Jet substructure and a possible determination of the QCD coupling

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Trento, 02/13/18

BERKELEY LAB

Jets at the LHC

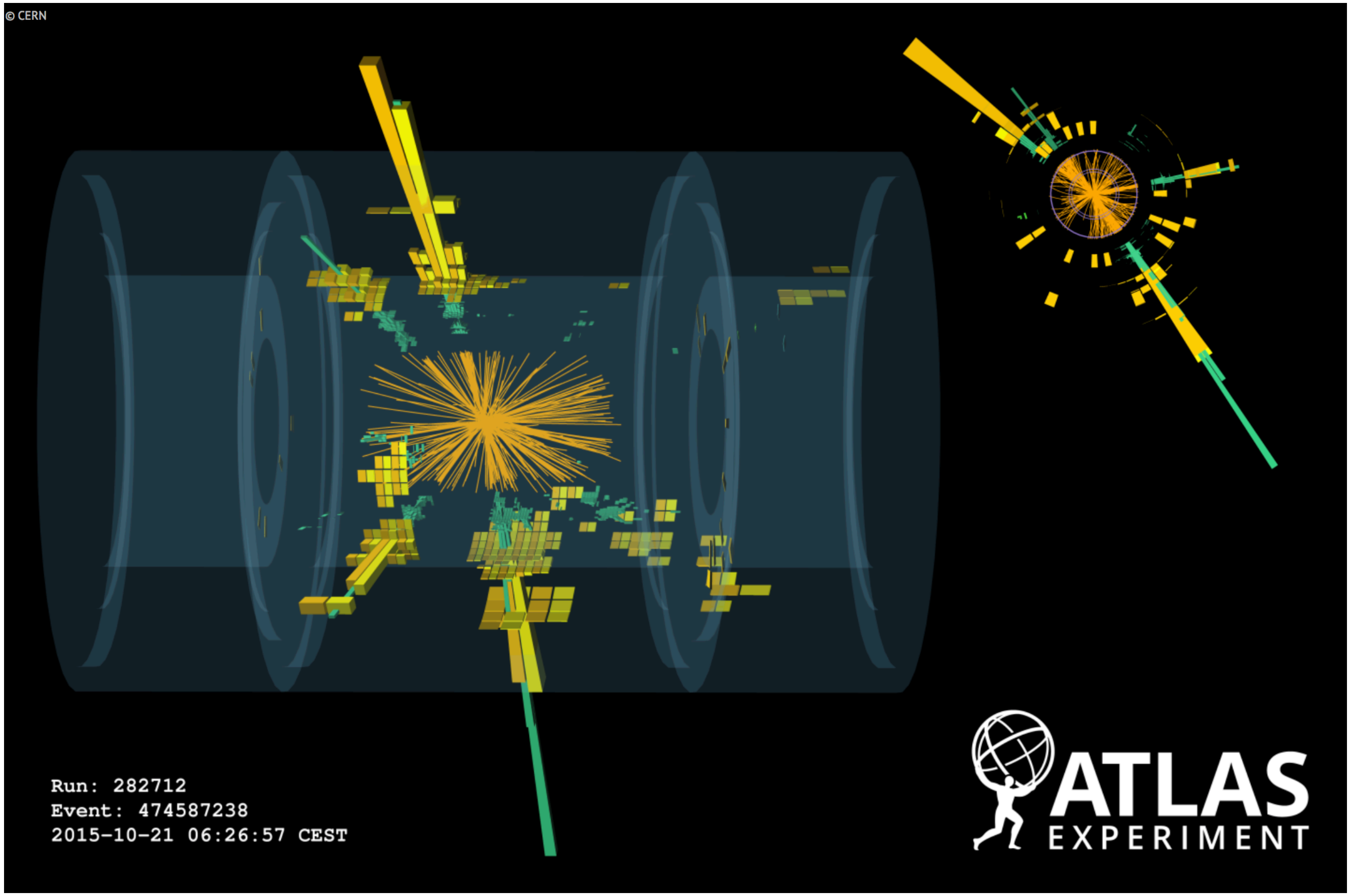
- Inclusive jet production

$$\longrightarrow \quad \frac{d\sigma^{pp\to \mathrm{jet}+X}}{dp_T d\eta}$$

see talk by Joao Pires

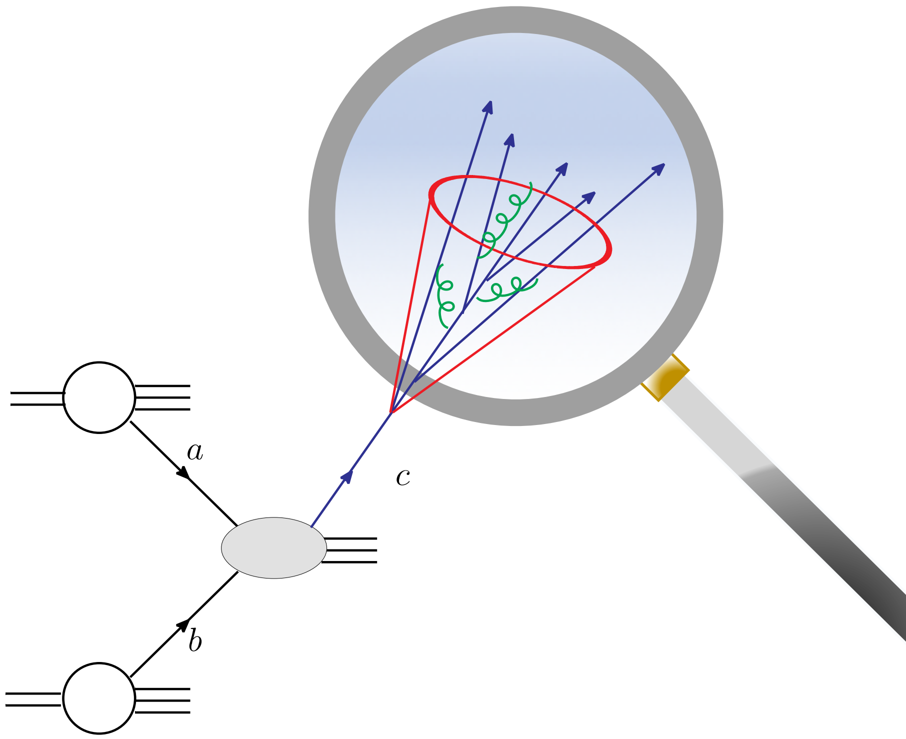
- Measure additional jet substructure

$$\longrightarrow \quad \frac{d\sigma^{pp\to (\mathrm{jet}\ \tau)X}}{dp_T d\eta d\tau}$$

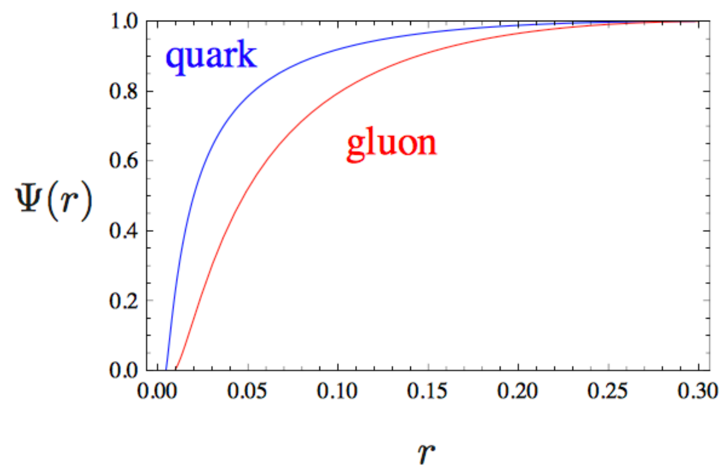


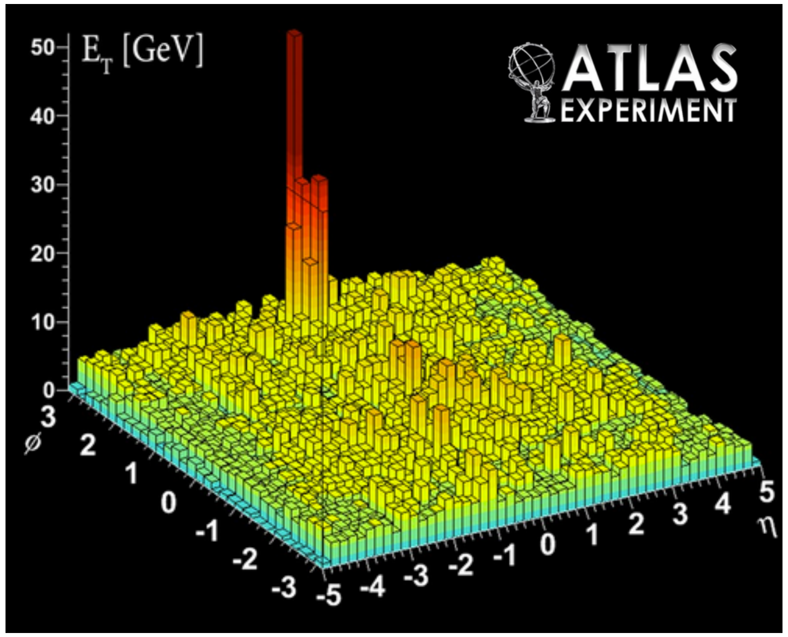
Jet substructure

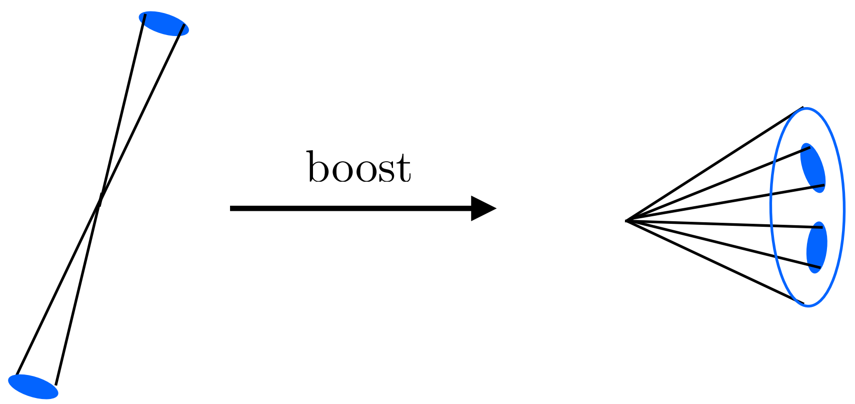
- Design observables to tag boosted objects
  Butterworth, Davison, Rubin, Salam `08
- Quark/gluon discrimination
- Search for BSM physics
- Probe in heavy-ion collisions
- Precision QCD studies …



Chien, Vitev `14

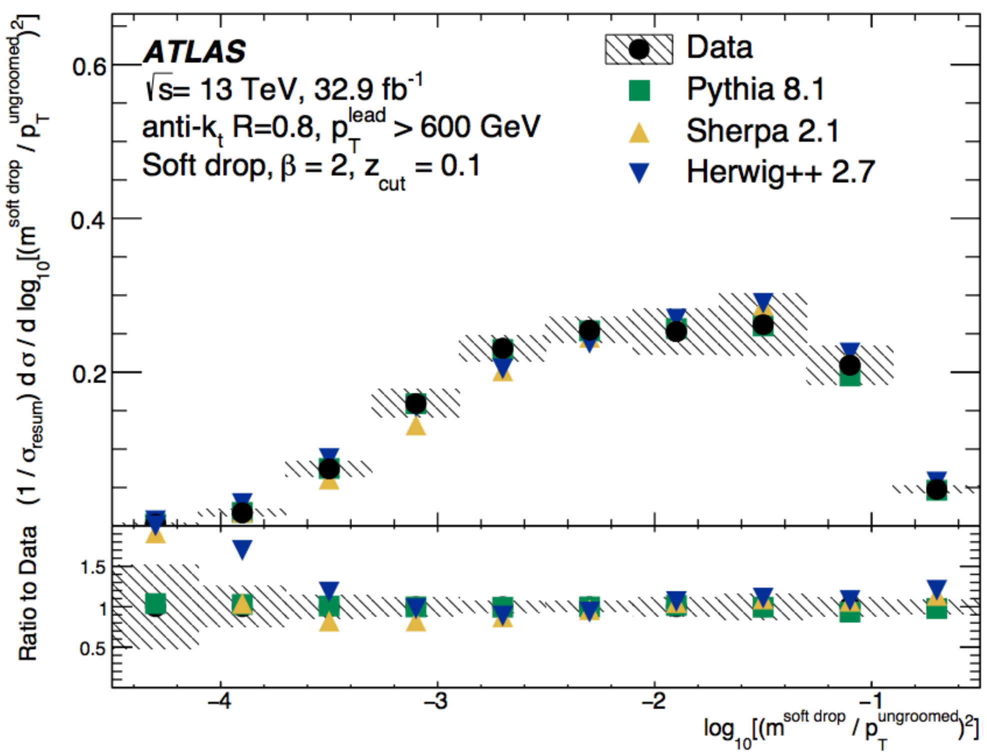




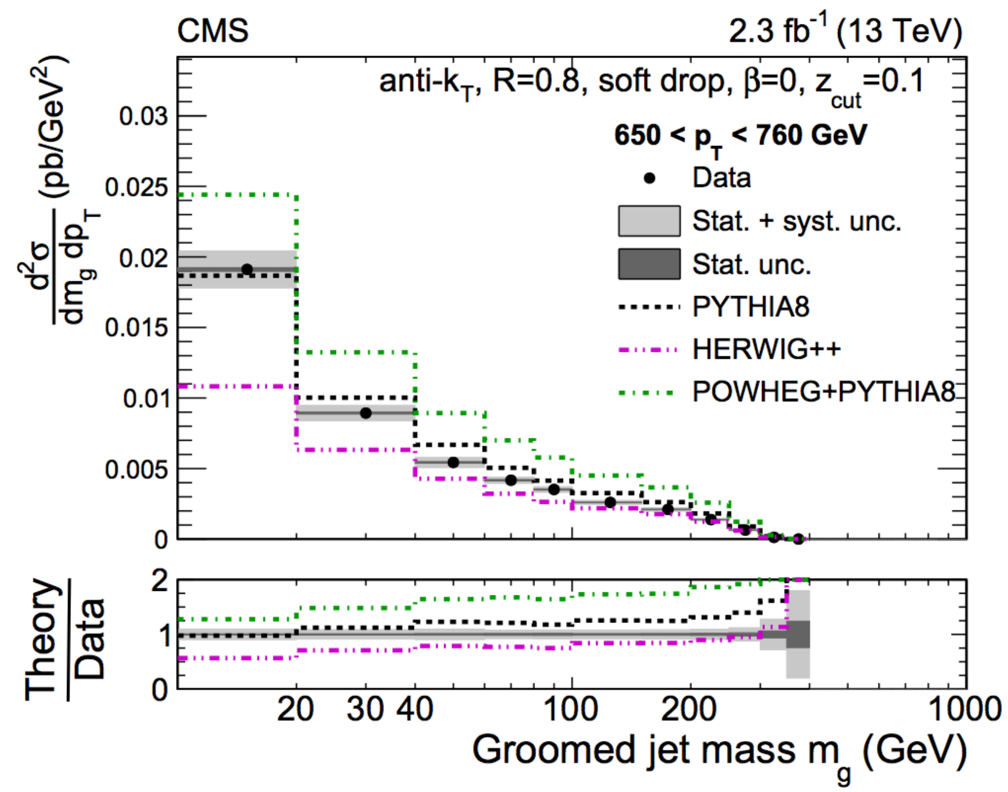


Jet substructure as a tool for precision QCD studies

- The soft drop groomed jet mass



ATLAS, PRL 121 (2018) 092001



CMS, JHEP 1811 (2018) 113

- Extraction of the QCD strong coupling constant

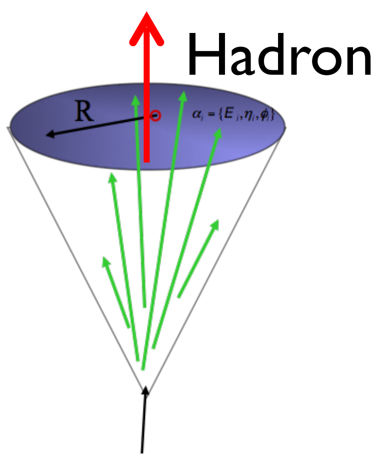
  Les Houches `17

- Three theory calculations for the LHC *Frye, Larkoski, Schwartz, Yan `16, Marzani, Schunk, Soyez `17 Kang, Lee, Liu, FR `18*

- e^+e^- *Baron, Marzani, Theeuwes `18, Kardos, Somogyi, Trocsanyi `18* ⟶ *See talk by Gabor Somogyi's talk*

Jet substructure as a tool for precision QCD studies

- Extraction of the QCD strong coupling constant
  Les Houches `17
- Fragmentation functions *Anderle, Kaufmann, FR, Stratmann, Vitev `16*

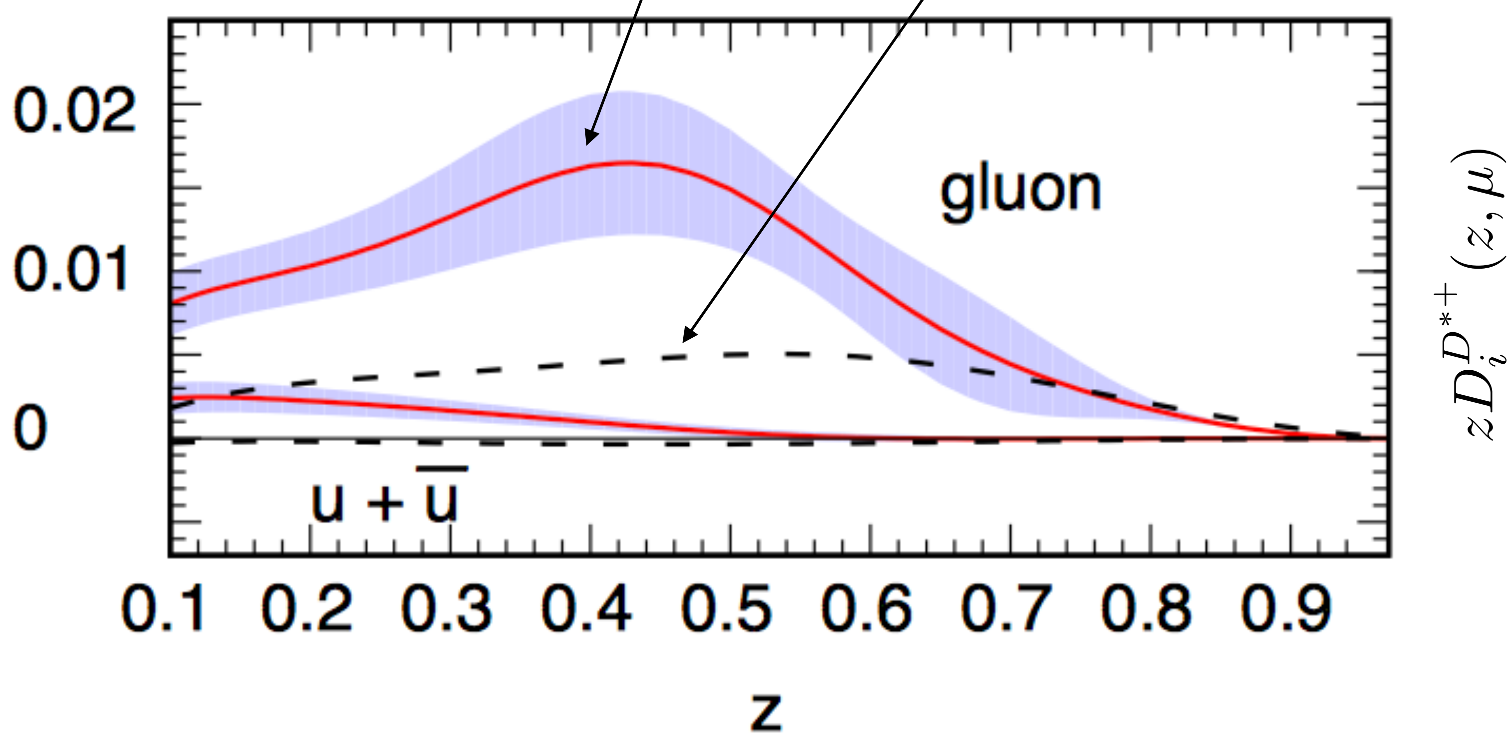


$z = p_T^h / p_T$

longitudinal momentum structure

Global fit with jet substructure data

Kneesch, Kniehl, Kramer, Schienbein `08



- Transverse structure TMDFFs

Jet substructure as a tool for precision QCD studies

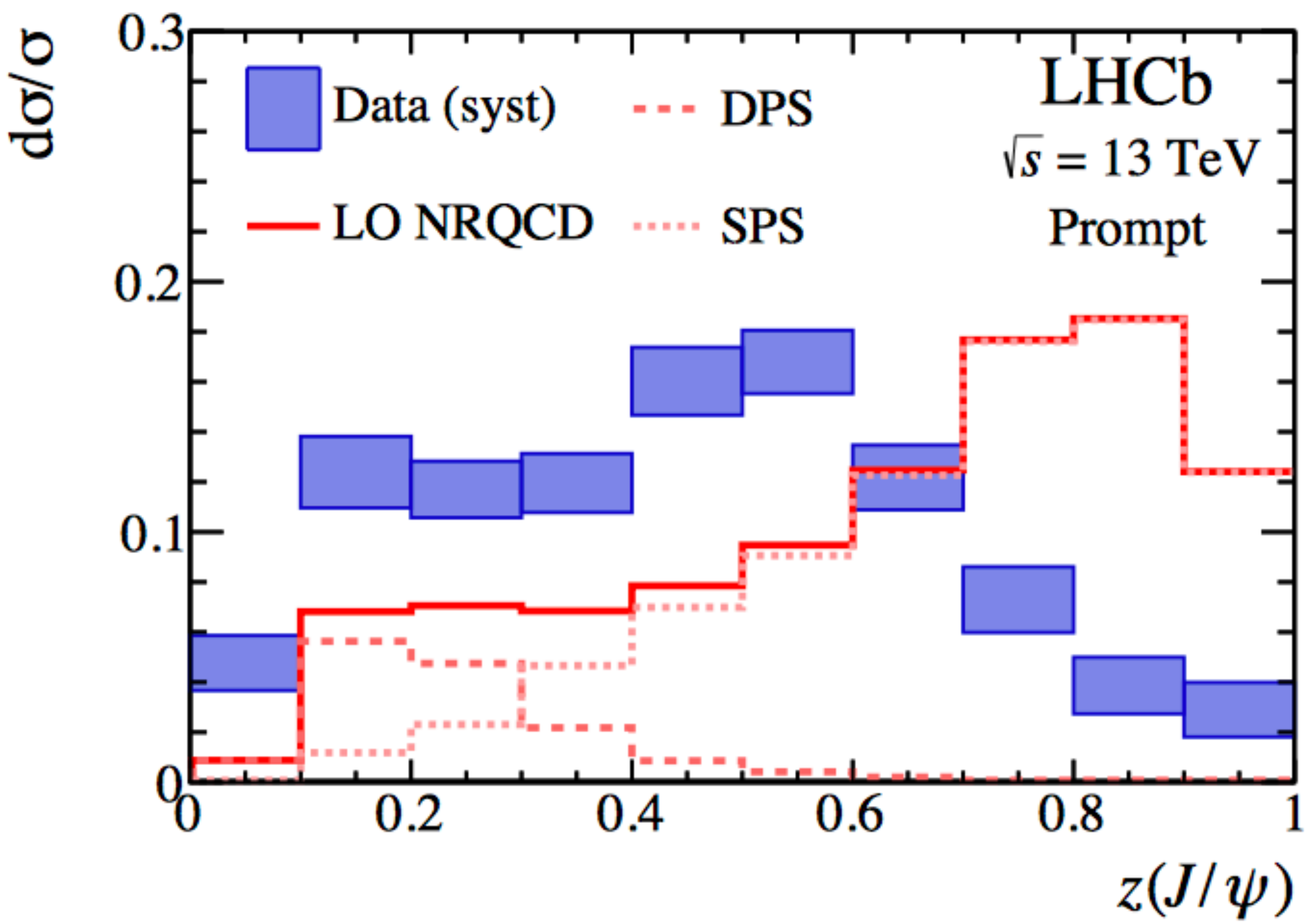
- Extraction of the QCD strong coupling constant

  Les Houches `17

- Fragmentation functions

- Quarkonium

  LHCb, PRL 118 (2017) 192001
  CMS-PAS-HIN-18-012



Jet substructure as a tool for precision QCD studies

- Extraction of the QCD strong coupling constant

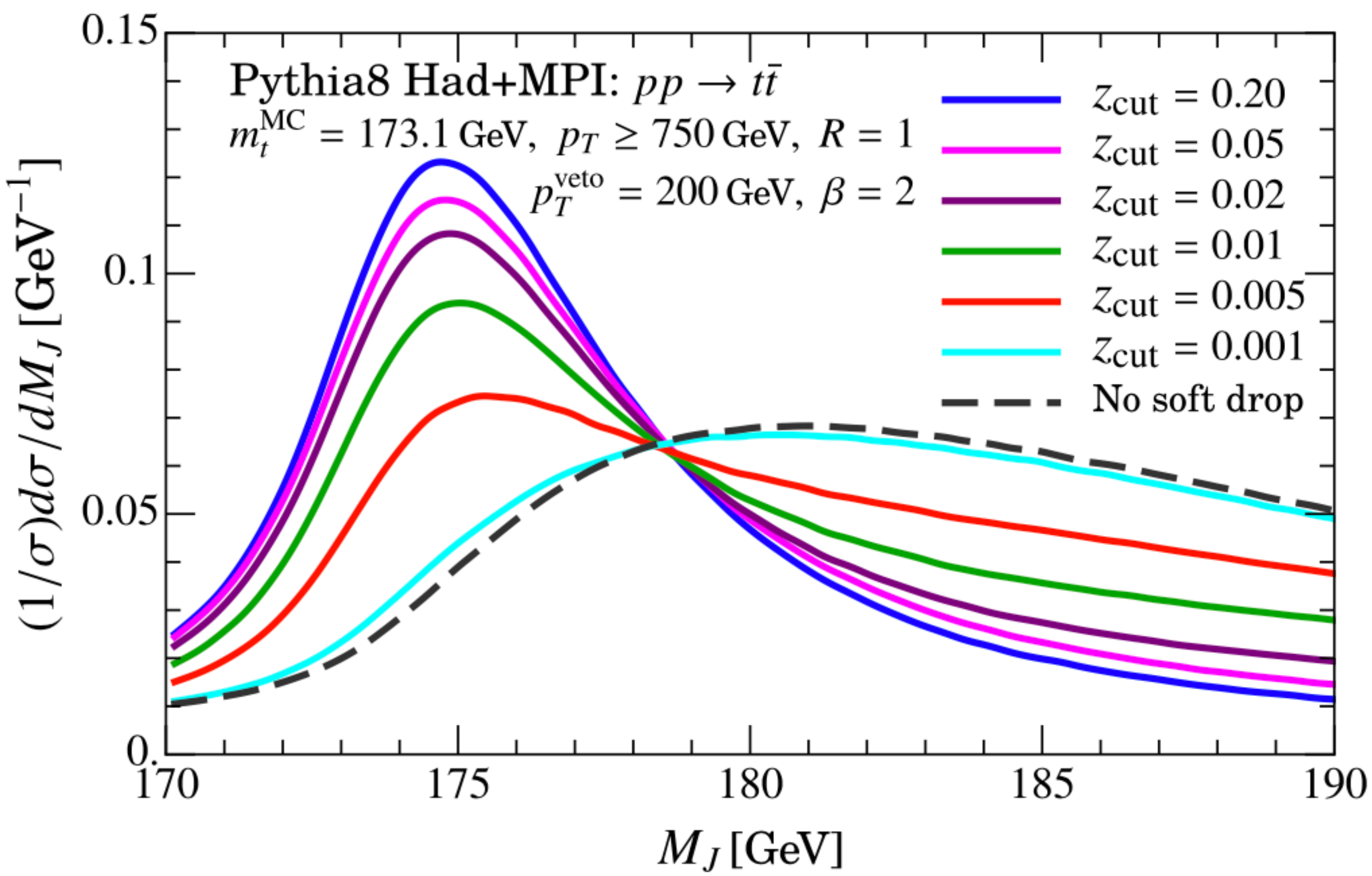
  Les Houches `17

- Fragmentation functions

- Quarkonium

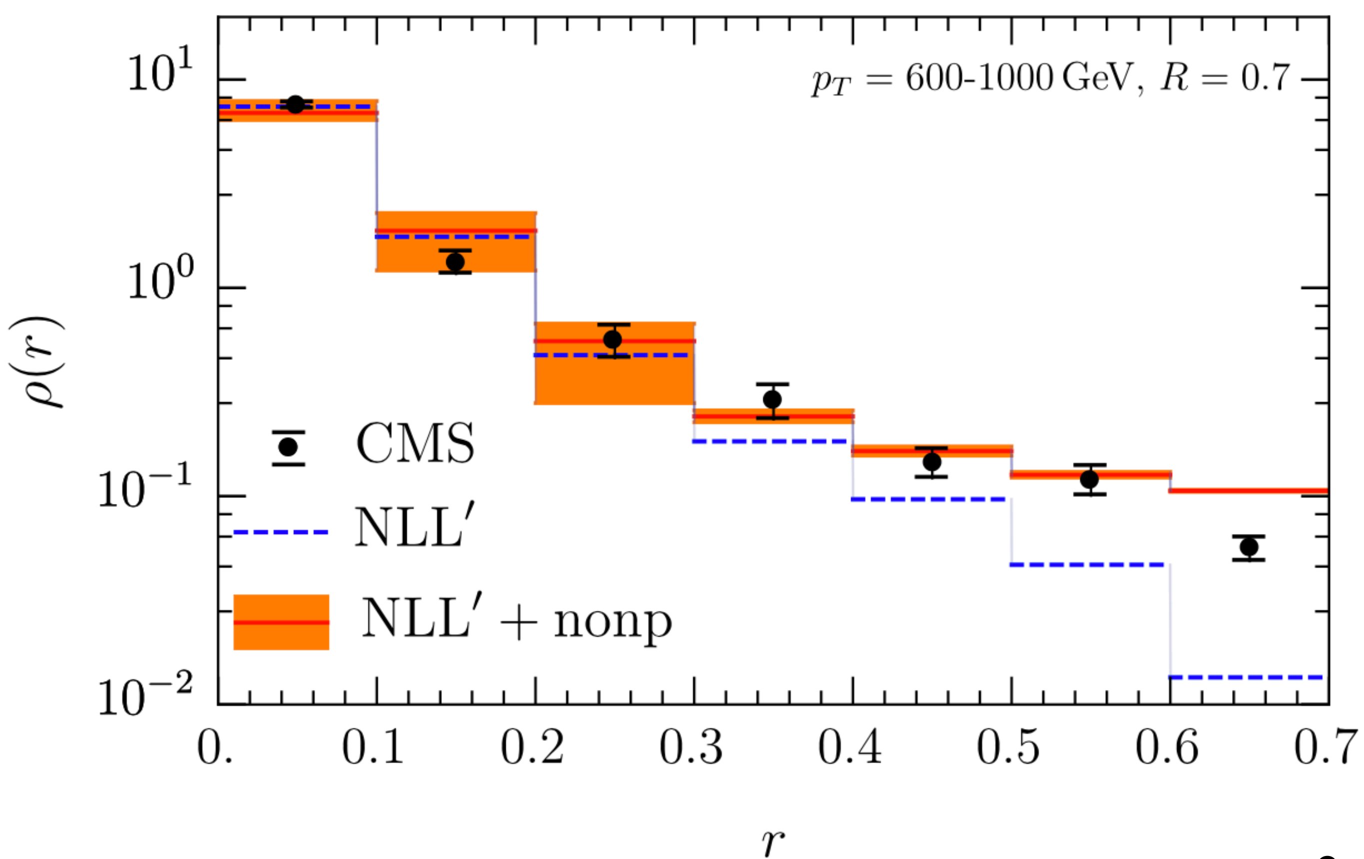
- Top quark mass

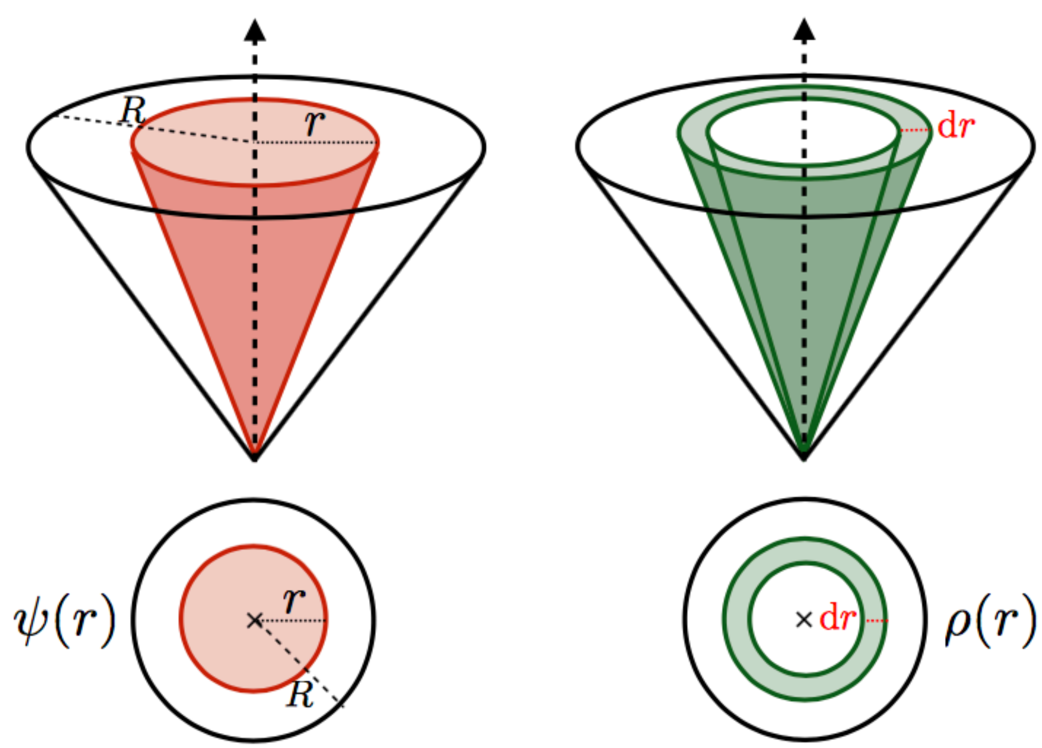
  Hoang, Mantry, Pathak, Stewart `17



Jet substructure as a tool for precision QCD studies

- Extraction of the QCD strong coupling constant
  Les Houches `17
- Fragmentation functions
- Quarkonium
- Top quark mass
  Hoang, Mantry, Pathak, Stewart `17
- Tuning of MCs, e.g. jet shape at NLL
  Cal, FR, Waalewijn `19





ATLAS, PRD 83 (2011) 052003,
CMS, JHEP 06 (2012) 160

Jet substructure as a tool for precision QCD studies

- Extraction of the QCD strong coupling constant

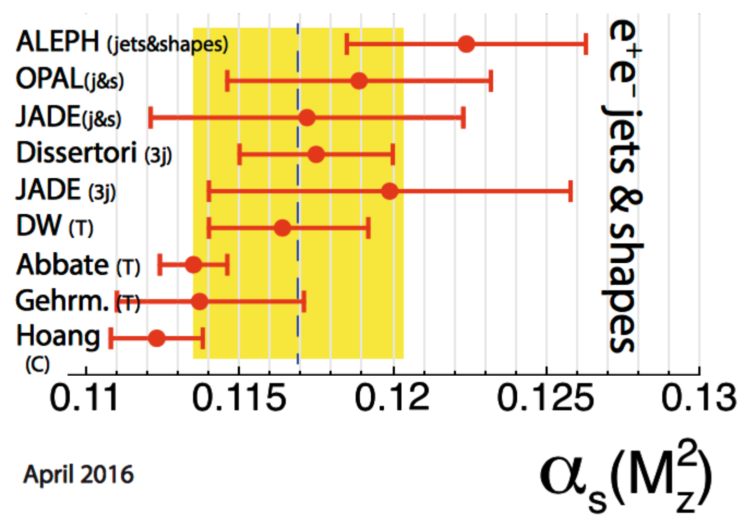
  Les Houches `17

- Hadron collider extraction

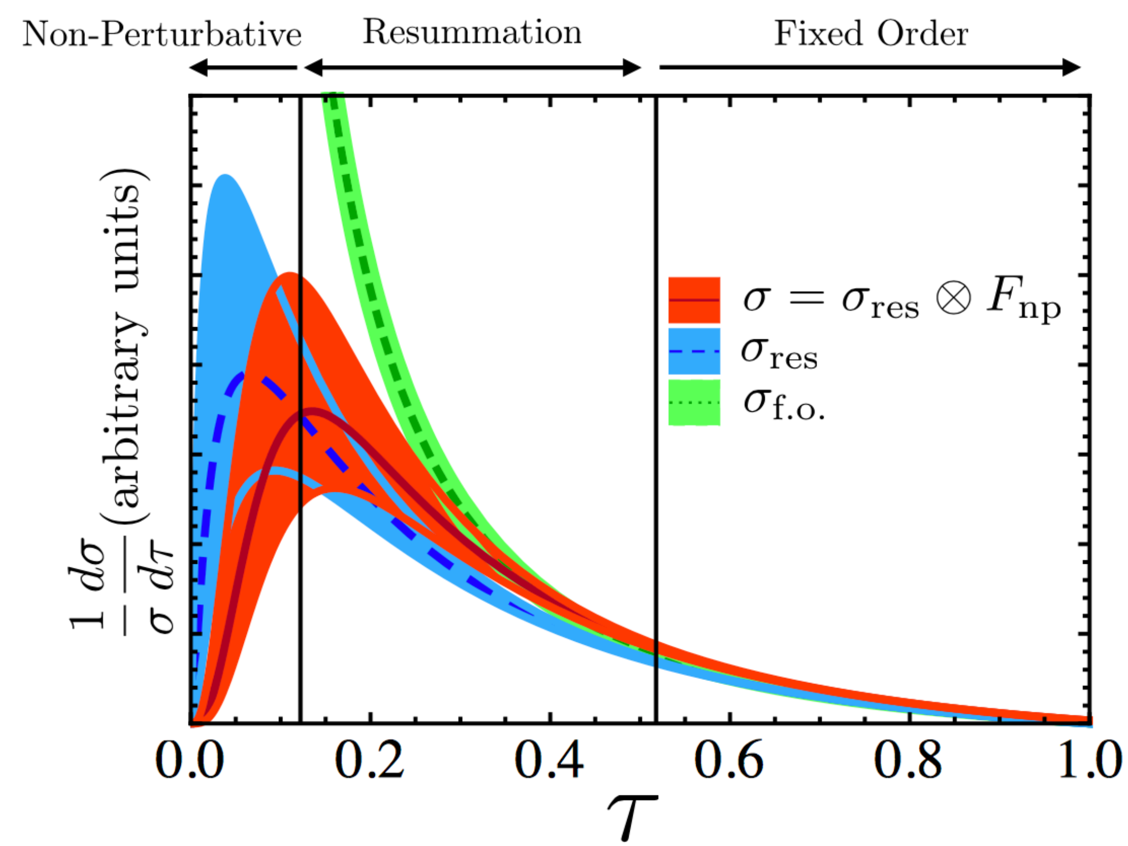
- Similarity to e^+e^- event shapes

  e.g. thrust, C-parameter

  Non-perturbative: Shape function vs. MC



$\alpha_s(M_Z) = 0.1169 \pm 0.0034$



Larkoski, Moult, Nachman `17

- Very challenging for both theory and experiment

  Current estimate ~10% *Les Houches `17*

Outline

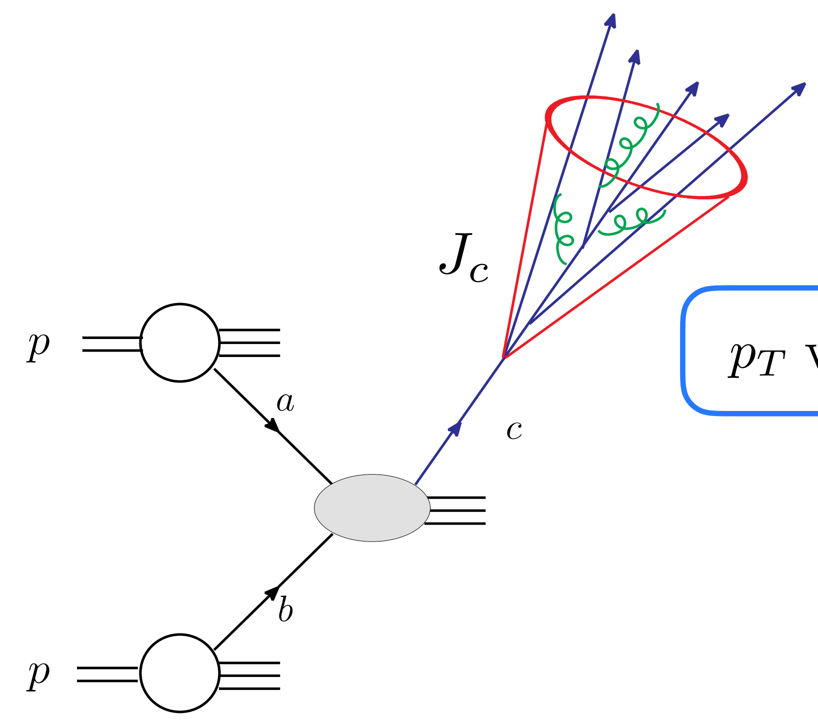
- Introduction
- Groomed jet substructure observables at the LHC
- Determination of the QCD coupling
- Conclusions

QCD factorization

- Inclusive jet production $pp \to \mathrm{jet} + X$

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H^c_{ab} \otimes J_c \quad + \mathcal{O}(R^2)$$

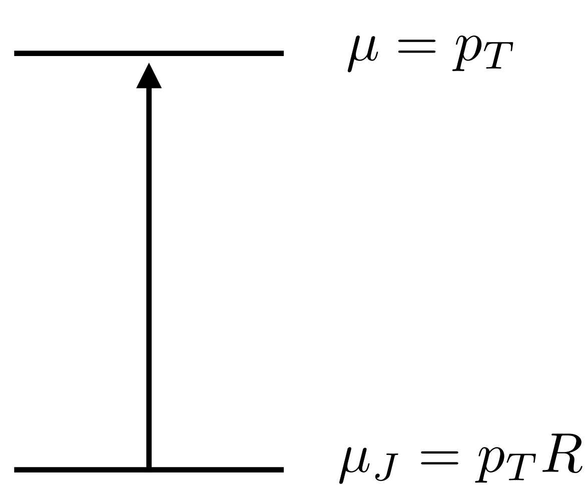
perturbatively calculable



p_T vs. $p_T\,R$

$$\mu \frac{d}{d\mu} J_i = \sum_j P_{ji} \otimes J_j$$

- Resummation of $\alpha_s^n \ln^n R$
- Scale dependence for small R



Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
Dai, Kim, Leibovich `16
Liu, Moch, FR `18

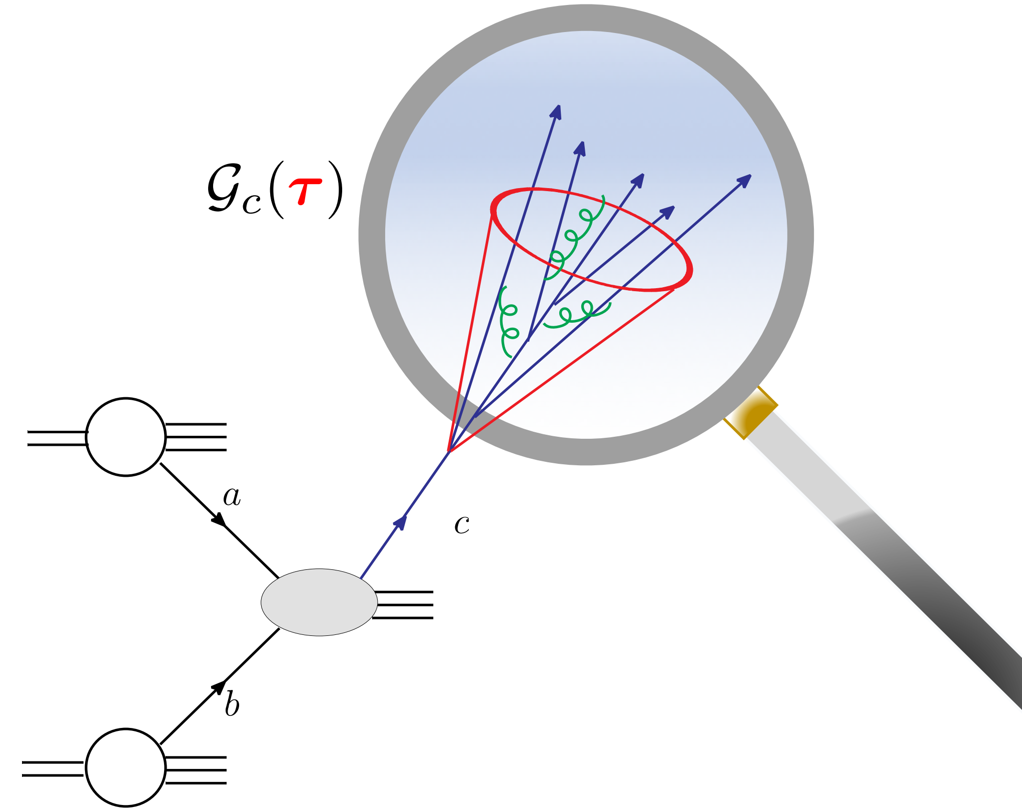
QCD factorization

- Inclusive jet production $pp \to \text{jet} + X$

$$\frac{d\sigma^{pp\to \text{jet}X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{J_c} + \mathcal{O}(R^2)$$

- Jet substructure $\boldsymbol{\tau}$

$$\frac{d\sigma^{pp\to (\text{jet}\,\boldsymbol{\tau})X}}{dp_T d\eta \boldsymbol{d\tau}} = \sum_{abc} f_a \otimes f_b \otimes H_{ab}^c \otimes \boxed{\mathcal{G}_c(\boldsymbol{\tau})} + \mathcal{O}(R^2)$$



- $\ln R$ resummation
- Definition of quark-gluon fractions beyond LO
- Mostly analytical calculations

Dasgupta, Dreyer, Salam, Soyez `15
Kaufmann, Mukherjee, Vogelsang `15
Kang, FR, Vitev `16
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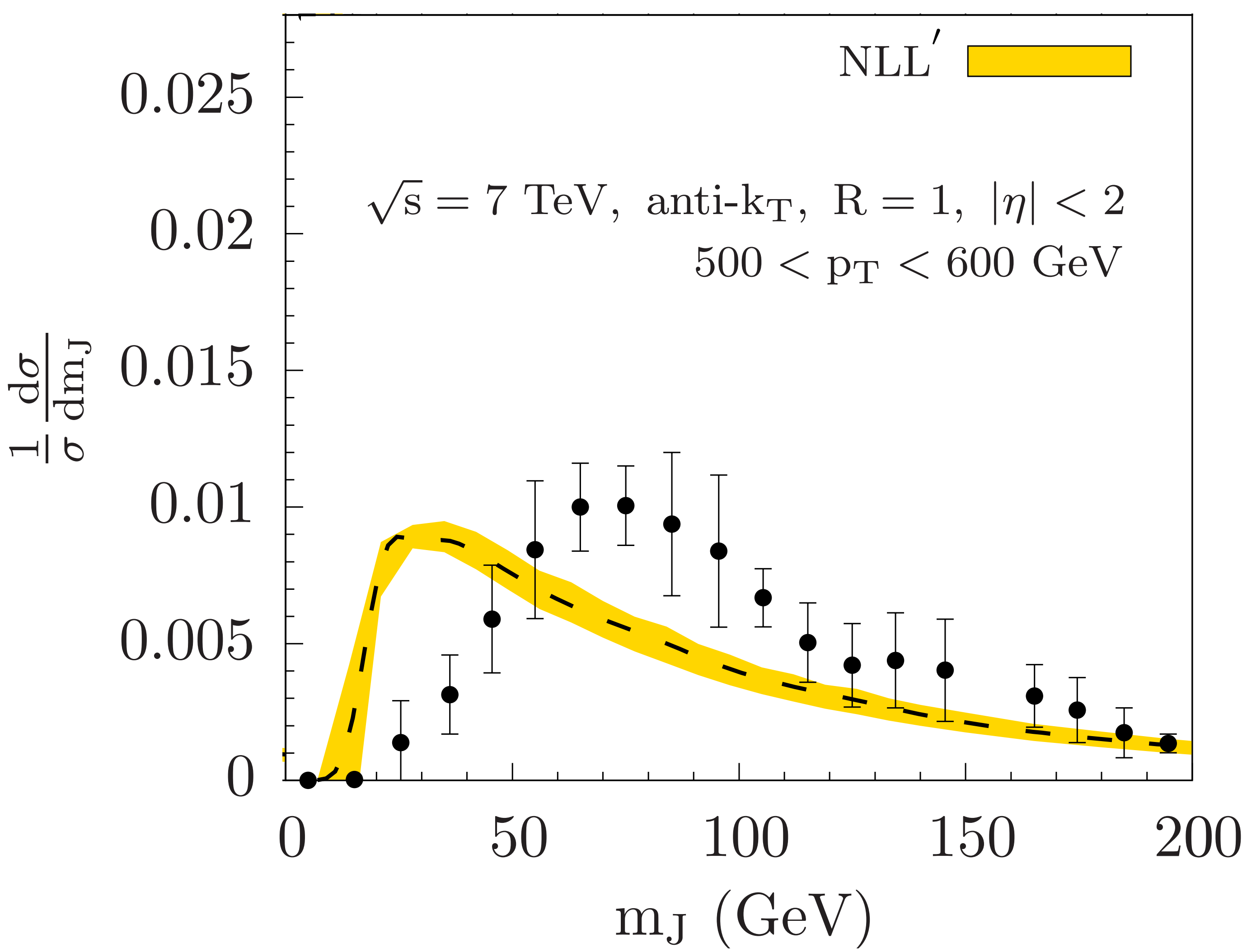
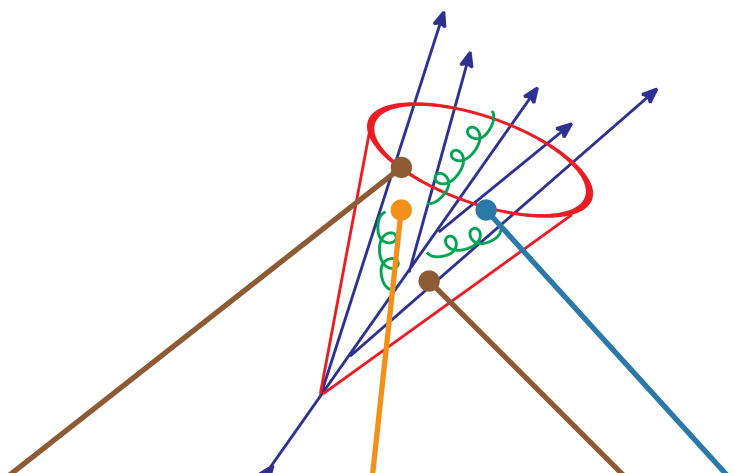
Jet mass distributions

Kang, Lee, Liu, FR `18

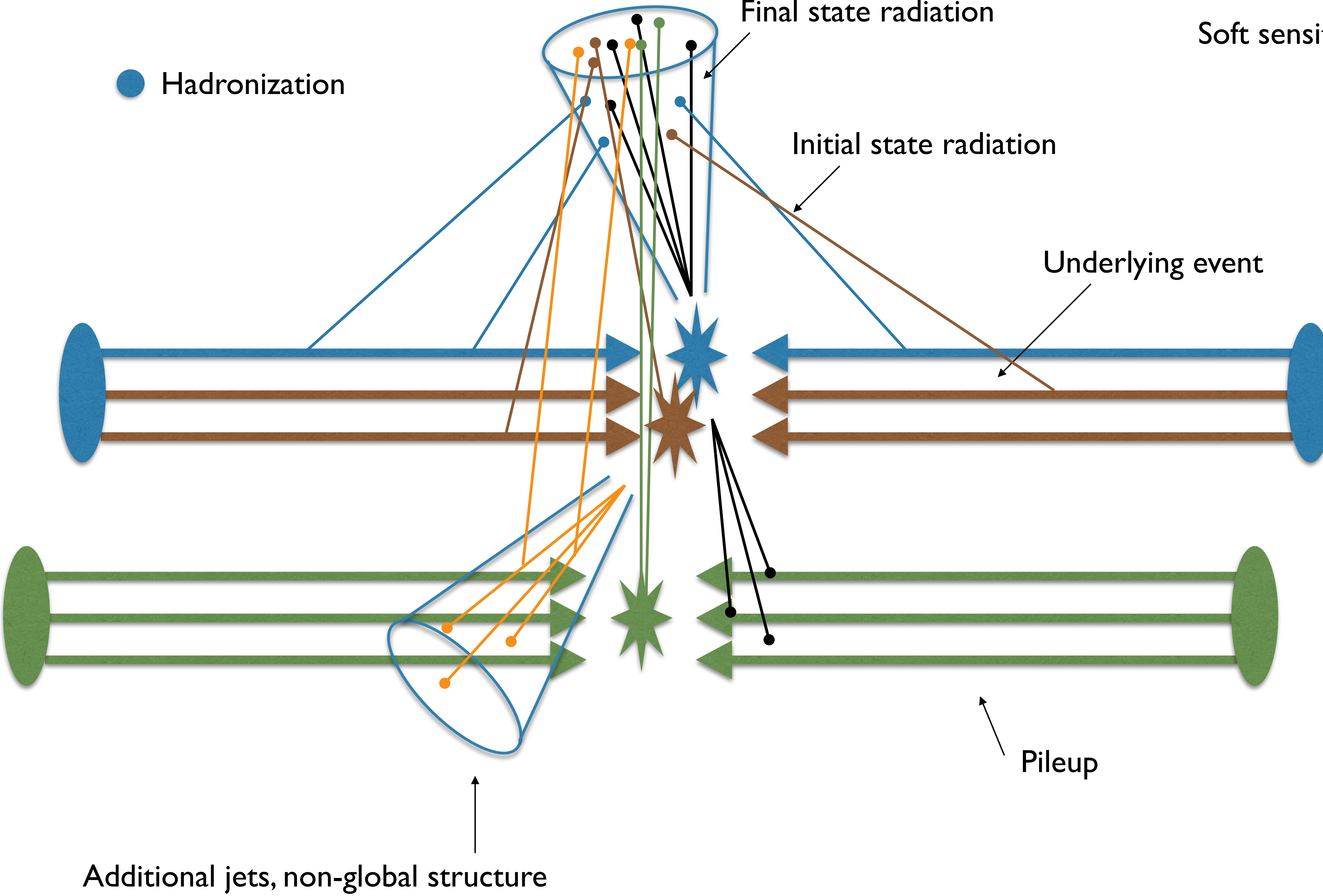
ATLAS, JHEP 05 (2012) 128





$pp \to \text{jet} + X$

Soft sensitivity

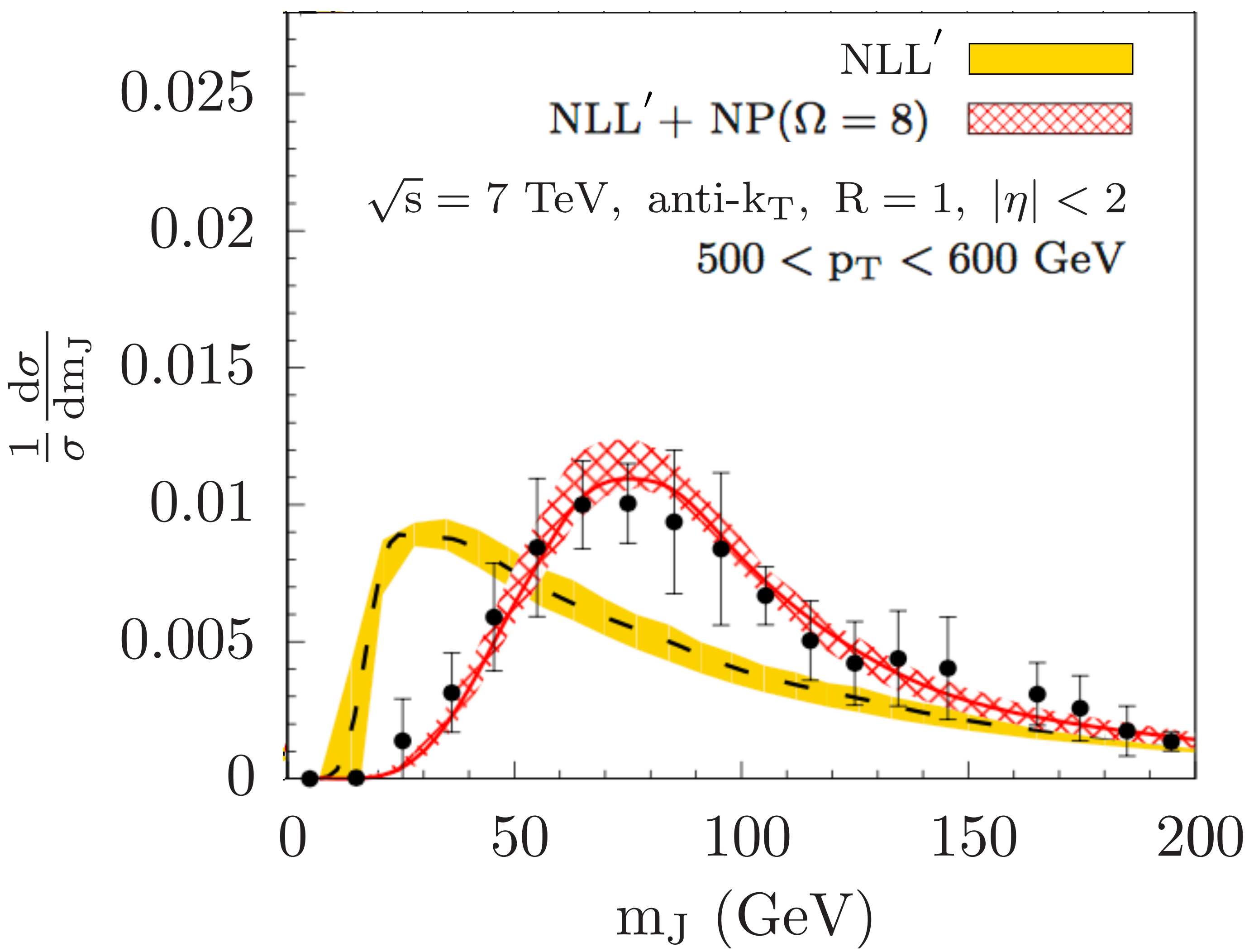


adapted from M. Schwartz `17

Jet mass distributions

Kang, Lee, Liu, FR `18

ATLAS, JHEP 05 (2012) 128



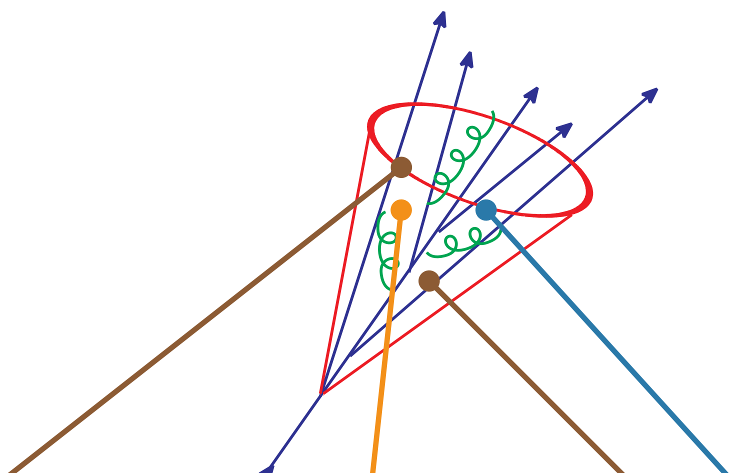
Capture hadronization and MPI using a shape function

$$F_i(k) = \frac{4k}{\Omega^2}\exp(-2k/\Omega)$$

$$\int_0^\infty dk\, k\, F_i(k) = \Omega \qquad \text{and normalized}$$

$$d\sigma = d\sigma^{\rm pert} \otimes F$$

For quarks there is a relation to thrust for $R \to 0$ in terms of the energy flow operator



Lee, Sterman `07
Dasgupta, Magnea, Salam `08
Stewart, Tackmann, Waalewijn `15
Kang, Lee, Stewart `15

Soft drop grooming

Dasgupta, Fregoso, Marzani, Salam `13
Larkoski, Marzani, Soyez, Thaler `14

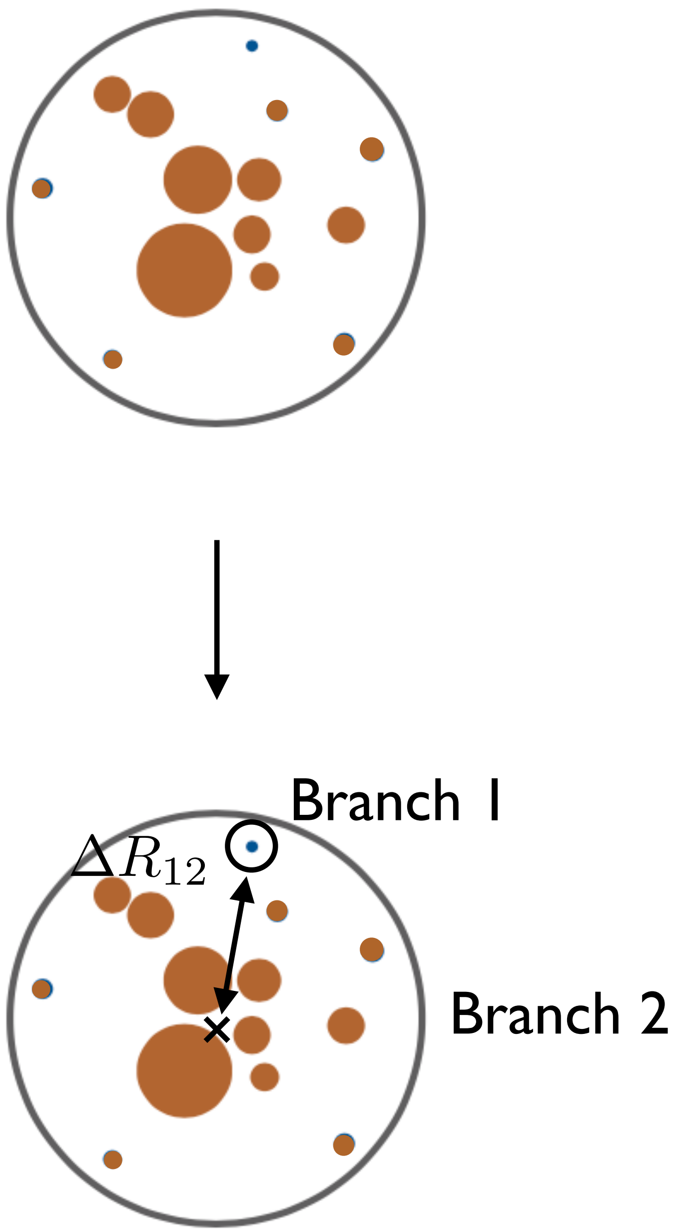
- Recluster jet constituents with the C/A algorithm
- Recursively decluster the jet and remove soft branches that fail the soft drop criterion

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

Geometric distance $\Delta R_{12}^2 = \Delta\eta^2 + \Delta\eta^2$

Soft threshold $z_{\rm cut}$

Angular exponent β



- Non-global logarithms largely removed $\beta = 0$ or power suppressed $\beta > 0$
- See also e.g. trimming, pruning

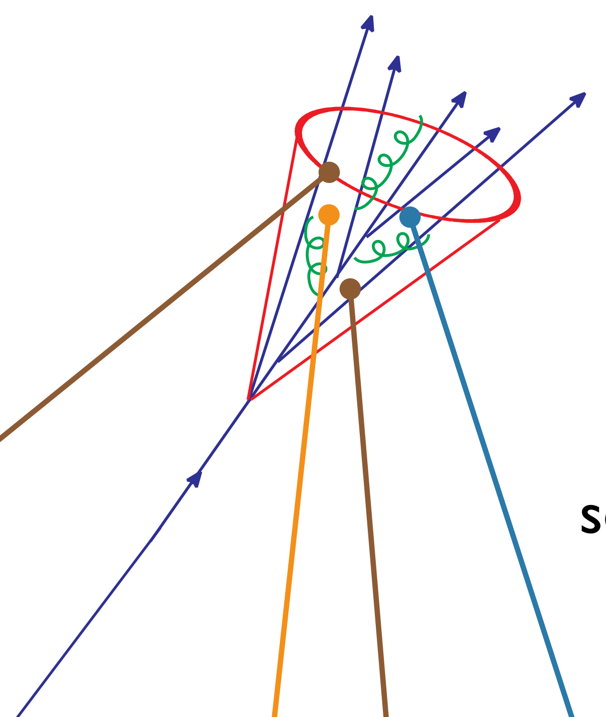
Krohn, Thaler, Wang `10, Ellis, Vermilion, Walsh `10

The soft drop groomed jet mass

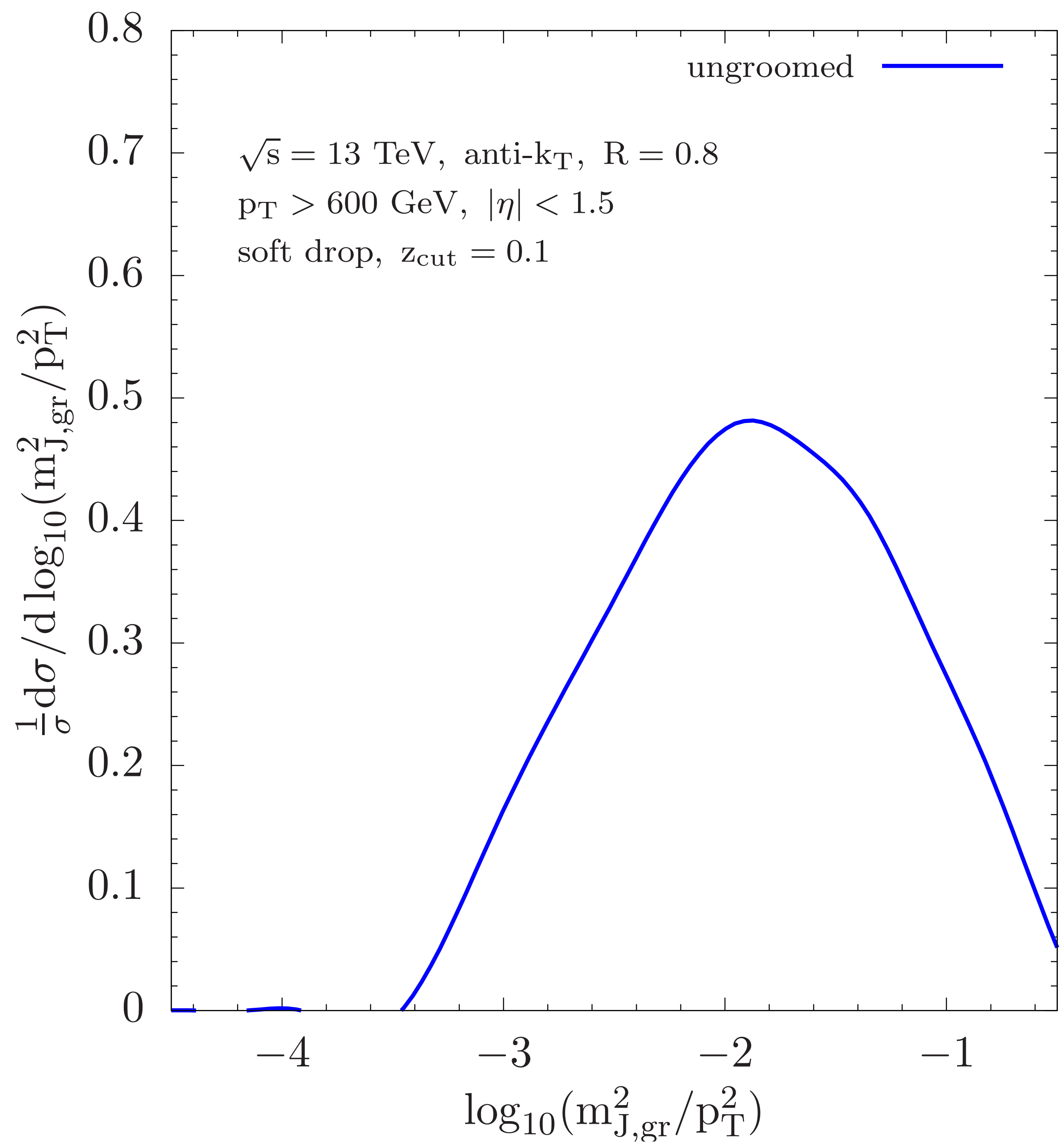
Frye, Larkoski, Schwartz, Yan `16
Marzani, Schunk, Soyez `17
Kang, Lee, Liu, FR `18

- Jet mass $m_J^2 = \left(\sum_{i\in J} p_i\right)^2$
- Reduced sensitivity to UE, NP, ISR …
  Larkoski, Marzani, Soyez, Thaler `14
- Resummation of logarithms in $m_J/p_T,\ R,\ z_{\rm cut}$

$$\frac{\min[p_{T1},p_{T2}]}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$



soft radiation



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Marzani, Schunk, Soyez `17
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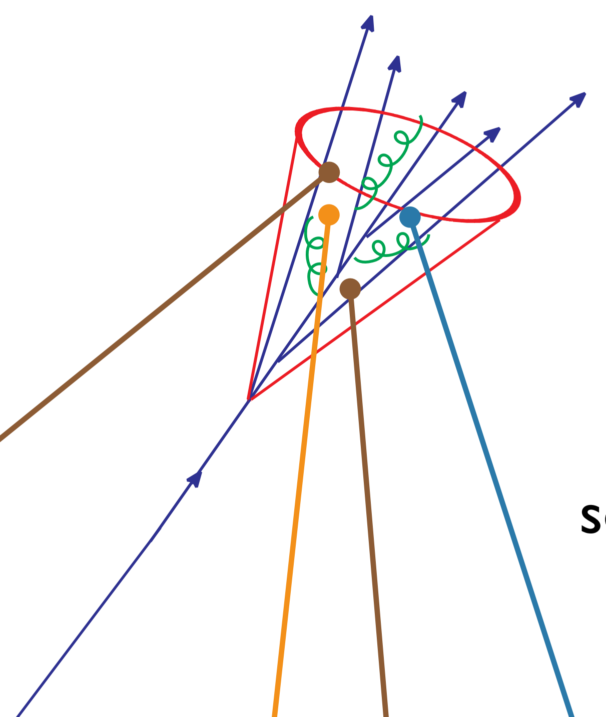

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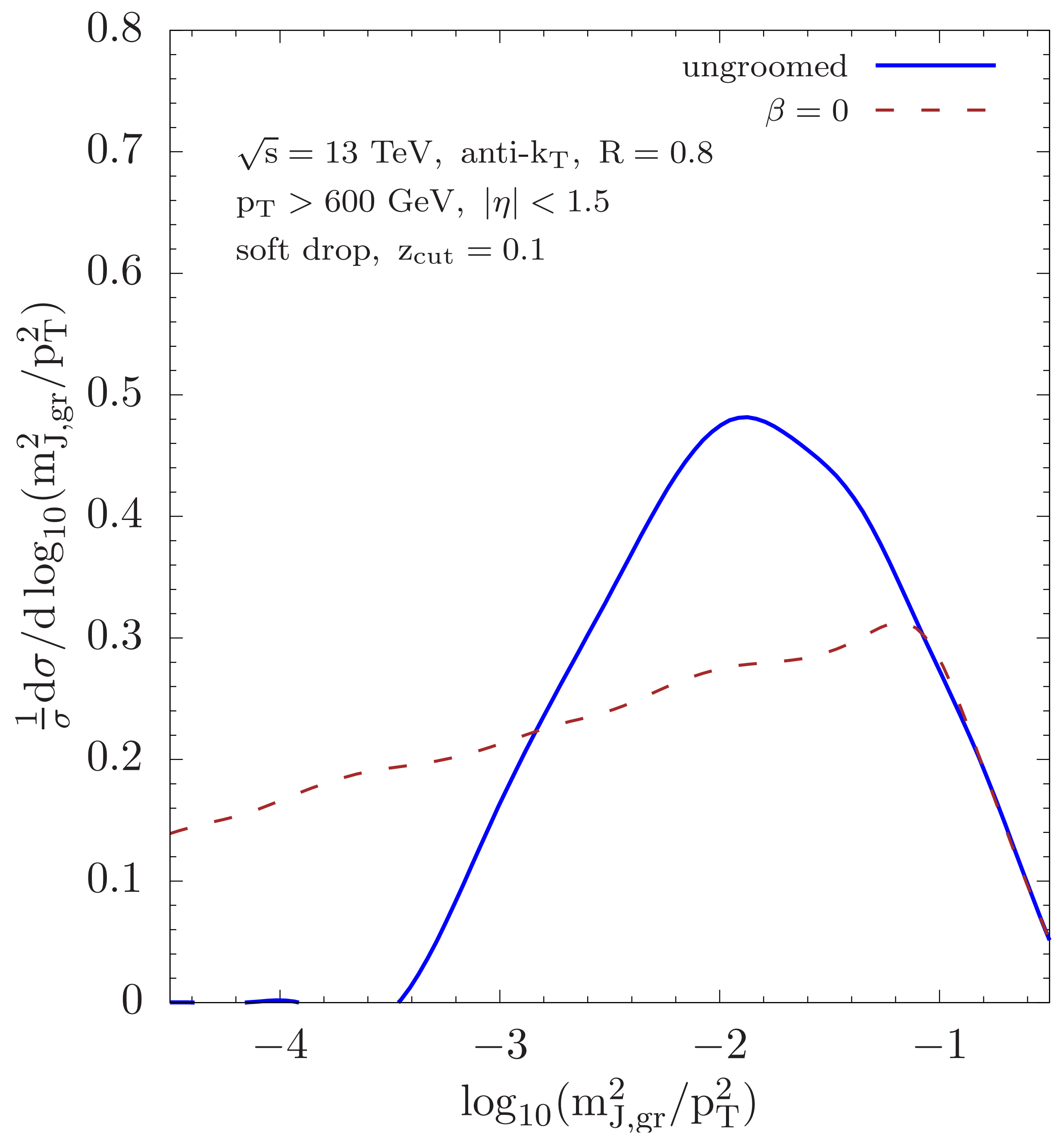

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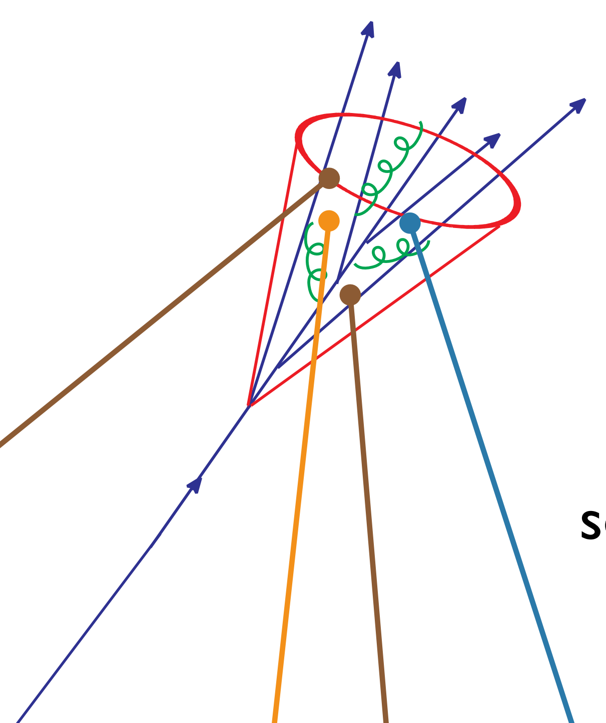

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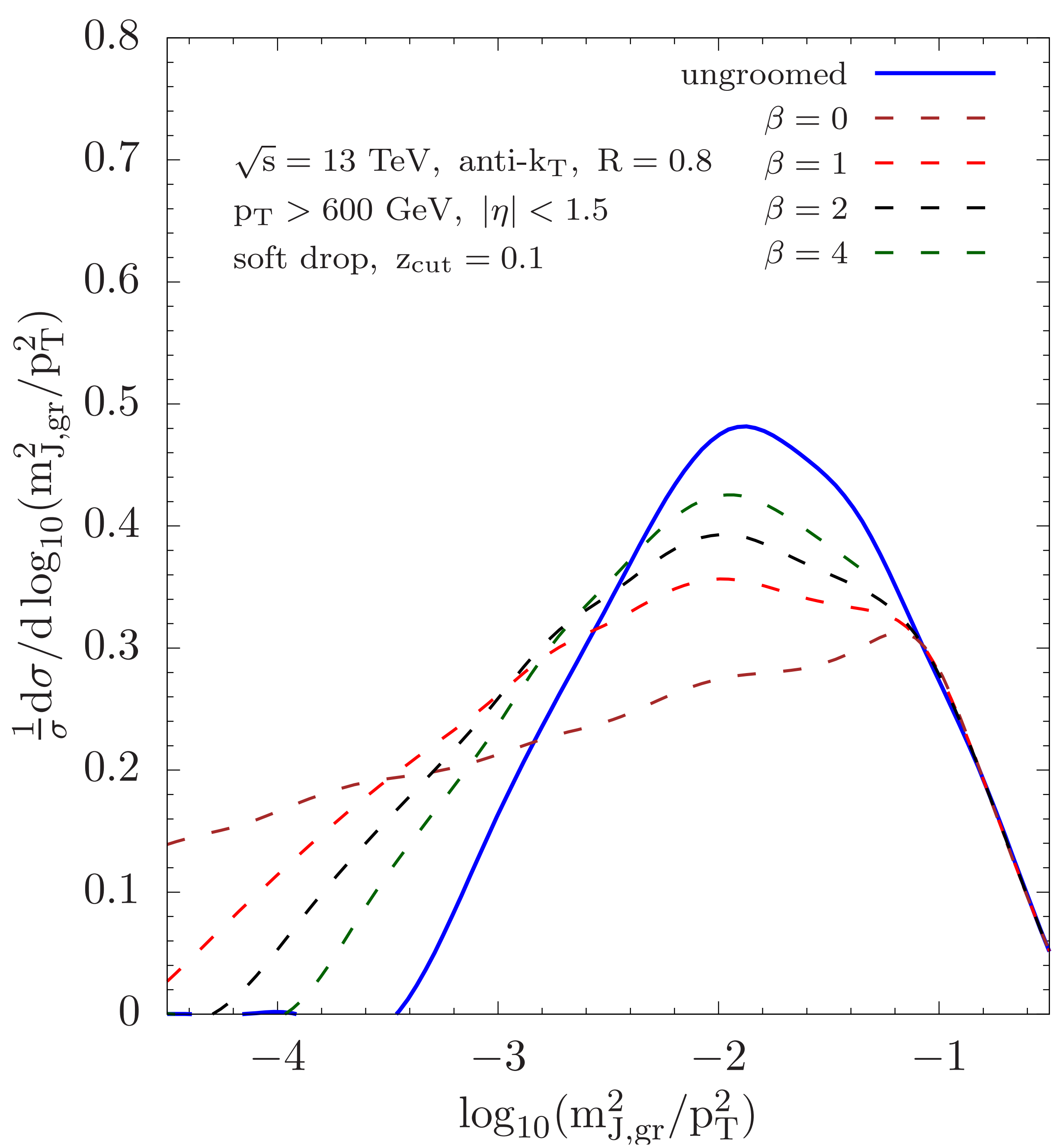


Jet mass distributions

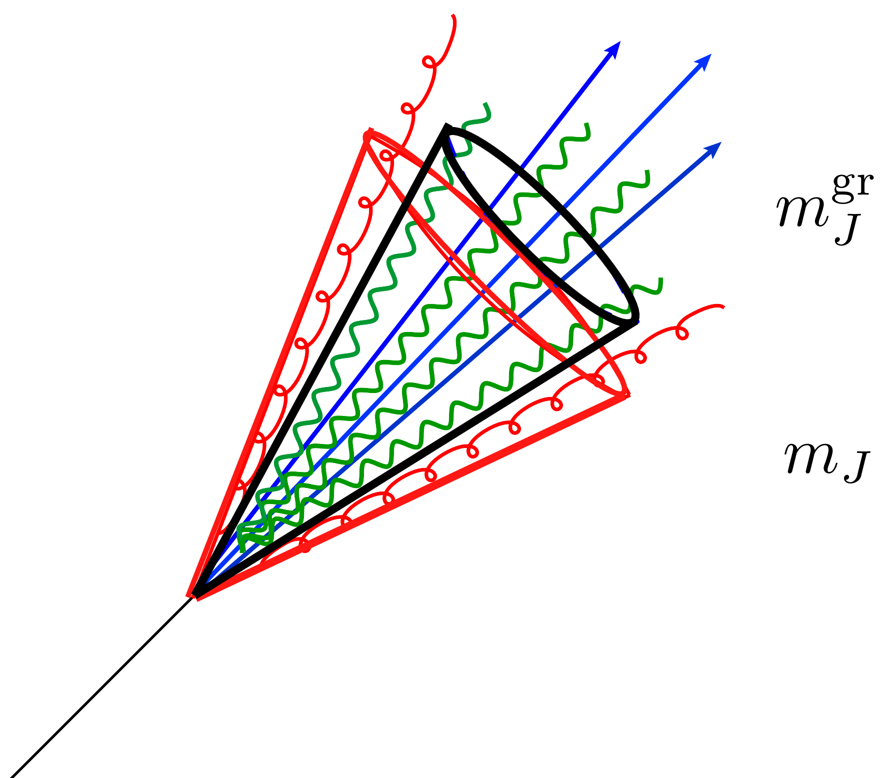
Kang, Lee, Liu, FR `18

- The ungroomed case $R \ll 1,\ \tau/R^2 \ll 1$

$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_i \mathcal{H}_{i\to j}(z, p_T R, \mu)\, C_j(\tau, p_T, \mu) \otimes S_j(\tau, p_T, R, \mu) \qquad \tau = \frac{m_J^2}{p_T^2}$$

- The groomed case $R \ll 1,\ \tau_{\rm gr}/R^2 \ll z_{\rm cut} \ll 1$

$$\mathcal{G}_i^{\rm gr}(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu)\, S_i^{\notin {\rm gr}}(z_{\rm cut} p_T R, \beta, \mu)\, C_i(\tau_{\rm gr}, p_T, \mu) \otimes S_i^{\rm gr}(\tau_{\rm gr}, p_T, R, z_{\rm cut}, \mu)$$



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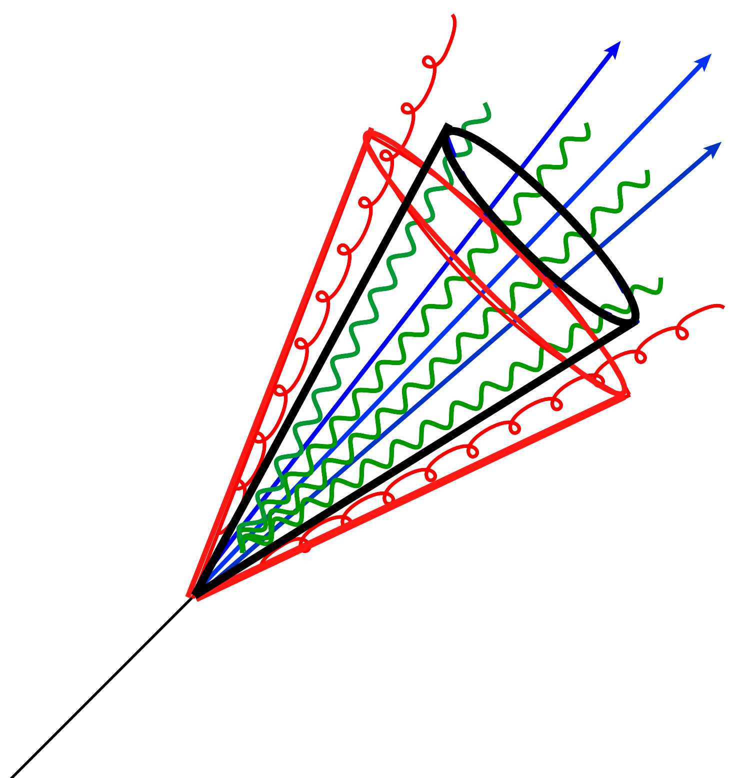
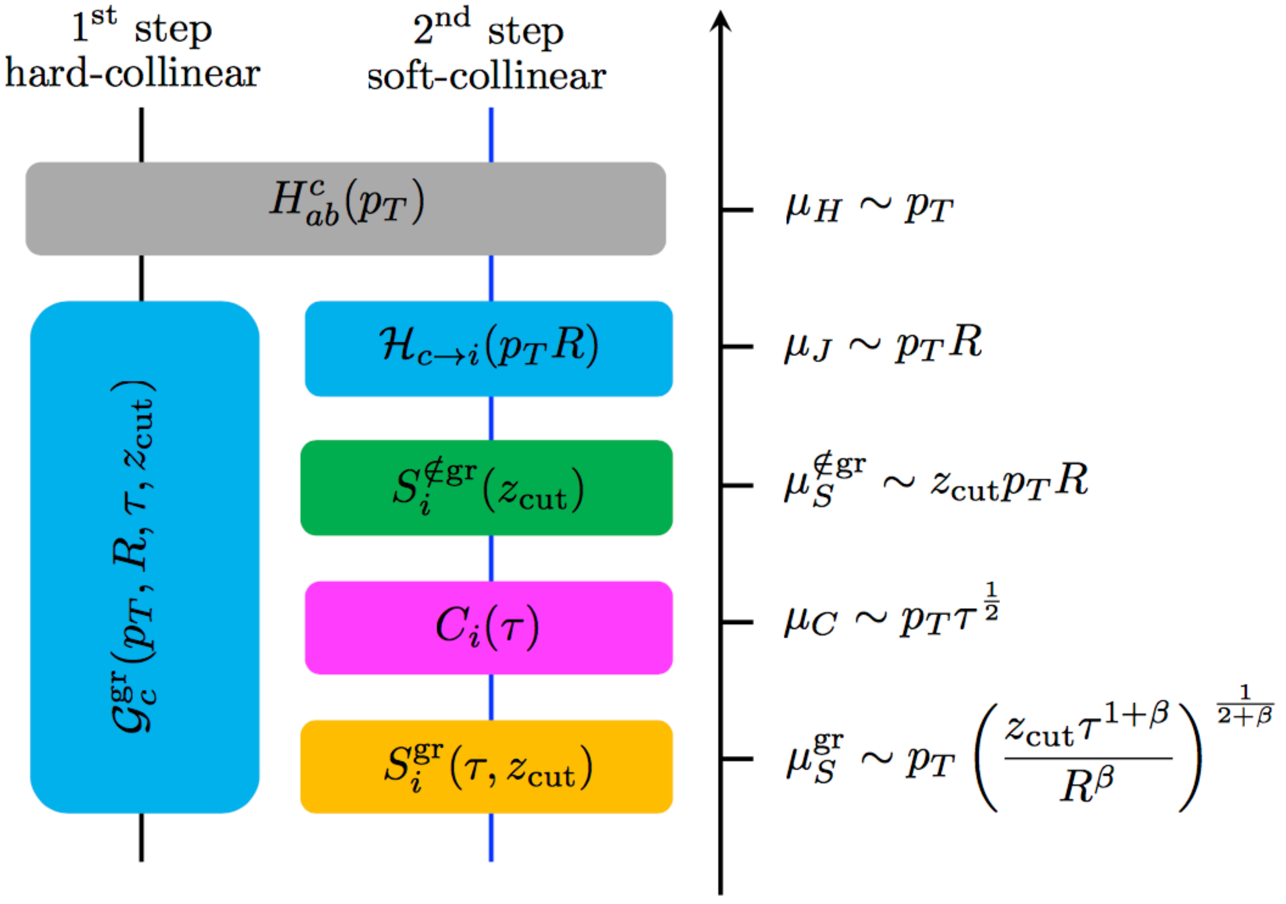
- Resummation of 3 classes of logarithms $\alpha_s^n \ln^n R,\ \alpha_s^n \ln^{2n}(m_J/p_T),\ \alpha_s^n \ln^{2n} z_{\rm cut}$

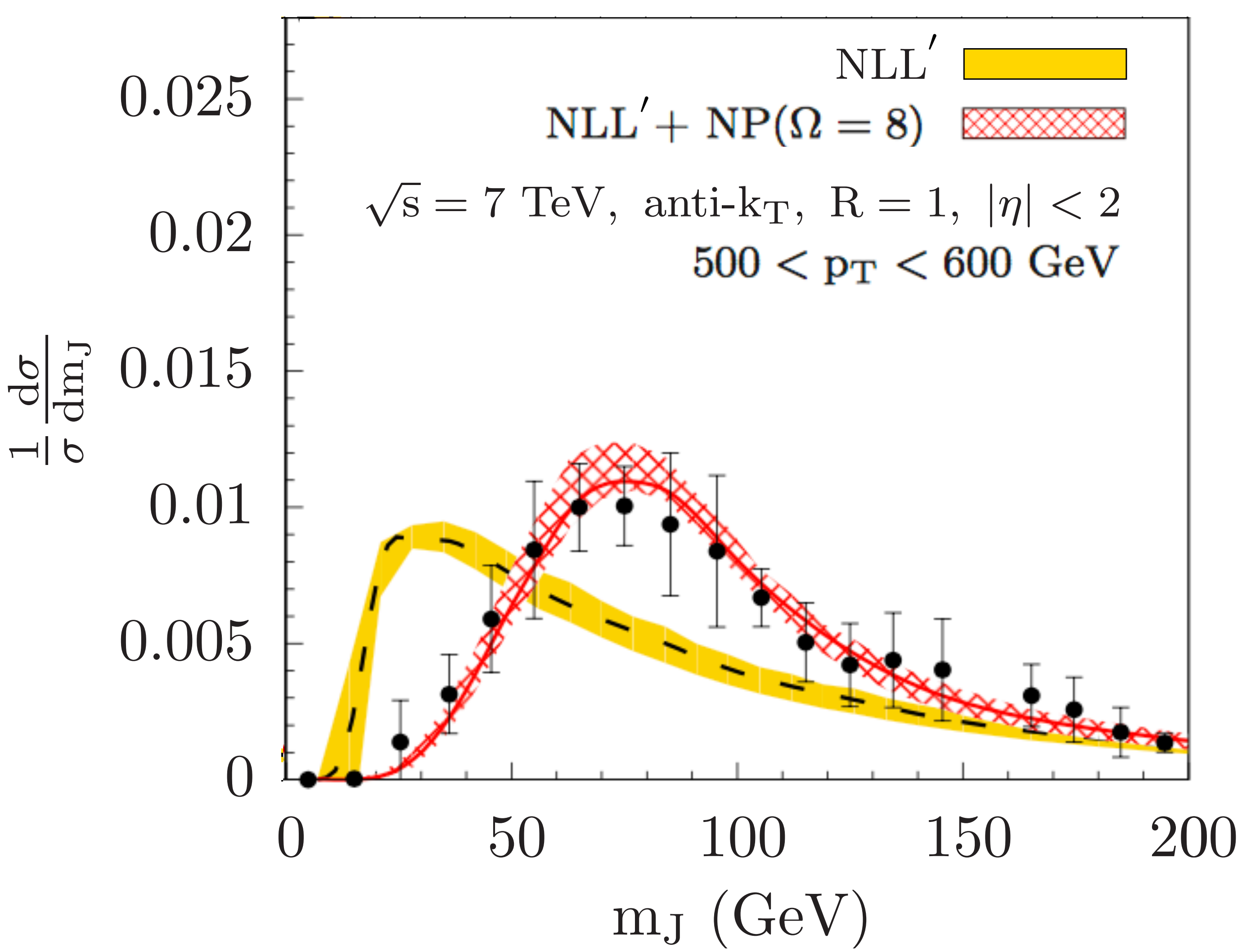




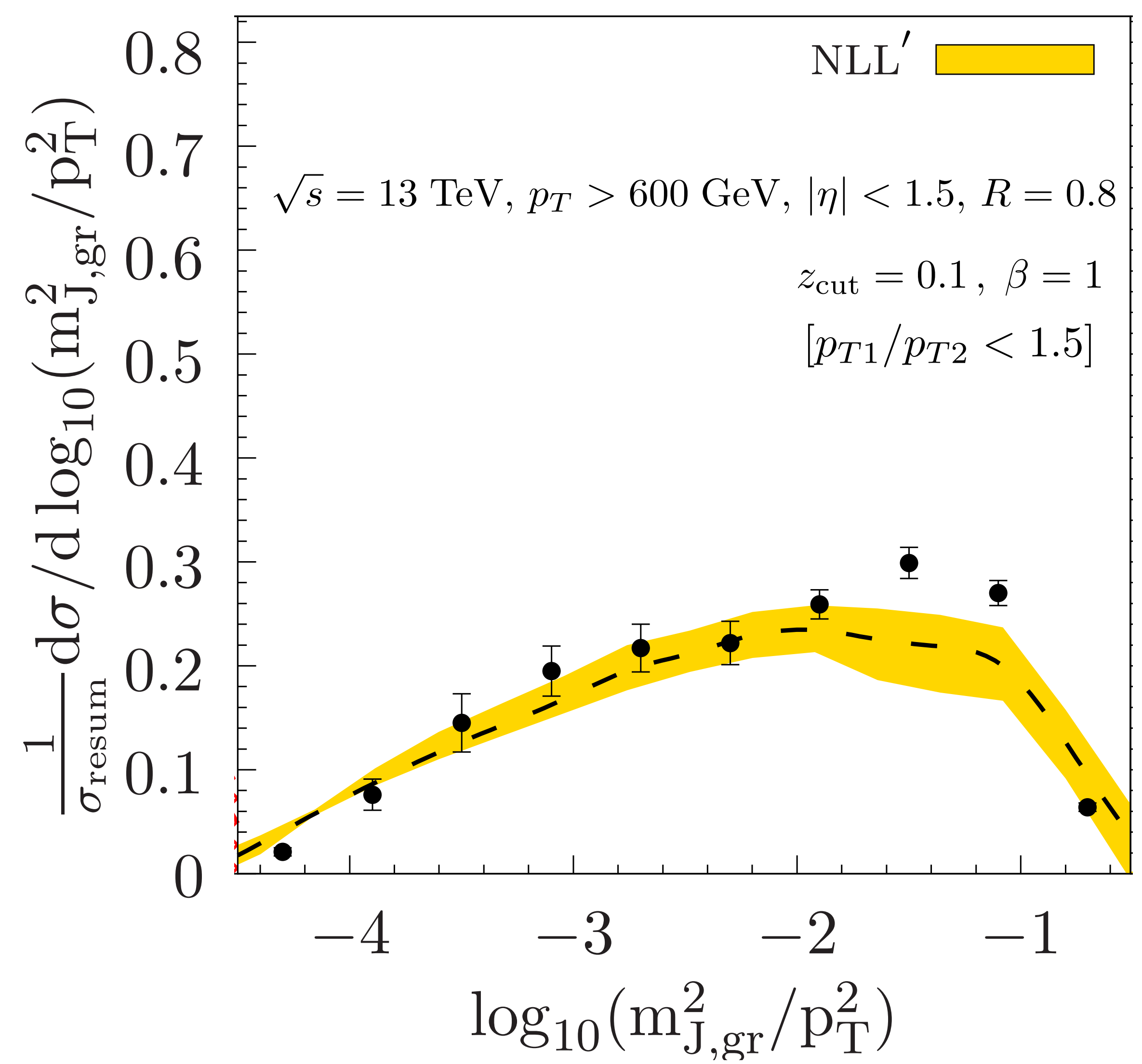
Jet mass distributions

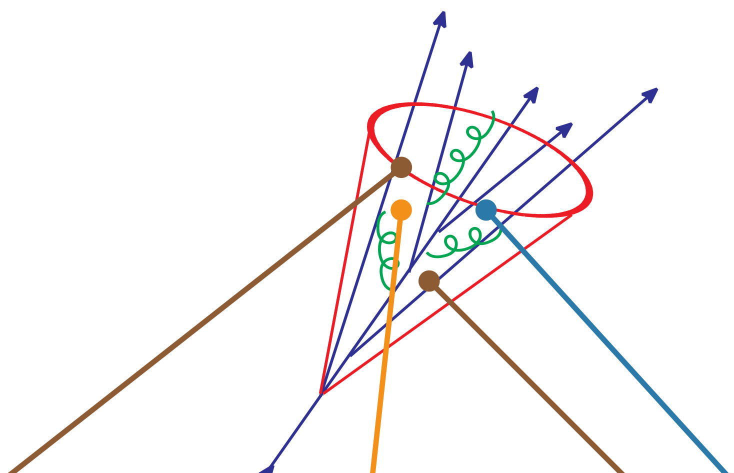
Kang, Lee, Liu, FR `18

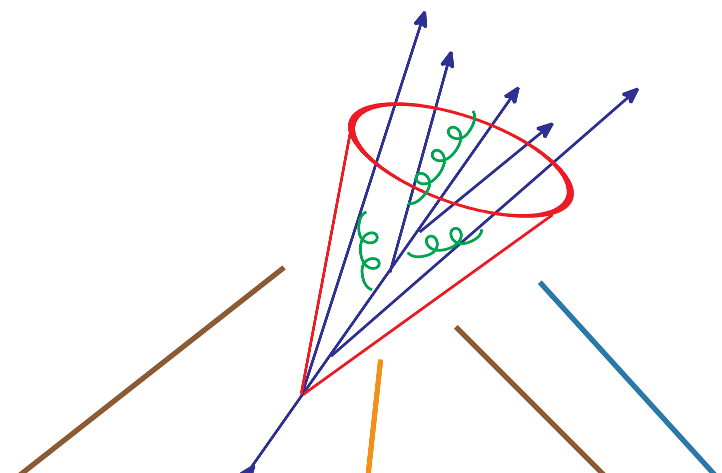
ATLAS, JHEP 05 (2012) 128



ATLAS, PRL 121 (2018) 092001



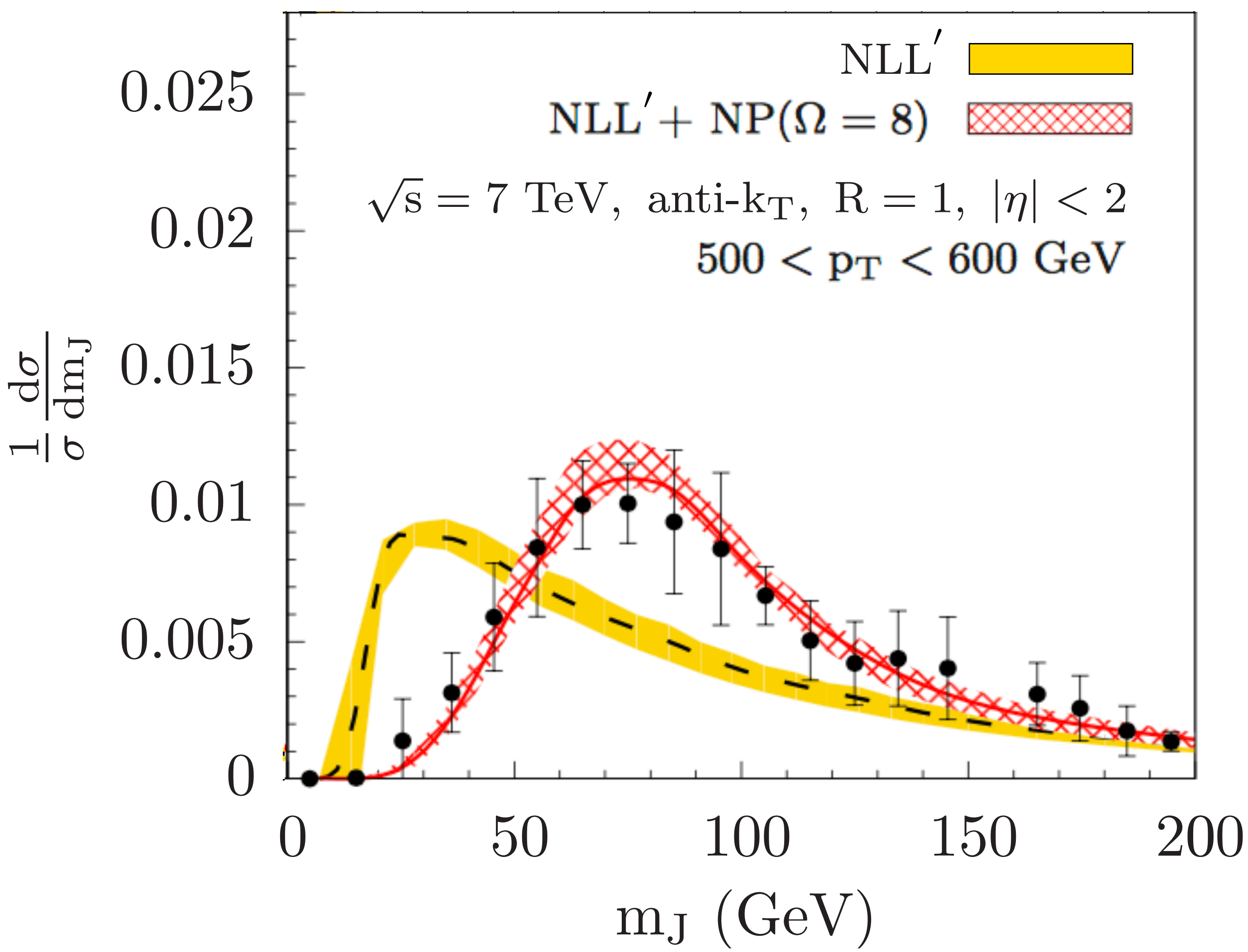




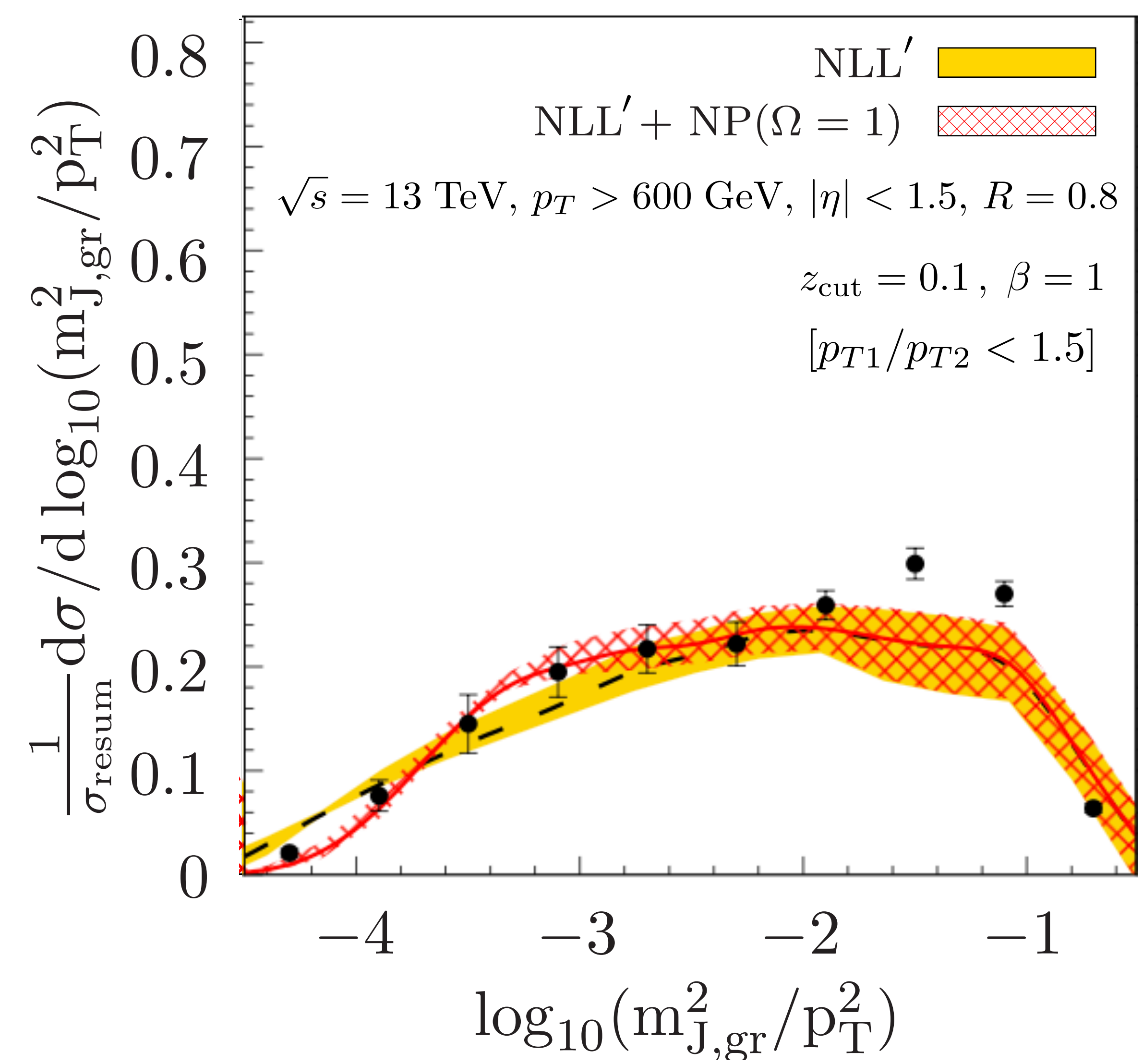
Jet mass distributions

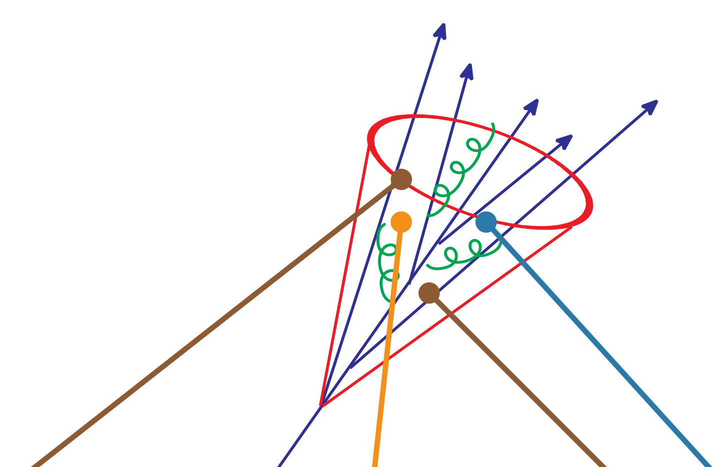
Kang, Lee, Liu, FR `18

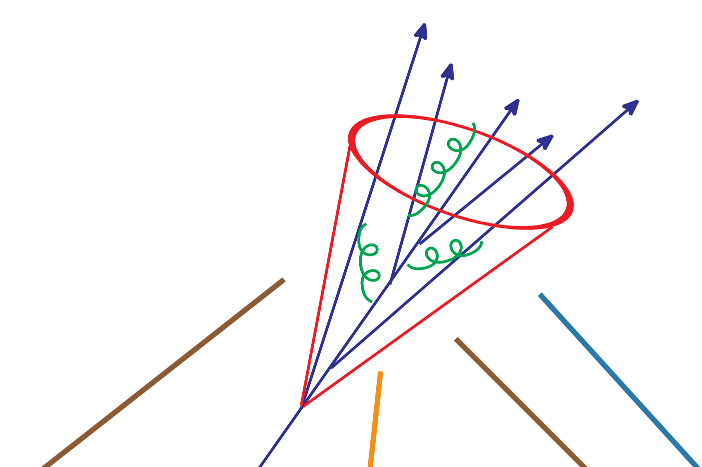
ATLAS, JHEP 05 (2012) 128



ATLAS, PRL 121 (2018) 092001

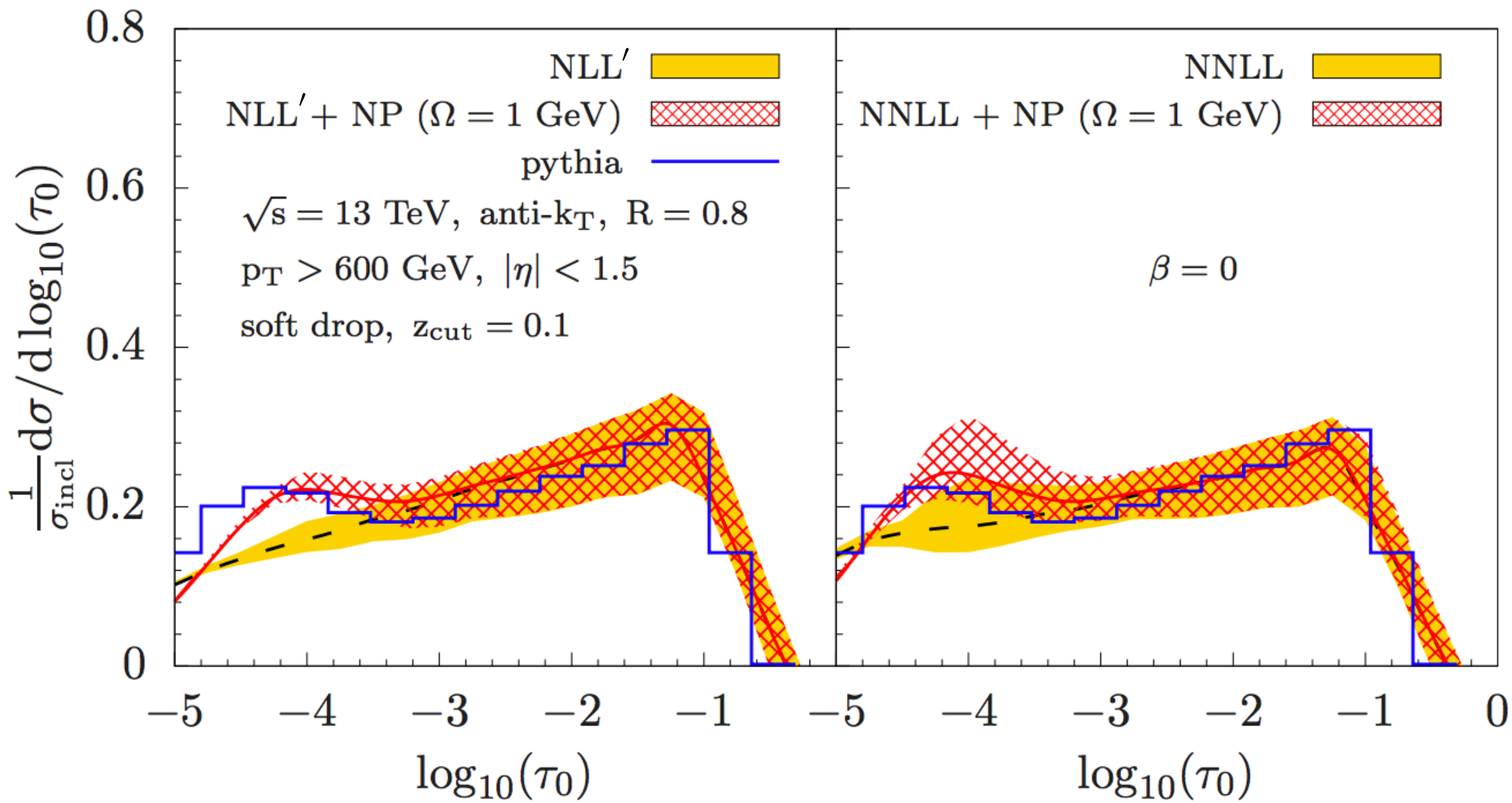






Jet mass distributions

Kang, Lee, Liu, FR `18



- Non-perturbative shape functions with grooming

  see: Hoang, Mantry, Pathak, Stewart - BOOST18

$\tau_0 = m_J^2/p_T^2$

Non-global logarithms

- The ungroomed case

Dasgupta, Salam `01,
Banfi, Marchesini, Smye `02
Larkoski, Moult, Neill `15
Becher, Rahn, Shao `17 …

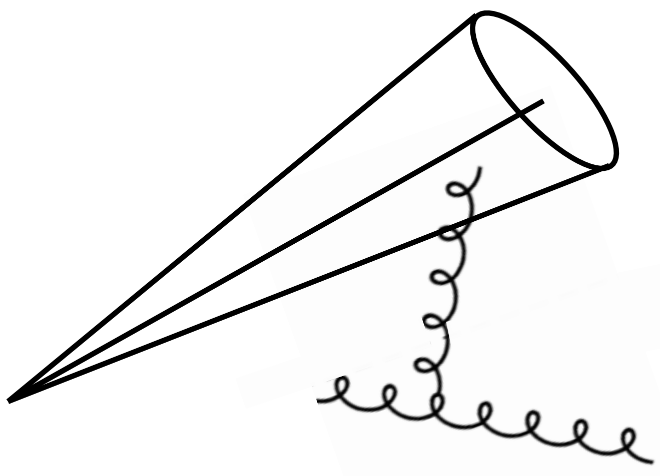
$$\mathcal{G}_i(z, p_T R, \tau, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu)\, C_i(\tau, p_T, \mu) \otimes S_i(\tau, p_T, R, \mu)$$

NGLs directly in the jet mass variable $\alpha_s^n \ln^n(\tau/R^2)$ $n \geq 2$

- The groomed case

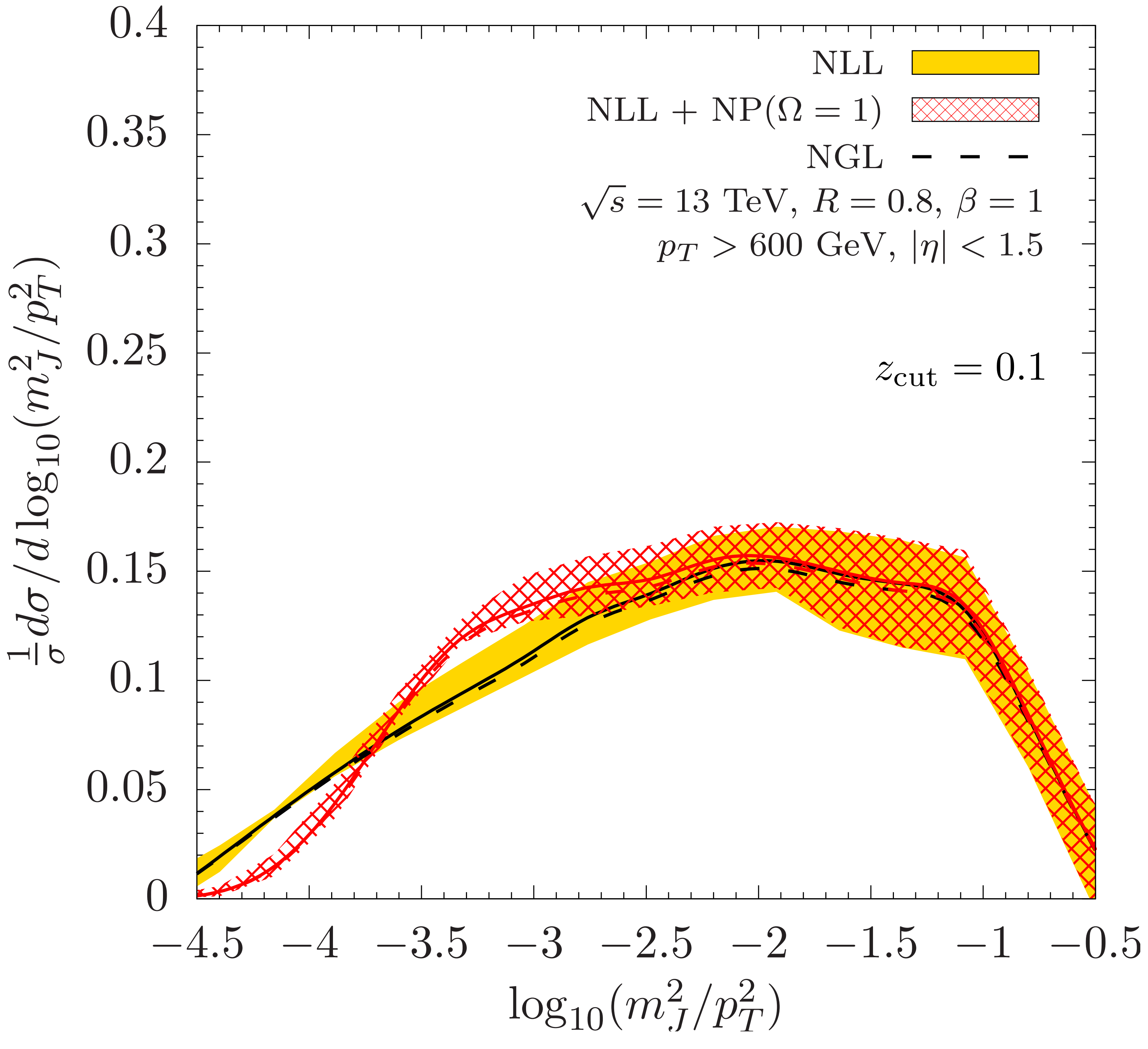
$$\mathcal{G}_i^{\rm gr}(z, p_T R, \tau_{\rm gr}, z_{\rm cut}, \mu) = \sum_j \mathcal{H}_{i\to j}(z, p_T R, \mu)\, S_i^{\notin {\rm gr}}(z_{\rm cut} p_T R, \beta, \mu)\, C_i(\tau_{\rm gr}, p_T, \mu) \otimes S_i^{\rm gr}(\tau_{\rm gr}, p_T, R, z_{\rm cut}, \mu)$$

NGLs affect the normalization and only indirectly affect the spectrum $\alpha_s^n \ln^n z_{\rm cut}$ $n \geq 2$

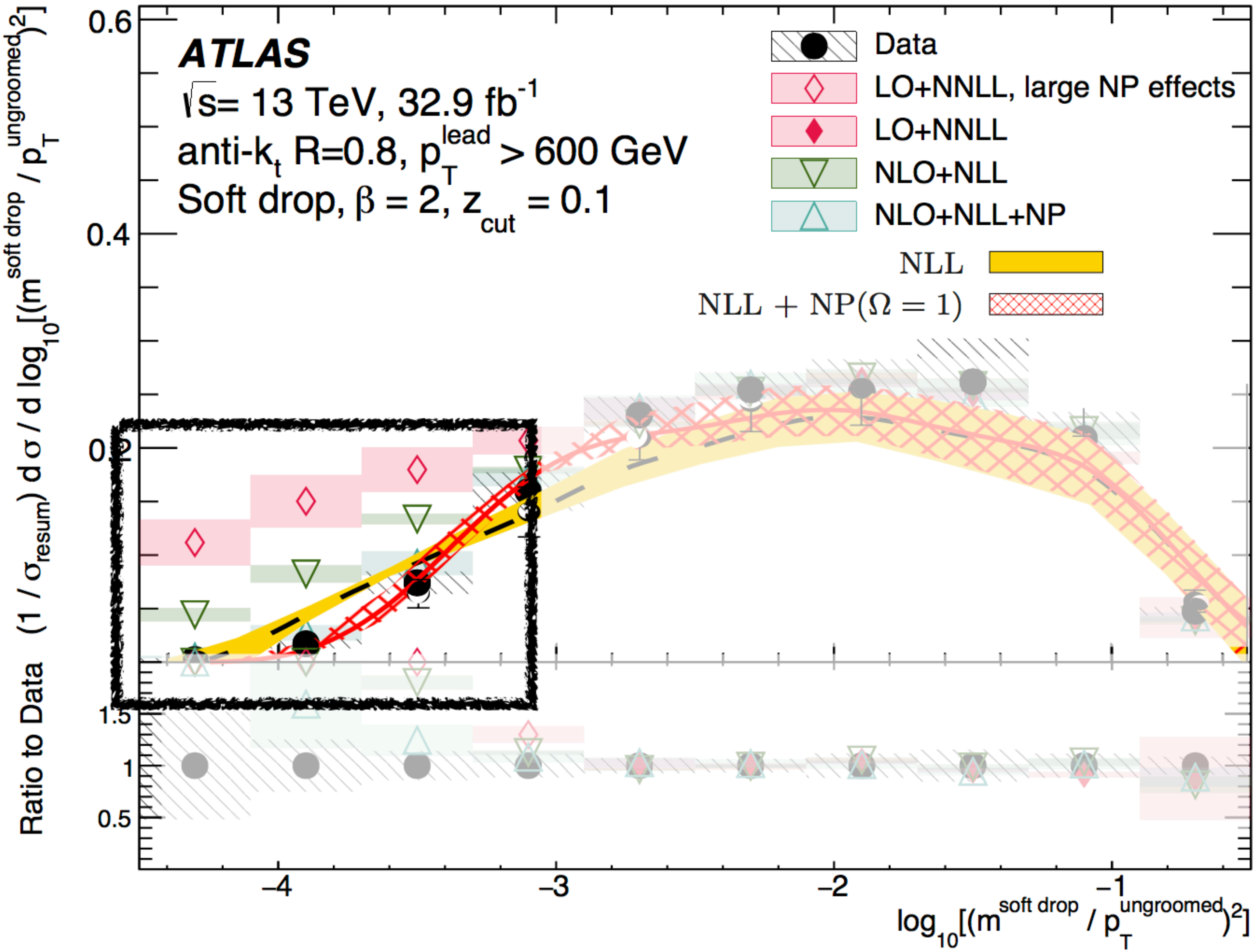


$\longrightarrow$ NGLs can be included in both cases

Non-global logarithms



courtesy of D. Neill



Frye, Larkoski, Schwartz, Yan `16
Marzani, Schunk, Soyez `17
Kang, Lee, Liu, FR `18

ATLAS, PRL 121 (2018) 092001

A lot of important progress but still work to do!

Ben Nachman, BOOST18

Comparison of the theory calculations

Frye, Larkoski, Schwartz, Yan `16

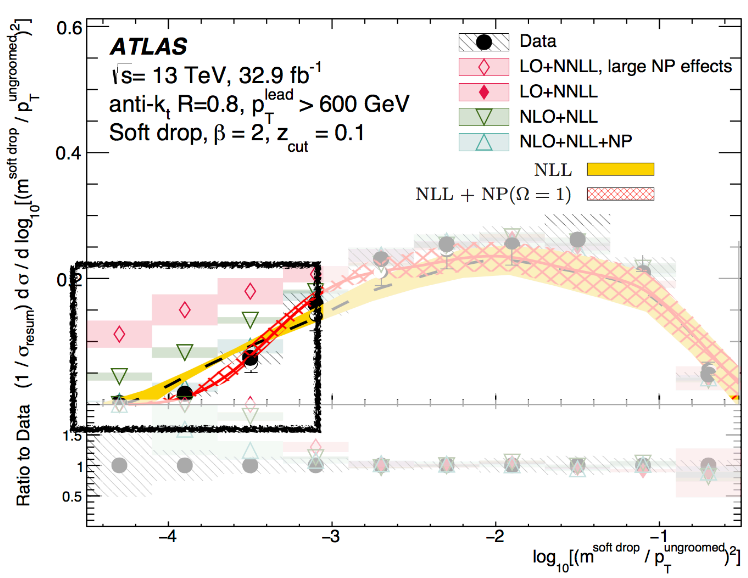
- NNLL
- Energy-energy correlation functions
- large R
- SCET

Marzani, Schunk, Soyez `17

- NLL, jet mass
- NLO fixed order matching
- Finite $z_{\rm cut}$ corrections
- large R
- pQCD

Kang, Lee, Liu, FR `18, `18

- (N)NLL, jet angularities
- small R, $\ln R$ resummation
- $\ln z_{\rm cut}$ resummation
- Q/g fractions beyond LO
- Possible to use universality of NP corrections
- NGLs can be included
- SCET



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Ideally combine advantages of the different calculations

Outline

- Introduction
- Groomed jet substructure observables at the LHC
- Determination of the QCD coupling
- Conclusions

Jet substructure at the LHC

- Groomed jet mass: Sensitivity to NP physics

Ungroomed: $\mu_S \sim \frac{p_T \tau}{R}$

SD groomed: $\mu_S \sim \frac{p_T \tau}{R} \left(\frac{z_{\rm cut} R^2}{\tau^2} \right)^{\frac{1}{2+\beta}}$

with $\mu_S = \Lambda_{\rm QCD} \sim 1 \text{ GeV}$

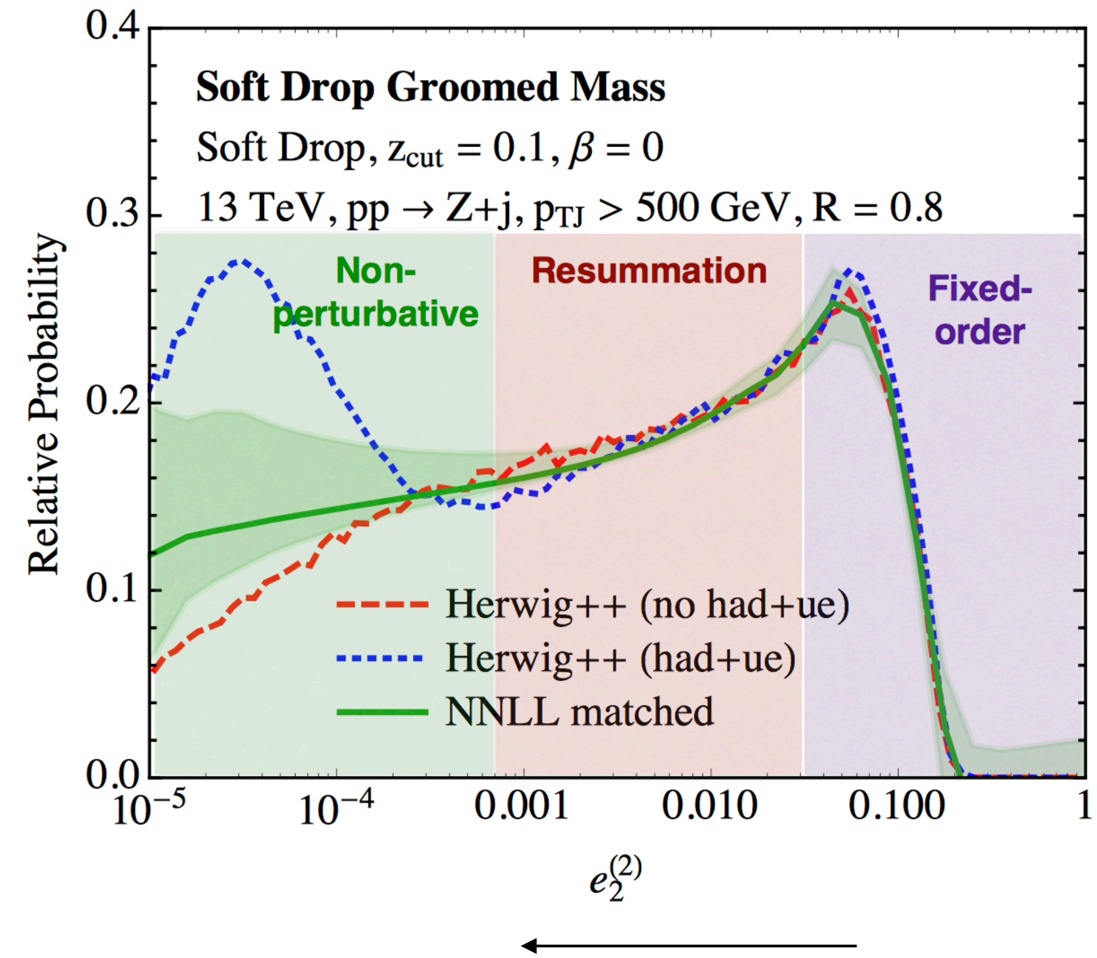
→ Onset of NP physics

$$\tau_{\rm gr} = \tau_{\rm ungr} \left(\frac{\Lambda_{\rm QCD}}{p_T R z_{\rm cut}} \right)^{\frac{1}{1+\beta}}$$

Potentially 2 orders of magnitude difference for a 1 TeV jet!

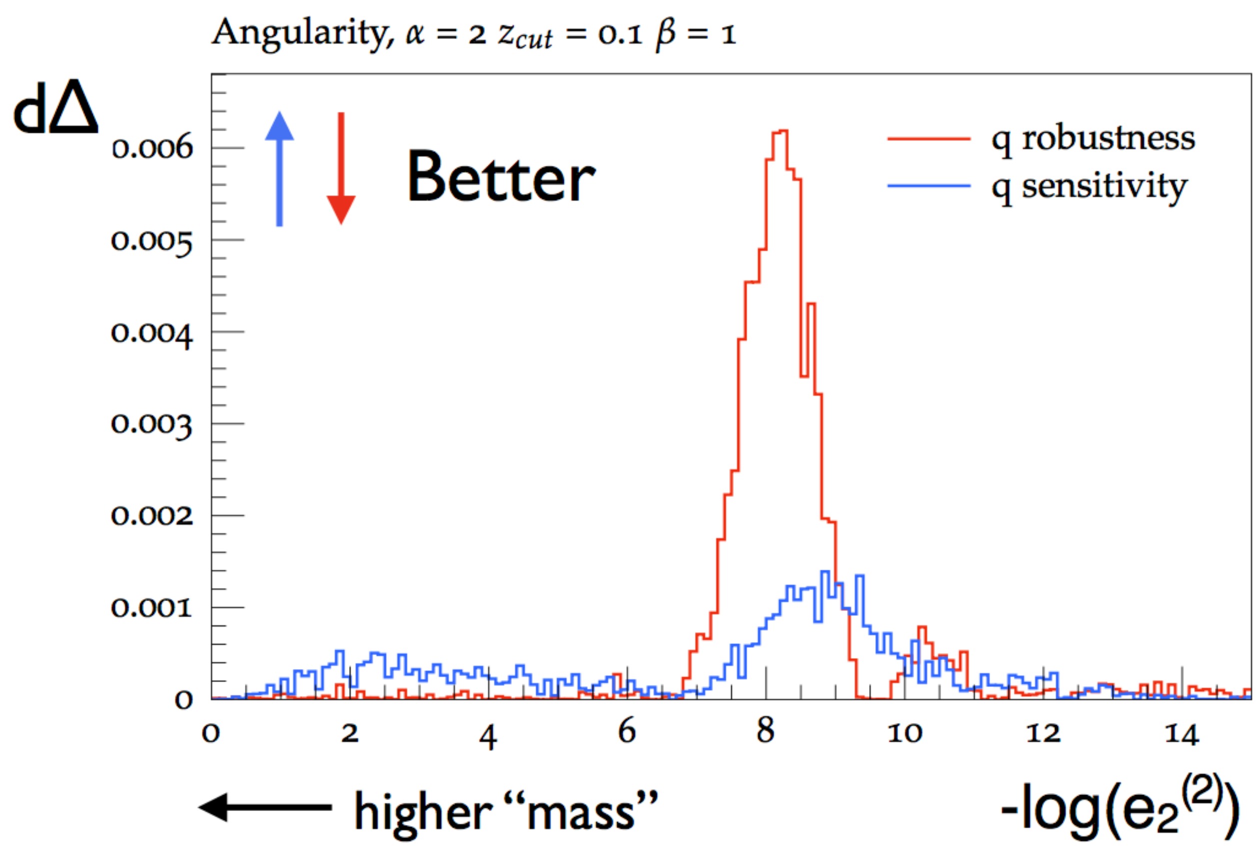
Les Houches `17

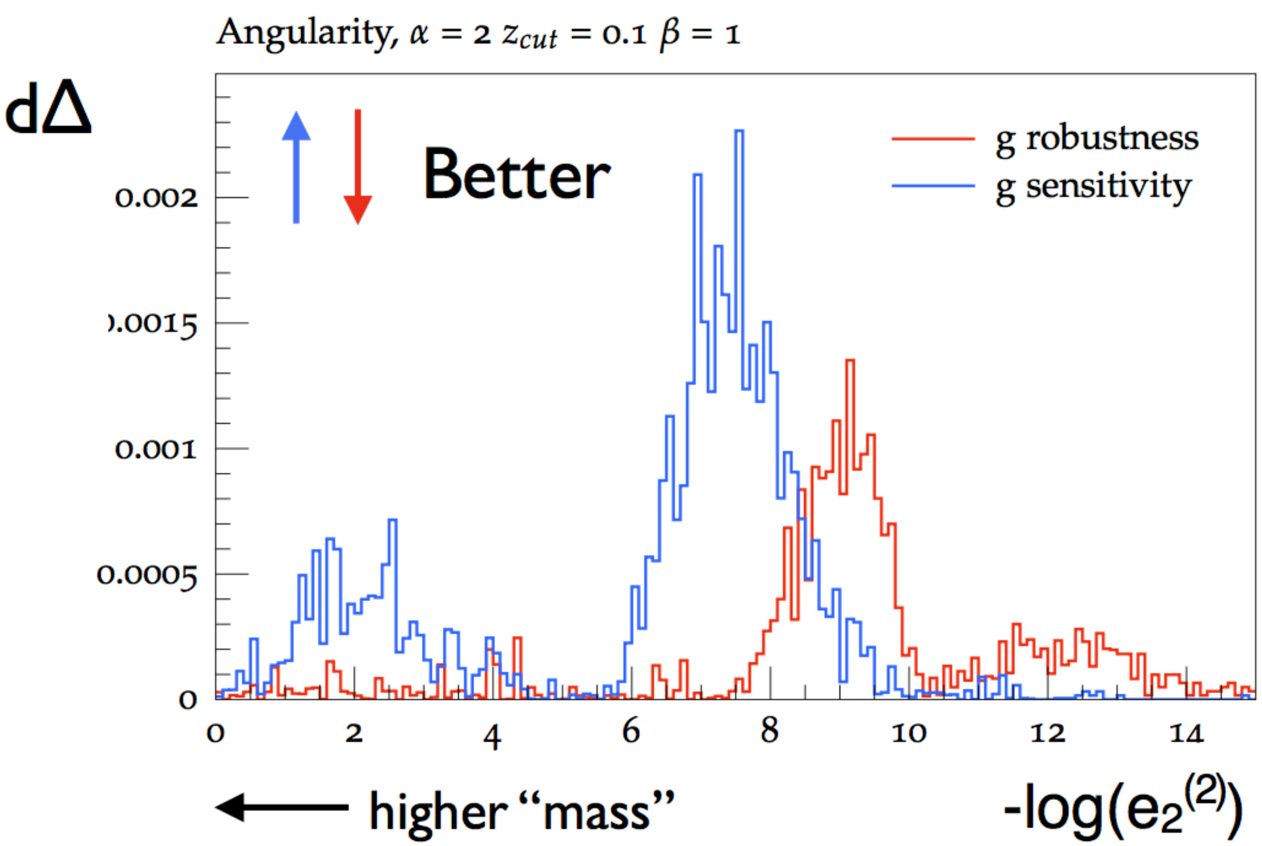
Frye, Larkoski, Schwartz, Yan `16



Sensitivity to α_s and NP effects

- Sensitivity $\alpha_s\ (+10\%)$
- NP robustness (had. on/off)





Herwig 7, Les Houches `17

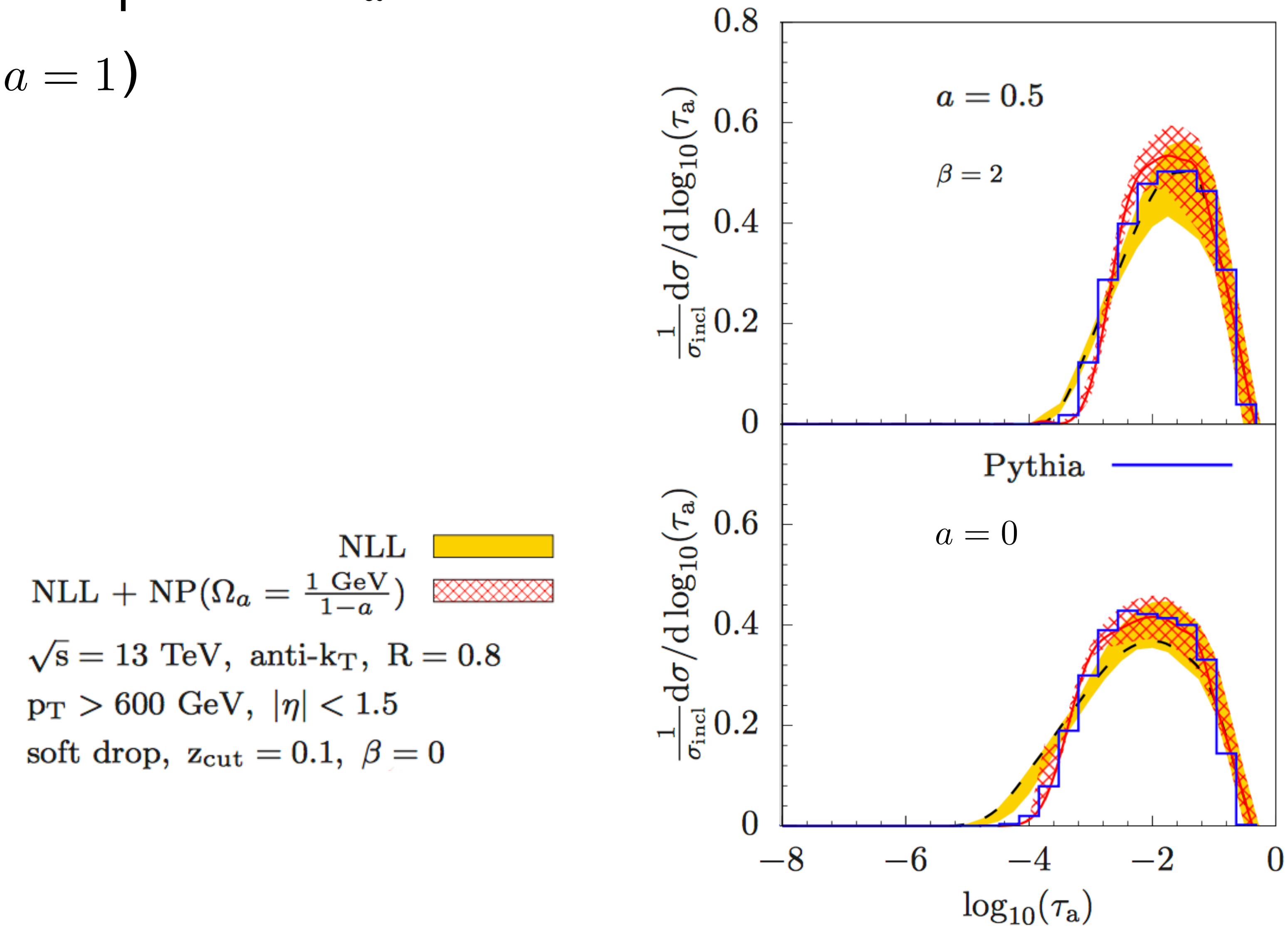
Choice of observables

- Jet angularities

Berger, Kucs, Sterman `03
Kang, Lee, Liu, FR `18

- Family of observables with a continuous parameter a
- Jet mass ($a=0$), jet broadening ($a=1$)

$$\tau_a = \frac{1}{p_T}\sum_{i\in J} p_{Ti}\,\Delta R_{iJ}^{2-a}$$



Choice of observables

- Jet angularities

Berger, Kucs, Sterman `03
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$$\tau_a = \frac{1}{p_T} \sum_{i \in J} p_{Ti}\, \Delta R_{iJ}^{2-a}$$

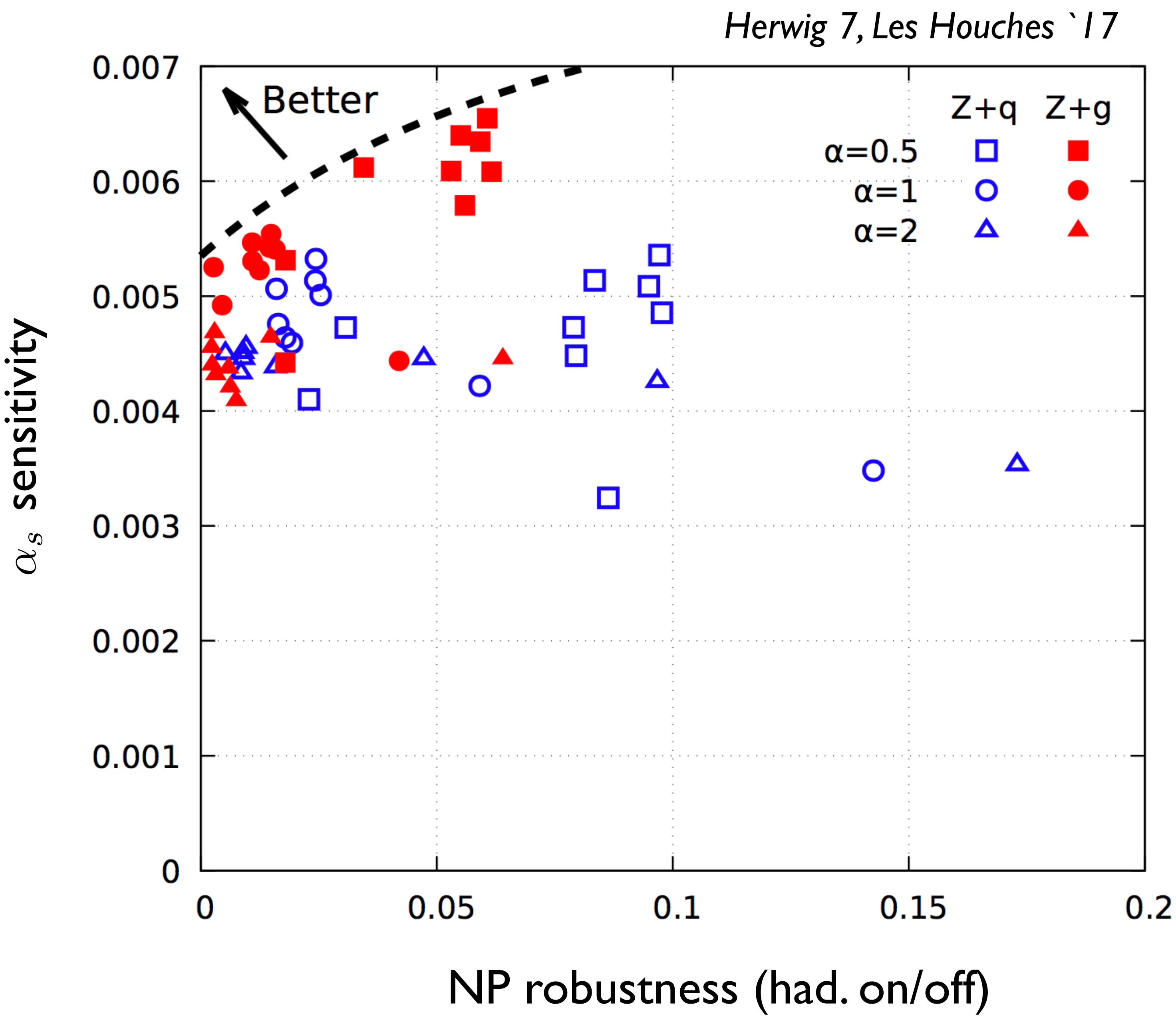
- Energy-energy correlation functions e.g. 2-point

Banfi, Salam, Zanderighi `05
Larkoski, Salam, Thaler `13
Frye, Larkoski, Schwartz, Yan `16

$$e_2^{(\alpha)} = \frac{1}{p_T^2} \sum_{i<j \in J} p_{Ti} p_{Tj} \Delta R_{ij}^{\alpha}$$

Choice of observables

- Scan of observables and grooming parameters $z_{\rm cut},\,\beta$
- Sensitivity to α_s vs. robustness to NP effects



Takeaways

- Gluons better
- Broadening better than mass …

Further considerations

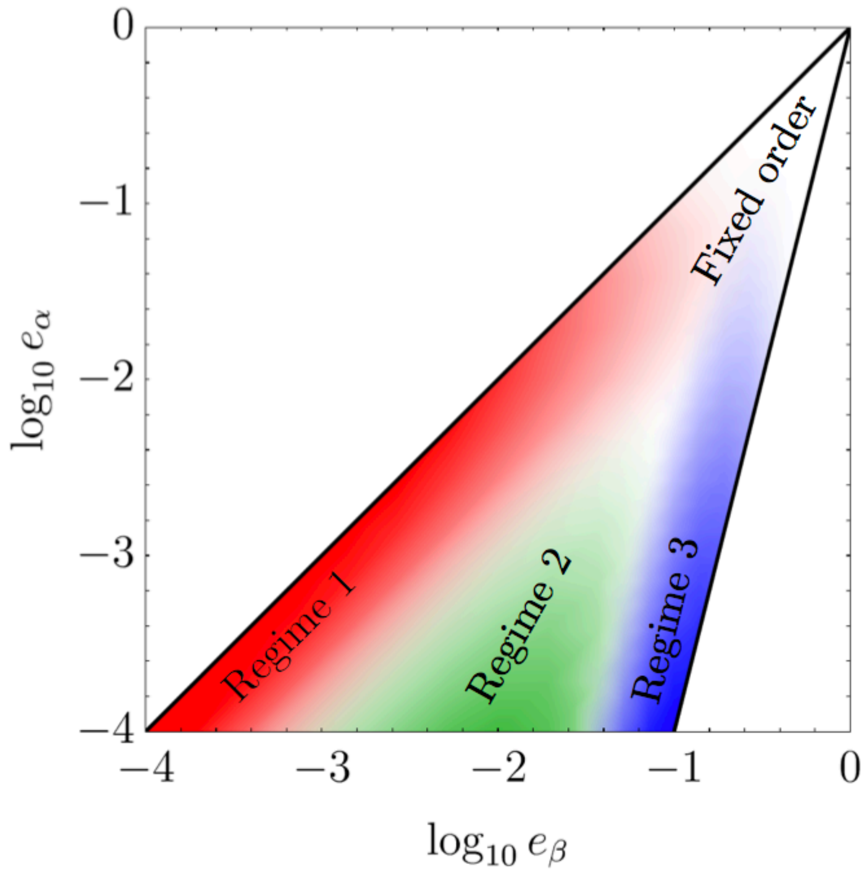
- Normalized vs. unnormalized distribution: LO $\mathcal{O}(\alpha_s^2)$ and involves PDFs
- Combined fit with PDFs?
- Jet angularities could break degeneracy of α_s and NP effects $\frac{\Omega}{1-a}$ *Lee, Sterman `07*

  But need double differential distributions

  ⟶ Correlations within multi observable fit

  Procura, Waalewijn, Zeune `18

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}e_\alpha\,\mathrm{d}e_\beta}$$



- Relate NP shape functions between different experiments
- Non-perturbative effects using shape functions?

  see: Hoang, Mantry, Pathak, Stewart - BOOST18

Future directions

- Theory
  - Precision goal NNLL' or N^{3}LL + $2 \to 3$ at NNLO
  - Observables: Different choices of the jet axis?
  - Double differential distributions?
  - Non-perturbative shape functions with grooming?

Badger, Biedermann, Uwer, Yundin `14
Gehrmann, Henn, Presti `15
Dunbar, Perkins `16
Abreu, Cordero, Ita, Page, Zeng `17
Badger, Hansen, Hartanto, Peraro `17
Moult, Zhu `18
…

- Experiment
  - Mass scale and resolution uncertainties
  - Pileup modeling and mitigation especially for high p_T jets for Run3+
  - Track based observables possible? *Chang, Procura, Thaler, Waalewijn `13*

Outline

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Conclusions

- Precision era of jet substructure at the LHC is just starting
- Possibility to extract α_s from jet substructure data
- Hadron collider observables, soft drop grooming
- Currently ~10% expected and interesting NP aspects
- Competitive extractions require advances from both theory and experiment