Impact of Jet Veto Resummation on SUSY Searches

Frank Tackmann, Wouter Waalewijn, LZ, [arXiv:1603.03052]

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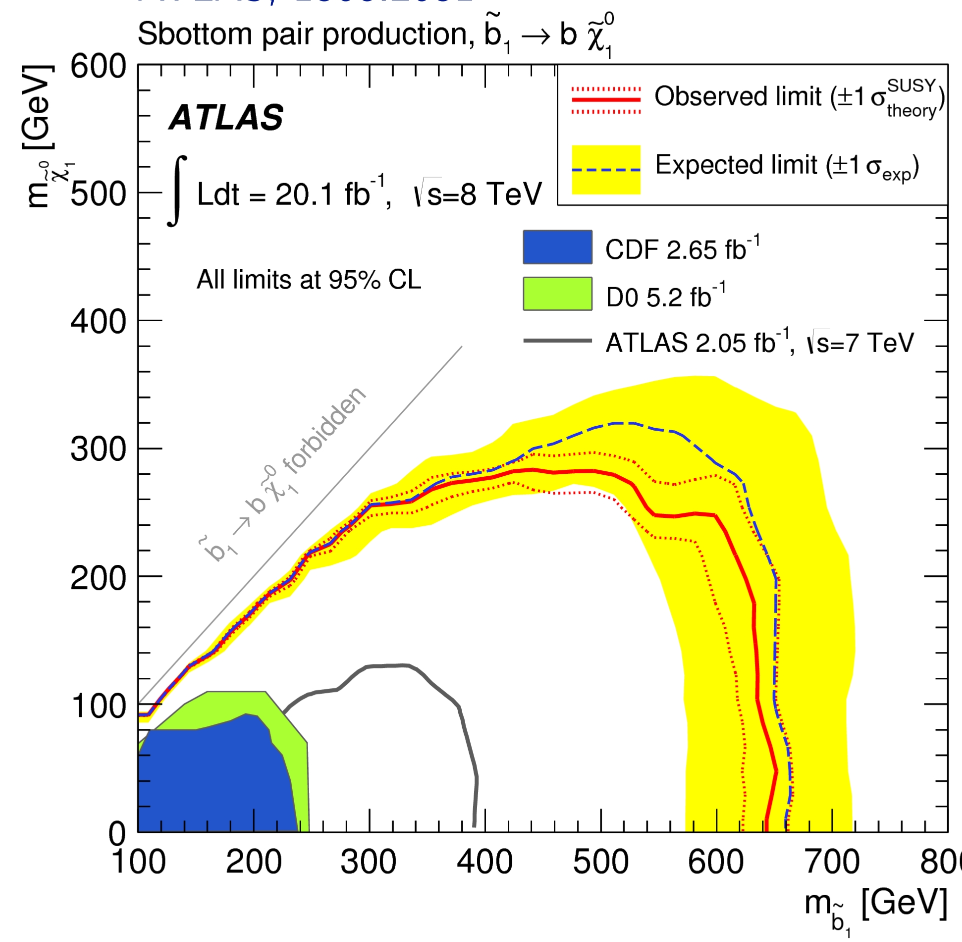
SCET 2016, DESY

23.03.2016

Introduction

- Several searches for new physics at the LHC require a fixed number of signal jets
- Jet vetoes introduce logarithms in the cross section $\log(p_T^{\text{cut}}/Q)$
- Large effect for SUSY particle production for which Q can easily be 1 TeV
  - ⤳ As long as the limits go up the effect is getting larger
- The experimental analyses take the jet-veto cut into account using parton shower Monte Carlos
  - ⤳ Uncertainty introduced by jet vetoes is not considered in the experimental exclusion limits

ATLAS, 1308.2631



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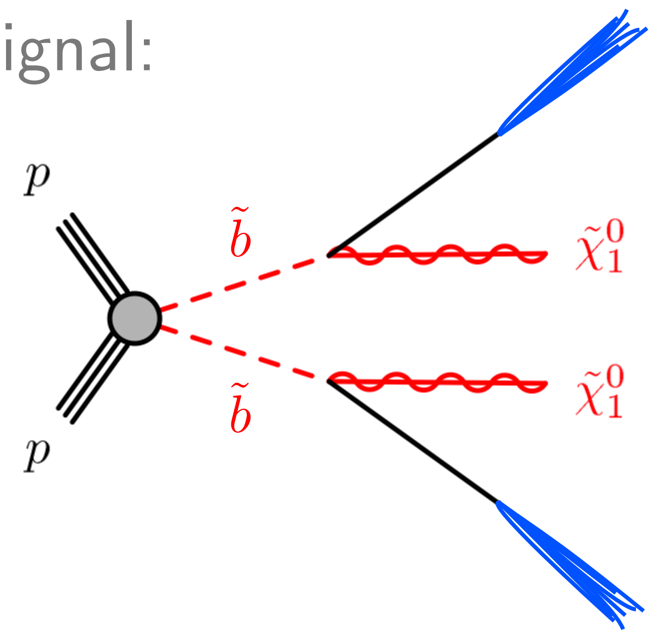
Focussing on slepton searches, we present results for the 0-jet cross section at NLL'+NLO and estimate theory uncertainty associated with the jet veto

New physics searches using jet vetos

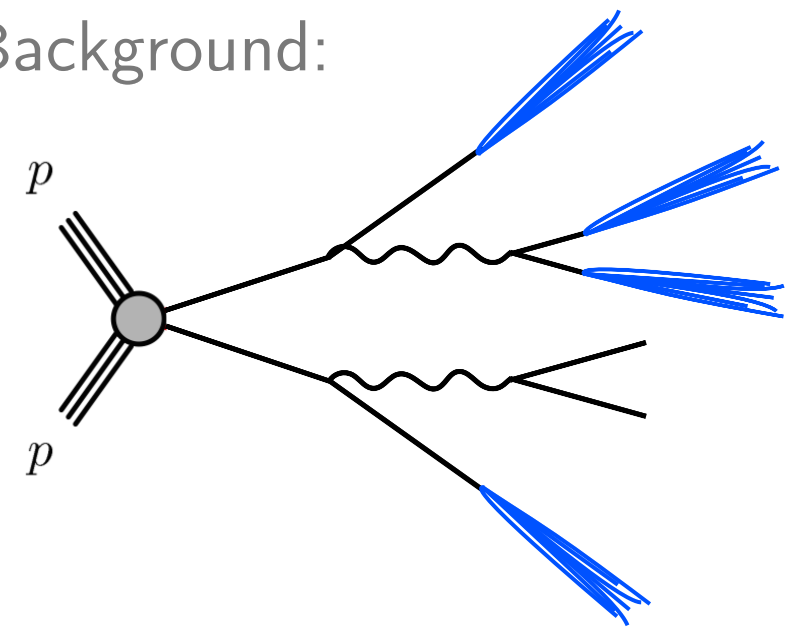
- Electroweakino and slepton searches typically requiring 0 jets
  ATLAS: 1407.0350, 1403.5294, 1501.07110, 1509.07152, **CMS:** 1405.7570

- Stop and sbottom searches vetoing a third jet
  ATLAS: 1308.2631, 1506.08616, **CMS:** CMS-PAS-SUS-13-018

Signal:



Background:



- Searches for large extra dimensions, unparticles and dark matter: mono-photon, mono-Z, mono-jet
  ATLAS: 1209.4625, 1404.0051, **CMS:** 1408.3583, 1511.09375 , CMS-PAS-EXO-12-047

- …

SUSY searches at the LHC

- Experimentalists define signal regions (sets of selection cuts) to increase the signal over background ratio

- Example analysis:
  ATLAS 8TeV 20.3 fb^{-1}
  JHEP 05 (2014) 071

  All jets with $p_T > 20$ GeV are vetoed

- Very similar for other analyses, also CMS

Signal regions

SR	m_{T2}^{90}	WWa
lepton flavour	DF,SF	DF,SF
central light jets	0	0
central b-jets	0	0
forward jets	0	0
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	> 10	> 10
$m_{\ell\ell}$ [GeV]	—	< 120
$E_{\mathrm{T}}^{\mathrm{miss,rel}}$ [GeV]	—	> 80
$p_{\mathrm{T},\ell\ell}$ [GeV]	—	> 80
m_{T2} [GeV]	> 90	—

Jet veto

SUSY searches at the LHC

- In each signal region: Compare number of events from SM background to observed number of events

Statistically consistent

	SR-m_{T2}^{90}	
	SF	DF
Expected background		
Total	38.2 ± 5.1	23.3 ± 3.7
Observed events	33	21
Observed σ_{vis}^{95} [fb]	0.63	0.55

- How many additional new physics (BSM) events are still statistically consistent with the observation?

$$N_{\text{BSM}}^{95} = \sigma_{\text{vis}}^{95} \times \mathcal{L}_{\text{int}}$$

- The reported BSM cross section upper limit, σ_{vis}^{95} :
  - Contains the experimental reconstruction efficiencies and acceptance cuts
  - Is model independent

SUSY searches at the LHC

Setting exclusion limits

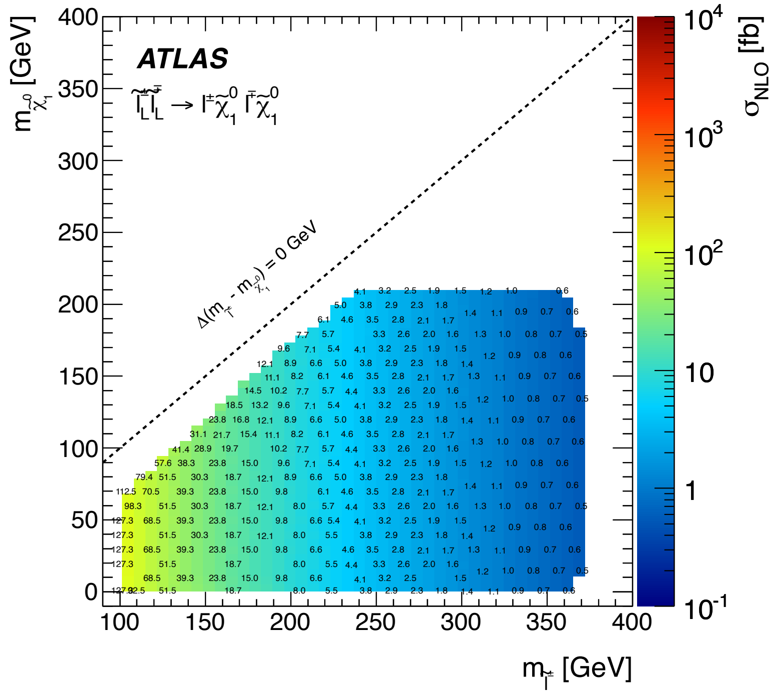
- One specific SUSY model is considered, typically a simplified model

  Particle content restricted to the particles appearing in the particular topology considered in a search

- For each parameter point $\sigma_{\text{vis}} = \sigma_{\text{SUSY}} \times \epsilon^{(\text{SR})}_{\text{SUSY}}$ is calculated and compared to σ^{95}_{vis} (for the signal region with highest expected sensitivity)

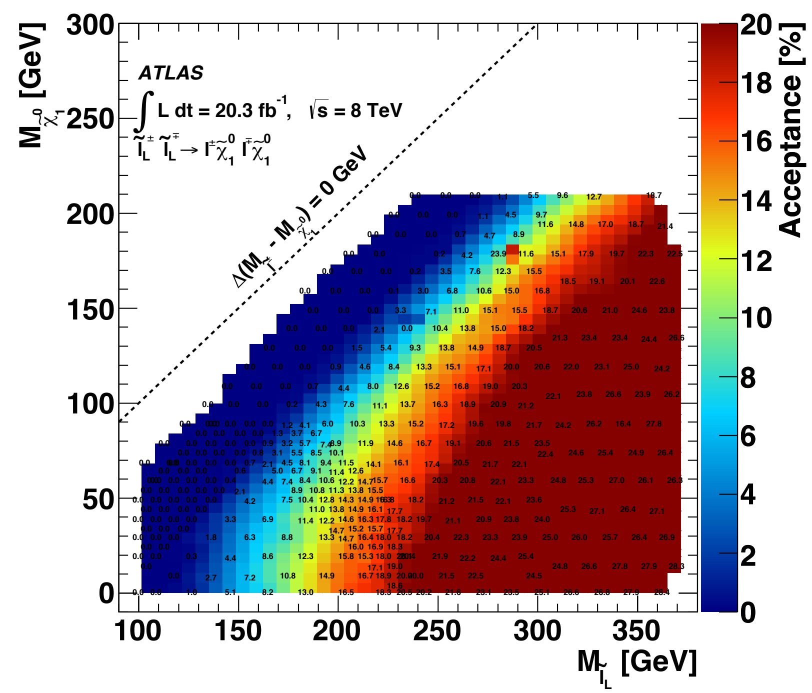
Total SUSY cross section

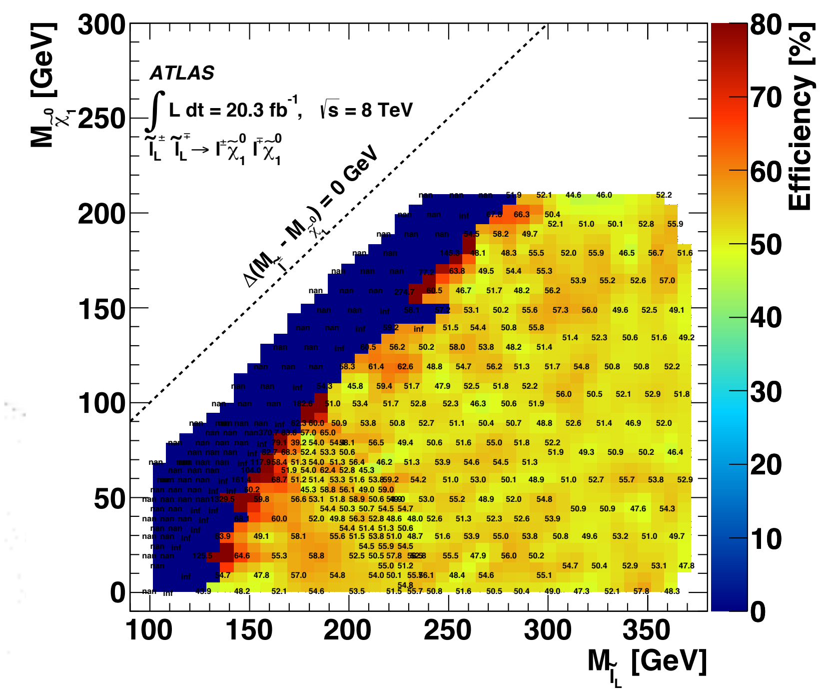
NLO: `Prospino` Beenakker et al, 9906298



Experimental reconstruction efficiency and acceptance

ATLAS, 1403.5294





SUSY searches at the LHC

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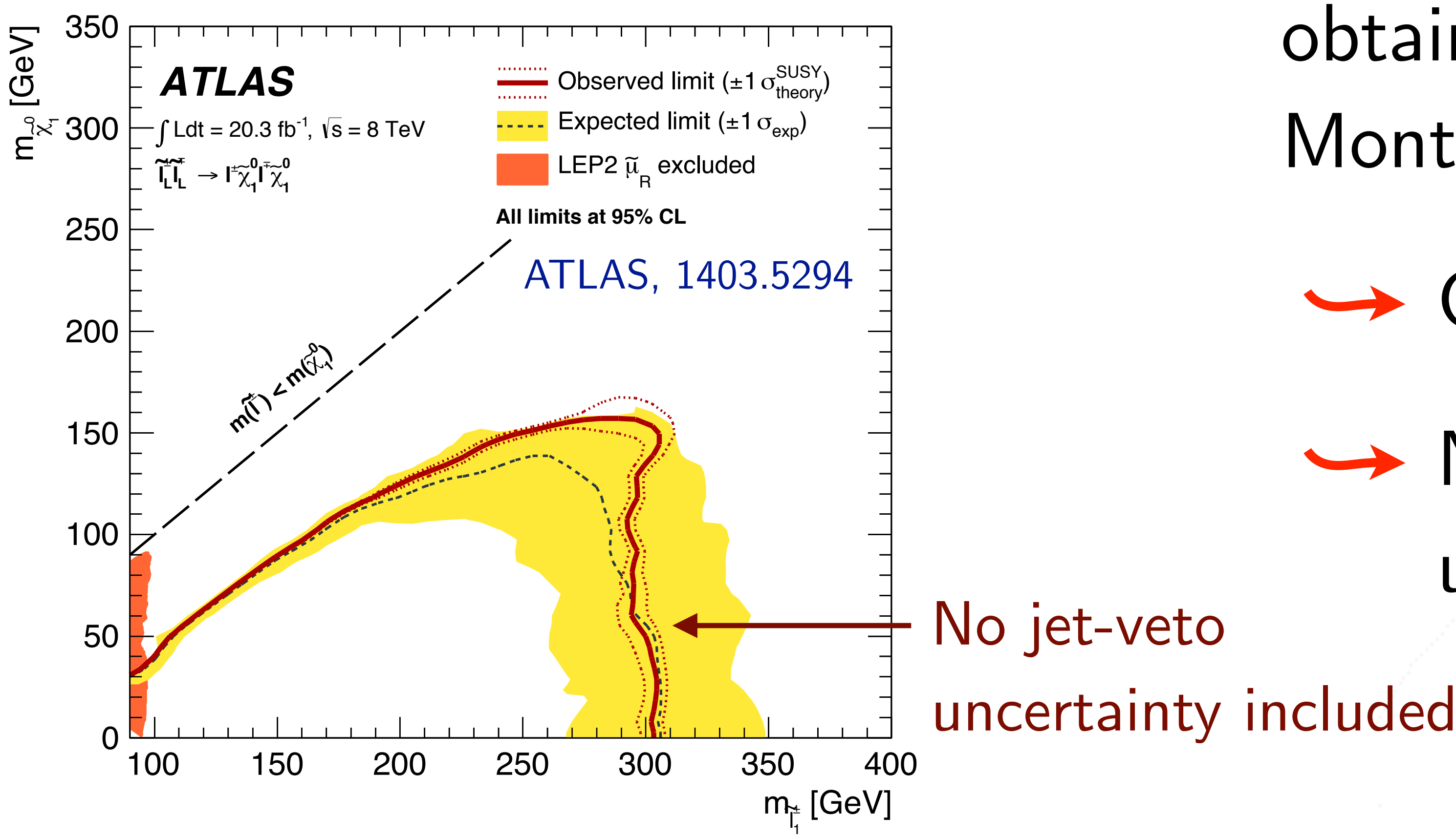
- Model dependent exclusion limit:



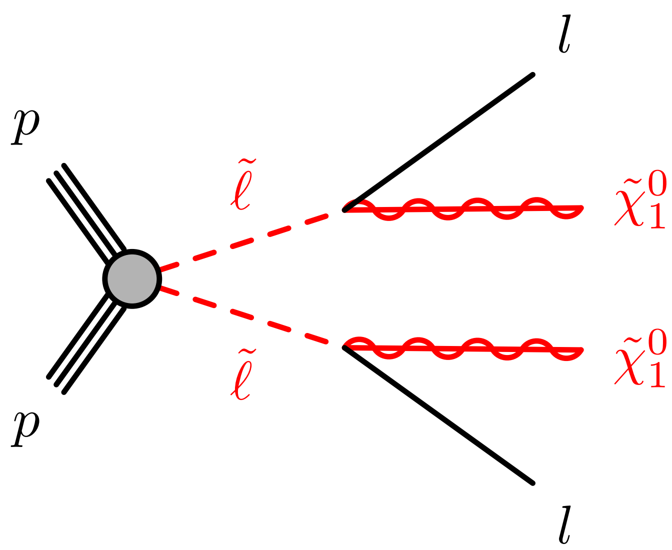
- $\epsilon^{(\text{SR})}_{\text{SUSY}}$ including the jet veto cut is obtained from parton shower Monte Carlo

  ⤻ Captures the leading logs

  ⤻ No control over jet-veto uncertainty

Slepton searches

- We focus on searches for sleptons (selectrons and smuons)
  $\tilde{\ell}_L$ and $\tilde{\ell}_R$ are the superpartners of left- and right-handed leptons
- Process: $pp \to \tilde{\ell}\tilde{\ell} \to \ell\chi_1^0\ell\chi_1^0$
- Slepton simplified model:
  - All SUSY particles decoupled, except the slepton $\tilde{\ell}$ and the lightest neutralino $\tilde{\chi}_1^0$
  - Branching ratio: $\mathcal{B}(\tilde{\ell} \to \ell\chi_1^0) = 1$
  - R-parity conserved, $\tilde{\chi}_1^0$ is stable



- Most important signal region cuts:
  - Two (same-flavour, opposite charge) leptons
  - No jets
  - Stransverse mass: $m_{T2} > 90$, 120 or 150 GeV

Lester, Summers, Barr, Stephens, 9906349, 0304226

Factorization formula

- We calculate the 0-jet slepton cross section at NLL'+NLO
- Utilize the SCET framework developed for Higgs $p_T^{\rm cut}$ resummation

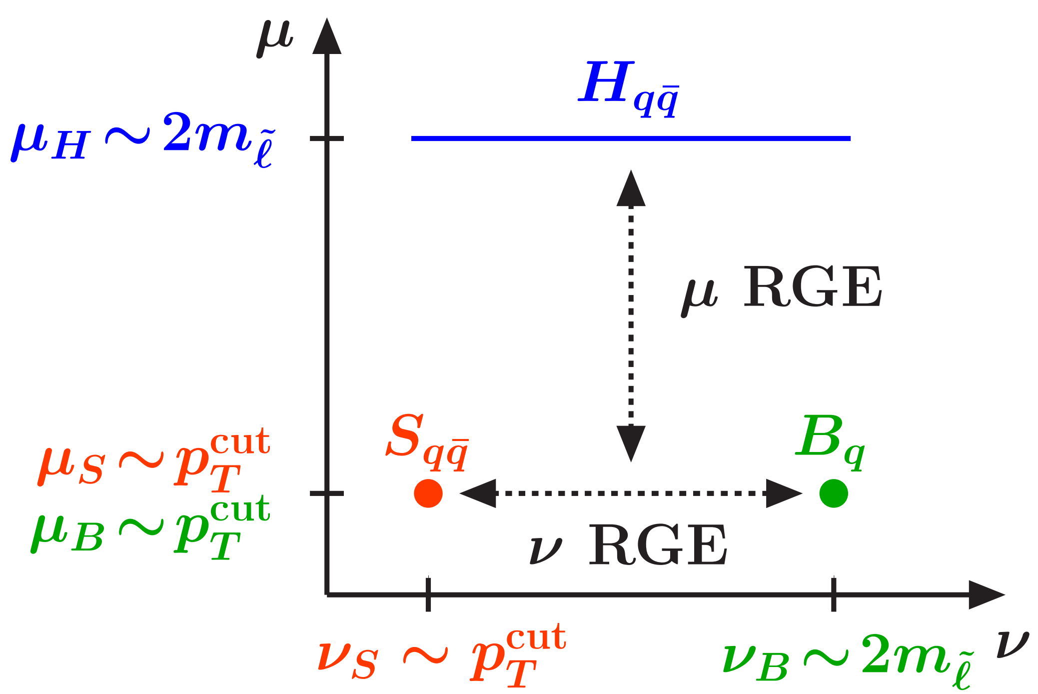
Stewart, Tackmann, Walsh, Zuberi, 1206.4312, 1307.1808;
See also: Becher, Neubert, Rothen, 1205.3806, 1307.0025

- Factorization formula

$$\begin{aligned}\sigma_0(p_T^{\rm cut}, m_{\rm SUSY}, {\rm cuts}) = \int {\rm d}Q^2\, {\rm d}Y\, & H_{q\bar q}(Q^2, Y, m_{\rm SUSY}, {\rm cuts}, \mu) \\ & \times B_q(p_T^{\rm cut}, x_a, \mu, \nu)\, B_{\bar q}(p_T^{\rm cut}, x_b, \mu, \nu)\, S_{q\bar q}(p_T^{\rm cut}, \mu, \nu) \\ & + \sigma_0^{\rm nons}(p_T^{\rm cut}, m_{\rm SUSY}, {\rm cuts})\end{aligned}$$

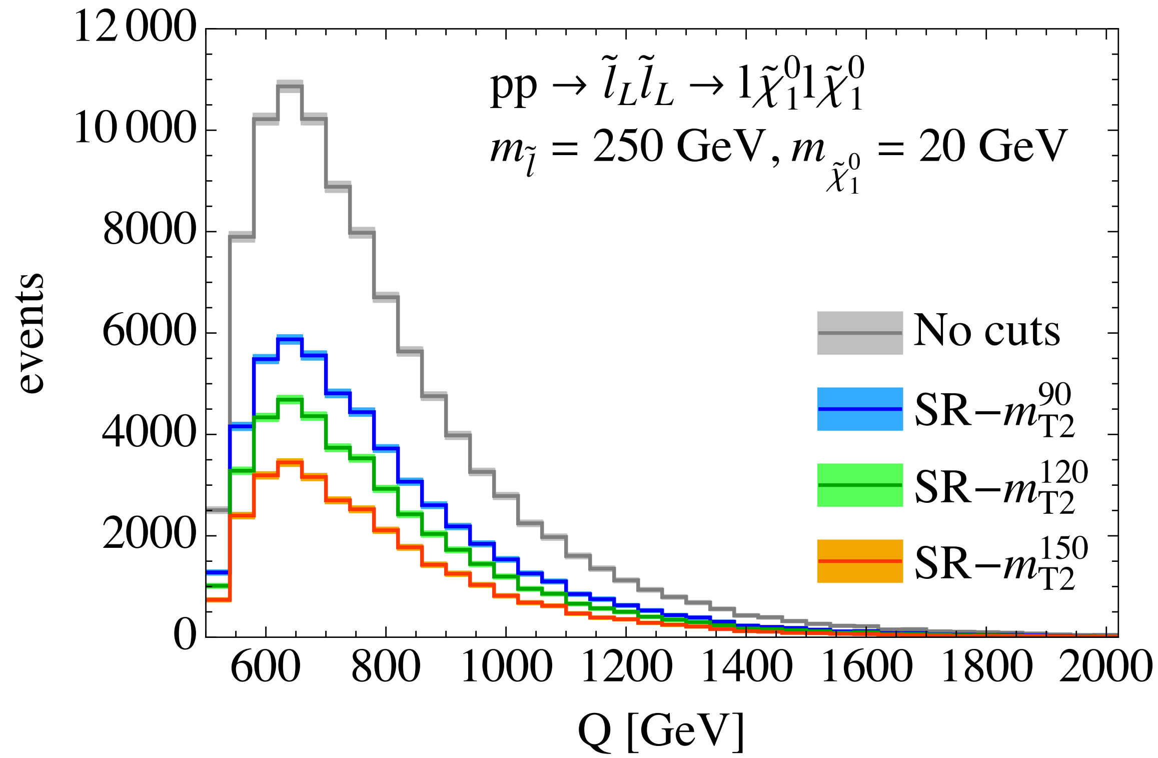
- Rapidity renormalised beam and soft functions obtained from Higgs/Drell-Yan

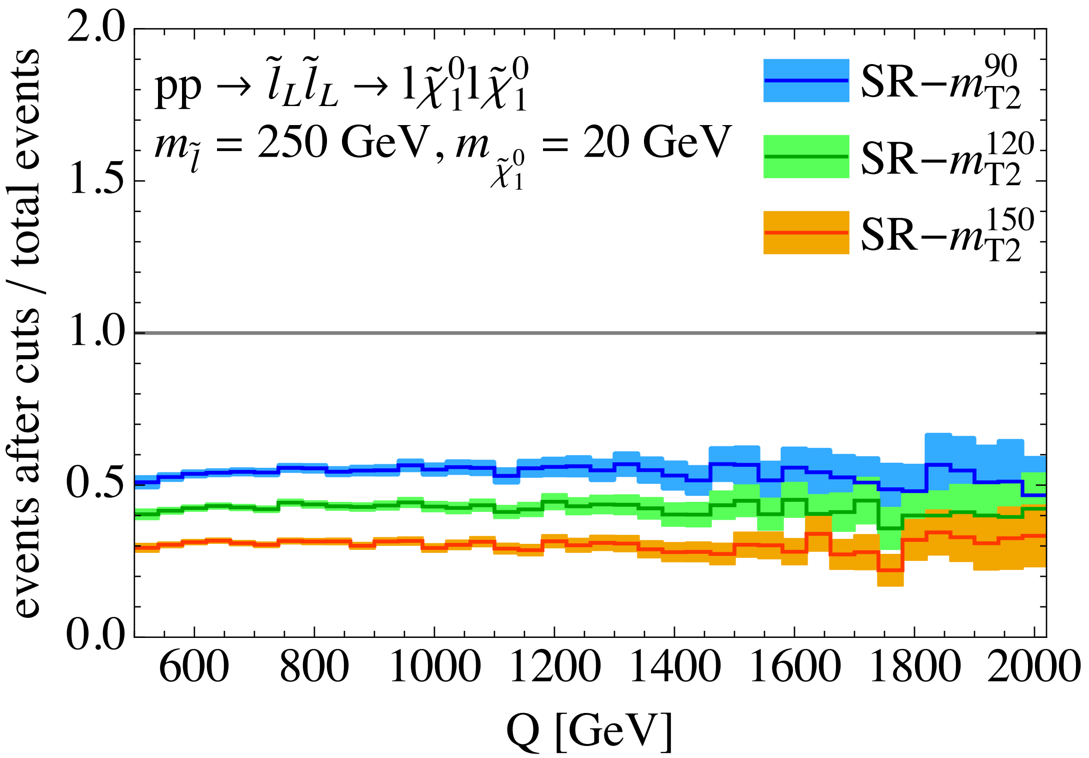
Liu, Petriello, 1210.1906;
Stewart, Tackmann, Walsh, Zuberi, 1307.1808



Correlations of jet veto with other cuts

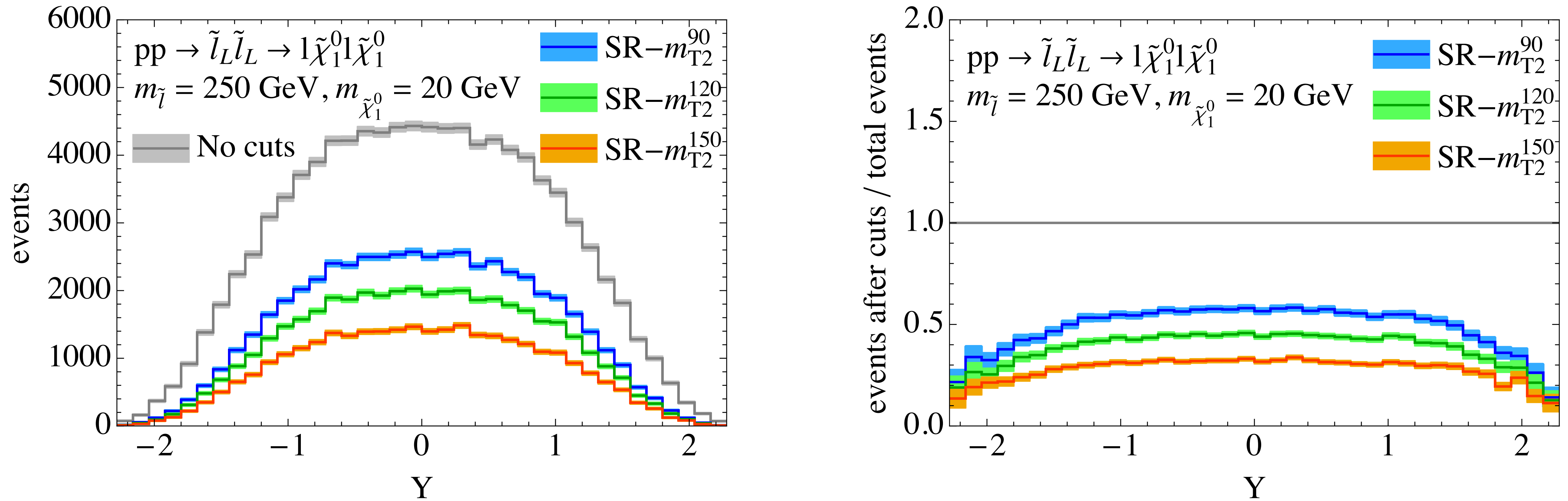
- Beam and soft function depend on jet veto, whereas hard function depends on other cuts
- Correlations via the common variables Q and Y?





Correlations of jet veto with other cuts

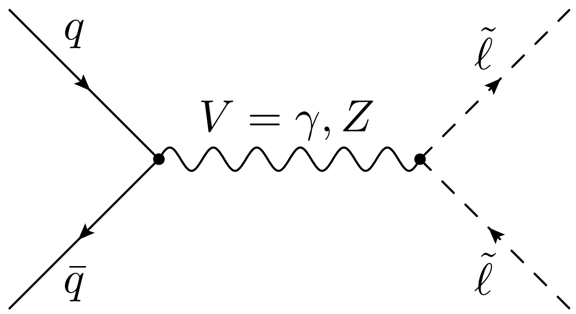
- Beam and soft function depend on jet veto, whereas hard function depends on other cuts
- Correlations via the common variables Q and Y?
  Other cuts do not affect the Q and Y shape
  ⇒ Factor them out and treat them as Q and Y independent correction



Slepton production

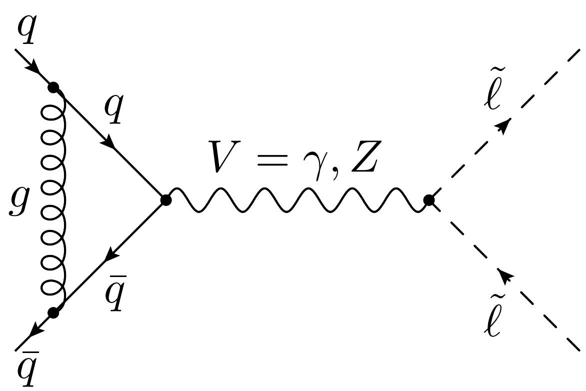
- Now $\mathcal{B}(\tilde{\ell} \to \ell \chi_1^0) = 1$ allows us to consider slepton production without decay

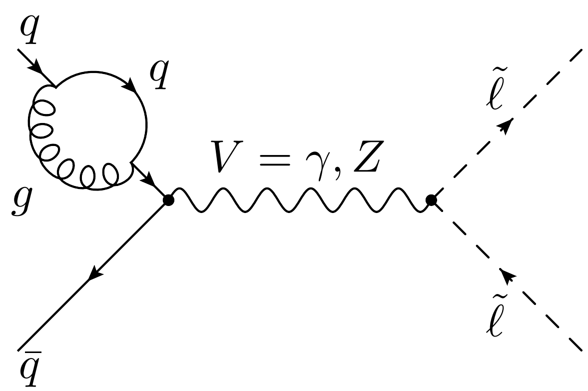
Tree-level:



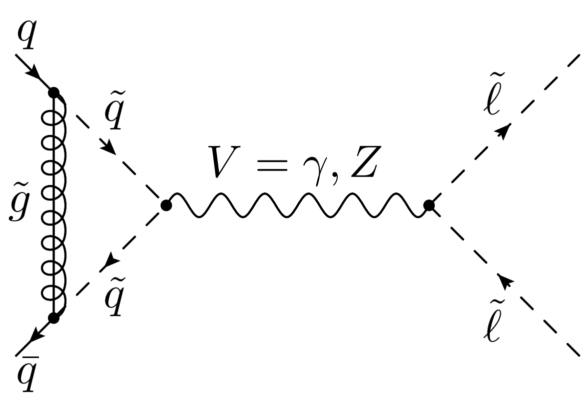
QCD corrections are clearly bigger than SUSY-QCD corrections, especially in simplified model

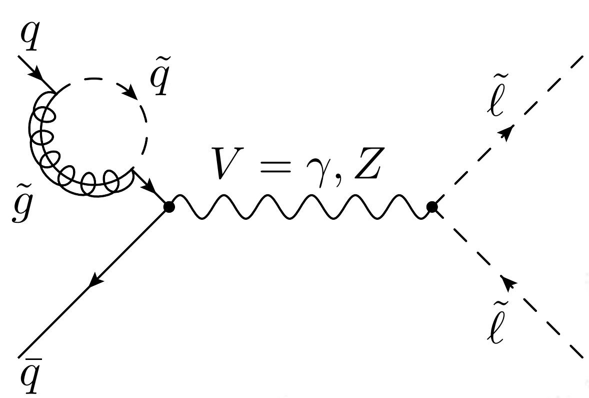
NLO QCD:





NLO SUSY-QCD:





- At NLO other production modes are possible, but negligible

Hard function

$$H_{q\bar{q}}(Q^2, m_{\mathrm{SUSY}}, \mu) = \sigma_B(1+V)$$

- Born cross section ($s = L, R$):

$$\sigma_B = \frac{\alpha_{\mathrm{em}}^2 \pi}{9Q^2} \frac{1}{E_{\mathrm{cm}}^2} \left(1 - \frac{4m_{\tilde{\ell}_s}^2}{Q^2}\right)^{3/2} h_{\tilde{\ell}_s \tilde{\ell}_s}$$

For right-handed sleptons cross-section is smaller ⇒ exclusion weaker

$$h_{\tilde{\ell}_s \tilde{\ell}_s} = Q_q^2 Q_\ell^2 + Q_q Q_\ell \frac{(g_q^- + g_q^+)(g_\ell^- \delta_{sL} + g_\ell^+ \delta_{sR})}{1 - m_Z^2/Q^2} + \frac{({g_q^-}^2 + {g_q^+}^2)({g_\ell^-}^2 \delta_{sL} + {g_\ell^+}^2 \delta_{sR})}{2(1 - m_Z^2/Q^2)^2}$$

electric charges fermion-Z-couplings

- Virtual corrections:

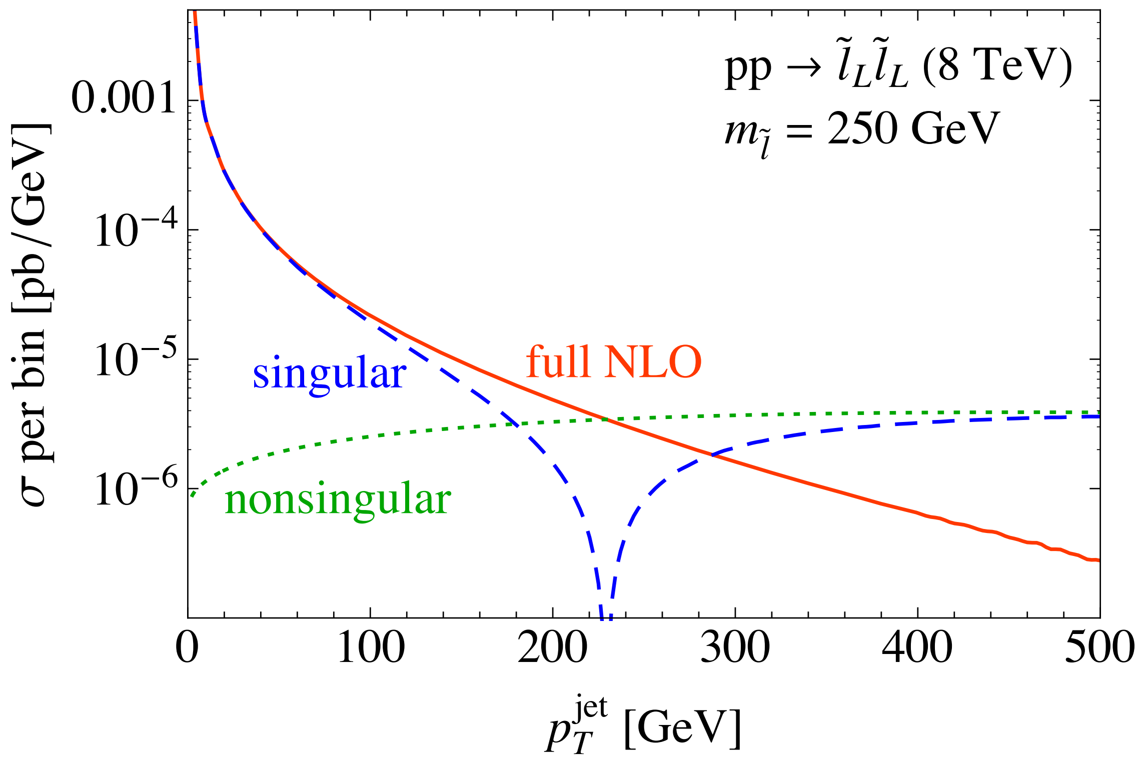
$$V = \frac{\alpha_s(\mu) C_F}{4\pi} (V_{\mathrm{QCD}} + V_{\mathrm{SUSY}}) + h.c.$$

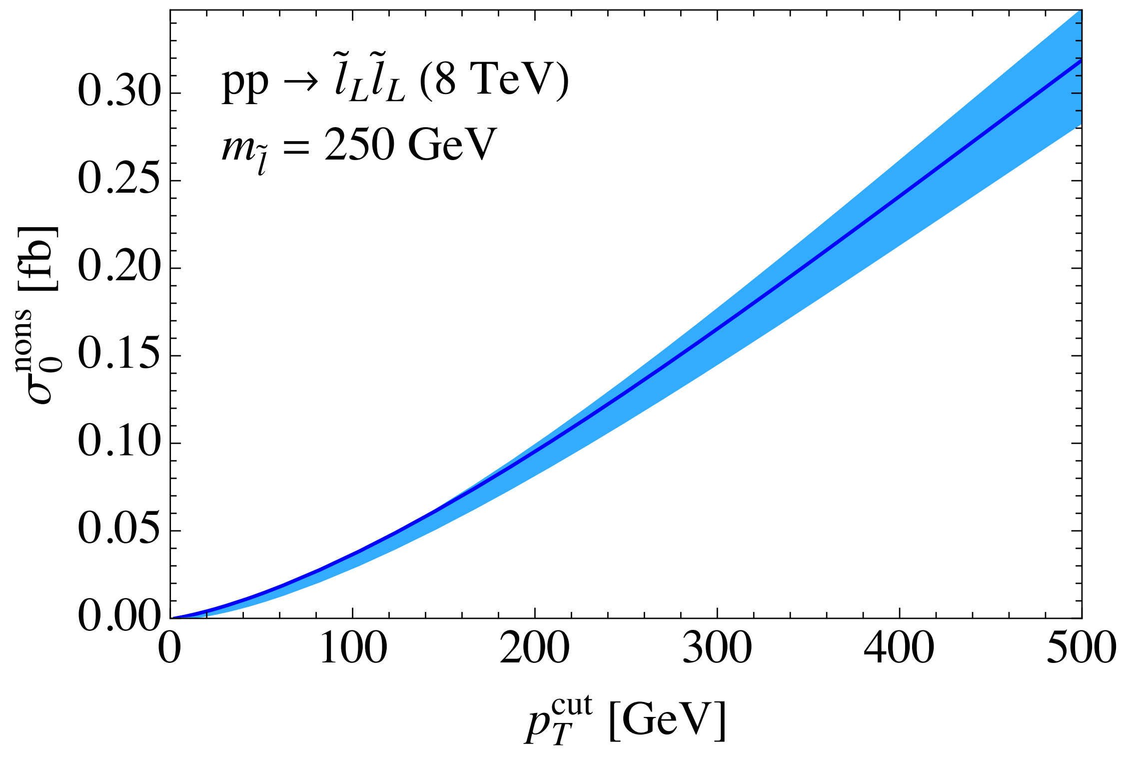
$$V_{\mathrm{QCD}} = -\ln^2\left(\frac{Q^2}{\mu^2}\right) + 3\ln\left(\frac{Q^2}{\mu^2}\right) - 8 + \frac{7\pi^2}{6}$$

V_{SUSY} has no IR divergencies, hence no explicit μ dependence

$$\begin{aligned} V_{\mathrm{SUSY}} = 1 &+ \frac{2\,m_{\tilde{g}}^2 - 2m_{\tilde{q}}^2}{Q^2}\left[B_0(Q^2, m_{\tilde{q}}^2, m_{\tilde{q}}^2) - B_0(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2)\right] + B_0(Q^2, m_{\tilde{q}}^2, m_{\tilde{q}}^2) \\ &+ 2\frac{m_{\tilde{g}}^4 + (Q^2 - 2m_{\tilde{q}}^2)\, m_{\tilde{g}}^2 + m_{\tilde{q}}^4}{Q^2} C_0(0, 0, Q^2, m_{\tilde{q}}^2, m_{\tilde{g}}^2, m_{\tilde{q}}^2) \\ &- B_0(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2) + (m_{\tilde{q}}^2 - m_{\tilde{g}}^2) B_0'(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2) \end{aligned}$$

Nonsingular contributions





- We include $\mathcal{O}(p_T^{\rm cut}/Q)$ suppressed non singular contributions to reproduce the full NLO result at large $p_T^{\rm cut}$

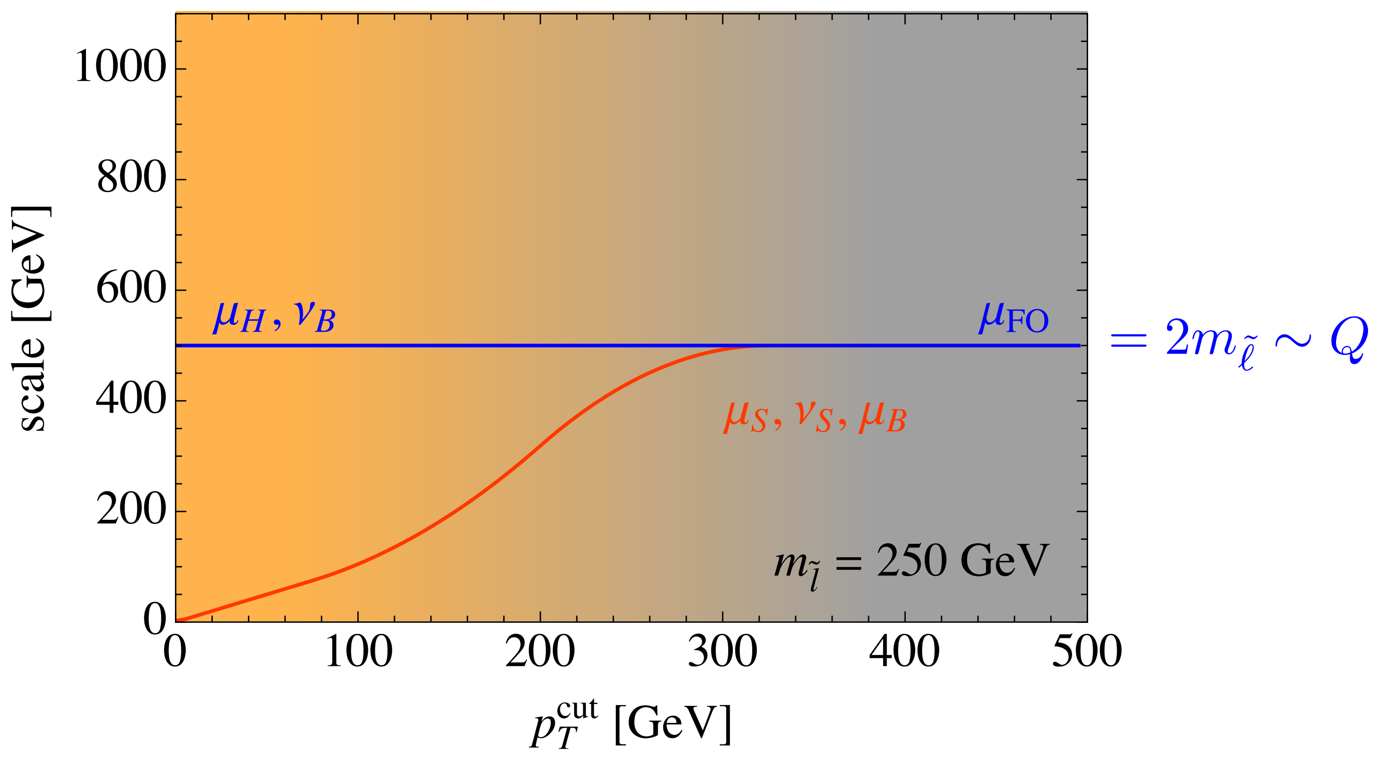
$$\sigma_0^{\rm nons}(p_T^{\rm cut}) = \int_{\epsilon\to 0}^{p_T^{\rm cut}} \mathrm{d}p_T^{\rm jet} \left(\frac{\mathrm{d}\sigma_0^{\rm FO}}{\mathrm{d}p_T^{\rm jet}} - \frac{\mathrm{d}\sigma_0^{\rm sing}}{\mathrm{d}p_T^{\rm jet}} \right)$$

Set all scales in NLL' result equal to the fixed-order scale

Generate $pp \to \tilde{\ell}\tilde{\ell} + j$ events in Madgraph

Fit: $$\frac{\mathrm{d}\sigma_0^{\rm nons}}{\mathrm{d}p_T^{\rm jet}} = a \ln \frac{p_T^{\rm jet}}{2m_{\tilde{\ell}}} + b + c\frac{p_T^{\rm jet}}{2m_{\tilde{\ell}}} \ln \frac{p_T^{\rm jet}}{2m_{\tilde{\ell}}} + d\frac{p_T^{\rm jet}}{2m_{\tilde{\ell}}}$$

Profile scales



- Resummation region: canonical scales (minimizing logarithms)
- Fixed-order region: common fixed order scale (resummation turned off)
- Smooth transition between resummation and fixed order region using profile scales:

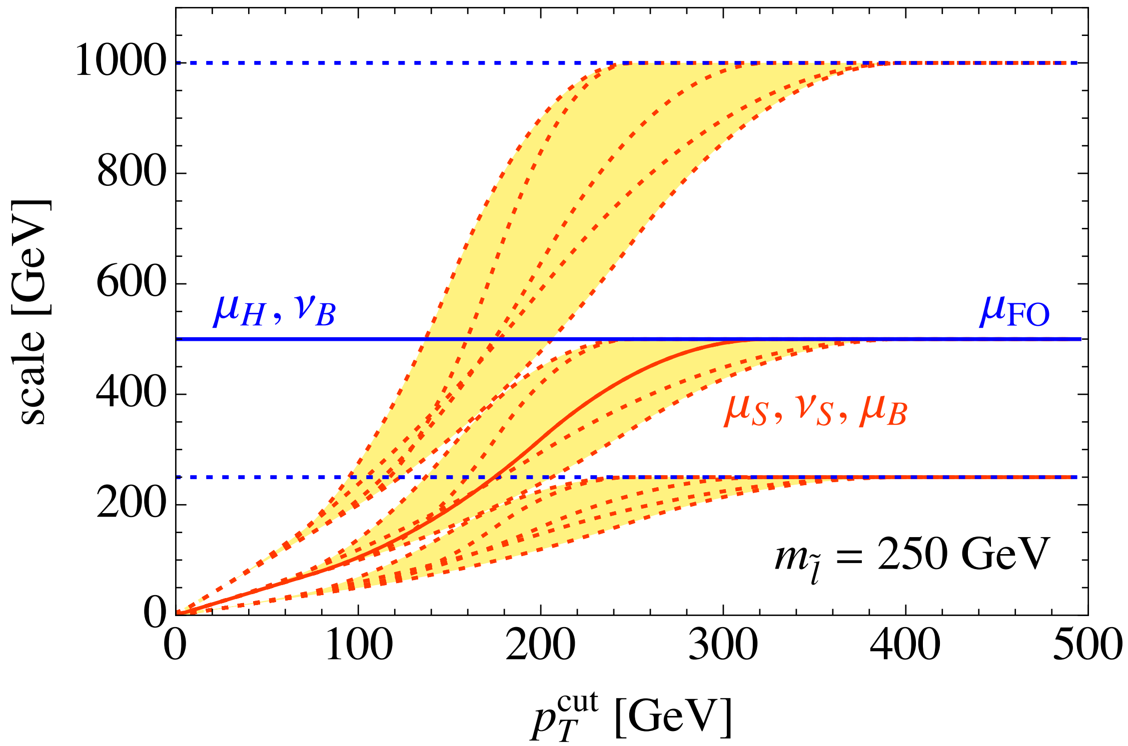
Ligeti, Stewart, Tackmann, 0807.1926; Abbate, Fickinger, Hoang, Mateu, Stewart, 1006.3080

$$\mu_H = \nu_B = \mu_{\rm FO}\,,$$
$$\mu_B = \mu_S = \nu_S = \mu_{\rm FO} \times f_{\rm run}\big(p_T^{\rm cut}/(2m_{\tilde\ell})\big)$$

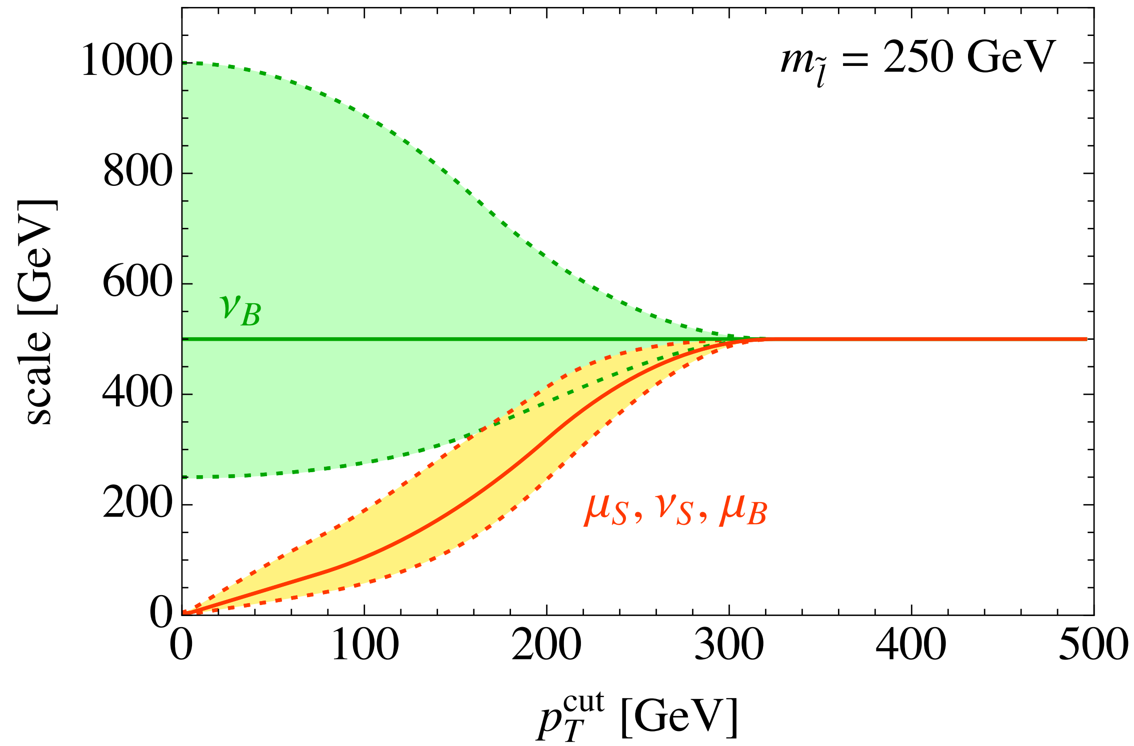
Stewart, Tackmann, Walsh, Zuberi, 1307.1808

Theory uncertainties

Fixed-order scale variations:



Resummation scale variations:



- Overall variation of the FO scale by factors 1/2 and 2
- Variation of the transition points

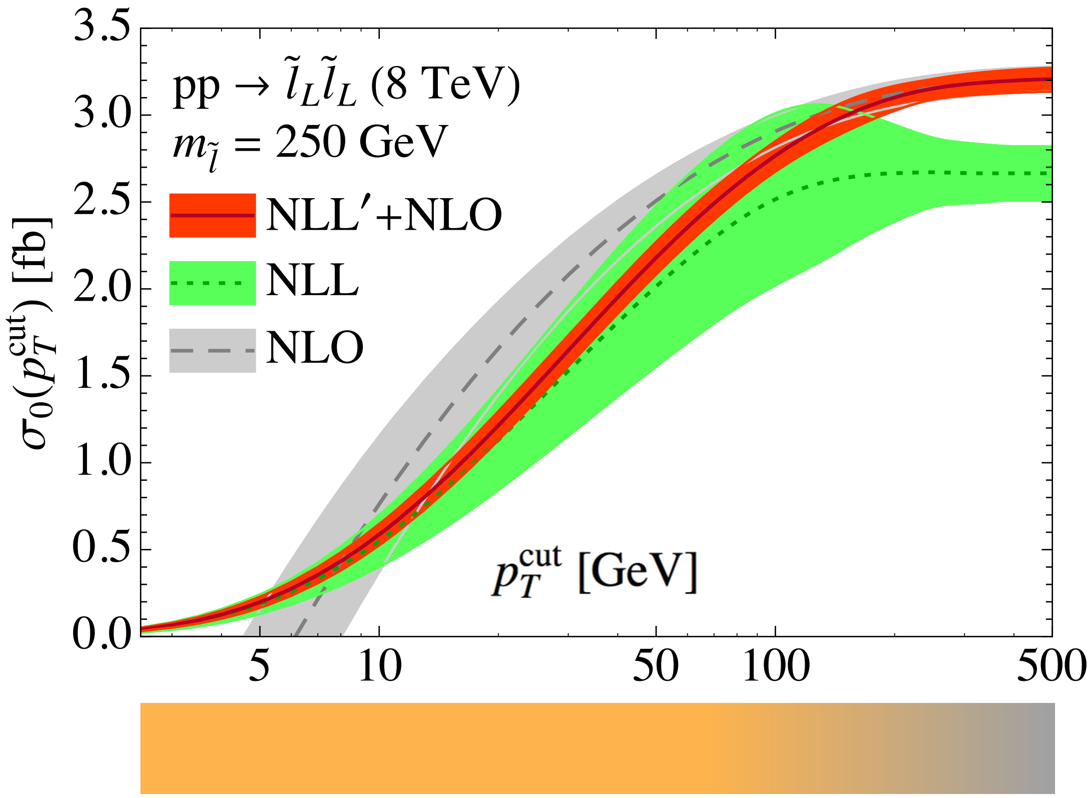
14 variations ⇒ take the maximum

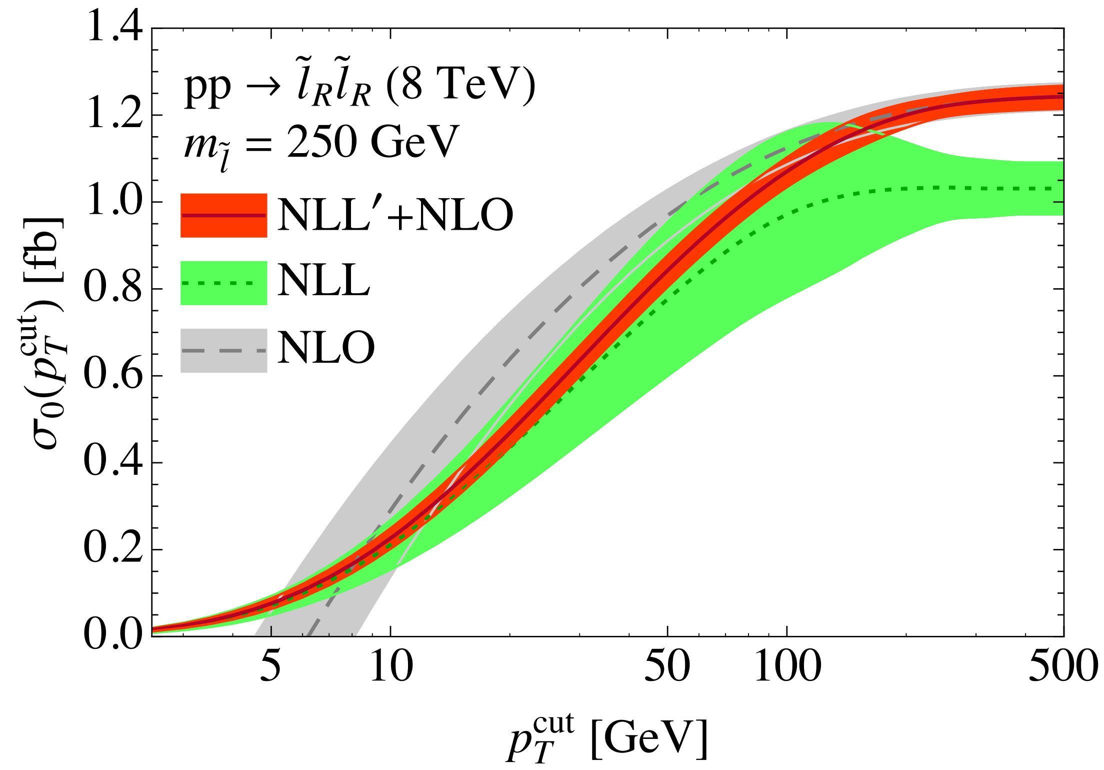
- Independent variations of beam and soft scales. Combinations within canonical restrictions.

35 variations ⇒ take the maximum

- Fixed-order as well as resummation uncertainties estimated by profile scale variations Stewart, Tackmann, Walsh, Zuberi, 1307.1808
- Fixed-order and resummation uncertainties added in quadrature

Results at 8 TeV





- Parameter point at the edge of the current exclusion limit: $m_{\tilde{\ell}} = 250$ GeV
- Fixed order uncertainties estimated with ST method
- Experimental value $p_T^{\text{cut}} = 20$ GeV deep in resummation region
- Comparing NLL'+NLO to NLL:
  Good convergence and substantial reduction of theory uncertainties

Impact on current exclusion limits

- Analysis gives $\sigma^{95}_{\mathrm{vis}}$ which is compared to $\sigma_{\mathrm{vis}} = \sigma_{\mathrm{SUSY}} \times \epsilon^{(\mathrm{SR})}_{\mathrm{SUSY}}$
- Define the upper limit on the 0-jet cross section:

$$\boxed{\sigma^{95}_{0,\mathrm{vis}} = \frac{\sigma^{95}_{\mathrm{vis}}}{\epsilon^{(\mathrm{SR-noJV})}_{\mathrm{SUSY}}}}$$

$$\epsilon^{(\mathrm{SR})}_{\mathrm{SUSY}} = \epsilon^{(\mathrm{JV})}_{\mathrm{SUSY}} \times \epsilon^{(\mathrm{SR-noJV})}_{\mathrm{SUSY}}$$

Jet veto efficiency

Signal region efficiency excluding the jet veto

- $\sigma^{95}_{0,\mathrm{vis}}$ is defined without reconstruction efficiencies and acceptance cuts
- $\epsilon^{(\mathrm{SR-noJV})}_{\mathrm{SUSY}}$ is calculated with the codes

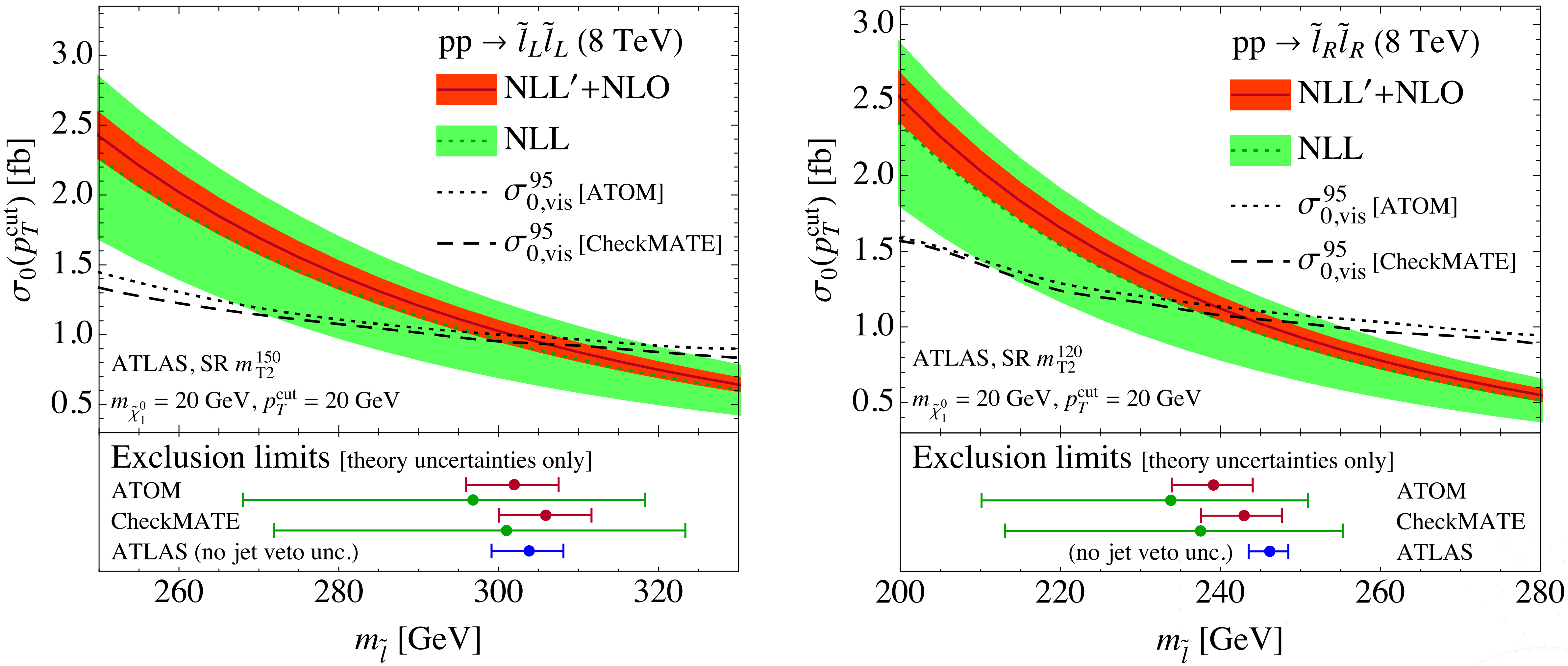
  `ATOM` Kim, Papucci, Sakurai, Weiler (in preparation)

  and `CheckMATE`: Drees, Dreiner, Kim, Schmeier, Tattersall, 1312.2591

  ⤳ Codes to estimate efficiencies taking detector effects into account

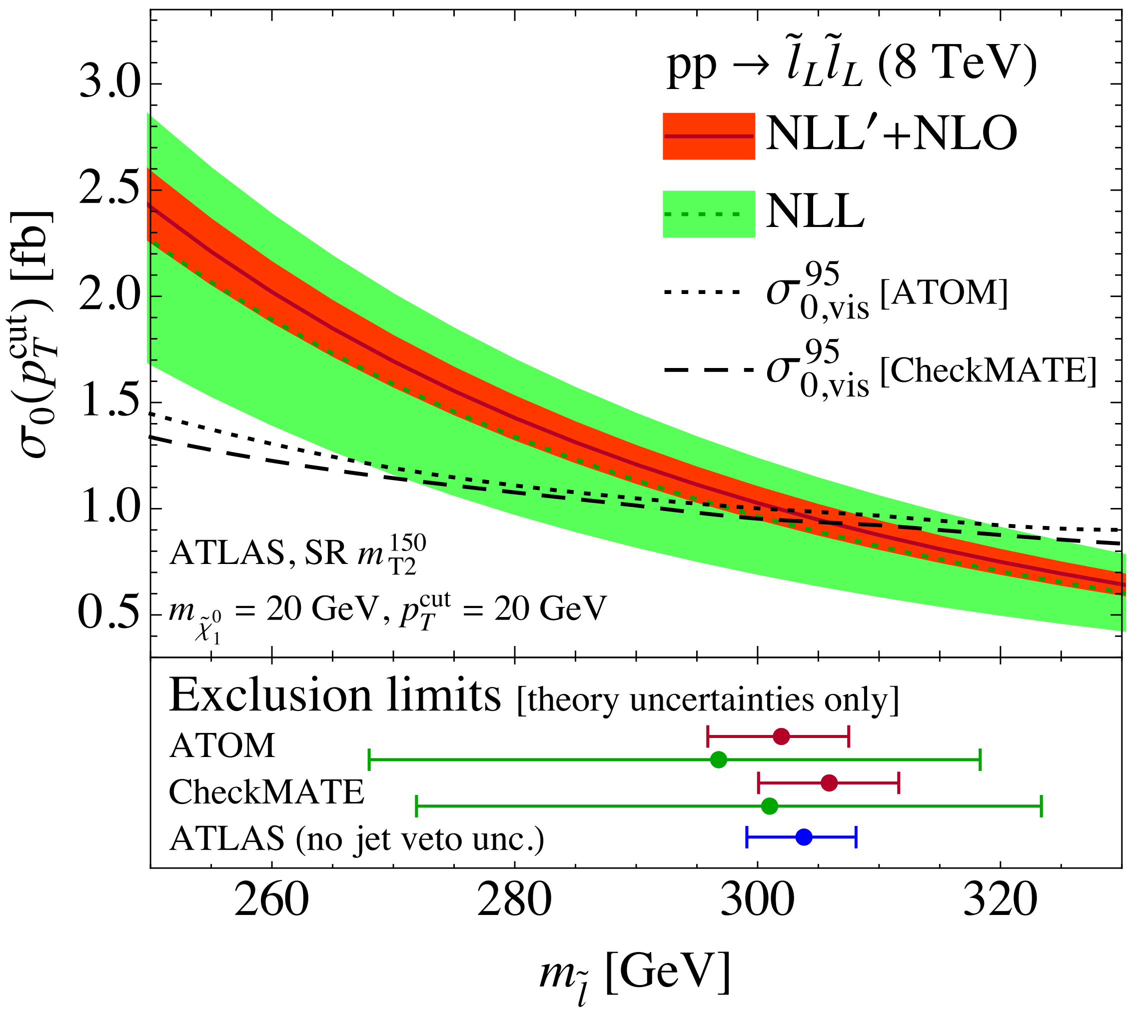
  ⤳ Many implemented and validated analyses

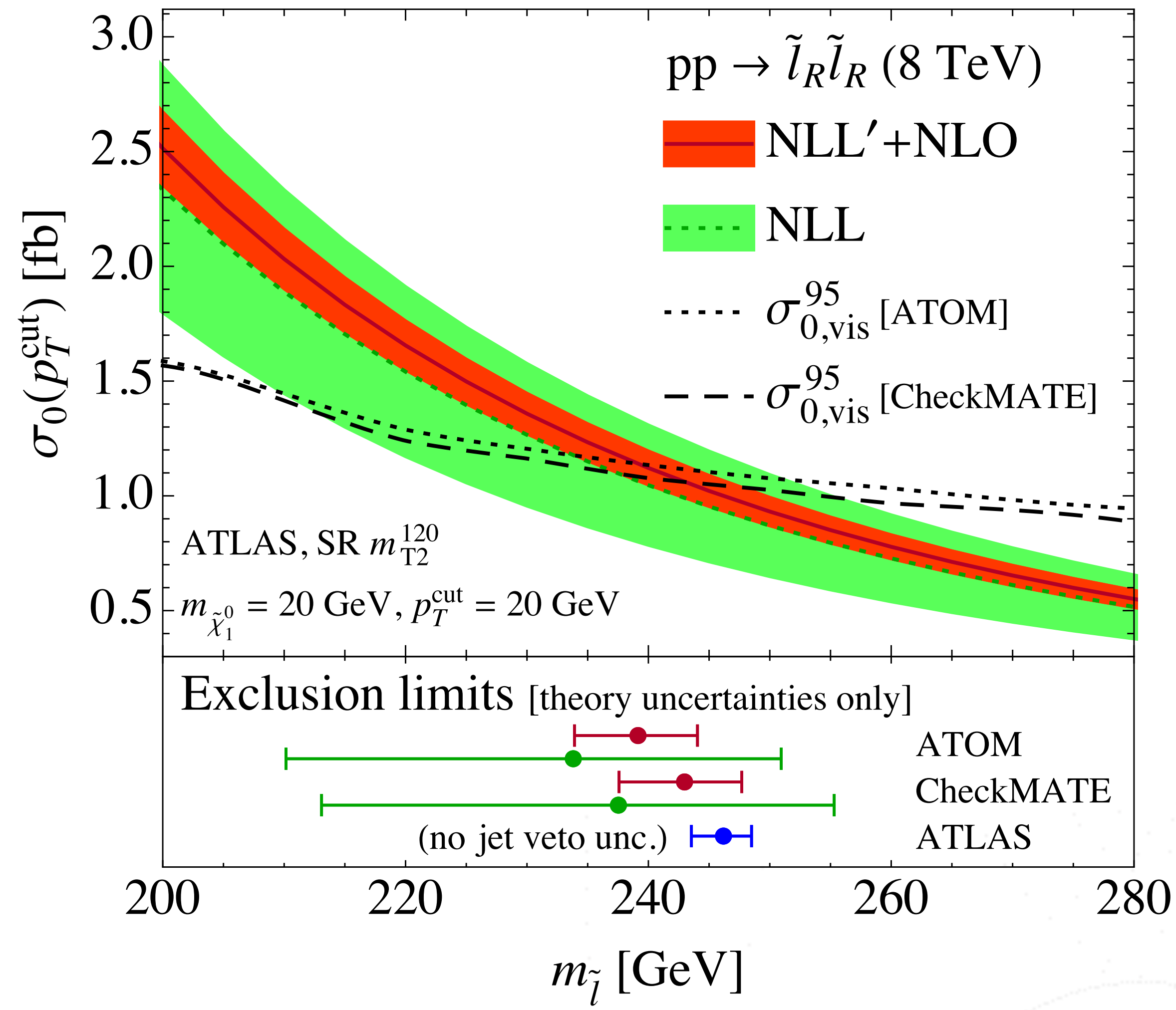
Impact on current exclusion limits



- Exclusion limit by ATLAS takes into account theory uncertainty on total cross section (including PDF uncertainty), but not the jet veto uncertainty
- Parton showers at best NLL:
  Jet veto uncertainty could easily be as large as our NLL uncertainty
- Even our NLL'+NLO result (without PDF uncertainty) has larger uncertainty than ATLAS

Impact on current exclusion limits



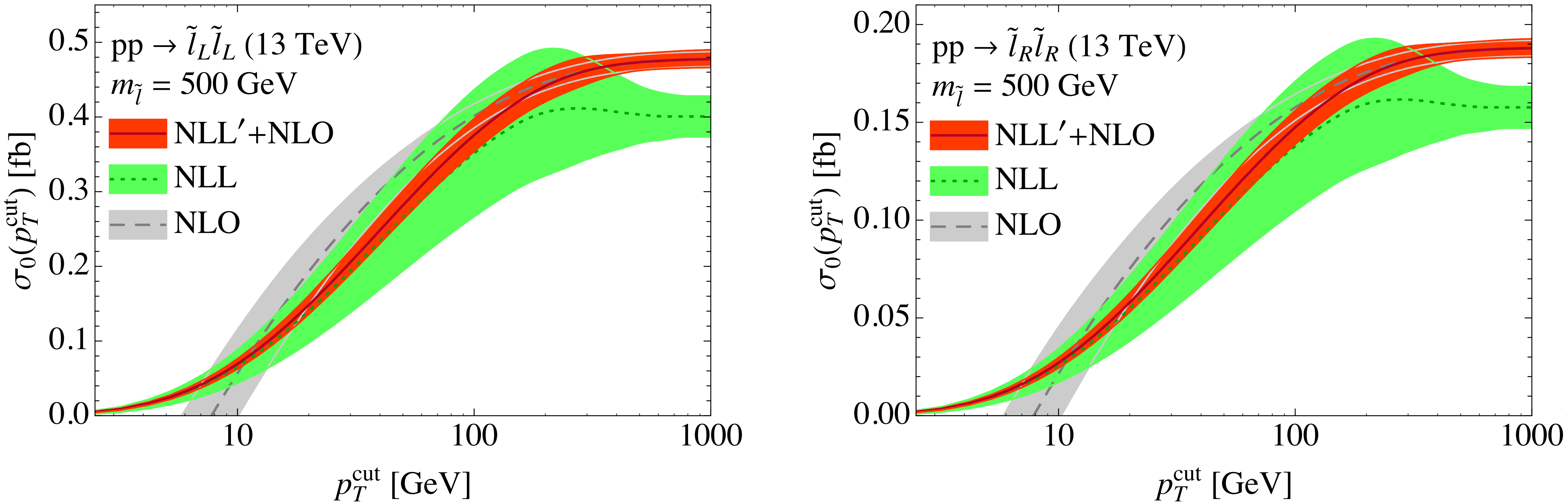


- At NLL the exclusion limits would be noticeably weaker:
  - ⤳ Down to $\sim$ 270 GeV for left-handed sleptons (compared to $\sim$ 305 GeV)
  - ⤳ Down to $\sim$ 210 GeV for right-handed sleptons (compared to $\sim$ 245 GeV)
- Central values are similar

  Caution: 5-10% uncertainty on central value from ATOM and CheckMATE

Results at 13 TeV

p_T^{cut} dependence for a slepton mass of 500 GeV:

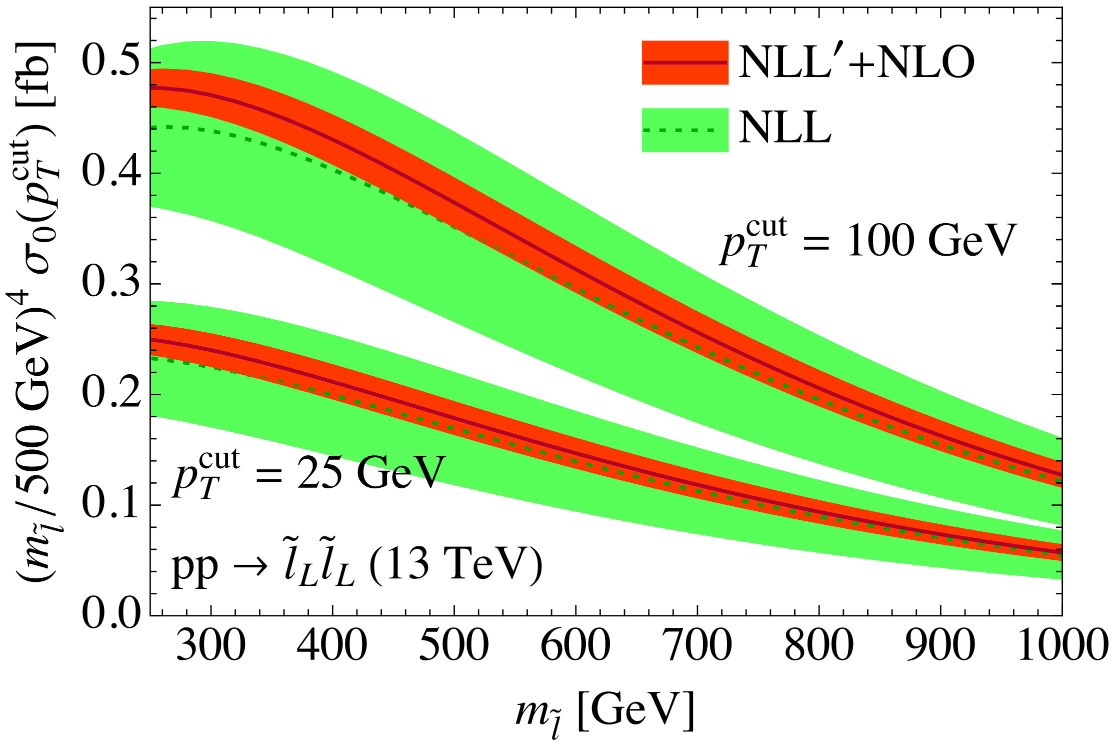


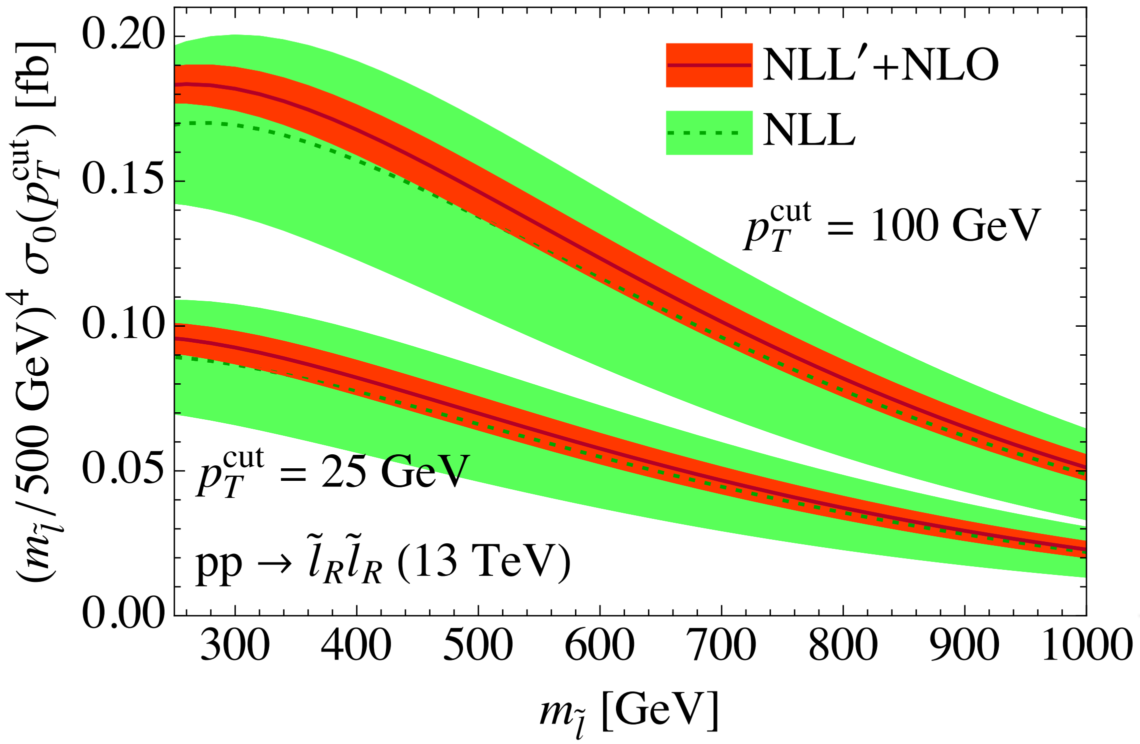
- Higher slepton mass leads to larger logarithms in the cross section

  → Increase of perturbative uncertainties compared to $m_{\tilde{\ell}} = 250$ GeV (8 TeV)

Results at 13 TeV

Slepton mass dependence for two fixed values of p_T^{cut}:

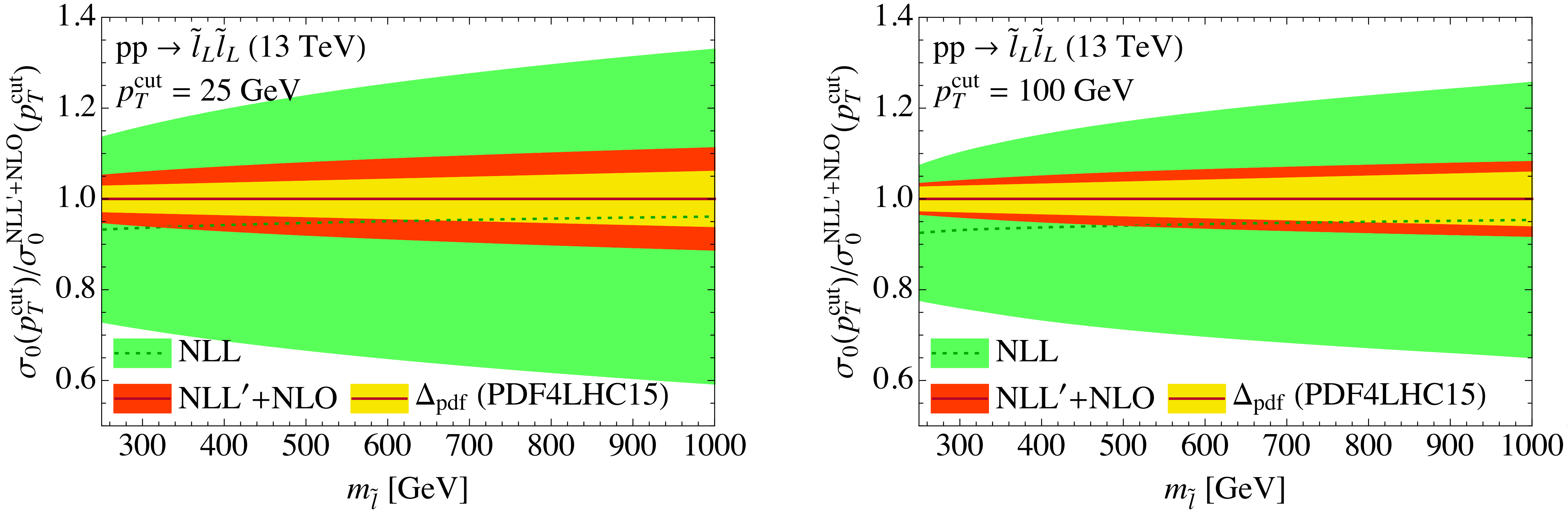




- Perturbative uncertainties increase with slepton mass

Results at 13 TeV

Slepton mass dependence for two fixed values of p_T^{cut}:



- Perturbative uncertainties increase with slepton
- PDF uncertainties:
  - ⤻ PDF4LHC15 recommendations
  - ⤻ Perturbative uncertainties still larger but become comparable for $p_T^{\mathrm{cut}} = 100$ GeV

Uncertainties for $\mathbf{p_T^{cut} = 25}$ GeV

	300 GeV	1000 GeV
NLL	24 %	38 %
NLL′+NLO	6 %	11 %

Summary

- Several LHC searches for new physics use jet vetoes
- First predictions of a SUSY cross section including jet-veto resummation

  ⤳ Slepton production at NLL'+NLO

- Significant impact on the current exclusion limits
- Impact of the jet veto increases further for higher SUSY masses
- Importance of jet vetoes increase when a new particle is discovered, allowing clean measurements

  ⤳ Accurate theory predictions important to precisely determine the properties and reveal the nature of any new particle

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Note:

Fuks, Klasen, Lamprea, Rothering, 1304.0790, 1310.2621; Broggio, Neubert, Vernazza, 1111.6624; Bozzi, Fuks, Klasen, 0701202

Threshold resummation for the total slepton production cross section has been studied - small effect for currently tested values of slepton masses

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Next step:

Extend our analysis to other new physics processes, including also those with final-state jets