Hadronic Production of Colored SUSY Particles with Electroweak NLO Contributions

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Outline

1. **Introduction**
   production of colored SUSY particles
2. **Production of Squarks and Gluinos**
   classification of processes
   QCD and EW contributions
3. **EW NLO Corrections**
   handling singularities
4. **Numerical Results**
   for $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{q}$ production at the LHC
5. **Summary**

Motivation

- Supersymmetry is a **possible and very attractive extension** of the Standard Model

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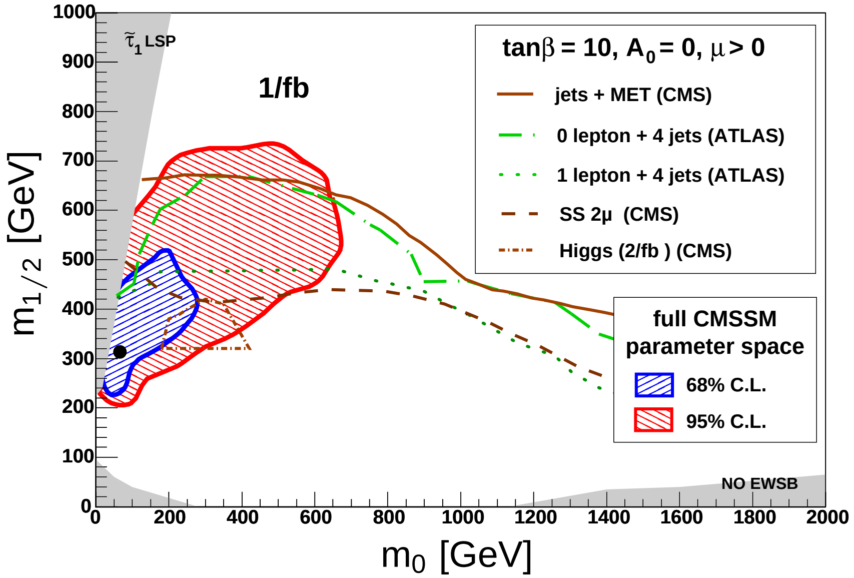
- Supersymmetry is a possible and very attractive extension of the Standard Model . . .
- SUSY has **predictive power** – good prospects for LHC!



[Buchmueller, Cavanaugh, De Roeck, Ellis, Flächer, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein '08]

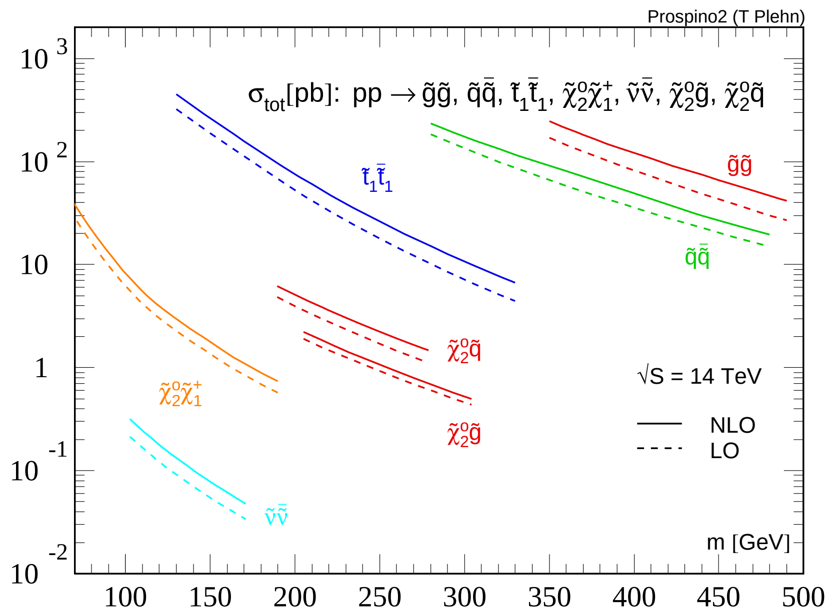
from combination of experimental, phenomenological, and cosmological information:

→ 95% C. L. area in the ($m_{1/2}$, m_0) plane of CMSSM lies largely within the region that **can be explored with 1fb^{-1} at 14 TeV**

Motivation II

Why studying production of colored SUSY particles at the LHC?

- pair production of gluinos and squarks proceeds via **strong interaction**
  $\longrightarrow$ **large cross sections**



- large top-Yukawa coupling: **top-squark $\tilde{t}_1$** candidate for **lightest squark**
  $\longrightarrow$ **high production rate**

- **cross section depend** essentially **on final state masses**
  $\longrightarrow$ bounds on cross section allow for lower mass bounds without specifying all other SUSY parameters

Top-Squarks (Stops)

- SUSY **partners of top-quarks**
- same quantum numbers as $t_{L/R}$, but are **scalar particles**
- not yet observed, heavy particles

- **large top-Yukawa coupling**

  $\longrightarrow$ **RGE's**: stops lighter than squarks of first generations

  $\longrightarrow$ **mixing**: gauge eigenstates $\tilde{t}_{L/R} \longrightarrow$ mass eigenstates $\tilde{t}_{1/2}$:

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$\longrightarrow$ **mixing**: gauge eigenstates $\tilde{t}_{L/R} \longrightarrow$ mass eigenstates $\tilde{t}_{1/2}$:

$$\mathcal{L}_{\tilde{t}\tilde{t}} = -(\tilde{t}_L^*, \tilde{t}_R^*) \begin{pmatrix} m_t^2 + A_{LL} & m_t B_{LR} \\ m_t B_{LR} & m_t^2 + C_{RR} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = -(\tilde{t}_1^*, \tilde{t}_2^*) \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix}$$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_t & \sin\theta_t \\ -\sin\theta_t & \cos\theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix},$$

$$\begin{aligned} A_{LL} &= \left(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right) m_Z^2 \cos 2\beta + m_{\tilde{Q}_3}^2 \\ B_{LR} &= A_t - \mu \cot\beta \\ C_{RR} &= \tfrac{2}{3}\sin^2\theta_W\, m_Z^2 \cos 2\beta + m_{\tilde{U}_3}^2 \end{aligned}$$

$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2}\left(A_{LL} + C_{RR} \mp \sqrt{(A_{LL} - C_{RR})^2 + 4 m_t^2 B_{LR}^2}\right)$$

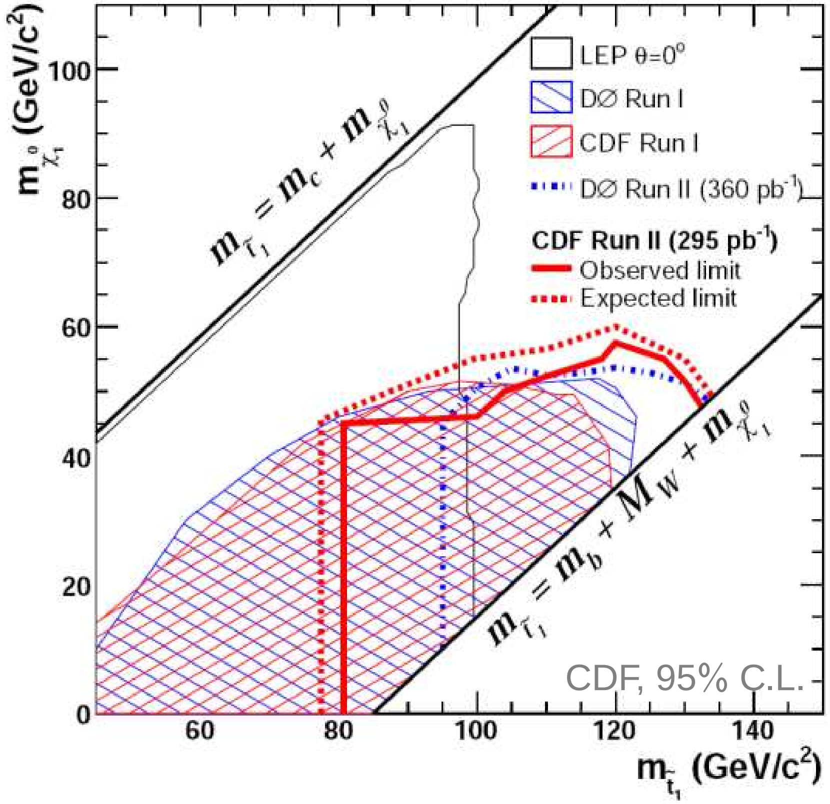
$\longrightarrow$ $\tilde{t}_1$ **lightest squark in many SUSY models!**

Experimental Searches – Stops

Experimental searches performed at

LEP [review e.g. Kraan hep-ex/0209026]
CDF Run I & II [hep-ex/9912018 & 0707.2567]
D0 Run I & II [hep-ex/0404028 & 0611003]

assumption: $BR(\tilde{t}_1 \to c\tilde{\chi}^0_1) = 100\%$



stop mass limits @ CDF Run II:

$m_{\tilde{t}_1} > 132$ GeV for $m(\tilde{\chi}^0_1) = 48$ GeV

QCD corrections included

- other discovery channels:
  reviews [Demina et al. hep-ph/9910275], [Abel et al. hep-ph/0003154]
- single stop production (R-parity violating SUSY) [Plehn '00]
  ep collisions: [H1: hep-ex/0405070, Zeus: hep-ex/0611018]

Experimental Searches – Squarks & Gluinos

Gluino & squark mass limits:

at CDF Run II [CDF note 9229 '08]

$m_{\tilde{q}\approx\tilde{g}} > 392$ GeV; $m_{\tilde{g}} > 280$ GeV

$A_0 = 0$ GeV, $\tan\beta = 5$, $\mu < 0$; L=2 fb^{-1}

at D0 Run II [0712.3805 hep-ex]

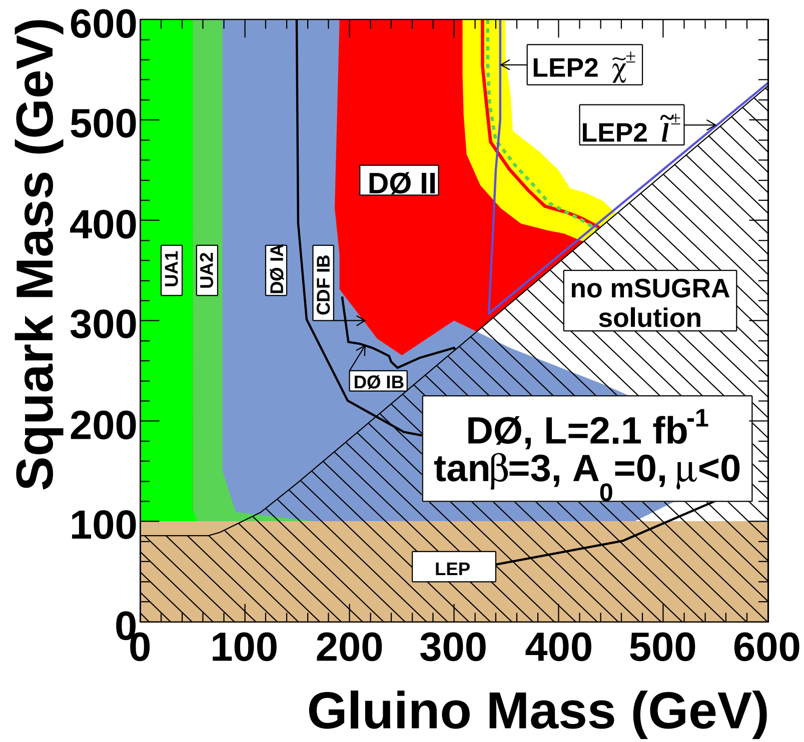
$m_{\tilde{q}\approx\tilde{g}} > 390$ GeV; $m_{\tilde{g}} > 308$ GeV

$A_0 = 0$ GeV, $\tan\beta = 3$, $\mu < 0$; L=2.1 fb^{-1}

at ALEPH & OPAL [0804.2477 hep-ph]

$m_{\tilde{g}} > 51$ GeV

model-independent; from thrust data



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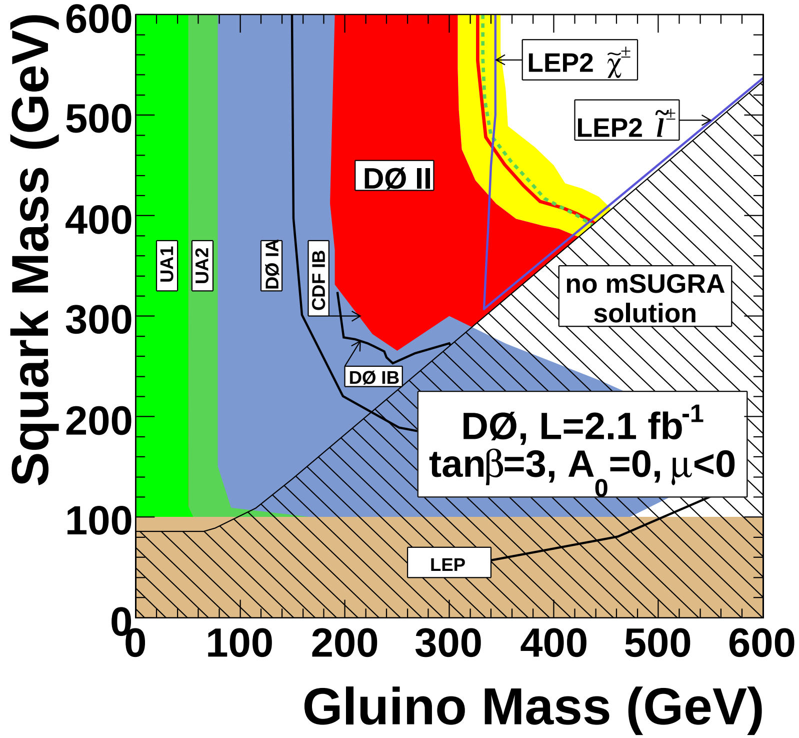


→ **until now: agreement** between data and SM expectations

→ comparison of exp. limits & theor. cross sections: restrictions on SUSY parameter space

Cross Sections at Hadron Colliders

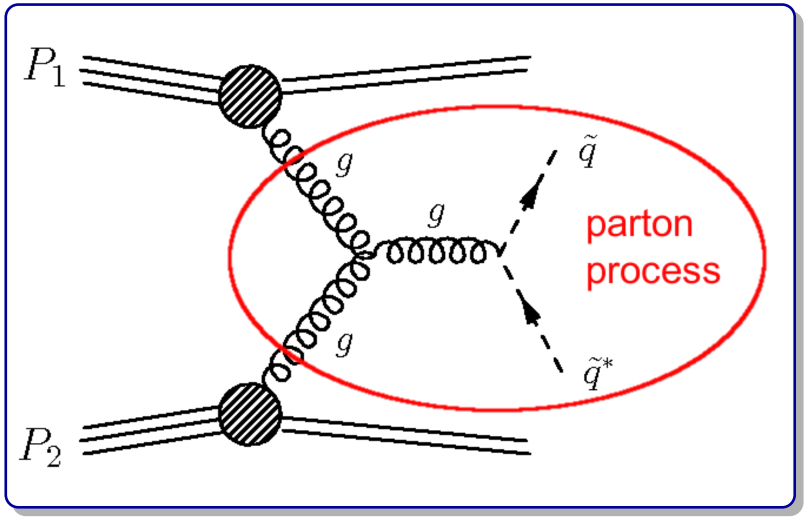
Distinguish **hadron level** and **parton level** :

$$\sigma_{P_1 P_2 \to \tilde{q}\tilde{q}^*}(P_1, P_2) = \sum_{i,j=g,q,\bar{q}} \int dx_1\, dx_2\; f_i(x_1)\, f_j(x_2)\; \hat{\sigma}_{ij \to \tilde{q}\tilde{q}^*}(p_1, p_2)$$

$$p_{1,2} = x_{1,2}\, P_{1,2}$$

$f_{g,q,\bar{q}}(x)$: **parton density function** (PDF)

$\longrightarrow$ probability to find a gluon g or (anti-)quark q with momentum fraction x (process independent)



Factorization

$$f_i(x) \;\longrightarrow\; f_i(x, \mu_F)$$

μ_F: factorization scale

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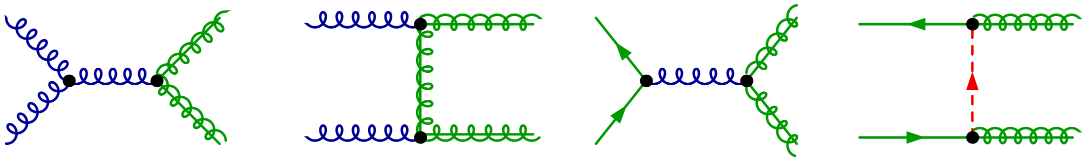
Overview: Squark & Gluino Production at LO

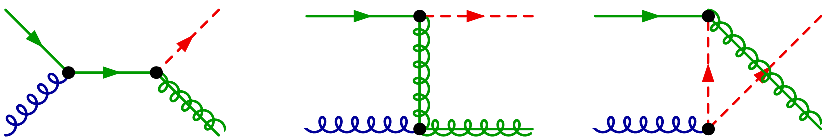
Squark and gluino production at LO is well known since many years

[Kane & Leveille ’82, Harrison & Llewellyn Smith ’83, Reya & Roy ’85, Dawson, Eichten, Quigg ’85, Baer & Tata ’85]

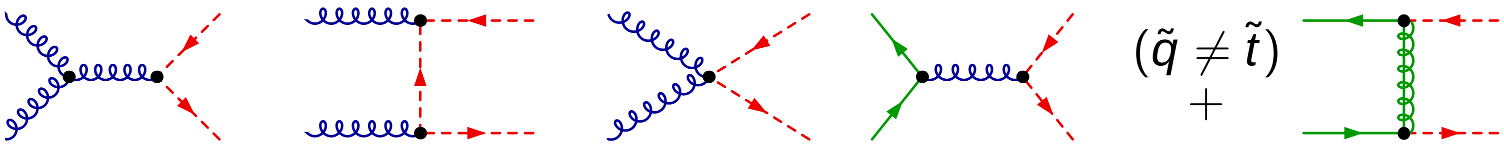
- $\mathcal{O}(\alpha_s^2)$: – $\tilde{g}\tilde{g}$ production



– $\tilde{g}\tilde{q}$ production



– $\tilde{q}\tilde{q}^*$, $\tilde{b}_i\tilde{b}_i^*$, $\tilde{t}_i\tilde{t}_i^*$ production



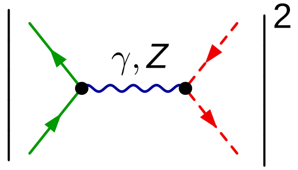
- stops & sbottoms: L–R mixing cannot be neglected; exp. distinguishable
- top-squark pair production is diagonal at LO

Tree-level Electroweak Contributions

$\tilde{t}\tilde{t}^*$ and $\tilde{q}\tilde{q}^*$ production is also possible by tree-level EW contributions!

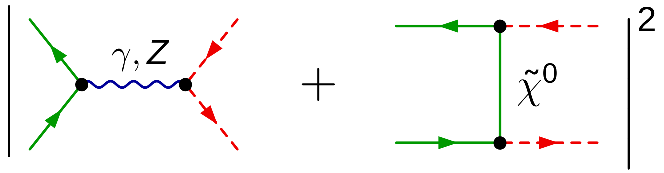
- $\mathcal{O}(\alpha^2)$: EW tree-level contributions to $\tilde{t}\tilde{t}^*$ production

[Bozzi, Fuks, Herrmann, Klasen '07]

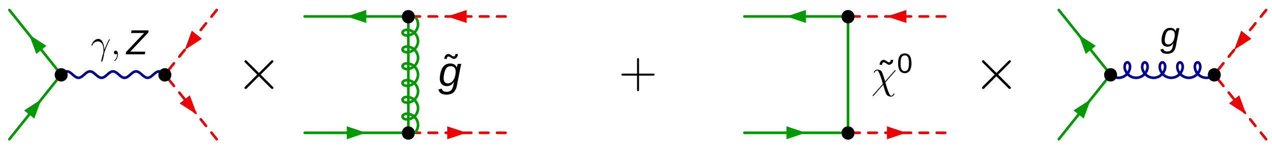


- $\mathcal{O}(\alpha^2 + \alpha_s\alpha)$: EW tree-level contributions to $\tilde{q}\tilde{q}^*$ production

[Bornhauser, Drees, Dreiner, Kim '07]



+ EW-QCD tree level interferences



Tree-level Electroweak Contributions II

New production channel for $\tilde{g}\tilde{q}$, $\tilde{t}\tilde{t}^*$, and $\tilde{q}\tilde{q}^*$ production:

- $\mathcal{O}(\alpha_s\alpha)$: photon induced processes

[Hollik, Kollar, MT '07], [Hollik, Mirabella '08]
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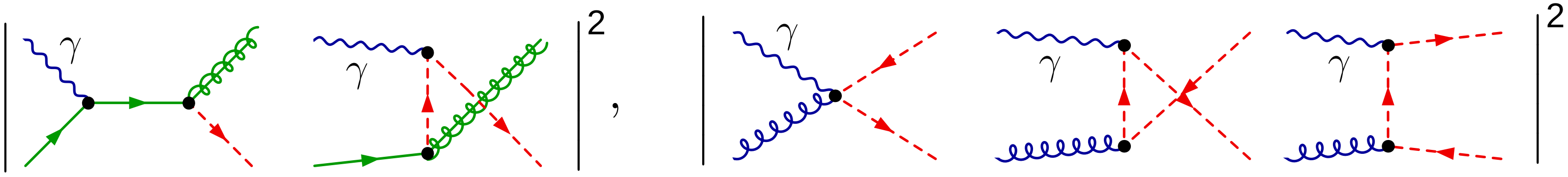
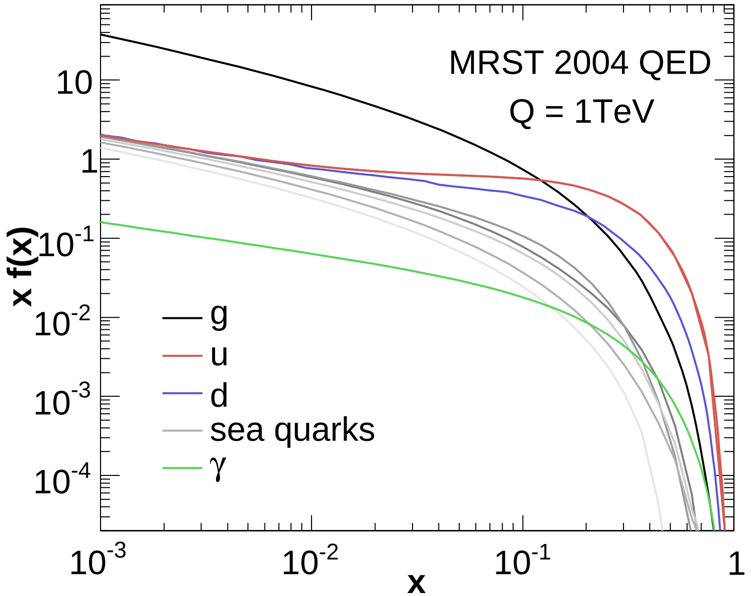


- not present at LO at the hadronic level

- **MRST 2004 QED**: inclusion of **NLO QED effects** in the evolution of PDFs
  - $\longrightarrow$ non-zero photon distribution
  - $\longrightarrow$ non-zero hadronic contributions

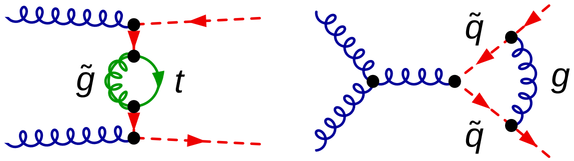


Higher Order Corrections – Squark Production

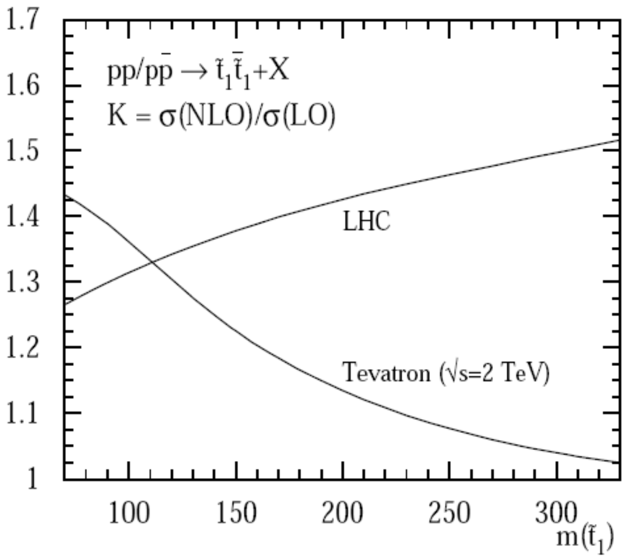
Important **higher order effects** due to **QCD corrections**:

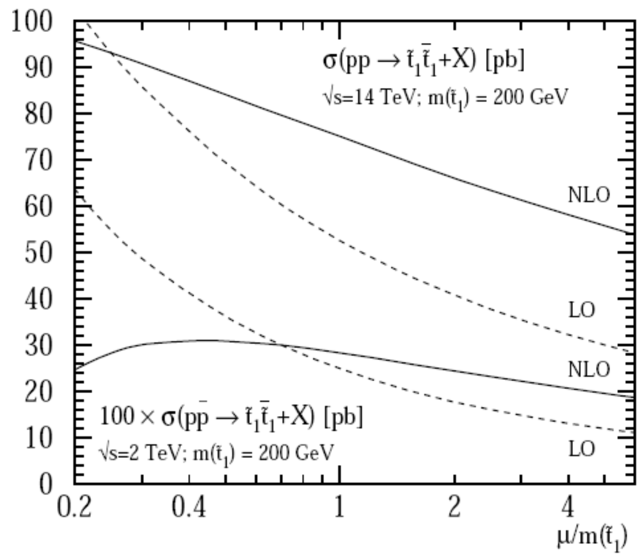
- $\mathcal{O}(\alpha_s^3)$: QCD NLO corrections

[Beenakker, Höpker, Spira, Zerwas '95 & '97] &
[Beenakker, Krämer, Plehn, Spira, Zerwas '98]
$\longrightarrow$ PROSPINO, also for $\tilde{g}\tilde{q}$, $\tilde{g}\tilde{g}$

QCD Born $\times$  + ...

$\tilde{t}_1\tilde{t}_1^*$ production:





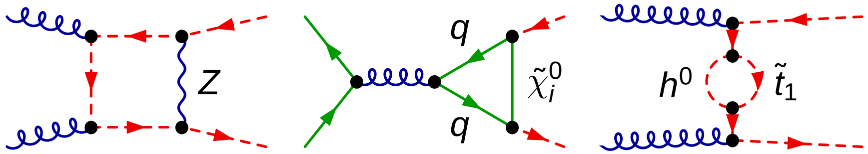
- large positive corrections
- reduced scale dependence

Higher Order Corrections – Squark Production II

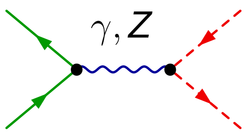
Known from SM processes: also **EW corrections** can be important!

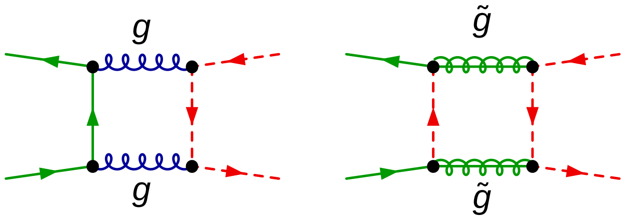
- $\mathcal{O}(\alpha_s^2\alpha)$: EW NLO corrections

[Hollik, Kollar, MT '07], [Beccaria et. al. '08]
[Hollik, Mirabella '08]

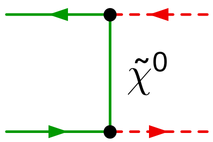
QCD Born $\times$  + . . .

+ EW-QCD one-loop interferences



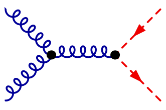
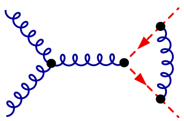
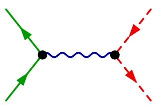
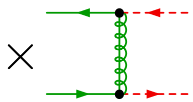
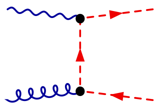
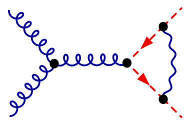
$\times$ 

$(\tilde{q} \neq \tilde{t})$
$+$



$\times$ full QCD 1-loop amplitude

Overview: Squark and Gluino Production @ LHC

	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s^2\alpha)$
$\tilde{g}\tilde{g}$	+	+	−	−	−	+
$\tilde{g}\tilde{q}$	+	+	−	−	+	+
$\tilde{t}\tilde{t}^*$	+	+	+	−	+	+
$\tilde{q}\tilde{q}^*$	+	+	+	+	+	+
						

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UV Singularities . . .

. . . arise in self energies and vertices from loop integrals

- UV finite result: **renormalization** required!

  $\longrightarrow$ **on-shell** renorm. of involved quarks and squarks

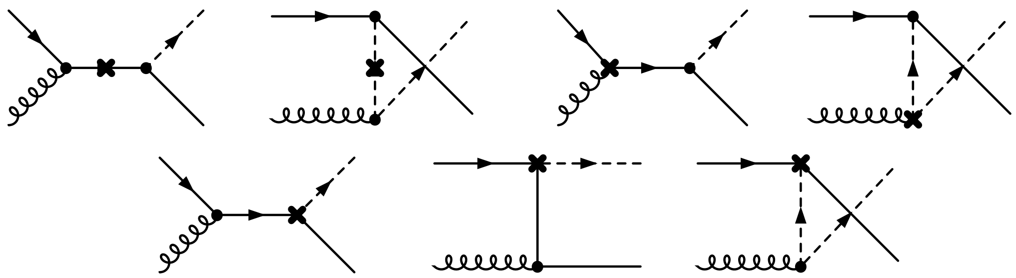
  $\longrightarrow$ $\tilde{t}\tilde{t}^*$, $\tilde{g}\tilde{q}$, $\tilde{g}\tilde{g}$: no renorm. of gluon, gluino, and α_s

  [different to $\tilde{q}\tilde{q}^*$ production,
  where the full one-loop QCD amplitude enters]

  $\longrightarrow$ $\tilde{t}_1\tilde{t}_1^*$ is diag.: no renorm. of mixing angle required

- add **counter term diagrams** at $\mathcal{O}(\alpha_s\alpha)$

for $\tilde{g}\tilde{q}$:

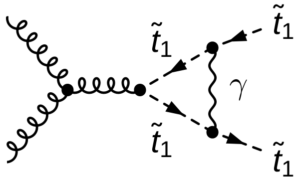


$\longrightarrow$ result is **UV finite**

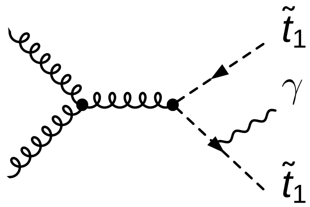
Soft Singularities . . .

$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{t}\tilde{t}^*$

. . . arise where external particles exchange a photon ($m_\gamma = 0$)



divergent
for $E_\gamma \to 0$

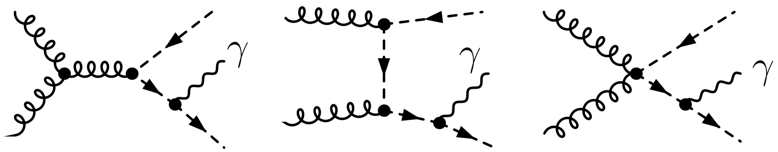


($E_\gamma \leq \Delta E$)

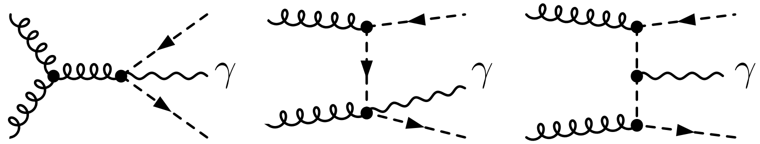
$\longrightarrow$ introduce photon mass $\lambda \neq 0$ as regulator, add real **soft photon contributions** that lead to the **same observable final state**

$\longrightarrow$ **Bloch-Nordsieck:** **sum** of virtual and real corrections is **IR finite** (and independent of λ & ΔE)

$\longrightarrow$ **phase space slicing**: dependency on cut-off parameter ΔE cancels when hard photon bremsstrahlung is added



IR singular

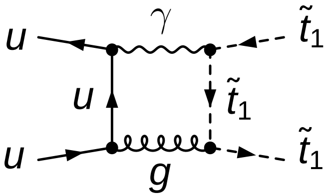


+ IR finite part

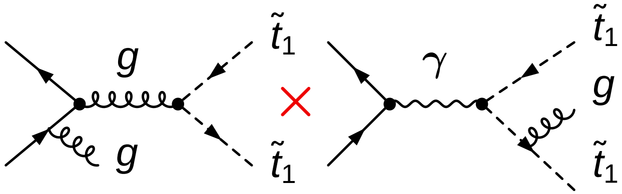
More Soft Singularities . . .

$\tilde{q}\tilde{q}^*, \tilde{t}\tilde{t}^*$

. . . arise where external particles exchange a gluon ($m_g = 0$)!



divergent
for $E_g \to 0$



$(E_g \le \Delta E)$

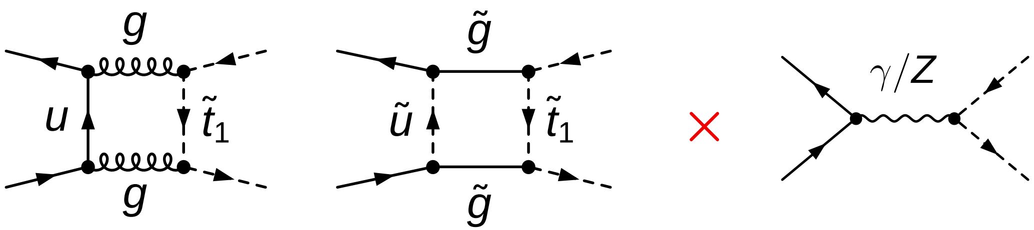
$\longrightarrow$ keep gluon mass $m_g \neq 0$, add **soft gluon bremsstrahlung** at $\mathcal{O}(\alpha_s^2\alpha)$

$\longrightarrow$ **mixing of QCD and EW interactions** ($\tilde{t}\tilde{t}^*$: vanishing at born level!)

$\longrightarrow$ color flux: $\tilde{t}\tilde{t}^*$: only **interference** of ISR and FSR contributes
$\tilde{q}\tilde{q}^*$: more fun due to t-channel diagrams

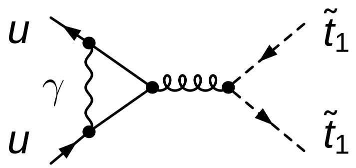
- also at $\mathcal{O}(\alpha_s^2\alpha)$:

QCD boxes × **EW born**

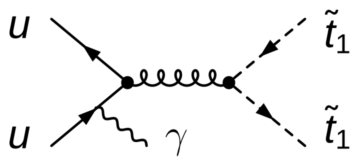


Collinear Singularities . . .

. . . arise where light initial state quark splits into quark and photon ($m_q = 0$)

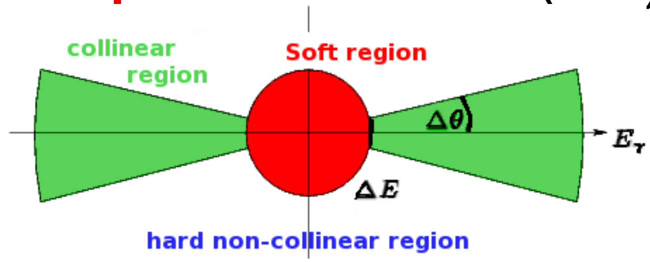


divergent
for $\theta_{u\gamma} \to 0$



$\theta_{u\gamma} \leq \Delta\theta$
$E_\gamma > \Delta E$

$\longrightarrow$ keep small quark mass $m_q \neq 0$, add **collinear photon radiation** (ISR), introduce **second cut-off parameter** $\Delta\theta$



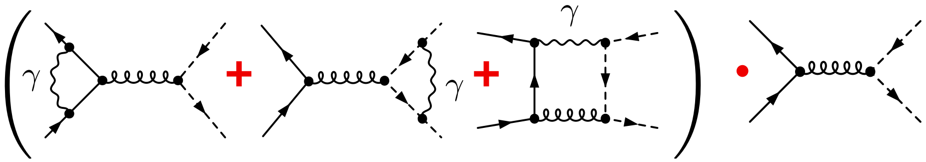
$\longrightarrow$ Sudakov **double log's** cancel in the sum of virtual + real corrections

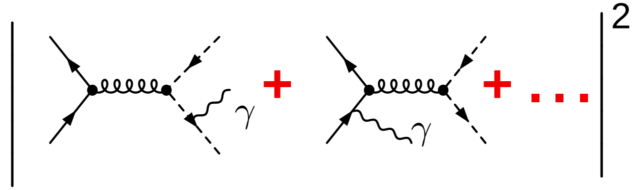
$\longrightarrow$ remaining **single log's** have to be absorbed into PDFs (**factorization**), **result is independent of m_q**, but depends on factorization scale

$\longrightarrow$ need PDFs that include NLO QED effects (**MRST 2004 QED**)

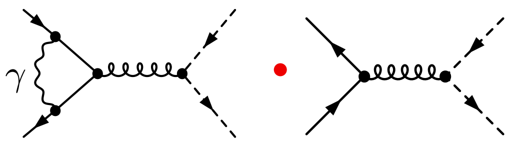
How to obtain a IR-finite cross section for $q\bar{q} \to \tilde{t}\tilde{t}^*$

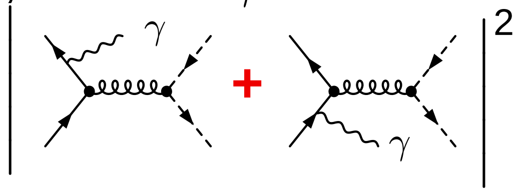
- soft divergent diagrams and soft photon bremsstrahlung





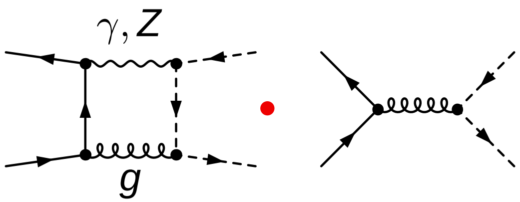
- collinear divergent diagram and hard, collinear γ bremsstrahlung

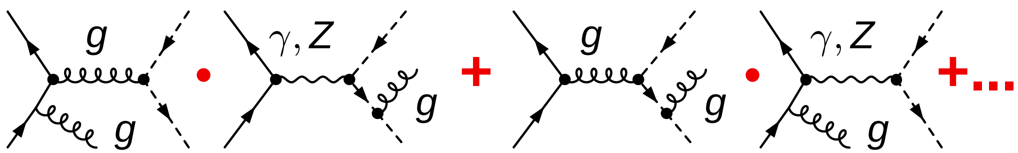




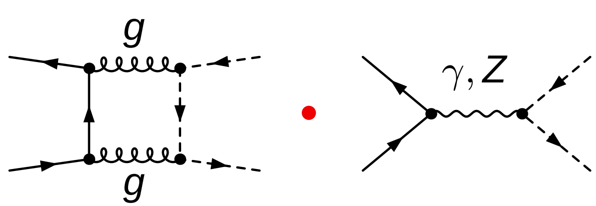
+ redefinition of PDFs: subtract $\ln(m_q^2)$-terms from $\sigma_{q\bar{q}}$

- soft gluon divergent diagrams and soft gluon bremsstrahlung





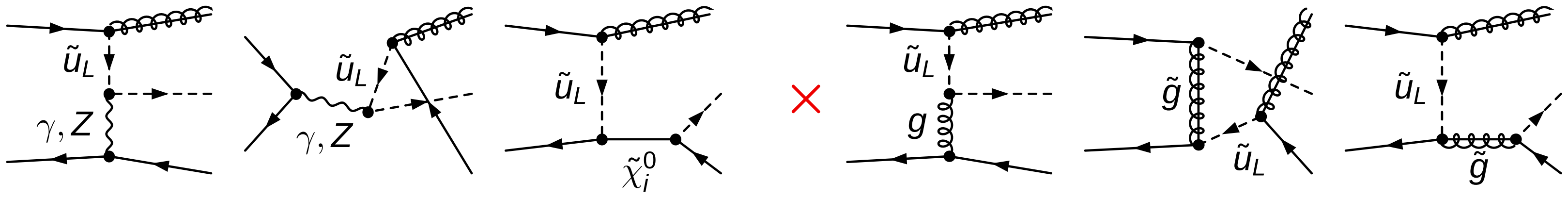
- interference of QCD boxes and EW born



Real (Anti-)Quark Radiation at $\mathcal{O}(\alpha_s^2\alpha)$

- **non-zero interference** of **EW** and **QCD** diagrams!

  $\longrightarrow$ many channels & diagrams (but small contributions)
  some examples for $u\bar{u} \to \tilde{g}\tilde{u}_L\bar{u}$:



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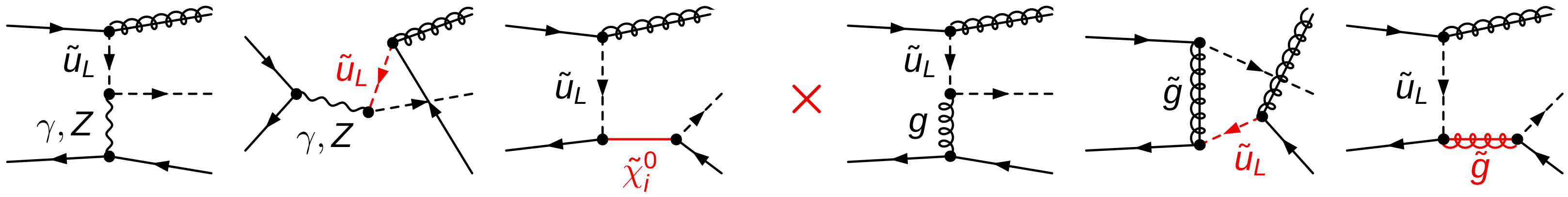
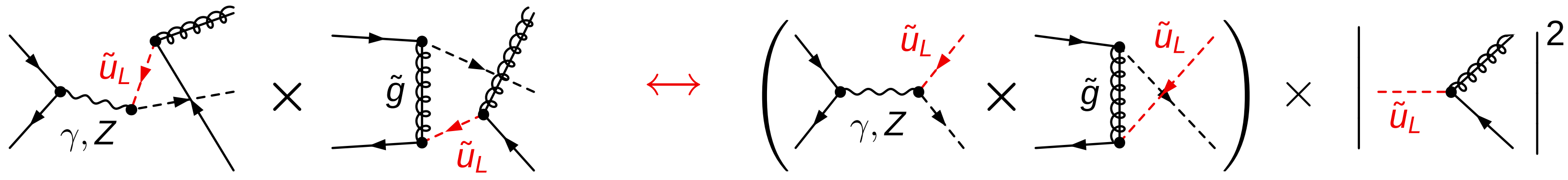


$\longrightarrow$ **on-shell internal particles**: insert widths to regularize propagators

$\longrightarrow$ in order to **avoid double counting**: subtract possible **resonances**



$\sigma(u\bar{u} \to \tilde{u}_L\,\tilde{g}\bar{u})$ $\qquad\qquad$ $\sigma(u\bar{u} \to \tilde{u}_L\tilde{u}_L^*)$ $\quad \times \quad BR(\tilde{u}_L^* \to \tilde{g}\bar{u})$

Outline

1. Introduction
2. Production of Squarks and Gluinos
3. EW NLO Corrections
4. **Numerical Results**
   for $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{q}\tilde{g}$ production at the LHC
5. Summary

Total Cross Sections for SPS1a'

final state	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\delta = \frac{\sigma^{NLO}-\sigma^{LO}}{\sigma^{LO}}$
$\tilde{t}_1\tilde{t}_1^*$	**1830 fb**	**$-$15.0 fb**	**34.1 fb**	**1.0 %**
$\tilde{u}_R\,\tilde{g} + \tilde{d}_R\,\tilde{g}$	8900 fb	14.6 fb	5.05 fb	0.2%
$\tilde{u}_L\,\tilde{g} + \tilde{d}_L\,\tilde{g}$	8220 fb	$-$197 fb	4.62 fb	$-$2.3%
$\tilde{g}\tilde{q}$	**17120 fb**	**$-$183 fb**	**9.67 fb**	**$-$1.0%**

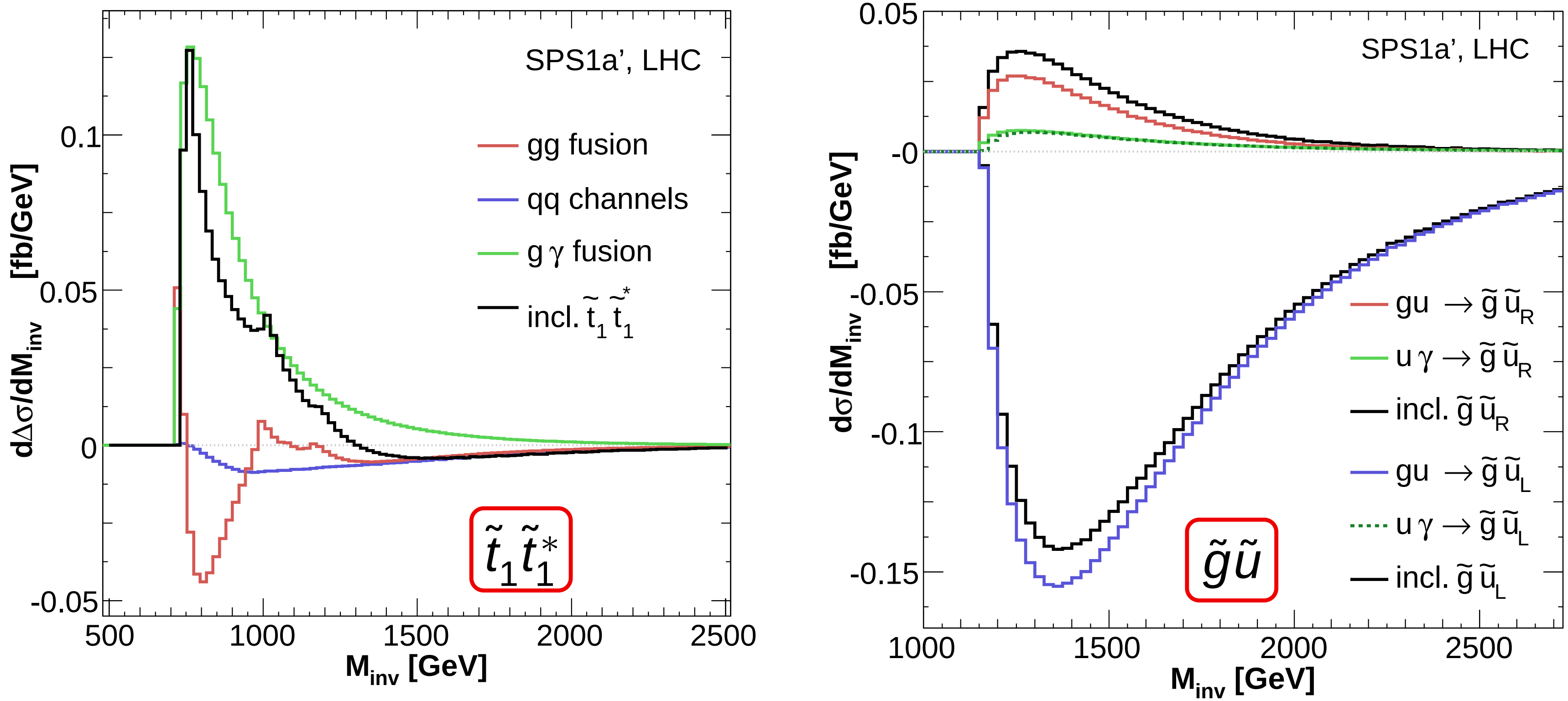
[$\mu_F = \mu_R =$ 1 TeV, MRST 2004 QED, $m_t = 170.9$ GeV;
$m(\tilde{t}_1) = 360$ GeV, $m(\tilde{u}_R) = 543$ GeV, $m(\tilde{d}_R) = 539$ GeV,
$m(\tilde{u}_L) = 561$ GeV, $m(\tilde{d}_L) = 566$ GeV, $m(\tilde{g}) = 609$ GeV]

- $\tilde{t}_1\tilde{t}_1^*$ production at $\mathcal{O}(\alpha^2)$: $\sigma^{EW,LO} = 1.11$ fb
- $\tilde{g}\tilde{q}$ processes: production of anti-squarks and of squarks of 2nd generation included (differing only in required PDF)

Absolute EW Contributions

- Interplay of the production channels? Invariant mass distribtuions:

(real quark radiation not shown expl.)



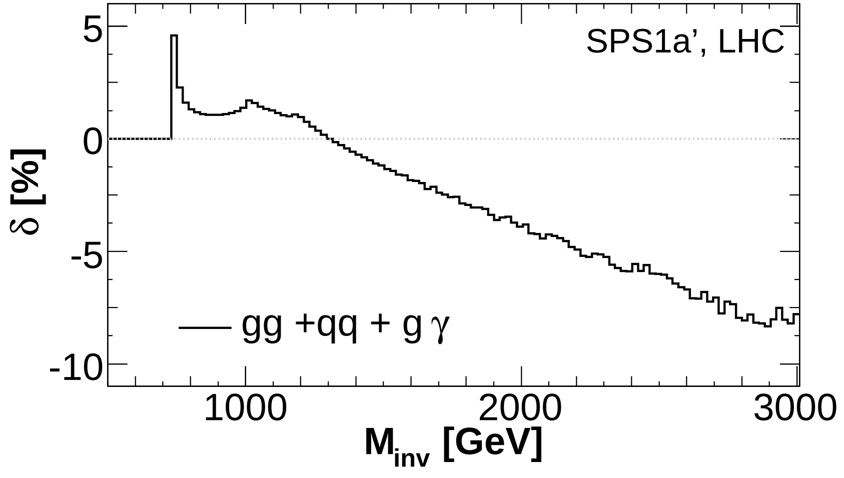
→ $\tilde{t}_1\tilde{t}_1^*$: **γg corrections** are **of the same size** and change the total EW corrections substantially!

→ $\tilde{g}\tilde{q}$: **γq corrections** do not depend on helicity state; contribute only moderate.

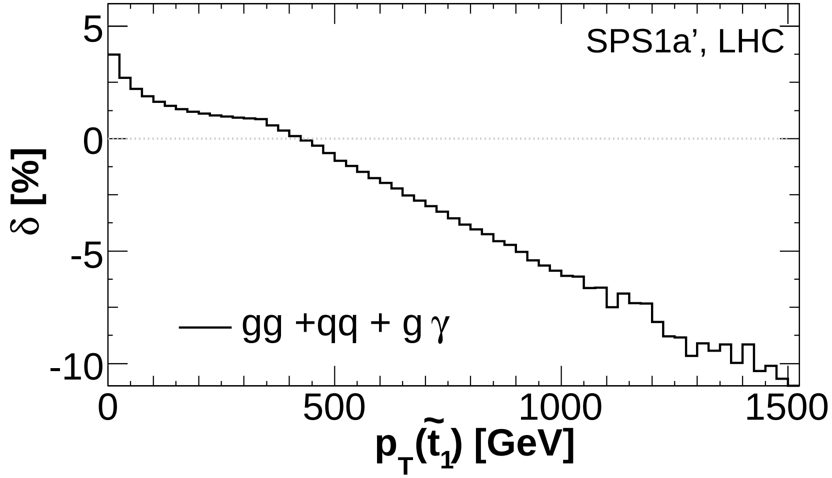
Relative Corrections $\delta = \Delta\sigma^{NLO}/\sigma^{LO}$

$\tilde{t}_1\tilde{t}_1^*$ prod.:

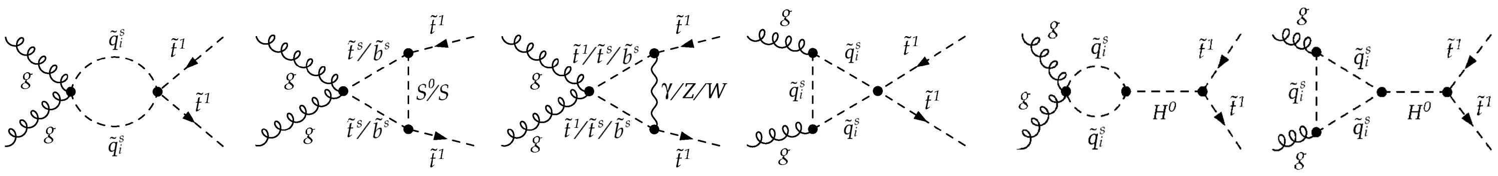
$M_{inv}(\tilde{t}_1\tilde{t}_1^*)$



$p_T(\tilde{t}_1)$



$\longrightarrow$ threshold effects from stop & sbottom pairs in loops



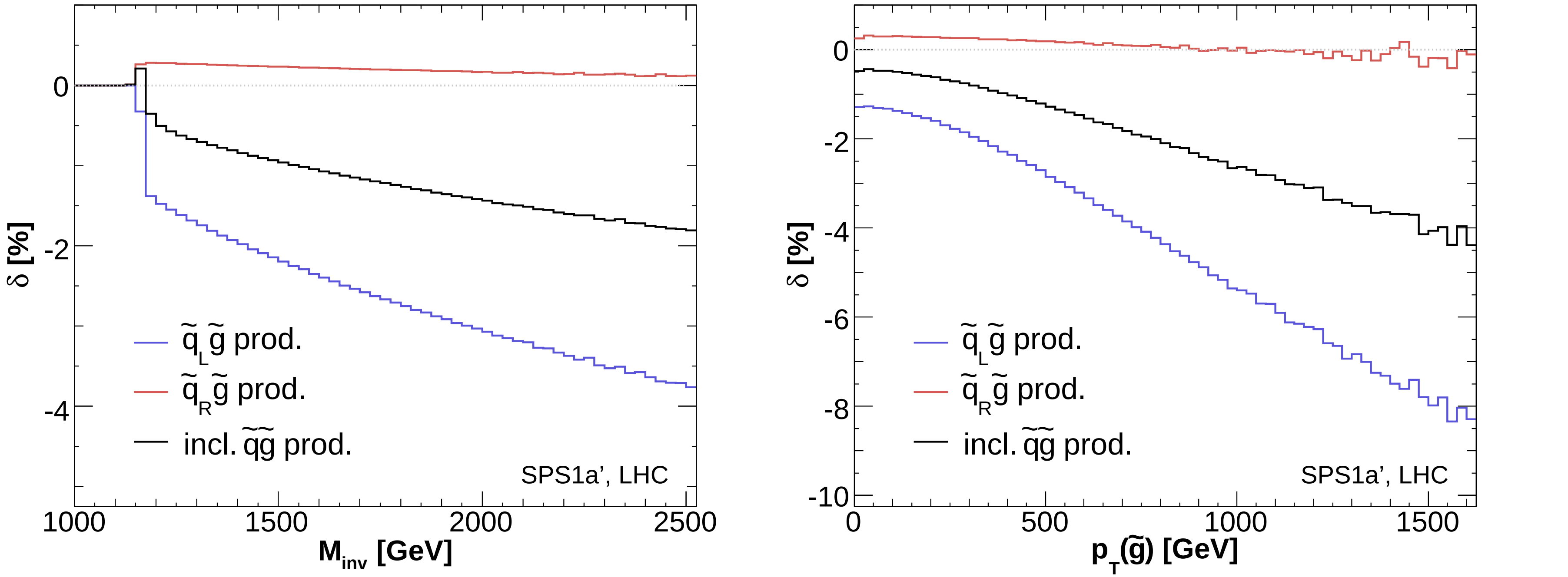
$\longrightarrow$ **EW corrections** grow **up to $\sim$ 10%** for large values of p_T & $M_{\tilde{t}_1\tilde{t}_1^*}$

Relative Corrections $\delta = \Delta\sigma^{NLO}/\sigma^{LO}$

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

$\tilde{g}\tilde{q}$ prod.:

$M_{inv}(\tilde{g}\tilde{q})$ $p_T(\tilde{g})$



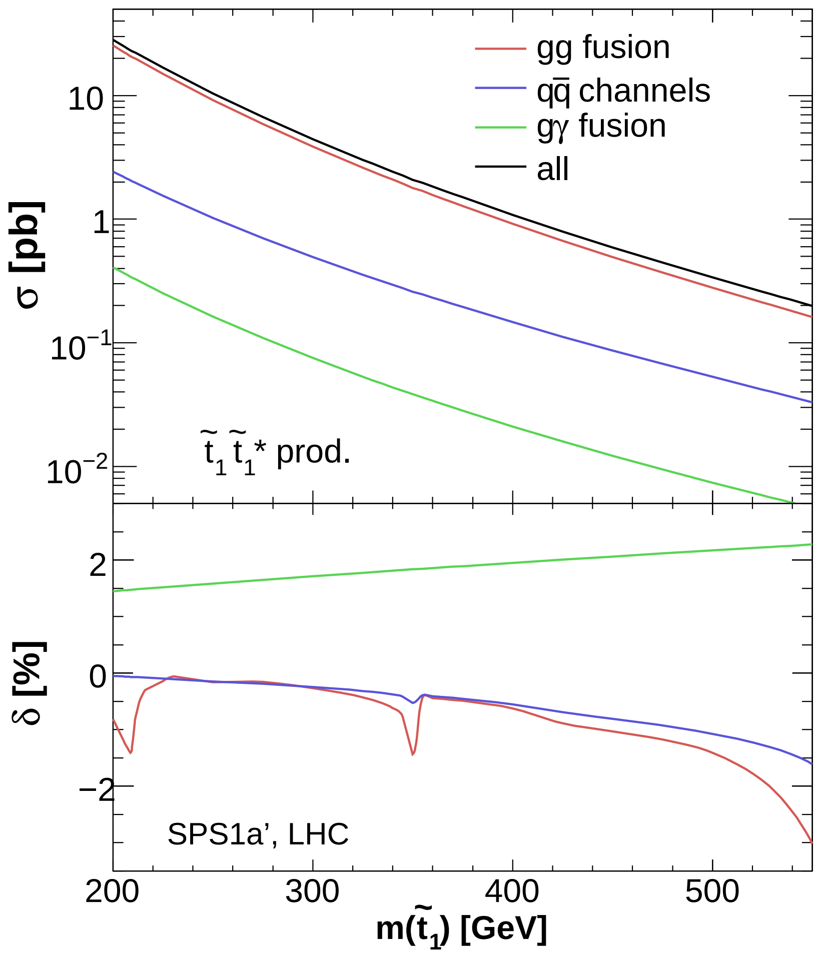
→ for $\tilde{g}\tilde{d}_L$ + $\tilde{g}\tilde{u}_L$ production EW NLO corrections grow **up to 10%**

→ corrections negligible for right-handed squarks

SUSY Parameter Dependence

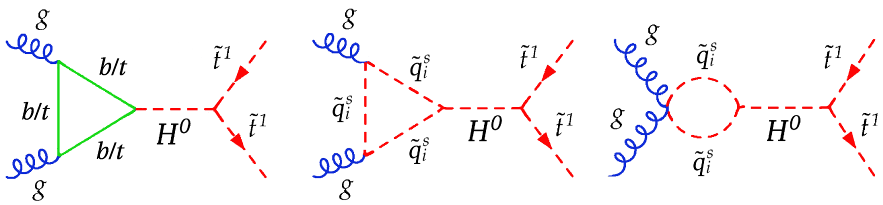
$\tilde{t}_1\tilde{t}_1^*$ prod.:

- Relative corrections δ with respect to total born cross section ($gg + q\bar{q}$),

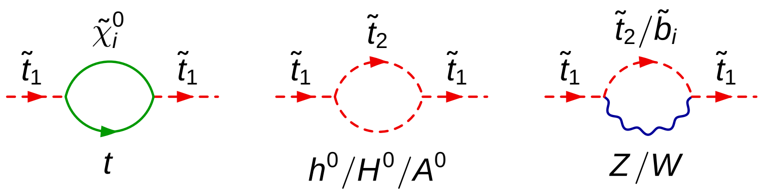


stop mass $m(\tilde{t}_1)$ **varied** around SPS 1a' value, all other parameters fixed

- moderate contributions, at percent level
- thresholds in H^0 diagrams

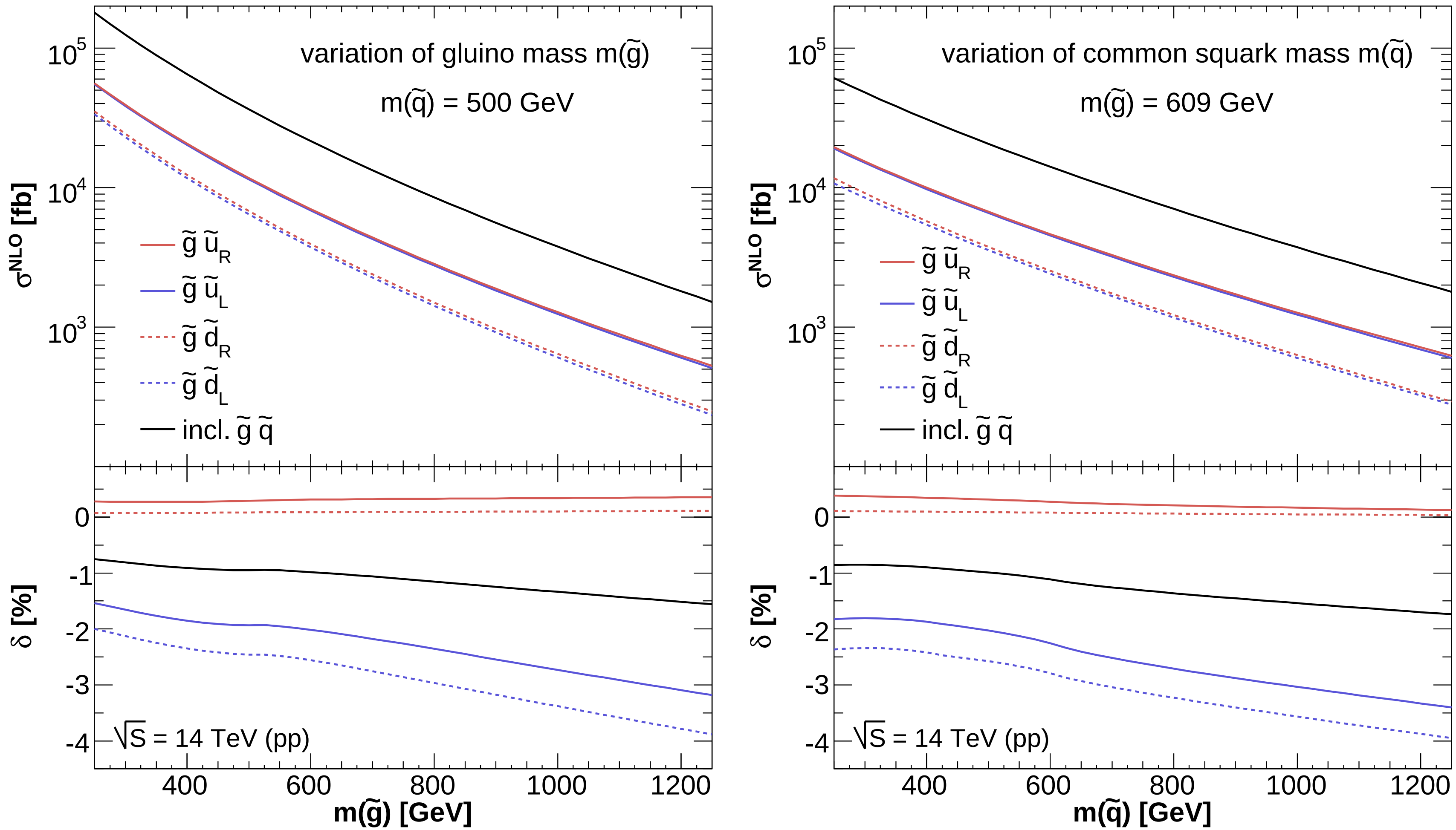


- thresholds in top-squark wave function renormalization



SUSY Parameter Dependence

$\tilde{g}\tilde{q}$ prod.:



Summary

- Exciting times ahead: SUSY will be probed at the LHC
  Squarks and gluinos will be produced at a **very high rate**

- QCD corrections already well known,
  missing **EW NLO corrections:** for $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, and $\tilde{g}\tilde{q}$ **completed**,
  for $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ in preparation

- **EW corrections** to the total cross section are small,
  but **important in the high-p_T** & high-M_{inv} range

- **PDF's include QED and QCD** contributions at NLO
  $\longrightarrow$ non-zero photon PDF opens **new production channel**
  $\longrightarrow$ need to include **QCD corrections for consistent picture** and for reduced scale dependence

Backup

Numerical Results: Input Parameters

- **SPA convention**: SUSY parameters defined in $\overline{DR}$ scheme
  here: (s)particles renormalized on-shell
  $\longrightarrow$ need consistent set of on-shell input parameters
  $\longrightarrow$ **translation $\overline{DR} \longrightarrow$ OS** required:

$$m^2_{\overline{\mathrm{DR}}} + \delta m^2_{\overline{\mathrm{DR}}} = m^2_{\mathrm{OS}} + \delta m^2_{\mathrm{OS}}$$

- **SU(2) invariance**: soft-breaking parameter $m_{\tilde{Q}}$ **identical** for up- and down-type squarks
  $\longrightarrow$ fourth squark is dependent, receives mass corrections

$$\left(m^2_{\tilde{d}_L}\right)^{\mathrm{1loop}} = \left(m^2_{\tilde{d}_L}\right)^{\mathrm{dep.}} + \delta m^2_{\tilde{d}_L} - \Re\Sigma_{\tilde{d}_{LL}}(m^2_{\tilde{d}_L})$$

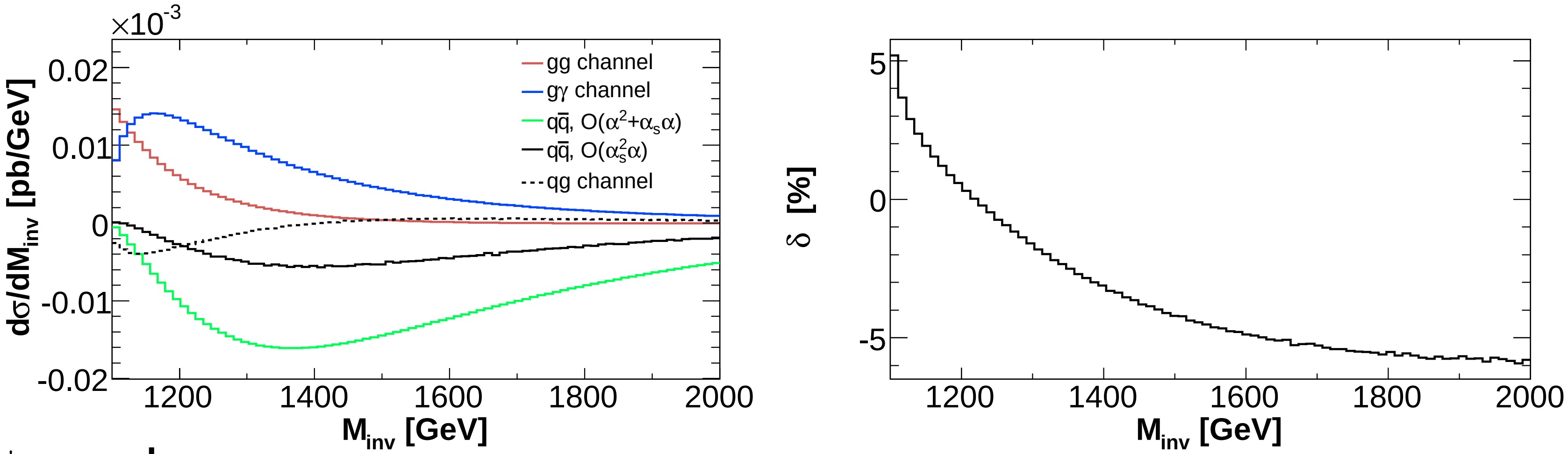
- Within the **SPS1a′ scenario**, the physical masses are

$$\begin{aligned} m_{\tilde{u}_R} &= 543\text{ GeV}, & m_{\tilde{u}_L} &= 561\text{ GeV}, & m_{\tilde{d}_R} &= 539\text{ GeV}, \\ m_{\tilde{d}_L} &= 566\text{ GeV}, & m_{\tilde{g}} &= 609\text{ GeV}, & m_{\tilde{t}_1} &= 360\text{ GeV}. \end{aligned}$$

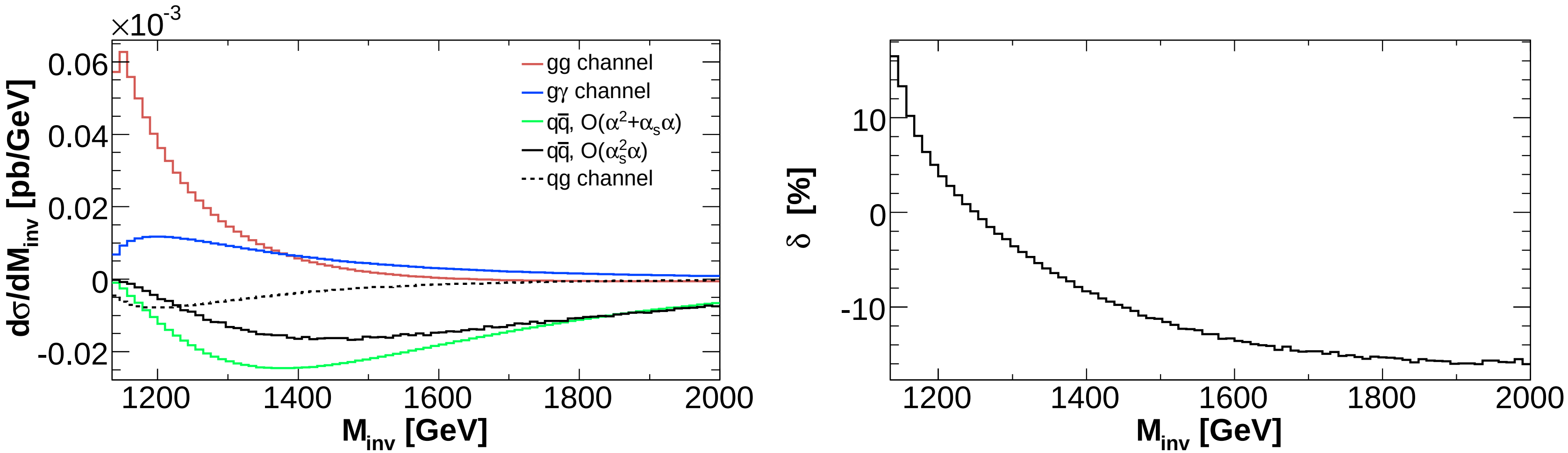
Abs. + Relative EW Corrections

[Hollik, Mirabella ’08]

$\tilde{u}_R \tilde{u}_R^*$ prod.:



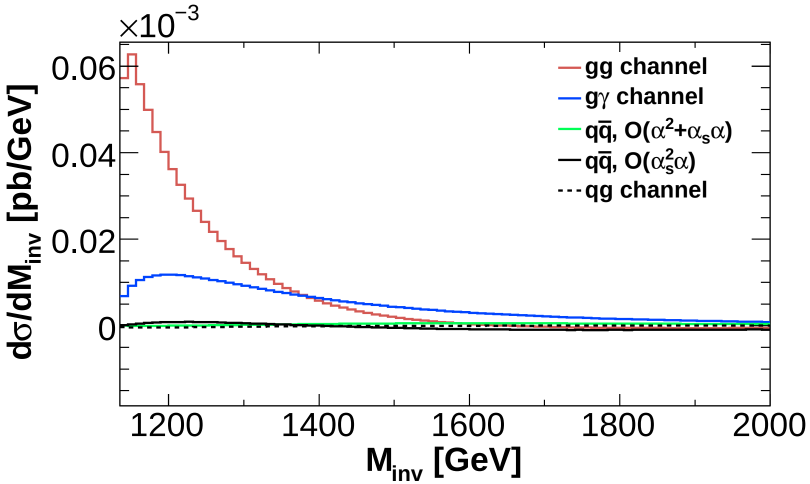
$\tilde{u}_L \tilde{u}_L^*$ prod.:

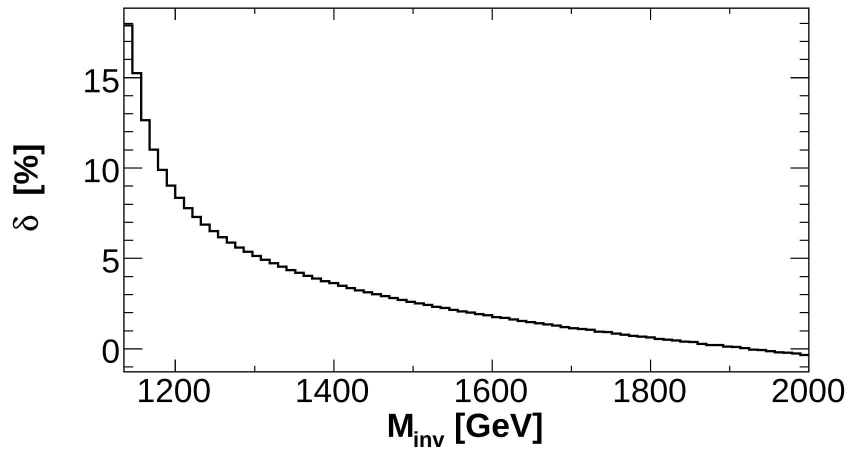


Abs. + Relative EW Corrections

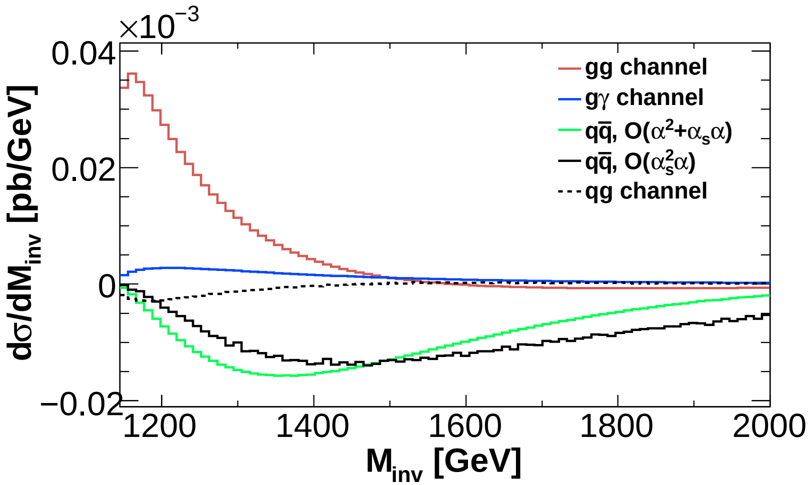
[Hollik, Mirabella '08]

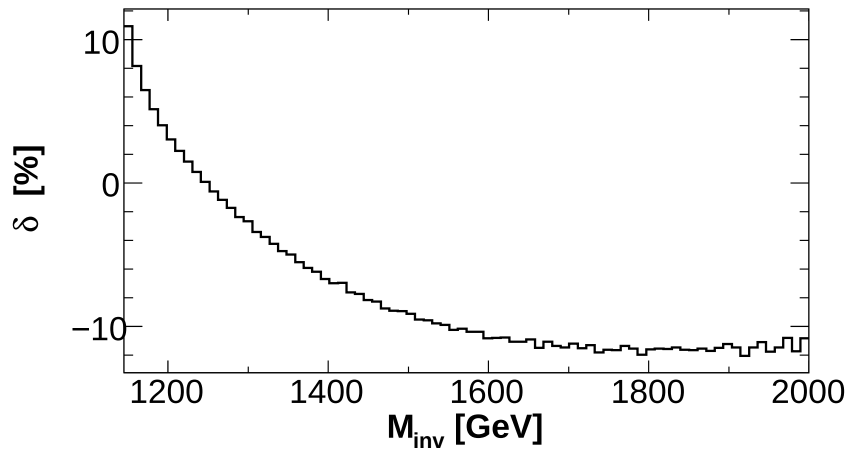
$\tilde{c}_L \tilde{c}_L^*$ prod.:





$\tilde{d}_L \tilde{d}_L^*$ prod.:





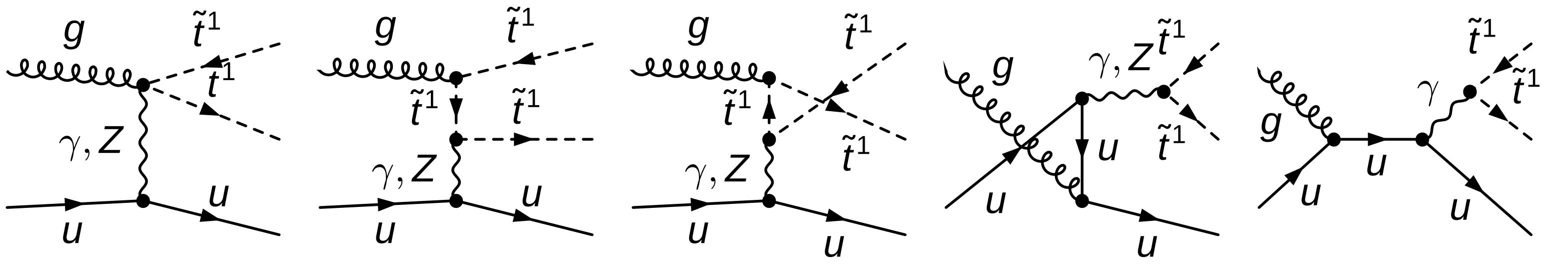
Results: More Total Cross Sections for SPS1a'

final state	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,LO}$ $\mathcal{O}(\alpha^2(+\alpha_s\alpha))$	$\delta = \frac{\sigma^{NLO}-\sigma^{LO}}{\sigma^{LO}}$
$\tilde{g}\,\tilde{u}_R$	5690 fb	12.6 fb	4.32 fb		0.3%
$\tilde{g}\,\tilde{d}_R$	3210 fb	1.97 fb	0.73 fb		0.1%
$\tilde{g}\,\tilde{u}_L$	5340 fb	−119 fb	3.98 fb		−2.2%
$\tilde{g}\,\tilde{d}_L$	2880 fb	−78.3 fb	0.64 fb		−2.7%
$\tilde{g}\tilde{q}$	**17120 fb**	**−183 fb**	**9.67 fb**		**−1.0%**
$\tilde{t}_1\tilde{t}_1^*$	**1830 fb**	**−15.0 fb**	**34.1 fb**	1.1 fb	**1.0%**
$\tilde{u}_R\,\tilde{u}_R^*$	370 fb	−3.1 fb	5.2 fb	−13.2 fb	2.6%
$\tilde{u}_L\,\tilde{u}_L^*$	310 fb	−11 fb	4.4 fb	−15.4 fb	−7.0%

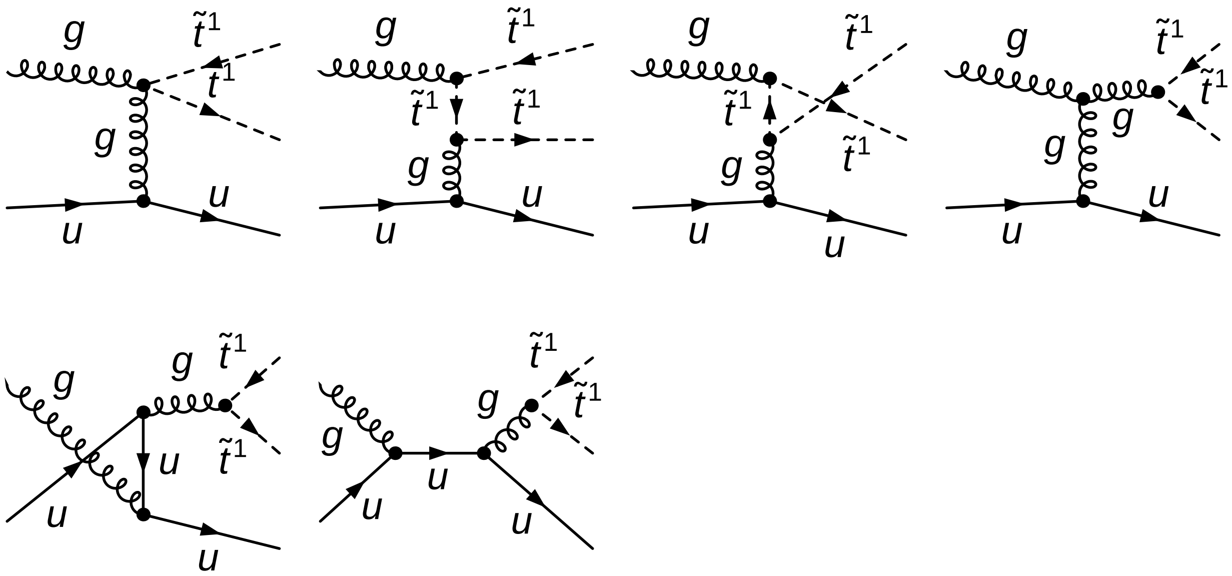
[$\mu_F = \mu_R = 1$ TeV, MRST 2004 QED, $m_t = 170.9$ GeV;
$m(\tilde{t}_1) = 360$ GeV, $m(\tilde{u}_R) = 543$ GeV, $m(\tilde{d}_R) = 539$ GeV,
$m(\tilde{u}_L) = 561$ GeV, $m(\tilde{d}_L) = 566$ GeV, $m(\tilde{g}) = 609$ GeV]

$\tilde{t}\tilde{t}^*$ prod.: Real Quark Radiation at $\mathcal{O}(\alpha_s^2\alpha)$

EW diagrams:



QCD diagrams:



Supersymmetry (SUSY)

SUSY relates fermions and bosons!

$Q|boson>=|fermion>$
$Q|fermion>=|boson>$

- **new partner particles** for all SM particles:
  same quantum numbers but **differ in spin by 1/2**
- SUSY as an exact symmetry predicts **m(SM)** $\stackrel{!}{=}$ **m(SUSY)**
  $\longrightarrow$ **SUSY** must be **broken** if realized
- **M**inimal **S**upersymmetric **S**tandard **M**odel (MSSM):

SM particle		**SUSY particle**	
quarks	q_L, q_R	squarks	$\tilde{q}_L, \tilde{q}_R$
leptons	ℓ_L, ℓ_R	sleptons	$\tilde{\ell}_L, \tilde{\ell}_R$
gluon	g	gluino	$\tilde{g}$
W/Z boson	W, Z	wino/zino	$\tilde{W}, \tilde{Z}$
photon	γ	photino	$\tilde{\gamma}$
Higgs	H_1, H_2	higgsino	$\tilde{H}_1, \tilde{H}_2$

(wino/zino, photino, higgsino:) neutralinos $\tilde{\chi}^0$, charginos $\tilde{\chi}^{\pm}$

SUSY Breaking

SUSY as exact symmetry predicts **m(SM)** $\stackrel{!}{=}$ **m(SUSY)**

but **no SUSY particle observed** so far
$\longrightarrow$ **SUSY** must be **broken** if realized in nature

- General **SUSY breaking mechanism** introduces a large amount of new, **free parameters** (**105**)
- Constrained SUSY models:

  assumption of **specific SUSY breaking** mechanisms and universal boundary conditions at the GUT scale

  $\longrightarrow$ e.g. **m**inimal**SU**per**GRA**vity models,
  only 5 **parameters** [m_0, $m_{1/2}$, A_0, $\tan\beta$, $sgn(\mu)$]

  $\longrightarrow$ low-energy spectrum from renormalization group equations

Motivation for Supersymmetry

Supersymmetry is a possible and very attractive extension of the Standard Model:

- **unique extension** of the Poincaré group
  gravitation can be **included** at the Planck scale
- SUSY particles alter the running of gauge couplings
  $\longrightarrow$ **unification of the coupling constants**
- **protective symmetry**: Higgs mass below 1 TeV is possible
  $\longrightarrow$ solution to the hierarchy problem
- provides **Dark Matter candidate**
  (if additionnal symmetry R-parity is assumed:
  stable massive, neutral, weakly interacting particle)