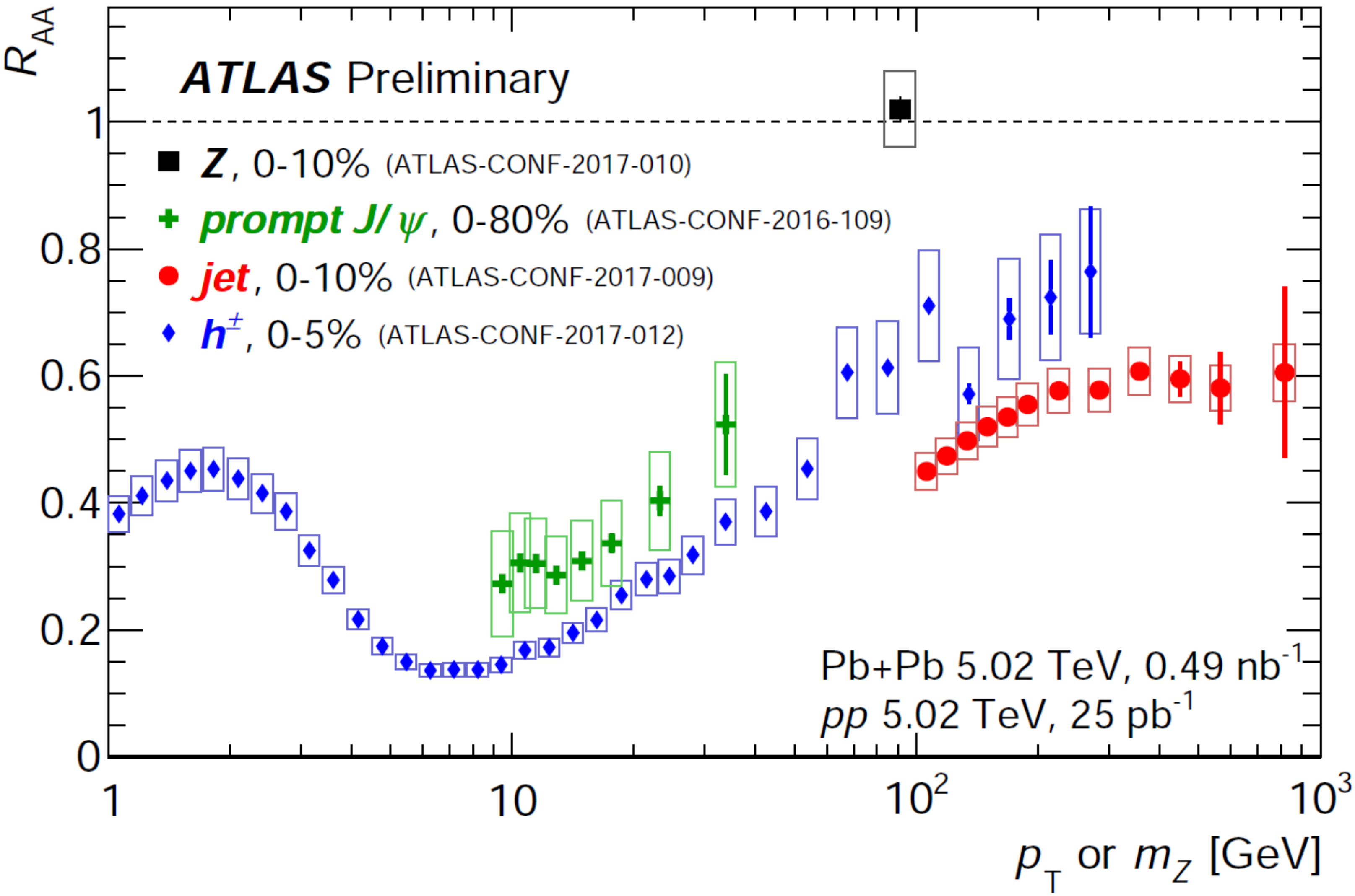
jet structure

Mateusz Ploskon, LBL

Sketches by
J. Thaler

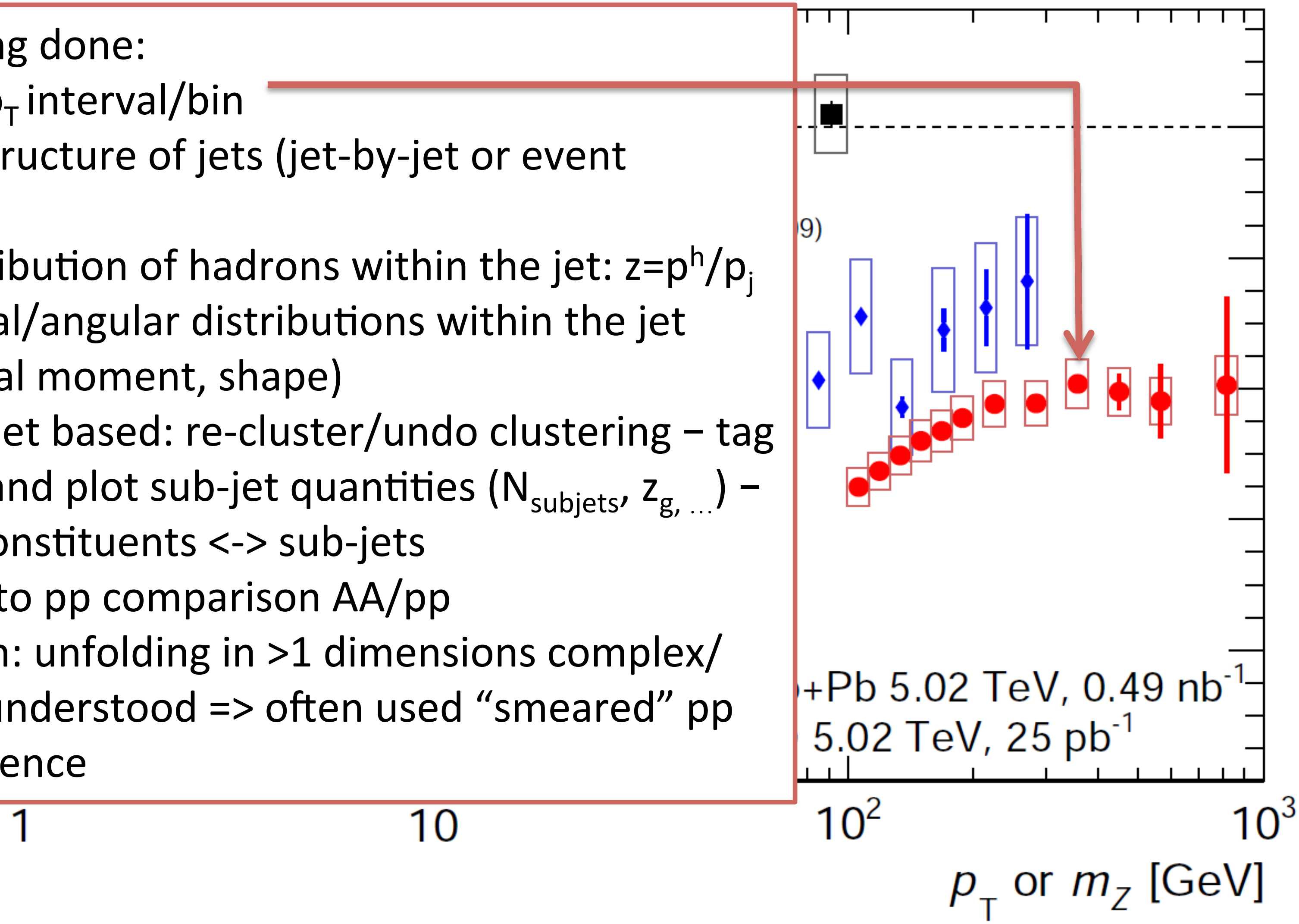
Substructure



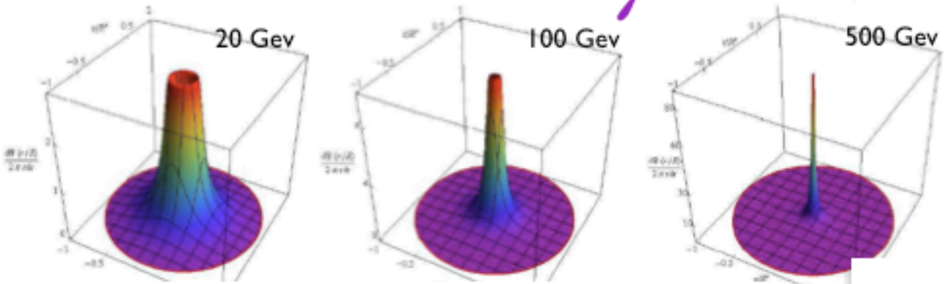
Substructure

What is being done:

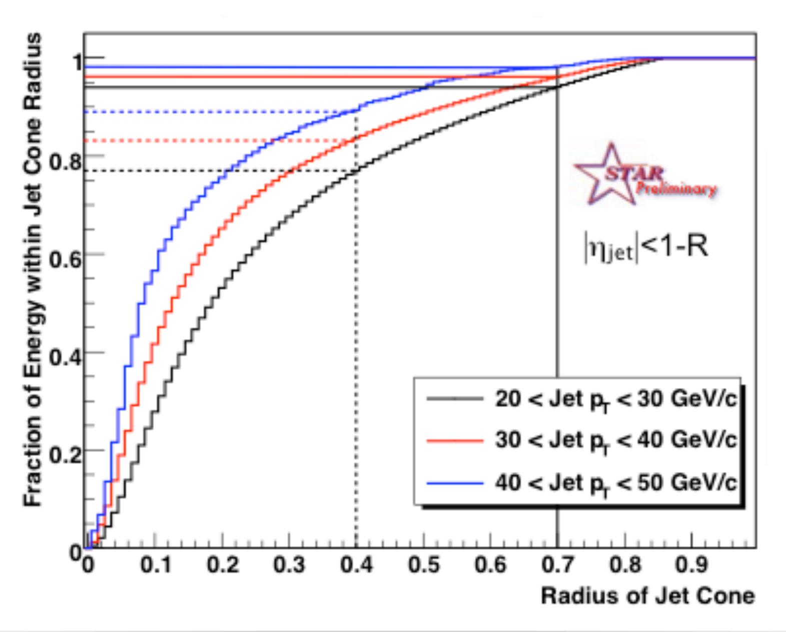
- Select a p_T interval/bin
- Extract structure of jets (jet-by-jet or event average)
    - Distribution of hadrons within the jet: $z=p^h/p_j$
    - Radial/angular distributions within the jet (radial moment, shape)
    - Sub-jet based: re-cluster/undo clustering – tag jets and plot sub-jet quantities ($N_{subjets}$, $z_{g, \dots}$) – jet constituents <-> sub-jets
- Build AA to pp comparison AA/pp
    - Warn: unfolding in >1 dimensions complex/ not understood => often used “smeared” pp reference

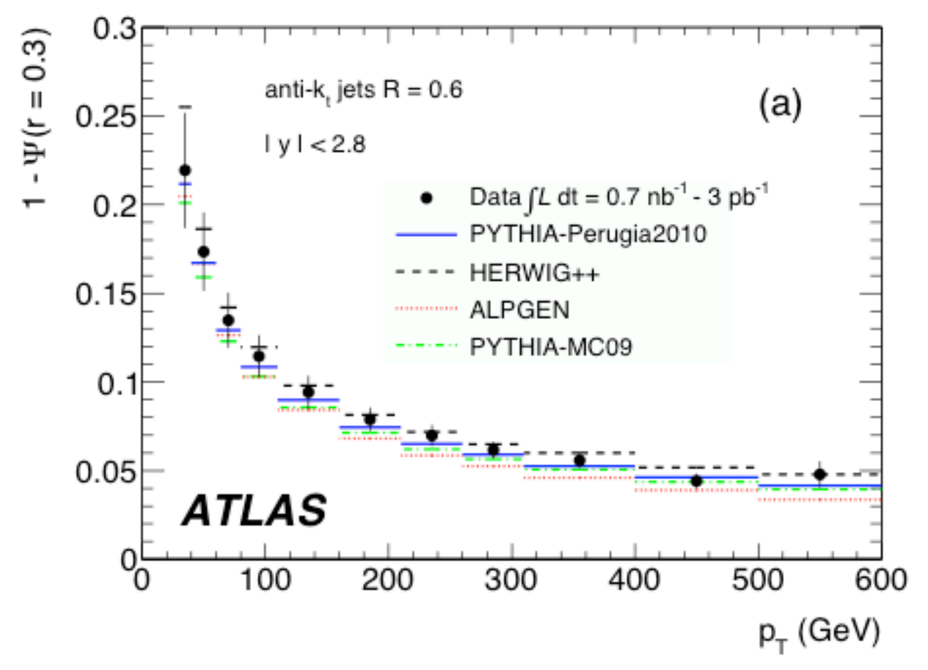


Jet shape - R-dependence



$$\Psi(r) = \frac{1}{N^{\mathrm{jet}}} \sum_{\mathrm{jets}} \frac{p_T(0,r)}{p_T(0,R)}$$

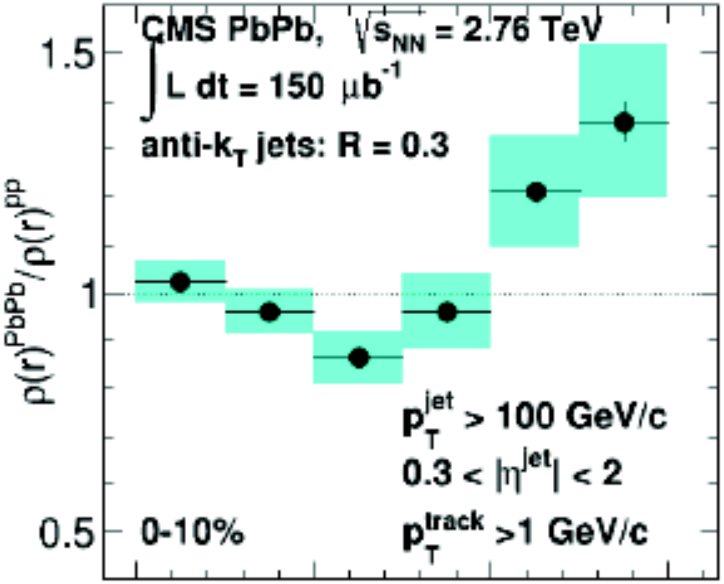




Jets get more collimated/narrower with increasing jet

Jet shape in AA

CMS PLB 730 (2014) 243



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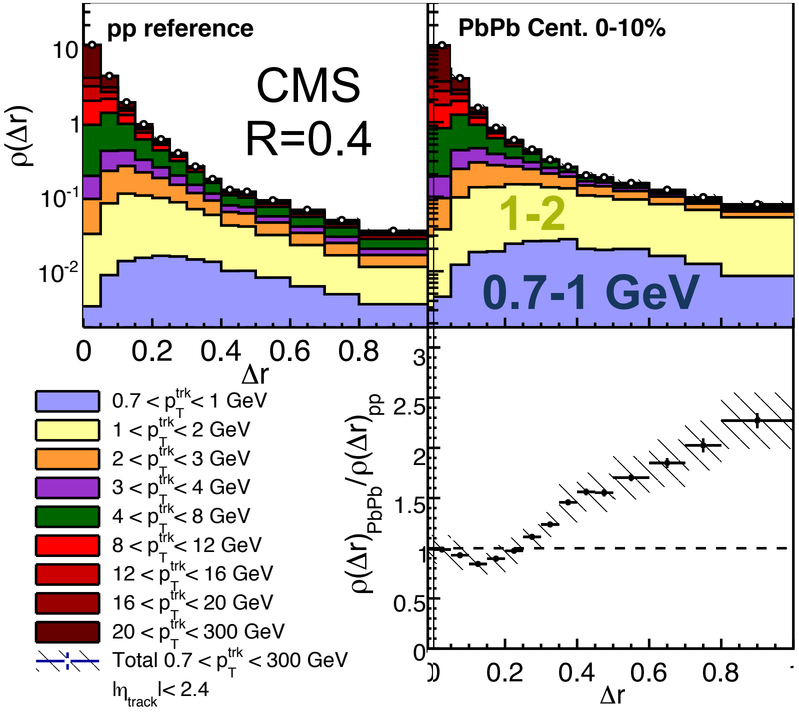
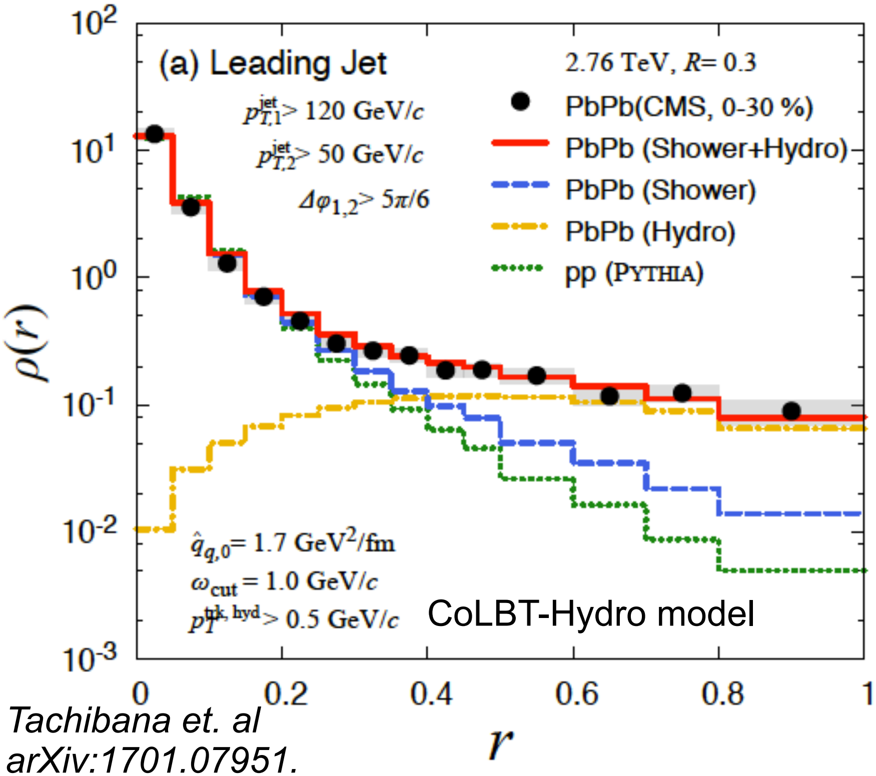




CoLBT-Hydro model

Tachibana et. al
arXiv:1701.07951.

Quenched parton shower
+ medium excitation

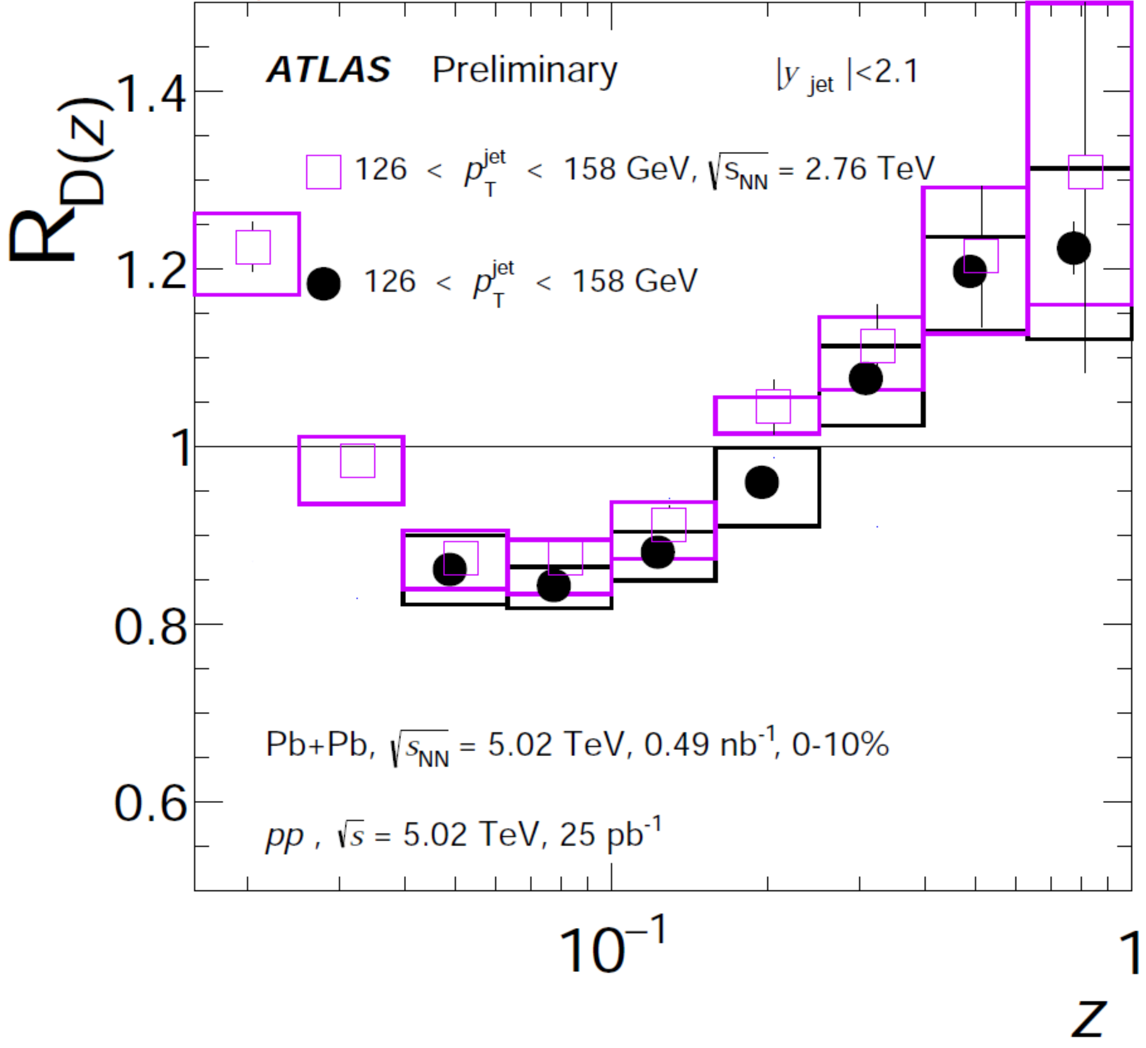
Quenched parton shower

Vacuum parton shower

Medium response needed to explain large angle measurements

Internal jet structure with particles

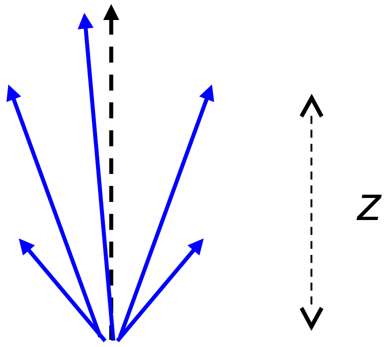
p_T^{hadron} > 4 GeV/c



$$R_{D(z)} = \frac{D(z)|_{\mathrm{cent}}}{D(z)|_{pp}}$$

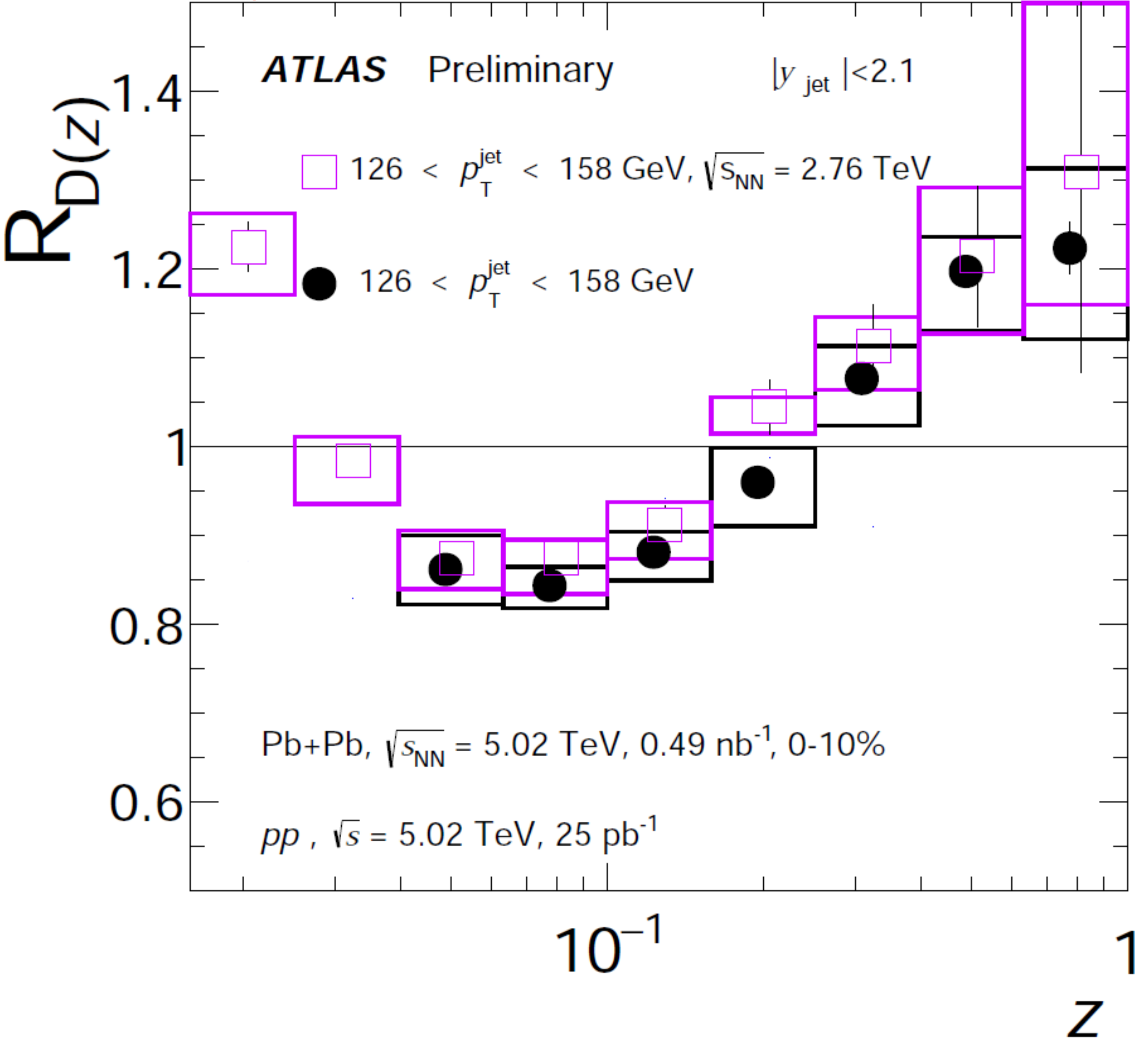
$$D(z) = \frac{1}{N_{jet}} \frac{\mathrm{d}N}{\mathrm{d}z}$$

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



Internal jet structure with particles

p_T^{hadron} > 4 GeV/c



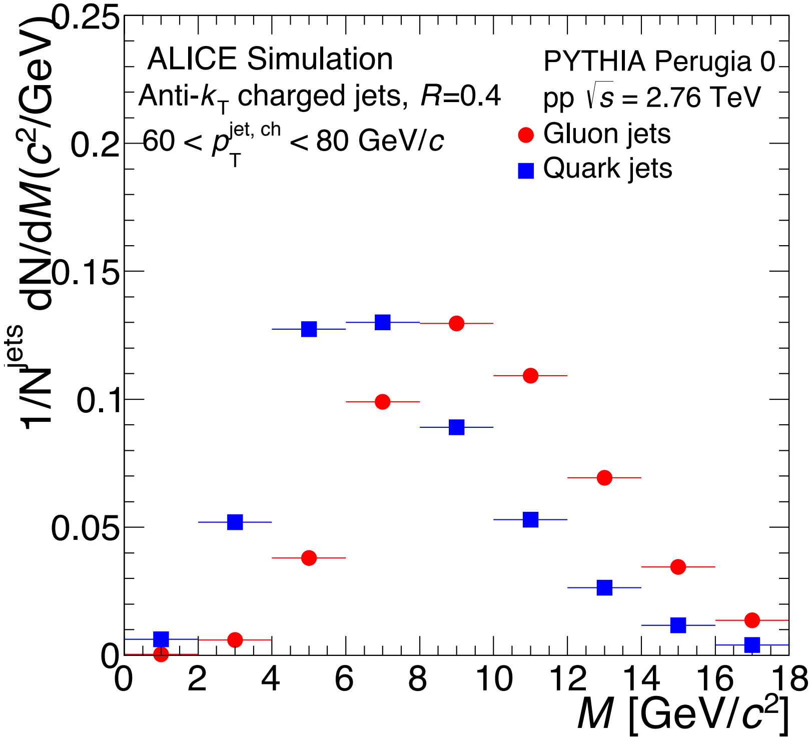
$$R_{D(z)} = \frac{D(z)|_{\mathrm{cent}}}{D(z)|_{pp}}$$

Gross features:
- Enhancement of high-z
- Depletion of low-z
- Enhancement at *very* low-z (?)
- Weak (none) jet p_T dependence

=> Medium “filter” promotes high-momentum fragments – more collimated jets

Mass of a jet

- **Jet Mass (*M*)**
  - Difference of the momentum of the jets and the energy of its constituents weighted by their pseudo-rapidity.
  - Related to the virtuality of the parton traversing the medium.



ALI−SIMUL−121659

- large M → soft constituents away from the jet axis
- small M → few hard constituents

$$M = \sqrt{p^2 - p_T^2 - p_z^2}.$$

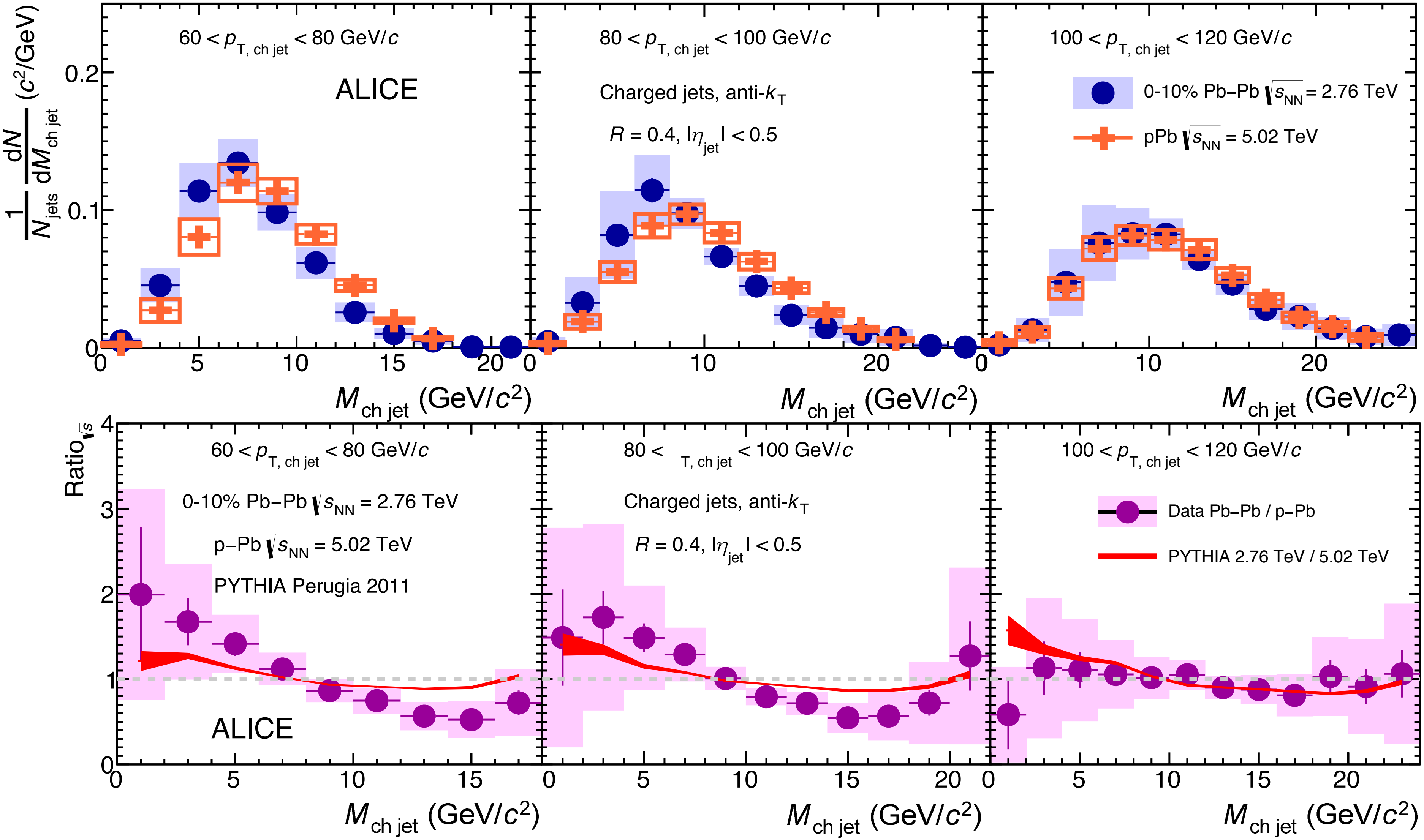
$$p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i, \quad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i.$$

J. Gallicchio, M.D. Schwartz, PRL 107 (2011) 172001

Mass of charged particle jets

ALICE, arXiv:1702.00804 submitted to PLB

Charged jets, $R = 0.4$, $60 < p_T < 120$ GeV/c



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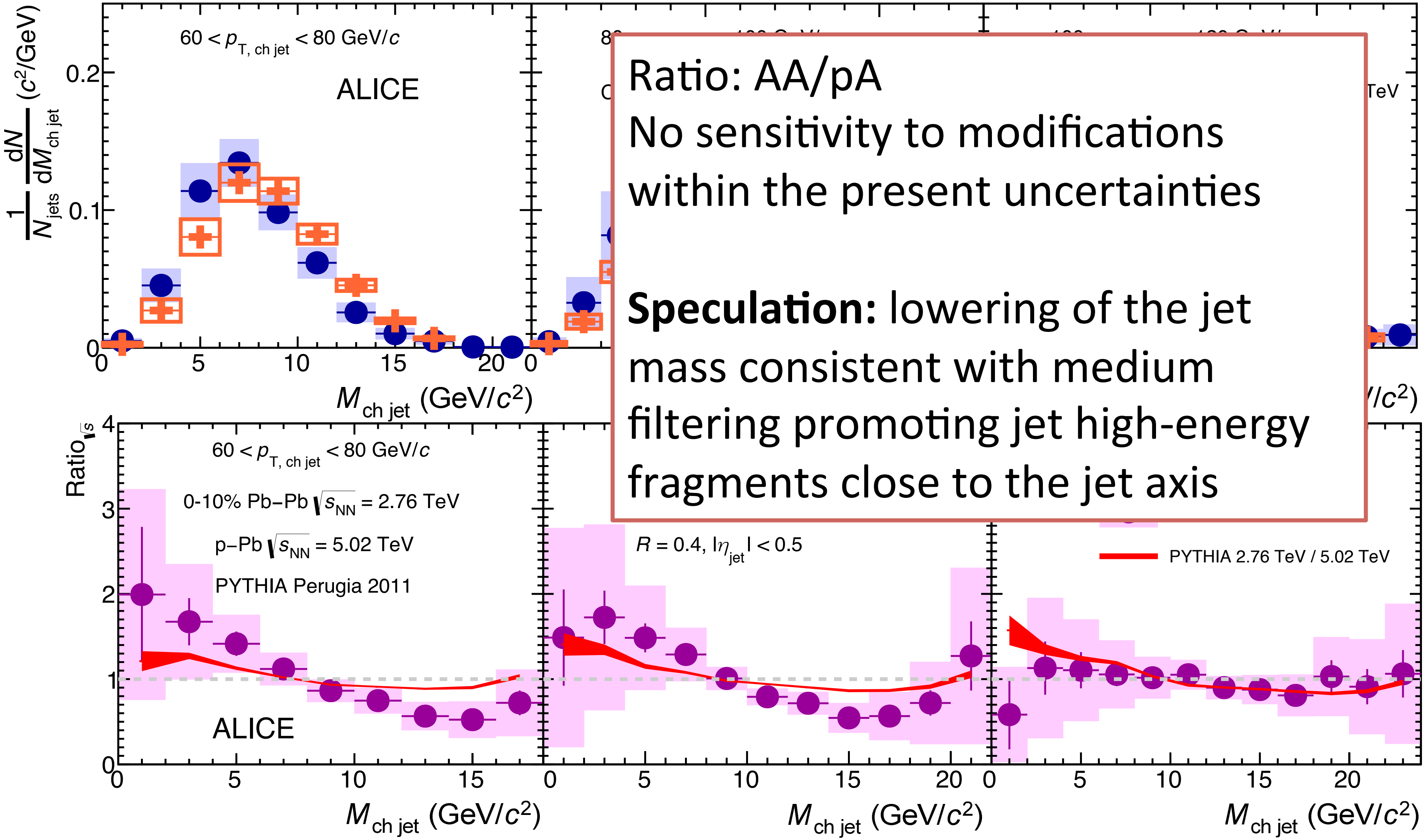


Ratio: AA/pA

No sensitivity to modifications within the present uncertainties

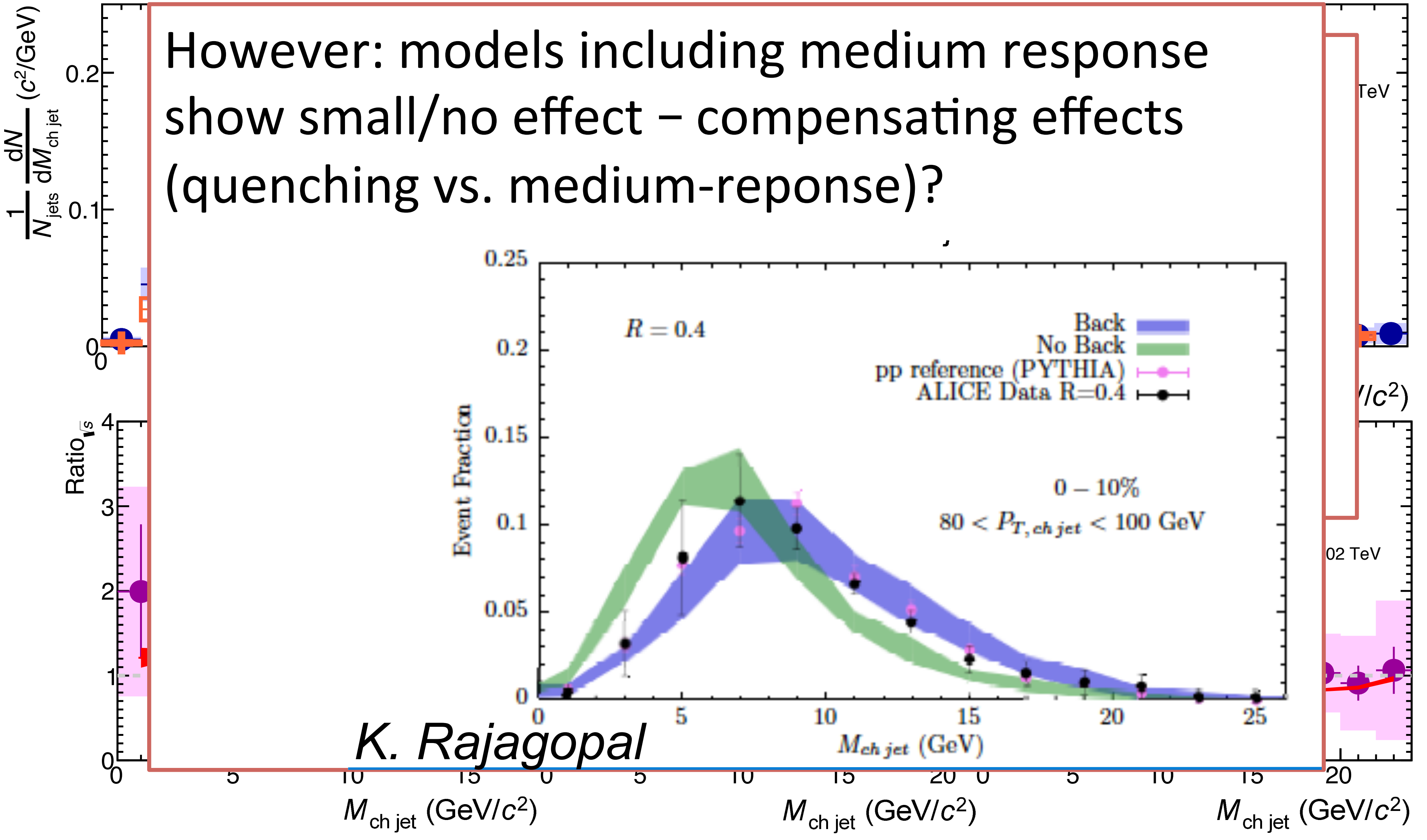
Speculation: lowering of the jet mass consistent with medium filtering promoting jet high-energy fragments close to the jet axis

Mass of charged particle jets

ALICE, arXiv:1702.00804 submitted to PLB

Charged jets, $R = 0.4$, $60 < p_T < 120$ GeV/c

However: models including medium response show small/no effect – compensating effects (quenching vs. medium-reponse)?

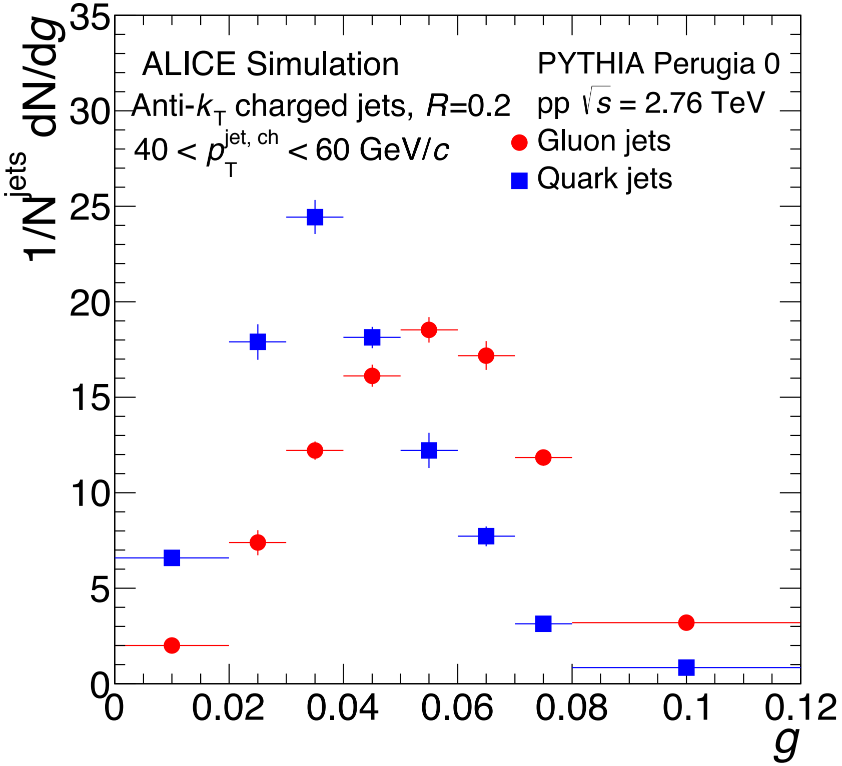


K. Rajagopal

Radial moment

- **Radial moment (*g*)**:
  - Measures the momentum re-distribution of jet constituents weighted by their distance from the jet axis.

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{\mathrm{jet}}} |r_i|$$



ALI-SIMUL-101543

- large g → more broadened jets
  - **gluon** jets have more likely large g
- smaller g → more collimated jets
  - **quark** jets have more likely smaller g

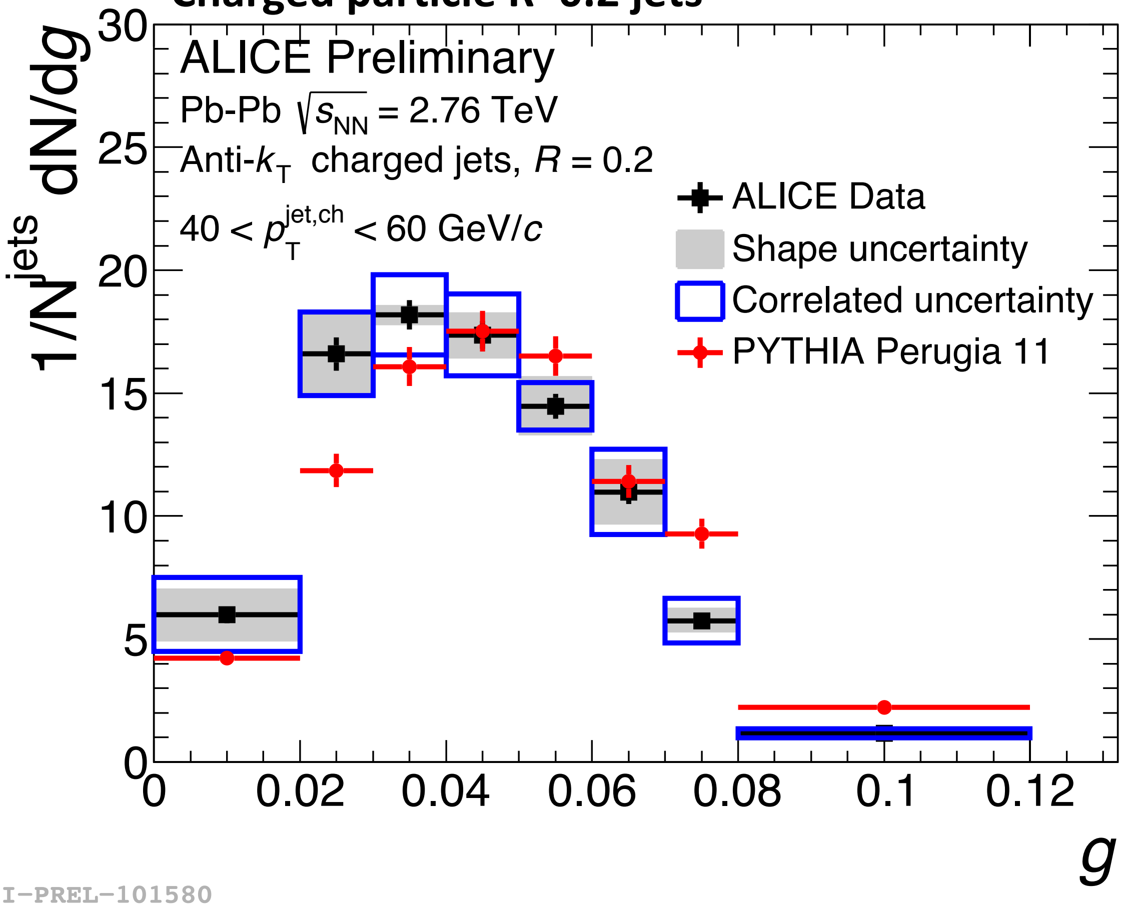
J. Gallicchio, M.D. Schwartz, PRL 107 (2011) 172001

Radial moment - g

$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{\mathrm{jet}}} |r_i|$$

g in AA shifted towards lower values
=> jet-medium interaction result in more collimated jets

Charged particle R=0.2 jets



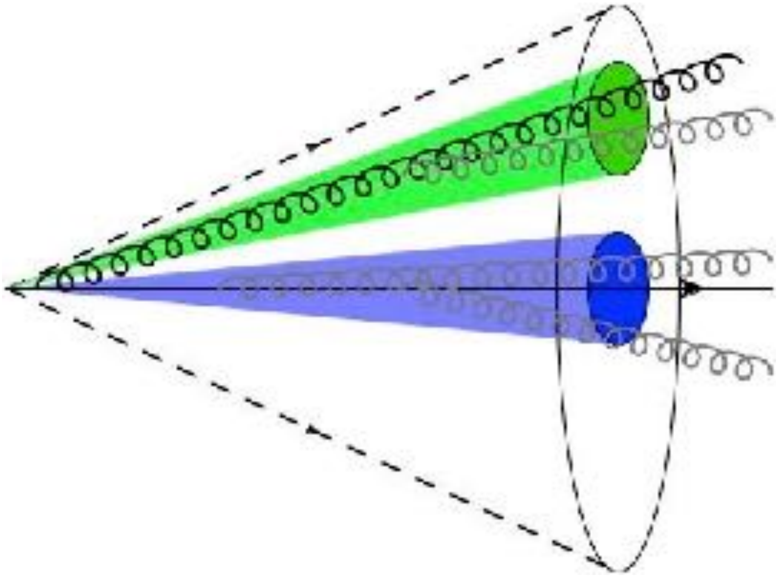
ALI-PREL-101580

Integrate hadronic degrees of freedom…

SUBJETS

SUBJETS

Result of a google search…



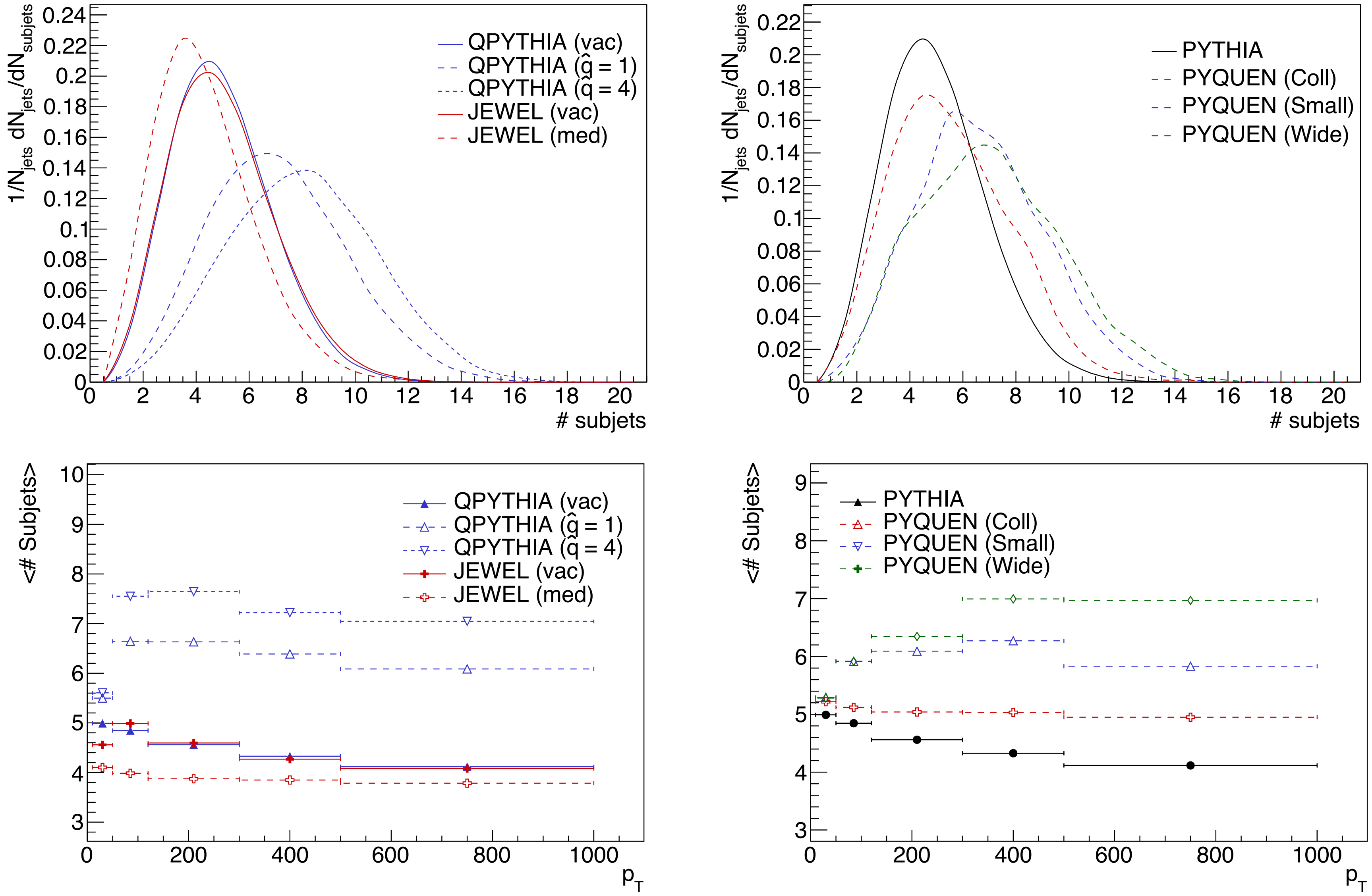
Integrate hadronic degrees of freedom…

SUBJETS

Sub-jets

- Recipe for sub-jets:
  - Find a jet
  - Using only its "constituents" re-cluster with $R_{sj}<R$
- $R_{sj} < R_{jet}$ – N-subjets depends on R_{sj}
- Choice of algorithm: theoretically preferable k_T or Cambridge/Aachen (better relation to splitting over anti-k_T)

Some sub-jet properties - N



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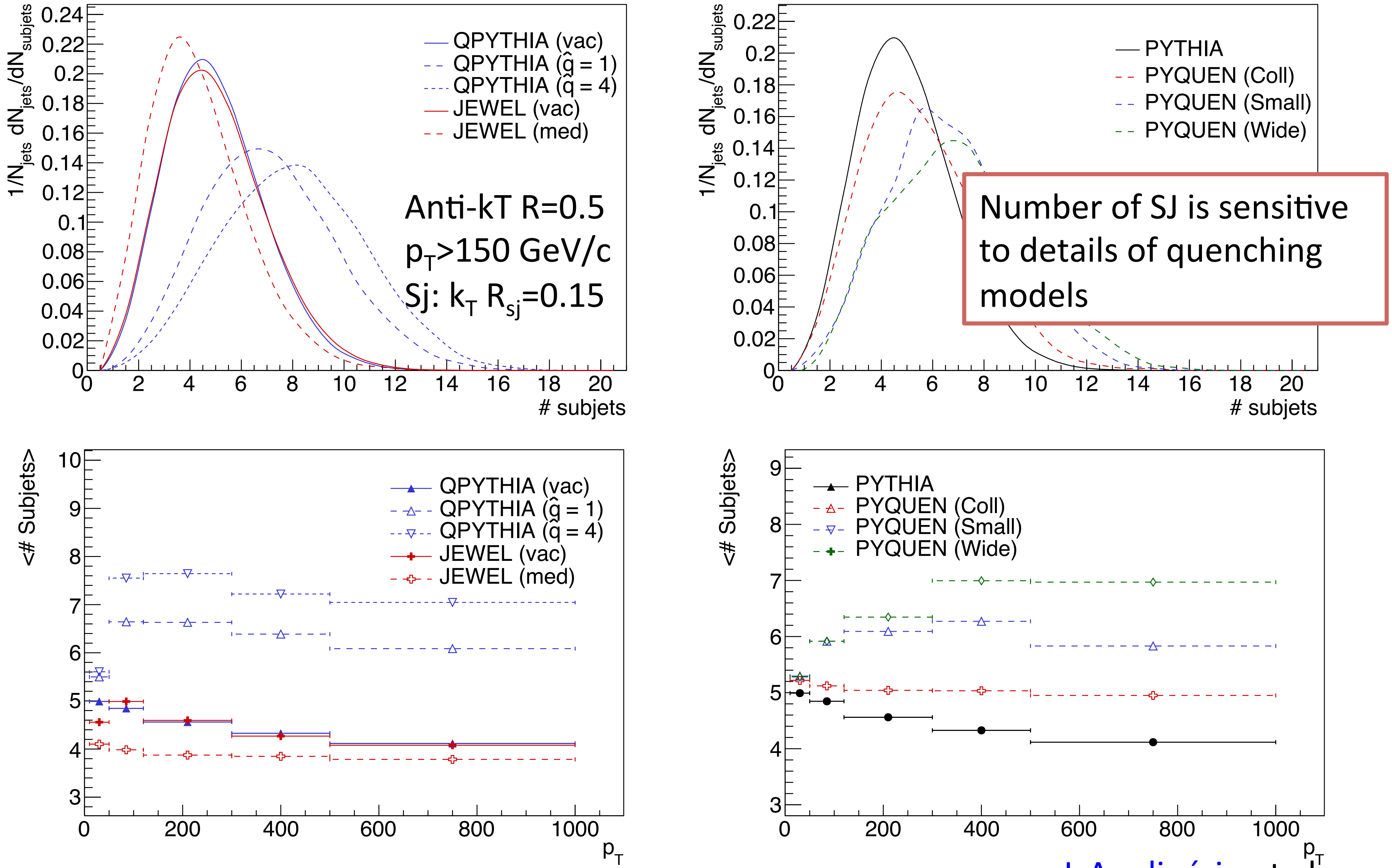
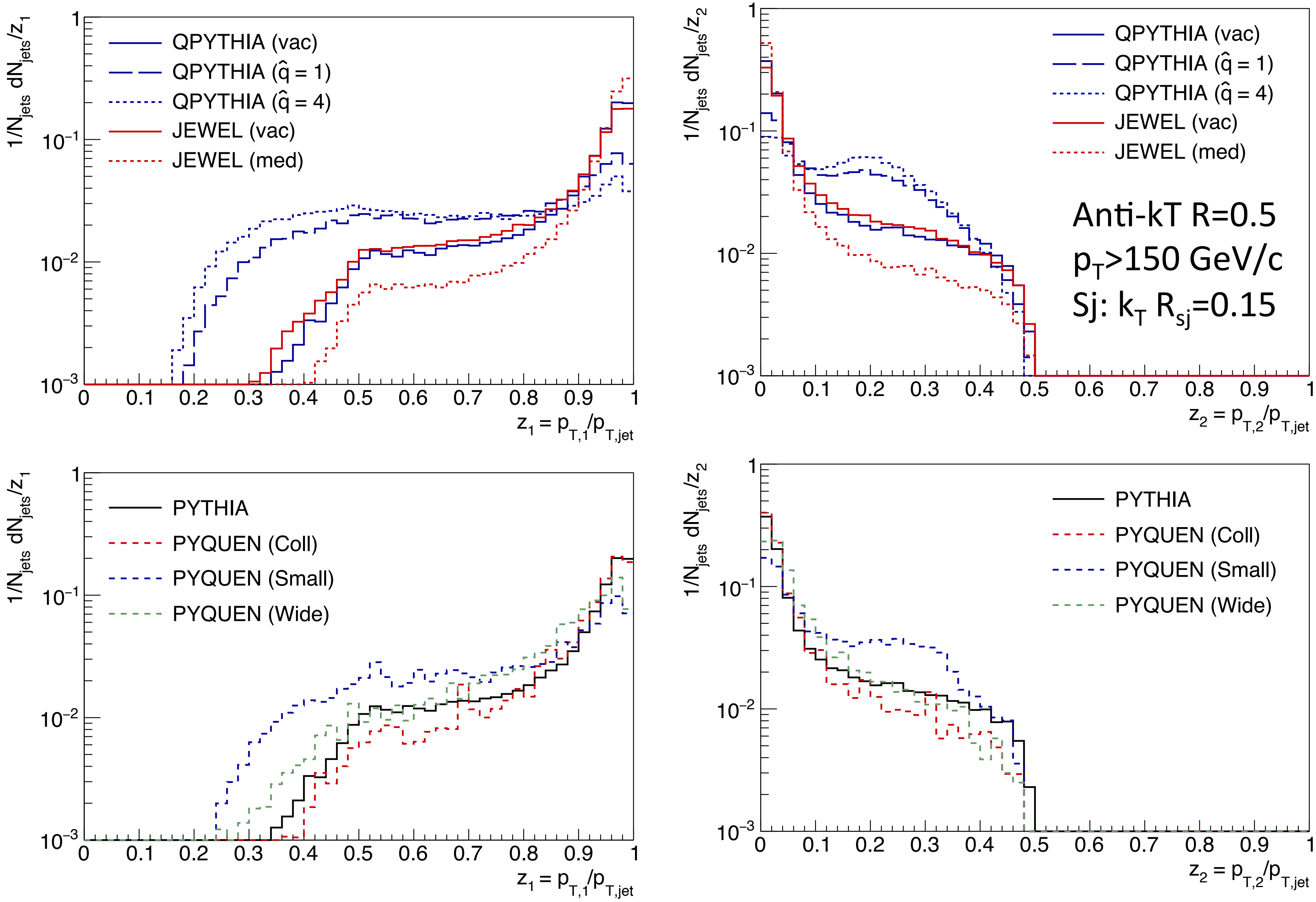


Number of SJ is sensitive to details of quenching models

L Apolinário et al

- Leading sub-jet distributions

Some sub-jet properties - z_{si}



- Leading sub-jet distributions

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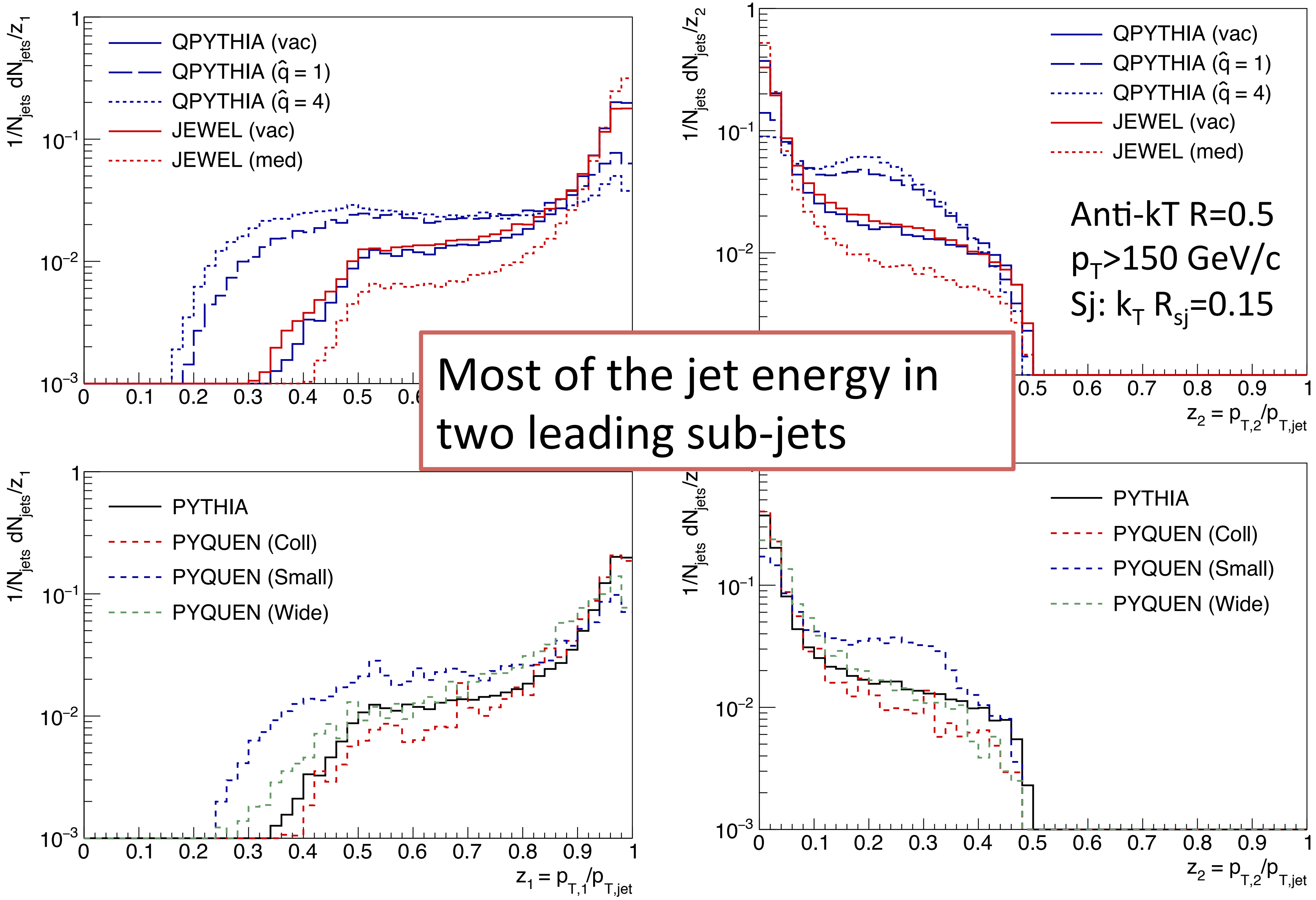


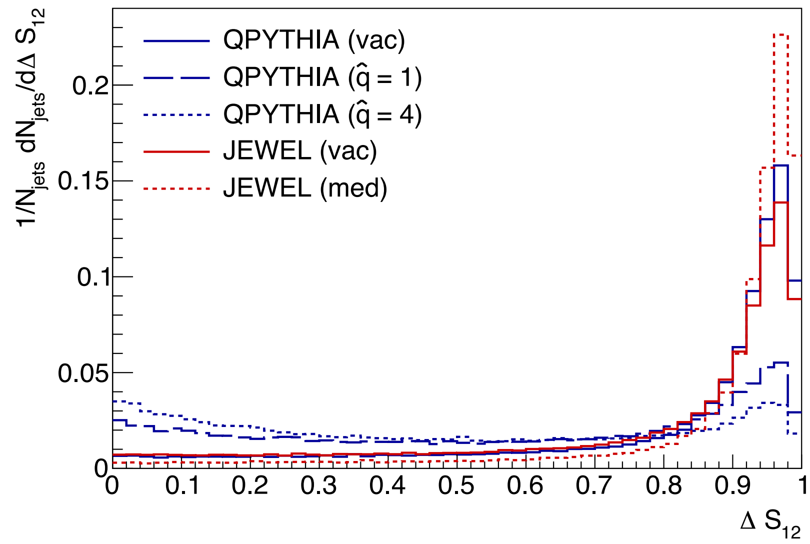
Most of the jet energy in two leading sub-jets

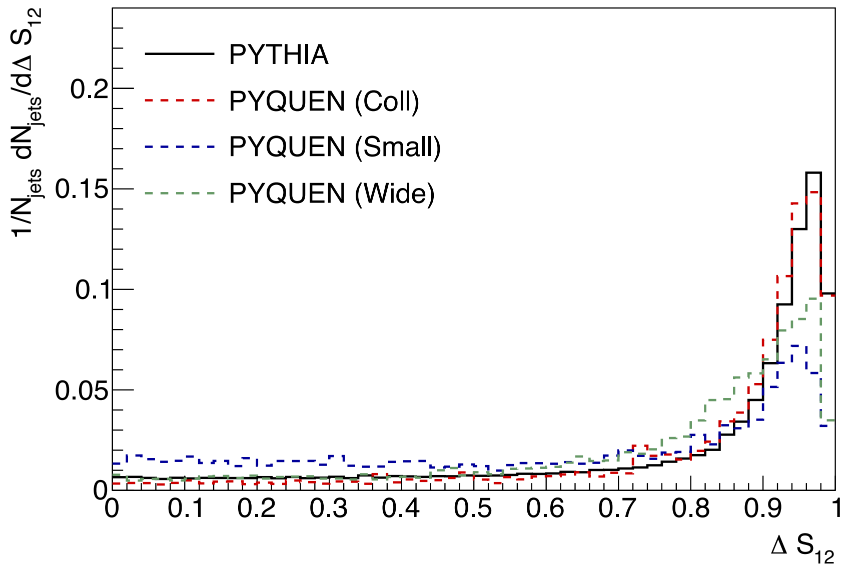
Some sub-jet properties - Δz_{sj}

"local" background cancelling $\rho_1=\rho_2$

Promising observable:

$$\Delta S_{12} = \frac{p_{T,1}^{true} - p_{T,2}^{true}}{p_{T,jet}} = \frac{(p_{T,1}^{rec} - \rho_1 A_1) - (p_{T,2}^{rec} - \rho_2 A_2)}{p_{T,jet}}$$





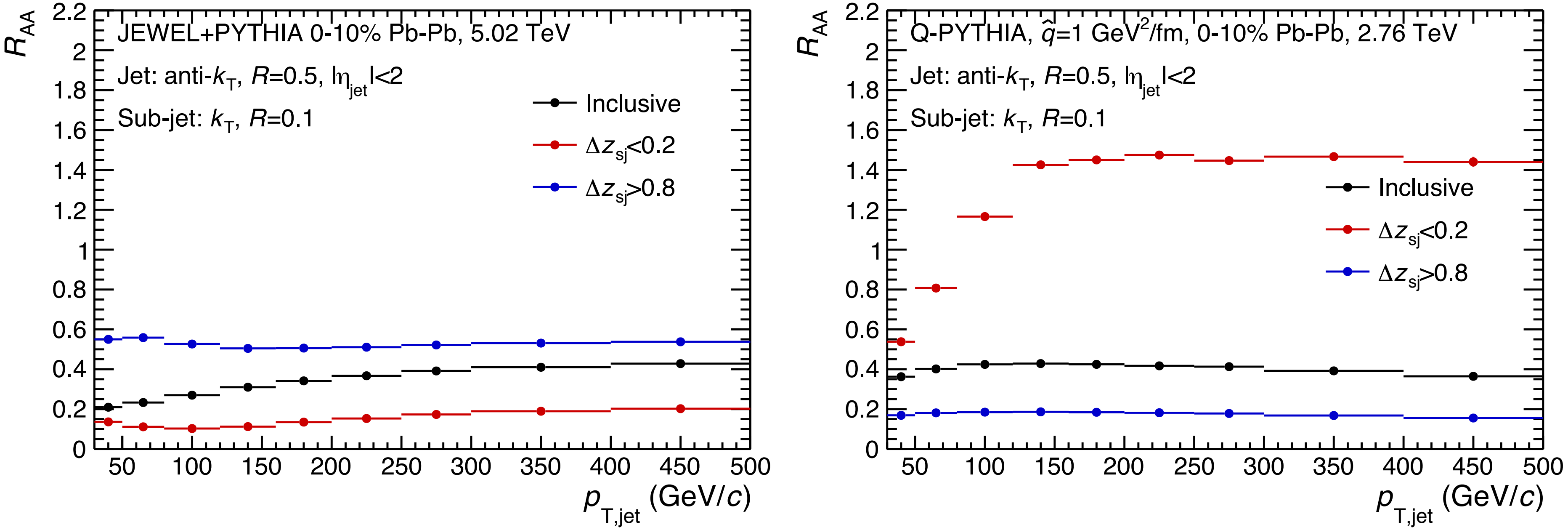
Some sub-jet properties - Δz_{sj}

Promising observable:

“local” background cancelling $\rho_1 = \rho_2$

$$\Delta S_{12} = \frac{p_{T,1}^{true} - p_{T,2}^{true}}{p_{T,jet}} = \frac{(p_{T,1}^{rec} - \rho_1 A_1) - (p_{T,2}^{rec} - \rho_2 A_2)}{p_{T,jet}}$$

Example use case: Tag with Dzj and measure RAA…

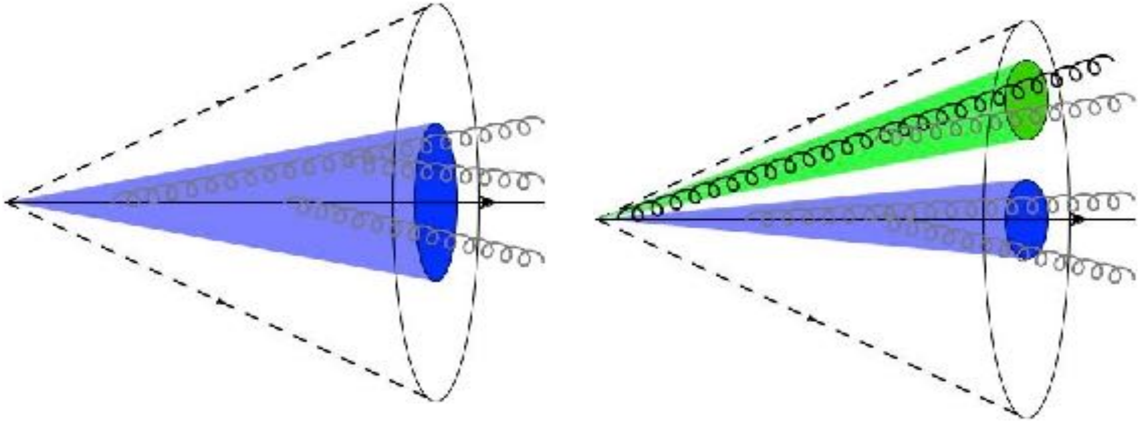


arXiv:1512.09255 [hep-ph]

NEW PICTURE OF JETS

Mehtar-Tani, Salgado, KT PRL (2011), PLB (2012), JHEP (2011-2012)
Casalderrey-Solana, Iancu JHEP (2012)
Casalderrey-Solana Mehtar-Tani, Salgado, KT PLB (2013)

number of medium-resolved substructures



critical angle (decoherence)	radiation as total charge	radiation as independent charges

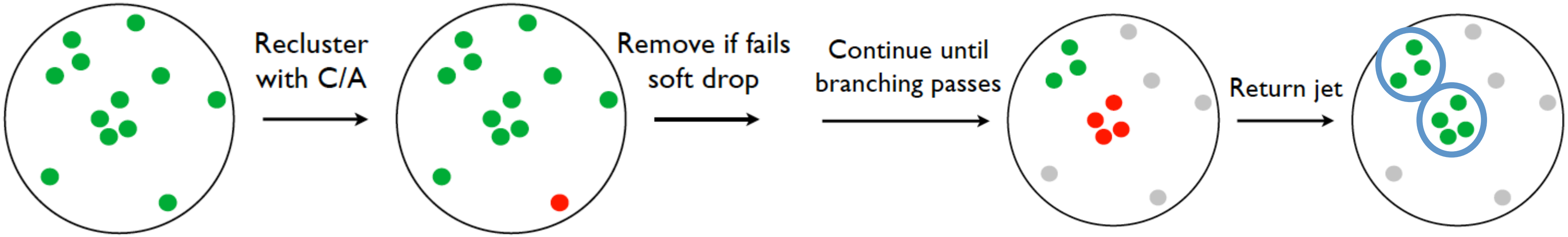
vacuum-like fragmentation within each substructure

Jet grooming

Jet grooming removes soft divergences and uncorrelated background
Common technique in HEP, now introduced in heavy ion collisions

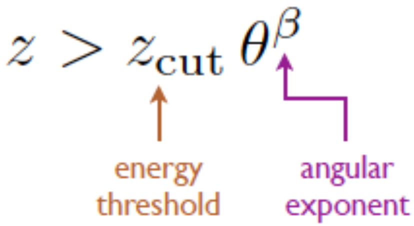
Measured anti-k_T jet

Groomed jet



Procedure finds splitting with largest angular separation

Soft Drop condition



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

We use $\beta = 0$ and $z_{\text{cut}} = 0.1$
Large-angle soft radiation + background is removed

M Verweji QM’17

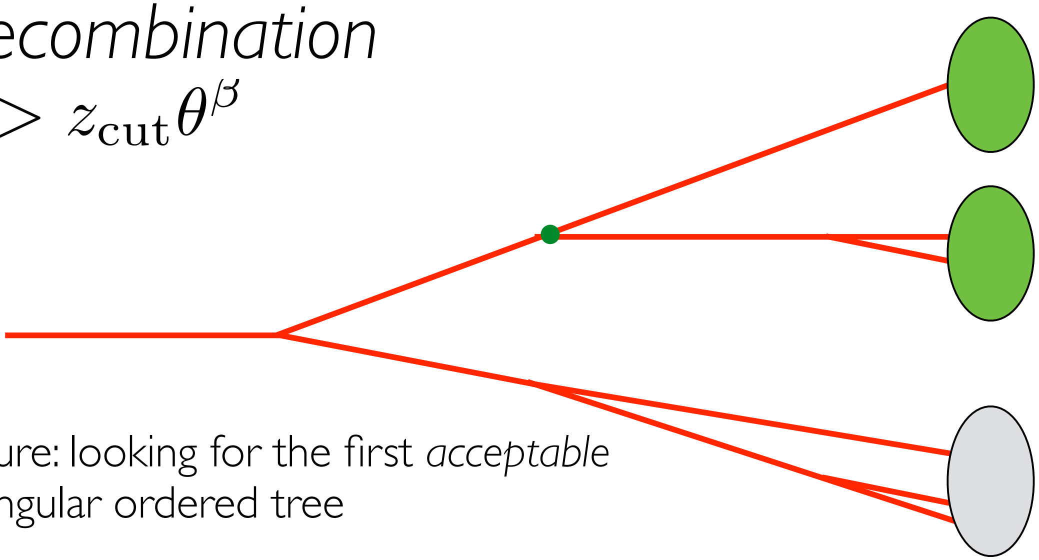
Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

JET GROOMING

Dasgupta, Fregoso, Marzani, Salam JHEP (2013)
Larkoski, Marzani, Soyez, Thaler JHEP (2014)
Larkoski, Marzani, Thaler PRD (2015)

C/A recombination

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



SoftDrop procedure: looking for the first *acceptable* branching of an angular ordered tree

Soft Drop condition

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

energy threshold

angular exponent

We use β = 0 and $z_{\rm cut}$ = 0.1
Large-angle soft radiation + background is removed

QCD splitting function:
(soft & collinear divergences)

$$\mathcal{P}^{\rm vac}(z,\theta) = \alpha_s \frac{P_{gg}(z)}{\theta}$$

Probability: $$p(z_g) = \int_0^R {\rm d}\theta\, \Delta(R,\theta)\mathcal{P}^{\rm vac}(z_g,\theta)\Theta_{\rm cut}(z_g,\theta)$$

Sudakov form factor
accounts for groomed emissions

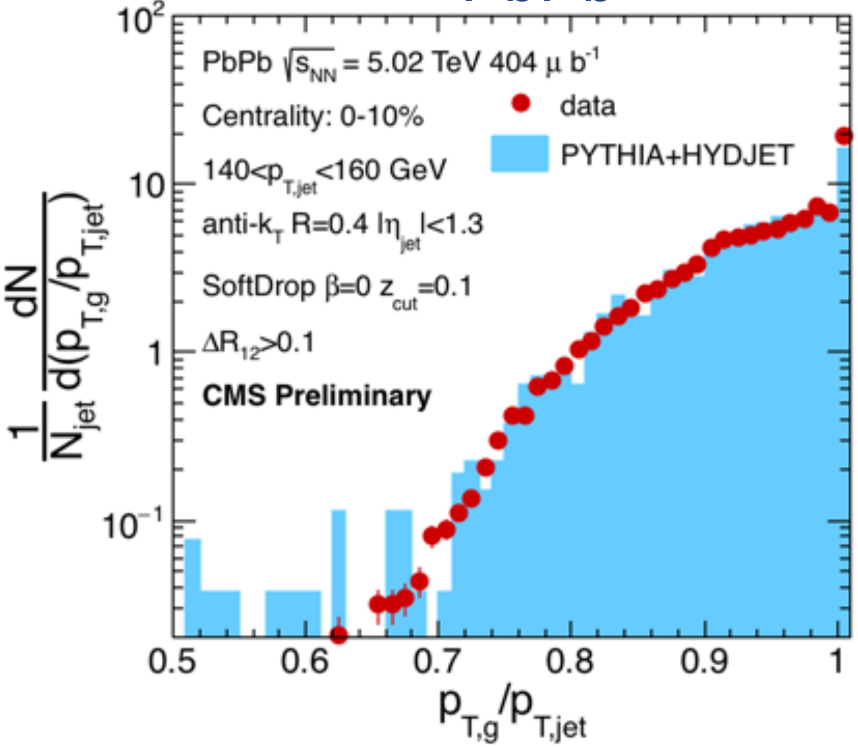
For β=0: splitting probability does not depend on α_s or flavour

$$p(z_g) \sim 1/[z(1-z)]$$

Soft-drop at work (vacuum & data)

- pT, N-subjets

PbPb



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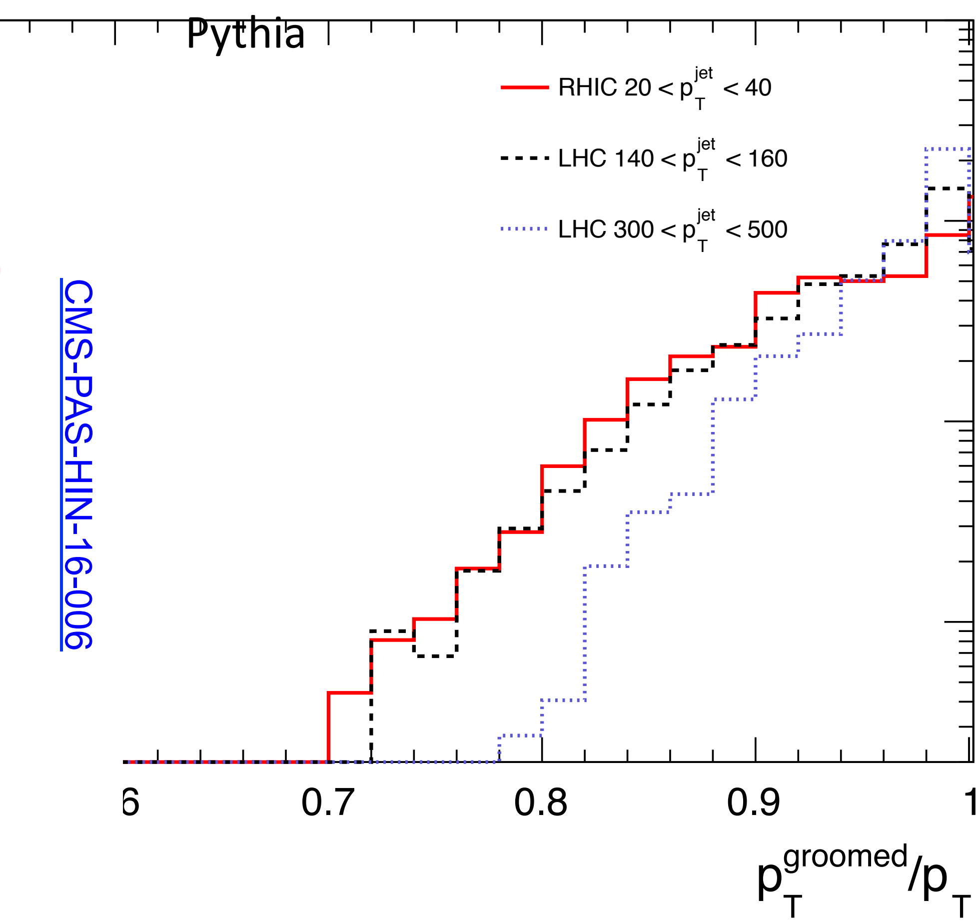

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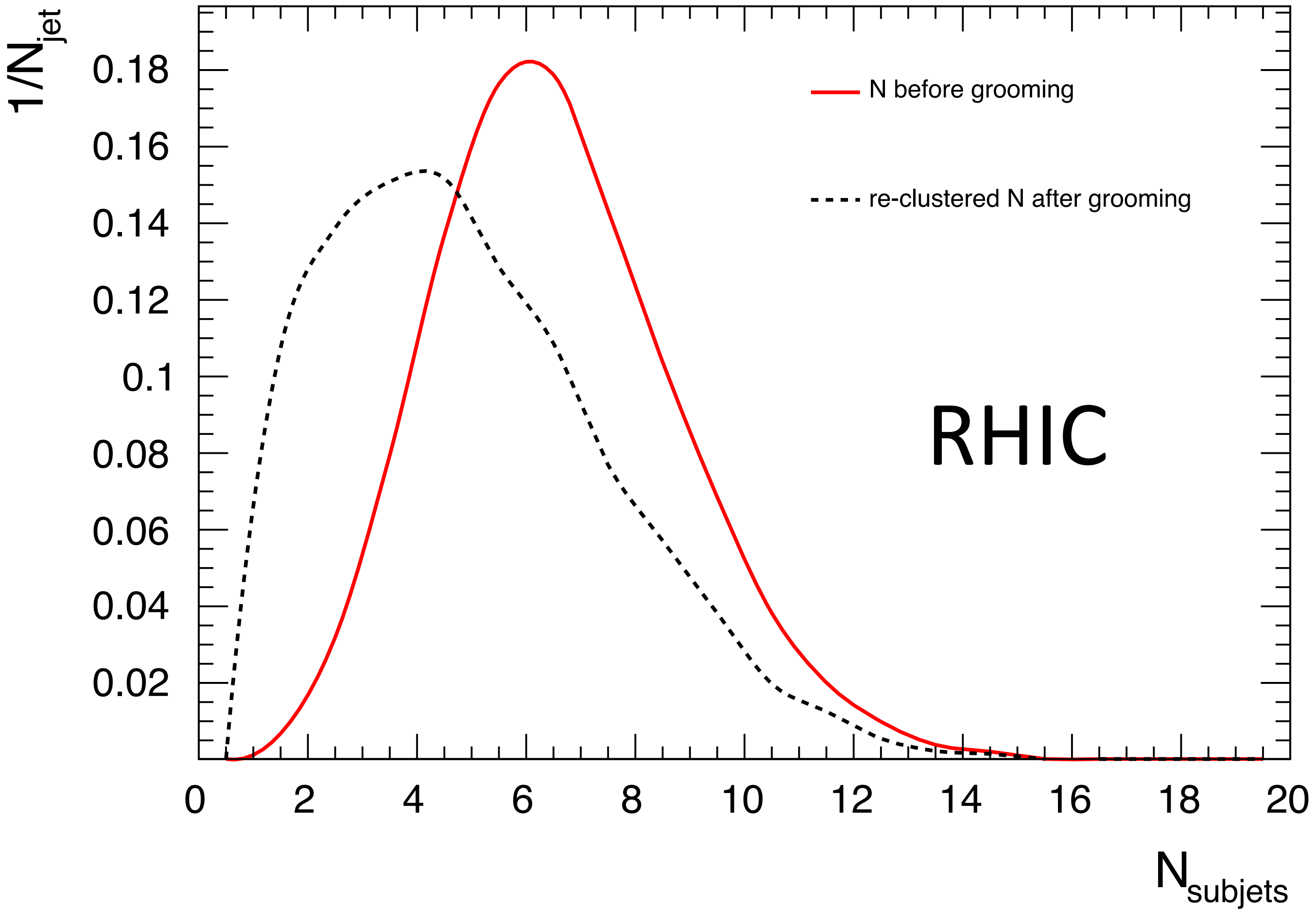
Soft-drop at work (vacuum & data)



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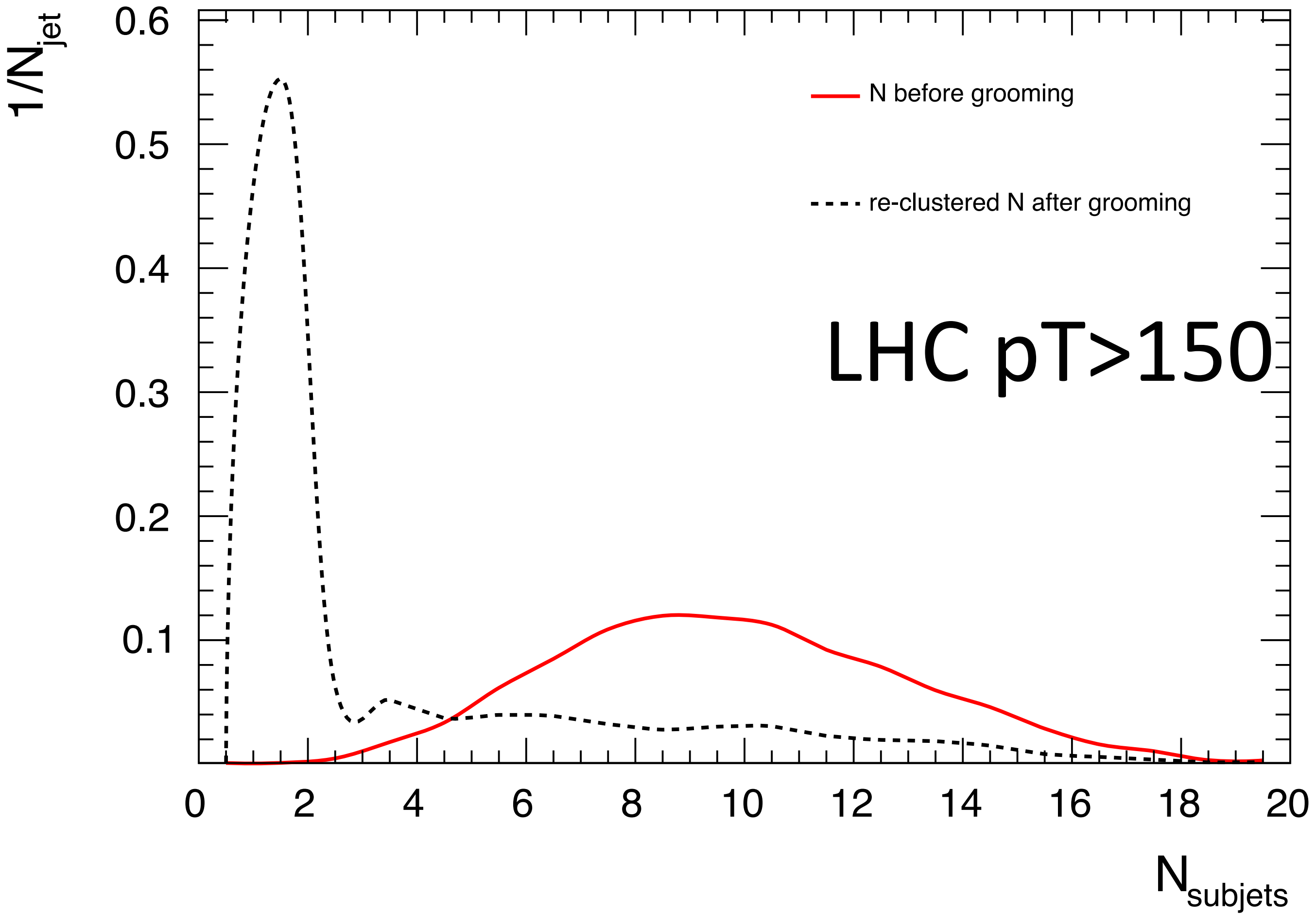
Soft-drop at work (vacuum & data)



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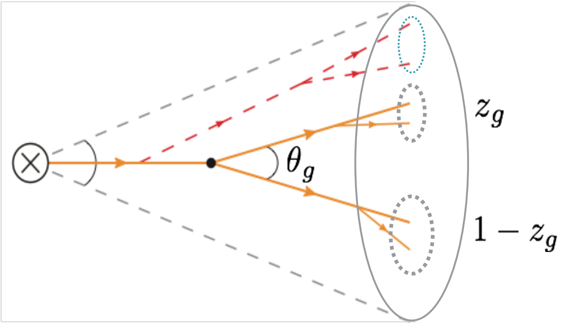
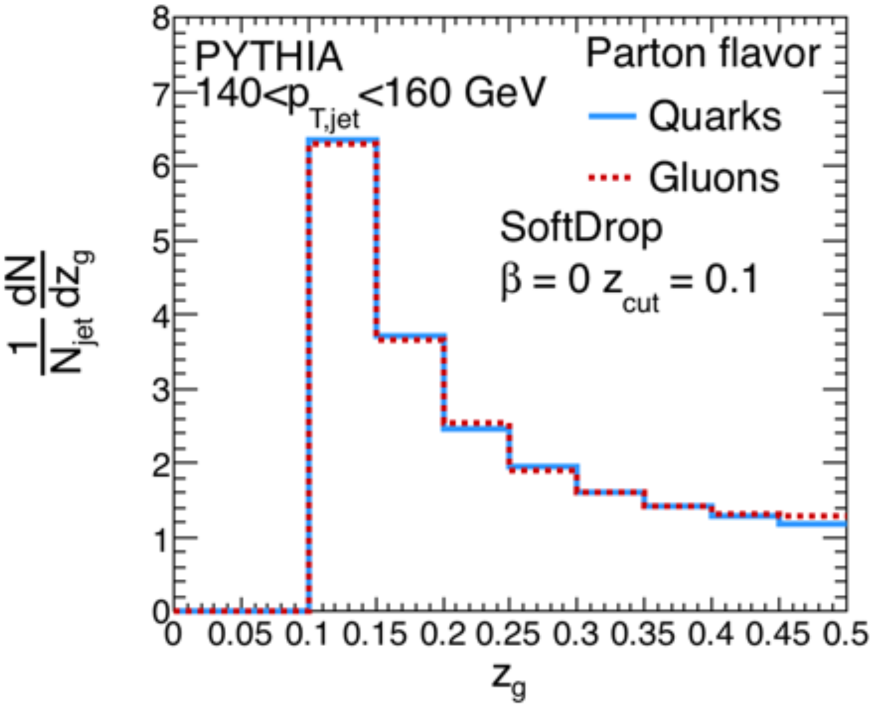
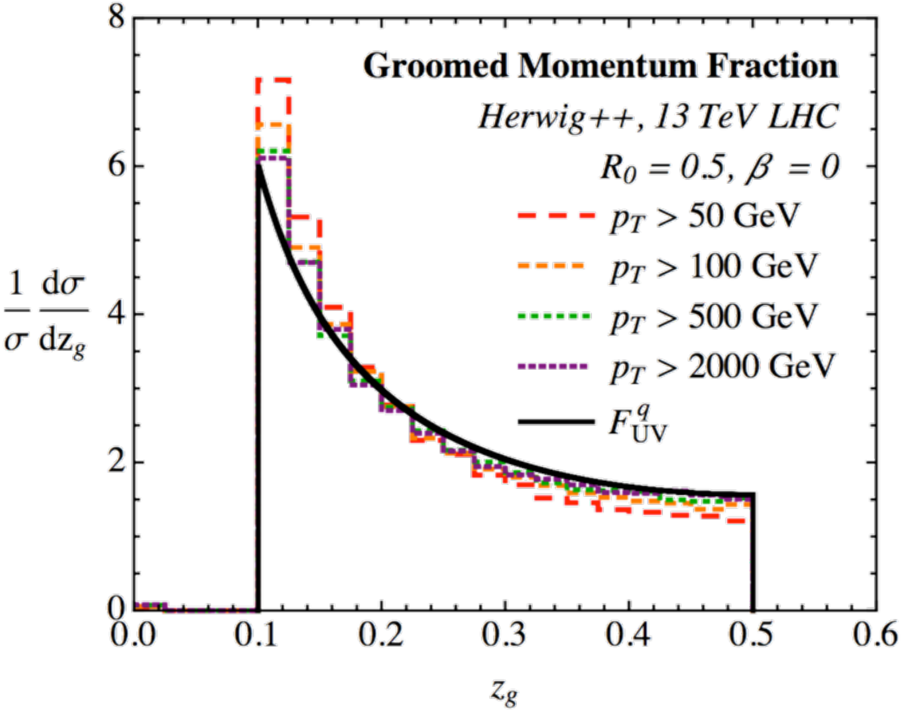
p_T symmetry in groomed jets

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

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



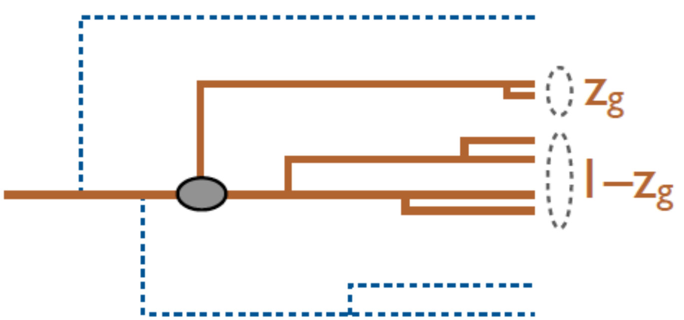




JHEP 1405 (2014) 146

p_T symmetry of groomed jets

- **p_T distribution of hard subjet (z_g)**
  - Momentum balance of the two hard sub-jets.
  - Observable connected to the hardest splitting. (splitting function)

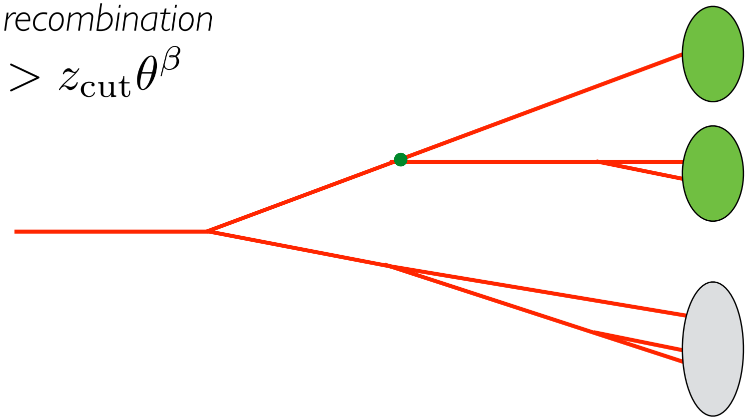


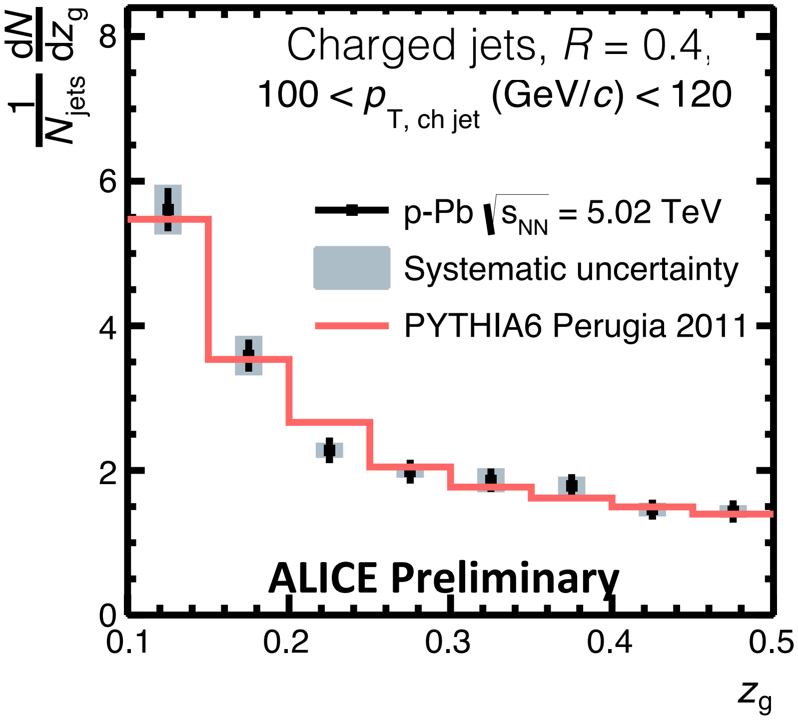
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler JHEP 05 (2014) 146

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

C/A recombination

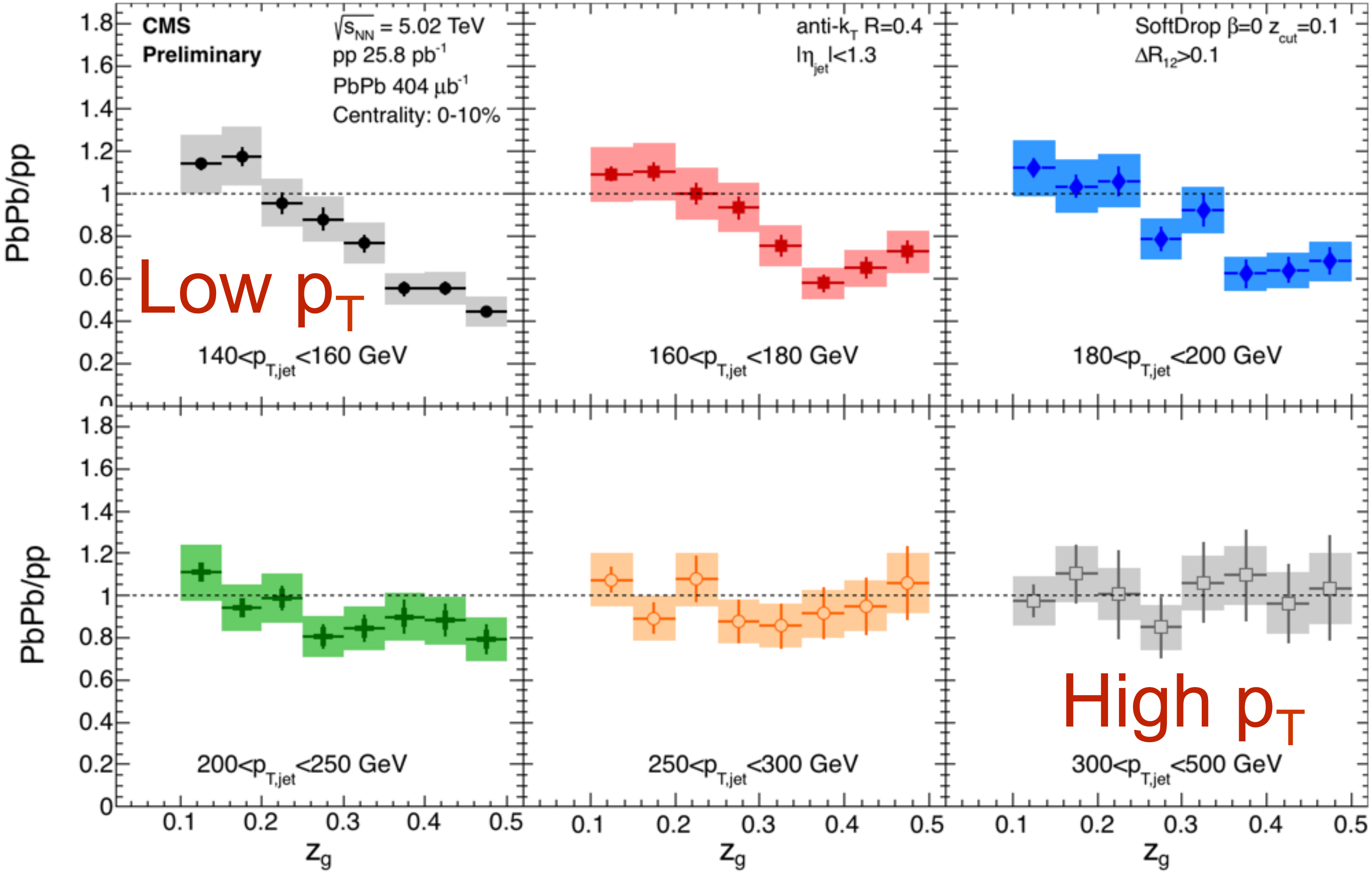
$$z > z_{\text{cut}}\theta^{\beta}$$





z_g at the LHC AA

Modification gets weaker when increasing jet p_T



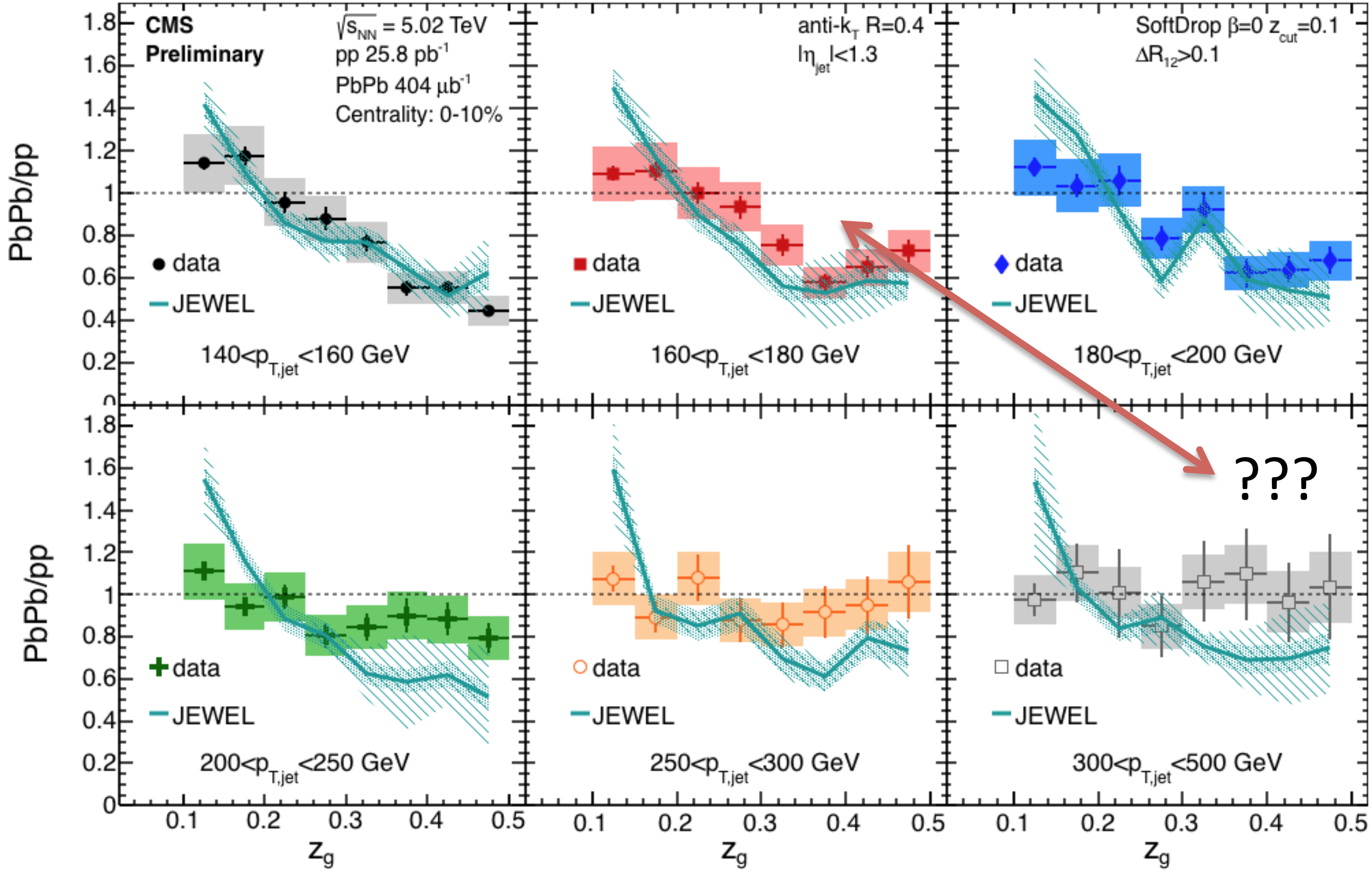
Due to normalization, cannot distinguish between increase at low z_g or suppression at high z_g

CMS-PAS-HIN-16-006

Model comparison

Comparison to jet quenching JEWEL MC event generator

General trend of data is described by JEWEL

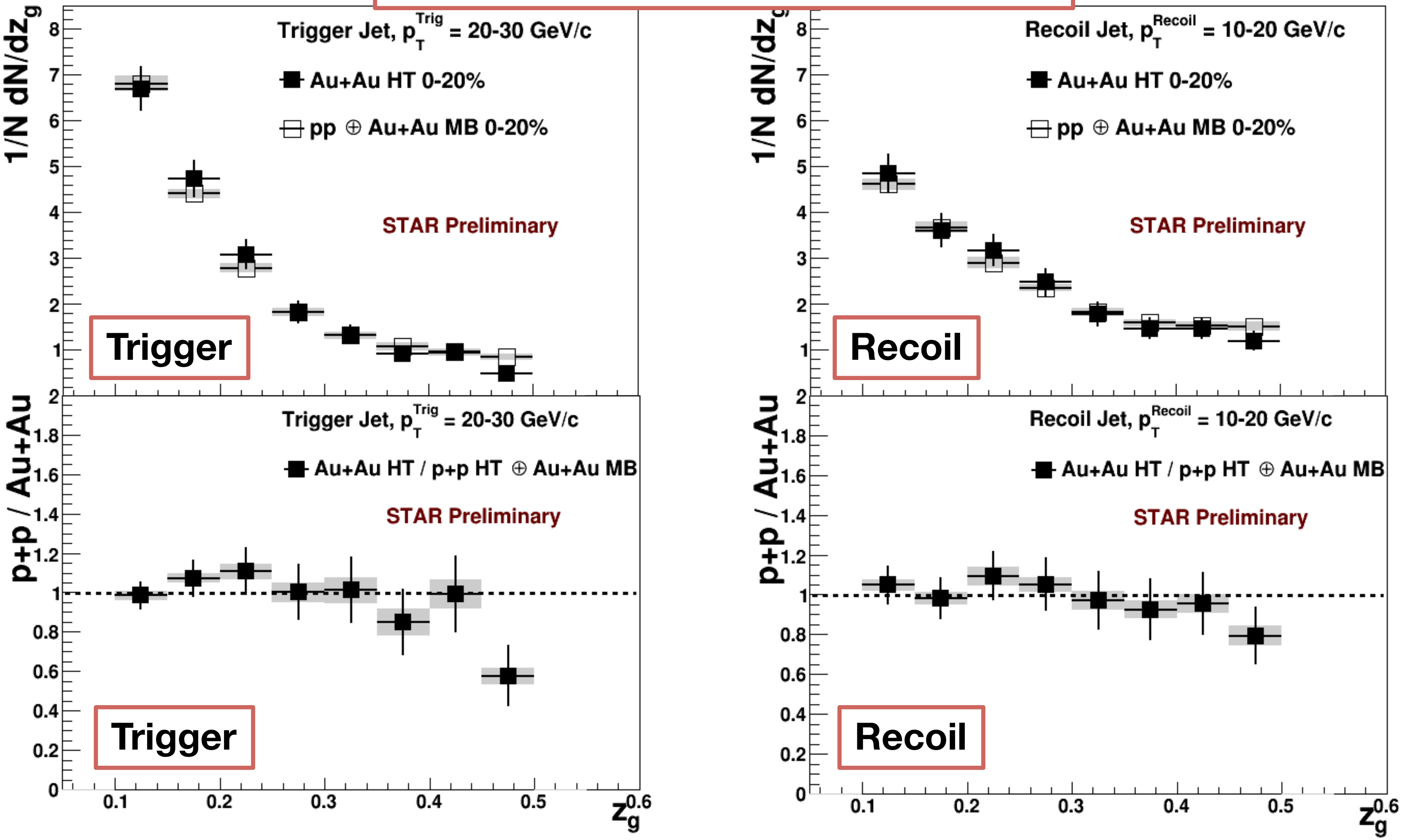


???

JEWEL MC, K. Zapp et al, JHEP03 (2013) 080. This calculation: R. Kunnawalkam Elayavalli and K. Zapp in preparation

z_g at the RHIC AA

No modifications from pp to AA



Trigger

Recoil

Trigger

Recoil

LHC vs RHIC

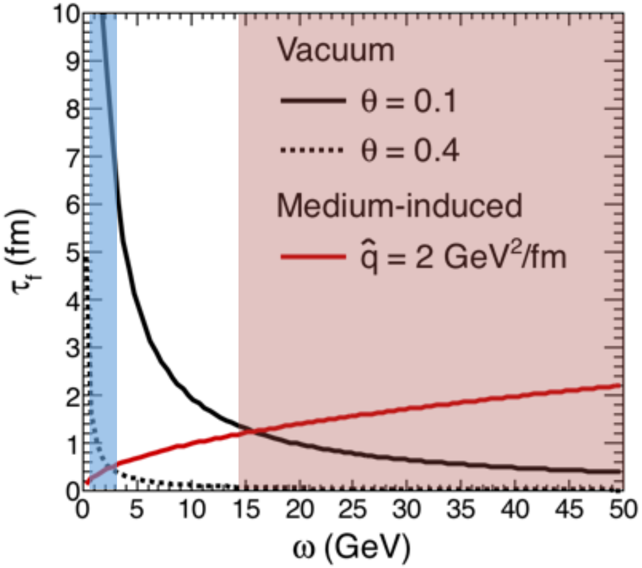
- Considerations:
  - $\Delta r_{\text{subjet}} > 0.1$ – CMS: angular resolution
  - Formation time / which splitting studied – where does it happen ?
  - Use/explore different soft-drop settings?

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

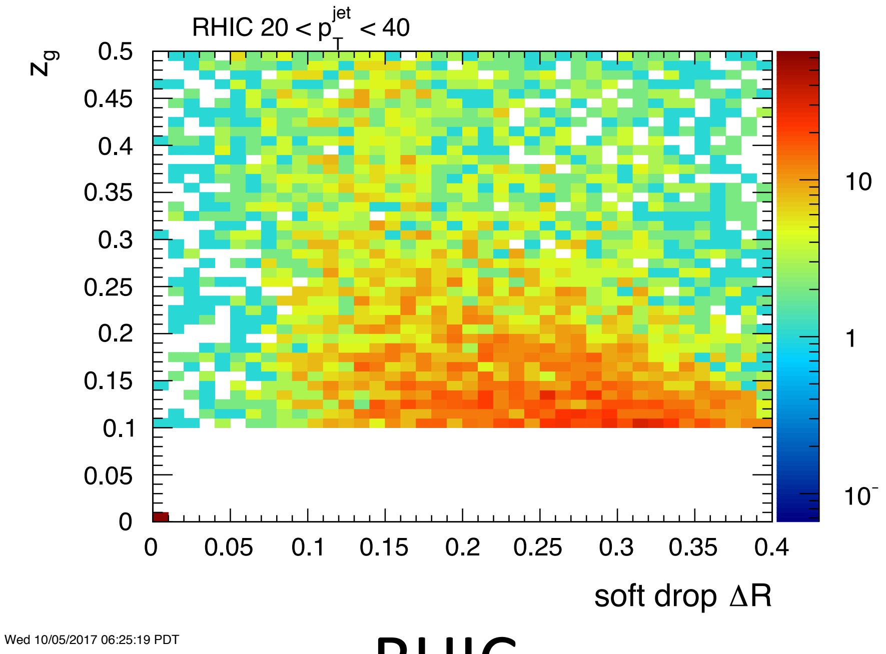
🟥 CMS

At RHIC can only see medium for rare large angle emissions or even splittings. Larger z_{cut} and/or ΔR_{12} selection would increase sensitivity

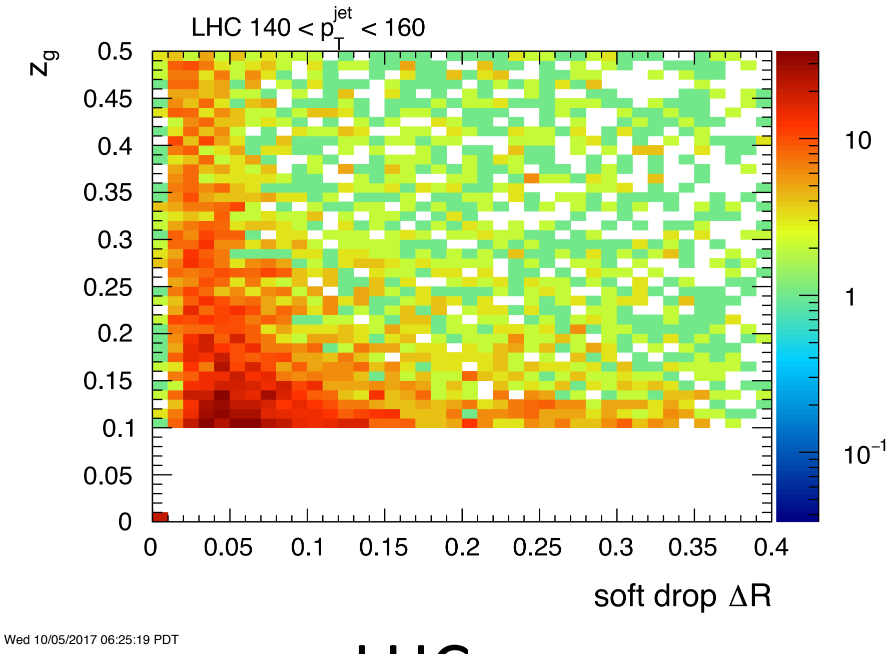
“Cut On One Look Elsewhere ”

- Cut on z_g and measure R_{sj}, g, mass, …, R_{AA}
- Role of the ΔR_{cut}?

No ΔR>0.1 cut



RHIC

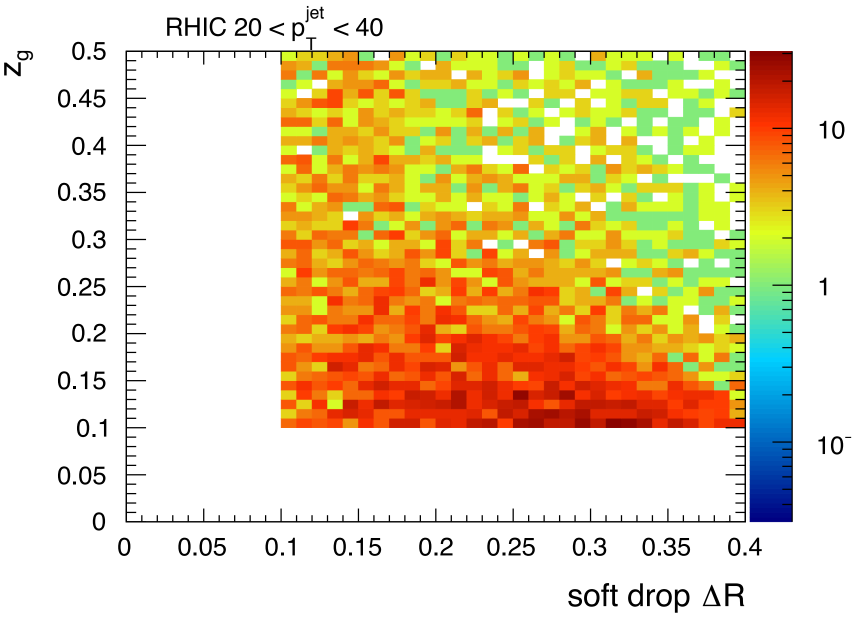


LHC

"Cut On One Look Elsewhere "

- Cut on z_g and measure R_{sj}, g, mass, …, R_{AA}
- Role of the ΔR_{cut}?

With ΔR>0.1 cut



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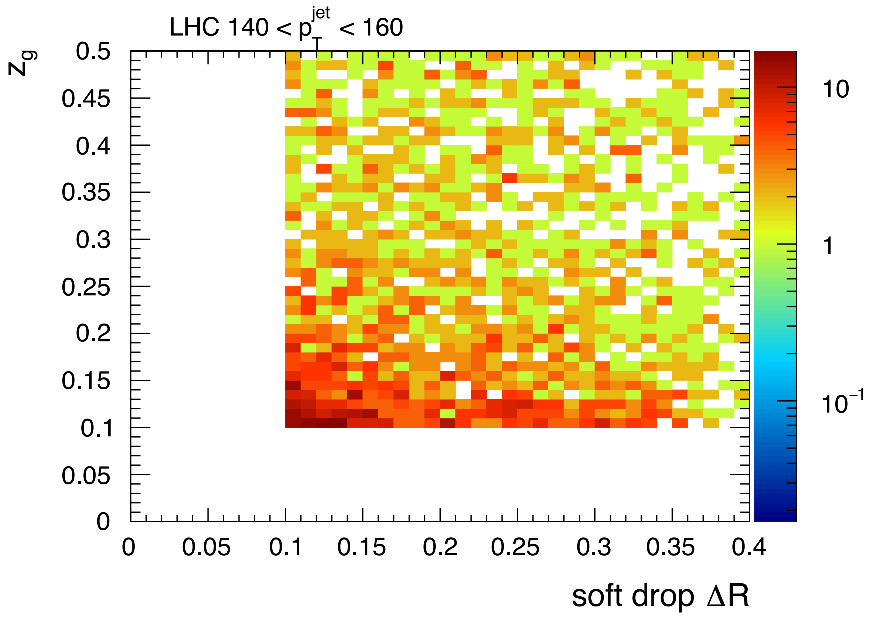
RHIC

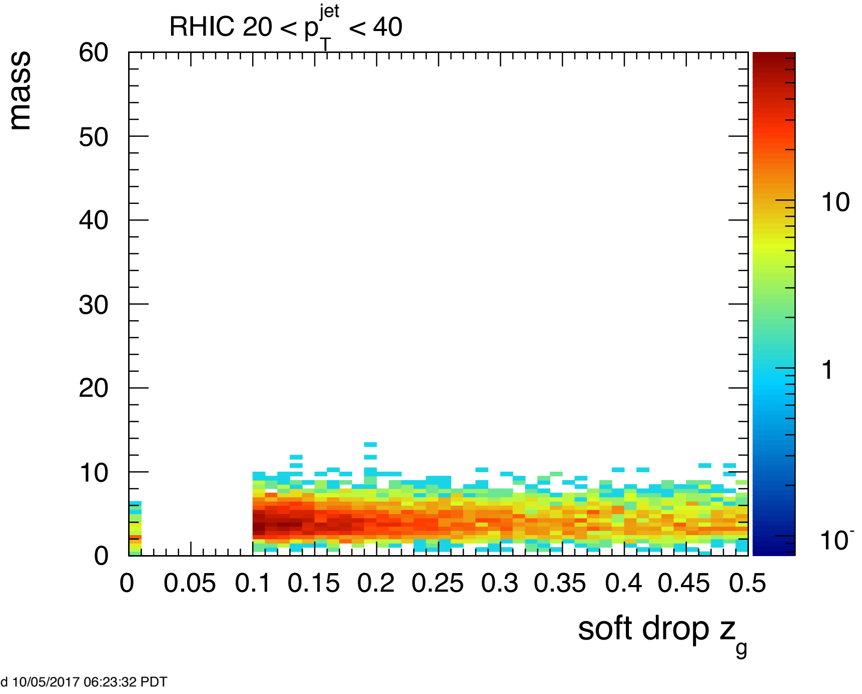


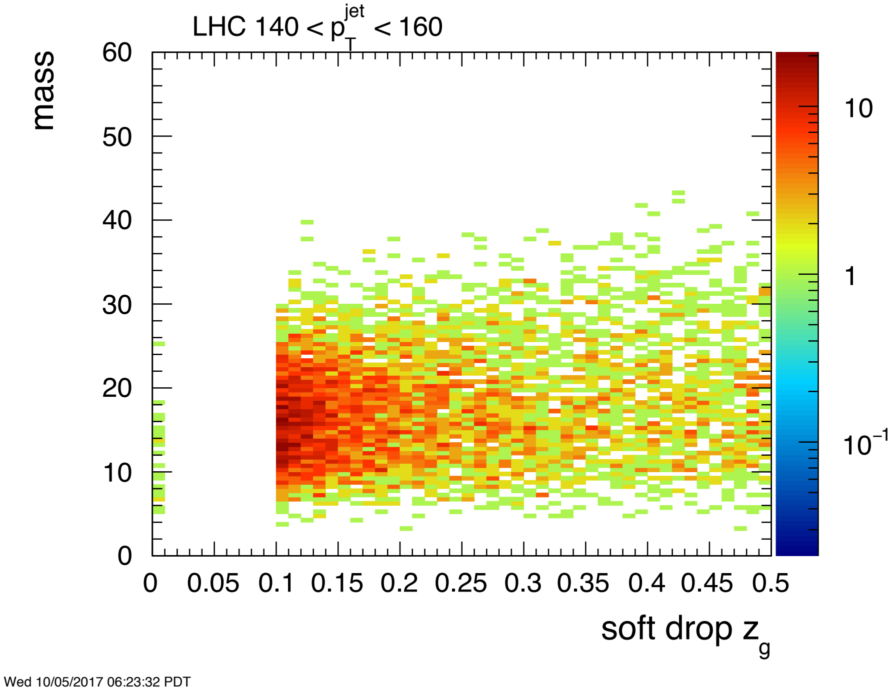
Wed 10/05/2017 07:38:52 PDT

LHC

Mass vs z_g

No $\Delta R > 0.1$ cut



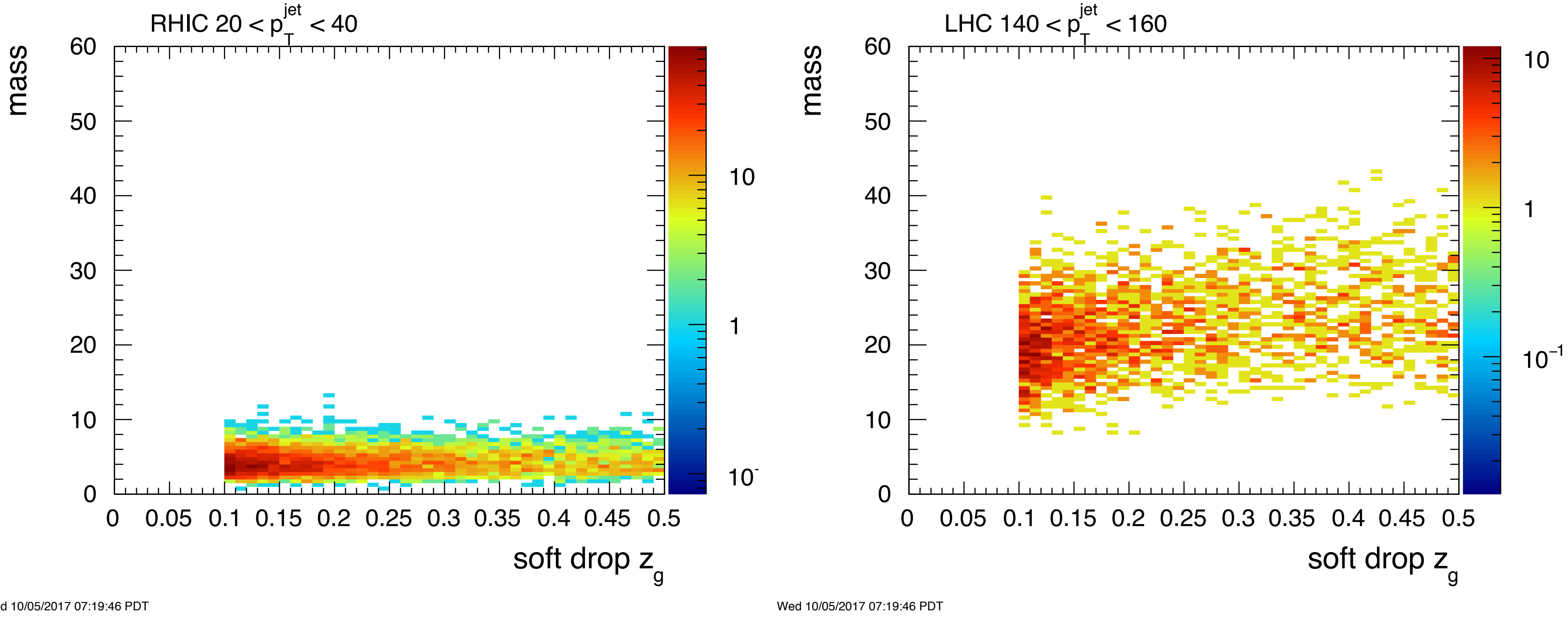


RHIC

LHC

Mass vs z_g

With ΔR>0.1 cut

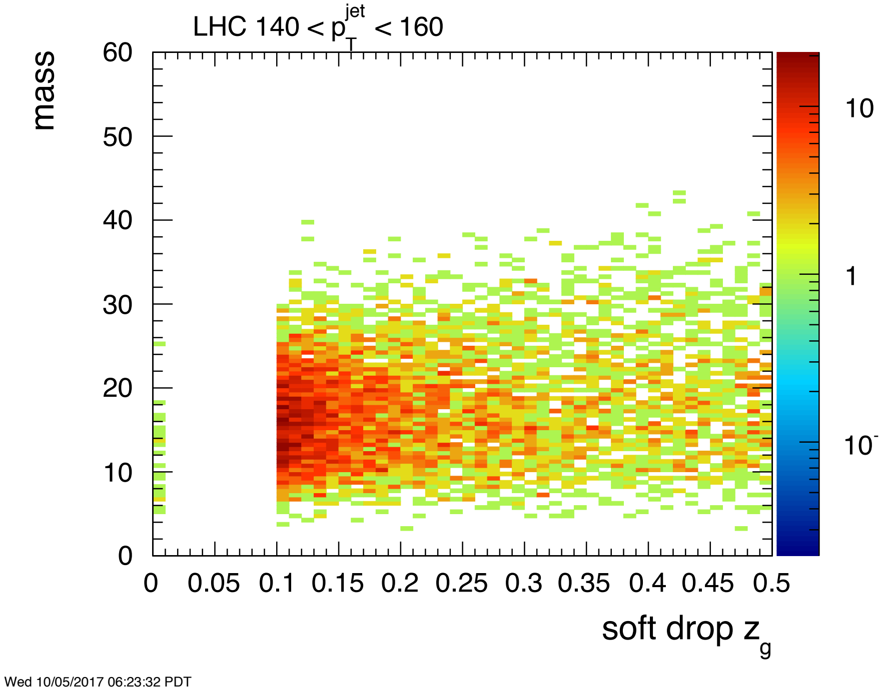


RHIC

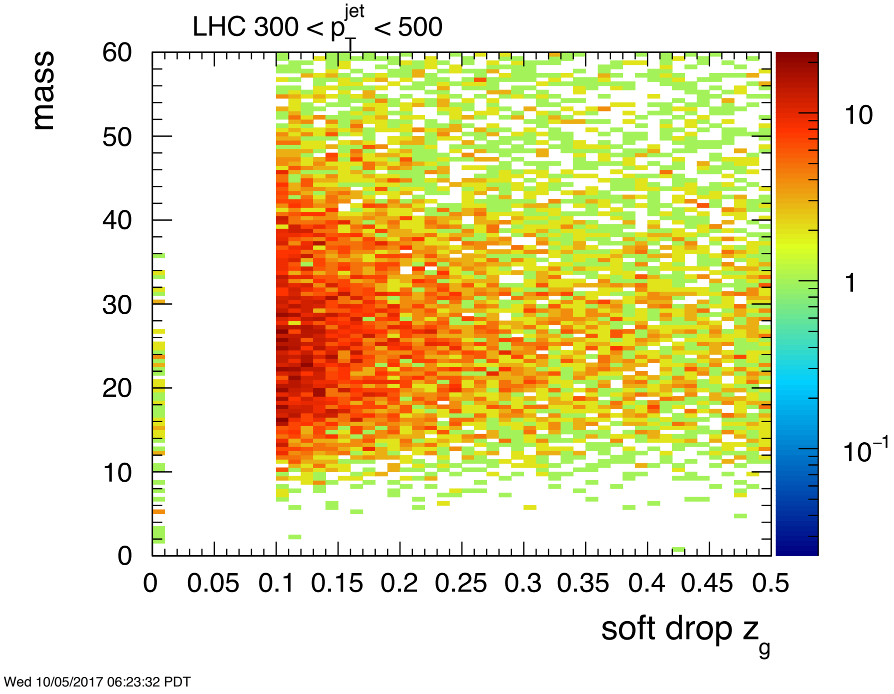
LHC

Mass vs z_g

No ΔR>0.1 cut



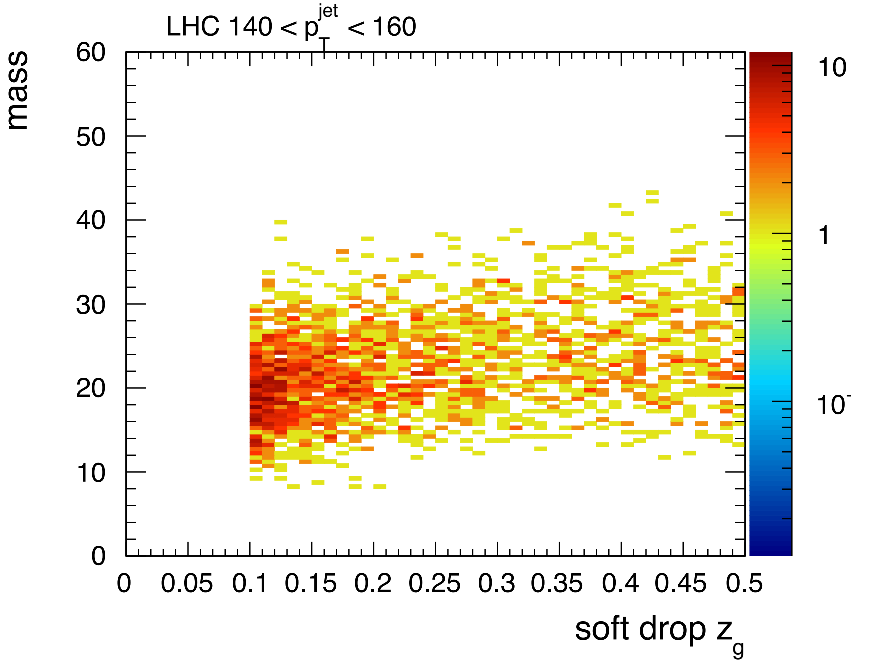
LHC low pT



LHC high-pT

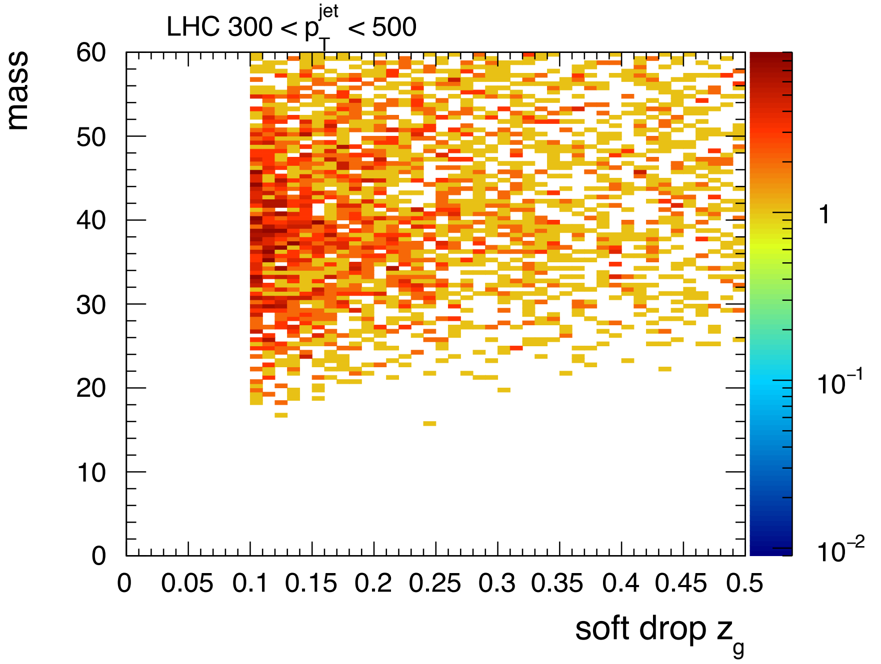
Mass vs z_g

With $\Delta R>0.1$ cut



Wed 10/05/2017 07:19:46 PDT

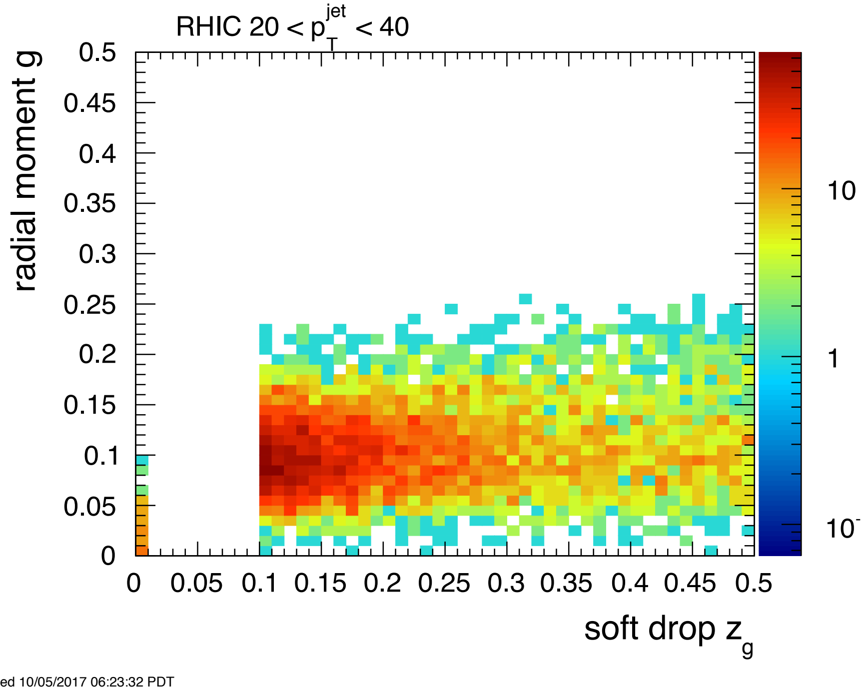
LHC low pT



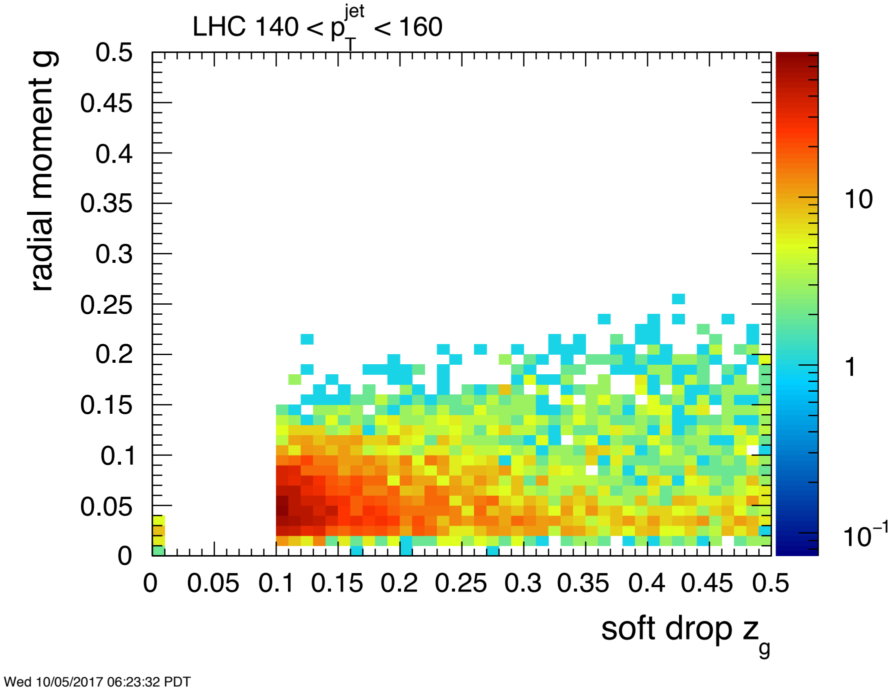
Wed 10/05/2017 07:19:46 PDT

LHC high-pT

Radial moment vs z_g No $\Delta R>0.1$ cut

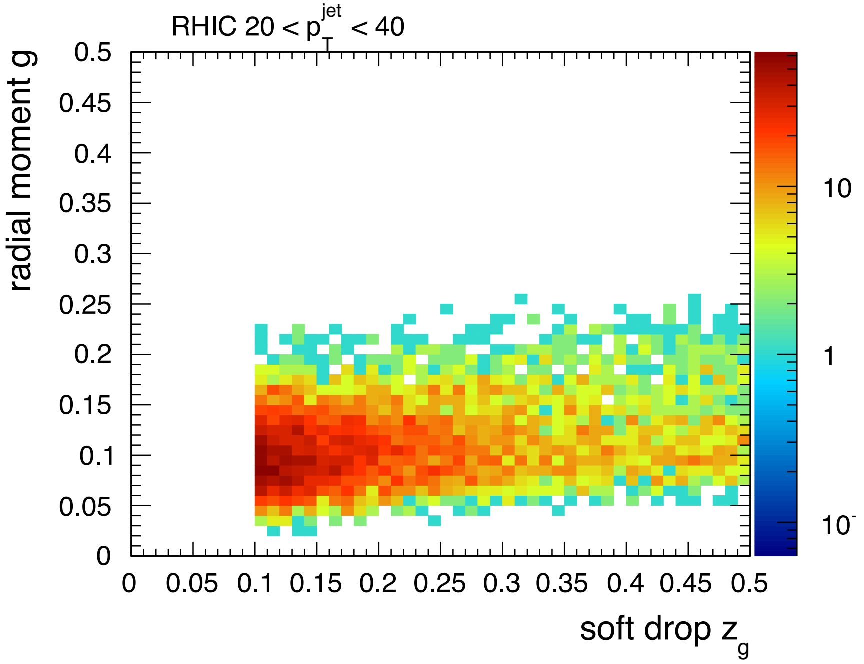


RHIC



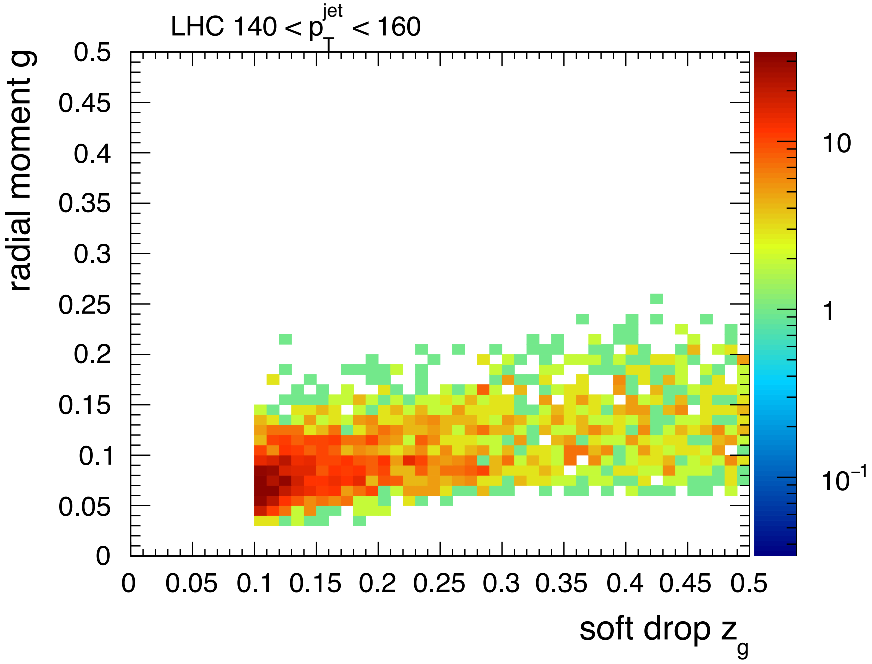
LHC

Radial moment vs z_g **With ΔR>0.1 cut**



Wed 10/05/2017 07:19:46 PDT

RHIC

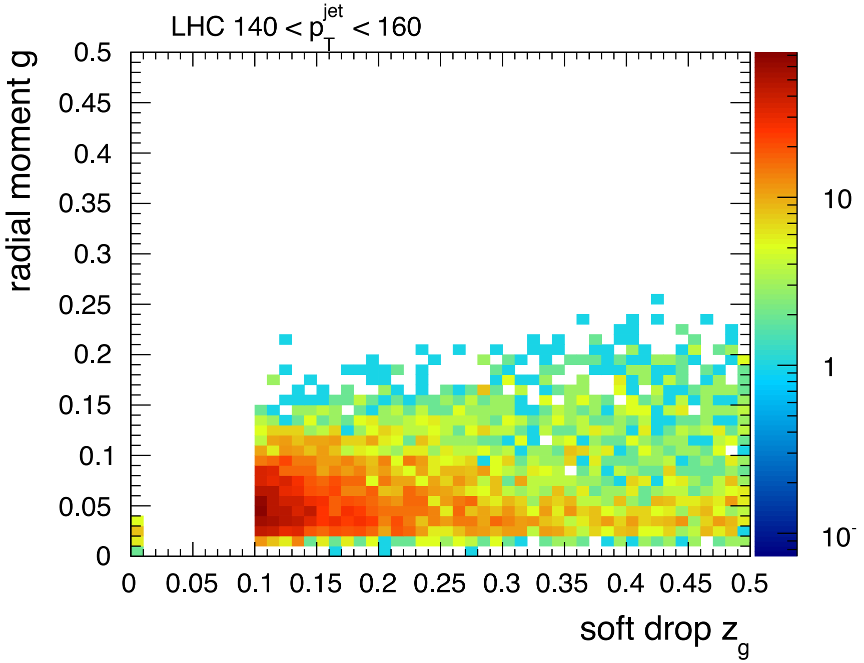


Wed 10/05/2017 07:19:46 PDT

LHC

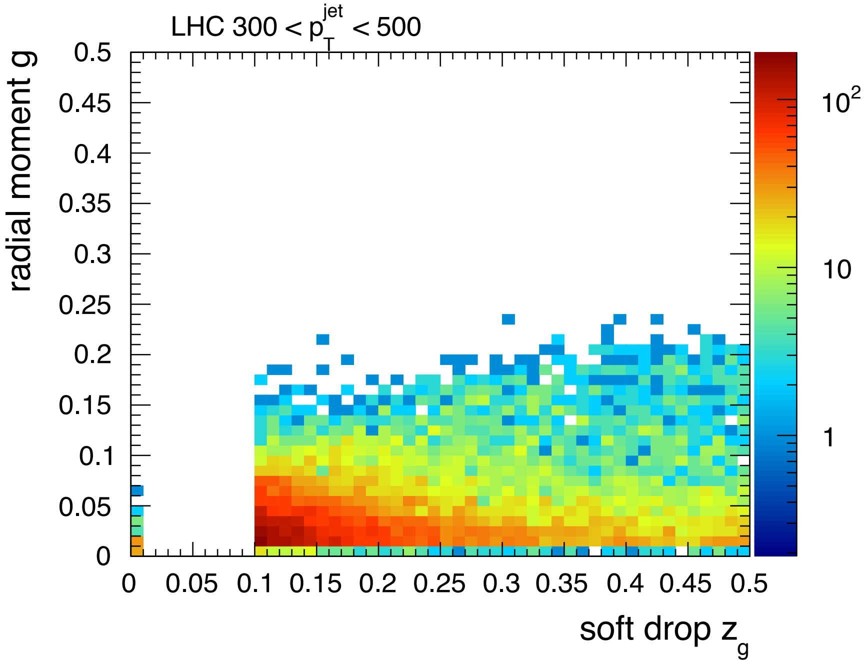
Radial moment vs z_g

No $\Delta R>0.1$ cut



Wed 10/05/2017 06:23:32 PDT

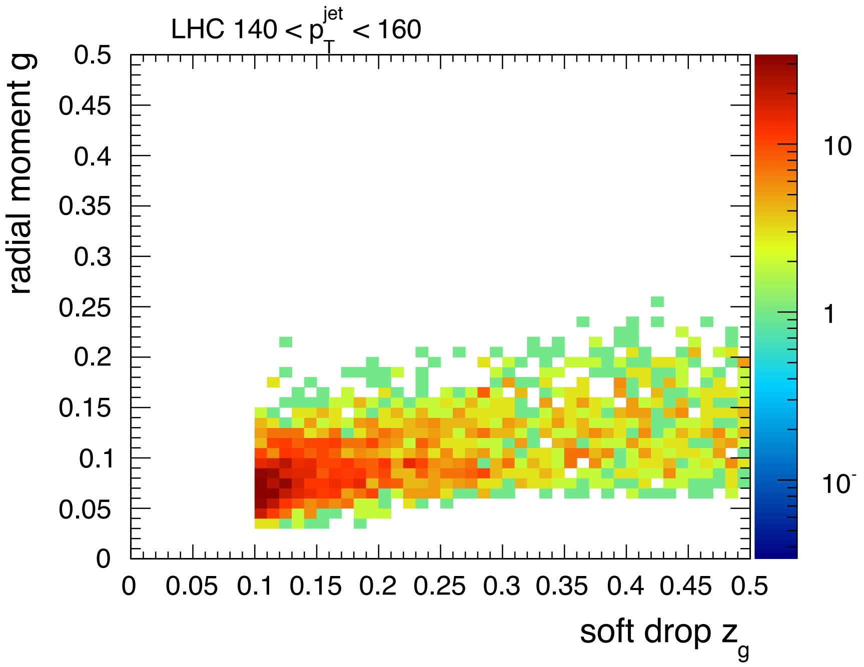
LHC low pT



Wed 10/05/2017 06:23:33 PDT

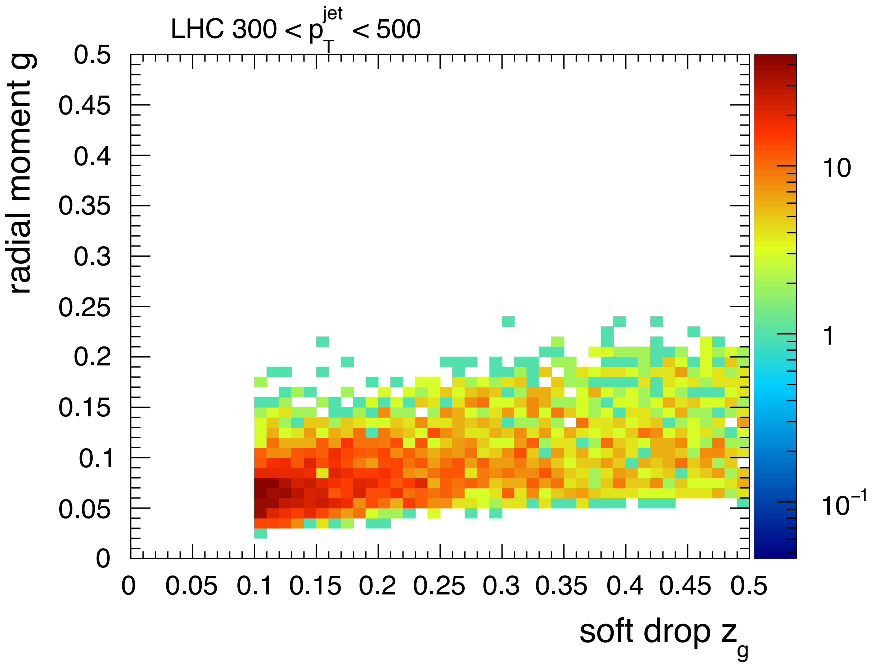
LHC high-pT

Radial moment vs z_g **With ΔR>0.1 cut**



Wed 10/05/2017 07:19:46 PDT

LHC low pT



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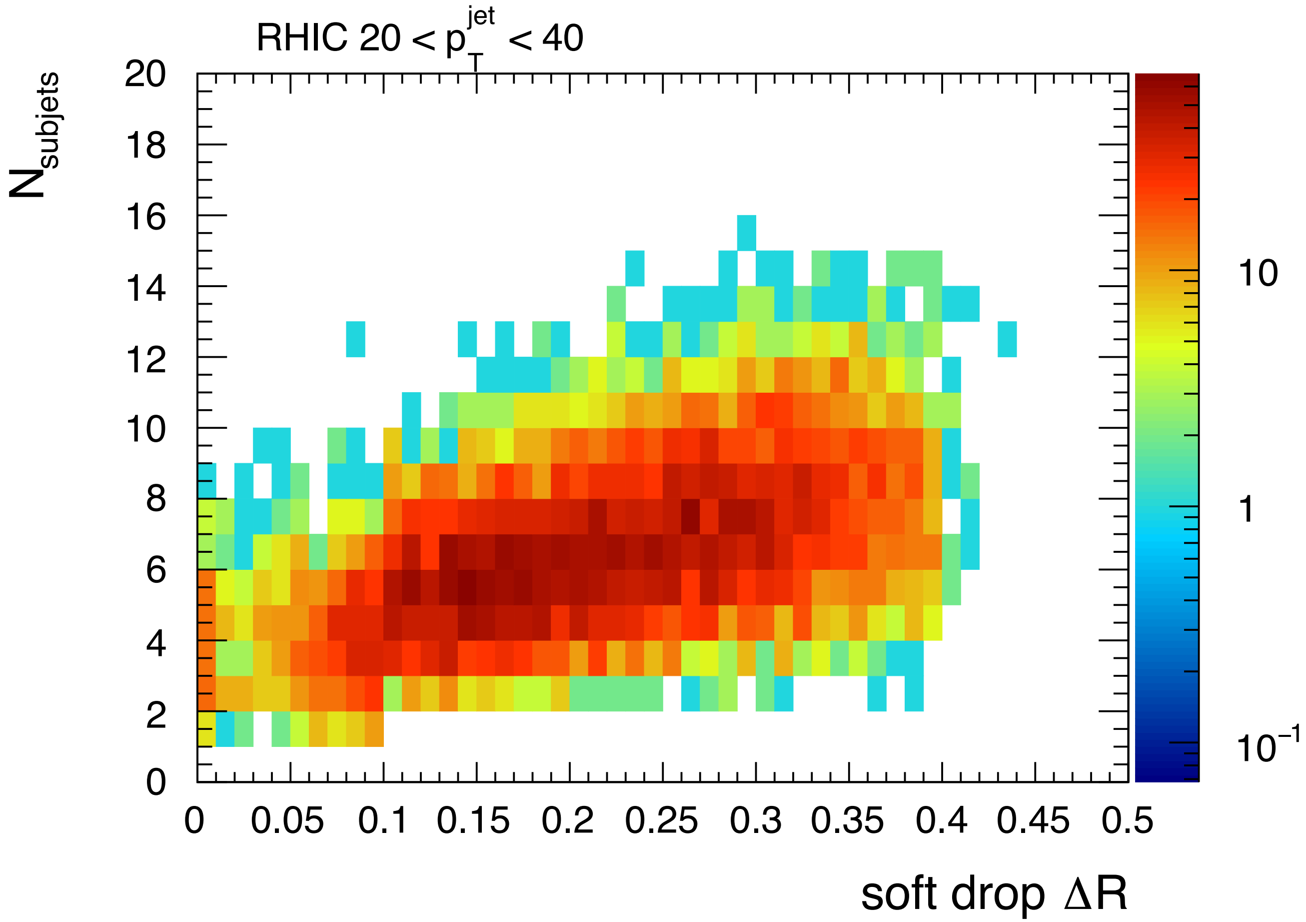
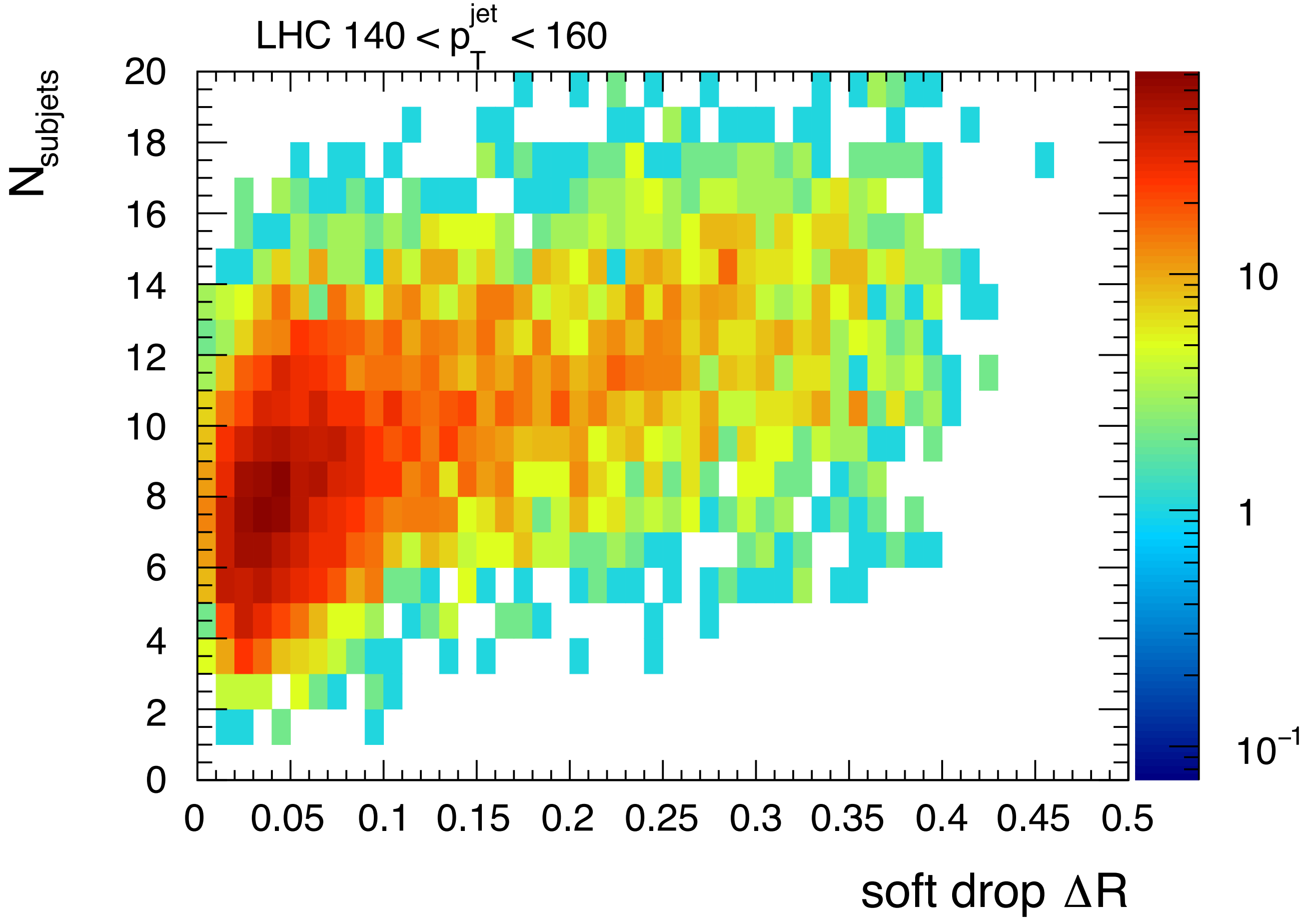
LHC high-pT

Cuts on ΔR?



Wed 10/05/2017 06:25:19 PDT

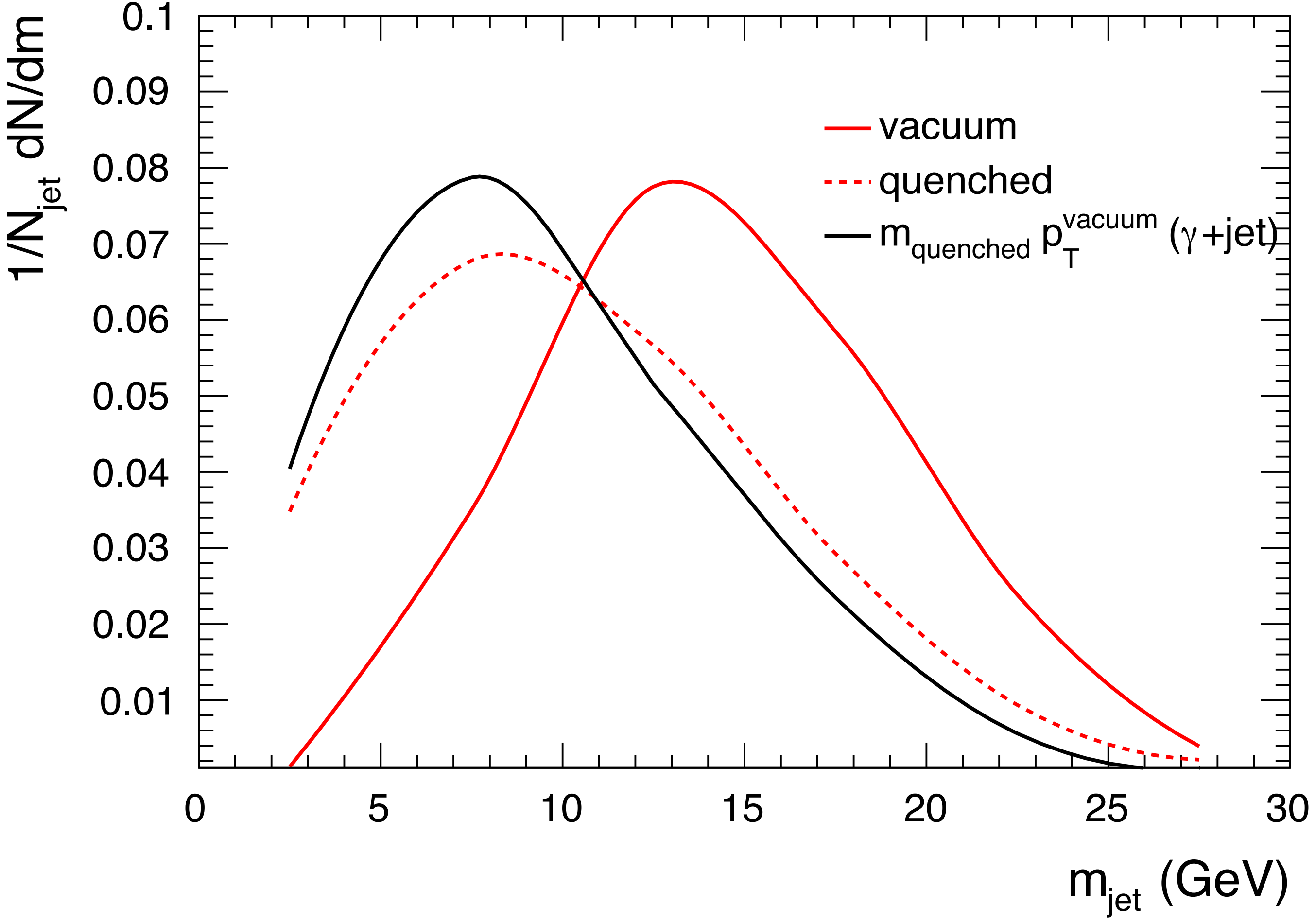
Cuts on ΔR?



Wed 10/05/2017 06:25:19 PDT

“Cut On One Look Elsewhere ”

“Analysis” cut on gamma pT

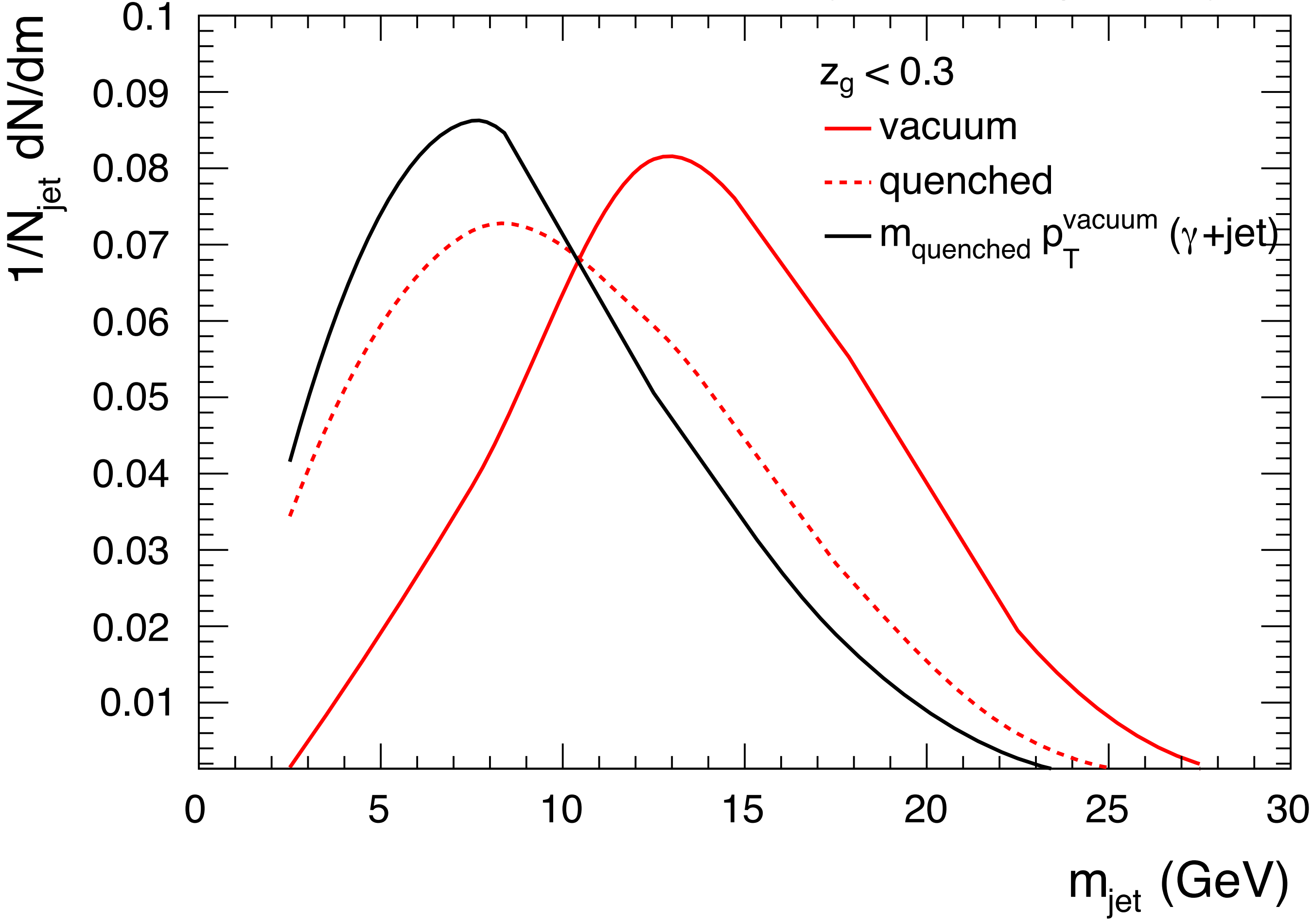


Wed 10/05/2017 07:57:24 PDT

“Cut On One Look Elsewhere ”

Low z_g and high-z_g different sensitivity

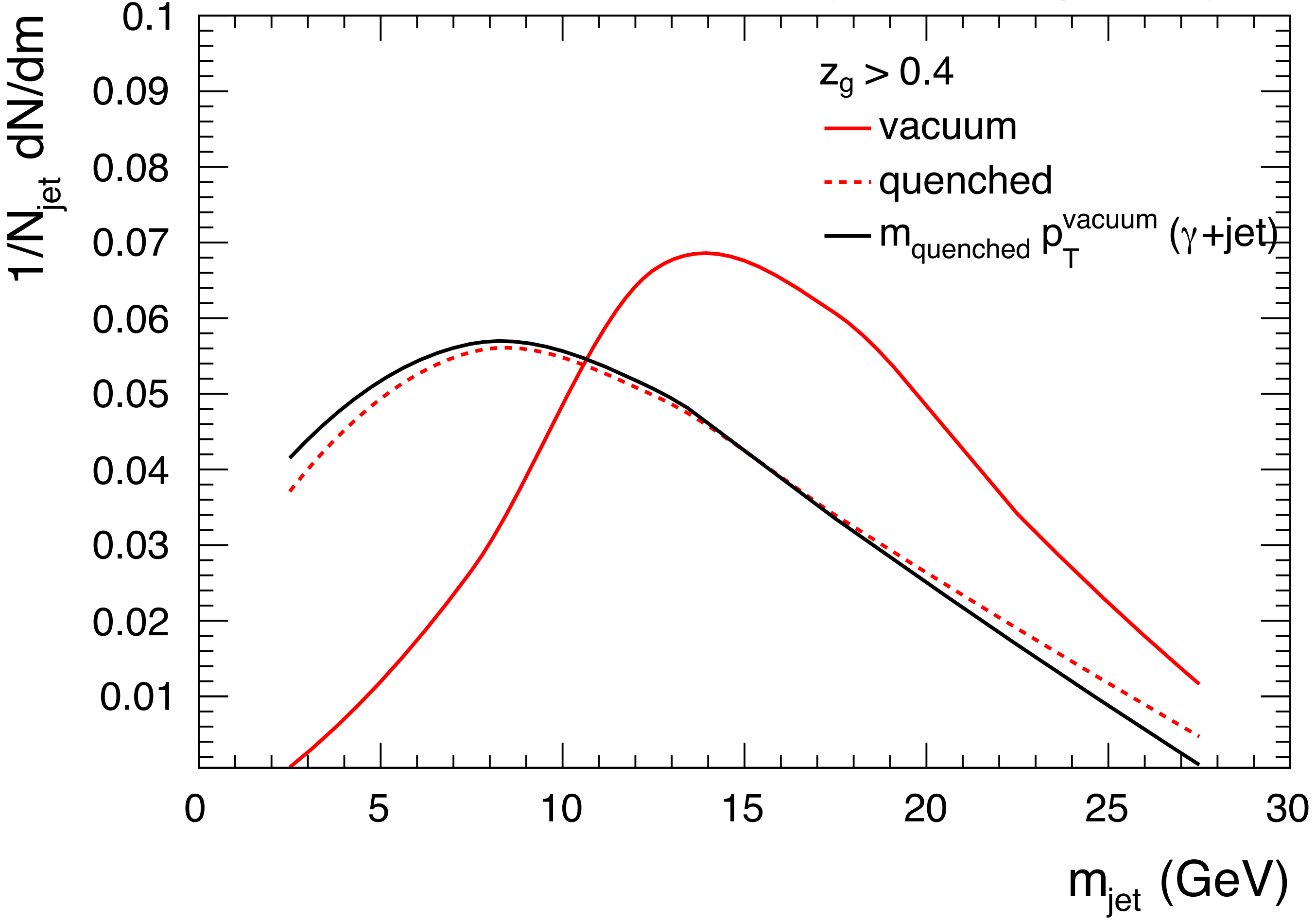
“Analysis” cut on gamma pT



Wed 10/05/2017 07:57:24 PDT

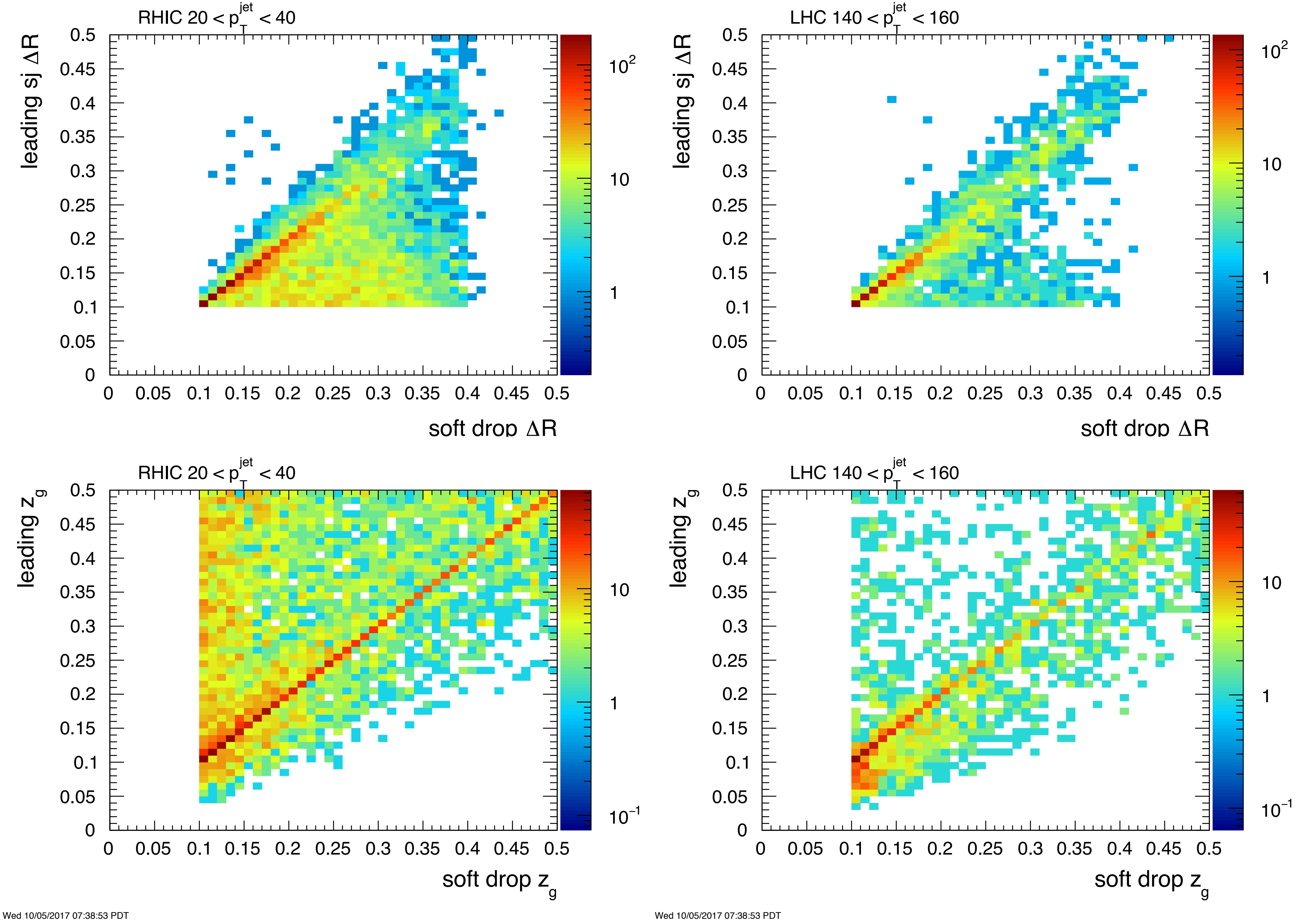
“Cut On One Look Elsewhere ”

Low z_g and high-z_g different sensitivity
“Analysis” cut on gamma pT

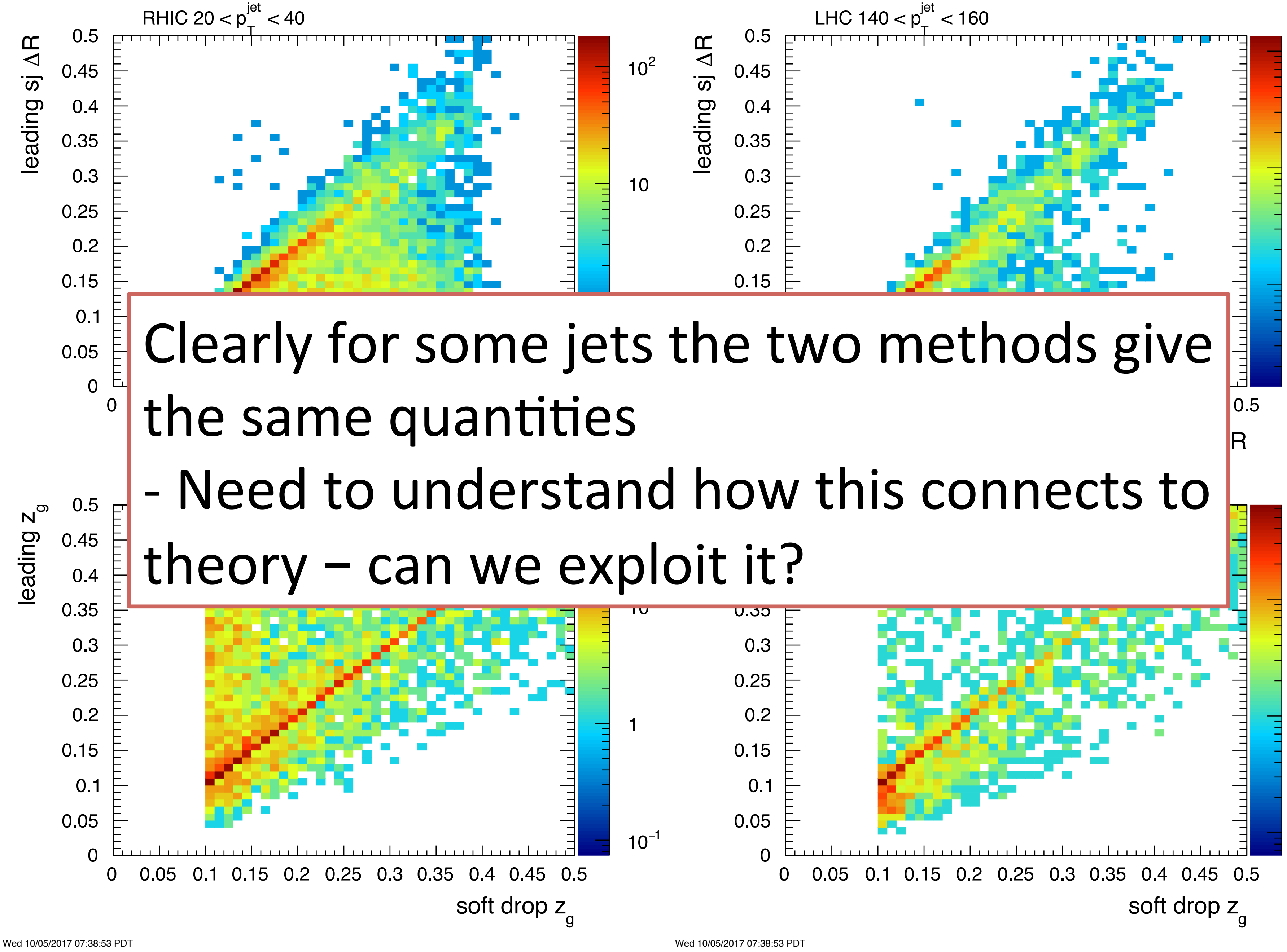


Wed 10/05/2017 07:57:24 PDT

Subjets in a groomed jet vs leading subjets in ungroomed jet



Subjets in a groomed jet vs leading subjets in ungroomed jet



Clearly for some jets the two methods give the same quantities

- Need to understand how this connects to theory – can we exploit it?

Qualitative progress wish list

- Ultimate tool: gamma/Z^0+jet coincidences
- Identified quark − jet coincidences
  - heavy-quarks (c,b) − ALICE focus for Run-3 − interesting hadron-jet (heavy-hadron takes up ~70% of the jet energy)
  - Within-shower qqbar production a solvable problem and possibly a tool(!)
- Boosted tops…

Summary

- New (HEP but HI-cooked) ideas turn into measurements − many already!
- Sub-jets is the qualitative new
  - Move away from hadronization (still present but potentially less of an issue)
- Trouble: multiple directions to choose from and difficulty in expressing the observables at the vacuum energy scale (unfolding fluctuations)
- Bottom line: good, I think we are learning and moving in a good direction

Slide credits – thank you!

- L Apolinario, D Caffari, M Spousta, J Thaller, K Tywoniuk, M Verweji
- ALICE, ATLAS, CMS, STAR

ADDITIONAL SLIDES

N-subjettiness

Thaler, van Tilburg arXiv:1011.2268

A measure of how consistent a jet is with having N subjets (τ_N)

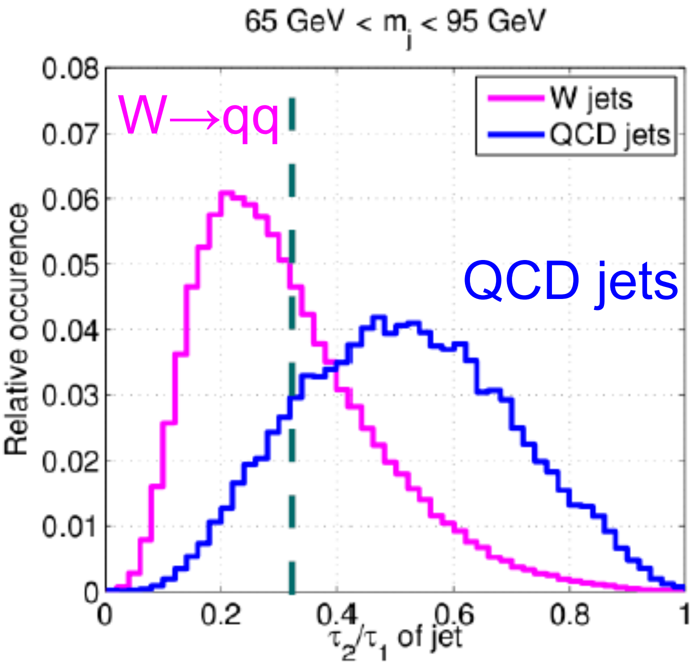
Used to find boosted W, Z, Higgs (2-prong), boosted top (3-prong) in pp

$$\tau_N = \frac{1}{d_0} \underbrace{\sum_k p_{T,k}}_{\text{Sum over all particles}} \underbrace{\min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}}_{\text{Minimize distance of each particle to subjets}}$$

QCD jets with 2 cores: small τ_2/τ_1

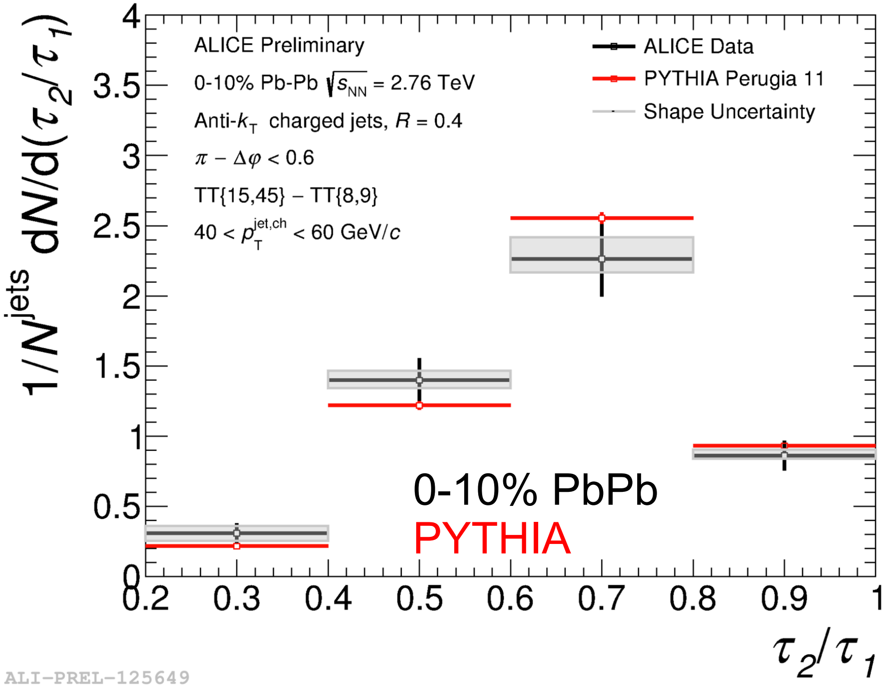
Does the medium absorb one of the substructures?

Can we probe the role of color coherence?



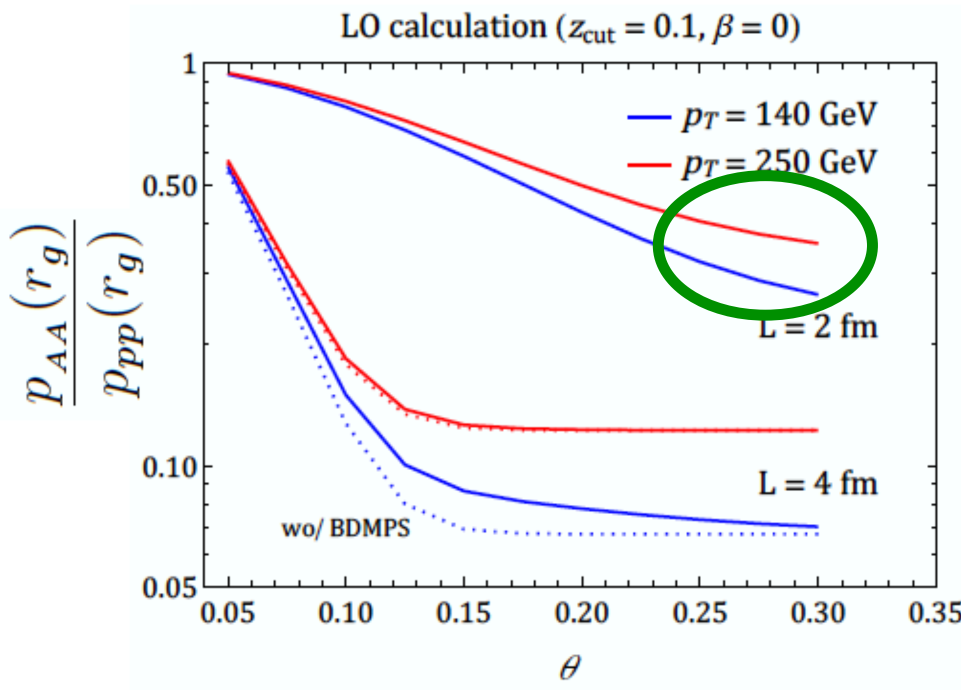
N-subjettiness

PbPb vs PYTHIA
√s = 2.76 TeV



2-prong jet

1-prong jet

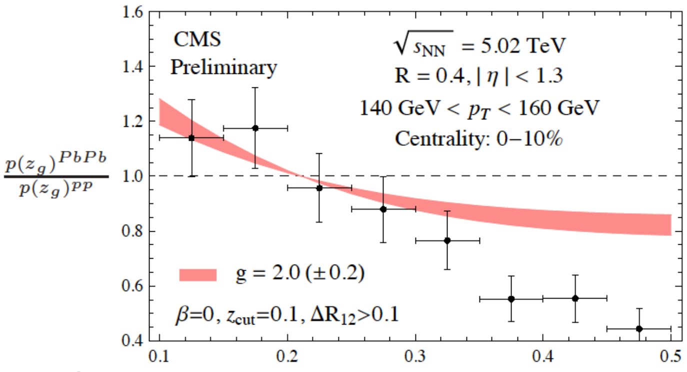


Yacine Mehtar Tani, Wed. 6.4

Color decoherence suppresses large angle radiation → Leads to jet collimation
Look at 2-pronged angular probability distributions

z_g modified – why?

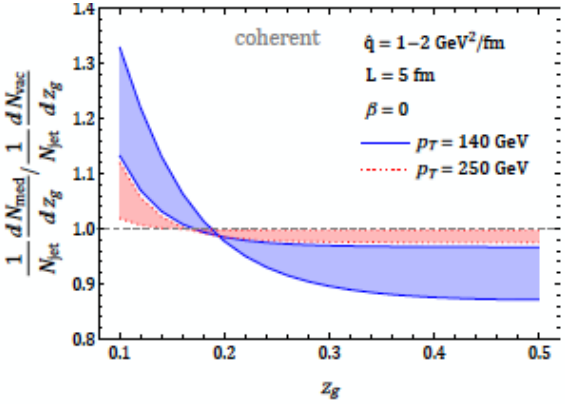
Medium modified splitting with SCET_G



LO diagrams dressed with vacuum like multiple emissions

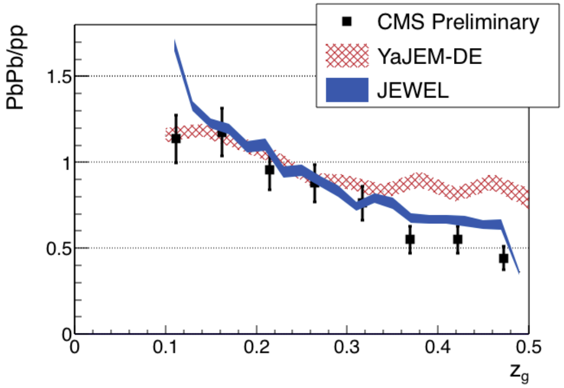
Chien and Vitev. arXiv:1608.07283

Coherent + semi-hard BDMPS radiation



Mehtar Tani and Tywoniuk arXiv:1610.08930

Jet quenching MCs

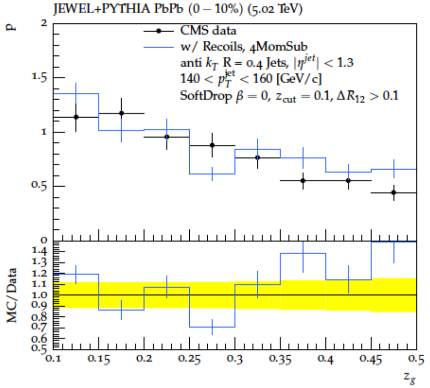


Kirill Lapidus, HP2016
R. Kunnawalkam Elayavalli, K. Zapp, G. Milhano

Jet-correlated medium

Promotion of splittings into sample due to medium push

Guilherme Milhano, Tue. 2.4



Large variety of concepts, describe general trend of data

Describing centrality and jet p_T dependence seems challenging