Jet (sub)Structure in Heavy Ions

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Rutgers University

Jet Substructure "Planning for the future" Event at the Fermilab LPC

from 30 November 2016 to 1 December 2016
Fermilab LPC
US/Central timezone

Search

Plan of action

- Quick Overview of the idea of jet structure in heavy ions and implications
- Summary of the latest jet structure results
- MC/Theory calculations and comparisons with data
- What is the next step (my personal thoughts and views)

Acknowledgements

- Thanks to Marta Verweij, Jesse Thaler, Yang-Ting Chien, Korinna Zapp, Sevil Salur and several others for useful discussions

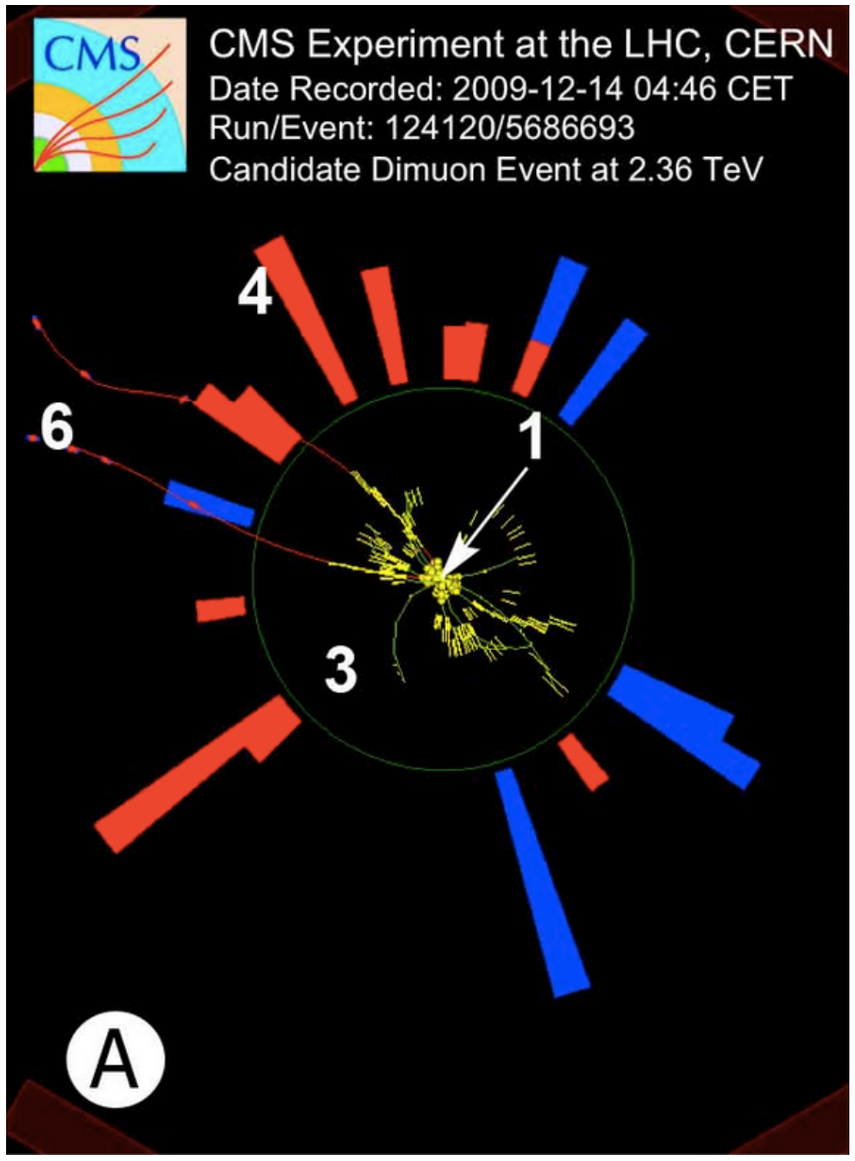
- Recent workshops/conferences where some of these results were shown

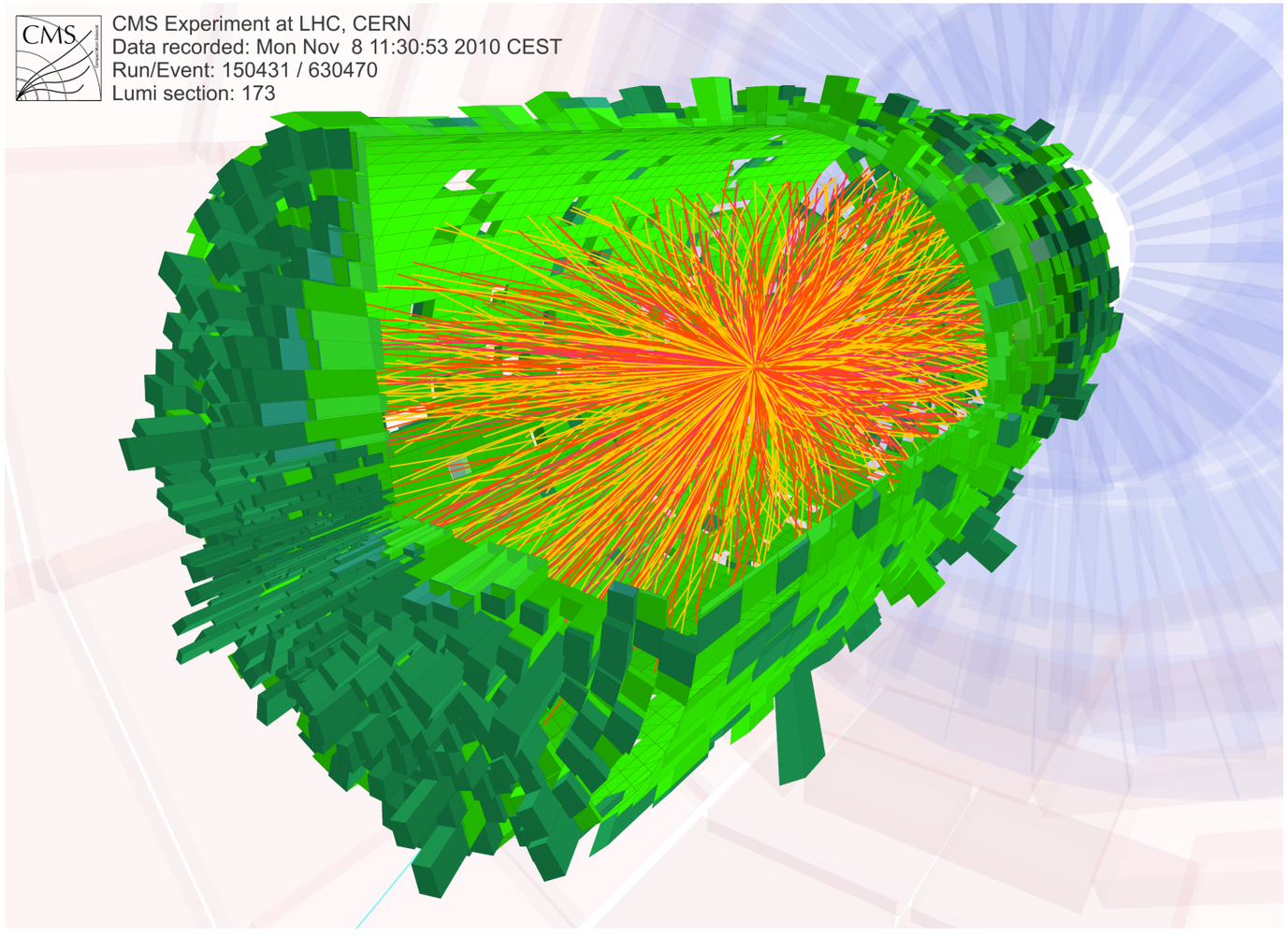
  - https://indico.cern.ch/event/558954/ MIT Workshop

  - https://indico.cern.ch/event/502239/ Hard Probes

  - https://indico.cern.ch/event/507670/ 4th Heavy Ion Jet Workshop

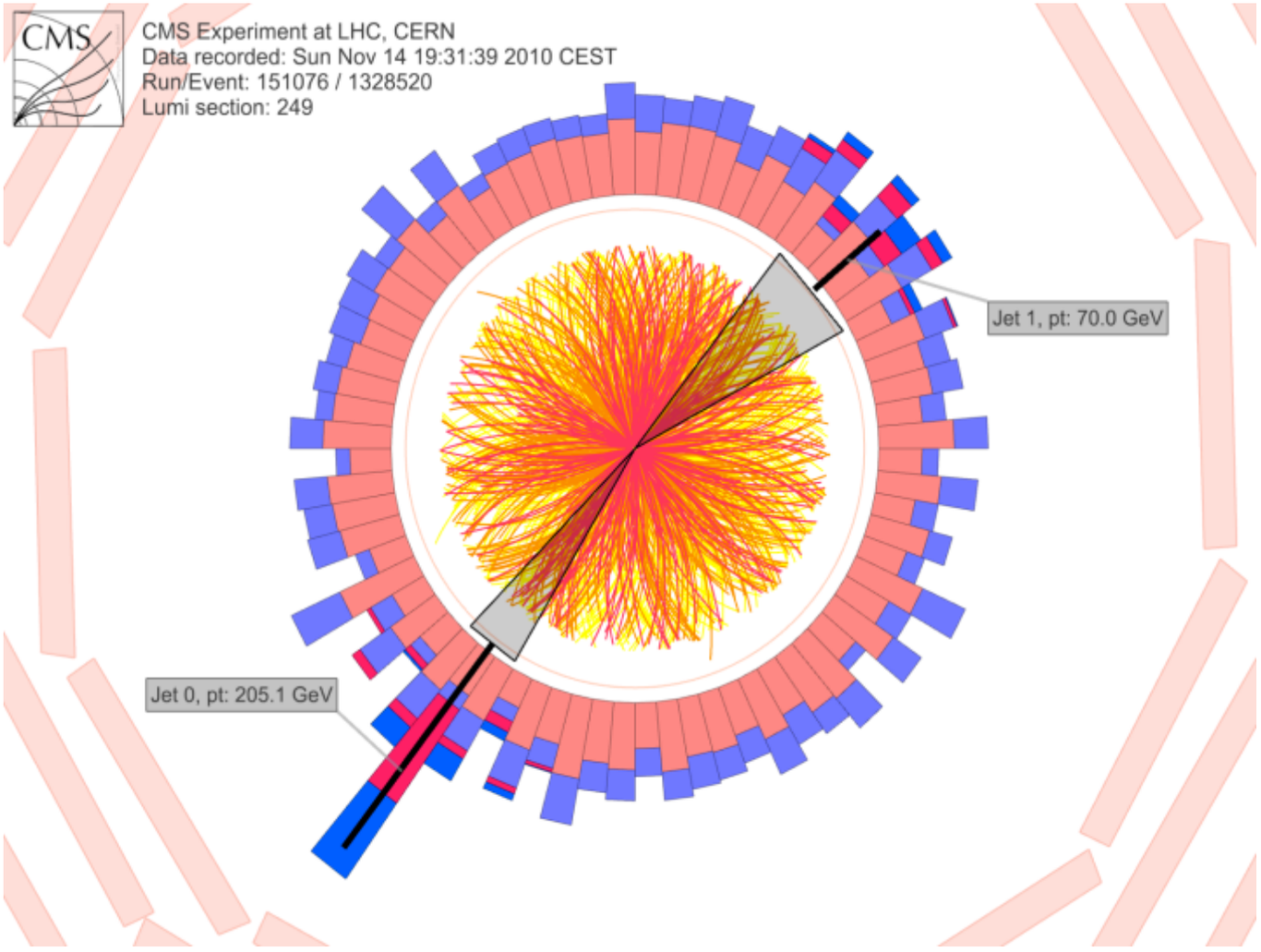
Quick introduction to HI



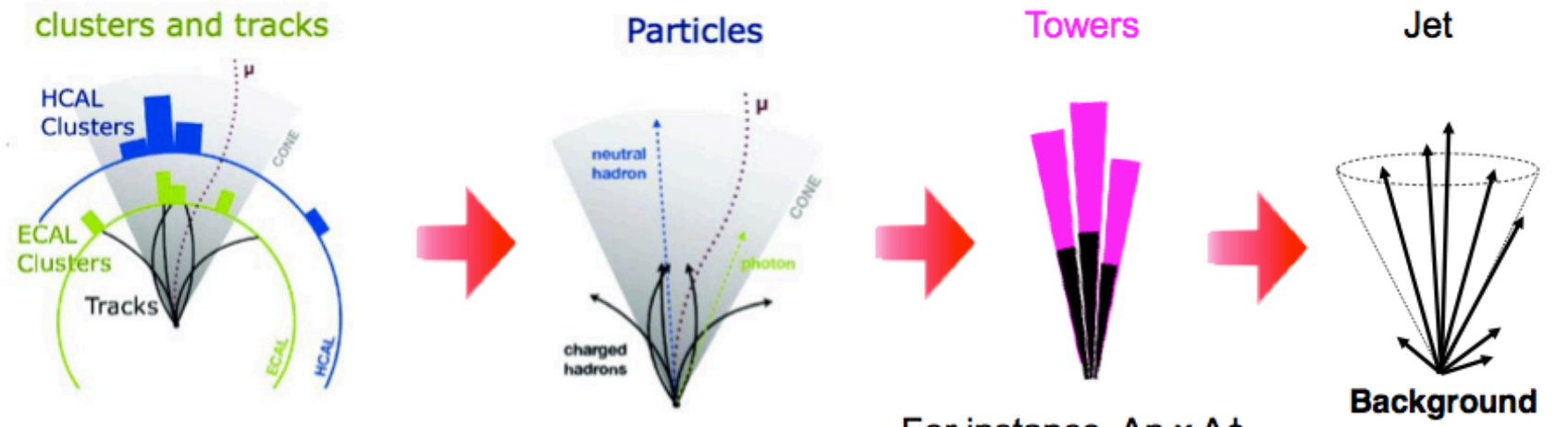


Jets are internal hard probes that help us characterize the QGP structure/properties

Jets in HIN events



- Background techniques employed to remove the fluctuating UE
- Issue a bit different than UE subtraction due to pileup



Anti-k_T algorithm is used in most of CMS publications

For instance, $\Delta\eta \times \Delta\phi$ 0.076 x 0.076 in barrel

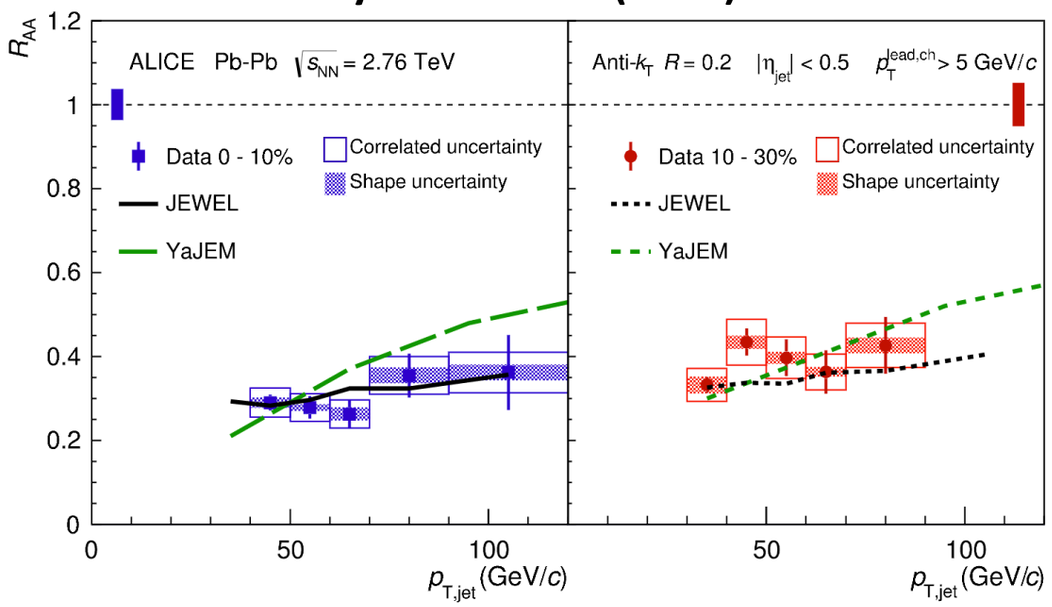
Background subtraction and jet clustering

Jet Quenching

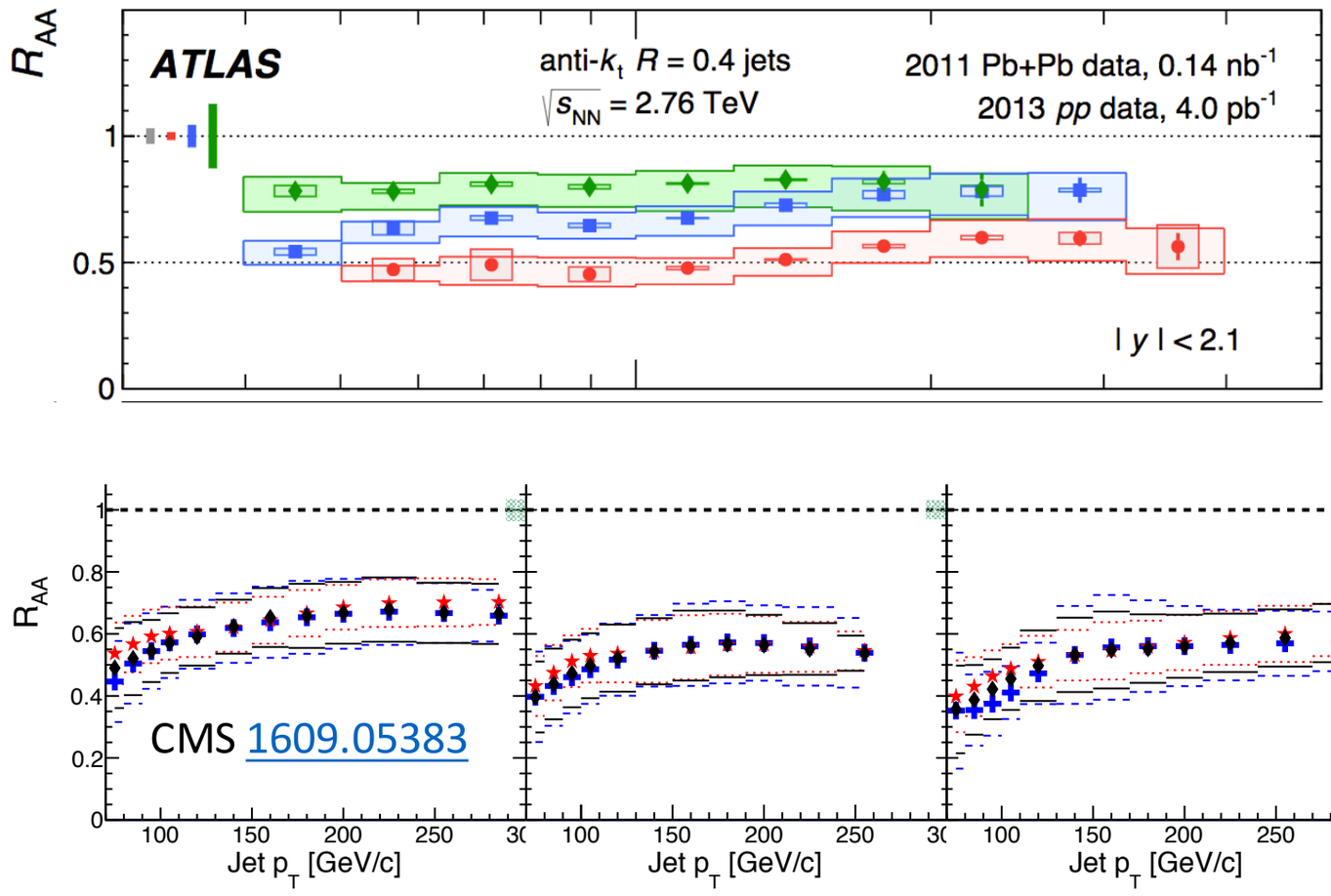
- Jets are quenched as they travel through the QGP

$$R_{AA} = \frac{dN^{AA}_{jets}/dp_T}{\langle N_{coll}\rangle\, dN^{pp}_{jets}/dp_T}$$

Phys.Lett. B746 (2015) 1-14



Phys.Rev.Lett. 114 (2015) no.7, 072302



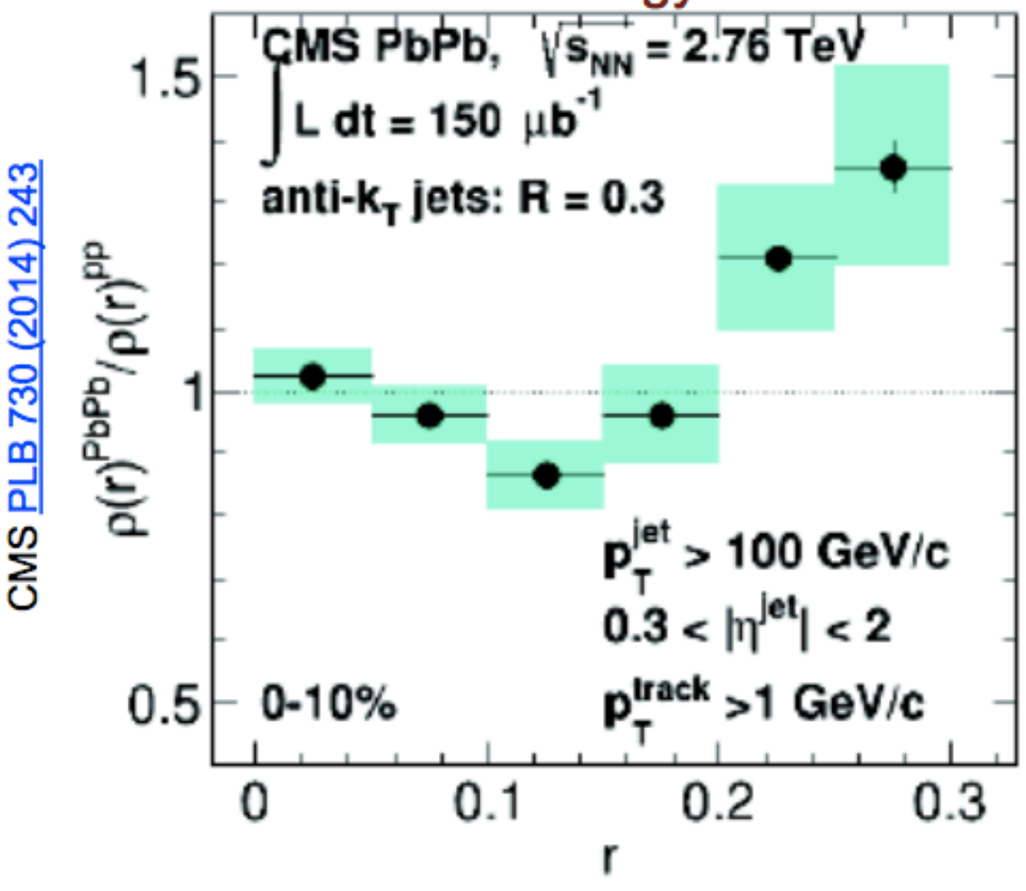
- Similar level of suppression between different jet resolution parameters (in the measured kinematic range)

- decrease in suppression as jet pT increases

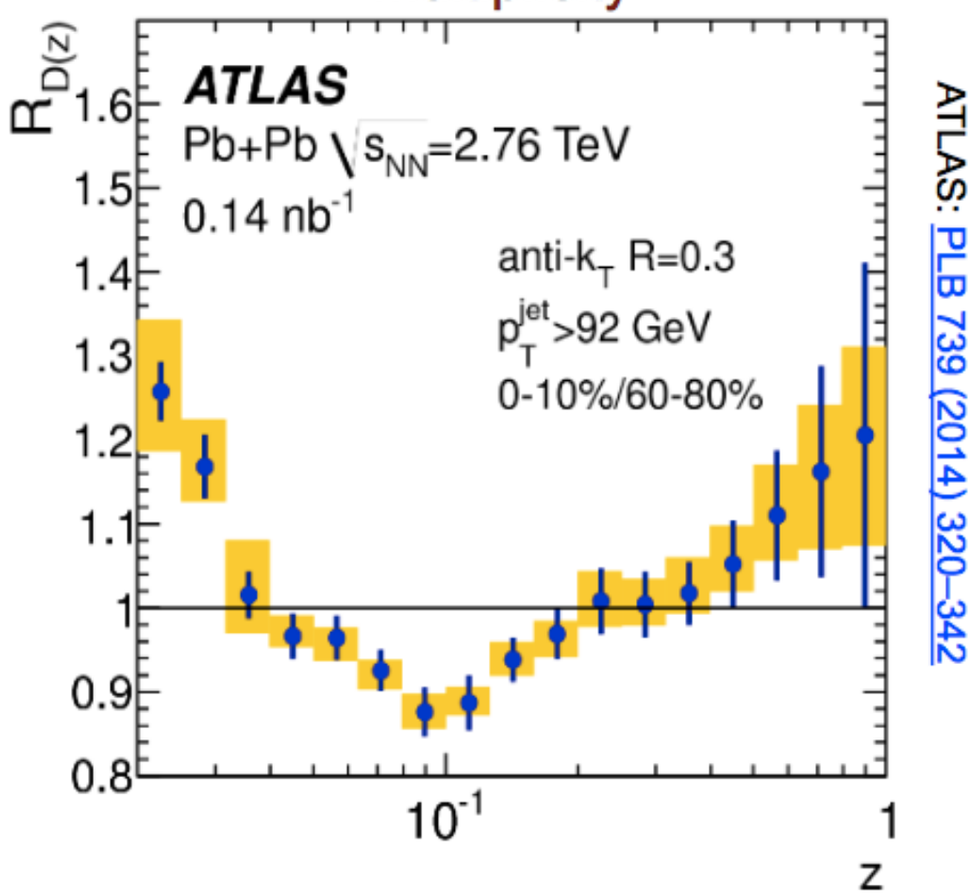
Jet Quenching and its effect on jet structure

Jet shape observables: energy + multiplicity distributions within a jet
Sensitive to the dynamics of parton shower

Radial profile
Transverse fragment distribution
Energy



'Fragmentation function'
Longitudinal fragment distribution
Multiplicity



Small enhancement at large *R* and small *z:* 1-2 GeV + ~2 particles
+ suppression at intermediate *R* and *z*

Slide by Marta, HP2016

What is the (new) goal?

- How is the inner jet structure modified -
  - core vs soft sector in the jets
  - Parton shower modifications, LPM effect
  - splitting? sensitivity to medium effect?

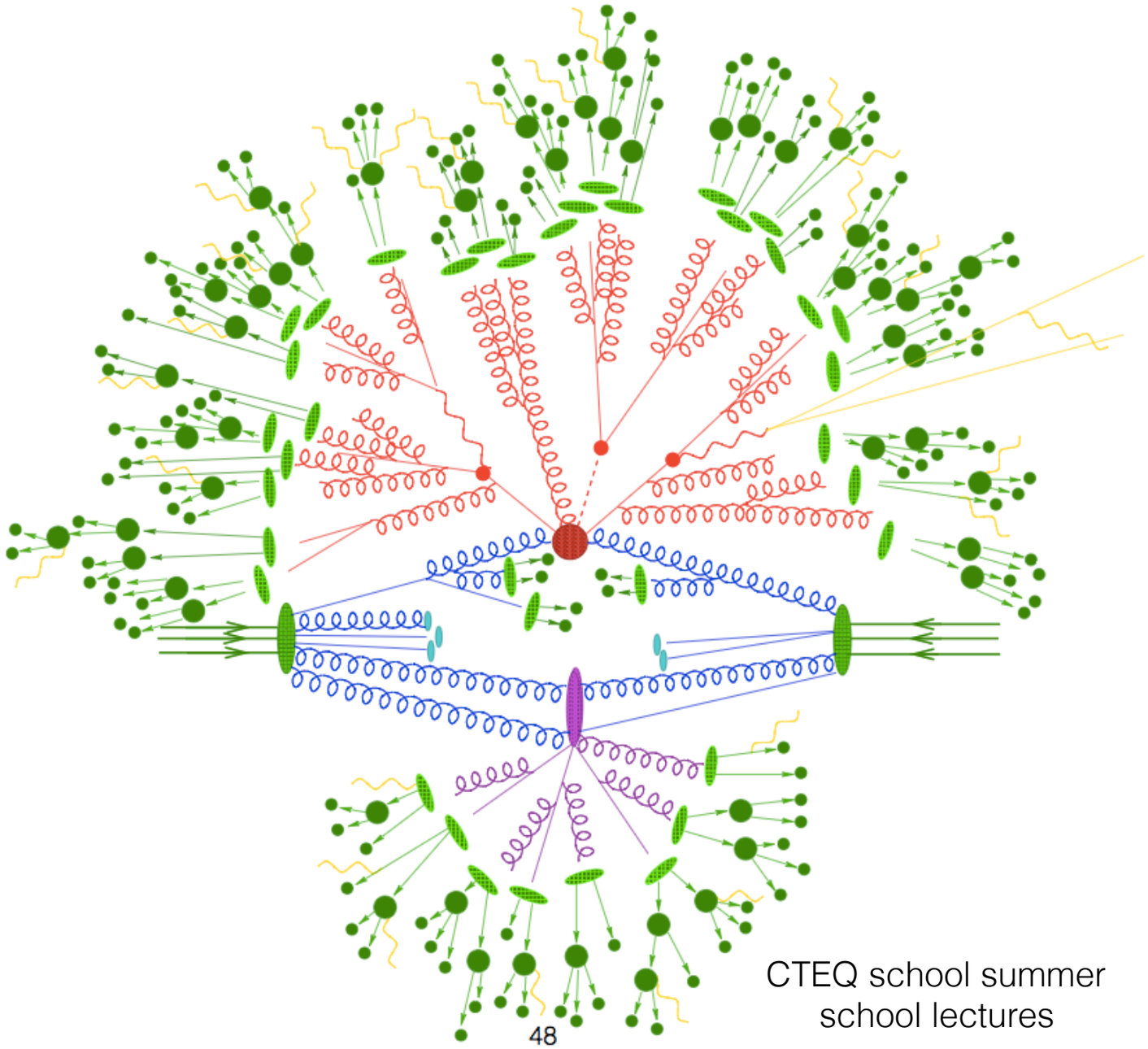
- Whats the status of the MC?

Monte Carlo Market

- JEWEL
  - 1111.6838,1212.1599
- HYBRID MODEL
  - 1405.3864,1508.00815
- LBT HYDRO
  - 1503.03313, 1605.06447
- Q-PYTHIA
  - 0907.1014, 0909.5118
- PYQUEN
  - 1103.1853
- MARTINI
  - 0909.2037, 0911.4470
- HYDJET
  - 0809.2708
- HIJING
  - 950.2021
- YAJEM
  - 1009.3740
- MATTER
  - 1301.5323

MC needs to do

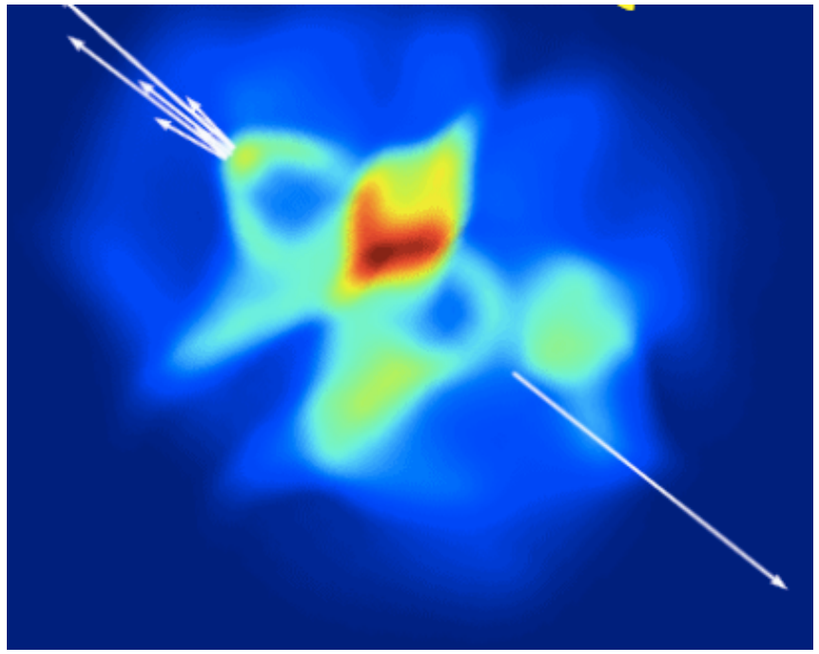
- PDFs
- Hard Scattering
- ISR
- FSR : parton shower
- Color reconnections
- Hadronization



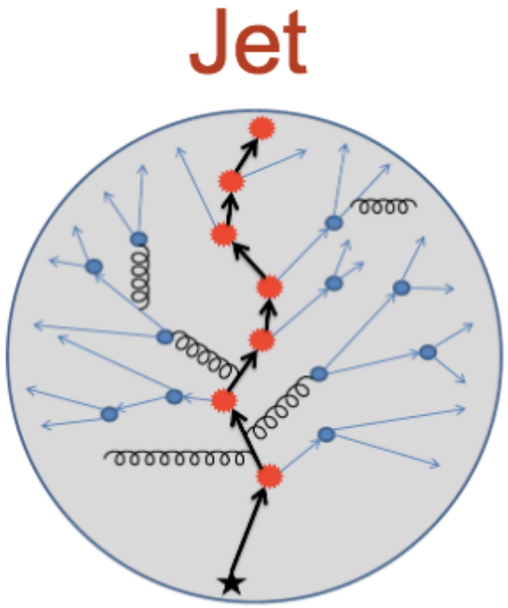
CTEQ school summer school lectures

Including the medium interaction

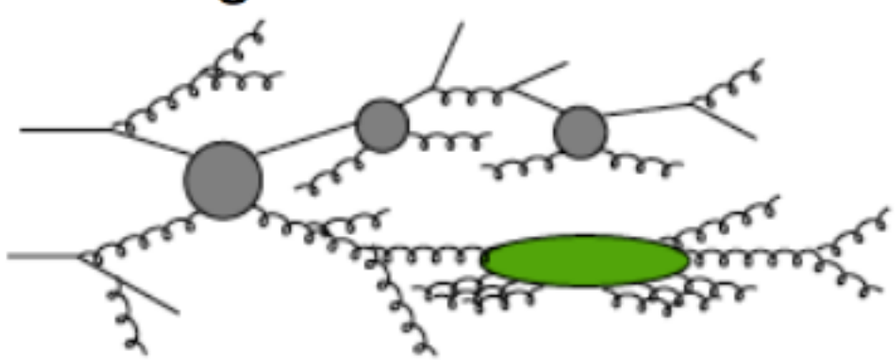
Modeling the jet-medium and medium-jet interactions

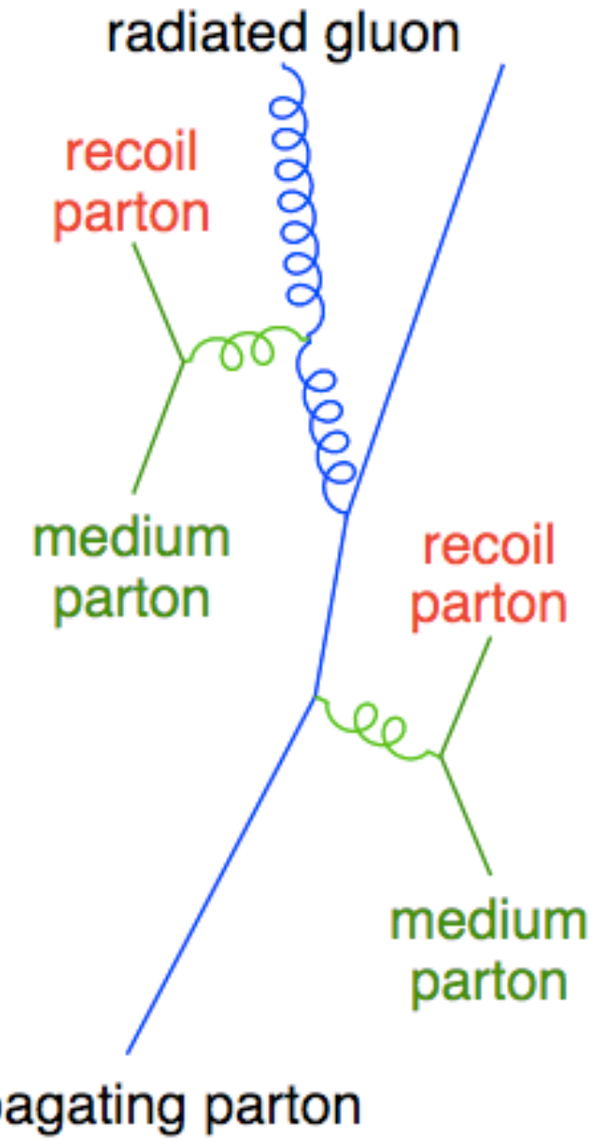


LBT wake



Scatterings with medium + LPM effect

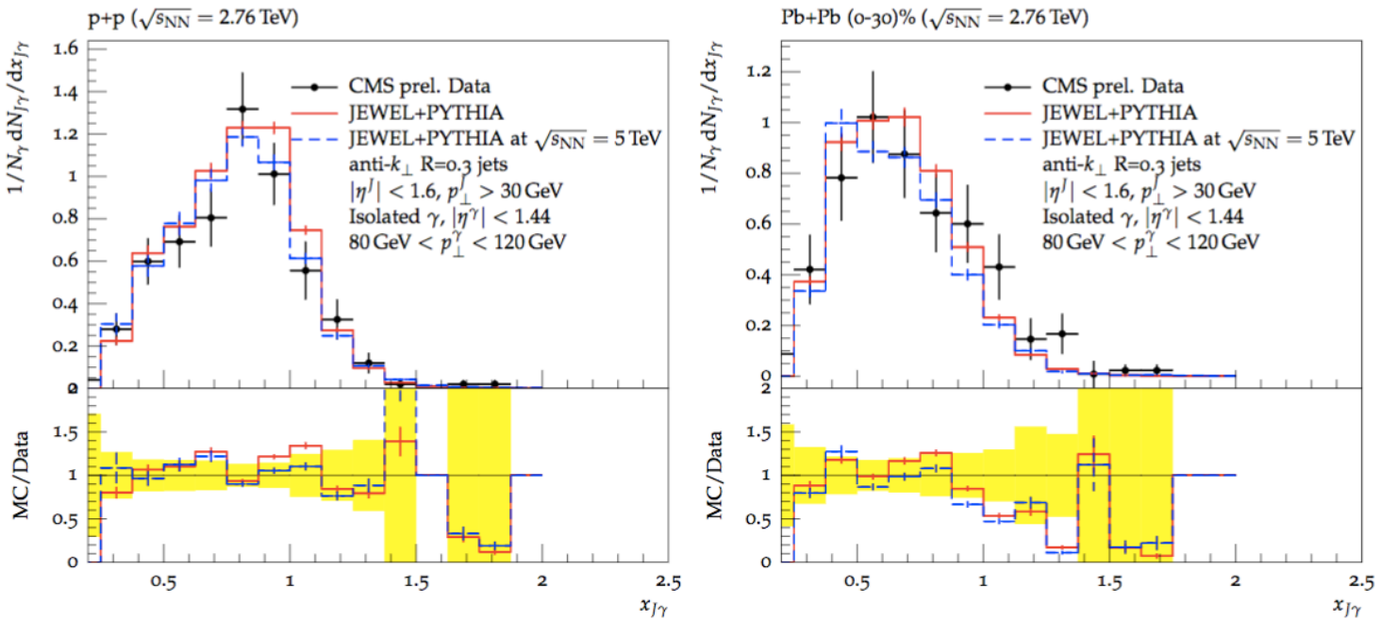




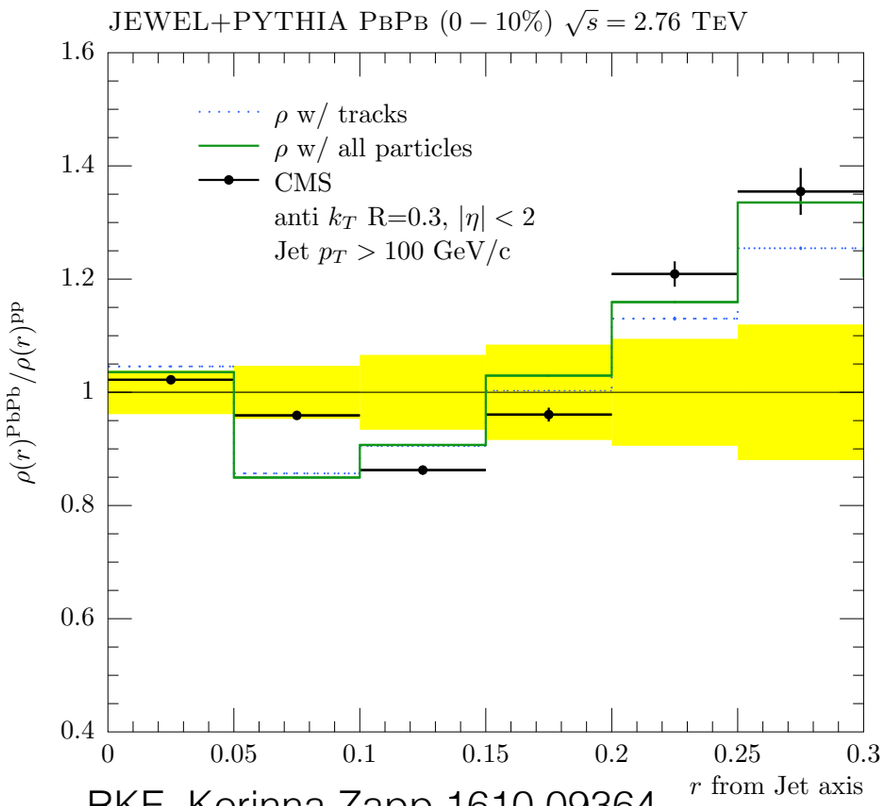
JEWEL

Importance of pp baseline!

- Heavy ion generators reproducing vacuum result introduces confidence in medium modeling
- If they match in PbPb, but not in pp, over quenching or under quenching or just some weird combination
- General structure is good, but important to close the gap for precision physics



RKE, Korinna Zapp 1608.03099

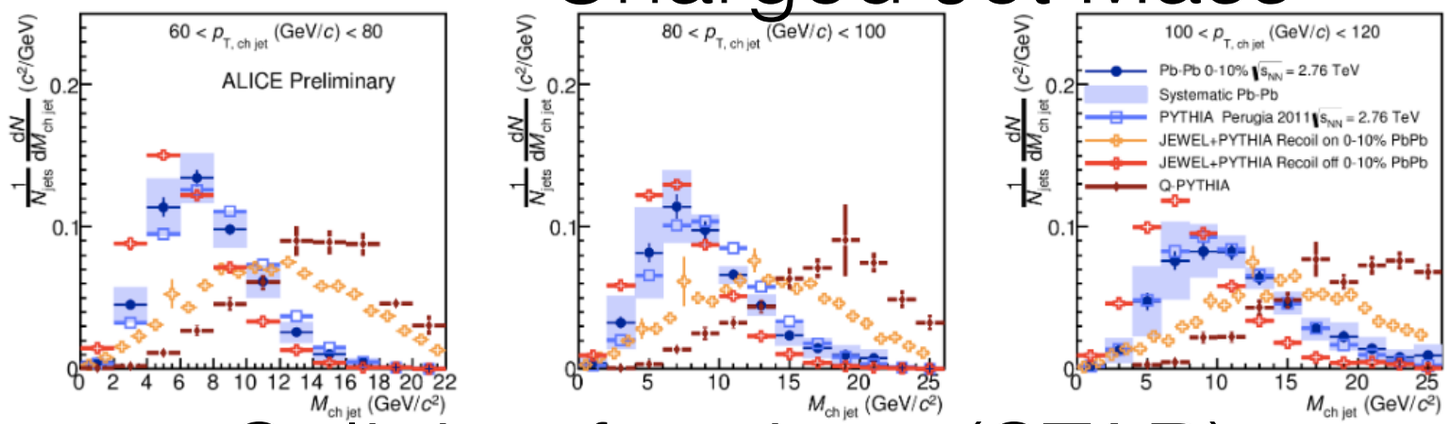


RKE, Korinna Zapp 1610.09364
RKE, Korinna Zapp in Prep

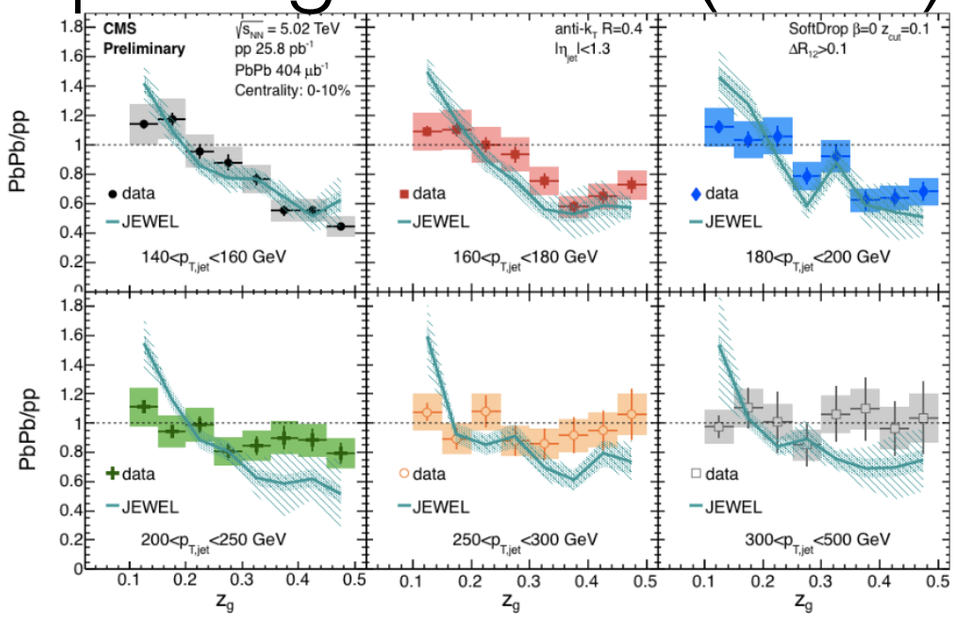
Results from the last year regarding Jet Sub-structure in Heavy Ions

Chiara Bianchin, HP 2016

Charged Jet Mass

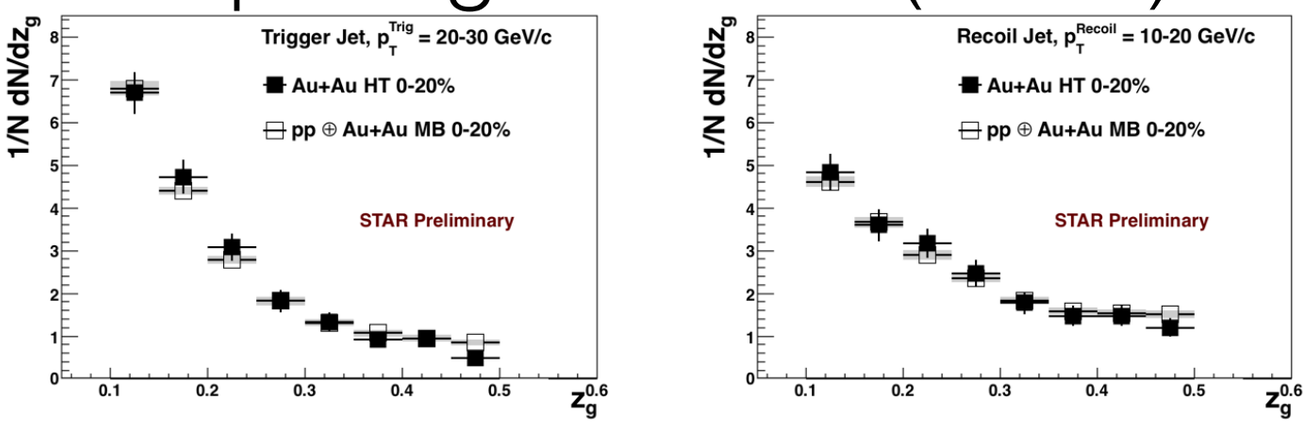


Splitting fraction (CMS)



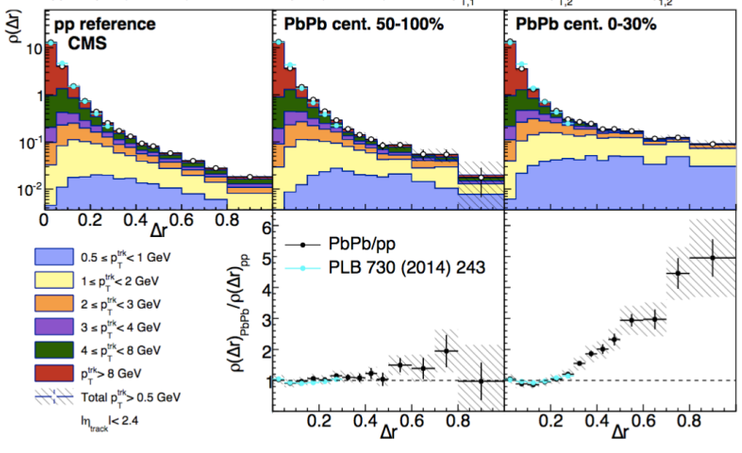
CMS-HIN-16-006

Splitting fractions (STAR)



Kolja Kauder, HP 2016

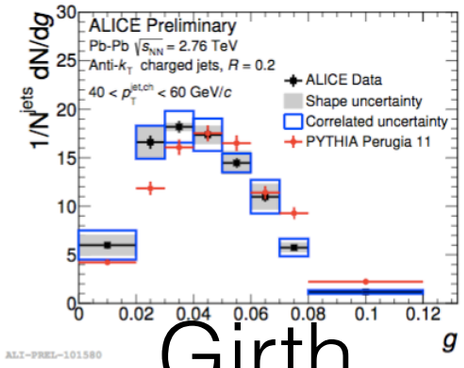
CMS 1609.02466



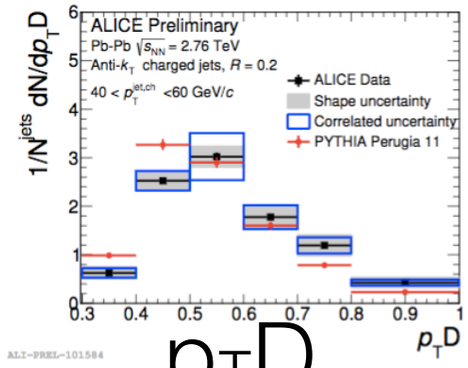
Jet Shape

Leticia, 1512.07882

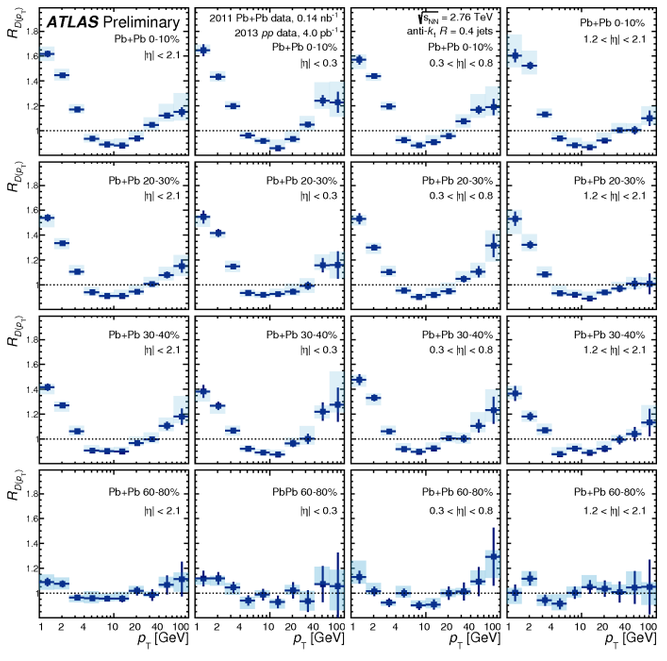
Girth



p_TD

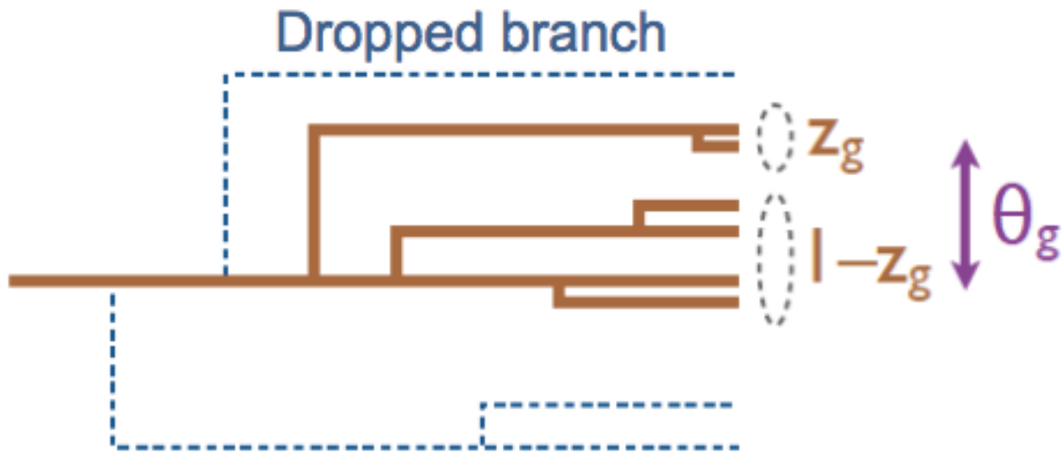


Fragmentation Fnc



ATLAS-CONF-2015-055/

Splitting Fraction



Role of β:
β>0 - IRC safe
β<0 - (IR)C unsafe
β=0 - IRC unsafe
– but Sudakov-safe

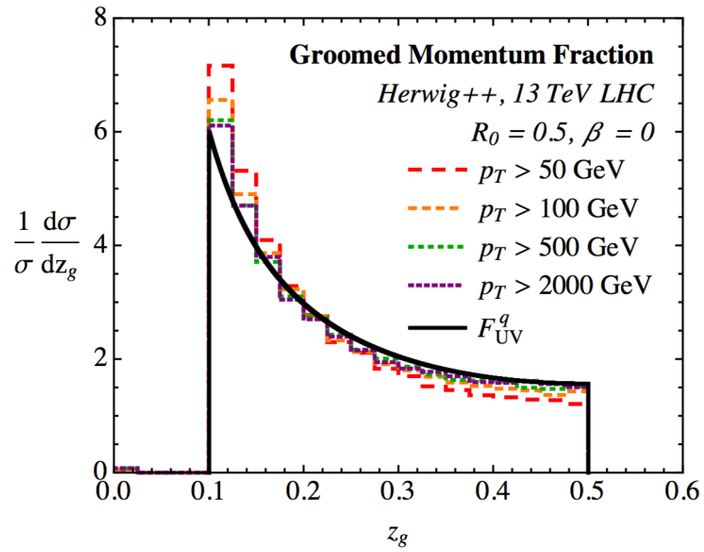
$$\text{For } \beta = 0, z_g > z_{\text{cut}}:$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} \propto \overline{P_i}(z_g) + \cancel{\mathcal{O}(\alpha_s^2)}$$

P_i: Altarelli-Parisi splitting functions (symmetrized)

q→qg, g→gg, g→qg

(Kernels in DGLAP)



Larkoski et al., PRD 91, 111501 (2015)

~ independent of α_s
~ independent of p_T (in UV limit)
Connection to fundamental QCD

Note: AP functions govern split *kinematics*, not *frequency*
→ Treated differently in E-loss models

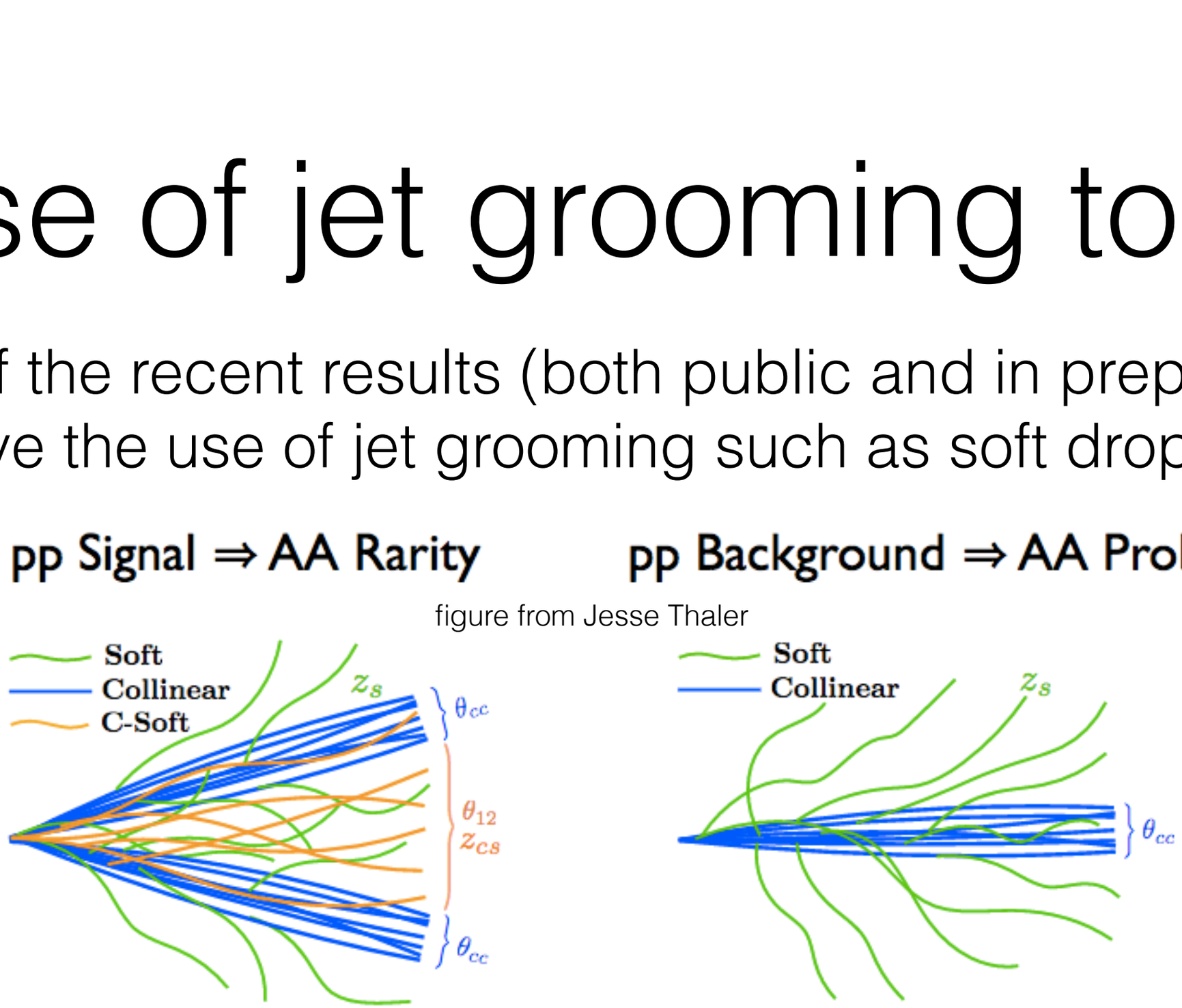
Kolja Kauder, Marta Verweij, HP2016

Use of jet grooming tools

A lot of the recent results (both public and in preparation) involve the use of jet grooming such as soft drop etc…

pp Signal ⇒ AA Rarity **pp Background ⇒ AA Probe**

figure from Jesse Thaler



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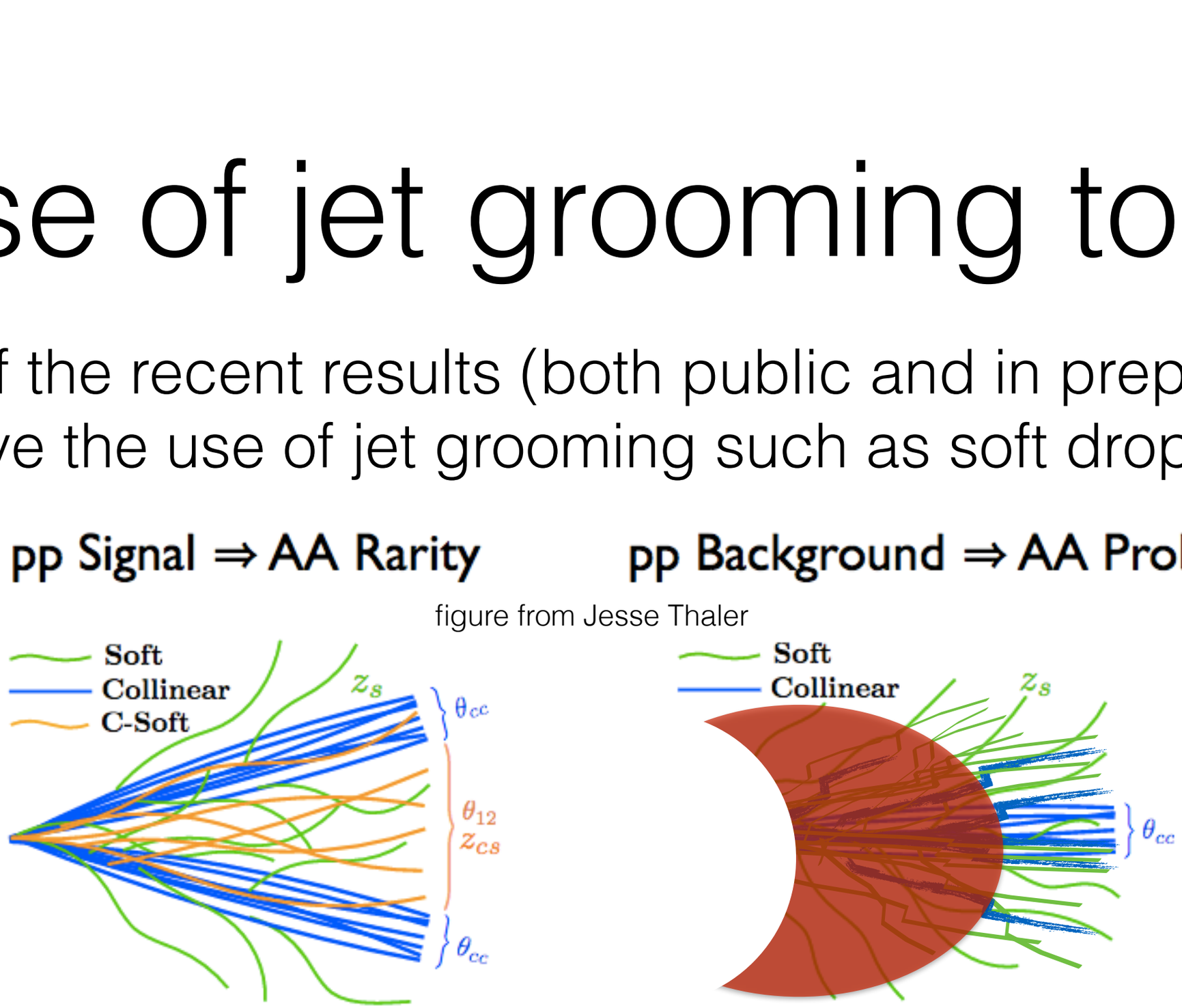
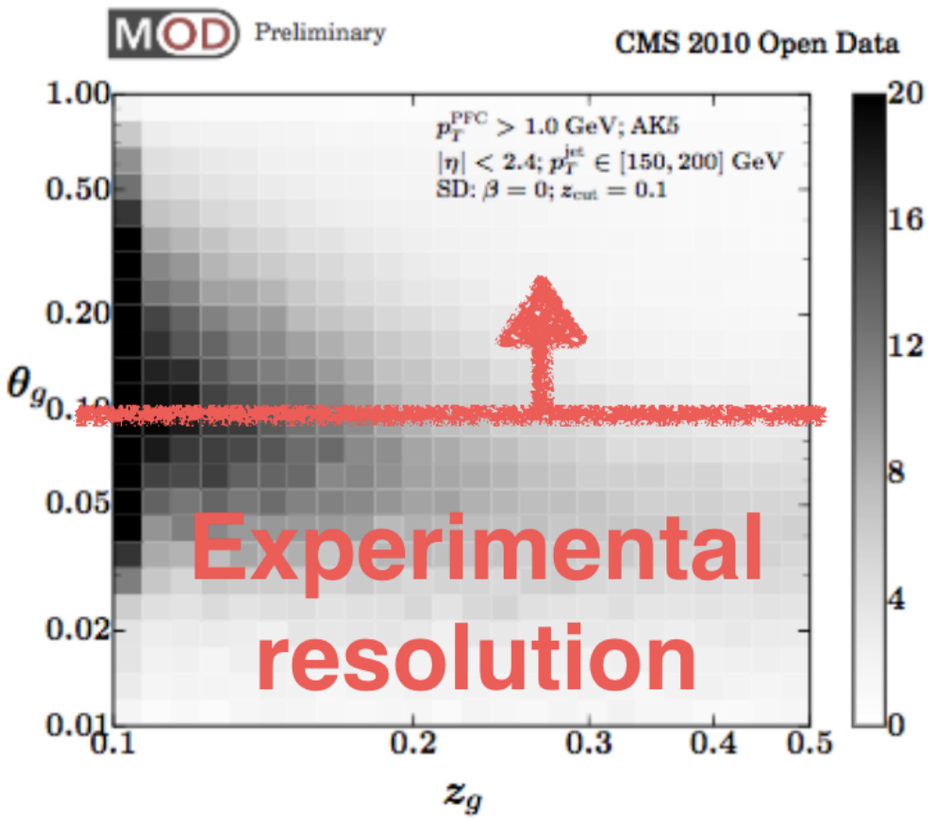


It is necessary to study the interplay between background subtraction and jet grooming in HIN events

Does it translate to splitting?

figure from Jesse Thaler



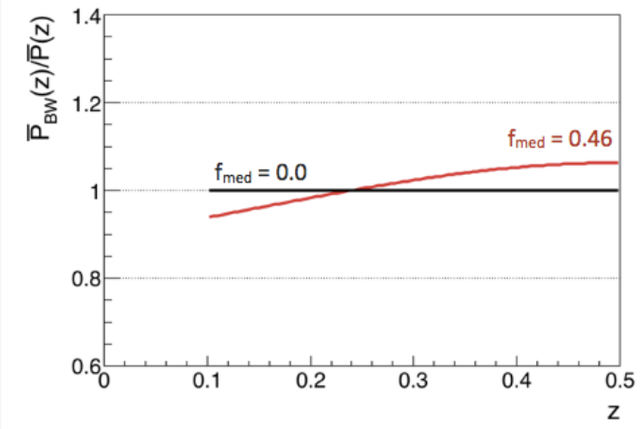
Does an explicit modification of the splitting function propagate to the z_g observable?

YaJEM-BW: $P_{q\to qg} = \frac{4}{3}\frac{1+z^2}{1-z} \Rightarrow \frac{4}{3}\left(\frac{2(1+f_{\mathrm{med}})}{1-z} - (1+z)\right)$

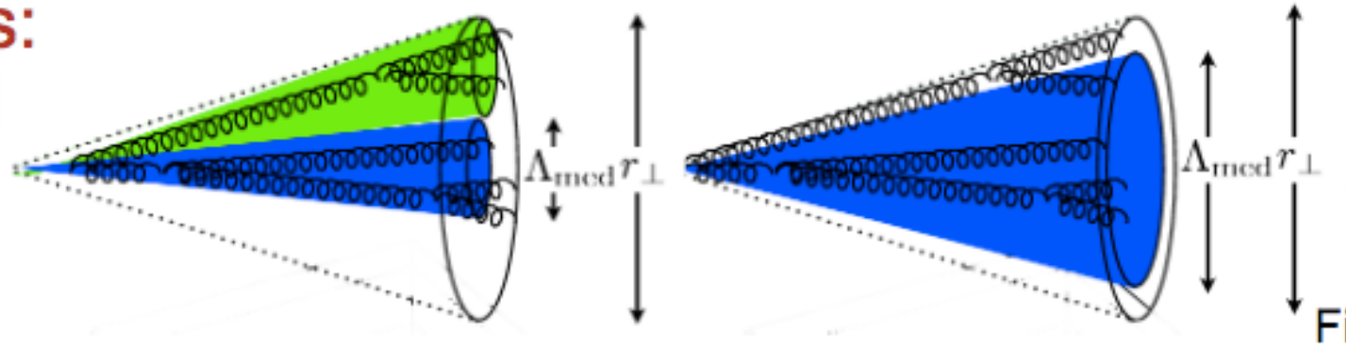
$$p(z_g) = \frac{\overline{P}_i(z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} dz\, \overline{P}_i(z)}\Theta(z_g - z_{\mathrm{cut}})$$

$$\overline{P}_i(z) = P_i(z) + P_i(1-z)$$

Slide from Kirill Iapidus HP2016



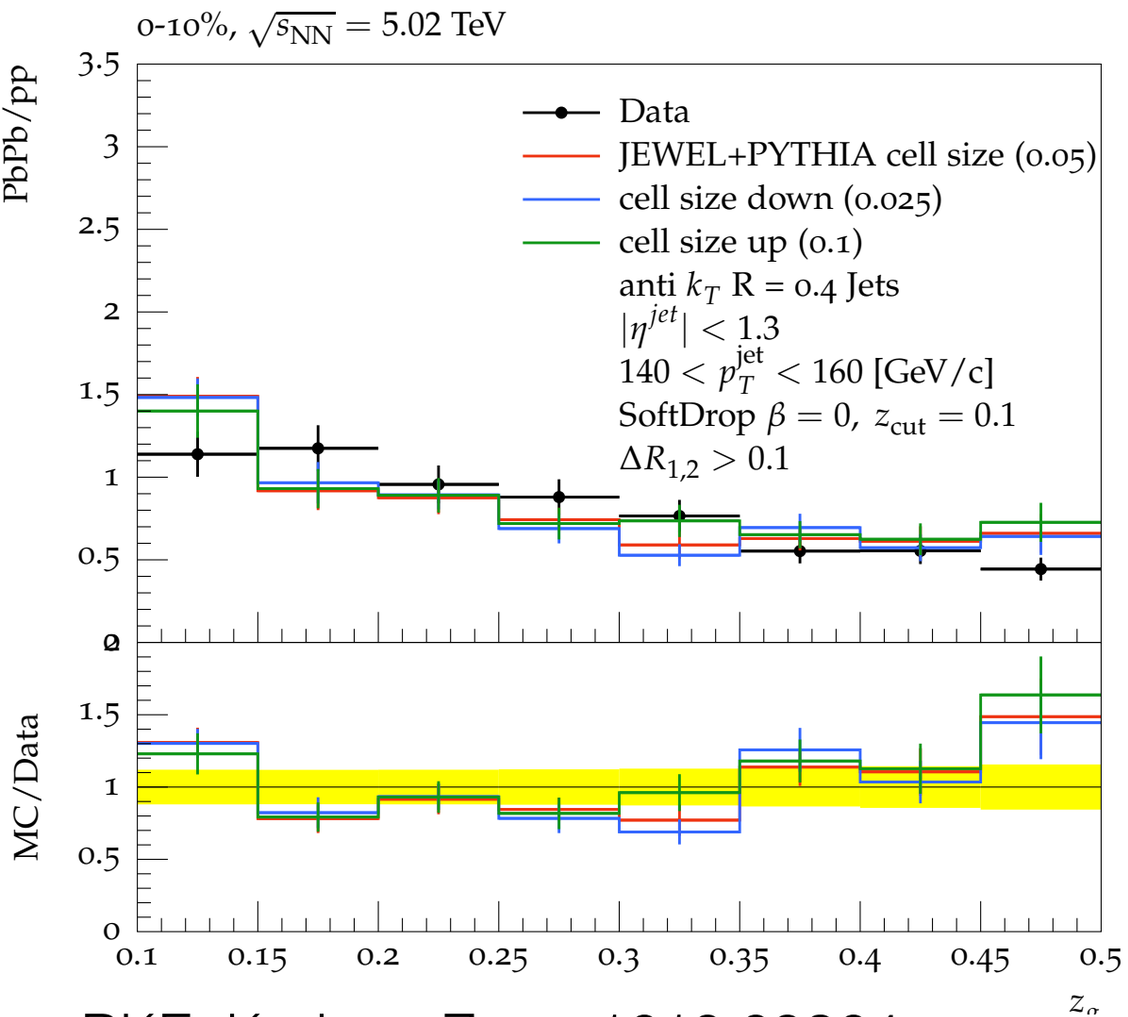
2 coherent emitters: color disconnected subjets

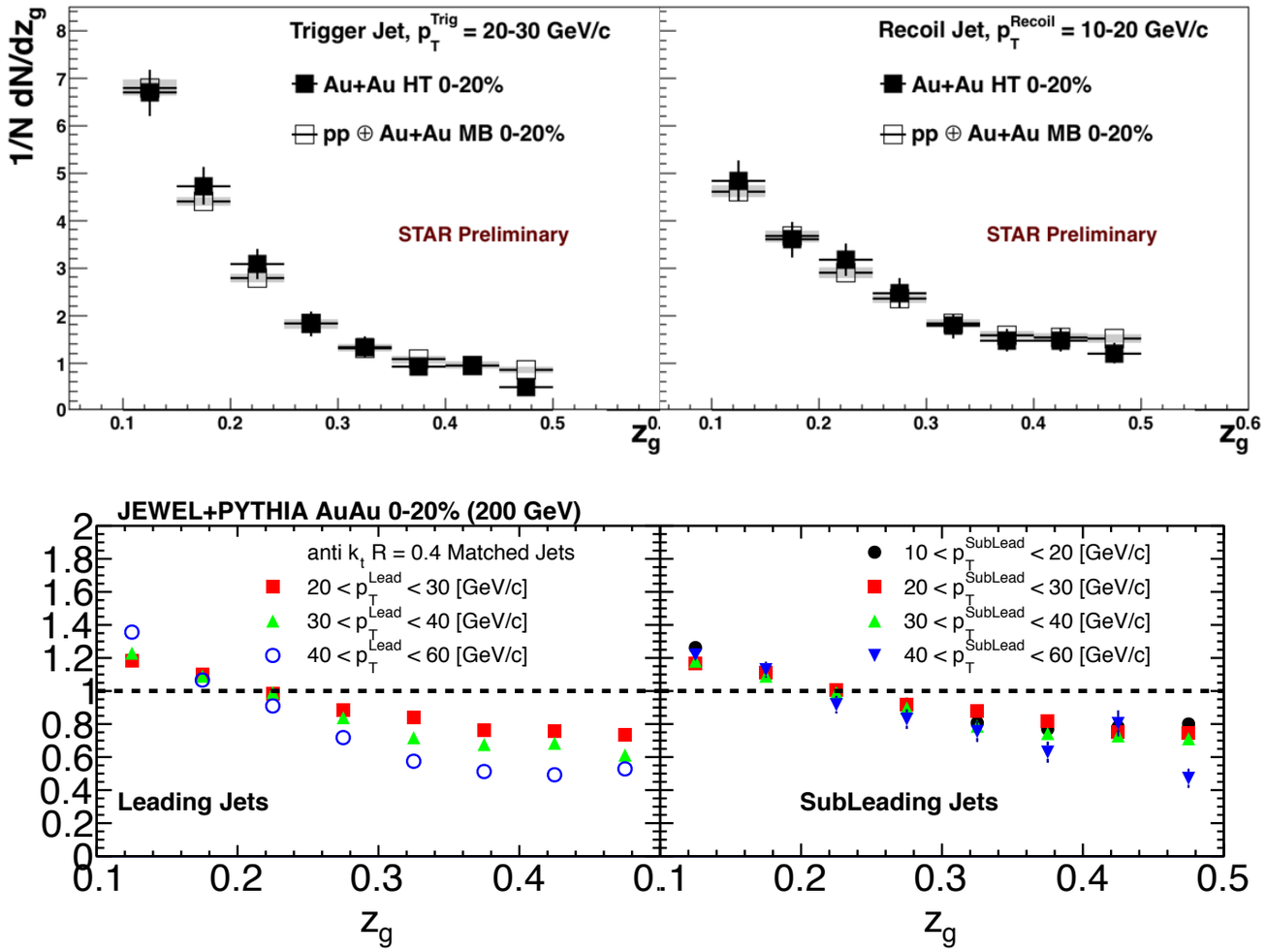


1 coherent emitter: color connected subjets

Fig. taken from *Phys.Lett.B* **725** (2013) 357–360

Comparison with Data - Splitting fraction





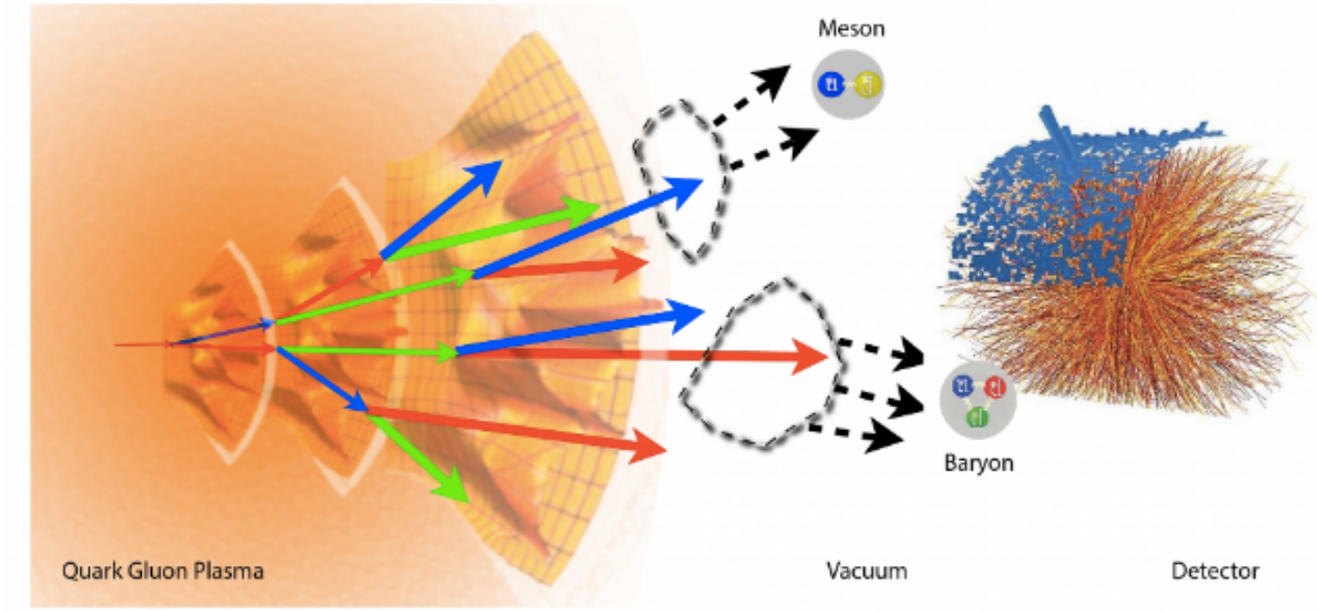
RKE, Korinna Zapp 1610.09364
RKE, Korinna Zapp in Prep

Milhano, MIT Workshop

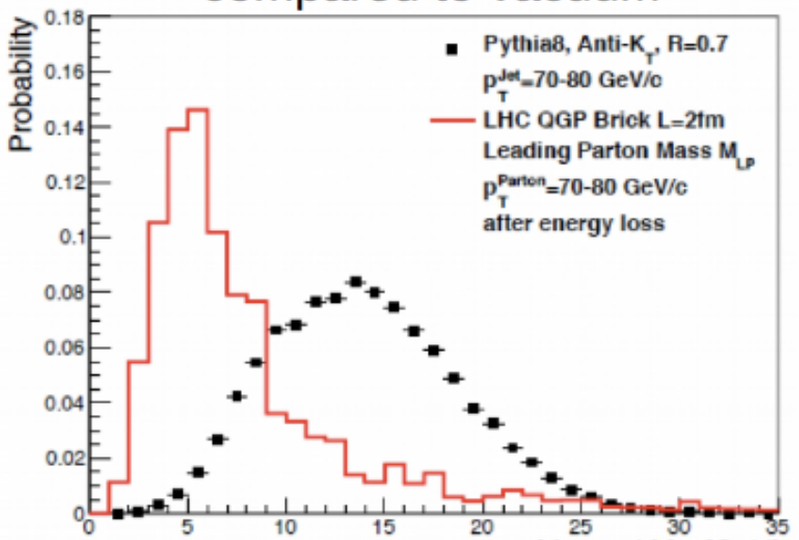
- correlated background 'refills' subjets and makes sub-leading ones in asymmetric collisions significantly fatter
- hops-in below z_g >0.1 configurations into sample: enhancement at low z_g
- z_g modification conceivably sensitive to correlated background

Jet Mass

$$M = \sqrt{p^2 - p_T^2 - p_z^2} \qquad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i, \quad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

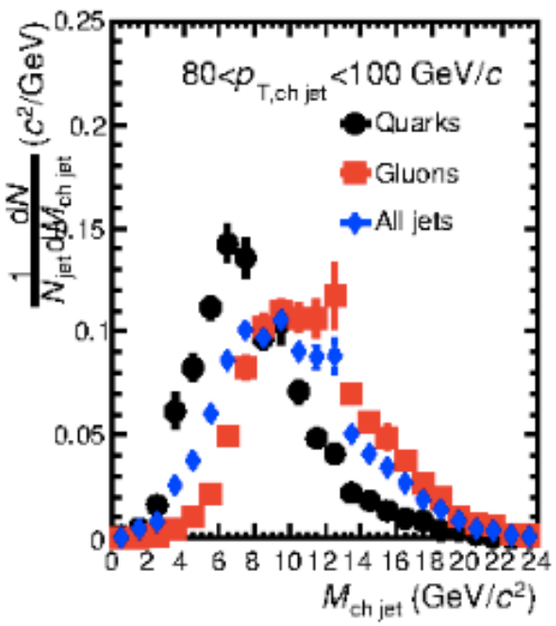


Mass of the LP in a medium in case of radiation at large angle compared to vacuum



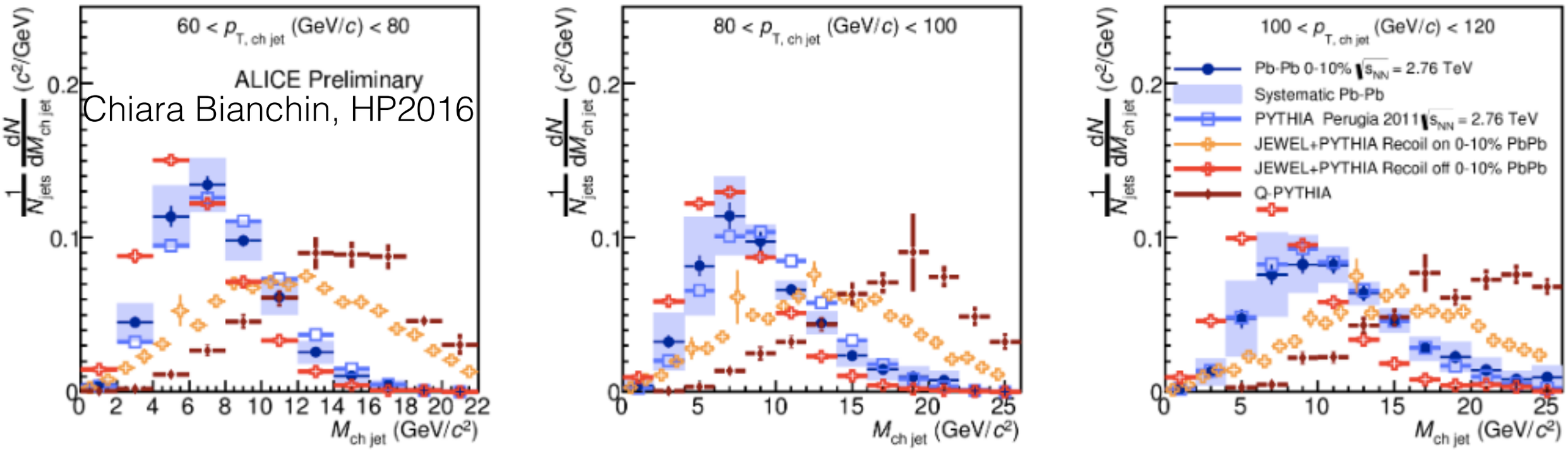
A. Majumder QM 2014

- Jet mass increases with the radial distance of the constituents from the jet axis
  - Soft constituents, away from the jet axis within the cone → larger mass
  - Few hard constituents → smaller mass
  - → E.g. gluon vs quark jets jet mass difference



Chiara Bianchin, HP2016

The puzzle



- Data lay in between PYTHIA and JEWEL "recoil off"
- Models with quenching produce too large mass

Why? What are the models missing?
Jet-Medium vs medium-Jet contributions to the jet Mass?

Conclusions

- Jet sub-structure studies in HIN are becoming increasingly important avenues
- Comparing data with predictions from MC offer some degree of meaning to deep questions
- Active collaboration with pp community is highly encouraging and important for the future
- There is still lots of “New Physics” to be learnt from the background :)

Future thoughts

- Highlighting the effect of medium on jet core vs soft contributions

- Can we use pPb as some mediator
  - Historically pPb always throws surprises so …

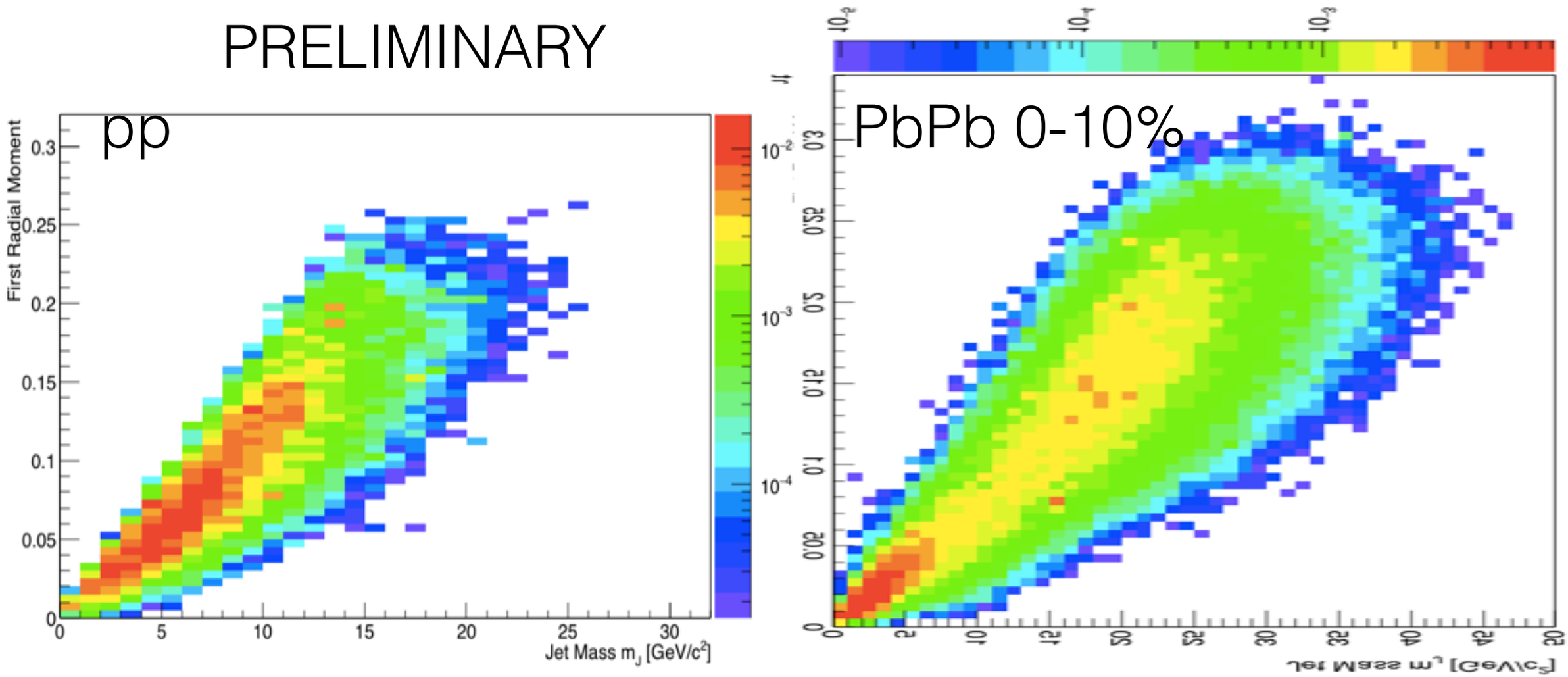
- Correlations between different observables
  - direct extraction of quenching parameters from comparison with MC

Correlations without detector smearing effects

JEWEL+PYTHIA
5.02 TeV
(with SoftDrop grooming)

PRELIMINARY

How does the QGP affect this correlation?
Extract transport properties

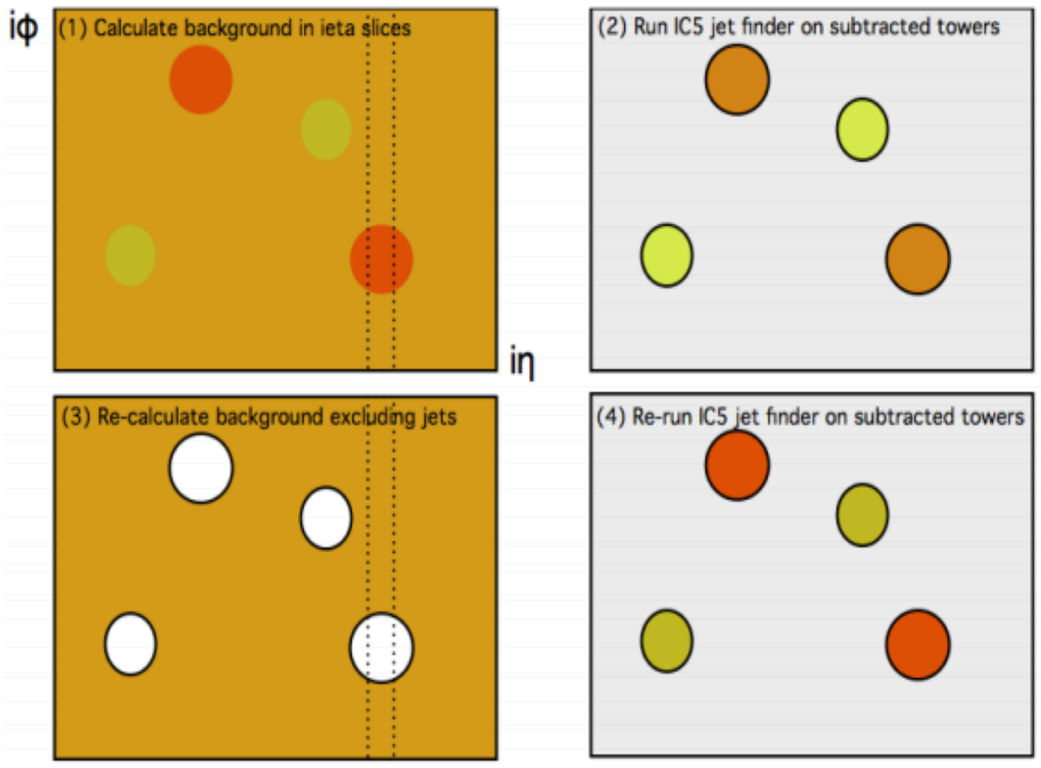


Note: x axis scale is a bit different for PbPb

Bonus Slides

Background subtraction techniques

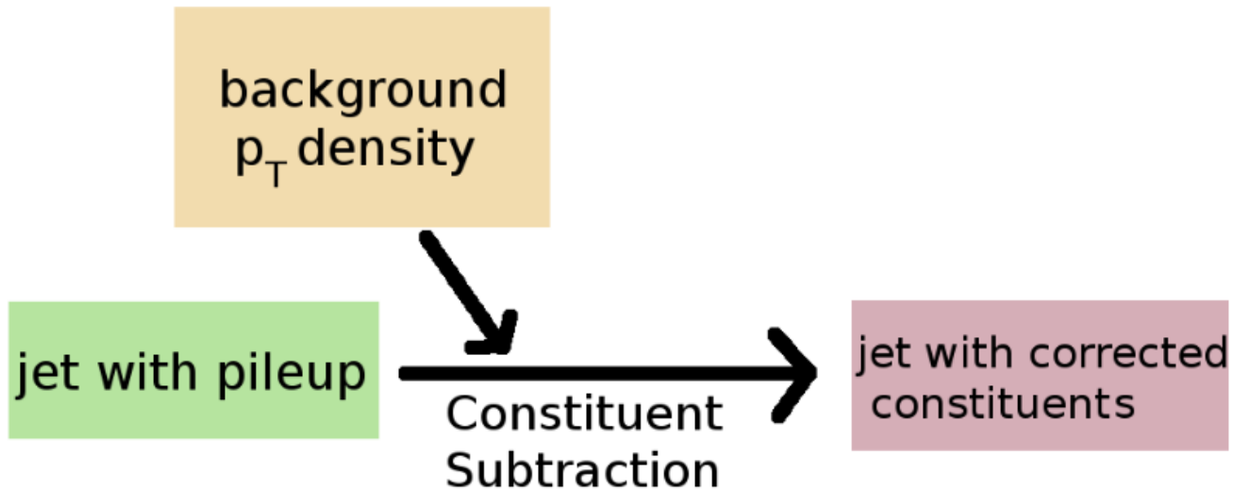
Eta slice pedestal subtraction



O.Kodolova et.al. EPJC (2007) 117.

Constituent subtraction

Familiar to pp community

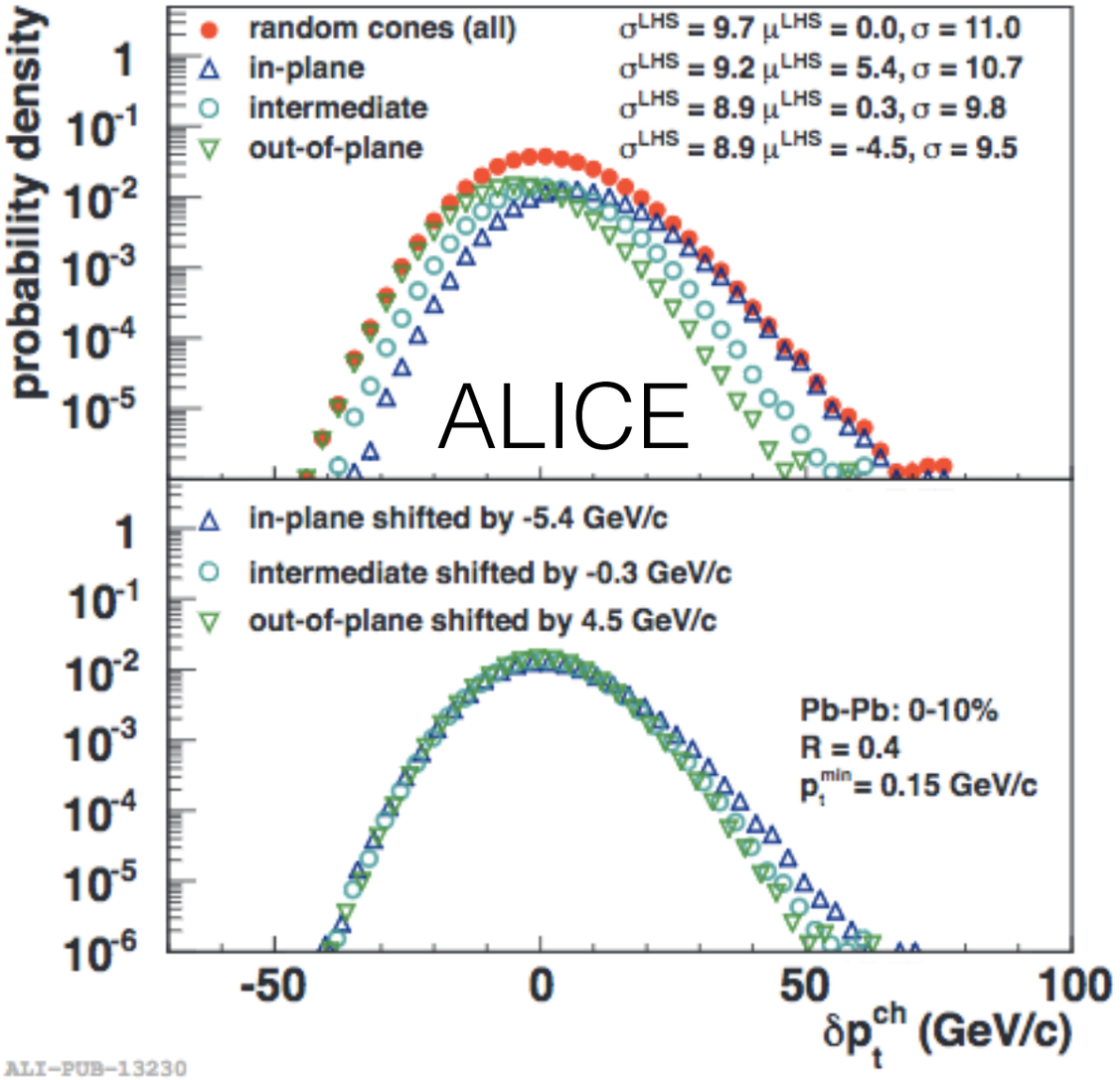


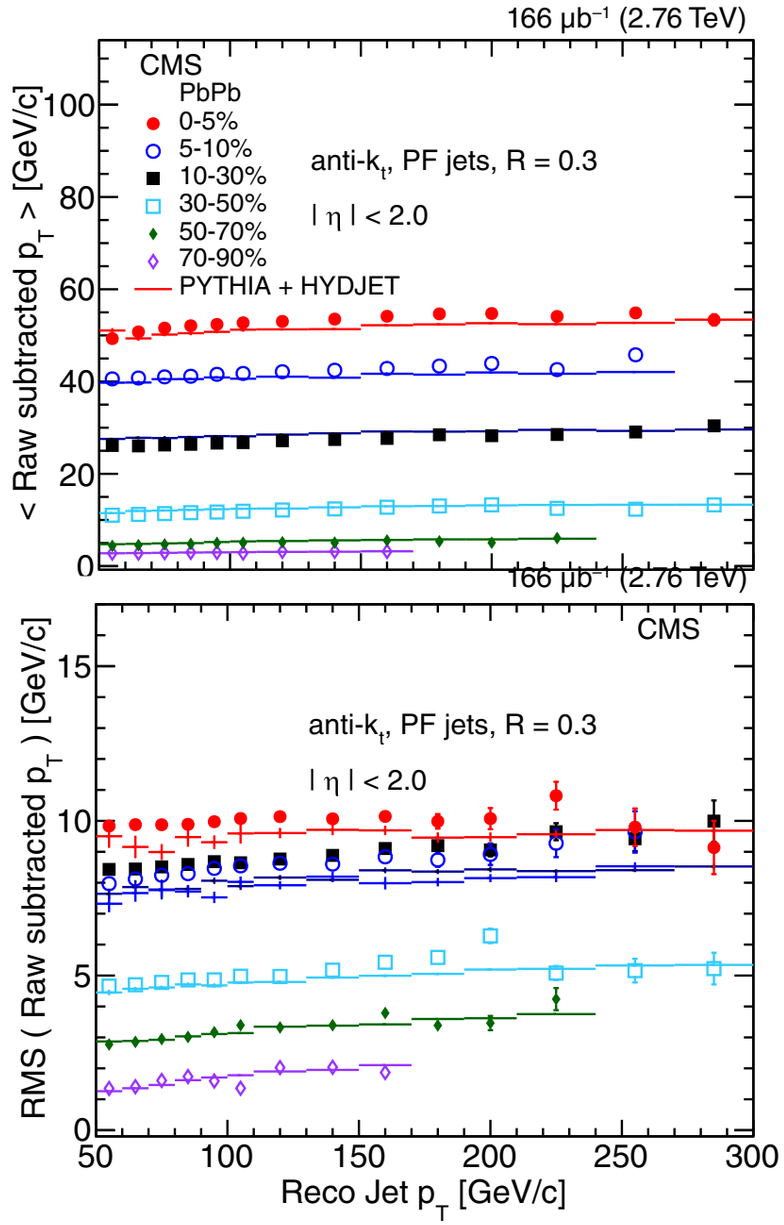
Curtesy Peter Berta, BOOST14

1403.3108

Jets sit on top of a large fluctuating background

random cones after subtraction



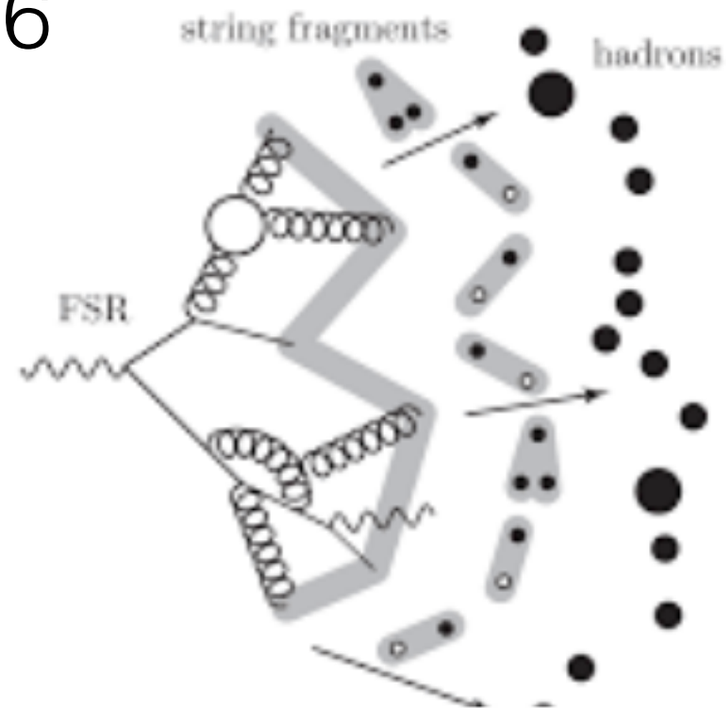


1609.05383

Slide by Marta, HP2016

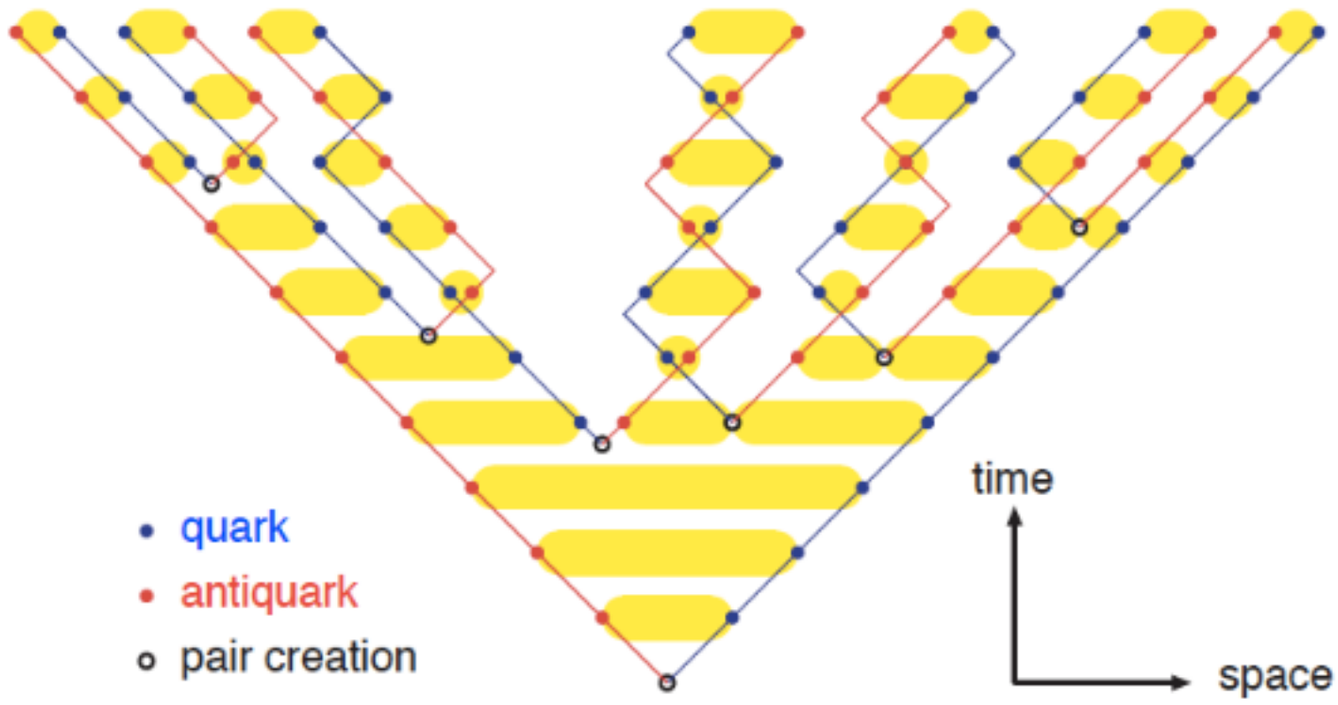
Hadronisation

All models assume hadronisation in vacuum
→ Uncertain if this is correct → large uncertainty



Hadronisation is a non-perturbative process

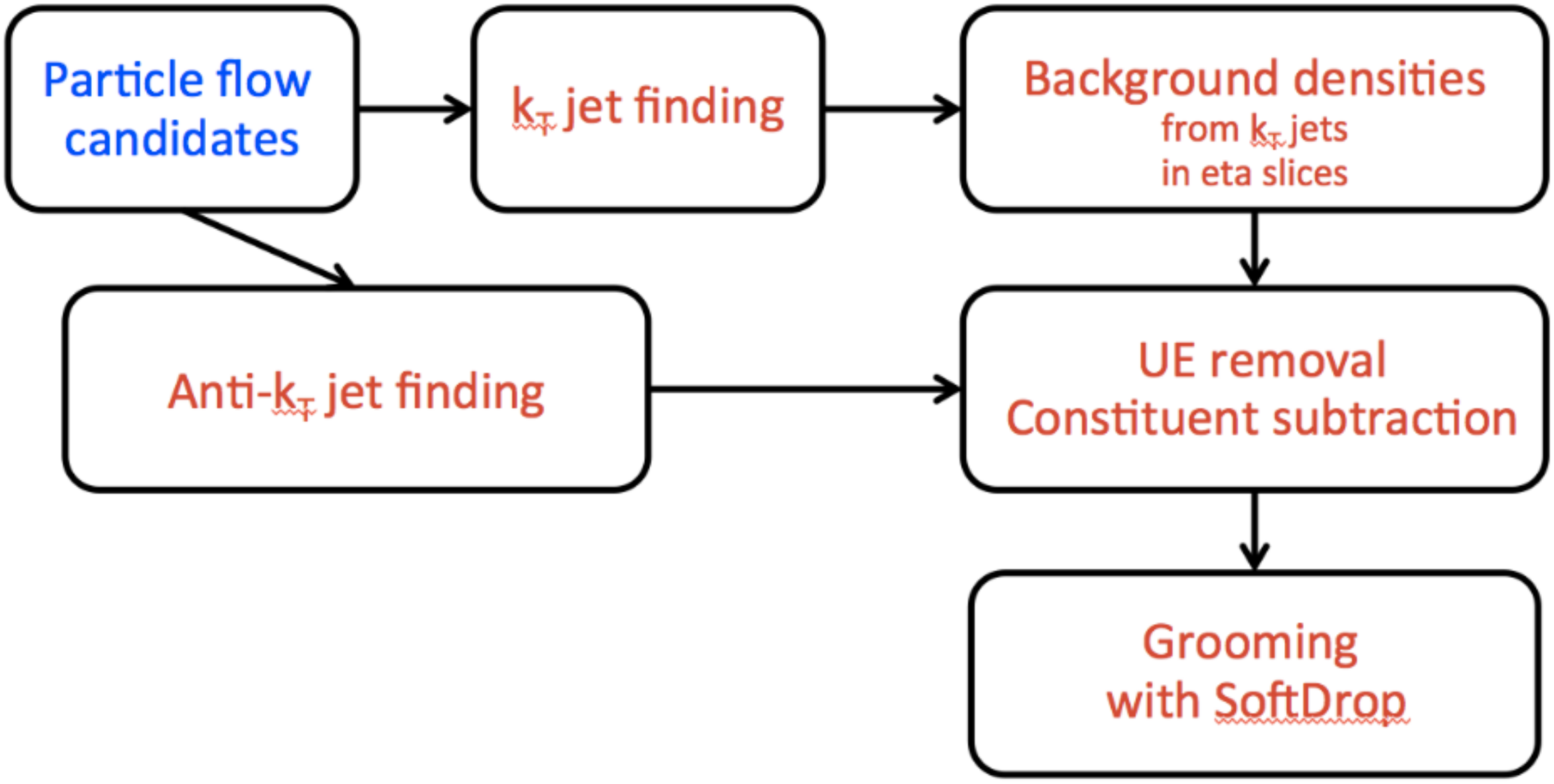
- Vacuum generators: modeled based on experimental data
- Jet quenching MCs: almost all Lund string fragmentation model. Same as vacuum MC



Open questions:

- How to deal with medium changing color structure?
- Interplay between jet and medium hadronisation?
- What if hadronisation starts in the medium?

Analysis techniques



UE removal only for PbPb since pp data set has low pileup (1.4)

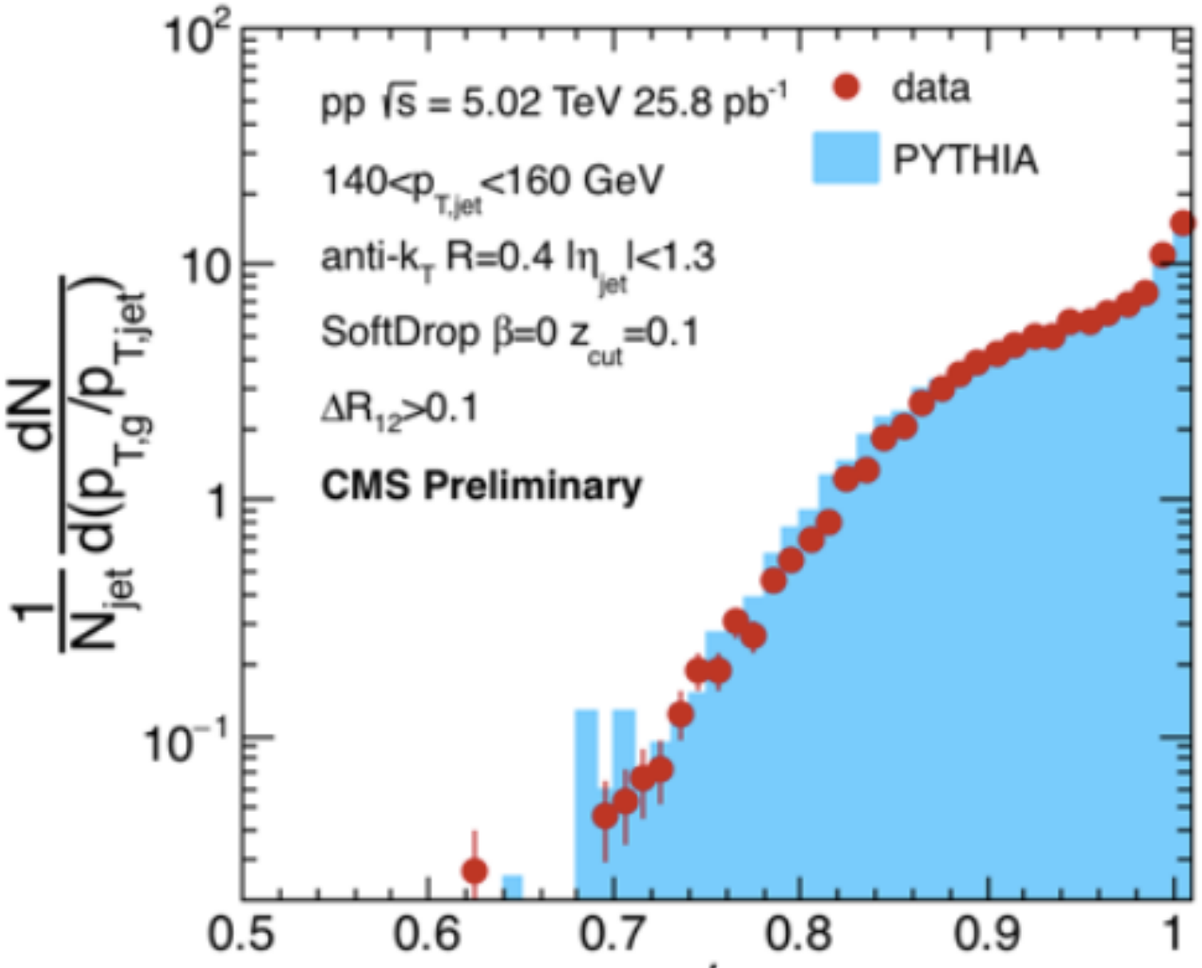
Constituent subtraction
Berta et al. arXiv:1403.3108

Groomed energy fraction

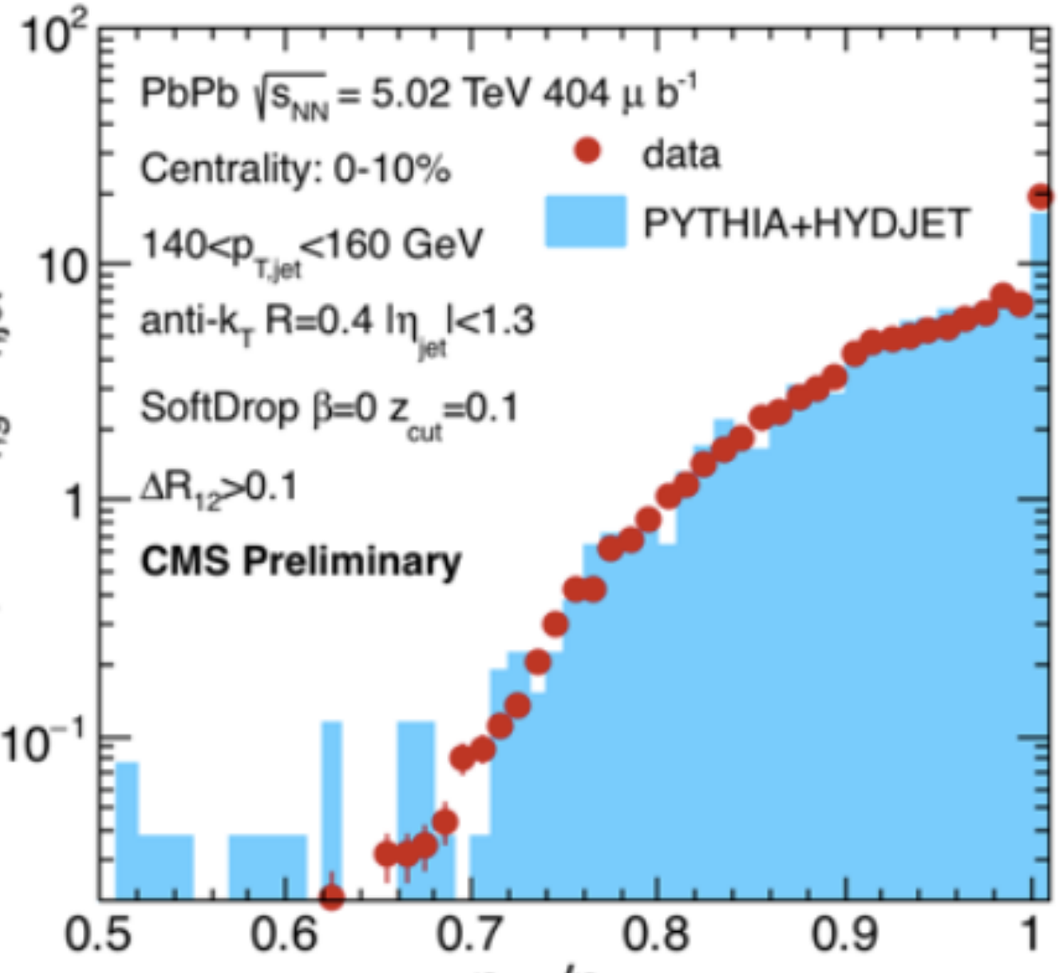
Larger amount of energy gets groomed away in PbPb collisions

Groomed energy fractions well described by MC

pp



PbPb



CMS-PAS-HIN-16-006

Slide by Marta, HP2016

Splitting function in pp

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

PYTHIA8 and HERWIG reproduce the pp data within 5-10%

Opposite trend for PYTHIA and HERWIG

CMS-PAS-HIN-16-006

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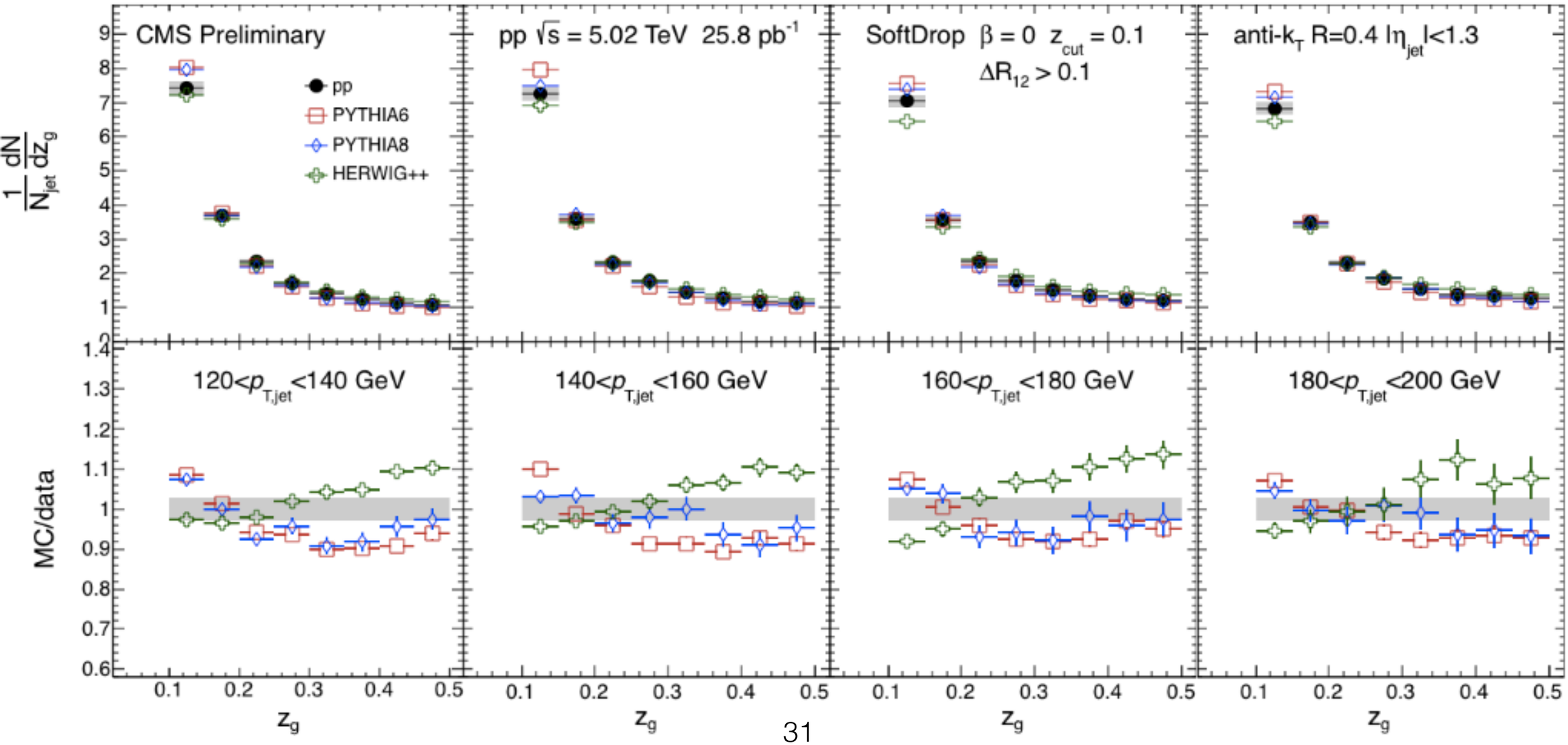
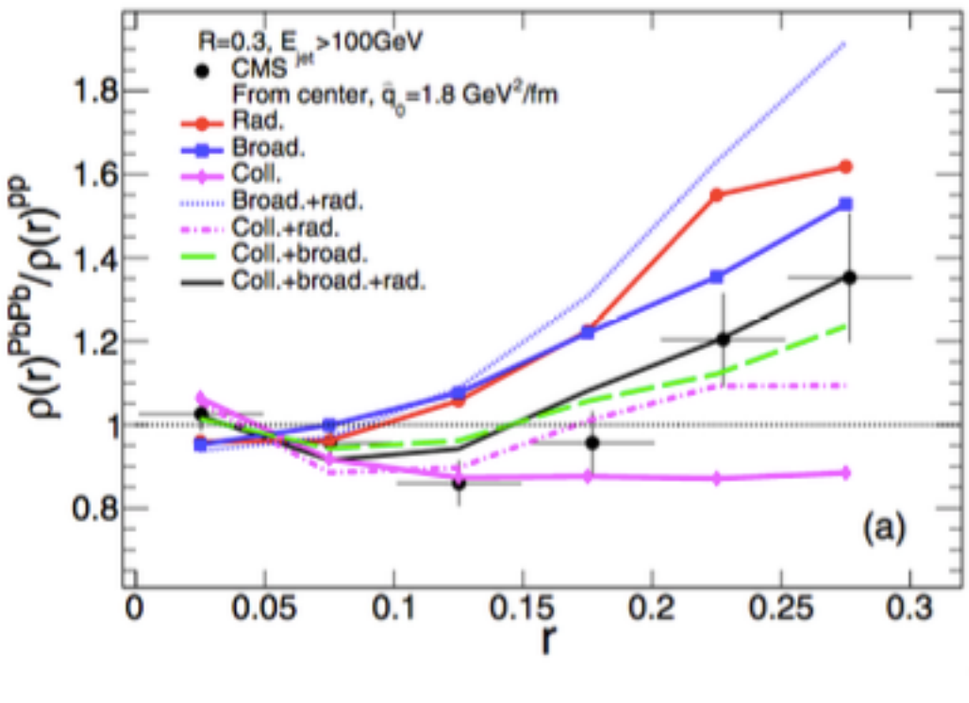
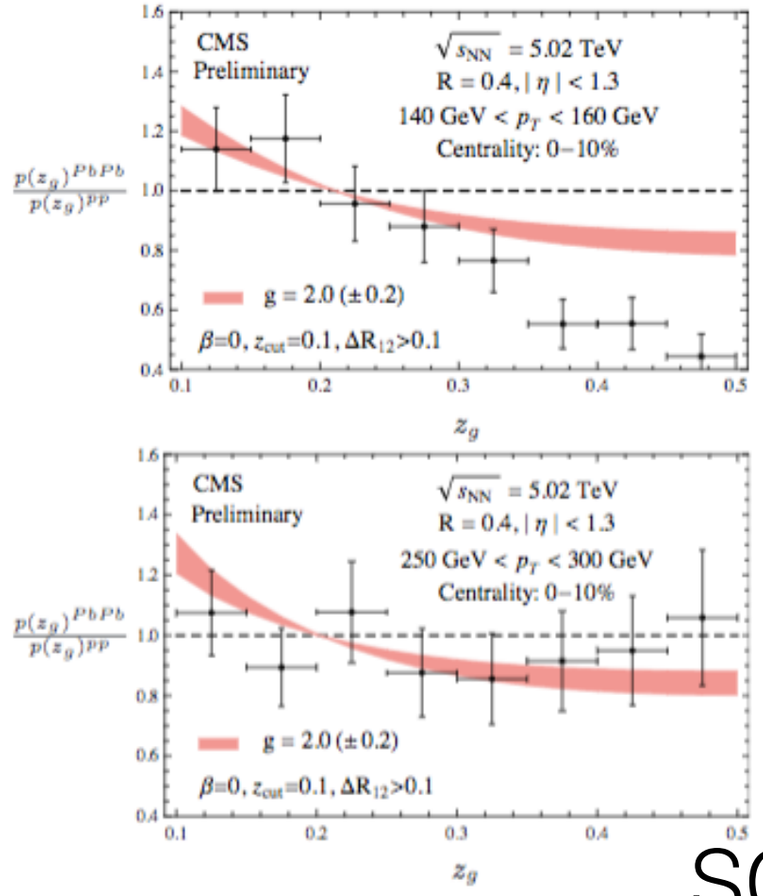


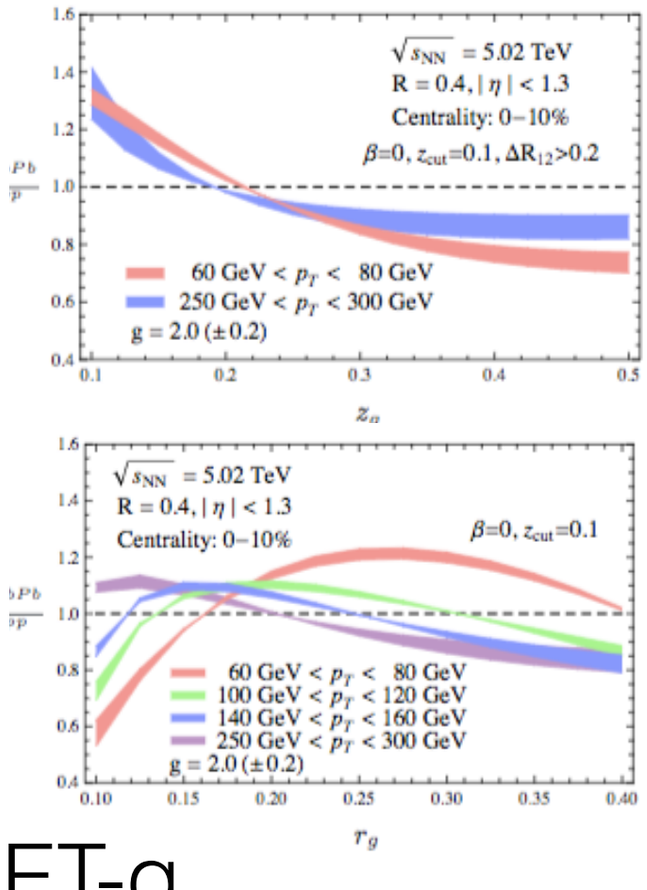
Theoretical Frameworks

1608.07283

N-B Chang, G-Y Qin
Phys.Rev. C94 (2016) no.2, 024902







SCET-g

Effect of color coherence/screening

1610.08930