Hadronic Production of Colored SUSY Particles with Electroweak NLO Contributions

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SUSY ’08 Conference, Seoul COEX Center, Korea

June 17, 2008

Outline

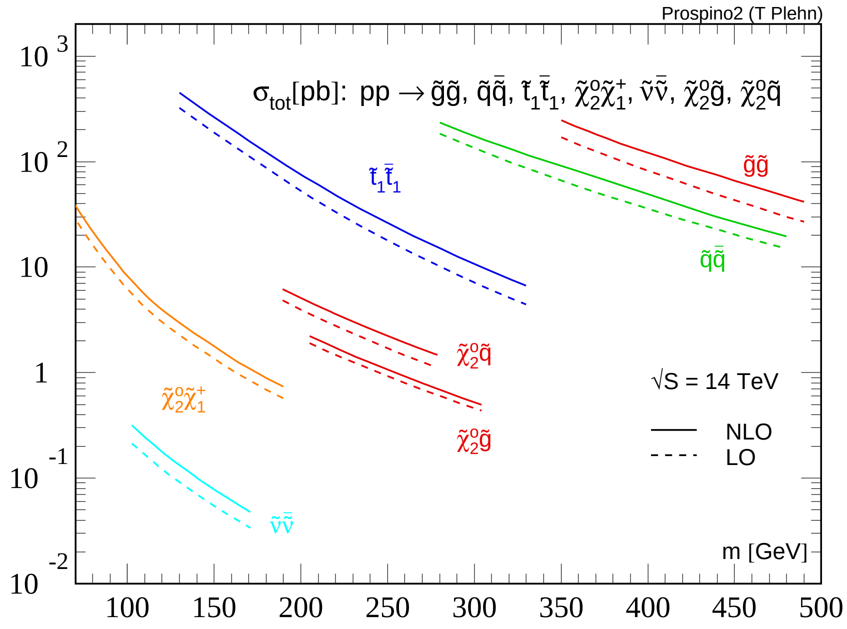
1. **Motivation**
2. **Production of Squarks and Gluinos**
   - classification
   - contributions
3. **$\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{q}$ production at EW NLO**
   - handling singularities
   - numerical results
4. **Summary**

1. Motivation

Why studying production of colored SUSY particles at the LHC?

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

  $\longrightarrow$ **large cross sections**



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

  $\longrightarrow$ **high production rate**

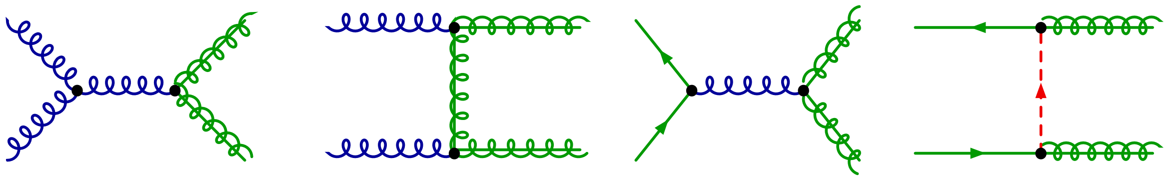
- **cross section depend** essentially **on final state masses**

  $\longrightarrow$ bounds on cross section allow for lower mass bounds without specifying all other SUSY parameters!

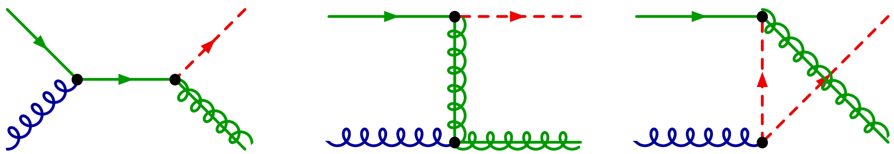
2. Overview: Gluino & Squark Production @ LO

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

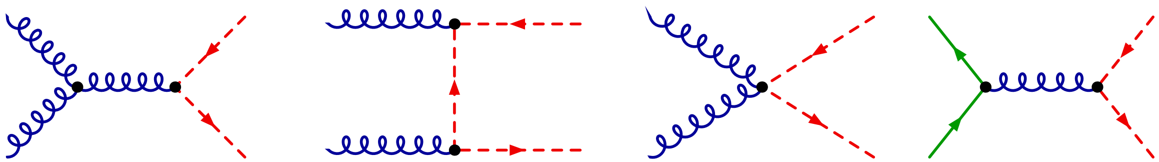
- $\tilde{g}\tilde{g}$ production



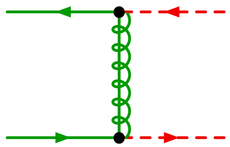
- $\tilde{g}\tilde{q}$ production



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



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



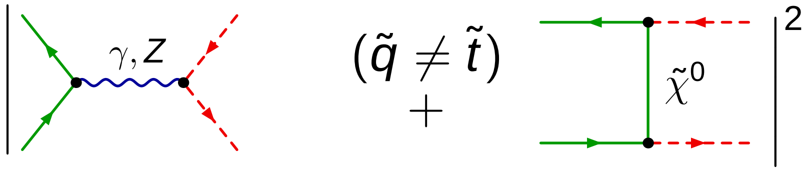
  - stops & sbottoms: L–R mixing cannot be neglected; exp. distinguishable
  - top-squark pair production is diagonal at LO

Tree-level Electroweak Contributions

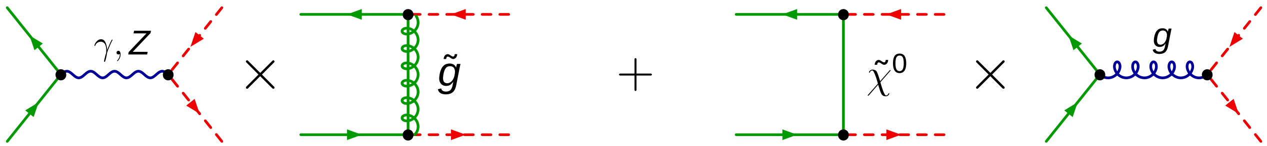
$\tilde{q}\tilde{q}^*$ and $\tilde{t}\tilde{t}^*$ production is also possible by tree-level EW contributions!

- $\mathcal{O}(\alpha^2 + \alpha_s \alpha)$: EW tree level contributions

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



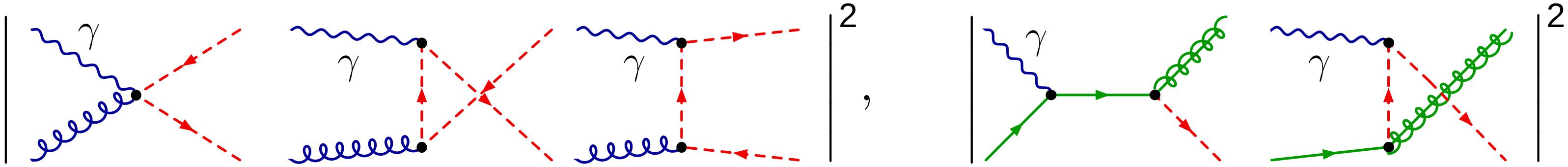
+ EW-QCD tree level interferences for $\tilde{q} \neq \tilde{t}$



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

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

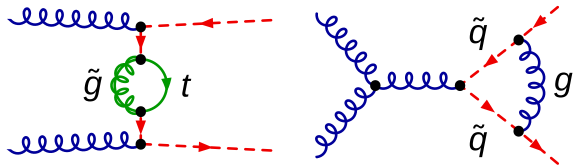
[Hollik, Kollar, MT '07], [Hollik, Mirabella '08]



Higher Order Corrections – Squark Production

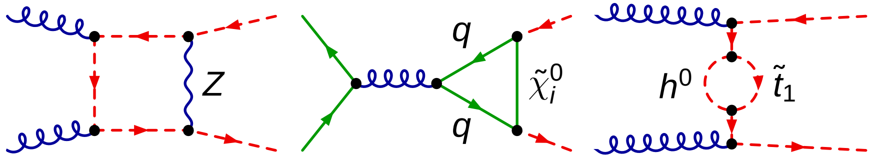
- $\mathcal{O}(\alpha_s^3)$: QCD NLO corrections

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

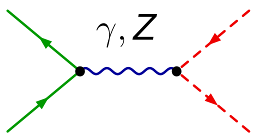
QCD Born $\times$  + . . .

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

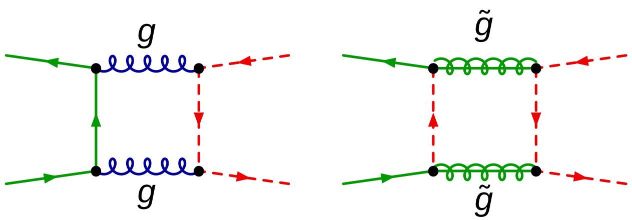
[Hollik, Kollar, MT ’07], [Beccaria et. al. ’08]
[Hollik, Mirabella ’08]

QCD Born $\times$  + . . .

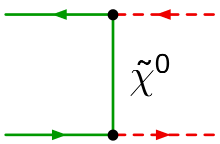
+ EW-QCD one-loop interferences



$\times$

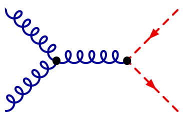
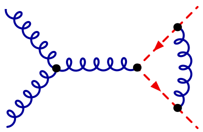
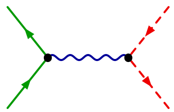
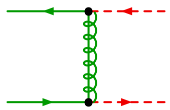
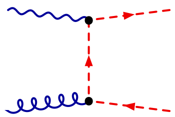
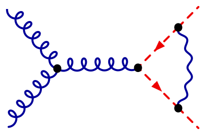


$(\tilde{q} \neq \tilde{t})$
$+$



$\times$ full QCD 1-loop amplitude

Overview: Squark and Gluino Production II

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

⋆⋆: [Hollik, Mirabella; in prep.]
⋆: [Hollik, Mirabella, MT; in prep.]

3. $\tilde{t}\tilde{t}^*$ EW NLO Corrections: **Singularities**

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

  $\longrightarrow$ **renormalization**

  (see talk by Edoardo Mirabella)

  [stop prod. is diagonal $\longrightarrow$ no renorm. of stop mixing angle; no renorm. of gluon field and α_s at this order]

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

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

  [technical: mass regularization + phase space slicing]

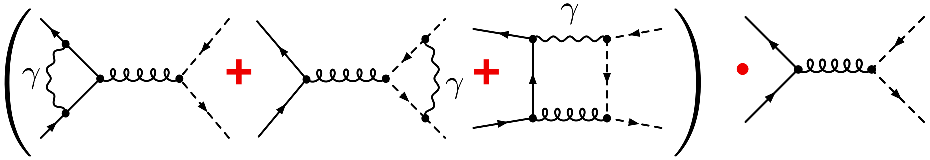
- **collinear singularities** from $m_q = 0$

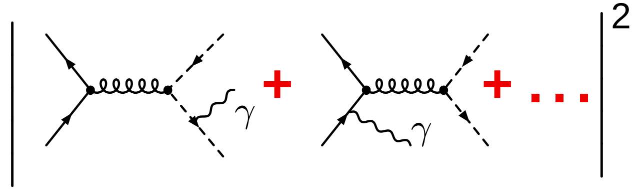
  $\longrightarrow$ real photon bremsstrahlung

  $\longrightarrow$ factorization and **redefinition of PDFs**

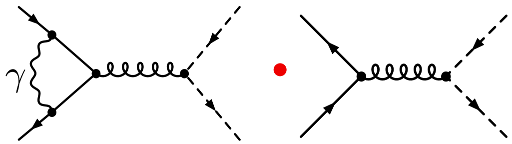
How to obtain a IR-finite cross section for $qq \to \tilde{t}\tilde{t}^*$

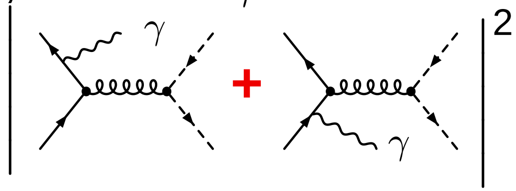
- soft divergent diagrams **and** soft photon bremsstrahlung





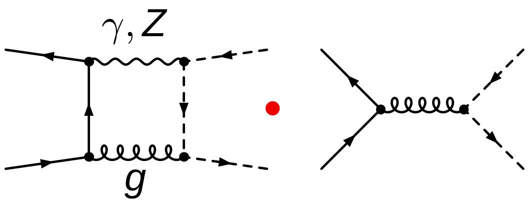
- collinear divergent diagram **and** hard, collinear γ bremsstrahlung

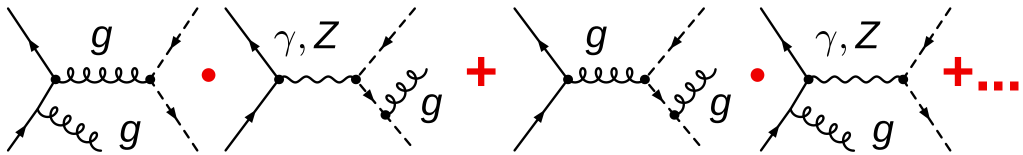




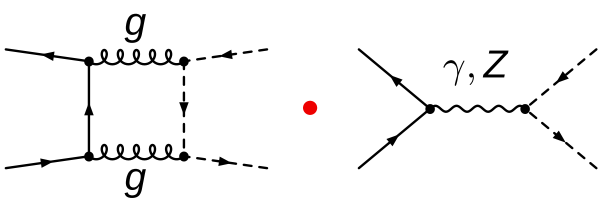
+ redefinition of PDFs: subtract $\ln(m_q^2)$-terms from $\sigma_{q\bar{q}}$

- soft gluon divergent diagrams **and** soft gluon bremsstrahlung





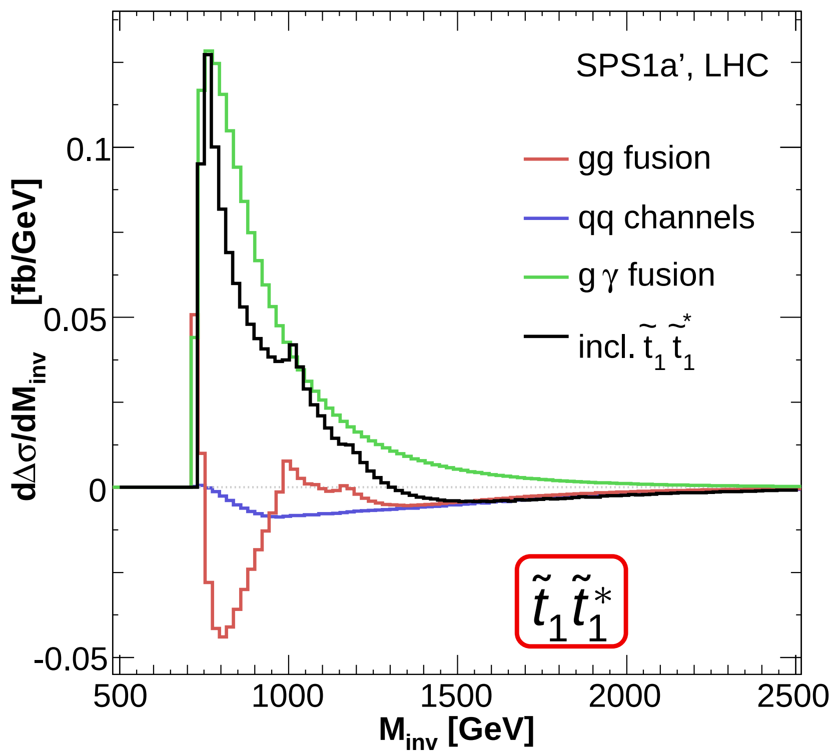
- interference of QCD boxes and EW born

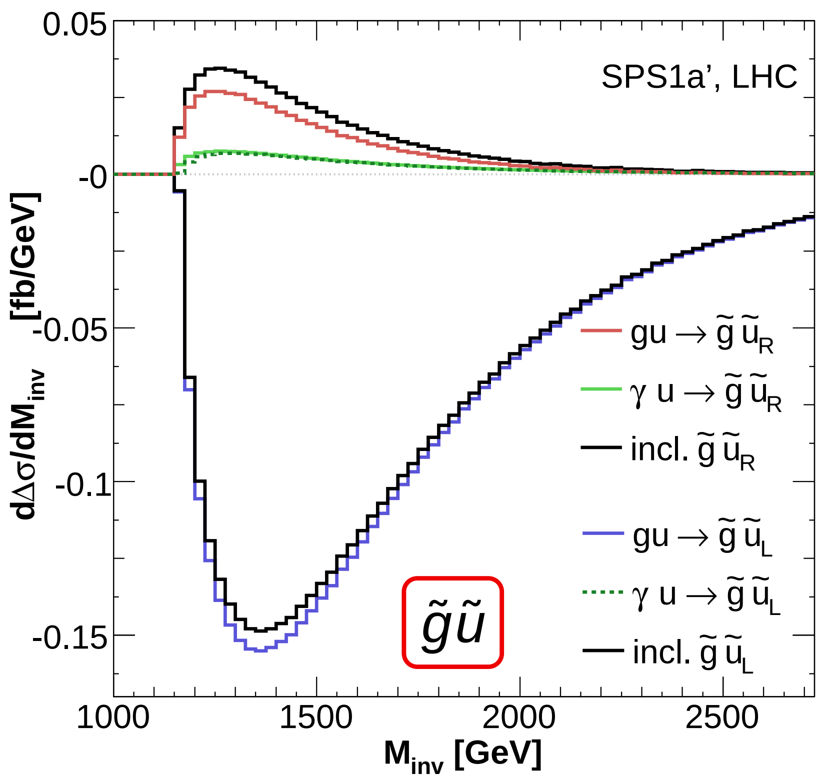


Numerical Results: Absolute Corrections

- Interplay of the production channels?

(SPS: **S**nowmass **P**oints and **S**lopes;
1a': "typical" mSugra scenario, exp. allowed)



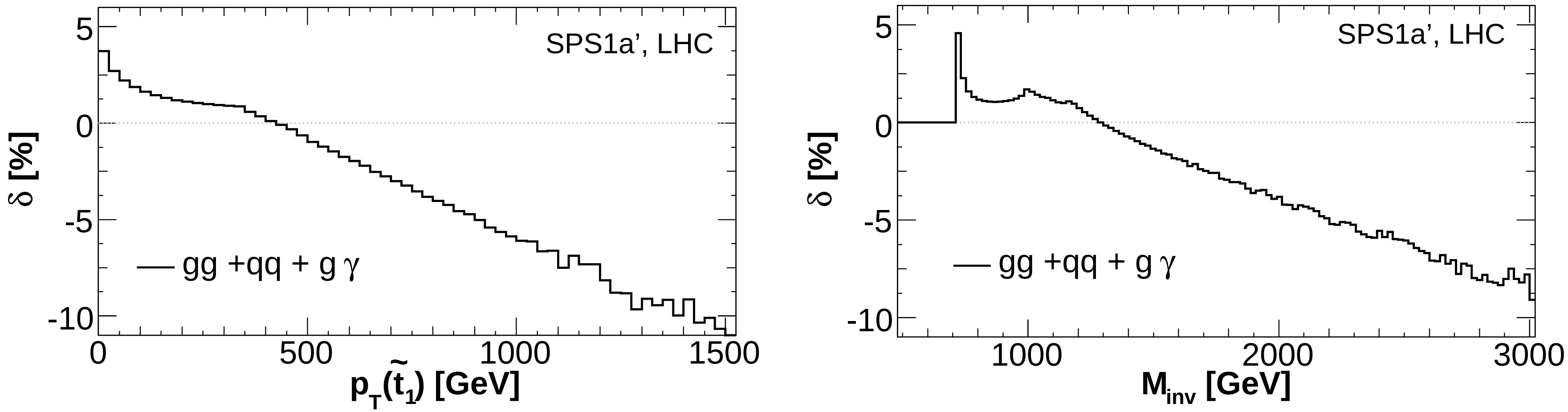


$\longrightarrow$ $\tilde{t}_1\tilde{t}_1^*$: **γg corrections** are **of the same size** and change the total EW corrections substantially!

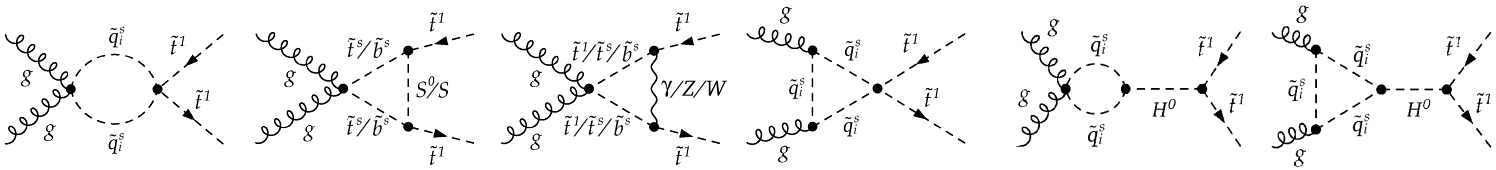
$\longrightarrow$ $\tilde{g}\tilde{q}$: **γq corrections** do not depend on helicity state; contribute considerably for $\tilde{g}\tilde{q}_R$ production.

$\tilde{t}_1\tilde{t}_1^*$ prod.: Relative Corrections $\quad \delta = \Delta\sigma^{NLO}/\sigma^{LO}$

$p_T(\tilde{t}_1)$ $\qquad$ $M_{inv}(\tilde{t}_1\tilde{t}_1^*)$



$\longrightarrow$ threshold effects from stop & sbottom pairs in loops

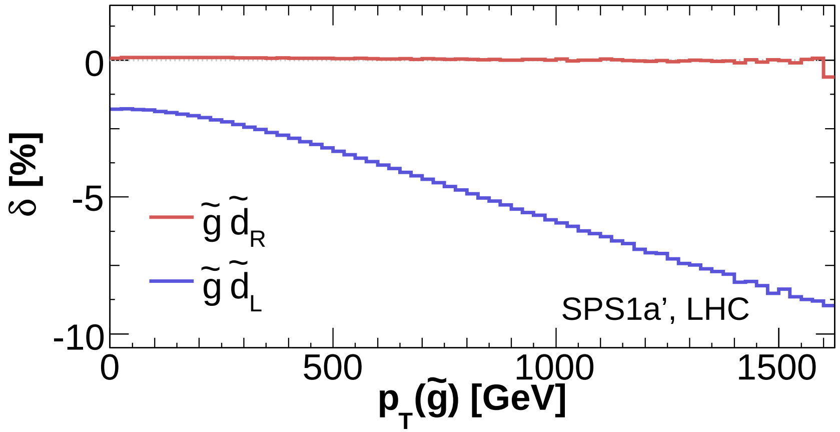


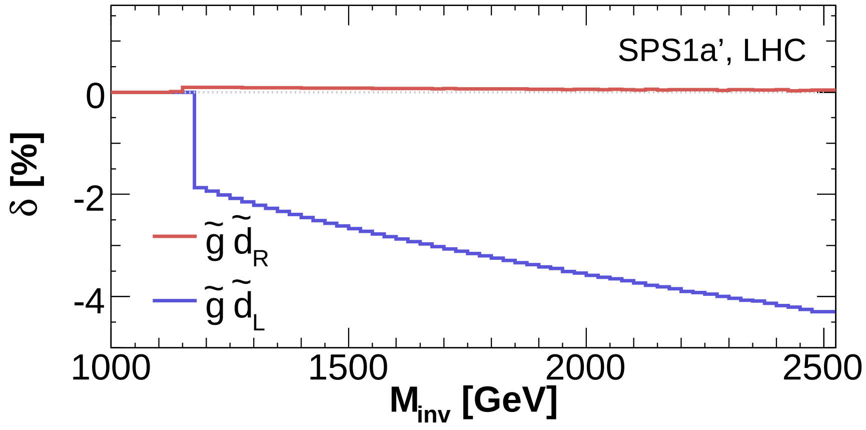
$\longrightarrow$ **EW corrections** grow **up to $\sim$ 10%** for large values of p_T & $M_{\tilde{t}_1\tilde{t}_1^*}$
(large double log's from W,Z exchange, not cancelled by real radiation)

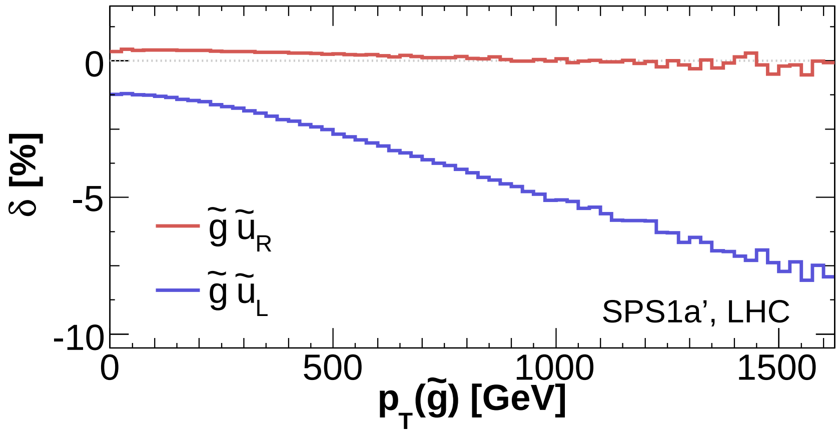
$\tilde{g}\tilde{q}$ production: Relative Corrections δ

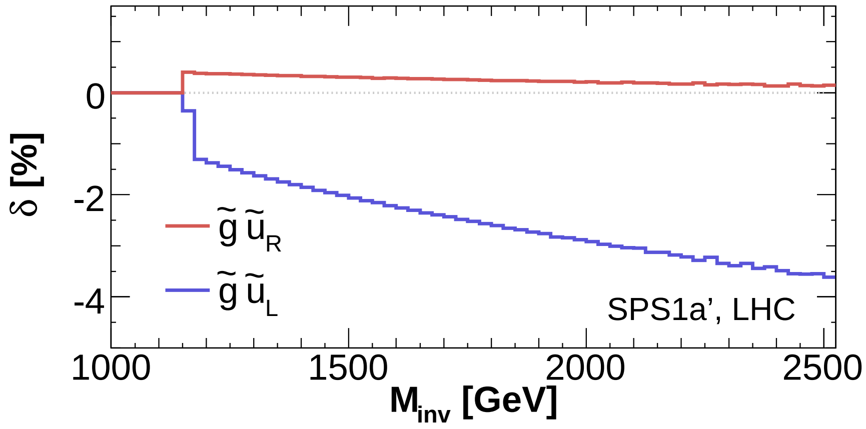
$p_T(\tilde{g})$

$M_{inv}(\tilde{g}\tilde{q})$









$\longrightarrow$ for $\tilde{g}\tilde{d}_L$, $\tilde{g}\tilde{u}_L$ production EW NLO corrections grow **up to 10%**

Total Cross Sections for SPS1a'

final state	σ^{LO} [fb] $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ [fb] $\mathcal{O}(\alpha_s^2\alpha)$	$\sigma^{\gamma g/\gamma q}$ [fb] $\mathcal{O}(\alpha_s\alpha)$	$\delta = \frac{\sigma^{NLO}-\sigma^{LO}}{\sigma^{LO}}$	$\sigma^{EW,LO}$ [fb] $\mathcal{O}(\alpha^2)$
$\tilde{t}_1\tilde{t}_1^*$	**1834**	-15.0	34.1	**1.04 %**	1.11
$\tilde{u}_R\,\tilde{g} + \tilde{d}_R\,\tilde{g}$	8896	13.6	5.05	0.21%	
$\tilde{u}_L\,\tilde{g} + \tilde{d}_L\,\tilde{g}$	8223	-204	4.62	-2.43%	
$\tilde{q}\,\tilde{g}$	**17120**			**-1.06%**	

($\mu_F = \mu_R = 1$ TeV, MRST 2004 QED, $m_t = 170.9$ GeV)

$m(\tilde{t}_1) = 360$ GeV, $m(\tilde{t}_2) = 582$ GeV, $m(\tilde{g}) = 609$ 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.

4. 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 $\tilde{t}\tilde{t}^*$ & $\tilde{q}\tilde{q}^*$ **completed**,
  for $\tilde{q}\tilde{g}$ & $\tilde{g}\tilde{g}$ publication in preparation

- **EW corrections** to the total cross section are small,
  but **important in the high-p_T** & high-M_{inv} range

- **PDF's include QED and QCD** contributions at NLO
  $\longrightarrow$ non-zero photon PDF opens **third production channel**
  $\longrightarrow$ need to include **QCD corrections for consistent picture**
  and for reduced scale dependence

- **next steps:** consider remaining processes of the class of colored SUSY particle production ($\tilde{q}\tilde{q}$ production, $\tilde{t}_2\tilde{t}_2$, . . .)

Backup

Exp. Searches for Squarks and Gluinos

Gluino & squark mass limits @ CDF Run II:

$m_{\tilde{q}\approx\tilde{g}} > 392$ GeV, $m(\tilde{g}) = 280$ GeV

$A_0 = 0\,\text{GeV}, \tan\beta = 5, \mu > 0$

[CDF note 9229 '08]

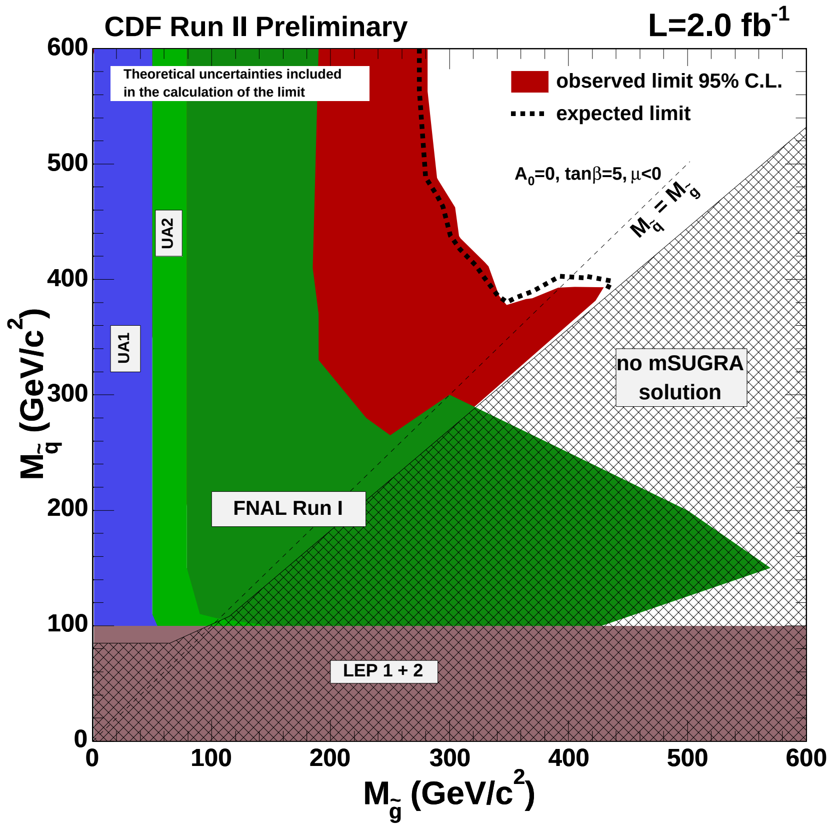
Stop mass limits @ CDF Run II:

$m_{\tilde{t}_1} > 132$ GeV for $m(\tilde{\chi}^0_1) = 48$ GeV

QCD corrections included

assumpt. $BR(\tilde{t}_1 \to c\tilde{\chi}^0_1) = 100\%$

[0707.2567 hep-ex]



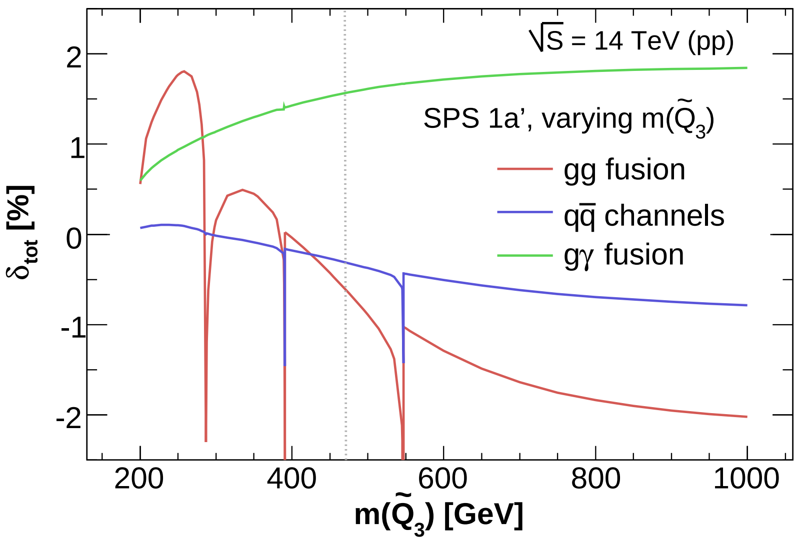
→ **until now: agreement** between data and SM expectations

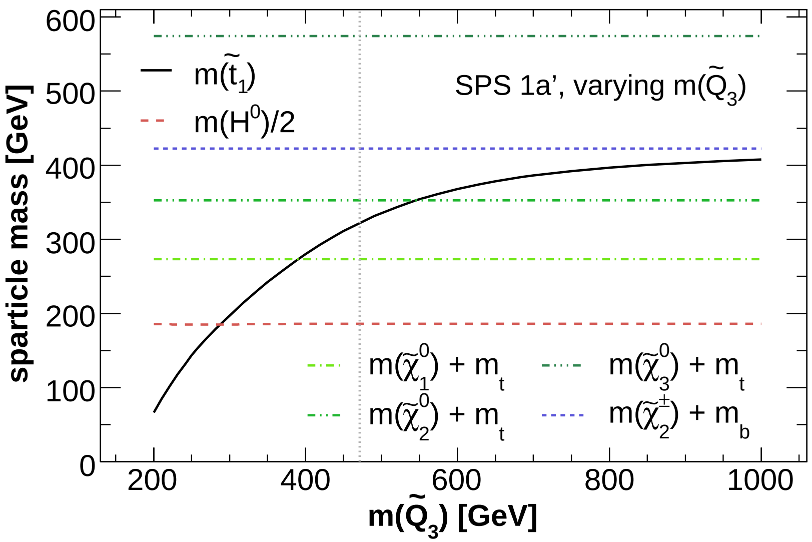
→ comparison of exp. limits & theor. cross sections: restrictions on SUSY parameter space

→ improved theor. predictions needed for more detailed searches!

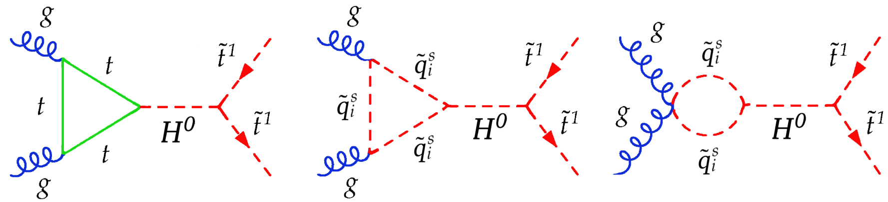
SUSY Parameter Dependence

- **Relative corrections** δ_{tot} with respect to total born cross section ($gg + q\bar{q}$), softbreaking parameter $m(\tilde{Q}_3)$ **varied** around SPS 1a' value, all other parameters as in **SPS 1a'** scenario

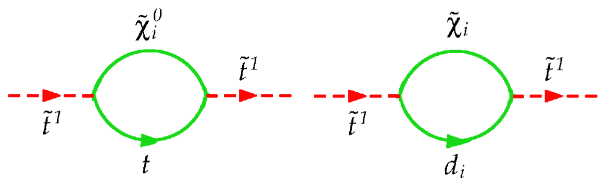




- moderate contributions, at percent level
- thresholds & resonances in H^0 diagrams

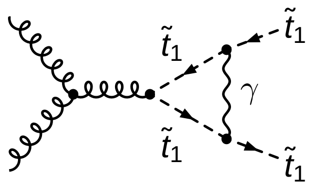


- thresholds in top-squark wave function renormalization

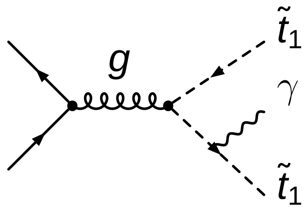


Soft Singularities . . .

. . . arise where external particles exchange a photon



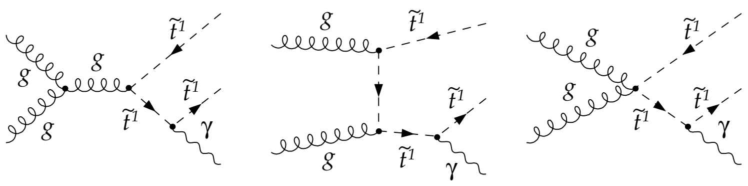
divergent
for $E_\gamma \to 0$



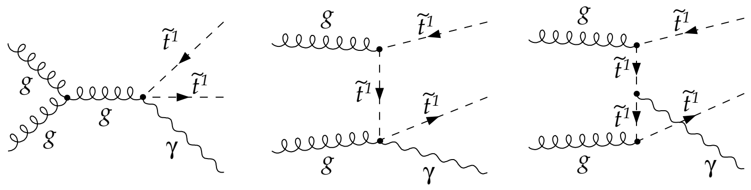
$(E_\gamma \leq \Delta E)$

$\longrightarrow$ introduce photon mass $\lambda \neq 0$ as regulator, add real **soft photon contributions** that lead to the **same observable final state**

$\longrightarrow$ **phase space slicing**: dependency on cut-off parameter ΔE cancels when hard photon bremsstrahlung is added



IR singular

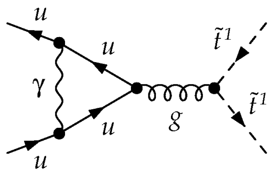


+ IR finite part

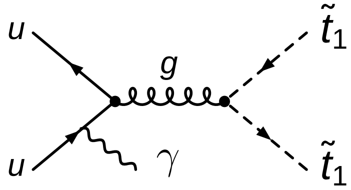
$\longrightarrow$ **Bloch-Nordsieck:** **sum** of virtual and real corrections is **IR finite** (and independent of λ & ΔE)

Collinear Singularities . . .

. . . arise where light initial state quark splits into quark and photon



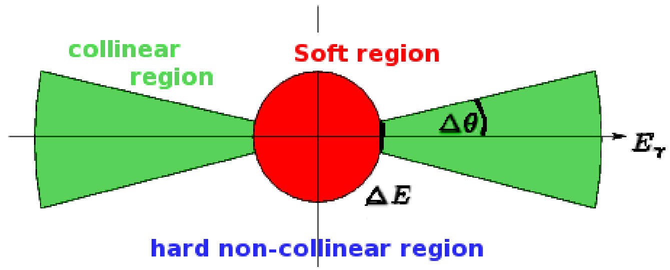
divergent
for $m_q = 0$,
$\theta_{u\gamma} \to 0$



$\theta_{u\gamma} \leq \Delta\theta$

$E_\gamma > \Delta E$

$\longrightarrow$ keep small quark mass $m_q \neq 0$, add **collinear photon radiation** (ISR), introduce **second cut-off parameter $\Delta\theta$**



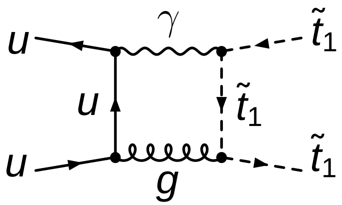
$\longrightarrow$ Sudakov **double log's** cancel in the sum of virtual + real corrections

$\longrightarrow$ remaining **single log's** have to be absorbed into PDFs (**factorization**), **result is independent of m_q**, but depends on factorization scale

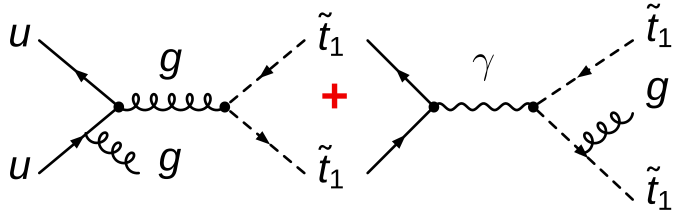
$\longrightarrow$ need PDFs that include NLO QED effects: **MRST 2004 QED** [Martin et al. '04]

More Soft Singularities . . .

. . . arise for **gluon exchange** between external particles!



divergent
for $E_g \to 0$



$(E_g \leq \Delta E)$

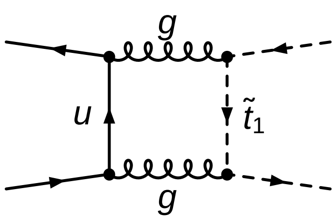
$\longrightarrow$ need small gluon mass $m_g \neq 0$ and **soft gluon bremsstrahlung** at $\mathcal{O}(\alpha\alpha_s^2)$

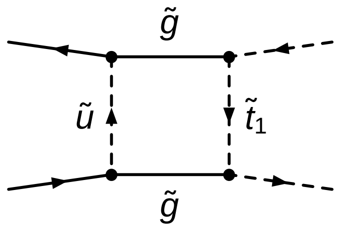
$\longrightarrow$ **mixing of QCD and EW interactions** (vanishing at born level!)

$\longrightarrow$ color flux: only **interference** of ISR and FSR contributes

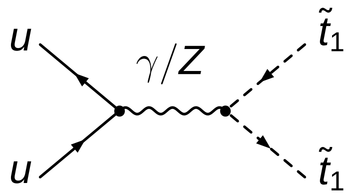
- also at $\mathcal{O}(\alpha\alpha_s^2)$:

QCD boxes + **EW born**





+



Soft Singularities in Detail

The **soft-photon parts** factorize in **universal factors** and the **LO cross section**:

$$d\hat{\sigma}^{q\bar{q}}_{soft,\gamma}(\hat{s}) = \frac{\alpha}{\pi}\left(e_q^2\,\delta^{in}_{soft} + e_t^2\,\delta^{fin}_{soft} + 2e_q e_t\,\delta^{int}_{soft}\right) d\hat{\sigma}^{q\bar{q}}_0(\hat{s})$$

$$d\hat{\sigma}^{gg}_{soft,\gamma}(\hat{s}) = \frac{\alpha}{\pi}\, e_t^2\,\delta^{fin}_{soft}\, d\hat{\sigma}^{gg}_0(\hat{s})$$

the $q\bar{q}$ **soft-gluon part** needs special **color matrix arrangement**:

$$d\hat{\sigma}^{q\bar{q}}_{soft,g}(\hat{s}) = \frac{\alpha_s}{\pi}\,\delta^{int}_{soft}\left[T^a_{ij}T^b_{ji}T^a_{lm}T^b_{ml}\right]\cdot\overline{\sum}\left(2\widetilde{\mathcal{M}}^{q\bar{q}\,*}_{0,g}\widetilde{\mathcal{M}}^{q\bar{q}}_{0,\gamma} + 2\widetilde{\mathcal{M}}^{q\bar{q}\,*}_{0,g}\widetilde{\mathcal{M}}^{q\bar{q}}_{0,Z}\right)\frac{d\hat{t}}{16\pi\hat{s}^2}$$

with
$$\delta^{in}_{soft} = \left[\ln\frac{4(\Delta E)^2}{\hat{s}} - \ln\frac{\lambda^2}{\hat{s}}\right]\left[\ln\frac{\hat{s}}{m_q^2} - 1\right] - \frac{1}{2}\ln^2\frac{\hat{s}}{m_q^2} + \ln\frac{\hat{s}}{m_q^2} - \frac{\pi^2}{3},$$

$$\delta^{fin}_{soft} = \left[\ln\frac{4(\Delta E)^2}{\hat{s}} - \ln\frac{\lambda^2}{\hat{s}}\right]\left[\frac{\hat{s}-2m^2_{\tilde{t}_i}}{\hat{s}\beta}\ln\left(\frac{1+\beta}{1-\beta}\right) - 1\right] + \frac{1}{\beta}\ln\left(\frac{1+\beta}{1-\beta}\right)$$
$$- \frac{\hat{s}-2m^2_{\tilde{t}_i}}{\hat{s}\beta}\left[2\mathrm{Li}_2\left(\frac{2\beta}{1+\beta}\right) + \frac{1}{2}\ln^2\left(\frac{1+\beta}{1-\beta}\right)\right], \qquad \beta = \sqrt{1-\frac{4m_{\tilde{t}_i}}{\hat{s}}},$$

$$\delta^{int}_{soft} = \left[\ln\frac{4(\Delta E)^2}{\hat{s}} - \ln\frac{\lambda^2}{\hat{s}}\right]\ln\left(\frac{1-\beta\cos\theta}{1+\beta\cos\theta}\right) - \mathrm{Li}_2\left(1-\frac{1-\beta}{1-\beta\cos\theta}\right)$$
$$- \mathrm{Li}_2\left(1-\frac{1+\beta}{1-\beta\cos\theta}\right) + \mathrm{Li}_2\left(1-\frac{1-\beta}{1+\beta\cos\theta}\right) + \mathrm{Li}_2\left(1-\frac{1+\beta}{1+\beta\cos\theta}\right).$$

Collinear Singularities in Detail

- **Approx.** of partonic cross section in the **collinear cones** ($p_\gamma = (1-z)p_a$):

$$d\hat{\sigma}_{coll}(\hat{s}) = \frac{\alpha}{\pi} e_q^2 \int_0^{1-\delta_s} dz\; d\hat{\sigma}_0^{q\bar{q}}(\hat{s})\; \kappa_{coll}(z), \qquad \kappa_{coll}(z) = \frac{1}{2} P_{qq}(z) \left[\ln\left(\frac{\tilde{s}}{m_q^2} \frac{\delta_\theta}{2} \right) - 1 \right] + \frac{1}{2}(1-z),$$

- **redefinition of PDFs** at NLO QED:

$$f_{a/A}(x) \to f_{a/A}(x,\mu_F) + f_{a/A}(x,\mu_F)\, \frac{\alpha}{\pi} e_q^2\, \kappa_{soft}^{PDF} + \frac{\alpha}{\pi} e_q^2 \int_x^{1-\delta_s} \frac{dz}{z} f_{a/A}\left(\frac{x}{z}, \mu_F\right) \kappa_{coll}^{PDF}(z)$$

with

$$\kappa_{soft}^{PDF} = -1 + \ln\delta_s + \ln^2\delta_s - \ln\left(\frac{\mu_F^2}{m_q^2}\right) \left[\frac{3}{4} + \ln\delta_s\right] + \frac{1}{4}\lambda_{sc}\left[9 + \frac{2\pi^2}{3} + 3\ln\delta_s - 2\ln^2\delta_s\right],$$

$$\kappa_{coll}^{PDF}(z) = \frac{1}{2} P_{qq}(z) \left[\ln\left(\frac{m_q^2 (1-z)^2}{\mu_F^2} \right) + 1 \right] - \frac{1}{2}\lambda_{sc} \left[P_{qq}(z) \ln\frac{1-z}{z} - \frac{3}{2}\frac{1}{1-z} + 2z + 3 \right].$$

- at hadronic level: mass singularities in $\kappa_{coll} + \kappa_{coll}^{PDF}$ cancel
- κ_{soft}^{PDF} cancels remaining mass singularities owing to soft photons

$\sim$ [Baur, Keller, Wackeroth '99], [Diener, Dittmaier, Hollik '04]