NLO electroweak contibutions to squark–pair production at the LHC

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Outline

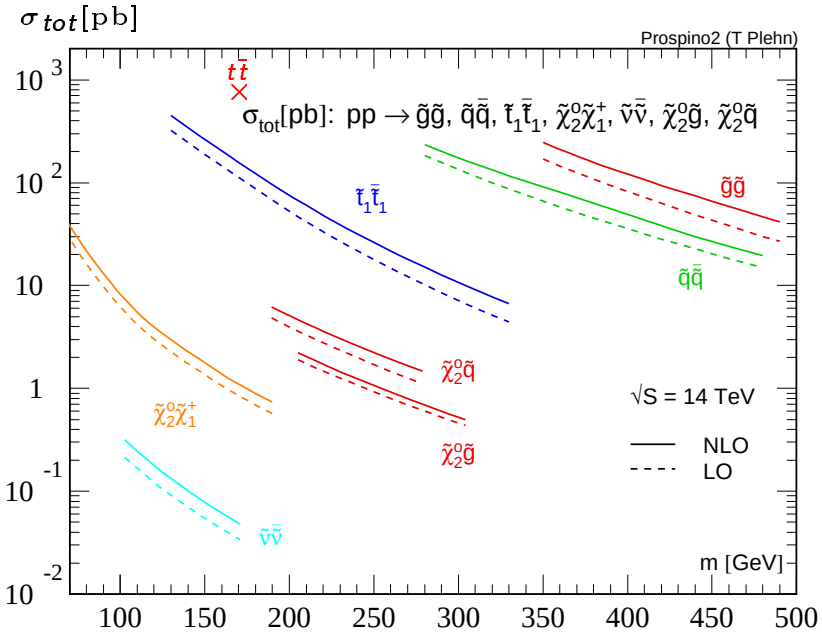
1. Introduction to **colored SUSY** particles @ LHC
   - Production processes
   - Status of higher order corrections.
2. **EW** contributions to **squark–squark** production:
   - **EW tree-level** contributions.
   - **NLO EW** contributions of $\mathcal{O}(\alpha_s^2\alpha)$:
     EW-type & **QCD-type** corrections.
     $\rightarrow$ Treatment of **singularities**.
3. Numerical results: **Total cross-sections**
4. Conclusions

Colored SUSY particles @ hadron colliders

- **Squarks** and **gluinos** are **strongly interacting** particles

Production rate further enhanced due to:

- $\tilde{t}_1\tilde{t}_1^*$: often **lightest squark** (large top-Yukawa coulpling).
- $\tilde{q}\tilde{q}^*$: **high multiplicity** (flavor, chirality).
- $\tilde{g}\tilde{g}$: **color-octet** representation.

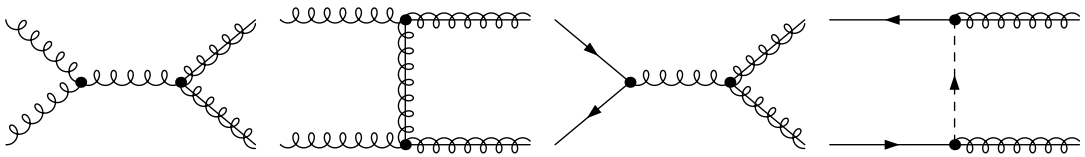


- **Squarks** and **gluinos** have **high production rates** at hadron colliders.

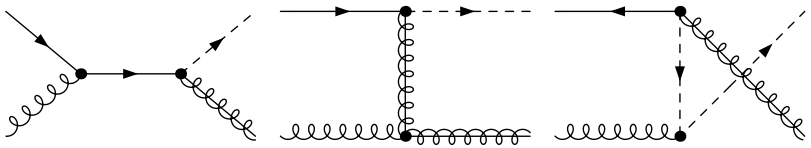
  At **LHC**: cross sections can become **comparable to $t\bar{t}$** production.

Overview: Production processes @ LO

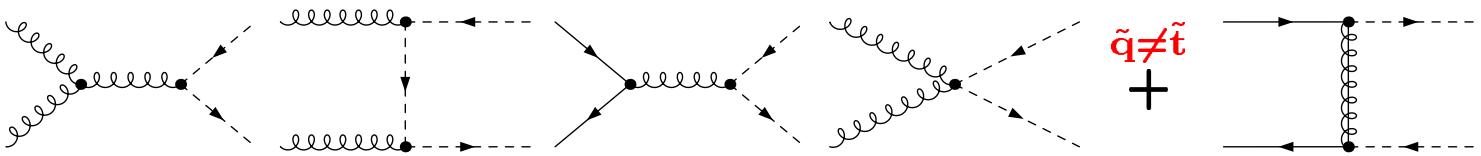
$\tilde{g}\tilde{g}$



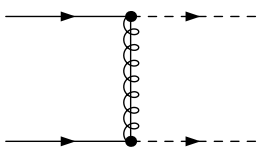
$\tilde{q}\tilde{g}$



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



$\tilde{q}_i\tilde{q}_j$



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

Status of higher order corrections

- $\mathcal{O}(\alpha_s^3)$: NLO QCD corrections for all production processes known
  [Beenakker, Höpker, Spira, Zerwas '95&'97],
  [Beenakker, Krämer, Plehn, Spira, Zerwas '98]
  → PROSPINO

- Beyond NLO QCD:
  - Approximate **NNLO** corrections ($\tilde{q}\tilde{q}^*$)
  - **NLL** resummation
    $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$

  [Langenfeld, Moch '09],
  [Kulesza, Motyka '08'09],
  [Beneke, Falgari, Schwinn '07'09],
  [Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen '09]

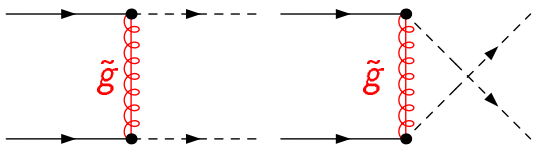
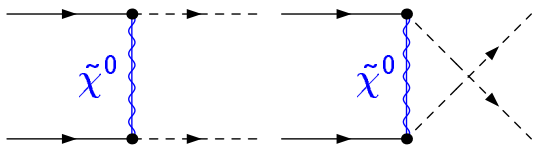
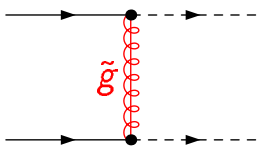
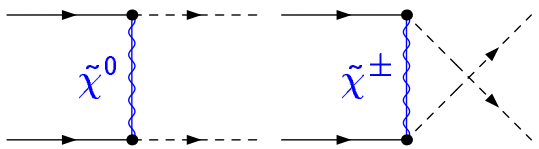
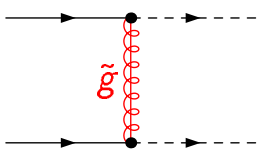
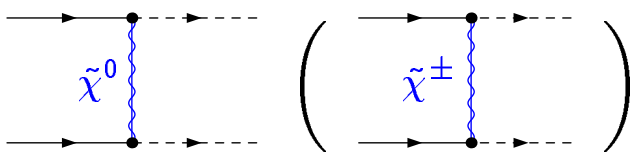
- **LO EW** contributions, **LO one-loop**
  (Tree-level, loop induced, Higgs enhanced)
  $\mathcal{O}(\alpha_s\alpha + \alpha^2 + \alpha_s^2\alpha^2 + \alpha_s^4)$

  [Bozzi, Fuks, Klasen '05],
  [Bornhauser, Drees, Dreiner, Kim '07 '09],
  [Arhrib, Benbrik, Cheung, Yuan '09]

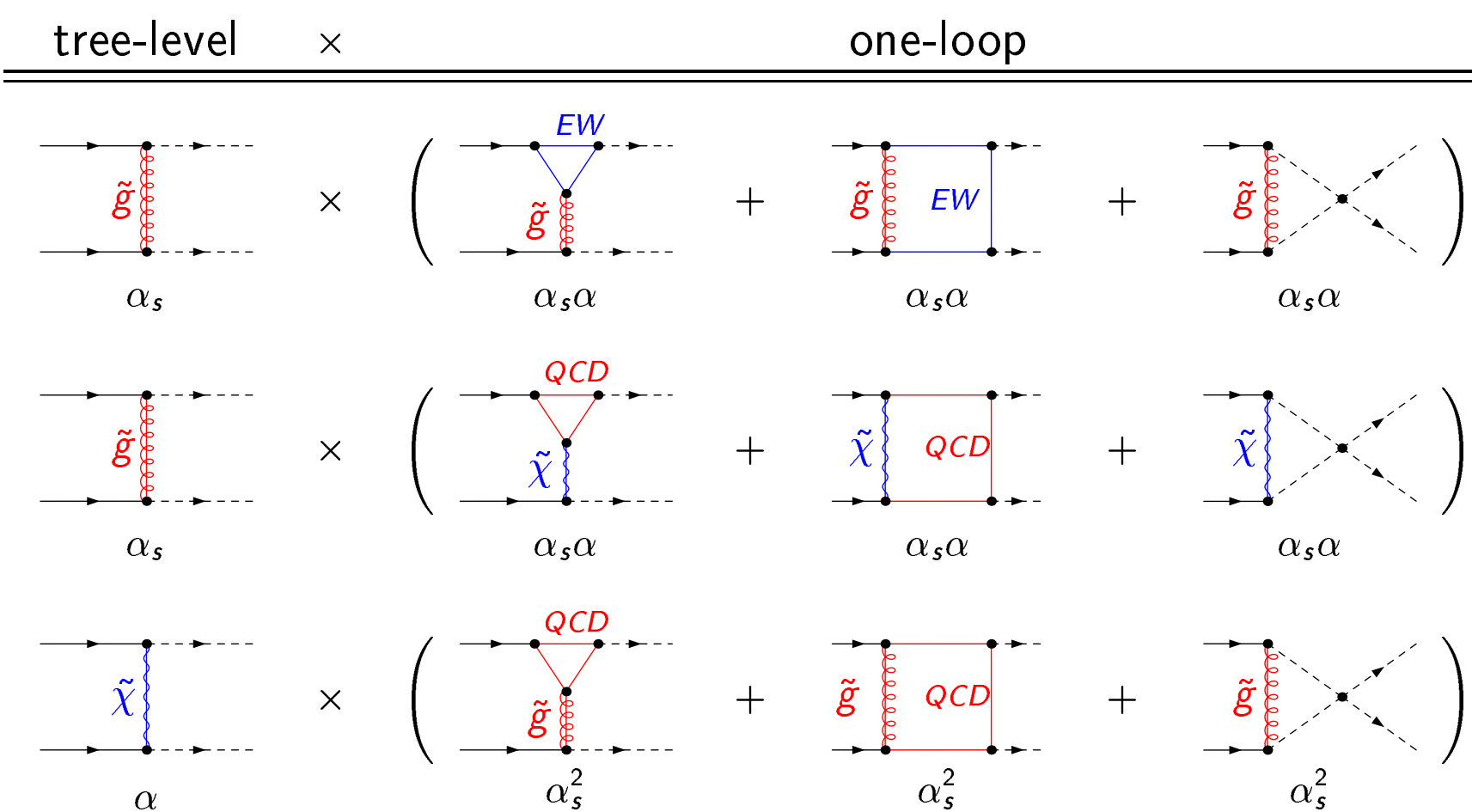
- $\mathcal{O}(\alpha_s^2\alpha)$: NLO EW corrections
  $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}^*$, $\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}$

  [Hollik, Kollar, Trenkel '07],
  [Beccaria et. al. '08],
  [Hollik, Mirabella '08],
  [Hollik, Mirabella, Trenkel '08],
  [Mirabella '09]
  [JG, Hollik, Mirabella, Trenkel '10]

Squark–squark production: EW production at tree level

Class	QCD diagram(s)	EW diagram(s)
$PP \to \tilde{q}_\alpha \tilde{q}_\beta$ same flavor $\mathcal{O}\left(\alpha_s^2 + \alpha_s\alpha + \alpha^2\right)$		+ 
$PP \to \tilde{q}_\alpha \tilde{q}'_\beta$ different flavor, same doublet $\mathcal{O}\left(\alpha_s^2 + \alpha_s\alpha + \alpha^2\right)$		+ 
$PP \to \tilde{q}_\alpha \tilde{q}'_\beta$ different flavor, different doublet $\mathcal{O}\left(\alpha_s^2 + \alpha^2\right)$		+ 

NLO EW: Contributions of $\mathcal{O}\left(\alpha_s^2\alpha\right)$



+ Counterterm diagrams.

+ Real photon, gluon and quark radiation.

Singularities & divergences

- **UV divergences**: Renormalization required.

  Renormalization constants have to be evaluated at $\mathcal{O}(\alpha)$ or $\mathcal{O}(\alpha_s)$.

  - **quarks, squarks, gluino** $\rightarrow$ **renormalized on-shell**
  - $\alpha_s \rightarrow$ **$\overline{\text{MS}}$ with five flavors** (same definition as in pdf)
    Caution with $\hat{g}_s$: needs supersymmetry restoring counterterm.

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

    [Methods: **mass regularization** & **phase space slicing**]

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

Total hadronic cross-section @ LHC

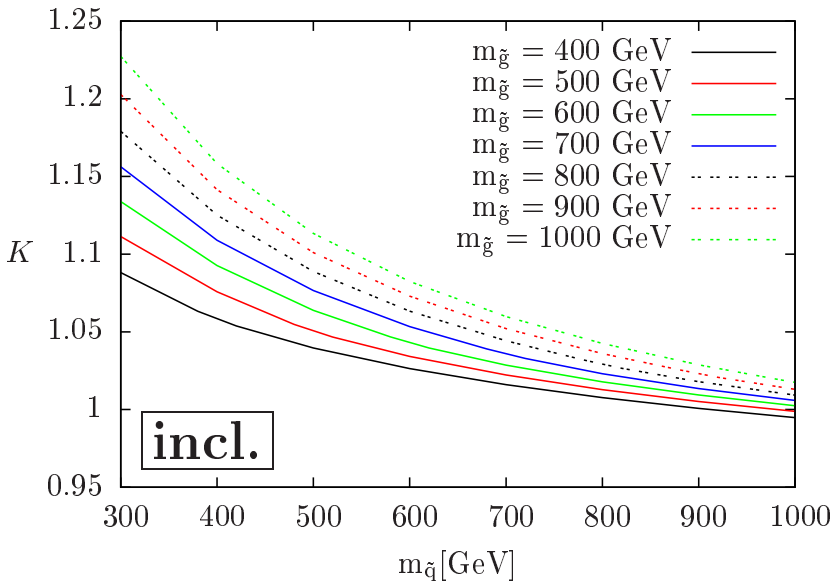
Born and **EW** contributions to the **total cross section**:

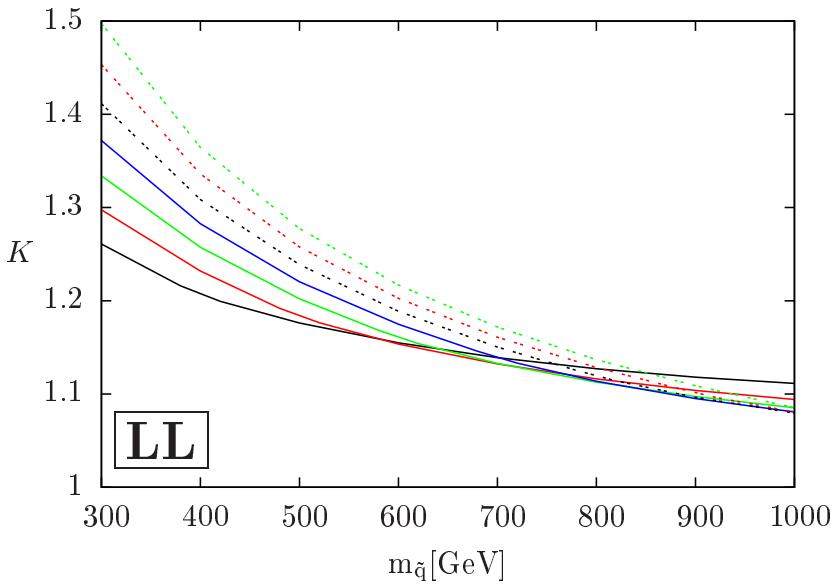
SPS1a′	σ^{LO} $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{LO\ EW}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	$\Delta\sigma^{NLO\ EW}$ $\mathcal{O}(\alpha_s^2\alpha)$	δ^{EW}
$\tilde{q}_L\tilde{q}'_L$	1718. fb	379. fb	−75. fb	17.7%
$\tilde{q}_R\tilde{q}'_R$	1982. fb	32. fb	−2. fb	1.5%
$\tilde{q}_L\tilde{q}'_R$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

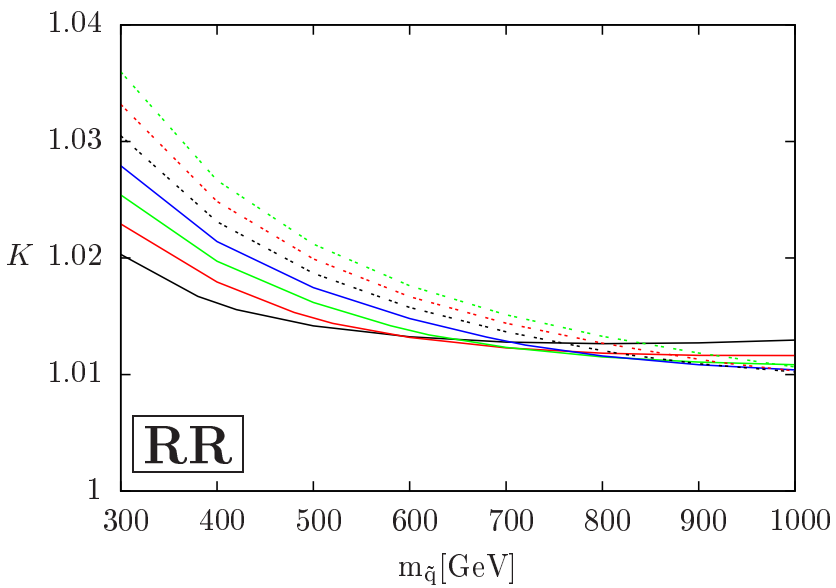
$(\sqrt{S} = 14\ \mathrm{TeV},\ \mu_F = \mu_R = 560\ \mathrm{GeV},$ MRST2004QED,
$\delta^{EW} = (\Delta\sigma^{NLO\ EW} + \Delta\sigma^{LO\ EW})/\sigma^{LO})$

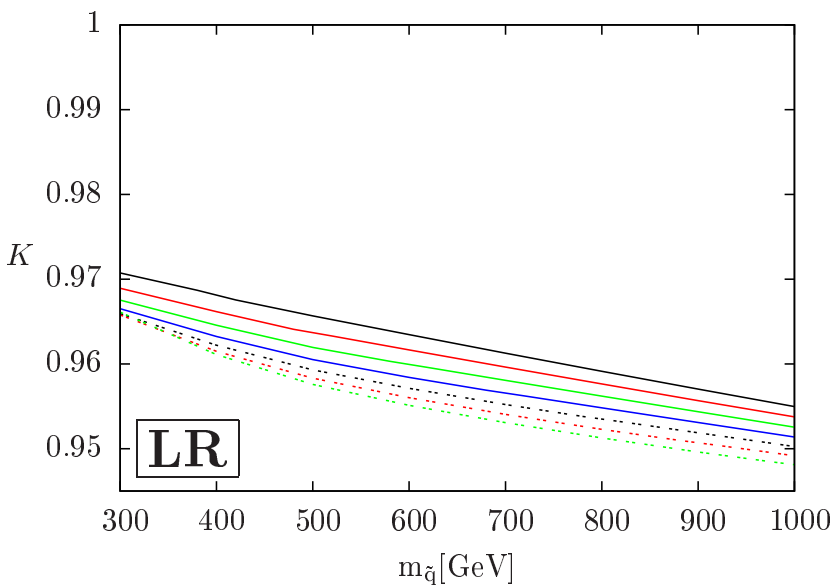
$m(\tilde{u}_L) = 560\mathrm{GeV},\ m(\tilde{d}_L) = 566\mathrm{GeV},\ m(\tilde{g}) = 609\mathrm{GeV},$
$m(\tilde{u}_R) = 543\mathrm{GeV},\ m(\tilde{d}_R) = 539\mathrm{GeV}$

$\tilde{q}\tilde{q}$ production: $m(\tilde{q})$ and $m(\tilde{g})$ dependence







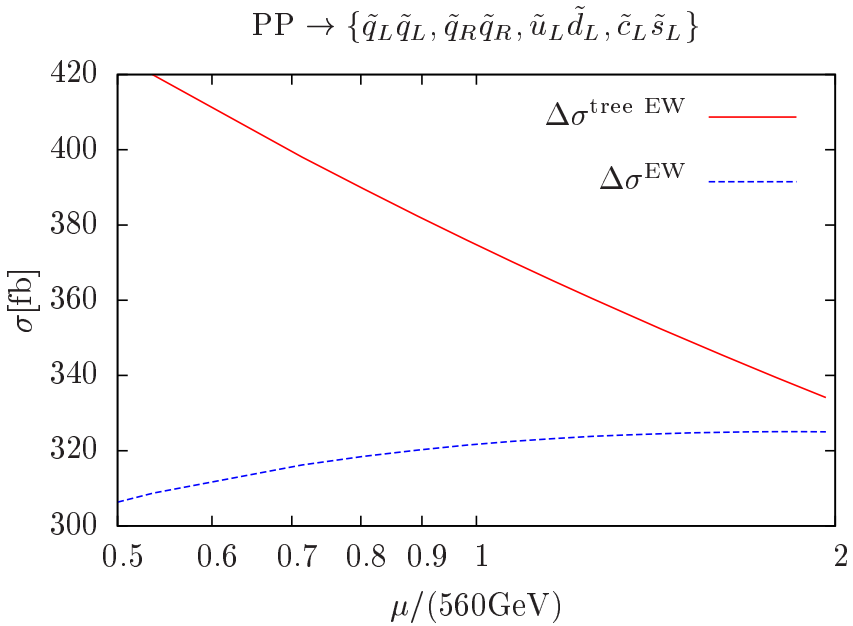


$$K = \sigma^{NLO}/\sigma^{LO}$$

[All other parameters are set to their SPS1a′ values.]

Scale dependence

Scale dependence of tree-level EW and NLO EW cross section:
(Consider only processes with non vanishing tree-level interference.)



- Renormalization scale (μ_{ren}) is set equal to factorization scale (μ_{fac}).
- Scale dependence reduces when NLO EW corrections are taken into account.

Summary & Conclusions

- If SUSY is realized at the TeV scale:
  Squarks and **gluinos** will be produced at a **very high rate** @LHC.
- **Presented:**
  EW contributions up to $\mathcal{O}(\alpha_s^2\alpha)$ to squark–squark production.
- **NLO EW** corrections **reduce** the net **EW contribution**.
- Size of **EW** contributions depends on **squark chirality**:
  $\rightarrow$ **Inclusive case:** $\approx$ **5%**.
  $\rightarrow$ **Left-handed** particle production: $\mathcal{O}$ **(20%)**

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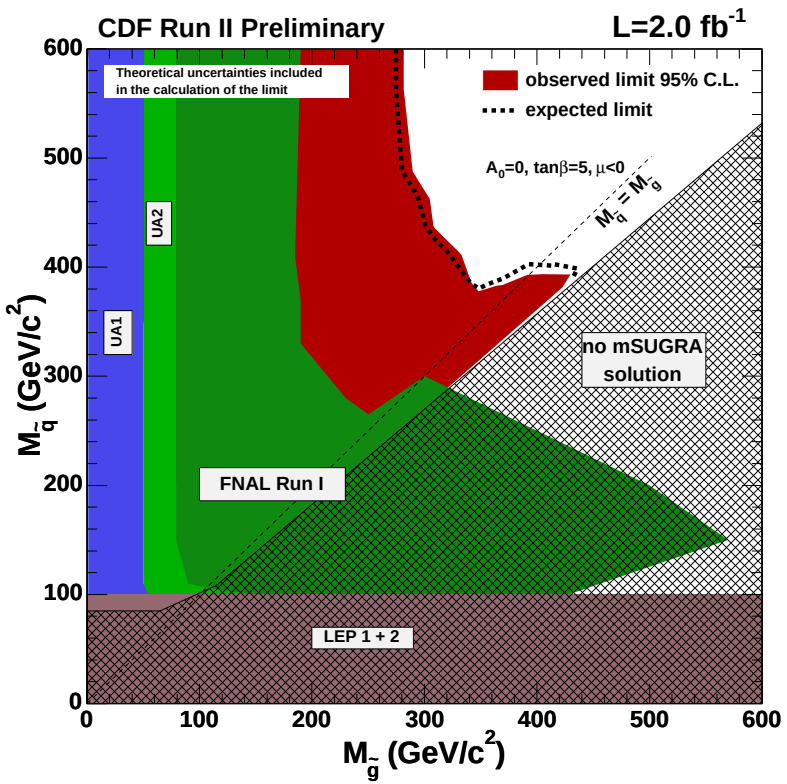
  $\rightarrow$ **Inclusive case:** $\approx$ **5%**.
  $\rightarrow$ **Left-handed** particle production: $\mathcal{O}$ **(20%)**
- **Outlook: NLO EW** contributions to $\tilde{b}\tilde{b}^*$ production.
  Interesting since:
  - Theoretical: $\tan\beta$ enhancement effects.
  - Experimental: Additional bottom-quarks in the final state.

Backup Slides

Experimental Searches for Squarks and Gluinos

- **Squark** & **gluino** mass limits
  CDF, Tevatron Run II
  $m_{\tilde{g}} \geq 280\text{GeV}$
  $m_{\tilde{q}} \geq 370\text{GeV}$
  [CDF Note 9229]

- **Stop** mass limits
  CDF, Tevatron Run II
  $m_{\tilde{t}} \geq 132\text{GeV}$ for $m_{\tilde{\chi}^0} = 132\text{GeV}$
  [0707.2567 hep-ex]



- Until now: agreement between experiment and SM predictions.

- Further analysis needs improved theoretical predictions.

Framework & Input parameters

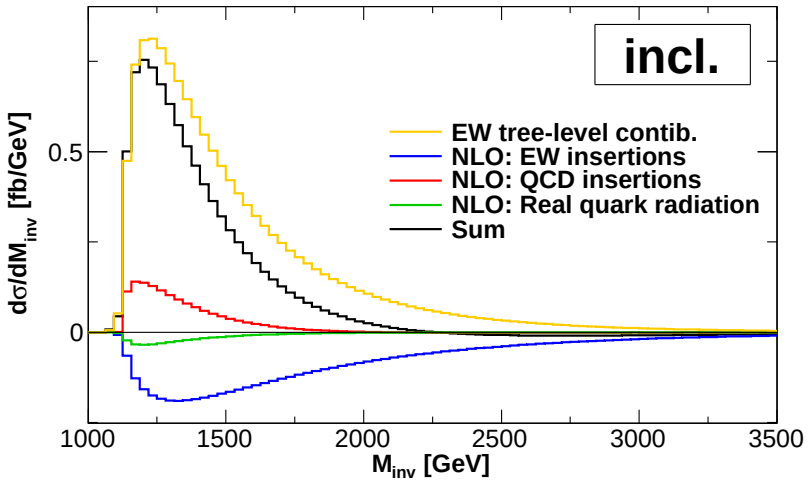
- **Feynman diagrams** and **amplitudes** were generated and calculated within the **FeynArts/FormCalc/Looptools** framework. [Hahn]
- Input: **SPS1a′** parameter set.
  - GUT-scale parameters evolved to 1TeV (softSUSY) [Allanach]
  - Compute **OS parameters**.

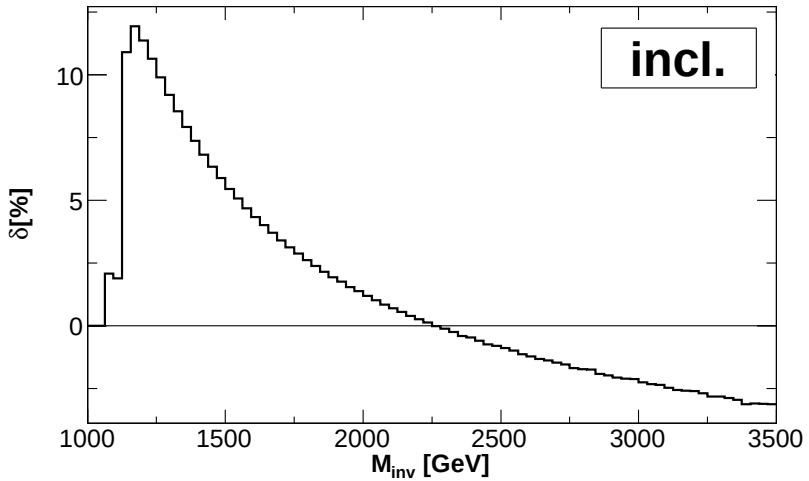
$$m(\tilde{u}_L) = 560\mathrm{GeV} \quad m(\tilde{d}_L) = 566\mathrm{GeV} \quad m(\tilde{g}) = 609\mathrm{GeV}$$
$$m(\tilde{u}_R) = 543\mathrm{GeV} \quad m(\tilde{d}_R) = 539\mathrm{GeV}$$

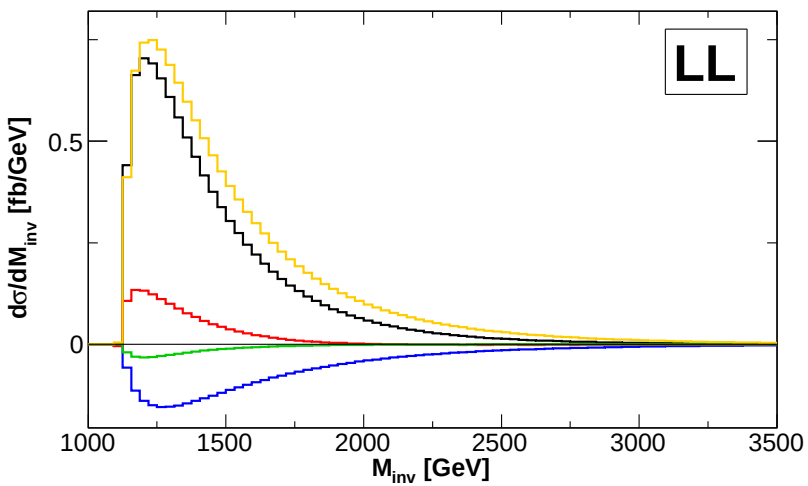
- **Renormalization scale** for α_s : 560 GeV $\quad [\mathcal{O}(m(\tilde{q}))]$
- **PDF** set: **MRST2004QED** [Martin, Roberts, Stirling, Thorne]

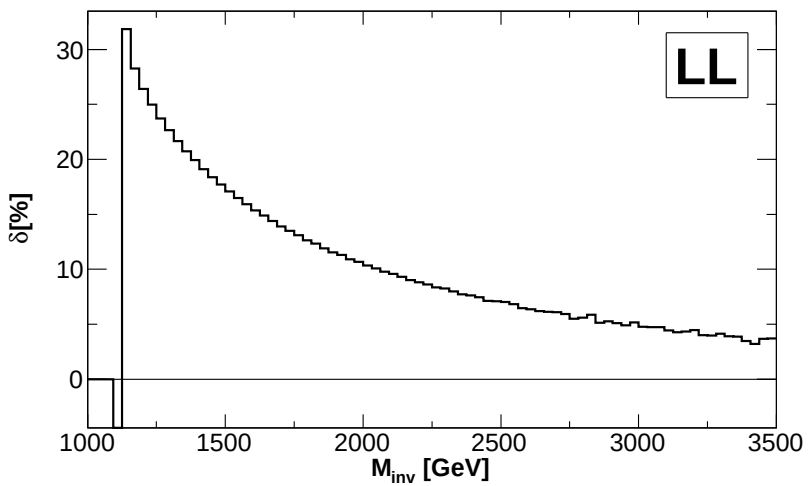
M_{inv} distributions

Electroweak contributions $\delta = \mathcal{O}(\alpha_s\alpha + \alpha^2 + \alpha_s^2\alpha)/\mathcal{O}(\alpha_s^2)$









p_T distributions

Electroweak contributions $\delta = \mathcal{O}(\alpha_s\alpha + \alpha^2 + \alpha_s^2\alpha)/\mathcal{O}(\alpha_s^2)$