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

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Outline

- **Introduction**
- **Production of Squarks and Gluinos**
  - classification of processes
  - QCD and EW contributions
- **$\tilde{t}_1\tilde{t}_1^*$, $\tilde{q}\tilde{q}^*$, and $\tilde{g}\tilde{q}$ production at EW NLO**
  - handling singularities
  - numerical results
- **Summary**

SUSY – Motivation

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

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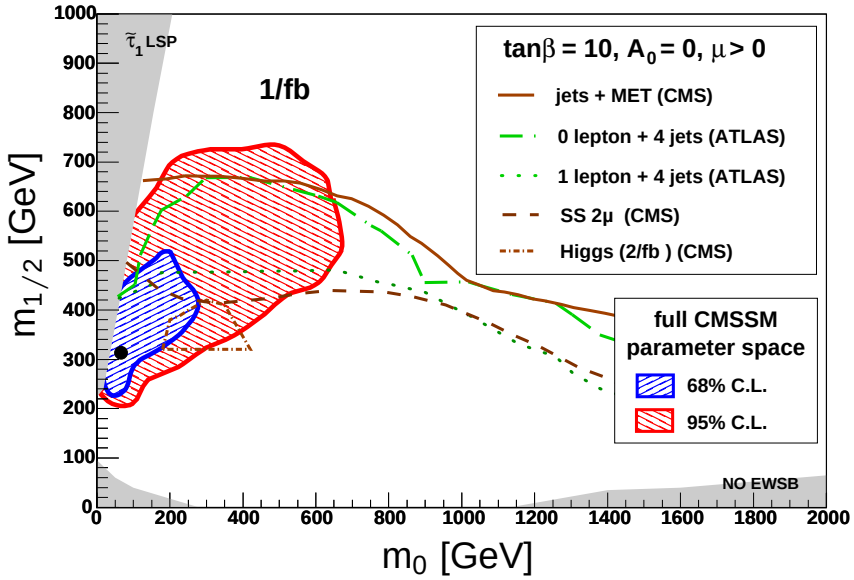
- Supersymmetry is a possible and very attractive extension of the Standard Model . . .
- SUSY has **predictive power** – good prospects for LHC!



[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)

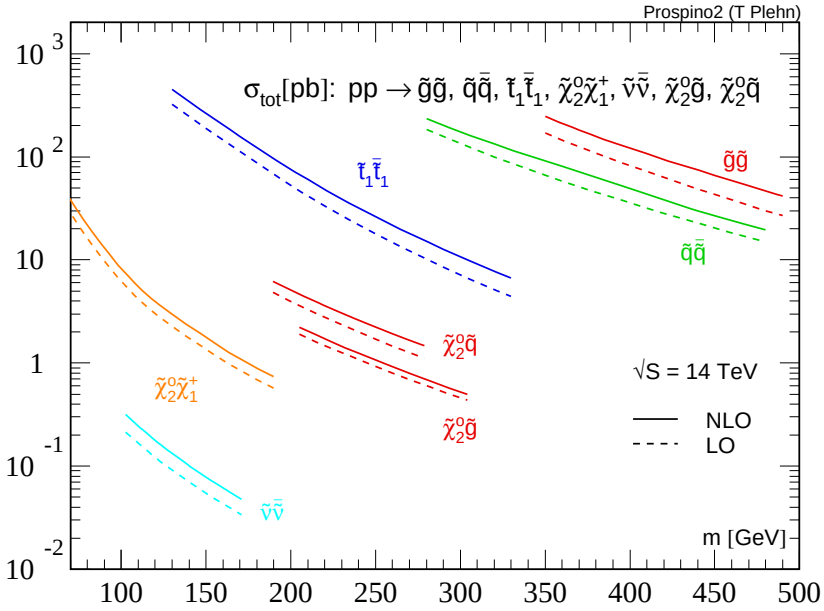
Why studying production of colored SUSY particles at the LHC?

- pair production of gluinos and squarks proceeds via **strong interaction**

  → **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

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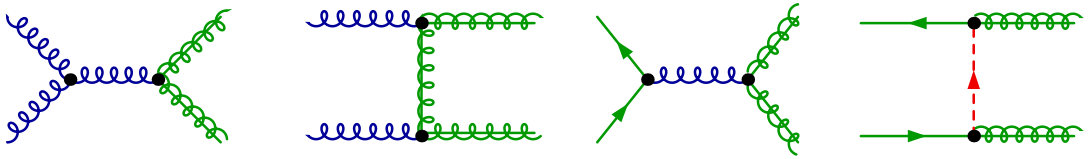
- **Summary**

Overview: Squark & Gluino Production at LO

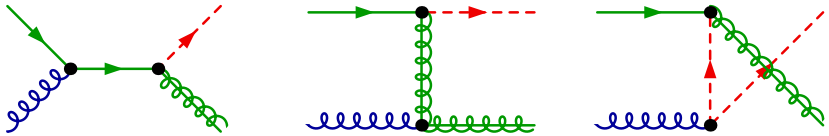
Squark and gluino production at LO is well known since many years

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

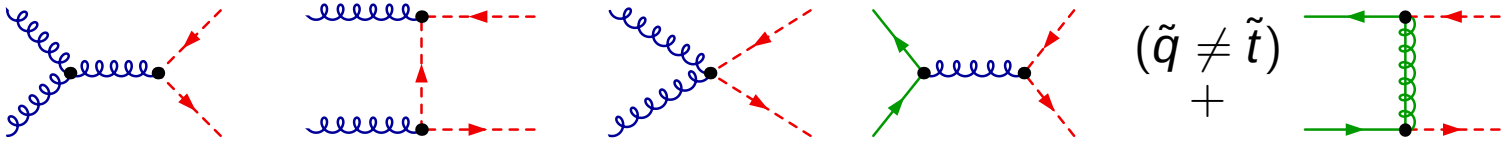
- $\mathcal{O}(\alpha_s^2)$: – $\tilde{g}\tilde{g}$ production



– $\tilde{g}\tilde{q}$ production



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



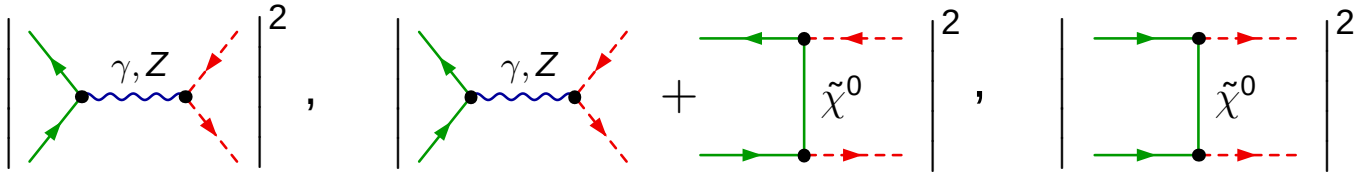
- stops & sbottoms: L–R mixing cannot be neglected; exp. distinguishable
- top-squark pair production is diagonal at LO

Tree-level Electroweak Contributions

Squark pair production is also possible by tree-level EW processes!

[Bornhauser, Drees, Dreiner, Kim '07]
[Bozzi, Fuks, Herrmann, Klasen '07]

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



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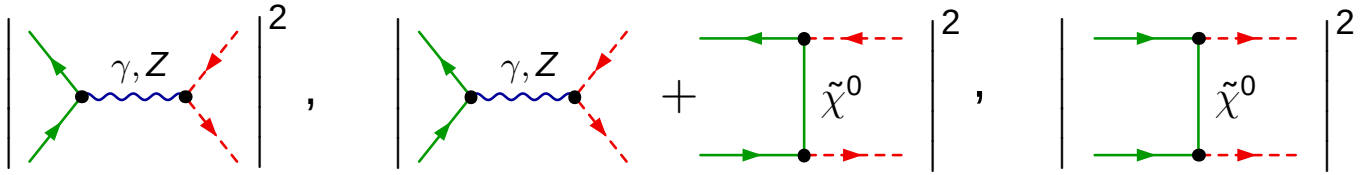

- $\mathcal{O}(\alpha_s\alpha)$: – EW-QCD tree-level interferences to $\tilde{q}\tilde{q}^*$ production

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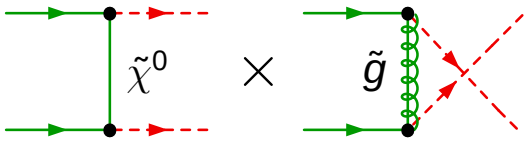

Tree-level Electroweak Contributions II

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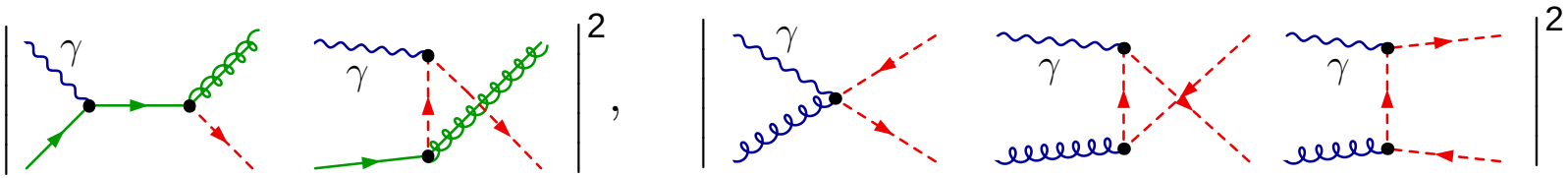
- $\mathcal{O}(\alpha_s\alpha)$: photon induced processes



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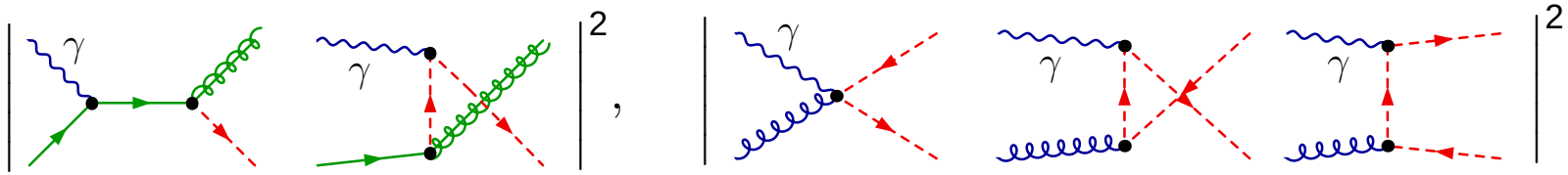
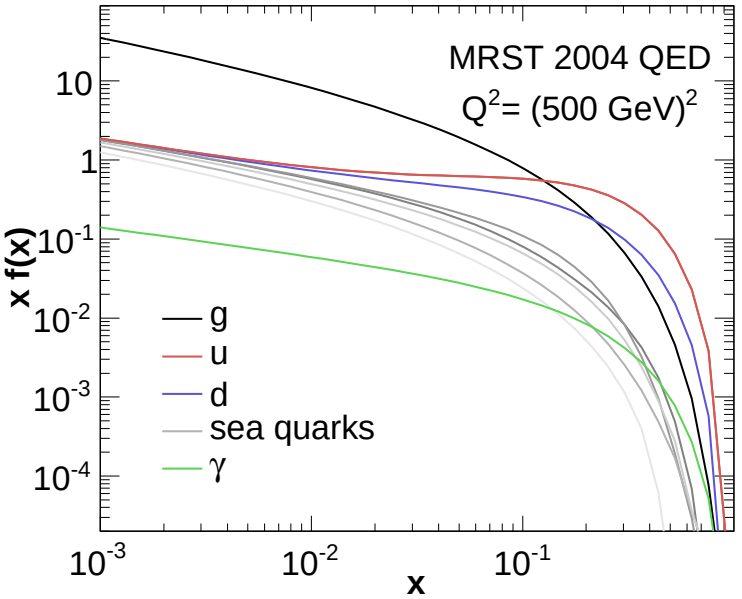


- not present at LO at the hadronic level
- **MRST 2004 QED**: inclusion of **NLO QED effects** in the evolution of PDFs
  - → non-zero photon distribution
  - → non-zero hadronic contributions

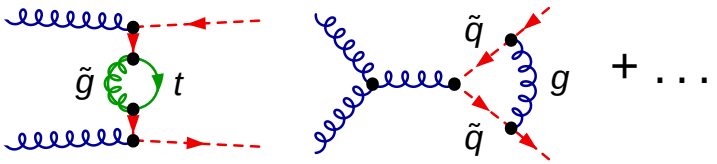


Higher Order Corrections – Squark Production

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

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

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

QCD Born $\times$ 

+ . . .

+ real gluon & real quark radiation

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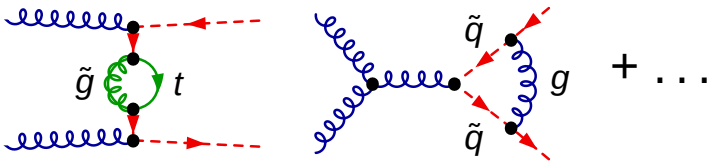

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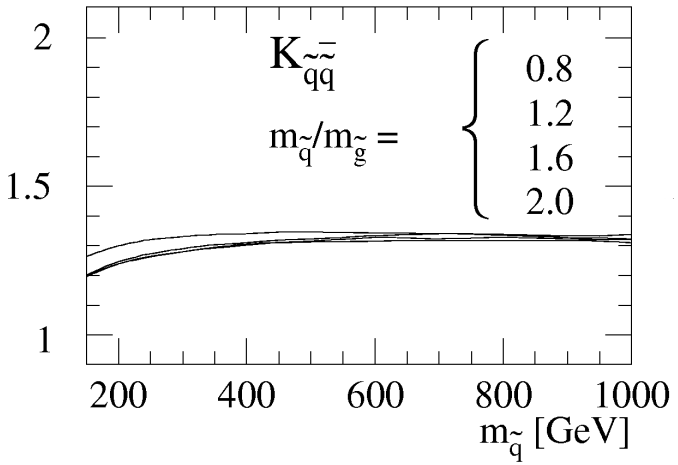
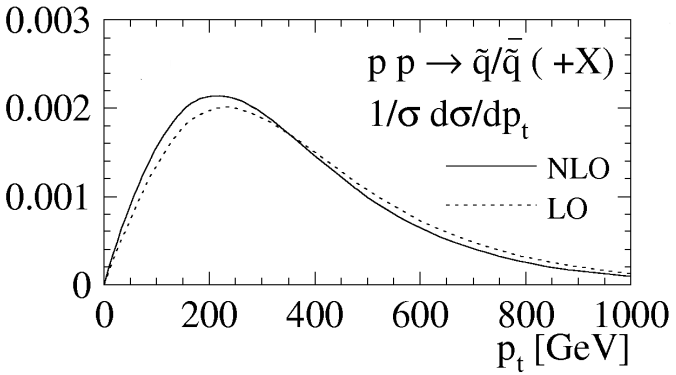
[$\tilde{q}\bar{\tilde{q}}^*$ production:]



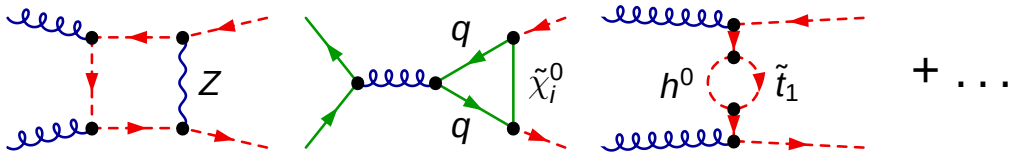


- large positive corrections
- reduced scale dependence
- negligible in normalized distributions

Higher Order Corrections – Squark Production II

Known from SM processes: also **EW corrections** can be important!
of comparable size to higher-order QCD corrections [NLL: Kulesza, Motyka '08] [approx. NNLO: Langenfeld, Moch '09]

- $\mathcal{O}(\alpha_s^2\alpha)$: EW NLO corrections [Hollik, Kollar, MT '07], [Beccaria et. al. '08] [Hollik, Mirabella '08]

QCD Born $\times$ 

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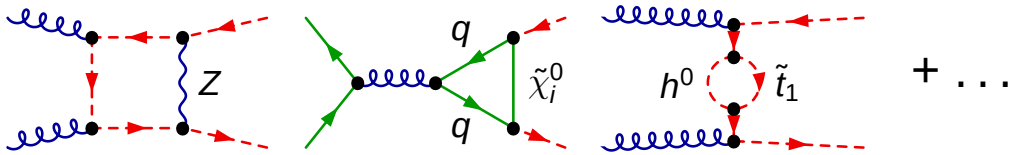
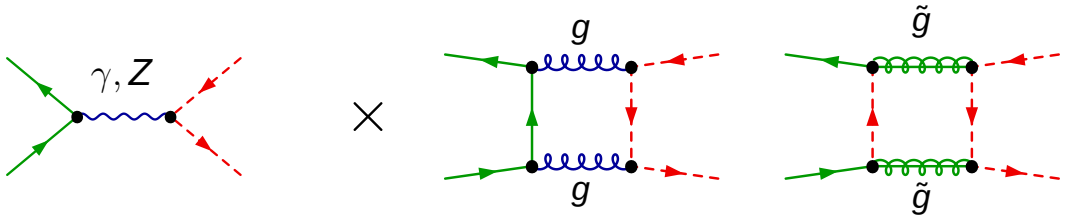
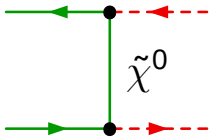
QCD Born $\times$ 

+ . . .

+ EW-QCD one-loop interferences



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

$\times$ full QCD 1-loop amplitude

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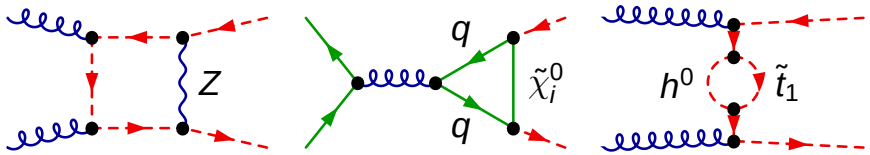
QCD Born $\times$ 

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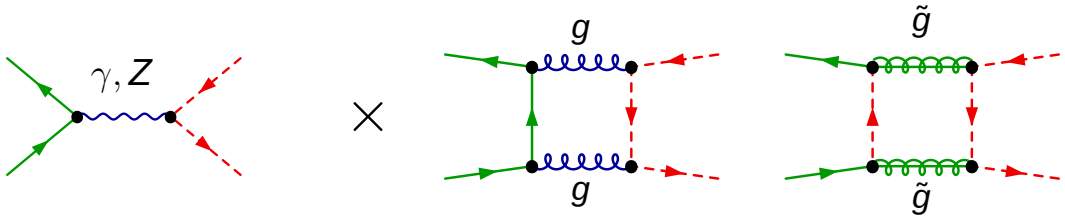
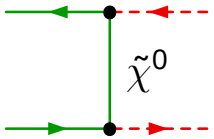
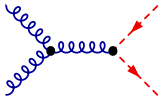
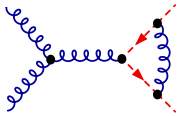
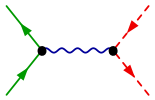
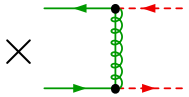
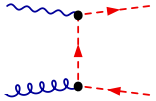
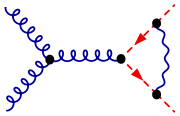


$(\tilde{q} \neq \tilde{t})$ + 

$\times$ full QCD 1-loop amplitude

+ real photon, gluon, and quark radiation

Overview: Squark and Gluino Production @ LHC

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

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

- **UV singularities** (self energies, vertices) from **loop integrals**

  $\longrightarrow$ **renormalization** of quarks & squarks

  [$\tilde{t}\tilde{t}^*, \tilde{g}\tilde{q}$: no renorm. of gluon, gluino, and α_s at this order;

  but $\tilde{q}\tilde{q}^{(*)}$: full QCD 1-loop amplitude enters, renorm. required

  $\longrightarrow$ use α_s in $\overline{MS}$ scheme, heavy particles decoupled;

  $\longrightarrow$ need SUSY-restoring counterterm for $\hat{g}_s$]

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- **IR (soft) singularities** from $m_\gamma = m_g = 0$

  $\rightarrow$ real **photon** and **gluon bremsstrahlung**

  [technical: mass regularization + phase space slicing / dipole subtr.]

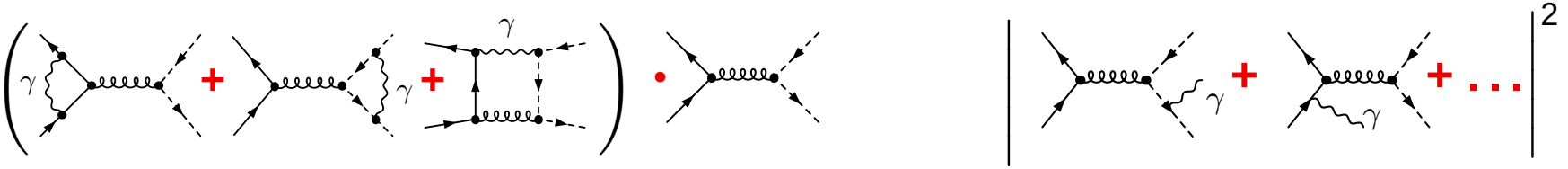
- **collinear singularities** from $m_q = 0$

  $\rightarrow$ real photon and gluon bremsstrahlung

  $\rightarrow$ factorization and **redefinition of PDFs** at $\mathcal{O}(\alpha)$ or $\mathcal{O}(\alpha_s)$

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 $\sigma_{q\bar{q}}$

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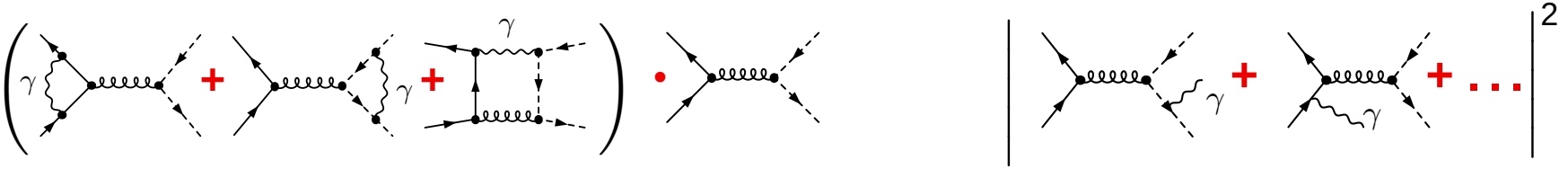

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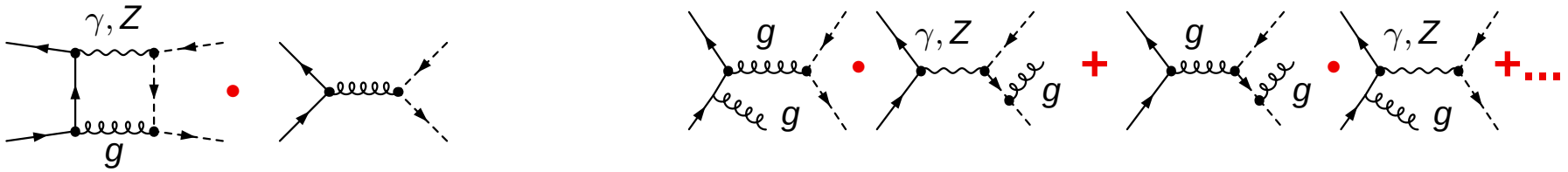
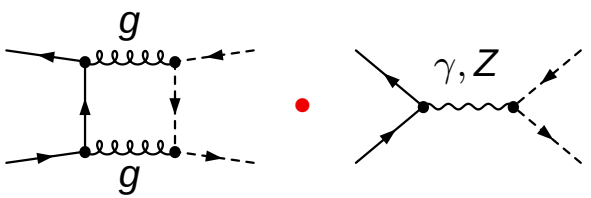


- interference of QCD boxes and EW Born

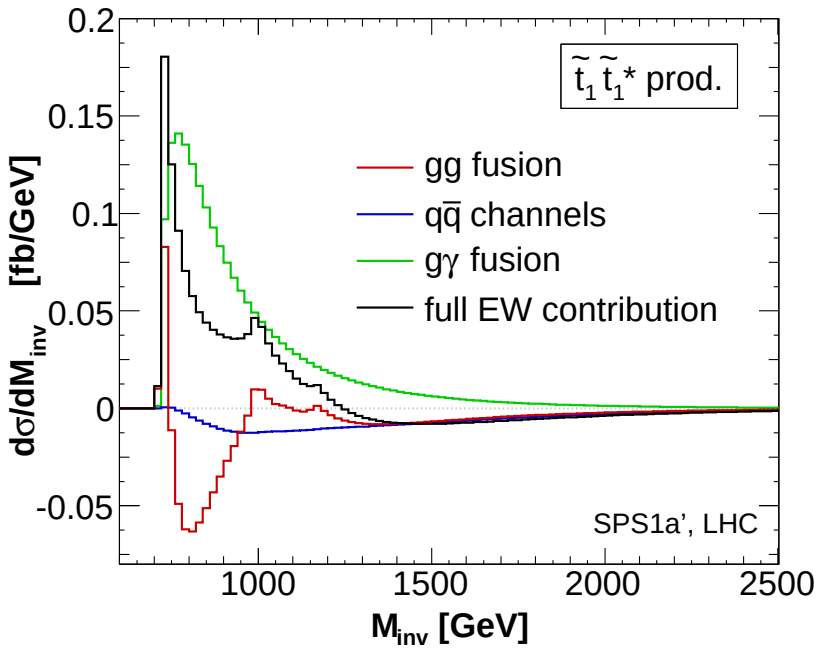


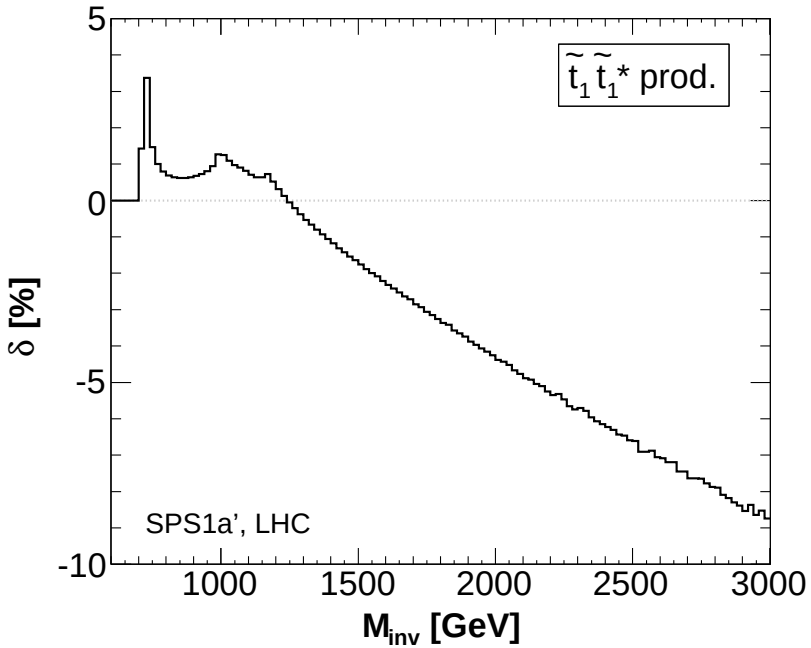
Numerical Results: Hadronic Cross Sections

[Hollik, Kollar, MT '08]

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

[SPS: Snowmass Points and Slopes; SPS1a′: typical mSUGRA scenario]





→ ***gγ* contributions** are **of comparable size** to EW NLO corrections!

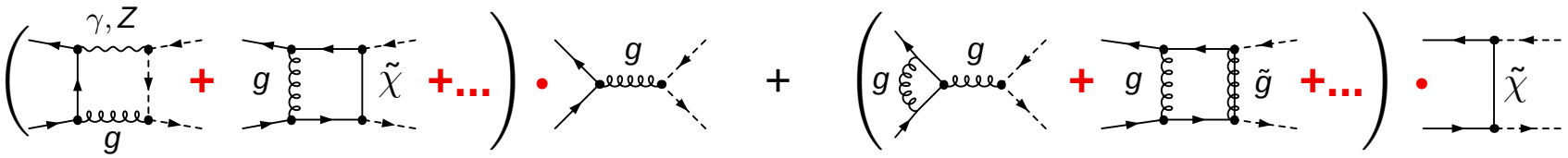
→ threshold effects from stop and sbottom pairs in the loops

→ **EW contributions** grow **up to ∼ 10%** for large values of $M_{\tilde{t}_1\tilde{t}_1^*}$

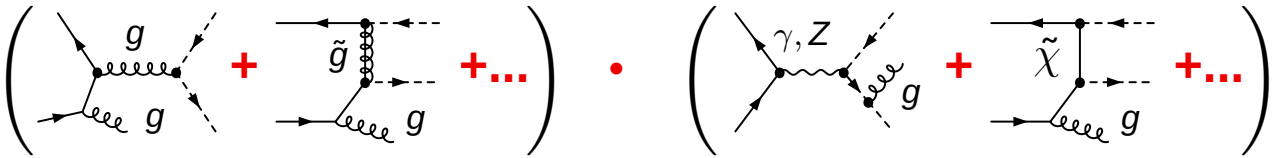
$\tilde{q}\tilde{q}^*$ Production – IR Singularities

- diagrams singular due to **soft & collinear photons**
  → need real photon bremsstrahlung **+** redefinition of quark PDF at $\mathcal{O}(\alpha)$

- diagrams singular due to **soft & collinear gluons**



  → need real gluon bremsstrahlung at $\mathcal{O}(\alpha_s^2\alpha)$



  → need redefinition of quark PDF at $\mathcal{O}(\alpha_s)$

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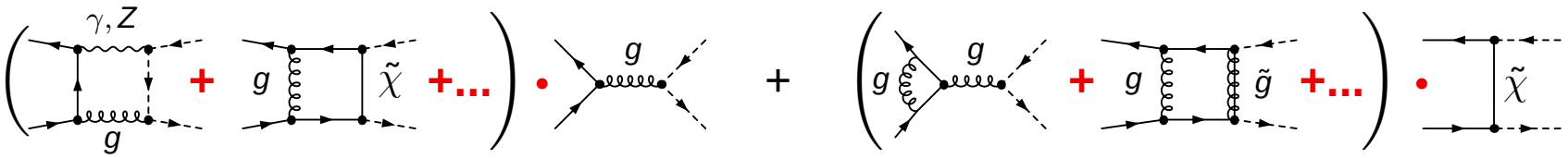
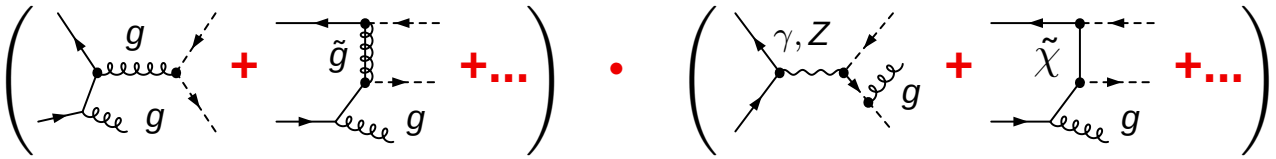
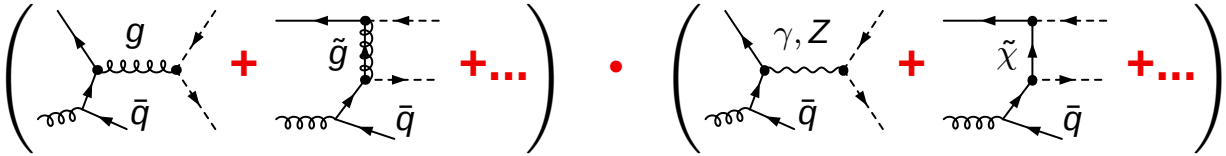


  → need real gluon bremsstrahlung at $\mathcal{O}(\alpha_s^2\alpha)$



  → need redefinition of quark PDF at $\mathcal{O}(\alpha_s)$

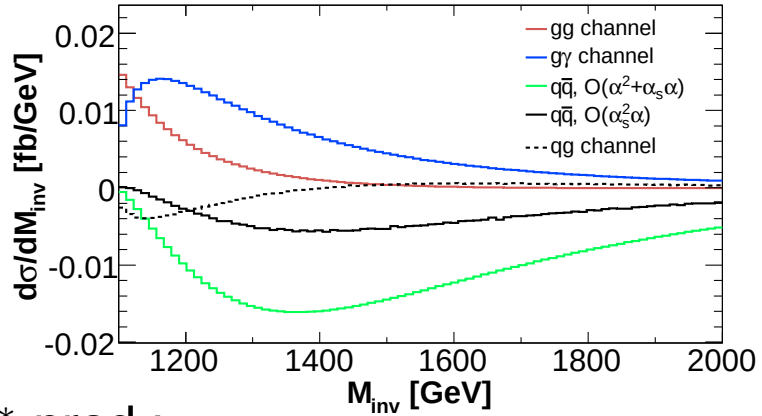
- diagrams singular due to **collinear** $g \to q\bar{q}$ **splitting**

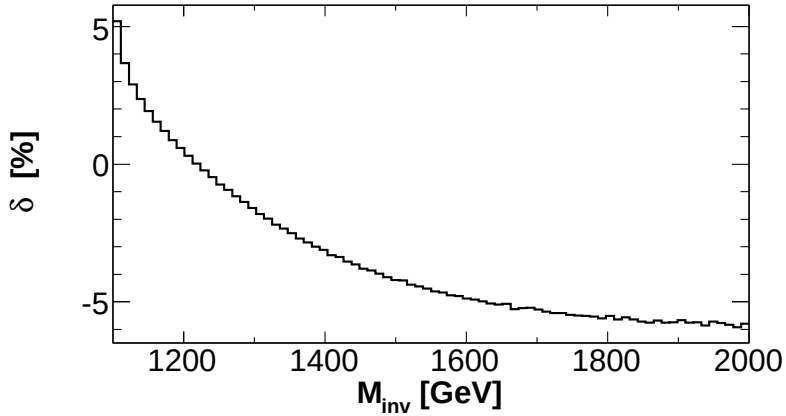


  → need redefinition of quark PDF at $\mathcal{O}(\alpha_s)$

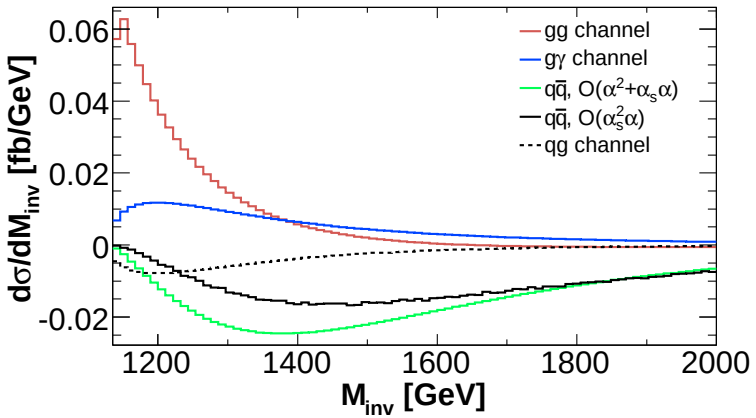
Numerical Results: Hadronic Cross Sections II

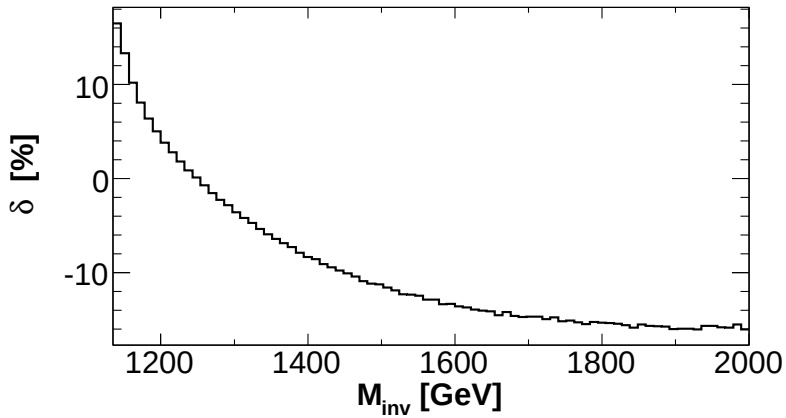
$\tilde{u}_R\tilde{u}_R^*$ prod.: [Hollik, Mirabella '08]





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





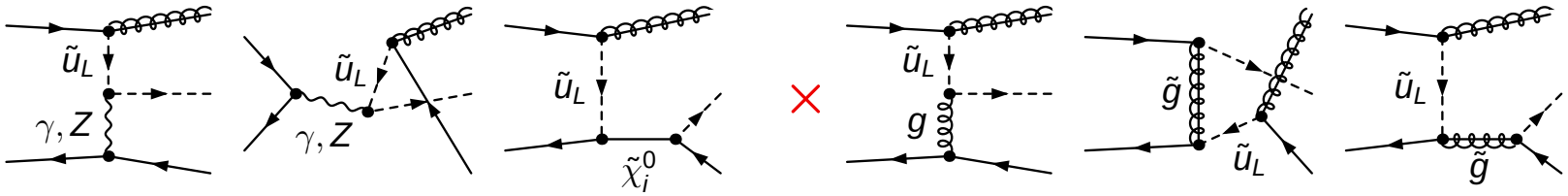
→ many contributions! **EW tree-level channels important**

→ total EW contributions grow **up to 5-10%**

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

- at $\mathcal{O}(\alpha_s^2\alpha)$: **non-zero interference** of **EW** and **QCD** diagrams!

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



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

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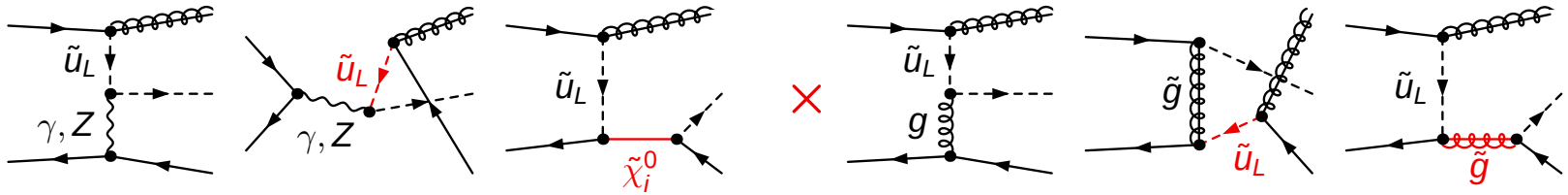
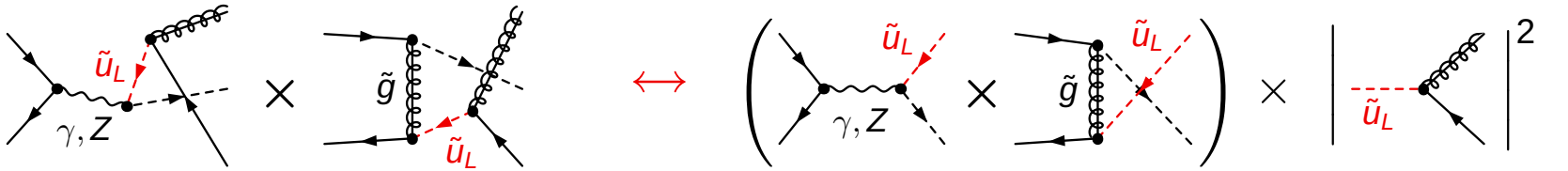


$\rightarrow$ **on-shell internal particles**: insert widths to regularize propagators

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

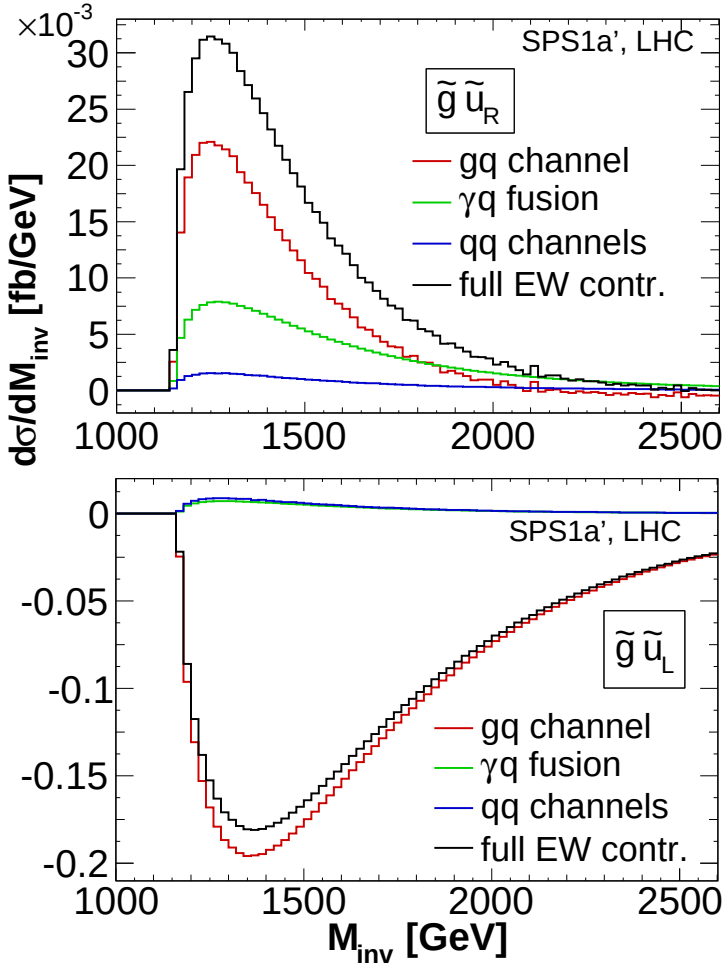


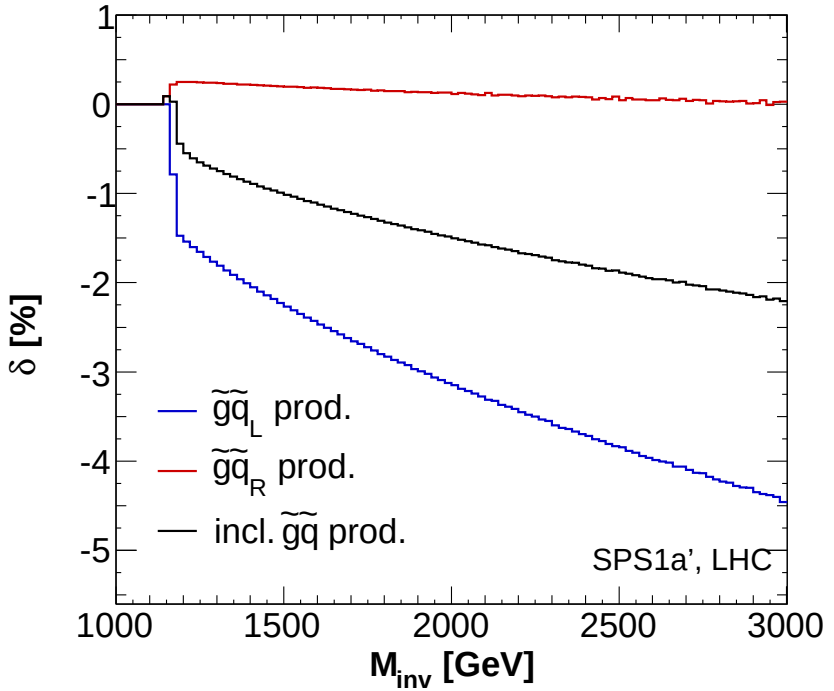
$\sigma(u\bar{u} \rightarrow \tilde{u}_L\,\tilde{g}\bar{u})$ $\qquad$ $\sigma(u\bar{u} \rightarrow \tilde{u}_L\tilde{u}_L^*)$ $\times$ $BR(\tilde{u}_L^* \rightarrow \tilde{g}\bar{u})$

Numerical Results: Hadronic Cross Sections III

[Hollik, Mirabella, MT '08]

$\tilde{g}\tilde{q}$ prod.: Invariant mass distribution





→ **$q\gamma$ & qq corrections** only moderate

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

$\tilde{g}\tilde{q}_L$ prod.: EW contrib's negligible

Total Cross Sections for SPS1a'

final state	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\sigma^{EW,LO}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	$\delta = \frac{\sigma^{NLO}-\sigma^{LO}}{\sigma^{LO}}$
$\tilde{t}_1\tilde{t}_1^*$	**2670 fb**	**−22 fb**	**38 fb**	1.2 fb	**0.6%**
$\tilde{u}_R\,\tilde{u}_R^*$	370 fb	−3.1 fb	5.2 fb	−13 fb	2.6%
$\tilde{u}_L\,\tilde{u}_L^*$	310 fb	−11 fb	4.4 fb	−15 fb	−7.0%
$\tilde{g}\,\tilde{u}_R + \tilde{g}\,\tilde{d}_R$	10820 fb	9.8 fb	5.3 fb	–	0.1%
$\tilde{g}\,\tilde{u}_L + \tilde{g}\,\tilde{d}_L$	10010 fb	−248 fb	4.9 fb	–	−2.4%
$\tilde{g}\tilde{q}$	**17120 fb**	**−183 fb**	**9.8 fb**	–	**−1.0%**

[$\mu_F = \mu_R$ =central, 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]

[$\tilde{g}\tilde{q}$: production of anti-squarks and of squarks of 2nd generation included (differing only in PDF)]

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 contributions** have a **rich structure**
  - $\rightarrow$ **EW tree-level** and EW-QCD interference contributions
  - $\rightarrow$ non-zero **photon PDF** opens important production channel
  - $\rightarrow$ **QCD-type corrections** enter at $\mathcal{O}(\alpha_s^2\alpha)$

- **EW contributions** to the total cross section are small,
  but **important in distributions**

Backup

Numerical Results: Input Parameters

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

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

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

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

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

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

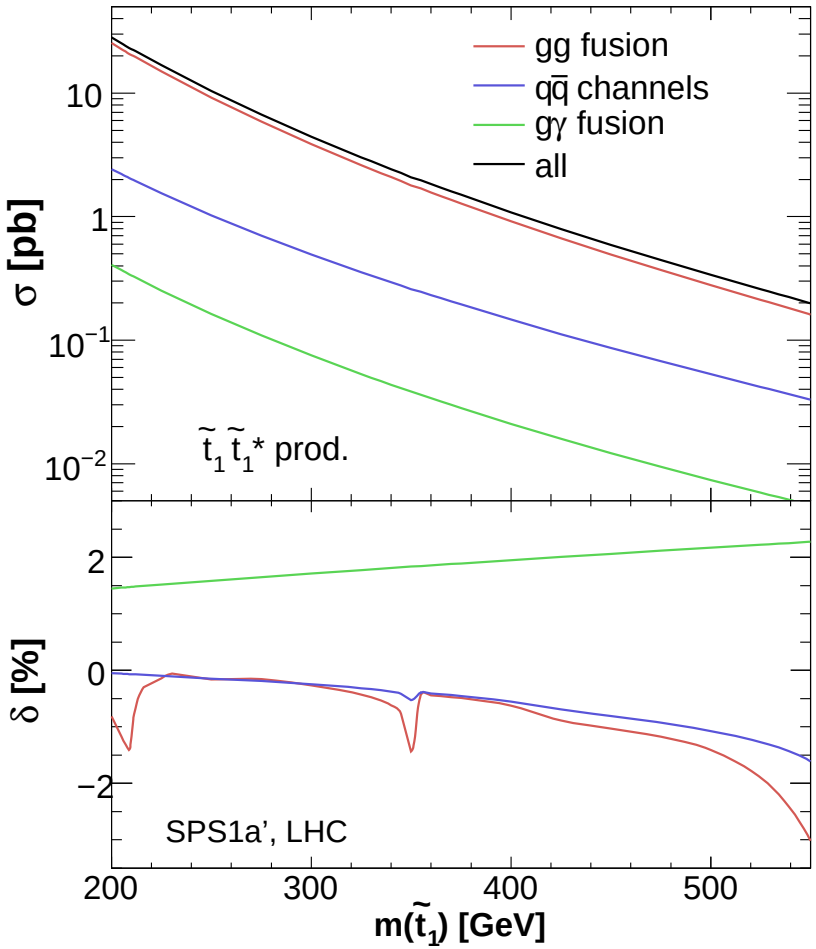
SUSY Parameter Dependence

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

[Hollik, Kollar, MT '08]

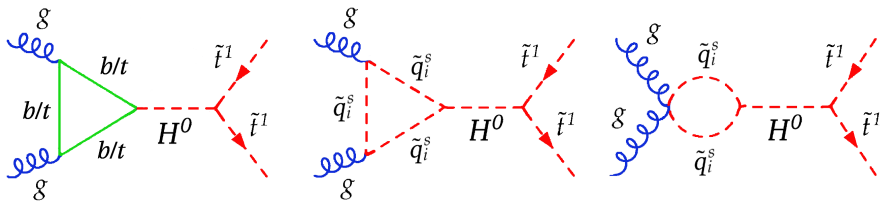
$\tilde{t}_1\tilde{t}_1^*$ prod.:

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

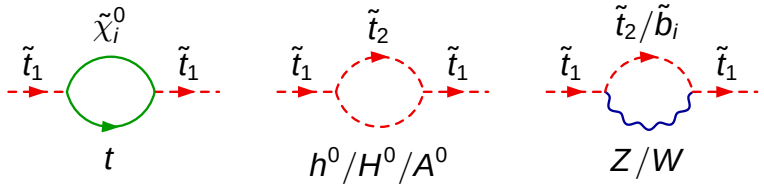


stop mass $m(\tilde{t}_1)$ **varied** around SPS 1a' value, all other parameters fixed

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



- thresholds in top-squark wave function renormalization

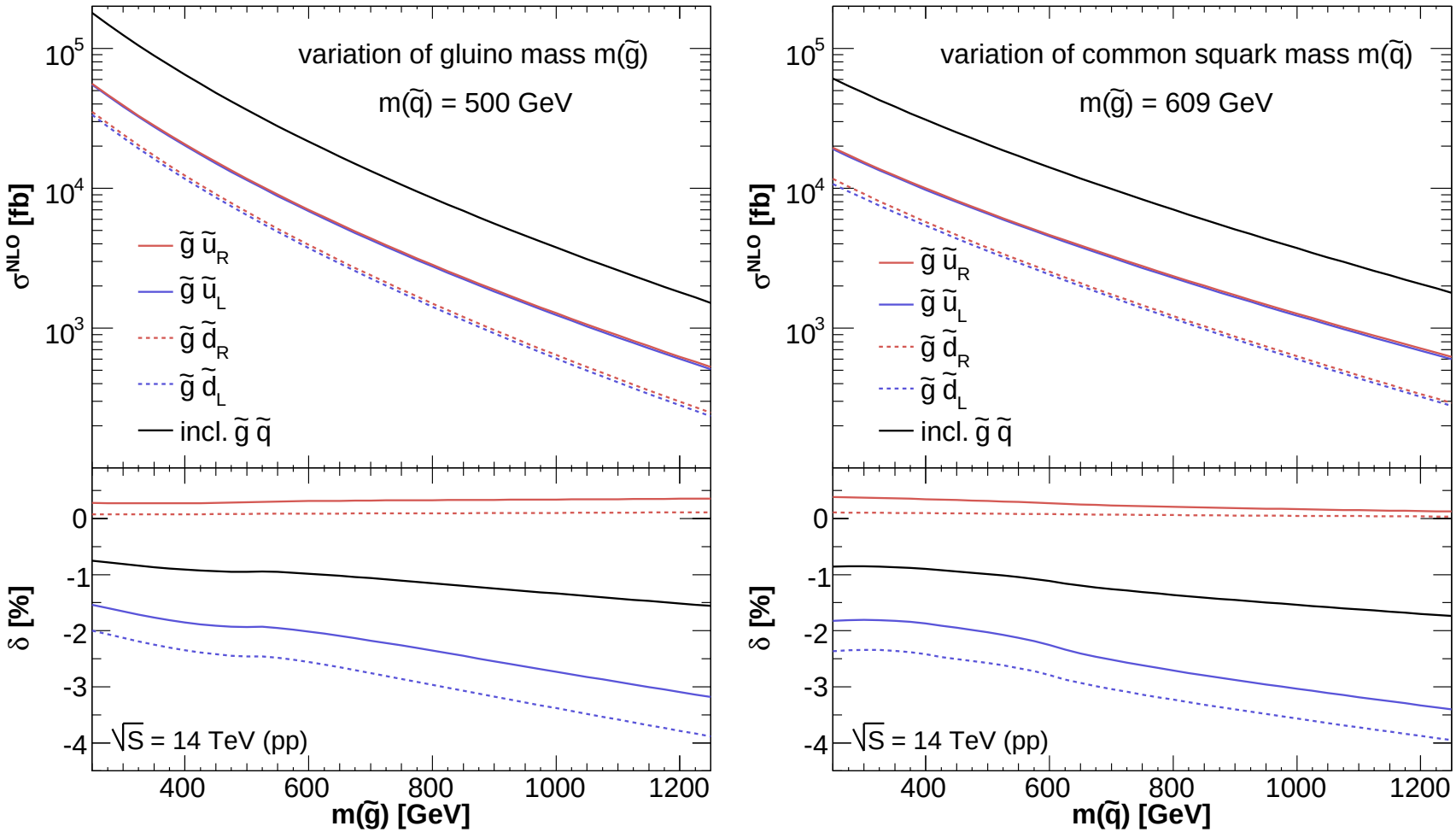


SUSY Parameter Dependence II

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

[Hollik, Mirabella, MT '08]

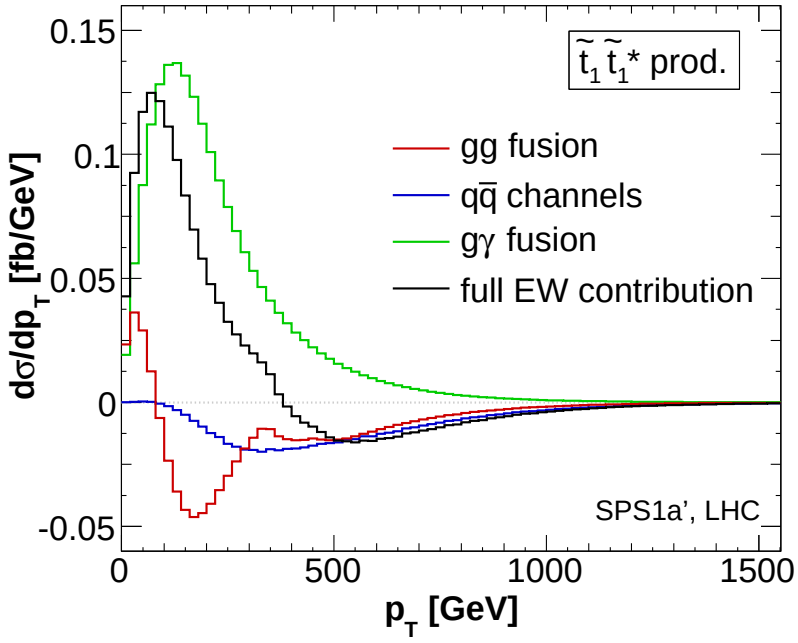
$\tilde{g}\tilde{q}$ prod.:

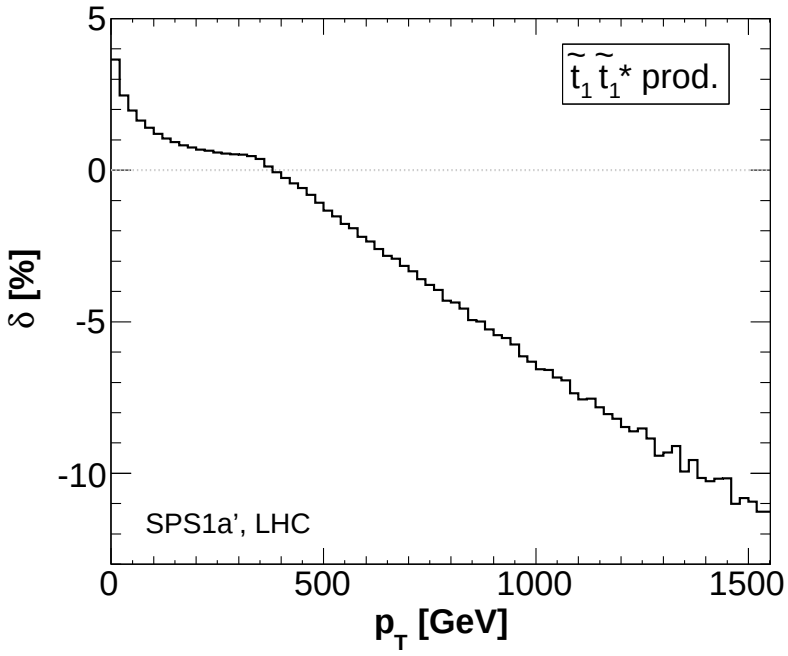


Numerical Results: Hadronic Cross Sections IV

[Hollik, Kollar, MT '08]

$\tilde{t}_1\tilde{t}_1^*$ prod.: $p_T(\tilde{g})$ distribution

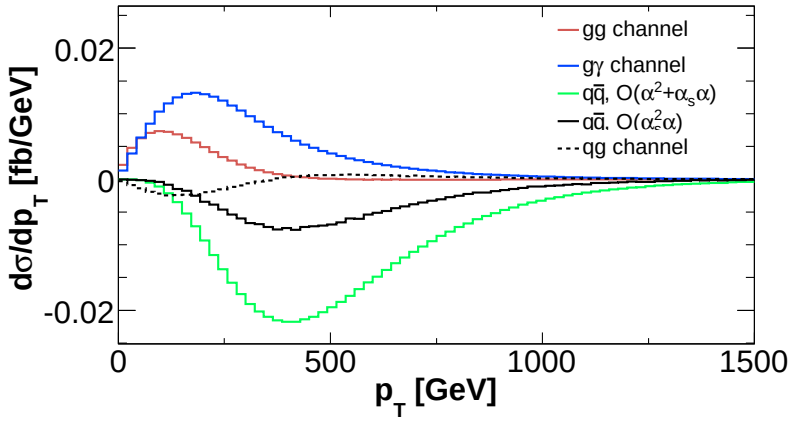


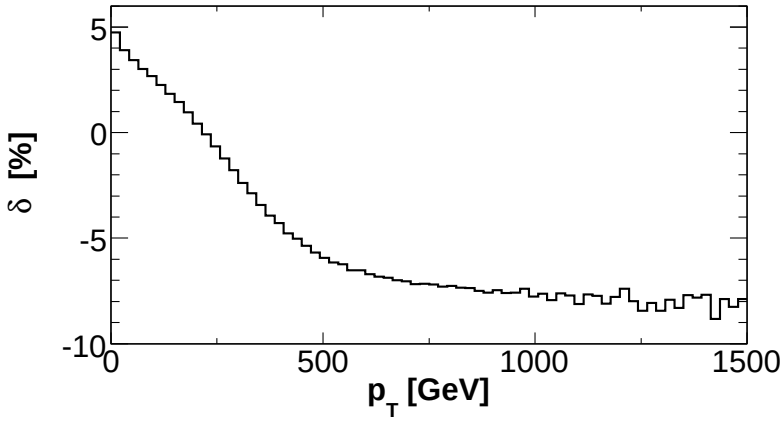


Numerical Results: Hadronic Cross Sections V

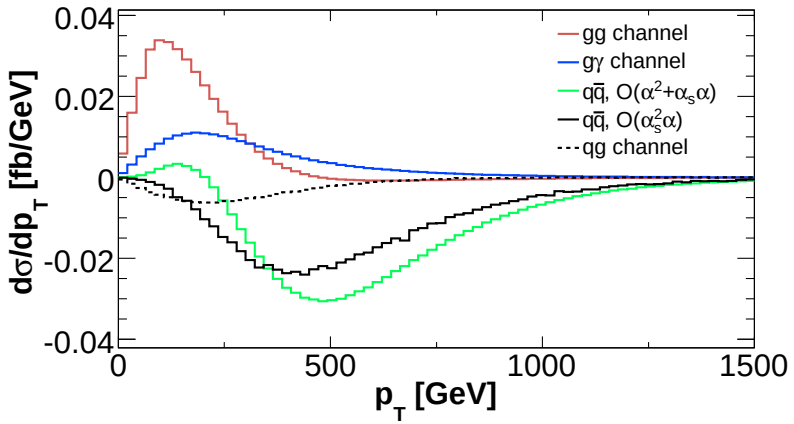
$\tilde{u}_R\tilde{u}_R^*$ prod.: $p_T(\tilde{g})$ distribution

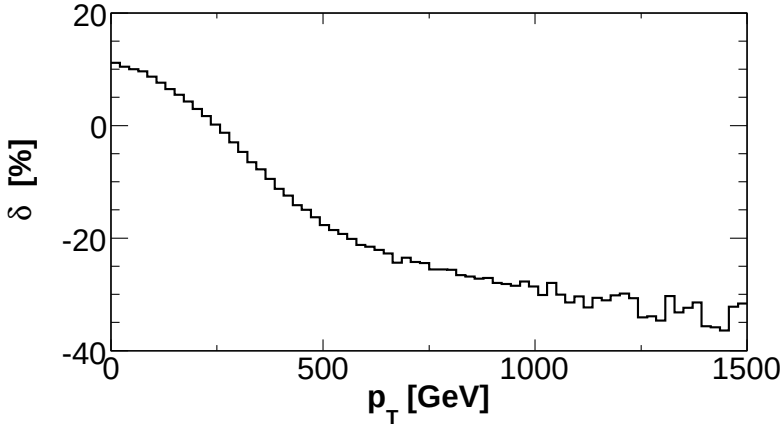
[Hollik, Mirabella '08]





$\tilde{u}_L\tilde{u}_L^*$ prod.: $p_T(\tilde{g})$ distribution

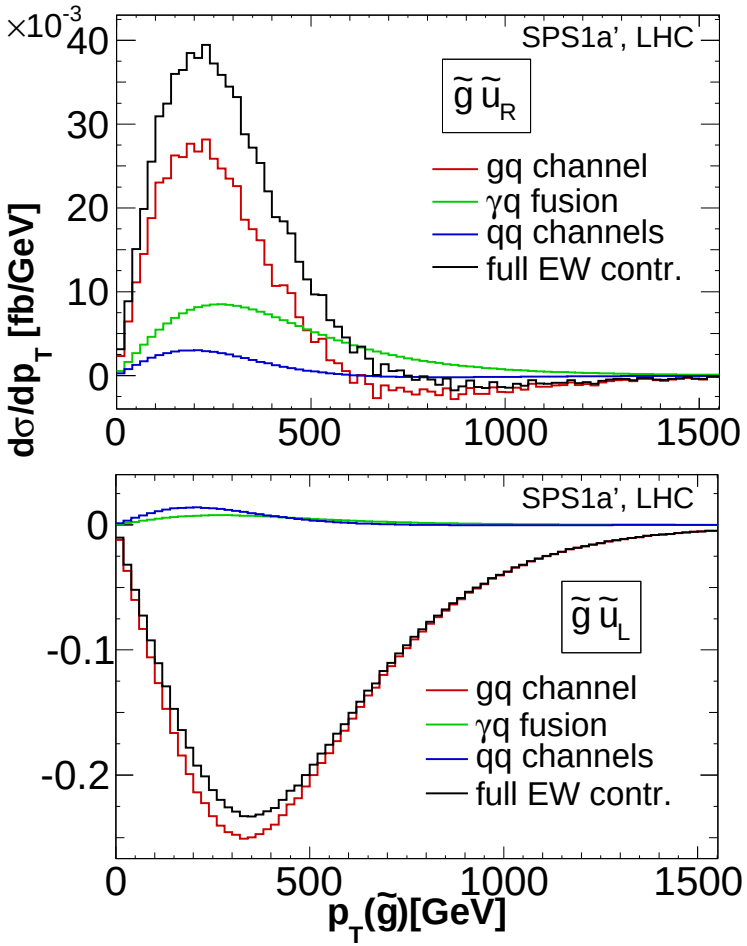


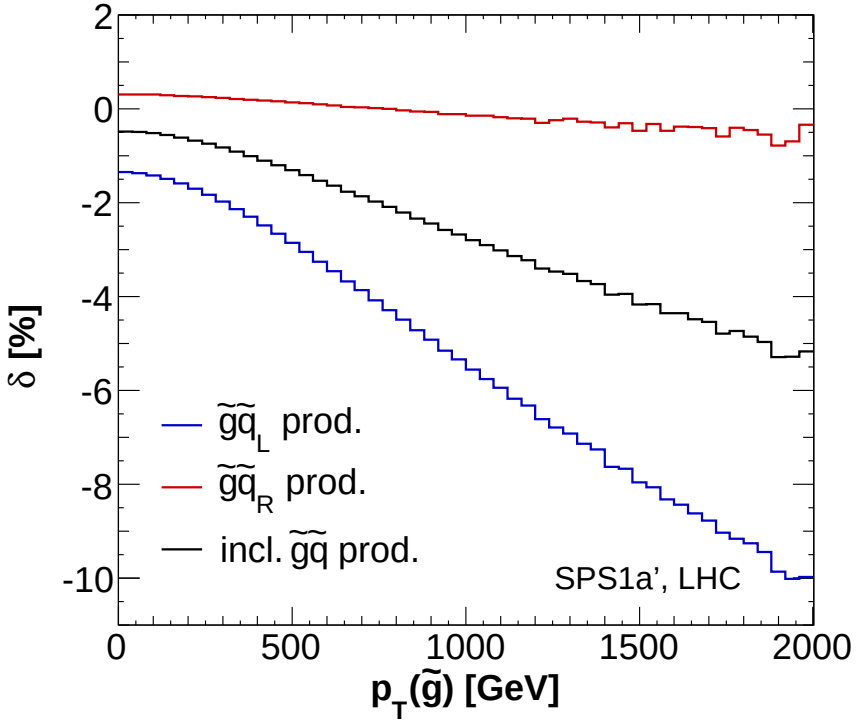


Numerical Results: Hadronic Cross Sections VI

[Hollik, Mirabella, MT '08]

$\tilde{g}\tilde{q}$ prod.: $p_T(\tilde{g})$ distribution

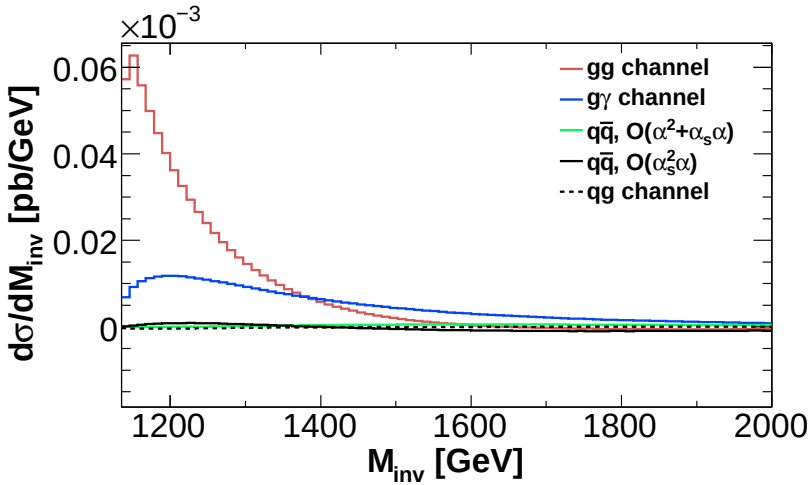


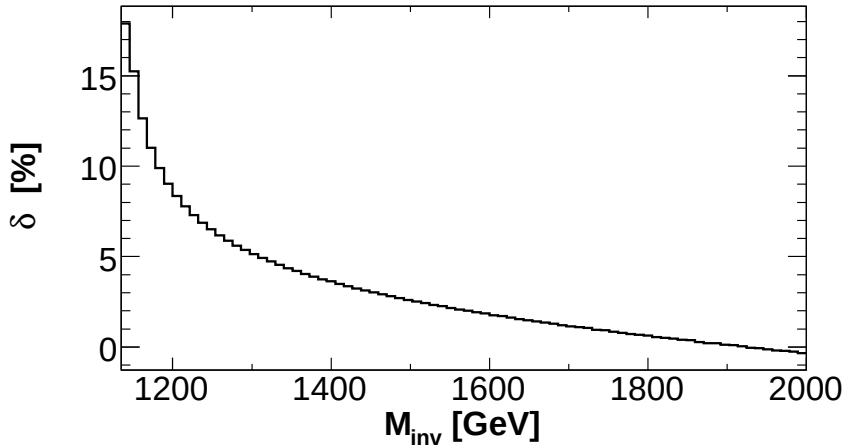


$\tilde{q}\tilde{q}^*$ prod.: different flavors

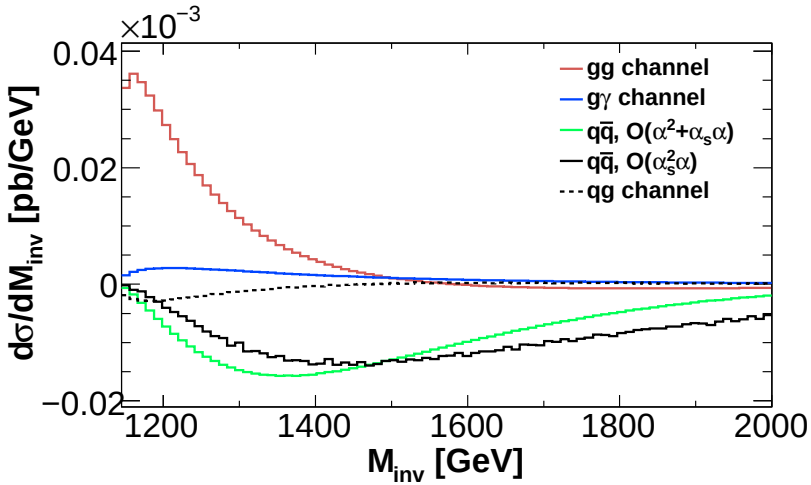
[Hollik, Mirabella '08]

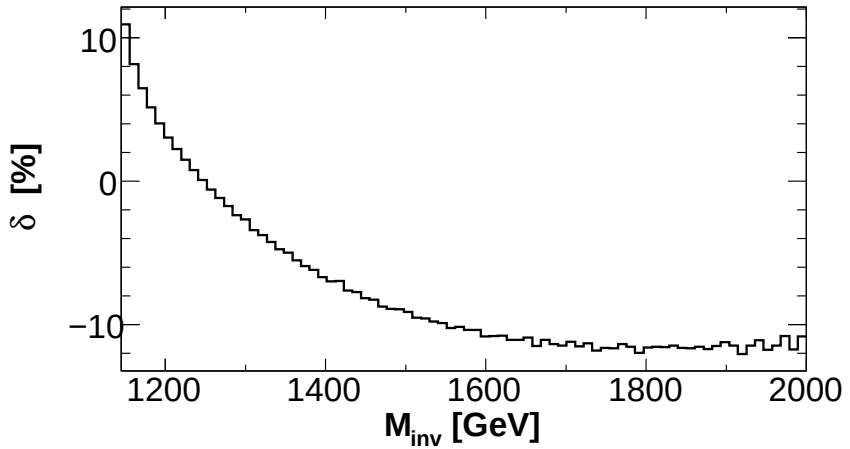
$\tilde{c}_L\tilde{c}_L^*$ prod.:





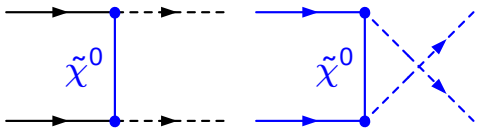
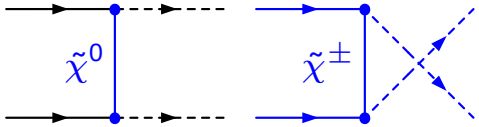
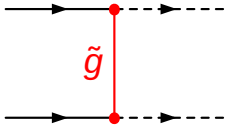
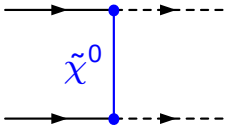
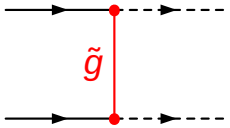
$\tilde{d}_L\tilde{d}_L^*$ prod.:





$\tilde{q}\tilde{q}$ production at tree-level

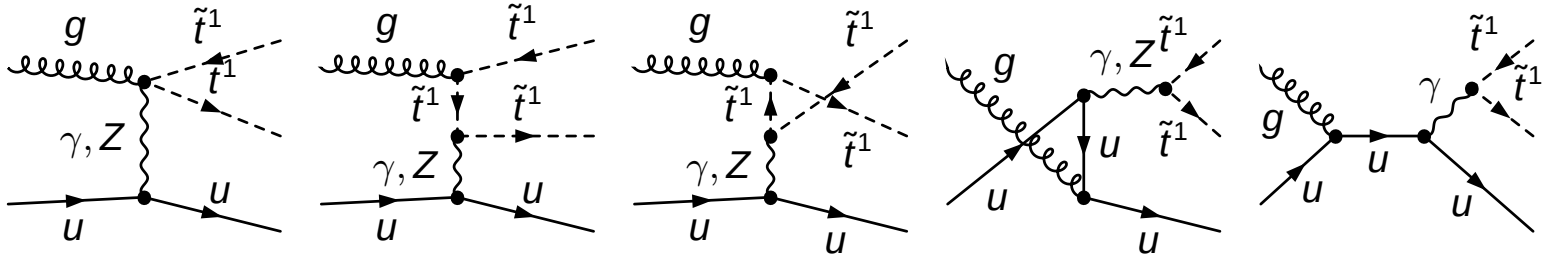
[slide: thanks to Jan Germer]

Subprocess	Electroweak contribution		Strong contribution
$qq \to \tilde{q}_a\tilde{q}_b$		+	
$qq' \to \tilde{q}_a\tilde{q}'_b$ same doublet		+	
$qq' \to \tilde{q}_a\tilde{q}'_b$ different doublet		+	

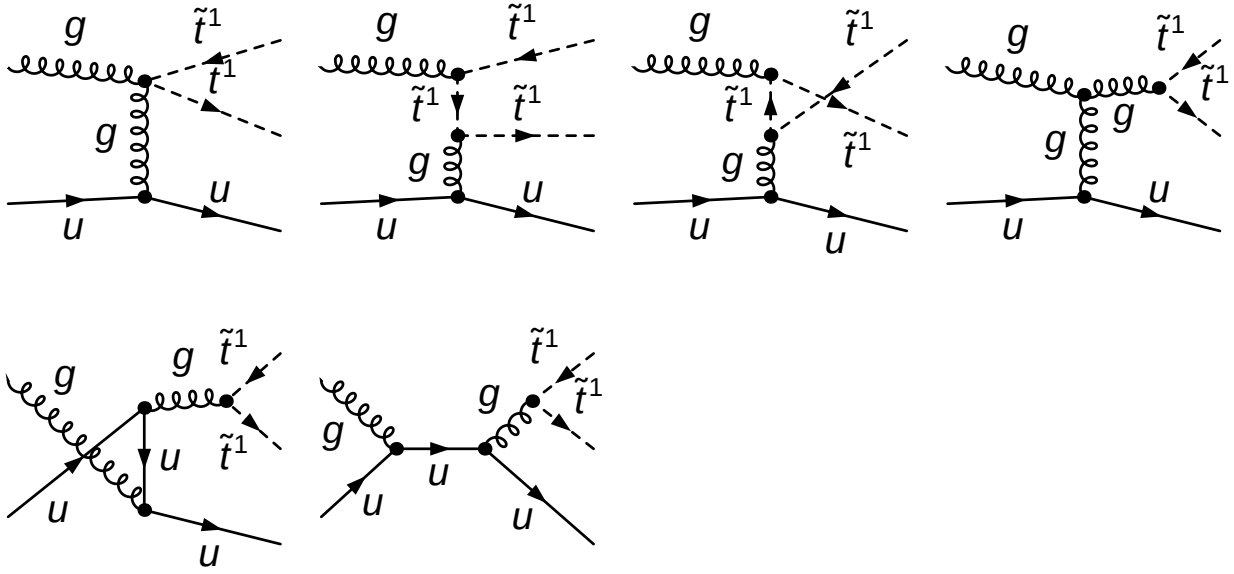
Squark- antisquark production $\to$ similar plus s-channel diagrams.

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

EW diagrams:



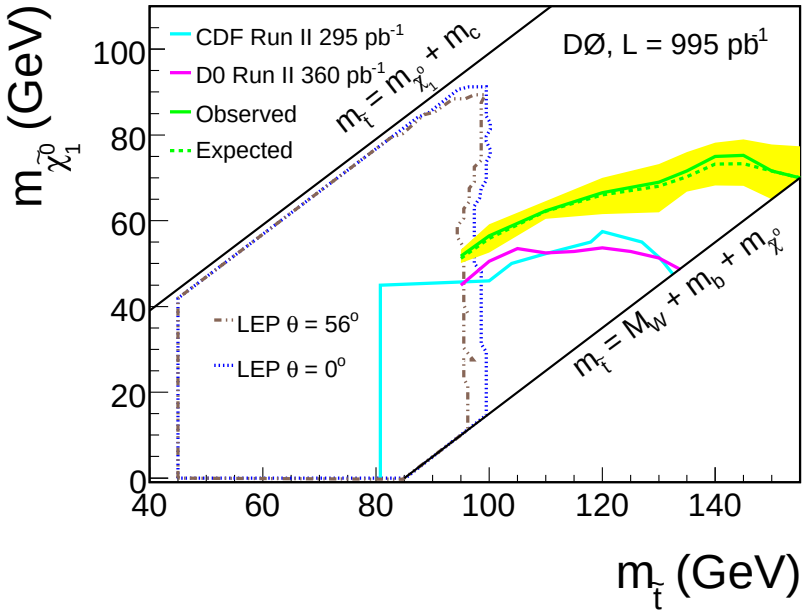
QCD diagrams:



Experimental Searches

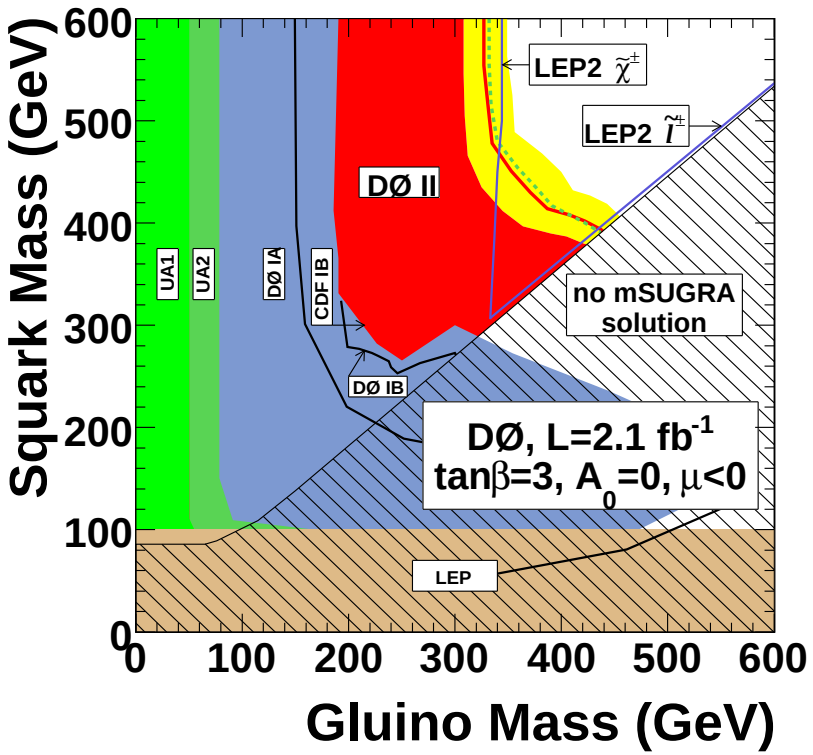
stop mass limits

[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