Gravitino productions at colliders

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VUB
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Outline

- Introduction
- Gravitino productions at the LHC
- Process $e^- e^+ \to \tilde{\chi}_1^0 \tilde{G}$
- Process $e^- \gamma \to \tilde{e}_{L/R} \tilde{G}$
- Outlook

Supersymmetry

- each SM particle has supersymmetric partner with spin differing by 1/2

- in local SUSY:
  gravitino = spin 3/2 superpartner of graviton

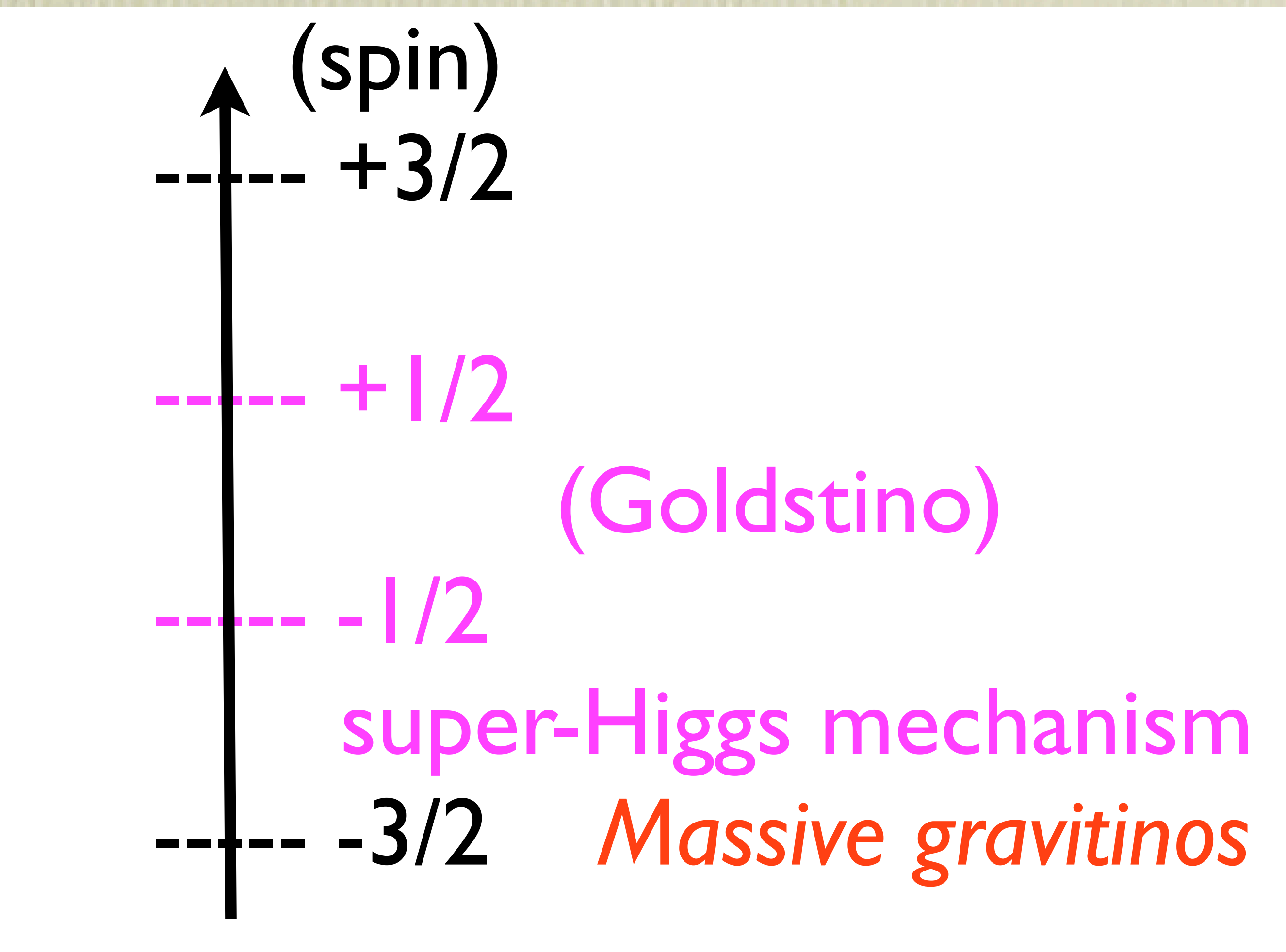
- $m_f = m_s$

~~Supersymmetry~~

- gravitino absorbs goldstino

→ becomes massive by super-Higgs-mechanism

$$m_{3/2} \sim \frac{M_{SUSY}^2}{M_{Pl}}$$



Gravitino-Goldstino equivalence

★ **Goldstino-equivalence theorem:**
replace gravitino by goldstino in high energy limit

$$\psi_\mu \sim \sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \psi$$

gravitino (spin 3/2) → ψ_μ

goldstino (spin 1/2) → ψ

Goldstino interactions

$$m_{3/2} \sim \frac{M^2_{SUSY}}{M_{Pl}}$$

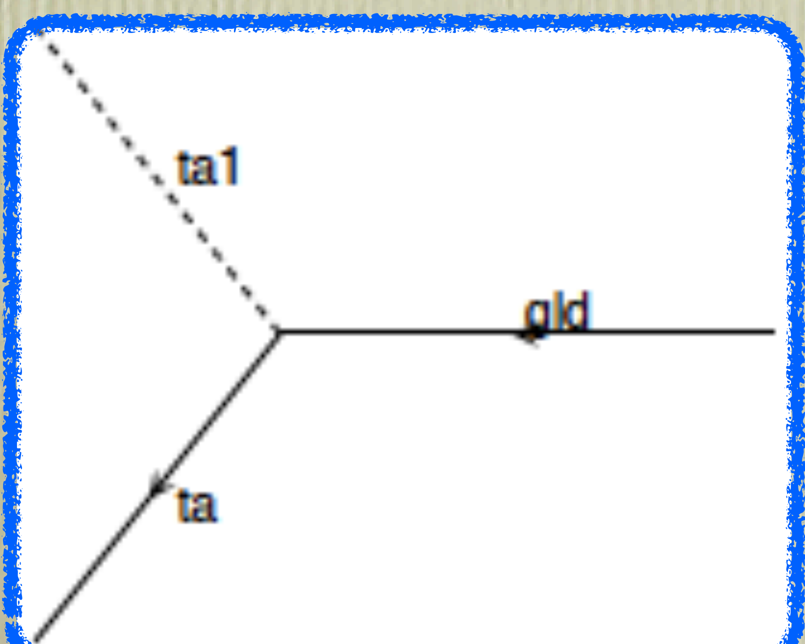
effective Goldstino interaction Lagrangian:

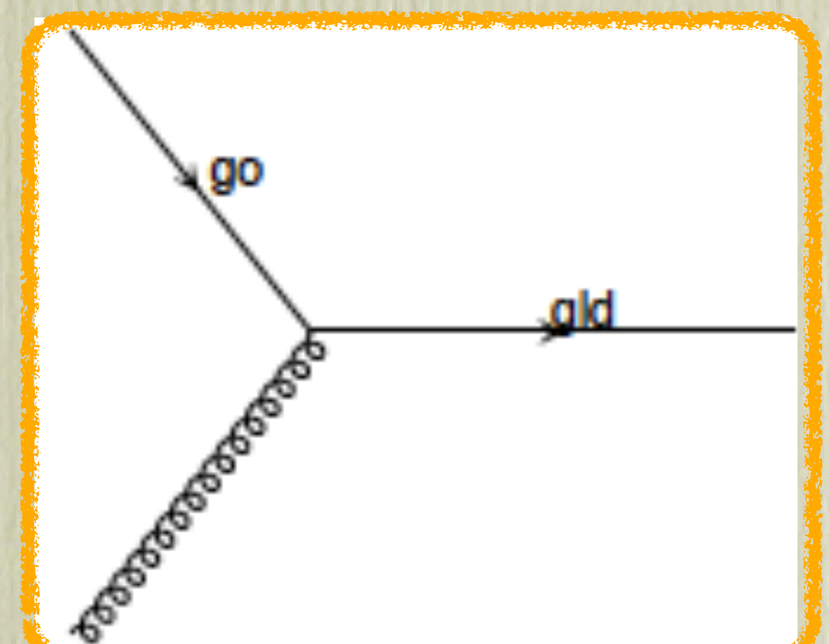
$$\mathcal{L}_{\rm int} = \frac{i(m^2_{\phi^i} - m^2_{f^i})}{\sqrt{3}\,\overline{M}_{\rm Pl}\, m_{3/2}} \left[\bar{\psi} P_L f^i (\phi^i_L)^* - \bar{f}^i P_R \psi\, \phi^i_L\right] - \frac{m_\lambda}{4\sqrt{6}\,\overline{M}_{\rm Pl}\, m_{3/2}} \bar{\psi}[\gamma^\mu, \gamma^\nu]\lambda^{(\alpha)a} F^{(\alpha)a}_{\mu\nu}$$

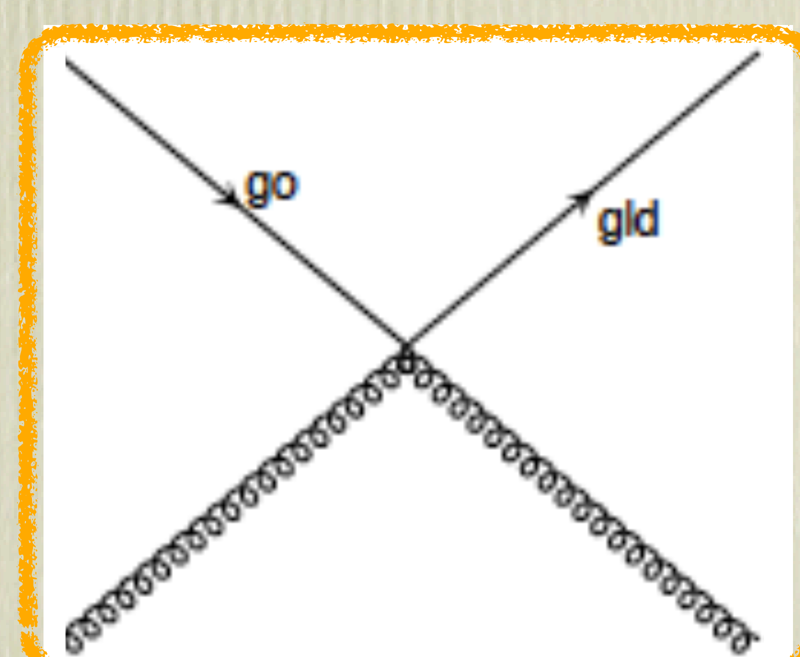
couplings

inversely proportional to the SUSY-breaking scale through the gravitino mass

proportional to the mass splitting inside the supermultiplet







gravitino production at colliders

★ $\tilde{G}$ for collider physics only interesting if it is the LSP

$$m_{3/2} \sim \frac{M^2_{SUSY}}{M_{Pl}}$$

★ in gauge mediated SUSY-breaking models:

M^2_{SUSY} small $\longrightarrow$ $\tilde{G}$ is (almost certainly) LSP!

gravitino production at colliders

$$m_{3/2} \sim \frac{M^2_{SUSY}}{M_{Pl}}$$

★ examples :

$$e^- e^+ \to \tilde{\chi}^0_1 \tilde{G} \to \gamma \, \tilde{G} \, \tilde{G}$$

$$e^- \gamma \to \tilde{e}_{L/R} \tilde{G} \to e^- \tilde{G} \, \tilde{G}$$

$$p \, p \to X \, \tilde{G} \to \mathrm{j} \, \tilde{G} \, \tilde{G}$$

we observe:
something +
missing energy

★ $$\sigma \sim \frac{1}{m^2_{3/2}}$$

★ lower bound from LEP: $m_{3/2} > 1.35 \cdot 10^{-14} \mathrm{GeV}$

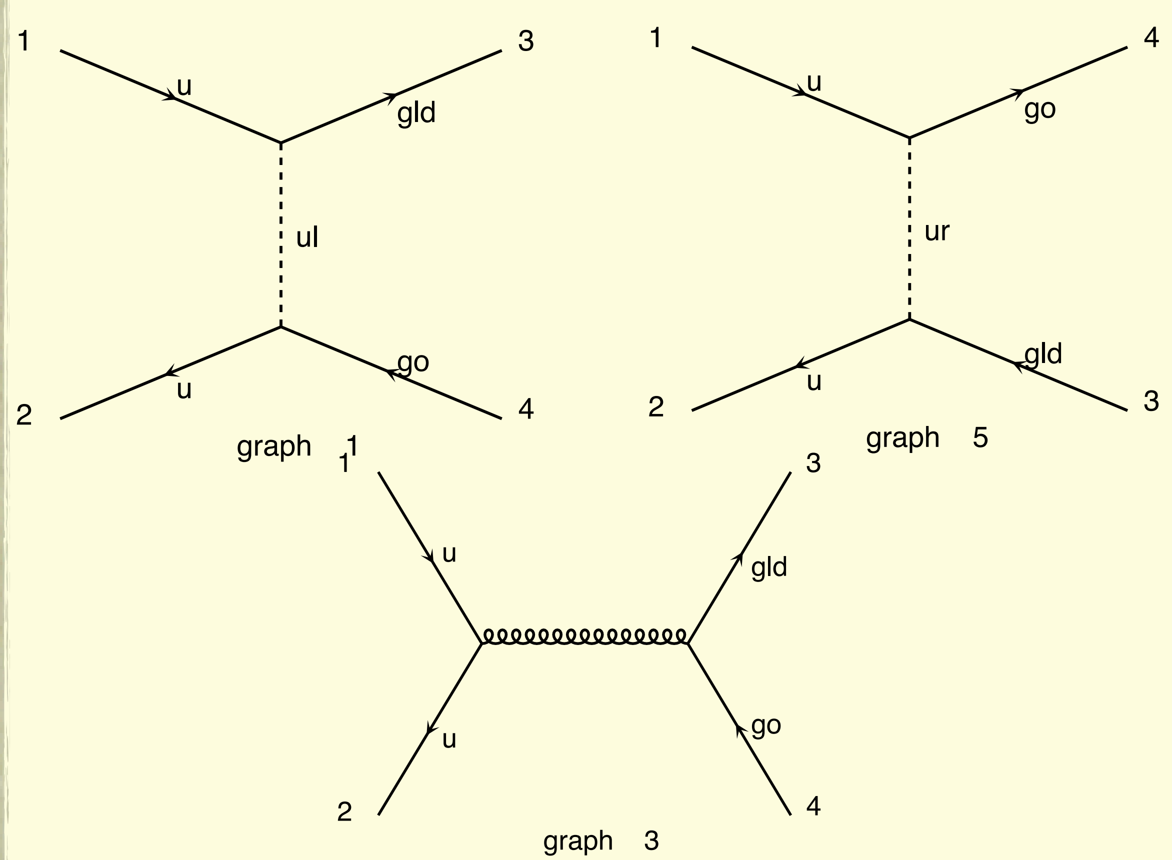
P. Achard et al. [L3 Collaboration], Phys. Lett. B 587, 16 (2004) [arXiv:hep-ex/0402002].

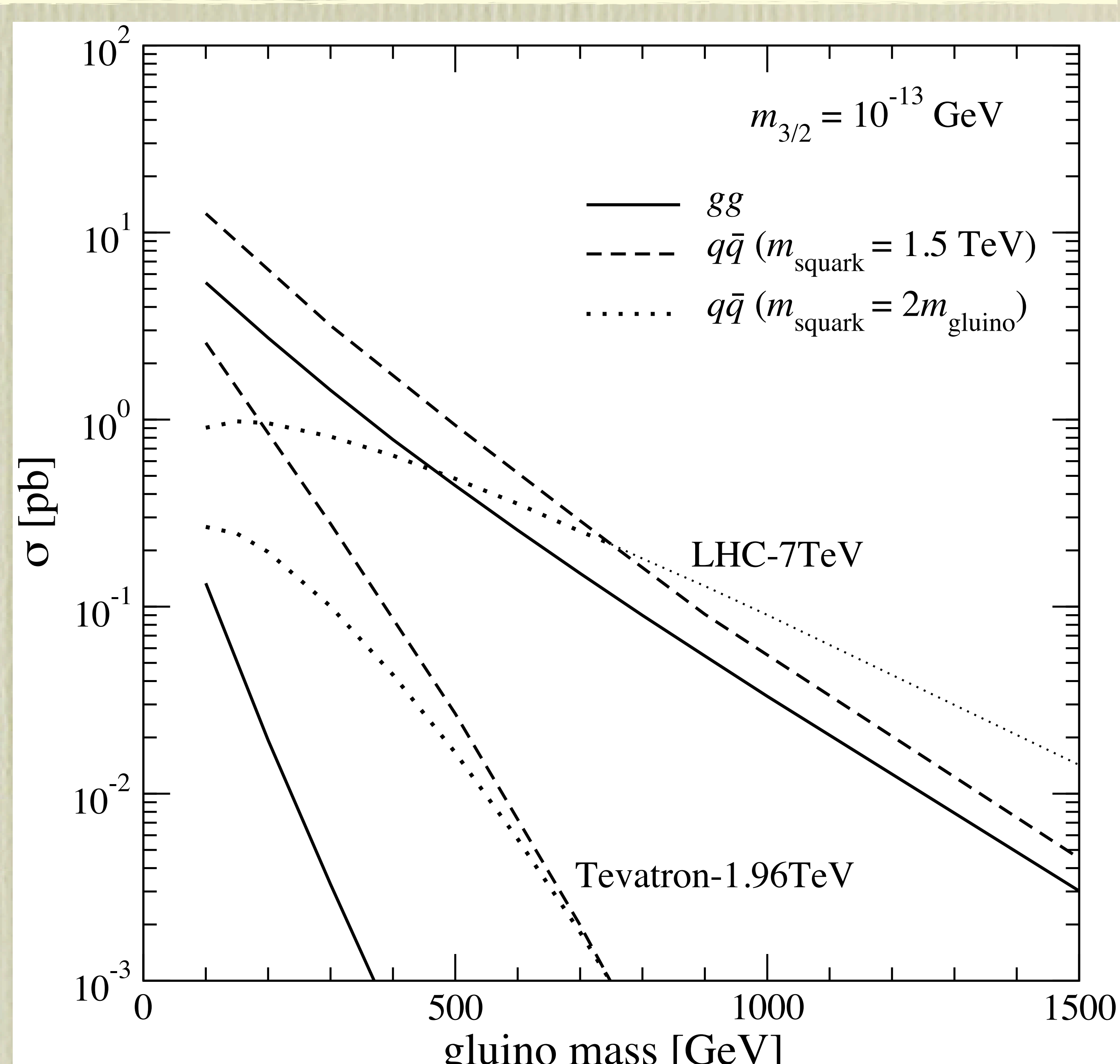
gravitino production at LHC

$$m_{3/2} \sim \frac{M_{SUSY}^2}{M_{Pl}}$$

goal: $\mathrm{p\,p} \to \tilde{G}\,\tilde{G}\,\mathrm{j}$ ➡ $m_{3/2}$ ➡ SUSY-breaking scale

$$\mathrm{q\bar{q}} \to \tilde{g}\tilde{G} \quad (\to \mathrm{g}\tilde{G}\tilde{G})$$





HELAS and MadGraph with goldstinos, K. Mawatari and Y. Takaesu, arXiv: 1101.1289 [hep-ph]

gravitino production at LHC

$m_{3/2} \sim \frac{M_{SUSY}^2}{M_{Pl}}$

goal: $\mathrm{p\,p} \to \tilde{G}\,\tilde{G}\,\mathrm{j}$ → $m_{3/2}$ → SUSY-breaking scale

jet+ missing energy

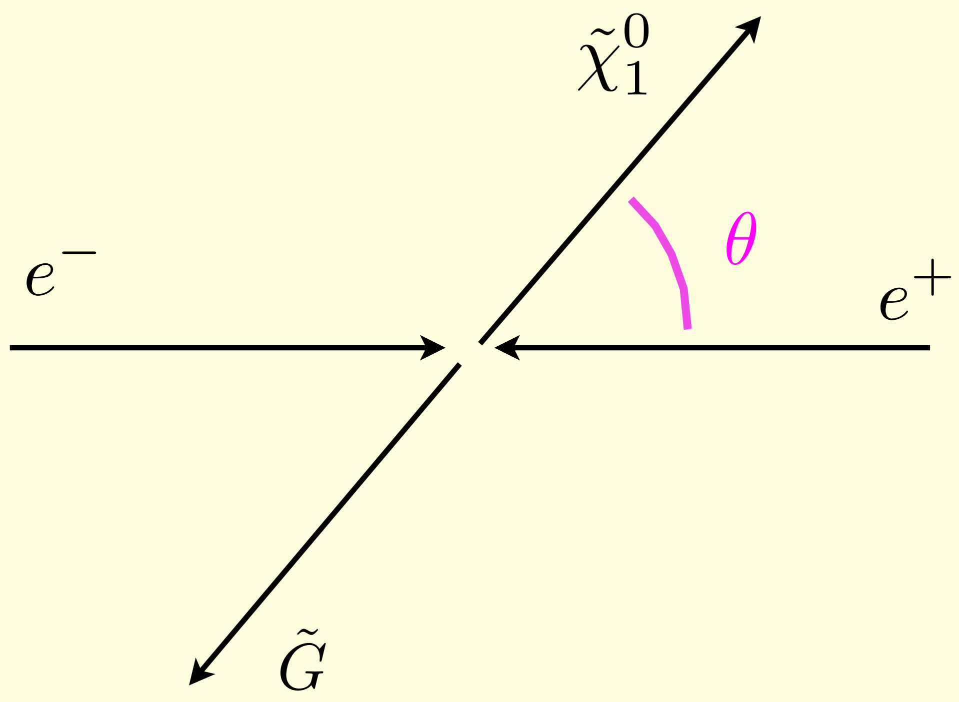
$\mathrm{q\bar{q}} \to \tilde{g}\tilde{G} \to \mathrm{g}\tilde{G}\tilde{G}$ → angular dependence of jet depends on angular distribution of gluino

angular distribution of gluino depends on squark-masses...

first step: consider processes with electrons

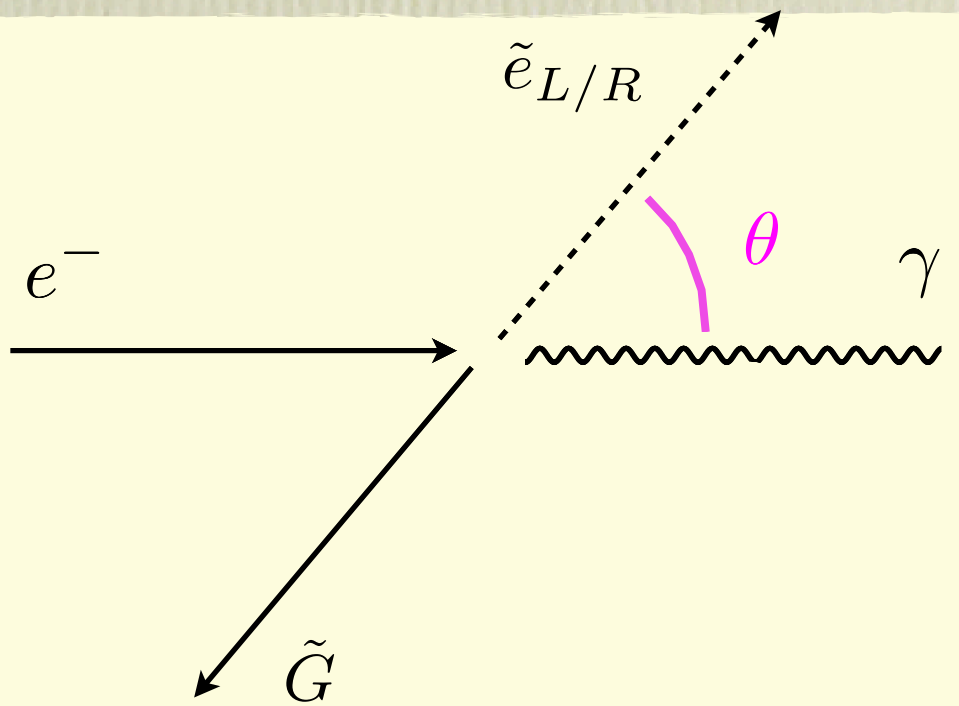
$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G} \to \gamma \tilde{G} \tilde{G}$$

(with $\tilde{\chi}_1^0$ NLSP)

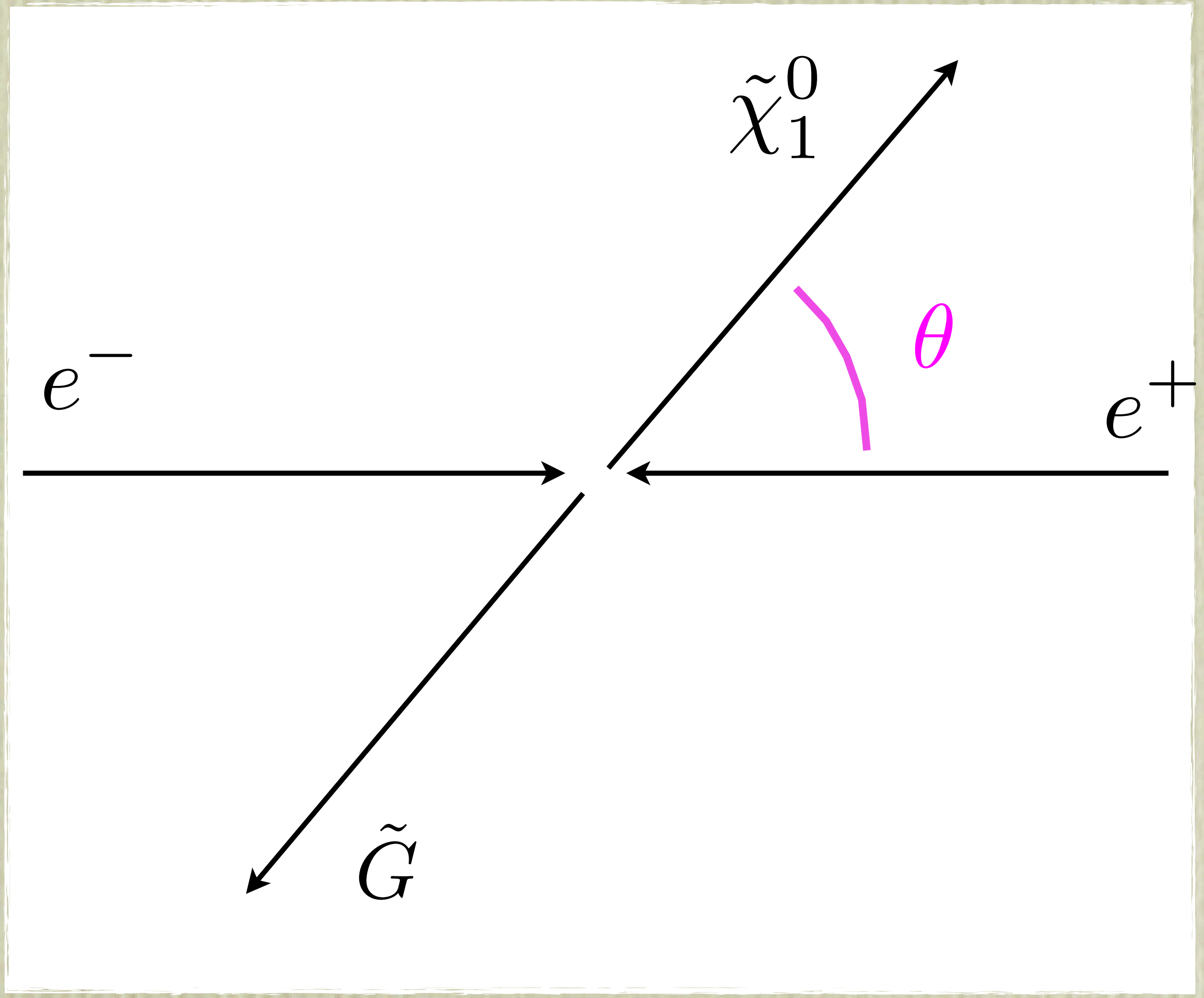


$$e^- \gamma \to \tilde{e}_{L/R} \tilde{G} \to e^- \tilde{G} \tilde{G}$$

(with $\tilde{e}_{L/R}$ NLSP)



$$e^-(p_1,\lambda_1) + e^+(p_2,\lambda_2) \to \tilde{\chi}_1^0(p_3,\lambda_3) + \tilde{G}(p_4,\lambda_4)$$



$$p_1 = \frac{\sqrt{s}}{2}(1,0,0,1)$$

$$p_2 = \frac{\sqrt{s}}{2}(1,0,0,-1)$$

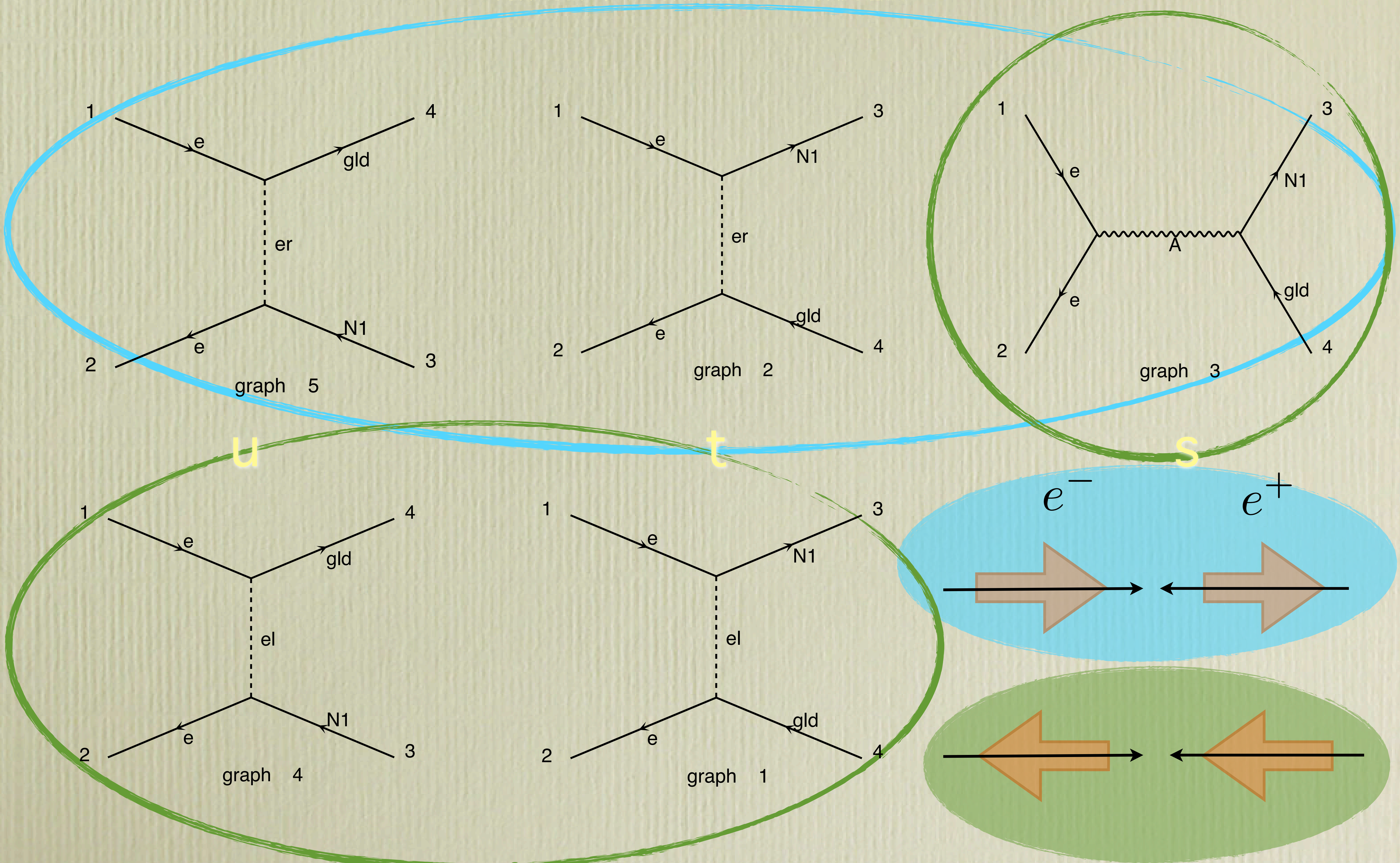
$$p_3 = \frac{\sqrt{s}}{2}\left(1+\frac{m^2_{\tilde{\chi}_1^0}}{s}, \beta\sin\theta, 0, \beta\cos\theta\right)$$

$$p_4 = \frac{\sqrt{s}}{2}\beta(1,-\sin\theta,0,-\cos\theta)$$

$$\text{with } \beta = 1 - \frac{m^2_{\tilde{\chi}_1^0}}{s}$$

$\tilde{\chi}_1^0$ = NLSP

$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G}$



total cross section:

$$\sigma = \frac{\beta}{32\pi s} \int \sum_{\lambda_i} \left| \mathcal{M}_{\lambda_1\lambda_2,\lambda_3\lambda_4} \right|^2 d\cos\theta$$

differential cross section:

$$\frac{d\sigma_{\lambda_1\lambda_2}}{d\cos\theta} = \frac{\beta}{32\pi s} \sum_{\lambda_3,\lambda_4} \left| \mathcal{M}_{\lambda_1\lambda_2,\lambda_3\lambda_4} \right|^2$$

helicity amplitude

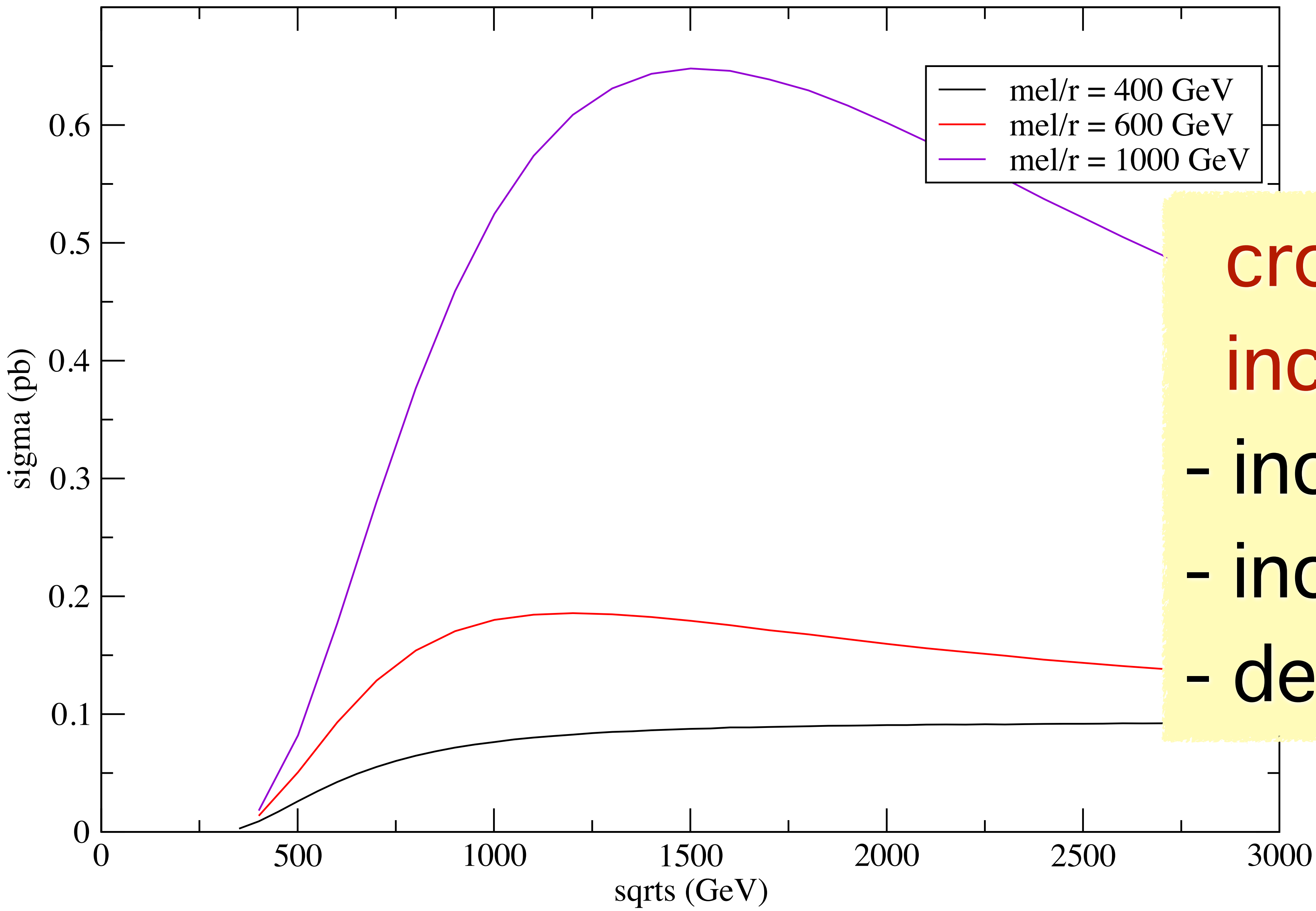
$$\mathcal{M}_{\lambda_1\lambda_2,\lambda_3\lambda_4} = \mathcal{M}^s_{\lambda_1\lambda_2,\lambda_3\lambda_4} + \mathcal{M}^t_{\lambda_1\lambda_2,\lambda_3\lambda_4} + \mathcal{M}^u_{\lambda_1\lambda_2,\lambda_3\lambda_4}$$

$$\sigma \sim \frac{1}{m_{3/2}^2}$$

$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G}$$

$$m_{\tilde{G}} = 10^{-13}\text{GeV}$$
$$m_{\tilde{\chi}_1^0} = 300\,\text{GeV}$$

total cross section



cross section increases with

- increasing $\sqrt{s}$
- increasing $m_{\tilde{e}_{L/R}}$
- decreasing $m_{3/2}$

$$e^-(p_1,\lambda_1) + e^+(p_2,\lambda_2) \to \tilde{\chi}_1^0(p_3,\lambda_3) + \tilde{G}(p_4,\lambda_4)$$

$\lambda_1\lambda_2\,\lambda_3\lambda_4$		$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
+ - - -	$-i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$ $\{$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}} W_1$		$+W_2\ \}$
+ - + +	$i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$ $\{$		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}} W_1$	$+W_2\ \}$
+ - + -	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\cos^2\frac{\theta}{2}$ $\{$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}} W_1$		$+\frac{m^2_{\tilde{\chi}_1^0}}{s} W_2\ \}$
+ - - +	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\sin^2\frac{\theta}{2}$ $\{$		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}} W_1$	$+\frac{m^2_{\tilde{\chi}_1^0}}{s} W_2\ \}$

$$u_{\tilde{e}_R} = -\frac{\beta s}{2}(1+\cos\theta) - m^2_{\tilde{e}_r}$$

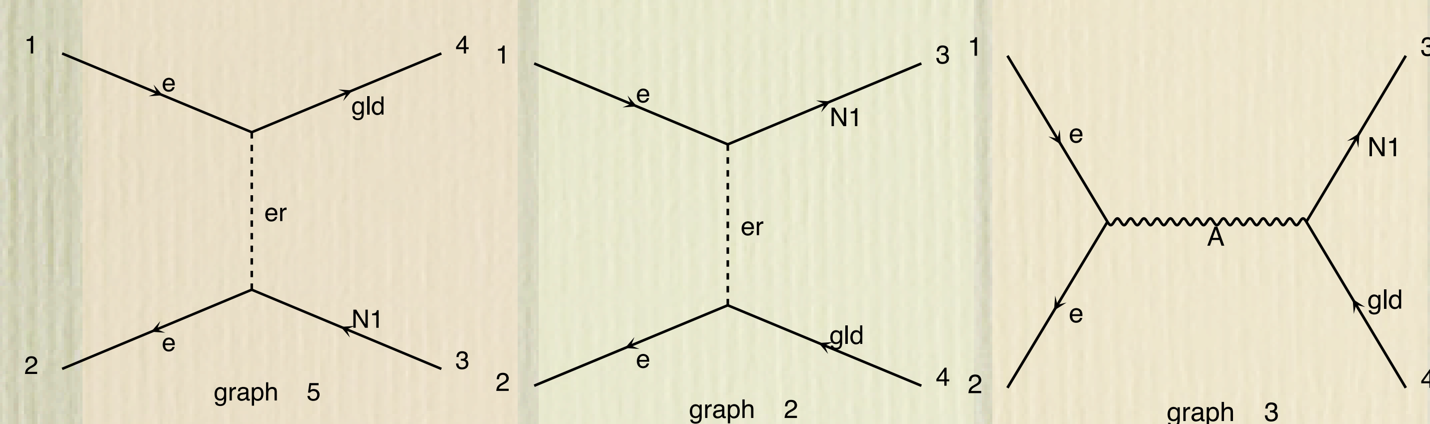
$$t_{\tilde{e}_R} = -\frac{\beta s}{2}(1-\cos\theta) - m^2_{\tilde{e}_r}$$

$$W_1 = \frac{U_{11}}{\cos\theta_w}$$

$$W_2 = U_{11}\cos\theta_w + U_{12}\sin\theta_w$$

$$\beta = 1 - \frac{m^2_{\tilde{\chi}_1^0}}{s}$$

$$F = \sqrt{3}\bar{M}_{Pl} m_{3/2}$$

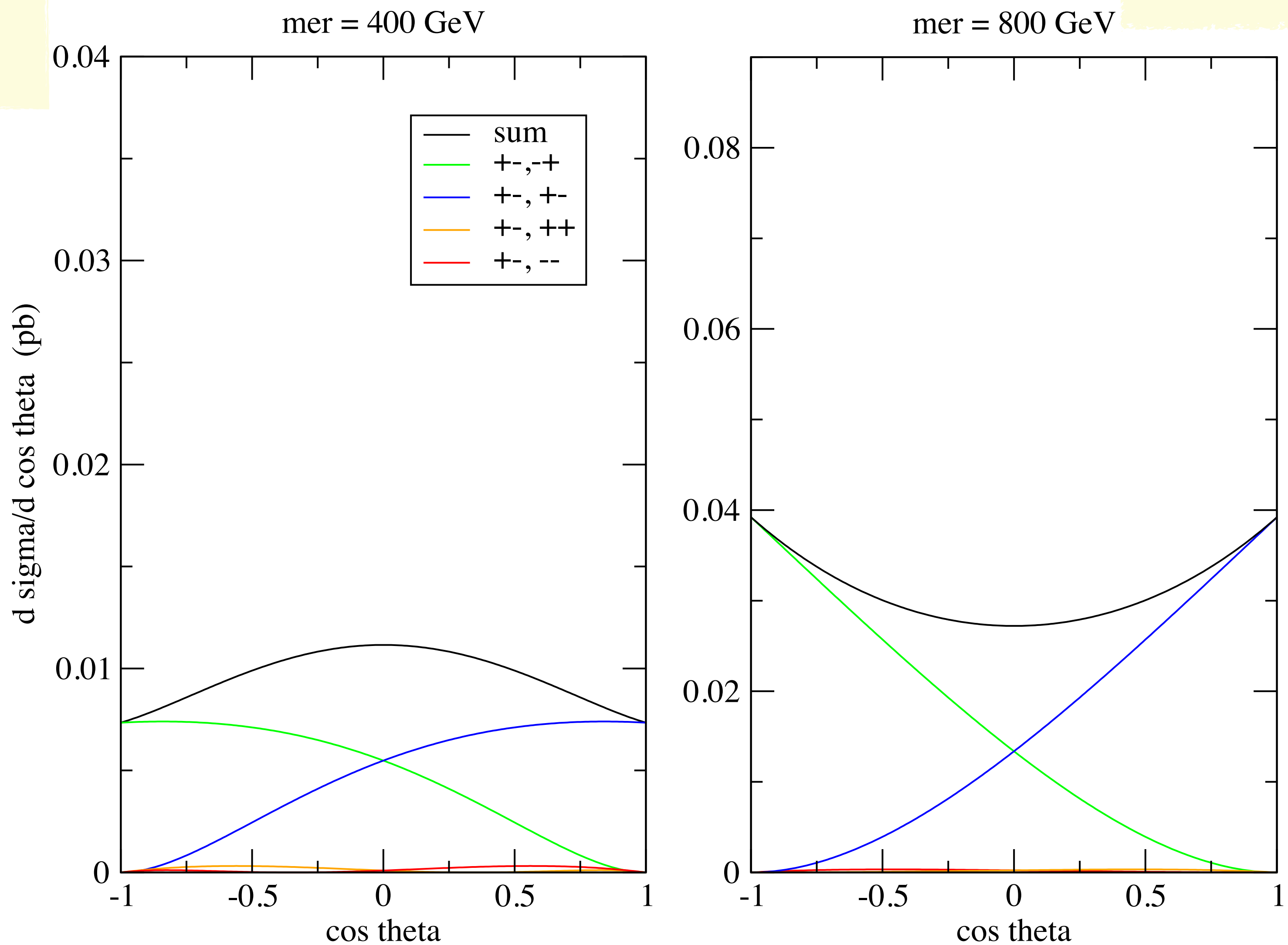


$$\sigma \sim \frac{1}{m_{3/2}^2}$$

$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G}$$

$$m_{\tilde{G}} = 10^{-13}\,\mathrm{GeV}$$
$$m_{\tilde{\chi}_1^0} = 300\,\mathrm{GeV}$$

sqrts = 500 GeV



depending on $m_{\tilde{e}_R}$ we obtain a different $\tilde{\chi}_1^0$ distribution !

$\lambda_1\lambda_2\,\lambda_3\lambda_4$		$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
+ - - -	$-i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$ $\{$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}} W_1$		$+W_2\ \}$
+ - + +	$i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$ $\{$		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}} W_1$	$+W_2\ \}$
+ - + -	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\cos^2\frac{\theta}{2}$ $\{$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}} W_1$		$+\frac{m^2_{\tilde{\chi}_1^0}}{s} W_2\ \}$
+ - - +	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\sin^2\frac{\theta}{2}$ $\{$		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}} W_1$	$+\frac{m^2_{\tilde{\chi}_1^0}}{s} W_2\ \}$

$$\sigma \sim \frac{1}{m_{3/2}^2}$$

$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G}$$

$$m_{\tilde{G}} = 10^{-13}\,\mathrm{GeV}$$
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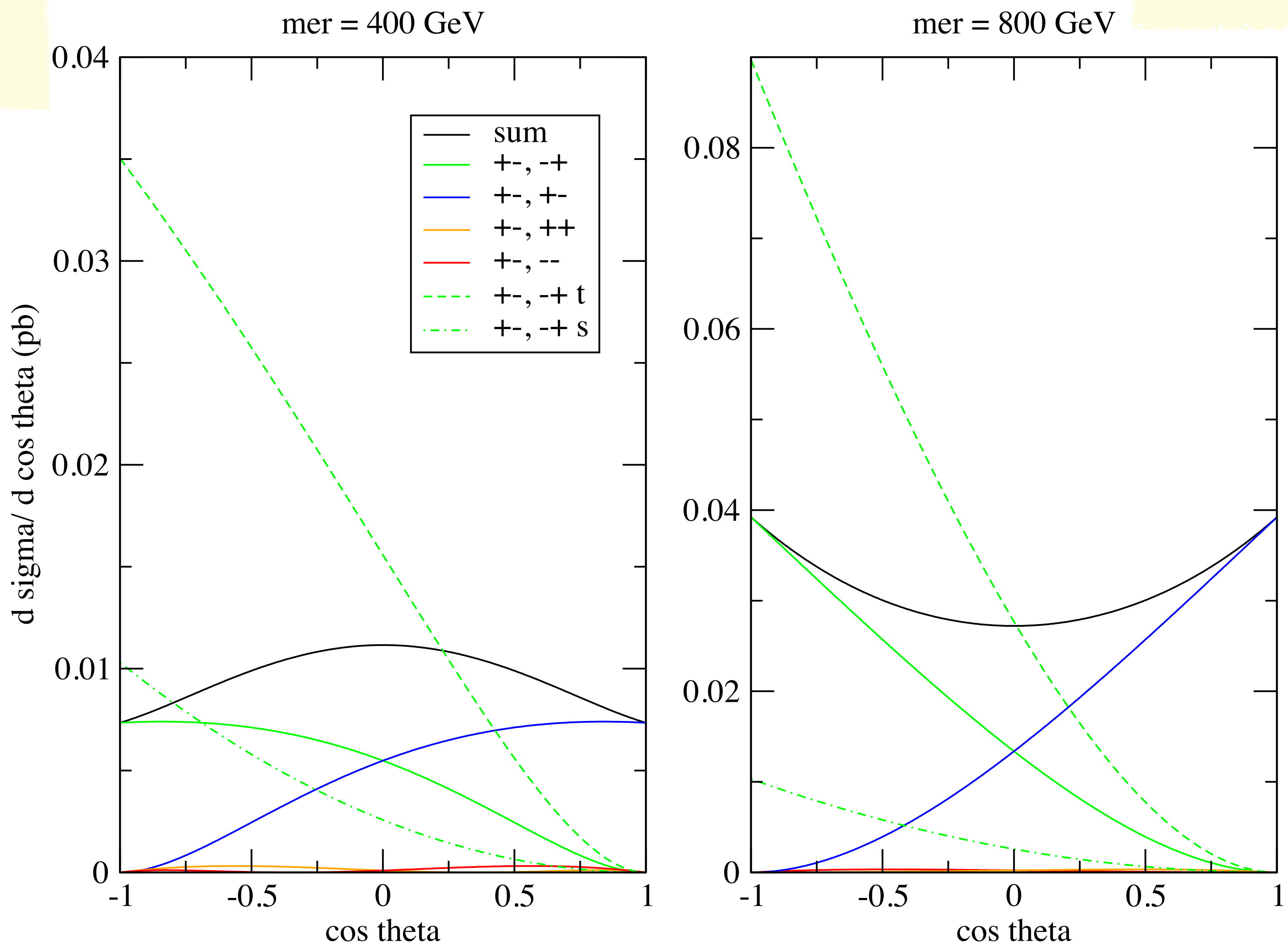


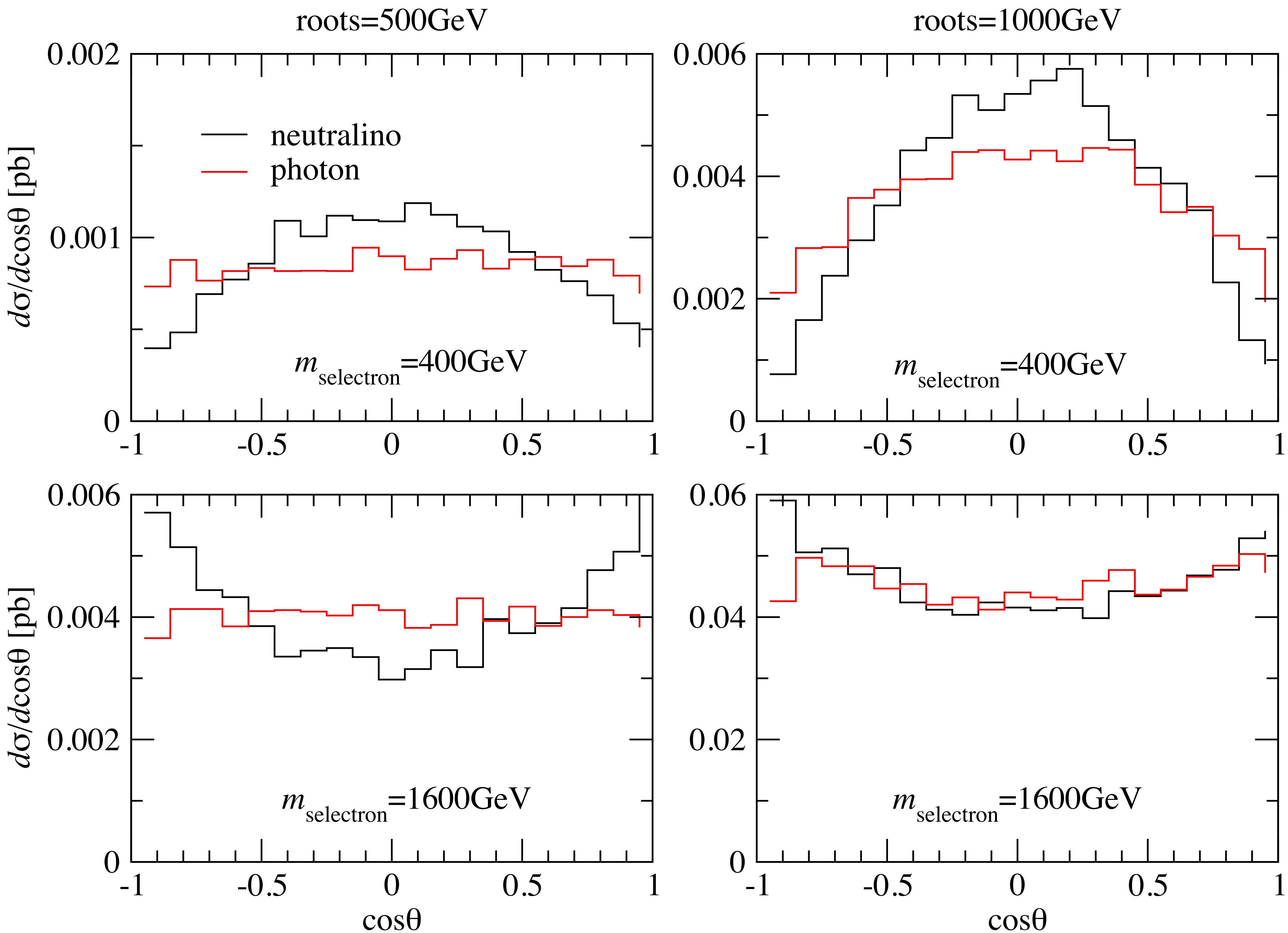
s-channel is independent of $m_{\tilde{e}_R}$

t-channel increases with $m_{\tilde{e}_R}$

$\lambda_1\lambda_2\,\lambda_3\lambda_4$			$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
+ - - -	$-i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$	{	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}}W_1$		$+W_2$ }
+ - + +	$i\frac{\sqrt{2}g}{F} m_{\tilde{\chi}_1^0}\sqrt{\beta s}\cos\frac{\theta}{2}\sin\frac{\theta}{2}$	{		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}}W_1$	$+W_2$ }
+ - + -	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\cos^2\frac{\theta}{2}$	{	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}}W_1$		$+\frac{m^2_{\tilde{\chi}_1^0}}{s}W_2$ }
+ - - +	$i\frac{\sqrt{2}g}{F}\beta^{1/2} s\sin^2\frac{\theta}{2}$	{		$\frac{m^2_{\tilde{e}_R^-}}{t_{\tilde{e}_R^-}}W_1$	$+\frac{m^2_{\tilde{\chi}_1^0}}{s}W_2$ }

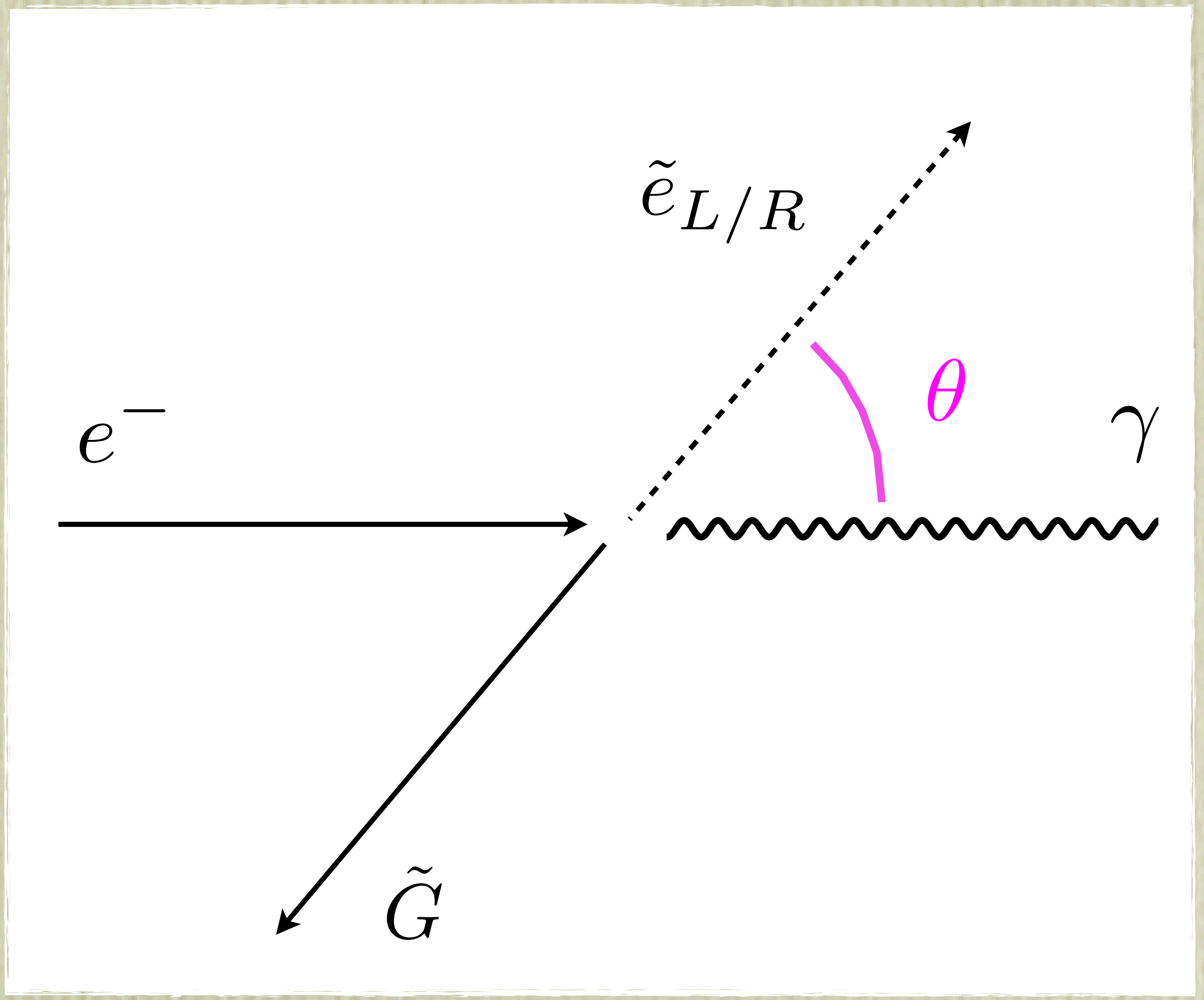
$$e^- e^+ \to \tilde{\chi}_1^0 \tilde{G} \to \gamma\, \tilde{G}\, \tilde{G}$$

$$m_{\tilde{G}} = 10^{-13}\text{GeV}$$
$$m_{\tilde{\chi}_1^0} = 300\,\text{GeV}$$



$\tilde{e}_R$= NLSP

$$e^- \gamma \to \tilde{e}_R^- \tilde{G}$$



$$p_1 = \frac{\sqrt{s}}{2}(1, 0, 0, 1)$$

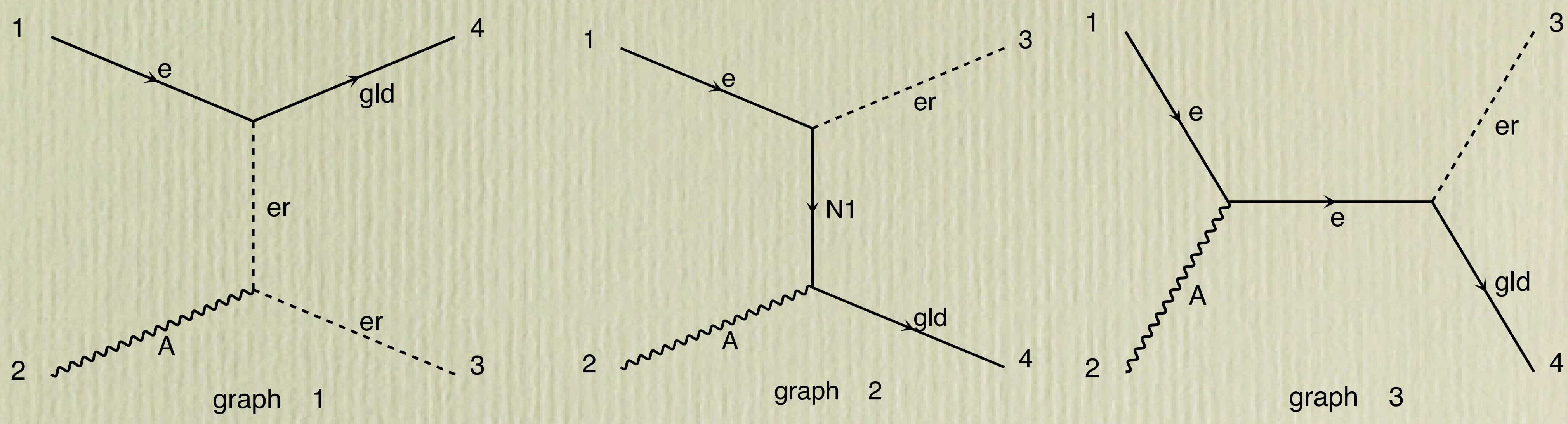
$$p_2 = \frac{\sqrt{s}}{2}(1, 0, 0, -1)$$

$$p_3 = \frac{\sqrt{s}}{2}(1 + \frac{m^2_{\tilde{e}_R}}{s}, \beta \sin\theta, 0, \beta\cos\theta)$$

$$p_4 = \frac{\sqrt{s}}{2}\beta(1, -\sin\theta, 0, -\cos\theta)$$

$$\text{with } \beta = 1 - \frac{m^2_{\tilde{e}_R}}{s}$$

$$e^-(p_1,\lambda_1) + \gamma(p_2,\lambda_2) \to \tilde{e}_R^-(p_3) + \tilde{G}(p_4,\lambda_4)$$



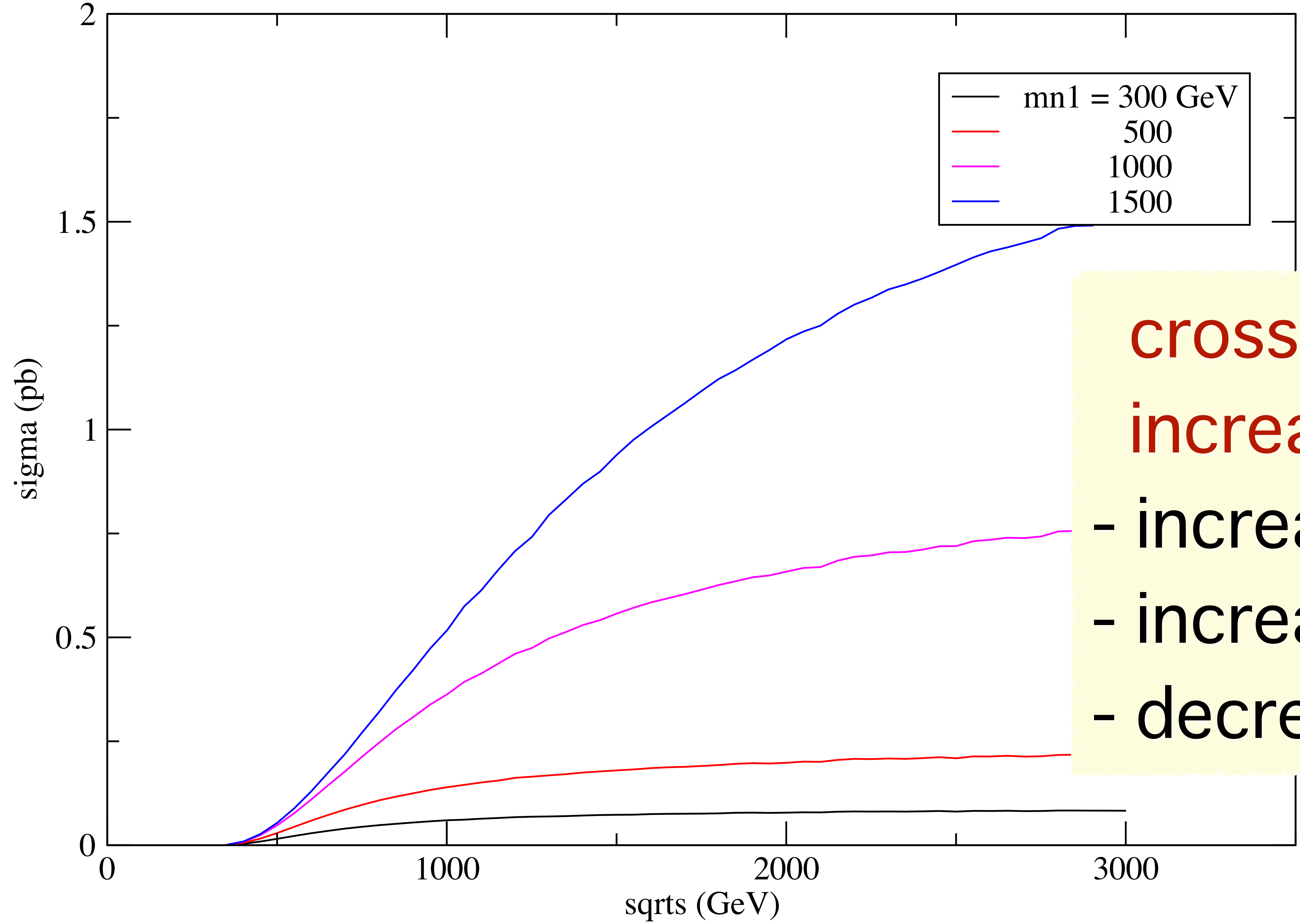
u t s

$\lambda_1\lambda_2\,\lambda_4$		$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
$+-\;+$	$-i\frac{\sqrt{2}g}{F}$		$W_3\frac{m_{\tilde{\chi}}}{t_{\tilde{\chi}}}(\beta s)^{3/2}\cos\frac{\theta}{2}\sin^2\frac{\theta}{2}$	
$+-\;-$	$i\frac{\sqrt{2}g}{F}$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}}s\beta^{3/2}\sin\frac{\theta}{2}\cos^2\frac{\theta}{2}$		
$++\;-$	$-i\frac{\sqrt{2}g}{F}\sin\frac{\theta}{2}$	$\{\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R}}s\beta^{3/2}\cos^2\frac{\theta}{2}$	$+W_3\frac{m^2_{\tilde{\chi}}}{t_{\tilde{\chi}}}\beta^{1/2}s$	$+m^2_{\tilde{e}_R^-}\beta^{1/2}\}$

$$\sigma \sim \frac{1}{m_{3/2}^2}$$

$$e^- \gamma \to \tilde{e}_R^- \tilde{G}$$

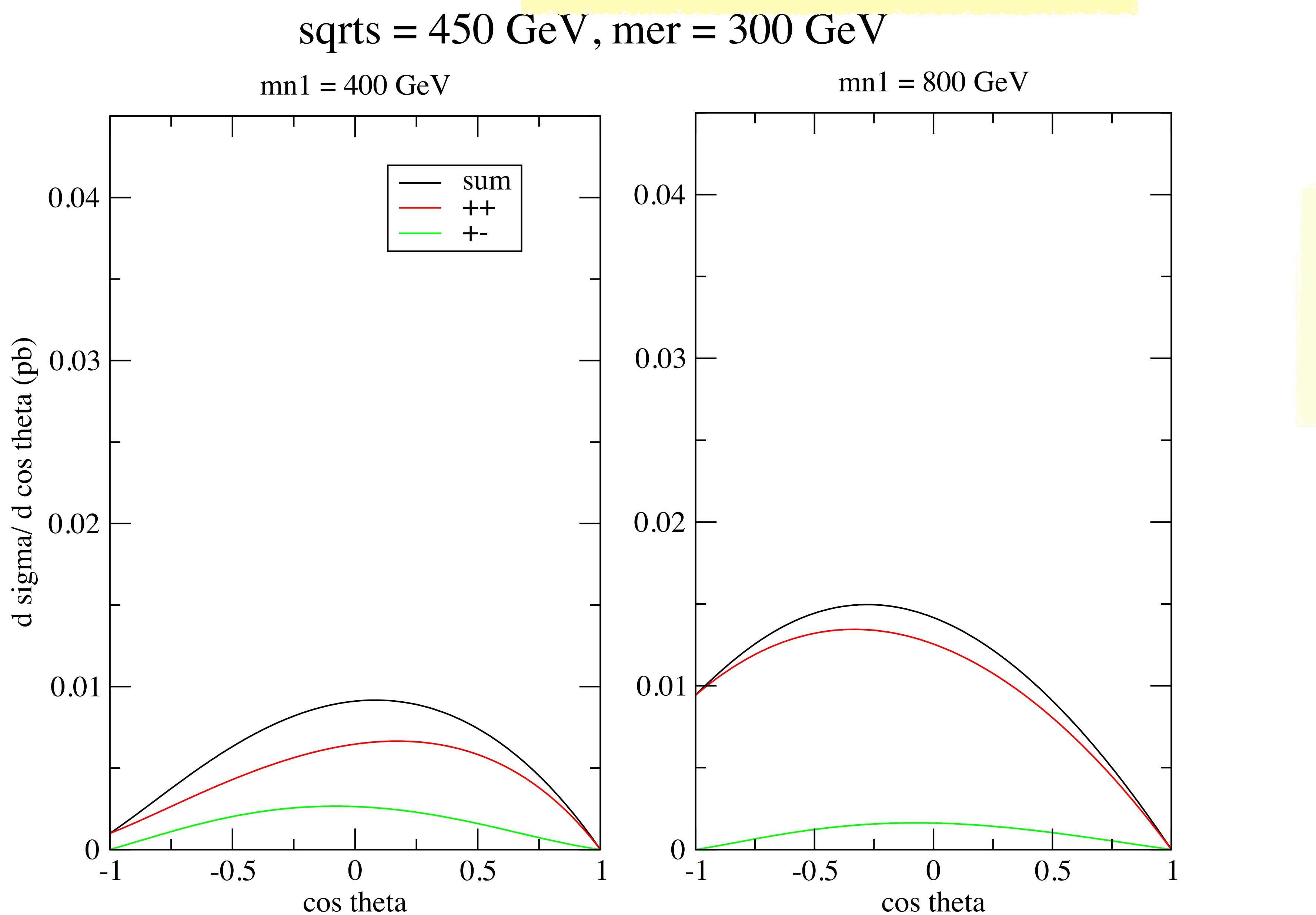
total cross section



cross section increases with

- increasing $\sqrt{s}$
- increasing $m_{\tilde{\chi}_1^0}$
- decreasing $m_{3/2}$

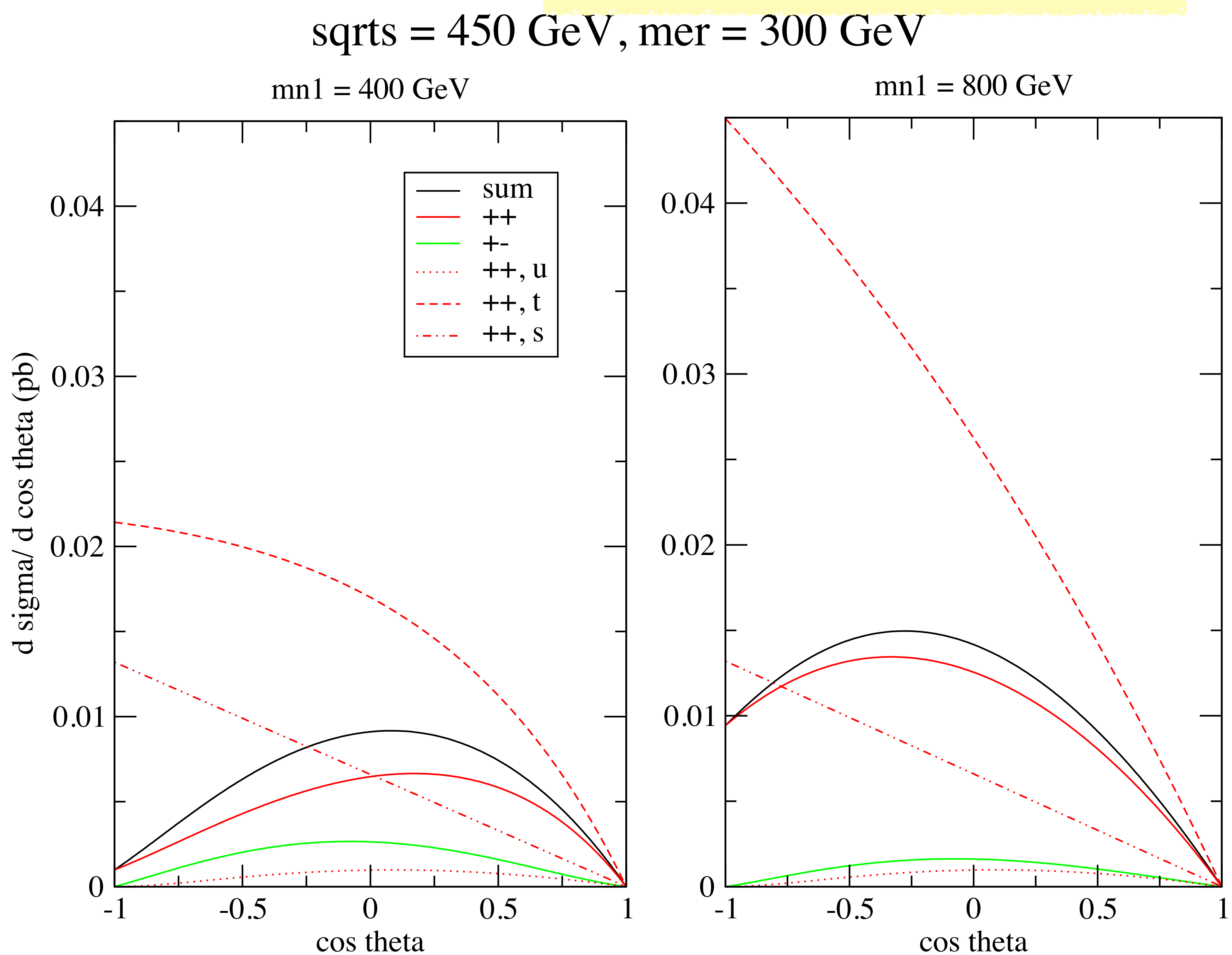
$e^-\gamma \to \tilde{e}_R^-\tilde{G}$



peak position depends on $m_{\tilde{\chi}_1^0}$

$\lambda_1\lambda_2\,\lambda_4$		$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
$+\,-\,+$	$-i\frac{\sqrt{2}g}{F}$		$W_3\frac{m_{\tilde{\chi}}}{t_{\tilde{\chi}}}(\beta s)^{3/2}\cos\frac{\theta}{2}\sin^2\frac{\theta}{2}$	
$+\,-\,-$	$i\frac{\sqrt{2}g}{F}$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}}s\beta^{3/2}\sin\frac{\theta}{2}\cos^2\frac{\theta}{2}$		
$+\,+\,-$	$-i\frac{\sqrt{2}g}{F}\sin\frac{\theta}{2}$	$\{\ \frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R}}s\beta^{3/2}\cos^2\frac{\theta}{2}$	$+W_3\frac{m^2_{\tilde{\chi}}}{t_{\tilde{\chi}}}\beta^{1/2}s$	$+m^2_{\tilde{e}_R^-}\beta^{1/2}\ \}$

$e^- \gamma \to \tilde{e}_R^- \tilde{G}$



s-channel constant

u-channel small

t-channel increases with $m_{\tilde{\chi}_1^0}$

$\lambda_1 \lambda_2\ \lambda_4$		$i\mathcal{M}^u$	$i\mathcal{M}^t$	$i\mathcal{M}^s$
$+\,-\ +$	$-i\frac{\sqrt{2}g}{F}$		$W_3 \frac{m_{\tilde{\chi}}}{t_{\tilde{\chi}}} (\beta s)^{3/2} \cos\frac{\theta}{2} \sin^2\frac{\theta}{2}$	
$+\,-\ -$	$i\frac{\sqrt{2}g}{F}$	$\frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R^-}} s\beta^{3/2} \sin\frac{\theta}{2} \cos^2\frac{\theta}{2}$		
$+\,+\ -$	$-i\frac{\sqrt{2}g}{F} \sin\frac{\theta}{2}$	$\{ \frac{m^2_{\tilde{e}_R^-}}{u_{\tilde{e}_R}} s\beta^{3/2} \cos^2\frac{\theta}{2}$	$+W_3 \frac{m^2_{\tilde{\chi}}}{t_{\tilde{\chi}}} \beta^{1/2} s$	$+m^2_{\tilde{e}_R^-} \beta^{1/2} \}$

Outlook

- include NLSP decay
- analysis for LHC $\mathrm{p\,p} \to \tilde{G}\,\tilde{G}\,\mathrm{j}$
- build e^+e^- collider ....