Jets and their substructure from LHC data

June 2nd, 2021

Soft drop momentum sharing fraction z_g beyond LL

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Wouter Waalewijn (Amsterdam)

arXiv: 2106.this_week

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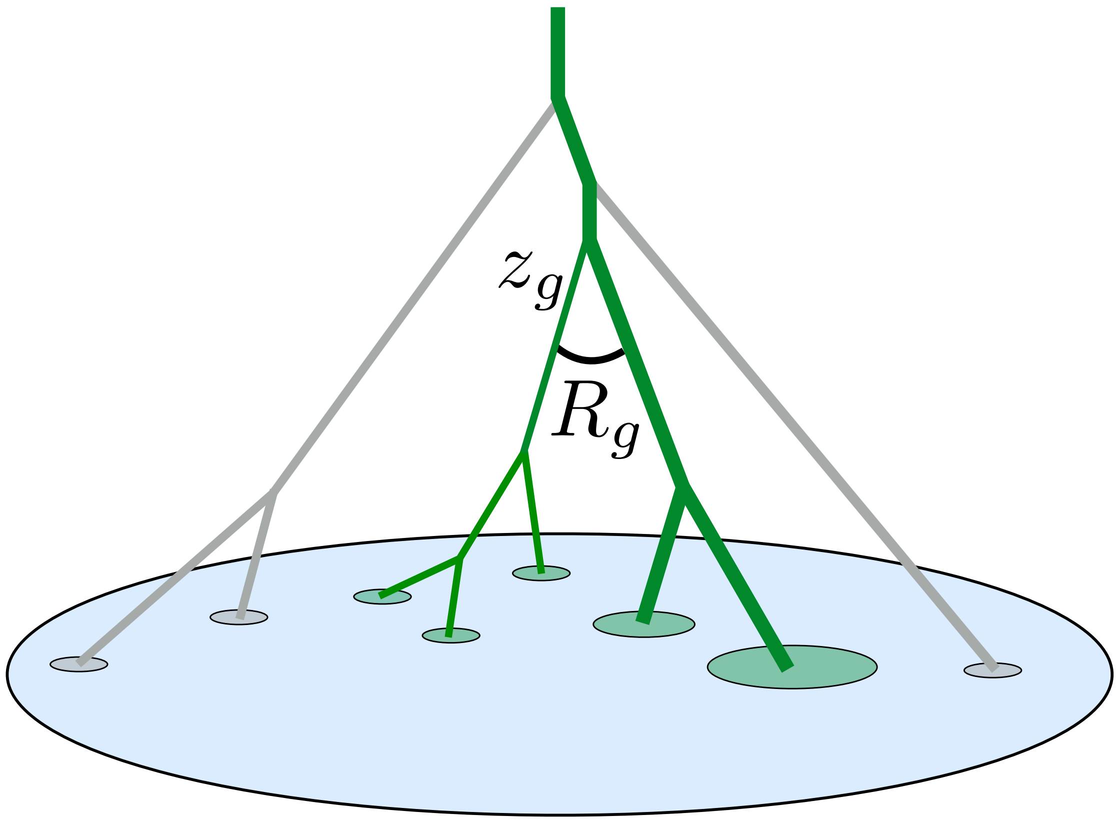
Nikhef

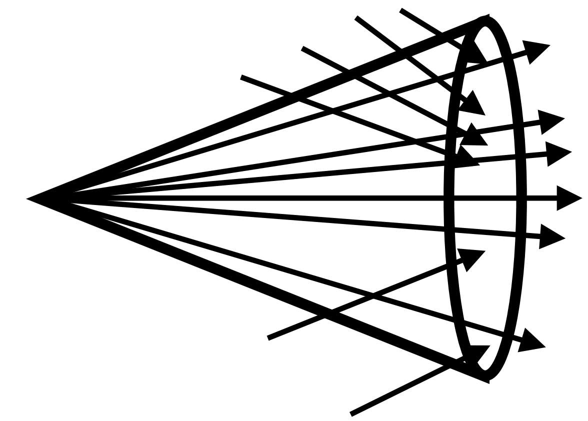
Outline

- Introduction
  - Soft Drop, z_g , and R_g
  - Why z_g?
  - Sudakov Safety

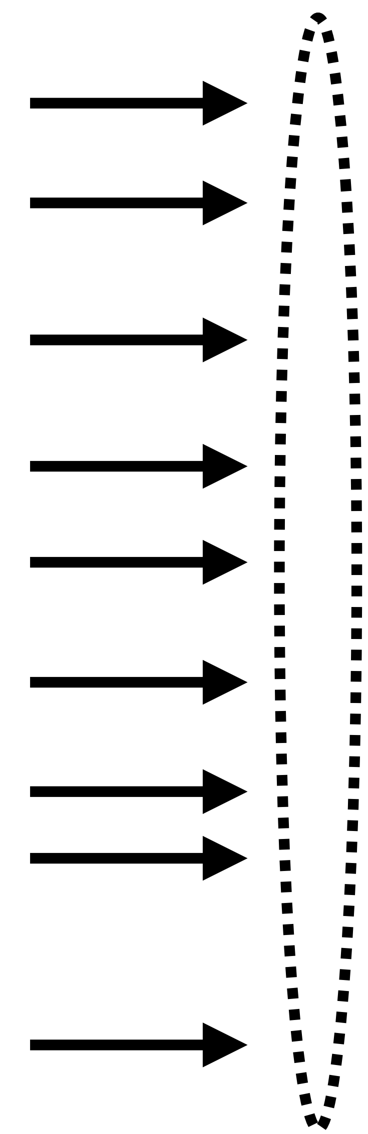


- z_g at NLL' accuracy
  - Jet production
  - Fixed-order computation
  - Refactorization and resummation
  - Non-global logarithms
  - Results
- Conclusions

Soft Drop, z_g, and R_g



- Use C/A to obtain angular-ordered tree

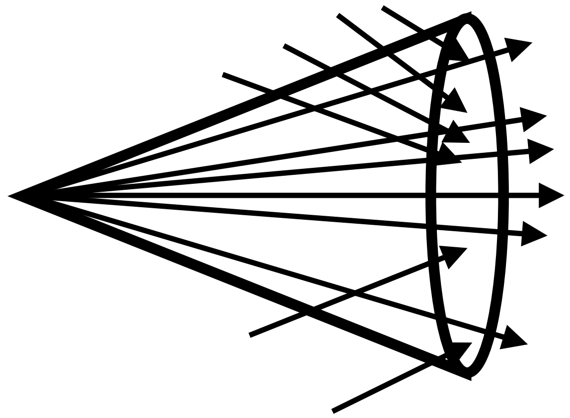


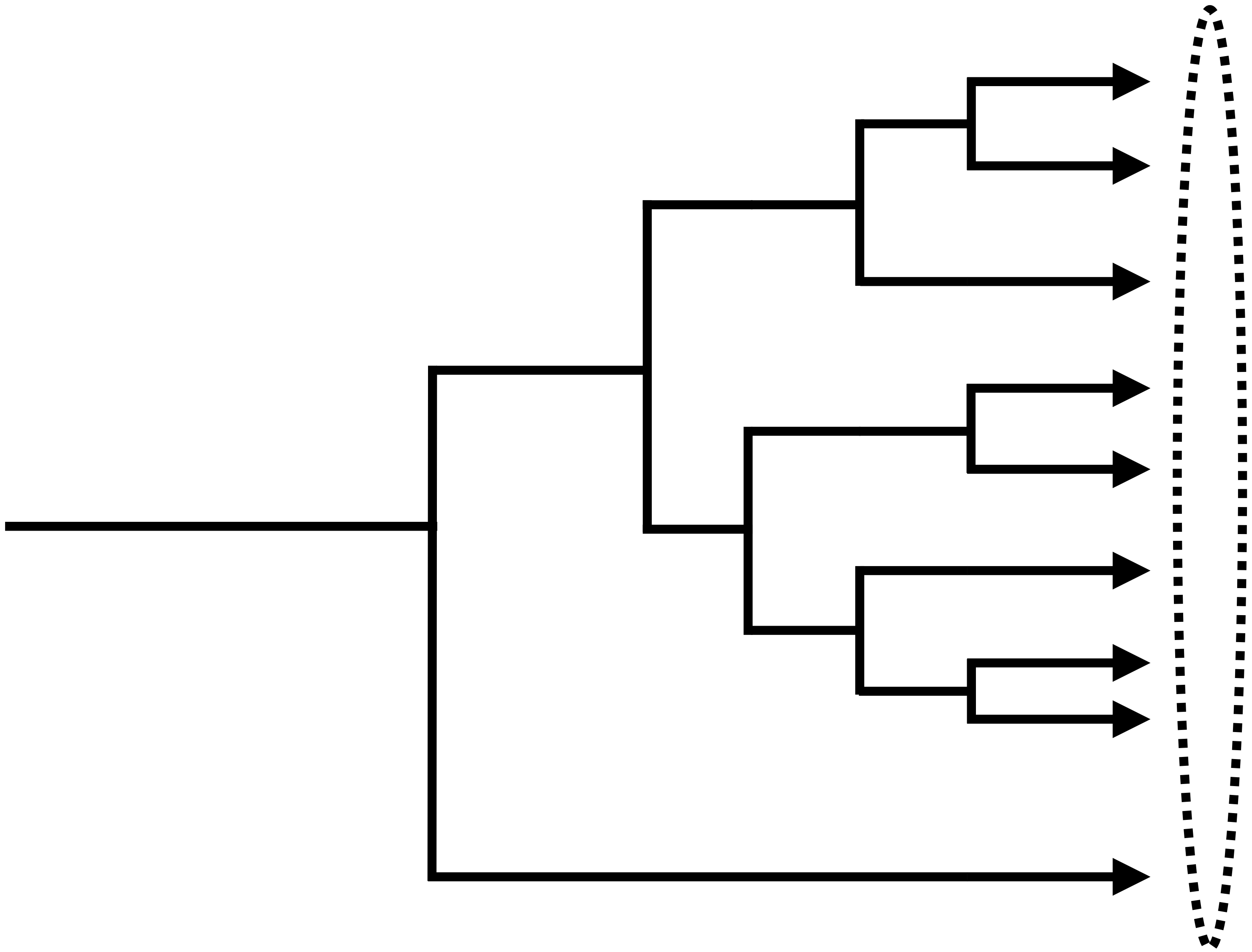
Larkoski, Marzani, Soyez, Thaler ’14

Larkoski, Marzani, Thaler ’15

Soft Drop, z_g, and R_g

- Use C/A to obtain angular-ordered tree



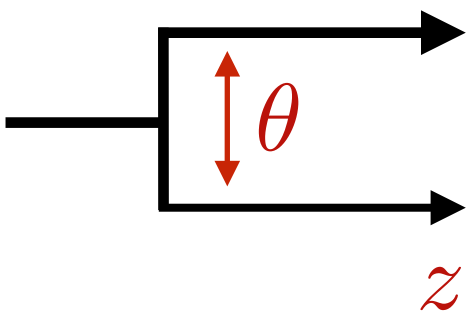


Larkoski, Marzani, Soyez, Thaler ’14

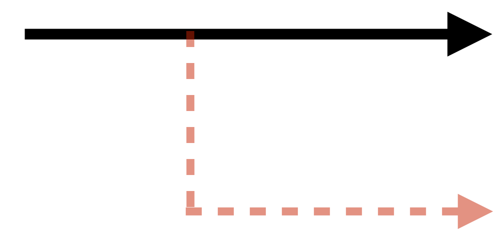
Larkoski, Marzani, Thaler ’15

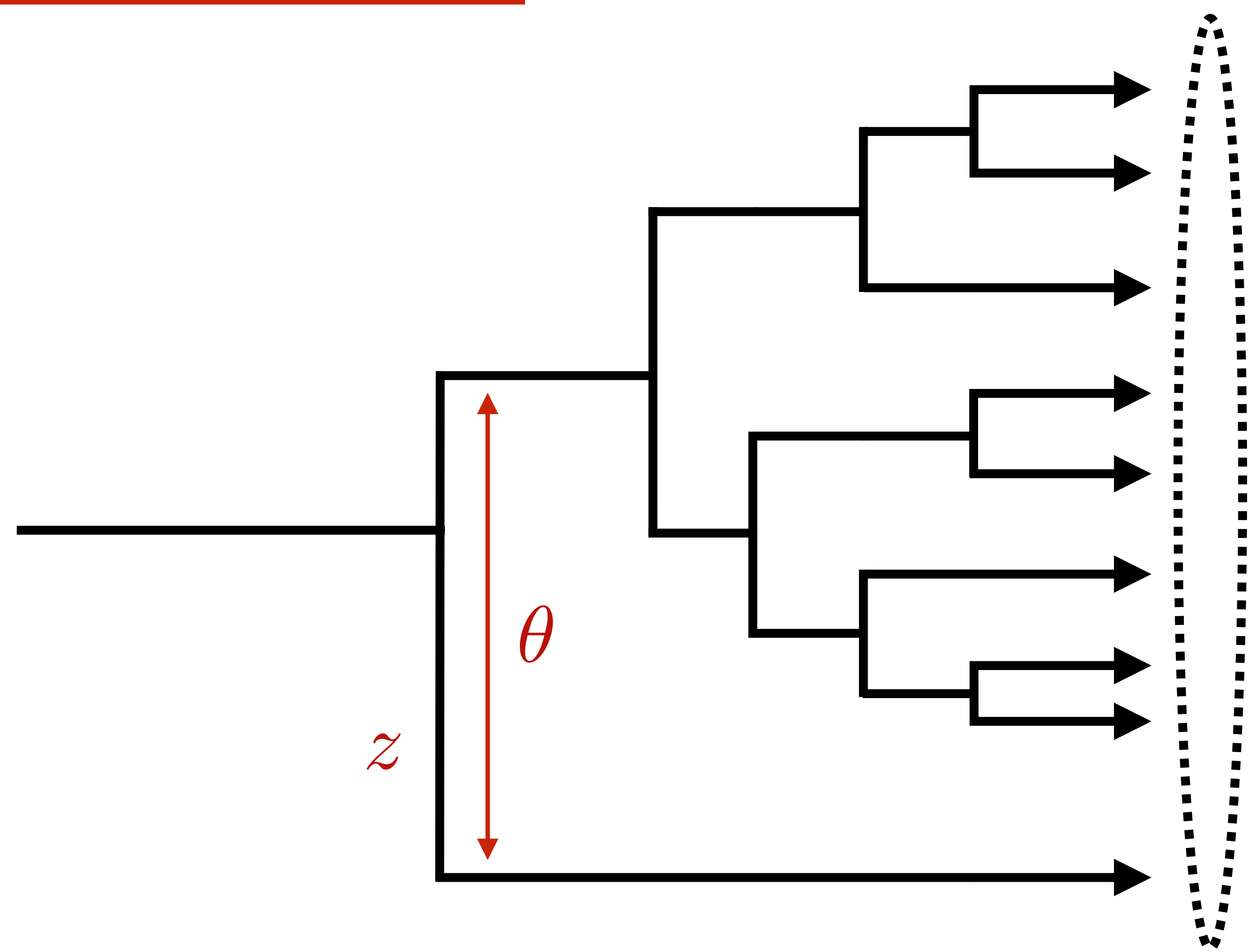
Soft Drop, z_g, and R_g

- SD criterium:



$$z < z_{\mathrm{cut}} \left(\frac{\theta}{R} \right)^{\beta}$$





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Soft Drop, z_g, and R_g

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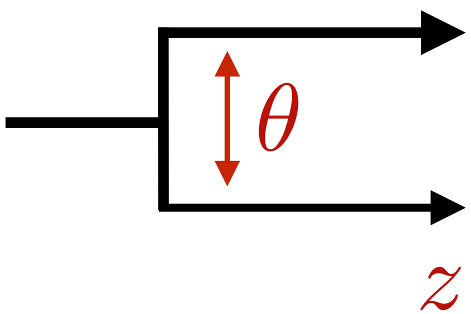

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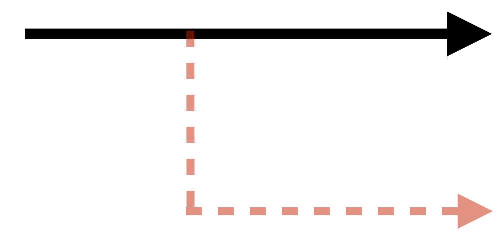

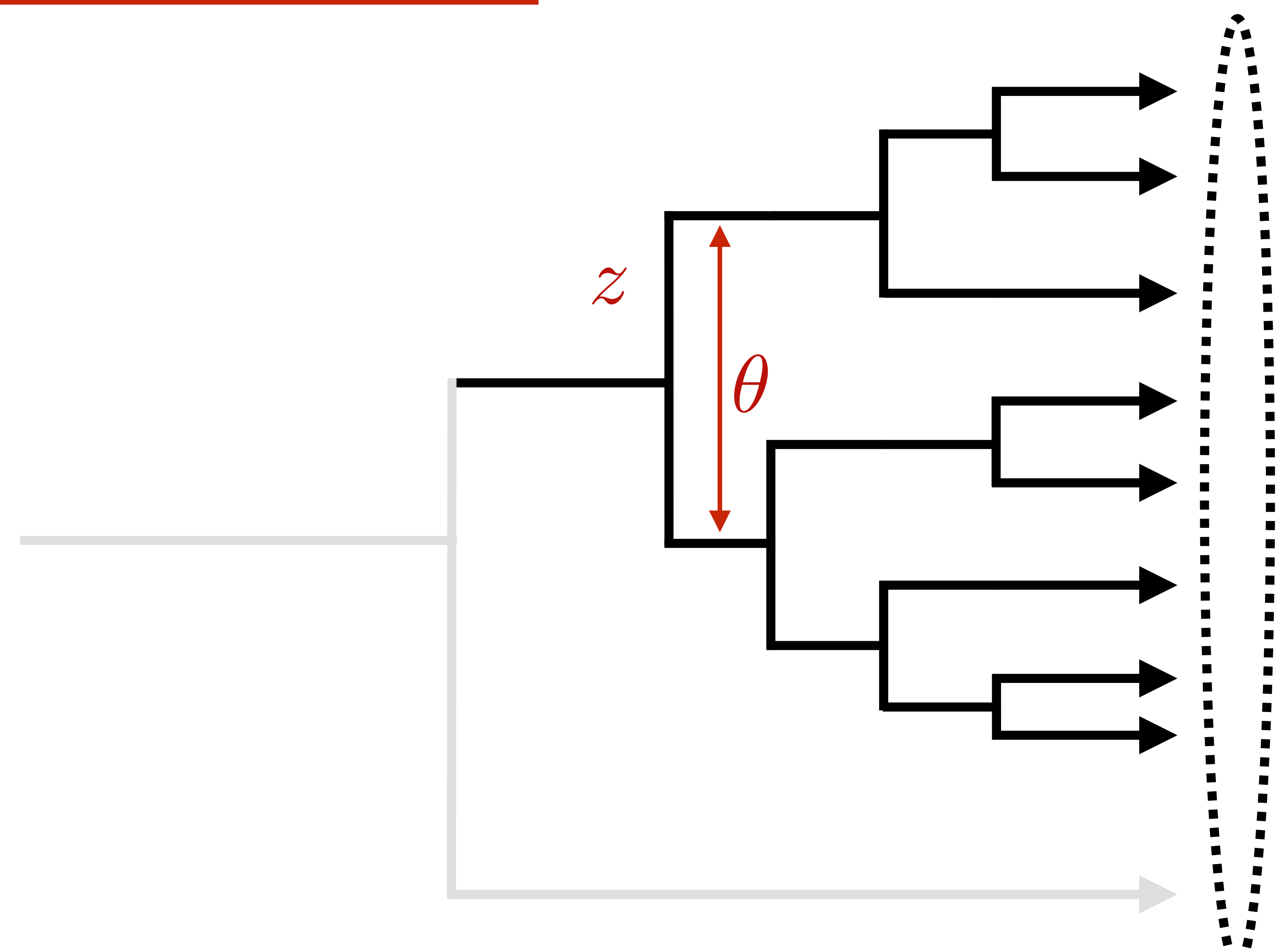

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Soft Drop, z_g, and R_g

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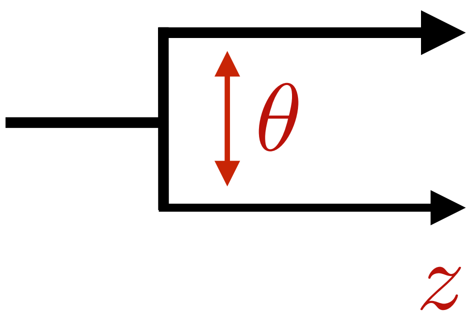
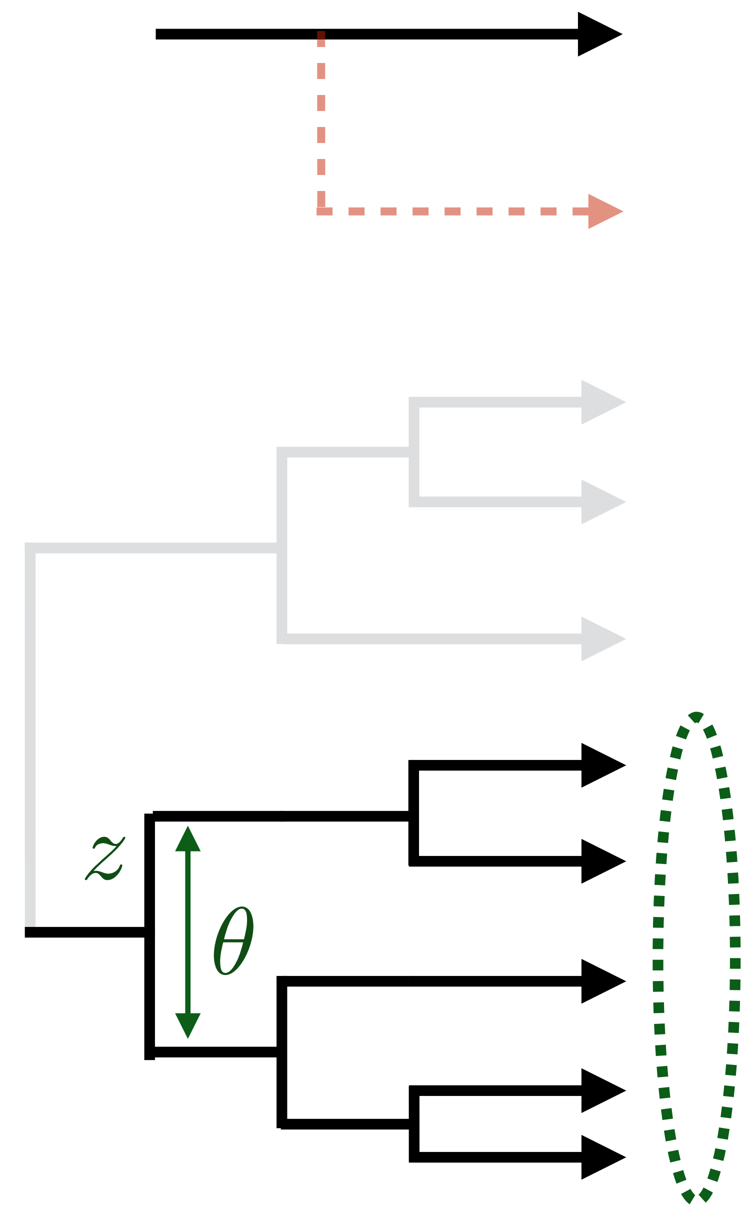


$$z > z_{\rm cut} \left(\frac{\theta}{R}\right)^{\beta}$$

Stop



Larkoski, Marzani, Soyez, Thaler '14

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Soft Drop, z_g, and R_g

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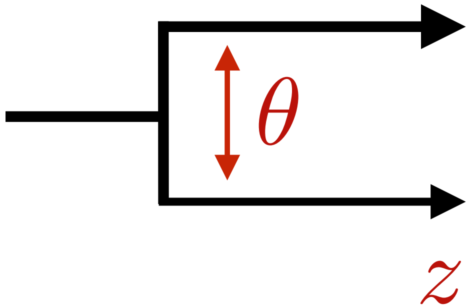

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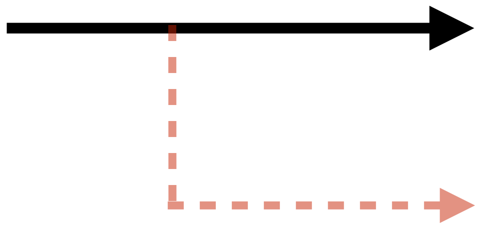
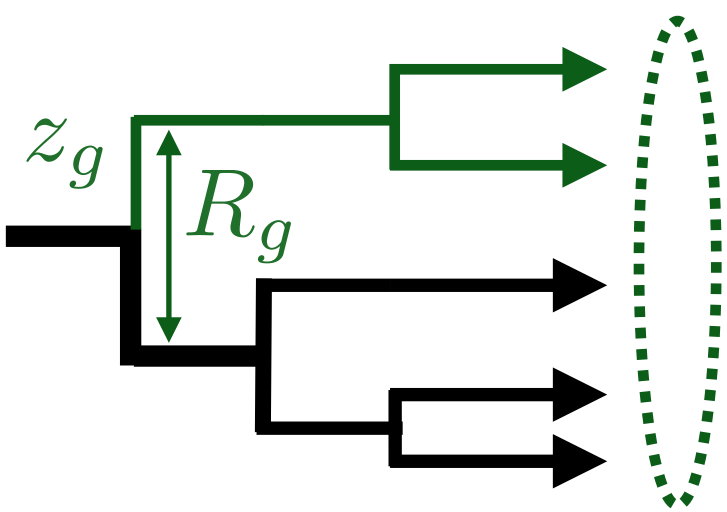


$$z_g \equiv z$$ of softer branch

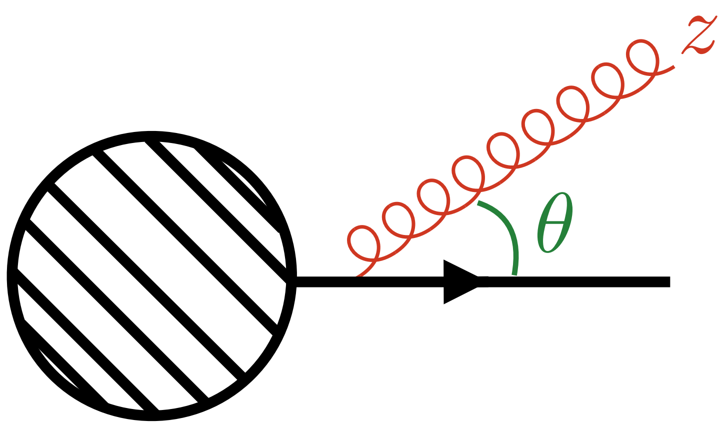
$$R_g \equiv \theta$$ between branches



Larkoski, Marzani, Soyez, Thaler '14

Larkoski, Marzani, Thaler '15

Why z_g?



$$\propto \alpha_s \int \frac{\mathrm{d}\theta}{\theta}\ \mathrm{d}z\, P_{gq}(z)$$

- Most direct measurement of the QCD splitting functions
- Measured at ATLAS, CMS, ALICE, STAR
- LL accuracy: Measurement probes color of parton initiating jet
- NLL' accuracy: Probes color **and spin**
- Heavy ion - probes hard-collinear splittings in Quark-Gluon Plasma

Sudakov safety

- For $\beta < 0$, z_g is infrared and collinear safe (IRC safe) ✓

- For $\beta \geq 0$, z_g is IRC unsafe ✗

Larkoski, Marzani, Thaler '15

$z_g = 0$

$z_g \neq 0$

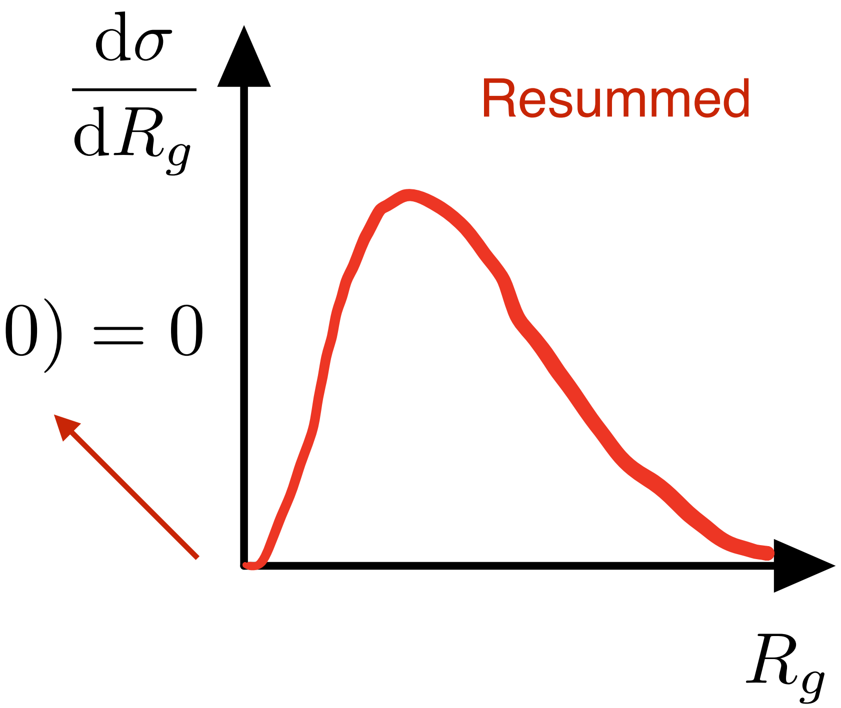
- What to do?

  1) Measure z_g <u>and</u> R_g

  2) Resum R_g, hence
  avoiding collinear configuration

  3) Integrate out R_g, obtaining $\frac{\mathrm{d}\sigma}{\mathrm{d}z_g}$

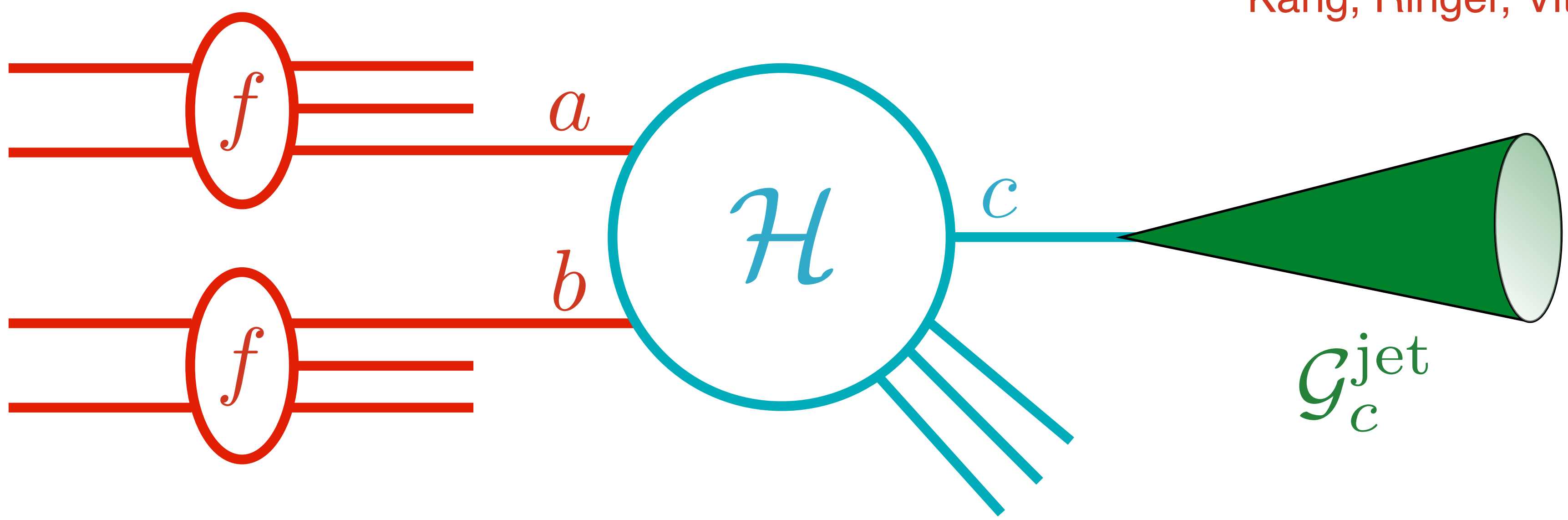
$$\frac{\mathrm{d}\sigma}{\mathrm{d}R_g}(R_g = 0) = 0$$



Jet production

- Collinear factorization

Dasgupta, Dreyer, Salam, Soyez ’14
Kaufmann, Mukherjee, Vogelsang ’15
Kang, Ringer, Vitev ‘16



$$\frac{d\sigma}{dp_T\, d\eta\, dz_g} = f_a \otimes f_b \otimes \mathcal{H}_{ab}^c \otimes \mathcal{G}_c^{\text{jet}} \left[1 + \mathcal{O}(R^2)\right]$$

- Schematically:

Cal, Ringer, Waalewijn ’19

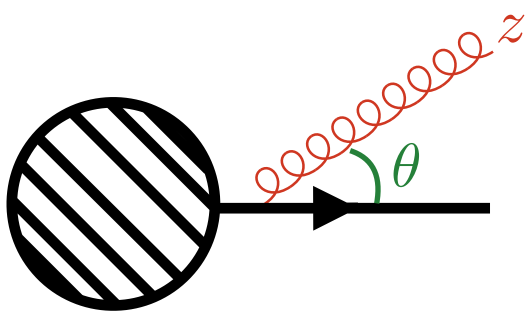
$$\mathcal{G}_c^{\text{jet}}(z_g) = \sum_d J_{cd} \tilde{\mathcal{G}}_d(z_g)$$

J_{cd}: talks to hard function

$\tilde{\mathcal{G}}_d(z_g)$: Sensitive to measurement

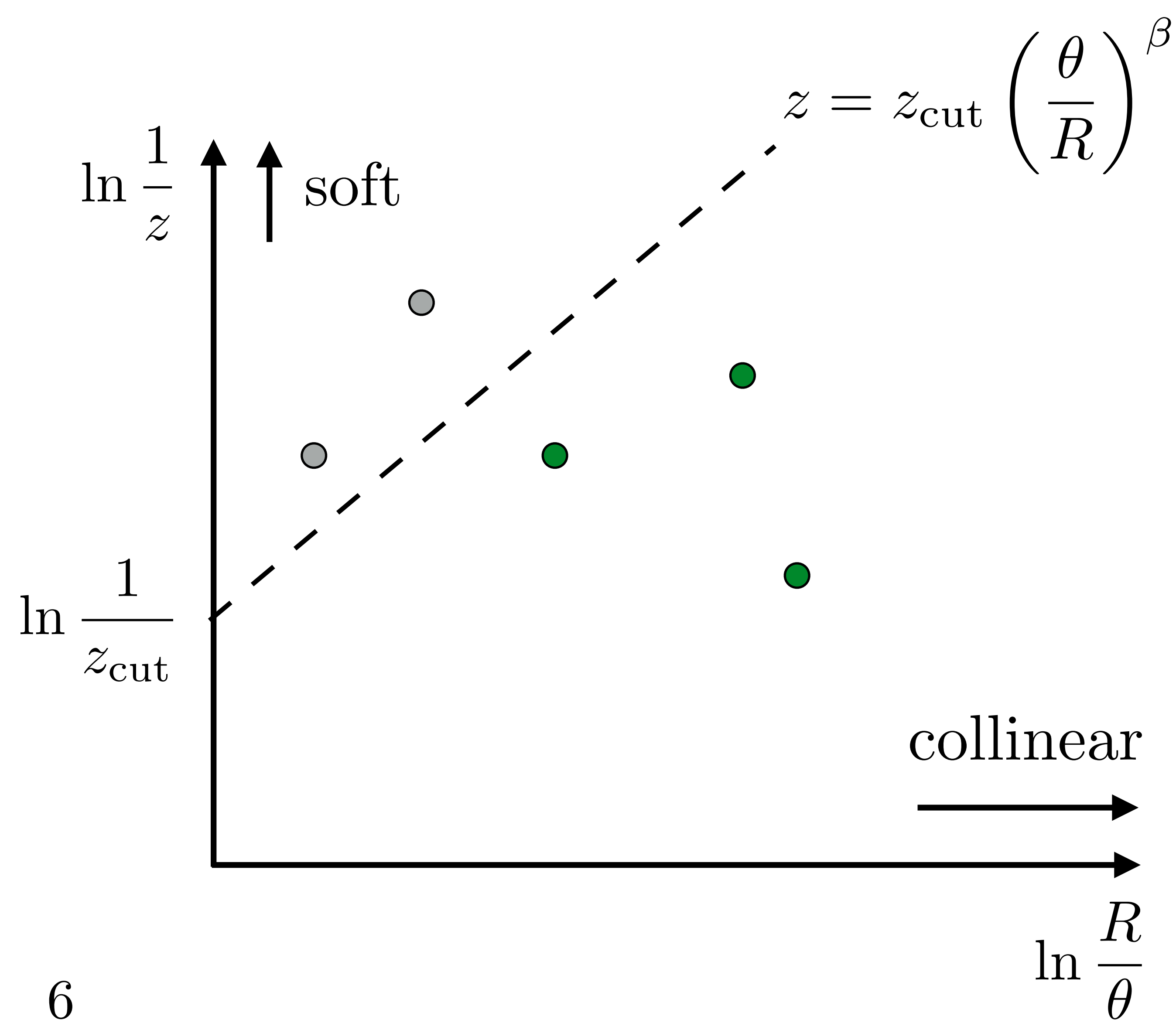
z_g at LL

- LL accuracy:
  - First computed by Larkoski, Marzani, Thaler 15'
  - Dominated by one soft-collinear emission



Soft and collinear limit: $\mathrm{dProb}(z,\theta) = \frac{2\alpha_s C_i}{\pi}\frac{\mathrm{d}z}{z}\frac{\mathrm{d}\theta}{\theta}$

- Lund plane:



z_g at LL

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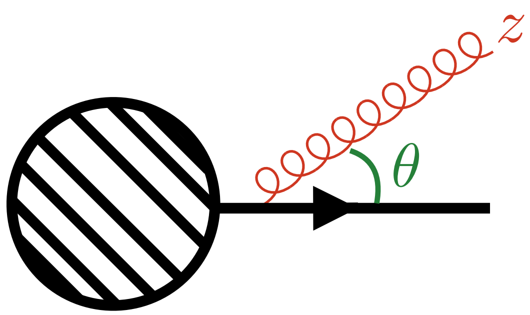

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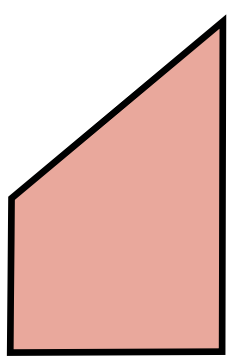
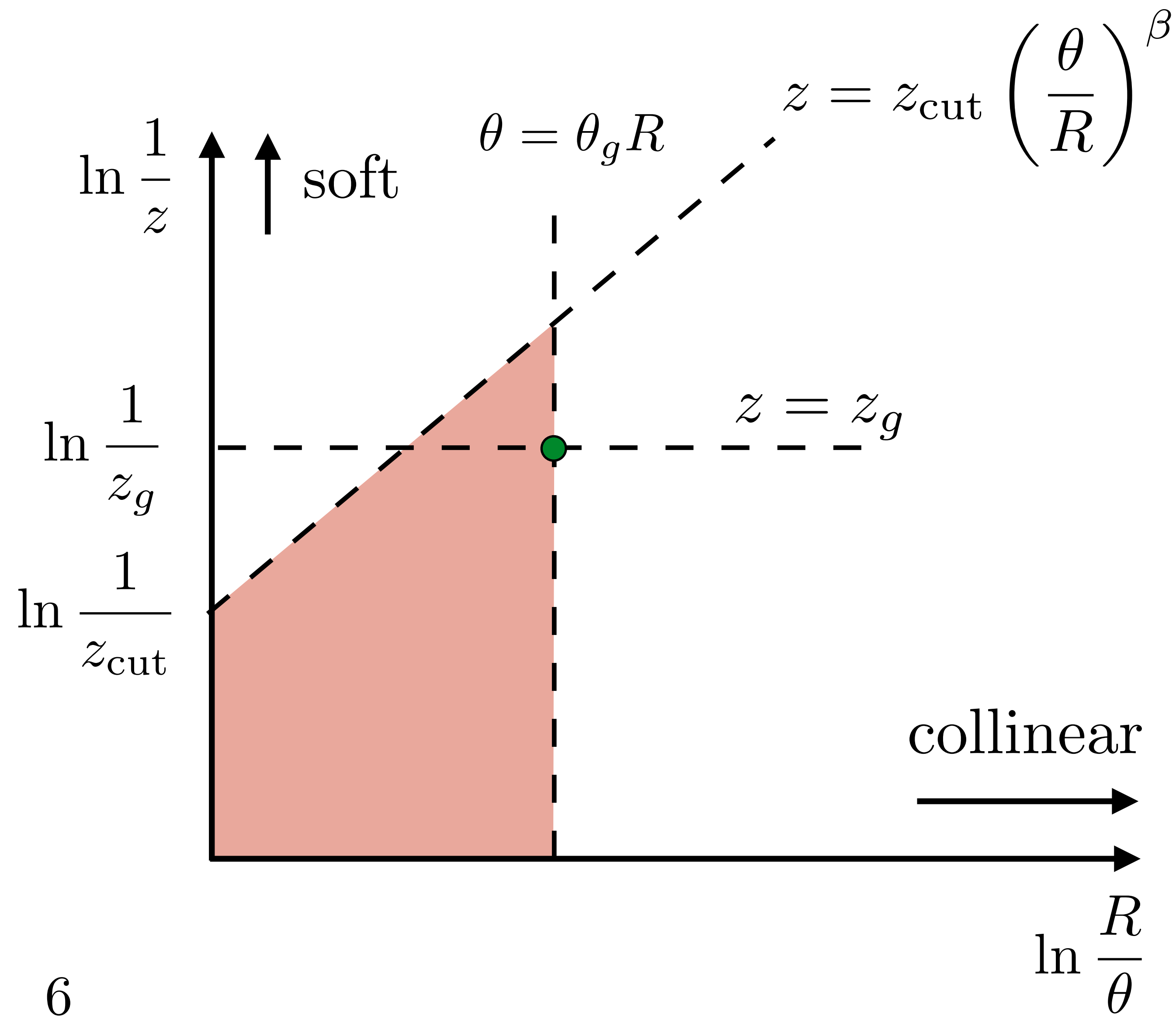


= vetoed

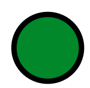
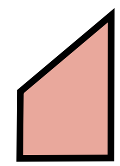
$$\theta_g \equiv \frac{R_g}{R}$$



z_g at LL

- <u>LL result:</u>

$$\theta_g \equiv \frac{R_g}{R}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g \mathrm{d}\theta_g} = \frac{2\alpha_s C_i}{\pi}$$  $$\times \exp\left[-\frac{2\alpha_s C_i}{\pi}\right.$$  $$\left.\right] \Theta(1/2 > z_g > z_{\mathrm{cut}}\theta_g^\beta)$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z_g \mathrm{d}\theta_g} = \frac{2\alpha_s C_i}{\pi} \frac{1}{z_g \theta_g} \exp\left[-\frac{\alpha_s C_i}{\pi}(\beta \ln^2 \theta_g + 2 \ln z_{\mathrm{cut}} \ln \theta_g)\right] \Theta(1/2 > z_g > z_{\mathrm{cut}}\theta_g^\beta)$$

- Integrating over θ_g agrees with Larkoski, Marzani, Thaler 15'

- LL result above:
  - Probes color factor C_i
  - Probes singular part of splitting function $P_i \sim \frac{1}{z}$
  - Fixed coupling

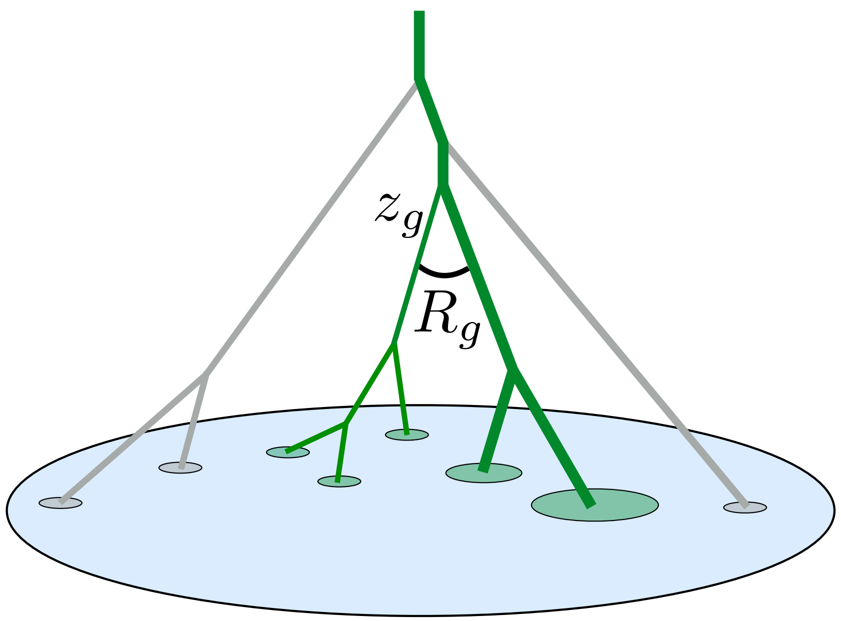
- Can we probe the **<u>full</u>** splitting function?
- Can we probe the **<u>spin</u>** of the initiating parton?

} $\Longrightarrow$ Need higher accuracy

z_g at NLL'

- First step: fixed order calculation

$$\tilde{\mathcal{G}}_q^{(1)} = \Theta(1/2 > z_g > z_{\rm cut}\theta_g^\beta)\,\Theta(\theta_g < 1)\frac{\alpha_s}{\pi}\frac{1}{\theta_g}\boxed{\left[P_{qq}(z_g) + P_{gq}(z_g)\right]}$$



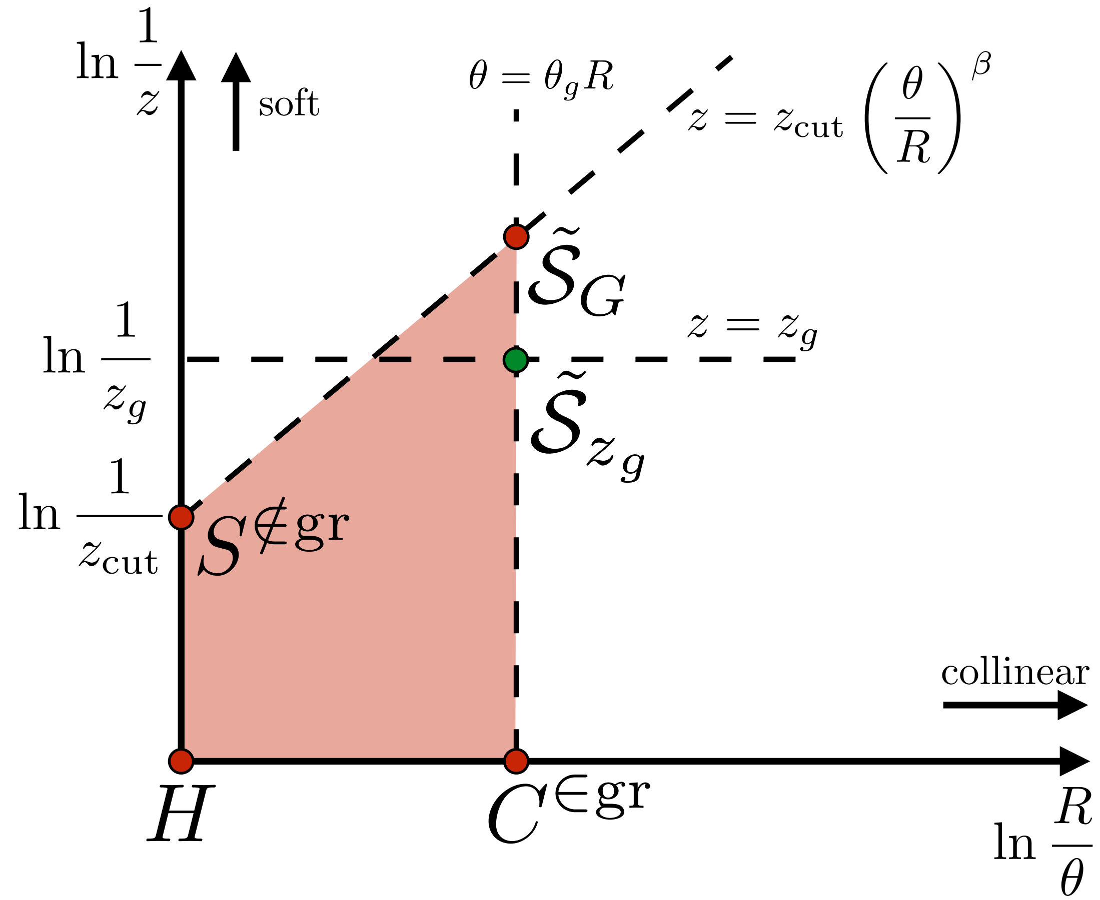
- Probes **full** splitting function
- Cannot integrate out θ_g for $\beta \geq 0$, it's IRC unsafe

↓

- Joint resummation to NLL' accuracy in θ_g and z_g
- Match to FO in order to probe non-singular
- Integrate out θ_g

- How to achieve NLL'? → Factorization theorem in **Soft Collinear Effective Theory** (SCET)

z_g at NLL'



$$\theta_g \equiv \frac{R_g}{R}$$

$$\tilde{\mathcal{G}}_i = \Theta(1/2 > z_g > z_{\rm cut}\theta_g^\beta)\, \tilde{H}_i\, C_i^{\in \rm gr} S^{\notin \rm gr} \tilde{\mathcal{S}}_G \times \frac{\mathrm{d}}{\mathrm{d}z_g}\frac{\mathrm{d}}{\mathrm{d}\theta_g}\tilde{\mathcal{S}}_{z_g}$$

Kang, Lee, Liu, Neill, Ringer 19'

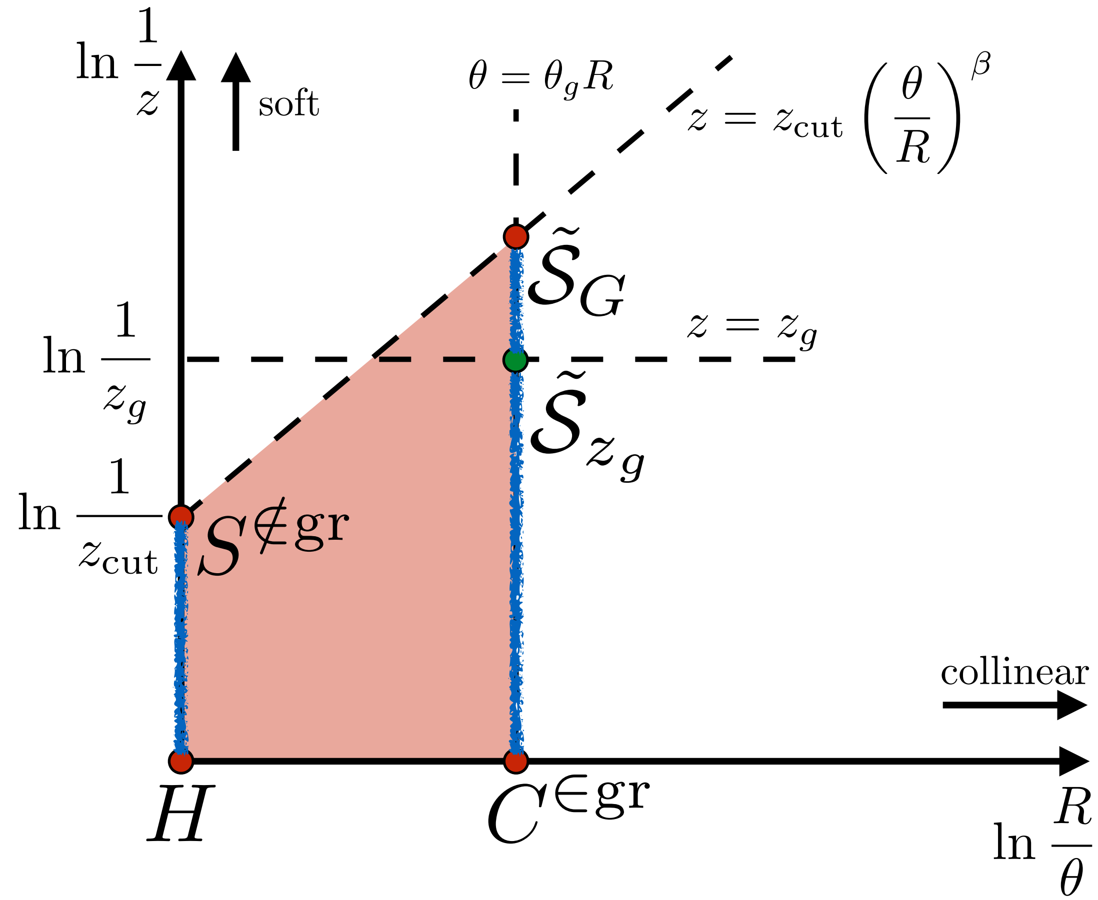
θ_g cross section at NLL'

sets z_g and θ_g

- Only RG consistent expression possible

See also Cal, Lee, Ringer, Waalewijn '20 for factorization of energy drop

z_g at NLL'



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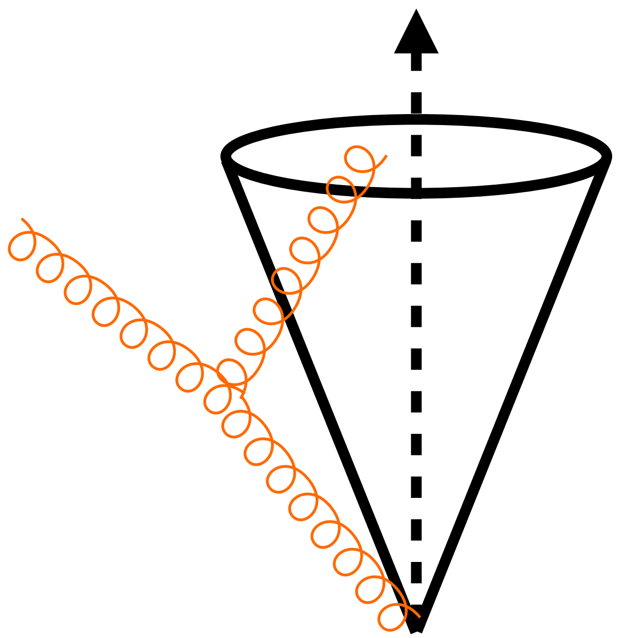


- Additional complication: Non Global Logarithms (NGLs) can also set θ_g and z_g
- NGL Numerical effects are small ~ 1%

Dasgupta, Salam 01'

Banfi, Marchesini, Smye '02

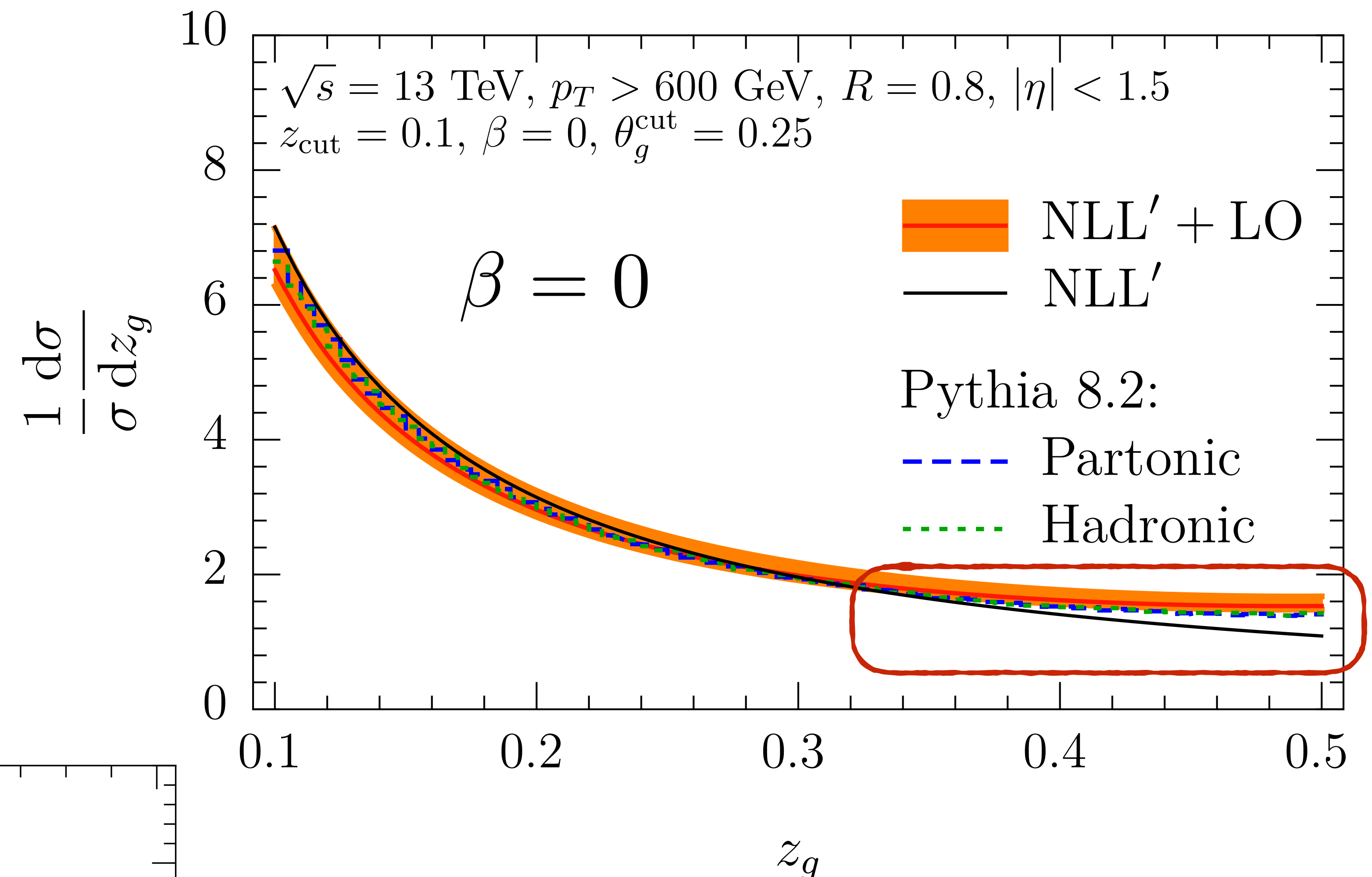
Schwartz, Zhu '14

$$\tilde{\mathcal{G}}_i = \Theta(1/2 > z_g > z_{\rm cut}\theta_g^\beta)\, \tilde{H}_i\, C_i^{\in \rm gr} S^{\notin \rm gr} \tilde{\mathcal{S}}_G \;\; S^{\rm NG}(z_{\rm cut})$$

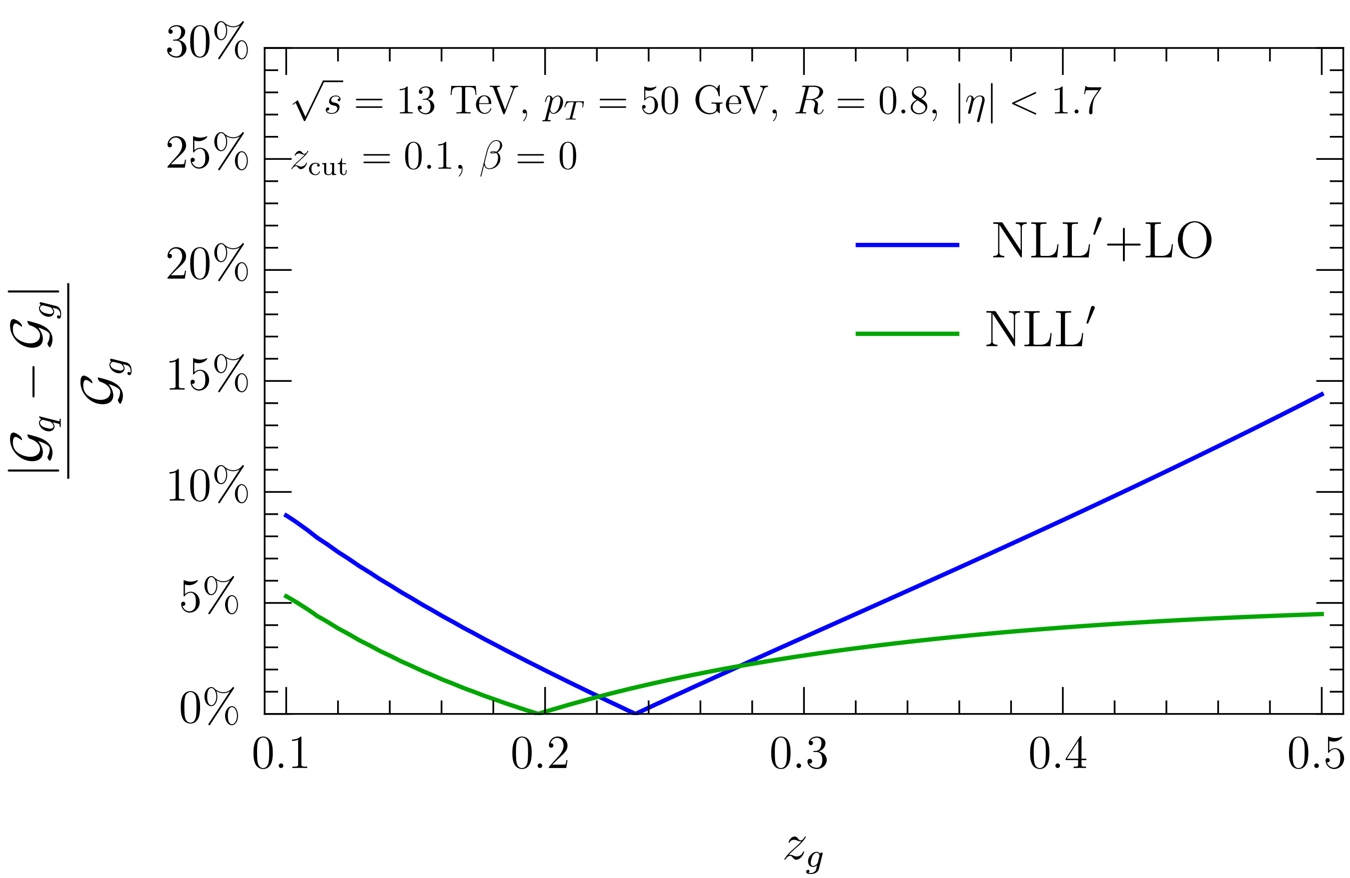
$$\times \left[\frac{\mathrm{d}}{\mathrm{d}z_g} \frac{\mathrm{d}}{\mathrm{d}\theta_g} \tilde{\mathcal{S}}_{z_g} + \tilde{\mathcal{S}}_1^{\prime \rm NG}(z_g) + \tilde{\mathcal{S}}_2^{\prime \rm NG}(z_{\rm cut}\theta_g^\beta / z_g) \right]$$

Results

- Comparison to Pythia



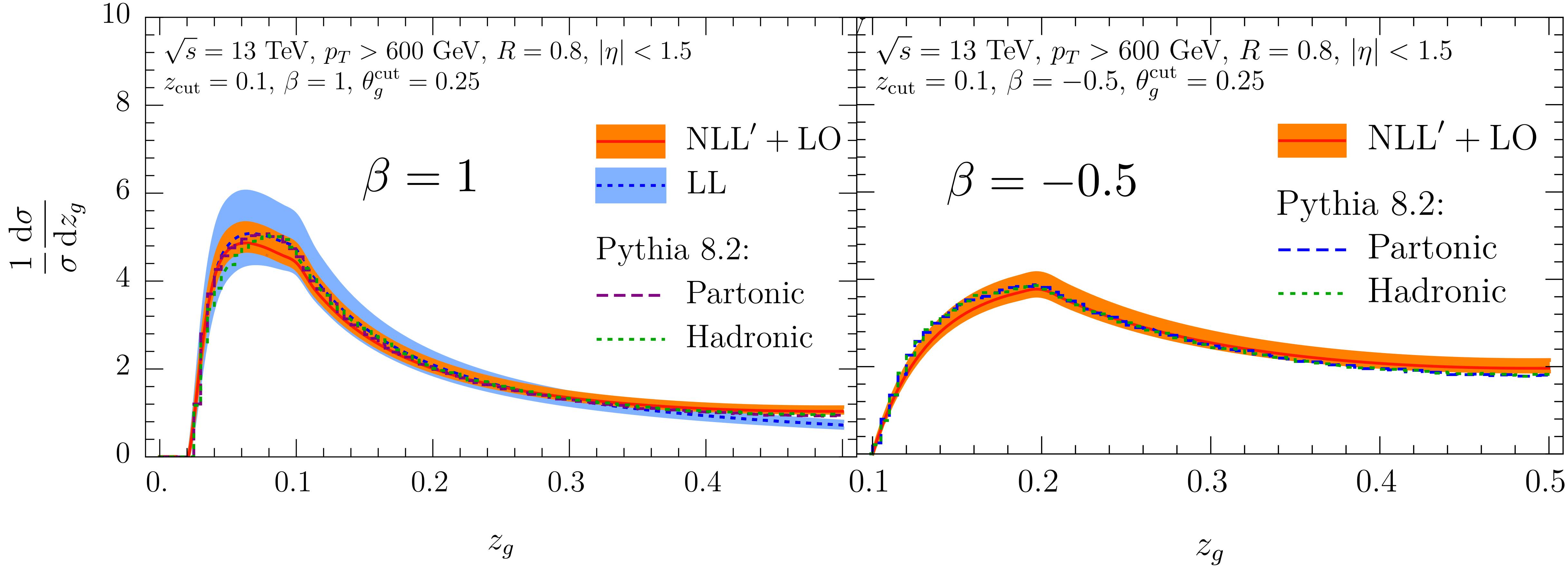
- NLL' uncertainties allow us to see effects of matching to full splitting function



- Around 10% difference between quark/gluon non-singular
- Observable difference between quark/gluon splitting function due to spin

Results

- Comparison to Pythia

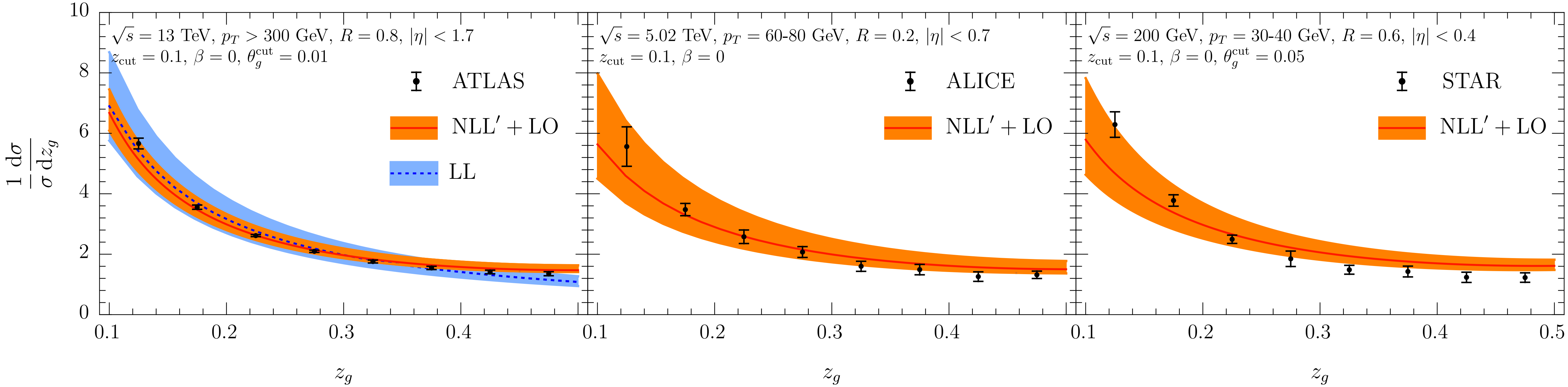


- Effects of matching to full splitting function similar to $\beta = 0$
- (SCET) LL compared to NLL’: Larger bands, no matching

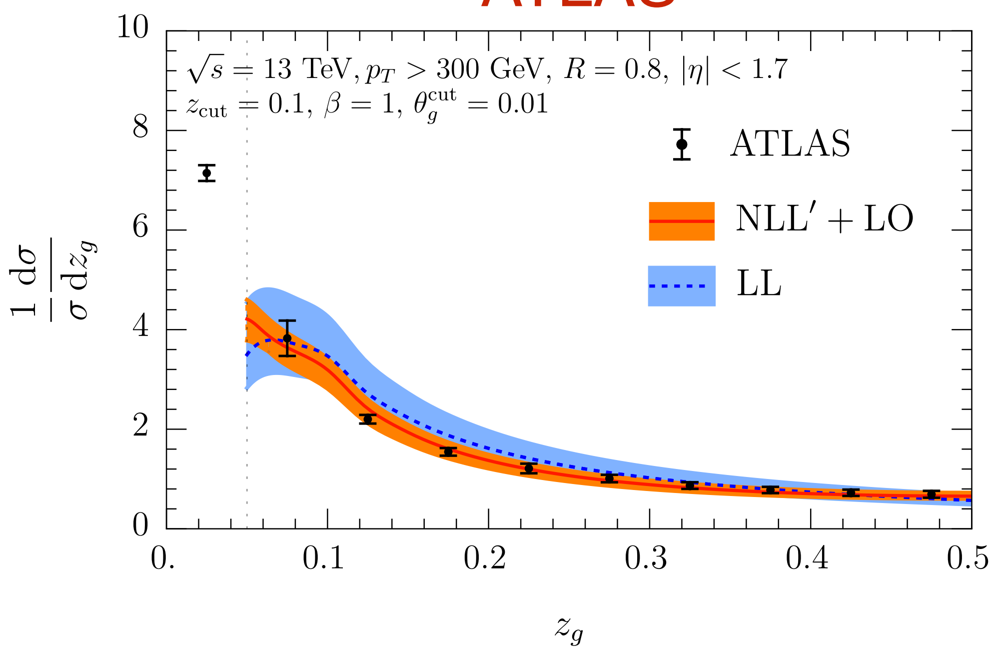
Results

- Comparison to Data

ATLAS ALICE STAR



ATLAS

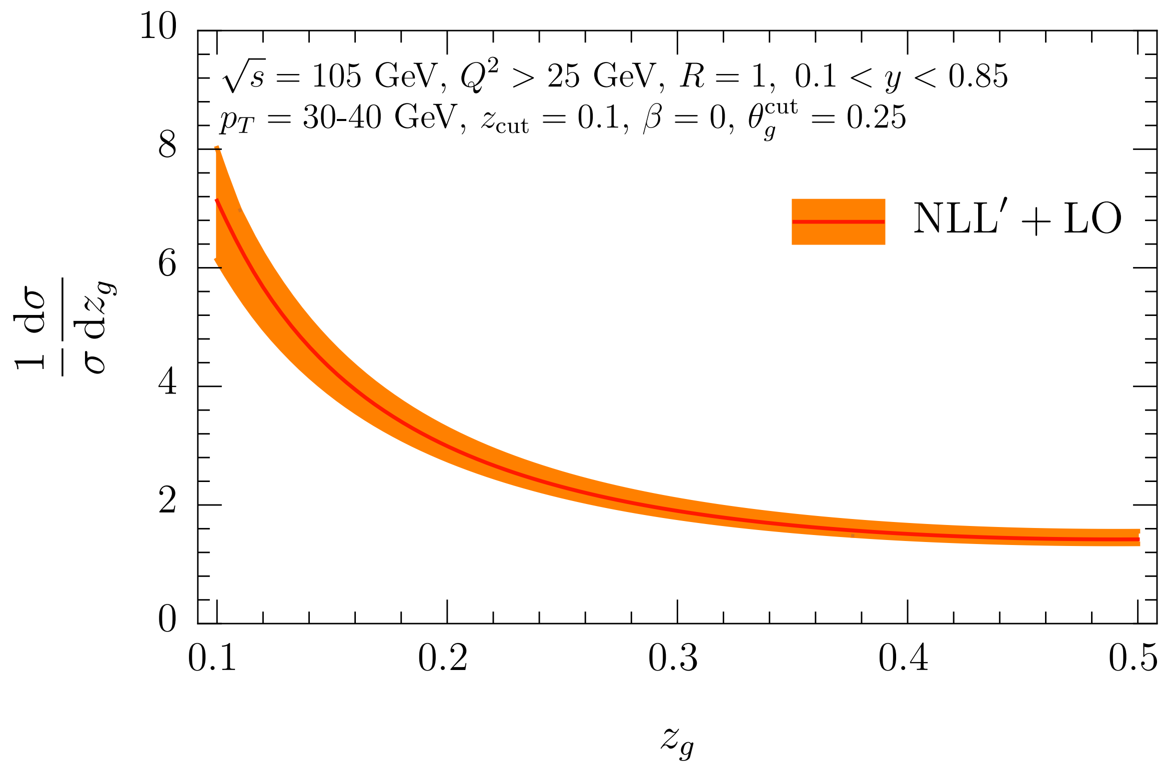


- Very good agreement with available data
- A higher $\theta_g^{\rm cut}$ would further improve the agreement
- Good benchmark for heavy-ion collisions

Conclusions

- Joint resummation in θ_g and z_g at NLL' accuracy achieved through factorization in SCET
- NLL' +LO accuracy probes the full splitting splitting function
- Excellent agreement with Pythia for any β
- Very good agreement with data from multiple collider experiments
- Important to have $\theta_g^{\rm cut}$ in order to control nonperturbative effects

Prediction for future EIC!



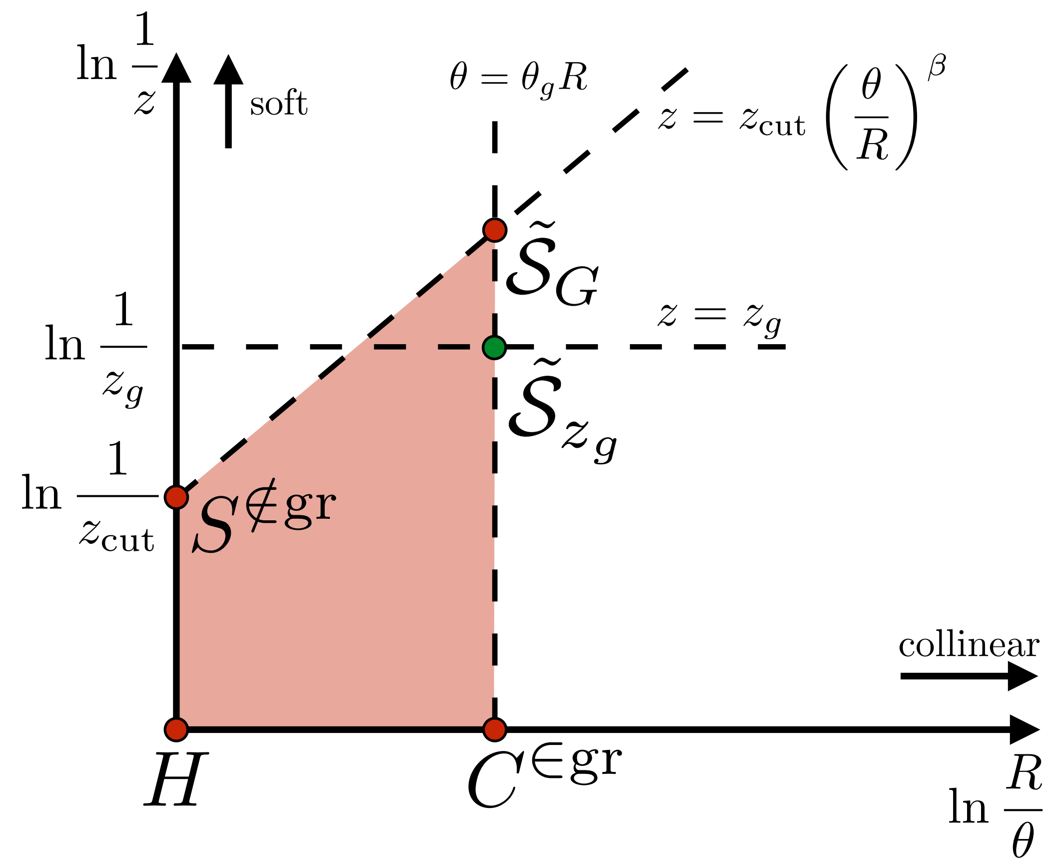
Backup slides

S_zg

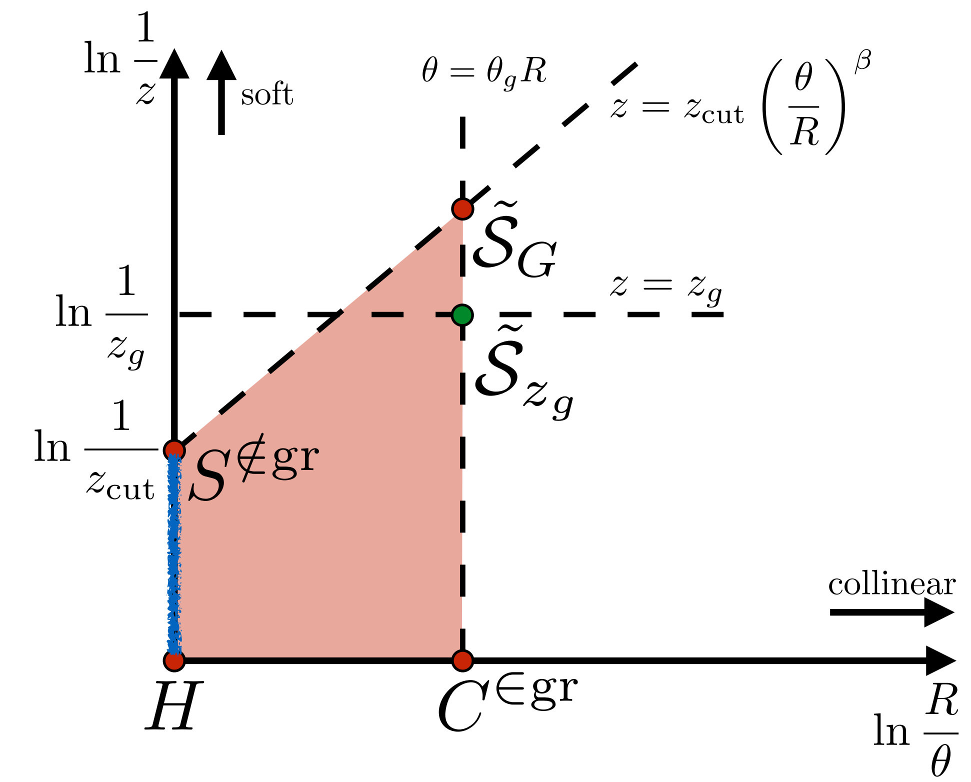
$$\tilde{\mathcal{S}}'_{z_g} \equiv \frac{\mathrm{d}}{\mathrm{d}\theta_g}\tilde{\mathcal{S}}_{z_g}$$

$$\tilde{\mathcal{S}}'_{z_g} = -\frac{2\alpha_s C_i}{\pi}\frac{1}{\theta_g}\ln\left(\frac{\mu}{z_g\theta_g p_T R}\right)$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\tilde{\mathcal{S}}'_{z_g} = -\frac{2\alpha_s C_i}{\pi}\frac{1}{\theta_g}$$



NGLs



Outer boundary:

- Standard hemisphere NGLs in $z_{\rm cut}$
- Anti-kt, hard boundary: no clustering effects

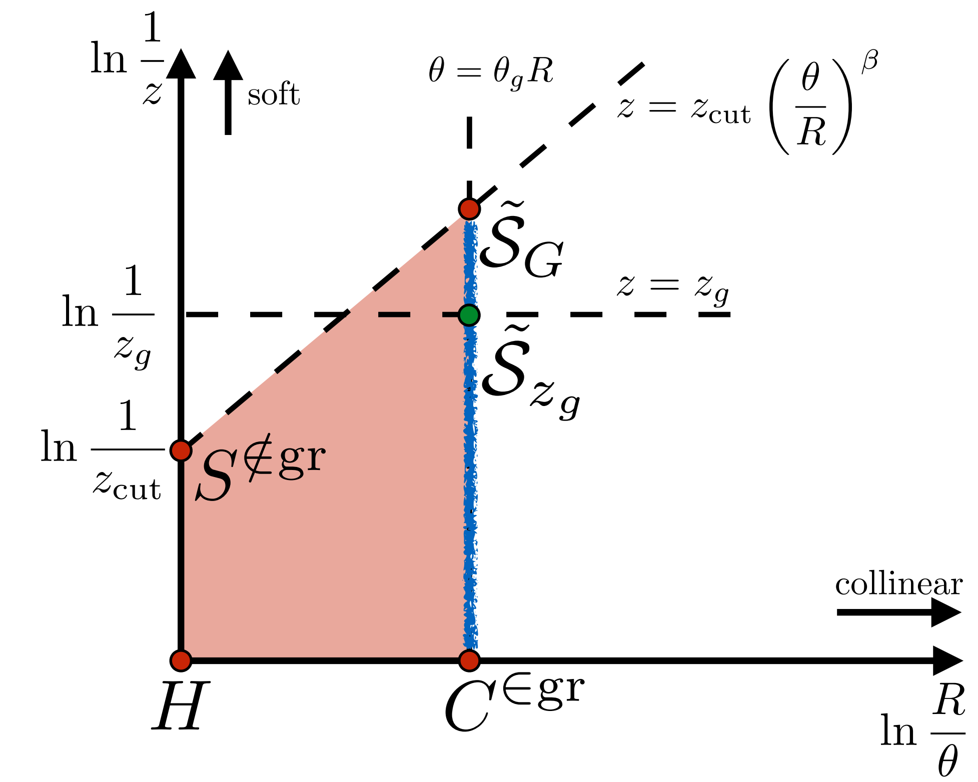
$$S_q^{\rm NG}(\widehat{L}) = 1 - \frac{\pi^2}{24}\widehat{L}^2 + \frac{\zeta_3}{12}\widehat{L}^3 + \frac{\pi^4}{34560}\widehat{L}^4 + \left(-\frac{\pi^2\zeta_3}{360} + \frac{17\zeta_5}{480}\right)\widehat{L}^5 + \mathcal{O}(L^6)$$

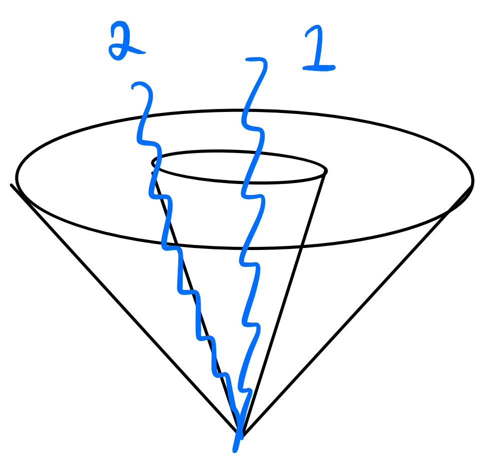
$$S_g^{\rm NG}(\widehat{L}) = \left[S_q^{\rm NG}(\widehat{L})\right]^2 .$$

$$\widehat{L} = -\frac{\alpha_s N_c}{\pi}\ln z_{\rm cut}$$

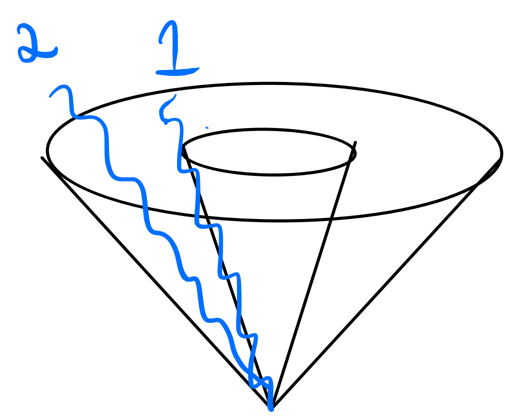
NGLs

- Inner boundary, two NGL contributions
- Need to work differentially in zg and tg





$$\tilde{S}_{z_g} \leftrightarrow C^{\in \text{gr}}$$



$$\tilde{S}_{z_g} \leftrightarrow \tilde{S}_G$$

$$\tilde{S}'^{\text{NG},(2)}_{i,1}(z_g) = 1.29 C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{1}{z_g \theta_g} \ln z_g \,, \qquad (7)$$

$$\tilde{S}'^{\text{NG},(2)}_{i,2}\left(\frac{z_{\text{cut}}\theta_g^\beta}{z_g}\right) = -1.29 C_i C_A \left(\frac{\alpha_s}{2\pi}\right)^2 \frac{1}{z_g \theta_g} \ln\left(\frac{z_{\text{cut}}\theta_g^\beta}{z_g}\right).$$