Monday Discussion Session

Connection between AA, pA, and DIS

- Overview of Day’s Talks
- Potential Topics for Discussion:
  - What can we do with EIC jets to compliment measurements already done at HERA
  - What can we do with EIC jet measurements that HERA could/did not
  - How can jet measurements in ep and eA increase our understanding of features seen in pA and AA

4. Outlook for Jets (at an EIC)

Jet cross sections will be an important part of DIS at EIC energies. The theory described above provides a secure starting point.

At expected EIC energies, jet cross sections will be remain sensitive to a range of nonperturbative effects associated with both vacuum and medium dynamics.

The dependence of jet properties on target size will shed light on both the time evolution of hadronization and on target structure.

Of special interest will be the dependence of jet-specific fragmentation functions on kinematic properties of the scattering.

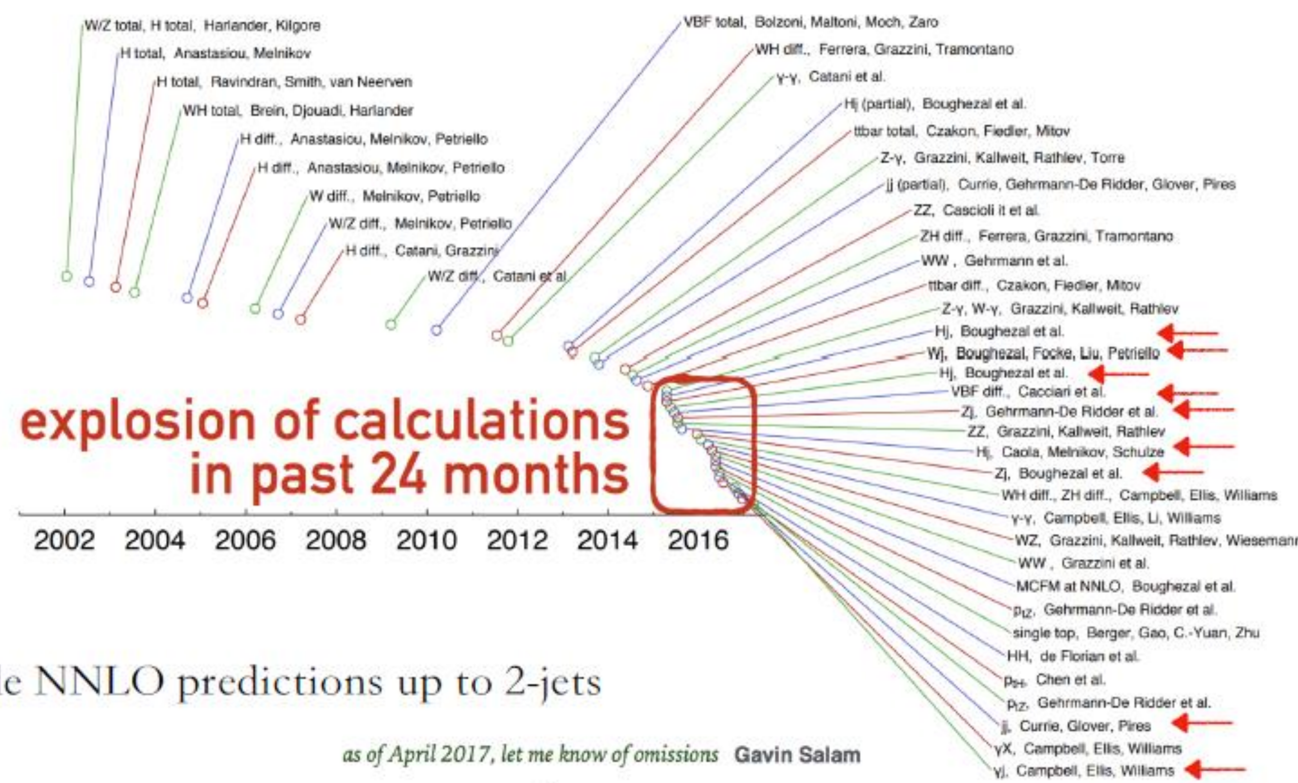
Tests of parton-hadron duality analyses are particularly promising. How is the perturbative probability distribution for parton production (re)distributed among observed hadrons?

G. Sterman

X. Liu

Status of arts

- Rapid progress in jet physics
  - NNLO

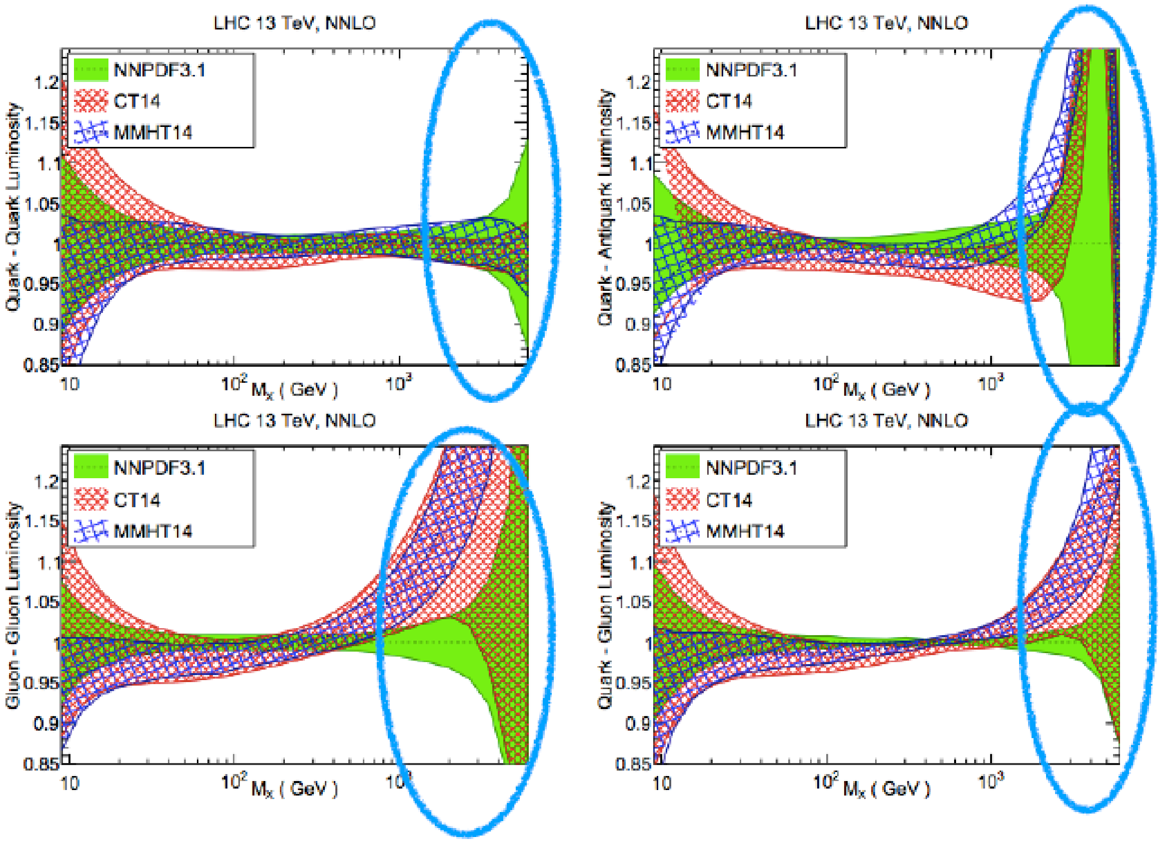


Available NNLO predictions up to 2-jets

X. Liu

Inclusive jet production

- Benchmark process at the LHC
  - alphas extraction
  - PDF fitting



- Still large discrepancies and uncertainties for different PDF fittings in large x region.
- Can be constrained by near future inclusive jet pT analysis.

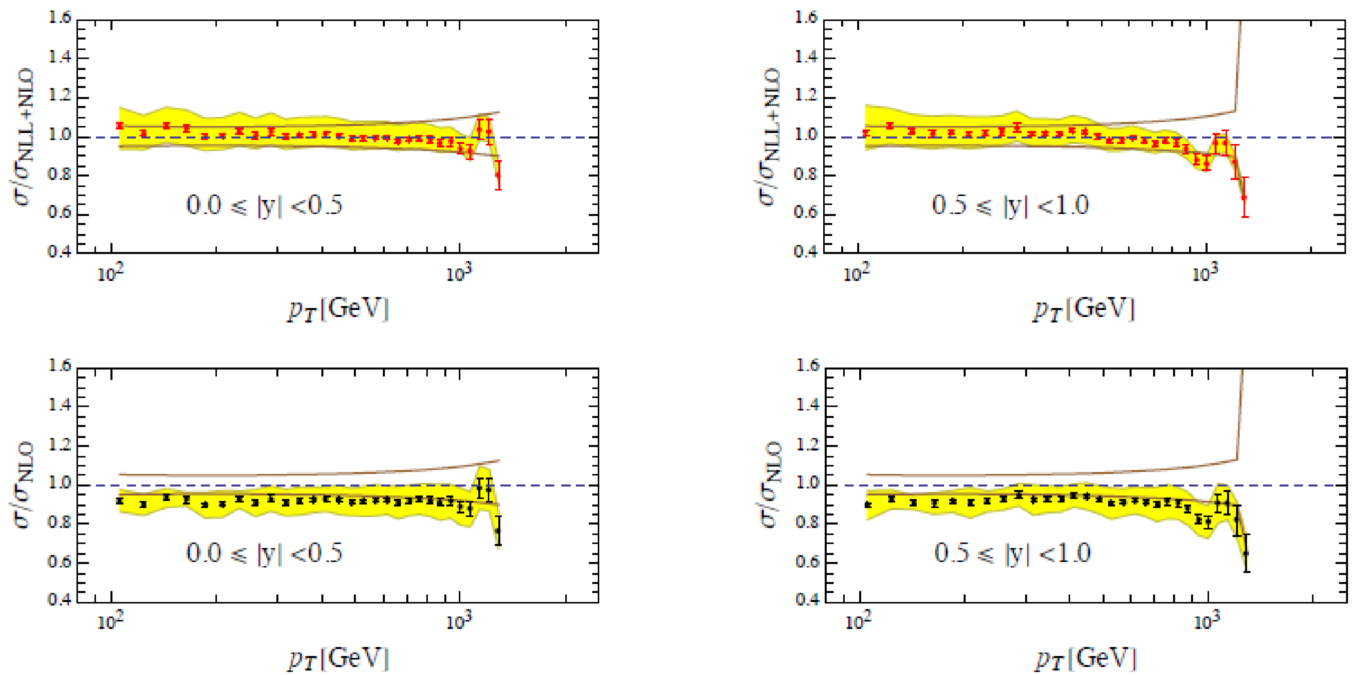
X. Liu

Inclusive jet production

- Phenomenology

  - compare with 7 TeV LHC data

with NLO CT10 PDF sets
NP effects included



similar story for higher rapidity bins

- NLO is higher than the data while NLL + NLO agrees well

Purposes of jet/QCD studies in DIS

- I: Studying QCD/jets to probe
  - Fundamental parameters of QCD: strong coupling constant
  - Parton structure of proton
  - Signature for BSM physics

NNLO + resummation

LHC THEORY — TOWARDS 1% PRECISION?

Gavin P. Salam, CERN

Joint CTEQ Meeting and 7th International Conference on Physics Opportunities at an EIC (POETIC 7)

- II: Studying QCD/jets to probe QCD medium
  - Cold nuclear matter in e+A collisions
  - Hot quark-gluon plasma in A+A collisions

NLO + resummation is probably sufficient at the moment

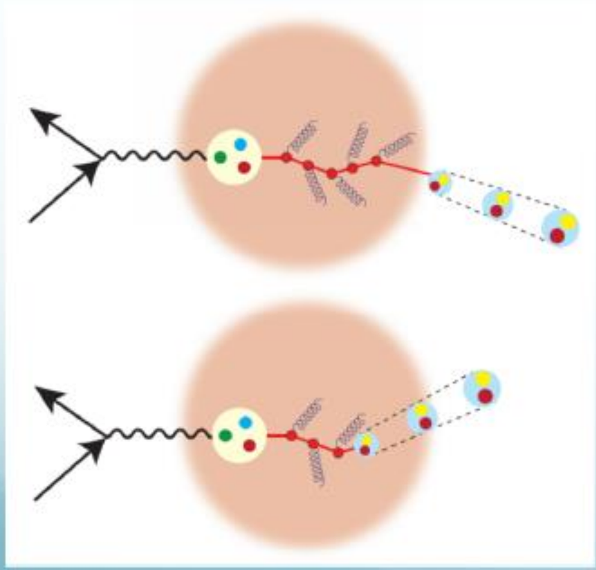
First e+A jet measurements are still yet to come at EIC

Too many effects need to be taken into account in A+A

Z. Kang

Open questions in e+A DIS

- What is the fundamental quark-gluon structure of light and heavy nuclei?
  - Distribution of quarks and gluons in a nucleus: shadowing, gluon saturation, ...
- Can the nucleus, serving as a color filter, provide novel insights into the propagation, attenuation and hadronization of colored quarks and gluons?
  - Parton propagation, parton energy loss, shower development, ... in the nucleus



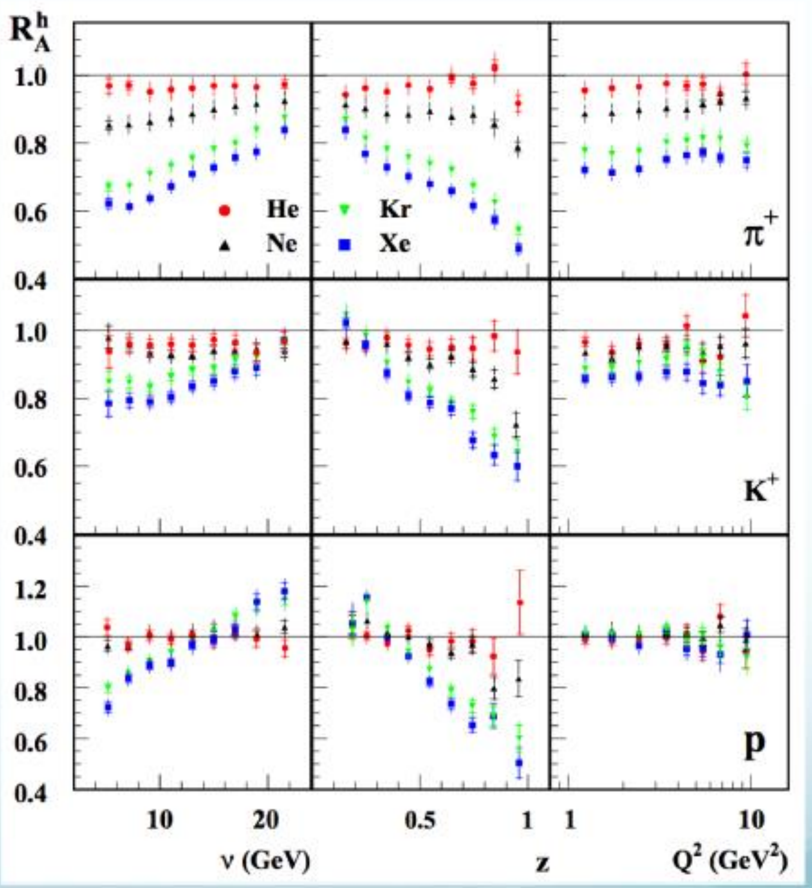
Initial-state effect
(from modification of PDFs)
+
Final-state effect
(propagation through the nucleus)

Z. Kang

Lesson learned: final-state interaction

- Normalized through inclusive DIS measurements
  - Effects of PDFs in nuclei cancel out in the ratio
  - Modification if there are, must come from final-state interaction in the nucleus

$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_D},$$



HERMES, arXiv:0704.3270

Z. Kang

Inclusive jets (H1 HERA-II)

Double-diff.

- Q^2 and $p_T^{\rm jet}$
- Phase space:

$0.2 < y < 0.6$

$-1 < \eta_{\rm lab}^{\rm jet} < 2.5$

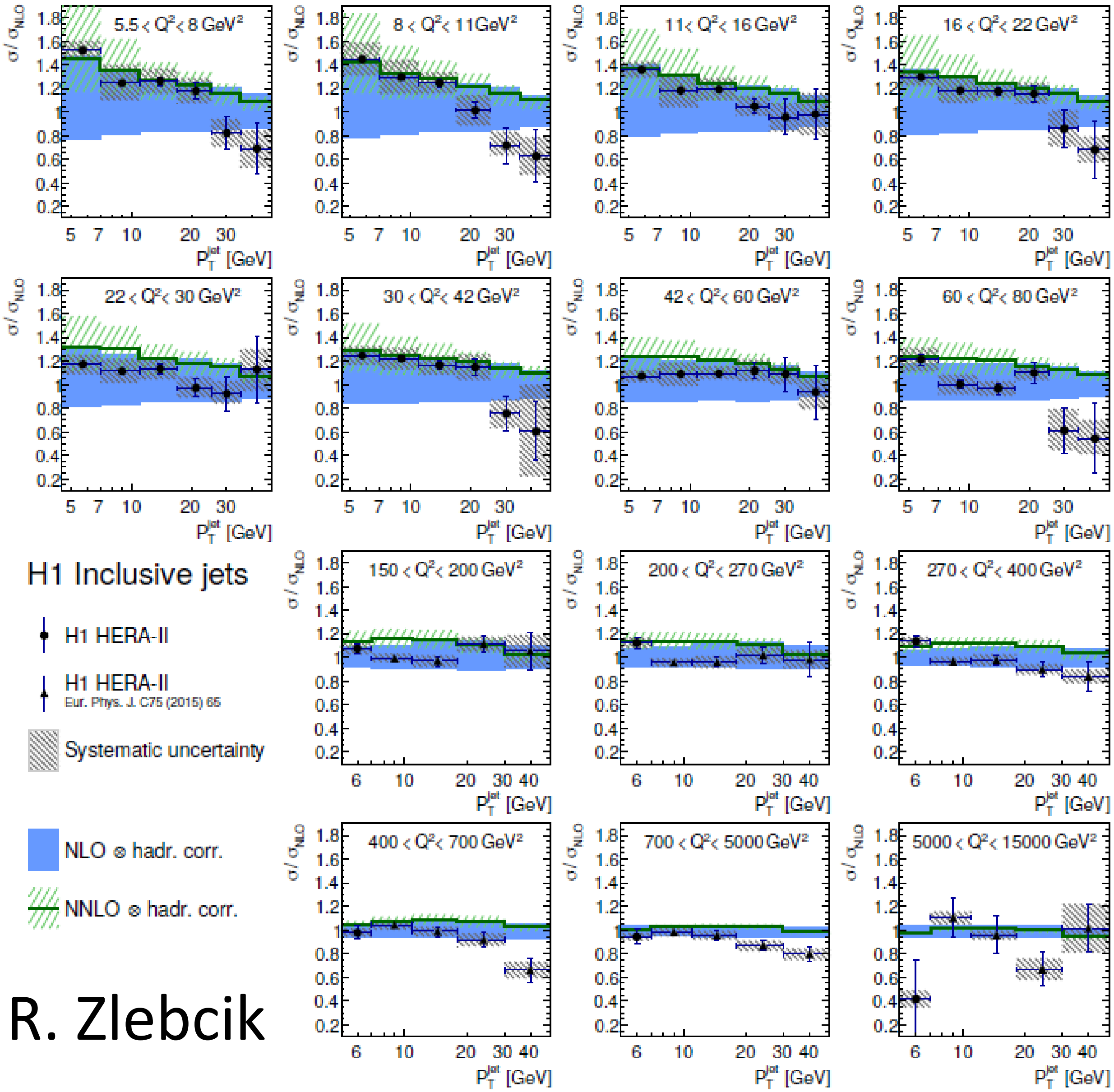
jets found in $\gamma^* p$ with k_T algo (R=1)

NLO predictions

- *NNPDF 3.0 NLO*
- Larger scale unc.
- Chi2/ndf = 1.7

NNLO predictions

- *NNPDF 3.0 NNLO*
- Smaller scale unc.
- Chi2/ndf = 1.3



R. Zlebcik

R. Zlebcik

Simultaneous PDF $+\alpha_S$ fit

- Resulting fit of inclusive+ jet/inclusive data sets:

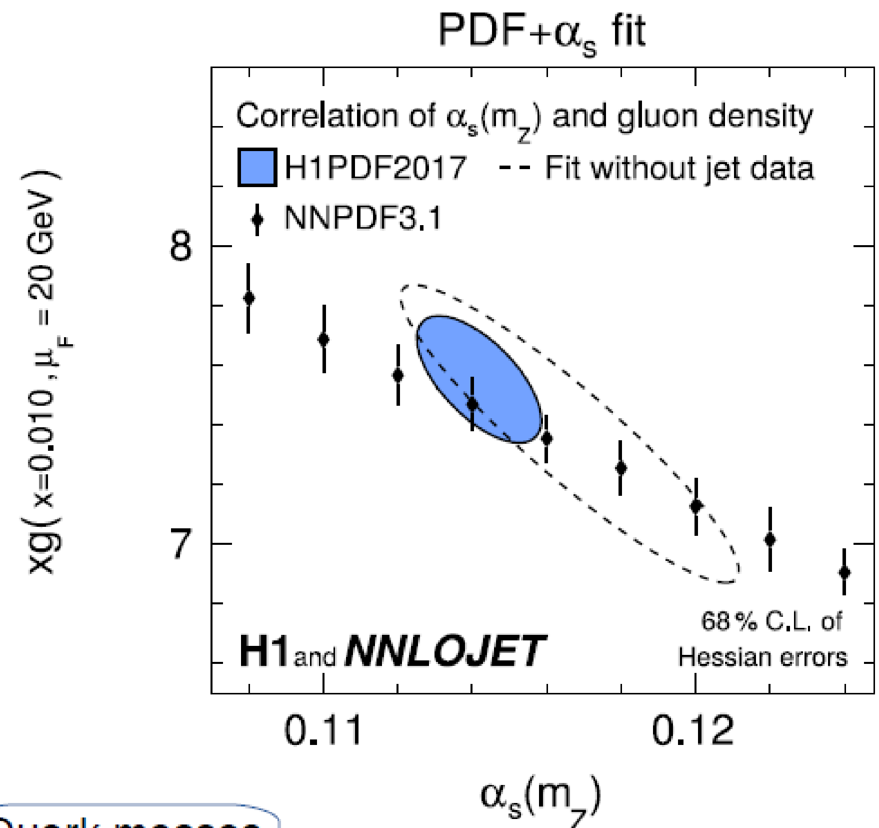
  $\chi^2/n_{df} = 1540/(1529 - 13)$

  (with 141 jet data points)

- Anti-correlation between gluon density and α_S

- Huge precision gain by including jet data

  → Jet data matter



Quark masses unc.

From simultaneous ren.+fact. scale variation

$$\alpha_S(m_Z) = 0.1142(11)_{\mathrm{exp,had,PDF}}(2)_{\mathrm{mod}}(2)_{\mathrm{par}}(26)_{\mathrm{scale}}$$

Data+had unc.

Parametrization unc.

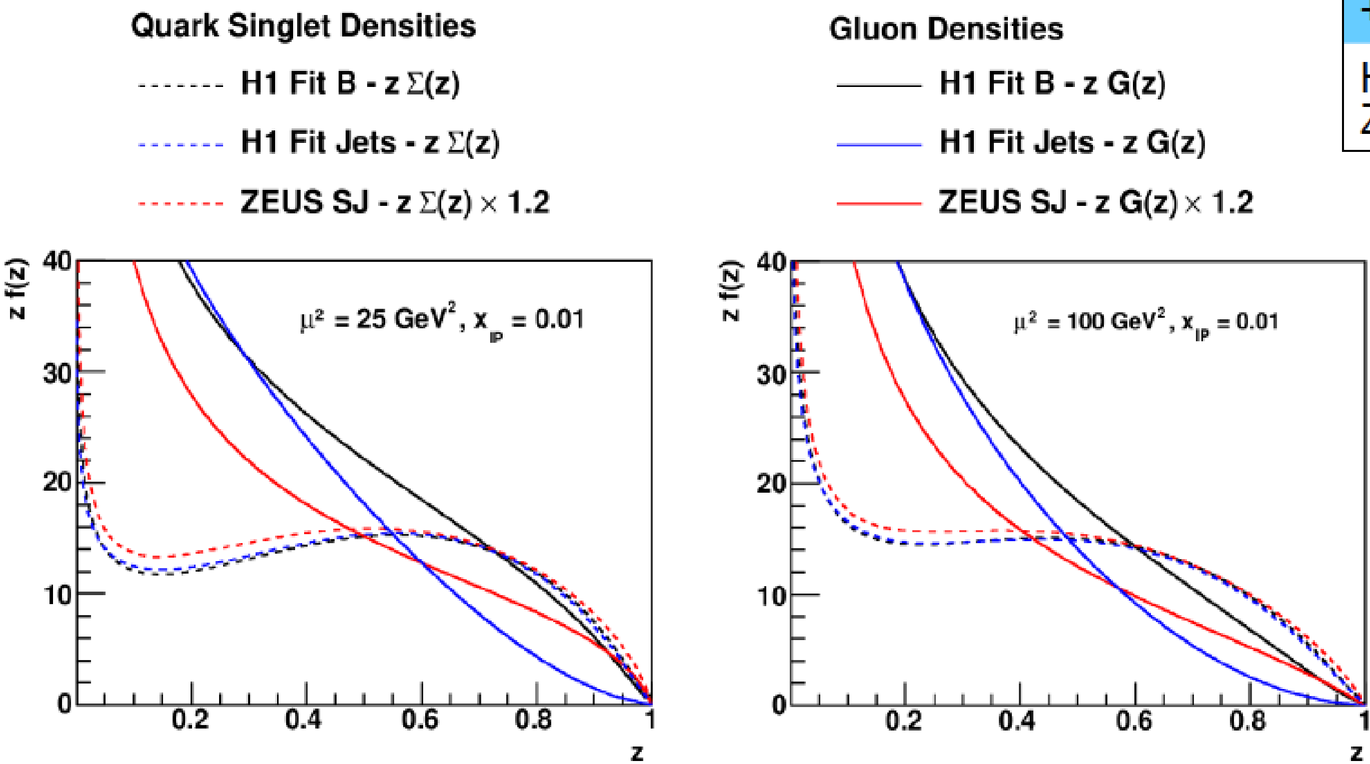
R. Zlebcik

NLO DPDFs

- DPDF sets differ mainly in gluon component which is weekly constrain from inclusive diffractive data
- For gluon dominated diffractive dijet production we have sizable DPDF uncertainty
- DPDFs obey standard DGLAP evolution equation

Fits of **inclusive** data
~~H1 2006 Fit A~~ **H1 2006 Fit B** MRW DPDF

Combined **inclusive + dijets** data fits
H1 2007 Fit Jets ZEUS 2009 Fit SJ



70% of diffractive exchange momentum carried by gluons

Flavor Dependence of Parton Energy Loss

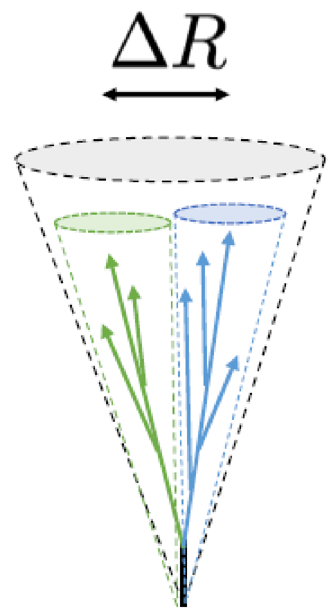
- Heavy quarks lose less energy than the light flavor:
  - Established in LHC data though model comparisons

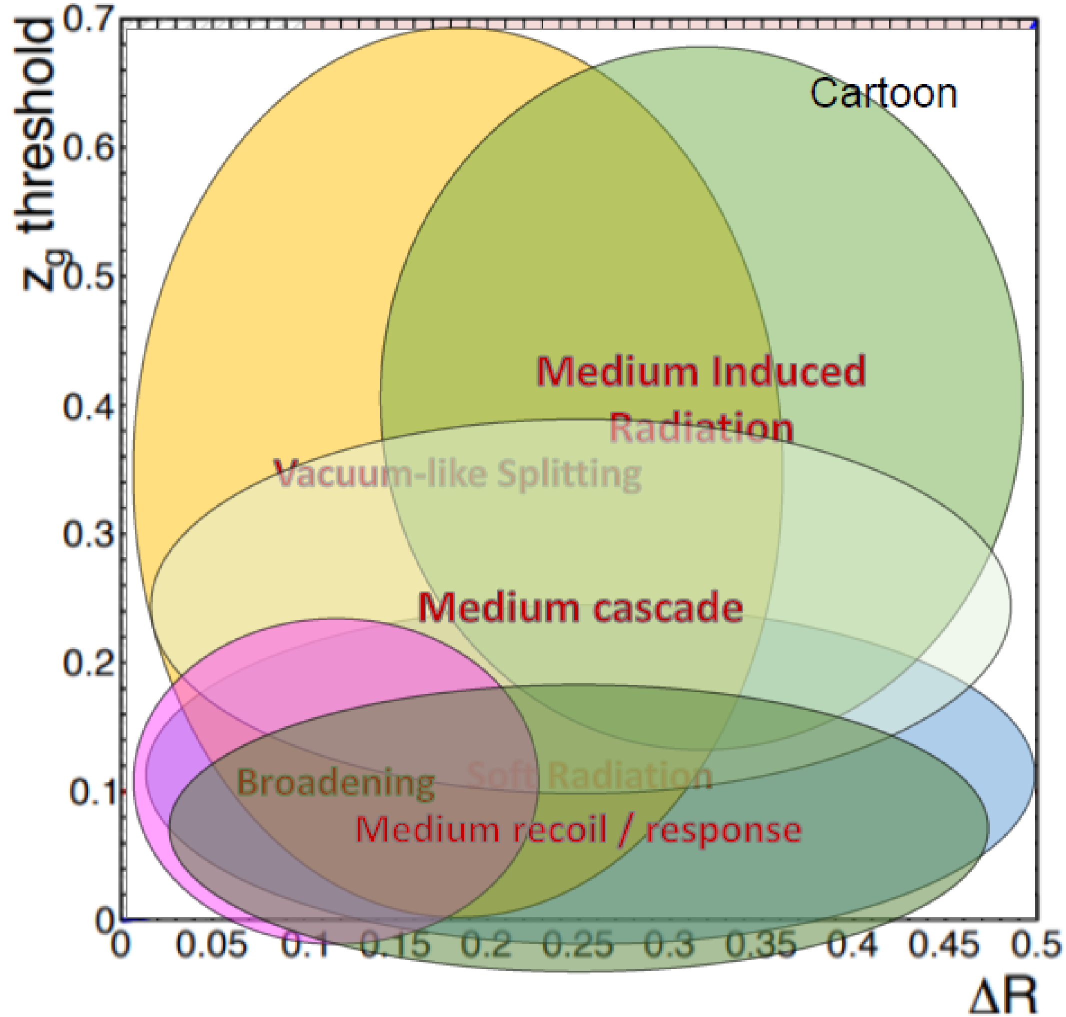
- Quark vs. gluon energy loss:
  - Collected hints from various jet substructure observables, ATLAS jet and charged particle R_{AA} measurements vs. η
  - Indication of Gluon E_{loss} > Quark E_{loss}

- Quarkonia production and suppression similar to open charm:
  - Eloss + Fragmentation process

Z_g vs. ΔR Phase Space

$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$





- The reality may be much more complicated than that
- The excitement: One could construct different observables which are sensitive to different part of the phase space and provide stress test on models

Summary

- **Energy flow with respect to jet**
  - Unprecedented wide p_T reach with high statistics data
  - Modification of jet shapes and fragmentation function
    - Narrowing of the jet core in inclusive jet with respect to pp reference
    - Possible differences between CMS and ATLAS need to be resolved

- **Hint of medium response from LHC data**
  - Different interpretations from theory groups

- **Observation of parton flavor dependence of jet quenching**
  - R_{AA} depends on meson flavor (light vs. charm vs. beauty) at low p_T
  - (Ungroomed) jet substructure become more quark-like in PbPb collisions: Gluons lose more energy than quarks

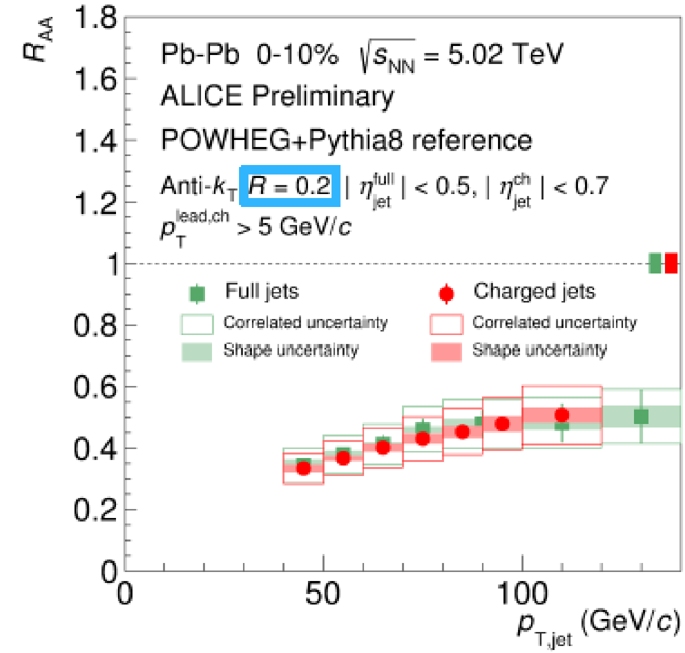
- **"Parton shower shape dependence" of jet quenching**
  - Toward the understanding of jet quenching as a function of the jet substructure

- **Jet Quenching in small system**
  - No significant evidence yet
  - Could be relevant for the interpretation of large systems

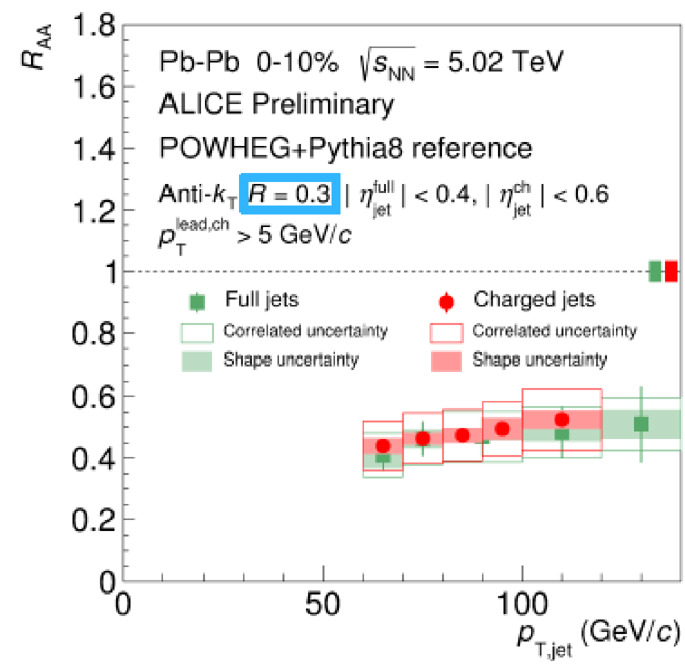
Jet R_{AA}

$$R_{AA} = \frac{\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{\mathrm{event}}} \frac{d^2 N}{d p_T d\eta}\Big|_{AA}}{\frac{d^2 \sigma}{d p_T d\eta}\Big|_{pp}}$$

- Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV measured, using Pythia8 + POWHEG pp reference
- Similar suppression observed in $R = 0.2$ and $R = 0.3$; stronger suppression at low p_T
- Charged particle jets and full jets are consistent



ALI-PREL-159649



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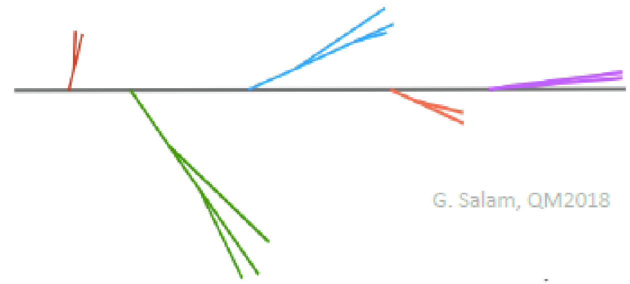
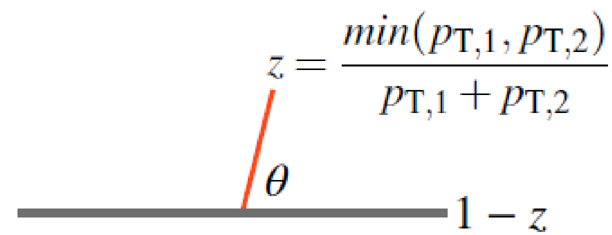
Groomed jet substructure

- Measurement procedure
  1. Cluster jets with the anti-k_T algorithm, then re-cluster each jet using the C/A algorithm
     - This produces an angularly ordered tree, similar to a parton shower
  2. Unwind the last clustering step and check the Soft Drop condition: $z > z_{\text{cut}} \left(\frac{\Delta R}{R_0} \right)^{\beta}$
  3. Discard the softer sub-jet and repeat





- The resulting hard splittings are described by:
  - n_{SD} is the number of splittings that pass the Soft Drop condition
  - z_g, R_g describe the momentum fraction and angular separation of the **first** splitting

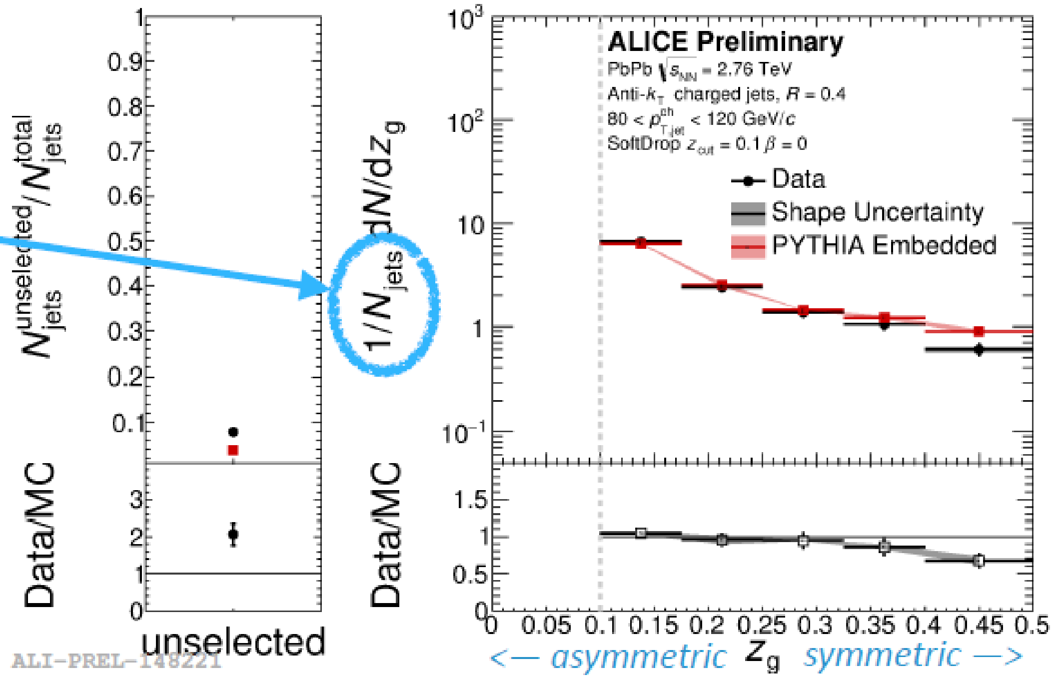
$\boxed{\text{We use } (z_{\text{cut}}, \beta) = (0.1, 0)}$

Groomed jet substructure – Pb-Pb

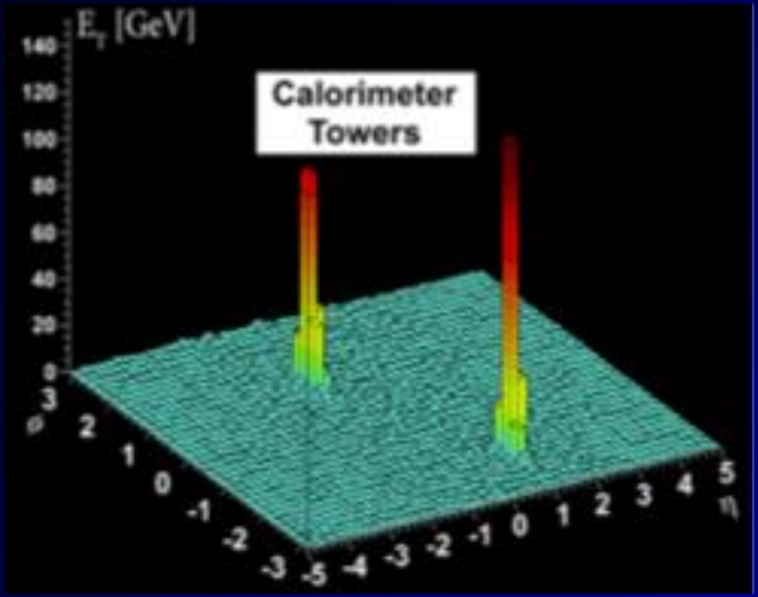
- The z_g distribution shows suppression at high z_g
  - That is, the hardest splittings are suppressed in Pb-Pb
- No enhancement at small z_g

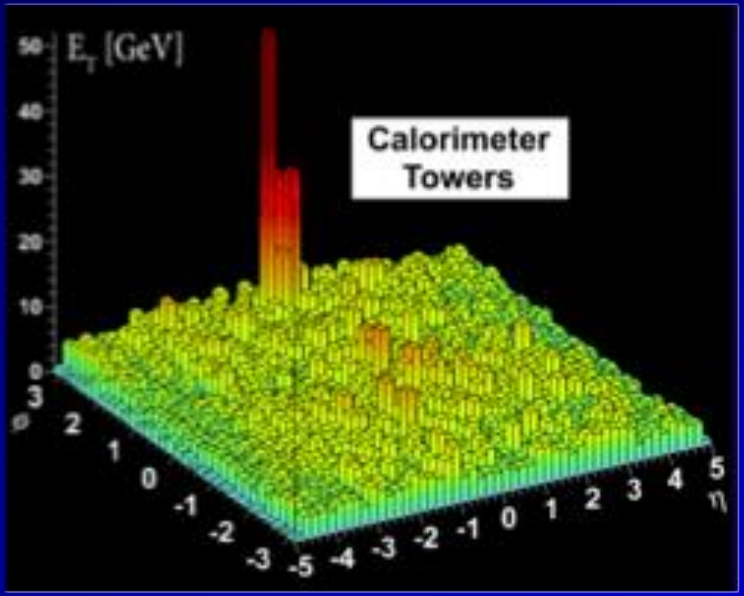
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

In order to interpret the results as absolute suppression/ enhancement, **must normalize by the number of inclusive jets**, including those that do not pass the Soft Drop condition



Jet energy and background subtraction



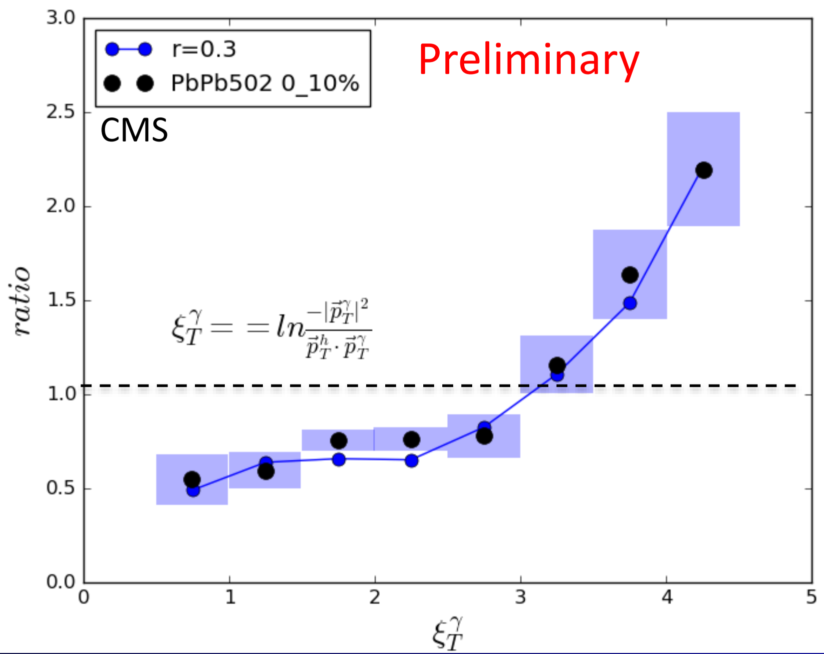


Jet energy as defined in the jet reconstruction algorithm
Uncorrelated background should be subtracted
Jet-induced medium response is correlated with jet: not background
Some of the energy lost by leading partons remain inside jet-cone

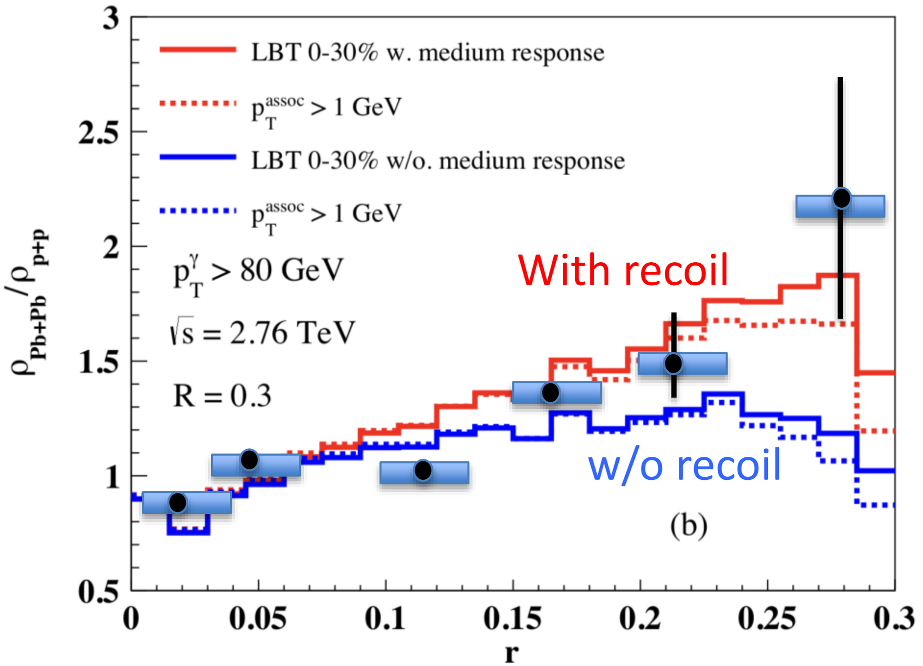
Xin-Nian Wang

Effect of medium response

Enhancement of Frag Function at small z



Enhancement of jet shape at larger r

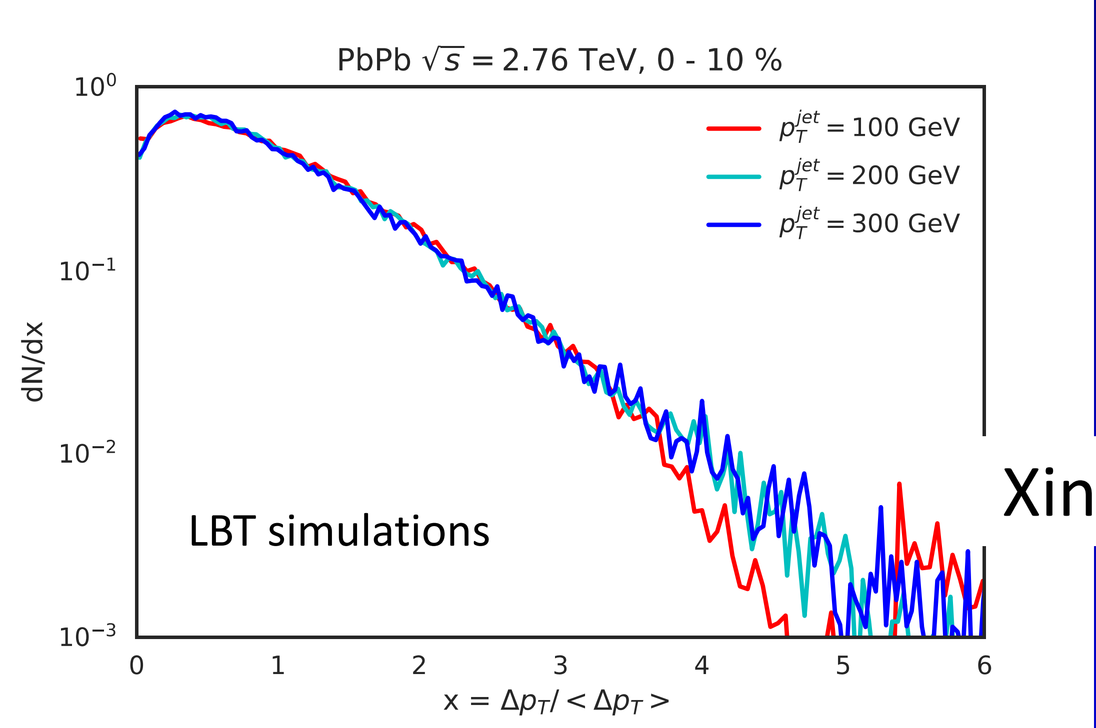


Luo, Cao, He & XNW, arXiv:1803.06785

Xin-Nian Wang

Data-driven extraction of jet energy loss

$$\frac{d\sigma_{\rm jet}^{\rm AA}}{dp_T dy} = \int d\Delta p_T W_{\rm AA}(\Delta p_T, p_T + \Delta p_T, R) \frac{d\sigma_{\rm pp}}{dp_T dy}|_{p_T = p_T + \Delta p_T}$$



Xin-Nian Wang

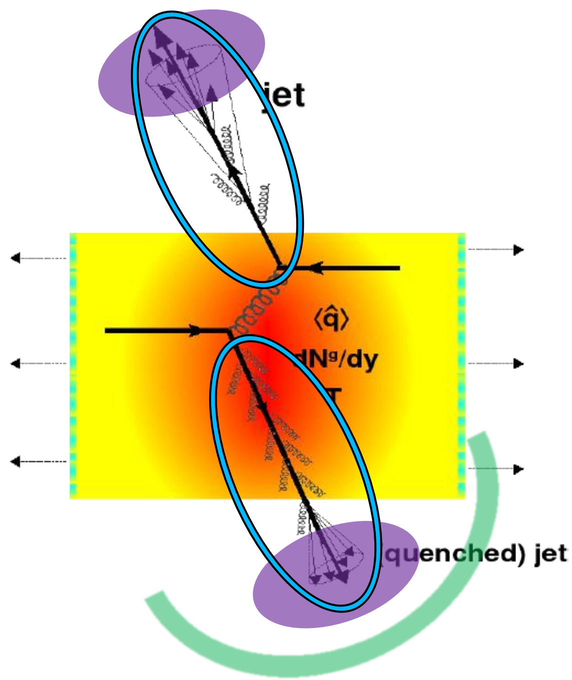
$$W_{\rm AA}(\Delta p_T, p_T, R) \approx W_{\rm AA}(\Delta p_T / \langle \Delta p_T \rangle, R)$$

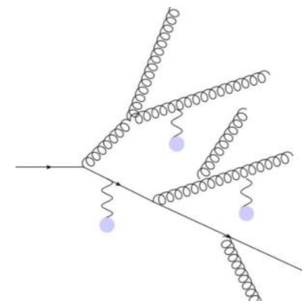
Flavor averaged jet energy loss distribution

Jets and Jet Substructure in HIC

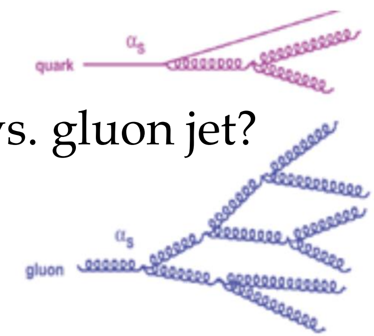
Traditional Questions: **Energy Flow**
- How much energy is (left) in the jet?
- And where did it go?

Substructure: **Focus on Shower**
- Where did energy flow **inside** the jet?
- Is the shower modified?

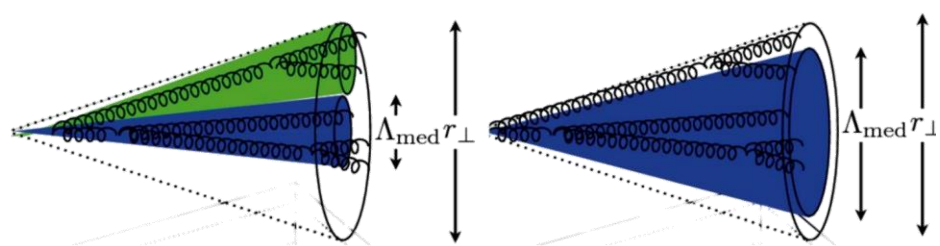




Splitting kernel?



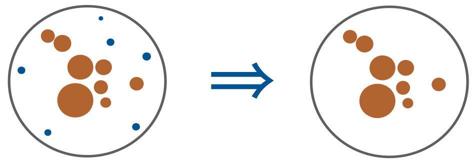
Quark vs. gluon jet?



De-coherent vs coherent E-loss?

Groomed Momentum Sharing z_g

- Soft Drop: Remove wide angle soft radiation

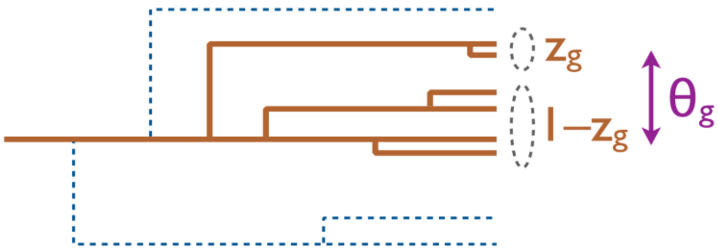


Soft Drop Condition:

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

energy threshold

angular exponent



Based on declustering an angular-ordered tree

With **β**=0 and Cambridge/Aachen:
"Groomed Momentum Sharing"
Relative z of the softer prong

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

J. Thaler
ALICE Jet Workshop (2015)

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

In vacuum:

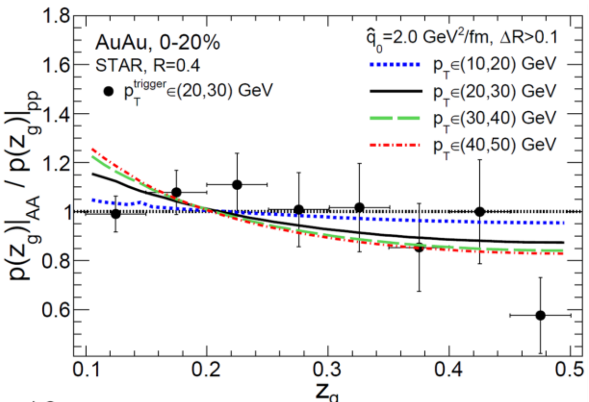
$$\frac{d\sigma}{dz_g} \propto \overline{P_i}(z_g) + \cancel{\mathcal{O}(\alpha_s^2)}$$

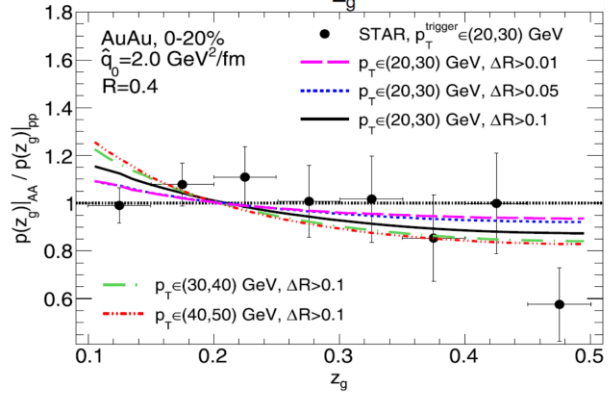
P_i: AP splitting functions

~ independent of α_s
~ independent of p_T (in UV limit)
~ independent of quark/gluon jet
Connection to fundamental QCD

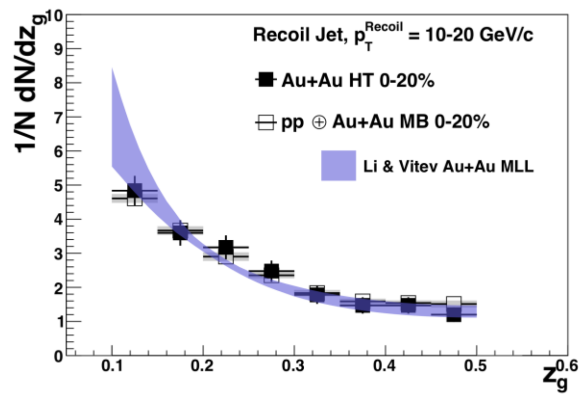
Jet Substructure: z_g in Hard Core Jets

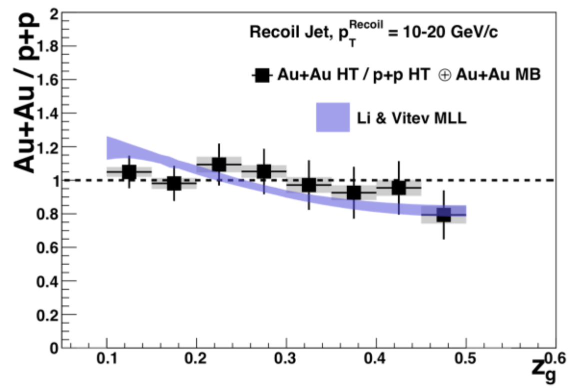
KK, HP16, QM17





Ning-Bo Chang
et al. QM18





Li & Vitev
arXiv: 1801.0008

- No significant modification on trigger and recoil side of hard-core dijets
- Theoretical models capture this well
- More statistics: Test downward slope

Modelers: Be mindful of cuts and detector effects