EW NLO Corrections to Pair Production of Top-squarks at the LHC

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July 27, 2007 – SUSY07 Karlsruhe

Introduction

Top-squark sector of the MSSM:

– in our calculation: R-parity conserving, MFV, real parameters

– large Yukawa coupling induces large L–R mixing

$$\mathcal{L} = -\left(\tilde{t}_L^{\,*}, \tilde{t}_R^{\,*}\right) \mathcal{M} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = -\left(\tilde{t}_1^{\,*}, \tilde{t}_2^{\,*}\right) \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

with $\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$ and

$$\mathcal{M} = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + c_{2\beta}\left(T_3 - Q\, s_W^2\right) M_Z^2 & m_t M_t^{LR} \\ m_t M_t^{LR} & M_{\tilde{t}_R}^2 + m_t^2 + Q\, c_{2\beta} s_W^2 M_Z^2 \end{pmatrix} \qquad M_t^{LR} = A_t - \mu / \tan\beta$$

– lighter than 1st and 2nd generation squarks
lightest squark in many scenarios

Motivation

squark pair production:

– at hadron colliders via strong interactions

→ relatively large cross sections

top-squark:

– lightest squark in many scenarios

→ popular candidate to search for at hadron colliders

– $\sigma_{\tilde{t}\tilde{t}^*}$ depends essentially on the stop mass

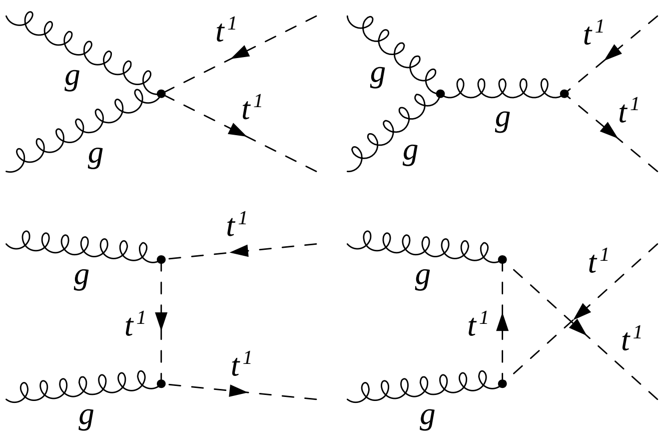
→ **extract stop mass directly from the cross section measurement**

Top-squark pair production at Born level

at hadron colliders:

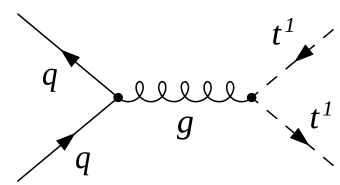
diagonal at LO

- light pair $\tilde{t}_1\tilde{t}_1^*$ — study numerically
- heavy pair $\tilde{t}_2\tilde{t}_2^*$



gg fusion

Low x



$q\bar{q}$ annihilation

High x

EW contributions

(*Bozzi et al. 2005*)

neglected

Higher order corrections - Status

at hadron colliders:

→ QCD corrections are largest

SUSY-QCD NLO (*Beenakker et al. 1996*, *Beenakker et al. 1997*)

- still diagonal
- theory prediction: *Prospino*
- Tevatron: no mass limit

→ also EW corrections have to be investigated

still missing

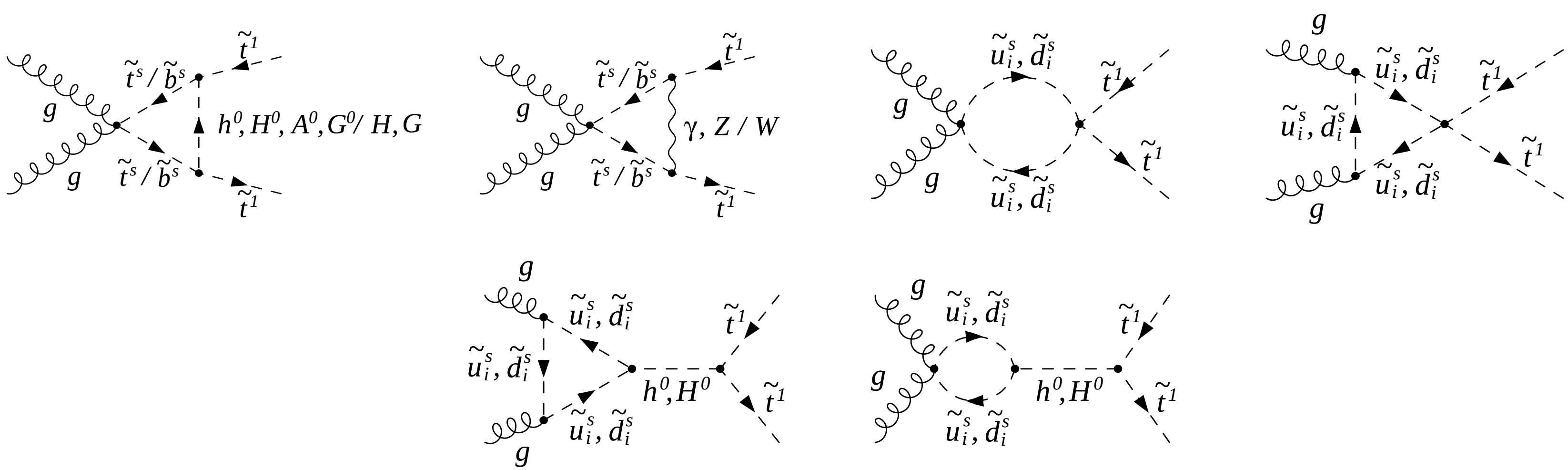
SUSY-EW corrections to $\sigma_{\tilde{t}\tilde{t}^*}$

Characteristics:

- not possible to separate SM-like corrections, result not UV finite
- not possible to split SUSY-QED corrections from the weak part

→ full EW corrections: # of diagrams > 500
$\rightarrow$ treatment with help of FeynArts & FormCalc

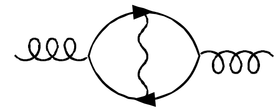
- threshold effects from heavy stop and two sbottom pair loop contributions
  sources: SSVV channel, *s*-channel Higgs exchange
  (contributions from squark pairs of 1st and 2nd generation suppressed)



Treatment of UV singularities:

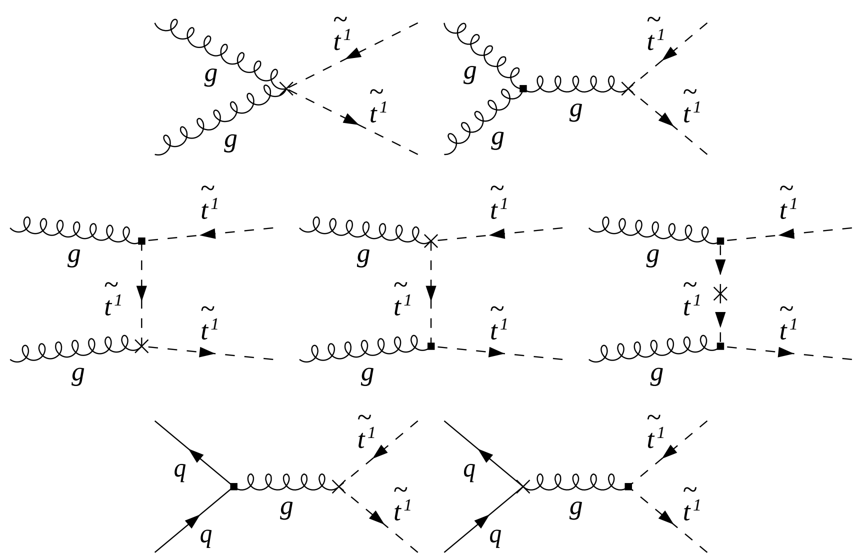
renormalization:

- renormalization of external quark/squark fields & stop mass
- no photon-gluon interaction at 1-loop
  - no gluon field renormalization



- Ward Identity: vertex + ren. quark/squark fields = UV finite
  - no α_s renormalization
- no mixing angle renormalization since $\tilde{t}\tilde{t}^*$ diagonal

counter terms:



UV finite result

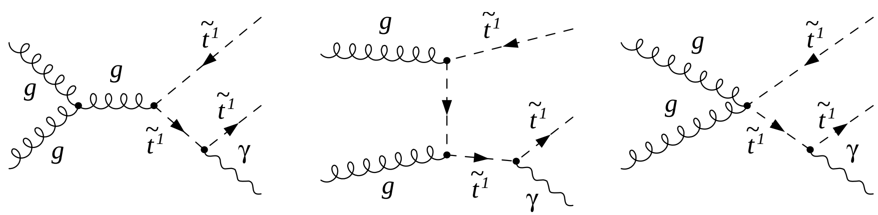
IR singularities

Treatment of IR singularities:

- origin: massless photon in the loop
- regularization by photon mass parameter λ (terms $\sim \ln \lambda$)
- Bloch-Nordsieck:
  - in the soft limit ($k \to 0$) virtual and real photons are undistinguishable
  - sum of virtual and real corrections is **IR finite** (independent of λ)

→ **need photon bremsstrahlung**

IR singular:



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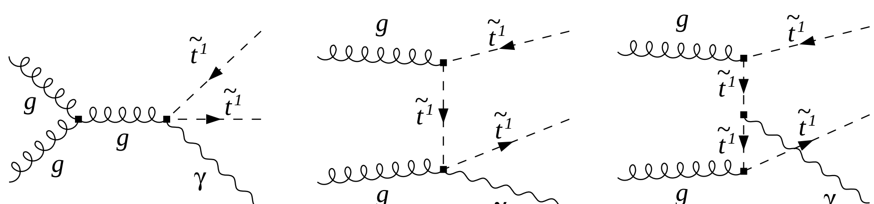
IR finite:



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Collinear effects

Collinear / mass singularities

- origin: light initial state quarks radiating a photon
- in the collinear limit: $p.k = p^0 k^0 (1 - \cos\theta) \to 0$ for $m_q=0$
- regularization by keeping quark mass in the loop integrals
- m_q not very well defined
  (terms $\sim \ln m_q^2/s$, $\sim \ln^2 m_q^2/s$)

photon in the loop

- Sudakov double logs cancel in the sum of virtual and real corrections

→ **single logs remain** → factorization

Z,W in the loop

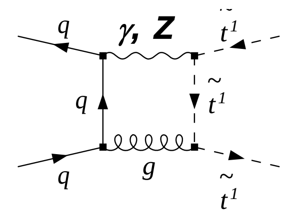
- Sudakov double logs (terms $\sim \ln^2 m_Z^2/s$, $\sim \ln^2 m_W^2/s$)
- not cancelled by the real corrections (different final state)

→ **double logs remain** → large negative contributions

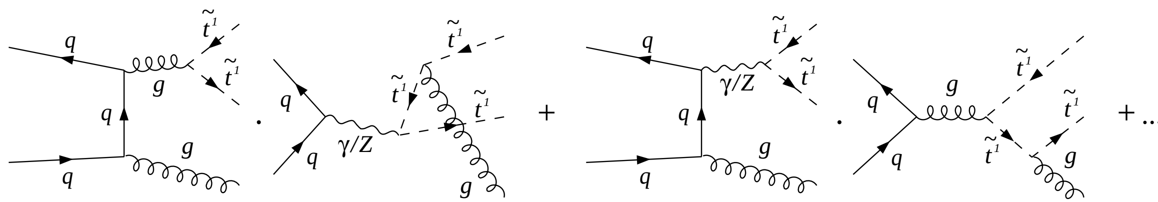
IR singularities because of gluons

gluon in the loop

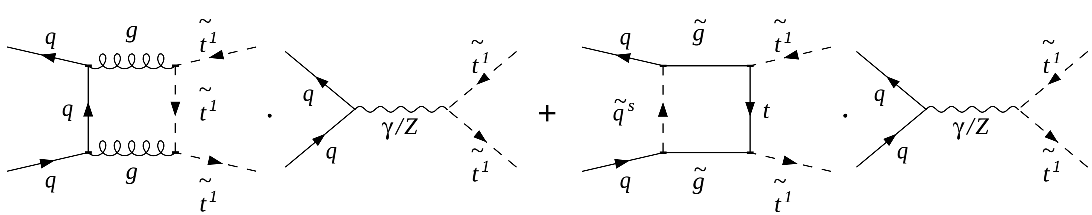
- IR singularities related to gluon
- Abelian-like: mass regularization
- photon bremsstrahlung cancels only the photonic IR singularities



need gluon bremsstrahlung of $\mathcal{O}(\alpha\alpha_S^2)$ QCD-EW interference



need complete QCD-EW interference of $\mathcal{O}(\alpha\alpha_S^2)$



QCD corrections to EW Born (additional IR finite boxes)

Treatment of real corrections

Phase space slicing:

soft part: $E_\gamma \leq \Delta E$

collinear part: $E_\gamma > \Delta E \quad \theta_{f\gamma} \leq \Delta\theta$

→ contain **singularities**

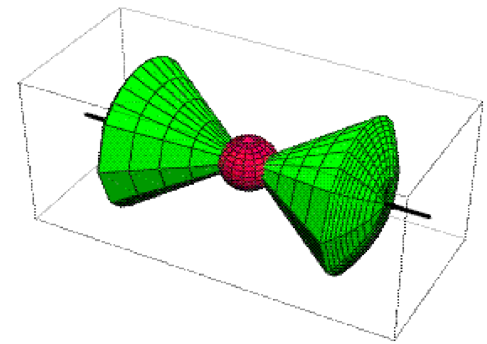
→ handled analytically using approximations

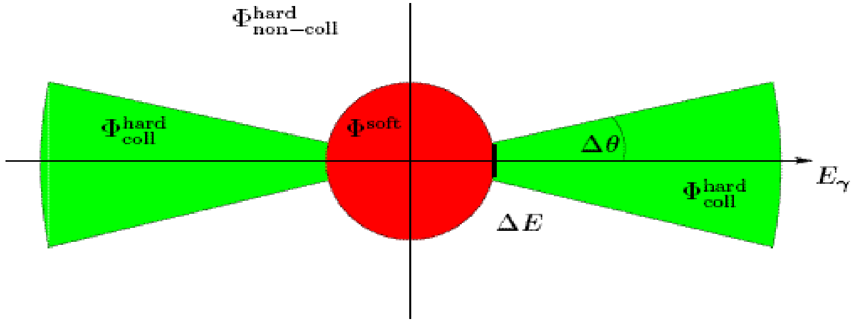
hard, non-collinear part:

$E_\gamma > \Delta E \qquad \theta_{f\gamma} > \Delta\theta$

→ no **singularities**

→ calculated numerically using Monte Carlo





Subtraction:

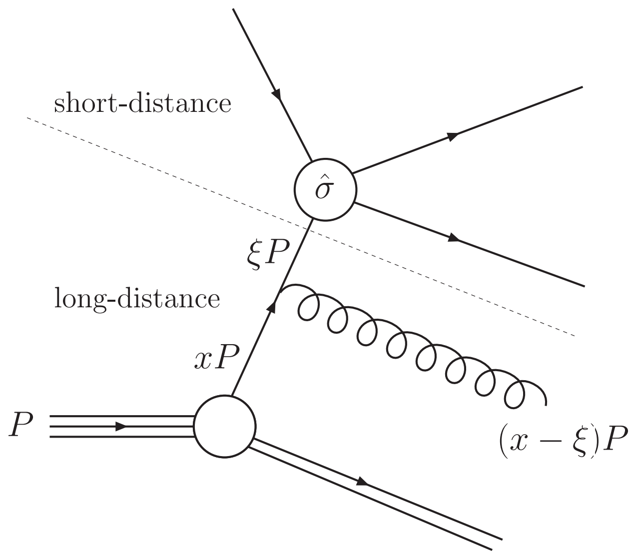
$$\int d\Phi_1 \sum_{\lambda\gamma} |\mathcal{M}_1|^2 = \int d\Phi_1 \left(\sum_{\lambda\gamma} |\mathcal{M}_1|^2 - |\mathcal{M}_{\text{sub}}|^2 \right) + \int d\Phi_1 \, |\mathcal{M}_{\text{sub}}|^2$$

singular — no singularities — analytically

Hadronic cross section

Factorization theorem:

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, Q) f_j(x_2, Q) \hat{\sigma}_{ij}(p_1, p_2, Q) \qquad p_{1,2} = x_{1,2} P_{1,2}$$



- short-distance effects:
  partonic cross section of the hard process → $\hat{\sigma}$
- long-distance effects:
  parton distributions functions (PDFs) → $f(x, Q)$
- collinear ISR is a long-distance effect
  (included in the data from which PDFs are extracted)

remaining mass singularities ~ $\ln m_q^2$ ➡

- absorb into PDFs
- subtract from $\hat{\sigma}$

<u>result becomes:</u>

- independent of m_q
- dependent on factorization scale Q $\quad (Q = \mu_{ren} = 2m_{\tilde{t}})$

PDFs at NLO QED

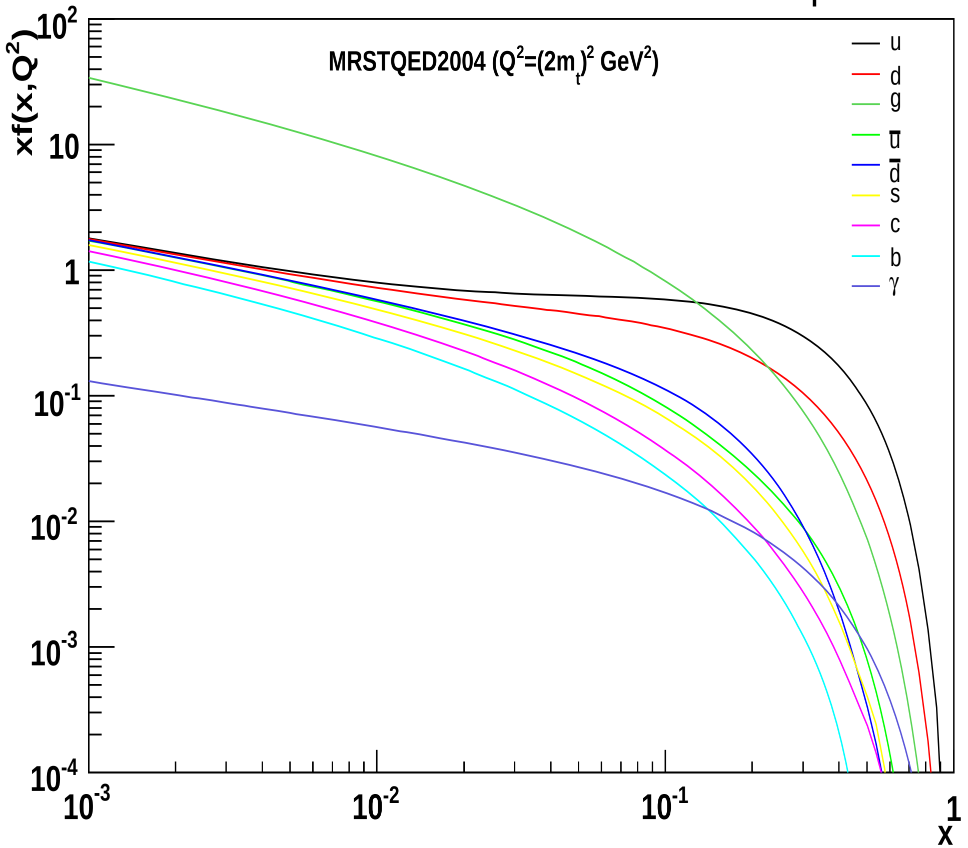
PDFs at NLO QED

- needed for a consistent treatment
- DGLAP evolution equations have to be modified
- determined in the same factorization scheme as $\hat{\sigma}$ to reduce dependence on Q

MRST2004QED

- *Martin et al. 2004*
- QED NLO in DIS scheme
- however: QCD NLO in PDFs leads to overestimation of Q dependence

proton

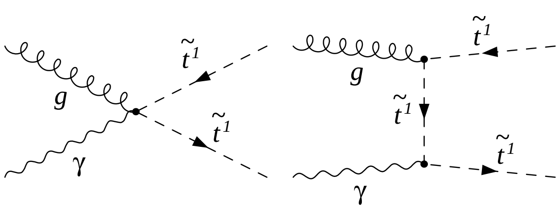


→ **non-zero photon density in the proton**

Photon-induced top-squark production

photon-induced hadronic contribution

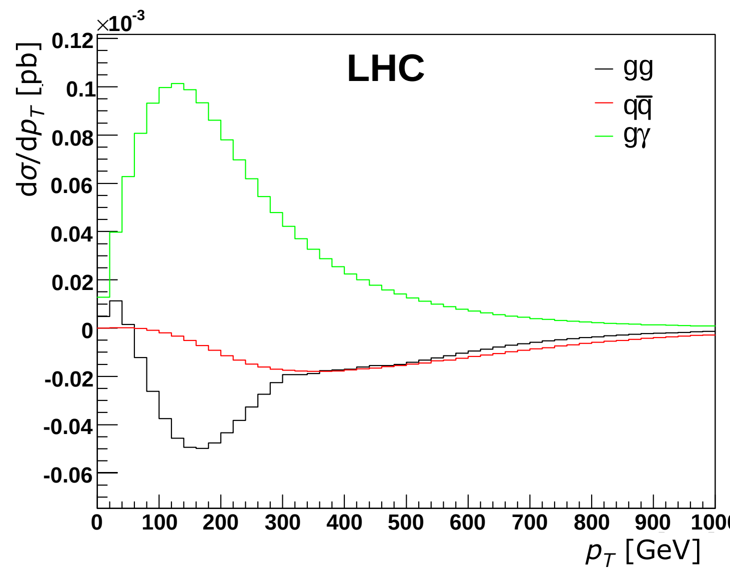
- zero at LO because of vanishing photon density in the proton
- becomes non-zero at NLO since non-zero photon density in the proton
- gluon-photon contributions are NLO QED (the NLO effects enter via PDFs)



- quark-photon contributions are NNLO due to additionnal collinear effects in the partonic cross section

  (not included in the calculation)

gluon-photon channel



γg is comparable in size with gg and $q\bar{q}$ corrections

cannot be neglected

Numerical results: total hadronic σ

apply kinematic cuts to obtain realistic result: $p_T > 200$ GeV and $\eta < 2.5$

scenario	prod. channel	σ_{LO} [fb]	$\sigma_{NLO} - \sigma_{LO}$ [fb]	$\delta = \sigma_{NLO}/\sigma_{LO} - 1$
SPS 1a ($m_{\tilde{t}_1}$=376.2 GeV)	$q\bar{q}$ gg $g\gamma$	220 1444	-9.65 -15.4 29.0	**total:** **0.24 %**
SPS 1a′ ($m_{\tilde{t}_1}$=322.1 GeV)	$q\bar{q}$ gg $g\gamma$	436 3292	-11.5 -14.6 58.5	**total:** **0.87 %**
SPS 2 ($m_{\tilde{t}_1}$=1005.7 GeV)	$q\bar{q}$ gg $g\gamma$	1.16 2.97	-0.089 -0.030 0.155	**total:** **0.84 %**
SPS 5 ($m_{\tilde{t}_1}$=203.8 GeV)	$q\bar{q}$ gg $g\gamma$	2870 31960	-13.2 499 405	**total:** **2.6 %**

NLO EW effects: ~ 1% → negligible

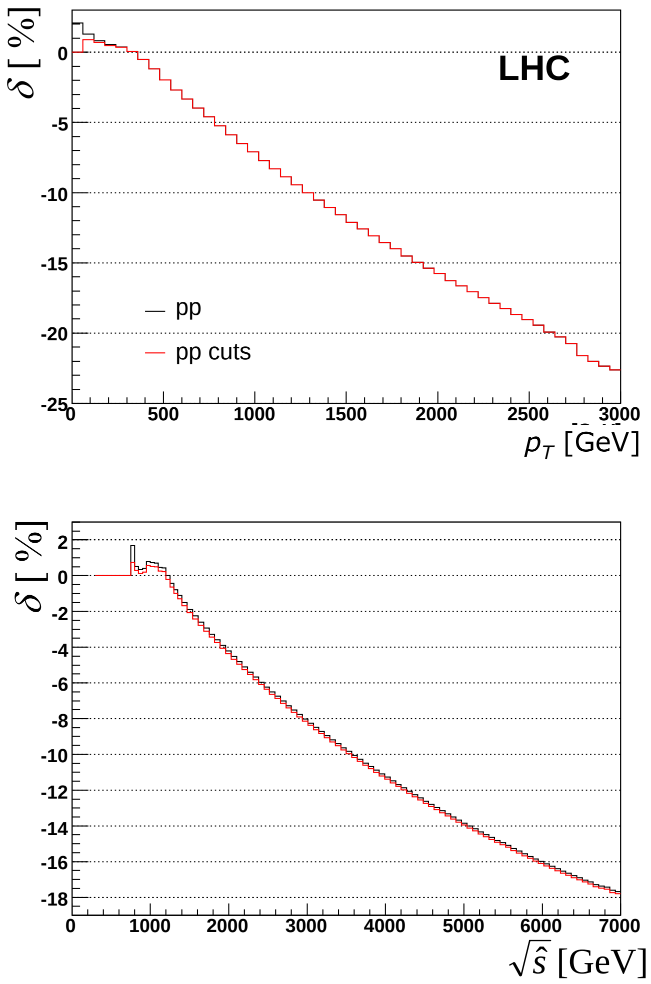
uncertainty from NLO QCD PDFs ~ 10%

→ NLO EW have small effects on total hadronic cross section

Numerical results: distributions

differential hadronic cross sections / distributions in p_T and invariant mass

for SPS 1a



– gg + gγ dominate for low p_T and low $\sqrt{\hat{s}}$, opposite signs

– $q\bar{q}$ takes over for high p_T and high $\sqrt{\hat{s}}$

relative correction $\delta = \sigma_{\text{NLO}}/\sigma_{\text{LO}} - 1$

– increases in size with p_T and $\sqrt{\hat{s}}$ and becomes negative

– mass logs from collinear photon radiation

– large double logs from W, Z (not cancelled by real corrections)

– reaches 15–20% level

→ **relevant for high p_T and high $\sqrt{\hat{s}}$**

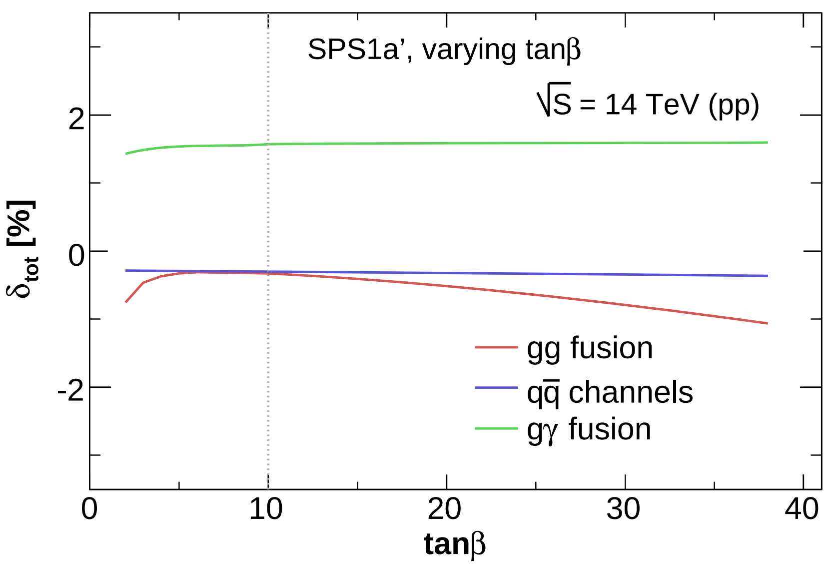
Variation of MSSM parameters

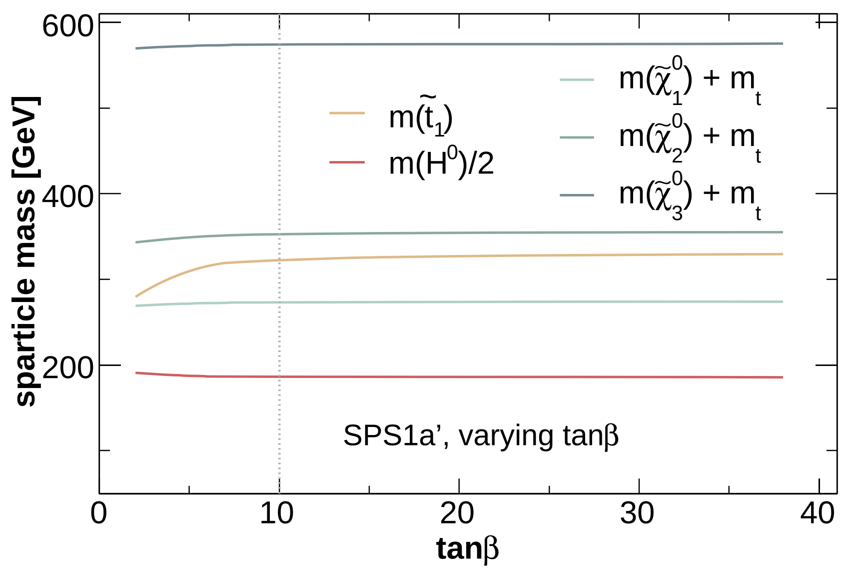
– we have studied the effects of variation of SUSY parameters:
tan β, μ, M_{Q3}, M_1, M_2, M_3

Example:

– variation of **tan β** in range 1–40

– impact on the SUSY-EW corrections to the total cross section: few %



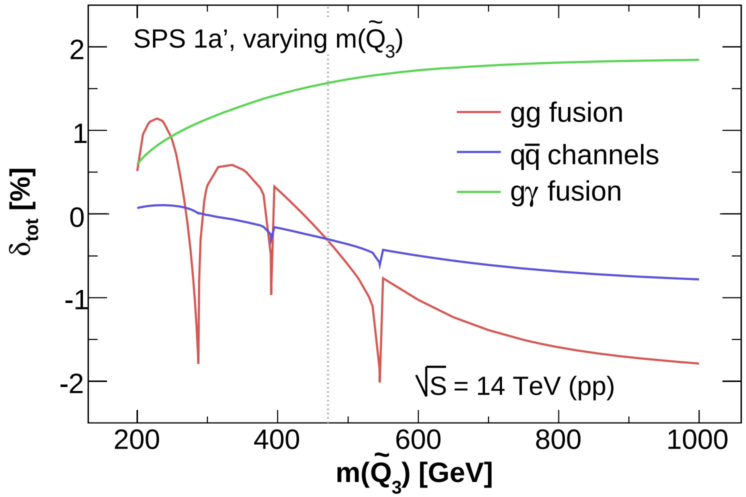


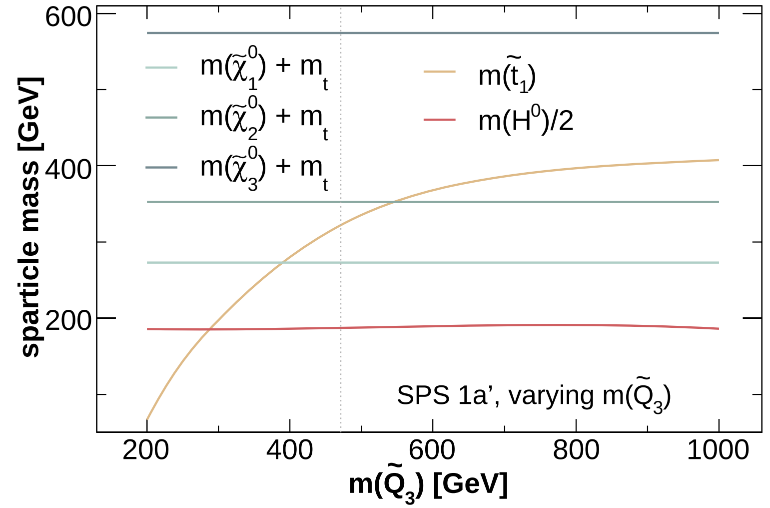
Variation of MSSM parameters (cont.)

2nd example:

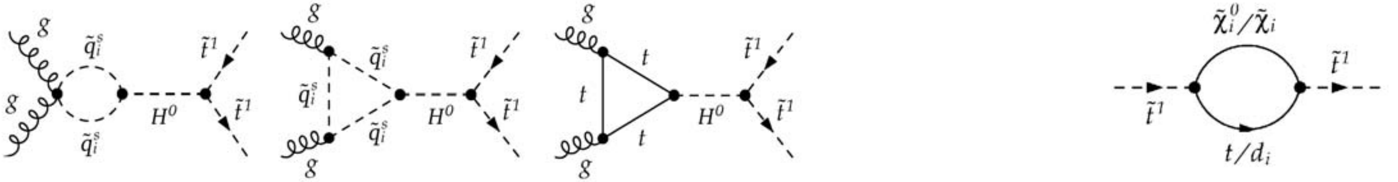
– variation of M_{Q3} in range 200–1000 GeV

– impact on the SUSY-EW corrections to the total cross section: few %





– resonance effects coming from heavy Higgs H^0 and light neutralinos:



Conclusions & Outlook

Top-squark pair production

- 1-loop picture completed
- NLO EW contributions are negligible for total cross sections
- but sizeable for distributions at high p_T and high $\sqrt{\hat{s}}$

Next steps

- combine EW and QCD
- include into standard MC generators