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Electroweakino pair production at the LHC in the POWHEG-BOX

GDR Terascale Workshop, **LPTHE Paris**

Julien Baglio | 24/11/2016

INSTITUT FÜR THEORETISCHE PHYSIK

Outline

1. Introduction
2. Electroweakino pair production at the LHC
3. Prospects

Why going beyond the Standard Model?

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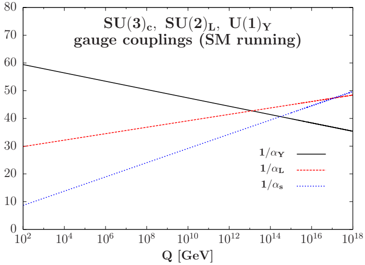
The Standard Model (SM) cannot be complete:

- Gauge interactions unification:

  How to unify strong (QCD) and electroweak (EW) interactions ? How to include gravity in the picture?



- Experimental issues:

  No satisfactory explanation for the baryonic asymmetry, no **dark matter candidate**, no satisfactory mechanism to generate neutrino masses

- Naturalness problem:

  How to stabilize the theoretical prediction of the Higgs boson mass? How to avoid the fine-tuning of the parameters?

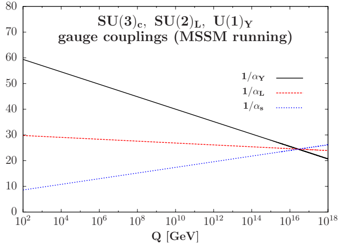
$$\Delta M_H^2 = \frac{3\Lambda_{\rm NP}^2}{8\pi^2 v^2}\left(M_H^2 + 2M_W^2 + M_Z^2 - 4M_t^2\right)$$

Supersymmetry (SUSY) offers avenues in order to answer some of these pressing questions

SUSY = fermion ↔ boson symmetry

The virtues of supersymmetry

- Unification: QCD and EW unification at the Grand Unification Theory (GUT) scale $M_{\mathrm{GUT}} \simeq 10^{16}$ GeV



New particles:

One SM fermion $\Leftrightarrow$ one new spin 0 boson (squarks, sleptons)

One SM boson $\Leftrightarrow$ one new fermion

- Dark matter candidate: SUSY + R parity
  $\Rightarrow$ **Lightest supersymmetric partner (LSP) stable**

- Naturalness: for a given SM particle,
  (standard quantum correction) = – (supersymmetric quantum correction)
  $\Rightarrow$ Higgs boson mass protected by SUSY

• **Minimal field content:** The Minimal Supersymmetric Standard Model (MSSM) with 2 Higgs doublets $\Rightarrow$ 5 Higgs bosons in the spectrum

MSSM electroweakino pair production at the LHC in the POWHEG-BOX

[J.B., B. Jäger, M. Kesenheimer, JHEP 07 (2016) 083]

SUSY spectrum

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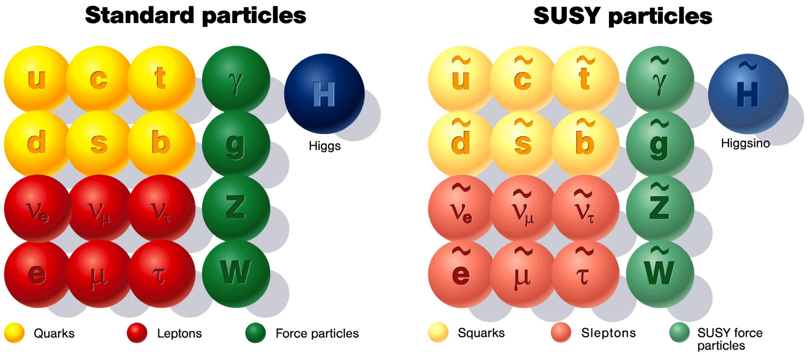
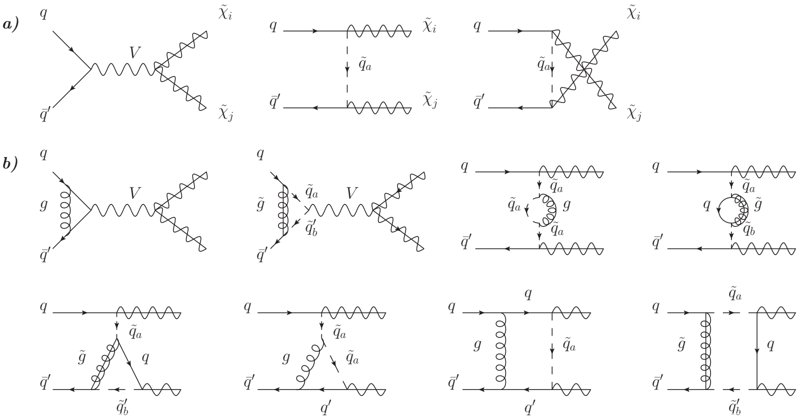
SUSY is broken: the spectrum is doubled



- Cancel gauge anomalies $\Rightarrow$ Two Higgs doublets in the minimal extension of the Standard Model, the MSSM
- Mixing in the SUSY electroweak sector $\Rightarrow$ $(\tilde{\gamma}, \tilde{Z}, \tilde{W}^{\pm}, \tilde{H}_{1,2}, \tilde{H}^{\pm}_{1,2}) \to \tilde{\chi}^0_{1..4}, \tilde{\chi}^{\pm}_{1,2}$

Neutralino and chargino pair production

a) Leading Order (LO): t and s-channels



b) Next-to-LO (NLO) QCD corrections: renormalization of the virtual corrections and calculation of the real corrections are needed

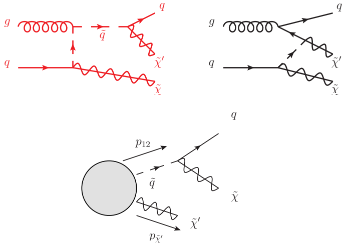
$\rightarrow$ dimensional regularization, on-shell renormalization for the quarks and squarks

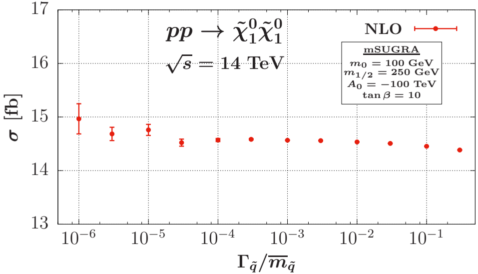
Technical subtleties at NLO

- **SUSY restoring counterterm:** NLO corrections calculated in the $\overline{\text{MS}}$-scheme $\Rightarrow$ SUSY broken hard in the gauge sector
  $\Rightarrow$ add a counterterm to restore SUSY between $\tilde{h}/q/\tilde{q}^*$ and $H/q/\bar{q}$ couplings [Martin, Vaughn, PLB 318 (1993) 331; Hollik, Stöckinger, EPJC 20 (2001) 105; Beenakker *et al*, PRL 83 (1999) 3780]:

$$\hat{g}_2 = g_2\left(1 - \frac{\alpha_s}{6\pi}\right)$$

- **On-shell subtraction term:** subtract on-shell $gq \to \tilde{q}^*\tilde{\chi} \to q\tilde{\chi}'\tilde{\chi}$ to avoid double counting [Beenakker *et al*, Nucl.Phys. B492 (1997) 51]





$$d\sigma^{\rm OS} = \theta(\hat{s} - (m_{\tilde{q}} + m_{\tilde{\chi}})^2)\theta(m_{\tilde{q}} - m_{\tilde{\chi}'})\frac{m_{\tilde{q}}^2\Gamma_{\tilde{q}}^2}{(p_{12}^2 - m_{\tilde{q}}^2)^2 + m_{\tilde{q}}^2\Gamma_{\tilde{q}}^2}|\mathcal{M}_{\tilde{q}}|^2\Big|_{\text{OS mapped}}$$

Infrared divergences in a Monte-Carlo code

How to handle infrared (IR) divergences in cross–section calculation? Soft and collinear singularities may arise, notably cumbersome as arising in different phase–spaces
⇒ subtraction method to handle them!

$$\sigma^{\rm NLO} = \int_{\phi_n} d\sigma^{\rm Born} + \int_{\phi_n} d\sigma^{\rm virt} + \int_{\phi_{n+1}} d\sigma^{\rm real}$$

with each contribution divergent ⇒ cancel soft & collinear singularities before Monte-Carlo integration:

$$\sigma^{\rm NLO} = \int_{\phi_n+1} \left(d\sigma^{\rm real}|_{\varepsilon=0} - d\sigma^{A}|_{\varepsilon=0} \right) + \int_{\phi_n} \left(d\sigma^{\rm Born} + d\sigma^{\rm virt} + \int_{\phi_1} d\sigma^{\rm A} \right) |_{\varepsilon=0}$$

where $d\sigma^{\rm A}$ a subtraction term with the following properties:

- $d\sigma^{\rm A}$ cancels soft & collinear divergences of $d\sigma^{\rm real}$
- $\int_{\phi_1} d\sigma^{\rm A}$ done (partially) analytically in d dimensions ⇒ universal operators, left–over collinear singularities absorbed into PDFs

Example of a subtraction scheme, the FKS scheme [Frixione, Kunszt, Signer, Nucl.Phys. B467 (1996) 399]: real emission written as a sum of terms with at most one collinear and one soft singularities for one given parton

Scale uncertainty at NLO in QCD

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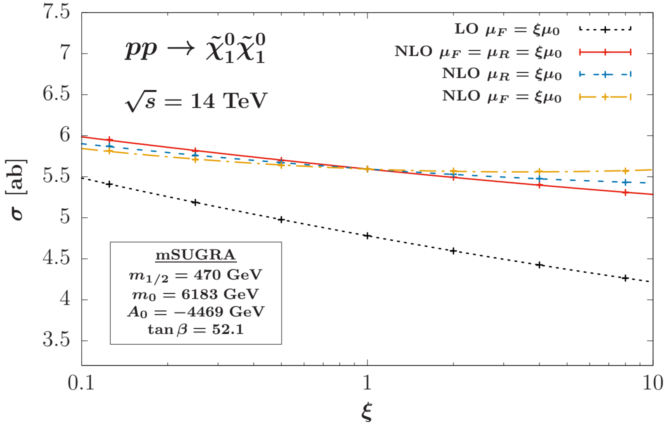
NLO SUSY-QCD corrections: +15% to +20%



Scale uncertainty $\Delta^\mu \sim \pm 3\%$ for $\xi \in [0.5\,;2] \Rightarrow$ **scale dependence stabilized**

From the hard event to the actual event

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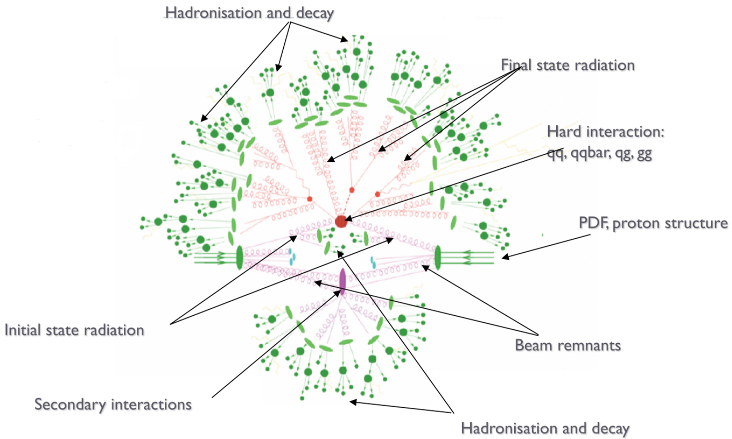
Predicting and simulating a LHC event is a formidable task!



(from P. Skands and F. Krauss)

The hard cross section is only one part of the game...

$\Rightarrow$ Parton-Shower (PS) program to handle the initial state and final state radiations

From the hard event to the actual event

POWHEG: Positive Weight Hardest Emission Generator

[Frixione, Nason, Oleari, JHEP 0711 (2007) 070]

- **The idea:**
  - NLO QCD accuracy for hard cross section, but bad description of the soft radiation (initial and/or final state)
  - Good description of soft radiation in PS programs, but LO accuracy

  $\Rightarrow$ combine the two approaches while avoiding double-counting

- **The POWHEG solution:** start with the NLO hard cross section which has the hardest radiation at NLO accuracy, then shower the subsequent p_T-ordered softer radiation

- **The POWHEG-BOX:** a practical computer framework to interface a NLO QCD hard cross section to the POWHEG method [Alioli, Nason, Oleari, Re, JHEP 1006 (2010) 043]

Flow of our implementation in the POWHEG-BOX

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- **Tools:**

  → FASTJET [Cacciari, Salam, Soyez, EPJC 72 (2012) 1896] for the jet combination, $R = 0.5$ and $|\eta^{\rm jet}| < 4.5$

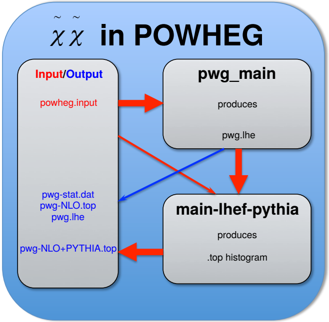
  → PYTHIA6.6 [Sjöstrand, Mrenna, Skands, JHEP 05 (2006) 026] for the parton shower

- **Additional tools for the physical parameters:**

  → SuSpect [Djouadi, Kneur, Moultaka, CPC 176 (2007) 426] for the mass spectrum (Les Houches file [Skands *et al*, JHEP 07 (2004) 036; Allanach *et al*, CPC 176 (2007) 426])

  → SDECAY [Mühlleitner, Djouadi, Mambrini, CPC 168 (2005) 46] for the decay widths and branching fractions (Les Houches file)

- **Flow of the program:**



→ **pwg_main:** calculates the total XS, fixed NLO histograms and Les Houches Event (LHE) file pwg.lhe

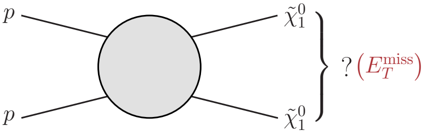
→ **main-lhef-pythia:** showers the LHE file with PYTHIA, produces the NLO+PS histograms

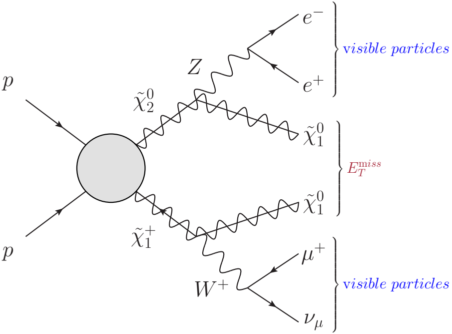
→ **(LO) decays can be simulated within PYTHIA**

Strategy for $\tilde{\chi}_1^0$ search

1. **Direct pair production:** the most straightforward way to produce DM at the LHC is $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \Rightarrow$ lots of $E_T^{\rm miss}$ **but lacks of a tagging particle to 'see' the process**
   $\Rightarrow$ production with an additional jet would be much better

2. **DM as decay remnants of main production process:** to tag the production of DM, production of partner particles and then decay into LSP
   $\Rightarrow E_T^{\rm miss}$ + visible SM particles as tagger: $\boldsymbol{pp \to \tilde{\chi}_2^0\tilde{\chi}_1^+}$ **production**





NLO QCD effects on distributions

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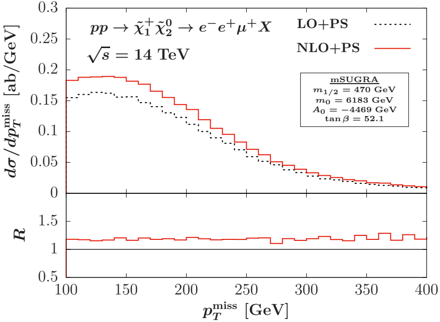
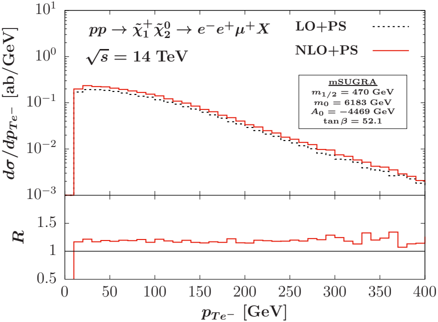
Neutralino + Chargino production:





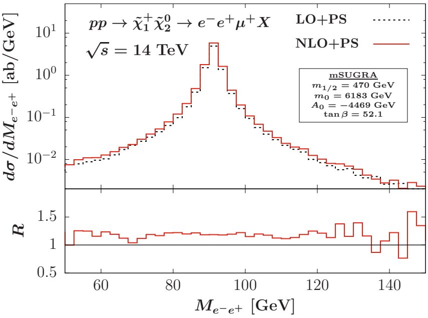
Flat QCD corrections of order $\sim +20$ %

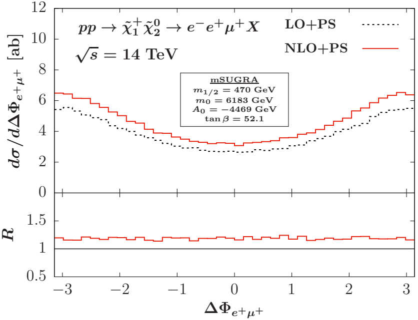
Spectrum used

$m_{\tilde{\chi}_1^0} = 207$ GeV, $m_{\tilde{\chi}_2^0} = 405.9$ GeV, $m_{\tilde{\chi}_1^\pm} = 405.8$ GeV

NLO QCD effects on distributions

Neutralino + Chargino production:





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The search for electroweakinos in ATLAS

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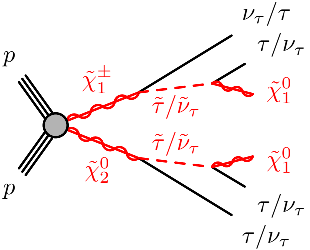
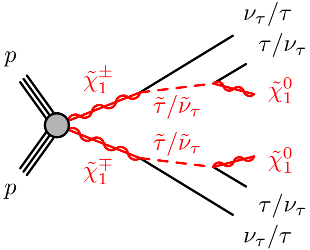
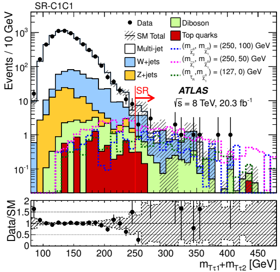
Lots of search strategies, one example: $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to x(\tau\nu_\tau) + 2\tilde{\chi}_1^0$





- **Characteristics:** two taus with opposite charge, no jets (or very low activity), large missing energy
- **Background:** $W+j$, $WW/WZ/ZZ$ production, multi-j production



The search for electroweakinos in ATLAS

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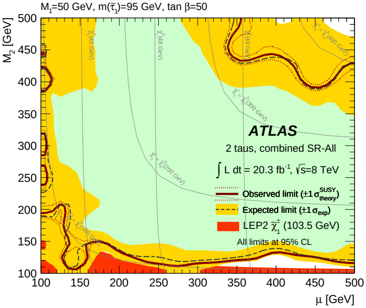
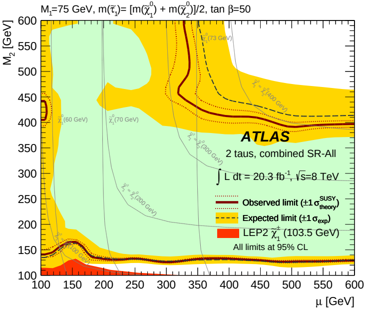
Neither charginos nor neutralinos have been seen yet at the LHC

$\Rightarrow$ Experiments give limits on SUSY parameters **depending on the model chosen for the interpretation of the results**

In [ATLAS Collaboration, JHEP 1410 (2014) 96], for example:

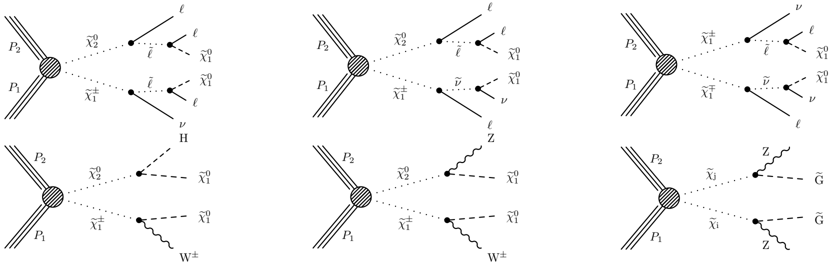
$m_{\tilde{q}}, m_{\tilde{g}}, m_{\tilde{e},\tilde{\mu}} > 3\text{TeV}, \tan\beta > 50, M_1 > 50\text{GeV}, 100 \leq \mu \leq 500$ GeV



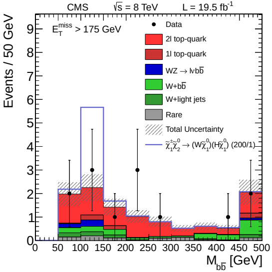


The search for electroweakinos in CMS

same as ATLAS, lots of search channels: $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0/\tilde{\chi}_1^{+}\tilde{\chi}_1^{-} \to x\ell/VV/+2\tilde{\chi}_1^0$



- Characteristics: 3 leptons/same-sign 2 leptons/ 2 leptons + 2 jets, large missing energy
- Background: $W+j$, $WW/WZ/ZZ$ production, multi-j production, Wt production, etc.



The search for electroweakinos in CMS

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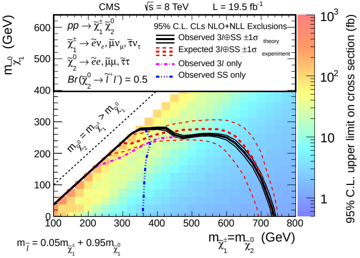
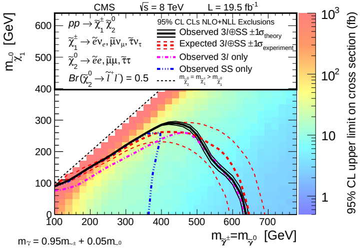
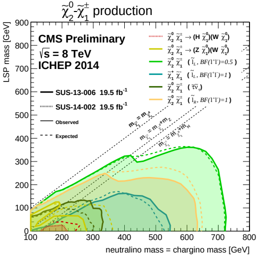
No discovery ⇒ limits on SUSY masses [CMS Collaboration, EPJC 74 (2014) 3036]

When assuming $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ and $\mathrm{BR}(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0 \to \tilde{\nu}_\ell \ell/\tilde{\ell}\ell)$ the same for all ℓ:





A summary of several channels for different assumptions:



Conclusion

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Electroweakino pair production at the LHC: now known fully differentially at NLO matched to parton shower

- **Scale dependence stabilized and low uncertainty:** $\sim \pm 3\%$ at 14 TeV
- **Resonant effects in the real corrections handled with diagram subtraction**
- **NLO QCD corrections flat and $\sim +20\%$, PS effects not sizable for non-jet observables**
- **POWHEG implementation practical:** flexible tool, user can define its own observables, generate LHE file to be showered
- **Public version of the code available with decays included!** Can be used for indirect Dark Matter production

Thanks for your attention!