UK Research and Innovation

# JET VETO RESUMMATION FOR $pp \to H + j$ WITH NNLL'+NNLO UNCERTAINTIES

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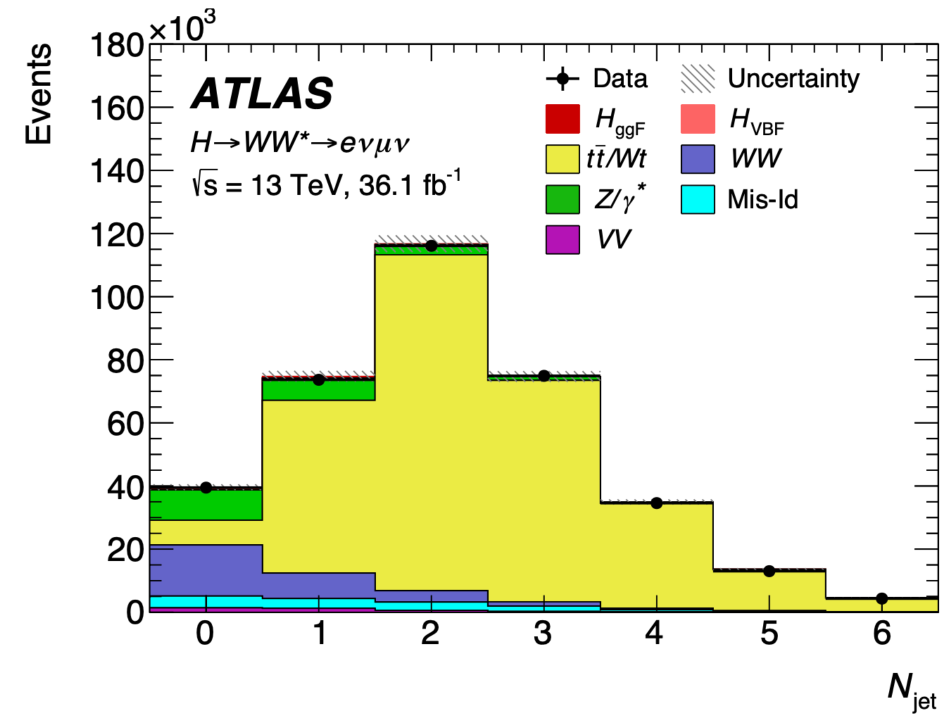
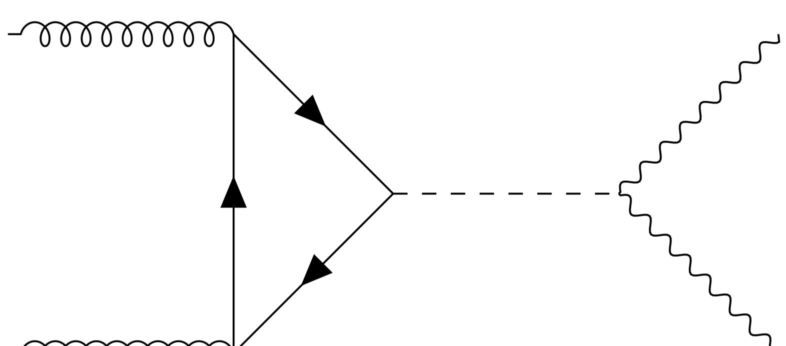
BASED ON WORK WITH P. CAL, D. SCOTT, F. TACKMANN, W. WAALEWIJN

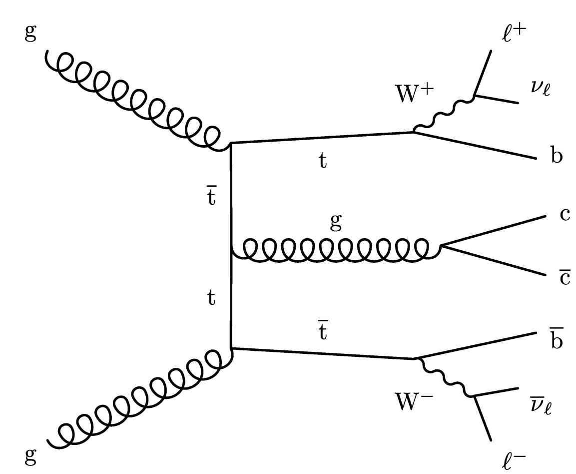
# JET VETO CROSS SECTIONS AT THE LHC

- Many Higgs analyses divide the data into exclusive jet bins
- Background decomposition changes with number of jets




ATLAS, 1808.09054



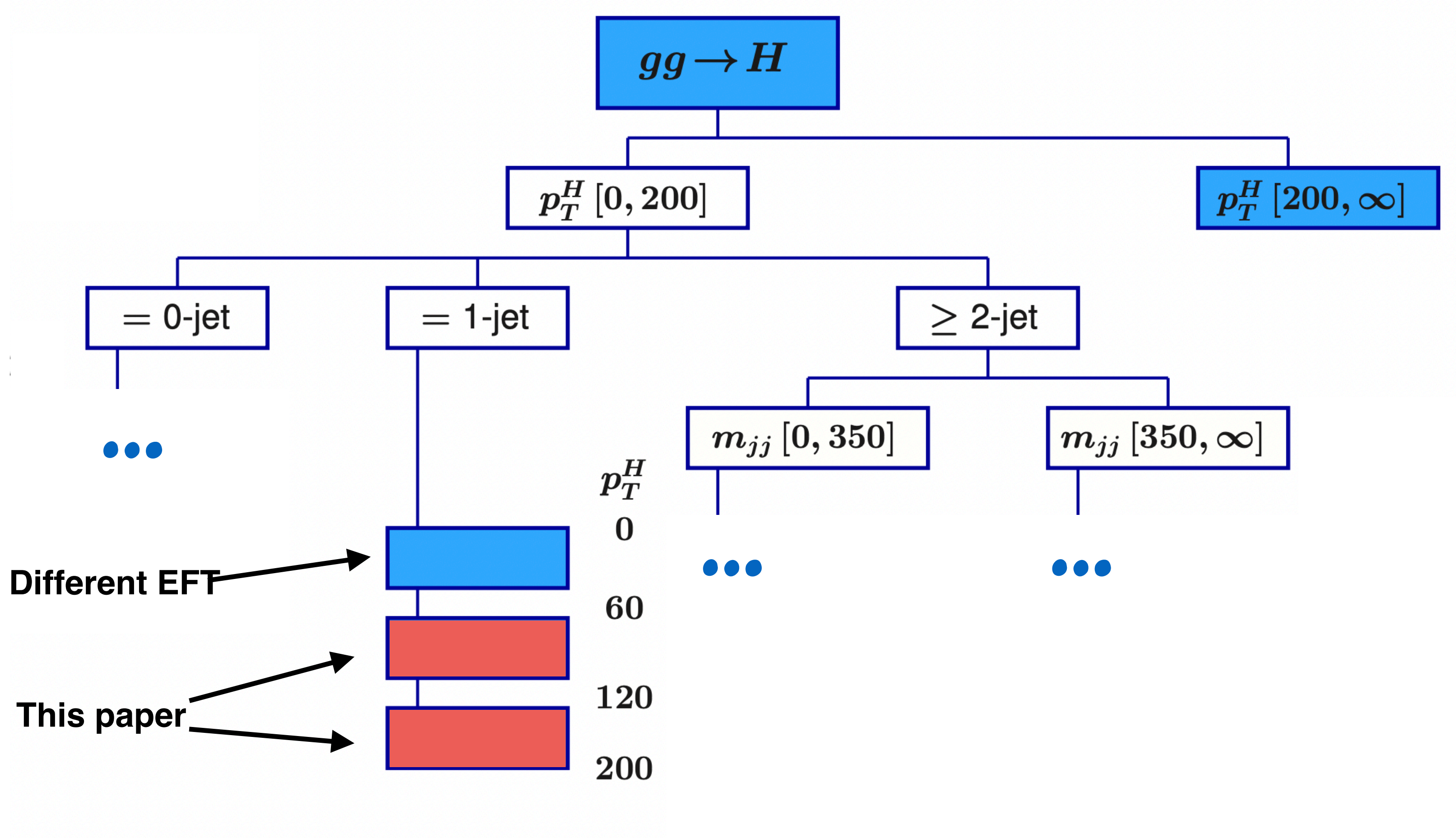



Signal

Background

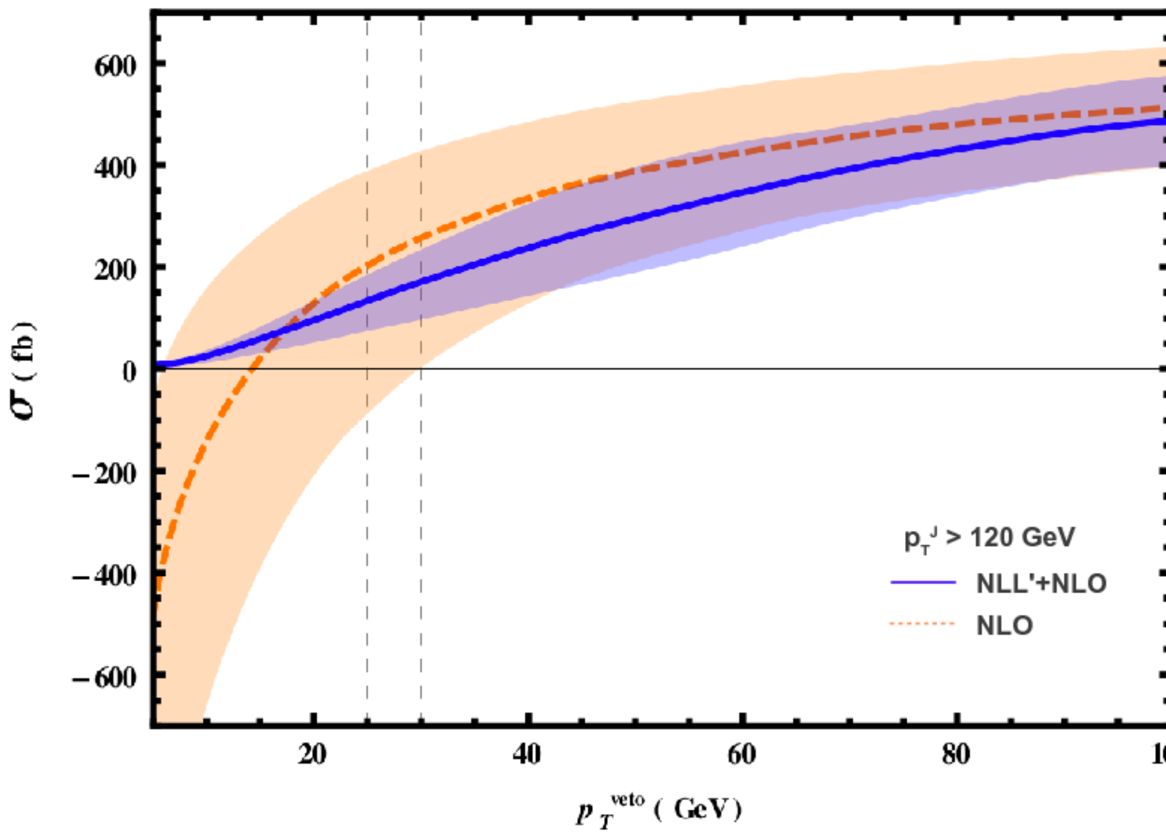
# JET VETO CROSS SECTIONS AT THE LHC

- Simplified Template Cross Sections (STXS) provide a common framework for Higgs measurements
- Used to combine different decay channels and experiments



# JET VETO CROSS SECTIONS AT THE LHC

- Demanding a veto on jets incurs logs of $p_T^{cut}/Q$ and $R$
- Resummation for colour singlet 0-jet bin has been achieved in direct QCD and SCET up to NNLL'
- Factorisation in a SCET approach demonstrated for 1-jet bin up to NLL'+NLO
- Aim for NNLL'+NNLO in Higgs+jet




Liu X., F. Petriello, 1210.1906, 1303.4405

T. Becher, M. Neubert, 1205.3806
F. Tackmann, J. Walsh, S. Zuberi, 1206.4312
A. Banfi, G. Salam, G. Zanderighi, 1203.5773
I. Stewart, F. Tackmann, J. Walsh, S. Zuberi, 1307.1808
T. Becher, M. Neubert, L. Rothen, 1307.0025

# JET VETO RESUMMATION FOR COLOUR-SINGLET PRODUCTION

- SCET-based approach: factorise cross section into single-scale functions

$$\frac{d\sigma}{d\Phi_0}(p_T^{\mathrm{cut}},\mu,\nu) = H(\Phi_0,\mu)[B_a \times B_b](Q,p_T^{\mathrm{cut}},R,\mu,\nu)S(p_T^{\mathrm{cut}},\mu,\nu)$$

- Soft/beam functions describe soft/collinear radiation
- No large logs when each is evaluated at its own scale
- Evolution to common scale via RGE $\Rightarrow$ resummation
- Rapidity scale separates soft/collinear modes

# FACTORISATION AND REFACTORISATION

- One signal jet, veto additional jets with $p_T > p_T^{\rm cut} \sim 30\,\mathrm{GeV}$
- Factorisation possible for $p_T^{\rm cut}/Q \ll 1, R_J \ll 1$

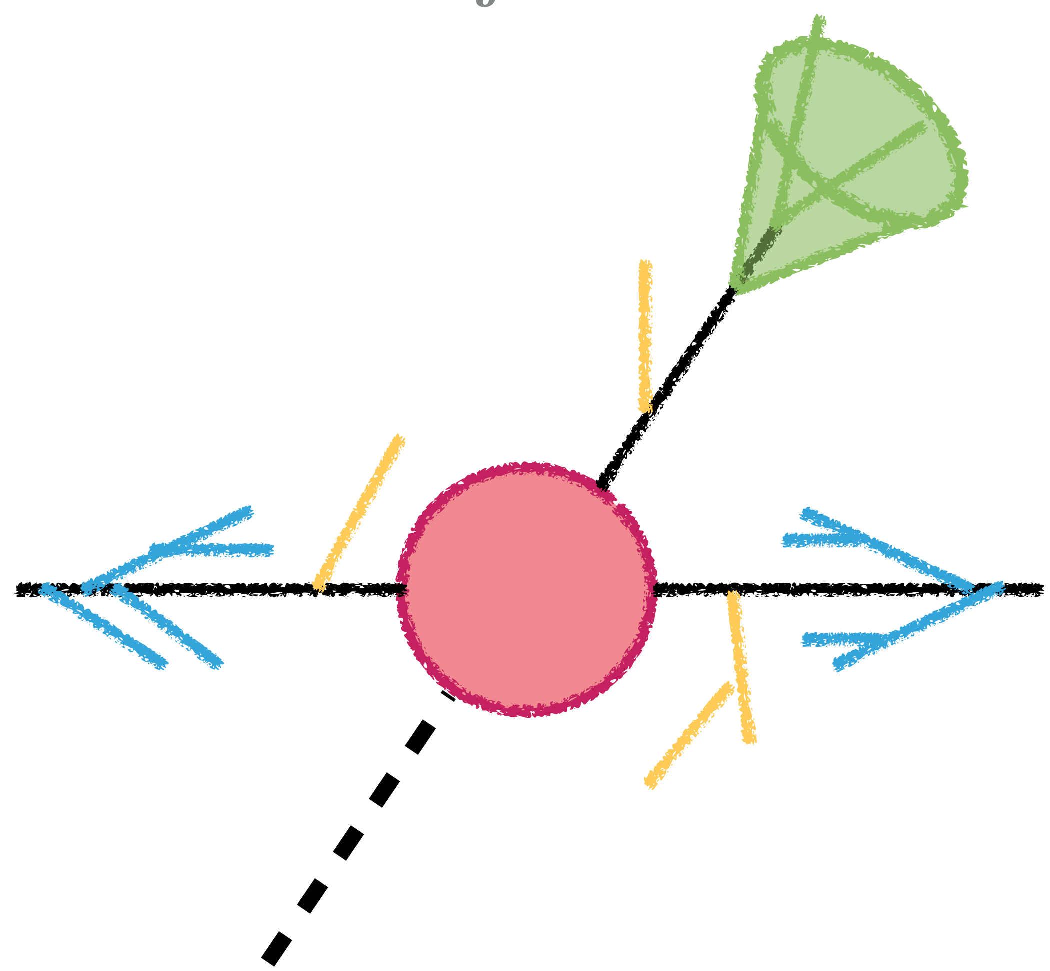
$H(p_T, Y, \eta_J)$

$J(p_T R_J)$

$B(p_T^{\rm cut})$

$S^T(p_T^{\rm cut}, p_T^{\rm cut} R_J)$

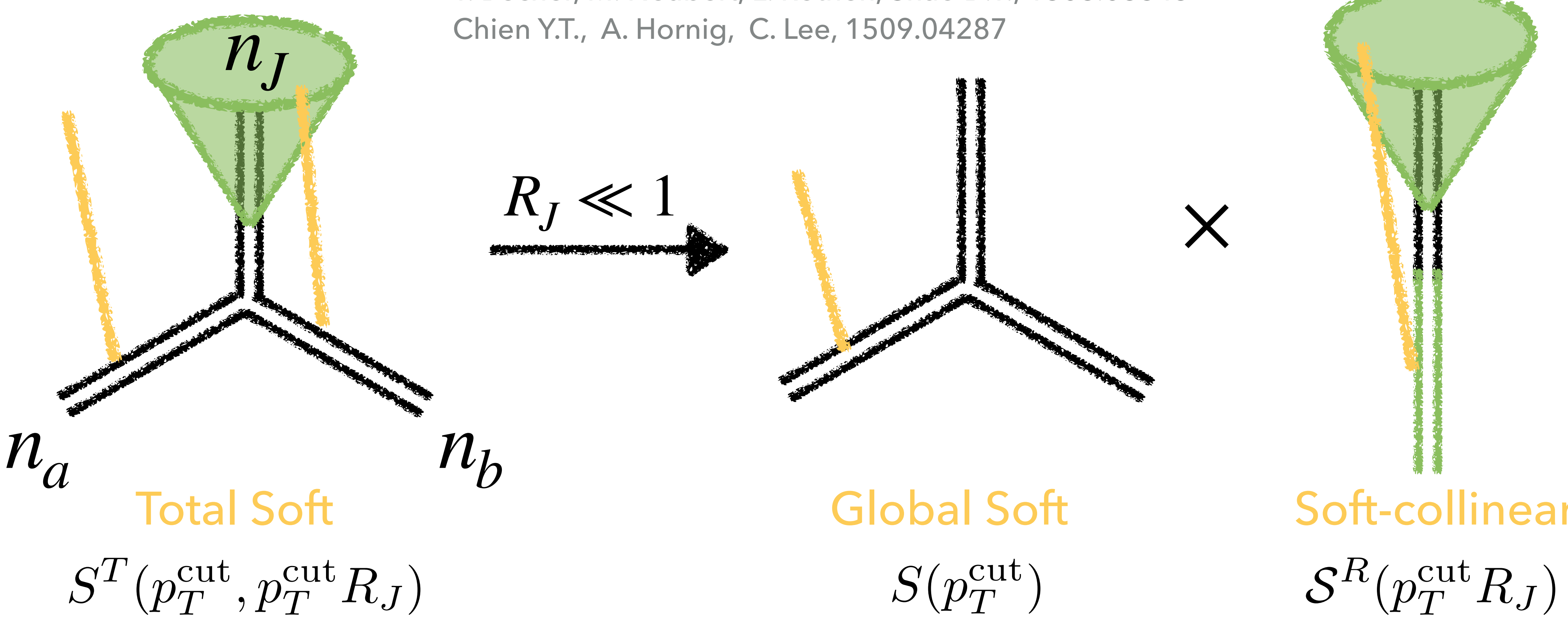
Depends on two parametrically separated scales - can be refactorised



# FACTORISATION AND REFACTORISATION

- In the $R_J \ll 1$ limit, the total soft function can be refactorised:

T. Becher, M. Neubert, L. Rothen, Shao D.Y., 1508.06645
Chien Y.T., A. Hornig, C. Lee, 1509.04287



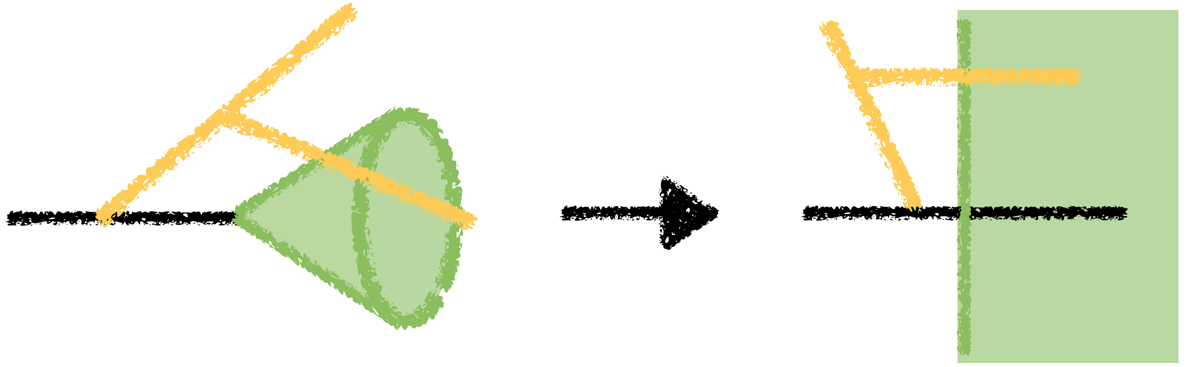

- Allows resummation of logs of $R_J$ in the soft sector

# NONGLOBAL LOGARITHMS

- Jet and soft-collinear functions have the same angular scaling but different virtuality - this leads to nonglobal logs

$$J(p_T R_J) \sim Q(R_J^2, 1, R_J)$$
$$\mathcal{S}^R(p_T^{\rm cut} R_J) \sim Q\lambda(R_J^2, 1, R_J)$$

- Related to hemisphere NGLs by a boost along jet axis



- Use 5-loop solution of BMS equation, percent level effect

$$\widehat{L} = \frac{\alpha_s N_c}{\pi} \ln \frac{p_T^J}{p_T^{\rm cut}}$$

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

M. Schwartz, Zhu H.X.,1403.4949

# FACTORISATION FORMULA

$$\sigma(p_T^{\text{cut}}) = H(p_T, Y, \eta_J) \times B_a(p_T^{\text{cut}}, \omega_a)\, B_b(p_T^{\text{cut}}, \omega_b) \times J(p_T R_J)$$
$$\times\, S(p_T^{\text{cut}}) \times \mathcal{S}^R(p_T^{\text{cut}} R_J) \times \mathcal{S}^{\text{NG}}(p_T^{\text{cut}}/p_T)$$

Global soft

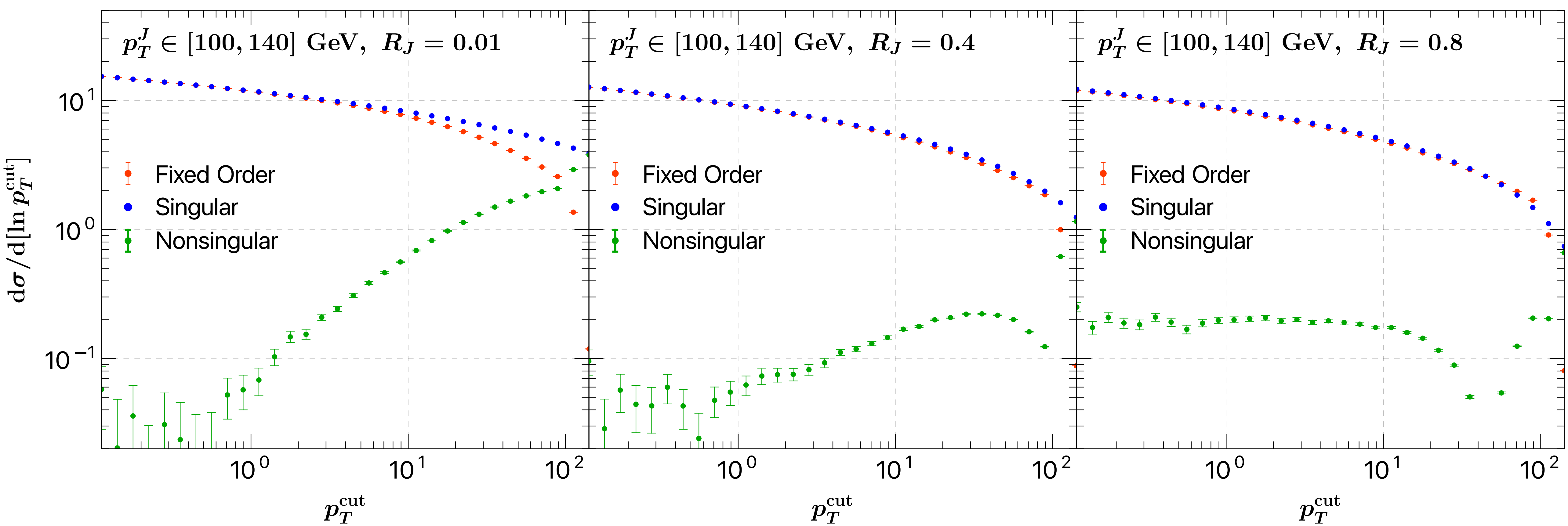
Soft-collinear

Nonglobal soft

- Measurement constrains emissions in each sector independently of other sectors
- Factorisation is a product, not a convolution
- Formula is for the resummed cumulant, not the spectrum

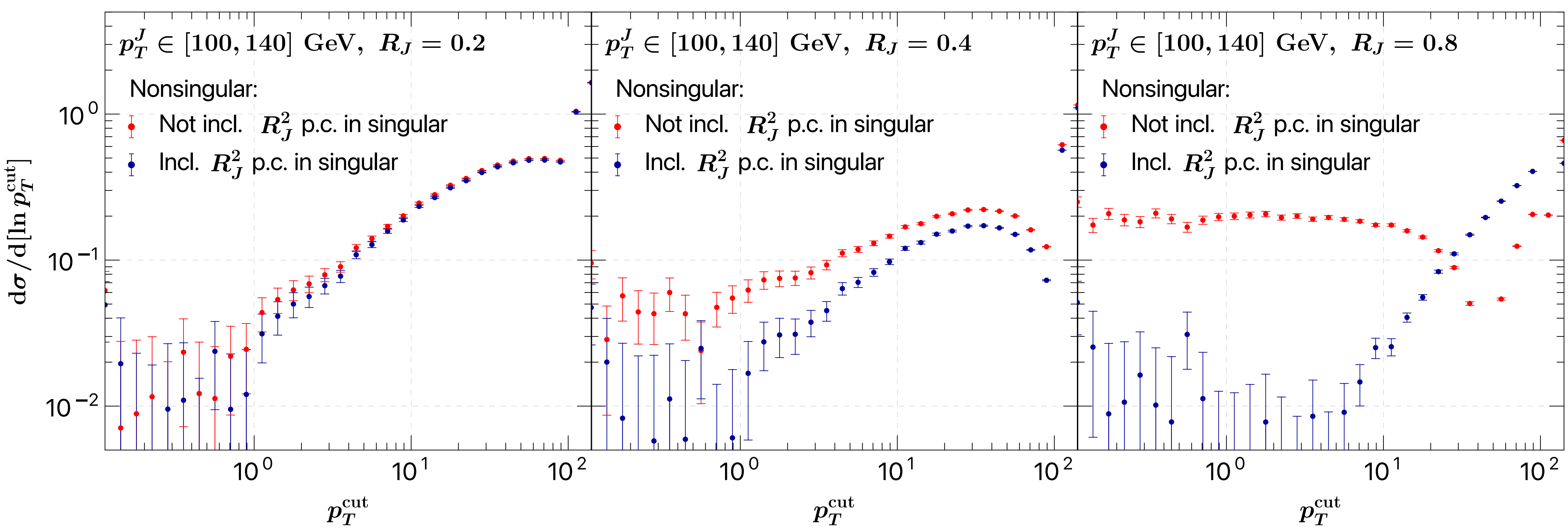
# FIXED ORDER EXPANSION AND NONSINGULAR TERMS

- Nonsingular at NLL' correctly power-suppressed for $R_J = 0.01$, but not for larger values



# FIXED ORDER EXPANSION AND NONSINGULAR TERMS

- Failure of nonsingular cancellation at large $R_J$ implies $R_J^2 \log(p_T^{\text{cut}})$ power corrections in the soft sector
- We computed $\mathcal{O}(R_J^2)$ power corrections to the 1-loop total soft function:



# EXTENSION TO NNLL′

- Require higher order ingredients:

| Accuracy | $\Gamma_{\text{cusp}}$ | $\gamma$ | $\beta$ | $C(\alpha_s)$ |
|---|---|---|---|---|
| NNLL′ | 3-loop | 2-loop | 3-loop | 2-loop |

- Cusp and beta function known to required order

| 2-loop | $H$ | | $B$ | | $J$ | | $S$ | | $\mathcal{S}^R$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\gamma$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ | $q$ | $g$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ |
| | $qgq$ | $gqg$ | | | | | $qgq$ | $gqg$ | | |
| $C(\alpha_s)$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ | $q$ | $g$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ |
| | $qgq$ | $gqg$ | | | | | $qgq$ | $gqg$ | | |

$=$ known

$=$ unknown

T. Gehrmann, M. Jaquier, N. Glover, A. Koukoutsakis, 1112.3554
S. Abreu, J. Gaunt, P. Monni, L. Rottoli, R. Szafron, 2207.07037
Liu H.Y., Liu X., S.O. Moch, 2103.08680

# EXTENSION TO NNLL'

- RG consistency gives most anomalous dimensions

$$\gamma_H^\kappa + \gamma_S^\kappa + \gamma_{\mathcal{S}}^j + \gamma_J^j + \gamma_B^a + \gamma_B^b = 0$$

- Treat missing ones as theory nuisance parameters

| 2-loop | $H$ | | $B$ | | $J$ | | $S$ | | $\mathcal{S}^R$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| $\gamma$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ | $q$ | $g$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ |
| | $qgq$ | $gqg$ | | | | | $qgq$ | $gqg$ | | |
| $C(\alpha_s)$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ | $q$ | $g$ | $ggg$ | $q\bar{q}g$ | $q$ | $g$ |
| | $qgq$ | $gqg$ | | | | | $qgq$ | $gqg$ | | |

= known

= unknown

= from consistency

# EXTENSION TO NNLL'

- Logarithmic structure of unknown boundary terms can be obtained by solving RGE perturbatively

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \ln \mathcal{S}_i^R(p_T^{\mathrm{cut}} R_J;\mu) = \gamma_{\mathcal{S}}^i(p_T^{\mathrm{cut}} R_J;\mu)$$

$$L_{\mathcal{S}} = \ln\left(\frac{\mu}{p_T^J R_J}\right)$$

$$\mathcal{S}_j^{R,(2)}(p_T^{\mathrm{cut}} R_J;\mu) = \frac{\Gamma_0^{j\,2}}{2} L_{\mathcal{S}}^4 - \Gamma_0^j\left(\frac{2}{3}\beta_0 + \gamma_{\mathcal{S}\,0}^j\right) L_{\mathcal{S}}^3 + \left[\beta_0\gamma_{\mathcal{S}\,0}^j + \frac{\gamma_{\mathcal{S}\,0}^{j\,2}}{2} - \Gamma_0^j s_j^{R,(1)} - \Gamma_1^j\right] L_{\mathcal{S}}^2 + \left[(2\beta_0 + \gamma_{\mathcal{S}\,0}^j) s_j^{R,(1)} + \gamma_{\mathcal{S}\,1}^j\right] L_{\mathcal{S}} + s_j^{R,(2)},$$

Theory nuisance parameter

# MATCHING TO FIXED ORDER

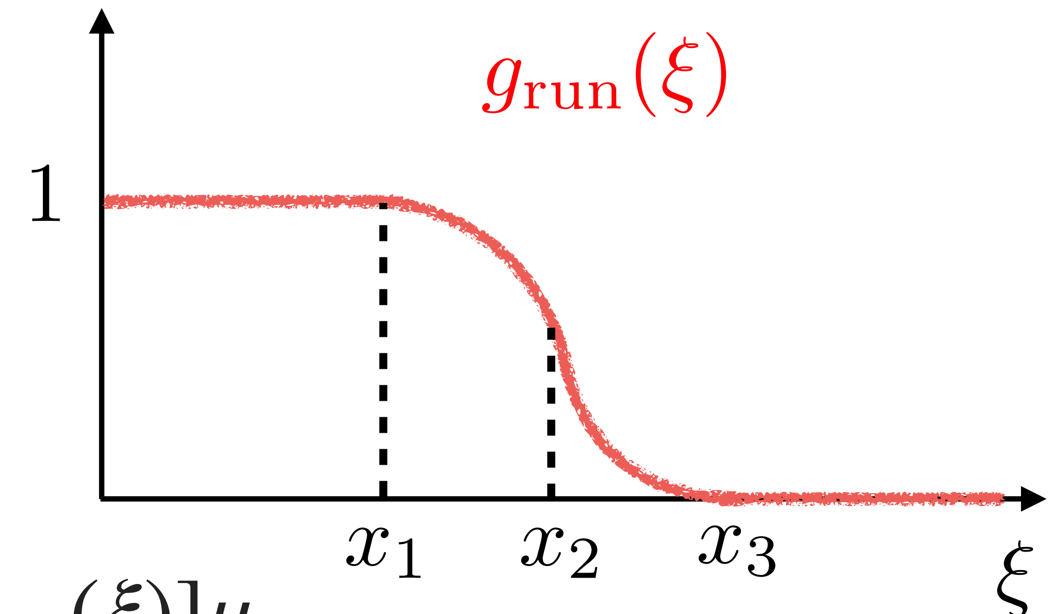
- Effective theory description/factorisation formula valid for small $p_T^{\text{cut}}$
- For larger values near hard scale, EFT breaks down $\Rightarrow$ need fixed order predictions to give correct behaviour
- Switch off resummation - RGE running stops when all scales approach a common value,

$$\mu_{\text{FO}} = \mu_H = \mu_B = \mu_S = \mu_J = \mu_{\mathcal{S}}$$

# HYBRID PROFILE SCALES

- Resummation turned off via hybrid profile scales for $p_T^{\rm cut} \sim p_T^H$

$$\mu_B = \mu_S = f_{\rm run}\left(\xi, p_T^{\rm cut}, \mu_{\rm FO}\right)$$
$$\mu_J = f_{\rm run}\left(\xi, p_T^J R_J, \mu_{\rm FO}\right)$$
$$\mu_{\mathcal{S}} = f_{\rm run}\left(\xi, p_T^{\rm cut} R_J, \mu_{\rm FO}\right)$$

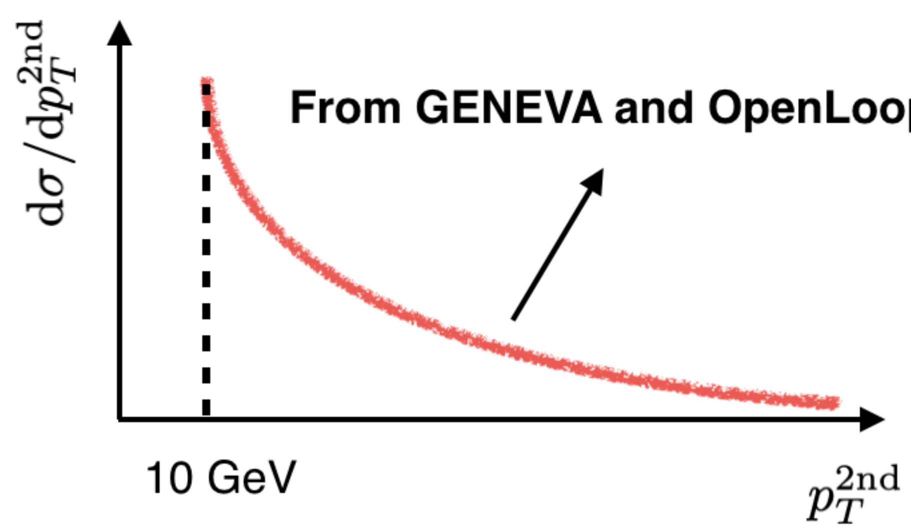


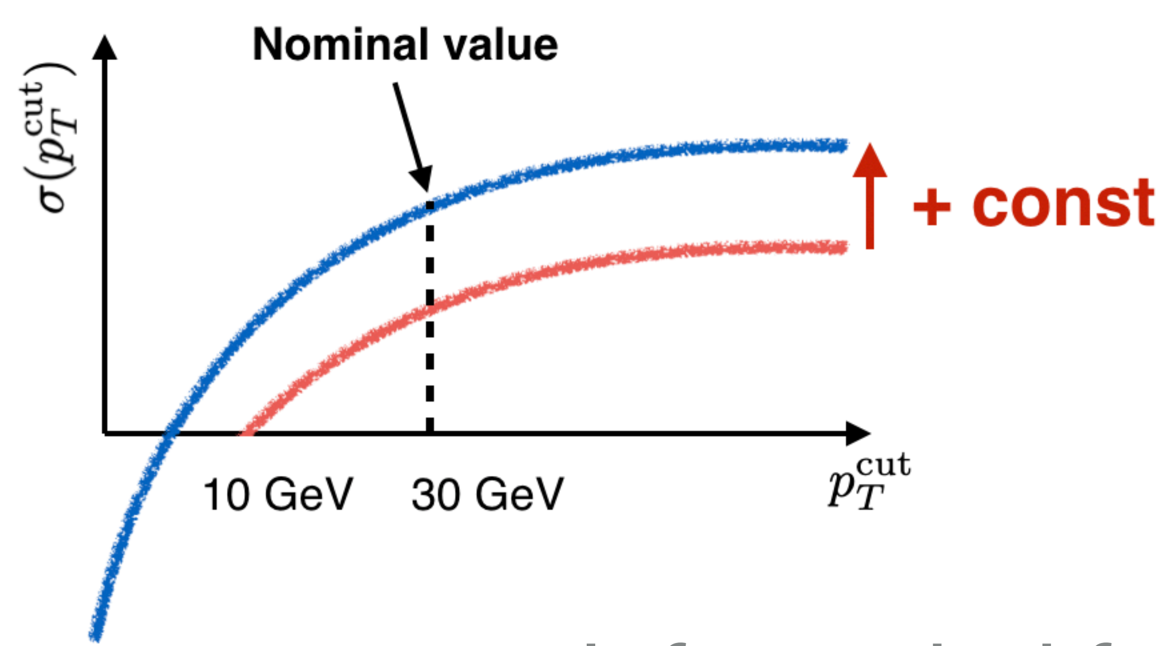

$$f_{\rm run}(\xi, \mu_0, \mu_{\rm FO}) = g_{\rm run}(\xi)\mu_0 + [1 - g_{\rm run}(\xi)]\mu_{\rm FO}$$

- All scales flow to $\mu_H = \mu_{\rm FO}$ as $\xi = p_T^{\rm cut}/p_T^H \to 1$
- Similar expressions for rapidity scales

# MATCHING TO FIXED ORDER

- Choose transition points $x_i$ based on size of singular/nonsingular, vary to obtain matching uncertainty
- No $\text{NNLO}_1$ calculation publicly available!



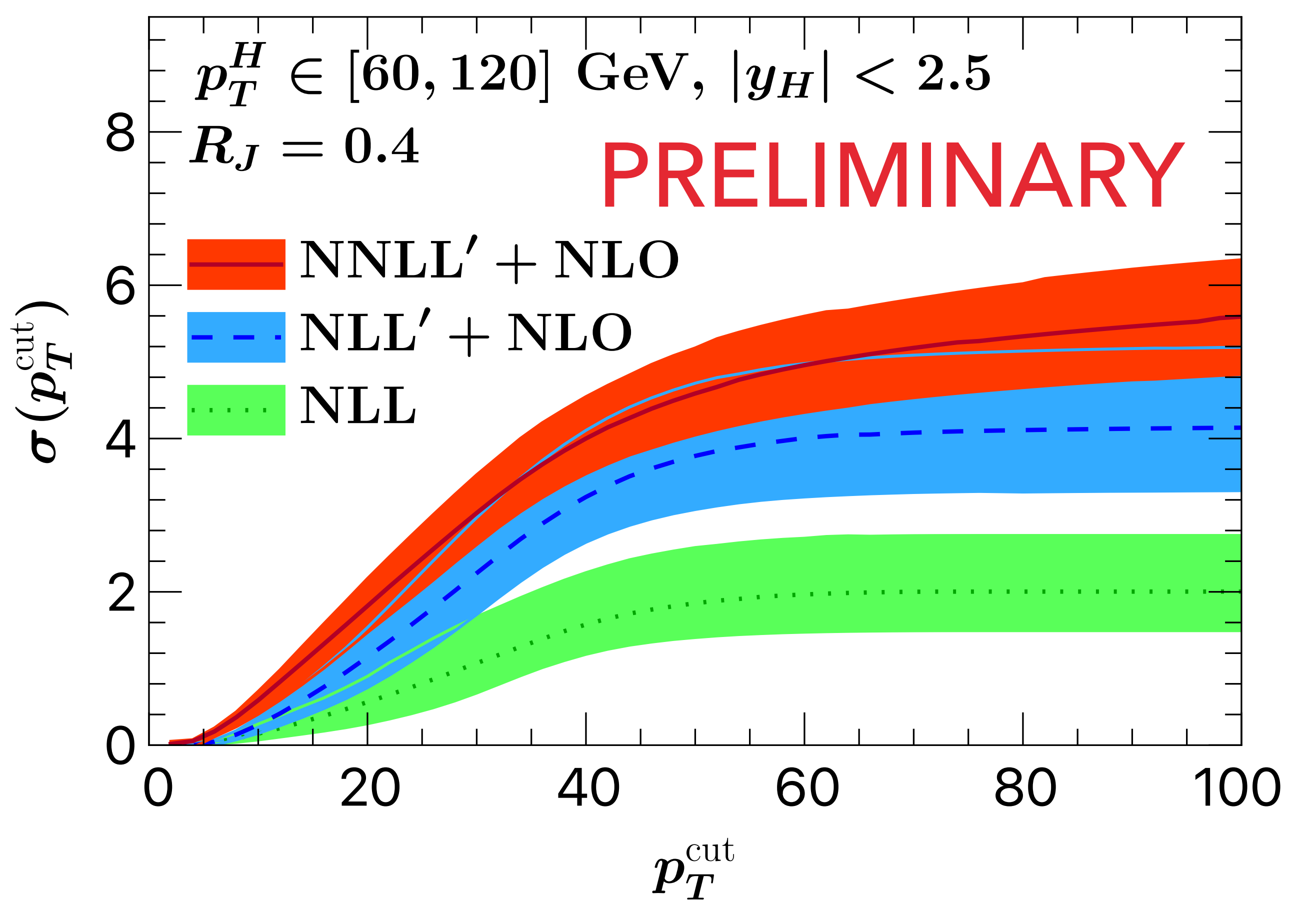




- Match to $\text{NLO}_2$ and determine ~constant shift needed from NNLO K-factor.

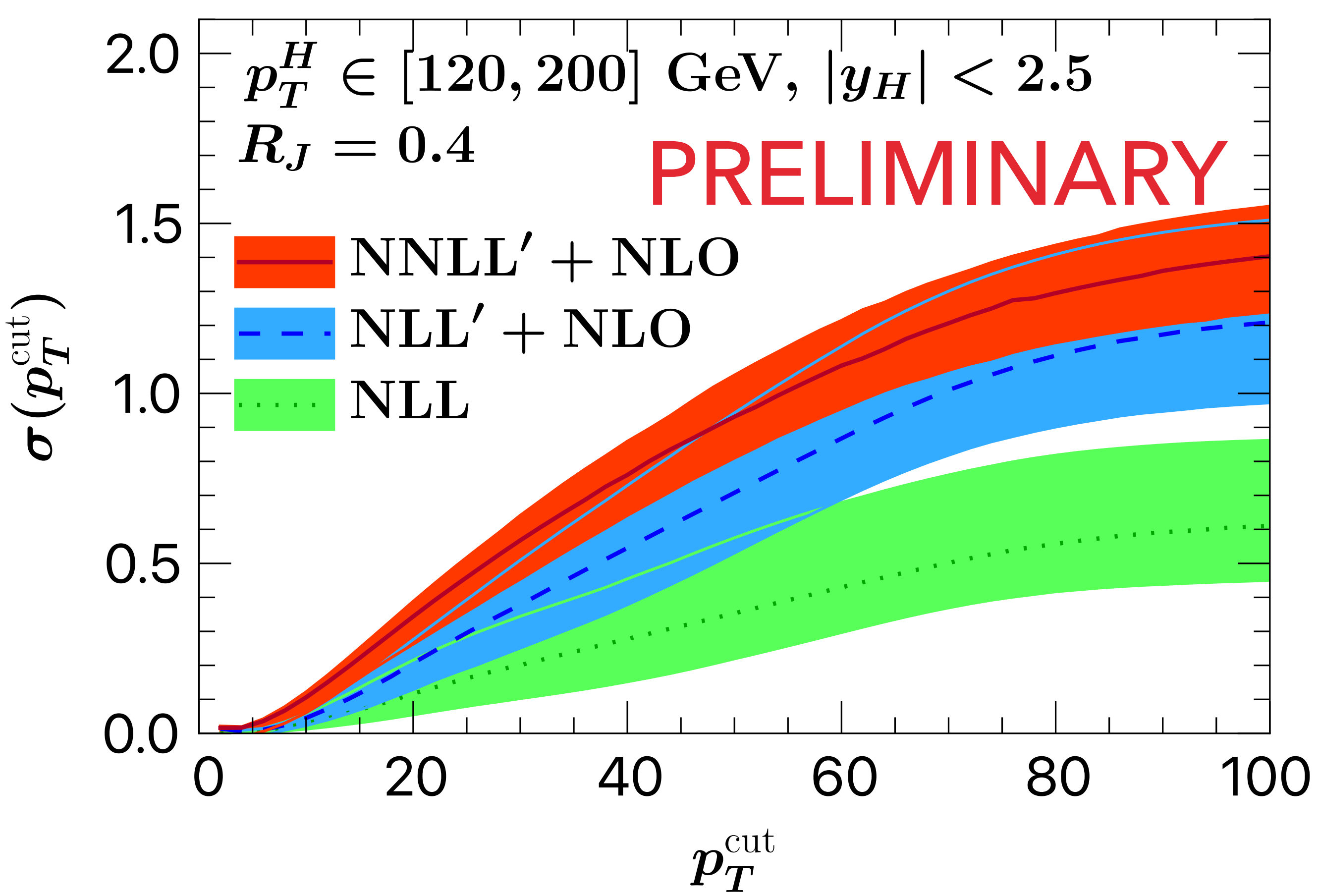
# RESULTS

- $p_T^{\rm cut}$ cumulant, integrated over Born variables

STXS1

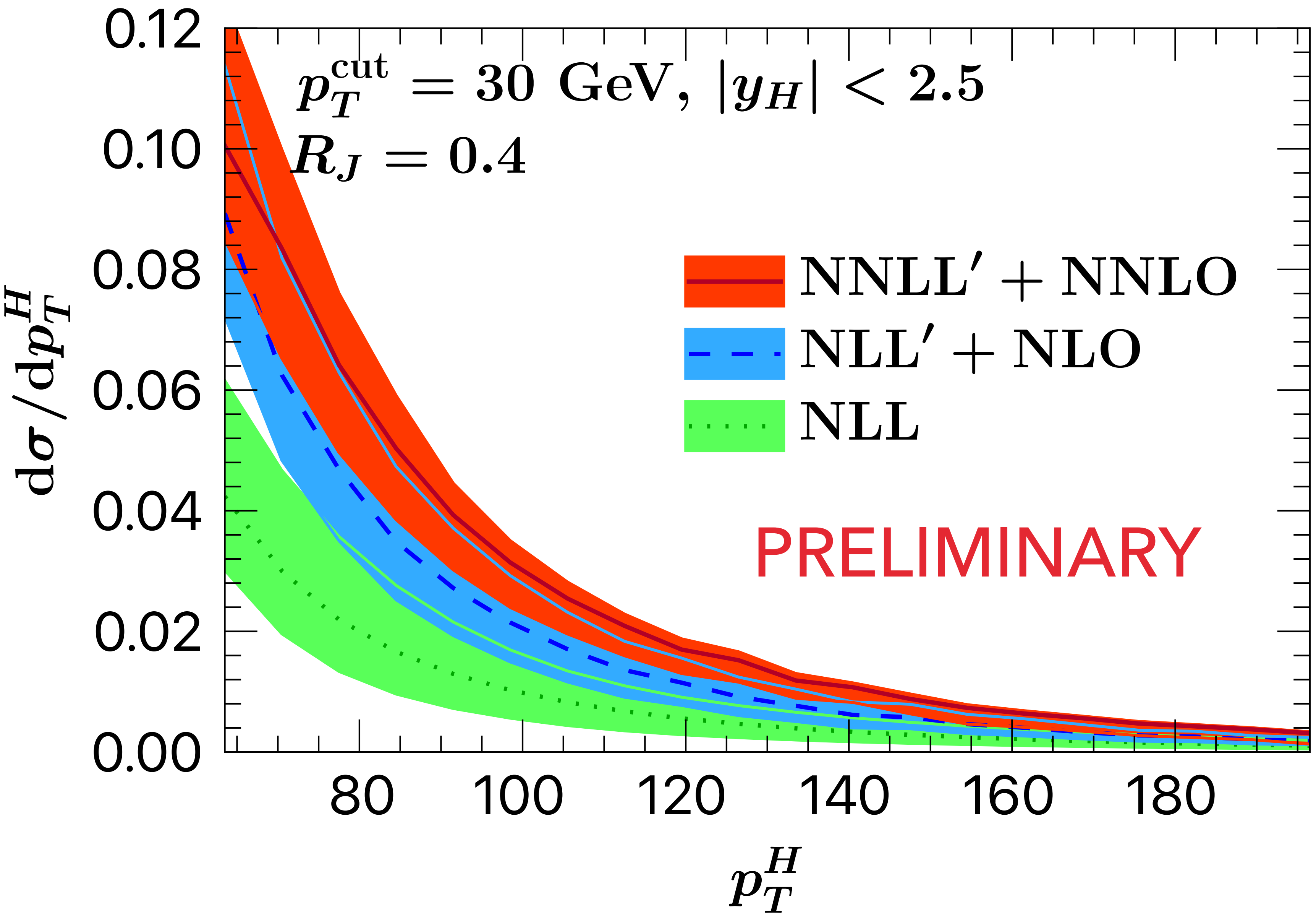



STXS2



# RESULTS

- $p_T^H$ spectrum at nominal $p_T^{\text{cut}} = 30$ GeV



# SUMMARY

- We also studied jet veto resummation for Higgs+jet production – this is important for experimental measurements of STXS bins
- Power corrections to the soft function in $R_J$ are crucial to obtain the correct nonsingular, and refactorisation of the soft sector can allow resummation of logs of $R_J$
- We were able to obtain approximate NNLL'+NNLO accuracy by bootstrapping anomalous dimensions and treating missing terms as theory nuisance parameters

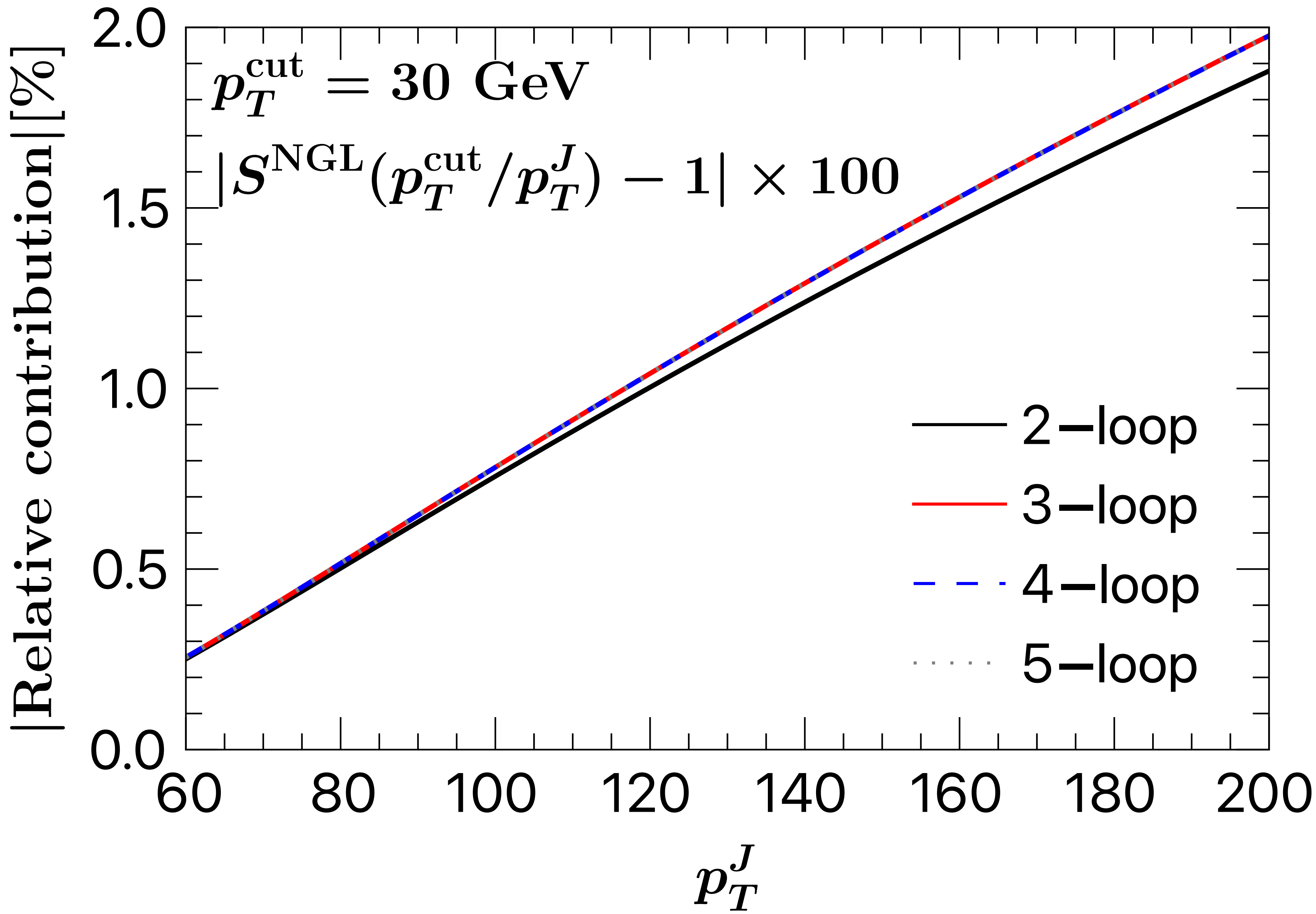
# OUTLOOK

- Future availability of missing two-loop ingredients would allow us to promote resummed accuracy to full NNLL'
- Likewise, a publicly available $\mathrm{NNLO}_1$ calculation would allow us to perform the matching exactly
- Studies of the STXS bin for $p_T^H \in [0, 60]$ GeV would require a different EFT treatment
- Higgs+2 jets studies would also be interesting

# BACKUP SLIDES

# NONGLOBAL LOGS AND THEIR CONVERGENCE

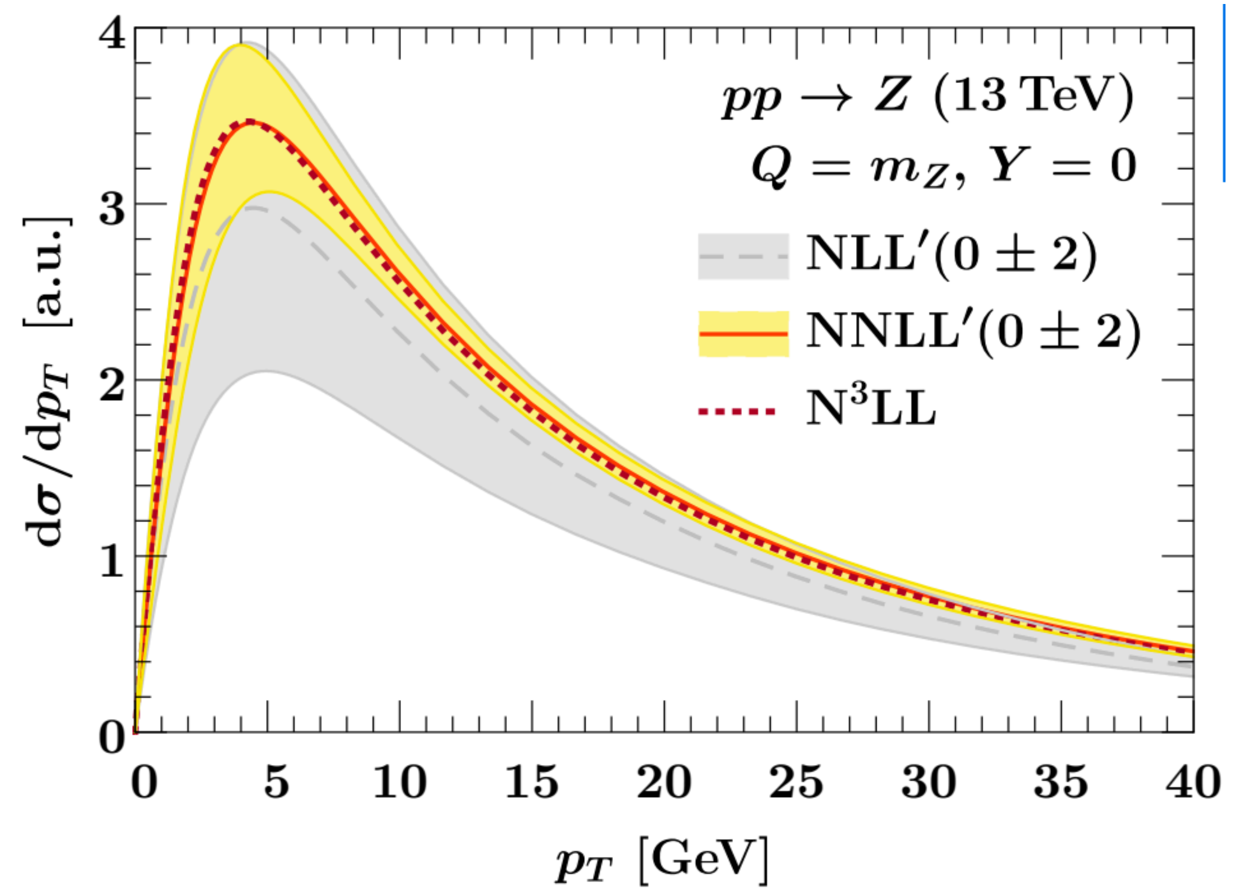
$$\mathcal{S}_q^{\rm NG}\left(\frac{p_T^{\rm cut}}{p_T^J}\right) = 1 - \frac{\pi^2}{24}\widehat{L}^2 + \frac{\zeta_3}{12}\widehat{L}^3 + \frac{\pi^4}{34560}\widehat{L}^4 + \left(-\frac{\pi^2\zeta_3}{360} + \frac{17\zeta_5}{480}\right)\widehat{L}^5 + \mathcal{O}(L^6)$$




$$\widehat{L} = \frac{\alpha_s N_c}{\pi} \ln \frac{p_T^J}{p_T^{\rm cut}}$$

# THEORY NUISANCE PARAMETERS

- Resummed calculations have a definite all-order structure - predictions at each order depend on a handful of (semi) universal parameters
- Unknown parameters at higher orders are the real source of theory uncertainty, not arbitrary scales
- Treat them as nuisance parameters and vary, many advantages (correlations correct, can fit to data,...)




Tackmann, F.