Progress on the POWHEG implementation of Chargino/Neutralino pair production in HERWIG++

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Motivation

- LO predictions give only the order of magnitude estimate of total cross sections and a qualitative prediction for some event shapes, and they have large scale variation.
- NLO normalisation, and better high-p_T behaviour of (real emission-sensitive) event shapes required.
- BSM processes commonly produce only modest cross sections. To see them we need to reduce the "theory error" (i.e. scale variation) of both the signal and the background cross sections.
- If SUperSYmmetry (SUSY) is broken softly (so that it still solves the hierarchy problem) we should be able to produce and detect SUSY particles at the LHC. A smoking gun signal: the trilepton signature (see later).

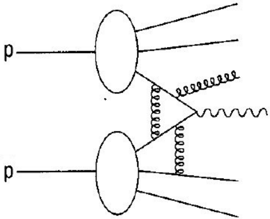
NLO corrections

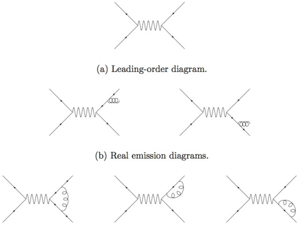
Full NLO hadronic cross sections receive QCD radiative corrections from two sources:

- The real emission and virtual corrections to the Matrix Element (ME).
- The NLO corrections to the Parton Distribution Functions (PDFs).

We will schematically review the NLO QCD corrections to Drell-Yan following [1].

NLO corrections to ME and factorisation





(a) Leading-order diagram.

(b) Real emission diagrams.

(c) Loop diagrams.

$$\sigma(p\bar{p} \to W^+ + j) = \sum_{i,j} \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2 \left[q_i(x_1)\bar{q}_j(x_2) + \bar{q}_i(x_1)q_j(x_2)\right] \hat{\sigma}(p\bar{p} \to W^+ + j) \; + \; \underbrace{\mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)}_{\text{higher twist}}$$

- This factorisation has been proven to all orders for Drell-Yan. [2]
- Must consider initial gluon real emission diagrams too.

- We want terms of $\mathcal{O} \leq \alpha_S$.
- $\alpha_S \propto g_S^2$, factor of g_S for every strong vertex.

$$|\mathcal{M}^{NLO}|^2 = |\mathcal{B} + \mathcal{V}|^2 + |\mathcal{R}|^2 = |\mathcal{B}|^2 + |\mathcal{V}|^2 + 2Re(\mathcal{B}\mathcal{V}^*) + |\mathcal{R}|^2$$

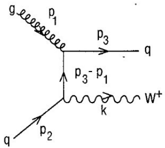
- Therefore:
  - $|\mathcal{B}|^2 \propto \alpha_S^0$,
  - $2Re(\mathcal{B}\mathcal{V}^*) \propto \alpha_S$
  - $|\mathcal{R}|^2 \propto \alpha_S$
  - $|\mathcal{V}|^2 \propto \alpha_S^2$

So to Next-to-Leading-Order (NLO):

$$|\mathcal{M}|^2_{NLO} = |\mathcal{B}|^2 + 2Re(\mathcal{B}\mathcal{V}^*) + |\mathcal{R}|^2$$

The origin of IR singularities: quark emission

Consider a quark emission diagram:



- Quark propagator goes as:

$$\frac{i}{\not{p}_3 - \not{p}_1} = -i\frac{\not{p}_3 - \not{p}_1}{2p_1 \cdot p_3} \sim \frac{1}{2E_1 E_3 (1 - \beta \cos\theta)}$$

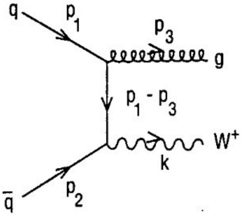
  where $\beta = v/c$. The collinear singularity is evident as $\theta \to 0$ ($\beta \sim 1$).
- Soft singularity as $E_3 \to 0$ is in fact not present here as spinor $\bar{u}(p_3) \to 0$ as $p_3 \to 0$ (for massless quark).
- In fact it turns out that in this case $|\mathcal{M}|^2 \sim \frac{1}{2p_1 \cdot p_3}$, so that (if we momentarily allow for quark masses) the angular phase space integral over $z = \cos\theta$ gives

$$\hat{\sigma} \sim \int_{-1}^{1} dz |\mathcal{M}|^2 \sim \int_{-1}^{1} dz \frac{1}{1 - \beta z} \sim \frac{1}{\beta} \ln\left(\frac{1+\beta}{1-\beta}\right) \xrightarrow{\beta \to 1} \ln\frac{4E_3^2}{m^2}$$

- In general: Collinear divergence $\Longrightarrow \ln\frac{E^2_{\text{emitted}}}{m^2}$
- Using massless quarks and dimensional regularisation, $\ln m^2 \Longrightarrow 1/\epsilon$ (collinear singularity), and $\ln E_3^2 \Longrightarrow \ln\frac{M_W^2}{Q^2}$ (collinear logarithm).

The origin of IR singularities: gluon emission

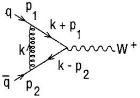
- Consider the real emission diagram which is equivalent to the previous diagram by crossing symmetry:



- The propagator here has the same form as previously but now a soft singularity exists too as the gluon goes soft, $E_3 \longrightarrow 0$.
- This is in fact a soft and collinear singularity, as the soft limit $p_3 \longrightarrow 0$ is a special case of the collinear limit $p_3 \propto p_1$.

The origin of IR singularities: virtual corrections

- Similarly, virtual diagrams (such as this vertex correction) have singularities too[1].



- The loop integral goes as

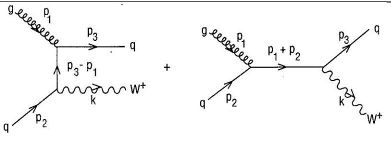
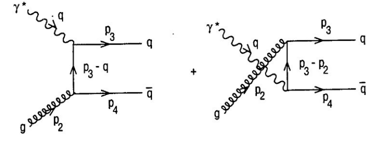
$$\int d^4k \frac{1}{k^2(k+p_1)^2(k-p_2)^2} = \int d^4k \frac{1}{k^2(k^2+2k\cdot p_1)(k^2-2k\cdot p_2)^2}$$
$$\sim \begin{cases} \frac{1}{k^2 2k\cdot p_1 2k\cdot p_2} \sim \frac{1}{k^4} & \text{for } k \to 0 \\ \frac{1}{k^2 k^2 2p_1\cdot p_2} \sim \frac{1}{k^4} & \text{for } k \propto p_1 \implies k^2 \to 0 \end{cases}$$

where $d^4k \sim k^3 dk$.

- So we see that in both of these limits we get a logarithmic divergence.
- The top case is a soft singularity and the bottom case is a collinear singularity (there is an analogous one also in the $k \propto p_2$ limit).

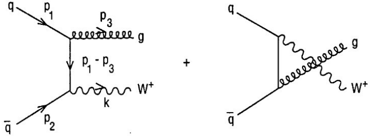
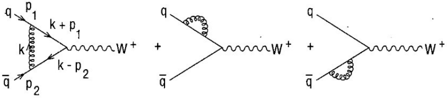
[1] Virtual corrections have UV divergences too, but they cancel when the vertex correction and the self energies of both incoming quarks are added together.

Initial gluon corrections

Diagrams	IR Singularities in $\Delta\sigma$	Logs
	$-\frac{1}{\epsilon}$	$\ln M_W^2$
	$+\frac{1}{\epsilon}$	$\ln Q^2$

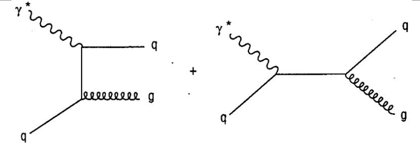
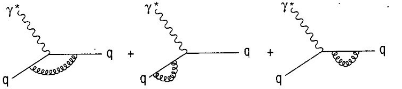
- When these two contributions are put together the collinear singularities $1/\epsilon$ cancel and the logs combine to give a term proportional to $\alpha_S \ln \frac{M_W^2}{Q^2}$.
- This log is large and spoils our perturbative expansion. It can be cancelled out to restore our expansion in α_S (see later).

Initial $q\bar{q}$ corrections: ME

Diagrams	IR Singularities in $\Delta\sigma$	Logs
	$\frac{2}{\epsilon^2}, \; -\frac{2}{\epsilon}$	None
	$-\frac{2}{\epsilon^2}, \; -\frac{3}{\epsilon}$	None

- When the real and virtual corrections to the ME are combined the soft and collinear singularity $(1/\epsilon^2)$ cancels but the collinear one remains. This will cancel with the collinear singularity in the PDF corrections on the next slide.

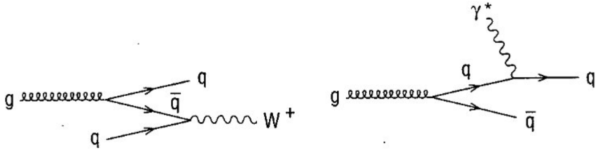
Initial $q\bar{q}$ corrections: PDFs

Diagrams	IR Singularities in $\Delta\sigma$	Logs
	$\frac{2}{\epsilon^2}, \frac{2}{\epsilon}$	None
	$-\frac{2}{\epsilon^2}, \frac{3}{\epsilon}$	None

- Once again when the corrections are combined the soft and collinear singularity $(1/\epsilon^2)$ cancels but the collinear one remains. This cancels the leftover collinear singularity in the PDF corrections on the previous slide and we are left with an IR-finite cross section, as desired.

Cancellations and logs

- Physically the cancellation of the collinear singularities (for example between the initial gluon corrections to the ME and the PDFs) can be understood intuitively: In the collinear limit the $g \longrightarrow q\bar{q}$ splitting factorizes from both and cancels when they are combined:



- The $\ln \frac{M_W^2}{Q^2}$ logs can be cancelled by evolving the PDFs used via the DGLAP equation from the scale they were measured at, Q^2, to the scale of the problem at hand, M_W^2: $q(x, Q^2) \longrightarrow q(x, M_W^2)$.
- Then using the explicit NLO expression for $q(x, M_W^2)$ to compute the hadronic cross section cancels the problematic logs.

The POWHEG Method

- The POsitive Weight Hardest Emission Generator (POWHEG) Method was proposed by P. Nason in 2004 (see [3]).
- Using this method the NLO cross section can be written as:

$$d\sigma = \overline{B}\left(\phi_n\right)\ d\phi_n \left[\Delta\left(0\right) + \frac{R\left(\phi_n, \phi_1\right)}{B\left(\phi_n\right)}\Delta\left(k_T\left(\phi_n, \phi_1\right)\right)\ d\phi_1\right]$$

- where the (positive definite) function $\bar{B}$ is defined as:

$$\overline{B}\left(\phi_n\right) = B\left(\phi_n\right) + V\left(\phi_n\right) + \int d\phi_1 \{R\left(\phi_n, \phi_1\right) - \sum_\alpha C_\alpha\left(\phi_n, \phi_1\right)\}$$

  and we have redefined the Sudakov form factor as:

$$\Delta\left(p_T\right) = \exp\left[-\int d\phi_1 \frac{R\left(\phi_n, \phi_1\right)}{B\left(\phi_n\right)}\theta\left(k_T\left(\phi_n, \phi_1\right) - p_T\right)\right]$$

- The difference between the POWHEG Method and the conventional parton shower is that $\overline{B}$ is used instead of B (thus guaranteeing positive weights) and that the R in the Sudakov is the full real emission contribution and not just an approximation to it in the soft and collinear limits.

Now lets apply these methods to do phenomenology. We will do cases that involve only initial state radiation.

SUSY

- The S-matrix in QFT has all the symmetries of the Poincarè group for bosonic operators. One symmetry more is possible if we allow for fermionic operators: Supersymmetry.
- Under this symmetry: (fermion) $\xrightarrow{\text{SUSY}}$ (boson), and viceversa.
- As with any other theory, SUSY is fully specified by a Lagrangian (see below) and the gauge charges assigned to the fields (see next slide).
- The Lagrangian has 3 parts:
  - Kähler potential $\Longrightarrow$ fermion kinetic terms.
  - Supersymmetric field strength term $\Longrightarrow$ gauge kinetic terms.
  - Superpotential $\Longrightarrow$ interaction terms (Yukawas, etc).
- Not much freedom in the kinetic terms, but the most general, renormalisable Superpotential with R-parity (i.e. no lepton or baryon number violating terms) is the one which defines the MSSM:

$$W_{\text{MSSM}} = Y_u Q H_u U^c + Y_d Q H_d D^c + Y_L L H_d E^c + \mu H_u H_d$$

MSSM

Turn usual SM fields into superfields with the following charge assignments:

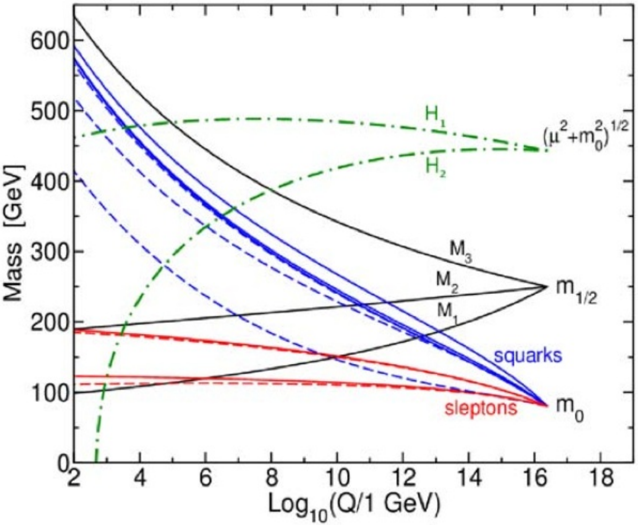
	LHχSF	spin 0	spin $\frac{1}{2}$	$(SU(3), SU(2), U_Y(1))$
squarks and quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, \frac{1}{6})$
	U	$\tilde{u}_R^\dagger$	$u_R^\dagger$	$(\bar{3}, 1, -\frac{2}{3})$
	D	$\tilde{d}_R^\dagger$	$d_R^\dagger$	$(\bar{3}, 1, \frac{1}{3})$
sleptons and leptons	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(1, 2, -\frac{1}{2})$
	E	$\tilde{e}_R^\dagger$	$e_R^\dagger$	$(1, 1, 1)$
higgs and higgsinos	H_u	(h_u^+, h_u^0)	$(\tilde{h}_u^+, \tilde{h}_u^0)$	$(1, 2, \frac{1}{2})$
	H_d	(h_d^0, h_d^-)	$(\tilde{h}_d^0, \tilde{h}_d^-)$	$(1, 2, -\frac{1}{2})$

Note that this (and the fact that SUSY generators commute with all gauge group generators) implies that sparticles have all the same gauge group charges as their SM counterparts.

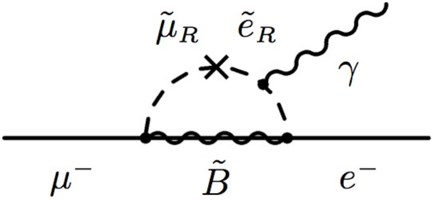
CMSSM

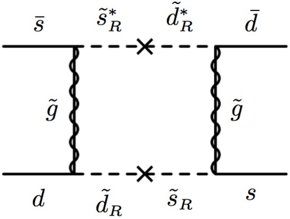
- Unbroken MSSM has 18 free parameters. SUSY breaking introduces 105 new parameters.
- Despite experimental constraints and theoretical prejudices, this parameter space is huge. To make it more tractable reduce the number of free parameters by making assumptions.
- The following assumptions reduce the number of free parameters to 4 parameters and a sign. This defines the Constrained MSSM (CMSSM) and the framework within which we will work.
  - Universality of gaugino masses at GUT scale: $M_1 = M_2 = M_3$ are set to $m_{1/2}$ at the GUT scale.
  - Universality of scalar masses at GUT scale: $m_Q = m_{U^c} = M_{D^c} = m_L = m_{E^c}$ are set to m_0.
  - Trilinear scalar couplings are set to A_0 at the GUT scale.
  - $\tan\beta$.
  - The sign of μ.

Mass and coupling RGE in the CMSSM



Flavour violation in the CMSSM

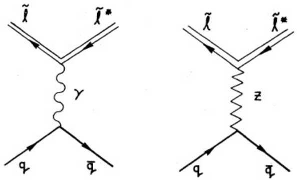




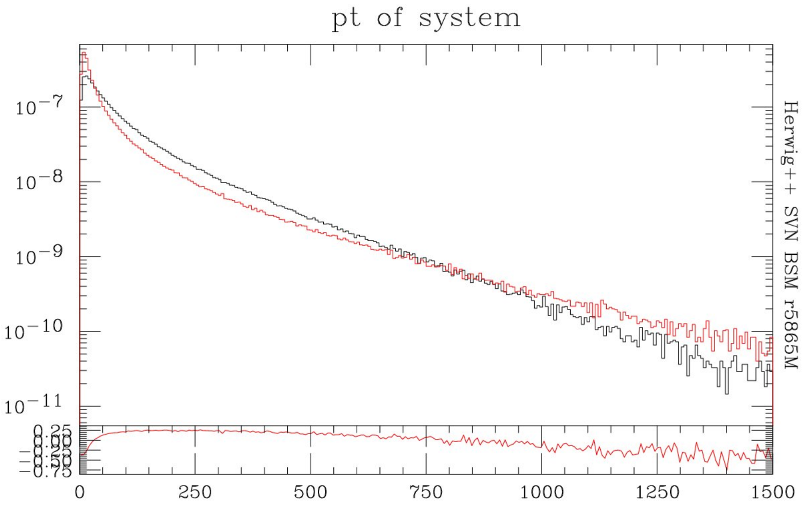
- $\mathrm{Br}(\mu \to e\gamma) < 10^{-11}$
- Similar experimental constraints for $K - \bar{K}$ mixing.

Slepton Pair Production Results

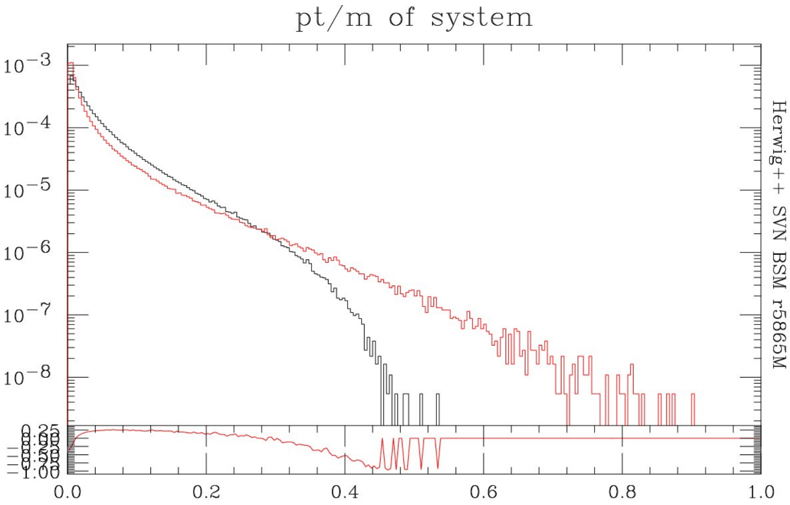
- The K factor for most slepton pair production processes is ~ 1.2.
- LO and NLO results now in agreement with Prospino. Differences of $\mathcal{O}(0.01\%)$.
- In general, cross sections $\mathcal{O}(1 \text{ fb})$.



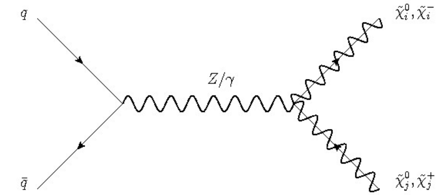
Plots

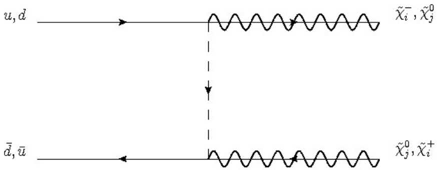

pt of system
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.25
0.00
−0.25
−0.50
−0.75
0
250
500
750
1000
1250
1500
Herwig++ SVN BSM r5865M

Plots

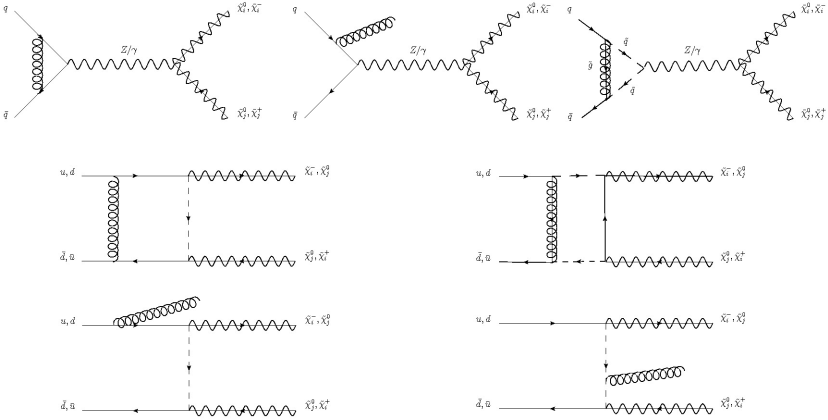

pt/m of system
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Herwig++ SVN BSM r5865M
0.25
0.50
0.75
1.00
0.0
0.2
0.4
0.6
0.8
1.0

LO diagrams


q
$\bar{q}$
Z/γ
$\tilde{\chi}_i^0, \tilde{\chi}_i^-$
$\tilde{\chi}_j^0, \tilde{\chi}_j^+$


u, d
$\bar{d}, \bar{u}$
$\tilde{\chi}_i^-, \tilde{\chi}_j^0$
$\tilde{\chi}_j^0, \tilde{\chi}_i^+$

NLO diagrams



Motivation: The trilepton signal

Process	$\sigma(\text{bkgd})/\sigma(\text{sig})$	What it has	What it needs
$WZ \to lll\nu$ $ZZ \to llll$ $WW \to ll\nu\nu$	$\sim$1	$3l + \not{E}_{\mathrm{T}}$ $\geq 3l$ $2l + \not{E}_{\mathrm{T}}$	- $\not{E}_{\mathrm{T}}$ one l
$t\bar{t} \to WbWb$	$\sim$10	$2l + \not{E}_{\mathrm{T}}$	one l
Drell-Yan$\to ll$ $Z\gamma \to ll\gamma$	$\sim$1000 $\sim$30	$2l$ $\geq 3l$	one $l + \not{E}_{\mathrm{T}}$ $\not{E}_{\mathrm{T}}$
$W \to l\nu$	$\sim$5000	one $l + \not{E}_{\mathrm{T}}$	two l

Figure: The signal to SM background ratios for the trilepton signal at the Tevatron. [4]

The trilepton signature

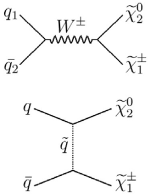


Figure: Tree level production of a Chargino and Neutralino pair.

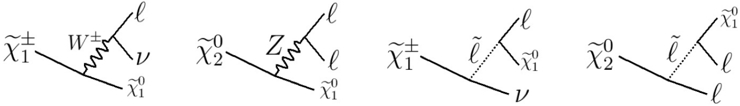
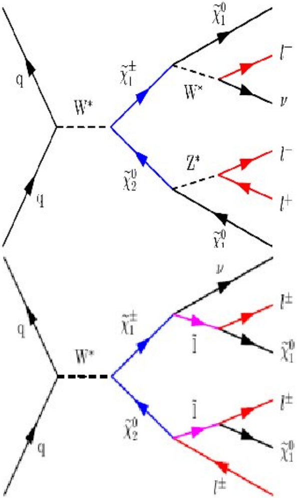


Table: Chargino and Neutralino trilepton decay modes.



q
q
W*
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$
l^-
W*
ν
Z*
l^-
l^+
$\tilde{\chi}_1^0$
q
q
W*
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
ν
$l^{\pm}$
$\tilde{l}$
$\tilde{\chi}_1^0$
$\tilde{l}$
$l^{\pm}$
$\tilde{\chi}_1^0$
$l^{\pm}$

Outlook

Done:

- LO Neutralino pair production ME has been written and validated against Prospino 2.1.
- NLO Neutralino pair production is getting there...

To do:

- Finish validation of Chargino-Neutralino LO ME.
- Write NLO Chargino-Neutralino ME.
- Validate both LO and NLO Chargino-Neutralino MEs against POWHEG.
- Use the finalised NLO POWHEG MEs to perform physics studies for the trilepton signature at the LHC.

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