Squark production at the LHC at electroweak NLO

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W. HOLLIK

MAX-PLANCK-INSTITUT FÜR PHYSIK, MUNICH

Outline

- Overview
- Squark–anti-squark production
  1st and 2nd generation, stop
- Squark–squark production
  1st and 2nd generation
- Sbottom pair production
- Conclusions

SUSY particle production

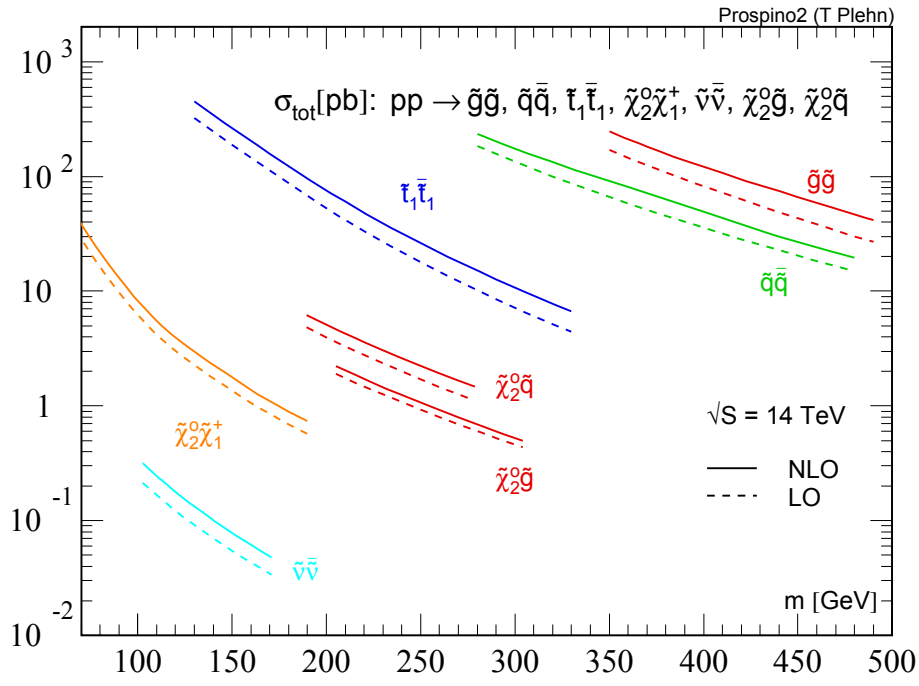
LHC: predominantly colored SUSY particles produced

- 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**



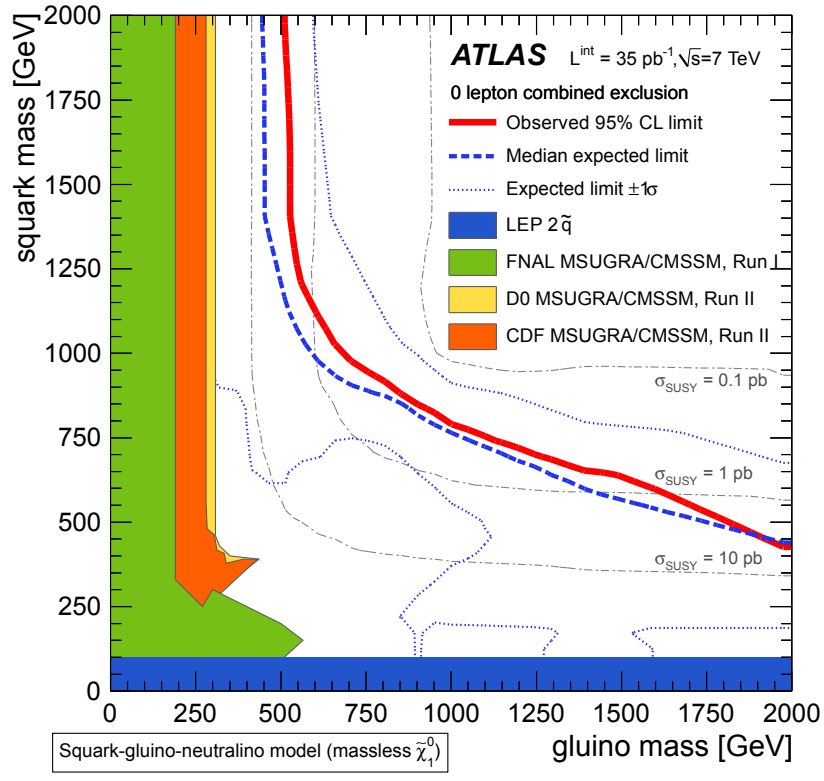
- **cross section depend** essentially **on final state masses**

Experimental searches for squarks and gluinos:

- **Squark** & **gluino** mass limits
  ATLAS, LHC 7 TeV

  $m_{\tilde{g}} \geq 500$ GeV
  $m_{\tilde{q}} \geq 450$ GeV

  [arXiv:1102:5290]

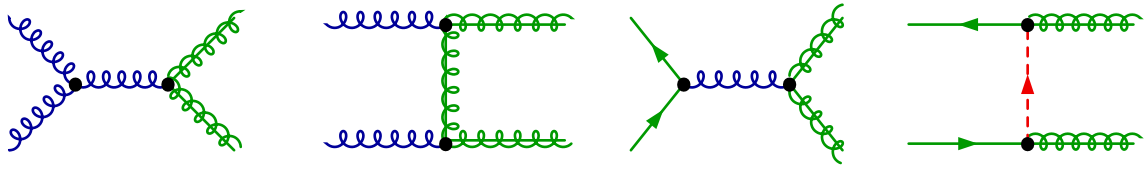


LO contributions to squark pair production (QCD tree level)

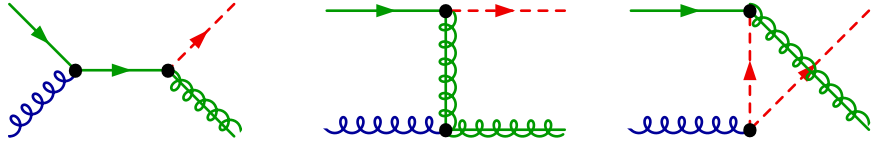
Kane,Leveille '82; Harrison, Llewellyn Smith '83; Reya, Roy '85;

Dawson, Eichten Quigg '85, Baer, Tata '85

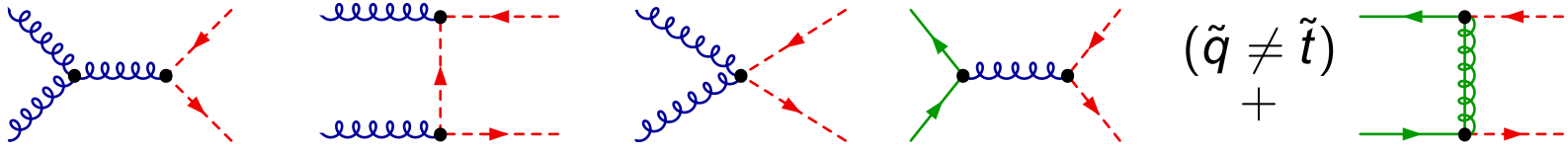
- $\mathcal{O}(\alpha_s^2)$: – $\tilde{g}\tilde{g}$ production



– $\tilde{g}\tilde{q}$ production



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



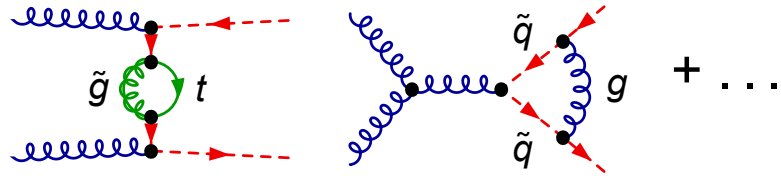
  - stops & sbottoms: L–R mixing cannot be neglected; exp. distinguishable
  - top-squark pair production is diagonal at LO

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

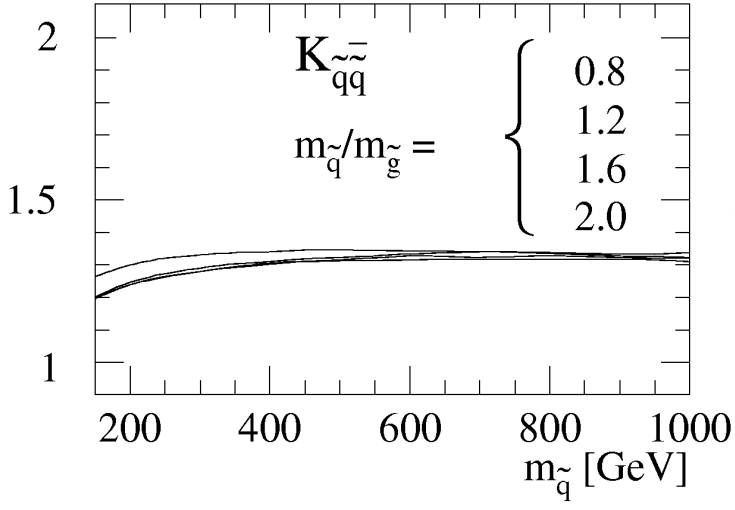
QCD Born ×

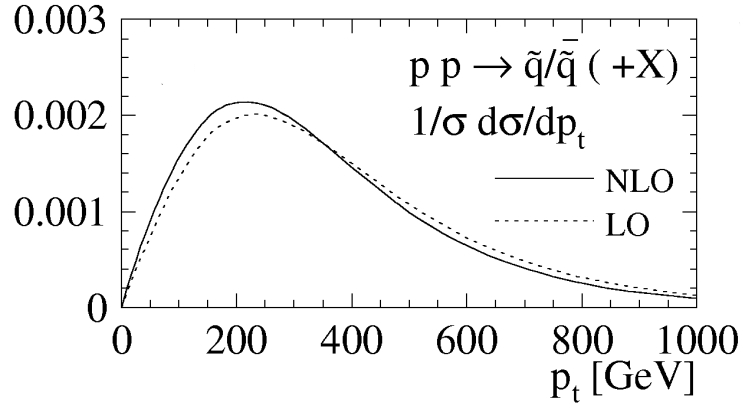


+ . . .

+ real gluon & real quark radiation

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

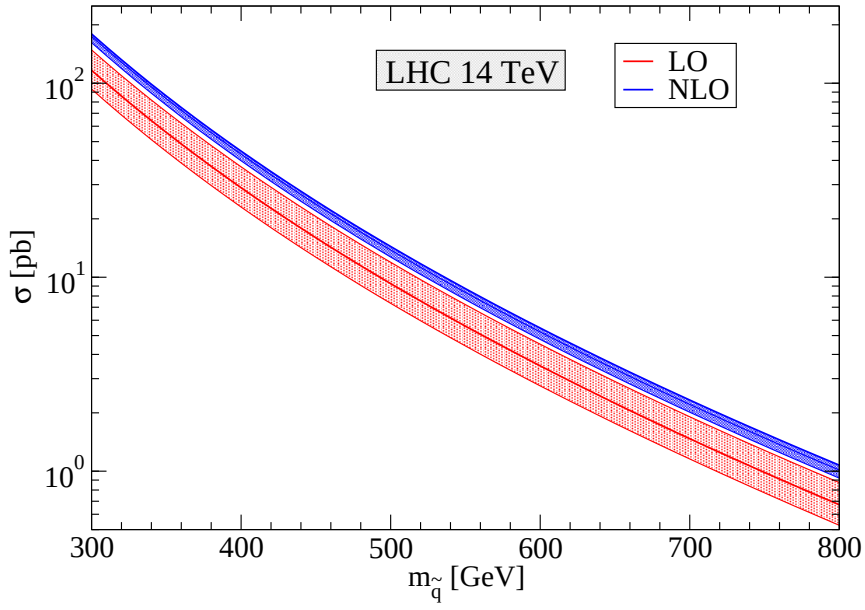


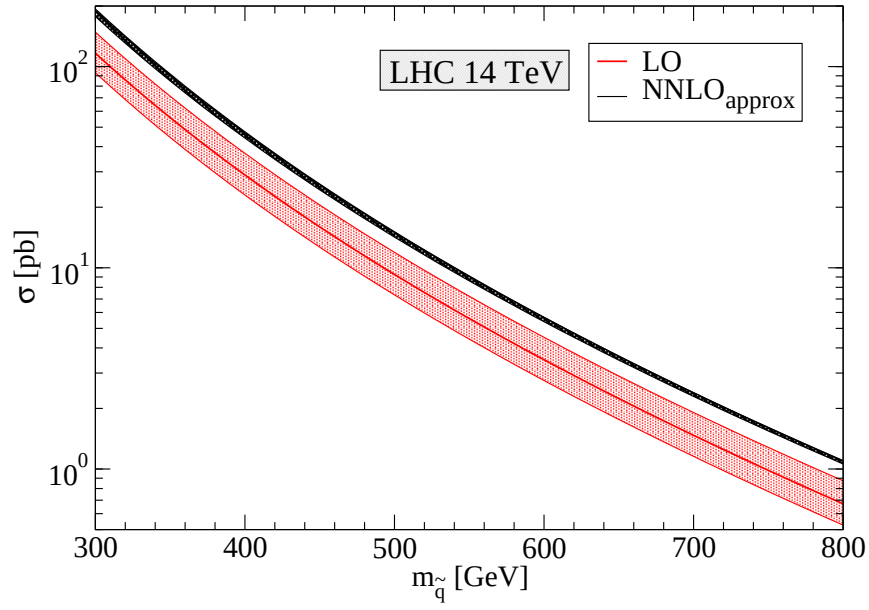


- large positive corrections
- reduced scale dependence
- negligible in normalized distributions

NNLO for squark production, dominant soft corrections

Kulesza et al. 2008/09; Langenfeld, Moch 2009; Beneke et al. 2009; Beenakker et al. 2011





– improved theoretical prediction

– reduction of scale uncertainty

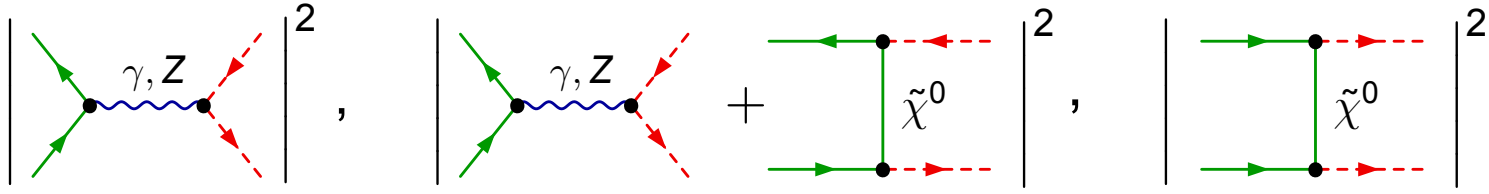
NNLO QCD contributions ∼ electroweak contributions

EW tree level contributions to squark pair production

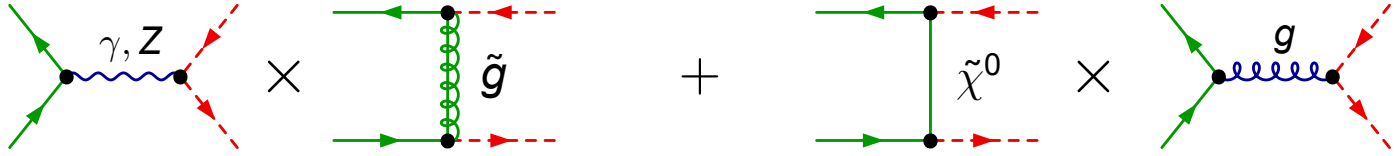
Bornhauser,Drees, Dreiner, Kim 2007

Bozzi, Fuks, Herrmann, Klasen 2007

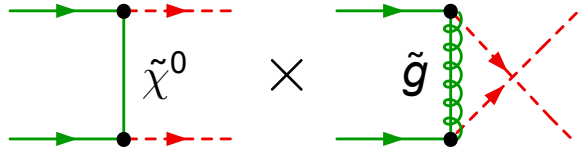
- $\mathcal{O}(\alpha^2)$: pure EW tree-level contributions ($\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$ prod.)



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



– EW-QCD tree-level interferences to $\tilde{q}\tilde{q}$ production

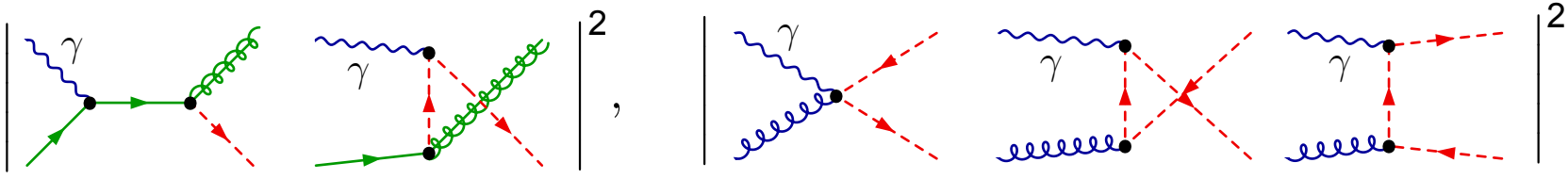


new production channel:

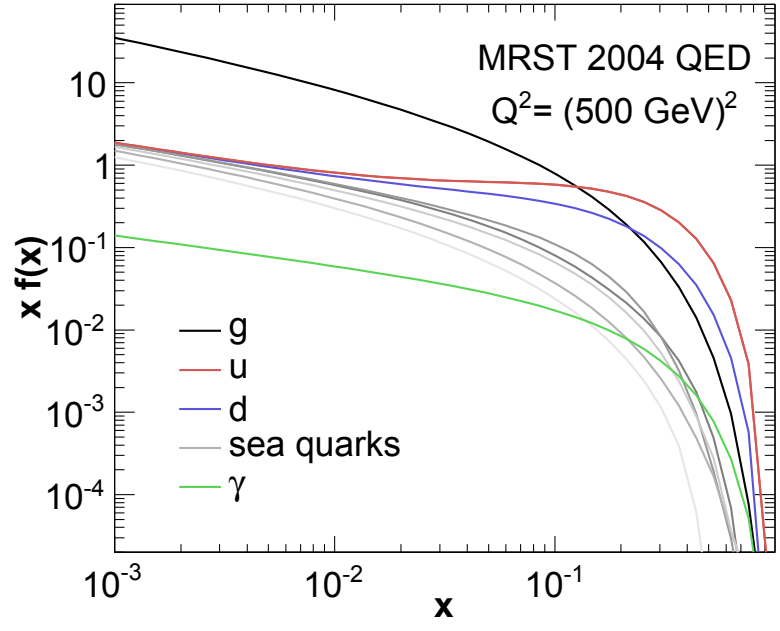
WH, Kollar, Trenkel 2007

WH, Mirabella 2008

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



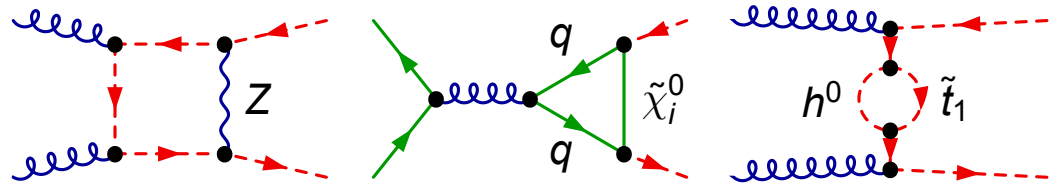
- not present at LO at the hadronic level
- **MRST 2004 QED**: inclusion of **NLO QED effects** in the evolution of PDFs
  - → non-zero photon distribution
  - → non-zero hadronic contributions



• $\mathcal{O}(\alpha_s^2\alpha)$: NLO EW contributions $(\tilde{t}\tilde{t}^*, \tilde{q}\tilde{q}^*)$

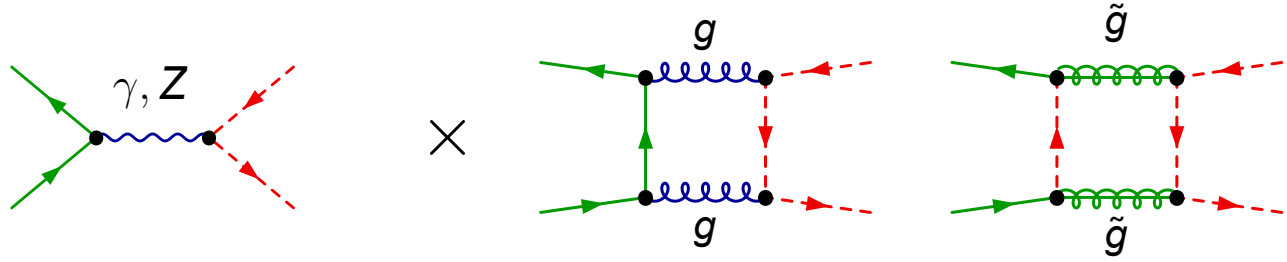
WH, Kollar, Mirabella, Trenkel 07,08

QCD Born $\times$

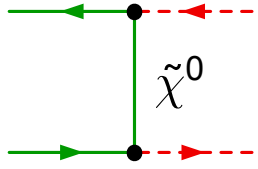


+ . . .

+ EW-QCD one-loop interferences



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

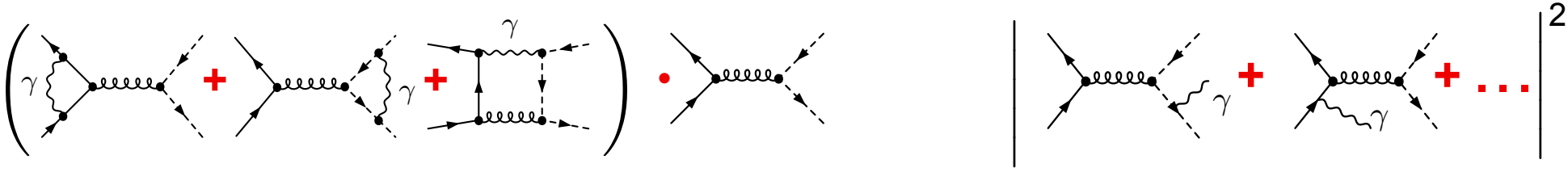


$\times$ full QCD 1-loop amplitude

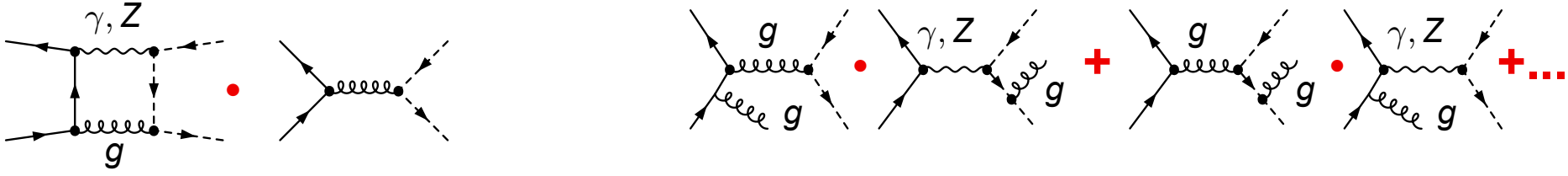
+ real photon, gluon, and quark radiation

IR divergences canceled by real photon and gluon bremsstrahlung

- soft divergent diagrams and soft photon bremsstrahlung



- soft gluon divergent diagrams and soft gluon bremsstrahlung

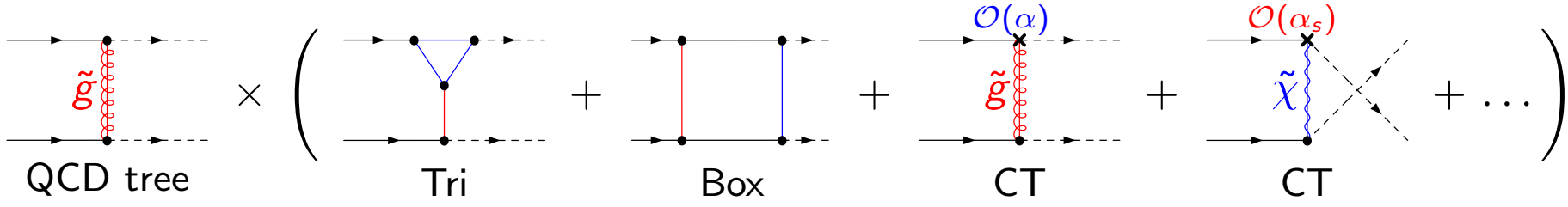


+ t-channel diagrams

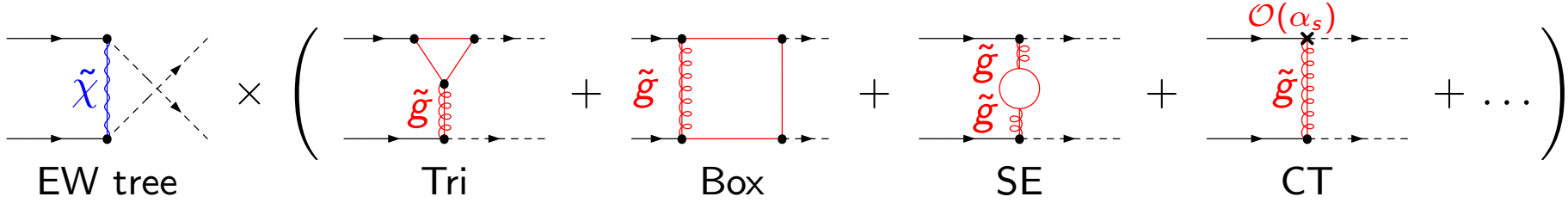
• $\mathcal{O}(\alpha_s^2\alpha)$: NLO EW contributions for $\tilde{q}\tilde{q}$ production $(\neq \tilde{t}, \tilde{b})$

Germer, WH, Mirabella, Trenkel 2010

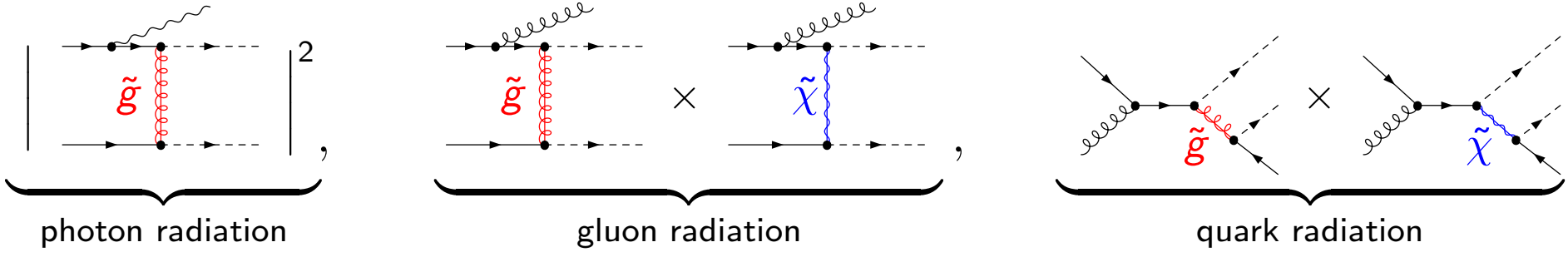
- QCD tree × 1-loop amplitude $\mathcal{O}(\alpha_s\alpha)$, e.g.



- EW tree × 1-loop amplitude $\mathcal{O}(\alpha_s^2)$, e.g.

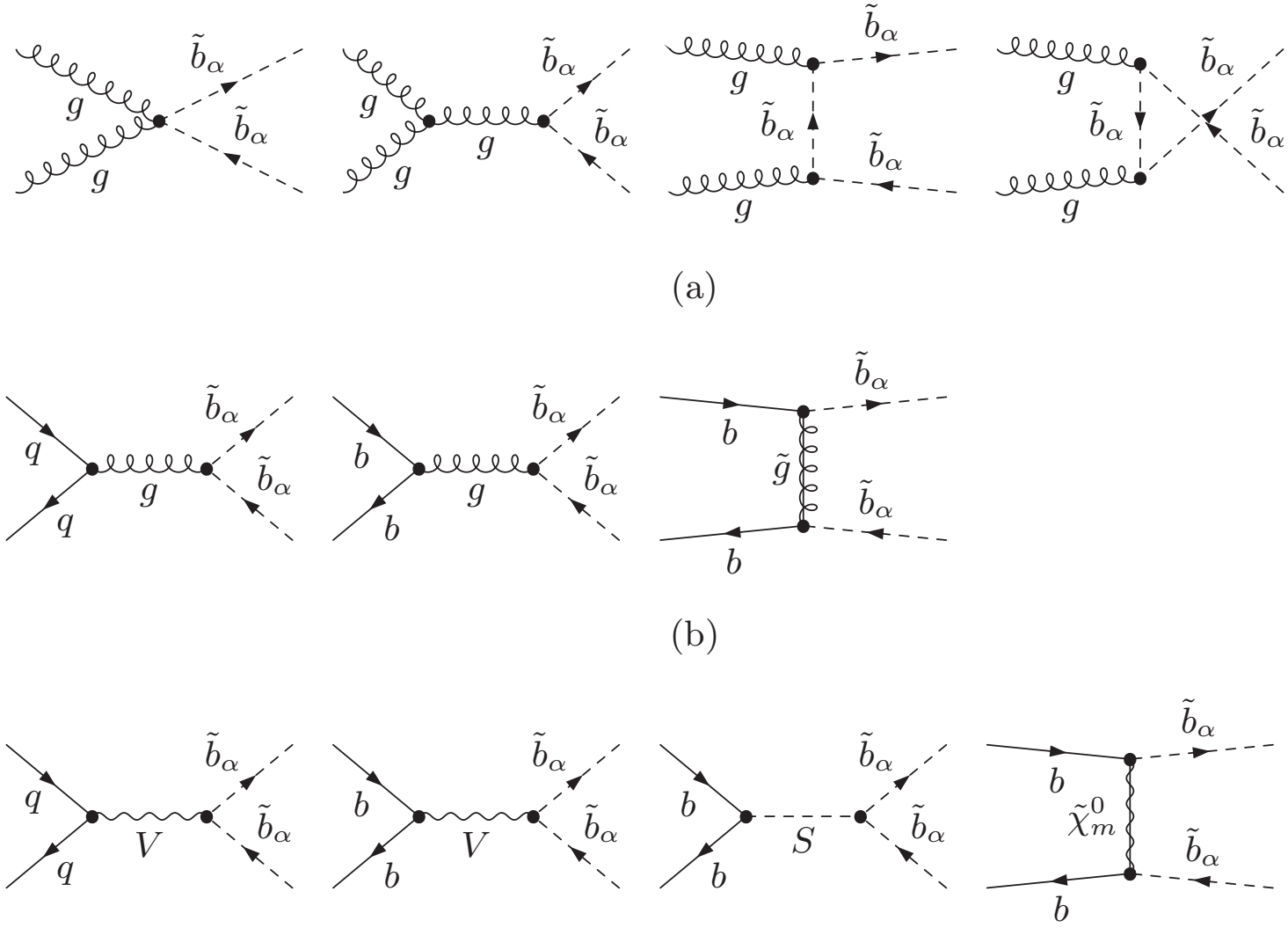


IR divergences canceled by real photon and gluon bremsstrahlung



• $\mathcal{O}(\alpha_s^2\alpha)$: NLO EW contributions for $\tilde{b}\tilde{b}^*$, $\tilde{b}\tilde{b}$ production

Germer, WH, Mirabella 2011



Status of higher-order corrections for all squark and gluino production processes.

		α_s^2	α_s^3	NLL	NNLO	α^2	$\alpha_s\alpha$	$\alpha_s^2\alpha$	#
$\alpha,\beta \in \{1,2\}$	$\tilde{g}\ \tilde{g}$	✓	✓	✓	×	–	–	✓	1
	$\tilde{g}\ \tilde{q}_\alpha$	✓	✓	✓	×	–	–	✓	8
	$\tilde{q}_\alpha\ \tilde{q}_\alpha^*$	✓	✓	✓	✓	✓	✓	✓	8
	$\tilde{q}_\alpha\ \tilde{q}_\beta'^*$	✓	✓	✓	×	✓	✓	×	28
	$\tilde{q}_\alpha\ \tilde{q}_\beta'$	✓	✓	✓	×	✓	✓	✓	36
	$\tilde{b}_\alpha\ \tilde{b}_\alpha^*$	✓	✓	✓	×	✓	✓	✓	2
	$\tilde{t}_\alpha\ \tilde{t}_\alpha^*$	✓	✓	✓	×	✓	–	✓	2

 # = number of parton processes

Renormalization

- **quarks, squarks, gluino** $\rightarrow$ **renormalized on-shell**
  Treat LH down-type squark as dependent quantity.
- **(s)bottom sector** $\rightarrow$ take $m^{OS}_{\tilde{b}_2}$, $m_b^{\overline{DR}}$, $A_b^{\overline{DR}}$ as independent quantities.
  $\tan\beta$ enhanced contributions resummed.

  - $\alpha_s \rightarrow$ **$\overline{\text{MS}}$ with five flavors** (same definition as in pdf)
    $\Rightarrow$ add finite parts to the counterterm to exclude the effects of heavy particles.

$$\delta g_s = -\frac{\alpha_s}{4\pi}\left[\frac{2}{3}\Delta + \frac{1}{3}Ln\left(\frac{m_t^2}{\mu^2}\right) + Ln\left(\frac{m_{\tilde{g}}^2}{\mu^2}\right) + \sum_{\tilde{f}^a}\frac{1}{12}Ln\left(\frac{m_{\tilde{f}^a}^2}{\mu^2}\right)\right]$$

Caution with $\hat{g}_s$ (scalar strong coupling – $q\tilde{q}\tilde{g}$ vertex):

- **SUSY demands $\hat{g}_s = g_s$** but $\overline{MS}$ spoils SUSY.
- Add symmetry restoring counterterm:

$$\delta\hat{g}_s = \delta g_s + \frac{\alpha_s}{3\pi}$$

- **IR singularities**:
  - Cancel after combining **virtual** and **real** corrections.

    [Methods: **mass regularization** & **phase space slicing**;
    gluonic corrections: **color correlations** in EW-QCD interferences.]

- **Collinear singularities**:
  - Real photon and gluon **bremsstrahlung**.
  - **Factorization** and **redefinition** of the **PDFs** at $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha)$.

EW contributions are chirality/flavour dependent

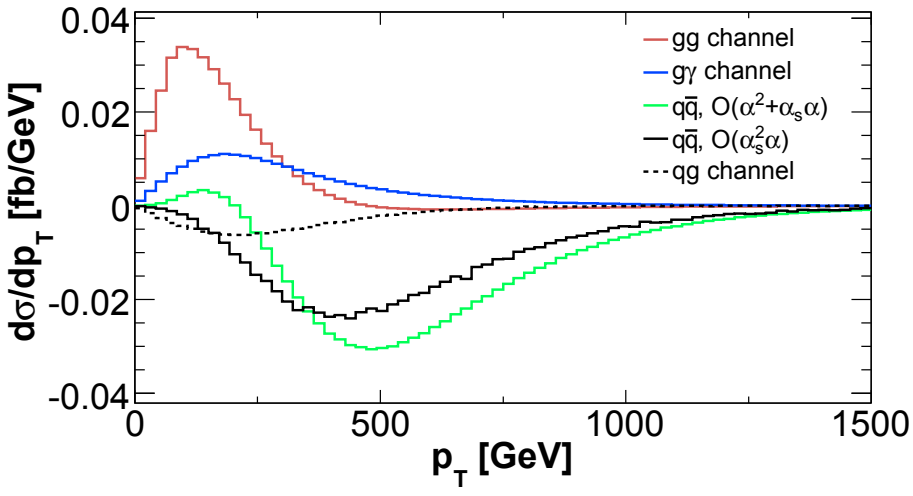
(xsection in pb, SPS1a′)

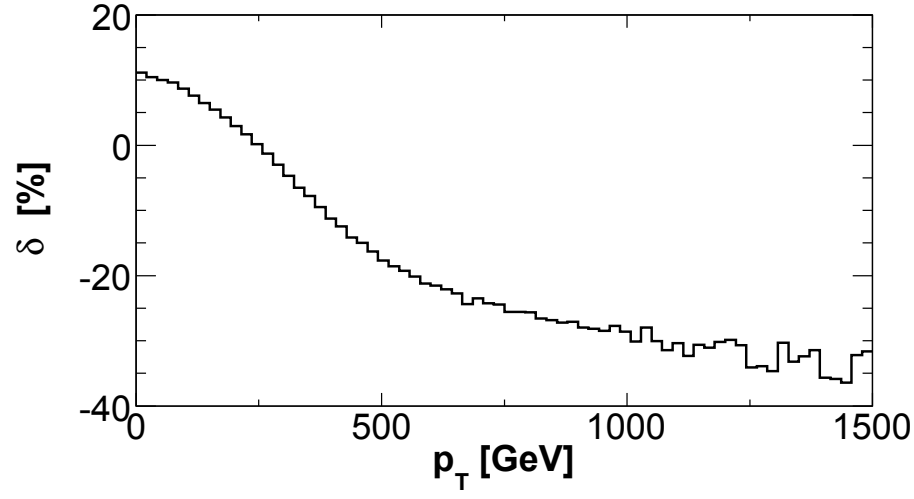
	$\tilde{u}^R\tilde{u}^{R*}$	$\tilde{u}^L\tilde{u}^{L*}$	$\tilde{d}^L\tilde{d}^{L*}$	$\tilde{c}^L\tilde{c}^{L*}$
$\mathcal{O}(\alpha_s^2)$	$(36.83 \pm 0.03) \cdot 10^{-2}$	$(31.31 \pm 0.01) \cdot 10^{-2}$	$(25.89 \pm 0.01) \cdot 10^{-2}$	$(22.65 \pm 0.01) \cdot 10^{-2}$
$\mathcal{O}(\alpha_s\alpha)$	$(-9.00 \pm 0.01) \cdot 10^{-3}$	$(-3.54 \pm 0.01) \cdot 10^{-2}$	$(-3.83 \pm 0.01) \cdot 10^{-2}$	$(2.82 \pm 0.01) \cdot 10^{-3}$
$\mathcal{O}(\alpha^2)$	$(2.42 \pm 0.01) \cdot 10^{-3}$	$(2.39 \pm 0.01) \cdot 10^{-2}$	$(3.20 \pm 0.01) \cdot 10^{-2}$	$(2.11 \pm 0.01) \cdot 10^{-3}$
$\mathcal{O}(\alpha_s^2\alpha)$	$(-3.09 \pm 0.05) \cdot 10^{-3}$	$(-1.05 \pm 0.01) \cdot 10^{-2}$	$(-7.82 \pm 0.07) \cdot 10^{-3}$	$(5.89 \pm 0.01) \cdot 10^{-3}$
$\delta(\%)$	-2.6	-7.0	-5.5	4.8

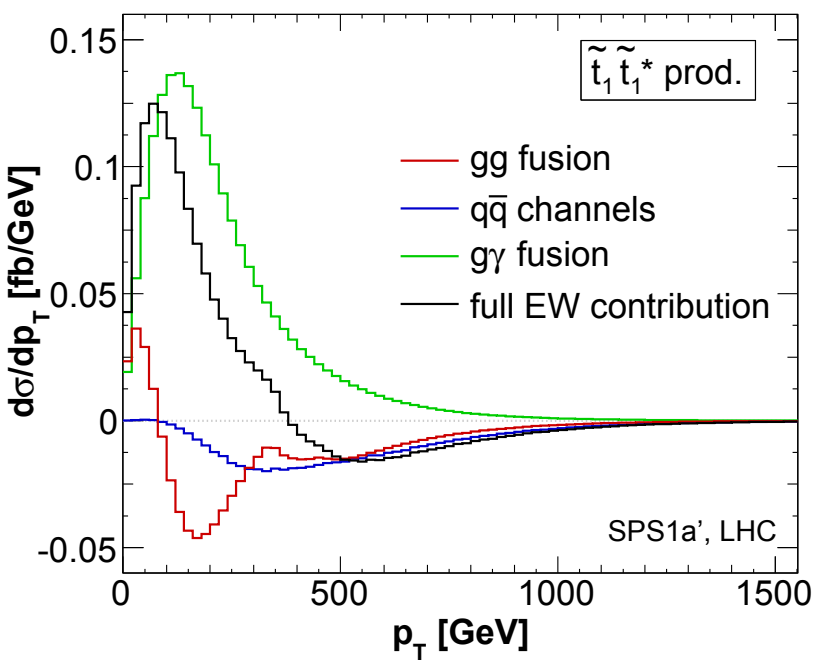
and fairly model dependent *(example: $u_L u_L^*$)*

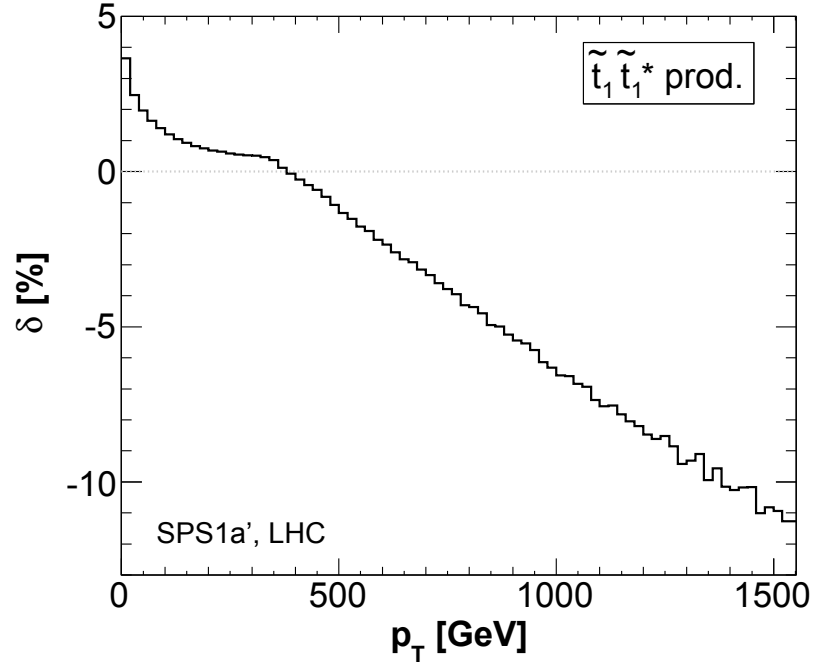
	SPS5	SU1	SU4
$\mathcal{O}(\alpha_s^2)$	$(10.62 \pm 0.01) \cdot 10^{-2}$	$(51.77 \pm 0.02) \cdot 10^{-3}$	$(16.14 \pm 0.01) \cdot 10^{-1}$
$\mathcal{O}(\alpha_s\alpha)$	$(-1.37 \pm 0.01) \cdot 10^{-2}$	$(-7.22 \pm 0.01) \cdot 10^{-3}$	$(-1.45 \pm 0.01) \cdot 10^{-1}$
$\mathcal{O}(\alpha^2)$	$(9.11 \pm 0.01) \cdot 10^{-3}$	$(4.73 \pm 0.01) \cdot 10^{-3}$	$(10.16 \pm 0.01) \cdot 10^{-2}$
$\mathcal{O}(\alpha_s^2\alpha)$	$(-4.83 \pm 0.03) \cdot 10^{-3}$	$(-2.75 \pm 0.02) \cdot 10^{-3}$	$(-2.61 \pm 0.01) \cdot 10^{-2}$
$\delta(\%)$	-8.9	-10.1	-4.3

$u_{\mathrm{L}}u_{\mathrm{L}}^{*}$, *SPS1a′*






$\tilde{t}_1\tilde{t}_1^*$ prod.
gg fusion
$q\bar{q}$ channels
$g\gamma$ fusion
full EW contribution
SPS1a', LHC
$d\sigma/dp_T$ [fb/GeV]
p_T [GeV]
0.15
0.1
0.05
0
-0.05
0
500
1000
1500


$\tilde{t}_1\tilde{t}_1^*$ prod.
SPS1a', LHC
δ [%]
p_T [GeV]
5
0
-5
-10
0
500
1000
1500

- **Squark–Squark** production:
  - Squarks of the **same flavor** (#12),

$$PP \to \tilde{u}_\alpha \tilde{u}_\beta,\ \tilde{d}_\alpha \tilde{d}_\beta,\ \tilde{c}_\alpha \tilde{c}_\beta,\ \tilde{s}_\alpha \tilde{s}_\beta, \qquad \{\alpha\beta\} = \{LL,\ RR,\ LR\}.$$

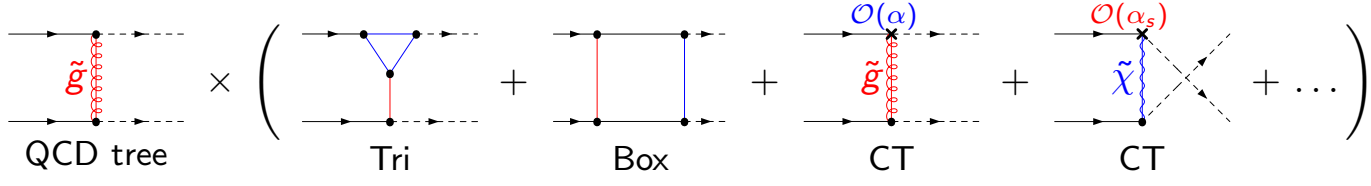
  - Squarks belonging to the **same SU(2) doublet** (#8),

$$PP \to \tilde{u}_\alpha \tilde{d}_\beta,\ \tilde{c}_\alpha \tilde{s}_\beta, \qquad \{\alpha\beta\} = \{LL,\ RR,\ LR,\ RL\}.$$

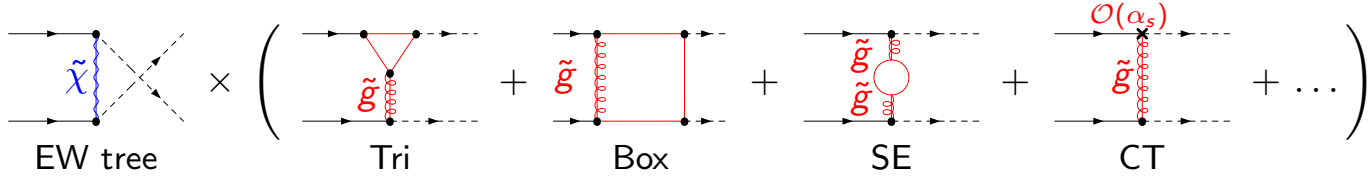
  - Squarks in **different SU(2) doublets** (#16),

$$PP \to \tilde{u}_\alpha \tilde{c}_\beta,\ \tilde{u}_\alpha \tilde{s}_\beta,\ \tilde{d}_\alpha \tilde{c}_\beta,\ \tilde{d}_\alpha \tilde{s}_\beta, \qquad \{\alpha\beta\} = \{LL,\ RR,\ LR,\ RL\}.$$

    - QCD tree $\times$ 1-loop amplitude $\mathcal{O}(\alpha_s\alpha)$, e.g.

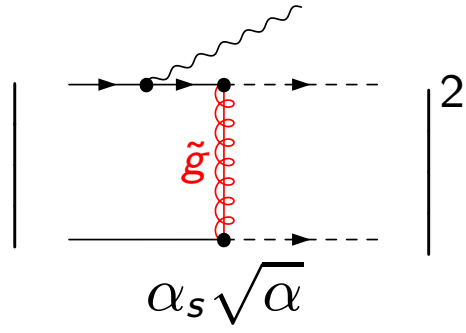


    - EW tree $\times$ 1-loop amplitude $\mathcal{O}(\alpha_s^2)$, e.g.

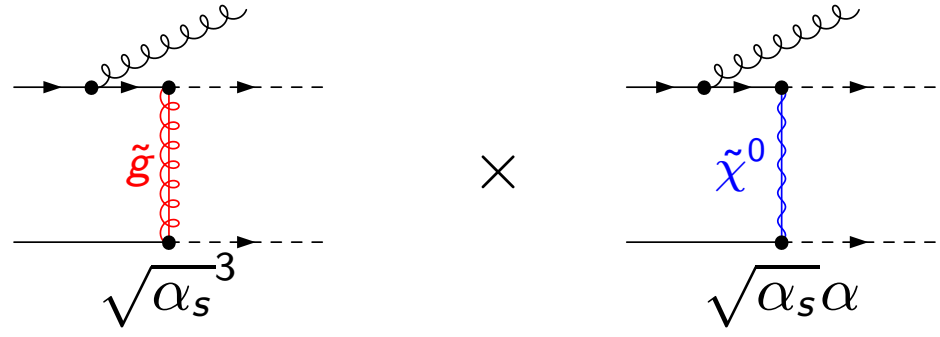


real NLO contributions $\mathcal{O}(\alpha_s^2\alpha)$

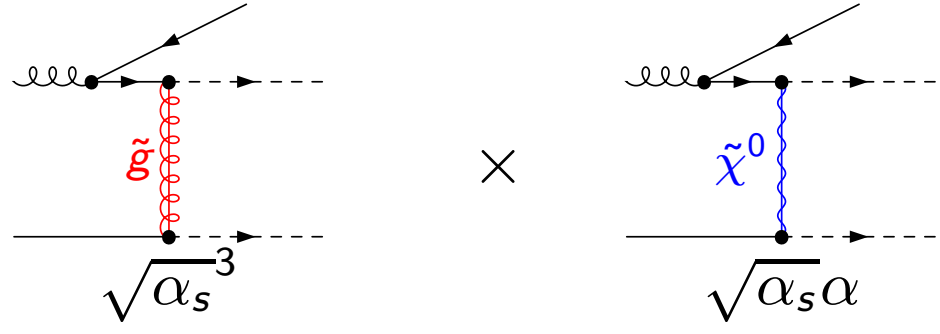
Photon bremsstrahlung



Gluon bremsstrahlung



Gluon splitting
(real quark radiation)



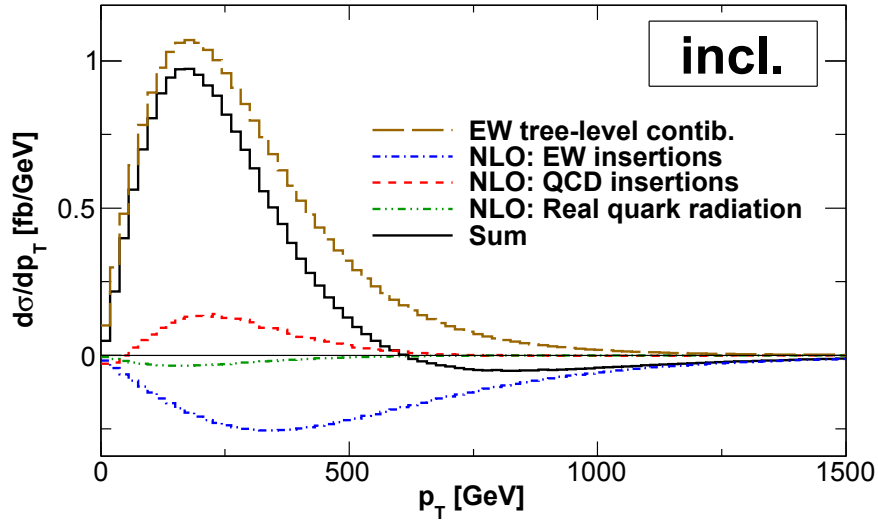
Total cross section [*fb*]

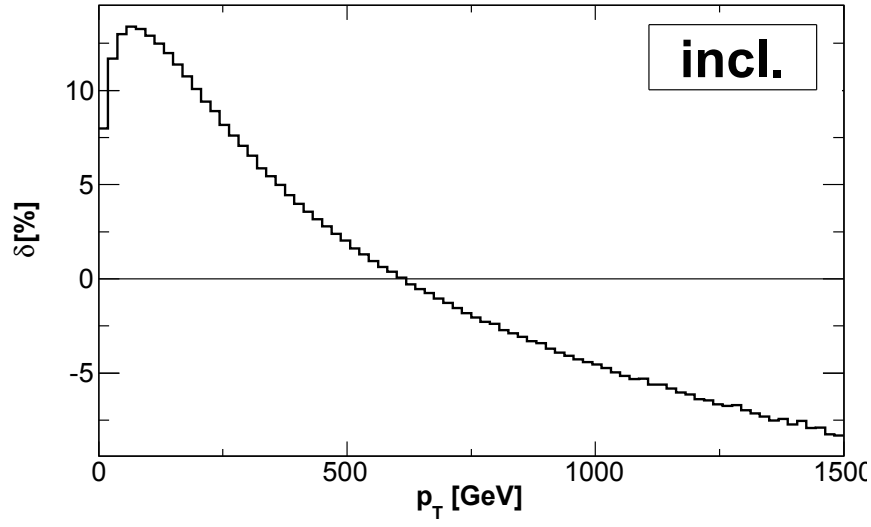
SPS1a′ 14 TeV	σ^{Born} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{\text{tree EW}}$ $\mathcal{O}(\alpha_s\alpha+\alpha^2)$	$\Delta\sigma^{\text{NLO EW}}$ $\mathcal{O}(\alpha_s^2\alpha)$	δ^{EW}
$\tilde{q}_L\tilde{q}'_L$	1718	379	−75	17.7 %
$\tilde{q}_R\tilde{q}'_R$	1982	32	−2	1.5 %
$\tilde{q}_L\tilde{q}'_R$	1744	3	−71	−3.9 %
$\tilde{q}\tilde{q}'$	5443	413	−147	4.9 %

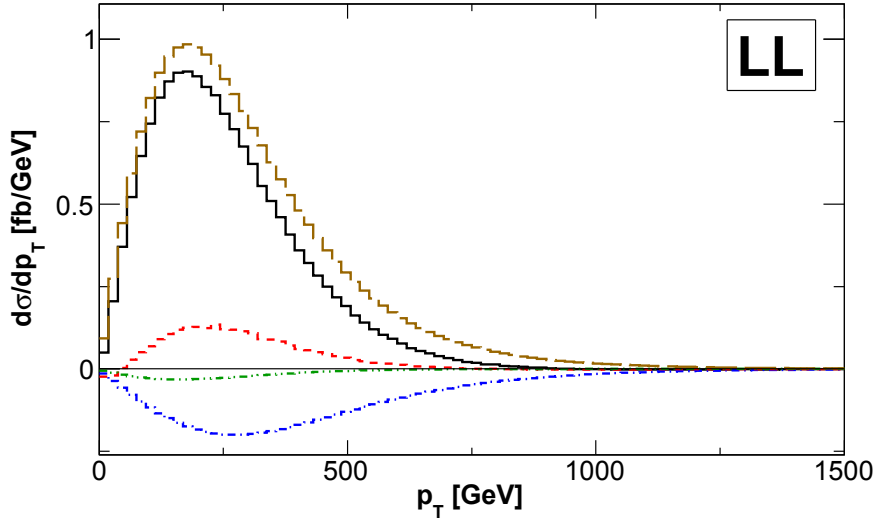
$[m_{\tilde{q}} \approx 560\ \text{GeV}]$

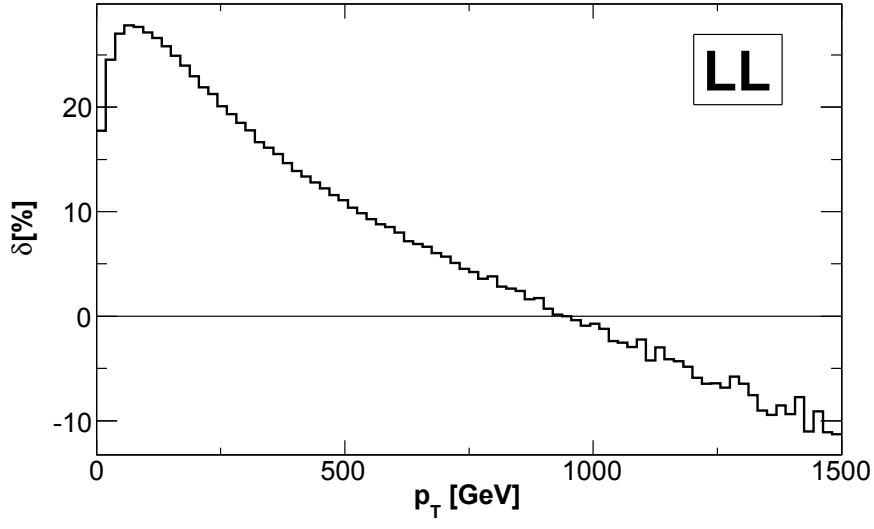
- Large cross section due to
  - → high squark multiplicity.
  - → initial state valence quarks.
- δ^{EW} strongly chirality-dependent.
- EW contributions largest for $\tilde{q}_L\tilde{q}'_L$ production.
  - → Large contribution of $\mathcal{O}(\alpha_s\alpha)$.
  - → Partially canceled by NLO EW contributions of $\mathcal{O}(\alpha_s^2\alpha)$.

SPS1a′	σ^{Born} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{\text{tree EW}}$ $\mathcal{O}(\alpha_s\alpha+\alpha^2)$	$\Delta\sigma^{\text{NLO EW}}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\delta^{\text{tree EW}}$	$\delta^{\text{NLO EW}}$	δ^{EW}
$\tilde{u}_L\tilde{u}_L$	486.8(3)	93.78(5)	−30.5(2)	19.27 %	−6.26 %	13.00 %
$\tilde{d}_L\tilde{d}_L$	143.83(8)	29.18(2)	−9.85(6)	20.29 %	−6.85 %	13.44 %
$\tilde{u}_L\tilde{d}_L$	692.6(7)	234.8(2)	−9.5(6)	33.90 %	−1.38 %	32.52 %
$\tilde{u}_L\tilde{s}_L$	211.3(2)	17.95(3)	−8.53(1)	8.50 %	−4.04 %	4.46 %
$\tilde{u}_L\tilde{c}_L$	102.96(8)	1.864(2)	−8.885(7)	1.81 %	−8.63 %	−6.82 %
$\tilde{d}_L\tilde{s}_L$	80.19(6)	1.390(2)	−7.526(4)	1.73 %	−9.39 %	−7.65 %
$\tilde{u}_R\tilde{u}_R$	537.1(4)	28.58(2)	−4.44(8)	5.32 %	−0.83 %	4.49 %
$\tilde{d}_R\tilde{d}_R$	173.1(1)	2.414(2)	−0.318(7)	1.39 %	−0.18 %	1.21 %
$\tilde{u}_R\tilde{d}_R$	799.1(6)	0.4458(8)	3.41(3)	0.06 %	0.43 %	0.48 %
$\tilde{u}_R\tilde{s}_R$	253.0(2)	0.1276(2)	1.36(1)	0.05 %	0.54 %	0.59 %
$\tilde{u}_R\tilde{c}_R$	118.95(9)	0.2365(4)	−1.337(8)	0.20 %	−1.12 %	−0.93 %
$\tilde{d}_R\tilde{s}_R$	100.65(8)	0.0126(1)	−0.281(2)	0.01 %	−0.28 %	−0.27 %
$\tilde{u}_L\tilde{u}_R$	629.7(4)	1.288(1)	−26.41(4)	0.20 %	−4.19 %	−3.99 %
$\tilde{d}_L\tilde{d}_R$	165.49(9)	0.0792(1)	−7.027(4)	0.05 %	−4.25 %	−4.20 %
$\tilde{u}_L\tilde{d}_R$	328.5(2)	0.1720(1)	−12.30(1)	0.05 %	−3.75 %	−3.69 %
$\tilde{u}_R\tilde{d}_L$	321.4(2)	0.6026(6)	−13.81(2)	0.19 %	−4.30 %	−4.11 %
$\tilde{u}_L\tilde{s}_R$	82.26(4)	0.0450(1)	−2.809(3)	0.05 %	−3.42 %	−3.36 %
$\tilde{u}_R\tilde{s}_L$	79.90(4)	0.1556(1)	−3.167(4)	0.19 %	−3.96 %	−3.77 %
$\tilde{u}_L\tilde{c}_R$	38.08(2)	0.0832(1)	−1.388(2)	0.22 %	−3.65 %	−3.43 %
$\tilde{u}_R\tilde{c}_L$	38.08(2)	0.0832(1)	−1.388(2)	0.22 %	−3.65 %	−3.44 %
$\tilde{d}_L\tilde{s}_R$	30.24(2)	0.0149(1)	−1.2015(9)	0.05 %	−3.97 %	−3.92 %
$\tilde{d}_R\tilde{s}_L$	30.24(2)	0.0149(1)	−1.2015(9)	0.05 %	−3.97 %	−3.92 %

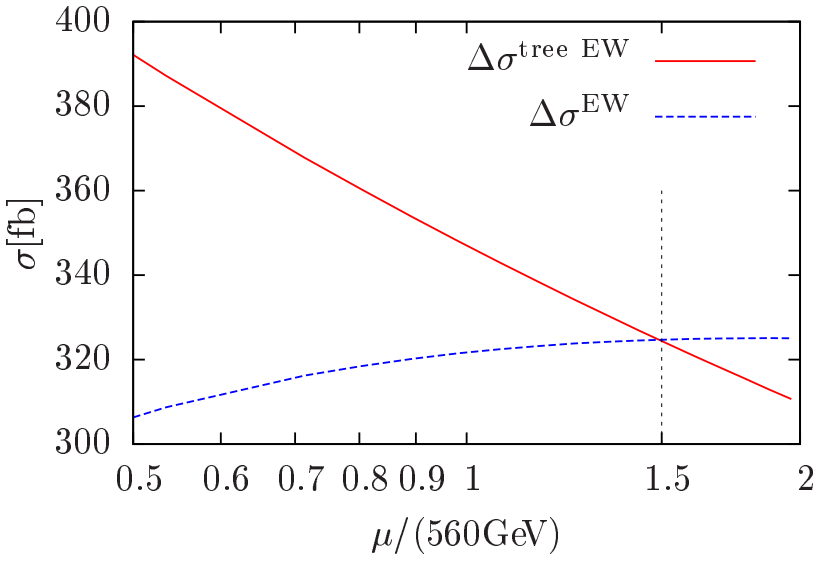

incl.
EW tree-level contib.
NLO: EW insertions
NLO: QCD insertions
NLO: Real quark radiation
Sum
dσ/dp_T [fb/GeV]
p_T [GeV]

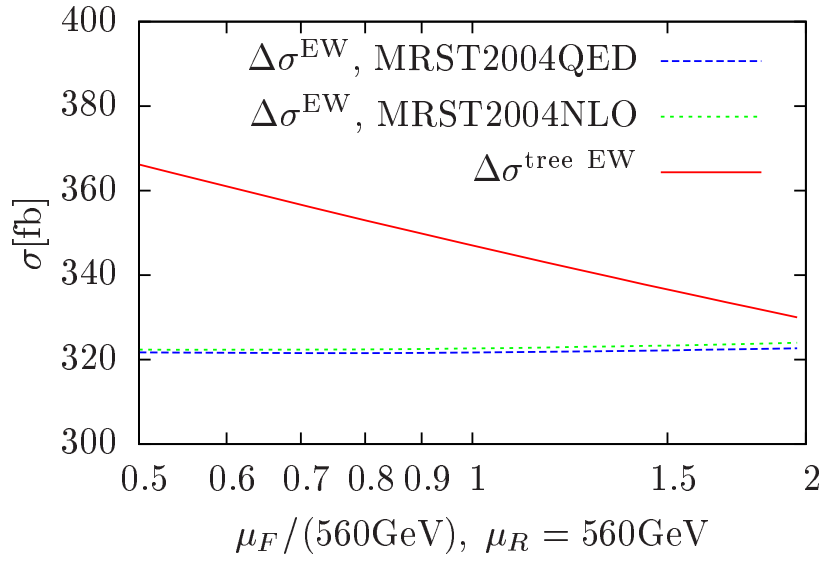

incl.
δ[%]
p_T [GeV]


LL
dσ/dp_T [fb/GeV]
p_T [GeV]


LL
δ[%]
p_T [GeV]

$$\mathrm{PP} \to \{\tilde{q}_L\tilde{q}_L, \tilde{q}_R\tilde{q}_R, \tilde{u}_L\tilde{d}_L, \tilde{c}_L\tilde{s}_L\}$$





PDF set used:
- MRST2001LO for LO EW.
- MRST2004QED for NLO EW.
- MRST2004NLO for NLO EW.

$\sigma^{\mathrm{NLO}} = \Delta\sigma^{\mathrm{tree\ EW}} + \Delta\sigma^{\mathrm{NLO\ EW}}$

SPS1a′ scenario: $m_{\tilde{q}} \approx 560$ GeV

- μ_R dependence reduced @ NLO EW.
- For $\mu = m_{\tilde{q}}/2$: LO EW contribution overestimated.
  $\to$ NLO EW corrections needed!
- μ_F dependence mild @ NLO EW.
  QED evolution of the PDF not important.

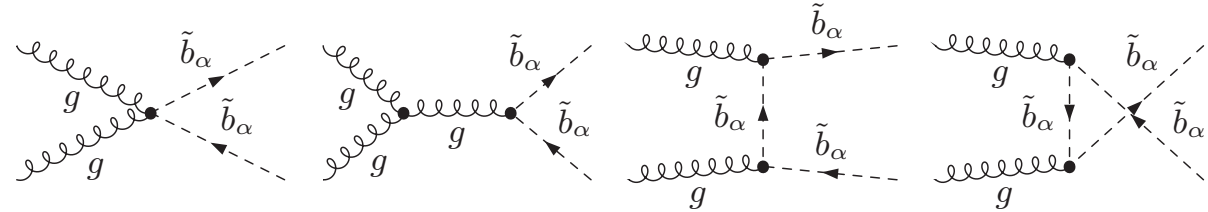
- **Sbottom–(anti-)Sbottom** production:
  - Chirality **diagonal** $\tilde{b}\tilde{b}^*$ production (#2):

    $$PP \to \tilde{b}_1\tilde{b}_1^*,\ \tilde{b}_2\tilde{b}_2^*.$$

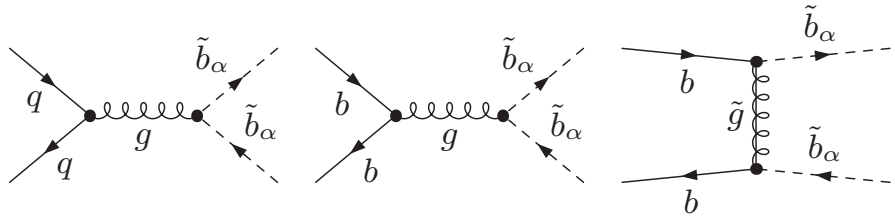
  - Chirality **non-diagonal** $\tilde{b}\tilde{b}^*$ production + $\tilde{b}\tilde{b}$ production (#5).

    $$PP \to \tilde{b}_1\tilde{b}_2^*,\ \tilde{b}_2\tilde{b}_1^*,$$

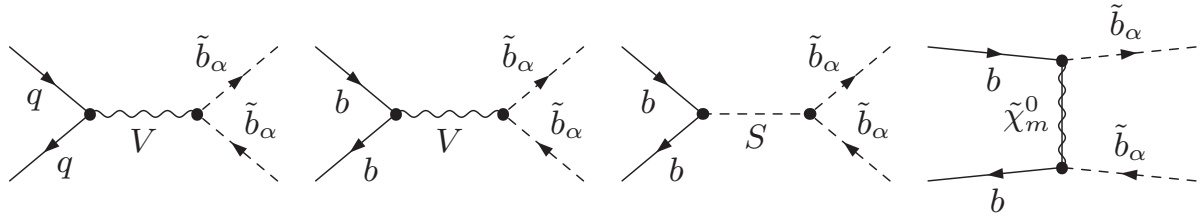
    $$PP \to \tilde{b}_1\tilde{b}_1,\ \tilde{b}_2\tilde{b}_2,\ \tilde{b}_1\tilde{b}_2.$$



(a)

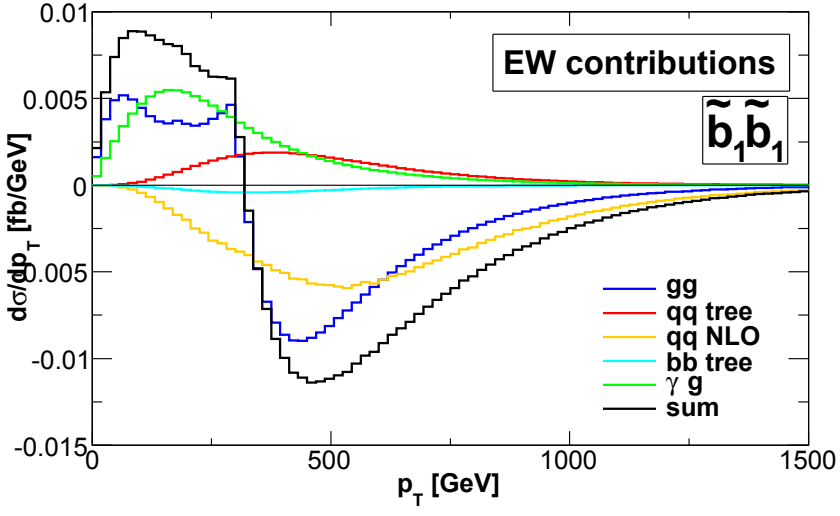


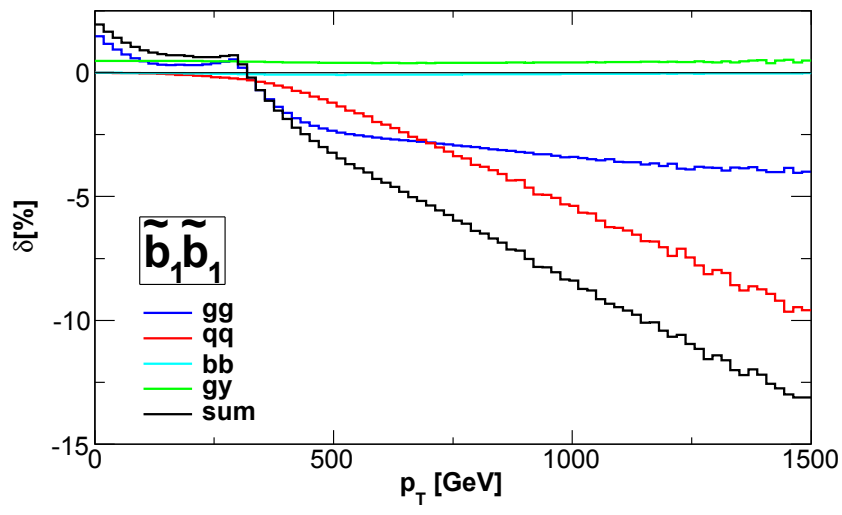
(b)



(c)

SPS1a′ 14 TeV	σ^{Born} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{\mathrm{tree\ EW}}$ $\mathcal{O}(\alpha_s\alpha+\alpha^2)$	$\Delta\sigma^{\mathrm{NLO\ EW}}$ $\mathcal{O}(\alpha_s^2\alpha)$	δ^{EW}
$\tilde{b}_1\tilde{b}_1^*$	444 fb	3 fb	−6 fb	−0.7 %
$\tilde{b}_2\tilde{b}_2^*$	310 fb	2 fb	−3 fb	−0.5 %





Conclusions

- Squark and gluino production are the important channels for SUSY search at the LHC
- QCD corrections are known at NLO and partially also at NNLO,
  significant in size and for stable predictions
- EW contributions of similar size as NNLO QCD,
  NLO contributions reduce scale uncertainty considerably
- EW contributions strongly depend on flavor and chirality,
  many different parton processes to be treated indivually,

  few percent in inclusive quantites, but larger in distributions

- EW contributions modify distributions,
  no global K-factor
- fully flexible code is available

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- fully flexible code is available

Many thanks to my collaborators

Jan Germer, Edoardo Mirabella, Maike Trenkel !