Precise predictions for top quark plus large missing energy signatures at the LHC

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Outline

- Motivations for looking at ttbar + large missing E_T in BSM models

- Discussion of the experimental searches

- Calculational framework:

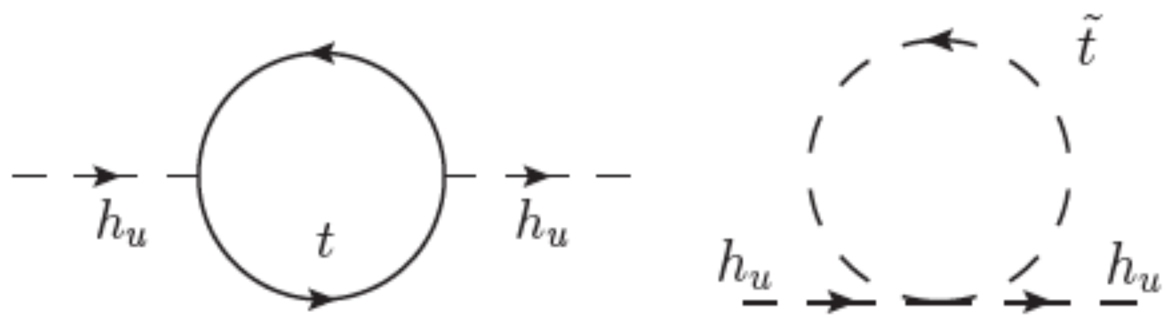
  - Presentation of the considered models
  - NLO QCD corrections to production and decay

- Results and Summary

Why look for light stops?

- *Natural SUSY*: masses of the superpartners with the closest ties to the Higgs must be near the EW scale

Large Higgs mass corrections:

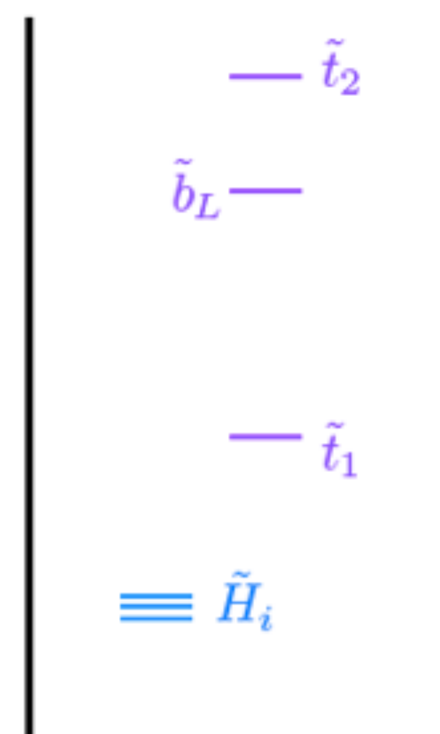


$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda_{UV}}{m_{\tilde{t}}}\right)$$

$$m_{\tilde{t}} \lesssim 400\mathrm{GeV}$$

- Higgsinos: $m \approx \mu \lesssim 200\,\mathrm{GeV}$
- Stops and LH sbottom: $m \lesssim 400\,\mathrm{GeV}$
- Gluino: $m \lesssim 1\,\mathrm{TeV}$

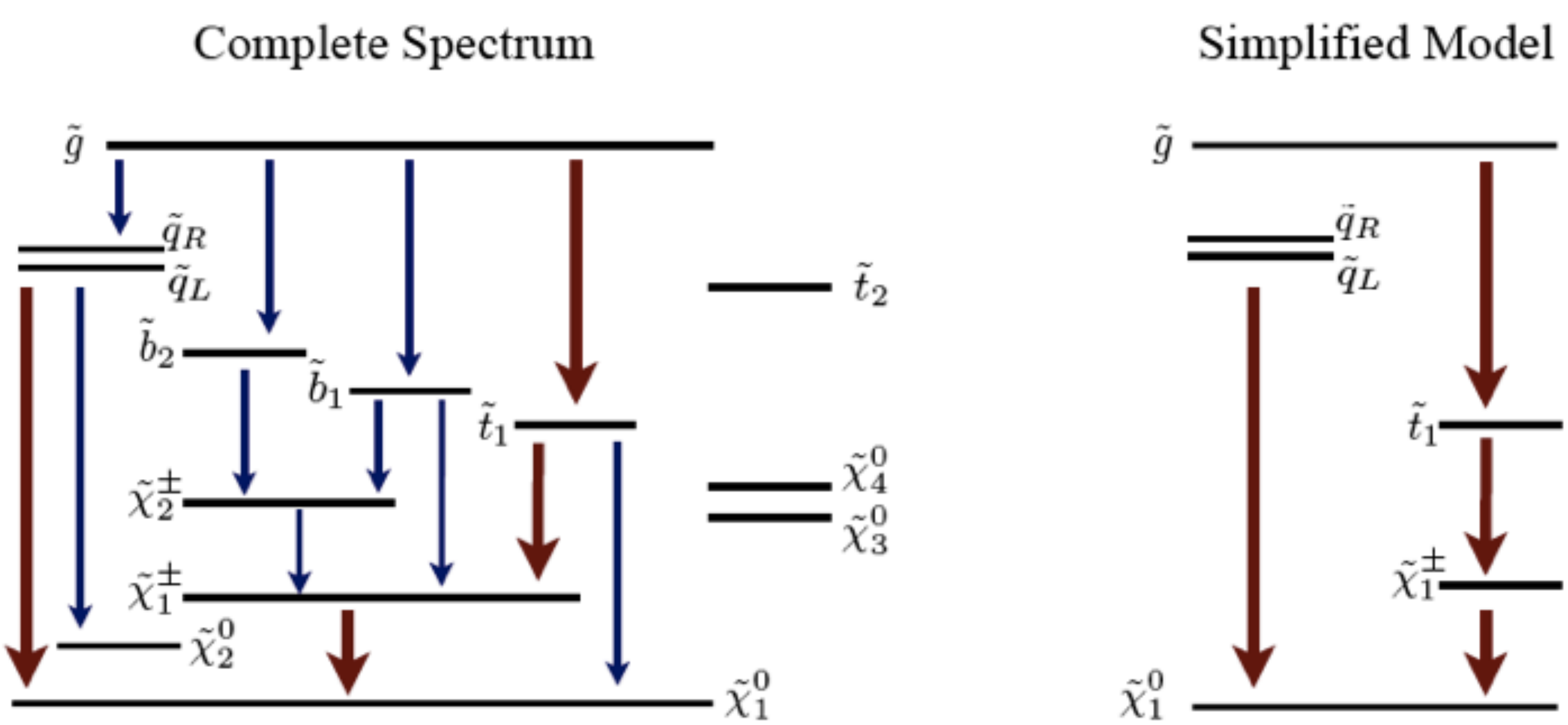
Sample spectrum:



- Other superpartners, including first two squark generations, can be heavy without significantly increasing fine-tuning

Why look for light stops?

- Direct stop production a useful experimental benchmark
- One of the *simplified models* chosen by joint theory/ATLAS/CMS effort to guide LHC searches (1105.2838): minimal particle content/ Lagrangian needed to produce a desired experimental signature

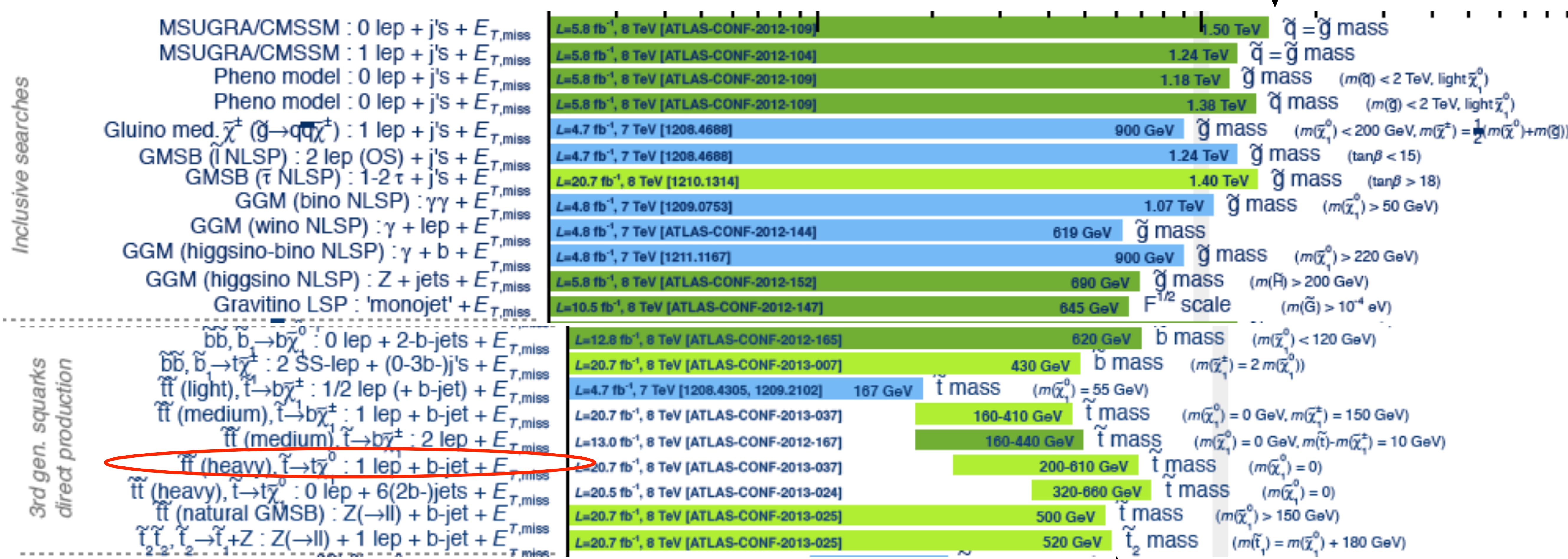


from M. Lisanti

Example reduction of a full SUSY spectrum to the light-stop simplified model

Experimental status of light stops

- ATLAS 2013 summary plot:



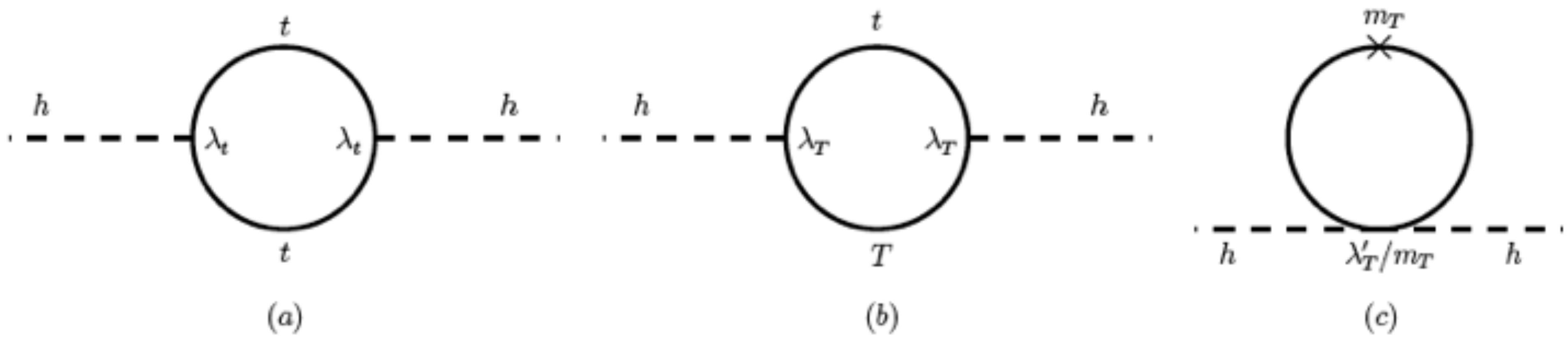
- <600 GeV limits for direct stop production, as compared to over 1 TeV limits for gluino-mediated production; more room left to explore!

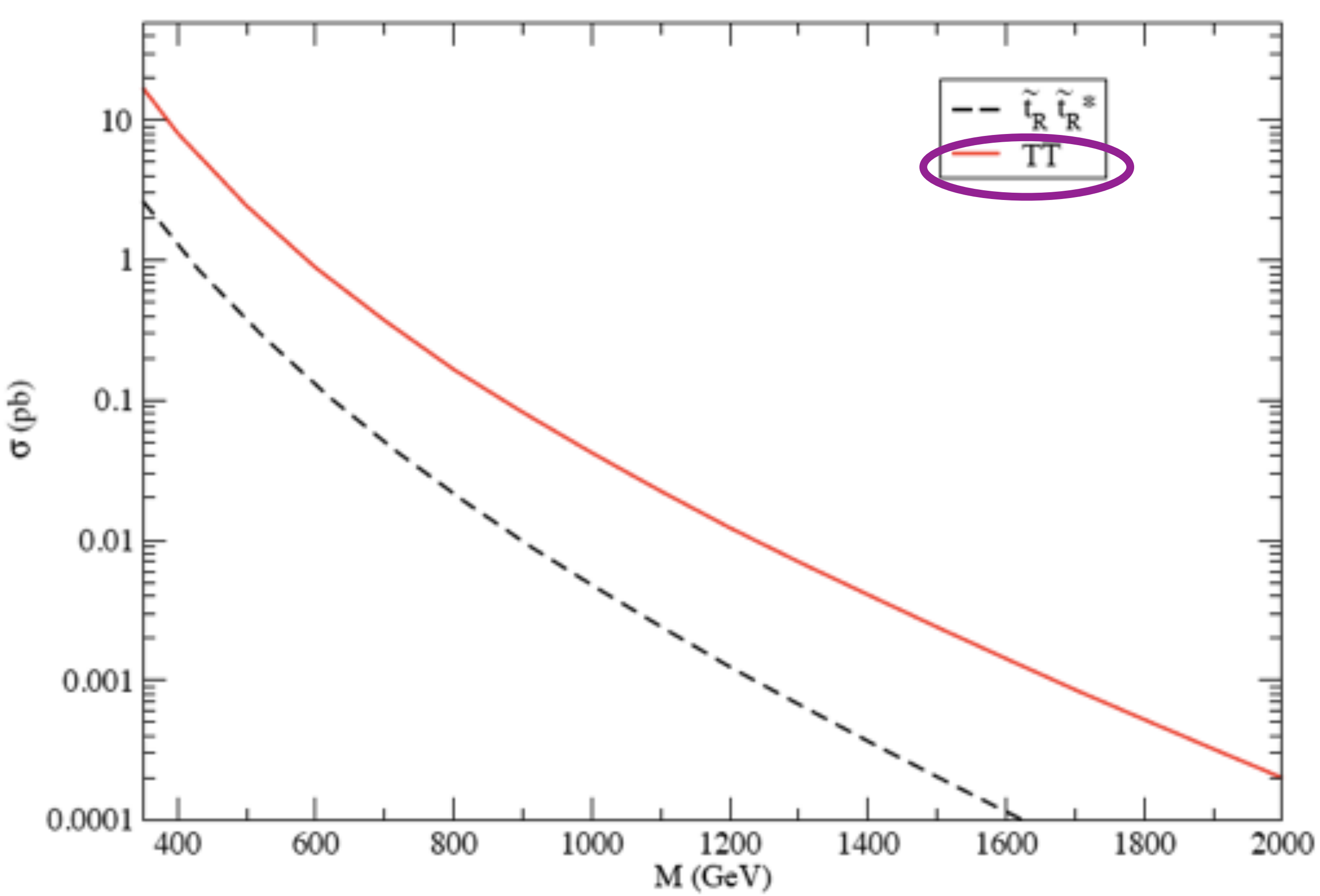
Fermionic top-partners

- The particle that cancels the quadratically divergent contribution of the top quark to the Higgs mass can be fermionic, and not a scalar like in SUSY

Example: Littlest Higgs with T-parity

Cheng, Low 2003



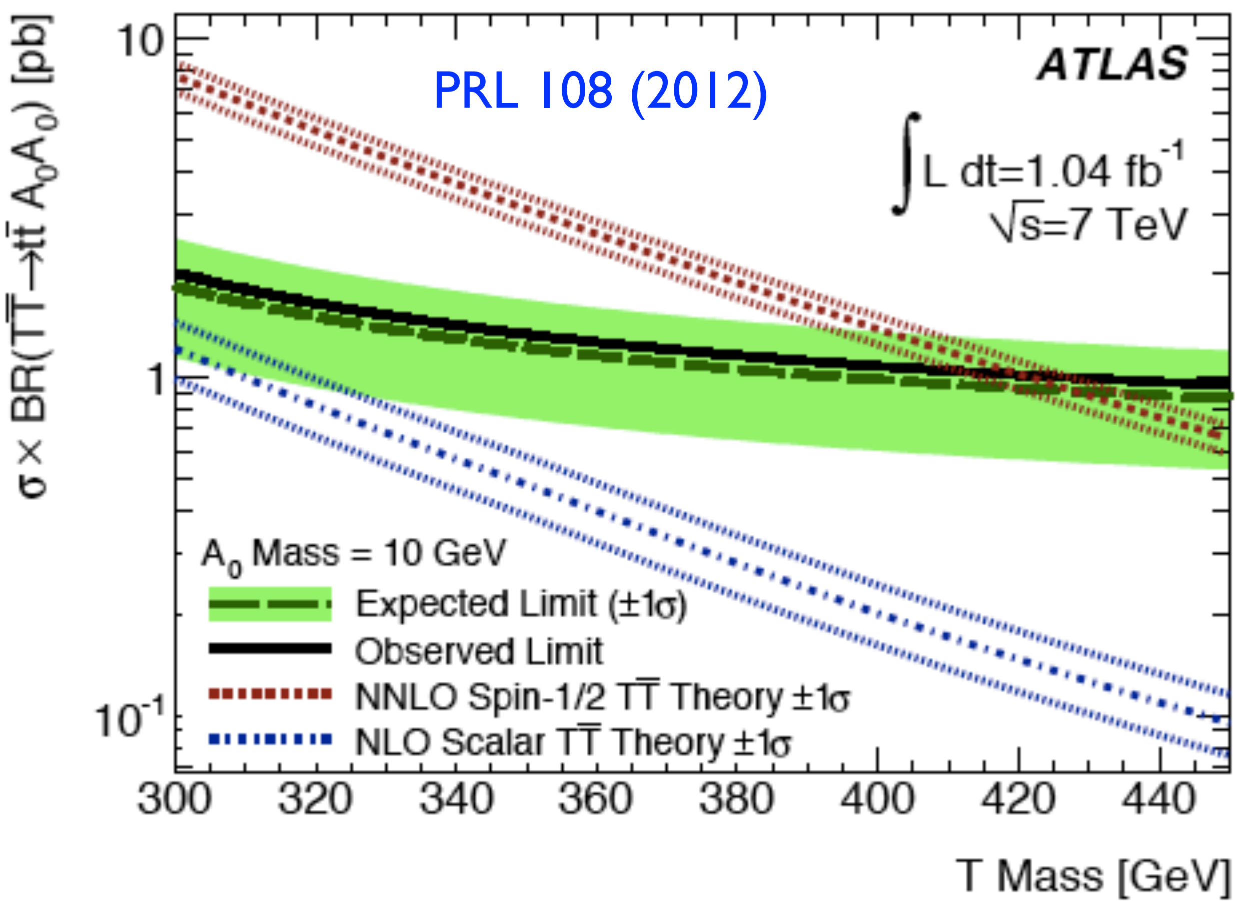


Cheng, Low, Wang 2005

- Sizable LHC production rate
- Important decay mode: T→tA, where A is a stable dark-matter candidate
- Gives ttbar+$E_{T,miss}$ signature

Experimental search details

- Examine the fine print from a typical experimental search PRL 108 (2012)
- Search for ttbar+large missing energy signature at ATLAS; from pair production of two top partners TT, which decay as $T \rightarrow t\chi$



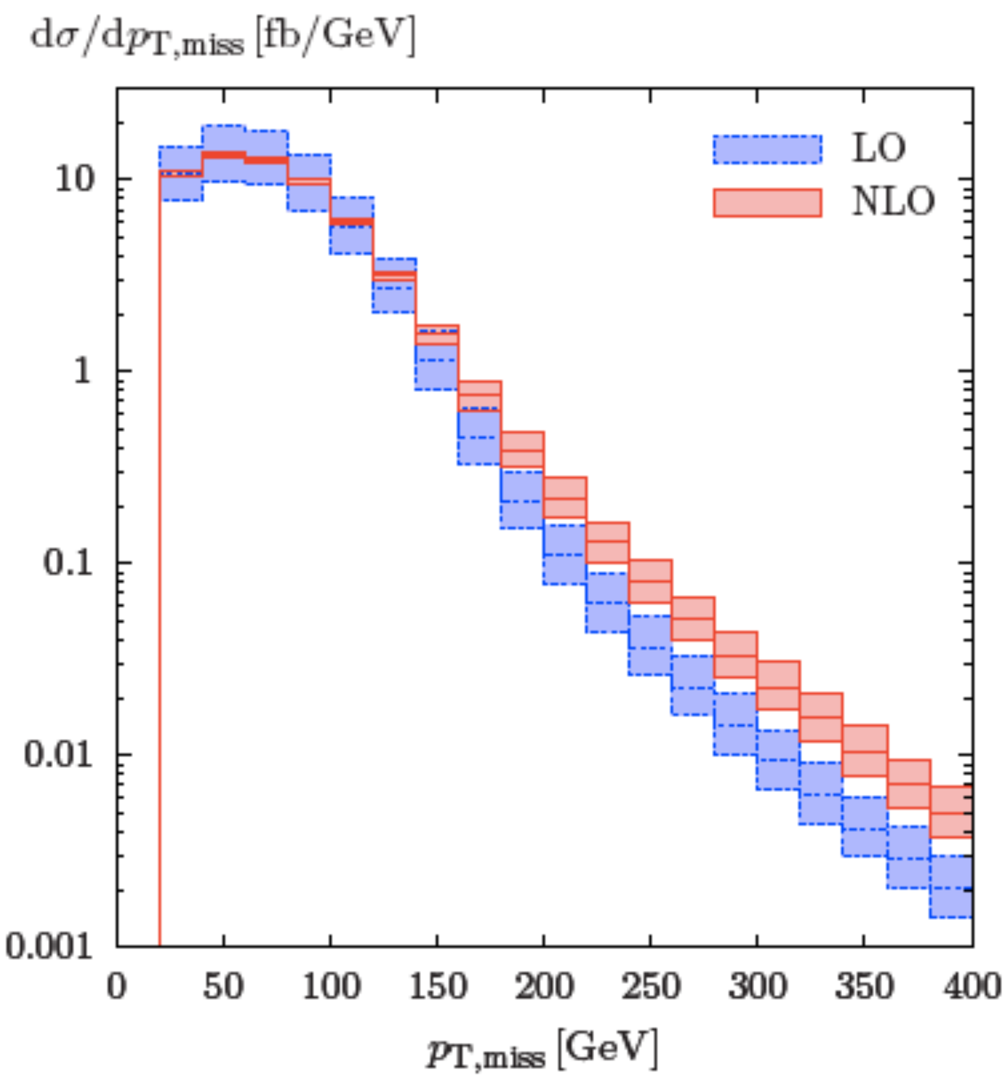
420 GeV bound for fermionic top partners

- Madgraph+Pythia (LO!) used to model the signal process
- Normalized to inclusive NLO cross section; search relies on looking in the tail of the $E_{T,miss}$ distribution, where K-factor might be very different
- No QCD corrections included in $T \rightarrow t\chi$ decay

- A more recent analysis excludes stop masses of roughly 400GeV for m_χ up to 125GeV arXiv:1208.2590

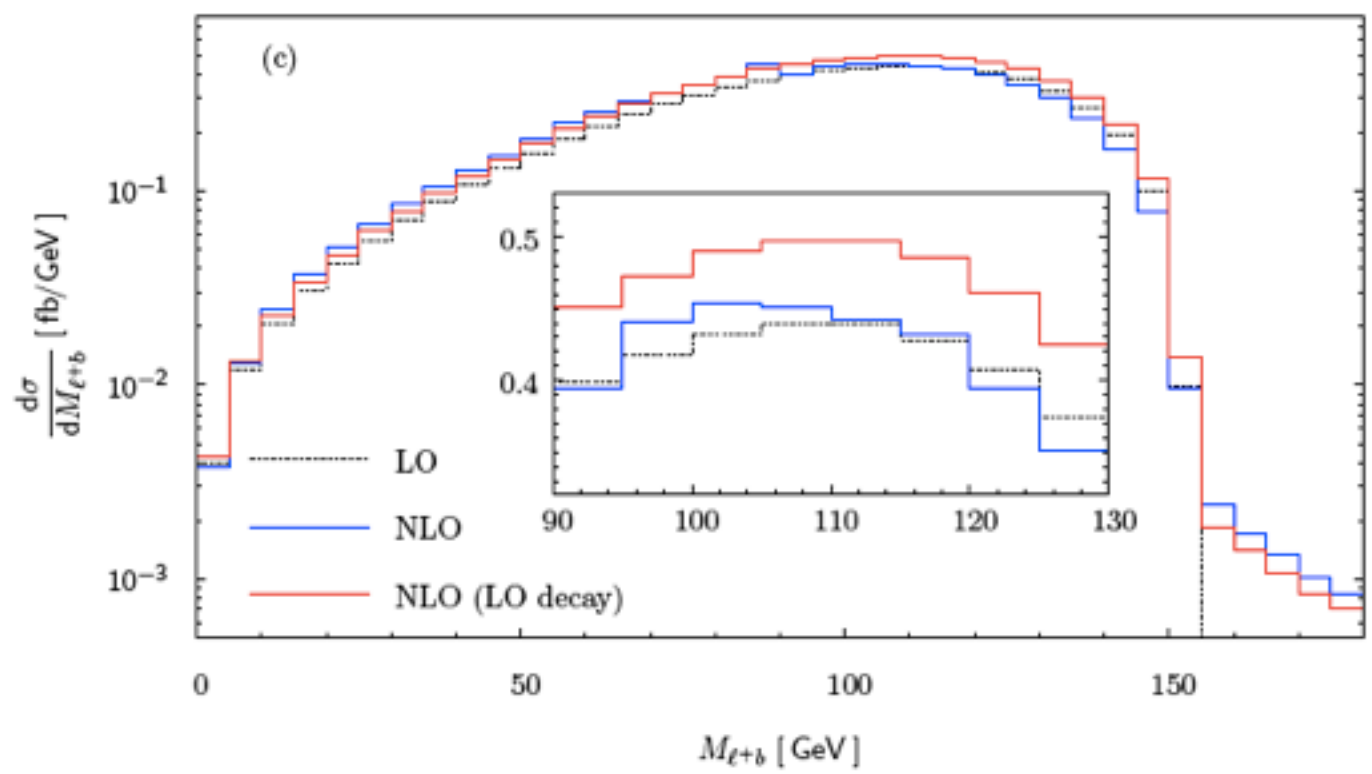
Lessons from top production

- How well do the approximations made for the signal simulation hold for the related top-pair production process?



Denner et al., 1207.5018

Larger K-factor in the high $E_{T,miss}$ tail



Melnikov, Schulze 0907.3090

Neglecting QCD effects in decay can shift predictions by sizable amounts

Goal and setup

- Motivated by these observations in top physics, we will calculate the NLO QCD corrections to ttbar+$E_{T,miss}$ arising from top-partner pair production

- We will include NLO QCD, and all spin correlations through production and decay to check the robustness of the exclusion limits

- We will consider both, scalar and fermionic top partners that have the same gauge quantum numbers as the SM top

- Following several experimental analysis, we work with the following simplified models:

$$\Delta\mathcal{L}_{\tilde{t}} = g_L \bar{t} P_L \chi_0 \tilde{t} + g_R \bar{t} P_R \chi_0 \tilde{t} + h.c.$$

$$\Delta\mathcal{L}_{T'} = g_L \bar{t} \gamma_\mu P_L T' A_0^\mu + g_R \bar{t} \gamma_\mu P_R T' A_0^\mu + h.c.$$

Technical aspects

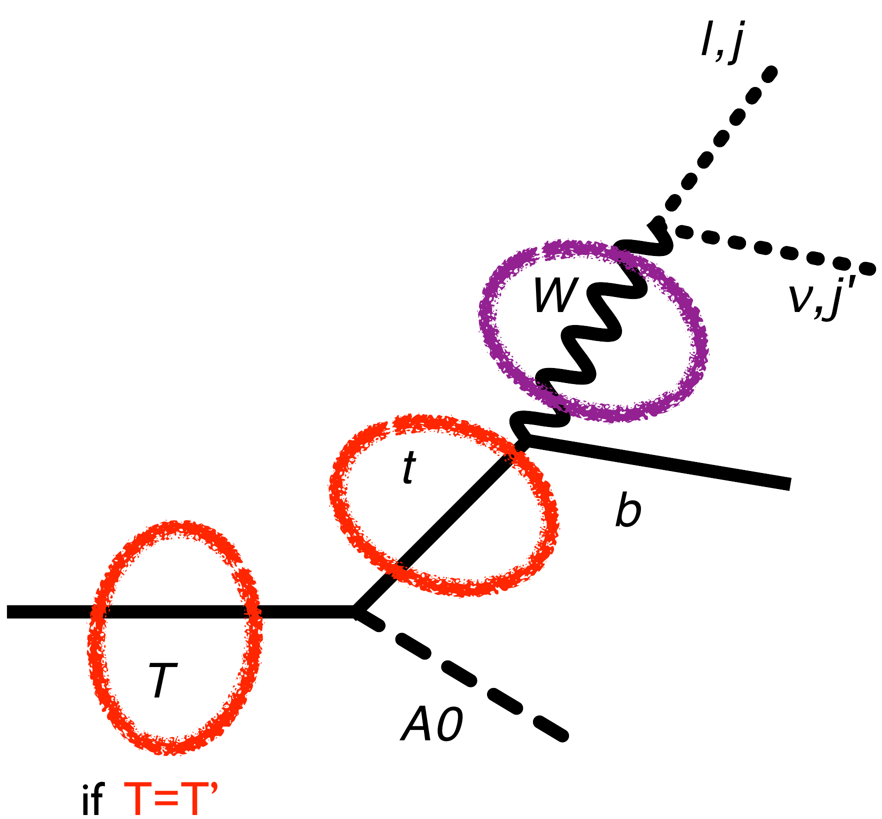
- Virtual corrections: Generalized D-dimensional unitarity + OPP

(Ellis,Giele,Kunszt,Melnikov; Ossola,Papadopoulus,Pittau), cross checked with the Feynman diagramatic approach

- Real corrections: Berends-Giele recursion relations,

Dipole subtraction with alpha-cutoff parameter (Catani,Dittmaier,Seymour,Trocsanyi) and results from arXiv:1204.1513 by Campbell, Ellis

- pp → TTbar → ttbar A_0A_0 → bblνjj A_0A_0 with T = stop or T'



$$\mathcal{M}(gg \to T\bar{T}) = \bar{u}(p_T)\tilde{\mathcal{M}}(gg \to T\bar{T})v(p_{\bar{T}})$$

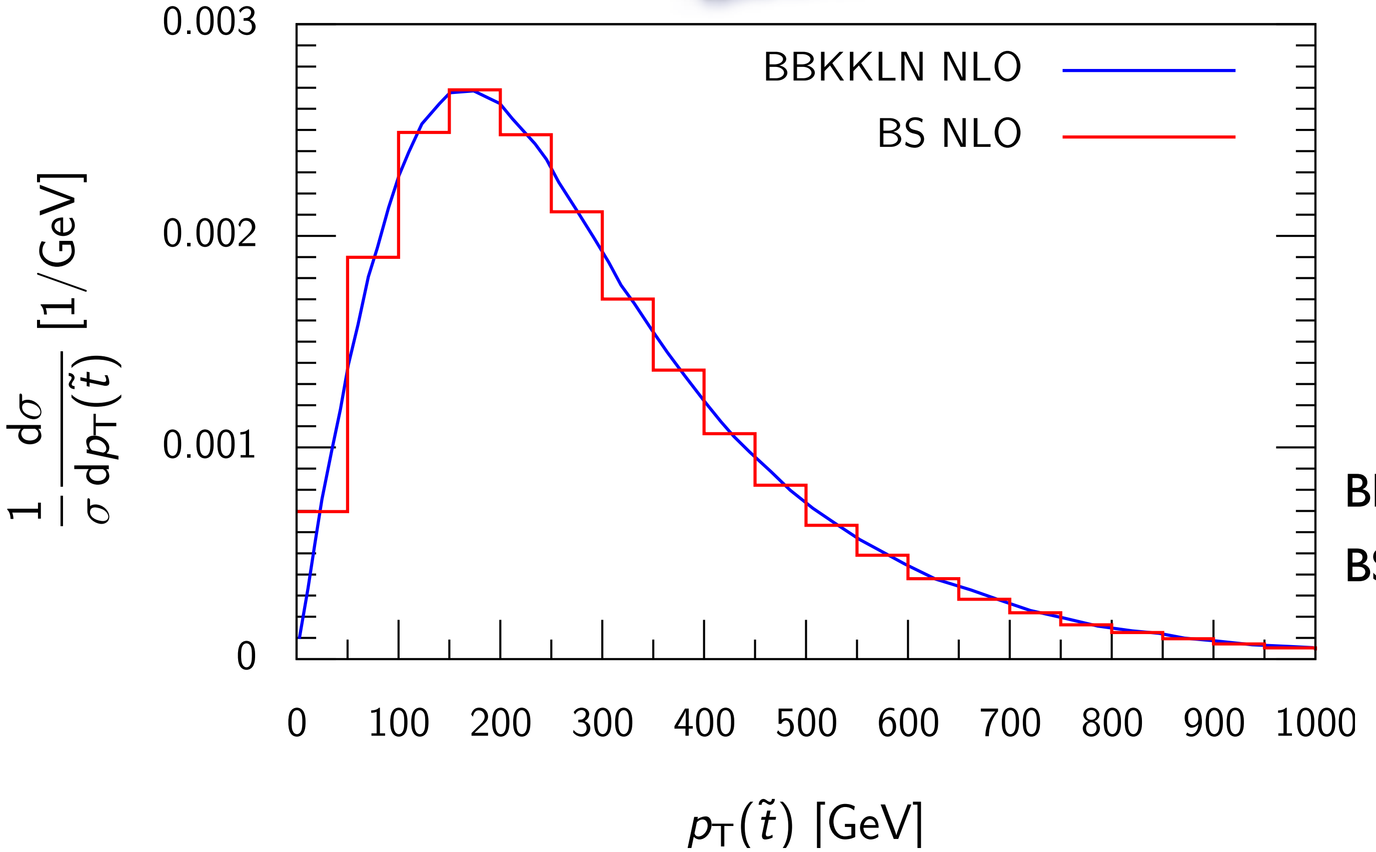
$$\bar{u}(p_T) \to \tilde{\bar{u}}(p_T) = \mathcal{M}(T \to tA_0)\, i\,\frac{(\not{p}_T + m_T)}{\sqrt{2m_T\Gamma_T}}$$

$$|\mathcal{M}|^2 = |\tilde{\bar{u}}(p_T)\tilde{\mathcal{M}}(gg \to T\bar{T})\tilde{v}(p_{\bar{T}})|^2 + \mathcal{O}\left(\frac{\Gamma_T}{m_T}\right)$$

Melnikov, Schulze (2010)

similar steps are followed for the top- and W-decay

Comparison with the literature



comparison of our P_T distribution for the stop with those of Beenakker et al (2012)

BBKKLN: Beenakker,Brensing,Kramer,Kulesza,Laenen,Niessen

BS: Boughezal,Schulze

- Very good agreement of the total cross section with results of *Prospino 2.1* (Spira et al) for stable stops in the heavy-gluino limit

- Decay checked through tests of factorization properties between production and decay matrix elements by removing all cuts on final state and integrating over the full phase space. This is compared with a separate evaluation of the product of the total cross section for stable stops times their branching fraction.

- Various other checks were performed: pole cancellation, multiple calculations of various ingredients, ...

Efficiency results for stops: semi- leptonic decay

pp → stop stop → bblνjj A_0A_0

Cross section	no cuts	with cuts	acceptance
σ_{LO}	$4.57^{+1.29}_{-2.01}$ fb	$0.91^{+0.26}_{-0.40}$fb	0.20^{+0}_{-0}
σ_{NLO}	$6.07^{+0.88}_{-0.77}$ fb	$1.77^{+0.36}_{-0.47}$fb	$0.29^{+0.02}_{-0.03}$

RB, Schulze, PRL 2013

45% enhancement in efficiency from NLO QCD corrections

- Results presented for:

  (m_{stop},m_{A0}) = (500GeV,100GeV),

  mu=500GeV for central value,

  $g_R = c_R$ mt/v; $g_L = c_L$ mt/v,

  c_R = 3/10, c_L = 1/10, mt = 172GeV, v = 246GeV

$$
\begin{aligned}
\Delta R_j &= 0.4, \quad p_{Tb} > 30\,\mathrm{GeV}, \\
|y_b| &< 2.5, \quad p_{Tj} > 30\,\mathrm{GeV}, \\
|y_j| &< 2.5, \quad p_{Tl} > 20\,\mathrm{GeV}, \quad |y_l| < 2.5, \\
E_{T,miss} &> 150\,\mathrm{GeV}, M_T > 120\,\mathrm{GeV},
\end{aligned}
$$

- Scale dependence:
  - For stable stops the scale uncertainty reduces from 32% at LO to 14% at NLO.
  - After including the cuts, it only reduces from 33% to 23%

Determining the uncertainty on the cross section using stable stops underestimates the theory error

The compressed spectrum region: semi-leptonic decay

• Same cuts and parameters as previous slide but $(m_{stop}, m_{A0}) = (250GeV, 50GeV)$, which is not yet excluded experimentally

$pp \rightarrow bbl\nu jj\, A_0A_0$

Cross section	no cuts	with cuts	acceptance
σ_{LO}	299 fb	13.8 fb	0.046
σ_{NLO}	407 fb	26.1 fb	0.064

RB, Schulze, preliminary

40% enhancement in efficiency from NLO QCD corrections

• In the compressed spectrum region, $m_{top}+m_{A0}$ is close to m_{stop}, therefore not much energy is released in the decay.

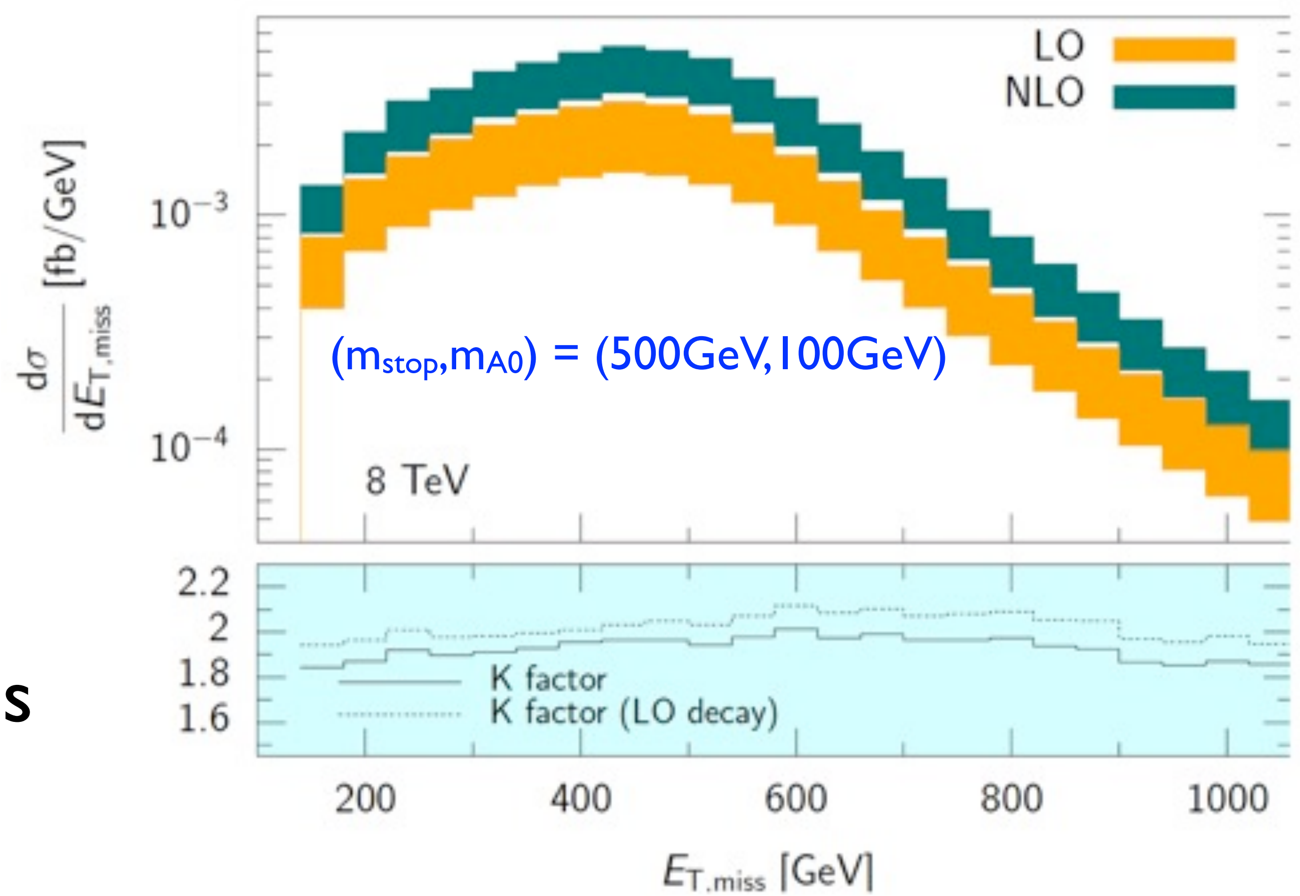
• E_{Tmiss} is roughly twice m_{A0}, therefore not enough energy is available to pass the cut E_{Tmiss} > 150GeV

• This makes it tough to study the compressed spectrum region, perhaps the experimental cuts should be relaxed to study it better

E_{Tmiss} Distribution: semi-leptonic decay

RB, Schulze, PRL 2013

- Large NLO QCD corrections:
  K = σ_{NLO}/σ_{LO} = 1.8 - 2



- Neglecting QCD corrections in the decay of the top partner overestimates the size of the corrections by 10%

- Kinematic dependence of the corrections depends on the observable: K-factor here begins at 1.8, plateau near 2 for E_{Tmiss} 600-800GeV then gradually reduces for higher E_{Tmiss}

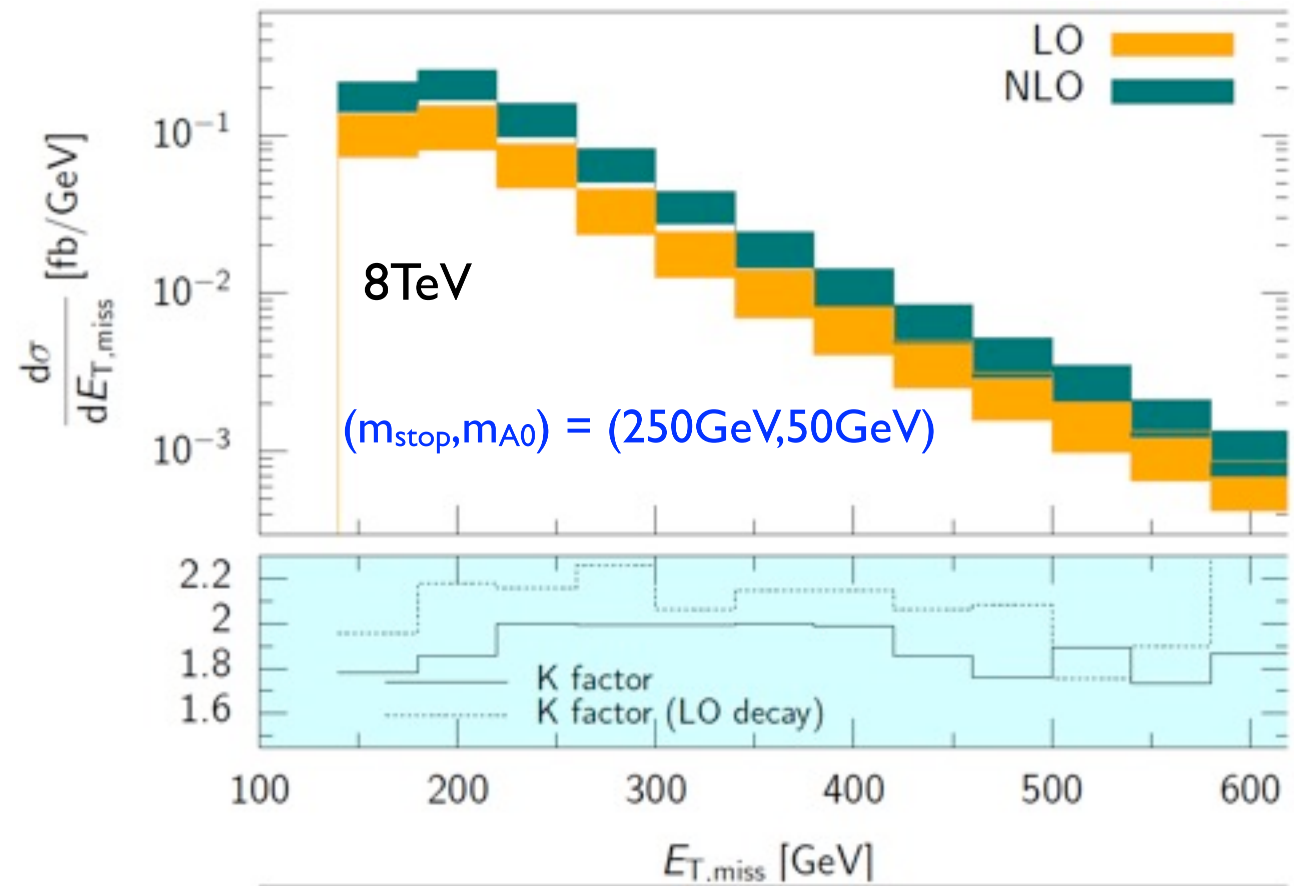
The compressed spectrum: semi-leptonic decay

- Large NLO QCD corrections:
  $K = \sigma_{NLO}/\sigma_{LO} = 1.8 - 2$

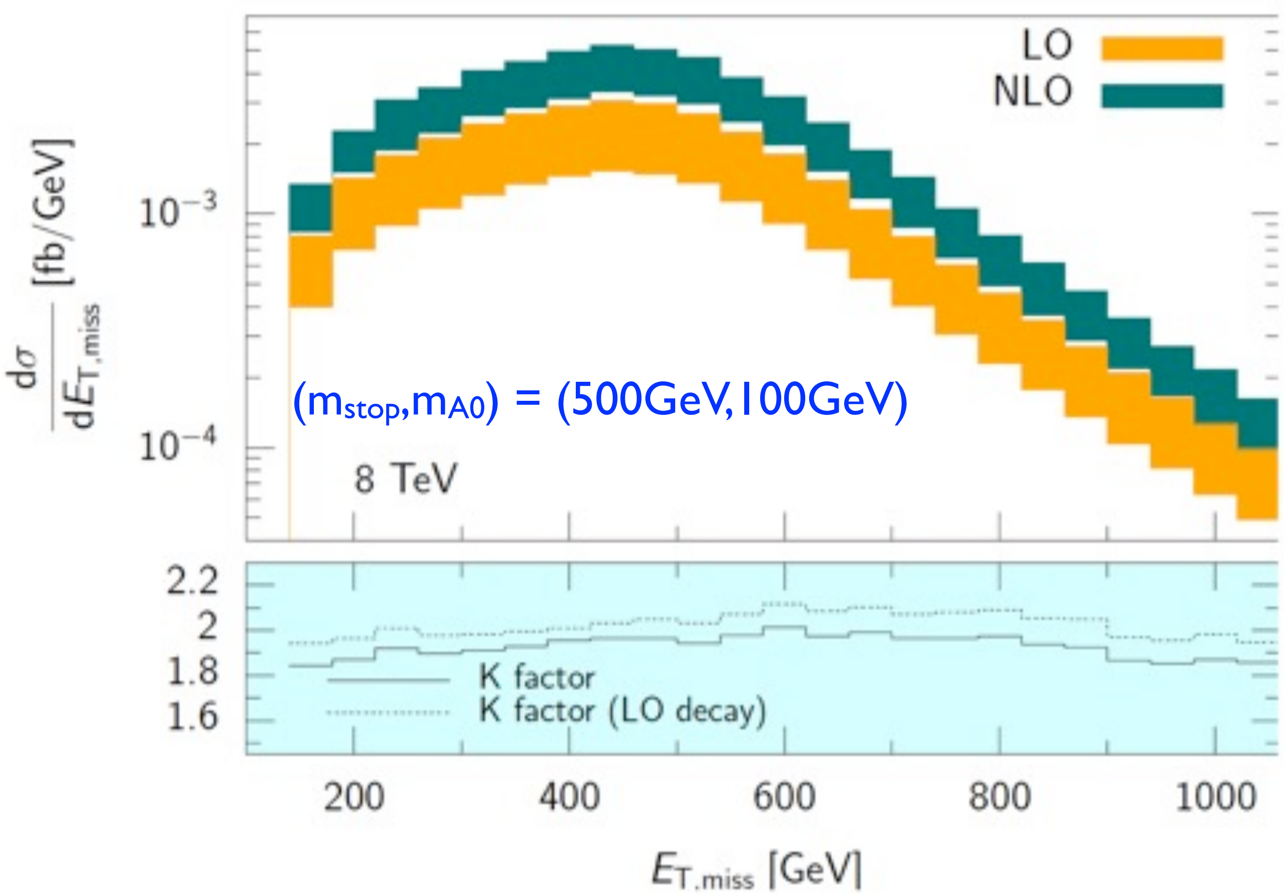
- Neglecting QCD corrections in the decay of the top partner overestimates the size of the corrections by 10%-30%

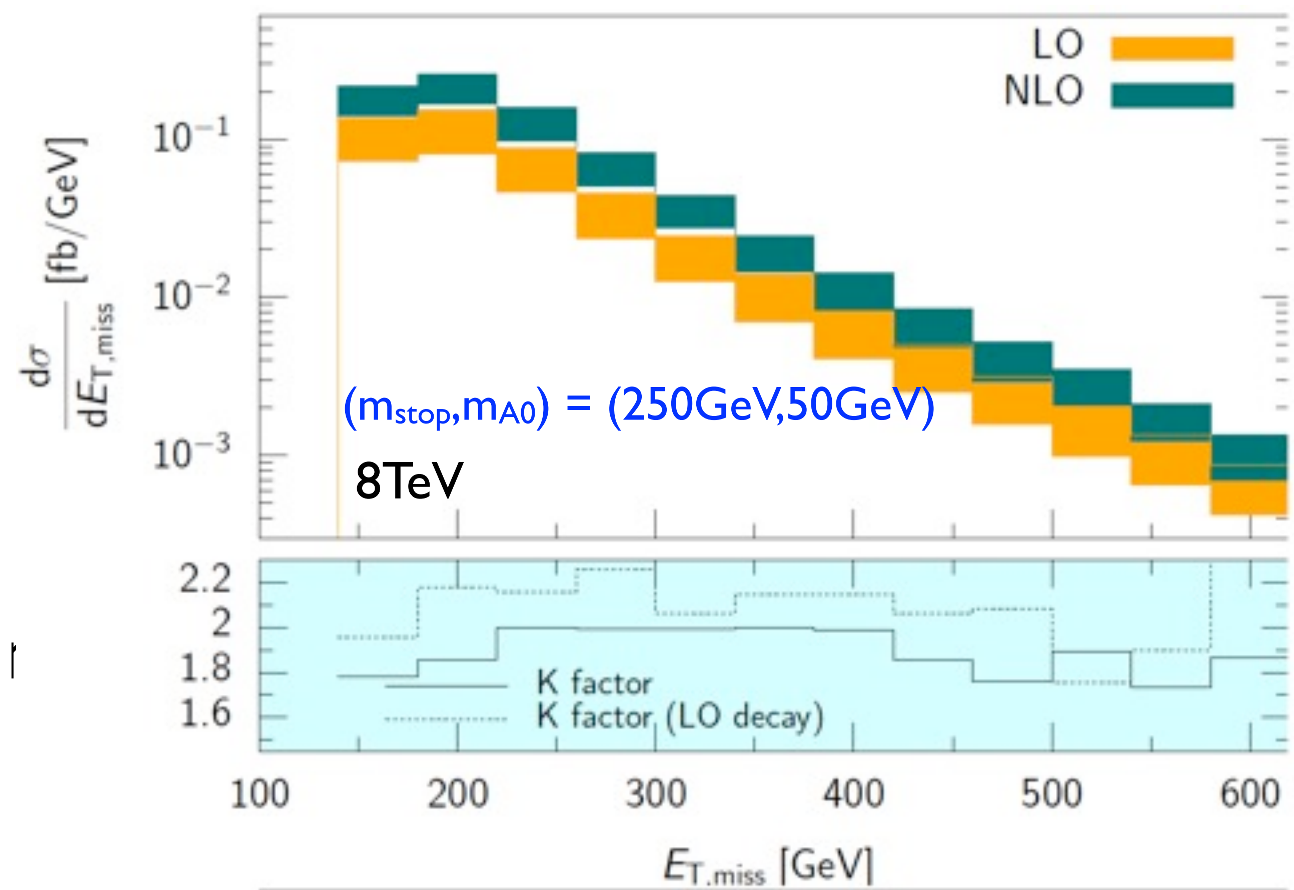
- Behaviour of K-factor is similar to the regular spectrum case

RB, Schulze, preliminary



Regular vs compressed spectrum





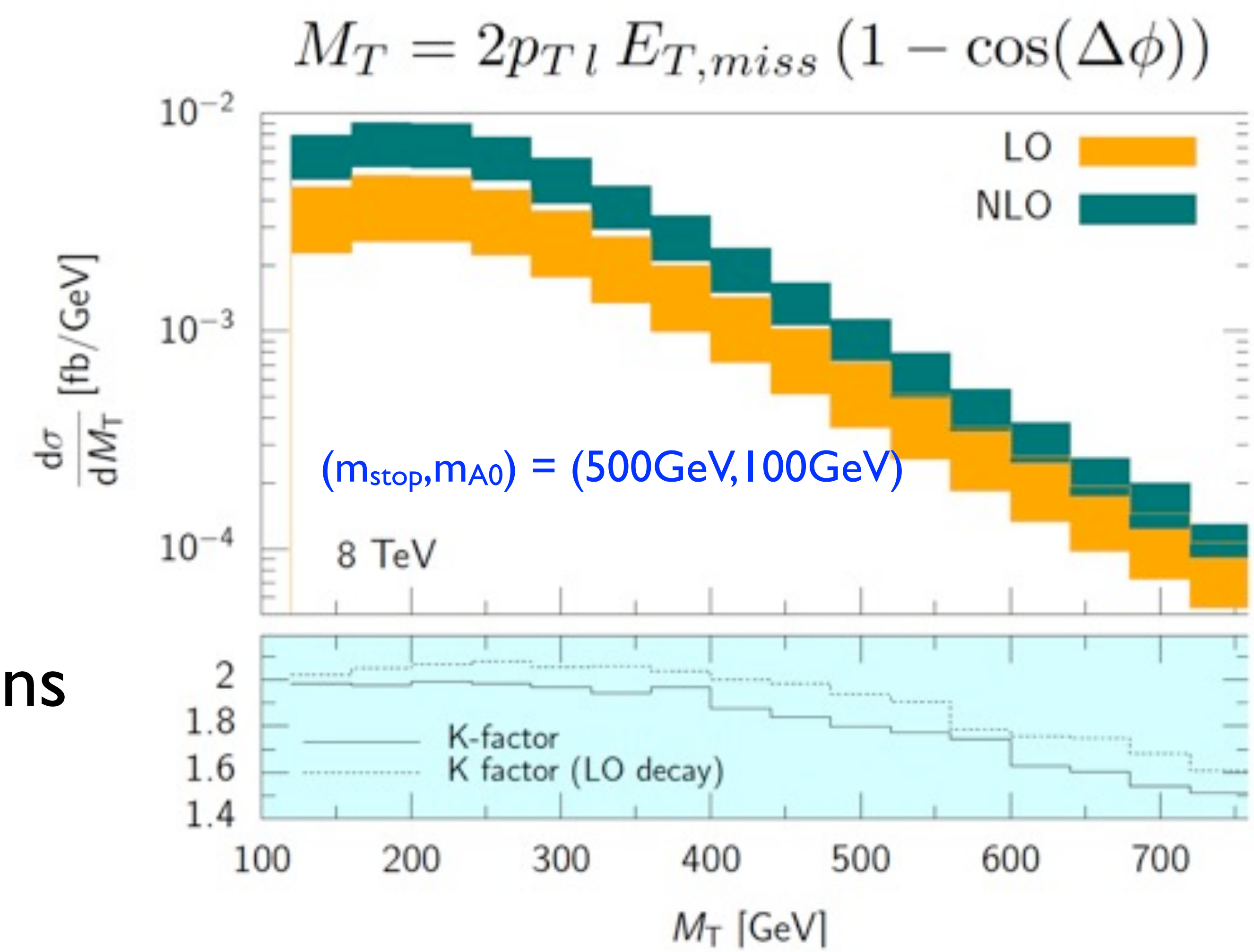
- Shape difference between regular and compressed spectrum drives the difference in efficiency

M_T Distribution: semi-leptonic decay

RB, Schulze, PRL 2013

- Large NLO QCD corrections:
  $K = \sigma_{NLO}/\sigma_{LO} = 1.4 - 2$

- Neglecting QCD corrections in the decay of the top partner overestimates the size of the corrections by 10-20% depending on M_T

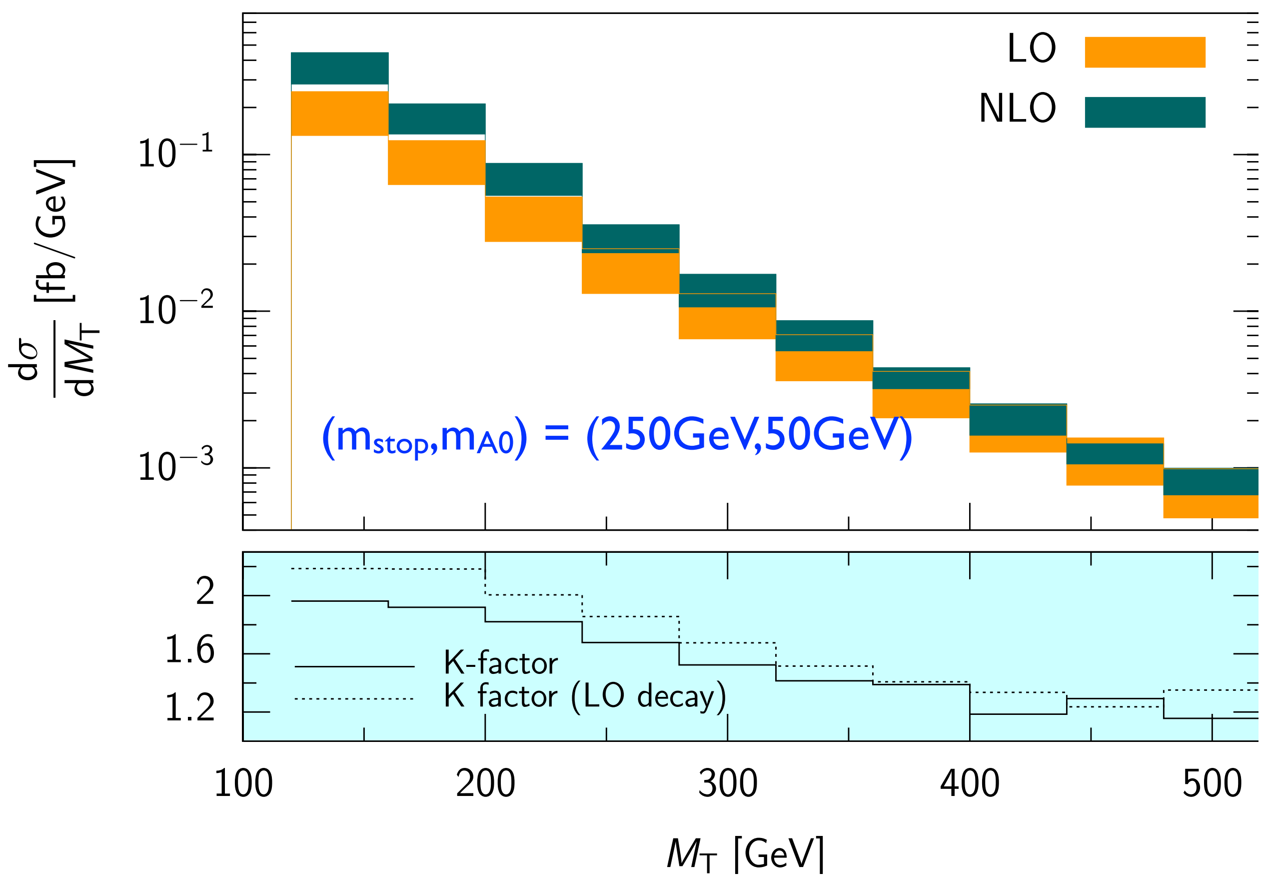


- Kinematic dependence of the corrections depends on the observable:
  K-factor begins at 2 near low M_T, it then monotonically decreases to 1.5 for M_T = 800GeV.

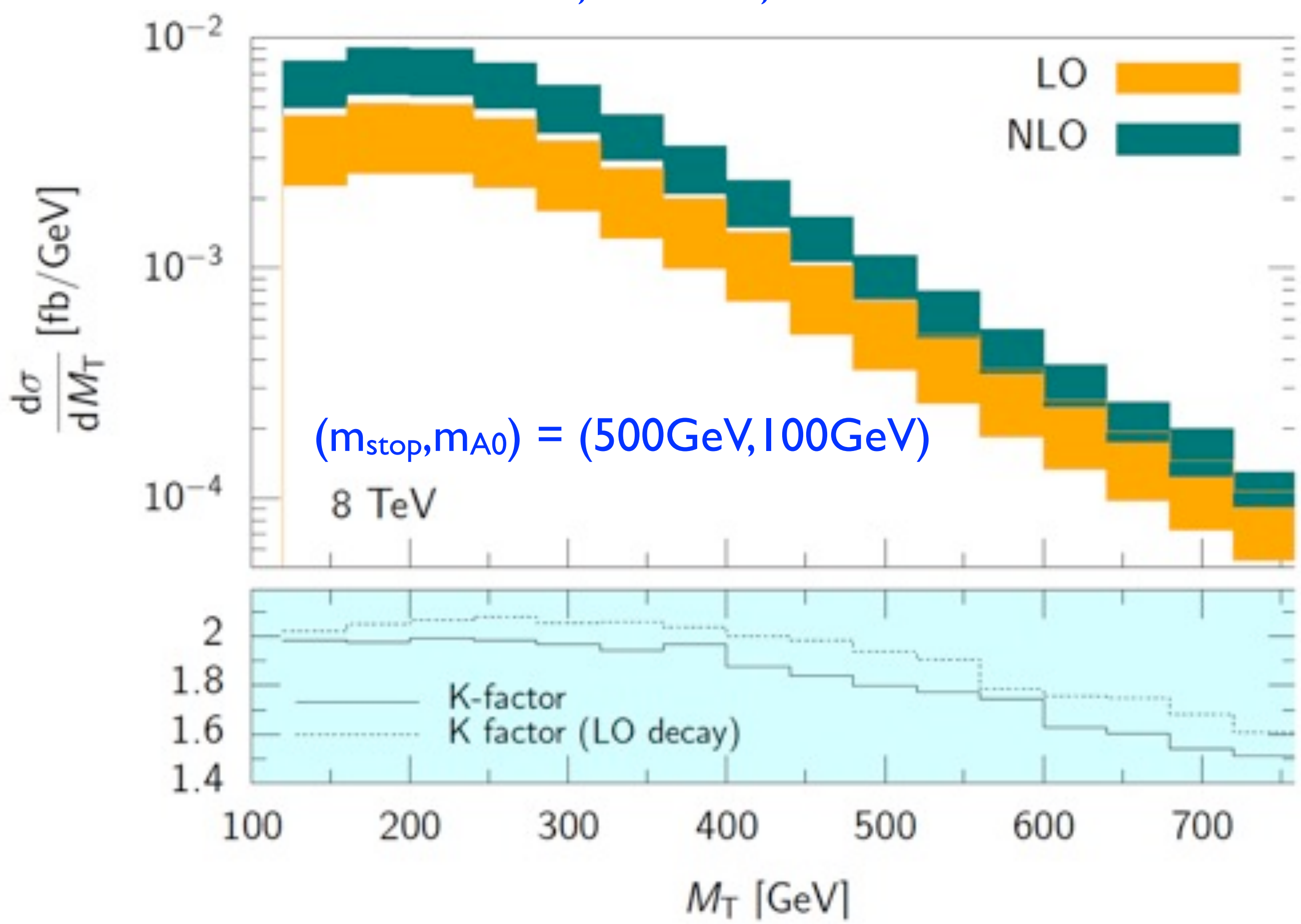
M_T Distribution: semi-leptonic decay

$$M_T = 2p_{T\,l}\, E_{T,miss}\,(1-\cos(\Delta\phi))$$

preliminary



RB, Schulze, PRL 2013



- Regular and compressed spectra have different M_T shapes as well as different K-factors at high M_T. For example at M_T=500GeV, K=1.8 for the regular spectrum vs 1.2 for the compressed one.

M_{Teff} Distribution: semi-leptonic decay

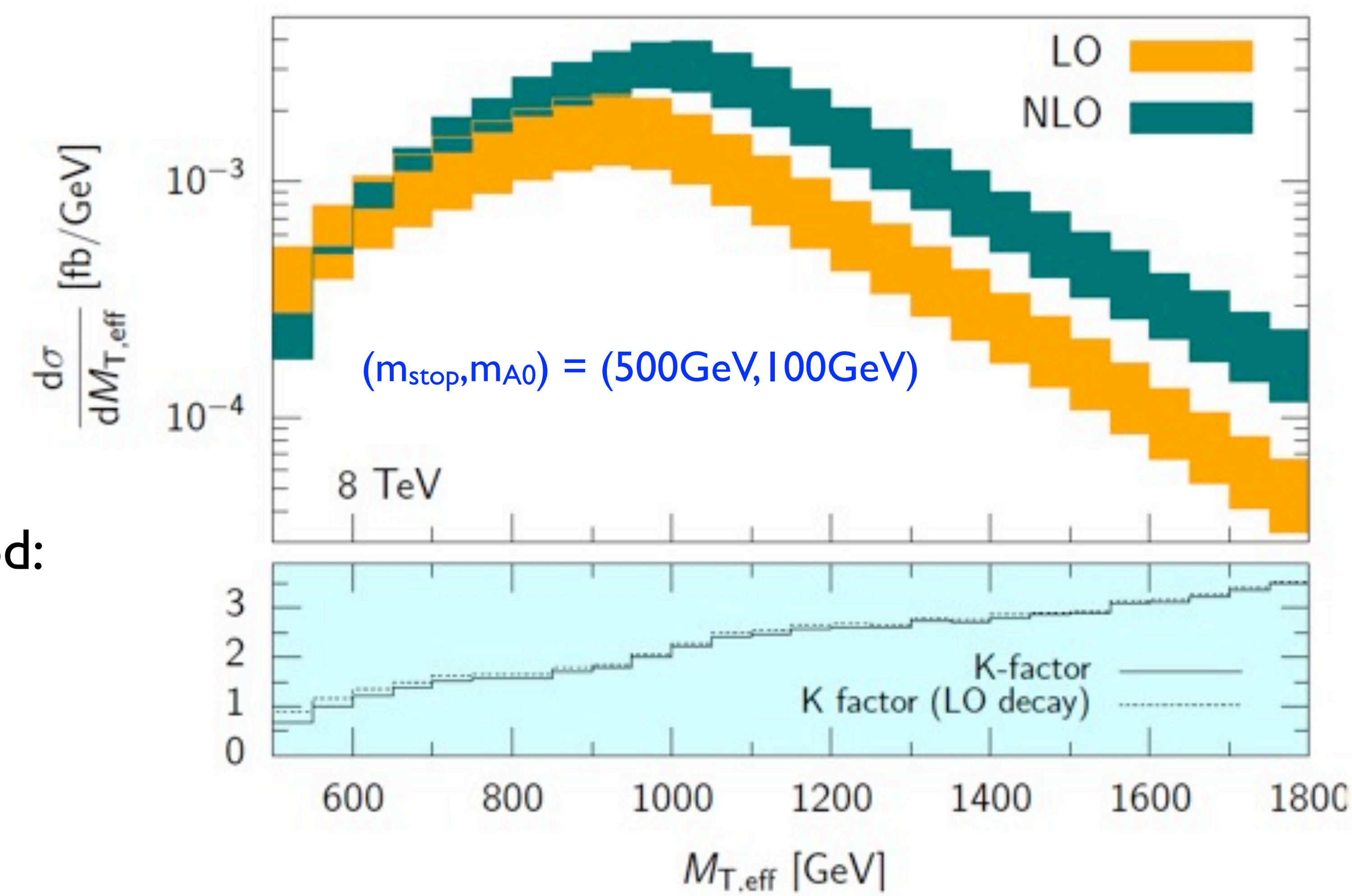
- M_{Teff}: its shape for large M_{Teff} was suggested as a useful diagnostic tool to determine the spin of the top-partner
  Chen, Freitas, Han, Lee 2012

- Large NLO QCD corrections:
  $K = \sigma_{NLO}/\sigma_{LO} = 0.6 - 3$

- Largeness of K-factor can be understood:

  - ATLAS and us demand 4 jets in final state
  - tops become boosted at high M_{Teff} and probability of finding 4 jets with anti-kT $\Delta R = 0.4$ is reduced.
  - issue alleviated at NLO by presence of additional radiation
  - K-factor reduced when $\Delta R = 0.1$

RB, Schulze, PRL 2013



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

$$E_{T,i} = \sqrt{m_i^2 + \boldsymbol{p}_{i,T}^2}$$

- Can not rely on LO to properly describe this observable

Model determination from kinematic shape

- It has been argued in the literature that the cross section for scalar and fermionic top-partners are different and therefore we can measure the total rate to distinguish them

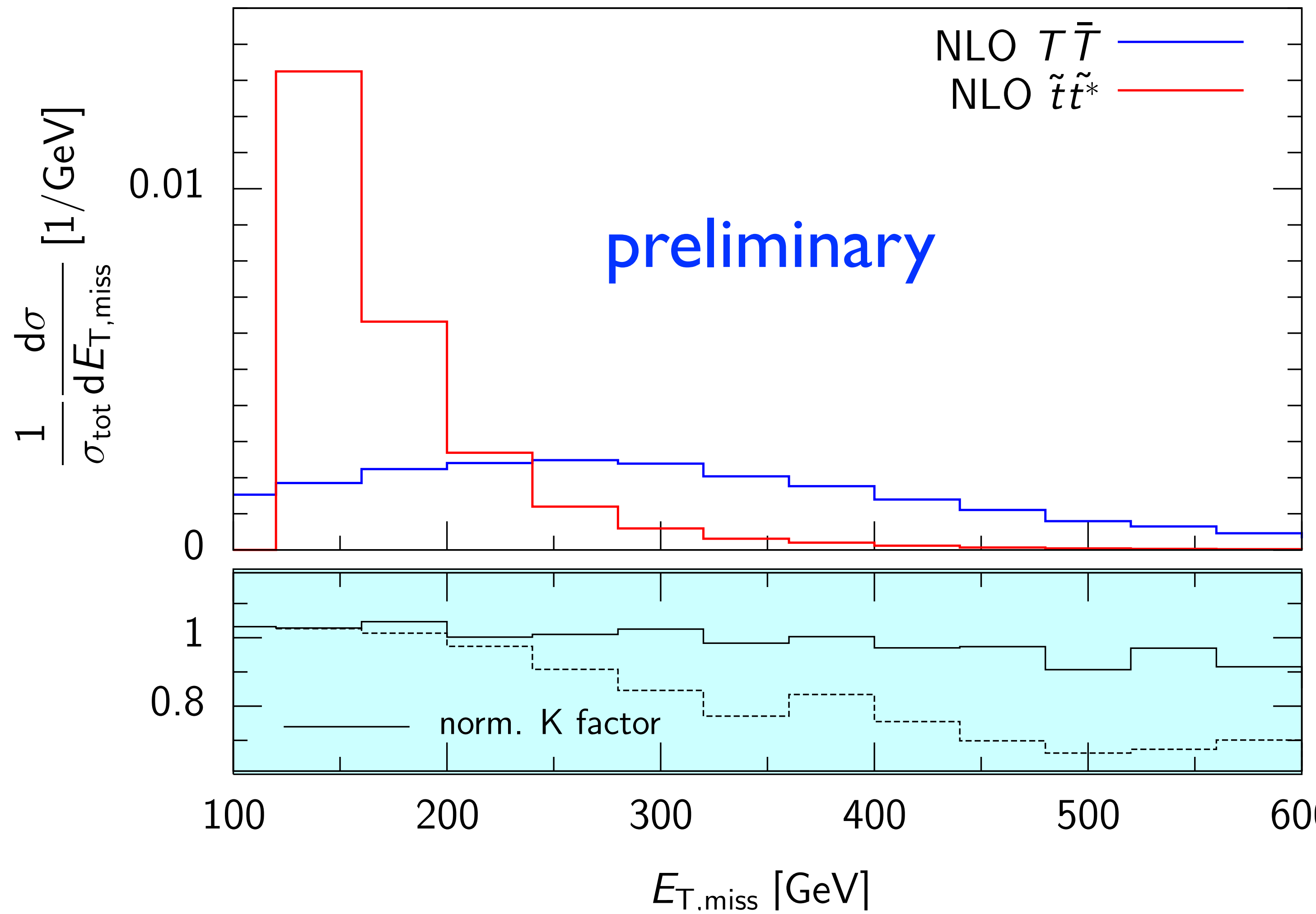
- Can always choose the mass parameters such that the cross section for the two top-partners is the same:

  $(m_{stop}, m_{A0}) = (250\text{GeV}, 50\text{GeV})$

  $(m_{T'}, m_{A0}) = (500\text{GeV}, 50\text{GeV})$

  $$\sigma_{\rm NLO}(\tilde{t}\tilde{t}^*) = 114 \text{ fb},$$

  $$\sigma_{\rm NLO}(T'\bar{T}') = 131 \text{ fb}$$



- Relying on the cross section does not allow in this case to distinguish the two models

- Fitting E_{Tmiss} distribution gives a powerful handle on what the spin is

Summary

- Discussed ttbar + large E_{Tmiss} signatures at the LHC, coming from direct stop- or fermionic-top partner production
- Considered QCD corrections in the production and decay maintaining spin correlations throughout the entire production and decay chains
- Kinematic dependence of the QCD corrections depends strongly on the observable; the K-factor for E_{Tmiss}, and transverse mass M_T were large and range between 1.4 - 2
- These results could significantly effect the current exclusion limits on top partners