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Jet veto resummation for Higgs+jet with NNLL$'$+NNLO uncertainties

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Based on: 2304.xxxxx

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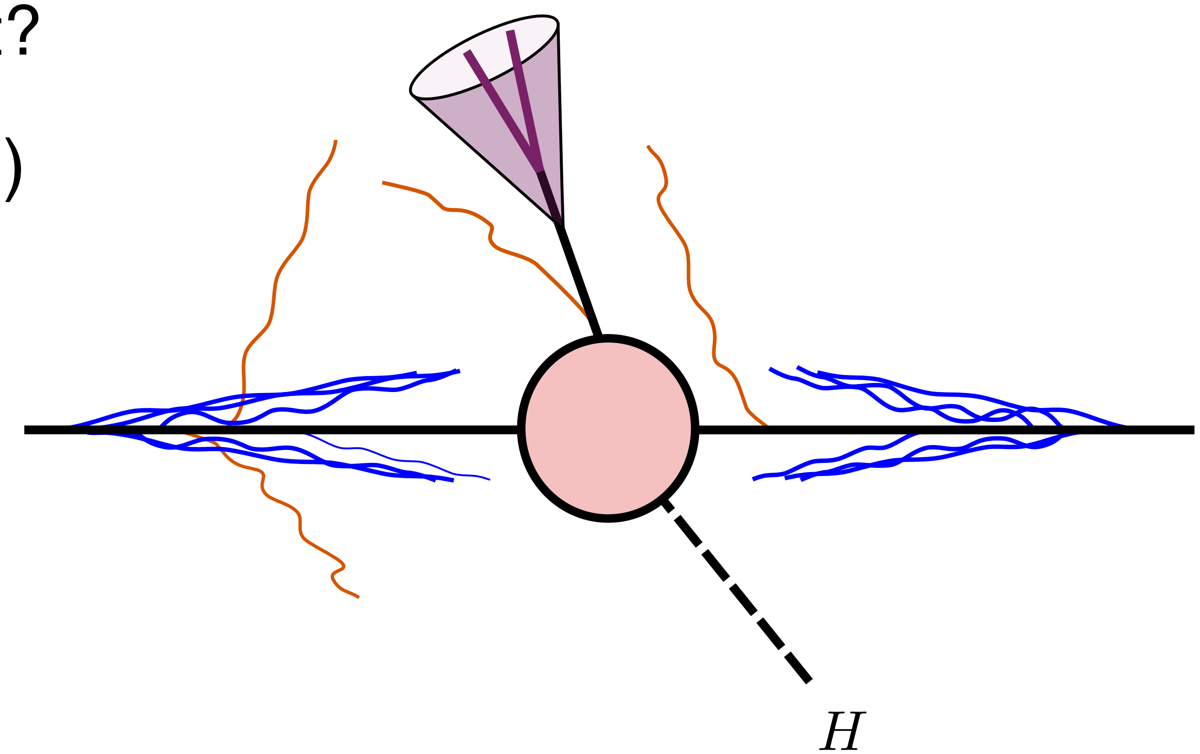
Outline

- **Intro**
  - Why are jet veto cross sections important?
  - Simplified template cross sections (STXS)
- **Jet veto resummation for Higgs+jet**
  - Factorization ingredients
  - Validation of the singular structure
  - NNLL’ resummation and theory nuisance parameters
  - NNLO matching
  - Results
- **Conclusions**



Intro

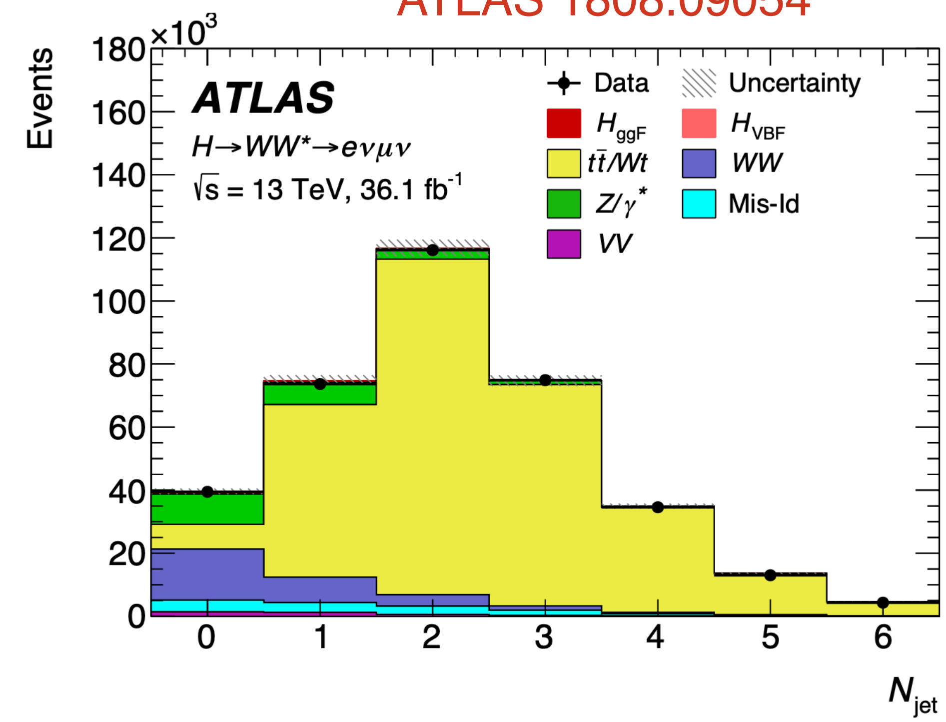
Why are jet veto XS important?

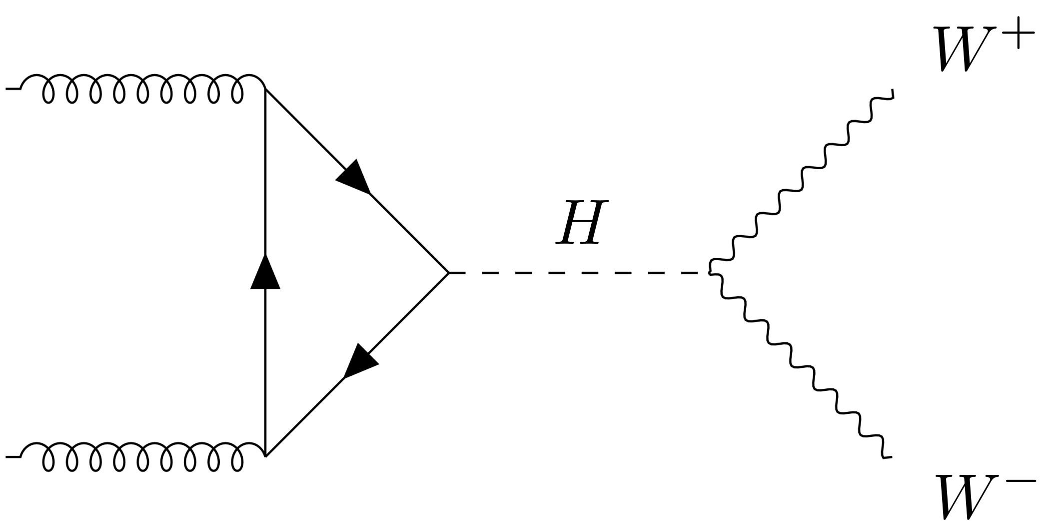
- Many Higgs analyses divide the data into exclusive jet bins

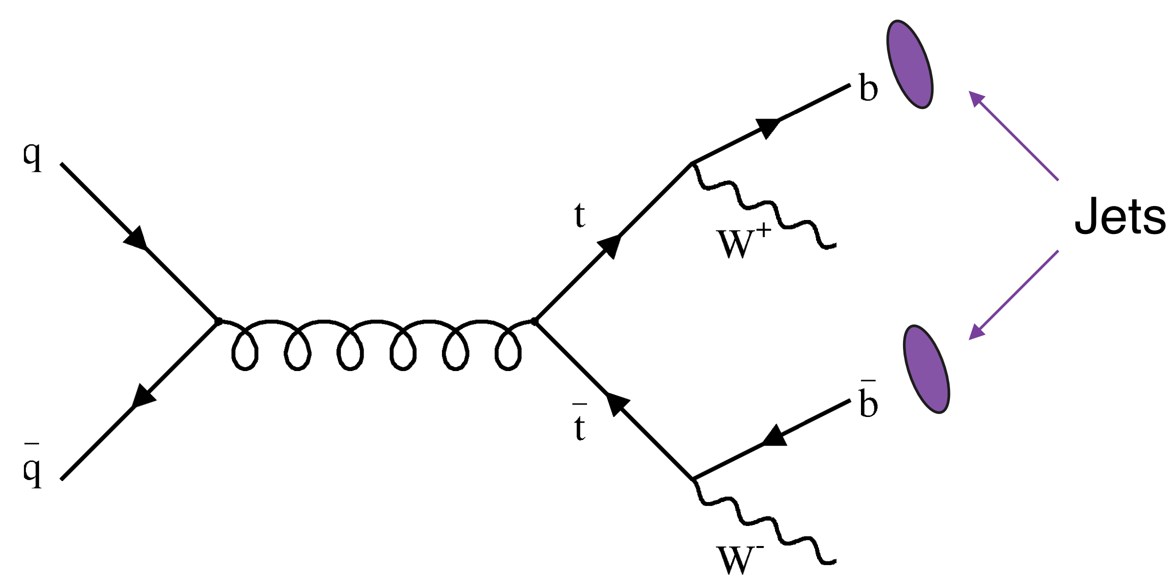
  - **Reason:** Background decomposition changes considerably with the # of jets

  - **Example:** $H \rightarrow WW^*$

ATLAS 1808.09054







Signal **Background**

Jet veto cross sections at the LHC

- **0-jet bin:**
  - Factorization worked out in: **Becher, Neubert '12**; **Tackmann, Walsh, Zuberi '12**
  - Results:
    - NLL+NNLO — **Banfi, Salam, Zanderighi '12**
    - NNLL′+NNLO — **Stewart, Tackmann, Walsh, Zuberi '13**; **Becher, Neubert, Rothen '13**
    - NNLL+N^{3}LO — **Banfi et al. '15**
- **1-jet bin:**
  - Factorization and results: NLL+NLO — **Liu, Petriello '12**; NLL′+NLO — **Liu, Petriello '13**

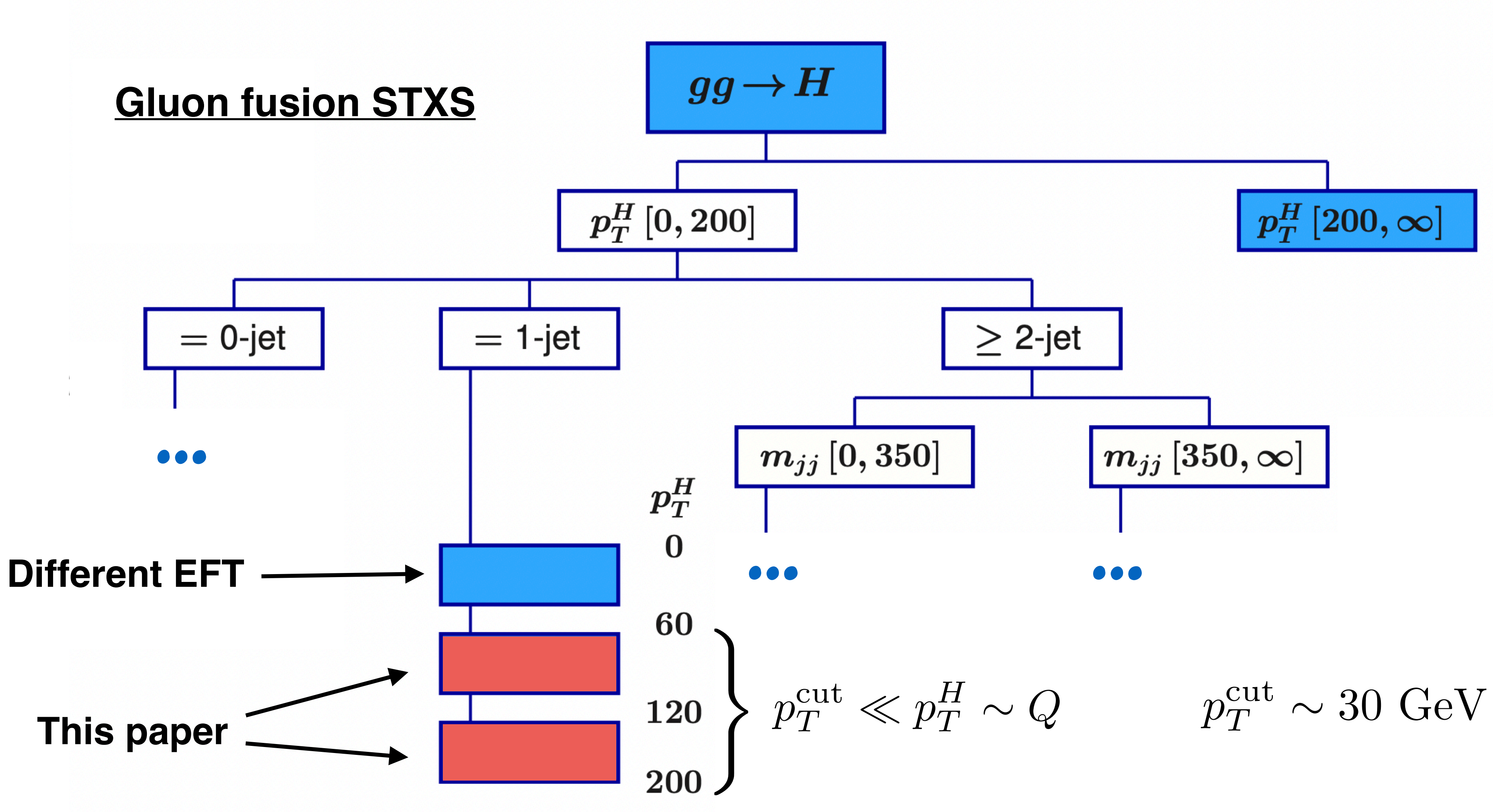
Our goal: Higgs+jet @ NNLL′ + NNLO

Logs of what? $p_T^{\rm cut}/Q$ and R_J

- **Some challenges:**
  - Different factorization theorem than previous results
  - R_J^2 power corrections are actually important
  - Not all pieces are known: theory nuisance parameters

Jet veto cross sections at the LHC

- **Simplified Template Cross Sections (STXS)** LHC Higgs XS working group '19
  - Common framework for Higgs measurements at LHC
  - Reduces theoretical uncertainties folded into measurements
  - Used to combine different decay channels and experiments

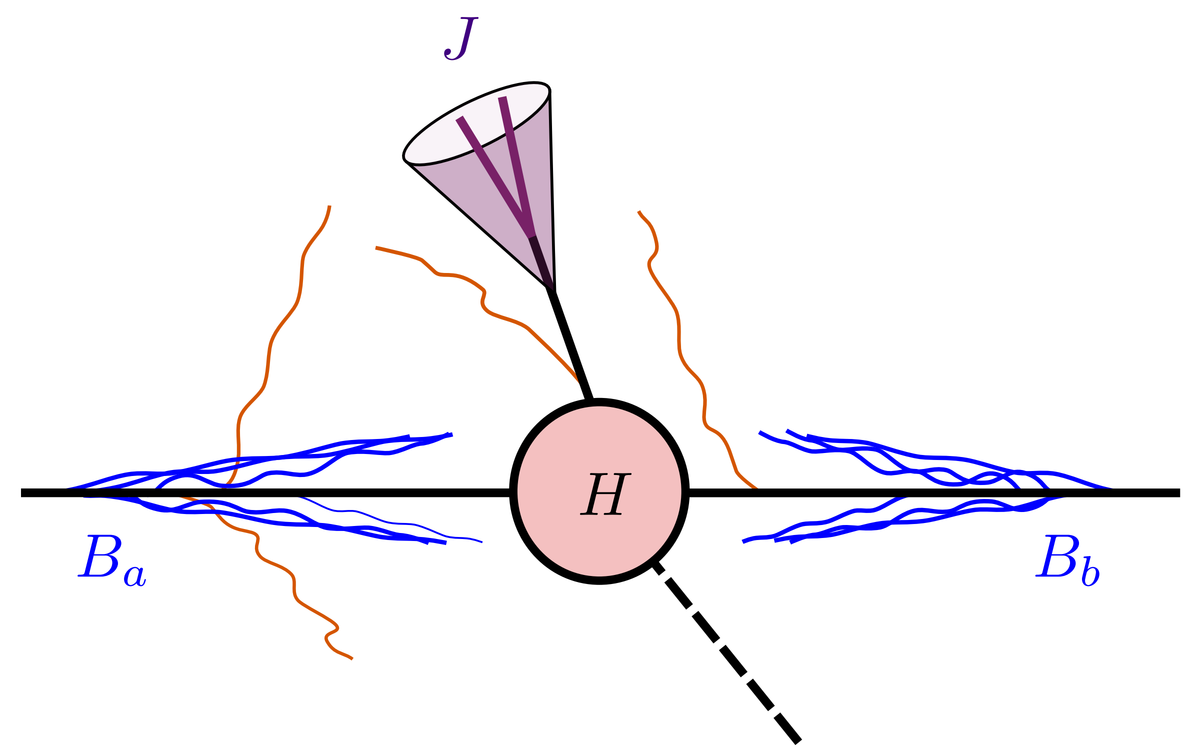


Higgs+jet

Factorization

- **1-signal jet + veto additional jets with** $p_T > p_T^{\rm cut} \sim 30\ {\rm GeV}$

- **Factorization:** $\frac{p_T^{\rm cut}}{Q} \ll 1,\ R_J \ll 1$



Hard: $H(p_T)$

Jet: $J(p_T R_J)$

Beams: $B_{a,b}(p_T^{\rm cut})$

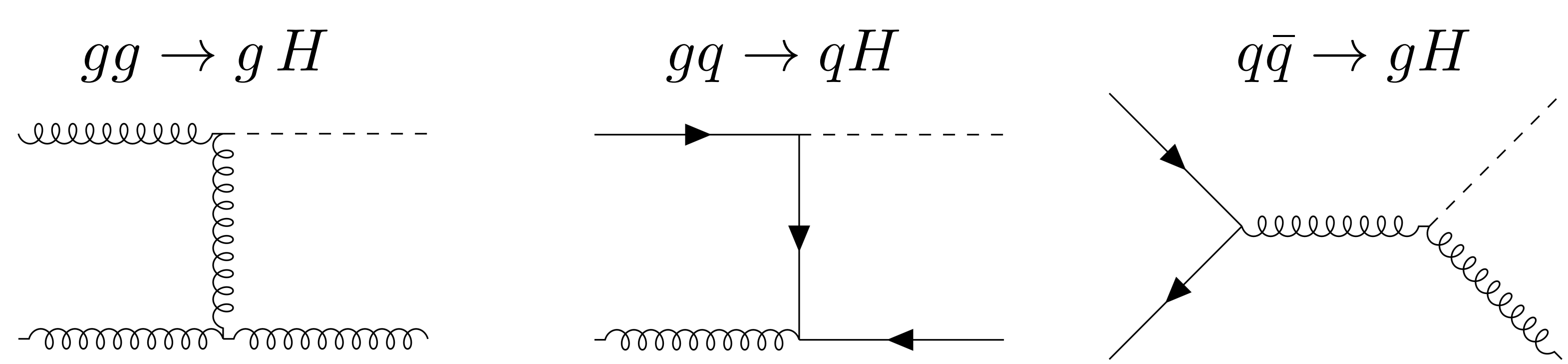
Soft-sector: $S^T(p_T^{\rm cut}, p_T^{\rm cut} R_J)$

↓

Depends on two parametrically separated scales: **requires further factorization**

Chien, Hornig, Lee '15

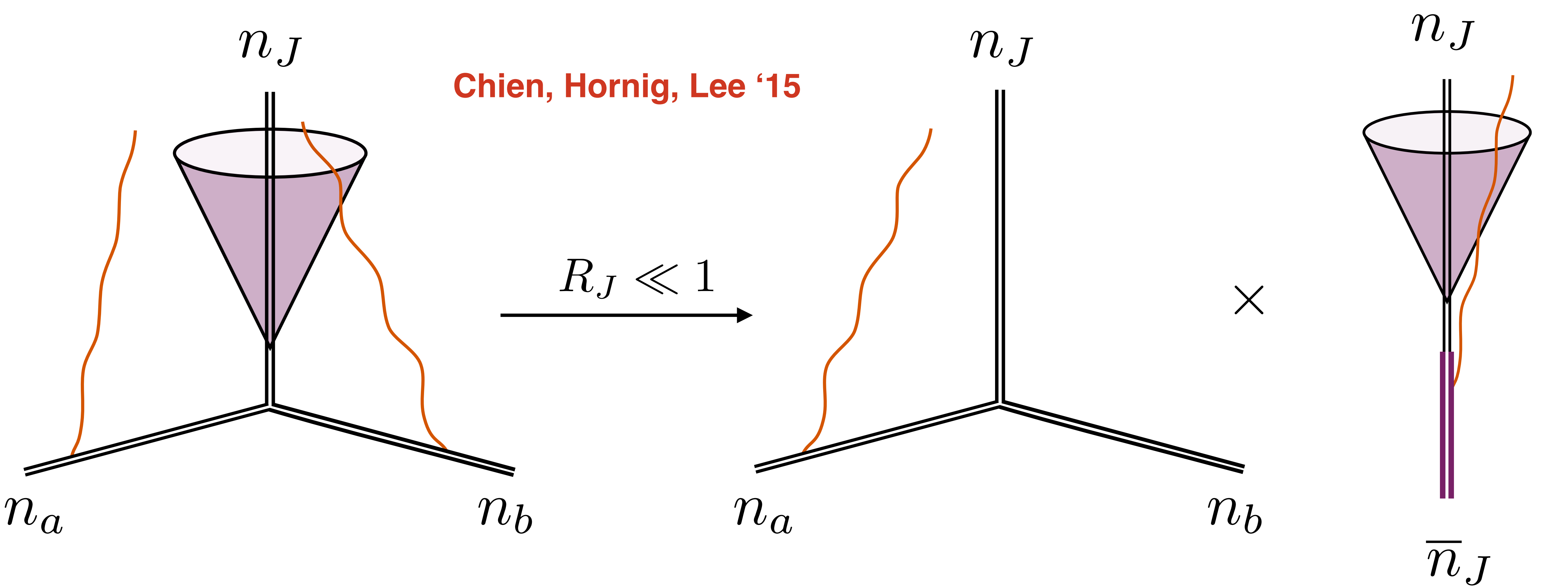
- **Born-level hard function:**



Soft sector

- Taking the $R_J \ll 1$ requires factorization of the **total soft function**

Chien, Hornig, Lee '15



Total Soft		**Global Soft**		**Soft-collinear**
$S^T(p_T^{\text{cut}}, p_T^{\text{cut}} R_J)$	$\xrightarrow{R_J \ll 1}$	$S(p_T^{\text{cut}})$	$\times$	$\mathcal{S}^R(p_T^{\text{cut}} R_J)$

- Allows us to resum logs of R_J **in the soft-sector**, not just the collinear sector

Nonglobal logarithms

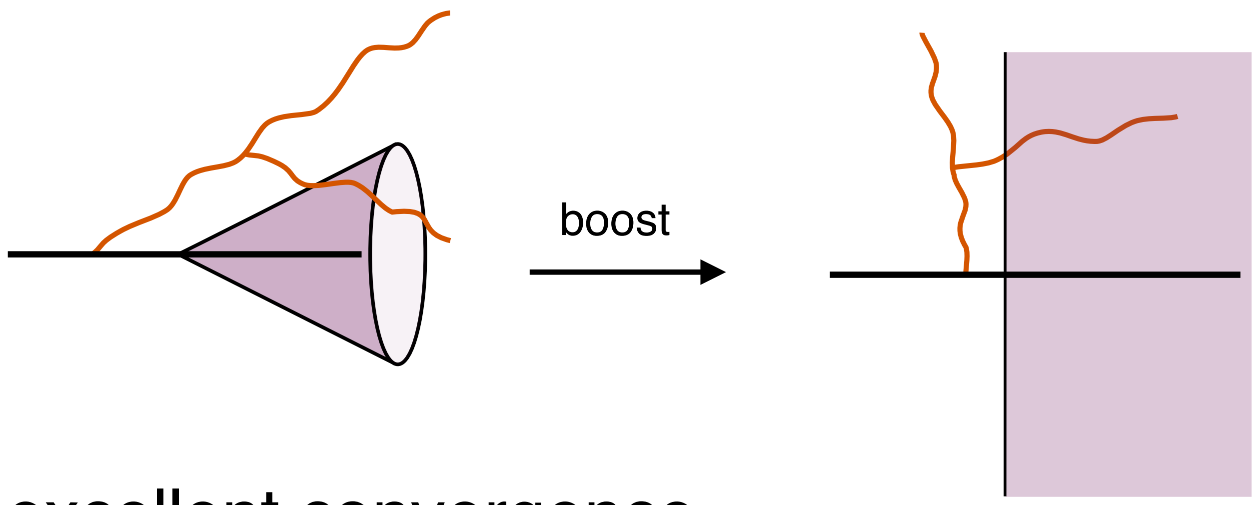
- Jet and soft-collinear function have the **same angular scaling** but different **virtuality.** This leads to **Nonglobal logs (NGLs)**

Dasgupta, Salam '02

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

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

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



- Use known 5-loop result, which displays excellent convergence

Schwartz, Zhu '14

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

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

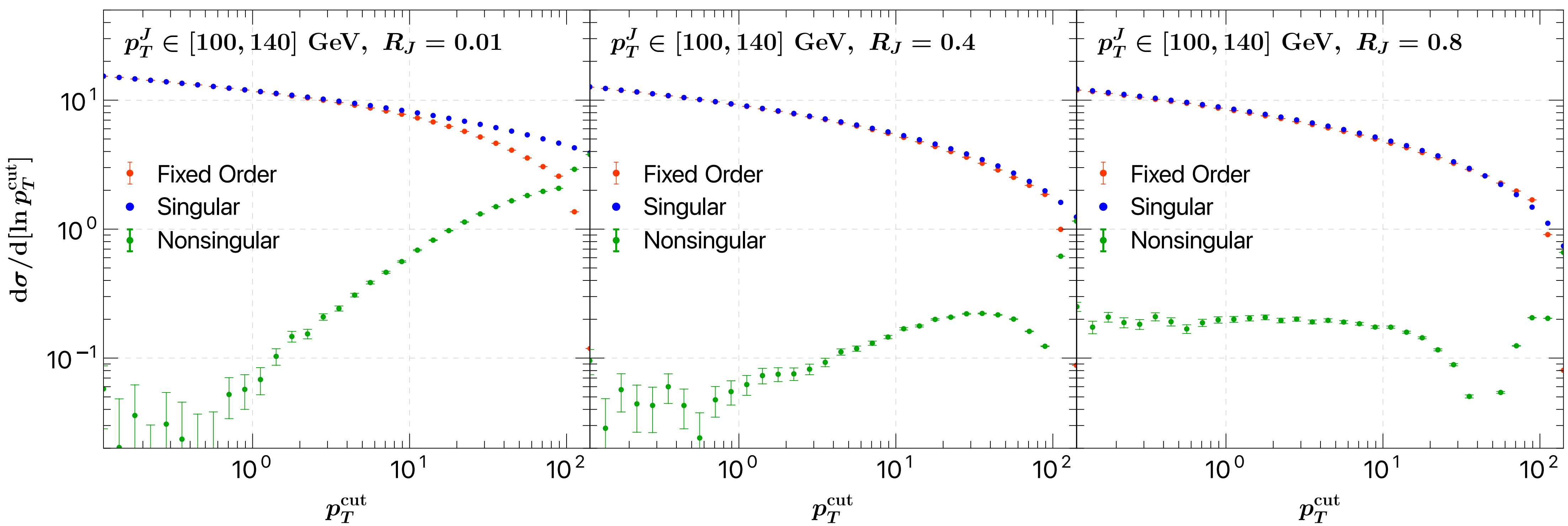
- Numerical effect is around 0.5 to 2%

Factorization

- **Full factorization:**

$$
\begin{aligned}
\sigma(p_T^{\text{cut}}) = \; & H(p_T, Y, y_J) \;\cdots\cdots\; \sim Q(1,1,1) \\
& \times B_a(p_T^{\text{cut}}, \omega_a) B_b(p_T^{\text{cut}}, \omega_b) \;\cdots\cdots\; \sim Q(\lambda^2, 1, \lambda) \\
& \times J(p_T R_J) \;\cdots\cdots\; \sim Q(R_J^2, 1, R_J) \\
& \times S(p_T^{\text{cut}}) \;\cdots\cdots\; \sim Q\lambda(1,1,1) \\
& \times \mathcal{S}^R(p_T^{\text{cut}} R_J) \;\cdots\cdots\; \sim Q\lambda(R_J^2, 1, R_J) \\
& \times S^{\text{NG}}(p_T^{\text{cut}}/p_T) \qquad\qquad (p^+, p^-, p_\perp)
\end{aligned}
$$

- Nonsingular properly power suppressed for $R_J = 0.01$, but not for larger values

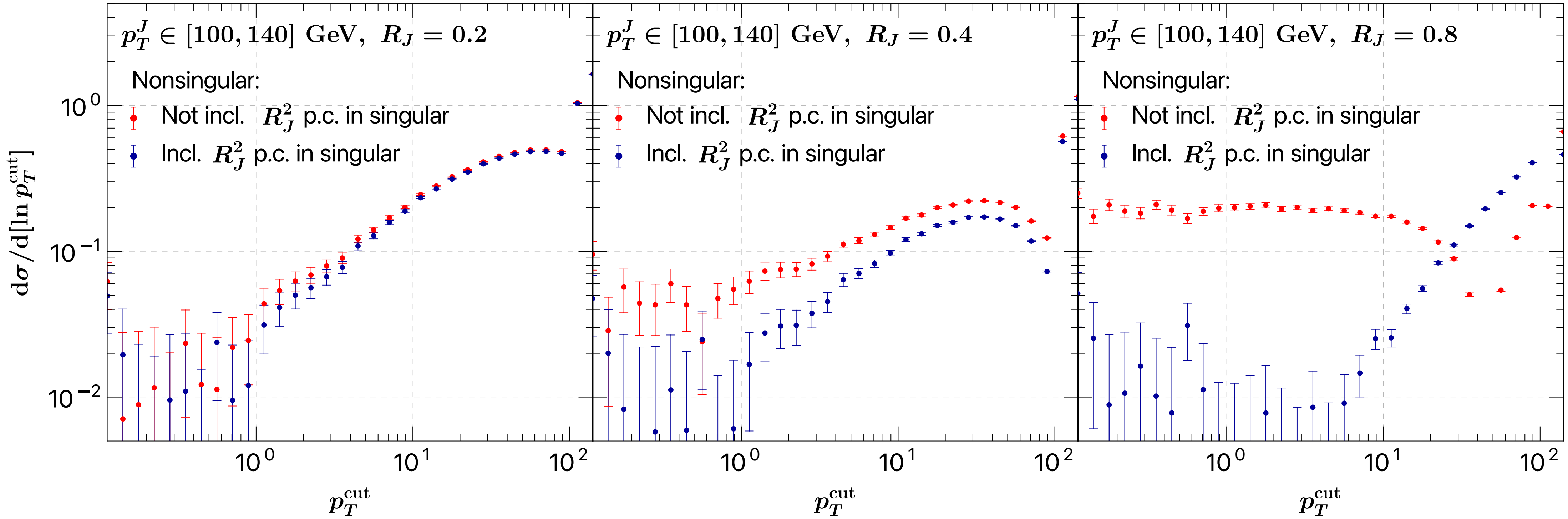


Singular structure

- This is indicative of $R_J^2 \ln(p_T^{\rm cut})$ power corrections
- Where do they come from? The **soft-sector** $\longrightarrow$ Knows about $p_T^{\rm cut}$ and R_J
- Compute $\mathcal{O}(R_J^2)$ power corrections to the **total-soft function**:

$$S_\kappa^{(1)} = \frac{\alpha_s}{4\pi}\Big\{(T_a^2+T_b^2)\left[-4\ln^2\left(\frac{\mu}{p_T^{\rm cut}}\right) - 8\ln\left(\frac{\mu}{\rm cut}\right)\ln\left(\frac{\nu}{\mu}\right) - \frac{\pi^2}{6} + 2R_J^2\ln\left(\frac{\mu}{p_T^{\rm cut}R_J}\right) + R_J^2\right]$$
$$+ 8y_J(T_a^2-T_b^2)\ln\left(\frac{\mu}{p_T^{\rm cut}}\right)$$
$$+ \mathbf{T}_j^2\left[-4\ln^2 R_J + 8\ln\left(\frac{\mu}{p_T^{\rm cut}}\right)\ln R_J - R_J^2\ln\left(\frac{\mu}{p_T^{\rm cut}R_J}\right) + \frac{R_J^2}{6}\right]\Big\}$$

It works 👍



Going NNLL′

- **What is needed for NNLL′ :**

Accuracy	$\Gamma_{\rm cusp}$	γ	β	$C(\alpha_s)$
NNLL′	3-loop	2-loop	3-loop	2-loop

- Cusp anom dim $\Gamma_{\rm cusp}$ and beta-function β to 3-loops ✓

- Non-cusp anom dim γ and boundary conditions $C(\alpha_s)$ to 2-loops?

<table>
<tr><th>2-loop</th><th colspan="2">H</th><th colspan="2">B</th><th colspan="2">J</th><th colspan="2">S</th><th colspan="2">S^R</th></tr>
<tr><td rowspan="2">γ</td><td>ggg</td><td>$q\bar{q}g$</td><td rowspan="2">q</td><td rowspan="2">g</td><td rowspan="2">q</td><td rowspan="2">g</td><td>ggg</td><td>$q\bar{q}g$</td><td rowspan="2">q</td><td rowspan="2">g</td></tr>
<tr><td>qgq</td><td>gqg</td><td>qgq</td><td>gqg</td></tr>
<tr><td rowspan="2">$C(\alpha_s)$</td><td>ggg</td><td>$q\bar{q}g$</td><td rowspan="2">q</td><td rowspan="2">g</td><td rowspan="2">q</td><td rowspan="2">g</td><td>ggg</td><td>$q\bar{q}g$</td><td rowspan="2">q</td><td rowspan="2">g</td></tr>
<tr><td>qgq</td><td>gqg</td><td>qgq</td><td>gqg</td></tr>
</table>

= known

= unknown

Hard: Gehrmann, Jaquier, Glover, Koukoutsakis ’12; Becher, Bell, Lorentzen, Marti ‘14

Beam: Bell, Brune, Das, Wald ’22; Abreu, Gaunt, Monni, Rottoli, Szafron ’22

Quark jet: Liu, Liu, Moch ‘21

Going NNLL'

- **RG consistency gives most anomalous dimensions:**

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

2-loop	H		B		J		S		$\mathcal{S}^R$	
γ	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

- We treat $\gamma_{\mathcal{S}}^{q}, \gamma_{\mathcal{S}}^{g}$ as **theory nuisance parameters** (TNP)

See Frank's San Diego Talk

- What about the unknown boundary conditions?

Going NNLL'

- **Unknown boundary conditions:** solving RGE perturbatively gives log structure

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

solve perturbatively

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

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

Theory Nuisance Parameter

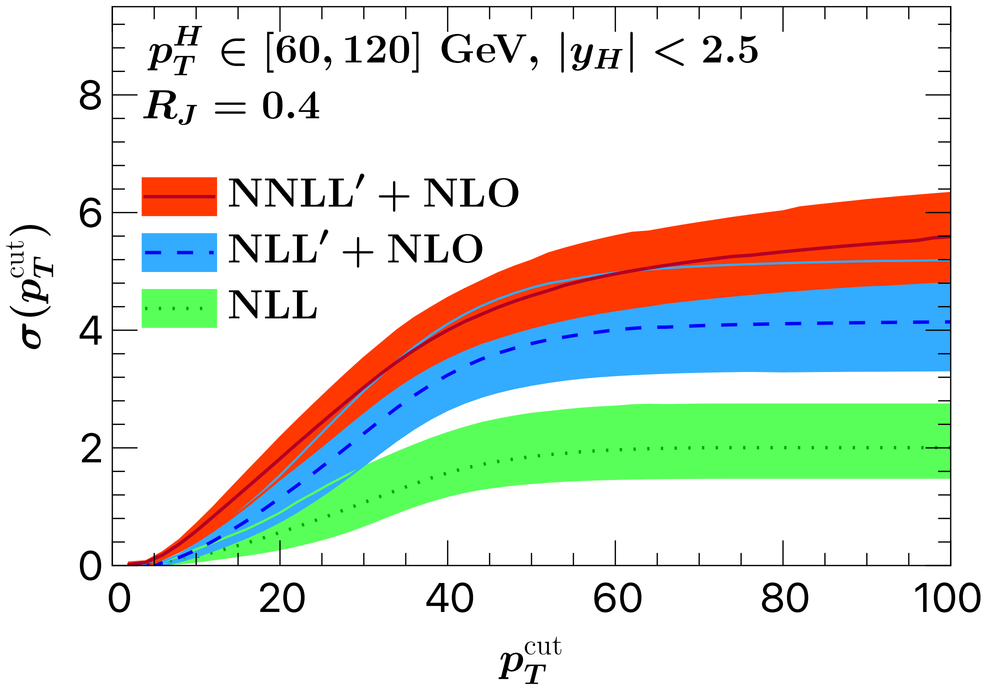
- Coefficients of logs written in terms of anom. dim.
- Constant piece $s_j^{R,(2)}$ treated as a TNP

See Frank's San Diego Talk

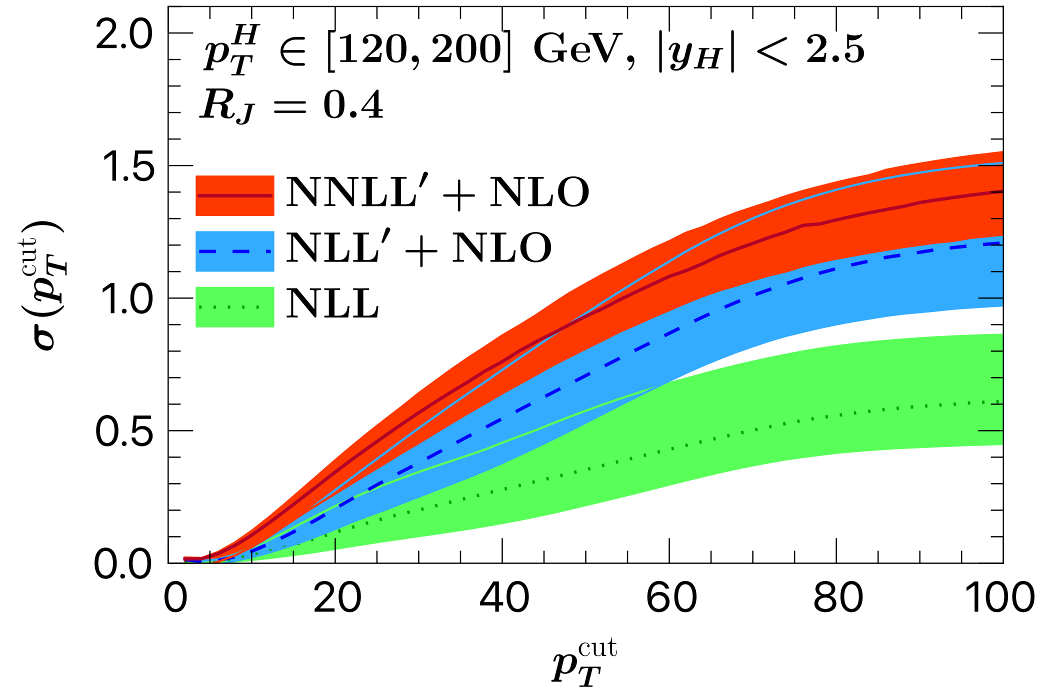
Preliminary results

- $p_T^{\rm cut}$ cumulant + integrated over p_T^H

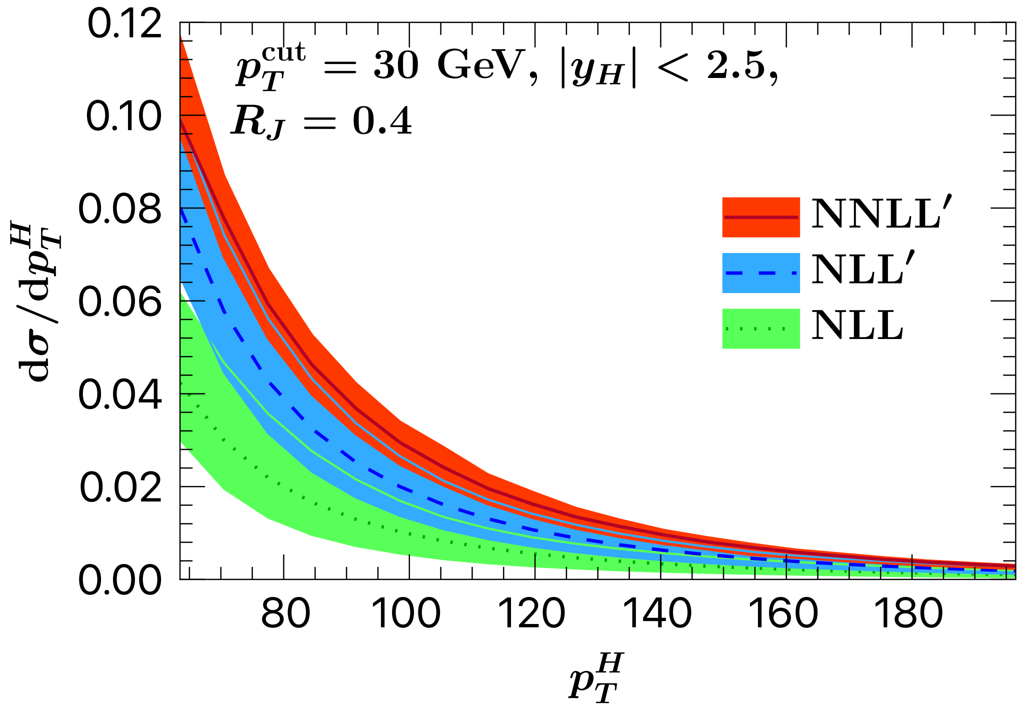
Low STXS bin



High STXS bin



- p_T^H spectrum @ nominal $p_T^{\rm cut} = 30$ GeV



Low⌒High STXS bins

Scales and uncertainties

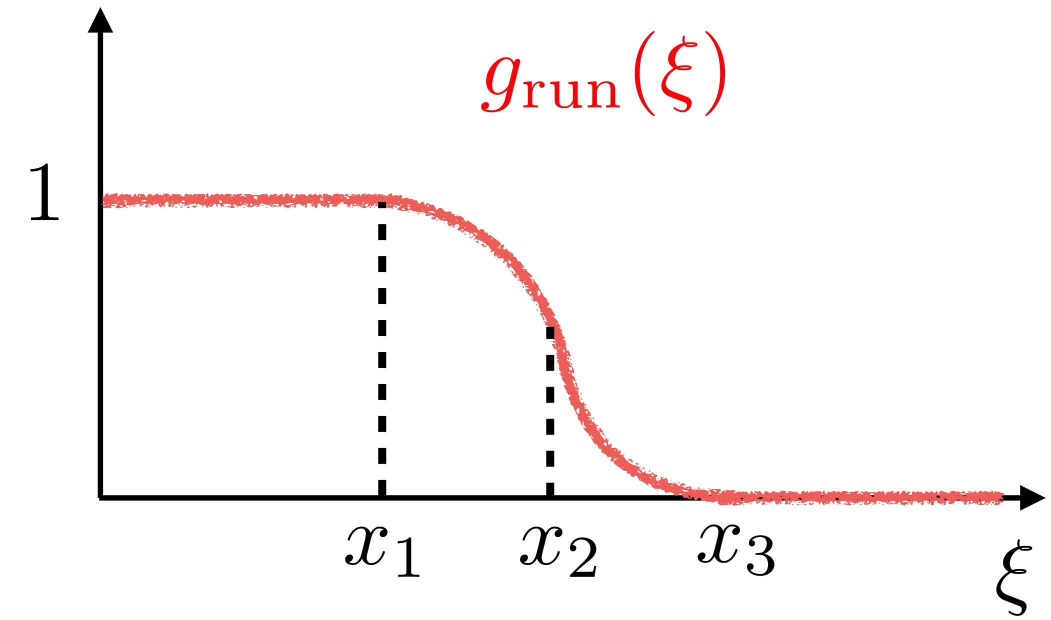
- E.g. Soft-collinear: $\mu_S^{\text{canonical}} = p_T^J R_J \longrightarrow \mu_{\text{FO}} = \sqrt{m_H^2 + (p_T^H)^2}$

  Resummation region — **Fixed order region**

▷ **Profile function:** implements this transition

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

$$\xi = p_T^{\text{cut}}/p_T^H$$



▷ **Profile scale:** $\mu_S = f_{\text{run}}(\xi;\, p_T^{\text{cut}} R_J, \mu_{\text{FO}})$

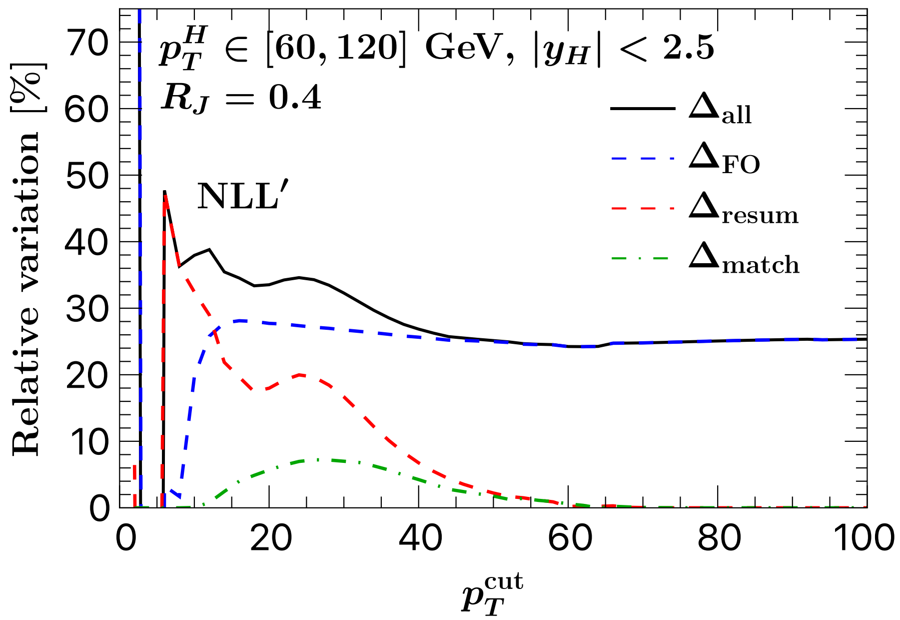
- **Uncertainties:** ▷ Nuisance parameter variations (not in plot yet)

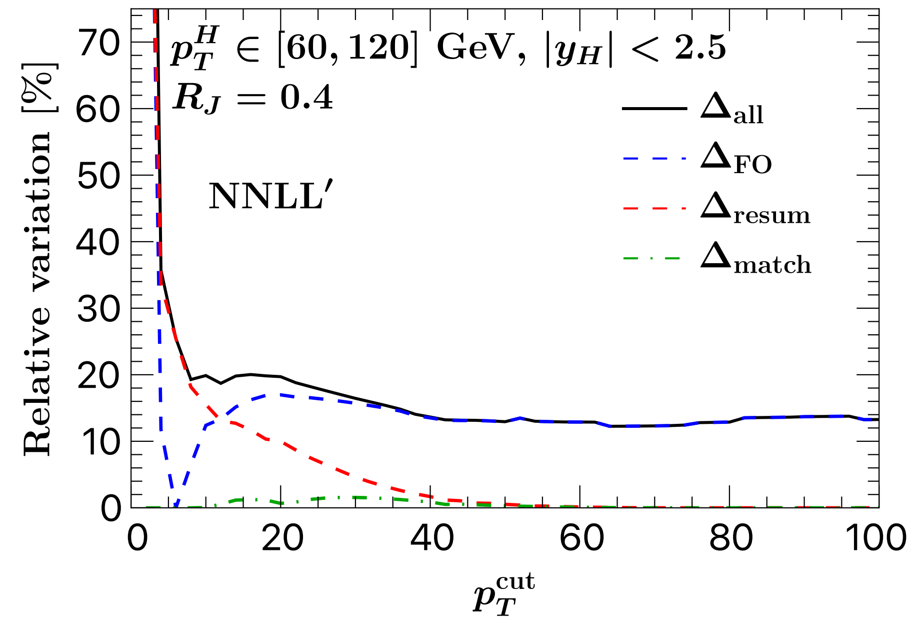
  ▷ Scale variations
  - $\Delta_{\text{FO}} \longrightarrow$ vary μ_{FO}
  - $\Delta_{\text{resum}} \longrightarrow$ vary μ_0
  - $\Delta_{\text{match}} \longrightarrow$ vary x_1, x_2, x_3

Scales and uncertainties

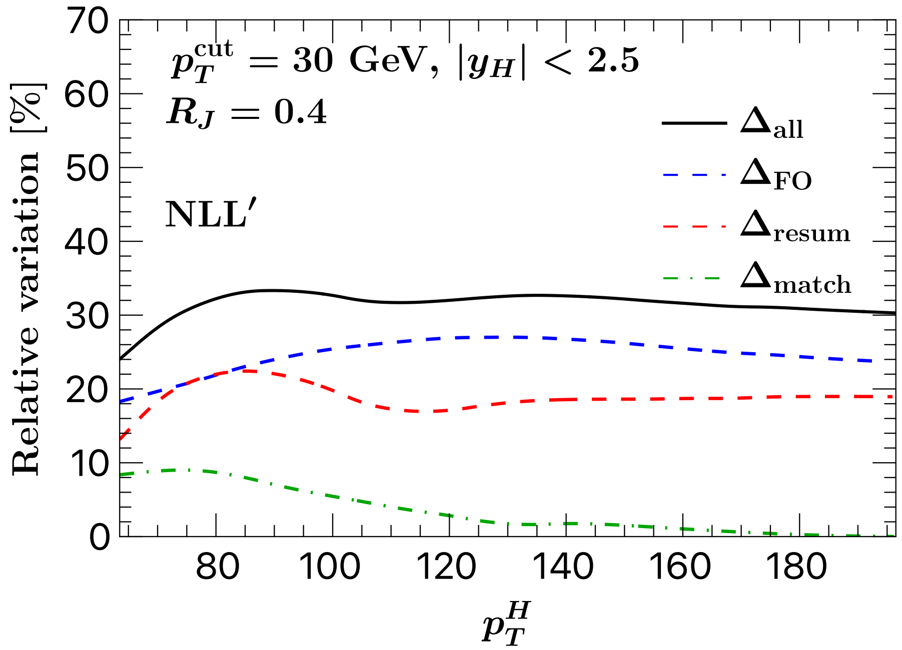
- **Impact plots:** good convergence

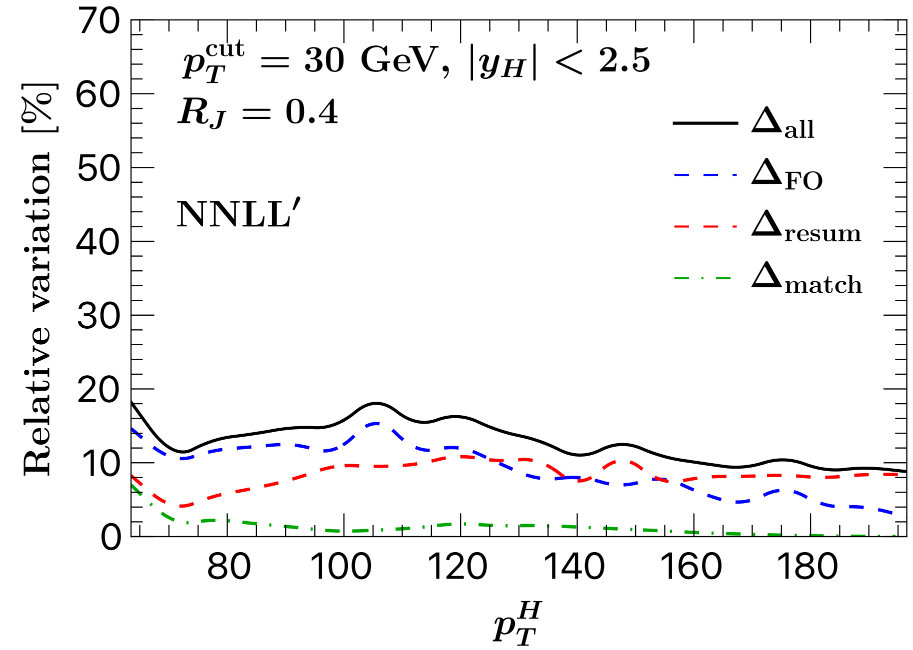
▶ p_T^{cut} cumulant + integrated over





▶ p_T^H spectrum @ nominal $p_T^{\text{cut}} = 30$ GeV

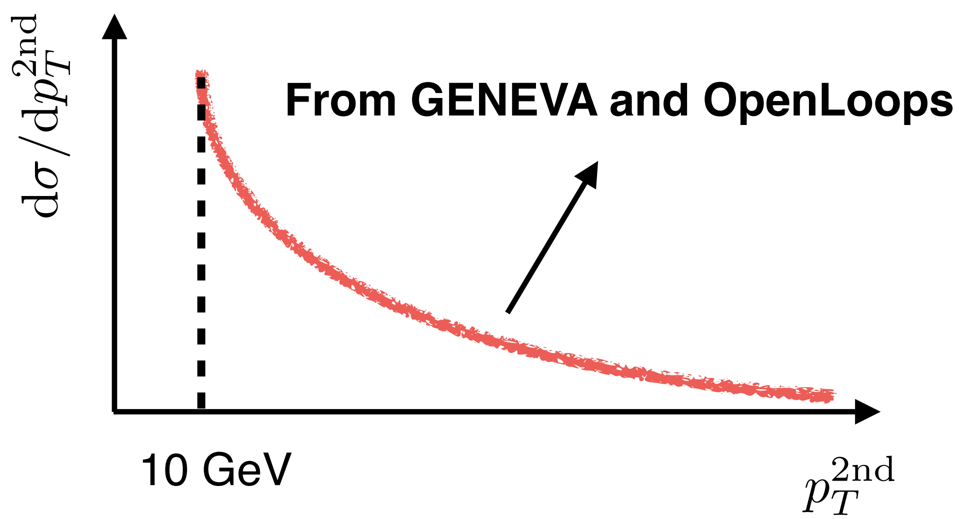


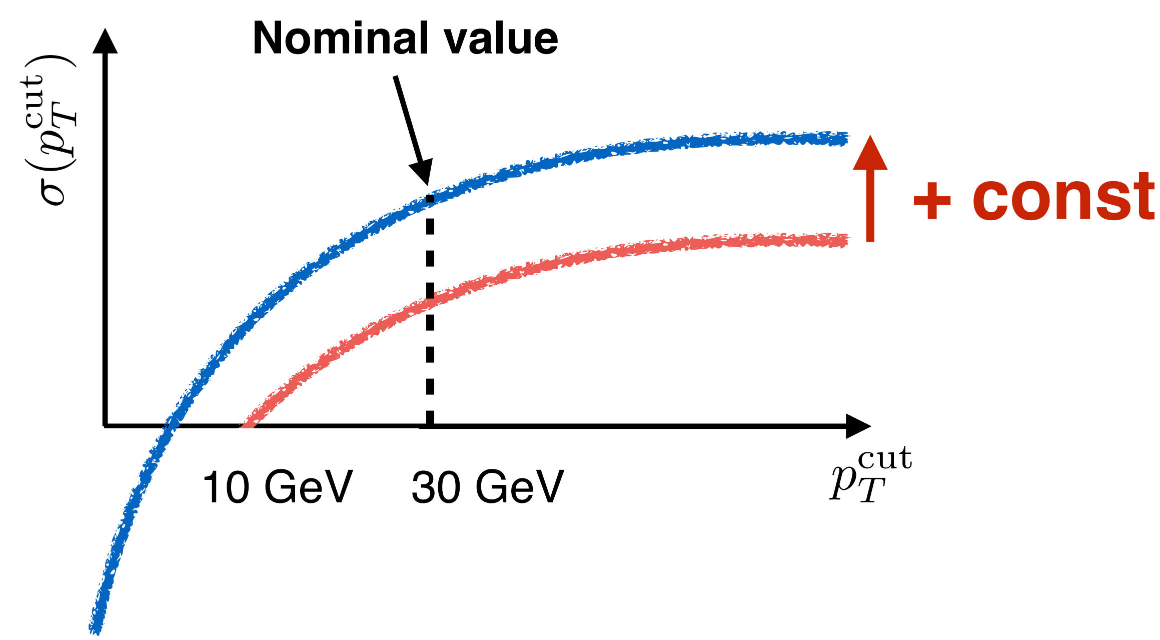


Missing

- **Matching to NNLO: how to get the nonsingular**

  - **What we have: NLO$_2$**, with second jet down to 10 GeV
  - **What we want: NNLO$_1$**





  - **+ const** can be obtained from the inclusive Higgs p_T spectrum at NNLO$_1$, which corresponds to the $p_T^{\mathrm{cut}} \to \infty$ limit.

- **Nuisance parameter variation**

Conclusions

- We compute the Higgs+jet exclusive cross section resumming logs of $p_T^{\rm cut}/Q$ and R_J at **NNLL′ + NNLO**
- Obtain the p_T^H spectrum for the **STXS** bins $p_T^H \in [60, 120]\mathrm{GeV}$ and $p_T^H \in [120, 200]\mathrm{GeV}$
- Resum all logs of R_J: in the collinear <u>and</u> soft sectors
- Included R_J^2 power corrections in the soft-sector
- Possible future directions:
  - Studying the EFT for the **STXS** bin $p_T^H \in [0, 60]\mathrm{GeV}$ $\begin{cases} p_T^H \sim p_T^{\rm cut} \ll Q \\ p_T^H \ll p_T^{\rm cut} \ll Q \end{cases}$
  - Higgs + 2 jets

Acknowledgements

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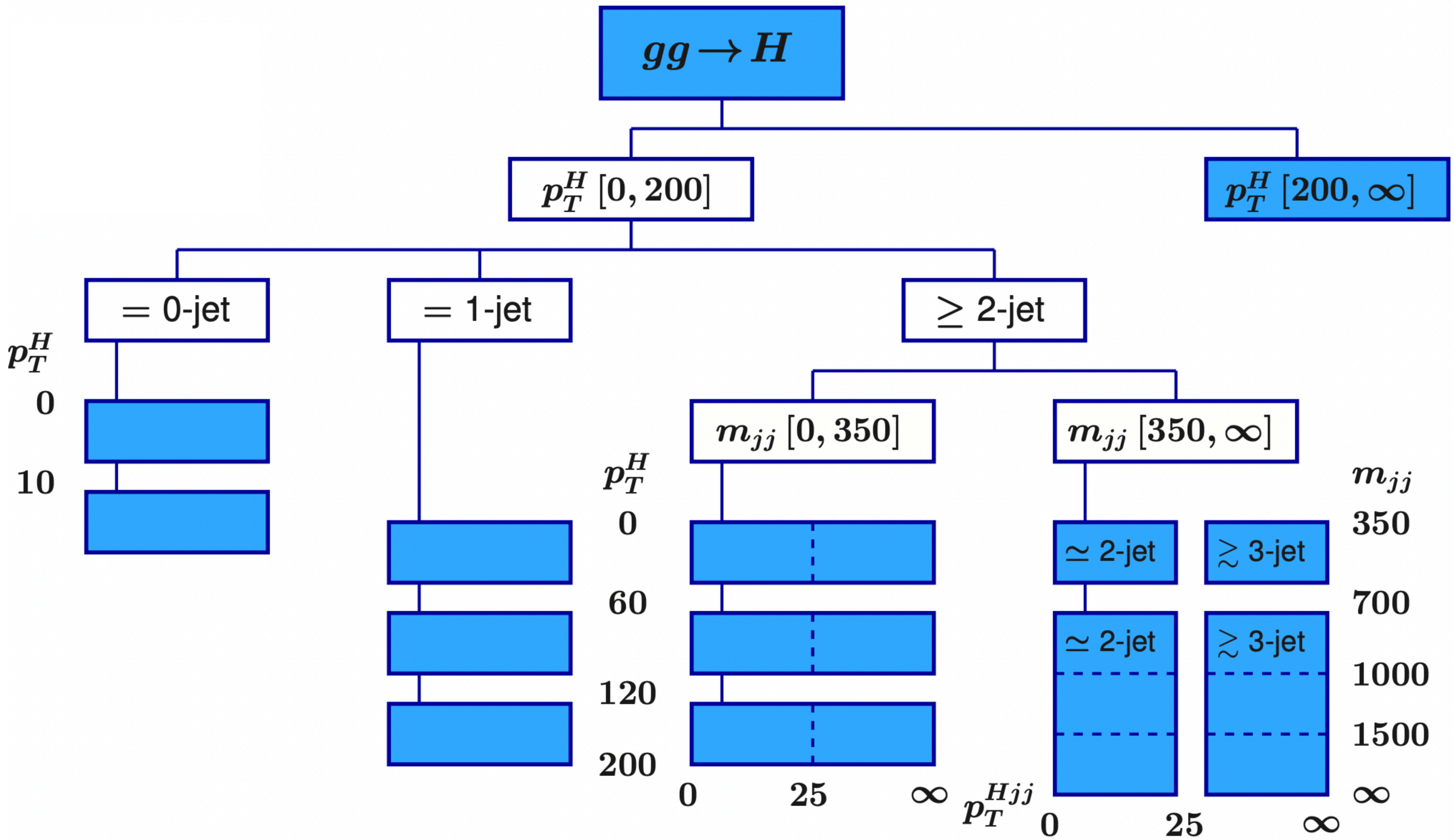
Backup

STXS bins



$gg \to H$
p_T^H [0, 200]
p_T^H [200, ∞]
= 0-jet
= 1-jet
≥ 2-jet
m_{jj} [0, 350]
m_{jj} [350, ∞]
p_T^H
0
10
p_T^H
0
60
120
200
0
25
∞
≃ 2-jet
≳ 3-jet
≃ 2-jet
≳ 3-jet
m_{jj}
350
700
1000
1500
∞
p_T^{Hjj}
0
25
∞

Going NNLL'

- **Unknown boundary conditions:** solving RGE perturbatively gives log structure

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\ln S_\kappa(p_T^{\mathrm{cut}};\mu,\nu) = \gamma_S^\kappa(p_T^{\mathrm{cut}};\mu,\nu)$$

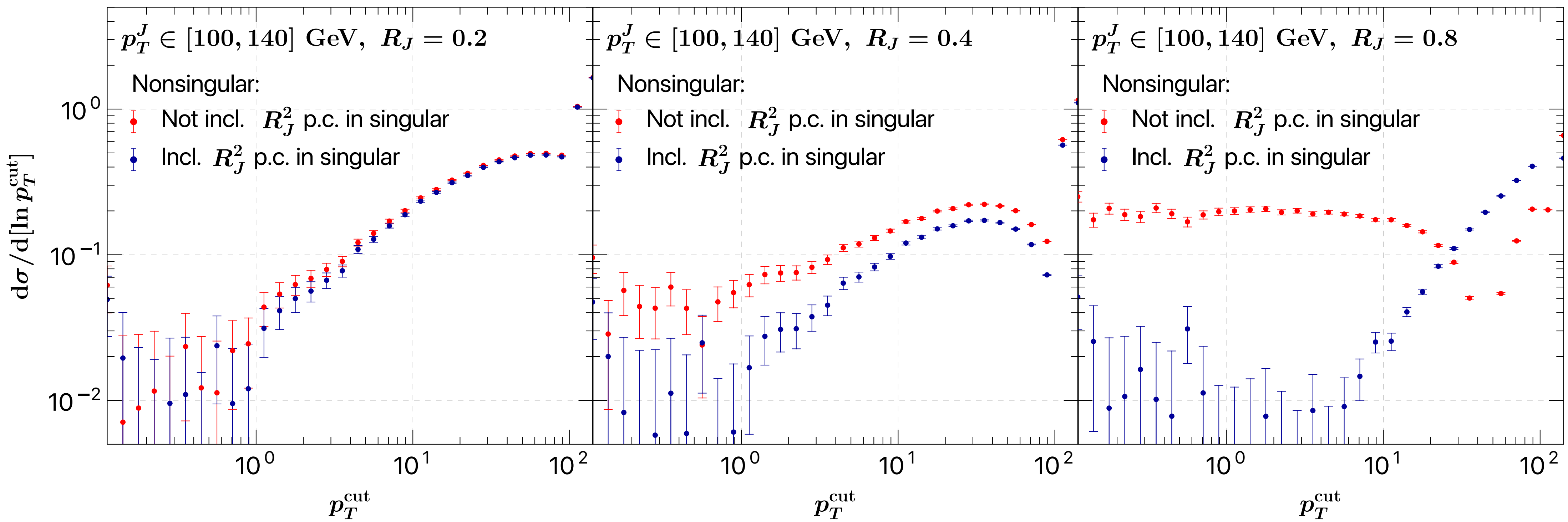
$$\nu\frac{\mathrm{d}}{\mathrm{d}\nu}\ln S_\kappa(p_T^{\mathrm{cut}};\mu,\nu) = \gamma_{\nu,S}^\kappa(p_T^{\mathrm{cut}};\mu)$$

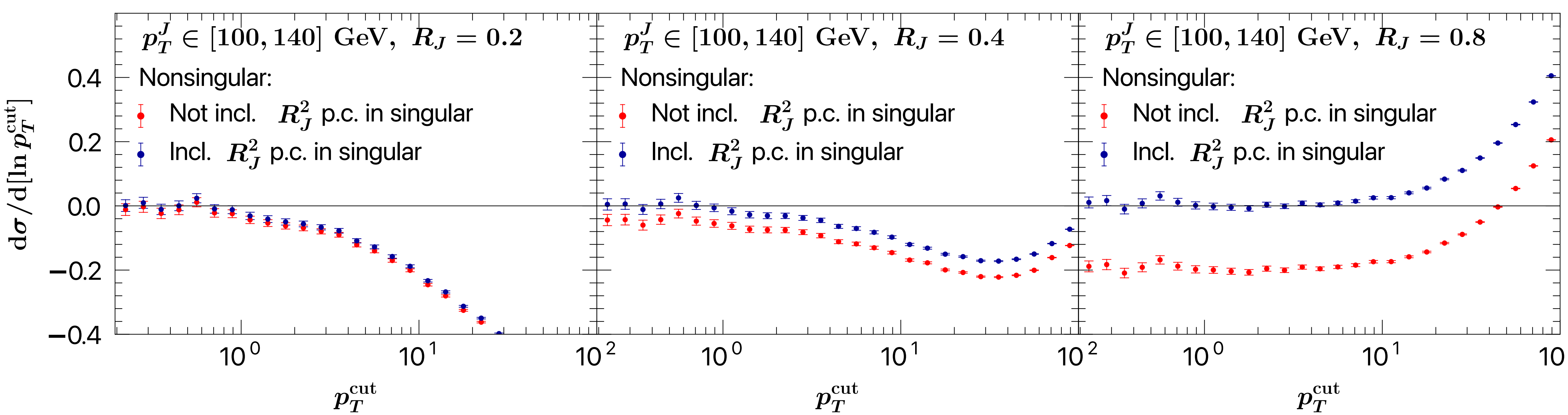
solve perturbatively

$$\begin{aligned}
&S_\kappa^{(2)}(p_T^{\mathrm{cut}}, y_J;\mu,\nu) = \\
&= \frac{1}{2}(C_a+C_b+C_j)^2\Gamma_0^2 L_S^4 \\
&\quad + \frac{2}{3}(C_a+C_b+C_j)\Gamma_0\left[\beta_0 + 3C_a\Gamma_0\ln\left(\frac{e^{y_J}p_T^{\mathrm{cut}}}{\nu}\right) + 3C_b\Gamma_0\ln\left(\frac{e^{-y_J}p_T^{\mathrm{cut}}}{\nu}\right)\right]L_S^3 \\
&\quad + \left\{(C_a+C_b+C_j)(\Gamma_0 s_\kappa^{(1)}+\Gamma_1) + 2\Gamma_0\left[C_a\ln\left(\frac{e^{y_J}p_T^{\mathrm{cut}}}{\nu}\right) + C_b\ln\left(\frac{e^{-y_J}p_T^{\mathrm{cut}}}{\nu}\right)\right]\right. \\
&\qquad\left.\times\left[\beta_0 + C_a\Gamma_0\ln\left(\frac{e^{y_J}p_T^{\mathrm{cut}}}{\nu}\right) + C_b\Gamma_0\ln\left(\frac{e^{-y_J}p_T^{\mathrm{cut}}}{\nu}\right)\right]\right\}L_S^2 \\
&\quad + \left\{2s_\kappa^{(1)}\beta_0 + \gamma_{S\,1}^{ab} + 2\left[s_\kappa^{(1)}\Gamma_0+\Gamma_1\right]\left[C_a\ln\left(\frac{e^{y_J}p_T^{\mathrm{cut}}}{\nu}\right) + C_b\ln\left(\frac{e^{-y_J}p_T^{\mathrm{cut}}}{\nu}\right)\right]\right\}L_S \\
&\quad + \gamma_{\nu,S\,1}^{ab}\ln\left(\frac{\nu}{p_T^{\mathrm{cut}}}\right) + s_\kappa^{(2)}\,, \qquad (2.38)
\end{aligned}$$

Singular structure

$$
\begin{aligned}
S_\kappa^{(1)} = \frac{\alpha_s}{4\pi}\Bigg\{ &(T_a^2+T_b^2)\left[-4\ln^2\left(\frac{\mu}{p_T^{\rm cut}}\right) - 8\ln\left(\frac{\mu}{\rm cut}\right)\ln\left(\frac{\nu}{\mu}\right) - \frac{\pi^2}{6} + 2R_J^2\ln\left(\frac{\mu}{p_T^{\rm cut}R_J}\right) + R_J^2\right] \\
&+ 8y_J(T_a^2-T_b^2)\ln\left(\frac{\mu}{p_T^{\rm cut}}\right) \\
&+ \mathbf{T}_j^2\left[-4\ln^2 R_J + 8\ln\left(\frac{\mu}{p_T^{\rm cut}}\right)\ln R_J - R_J^2\ln\left(\frac{\mu}{p_T^{\rm cut}R_J}\right) + \frac{R_J^2}{6}\right]\Bigg\}
\end{aligned}
$$





NGLS and their convergence

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

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