Dissecting groomed soft radiation with Factorization

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Advancing the understanding of non-perturbative QCD with energy flows

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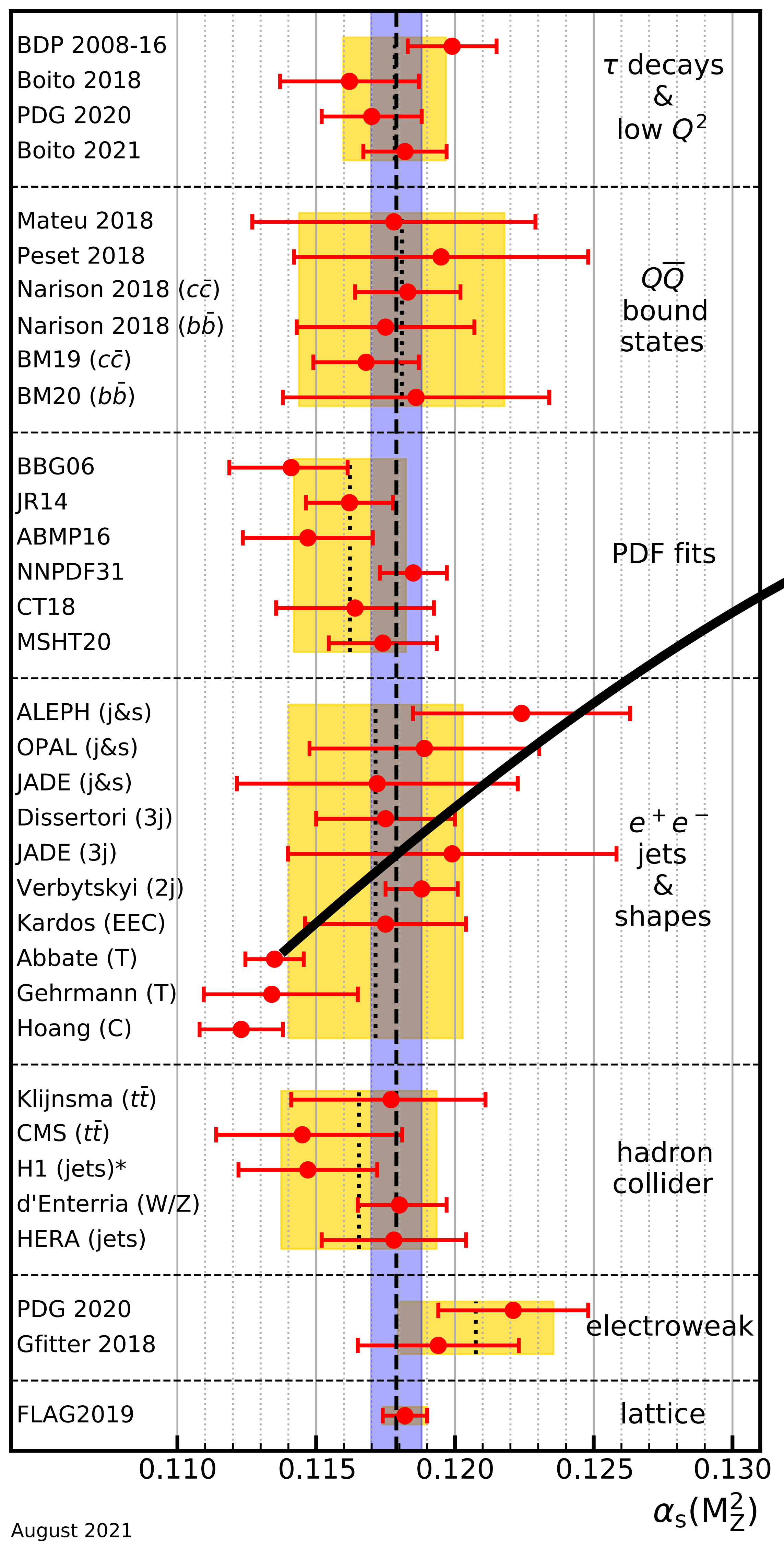
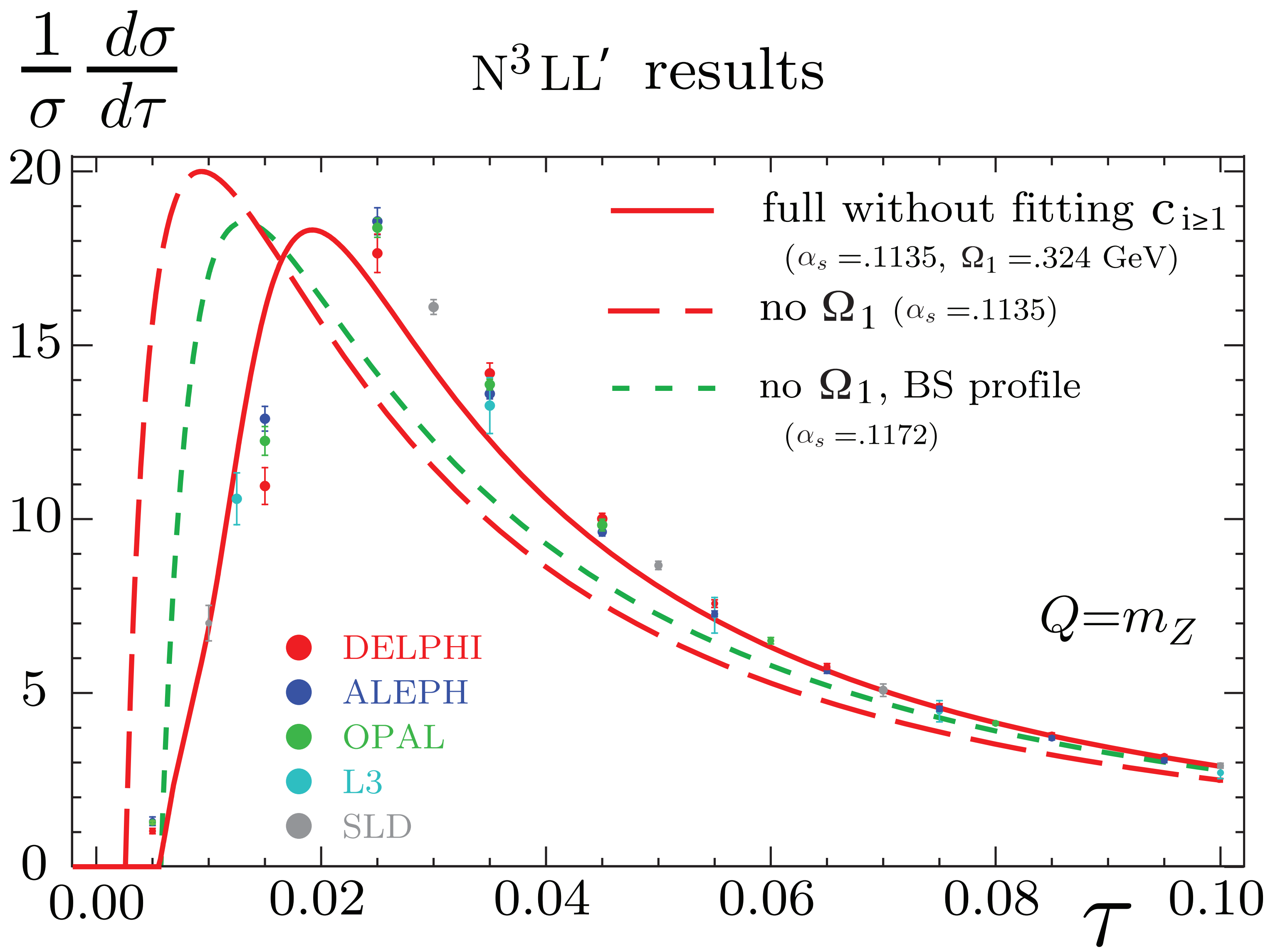
Understanding NP corrections is crucial for precision physics

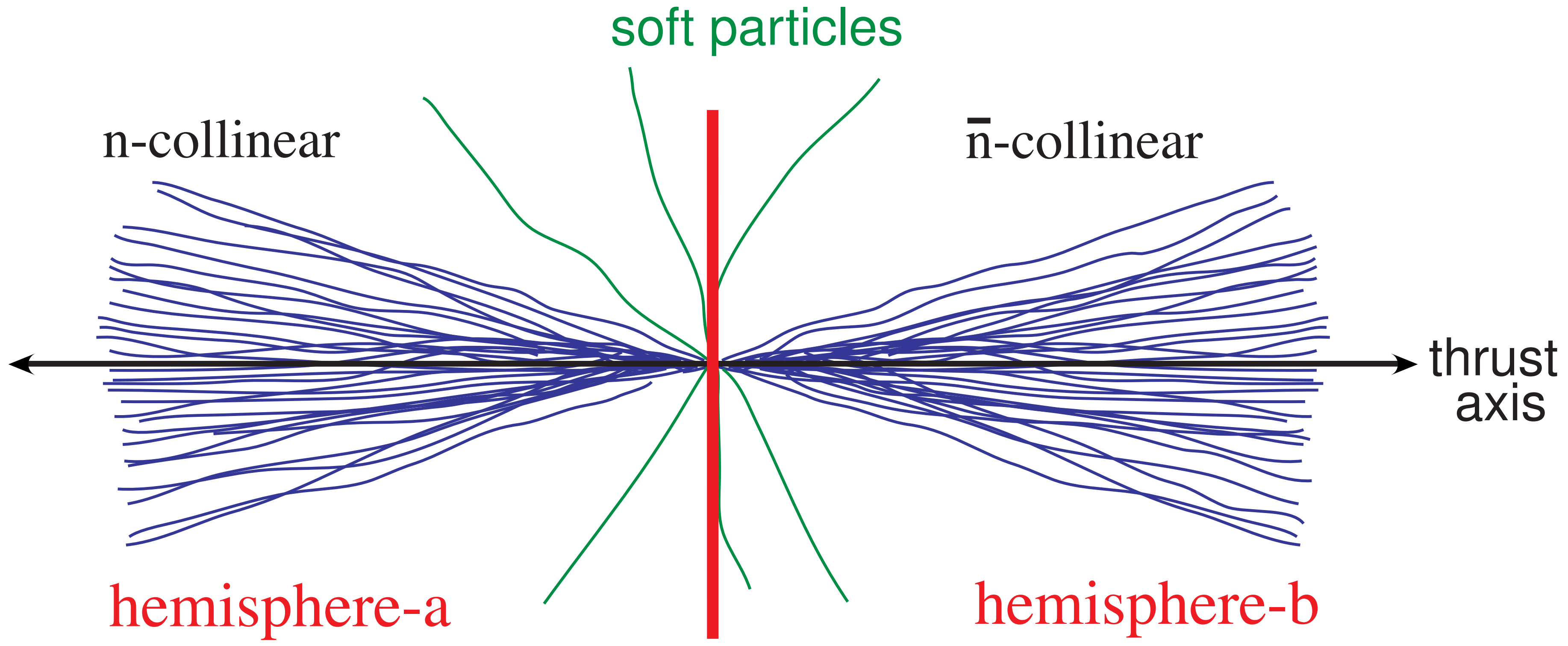
PDG



α_s world average: $\alpha_s(m_Z) = 0.1179 \pm 0.0010$



Abbate et al. 2010

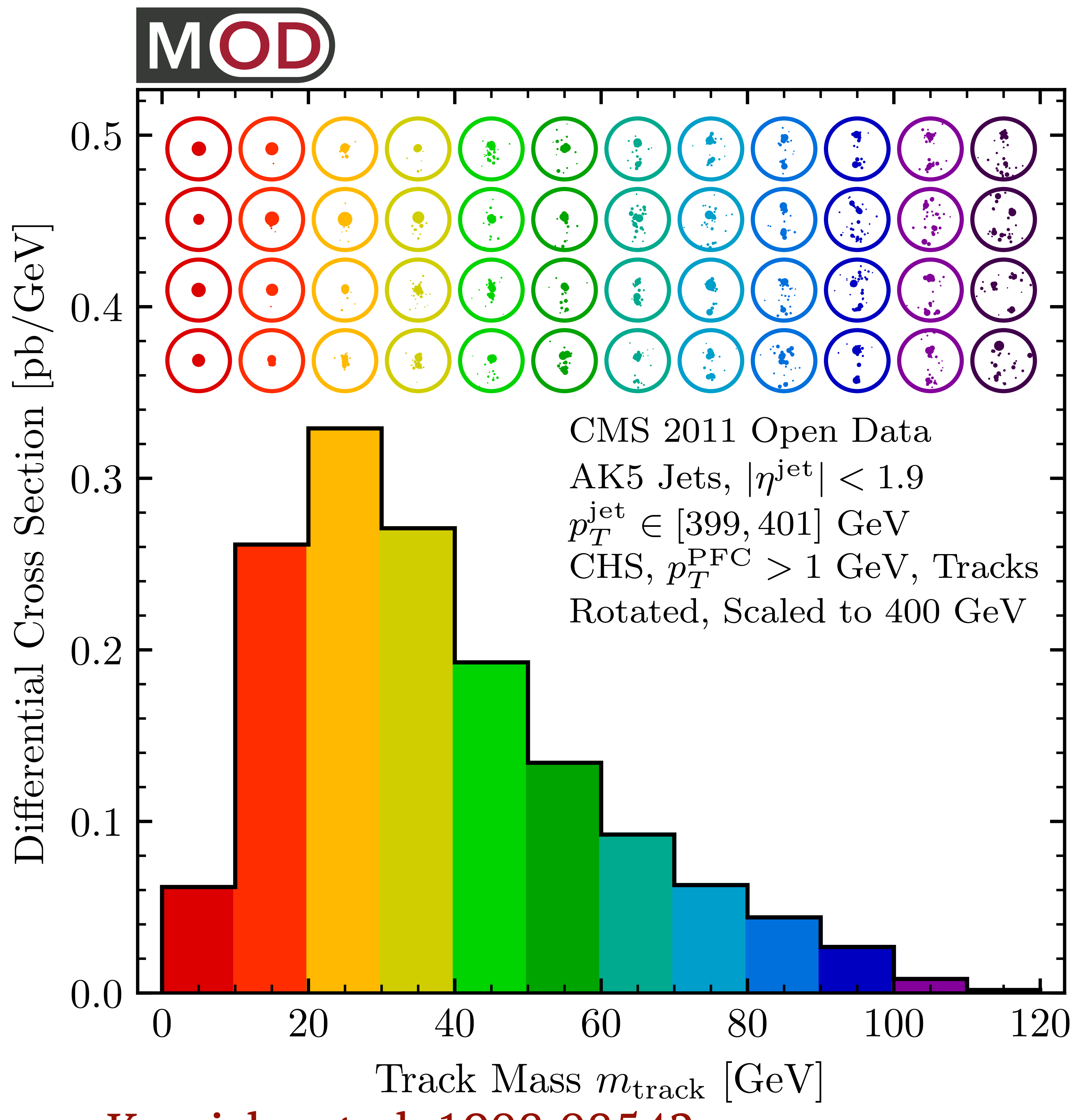


$$\frac{\mathrm{d}\sigma^{\mathrm{had}}}{\mathrm{d}\tau} = \int \mathrm{d}k\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\tau}\left(\tau - \frac{k}{Q}\right) S_\tau^{\mathrm{mod}}(k)$$

Nonperturbative corrections are clearly important, but does a simple shape function in the dijet region suffices?

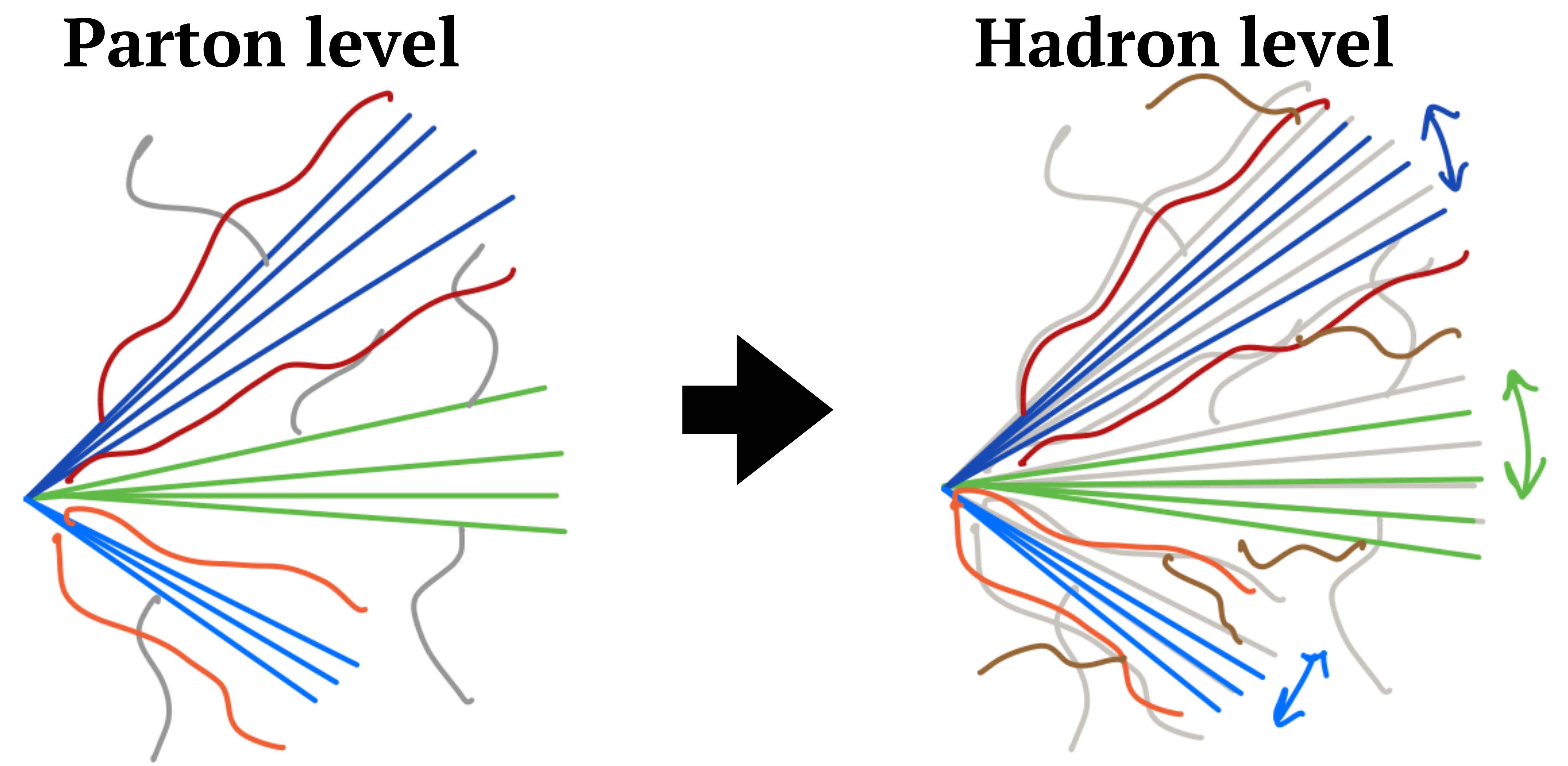
"Onginess" matters for hadronization

NP corrections in the $m_J \to 0$ region: $$\frac{(m_J^{\rm had})^2}{p_T^2R^2} = \frac{m_J^2}{p_T^2R^2} + \frac{\Omega_{1\kappa}}{p_TR} + \dots$$



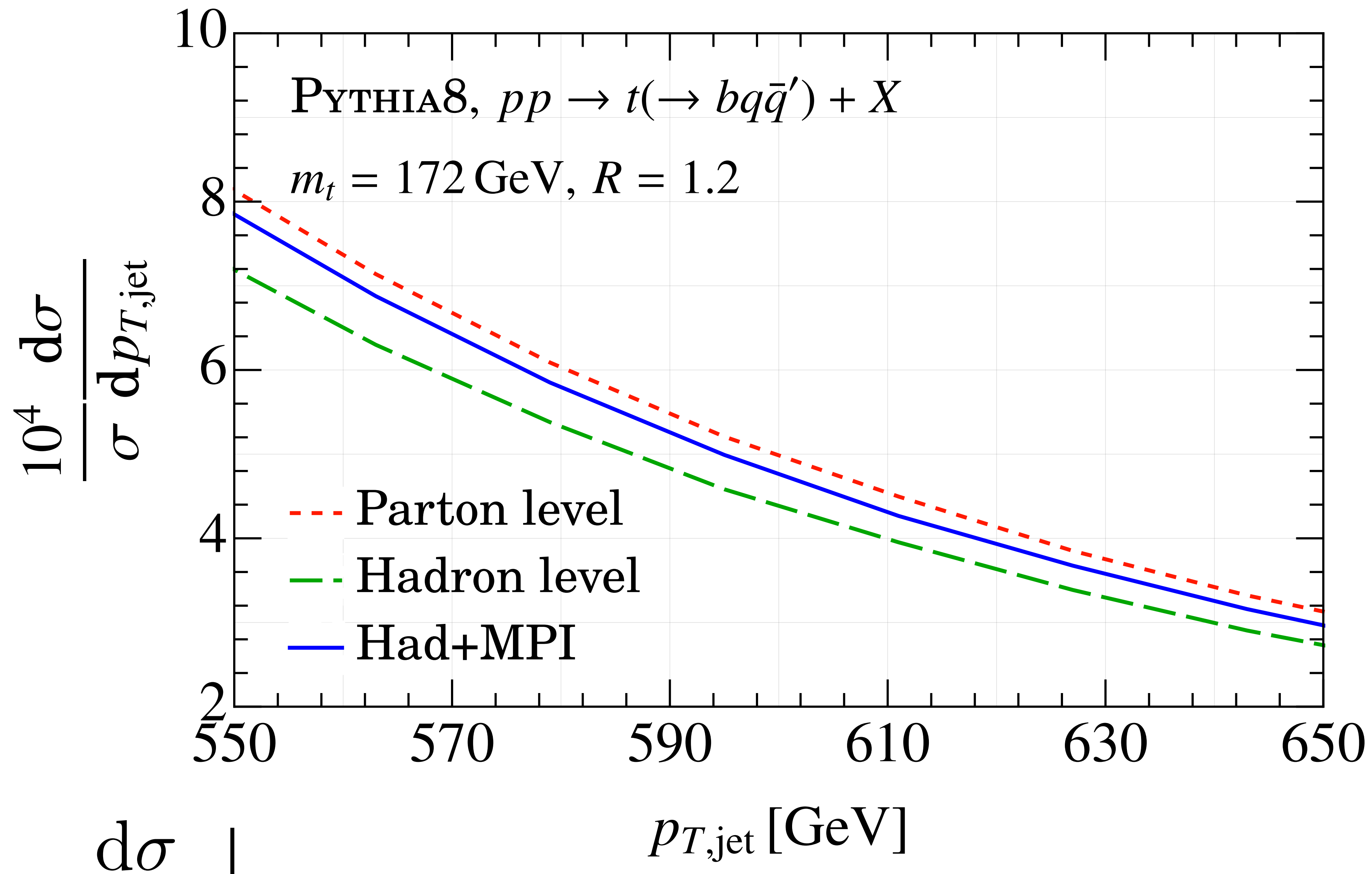
Komiske et al. 1908.08542

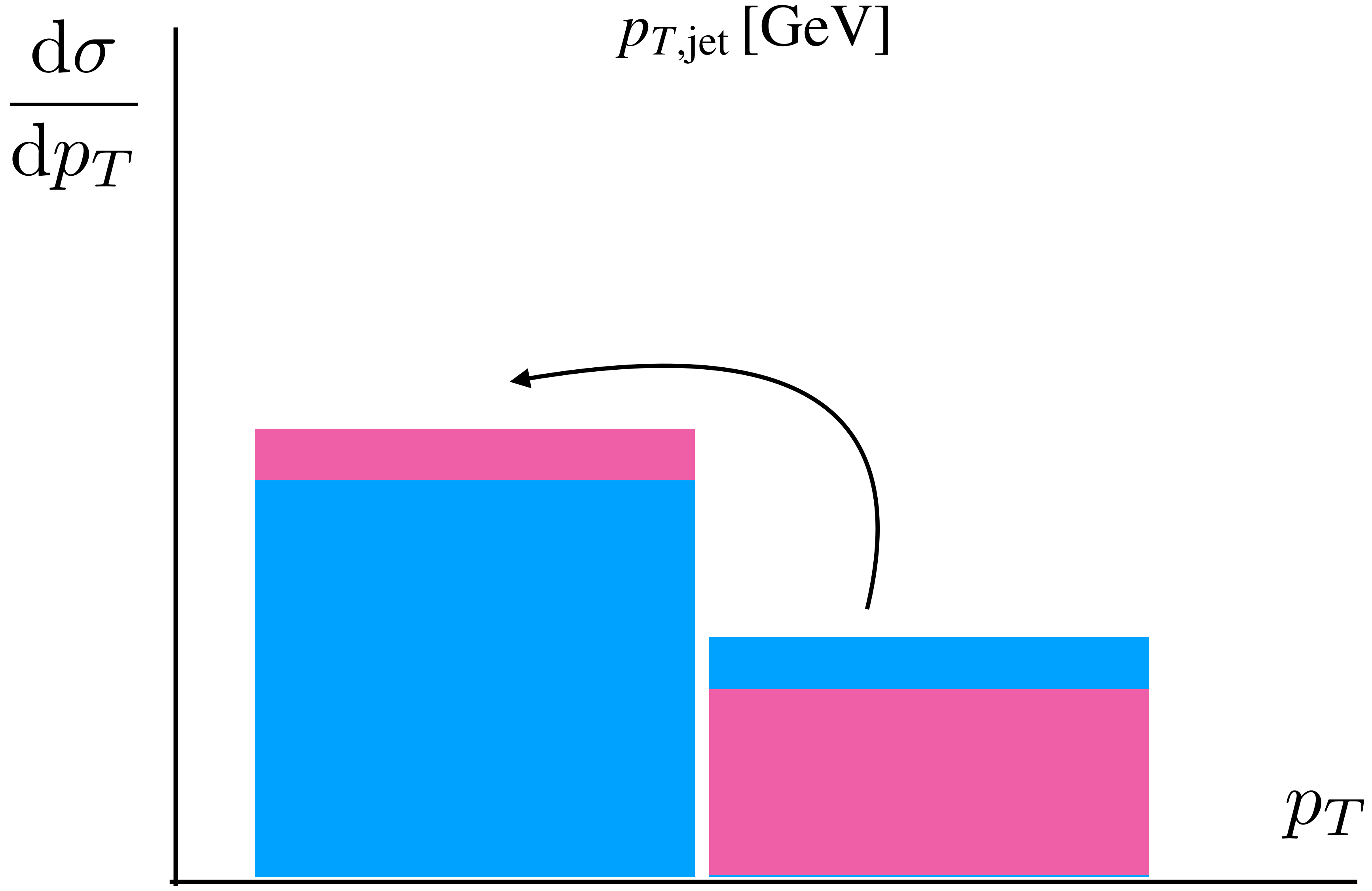
For larger jet masses we need to account for multi pronged nature of the radiation pattern of the jet:



NP corrections in multi pronged jets cannot be simply captured by a single $\mathcal{O}(\Lambda_{\rm QCD})$ constant

Boundary correction whenever there is a veto





Another type of hadronization effect whenever there is a veto of some sort:

$$p_T^{\mathrm{had}} R = p_T R + \Upsilon_{1\kappa} + \ldots$$

$$\Upsilon_{1\kappa} \sim \Lambda_{\mathrm{QCD}} < 0$$

Dasgupta, Magnea, Salam 2007

1. Leads to migration of events to lower p_T bin

2. Events at the edges of the bin are impacted

3. Impacts the normalisation: not a shift in the jet mass

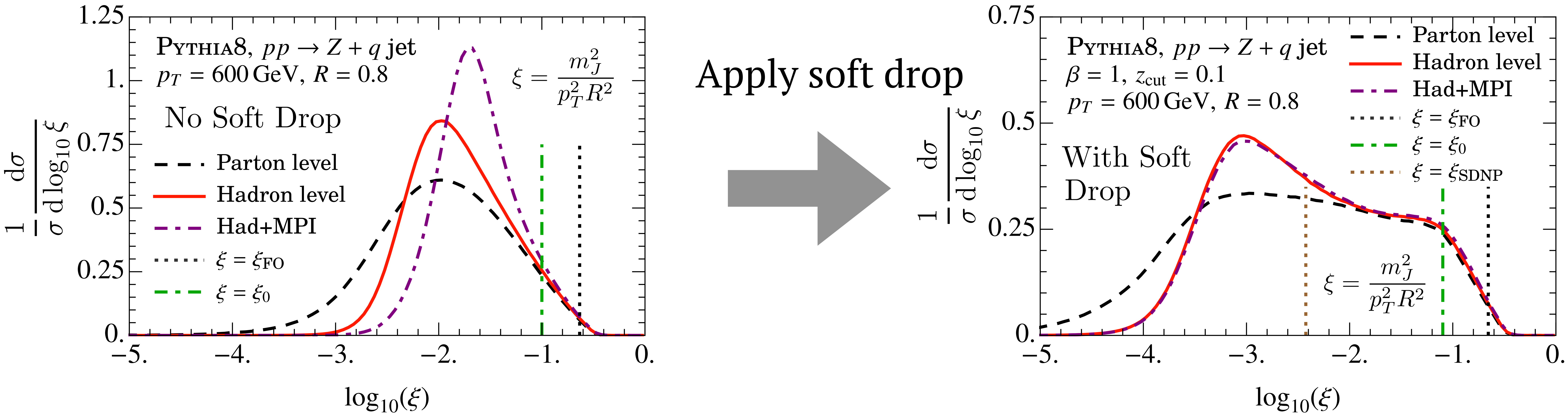
Outline

1. NP corrections in soft drop jet mass

2. Calibrating MC Hadronization models

3. Application for α_s measurement

Why soft drop jet mass?



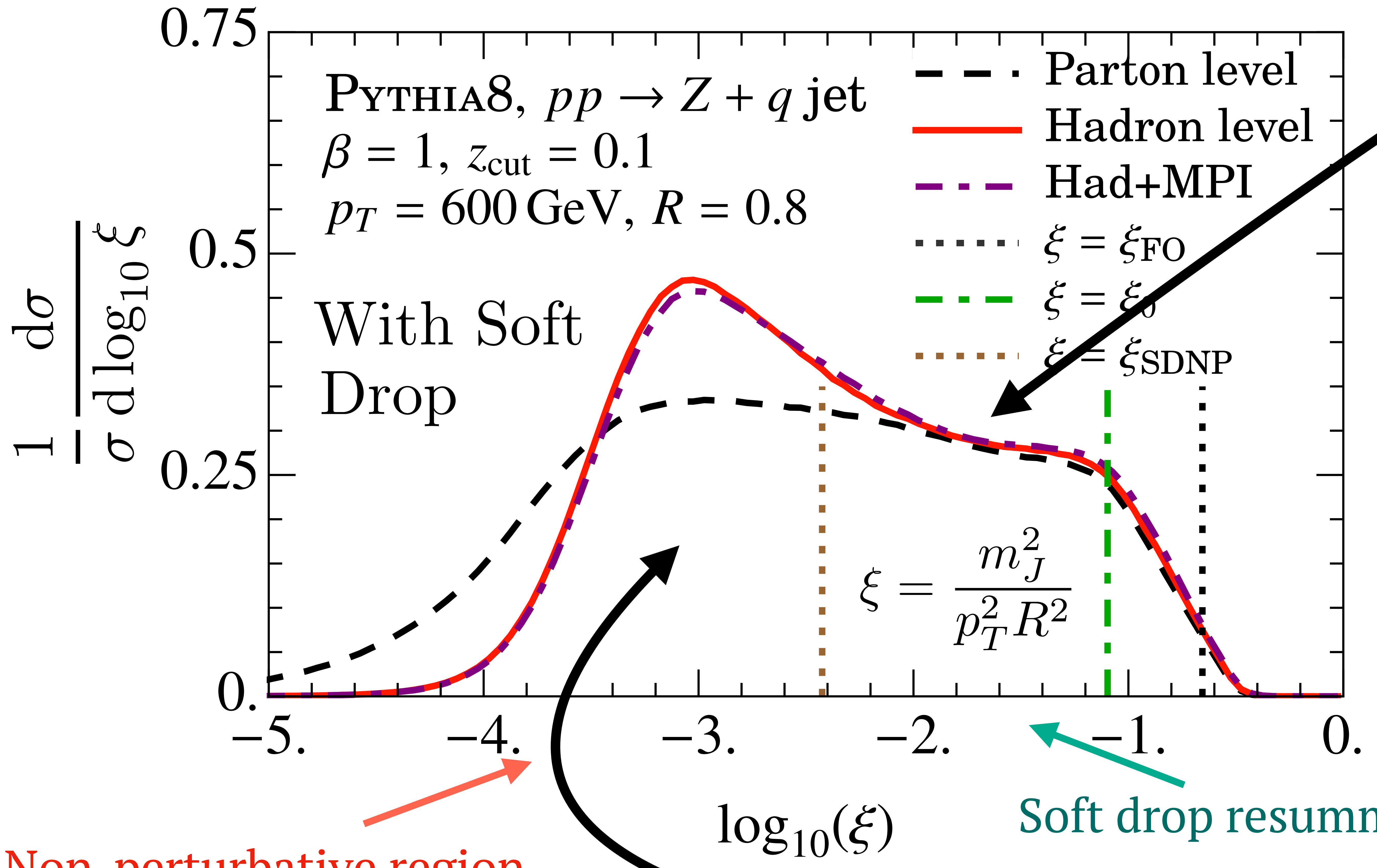
- **Measurable** and **calculabe** observable for hadron colliders
- Reduces sensitivity to underlying event & hadronization effects

[Les Houches 2017] [Larkoski, Marzani, Soyez, Thaler 2014]

Perturbative region is two-pronged

The region where soft drop is active and perturbatively calculable has an interesting two pronged geometry

Hoang, Mantry, AP, Stewart, 2019

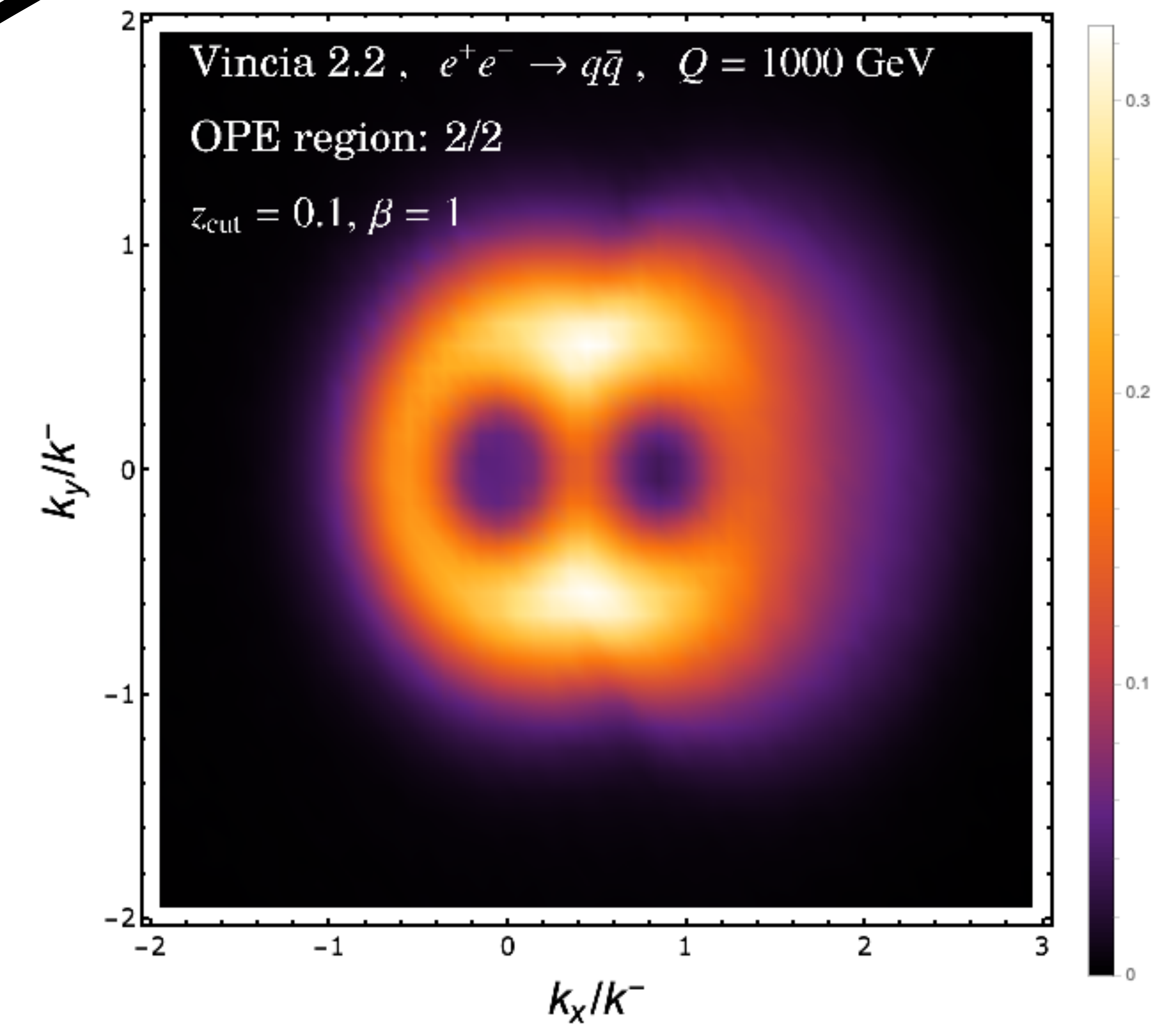


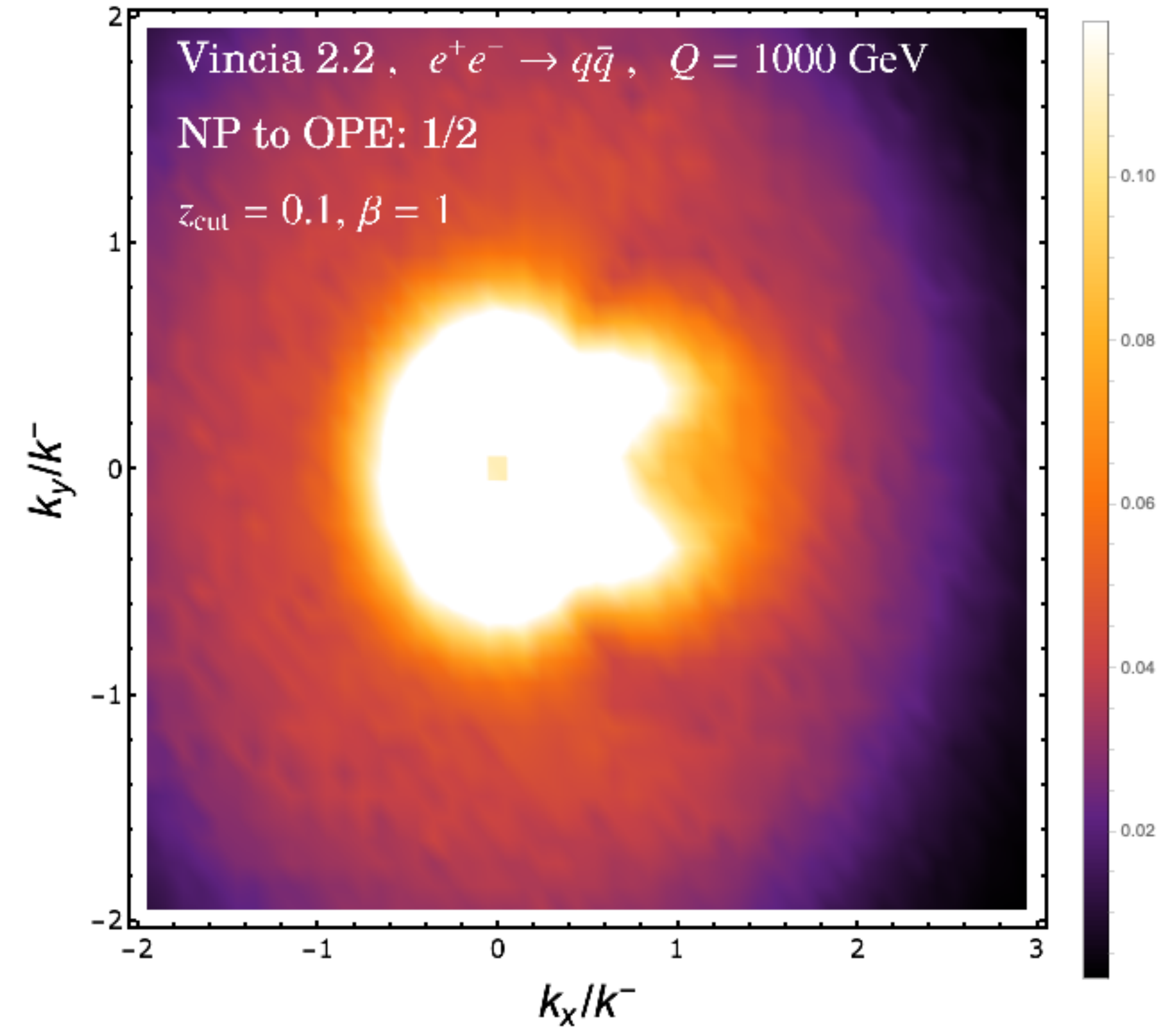
Non-perturbative region

(no theoretical control)

Soft drop resummation region

(perturbatively calculable)



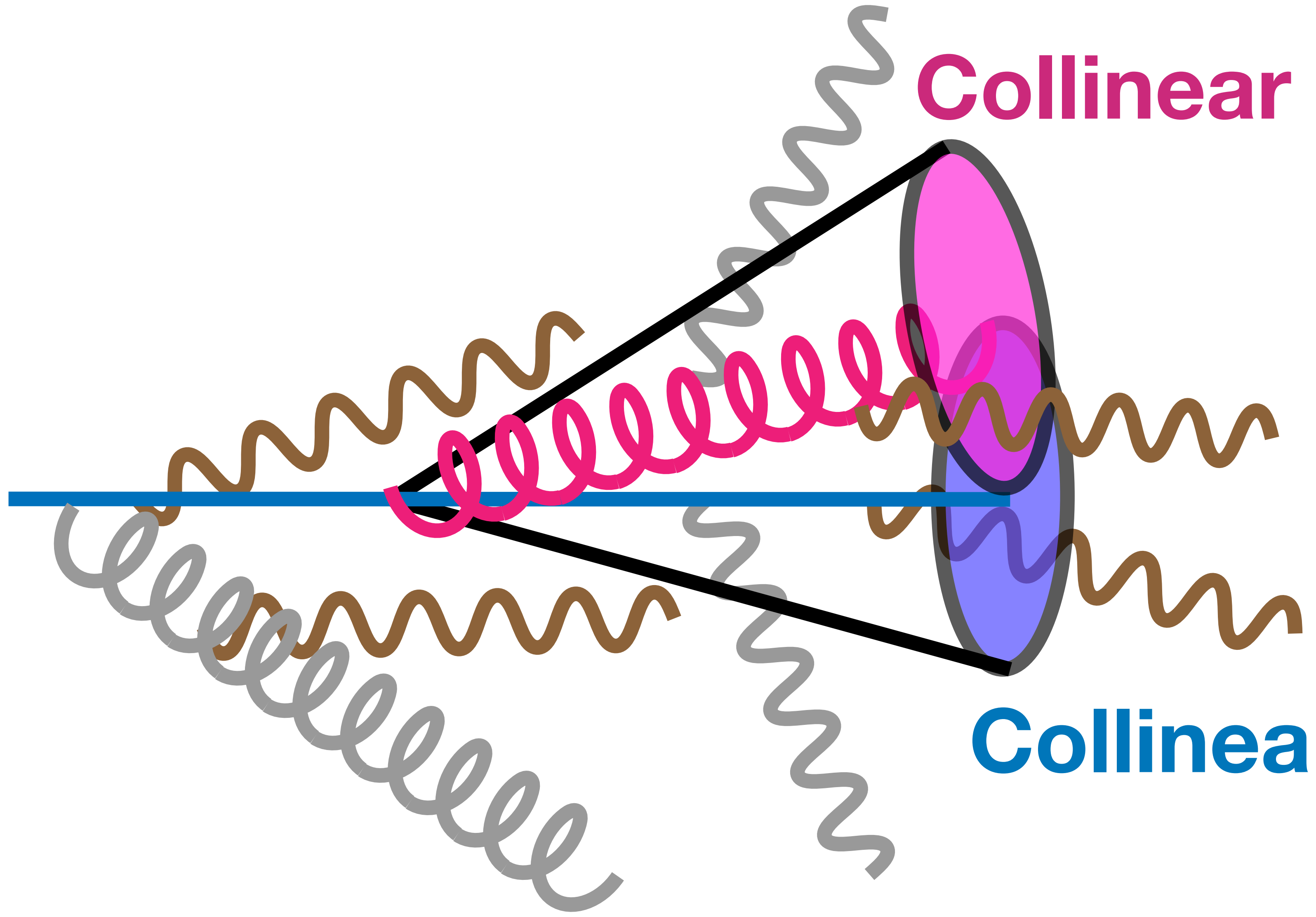


Shift and boundary corrections in SD jet mass

Shift correction in the groomed jet mass involves $R \to R_g$

Hoang, Mantry, AP, Stewart, 2019

$$\frac{(m_{J,\mathrm{gr}}^{\mathrm{had}})^2}{p_T^2 R_g^2} = \frac{m_{J,\mathrm{gr}}^2}{p_T^2 R_g^2} + \frac{\Omega_{1\kappa}^{\circledcirc}}{p_T R_g} + \ldots$$



Note that jet mass alone cannot describe the NP corrections:

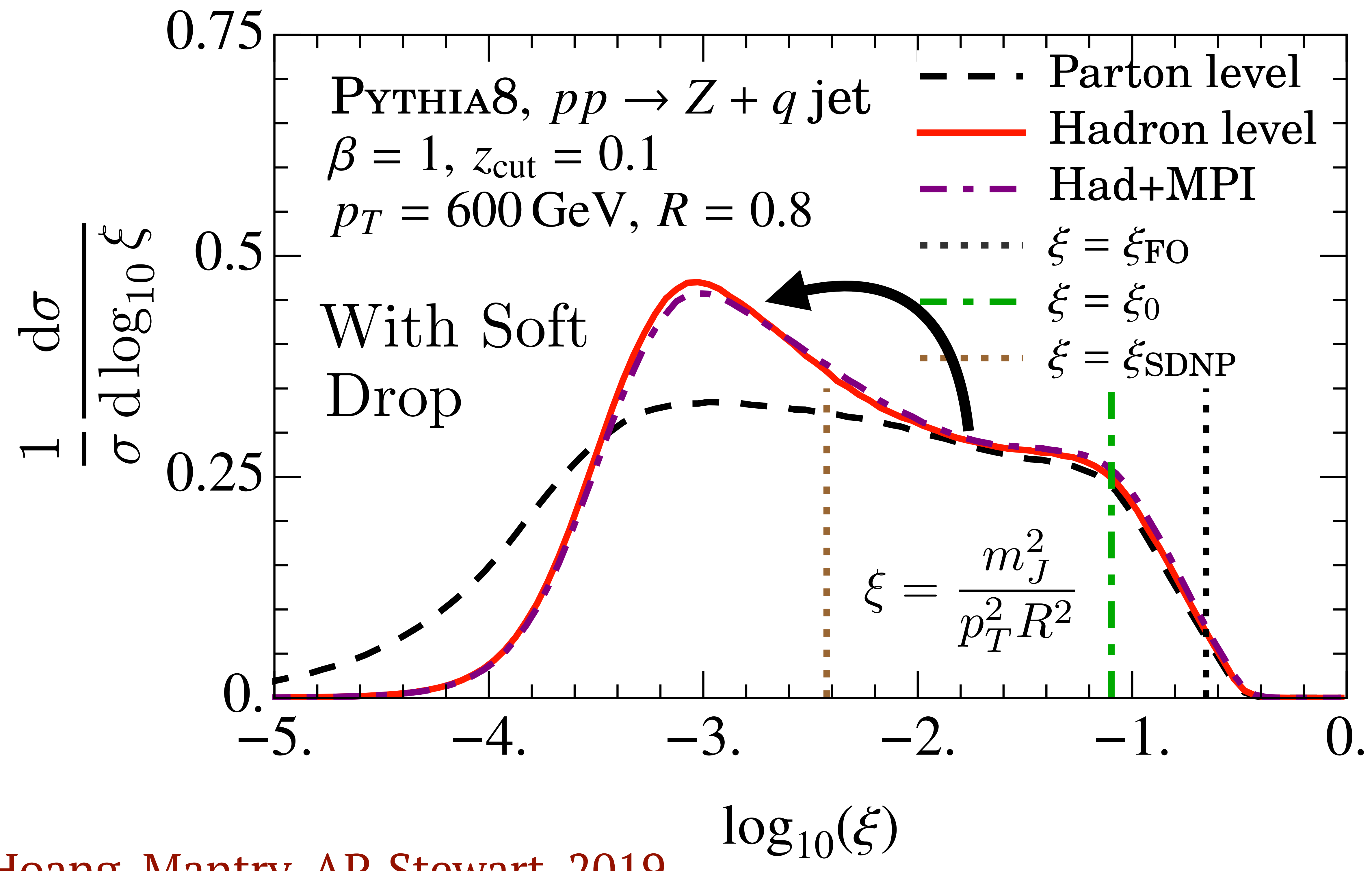
- Need an auxiliary measurement of R_g for the two pronged jet

$$\frac{1}{\sigma_\kappa}\frac{\mathrm{d}\sigma_\kappa^{\mathrm{had}}}{\mathrm{d}\xi}\bigg|_{\mathrm{shift}} = \frac{1}{\hat\sigma_\kappa}\frac{\mathrm{d}\hat\sigma_\kappa}{\mathrm{d}\xi} - \frac{\Omega_{1\kappa}^{\circledcirc}}{Q}\frac{\mathrm{d}}{\mathrm{d}\xi}\left(\int \mathrm{d}r_g\, r_g\,\frac{1}{\hat\sigma_\kappa}\frac{\mathrm{d}^2\hat\sigma_\kappa}{\mathrm{d}\xi\,\mathrm{d}r_g}\right) \qquad r_g = \frac{R_g}{R}\,, \qquad Q = p_T R$$

Final correction obtained by **marginalizing over** R_g

Shift and boundary corrections in SD jet mass

Despite the fact that SD is NOT a veto on jets, 2-pronged jets can turn into 1-pronged jets if they fail SD



Hoang, Mantry, AP, Stewart, 2019

$$z_g < z_{\rm cut} R_g^\beta \,, \qquad \text{(subjet fails soft drop)}$$

Analogous to the effect on $p_{T,\rm jet}$:

$$z_g^{\rm had} R_g = z_g R_g + \frac{\Upsilon^{\circledcirc}_{1,0\kappa}}{p_T} + \ldots \,,$$

$$R_g^{\rm had} = R_g - \frac{\Upsilon^{\circledcirc}_{1,1\kappa}}{p_T} \,.$$

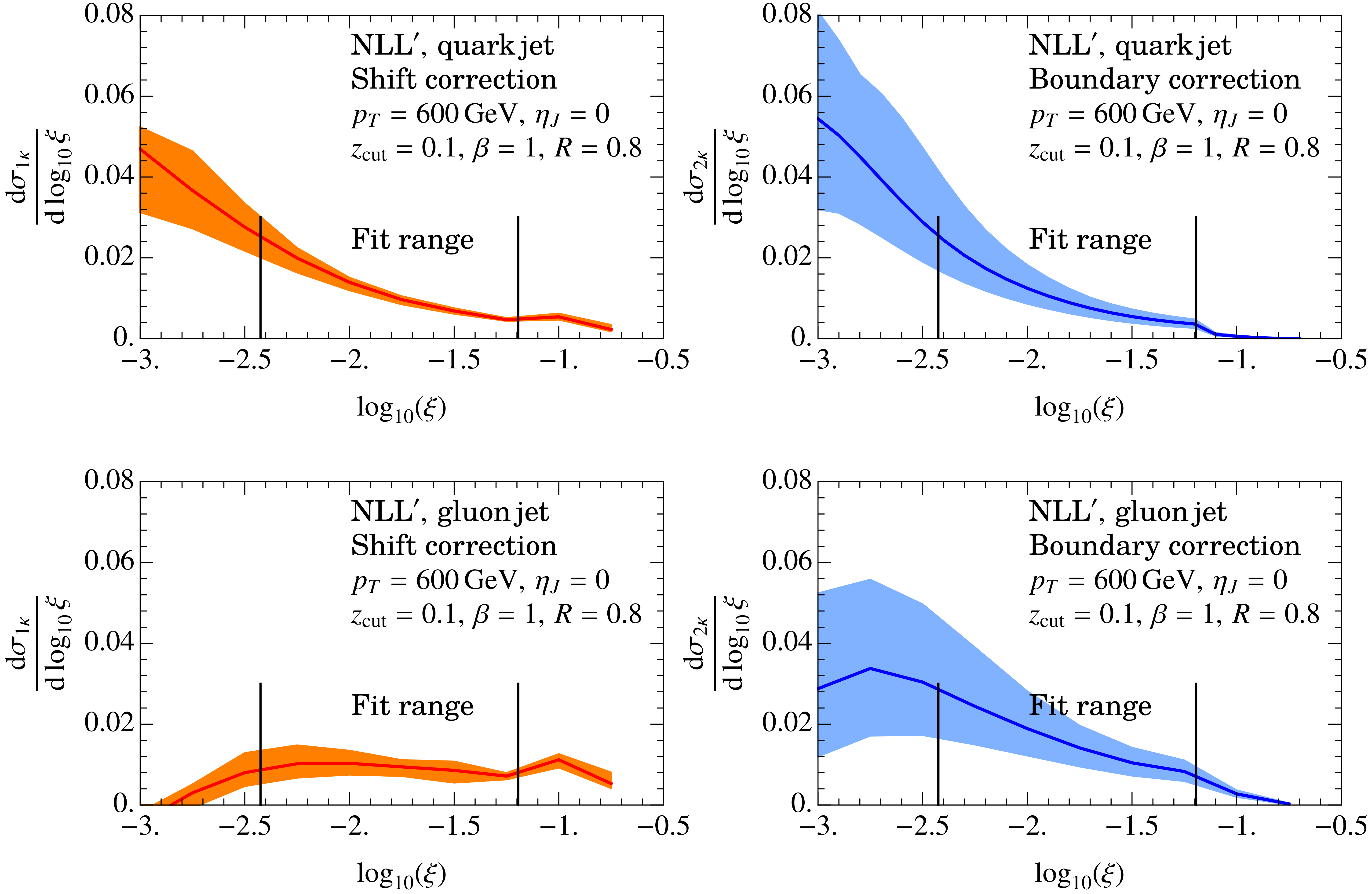
$$\frac{1}{\sigma_\kappa}\frac{d\sigma_\kappa^{\rm had}}{d\xi}\bigg|_{\rm bndry} = \frac{\Upsilon^{\circledcirc}_{1,0\kappa} + \beta\Upsilon^{\circledcirc}_{1,1\kappa}}{Q}\int dr_g \int dz_g \,\frac{1}{r_g}\,\frac{1}{\hat\sigma_\kappa}\,\frac{d^3\hat\sigma_\kappa}{d\xi\, dr_g\, dz_g}\,\delta(z_g - z_{\rm cut} r_g^\beta)$$

Here we need both R_g and z_g auxiliary measurements at the boundary of the soft drop

Jet mass dependence of NP corrections

Hoang, Mantry, AP, Stewart, 2019

$$\frac{1}{\sigma_\kappa}\frac{d\sigma_\kappa}{d\xi} = \frac{1}{\hat{\sigma}_\kappa}\frac{d\hat{\sigma}_\kappa}{d\xi} + \Omega^{\circledast}_{1\kappa}\frac{1}{\sigma_\kappa}\frac{d\hat{\sigma}_{1\kappa}}{d\xi} + \left(\Upsilon^{\circledcirc}_{1,0\kappa} + \beta\Upsilon^{\circledcirc}_{1,1\kappa}\right)\frac{1}{\sigma_\kappa}\frac{d\hat{\sigma}_{2\kappa}}{d\xi}$$



Studying soft drop jet mass makes it clear that multi-pronged jets cannot be described by constant NP parameters alone:

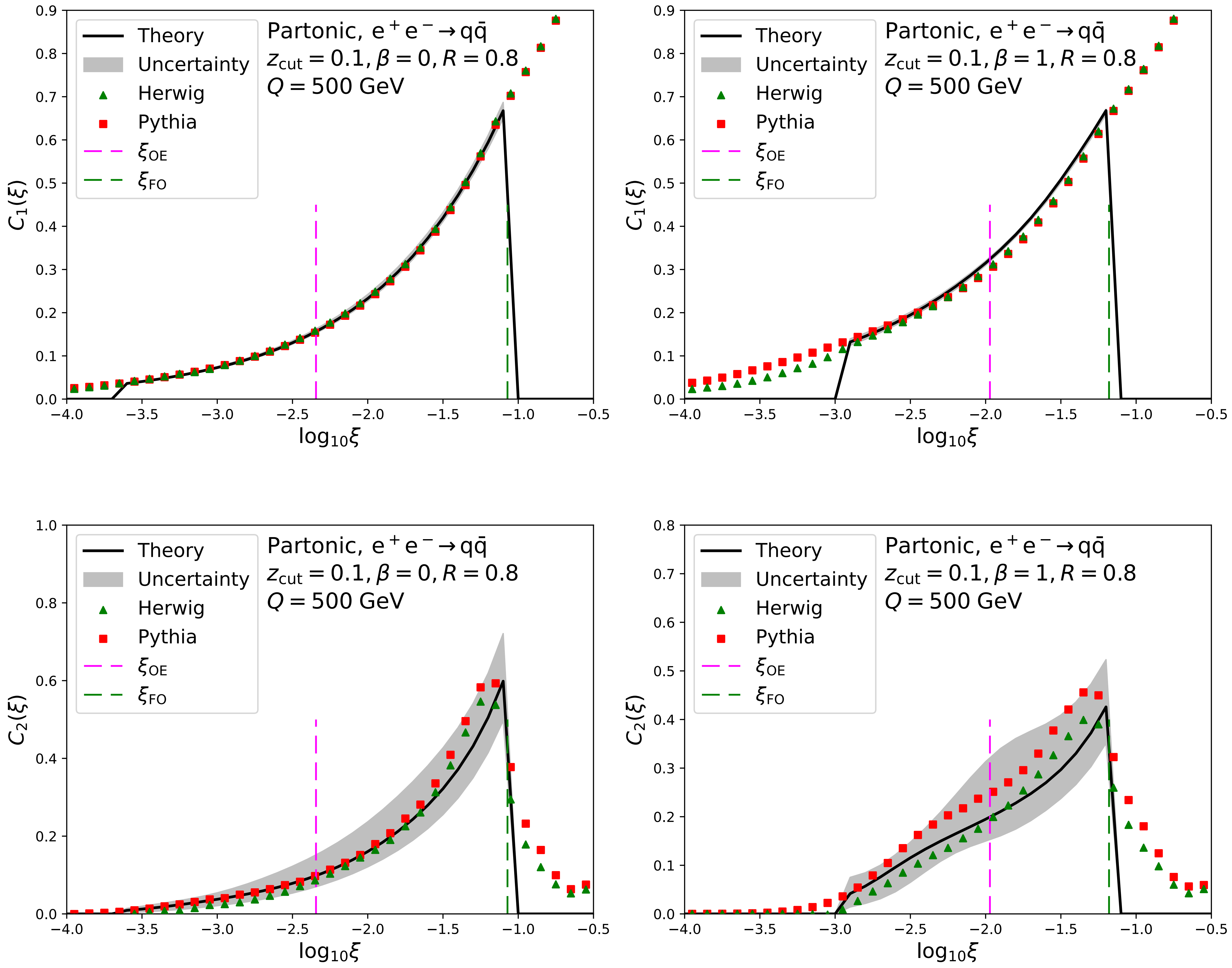
- Need non-trivial jet mass dependent weighted cross sections

These weights are perturbatively calculable

[AP, Stewart, Vaidya, Zoppi 2020] [AP, to appear]

MC agrees well with parton level weights

Hoang, Mantry, AP, Stewart, 2019



Compare the weighted cross sections with parton showers by normalizing with jet mass cross section:

$$C_1(\xi) \equiv \frac{1}{\mathrm{d}\hat{\sigma}/\mathrm{d}\xi} \int \mathrm{d}r_g \, r_g \frac{\mathrm{d}^2\hat{\sigma}_\kappa}{\mathrm{d}\xi \mathrm{d}r_g}$$

$$C_2(\xi) \equiv \frac{1}{\mathrm{d}\hat{\sigma}/\mathrm{d}\xi} \int \mathrm{d}r_g \int \mathrm{d}z_g \, \frac{1}{r_g} \frac{1}{\hat{\sigma}_\kappa} \frac{\mathrm{d}^3\hat{\sigma}_\kappa}{\mathrm{d}\xi \mathrm{d}r_g \mathrm{d}z_g} \delta(z_g - z_{\mathrm{cut}} r_g^\beta)$$

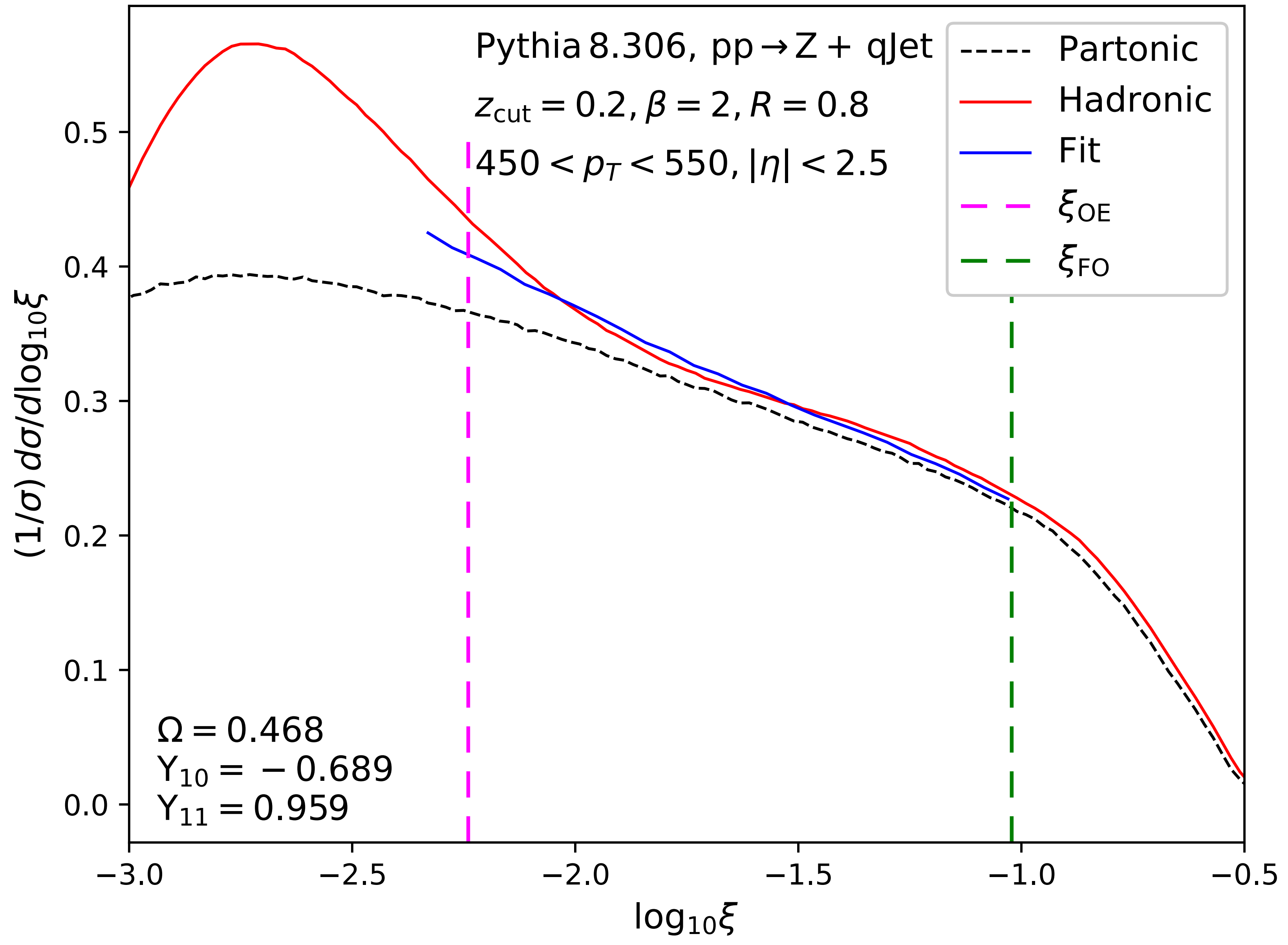
Good agreement of NLL$'$ calculation within perturbative uncertainty

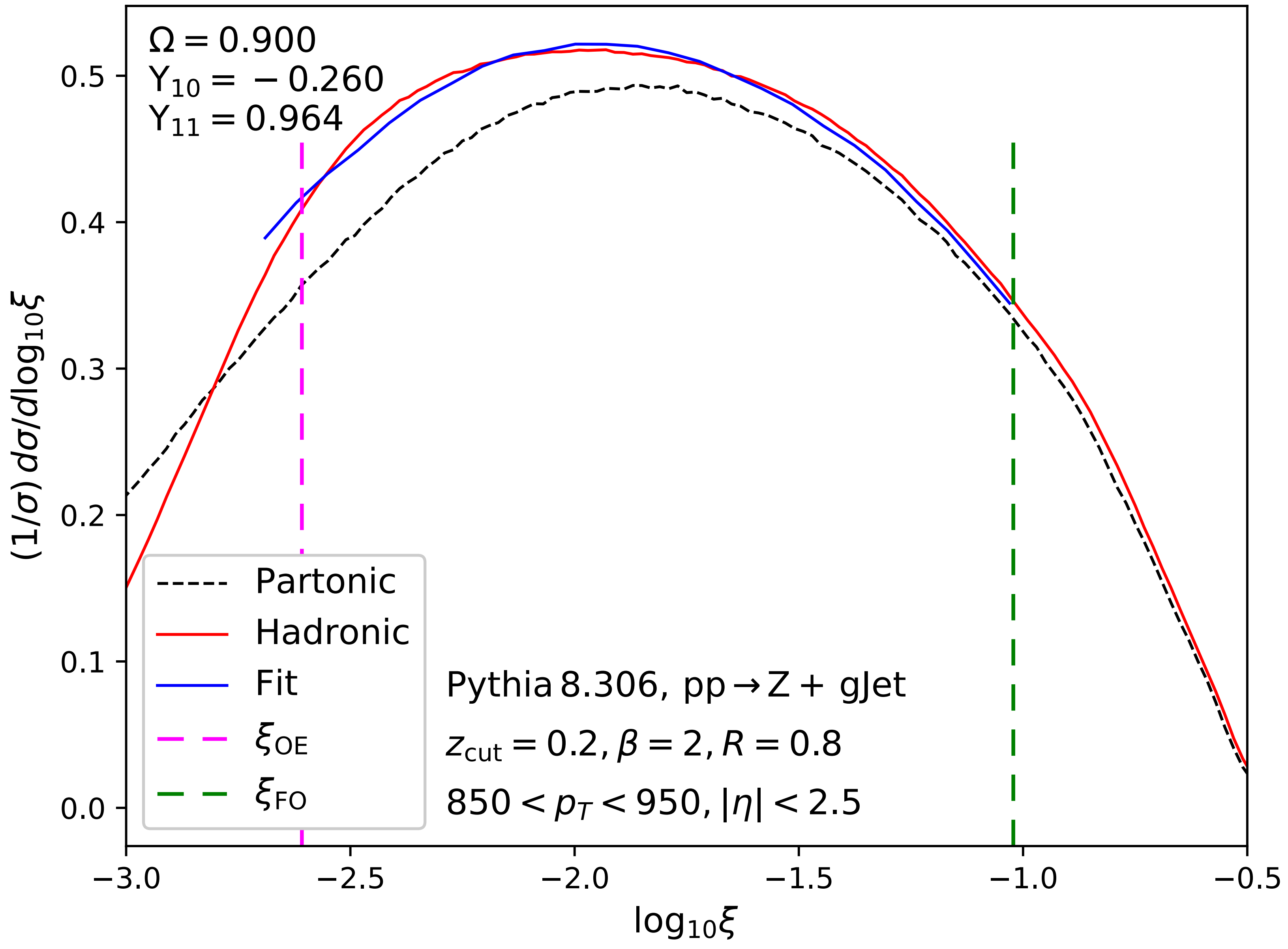
Calibrating the MC Hadronization models using soft drop jet mass

Ferdinand, Lee, AP (to appear)

Test predictions against MC

The NP parameters are found through least squares fitting from parton to the hadron level using theory calculations of C_1 and C_2



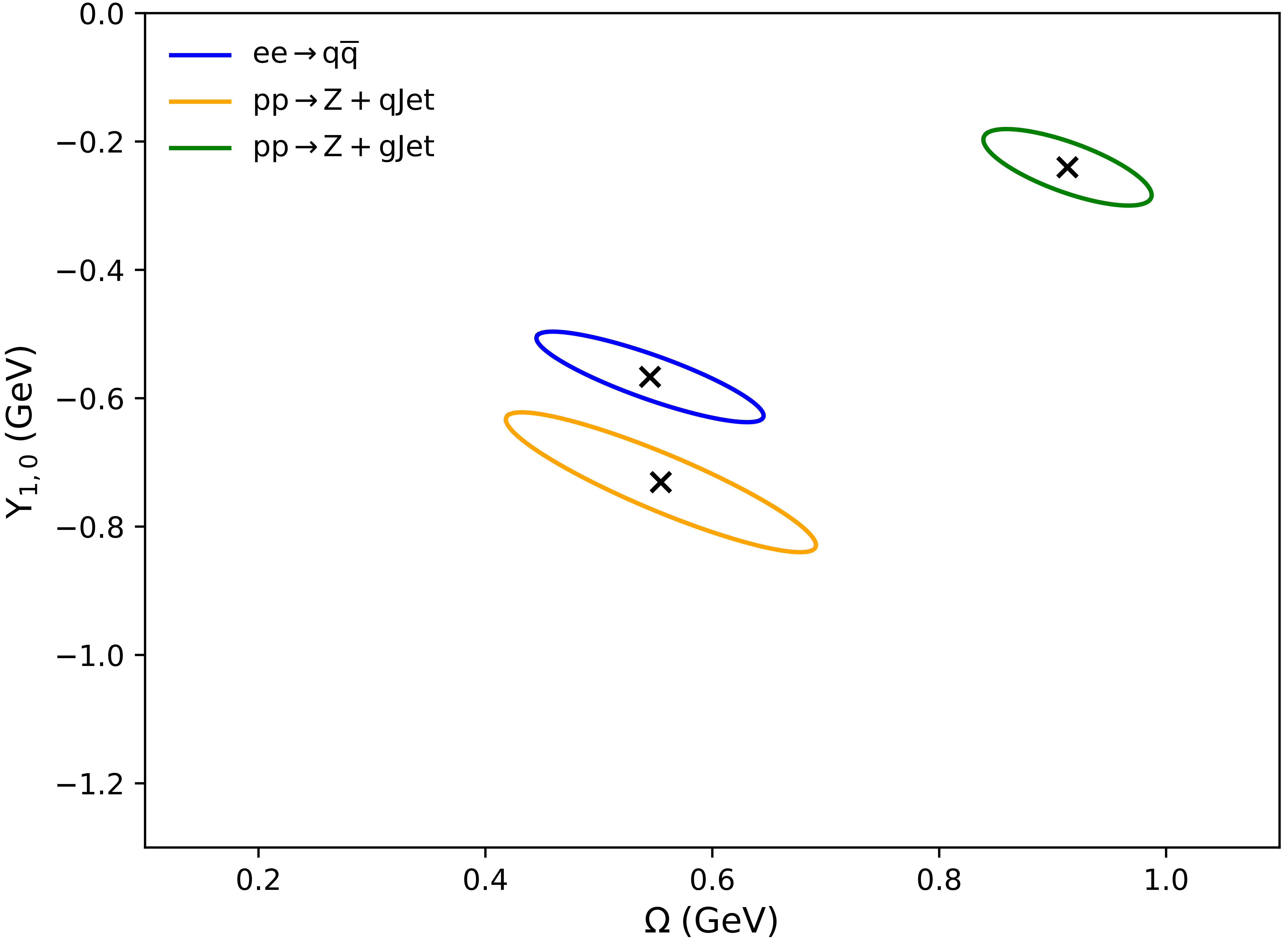


From theory we expect:

1. The parameters to be $\mathcal{O}(1\text{ GeV})$
2. Universal for quark jets
3. Universal for soft drop parameters

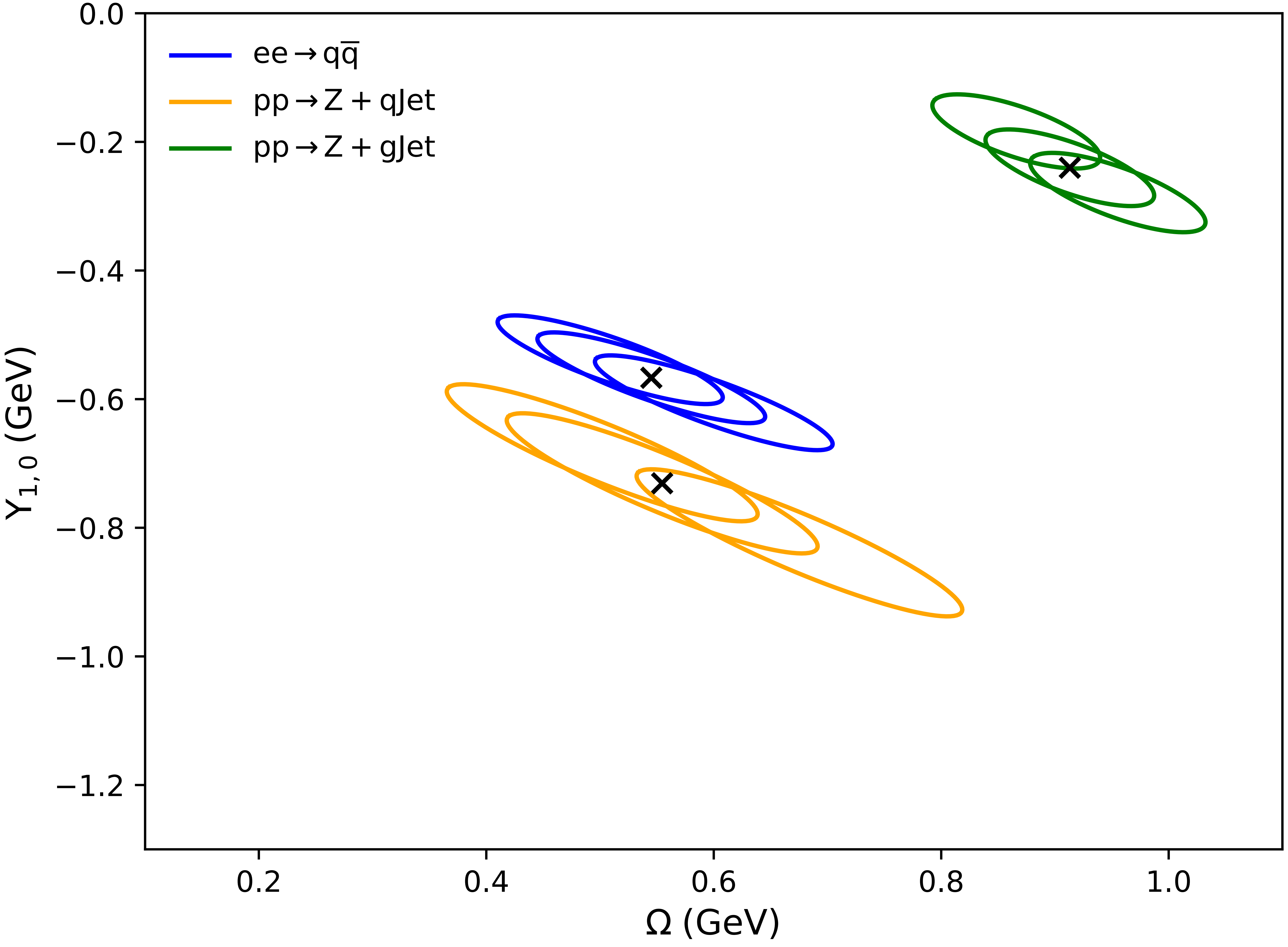
Testing quark jet universality

Let us test universality by testing if fit parameters for $e^+e^- \to q\bar{q}$ and $pp \to Z + q$ Jet agree



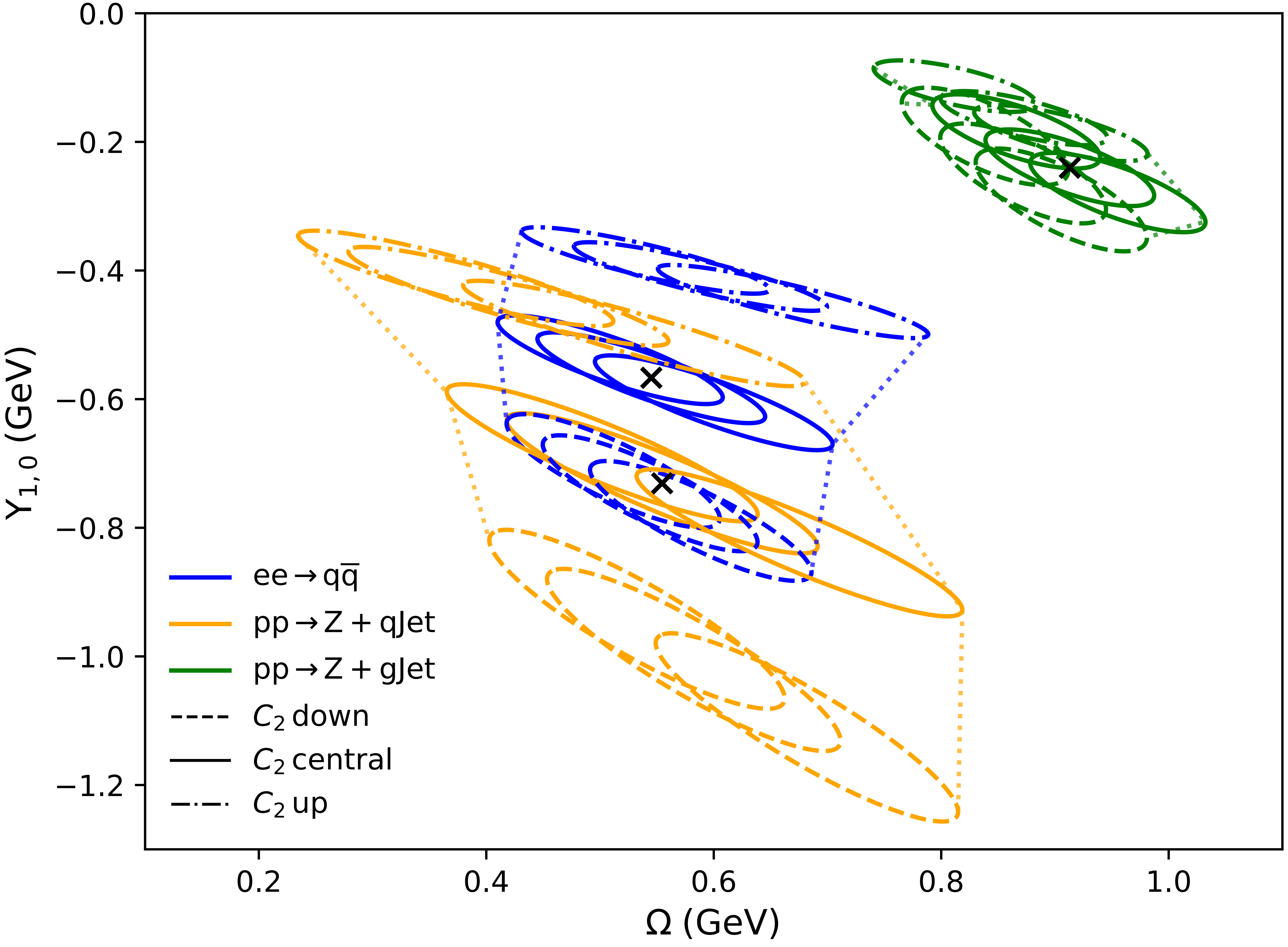
Testing quark jet universality

Now add the include variation due to perturbative uncertainty in C_1



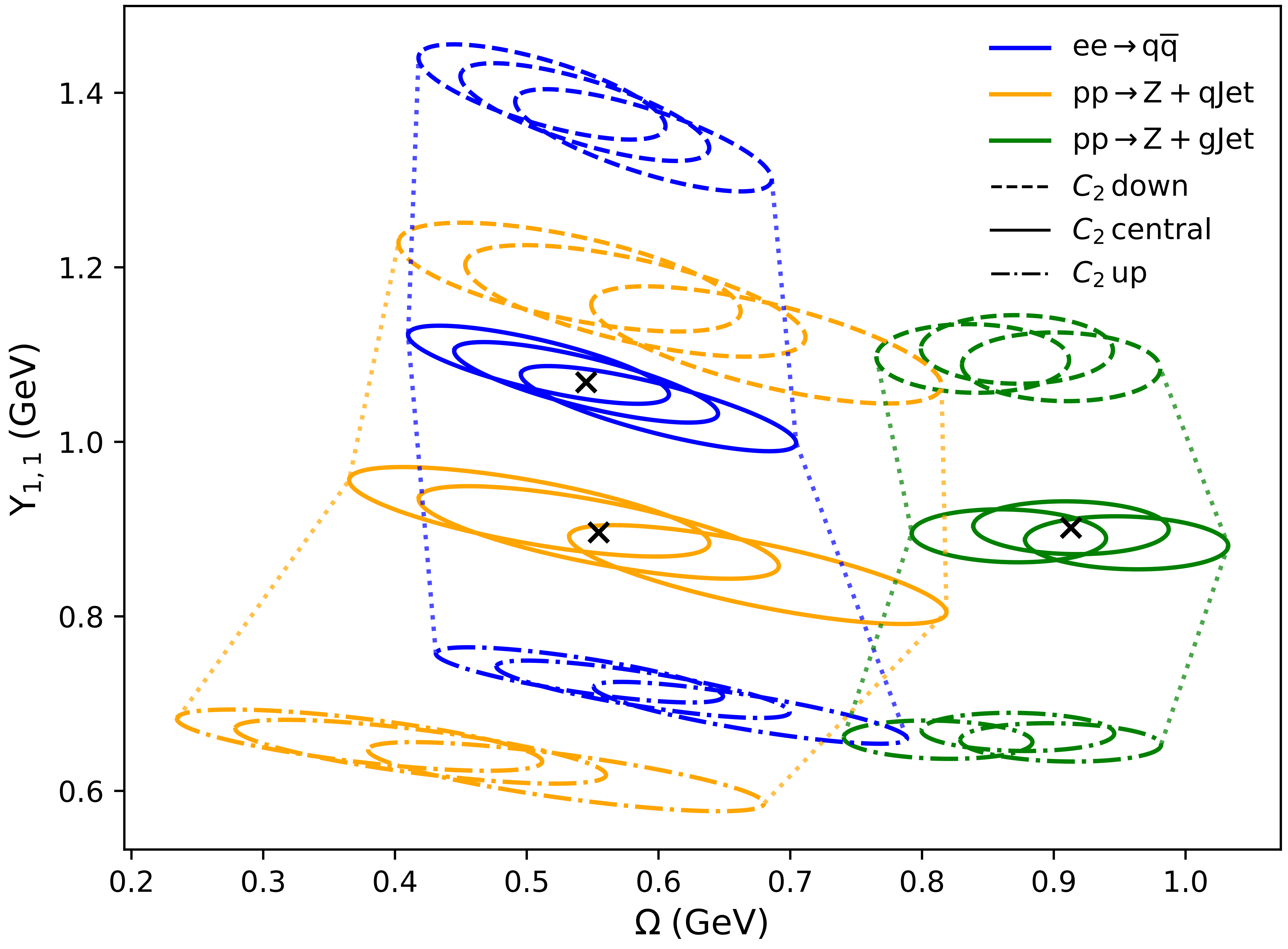
Testing quark jet universality

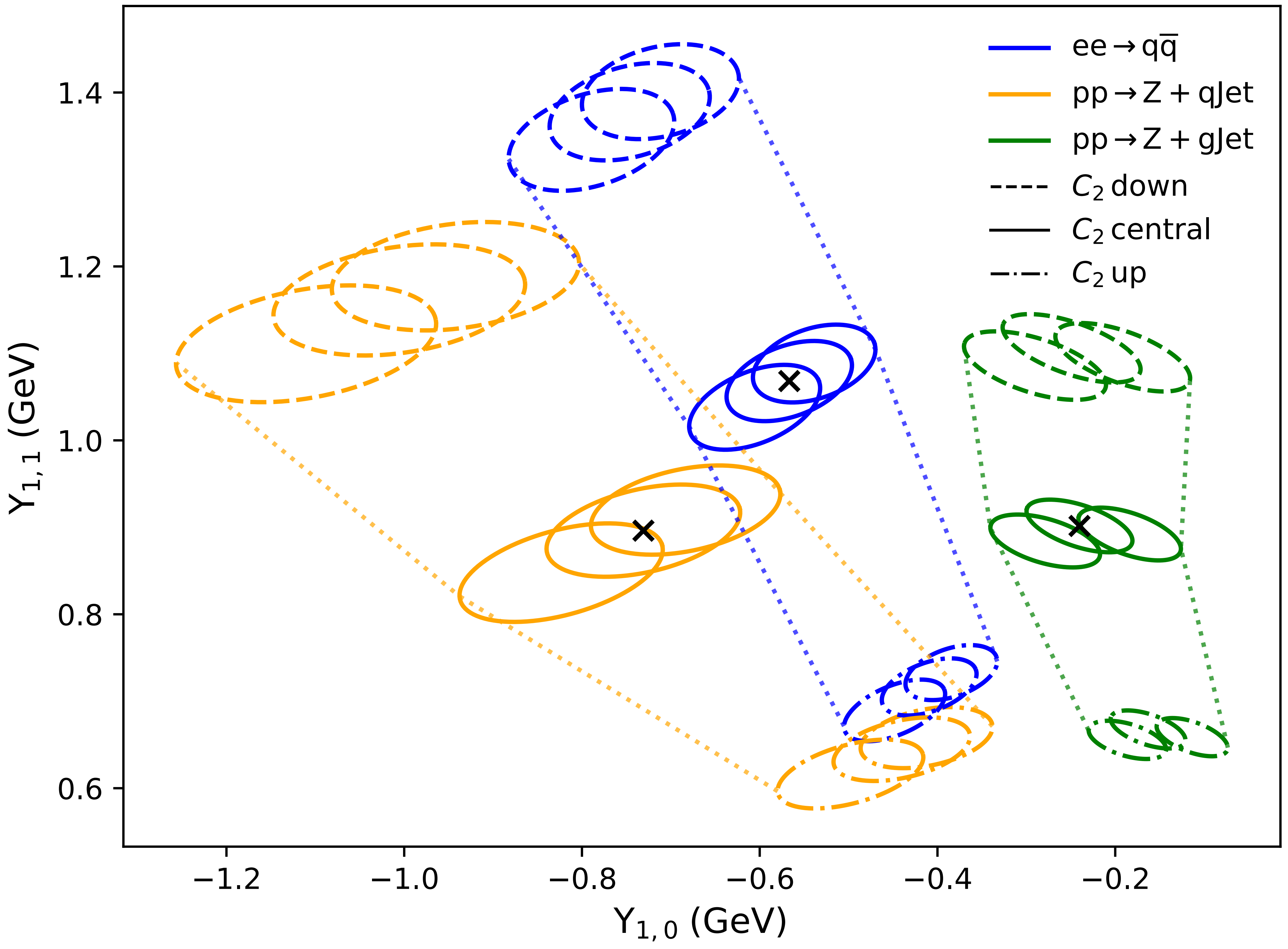
Include perturbative uncertainty in C_2 as well:



Testing quark jet universality

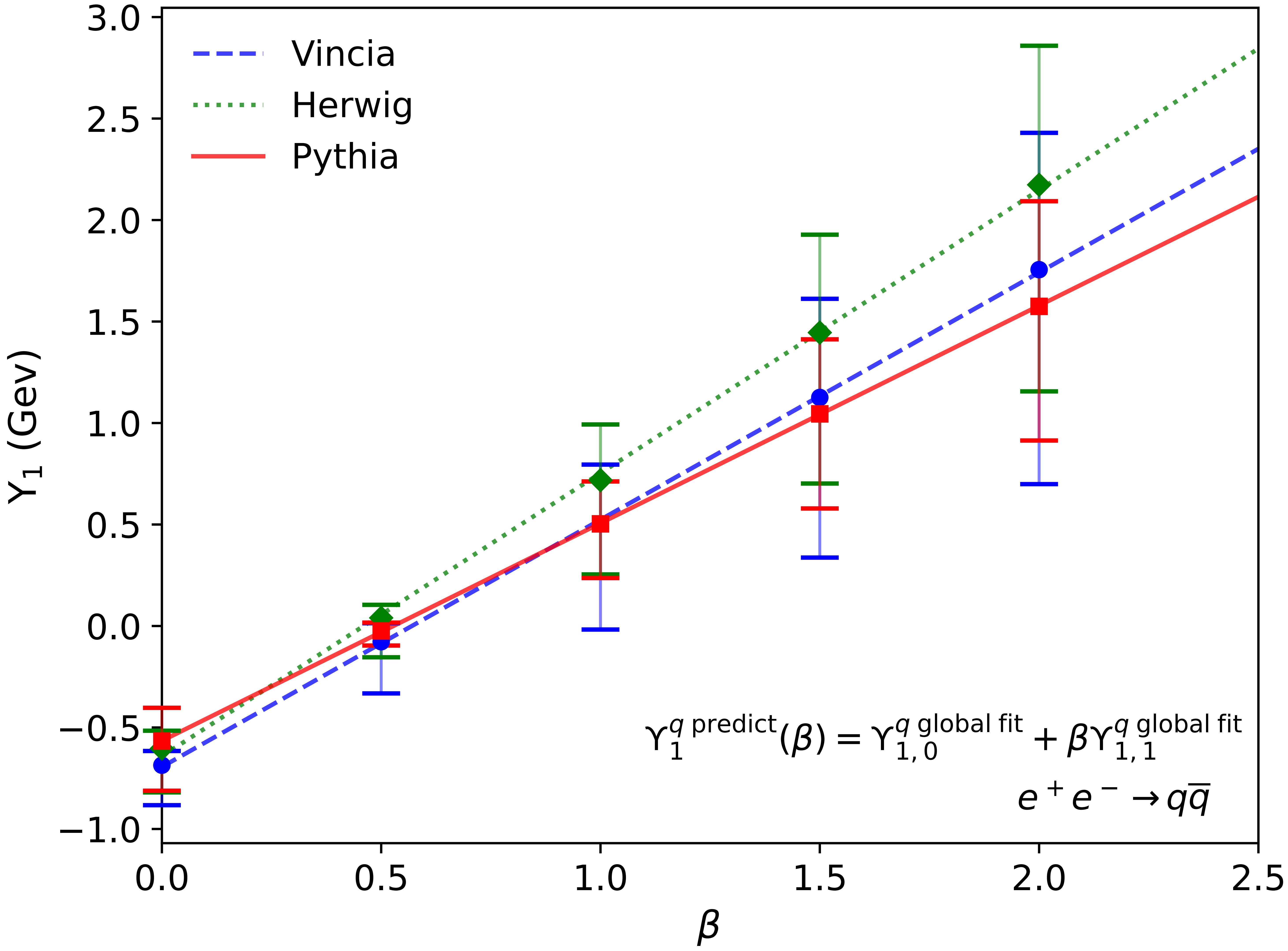
Quark jets in the two process display compatible behaviour for the two processes in Pythia8





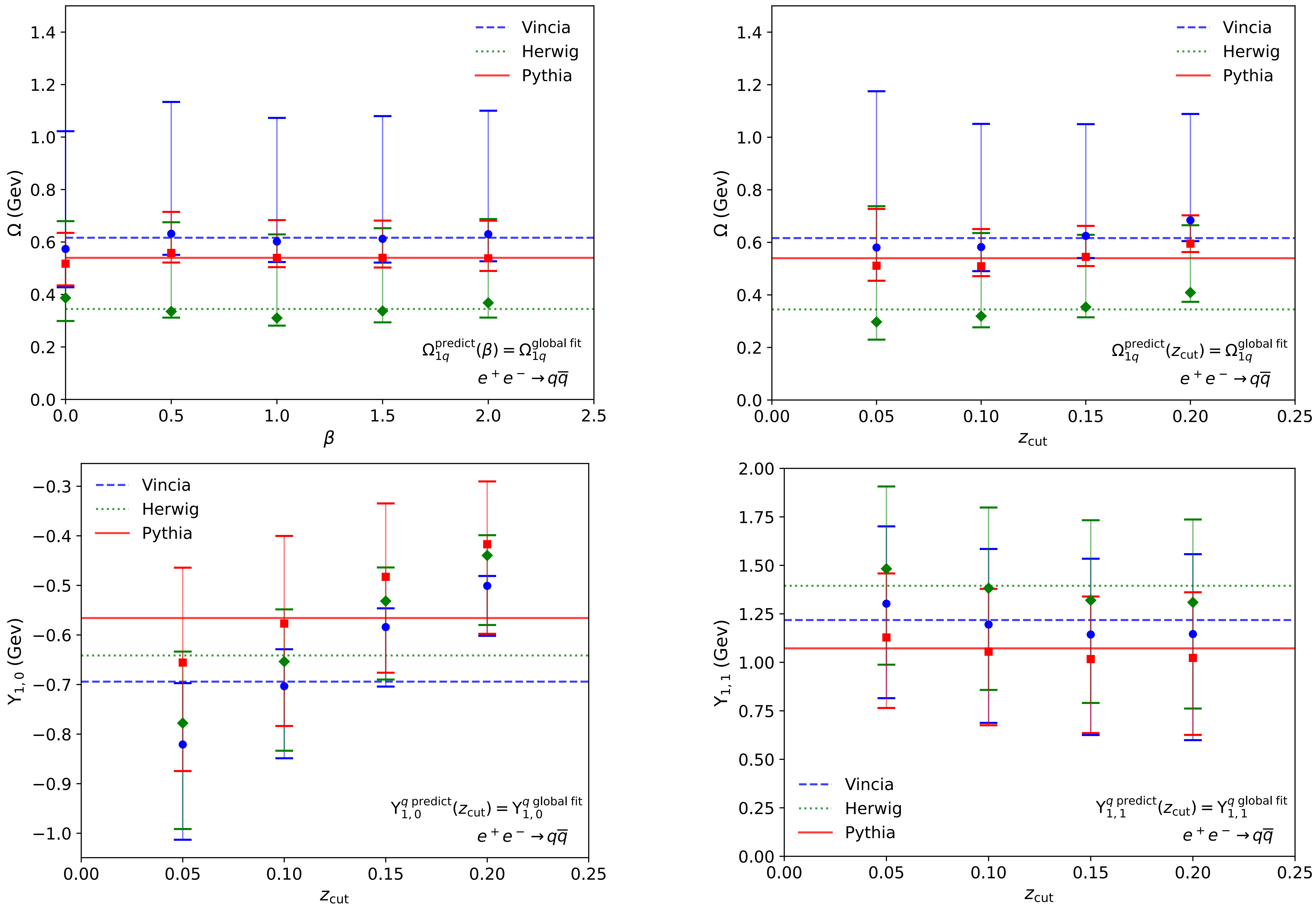
Testing soft drop parameters (in)dependence

We predicted that the boundary correction is linear in β:



Testing soft drop parameters (in)dependence

Verify other universality cases: good agreement within perturbative uncertainty



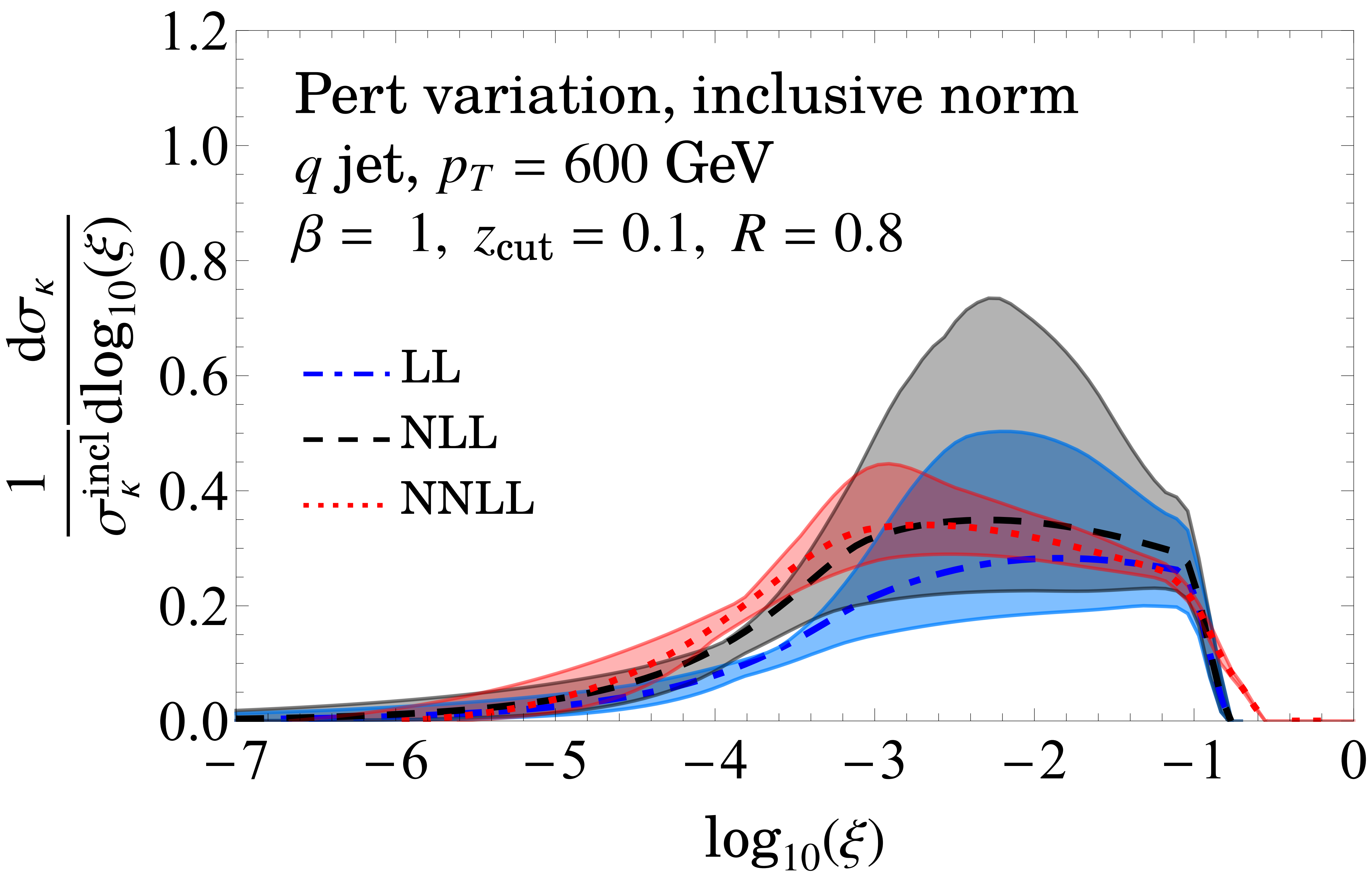
Prospects for SD jet mass for α_s measurement

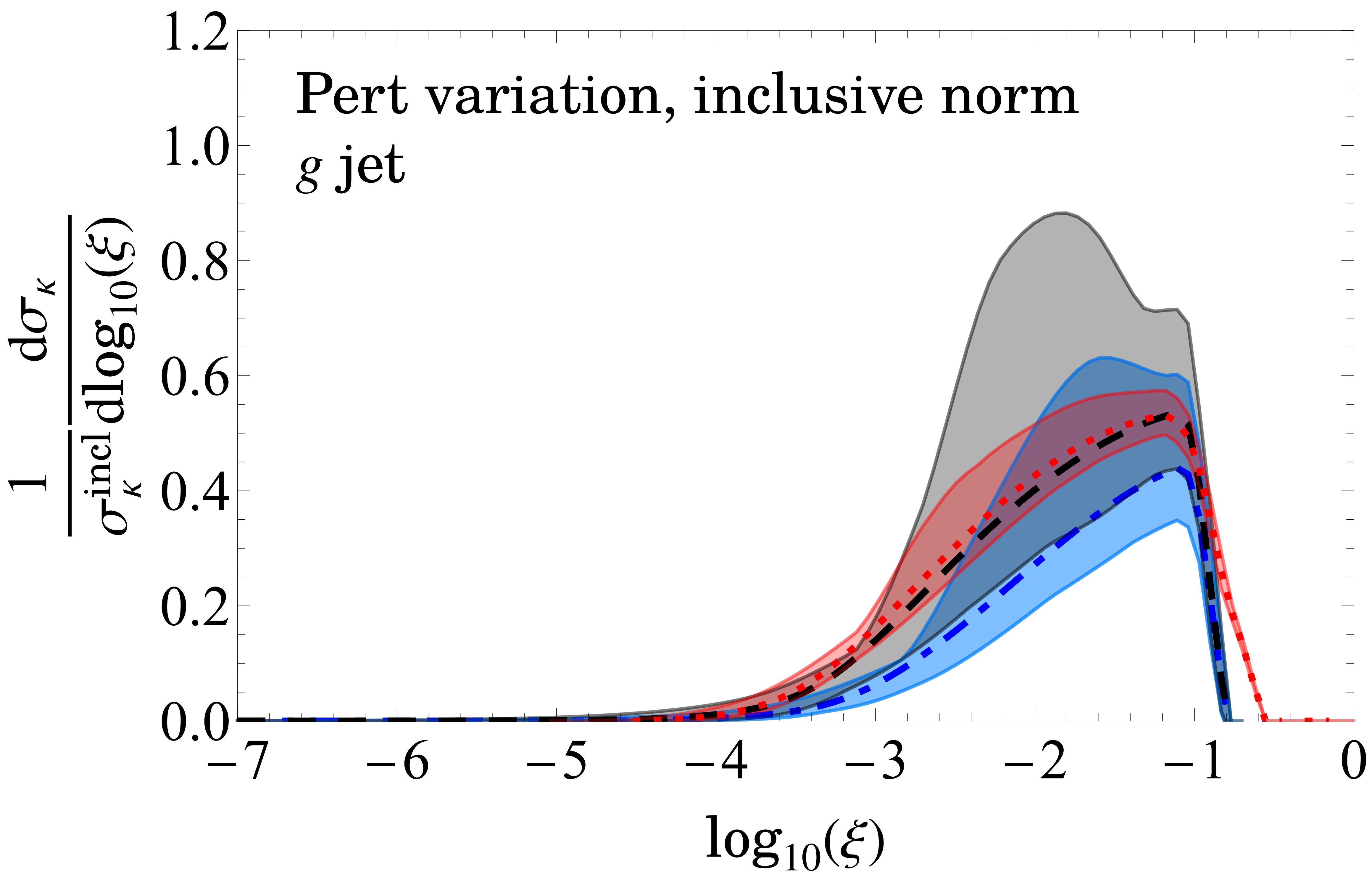
Hannesdottir, AP, Schwartz, Stewart (to appear)

Perturbative uncertainty and NP corrections

Compute LO matched, NNLL resummed cross section for inclusive jets:

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





[Kang, Lee, Liu, Ringer 2018] [Hannesdottir, Pathak, Schwartz, Stewart (to appear soon)]

Perturbative uncertainty and NP corrections

Ideally, fit for 7 parameters to stay model independent — a bit challenging?

$$(\alpha_s, \Omega_1^q, \Omega_1^g, \Upsilon^q_{1,0}, \Upsilon^g_{1,0}, \Upsilon^q_{1,1}, \Upsilon^g_{1,1})$$

Instead treat as nuisance parameters

Take uncertainty as difference between parton level and hadron level:

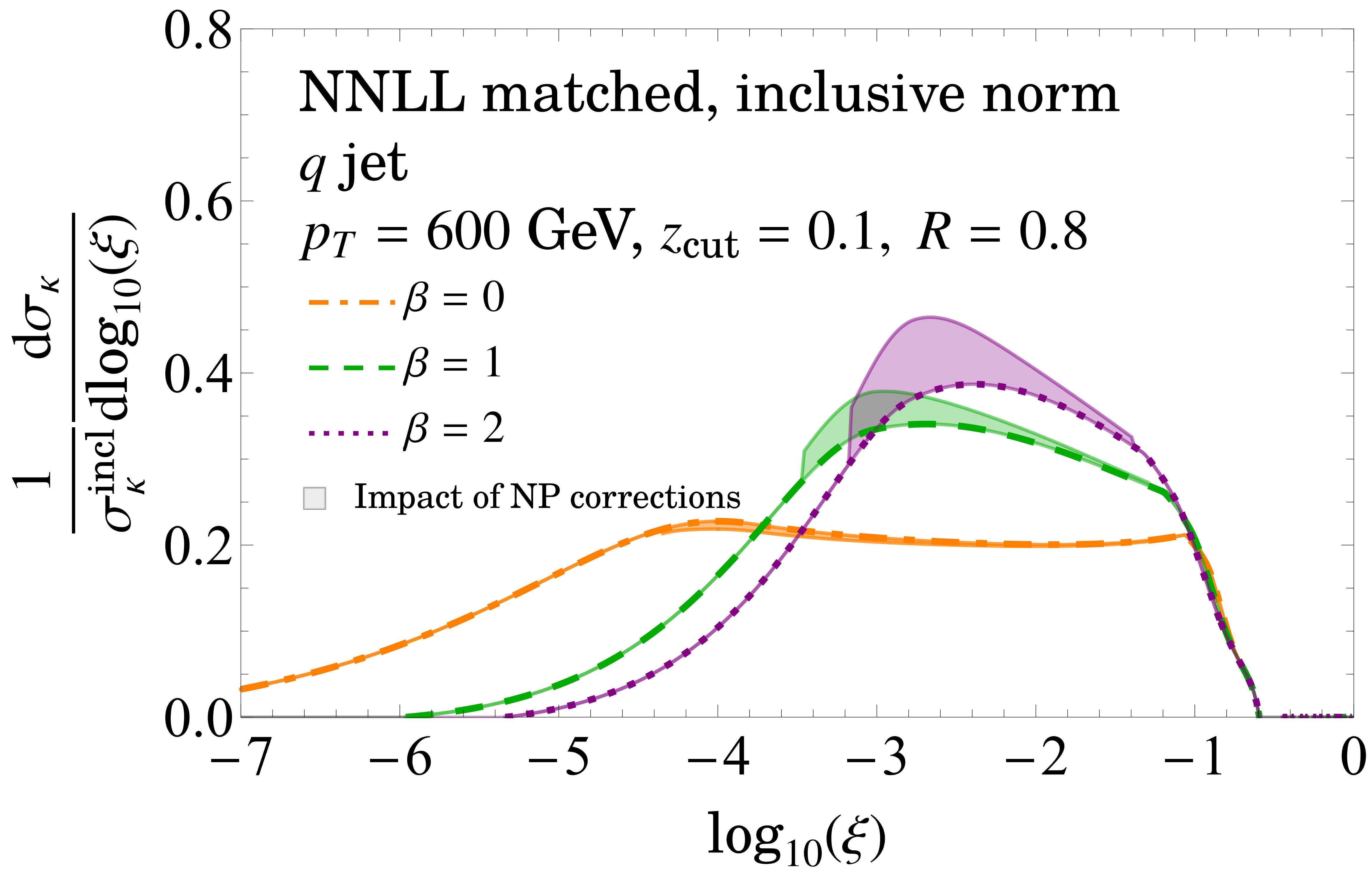
$$\Omega^{\infty}_{1,q} = 0.14, \qquad \Upsilon^q_{1,0} = -0.4, \qquad \Upsilon^q_{1,1} = 1.1, \qquad \text{for quarks},$$
$$\Omega^{\infty}_{1,g} = 0.93, \qquad \Upsilon^g_{1,0} = -0.07, \qquad \Upsilon^g_{1,1} = 0.68, \qquad \text{for gluons}.$$

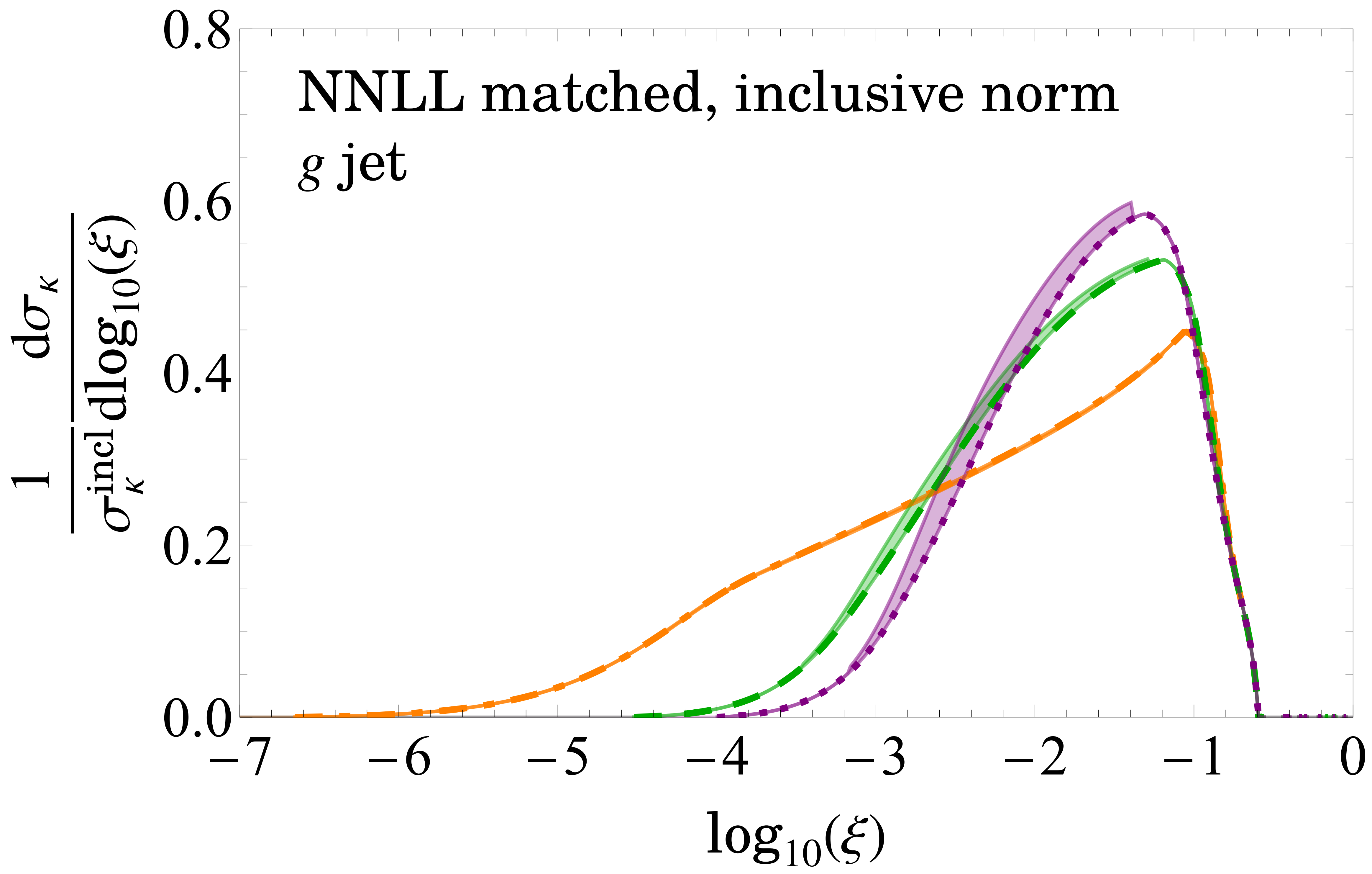
(Values obtained from fit to Pythia8)

Ferdinand, Lee, AP

Perturbative uncertainty and NP corrections

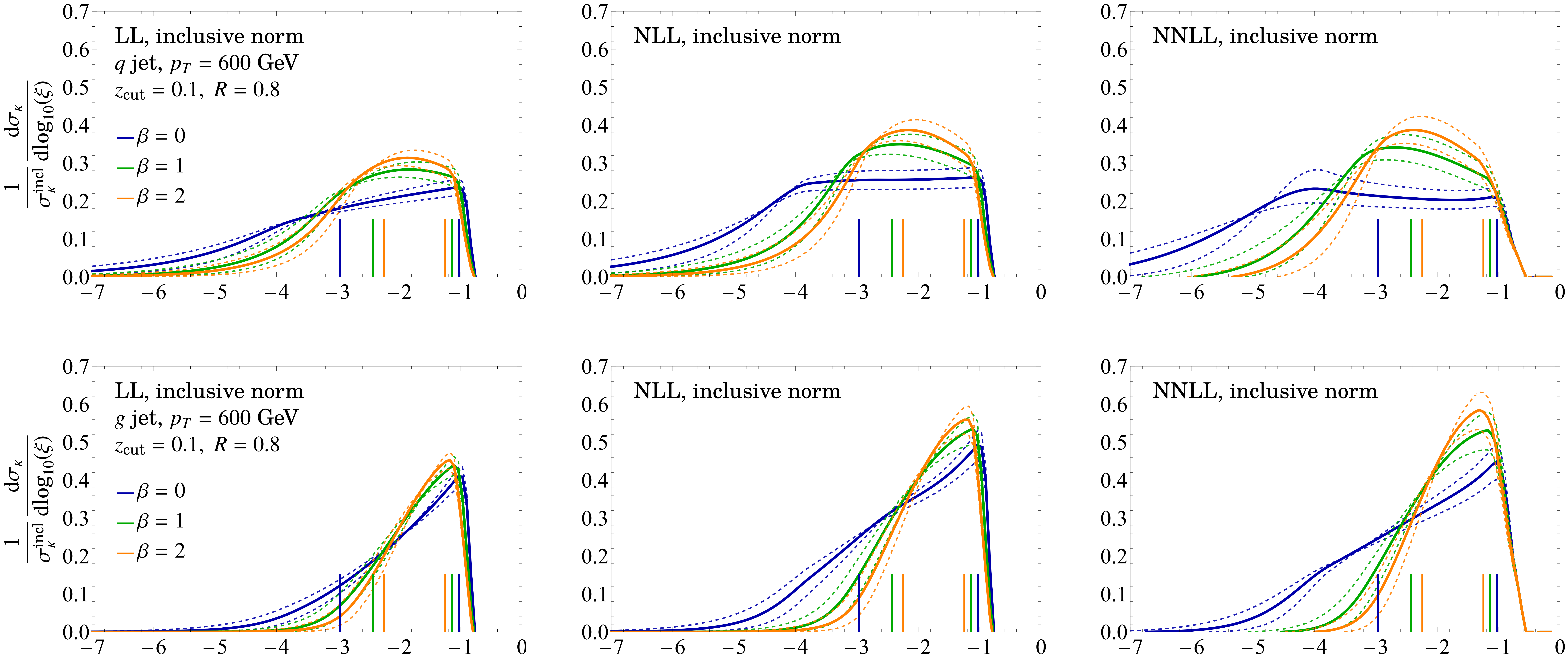
Knowing the perturbative weights associated with NP parameters enables us to accurately capture the jet mass and grooming parameters dependence





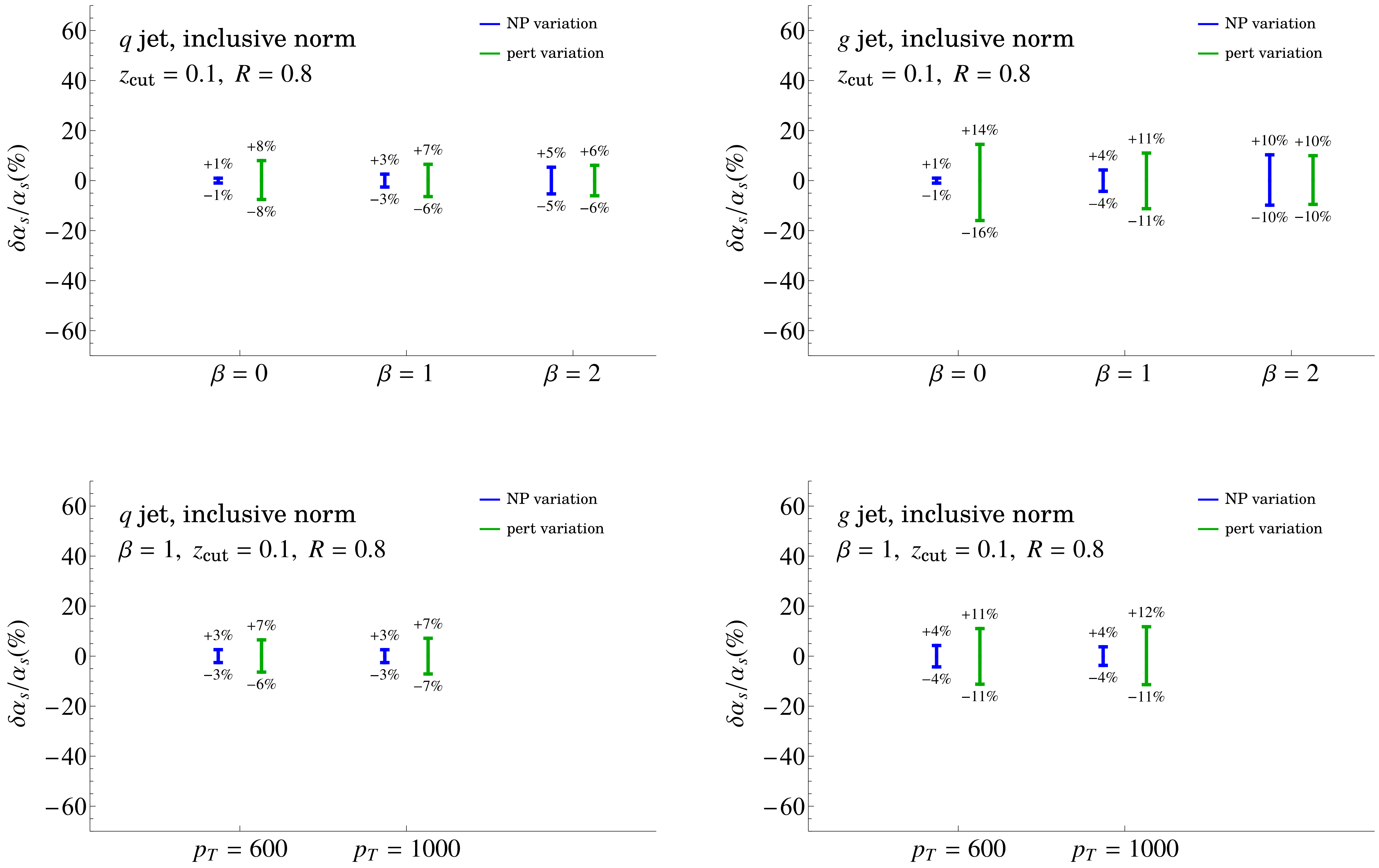
Variation in α_s

Variations in α_s (10% below) modify both shape and normalization:



Projections for α_s measurements

[Hannesdottir, Pathak, Schwartz, Stewart]



1. NNLL perturbative uncertainty dominates
2. Not constraining NP parameters leads to an irreducible $\mathcal{O}(1\%)$ uncertainty on α_s measurement
3. Quark and gluon jets have comparable sensitivity

Conclusions

- New insights into hadronization corrections in multi pronged jets using soft drop jet mass
- NP corrections in 2-pronged jets require non-trivial auxiliary measurements
- Calibrate MC hadronization models in this framework — uncertainty set by perturbative uncertainty on $C_1(m^2_{J,\mathrm{gr}})$ and $C_2(m^2_{J,\mathrm{gr}})$
- Use this formalism to determine ultimate prospects for α_s measurements using soft drop jet mass

Thank you