Electroweak contributions to squarks and gluinos production processes at the LHC

Edoardo Mirabella

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

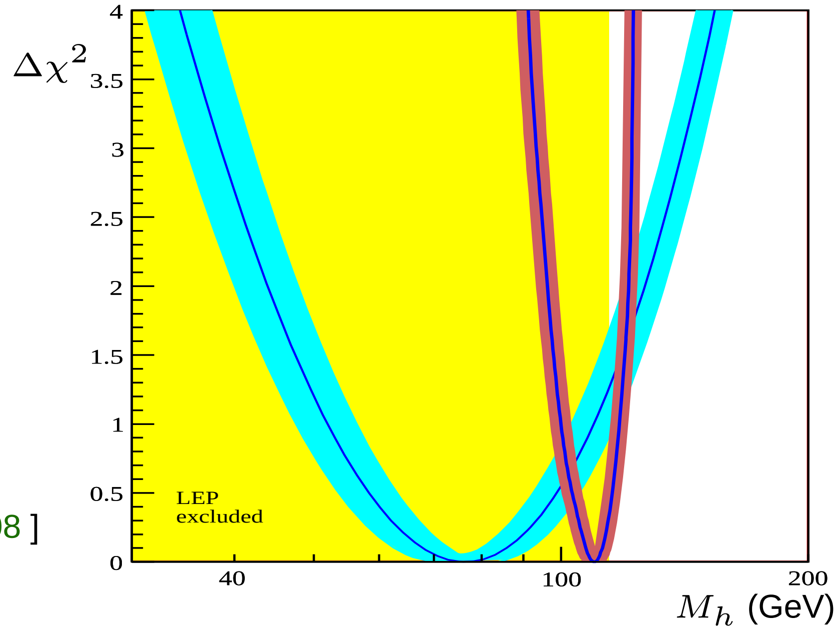
In collaboration with J. Germer, W. Hollik & M. Trenkel.

- Motivations
- Production of squarks and gluinos
  - LO contributions
  - NLO QCD contributions
  - EW contributions
- Closer look into EW contributions
  - UV divergences
  - IR divergences
- Numerical discussion
- Conclusions

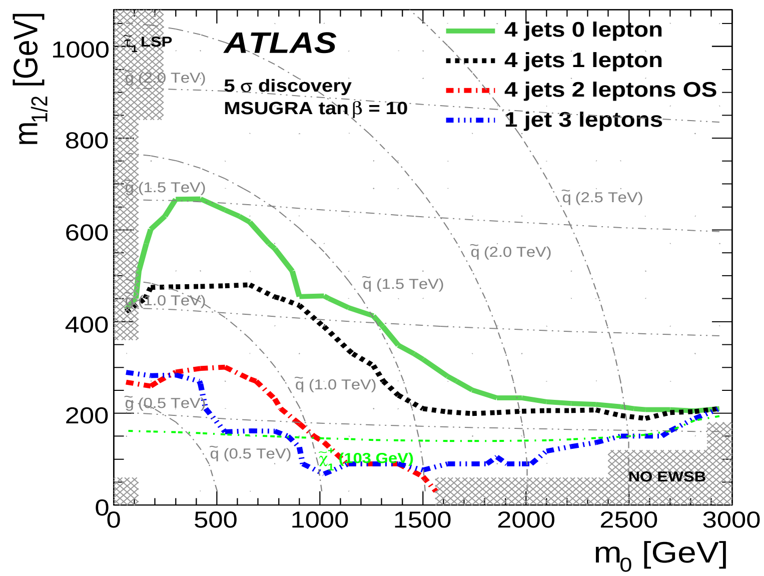
- Motivations
- Production of squarks and gluinos
  - LO contributions
  - NLO QCD contributions
  - EW contributions
- Closer look into EW contributions
  - UV divergences
  - IR divergences
- Numerical discussion
- Conclusions

Motivations

- **M**inimal **S**upersymmetric **S**tandard **M**odel:
  - Theoretically consistent extension of the SM
  - phenomenologically consistent
  - it allows quantitative predictions



[Buchmüller *et al.*,08]

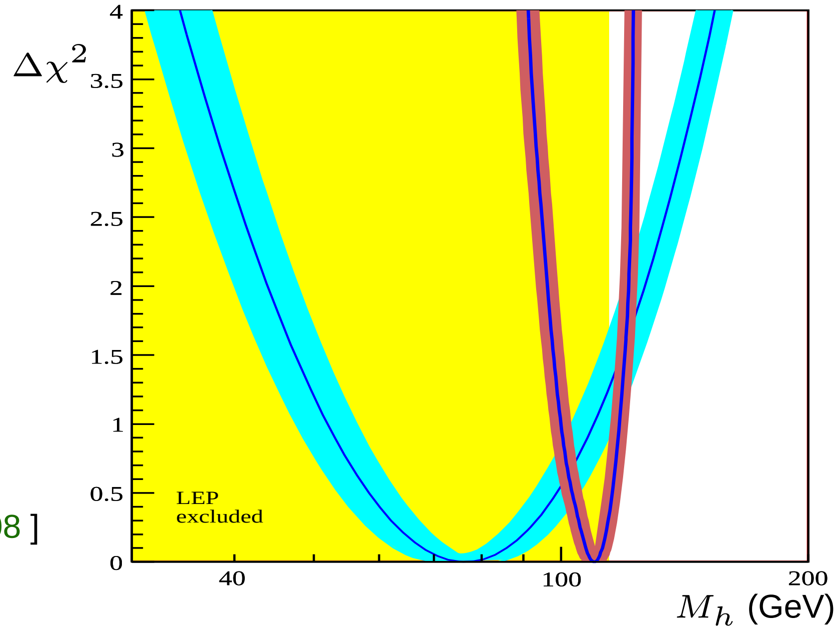


- **L**arge **H**adron **C**ollider:
  - It will probe SUSY and MSSM
  - Early discovery of TeV-scale SUSY

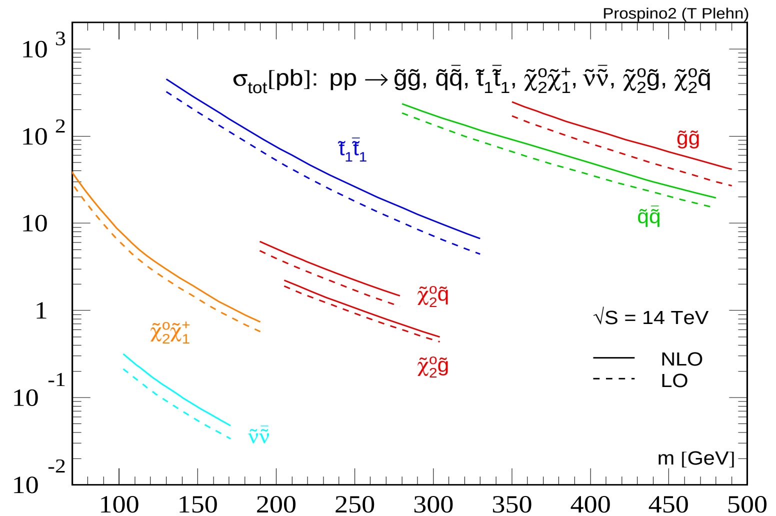
Motivations

- Minimal Supersymmetric Standard Model:
  - Theoretically consistent extension of the SM
  - phenomenologically consistent
  - it allows quantitative predictions

[Buchmüller *et al.*,08]



- Large Hadron Collider:
  - It will probe SUSY and MSSM
  - Early discovery of TeV-scale SUSY
  - Mainly via direct production of colored particles



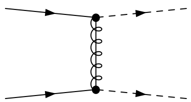
- Motivations
- Production of squarks and gluinos
  - LO contributions
  - NLO QCD contributions
  - EW contributions
- Closer look into EW contributions
  - UV divergences
  - IR divergences
- Numerical discussion
- Conclusions

Squark and Gluino production – LO

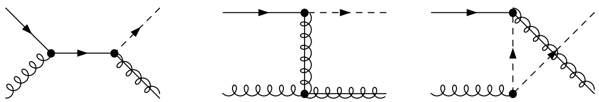
- QCD based, of $\mathcal{O}(\alpha_s^2)$, known since many years

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

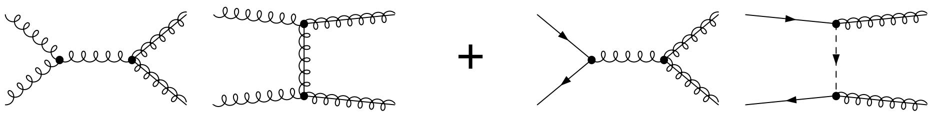
- Different processes (and different channels):
  - $\tilde{q}\tilde{q}'$ & $\tilde{q}^*\tilde{q}'^*$



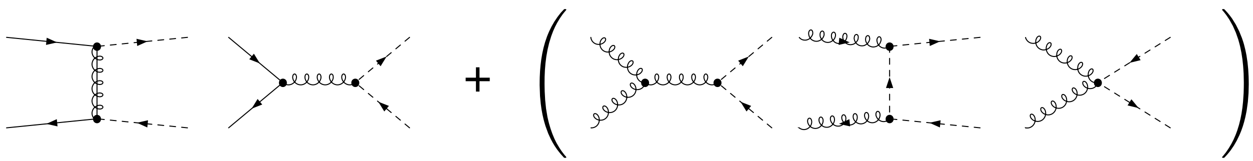
  - $\tilde{g}\tilde{q}$ & $\tilde{g}\tilde{q}^*$



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



  - $\tilde{q}\tilde{q}'^*$



$\cdot\, \delta_{\tilde{q}\tilde{q}'}$

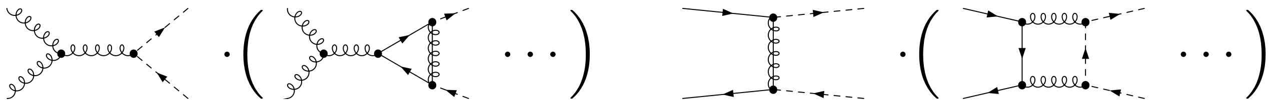
- Comments:
  - Stops and sbottoms experimentally distinguishable
  - Other squarks have to be considered inclusively

Squark and Gluino production – NLO QCD

- NLO QCD corrrections, of $\mathcal{O}(\alpha_s^3)$, computed ten years ago

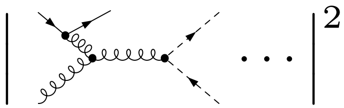
  [Beenakker, Höpker, Spira, Zerwas '96 '97] &
  [Beenakker, Krämer, Plehn, Spira, Zerwas '98]

- Different contributions *e.g.* in the $\tilde{q}\tilde{q}^*$ production:
  - virtual corrections



  - real gluon emission

  - real quark emission

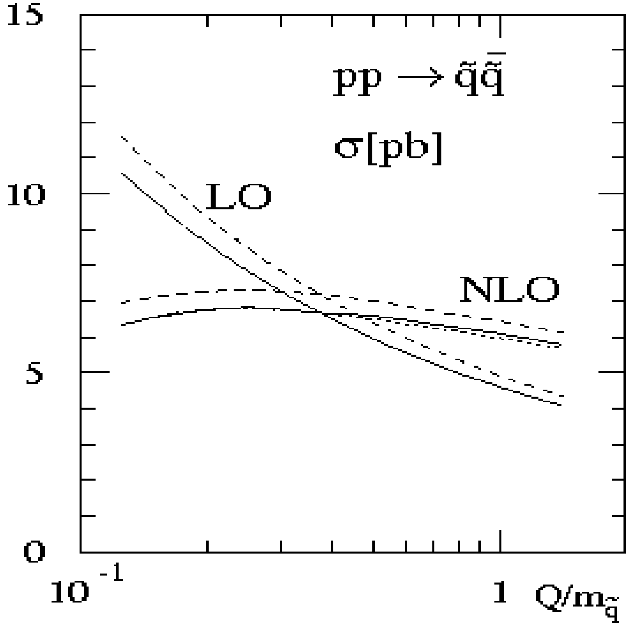


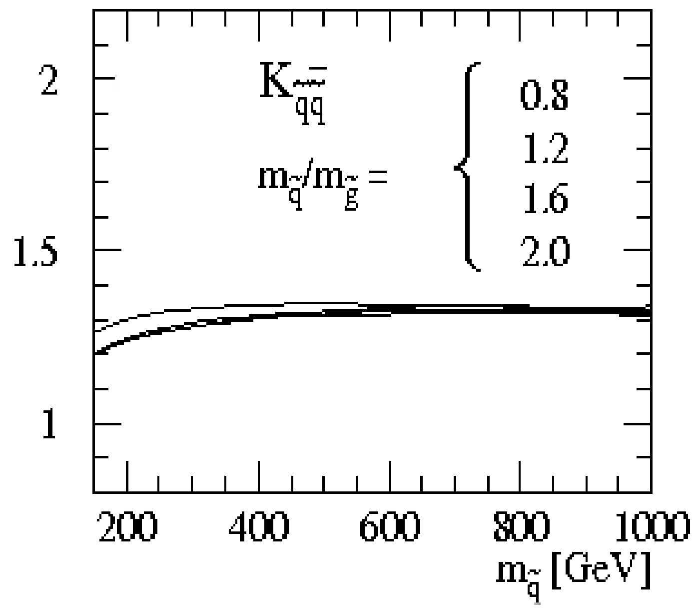
- Comments:
  - real emission treated fully inclusively
  - proper subtraction of resonant contributions
  - total cross section @ NLO QCD implemented in publicly available code

  [PROSPINO, Beenakker, Höpker & Spira, '97]

Squark and Gluino production – NLO QCD

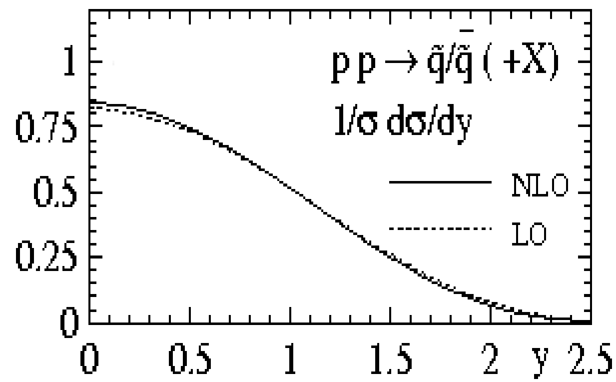
- Some results:





NLO QCD corrections:

- reduced scale dependence
- important in the total rate
- negligible in (properly normalized) distributions

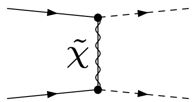


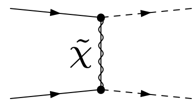
Squark and Gluino production – tree level EW

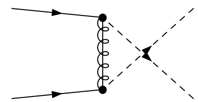
- Contributions of $\mathcal{O}(\alpha_s\alpha + \alpha^2)$, completely known

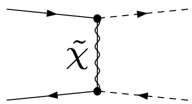
  [Kollar, Hollik, Trenkel '07; Hollik, EM '08; Hollik, EM, Trenkel '08] &
  [Bozzi, Fuks, Hermann, Klasen '07; Bornhauser, Dress, Dreiner, Kim'07]

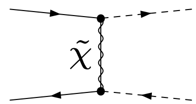
- Contributions from qq-, $q\bar{q}$-initiated processes:

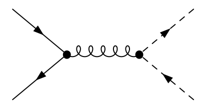
  - $\tilde{q}\tilde{q}'$ & $\tilde{q}^*\tilde{q}'^*$ $\mathcal{O}(\alpha^2) \rightsquigarrow$ $\Big|$ 

$\Big|^2$ $\mathcal{O}(\alpha_s\alpha) \rightsquigarrow$ 

$\cdot$  $\cdot\, \delta_{\tilde{q}\tilde{q}'}$

  - $\tilde{q}\tilde{q}'^*$ $\mathcal{O}(\alpha^2) \rightsquigarrow$ $\Big|$ 

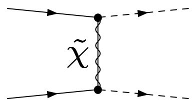
$\Big|^2$ $\mathcal{O}(\alpha_s\alpha) \rightsquigarrow$ 

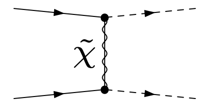
$\cdot$  $\cdot\, \delta_{\tilde{q}\tilde{q}'}$

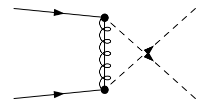
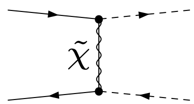
Squark and Gluino production – tree level EW

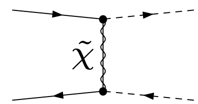
- Contributions of $\mathcal{O}(\alpha_s\alpha + \alpha^2)$, completely known

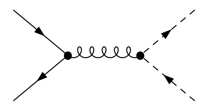
  [Kollar, Hollik, Trenkel '07; Hollik, EM '08; Hollik, EM, Trenkel '08] &
  [Bozzi, Fuks, Hermann, Klasen '07; Bornhauser, Dress, Dreiner, Kim'07]

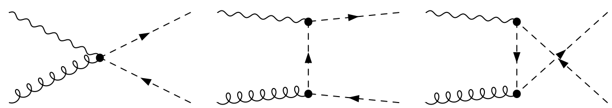
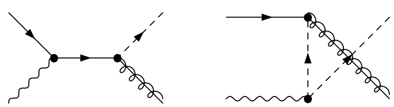
- Contributions from qq-, $q\bar{q}$-initiated processes:
  - $\tilde{q}\tilde{q}'$ & $\tilde{q}^*\tilde{q}'^*$ $\quad \mathcal{O}(\alpha^2) \rightsquigarrow \Big|$ 

$\Big|^2 \quad \mathcal{O}(\alpha_s\alpha) \rightsquigarrow$ 

$\cdot$  $\cdot\, \delta_{\tilde{q}\tilde{q}'}$
  - $\tilde{q}\tilde{q}'^*$ $\quad \mathcal{O}(\alpha^2) \rightsquigarrow \Big|$ 

$\Big|^2 \quad \mathcal{O}(\alpha_s\alpha) \rightsquigarrow$ 

$\cdot$  $\cdot\, \delta_{\tilde{q}\tilde{q}'}$

- Contributions from photon-induced processes:
  - $\tilde{q}\tilde{q}'^*$ $\quad \mathcal{O}(\alpha_s\alpha) \rightsquigarrow \Big|$  $\Big|^2$
  - $\tilde{g}\tilde{q}$ & $\tilde{g}\tilde{q}^*$ $\quad \mathcal{O}(\alpha_s\alpha) \rightsquigarrow \Big|$  $\Big|^2$

Squark and Gluino production – NLO EW

- Contributions of $\mathcal{O}(\alpha_s^2\alpha)$, still work in progress.

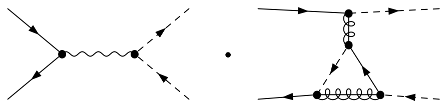
  [Kollar, Hollik, Trenkel ’07; Hollik, EM ’08; Hollik, EM, Trenkel ’08]

- Their pattern is process-dependent (example here $\tilde{q}\tilde{q}^*$)

Virtual Corrections

- QCD Born $\times$ 1-loop EW:

- EW Born $\times$ 1-loop QCD:



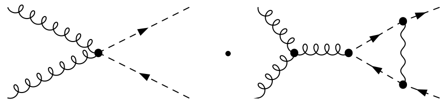
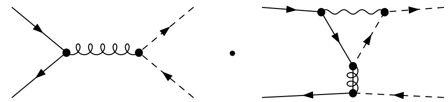
Squark and Gluino production – NLO EW

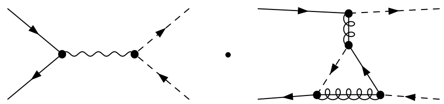
- Contributions of $\mathcal{O}(\alpha_s^2 \alpha)$, still work in progress.

  [Kollar, Hollik, Trenkel '07; Hollik, EM '08; Hollik, EM, Trenkel '08]

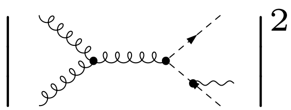
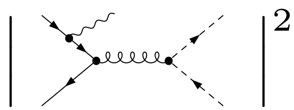
- Their pattern is process-dependent (example here $\tilde{q}\tilde{q}^*$)

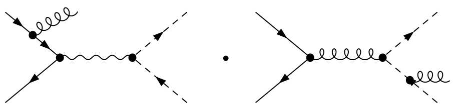
Virtual Corrections

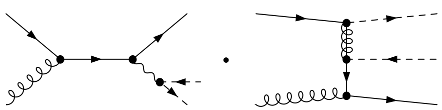
- QCD Born $\times$ 1-loop EW:  

- EW Born $\times$ 1-loop QCD: 

Real Corrections

- real photon emission:  

- real gluon emission: 

- real quark emission: 

- Motivations
- Production of squarks and gluinos
  - LO contributions
  - NLO QCD contributions
  - EW contributions
- Closer look into EW contributions
  - UV divergences
  - IR divergences
- Numerical discussion
- Conclusions

Renormalizing the strong coupling

$$\mathcal{L}_{\text{strong}} = -\ \tfrac{1}{4}G^A_{\mu\nu}G^{A,\mu\nu} + g_s T^A \bar{\Psi}_u \gamma^\mu \Psi_u G^A_\mu$$
$$-\ \sqrt{2}\hat{g}_s \left[T^A \bar{\Psi}^A_{\tilde{g}}\, \omega_-\ \Psi_u \Phi^*_{\tilde{u},L} + h.c.\right] + \ \ldots$$

one field and two couplings to reparametrize:

$$G^A_\mu \to \left(1 + \tfrac{\delta Z_G}{2}\right) G^A_\mu, \qquad g_s \to g_s + \delta g_s, \qquad \hat{g}_s \to \hat{g}_s + \delta\hat{g}_s$$

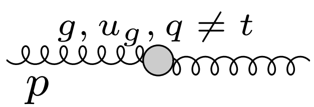
Renormalizing the strong coupling

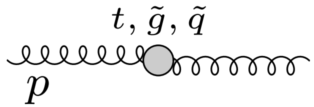
$$\mathcal{L}_{\text{strong}} = -\tfrac{1}{4}G^A_{\mu\nu}G^{A,\mu\nu} + g_s T^A \bar{\Psi}_u \gamma^\mu \Psi_u G^A_\mu$$
$$- \sqrt{2}\hat{g}_s \left[T^A \bar{\Psi}^A_{\tilde{g}}\, \omega_-\, \Psi_u \Phi^*_{\tilde{u},L} + h.c.\right] + \ldots$$

one field and two couplings to reparametrize:

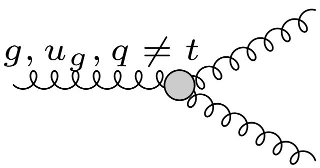
$$G^A_\mu \to \left(1 + \frac{\delta Z_G}{2}\right) G^A_\mu, \qquad g_s \to g_s + \delta g_s, \qquad \hat{g}_s \to \hat{g}_s + \delta\hat{g}_s$$

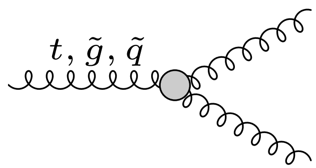
- Definition of δg_s, δZ_G:



$|\Delta$ $+$


$|\Delta - \ln(M^2/\mu^2)$ $\stackrel{!}{=} 0$



$|\Delta$ $+$


$|\Delta - \ln(M^2/\mu^2)$ $\stackrel{!}{=} 0$

- Divergences within DREG, $\Delta = 2/\epsilon - \gamma + \ln 4\pi$
- $\overline{\text{MS}}$ (DREG + UV poles subtraction) if light particles in loops
- Zero momentum subtraction scheme if heavy particles in loops
  - $\hookrightarrow$ SM-like running of g_s

Renormalizing the strong coupling

$$\mathcal{L}_{\text{strong}} = -\tfrac{1}{4} G^A_{\mu\nu} G^{A,\mu\nu} + g_s T^A \bar{\Psi}_u \gamma^\mu \Psi_u G^A_\mu$$
$$- \sqrt{2}\hat{g}_s \left[T^A \bar{\Psi}^A_{\tilde{g}}\, \omega_- \, \Psi_u \Phi^*_{\tilde{u},L} + h.c. \right] + \ldots$$

one field and two couplings to reparametrize:

$$G^A_\mu \to \left(1 + \frac{\delta Z_G}{2}\right) G^A_\mu, \qquad g_s \to g_s + \delta g_s, \qquad \hat{g}_s \to \hat{g}_s + \delta \hat{g}_s$$

- Definition of $\delta\hat{g}_s$:
  - Owing to SUSY should be a dependent parameter
    $\hookrightarrow \hat{g}_s = g_s; \qquad \delta\hat{g}_s = \delta g_s$
  - But DREG spoils SUSY @ NLO [Beenakker *et al.*'96,98]
    $\hookrightarrow$ SUSY restored setting: $\hat{g}_s = g_s + g_s \frac{\alpha_s}{3\pi}; \qquad \delta\hat{g}_s = \delta g_s$
  - The mismatch between g_s and $\hat{g}_s$ is reabsorbed into $\delta\hat{g}_s$:
    $\hookrightarrow \hat{g}_s = g_s; \qquad \delta\hat{g}_s = \delta g_s + g_s \frac{\alpha_s}{3\pi}$

Renormalizing the squark sector, I

$$\mathcal{L}_{\text{squark}} = \sum_{\tilde{q}=\tilde{t},\tilde{b}} \left\{ \left(\partial_\mu \Phi^*_{\tilde{q}_L}, \partial_\mu \Phi^*_{\tilde{q}_R}\right) \begin{pmatrix} \partial^\mu \Phi_{\tilde{q}_L} \\ \partial^\mu \Phi_{\tilde{q}_R} \end{pmatrix} - \left(\Phi^*_{\tilde{q}_L}, \Phi^*_{\tilde{q}_R}\right) \mathbf{M^2}_{\tilde{q}} \begin{pmatrix} \Phi_{\tilde{q}_L} \\ \Phi_{\tilde{q}_R} \end{pmatrix} \right\}$$

where:

$$\mathbf{M^2}_{\tilde{q}} = \begin{pmatrix} {M_L}^2 + {m_q}^2 + M_Z^2 \cos 2\beta (T_q^3 - e_q \sin^2\theta_W) & m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) \\ m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) & {M_{\tilde{q},R}}^2 + {m_q}^2 + e_q M_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}.$$

[(SU(2) invariance) $\Rightarrow M_{\tilde{t},L} = M_{\tilde{b},L} = M_L$]

[$\lambda_{\tilde{t}} = 1/\tan\beta$ & $\lambda_{\tilde{b}} = \tan\beta$]

Renormalizing the squark sector, I

$$\mathcal{L}_{\text{squark}} = \sum_{\tilde{q}=\tilde{t},\tilde{b}} \left\{ \left(\partial_\mu \Phi^*_{\tilde{q}_L}, \partial_\mu \Phi^*_{\tilde{q}_R}\right) \begin{pmatrix} \partial^\mu \Phi_{\tilde{q}_L} \\ \partial^\mu \Phi_{\tilde{q}_R} \end{pmatrix} - \left(\Phi^*_{\tilde{q}_L}, \Phi^*_{\tilde{q}_R}\right) \mathbf{M^2}_{\tilde{q}} \begin{pmatrix} \Phi_{\tilde{q}_L} \\ \Phi_{\tilde{q}_R} \end{pmatrix} \right\}$$

where:

$$\mathbf{M^2}_{\tilde{q}} = \begin{pmatrix} {M_L}^2 + {m_q}^2 + M_Z^2 \cos 2\beta (T_q^3 - e_q \sin^2\theta_W) & m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) \\ m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) & {M_{\tilde{q},R}}^2 + {m_q}^2 + e_q M_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix} .$$

[(SU(2) invariance) $\Rightarrow M_{\tilde{t},L} = M_{\tilde{b},L} = M_L$]

[$\lambda_{\tilde{t}} = 1/\tan\beta$ & $\lambda_{\tilde{b}} = \tan\beta$]

5 independent parameters: $M_L, M_{\tilde{b},R}, M_{\tilde{t},R}, A_{\tilde{b}}, A_{\tilde{t}}$

Renormalizing the squark sector, I

$$\mathcal{L}_{\text{squark}} = \sum_{\tilde{q}=\tilde{t},\tilde{b}} \left\{ \left(\partial_\mu \Phi^*_{\tilde{q}_L}, \partial_\mu \Phi^*_{\tilde{q}_R}\right) \begin{pmatrix} \partial^\mu \Phi_{\tilde{q}_L} \\ \partial^\mu \Phi_{\tilde{q}_R} \end{pmatrix} - \left(\Phi^*_{\tilde{q}_L}, \Phi^*_{\tilde{q}_R}\right) \mathbf{M^2}_{\tilde{q}} \begin{pmatrix} \Phi_{\tilde{q}_L} \\ \Phi_{\tilde{q}_R} \end{pmatrix} \right\}$$

where:

$$\mathbf{M^2}_{\tilde{q}} = \begin{pmatrix} {M_L}^2 + {m_q}^2 + M_Z^2 \cos 2\beta (T_q^3 - e_q \sin^2\theta_W) & m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) \\ m_q (A_{\tilde{q}} - \mu \lambda_{\tilde{q}}) & {M_{\tilde{q},R}}^2 + {m_q}^2 + e_q M_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}.$$

[(SU(2) invariance) $\Rightarrow M_{\tilde{t},L} = M_{\tilde{b},L} = M_L$]

[$\lambda_{\tilde{t}} = 1/\tan\beta$ & $\lambda_{\tilde{b}} = \tan\beta$]

5 independent parameters: $M_L, M_{\tilde{b},R}, M_{\tilde{t},R}, A_{\tilde{b}}, A_{\tilde{t}}$ & $\mu, \tan\beta, m_t, m_b \ \ldots$

Renormalizing the squark sector, I

$$\mathcal{L}_{\text{squark}} = \sum_{\tilde{q}=\tilde{t},\tilde{b}} \left\{ \left(\partial_\mu \Phi^*_{\tilde{q}_L}, \partial_\mu \Phi^*_{\tilde{q}_R}\right) \begin{pmatrix} \partial^\mu \Phi_{\tilde{q}_L} \\ \partial^\mu \Phi_{\tilde{q}_R} \end{pmatrix} - \left(\Phi^*_{\tilde{q}_L}, \Phi^*_{\tilde{q}_R}\right) \mathbf{M^2}_{\tilde{q}} \begin{pmatrix} \Phi_{\tilde{q}_L} \\ \Phi_{\tilde{q}_R} \end{pmatrix} \right\}$$

where:

$$\mathbf{M^2}_{\tilde{q}} = \begin{pmatrix} {M_L}^2 + {m_q}^2 + M_Z^2 \cos 2\beta (T_q^3 - e_q \sin^2\theta_W) & m_q (A_{\tilde{q}} - \mu\lambda_{\tilde{q}}) \\ m_q (A_{\tilde{q}} - \mu\lambda_{\tilde{q}}) & {M_{\tilde{q},R}}^2 + {m_q}^2 + e_q M_Z^2 \cos 2\beta \sin^2\theta_W \end{pmatrix}.$$

[(SU(2) invariance) $\Rightarrow M_{\tilde{t},L} = M_{\tilde{b},L} = M_L$]

[$\lambda_{\tilde{t}} = 1/\tan\beta$ & $\lambda_{\tilde{b}} = \tan\beta$]

5 independent parameters: $M_L, M_{\tilde{b},R}, M_{\tilde{t},R}, A_{\tilde{b}}, A_{\tilde{t}}$ & $\mu, \tan\beta, m_t, m_b \quad \ldots$

after diagonalization $\begin{pmatrix} \Phi_{\tilde{q}_1} \\ \Phi_{\tilde{q}_2} \end{pmatrix} = \begin{pmatrix} c_{\theta\tilde{q}} & s_{\theta\tilde{q}} \\ -s_{\theta\tilde{q}} & c_{\theta\tilde{q}} \end{pmatrix} \begin{pmatrix} \Phi_{\tilde{q}_L} \\ \Phi_{\tilde{q}_R} \end{pmatrix}$

$$\mathbf{M^2}_{\tilde{q}} = \begin{pmatrix} c^2_{\theta\tilde{q}} m^2_{\tilde{q},1} + s^2_{\theta\tilde{q}} m^2_{\tilde{q},2} & c_{\theta\tilde{q}} s_{\theta\tilde{q}} (m^2_{\tilde{q},1} - m^2_{\tilde{q},2}) \\ c_{\theta\tilde{q}} s_{\theta\tilde{q}} (m^2_{\tilde{q},1} - m^2_{\tilde{q},2}) & c^2_{\theta\tilde{q}} m^2_{\tilde{q},2} + s^2_{\theta\tilde{q}} m^2_{\tilde{q},1} \end{pmatrix}$$

SO one can choose different independent set:

- $\{m_{\tilde{t},1},\ m_{\tilde{t},2},\ m_{\tilde{b},2},\ \theta_{\tilde{t}},\ \theta_{\tilde{b}}\}$
- $\{m_{\tilde{t},1},\ m_{\tilde{t},2},\ m_{\tilde{b},2},\ \theta_{\tilde{t}},\ A_{\tilde{b}}\}$
- ...

Renormalizing the squark sector, II

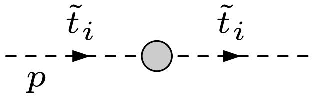
"m_b $\overline{\text{DR}}$ scheme": $\{m_{\tilde{t},1},\ m_{\tilde{t},2},\ m_{\tilde{b},2},\ \theta_{\tilde{t}},\ A_{\tilde{b}}\ \}$

Stop sector

reparametrizing:

$$m^2_{\tilde{t},i} \longrightarrow m^2_{\tilde{t},i} + \delta m^2_{\tilde{t},i};\quad \theta_{\tilde{t}} \longrightarrow \theta_{\tilde{t}} + \delta\theta_{\tilde{t}};\quad \begin{pmatrix} \Phi_{\tilde{t},1} \\ \Phi_{\tilde{t},2} \end{pmatrix} \rightarrow \left[1 + \frac{1}{2} \begin{pmatrix} \delta Z^{\tilde{t}}_{1,1} & \delta Z^{\tilde{t}}_{1,2} \\ \delta Z^{\tilde{t}}_{2,1} & \delta Z^{\tilde{t}}_{2,2} \end{pmatrix} \right] \begin{pmatrix} \Phi_{\tilde{t},1} \\ \Phi_{\tilde{t},2} \end{pmatrix}$$

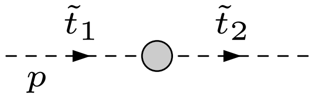
- $\delta m^2_{\tilde{t},i}$ and $\delta Z^{\tilde{t}}_{i,i}$ are fixed in the *on-shell* scheme



$$= \frac{i}{p^2 - m^2_{\tilde{t},i}} + \frac{i}{p^2 - m^2_{\tilde{t},i}} \hat{\Sigma}_{i,i}(p^2) \frac{i}{p^2 - m^2_{\tilde{t},i}} \stackrel{!}{=} \frac{i}{p^2 - m^2_{\tilde{t},i}} \qquad p^2 \longrightarrow m^2_{\tilde{t},i};$$

$$[\hat{\Sigma}_{i,i} = \Sigma_{i,i} + (p^2 - m^2_{\tilde{t},i})\delta Z^{\tilde{t}}_{i,i} - \delta m^2_{\tilde{t},i}\ ]$$

- $\delta Z^{\tilde{t}}_{i,j}$ and $\delta\theta_{\tilde{t}}$ imposing zero squark mixing on-shell:



$$\stackrel{!}{=} \quad 0 \qquad \text{if } p^2 \longrightarrow m^2_{\tilde{t},1} \text{ or } p^2 \longrightarrow m^2_{\tilde{t},2}$$

- $\delta A_{\tilde{t}}$ dependent, function of $\delta\mu$, $\delta\tan\beta$, δm_t $\hookrightarrow$ [on shell scheme]

Renormalizing the squark sector, II

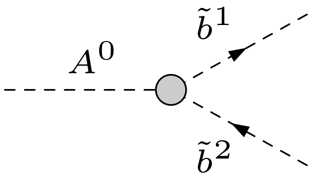
"m_b $\overline{\text{DR}}$ scheme": $\{m_{\tilde{t},1},\ m_{\tilde{t},2},\ m_{\tilde{b},2},\ \theta_{\tilde{t}},\ A_{\tilde{b}}\ \}$

<u>Sbottom sector</u>

reparametrizing:

$$m^2_{\tilde{b},2} \to m^2_{\tilde{b},2} + \delta m^2_{\tilde{b},2}; \quad A_{\tilde{b}} \to A_{\tilde{b}} + \delta A_{\tilde{b}}; \quad \begin{pmatrix} \Phi_{\tilde{b},1} \\ \Phi_{\tilde{b},2} \end{pmatrix} \to \left[1 + \frac{1}{2}\begin{pmatrix} \delta Z^{\tilde{b}}_{1,1} & \delta Z^{\tilde{b}}_{1,2} \\ \delta Z^{\tilde{b}}_{2,1} & \delta Z^{\tilde{b}}_{2,2} \end{pmatrix}\right]\begin{pmatrix} \Phi_{\tilde{b},1} \\ \Phi_{\tilde{b},2} \end{pmatrix}$$

- $\delta m^2_{\tilde{b},2}$ and $\delta Z^{\tilde{b}}_{i,j}$ fixed as in the $\tilde{t}$ case.
- $\delta A_{\tilde{b}}$ defined imposing:



$$|_{\Delta} \stackrel{!}{=} 0$$

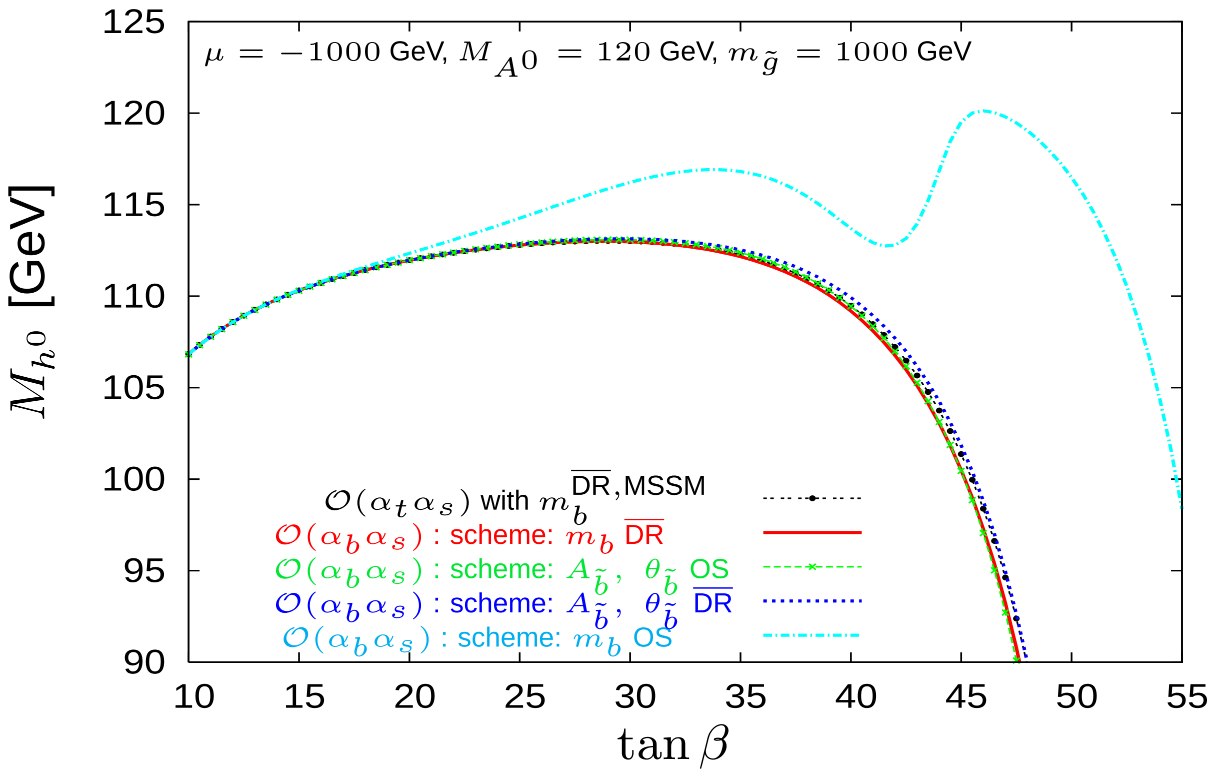
  - Divergences wthin DRED; $\Delta = 2/\epsilon - \gamma + \ln 4\pi$
  - $\overline{\text{DR}}$ scheme (DRED + UV poles subtraction)

- $\delta\theta_{\tilde{b}}$ dependent, function of $\delta\mu$, $\delta \tan\beta$, δm_t, $\underline{\delta m_b}$ $\hookrightarrow$ [fixed via the $\overline{\text{DR}}$ prescription]

- <u>Difference</u> beetween stops and sbottoms . . . Why?

Renormalizing the squark sector, II

A good reason: M_{h^0} including dominant two loops contribution:



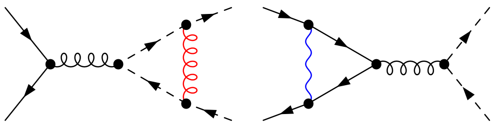
[Heinemeyer, Hollik, Rzehak, Weiglein '05]

- m_b OS scheme: sbottoms treated as stops
- $A_{\tilde{b}}$ dependent and: $\frac{\delta A_{\tilde{b}}}{A_{\tilde{b}}} \sim \frac{\delta m_b}{m_b} \frac{A_{\tilde{b}} - \mu \tan\beta}{A_{\tilde{b}}} \sim \alpha_s \frac{m_{\tilde{g}}}{m_b} \frac{A_{\tilde{b}} - \mu\tan\beta}{A_{\tilde{b}}}$

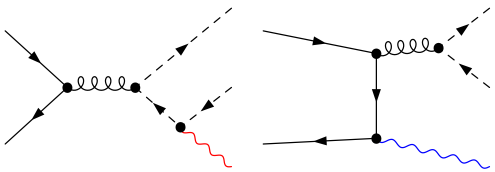
  $\hookrightarrow$ $\delta A_b \sim A_b$ if $\tan\beta$ big ($\delta A_{\tilde{b}} \sim 3 A_{\tilde{b}}$ if $\tan\beta = 50$)

  $\hookrightarrow$ m_b OS scheme not reliable.

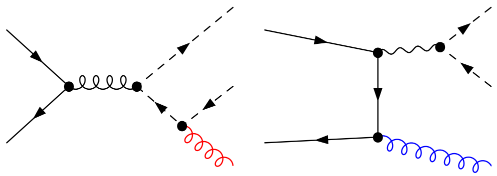
IR & Collinear Divergences



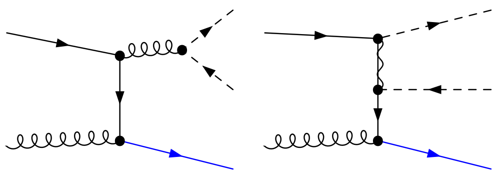
$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}$



$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*} \gamma$

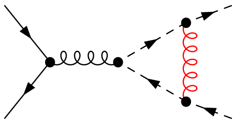
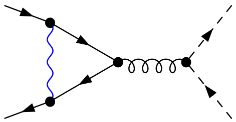


$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*} g$

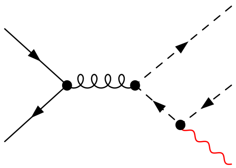
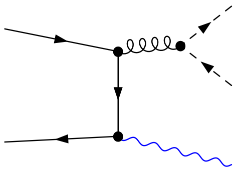


$\ldots \rightsquigarrow$ Collinear singularities in $qg \to \tilde{Q}^a \tilde{Q}^{a*} q$

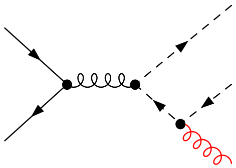
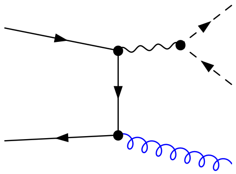
IR & Collinear Divergences

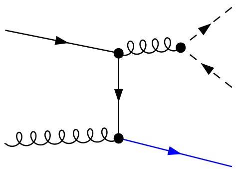
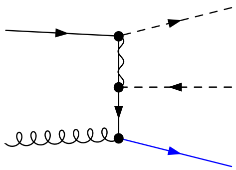
$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}$ +

$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}\gamma$ +

$\ldots \rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*} g$ +

$\ldots \rightsquigarrow$ Collinear singularities in $qg \to \tilde{Q}^a \tilde{Q}^{a*} q$ +

PDF factorization =

[KLN theorem] IR & Collinear Safe

Mass singularities in real life

Problem: how to regularize and extract IR & collinear singularities in real emission processes.

- Introduction of m_γ, m_g and m_q regularizes IR & collinear singularities

Mass singularities in real life

Problem: how to regularize and extract IR & collinear singularities in real emission processes.

- Introduction of m_γ, m_g and m_q regularizes IR & collinear singularities

Caveat gluon mass is dangerous: it spoils Ward identities & gauge invariance

But QCD enters in $q\bar{q} \to \tilde{Q}\tilde{Q}$

- no gluon as external state
- IR structure QED-like

So the technology developed for γ singularities applies to g singularities ...
... After performing the color algebra properly †

† more on this upon request

Mass singularities in real life

Problem: how to regularize and extract IR & collinear singularities in real emission processes.

- Introduction of m_γ, m_g and m_q regularizes IR & collinear singularities

Caveat gluon mass is dangerous: it spoils Ward identities & gauge invariance

But QCD enters in $q\overline{q} \to \tilde{Q}\tilde{Q}$

  - no gluon as external state
  - IR structure QED-like

So the technology developed for γ singularities applies to g singularities . . .
. . . After performing the color algebra properly †

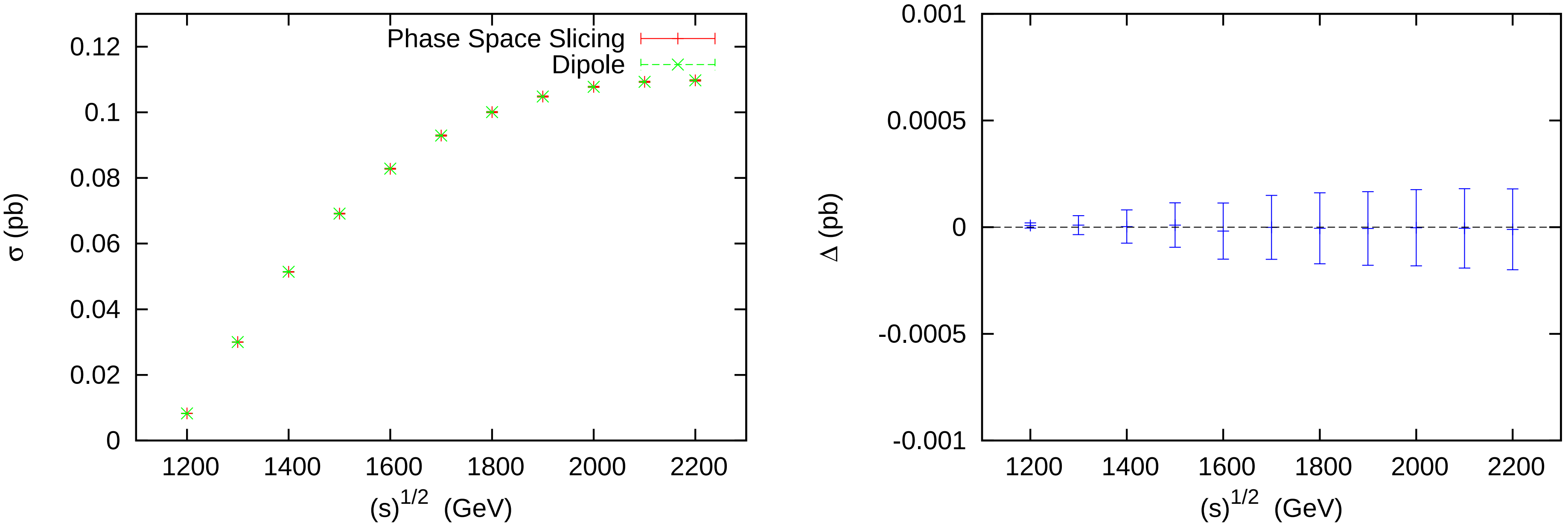
- Two methods † to extract singularities from γ (g) phase space integration:
  - Phase Space Slicing
  - Dipole Subtraction

Singular contributions known analitically and numerics involve regular functions.

† more on this upon request

Mass singularities in real life

- Slicing & Subtraction
  - Two completely different approaches to the problem
  - Their comparison is a non trivial check for IR treatment
- Result of the comparison for the process $u\overline{u} \rightarrow \tilde{u}^L \tilde{u}^{L*} \gamma$



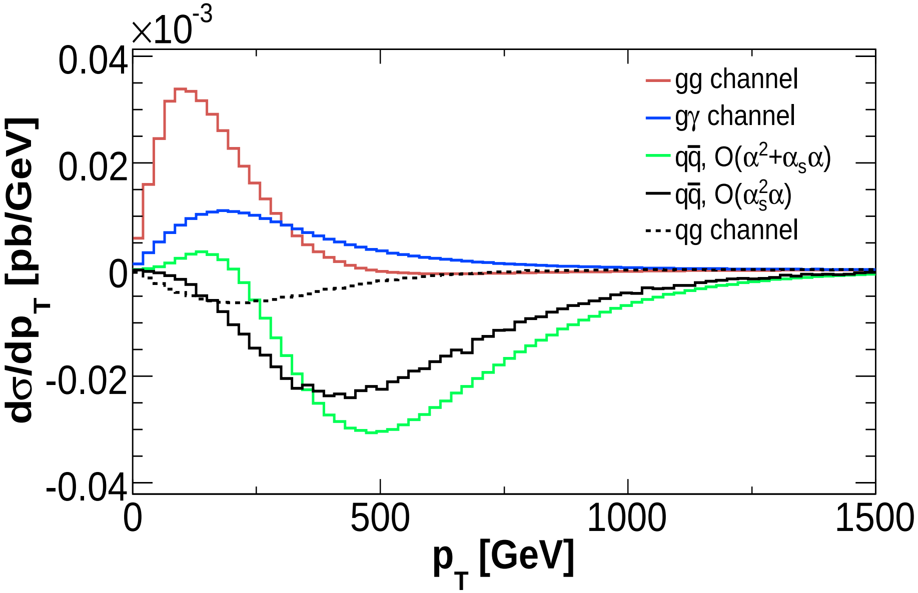
$\Delta = ($Dipole $-$ Slicing$)$, point SPS1a$'$

- Motivations
- Production of squarks and gluinos
  - LO contributions
  - NLO QCD contributions
  - EW contributions
- Closer look into EW contributions
  - UV divergences
  - IR divergences
- Numerical discussion
- Conclusions

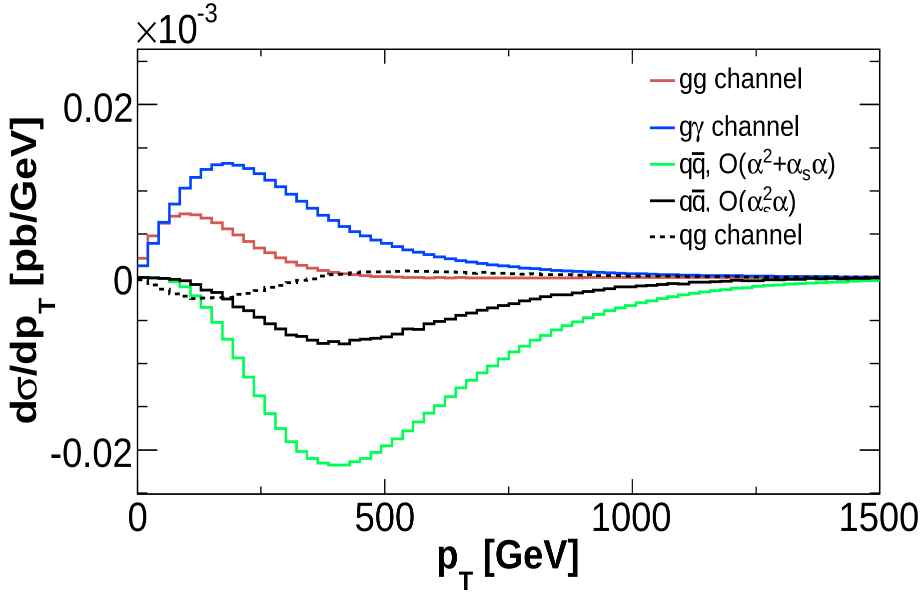
EW corrections – Some feature

Transverse Momentum (p_T) distribution, point SPS1a′

$PP \rightarrow \tilde{u}^L \tilde{u}^{L*}$



$PP \rightarrow \tilde{u}^R \tilde{u}^{R*}$



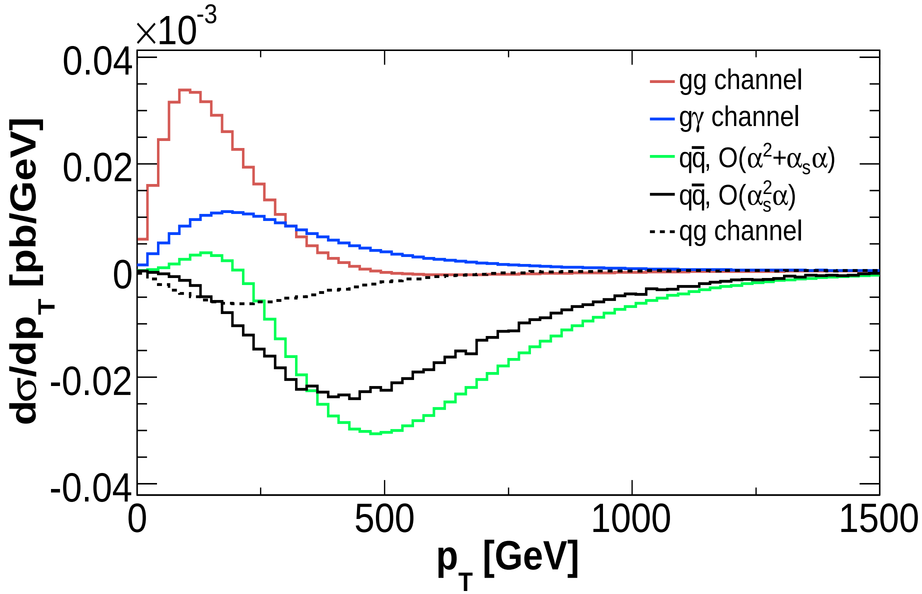
Electroweak Corrections

- Complicate Pattern
  - Different channels dominate in different regions

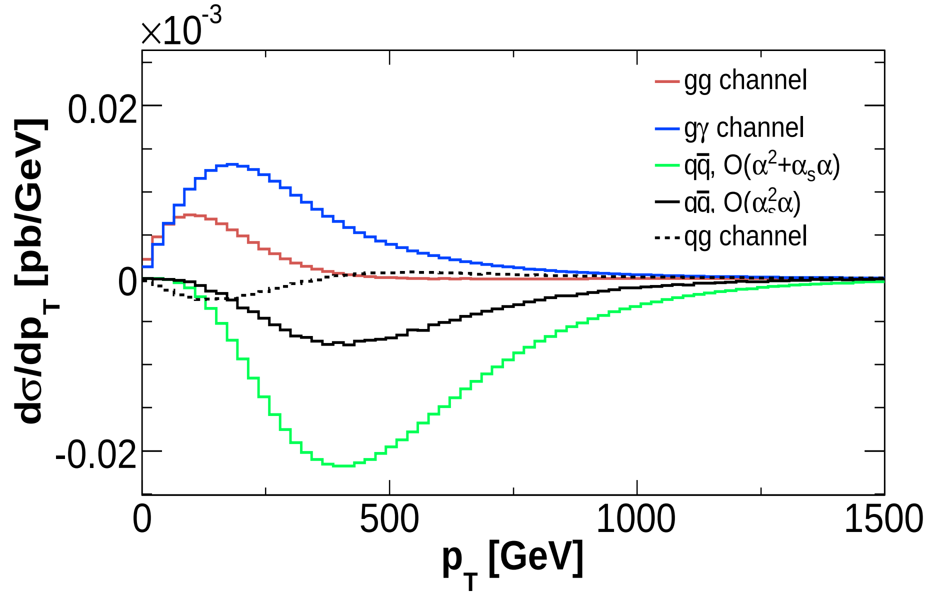
EW corrections – Some feature

Transverse Momentum (p_T) distribution, point SPS1a′

$PP \to \tilde{u}^L \tilde{u}^{L*}$



$PP \to \tilde{u}^R \tilde{u}^{R*}$



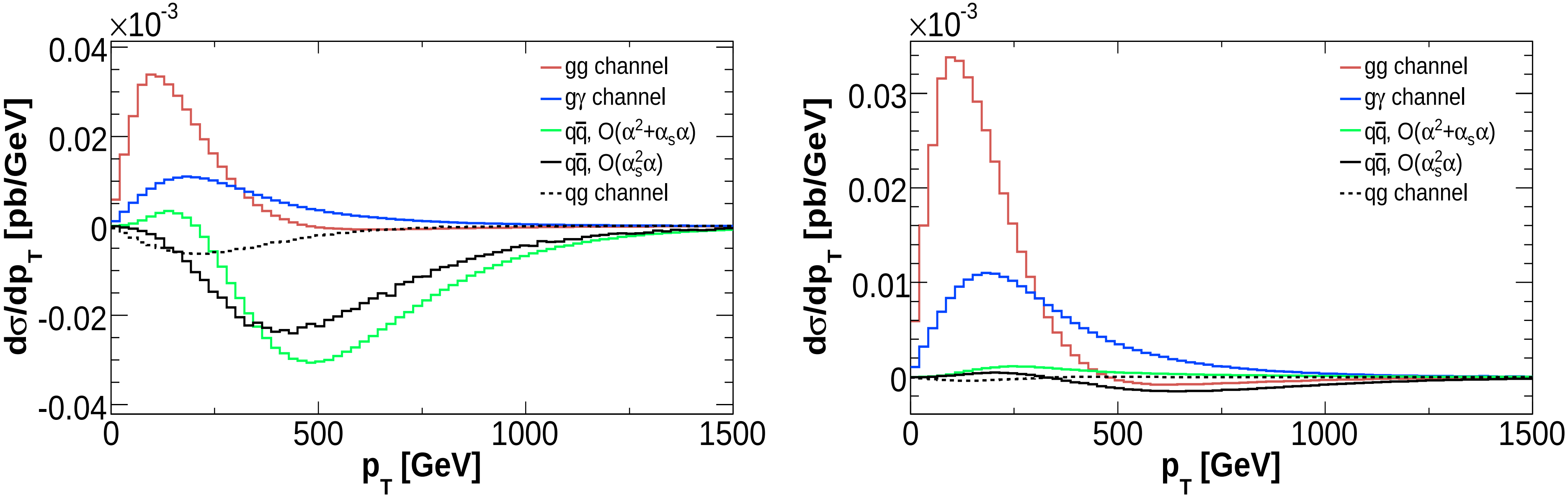
Electroweak Corrections

- Complicate Pattern
- Chirality-Dependent
  - bigger corrections in the left-handed case
  - $q\bar{q}$ @ $\mathcal{O}(\alpha_s^2\alpha)$ comparable with $q\bar{q}$ @ $\mathcal{O}(\alpha_s\alpha + \alpha^2)$ (left-handed case)
  - different behaviour in the low p_T region

EW corrections – Some feature

Transverse Momentum (p_T) distribution,   point SPS1a′

$PP \to \tilde{u}^L \tilde{u}^{L*}$ $\qquad$ $PP \to \tilde{c}^L \tilde{c}^{L*}$



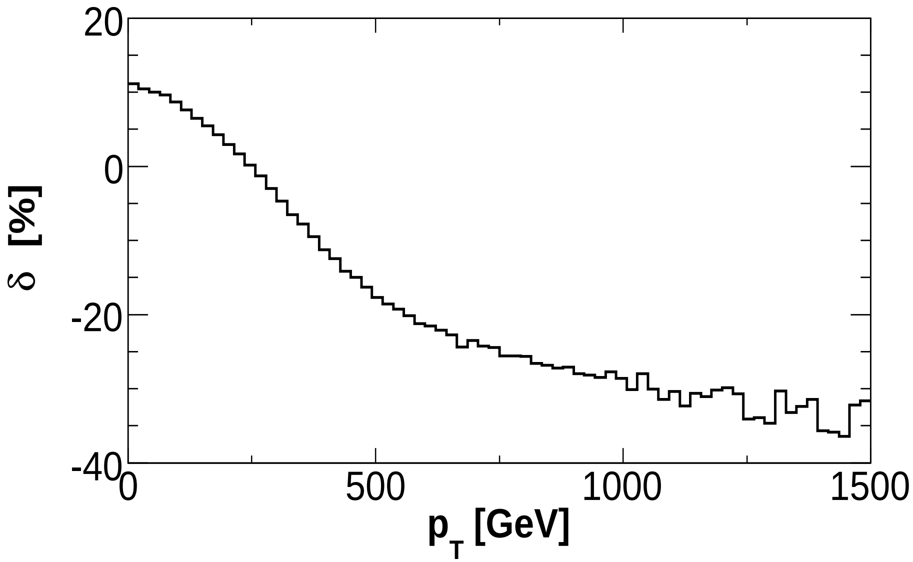
Electroweak Corrections

- Complicate Pattern
- Chirality-Dependent
- Flavour-Dependent
  - @ parton level, $u\bar{u} \to \tilde{u}\tilde{u}^*$ = $c\bar{c} \to \tilde{c}\tilde{c}^*$
  - PDF convolution spoils such relation

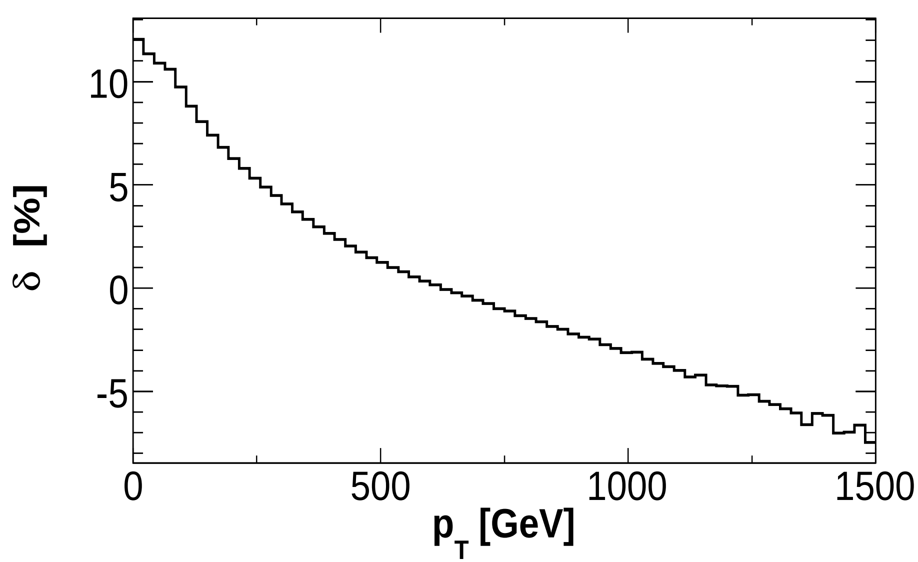
EW corrections – Some feature

Transverse Momentum (p_T) distribution, point SPS1a$'$

$PP \to \tilde{u}^L \tilde{u}^{L*}$



$PP \to \tilde{c}^L \tilde{c}^{L*}$

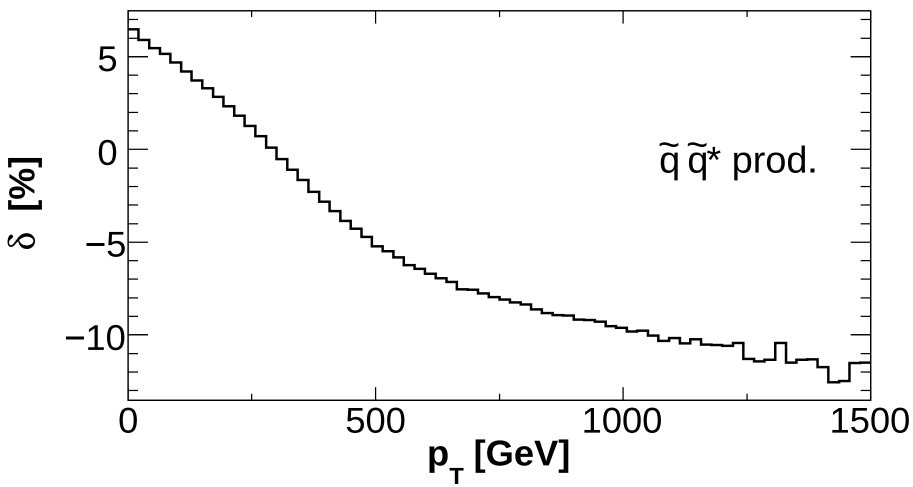


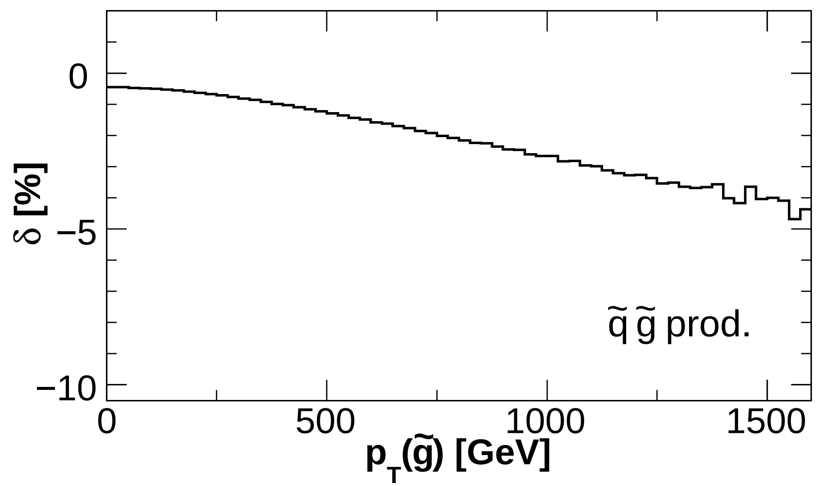
Electroweak Corrections

- Complicate Pattern
- Chirality-Dependent
- Flavour-Dependent
  - @ parton level, $u\bar{u} \to \tilde{u}\tilde{u}^*$ = $c\bar{c} \to \tilde{c}\tilde{c}^*$
  - PDF convolution spoils such relation
  - @ hadron level, different behaviour in the high energy region

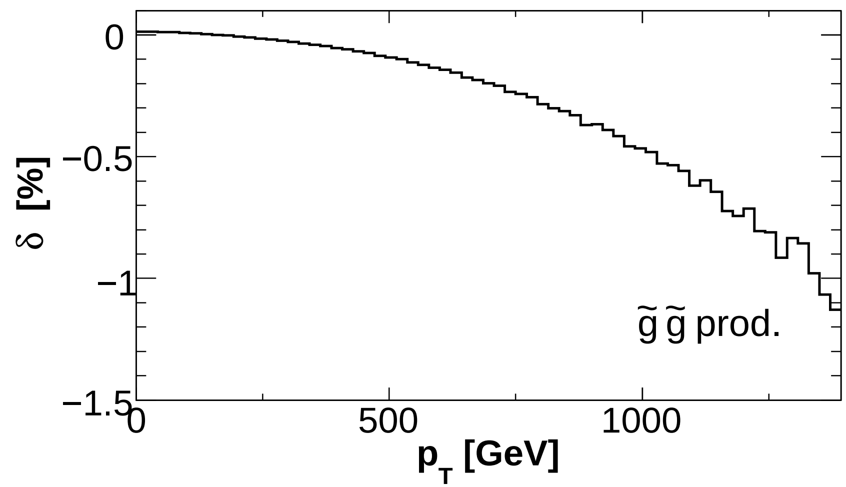
EW corrections – Relative contributions

Fully inclusive transverse momentum distribution



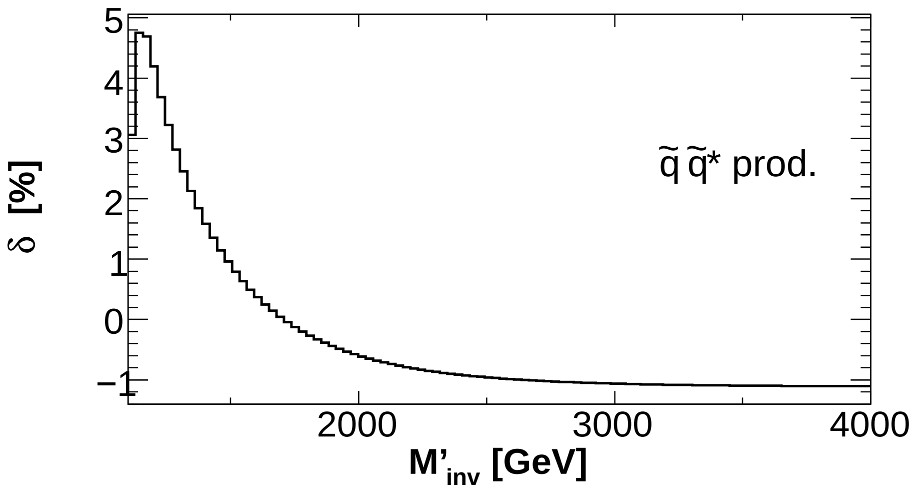


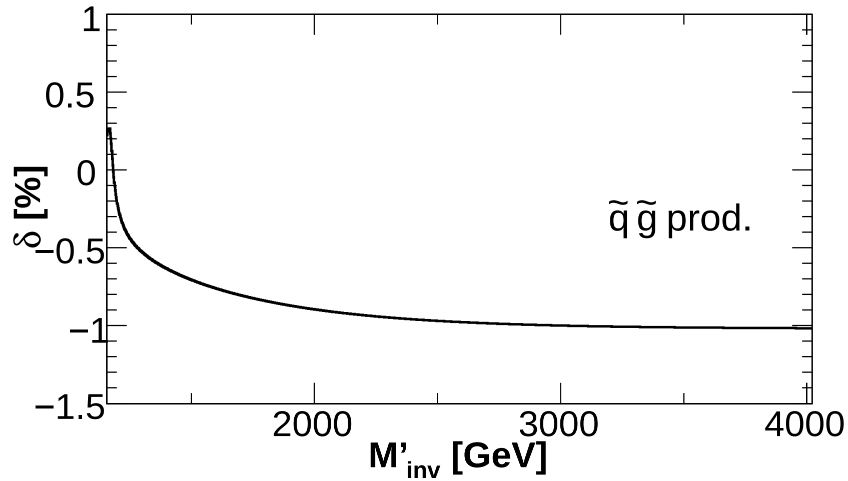
- $\delta = (\sigma^{\text{NLO}} - \sigma^{\text{LO}})/\sigma^{\text{LO}}$
- big contributions from $\tilde{q}^L \tilde{q}^{L*}$ production washed out
- corrections of the order of several percents
- $\tilde{q}\tilde{q}^*$, corrections bigger than $10\ \%$ in the high p_T region



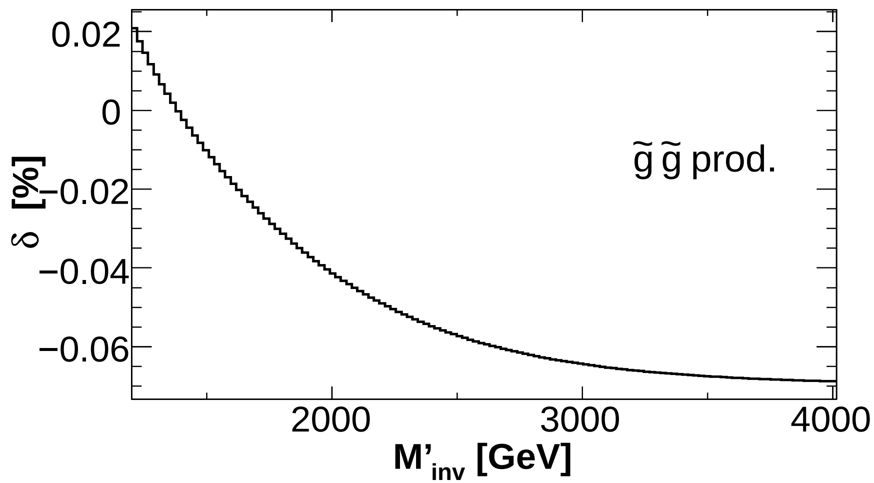
EW corrections – Relative contributions

Fully inclusive cumulative invariant mass, *e.g.* $\sigma(M'_{\text{inv}}) = \int_{\text{th.}}^{M'_{\text{inv}}} \frac{d\sigma}{dM_{\text{inv}}}\, dM_{\text{inv}}$



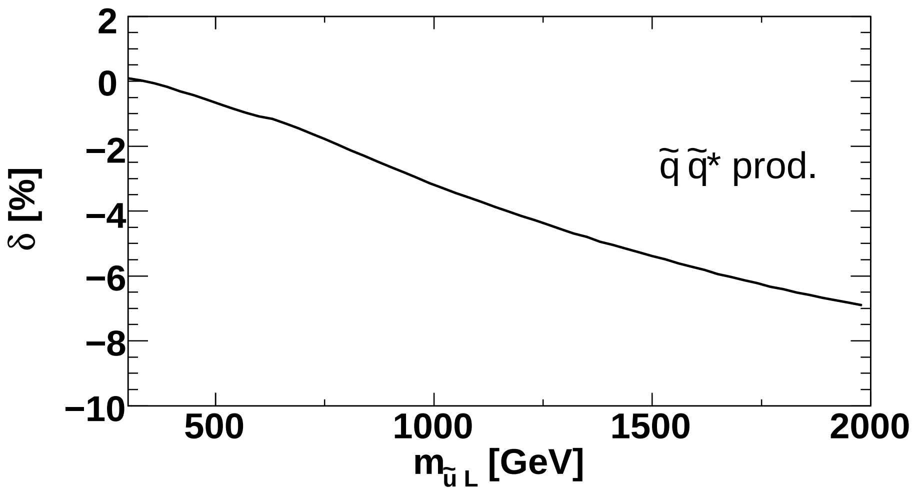


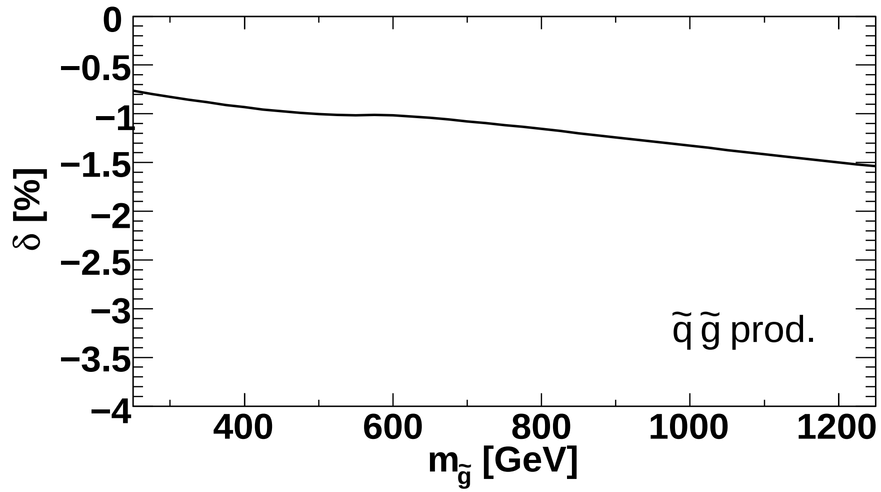
- $\delta = (\sigma^{\text{NLO}} - \sigma^{\text{LO}})/\sigma^{\text{LO}}$
- total Cross Section recovered when $M'_{\text{inv}} \to \infty$
- EW contributions positive near threshold
- contribution to the total cross section negative and at percent level



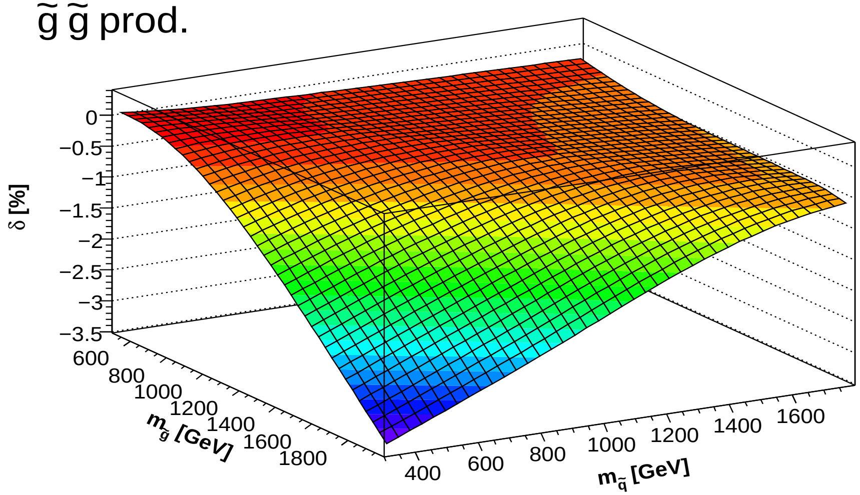
EW corrections – Relative contributions

Total Cross Section Vs Squark and / or Gluino masses





- $\delta = (\sigma^{\text{NLO}} - \sigma^{\text{LO}})/\sigma^{\text{LO}}$
- Total cross section enhanced in the high mass region
- contribution to the total cross section negative and at below 10%



Conclusions & Outlook

- TeV-scale SUSY will be probed at the LHC
- Direct prodution of squarks and gluinos important discovery channels
- NLO QCD corrections to these processes:
  - sizable
  - publicly available
- NLO EW contributions to these processes:
  - under investigation
  - do not affect the total cross section
  - can be important in the high energy region

Road map:

- Compute the processes which are still missing.
  - $\tilde{q}\tilde{q}^{'}$ production $\longrightarrow$ w.i.p.
  - non-diagonal $\tilde{q}\tilde{q}^{'*}$ production $\longrightarrow$ on the wish list
- Merge EW corrections with the NLO QCD ones.

Backup Slides

Phase Space Slicing & Dipole

Consider the process $q \;\; \bar{q} \;\; \rightarrow \;\; \tilde{Q}^a \;\; \tilde{Q}^{a*} \;\; \gamma$

$$\sigma_{q\bar{q}\rightarrow\tilde{Q}^a\tilde{Q}^{a*}\gamma} = \int \qquad d\Phi_3 \;\; |\mathcal{M}|^2$$

$d\phi_3$ $=$ phase space measure

Phase Space Slicing & Dipole

Consider the process $q \;\; \bar{q} \;\; \rightarrow \;\; \tilde{Q}^a \;\; \tilde{Q}^{a*} \;\; \gamma$

$$\sigma_{q\bar{q}\rightarrow\tilde{Q}^a\tilde{Q}^{a*}\gamma} = \int_{\substack{E_\gamma \,>\, \Delta E \\ \theta_{q\gamma},\, \theta_{\bar{q}\gamma} \,<\, \Delta\theta}} d\Phi_3 \;\; |\mathcal{M}|^2 + \boxed{\int_{\text{singular region}} d\Phi_3 \;\; |\mathcal{M}|^2}$$

computed in eikonal approx.

$d\phi_3$ = phase space measure
$\theta_{i\gamma}$ = angle between γ and i
E_γ = energy of γ

- Phase Space Slicing. The photon phase space is divided into two parts introducing cuts:
  - regular region integrated numerically
  - singular region eikonal approximation after mass regularization
  - Remarks:
    - \+ Intutive method
    - – Cuts have to be small (eikonal approximation) . . .
    - – . . . But not too much (numerical instabilities)

Phase Space Slicing & Dipole

Consider the process $q \; \bar{q} \; \rightarrow \; \tilde{Q}^a \; \tilde{Q}^{a*} \; \gamma$

$$\sigma_{q\bar{q}\rightarrow\tilde{Q}^a\tilde{Q}^{a*}\gamma} = \int d\Phi_3 \left[\, |\mathcal{M}|^2 - |\mathcal{M}_{\text{sub}}|^2 \, \right] + \boxed{\int d\Phi_3 |\mathcal{M}_{\text{sub}}|^2}$$

exactly computed

$d\phi_3$ = phase space measure

- Subtraction method. Add and subtract a function $\mathcal{M}_{\text{sub}}$ such that
  - $i)$ $\mathcal{M}_{\text{sub}}$ and $\mathcal{M}$ have same singularity structure
  - $ii)$ $\mathcal{M}_{\text{sub}}$ easy enough to be analitically computed
- $(|\mathcal{M}_{\text{sub}}|^2 - |\mathcal{M}|^2)$ is regular and evaluated numerically
- $\int d\Phi_3 |\mathcal{M}_{\text{sub}}|^2$ exactly evaluated (after mass regularization)
- Remarks:
  - + All numerics involve regular functions
  - + No cut off are needed
  - + leads to more precise results

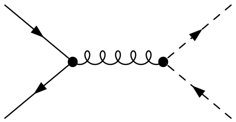
Gluon emission & color algebra

Caveat Gluon carries charge $\Rightarrow$ color correlation after gluon emission.

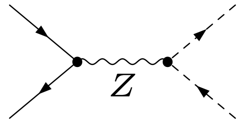
$\hookrightarrow$ Color algebra has to be considered when extracting singularities

consider the colored amplitudes

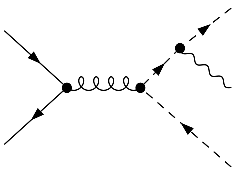
$$\mathcal{M}_g^{c_q\ c_{\bar q}\ c_{\tilde Q}\ c_{\tilde Q^*}} =$$



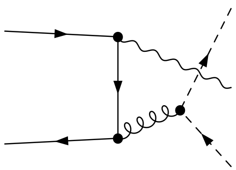
$$\mathcal{M}_Z^{c_q\ c_{\bar q}\ c_{\tilde Q}\ c_{\tilde Q^*}} =$$



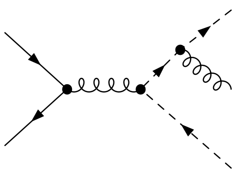
so in the soft limit we have:



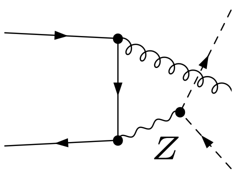
$\times$



$$\sim \sum_c \quad e_q \quad e_{\tilde Q} \quad \mathcal{M}_g^{c_q\ c_{\bar q}\ c_{\tilde Q}\ c_{\tilde Q^*}} \left(\mathcal{M}_g^{c_q\ c_{\bar q}\ c_{\tilde Q}\ c_{\tilde Q^*}}\right)^*$$



$\times$



$$\sim \sum_{c,b} \quad t^A_{b_q c_q}\, t^A_{c_{\tilde Q} b_{\tilde Q}} \mathcal{M}_g^{c_q\ c_{\bar q}\ c_{\tilde Q}\ c_{\tilde Q^*}} \left(\mathcal{M}_Z^{b_q\ c_{\bar q}\ b_{\tilde Q}\ c_{\tilde Q^*}}\right)^*$$

$\hookrightarrow$ In case of g emission amplitudes with different color structure interfere.