Guaranteed Deliverables at the Muon Collider

Second Annual USMCC Meeting

University of Chicago

Aug 07, 2025

Rodolfo Capdevilla
Fermilab

Electroweak Symmetry Restoration and Radiation Amplitude Zeros

Rodolfo Capdevilla (Fermilab), Tao Han (Carnegie Mellon U.) (Dec 16, 2024)

e-Print: 2412.12336 [hep-ph]

Testing the neutrino content of the muon at muon colliders

Rodolfo Capdevilla (Fermilab), Francesco Garosi (Garching, Max Planck Inst. and SISSA, Trieste and INFN, Trieste), David Marzocca (INFN, Trieste), Bernd Stechauner (CERN and Vienna, Tech. U.) (Oct 28, 2024)

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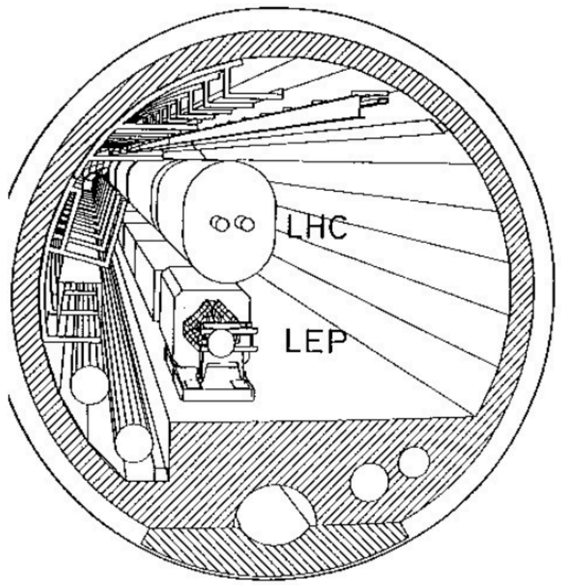
Outline

1. Introduction
    - The Higgs
2. Other Deliverables
    - Neutrino PDF
    - EW Symmetry Restoration

Conclusions

- **Before LHC:**



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

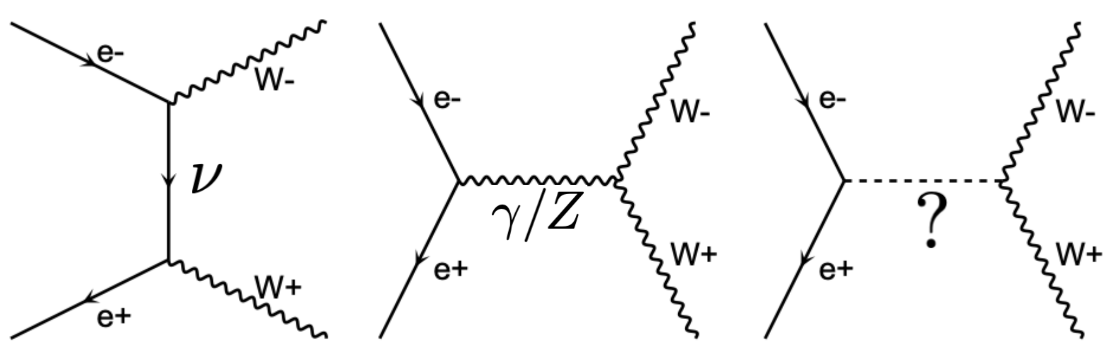
PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Satisfied with these successes,
we have now to face deeper questions such

what is the origin of mass? *Higgs? (*)*
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

(*) A no-lose theorem for the LHC:



We give an S-matrix theoretic demonstration that if the Higgs boson mass exceeds $M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}}$ partial-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation

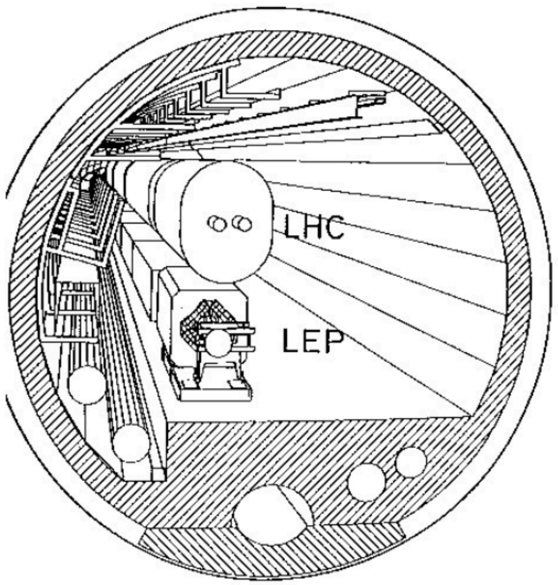
$$M_h \leq M_c = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}} \simeq 1\ \mathrm{TeV}/c^2$$

Lee, Quigg, Thacker, Phys. Rev. D **16** (1977) 1519

"If the Higgs boson did not exist, we should have to invent something very much like it"

- Chris Quigg

- **Now:**



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Satisfied with these successes,

we have now to face deeper questions such

~~what is the origin of mass?~~ → *Yes, the Higgs! … yet (*)*

what kind of unification may exist beyond the standard model?

what is the origin of flavour?

is there a deeper reason for gauge symmetry?

(*) We only got more questions:

Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the Higgs mass?

Other questions include:

What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! What's new at the 10TeV c.o.m. scale?

- **The Higgs:**

What kind of unification may exist beyond the SM?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?
Is there a more fundamental description of EWSB?
What mechanism sets the scale and stabilizes the Higgs mass?

What is the nature of Dark Matter?
What is the mechanism for Baryogenesis?
What is the mechanism for neutrino masses?
The unknown! How can nature surprise us?

The Higgs might be the key!

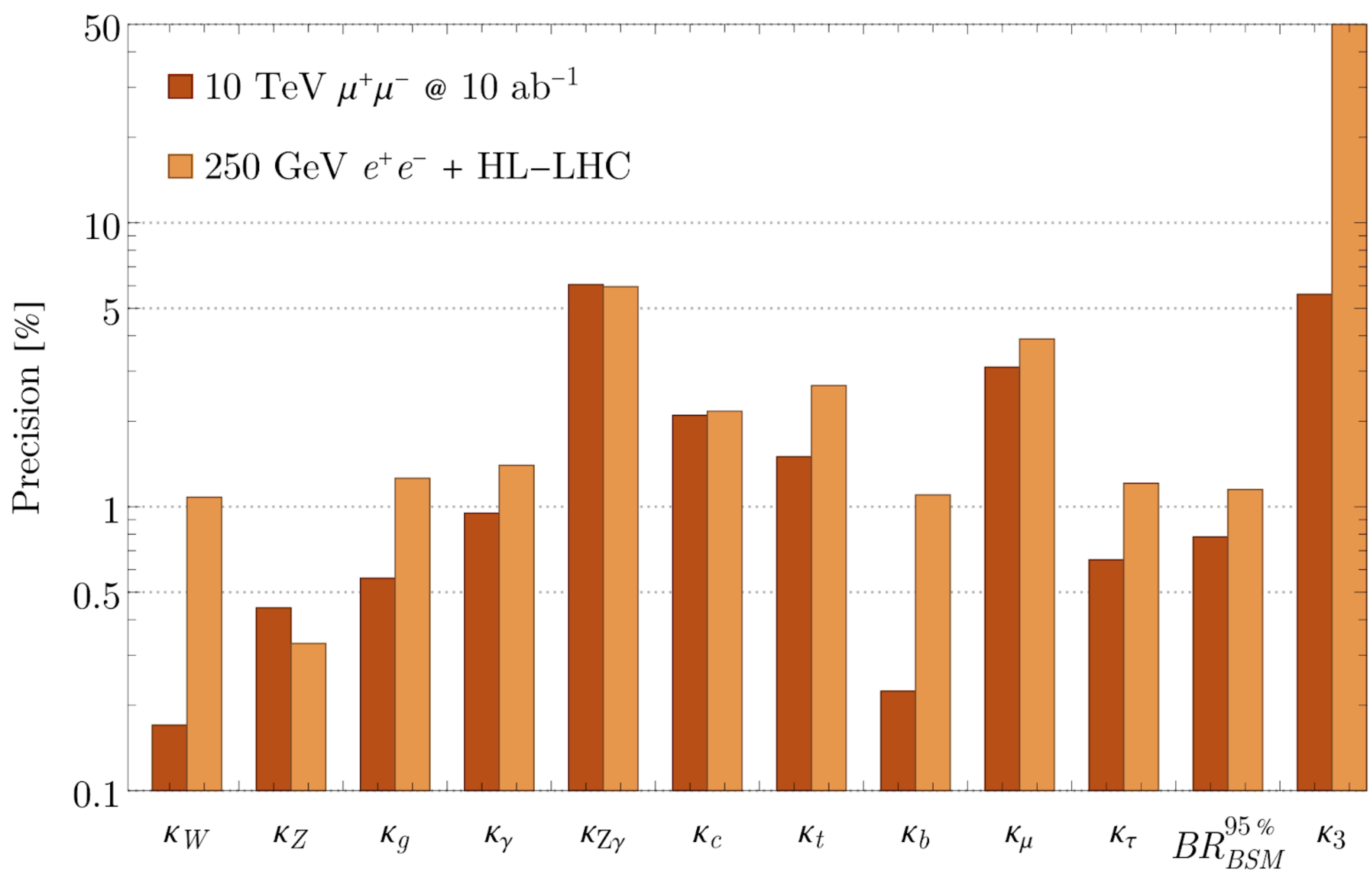
*Measuring **Higgs couplings** might answer some of the fundamental questions!*

*The **Higgs** might be the **portal** to new physics!*

WE NEED TO PUT THE HIGGS UNDER A 'MICROSCOPE' STUDY IT TO DEATH!

- **Higgs couplings @ Muon Collider:**

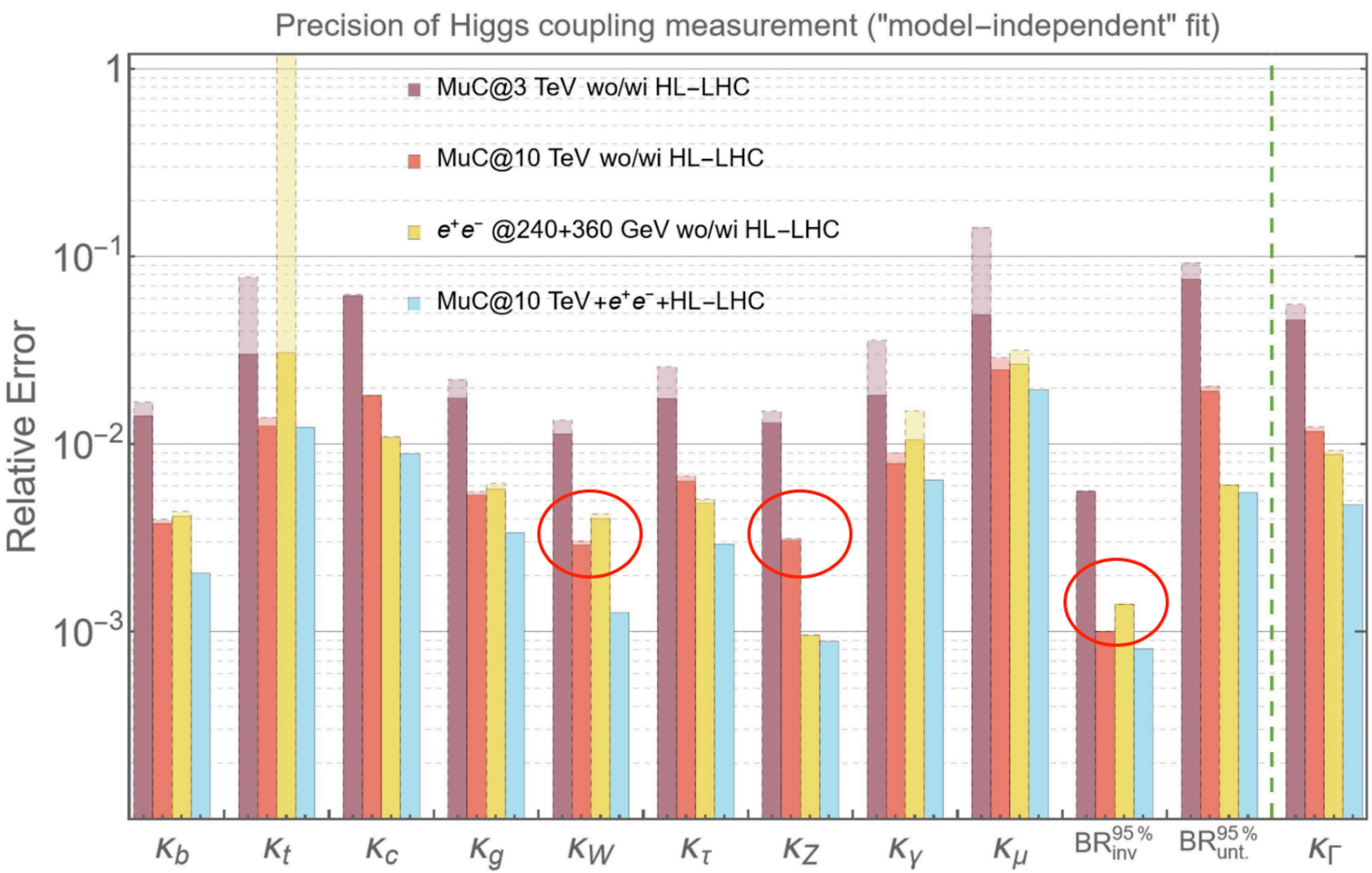
Percent level Higgs couplings!



Han, Liu, Low, Wang, Phys. Rev. D 103 (2021) 1, 013002
Buttazzo, Franceschini, Wulzer, JHEP 05 (2021) 219
Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185
C. Accettura et al., Eur. Phys. J. C 83 (2023) 9, 864
Matthew Forslund, Patrick Meade, JHEP 01 (2024) 182 *
P. Andreetto et al, arXiv:2405.19314

- **Forward Muons:**

BR(inv) comparable to a Higgs factory
ZZH coupling comparable to WWH



Matthew Forslund, Patrick Meade, JHEP 08 (2022) 185
Ruhdorfer, Salvioni, Wulzer, PRD 107 (2023) 9, 095038
Matthew Forslund, Patrick Meade, JHEP 01 (2024) 182
Li, Liu, Lyu, PRD 109 (2024) 7, 073009 *

Outline

1. Introduction

- The Higgs

2. Other Deliverables **?**

Electroweak Radiation

Buttazzo, Franceschini, Wulzer, JHEP 05 (2021) 219
Han, Ma, Xie, Phys. Rev. D 103 (2021) 3, L031301
Han, Ma, Xie, JHEP 02 (2022) 154
Garosi, Marzocca, Trifinopoulos, JHEP 09 (2023) 107

Precision Electroweak

Han, Liu, Low, Wang, Phys. Rev. D 103 (2021) 1, 013002
Ma, Pagani, Zaro, Phys. Rev. D 111 (2025) 5, 053002
DeGouvea, Thompson, e-Print: 2505.00152

Yukawas: muon, top,...

Chen, Liu, Phys. Rev. D 109 (2024) 7, 075020
Liu, Lyu, Mahbub, Wang, Phys. Rev. D 109 (2024) 3, 035021
Cassidy, Dong, Kong, Lewis, Zhang, Zheng, JHEP 05 (2024) 176
Han, Kilian, Kreher, Ma, Reuter, Striegl, JHEP 12 (2021) 162
Celada, Han, Kilian, et al., JHEP 08 (2024) 021

- Neutrino PDF

- EW Symmetry Restoration

Conclusions

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- **Neutrino PDF**

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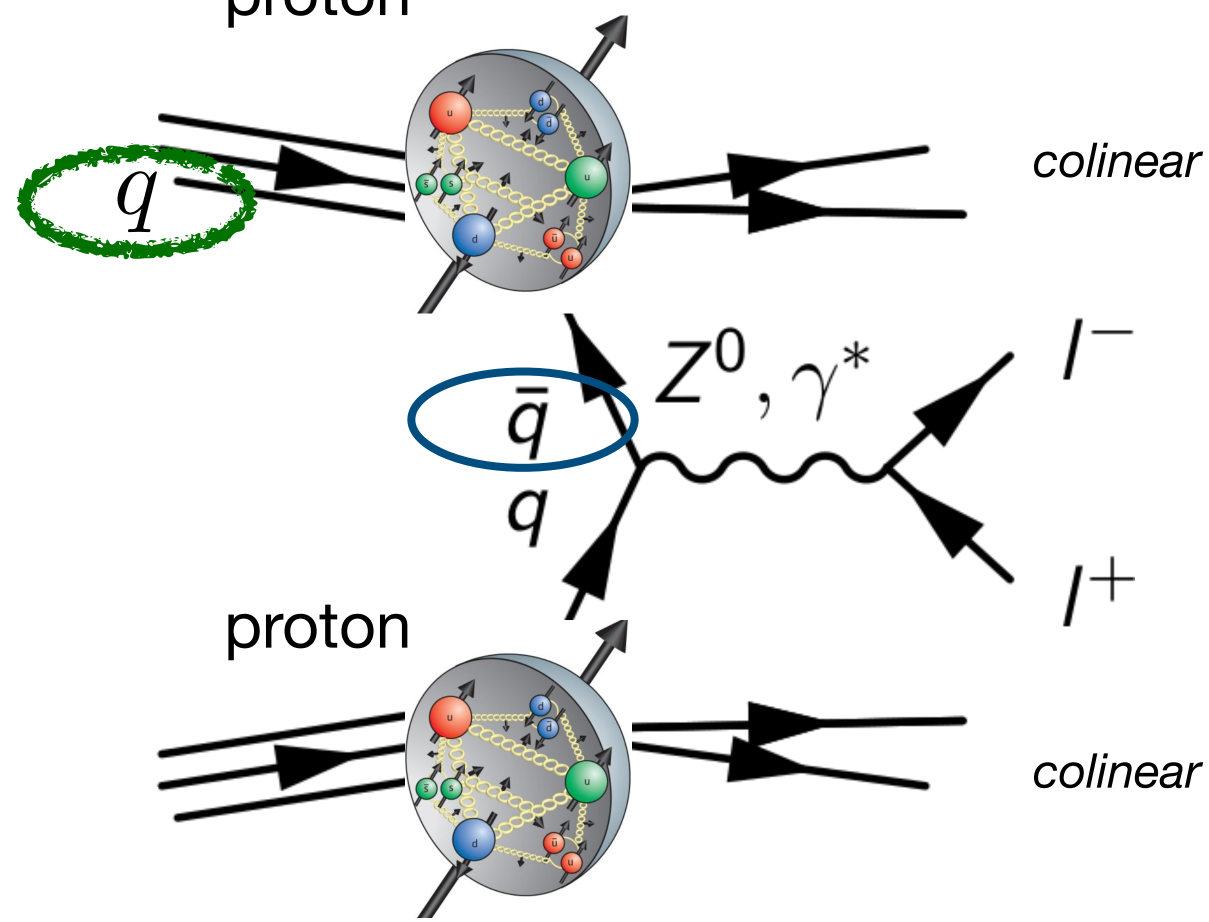
- EW Symmetry Restoration

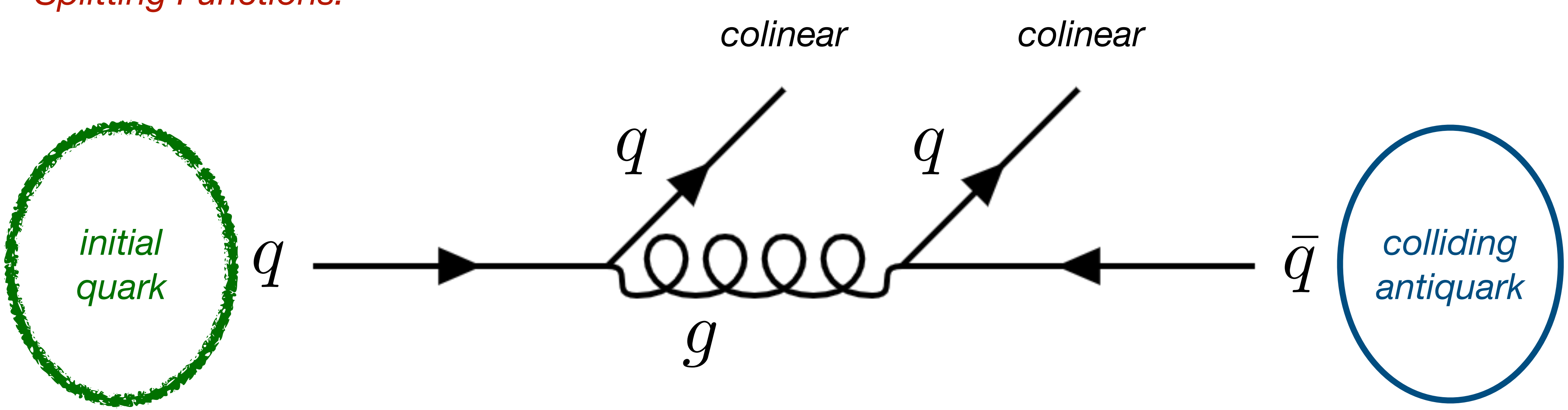
Conclusions

- **Splitting Functions**

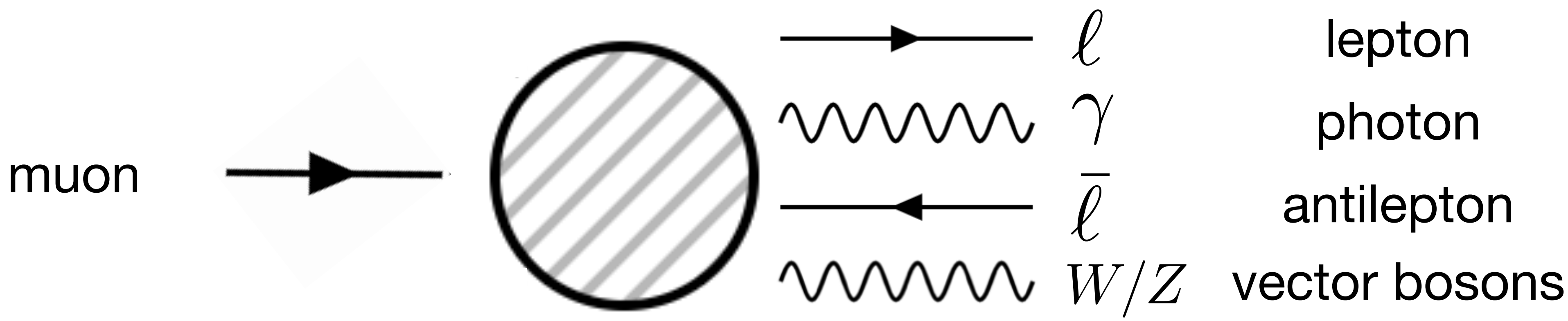


The proton is a 'soup' of particles?

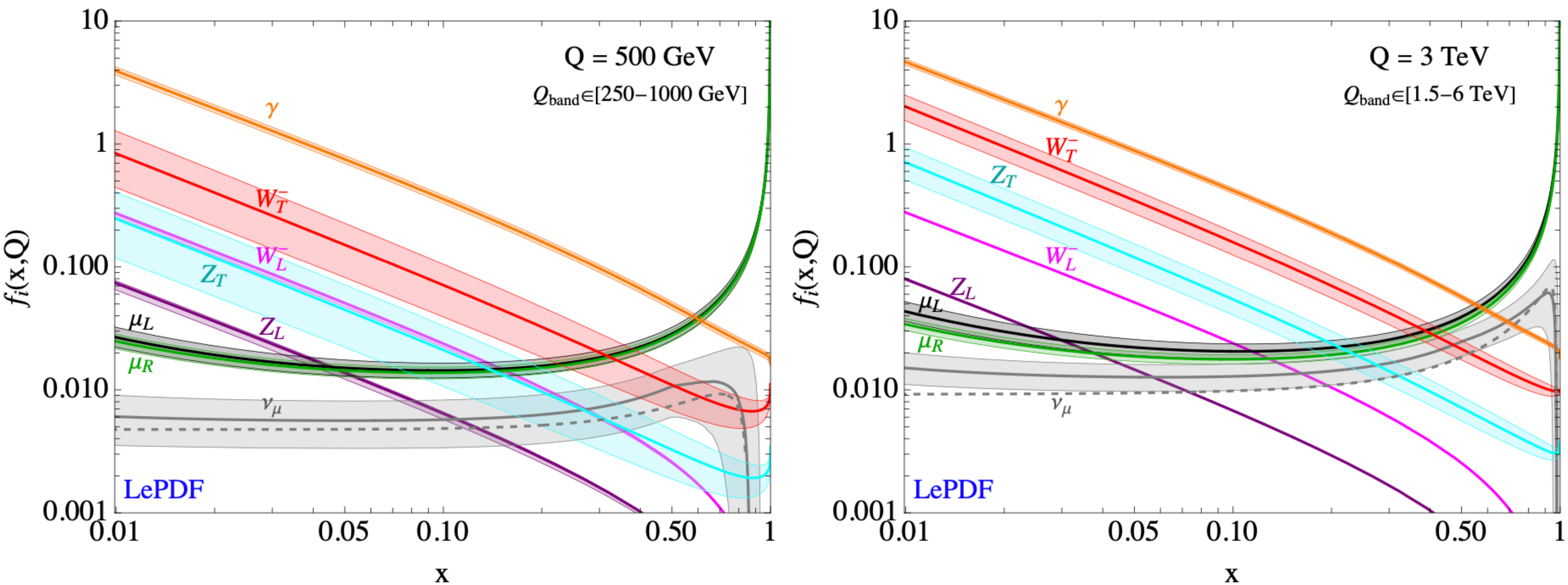
Splitting Functions!



- **Muon PDFs**



F. Garosi, D. Marzocca, S. Trifinopoulos, JHEP 09 (2023) 107



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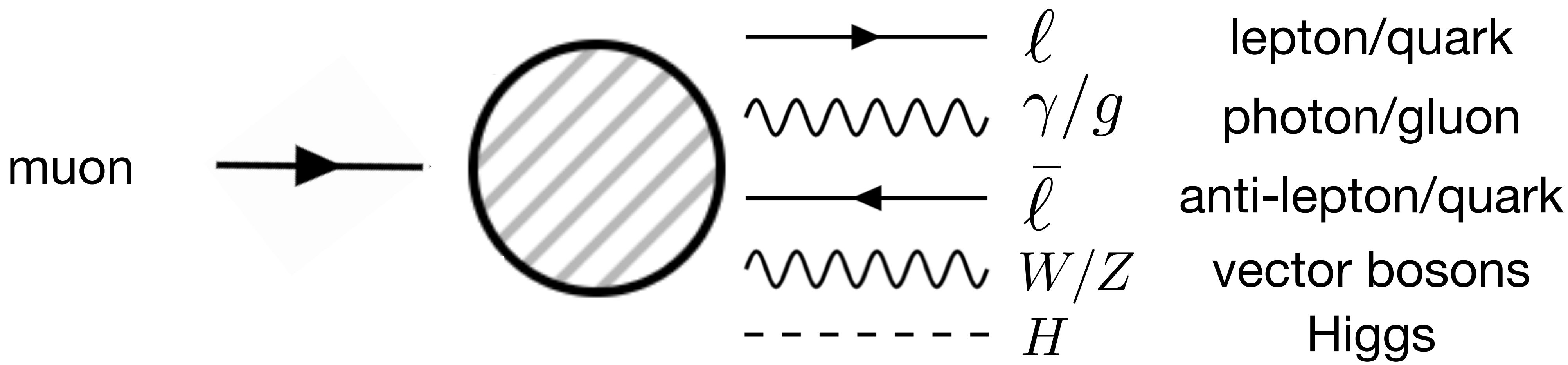

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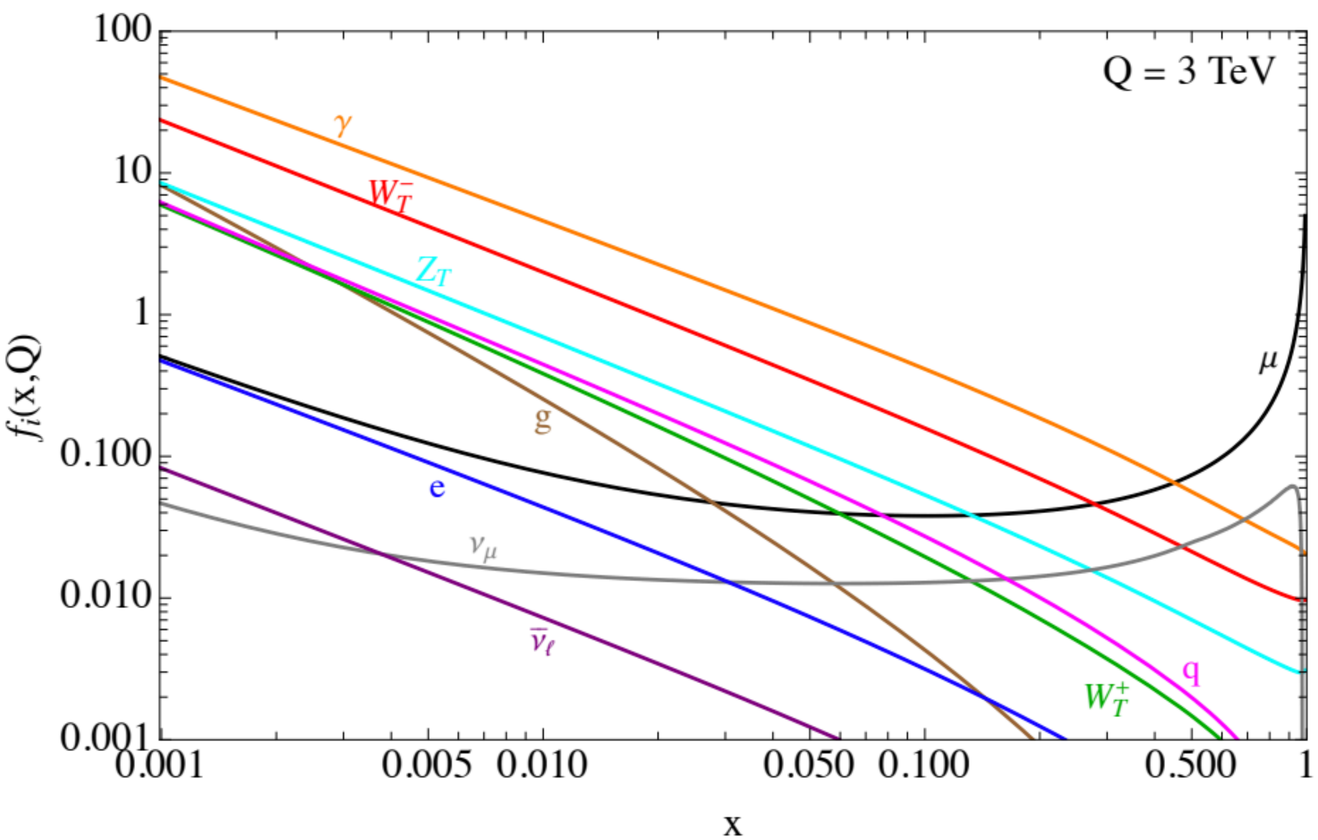
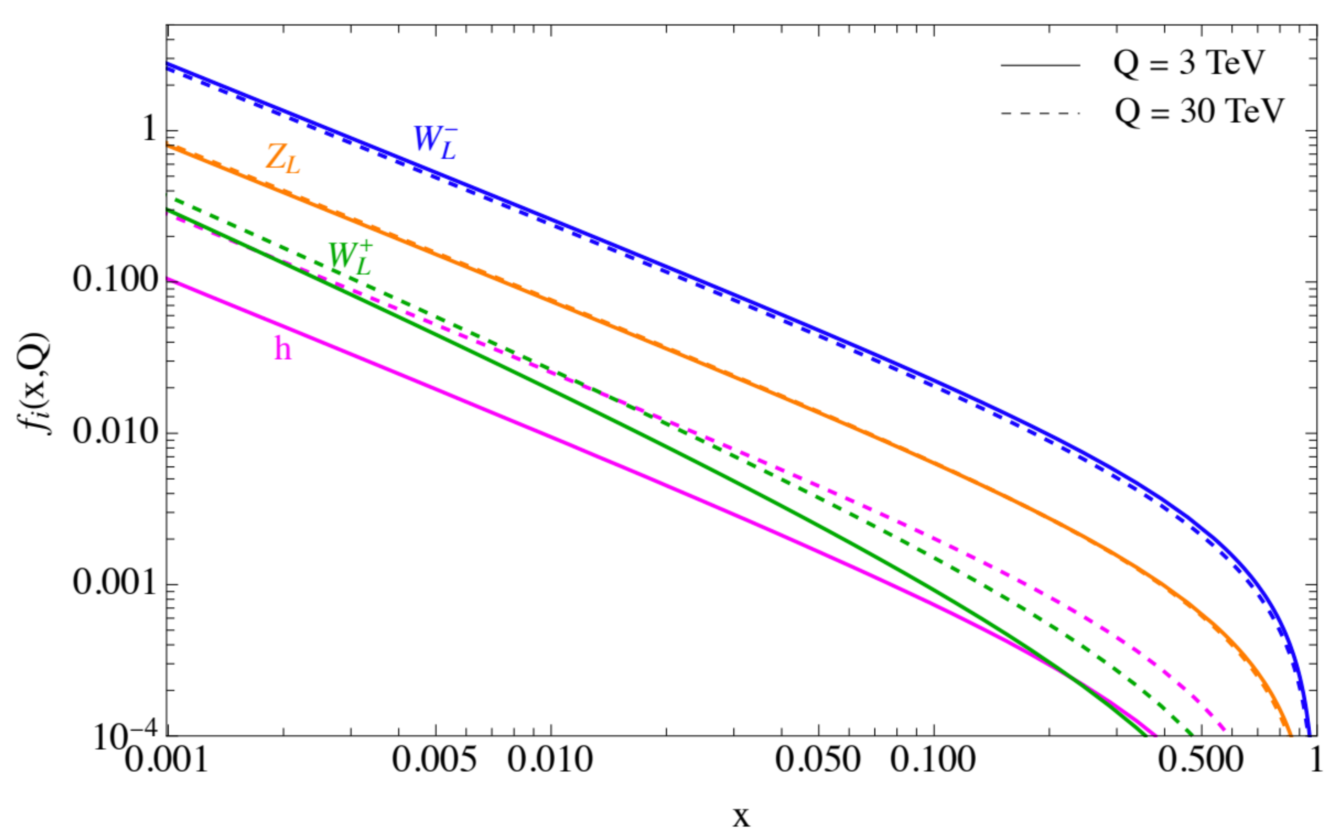
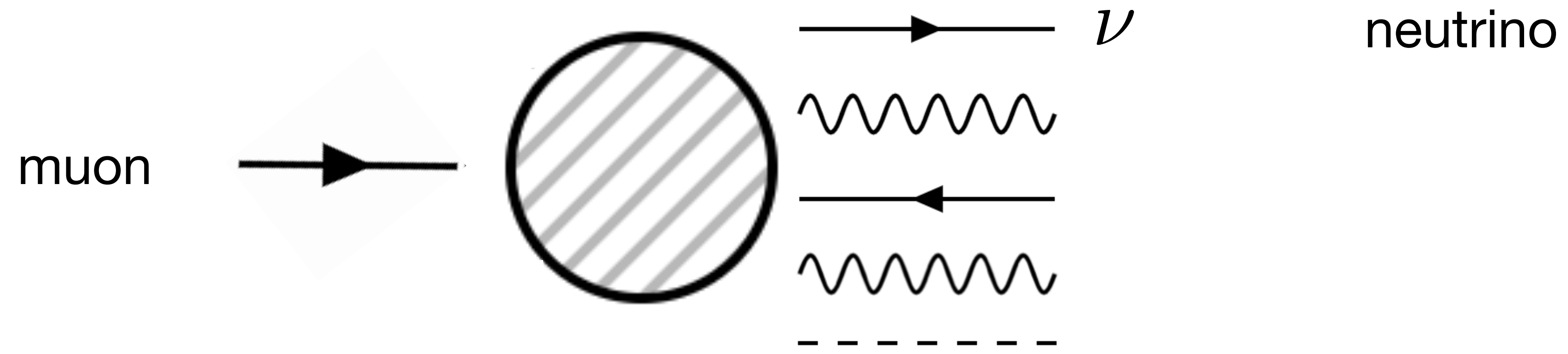




- **Neutrino PDF**



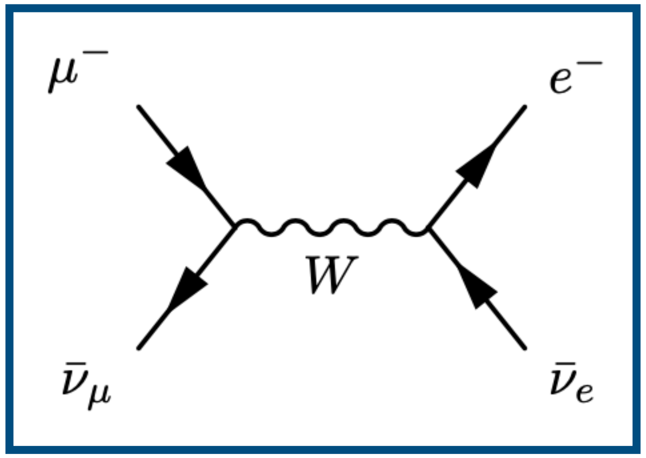
Calculable! A prediction of the SM

How can we 'measure' these predictions? **(Does it make sense?)**

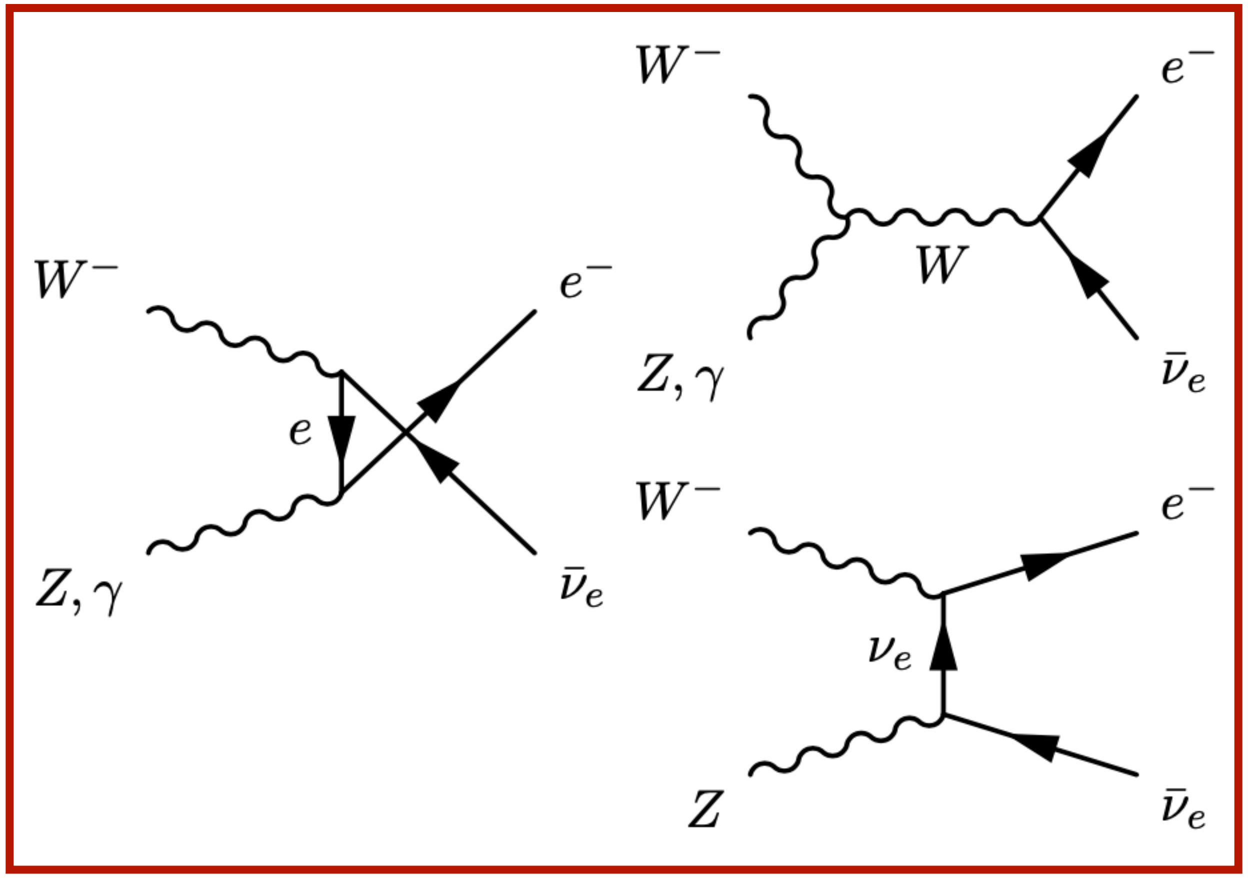
Testing the SM at multi-TeV energies

- **Monolepton**

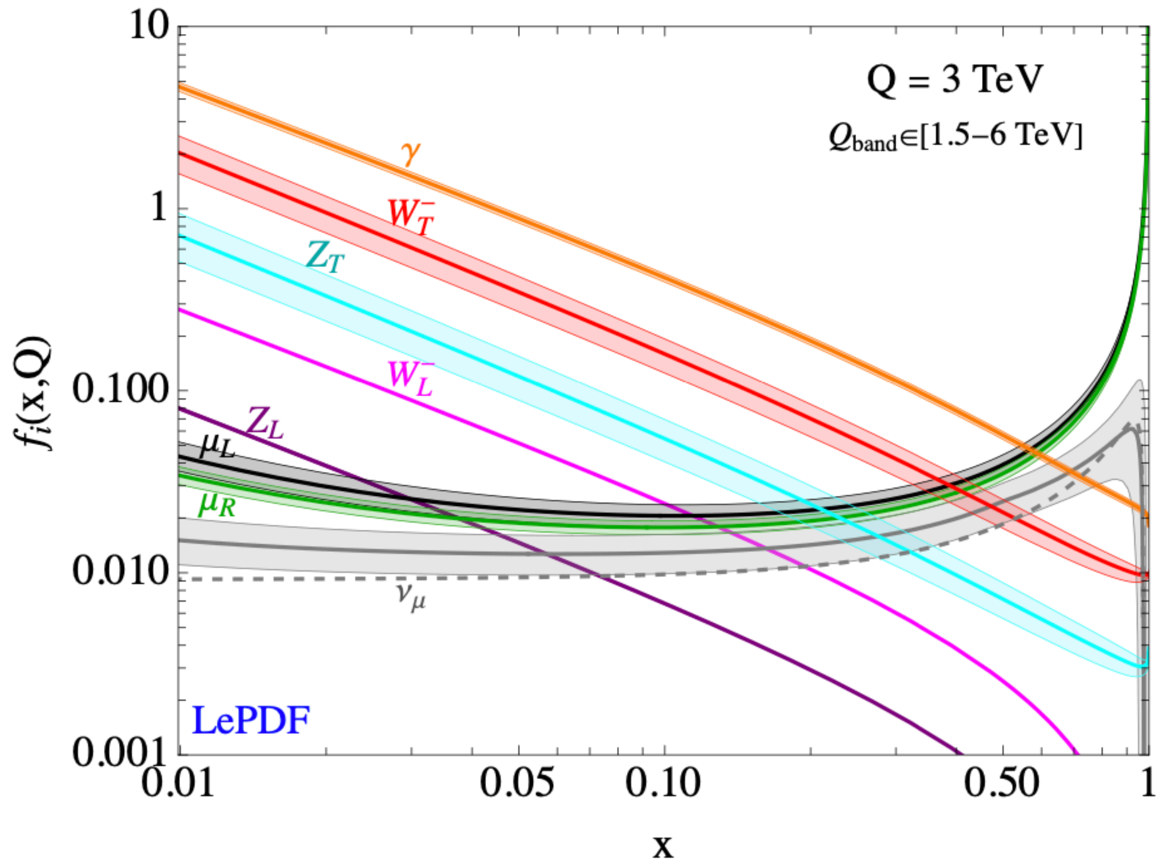
Signal



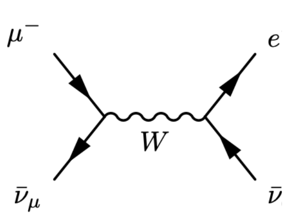
Background

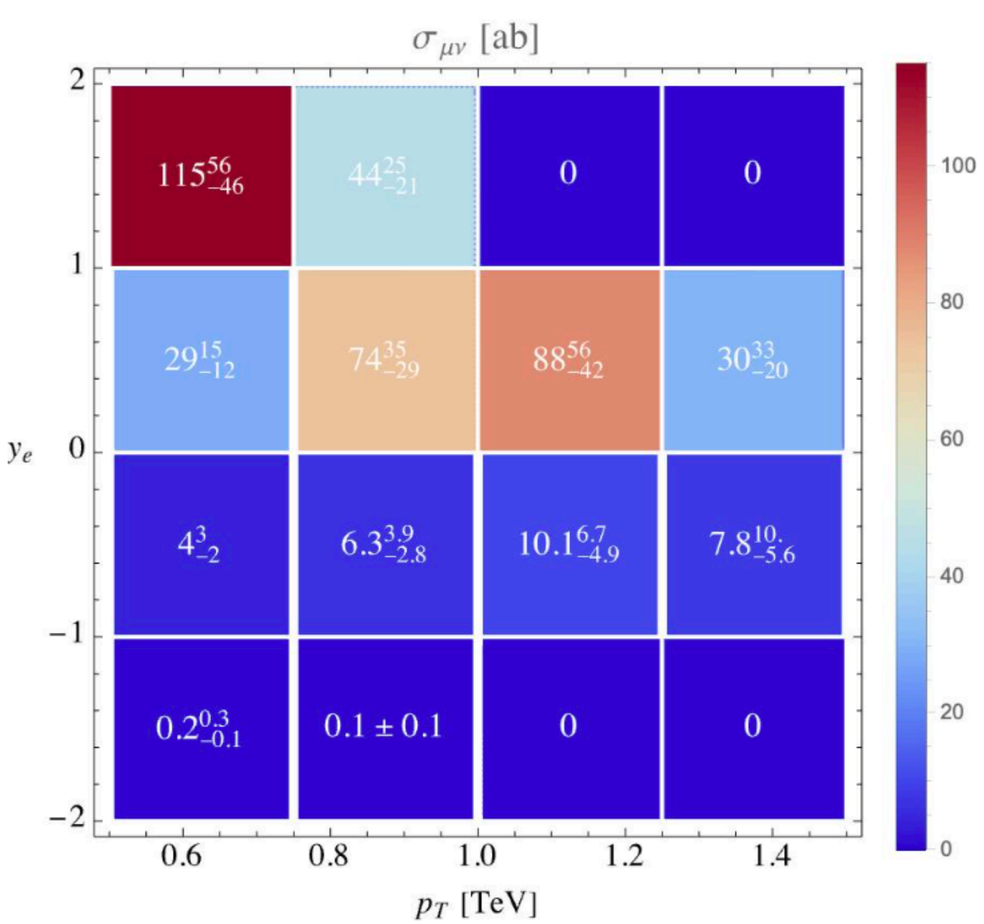


- **Monolepton**



Signal





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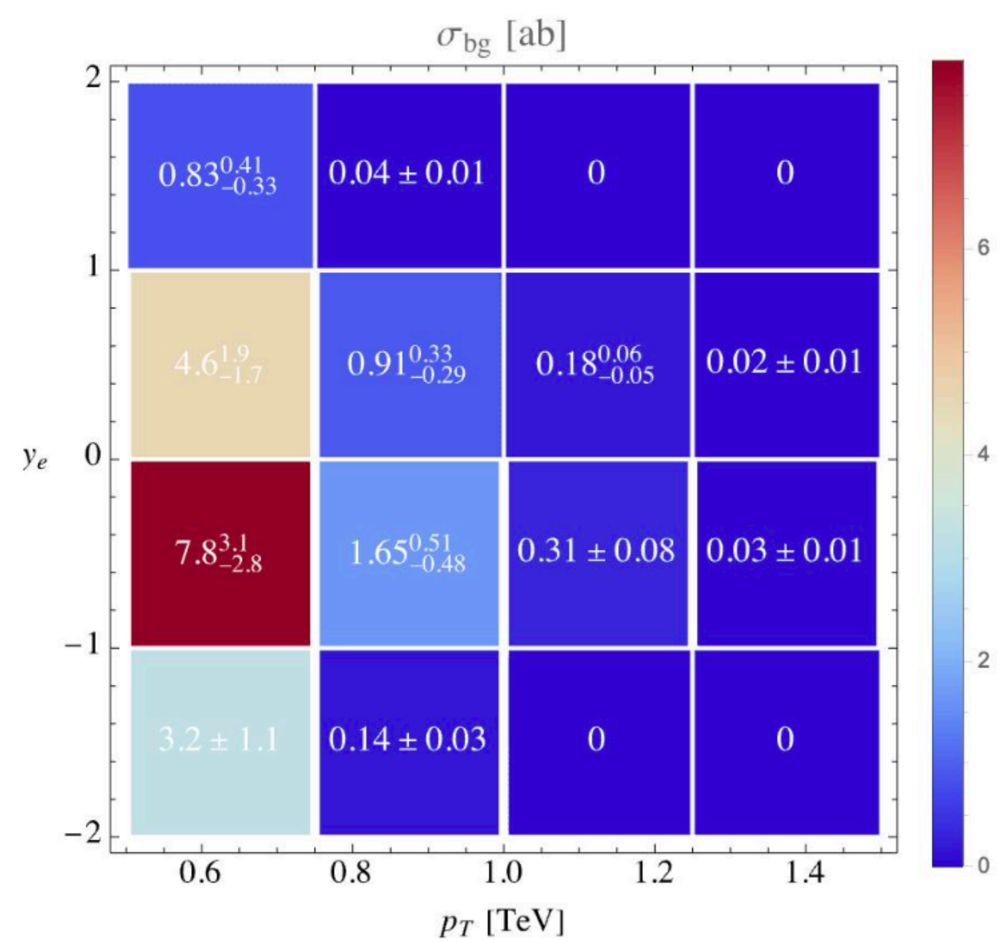
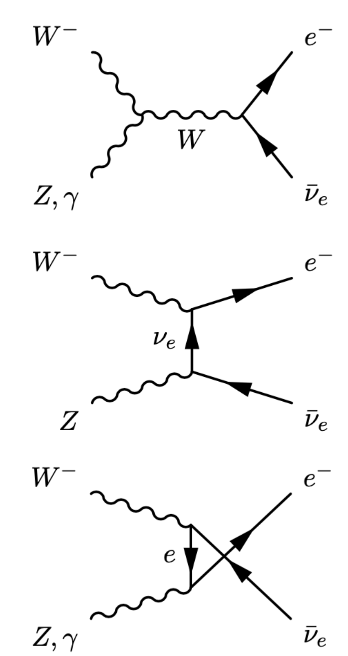
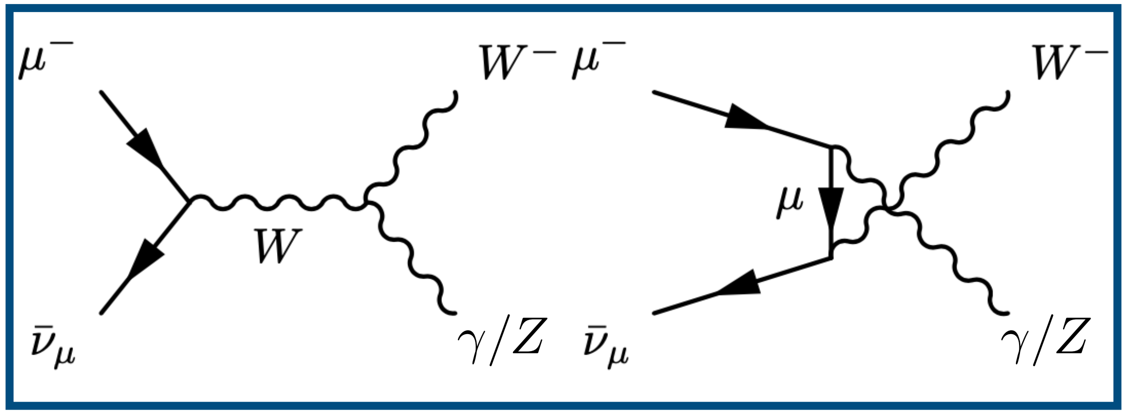
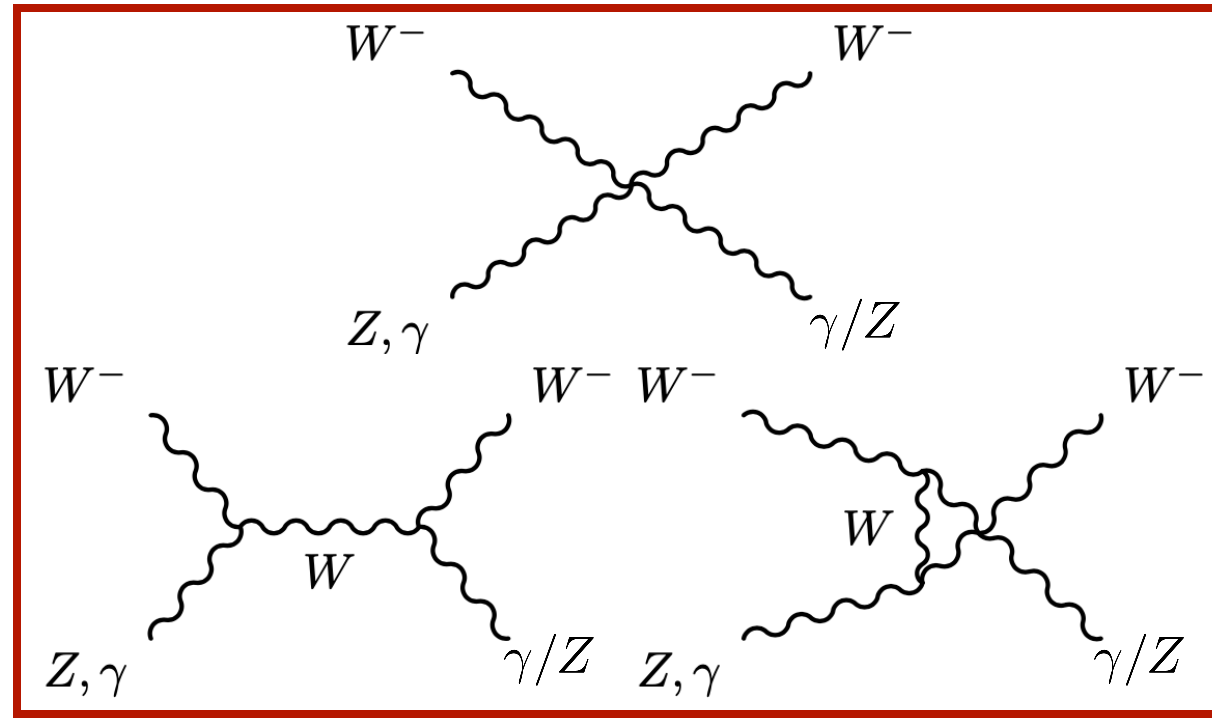




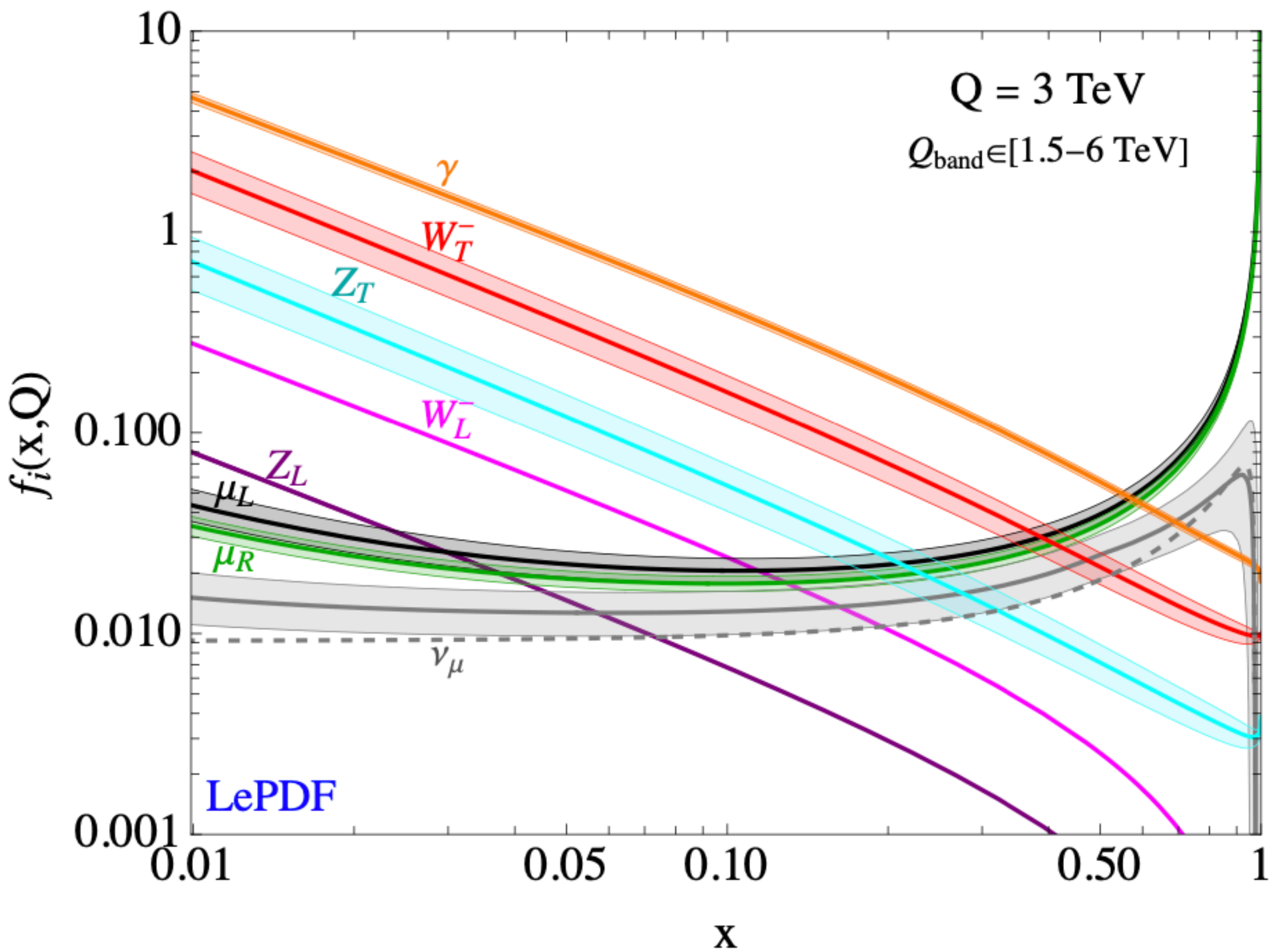
- **W + gamma/Z**



Signal



Background



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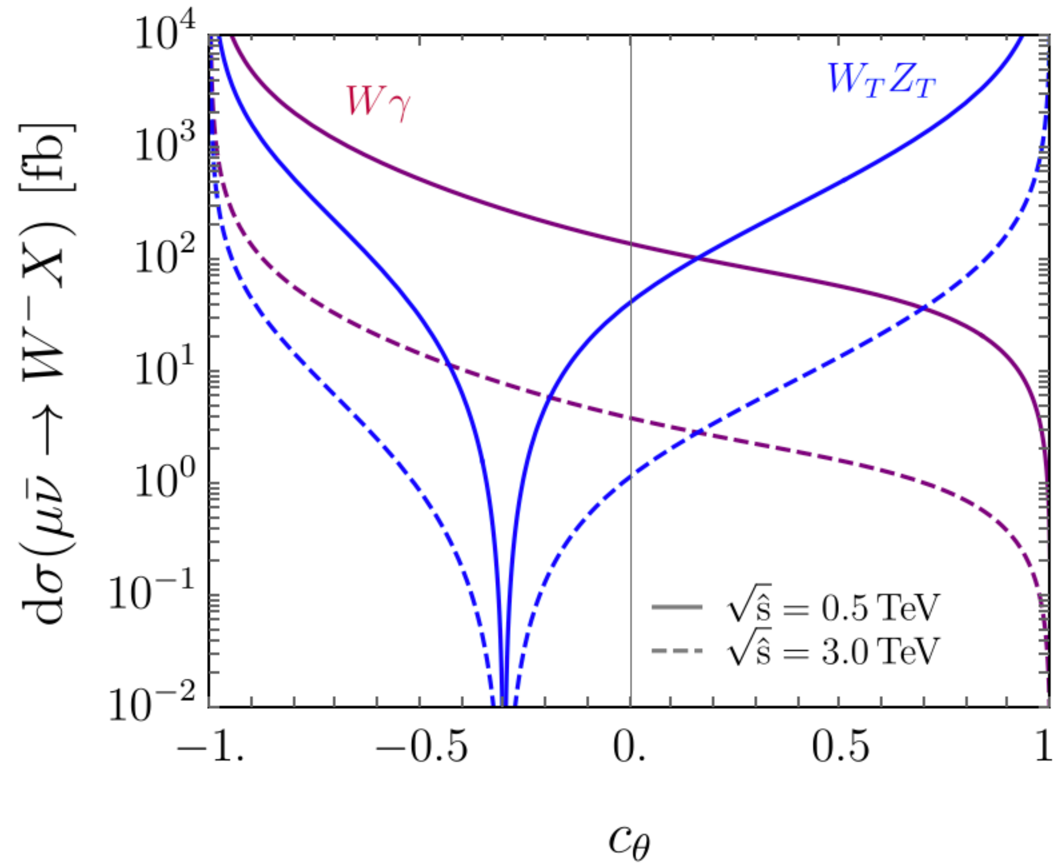
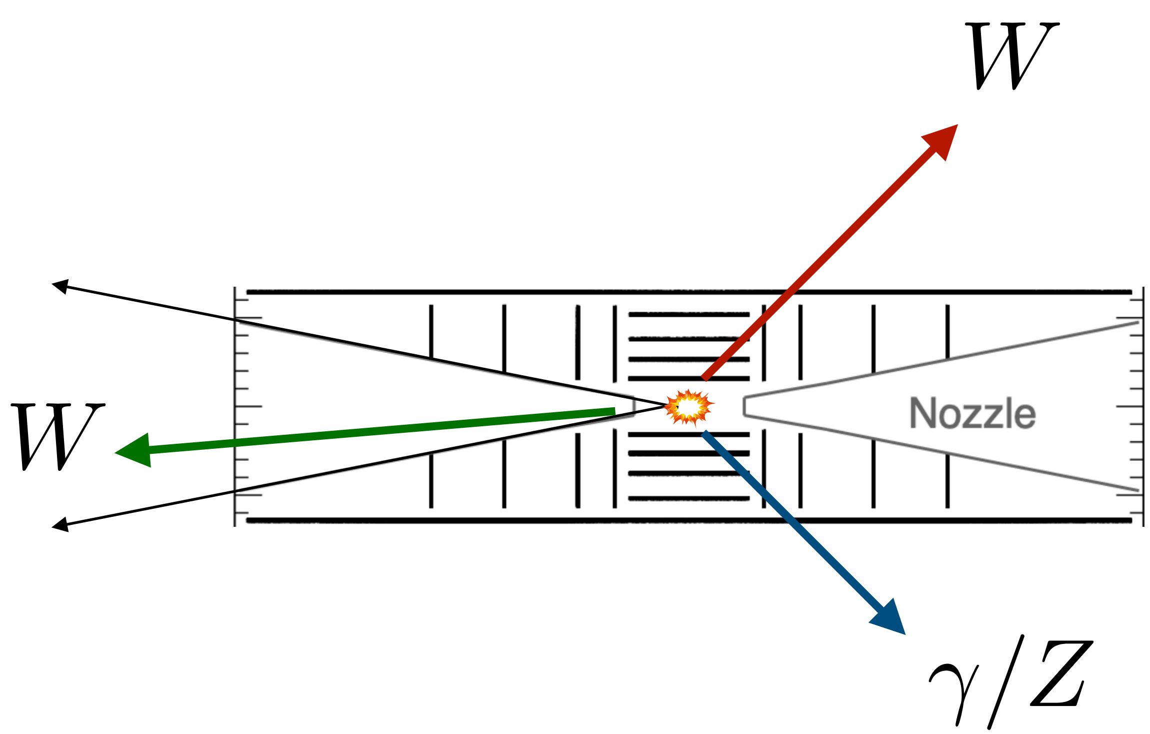
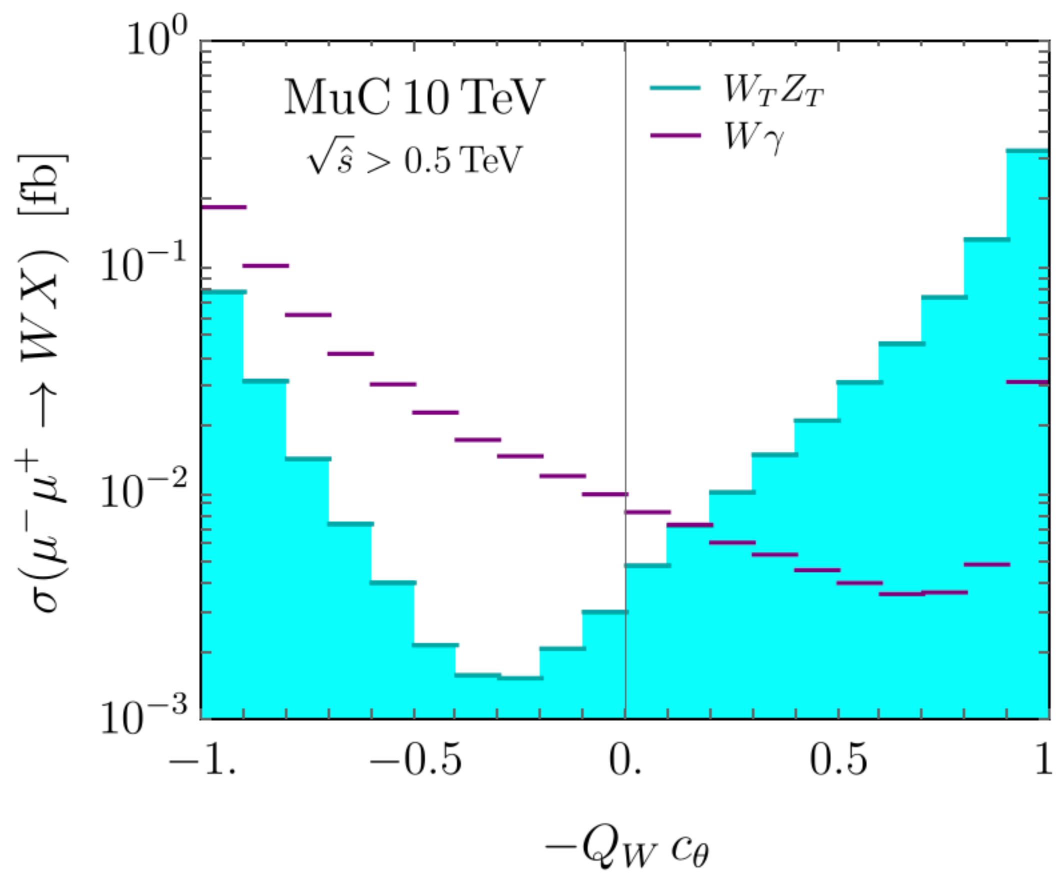
- **Radiation Amplitude Zero**

$$\mathcal{M}^{W\gamma}_{\pm\mp} \approx -\frac{geV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[Q_{(1-2)}c_\theta - Q_{(1+2)}\right]$$

$$\mathcal{M}^{WZ}_{\pm\mp} \approx \frac{gg_zV_{12}}{\sqrt{2}}\frac{(\lambda_{\rm w}-c_\theta)}{s_\theta}\left[g_-^{(1-2)}c_\theta - g_-^{(1+2)}\right]$$







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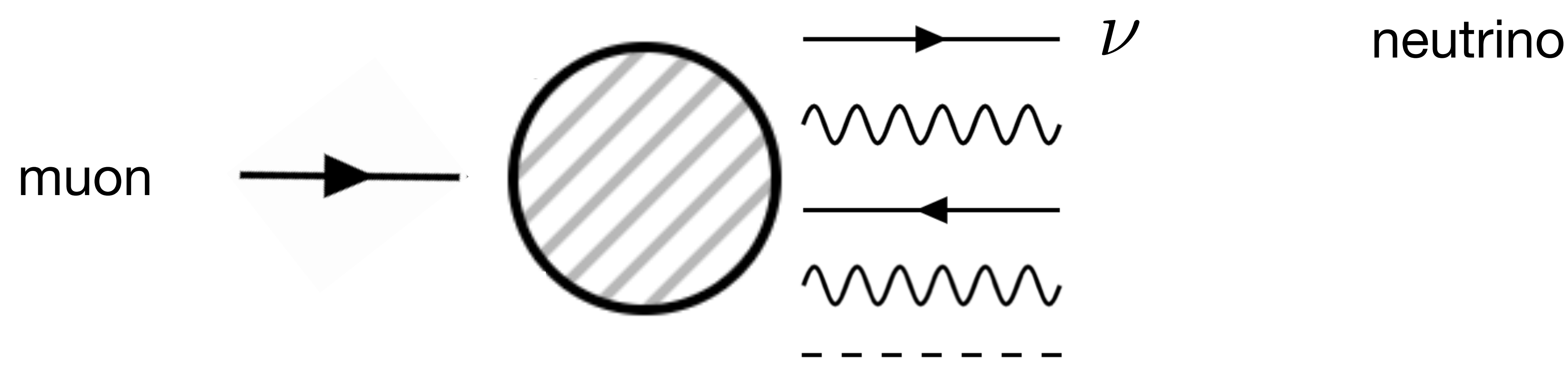
- **Neutrino PDF:**



Calculable! A prediction of the SM

How can we 'measure' these predictions? → *A combination of rates (monolepton) and spectral features (RAZ) will help us measure the prediction and reduce theoretical uncertainties!*

Testing the SM at multi-TeV energies

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- **EW Symmetry Restoration**

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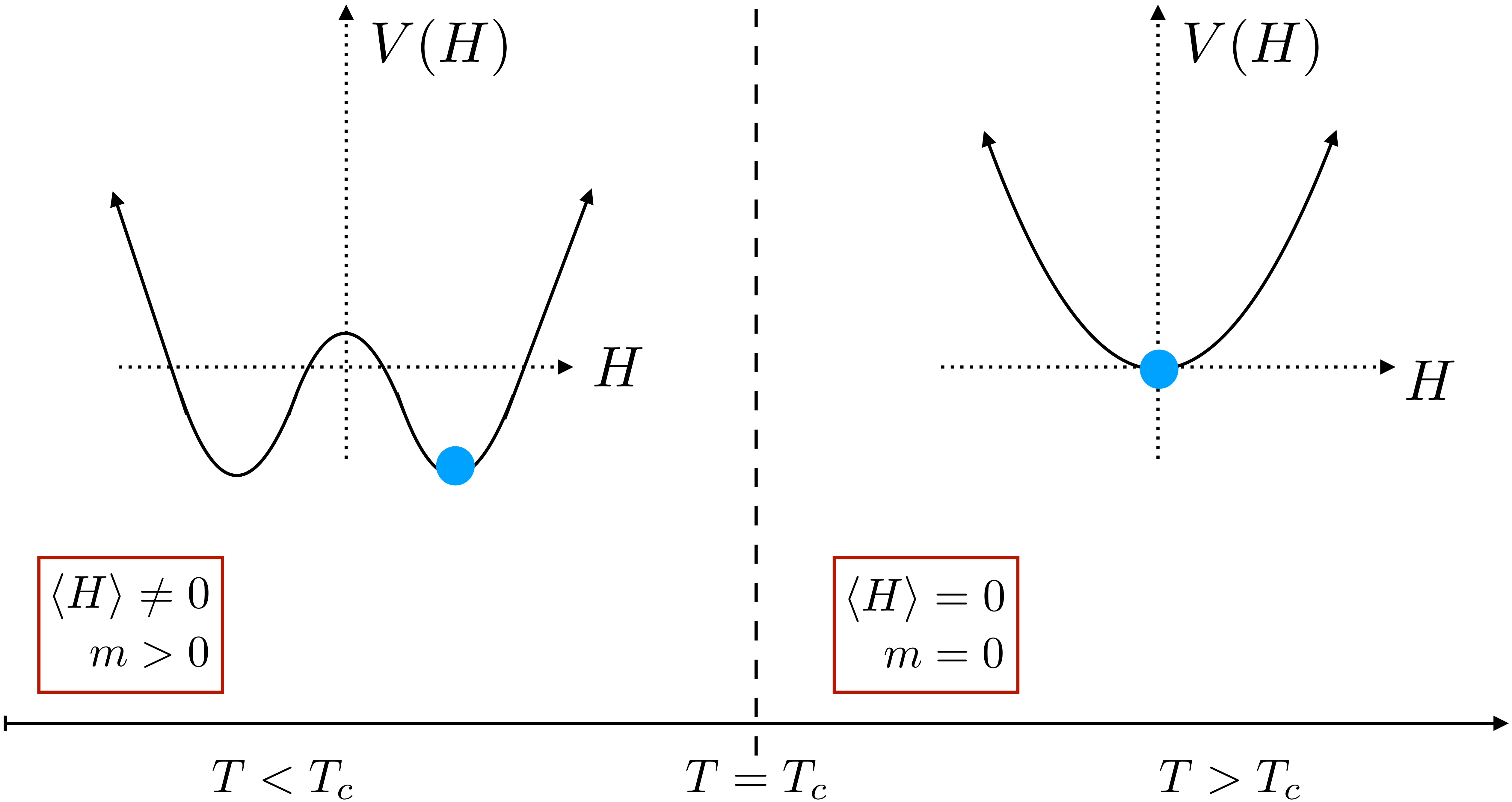
Conclusions

- **How do we probe this?**



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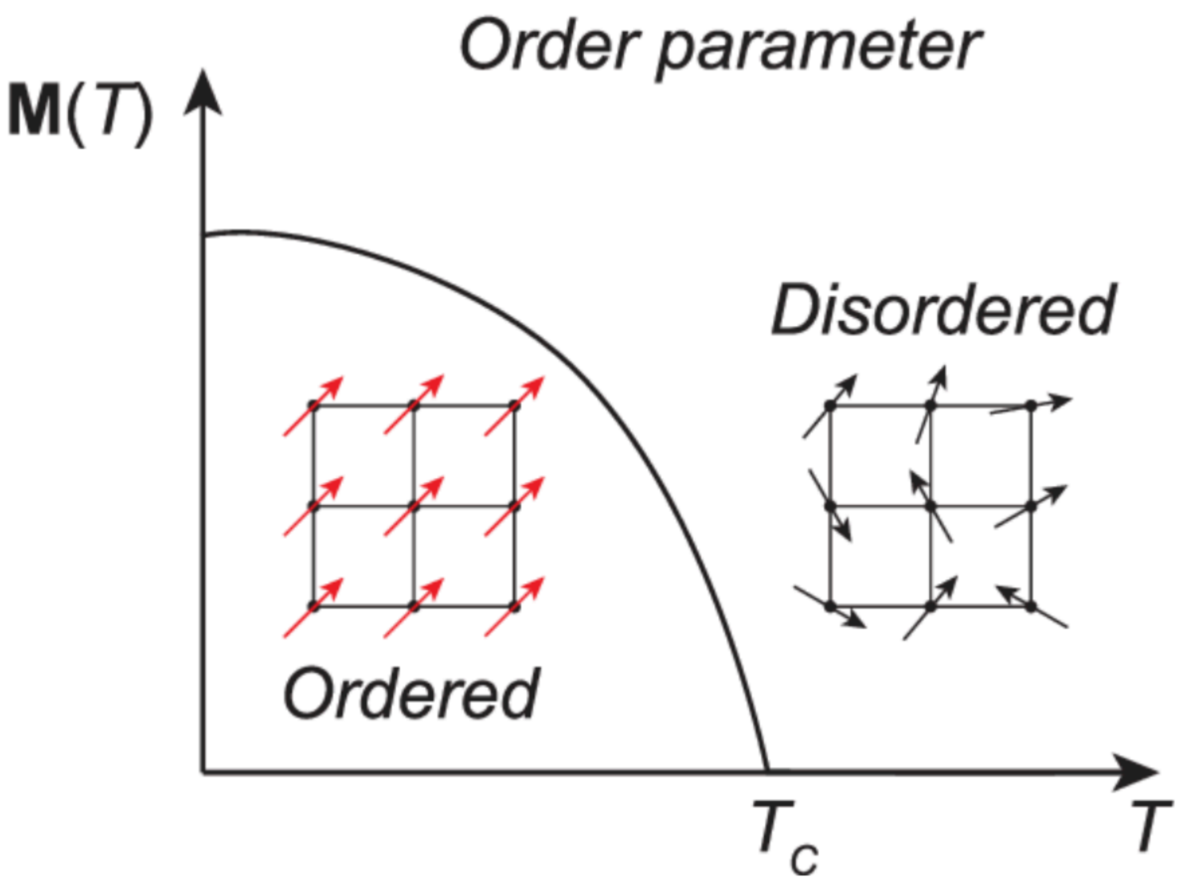
- **Order parameter:**

Is there an order parameter for the Higgs?

… the Higgs vev… but, can we measure it at different T?

Not at a collider… maybe Cosmology?

… what can be done at a collider?



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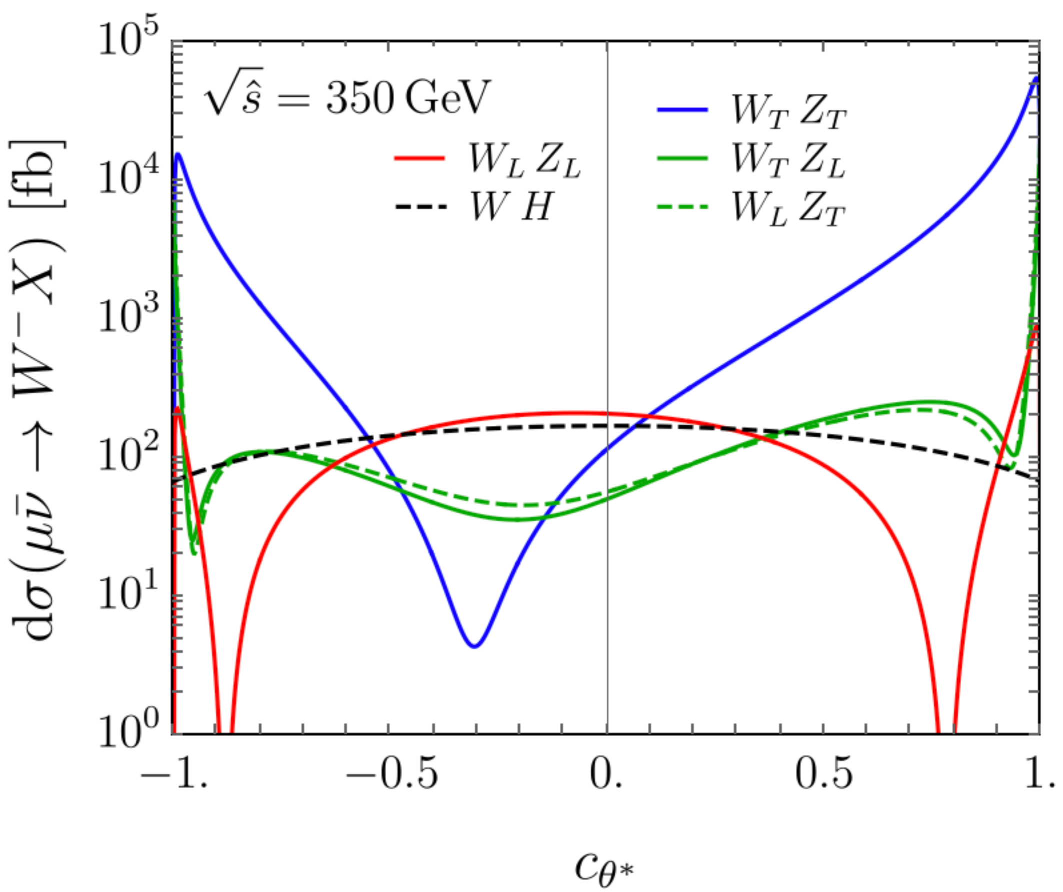
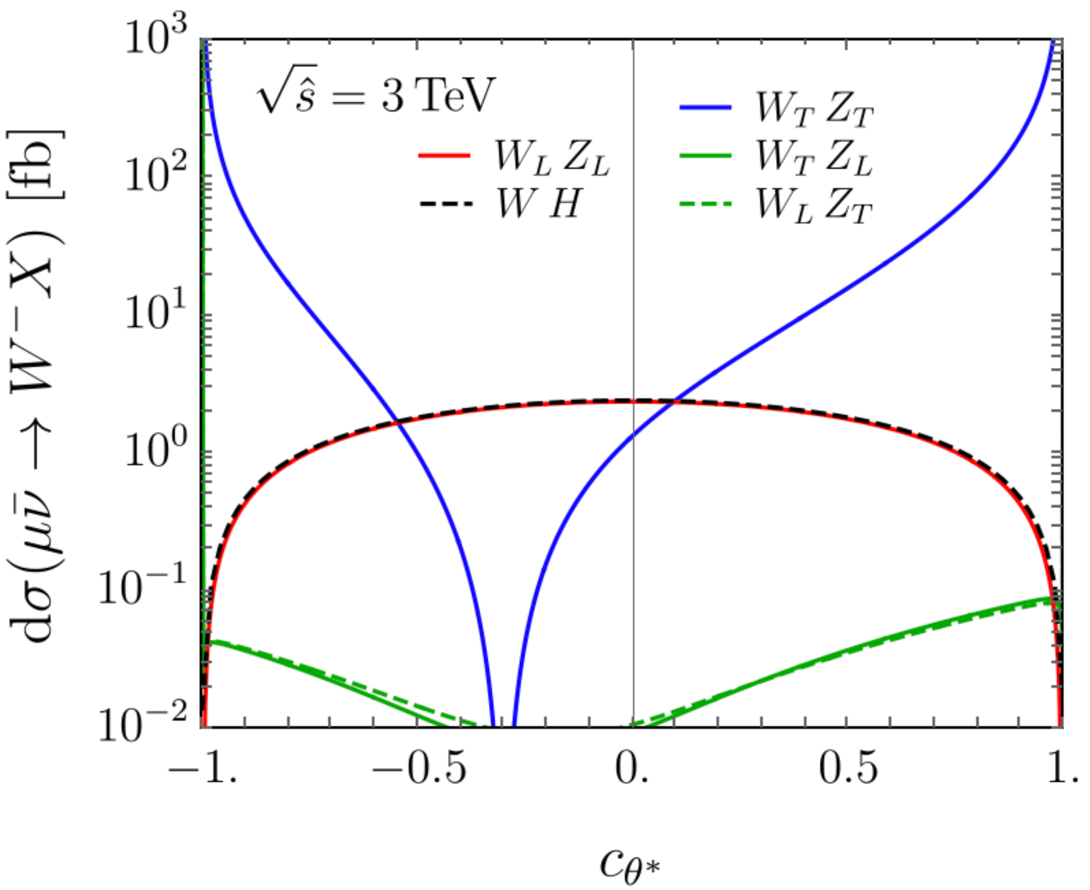
- **Diboson:**

Low Energy:



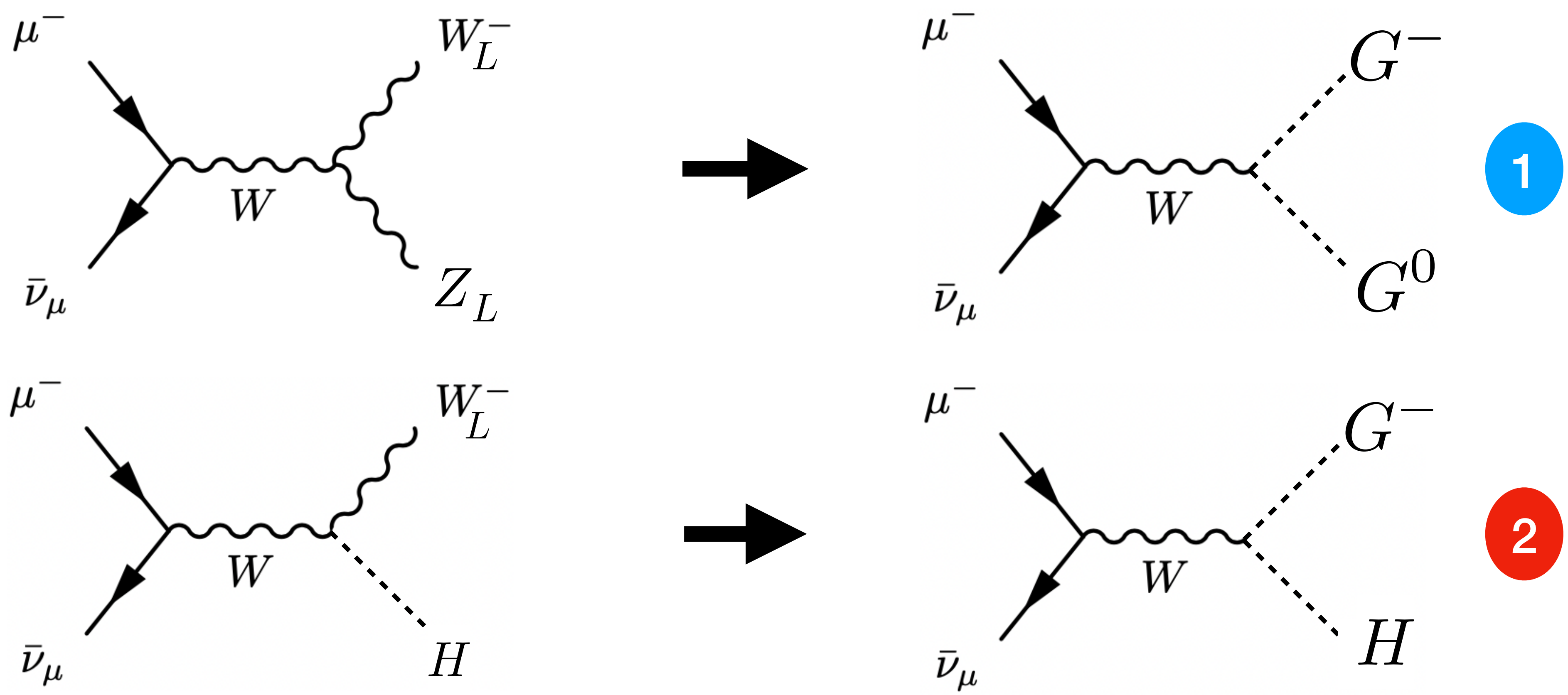
High Energy:



$$\sigma(W_L Z_L) \neq \sigma(W H)$$

$$\sigma(W_L Z_L) = \sigma(W H)$$

- **Diboson:**



$$\Phi = \begin{pmatrix} G^+ \\ H + iG^0 \end{pmatrix}$$

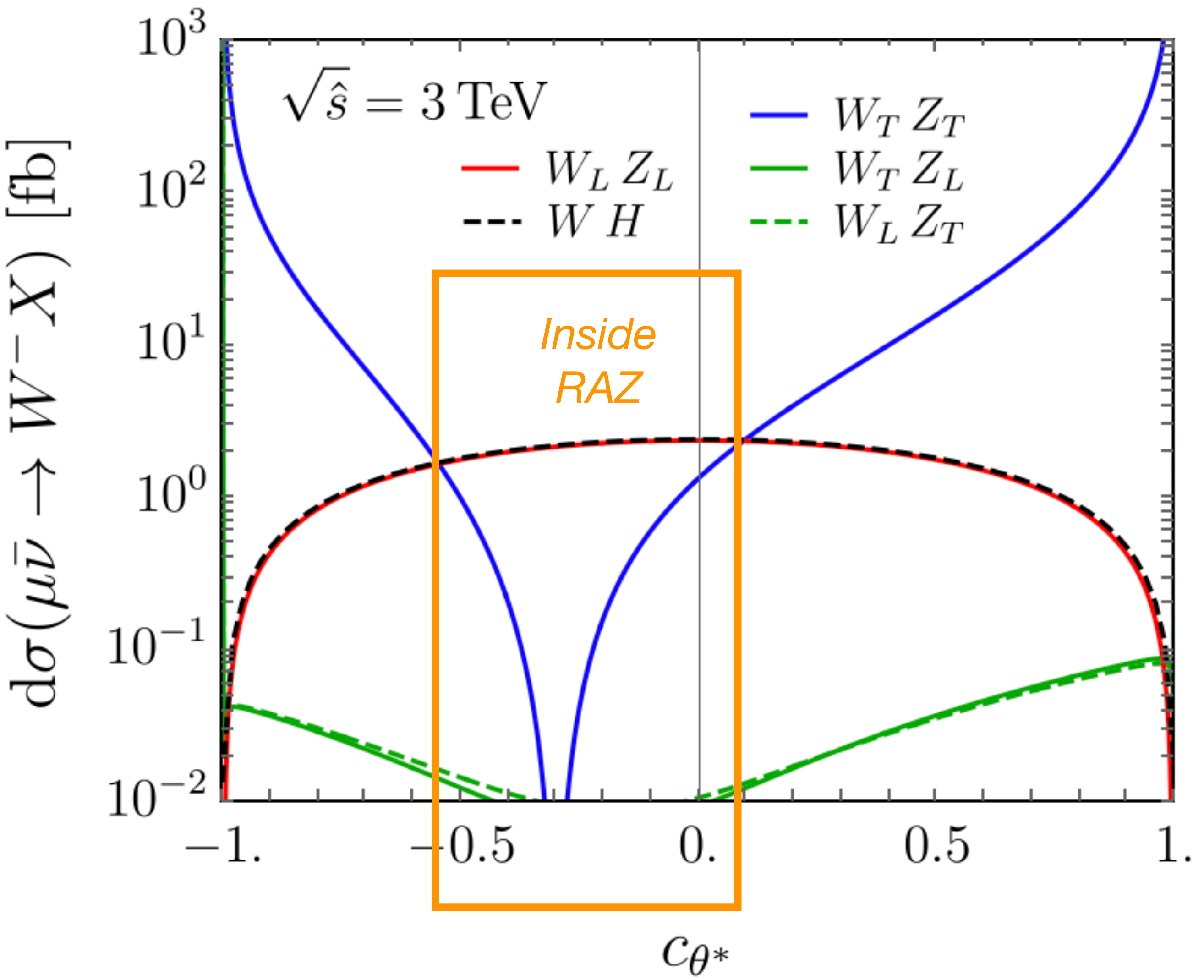
2 (G^+, H) 1 (G^+, G^0)

Higgs

$$\epsilon_L^\mu(p) = \frac{E}{M}(\beta, \hat{p}) = \underbrace{\frac{p^\mu}{M}}_{\text{Goldstone}} - \underbrace{\frac{1}{1+\beta}\frac{M}{E}n^\mu}_{\text{Low E}}$$

- **Diboson:**

$$r_{LL} = \frac{\sigma(W_L Z_L)}{\sigma(W H)} \quad \longrightarrow \quad \tilde{r}_{LL} = \left.\frac{\sigma(W Z)}{\sigma(W H)}\right|_{\text{Inside RAZ}}$$



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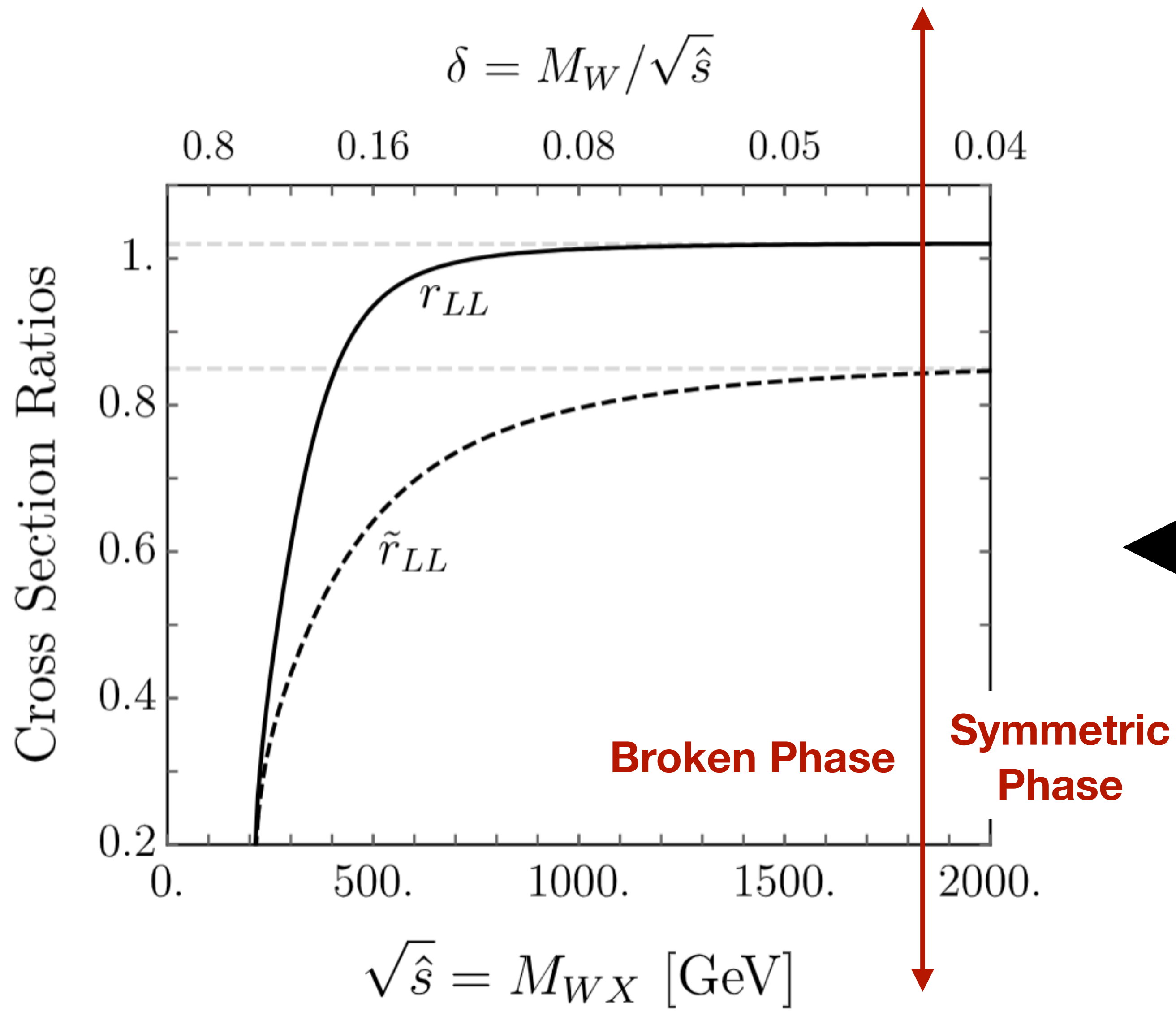
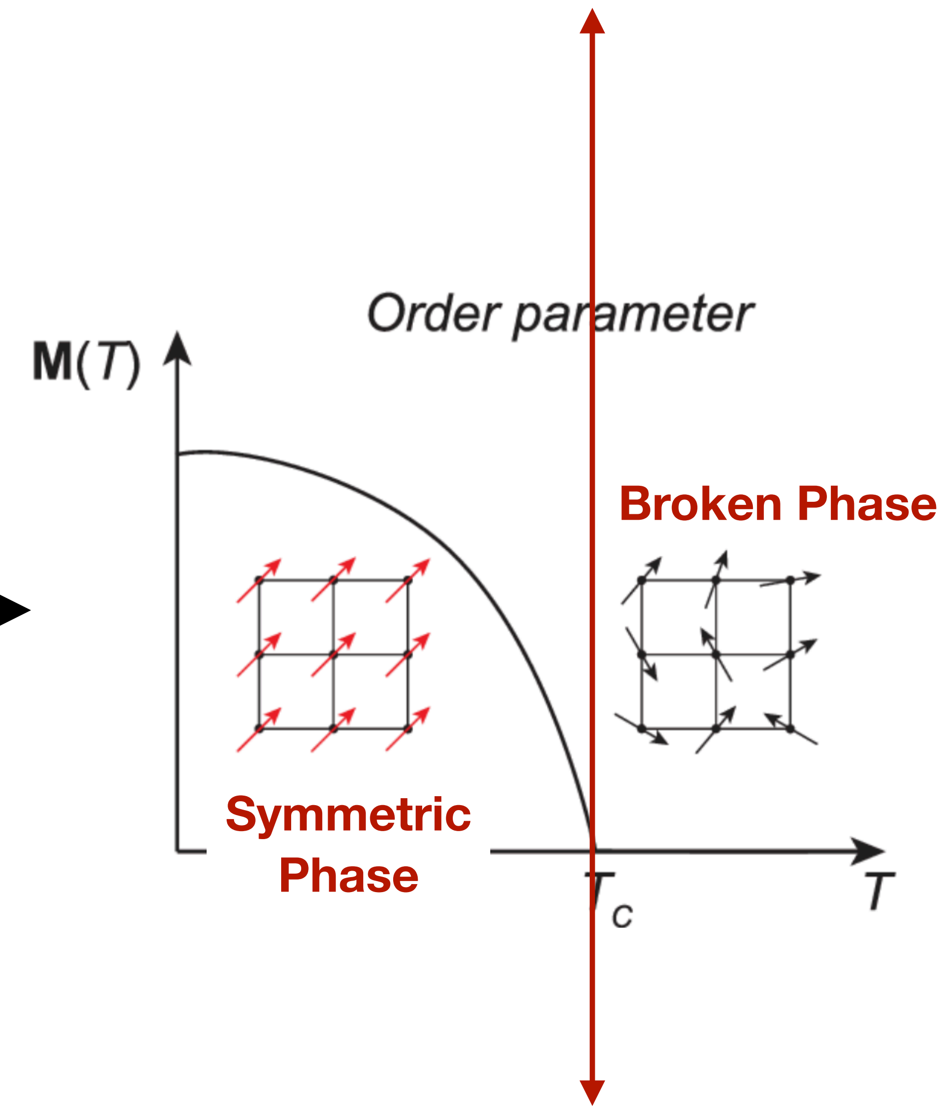
- **Diboson:**

$$r_{LL} = \frac{\sigma(W_L Z_L)}{\sigma(WH)} \qquad \tilde{r}_{LL} = \left.\frac{\sigma(WZ)}{\sigma(WH)}\right|_{\text{Inside RAZ}}$$





Summary

1. In order to understand the microscopic theory behind the Higgs mechanism we need to put the Higgs under a “microscope.” A muon collider will be able to measure the couplings of the Higgs at the 0.1% level.

2. Besides the Higgs, the muon collider program has a series of deliverables based on the fact that this machine will test the SM at new energy regimes. We studied the neutrino content of the muon beam, also known as the neutrino PDF, and we proposed an attempt to test the idea of electroweak symmetry restoration.

Thank You!