Jets at the LHC

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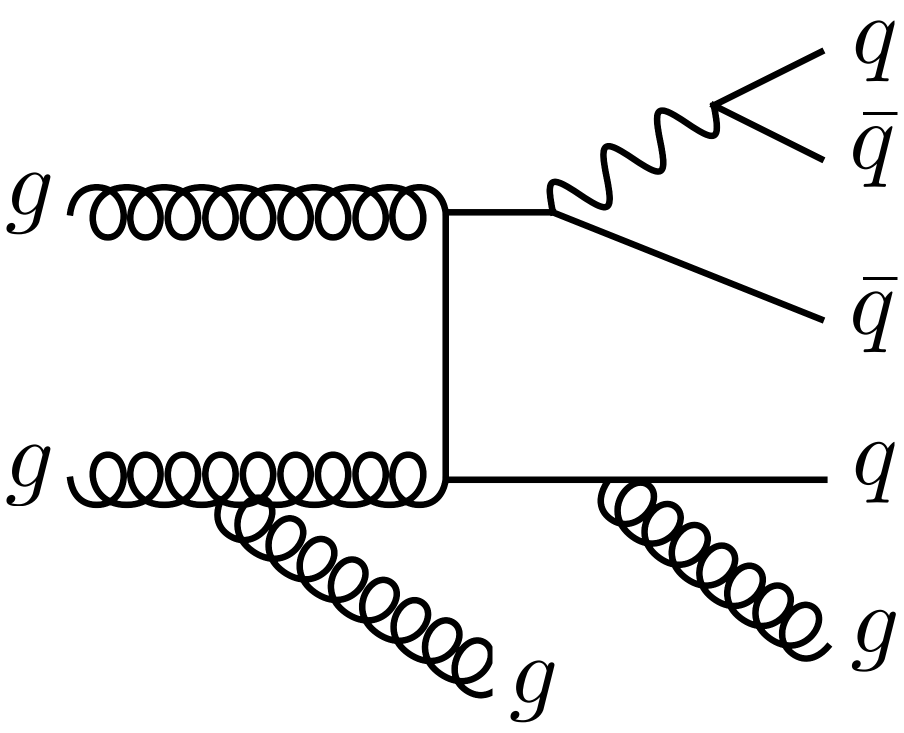
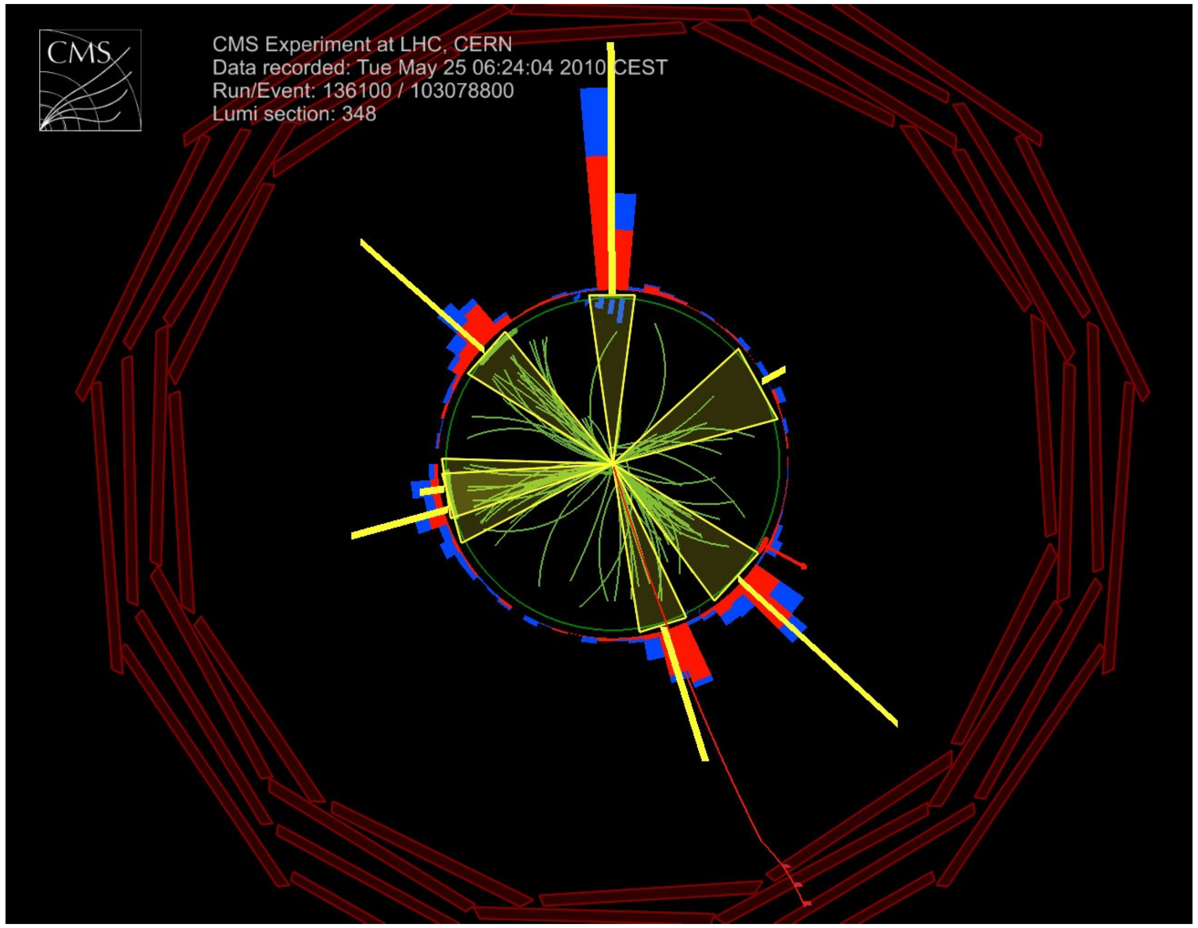
What is a jet?

- Energetic quarks and gluons radiate and hadronize
  → Produce sprays of collimated hadrons





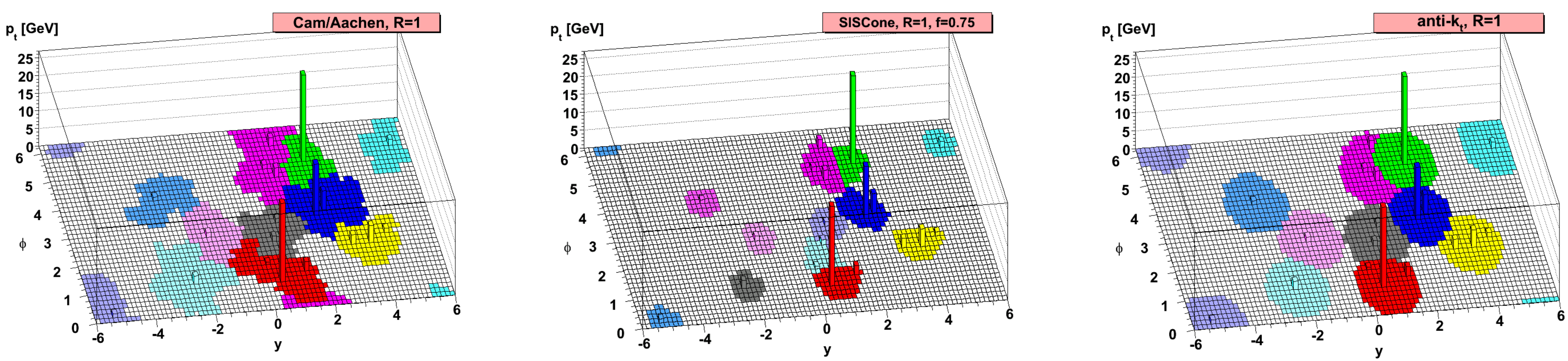
What is a jet?

- Jet definition must be easy to implement and infrared safe
- Two basic approaches:

Cone: Sterman-Weinberg, UA1, Midpoint, SISCone

1980 — 1990 — 2000 — 2010

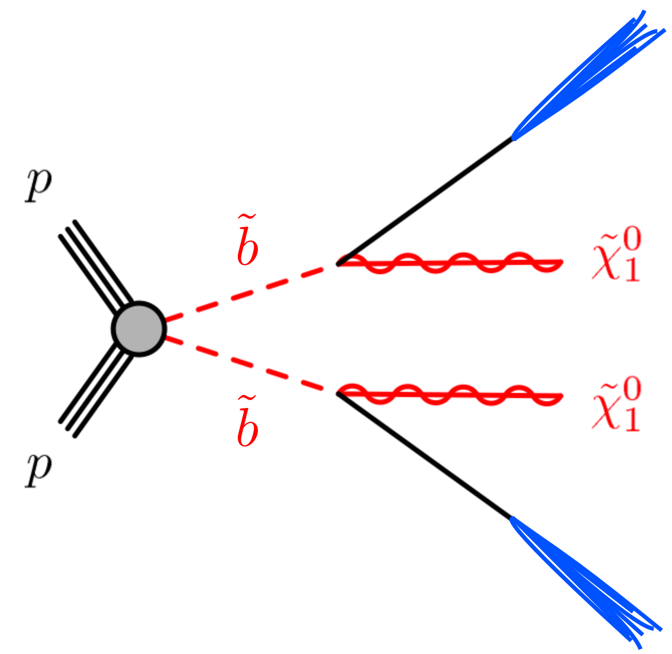
Clustering: Jade, k_T, Cambridge/Aachen, anti-k_T



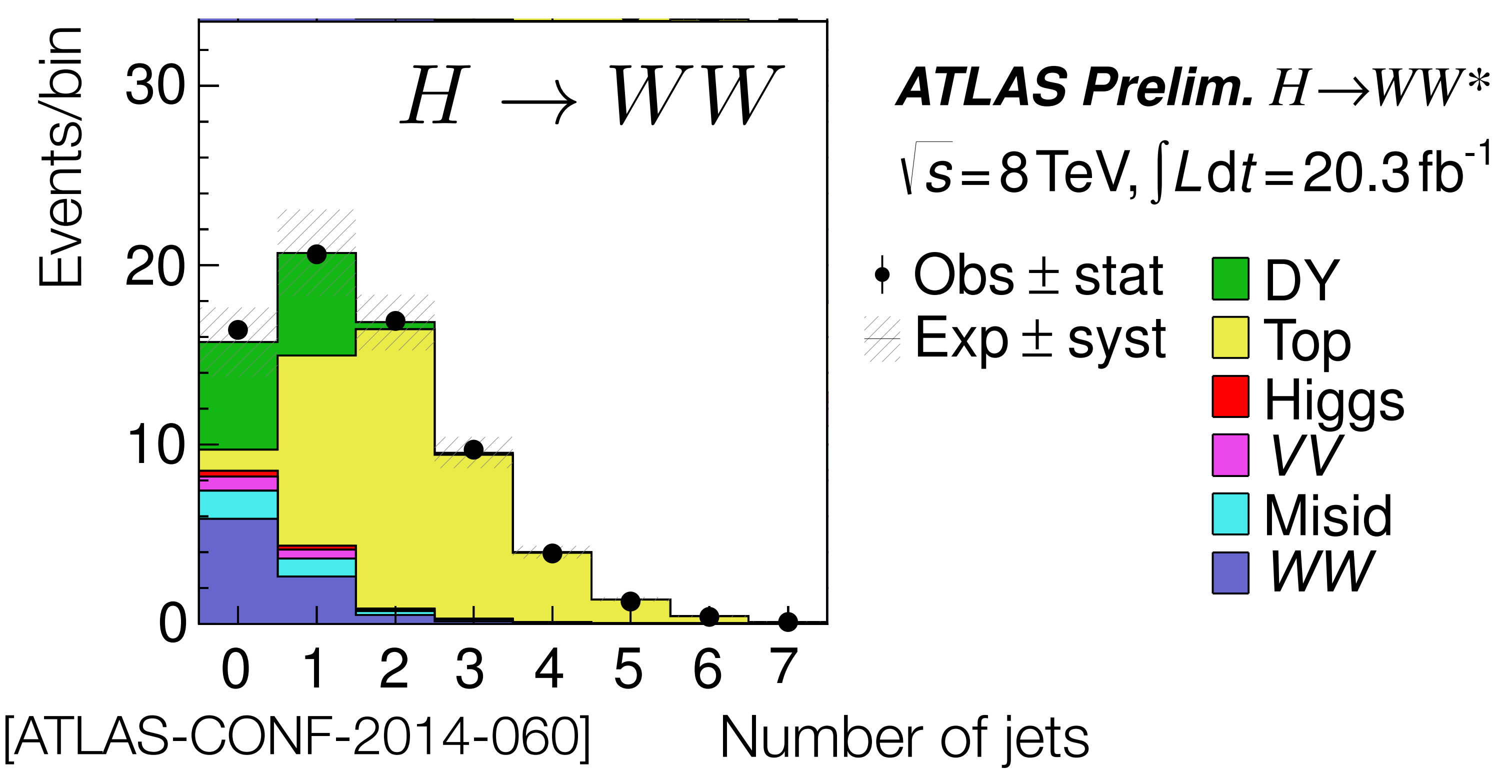
[Cacciari, Salam, Soyez]

Why do jets matter?

- Jets enter in many LHC analyses
  E.g. supersymmetry searches



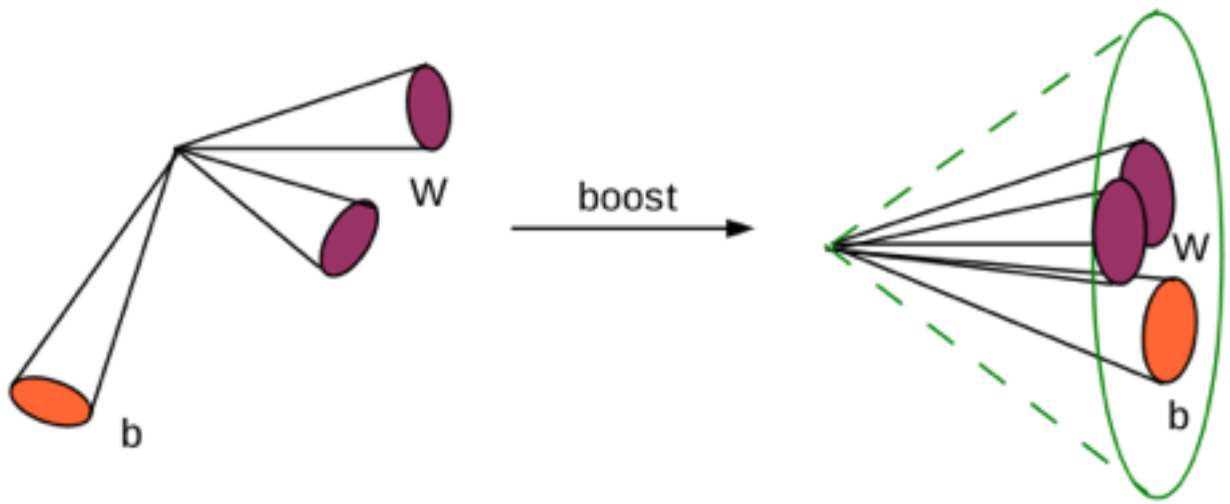
- Backgrounds can depend strongly on number of jets



[ATLAS-CONF-2014-060]

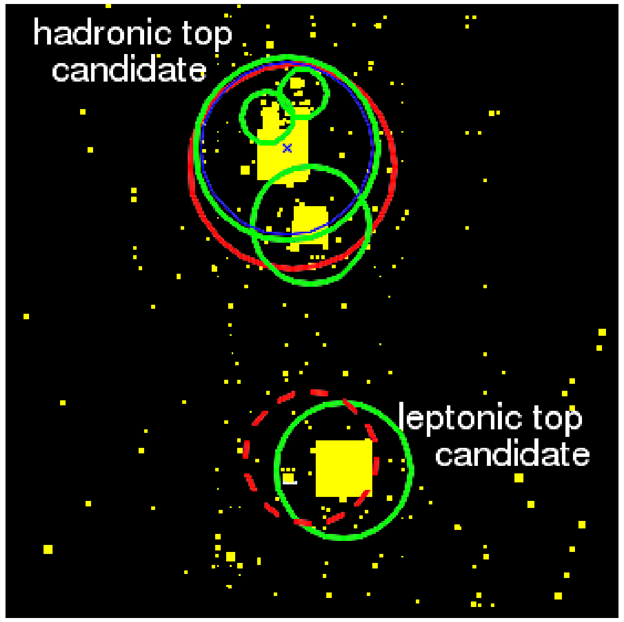
Why does jet substructure matter?

- Jets are key to tag heavy particles at high energies



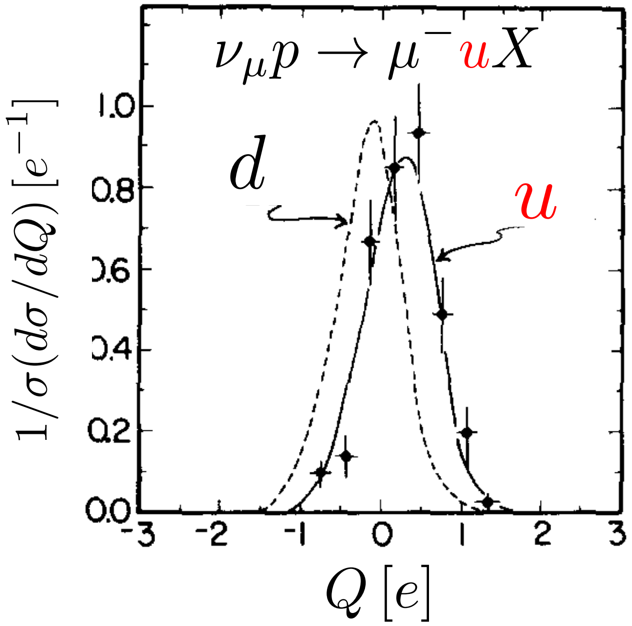
3 jets

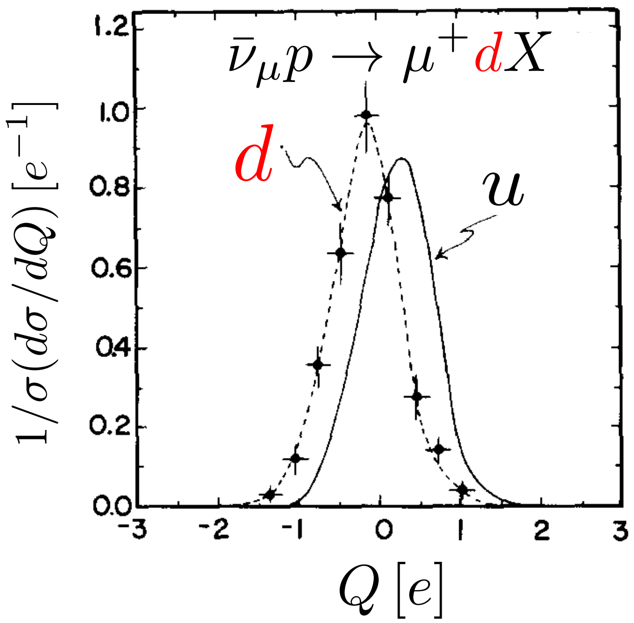
3 subjets



[ATLAS-CONF-2013-052]

- Jet substructure probes initiating parton, e.g. jet charge

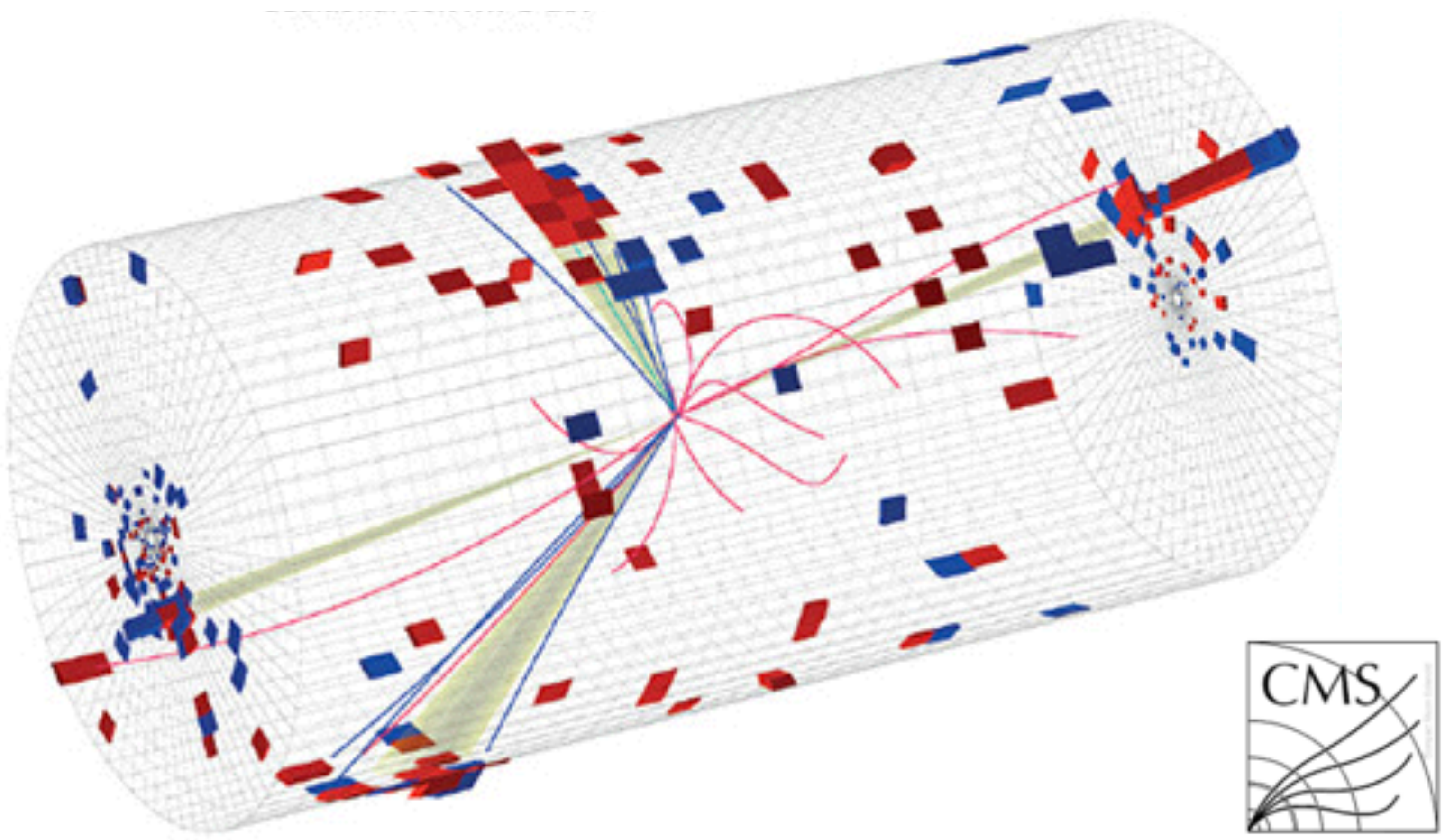




[Fermilab (1981)]

Outline

1. Jet cross sections
2. Jet substructure for boosted objects
3. Probing partons with substructure
4. Probing the medium with jets

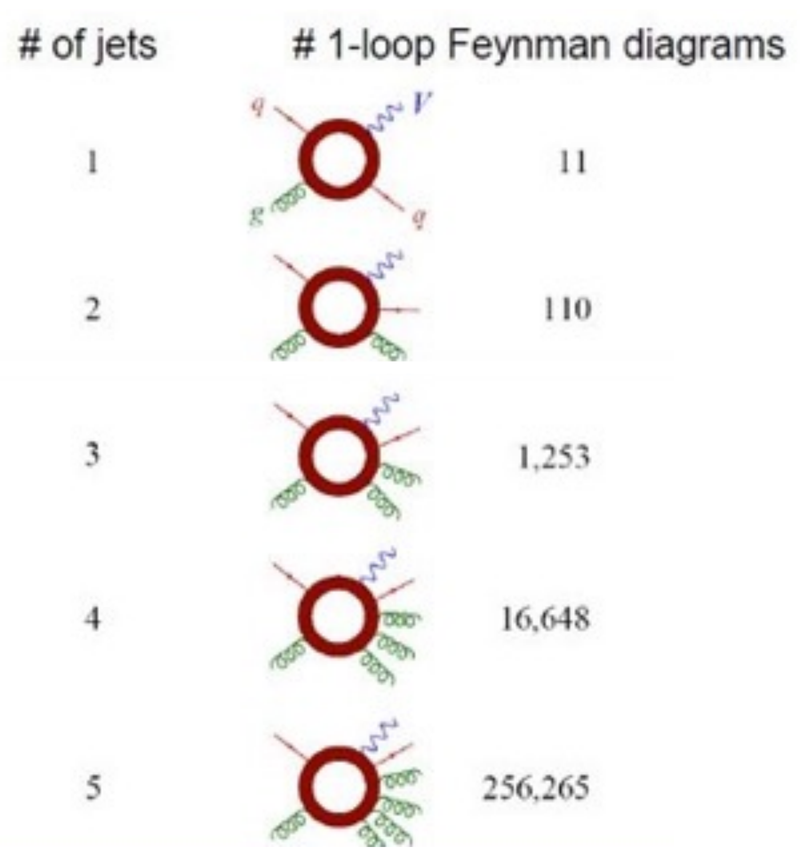


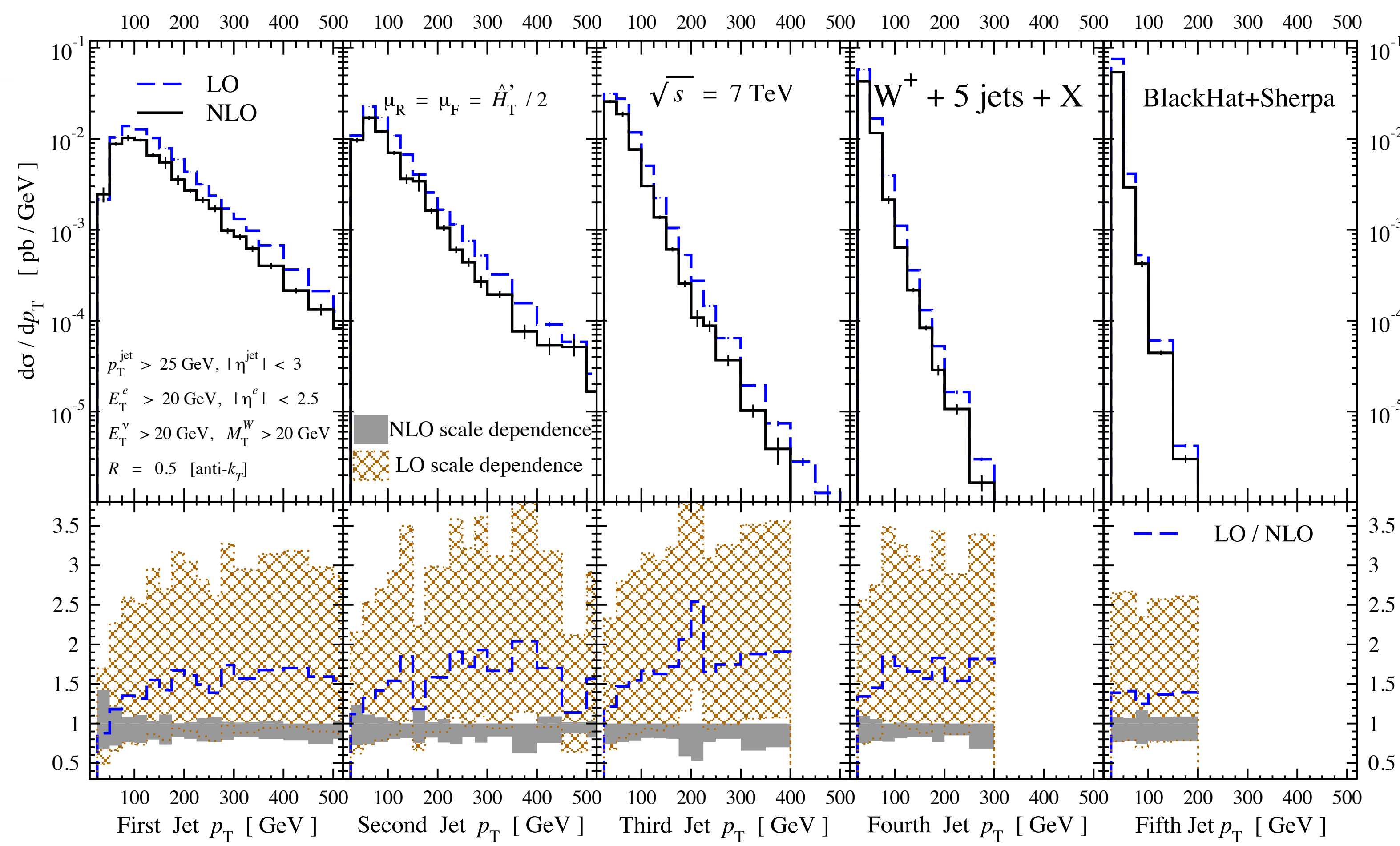
1. Jet cross sections

Fixed-order calculations

- NLO calculations are automated [MCFM, BlackHat, Rocket, NJet, MadLoop, …]

$pp \to W + n$ jets



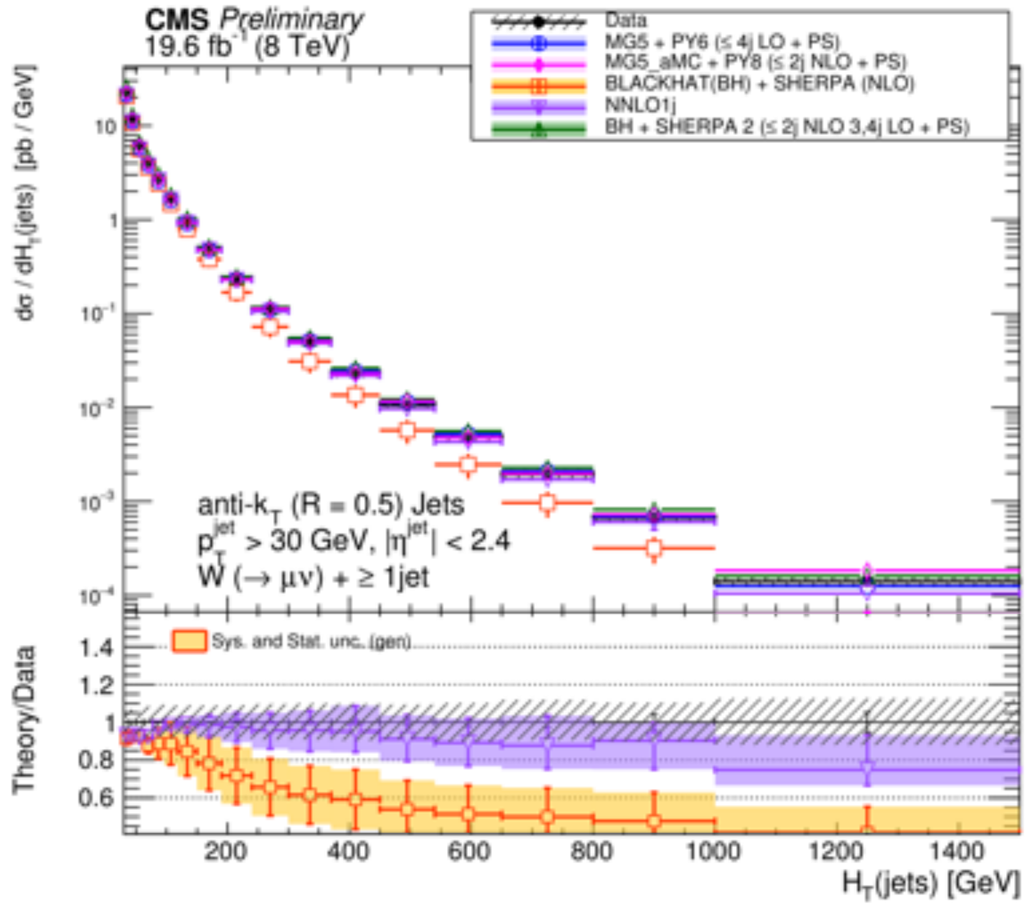


[Bern, Dixon, Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren]

- Large uncertainties at LO reduced at NLO

Fixed-order calculations

- Certain observables require NNLO precision. E.g.



[CMS-PAS-SMP-14-023]

- Lots of new NNLO results due to slicing with N-jettiness $\mathcal{T}_N$
[Stewart, Tackmann, WW; Boughezal, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh]

$$\sigma(X) = \int_0^\delta d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N} + \int_\delta d\mathcal{T}_N \frac{d\sigma(X)}{d\mathcal{T}_N}$$

analytic up to $\mathcal{O}(\delta)$ from NLO

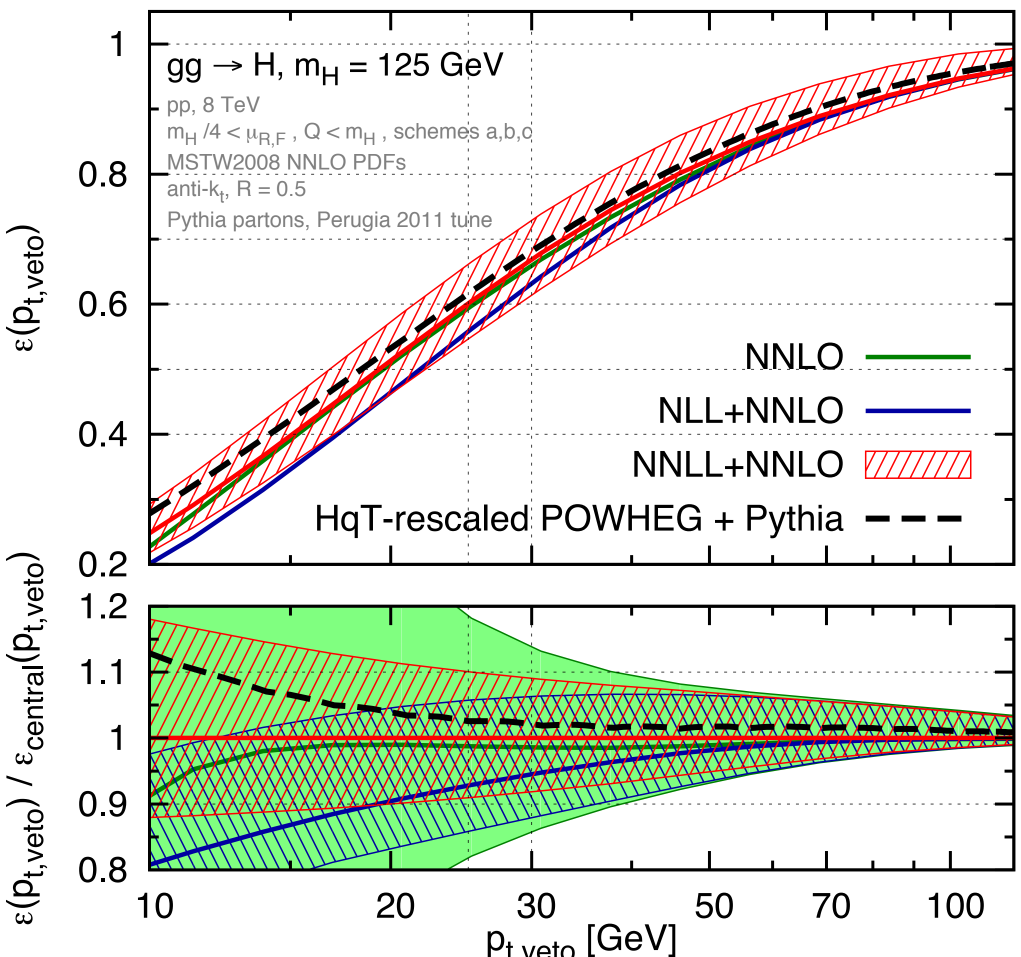
Resummed calculations

- Tight restriction on radiation → large logarithms and uncertainties

$$\sigma(H + 0\ \text{jets}) \propto 1 - \frac{6\alpha_s}{\pi} \ln^2 \frac{p_T^{\text{veto}}}{m_H} + \ldots$$

no jets above this p_T

- Resummation captures dominant effect of all emissions



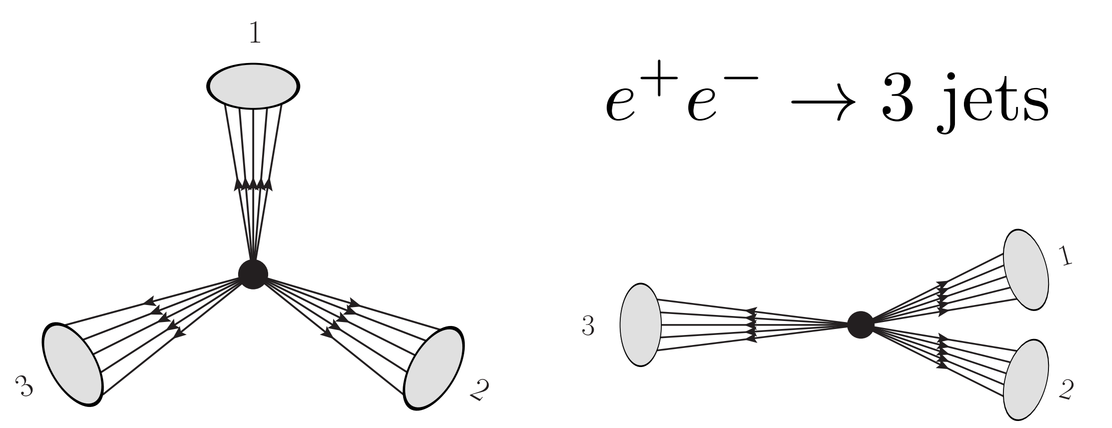
[Banfi, Monni, Salam, Zanderighi]

Resummation for jets

- Jet radius resummation
  [Dasgupta, Dreyer, Salam, Soyez; Chien, Hornig, Lee; Kolodrubetz, Pietrulewicz, Stewart, Tackmann, WW; Kang, Ringer, Vitev; Dai, Kim, Leibovich; …]

- Nonglobal logarithms
  [Caron-Huot; Larkoski, Moult, Neill; Becher, Neubert, Rothen, Shao,…]

- Resummation of kinematic jet hierarchies
  [Bauer, Tackmann, Walsh, Zuberi; Larkoski, Moult, Neill; Pietrulewicz, Tackmann, WW]



(a) $m_J^2 \ll s_{12} \sim s_{13} \sim s_{23} \sim Q^2$ (b) $m_J^2 \ll s_{12} \ll s_{13} \sim s_{23} \sim Q^2$

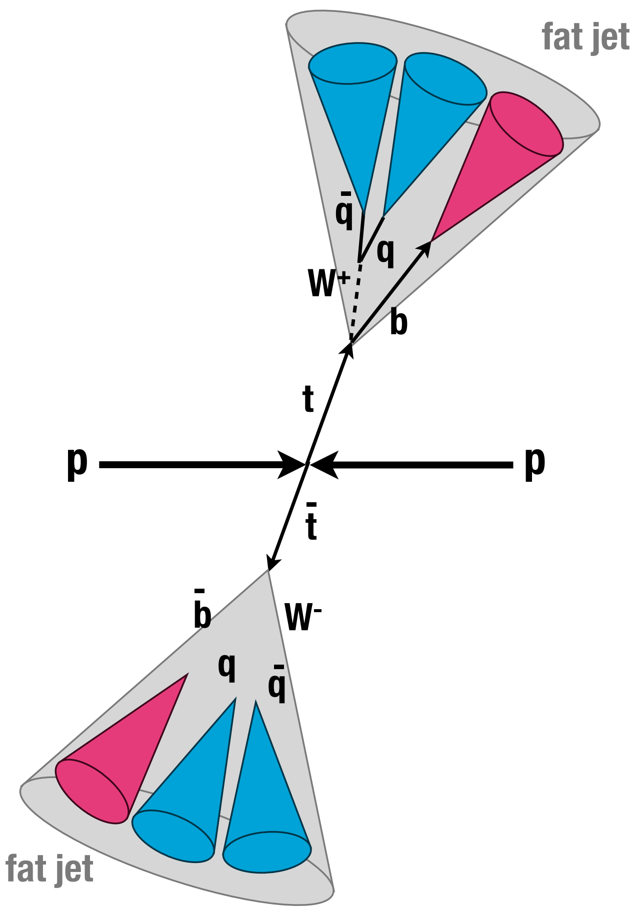
(c) $m_J^2 \ll s_{12} \sim s_{13} \ll s_{23} \sim Q^2$ (d) $m_J^2 \ll s_{12} \ll s_{13} \ll s_{23} \sim Q^2$

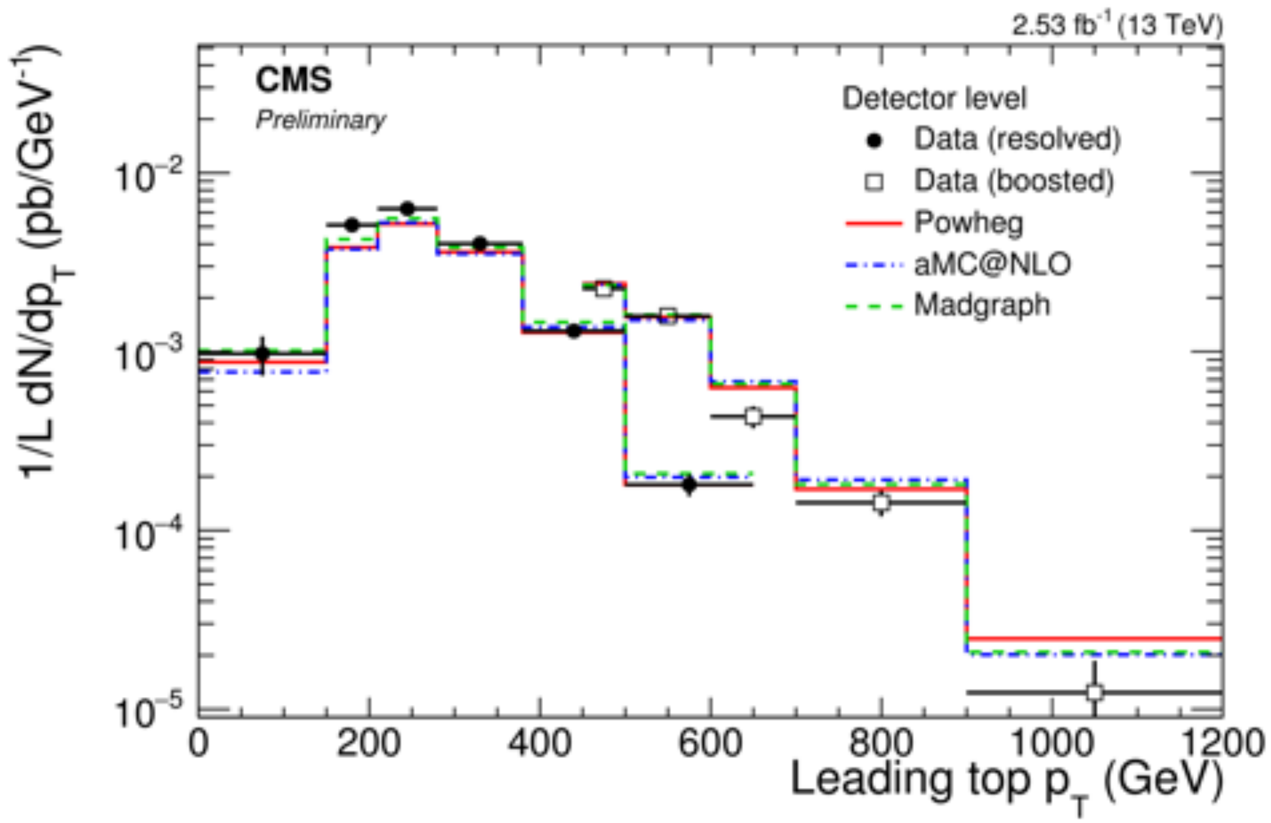
[Pietrulewicz, Tackmann, WW]

2. Jet substructure for boosted objects

When does a top quark become a jet?

- Boosted analysis overtakes resolved at $p_T^{\text{top}} \sim 400\,\text{GeV}$





[CMS-PAS-TOP-16-013]

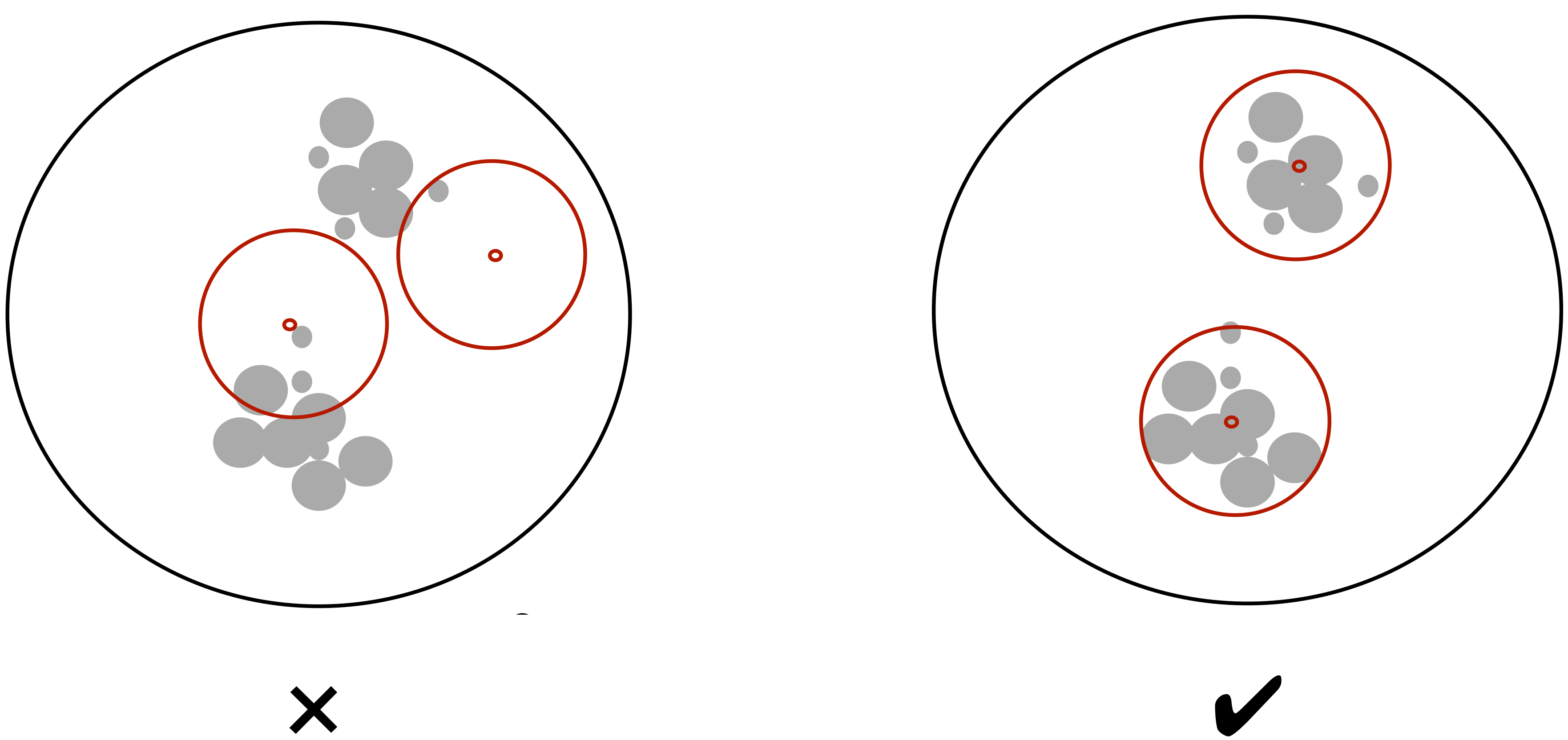
- Important as BSM searches move to ever higher energies

Tagging by kinematics

- Test whether jet consists of three subjets with kinematics of top decay, using templates T [Almeida, Lee, Perez, Sterman, Sung]

$$\text{Overlap} = \max_T \exp\left[-\sum_{i\in T} \frac{1}{2\sigma_i^2}\left(\sum_{\theta_{ij}<r} E_j - E_i\right)\right]$$

- Output is not only overlap but also the best matching template



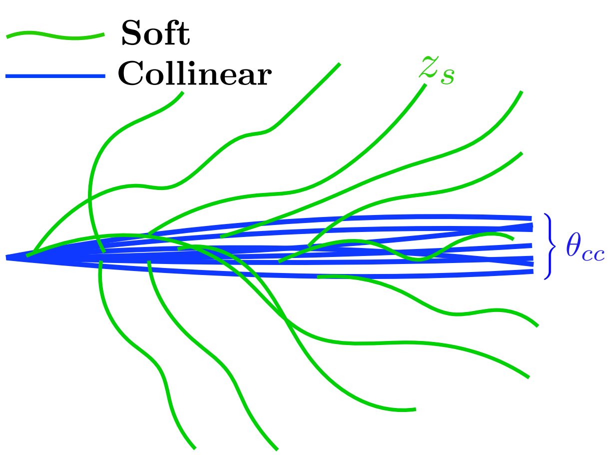
Tagging by power counting

- Start from energy correlation functions [Larkoski, Salam,Thaler]

$$e_2^{(\beta)} = \sum_{i<j\in J} z_i z_j \theta_{ij}^{\beta} \qquad e_3^{(\beta)} = \sum_{i<j<k\in J} z_i z_j z_k \theta_{ij}^{\beta}\theta_{ik}^{\beta}\theta_{jk}^{\beta}$$

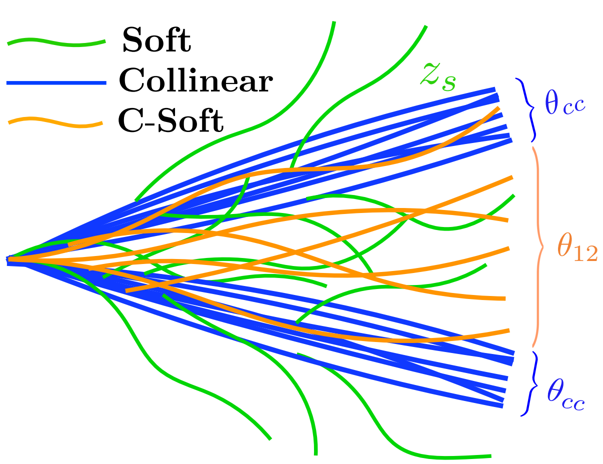
with z_i the energy fraction of *i* and θ_{ij} the angle between *i* and *j*

- Parametric discrimination of 1 vs. 2 prong [Larkoski, Moult, Neill]



$$e_2^{(\beta)} \sim \theta_{cc}^{\beta} + z_s$$

$$e_3^{(\beta)} \sim \theta_{cc}^{3\beta} + \theta_{cc}^{\beta} z_s + z_s^2 \qquad (e_2^{(\beta)})^3 \lesssim e_3^{(\beta)}$$

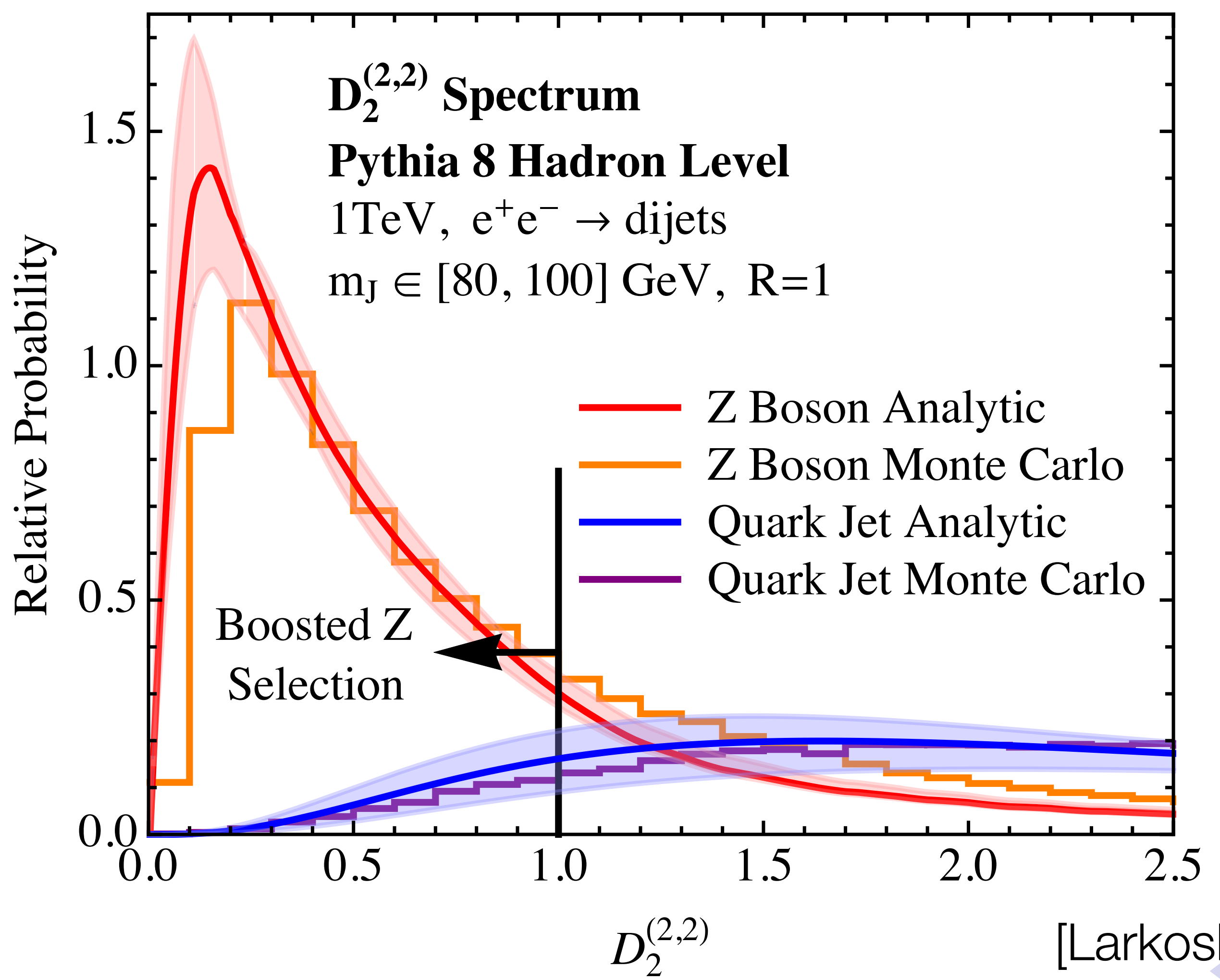


$$e_2^{(\beta)} \sim \theta_{12}^{\beta} \qquad e_3^{(\beta)} \ll (e_2^{(\beta)})^3$$

$$e_3^{(\beta)} \sim \theta_{12}^{\beta} z_s + \theta_{12}^{2\beta}\theta_{cc}^{\beta} + \theta_{12}^{3\beta} z_{cs}$$

Predicting the tagger efficiency

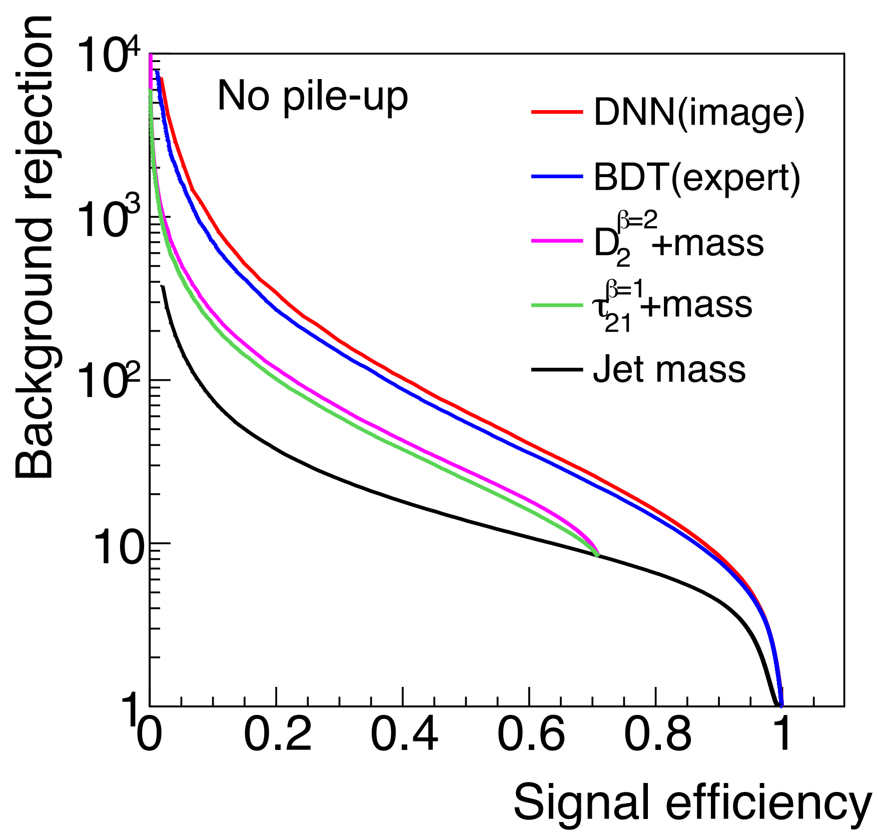
- Tag *W* boson jets using $D_2^{(\beta,\beta)} \equiv \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$
- Soft-Collinear Effective Theory yields resummed prediction for the cross section of D_2, compatible with Monte Carlos



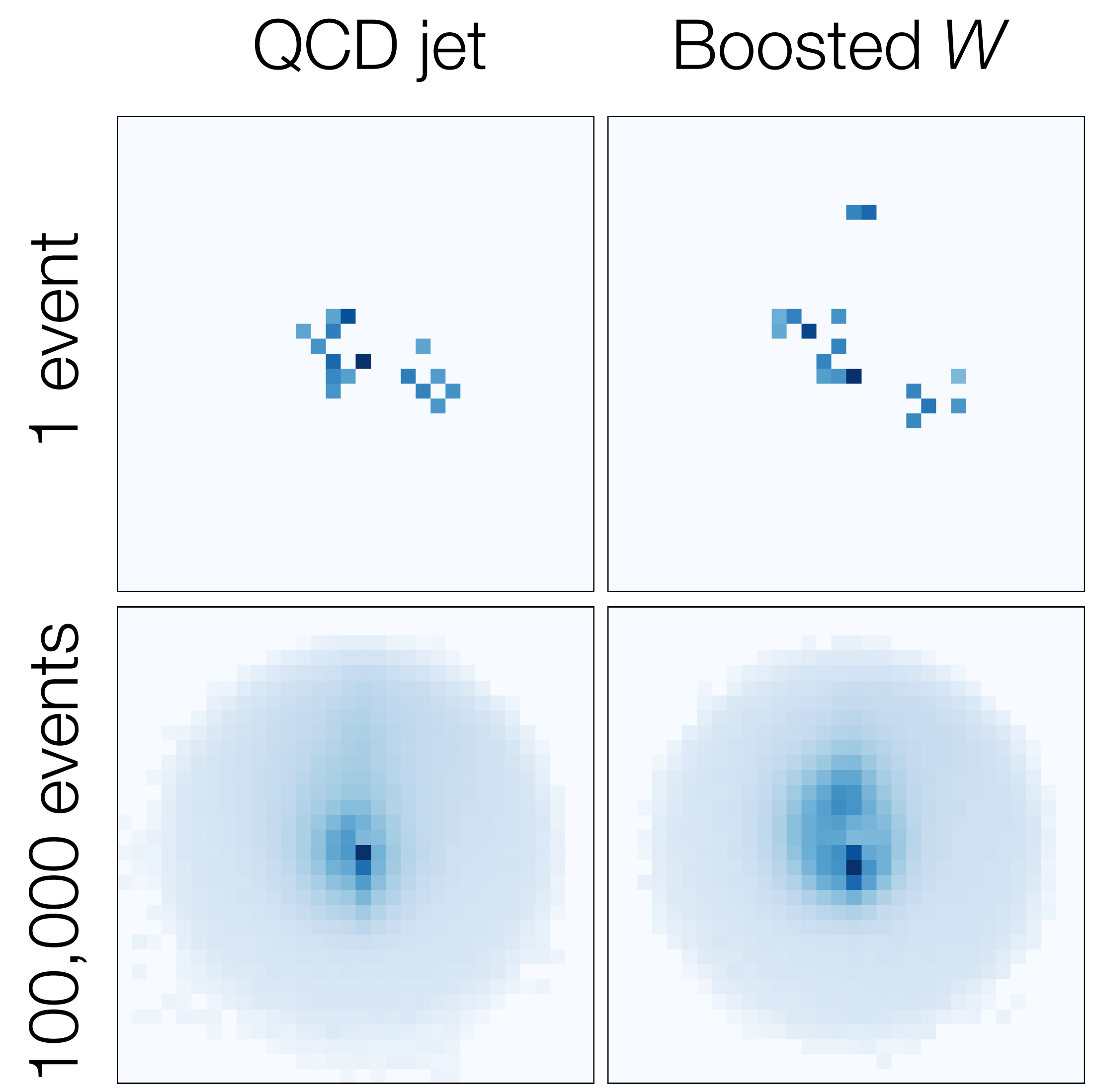
[Larkoski, Moult, Neill]

Tagging with deep learning

- Use methods from image recognition
- As powerful as combination of (expert) substructure observables



[Baldi, Bauer, Eng, Sadowski, Whiteson]



- Reliability of training sample is a potential concern

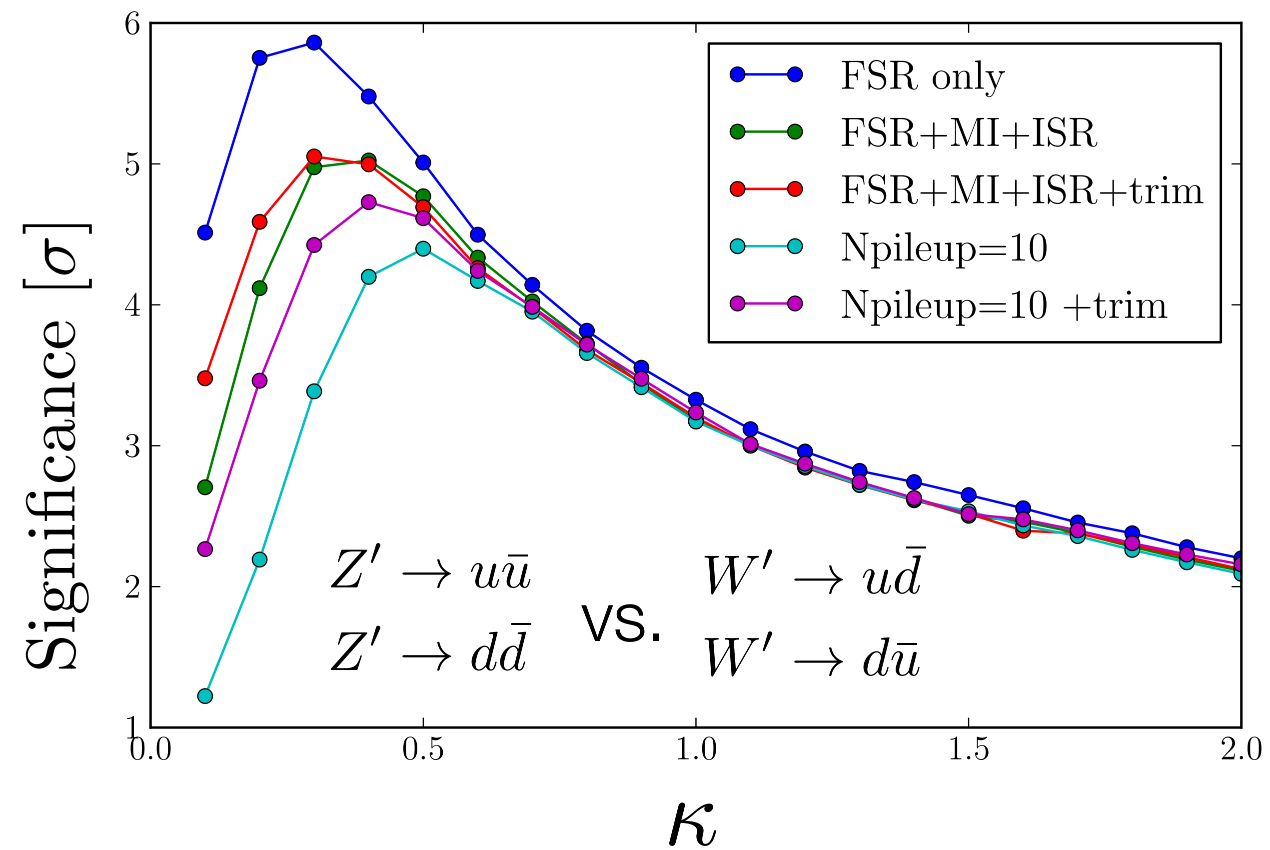
3. Probing partons with substructure

Jet charge as discriminant

- Jet charge can help characterize BSM. E.g. hadronic *Z'* vs. *W'*

$$Q_\kappa = \sum_{i \in \text{jet}} Q_i \left(\frac{p_{iT}}{p_T^{\text{jet}}} \right)^\kappa$$

[Feynman, Field]

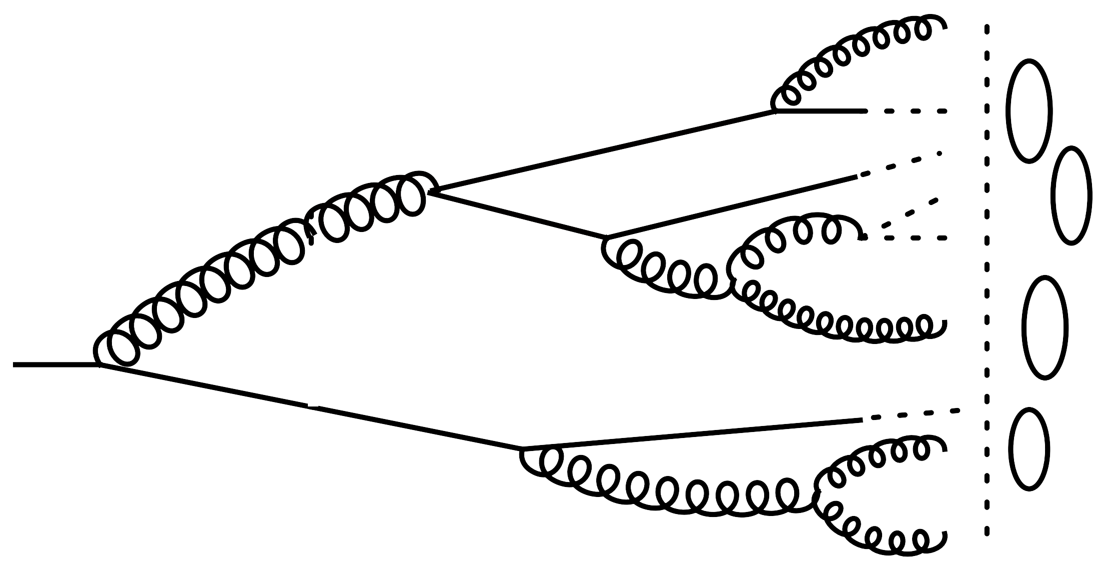


[Krohn, Lin, Schwartz, WW]

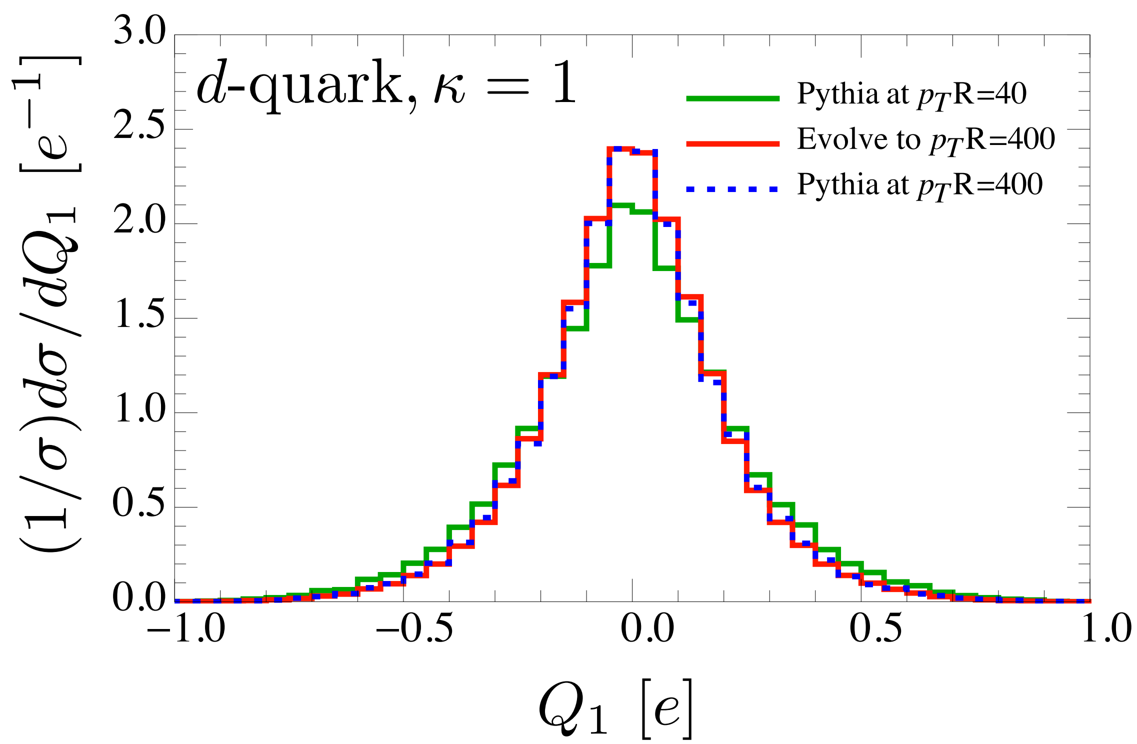
- Optimal κ: trade off between soft contamination vs. sensitivity
- Jet charge not infrared safe → only evolution calculable

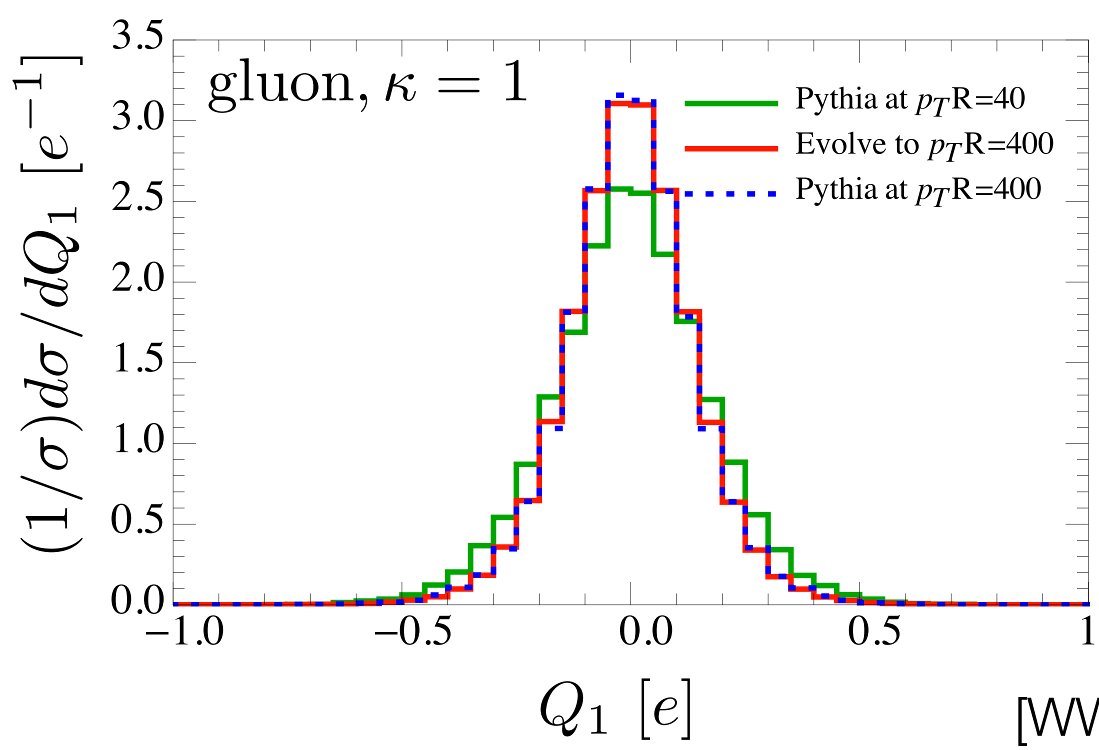
Calculating jet charge

- Jet charge = nonlinear DGLAP evolution $\otimes$ hadronization



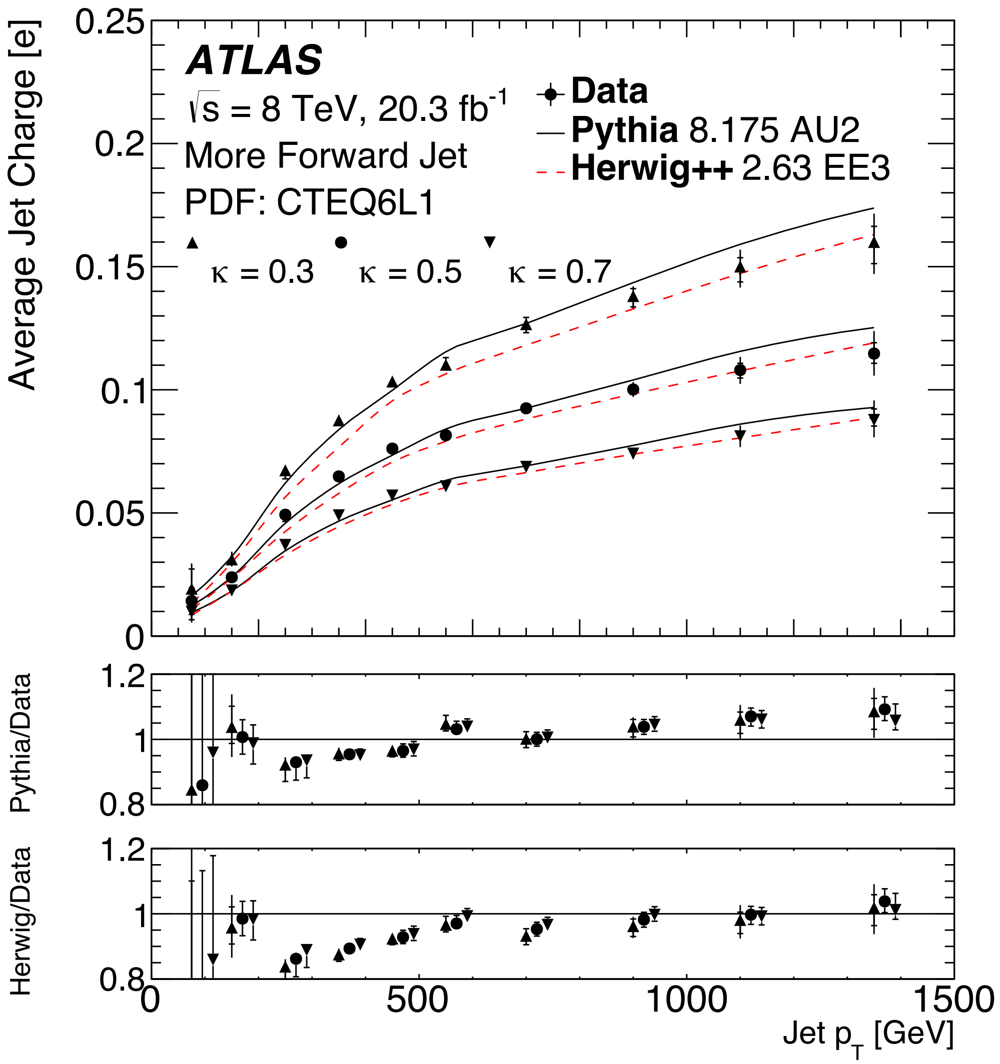
- Taking Pythia as input and evolving gives good agreement:

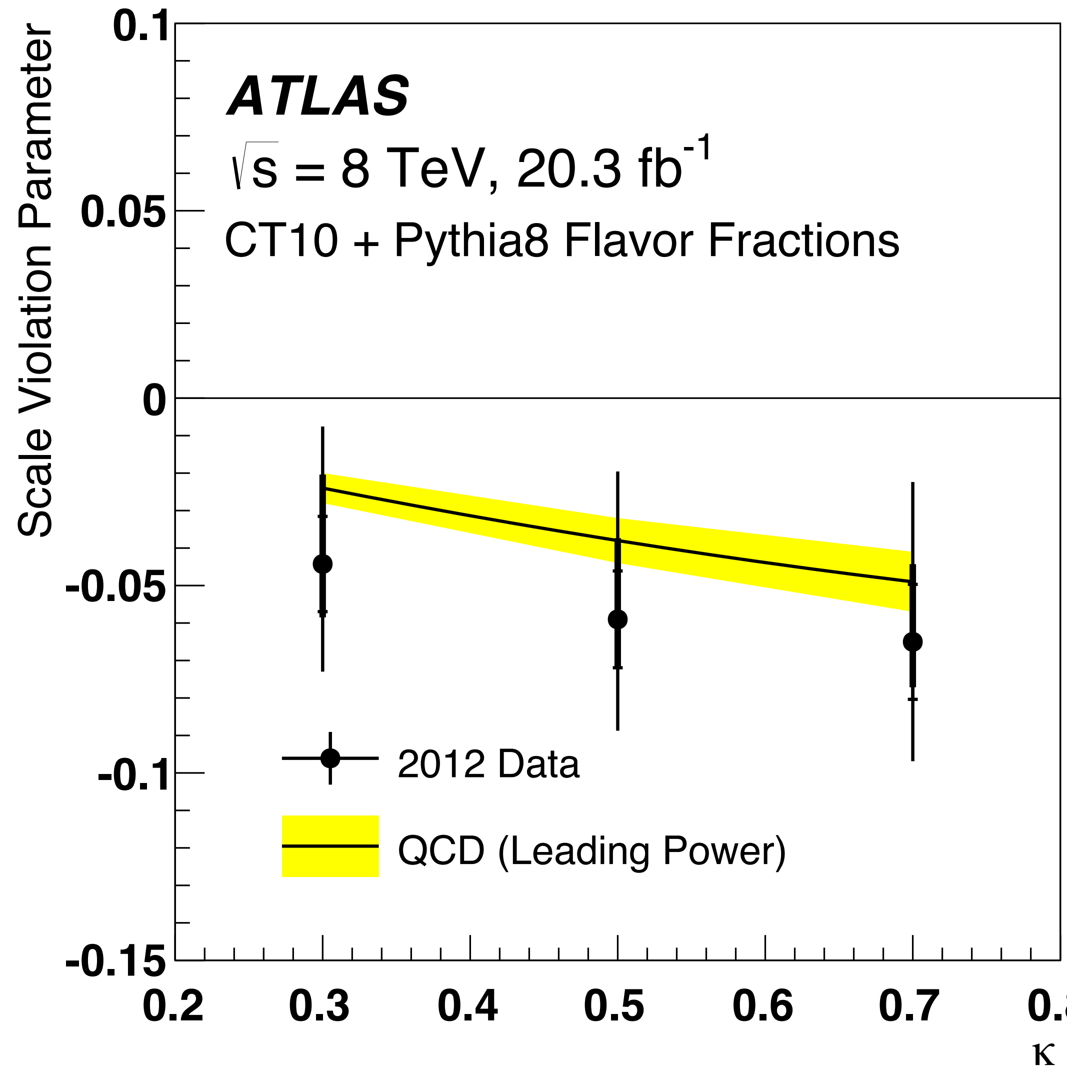




[WW]

Jet charge measurements



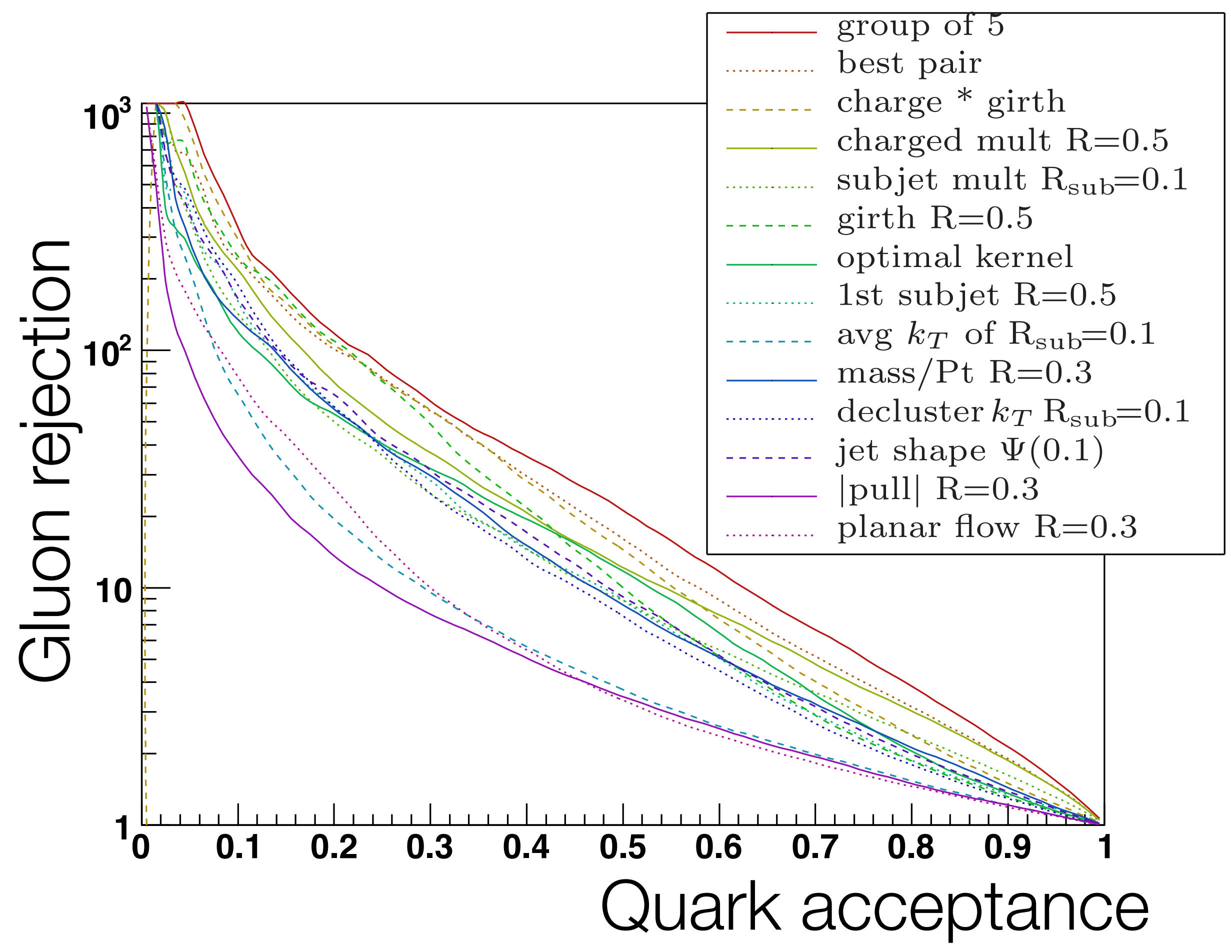


[*Phys. Rev. D* 93 (2016) 052003]

- The largest dependence on jet p_T is the flavor composition
- Observing scale violation is therefore challenging but possible

Quark-gluon discrimination

- New physics often more quarks than QCD backgrounds
- Largest difference between quark and gluon jet is color charge
- Extensive Pythia study: track multiplicity + girth are best two

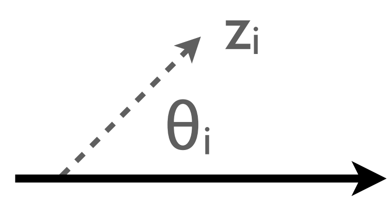


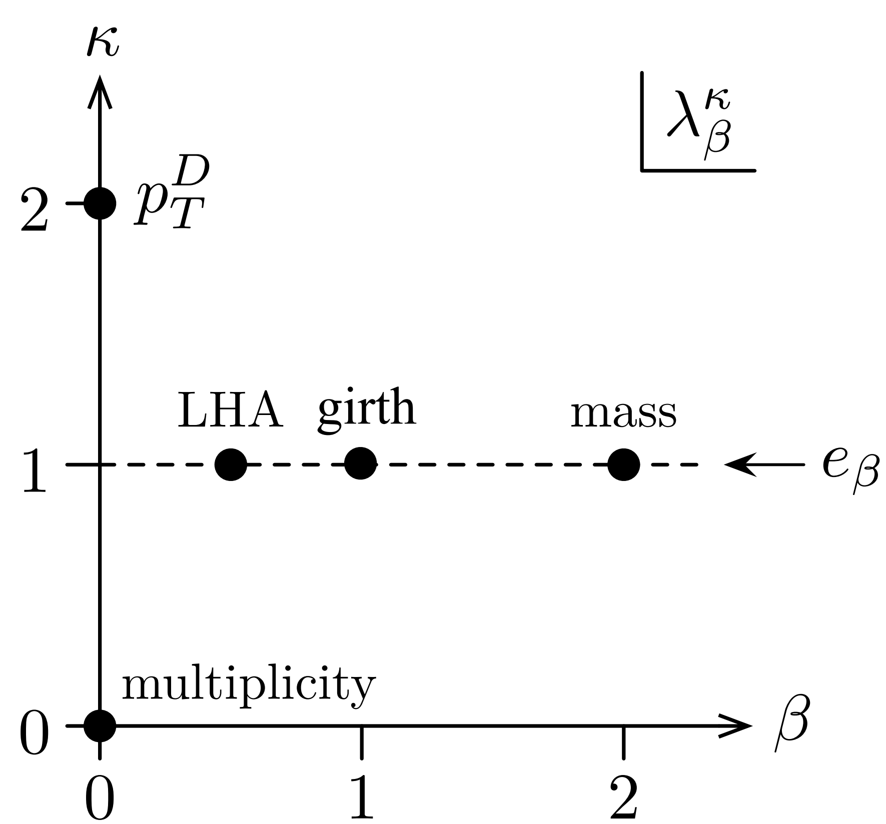
[Gallicchio, Schwartz]

Current limitations of Monte Carlos

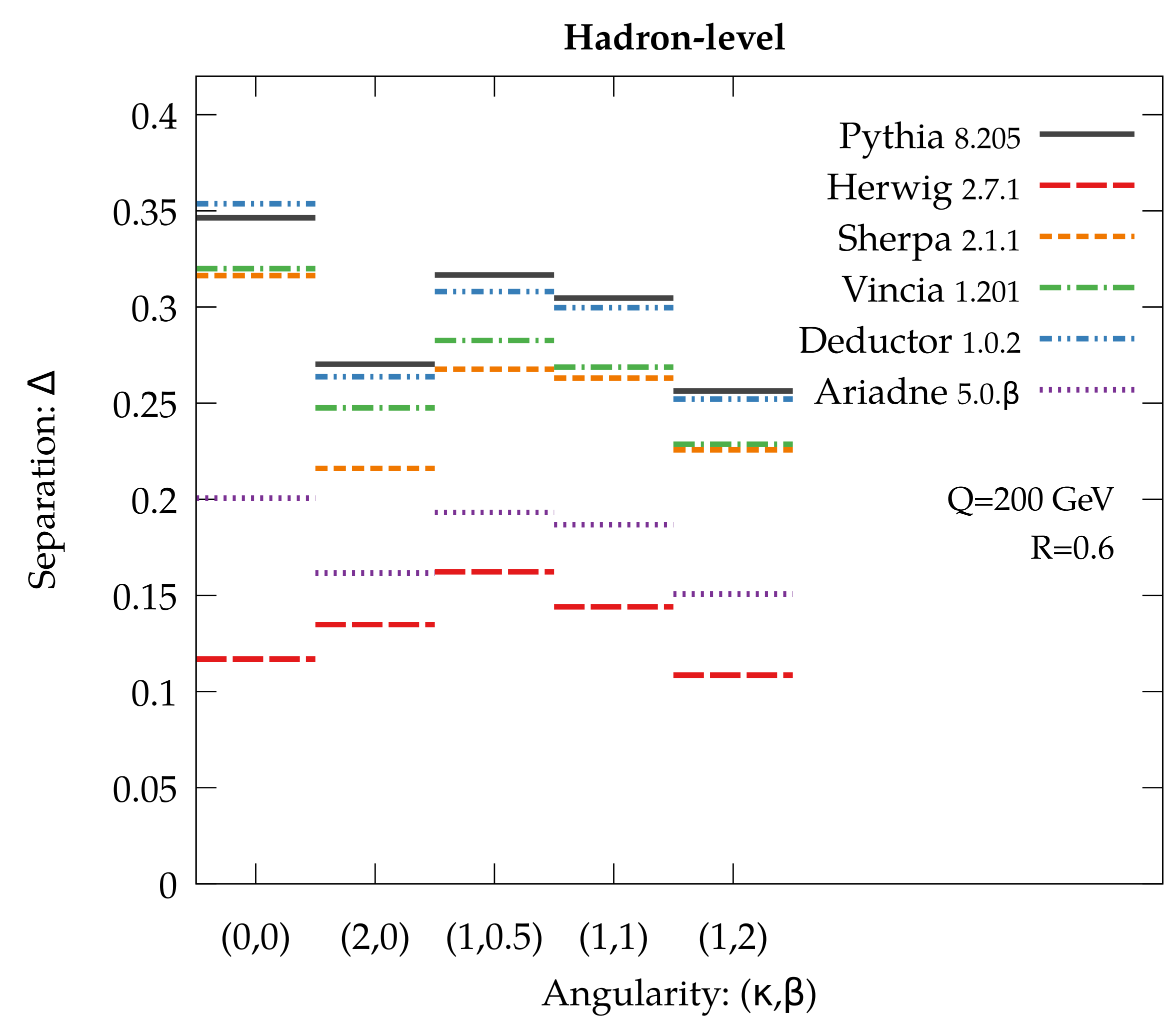
- Many quark-gluon discriminants are generalized angularities
- Big spread between predictions from different Monte Carlos

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$





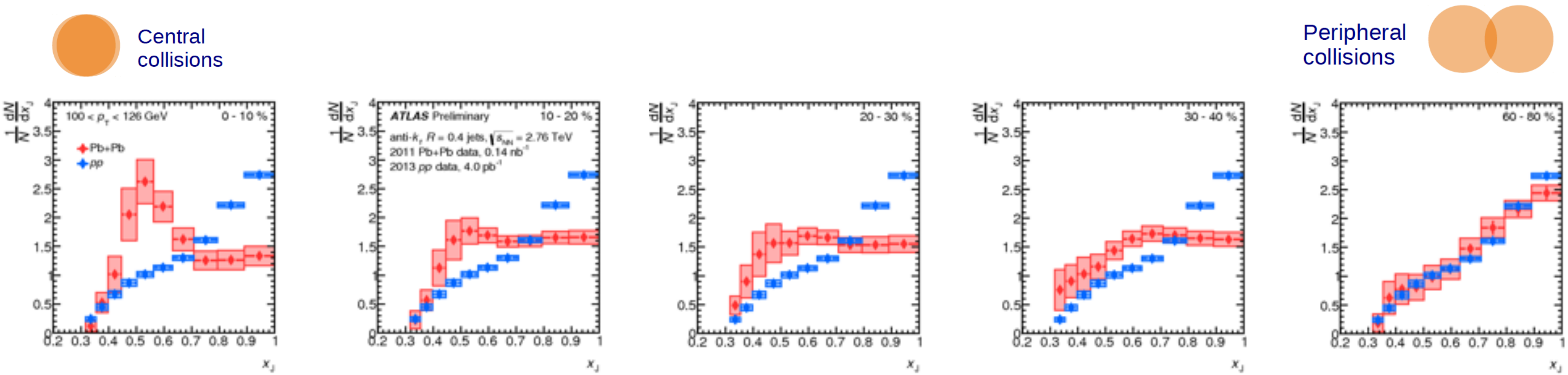
[Larkoski, Thaler, WW]



[Les Houches 2015]

4. Probing the medium with jets

Dijet inbalance



[ATLAS-CONF-2015-052]

- Jets lose energy as they propagate in medium (quenching)
- Leads to a distortion of the p_T balance of dijets

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

Splitting fraction

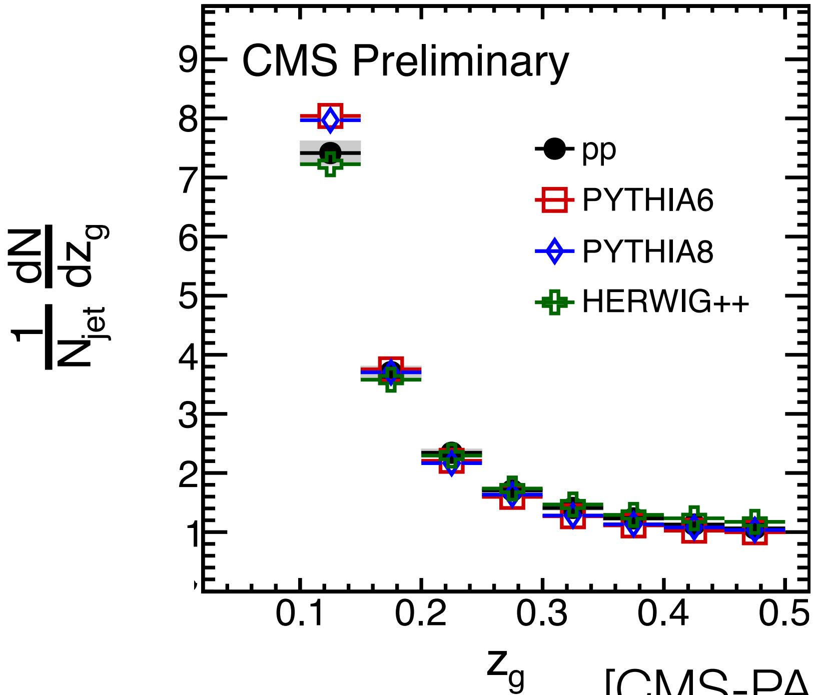
- Cluster jet using Cabridge/Aachen (purely angular)
- Go through clustering tree until splitting satisfies

$$z_g \equiv \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\mathrm{cut}} \qquad r_g \equiv \Delta R_{12} > \Delta$$

[Larkoski, Marzani, Soyez, Thaler]

- At LO this is proportional to Altarelli-Parisi splitting function

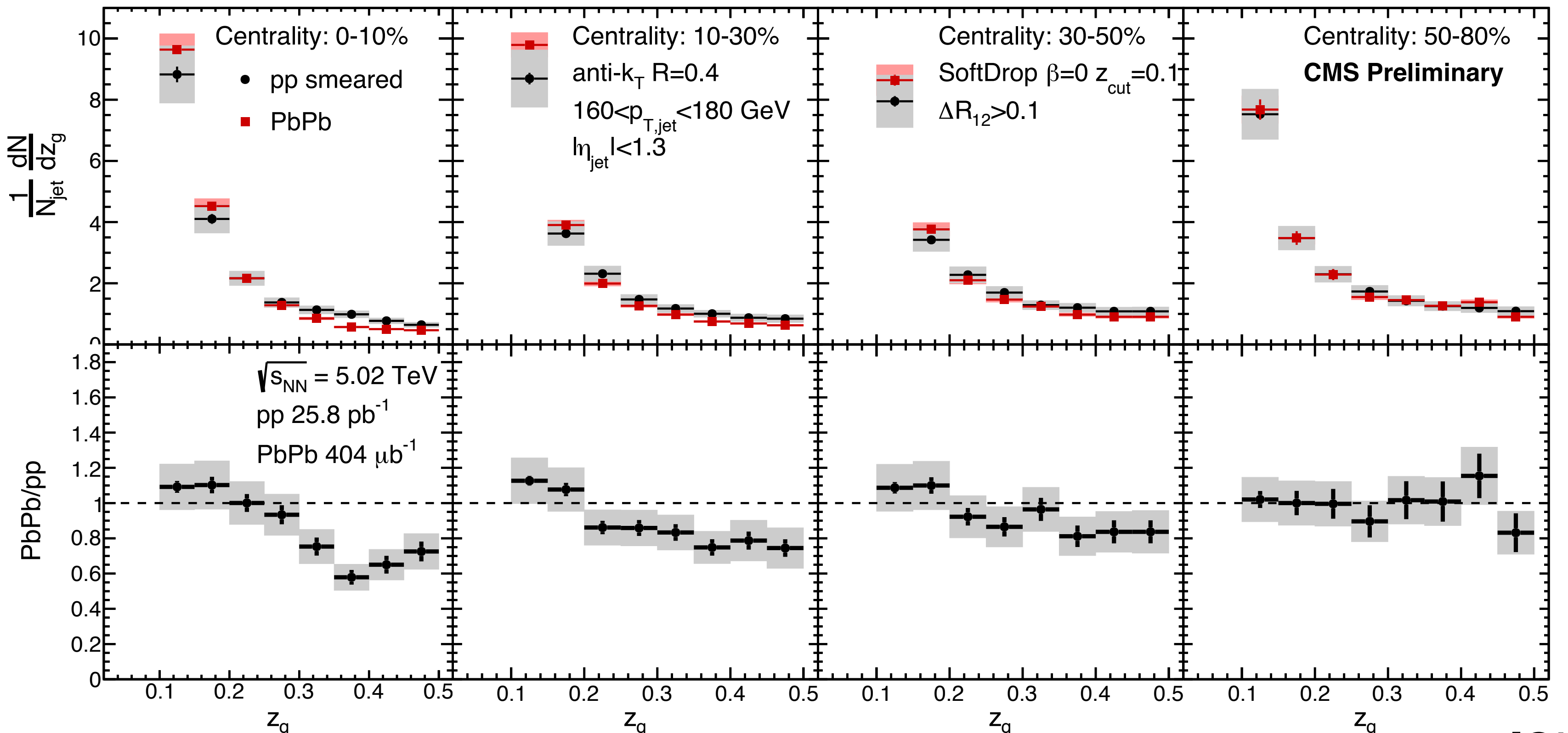
$$\frac{d\sigma}{dz_g} \sim \frac{1}{z_g}$$



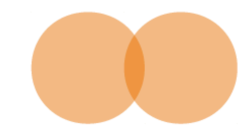
[CMS-PAS-HIN-16-006]

Medium modifications of splitting function

Central collisions

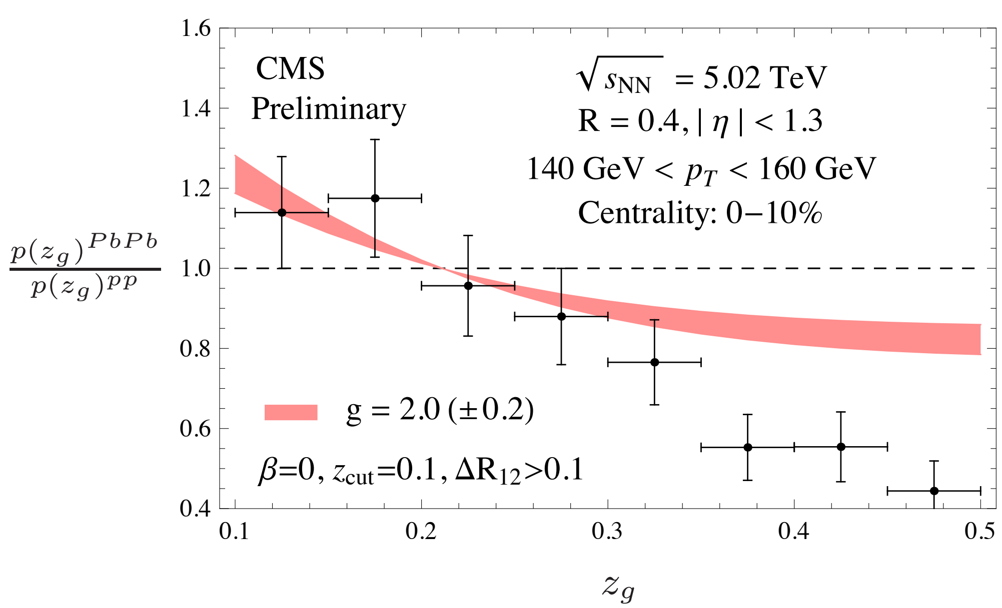


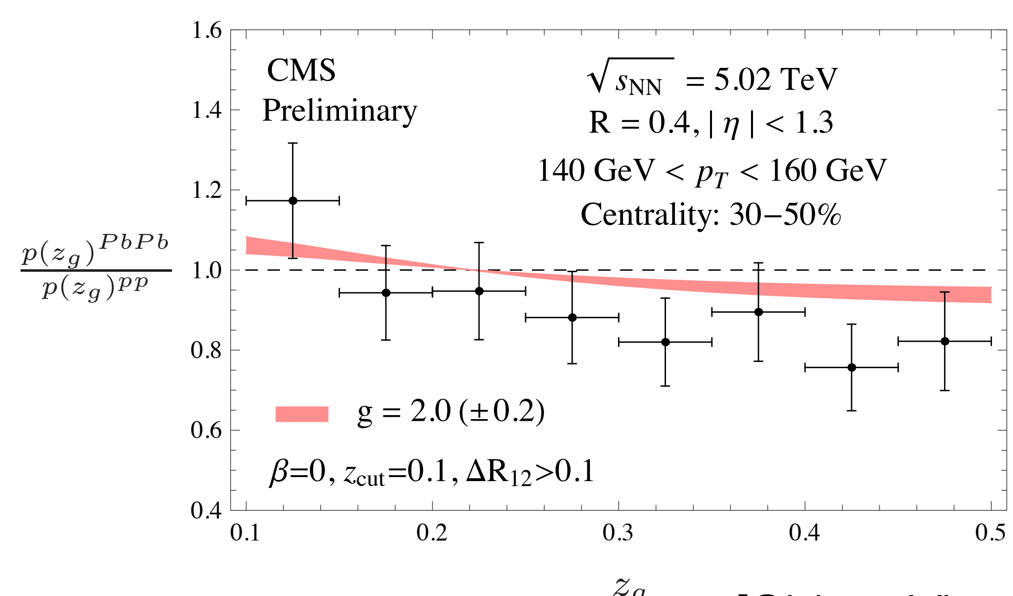
Peripheral collisions



[CMS-PAS-HIN-16-006]

- Medium effect on splitting functions described by Glauber gluons





[Chien, Vitev]

Conclusions

- Jets play a crucial role in many LHC measurements
- Jet (substructure) as probe of
  - boosted heavy particles
  - initiating parton of QCD jets
  - medium in heavy ion collisions
- There is room for new ideas, new observables, new calculations…

Thank you!