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THE ROLE OF THE TOP QUARK IN THE CONSTRUCTION OF BSM PHYSICS

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“SEGUNDO TALLER MÁS ALLÁ DEL MODELO ESTÁNDAR Y ASTROPARTÍCULAS”

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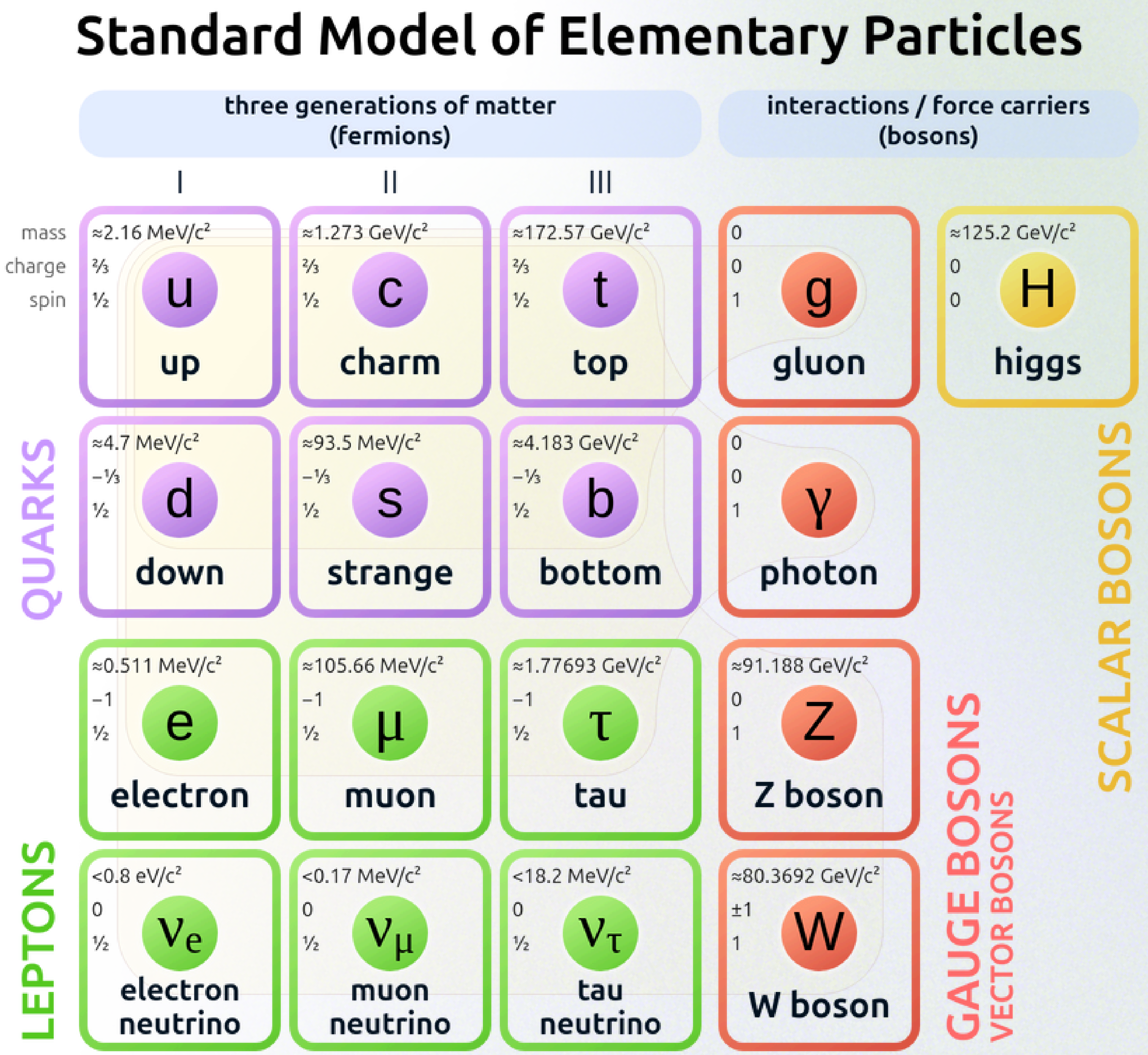
STANDARD MODEL

So far, the most complete description of the observed fundamental particles: Fermions and Bosons.

But it cannot explain several modern concepts like:

- Matter-antimatter asymmetry.
- Neutrino masses.
- Dark sector.



TOP QUARK GENERALITIES

Last discovered particle in the Standard Model.

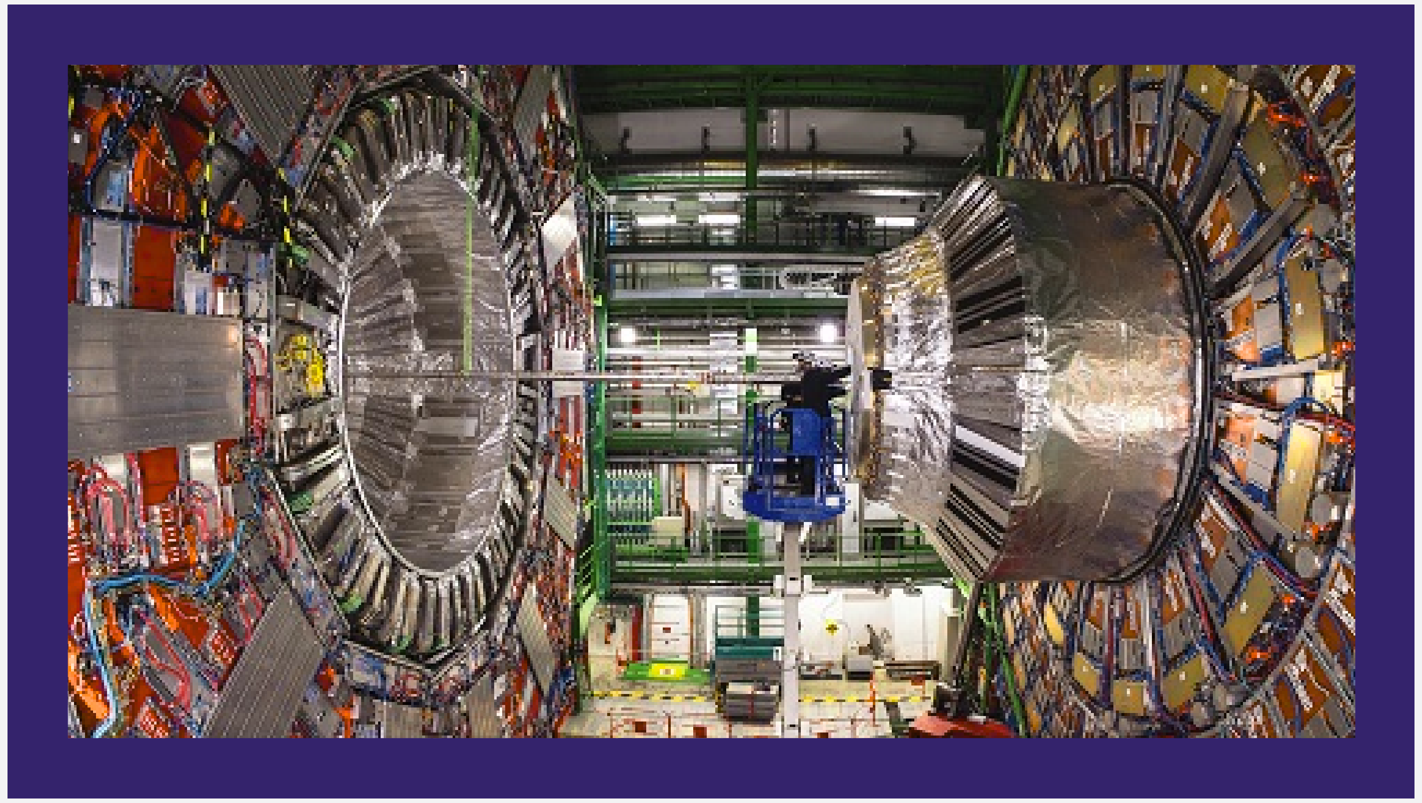
Electric charge +2/3, **spin** 1/2, **mass around** 172.5 GeV, large abundance of produced left-handed tops.

- extremely short lifetime (~5×10^{-25} s)
- decorrelation time (~ $10^{-2}4$ s)
- hadronization time (~ 10^{-25} s)

DETECTIONS

First measuments at Tevatron (DØ and CDF experiments) in 1995. High energy was required to produce it in a proton-proton collision.

TEVATRON



LHC

2009 - ATLAS and CMS experiments.

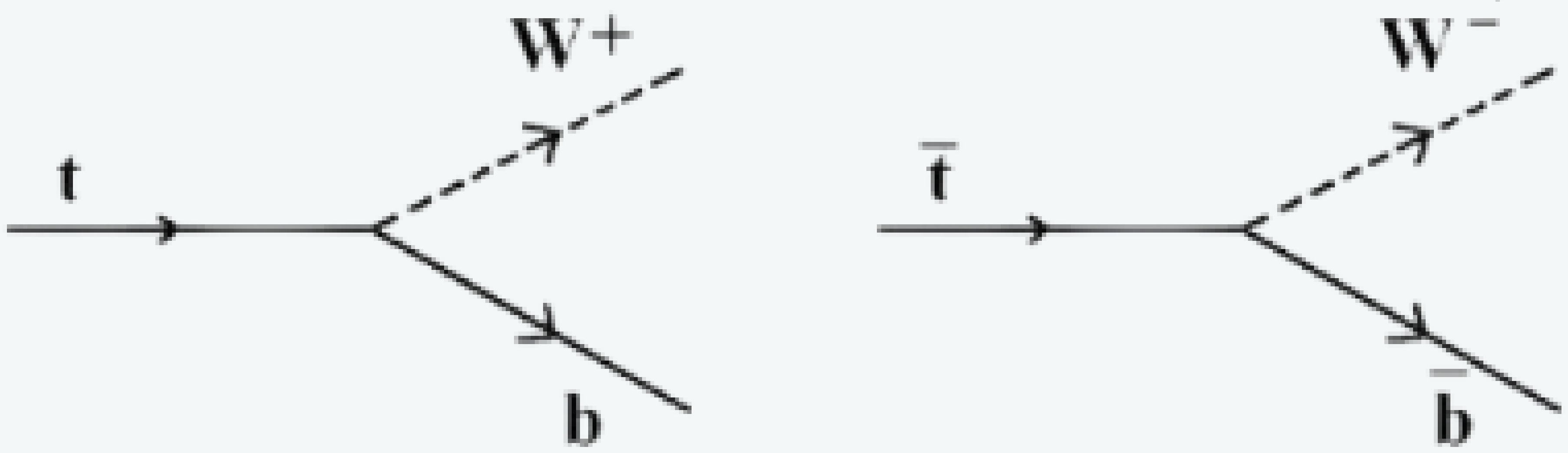
- Run 1 (2010). $\sqrt{s} = 7$ TeV
- Run 2 (2015). $\sqrt{s} = 13$ TeV
- Run 3 (2022-now). $\sqrt{s} = 13.6$TeV
- Future, with HL-LHC (~2029).

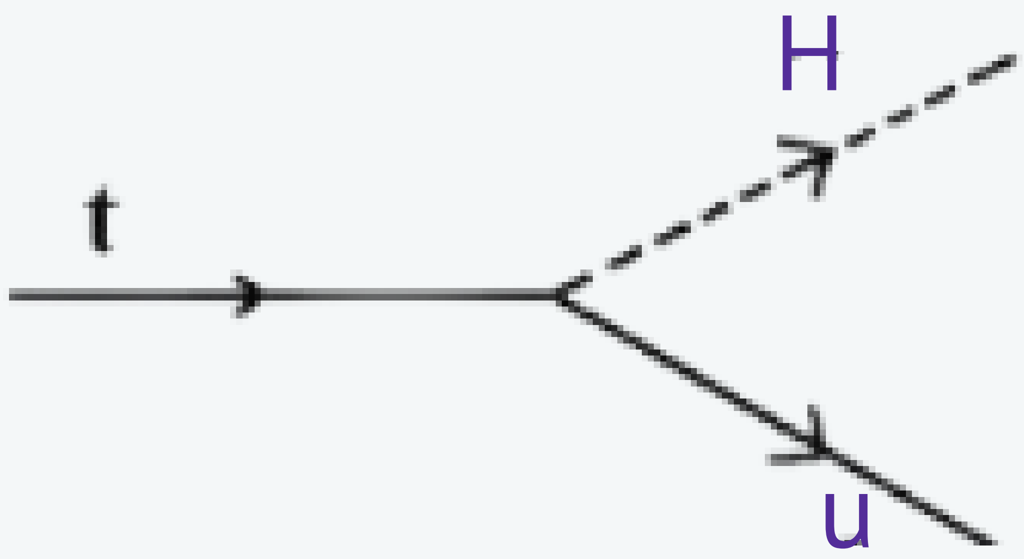
DECAY MODES, SM

In the **Standard Model** only three decay modes for t quark are possible.

$$t \longrightarrow W^+ b, \quad t \longrightarrow W^+ d, \quad t \longrightarrow W^+ s$$

Where the last two are suppressed by th CKM matrix elements, V_{td} and V_{ts} then,





FCNC

Flavor Changing Neutral Currents

Processes where the quark (t) changes its flavor, while maintaining its electric charge.

These transitions are mediated by <u>neutral</u> bosons,

Z, γ, g and H

Forbiden at tree level in the SM.

They appear in loops, but are strongly suppressed by the GIM mechanism.

SPOILES: THEY ARE ENHANCED IN SOME BSM THEORIES

BEYOND THE STANDARD MODELS

Two Doublets Higgs Models

- The SM Higgs is an SU(2) doublet with hypercharge Y=1.
- Complex field of four degrees of freedom.

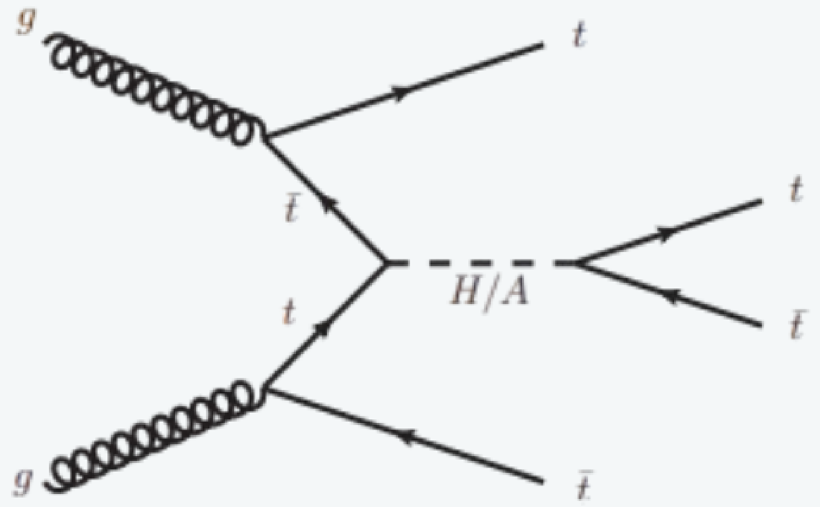
When symmetry breaks.

- Three degrees give mass to the bosons.
- One degree corresponds to the Higgs Boson.

The SM higgs could be an ET

2DHM

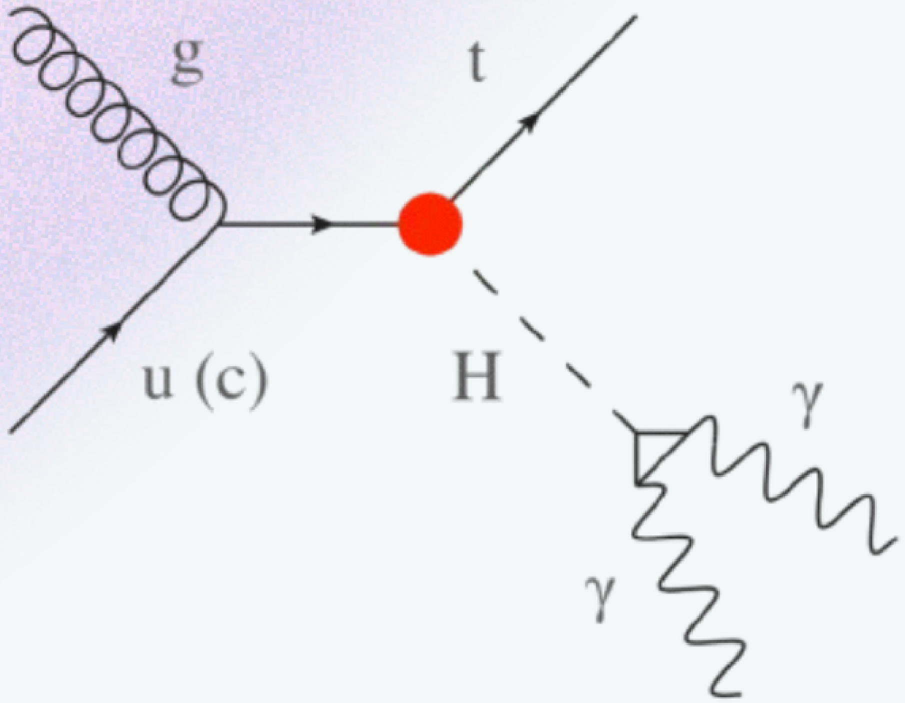
- A **2HDM** uses two complex scalar doublets (8 degrees of freedom), resulting in **five physical Higgs bosons**.

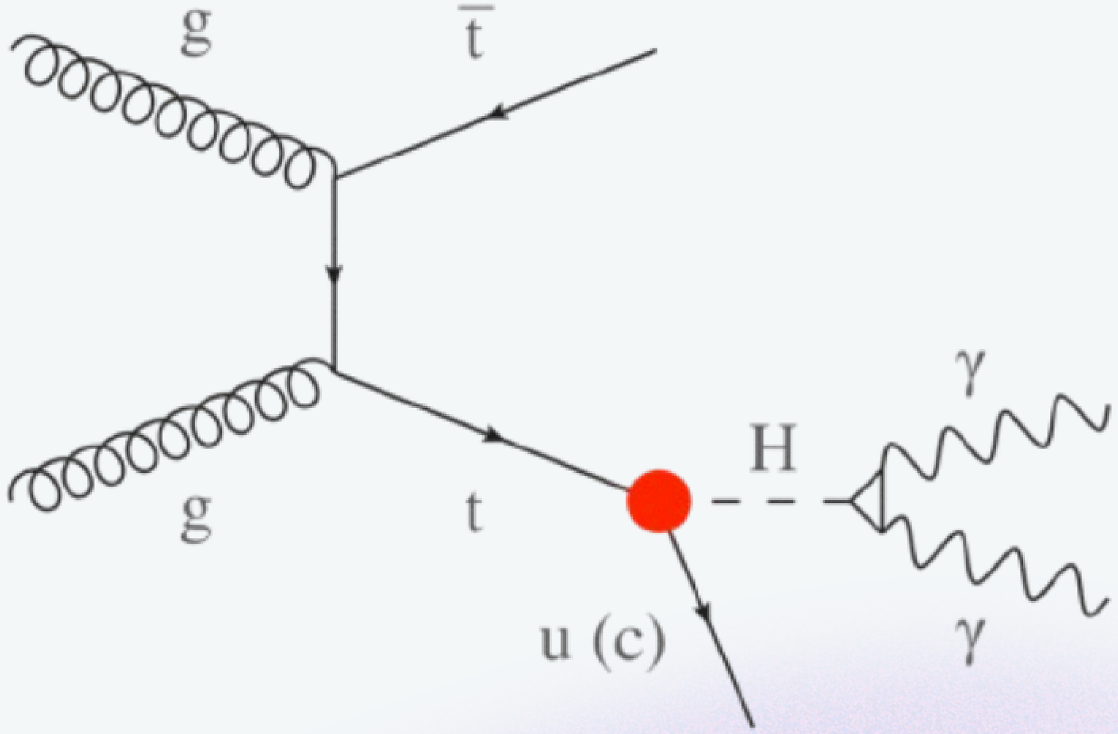


THEY PREDICT ENHANCED FCNC!

FCNC

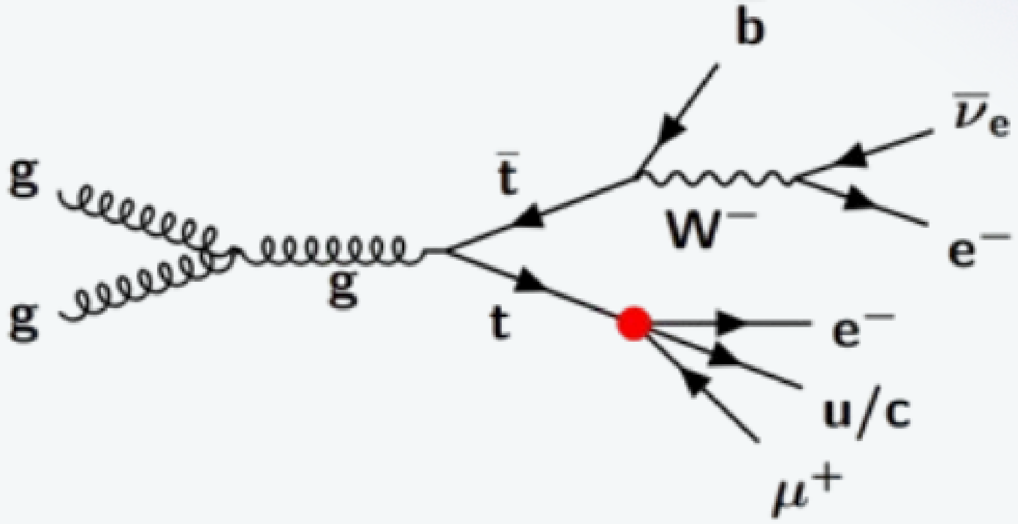
These diagrams are supposed to be very suppressed in SM but in BSM not necessarily.

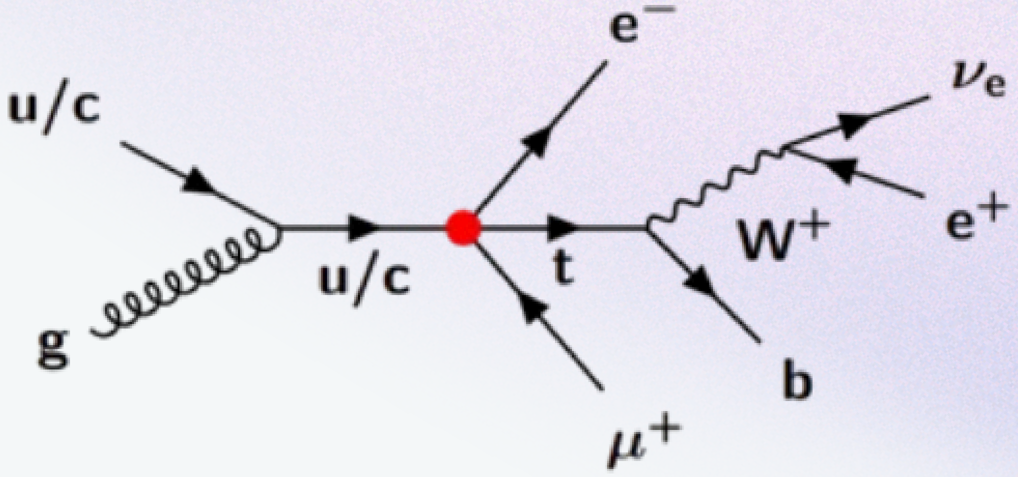


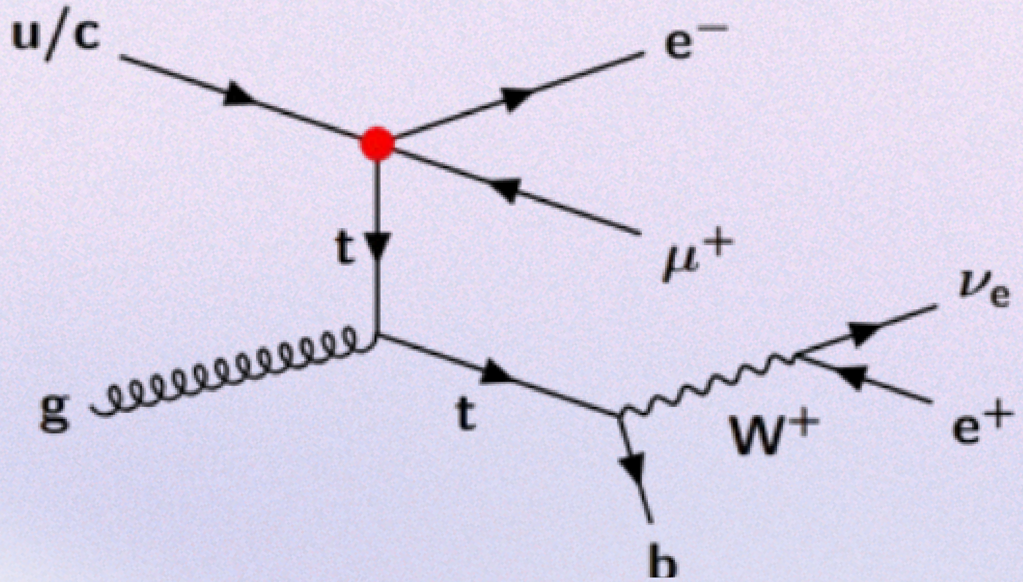


cLFV

We can also consider the Charge Lepton Flavor Violation cLFV







BEYOND THE STANDARD MODELS

Models with vector-like quarks

SUSY

A Vector-Like Quark (VLQ): quark whose left-handed and right-handed components transform in the same way under the SU(2)_L gauge group.

- They address the hierarchy problem.
- Explain the mass and mixing patterns of fermions.

Supersymmetry's new particle mixings create un-suppressed flavor-changing loops, making rare decays like t→cH potentially visible at the LHC.

They naturally give rise to enhanced FCNCs, making processes like t → qH potentially observable at the LHC.

The LHC cannot observe processes at the level predicted by the SM:

$$\mathcal{B}(t \longrightarrow uH) \sim 10^{-17}$$

$$\mathcal{B}(t \longrightarrow cH) \sim 10^{-15}$$

But BSM Predictions (e.g., 2HDM):

$$\mathcal{B}(t \longrightarrow qH) \sim 10^{-5}$$

Recently, using improved tools and computational methods, we can probe branching ratios of the order of:

$$\mathcal{B}(t \longrightarrow qH) \sim 10^{-5}$$

If a BSM process produces a signal in this range, we could detect it. This is why it is crucial to improve:

- Computational methods and simulations.
- Experimental sensitivity and exclusion limits.

WE NEED ACCURACY!

TOP PAIR PRODUCTION: $\sigma_{t\bar{t}WW} = \sum_{ij} \int dx_1 dx_2 f_i(x_1;\mu) f_j(x_2;\mu) \hat{\sigma}(x_1 P_1, x_2 P_2; m_t^2, \mu)$

Using Monte Carlo simulations, for proton-proton collisions we run:

- Simulation of the hard process.
- Parton Shower.
- Compare LO+PS to NLO+PS.

Pythia
LHAPDF6:CT18NLO
POWHEG-BOX

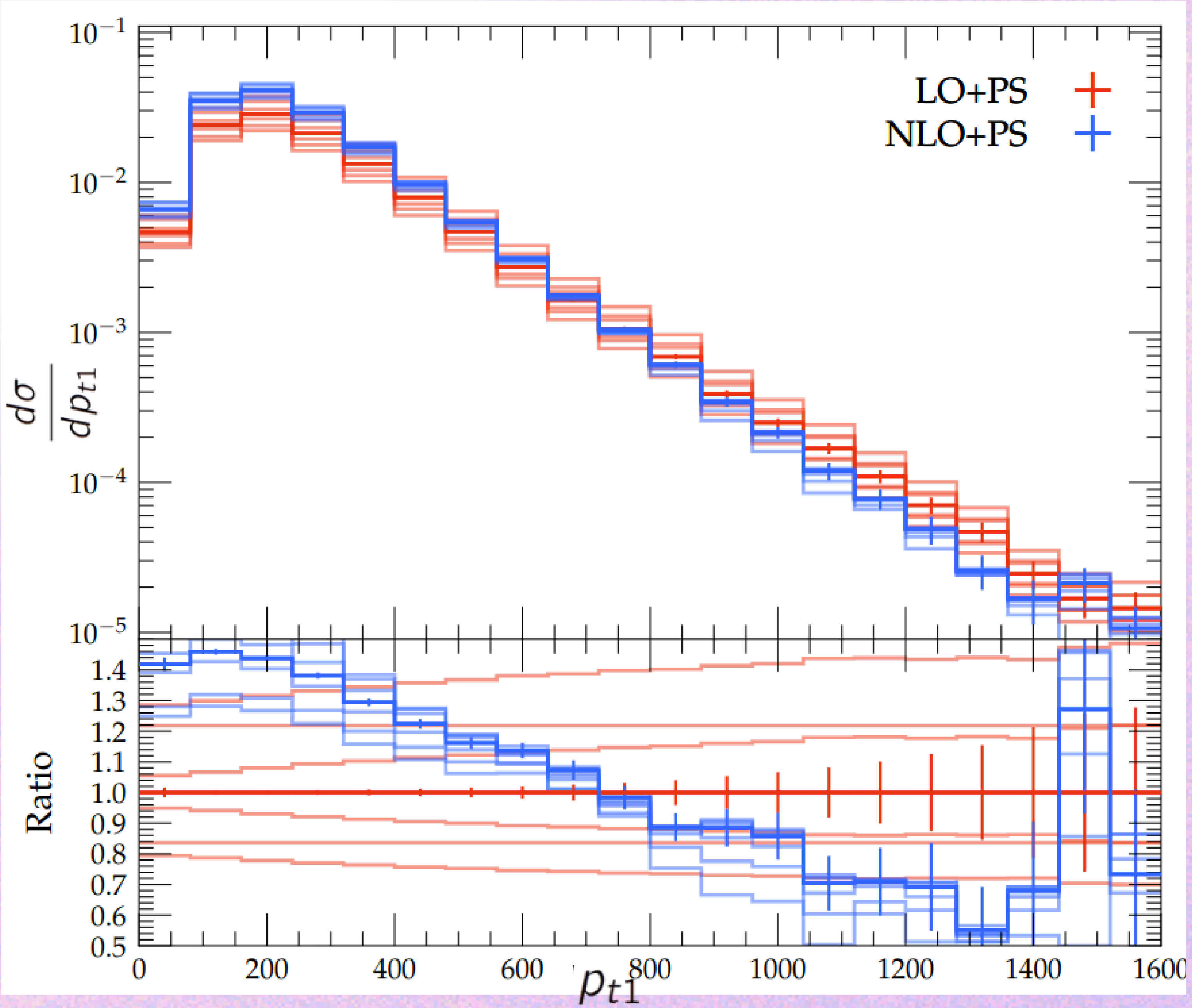


Fig. 1. Simulated process for pp collision to obtain ttWW at LO and NLO and adding Parton Showers

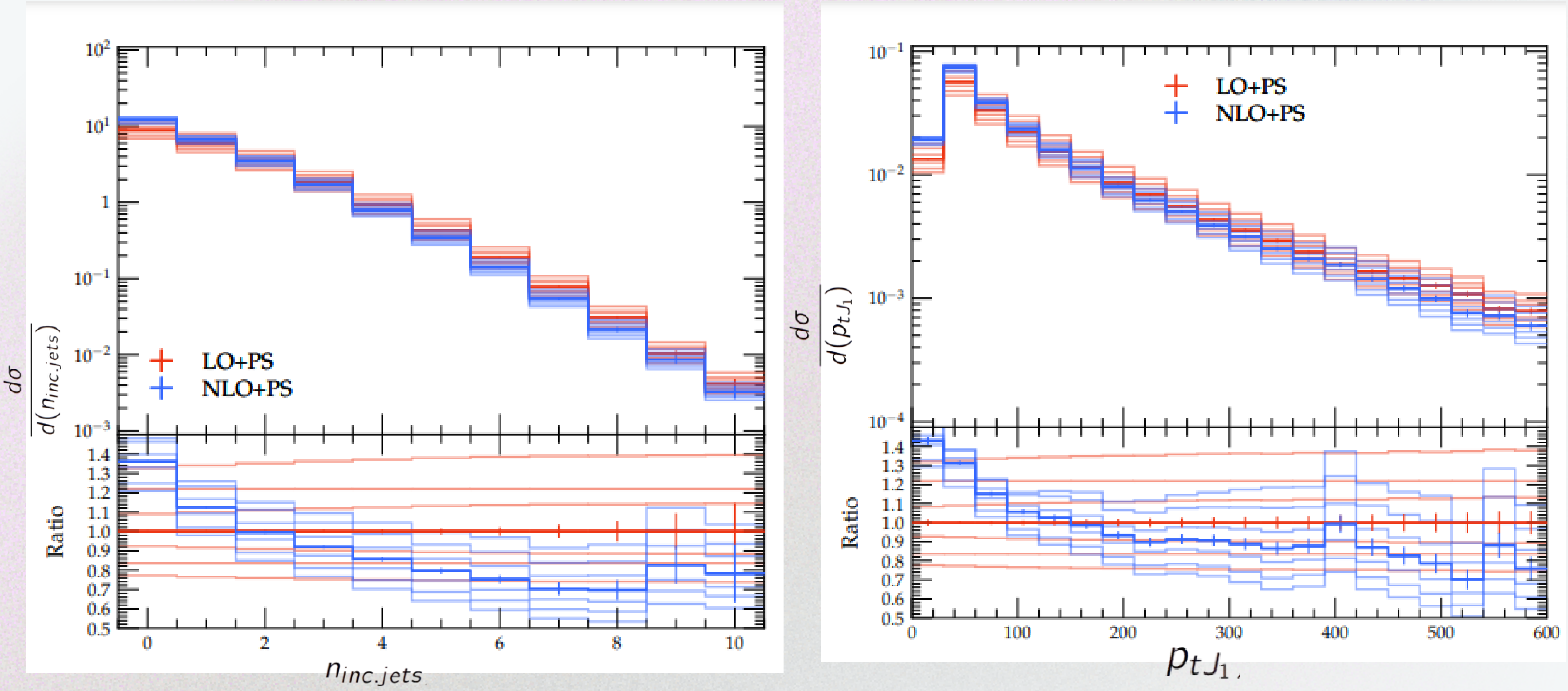


Fig. 2, 3. Simulated process for pp collision to obtain ttWW at LO and NLO + Parton Showers

MAIN IDEAS

- We cannot stop working on SM.

- Improving Standard Model (SM) calculations (going from LO to NLO, or even NNLO, and including PS) reduces theoretical uncertainties.

  - This is essential to distinguish SM predictions from possible Beyond the Standard Model (BSM) signals.

  - The Top Quark represents a window to study these kind of physics because of it pecularities.

THANK YOU!

ATLAS Collaboration. Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in proton−proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the ATLAS detector. *Eur. Phys. J. C* **85**, 573 (2025). https://doi.org/10.1140/epjc/s10052-025-14041-z

ATLAS . (2025) “Search for The ATLAS Collaboration. (2022). *Search for new phenomena in the top quark sector with the ATLAS detector at the LHC* (ATLAS-CONF-2022-XXX). CERN. https://cds.cern.ch/record/2872677

Wuchterl, S. (2024). Top quark properties measurements and searches at ATLAS and CMS. En Actas de [Nombre de la Conferencia]. CERN. https://cds.cern.ch/record/2872677

Schaarschmidt, J. (2018). Search for heavy Higgs bosons with the ATLAS detector. In Proceedings of the 21st Particles and Nuclei International Conference (PANIC 2017). International Journal of Modern Physics: Conference Series, *46*, 1860056. https://doi.org/10.1142/S201019451860056X