Higgs Boson Plus Dijets: Predictions for Large M_{jj}

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QCD at High Energy

- At LHC, events with large numbers of jets (e.g. 4, 5, 6) are much more common: many jets come with many scales

- Stability associated with NLO fails in difficult regions of phase space

- Extra power of α_s compensated by large real-emission phase space and large logarithms - **especially at 13 TeV, 100 TeV…**

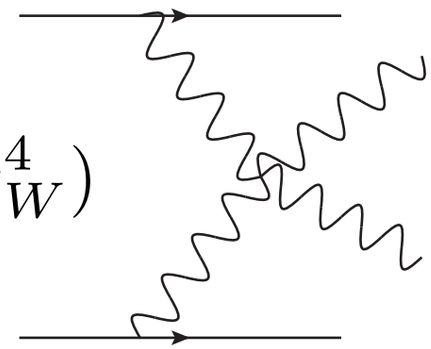
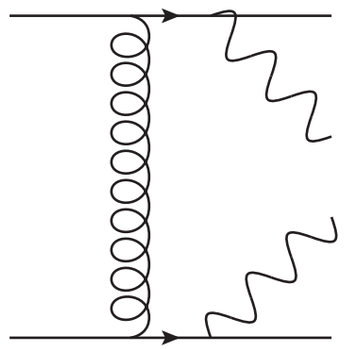
- Large rapidity separations or large invariant mass enhance (multi-)jet production (e.g. VBF and VBS)

Higgs boson analyses and searches for new physics put us right into the most difficult regions

Vector Boson Scattering

Vector Boson Scattering (VBS) sensitive probe of EWSB

Example: $pp \to W^+W^+jj$ proceeds through various diagrams including

$\mathrm{EW} = O(\alpha_W^4)$  +...  $\mathrm{QCD} = O(\alpha_W^2 \alpha_s^2)$

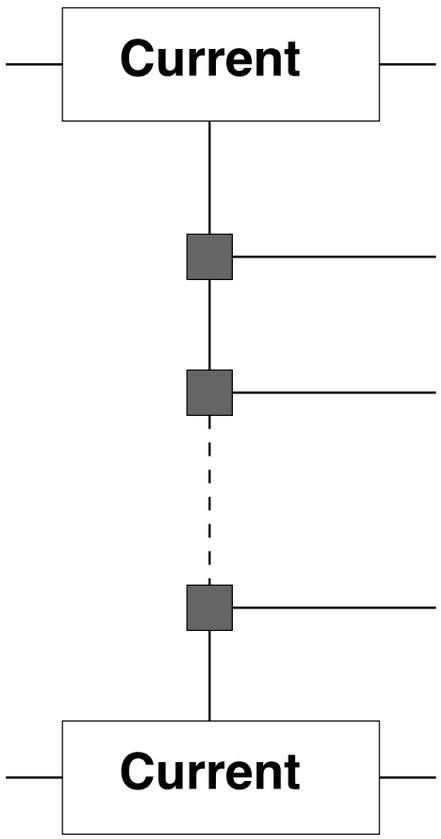
We would like to separate the EW and QCD channels, justified by assessing interference between the two to be small **Ballestrero et al arXiv:1803.07943**

To isolate EW component, typically apply VBS cuts of large rapidity and/or large invariant mass on the jets.

This is very similar to the setup/cuts applied in $pp \to Hjj$

This talk: Describe new results of the QCD (GF) component indicating importance of log corrections at all orders in α_s **Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072**

High Energy Jets (HEJ)



Amplitudes simplify in the high energy limit:

$$s_{ij} \to \infty, \quad p_{\perp,i} \text{ finite}, \quad i,j = 1,\ldots,n$$

Applies to loop diagrams too, and generates leading logs in $\hat{s}/p_\perp^2$

Can use this simpler structure to make an efficient event generator for arbitrary numbers of quarks/gluons.

Implemented for $\geq 2j,\ H+ \geq 2j,$
$W(\to \ell\nu)+ \geq 2j,\ Z(\to \ell\bar{\ell})+ \geq 2j$

HEJ2 event generator: http://hej.web.cern.ch

Andersen, Hapola, Heil, Maier & JMS arXiv:1902.08430

Main Equations

Squared Matrix Element

$$\overline{\left|\mathcal{M}^{\text{reg}}_{\text{HEJ}}(\{p_i\})\right|}^2 = \frac{1}{4\ (N_C^2-1)}\ \|S_{f_1 f_2\to f_1 f_2}\|^2$$
$$\cdot\ \left(g^2\ K_{f_1}\ \frac{1}{t_1}\right)\cdot\ \left(g^2\ K_{f_2}\ \frac{1}{t_{n-1}}\right)$$
$$\cdot\prod_{i=1}^{n-2}\left(g^2 C_A\ \left(\frac{-1}{t_i t_{i+1}}V^{\mu}(q_i,q_{i+1})V_{\mu}(q_i,q_{i+1})-\frac{4}{\mathbf{p}_i^2}\ \theta\left(\mathbf{p}_i^2<\lambda^2\right)\right)\right)$$
$$\cdot\prod_{j=1}^{n-1}\exp\left[\omega^0(q_j,\lambda)(y_j-y_{j+1})\right],$$

Cross Section

$$\sigma_{2j}^{\text{resum,match}} = \sum_{f_1,f_2}\sum_{n=2}^{\infty}\prod_{i=1}^{n}\left(\int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty}\frac{\mathrm{d}^2\mathbf{p}_{i\perp}}{(2\pi)^3}\int\frac{\mathrm{d}y_i}{2}\right)\ \frac{\overline{\left|\mathcal{M}^{f_1 f_2\to f_1 g\cdots g f_2}_{\text{HEJ}}(\{p_i\})\right|}^2}{\hat{s}^2}$$
$$\times\ \sum_m \mathcal{O}^e_{mj}(\{p_i\})\ w_{m-\text{jet}}$$
$$\times\quad x_a f_{A,f_1}(x_a,Q_a)\ x_2 f_{B,f_2}(x_b,Q_b)\ (2\pi)^4\ \delta^2\left(\sum_{i=1}^{n}\mathbf{p}_{i\perp}\right)\ \mathcal{O}_{2j}(\{p_i\})$$

$$\sigma_{2j} = \sigma_{2j}^{\text{resum,match}} + \sum_n \sigma_{nj}^{\text{non-FKL}}$$

Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

Main Equations

$$\overline{\left|\mathcal{M}^{\text{reg}}_{\text{HEJ}}(\{p_i\})\right|}^2 = \frac{1}{4\ (N_C^2-1)}\ \|S_{f_1 f_2\to f_1 f_2}\|^2$$

Skeleton/Born Process

$$\cdot\ \left(g^2\ K_{f_1}\ \frac{1}{t_1}\right)\cdot\left(g^2\ K_{f_2}\ \frac{1}{t_{n-1}}\right)$$

$$\cdot\prod_{i=1}^{n-2}\left(g^2 C_A\left(\frac{-1}{t_i t_{i+1}}V^{\mu}(q_i,q_{i+1})V_{\mu}(q_i,q_{i+1})-\frac{4}{\mathbf{p}_i^2}\ \theta\left(\mathbf{p}_i^2<\lambda^2\right)\right)\right)$$

Resolved Real Emissions

$$\cdot\prod_{j=1}^{n-1}\exp\left[\omega^0(q_j,\lambda)(y_j-y_{j+1})\right]$$

Virtual + Unresolved Real (finite)

$$\sigma^{\text{resum,match}}_{2j} = \sum_{f_1,f_2}\sum_{n=2}^{\infty}\prod_{i=1}^{n}\left(\int_{p_{i\perp}=\lambda}^{p_{i\perp}=\infty}\frac{\mathrm{d}^2\mathbf{p}_{i\perp}}{(2\pi)^3}\int\frac{\mathrm{d}y_i}{2}\right)\frac{\overline{\left|\mathcal{M}^{f_1 f_2\to f_1 g\cdots g f_2}_{\text{HEJ}}(\{p_i\})\right|}^2}{\hat{s}^2}$$

Merging

$$\times\ \sum_m \mathcal{O}^e_{mj}(\{p_i\})\ w_{m-\text{jet}}$$

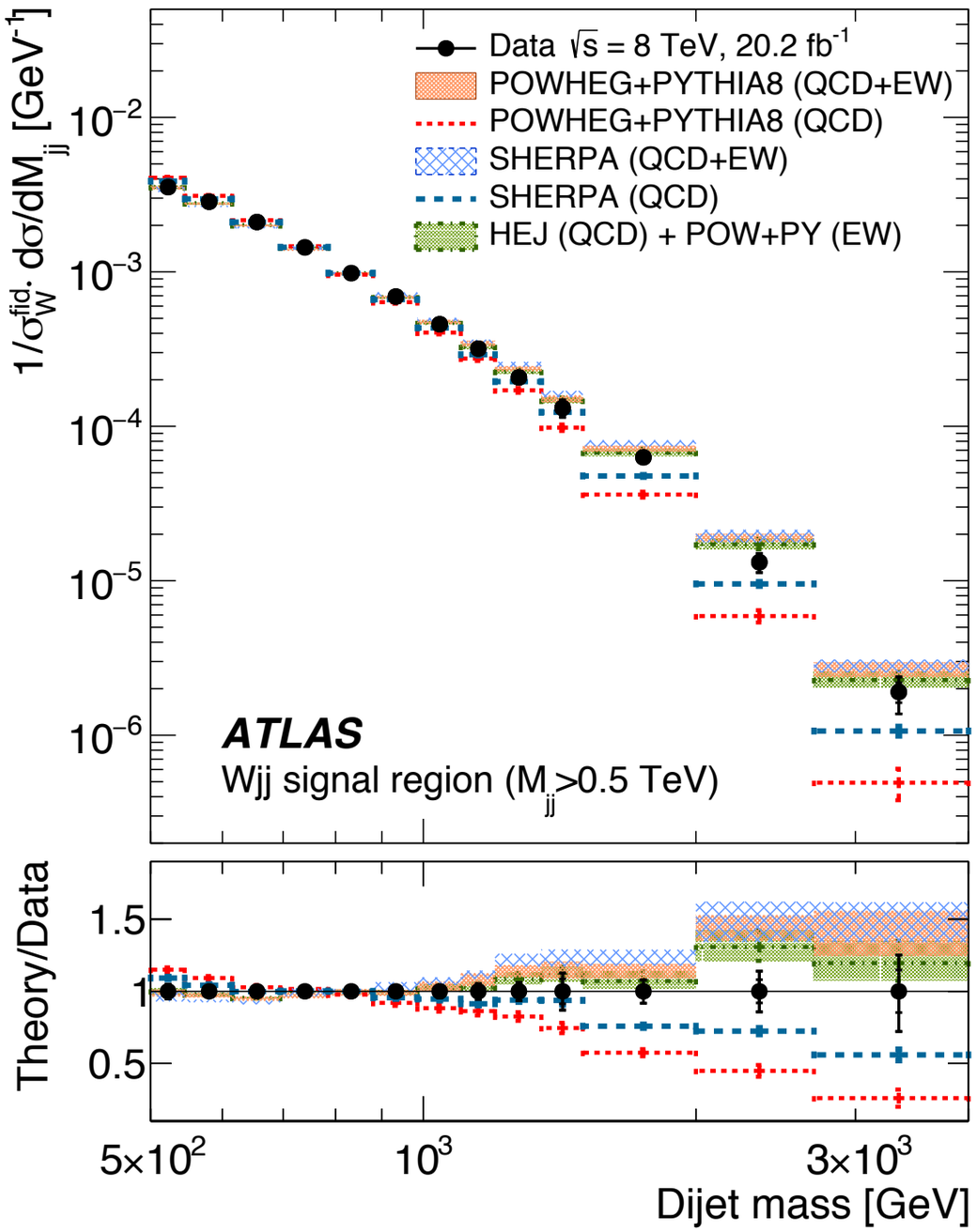
$$\times\quad x_a f_{A,f_1}(x_a,Q_a)\ x_2 f_{B,f_2}(x_b,Q_b)\ (2\pi)^4\ \delta^2\left(\sum_{i=1}^{n}\mathbf{p}_{i\perp}\right)\ \mathcal{O}_{2j}(\{p_i\})$$

$$\sigma_{2j} = \sigma^{\text{resum,match}}_{2j} + \sum_n \sigma^{\text{non-FKL}}_{nj}$$

Matching

Andersen & JMS arXiv:0908.2786, 0910.5113, 1101.5394

2017 ATLAS W+2j

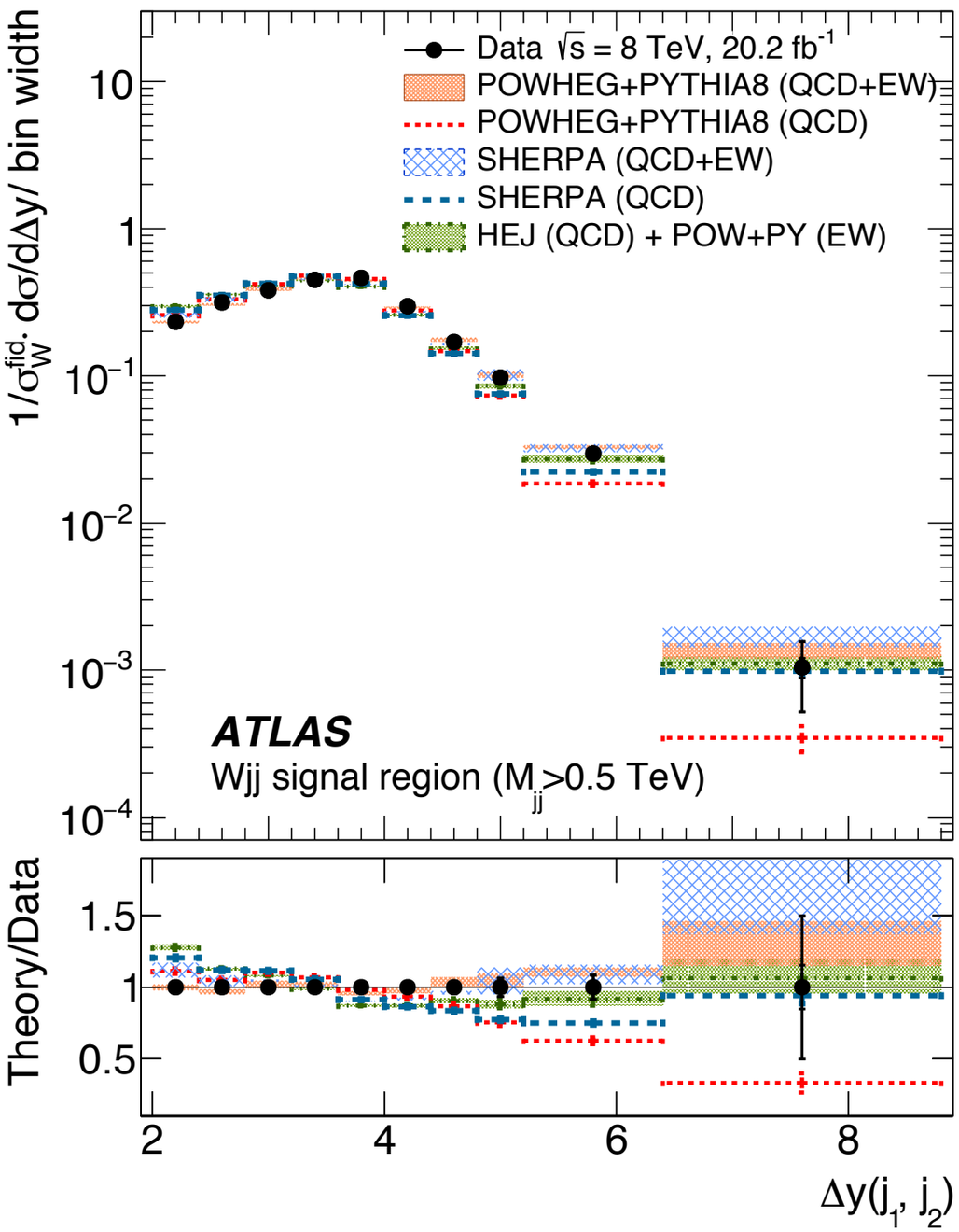


W+2j study to investigate separation of QCD/EW contributions compared to NLO+PS (Powheg/Sherpa) and HEJ+EW from Powheg

- QCD contribution decreases at large dijet mass, but remains significant
- NLO+PS slightly overshoot, and increasing

ATLAS arXiv:1703.04362

2017 ATLAS W+2j



ATLAS arXiv:1703.04362

- Similar conclusions when plotted as a function of rapidity separation of hardest jets

- Similarity between Powheg and HEJ also seen in earlier jet studies, despite very different construction

for discussion see Andersen et al arXiv:1202.1475

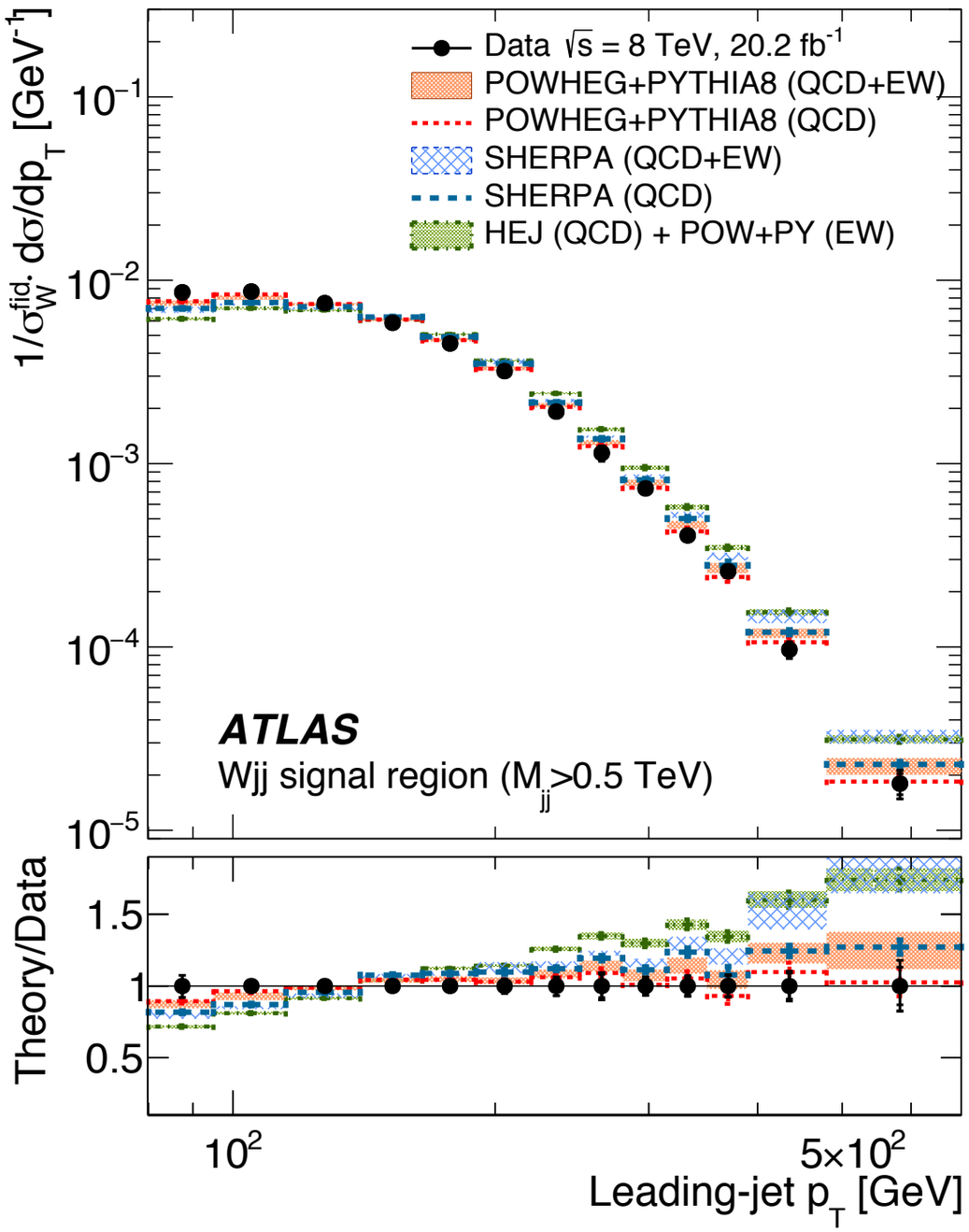
2017 ATLAS W+2j

- Different picture when plotted vs leading-jet p_T

- QCD contribution is no longer suppressed compared to EW

- No systematic evolution in p_T in HEJ, and in regions of large p_T the description is poorer

- Adding formerly subleading contributions to HEJ will help here

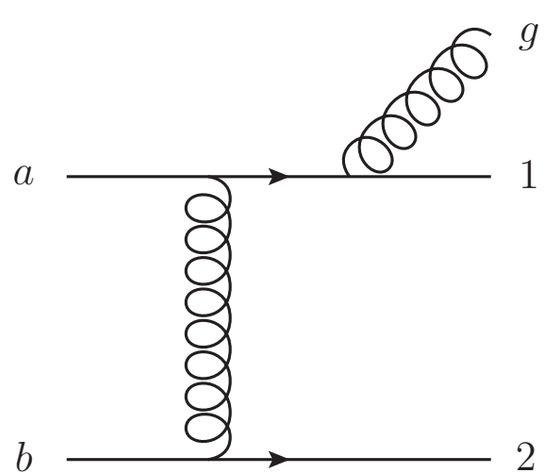


ATLAS arXiv:1703.04362

HEJ Beyond LL

- Have found HEJ description worsens in regions where matching component is more significant, e.g. large momentum
- Description already leading-log in inclusive (X+)dijets, but is <u>not</u> leading-log for all subprocesses
- Adding these will move more of the cross section into part subject to resummation

Example: allow a gluon emission outside in rapidity of a quark



+ …

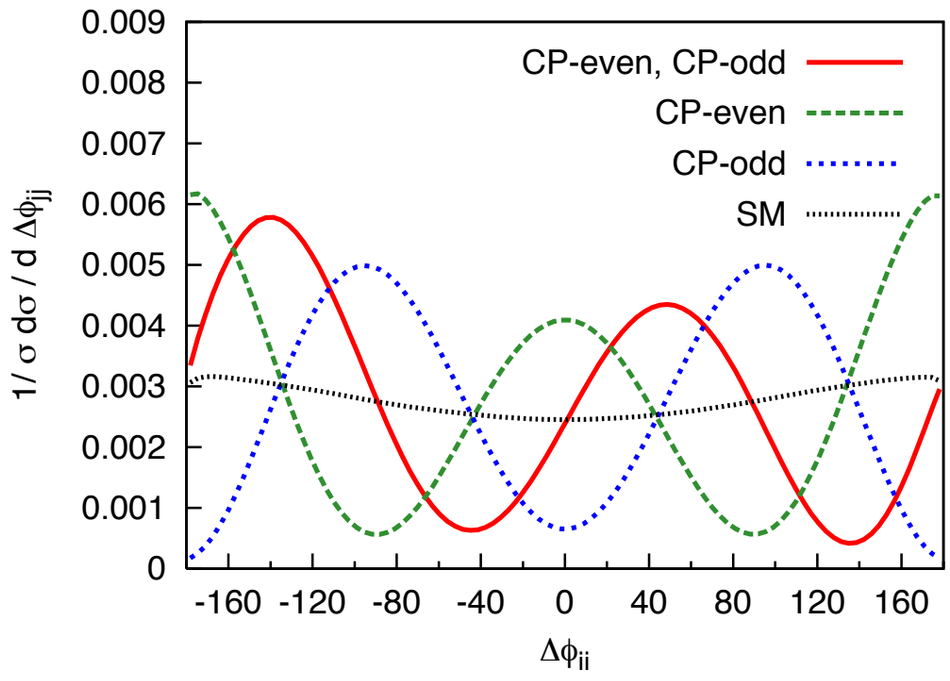
- These are included in all HEJ H+2j predictions
- They are formally next-to-leading-log, but are still numerically significant

Higgs Boson + Dijets

Higgs boson looks like SM so far, but critical to check CP structure of couplings to bosons

Azimuthal angle between the dijets is sensitive to this

Figy et al **hep-ph/0609075**



Use distinctive event shape to separate channels with “VBF cuts”

$$\text{e.g.} \quad \Delta y_{jj} > 2.8, \; m_{jj} > 400 \text{ GeV}$$

BUT this precisely enhances higher orders in pert. expansion

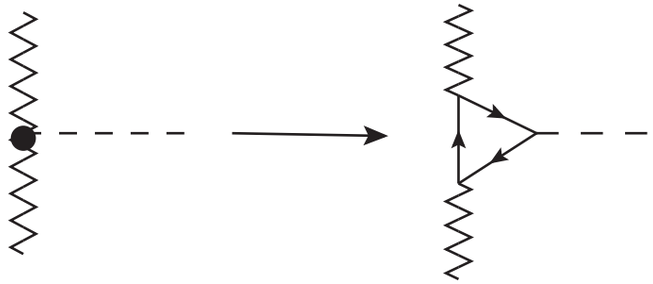
Finite Quark Masses in H+2j

Fixed-order stalled for full quark mass effects because LO = 1-loop.
LO results only for 2 and 3 jets (no NLO)

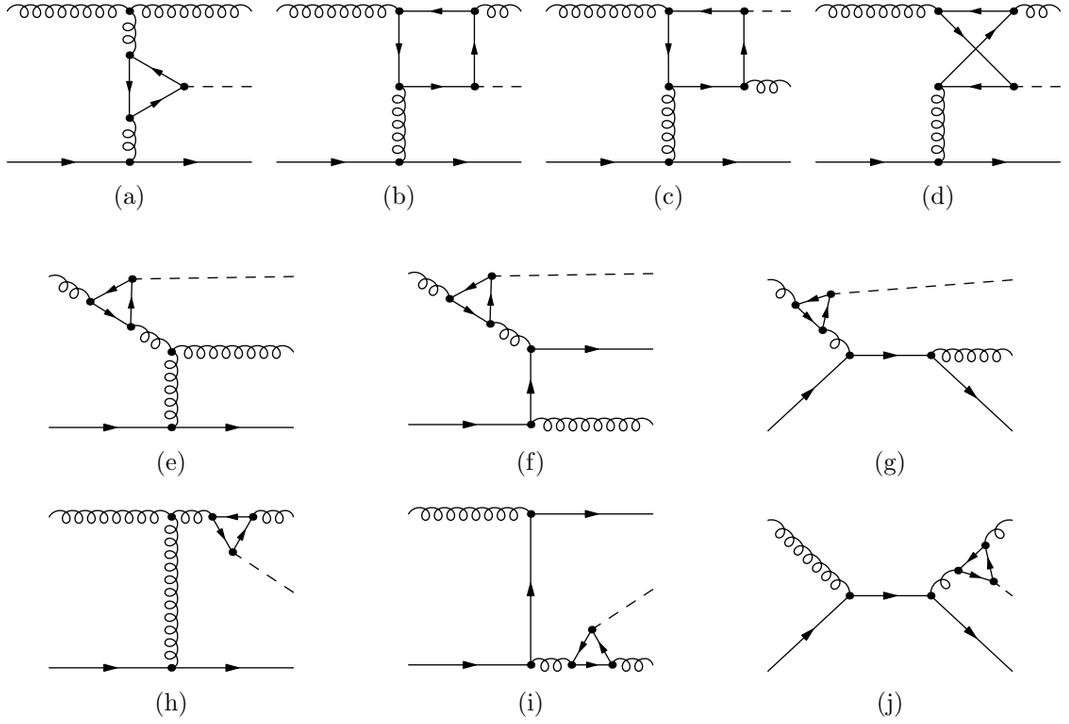
Del Duca et al hep-ph/0105129, hep-ph/0108030
Greiner et al arXiv:1608.01195

In HEJ, factorised structure removes complexity from increasing number of jets

Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072



Straight-forward
e.g. $qQ \to qHQ$



External Higgs more involved but calculated

Finite Quark Masses in HEJ

HEJ can include finite quark mass and loop propagator effects for *any* number of jets

Performed at amplitude level so we include mass effects from top quark, bottom quark *and* the interference between the two

Fixed-order matching performed to highest-available accuracy

Here use Sherpa and OpenLoops

Gleisberg et al arXiv:0811.4622; Cascioli, Maierhöfer, Pozzorini arXiv:1111.5206

Highest available =

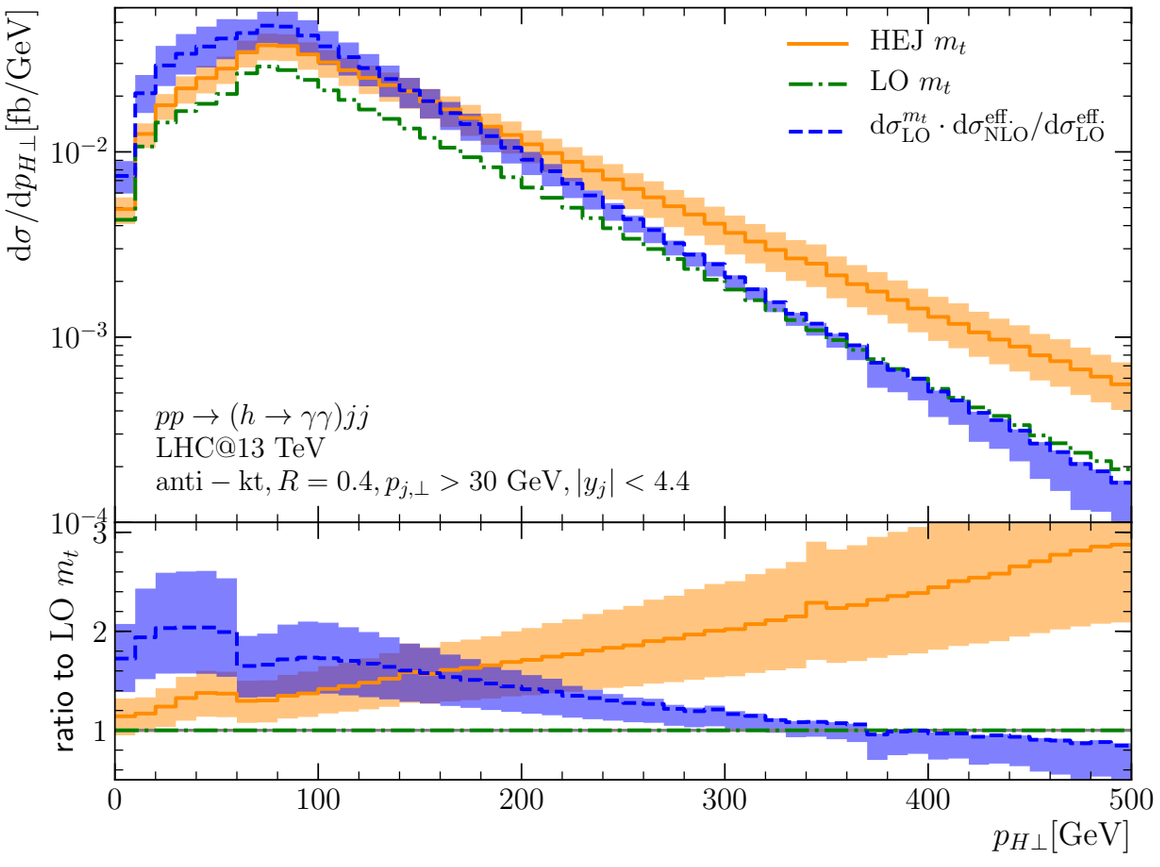
finite m_t	$H+2j$	at LO ($3j$ results exist, but not usable)
infinite m_Q	$H+2j$	at NLO
	$H+5j$	at LO

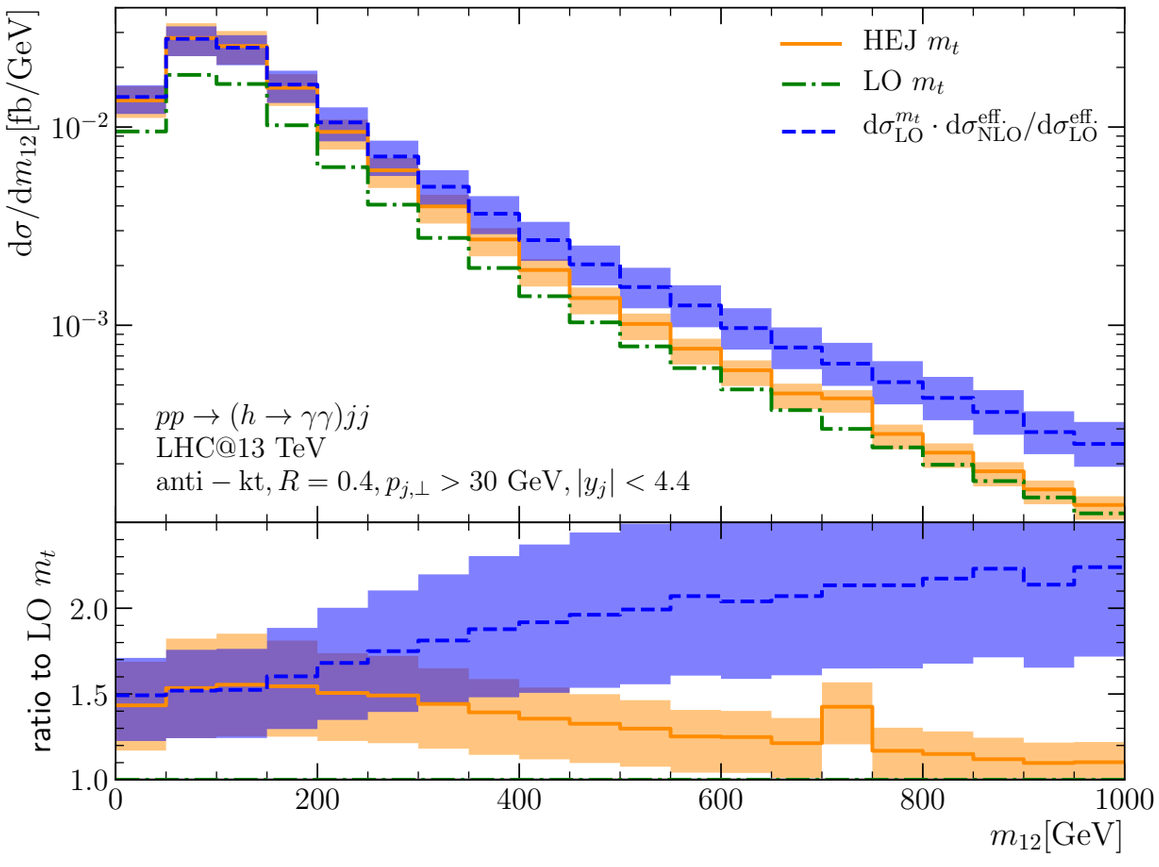
All predictions shown with $\mu_F = \mu_R = \max(m_H, m_{12})$ with indt variations by 1/2,2

Finite Quark Mass Results

First probe the impact of higher orders in α_s **Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072**

HEJ here temporarily without m_b





NLO K-factors clearly not flat, very scale-dependent, all choices have problems

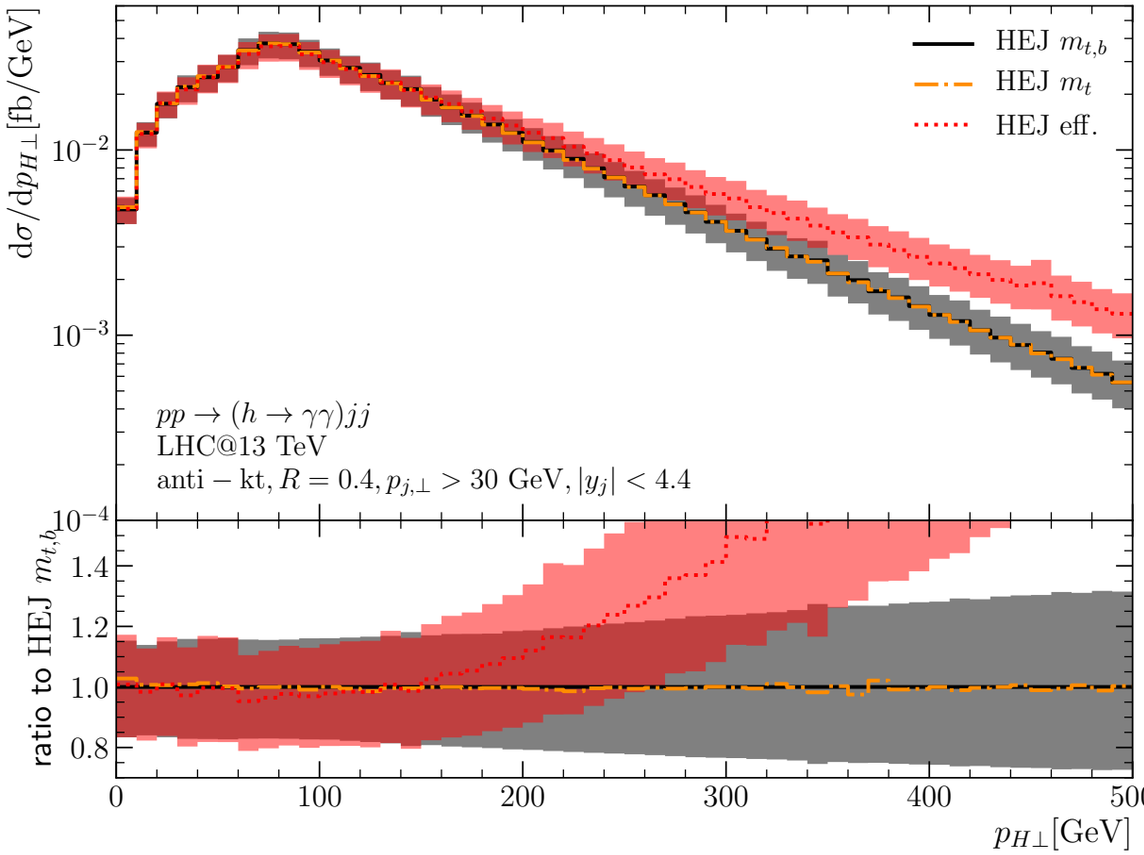
HEJ harder $p_{H\perp}$ spectrum

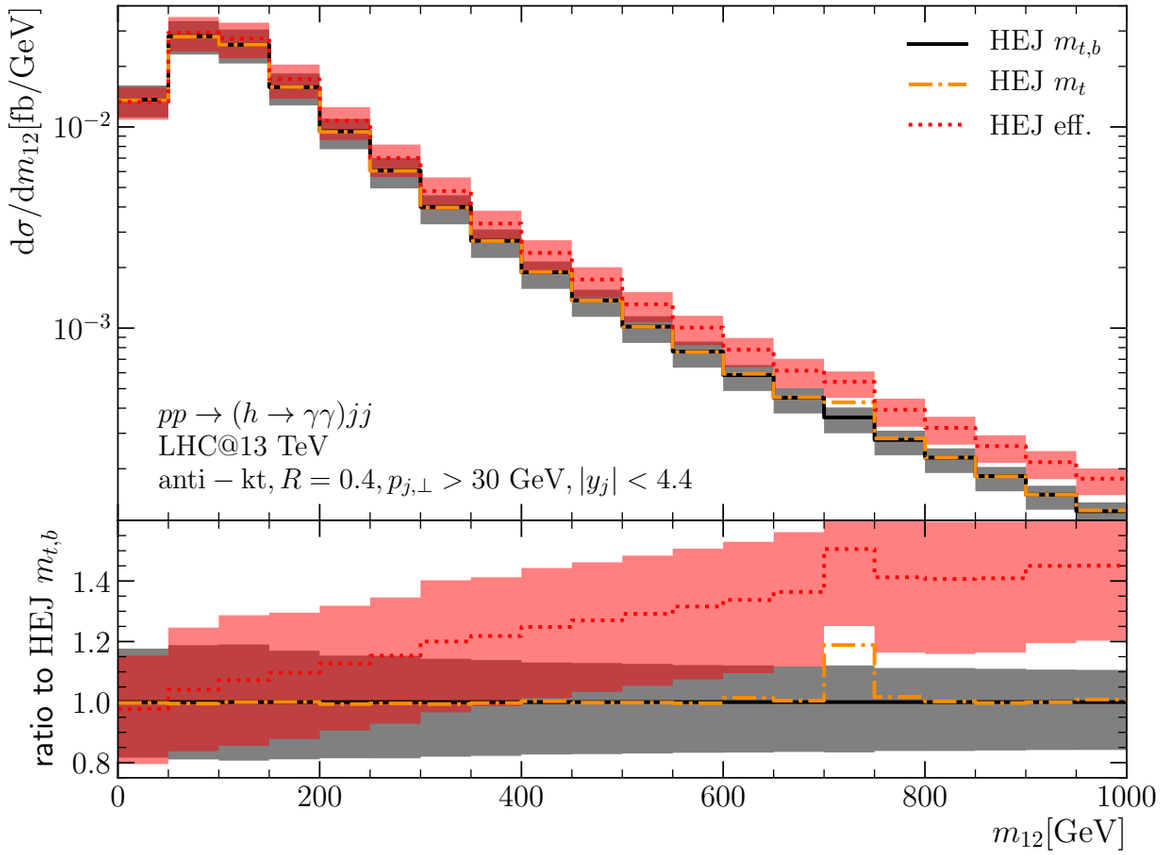
HEJ much steeper drop with m_{12}

Finite Quark Mass Results

Now probe the impact of quark masses

Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072





Importance of finite quark mass increases with $p_{H\perp}$

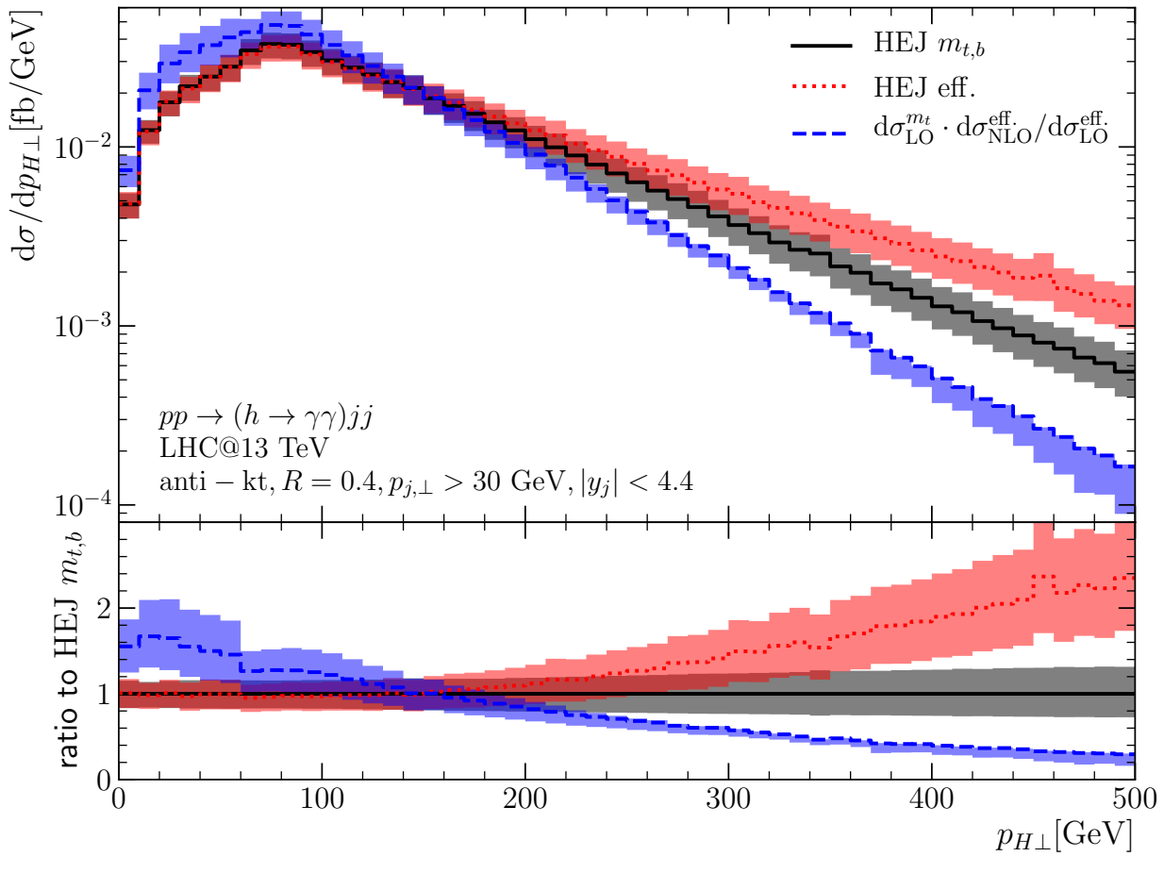
Relatively small impact of m_b, finite m_t lowers predictions at large m_{12}

Therefore finite quark mass effects make VBF cuts more effective

Finite Quark Mass Results

Full HEJ prediction vs “best” fixed-order

Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072



Finite quark mass effects - significant reduction (up to 50%)

HEJ $p_{H\perp}$ spectrum much harder - increases sensitivity to loop momenta

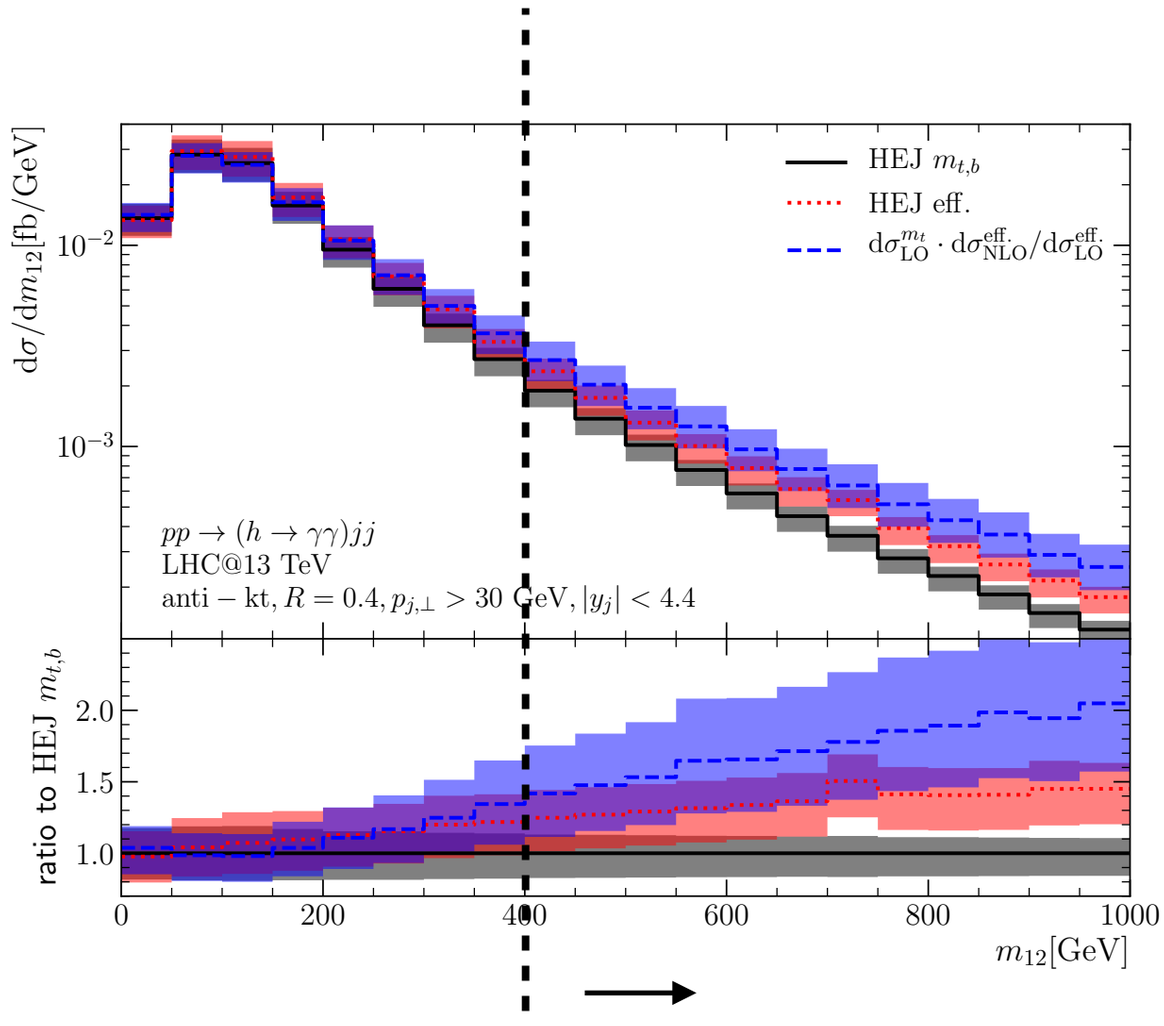
Finite Quark Mass Results

Full HEJ prediction vs “best” fixed-order

Andersen, Cockburn, Heil, Maier & JMS arXiv:1812.08072

- Resummation alone reduces cross section at large values
- Also gives harder $p_{H\perp}$ spectrum which enhances finite quark mass/ loop effects which reduce x-section in VBF cuts by *further* 11%

Prediction	xs after VBF cuts
Fixed order	9%
HEJ	4%



Typical VBF cut

Impact of VBF Cuts

- Same effect seen in effective theory (ie not induced by the finite quark mass effect).
- See e.g. LHC HIGGS XS WG 2013

	Dijet selection	WBF selection	Effect of WBF cut
MCFM	1.73 pb	0.192 pb	0.111
HEJ	2.20 pb	0.127 pb	0.058
POWHEGBOX	2.41 pb	0.237 pb	0.098
SHERPA	2.38 pb	0.225 pb	0.094

LHC HIGGS XS WG Report (table 32, pg 118) arXiv:1307.1347

- The all-order high-energy logs have a greater impact within WBF cuts, enhanced by large m_{jj} and large Δy_{jj}
- Expect the same significant impact to be induced in VBS. HEJ implementation in progress.

Conclusions

- Huge phase space for extra hard jets, and for enhancements of higher-order coefficients which damage convergence of fixed-order expansion

- Sizable effects and implications for Higgs VBF analyses

- HEJ allows inclusion of finite quark mass effects combined with all order predictions:
  Find VBF cuts more severe than fixed-order estimates

- Expect similar large impact in VBS (work in progress)

- Public code, documentation, sample analyses, …

https://hej.web.cern.ch