Production of Squarks and Gluinos at the LHC:
The Electroweak Contributions

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Outline

- **Introduction**
  - supersymmetry at colliders
- **Production of Squarks and Gluinos**
  - motivation
  - classification of processes
- **EW contributions to $\tilde{t}\tilde{t}^*$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$ production**
  - tree-level and one-loop EW contributions
  - numerical results
- **Summary**

Supersymmetry (SUSY)

SUSY relates fermions and bosons!

- **new partner particles** for all SM particles postulated,
  same quantum numbers but **differ in spin by 1/2**

- SUSY as an exact symmetry predicts **m(SM)** $\stackrel{!}{=}$ **m(SUSY)**
  ➡ if realized, **SUSY** must be **broken** at low energies
  SUSY masses around TeV scale are well motivated ➡ **prod. at LHC?**

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- **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	$\tilde{H}_1$, $\tilde{H}_2$

neutralinos $\tilde{\chi}^0$
charginos $\tilde{\chi}^\pm$

R-parity conservation: SUSY particles are produced **in pairs**

Motivation

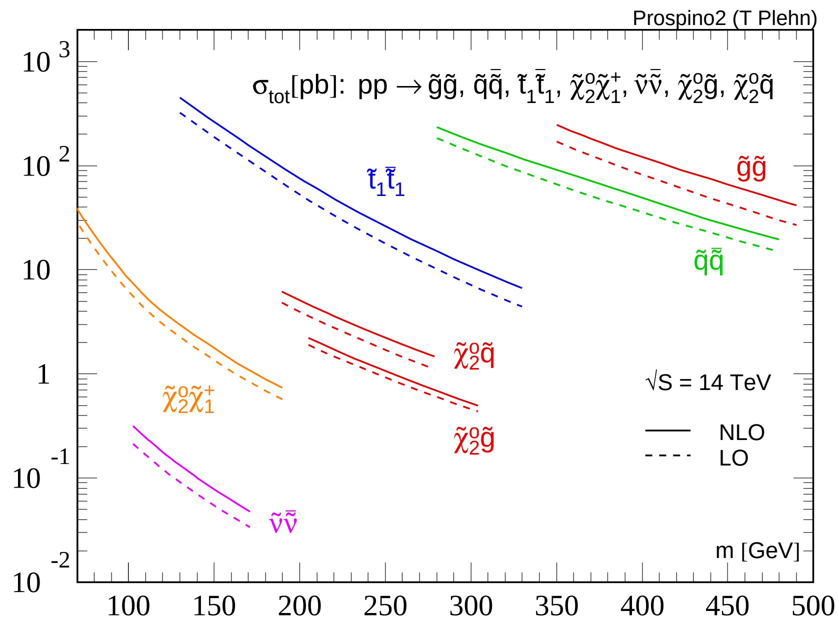
Why studying production of **squarks and gluinos** at the LHC?

- pair production of color-charged SUSY particles proceeds via **strong interaction**

  ➡ **large cross sections**

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

  ➡ **high production rate**



- **cross section depend** essentially **on final state masses**

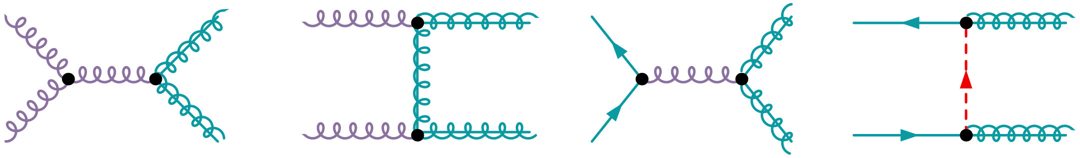
  ➡ bounds on cross section allow for lower mass bounds without specifying all other SUSY parameters

Overview: Squark & Gluino Production at LO

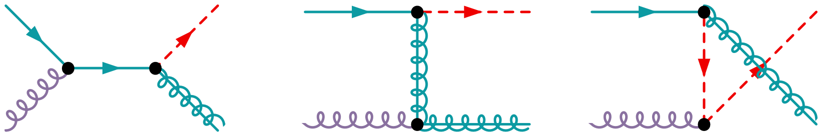
Squark and gluino production at LO is well known since many years

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

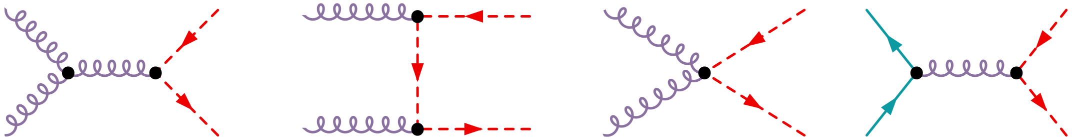
- $\mathcal{O}(\alpha_s^2)$: – $\tilde{g}\tilde{g}$ production



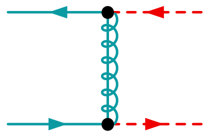
– $\tilde{g}\tilde{q}$ production



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



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



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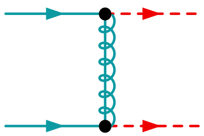
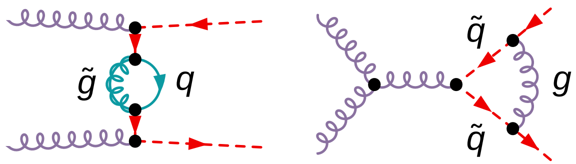


Higher Order Corrections

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

[Beenakker, Höpker, Spira, Zerwas '95 & '97] &
[Beenakker, Krämer, Plehn, Spira, Zerwas '98]
$\longrightarrow$ PROSPINO

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

QCD Born $\times$  $+ \ldots$

+ real gluon & real quark radiation

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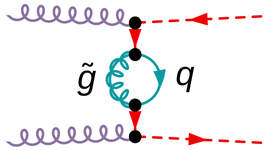

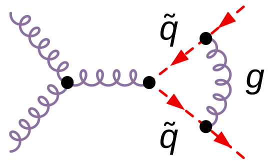

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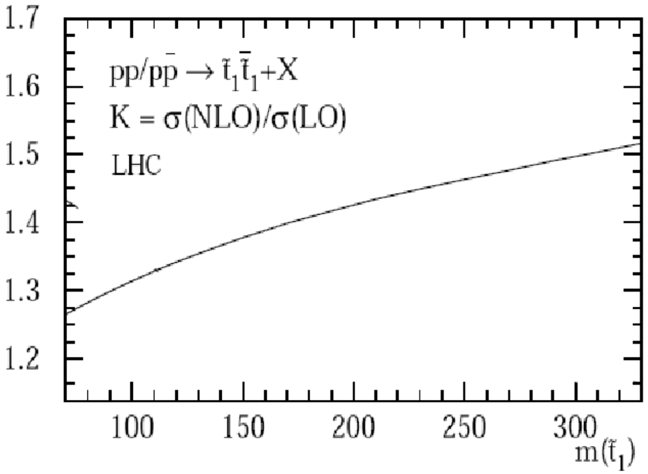
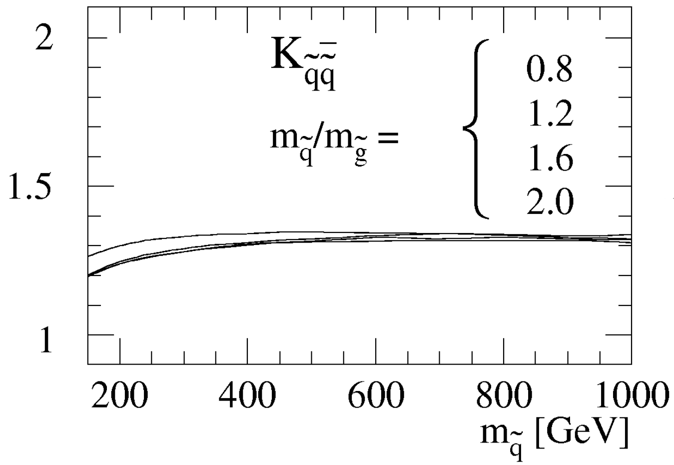
$\tilde{t}_1\tilde{t}_1^*$ production:



$\tilde{q}\tilde{q}^*$ production:



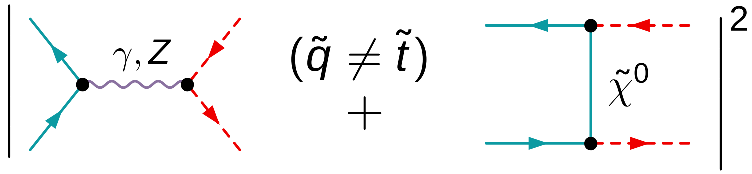
- large positive corrections
- reduced scale dependence
- negligible in normalized distributions

Electroweak Contributions – at Born level

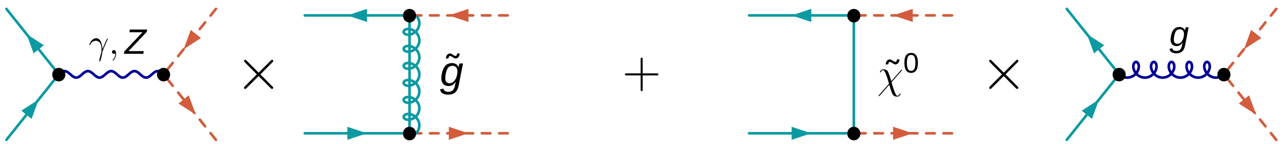
$\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, and $\tilde{q}\tilde{q}$ production also possible by **tree-level EW processes**!

[Bornhauser, Drees, Dreiner, Kim '07]
[Bozzi, Fuks, Herrmann, Klasen '07],[Arhrib, Benbrik, Cheung, Yuan '09]

- $\mathcal{O}(\alpha^2 + \alpha_s\alpha)$: **pure EW tree-level** contributions ($\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$ prod.)



+ EW-QCD tree-level **interferences** to $\tilde{q}\tilde{q}^{(*)}$ production



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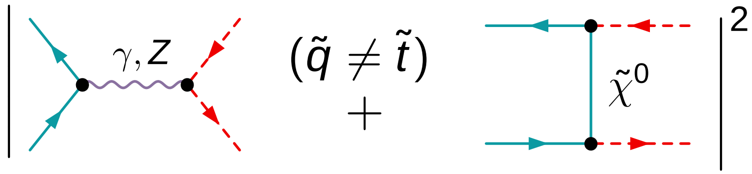

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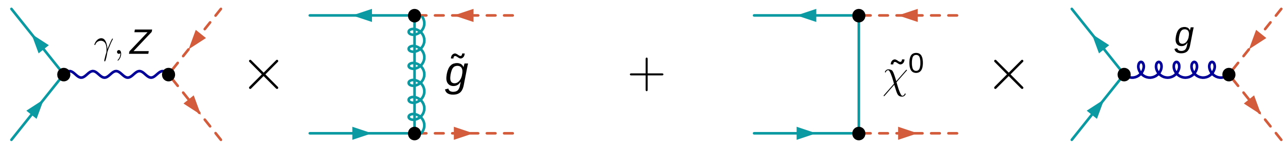
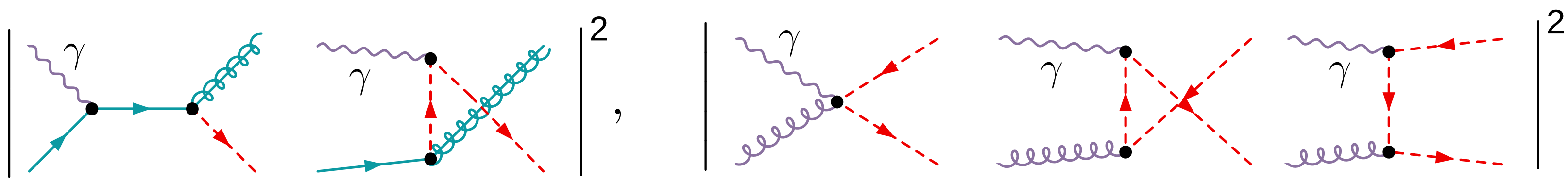


New production channel for $\tilde{g}\tilde{q}$, $\tilde{t}\tilde{t}^*$, and $\tilde{q}\tilde{q}^*$ production:

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

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



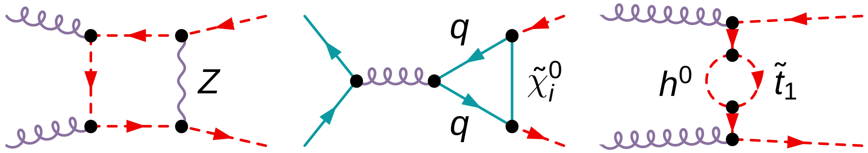
Electroweak Contributions – at one-loop level

- of comparable size to higher-order QCD corrections [NLL: Kulesza, Motyka '08 & '09] [approx. NNLO: Langenfeld, Moch '09]

[Hollik, Kollar, MT '07], [Beccaria et. al. '08] [Hollik, Mirabella '08], [Hollik, Mirabella, MT '09] [Mirabella '09], [Germer, Hollik, Mirabella, MT '09]

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

QCD Born $\times$



$+ \ldots$

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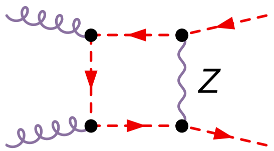
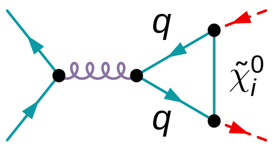
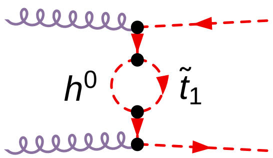
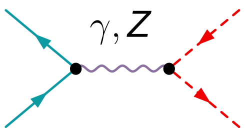




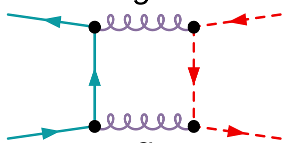


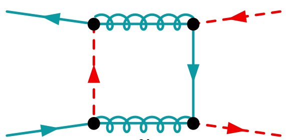
$+ \ldots$

+ EW-QCD one-loop interferences for $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^{(*)}$ production



$\times$





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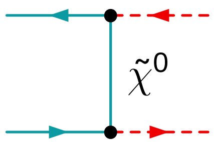

$\times$ full QCD 1-loop amplitude

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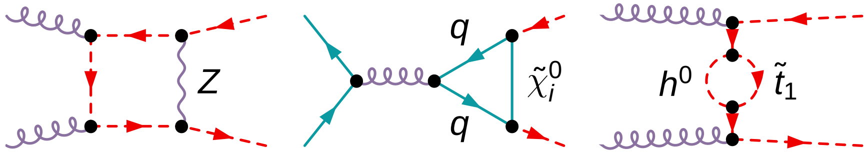

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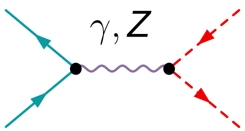
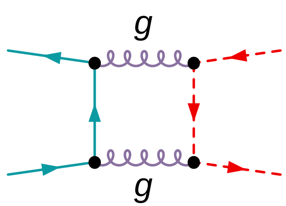
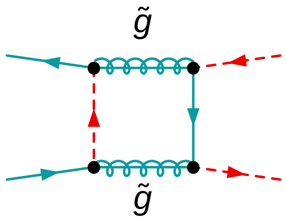


$\times$





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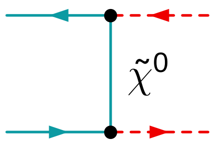

$\times$ full QCD 1-loop amplitude

+ real photon, gluon, and quark radiation

EW NLO Corrections: Singularities at $\mathcal{O}(\alpha_s^2\alpha)$

We use **FeynArts & FormCalc** to automatize the calculation.
Process-dependent solutions are necessary in singular regions:

- **UV singularities** (self energies, vertices) from **loop integrals**
  ➡ **renormalization** required
  [$\tilde{t}\tilde{t}^*, \tilde{g}\tilde{q}$: on-shell renorm. of quarks & squarks at $\mathcal{O}(\alpha)$;
  $\tilde{q}\tilde{q}^{(*)}$: full QCD 1-loop amplitude enters, full $\mathcal{O}(\alpha_s)$ renorm. required]

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- **IR soft singularities** from $m_\gamma = m_g = 0$
  ➡ real **photon** and **gluon bremsstrahlung**
  [technical: mass regularization + phase space slicing/ dipole subtraction;
  gluonic corrections: color correlations, EW-QCD interferences!]

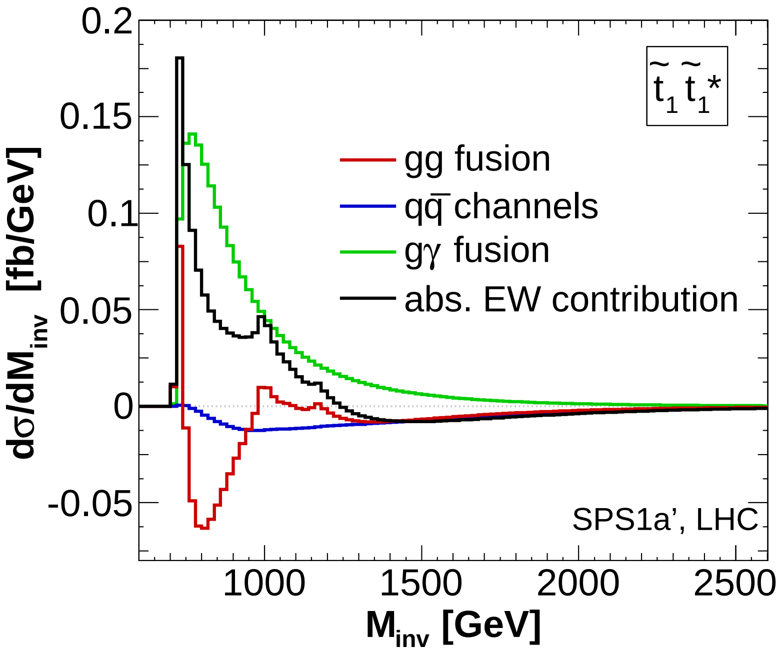
- **IR collinear singularities** from $m_q = 0$
  ➡ real photon and gluon bremsstrahlung
  ➡ factorization and **redefinition of PDFs** at $\mathcal{O}(\alpha)$ or $\mathcal{O}(\alpha_s)$

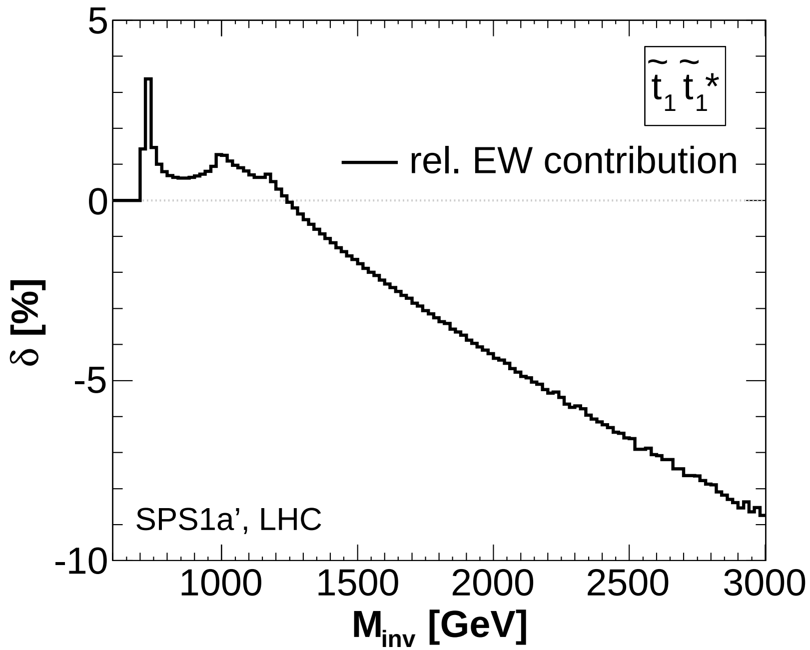
Numerical Results: Hadronic Cross Sections

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

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2)$	δ
$\tilde{t}_1\tilde{t}_1^*$	2670 fb	-22 fb	38 fb	1.2 fb	0.6%

[SPS1a': typical mSUGRA scenario]
[$m(\tilde{t}_1) = 360$ GeV, MRST 2004 QED]





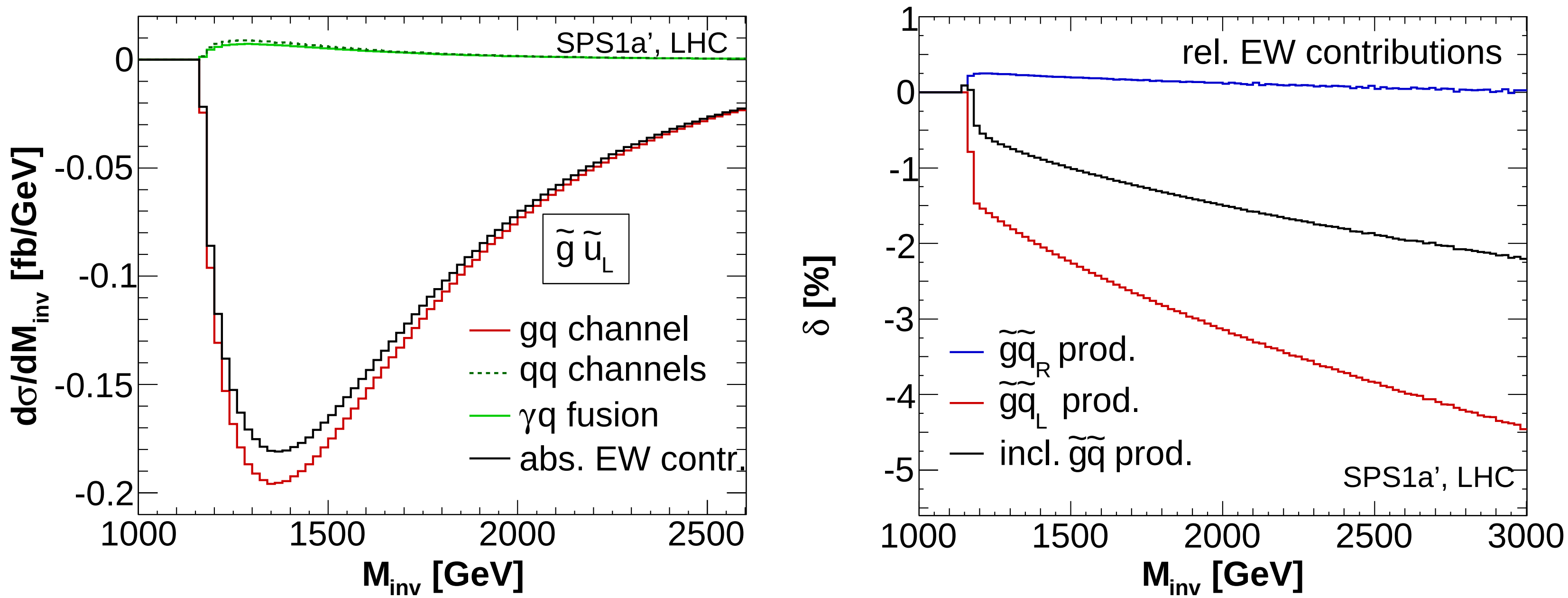
- ➡ ***$g\gamma$* contributions** are **of comparable size** to EW NLO corrections!
- ➡ threshold effects from stop and sbottom pairs in the loops
- ➡ **EW contributions** grow **up to $\sim$ 10%** for large values of M_{inv}

Numerical Results – $\tilde{g}\tilde{q}$ production

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

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	δ
$\tilde{g}\,\tilde{q}_R$	10820 fb	9.8 fb	5.3 fb	–	0.1%
$\tilde{g}\,\tilde{q}_L$	10010 fb	-248 fb	4.9 fb	–	-2.4%

[$m(\tilde{q}_L) \approx 565$ GeV, $m(\tilde{q}_R) \approx 540$ GeV, $m(\tilde{g}) = 609$ GeV, MRST 2004 QED]



➡ **γq and real quark channels** only moderate;

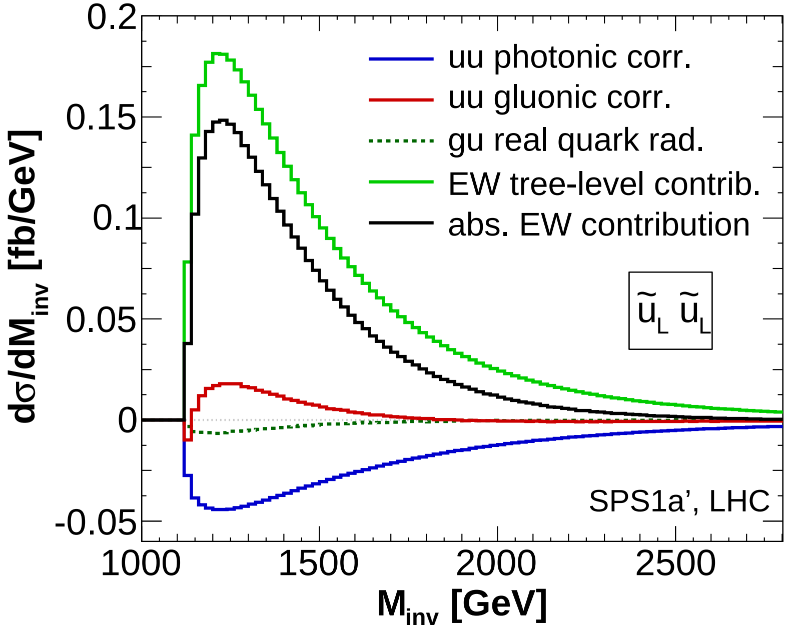
➡ $\tilde{g}\tilde{q}_L$ prod.: EW contrib's grow **up to 5-10%** in distributions

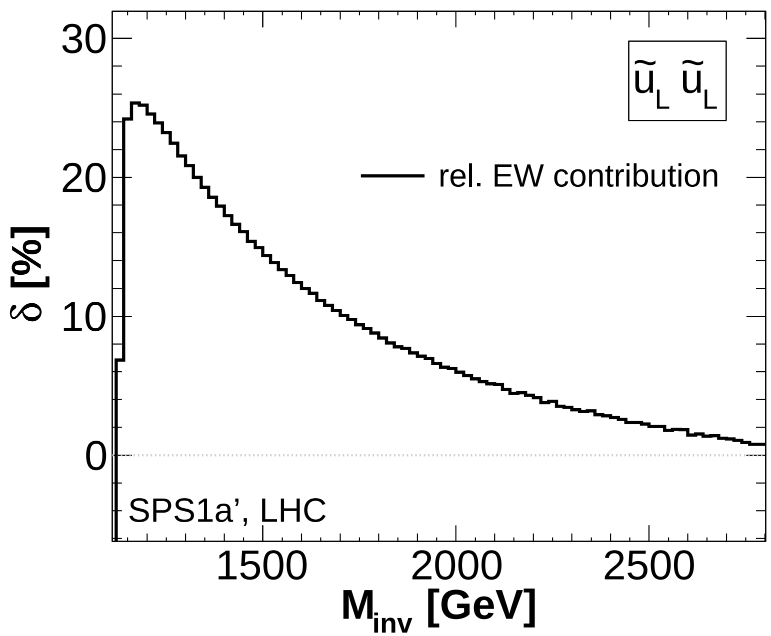
Numerical Results – $\tilde{q}\tilde{q}$ production

$\tilde{u}\tilde{u}$ prod.:

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\Delta\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2{+}\alpha_s\alpha)$	δ
$\tilde{u}_R\,\tilde{u}_R$	537 fb	-4.5 fb	–	29 fb	4.5 %
$\tilde{u}_L\,\tilde{u}_L$	487 fb	-30 fb	–	94 fb	13%
$\tilde{u}_R\,\tilde{u}_L$	630 fb	-26 fb	–	1.3 fb	-4.0 %

[$m(\tilde{u}_L) = 561$ GeV, $m(\tilde{u}_R) = 543$ GeV, MRST 2004 QED]





➡ many interference contributions! **EW tree-level channels important**

➡ total EW contributions significant for left-handed squarks

Summary

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

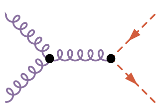
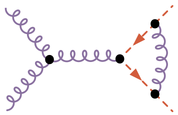
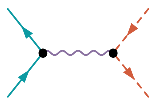
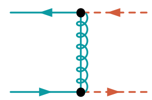
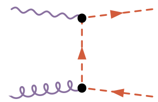
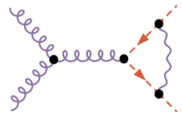
- QCD corrections already well known,
  EW NLO corrections to $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{t}\tilde{t}^*$ prod. **completed**,
  for $\tilde{q}\tilde{q}$ production publication in preparation

- **EW contributions** have a **rich structure**
  ➡ strongly **dependent on chirality** of produced particles
  ➡ non-zero **photon PDF** opens important production channel
  ➡ **EW tree-level** and involved EW-QCD interference contributions

- **EW contributions** to integrated cross sections are often small,
  but become **important in distributions**

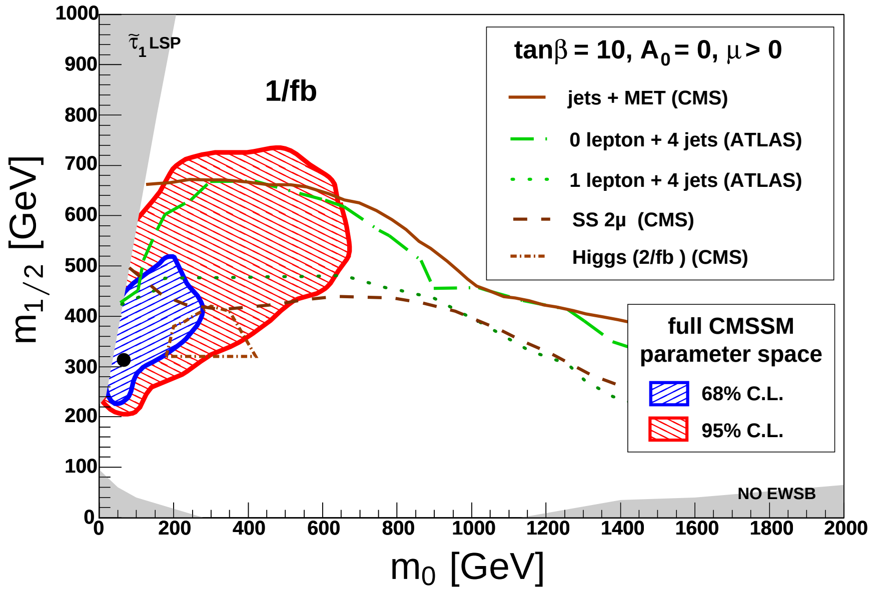
Backup

Overview: Squark and Gluino Production @ LHC

	LO	NLO QCD	EW contributions			
	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s^2\alpha)$
$\tilde{g}\tilde{g}$	+	+	−	−	−	+
$\tilde{g}\tilde{q}$	+	+	−	−	+	+
$\tilde{t}\tilde{t}^*$	+	+	+	−	+	+
$\tilde{q}\tilde{q}^*$	+	+	+	+	+	+
$\tilde{q}\tilde{q}$	+	+	+	+	−	+
				$\times$ 		

SUSY Phenomenology – Motivation

- SUSY has **predictive power** – good prospects for LHC!



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

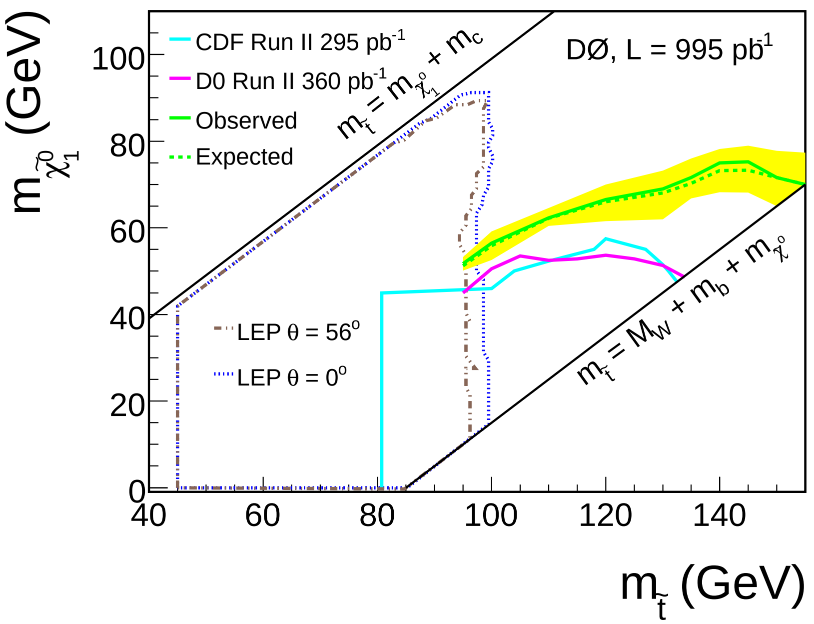
from combination of experimental, phenomenological, and cosmological information:

➡ 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**

Experimental Searches

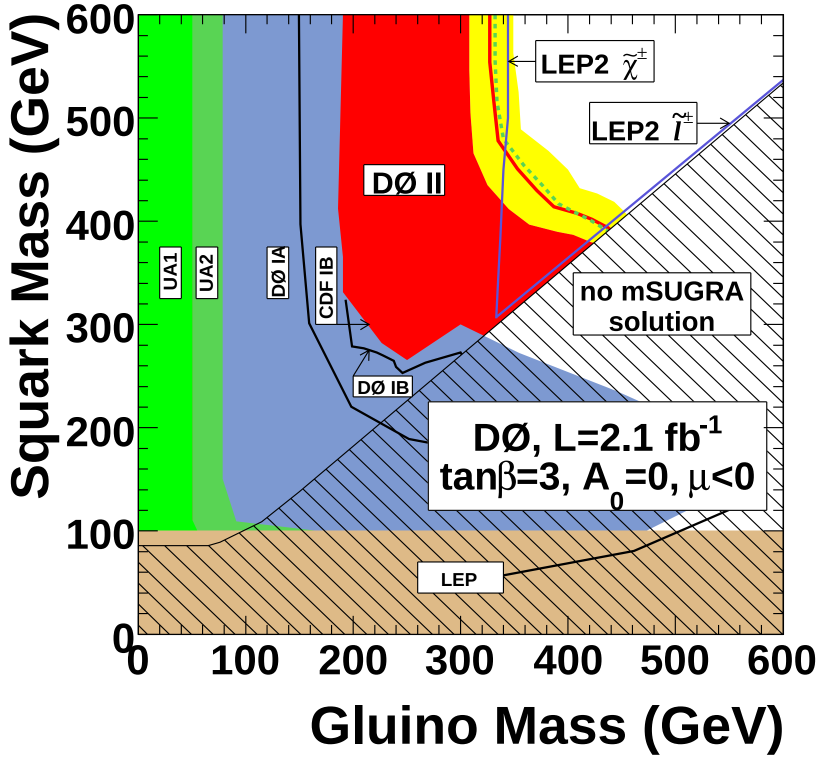
stop mass limits

[D0, 0803.2263 hep-ex]



squark & gluino mass limits

[D0, 0712.3805 hep-ex]



➡ **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

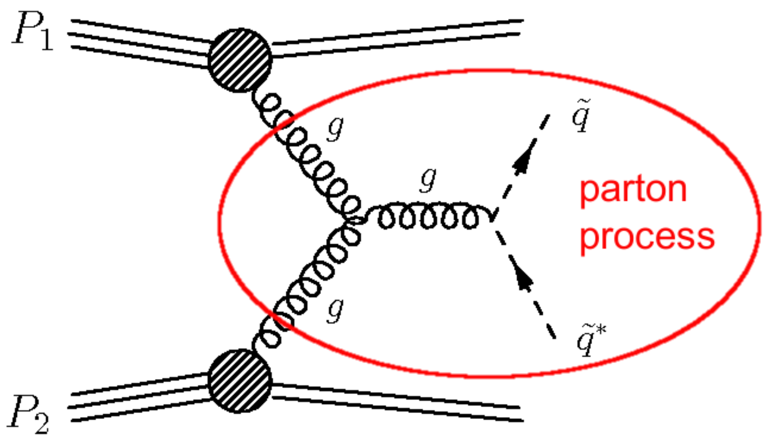
Distinguish **hadron level** and **parton level** :

$$\sigma_{P_1P_2\to\tilde{q}\tilde{q}^*}(P_1,P_2) = \sum_{i,j=g,q,\bar{q}} \int dx_1\, dx_2\; f_i(x_1)\, f_j(x_2)\; \hat{\sigma}_{ij\to\tilde{q}\tilde{q}^*}(p_1,p_2)$$

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

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

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



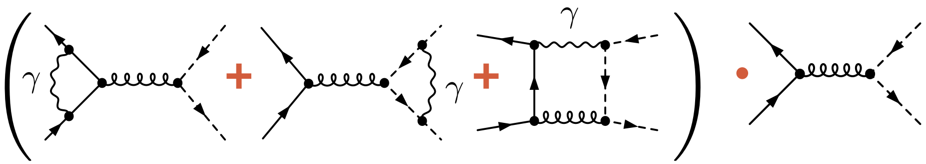
Factorization

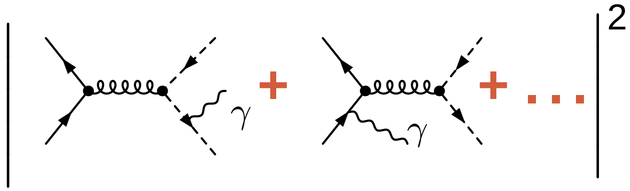
$$f_i(x) \longrightarrow f_i(x, \mu_F)$$

μ_F: factorization scale

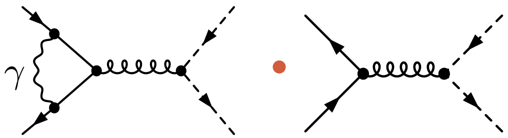
How to obtain a IR-finite cross section for $q\bar{q} \to \tilde{t}\tilde{t}^*$

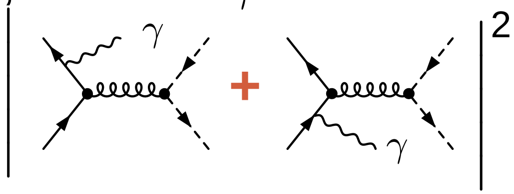
- soft divergent diagrams and soft photon bremsstrahlung





- collinear divergent diagram and hard, collinear γ bremsstrahlung





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

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

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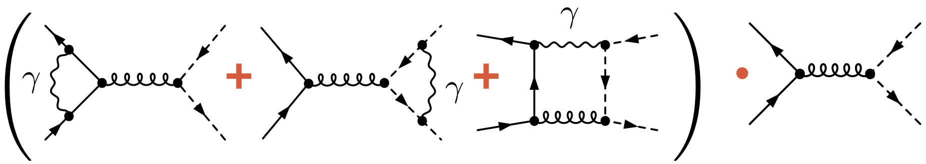

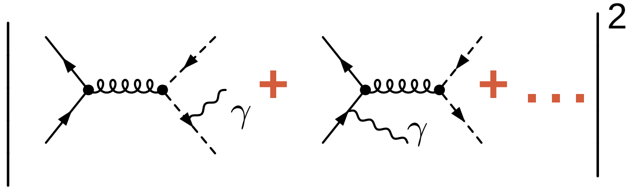

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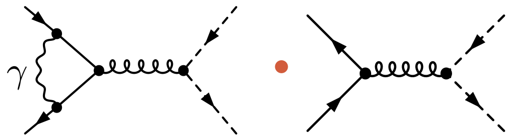

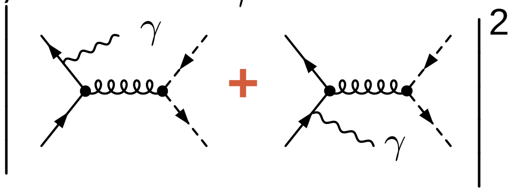

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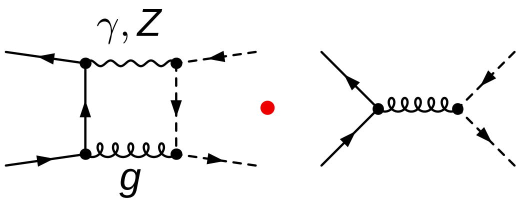
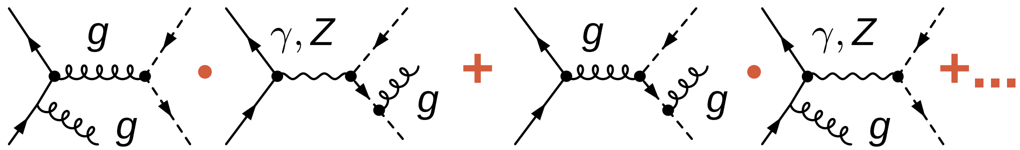
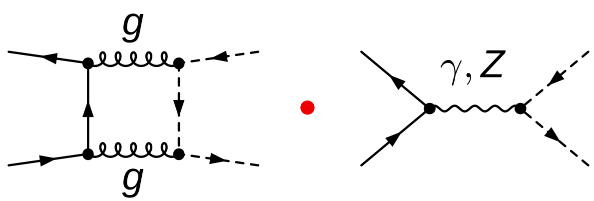


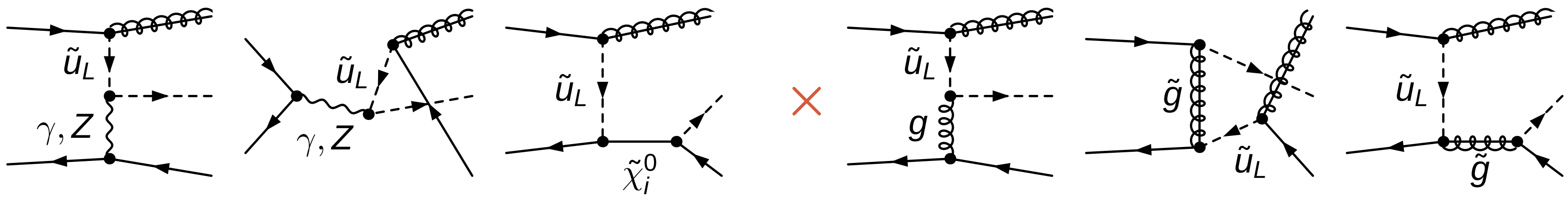


- interference of QCD boxes and EW Born



$\tilde{g}\tilde{q}$ **production** – Real Quark Radiation

- at $\mathcal{O}(\alpha_s^2\alpha)$: **non-zero interference** of **EW** and **QCD** diagrams!
  ➡ many channels & diagrams (but small contributions)
  some examples for $u\bar{u} \to \tilde{g}\tilde{u}_L\bar{u}$:



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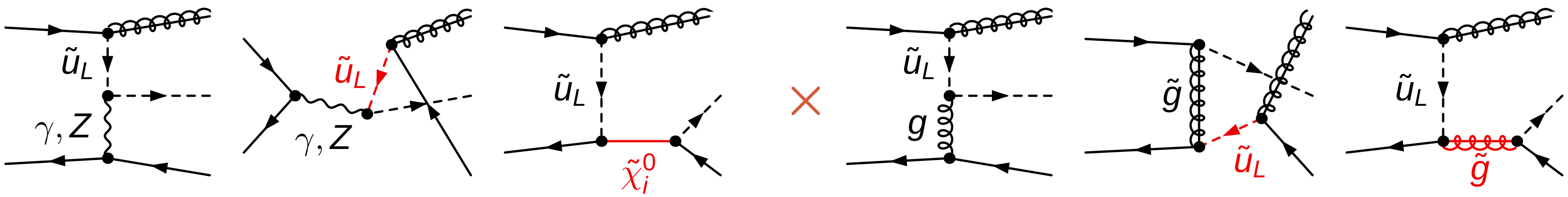
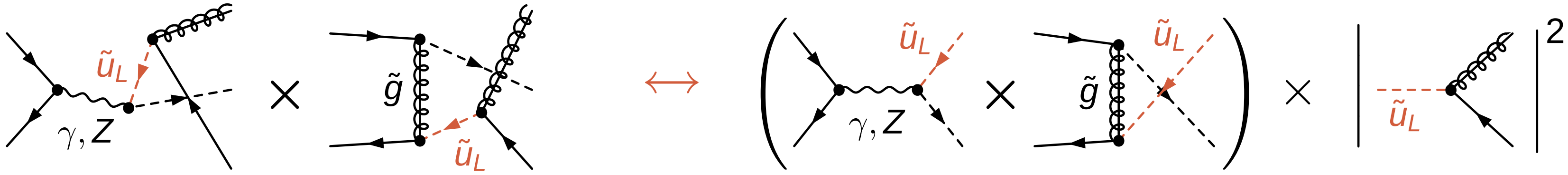


➡ **on-shell internal particles**: insert widths to regularize propagators

➡ in order to **avoid double counting**: subtract possible **resonances**

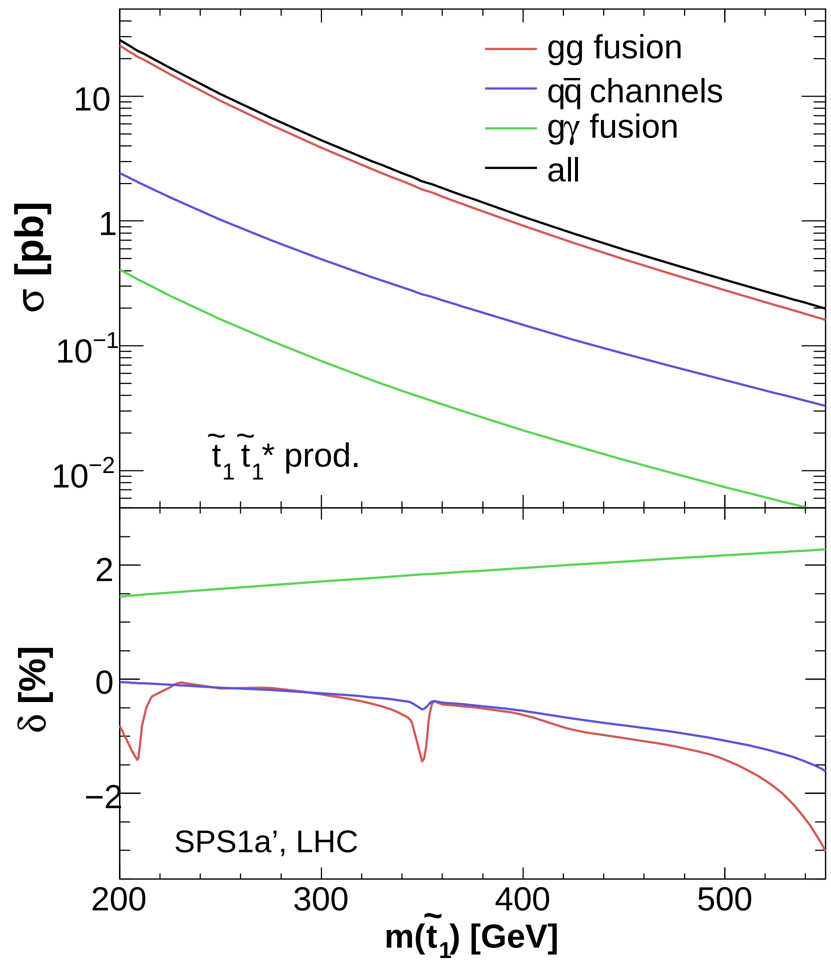


$\sigma(u\bar{u} \to \tilde{u}_L\,\tilde{g}\bar{u})$ $\qquad\qquad$ $\sigma(u\bar{u} \to \tilde{u}_L\tilde{u}_L^*) \quad \times \; BR(\tilde{u}_L^* \to \tilde{g}\bar{u})$

SUSY Parameter Dependence

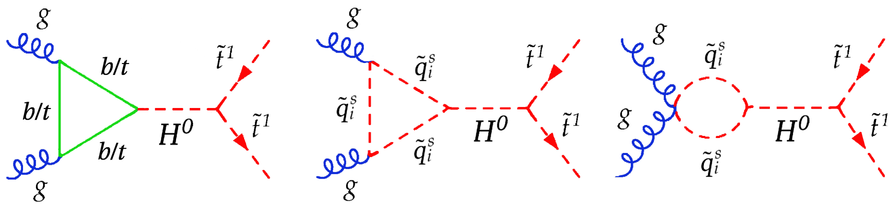
$\tilde{t}_1\tilde{t}_1^*$ prod.:

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

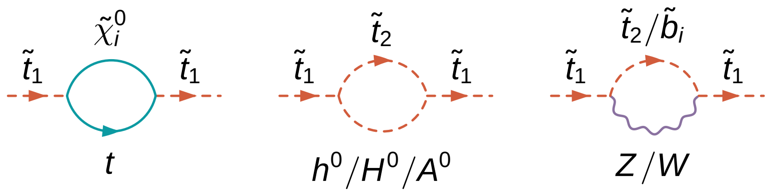


stop mass $m(\tilde{t}_1)$ **varied** around SPS 1a' value, all other parameters fixed

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

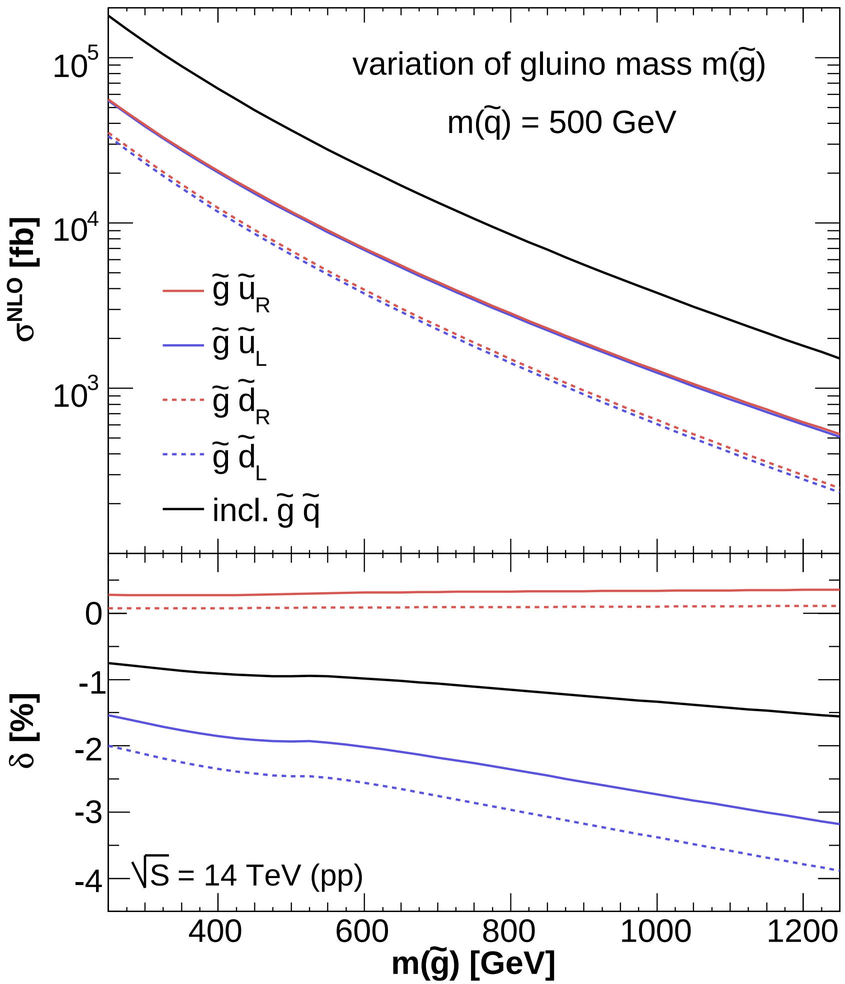


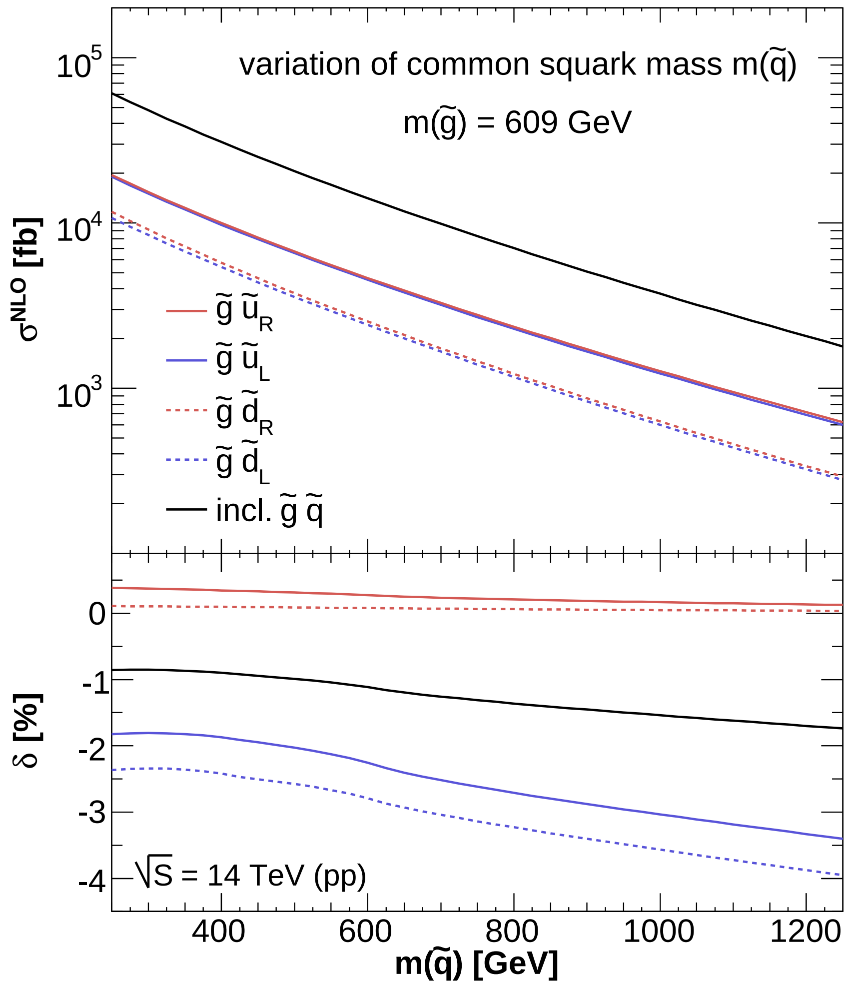
- thresholds in top-squark wave function renormalization



SUSY Parameter Dependence II

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



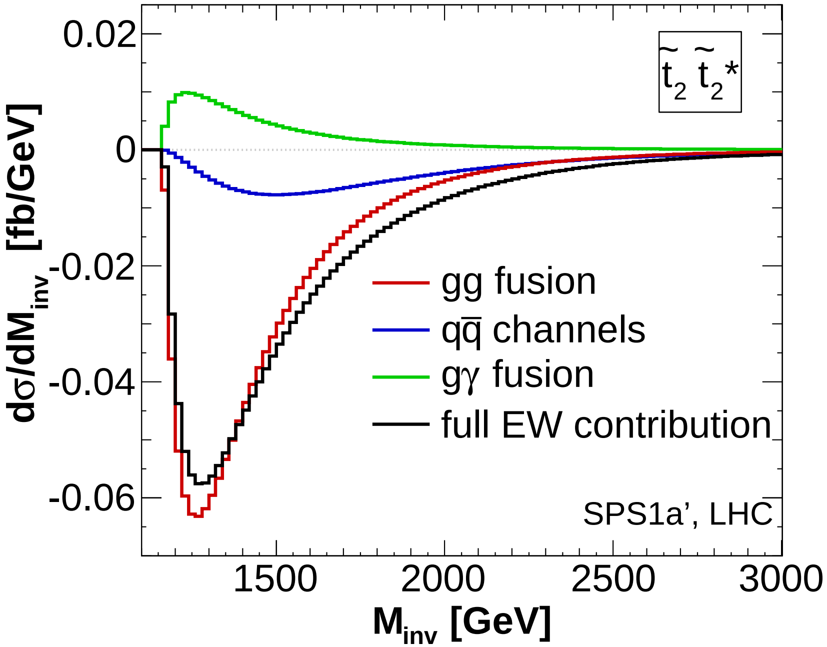


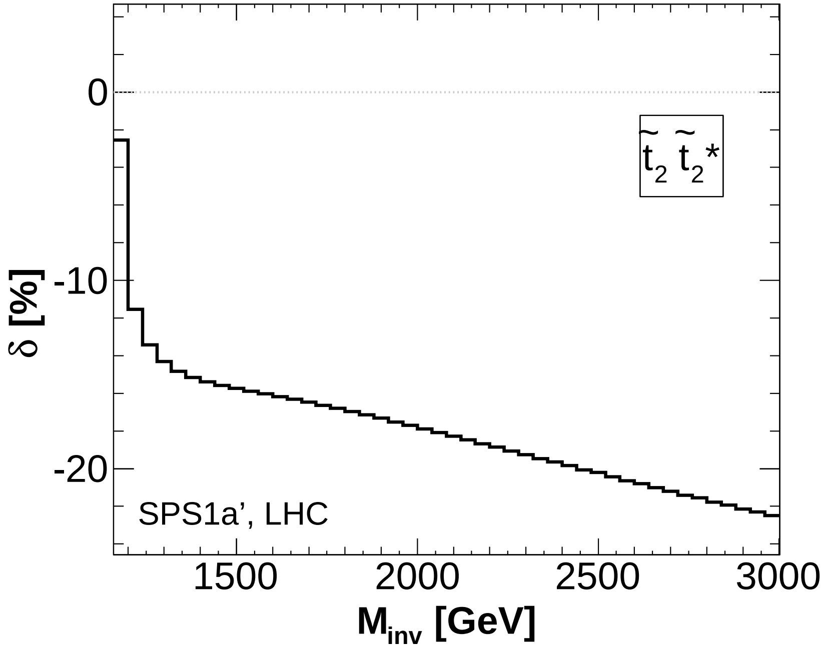
Numerical Results – $\tilde{t}_2\tilde{t}_2^*$ production

$\tilde{t}_2\tilde{t}_2^*$ prod.:

	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,tree}$ $\mathcal{O}(\alpha^2)$	δ
$\tilde{t}_1\tilde{t}_1^*$	2670 fb	-22 fb	38 fb	1.2 fb	0.6%
$\tilde{t}_2\tilde{t}_2^*$	190 fb	-32 fb	3.8 fb	0.3 fb	-15%

[$m(\tilde{t}_1) = 360$ GeV, $m(\tilde{t}_2) = 580$ GeV, MRST 2004 QED]





➡ integrated cross section suppressed from heavy $\tilde{t}_2$-mass,

➡ but $\mathcal{O}(\alpha_s^2\alpha)$ **corrections enhanced** for more left-handed $\tilde{t}_2$