GRACE for BSM

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&
GRACE group

MC4BSM 2016 @ UCAS/IHEP

Outline

- What is GRACE?
- BSM in GRACE
  - MSSM
    - Tree level calculations (selectron search)
    - Full ELWK Loop corrections (zH, $t\bar{t}$)
- Summary

What is GRACE ?

What is GRACE ?

GRACE is a system to calculate tree- and ELWK loop-cross sections automatically with beam-polarizations based on SM and MSSM (+ more*).

Physics Report **430**, 117 (2006)

* • New Higgs sector (Collaboration w/ CompHEP)
• Majorana neutrino serch @ ILC

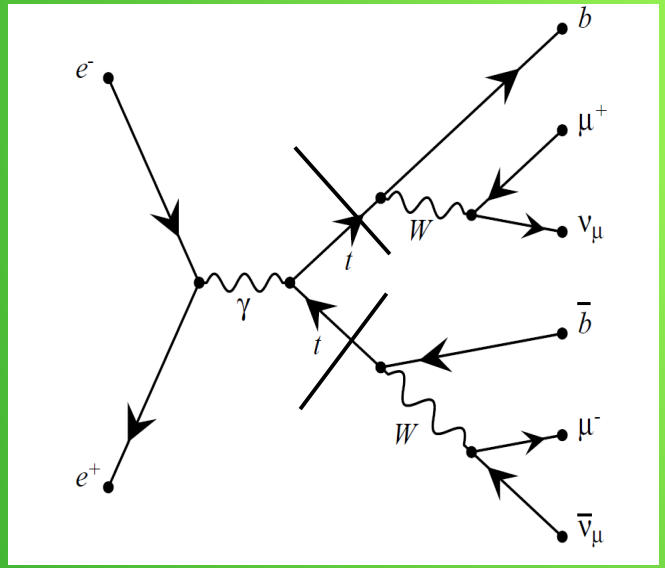
MSSM w/ beam-pol is not completed yet.

What is GRACE ? recent results

SM processes:

$e^+e^- \to t\bar{t}\gamma$ Loop Eur. Phys. J. C **73**, 2400 (2013)

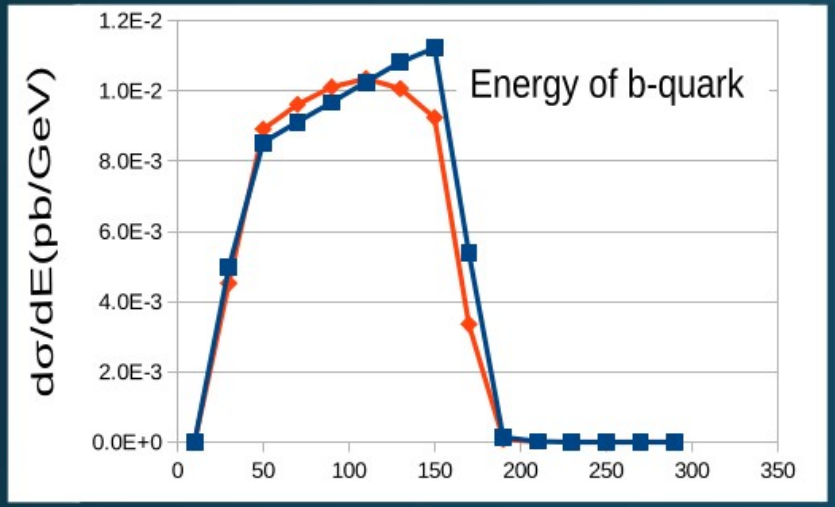
$e^+e^- \to e^+e^-\gamma$ Loop Phys. Lett. **B740,** 192 (2014)

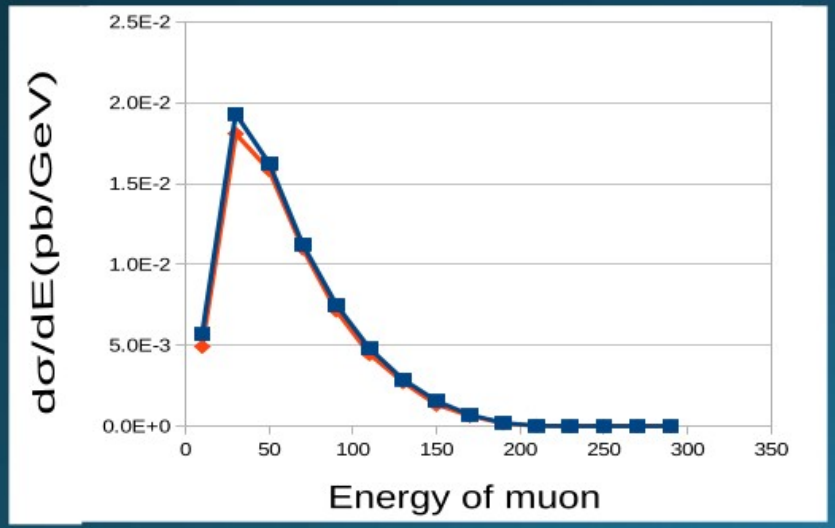


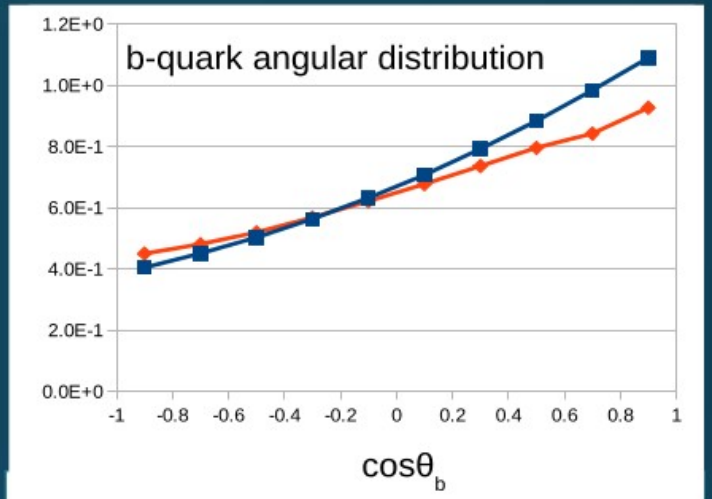
Loop (on-shell approx.) Top@LC2016

Beam-spin, spin corri.

Full EW results for 6-body final process (L-R)







$$e^- e^+ \to b\bar{b}\ \mu^- \mu^+ \nu\bar{\nu}$$

√s=500GeV
Electron : 100% Left
Positron : 100% Right

Blue : NWA Tree
Orange : NWA NLO(ELWK)

N.M.U. Quch,
Workshop on Top physics at the LC 2015

What is GRACE ? recent results

MSSM processes:

$e^- e^\pm \to e^- e^\pm \tilde{\chi}^0_{1,2} \tilde{\chi}^0_{1,2}$	Tree Beam-spin	JPS September, 2014
$e^+e^- \to Z\,h$	Loop	JPS Spring, 2015
$e^+e^- \to t\,\bar{t}$	Loop	ALCWS, 2015

What is GRACE ?

Precision Control

NLG fixing (Phys. Rep. **430**, 117 (2006))

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W} \mid (\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^{\mu+} + \xi_W\frac{g}{2}(v + \tilde{\delta}H + i\tilde{\kappa}\chi_3)\chi^+ \mid^2$$

$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z\frac{g}{2c_W}(v + \tilde{\epsilon}H)\chi_3)^2 - \frac{1}{2\xi_A}(\partial.A)^2.$$

The results must be independent of non-linear gauge parameters ($\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\kappa}, \tilde{\epsilon}$).

What is GRACE ?

Precision Control

$$\sigma_{full} = \sigma_{Tree} + \sigma_{Loop}(C_{UV}, \tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\epsilon}, \tilde{\kappa}, \lambda)$$
$$+ \sigma_{Tree}\delta_{soft}(\lambda, E_\gamma < k_c) + \sigma_{Hard}(k_c)$$

Soft photon: $E_\gamma < k_c$

Hard photon: $E_\gamma \geq k_c$

- C_{UV} (Ultra violet coefficient) independence
- Photon mass (λ) independence
- Gauge invariance
- k_c independence

What is GRACE ? Precision Control

$\sqrt{s}$=500 GeV, $e^+e^- \to t\bar{t}$

λ	NLG	Cuv	pol (-,+)	Tree (pb)	loop	soft	T+L+S	δ
1E-17	(0,0,0,0,0)	0	(0,0)	5.0510E-01	-2.4358E+00	1.7120E+00	-2.1868E-01	0.0000E+00
			(L,R)	1.4026E+00	-6.8130E+00	4.7463E+00	-6.6402E-01	0.0000E+00
			(R,L)	6.1782E-01	-2.9304E+00	2.1016E+00	-2.1097E-01	0.0000E+00
1E-17	(0,0,0,0,0)	1000	(0,0)	5.0510E-01	-2.4358E+00	1.7120E+00	-2.1868E-01	1.0000E+00
			(L,R)	1.4026E+00	-6.8129E+00	4.7463E+00	-6.6393E-01	1.3554E-04
			(R,L)	6.1782E-01	-2.9304E+00	2.1016E+00	-2.1097E-01	1.0000E+00
1E-17	(10,20,30,40,50)	0	(0,0)	5.0510E-01	-2.4358E+00	1.7120E+00	-2.1868E-01	0.0000E+00
			(L,R)	1.4026E+00	-6.8129E+00	4.7463E+00	-6.6393E-01	1.3554E-04
			(R,L)	6.1782E-01	-2.9304E+00	2.1016E+00	-2.1097E-01	0.0000E+00
1E-19	(0,0,0,0,0)	0	(0,0)	5.0510E-01	-2.7340E+00	2.0099E+00	-2.1893E-01	-1.1066E-03
			(L,R)	1.4026E+00	-7.6397E+00	5.5727E+00	-6.6438E-01	-5.2860E-04
			(R,L)	6.1782E-01	-3.2962E+00	2.4670E+00		

What is GRACE ?

Precision Control

$e^+e^- \to t\bar{t}$

√s=500 GeV, λ=1e-17 GeV

(pb)

Kc (GeV)	H	T+S	sum	δ
1e-3	0.74172	2.2168	2.9585	2.9E-06
1e-4	0.89080	2.0677	2.9585	0.0E+00
1e-5	1.0399	1.9187	2.9585	-2.1E-06

δ ~0.1%

BSM in GRACE

MSSM: tree

N.M.U. Quach,
TYL/FKPPL2014

Processes

Signal

e^-e^- $\qquad$ e^-e^+

$$e^-e^- \longrightarrow \tilde{e}^-_{1,2}\tilde{e}^-_{1,2} \qquad e^-e^+ \longrightarrow \tilde{e}^-_{1,2}\tilde{e}^+_{1,2}$$

$$\tilde{e}^-_{1,2} \longrightarrow e^-\chi^0_1$$

$$\begin{cases} \tilde{e}^-_{1,2} \longrightarrow e^-\chi^0_1 \\ \tilde{e}^+_{1,2} \longrightarrow e^+\chi^0_1 \end{cases}$$

$$e^-e^- \longrightarrow e^-e^-\chi^0_1\chi^0_1 \qquad e^-e^+ \longrightarrow e^-e^+\chi^0_1\chi^0_1$$

Background

$$e^-e^- \longrightarrow e^-e^-\nu\bar{\nu} \qquad e^-e^+ \longrightarrow e^-e^+\nu\bar{\nu}$$

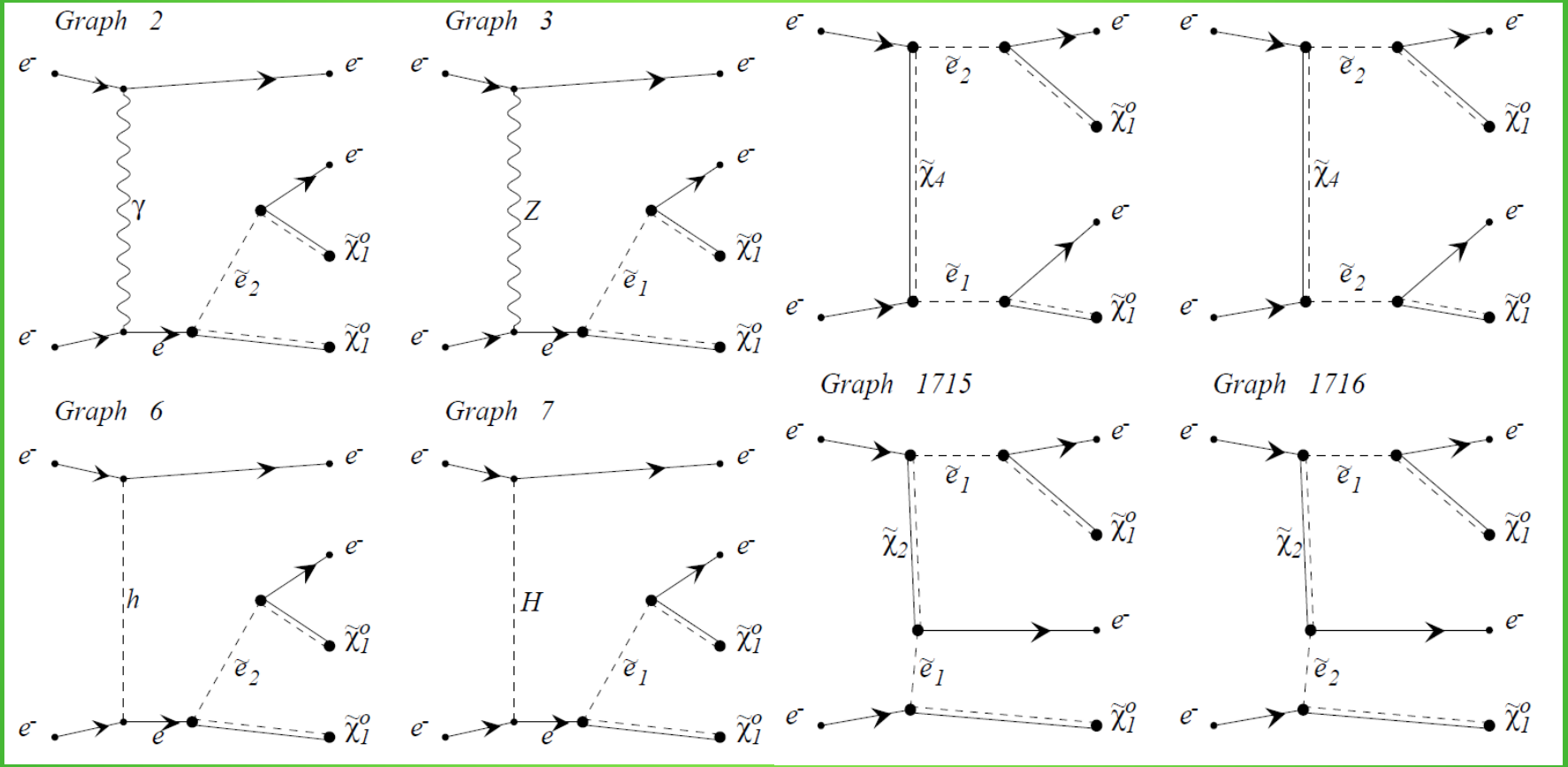
SUSY parameters (MSSM)

	Light Mass	Heavy Mass
$m_{\tilde{e}_1}$	200 GeV	400 GeV
$m_{\tilde{e}_2}$	220 GeV	440 GeV
$\Gamma_{\tilde{e}_1}$	0.0488 GeV	0.3118 GeV
$\Gamma_{\tilde{e}_2}$	0.3679 GeV	1.6741 GeV
$\theta_{\tilde{e}}$	0.05π	0.05π
tan_β	30	30
μ	400 GeV	400 GeV
M_2	310 GeV	310 GeV
$m_{\chi_1^0}$	149.19 GeV	149.19 GeV

N.M.U. Quach,
TYL/FKPPL2014

N.M.U. Quach,
TYL/FKPPL2014

Typical diagrams



532 diagrams in unitary gauge

Cuts:

N.M.U. Quach, TYL/FKPPL2014

E_{cut} : $10\text{GeV} \leq E_e \leq 320$ GeV

$\not{E}_T$: > 10 GeV — To kill radiative $e^-e^{\pm}$

$\cos\theta_{cut}$: $|\cos\theta| < 0.8$ — To kill forward scat.

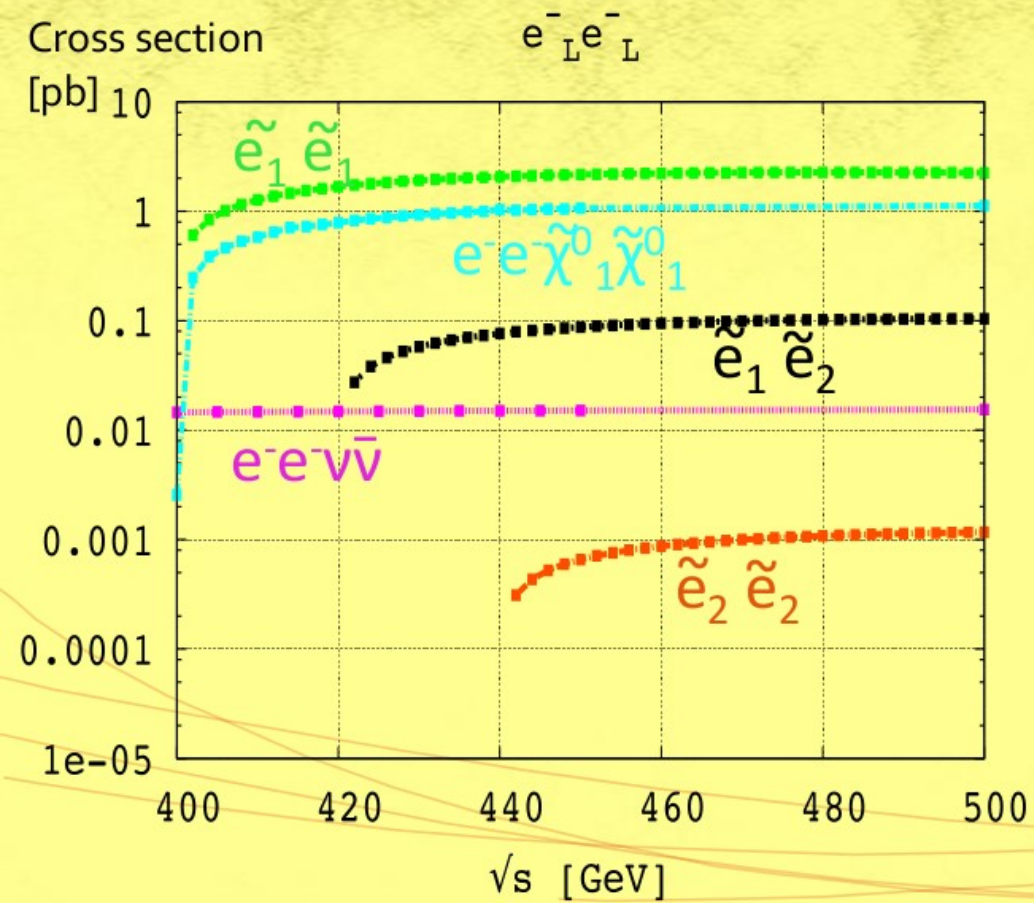
Cuts only for e^+e^-:

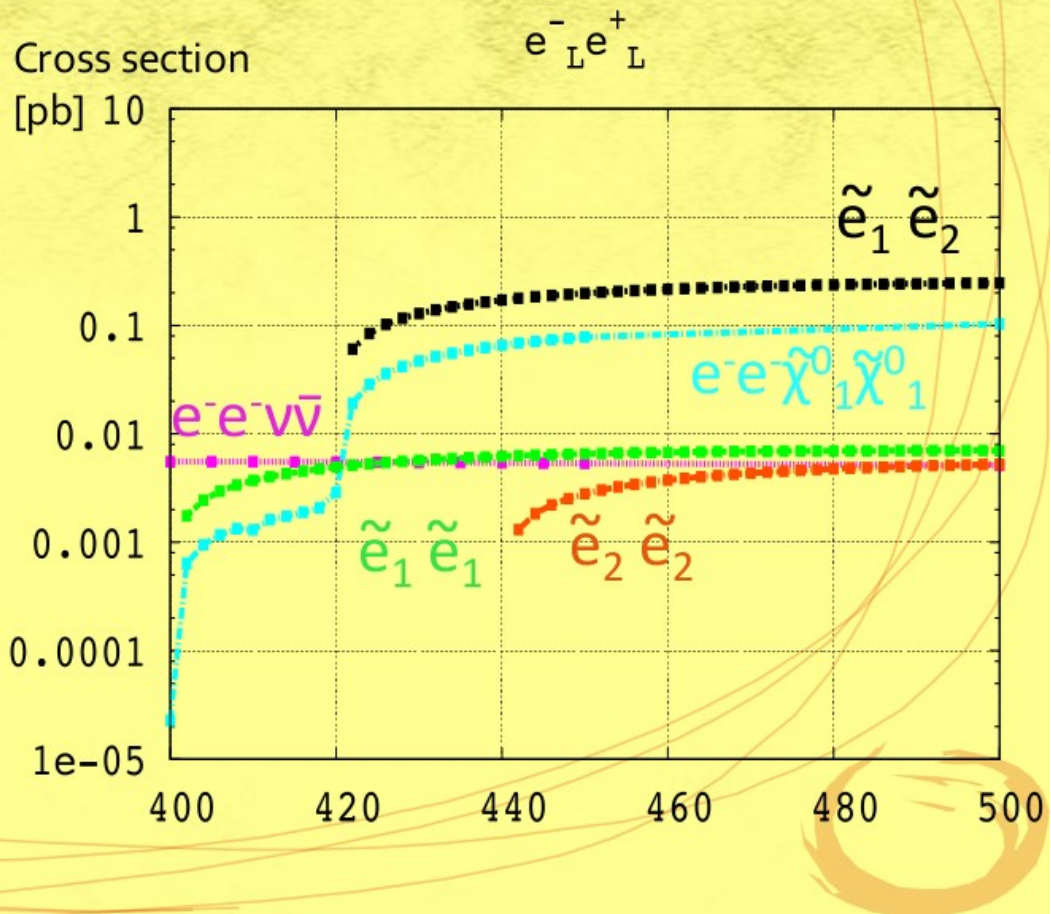
$|m_{ee} - m_Z| > 3\Gamma_Z$ — To kill Z-boson pair

N.M.U. Quach, TYL/FKPPL2014

Light $\tilde{e}$, L-L Pol.

$$e_L^- \longleftrightarrow \tilde{e}_1^- \qquad e_L^+ \longleftrightarrow \tilde{e}_2^+$$
$$e_R^- \longleftrightarrow \tilde{e}_2^- \qquad e_R^+ \longleftrightarrow \tilde{e}_1^+$$

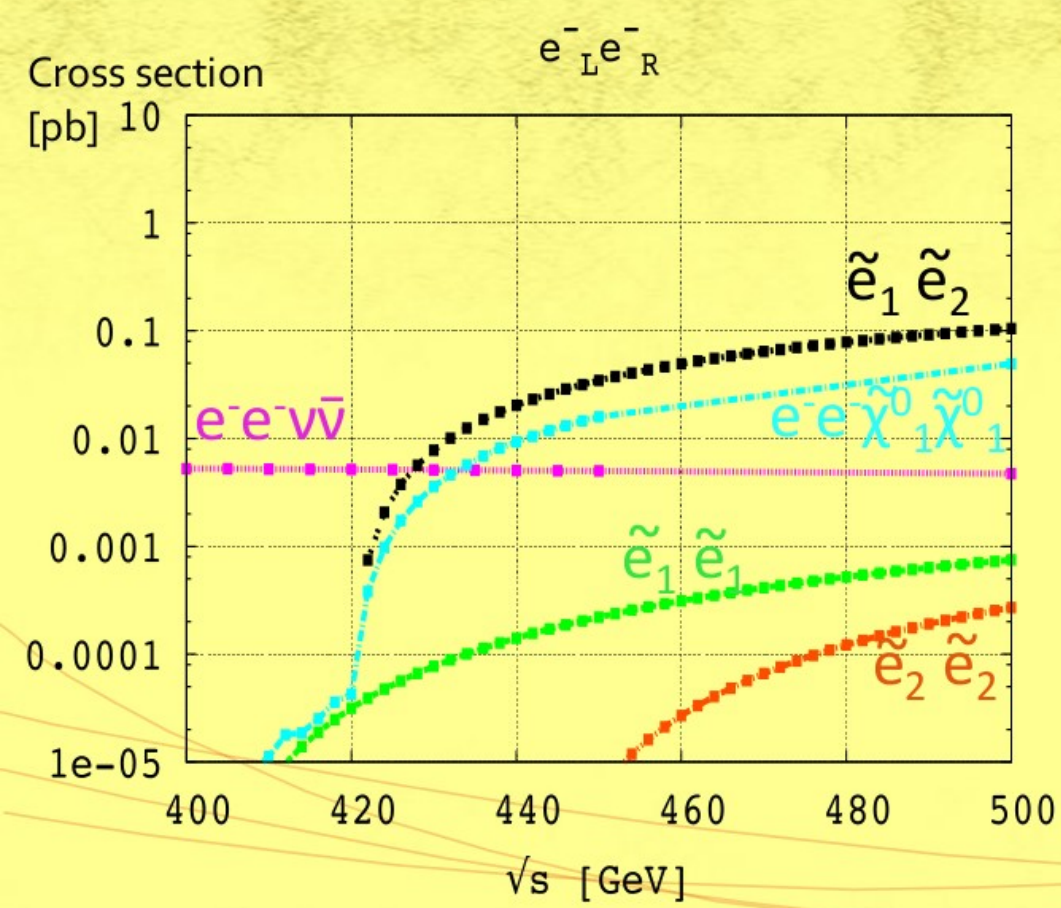


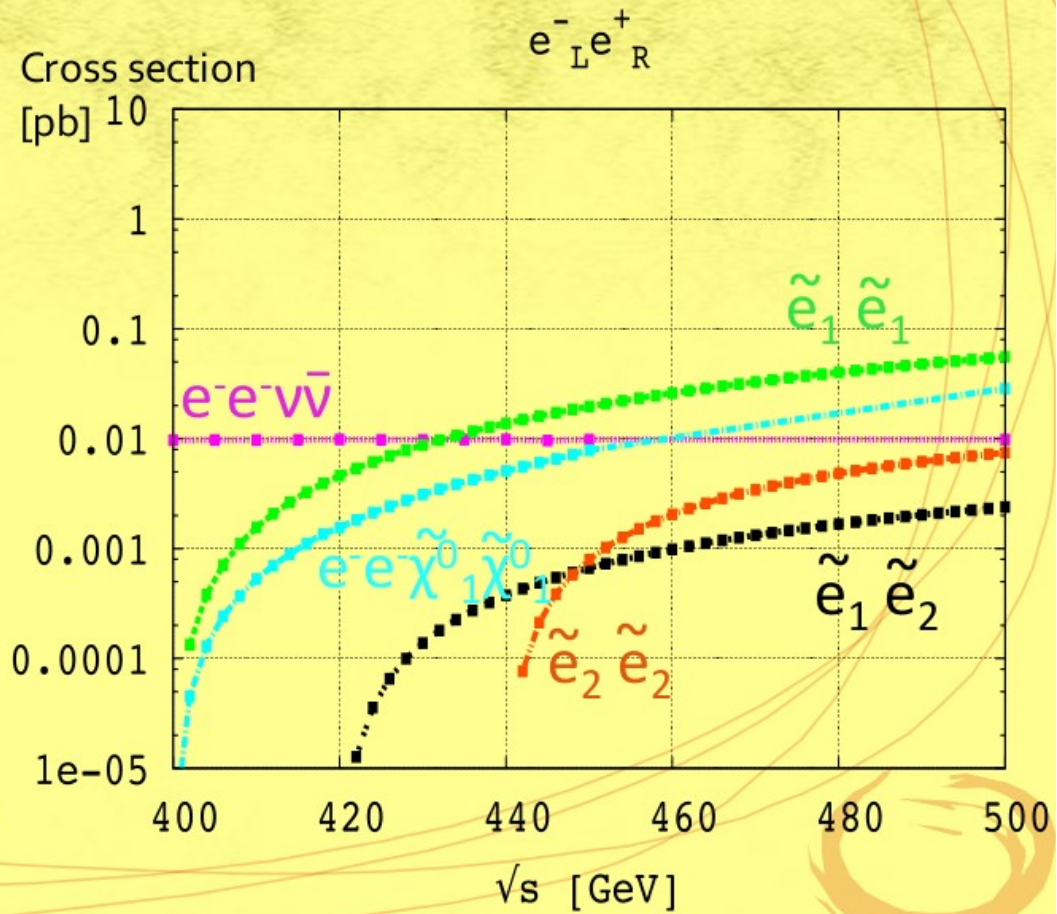


N.M.U. Quach, TYL/FKPPL2014

Light $\tilde{e}$, L-R Pol.

$$e_L^- \longleftrightarrow \tilde{e}_1^- \qquad e_L^+ \longleftrightarrow \tilde{e}_2^+$$
$$e_R^- \longleftrightarrow \tilde{e}_2^- \qquad e_R^+ \longleftrightarrow \tilde{e}_1^+$$

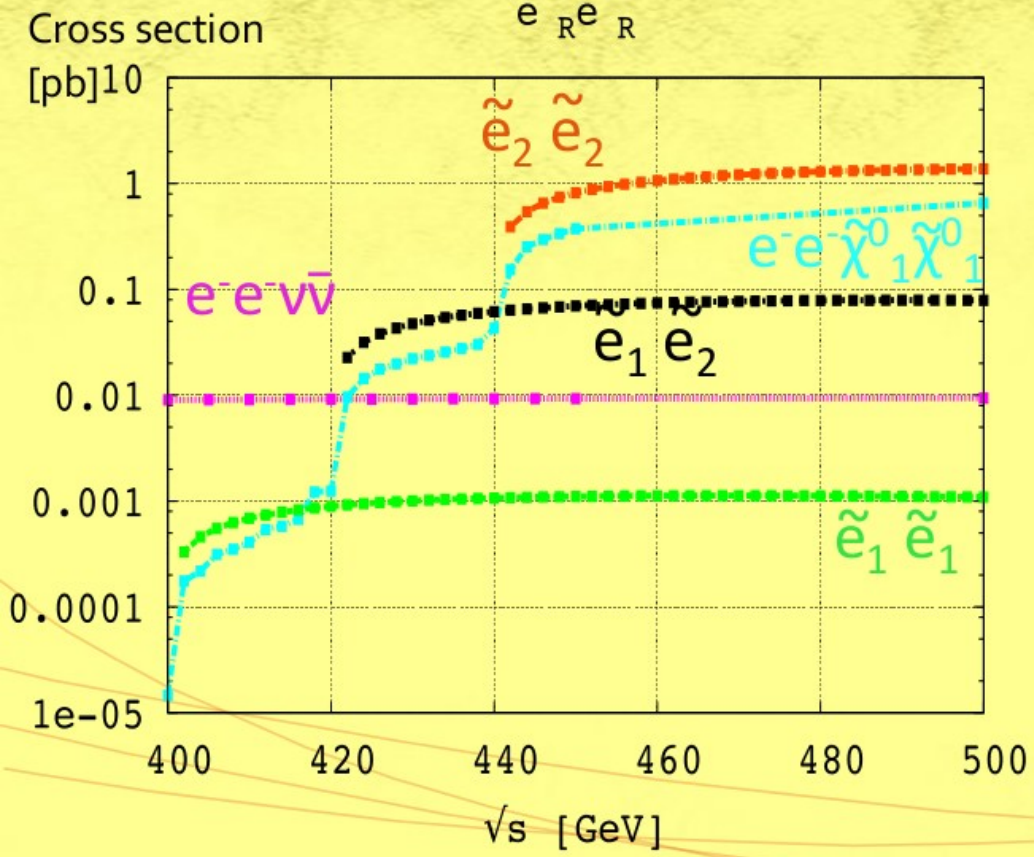


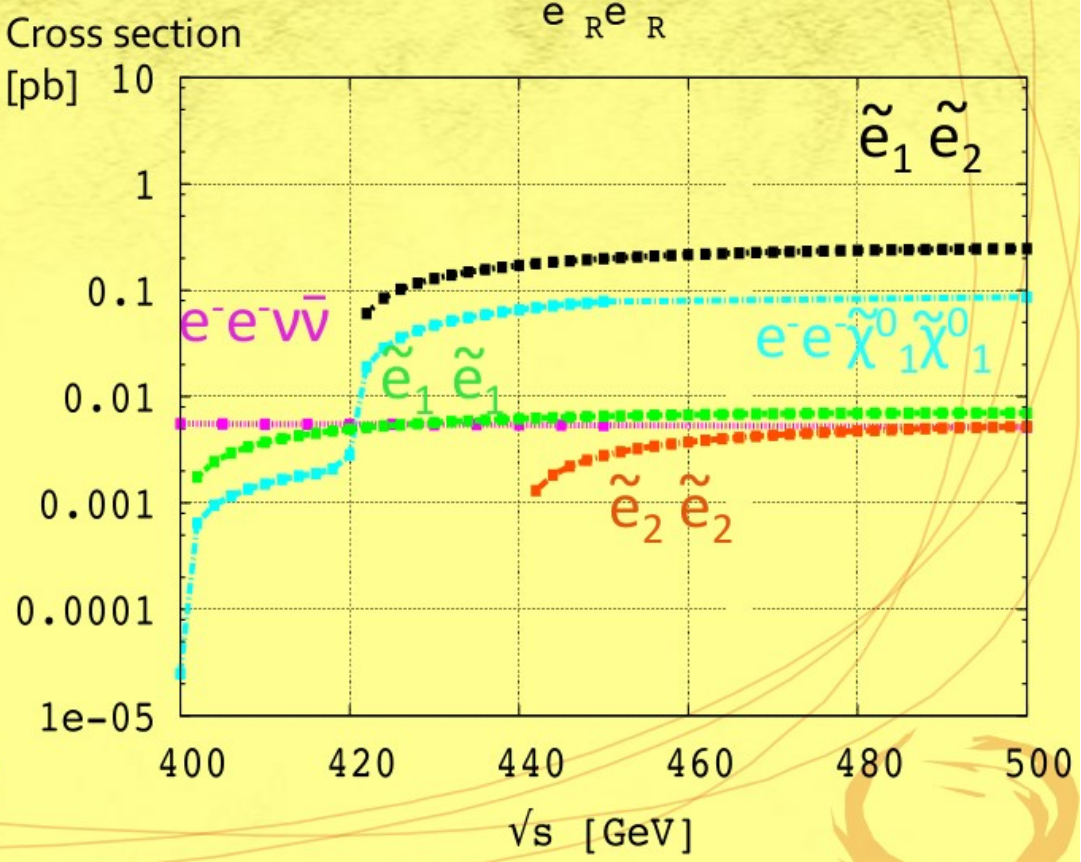


N.M.U. Quach, TYL/FKPPL2014

Light $\tilde{e}$, R-R Pol.

$$e_L^- \longleftrightarrow \tilde{e}_1^- \qquad e_L^+ \longleftrightarrow \tilde{e}_2^+$$
$$e_R^- \longleftrightarrow \tilde{e}_2^- \qquad e_R^+ \longleftrightarrow \tilde{e}_1^+$$





Expected number of events

Pol.	e−(80%) e−(80%)		e+(30%) e−(80%)	
	S/B	Channel	S/B	Channel
LL	45428/624=72.8	$\tilde{e}_1\tilde{e}_1$	21870/1080=20.3	$\tilde{e}_1\tilde{e}_2$
LR	222/21=10.6	$\tilde{e}_1\tilde{e}_2$	3252/1119=2.9	$\tilde{e}_1\tilde{e}_1$
RR	3271/4=818	$\tilde{e}_2\tilde{e}_2$	5288/315=16.8	$\tilde{e}_1\tilde{e}_2$
Integ. Lumi.	50 fb^{-1}		500 fb^{-1}	

$\sqrt{s}$=500 GeV, light $\tilde{e}$ mass

e^-e^- luminosity is 1/8 smaller than e^+e^- due to anti-pinch effect. (Prof. K. Yokoya, KEK)

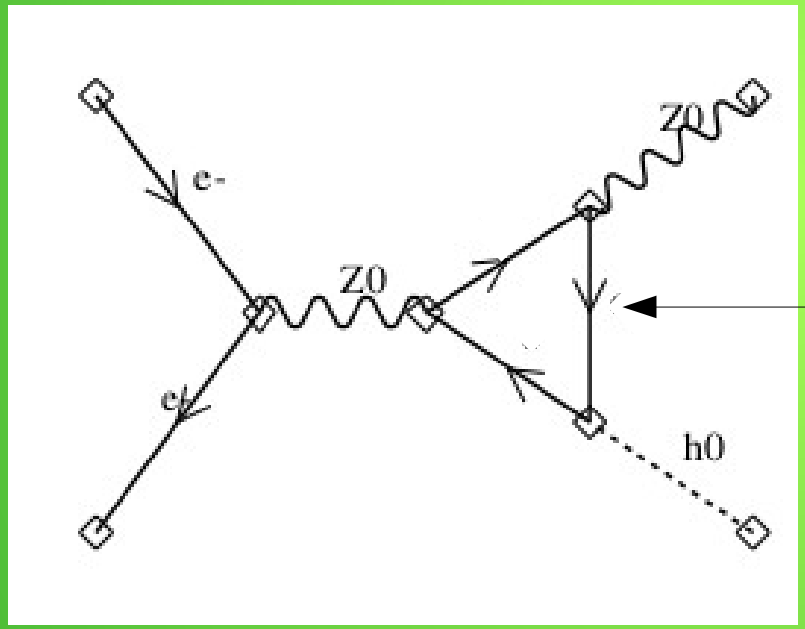
BSM in GRACE

MSSM: Full ELWK $O(\alpha)$ corrections

BSM in GRACE

MSSM/Full ELWK $O(\alpha)$ corrections

$$e^+e^- \to Z\,h$$



Any SUSY particles

2863 diagrams

Y. Kouda

BSM in GRACE MSSM/Full ELWK $O(\alpha)$ corrections

Table 2 mass spectra in each scenario(mass unit is GeV)

scenario 1 (GeV)			
$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$		
368.9	616.8		
$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$
149.0	369.0	604.2	616.1
$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$	
362.5	367.9	359.6	
$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$	
161.1	296.1	228.2	
$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$
1720	1739	1740	1741
$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
315.2	2078	800.0	2061
θ_τ	θ_b	θ_t	
0.8071	1.557	1.456	
M_1	M_2	M_3	
150.0	380.0	1500	
μ=600, $\tan\beta$=30			

scenario 2 (GeV)			
$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$		
508.1	636.8		
$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$
277.9	508.5	603.4	637.1
$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$	
317.8	323.3	313.8	
$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$	
283.9	377.1	327.4	
$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$
1720	1739	1740	1741
$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
1799	2245	1998	2063
θ_τ	θ_b	θ_t	
0.8150	1.376	0.8533	
M_1	M_2	M_3	
280.0	540.0	1500	
μ=600, $\tan\beta$=30			

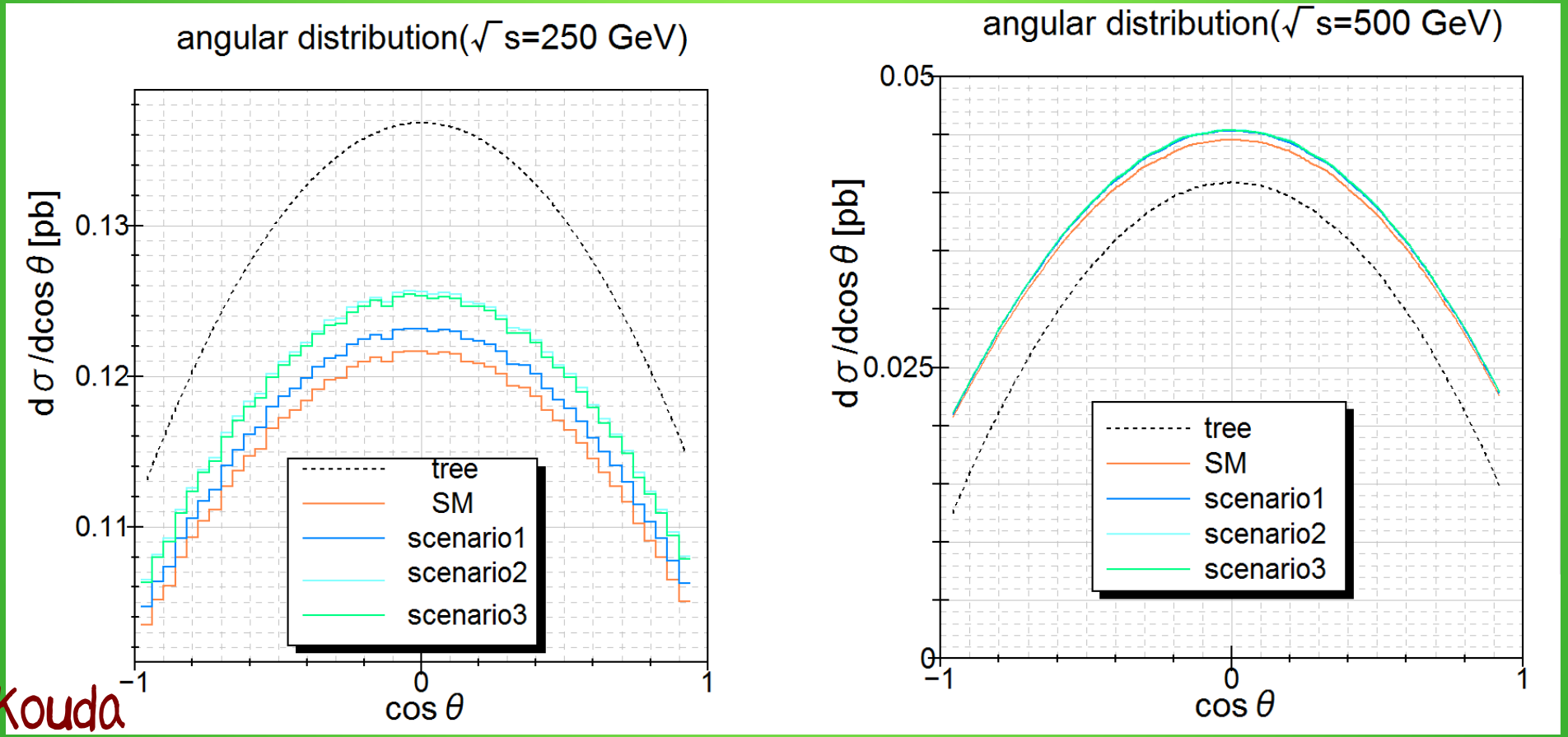
scenario 3 (GeV)			
$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$		
467.5	626.7		
$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$
242.8	467.6	603.6	626.7
$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$	
322.8	328.3	318.9	
$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$	
320.1	405.3	359.6	
$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$
1720	1739	1740	1741
$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
280.0	2078	800.0	2061
θ_τ	θ_b	θ_t	
0.8175	1.557	1.456	
M_1	M_2	M_3	
244.5	489.0	2000	
μ=600, $\tan\beta$=30			

Y. Kouda

These MSSM parameter sets are still survived from recent experiments.

BSM in GRACE MSSM/Full ELWK $O(\alpha)$ corrections

$e^+e^- \to Z\,h$



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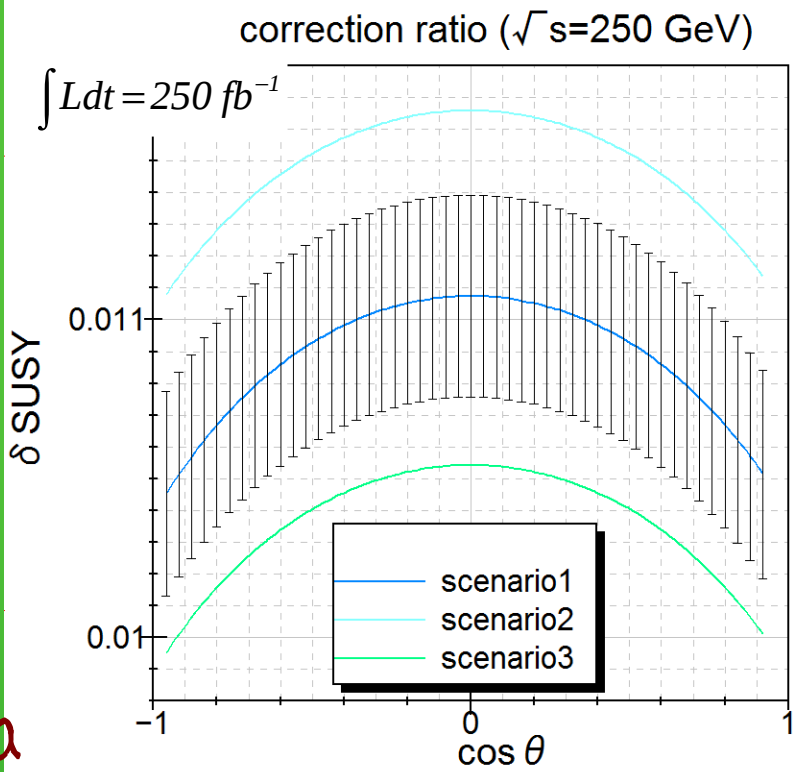
BSM in GRACE

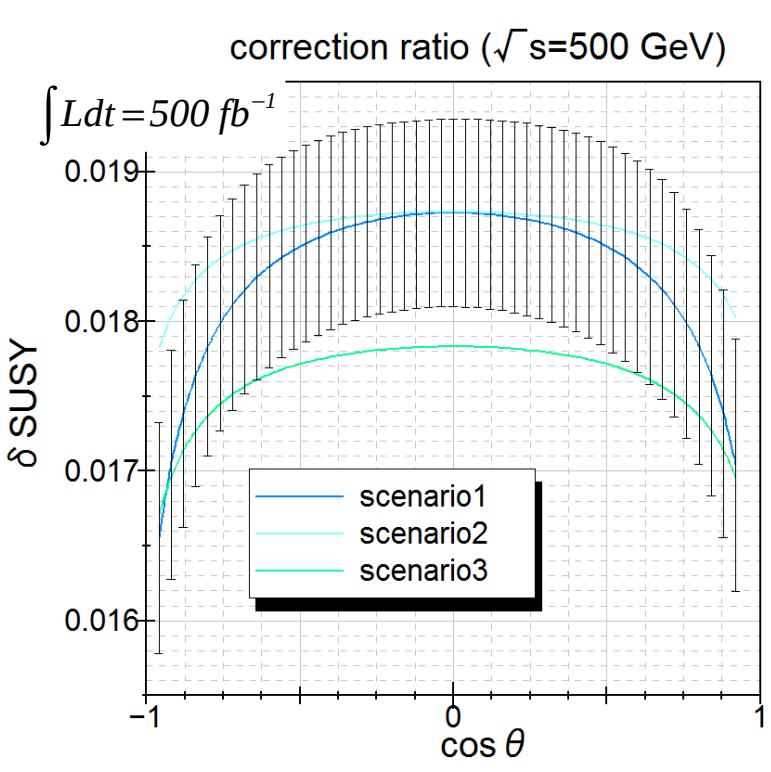
MSSM/Full ELWK $O(\alpha)$ corrections

$$e^+e^- \to Z\,h$$

$$\delta_{SUSY} = \frac{\frac{d\sigma_{SUSY1-loop}}{dcos\theta} - \frac{d\sigma_{SM}}{dcos\theta}}{\frac{d\sigma_{tree}}{dcos\theta}}$$

The International Linear Collider Technical Design Report , Volume 2: Physics (2013)





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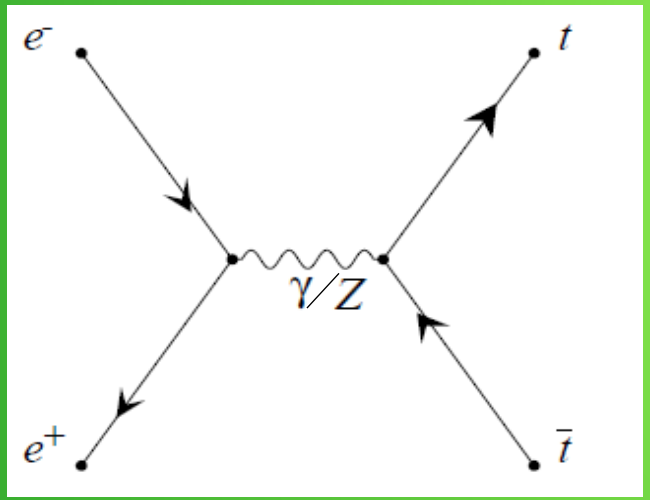
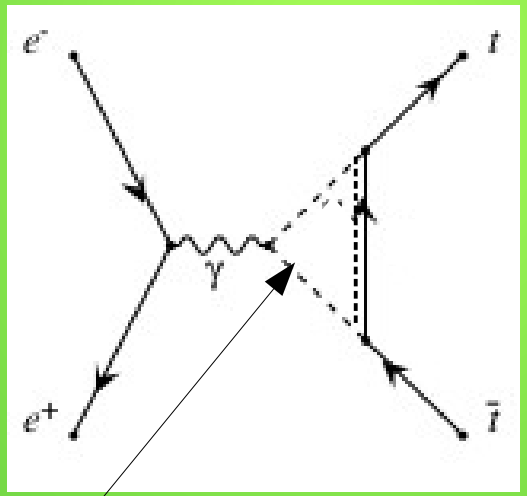
BSM in GRACE

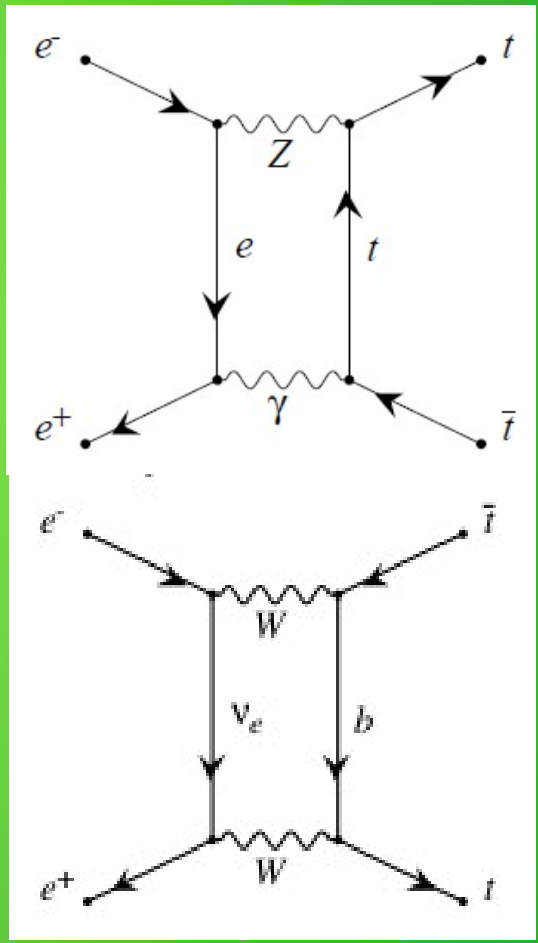
MSSM/Full ELWK $O(\alpha)$ corrections

$$e^+e^- \to t\bar{t}$$

Beam-pol. is important!







Any SUSY particles

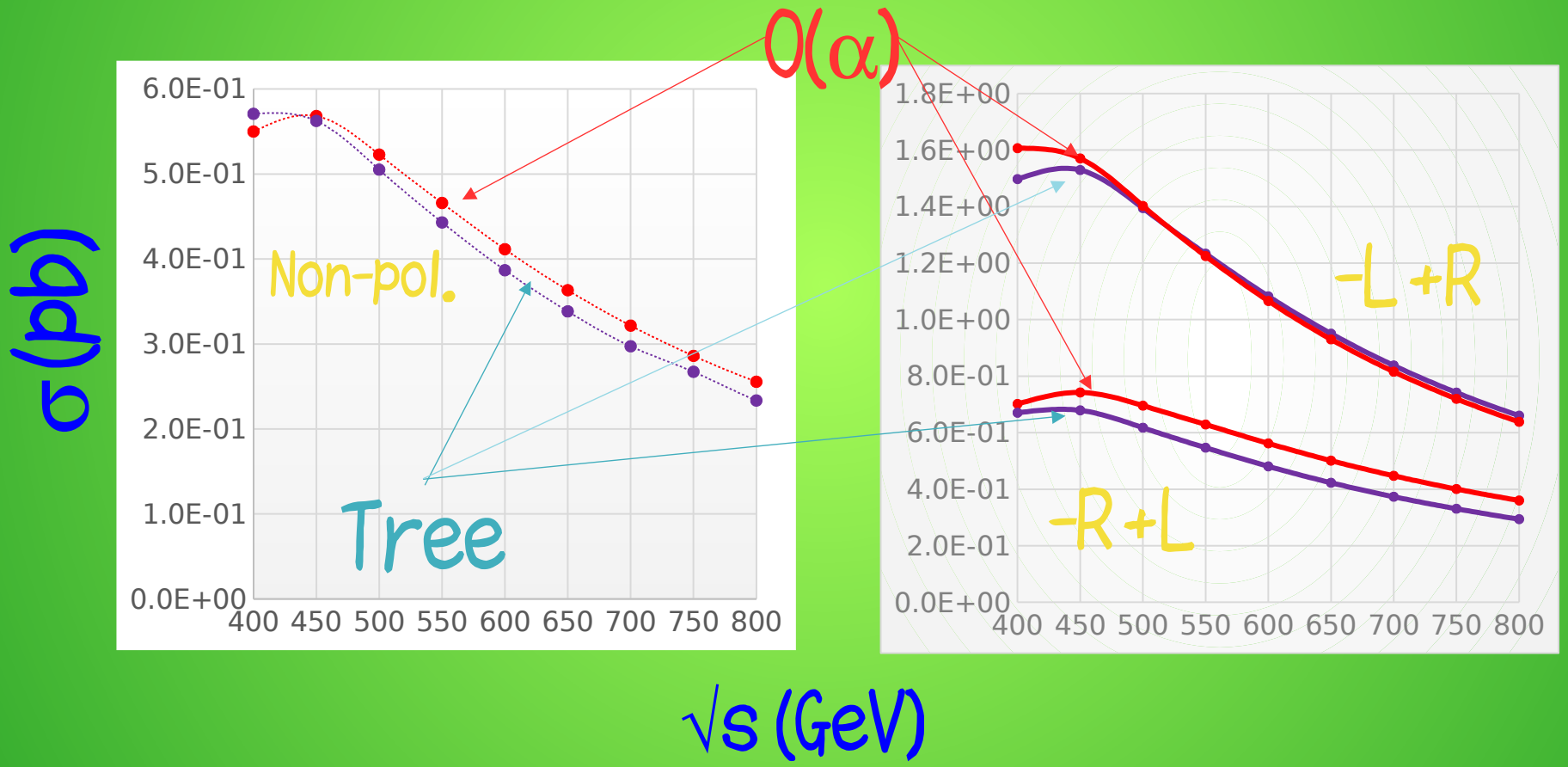
150 diagrams for SM
1114 diagrams for MSSM

BSM in GRACE

MSSM/Full ELWK $O(\alpha)$ corrections

$e^+e^- \to t\bar{t}$

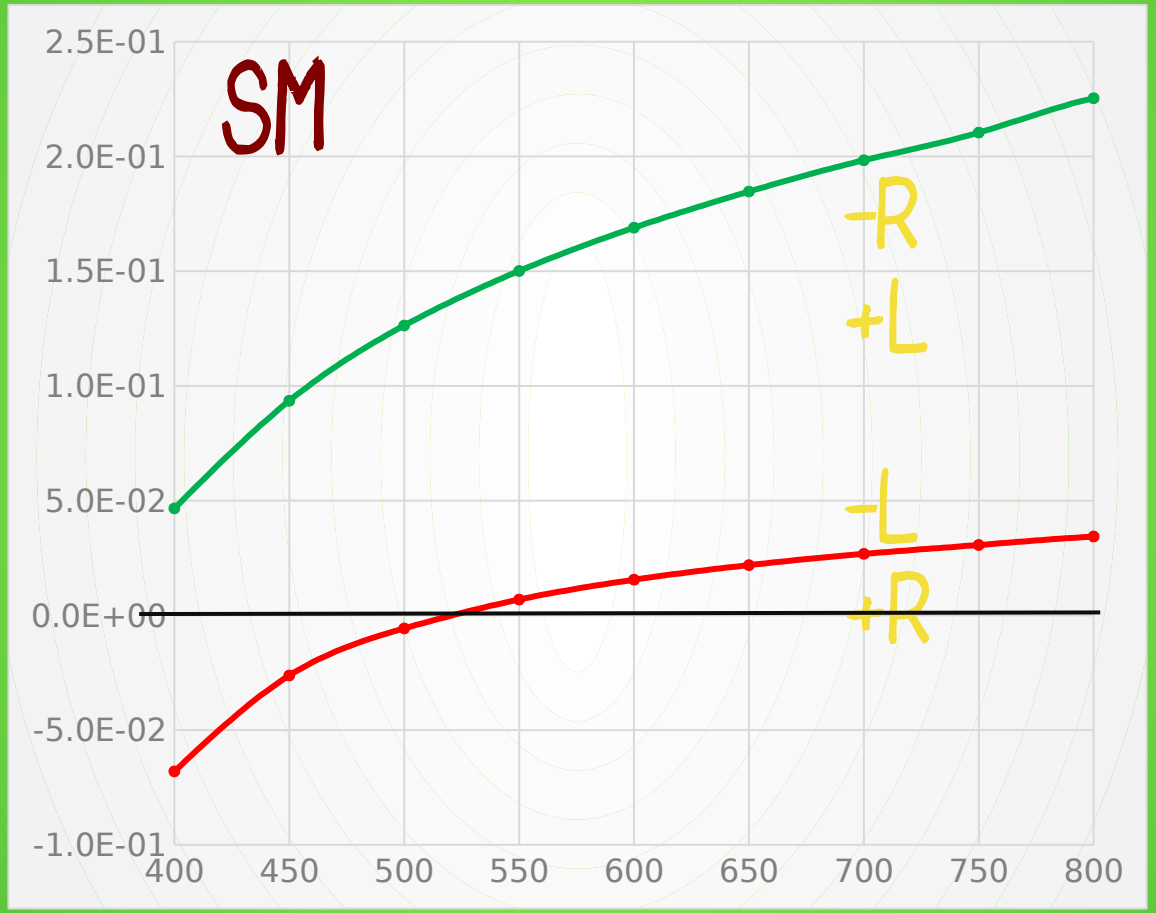
Total Cross sections for SM



BSM in GRACE

MSSM/Full ELWK $O(\alpha)$ corrections

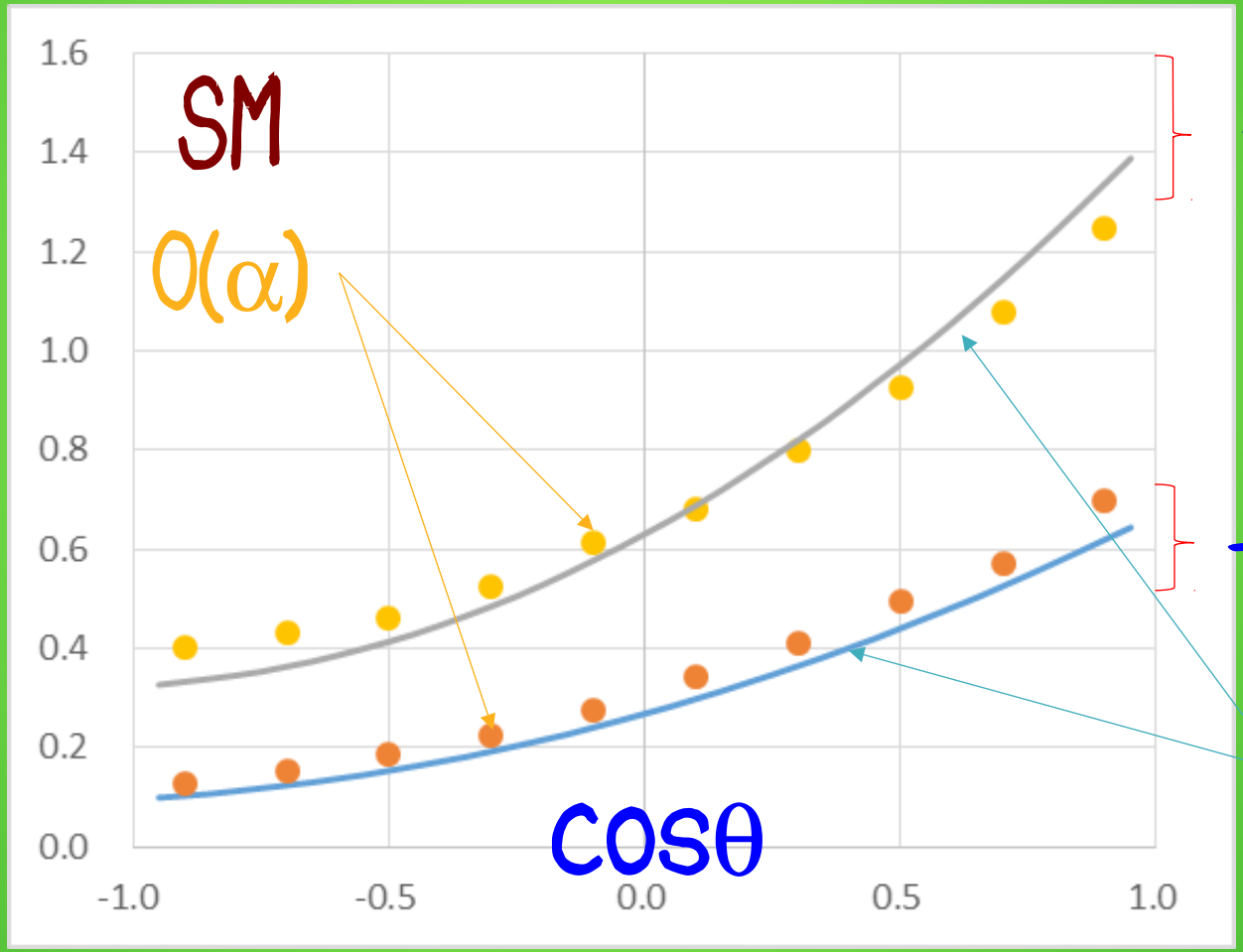
$e^+e^- \to t\bar{t}$



BSM in GRACE MSSM/Full ELWK $O(\alpha)$ corrections

$e^+e^- \to t\bar{t}$

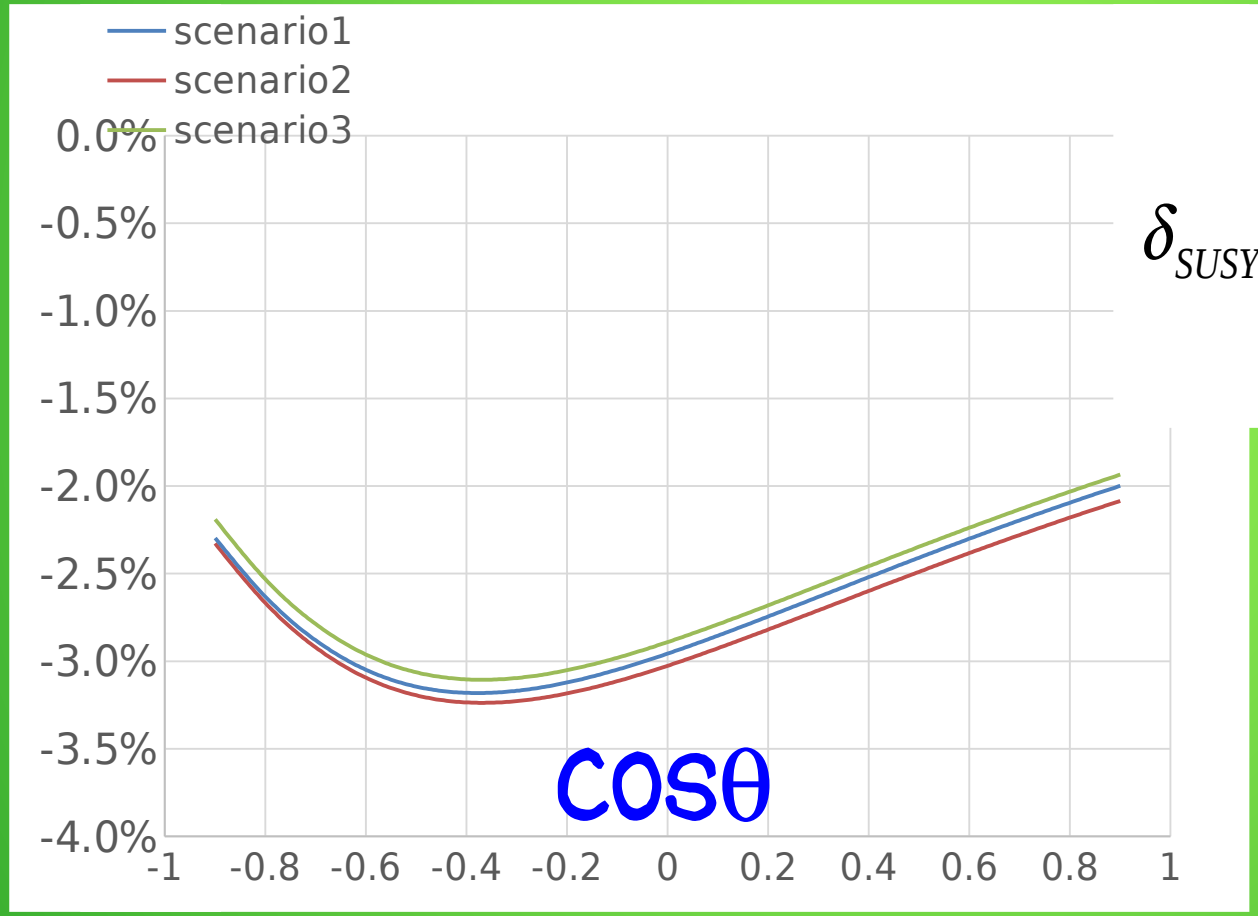
$\sqrt{s}$=500 GeV



BSM in GRACE

MSSM/Full ELWK $O(\alpha)$ corrections

$e^+e^- \to t\bar{t}$ $\sqrt{s}$=500 GeV



$$\delta_{SUSY} = \frac{\frac{d\sigma_{SUSY,1loop}}{d\cos\theta} - \frac{d\sigma_{SM,1loop}}{d\cos\theta}}{\frac{d\sigma_{tree}}{d\cos\theta}}$$

MSSM non-pol.

Y. Kouda, ALCWS2015

Summary

- GRACE can treat:
  - SM tree w/ pol.
  - SM full ELWK 1-loop w/ pol.
  - MSSM tree w/ pol.
  - MSSM full ELWK 1-loop
  - New Model tree w/ pol.
- Precision control ~0.1%
- Higher order QED-resummation:
  - Structure Function
  - QEDPS