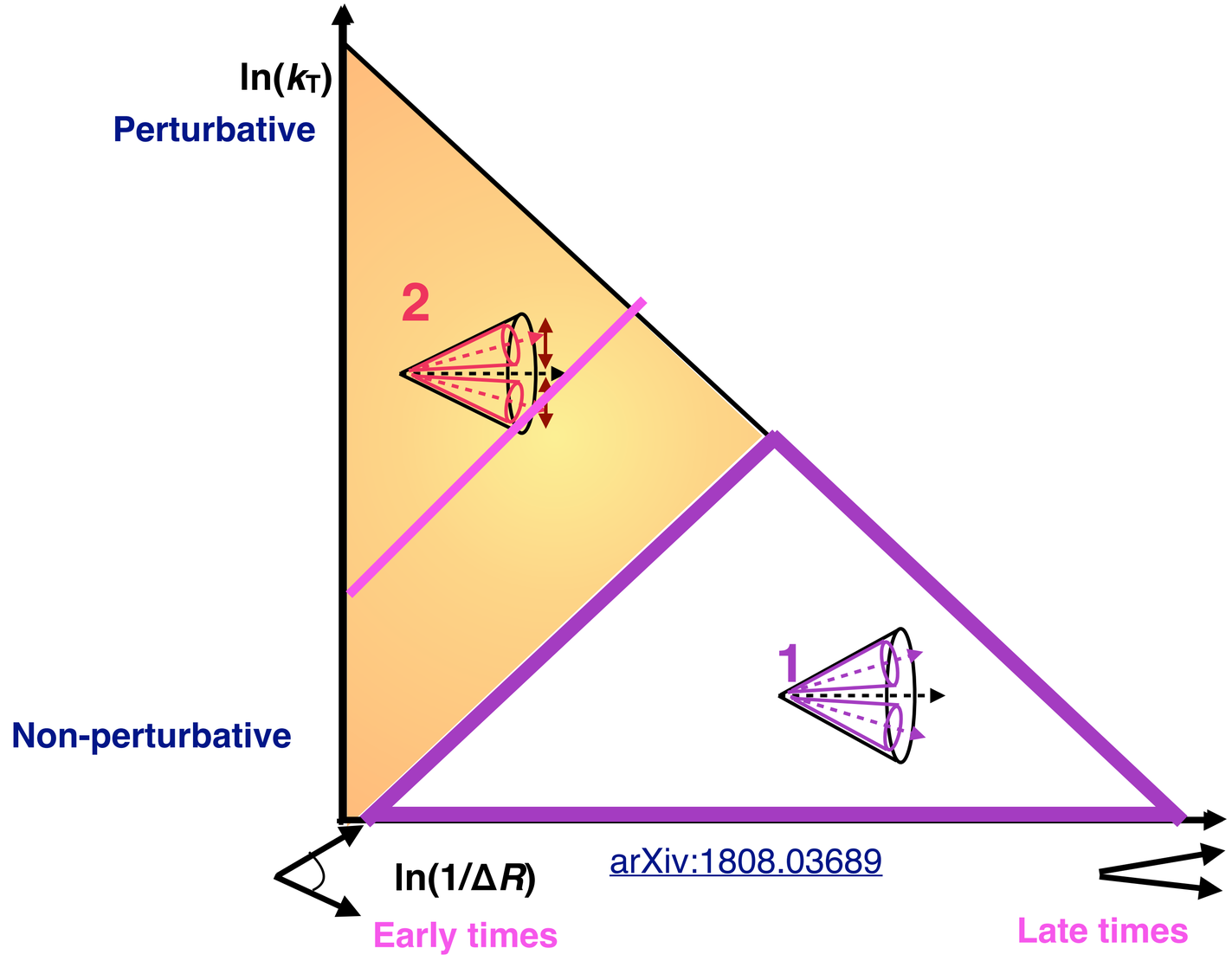


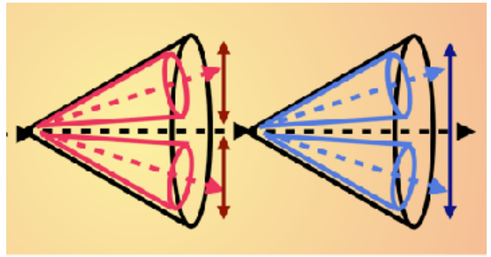
arXiv:1808.03689

Lund Plane: space-time structure of QGP

1: Outside of medium

2: Decoherence

3: Coherence



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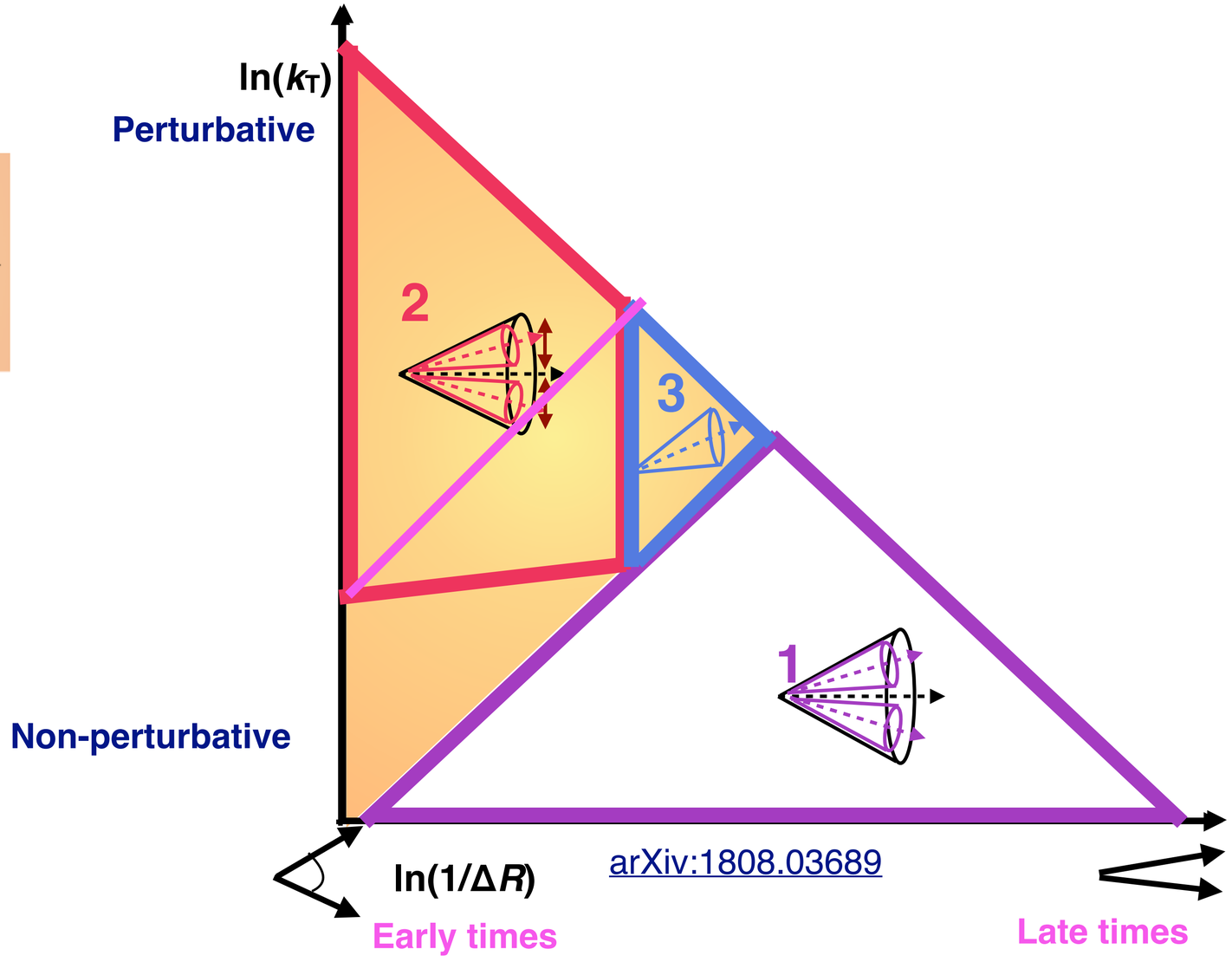

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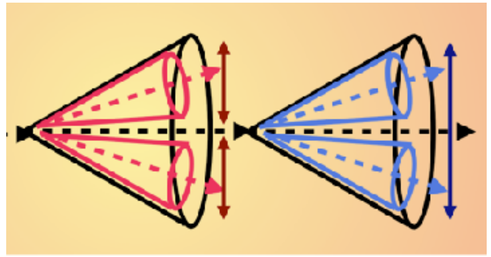

4: Medium-induced splittings

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Y. L. Dokshitzer, et.al.

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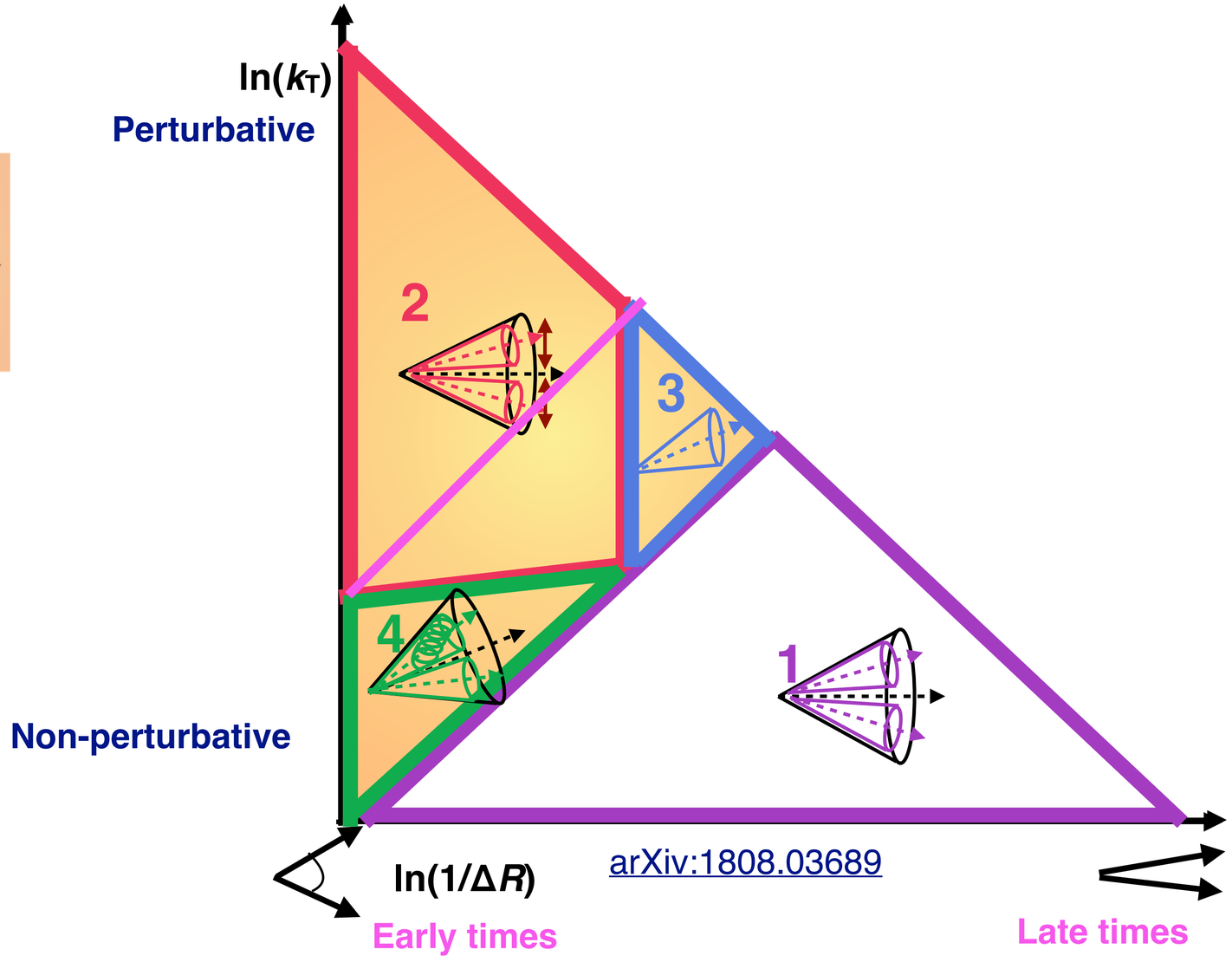

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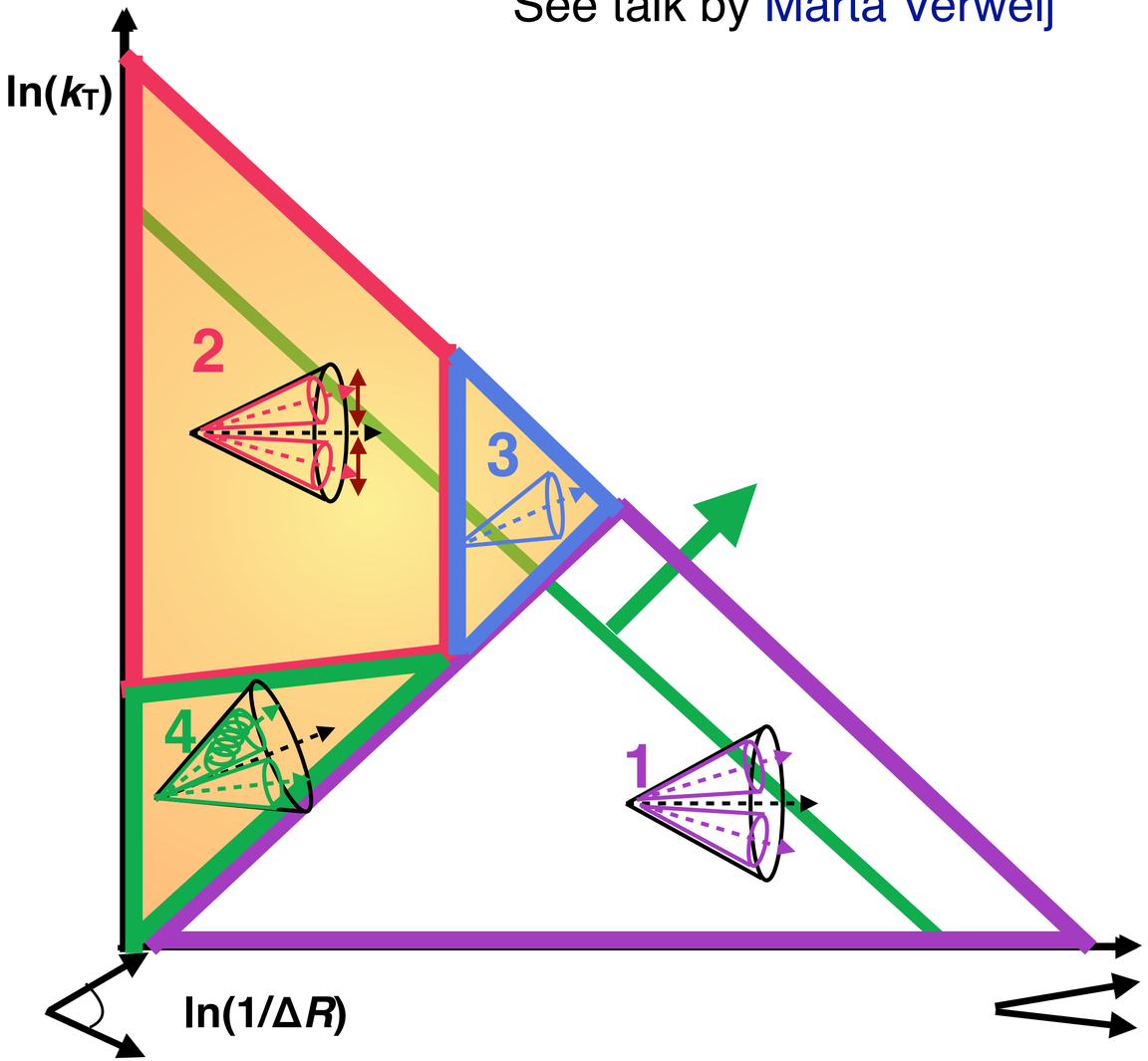
Soft drop grooming: in-medium

- Recluster jets with C/A* *JHEP 9708:001,1997
  - Apply grooming to access first hard splitting

$$z_g > z_{cut}\,\theta^{\beta}$$

$$\theta = \frac{\Delta R}{R}$$

See talk by Marta Verweij



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- Recluster jets with C/A* *JHEP 9708:001,1997
  - Apply grooming to access first hard splitting

$$z_g > z_{cut}\theta^{\beta}$$

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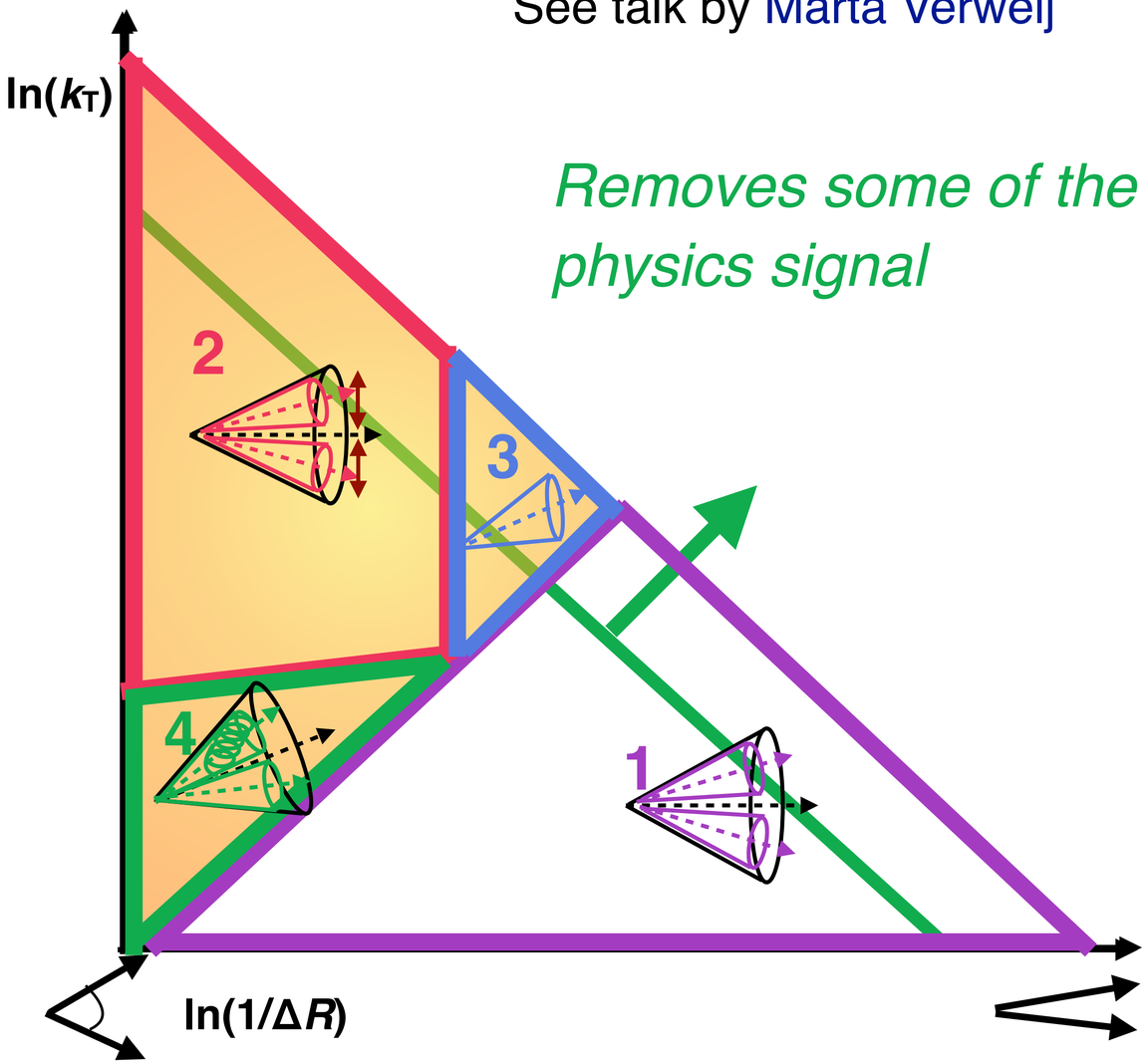
- Helps remove soft background for UE in HI collisions
- Removes soft signal from softening of jet constituents and medium response to focus on hard structure modification

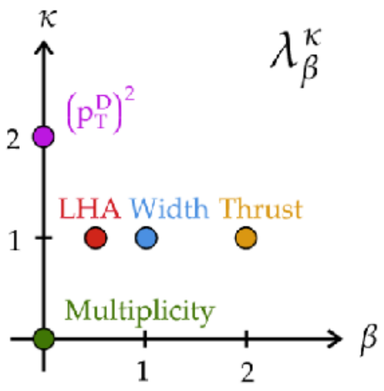
See talk by Marta Verweij



Removes some of the physics signal

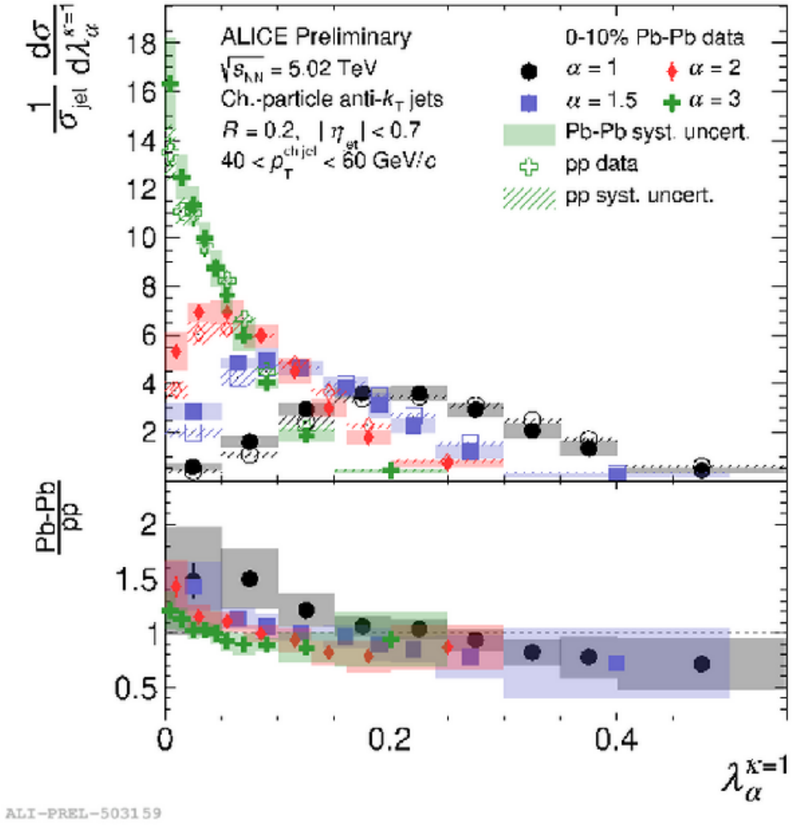
Groomed jet angularities

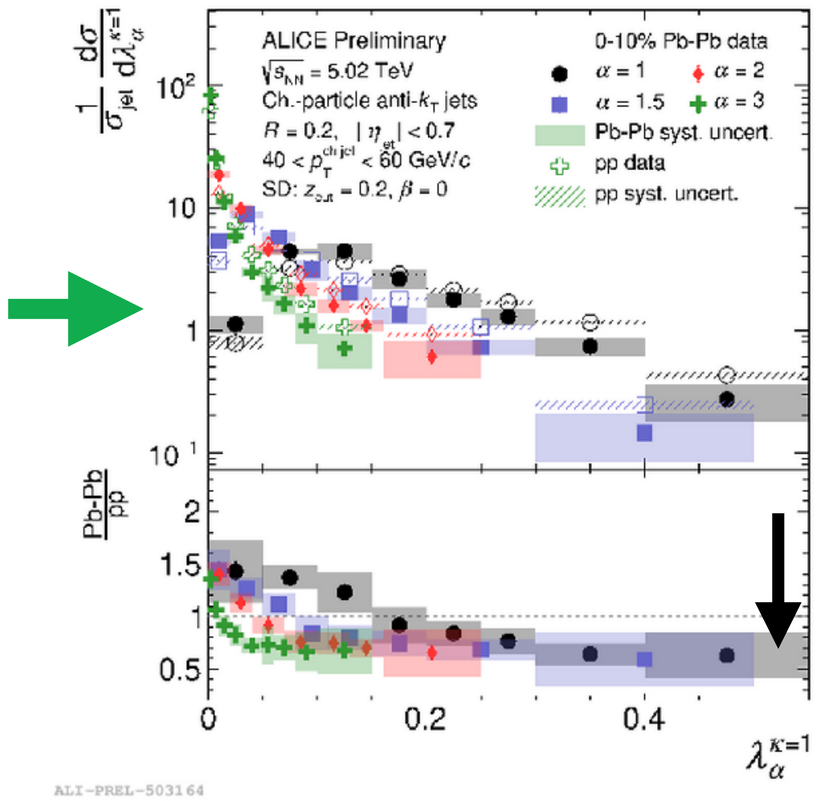
- Class of IRC-safe observables to summarize all substructure



$$\lambda_\beta^\kappa = \sum_{i \in jet} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta$$

Related to jet shapes:
Angularity (girth) g α=1
~Mass α=2



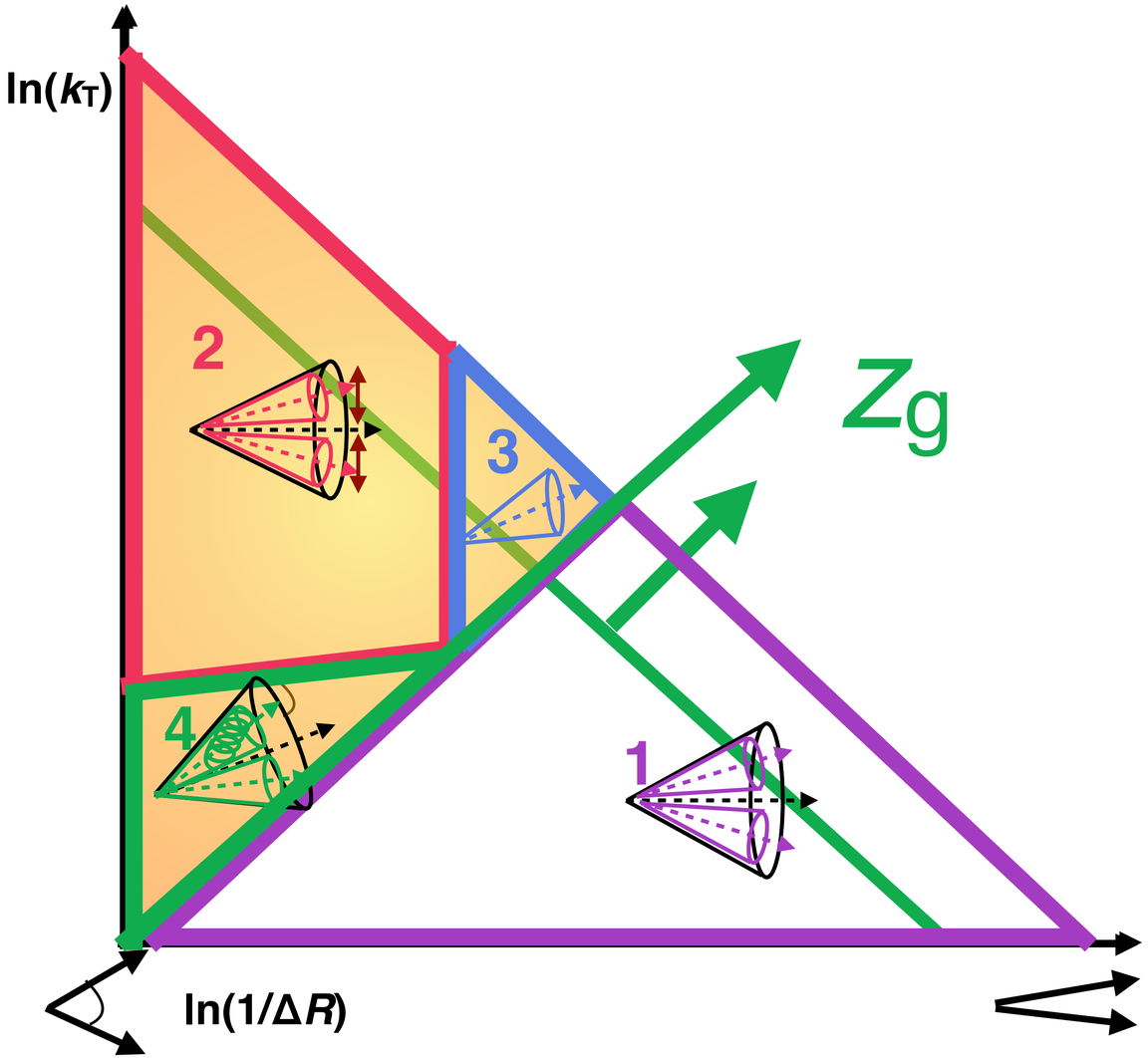


- Grooming reduces systematics and reveals narrowing feature
  - *Grooming reduces intra-jet broadening and recoil effects*

SD grooming variables

Modifications to splitting function?

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$



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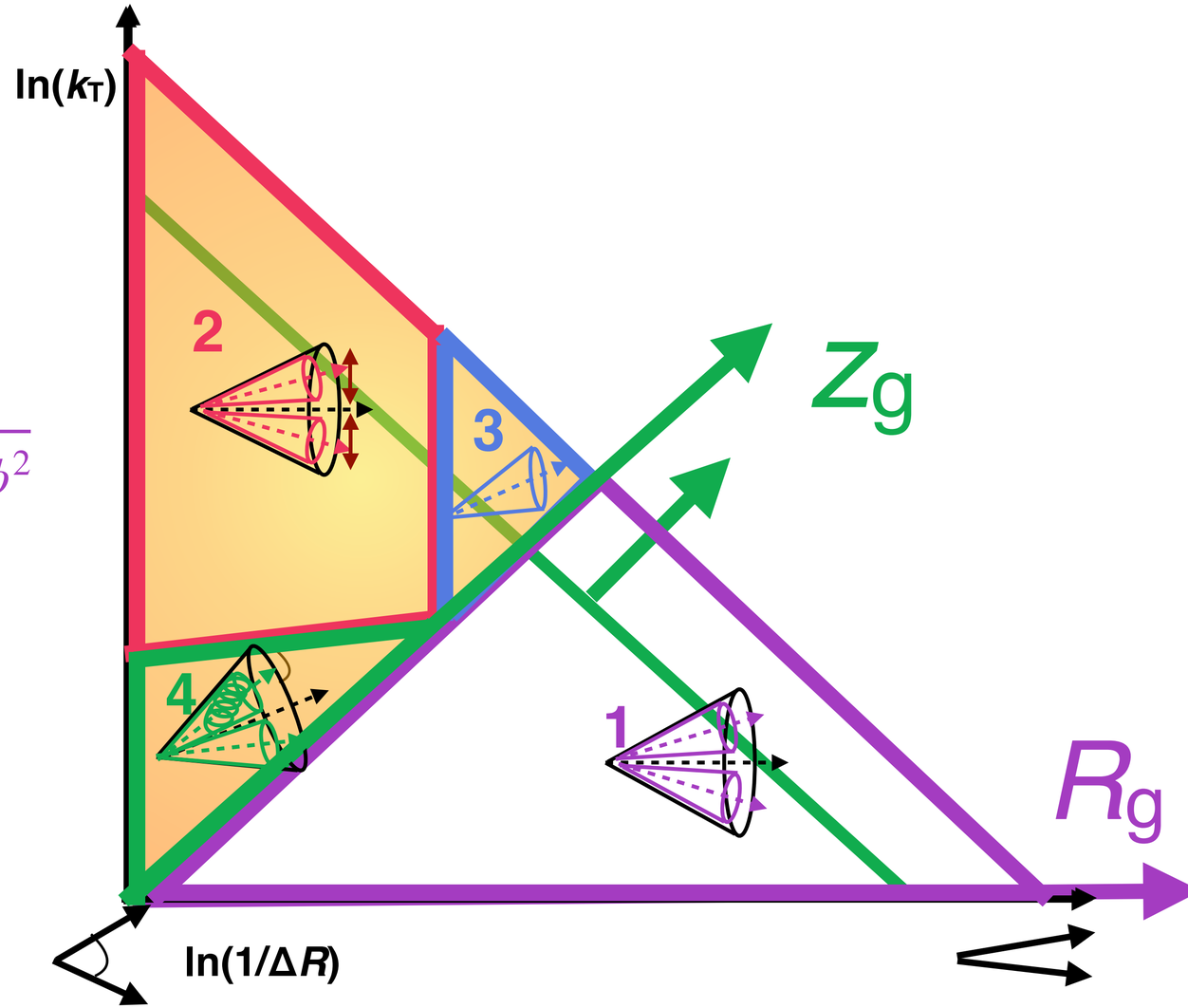
Resolution length of the QGP?

$$R_g = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



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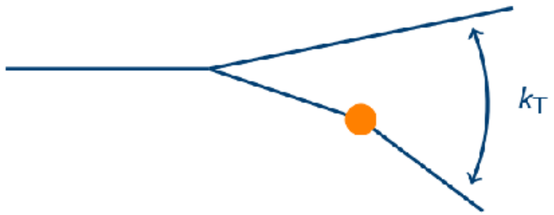
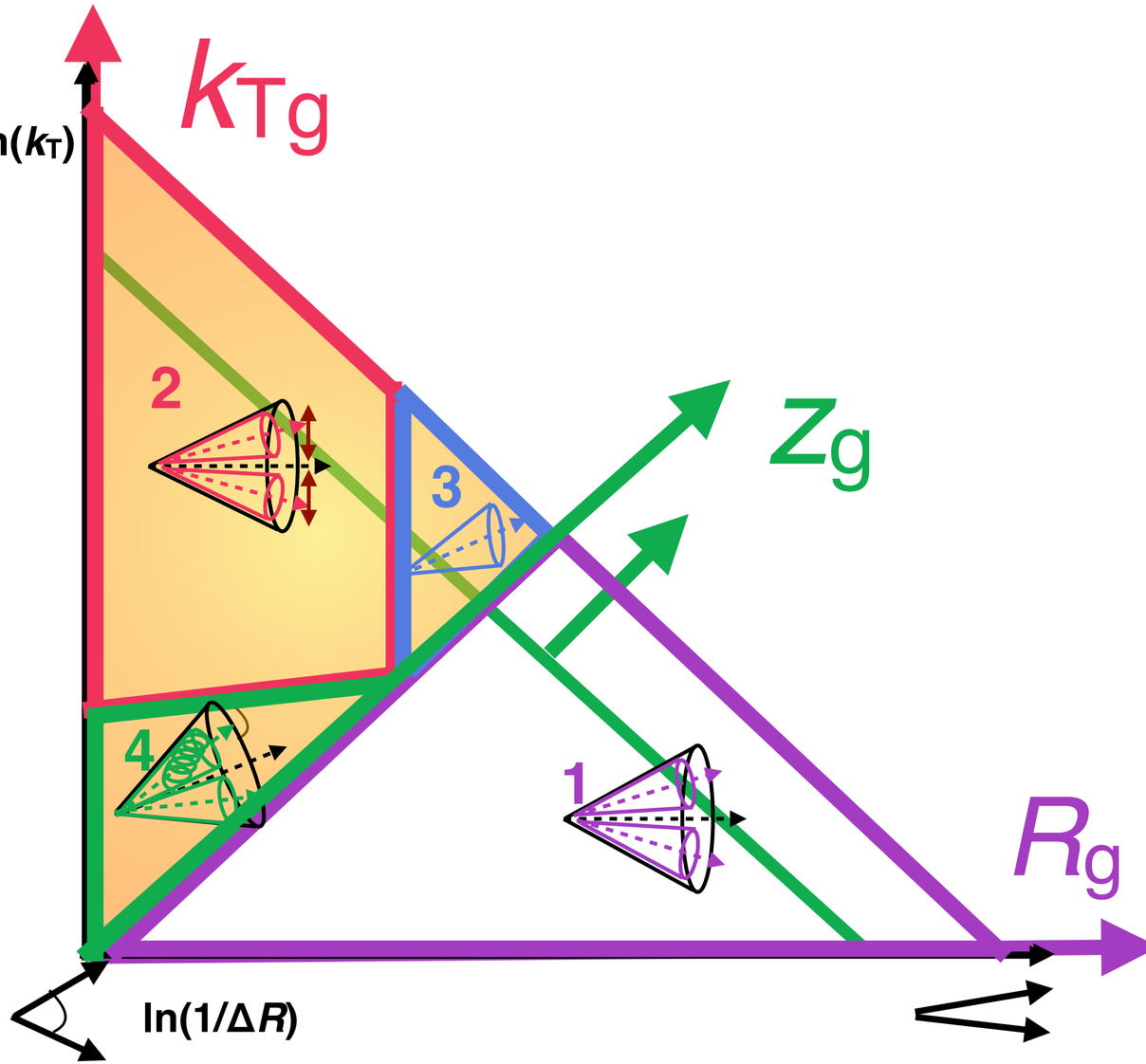
In-medium Moliere scattering?

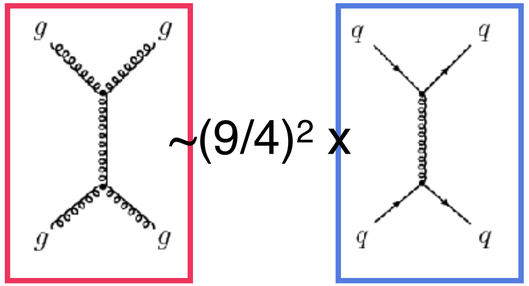


$$k_{Tg} \sim z_g p_T R_g$$

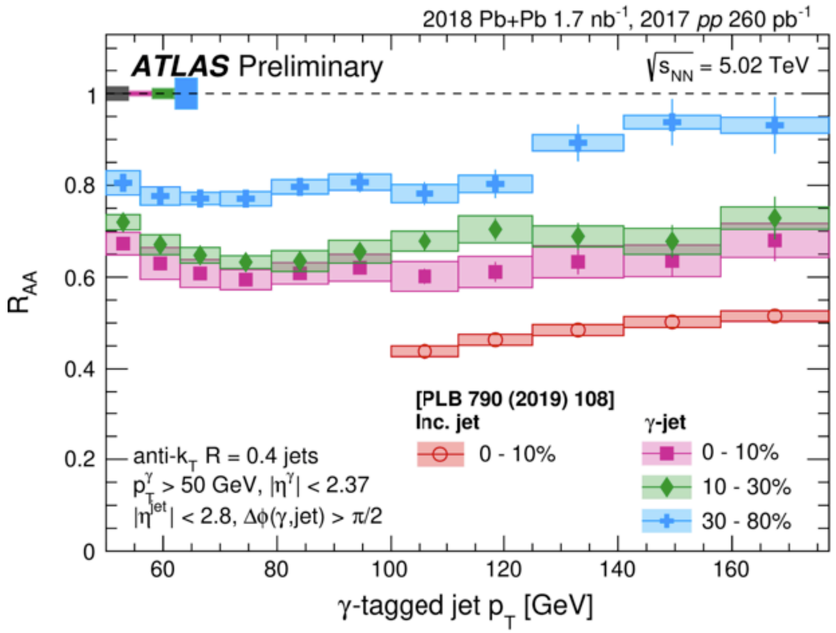


Flavor dependence

- The energy loss by quarks is predicted to be less than the energy loss by gluons



See talk by Sebastian Tapia Araya



ATLAS-CONF-2022-019

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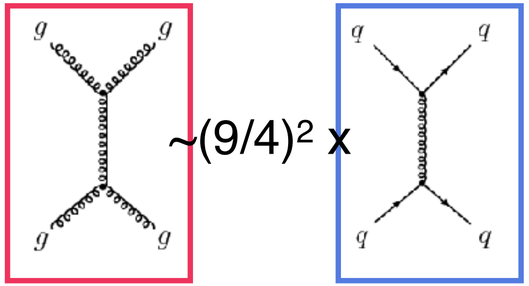

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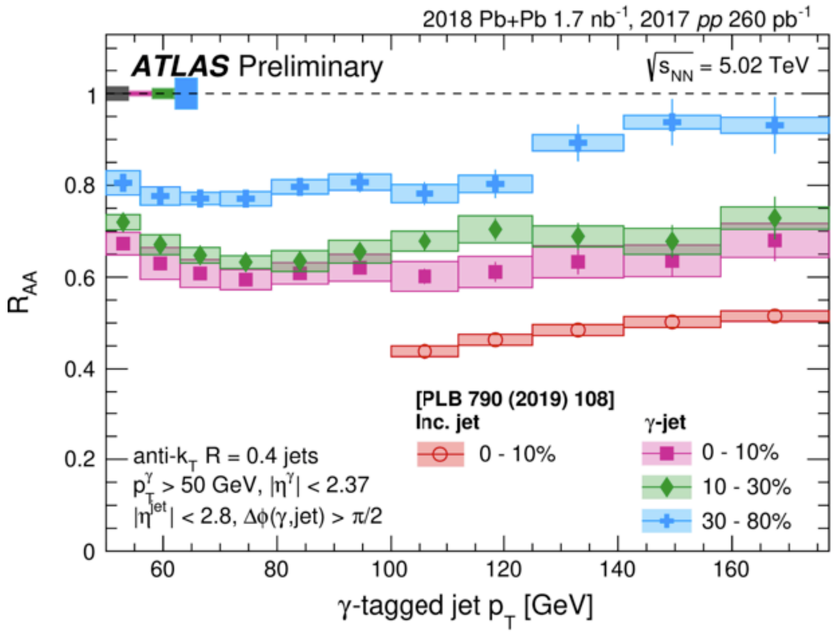

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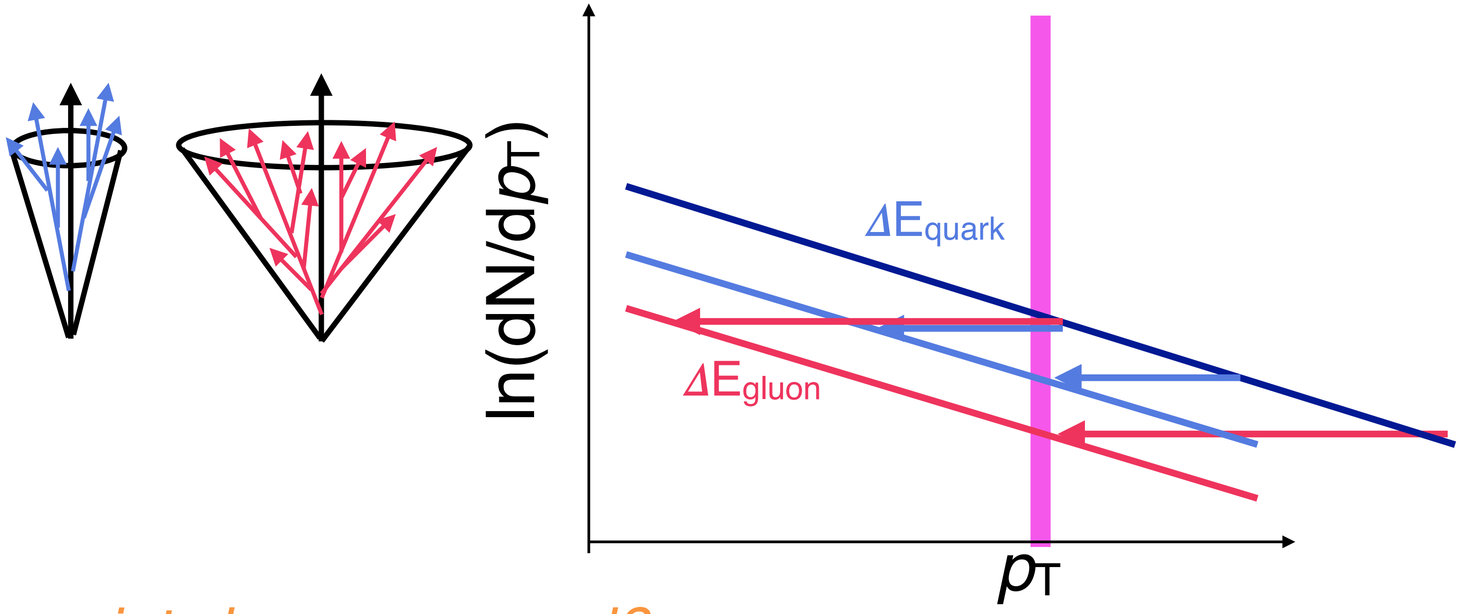
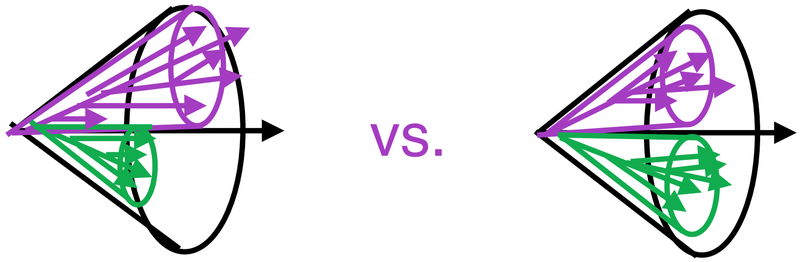
- Quark jets are narrower and have less structure than gluon jets



Will wider gluon jets be suppressed?

Jet splittings: z_g

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$



Modification of splitting function?

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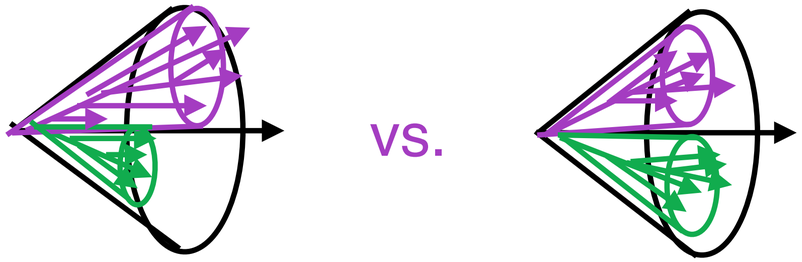
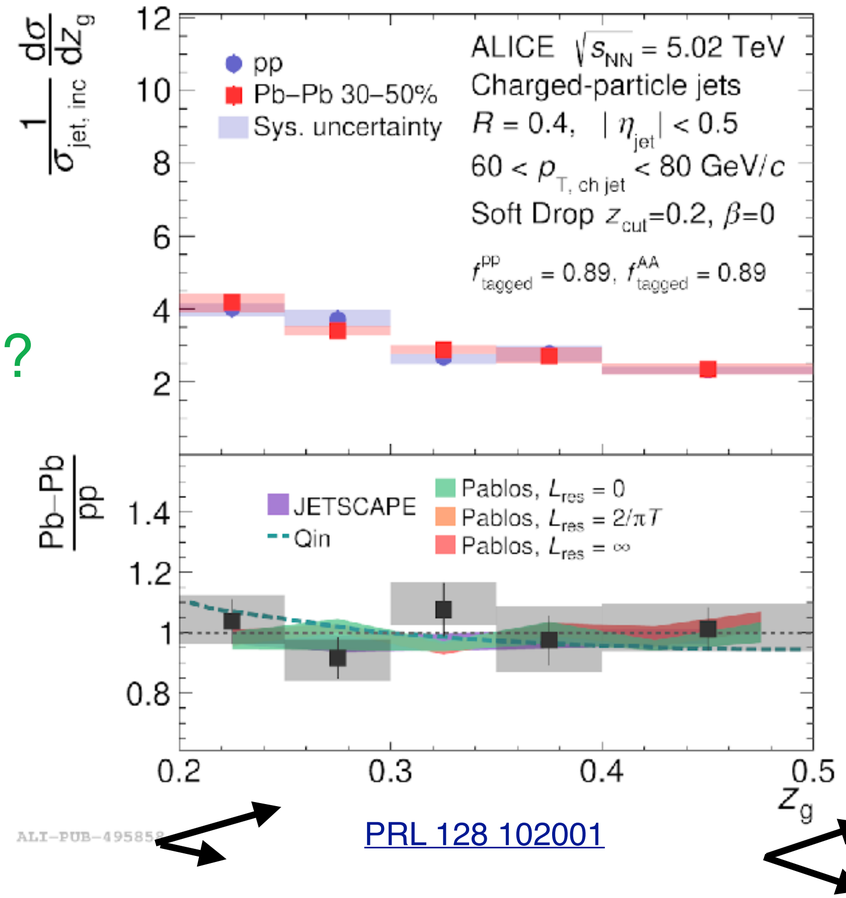
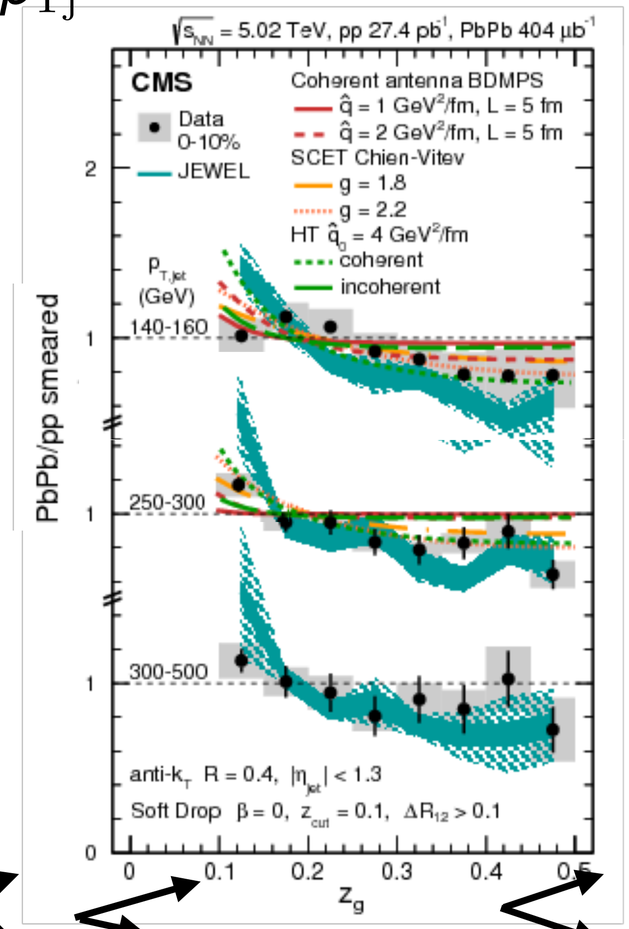


Modification of splitting function?

- *Low p_T: no significant modification, mostly consistent with models*
- *High p_T: hint of suppression at high z_g*



PRL 128 102001



PRL 120, 142302 (2018)

ALICE: low p_T, z_{cut}=0.2, unfolded

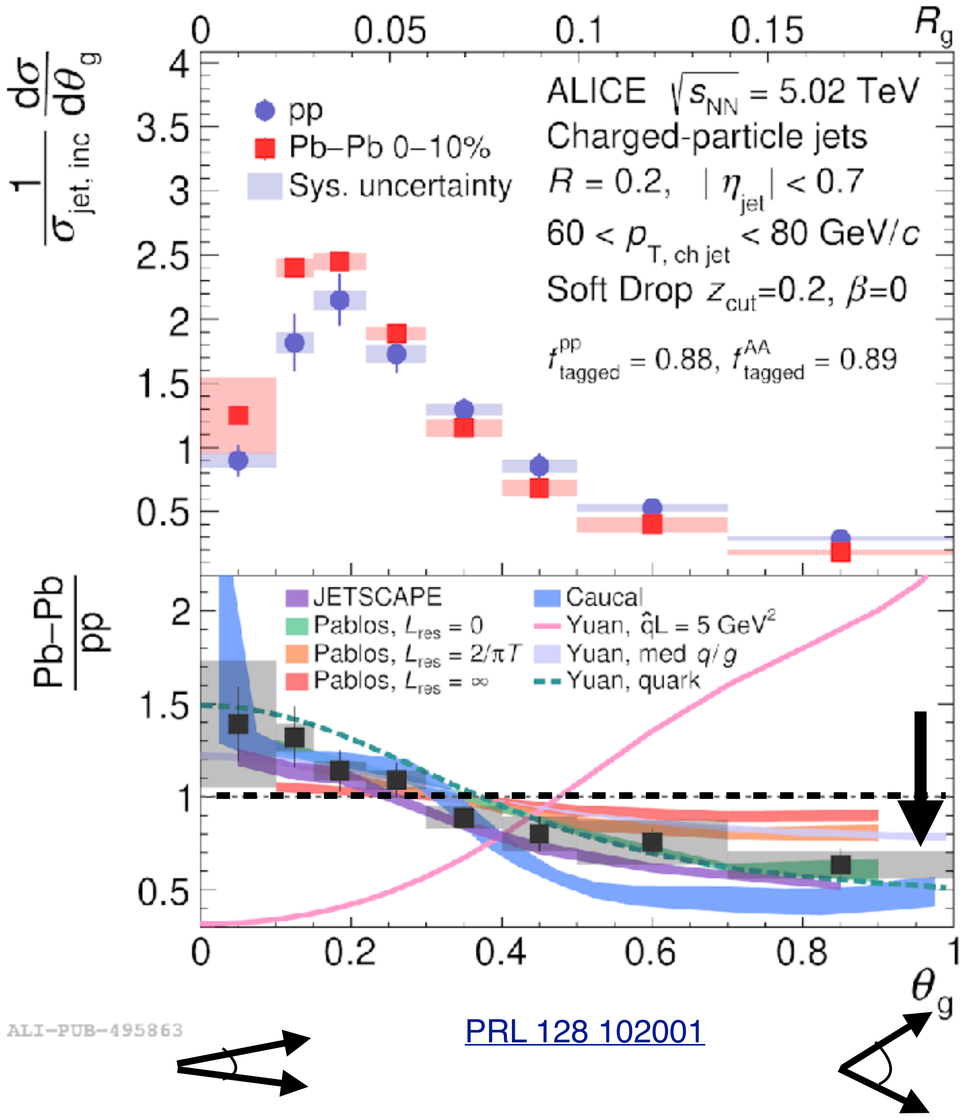
CMS: high p_T, z_{cut}=0.1, smeared

Jet splittings: R_g

Resolution length of QGP?

Jet splittings: R_g

Resolution length of QGP?

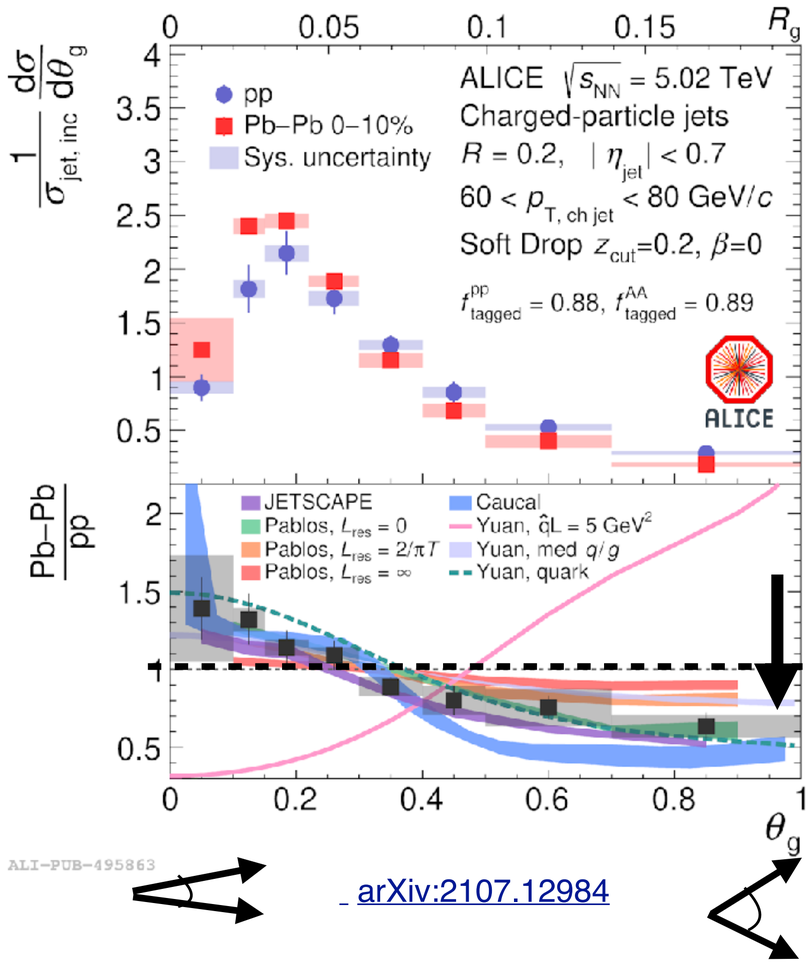


PRL 128 102001

- *Modification with large angle suppression (narrowing)*

Jet splittings: narrowing?

- *Narrowing reproduced by models with different implementations of jet-medium interactions*



arXiv:2107.12984

Jet splittings: narrowing?

- *Narrowing reproduced by models with different implementations of jet-medium interactions*

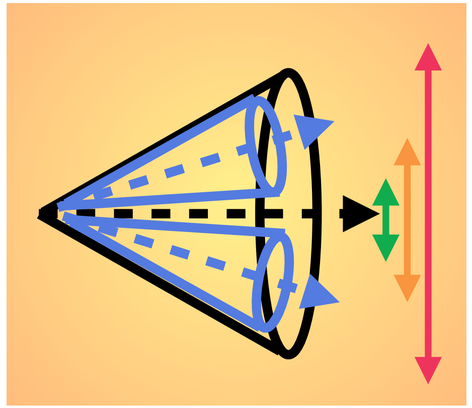
- Model 1: role of color coherence?

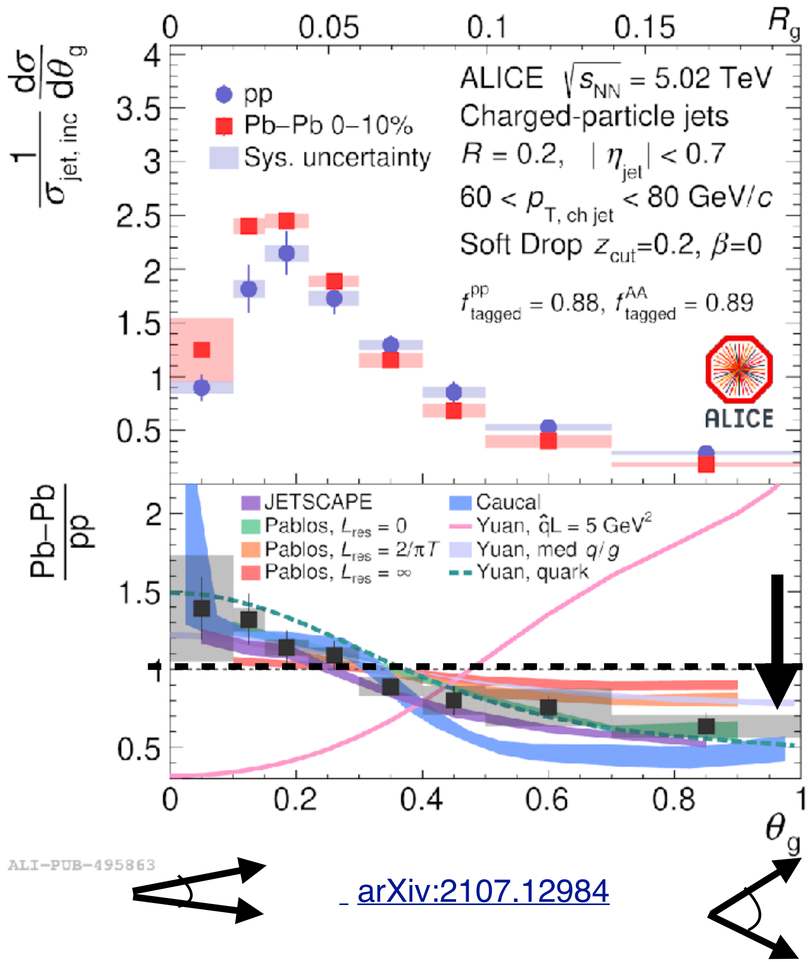
Pablos et al JHEP (2020) 044

-$L_{res} = 2/\pi T$

-$L_{res} = \infty$, coherence

-$L_{res} = 0$, decoherence





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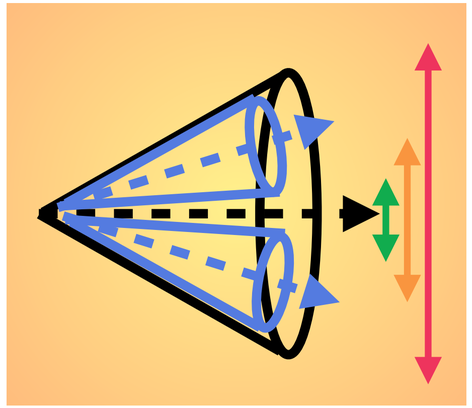
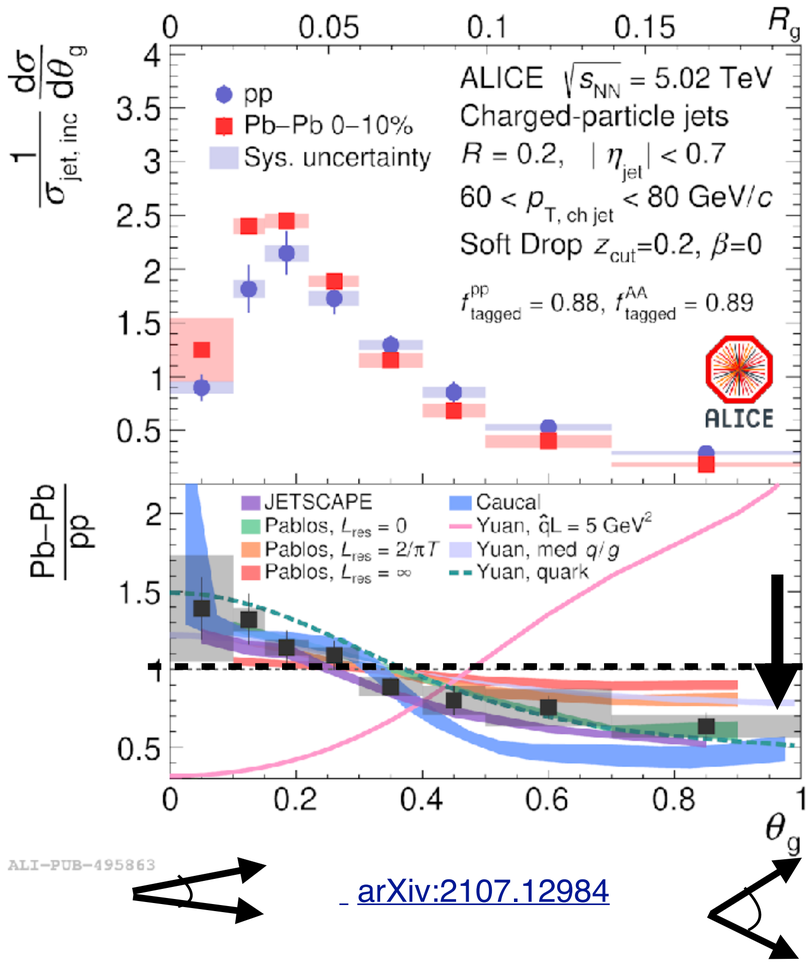




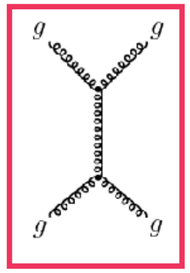
arXiv:2107.12984

- Model 2: coherence with changing q/g fractions?

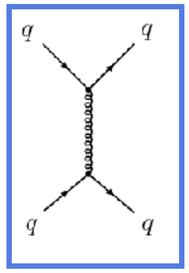
Yuan et al arXiv:1907.12541

-quark only

-medium q/g



~(9/4)^2 x



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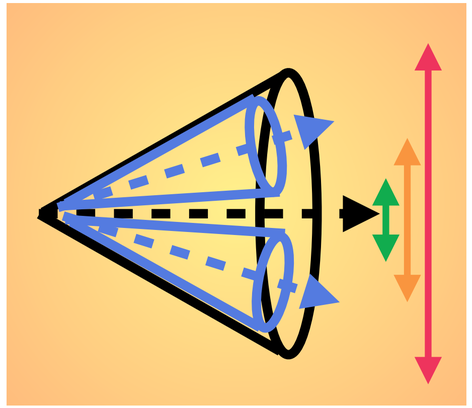

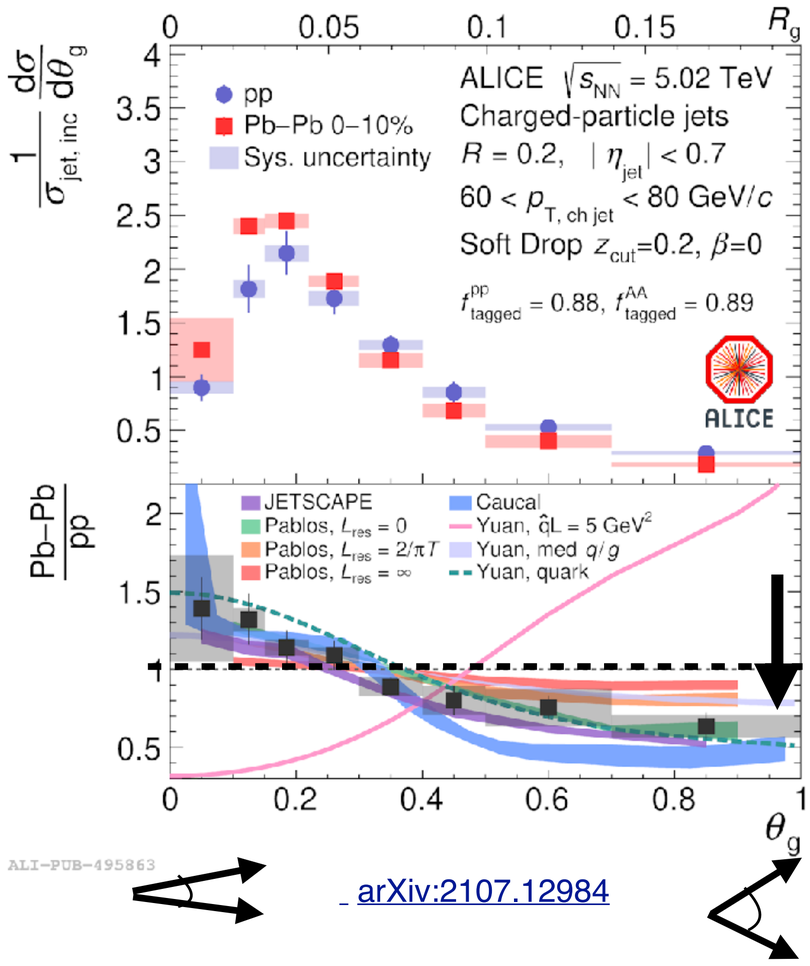

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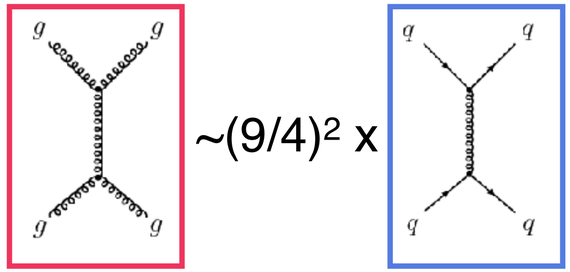
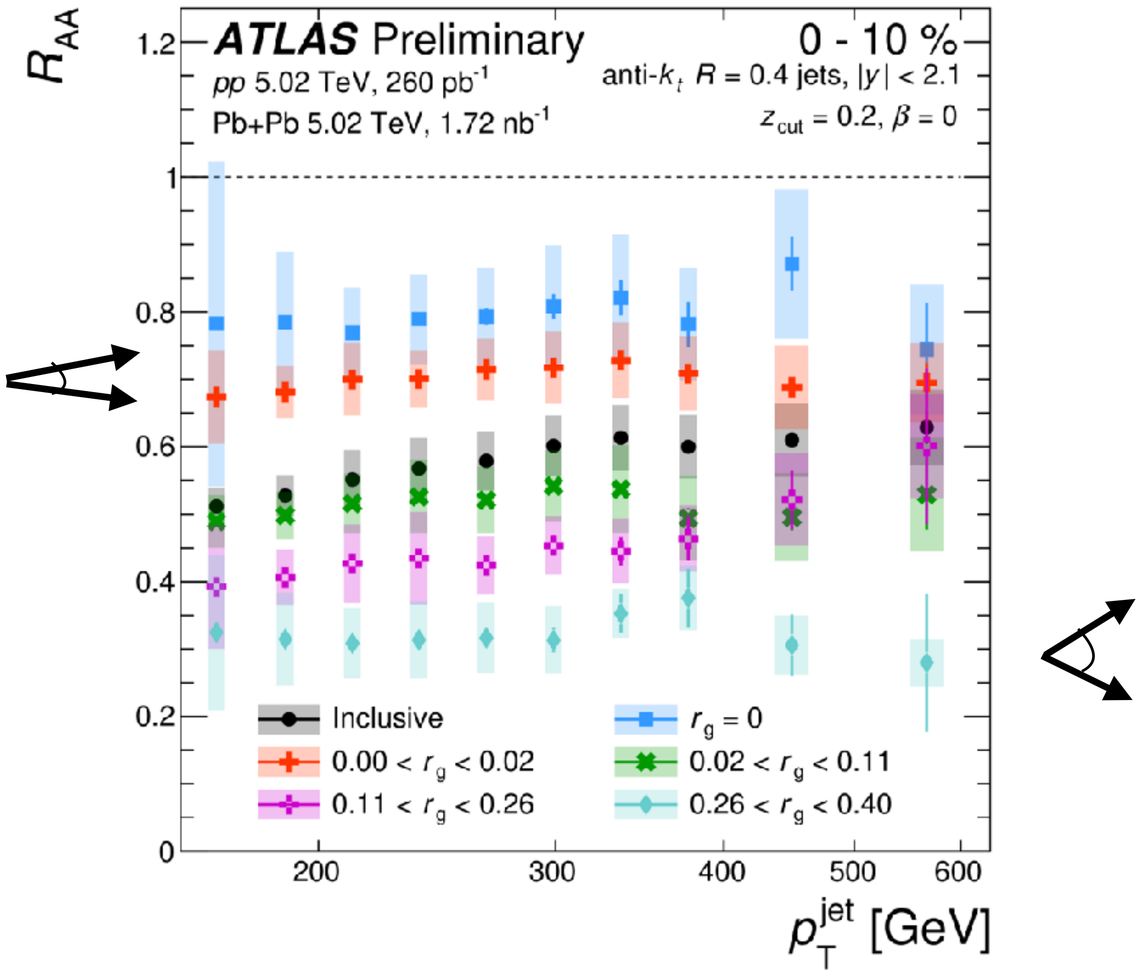


Jet splittings: R_g suppression

Resolution length of QGP?

- ATLAS measurement at higher p_T
- Absolute suppression with RAA instead of per-jet, differential in p_T

  - *Larger jets are more suppressed*



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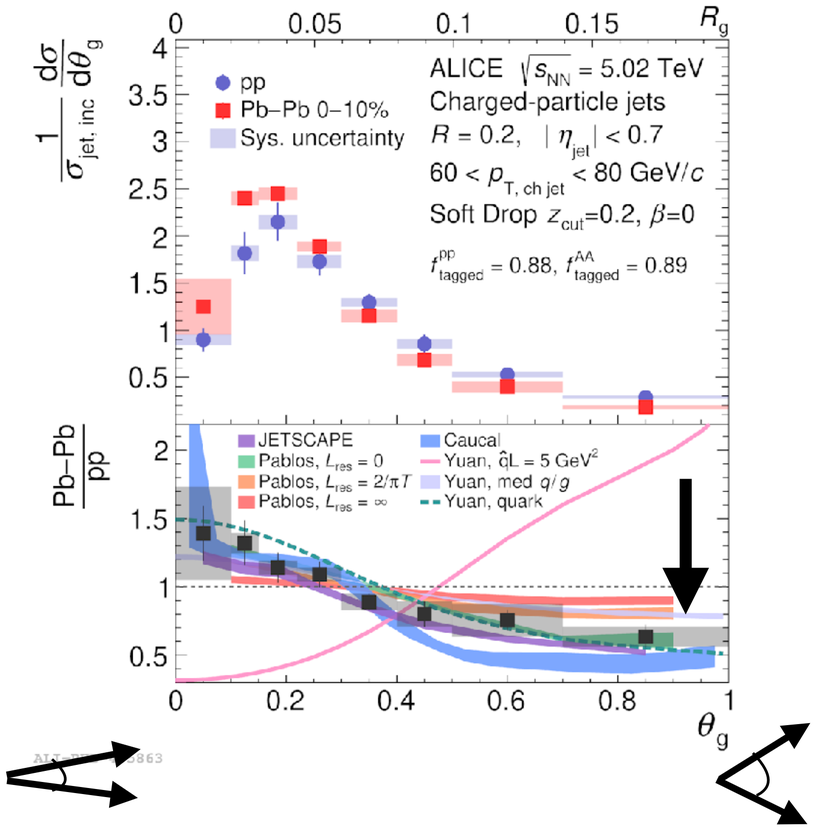
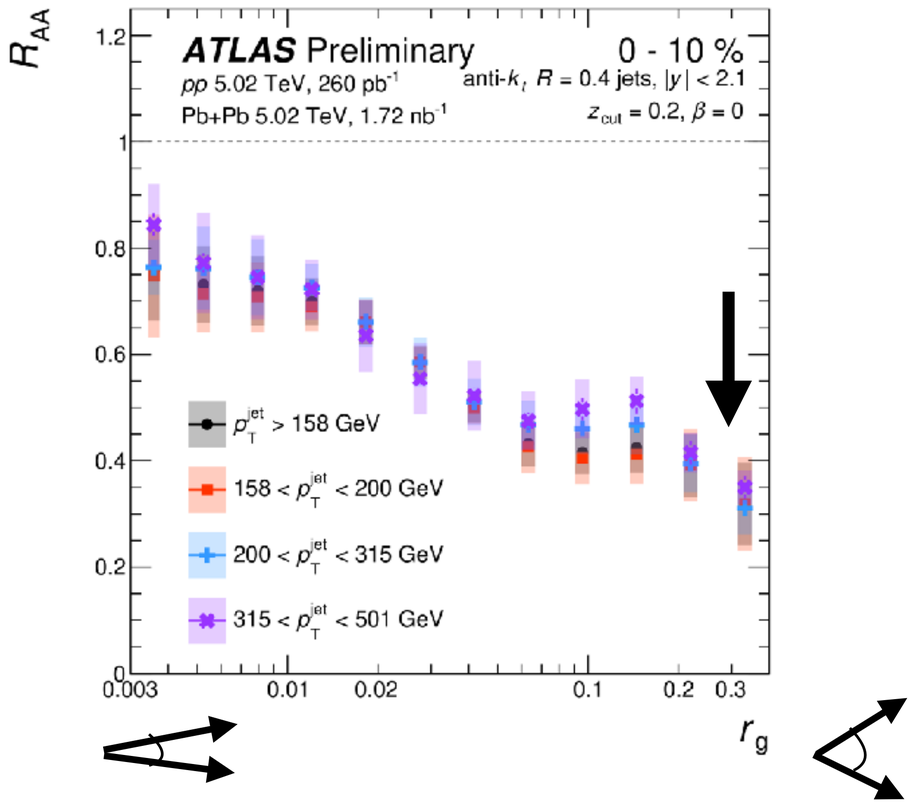
R_g: consistent picture?

- ALICE: 60-80 GeV (charged jets)

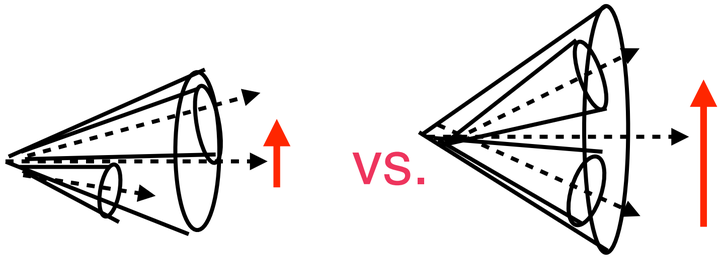


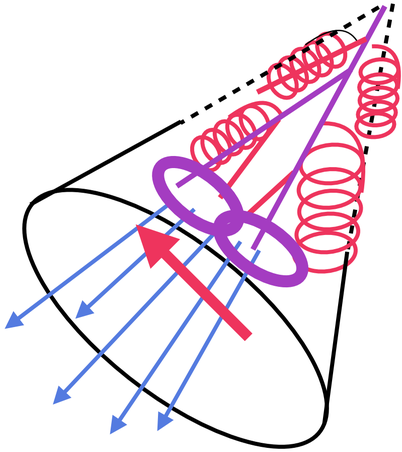
- ATLAS: 158-501 GeV



- *Both see larger jets more suppressed i.e. the jets are narrower*

Jet splittings: hardest k_{Tg}

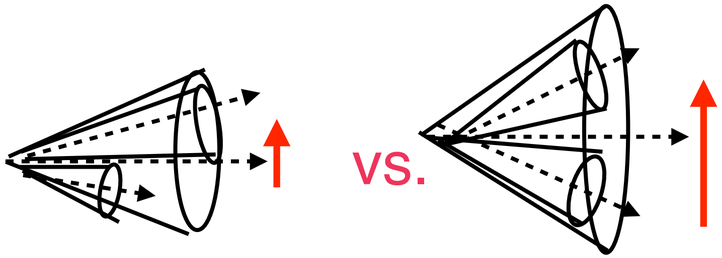




Quasi-particle nature of QGP?

See next talk by Raymond Ehlers for more details

Jet splittings: hardest k_{Tg}

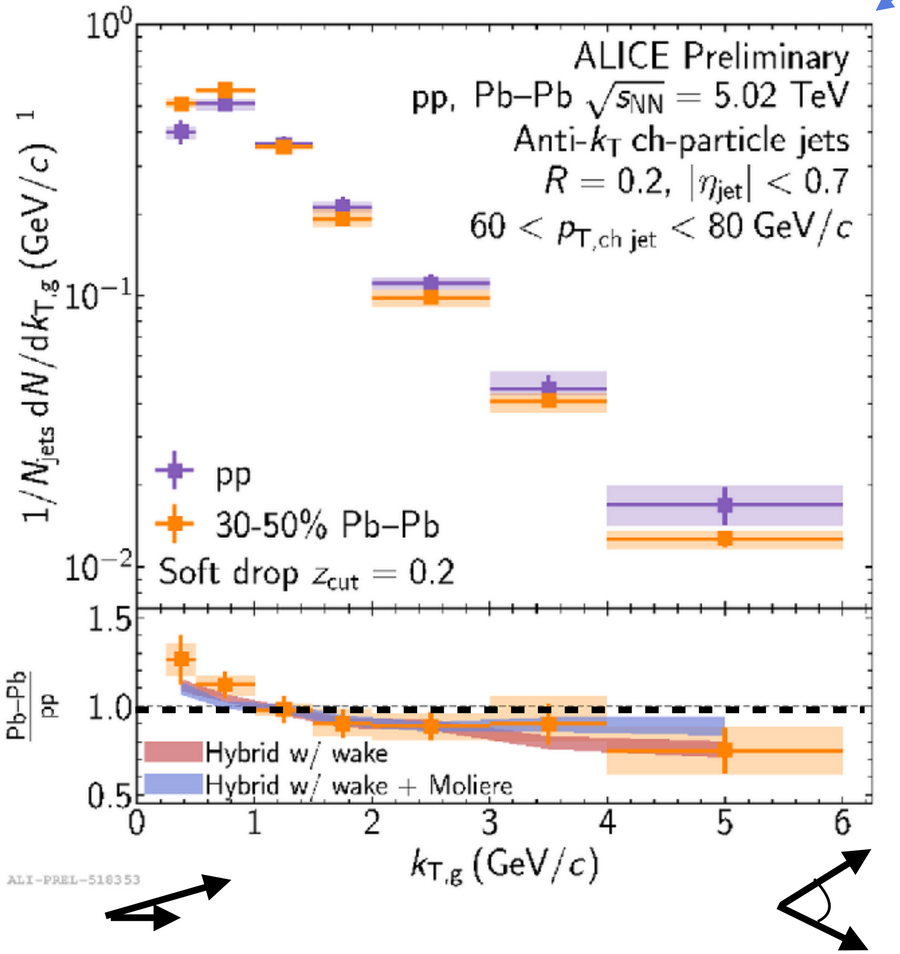


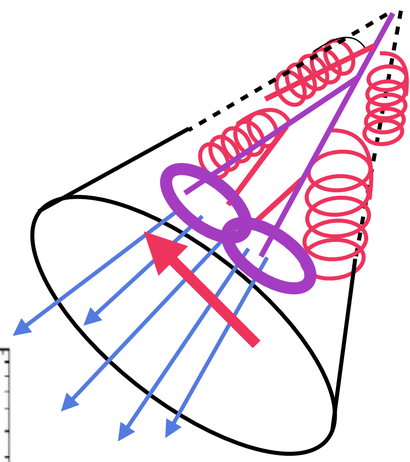
Quasi-particle nature of QGP?

- Hybrid model: role of Moliere scattering?
  - -without Moliere
  - -with Moliere

Pablos et al JHEP (2020) 044

- *Not sensitive enough to distinguish models yet*





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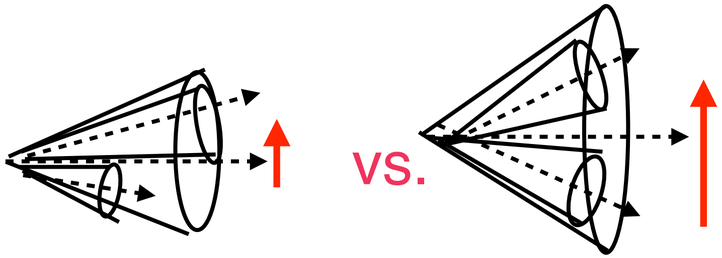
Jet splittings: hardest k_{Tg}



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  - -without Moliere
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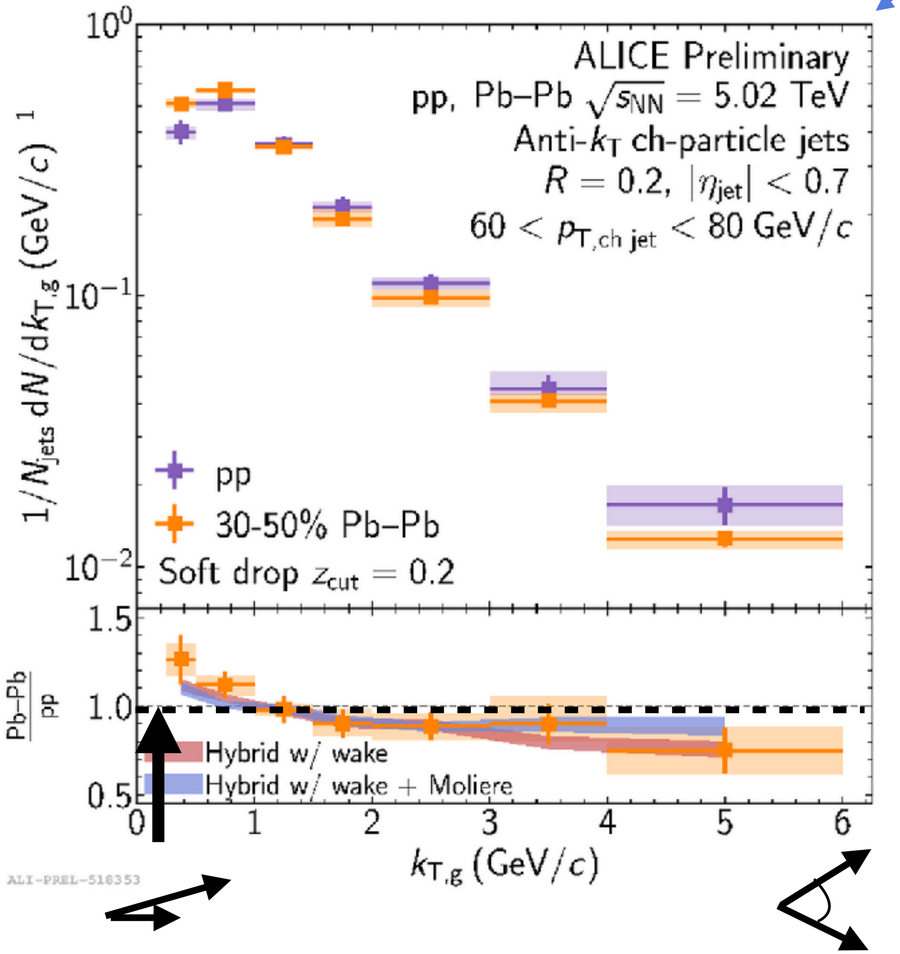
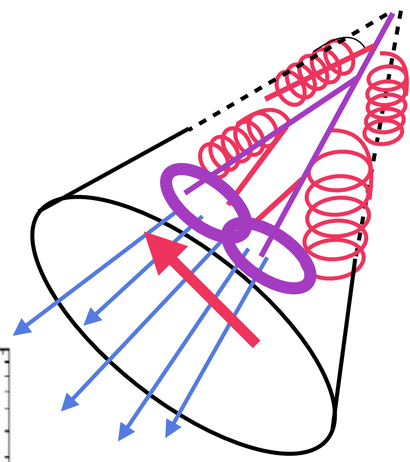
Pablos et al JHEP (2020) 044

- *Not sensitive enough to distinguish models yet*

- *Hint of enhancement at small k_{Tg}-> consistent with narrowing picture?*





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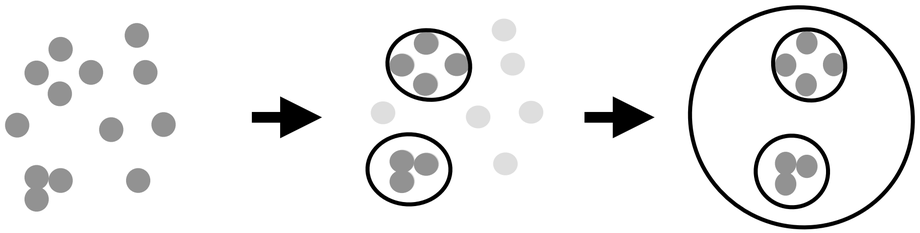
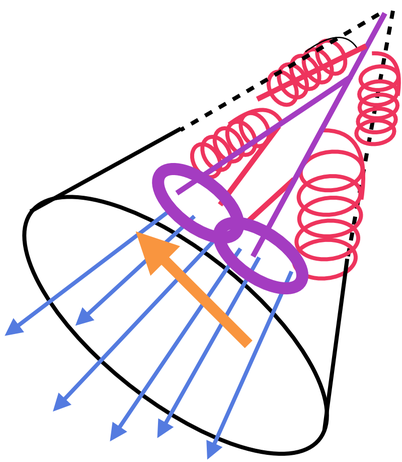
Jet splittings: large *R* trimming

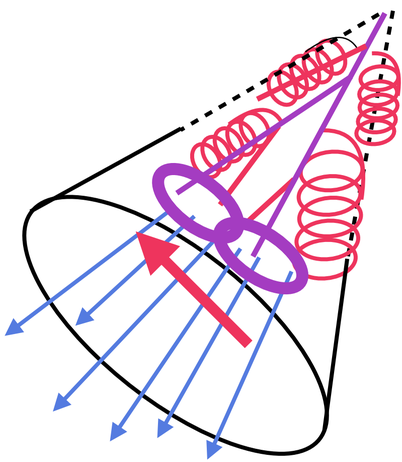
- Combining *R*=0.2 into *R*=1.0 jets removes energy radiated between subjets





ATLAS-CONF-2019-054

Jet splittings: large *R* trimming



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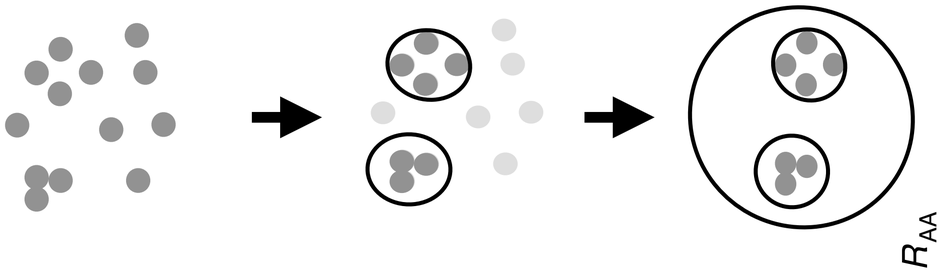
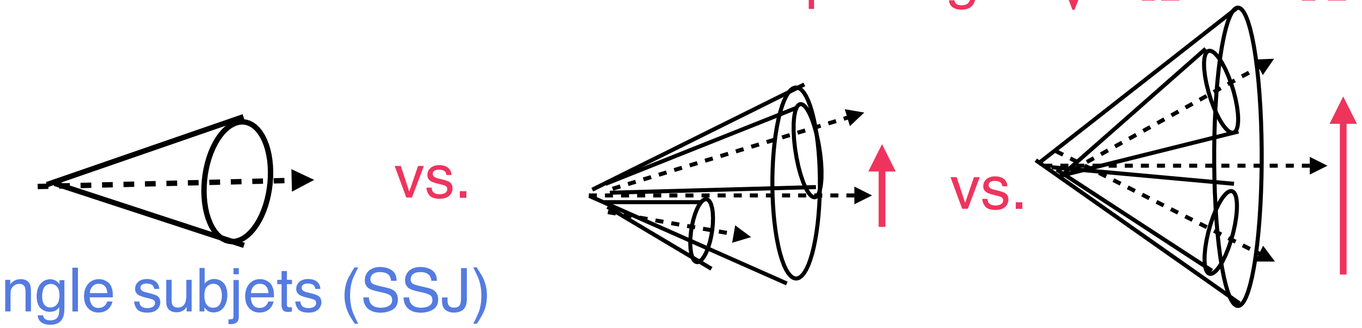
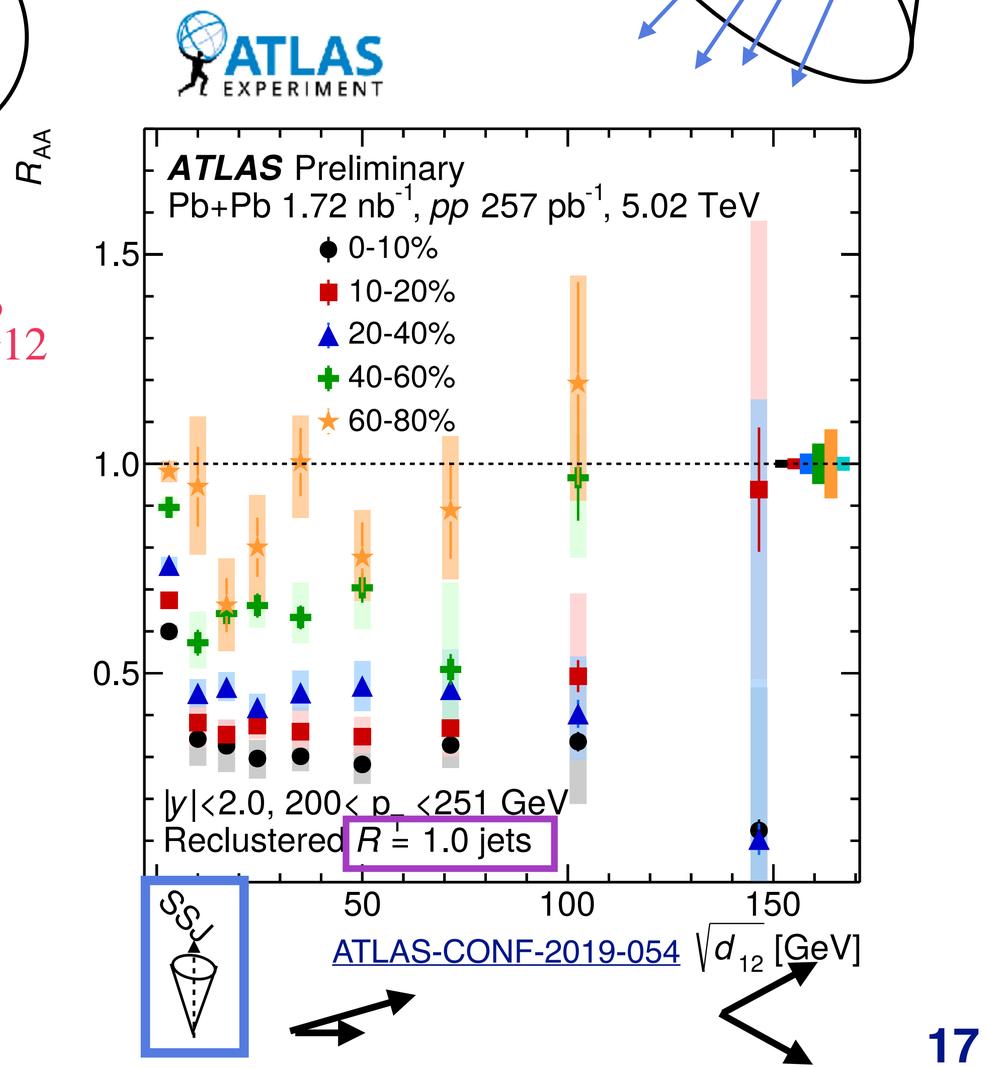


Recluster with k_T algorithm to access k_T

How hard is the resolved splitting? $\sqrt{d_{12}} = p_{T2}\Delta R_{12}$



single subjets (SSJ)



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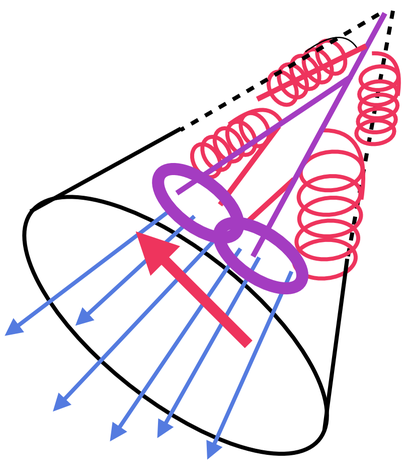

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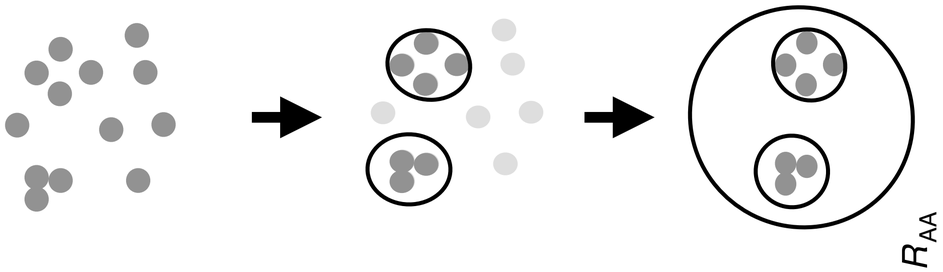

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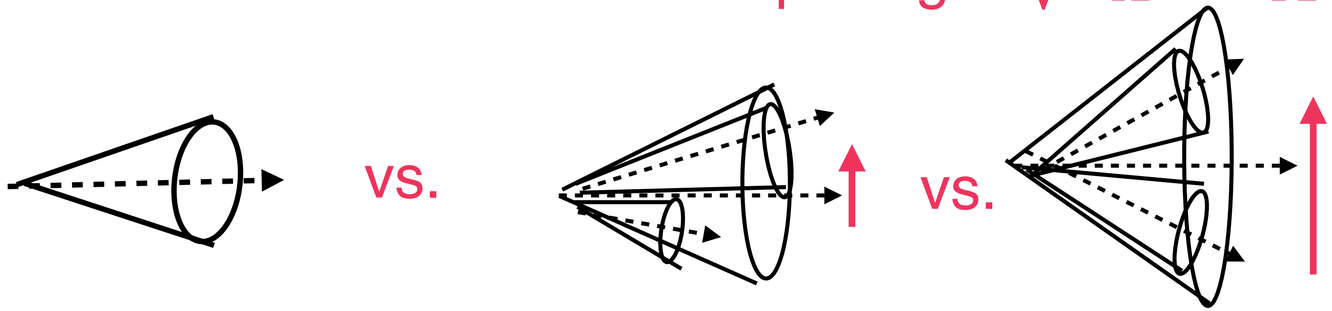
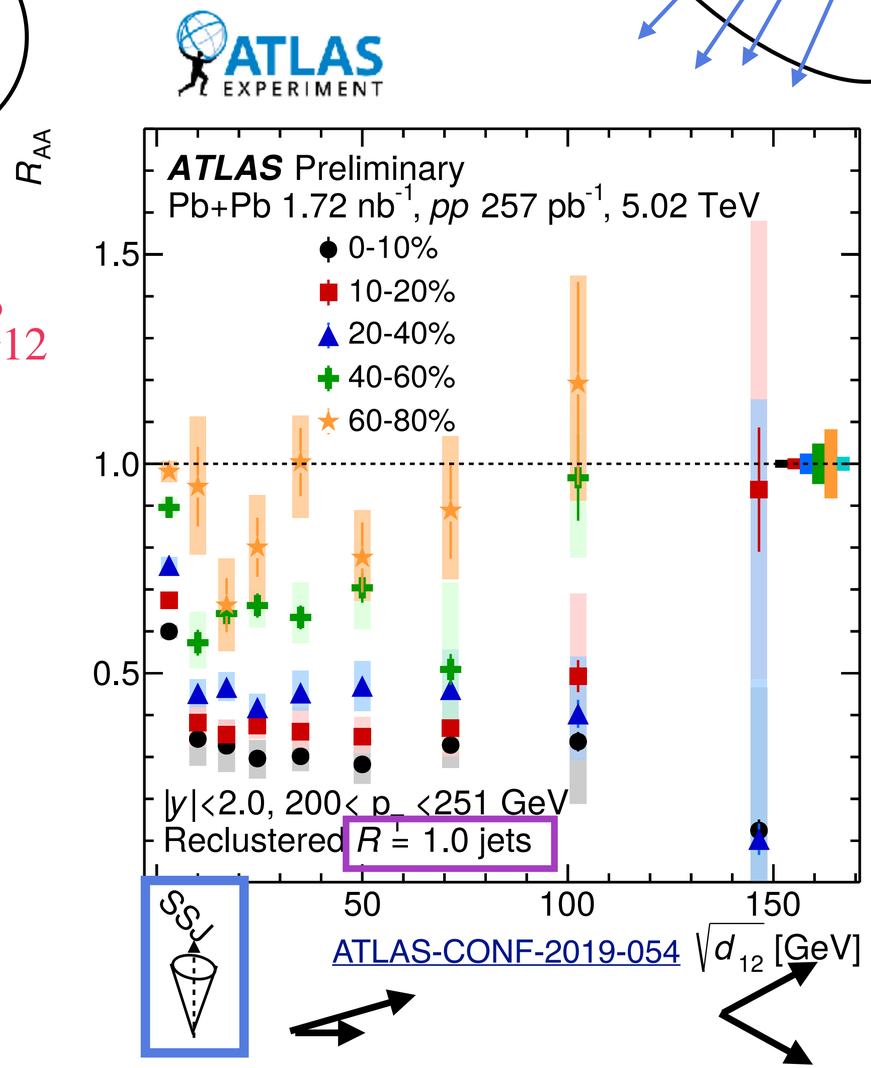




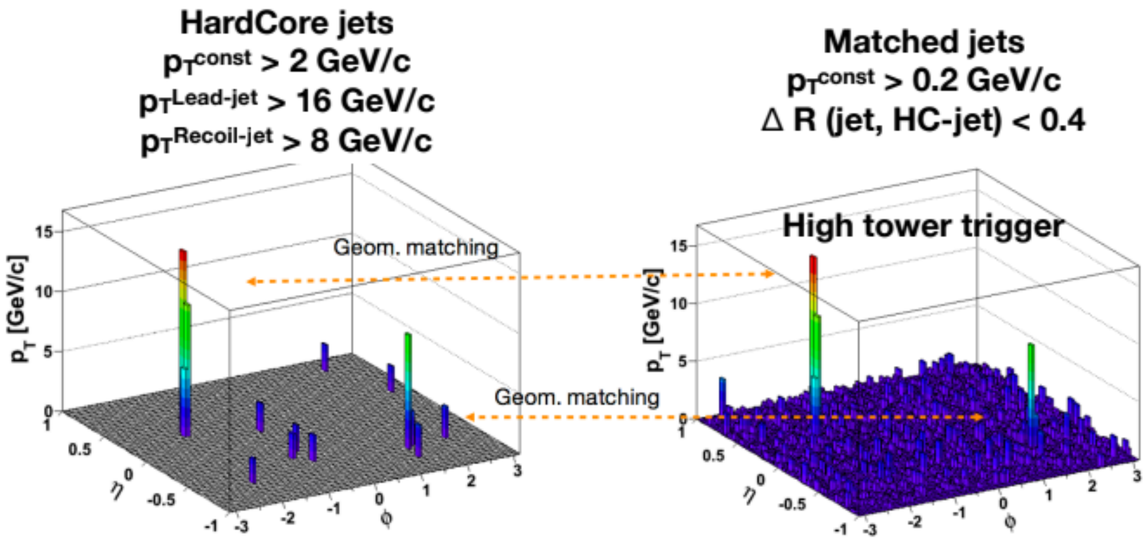
ATLAS-CONF-2019-054

- Jets with a substructure more suppressed than jets without (single subjets SSJ)

Is the medium resolving the splittings?

Jet substructure at RHIC

- STAR uses a HardCore selection to suppress the background
- Then matches to original jet to recover constituents



STAR, PRL 119 062301 (2017)

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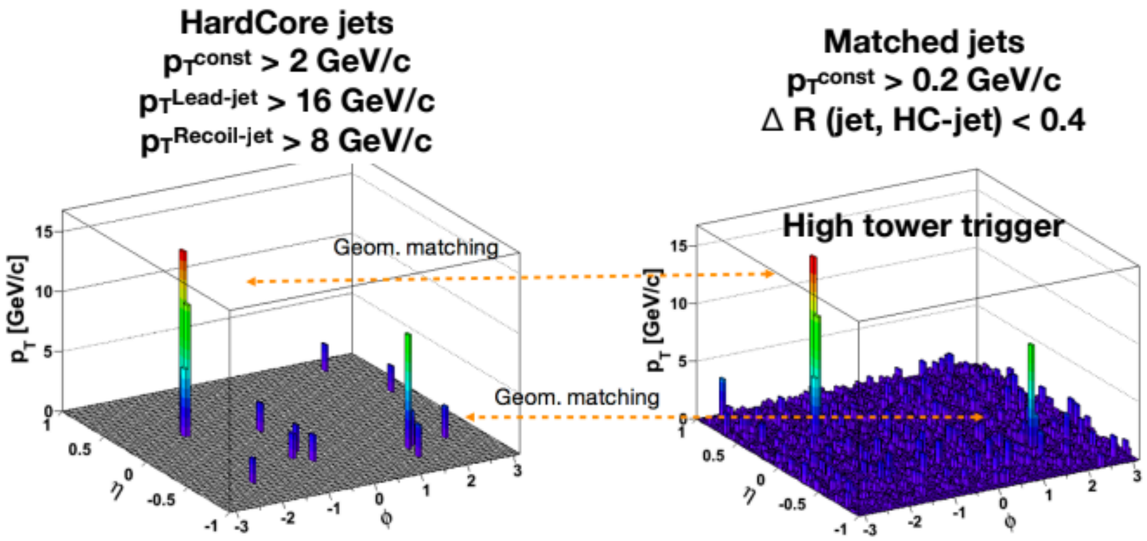
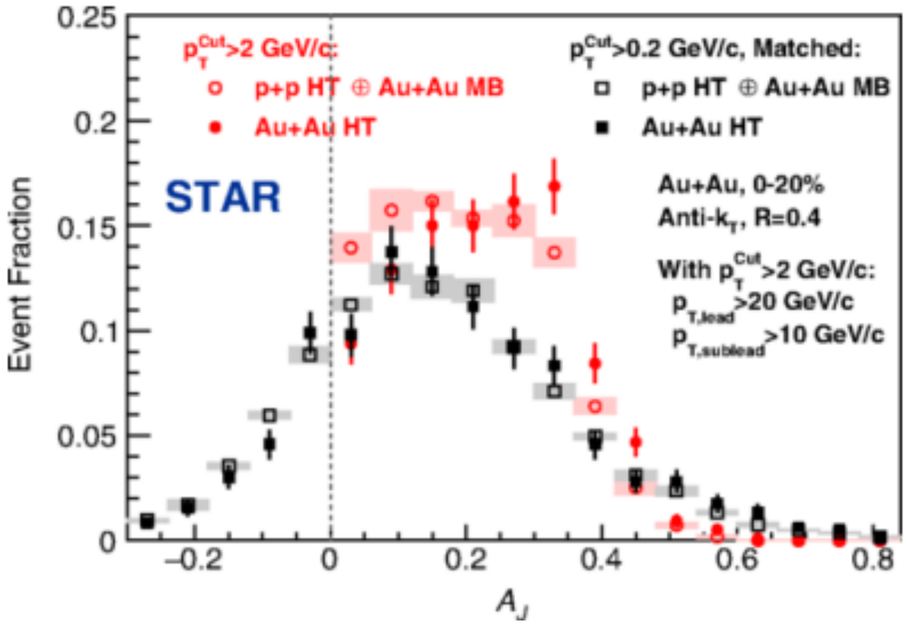
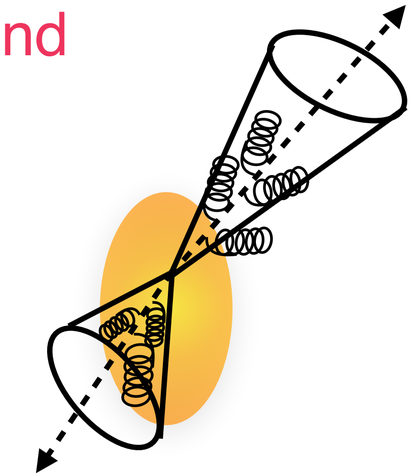




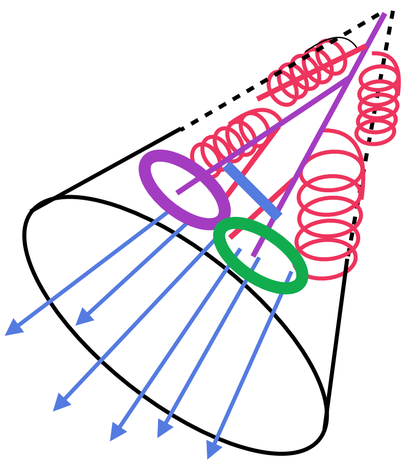
- HardCore jets are imbalanced and matched jets are balanced

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$



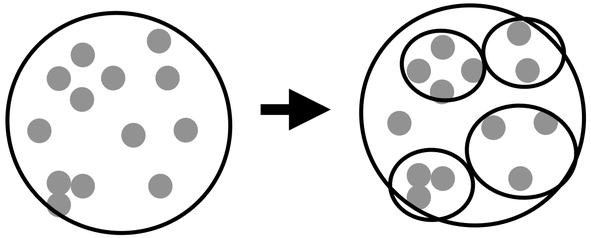
STAR, PRL 119 062301 (2017)

Substructure with subjets



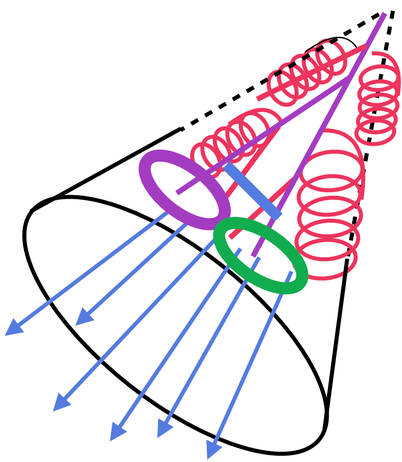
- Recluster constituents of *R*=0.4 jets into r=0.1 jets

$$\theta_{\mathrm{SJ}} = \Delta R_{1,2}$$



- Find the leading (1) and subleading (2) jet

Substructure with subjets



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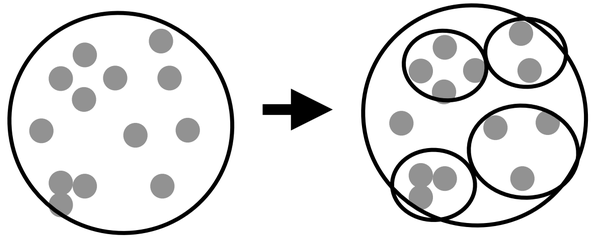
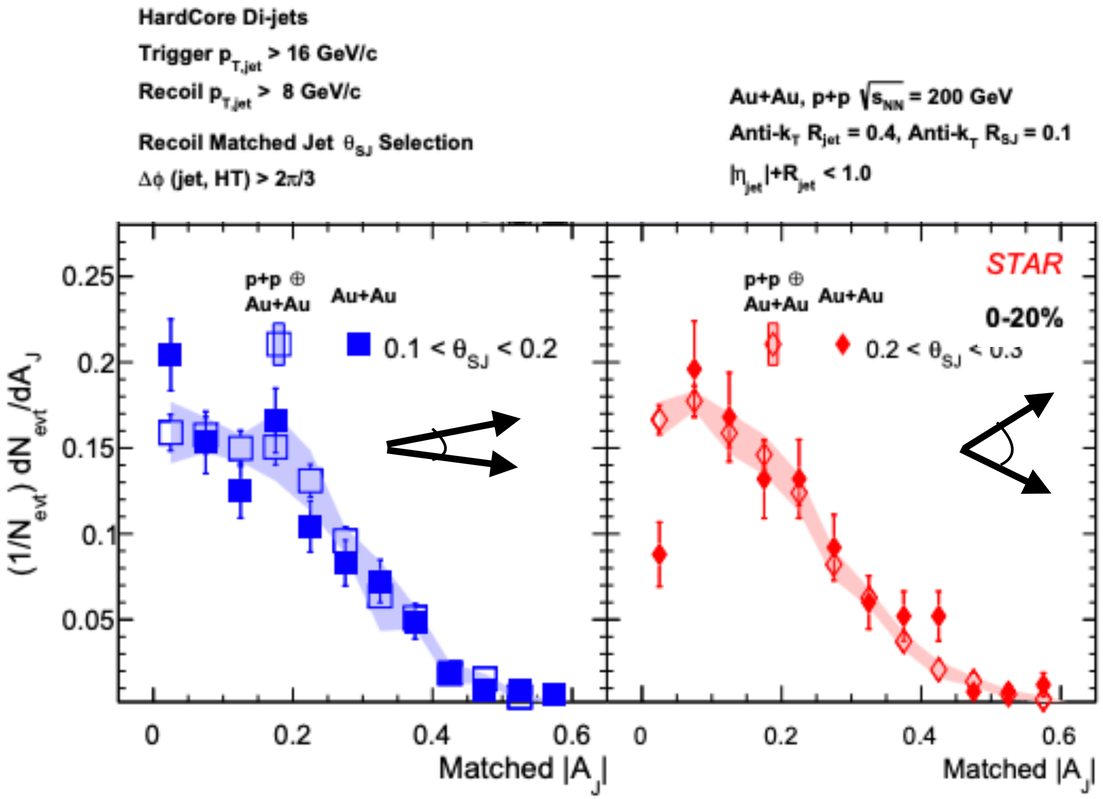
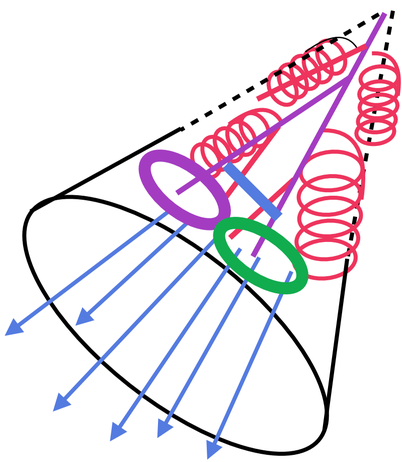


- Find the leading (1) and subleading (2) jet
- No modification with angle



arXiv:2109.09793

Substructure with subjets



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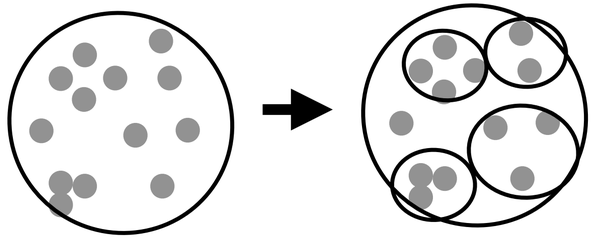

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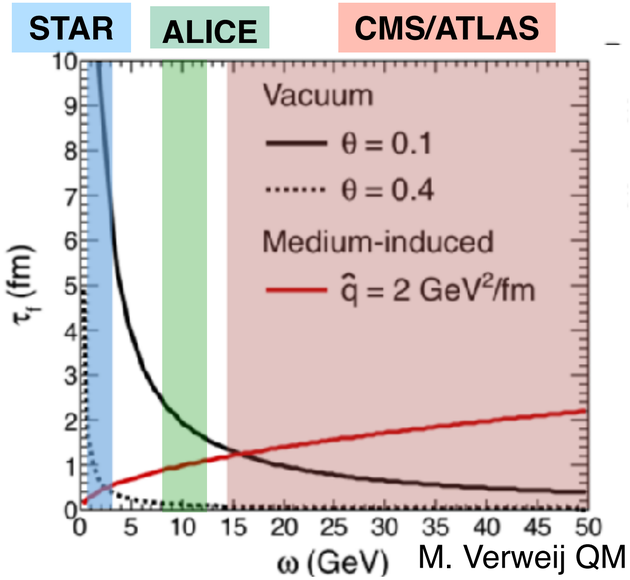
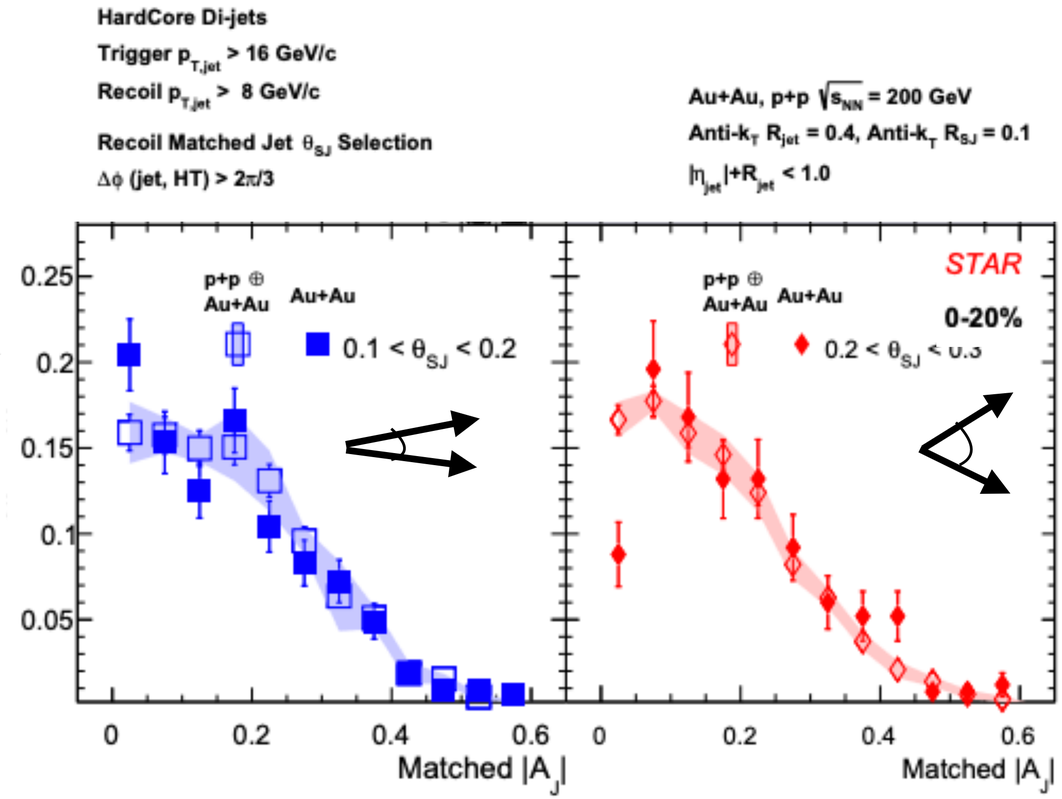


M. Verweij QM 17

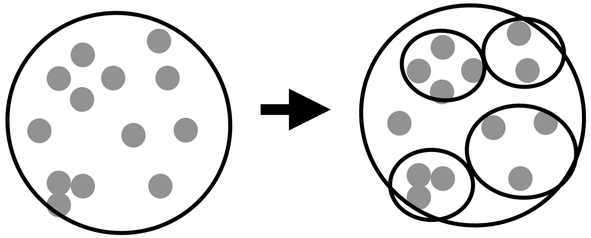


- Contradiction with R_g
  - RHIC later formation times outside of medium?

arXiv:2109.09793

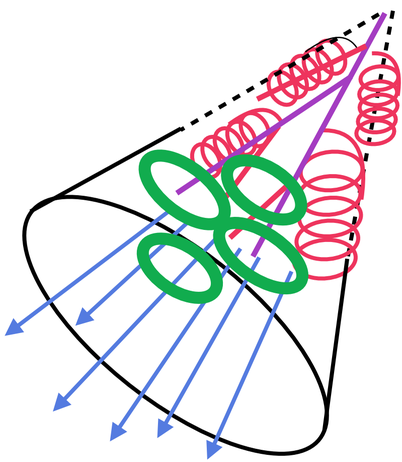
Subjet fragmentation

- Recluster constituents of R=0.4 jets into r=0.1 jets

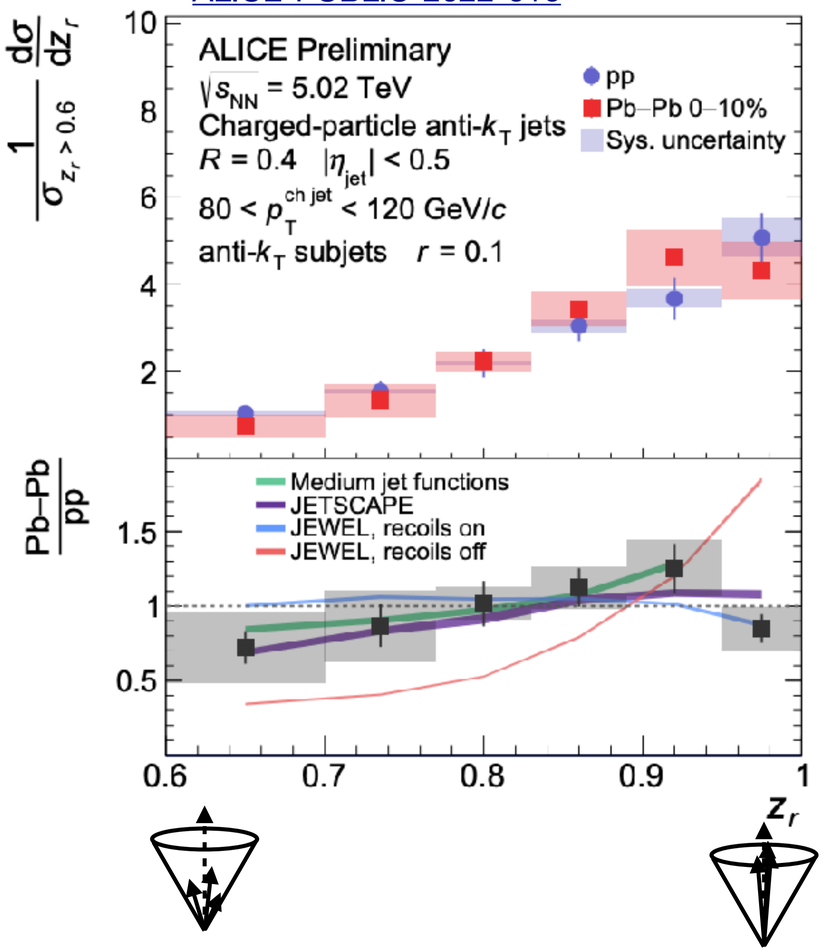


$$F(z_r) = \frac{1}{N_{\text{jet}}} \frac{dN}{dz_r}$$

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$



ALICE-PUBLIC-2022-016



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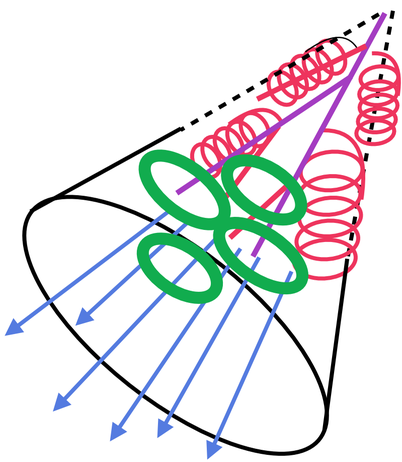
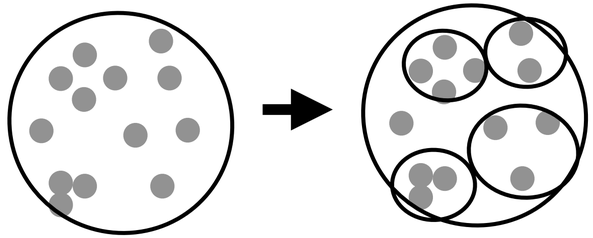
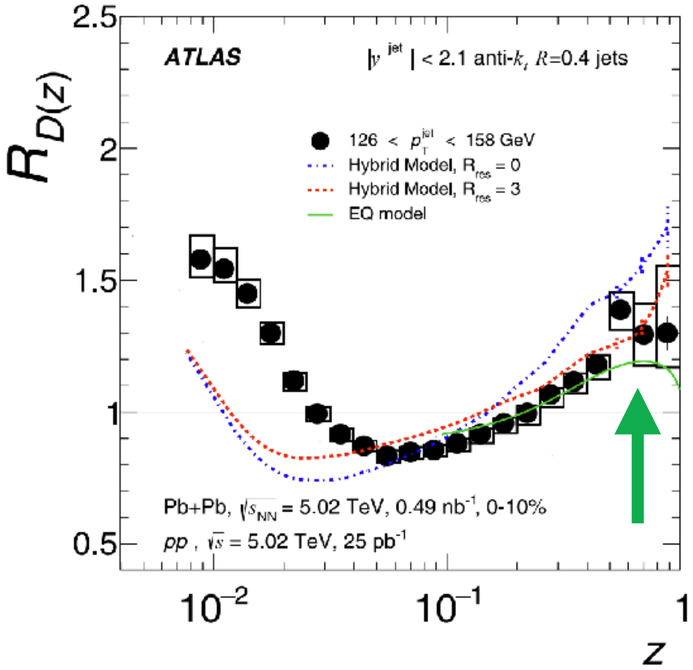


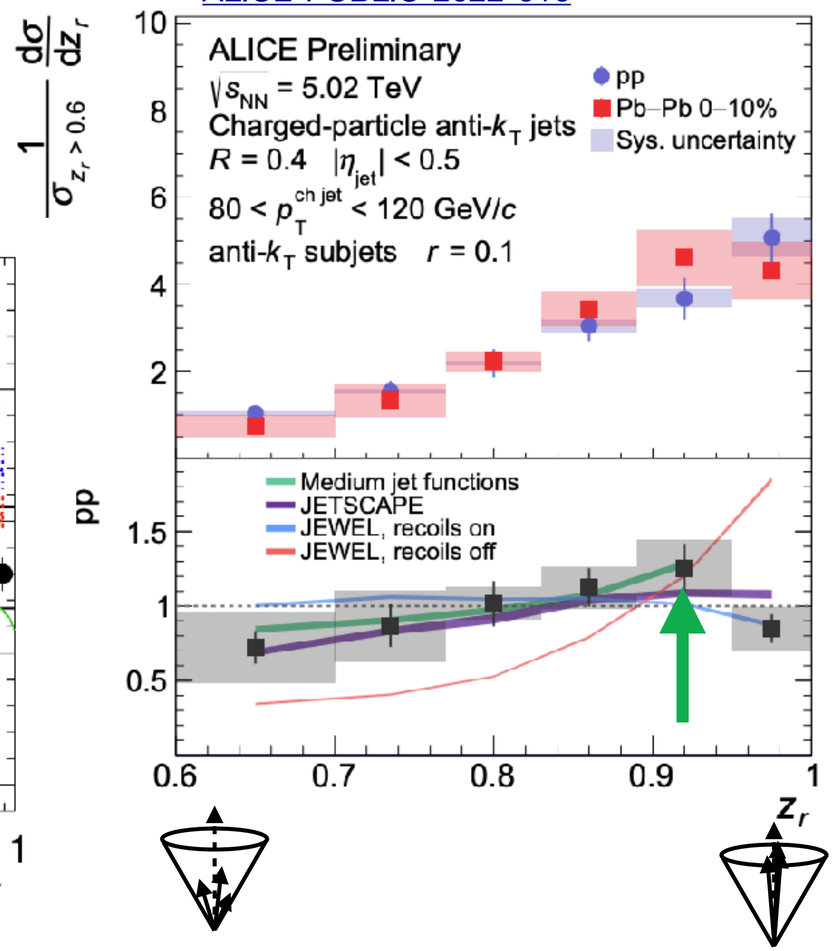
- Recluster constituents of R=0.4 jets into r=0.1 jets



- Hint of hardening at intermediate z -> similar to R_g and hadron FF



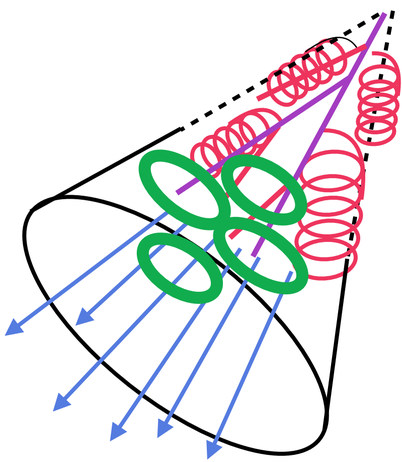
ALICE-PUBLIC-2022-016



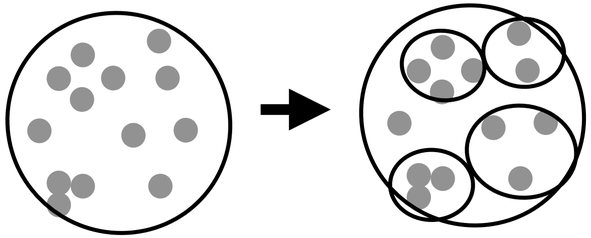
Subjet fragmentation

$$F(z_r) = \frac{1}{N_{\text{jet}}}\frac{dN}{dz_r}$$

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

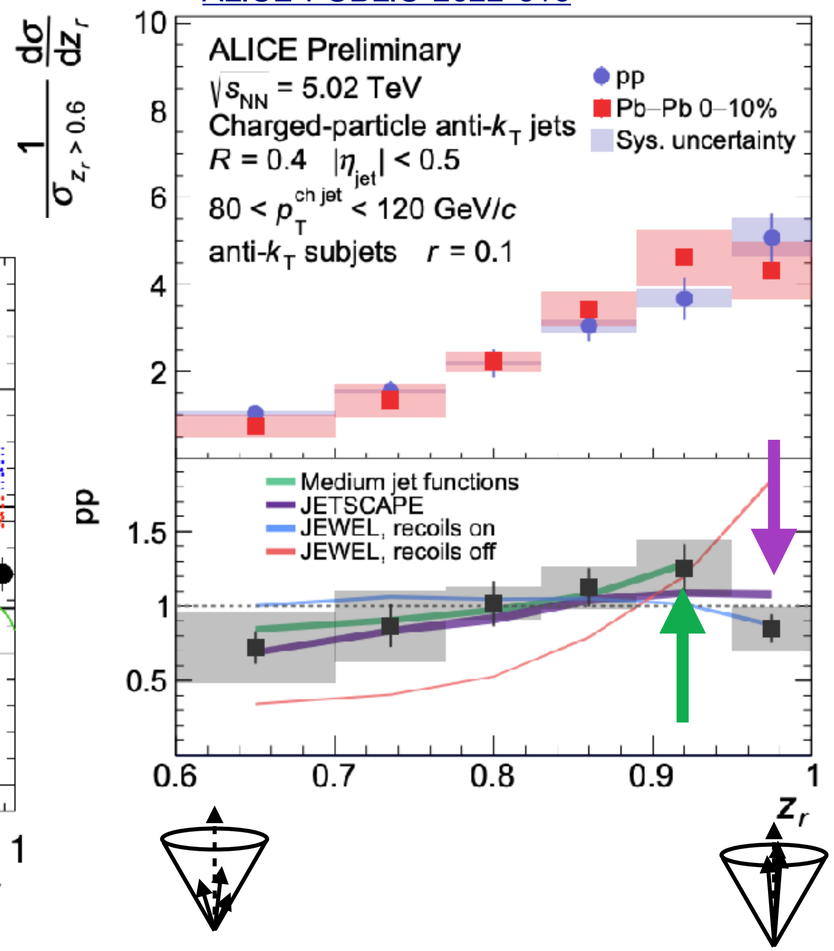


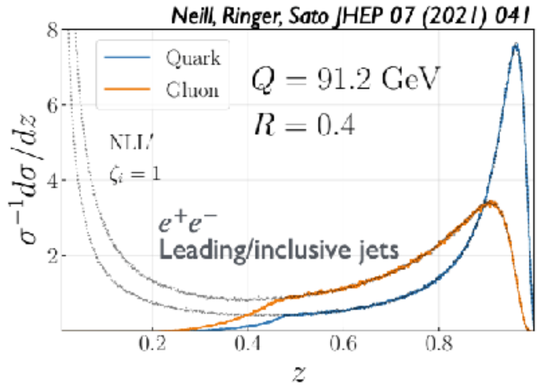
- Recluster constituents of R=0.4 jets into r=0.1 jets

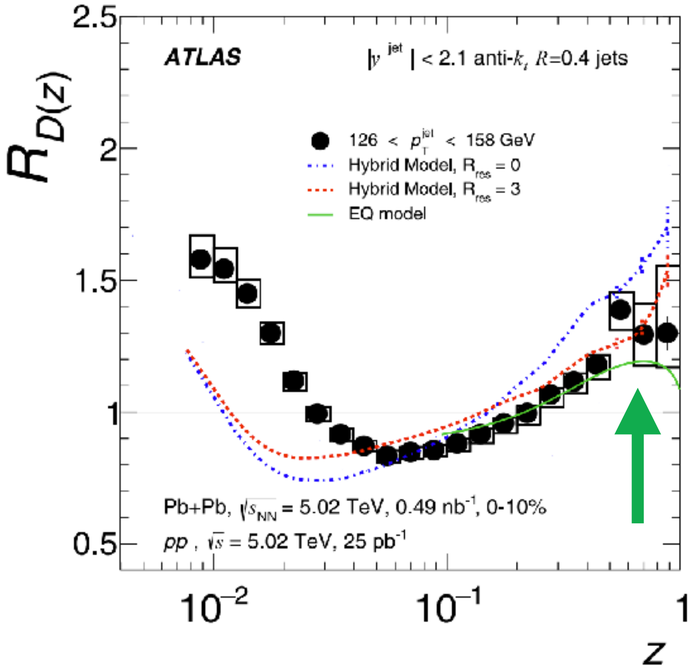


- Hint of hardening at intermediate z -> similar to R_g and hadron FF

ALICE-PUBLIC-2022-016

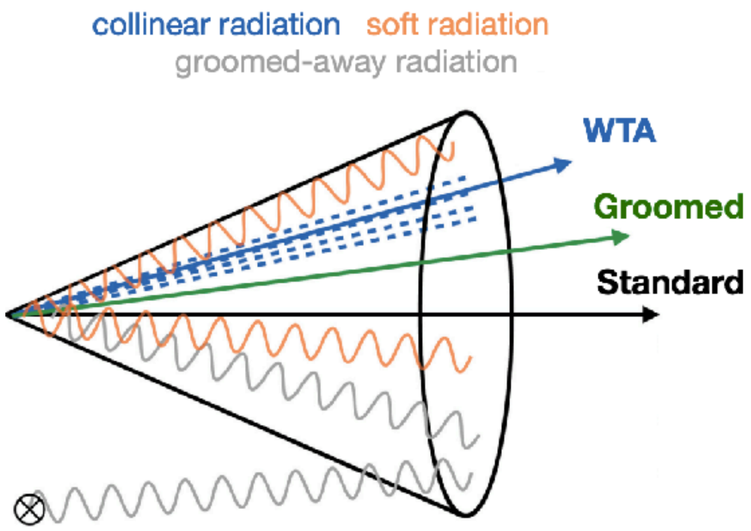






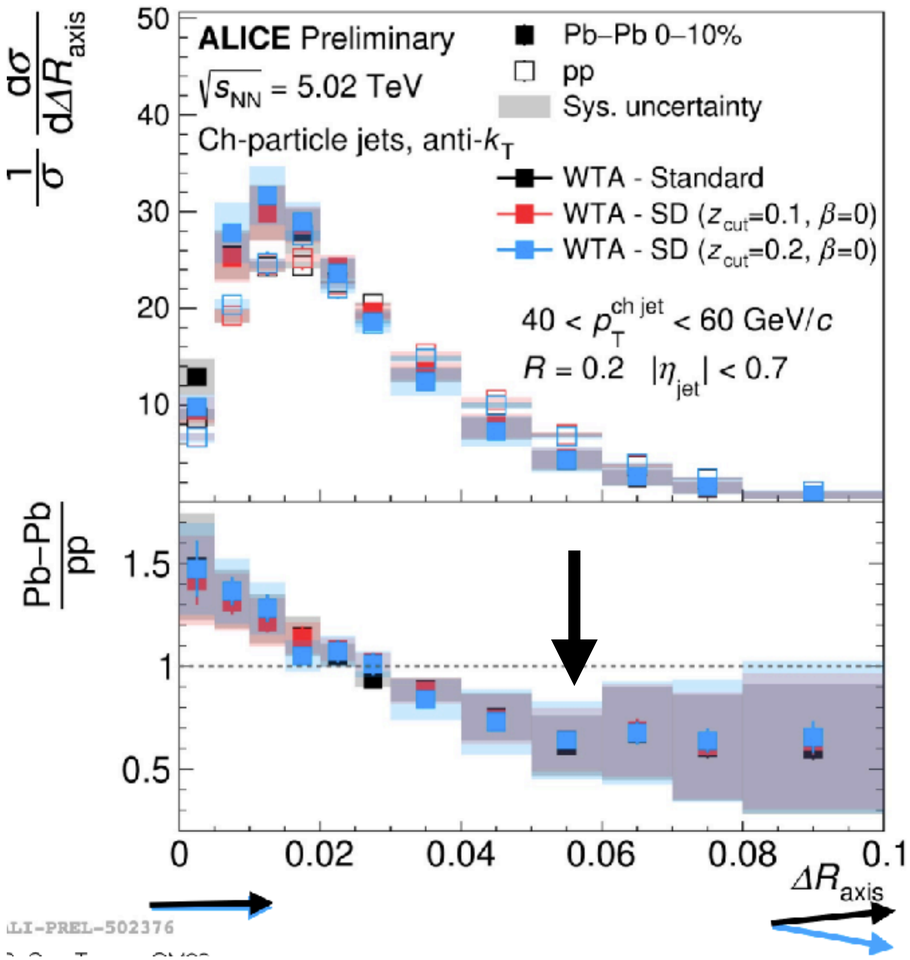
- Hint of suppression as z -> 1, energy loss of pure quarks?

Jet axis



P. Cal et al., JHEP 04 (2020) 211

: $\Delta R_{\text{axis}} = \sqrt{(y_2 - y_1)^2 + (\varphi_2 - \varphi_1)^2}$

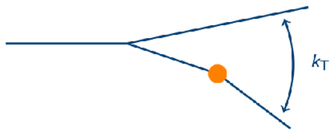


- *See narrowing effect*
- Not sensitive to grooming: does not change jet direction

Jet axis: model comparisons

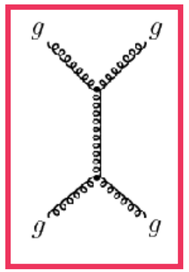
- Hybrid model: role of Moliere scattering?
  - -without Moliere
  - -with Moliere

Pablos et al JHEP (2020) 044

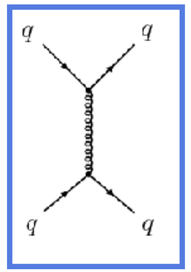


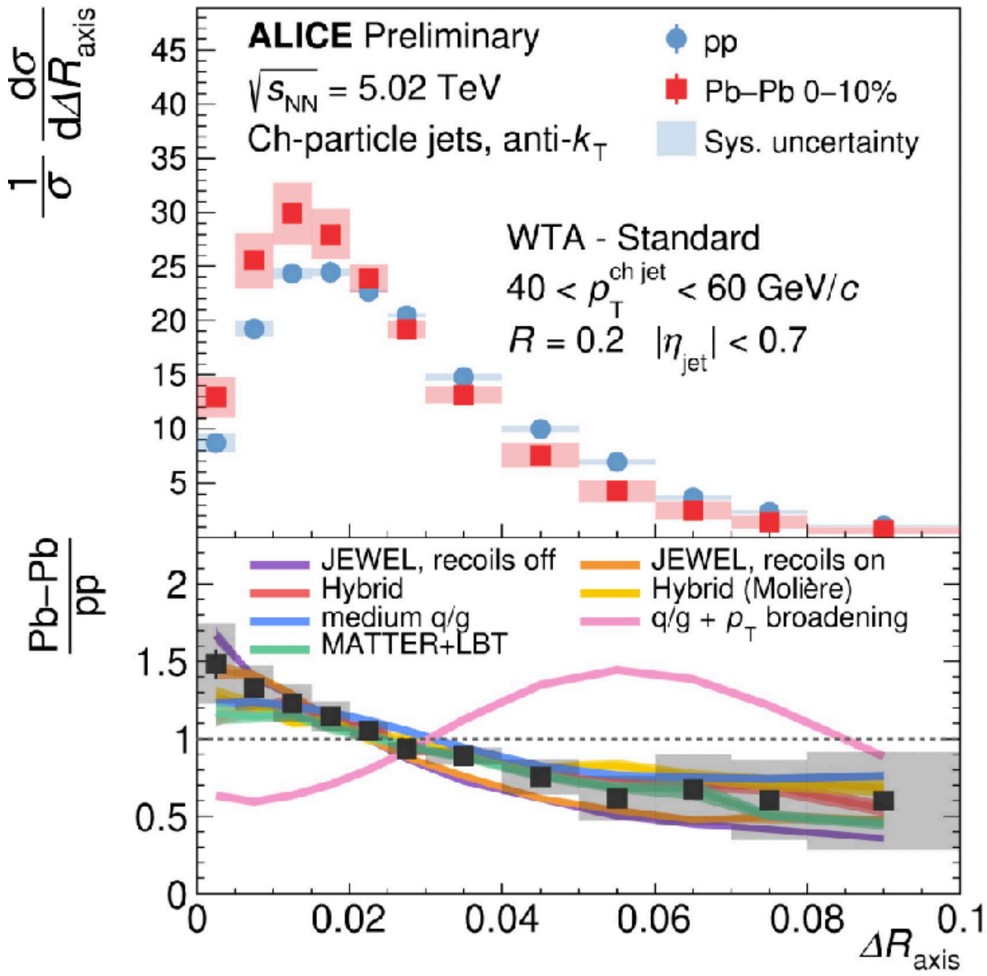
- Model: coherence with changing q/g fractions?
  - -medium q/g

Yuan et al arXiv:1907.12541



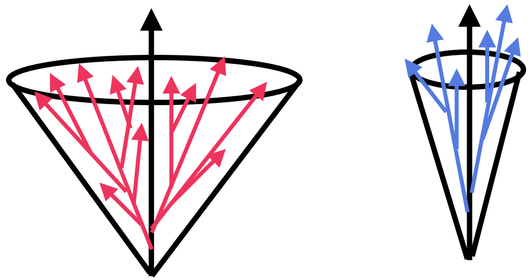
~(9/4)^2 x





Summary

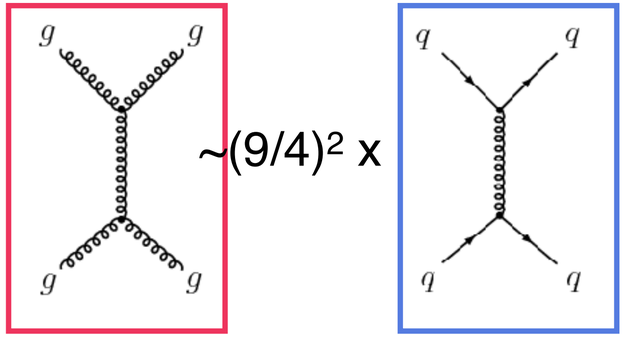
1. Narrowing effect in measurements sensitive to angular scale of jet: decoherence or quark vs. gluon jets?



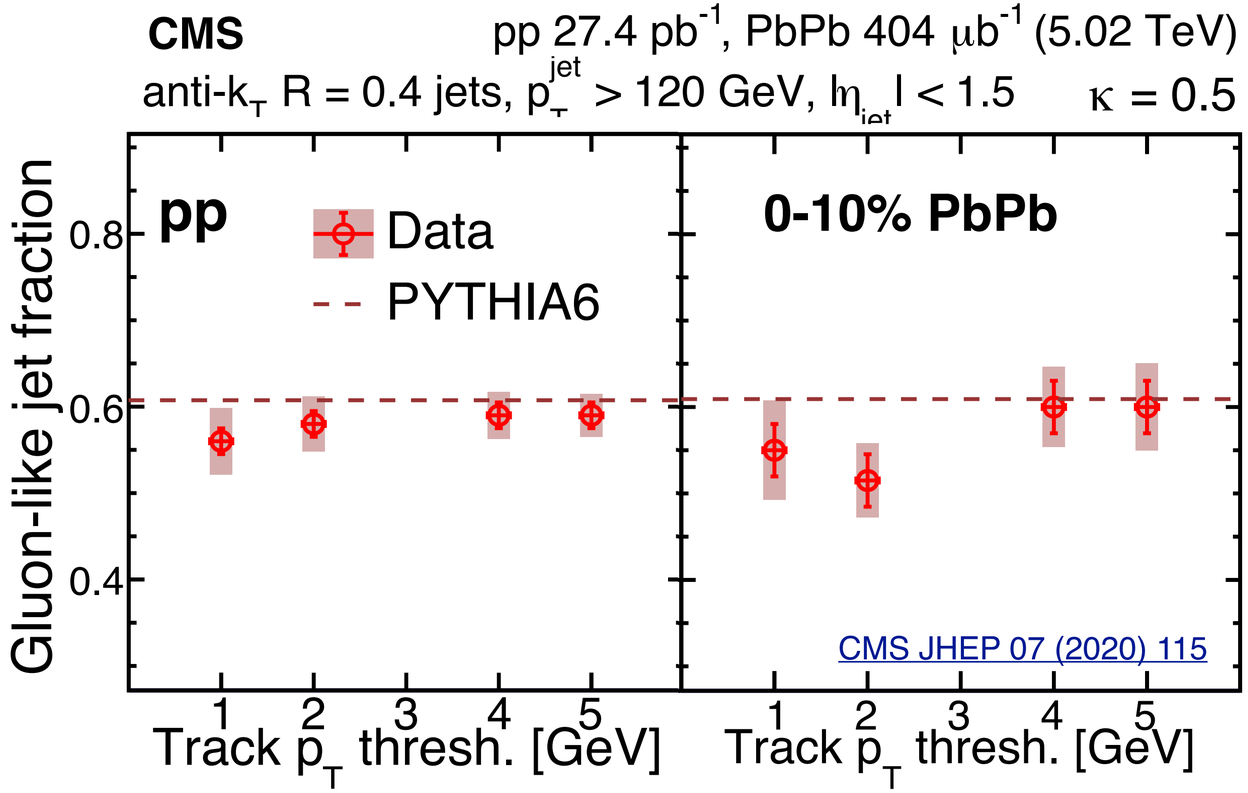
Jet charge: q/g fraction modification?

- Jet charge sensitive to electric charge of initial parton

$$Q^k = \frac{1}{p_T^{jet}} \sum_{i \in jet} q_i p_{T,i}^k$$



- Fractions in pp and Pb-Pb similar -> no modification of gluon fraction?

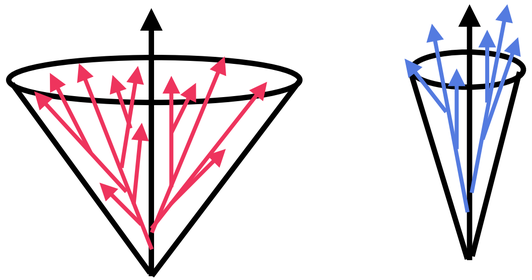


- *Possibly indicates that narrowing is due to decoherence effects!*
- Is this measurement sensitive to same effects as jet mass?

Summary

1. Narrowing effect in measurements sensitive to angular scale of jet: decoherence or quark vs. gluon jets?

    “Survivor bias”?



“Survivor Bias”

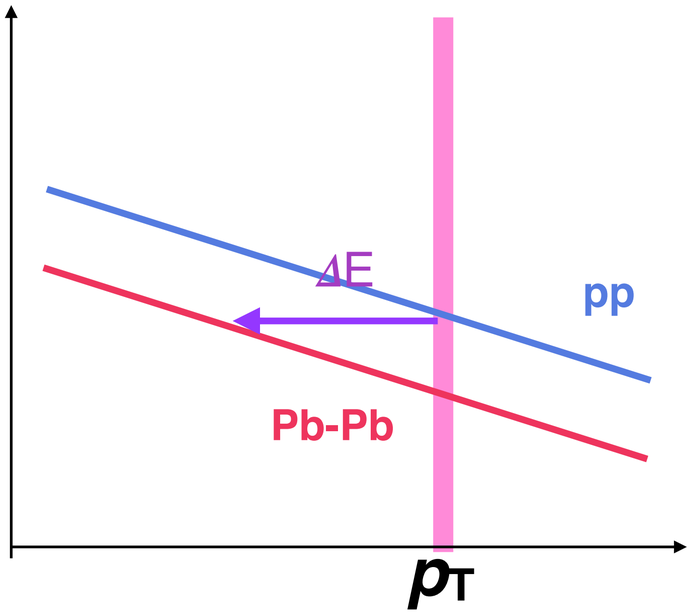
C. Nattrass recent talk at INT

Comparing final modified Pb-Pb jet to unmodified pp jets instead of comparing the initial unmodified jets

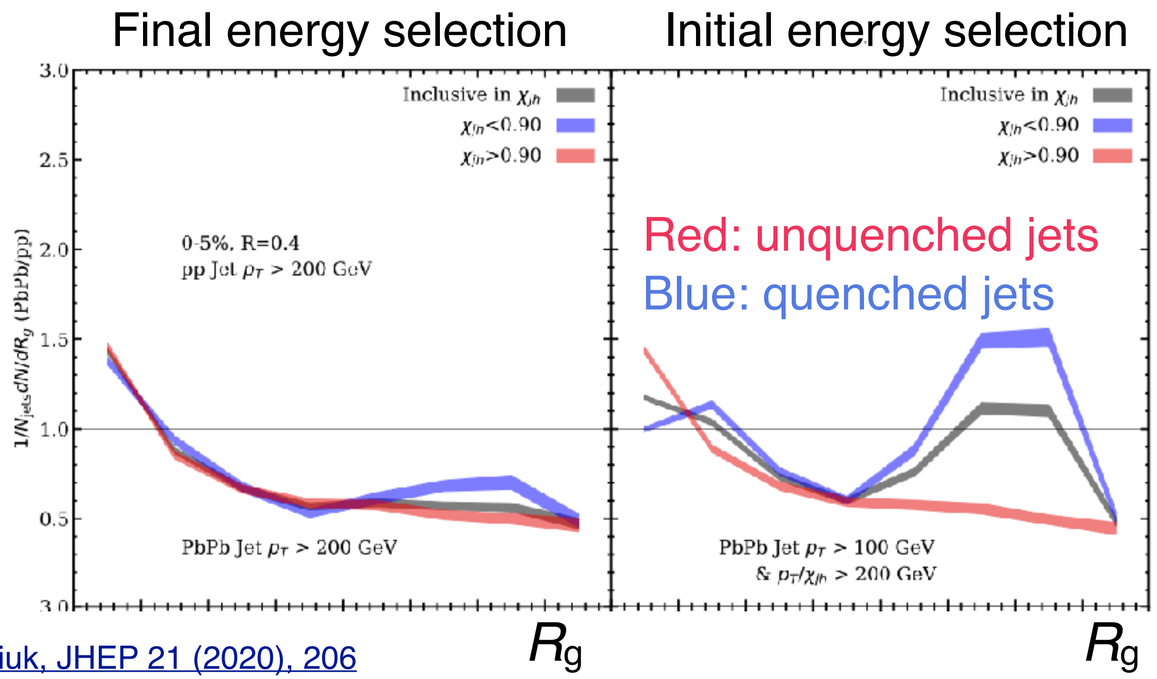
“Survivor bias” where at a fixed p_T bin we are left with less quenched narrower jets

Cole, Spousta EPJ C76 (2016) 50
Caucal et al *JHEP* **2020,** 204 (2020)

Brewer, et al PRL **122**, 222301
Brodsky et al arXiv:2009.03316



- Selection on the initial instead of final energy removes narrowing effect for more quenched jets in hybrid model



Du, Pablos, Tywoniuk, JHEP 21 (2020), 206

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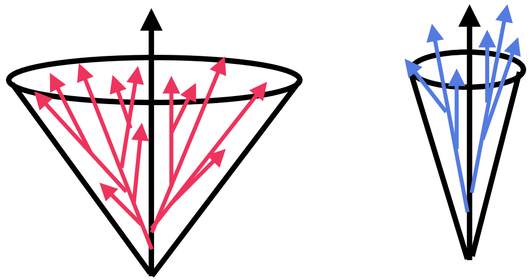

2. No modification to splitting function?

Summary

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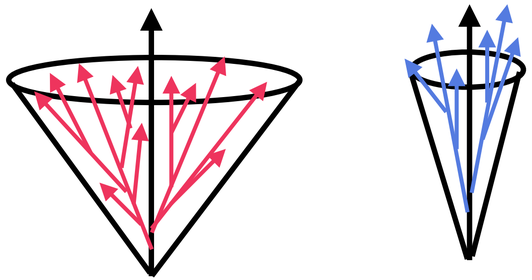
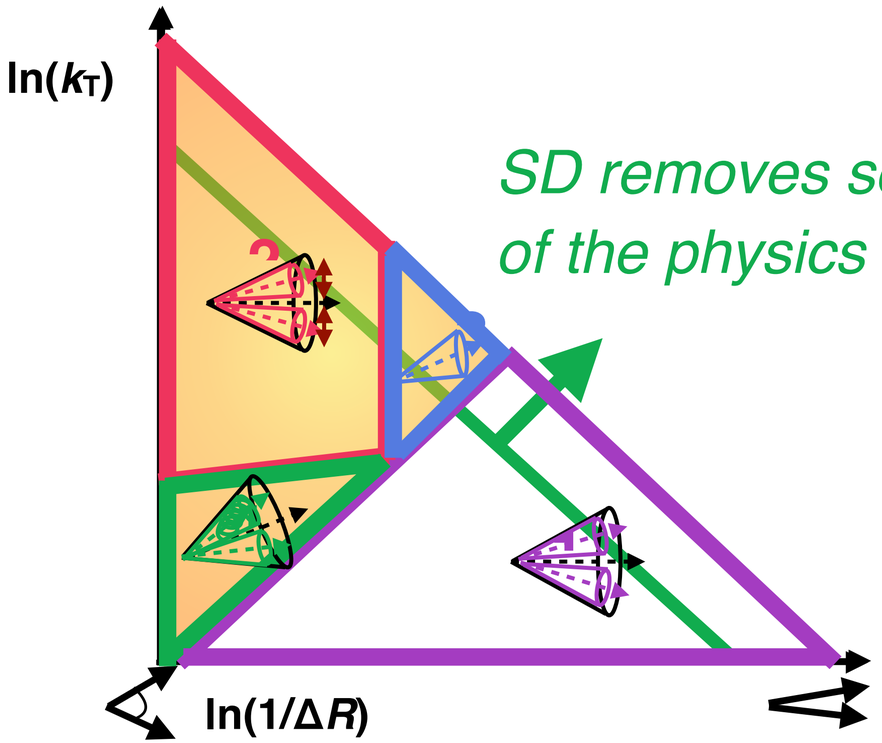


2. No modification to splitting function?

Could we be removing in-medium splittings with grooming?

Subjet fragmentation sensitive to this at high z!



SD removes some of the physics

Summary

1. Narrowing effect in measurements sensitive to angular scale of jet: decoherence or quark vs. gluon jets?

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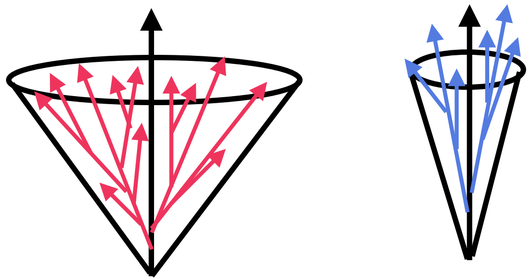

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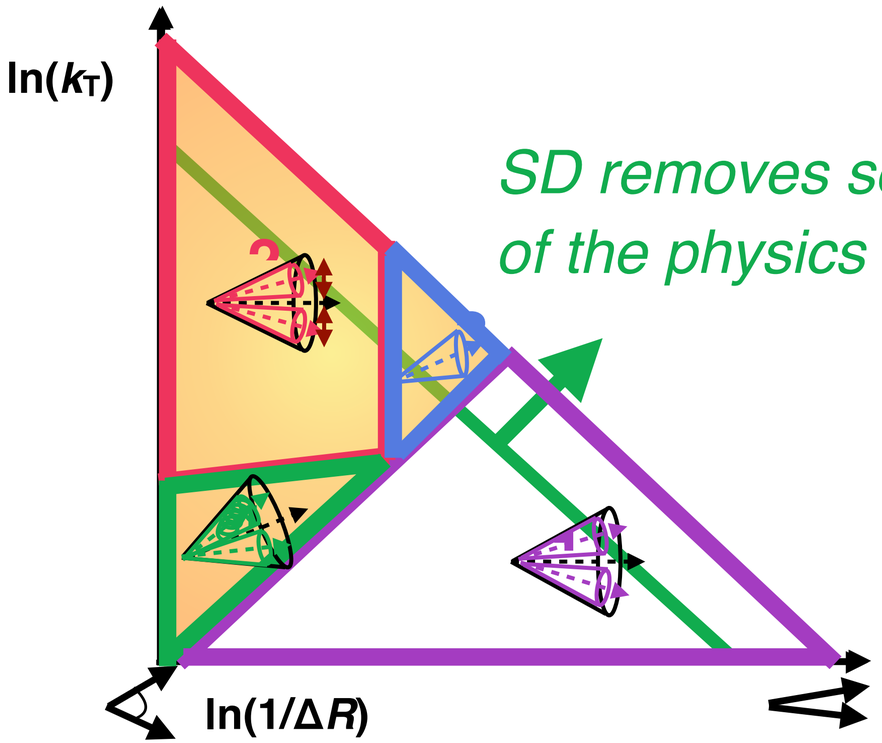


SD removes some of the physics

3. Measurement not sensitive enough to measure Moliere scattering

   Seen in acoplanarity measurements (Peter's talk)

See Raymond's talk for future ideas!

Thank you!

Backup

Jet quenching expectations

- Jet energy loss -> jet suppression

Depends on the path traveled in the medium

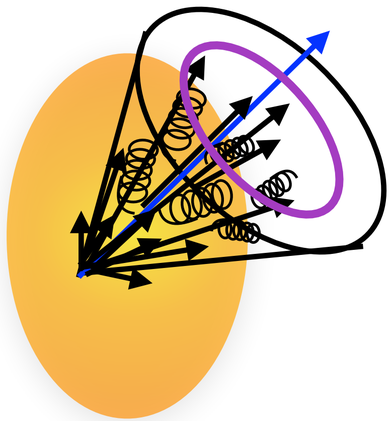
Flavor dependence

See talk by Anne

- Complicated internal structure is modified in the medium

- Jet-medium interactions:

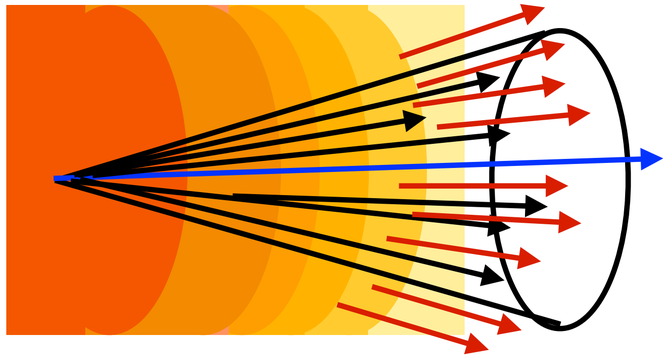
➡ Momentum broadening widens jet

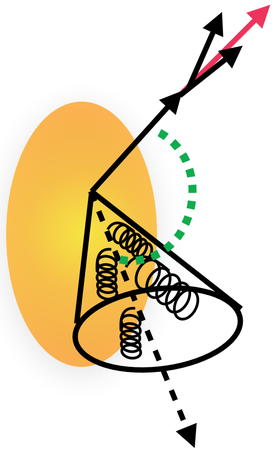


➡ Wide-angle deflection

See talk by Peter

➡ Medium response, causing a wake of soft particles





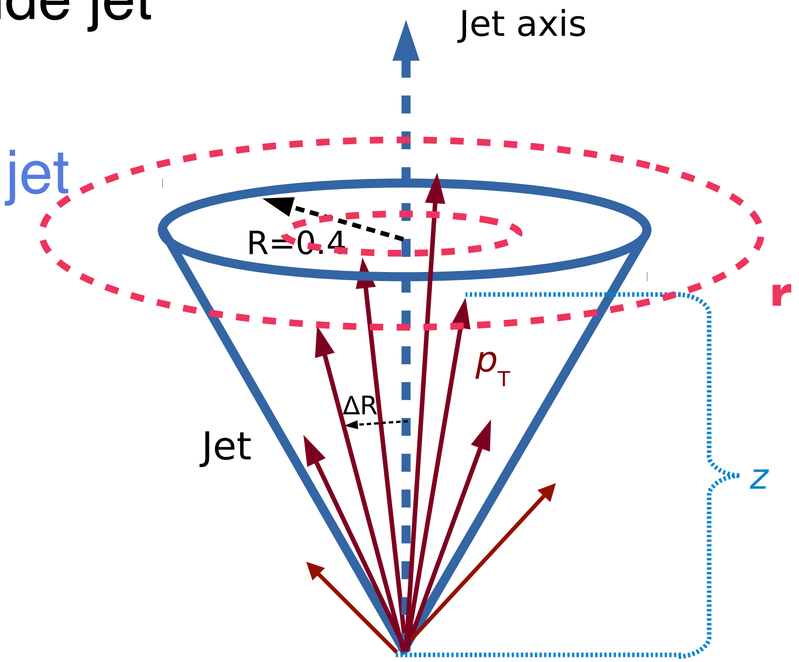
Hadron-level observables

- Distributions of particles inside jet

Jet fragmentation: longitudinal profile of charged particles in a jet

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{\mathrm{d}N_{ch}}{\mathrm{d}z}$$

$$z = \frac{p_{\mathrm{T}} \cos \Delta R}{p_{\mathrm{T}}^{\text{jet}}}$$

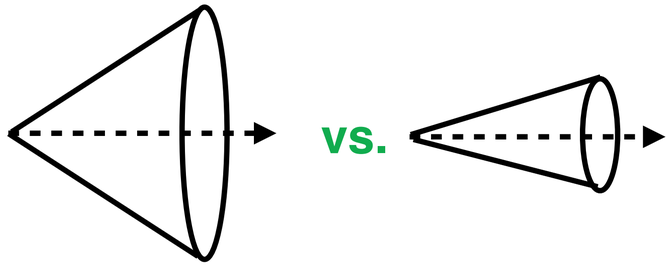


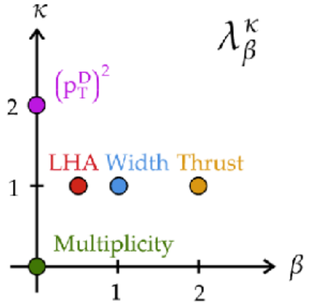
Jet shape: radial profile of charged particles in a jet

$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \frac{\sum_{\text{jets}} \sum_{\text{tracks} \in (\Delta r_a, \Delta r_b)} p_{\mathrm{T}}^{\text{ch}}}{\sum_{\text{jets}} \sum_{\text{tracks} \in \Delta r \leq 1} p_{\mathrm{T}}^{\text{ch}}}$$

- Properties of the jet (generalized angularities)

How wide are the jets?

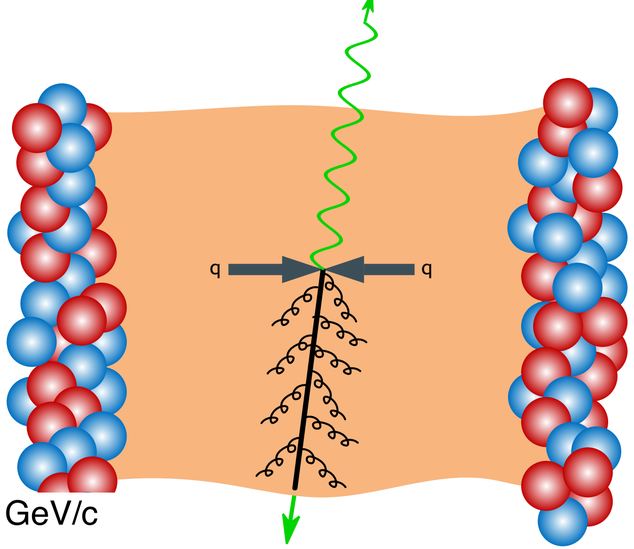




$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$

Related to jet shapes:
Angularity (girth) g α=1
~Mass α=2

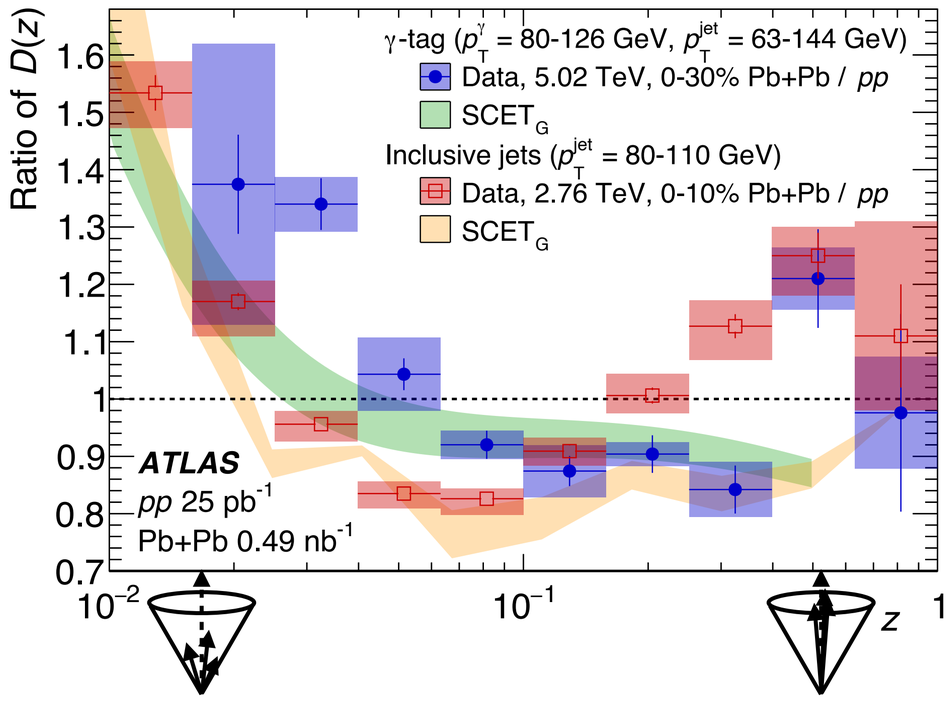
Boson-tagged jet structure



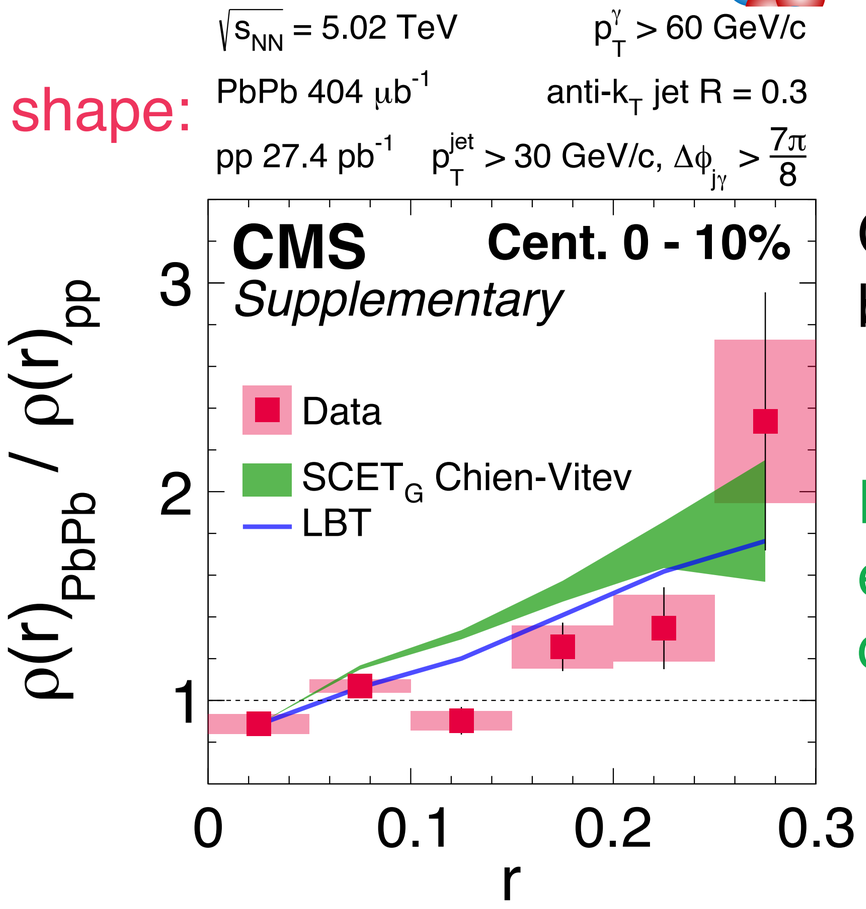
- Boson-jets dominated by quark jets
- Boson tag provides approximate initial momentum of jet (no energy loss)

- Photon-jet fragmentation

PRL 123 (2019) 042001



- Photon-jet shape:



Qualitatively similar behavior to inclusive

Except high z enhancement disappears?

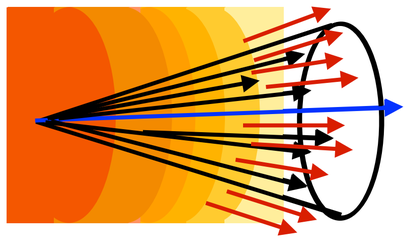
PRL 122 (2019) 1520

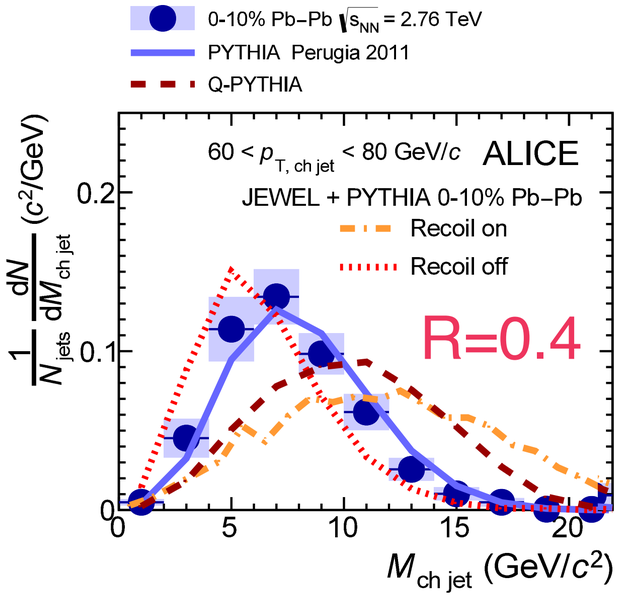
Groomed jet angularities

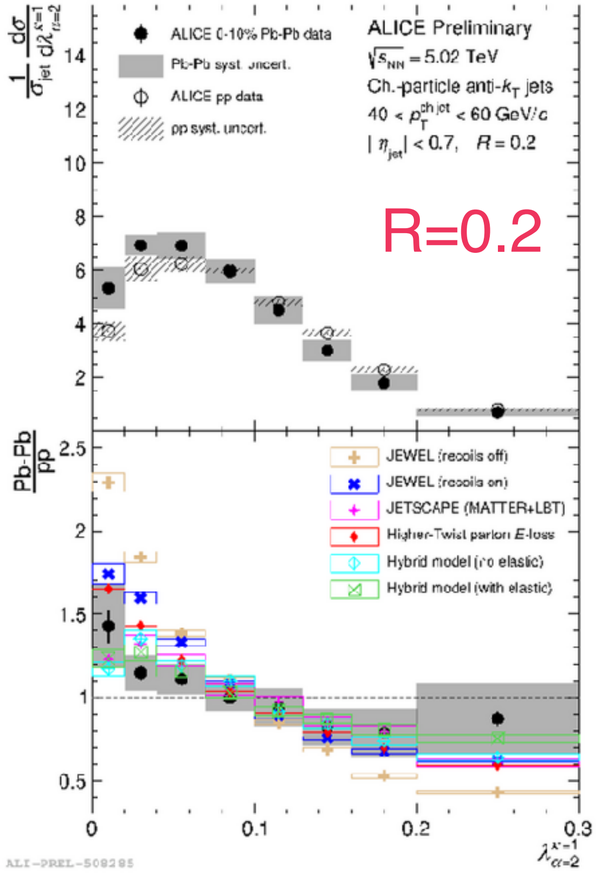
- See grooming reduce sensitivity to medium recoil

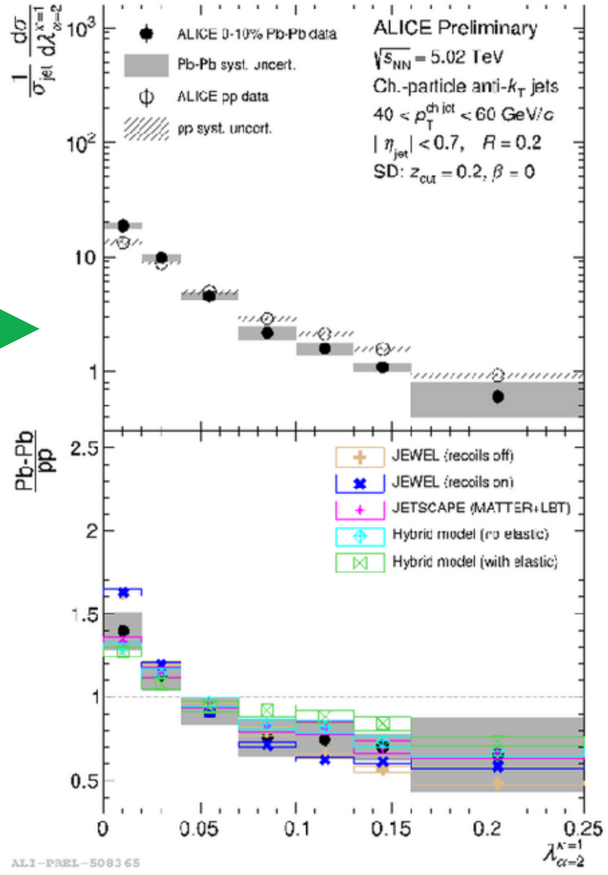
Jewel with recoil

Jewel without recoil









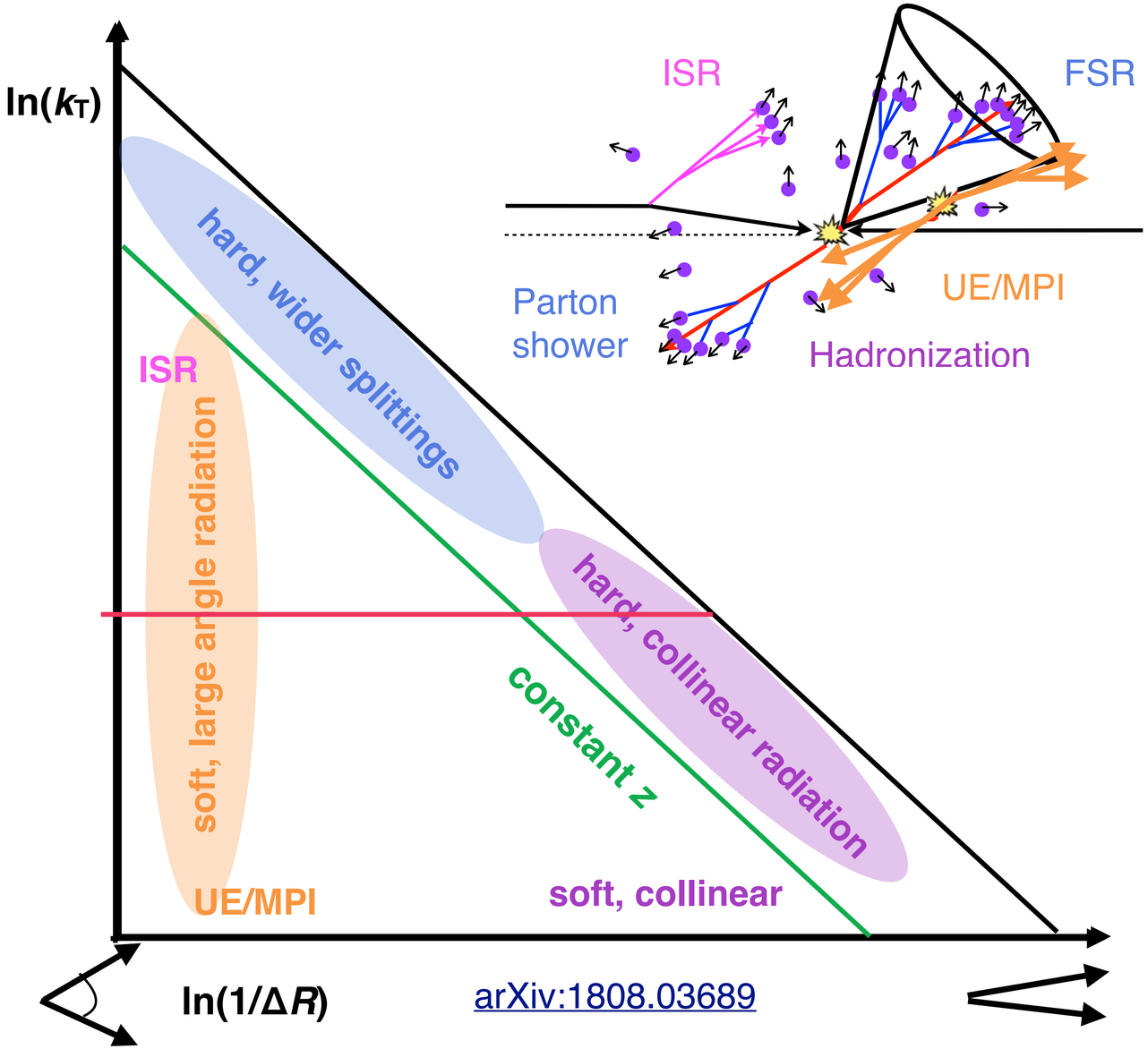
- Not as sensitive as jet mass measurement but uses different jet radii

Laura Havener, Yale University

Vacuum: exploring phase space of QCD

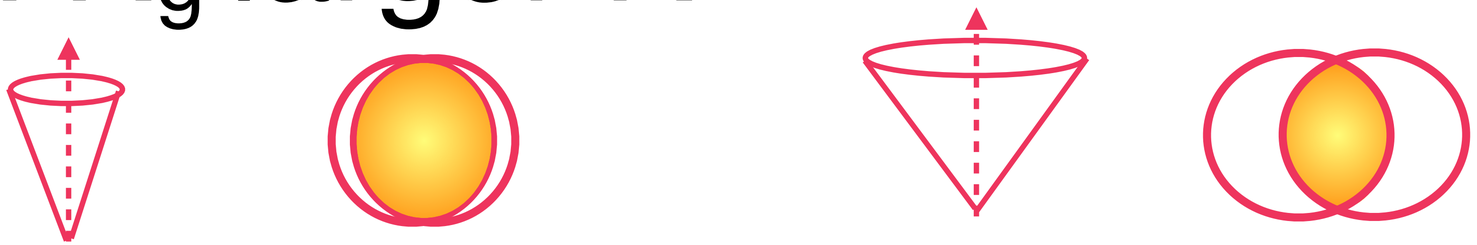
- Isolate different QCD effects like ISR, UE, MPI, hadronization, perturbative vs. non-perturbative emissions, etc. and tune MC models

- $k_T \sim \Lambda_{QCD}$ separates perturbative from non-perturbative regime

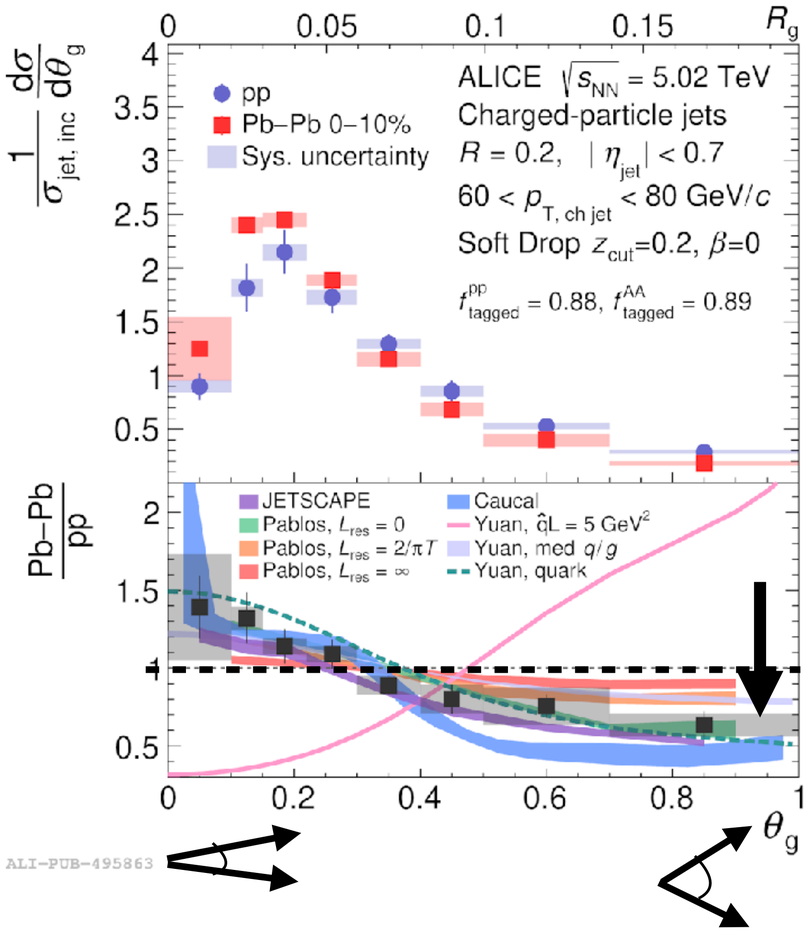


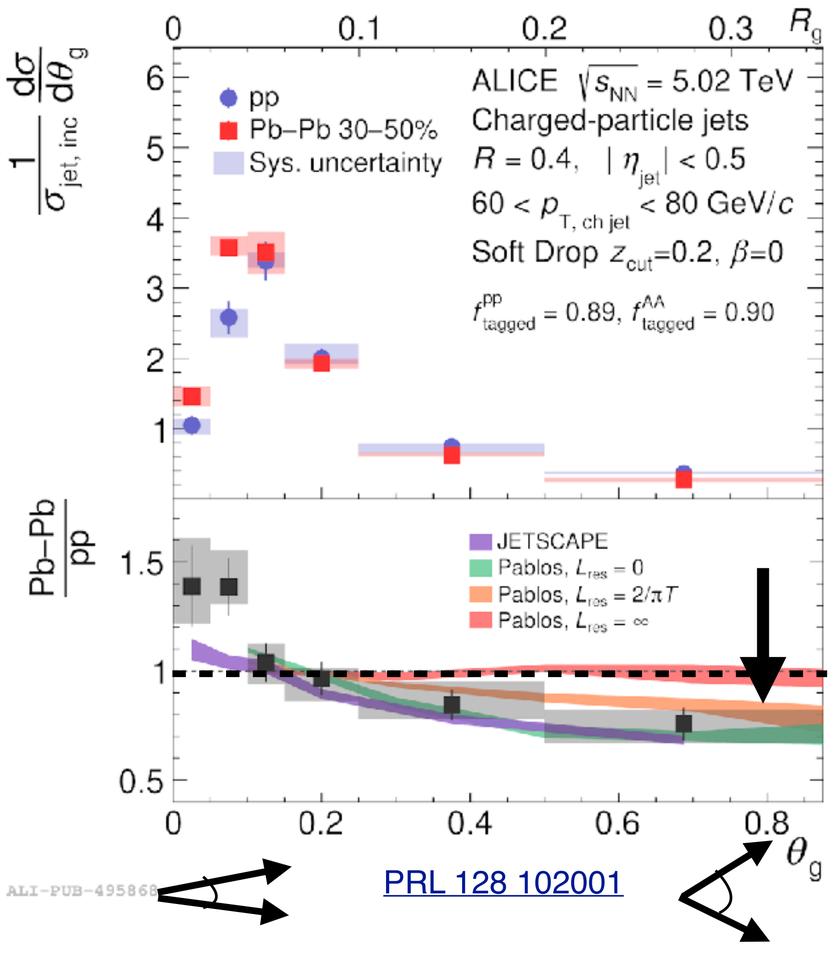
arXiv:1808.03689

Jet splittings: R_g larger R



- *Narrowing remains for larger R in more semi-central collisions*

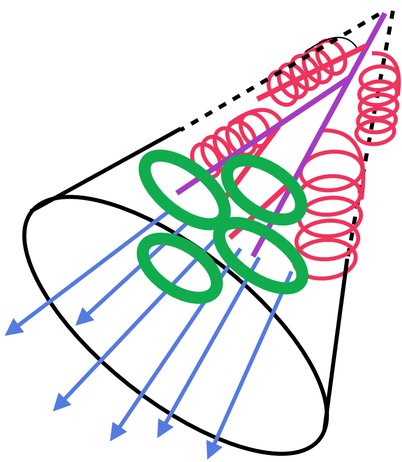




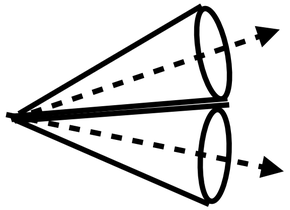
PRL 128 102001

N-subjettiness

$$\tau_N = \frac{\sum_{i\in\text{jet}} p_{T,i} \min \Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N}}{R p_{T,\text{jet}}}$$

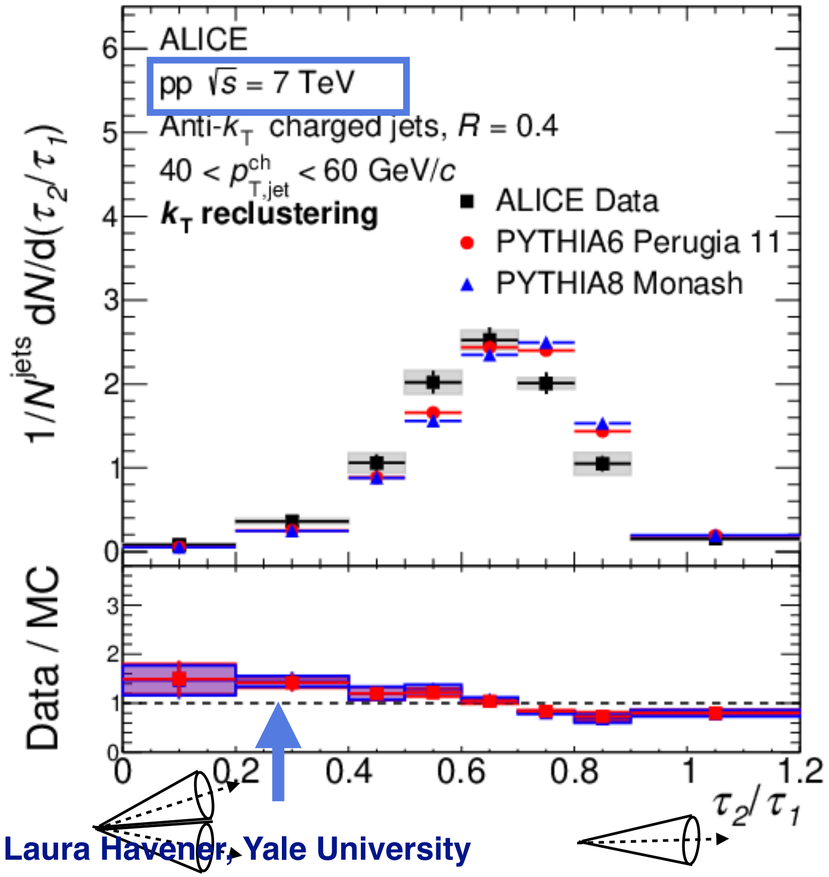


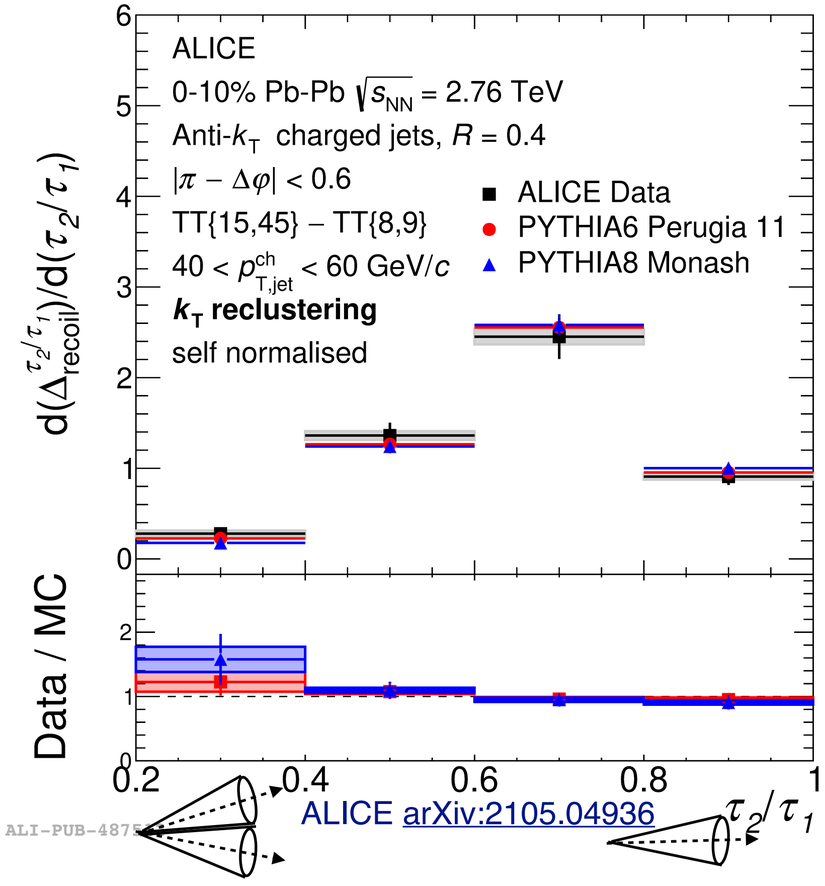
- k_T reclustering selects hard subjets



$\tau_2/\tau_1 -> 0$
Jet has 2 prongs

Are the prongs resolved by the medium?





ALICE arXiv:2105.04936

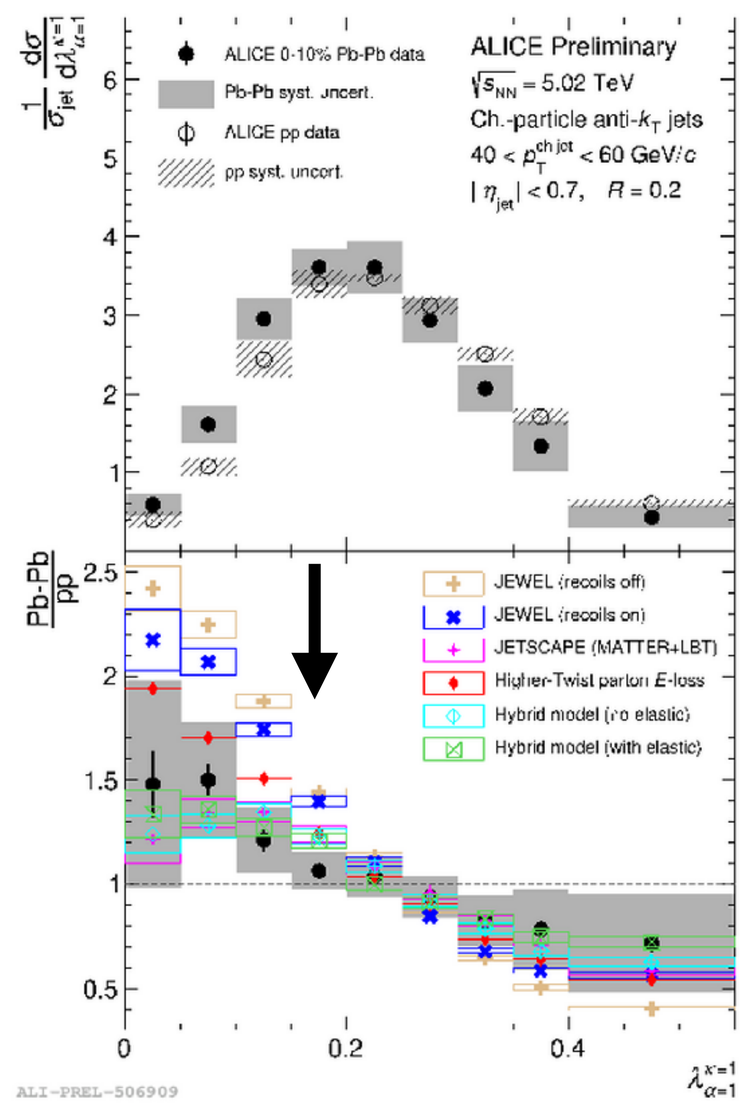
- Fully corrected τ_2/τ_1 in pp and Pb-Pb data compared to PYTHIA

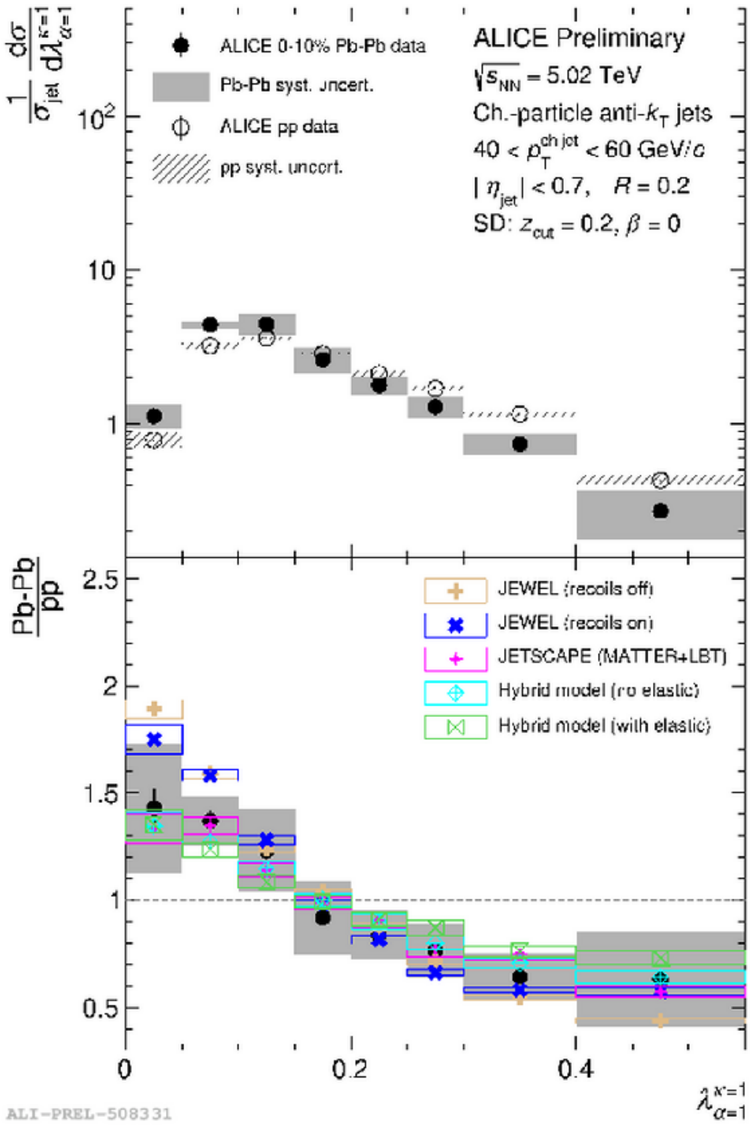
p/MC > 1 Pb-Pb/MC ~ 1

Pb-Pb/pp < 1

Hint of suppression of 2-prongness in HIs

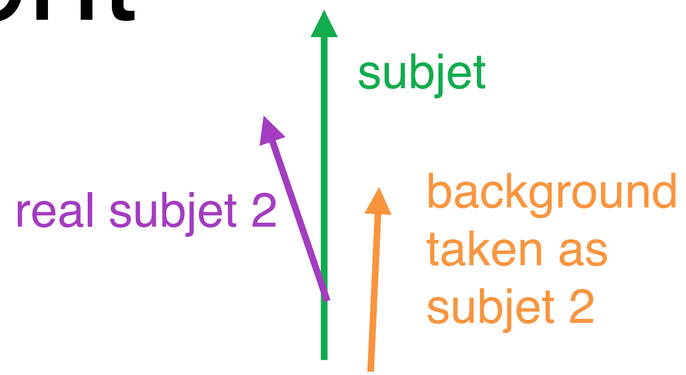
Groomed jet angularities



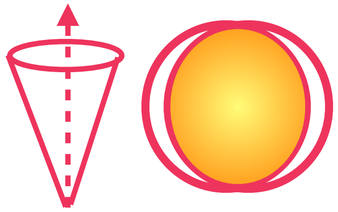


Background treatment

- Uncorrelated background leads to incorrect splittings
- Solutions:

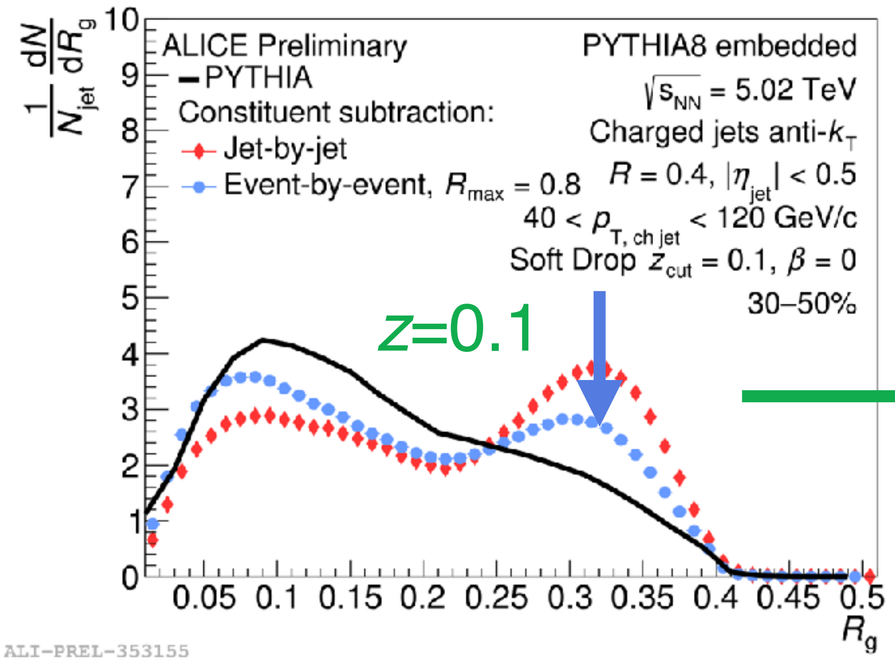


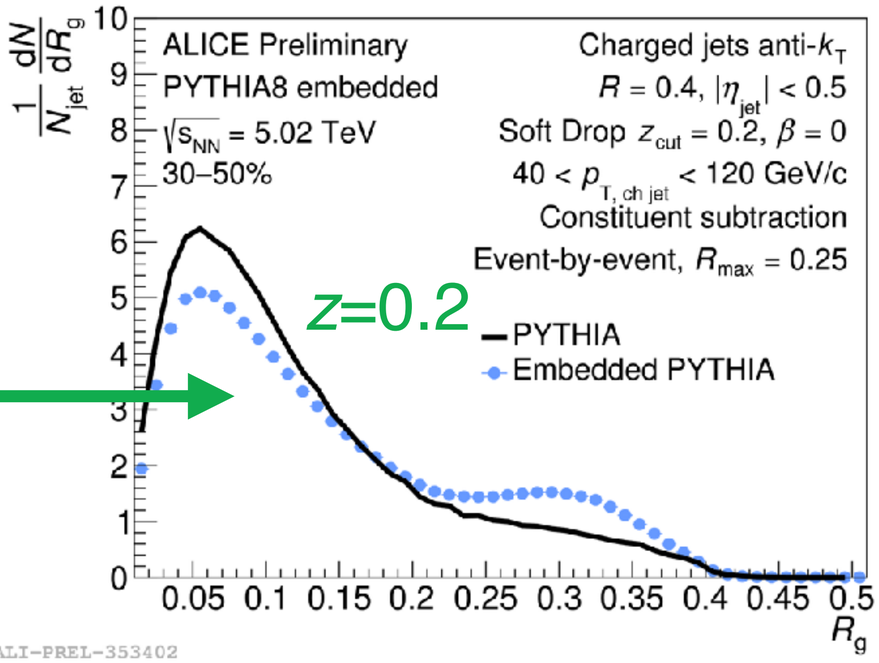
1. smaller jet radii



or semi-central collisions

2. tighter SD condition





ALICE R-scan: narrowing

- ALICE ML-based R_{AA}
- Seems to imply a narrowing of the jet

See Hannah Bossi's talk at QM for details