Finite quark mass effects for the production of Higgs-boson with Dijet

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arxiv:1812.08072

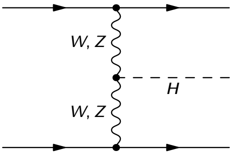
IPPP, Durham

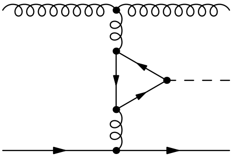
DIS 2019, Turin 09/04/2019

Higgs to gauge boson coupling

- Distinction between WBF and gF

⇒ Small quantum interference



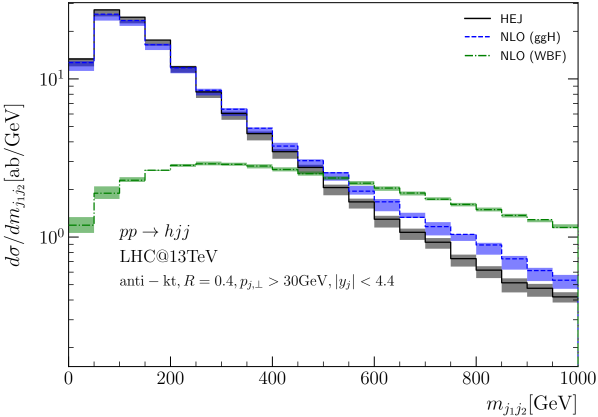


Coupling:	h to Z/W	top-loop
Add. emission:	on external quark	on t-channel gluon
Known Fixed Order:	NNLO	LO with finite m_t NLO with $m_t \to \infty$

⇒ experimental result still *work in progress*

Weak boson vs. Gluon fusion

Invariant jet mass



- *gF* dominated by initial gluon $\Rightarrow$ Peak at low m_{12}

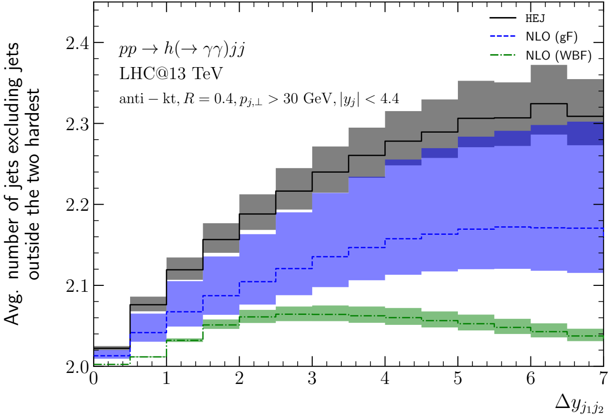
$\Rightarrow$ *VBF-cut*: $m_{12} > 400$ GeV & $y_{j_1j_1} > 2.8 \Rightarrow$ reduce *gF* by $\sim 90\%$

$\Rightarrow$ Sensitive to High Energy Effects

arxiv:1803.07977

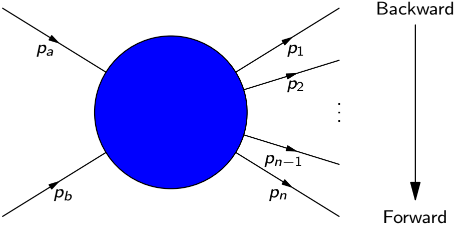
Weak boson vs. Gluon fusion

Rapidity separation



- *gF*: extra emissions inside rapidity gap ⇒ logarithmically enhanced

What is *High Energy Jets*?



High Energy Limit:	Large $\Delta y_{ij}, p_{i\perp} \sim p_{j\perp} \Leftrightarrow$ Large s_{ij}, $t_{ij} =$ const. $\forall i, j$
$\Rightarrow$	$\mathcal{M}$ becomes independent of $y \Rightarrow \sigma \propto \Delta y$
Goal:	Resumming large $\log s/t \sim \Delta y$
Approximation:	Only on Matrix Element
$\Rightarrow$	Keep full phase space (MC integration)
$\Rightarrow$	Keep full quark-mass dependence for any multiplicity

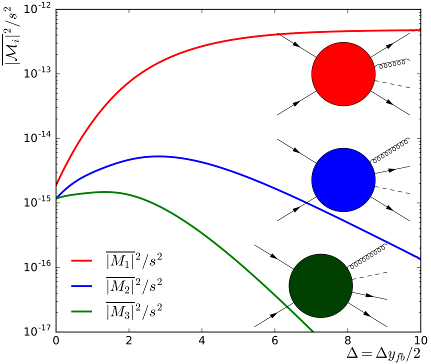
High Energy limit

Multi Regge theory (Brower DeTar, Weis '74 & Fadin, Fiore, Kozlov, Reznichenko '06)

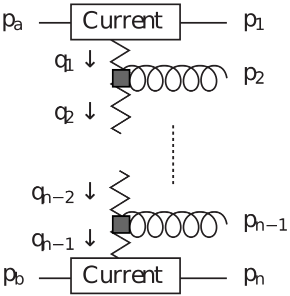
For $s_{ij} \to \infty$ and $t_i = \text{const.}$, with α_i spin of *exchange particle*:

$$\mathcal{M} \sim \; s_{12}^{\alpha_1(t_1)} \dots s_{n-1,n}^{\alpha_{n-1}(t_{n-1})} \cdot \gamma\left(\{p_{i\perp}\}, \dots\right)$$

- Gluon exchange (FKL)
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1 j_2}^2 s_{j_2 H}^2 s_{j_3 H}^2$
- Quark exchange (unordered)
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1 j_2} s_{j_2 H}^2 s_{j_3 H}^2$
- Higgs outside quarks
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1 H} s_{j_2 H} s_{j_2 j_3}^2$



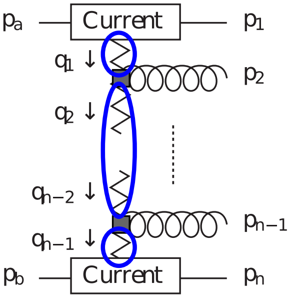
HEJ Matrix element



$$= \frac{1}{4\,(N_C^2-1)} \left\| S_{f_a f_b \to f_1 f_n} \right\|^2 \cdot \left(g_s^2\ K_{f_1}\ \frac{1}{t_1} \right) \cdot \left(g_s^2\ K_{f_n}\ \frac{1}{t_{n-1}} \right) \cdot \prod_{i=1}^{n-2} \left(\frac{-g_s^2\, C_A}{t_i t_{i+1}}\ V^{\mu}(q_i, q_{i+1}) V_{\mu}(q_i, q_{i+1}) \right) \cdot \prod_{j=1}^{n-1} \exp\left[\omega^0(q_{j\perp})(y_{j+1} - y_j) \right]$$

Processes $\Leftrightarrow$ currents, e.g. $\mathcal{S}_{qQ\to qHQ} = j_\mu(p_1, p_a) V_H^{\mu\nu}(q_j, q_{j+1}) j_\nu(p_b, p_n)$.

arxiv:1706.01002



$$= \frac{1}{4\,(N_C^2-1)} \left\| S_{f_a f_b \to f_1 f_n} \right\|^2 \cdot \left(g_s^2\ K_{f_1}\ \frac{\mathbf{1}}{\mathbf{t_1}} \right) \cdot \left(g_s^2\ K_{f_n}\ \frac{\mathbf{1}}{\mathbf{t_{n-1}}} \right) \cdot \prod_{i=1}^{n-2} \left(\frac{-g_s^2 C_A}{\mathbf{t_i t_{i+1}}}\ V^\mu(q_i,q_{i+1}) V_\mu(q_i,q_{i+1}) \right) \cdot \prod_{j=1}^{n-1} \exp\left[\omega^{\mathbf{0}}(\mathbf{q_{j\perp}})(\mathbf{y_{j+1}}-\mathbf{y_j})\right]$$

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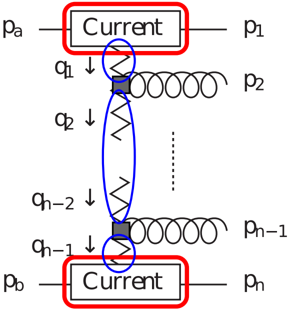

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Processes ⇔ currents, e.g. $\mathcal{S}_{qQ\to qHQ} = j_\mu(p_1, p_a) V_H^{\mu\nu}(q_j, q_{j+1}) j_\nu(p_b, p_n)$.

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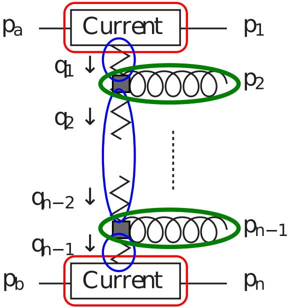
HEJ Matrix element



$$= \frac{1}{4\,(N_C^2-1)}\,\left\|S_{f_a f_b \to f_1 f_n}\right\|^2 \cdot \left(g_s^2\,K_{f_1}\,\frac{1}{t_1}\right)\cdot\left(g_s^2\,K_{f_n}\,\frac{1}{t_{n-1}}\right) \cdot \prod_{i=1}^{n-2}\left(\frac{-\mathbf{g_s^2 C_A}}{t_i t_{i+1}}\,\mathbf{V}^{\mu}(\mathbf{q_i},\mathbf{q_{i+1}})\mathbf{V}_{\mu}(\mathbf{q_i},\mathbf{q_{i+1}})\right) \cdot \prod_{j=1}^{n-1}\exp\left[\omega^0(q_{j\perp})(y_{j+1}-y_j)\right]$$

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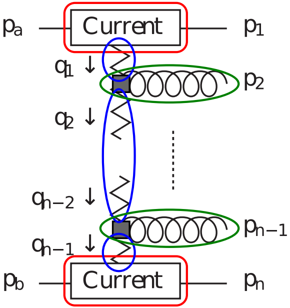

$$= \frac{1}{4\,(N_C^2-1)}\,\left\|S_{f_a f_b \to f_1 f_n}\right\|^2 \cdot \left(g_s^2\,K_{f_1}\,\frac{1}{t_1}\right)\cdot\left(g_s^2\,K_{f_n}\,\frac{1}{t_{n-1}}\right) \cdot \prod_{i=1}^{n-2}\left(\frac{-g_s^2 C_A}{t_i t_{i+1}}\,V^\mu(q_i,q_{i+1})V_\mu(q_i,q_{i+1})\right) \cdot \prod_{j=1}^{n-1} \exp\left[\omega^0(q_{j\perp})(y_{j+1}-y_j)\right]$$

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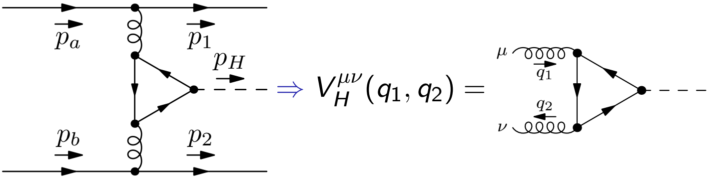
Finite quark mass effects

Simplest case: $qQ \to qHQ$

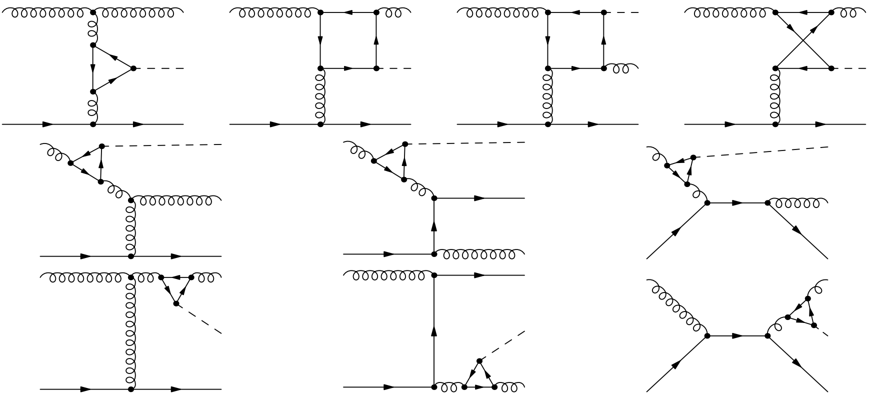
Higgs coupling factorises:



$$V_H^{\mu\nu}(q_i, q_{i+1}) = \frac{\alpha_s m^2}{\pi v}\left[g^{\mu\nu} T_1(q_i, q_{i+1}) - q_{i+1}^{\mu} q_i^{\nu} T_2(q_i, q_{i+1})\right]$$
$$\xrightarrow{m\to\infty} \frac{\alpha_s}{3\pi v}\left(g^{\mu\nu} q_i q_{i+1} - q_{i+1}^{\mu} q_i^{\nu}\right)$$

with form factors T_1 and T_2.

Finite quark mass effects

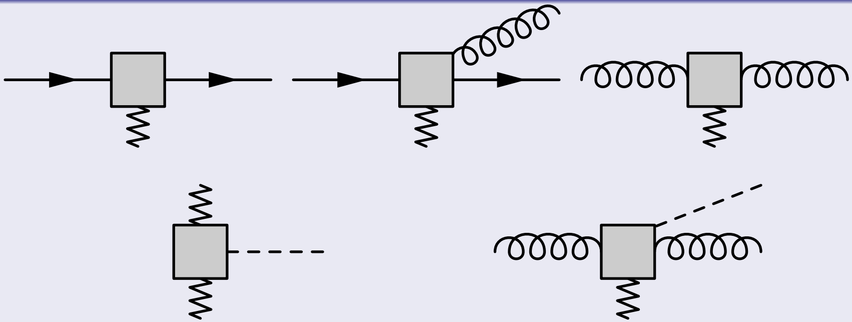


$\Rightarrow$ Rapidity ordering matters, e.g. Higgs boson outside or inside jets

Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '03

Finite quark mass effects

Building pieces in HEJ (currents) arxiv:1812.08072



Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '03

Matching & merging with Fixed Order

$$
\begin{aligned}
\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2} \sum_m \prod_{j=1}^{m} & \left(\int_{p_{j\perp}^B=0}^{p_{j\perp}^B=\infty} \frac{\mathrm{d}^2\mathbf{p}_{j\perp}^B}{(2\pi)^3} \int \frac{\mathrm{d}y_j^B}{2} \right) (2\pi)^4 \ \delta^{(2)}\left(\sum_{k=1}^{m} \mathbf{p}_{k\perp}^B \right) \\
& \cdot \ x_a^B \ f_a(x_a^B, Q_a^B) \ x_b^B \ f_b(x_b^B, Q_b^B) \ \frac{\overline{|\mathcal{M}^B|}^2}{(\hat{s}^B)^2} \\
& \cdot \overline{|\mathcal{M}_{\text{HEJ}}^{tree}|}^{-2} \ (2\pi)^{-4+3m} \ 2^m \frac{(\hat{s}^B)^2}{x_a^B \ f_{a,f_1}(x_a^B, Q_a^B) \ x_b^B \ f_{b,f_2}(x_b^B, Q_b^B)} \\
& \cdot \sum_{n=2}^{\infty} \int_{p_{1\perp}=.9p_{j,\perp}}^{p_{1\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{1\perp}}{(2\pi)^3} \int_{p_{n\perp}=.9p_{j,\perp}}^{p_{n\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{n\perp}}{(2\pi)^3} \prod_{i=2}^{n-1} \int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{i\perp}}{(2\pi)^3} \ (2\pi)^4 \ \delta^{(2)}\left(\sum_{k=1}^{n} \mathbf{p}_{k\perp} \right) \\
& \cdot \ \mathbf{T}_y \prod_{i=1}^{n} \left(\int \frac{\mathrm{d}y_i}{2} \right) \mathcal{O}_{mj}^e \ \left(\prod_{l=1}^{m-1} \delta^{(2)}(\mathbf{p}_{\mathcal{J}_l\perp}^B - \mathbf{j}_{l\perp}) \right) \left(\prod_{l=1}^{m} \delta(y_{\mathcal{J}_l}^B - y_{\mathcal{J}_l}) \right) \mathcal{O}_{2j}(\{p_i\}) \\
& \cdot x_a f_{a,f_1}(x_a, Q_a) \ x_b f_{b,f_2}(x_b, Q_b) \ \frac{\overline{|\mathcal{M}_{\text{HEJ}}^{f_1 f_2 \to f_1 g \cdots g f_2}(\{p_i\})|}^2}{\hat{s}^2} .
\end{aligned}
$$

- Generate Fixed Order independently

$\Rightarrow$ computationally effective, merging limited by Fixed Order ($\sim$ 5 jets)

arxiv:1805.04446

Matching & merging with Fixed Order

$$\sigma_{2j}^{\mathrm{resum,match}} = \sum_{f_1,f_2} \sum_m \prod_{j=1}^{m} \left(\int_{p_{j\perp}^B=0}^{p_{j\perp}^B=\infty} \frac{\mathrm{d}^2\mathbf{p}_{j\perp}^B}{(2\pi)^3} \int \frac{\mathrm{d}y_j^B}{2} \right) (2\pi)^4\, \delta^{(2)}\!\left(\sum_{k=1}^{m} \mathbf{p}_{k\perp}^B\right) \cdot x_a^B\, f_a(x_a^B, Q_a^B)\, x_b^B\, f_b(x_b^B, Q_b^B)\, \frac{\overline{|\mathcal{M}^B|}^2}{(\hat{s}^B)^2}$$

Fixed Order

$$\cdot\, \overline{|\mathcal{M}_{\mathrm{HEJ}}^{tree}|}^{-2}\, (2\pi)^{-4+3m}\, 2^m\, \frac{(\hat{s}^B)^2}{x_a^B\, f_{a,f_1}(x_a^B, Q_a^B)\, x_b^B\, f_{b,f_2}(x_b^B, Q_b^B)}$$

Overlap

$$\cdot \sum_{n=2}^{\infty} \int_{p_{1\perp}=.9p_{j,\perp}}^{p_{1\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{1\perp}}{(2\pi)^3} \int_{p_{n\perp}=.9p_{j,\perp}}^{p_{n\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{n\perp}}{(2\pi)^3} \prod_{i=2}^{n-1} \int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty} \frac{\mathrm{d}^2\mathbf{p}_{i\perp}}{(2\pi)^3}\, (2\pi)^4\, \delta^{(2)}\!\left(\sum_{k=1}^{n} \mathbf{p}_{k\perp}\right)$$

$$\cdot\, \mathbf{T}_y \prod_{i=1}^{n} \left(\int \frac{\mathrm{d}y_i}{2} \right) \mathcal{O}_{mj}^{e} \left(\prod_{l=1}^{m-1} \delta^{(2)}(\mathbf{p}_{\mathcal{J}_l\perp}^B - \mathbf{j}_{l\perp}) \right) \left(\prod_{l=1}^{m} \delta(y_{\mathcal{J}_l}^B - y_{\mathcal{J}_l}) \right) \mathcal{O}_{2j}(\{p_i\})$$

$$\cdot\, x_a f_{a,f_1}(x_a, Q_a)\, x_b f_{b,f_2}(x_b, Q_b)\, \frac{\overline{|\mathcal{M}_{\mathrm{HEJ}}^{f_1 f_2 \to f_1 g \cdots g f_2}(\{p_i\})|}^2}{\hat{s}^2}.$$

HEJ

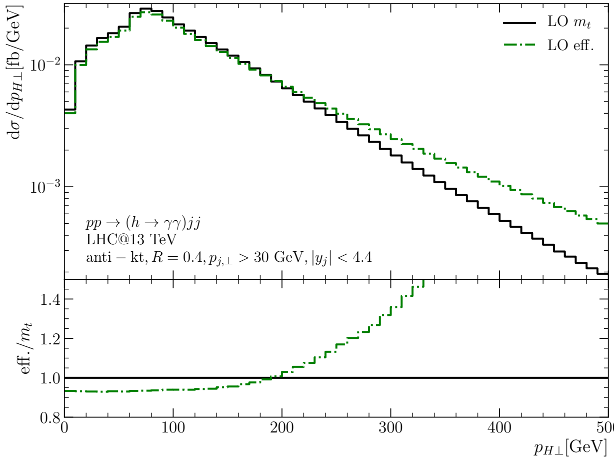
- Generate Fixed Order independently

$\Rightarrow$ computationally effective, merging limited by Fixed Order ($\sim$ 5 jets)

arxiv:1805.04446

Test setup at LO

Higgs $p_\perp$

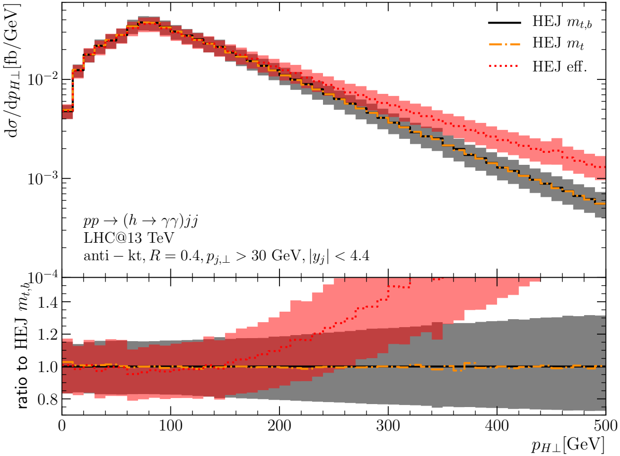


⇒ LO $m_t \to \infty$: -5% at 0 GeV, $+50\%$ at 350 GeV

⇒ "accidental" cancellation $\sigma_{FO}^{\text{eff}} \sim \sigma_{FO}^{m_t}$

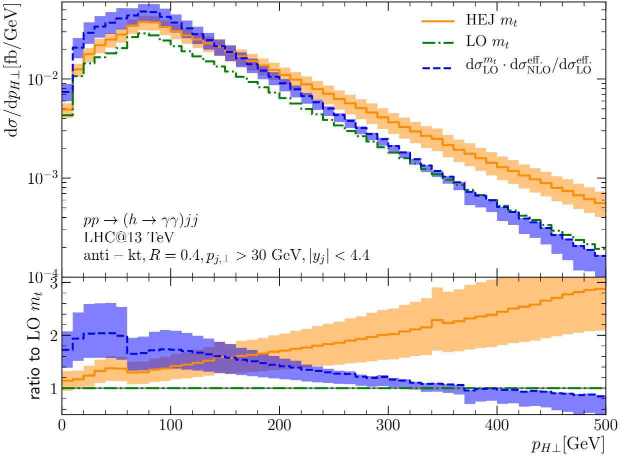
Higgs $p_\perp$

finite m_b



$\Rightarrow$ no visible effect from finite m_b

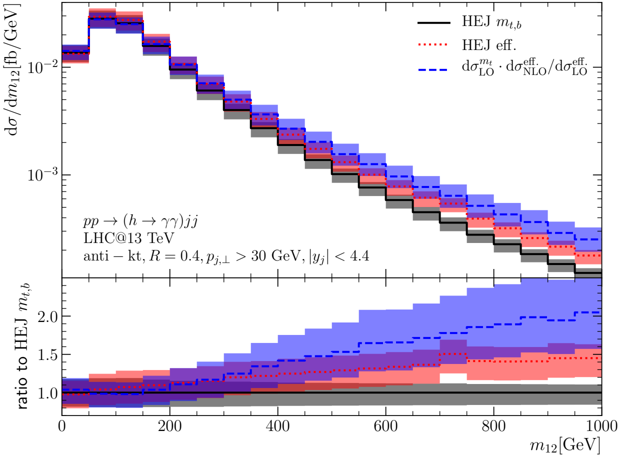
Higgs $p_\perp$



$\Rightarrow$ HEJ harder in $p_{H\perp}$ $\Rightarrow$ more sensitive to finite m_t effect

$\Rightarrow$ $\sigma_{\text{HEJ}}^{\text{eff}} \sim 1.1 \times \sigma_{\text{HEJ}}^{m_t}$

Invariant jet mass



⇒ After VBF-cuts: $\sigma^{m_t\to\infty}_{\mathrm{HEJ}} \approx 1.1 \cdot \sigma_{\mathrm{HEJ}} \approx 0.5 \cdot \sigma_{\mathrm{NLO}}$

⇒ Large difference between different theory calculations

Summary

- HEJ provides all-order resummation for large $\log(s/t) \sim \Delta y$
- VBF cuts: rapidity separation & large invariant mass

$\Rightarrow$ Cross section with HEJ resummation 50% *smaller* compared to NLO

- Finite top-mass

$\Rightarrow$ Stronger effect in HEJ

$\Rightarrow$ Cross section $\sim -10\%$ ($< 1\%$ from finite m_b)

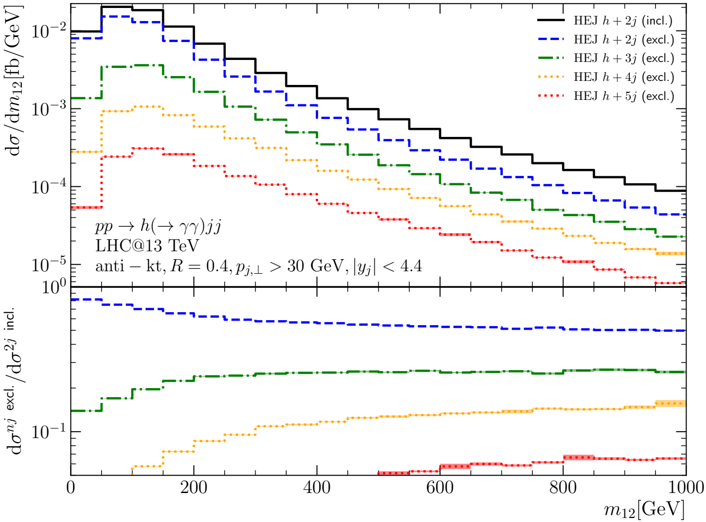
$\Rightarrow$ Increasing with $p_\perp$

- Public code, (library) documentation, docker, ...

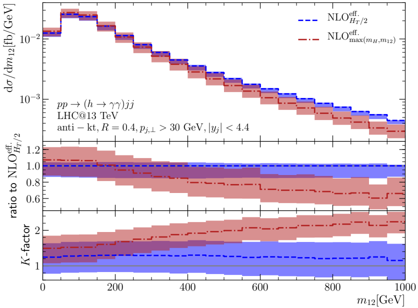
https://hej.web.cern.ch

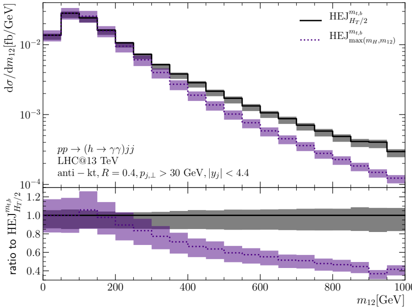
Backup slides

Contributions from higher Jets



Different scale choices

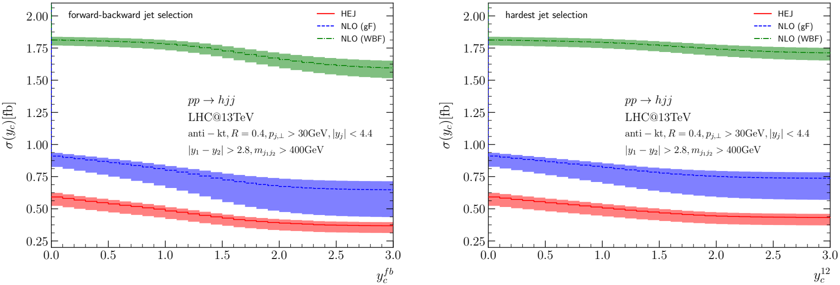




σ_{VBF}	$\mu = \max(m_H, m_{12})$	$\mu = H_T/2$	δ_μ
Fixed Order	$0.53^{+0.15}_{-0.13}$ fb	$0.82^{+0.02}_{-0.11}$ fb	+55%
HEJ	$0.23^{+0.02}_{-0.03}$ fb	$0.52^{+0.03}_{-0.08}$ fb	+26%
δ_{HEJ}	−57%	−36%	

Central jet veto

Veto event if jet inside $|y_j - y_0| \leq y_c$, $y_0 = \frac{y_{t_1} + y_{t_2}}{2}$
tagging jets: forward-backward (fb) or hardest (12)



- $20 - 30\%$ reduction of gF contribution
- WBF nearly constant up to $y_c \approx 1$

arxiv:1803.07977