

Impact of Jet Veto Resummation on Slepton Searches

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[arXiv:1603.03052]

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SUSY 2016, Melbourne
05.07.2016



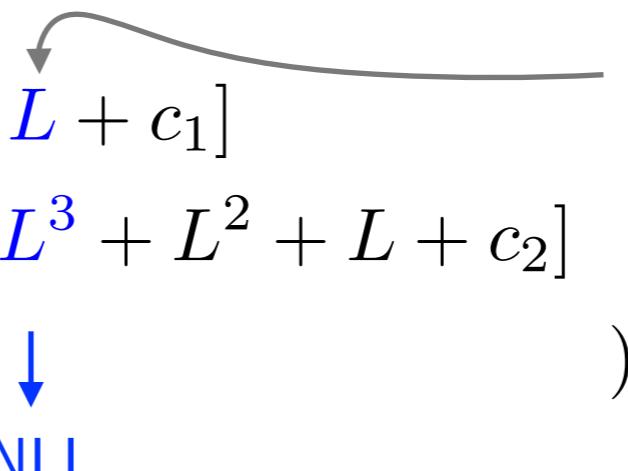
Introduction

- Several searches for new physics at the LHC require a fixed number of signal jets and veto additional jets with $p_T > p_T^{\text{cut}}$
- Jet vetoes introduce logarithms in the cross section \Rightarrow **Resummation**

$$\begin{aligned}\sigma(p_T^{\text{cut}}) \sim \sigma_0 \times & (1 + \alpha_s [L^2 + L + c_1] \\ & + \alpha_s^2 [L^4 + L^3 + L^2 + L + c_2] \\ & + \dots)\end{aligned}$$

Large logarithms
 $L = \ln(p_T^{\text{cut}}/Q)$

LL NLL



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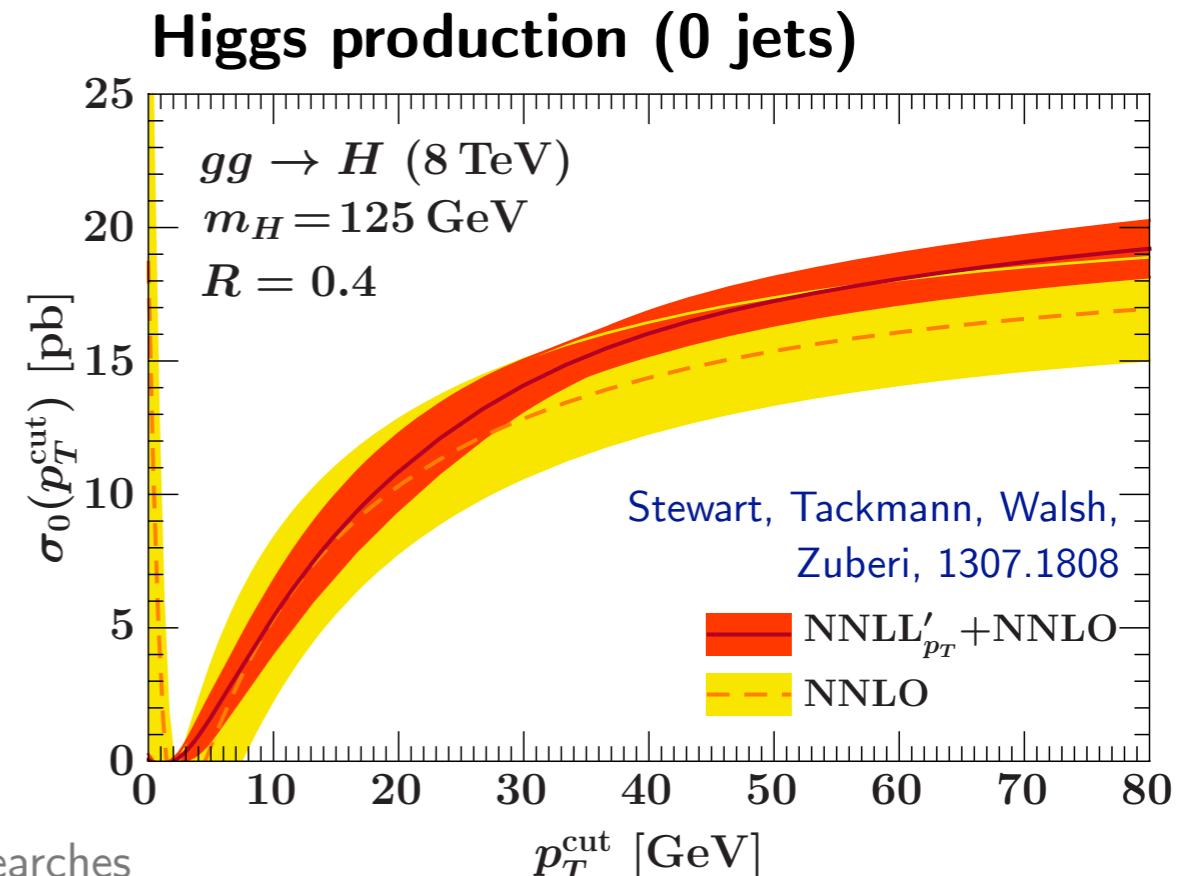
- Sizeable effect in Higgs production

$p_T^{\text{veto}} \sim 30 \text{ GeV}$

Higgs: $Q \sim 125 \text{ GeV}$

New physics: $Q \sim 1000 \text{ GeV}$

Jet veto effect more significant
for new physics processes!



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LL NLL

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

8 TeV BSM searches using jet vetoes

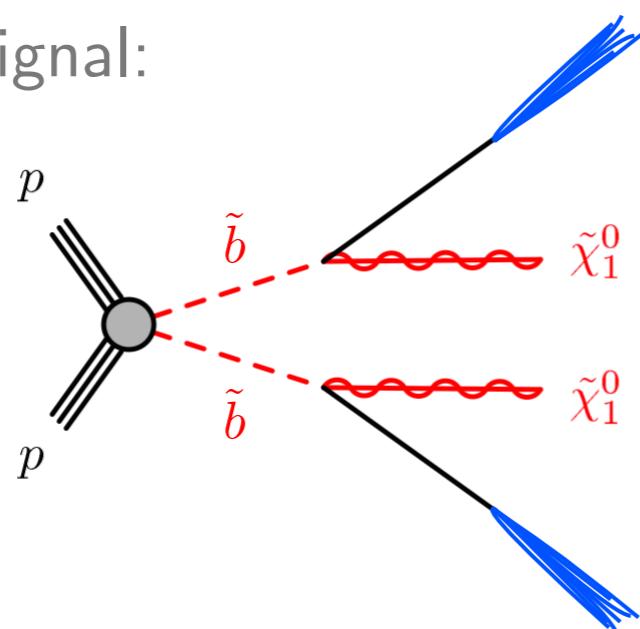
- Electroweakino and slepton searches typically requiring 0 jets

ATLAS: 1407.0350, 1403.5294, 1501.07110, 1509.07152, **CMS:** 1405.7570

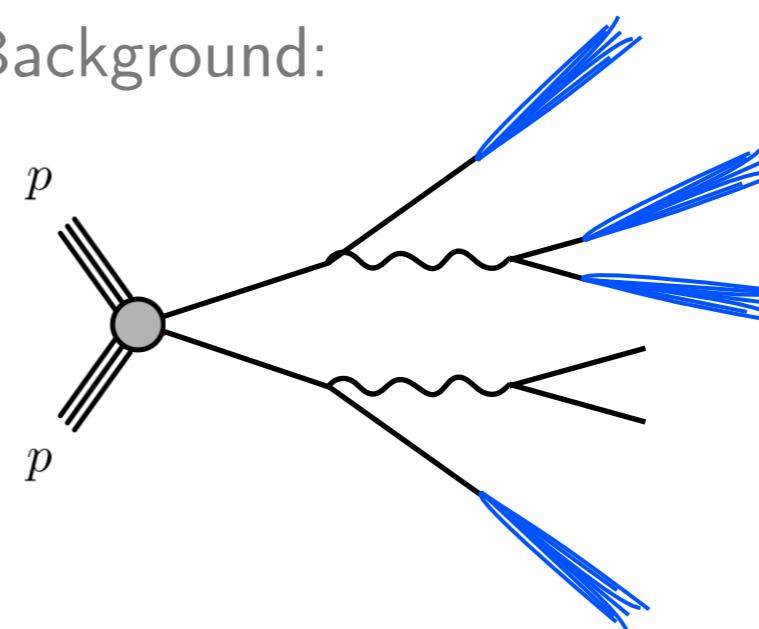
- Stop and sbottom searches vetoing a third jet

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

- ...

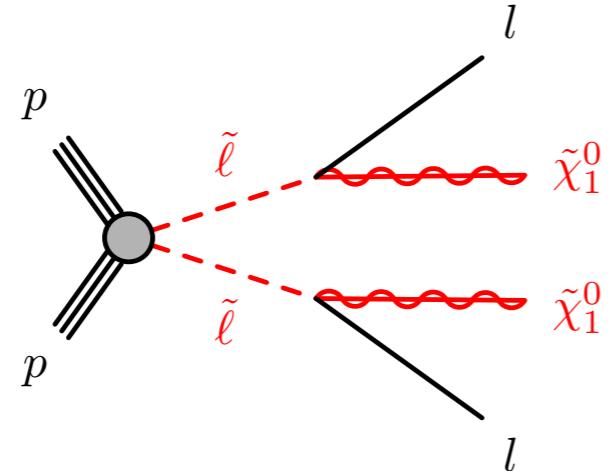
SUSY searches at the LHC

- Example analysis:

ATLAS 8TeV 20.3 fb⁻¹

JHEP 05 (2014) 071, 1403.5294

- Targeting EWkino and Slepton production



- All jets with $p_T > 20$ GeV are vetoed
- Very similar for other analyses, also CMS

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

	Results	
	SR- m_{T2}^{90}	DF
	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

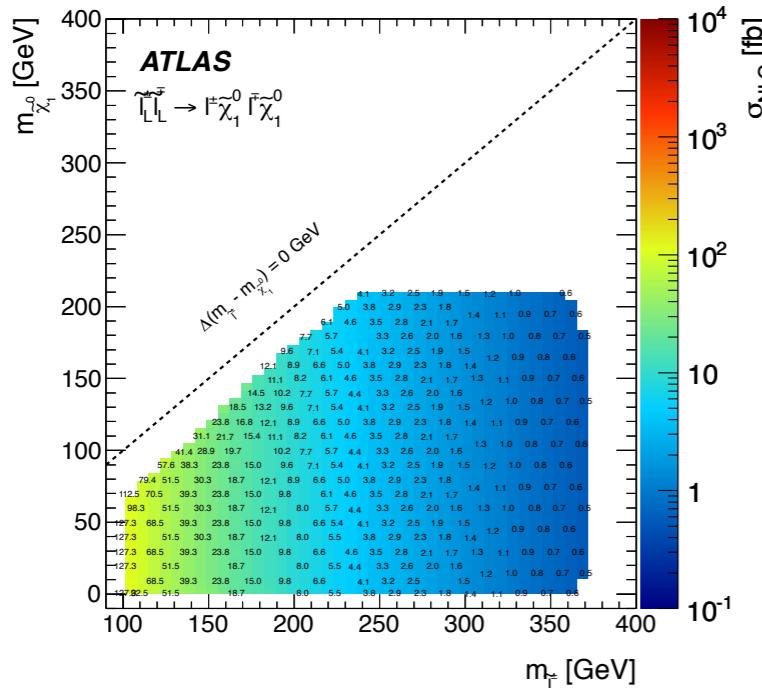
SUSY searches at the LHC

Setting exclusion limits

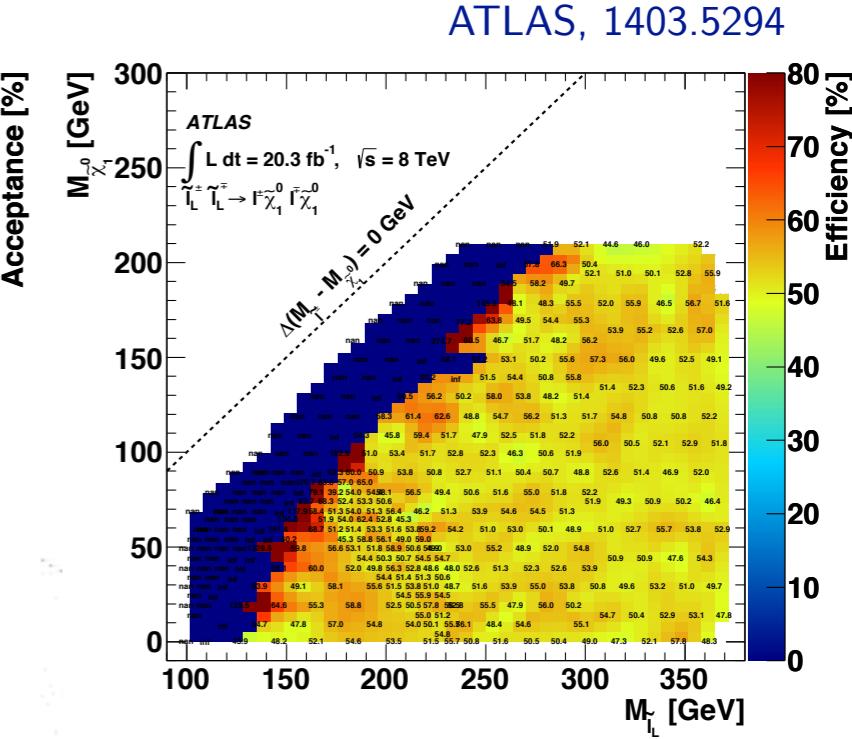
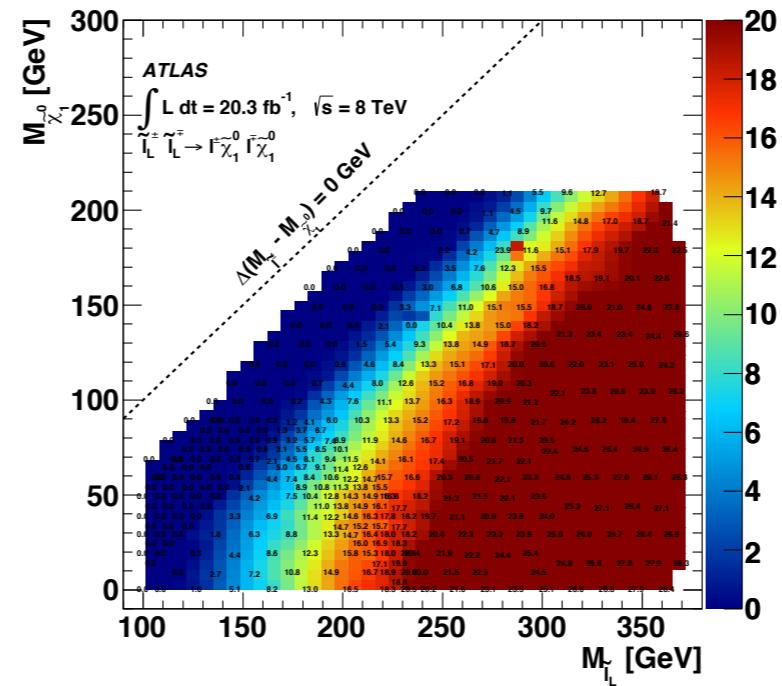
- One specific SUSY model is considered, typically a simplified model
- For each parameter point $\sigma_{\text{vis}} = \sigma_{\text{SUSY}} \times \epsilon_{\text{SUSY}}^{(\text{SR})}$ is calculated and compared to σ_{vis}^{95} (for the signal region with highest expected sensitivity)

Total SUSY cross section

NLO: Prospino Beenakker et al,
9906298



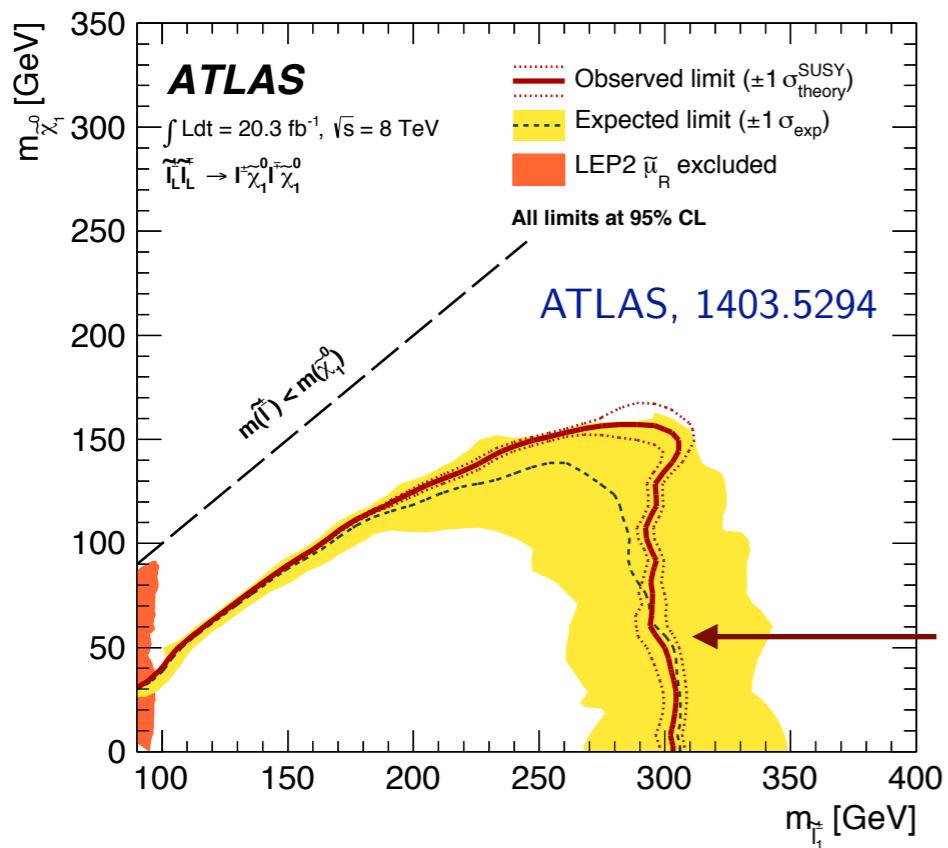
Experimental reconstruction efficiency
and acceptance



SUSY searches at the LHC

Setting exclusion limits

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- Model dependent exclusion limit:
 - $\epsilon_{\text{SUSY}}^{(\text{SR})}$ including the jet veto cut is obtained from parton shower Monte Carlo

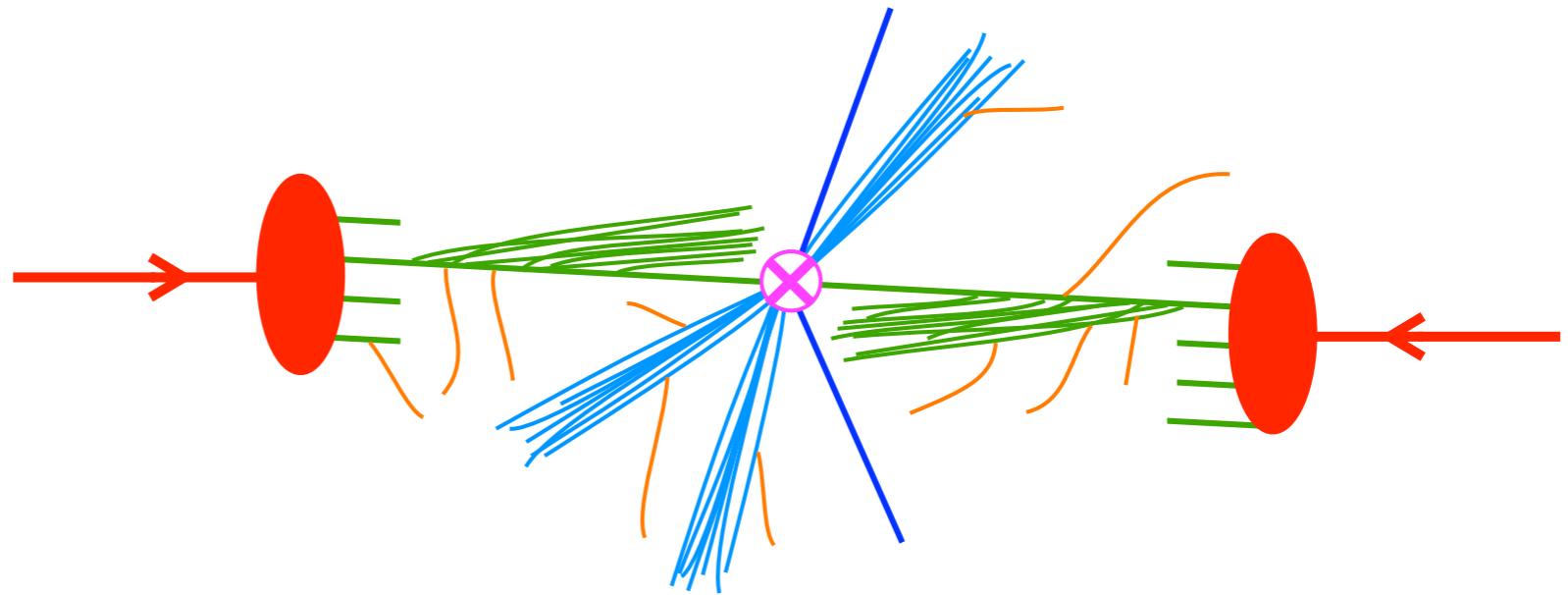


No jet-veto uncertainty included

- Captures the leading logs
- No control over jet-veto uncertainty

Factorization and resummation in SCET

PDFs
Initial-state radiation
Hard scattering
Final-state radiation
Soft radiation



- Calculations with multiple scales lead to large logarithms, e.g. $\alpha_s \ln^2 \frac{p_T^{\text{cut}}}{Q}$
- Factorization: separate the physics associated with the different scales

$$d\sigma = H \times BB \times S \times \prod_i J_i \quad (B = I \times f)$$

- Each component depend only on one scale, e.g. $H(Q)$ contains $\alpha_s \ln^2 \frac{\mu}{Q}$
→ Remove logs by natural scale choice $\mu \rightarrow \mu_H = Q$
- Resummation: Use RGEs to obtain all ingredients (H, B, S, J) at a common scale

$$H(\mu, Q) \simeq \exp \left[\alpha_s \ln^2 \frac{Q^2}{\mu^2} + \dots \right] H(\mu_H = Q, Q)$$

Factorization formula

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

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

$$\begin{aligned} \sigma_0(p_T^{\text{cut}}, m_{\text{SUSY}}, \text{cuts}) = & \int dQ^2 dY \, \textcolor{magenta}{H}_{q\bar{q}}(Q^2, Y, m_{\text{SUSY}}, \text{cuts}) \\ & \times \textcolor{green}{B}_q(p_T^{\text{cut}}, x_a) \, B_{\bar{q}}(p_T^{\text{cut}}, x_b) \, \textcolor{brown}{S}_{q\bar{q}}(p_T^{\text{cut}}) + \sigma_0^{\text{nons}}(p_T^{\text{cut}}, m_{\text{SUSY}}, \text{cuts}) \end{aligned}$$

Order	$\textcolor{magenta}{H}, \textcolor{green}{B}, \textcolor{brown}{S}$	γ_F^i	$\Gamma_{\text{cusp}}^i, \beta$
LL	LO		1-loop
NLL	LO	1-loop	2-loop
NLL'	NLO	1-loop	2-loop
NNLL	NLO	2-loop	3-loop

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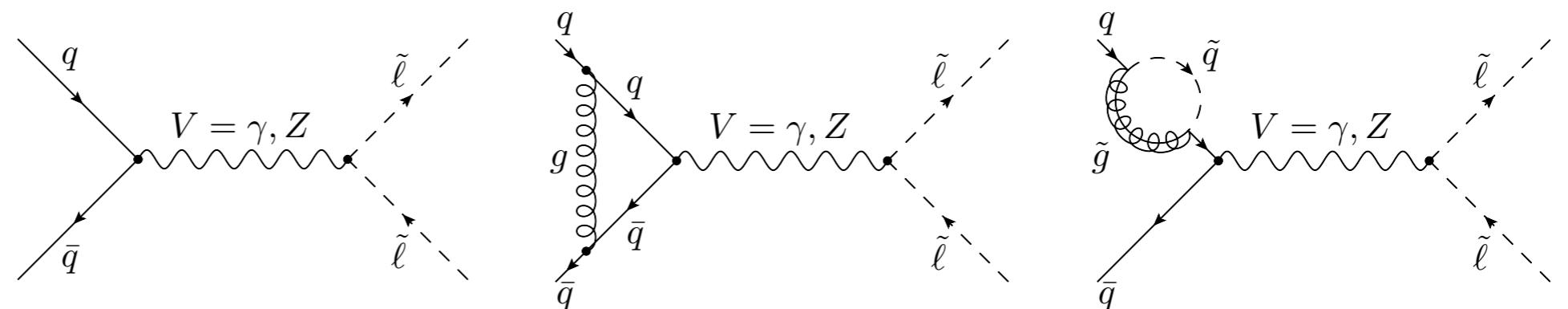
$$\begin{aligned} \sigma_0(p_T^{\text{cut}}, m_{\text{SUSY}}, \text{cuts}) &= \int dQ^2 dY H_{q\bar{q}}(Q^2, Y, m_{\text{SUSY}}, \text{cuts}) \\ &\quad \times B_q(p_T^{\text{cut}}, x_a) B_{\bar{q}}(p_T^{\text{cut}}, x_b) S_{q\bar{q}}(p_T^{\text{cut}}) + \sigma_0^{\text{nons}}(p_T^{\text{cut}}, m_{\text{SUSY}},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

- Beam and **soft** functions obtained from Drell-Yan

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

- Hard function: $H_{q\bar{q}}(Q^2, m_{\text{SUSY}}, \mu) = \sigma_B(1 + V)$

Virtual corrections
Born cross section



Factorization formula

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Stewart, Tackmann, Walsh, Zuberi, 1206.4312, 1307.1808;
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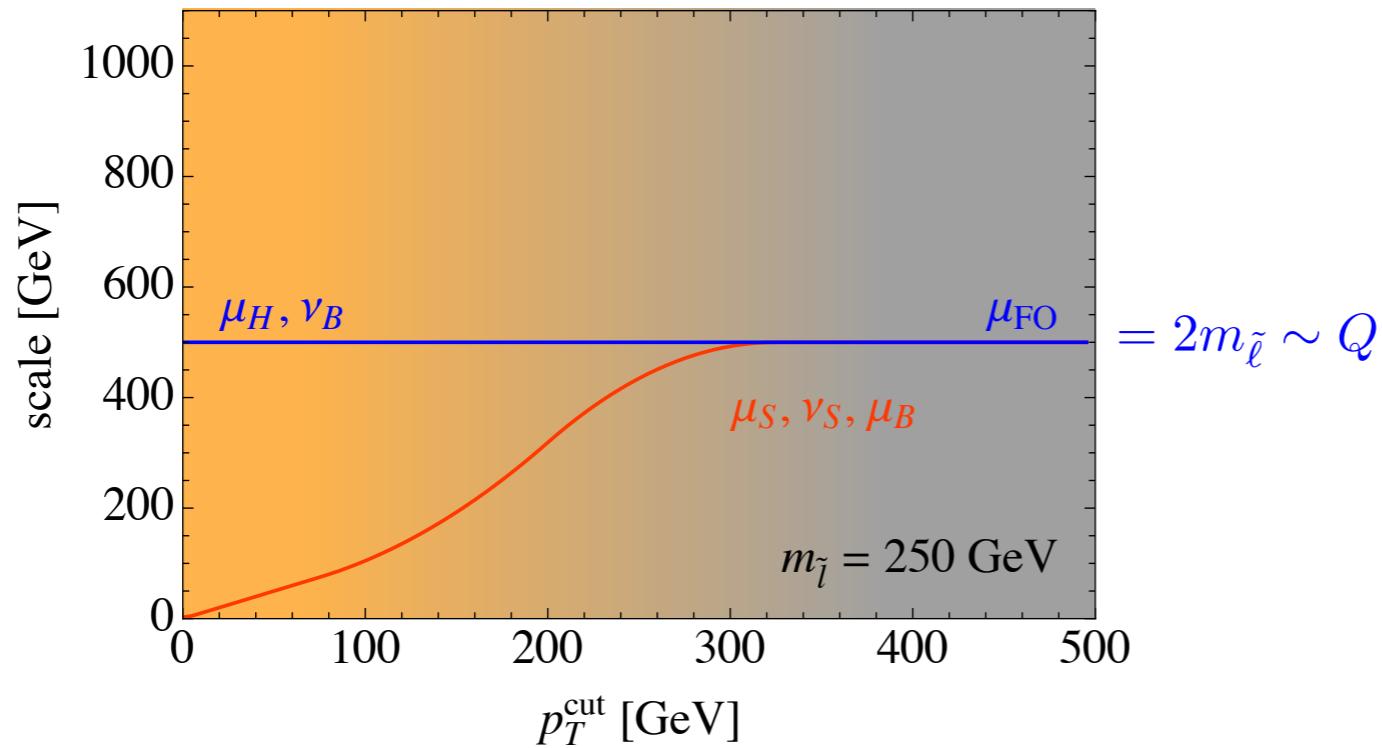
- Non-singular contributions obtained using Madgraph

$$\begin{aligned} \sigma(p_T^{\text{cut}}) \sim \sigma_0 \times & (1 + \alpha_s [L^2 + L + c_1] \\ & + \alpha_s^2 [L^4 + L^3 + L^2 + L + c_2] \\ & + \dots) \end{aligned}$$

Large logarithms
 $L = \ln(p_T^{\text{cut}}/Q)$

LL NLL

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:

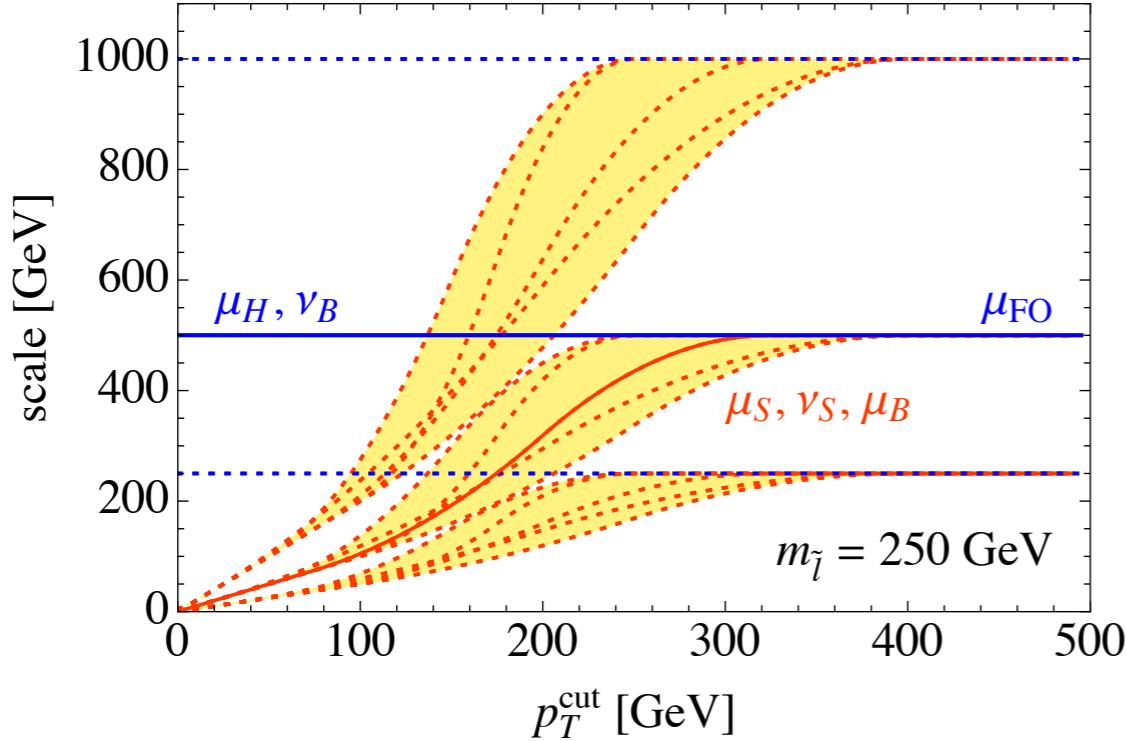
Ligeti, Stewart, Tackmann,
0807.1926; Abate,
Fickinger, Hoang, Mateu,
Stewart, 1006.3080

$$\begin{aligned}\mu_H &= \nu_B = \mu_{\text{FO}}, \\ \mu_B &= \mu_S = \nu_S = \mu_{\text{FO}} \times f_{\text{run}}(p_T^{\text{cut}} / (2m_{\tilde{l}}))\end{aligned}$$

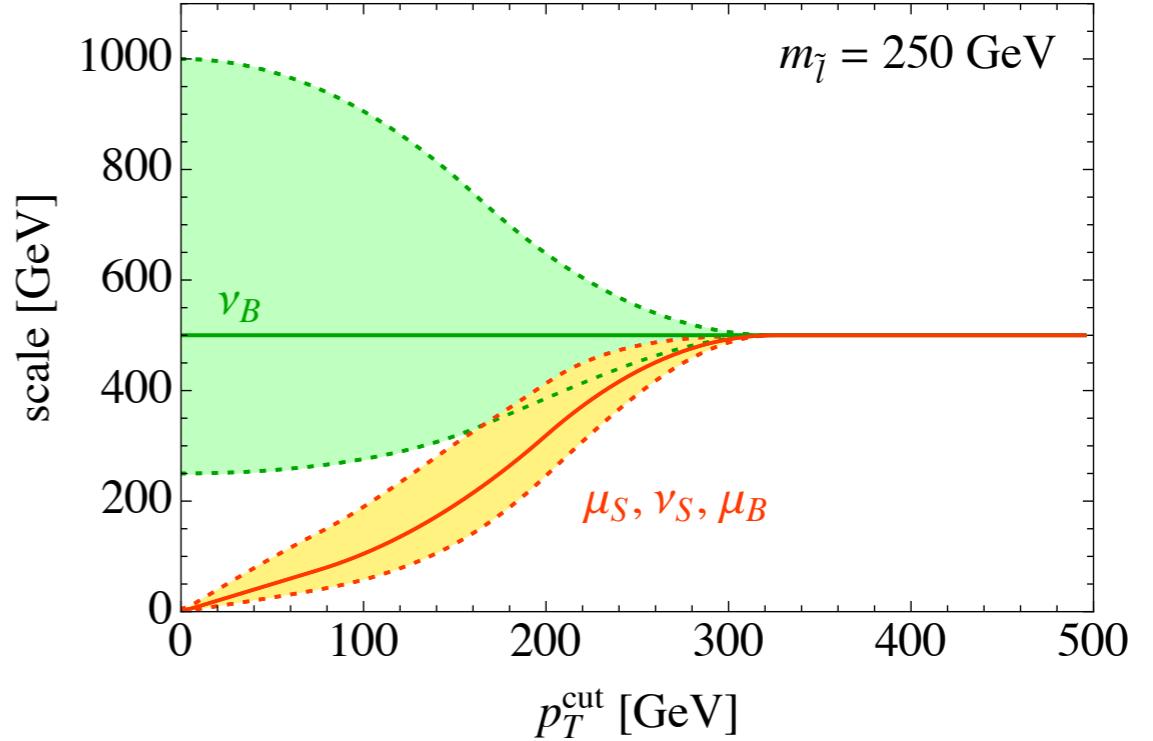
Stewart, Tackmann, Walsh, Zuberi, 1307.1808

Theory uncertainties

Fixed-order scale variations:



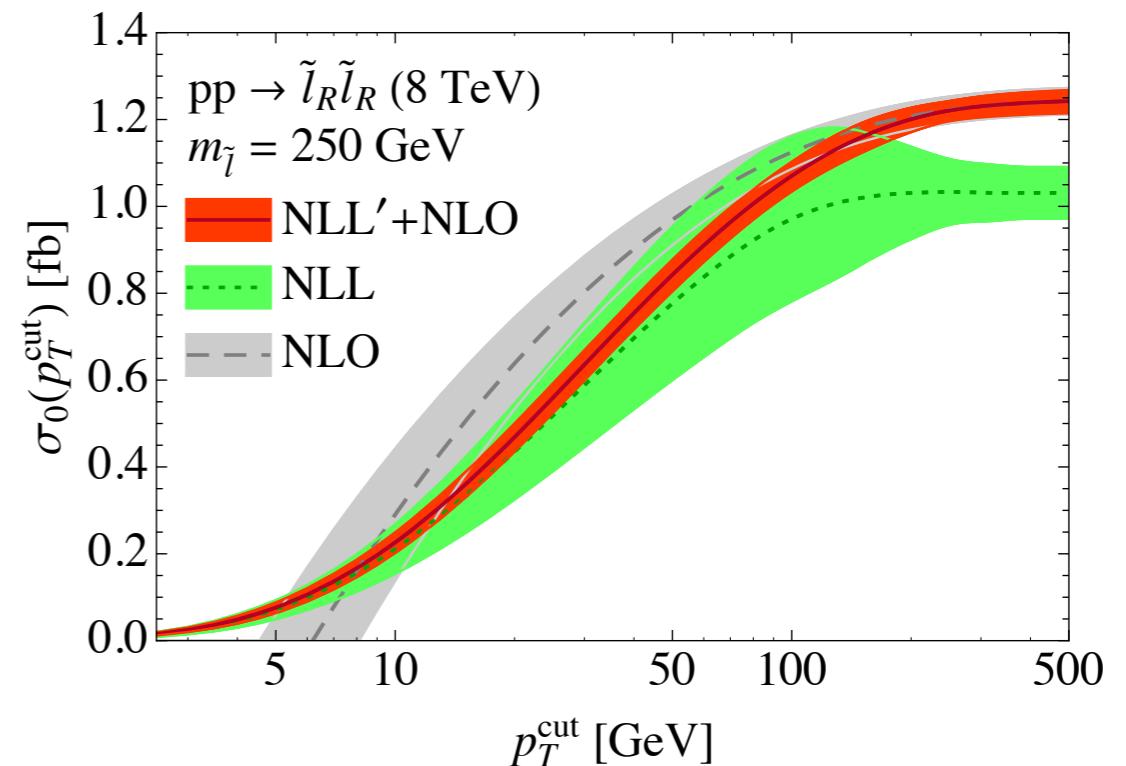
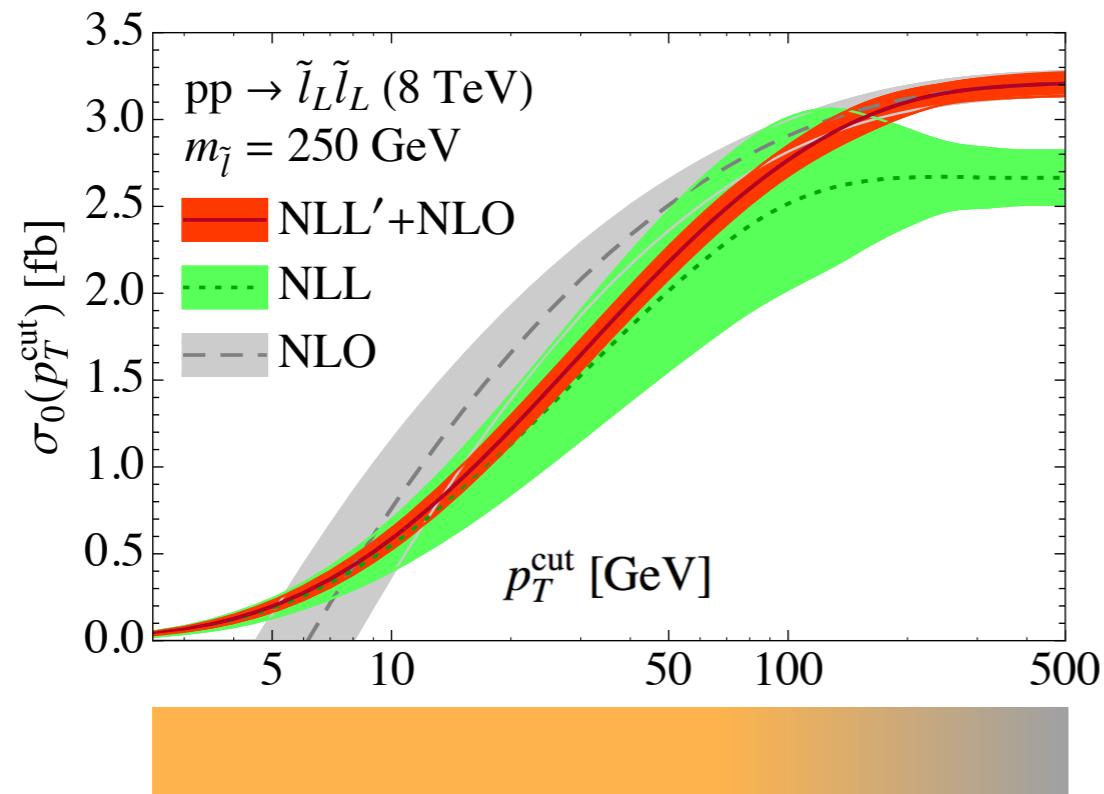
Resummation scale variations:



- Fixed-order as well as resummation uncertainties estimated by profile scale variations
- Fixed-order and resummation uncertainties added in quadrature
- Follows the procedure developed for Higgs production

Stewart, Tackmann, Walsh, Zuberi, 1307.1808

Results at 8 TeV



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

Impact on current exclusion limits

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

$$\sigma_{0,\text{vis}}^{95} = \frac{\sigma_{\text{vis}}^{95}}{\epsilon_{\text{SUSY}}^{(\text{SR}-\text{noJV})}}$$

$$\epsilon_{\text{SUSY}}^{(\text{SR})} = \epsilon_{\text{SUSY}}^{(\text{JV})} \times \epsilon_{\text{SUSY}}^{(\text{SR}-\text{noJV})}$$

↑
Jet veto efficiency ↑
Signal region efficiency
excluding the jet veto

- $\sigma_{0,\text{vis}}^{95}$ is defined without reconstruction efficiencies and acceptance cuts
- $\epsilon_{\text{SUSY}}^{(\text{SR}-\text{noJV})}$ is calculated with the codes

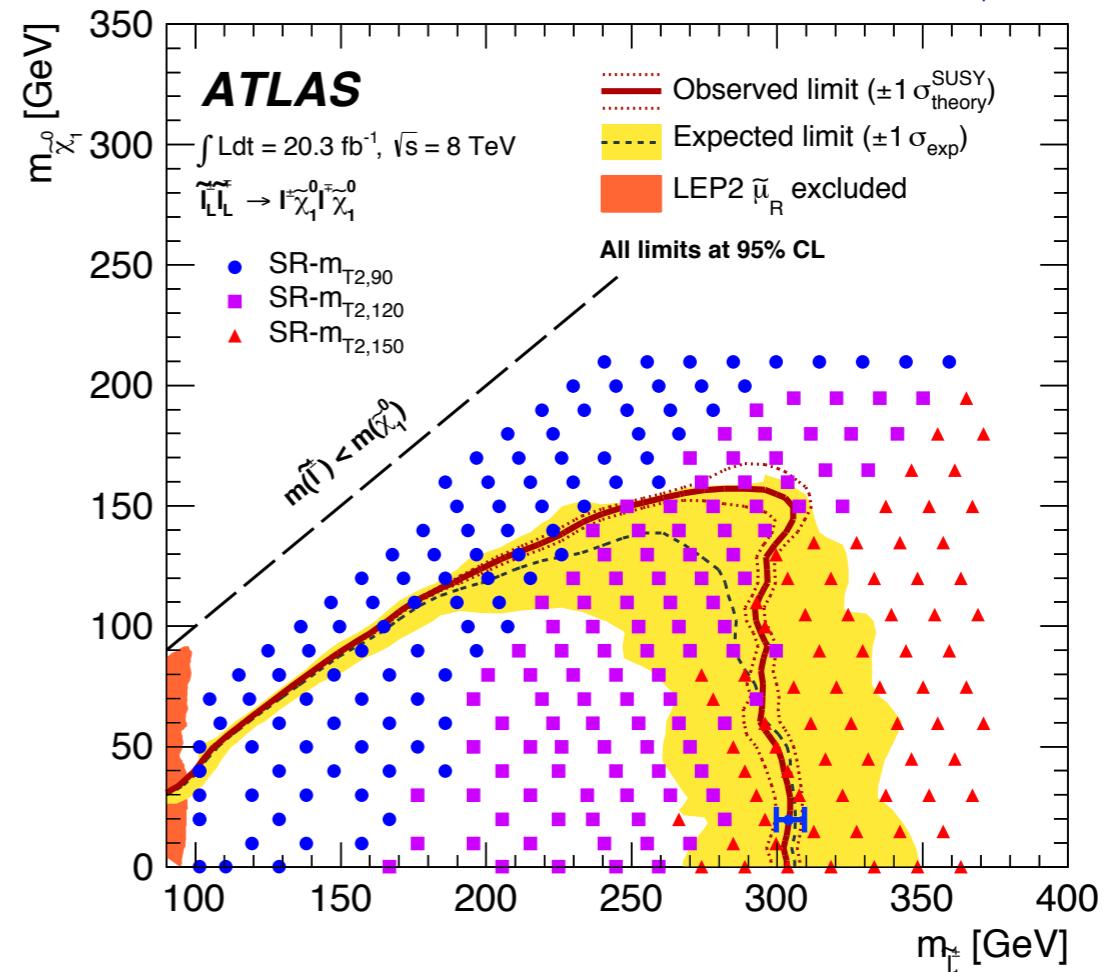
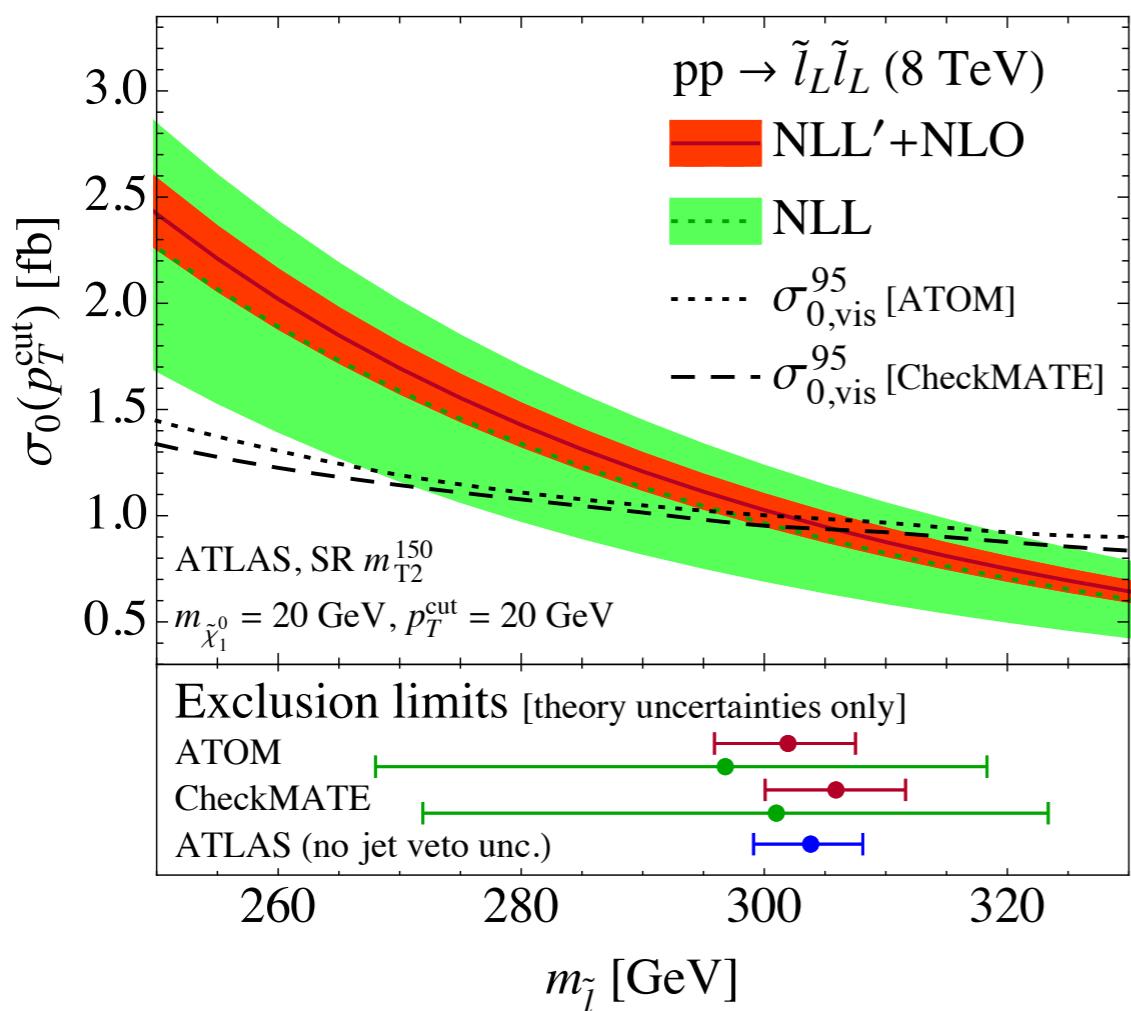
ATOM Kim, Papucci, Sakurai, Weiler (in preparation)

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

- Codes to estimate efficiencies taking detector effects into account
- Many implemented and validated analyses

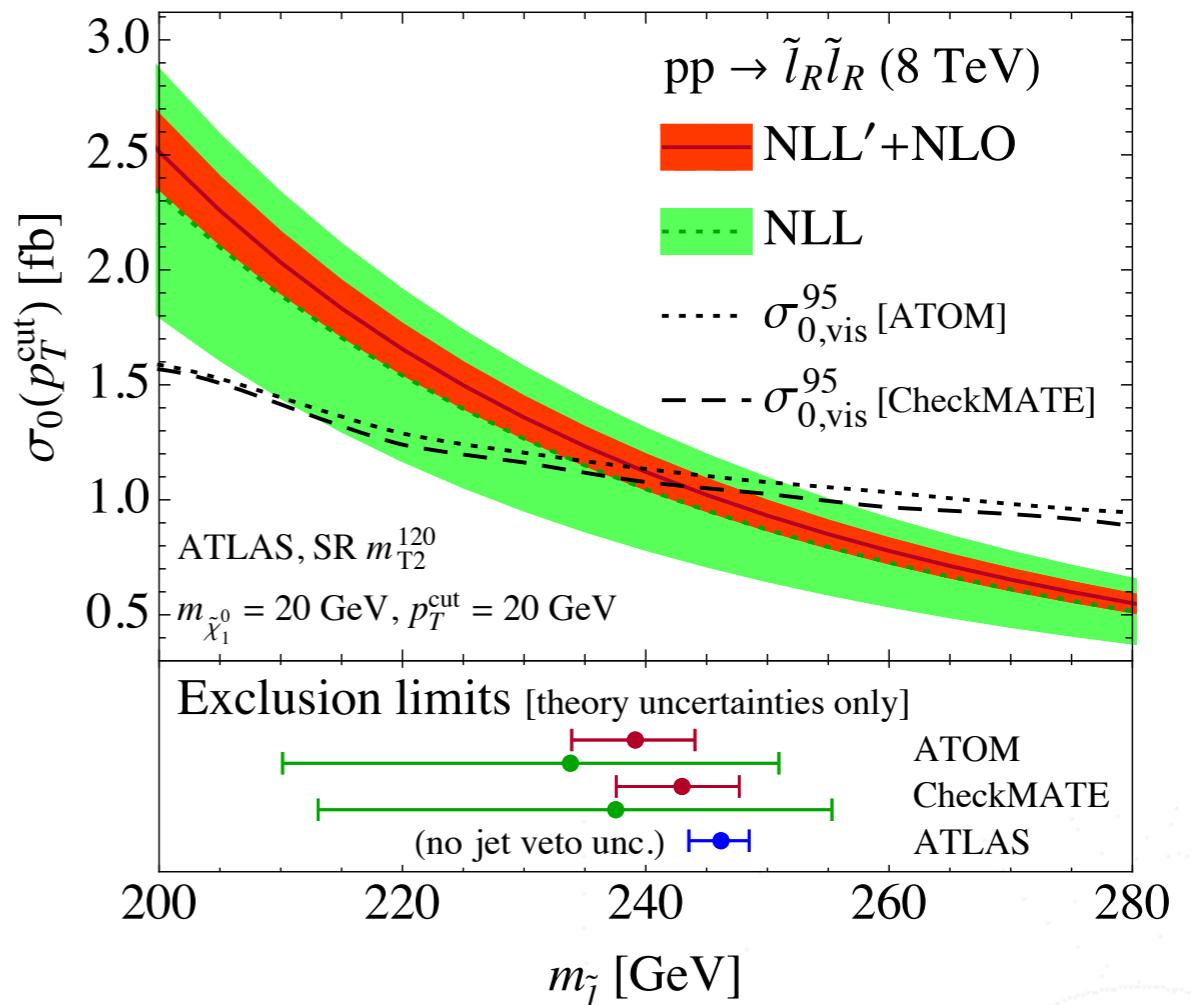
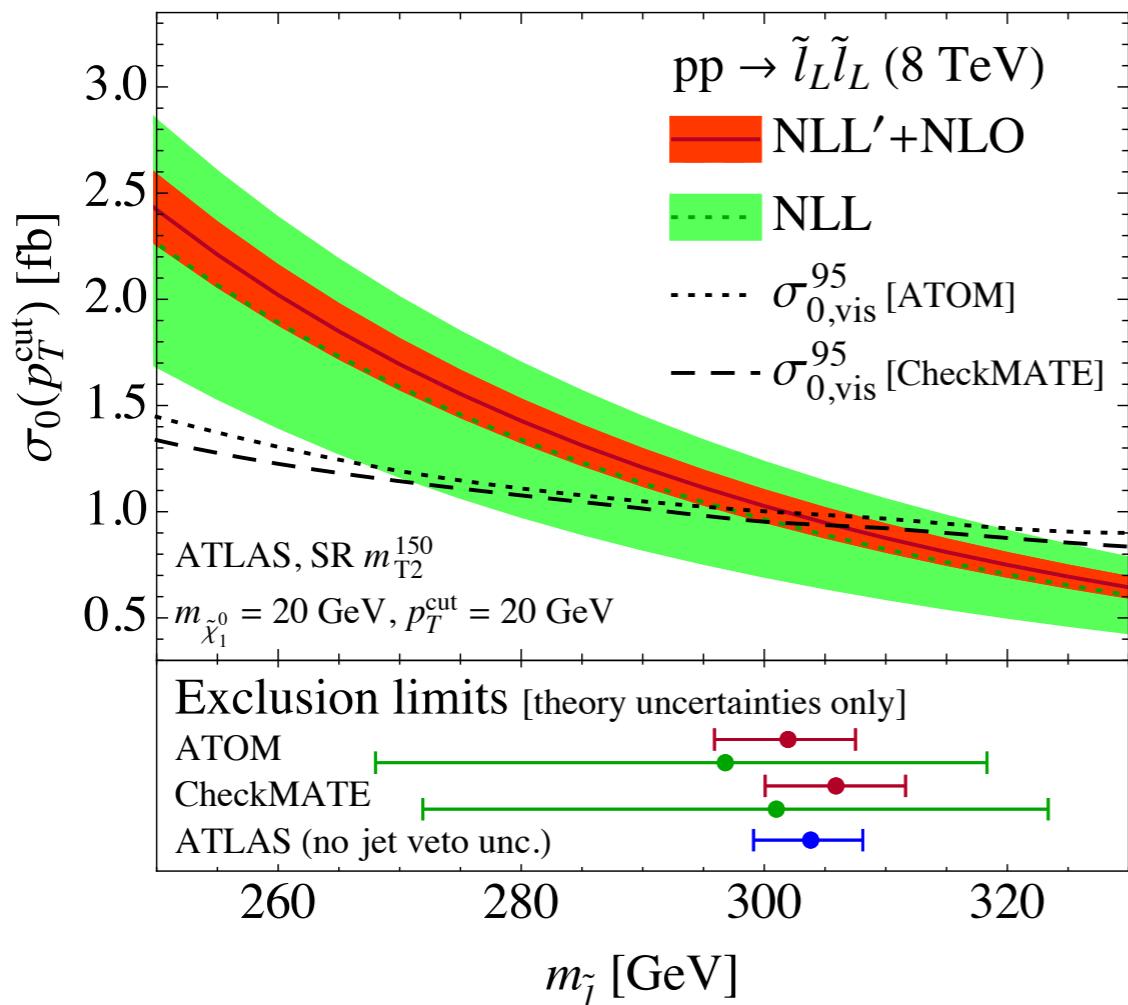
Impact on current exclusion limits

ATLAS, 1403.5294



- 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

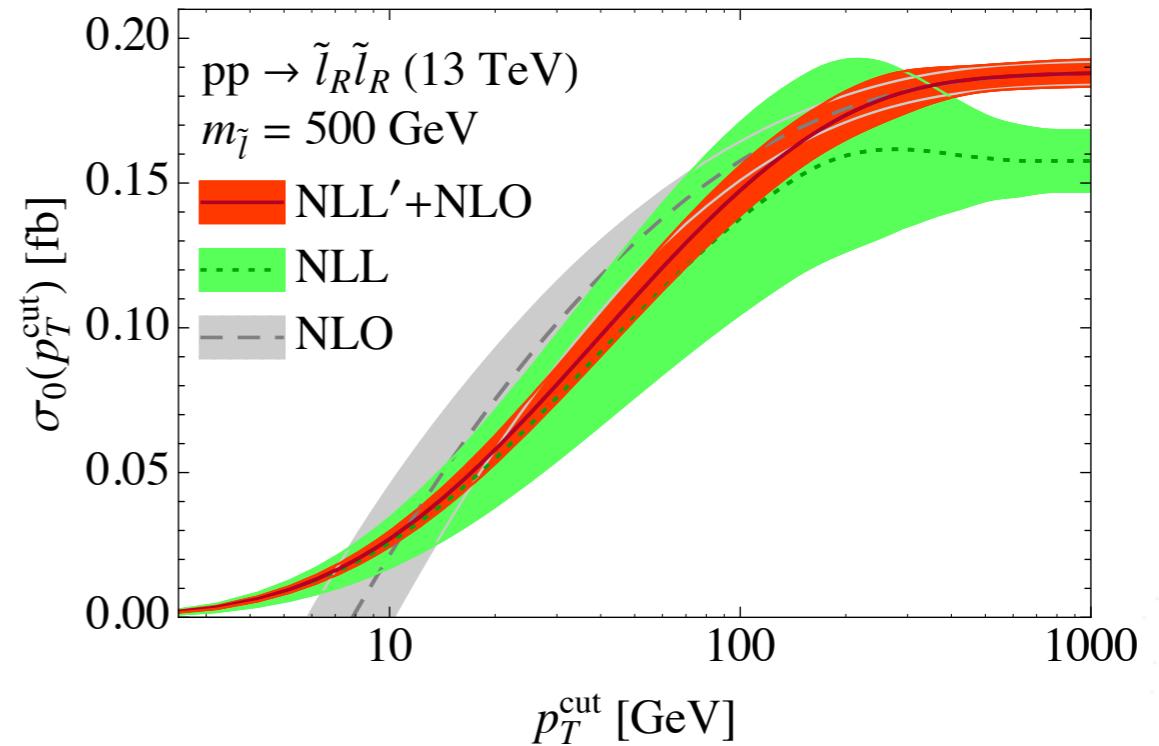
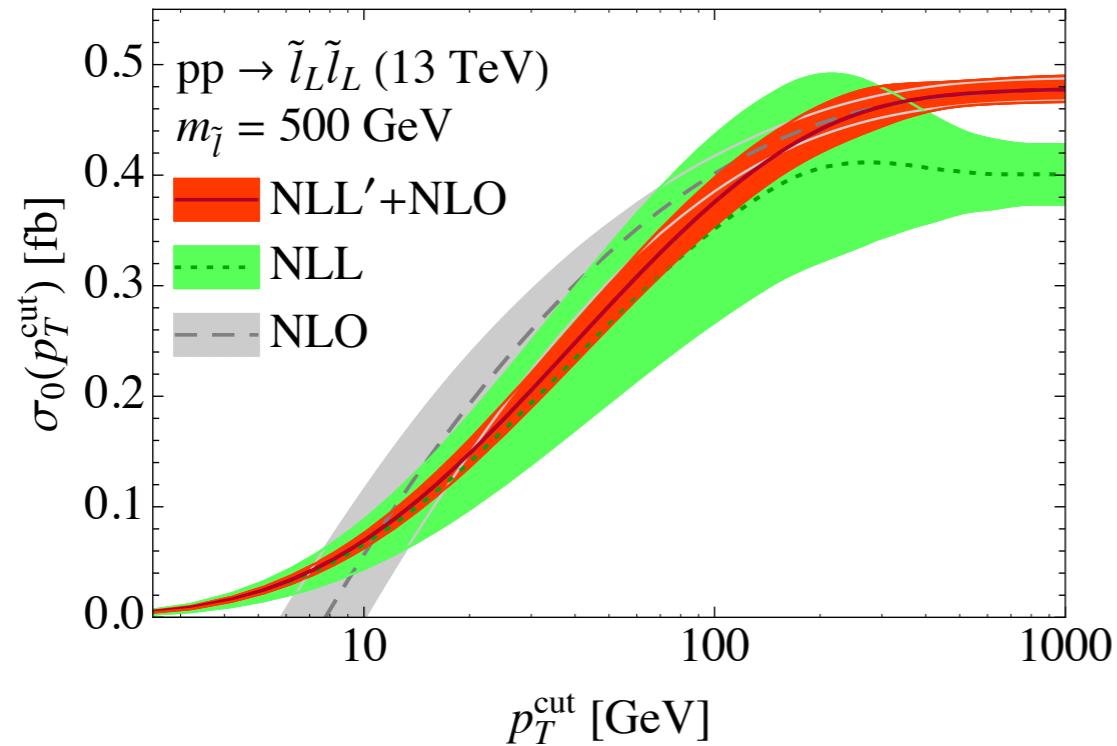
Impact on current exclusion limits



- At NLL the exclusion limits would be noticeably weaker:
 - Down to ~ 270 GeV for left-handed sleptons (compared to ~ 305 GeV)
 - Down to ~ 210 GeV for right-handed sleptons (compared to ~ 245 GeV)
- Central values are similar
Caution: 5-10% uncertainty on central value from ATOM and CheckMATE

Results at 13 TeV

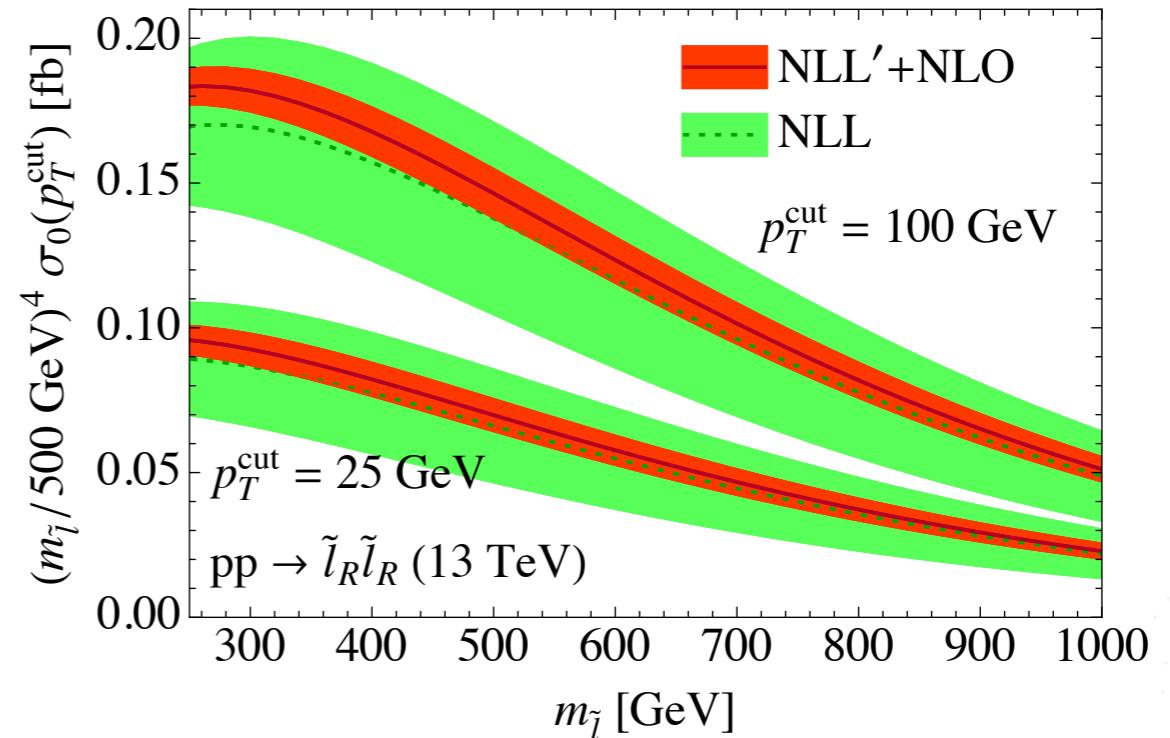
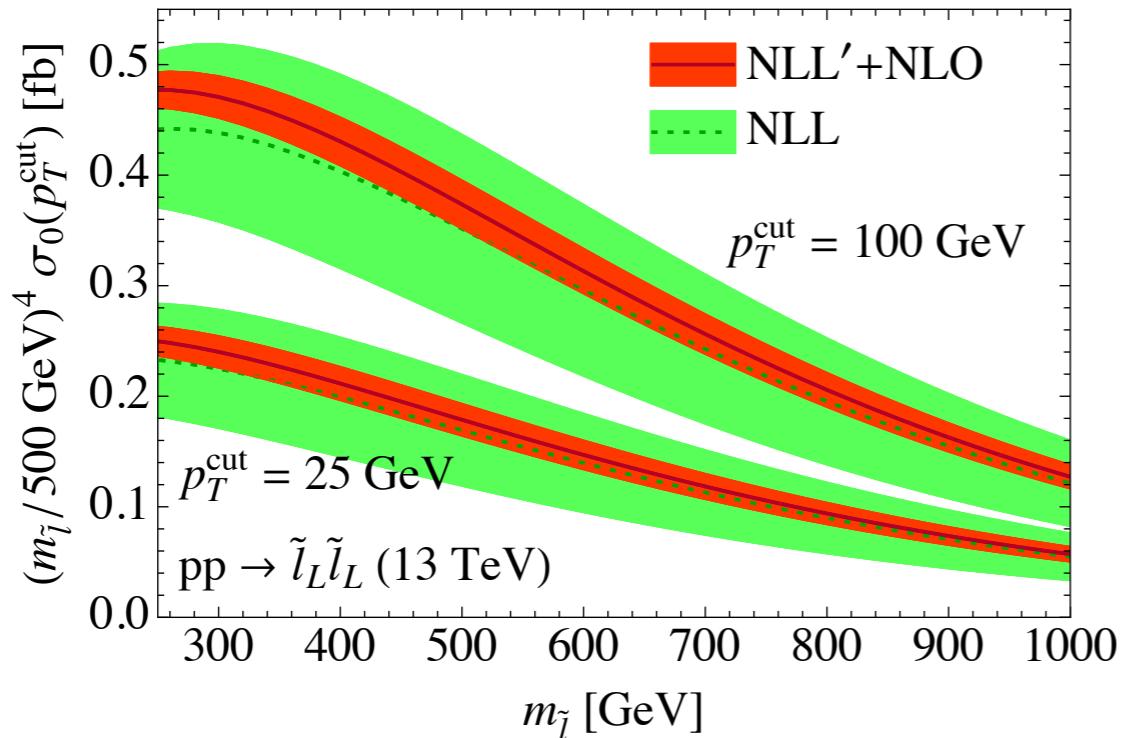
p_T^{cut} dependence for a slepton mass of 500 GeV:



- 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

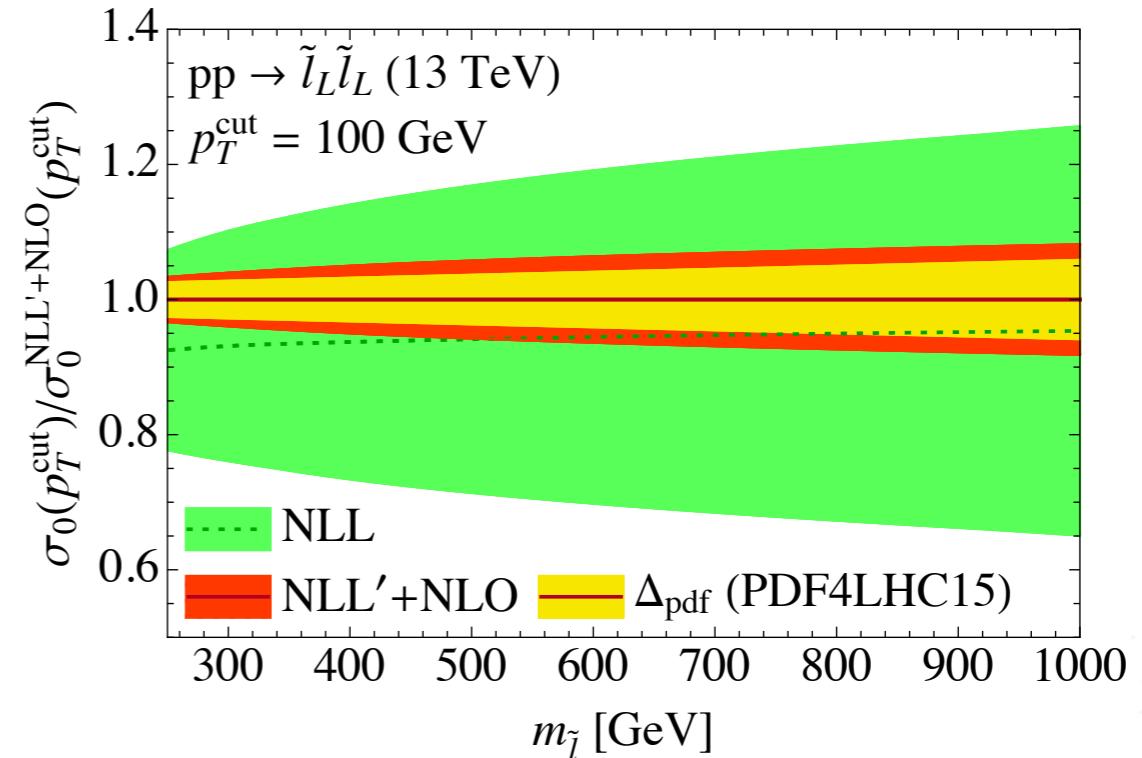
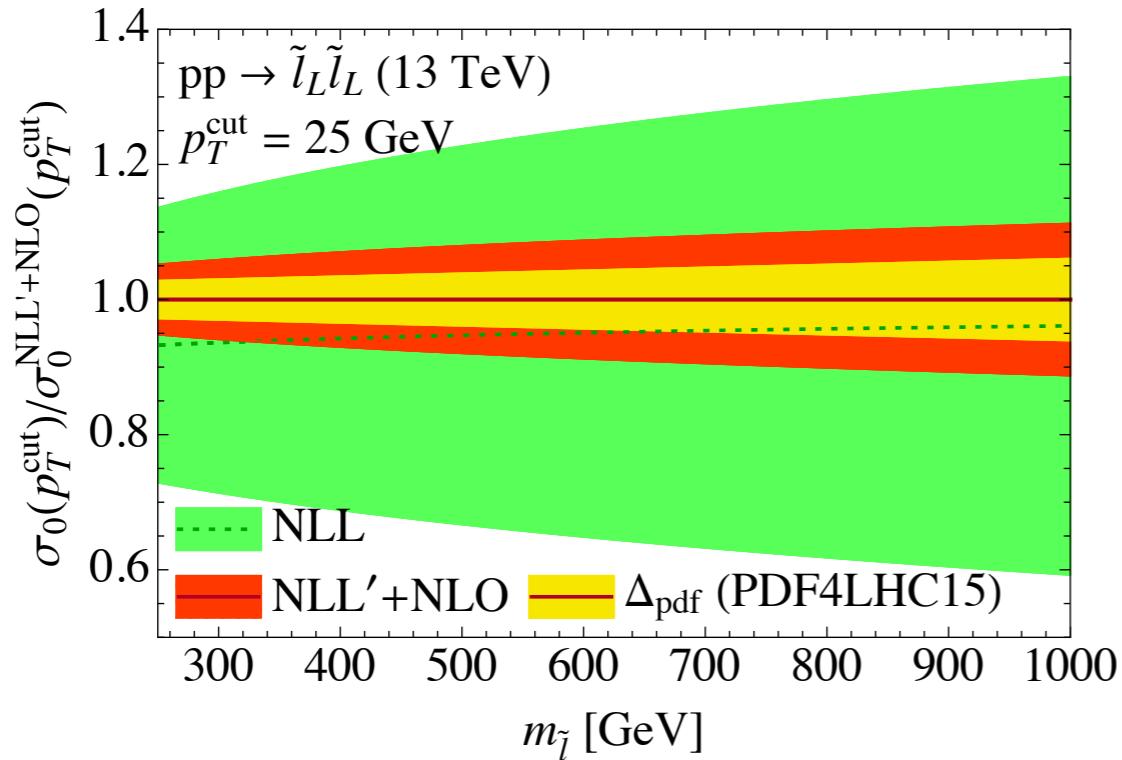
Slepton mass dependence for two fixed values of p_T^{cut} :



- 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 $p_T^{\text{cut}} = 100$ GeV

Uncertainties for $p_T^{\text{cut}} = 25$ 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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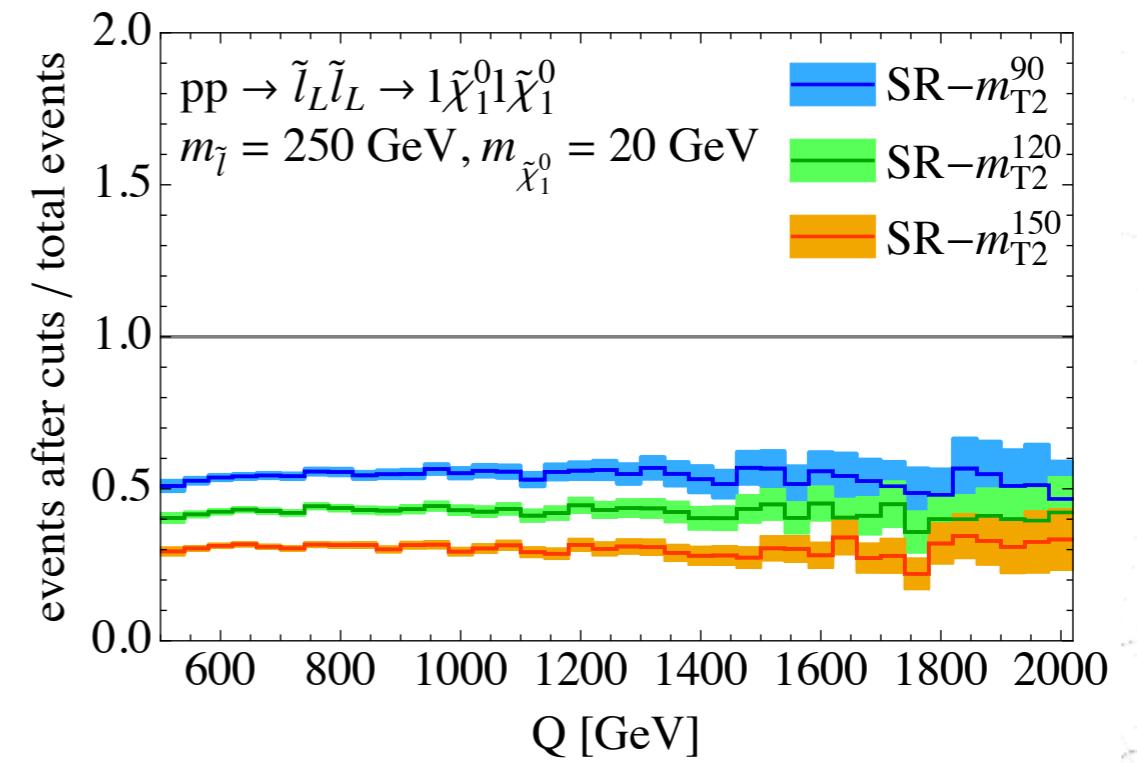
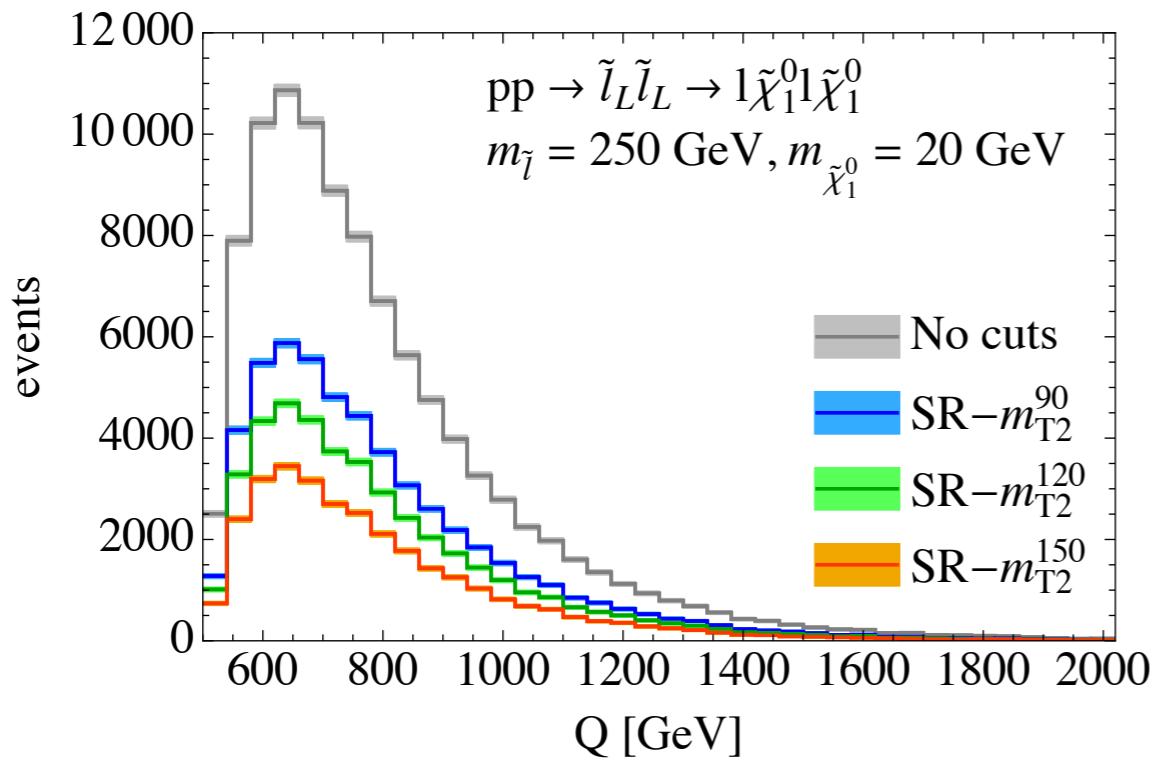
Next step:

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

Backup Slides

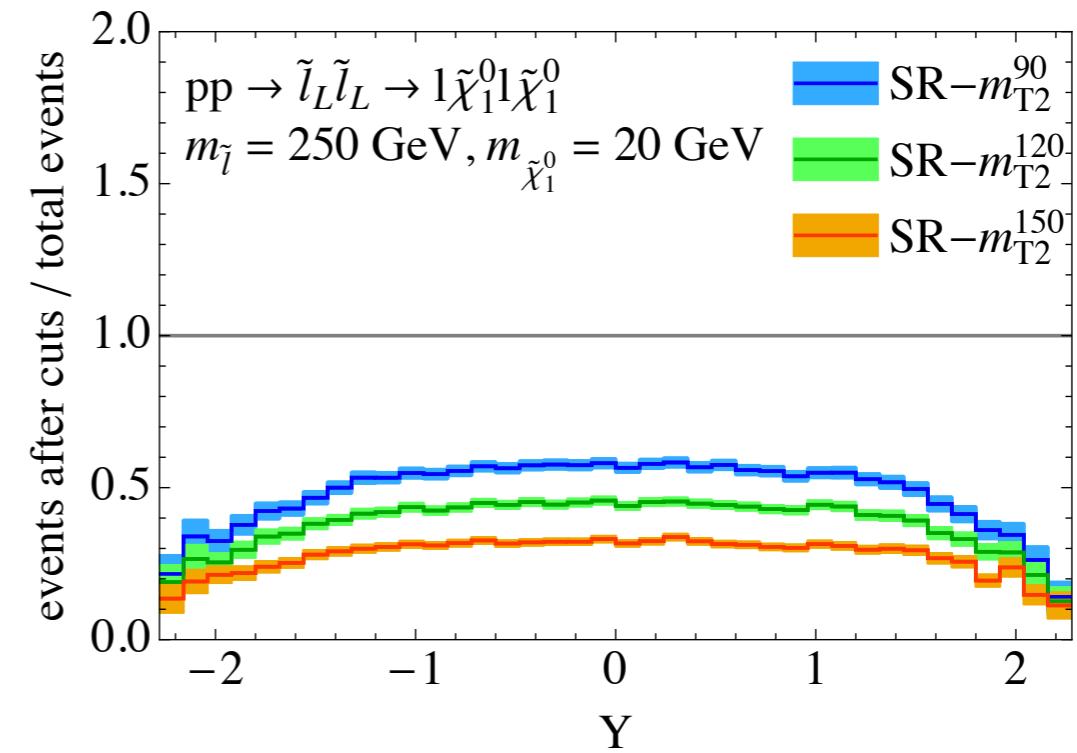
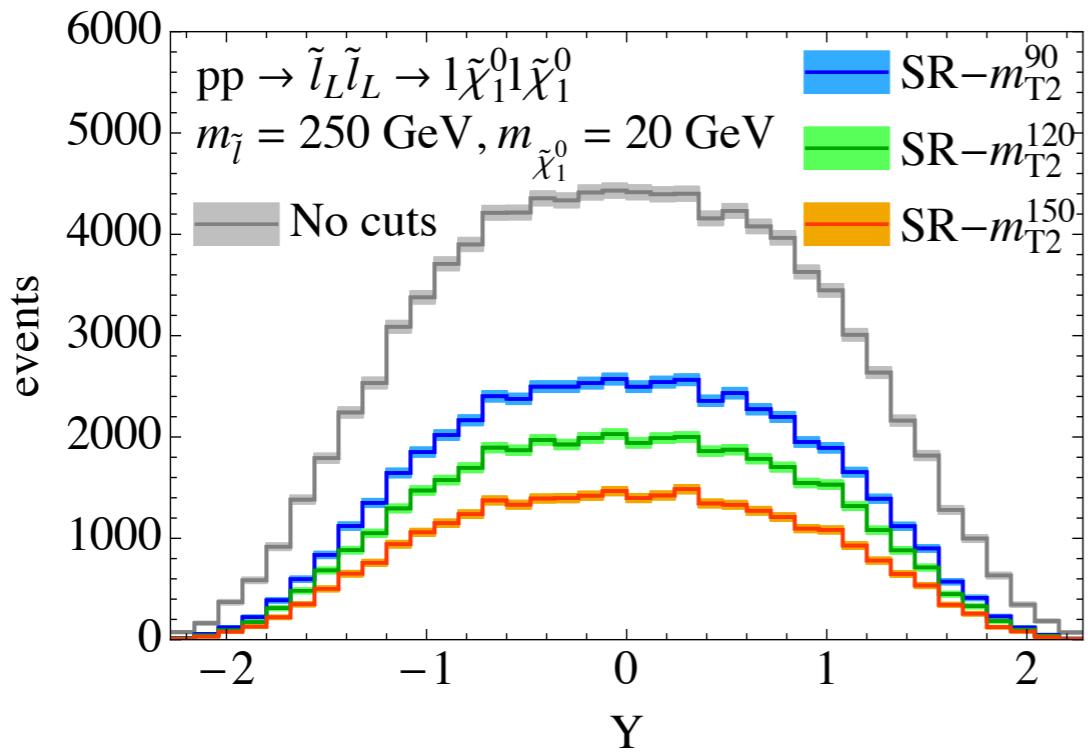
Correlations of jet veto with other cuts

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

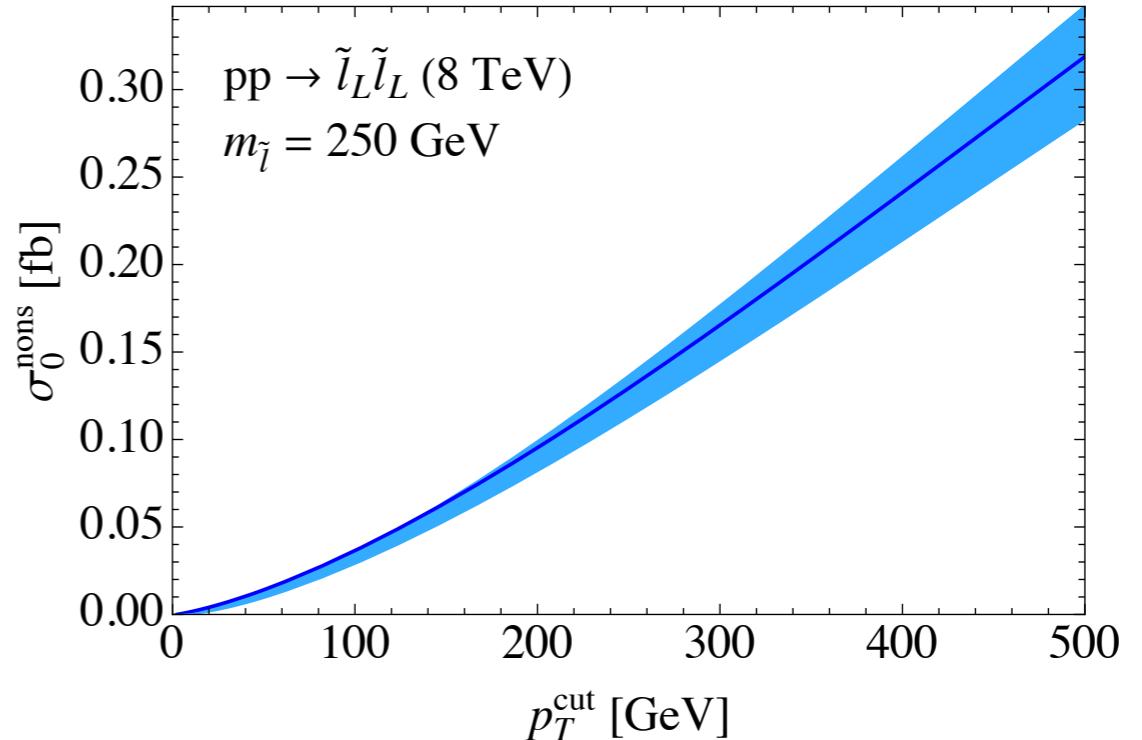
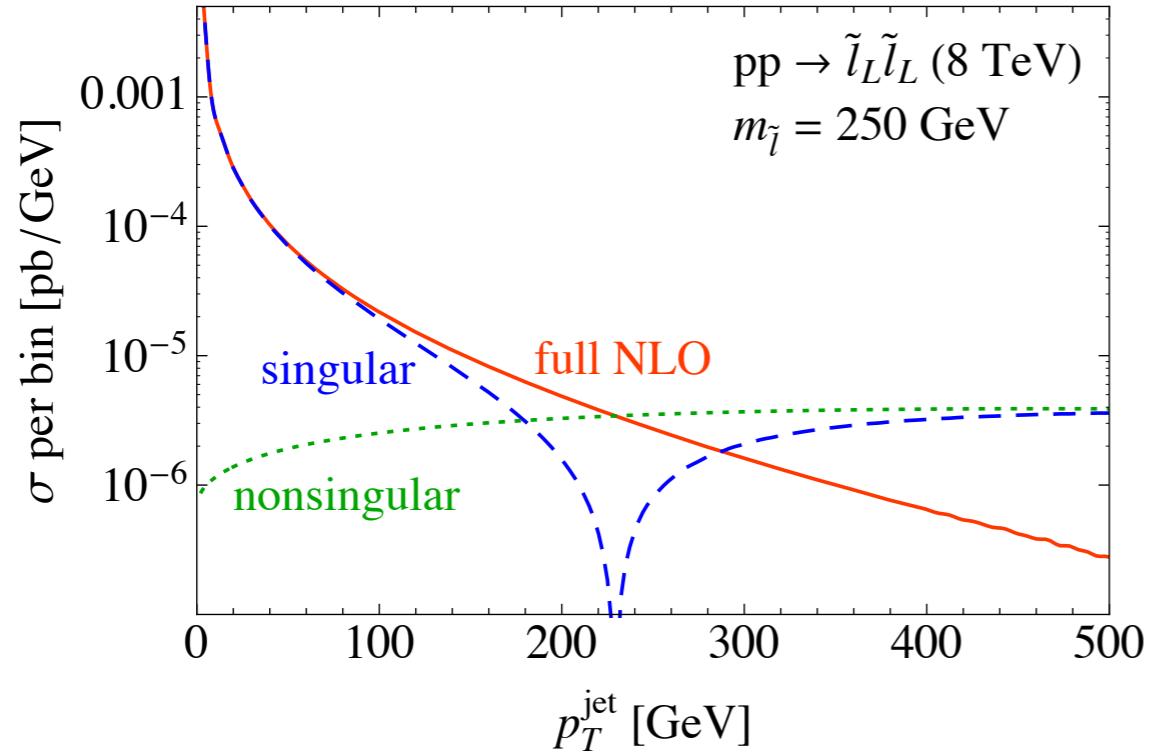


Correlations of jet veto with other cuts

- 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



Nonsingular contributions



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

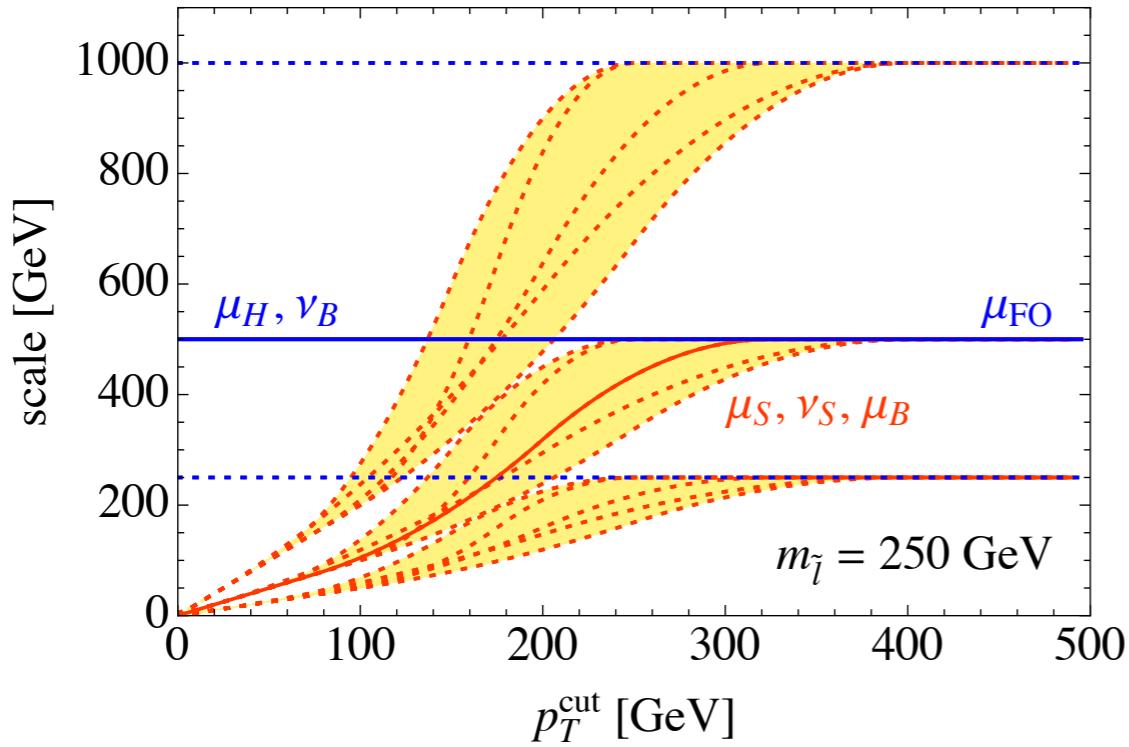
$$\sigma_0^{\text{nons}}(p_T^{\text{cut}}) = \int_{\epsilon \rightarrow 0}^{p_T^{\text{cut}}} dp_T^{\text{jet}} \left(\frac{d\sigma_0^{\text{FO}}}{dp_T^{\text{jet}}} - \frac{d\sigma_0^{\text{sing}}}{dp_T^{\text{jet}}} \right)$$

Fit: $\frac{d\sigma_0^{\text{nons}}}{dp_T^{\text{jet}}} = a \ln \frac{p_T^{\text{jet}}}{2m_{\tilde{l}}} + b + c \frac{p_T^{\text{jet}}}{2m_{\tilde{l}}} \ln \frac{p_T^{\text{jet}}}{2m_{\tilde{l}}} + d \frac{p_T^{\text{jet}}}{2m_{\tilde{l}}}$

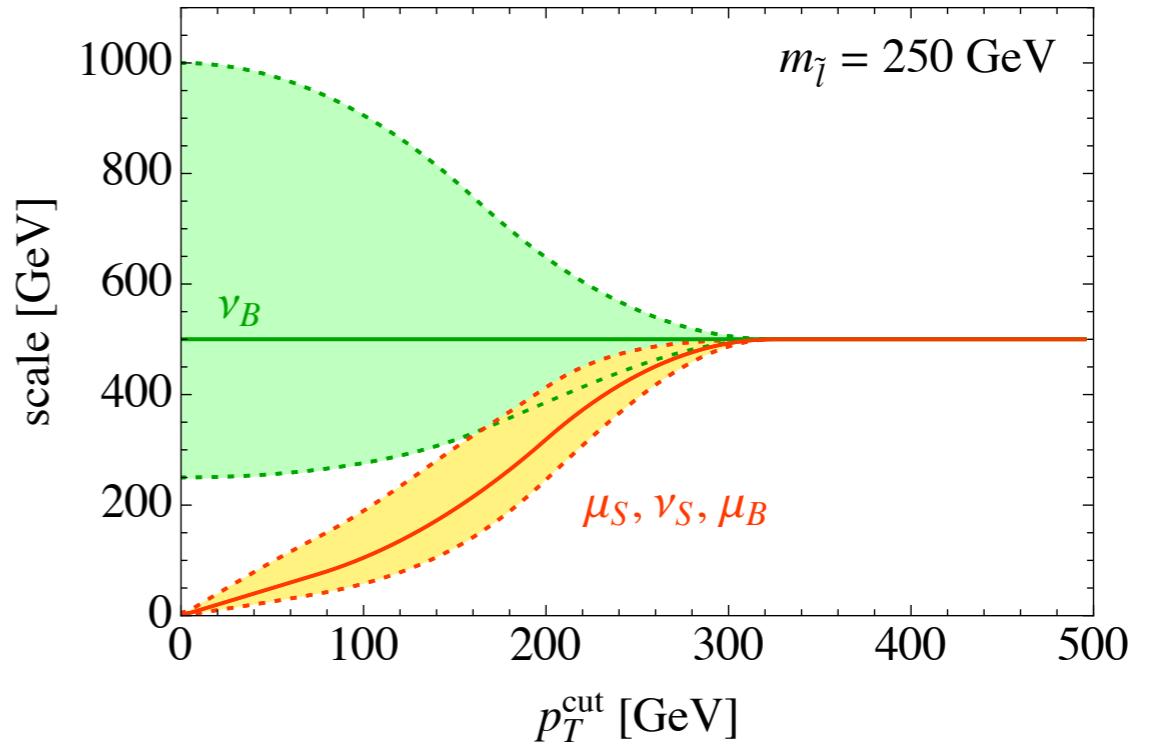
Set all scales in NLL' result
 equal to the fixed-order scale
 Generate $pp \rightarrow \tilde{l}\tilde{l} + j$ events in
 Madgraph

Theory uncertainties

Fixed-order scale variations:



Resummation scale variations:

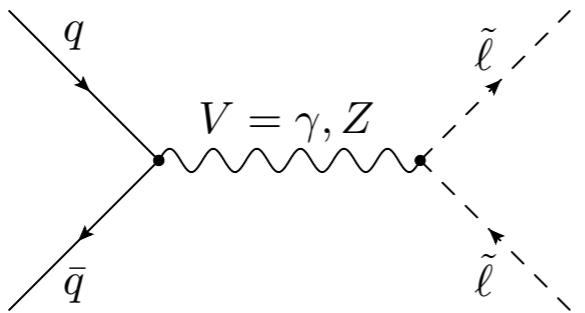


- ▶ Overall variation of the FO scale by factors 1/2 and 2
- ▶ Variation of the transition points 14 variations \Rightarrow take the maximum
- ▶ Independent variations of beam and soft scales. Combinations within canonical restrictions.
35 variations \Rightarrow take the maximum
- Fixed-order as well as resummation uncertainties estimated by profile scale variations [Stewart, Tackmann, Walsh, Zuberi, 1307.1808](#)
- Fixed-order and resummation uncertainties added in quadrature

Slepton production

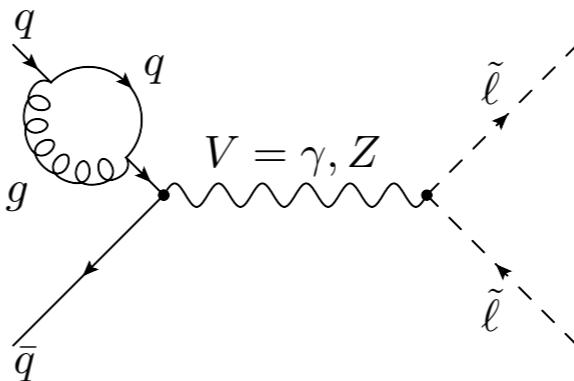
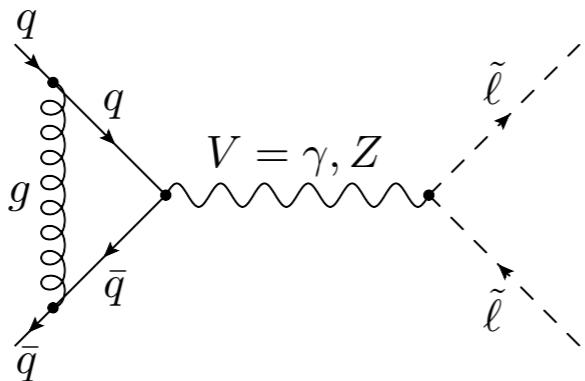
- Now $\mathcal{B}(\tilde{\ell} \rightarrow \ell \chi_1^0) = 1$ allows us to consider slepton production without decay

Tree-level:

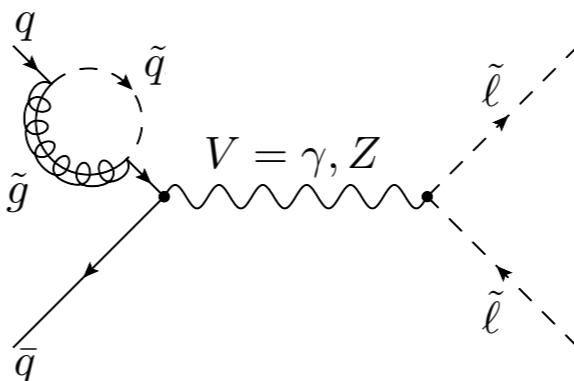
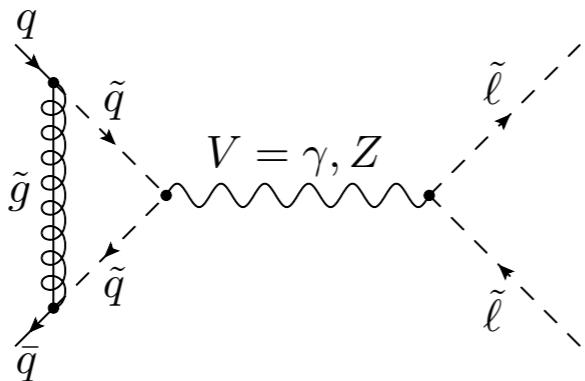


QCD corrections are clearly bigger than SUSY-QCD corrections, especially in simplified model

NLO QCD:



**NLO
SUSY-QCD:**



- At NLO other production modes are possible, but negligible

Hard function

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

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

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

For right-handed sleptons cross-section
is smaller \Rightarrow 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:

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

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

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

$$\begin{aligned} V_{\text{SUSY}} = & 1 + \frac{2m_{\tilde{g}}^2 - 2m_{\tilde{q}}^2}{Q^2} [B_0(Q^2, m_{\tilde{q}}^2, m_{\tilde{q}}^2) - B_0(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2)] + B_0(Q^2, m_{\tilde{q}}^2, m_{\tilde{q}}^2) \\ & + 2\frac{m_{\tilde{g}}^4 + (Q^2 - 2m_{\tilde{q}}^2)m_{\tilde{g}}^2 + m_{\tilde{q}}^4}{Q^2} C_0(0, 0, Q^2, m_{\tilde{q}}^2, m_{\tilde{g}}^2, m_{\tilde{q}}^2) \\ & - B_0(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2) + (m_{\tilde{q}}^2 - m_{\tilde{g}}^2) B'_0(0, m_{\tilde{g}}^2, m_{\tilde{q}}^2) \end{aligned}$$