Squark–anti-squark pair production at the LHC: electroweak contributions

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Outline

- Squark–anti-squark P.P.: Overview.
  - Introduction
  - State of the art
- Closer look into 1 loop EW corrections.
  - Squark–anti-squark P.P. at the parton level
  - UV divergences - Renormalization
  - IR & Collinear divergences
- Numerical Results
- Conclusions

Squark–anti-squark pair production at the LHC: electroweak contributions

Introduction

$$P\ P\ \rightarrow\ \tilde{Q}^{a}\ \tilde{Q}^{a*}\quad @\ \mathcal{O}(\alpha_s^2\alpha)$$

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- One among the possible squark production processes at the LHC
- Importance of such process in the hunting for SUSY is beyond dispute
- $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ are the largest contributions . . .

  . . . but EW corrections $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha_s^2\alpha)$ important as well.

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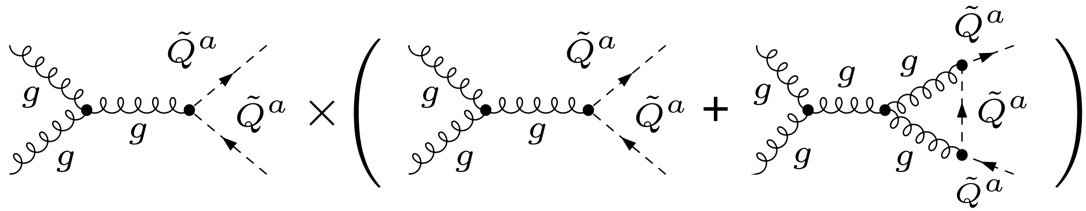
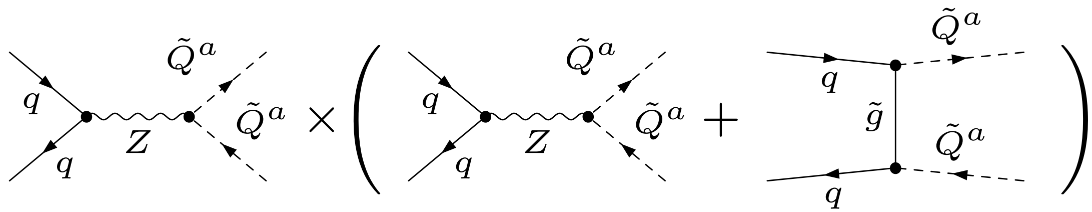
  . . . but EW corrections $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha_s^2\alpha)$ important as well.
- We will describe one loop EW corrections $\mathcal{O}(\alpha_s^2\alpha)$

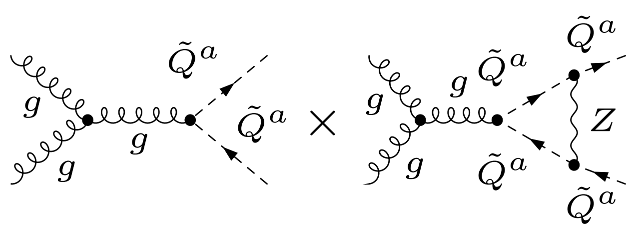
State of the art

- $\mathcal{O}(\alpha_s^2 + \alpha_s^3)$: 

  $\hookrightarrow$ LO and NLO QCD contributions [Kane & Leveille ’82, Harrison & Llewellyn Smith ’83 Reya & Roy ’85, Dawson *et al.* ’85, Baer & Tata ’85, Beenakker *et al.*’96,’97, Beenakker *et al.*’98]

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

  $\hookrightarrow$ Tree level EW corrections [Bornhauser,Drees, Dreiner & Kim ’07, Bozzi, Fuks & Klasen ’07]

- $\mathcal{O}(\alpha_s^2\alpha)$: stop case only 

  $\hookrightarrow$ One loop EW contributions [Hollik, Kollar & Trenkel ’07, Beccaria *et al.* ’07]

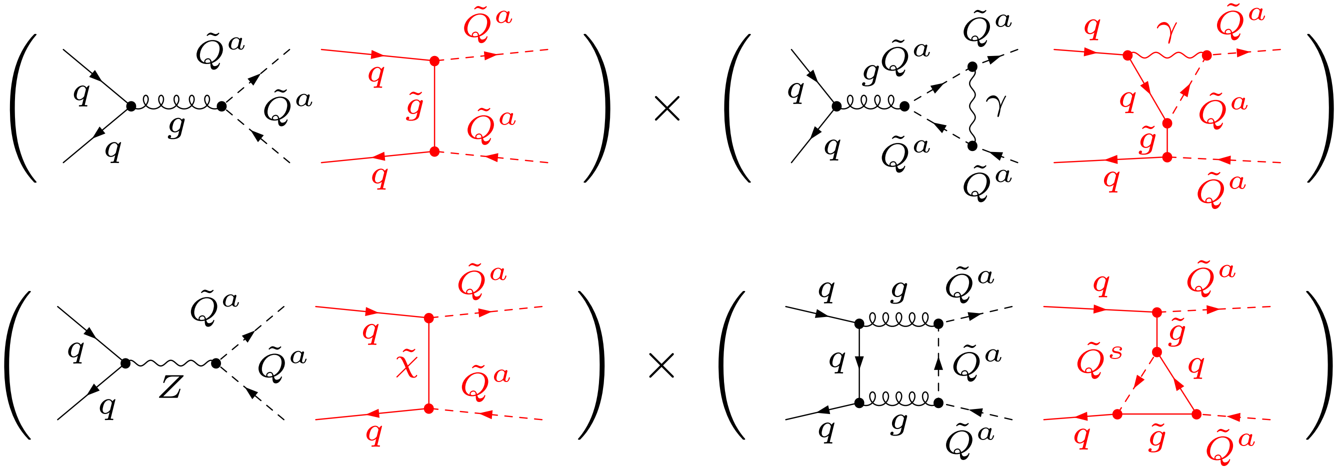
- $\mathcal{O}(\alpha_s^2\alpha)$ corrections for arbitrary recently available [Hollik & Mirabella ’08] . . .

  . . . And the generalization from the stop case is not trivial!

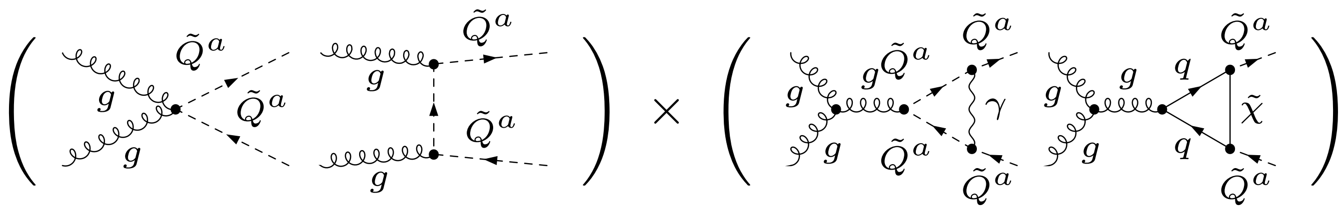
Squark–anti-squark P.P. at the parton level

$\mathcal{O}(\alpha_s^2\alpha)$, virtual corrections

- $q\bar{q} \longrightarrow \tilde{Q}^a\tilde{Q}^{a*}$



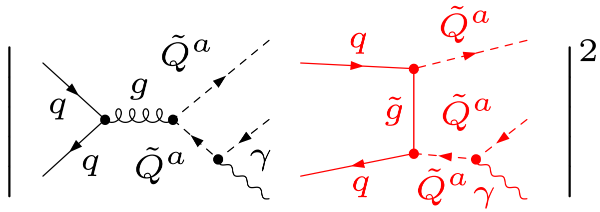
- $gg \longrightarrow \tilde{Q}^a\tilde{Q}^{a*}$



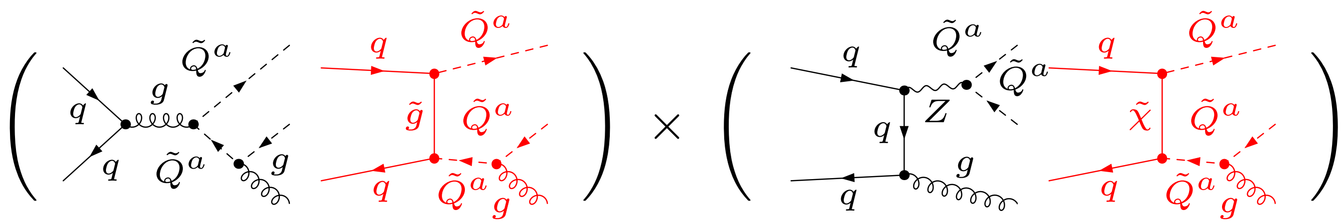
Squark–anti-squark P.P. at the parton level

$\mathcal{O}(\alpha_s^2\alpha)$, Real Corrections

- $q\bar{q} \longrightarrow \tilde{Q}^a\tilde{Q}^{a*}\gamma$



- $q\bar{q} \longrightarrow \tilde{Q}^a\tilde{Q}^{a*}g$



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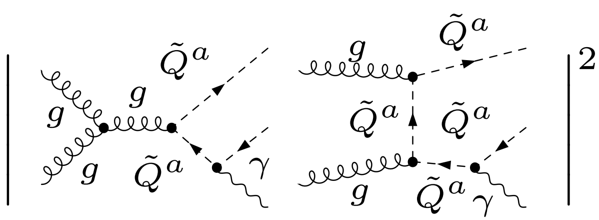

Squark–anti-squark P.P. at the parton level

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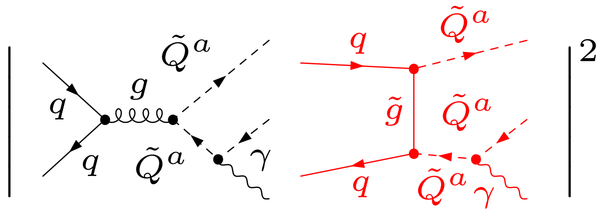

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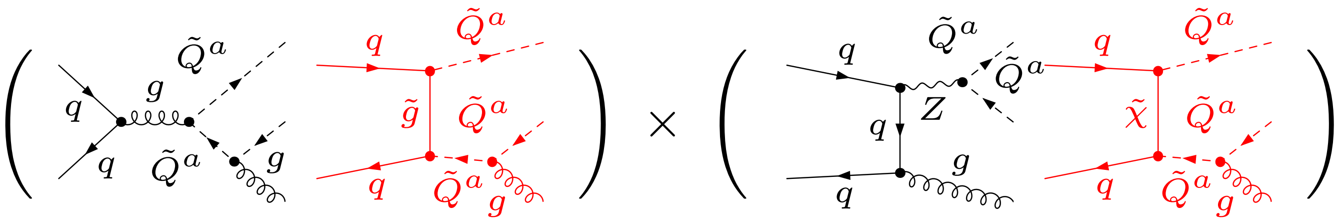

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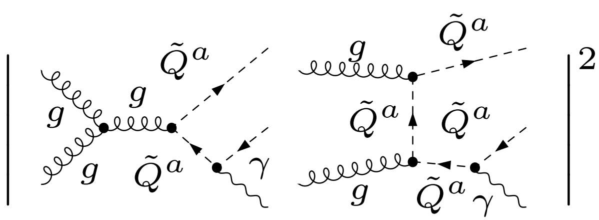
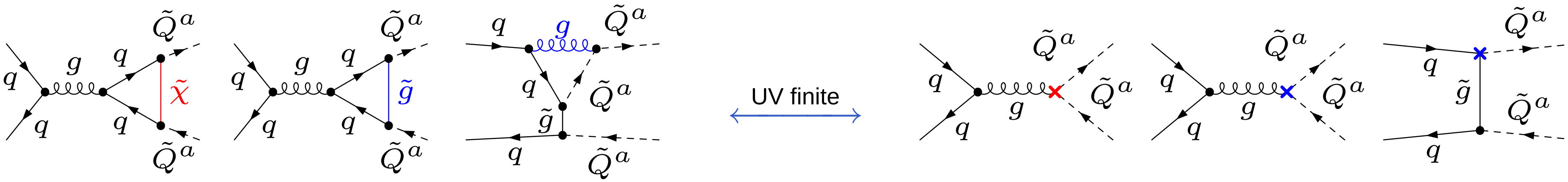


w.r.t. the stop case:

- New diagrams, full one loop QCD diagrams needed
- New interferences (that can be numerically important)
- New UV divergences
- Richer IR structure

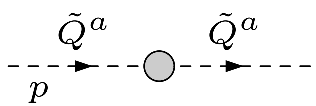
UV divergences - Renormalization



- Renormalization of the squarks sector @ $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s)$

$$\Phi_{\tilde{Q},a} \rightarrow \Phi_{\tilde{Q},a}\left(1+\frac{\delta Z_{\tilde{Q}^a}}{2}\right); \qquad m^2_{\tilde{Q},a} \rightarrow m^2_{\tilde{Q},a} + \delta m^2_{\tilde{Q},a}$$

On Shell conditions for the (independent set of) renormalized parameters:

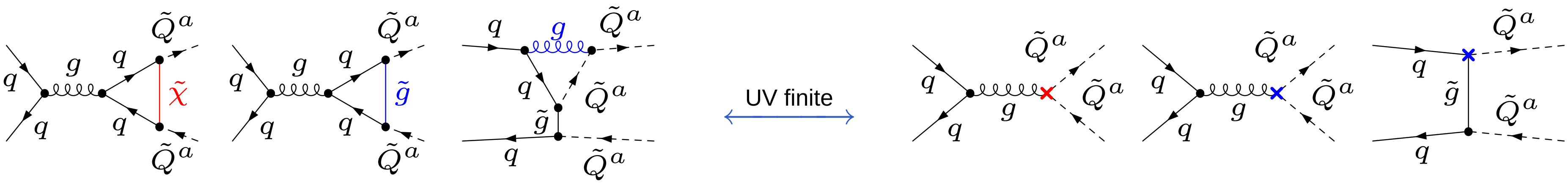


$$= \quad \frac{i}{p^2 - m^2_{\tilde{Q},a}} \quad \text{for} \quad p^2 \rightarrow m^2_{\tilde{Q},a}$$

- Also the gluino sector is renormalized on shell . . .

- . . . And quarks mass and wavefunctions as well.

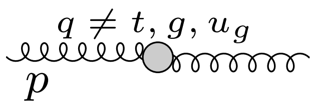
UV divergences - Renormalization

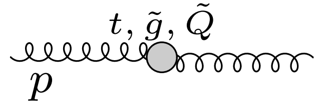


- Renormalization of g_s and the $q\tilde{Q}\tilde{g}$ Yukawa coupling $\hat{g}_s$ at $\mathcal{O}(\alpha_s)$:

$$g_s \longrightarrow g_s + \delta g_s; \qquad \hat{g}_s \longrightarrow \hat{g}_s + \delta \hat{g}_s$$

- Definition of δg_s:

$$\delta g_s \quad \sim \quad \frac{\partial}{\partial p^2}$$


$$|_\Delta \quad + \quad \frac{\partial}{\partial p^2}$$


$$|_{\Delta - \ln(M^2/\mu^2)}$$

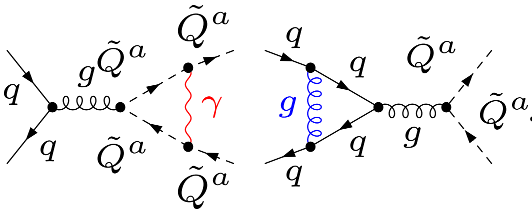
  - $\overline{\text{MS}}$ (DREG $+$ UV poles subtraction) for diagrams with light particles in loops
  - Zero momentum subtraction scheme for diagrams with heavy particles in loops

    $\hookrightarrow$ SM-like running of g_s

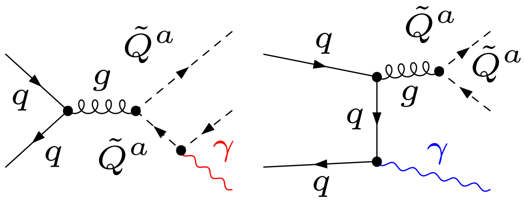
- Definition of $\delta \hat{g}_s$:
  - should be equal to δg_s due to SUSY but ...
  - ... DREG spoils SUSY *i.e.* $g_s \neq \hat{g}_s$ @ NLO [Beenakker *et al.*'96,98]
  - The mismatch between g_s and $\hat{g}_s$ is absorbed into $\delta \hat{g}_s$:

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

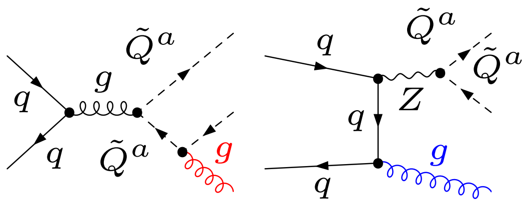
IR & Collinear divergences



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

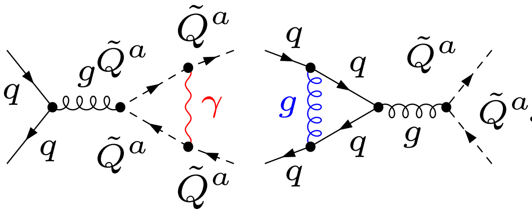


$\ldots$ $\rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}\gamma$

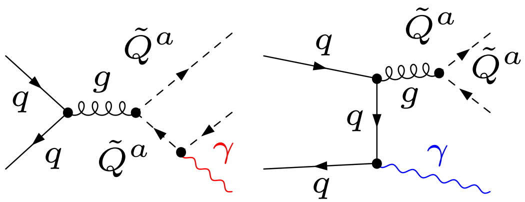


$\ldots$ $\rightsquigarrow$ IR & Collinear singularities in $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*} g$

IR & Collinear divergences



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



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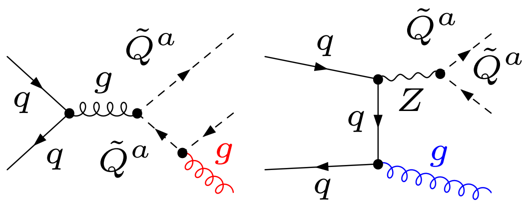

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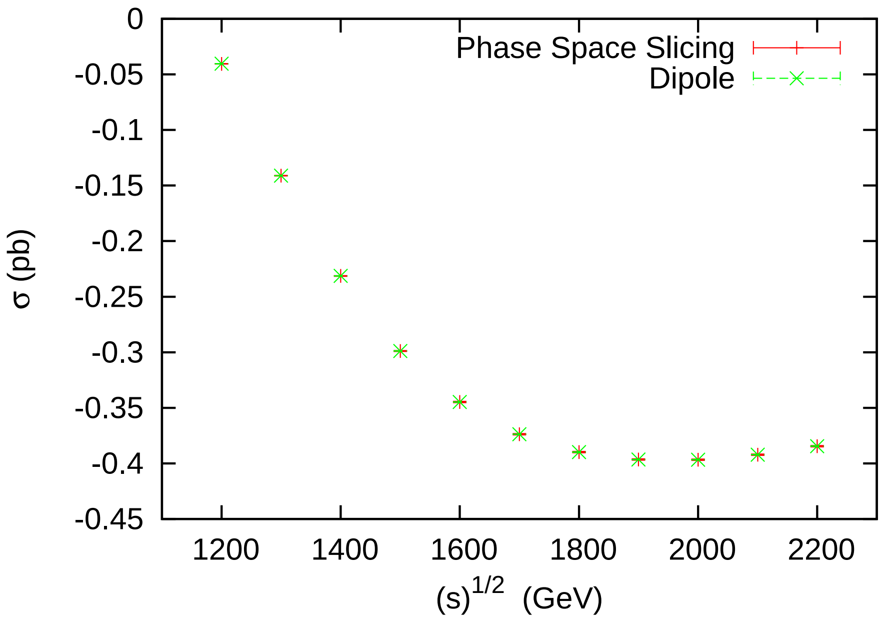
PDF factorization =

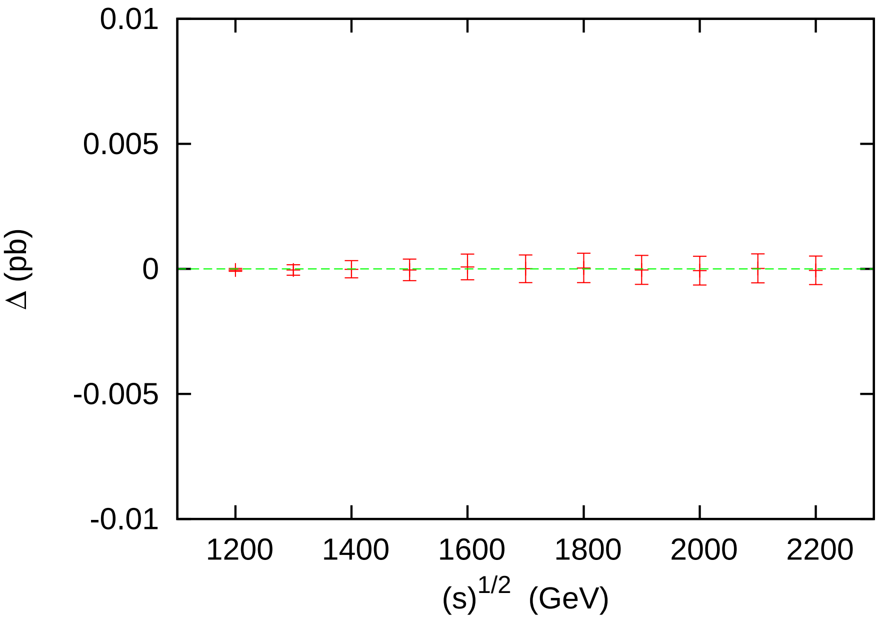
[KLN theorem] IR & Collinear Safe

- Mass regularization in both cases (g singularities essentially Abelian)
- Two methods for γ (g) phase space integration: { Phase Space Slicing / Dipole Formalism }
- Color Algebra introducing color-charge operators in color space

IR & Collinear divergences

cross check, $u\overline{u} \longrightarrow \tilde{u}^L \tilde{u}^{L*} g$





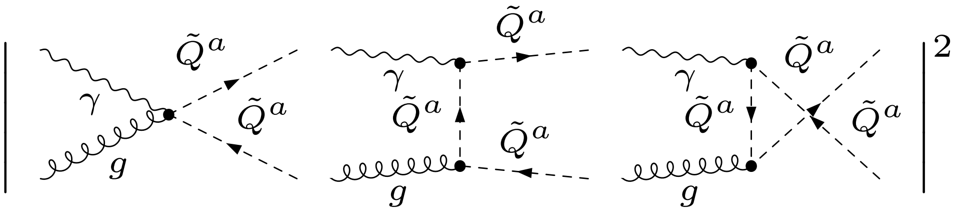
$\Delta = (\text{Dipole} - \text{Slicing})$, point SPS1a$'$

Numerical Results

General Information

- The $\mathcal{O}(\alpha_s\alpha+\alpha^2)$ contributions have been included
  $\hookrightarrow$ their importance already known [Bornhauser, Drees, Dreiner & Kim, ’07]

- The partonic process $g\gamma \to \tilde{Q}^a\tilde{Q}^{a*}$:

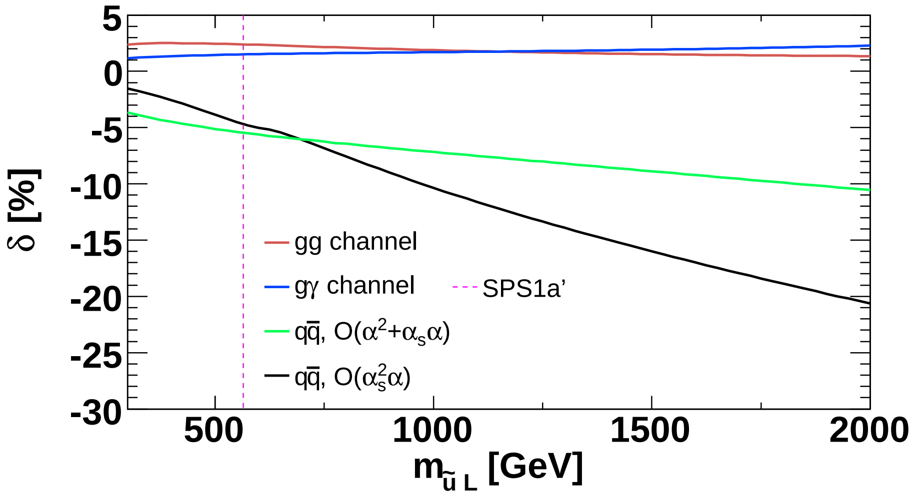


  has been included
  $\hookrightarrow$ Photon induced $\mathcal{O}(\alpha_s\alpha)$ process
  $\hookrightarrow$ included in the stop case, found to be important [Hollik, Kollar & Trenkel, ’07]

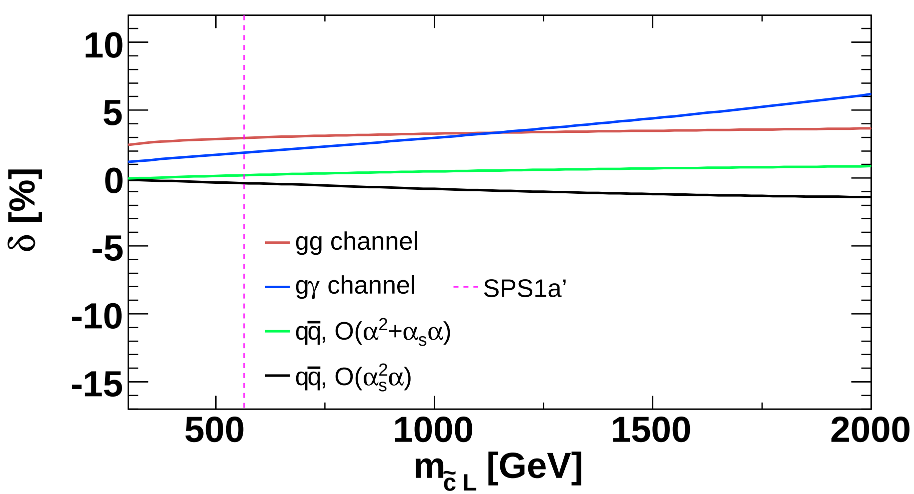
Numerical Results

Dependence on the Flavour (Total Cross Section $V s$ squark mass), $\left[\delta = \frac{\mathcal{O}^{\text{NLO}} - \mathcal{O}^{\text{LO}}}{\mathcal{O}^{\text{NLO}}}\right]$

$\tilde{u}^L$



$\tilde{c}^L$



- key role of $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}$ with q & $\tilde{Q}$ in the same SU(2) doublet
  - $\hookrightarrow$ $\tilde{c}$ case: suppressed by charm PDF
  - $\hookrightarrow$ $\tilde{u}$ case: dominates and enhances EW corrections

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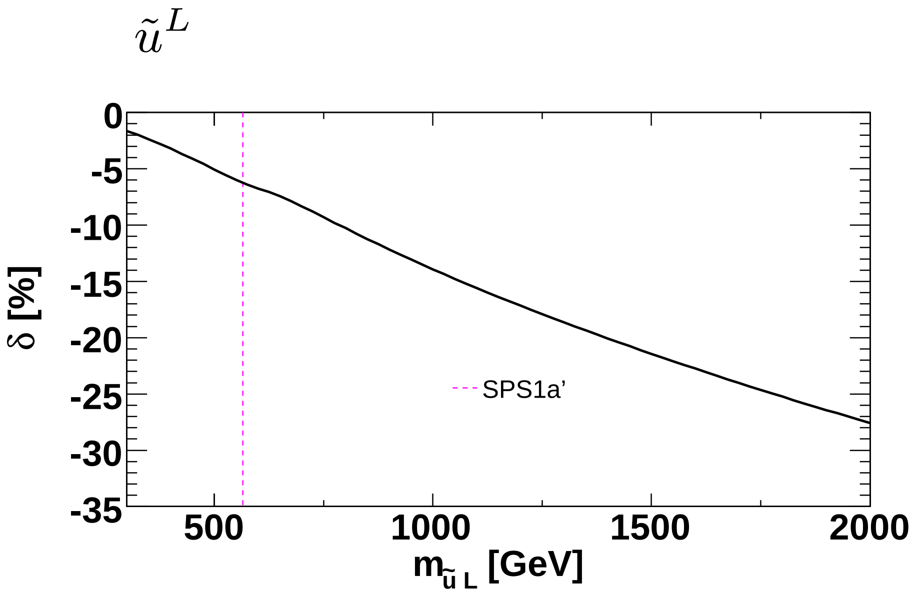
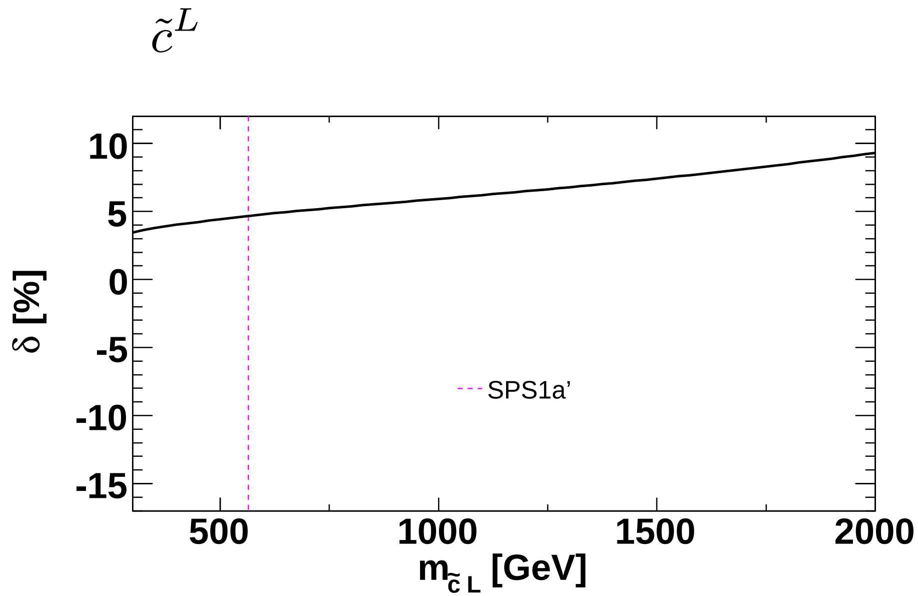


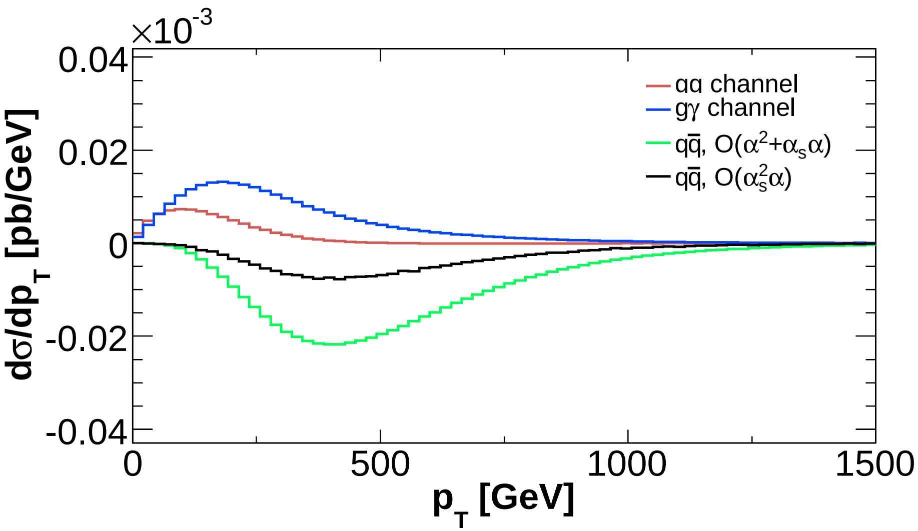


- key role of $q\bar{q} \to \tilde{Q}^a \tilde{Q}^{a*}$ with q & $\tilde{Q}$ in the same SU(2) doublet
  - $\hookrightarrow$ $\tilde{c}$ case: suppressed by charm PDF
  - $\hookrightarrow$ $\tilde{u}$ case: dominates and enhances EW corrections
- EW corrections differ in the two cases $\begin{cases} \tilde{u}: & \text{Negative, enhanced if } m_{\tilde{u}} \text{ big} \\ \tilde{c}: & \text{Positive, below } 10\ \% \end{cases}$

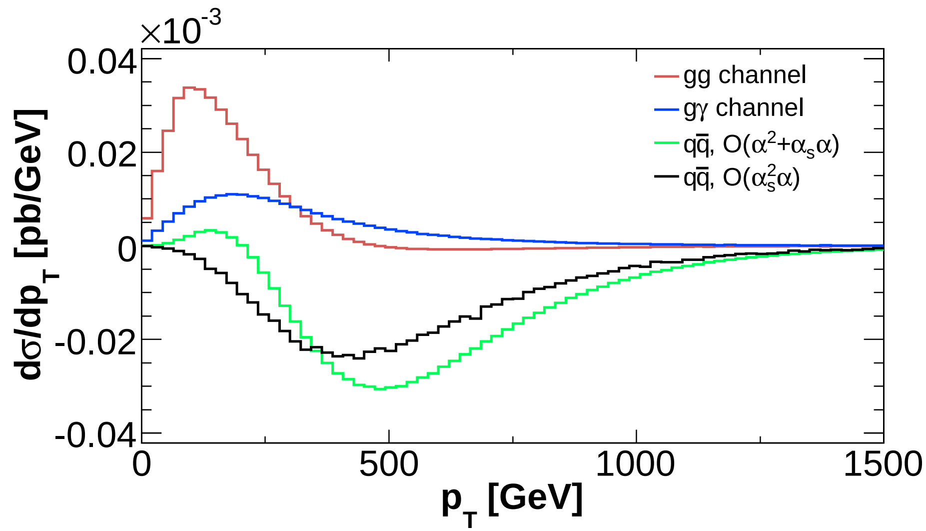
Numerical Results

Dependence on the Chirality (Transverse Momentum distribution), $\left[\delta = \frac{\mathcal{O}^{\text{NLO}} - \mathcal{O}^{\text{LO}}}{\mathcal{O}^{\text{NLO}}}\right]$

$\tilde{u}^R$, point SPS1a′



$\tilde{u}^L$, point SPS1a′



- $g\gamma$ channel chirality-independent, the others more important in the $\tilde{u}^L$ case
- $\mathcal{O}(\alpha_s^2\alpha)$ & $\mathcal{O}(\alpha_s\alpha + \alpha^2)$ comparable (at least in the left handed case)
- $q\bar{q}$ @ $\mathcal{O}(\alpha_s\alpha + \alpha^2)$ different behaviour in the low p_T region
  $\hookrightarrow$ MSSM is chiral $\Rightarrow$ $d\ \tilde{u}\ \chi^{\pm}$ vertex is chiral dependent

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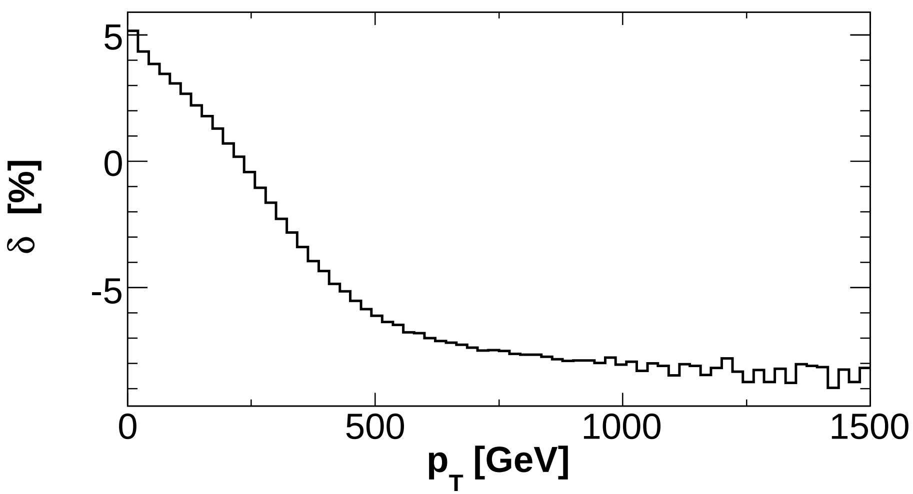

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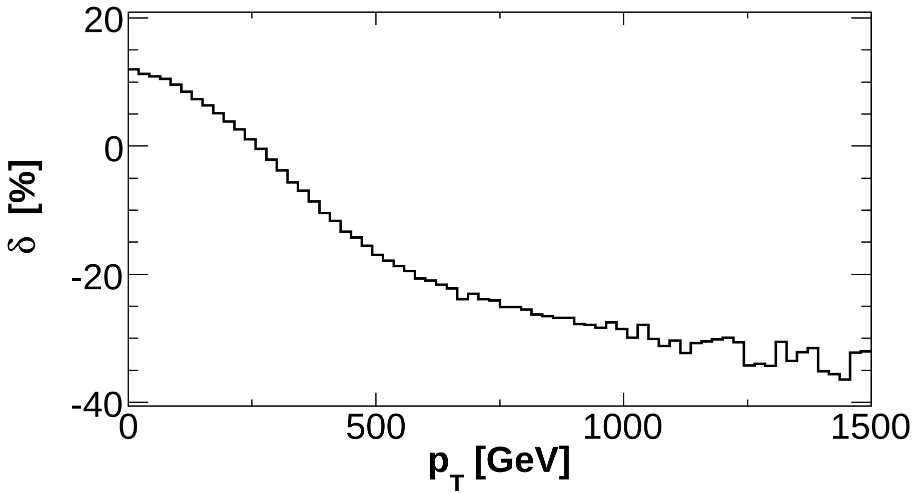

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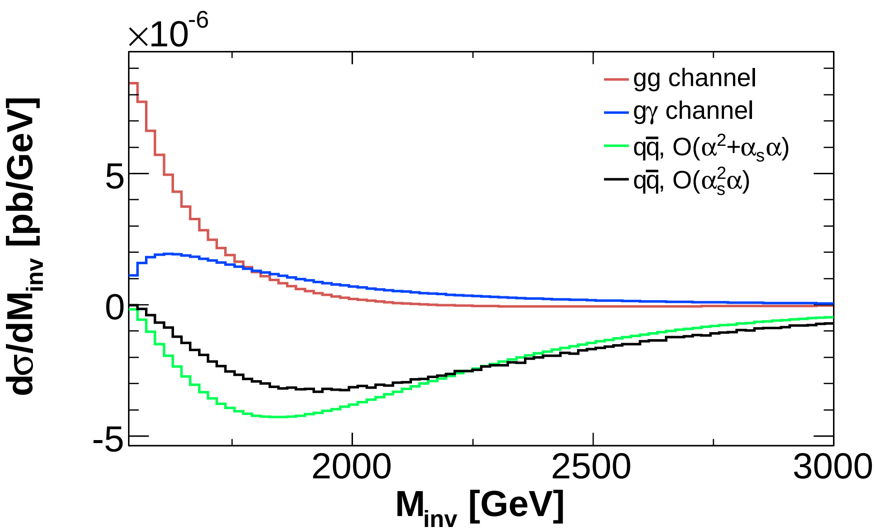
  $\hookrightarrow$ MSSM is chiral $\Rightarrow$ $d\ \tilde{u}\ \chi^{\pm}$ vertex is chiral dependent
- EW corrections important (at least in the left handed case).

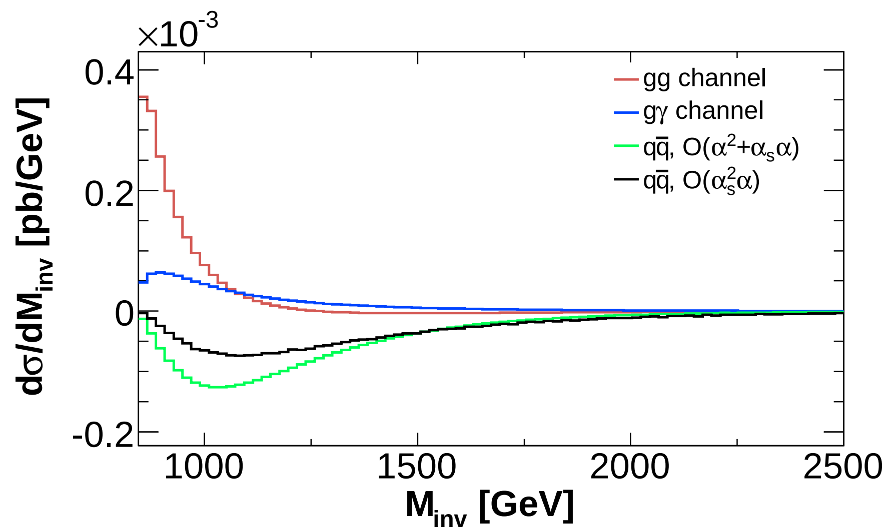
Numerical Results

Dependence on the Benchmark Point (Invariant Mass distribution for $\tilde{u}^L$ prod.)

point SU1, $m_{\tilde{u},L} = 766$ GeV



point SU4, $m_{\tilde{u},L} = 420$ GeV



- The size of the contributions decrease as the squark mass increases
- Corrections dominated by $\left\{\begin{array}{l} gg, \quad g\gamma \\ q\,\bar{q} \end{array}\right.$ channels in the $\left\{\begin{array}{l} \text{low} \\ \text{high} \end{array}\right.$ M_{inv} region

Numerical Results

Dependence on the Benchmark Point (Invariant Mass distribution for $\tilde{u}^L$ prod.)

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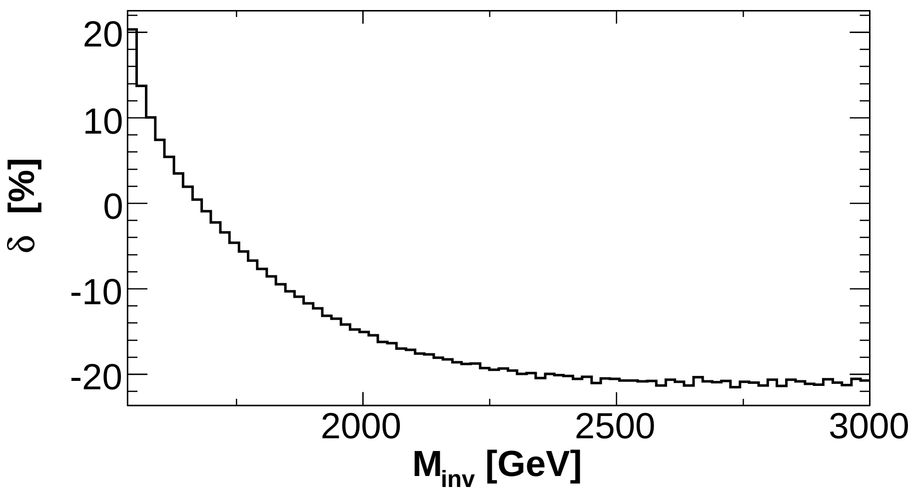

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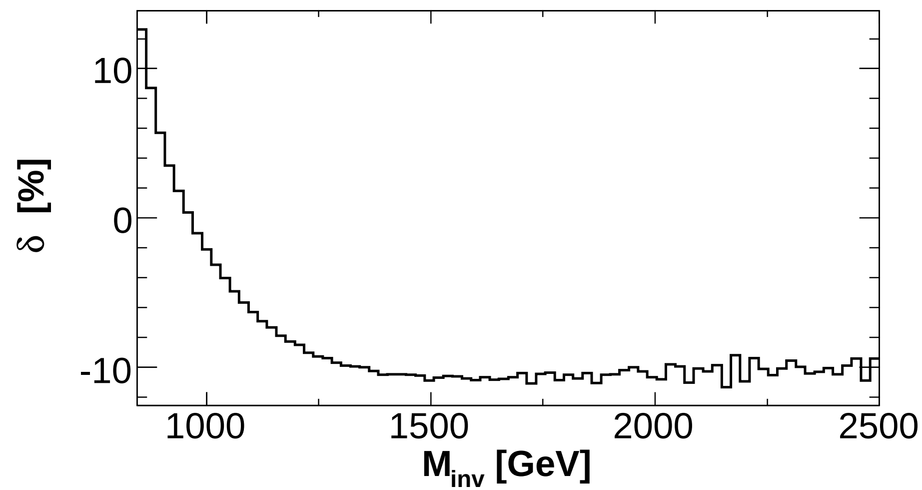

- The size of the contributions decrease as the squark mass increases
- Corrections dominated by $\left\{ \begin{array}{l} gg, \quad g\gamma \\ q\,\bar{q} \end{array} \right.$ channels in the $\left\{ \begin{array}{l} \text{low} \\ \text{high} \end{array} \right.$ M_{inv} region
- EW corrections sizable, increasing as the squark mass increases

Conclusions & Outlook

- $P\ P\ \rightarrow\ \tilde{Q}^a\ \tilde{Q}^{a*}$ important process in the hunting for SUSY
- $\mathcal{O}(\alpha_s^2\alpha)$ corrections to this process available for arbitrary $\tilde{Q}^a\ \tilde{Q}^{a*}$ pair:
  - depend on flavour, chirality and mass of the squarks,
  - sizable, not only in the distributions but also in the total cross section . . .
  - . . . Not trivial to compute.

Road map:

- Compute the $\mathcal{O}(\alpha_s^2\alpha)$ corrections to other processes of production of SUSY colored particle:
  - gluino pair production $\longrightarrow$ completed
  - associated production of a squark and a gluino $\longrightarrow$ w.i.p.
  - squark-squark pair production $\longrightarrow$ on the wish list
- Merge EW corrections with the NLO QCD ones

Backup Slides

Backup Slides

Phase space Slicing & Dipole subtraction method

In the Real Corrections singularities in the phase space integral:

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

two methods to handle with this:

Phase space Slicing & Dipole subtraction method

In the Real Corrections singularities in the phase space integral:

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

computed in eikonal approx.

two methods to handle with this:

- Phase Space Slicing. The photon phase space is divided into two parts:
  - ↪ Intutive method
  - ↪ Cuts have to be small (eikonal approximation) . . .
  - ↪ but not too much (numerical instabilities)

Backup Slides

Phase space Slicing & Dipole subtraction method

In the Real Corrections singularities in the phase space integral:

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

exactly computed

two methods to handle with this:

- Phase Space Slicing. The photon phase space is divided into two parts:
  - ↪ Intutive method
  - ↪ Cuts have to be small (eikonal approximation) . . .
  - ↪ but not too much (numerical instabilities)
- Subtraction method. Add and subtract a function with the same beahaviour of $|\mathcal{M}|^2$ and easy enought to be analitically computed:
  - ↪ All numerics involve regular functions
  - ↪ No cut off are needed
  - ↪ Gives results more precise than PSS