Vector Boson Scattering to $\alpha_W^2 \alpha_s^{n+2} \ln^n(s/|t|)$

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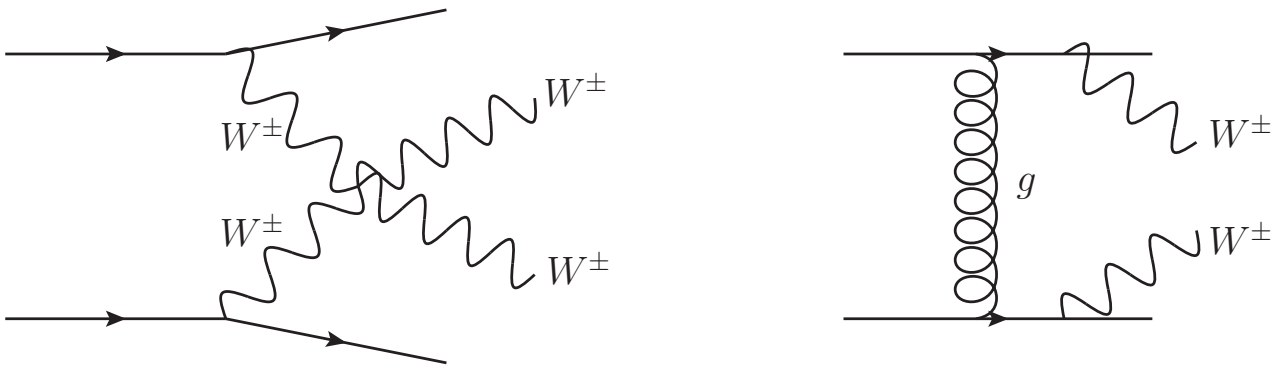
J. R. Andersen, B.D., C. Elrick, G. Nail, J. M. Smillie, in preparation

Motivations

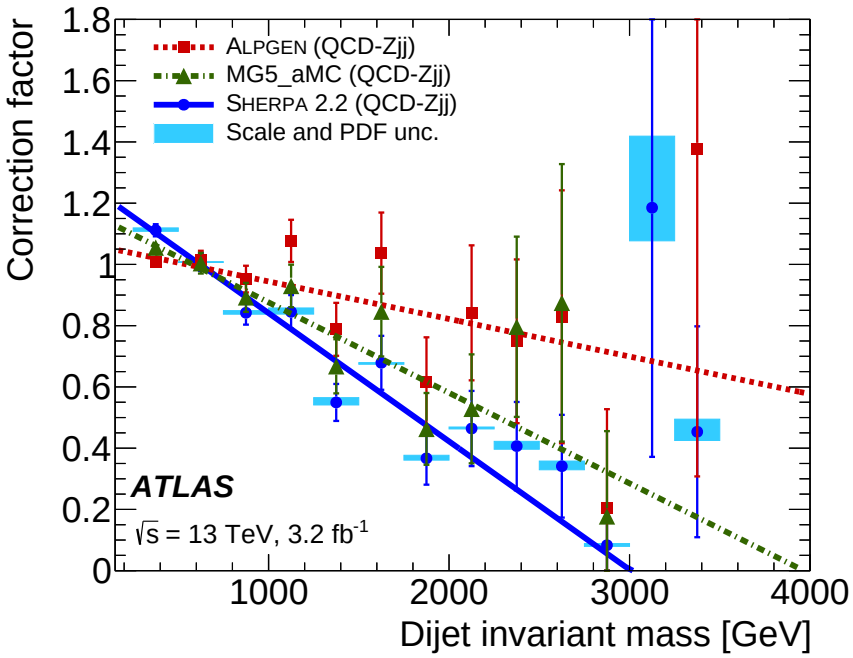
Vector boson scattering (VBS) provides a key opportunity to study the mechanism of electroweak symmetry breaking

The same final state (here we consider $W^{\pm}W^{\pm}$) can also be generated by gluon exchange between the quark lines, contributing at $\mathcal{O}(\alpha_W^2 \alpha_s^2)$



A precise extraction of the EW contribution from experimental data requires a good understanding of the QCD one. In this talk we will focus on the behaviour of the latter one at high energy, which is relevant in the LHC kinematics

The problem of describing multi-jet production at high energy appears in many processes, e.g. Z+jets production at ATLAS (arXiv:1709.10264):



The so-called 'control region' is actually not really under control

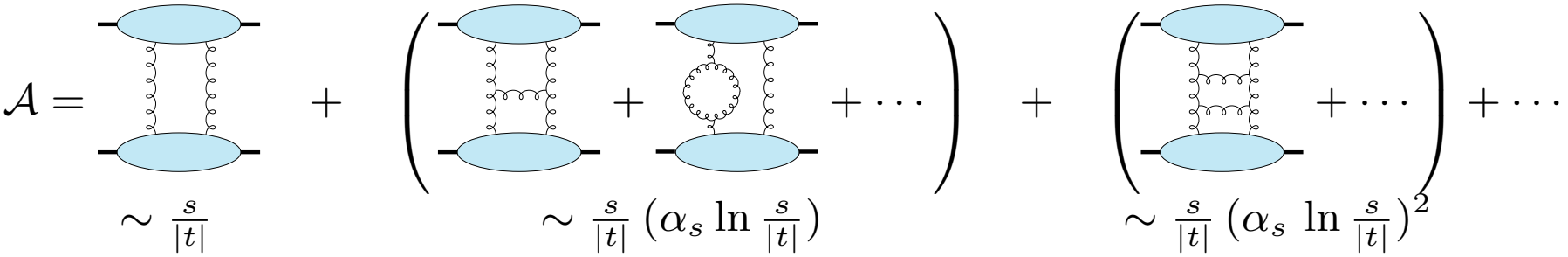
A general issue of processes with a large invariant mass or rapidity separation between jets (i.e. large phase space which allows additional emissions)

QCD in the perturbative Regge limit

One of the important longstanding theoretical questions about QCD is its behaviour in the perturbative Regge limit $s \gg |t|$

Region of interest: semi-hard processes with $s \gg p_{T\,i}^2 \gg \Lambda_{QCD}^2$ where $p_{T\,i}^2$ are typical transverse scales

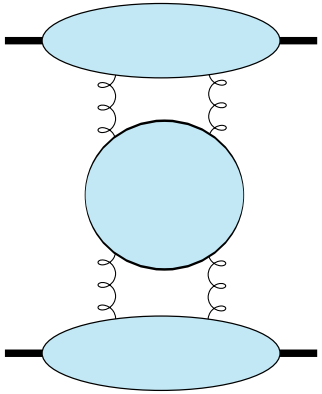
At leading logarithmic (LL) accuracy, i.e. resumming terms $(\alpha_s \ln \frac{s}{|t|})^n$, the scattering amplitude can be written as:



In the Regge limit all these contributions are of the same order despite the small value of the strong coupling

One possible way to resum all these contributions: make additional approximations and solve analytically $\rightarrow$ leads to the BFKL equation (Balitsky, Fadin, Kuraev, Lipatov)

The process is factorized in the following form:



$\leftarrow$ Impact factor

$\leftarrow$ Green's function

$\leftarrow$ Impact factor

- The impact factors are process-dependent
- The Green's function obeys the BFKL equation

The HEJ framework

The HEJ (High Energy Jets) approach (Andersen, Smillie, arXiv:0908.2786): based on the same general assumptions (dominance of the t-channel colour octet exchange), but:

- Work at the amplitude level

  $\rightarrow$ Possible to take interference effects into account

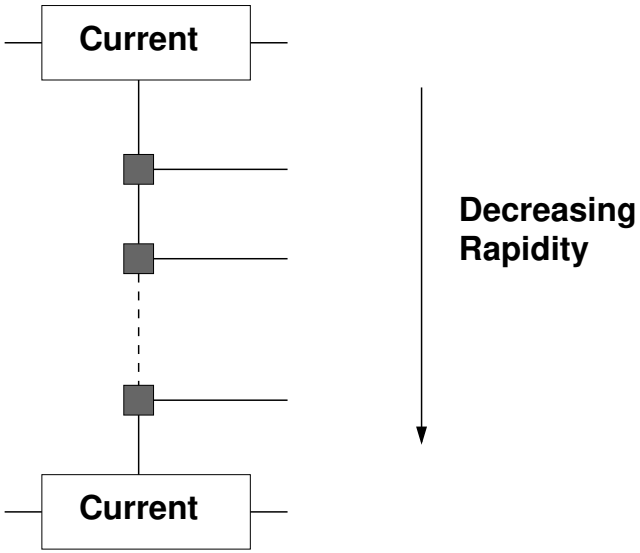
- No kinematic approximations in invariants
- Full gauge invariance of the matrix elements
- Use Monte Carlo sampling to sum over emissions and integrate phase space

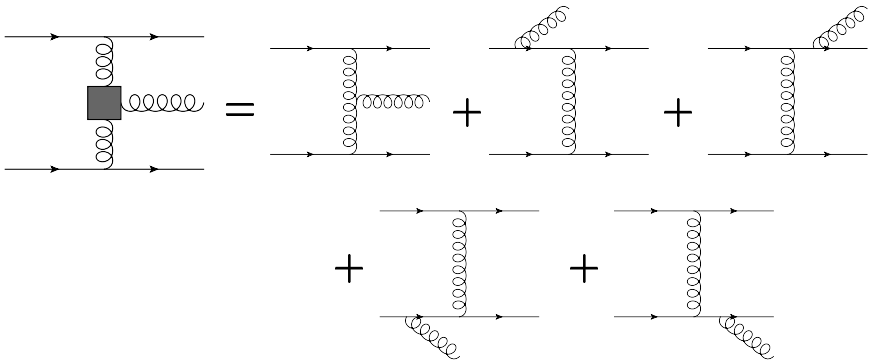
  $\rightarrow$ Fewer approximations, exclusive final states

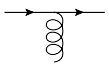
Variety of processes: pure QCD, H+jets, W+jets, now WW+jets

Public code, available at `https://hej.web.cern.ch`

General structure of an amplitude in HEJ: current-current scattering

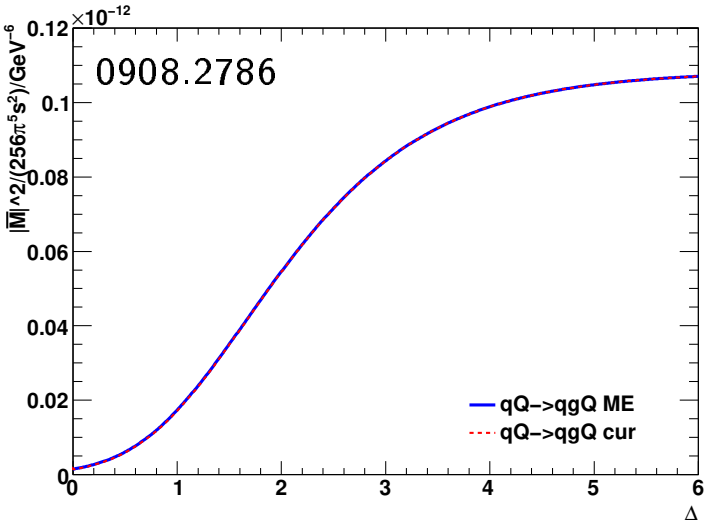


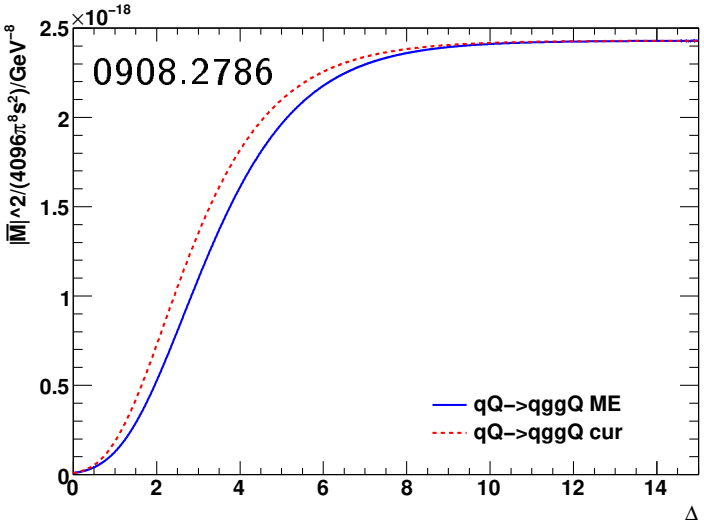


- Currents describe the transition from incoming to outgoing particles
  e.g. the current for $q \to q$ is simply  $\propto \bar{u}\gamma^\mu u$
- Additional emissions in the rapidity interval between the extremal particles are generated by inserting Lipatov vertices (■)

Using this factorized form of the amplitude allows to generate an arbitrary (in practice up to ~ 30) number of additional emissions by inserting the corresponding number of Lipatov vertices

Some approximations are needed to obtain this factorized structure
→ slightly worse description at higher multiplicities





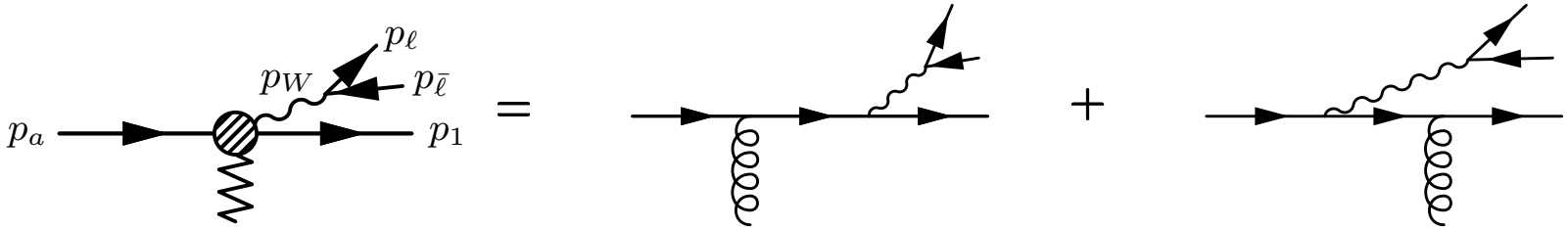
But still far better in realistic kinematics than the strict high energy limit which corresponds to what would be used in BFKL calculations

Matching to fixed order: matrix element weight $\propto |\mathcal{M}_{\text{HEJ}}|^2 \frac{|\mathcal{M}_{\text{LO}}|^2}{|\mathcal{M}_{\text{HEJ,LO}}|^2}$
→ expand to lowest order: recover the exact LO result

Example: W+jets production

To go beyond pure QCD processes: new currents needed

E.g. current for W boson emission:



$$\frac{g_W^2}{2}\,\frac{1}{p_W^2 - M_W^2 + i\,\Gamma_W M_W}\,\bar{u}^-(p_\ell)\gamma_\alpha v^-(p_{\bar{\ell}})\left(\frac{\bar{u}^-(p_1)\gamma^\alpha(\not{p}_1 + \not{p}_W)\gamma^\mu u^-(p_a)}{(p_1+p_W)^2} + \frac{\bar{u}^-(p_1)\gamma^\mu(\not{p}_a - \not{p}_W)\gamma^\alpha u^-(p_a)}{(p_a-p_W)^2}\right)$$

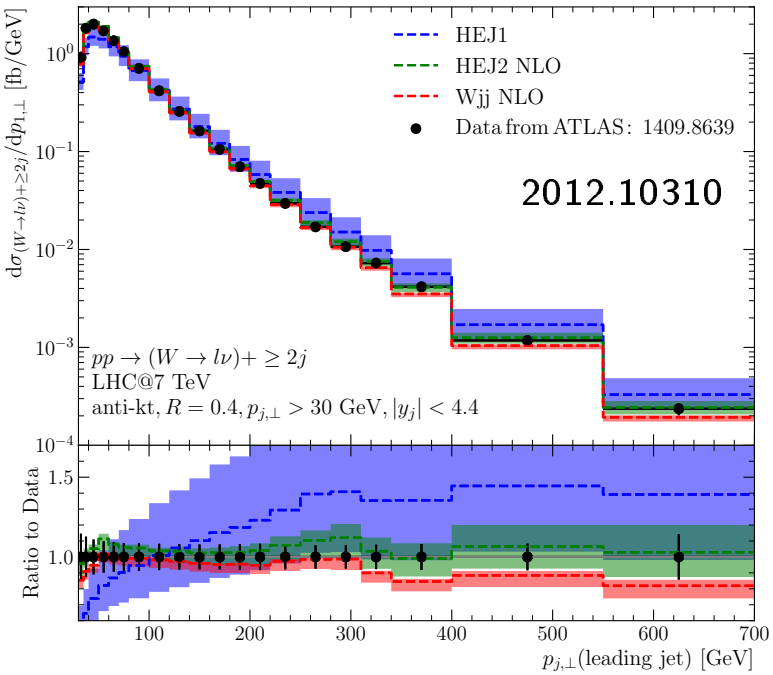
Contracting this current with the $q \to q$ current one gets the ME for $qq \to Wqq$

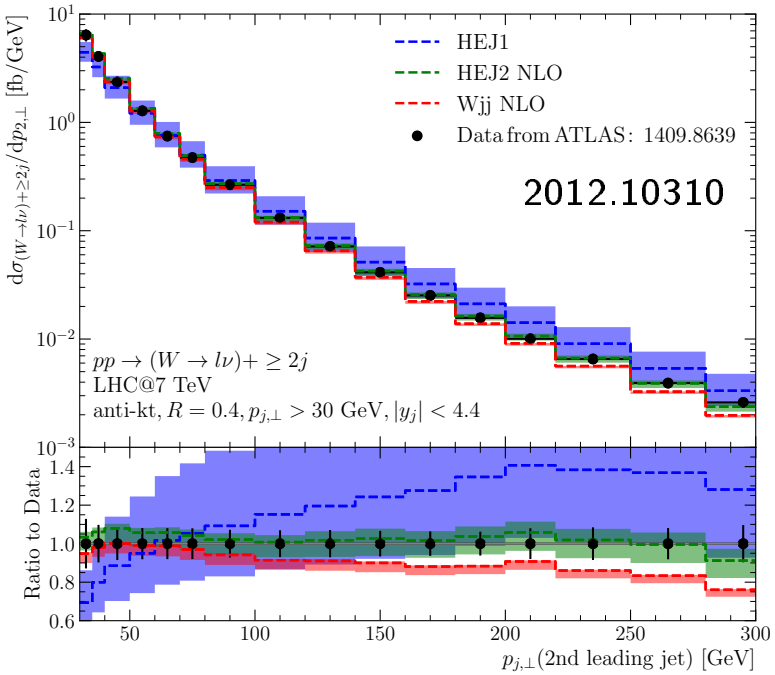
Inserting additional Lipatov vertices yields the MEs for $qq \to Wqg...gq$

Example: W+jets production

Very good description of LHC data for several observables:

J. R. Andersen, J. A. Black, H. M. Brooks, E. P. Byrne, A. Maier, J. M. Smillie



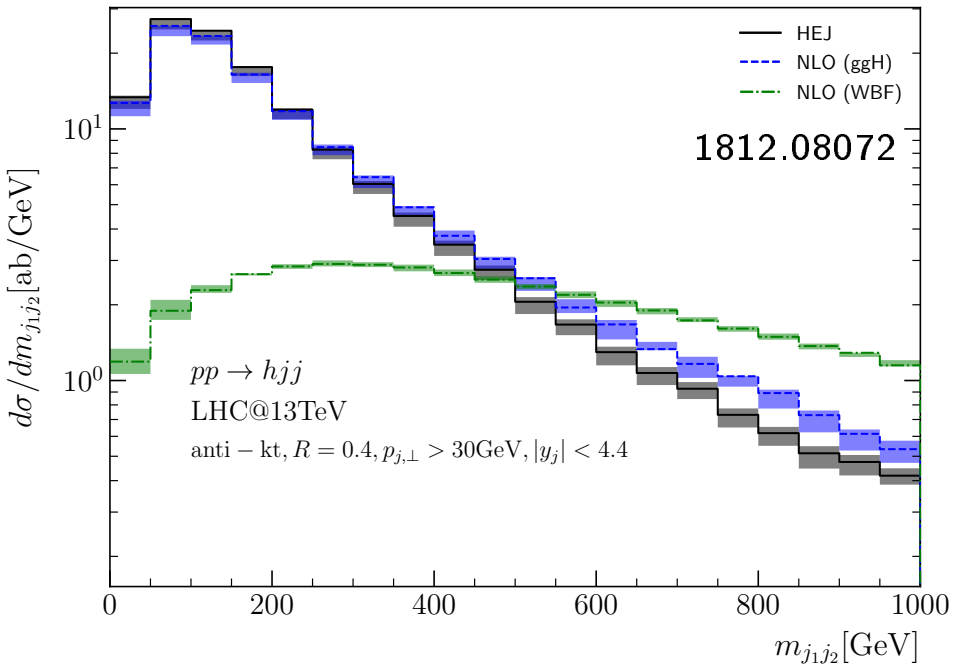


Note that this work also takes into account part of the subleading corrections + bin-by-bin matching to NLO

Example: H+jets production

Typical example of trying to extract the EW contribution to a process with a QCD background: gluon fusion vs. vector boson fusion in H+jets production

J. R. Andersen, J. D. Cockburn, M. Heil, A. Maier, J. M. Smillie



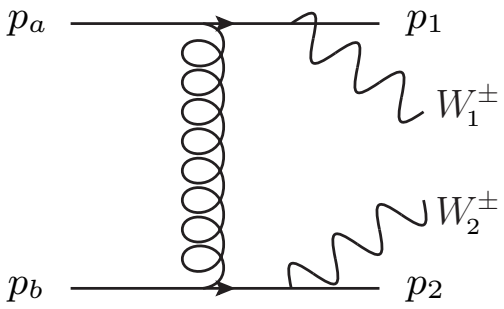
The gluon fusion contribution is peaked at low invariant mass
$\to$ VBF cut: $m_{12} > 400$ GeV & $y_{j_1j_2} > 2.8$

But the remaining gluon fusion contribution is now concentrated in a region more sensitive to high energy resummation effects. Difference with NLO

The VBF cut is more effective at suppressing the QCD contribution than expected from fixed order calculations (+ full dependence on m_t and m_b)

$W^\pm W^\pm$ production in HEJ

Typical LO diagram for the QCD contribution to same sign W production:



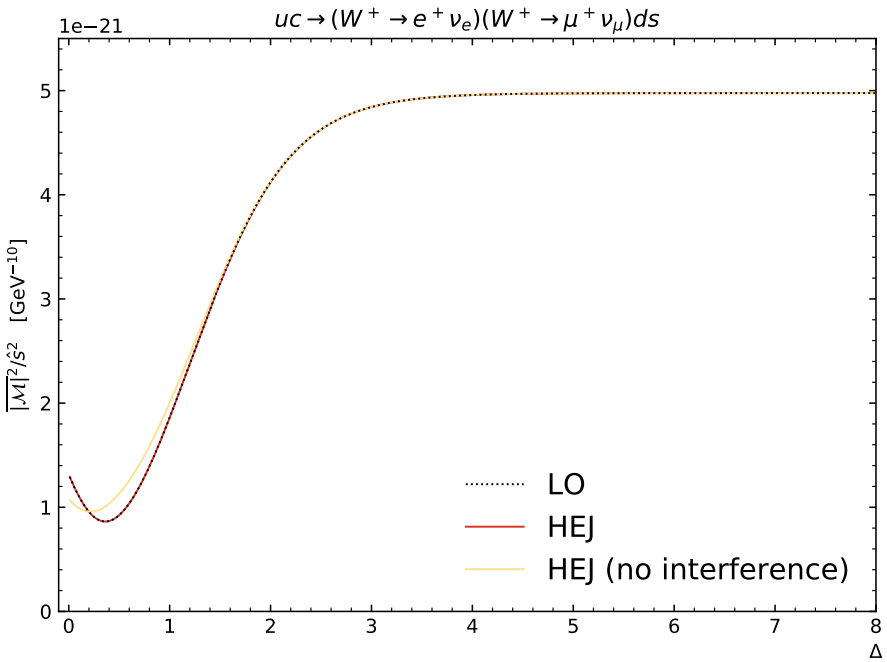
Using the same W emission current as for single W production, we can write the amplitude as

$$i\mathcal{M} = g_s^2 \left(\frac{j_\mu^W(p_a, p_1, p_{\ell_1}, p_{\bar{\ell}_1}) g^{\mu\nu} j_\nu^W(p_b, p_2, p_{\ell_2}, p_{\bar{\ell}_2})}{q^2} + \frac{j_\mu^W(p_a, p_1, p_{\ell_2}, p_{\bar{\ell}_2}) g^{\mu\nu} j_\nu^W(p_b, p_2, p_{\ell_1}, p_{\bar{\ell}_1})}{\tilde{q}^2} \right)$$

The two terms correspond to the two possible emission configurations

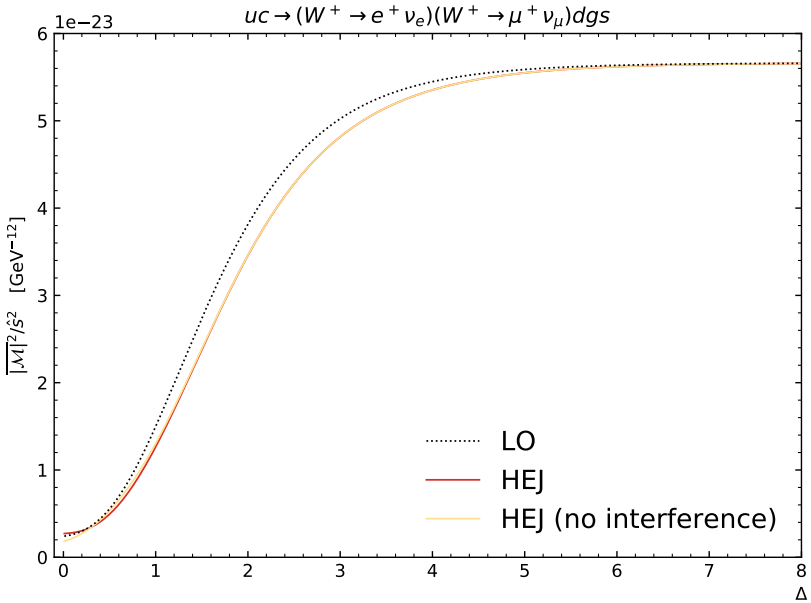
Work at the amplitude level: can take into account the interference term

Comparison of the HEJ and exact matrix elements for the $uc \to ds$ channel:

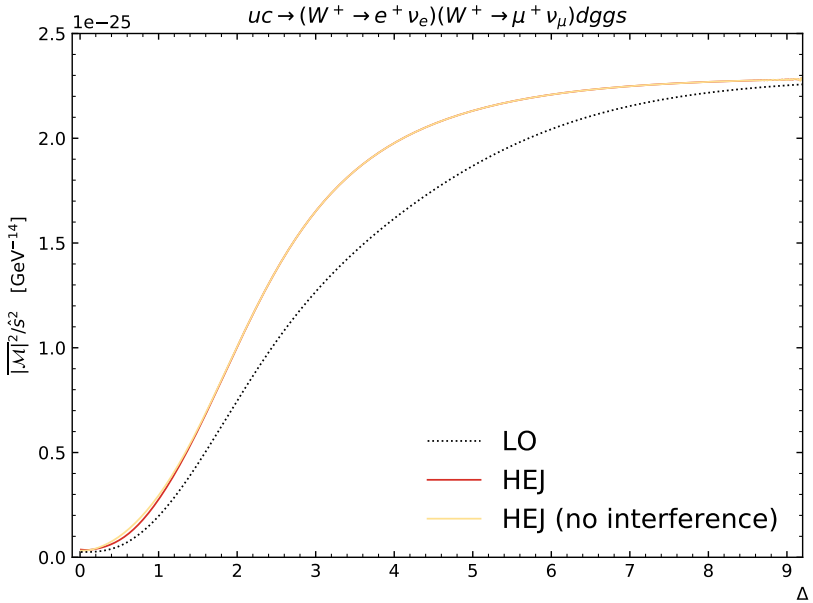


Agreement with the exact LO result when the interference term is taken into account

Thanks to the factorized form of the matrix element in HEJ, one can easily generate additional emissions by inserting Lipatov vertices



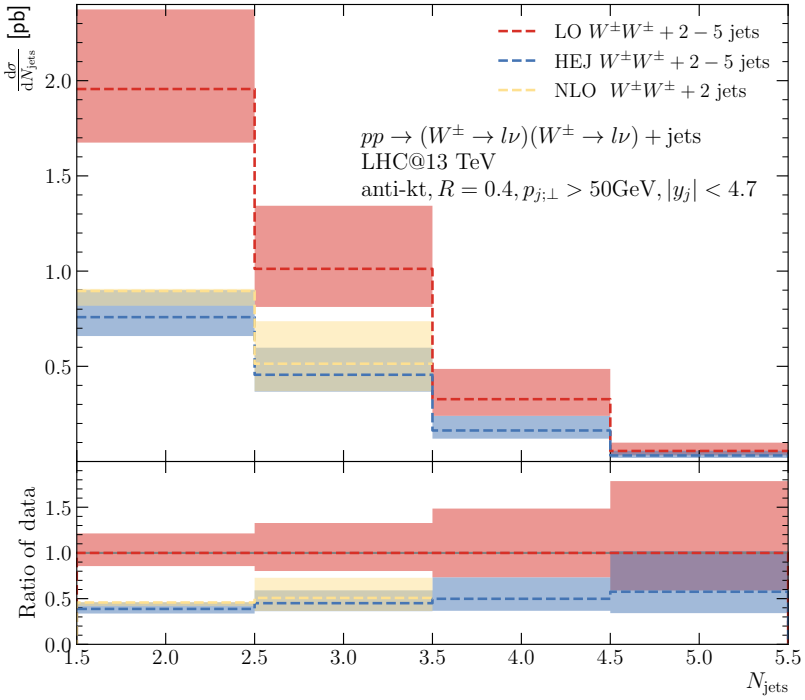
$W^+W^+ + 3$ partons



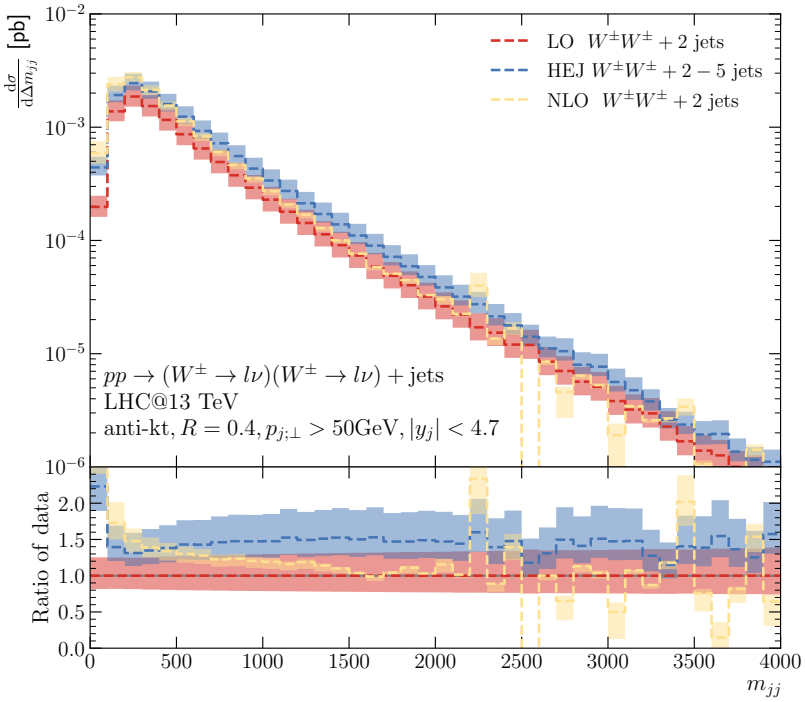
$W^+W^+ + 4$ partons

Reasonable description for these higher multiplicities, correct high energy limit

Preliminary results (W^+W^+ only)



Exclusive jet rates



Invariant mass distribution

- The $(n+1)$-jet rates are not small compared to the n-jet rates
  $\rightarrow$ important to take higher multiplicities into account
- Significant difference between HEJ and fixed order LO or NLO at large m_{jj}
  $\rightarrow$ interesting with respect to future measurements

Conclusions

- A precise extraction of the EW contribution to vector boson scattering requires a good understanding of the QCD contribution
- Typical VBS cuts increase the EW/QCD ratio but the QCD contribution is concentrated in a region sensitive to high energy resummation
- HEJ provides a framework for all-order resummation of high energy logarithms (+ subleading corrections for some processes)
- $W^{\pm}W^{\pm}$ production in HEJ: new developments (emission of 2 bosons + interference contributions)
- Preliminary $W^{+}W^{+}$ results: significant differences compared to fixed order for several observables
- Outlook: possible to combine with the EW contribution obtained by other groups to predict the total yield