Prospects for strong coupling measurement using jet grooming at hadron colliders

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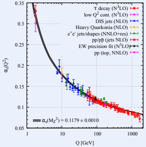
with Aditya Pathak, Matthew Schwartz and Iain Stewart

Outline

1. Introduction: Soft-drop jet mass for α_s measurement



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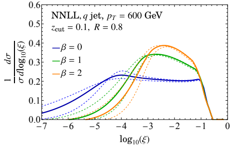

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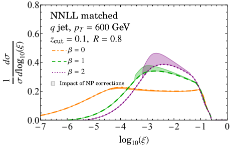

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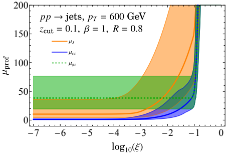

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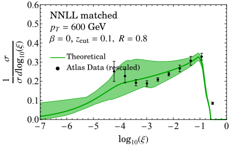


Motivation

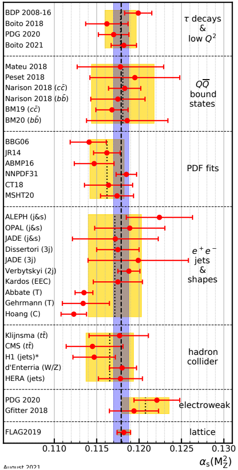
Uncertainties in strong coupling constant α_s propagate into (almost all) precision measurements at the LHC

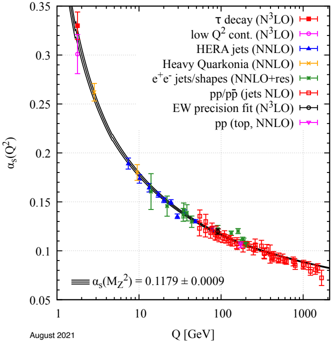
Tension between different measurements (LEP, lattice, hadron colliders,...)

Can we get new, independent measurements of α_s using soft drop jet mass at hadron colliders?

What are the advantages and challenges?

PREVIOUS α_s MEASUREMENTS





World average:

$\alpha_s(m_Z) = 0.1179 \pm 0.0010$

Here:

Investigate prospects for using jet mass for a new precision measurement of α_s

[Figures from Workman et al. (Particle Data Group) 2022]

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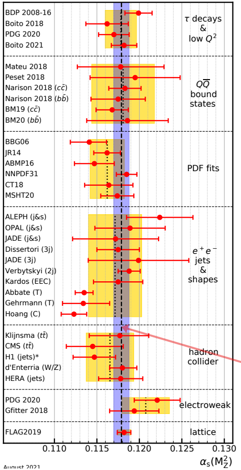

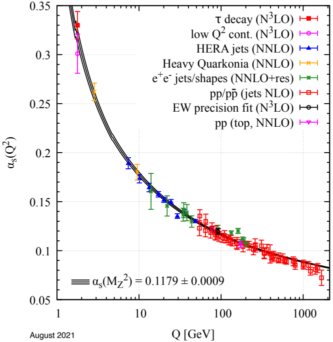

Tension between measurements

World average:

$\alpha_s(m_Z) = 0.1179 \pm 0.0010$

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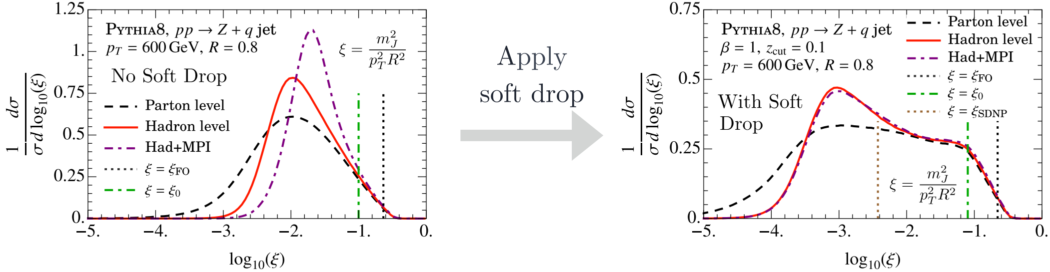
WHY SOFT DROP JET MASS?

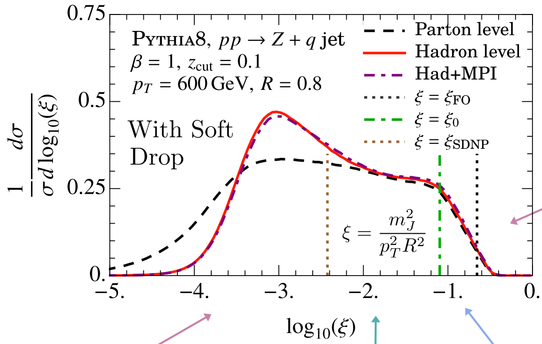


- **Measurable** and **calculable** observable for hadron colliders

- Reduces sensitivity to underlying-event & hadronization effects

[Les Houches 2017: Moult, Nachman, Soyez, Thaler; Chatterjee, Dreyer, Garzelli, Gras, Larkoski, Marzani, Siódmok, Papaefstathiou, Richardson, Samui], [Larkoski, Marzani, Soyez, Thaler 2014]

Calculation of matched cross section



Fixed-order region

Non-perturbative region (no theoretical control)

Soft drop resummation region

Resummation region, fixed-order soft drop

Calculation of matched cross section

Hard function for production of patron c

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi} = \sum_{abc}\int \frac{\mathrm{d}x_a\mathrm{d}x_b\mathrm{d}z}{x_a x_b z} f_a(x_a) f_b(x_b) H_{ab}^c\left(\frac{p_T}{z}\right)\mathcal{G}_c(z,\xi)\,, \qquad \xi = \frac{m_J^2}{p_T^2 R^2}$$

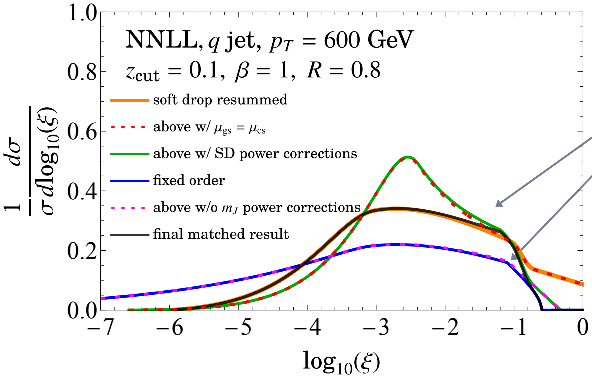
Parton distribution functions

Inclusive jet function

1. Non-perturbative region
2. Soft-drop resummation region
   Resum logs in $\frac{\xi}{z_{\rm cut} R^\beta}$
3. Plain jet mass region with SD power corrections
   Resum logs in ξ*, treat soft-drop as fixed-order corrections*
4. Fixed-order region

[Kang, Lee, Liu, Ringer 2018]
[Hannesdottir, Pathak Schwartz, Stewart]

Result for quark jets



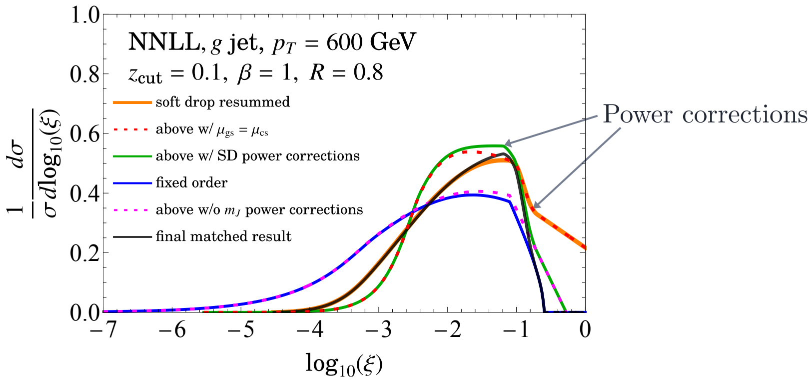
Power corrections

(When factoring out DGLAP evolution)

$$\tilde{\mathcal{G}}^{\rm matched}_{\kappa,{\rm sd}}(\xi) \equiv \tilde{\mathcal{G}}^{\rm resum}_{\kappa,{\rm sd}}\big(\xi, \mu_{{\rm sd}\to{\rm plain}}\big) + \tilde{\mathcal{G}}^{\rm plain}_{\kappa,{\rm sd}}\big(\xi, \mu_{\rm plain}\big) - \tilde{\mathcal{G}}^{\rm resum}_{\rm sd}\big(\xi, \mu_{\rm plain}\big)$$
$$+ \tilde{\mathcal{G}}^{\rm min}_{\kappa,{\rm sd}}\big(\xi, \mu_{{\rm min}\to{\rm plain}}\big) - \tilde{\mathcal{G}}^{\rm int}_{\rm sd}\big(\xi, \mu_{{\rm min}\to{\rm plain}}\big)\,.$$

[Cal, Ringer, Waalewijn 2019]

Result for gluon jets



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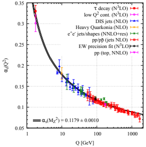

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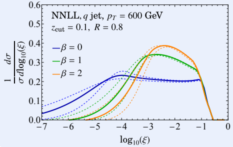

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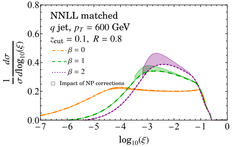

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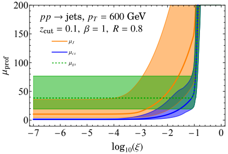

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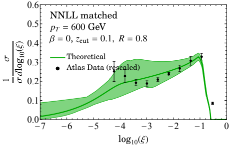


Calculating quark-gluon fraction

PDF	α_s used	$f = \frac{\sigma_q}{\sigma_g}$	% change
NNPDF 23 LO	0.119	0.479	-6.0
NNPDF 23 NLO	0.119	0.517	1.3
NNPDF 23 NNLO	0.119	0.523	2.5
NNPDF 23 NNLO	0.120	0.514	0.84
CT18NLO_as_0119	0.119	0.514	0.87
CT18NNLO_as_0119	0.119	0.507	-0.49
MSTW2008nlo68cl	0.120	0.510	0.063
MSTW2008nlo68cl	0.117	0.514	0.87
mean	–	0.510	1.6

q/g fraction is **well-defined in theoretical calculations**

(not an external input, not taken from experiments)

Using PDF and hard functions: **calculable** prediction

$$f_{\mathrm{LO}} = 0.507, \quad f_{\mathrm{NLO}} = 0.530, \quad f_{\mathrm{NNLO}} = 0.538$$

Sub-dominant effect on α_s uncertainty

(Note: different from LeBlanc, Nachman, Sauer 2022)

Dependence on slope

According to **leading-logarithmic** estimate,

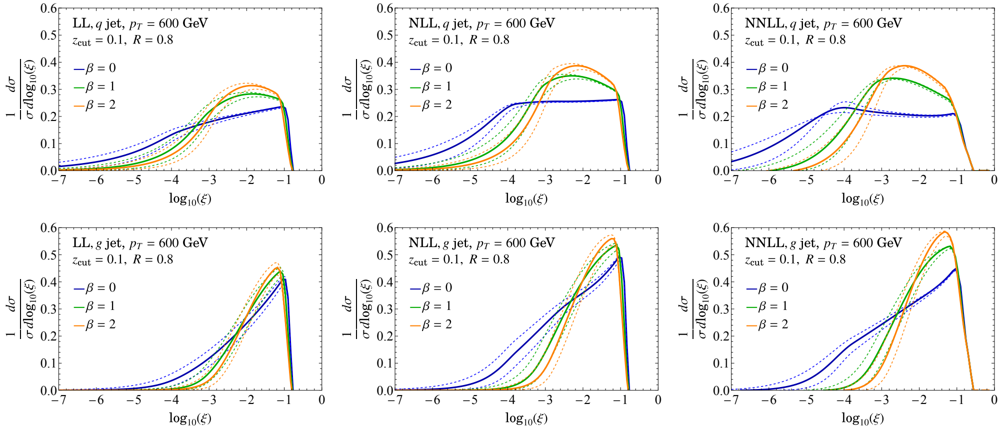
Independent of $\boldsymbol{\alpha_s}$, $\boldsymbol{\xi}$

$$\frac{d\sigma^{\kappa}_{\text{resum}}}{d\log_{10}(\xi)} \propto \exp\Big[-\alpha_s(\mu)a_\kappa \log_{10}(\xi)\Big] \approx 1 - \underline{\alpha_s(\mu)a_\kappa} \log_{10}(\xi) + \dots$$

Slope depends linearly on $\boldsymbol{\alpha_s}$

[Les Houches 2017: Moult, Nachman, Soyez, Thaler; Chatterjee, Dreyer, Garzelli, Gras, Larkoski, Marzani, Siódmok, Papaefstathiou, Richardson, Samui]

Order dependence on slope



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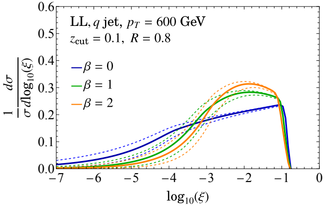
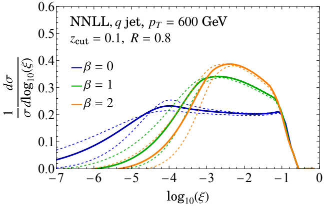
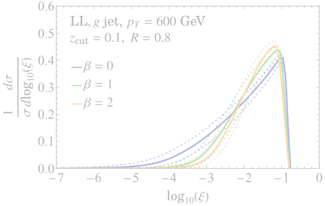
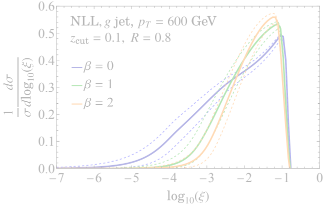
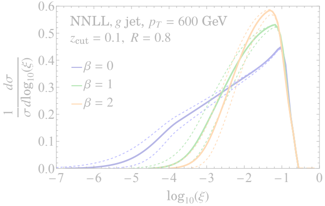




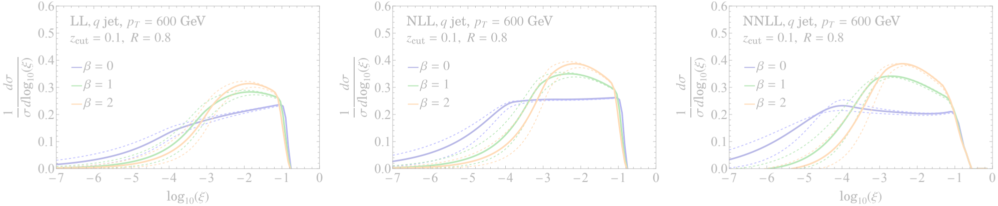
Quark jets: slope flattens

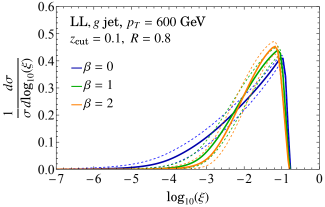




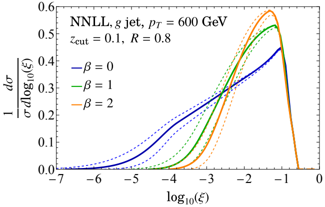


Order dependence on slope





Gluon jets: retain shape



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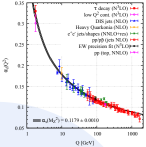

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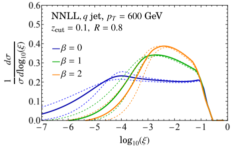

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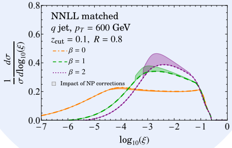

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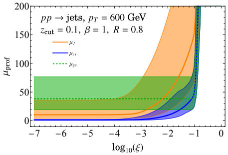

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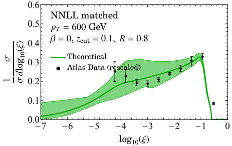


Hadronization corrections

Power-corrections to hadronization effects:

$$\frac{d\sigma^{\text{had}}}{dm_J^2} = \frac{d\sigma^{\text{part}}}{dm_J^2} - p_T R\,\Omega \frac{d}{dm_J^2}\left[C_1(m_J^2)\frac{d\sigma^{\text{part}}}{dm_J^2}\right] + \frac{p_T R}{m_J^2}\left(\Upsilon_0 + \beta\Upsilon_1\right) C_2(m_J^2)\frac{d\sigma^{\text{part}}}{dm_J^2} + \ldots$$

[Hoang, Mantry, Pathak, Stewart 2019]

[Ferdinand, Lee, Pathak; See talk by Ferdinand]

Hadronization corrections

Model-independent power-corrections to hadronization effects:

Calculable using field theory

$$\frac{d\sigma^{\rm had}}{dm_J^2} = \frac{d\sigma^{\rm part}}{dm_J^2} - p_T R\,\Omega \frac{d}{dm_J^2}\left[C_1(m_J^2)\frac{d\sigma^{\rm part}}{dm_J^2}\right] + \frac{p_T R}{m_J^2}\left(\Upsilon_0 + \beta\Upsilon_1\right) C_2(m_J^2)\frac{d\sigma^{\rm part}}{dm_J^2} + \ldots$$

Partonic cross section

Constant, non-perturbative parameters

[Hoang, Mantry, Pathak, Stewart 2019]

[Ferdinand, Lee, Pathak; See talk by Ferdinand]

What to do about hadronization?

Ideally, fit for 7 parameters to stay model independent. Too difficult?

$$(\alpha_s,\, \Omega^q,\, \Omega^g,\, \Upsilon_0^q,\, \Upsilon_0^g,\, \Upsilon_1^q,\, \Upsilon_1^g)$$

Instead, treat as nuisance parameters

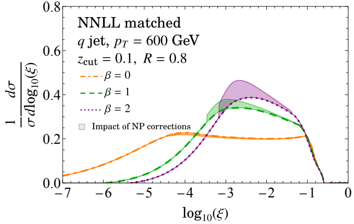
Take uncertainty as difference between parton level and hadron level:

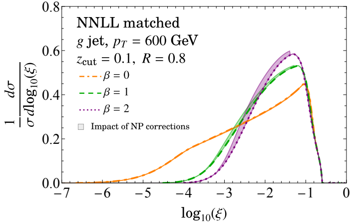
$$\begin{aligned}
&\Omega^q = 0.51, \qquad \Upsilon_0^q = -0.69, \qquad \Upsilon_1^q = 1.1, \qquad \text{for quarks}\\
&\Omega^g = 0.93, \qquad \Upsilon_0^g = -0.07, \qquad \Upsilon_1^g = 0.68, \qquad \text{for gluons}
\end{aligned}$$

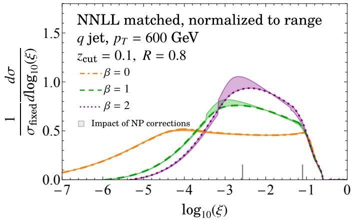
(Values obtained from fit to Pythia)

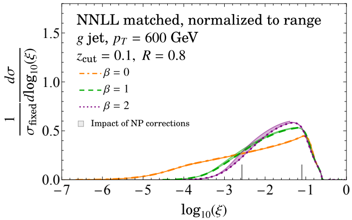
[Ferdinand, Lee, Pathak; See talk by Ferdinand]

Impact of hadronization corrections









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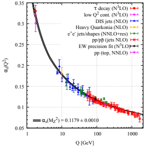

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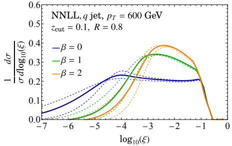

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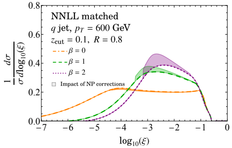

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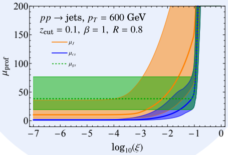

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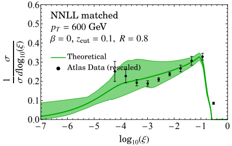

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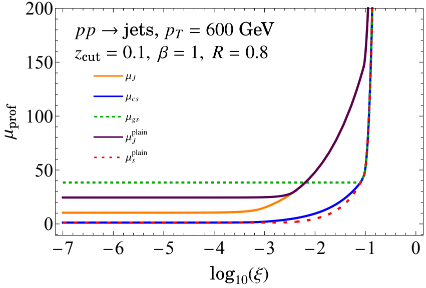
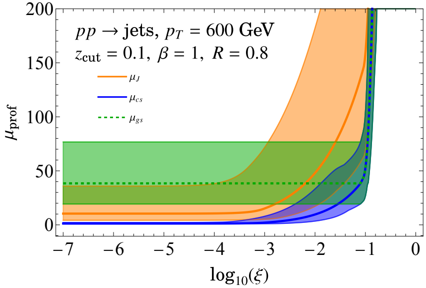
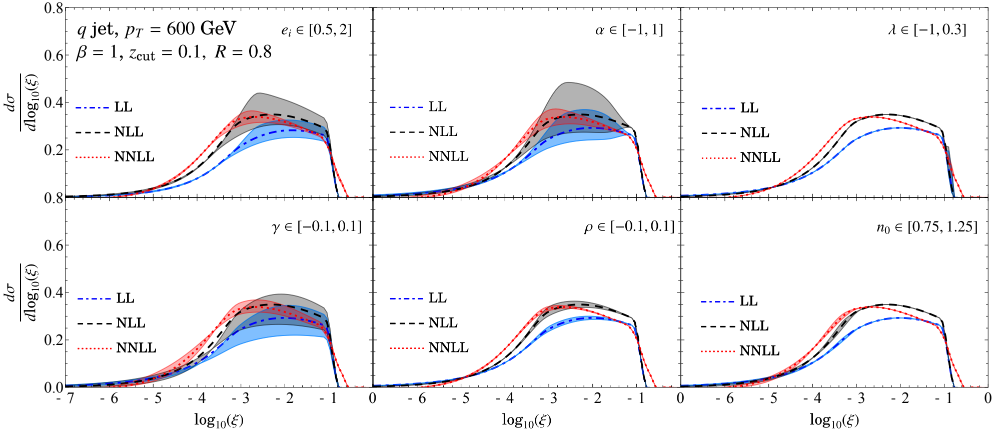




Assess perturbative uncertainty by varying 6 renormalization-scale parameters

(overall scale, shape, break canonical relations)

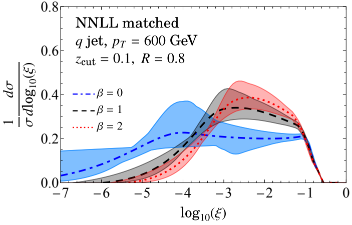
Scale variations

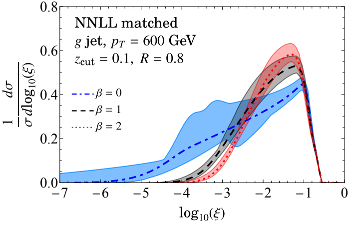


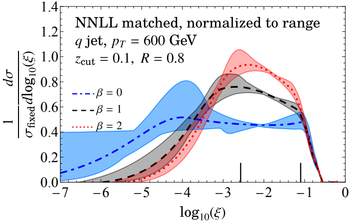
Impact of scale variations

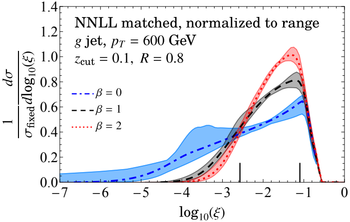
Quark jets:

Gluon jets:









Prospects for reducing scale-variations

- Uncertainties can be reduced by going to **higher logarithmic orders**

- All **NNLL** data known [Bell, Rahn, Talbert 2018-2020. See Frye, Larkoski, Schwartz, Yan 2016]

- Recent calculations at **N³LL** for β=0 [Kardos, Larkoski, Trócsányi]

Collinear-soft 2-loop constant, 3-loop non-cusp. Global soft constant known for $R=\pi/2$.

- **N³LL** for soft drop jet mass requires new 2-loop calculations

$\rightarrow$*need constants for collinear soft and global soft for* $\beta>0$

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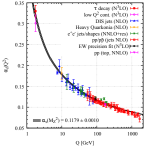

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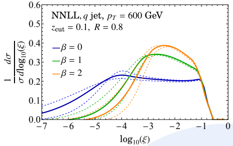

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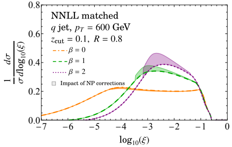
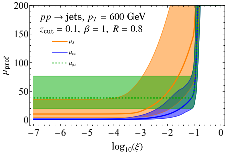
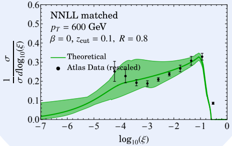


4. Scale variations



5. Results

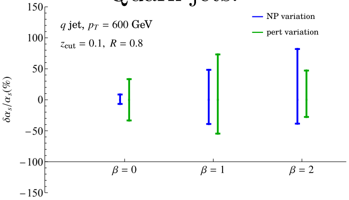


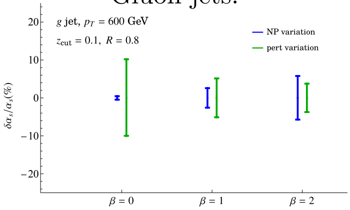
Results when normalizing in a fixed range

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi} \Big/ \int_{\xi_{\mathrm{SDOE}}}^{\xi_0'} \mathrm{d}\xi\, \frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi}$$

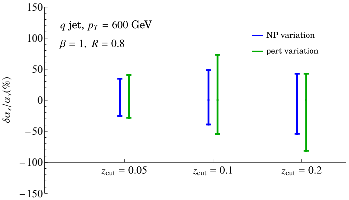
Quark jets: **Gluon jets:**

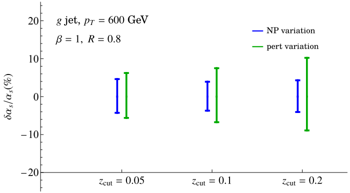
Vary β:





Vary z_{cut}:





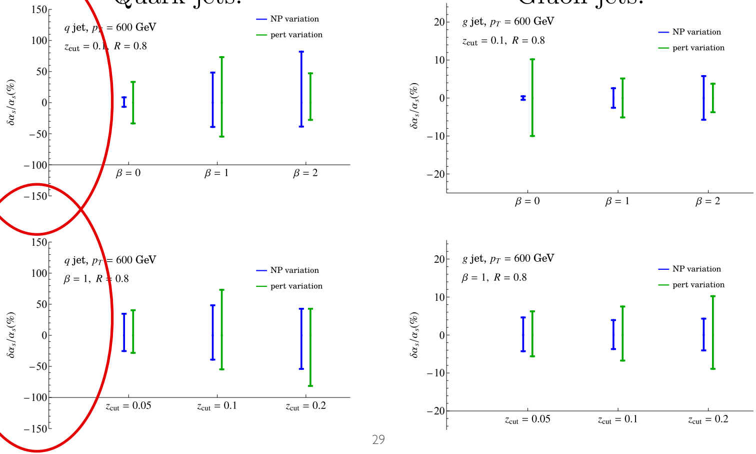
Results when normalizing in a fixed range

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi}\Big/\int_{\xi_{\mathrm{SDOE}}}^{\xi_0'}\mathrm{d}\xi\,\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi}$$

Quark jets:

Gluon jets:

Fixed-range normalization removes almost all α_s sensitivity of quark jets



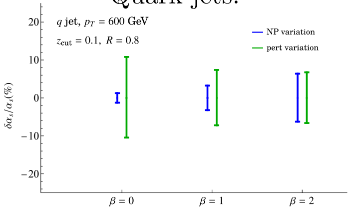
Results when normalizing to inclusive σ

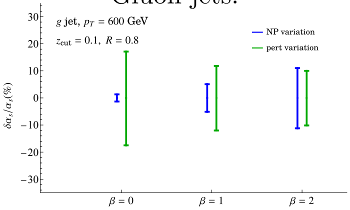
$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi}\bigg/\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}\eta}$$

Quark jets:

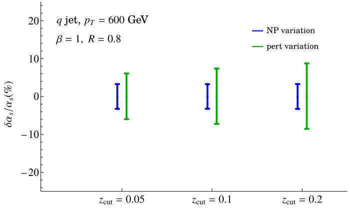
Gluon jets:

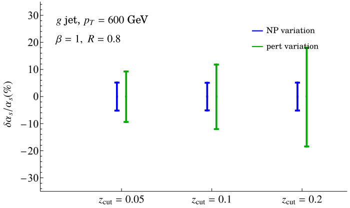
Vary β:





Vary z_{cut}:



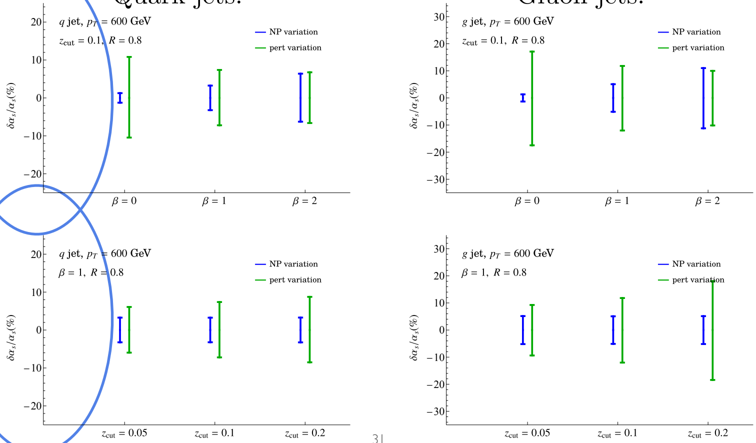


Results when normalizing to inclusive σ

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}\xi}\bigg/\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}\eta}$$

Quark jets:

Gluon jets:



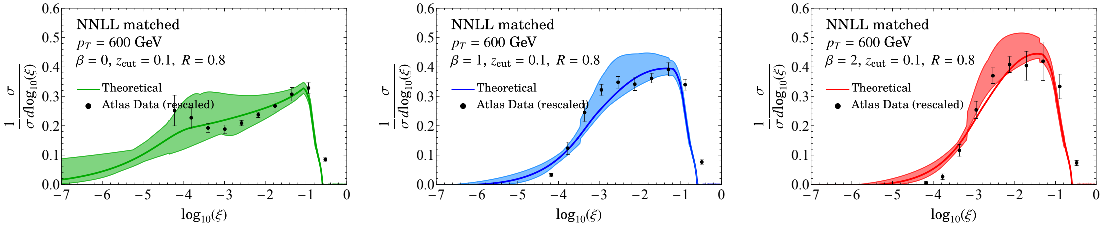
Normalizing to full spectrum retains some sensitivity

Comparison with Atlas data

$$\sqrt{s} = 13 \text{ TeV}, 32.9\text{fb}^{-1}$$

$$\text{anti-k}_t\ R = 0.8,\ p_T^{\text{lead}} > 600 \text{ GeV}$$

$$\text{Soft drop, } z_{\text{cut}} = 0.1$$



[Data from Atlas collaboration; Aaboud, Morad et al., 1711.08341]

Conclusion and Outlook

Prospects for using soft-drop jet mass to measure α_s at the LHC:

- q/g fraction **well defined** in theoretical calculations
- **Gluon jets** most sensitive to α_s variations
- Estimate **hadronization** corrections (7 free parameters?)
- **N^{3}LL calculations** would reduce perturbative uncertainty
- Measure **different samples**, at different energies would improve fit
- Normalizing to the **inclusive cross section** retains sensitivity to α_s

THANKS!