Status of High Precision Calculation Study at the CEPC

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For “2025 European Edition of the International Workshop on the Circular Electron-Positron Collider (CEPC)”, Barcelona, Spain, 16-19 Jun 2025

A Disclaimer

- As a short overview of the theoretical status, I will focus on:
  - The important physics at CEPC, and why they are important.
  - To understand these physics, what accuracy will be needed and the current status.
  - What we know we do not know.
  - Higgs physics.

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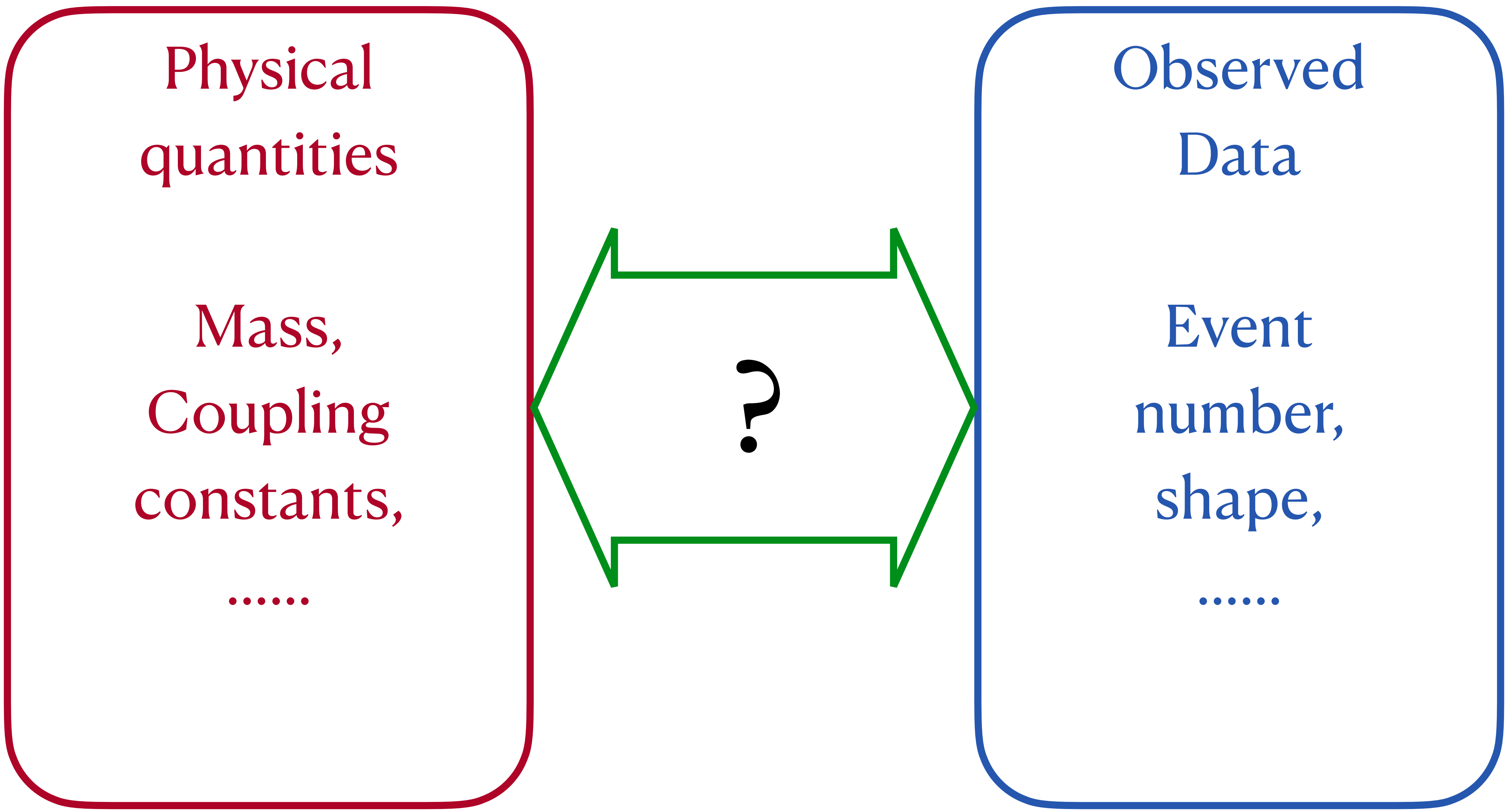
  - The important physics at CEPC, and why they are important.
  - To understand these physics, what accuracy will be needed and the current status.
  - What we know we do not know.
  - Higgs physics.

- I will not discuss:
  - The new development of the technologies (e.g., AMFlow, amplituhedron, ...).
  - Some interesting new methods (e.g., quantum computing).

Why?

- Why do we need high precision calculation?



Why?

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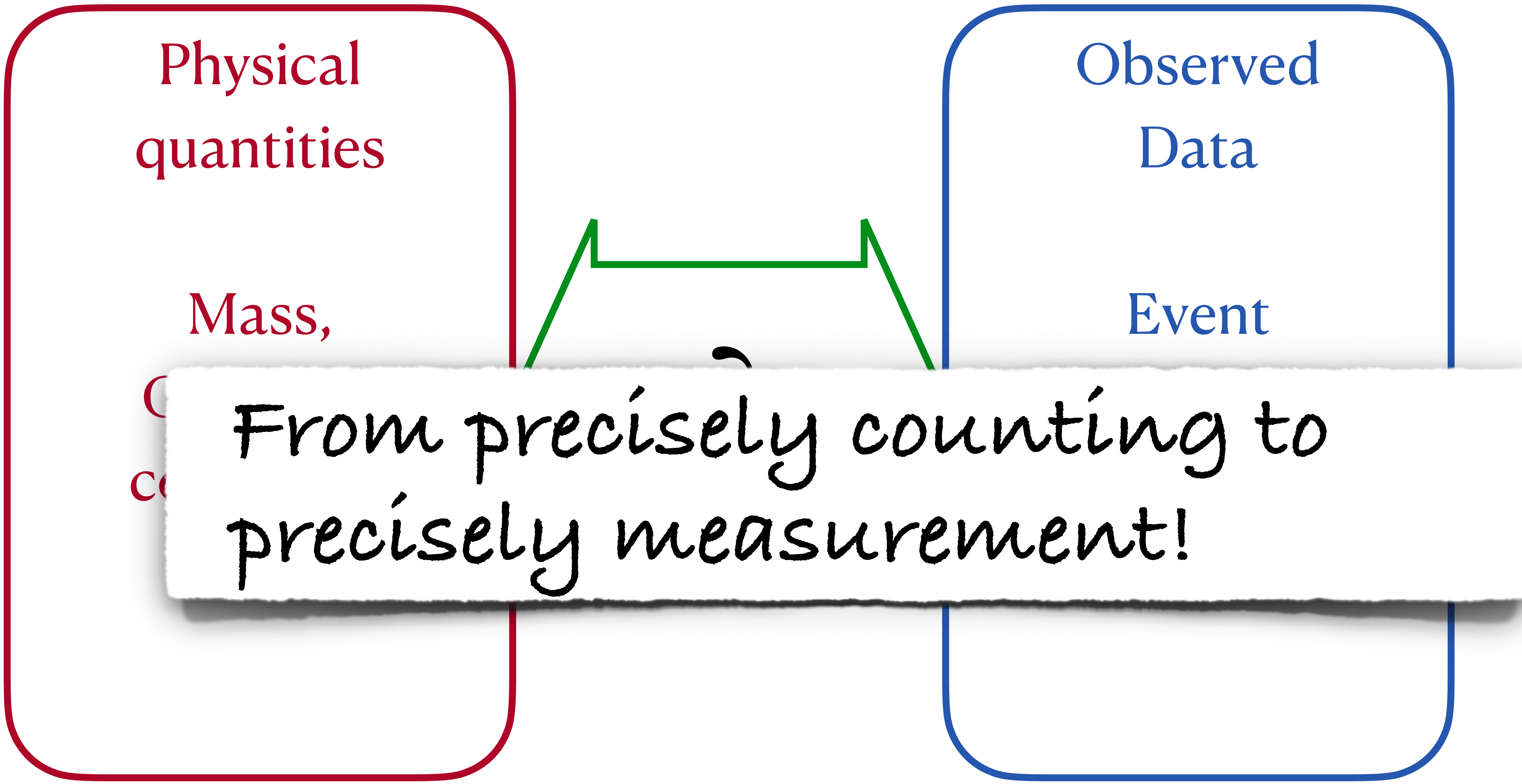


The Goal

- The machine

Table 3.1: CEPC operation plan (@ 30 MW)

Particle	$E_{\text{c.m.}}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	5	1.3	10	13	2.6×10^6
Z	91	115*	30	2	60	2.5×10^{12}
W	160	16	4,2	1	4.2	1.3×10^8
$t\bar{t}$**	360	0.5	0.13	5	0.65	0.4×10^6

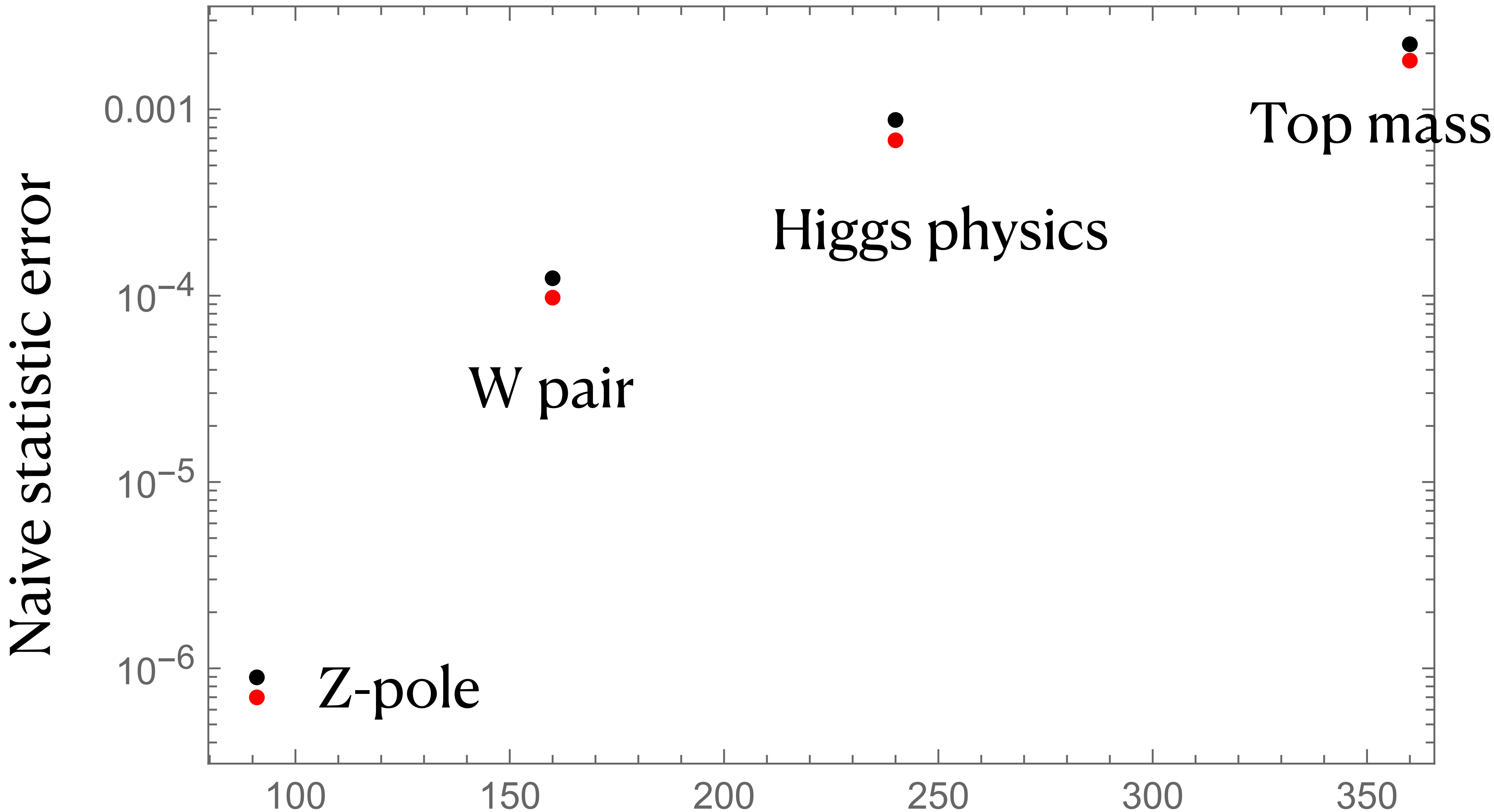
Table 3.2: CEPC operation plan (@ 50 MW)

Particle	$E_{\text{c.m.}}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	8.3	2.2	10	21.6	4.3×10^6
Z	91	192*	50	2	100	4.1×10^{12}
W	160	26.7	6.9	1	6.9	2.1×10^8
$t\bar{t}$**	360	0.8	0.2	5	1.0	0.6×10^6

Gao, J. CEPC Technical Design Report: Accelerator. Radiat Detect Technol Methods 8, 1–1105 (2024).

The Goal

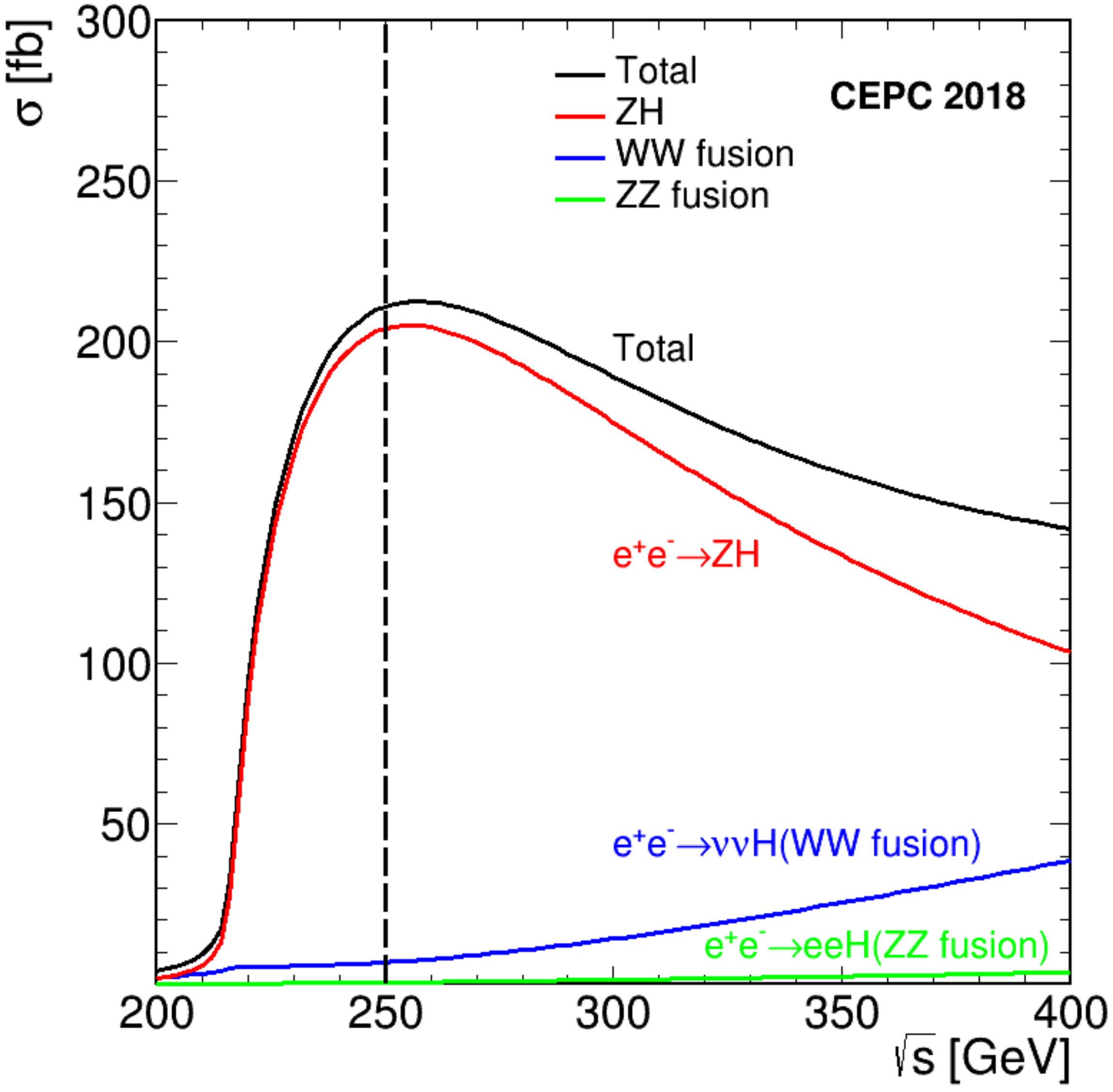
- Naive statistic error?



Higgs Physics

Higgs Physics

- Precisely Higgs physics is one of the most important job of Higgs factory.



F. An, et. al., Precision Higgs Physics at the CEPC, Chin. Phys. C 43 (2019) 043002.

Higgs Physics

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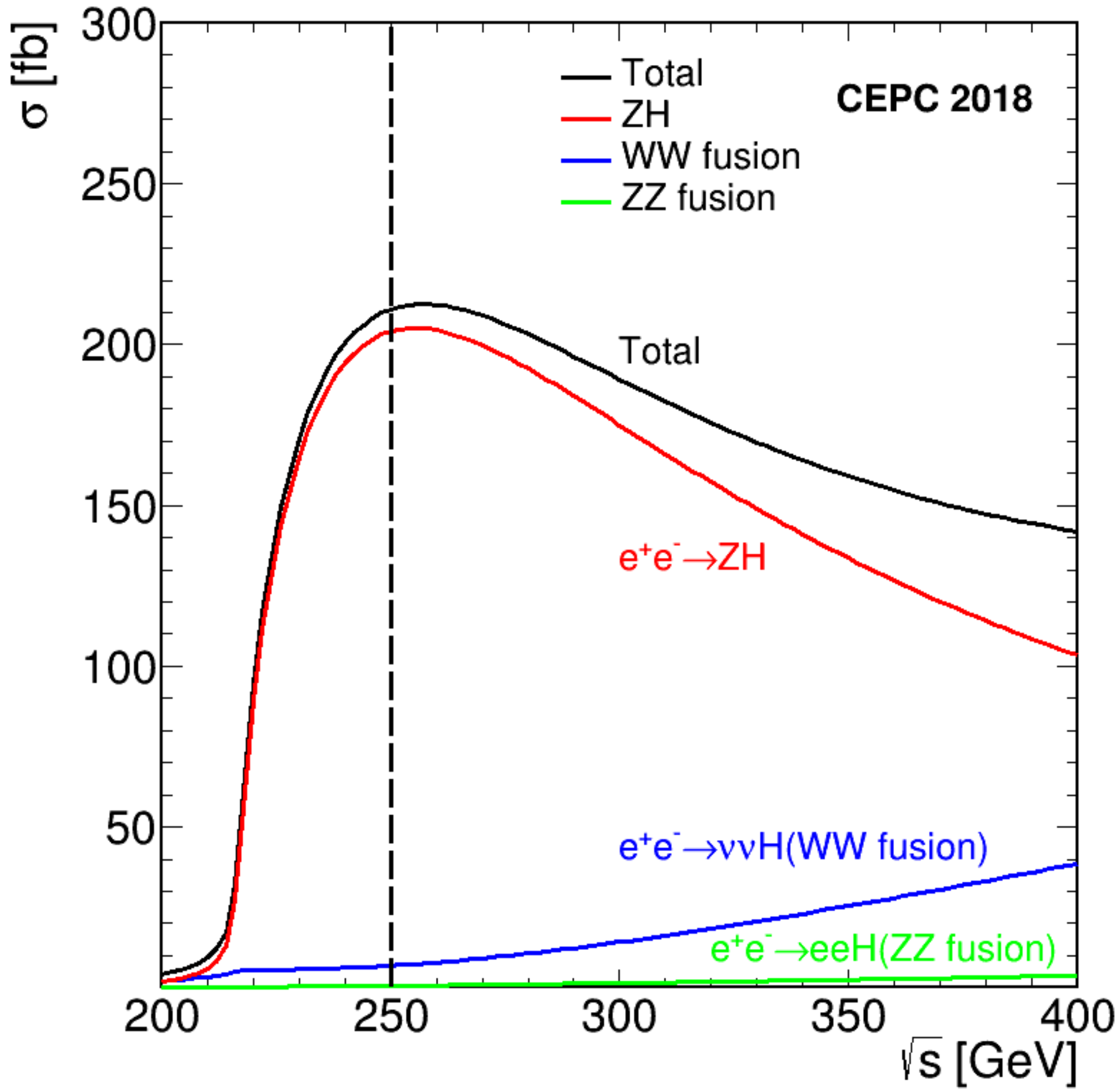

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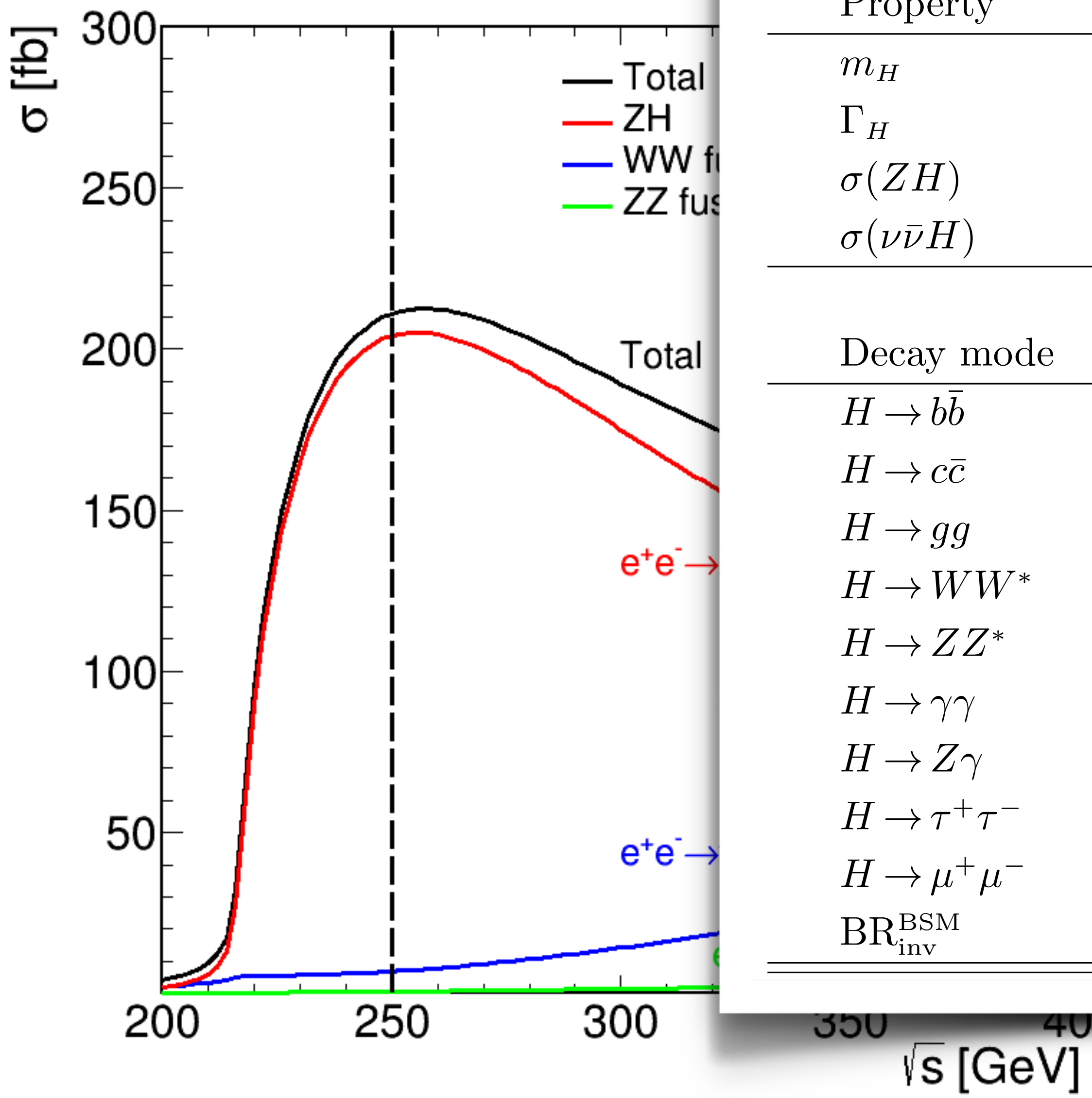

	Estimated Precision			
Property	CEPC-v1		CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	$\sigma \times \mathrm{BR}$	BR	$\sigma \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \to gg$	1.2%	1.3%	1.3%	1.4%
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \to Z\gamma$	13%	13%	16%	16%
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$< 0.28\%$	–	$< 0.30\%$

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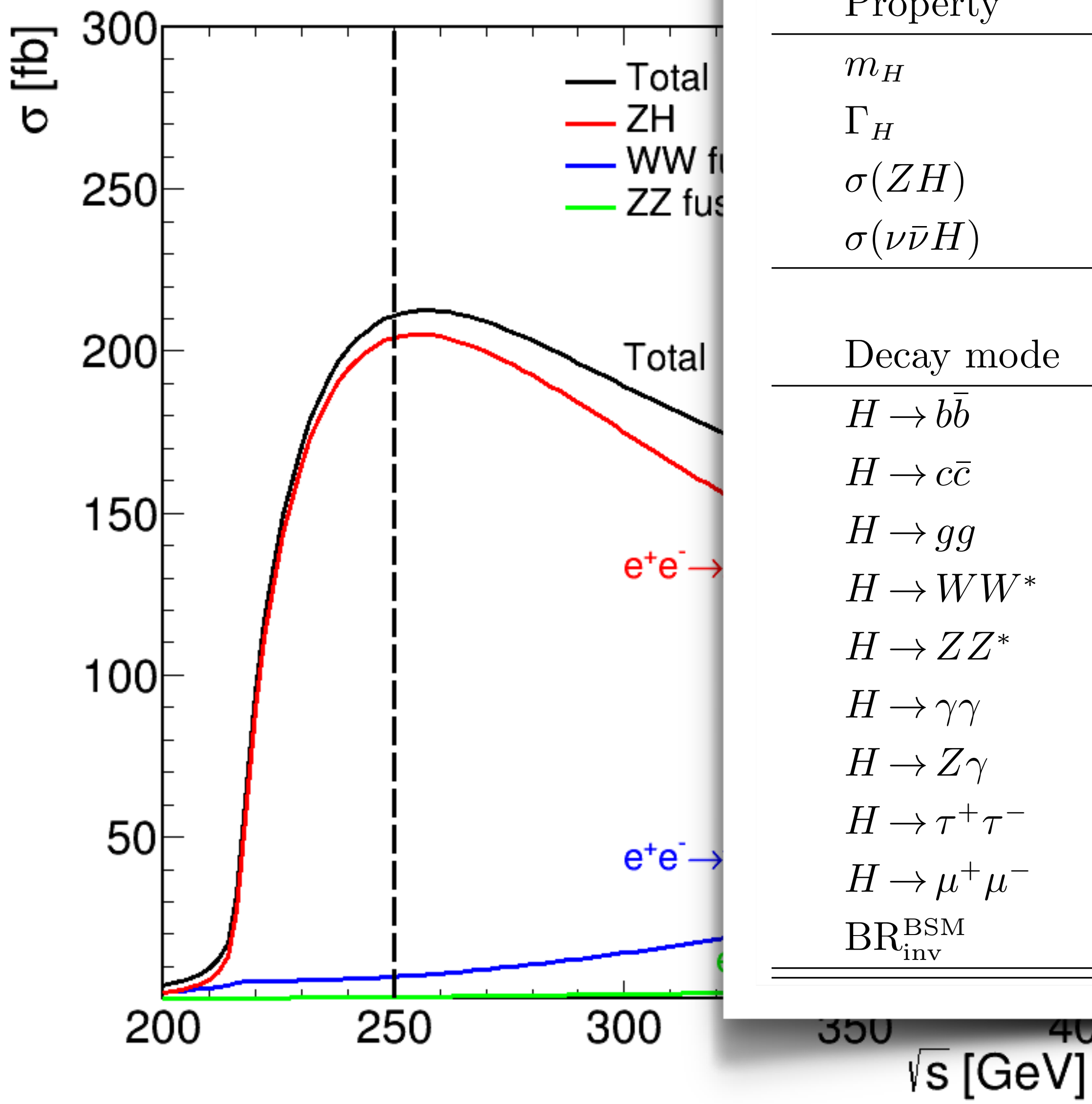

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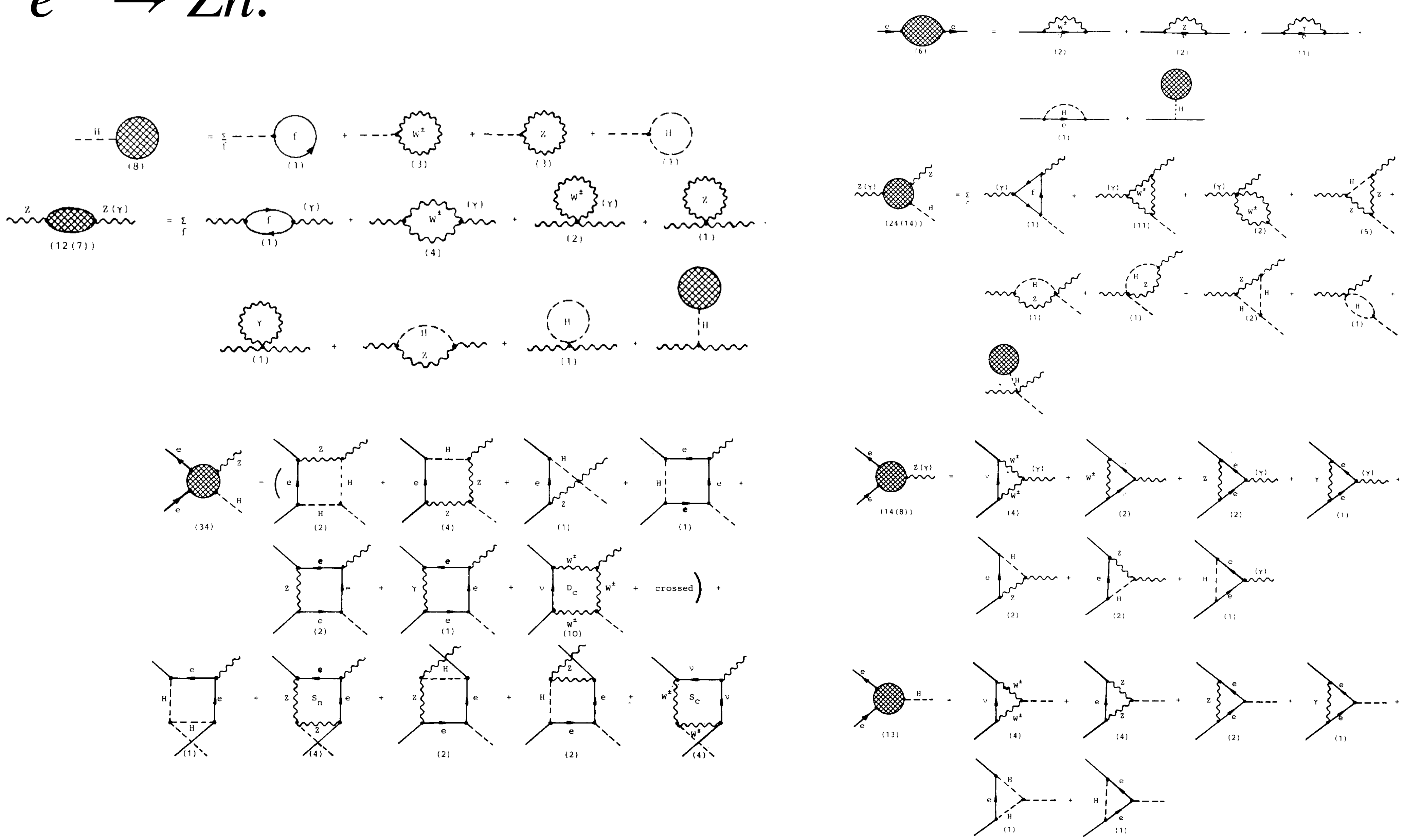
Higgs Physics

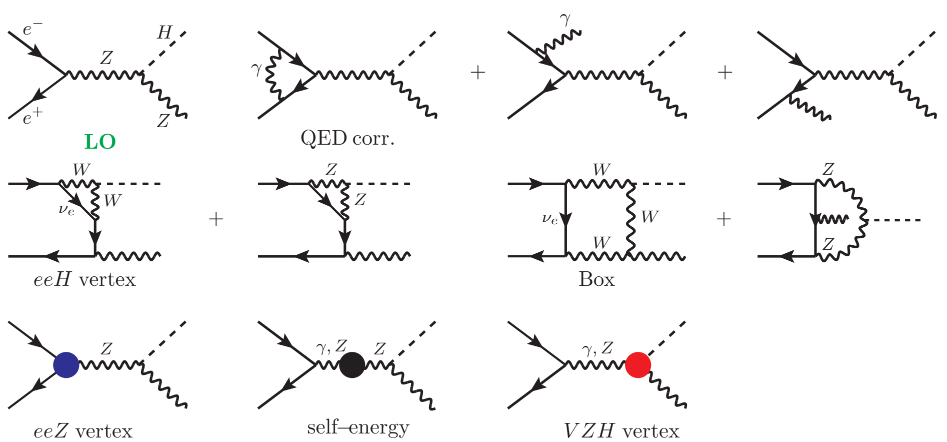
- We need accurate estimation of the cross section of (at least) $e^+e^- \to Zh$.

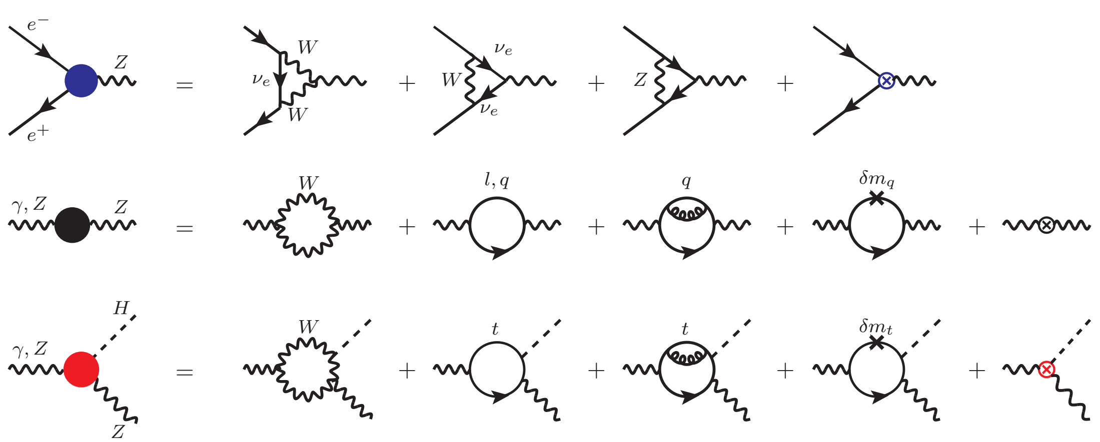


J. Fleischer and F. Jegerlehner, Nucl. Phys. B 216 (1983) 469–492; B. A. Kniehl, Z. Phys. C 55 (1992) 605–618; Denner, J. Kublbeck, R. Mertig, and M. Bohm, Z. Phys. C 56 (1992) 261–272.

Higgs Physics

- Mixed NLO EW-QCD correction to $e^+e^- \to Zh$.





Y. Gong, Z. Li, X. Xu, L. L. Yang, Phys. Rev. D 95 (2017) 093003; Q.-F. Sun, F. Feng, Y. Jia, W.-L. Sang, Phys. Rev. D 96 (2017) 051301.

Higgs Physics

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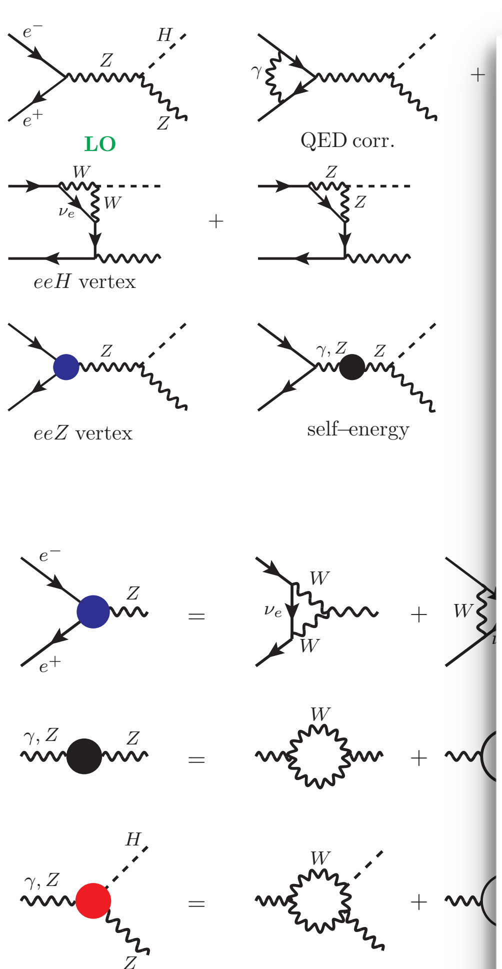

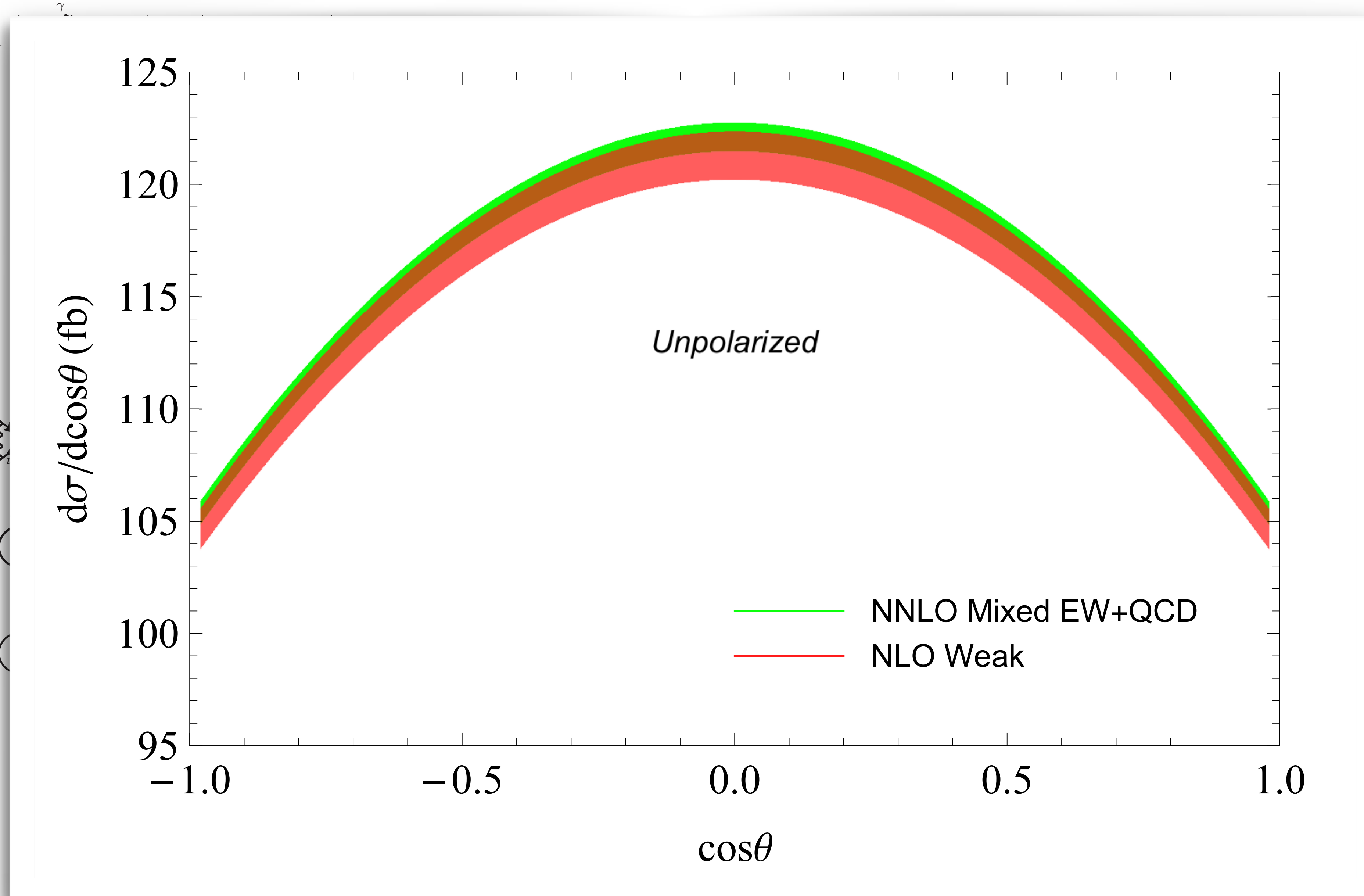

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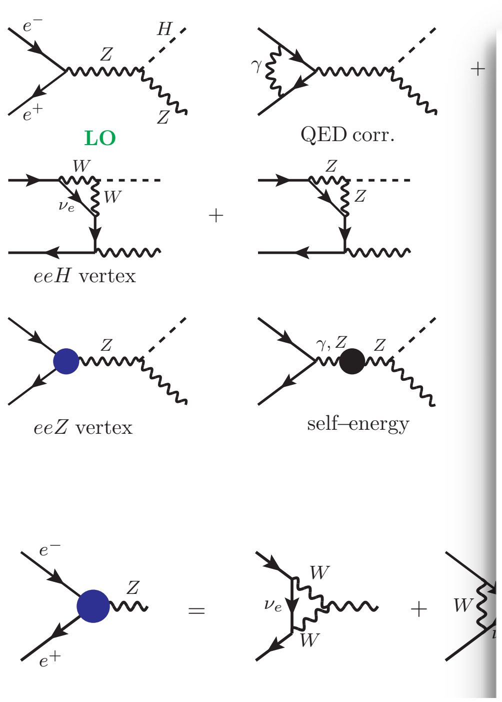

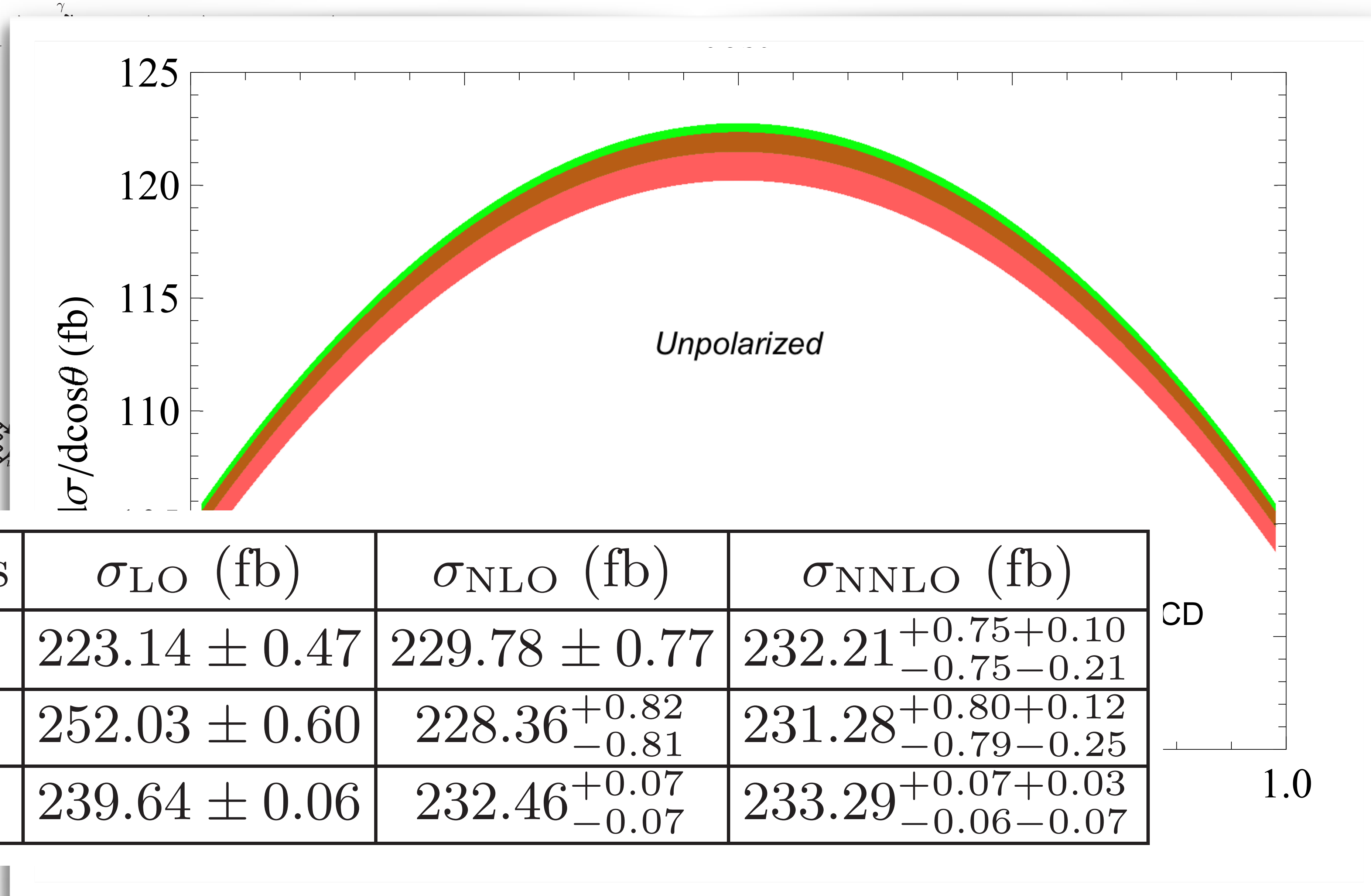

$\sqrt{s}$	schemes	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
240	$\alpha(0)$	223.14 ± 0.47	229.78 ± 0.77	$232.21^{+0.75+0.10}_{-0.75-0.21}$
	$\alpha(M_Z)$	252.03 ± 0.60	$228.36^{+0.82}_{-0.81}$	$231.28^{+0.80+0.12}_{-0.79-0.25}$
	G_μ	239.64 ± 0.06	$232.46^{+0.07}_{-0.07}$	$233.29^{+0.07+0.03}_{-0.06-0.07}$

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Higgs Physics

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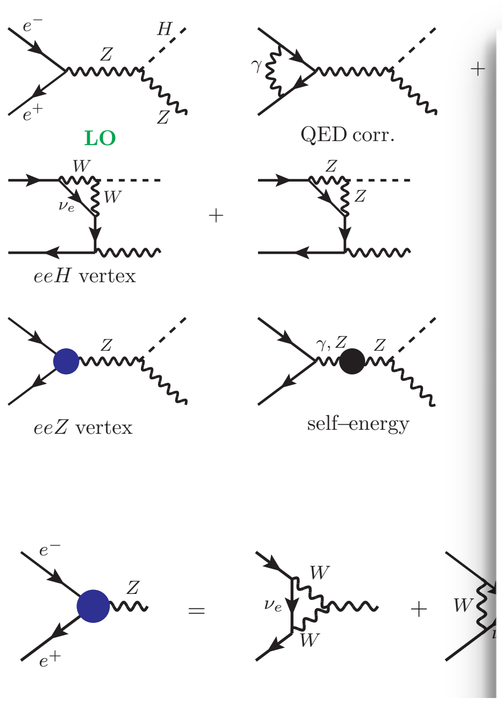

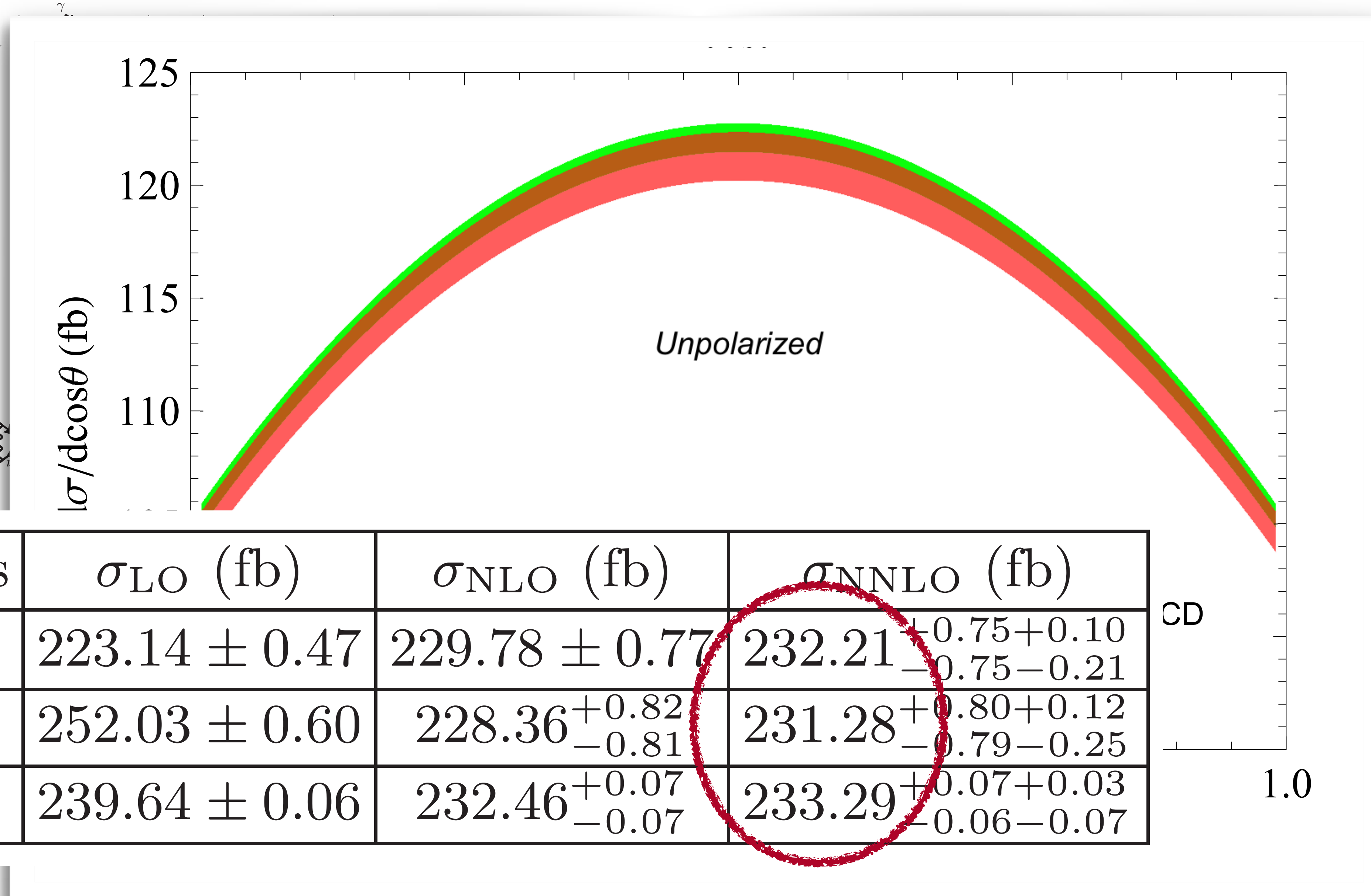

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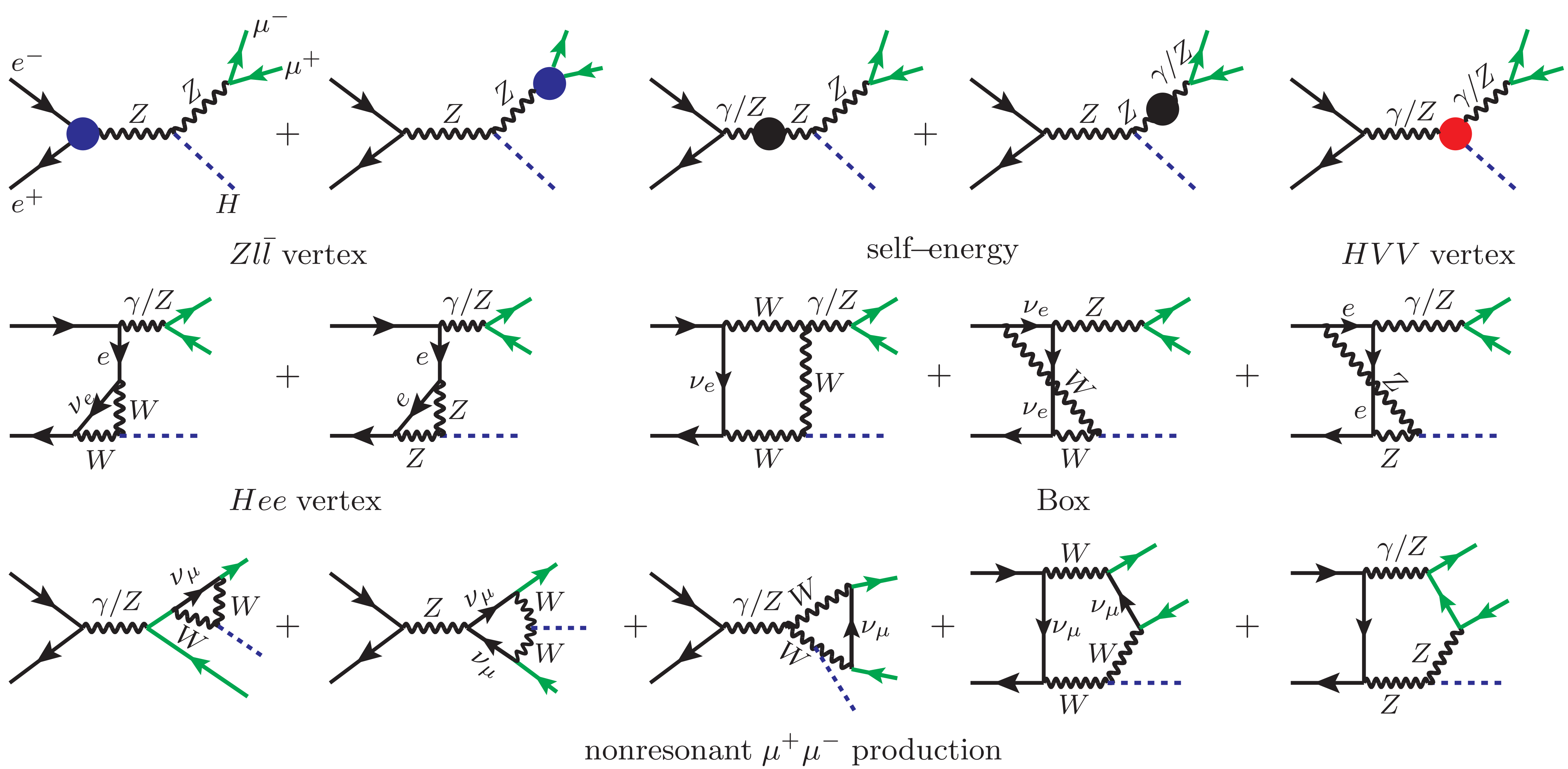
Higgs Physics

- Mixed NLO EW-QCD correction to $e^+e^- \to Zh$, with finite width effect of the Z boson.



W. Chen, F. Feng, Y. Jia, W.-L. Sang, Chin. Phys. C 43 (2019) 013108.

Higgs Physics

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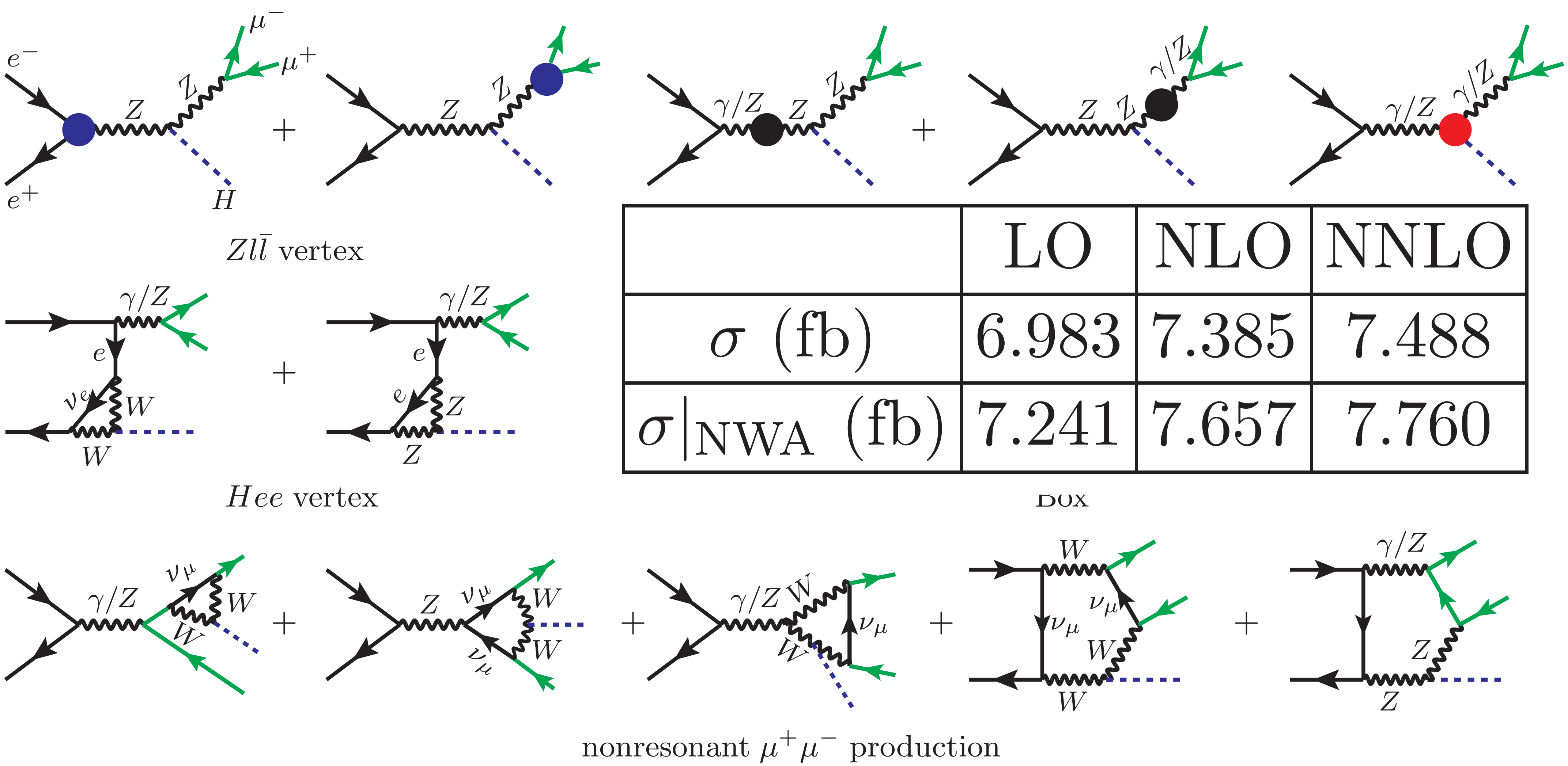
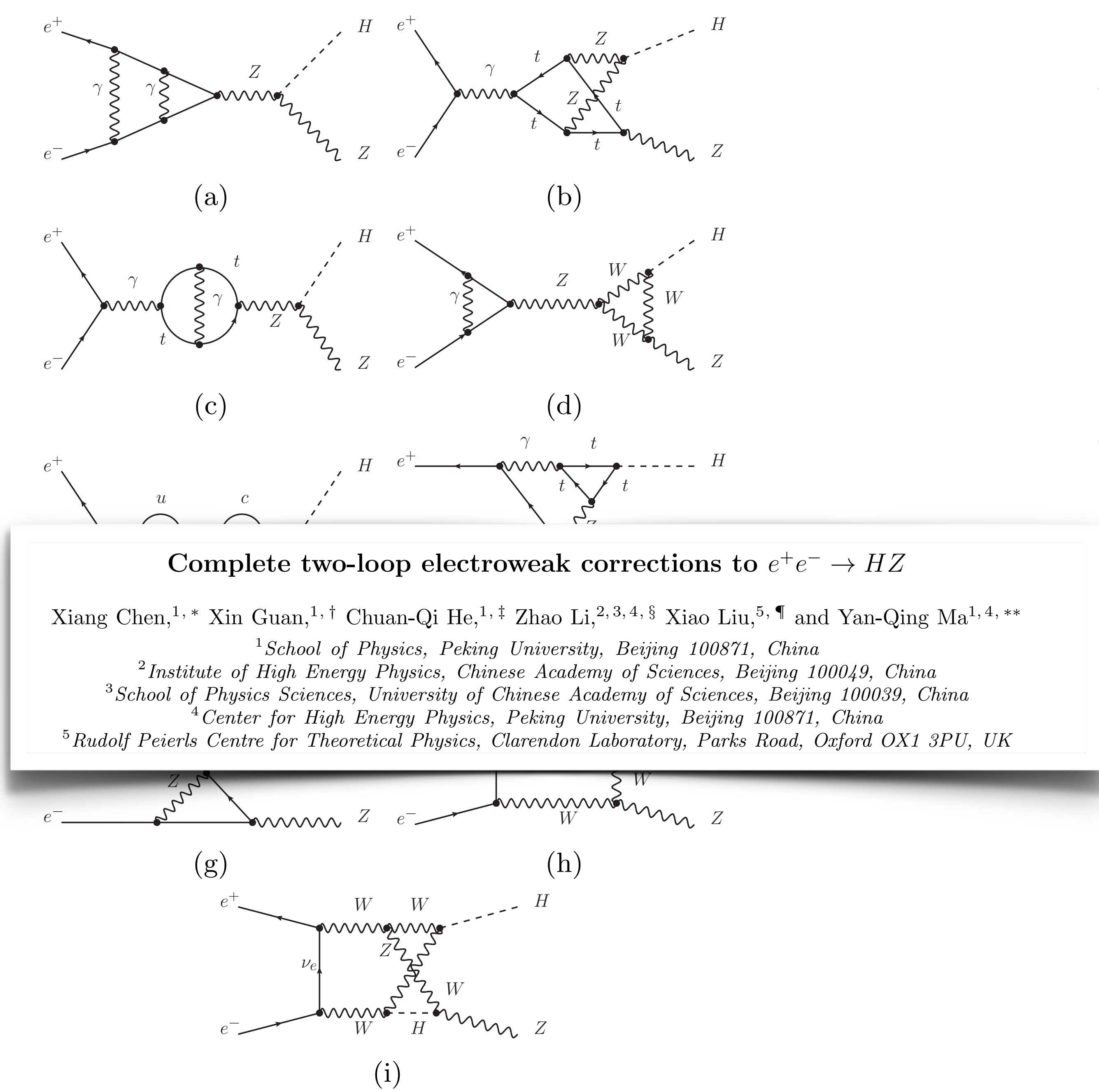


	LO	NLO	NNLO
σ (fb)	6.983	7.385	7.488
$\sigma\vert_{\mathrm{NWA}}$ (fb)	7.241	7.657	7.760

W. Chen, F. Feng, Y. Jia, W.-L. Sang, Chin. Phys. C 43 (2019) 013108.

Higgs Physics

- Beyond NLO EW-QCD correction, NNLO EW?


Complete two-loop electroweak corrections to $e^+e^- \to HZ$

Xiang Chen,[1,*] Xin Guan,[1,†] Chuan-Qi He,[1,‡] Zhao Li,[2,3,4,§] Xiao Liu,[5,¶] and Yan-Qing Ma[1,4,**]

[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[3]*School of Physics Sciences, University of Chinese Academy of Sciences, Beijing 100039, China*
[4]*Center for High Energy Physics, Peking University, Beijing 100871, China*
[5]*Rudolf Peierls Centre for Theoretical Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*

~ 30,000 Feynman diagrams;

7675 master integrals after reduction;

only ~10[4] CPU · h with AMFlow;

More labors and CPU · h are needed;

Full result is still on the way!

X. Chen, X. Guan, C.-Q. He, Z. Li, X. Liu, Y.-Q. Ma, arXiv:2209.14953[hep-ph].

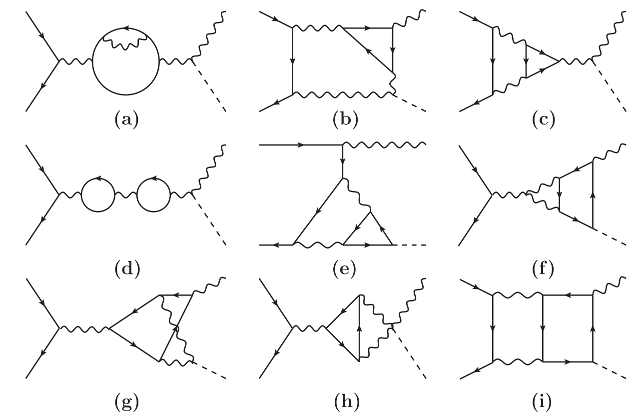
Higgs Physics

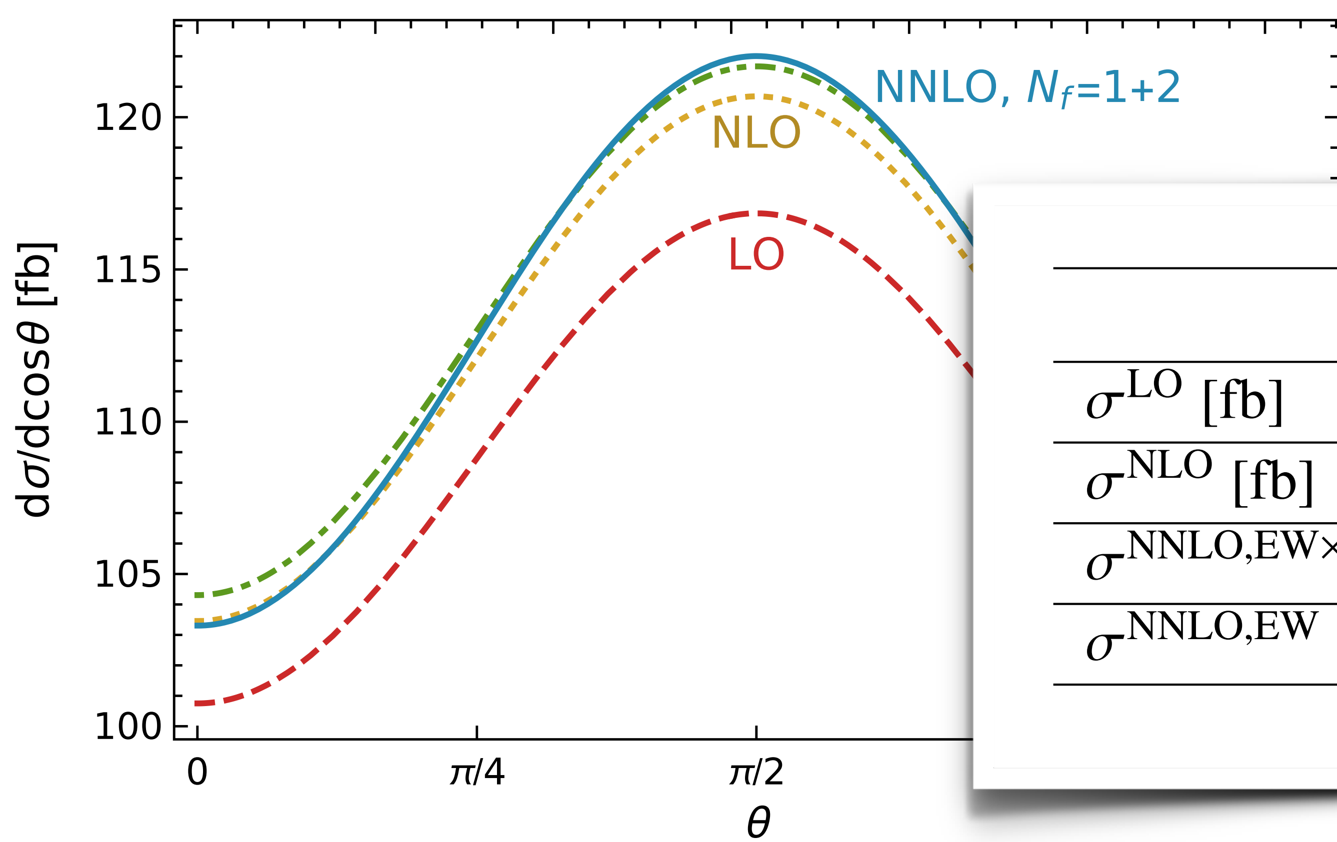
- Beyond NLO EW-QCD correction, NNLO EW?

PHYSICAL REVIEW LETTERS **130,** 031801 (2023)

Two-Loop Electroweak Corrections with Fermion Loops to $e^+e^- \to ZH$

Ayres Freitas* and Qian Song†
Pittsburgh Particle-physics Astro-physics and Cosmology Center (PITT-PACC) Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA





	$\alpha(0)$ scheme	G_μ scheme
σ^{LO} [fb]	223.14	239.64
σ^{NLO} [fb]	229.78	232.46
$\sigma^{\mathrm{NNLO,EW\times QCD}}$ [fb]	232.21	233.29
$\sigma^{\mathrm{NNLO,EW}}$ [fb]	233.86	233.98

A. Freitas, Q. Song, Phys. Rev. Lett. 130 (2023) 031801; A. Freitas, Q. Song, PoS (LL2024) 001;

Higgs Physics

- Distribution of the decay products from the Higgs boson.
- Mixed NLO EW-QCD corrections to leptonic decay via HWW.

$\alpha(m_Z)$ scheme

	LO	NLO EW	NNLO QCD-EW
Γ (10^{-5} GeV)	4.597	4.474	4.518
$\delta\Gamma$ (10^{-5} GeV)		-0.123	$+0.044$
$\delta\Gamma/\Gamma_{\mathrm{LO}}$		-2.7%	$+1.0\%$

G_μ scheme

	LO	NLO EW	NNLO QCD-EW
Γ (10^{-5} GeV)	4.374	4.524	4.531
$\delta\Gamma$ (10^{-5} GeV)		$+0.150$	$+0.007$
$\delta\Gamma/\Gamma_{\mathrm{LO}}$		$+3.4\%$	$+0.2\%$

C. Ma, Y. Wang, X. Xu, L. L. Yang, B. Zhou, JHEP09 (2021) 114.

Higgs Physics

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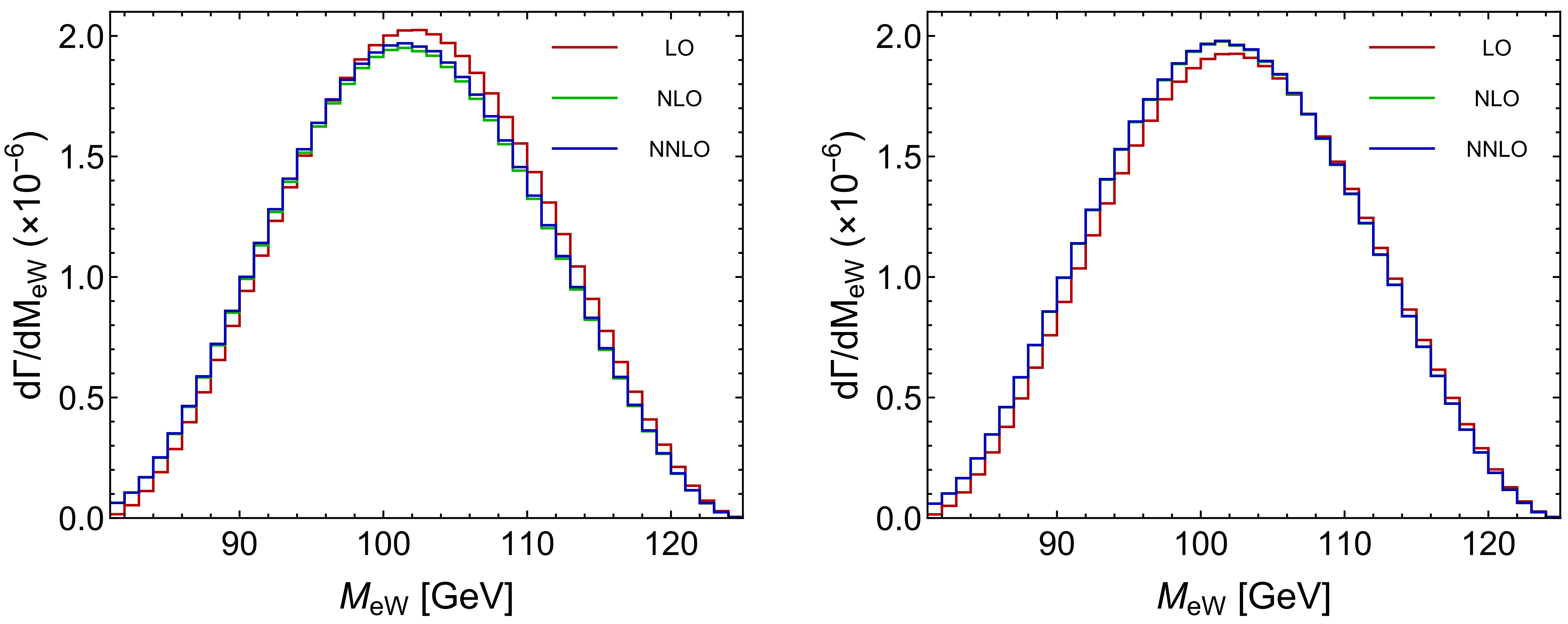
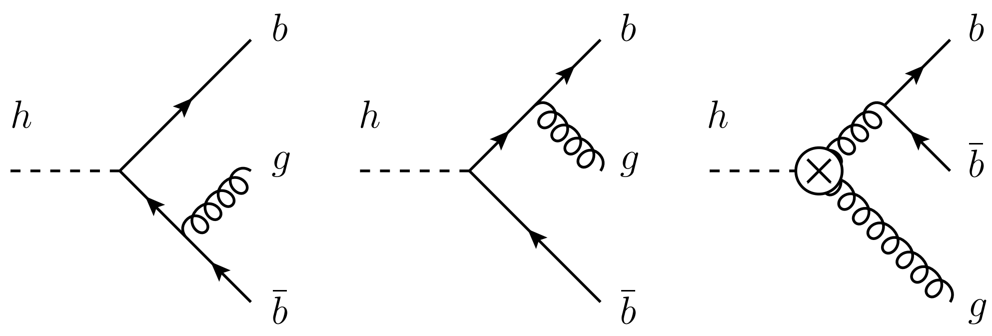
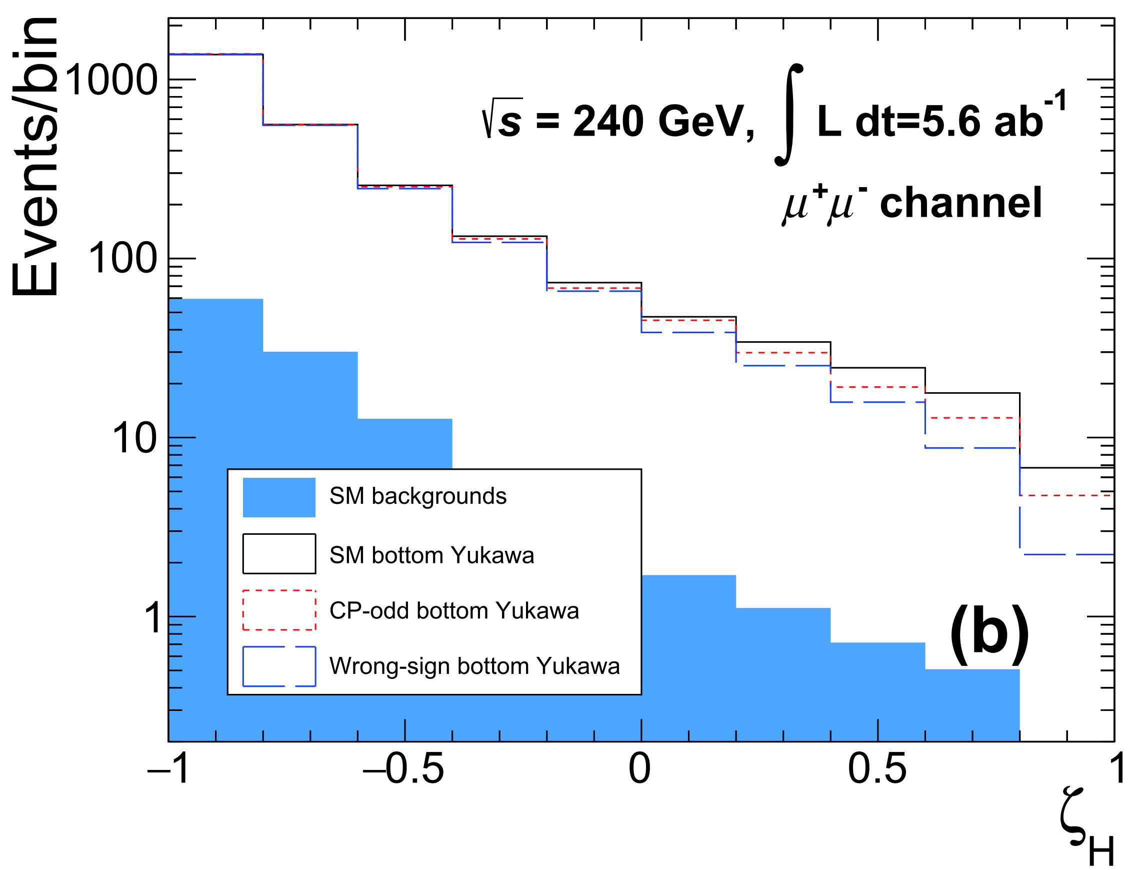


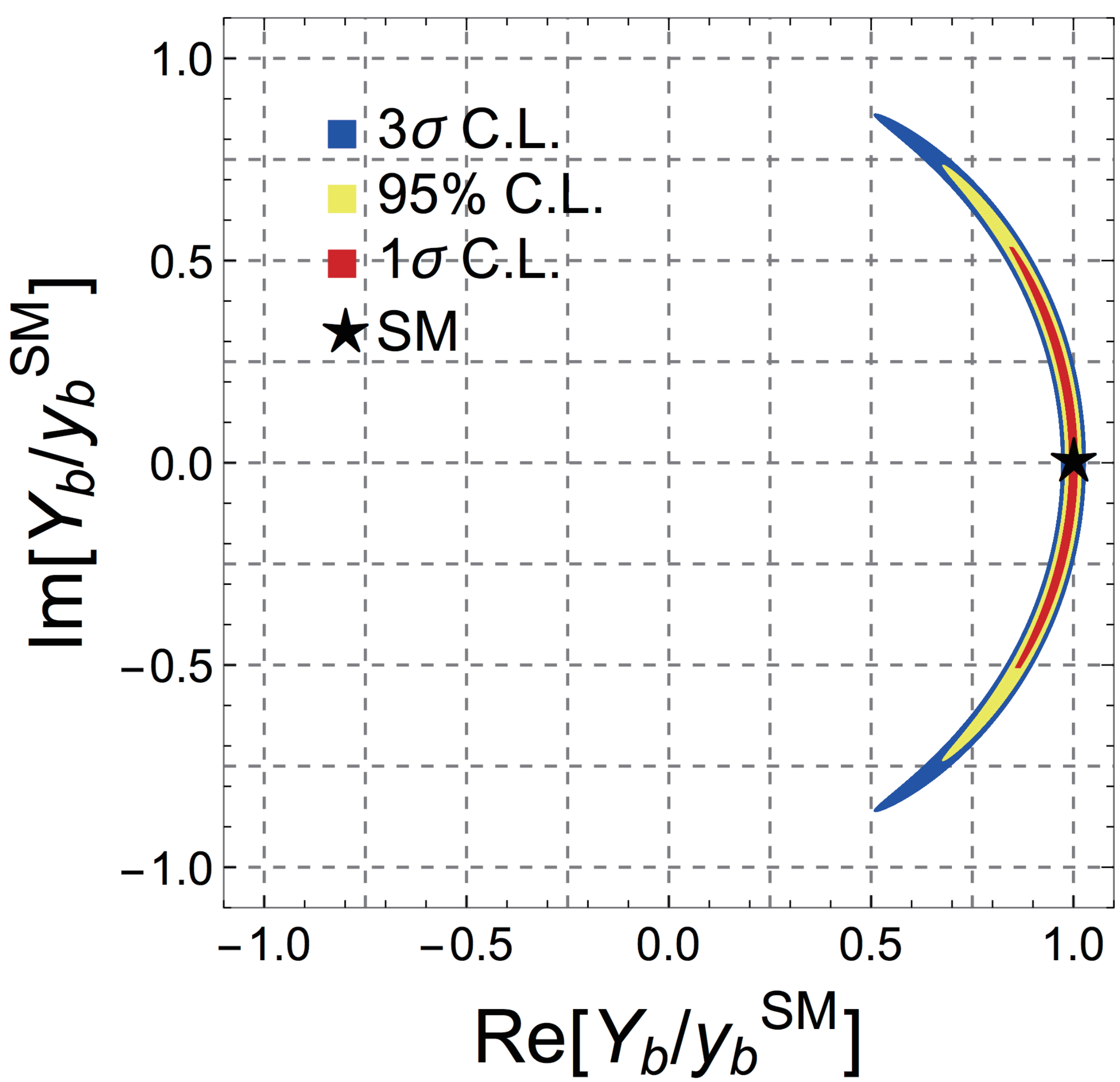
C. Ma, Y. Wang, X. Xu, L. L. Yang, B. Zhou, JHEP09 (2021) 114.

Higgs Physics

- Distribution of the decay products from the Higgs boson contains information of new physics!







Q. Bi, K. Chai, J. Gao, HZ, Chin. Phys. C 45 (2021) 023105.

Higgs Physics

- New result for specific new physics model.

JHEP

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One-loop radiative corrections to $e^+e^- \to Zh^0/H^0A^0$ in the Inert Higgs Doublet Model

Hamza Abouabid,[a] Abdesslam Arhrib,[a] Rachid Benbrik,[b] Jaouad El Falaki,[c] Bin Gong,[d,e] Wenhai Xie[d,e] and Qi-Shu Yan[e,f]

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19A Yuquan Road, Shijingshan Dis
[f] *Center for Future High Energy Phy*
19B Yuquan Road, Shijingshan Dis

E-mail: hamza.abouabid@gmail
jaouad.elfalaki@gmail.com, t
yanqishu@ucas.ac.cn

$$H_1 = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v + h^0 + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

$$\begin{aligned} V = {} & \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 \\ & + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 \\ & + \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + \text{H.c.}\}. \end{aligned}$$

PHYSICAL REVIEW D **109,** 015009 (2024)

Full one-loop radiative corrections to $e^+e^- \to H^+H^-$ in the inert doublet model

Hamza Abouabid,[1,*] Abdesslam Arhrib,[1,†] Jaouad El Falaki,[2,‡] Bin Gong,[3,4,§] Wenhai Xie,[3,4,∥] and Qi-Shu Yan[4,5,¶]

[1] *Université Abdelmalek Essaadi, FSTT, B. 416, Tangier, Morocco*
[2] *LPTHE, Physics Department, Faculty of Sciences, Ibnou Zohr University, P.O.B. 8106 Agadir, Morocco*
[3] *Theory Division, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[4] *School of Physics Sciences, University of Chinese Academy of Sciences, Beijing 100049, China*
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Higgs Physics

- For SMEFTers

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$e^+e^- \to ZH$ process in the SMEFT beyond leading order

Konstantin Asteriadis,[a] **Sally Dawson**,[b] **Pier Paolo Giardino**[c] **and Robert Szafron**[b]

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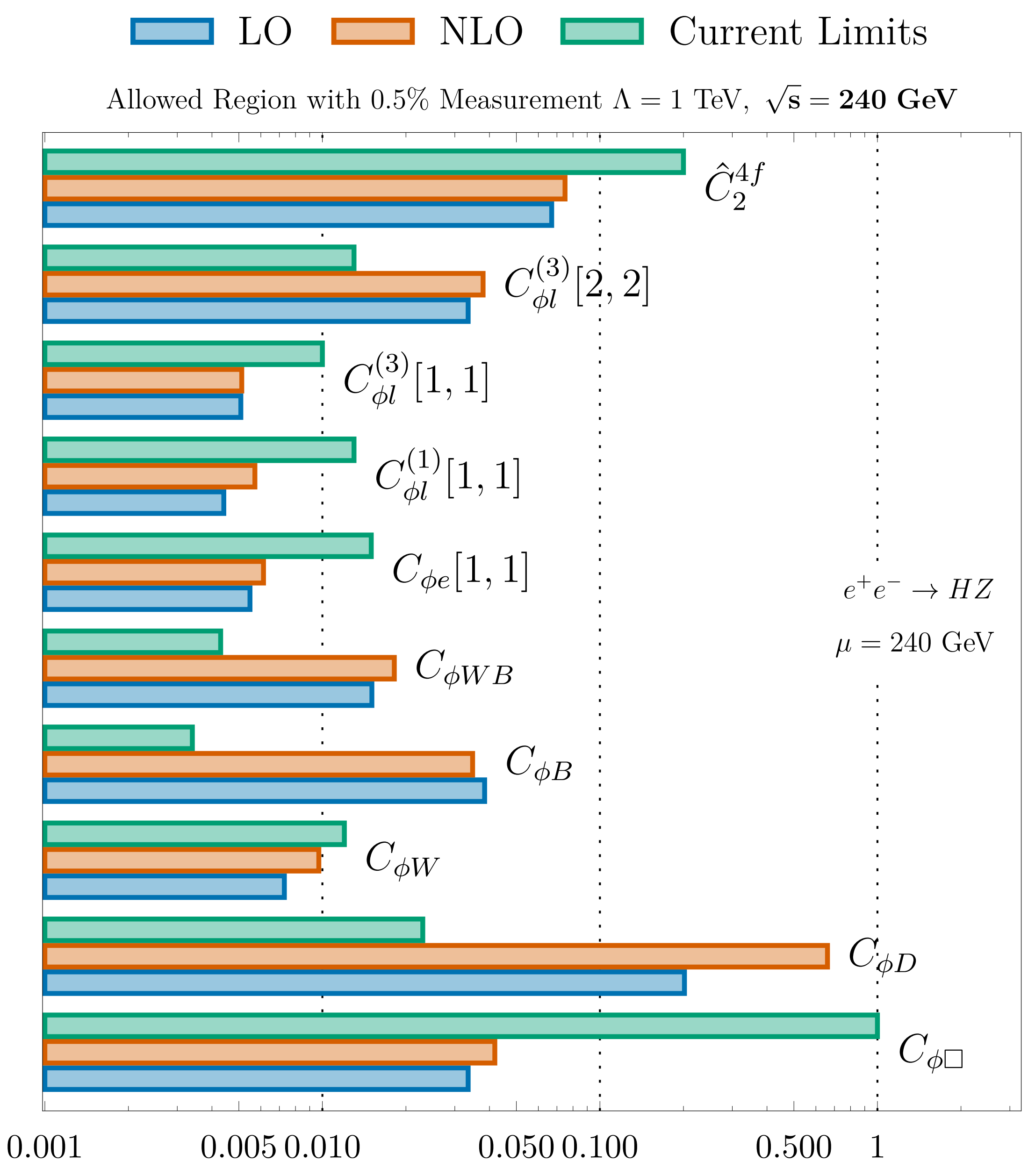
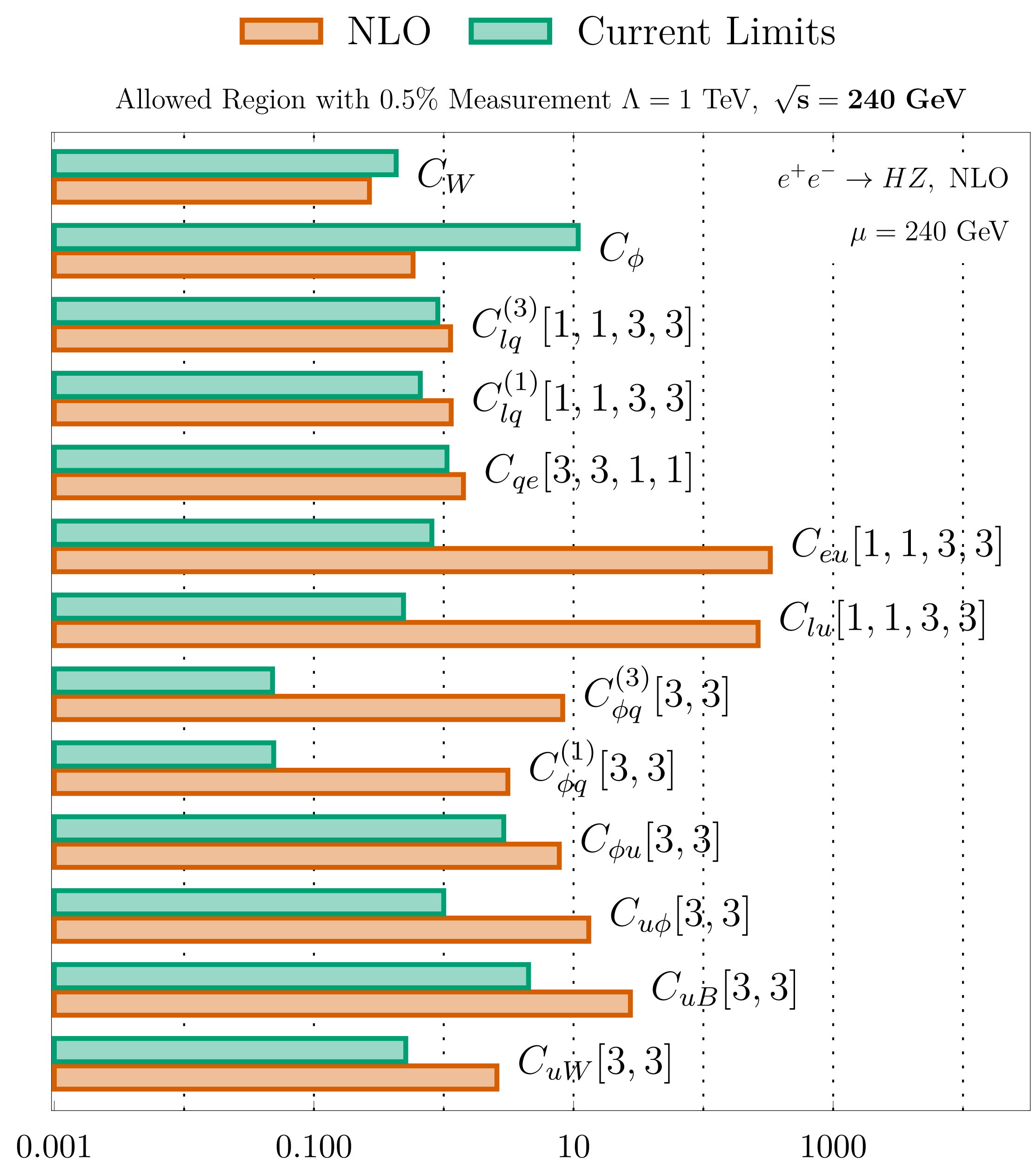
[b]*High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.*

[c]*Departamento de Física Teórica and Instituto de Física Teórica UAM/CSIC, Universidad, Autónoma de Madrid, Cantoblanco, 28049, Madrid, Spain*

Higgs Physics

- For SMEFTers

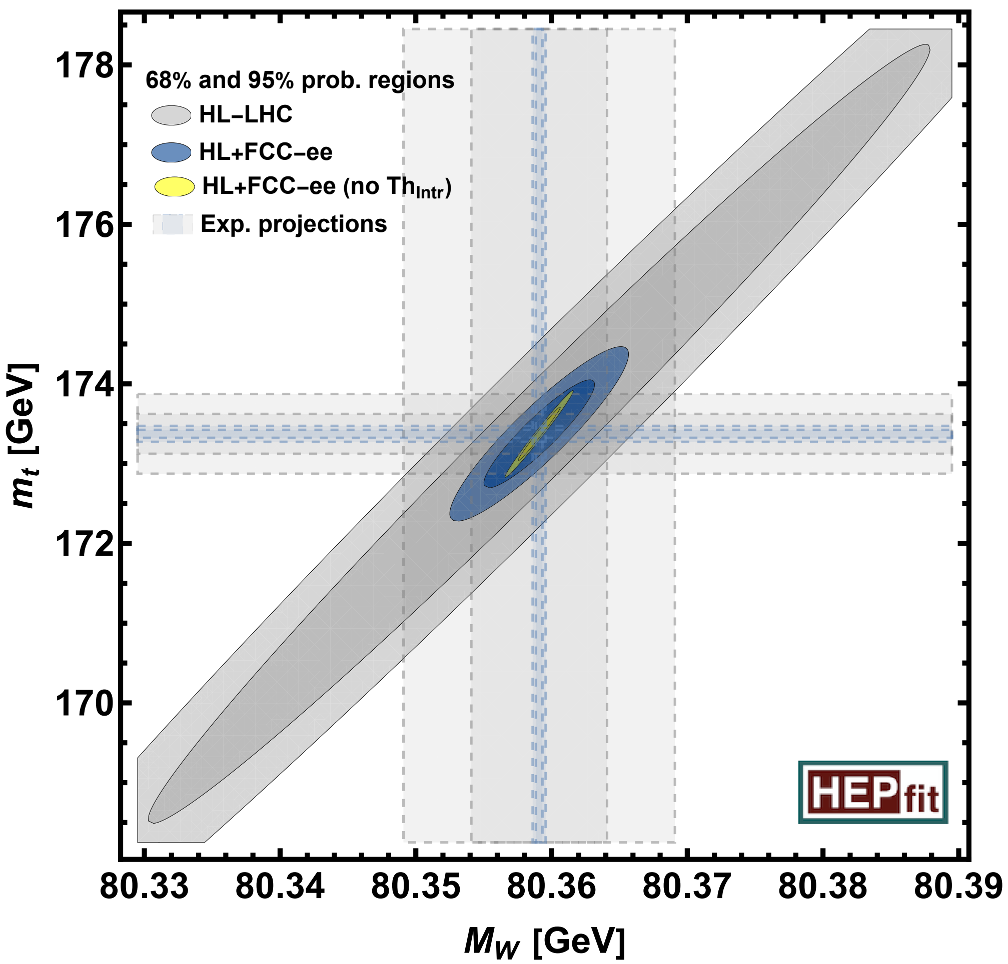


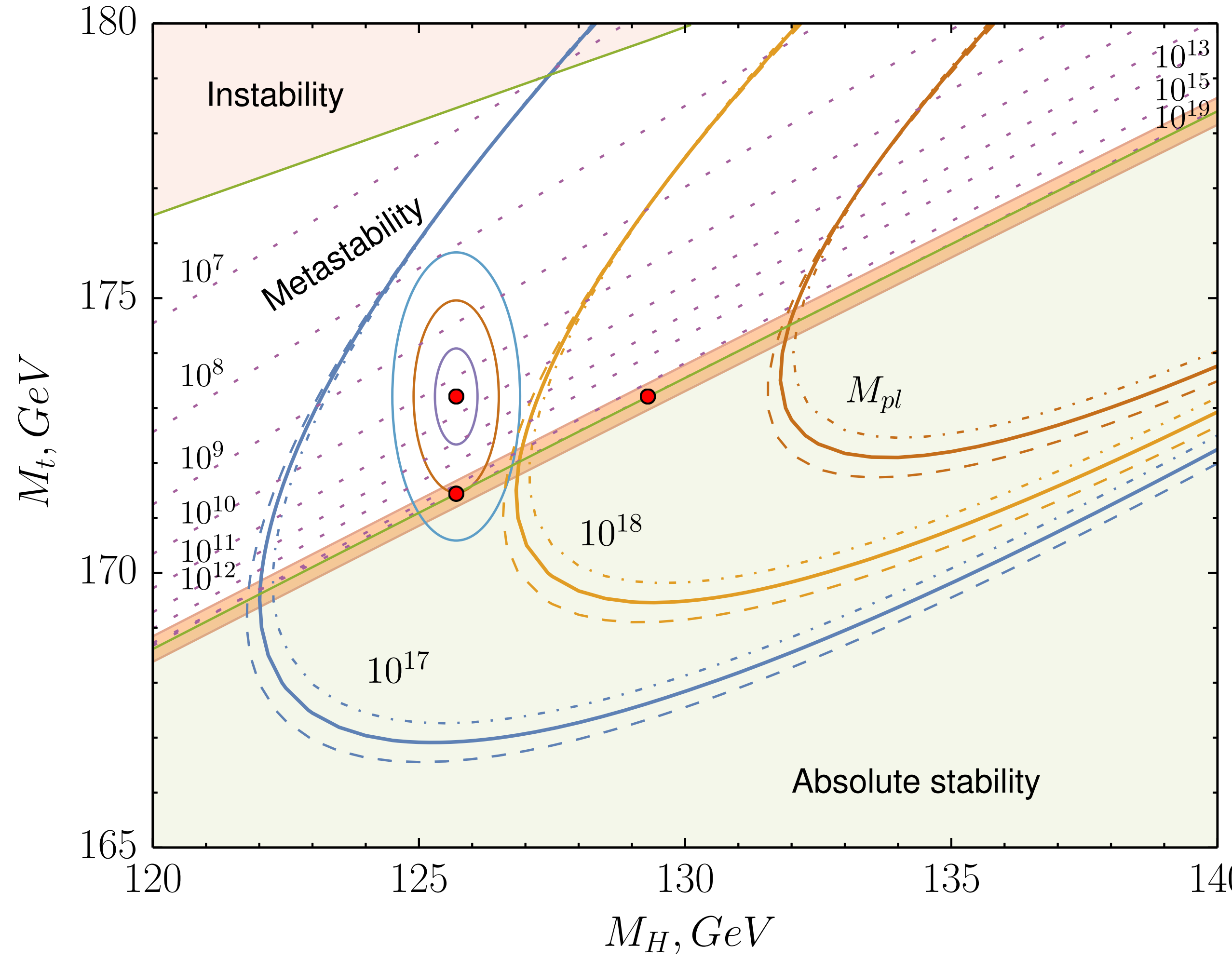


Top Physics and Electroweak Physics

Top Physics and EW Physics

- Why is it so important?

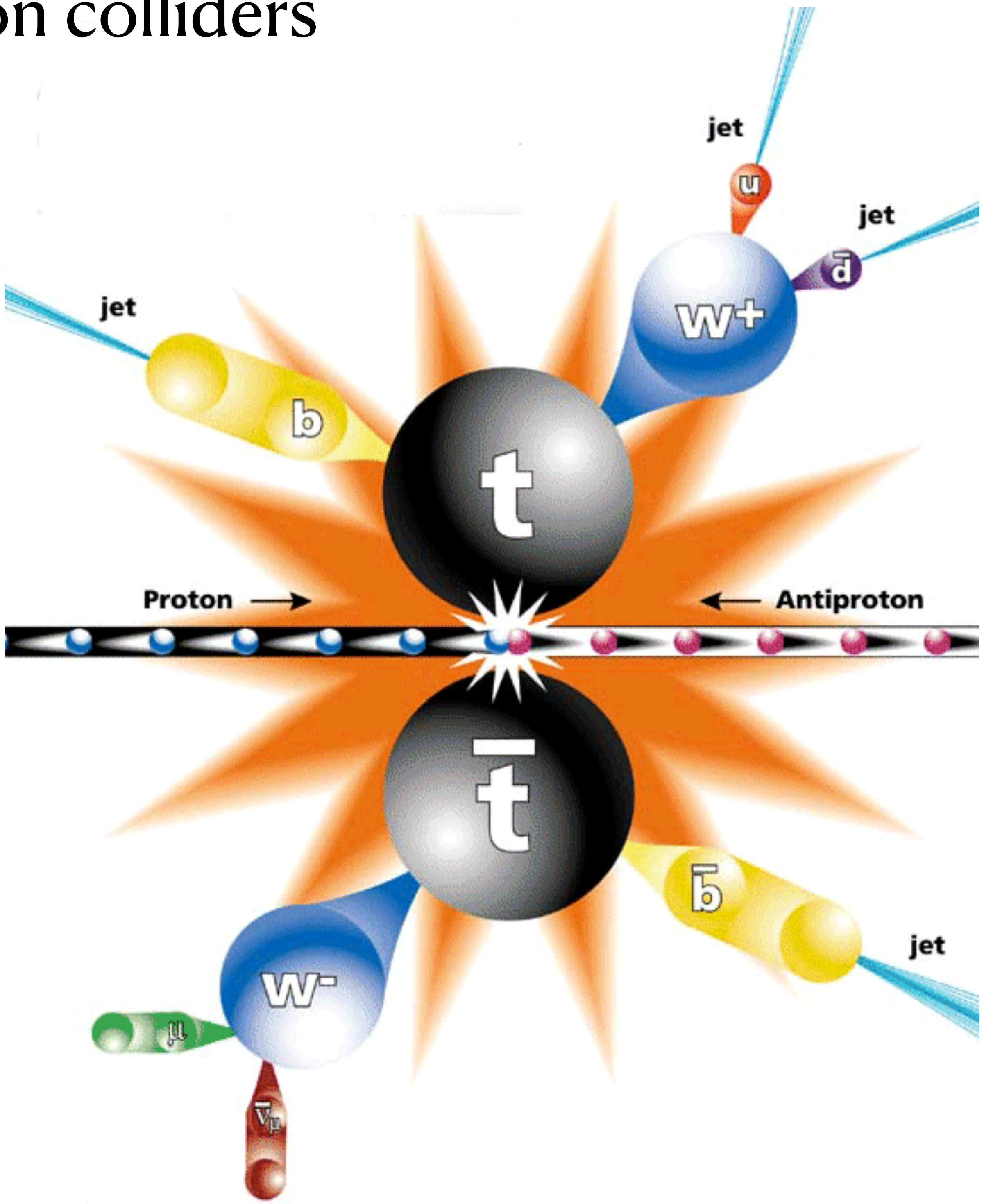




M. M. Defranchis, J. de Blas, A. Mehta, M. Selvaggi, M. Vos, arXiv:2503.18713[hep-ph]; A. V. Bednyakov, B. A. Kniehl, A. F. Pikelner, O. L. Veretin, Phys. Rev. Lett. 115 (2015) 201802.

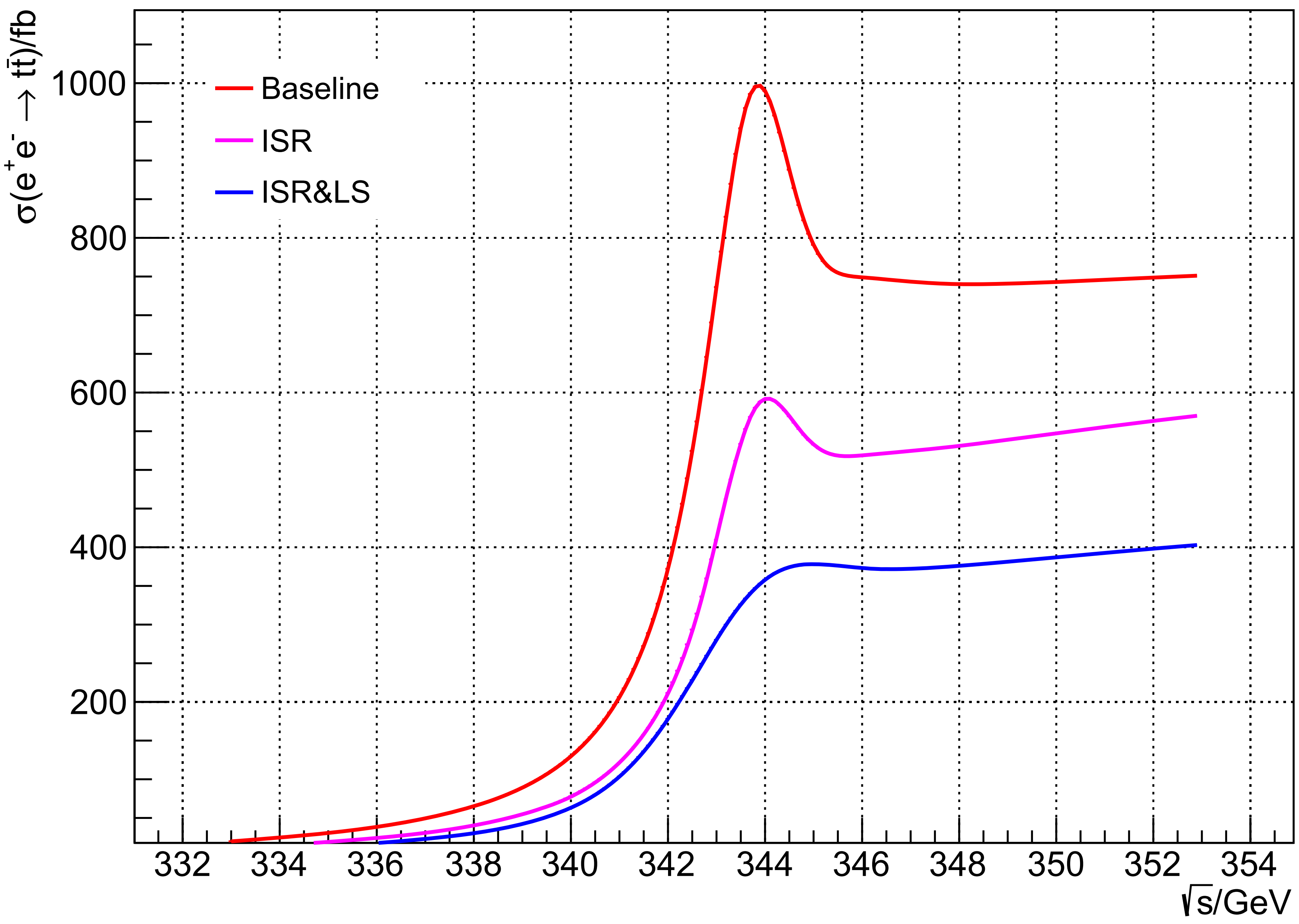
Top Physics and EW Physics

- Essentially difficult at hadron colliders



Top Physics and EW Physics

- Top quark mass at CEPC and the meaning of the curve.



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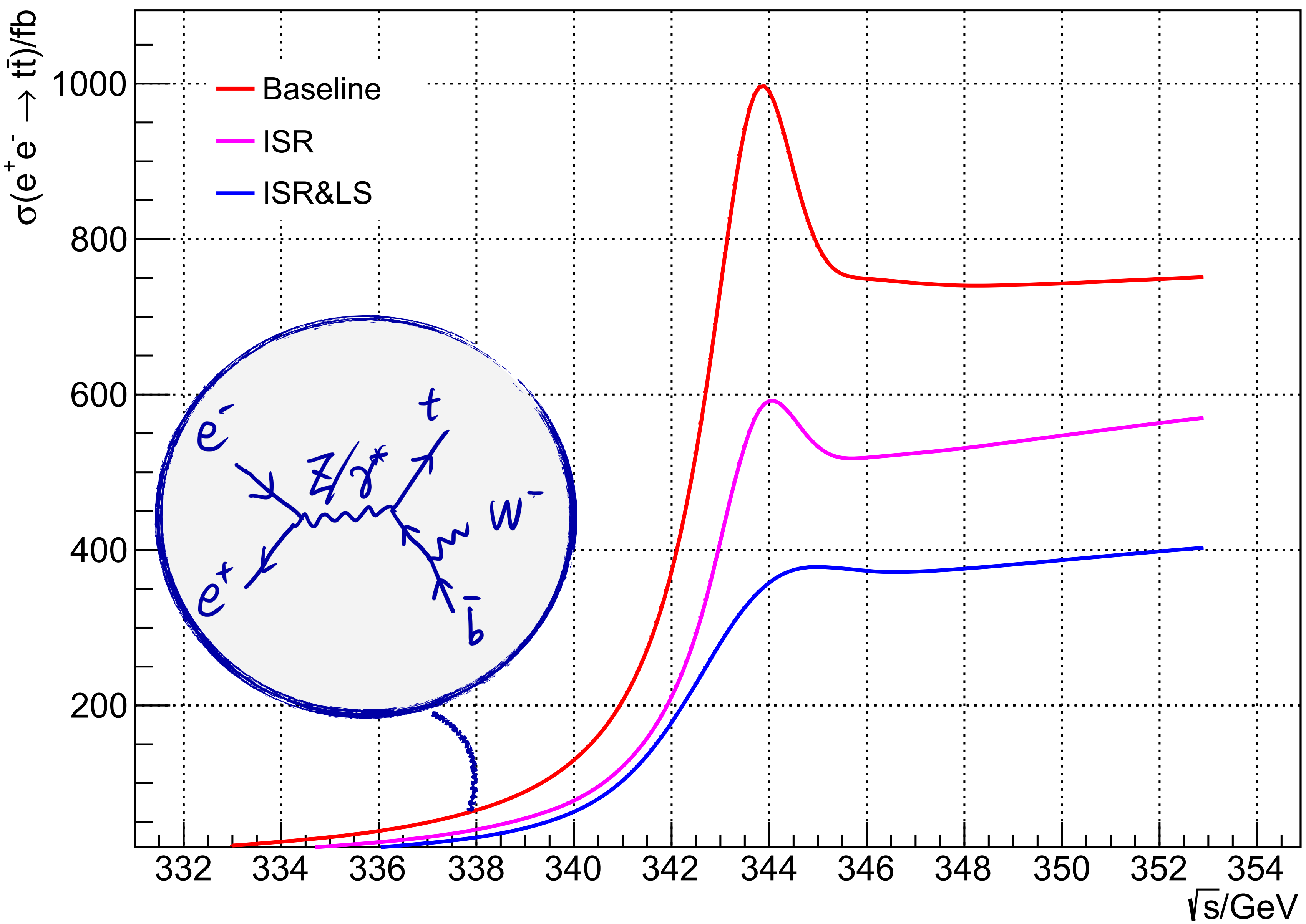

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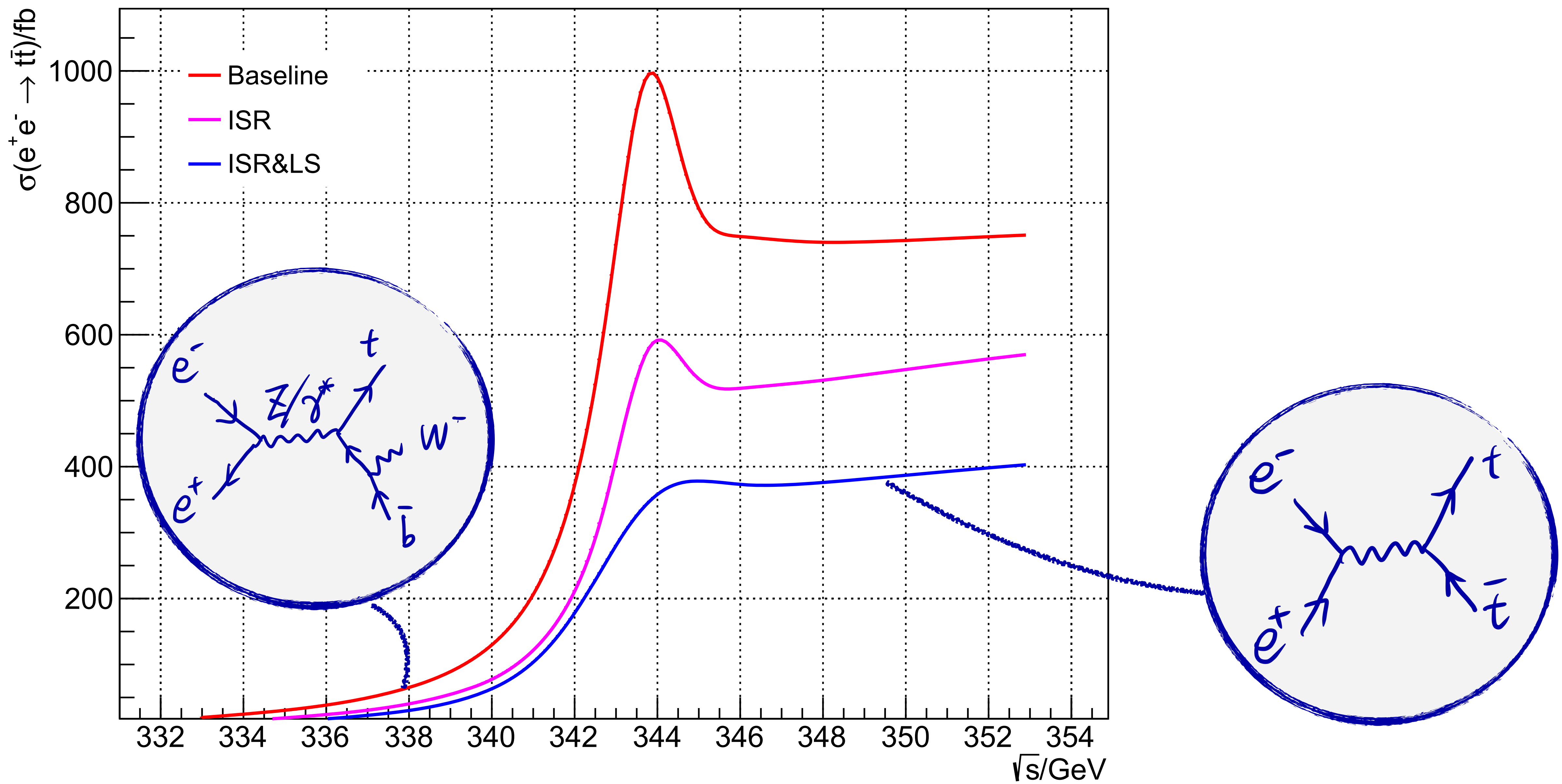

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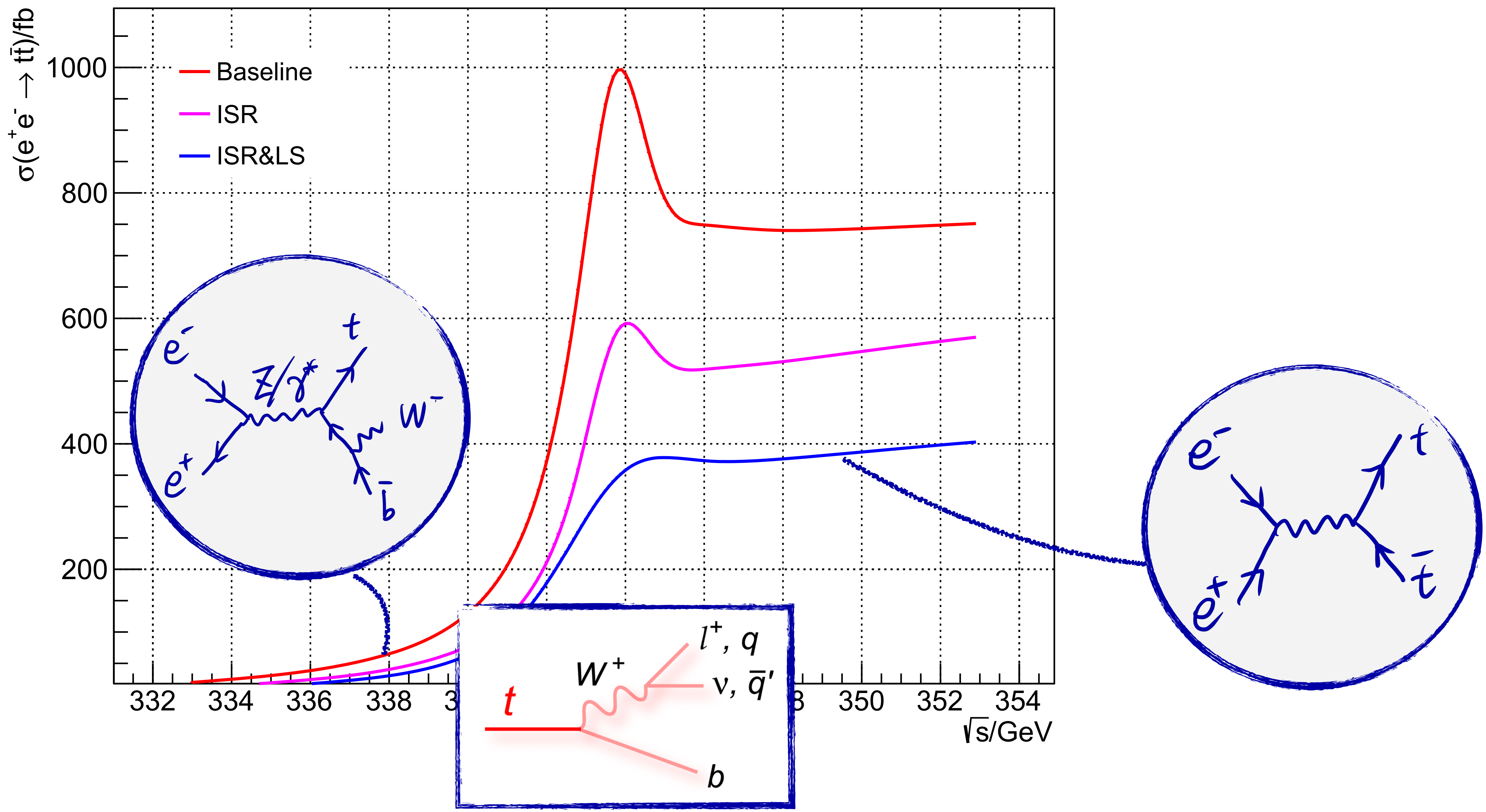

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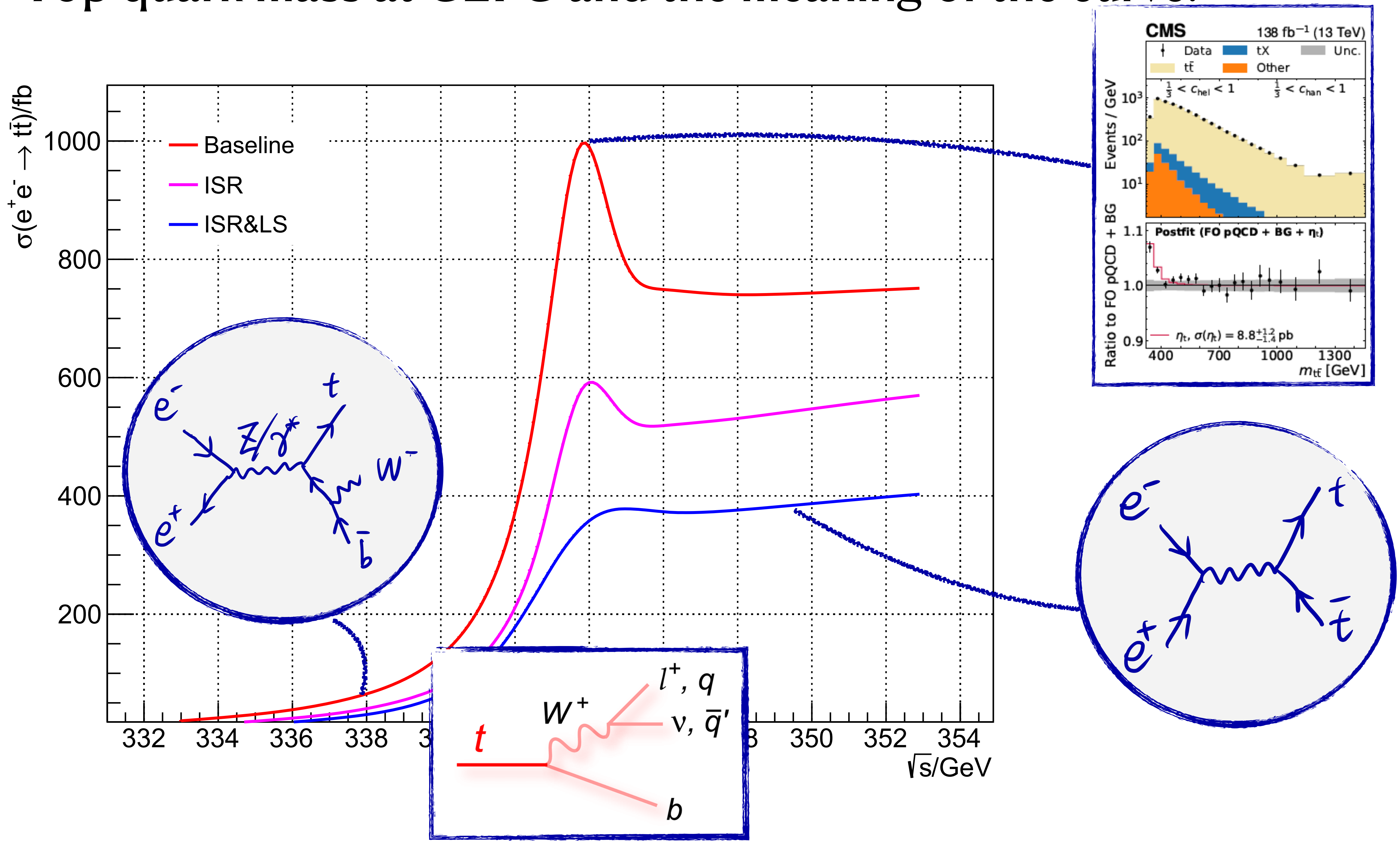

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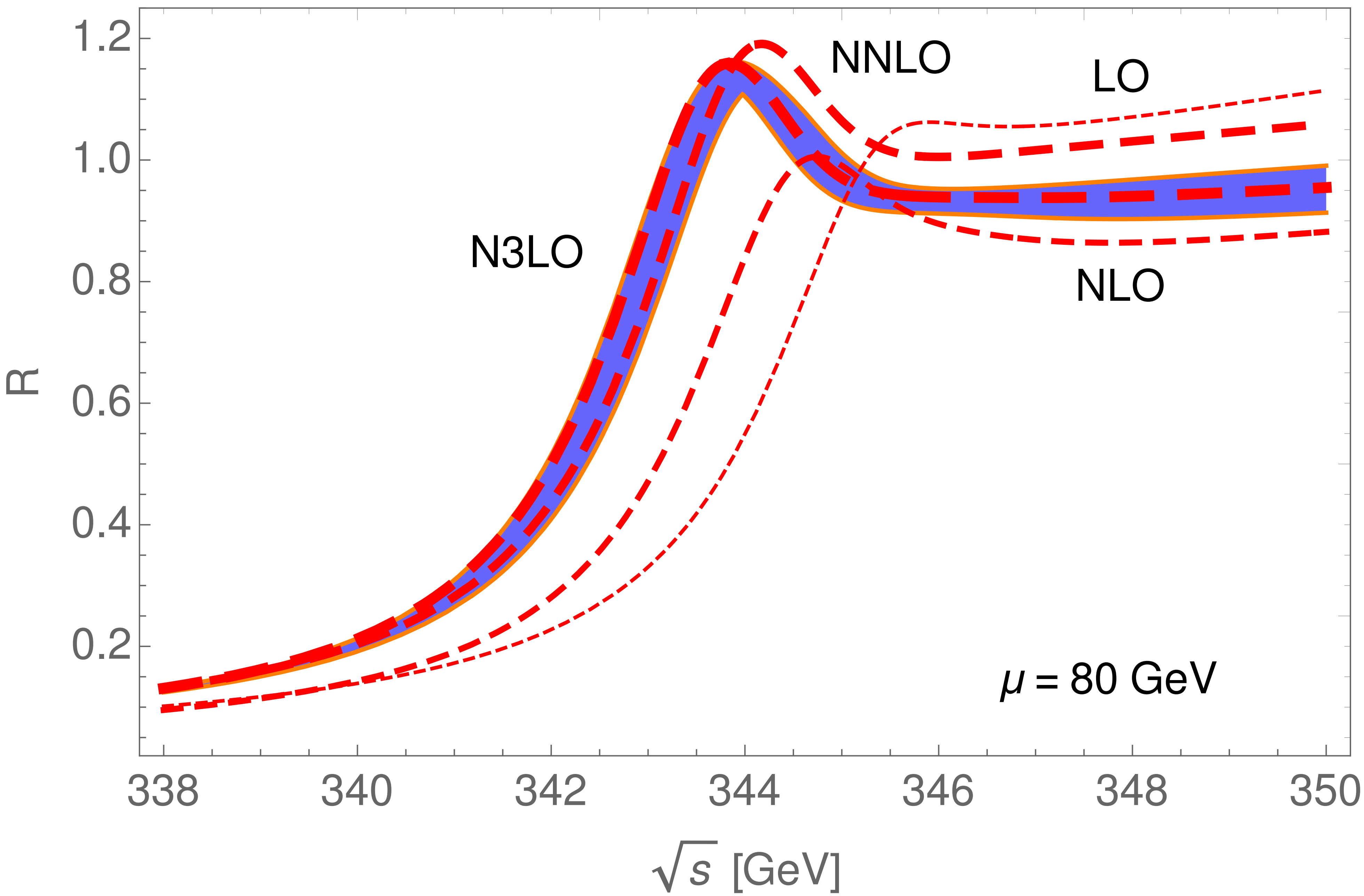
Top Physics and EW Physics

- A little about the “mass”.



M. Beneke, Y. Kiyo, arXiv:2409.05960[hep-ph].

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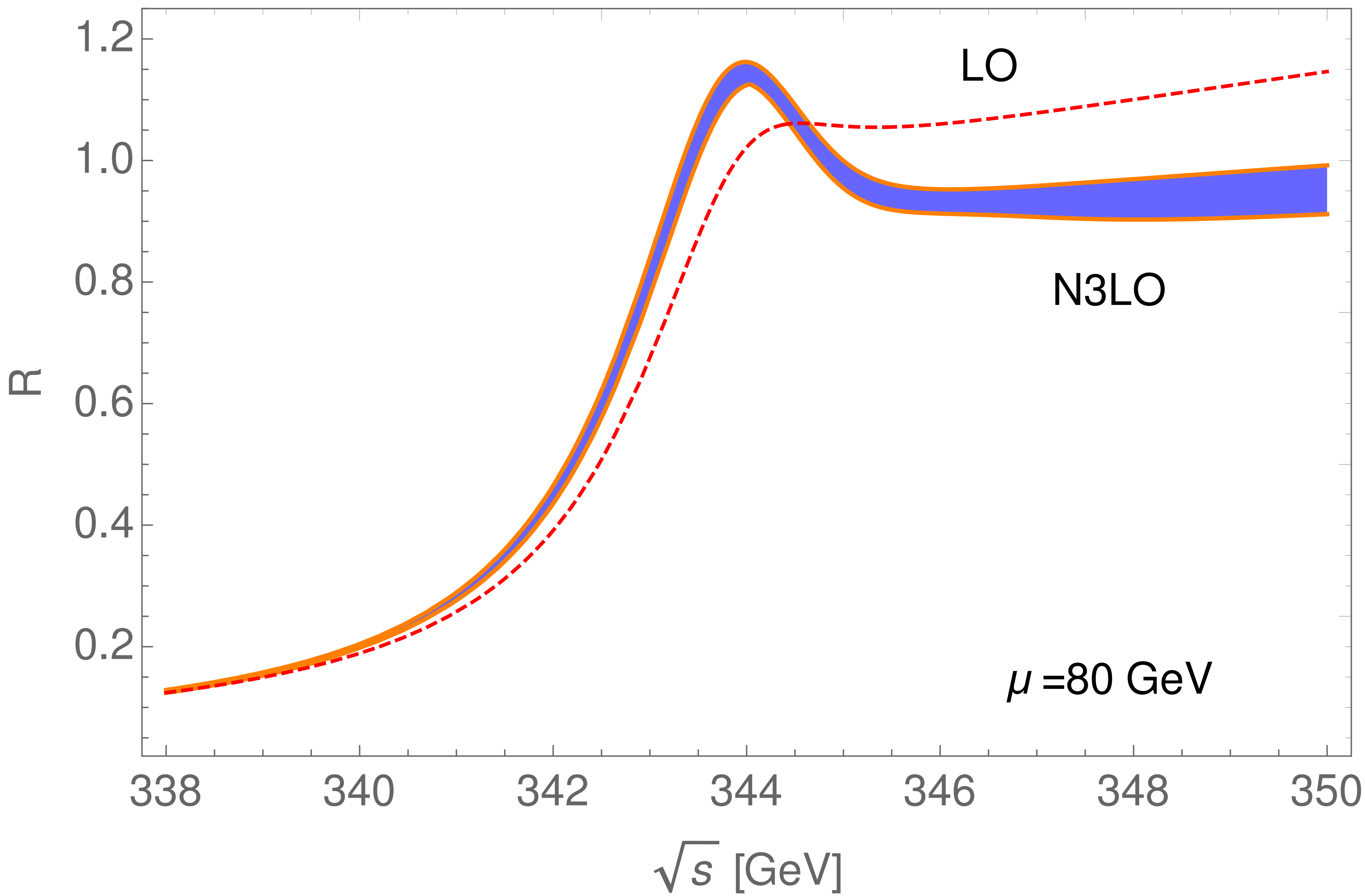

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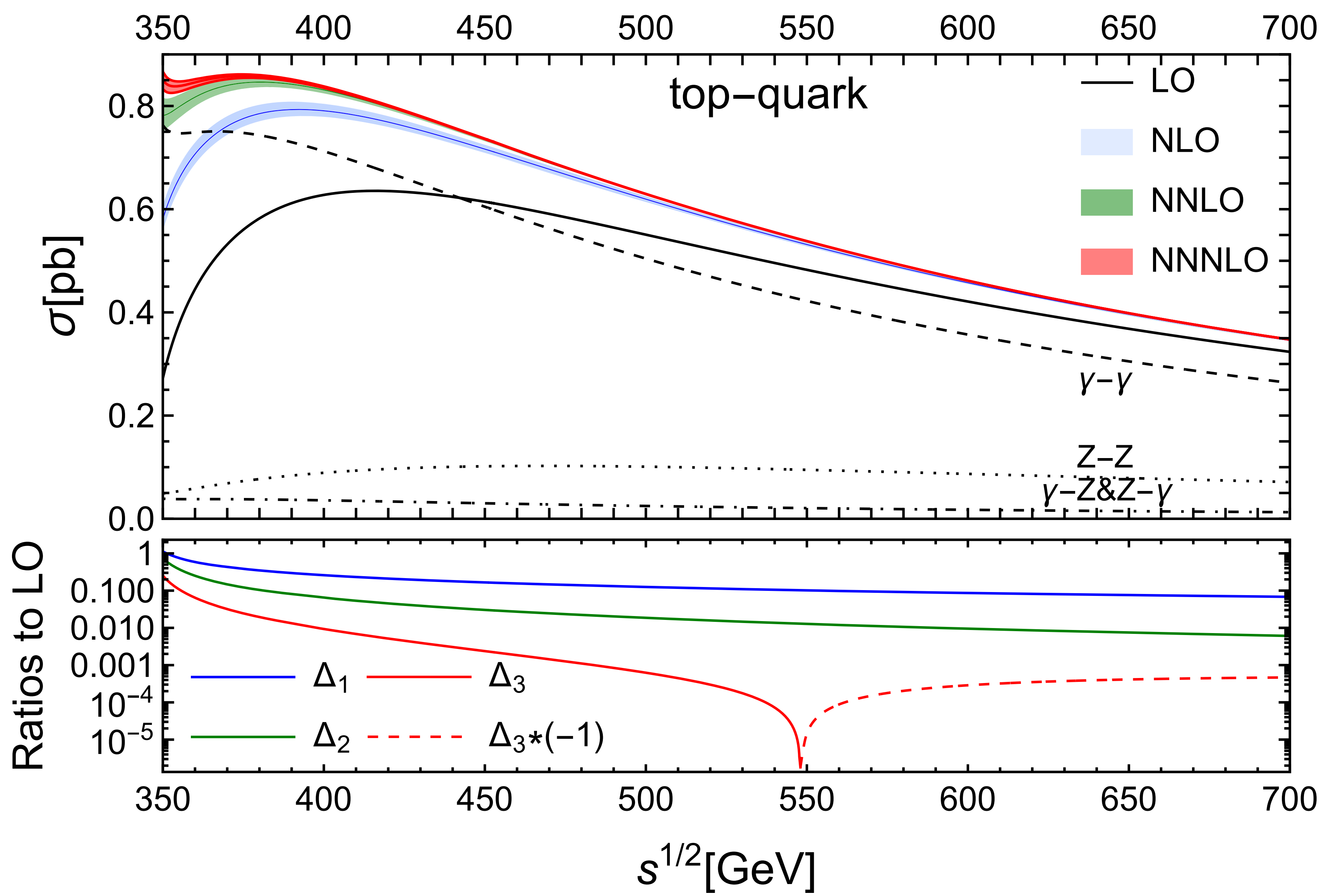
Top Physics and EW Physics

- New results beyond `QQbar_threshold` ("N3LO" QCD+NNLO EW).



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Top Physics and EW Physics

- Forward-backward asymmetry in top-pair production.

Beam polarization	LO		NLO		NNLO	
$(e_L^-,\ e_R^+)$	σ_S [pb]	$A_{\mathrm{FB}}^{\mathrm{LO}}$	σ_S [pb]	A_1 $[10^{-2}]$	σ_S [pb]	A_2 $[10^{-2}]$
$(0,\ 0)$	0.58477	0.2342	$0.78874^{-0.01484}_{+0.01741}$	$3.67^{+0.313}_{-0.267}$	$0.85037^{-0.01009}_{+0.01002}$	$2.92^{+0.188}_{-0.168}$
$(-80\%,\ +30\%)$	0.32039	0.2549	$0.43232^{-0.00814}_{+0.00955}$	$3.62^{+0.309}_{-0.263}$	$0.46633^{-0.00556}_{+0.00553}$	$2.86^{+0.183}_{-0.163}$
$(+80\%,\ -30\%)$	0.56846	0.2226	$0.76657^{-0.01441}_{+0.01691}$	$3.70^{+0.316}_{-0.270}$	$0.82623^{-0.00977}_{+0.00970}$	$2.95^{+0.191}_{-0.170}$
$(+80\%,\ +30\%)$	0.99800	0.2196	$1.34571^{-0.02530}_{+0.02968}$	$3.71^{+0.317}_{-0.270}$	$1.45035^{-0.01714}_{+0.01701}$	$2.96^{+0.192}_{-0.171}$
$(-80\%,\ -30\%)$	0.45224	0.2664	$0.61037^{-0.01151}_{+0.01350}$	$3.59^{+0.306}_{-0.261}$	$0.65856^{-0.00788}_{+0.00784}$	$2.82^{+0.180}_{-0.160}$

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Top and bottom quark forward-backward asymmetries at next-to-next-to-leading order QCD in (un)polarized electron positron collisions

Werner Bernreuther,[a,*] **Long Chen,**[b,*] **Peng-Cheng Lu**[b,*] **and Zong-Guo Si**[b,*]

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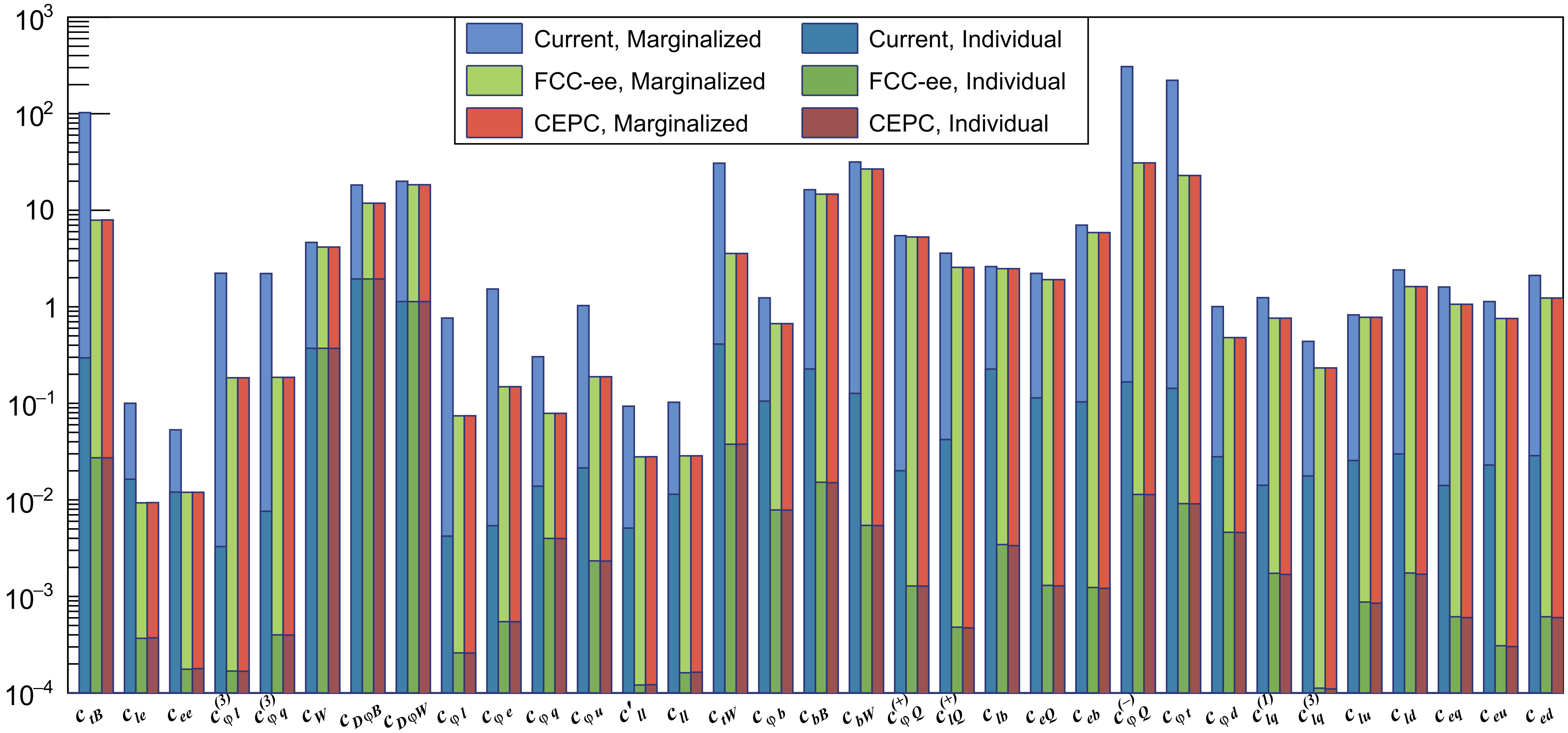
[b] *School of Physics, Shandong University, Jinan, Shandong 250100, China*

Top Physics and EW Physics

- SMEFT



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Some Memorandum and New Topics

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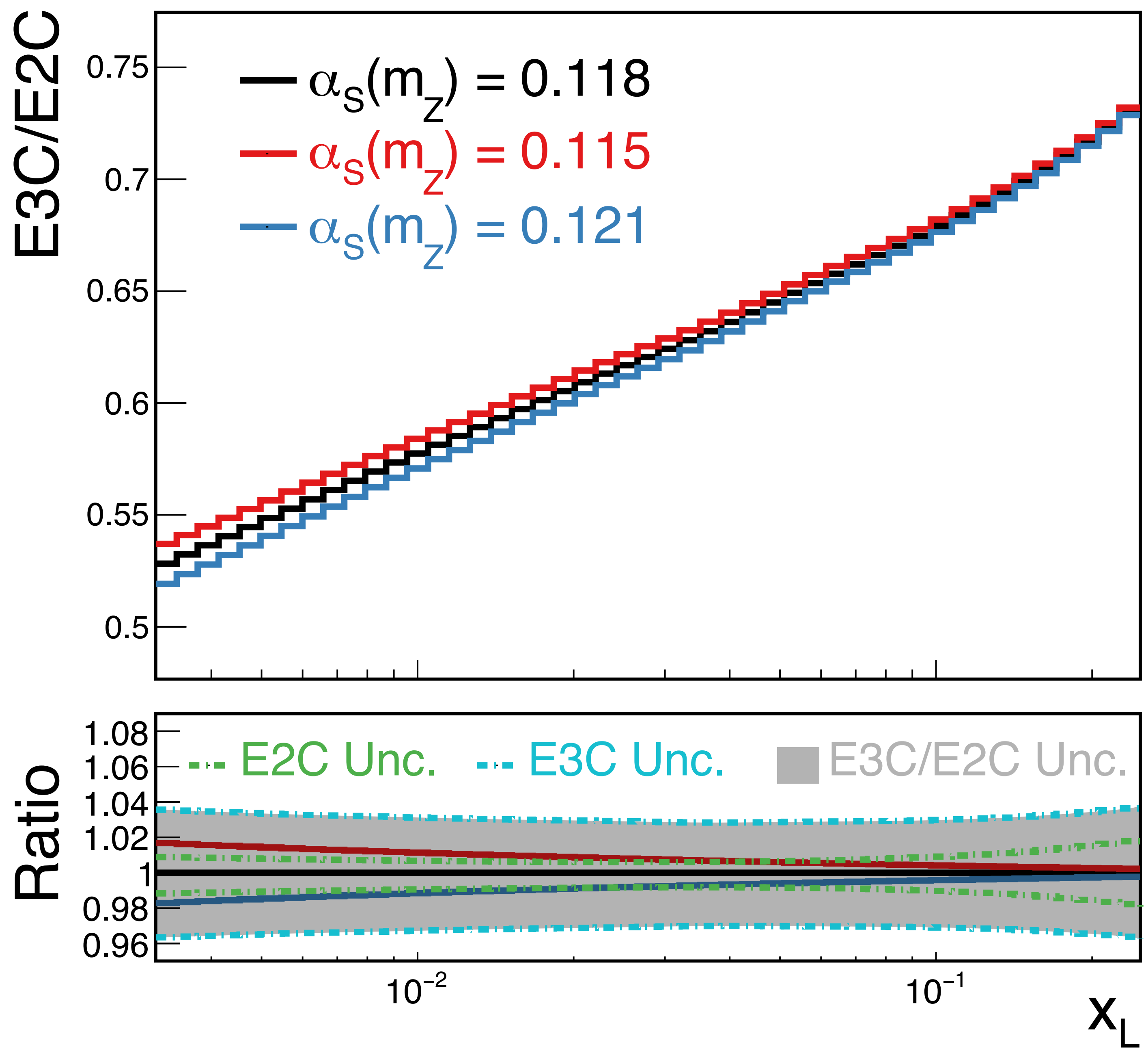
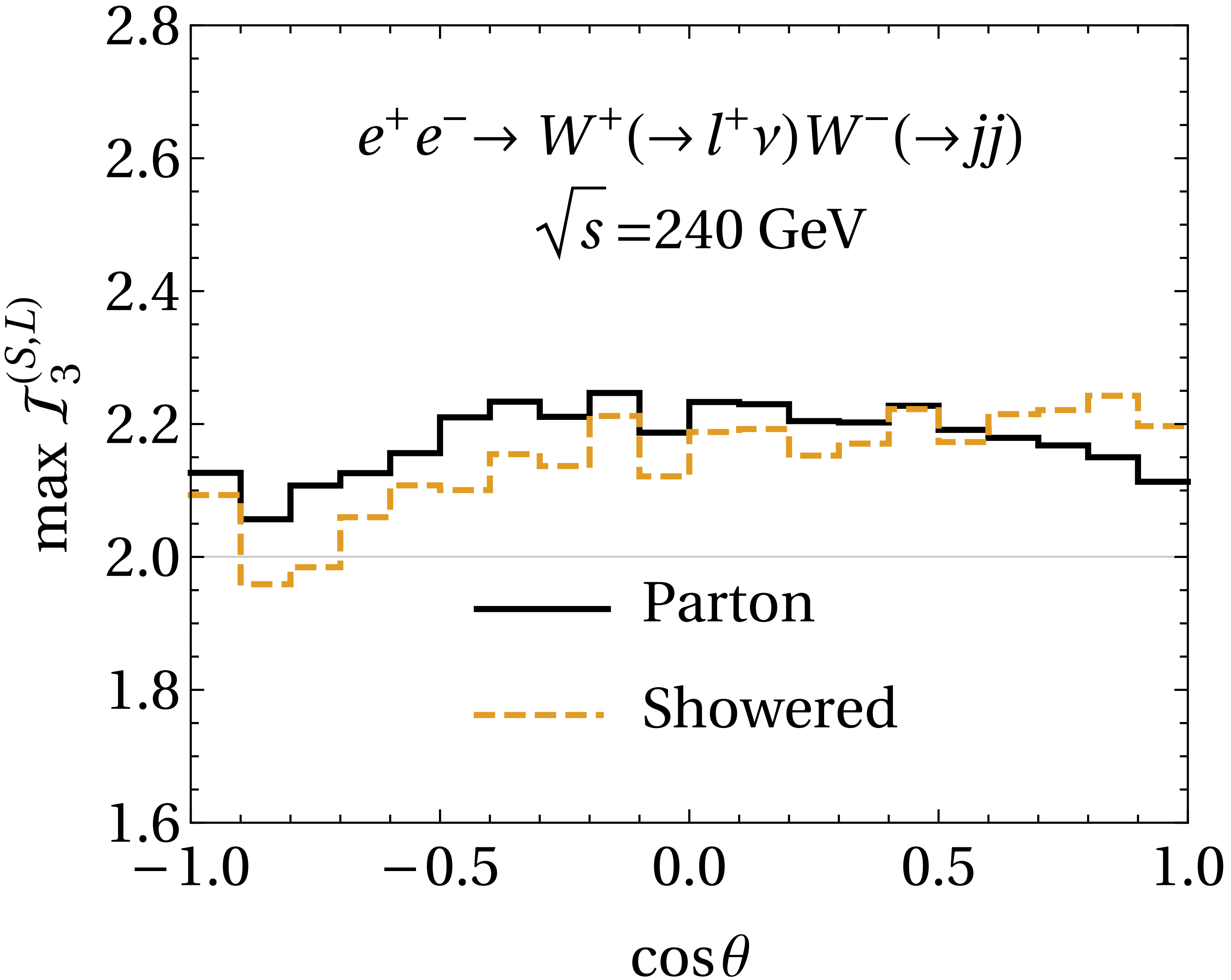
- Energy correlators and QCD.



Z. Liu, M. Ruan, M. Xiao, Z. Xu, arXiv:2406.10946[hep-ph].

Some Memorandum and New Topics

- Testing the violation of the Bell inequality at CEPC.



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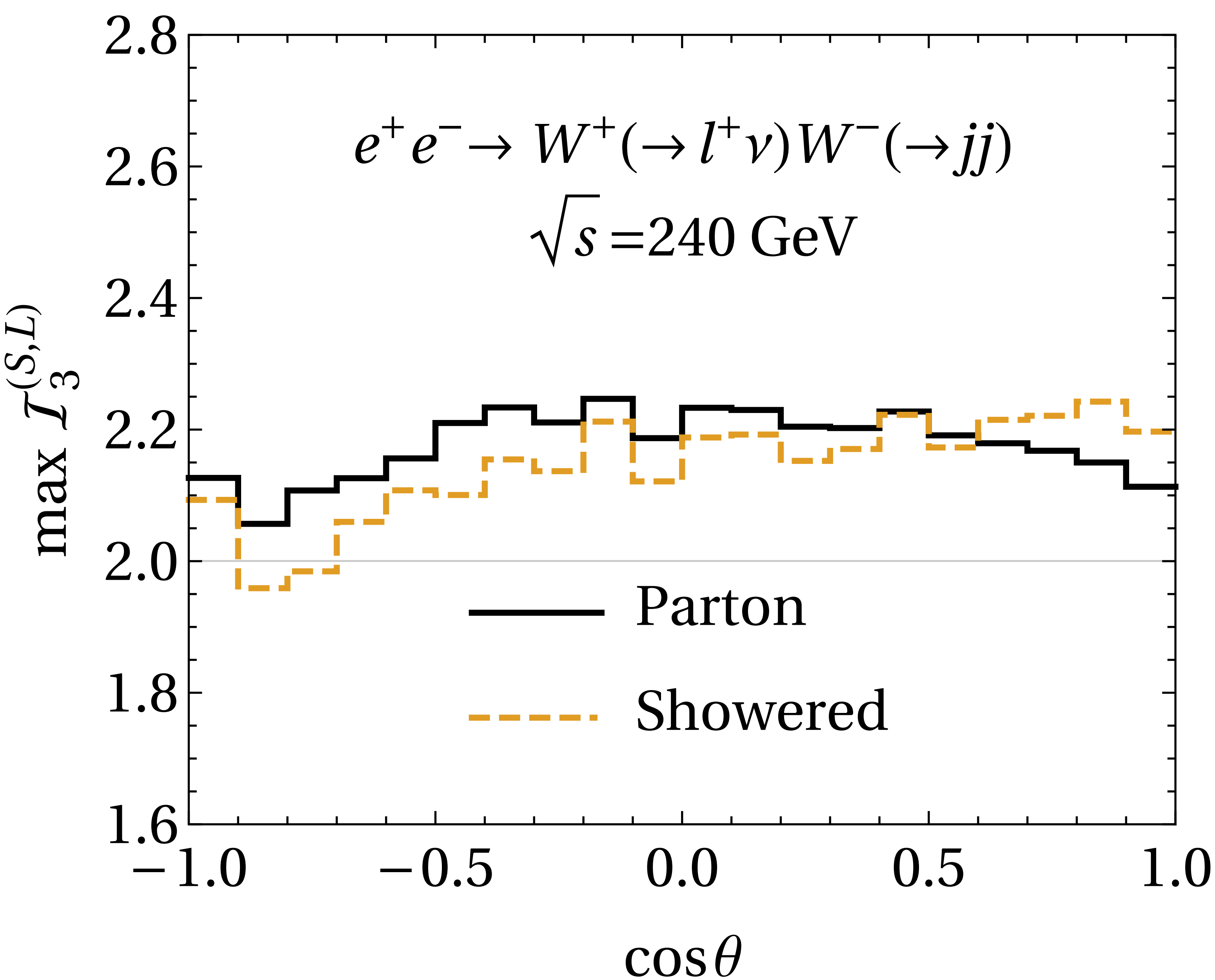

¡Gracias!

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