High Energy effects for Higgs-boson plus Dijet production

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arxiv:1812.08072

IPPP, Durham

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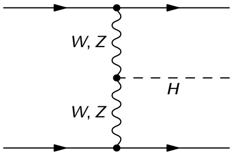
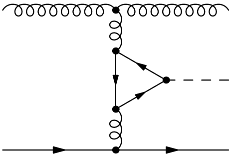
Higgs to gauge boson coupling

- Distinction between WBF and gF

$\Rightarrow$ Small quantum interference



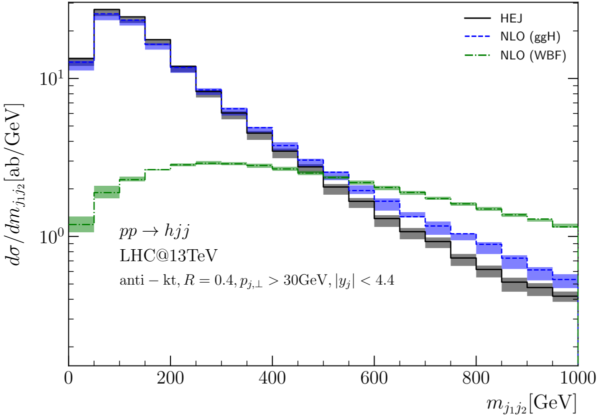


Coupling:	h to Z/W	top-loop
Add. emission:	on external quark	on t-channel gluon
Known Fixed Order:	NNLO	LO with finite m_t NLO with $m_t \to \infty$

$\Rightarrow$ experimental result still *work in progress*

Weak boson vs. Gluon fusion

Invariant jet mass



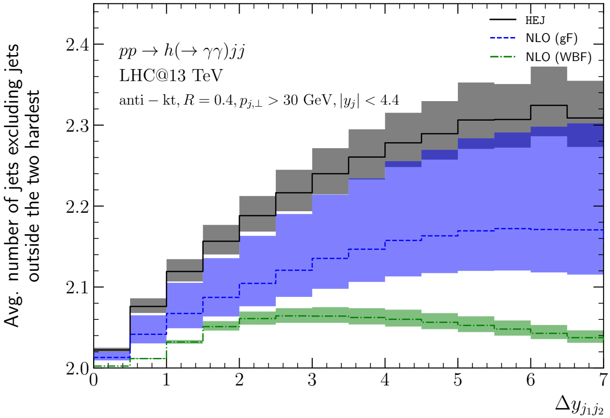
- *gF* dominated by initial gluon $\Rightarrow$ Peak at low m_{12}

$\Rightarrow$ *VBF-cut*: $m_{12} > 400$ GeV & $y_{j_1j_1} > 2.8$ $\Rightarrow$ High Energy Effects

arxiv:1803.07977

Weak boson vs. Gluon fusion

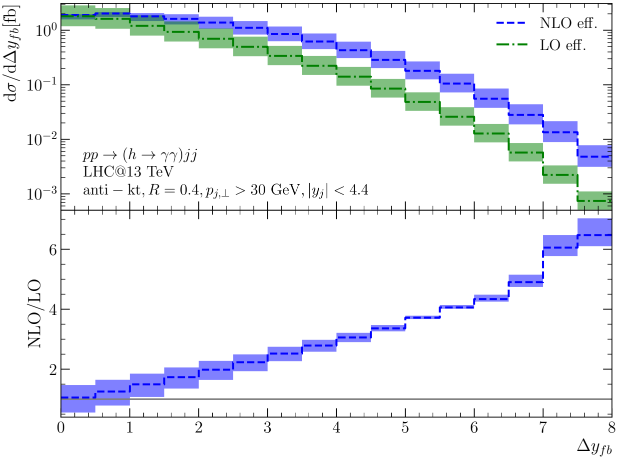
Rapidity separation



- *gF*: extra jets central in rapidity gap

⇒ NLO *k*-Factor: 1.6 (inclusive) & 2.2 (VBF-cuts)

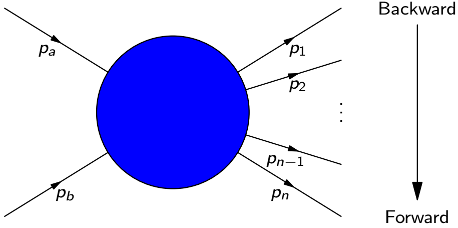
Breakdown of Fixed Order



- FO unstable for large Δy_{fb}

$\Rightarrow$ Large $\log(s/t) \sim \Delta y \Rightarrow$ Resummation: *High Energy Jets*

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. $\forall i, j$

$\Rightarrow$ Matrix Element becomes constant $\Rightarrow \sigma \propto \Delta y$

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

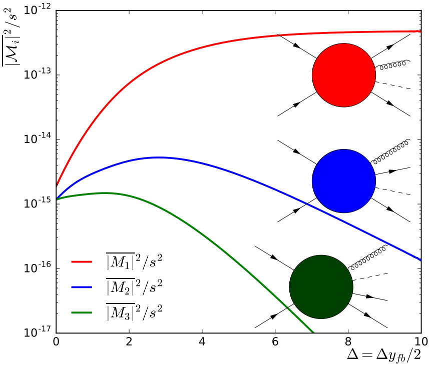
High Energy limit

Multi Regge theory

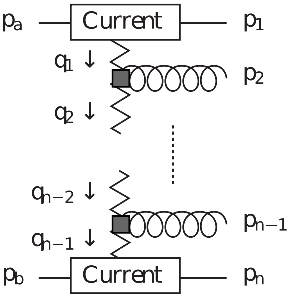
For $s_{ij} \to \infty$ and $t_i = \text{const.}$, with α_i spin of *exchange particle*:

$$\mathcal{M} \sim \; s_{1H}^{\alpha_1(t_1)} \; s_{2H}^{\alpha_2(t_2)} \cdot \gamma\left(t_1, t_2, s_{12}/(s_{1H}s_{2H})\right)$$

- Gluon exchange (FKL)
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1j_2}^2 s_{j_2H}^2 s_{j_3H}^2$
- Quark exchange (unordered)
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1j_2} s_{j_2H}^2 s_{j_3H}^2$
- Higgs outside quarks
  $\Rightarrow \; |\mathcal{M}|^2 \propto s_{j_1H} s_{j_2H} s_{j_2j_3}^2$



HEJ Matrix element

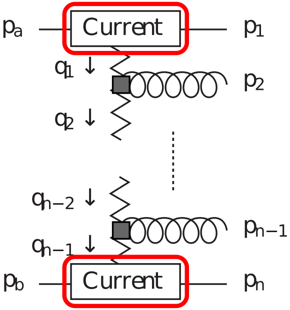


$$
= \frac{1}{4\,(N_C^2-1)}\ \left\|S_{f_a f_b \to f_1 f_n}\right\|^2
\cdot \left(g_s^2\ K_{f_1}\ \frac{1}{t_1}\right) \cdot \left(g_s^2\ K_{f_n}\ \frac{1}{t_{n-1}}\right)
\cdot \prod_{i=1}^{n-2} \left(\frac{-g_s^2\,C_A}{t_i t_{i+1}}\ V^{\mu}(q_i,q_{i+1})V_{\mu}(q_i,q_{i+1})\right)
\cdot \prod_{j=1}^{n-1}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

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

HEJ Matrix element



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

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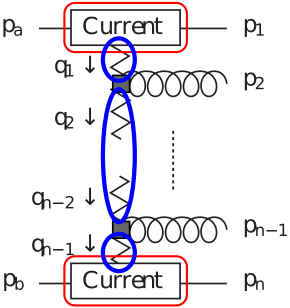

$$= \frac{1}{4\,(N_C^2-1)} \left\| S_{f_a f_b \to f_1 f_n} \right\|^2 \cdot \left(g_s^2\, K_{f_1}\, \frac{\mathbf{1}}{\mathbf{t_1}} \right) \cdot \left(g_s^2\, K_{f_n}\, \frac{\mathbf{1}}{\mathbf{t_{n-1}}} \right) \cdot \prod_{i=1}^{n-2} \left(\frac{-g_s^2 C_A}{\mathbf{t_i t_{i+1}}}\, V^\mu(q_i, q_{i+1})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

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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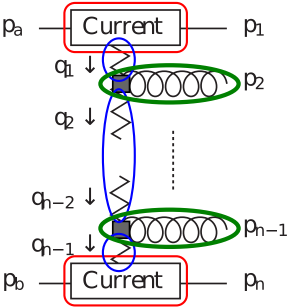
HEJ Matrix element



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

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

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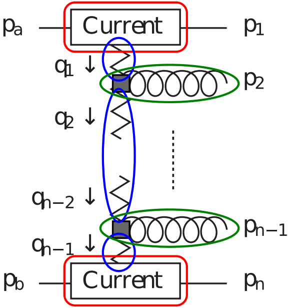

$$= \frac{1}{4\,(N_C^2-1)} \left\| S_{f_a f_b \to f_1 f_n} \right\|^2 \cdot \left(g_s^2\ K_{f_1}\ \frac{1}{t_1} \right) \cdot \left(g_s^2\ K_{f_n}\ \frac{1}{t_{n-1}} \right) \cdot \prod_{i=1}^{n-2} \left(\frac{-g_s^2\,C_A}{t_i t_{i+1}}\ V^{\mu}(q_i, q_{i+1}) V_{\mu}(q_i, q_{i+1}) \right) \cdot \prod_{j=1}^{n-1}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

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

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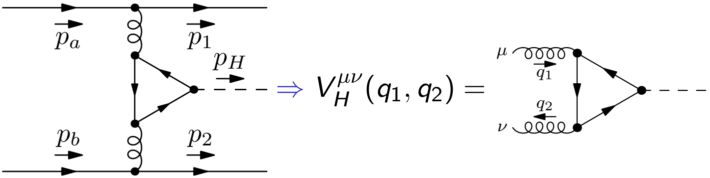
Finite quark mass effects

Simplest case: $qQ \to qHQ$

Higgs coupling factorises:

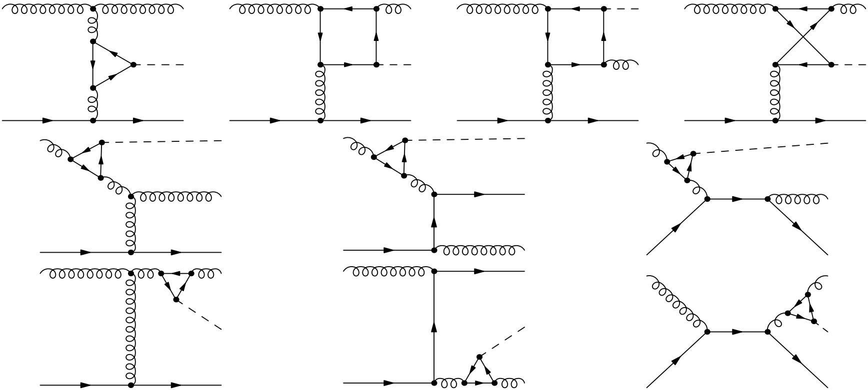


$$V_H^{\mu\nu}(q_1, q_2) =$$

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

with form factors T_1 and T_2.

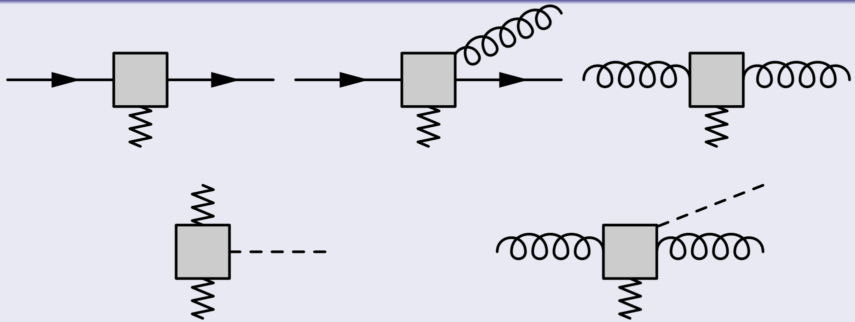
Finite quark mass effects



$\Rightarrow$ Position of Higgs boson matters

Finite quark mass effects

Building pieces in HEJ (currents)



⇒ Position of Higgs boson matters

Matching & merging with Fixed Order

$$\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2} \sum_m \prod_{j=1}^{m} \left(\int_{p_{j\perp}^B=0}^{p_{j\perp}^B=\infty} \frac{\mathrm{d}^2\mathbf{p}_{j\perp}^B}{(2\pi)^3} \int \frac{\mathrm{d}y_j^B}{2} \right) (2\pi)^4 \, \delta^{(2)}\left(\sum_{k=1}^{m} \mathbf{p}_{k\perp}^B\right)$$

$$\cdot \; x_a^B \; f_a(x_a^B, Q_a^B) \; x_b^B \; f_b(x_b^B, Q_b^B) \; \frac{\overline{|\mathcal{M}^B|}^2}{(\hat{s}^B)^2}$$

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

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

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

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

arxiv:1805.04446

Matching & merging with Fixed Order

$$\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2} \sum_m \prod_{j=1}^{m} \left(\int_{p_{j\perp}^B=0}^{p_{j\perp}^B=\infty} \frac{\mathrm{d}^2 \mathbf{p}_{j\perp}^B}{(2\pi)^3} \int \frac{\mathrm{d}y_j^B}{2} \right) (2\pi)^4 \, \delta^{(2)}\left(\sum_{k=1}^{m} \mathbf{p}_{k\perp}^B \right)$$

$$\cdot \; x_a^B \; f_a(x_a^B, Q_a^B) \; x_b^B \; f_b(x_b^B, Q_b^B) \; \frac{\overline{|\mathcal{M}^B|}^2}{(\hat{s}^B)^2}$$

Fixed Order

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

Overlap

HEJ

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

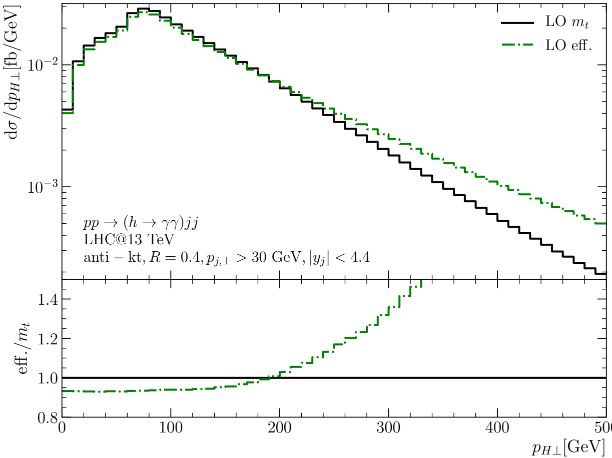
$$\cdot \; \mathbf{T}_y \prod_{i=1}^{n} \left(\int \frac{\mathrm{d}y_i}{2} \right) \mathcal{O}_{mj}^{e} \; \left(\prod_{l=1}^{m-1} \delta^{(2)}(\mathbf{p}_{\mathcal{J}_l\perp}^B - \mathbf{j}_{l\perp}) \right) \left(\prod_{l=1}^{m} \delta(y_{\mathcal{J}_l}^B - y_{\mathcal{J}_l}) \right) \mathcal{O}_{2j}(\{p_i\})$$

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

arxiv:1805.04446

Test setup at LO

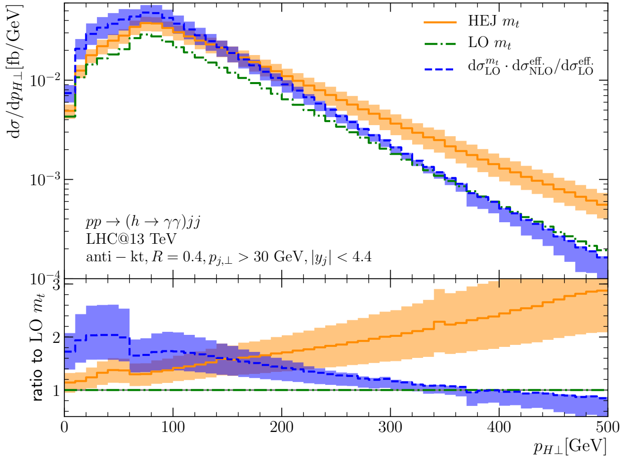
Higgs $p_\perp$



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

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

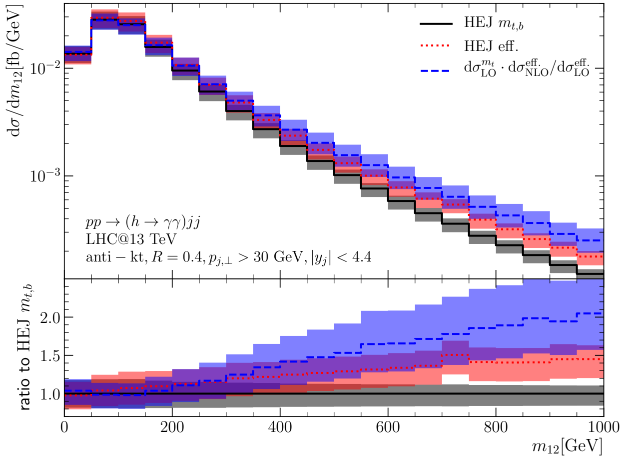
Higgs $p_\perp$



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

⇒ $\sigma^{\text{eff}}_{\text{HEJ}} \sim 1.1 \times \sigma^{m_t}_{\text{HEJ}}$

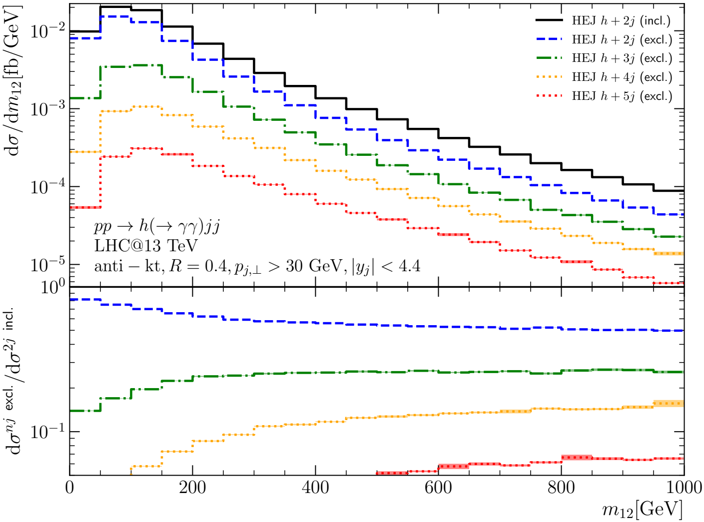
Invariant jet mass



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

⇒ Large difference between different theory calculations

Contributions from higher Jets



Summary

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

$\Rightarrow$ cross section of gF 50% *smaller* in HEJ compared to NLO

- Finite top-mass

$\Rightarrow$ Included within HEJ-framework

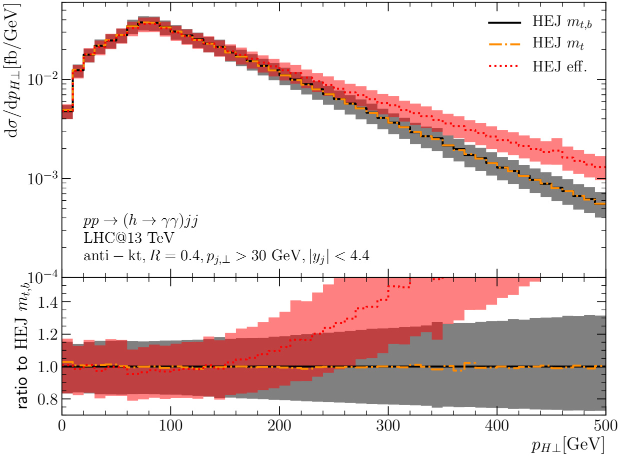
$\Rightarrow$ Correction on cross section $\sim -10\%$ ($< 1\%$ from finite m_b)

$\Rightarrow$ More for $p_\perp$ bases observables

Backup slides

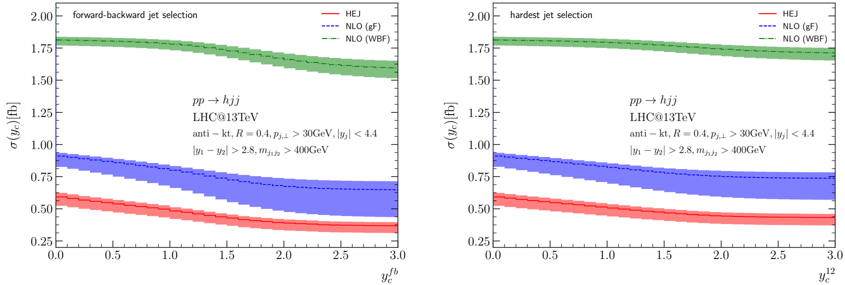
Higgs $p_\perp$

finite m_b



$\Rightarrow$ no visible effect from finite m_b

Veto event if jet inside $\left|y_j - y_0\right| \leq y_c$, $y_0 = \frac{y_{t_1} + y_{t_2}}{2}$
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