Resummation of jet vetoes

Jonathan Gaunt (U. of Manchester)

Based on:
Gangal, JG, Stahlhofen, Tackmann, arXiv:1608.01999
Gangal, JG, Tackmann, Vryonidou, arXiv:2003.04323
Abreu, JG, Monni, Szafron, arXiv:2204.02987
Abreu, JG, Monni, Rottoli, Szafron, arXiv:2207.07037

QCD@LHC 2023
Durham, 5th September 2023

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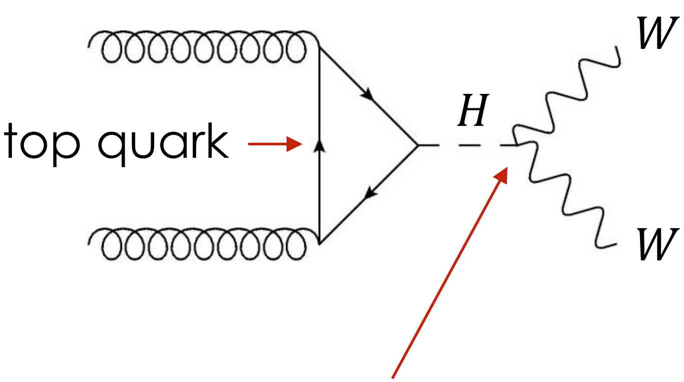
JET VETOES

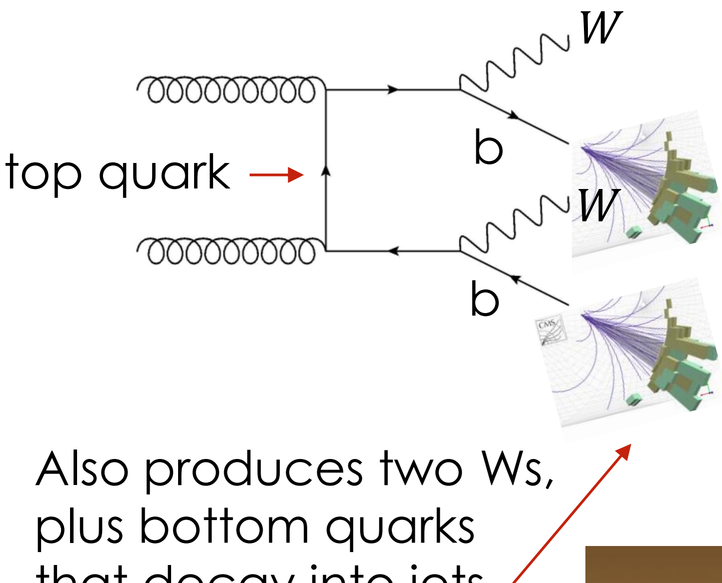
Common tool at LHC to separate different hard processes, reduce backgrounds. Example:

Signal:



Study Higgs coupling to W bosons

Background:

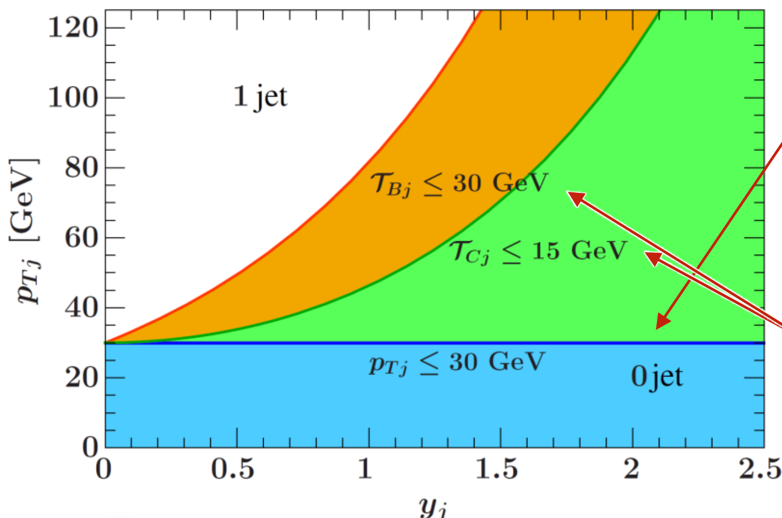


Also produces two Ws, plus bottom quarks that decay into jets

To enhance signal/background, enforce **veto** on energetic jets. When scale of veto $\mathcal{T}$ << scale of hard process Q, double logs of $Q/\mathcal{T}$ appear in perturbative series and must be resummed.

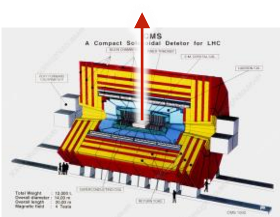
From talk by A. Banfi

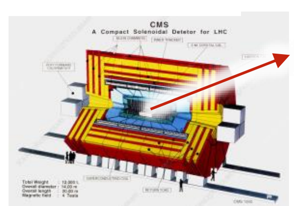
DIFFERENT JET VETOES



Traditional jet veto: apply uniform cut on p_T of jets, regardless of rapidity

Can also have a jet veto that is tightest at central rapidity, and becomes looser as one goes forward





$$\mathcal{T}_{B,j} = m_{Tj} e^{-|y_j - Y|}$$

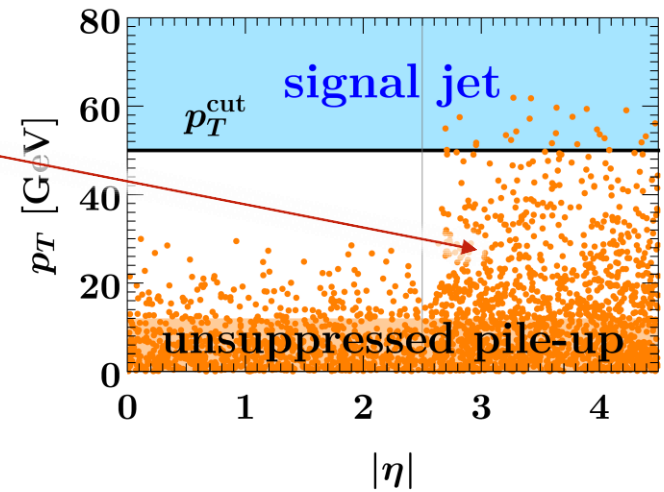
$$\mathcal{T}_{C,j} = \frac{m_{Tj}}{2\cosh(y_j - Y)}$$

Tackmann, Walsh, Zuberi, arXiv:1206.4312
Gangal, Stahlhofen, Tackmann, arXiv:1412.4792

WHY ALTERNATIVE JET VETOES?

Why consider such alternative jet vetoes?

- Contamination from pile-up predominantly in forward region of detector, difficult to disentangle due to no tracking.



Michel, Pietrulewicz, Tackmann, arXiv:1810.12911

- Resummation structure very different. Technically: SCET_I observable rather than SCET_II.

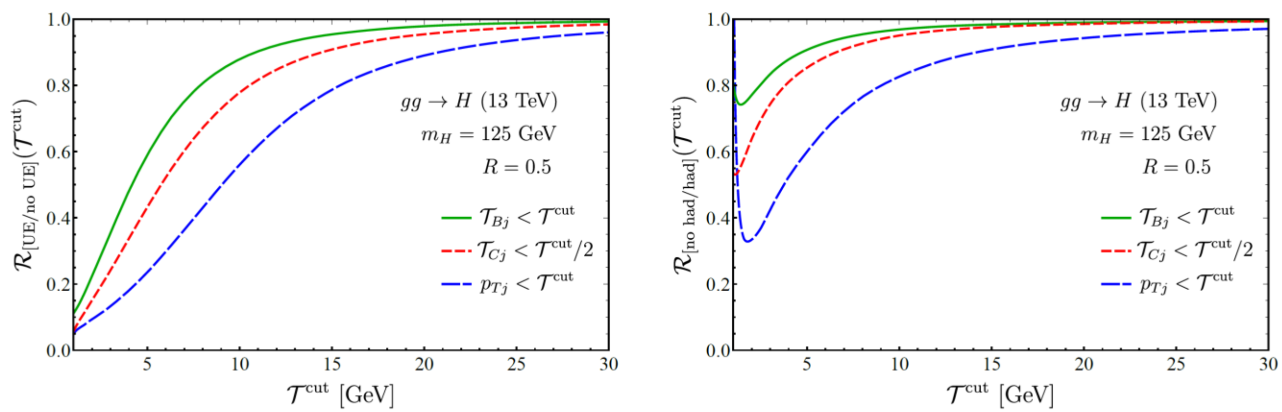
- Different way to divide cross section into jet bins.

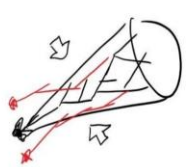
WHY ALTERNATIVE JET VETOES?

Why consider such alternative jet vetoes?

- $\mathcal{T}_{B/C,j}$ is more inclusive (tight veto over smaller range) → less strongly impacted by UE and hadronisation than p_{Tj} for same central veto

NLO+PS study: Gangal, JG, Tackmann, Vryonidou, arXiv:2003.04323





Underlying Event

Hadronisation

FACTORISATION FOR $\mathcal{T}_{B/Cj}$

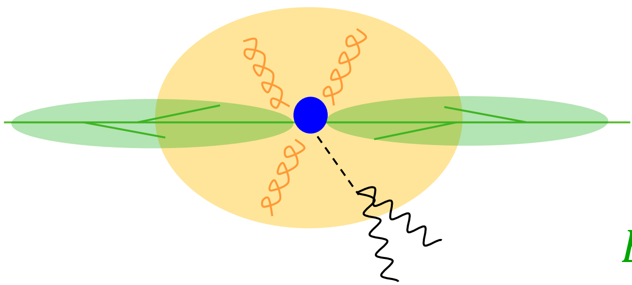
Consider colour singlet production with $\mathcal{T}_{B/Cj}$ veto.

For $\mathcal{T}_{B/Cj} \ll Q$, cross section factorises:

R = Jet radius

$$\frac{d\sigma_0}{dY}(\mathcal{T}_j < \mathcal{T}^{cut}) = \sigma_B H(Q,\mu) B_i(Q\mathcal{T}^{cut}, x_a, R, \mu) B_i(Q\mathcal{T}^{cut}, x_b, R, \mu) \times S(\mathcal{T}^{cut}, R, \mu)$$

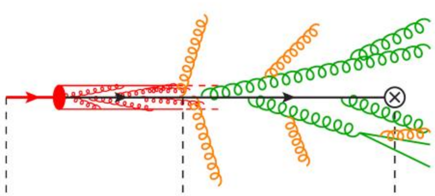
Tackmann, Walsh, Zuberi, arXiv:1206.4312



For $\mathcal{T}_{B/Cj} \gg \Lambda_{QCD}$ we also have:

$$B_i(Q\mathcal{T}^{cut}, x, R, \mu) = \mathfrak{I}_{ij}(Q\mathcal{T}^{cut}, x, R, \mu) \otimes_x f_j(x,\mu)$$

Figure from Stewart, Tackmann, Waalewijn, arXiv:0910.0467



Perturbative coefficient

Usual PDFs

$$\ln^2\left(\frac{\mathcal{T}^{cut}}{Q}\right) = 2\ln^2\left(\frac{Q}{\mu}\right) - \ln^2\left(\frac{\mathcal{T}^{cut}Q}{\mu^2}\right) + 2\ln^2\left(\frac{\mathcal{T}^{cut}}{\mu}\right)$$

RESUMMATION FOR $\mathcal{T}_{B/cj}$

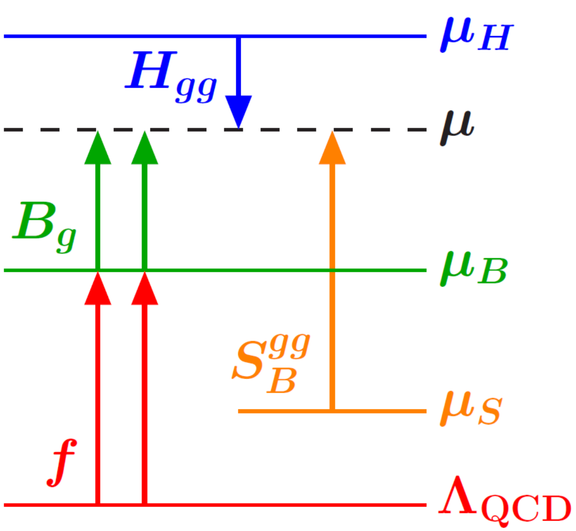
Resum logs using RGEs of different pieces:

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \ln\left[B_g(t^{\mathrm{cut}}, x, R, \mu)\right] = \gamma_B^g(t^{\mathrm{cut}}, R, \mu)$$

Anomalous dimension

$$\gamma_B^g(t^{\mathrm{cut}}, R, \mu) = -2\Gamma^g_{\mathrm{cusp}}[\alpha_s(\mu)] \ln \frac{t^{\mathrm{cut}}}{\mu^2} + \gamma_B^g[\alpha_s(\mu), R]$$

Non-cusp anomalous dimension



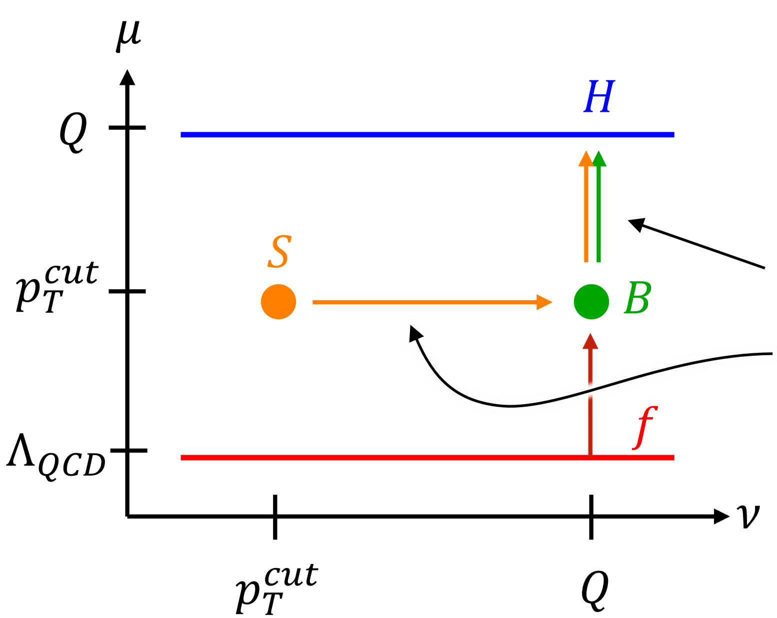
RESUMMATION FOR p_{Tj}

Becher, Neubert, arXiv:1205.3806
Becher, Neubert, Rothen, arXiv:1307.0025
Tackmann, Walsh, Zuberi, arXiv:1206.4312
Stewart, Tackmann, Walsh, Zuberi, arXiv:1307.1808

Factorisation for p_{Tj} is slightly different:

$$\frac{d\sigma_0}{dY}(p_{Tj} < p_T^{cut}) = \sigma_B H(Q,\mu) B_i\big(x_a, Q, p_T^{cut}, R, \mu, \nu\big) B_i\big(x_b, Q, p_T^{cut}, R, \mu, \nu\big) \times S\big(p_T^{cut}, R, \mu, \nu\big)$$

Rapidity regularisation scale



RGEs in both μ and ν:

$$\frac{d}{d\ln\mu} \ln \mathcal{S}(p_T^{\rm veto}, R^2; \mu, \nu) = 4\,\Gamma^F_{\rm cusp}(\alpha_s(\mu)) \ln\frac{\mu}{\nu} + \gamma^F_S(\alpha_s(\mu))\,,$$

$$\frac{d}{d\ln\nu} \ln \mathcal{S}(p_T^{\rm veto}, R^2; \mu, \nu) = -4 \int_{p_T^{\rm veto}}^{\mu} \frac{d\mu'}{\mu'} \Gamma^F_{\rm cusp}(\alpha_s(\mu')) + \gamma^F_\nu(p_T^{\rm veto}, R^2)$$

RESUMMATION PRECISION

To achieve higher resummation precision, require B, H, S and γs at higher orders.

GOAL: State-of-the-art **NNLL'** (partial N^{3}LL) precision :

	$\boldsymbol{B, H, S}$	$\boldsymbol{\gamma_{H,B,S}, \gamma_\nu}$	$\boldsymbol{\Gamma_{cusp}}$	$\boldsymbol{\beta}$
NNLL'	NNLO	2-loop	3-loop	3-loop

✓ Moch, Vermaseren, Vogt, [hep-ph/0403192] Korchemsky, Radyushkin, Nucl. Phys. B283 (1987) 342–364

✓ Tarasov, Vladimirov, Zharkov, Phys. Lett. B 93 (1980) 429–432. Larin, Vermaseren, [hep-ph/9302208]

Must compute these via two-loop computations of B, S: this talk!

CALCULATION: APPROACH

Approach here: **direct** computation, as much of it **analytic** as possible.

Full *R* dependence difficult to obtain analytically – we compute expansion in *R*.

Only need first few terms for commonly used *R* values < 1

$$\mathbb{F}(R) = -\frac{1}{2} + \ln R - \frac{1}{6}\Big(\frac{R}{2}\Big)^2 - \frac{1}{90}\Big(\frac{R}{2}\Big)^4 - \frac{1}{567}\Big(\frac{R}{2}\Big)^6 + \mathcal{O}(R^8)$$

$$\mathcal{U}_B(R) = -\Big(\frac{R}{2}\Big)^2 - \frac{64}{45\pi}\Big(\frac{R}{2}\Big)^3 - \frac{1}{9}\Big(\frac{R}{2}\Big)^4 + \frac{1}{135}\Big(\frac{R}{2}\Big)^6 - \frac{1}{945}\Big(\frac{R}{2}\Big)^8 + \mathcal{O}(R^{10})$$

$$\mathcal{U}_C(R) = -2\Big(\frac{R}{2}\Big)^2 - \frac{2}{9}\Big(\frac{R}{2}\Big)^4 + \frac{2}{135}\Big(\frac{R}{2}\Big)^6 - \frac{2}{945}\Big(\frac{R}{2}\Big)^8 + \mathcal{O}(R^{10})\,.$$

Gangal, JG, Stahlhofen, Tackmann, arXiv:1608.01999

Effective expansion parameter seems to be *R*/2 or even smaller!

For p_{Tj}: Numerical extraction from NNLO calculations was performed in Stewart, Tackmann, Walsh, Zuberi, [arXiv:1307.1808]. Direct numerical computation also recently available Bell, Rahn, Talbert, 1812.08690, arXiv:2004.08396, Bell, Brune, Das, Wald, arXiv:2207.05578 [see talk by Brune]

CALCULATION: APPROACH

Strategy: compute **difference** from a **simpler reference measurement**, which however **coincides with jet veto for one emission**

For $\mathcal{T}_{B/Cj}$: $B_{\text{jet}}(m_H\mathcal{T}^{cut}, x, R, \mu) = B_{\text{ref}}(m_H\mathcal{T}^{cut}, x, \mu) + \Delta B(m_H\mathcal{T}^{cut}, x, R, \mu)$

Reference measurement:
Beam thrust/0-jettiness

Known analytically to two loops
JG, Stahlhofen, Tackmann, JHEP 1404 (2014) 113, JHEP 1408 (2014) 020 (and now to three loops: Ebert, Mistlberger, Vita, arXiv:2006.03056, Baranowski et al, arXiv:2211.05722)

$\Delta B = 0$ for one emission – only need double-real graphs, most of UV/IR divergences absent.

For p_{Tj}: $B_{\text{jet}}(x, Q, p_T^{cut}, R, \mu, \nu) = B_{\text{ref}}(x, Q, p_T^{cut}, R, \mu, \nu) + \Delta B(x, Q, p_T^{cut}, R, \mu, \nu)$

Reference measurement: Vector transverse momentum sum of all QCD radiation. Known up to 3 loops. Luo et al., arXiv:1912.05778, Ebert, Mistlberger, Vita, arXiv:2006.05329

STRUCTURE OF BEAM FUNCTION

Structure of (bare) ΔB for $\mathcal{T}_{B/Cj}$:

$$\Delta B(t^{cut}, x, R) = \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{\mu^2}{t^{cut}}\right)^{2\epsilon} \Bigg[\delta(1-x) \left\{ \frac{1}{\epsilon} [\#\log(R) + \overbrace{\# + \#R^2 + \#R^4 + \cdots}^{f(R)}] \right.$$
$$\left. + [\#\log^2(R) + \#\log(R) + \overbrace{\# + \#R^2 + \#R^2\log(R) + \#R^4}^{g(R)} + \cdots] \right\}$$
$$+ \left(\frac{1}{1-x}\right)_+ \{\#(x)\log(R) + h(x) + \#(x)R^2 + \#(x)R^4 + \cdots\}$$
$$+ \left\{ \frac{1}{\epsilon^2}\#(x) + \frac{1}{\epsilon}\left(\#(x) + \#(x)R^2\right) + \#(x)R^2 \right.$$
$$\left. + \#(x)R^2\log(R) + \#(x)R^4 + \cdots \right\} \Bigg]$$

Coefficients in blue (and for certain cases purple) obtained analytically. Leaves three 1D functions: $f(R)$, $g(R)$, $h(x)$, which were fitted from numerical evaluations of $\Delta B(t^{cut}, x, R)$.

Gangal, JG, Stahlhofen, Tackmann, arXiv:1608.01999

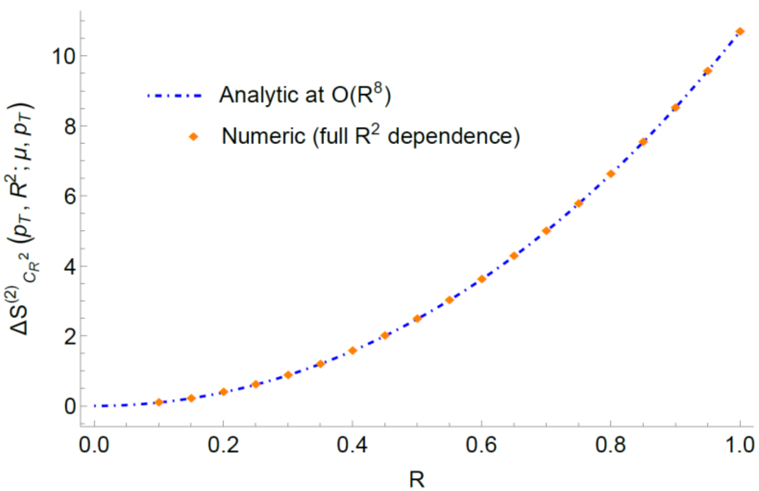
For p_{Tj} calculation, equivalent of $f(R)$ and $g(R)$ obtained analytically up to terms of order R^8, and R-dependence of $\left(\frac{1}{1-x}\right)_+$ piece obtained up to R^8

Abreu, JG, Monni, Szafron, arXiv:2204.02987
Abreu, JG, Monni, Rottoli, Szafron, arXiv:2207.07037

CHECKS: NUMERICAL CALCULATION

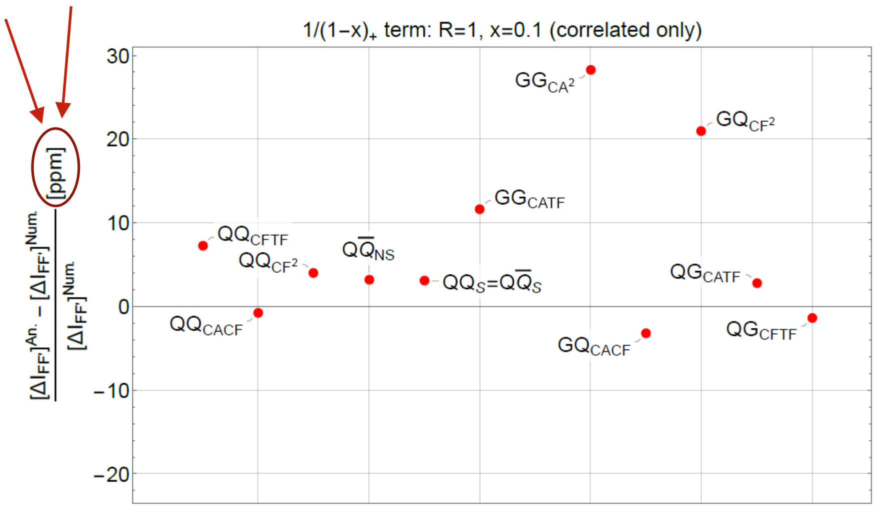
In p_{Tj} case, analytic results cross-checked with a completely separate numerical computation retaining full R dependence:

Soft function



Abreu, JG, Monni, Szafron, arXiv:2204.02987

Beam function



Abreu, JG, Monni, Rottoli, Szafron, arXiv:2207.07037

CHECKS: SLICING

Can cross-check two-loop beam and soft functions by using them to do an NNLO computation for the production of a colour singlet X:

$$\sigma(X) = \sigma(X, \mathcal{T} < \mathcal{T}^{cut}) + \sigma(X, \mathcal{T} > \mathcal{T}^{cut})$$

NNLO cross section for *X* production

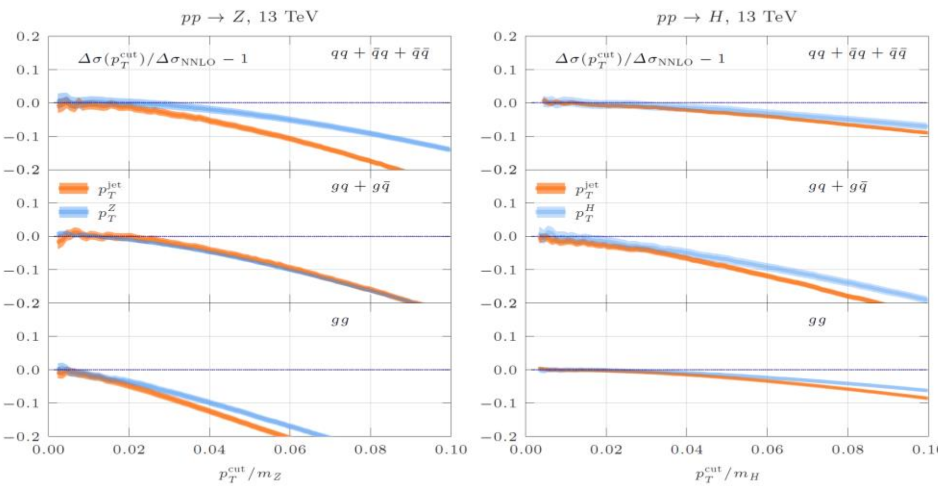
Can use factorisation formula with two loop *B, H, S* if $\mathcal{T}^{cut} \ll Q$

Must have an emission – NLO *X*+jet calculation

NNLO 'slicing' calculation

Catani, Grazzini, hep-ph/0703012, Boughezal, Focke, Liu, Petriello, arXiv:1504.02131, JG, Stahlhofen, Tackmann, Walsh, arXiv:1505.04794, ...

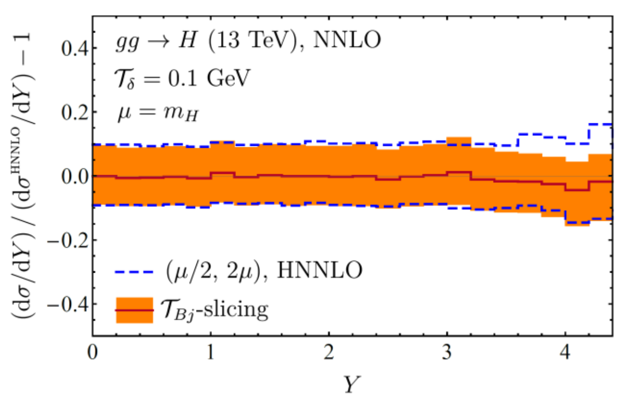
CHECKS: SLICING

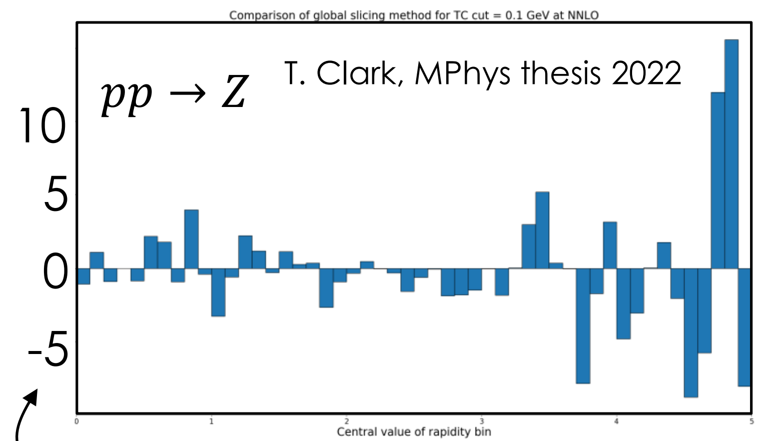


Checks for p_{Tj}. Uses implementation in RadISH.

Abreu, JG, Monni, Rottoli, Szafron, arXiv:2207.07037

Checks for $\mathcal{T}_{B/Cj}$:

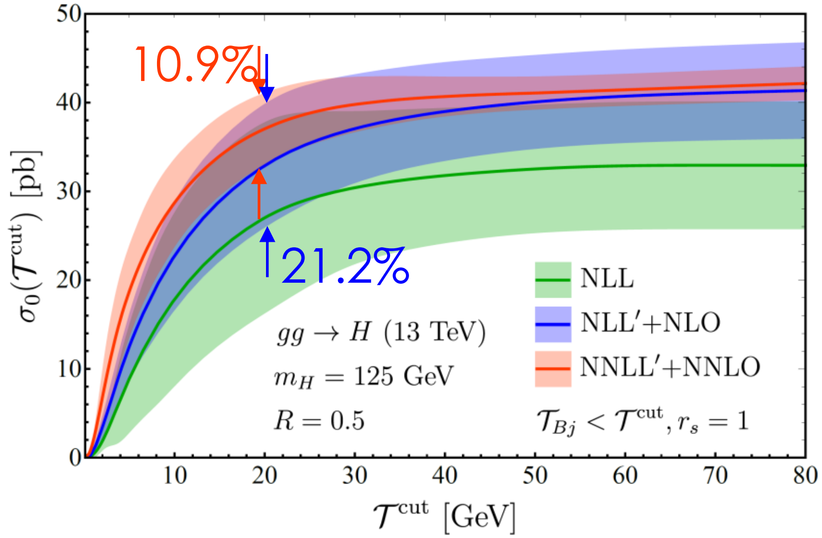


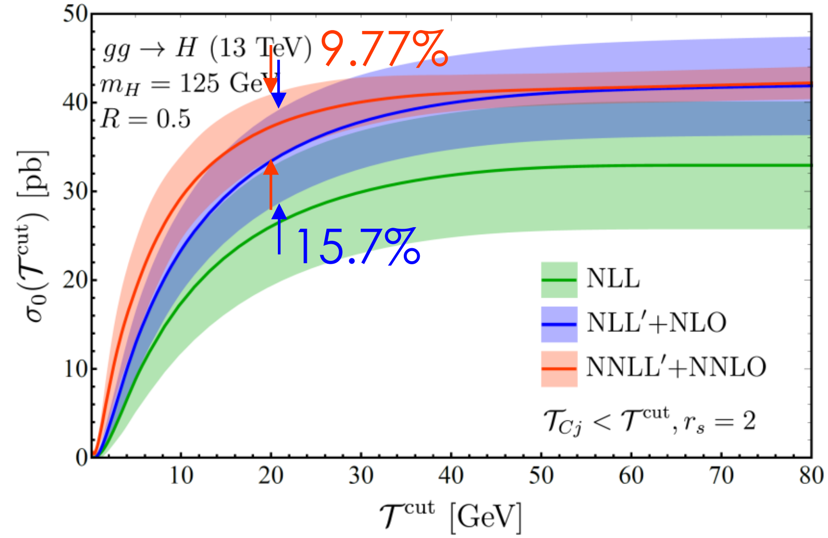


% Deviation from DYNNLO

HIGGS WITH $\mathcal{T}_{B/Cj}$ VETO

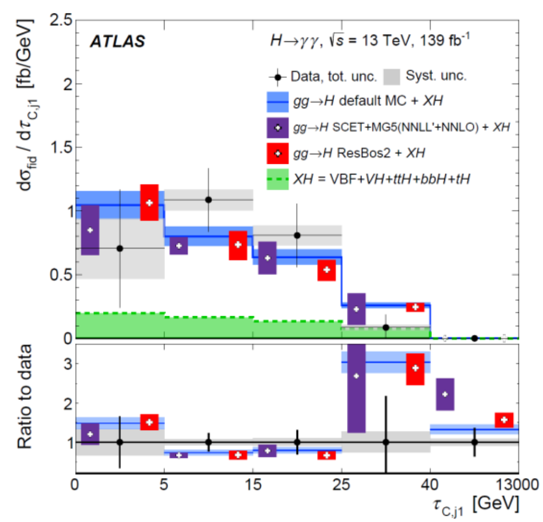
Gangal, JG, Tackmann, Vryonidou, JHEP 05 (2020) 054





Higgs cross section with $\mathcal{T}_{B/Cj}$ veto, with NNLL' resummation matched to NNLO.

Comparison to ATLAS data



ATLAS collaboration, arXiv:2202.00487

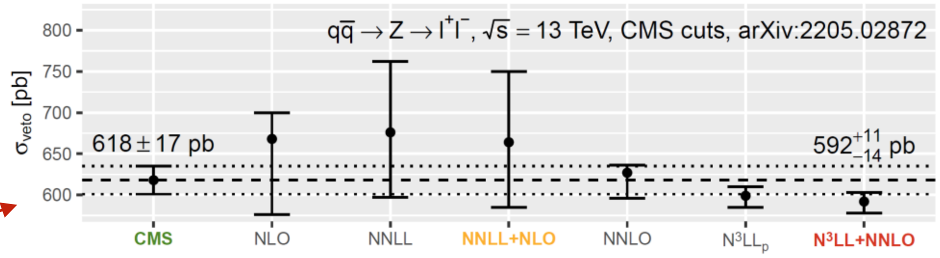
W AND Z WITH p_{Tj} VETO

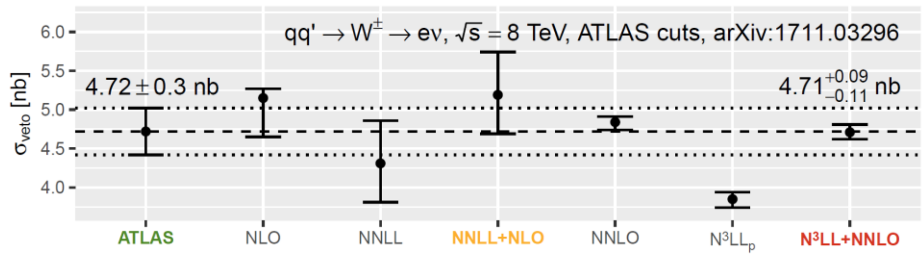
Implementation of p_{Tj} resummation in MCFM, using our two-loop *B* and *S*

Campbell, Ellis, Neumann, Seth, arXiv:2301.11768

For W and Z measurements, logs don't seem to be large enough to need resummation

$y_{cut} = 2.4,\ p_T^{cut} = 30$ GeV



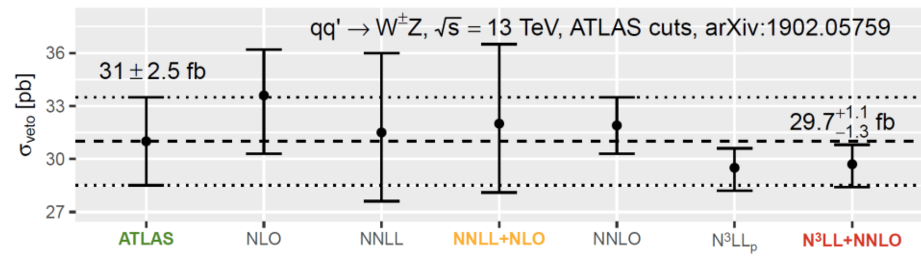


$y_{cut} = 4.4,\ p_T^{cut} = 30$ GeV

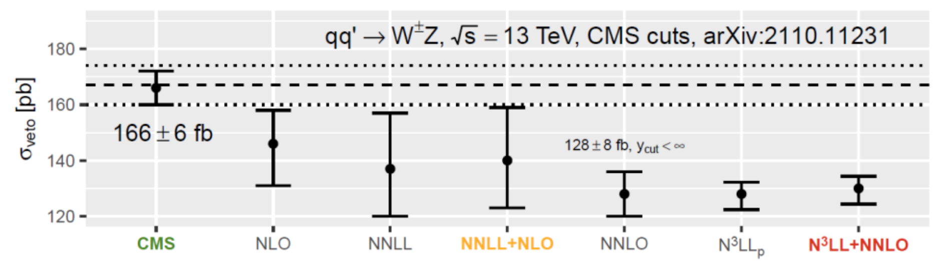
WZ AND WW WITH p_{Tj} VETO

$y_{cut} = 4.5,\ p_T^{cut} = 25$ GeV

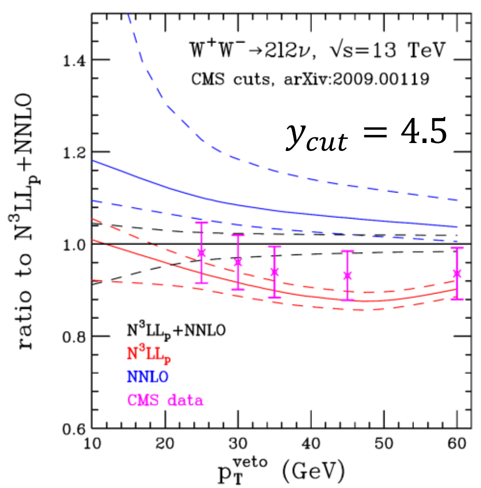
ATLAS WZ cuts, noticeable effect of resummation. More data needed.



CMS WZ cuts: p_{Tj} cut imposed over more limited rapidity range. Not accounted for in theory prediction.



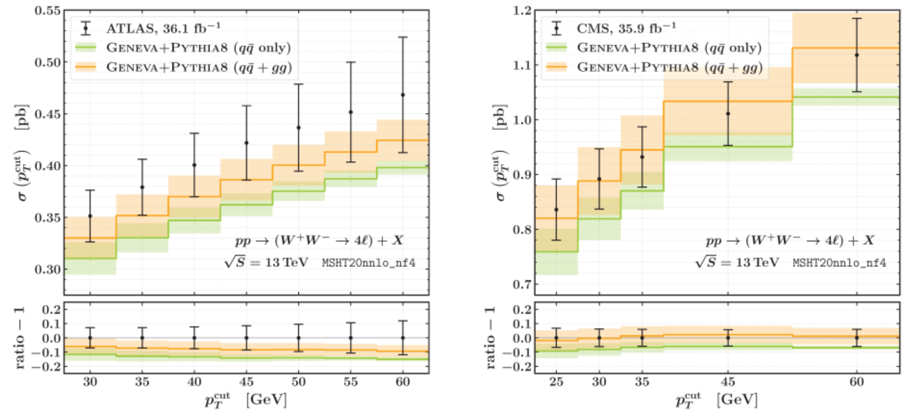
$y_{cut} = 2.5,\ p_T^{cut} = 25$ GeV



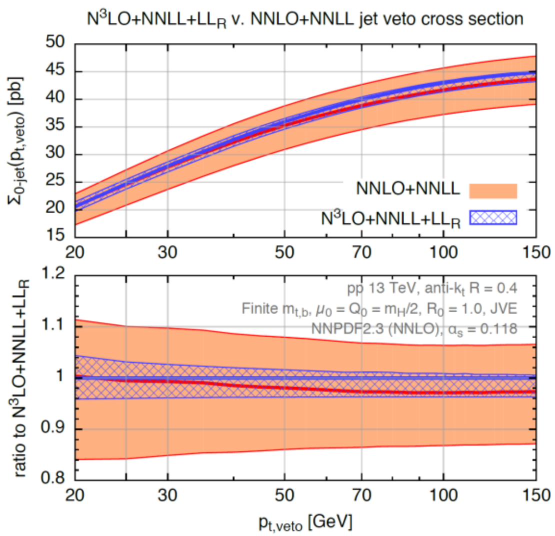
For CMS WW measurement, important impact of resummation

OTHER RESULTS WITH WITH p_{Tj} VETO

New ‘flavour’ of GENEVA using resummation of jet veto logs to achieve NNLO + PS matching (incorporates info from two-loop B and S). Compared to ATLAS and CMS WW data:



Gavardi, Lim, Alioli, Tackmann, [arXiv:2308.11577]



Various results at NNLL(′) +(N)NNLO for Higgs production: Stewart, Tackmann, Walsh, Zuberi [arXiv:1307.1808], Becher, Neubert, Rothen [arXiv:1307.0025], Banfi, Monni, Salam, Zanderighi [arXiv:1206.4998] (+Z production), Banfi, Caola, Dreyer, Monni, Salam, Zanderighi, Dulat [arXiv:1511.02886]

SUMMARY

- Two loop beam and soft functions computed for production of a colourless state in the presence of various jet vetoes: $\mathcal{T}_{Bj}$, $\mathcal{T}_{Cj}$ and p_{Tj}.
- Computed mostly analytically as an expansion in *R*. Checked using numerical computation + NNLO slicing calculation.
- Enables NNLL′ resummed computations. For full N^3LL missing ingredient is a 3-loop rapidity/non-cusp anomalous dimension – WIP.