High-energy resummation for Higgs boson plus jets production

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1 June 2023

In collaboration with

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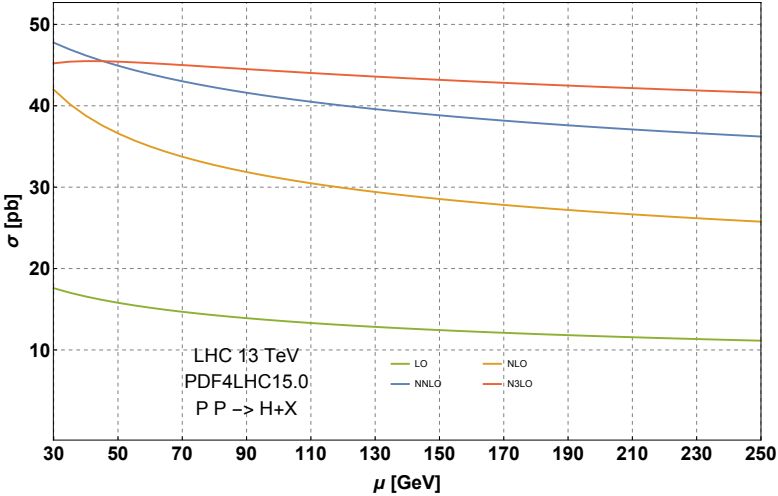
JHEP 03 (2023) 001
JHEP 04 (2019) 127

Motivation

Fixed-order perturbative corrections are

- very important in Higgs physics



[Mistlberger 2018]

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Fixed-order perturbative corrections are

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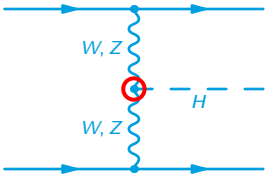
Solutions:

- Kinematic approximations, e.g. $m_t \to \infty$
- All-order resummation [this talk]

Weak Boson Fusion



- Allows direct measurement of Higgs couplings to W,Z
- Known at N^3LO QCD + NLO electroweak

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015] [Cruz-Martinez, Gehrmann, Glover, Huss 2018] [Dreyer, Karlberg 2016]

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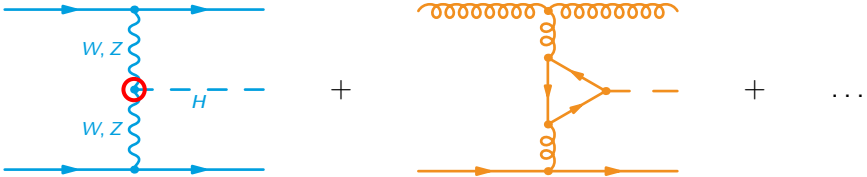
Weak Boson Fusion



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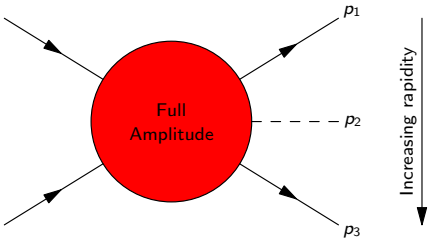
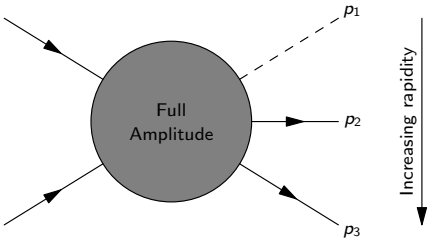
- Large background from gluon fusion
  - Only known exactly at leading order [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld 2001]
  - Suppress with Weak Boson Fusion cuts

$$m_{j_1 j_2} \gtrsim 400\,\text{GeV}, \qquad \Delta y_{12} \gtrsim 2.8$$

Gluon fusion in the high-energy limit





High-energy limit

$y_1 \ll y_2 \ll \cdots \ll y_n$, no strong hierarchy in $p_{i\perp}$

equivalent:

$m_{ij} \gg$ transverse scales

Gluon fusion in the high-energy limit

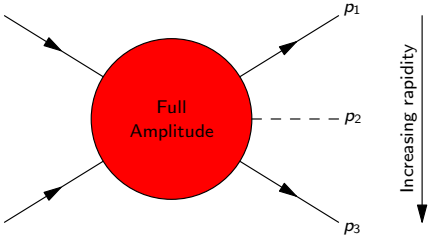
Scaling of amplitudes

Regge scaling

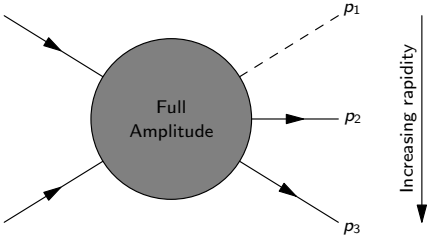
$$\mathcal{M} \sim m_{12}^{\alpha_1} m_{23}^{\alpha_2}$$

α_i: maximum spin exchanged between i and $i+1$

"Maximum number of t-channel gluons", gauge invariant



2 t-channel gluons, leading



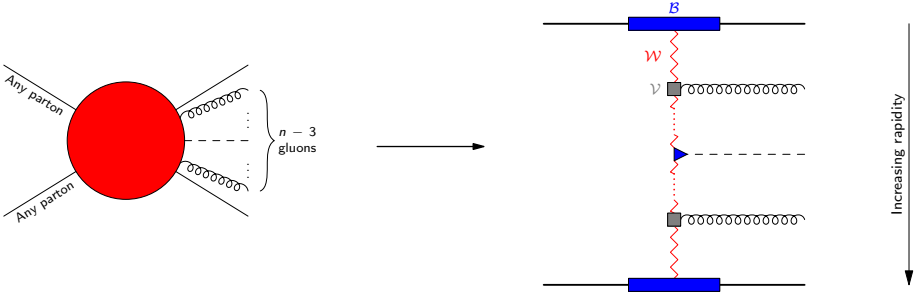
1 t-channel gluon, subleading

High Energy Jets (HEJ)

- All-order resummation of leading high-energy logarithms $\alpha_s^2 \left(\alpha_s \ln \frac{m_{ij}}{p_\perp}\right)^N$
  + partial NLL resummation
  soon: + soft-collinear resummation $\Rightarrow$ Talk by Sebastian Jaskiewicz
- Minimal approximations to amplitude: tree-level exact for simple processes
- Exact Monte Carlo phase space integration
- Exact tree-level gauge invariance
- Matched to fixed order (LO)

High Energy Jets (HEJ)

All-order amplitudes for $H+ \geq 2$ jets



$$|\mathcal{M}|^2 = \mathcal{B}_{f_a,H,f_b} \cdot \prod_{\substack{i=1\\ i\neq j}}^{n-2} \mathcal{V} \cdot \prod_{i=1}^{n-1} \mathcal{W}$$

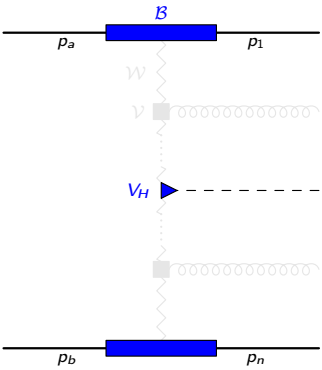
Born level

resolved real corrections

virtual + unresolved real corrections

High Energy Jets (HEJ)

Born function



$$\mathcal{B}_{f_a,H,f_b} = \frac{1}{4(N_C^2-1)} \frac{g_s^2 K_{f_a}(p_1^-, p_a^-)}{t_1} \frac{g_s^2 K_{f_b}(p_n^+, p_b^+)}{t_n} \times \frac{1}{t_j t_{j+1}} \sum_{\text{helicities}} |j_\mu V_H^{\mu\nu} j_\nu|^2,$$

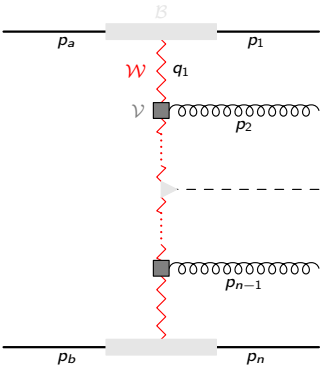
- Higgs-gluon-gluon vertex $V_H^{\mu\nu}$ with full dependence on top and bottom masses
- Colour acceleration modifiers:

$$K_q = K_{\bar{q}} = C_F,$$

$$K_g(p_1^-, p_a^-) = \frac{1}{2}\left(\frac{p_1^-}{p_a^-} + \frac{p_a^-}{p_1^-}\right)\left(C_A - \frac{1}{C_A}\right) + \frac{1}{C_A}$$

High Energy Jets (HEJ)

Resolved real and virtual + unresolved real corrections



Real corrections:

$$\mathcal{V} = \frac{-C_A g_s^2}{t_j t_{j+1}} V^\mu V_\mu + (\text{subtr.}),$$

$$\begin{aligned} V^\mu = & -(q_i + q_{i+1})^\mu \\ & + \frac{p_a^\mu}{2}\left(\frac{q_i^2}{p_{i+1}\cdot p_a} + \frac{p_{i+1}\cdot p_b}{p_a\cdot p_b} + \frac{p_{i+1}\cdot p_n}{p_a\cdot p_n}\right) + p_a \leftrightarrow p_1 \\ & - \frac{p_b^\mu}{2}\left(\frac{q_{i+1}^2}{p_{i+1}\cdot p_b} + \frac{p_{i+1}\cdot p_a}{p_b\cdot p_a} + \frac{p_{i+1}\cdot p_1}{p_b\cdot p_1}\right) - p_b \leftrightarrow p_n \end{aligned}$$

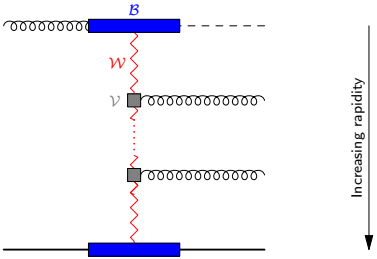
Virtual corrections:

$$\mathcal{W} = \exp[(y_j - y_{j+1})\omega^0(q_j)]$$

Radiative corrections are process-independent

High Energy Jets (HEJ)

All-order amplitudes for $H+ \geq 1$ jets



$$|\mathcal{M}|^2 = \mathcal{B}_{H,f_b} \cdot \prod_{i=1}^{n-2} \mathcal{V} \cdot \prod_{i=1}^{n-1} \mathcal{W}$$

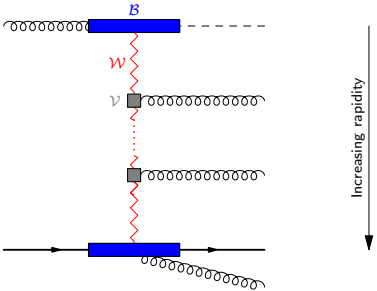
Born level

resolved real corrections

virtual + unresolved real corrections

High Energy Jets (HEJ)

Subleading amplitudes



$$|\mathcal{M}|^2 = \mathcal{B}_{H,qg} \cdot \prod_{i=1}^{n-2} \mathcal{V} \cdot \prod_{i=1}^{n-1} \mathcal{W}$$

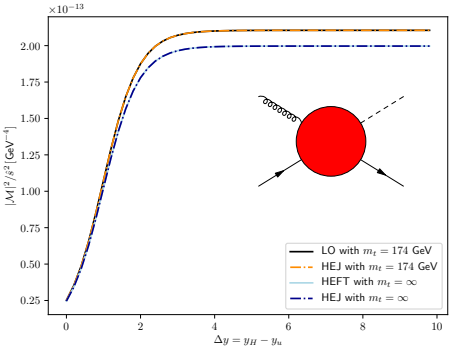
Born level

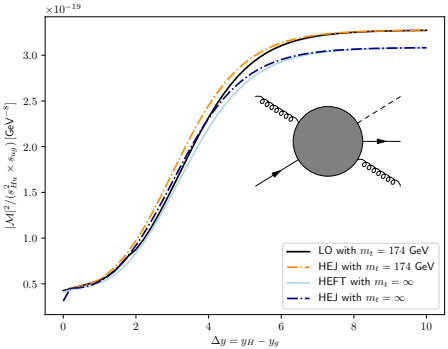
resolved real corrections

virtual + unresolved real corrections

High Energy Jets (HEJ)

Comparison to exact tree level amplitudes





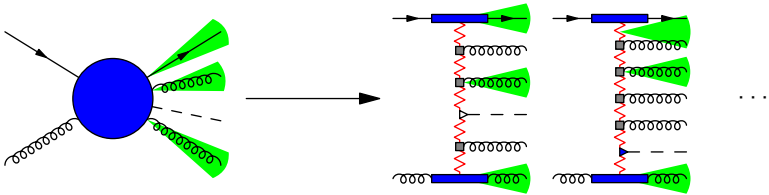
- Good agreement with exact amplitudes over whole phase space

High Energy Jets (HEJ)

Matching to fixed order

- Event-by-event leading-order matching

[Andersen, Hapola, Heil, Maier, Smillie 2018]



Leading-order event
Sherpa + OpenLoops
$\sim |\mathcal{M}_{\mathrm{LO}}|^2$

Resummation events
Keep Higgs + jet rapidities, shift $p_\perp$
$\sim |\mathcal{M}_{\mathrm{HEJ}}|^2$

- $\mathcal{M}_{\mathrm{LO}}$ with full dependence on m_t for ≤ 2 jets
- $\mathcal{M}_{\mathrm{LO}}$ with $m_t \to \infty$ for 3–5 jets
- Pure HEJ predictions for > 5 jets
- $\mathcal{M}_{\mathrm{HEJ}}$ with full dependence on m_t, m_b

Final resummation event weight $\sim \frac{|\mathcal{M}_{\mathrm{LO}}|^2 |\mathcal{M}_{\mathrm{HEJ}}|^2}{|\mathcal{M}_{\mathrm{HEJ,\,LO}}|^2}$

High Energy Jets (HEJ)

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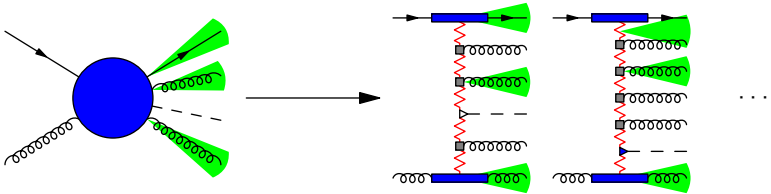

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Keep Higgs + jet rapidities, shift $p_\perp$
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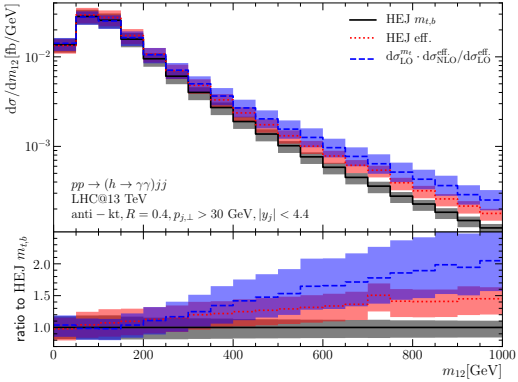
- Overall normalisation:

$$\frac{d\sigma}{d\mathcal{O}} \to \frac{\sigma_{\mathrm{NLO}}^{m_t \to \infty}}{\sigma_{\mathrm{HEJ}}} \frac{d\sigma}{d\mathcal{O}}$$

Results

Invariant mass distribution

$H+ \geq 2$ jets [Andersen, Cockburn, Heil, Maier, Smillie 2019]



- Resummation $\Rightarrow$ steeper fall-off with increasing invariant masses
- Finite top-quark mass important for $m_{12} > 400\,\text{GeV}$

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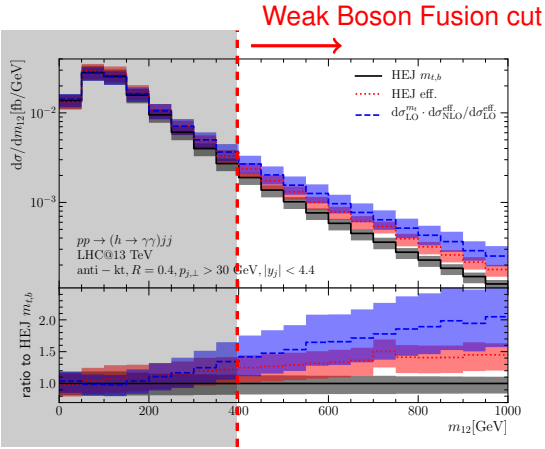
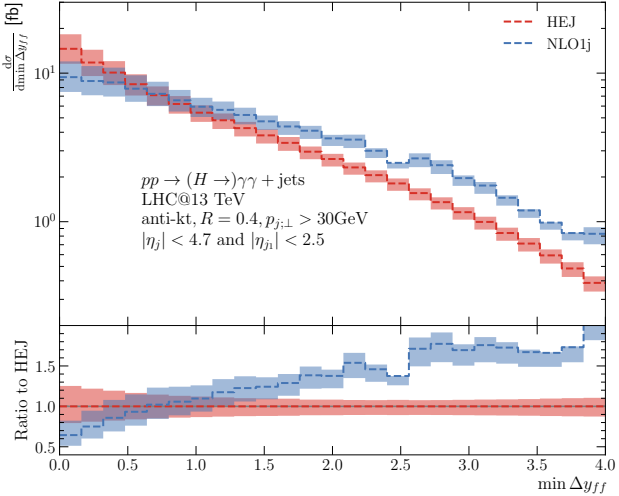


- Resummation $\Rightarrow$ steeper fall-off with increasing invariant masses
- Finite top-quark mass important for $m_{12} > 400$ GeV
- Weak Boson Fusion cuts more effective:

Prediction	σ after cuts
Fixed order	9%
HEJ	4%

Rapidity separation

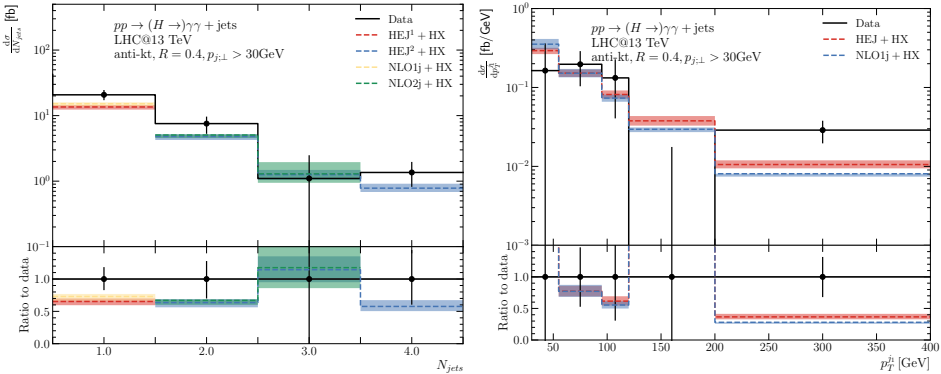
$H+ \geq 1$ jet [Andersen, Hassan, Maier, Paltrinieri, Papaefstathiou, Smillie 2022]



- Resummation $\Rightarrow$ steeper fall-off with increasing rapidity separations

Comparison to 13 TeV data

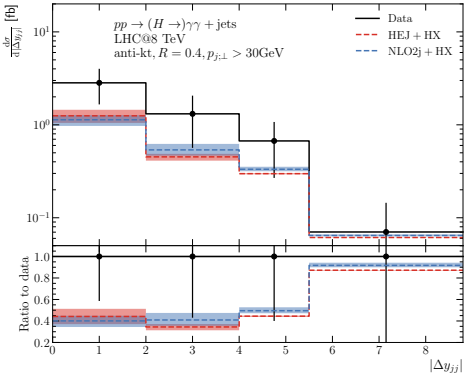
[CMS JHEP 01 (2019) 183 & arXiv:2208.12279]

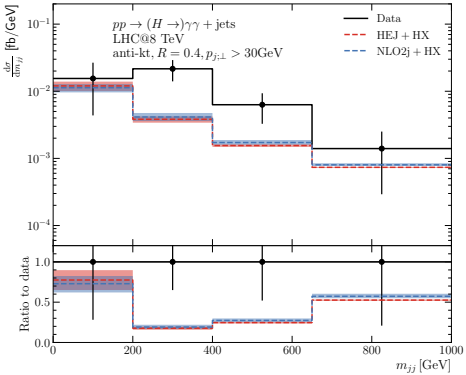


- Contributions from Weak Boson Fusion, VH, $t\bar{t}H, \ldots$ added
- HEJ transverse momentum spectrum harder than at NLO

Comparison to 8 TeV data

[ATLAS JHEP 09 (2014) 112]





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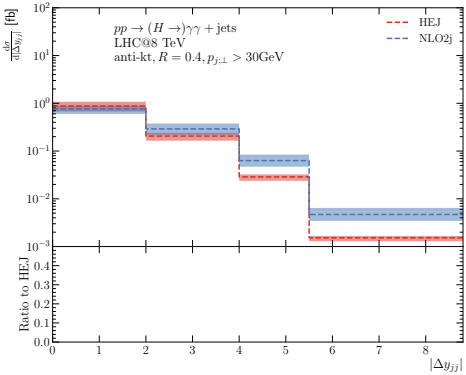
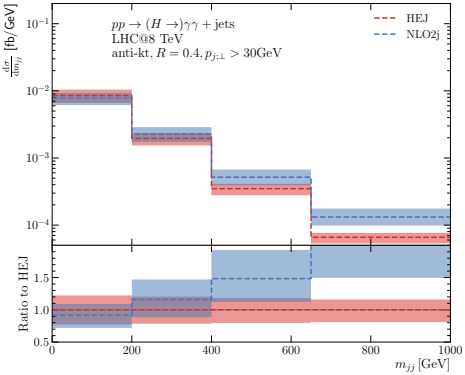
Only gluon fusion:





- Resummation $\Rightarrow$ steeper fall-off

Conclusions

- First high-energy resummation for single-jet process within *High Energy Jets*
- Suppression at large invariant masses / large rapidity separation
  Important for Weak Boson Fusion background
- Included in latest *High Energy Jets* 2.2 release:

`https://hej.hepforge.org/`

arXiv:2303.15778