$W^+W^+ + 2$ Jets at the LHC at NLO in QCD

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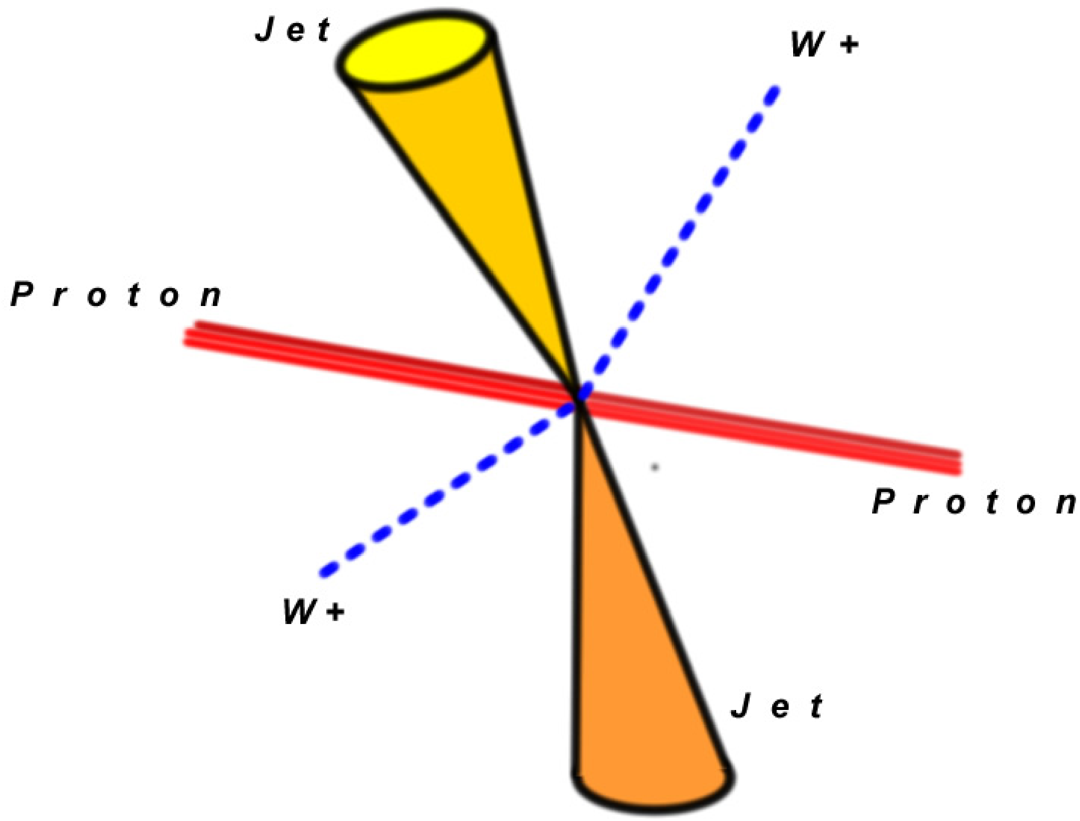

Work with Raoul Rontsch, Kirill Melnikov and Giulia Zanderighi

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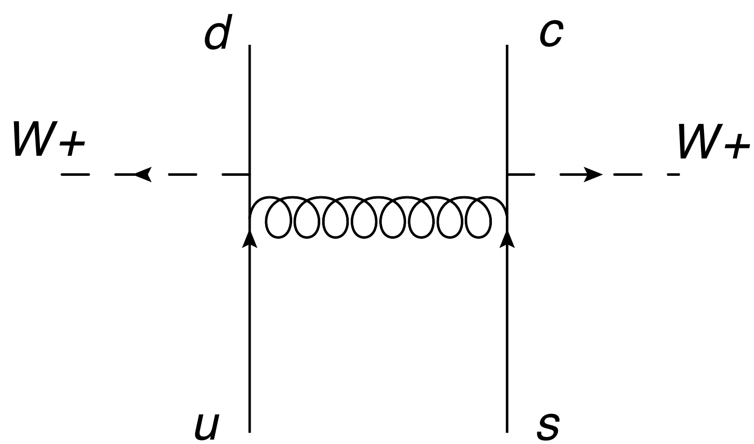
Oxford Theoretical Physics

1. W^+W^+ 2 jet at the LHC

- Start with a Feynman diagram, because it's a funny process. Quirky both theoretically and experimentally.



- Need W-bosons on separate quark lines. This means cross-section is infra-red safe as the jet p_T go to zero.
- We consider the leptonic decay of both W-bosons as this is a clean signature and shows up the double positive sign.
- Cross-section for this decay is around 6fb at 14TeV (l^-l^- is 40% of the size).

1. W^+W^+ 2 jet at the LHC

- Exotic SM signal!

And a background process to

- Double parton scattering (c.f. LHCphenonet: Ed Berger)

  e.g. J. R. Gaunt, C. H. Kom, A. Kulesza and W. J. Stirling, hep-ph/1003.3953

- R-parity violating smuon production

  e.g. H. K. Dreiner, S. Grab, M. Kramer and M. K. Trenkel, Phys. Rev. D75 (2007)

- Doubly charged Higgs production (c.f. LHCphenonet: Janusz Gluza)

  e.g. J. Maalampi and N. Romanenko, Phys. Lett. B 532, 202 (2002)

- Di-quark production (c.f. LHCphenonet: Riccado Torre)

  e.g. T. Han, I. Lewis and T. McElmurry, JHEP 1001, 123 (2010)

Also theoretical incentives.

2. Method of Calculation

NLO QCD for > 5 particles is difficult. For the virtual amplitude, the number of Feynman diagrams grows as $N!$.

In the past three years, methods of D-dimensional unitarity *(Bern, Dixon, Kosower; Cachazo, Britto, Feng; Ellis, Kunszt, Giele, Melnikov and more)* along with Ossola-Papadopoulos-Pittau (OPP) reduction have simplified the calculation of the virtual amplitude enormously.

Unitarity method: We write the amplitude

$$\mathcal{A}_N(p_1,\ldots,p_N) = \sum_{1\leq i_1<i_2<i_3<i_4\leq N} d_{i_1i_2i_3i_4} I_{i_1i_2i_3i_4} + \sum_{1\leq i_1<i_2<i_3\leq N} c_{i_1i_2i_3} I_{i_1i_2i_3} + \sum_{1\leq i_1<i_2\leq N} b_{i_1i_2} I_{i_1i_2} + \sum_{1\leq i_1\leq N} a_{i_1} I_{i_1}$$

where

$$I_{i_1\ldots i_k} = \int \frac{[dl]}{D_1\ldots D_k} \quad , \qquad D_i = (l+\sum_{j=1}^{i} p_j)^2 - m^2.$$

To find the coefficients $d_{i_1 i_2 i_3 i_4} \dots a_{i_1}$, we can write the 1-loop amplitude as

$$\mathcal{A}_N(p_1, \dots, p_N) = \int [dl] \frac{N(p_i; l)}{D_1 \dots D_N}$$

and the numerator

$$\begin{aligned} N(p_i; l) &= \sum_{1 \le i_1 < i_2 < i_3 < i_4 \le N} \left(d_{i_1 i_2 i_3 i_4} + \tilde{d}_{i_1 i_2 i_3 i_4}(l) \right) \prod_{i \ne i_1 i_2 i_3 i_4} D_i \\ &+ \sum_{1 \le i_1 < i_2 < i_3 \le N} (c_{i_1 i_2 i_3} + \tilde{c}_{i_1 i_2 i_3}(l)) \prod_{i \ne i_1 i_2 i_3} D_i \\ &+ \sum_{1 \le i_1 < i_2 \le N} \left(b_{i_1 i_2} + \tilde{b}_{i_1 i_2}(l) \right) \prod_{i \ne i_1 i_2} D_i \\ &+ \sum_{1 \le i_1 \le N} (a_{i_1} + \tilde{a}_{i_1}(l)) \prod_{i \ne i_1} D_i \end{aligned} \tag{1}$$

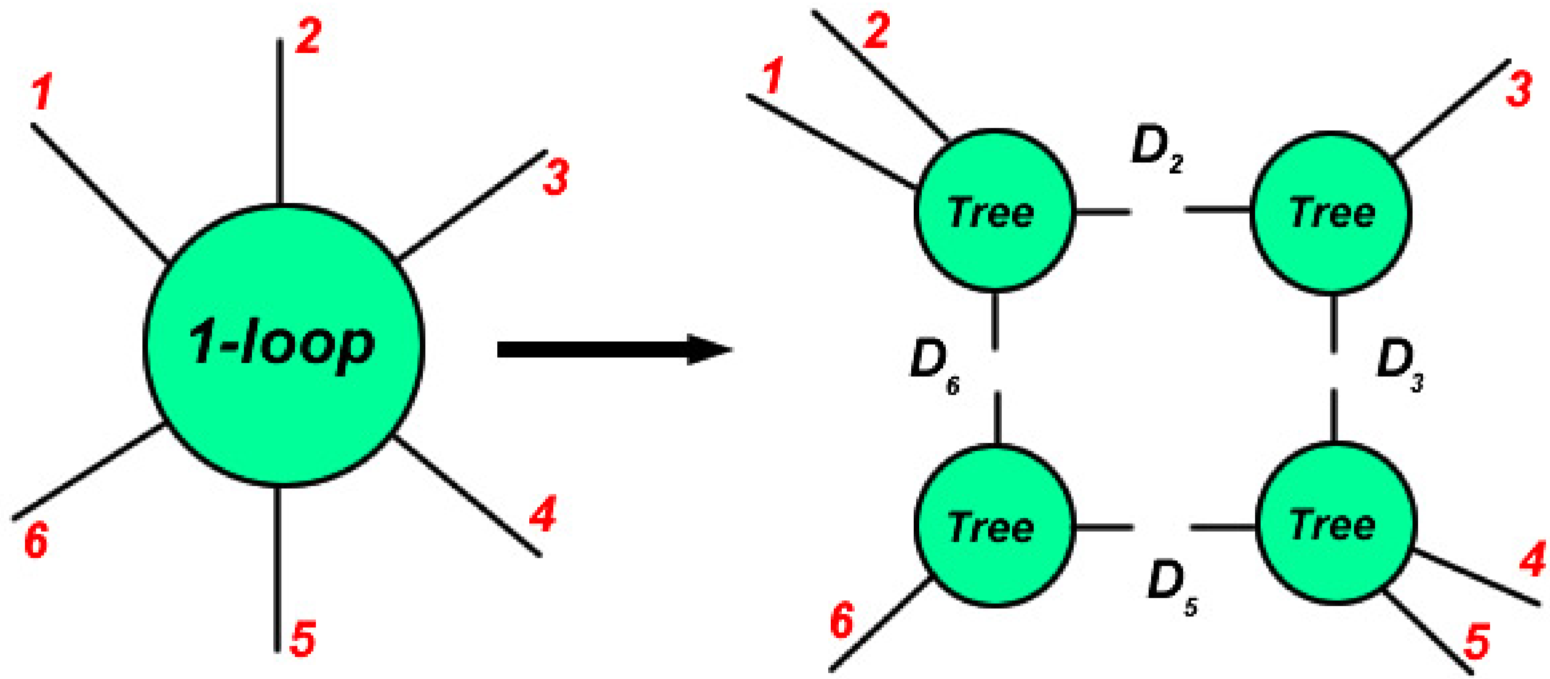
where the tilde terms vanish upon integration over l.

OPP tells us the analytical form in l of the coefficients.

For example, to find the coefficient $\bar{d}_{2356}(l) = d_{2356} + \tilde{d}_{2356}(l)$, look for $l = \hat{l}$ so that $D_2 = D_3 = D_5 = D_6 = 0$. Then eqn (1) becomes

$$N(p, \hat{l}) = \bar{d}_{2356}(\hat{l}) \prod_{i \neq 2,3,5,6} D_i(\hat{l}).$$

What is more, the 1-loop amplitude factorises at this point:



so $\bar{d}_{2356} = A_{12}^{tree} \times A_3^{tree} \times A_{45}^{tree} \times A_6^{tree}$.

Repeat this process to find all coefficients and therefore the full amplitude (...almost).

- Analytically (using dim.reg.) one finds 'rational' terms from parts of the coefficients which are $\mathcal{O}(\epsilon)$ hitting UV poles which are $\mathcal{O}(1/\epsilon)$.

- But we want to do this numerically: we can't work to $\mathcal{O}(\epsilon)$.

- So we do this with loop momentum in $D = 5$ dimensions and the internal particles' spin in both $D_s = 6$ and $D_s = 8$ dimensions.

- The extra-dimensional part of l enters into the analytical form of $\tilde{d}(l) \ldots \tilde{a}(l)$ as (coeff.) $\times$ $\mathrm{l}_{\mathrm{XD}}^2$ or (coeff.) $\times$ $(\mathrm{l}_{\mathrm{XD}}^2)^2$.

- We pick up the rational terms from the new integrals involving extra-dimensional parts of l, such as

$$\int [dl] \frac{l_{\mathrm{XD}}^2}{D_1 D_2 D_3 D_4}$$

- The amplitude is essentially *linear* in D_s. Extrapolate back to e.g. $D_s = 4$ or $D_s = 4 - 2\epsilon$ (FDH Scheme, 't H-V scheme).

Checks

- **Tree level:** Born, real and cross-section checked with MG/ME.

- **Virtual:** Poles reproduced correctly. In addition we cross-check the *full* 1-loop amplitude at individual phase-space points with an independent Feynman-diagram based program.

- **Catani-Seymour dipoles:** - Collinear limits - Cancellation of virtual poles with integrated dipoles - Independence of cross-section on α parameter.

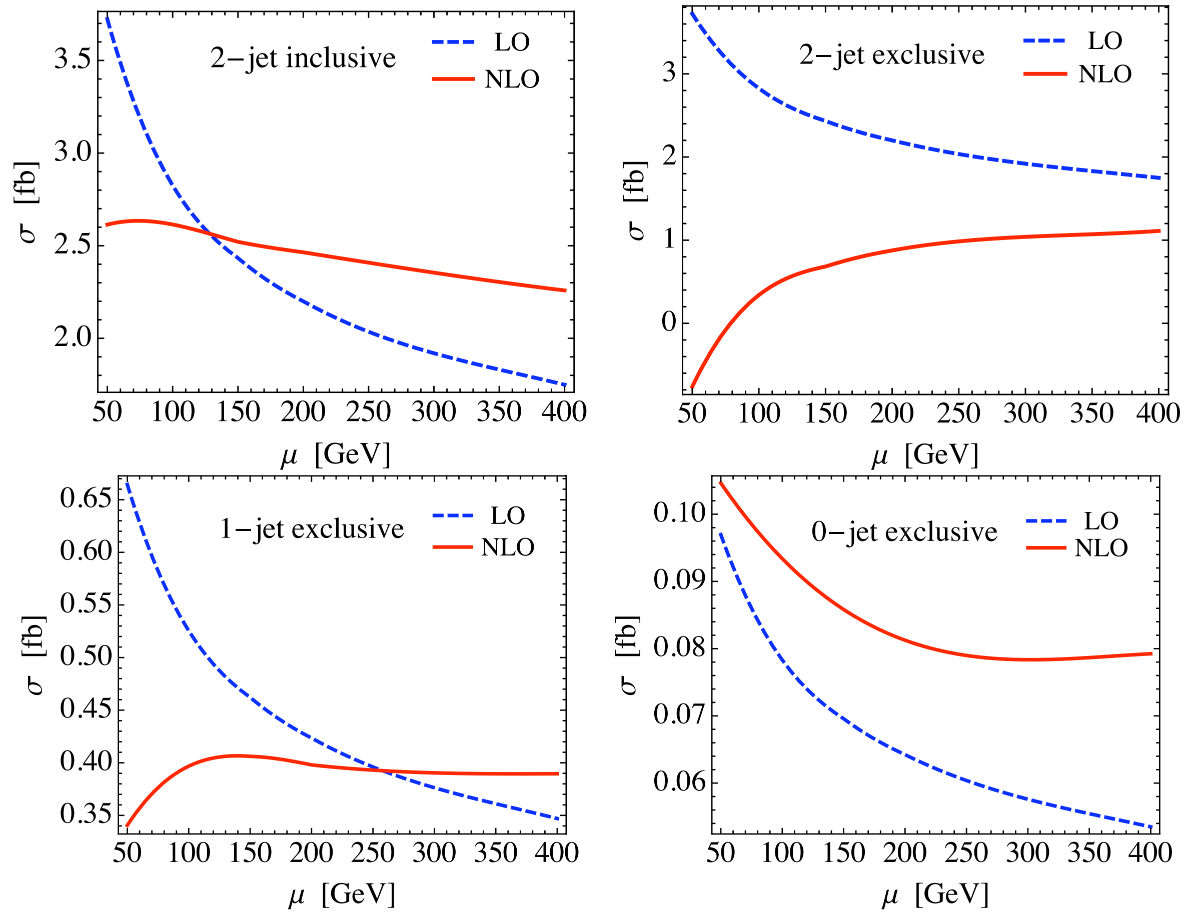
3. Results

Cuts and Input Parameters:

pp collisions with $\sqrt{s}$ =14TeV
Allow W-bosons to decay leptonically into $e^+\mu^+$
(full l^+l^+ is a factor of 2 greater)

- Jets are reconstructed with anti-k_T algorithm with $R = 0.4$.
- Jet cuts: $p_{T,j}$ >30GeV.
- Lepton cuts: $p_{T,j}$ >20GeV, $|\eta_l|$ <2.4.
- Missing transverse momentum cut: $p_{T,miss}$ >30GeV.
- MSTW08LO and MSTW08NLO parton distributions.
- $\alpha_s(M_Z) = 0.13939$ and 0.12018 respectively.
- α_{QED}=1/128.802, $\sin^2\theta_W$=0.2222.
- M_W=80.419 GeV, Γ_W=2.141 GeV, Γ_Z=2.490 GeV.
- **In the distributions, no cut on $p_{T,j}$ is applied.**

Cross-sections and μ dependence



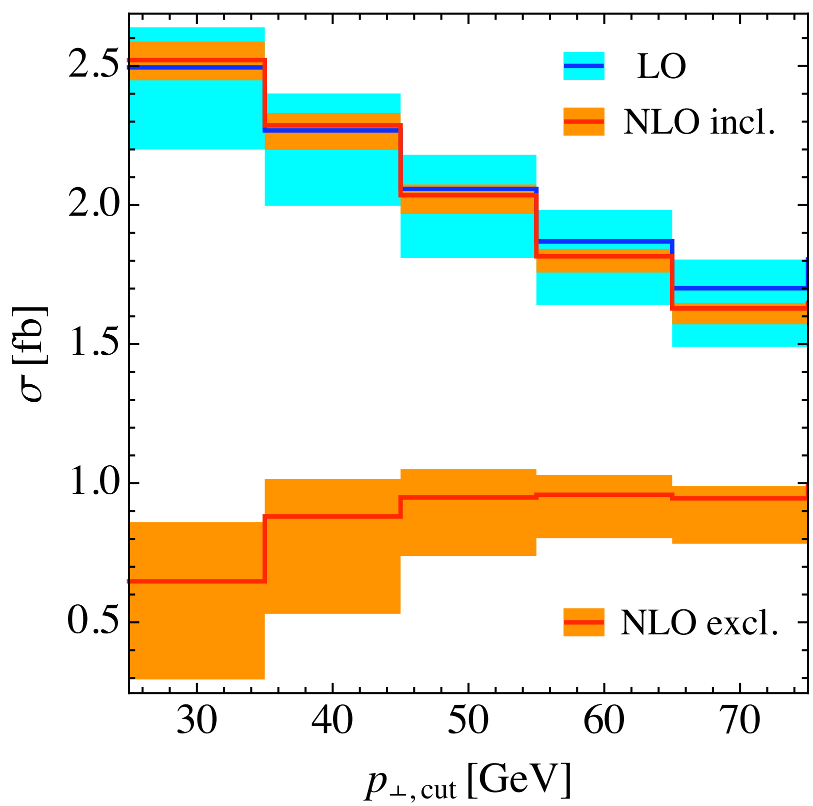
$$\mu = \mu_R = \mu_F.$$

NLO cross section dependence on μ reduced significantly compared to LO.

σ^{LO} =2.7±1.0 fb, σ^{NLO} =2.44±0.18 fb (∼60 l^+l^+ events for 10 fb^{-1})

Notably larger cross section for 2-jet inclusive than for 2-jet exclusive
→ presence of a relatively hard third jet in quite a large fraction of events.

Dependence on the jet p_T cut



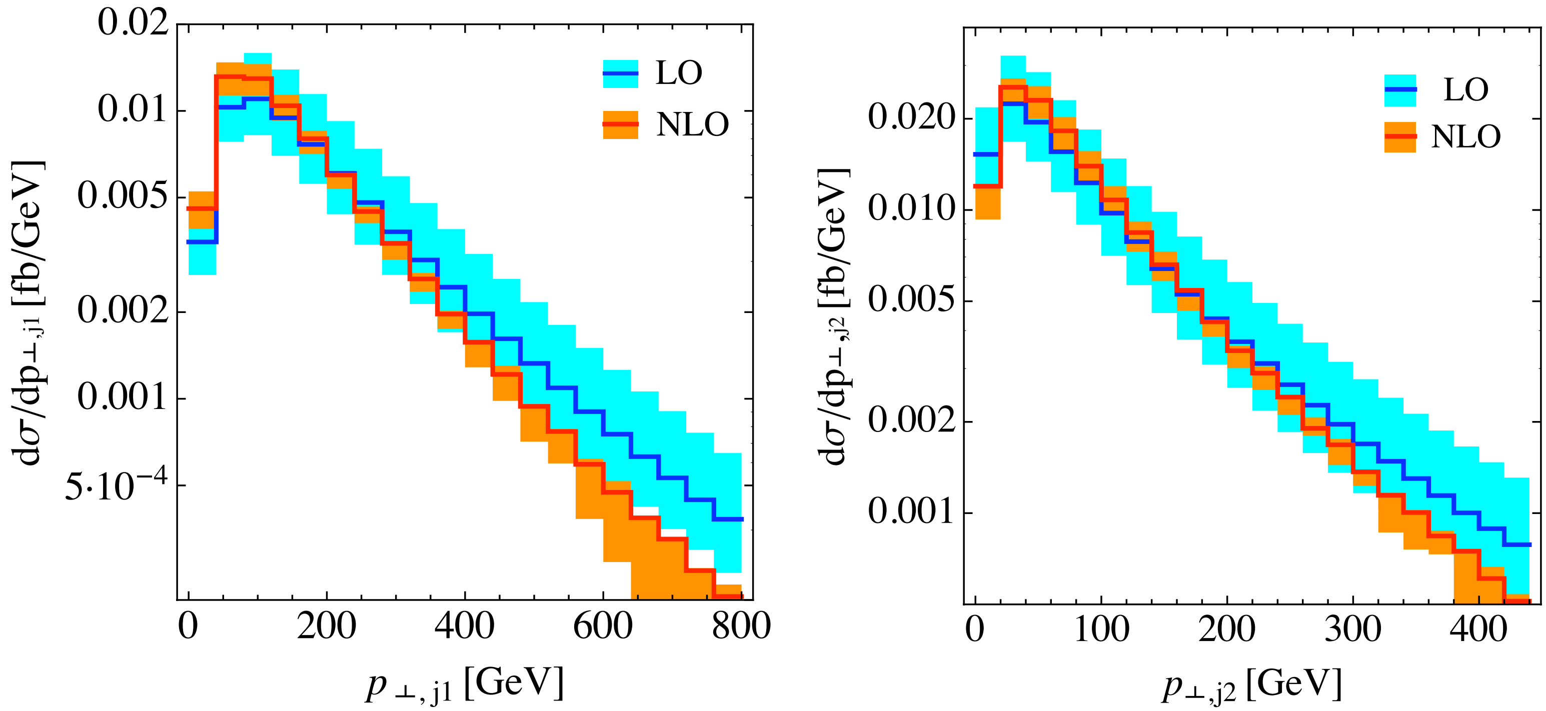
Here μ is varied between 100GeV and 200GeV, and the central value is 140GeV.

Shows reduction in scale dependence for a jet cut >40-50 GeV.

Whatever the exact value of exclusive 2 jet cross-section, still significantly less than the 2 jet inclusive.

Kinematic Distributions

In all of the following predictions, the solid line gives $\mu = 150$GeV, where the bands show theoretical uncertainty with μ varied between 50GeV and 400GeV.



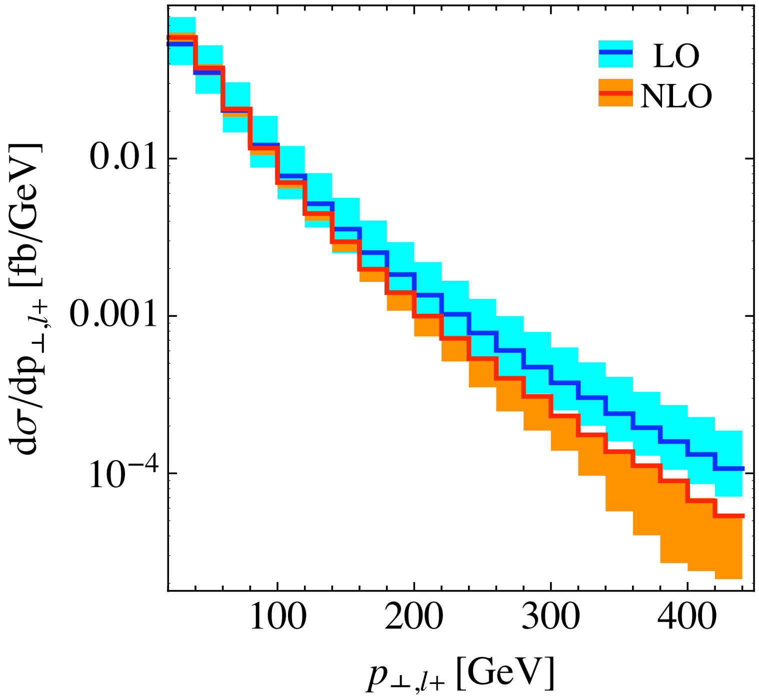
Jet distributions

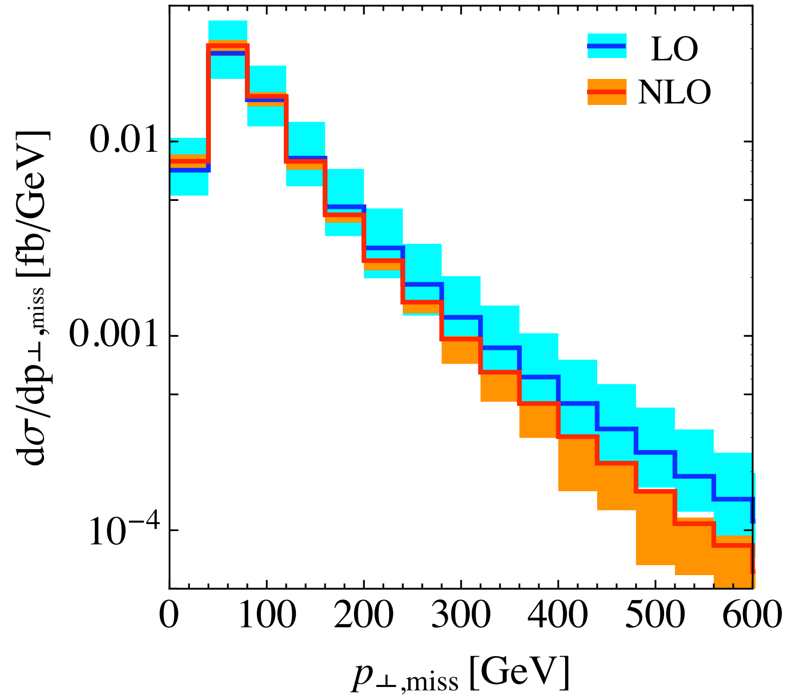
Reduction in uncertainty due to scale μ in going from LO to NLO.

Typical p_T of hardest jet (left *diag.*) is ∼60GeV; second hardest ∼40GeV.

LO overshoots the NLO prediction at high p_T. This is a characteristic effect of using a fixed rather than a dynamical scale in LO calculation.

Kinematic Distributions



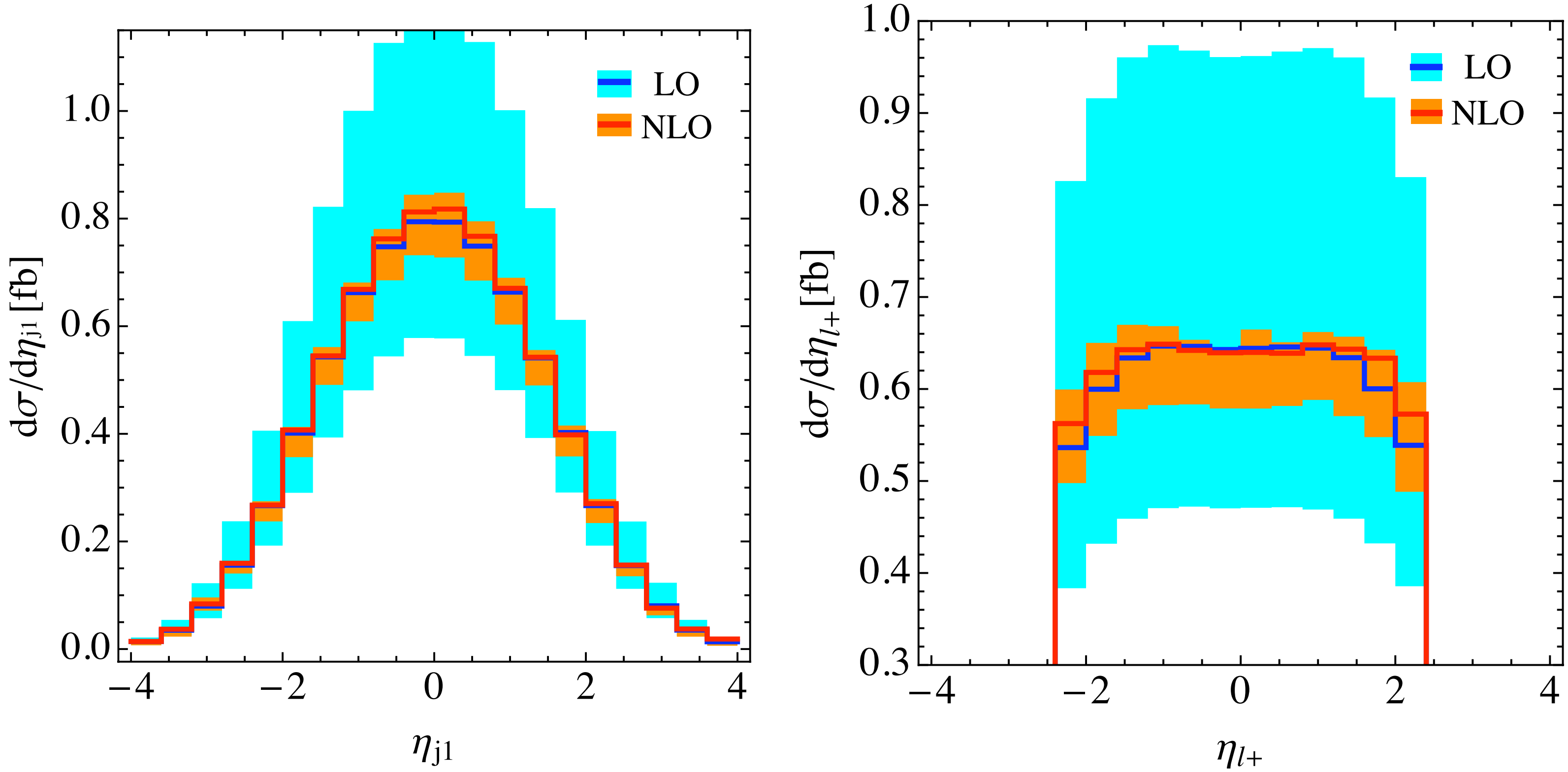


Lepton distributions

p_T of l^+ (left *diag.*) and missing p_T (right *diag.*).

Very similar effects to the jet p_T distributions.

Kinematic Distributions

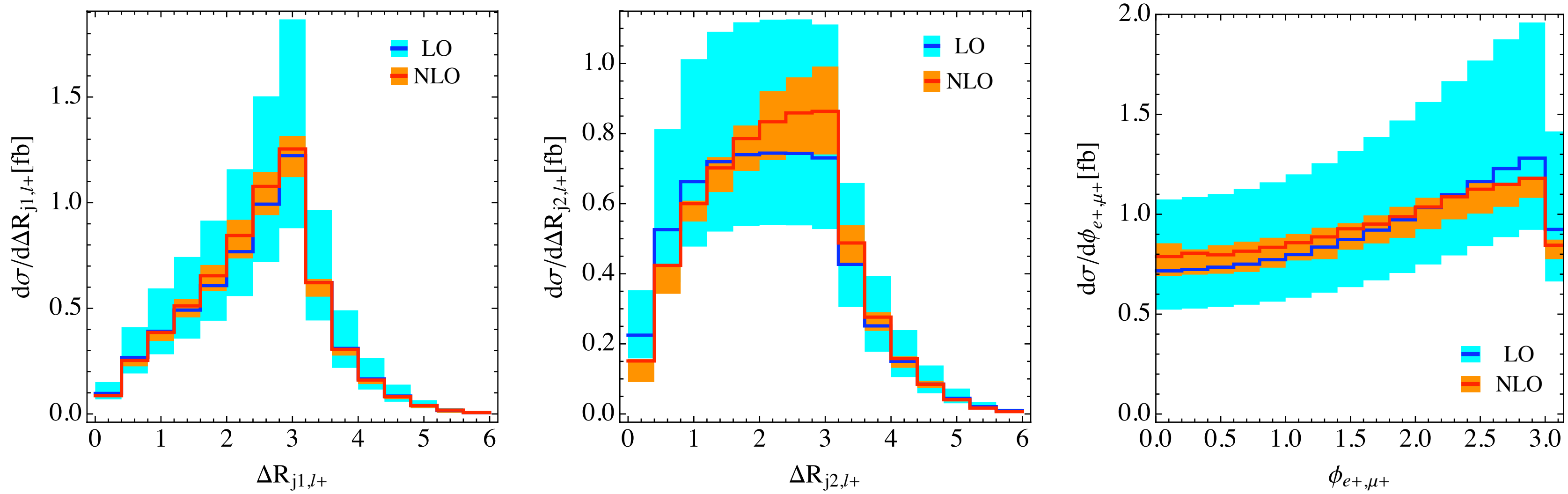


Rapidity distributions

Hardest jet rapidity (left *diag.*) and lepton rapidity (right *diag.*).

Very similar shapes at LO and NLO, but significant reduction in scale uncertainty.

Kinematic Distributions



Angular distributions

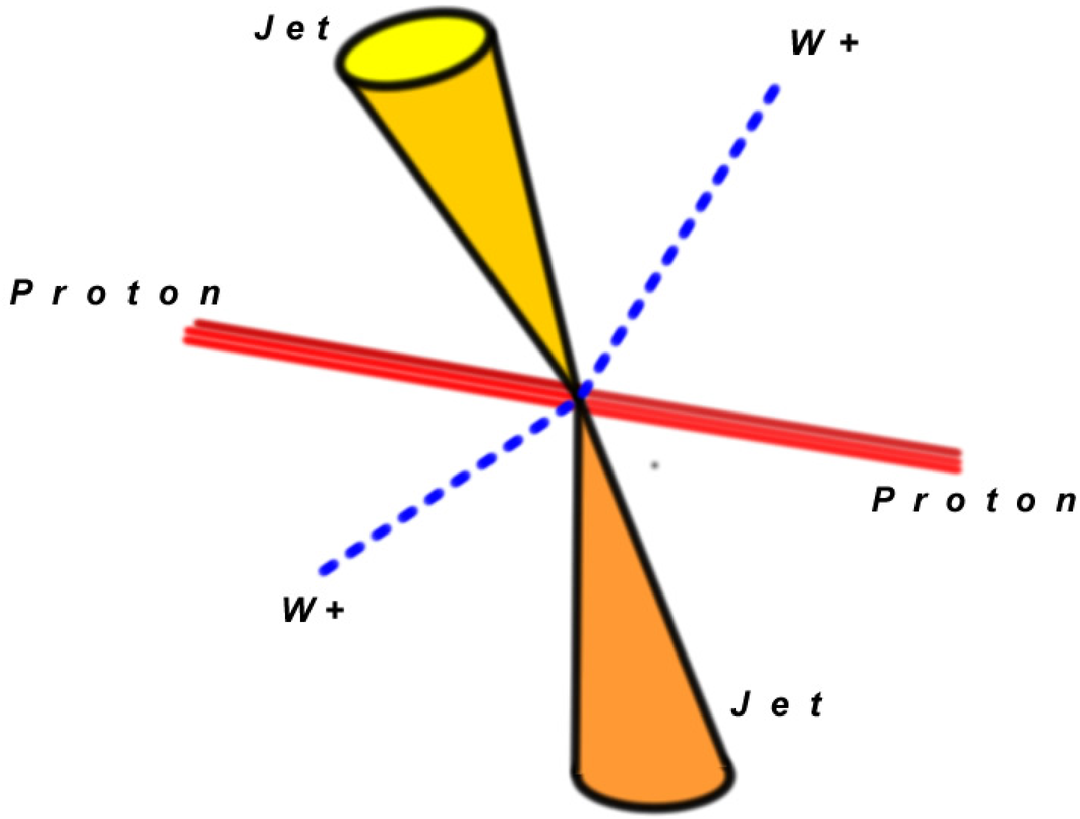
Showing $\Delta R_{j1,l}$, $\Delta R_{j2,l}$ and ϕ_{ll}.

Broad angular distribution between jet and lepton, peaking at ΔR=3. NLO enhances this peak slightly.

Leptons prefer to be back-to-back (less so at NLO).

In DPS lepton directions are uncorrelated - cut on ϕ_{ll} would reduce background.

4. Outlook



Presented a calculation of an interesting process with a distinct signature.

Look forward to measurements at the LHC!