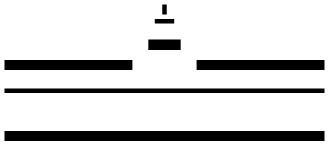
Direct SUSY Production at the LHC: Theory Status

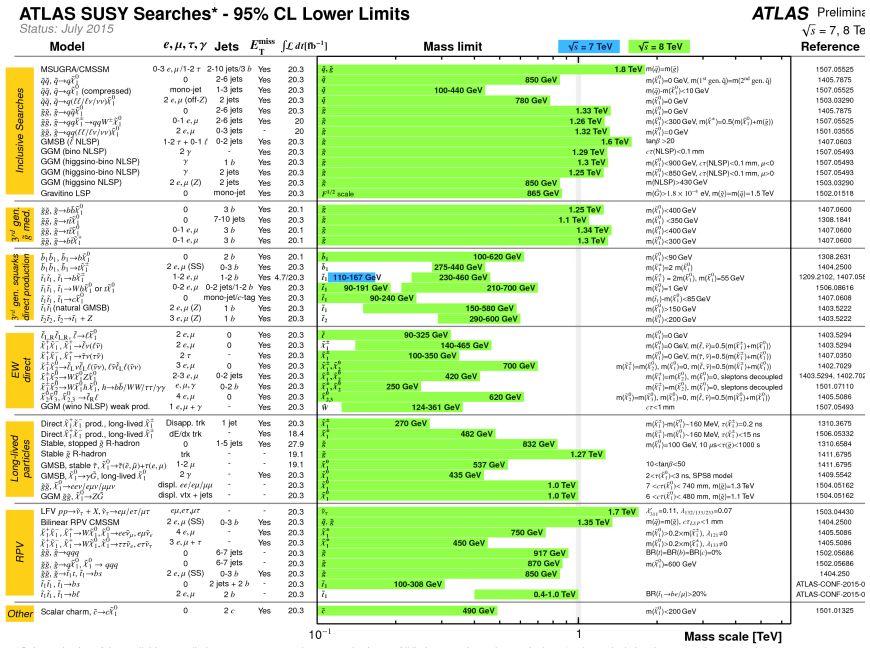
Anna Kulesza

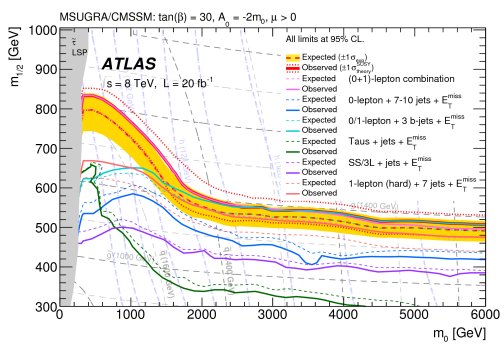


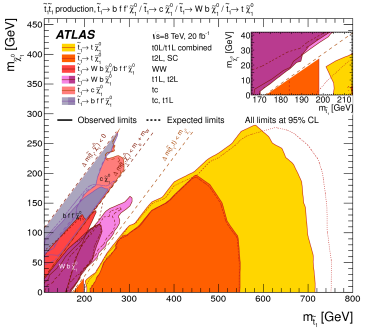
Westfälische Wilhelms-Universität Münster

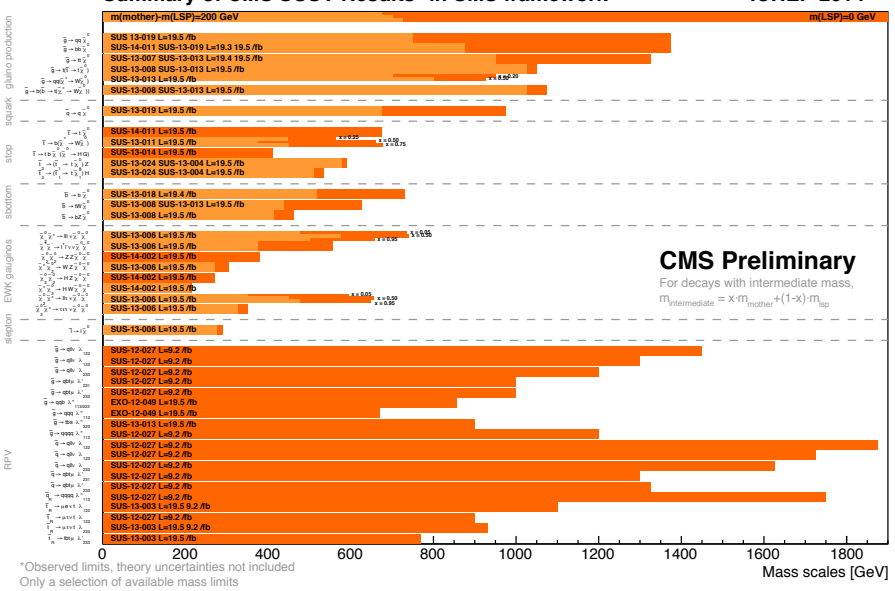
DESY Theory Workshop "Physics at the LHC and Beyond", 29.09.2015

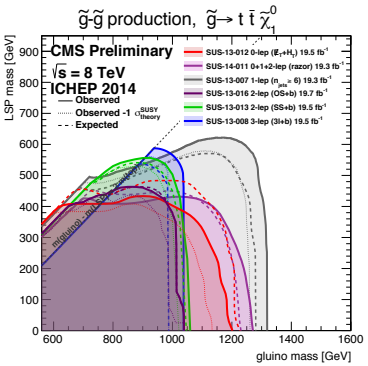
HOUSTON, WE HAVE A PROBLEM

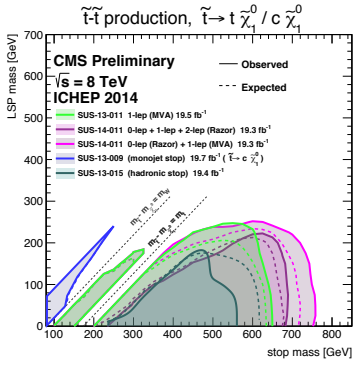






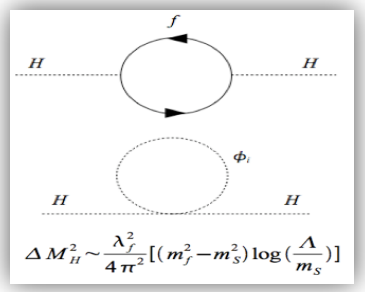


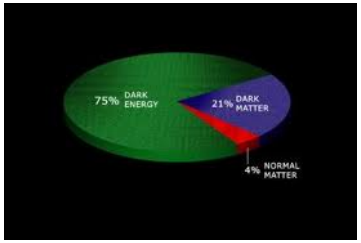


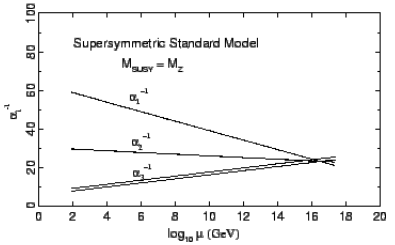


WHAT NOW?

- Negative result of the LHC Run1 SUSY searches and the SM-like Higgs boson discovery are putting natural SUSY under pressure
- Supersymmetry is still one of the most compelling theoretical frameworks for BSM physics (hierarchy problem, dark matter candidate, gauge coupling unification,..)
- Plenty of ways to reconcile information from Run1 with supersymmetry:
  - more sophisticated models
  - more unusual scenarios/signatures (RPV, compressed spectra, stealth SUSY, ..)
  - more patience
- Either way, search for New Physics, and in particular SUSY, will be the most important goal for LHC Run2







RUN2

It is absolutely mandatory to fully exploit all the physics of Run2

Need good understanding and precision predictions for the BSM signal

discovery (properties)

exclusion (limits)

"no stone left unturned"
also on theory side

How well do we know signal predictions for direct SUSY production?

- Usual playground: MSSM (minimal content of particles, R-parity)
- Develop ideas/techniques/codes (quantitatively results may defer depending on the model)

DIRECT SUSY PRODUCTION

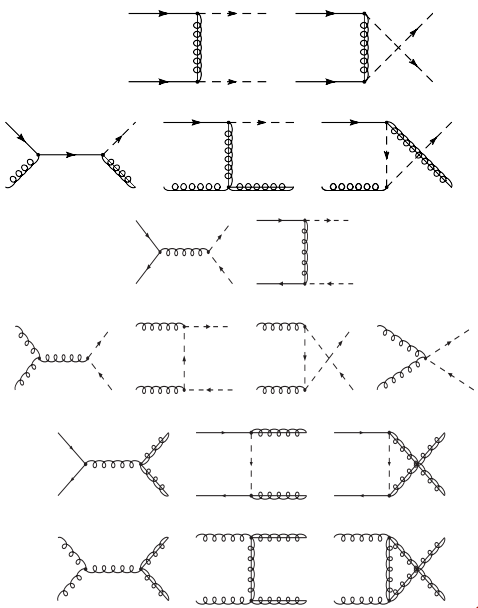
Coloured sector: squarks (stops) and gluinos

$\tilde{q}\tilde{q}$

$\tilde{q}\tilde{g}$

$\tilde{q}\bar{\tilde{q}}$

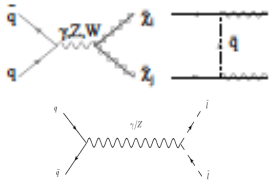
$\tilde{g}\tilde{g}$



EW sector: charginos, neutralinos and sleptons

$\tilde{\chi}_i\tilde{\chi}_j$

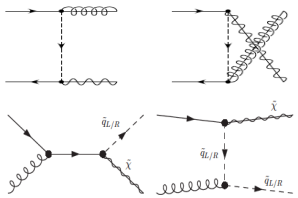
$\tilde{l}\bar{\tilde{l}}'$



Mixed squark/gluino-gaugino

$\tilde{g}\tilde{\chi}$

$\tilde{q}\tilde{\chi}$



dominant at the LHC

DIRECT SUSY PRODUCTION

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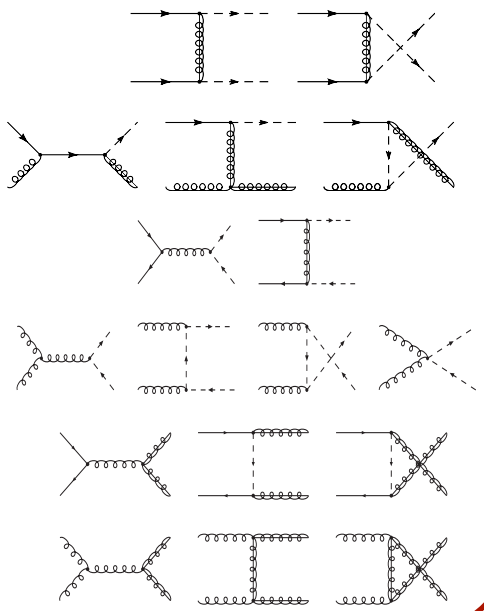

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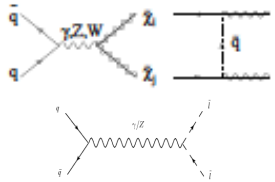

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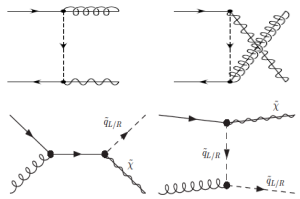
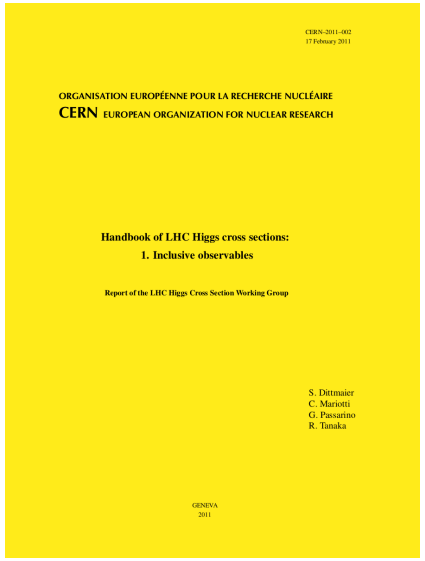


Higgs sector



CERN-2011-002
17 February 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

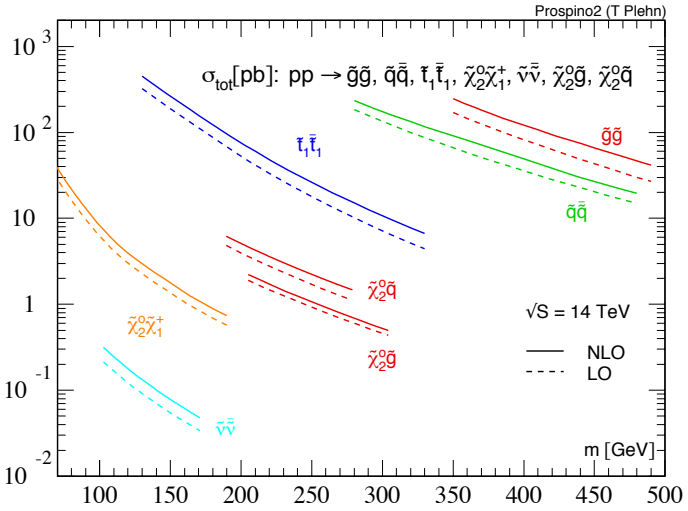
GENEVA
2011

dominant at the LHC

Part I: Inclusive cross sections

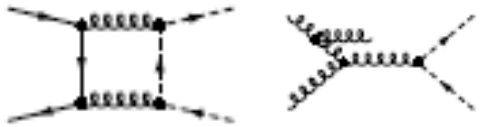
NLO SUSY-QCD

- NLO SUSY-QCD corrections for 2⟶2 sparticle production *[Beenakker, Höpker, Spira, Zerwas'96] [Beenakker, Krämer, Plehn, Spira, Zerwas'97] [Beenakker,Klasen, Krämer, Plehn, Spira, Zerwas'99][Berger, Klasen, Tait'00][Spira'02]*; implemented in PROSPINO(2)



$\mathcal{O}(\alpha_s)$ correction

e.g.



...

- Typically, order of a few tens of percent correction

NLO SUSY-QCD

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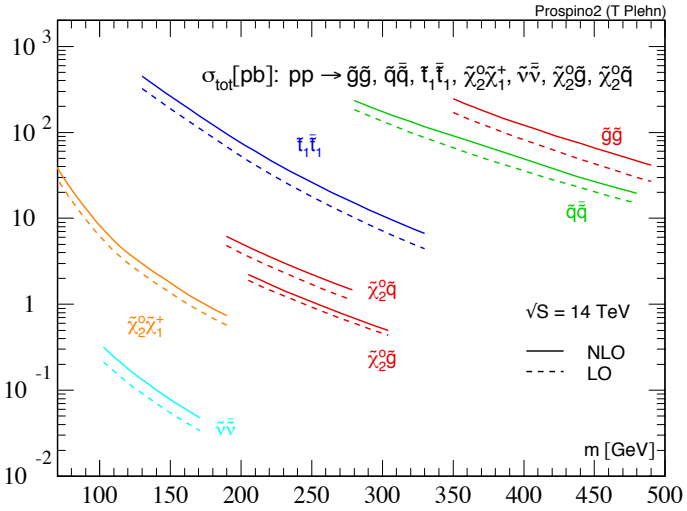


- Assumption of mass degeneracy for light flavour squarks, removed at LO level in PROSPINO2

- Typically, order of a few tens of percent correction

NLO SUSY-QCD CTND.

- NLO SUSY-QCD corrections with each flavour and chirality combination treated individually
  [Goncalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore'12] [Gavin, Hangst, Krämer, Mühlleitner, Popenda, Spira'14][Hollik, Lindert, Pagani'12]

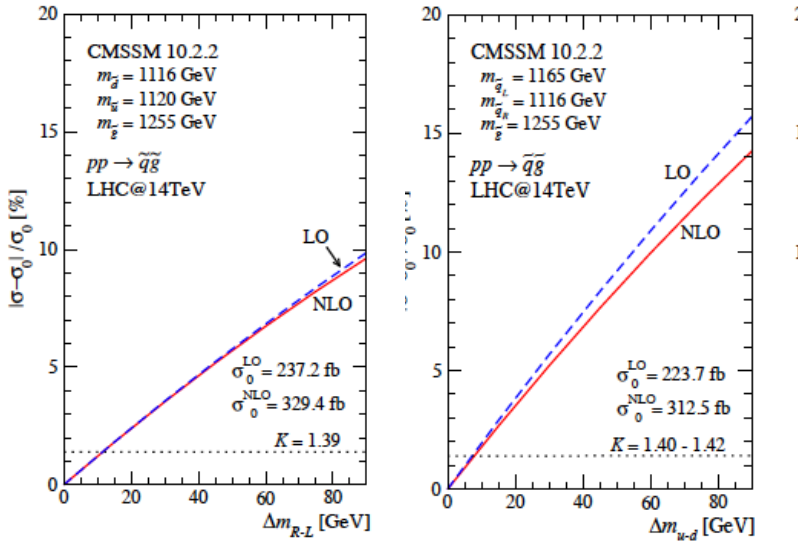
Process	$\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K-factor
$\tilde{u}_L\bar{\tilde{u}}_L$	$9.51 \cdot 10^{-2}$	$1.43 \cdot 10^{-1}$	1.50
$\tilde{u}_R\bar{\tilde{u}}_R$	$1.14 \cdot 10^{-1}$	$1.72 \cdot 10^{-1}$	1.51
$\tilde{d}_L\bar{\tilde{d}}_L$	$5.50 \cdot 10^{-2}$	$8.79 \cdot 10^{-2}$	1.60
$\tilde{d}_R\bar{\tilde{d}}_R$	$6.89 \cdot 10^{-2}$	$1.11 \cdot 10^{-1}$	1.61
$\tilde{u}_L\bar{\tilde{u}}_R$	$3.75 \cdot 10^{-1}$	$5.12 \cdot 10^{-1}$	1.37
$\tilde{d}_L\bar{\tilde{d}}_R$	$1.41 \cdot 10^{-1}$	$1.70 \cdot 10^{-1}$	1.21
$\tilde{u}_L\bar{\tilde{d}}_L$	$6.98 \cdot 10^{-2}$	$7.89 \cdot 10^{-2}$	1.13
$\tilde{u}_L\bar{\tilde{d}}_R$	$2.98 \cdot 10^{-1}$	$3.54 \cdot 10^{-1}$	1.19
$\tilde{u}_R\bar{\tilde{d}}_L$	$2.94 \cdot 10^{-1}$	$3.49 \cdot 10^{-1}$	1.19
$\tilde{u}_R\bar{\tilde{d}}_R$	$8.36 \cdot 10^{-2}$	$9.54 \cdot 10^{-2}$	1.14
Sum	1.59	2.07	1.30

40% difference

K_{avg}=1.39

line 10.3.6*

[Gavin, Hangst, Krämer, Mühlleitner, Popenda, Spira'14]



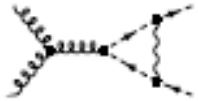
[Goncalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore'12]

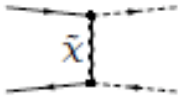
- Bulk of NLO effects of QCD origin ⟶ K-factors with mass splittings not too different from K-factors for averaged masses

AUTOMATIZATION OF NLO CORRECTIONS

- MadGolem = MadGraph + Qgraf + MadDipole + Golem
  - squark-neutralino pairs *[Binoth, Goncalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore'11]*
  - squark- and gluino- pairs *[Goncalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore'12]*
  - sgluon pairs *[Goncalves-Netto, Lopez-Val, Mawatari, Plehn, Wigmore'12]*
  - stop-pairs and stop-chargino pairs *[Goncalves-Netto, Lopez-Val, Mawatari, Plehn'14]*
- aMC@NLO… ongoing
  - coloured scalar pairs (stops and sgluons) in simplified models *[Degrande, Fuks, Hirschi,Proudom, Shao'14]*
  - Heavy charged Higgs in type-II two Higgs doublet model *[Degrande, Ubiali, Wiesemann, Zaro'15]*
- Intense efforts to incorporate BSM (@ LO/ NLO matching) into MC event generators ⟶ MC4BSM activity

NLO SUSY-EW

- For coloured production, two types:
  - $\mathcal{O}(\alpha)$ corrections to $\mathcal{O}(\alpha_s^2)$ processes  ...
  - QCD-EW interference and photon-induced contributions, tree-level EW



 etc.

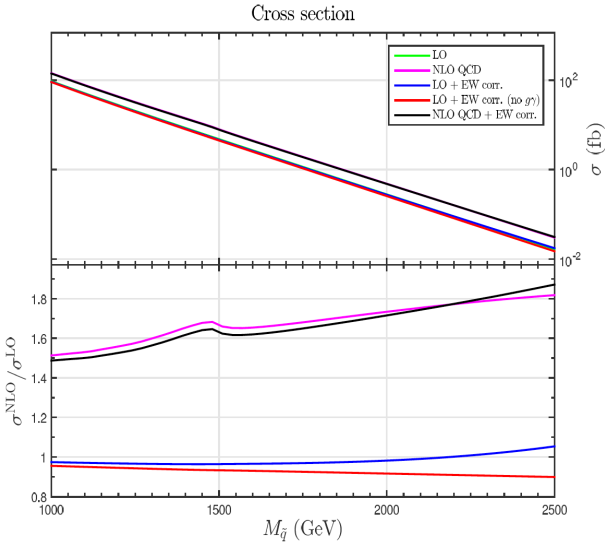
- Available for all channels
  - stop- and sbottom-pairs *[Hollik, Kollar, Trenkel'07] [Beccaria et al.'08] [Germer, Hollik, Mirabella'11] [Germer, Hollik, Lindert, Mirabella'14]*
  - squark-(anti)squark pairs *[Bozzi, Fuks, Klasen'05] [Alan, Cankocak, Demir'07] [Bornhauser et al.'07-'09] [Hollik, Mirabella'08] [Beccaria et al.'08] [Germer, Hollik, Mirabella, Trenkel'10] [Hollik, Lindert, Mirabella, Pagani'15]*
  - squark-gluino *[Hollik, Mirabella, Trenkel'08]* and gluino-pair *[Mirabella'09]*

NLO EW AND QCD

[Germer, Hollik, Lindert, Mirabella'14] [Hollik, Lindert, Mirabella, Pagani'15]

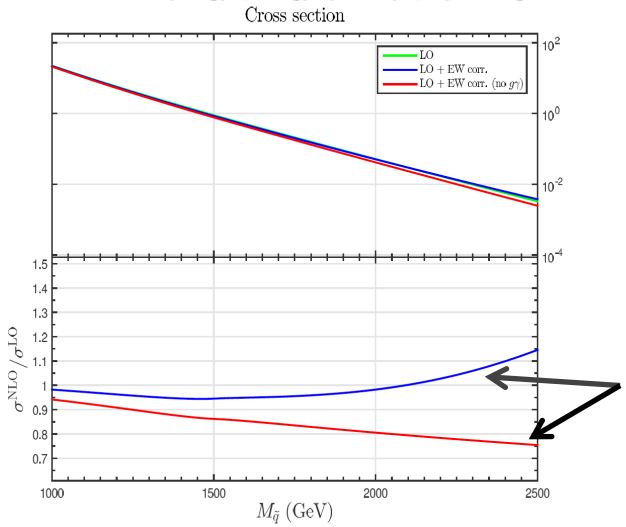
Squark-antisquark production

Degenerate squark masses



Non-degenerate squark masses

$(M_{\tilde{q},\mathrm{L}}, M_{\tilde{q},\mathrm{R}}) = (1,2) \cdot M_{\tilde{q}}$



m_{A_0}	700 GeV	$\tan\beta$	20
X_t	$2M_{\tilde{q}_3}$	μ	350 GeV
M_2	350 GeV	$m_{\tilde{g}}$	1500 GeV
$M_{\tilde{q},\mathrm{L}}$	1500 GeV	$M_{\tilde{q},\mathrm{R}}$	1500 GeV
$M_{\tilde{q}_3}$	500 GeV	$M_{\tilde{\ell}_3}$	1000 GeV
$M_{\tilde{\ell}}$	500 GeV		

NNPDF2.3QED

predominantly LL

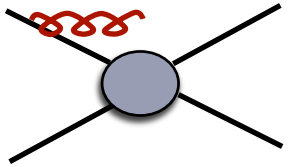
- At the inclusive level NLO QCD corrections dominate, NLO EW typically a few percent effect; corrections above 10% can appear at large masses for particular chiralities or mass splittings
- Gluon-photon initial state contributions very important; large pdf uncertainties!
- Similar situation for stop-pair production: above 10% corrections for heavy stops, *gγ* channel v. important

TOWARDS HIGHER ORDERS IN QCD

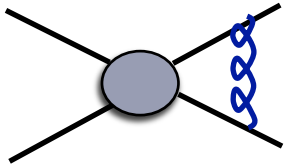
- Large masses of SUSY particles ⇒ production close to threshold $\hat{s} \sim 4m^2$
- General structure of the NLO correction in the threshold limit $\beta \to 0, \quad \beta^2 = 1 - 4m^2/\hat{s}$

$$\Delta\hat{\sigma}_i^{\mathrm{NLO}} \sim \alpha_s \, \hat{\sigma}_i^{\mathrm{LO}} \left\{ A^{(i)} \log^2(\beta^2) + B^{(i)} \log(\beta^2) + C^{(i)} \frac{1}{\beta} + D^{(i)} \right\}$$

Soft/collinear gluon emission



Coulomb gluons



for coloured final states

- Large corrections in the limit of threshold production $\beta \to 0$
- At higher orders $\sim \alpha_s^n \log^{2n}(\beta)$ and $\sim \alpha_s^n / \beta^n$ structures
- Both types of corrections can be resummed to all orders

SOFT GLUON RESUMMATION

$$\sigma^{\rm res} \sim \sigma_0 \otimes C(\alpha_s) \otimes \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

$\mathrm{LL} : \sim \sum_n \alpha_s^n L^{n+1}$

$\mathrm{NLL} : \sim \sum_n \alpha_s^n L^n$

$\mathrm{NNLL} : \sim \sum_n \alpha_s^n L^{n-1}$

$L = \log(\text{threshold variable})$

[Beneke, Falgari, Schwinn'10]:

$$C(\alpha_s) = C^{\rm Coul}(\alpha_s) \otimes C^{\rm hard}(\alpha_s) = 1 + \alpha_s C^{\rm Coul}_{(1)} + \alpha_s C^{\rm hard}_{(1)} + \ldots$$

can be resummed in NRQCD

NNLL

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can be resummed in NRQCD

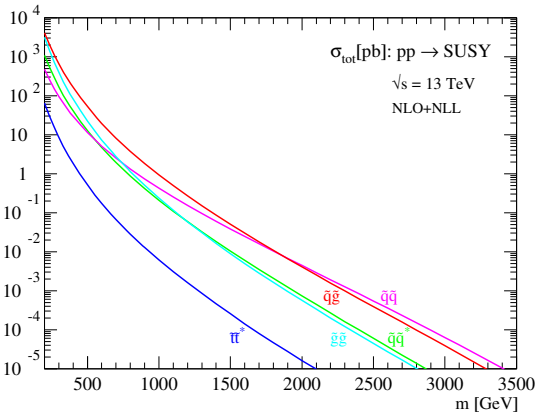
NNLL

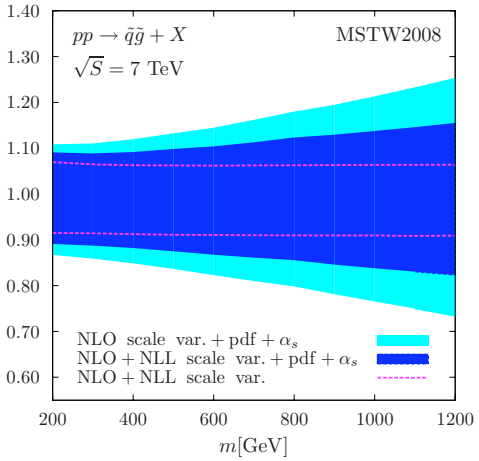
Resummation not only systematically takes into account dominant parts of the higher order corrections but also:

- typically reduces theory (scale variation) error
- predicts set of terms in the next order of perturbation theory: approximation of $\mathrm{N^xLO}$

...AND ACTION: RESUMMATION FOR COLOURED SPARTICLES

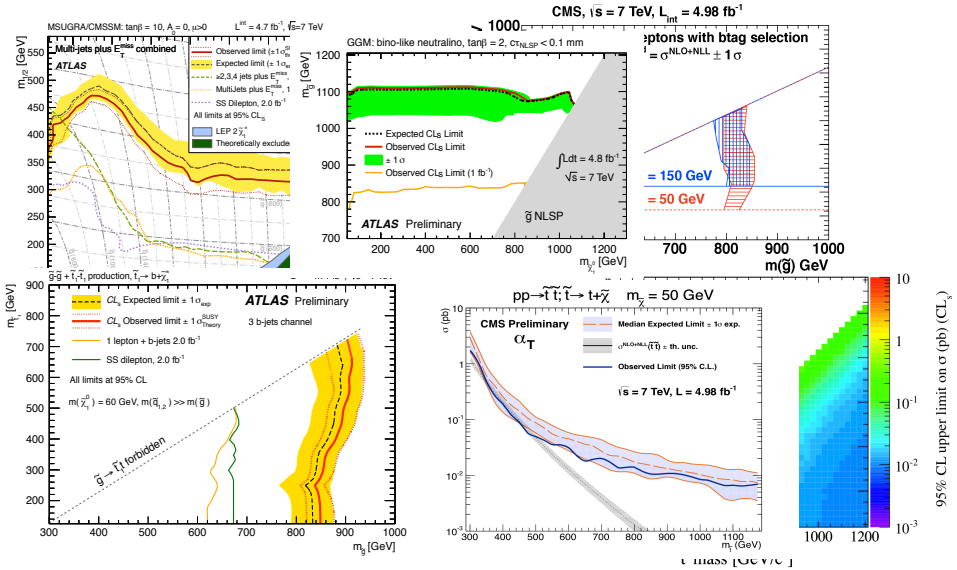
[Borschensky, Krämer, AK, Mangano, Padhi, Plehn, Portell'14]





- NLL calculations for squark (stops) and gluino pair production *[AK, Motyka'09-'10][Beenakker,Brensing, AK, Krämer,Laenen, Niessen'09-10]*, matched to NLO, implemented in publicly available package NLL-FAST

- predictions used in experimental analysis of 7 and 8 TeV data



THE NNLL FRONT

- NLO+NNLL for squark-antisquark production; with $\mathcal{O}(\alpha_s)$ Coulomb and hard-matching coefficients *[Beenakker, Brensing, Krämer, AK, Laenen, Niessen'11]*
- $\text{NNLO}_{\text{approx.}}$+NNLL for the four processes of squark and gluino production; with $\mathcal{O}(\alpha_s^2)$ Coulomb and $\mathcal{O}(\alpha_s)$ hard-matching coefficients *[Beenakker, Janssen, Krämer, AK, Laenen, Lepoeter, Niessen, Thewes, Van Daal'13] [Beenakker, Borschensky, Krämer, AK, Laenen, Thewes, Theeuwes'14]*
- $\text{NNLO}_{\text{approx.}}$+NNLL for gluino-pair production *[Pfoh'13]*
- $\text{NNLO}_{\text{approx.}}$+NNLL for the four processes of squark and gluino; with Coulomb resummation, $\mathcal{O}(\alpha_s)$ hard-matching coefficient *[Beneke, Falgari, Piclum, Schwinn, Wever'13]*
- NLO+NNLL for stop-pair production; with $\mathcal{O}(\alpha_s)$ Coulomb and hard-matching coefficients *[Broggio ,Ferroglia, Neubert, Vernazza, Yang'13]*

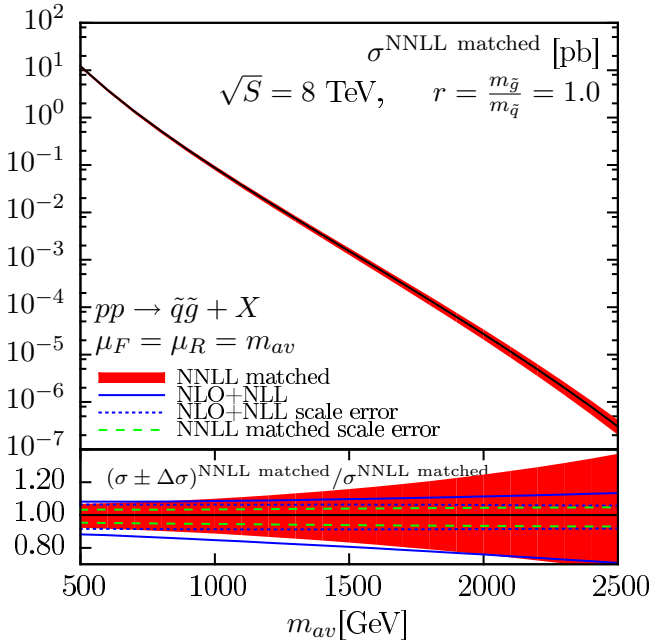
direct QCD (Mellin space)

SCET

Approximations of the NNLO result based on NNLL resummation:

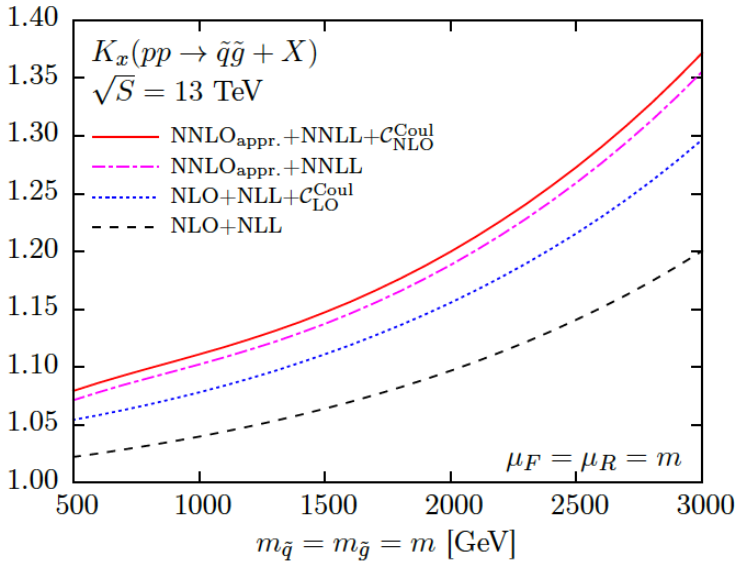
[Langenfeld, Moch'09] Langenfeld'09] [Langenfeld. Moch,Pfoh'12] [Broggio ,Ferroglia, Neubert, Vernazza, Yang'13]

LATEST FROM THE NNLL FRONT



[Beenakker, Borschensky, Krämer, AK, Laenen, Thewes, Theeuwes'14]

- NNLL resummation for total cross sections in direct QCD (Mellin space) now also includes Coulomb resummation



$$K_x = \frac{\sigma_x}{\sigma_{NLO}}$$

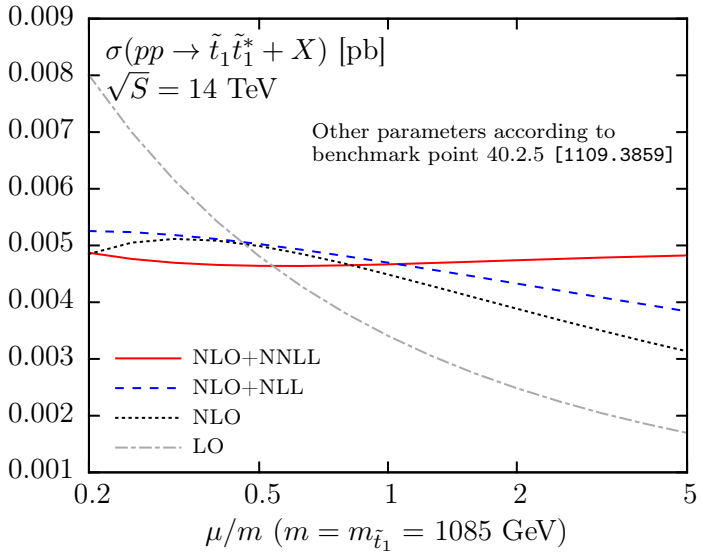
$C^{coul}_{(N)LO}$: Green's function at (N)LO

[Beenakker, Borschensky, Krämer, AK, Laenen, in preparation]

LATEST FROM THE NNLL FRONT 2

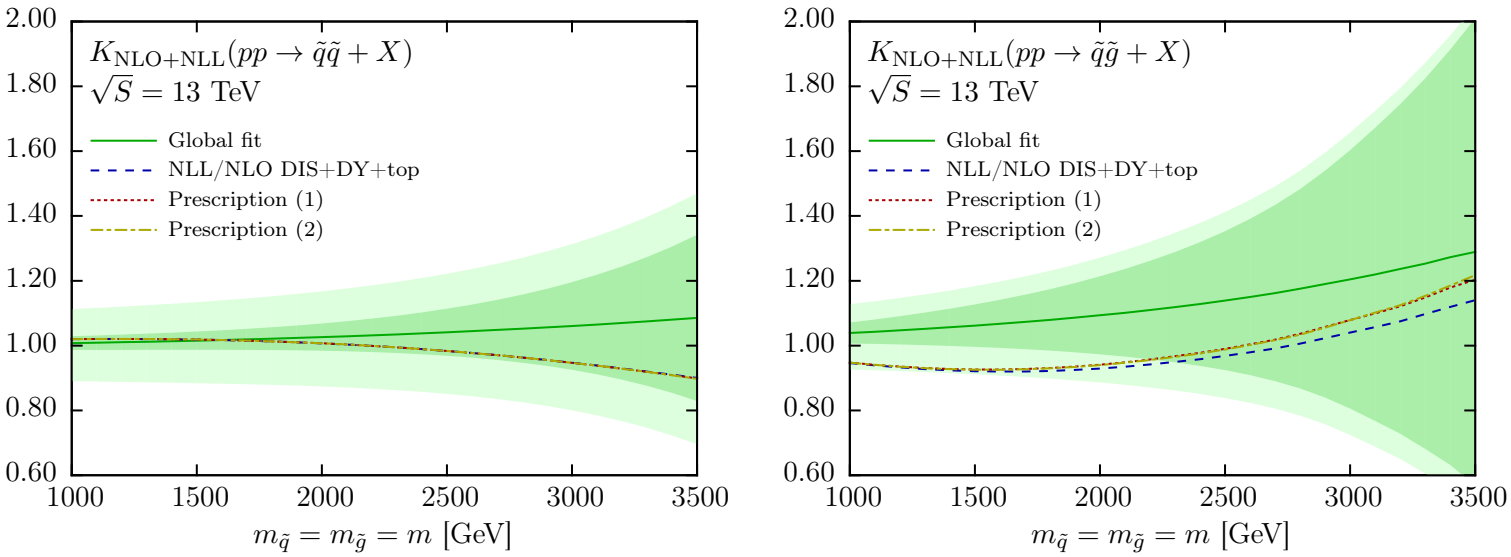
[Beenakker, Borschensky, Heger, Krämer, AK, Laenen, in preparation]

- $NNLO_{approx.}$+NNLL for stop-pair production; with $\mathcal{O}(\alpha_s^2)$ Coulomb and $\mathcal{O}(\alpha_s)$ hard-matching coefficient *[Broggio ,Ferroglia, Neubert, Vernazza, Yang'13]*



IMPACT OF PDFS

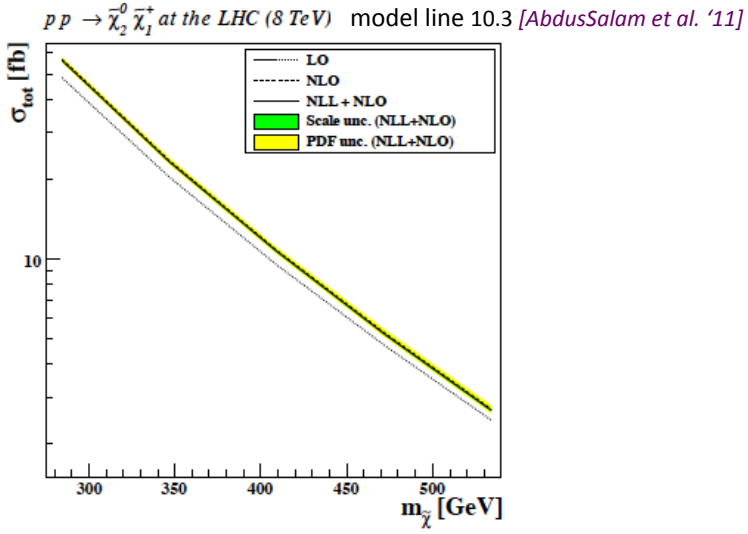
- Threshold-improved NNPDF3.0 *[Bonvini et al.'15]* extracted from experimental data using partonic cross sections at (N)NLO+(N)NLL accuracy; dataset limited (DY+DIS+top)



[Beenakker, Borschensky, Krämer, AK, Laenen, Marzani, Rojo, in preparation]

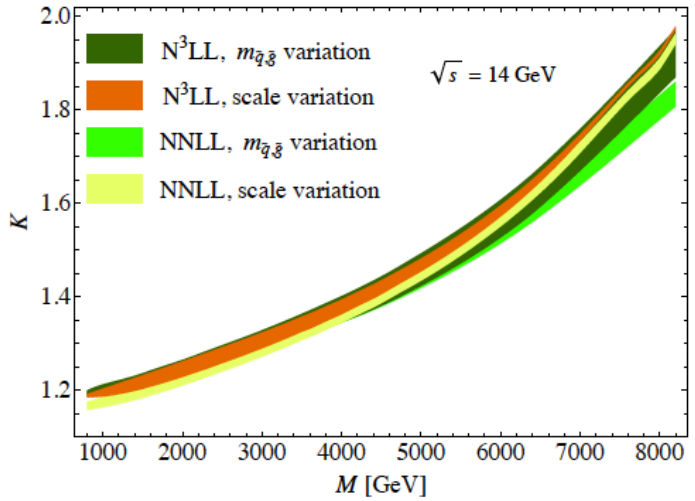
GAUGINO- AND SLEPTON-PAIR PRODUCTION

- Resummed results also available for chargino/neutralino production *[Li, Li, Oakes, Yang'07]* *[Debove, Fuks, Klasen'09-'11]* and slepton pair-production *[Fuks, Klasen, Lamprea, Rothering'12-'13]* *[Broggio, Neubert, Vernazza'12]*



model line 10.3 *[AbdusSalam et al. '11]*

[Debove, Fuks, Klasen'09-'11]



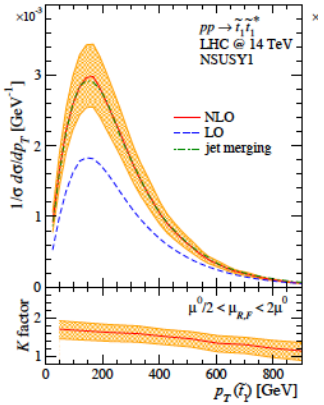
[Broggio, Neubert, Vernazza'12]

- public code RESUMMINO for NLO+NLL

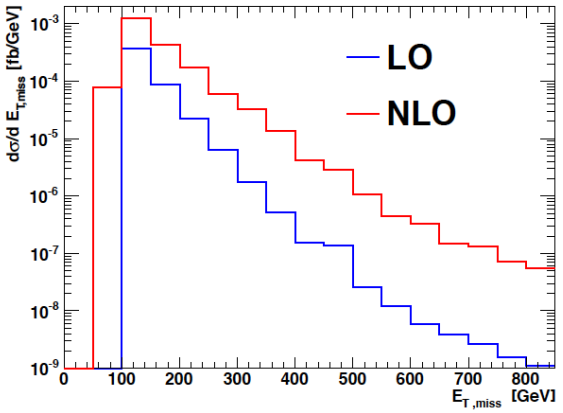
Part II: Distributions

DISTRIBUTIONS

- MC event generators simulate SUSY (BSM) at LO+(N)LL accuracy
  - HERWIG++, PYTHIA, SHERPA, WHIZARD
- Typical experimental strategy so far:
  - reweight the LO cross section with an NLO+NLL K-factor
  - multiply each channel by NLO branching ratios
  - process with an MC event generator
- NLO calculations technically feasible; (re)calculated by various group
  - impact of NLO (+N^{x}LL) QCD and NLO EW corrections on many differential distributions for SUSY production processes has been studied, significant effects observed



[Goncalves-Netto, Lopez-Val, Mawatari, Plehn'14]

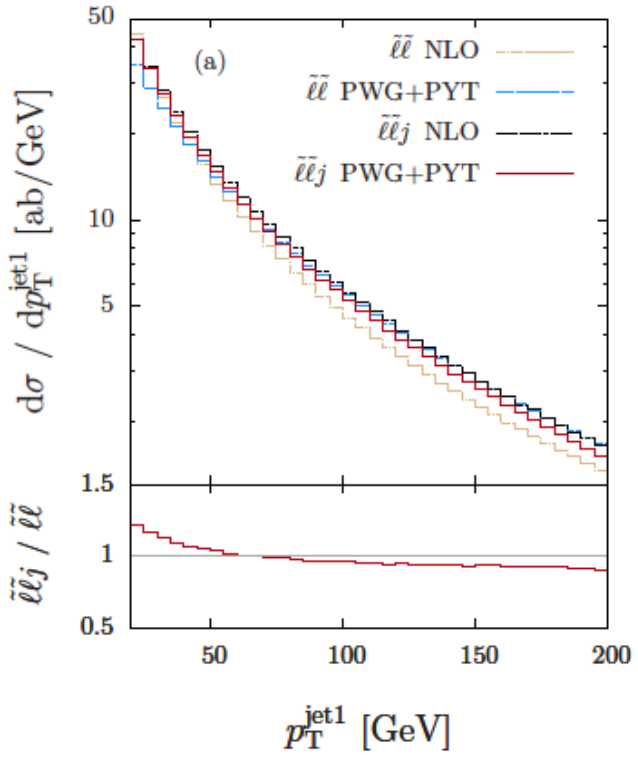


[Cullen, Greiner, Heinrich'12]

NLO+ PS FOR SLEPTONS

[Jäger, van Manteuffel, Thier'12-'14][Fridman-Rojas, Richardson'12]

- Slepton-pair production (+jet) : no coloured sparticles in the final state ⟶ for NLO SUSY-QCD accuracy tree level decays of sleptons can be simulated with a parton shower
- Matching with parton shower in the POWHEG-BOX framework
- Slepton-pair in association with a jet: correct description of the hardest emission at NLO ⟶ important for monojet searches in scenarios with similar masses of sleptons and neutralinos
- Public implementation



ENTER THE DECAY

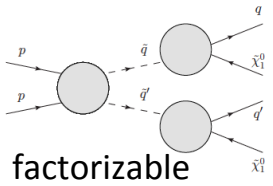
[Hollik, Lindert, Pagani'12-'13]

- Contributions to cross sections for the experimental signature

$$2j + \not{E}_T(+X) \quad \Leftrightarrow \quad pp \to \tilde{q}\tilde{q}' \to q\tilde{\chi}_1^0 q' \tilde{\chi}_1^0$$

- Each flavour and chirality combination treated separately
- NLO SUSY-QCD corrections for both production and decay, NWA used

$$\Gamma_{\tilde{q}} / m_{\tilde{q}} \to 0$$



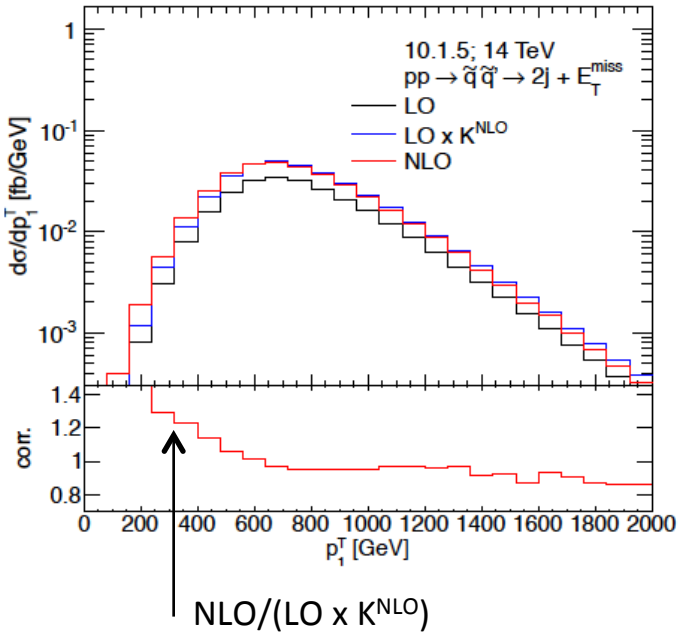
factorizable

$$d\sigma = d\sigma_{prod} \frac{d\Gamma^{\tilde{q}\to q\tilde{\chi}_0^1}}{\Gamma_{tot}^{\tilde{q}}} \frac{d\Gamma^{\tilde{q}'\to q'\tilde{\chi}_0^1}}{\Gamma_{tot}^{\tilde{q}}}$$

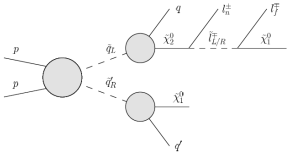
expanded up to $\mathcal{O}(\alpha_s)$

- NLO resonant production via on-shell-gluino subtracted by diagram removal

10.1.5	$\tilde{u}_L$	$\tilde{u}_R$	$\tilde{d}_L$	$\tilde{d}_R$	$\tilde{g}$	$\tilde{\chi}_1^0$
mass (GeV)	1437.7	1382.3	1439.7	1376.9	1568.6	291.3



- For $2j + l^+l^- + \not{E}_T(+X)$ invariant mass distributions stable wrt. (S)QCD corrections



$$2j + l^+l^- + \not{E}_T(+X) \quad \Leftrightarrow \quad pp \to \tilde{q}_L\tilde{q}_R'$$

$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to ql^{\pm}\tilde{l}_{L/R}^{\pm} \to ql^{\pm}l^{\mp}\tilde{\chi}_1^0, \quad \tilde{q}_R \to q\tilde{\chi}_1^0$$

NLO PRODUCTION+ NLO DECAY+PS

[Gavin, Hangst, Krämer,Mühlleitner,Pellen, Popenda,Spira'13-'14]

- NLO SUSY-QCD corrections to squark-pair and squark-antisquark production with squarks decaying into a lightest neutralino and a quark (antiquark)

$$2j + \not{E}_T(+X) \quad \Leftrightarrow \quad pp \to \tilde{q}\tilde{q}' \to q\tilde{\chi}_1^0 q' \tilde{\chi}_1^0$$

- Production and decay treated separately for each flavour and chirality, NWA used

$$\mathrm{d}\sigma_{\mathrm{tot}} = (\mathrm{d}\sigma_0 + \alpha_s \mathrm{d}\sigma_1)\, \frac{\mathrm{d}\Gamma_0^{\tilde{q}_1 \to \tilde{\chi}_1^0 q} + \alpha_s \mathrm{d}\Gamma_1^{\tilde{q}_1 \to \tilde{\chi}_1^0 q}}{\Gamma_{\mathrm{tot},0}^{\tilde{q}_1} + \alpha_s \Gamma_{\mathrm{tot},1}^{\tilde{q}_1}} \, \frac{\mathrm{d}\Gamma_0^{\tilde{q}_2 \to \tilde{\chi}_1^0 q} + \alpha_s \mathrm{d}\Gamma_1^{\tilde{q}_2 \to \tilde{\chi}_1^0 q}}{\Gamma_{\mathrm{tot},0}^{\tilde{q}_2} + \alpha_s \Gamma_{\mathrm{tot},1}^{\tilde{q}_2}}$$

  - $\mathcal{O}(\alpha_s)$ expansion can be done for the full expression or only the numerator

- NLO contributions from resonant gluinos removed locally by a gauge-invariant counterterm (modification of diagram subtraction)

- Implementation in the POWHEG-BOX V2 (public)

NLO PRODUCTION+ NLO DECAY+PS

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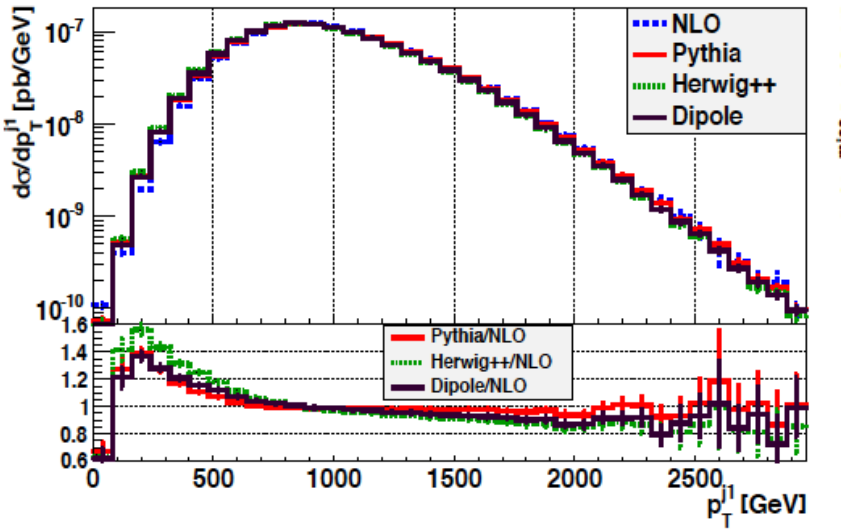


Scenario	$m_{\tilde{u}_L} = m_{\tilde{c}_L}$	$m_{\tilde{u}_R} = m_{\tilde{c}_R}$	$m_{\tilde{d}_L} = m_{\tilde{s}_L}$	$m_{\tilde{d}_R} = m_{\tilde{s}_R}$	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$ [GeV]
10.3.6*	1799.53	1760.21	1801.08	1756.40	1602.96	290.83

- effects of different approaches to resonance subtraction and NWA application amount to a few % for total cross sections, and are above 10% at the differential level
- In agreement with *[Hollik, Lindert, Pagani'12]* NLO differential K-factors not flat for many observables: up to ±40% difference found
- Effect of PS on the distributions at most of $\mathcal{O}$(10-20%) except for threshold regions
- ATLAS selection cuts motivated analysis: 15-20% difference between full NLO cross section and simulation based on average K-factors in squark-antisquark production

A SHOWSTOPPER

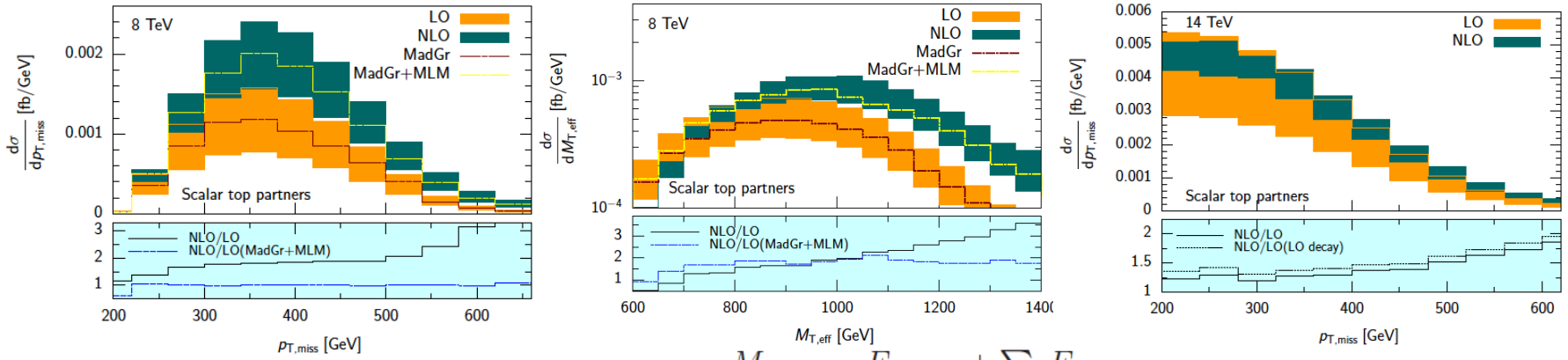
[Boughezal, Schulze'12-'13]

- NLO QCD corrections to pair-production of scalar top quark partners T in a simplified model with only one decay mode $T \longrightarrow tA_0$ and A_0 a neutral Majorana fermion (dark matter candidate)

$$t\bar{t} + \not{E}_T(+X) \quad \Leftrightarrow \quad pp \to T\bar{T} \to t\bar{t}A_0\bar{A}_0 \qquad t \to bW \quad W \to l\nu \,/\, jj$$

$$(m_T, m_{A_0}) = (600\text{GeV}, 50\text{GeV})$$

ATLAS analysis-driven cuts and couplings of T to t and A_0



$$M_{T,eff} = E_{T,miss} + \sum_i E_{T,i},$$

- Agreement between tree level jet merged results and NLO shapes observed also at the production level *[Goncalves-Netto, Lopez-Val, Mawatari, Plehn et al.'12-'14]*

SUMMARY

- Precision knowledge of SUSY cross sections needed for optimizing search strategies at the LHC
- Experience from Standard Model calculations proves invaluable for precision SUSY
- Inclusive cross sections: SUSY-QCD NLO+(N)NLL; NLO EW
- Differential distributions: first NLO results for production and decay of squarks; NLO EW
- Automatization of NLO for SUSY/BSM actively pursued

DISCLAIMER

Impossible to cover all aspects of SUSY production… apologies !

- Boundstate production
- Decays of sparticles
- Production in models beyond MSSM
- Simplified models
- Long-lived sparticles
- Indirect precision observables