GRACE for LC

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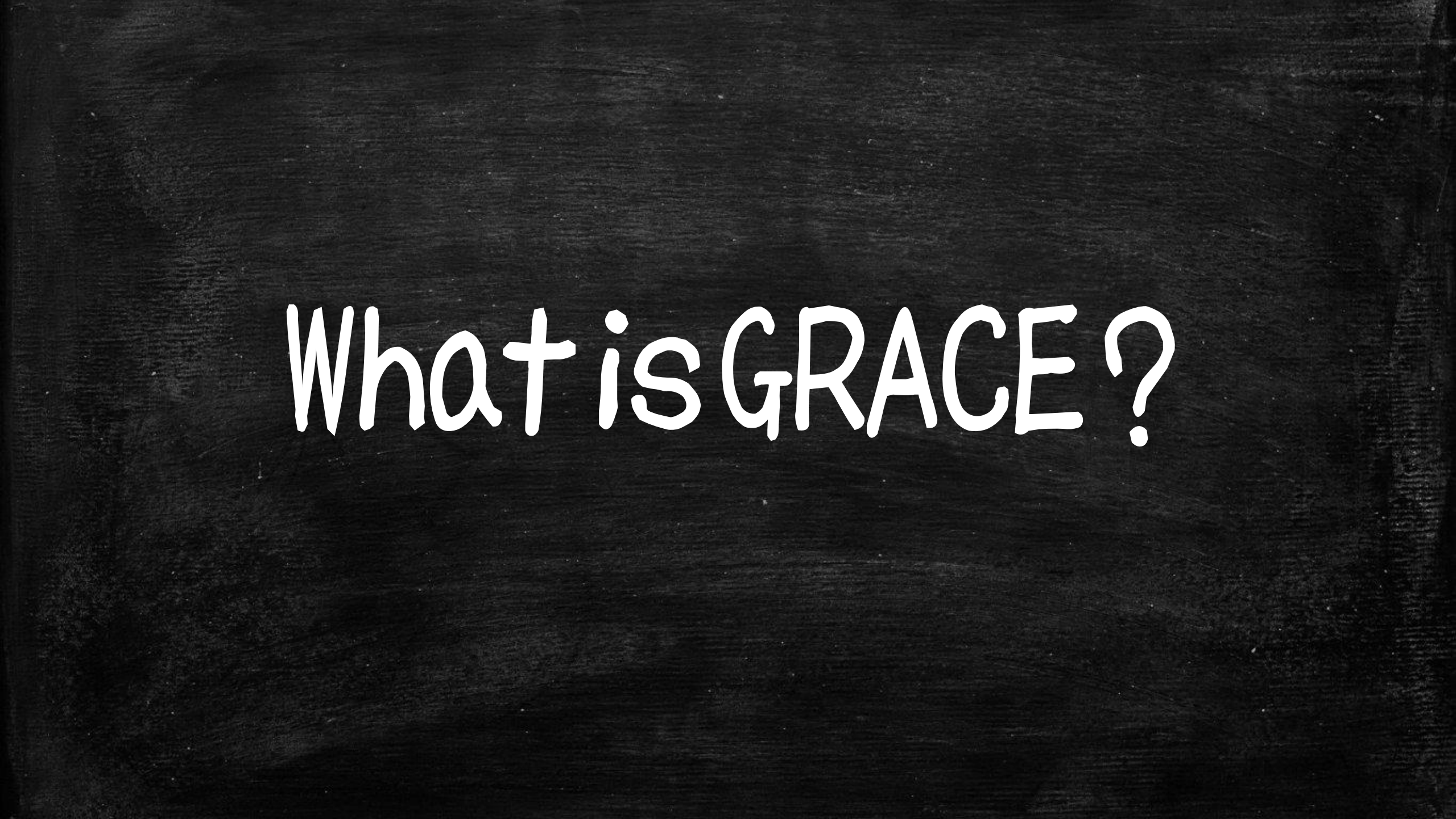
    - W-fusion
- Summary


What is GRACE?

What is GRACE

- GRACE is an automatic system to calculate tree and ELWK-loop cross sections with spin-polarizations based on SM and MSSM.

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

$e^+e^- \to e^+e^-\gamma$

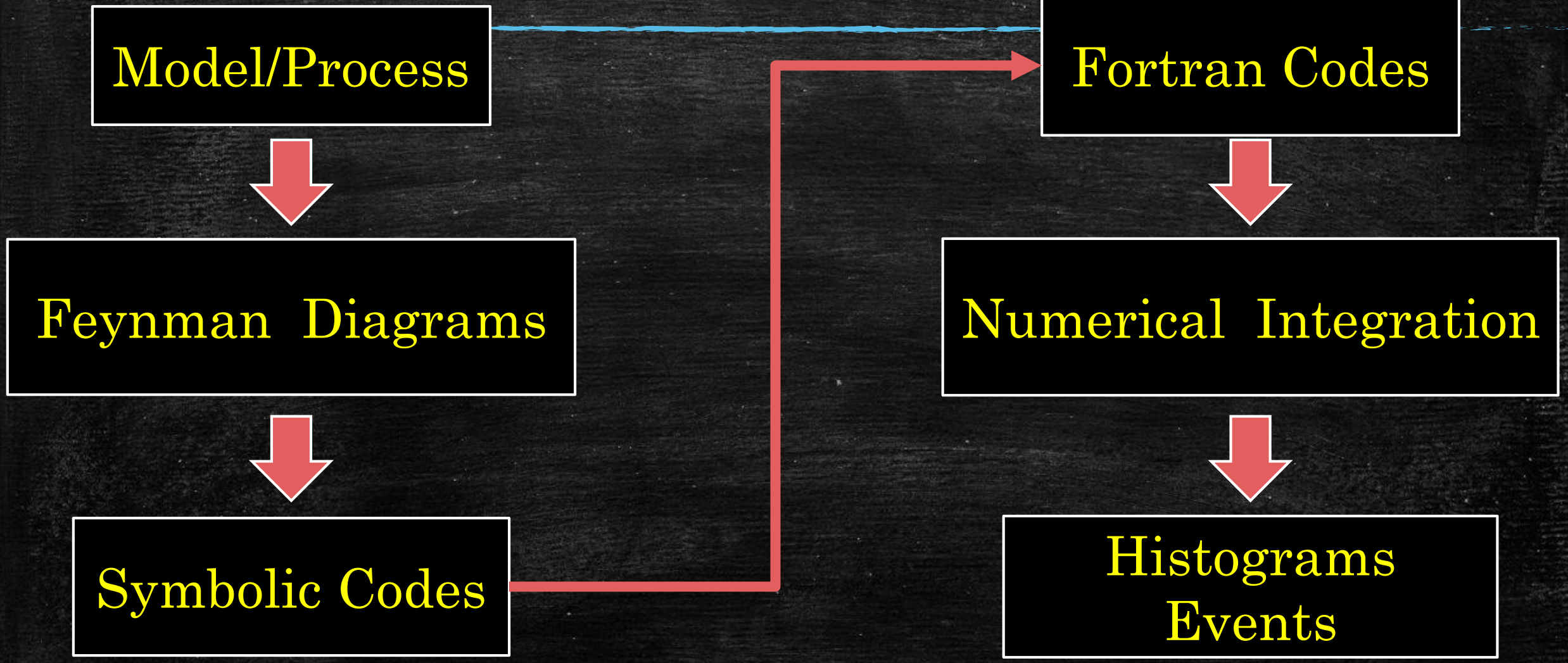
$e^+e^- \to t\bar{t}$ w/ beam pol.

Full-ELWK Eur. Phys. J. C **73**, 2400 (2013)

Full-ELWK Phys. Lett. **B740,** 192 (2014)

Full-ELWK Eur. Phys. J. C **78**, 422 (2018)

What is GRACE



What is GRACE

On-shell renormalization scheme (Kyoto-Scheme)

m_e	$0.51099906 \times 10^{-3}$ GeV	Γ_Z	2.0 GeV
m_t	173.5 GeV	α	$1/137.0359895$
m_u	58.0×10^{-3}GeV	$\sin^2\theta_W$	$1 - \frac{m_W^2}{m_Z^2}$
m_c	1.50 GeV	$m_{\rm Higgs}$	126.00 GeV
m_d	58.0×10^{-3}GeV	m_Z	91.187 GeV
m_s	92.0×10^{-3}GeV	m_W	80.22 GeV
m_b	4.7 GeV		

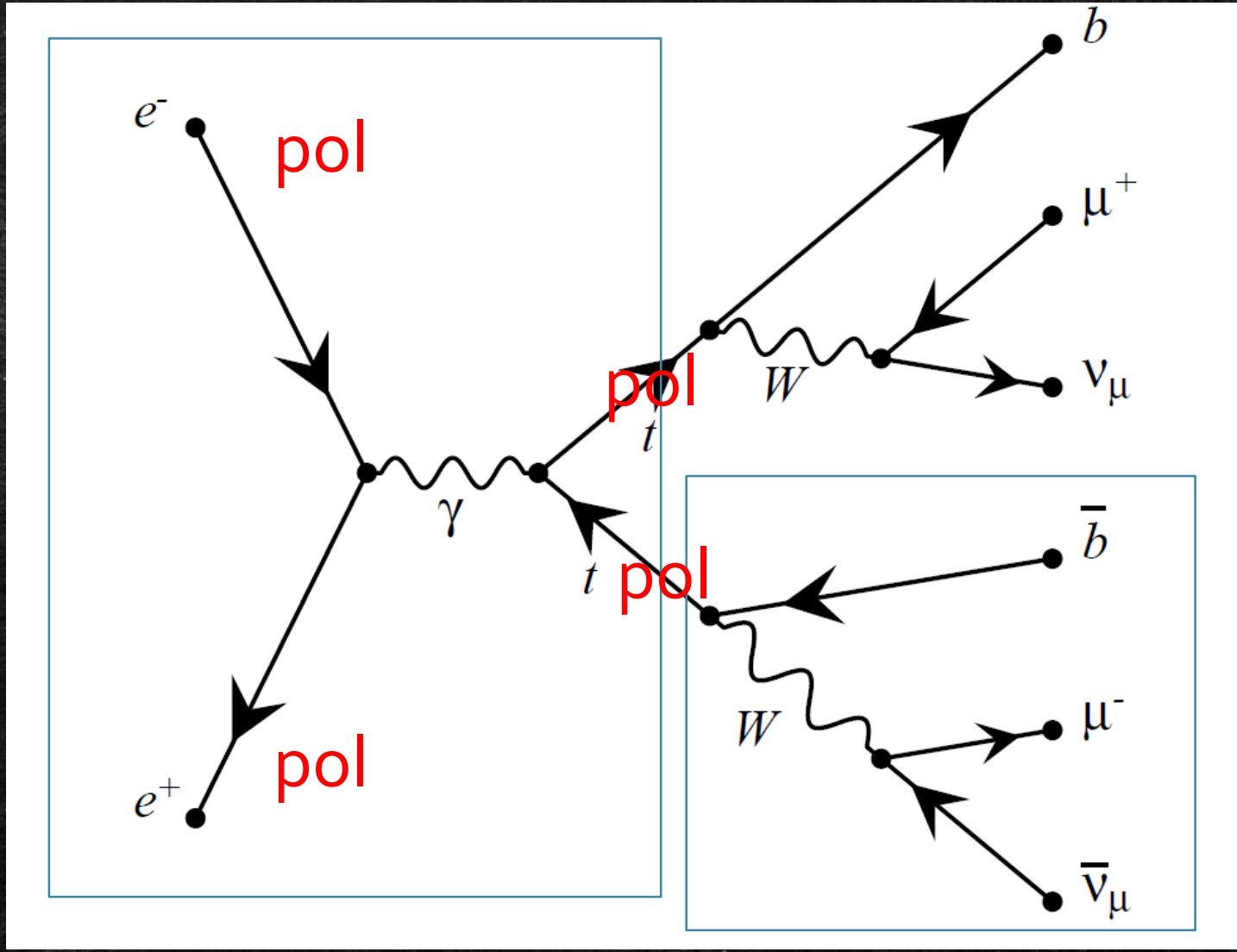
[1] K. Aoki et al, Suppl. Prog. Theor. Phys. **73 (1982) 1**.

[2] G. Belanger, F. Boudjema, J. Fujimoto, T. Ishikawa, T. Kaneko, K. Kato, Y. Shimizu Phys, Rept. **430**, 117 (2006)

Recent results:
Top-pair

Narrow width approx.

Double-pole approx.



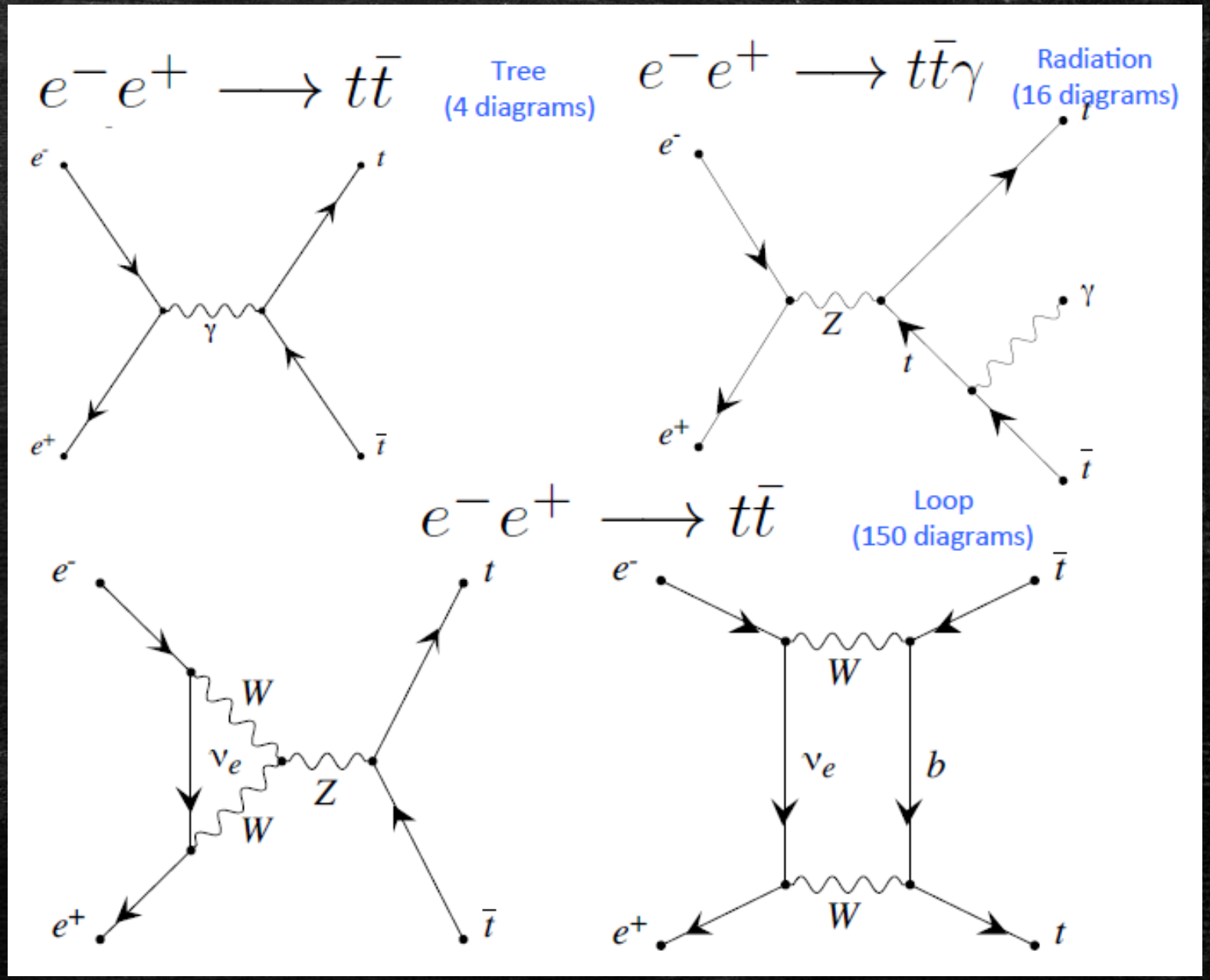
#diagrams
Tree ~ 4
Loop ~ 150

#diagrams
Tree ~ 2
Loop ~ 80

Top-pair: O(α) ELWK corrections

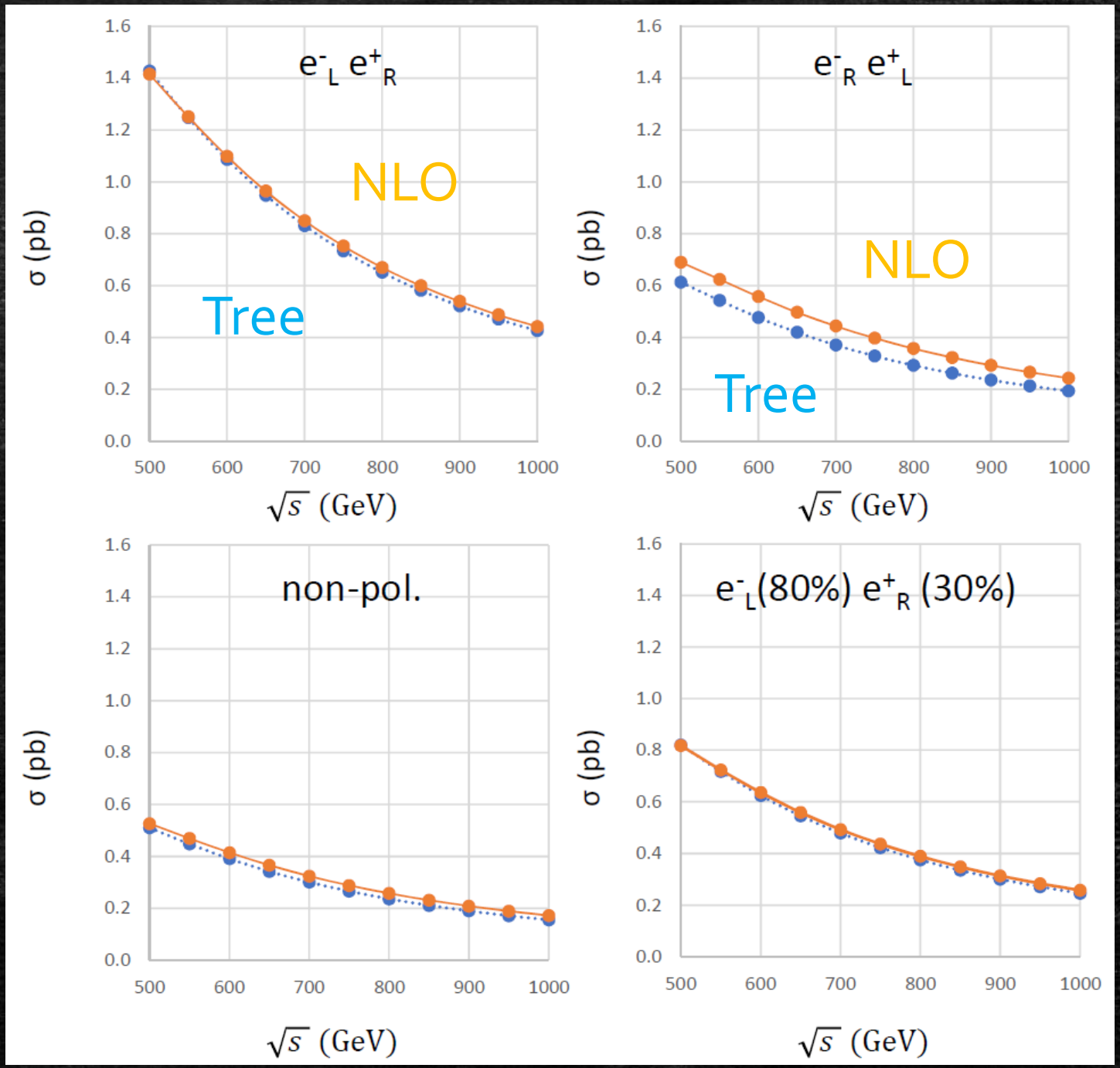
O(α) ELWK correction

Examples of loop diagrams



O(α) ELWK correction

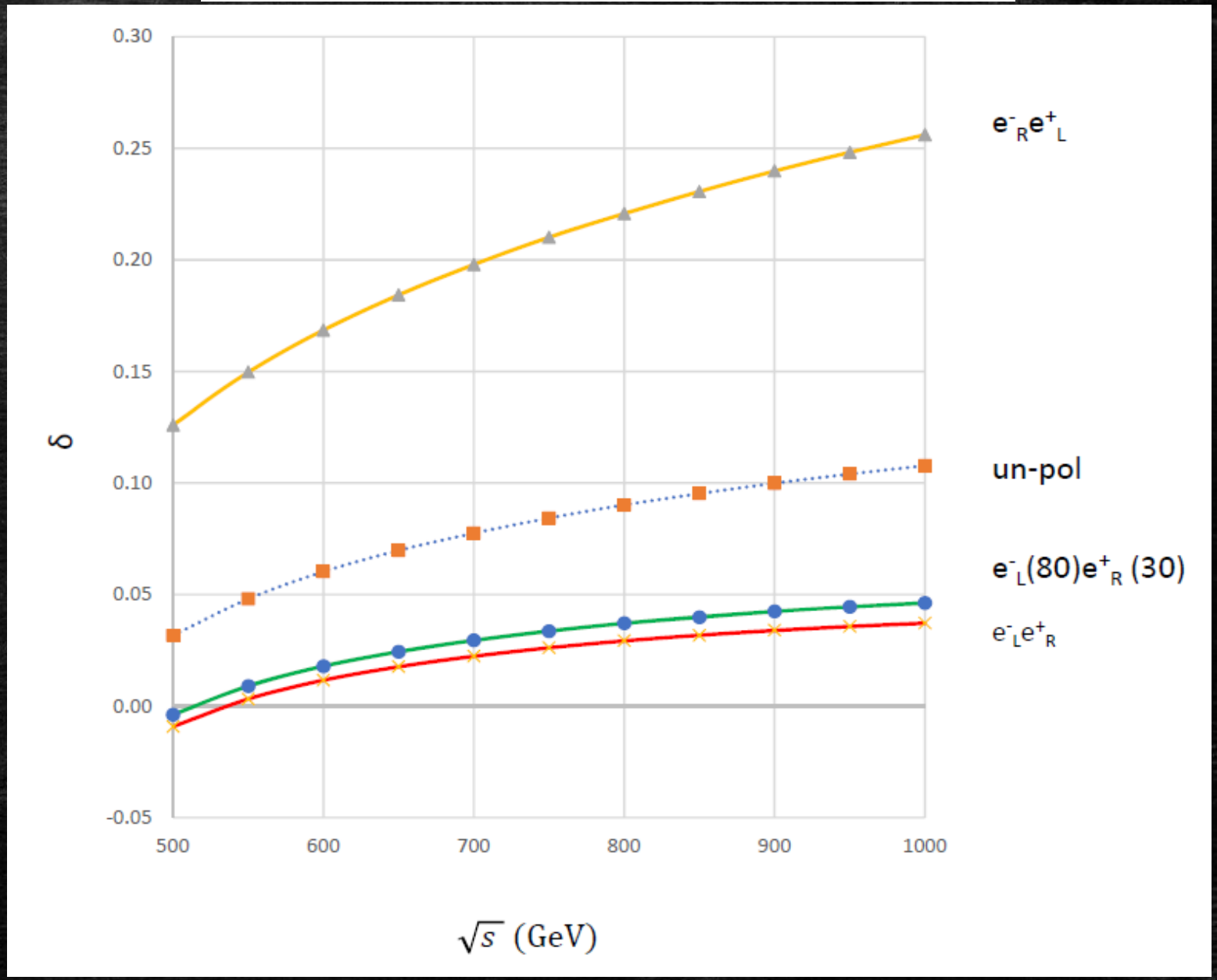
Total cross sections



O(α) ELWK correction

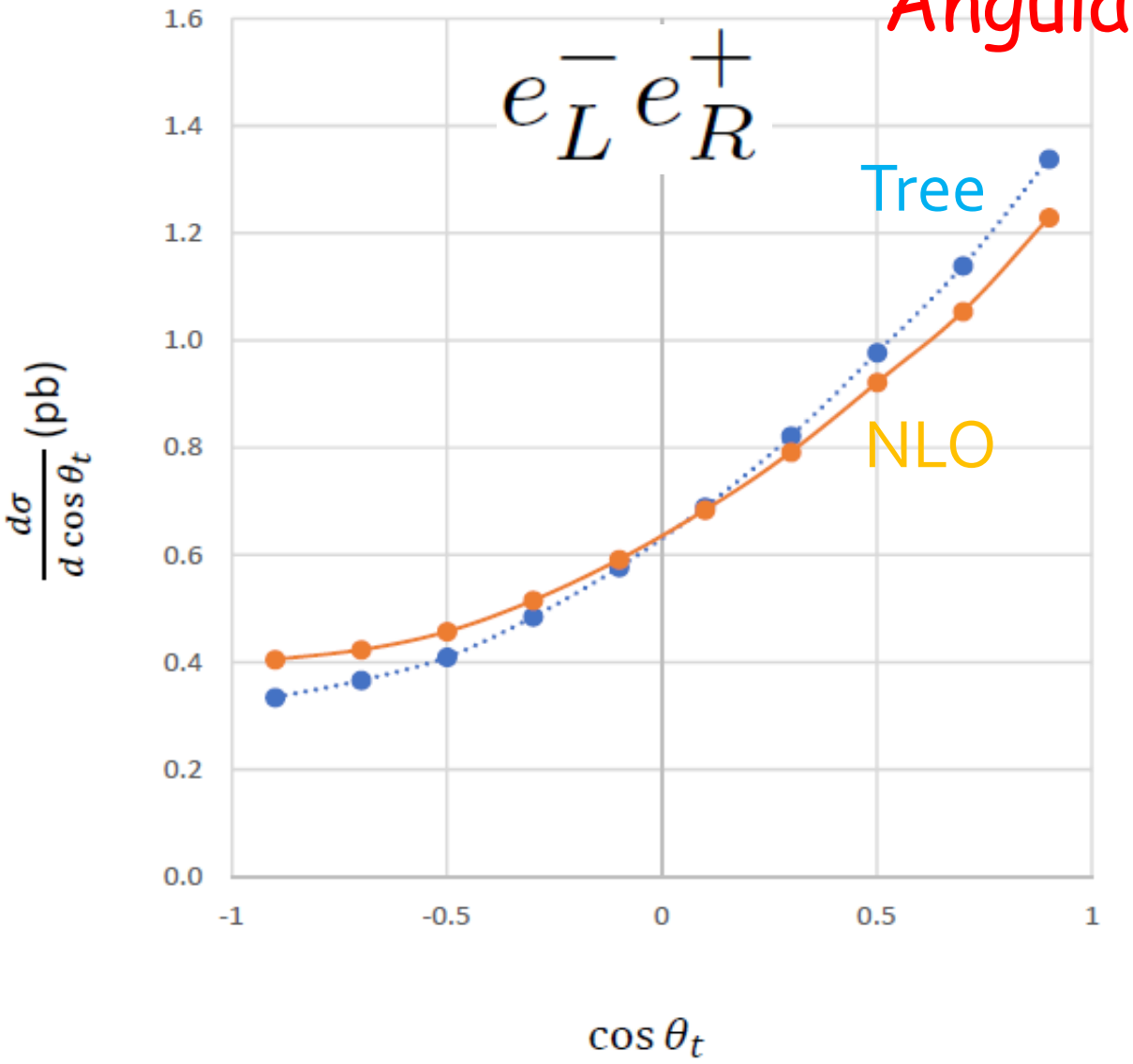
$$\delta = (\sigma_{NLO} - \sigma_{Tree})/\sigma_{Tree}$$

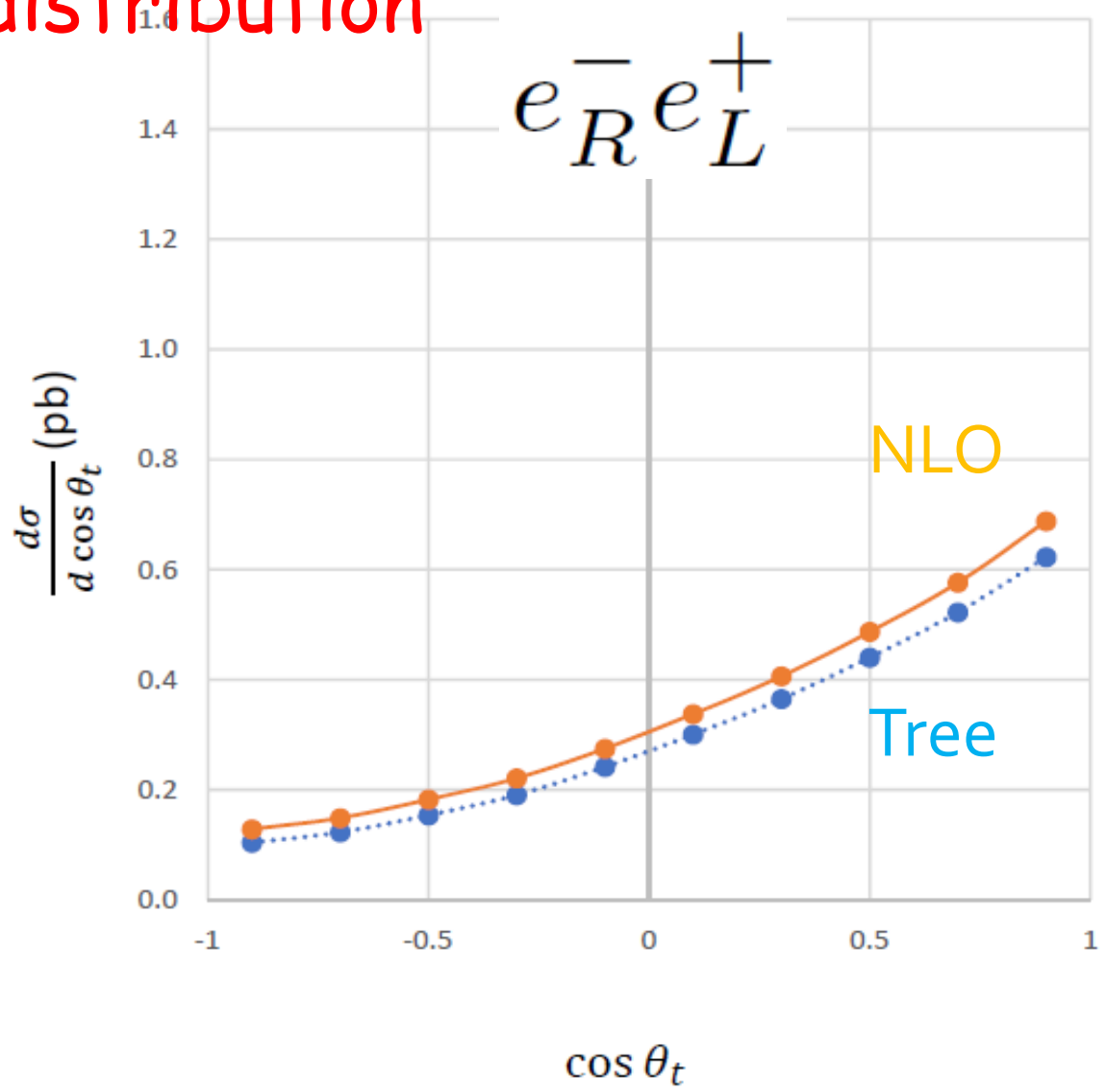
Total cross sections



O(α) ELWK correction

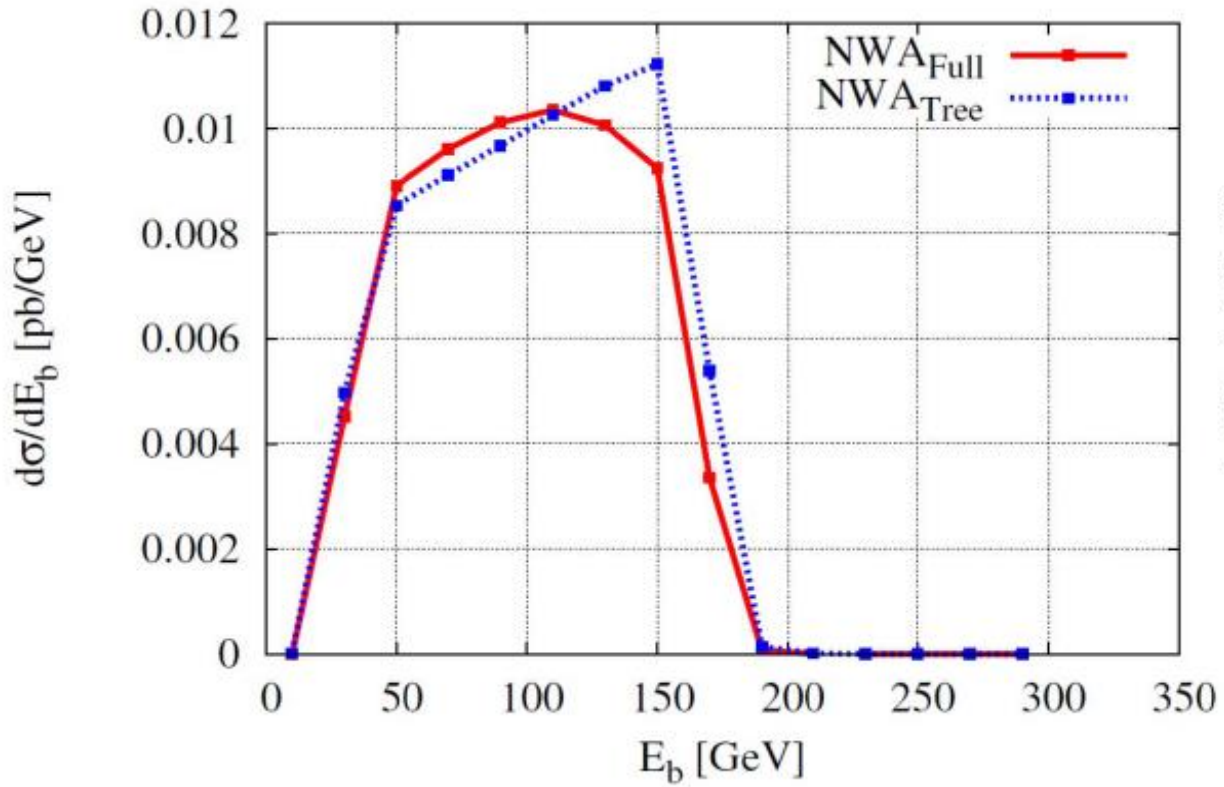
Angular distribution

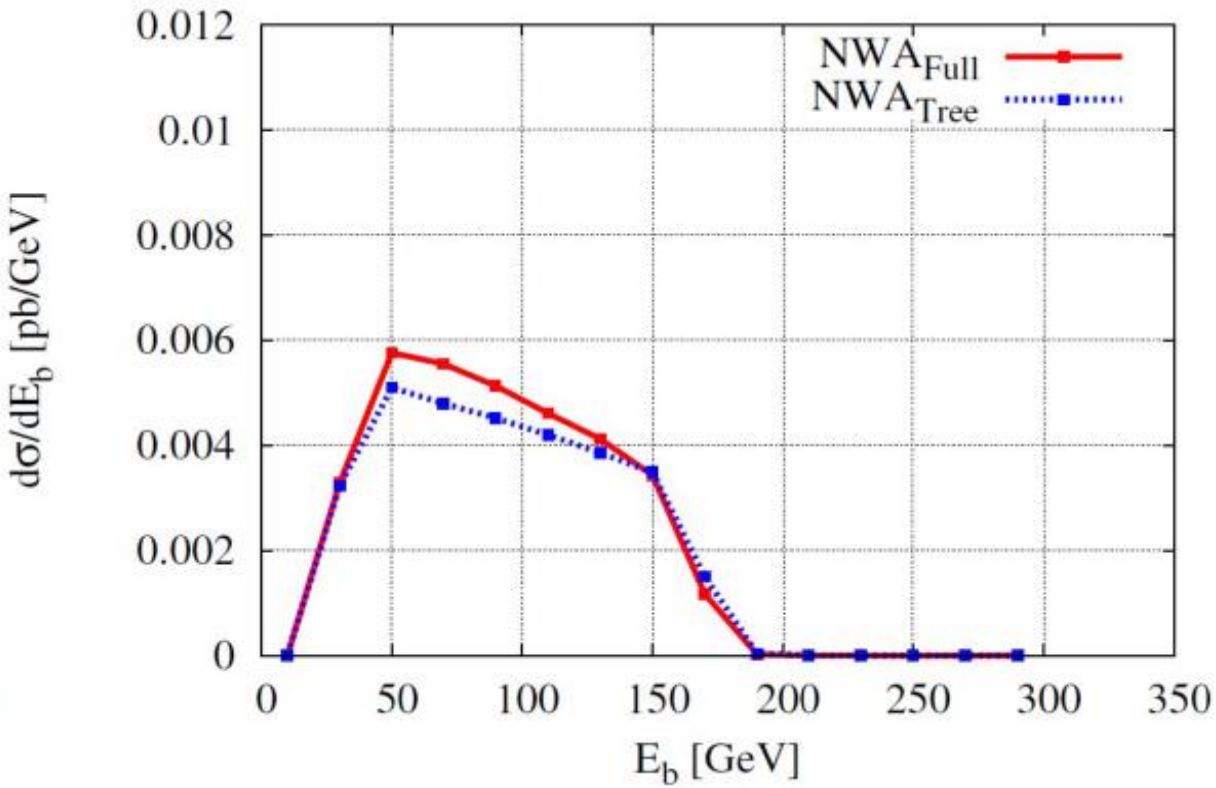




O(α) ELWK correction

$e_L^- e_R^+$ 6-body final process $e_R^- e_L^+$



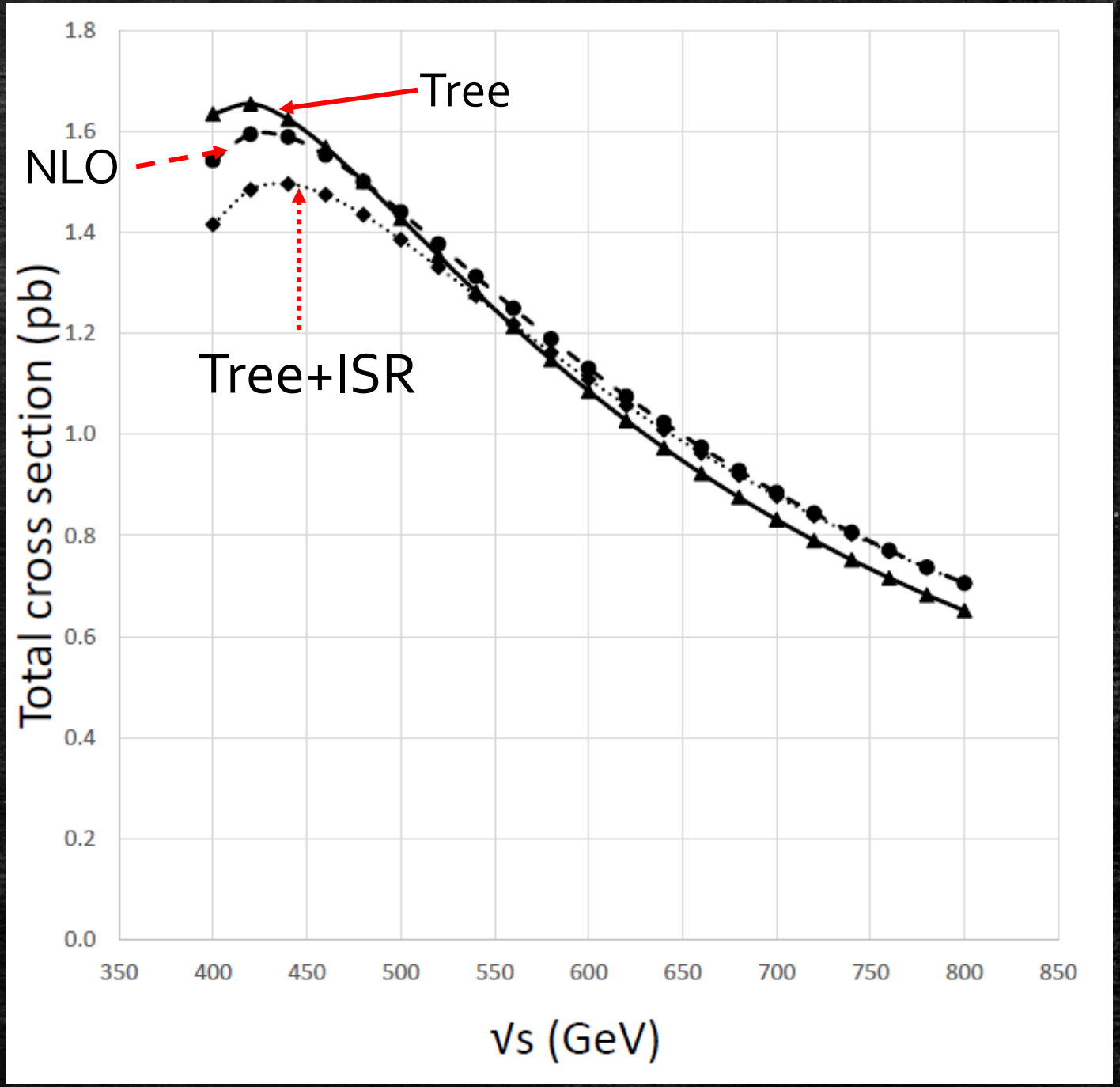


$\bar{b}$-quark energy

Top-pair: ISR re-summation

ISR re-summation

The ISR correction gives a main correction



ISR re-summation

$$\sigma_{NLO;fixed} = \sigma_{Loop} + \sigma_{Soft} + \sigma_{Hard} + \sigma_{Tree}$$

λ (photon mass)

k_c

ISR re-summation

$$\sigma_{NLO;fixed} = \sigma_{Loop} + \sigma_{Soft} + \sigma_{Hard} + \sigma_{Tree}$$

$$\sigma_{NLO;ISR} = (\sigma_{Loop} - \sigma_{Tree}\delta_{ISL}) + \widetilde{\sigma}^{final}_{Soft} + \sigma_{Hard} + \sigma_{ISR}$$

λ
(photon mass)

k_c

ISR re-summation

$$\sigma_{NLO;fixed} = \sigma_{Loop} + \sigma_{Soft} + \sigma_{Hard} + \sigma_{Tree}$$

$$\sigma_{NLO;ISR} = (\sigma_{Loop} - \sigma_{Tree}\delta_{ISL}) + \widetilde{\sigma}^{final}_{Soft} + \sigma_{Hard} + \sigma_{ISR}$$

$$\sigma_{ISR} = \int_0^{k_c^2/s} dx_1 \int_0^{1-x1} dx_2 \; D(x_1,s)D(x_2,s)\sigma_{Tree}(sx_1x_2))$$

ISR re-summation

Radiator

$$D(1-x,s)^2 = H(x,s) = \Delta_2 \beta x^{\beta-1} - \Delta_1 \beta \left(1 - \frac{x}{2}\right) + \frac{\beta^2}{8}\left[-4(2-x)\log x - \frac{1+3(1-x)^2}{x}\log(1-x) - 2x\right]$$

$$\beta = \frac{2\alpha}{\pi}\left(\log\frac{s}{m_e^2} - 1\right),$$

$$\Delta_2 = 1 + \delta_1 + \delta_2, \qquad \Delta_1 = 1 + \delta_1$$

$$\delta_1 = \frac{\alpha}{\pi}\left(\frac{3}{2}L + \frac{\pi^2}{3} - 2\right), \qquad \delta_2 = \left(\frac{\alpha L}{\pi}\right)^2\left(-\frac{1}{18}L + \frac{119}{72} - \frac{\pi^2}{3}\right)$$

ISR re-summation

$$\sigma_{NLO;fixed} = \sigma_{Loop} + \sigma_{Soft} + \sigma_{Hard} + \sigma_{Tree}$$

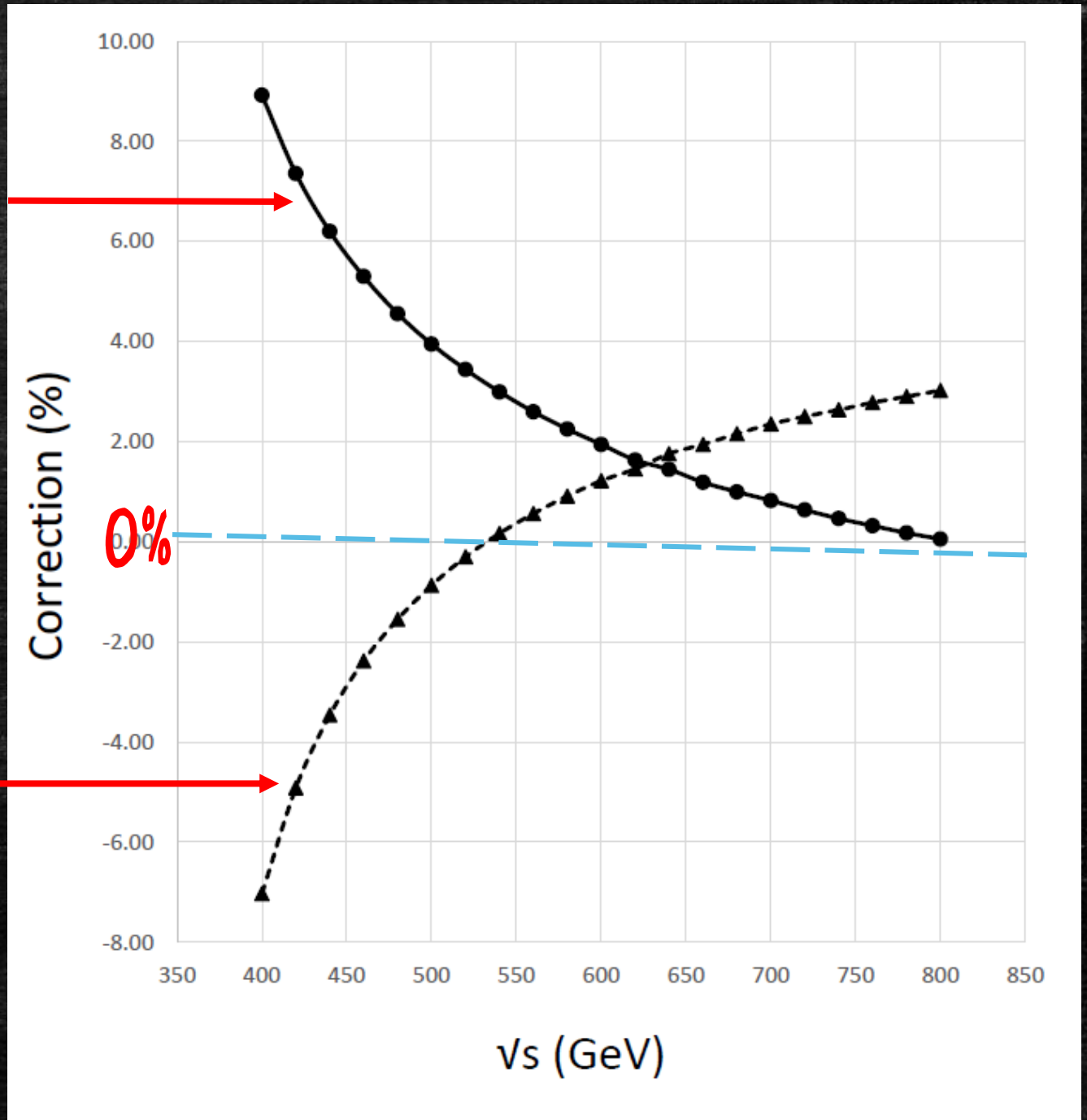
$$\sigma_{NLO;ISR} = (\sigma_{Loop} - \sigma_{Tree}\delta_{ISL}) + \widetilde{\sigma}^{final}_{Soft} + \sigma_{Hard} + \sigma_{ISR}$$

$$\delta_{ISL} = \frac{2\alpha}{\pi}\left(-(L-1)\log\frac{m_e}{\lambda} - \frac{1}{4}L^2 + \frac{3}{4}L + \frac{\pi^2}{3} - 1\right)$$

ISR re-summation

$$\delta_{weak} = \frac{\sigma_{NLO;ISR} - \sigma_{ISR}}{\sigma_{ISR}}$$

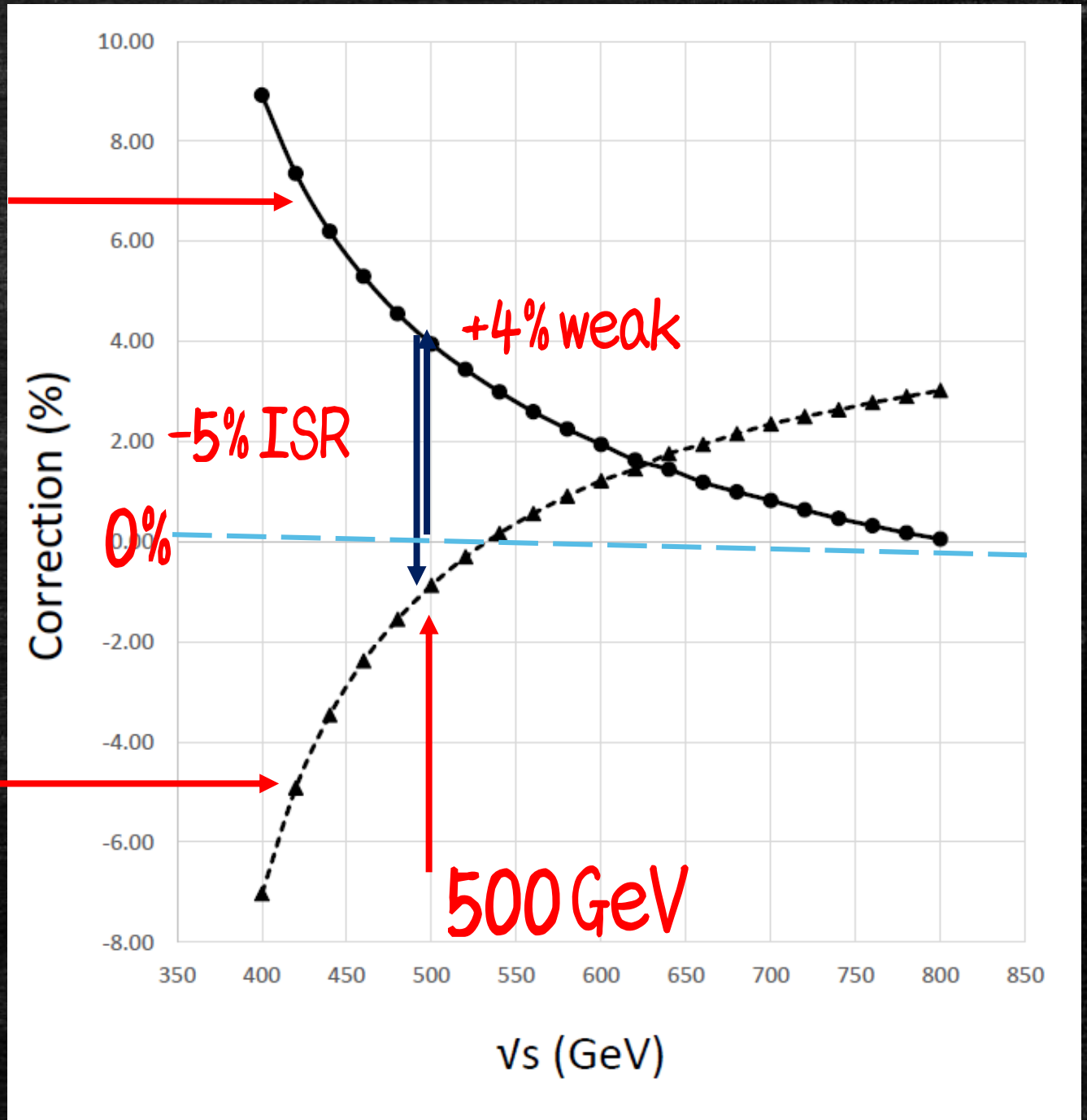
$$\delta_{NLO} = \frac{\sigma_{NLO;fixed} - \sigma_{Tree}}{\sigma_{Tree}}$$



ISR re-summation

$$\delta_{weak} = \frac{\sigma_{NLO;ISR} - \sigma_{ISR}}{\sigma_{ISR}}$$

$$\delta_{NLO} = \frac{\sigma_{NLO;fixed} - \sigma_{Tree}}{\sigma_{Tree}}$$



ISR re-summation

Improved Born

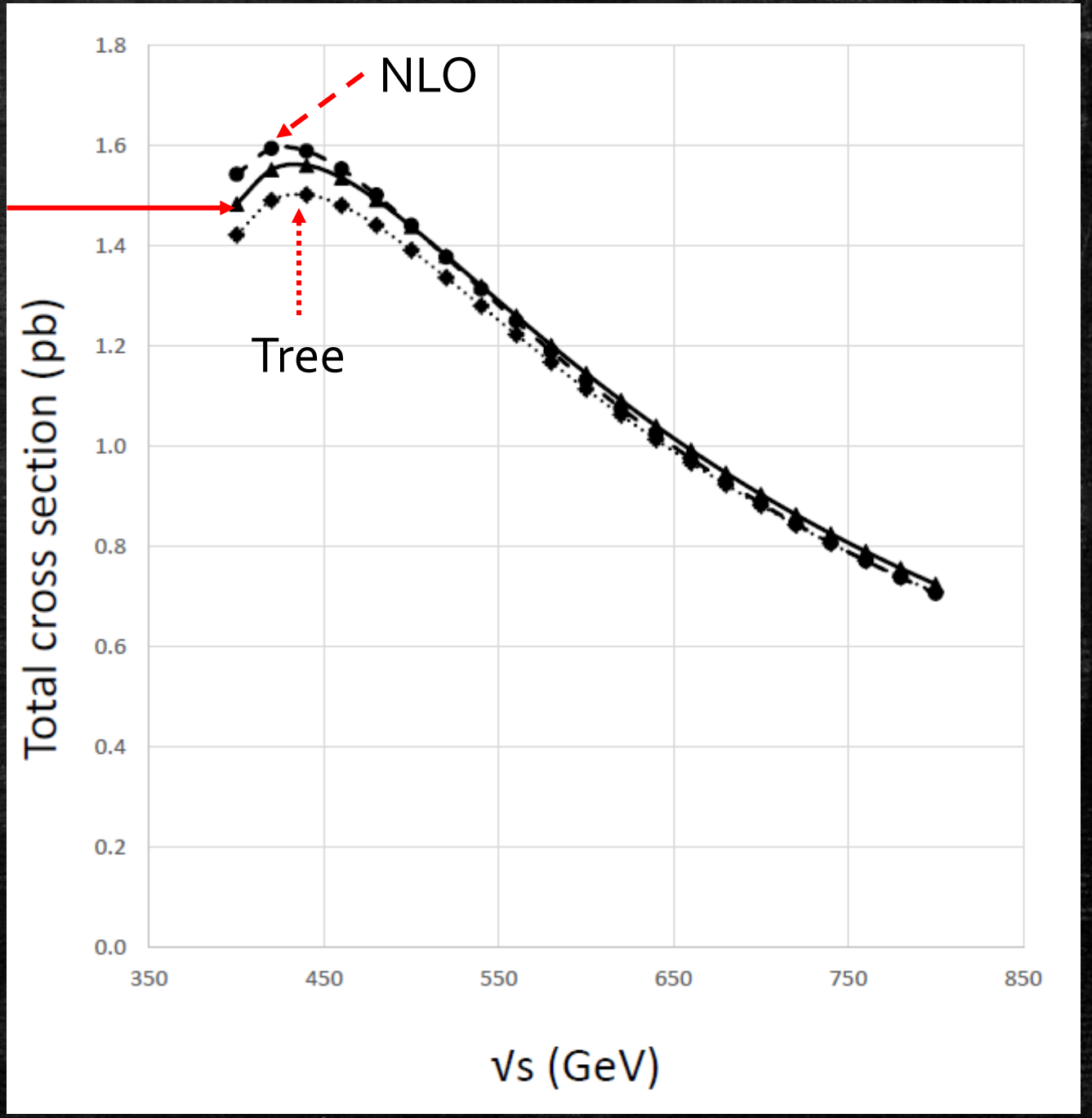
$$\sigma_{imp} = \int_0^1 dx_1 \int_0^{1-x_1} dx_2 \; D(x_1,s)D(x_2,s)$$

$$\sigma_{Tree}\left(\alpha\left(sx_1x_2\right); sx_1x_2\right)$$

$$\alpha\left(|q^2|\right) = \frac{\alpha\left(\mu^2\right)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log\left(\frac{|q^2|}{\mu^2}\right)}$$

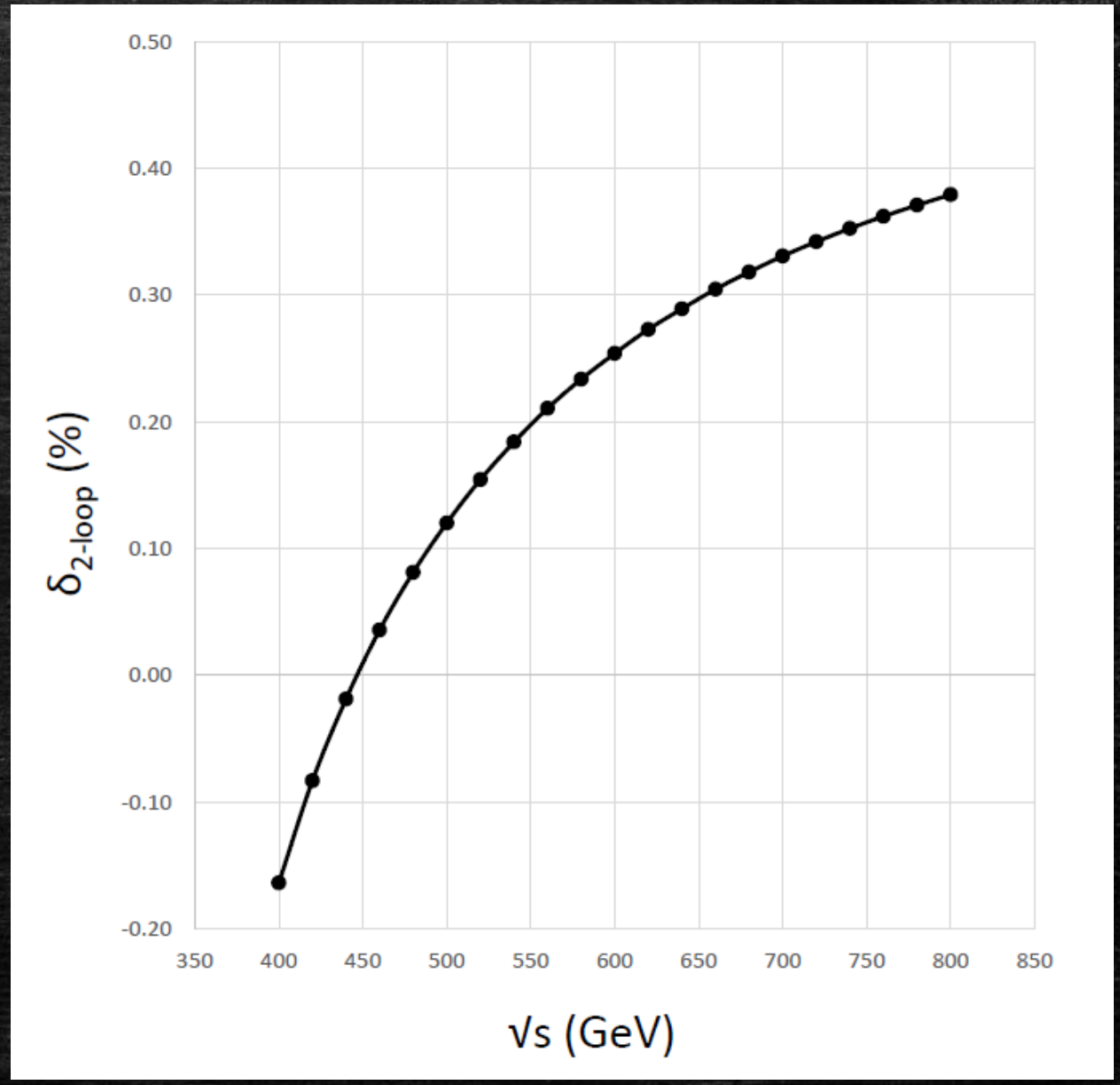
$$\sin^2\theta_W = \frac{\pi\alpha\left(|q^2|\right)}{\sqrt{2}G_F m_W^2}$$

Improved Born



ISR re-summation

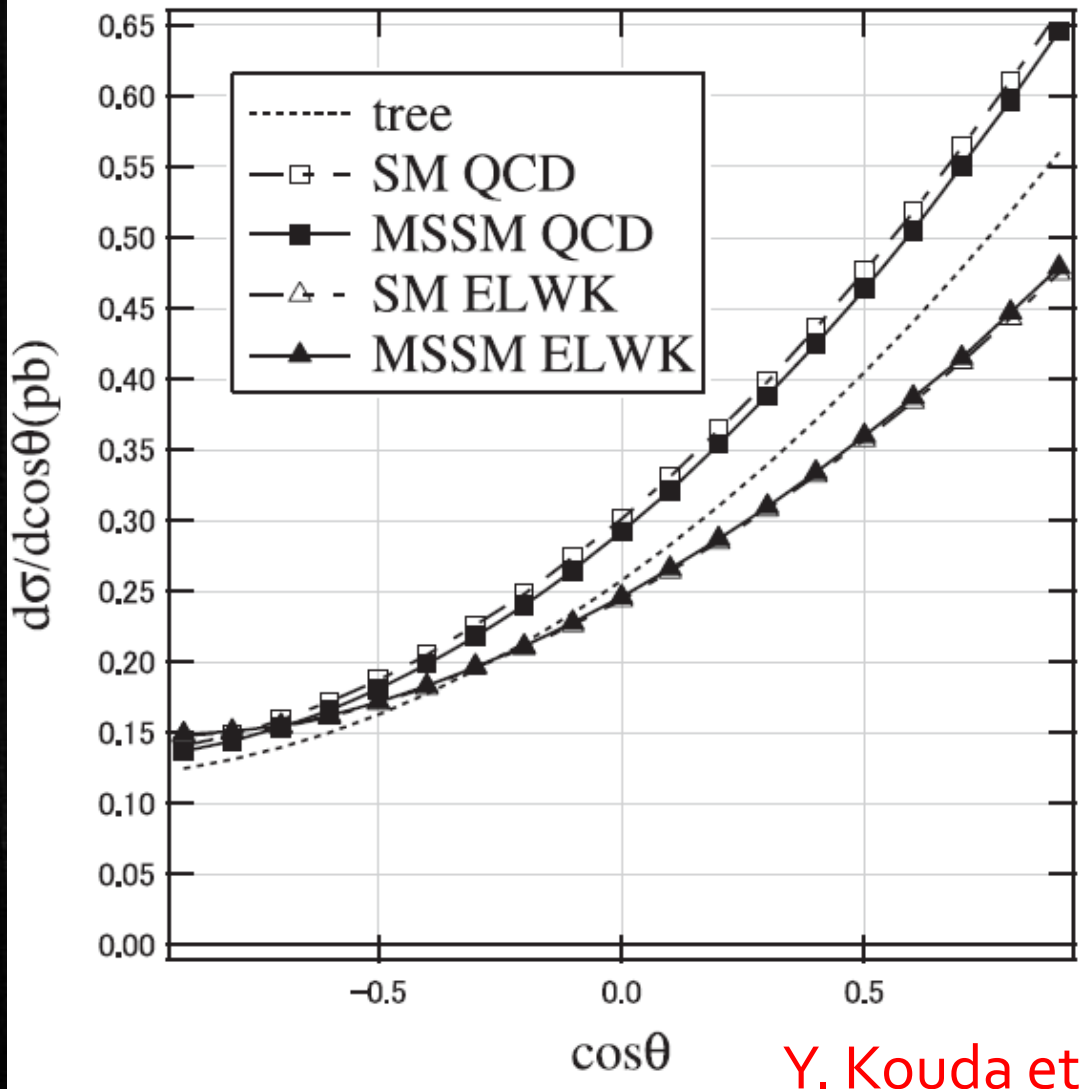
$$\delta_{2-loop} = \frac{\sigma_{ISR} - \sigma_{ISR}^{(1)}}{\sigma_{ISR}^{(1)}}$$

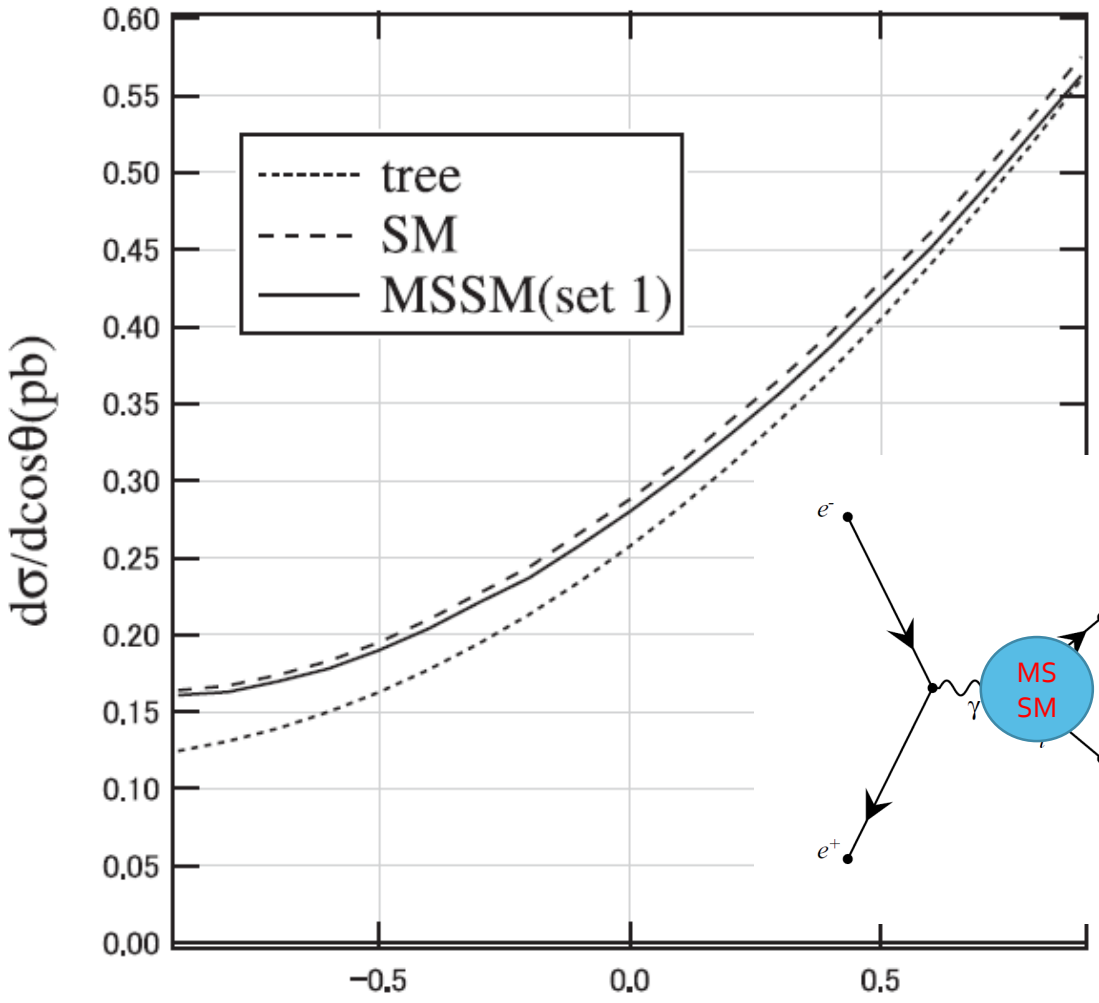


Top-pair: MSSM

MSSM

$\sqrt{s}$=500GeV no beam polarization





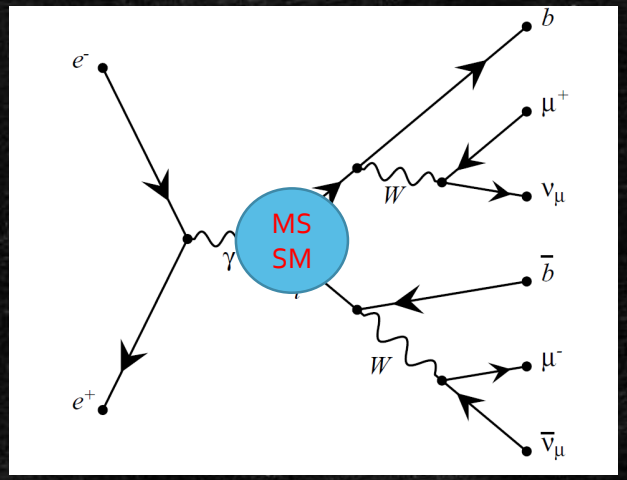
Y. Kouda et al, PTEP (2017) 053B02

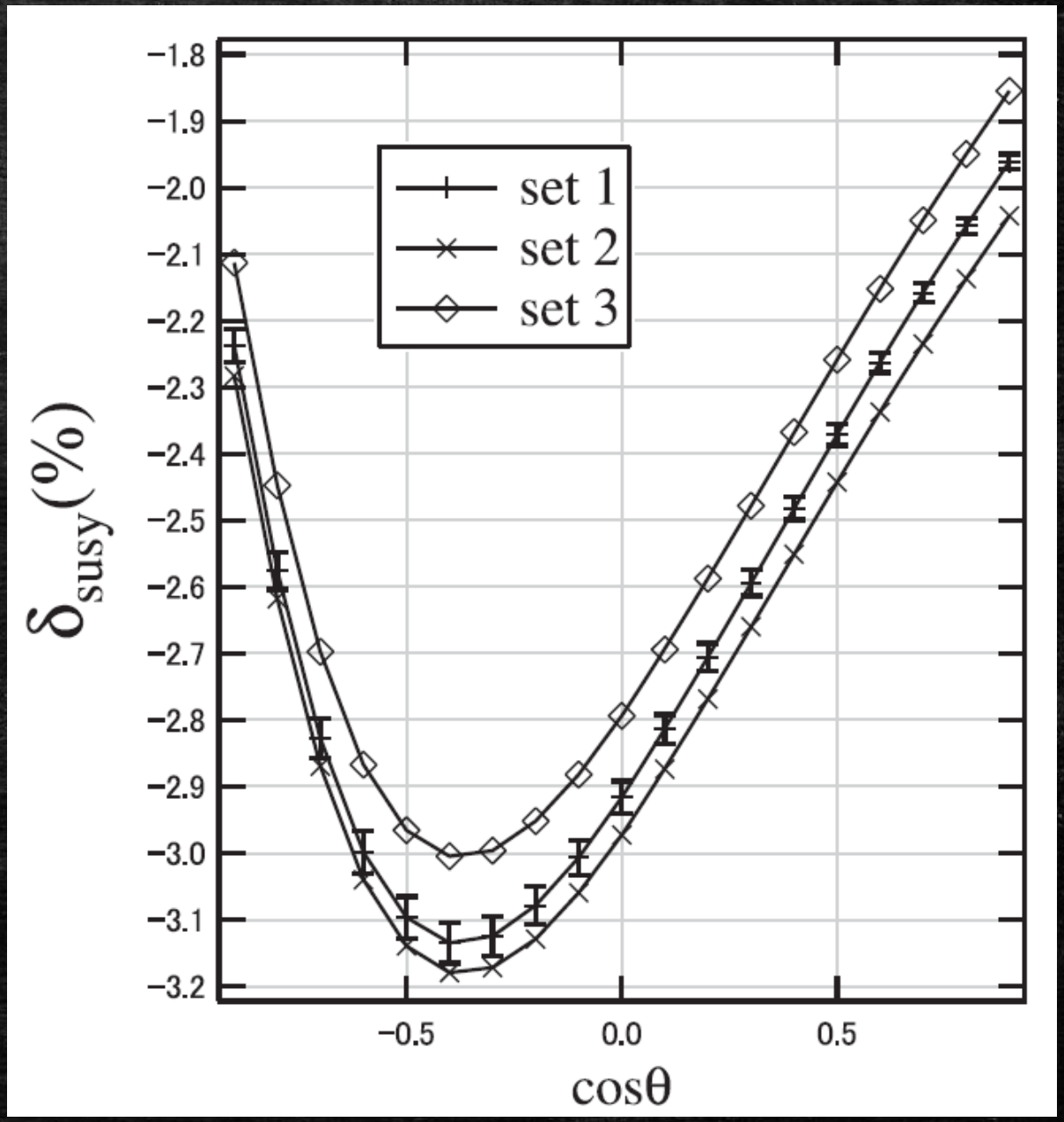
MSSM

$\sqrt{s}$=500GeV no beam polarization

$$\delta^{G}_{susy} \equiv \frac{d\sigma^{MSSM,G}_{1loop} - d\sigma^{SM,G}_{1loop}}{d\sigma_{tree}}$$

G = (ELWK or QCD)

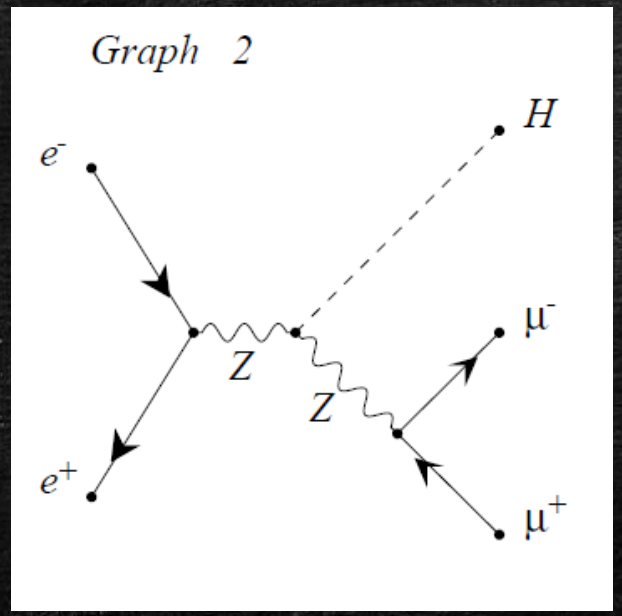


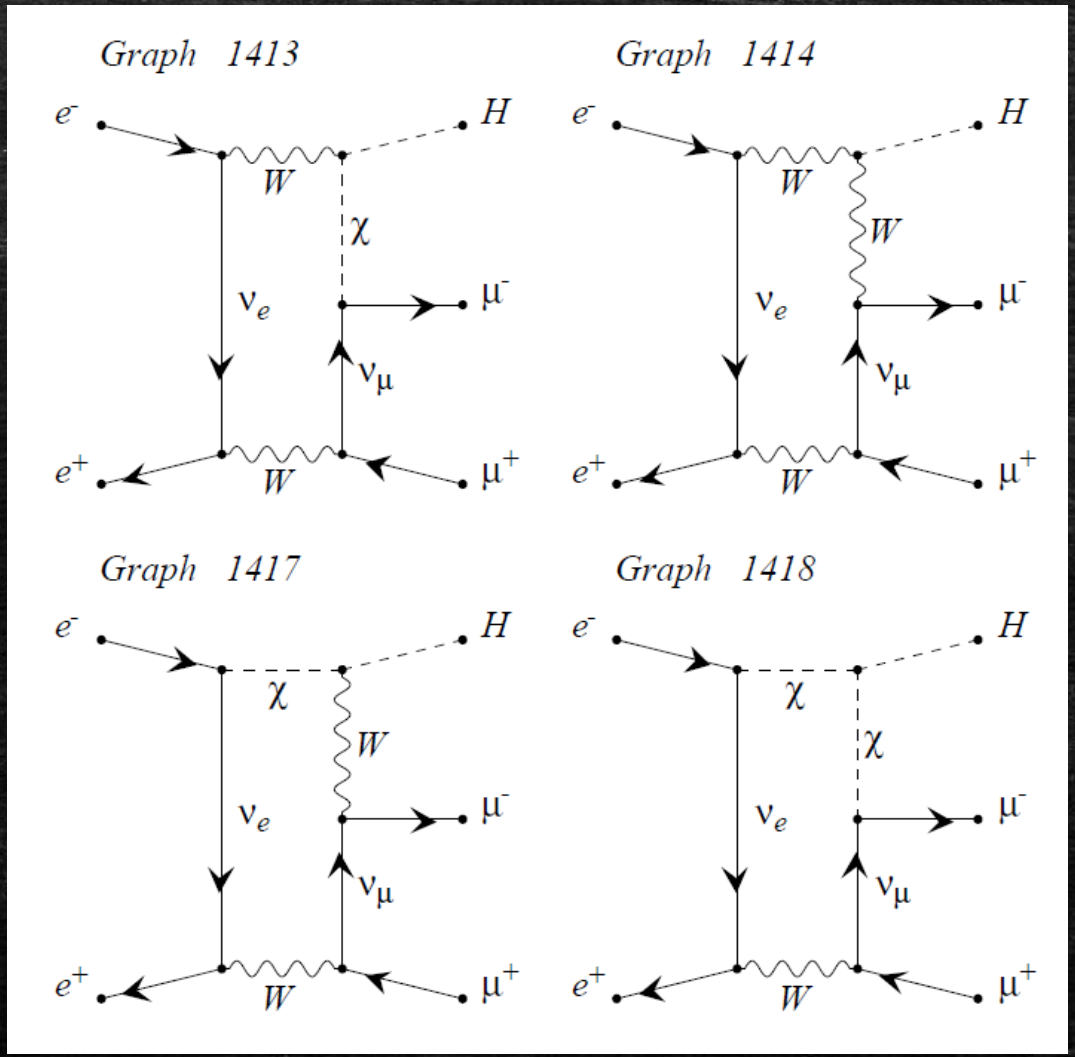


Y. Kouda et al, PTEP (2017) 053B02

Recent results: Higgs productions

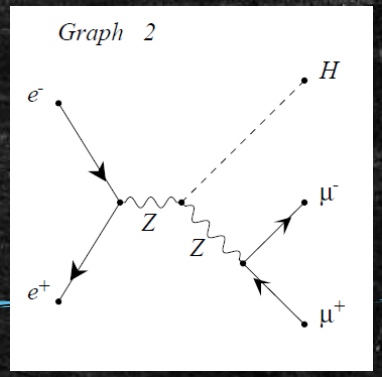
Recent results: $e^+e^- \to H\mu^+\mu^-$



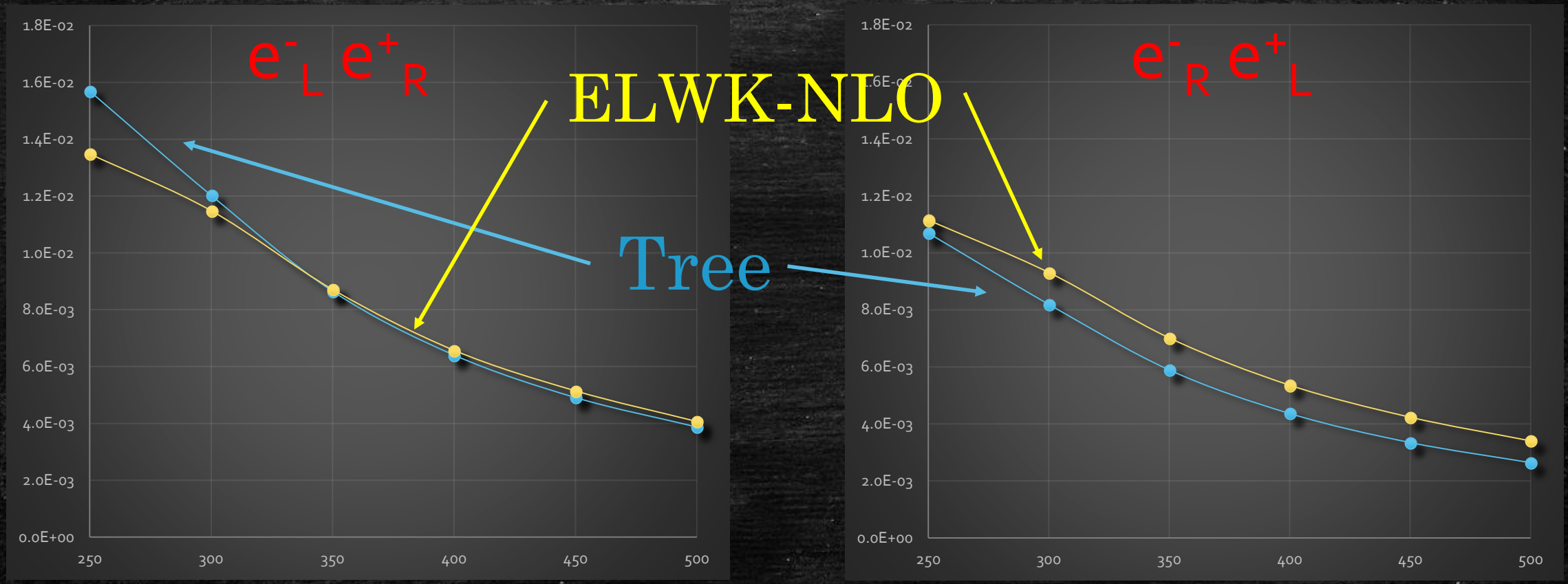


2235 loop diagrams

Recent results: $e^+e^- \rightarrow H\mu^+\mu^-$



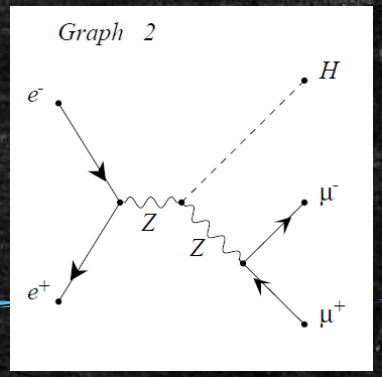
Cross section (pb)



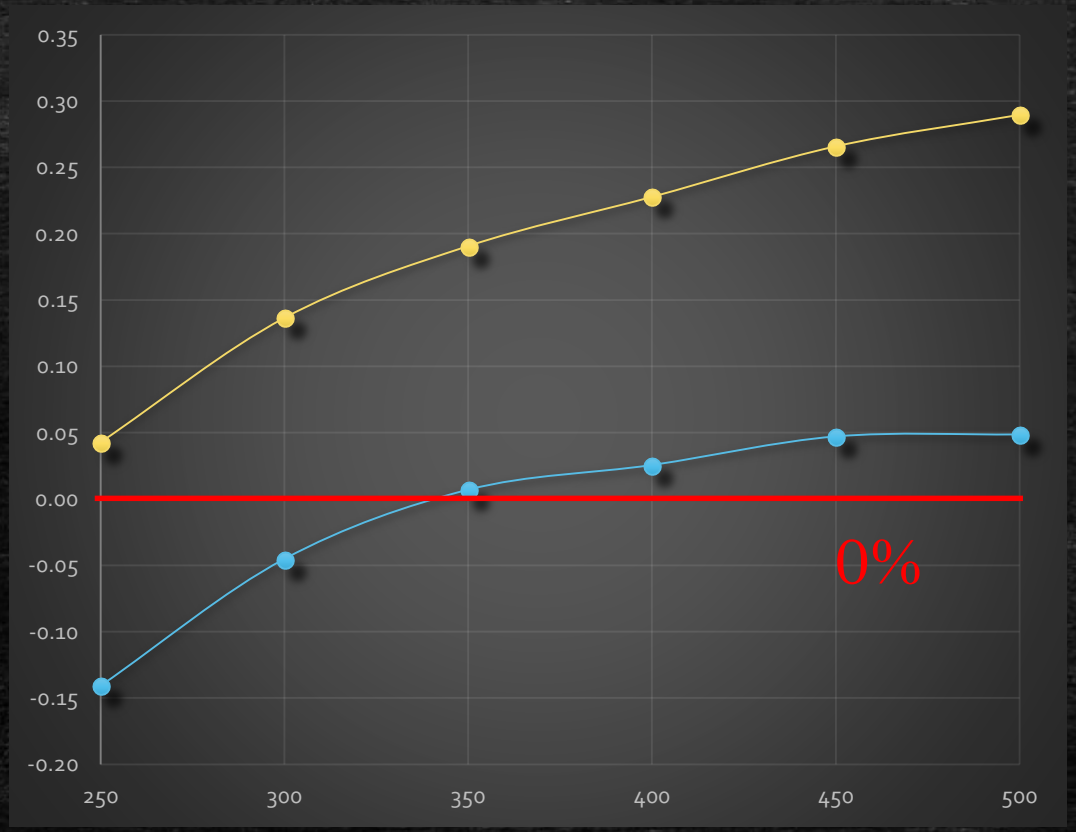
√s GeV

√s GeV

Recent results: $e^+e^- \rightarrow H\mu^+\mu^-$



$\delta_{NLO}=(\sigma_{NLO}-\sigma_{Tree})/(\sigma_{NLO}+\sigma_{Tree})$



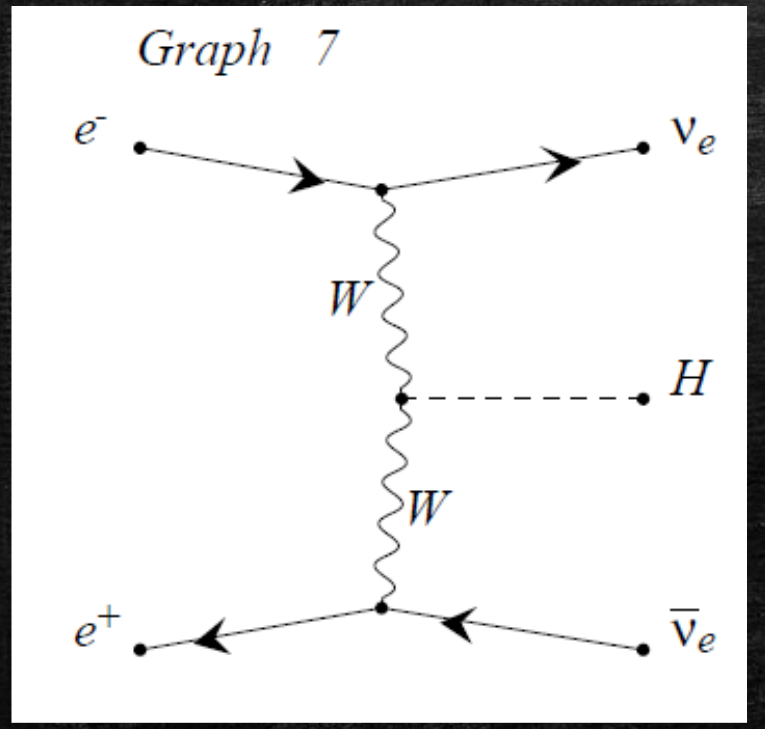
δ_{NLO}

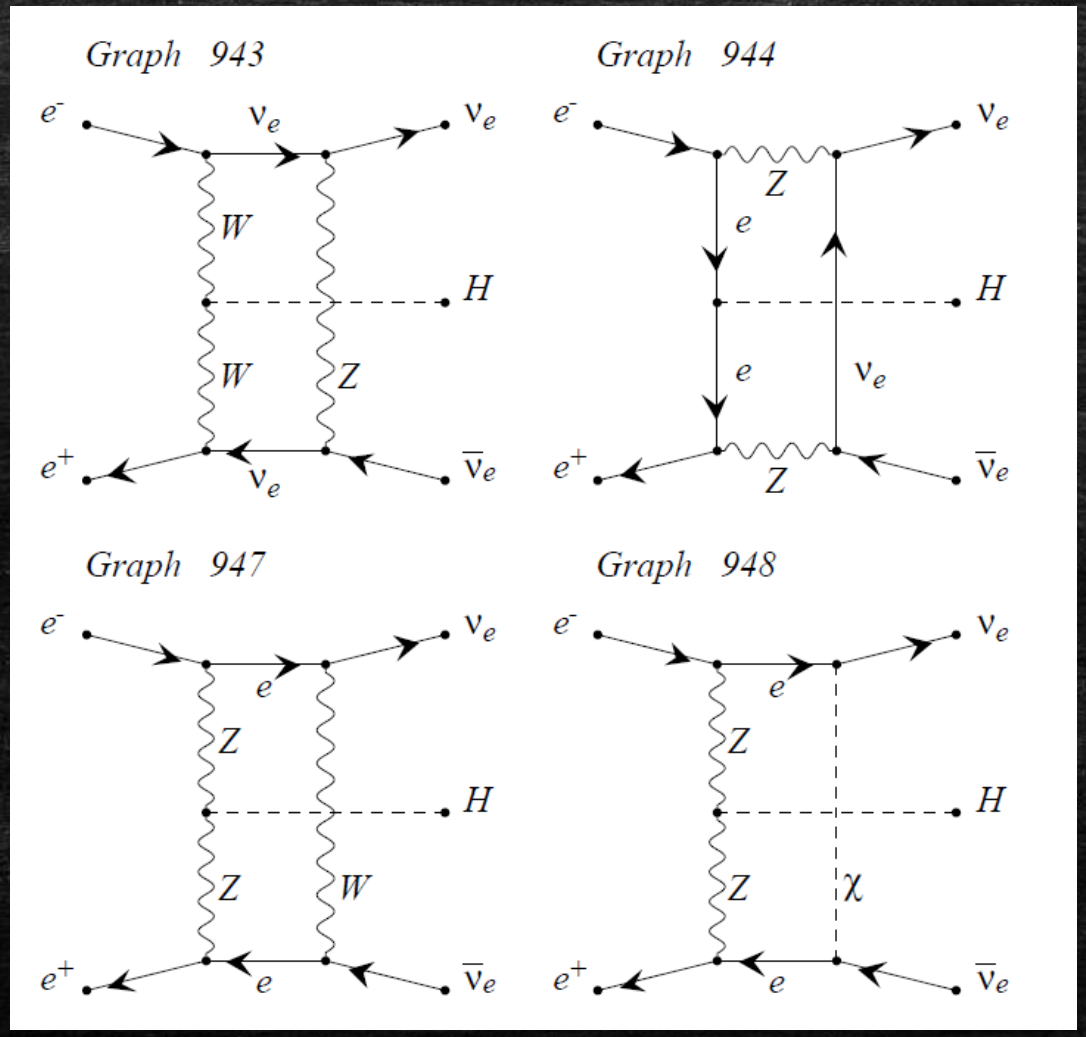
$e^-_R e^+_L$

$e^-_L e^+_R$

$\sqrt{s}$ GeV

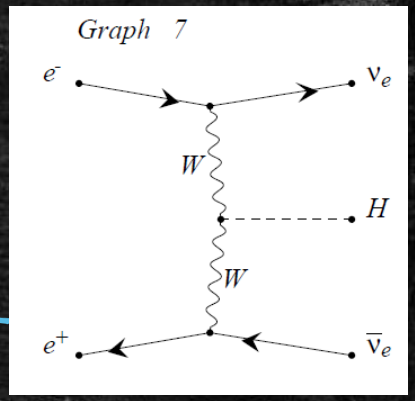
Recent results: $e^+e^- \to H\bar{\nu}_e\,\nu_e$



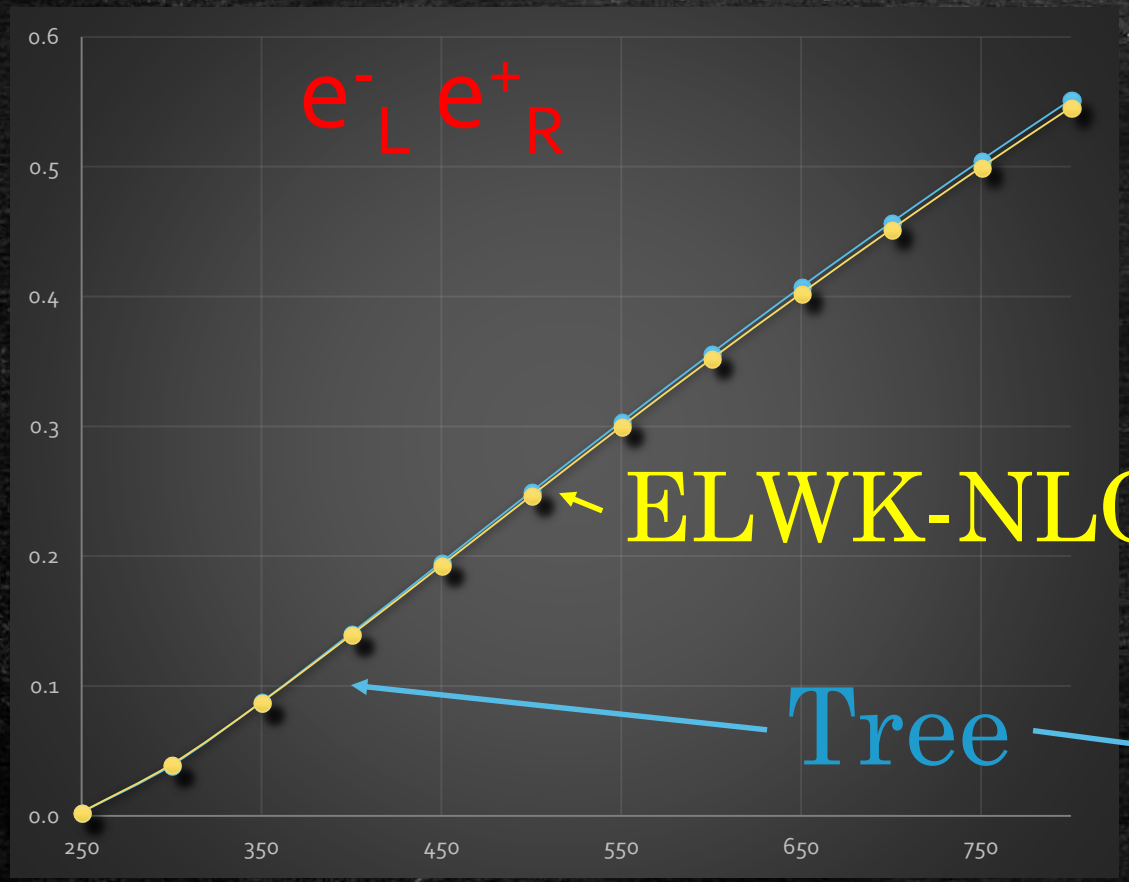


1350 loop diagrams

Recent results: $e^+e^- \to H\bar{\nu}_e \nu_e$

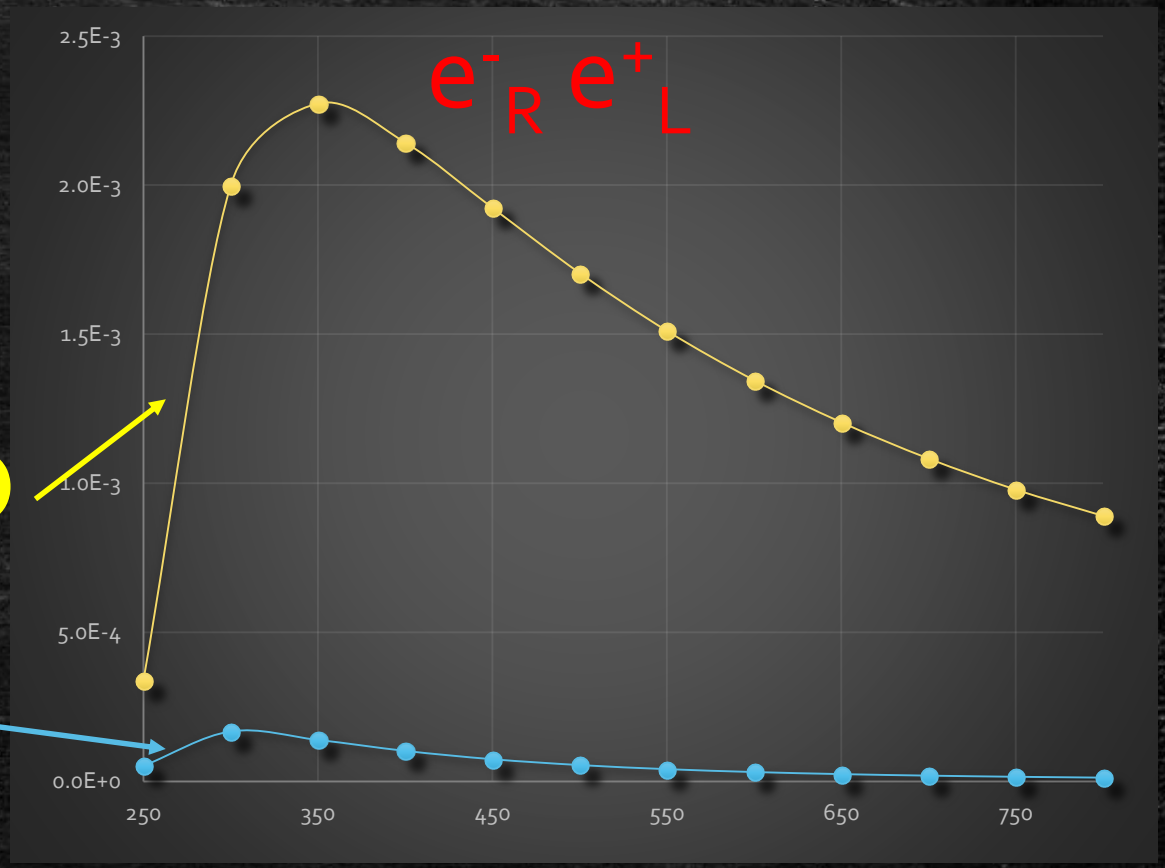


Cross section (pb)



ELWK-NLO

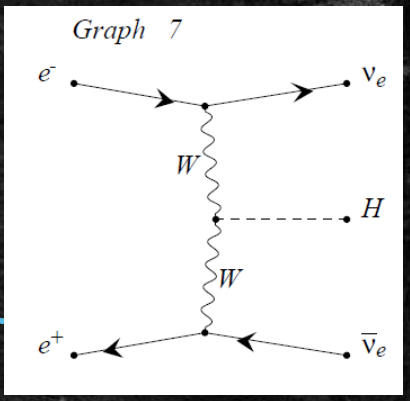
Tree

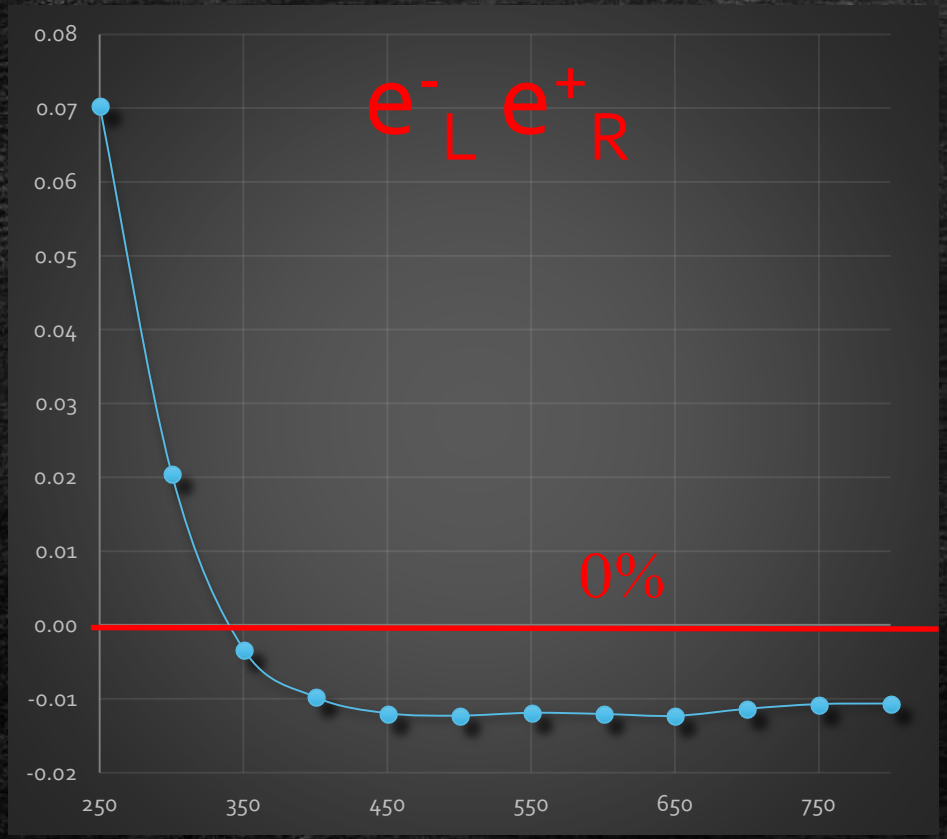


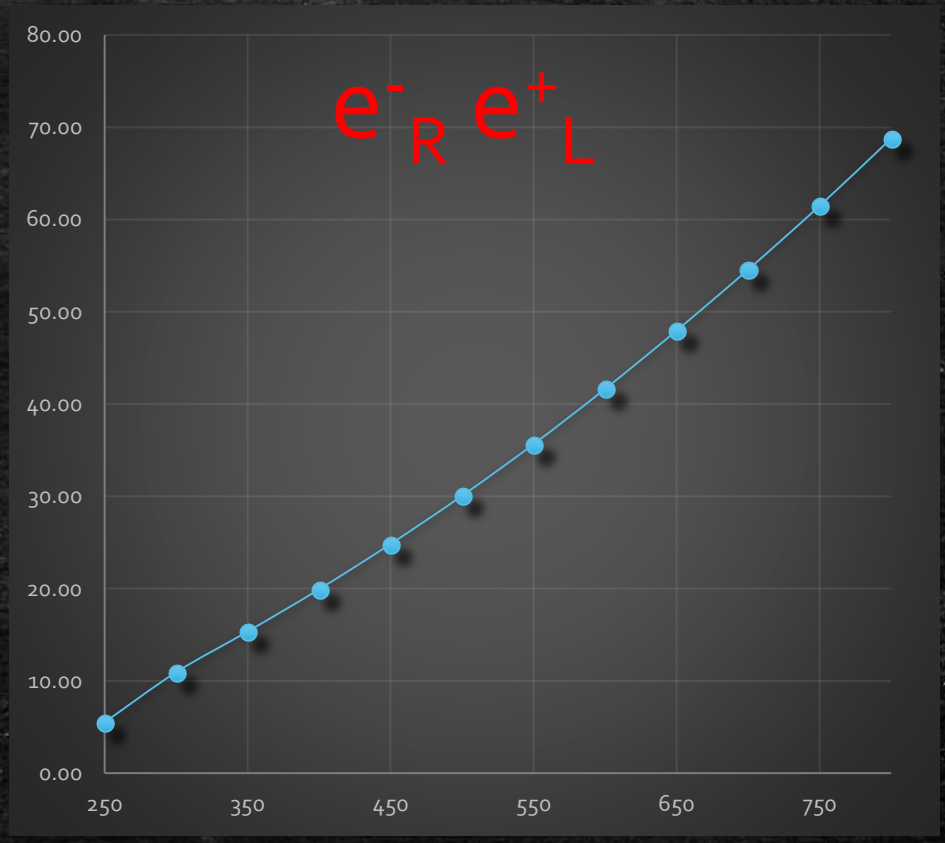
√s GeV

√s GeV

Recent results: $e^+e^- \to H\bar{\nu}_e \nu_e$







Summary

Summary:

.What is GRACE system?

.Full O(α) electroweak corrections on SM/MSSM w/ Beam pol.

.Recent results:

.$e^+e^- \to t\bar{t} \to bbffff$ x $\not{p}$'s

.Z-Higgs production / W-fusion

Goal: Precision Control ≈ 0.1% @ ILC energies

BP

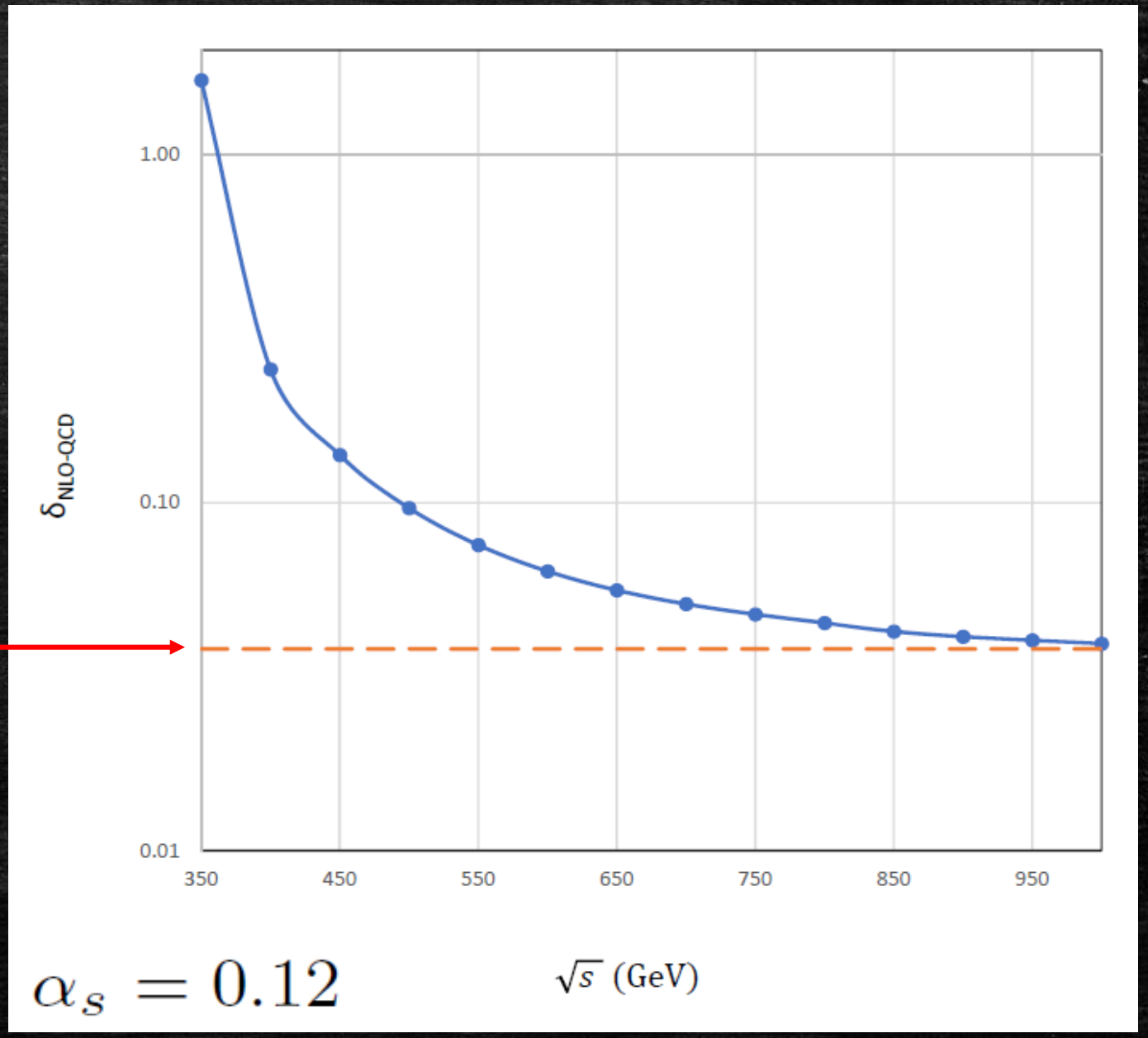
Set 1				Set 2				Set 3			
$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$			$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$			$\tilde{\chi}_1^+$	$\tilde{\chi}_2^+$		
419.9	620.5			508.1	636.8			467.5	626.7		
$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_4^0$
218.4	420.0	603.7	620.2	277.9	508.5	603.4	637.1	242.8	467.6	603.6	626.7
$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$		$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$		$\tilde{\ell}_1$	$\tilde{\ell}_2$	$\tilde{\nu}_\ell$	
352.5	358.0	349.4		317.8	323.3	313.8		322.8	328.3	318.9	
$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$		$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$		$\tilde{\tau}_1$	$\tilde{\tau}_2$	$\tilde{\nu}_\tau$	
228.4	336.3	277.9		283.9	377.1	327.4		320.1	405.3	359.6	
$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{d}_1$	$\tilde{d}_2$
1719	1739	1740	1740	1720	1739	1740	1741	1720	1739	1740	1741
$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$	$\tilde{t}_1$	$\tilde{t}_2$	$\tilde{b}_1$	$\tilde{b}_2$
344.0	2078	899.9	2060.9	1802	2244	1998	2063	279.6	2078	800.0	2061
θ_τ	θ_b	θ_t		θ_τ	θ_b	θ_t		θ_τ	θ_b	θ_t	
0.7970	1.556	1.4502		0.8150	1.376	0.8533		0.8175	1.557	1.456	
M_1	M_2	M_3		M_1	M_2	M_3		M_1	M_2	M_3	
220.0	435.0	2000		280.0	540.0	1500		244.5	489.0	2000	
$\mu = 600, \quad \tan\beta = 30$				$\mu = 600, \quad \tan\beta = 30$				$\mu = 600, \quad \tan\beta = 30$			

QCD corrections

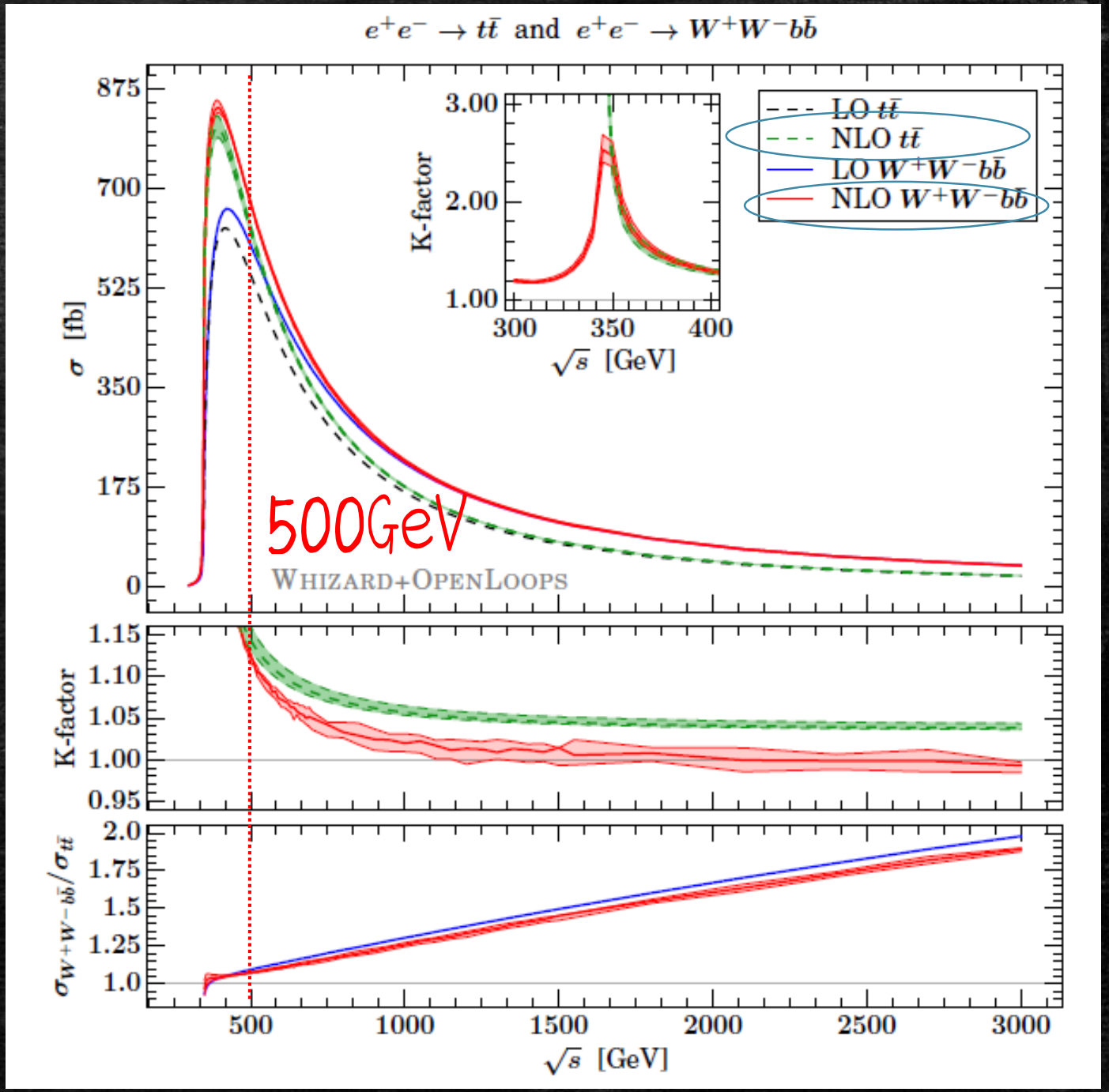
QCD Correction

Total cross sections w/ a QCD correction on a t-pair production only

$$\alpha_s/\pi \simeq 3.8\%$$



NLO QCD correction w/ double-pole approx.



B.C. Nejad, et al., JHEP12 (2016) 075

NLO QCD correction w/ double-pole approx.

	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2	$320.7^{+1.1\%}_{-0.7\%}$	1.03
1000	166.4	$175.9^{+0.7\%}_{-0.3\%}$	1.06	217.2	$221.6^{+1.1\%}_{-1.0\%}$	1.02
1400	86.62	$90.66^{+0.6\%}_{-0.2\%}$	1.05	126.4	$127.9^{+0.7\%}_{-1.5\%}$	1.01
3000	19.14	$19.87^{+0.5\%}_{-0.2\%}$	1.04	37.89	$37.63^{+0.4\%}_{-0.9\%}$	0.993

		$\sqrt{s} = 800$ GeV			$\sqrt{s} = 1500$ GeV		
$P(e^-)$	$P(e^+)$	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
0%	0%	253.7	272.8	1.075	75.8	79.4	1.049
−80%	0%	176.5	190.0	1.077	98.3	103.1	1.049
80%	0%	176.5	190.0	1.077	53.2	55.9	1.049
−80%	30%	420.8	452.2	1.074	124.9	131.0	1.048
−80%	60%	510.7	548.7	1.074	151.6	158.9	1.048
80%	−30%	208.4	224.5	1.077	63.0	66.1	1.049
80%	−60%	240.3	258.9	1.077	72.7	76.3	1.049

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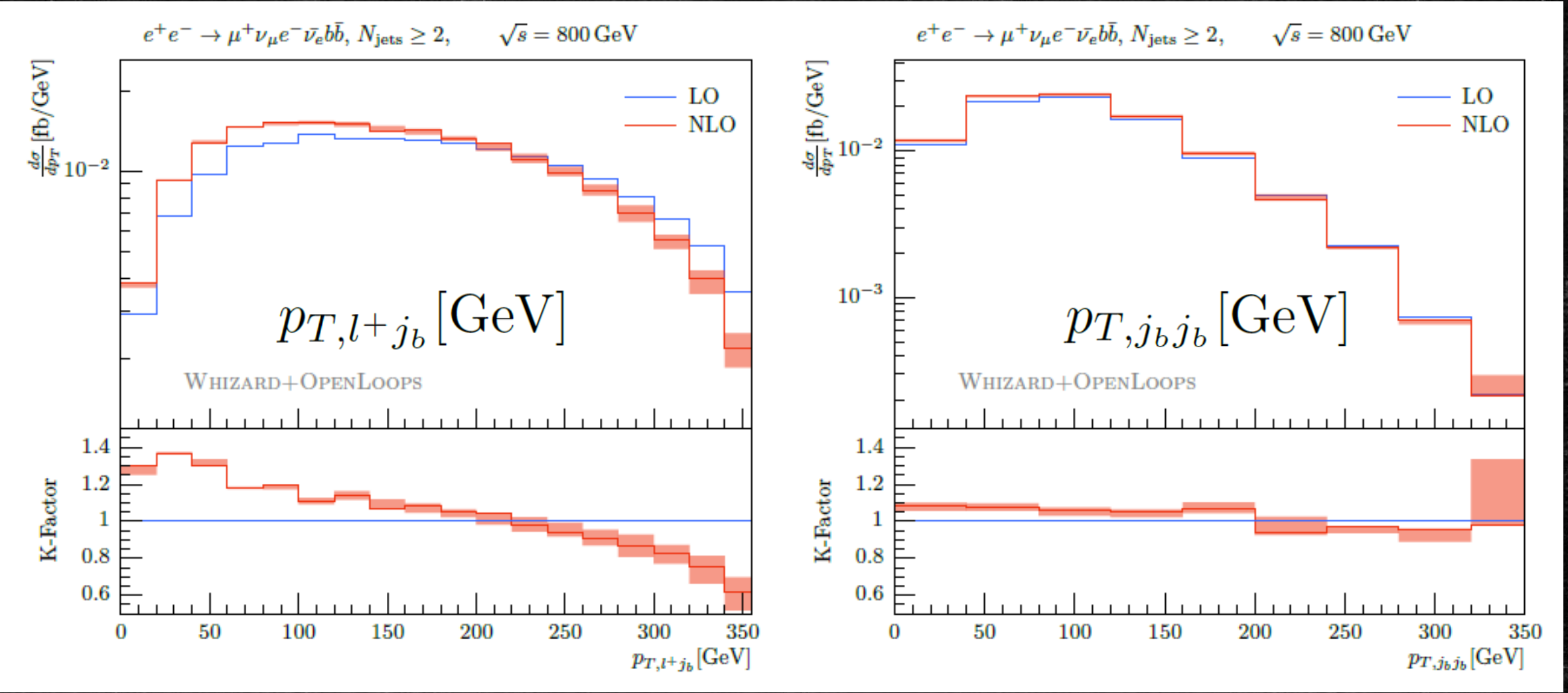
NLO QCD correction w/ double-pole approx.



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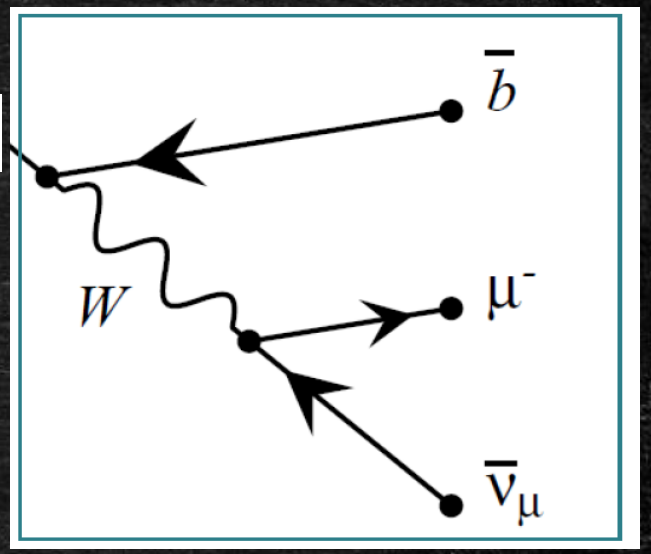
NLO QCD correction for top decay

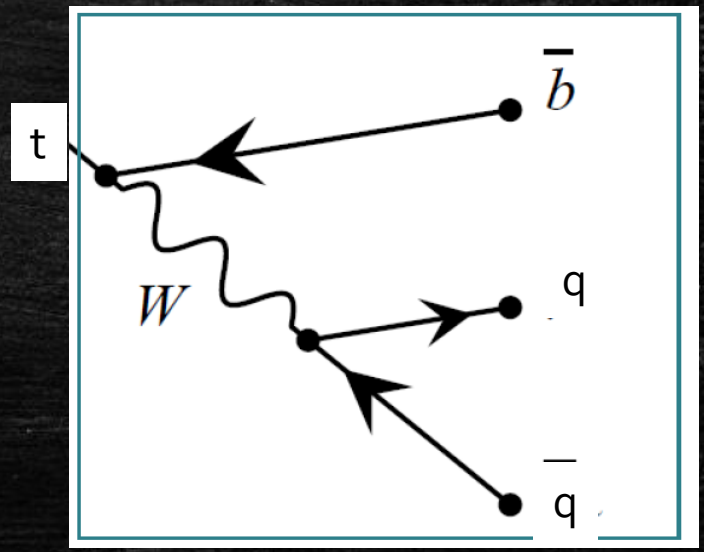
Semi leptonic

	OCSM
$\Gamma^{(0)}_{\text{lept}}$ / GeV	0.1610645(3)
$\delta^{(1),\text{QCD}}_{\text{lept}}$ /%	−9.379(3)
$\delta^{(1),\text{EW}}_{\text{lept}}$ /%	1.335(2)
$\Gamma^{\text{NLO}}_{\text{lept}}$ / GeV	0.148108(6)



Hadronic

	OCSM
$\Gamma^{(0)}_{\text{hadr}}$ / GeV	0.48319351(5)
$\delta^{(1),\text{QCD}}_{\text{hadr}}$ /%	−5.58(2)
$\delta^{(1),\text{EW}}_{\text{hadr}}$ /%	1.2896(5)
$\Gamma^{\text{NLO}}_{\text{hadr}}$ / GeV	0.46248(9)



L. Oggero, Ph.D thesis