



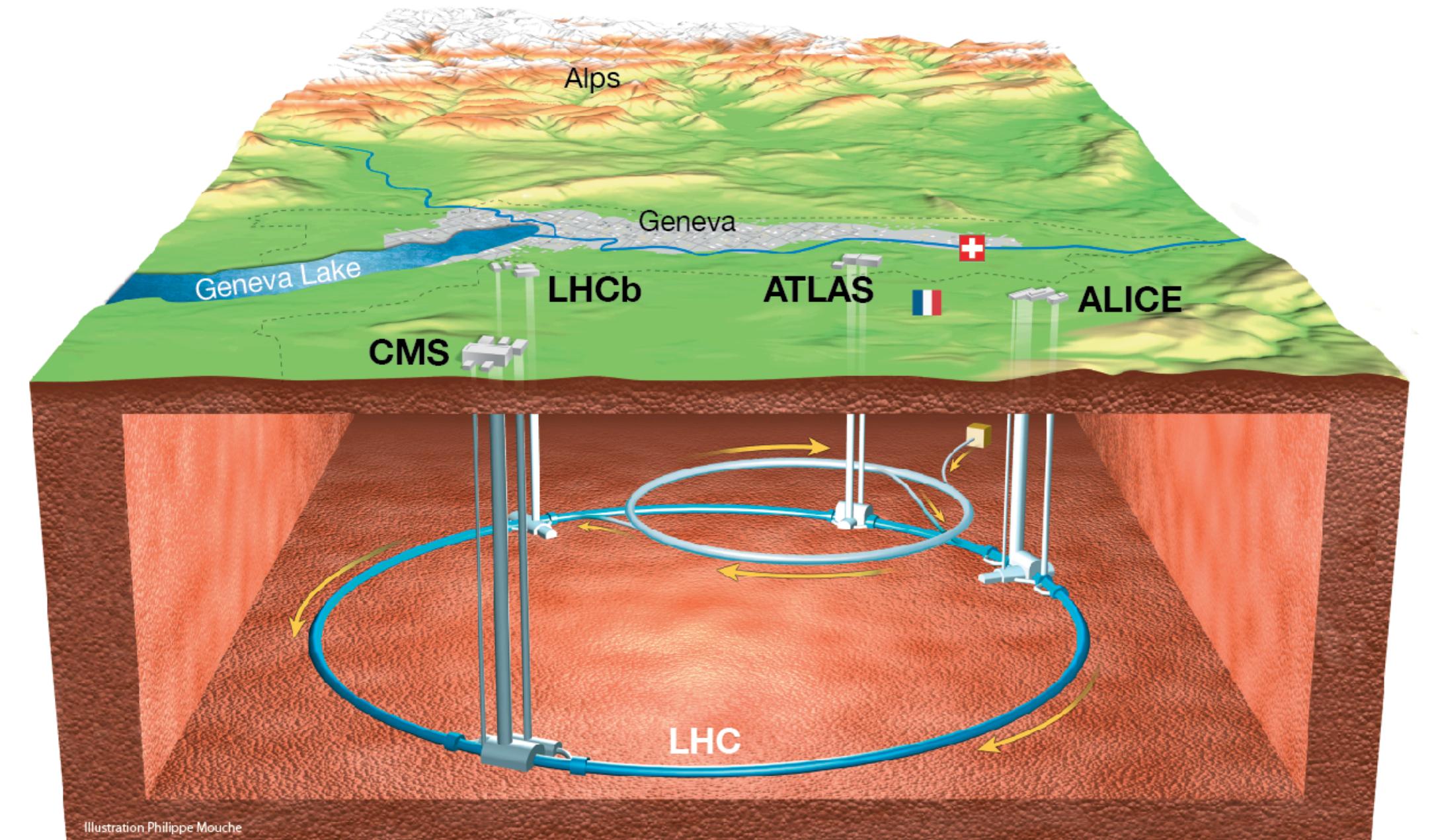
UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386

# EXPLORING THE LIMITS OF NEW PHYSICS AT THE LHC

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# The Large Hadron Collider (LHC)

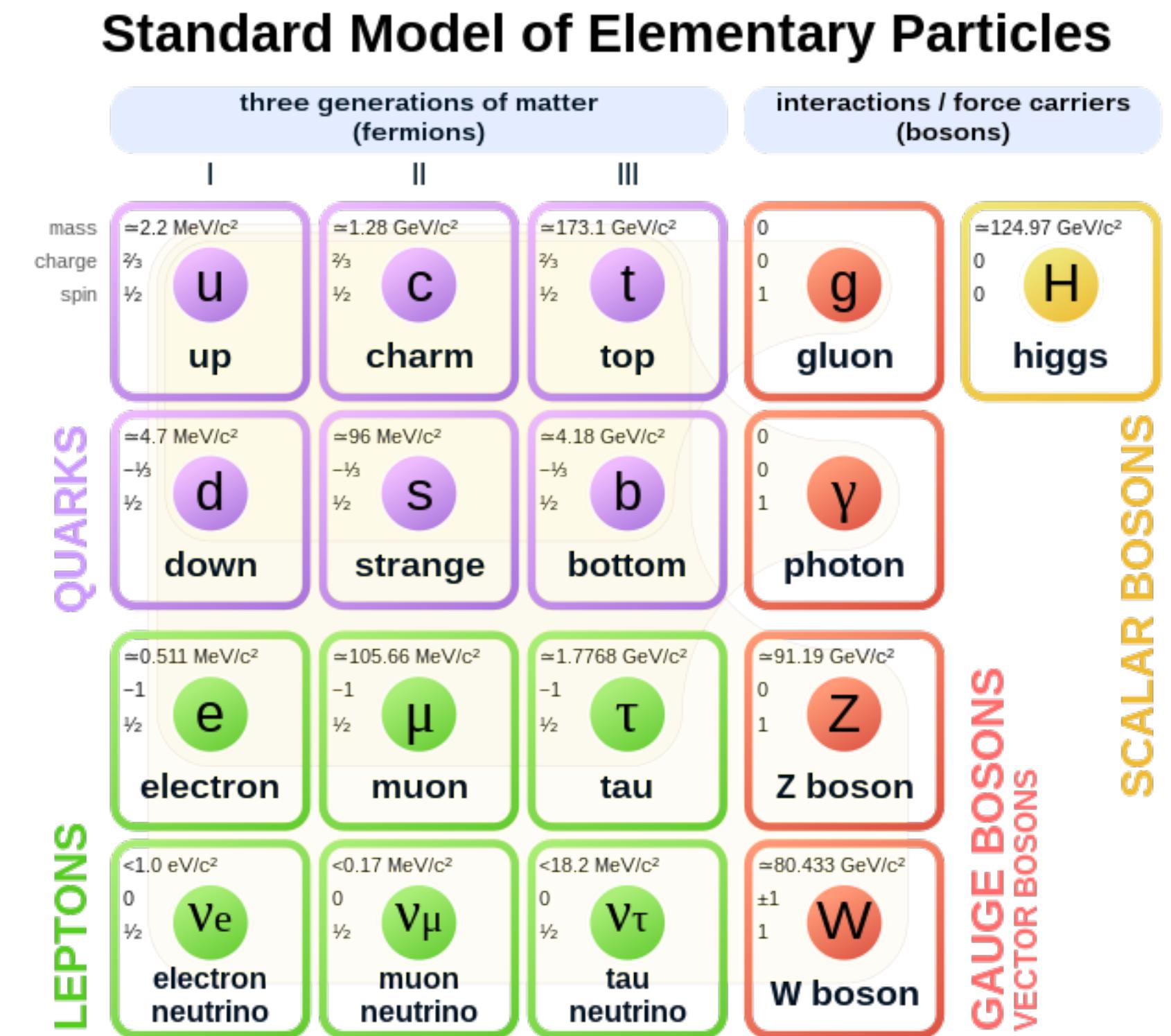
- Particle accelerator with 27km circumference
- Four different interaction points (ATLAS, CMS, LHCb, ALICE)
- Protons with energies of 6.5 TeV collide **every 25 ns** (Run 2)
- Dataflow of order PB/s



Source: [https://www.physi.uni-heidelberg.de/Forschung/he/ATLAS/pics-new/lhc\\_overview.png](https://www.physi.uni-heidelberg.de/Forschung/he/ATLAS/pics-new/lhc_overview.png)

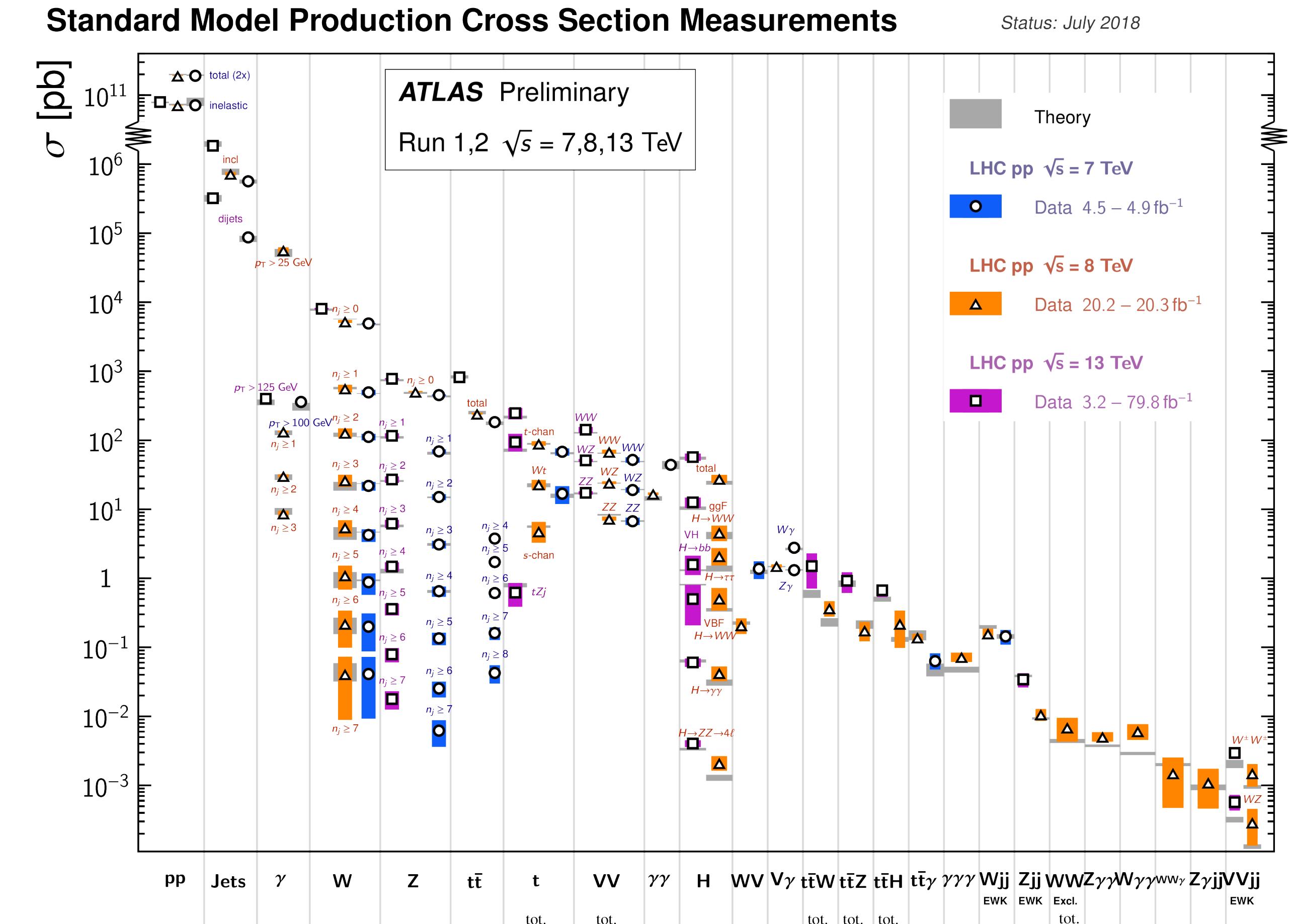
# The Standard Model of Particle Physics

- Theoretical framework describing our current understanding of particle physics
- Experimental discovery of the Higgs boson at the LHC ‘completed’ the Standard Model
- Shows **great success** at describing large number of observations



# The Standard Model of Particle Physics

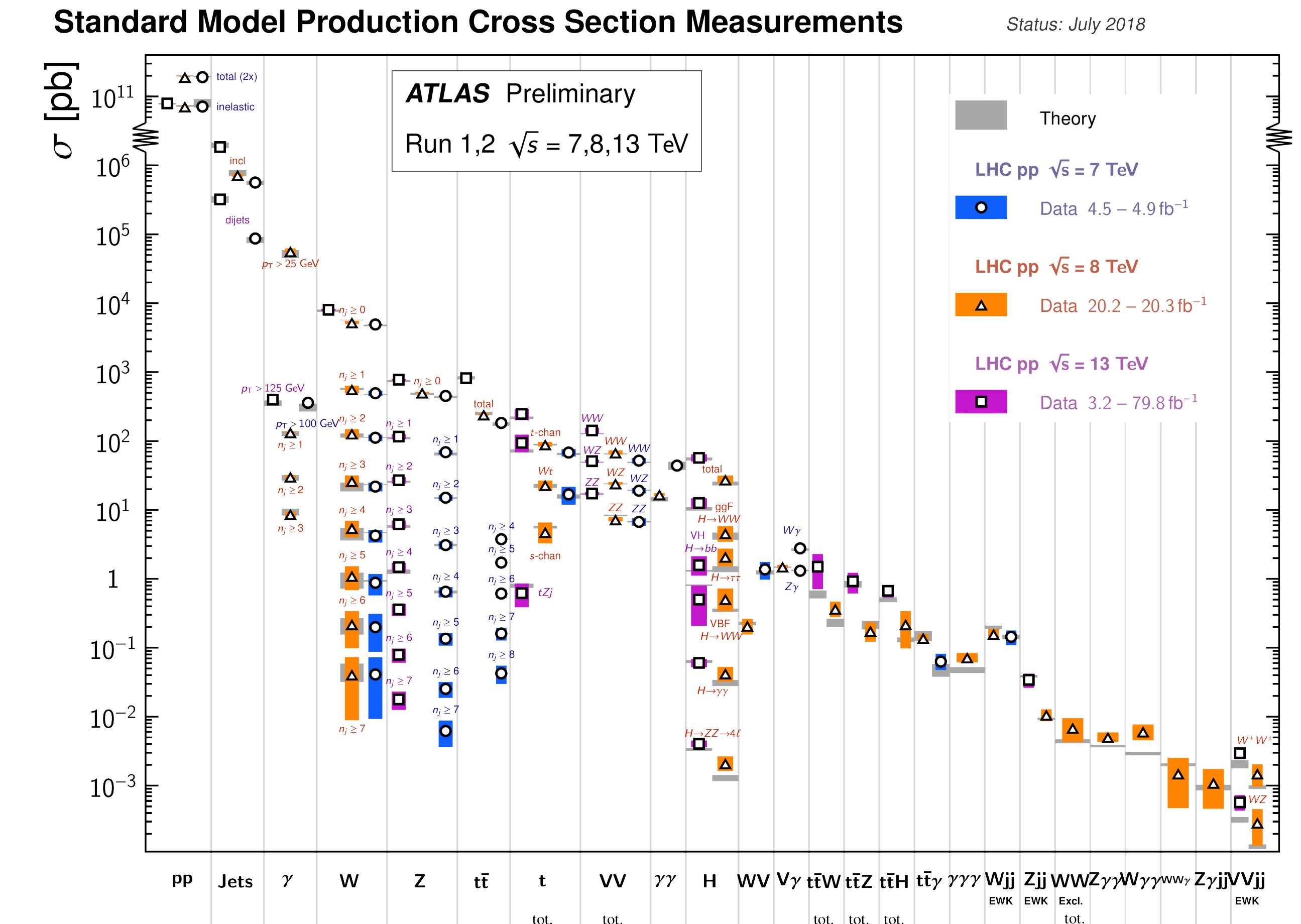
- Impressive agreement for large number of different measurements



# The Standard Model of Particle Physics

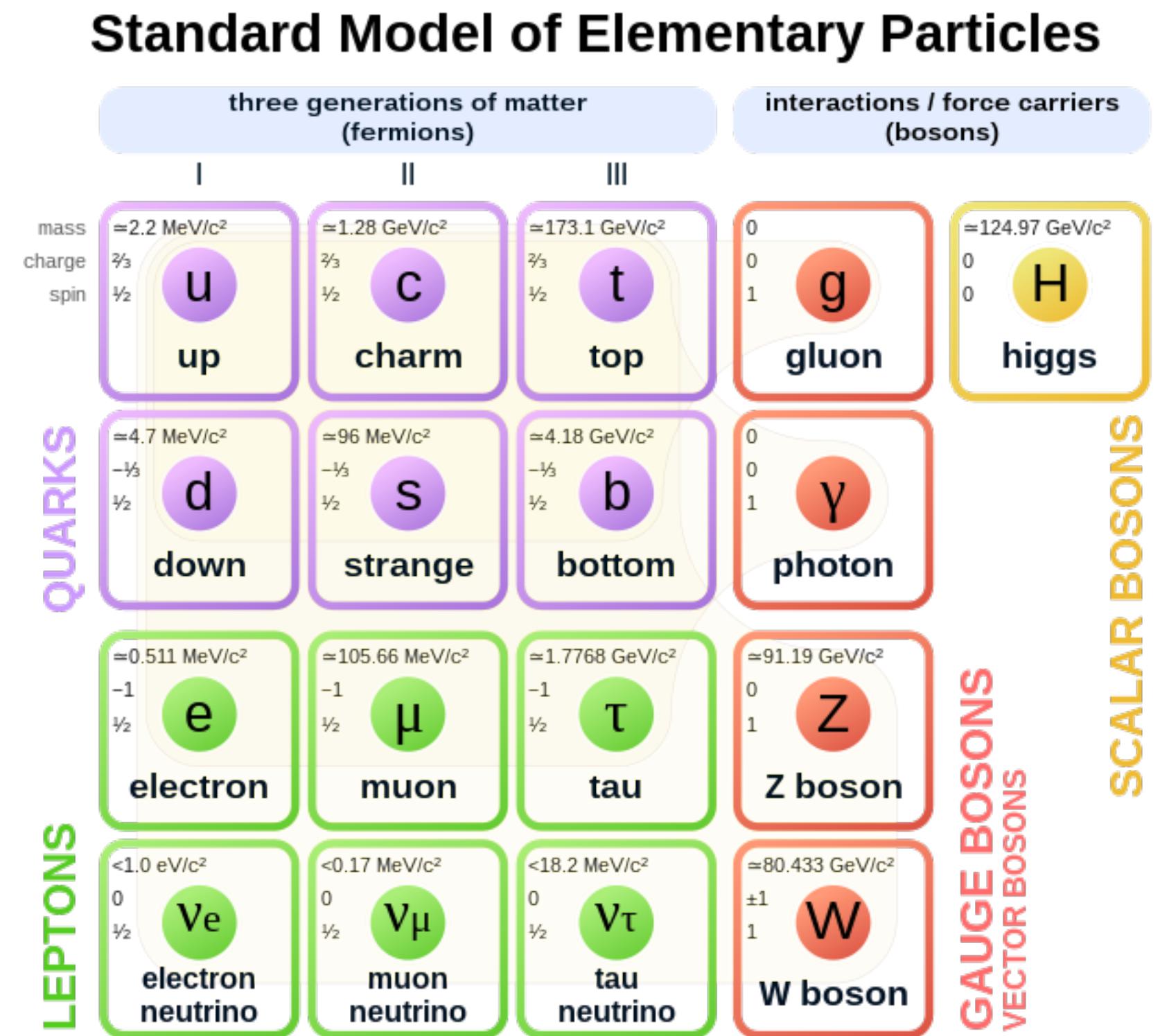
- Impressive agreement for large number of different measurements

- However: Large number of unanswered questions
  - Dark matter/energy
  - Matter/Antimatter asymmetry
  - Neutrino masses
  - Strong CP problem



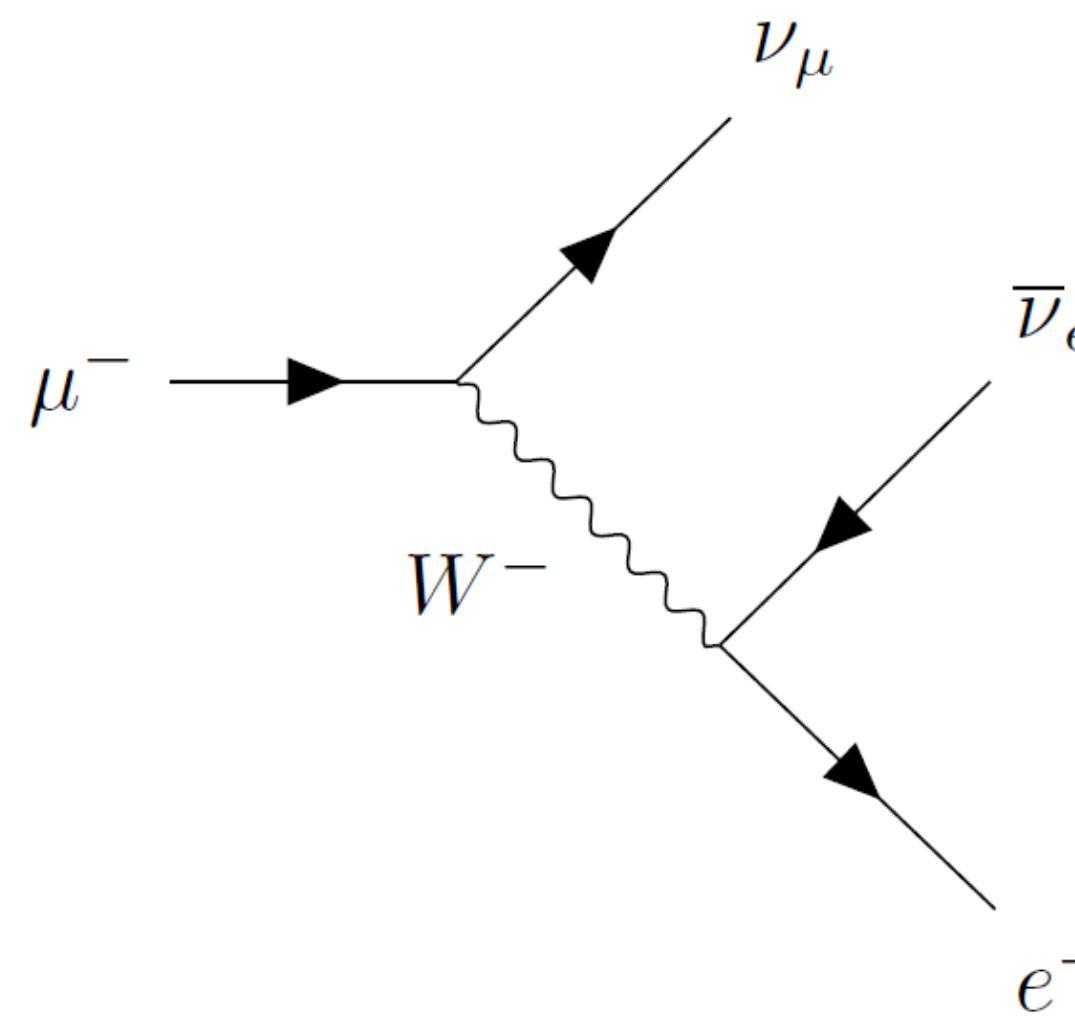
# Going beyond the Standard Model

- **Idea:** Introduce additional new particles (axions, sterile neutrinos, supersymmetry)
- **Problem:** Countless number of possible models to test individually
- **Solution:** Use a model agnostic approach to look for new physics



# Standard Model Effective Field Theory

- **Solution:** Extend the SM via a so-called Effective Field Theory approach
- Consider the decay:  $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$

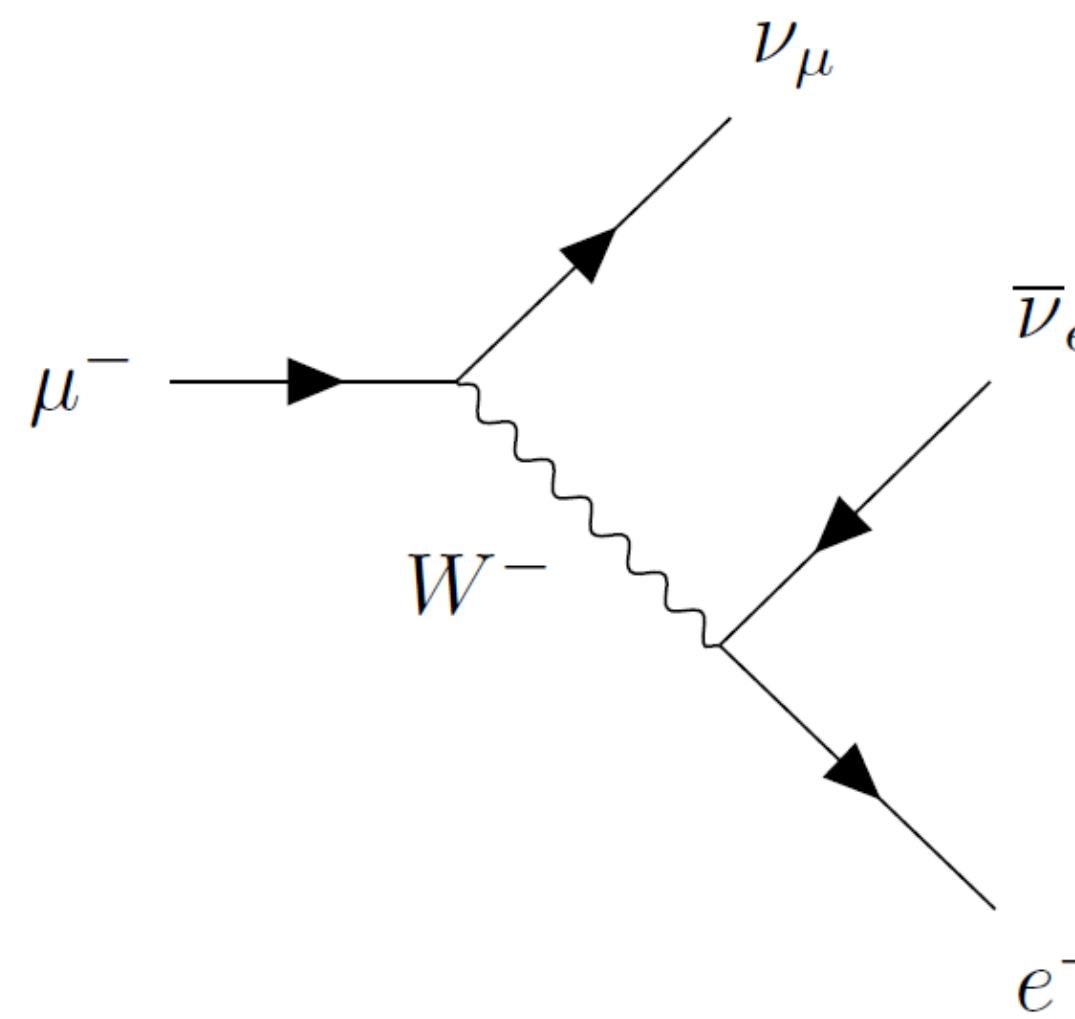


Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III	gluon	Higgs
mass charge spin	=2.2 MeV/c <sup>2</sup> 2/3 1/2	=1.28 GeV/c <sup>2</sup> 2/3 1/2	=173.1 GeV/c <sup>2</sup> 2/3 1/2	0 0 1 g =124.97 GeV/c <sup>2</sup> 0 0 1 H
QUARKS	up	charm	top	gluon
d	s	b	photon	higgs
down	strange	bottom	gamma	
LEPTONS	electron	muon	tau	
V <sub>e</sub>	V <sub>μ</sub>	V <sub>τ</sub>	Z boson	
electron neutrino	muon neutrino	tau neutrino	W boson	
SCALAR BOSONS				
GAUGE BOSONS VECTOR BOSONS				

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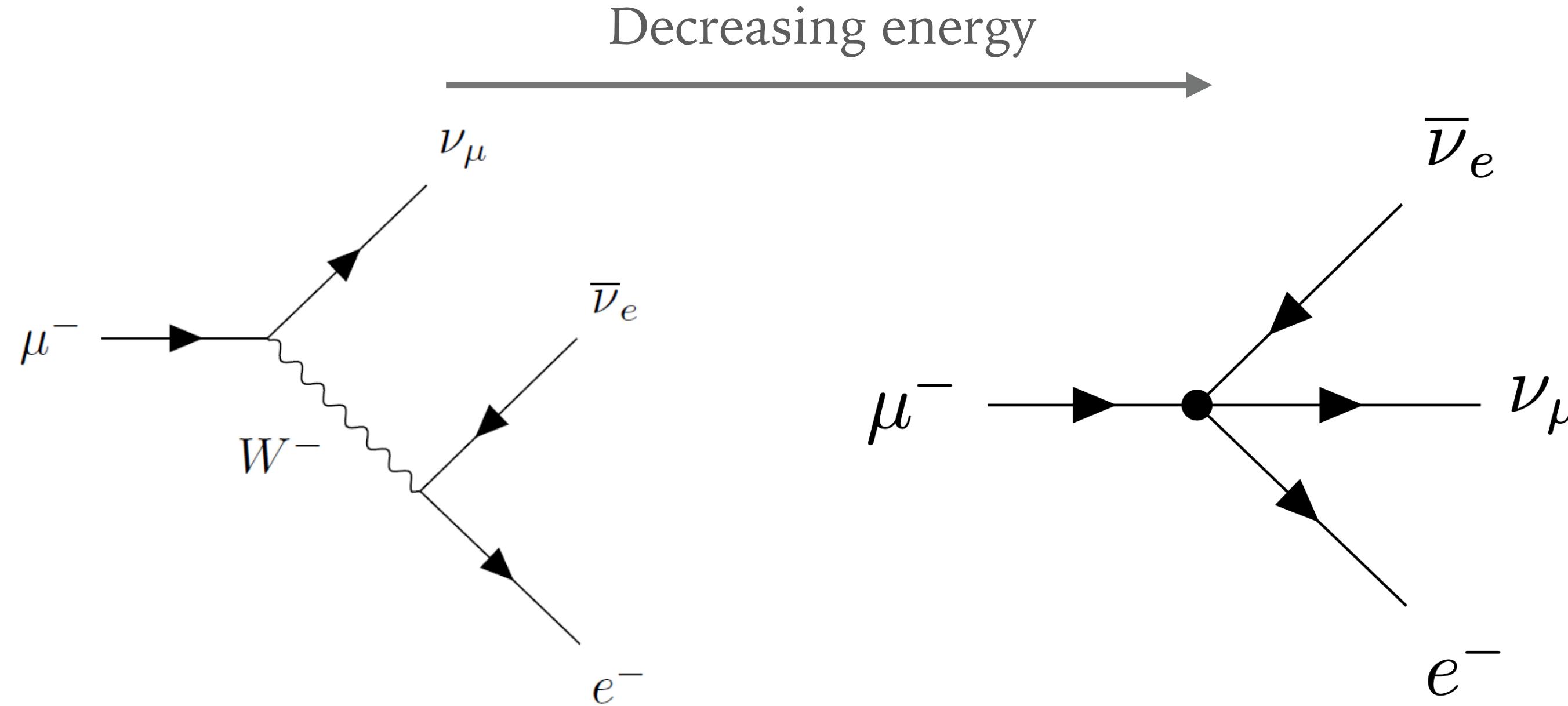


Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III	gluon	Higgs
mass charge spin	$=2.2 \text{ MeV}/c^2$ $2/3$ $1/2$ up	$=1.28 \text{ GeV}/c^2$ $2/3$ $1/2$ charm	$=173.1 \text{ GeV}/c^2$ $2/3$ $1/2$ top	$=124.97 \text{ GeV}/c^2$ $0$ $0$ g $=124.97 \text{ GeV}/c^2$ $0$ $0$ Higgs
QUARKS	d down	s strange	b bottom	$\gamma$ photon
LEPTONS	e electron	$\mu$ muon	$\tau$ tau	Z Z boson
	$<1.0 \text{ eV}/c^2$ 0 $1/2$ $\nu_e$ electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $1/2$ $\nu_\mu$ muon neutrino	$<18.2 \text{ MeV}/c^2$ 0 $1/2$ $\nu_\tau$ tau neutrino	$<80.433 \text{ GeV}/c^2$ $\pm 1$ 1 W W boson
SCALAR BOSONS				
GAUGE BOSONS VECTOR BOSONS				

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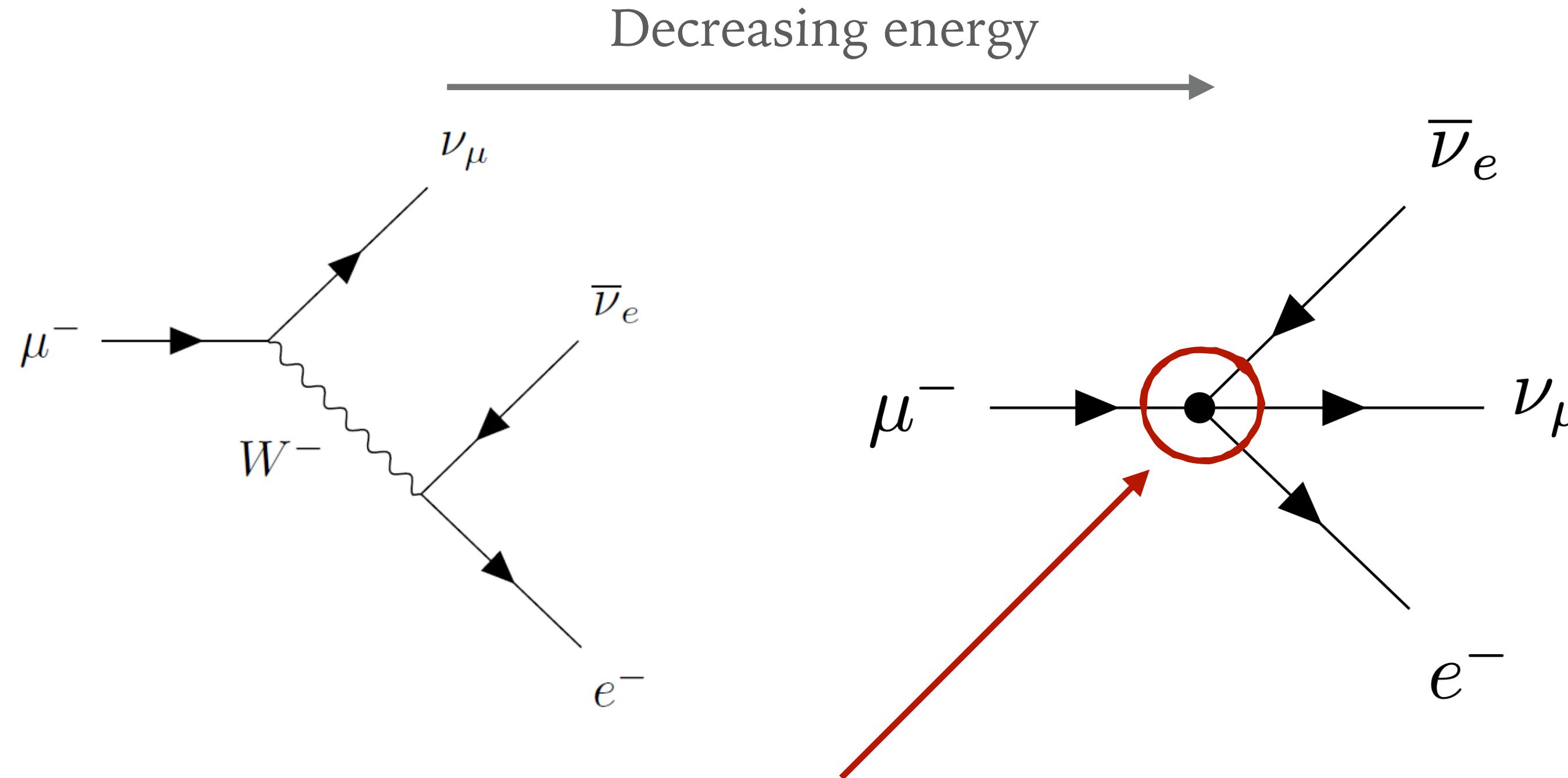


**Standard Model of Elementary Particles**

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III	g gluon	H higgs
mass charge spin	$=2.2 \text{ MeV}/c^2$ $2/3$ $1/2$ u up	$=1.28 \text{ GeV}/c^2$ $2/3$ $1/2$ c charm	$=173.1 \text{ GeV}/c^2$ $2/3$ $1/2$ t top	$=124.97 \text{ GeV}/c^2$ 0 0 1 g gluon
QUARKS	d down	s strange	b bottom	$\gamma$ photon
LEPTONS	$=4.7 \text{ MeV}/c^2$ $-1/3$ $1/2$ e electron	$=96 \text{ MeV}/c^2$ $-1/3$ $1/2$ $\mu$ muon	$=4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ $\tau$ tau	$=91.19 \text{ GeV}/c^2$ 0 1 Z boson
	$=0.511 \text{ MeV}/c^2$ -1 $1/2$ Ve electron neutrino	$=105.66 \text{ MeV}/c^2$ -1 $1/2$ V $\mu$ muon neutrino	$=1.7768 \text{ GeV}/c^2$ -1 $1/2$ V $\tau$ tau neutrino	$=80.433 \text{ GeV}/c^2$ $\pm 1$ 1 W boson
SCALAR BOSONS				GAUGE BOSONS VECTOR BOSONS

# Standard Model Effective Field Theory

- **Solution:** Extend the SM via a so-called Effective Field Theory approach
- Consider the decay:  $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$



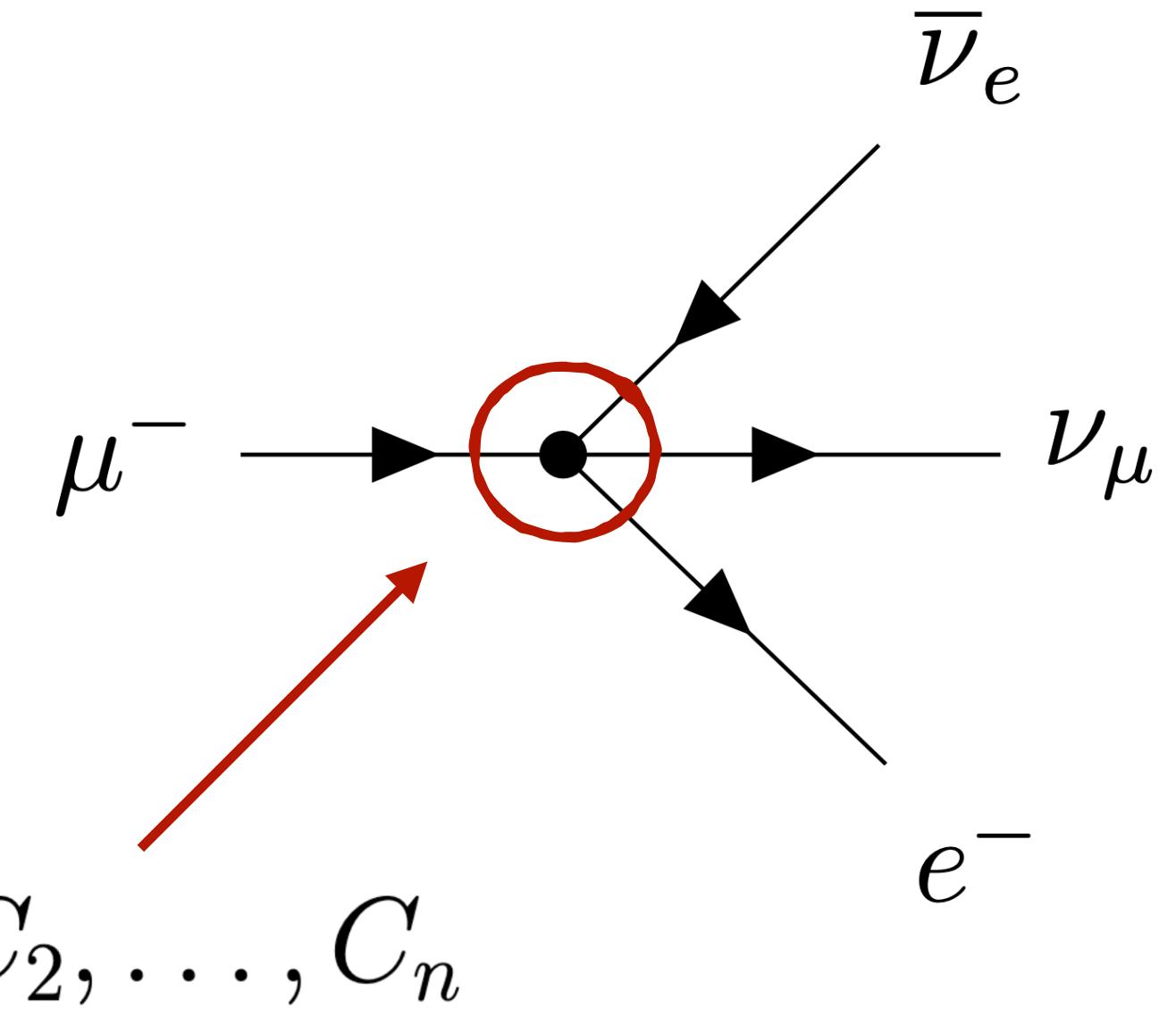
The interesting physics happening here  
cannot be resolved

Standard Model of Elementary Particles			
three generations of matter (fermions)			interactions / force carriers (bosons)
I	mass = charge spin	$U$ up	$g$ gluon
II	$=2.2 \text{ MeV}/c^2$ $2/3$ $1/2$	$C$ charm	$H$ higgs
III	$=1.28 \text{ GeV}/c^2$ $2/3$ $1/2$	$t$ top	
QUARKS	$=173.1 \text{ GeV}/c^2$ $2/3$ $1/2$		
	$d$ down	$b$ bottom	$\gamma$ photon
	$=4.7 \text{ MeV}/c^2$ $-1/3$ $1/2$	$s$ strange	
LEPTONS	$=96 \text{ MeV}/c^2$ $-1/3$ $1/2$	$\tau$ tau	$Z$ Z boson
	$=4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$	$e$ electron	$W$ W boson
	$=0.511 \text{ MeV}/c^2$ $-1$ $1/2$	$\mu$ muon	
SCALAR BOSONS	$=105.66 \text{ MeV}/c^2$ $-1$ $1/2$	$\tau$ tau neutrino	
	$=1.7768 \text{ GeV}/c^2$ $-1$ $1/2$	$\nu_e$ electron neutrino	
GAUGE BOSONS	$=91.19 \text{ GeV}/c^2$ $0$ $1$	$\nu_\mu$ muon neutrino	
VECTOR BOSONS	$<1.0 \text{ eV}/c^2$ $0$ $1/2$	$\nu_\tau$ tau neutrino	

# Standard Model Effective Field Theory

- SMEFT framework **parametrizes the new physics** in such vertices

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^n \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$



- We use these parameters to put limits on new physics:
- **Large number** of possible contributions
- Contributions depend on **processes considered**
- **Goal:** Put constraints on these contributions

$$C_1, C_2, \dots, C_n$$

# Performing statistical analyses

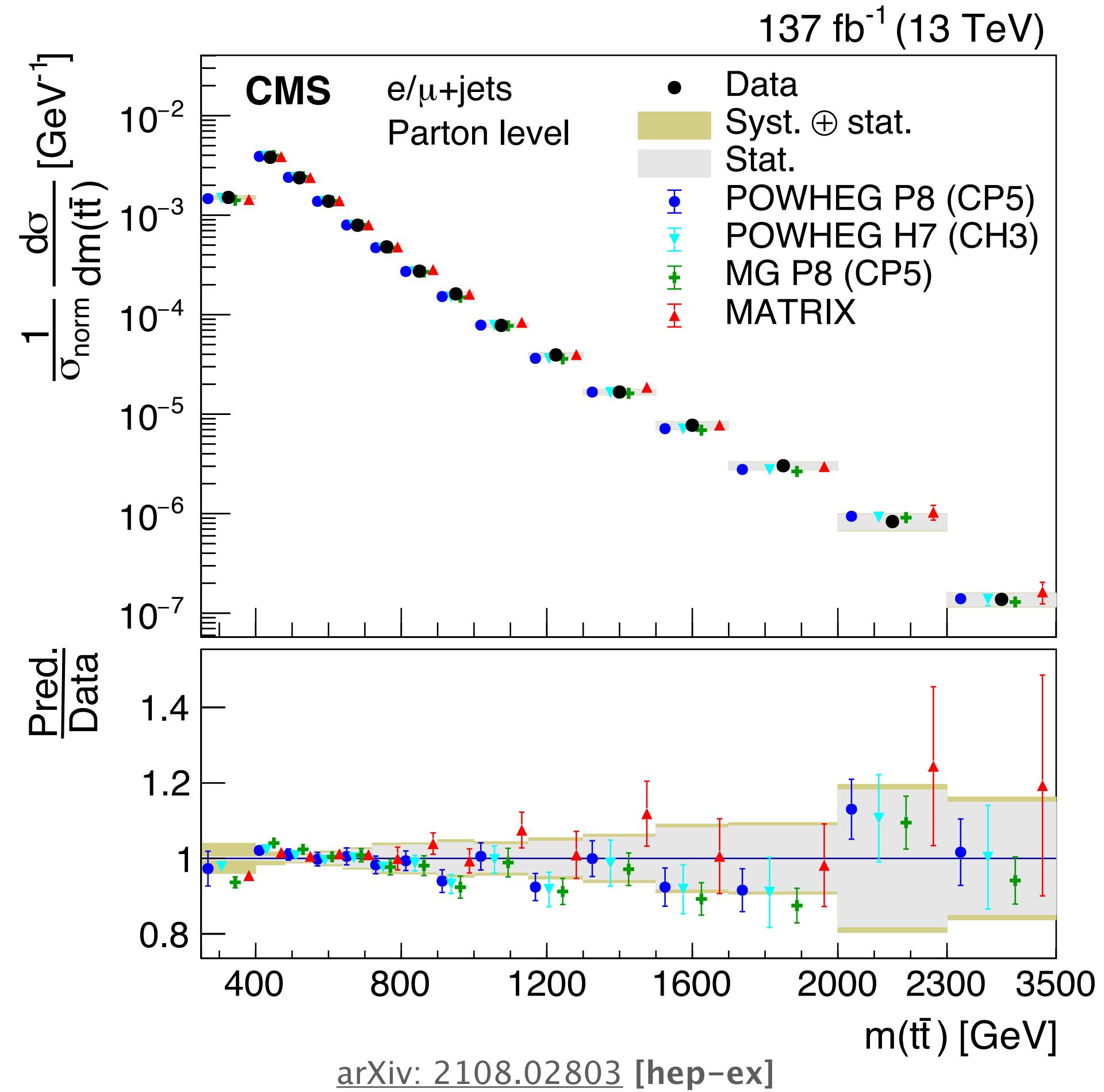
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- Compute the likelihood that given data matches theory

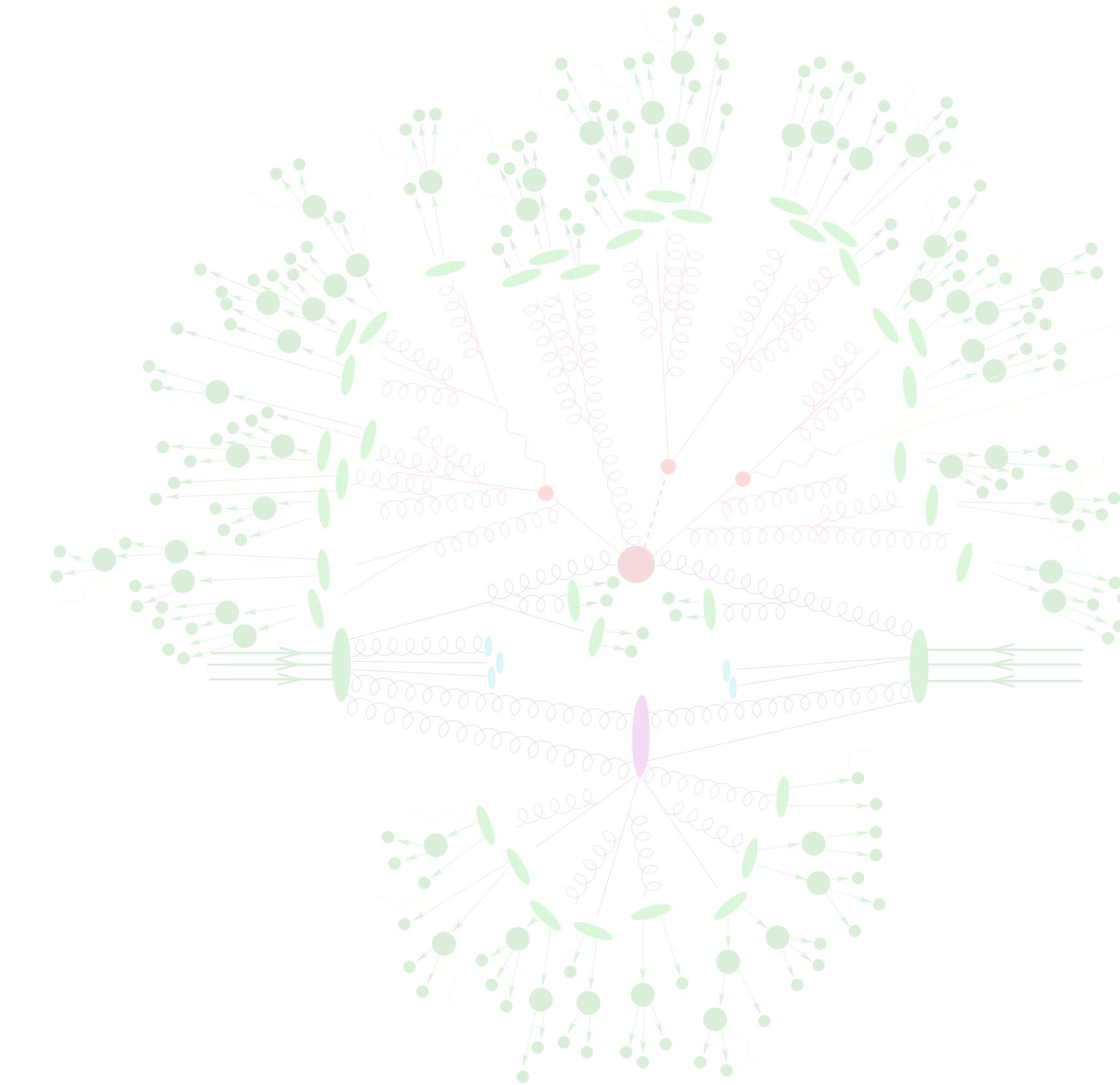
$$\mathcal{L}_{excl} = \text{Pois}(d|p(\alpha_n, \theta_i, b)) \text{Pois}(b_{CR}|b k) \prod_i \mathcal{C}(\theta_i, \sigma_i)$$

- We use LHC data published by both the ATLAS and CMS experiments
  - For results shown here Higgs, Di-Boson and electroweak data (LEP);  
~ 400 datapoints
  - Sufficiently **accurate theory predictions** are necessary
    - This is where **NEMO** comes in

# Computing theory predictions



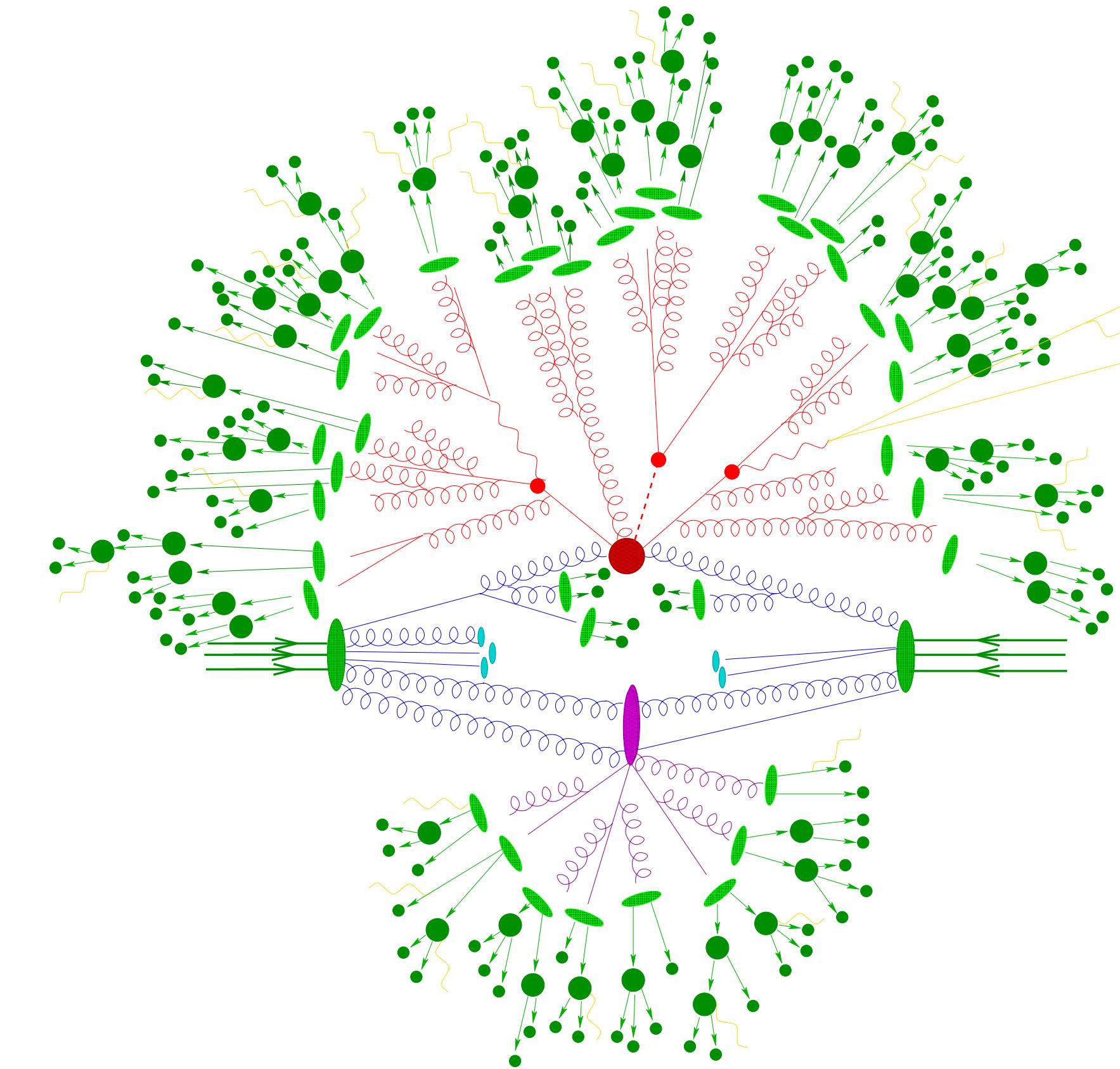
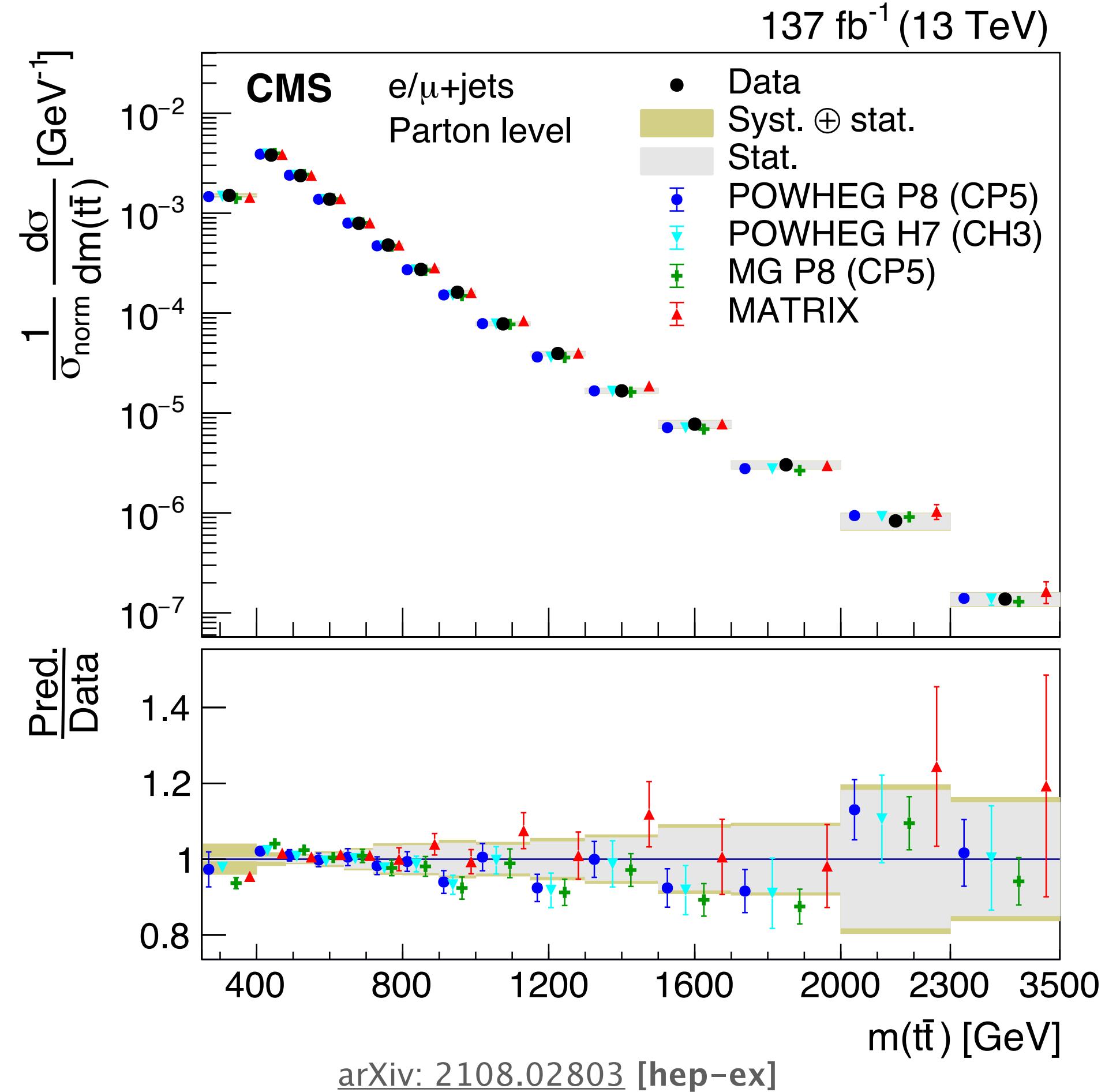
arXiv: 2108.02803 [hep-ex]



Credit: Stefan Hoche

- Analyses require computation of theory predictions

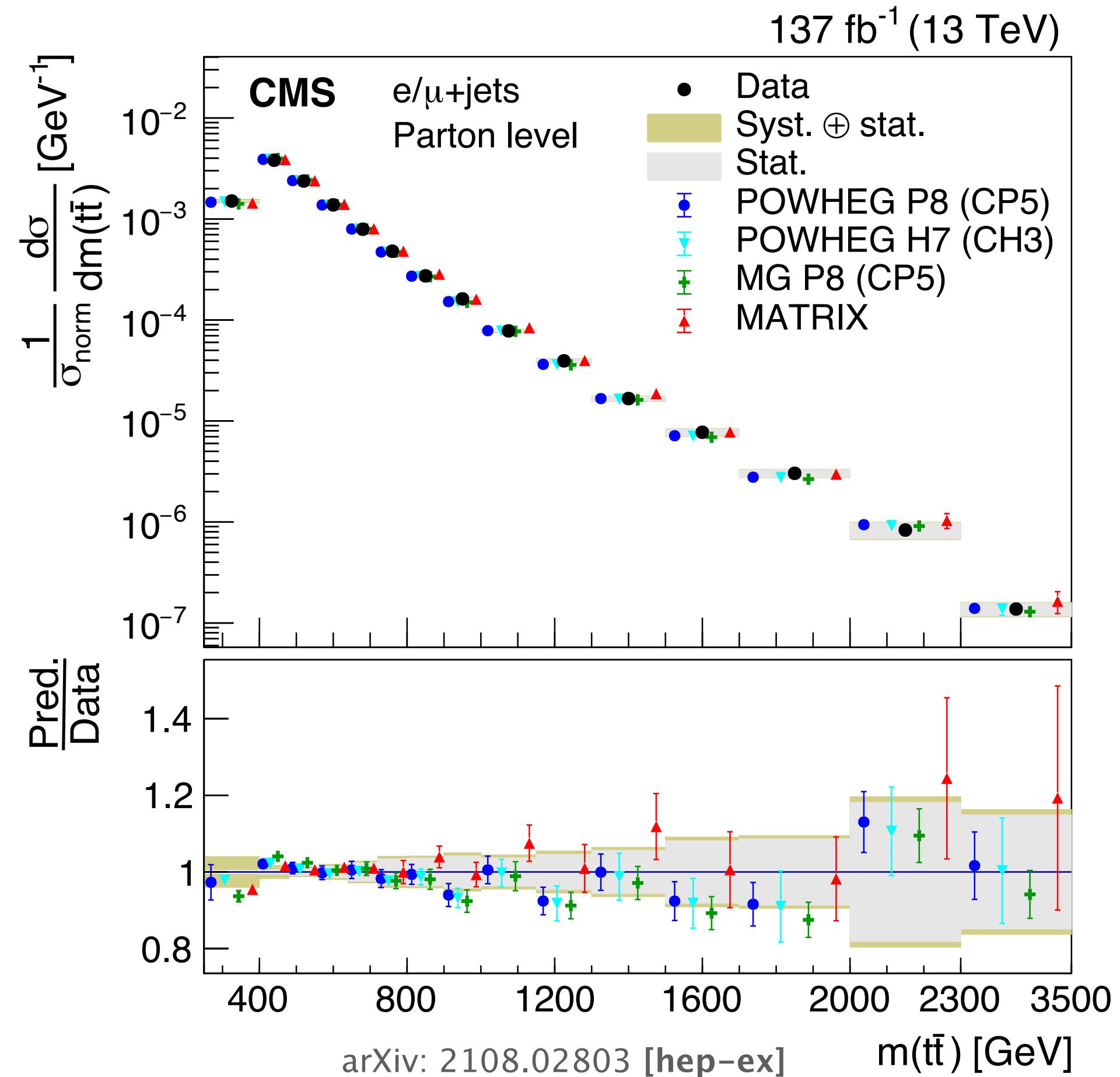
# Computing theory predictions



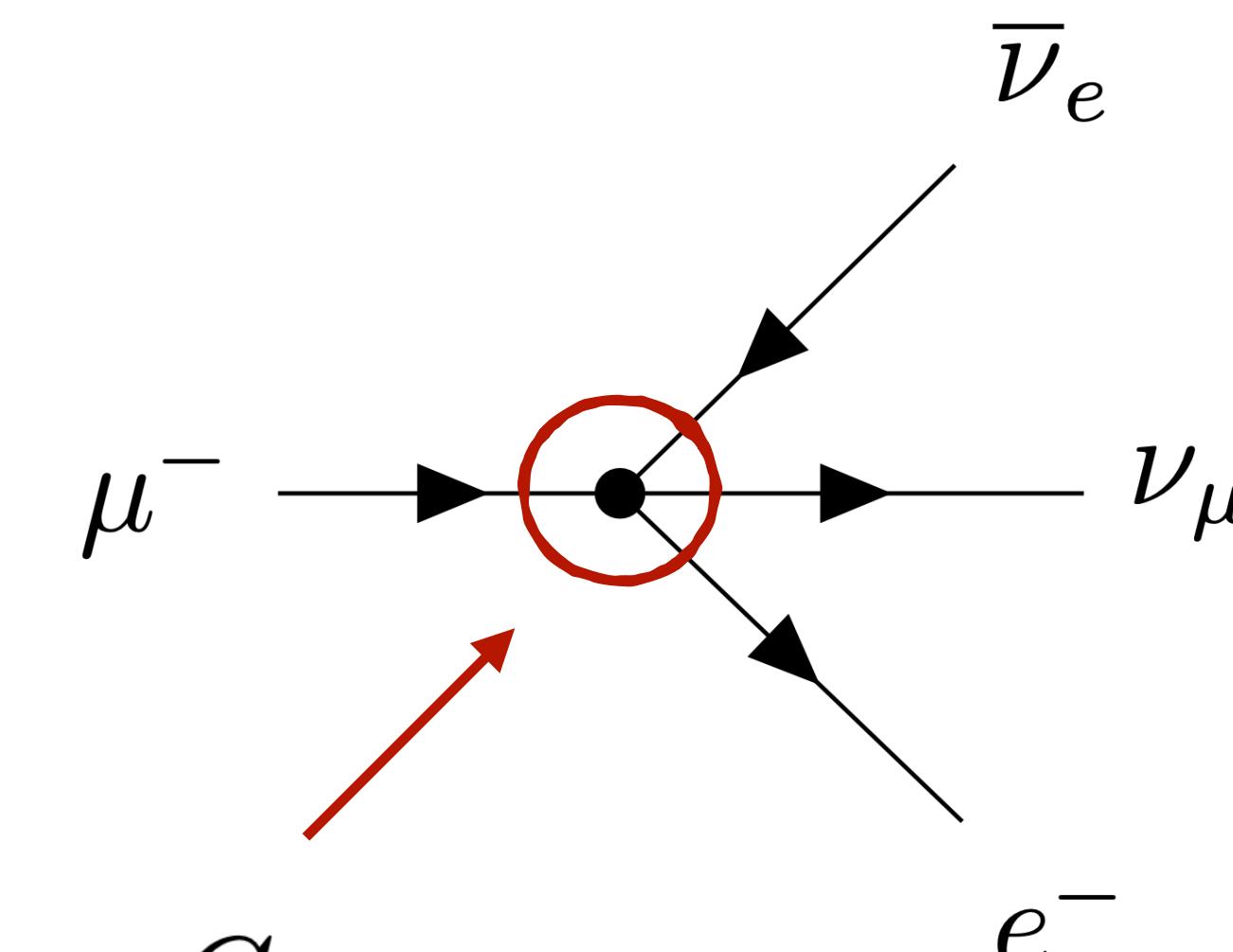
Credit: Stefan Hoche

- Analyses require computation of complex theory predictions

# Computing theory predictions

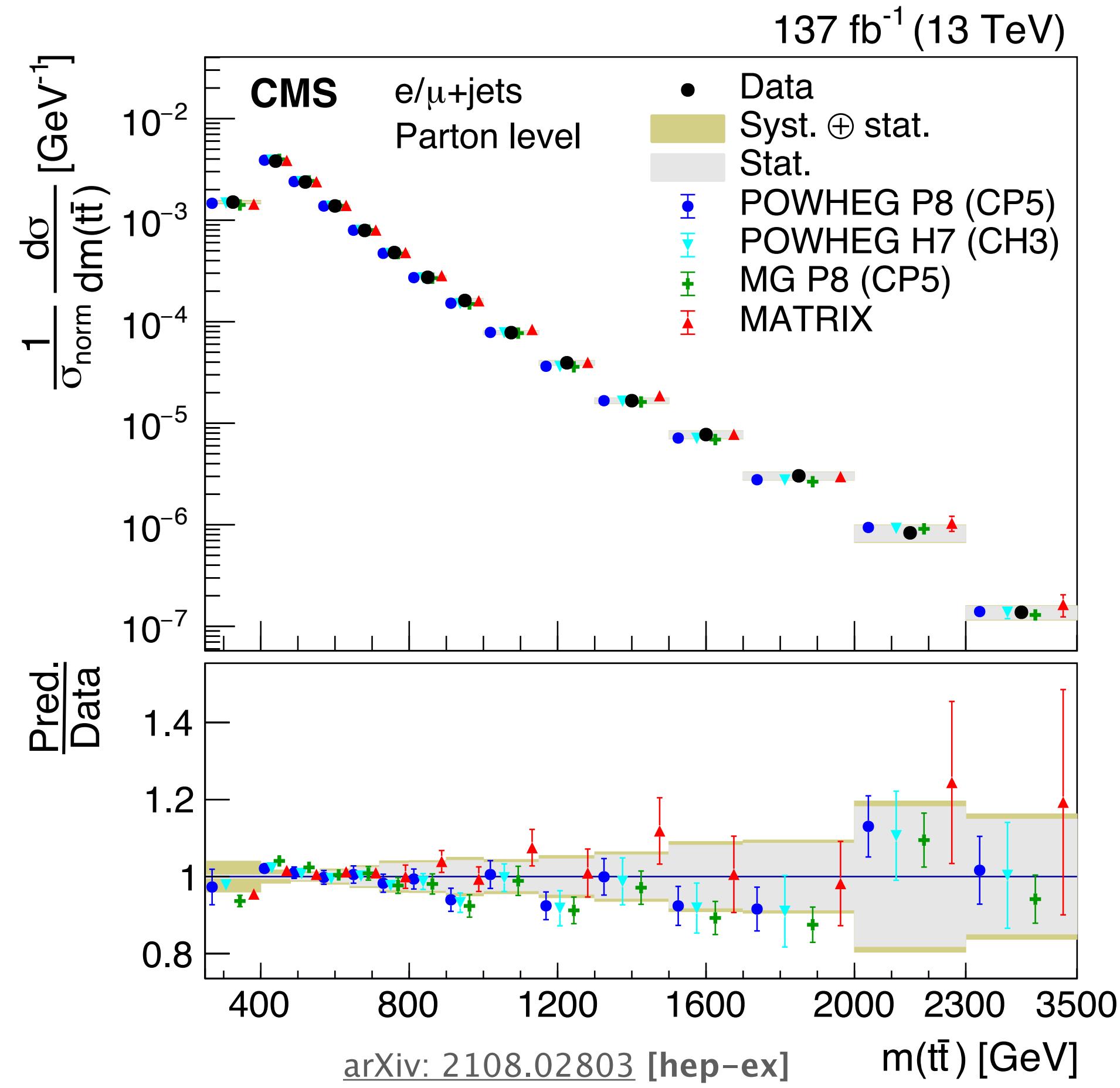


► Earlier Example:  $\mu^- \rightarrow e^- \nu_e \nu_\mu$

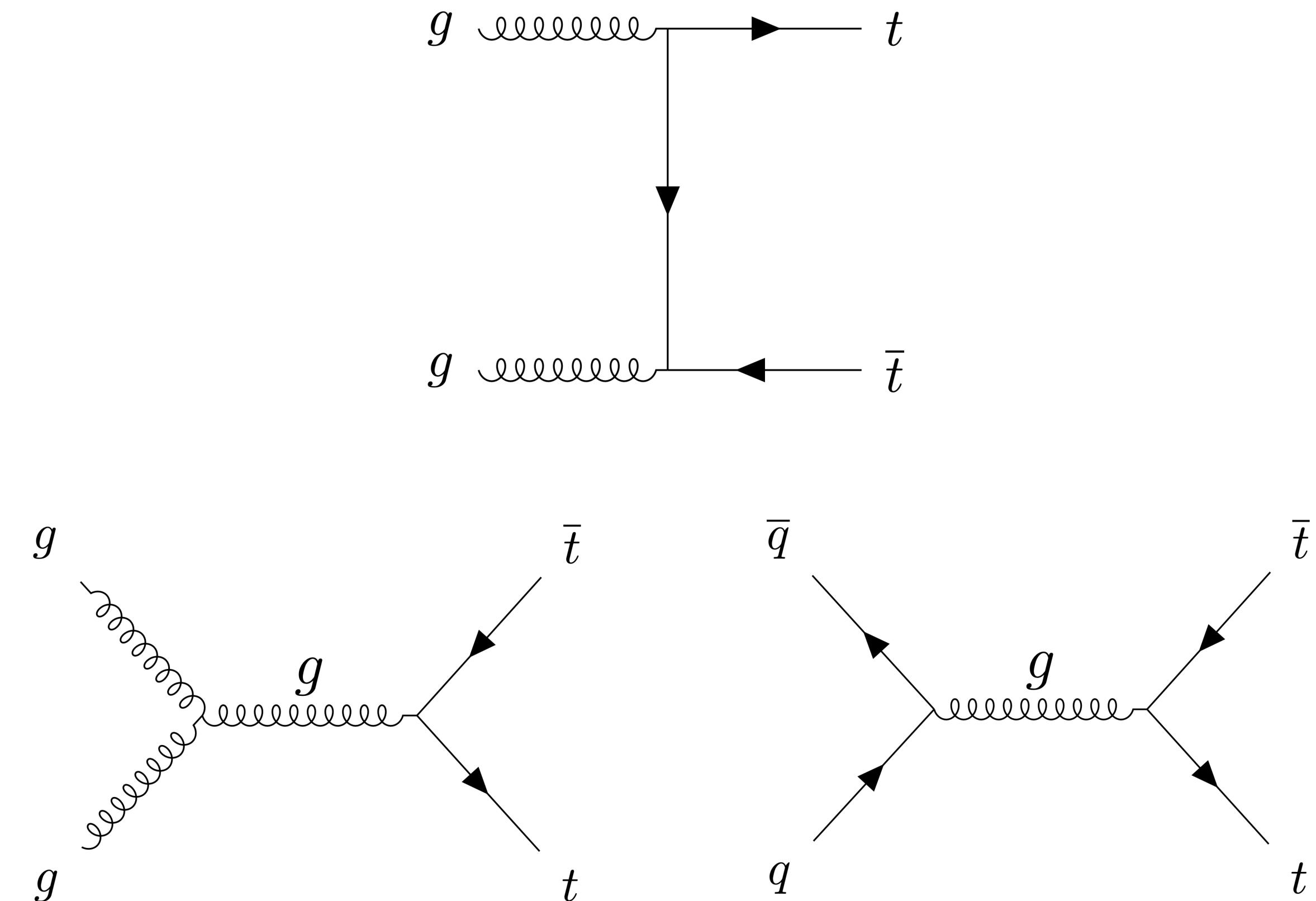


$$C_1, C_2, \dots, C_n$$

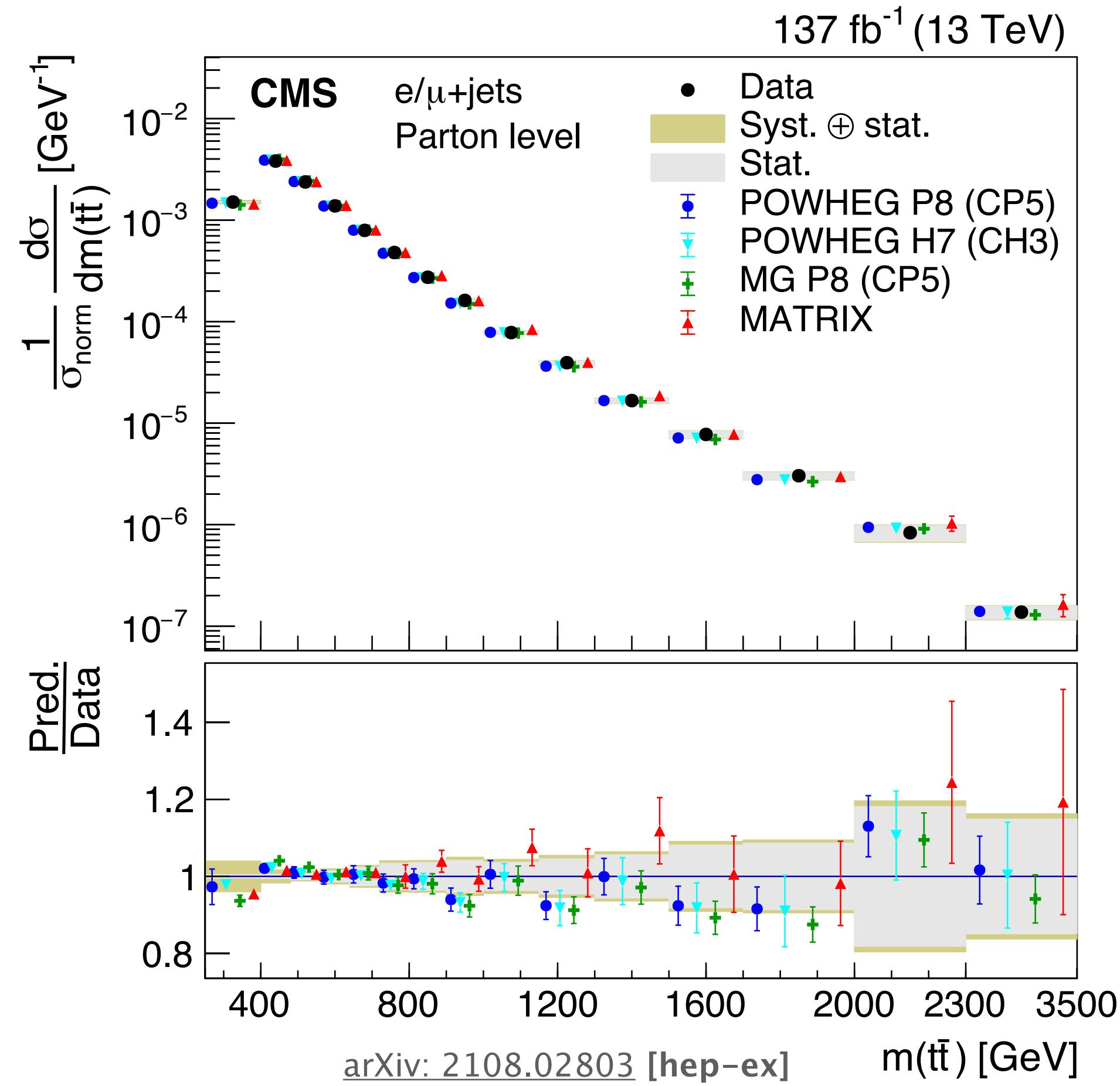
# Computing theory predictions



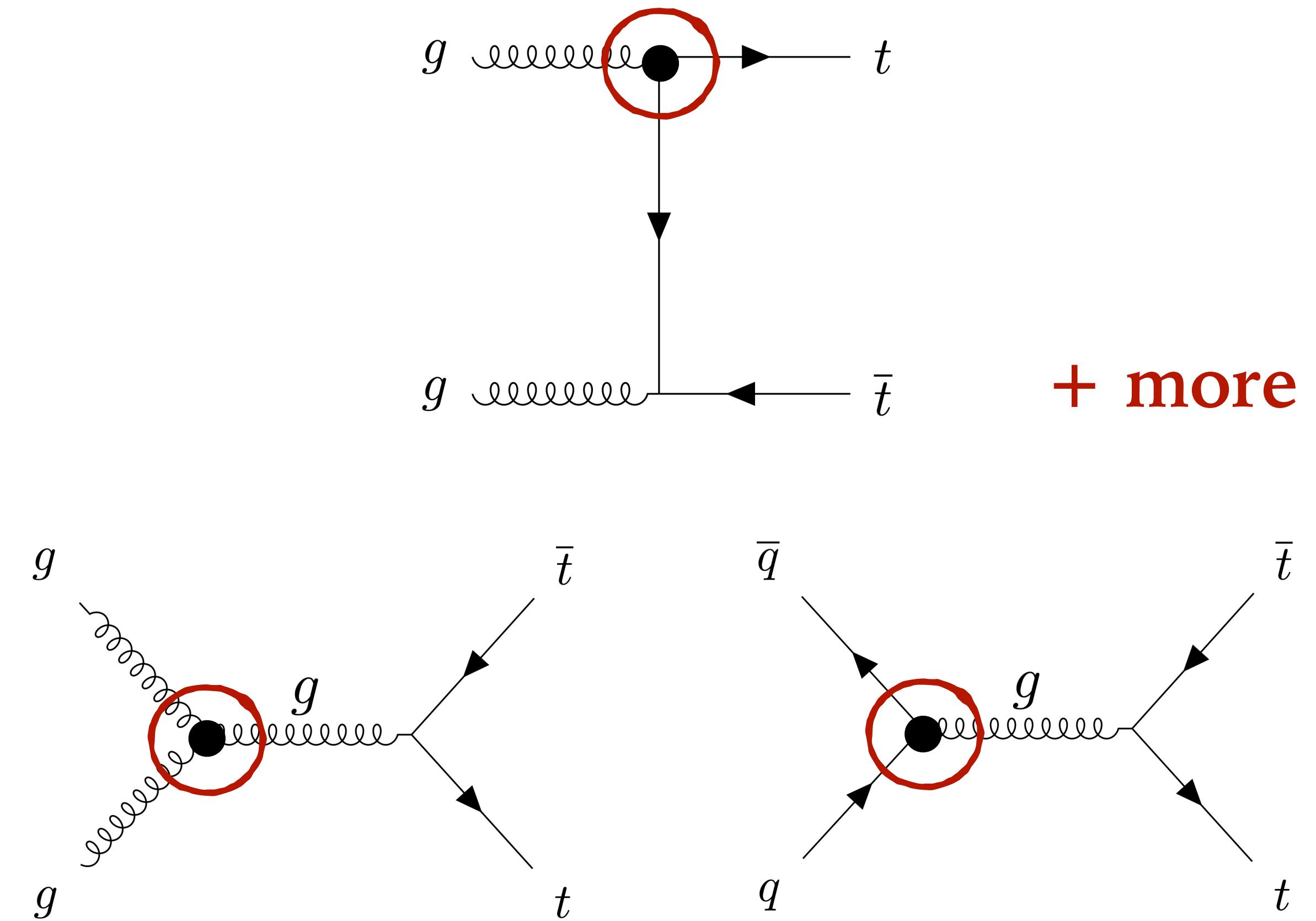
► For the measurement shown:



# Computing theory predictions



► For the measurement shown:



# Performing statistical analyses

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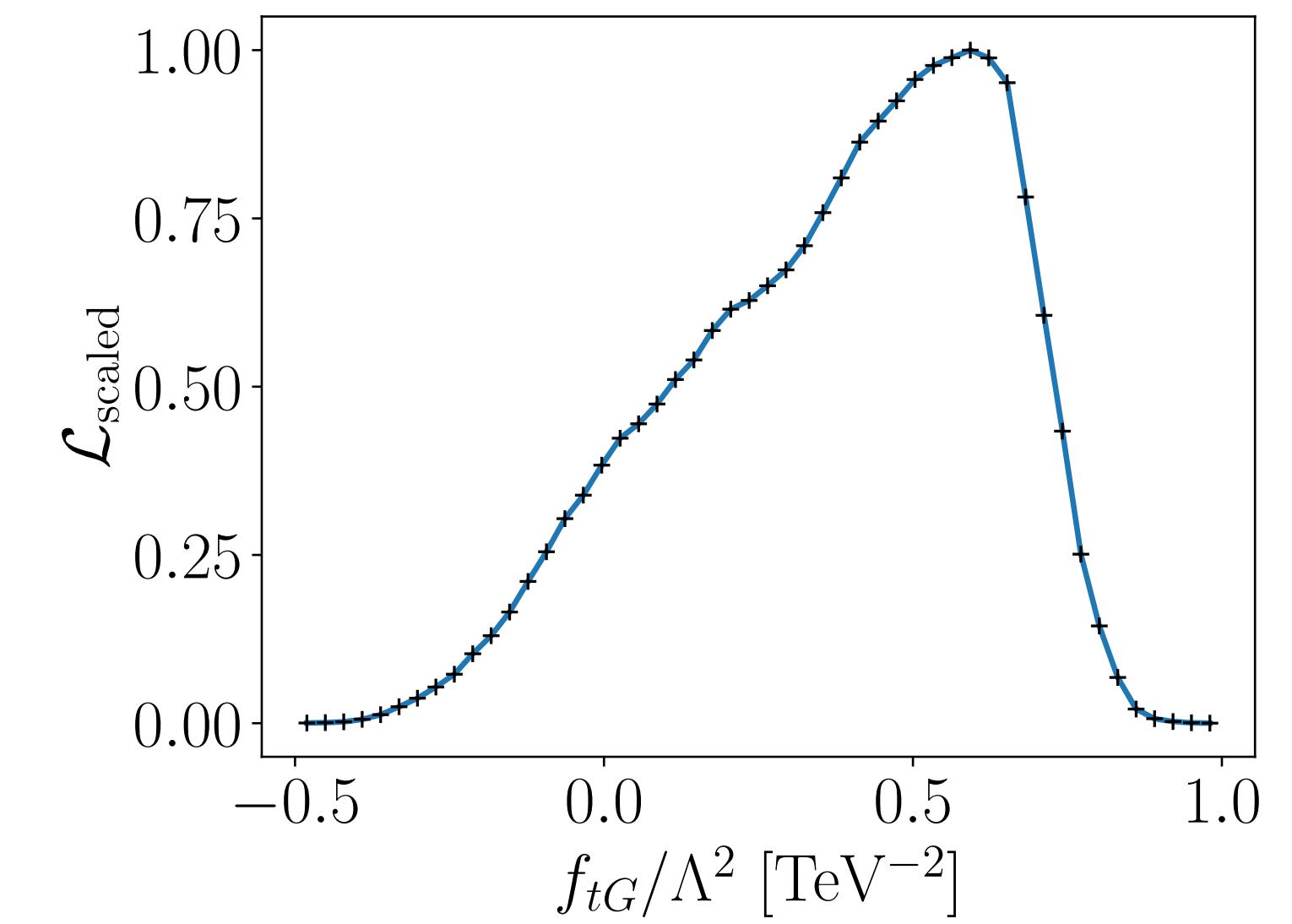
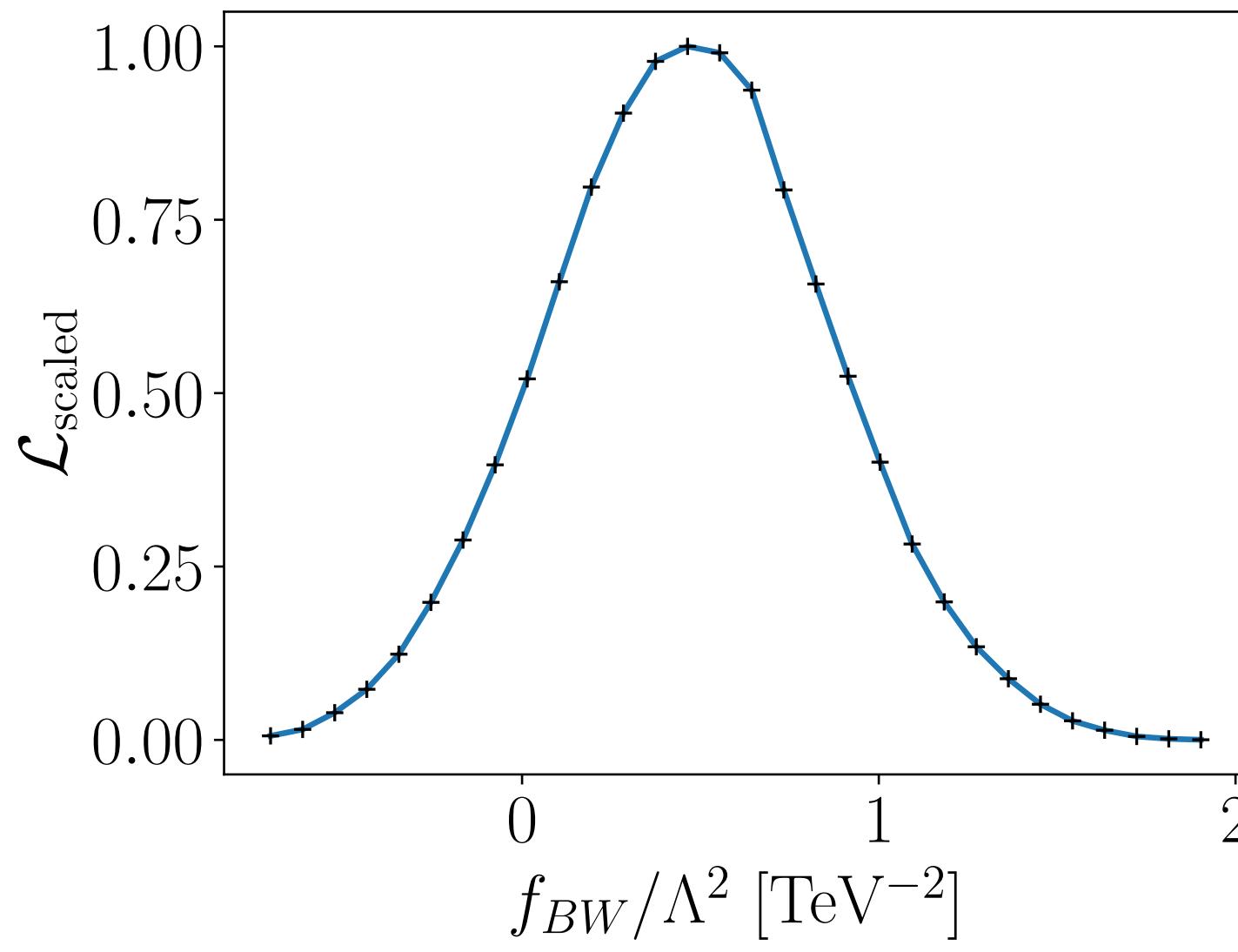
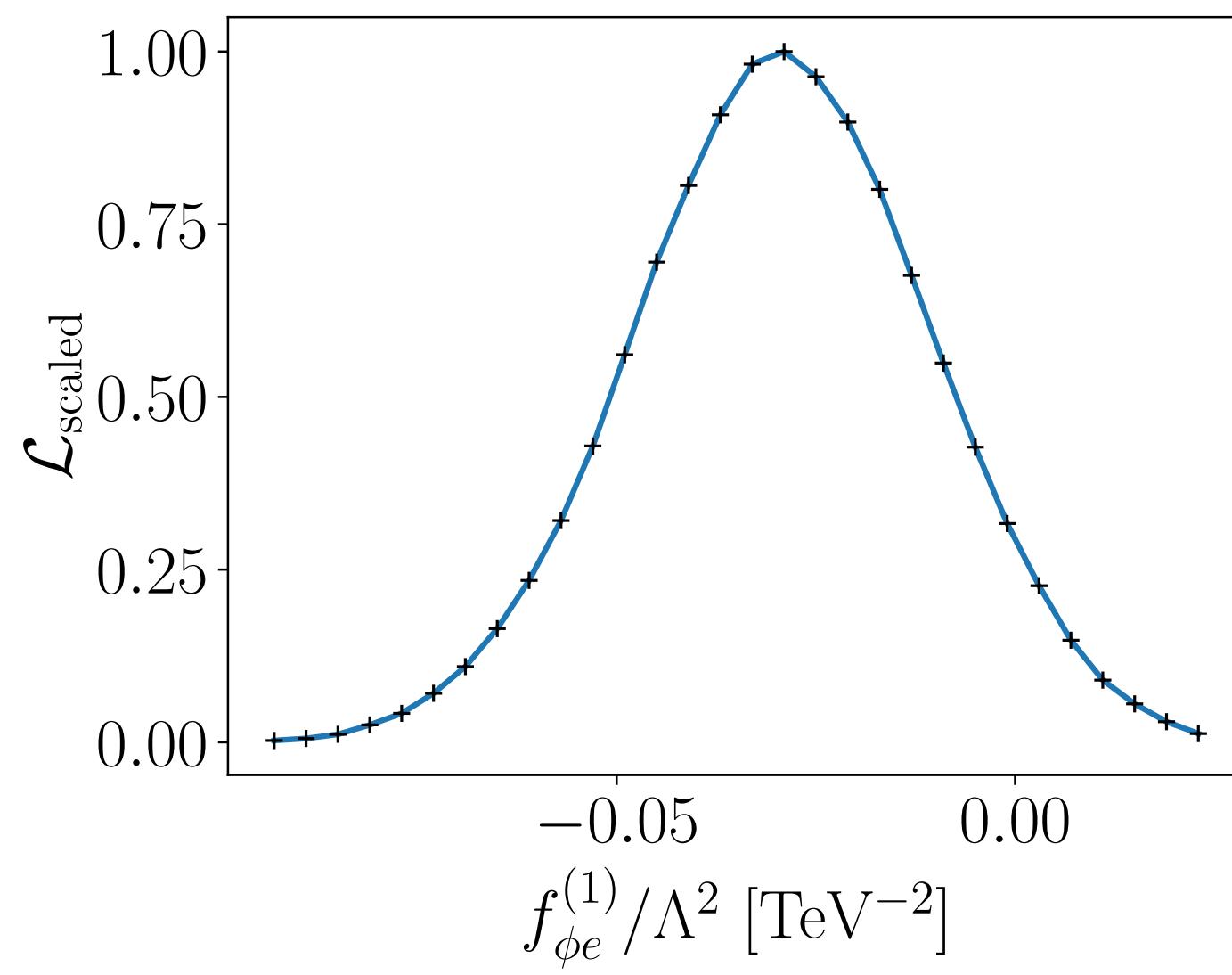
- Compute the likelihood that given data matches theory

$$\mathcal{L}_{excl} = \text{Pois}(d|p(\alpha_n, \theta_i, b)) \text{Pois}(b_{CR}|b k) \prod_i \mathcal{C}(\theta_i, \sigma_i)$$

- Theory predictions are computed using **NEMO**
  - Large number of **different processes**
  - Effects from all **21 additional parameters** describing new physics
- **21-dimensional likelihood** now needs to be mapped
  - Use **NEMO** to run multiple Markov chains

# Results from a global SMEFT analysis

## One-dimensional results

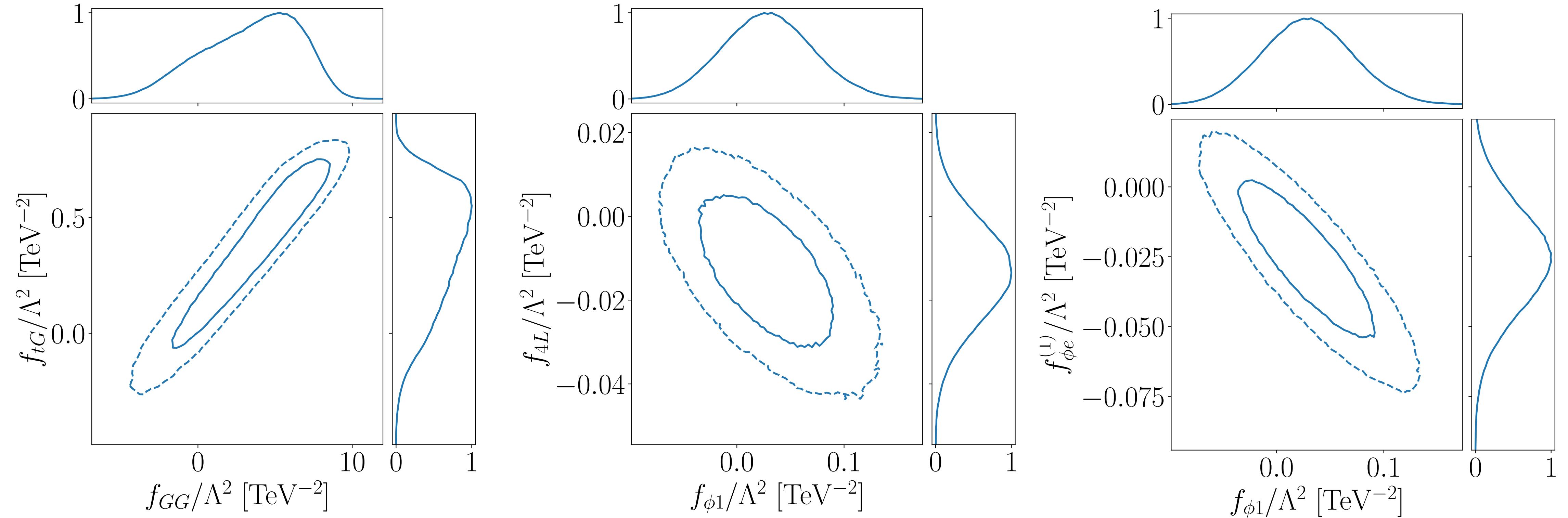


[arXiv:2208.08454 \[hep-ph\]](https://arxiv.org/abs/2208.08454)

- Each distribution describes one of the parameters for new physics effects
- Extract **limits for new physics** from these

# Results from a global SMEFT analysis

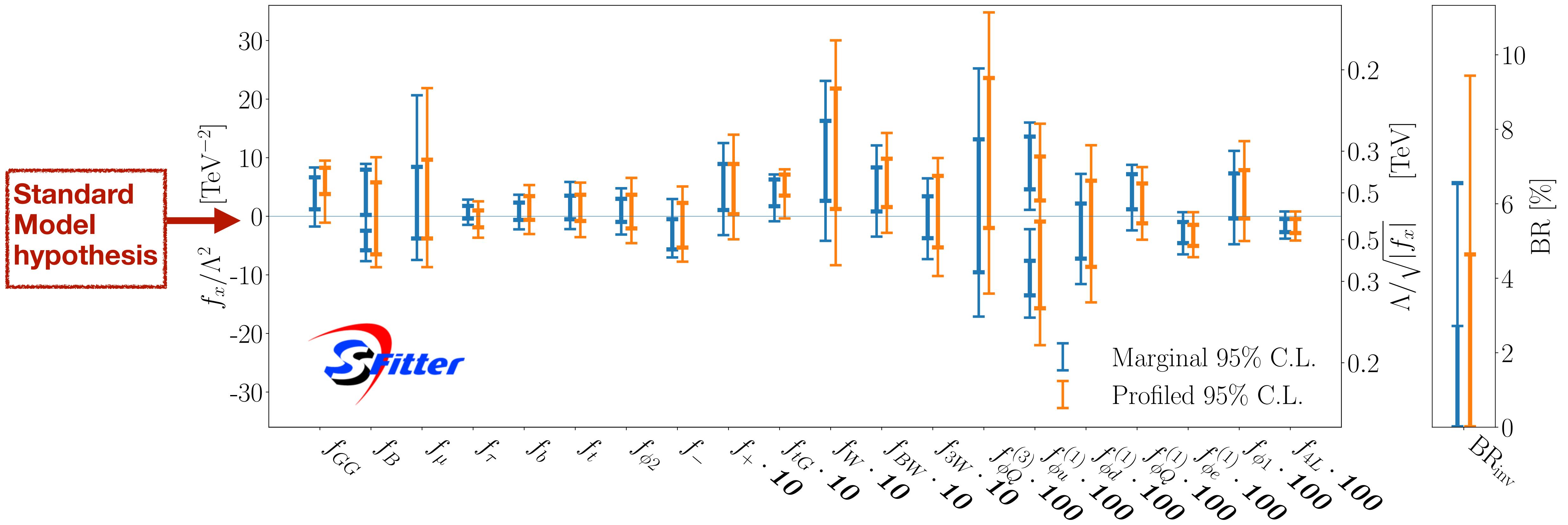
## Two-dimensional results



- Study **correlations** between different parameters

# Results from a global SMEFT analysis

## Extracted limits



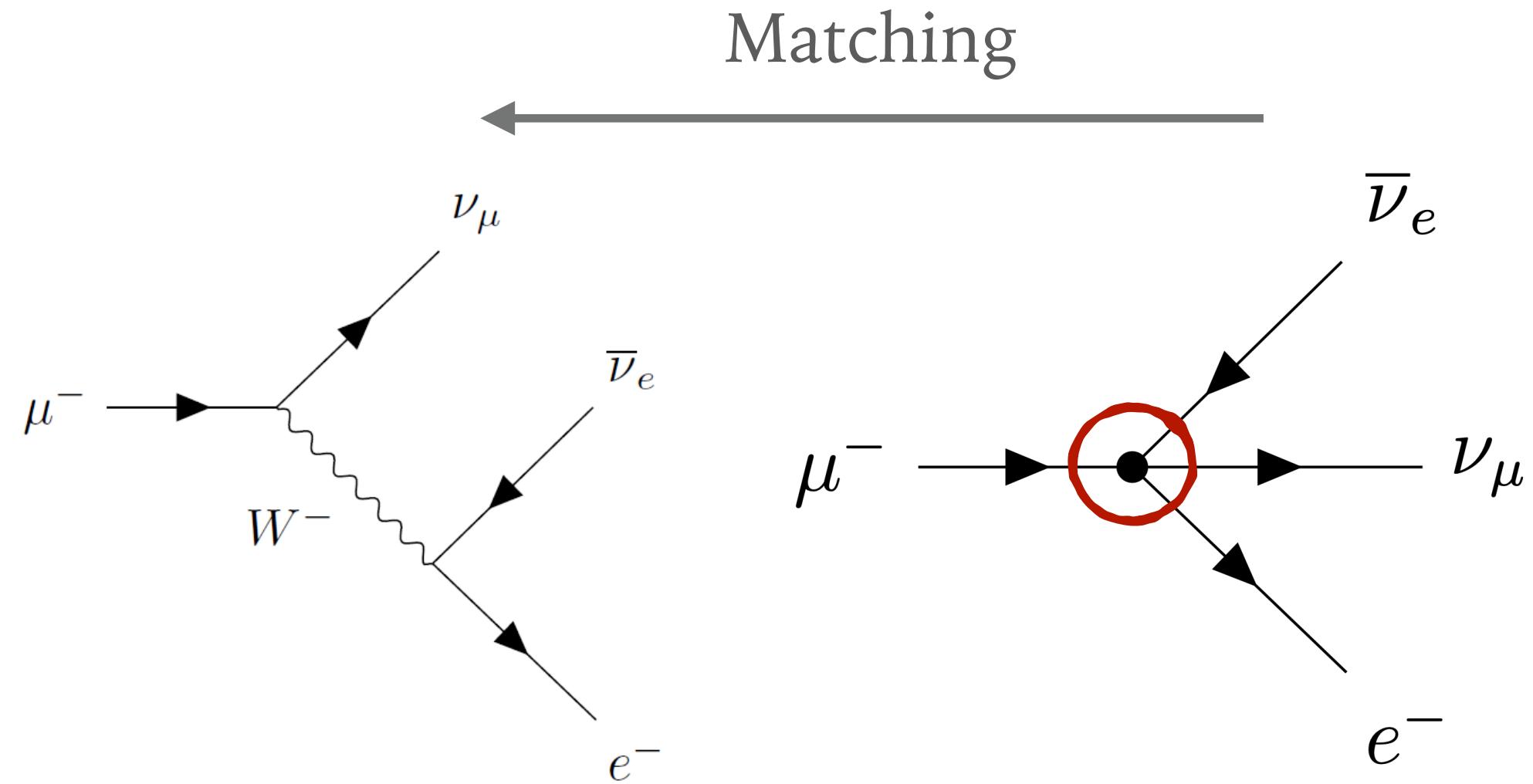
- What do these limits tell us?

arXiv:2208.08454 [hep-ph]

# Results from a global SMEFT analysis

## Matching constraints to models

- Back to our example:

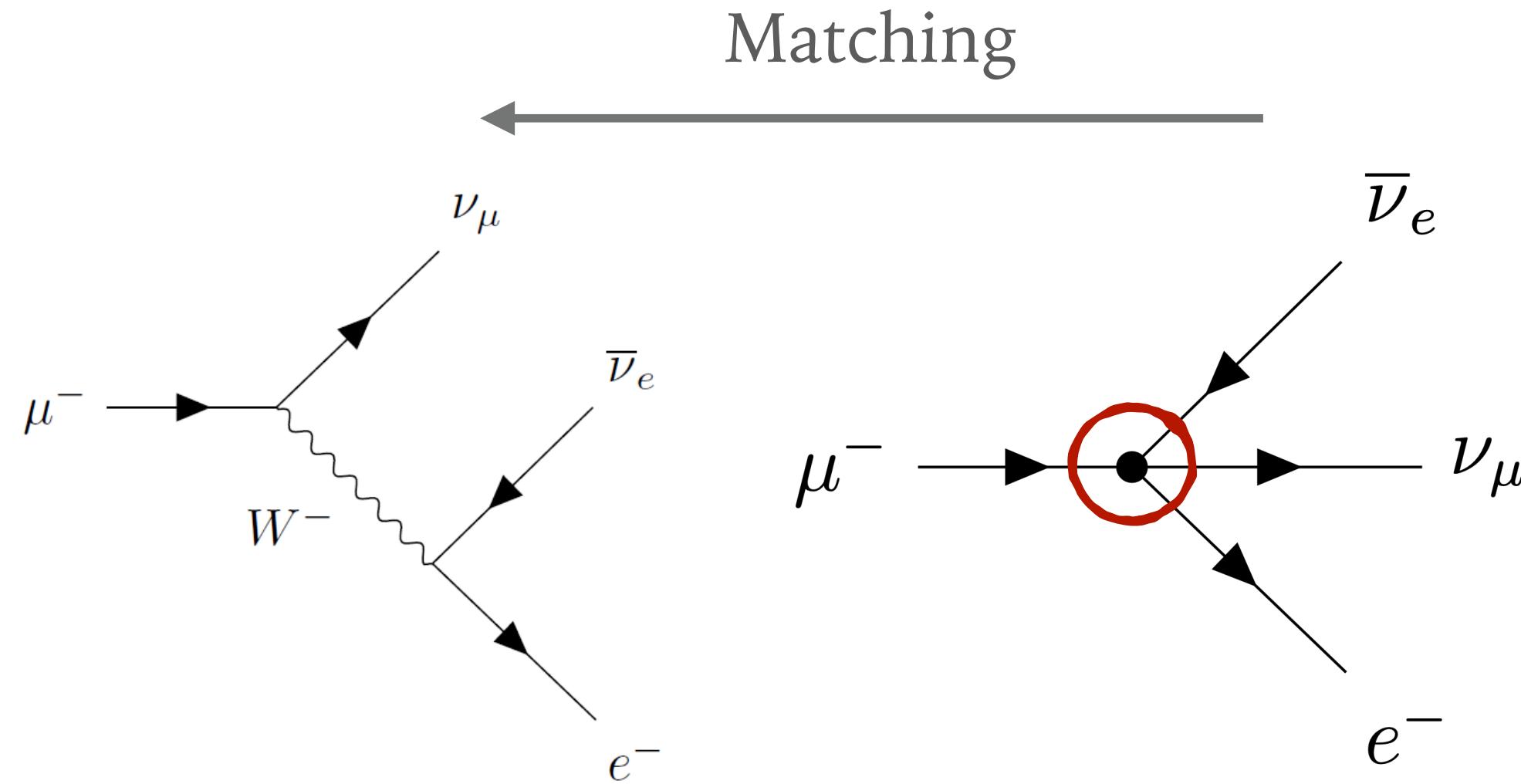


Matching to model with W-Boson  
**predicts new physics at  $\approx 100$  GeV**

# Results from a global SMEFT analysis

## Matching constraints to models

- Back to our example:



Matching to model with W-Boson  
**predicts new physics at  $\approx 100$  GeV**  
Nowadays we know:  $m_W \approx 81$  GeV

- Matching for one of our studies in [arXiv:2108.01094 \[hep-ph\]](https://arxiv.org/abs/2108.01094)

# Outlook and Summary

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- Where do we go from here?
  - Shown results from an analysis using 21 parameters; ~400 datapoints
  - Current work extends parameters space up to 39 and extends the dataset
- Why **NEMO** is indispensable:
  - Computation of **numerous complex theory predictions**
  - Mapping of **high-dimensional parameter spaces**

# Thank you for your attention!