Progress in Describing Processes at Large m_{jj}

Developments with HEJ during MCnetITN3

High **E**nergy **J**ets/Jeppe R. Andersen

December 8, 2021

Overview of Talk

1. The problem of the $\alpha_s^2\alpha_W$-contribution to $\{Z/W\}$JJ, $\alpha_s^2\alpha_W^2$-contribution to $\{W^\pm\}^2$JJ, $\alpha_s^4 y_t^2$ HJJ and dijets at large m_{JJ}
2. Description within **H**igh **E**nergy **J**ets
3. Progress during the MCnetITN3 period:
   - a Sub-leading logarithms
   - b Matching to higher multiplicity and to NLO
   - c Match and merging with shower

Logarithmic Corrections at large m_{jj}

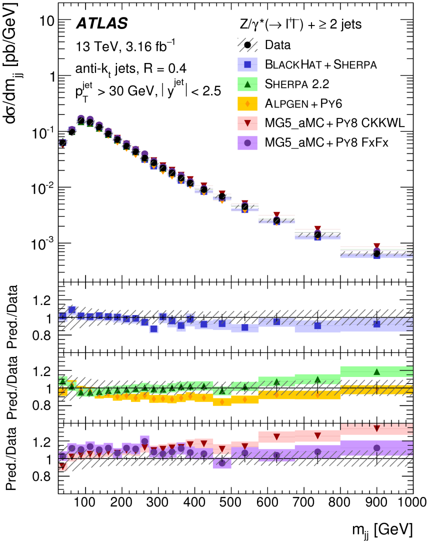
Zjj, Wjj, Hjj: interest in region of large m_{jj}, e.g. $m_{jj} > 400$GeV, $p_{\perp,j} > 30$GeV.

While the perturbative corrections for the EWK process are stable, the perturbative corrections to the QCD contribution of $\alpha_s^2\alpha_w$ for Zjj, Wjj, $\alpha_s^4 y_t^2$ for Hjj is dominated at large m_{jj} by logarithmic corrections $(\alpha_s \log(s/p_t^2))^n$. For large m_{jj} : $s \sim m_{jj}^2$.

These logarithmic corrections also arise for the pure dijet process, and complicates the convergence of the perturbative description

Many techniques for suppressing the QCD contribution beyond requiring large m_{jj} rely on the different behaviour of the higher order corrections for signal and background.

Zjj-production



Good description of inclusive $d\sigma/dm_{jj}$ $\alpha_s^2\alpha_W$-component and agreement between approaches.

Problem arises in the description of the perturbative corrections…

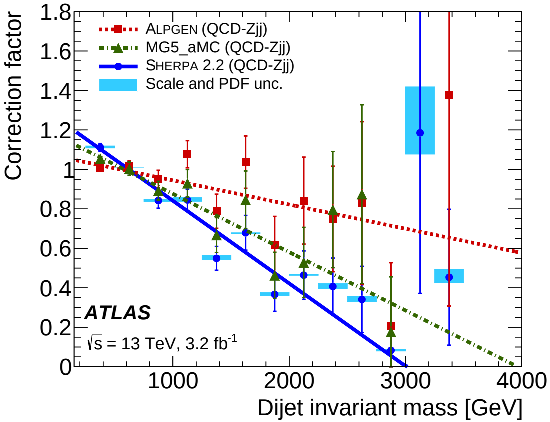
arXiv: 1702.05725

Extraction of Electroweak Zjj-production

Study electroweak Zjj production. Background from $\alpha_s^2\alpha$-component. Compare the description of a control region requiring an additional jet ($p_\perp > 25$GeV).

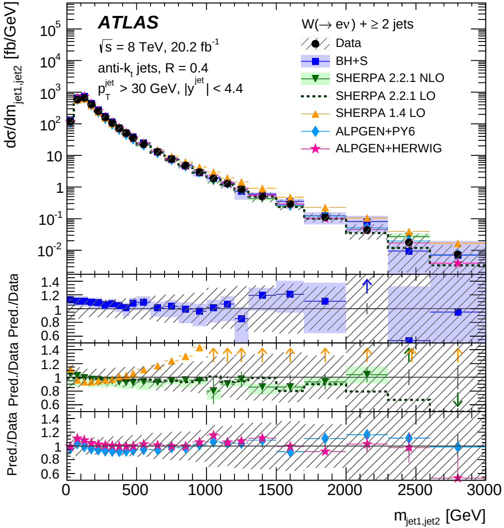
Bin-by-bin corrections factors very different from unity and differing wildly.

Indicates problem in perturbative description at large m_{jj}, and leads to large uncertainties on the extraction of the EWK component



arXiv: 1709.10264

QCD Wjj-production

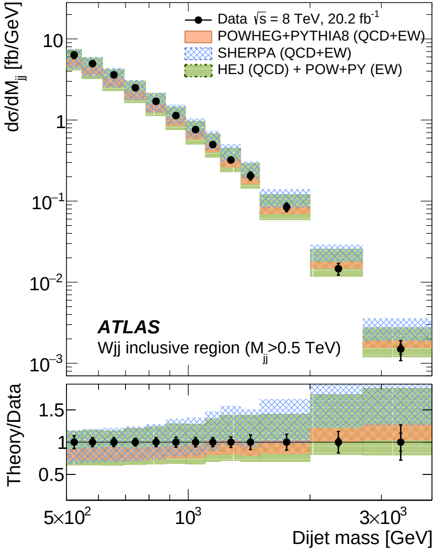


Similar message for *WJJ*:

Good description of inclusive $d\sigma/dm_{jj}$ $\alpha_s^2\alpha_w$ QCD component

arXiv: 1711.03296

Extraction of Electroweak Wjj-production

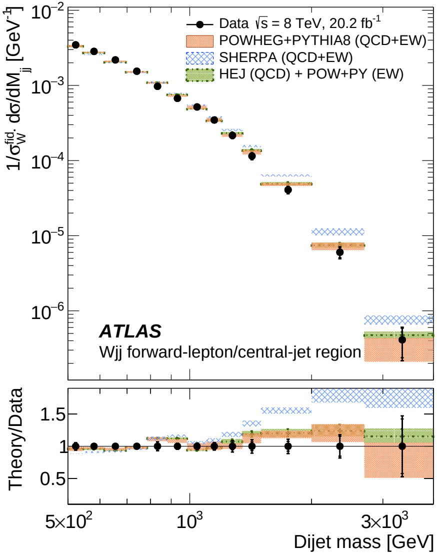


Study electroweak Wjj production. Background from $\alpha_s^2\alpha_W$-component. Control region defined by lepton, rather than additional jets.

Good description of $d\sigma/dm_{jj}$ $\alpha_s^2\alpha_W$-component
For control region

arXiv: 1703.04362

Extraction of Electroweak Wjj-production

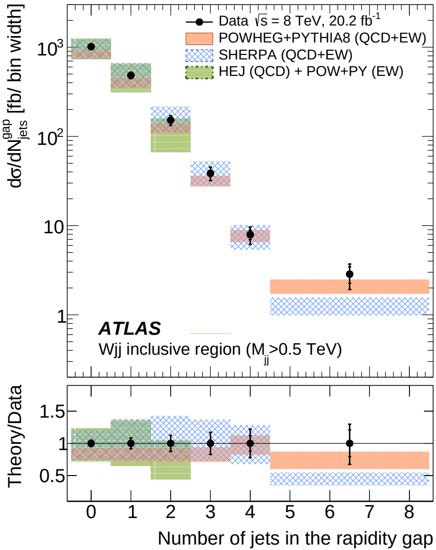


Study electroweak Wjj production. Background from $\alpha_s^2\alpha_W$-component. Control region defined by lepton, rather than additional jets.

Good description of $d\sigma/dm_{jj}$ $\alpha_s^2\alpha_w$-component ..and for EWK signal region.

arXiv: 1703.04362

Perturbative corrections well described for modest m_{jj}

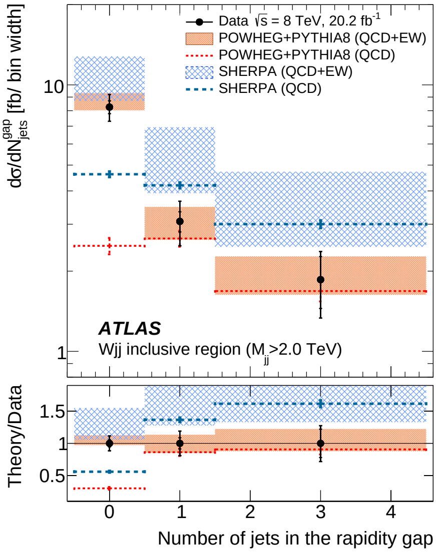


arXiv: 1703.04362

Extraction of Electroweak Wjj-production

Perturbative corrections well described for modest m_{jj}

…less so for large m_{jj}



arXiv: 1703.04362

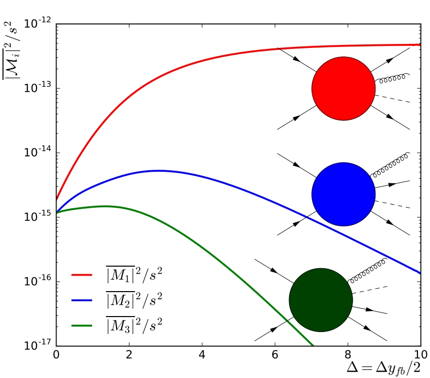
Improvements (2017-) in the precision of the description

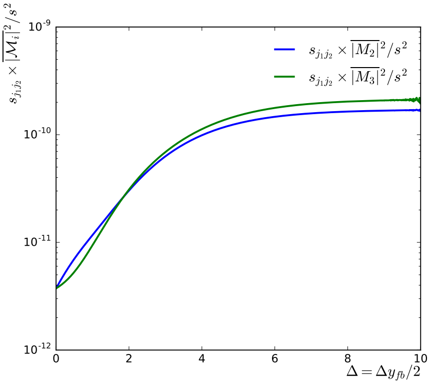
Many measurement involve cuts and observables with effects which are beyond leading logarithmic control or would require higher order matching. Much work in this funding period on improving the precision of the predictions by

1. Complete reformulation of the phase space generation - start from fixed order jets, then add resummation; allows for matching to any multiplicity where the Born level can be calculated (arxiv:1805.04446)
2. Include next-to-leading logarithmic processes in the resummation (arxiv:1706.01002, arxiv:2012.10310) [Emmet's talk]
3. Match/merge with the Pythia parton shower (arxiv:1712.00178) [Hitham's talk]

Also process specific improvements: Quark-mass effects in H+jets (full triangle and box dependence) arxiv:1812.08072; Same sign W-production arxiv:2107.06818

Scaling of Next-to-leading Contributions





The **scaling** for different kinematic evaluations of the same amplitude is exactly as predicted by the spin states of the **planar graph** connecting the rapidity-ordered configuration.

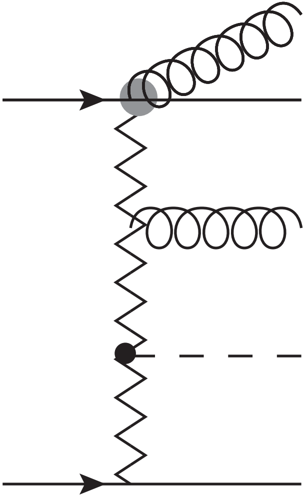
M. Heil, A. Maier, J.M. Smillie, JRA, arXiv:1706.01002

Subleading Corrections

The first **subleading correction** can be included by **relaxing** the constraint between two emissions: **Quasi** Multi Regge Kinematics

Effective currents can be extracted from the full amplitude, now dependent on more momenta. These currents obey **crossing** ($q \to qgg^*$ related to $g \to q\bar{q}g^*$)

The study of sub-leading contributions to W+jets include even central $q\bar{q}'W$-production



M. Heil, A. Maier, J.M. Smillie, JRA, arXiv:1706.01002,1812.08072

Calculation of First Set of Subleading Corrections

$$\mathcal{M}^{\text{HEJ}}_{\text{tree}\ qQ\to gqQ} = -g_s^3\, T^d_{2b}\ \frac{j^{\text{uno}\ cd}_{\mu}(p_1,p_g,p_a) j^{\mu}(p_2,p_b)}{t_{b2}}$$

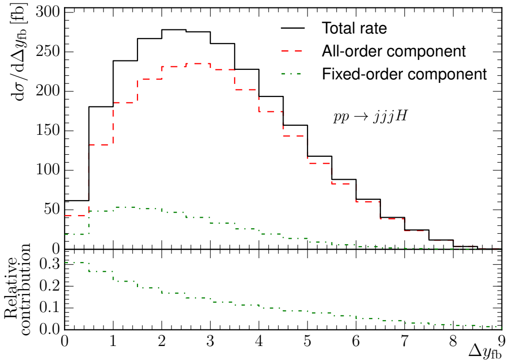
$$j^{\text{uno}\ \mu\ cd}(p_1,p_g,p_a) = i\varepsilon_{g\nu}\left(T^c_{1i}T^d_{ia}\ \left(U_1^{\mu\nu}-L^{\mu\nu}\right) + T^d_{1i}T^c_{ia}\ \left(U_2^{\mu\nu}+L^{\mu\nu}\right)\right).$$

$$U_1^{\mu\nu} = \frac{1}{s_{1g}}\left(j^{\nu}_{1g}j^{\mu}_{ga} + 2p_1^{\nu}j^{\mu}_{1a}\right) \qquad U_2^{\mu\nu} = \frac{1}{t_{ag}}\left(2j^{\mu}_{1a}p_a^{\nu} - j^{\mu}_{1g}j^{\nu}_{ga}\right)$$

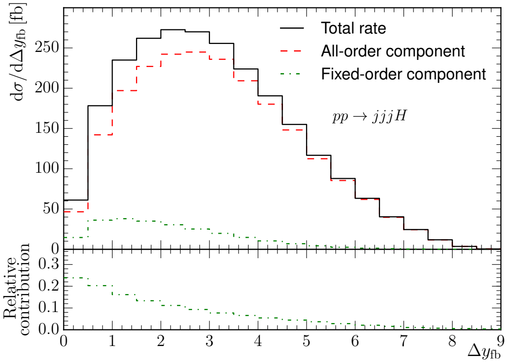
$$L^{\mu\nu} = \frac{1}{t_{a1}}\left(-2p_g^{\mu}j^{\nu}_{1a} + 2p_g.j_{1a}g^{\mu\nu} + (q_1+q_2)^{\nu}j^{\mu}_{1a} + \frac{t_{b2}}{2}j^{\mu}_{1a}\left(\frac{p_2^{\nu}}{p_g.p_2} + \frac{p_b^{\nu}}{p_g.p_b}\right)\right).$$

Gauge-invariant. Respects crossing symmetry.
True for the NLL components for all the processes.

Impact of Subleading Corrections



Leading logs only + matching

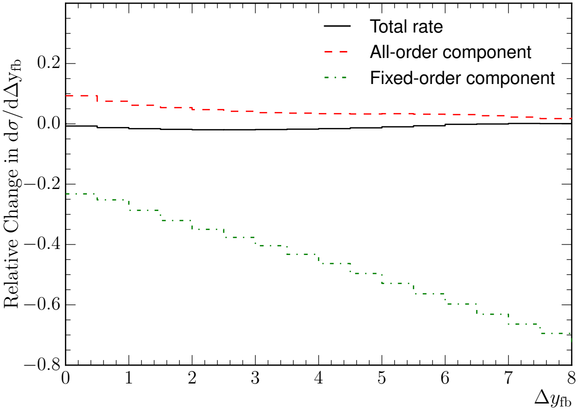


LL, one unordered emission + matching

The **all-order component** of the cross section **increases**, the impact from **matching is decreased**, but the **total result** changes only **little.**

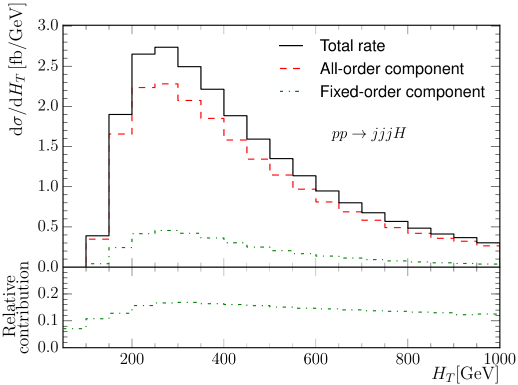
M. Heil, A. Maier, J.M. Smillie, JRA, arXiv:1706.01002

Subleading Corrections as Expected

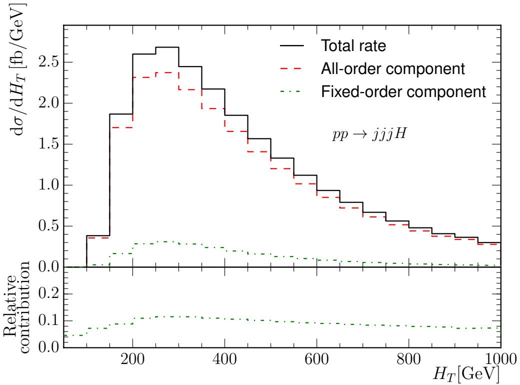


The fixed-order component of the cross section is **systematically reduced** by a component growing with Δy_{fb} (as expected, of course).

Impact of Subleading Corrections for H_T



Leading logs only + matching

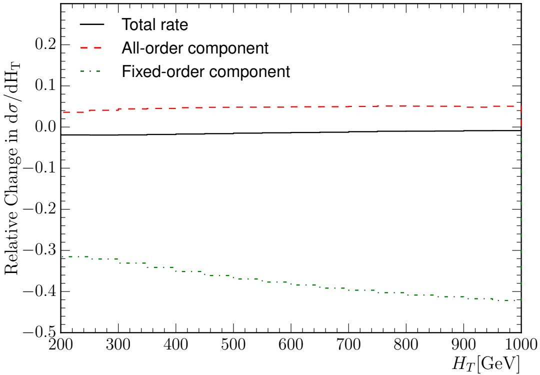


LL, one unordered emission + matching

The **all-order component** of the cross section **increases**, the impact from **matching is decreased**, but the **total result** changes only **little.**

arXiv:1706.01002

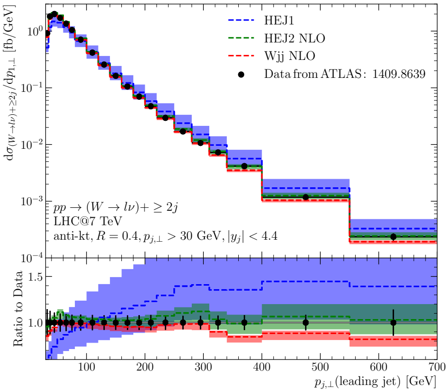
Subleading Corrections for H_T



The all-order and fixed-order component of the cross section is **changed uniformly**, but their **sum changes only little.**

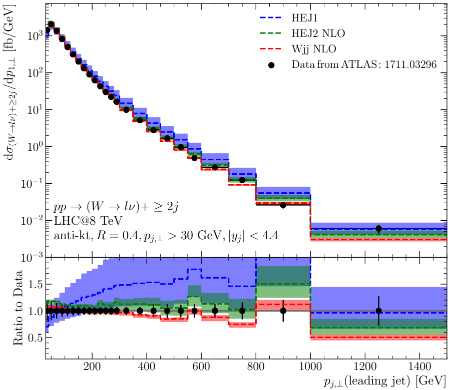
Conclusion: The **all-order perturbative treatment** is very **stable.** Also for W+jets.

Subleading effects in W+jets



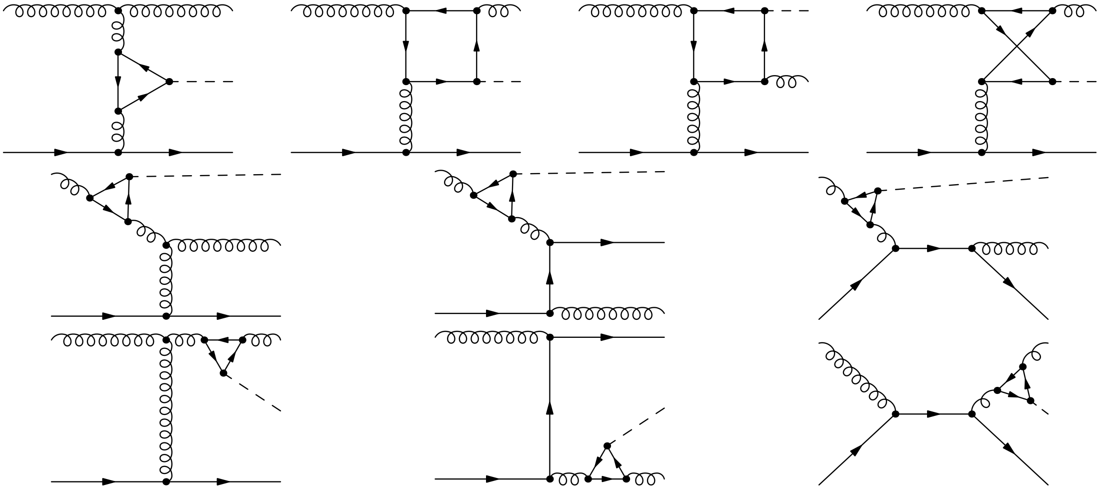
The sub-leading effects (and the NLO matching) ensures a good description also in regions away from the dominance of leading logarithmic effects. arxiv:2012.10310

Subleading effects in W+jets



The sub-leading effects (and the NLO matching) ensures a good description also in regions away from the dominance of leading logarithmic effects. arxiv:2012.10310

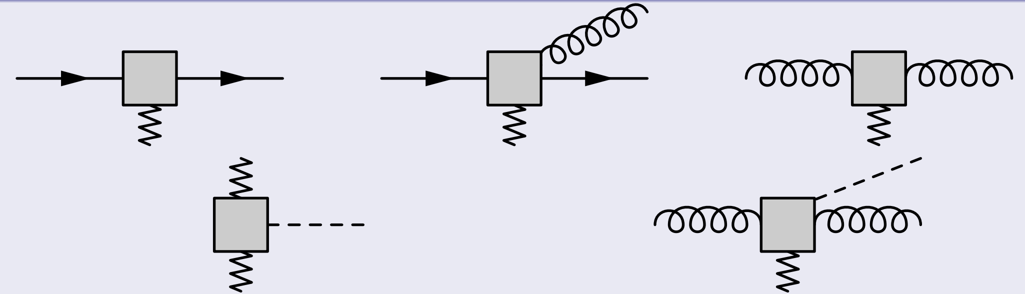
Finite quark mass effects



Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld, hep-ph/0105129

Finite quark mass effects

Building pieces in HEJ (currents) arxiv:1812.08072



Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld, hep-ph/0105129

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, explore all of higher-order phase space

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

arXiv:1805.04446

Matching & merging with Fixed Order

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

$$\cdot\ x^B_a\, f_a(x^B_a, Q^B_a)\, x^B_b\, f_b(x^B_b, Q^B_b)\, \frac{\overline{|\mathcal{M}^B|}^2}{(\hat{s}^B)^2}$$

Fixed Order

$$\cdot\ \overline{|\mathcal{M}^{tree}_{\text{HEJ}}|}^{-2}\, (2\pi)^{-4+3m}\, 2^m\, \frac{(\hat{s}^B)^2}{x^B_a\, f_{a,f_1}(x^B_a, Q^B_a)\, x^B_b\, f_{b,f_2}(x^B_b, Q^B_b)}$$

Matching

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

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

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

All order

- Generate Fixed Order, explore all of higher-order phase space

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

arXiv:1805.04446

Summary

During this funding period the precision of the predictions from High Energy Jets have been improved by

- Increased usage of fixed order (higher multiplicity Born and simple NLO matching)
- Including next-to-leading logarithmic ($\log(s)$) contribution
- Matching to parton shower

Further work in all three directions is ongoing.
Two software releases during this grant period.