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JET VETO RESUMMATION FOR

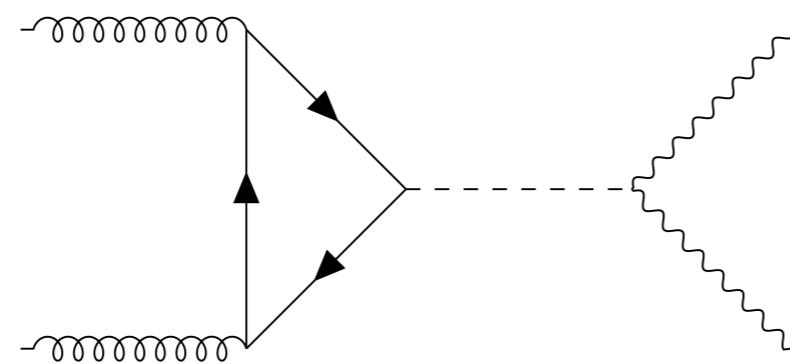
$pp \rightarrow H + j$ WITH
NNLL'+NNLO UNCERTAINTIES

MATTHEW A. LIM, HIGGS 2023

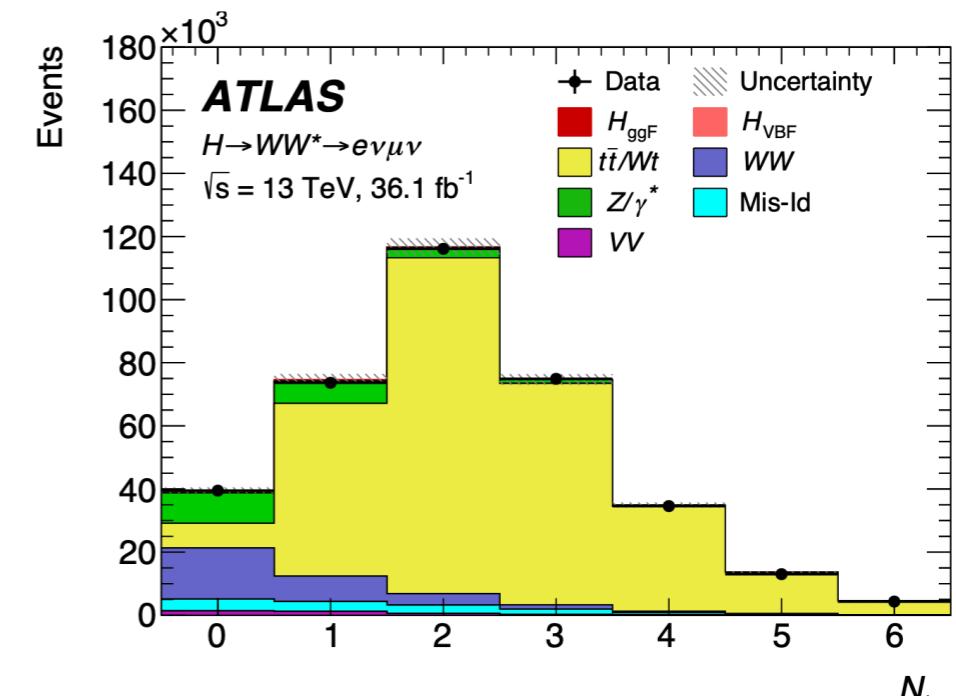
BASED ON WORK WITH P. CAL,
D. SCOTT, F. TACKMANN, W. WAALEWIJN

JET VETO CROSS SECTIONS AT THE LHC

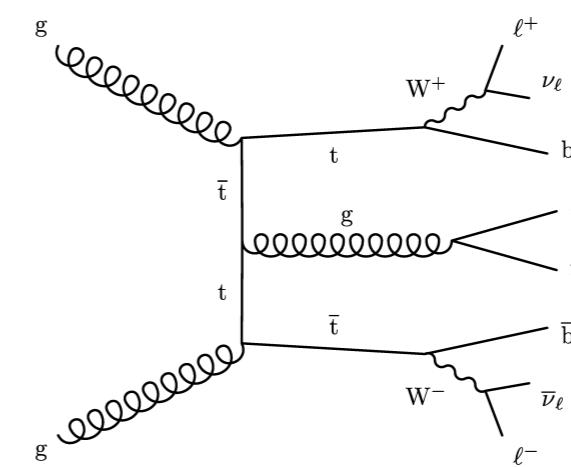
- ▶ Many Higgs analyses divide the data into exclusive jet bins
- ▶ Background decomposition changes with number of jets



Signal



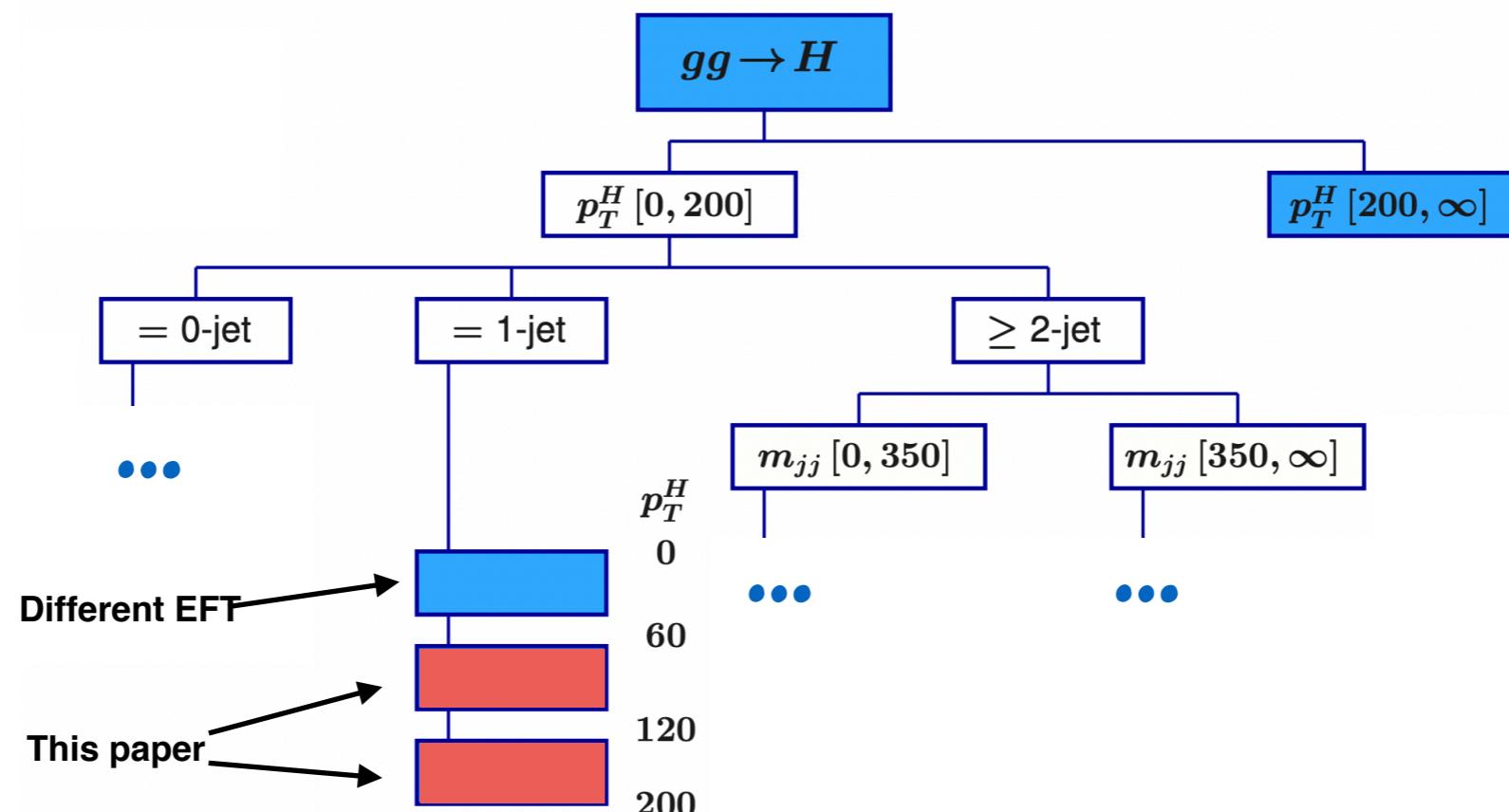
ATLAS, 1808.09054



Background

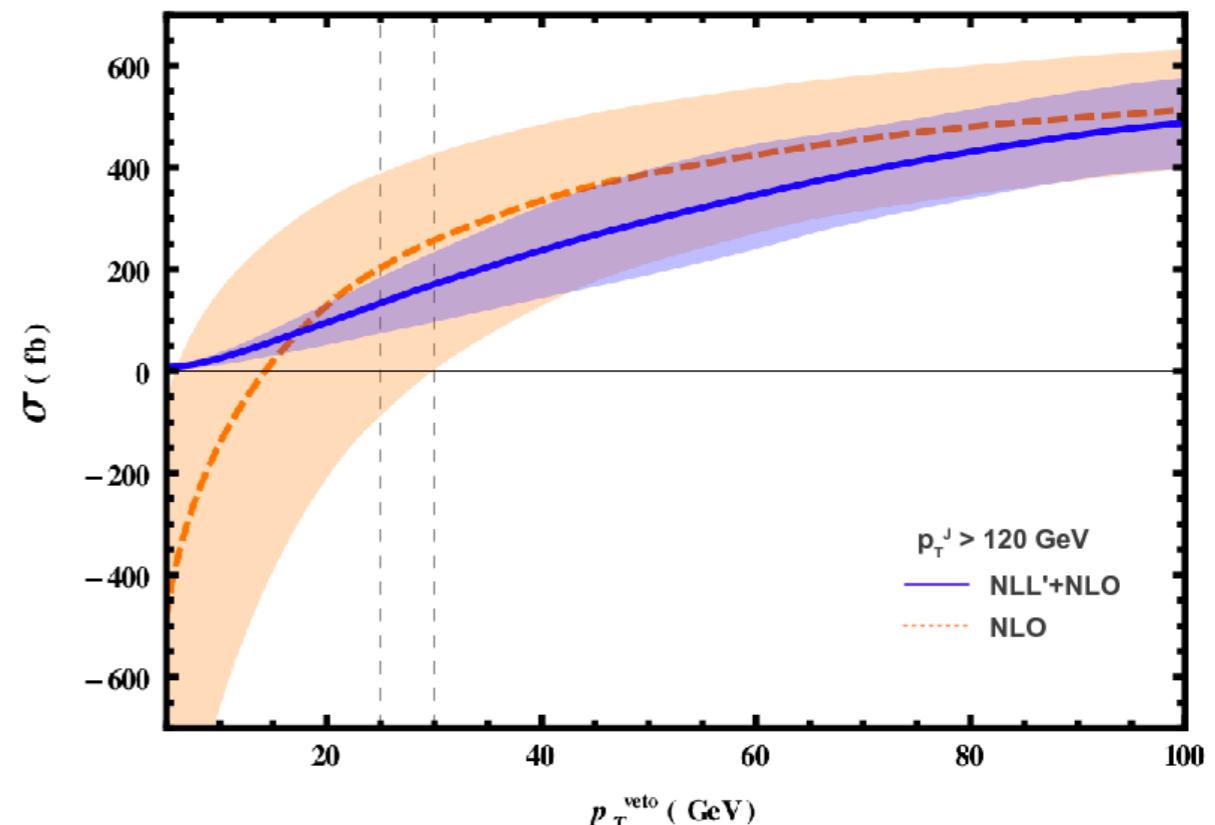
JET VETO CROSS SECTIONS AT THE LHC

- ▶ 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**

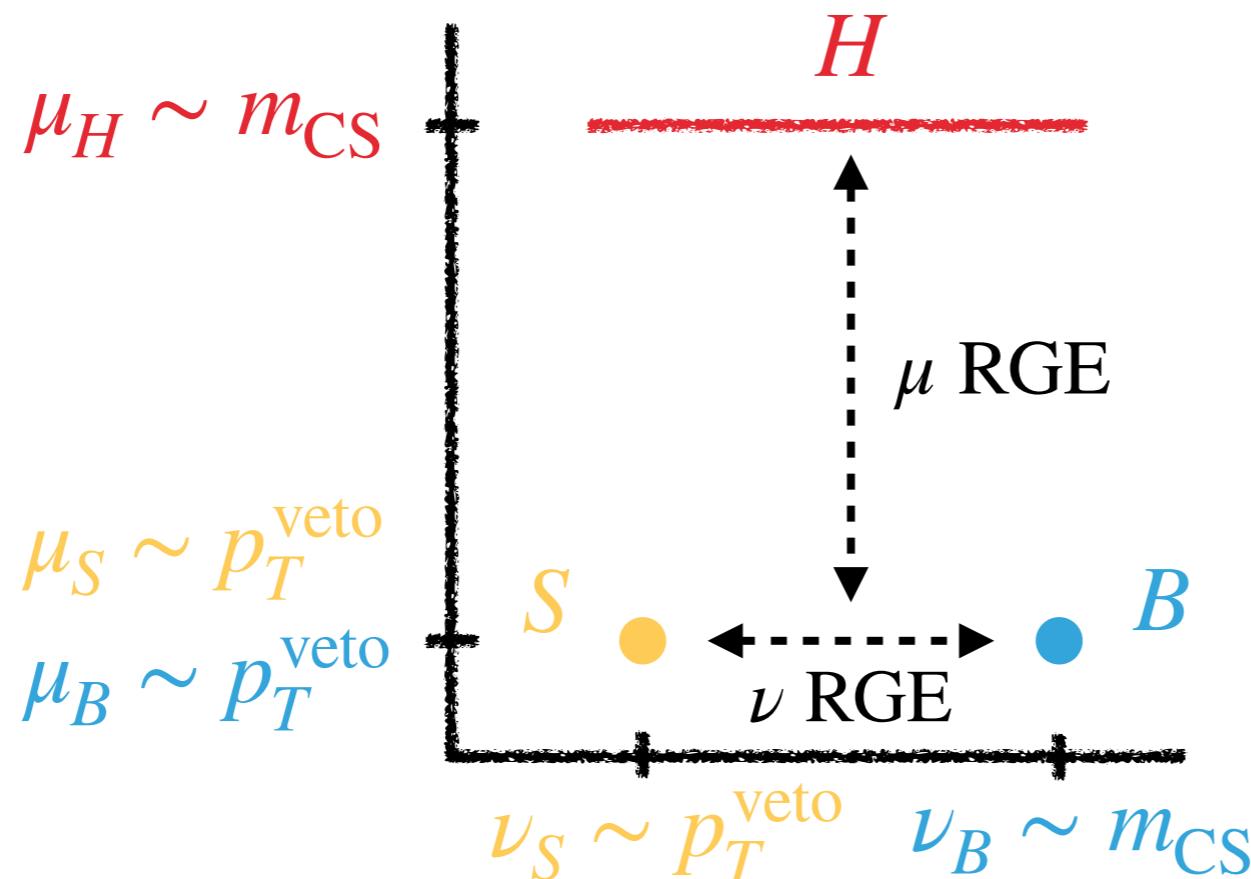
$$\frac{d\sigma}{d\Phi_0}(p_T^{\text{cut}}, \mu, \nu) = H(\Phi_0, \mu) [B_a \times B_b](Q, p_T^{\text{cut}}, R, \mu, \nu) S(p_T^{\text{cut}}, \mu, \nu)$$

- ▶ **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

RESUMMATION OF JET VETO LOGS FOR COLOUR SINGLET

- ▶ Resummation achieved by RGE evolution of hard, soft, beam functions to common scales μ, ν , e.g.

$$\frac{d}{d \ln \mu} \ln H(\Phi_0, \mu) = \Gamma_{\text{cusp}} \ln \frac{\mu_H^2}{\mu^2} + \gamma_H$$



FACTORISATION AND REFACTORISATION

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

$H(p_T, Y, \eta_J)$

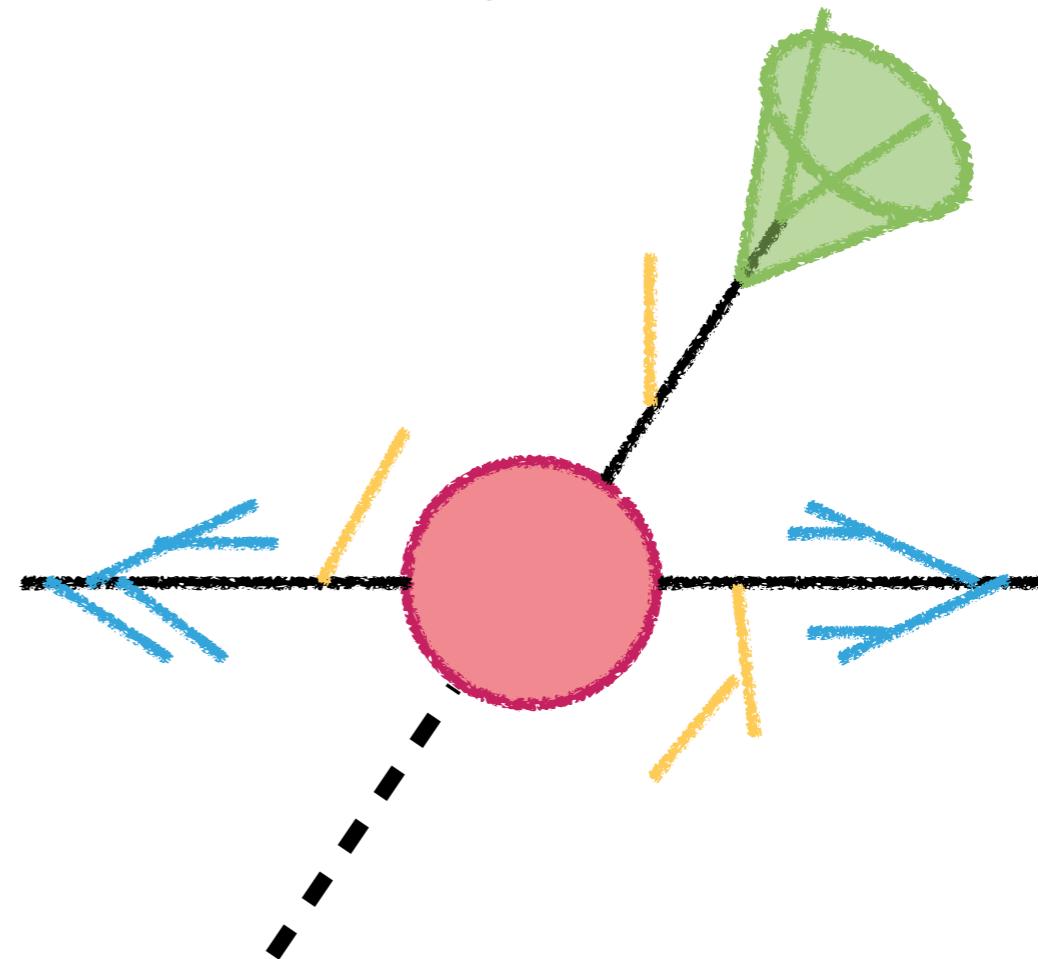
$J(p_T R_J)$

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

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



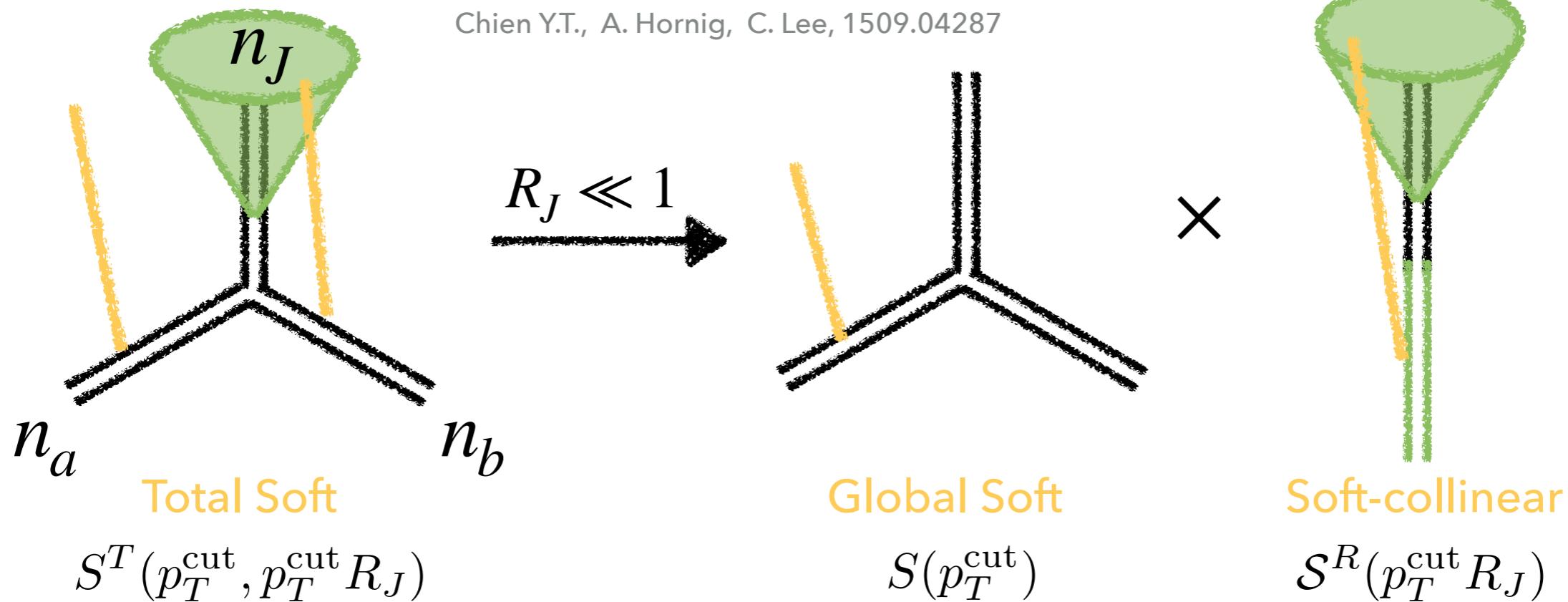
Depends on two parametrically separated scales - can be refactored



FACTORIZATION 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

FACTORISATION FORMULA

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

The equation shows the factorisation of the cross-section into several components. Three specific components are highlighted with colored boxes and arrows pointing to them from labels below:

- A yellow box around $S(p_T^{\text{cut}})$ with a yellow arrow pointing to it labeled "Global soft".
- A pink box around $\mathcal{S}^R(p_T^{\text{cut}} R_J)$ with a pink arrow pointing to it labeled "Soft-collinear".
- A teal box around $\mathcal{S}^{\text{NG}}(p_T^{\text{cut}}/p_T)$ with a teal arrow pointing to it labeled "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

EXTENSION TO NNLL'

- ▶ Require higher order ingredients:
- ▶ Cusp and beta function known to required order

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

 = known
 = unknown

EXTENSION TO NNLL'

- ▶ RG consistency gives most anomalous dimensions

$$\gamma_H^\kappa + \gamma_S^\kappa + \gamma_S^j + \gamma_J^j + \gamma_B^a + \gamma_B^b = 0$$

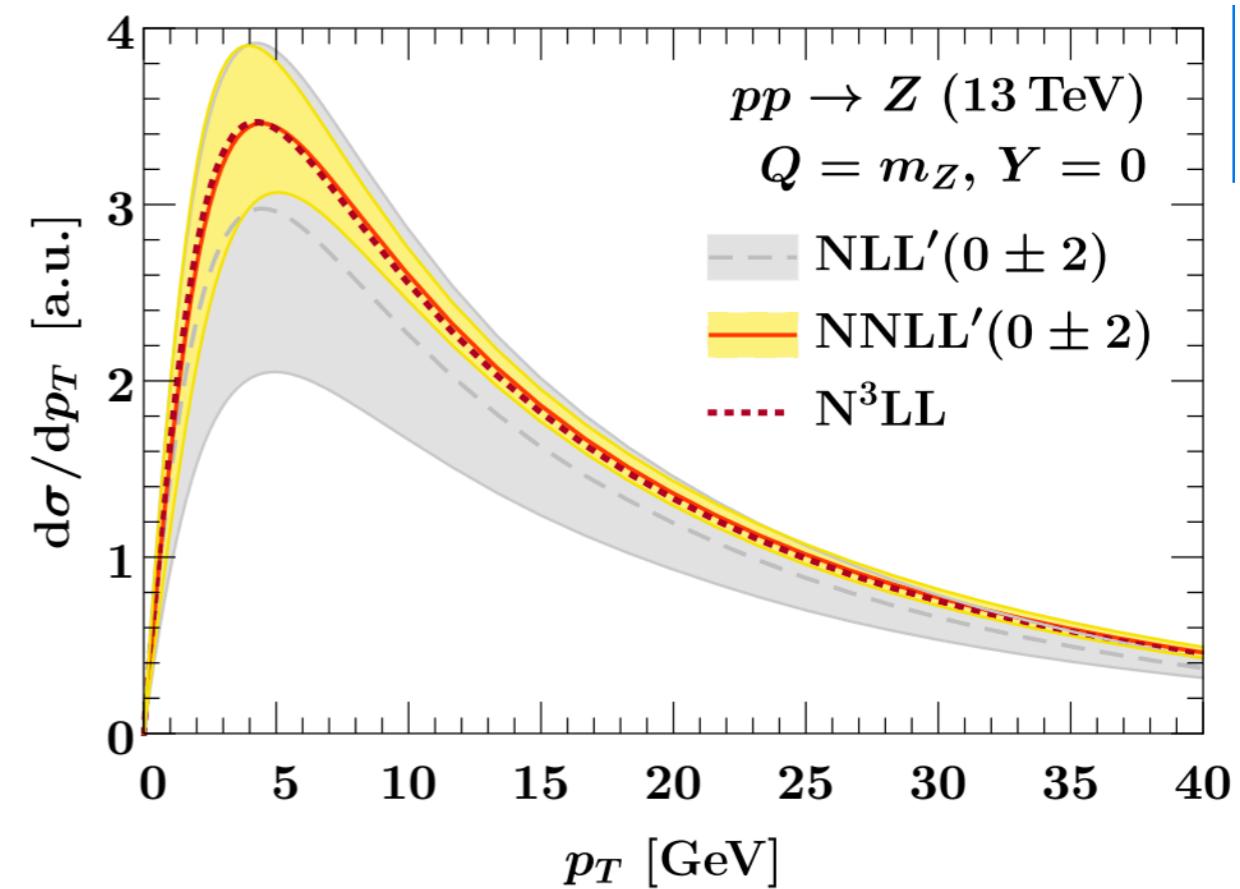
- ▶ Treat missing ones as theory nuisance parameters

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

= known
 = unknown
 = from consistency

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.

EXTENSION TO NNLL'

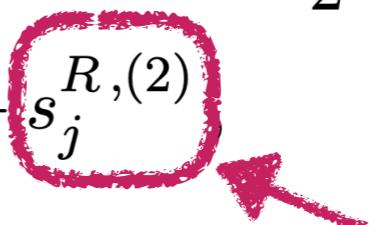
- Logarithmic structure of unknown boundary terms can be obtained by solving RGE perturbatively

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



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

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

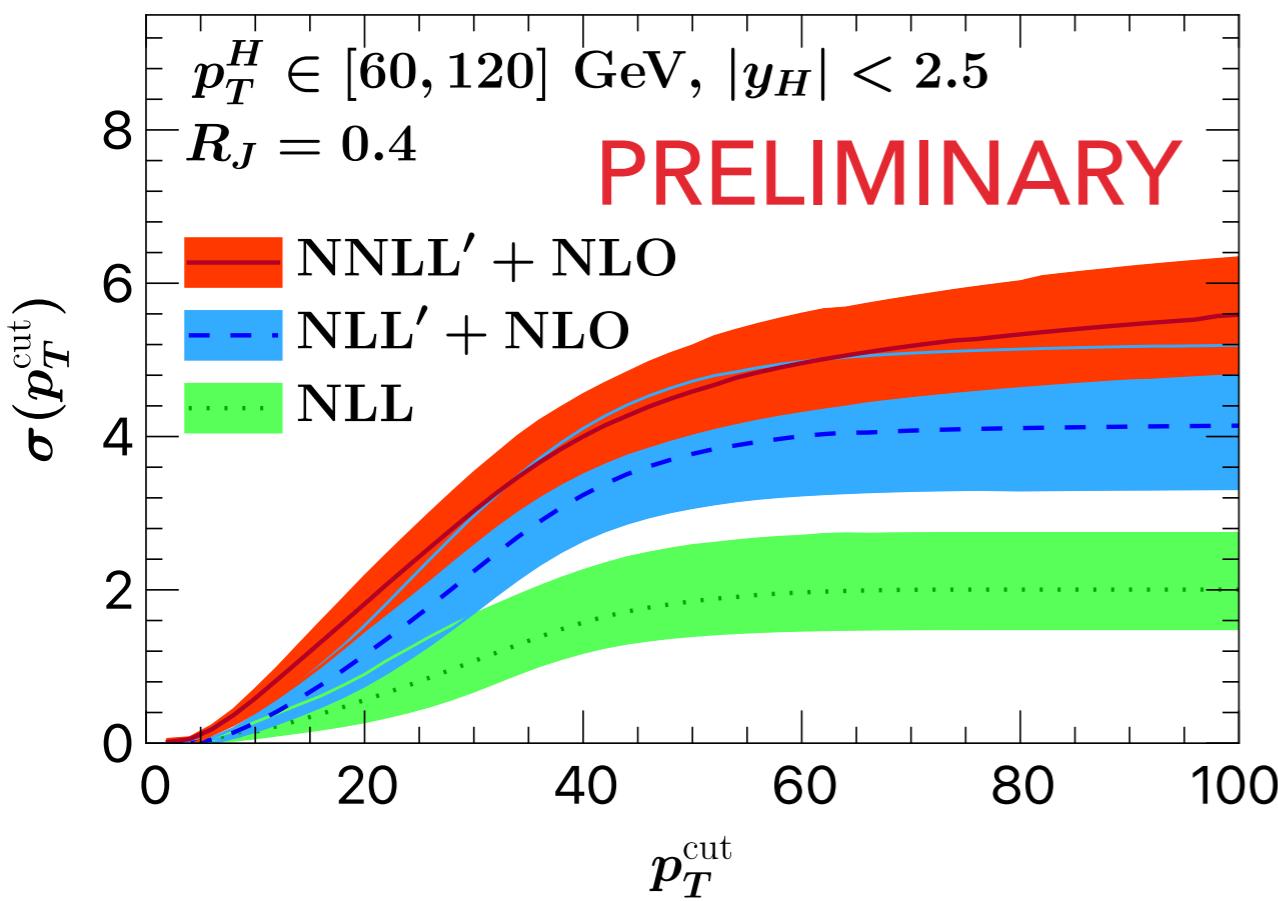


Theory nuisance parameter

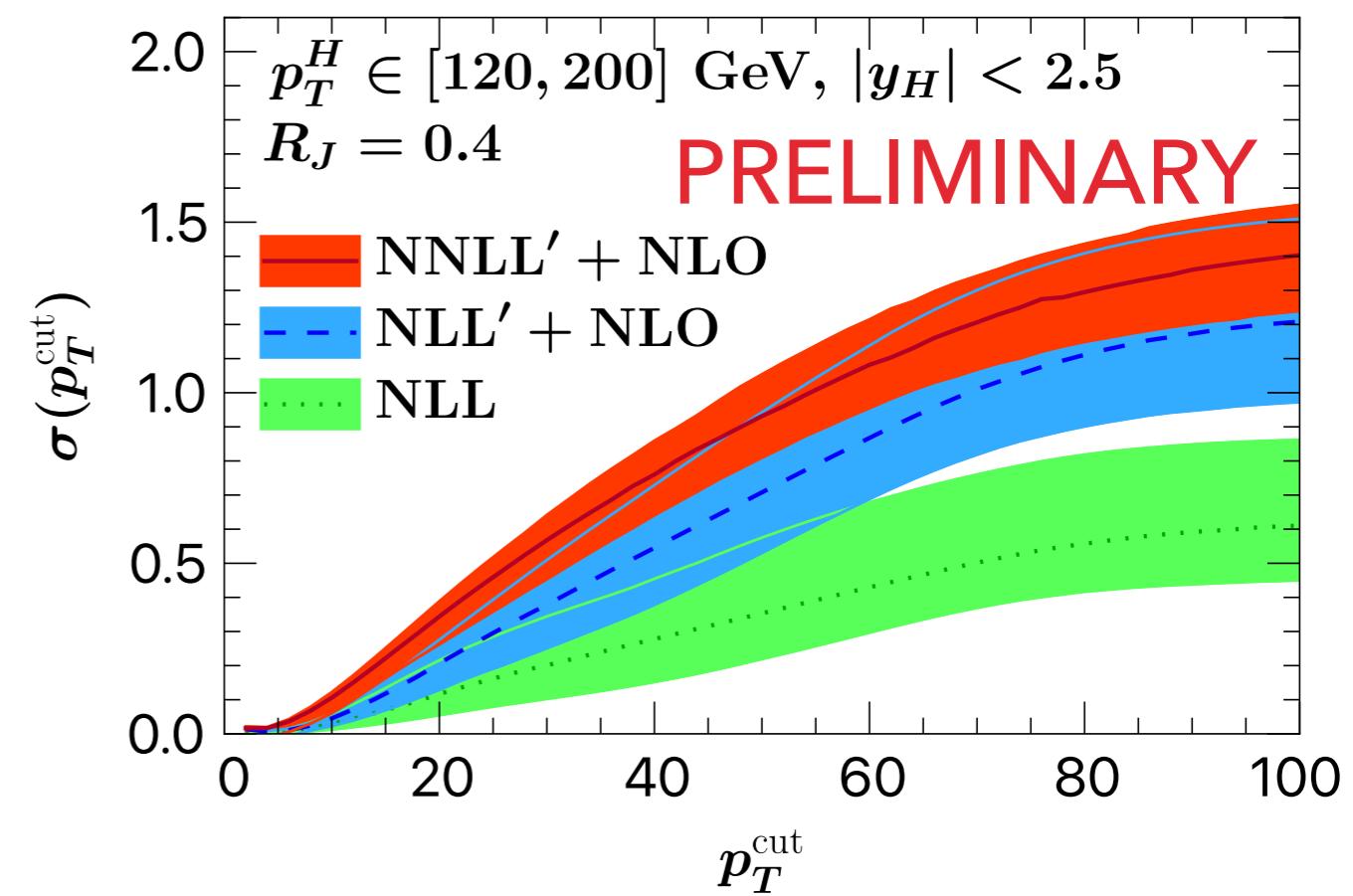
RESULTS

- ▶ p_T^{cut} cumulant, integrated over Born variables

STXS1

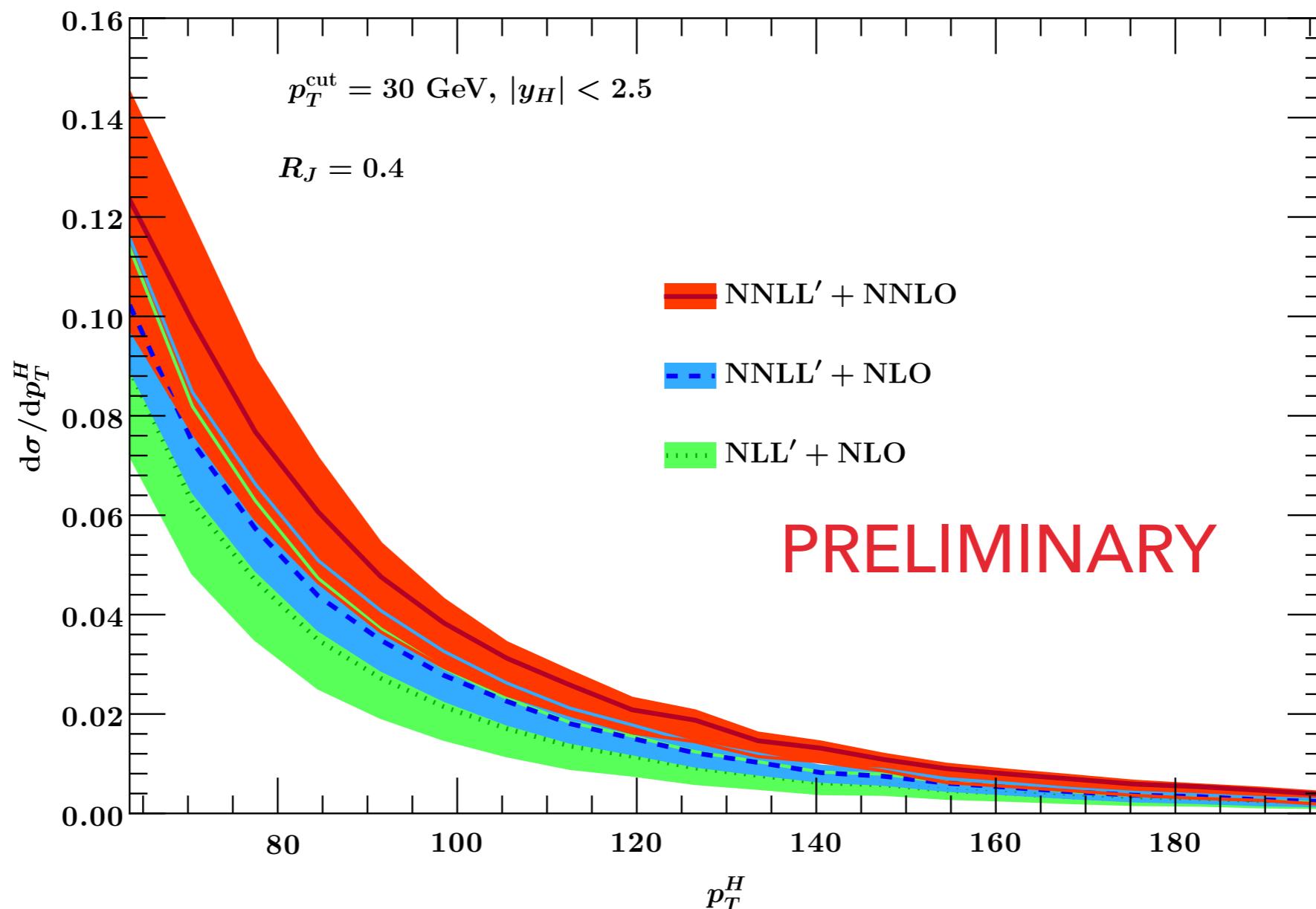


STXS2



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 NNLO₁ 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

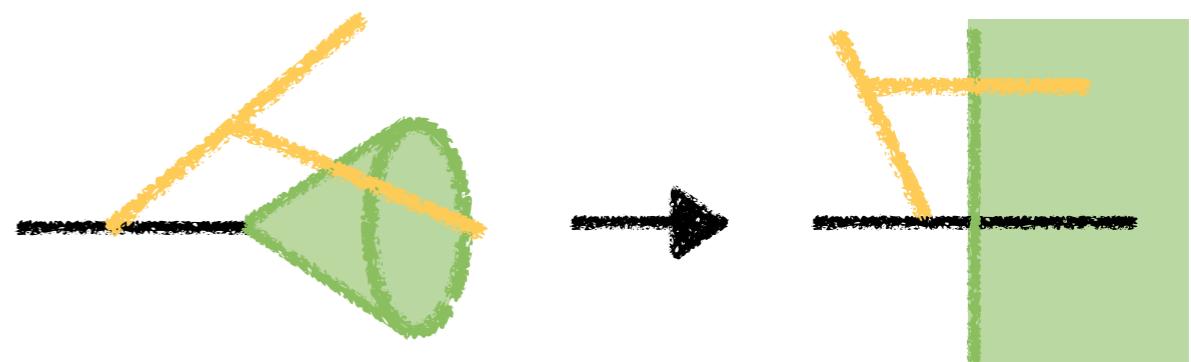
NONGLOBAL LOGARITHMS

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

$$J(p_T R_J) \sim Q(R_J^2, 1, R_J)$$

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

- ▶ Related to hemisphere NGLs by a boost along jet axis



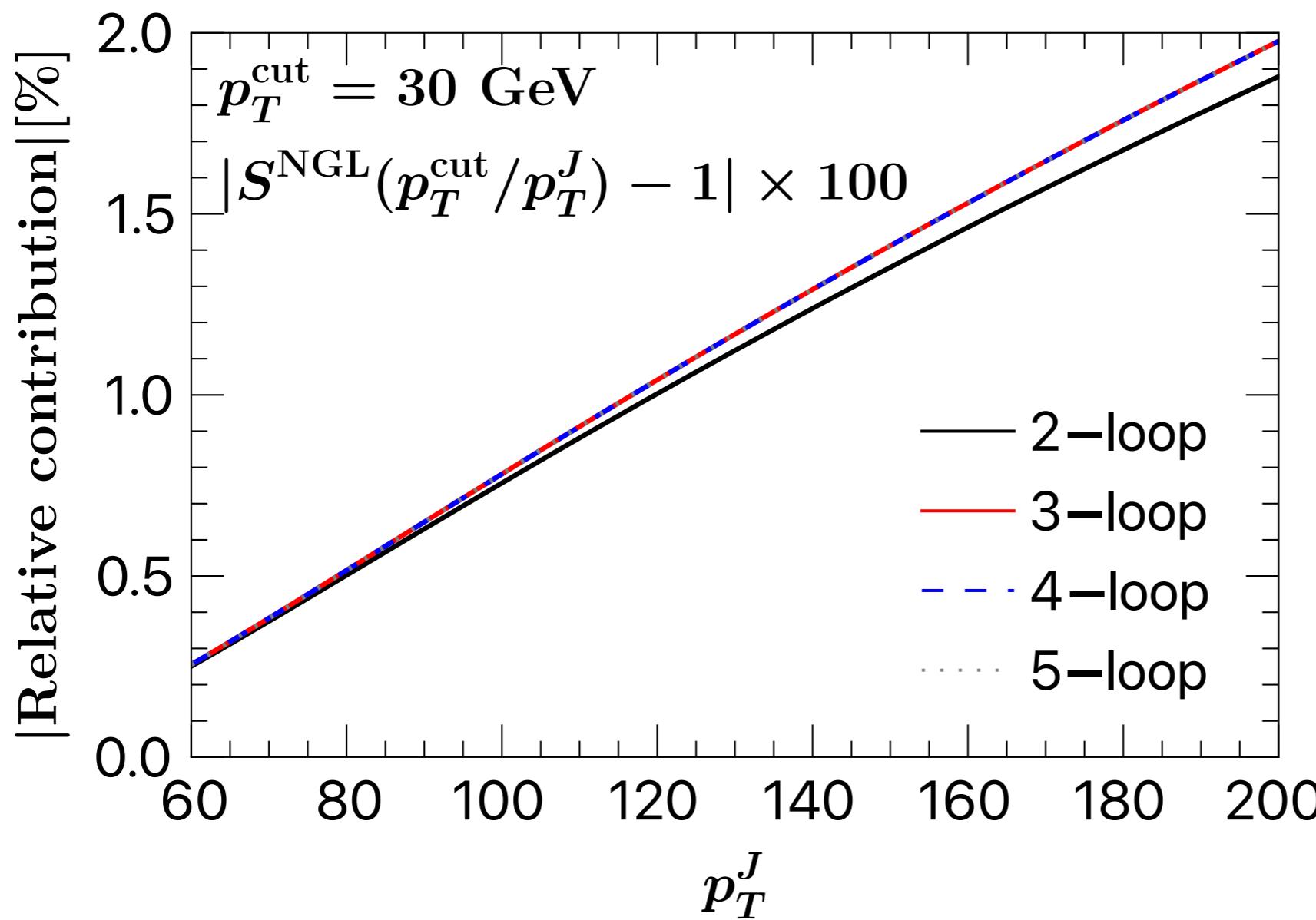
- ▶ Use 5-loop solution of BMS equation, percent level effect

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

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

NONGLOBAL LOGS AND THEIR CONVERGENCE

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



$$\hat{L} = \frac{\alpha_s N_c}{\pi} \ln \frac{p_T^J}{p_T^{\text{cut}}}$$

MATCHING TO FIXED ORDER

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

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

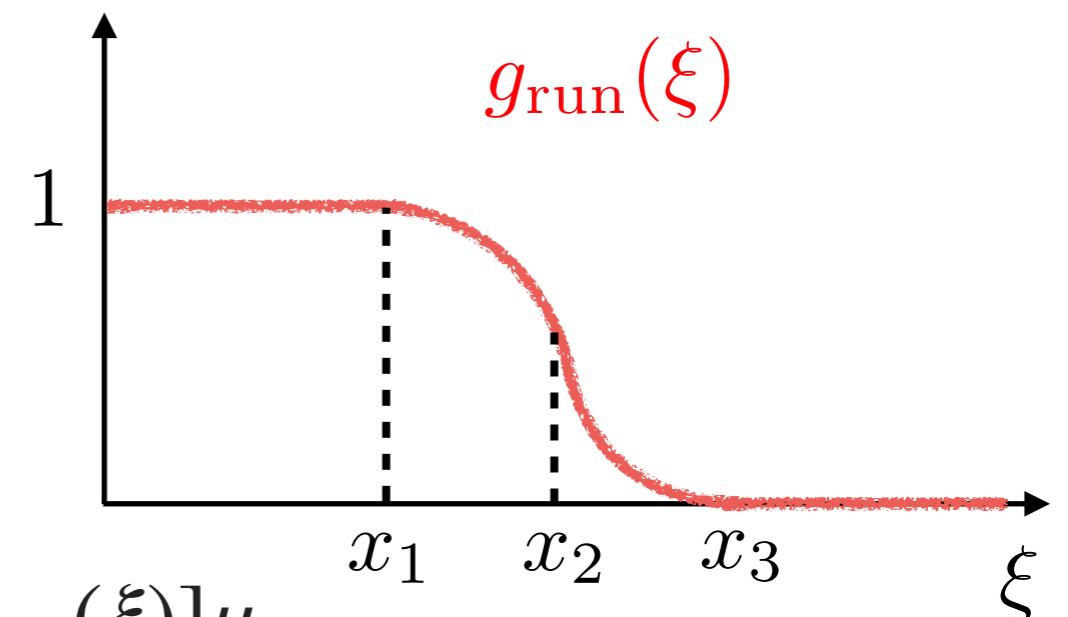
HYBRID PROFILE SCALES

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

$$\mu_B = \mu_S = f_{\text{run}}(\xi, p_T^{\text{cut}}, \mu_{\text{FO}})$$

$$\mu_J = f_{\text{run}}(\xi, p_T^J R_J, \mu_{\text{FO}})$$

$$\mu_{\mathcal{S}} = f_{\text{run}}(\xi, p_T^{\text{cut}} R_J, \mu_{\text{FO}})$$

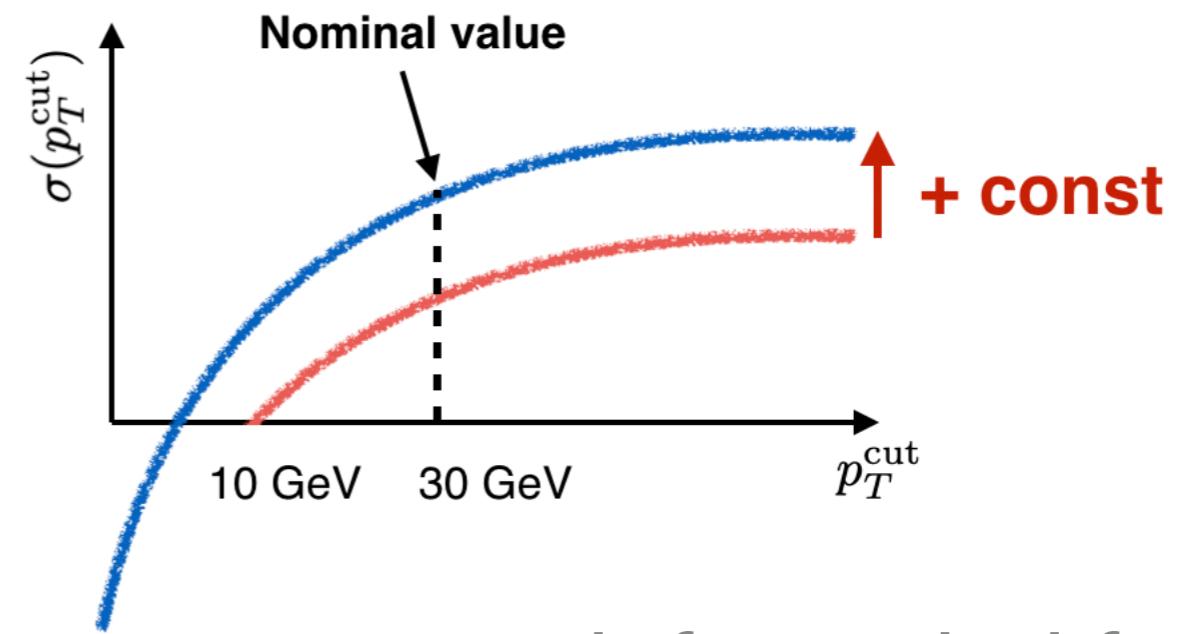
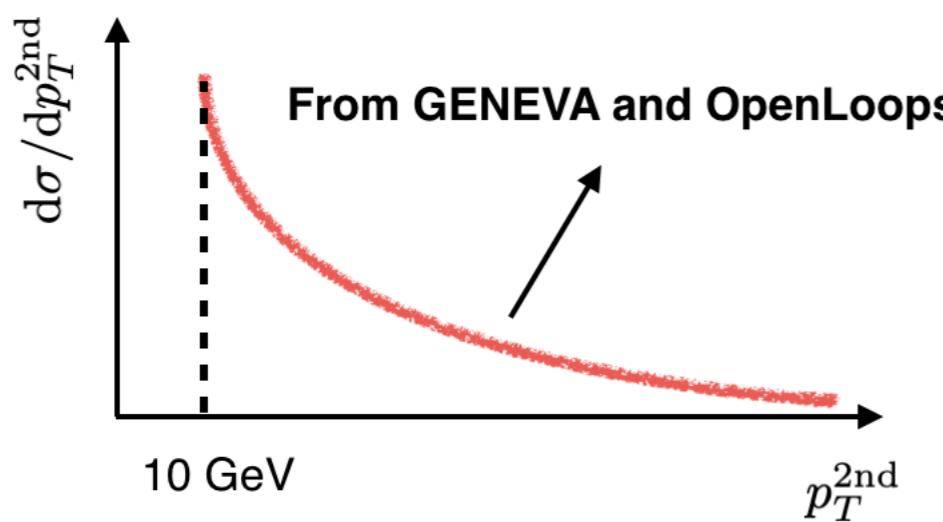


$$f_{\text{run}}(\xi, \mu_0, \mu_{\text{FO}}) = g_{\text{run}}(\xi)\mu_0 + [1 - g_{\text{run}}(\xi)]\mu_{\text{FO}}$$

- ▶ All scales flow to $\mu_H = \mu_{\text{FO}}$ as $\xi = p_T^{\text{cut}}/p_T^H \rightarrow 1$
- ▶ 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 NNLO₁ calculation publicly available!



- ▶ Match to NLO₂ and determine ~constant shift needed from NNLO K-factor.

RESULTS WITH NUISANCE PARAMETERS

