Habilitation à Diriger des Recherches

Physics with boson pairs

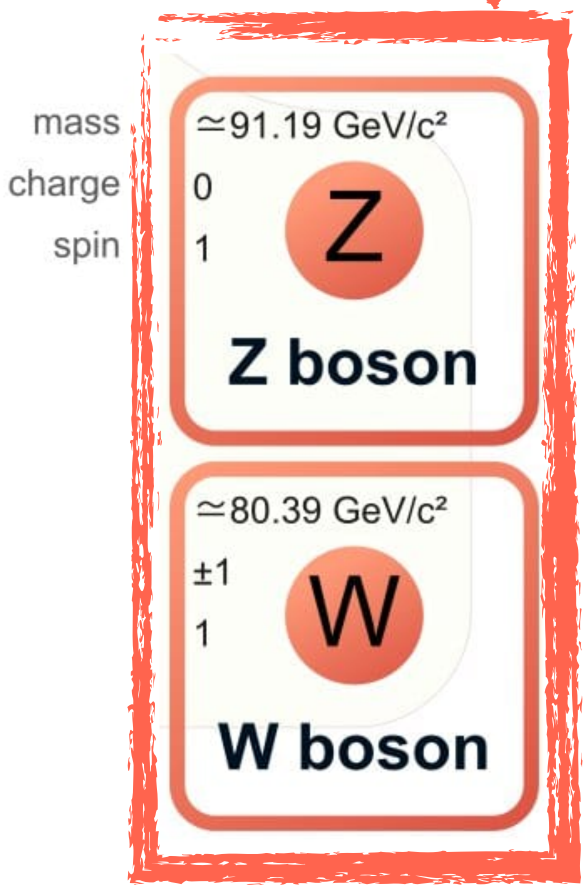
J. Manjarrés Ramos

Jury members:

Oscar ÉBOLI
Gautier HAMEL de MONCHENAULT
Ursula BASSLER
Pierre PUJOL
Jan STARK

In this seminar

the main actors



challenge

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

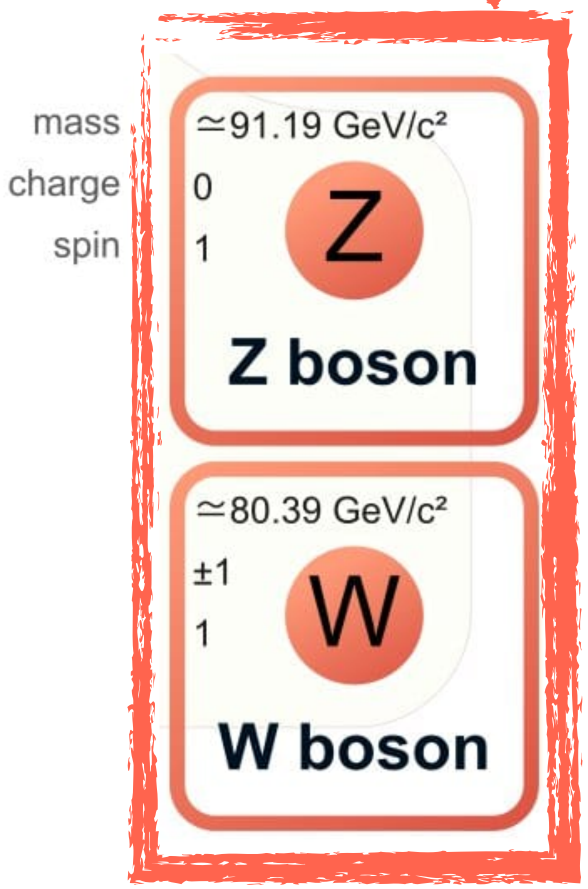
We have our actors, and the main stage is the center of the ATLAS detector at the LHC

the stage

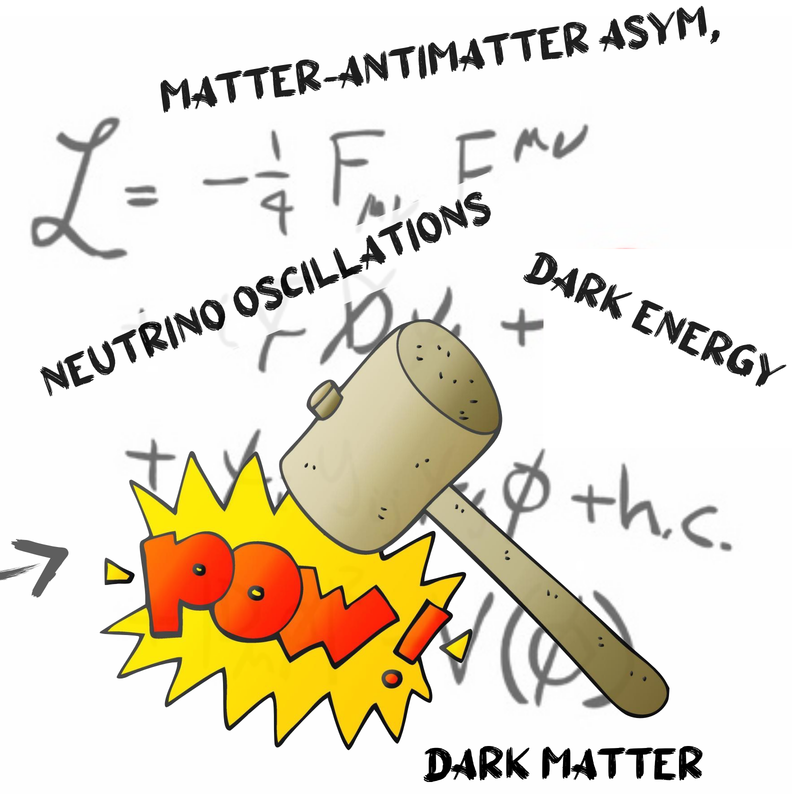
supporting actor

In this seminar

the main actors



New physics



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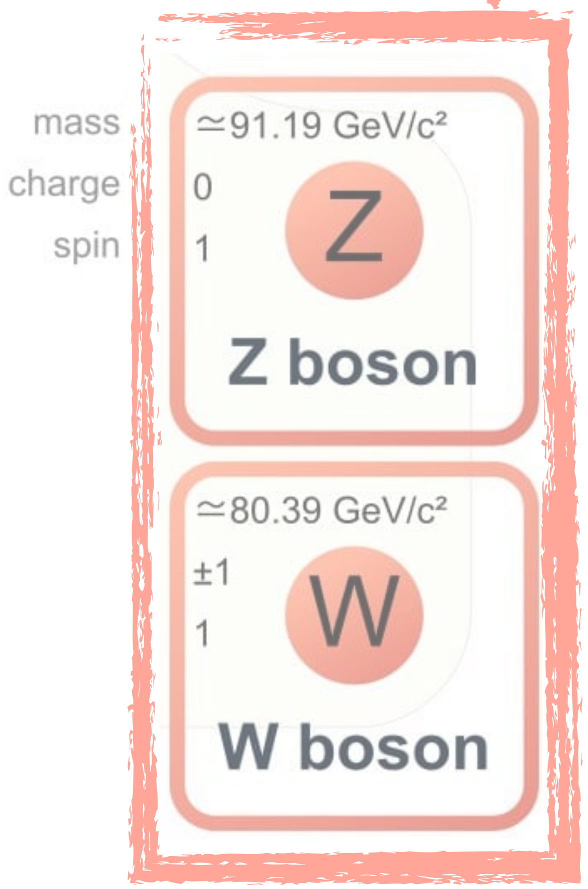
With boson pairs

the main actors

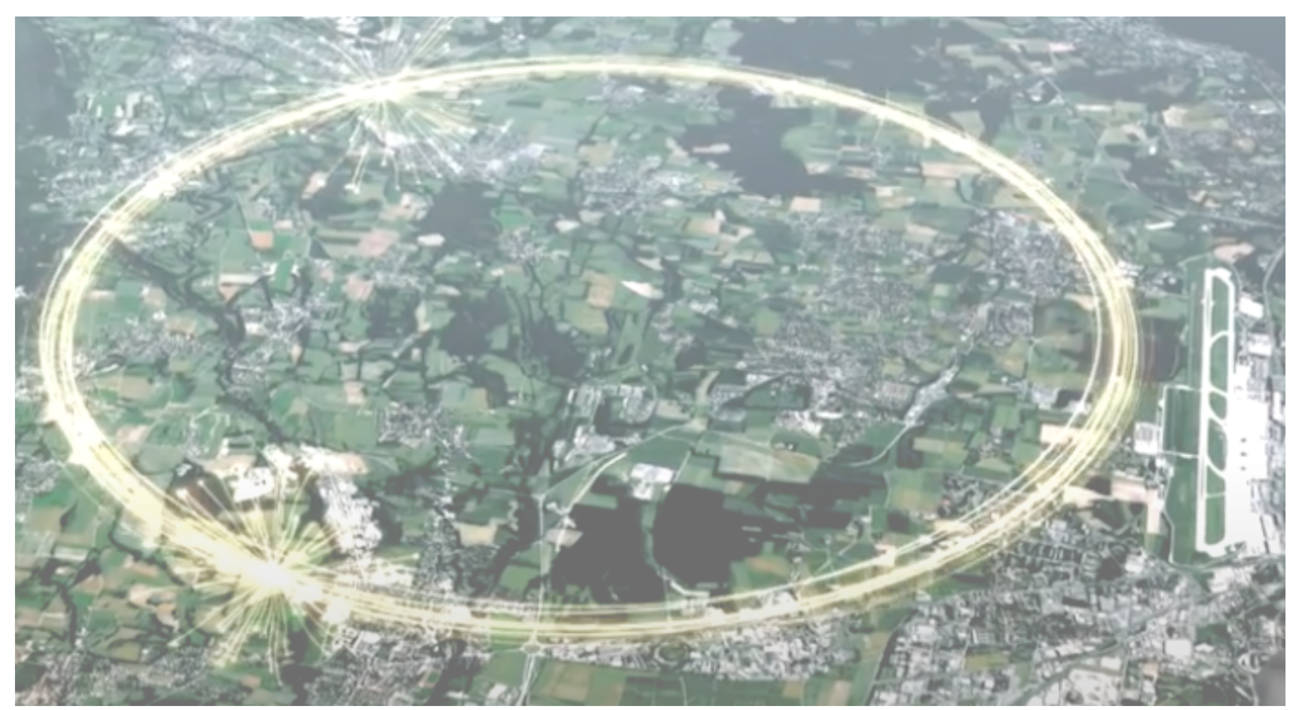


Challenge the SM

Look for New physics

We have our actors, and the main stage is the center of the ATLAS detector at the LHC

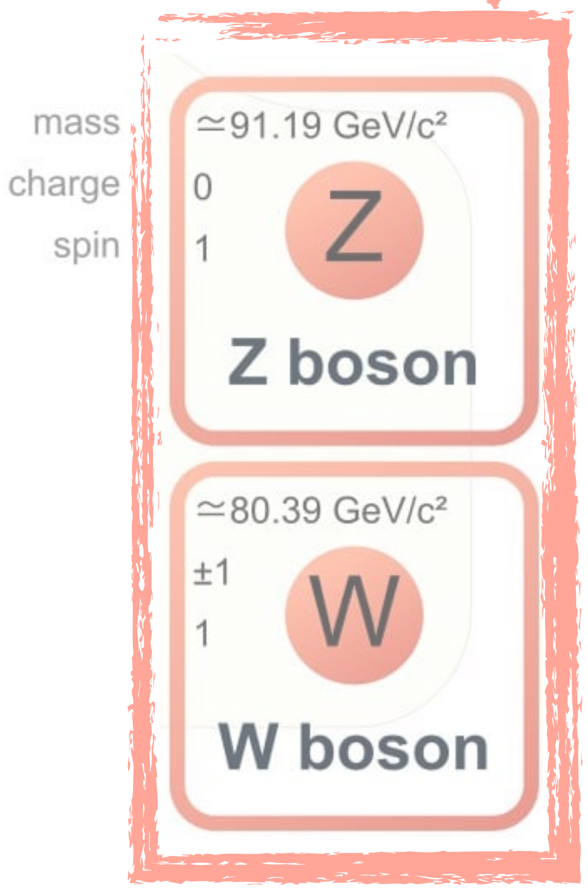
the stage

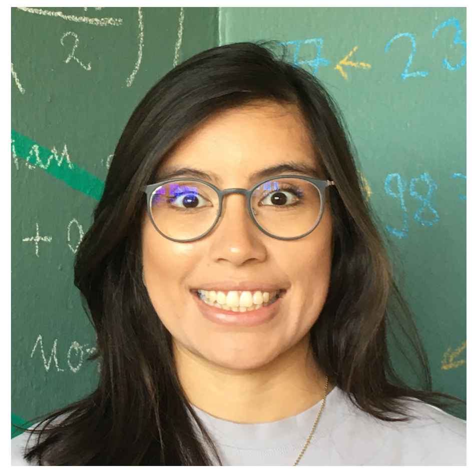


supporting actor

Meet the Speaker

the main actors





Challenge the SM

Look for New physics

the stage

We have our actors, and the main stage is the center of the ATLAS detector at the LHC

supporting actor

Curriculum Vitae

2008	BSc. in Physics Universidad de Los Andes, Venezuela
2009	Internship High Energy Latin-American European Network 8 mois, CMS, CEA-Saclay, France
2010	Master en physique Nucléaire, des Particules, des Astroparticules et Cosmologie (NPAC) Université Paris-Sud, Orsay, France.
2013	Doctorat en Physique des Particules ATLAS, CEA Saclay, Université Paris-Diderot, France
2013-2016	Postdoc York University, Toronto, Canada, based at CERN
2017- 2022	Leading postdoc Technische Universität Dresden, Germany
Since 2022	Chaire de Professeur Junior L2IT, Université de Toulouse, France

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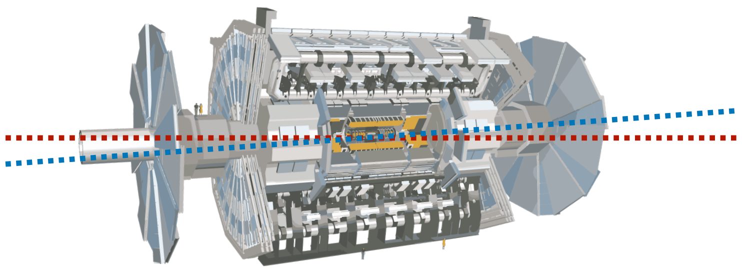
ATLAS
EXPERIMENT

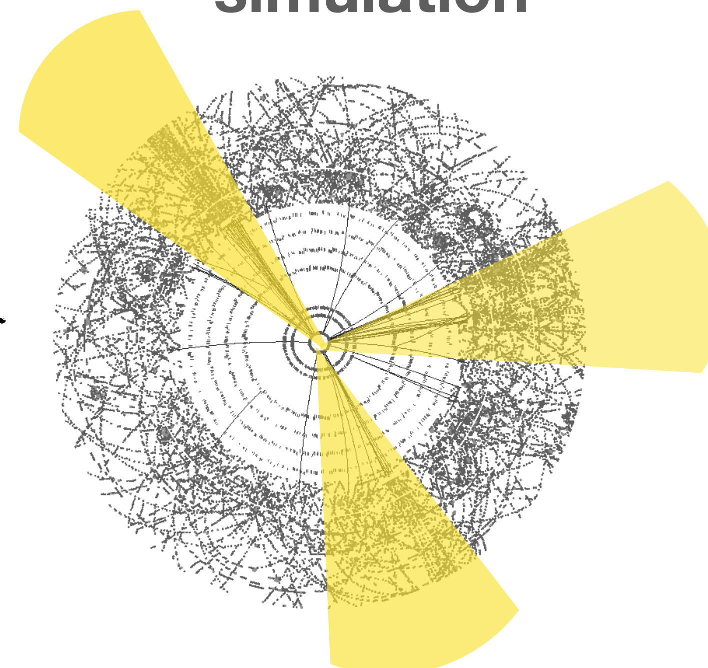
My contributions within ATLAS in a nutshell

Detector



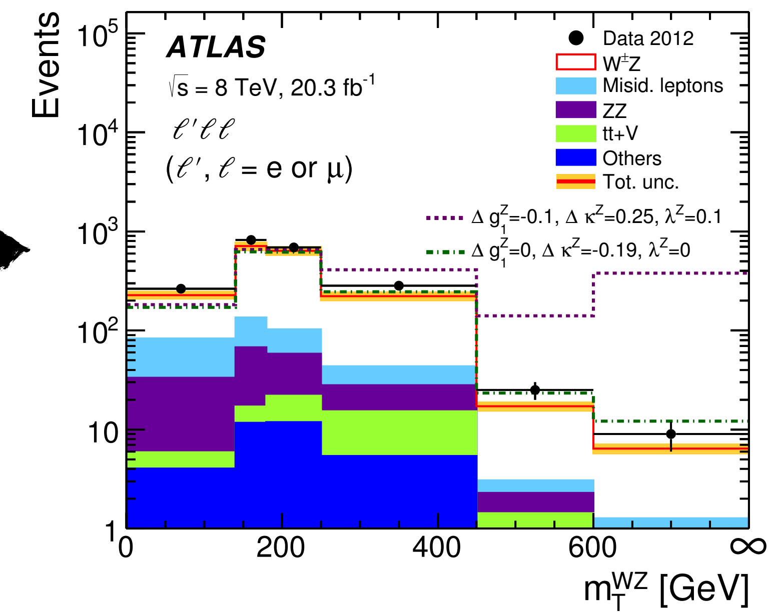
- ✓ Detector optimizations for the ATLAS upgrades

Data reconstruction simulation



- ✓ Coordination of TRT software team (~20 persons)
- ✓ MC simulation / modelling studies

Physics Analysis



- ✓ Analyst of 9 ATLAS publications
- ✓ Analysis contact of 4 publications. ~ 10-20 persons
- ✓ Convener of the ATLAS Standard Model **Electroweak Group** (~ 250 persons)
- ✓ Convener of the ATLAS-Germany Standard Model Group (14 Universities + DESY + MPI)
- ✓ Convener of the ATLAS **Diboson resonance search group** (~ 100 persons)

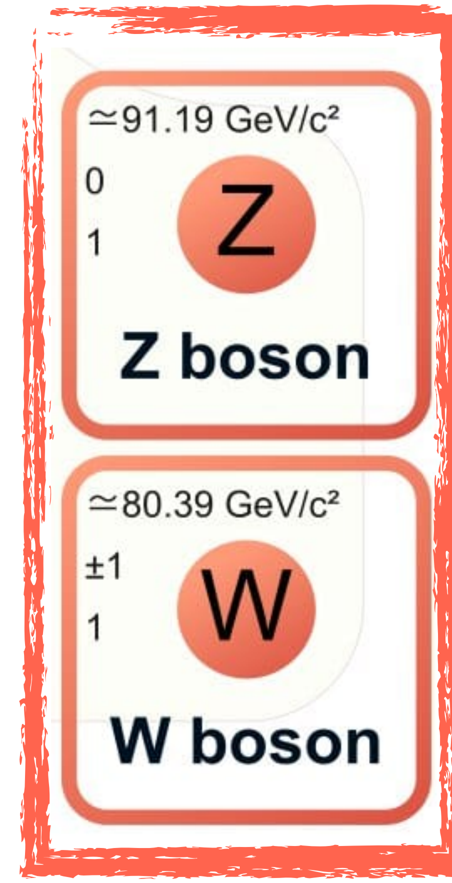
Representing ATLAS

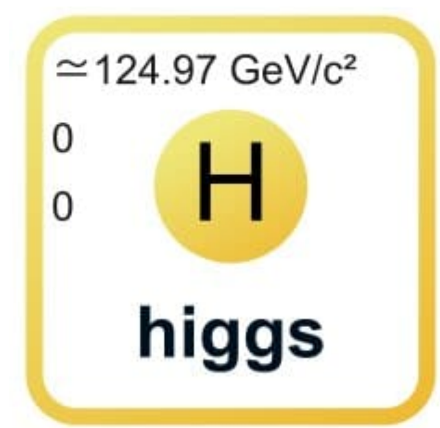
- ✓ LHC Electroweak Multibosons working group
- ✓ VBSCan EU COST Network
- ✓ COMETA EU COST Network

In this talk:
Direct participation

PhD student supervision

	Defence Year		
TUD - Dresden	2020	Carsten Bittrich *	**WZ** VBS CERN-THESIS-2020-039
	2022	Stefanie Todt *	Same sign **WW** VBS EFT interpretations CERN-THESIS-2022-268
	2022	Abhishek Nag *	VBF **WZ** Resonance search CERN-THESIS-2022-115
	2023	Tim Herrmann *	Same sign **WW** VBS CERN-THESIS-2023-419
	2024	Jan Eric Nitschke *	**WZ** Polarisation CERN-THESIS-2024-044
L2IT	2026	Anna Tegetmeier	VBF **HH** EFT interpretations
	2026	Thiziri Amezza *	VBF **HH**
	2027	Alexandro Martone	VBS **WWH**





* co-supervisions

PhD student supervision

the main actors

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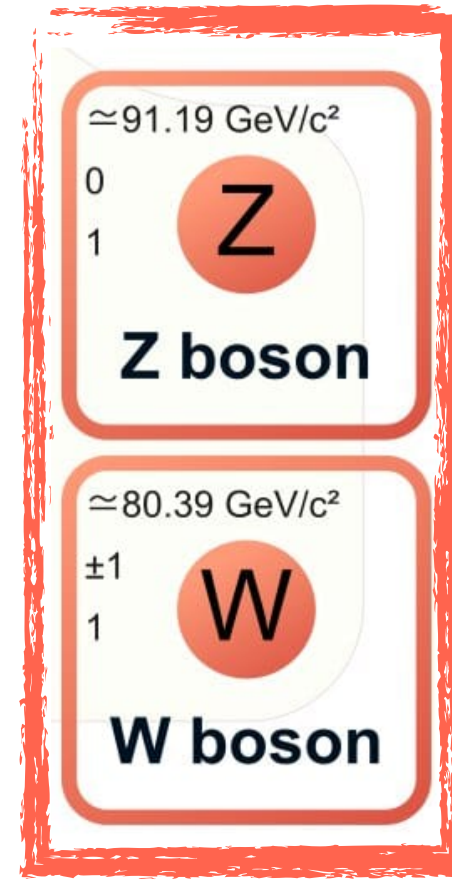
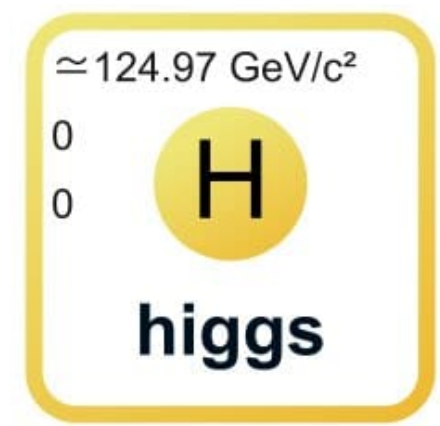


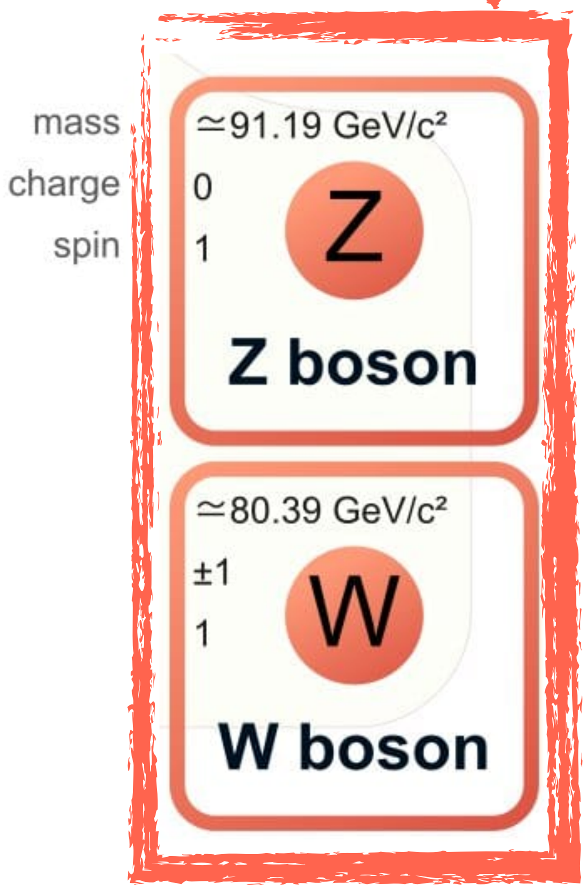


supporting actor taking the stage

* co-supervisions

With boson pairs

the main actors



1. Challenge the SM
2. Look for New physics

the stage

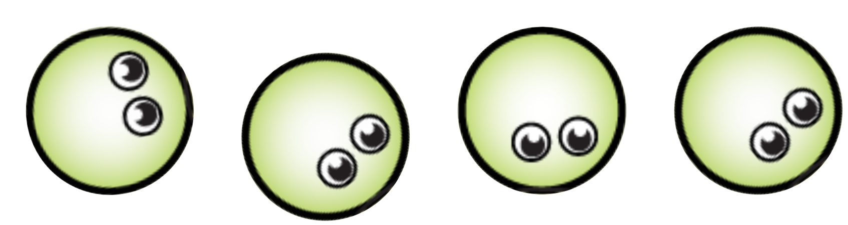
supporting actor

Where the actors meet

the main actors

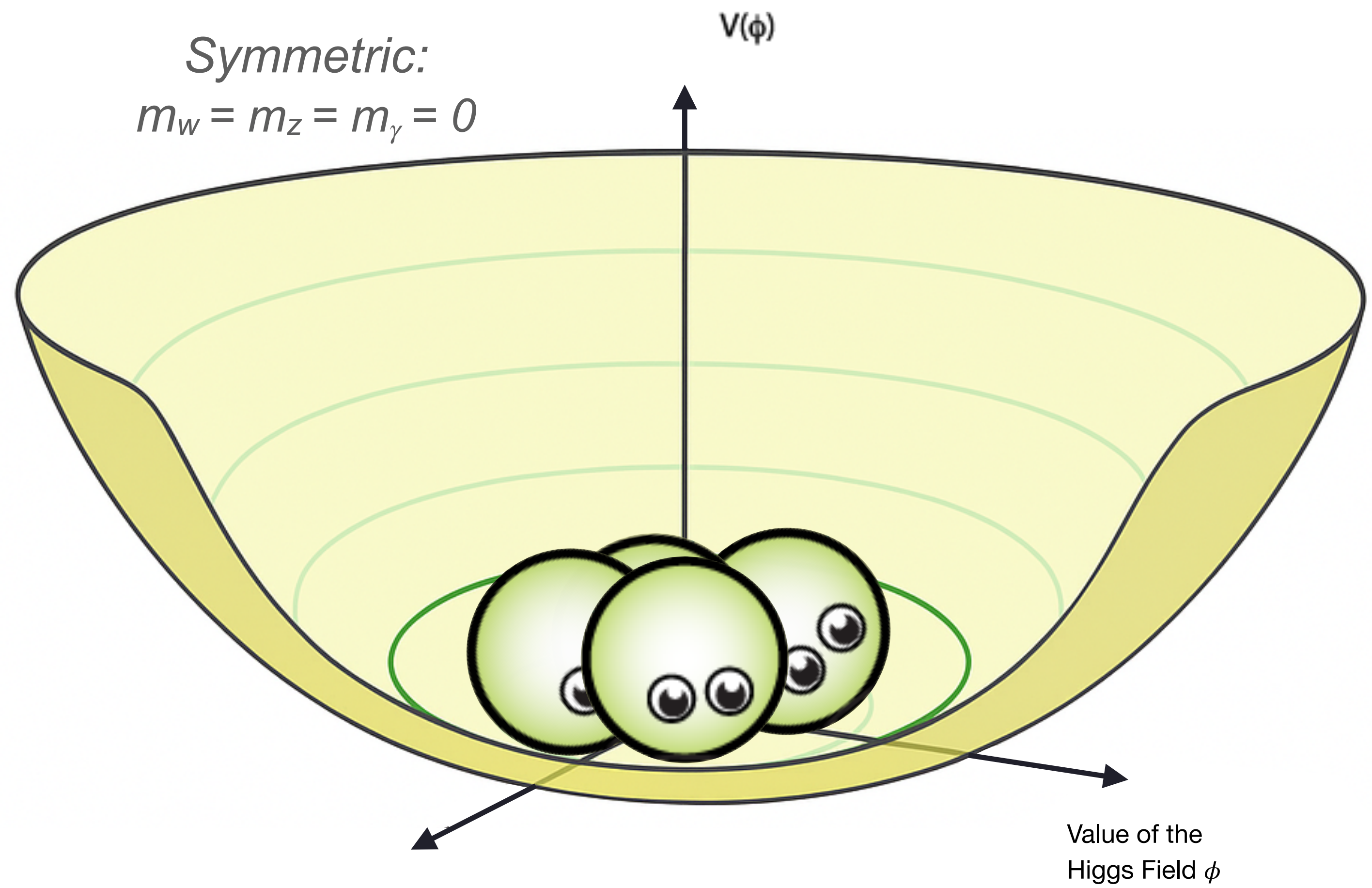
supporting actor

the Electroweak symmetry breaking



Before Electroweak symmetry breaking

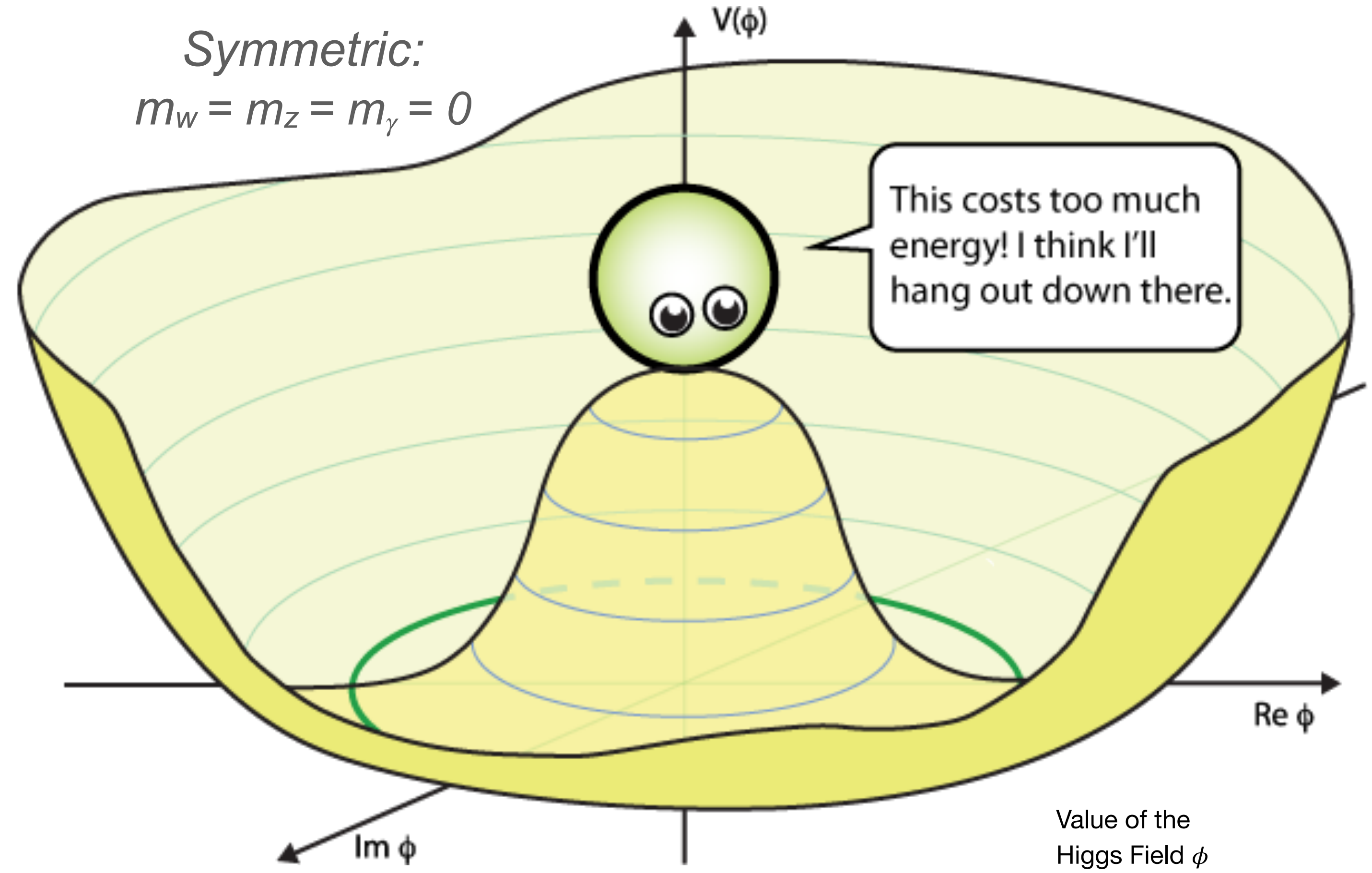
Symmetric:
$m_W = m_Z = m_\gamma = 0$



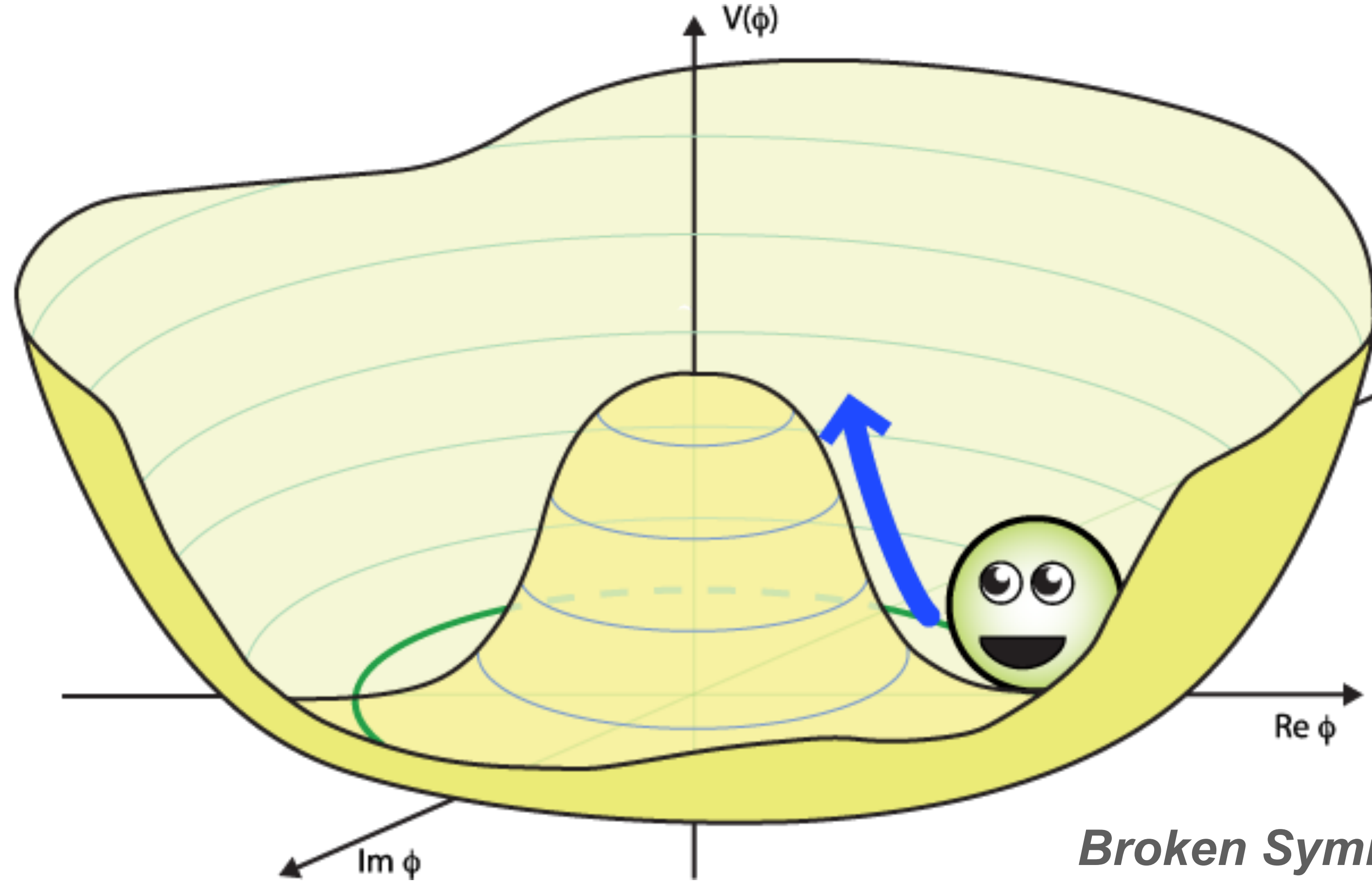
4 massless gauge bosons
(Only Transversal polarization states)

Electroweak symmetry breaking

Symmetric:
$m_W = m_Z = m_\gamma = 0$



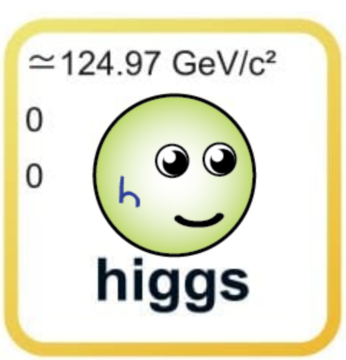
Electroweak symmetry breaking



Broken Symmetry!

$m_\gamma = 0$

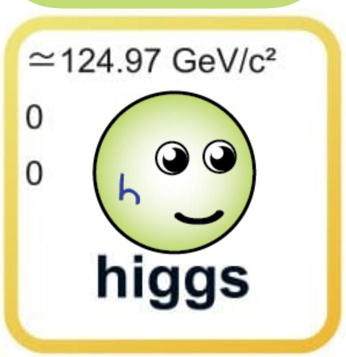
m_W, $m_Z \neq 0$

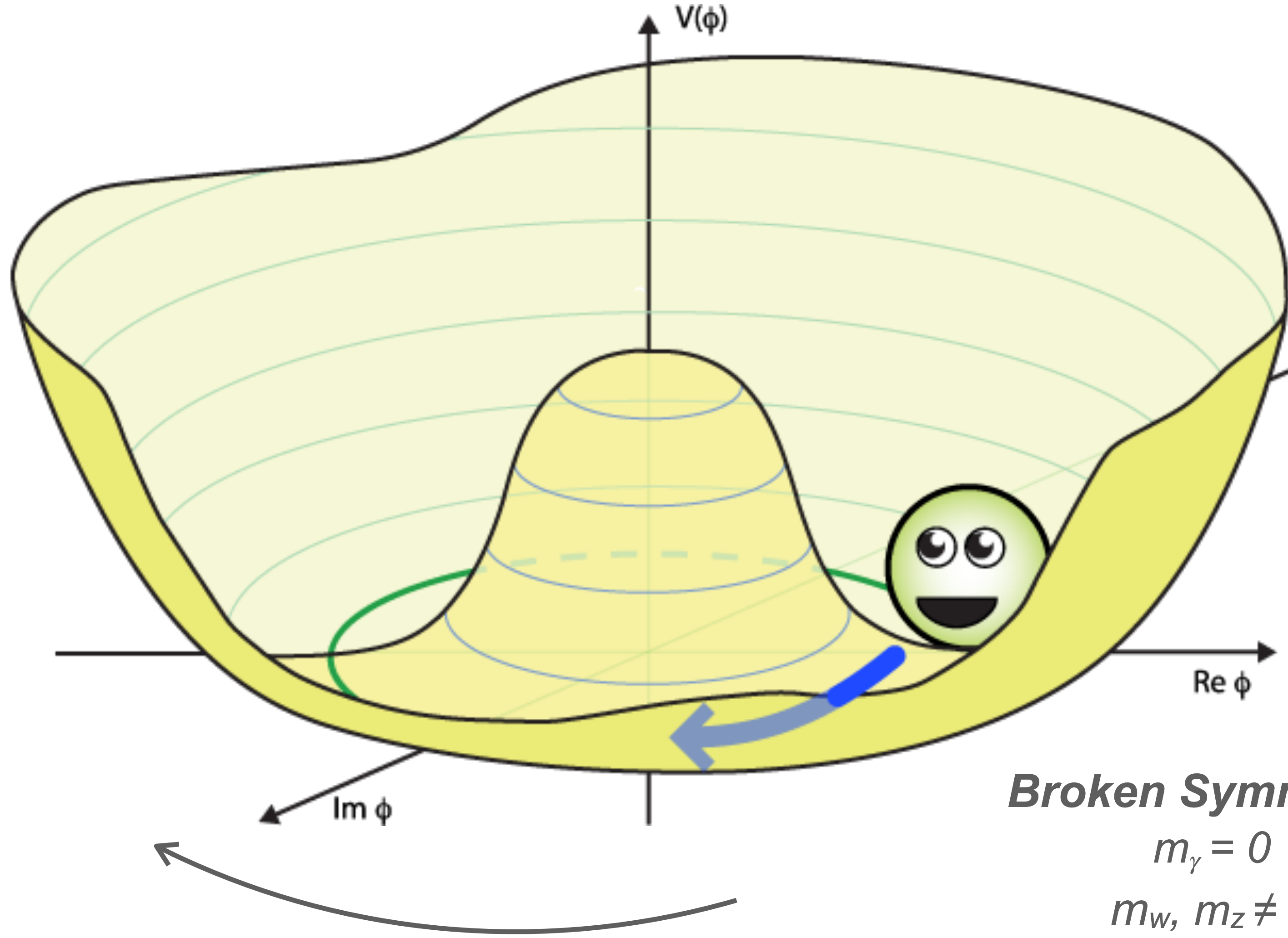


supporting actor

Electroweak symmetry breaking

The Goldstone bosons





Broken Symmetry!

$m_\gamma = 0$

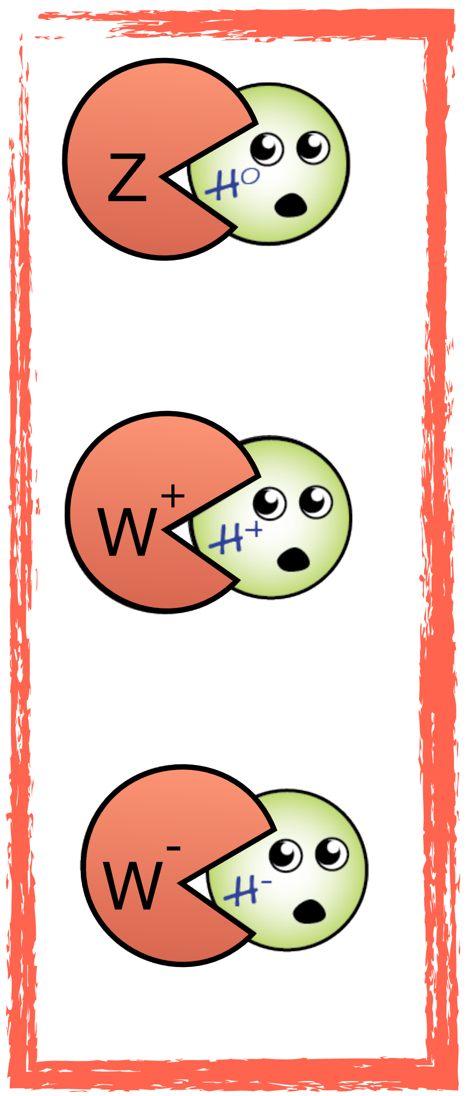
m_W, $m_Z \neq 0$

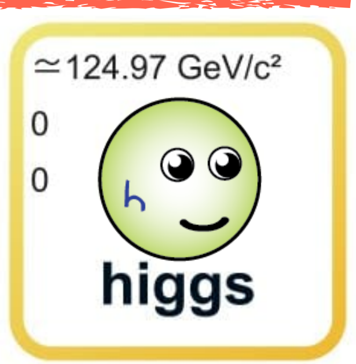
W,Z longitudinal polarization

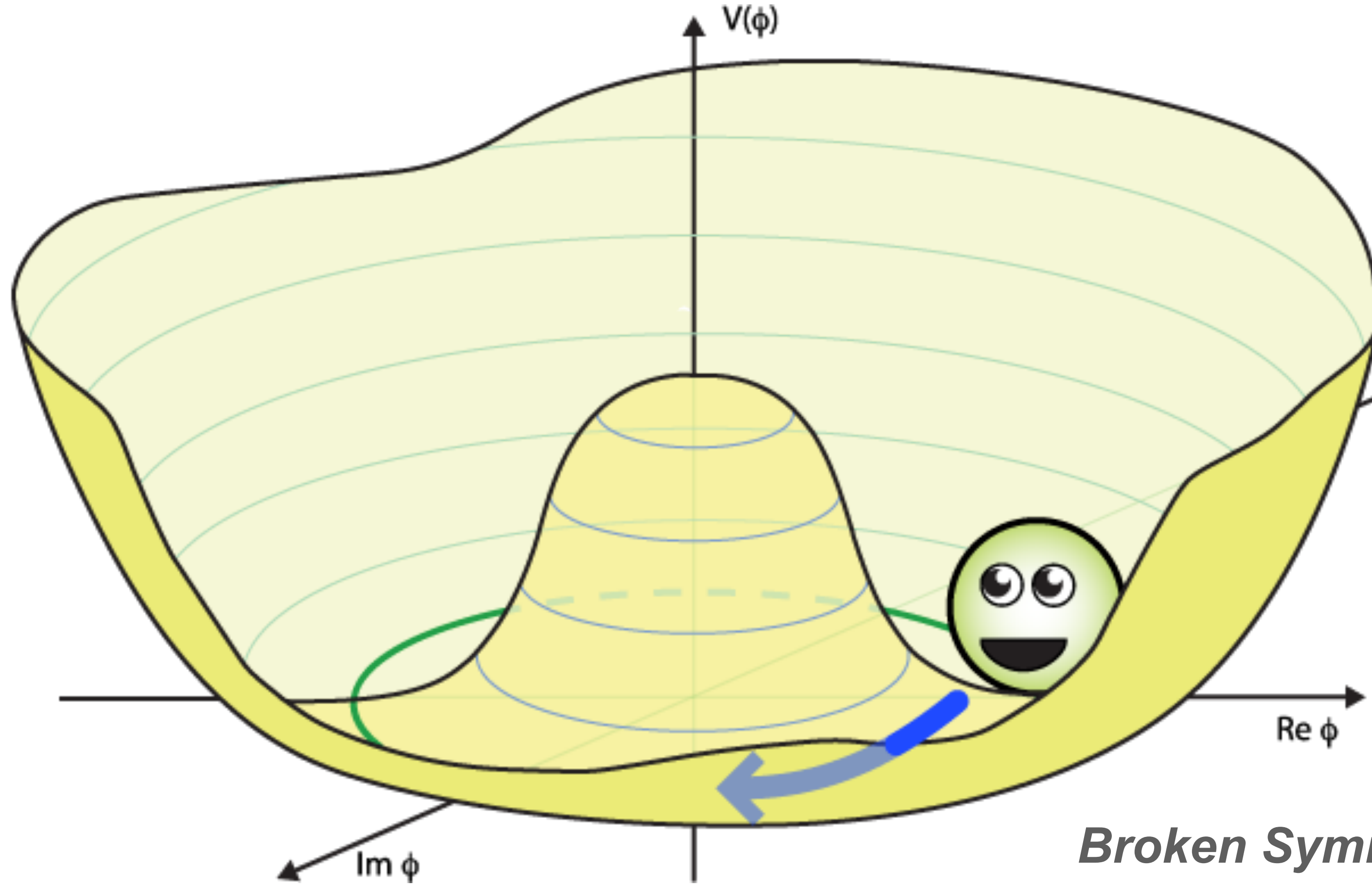
Electroweak symmetry breaking

Goldstone boson Equivalence theorem
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"

The Goldstone bosons are absorbed becoming the W and Z
Longitudinal polarization ($V_0 = Z_0, W_0$)





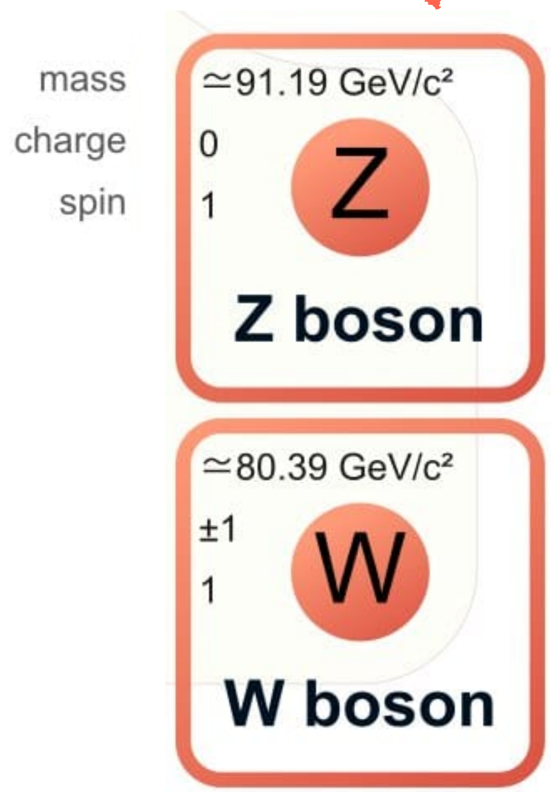


Broken Symmetry!
$m_\gamma = 0$
$m_W,\ m_Z \neq 0$

The photon remains massless and with only transversal polarization

Now we know that the cast is all related

the main actors

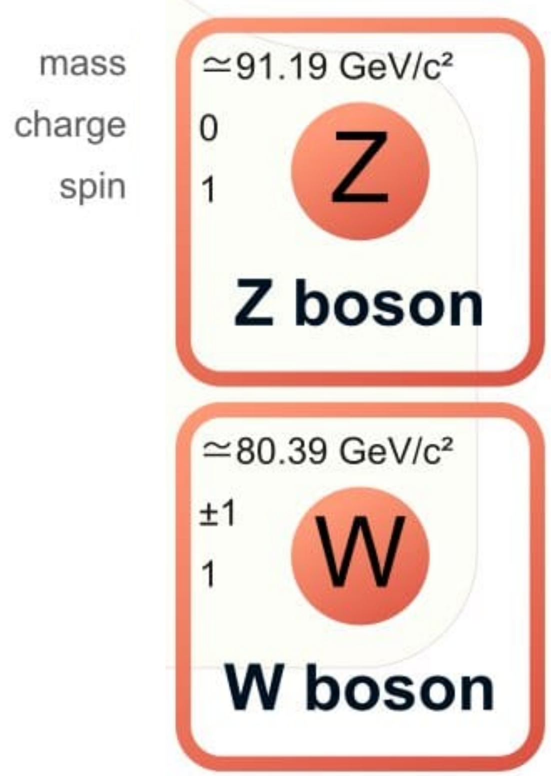


Longitudinal polarization ($V_0 = Z_0, W_0$)

supporting actor

Now we know that the cast is all related

the main actors

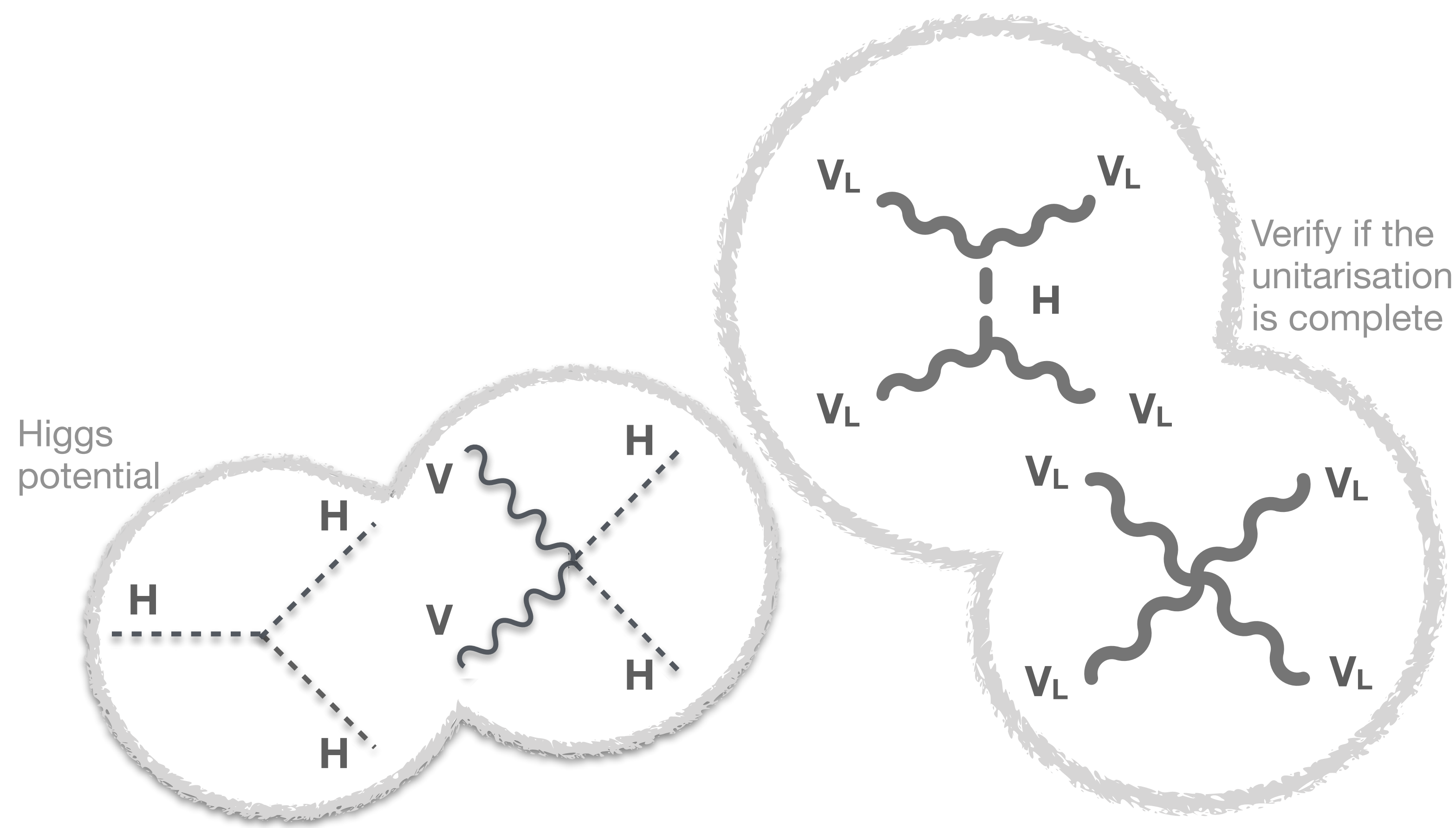


Longitudinal polarization ($V_0 = Z_0, W_0$)

supporting actor

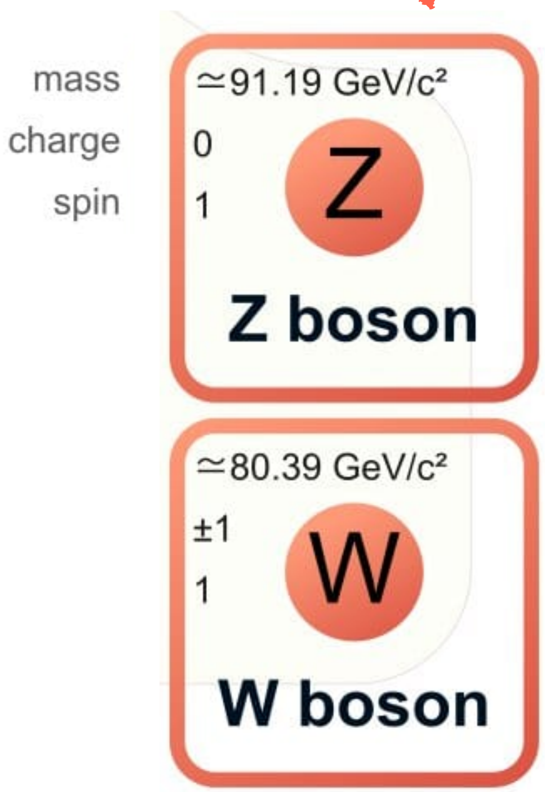
1. Challenge the SM

Quartic Bosons interactions ○
Longitudinally polarized boson interactions ○
Higgs Boson self interactions ○



The Outline

the main actors



Longitudinal polarization $(V_0 = Z_0, W_0)$

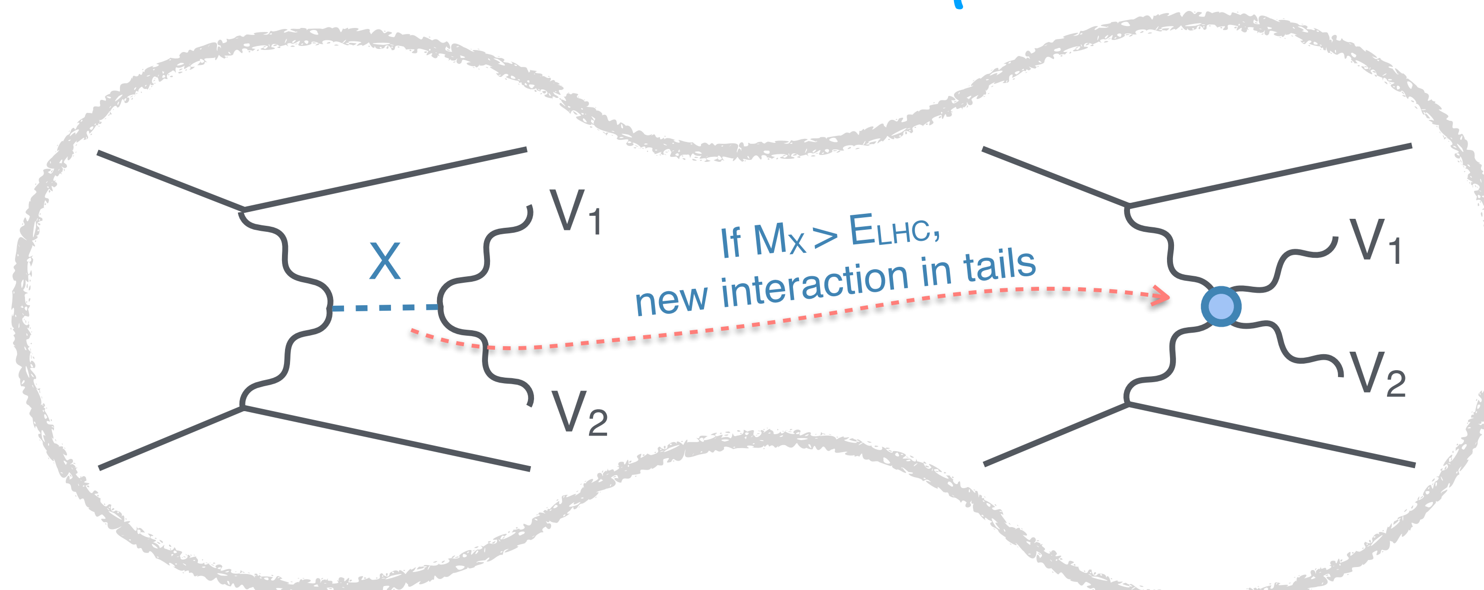
supporting actor

1. Challenge the SM

- Quartic Bosons interactions
- Longitudinal polarised bosons interactions
- Higgs Boson self interactions

2. Look for New physics

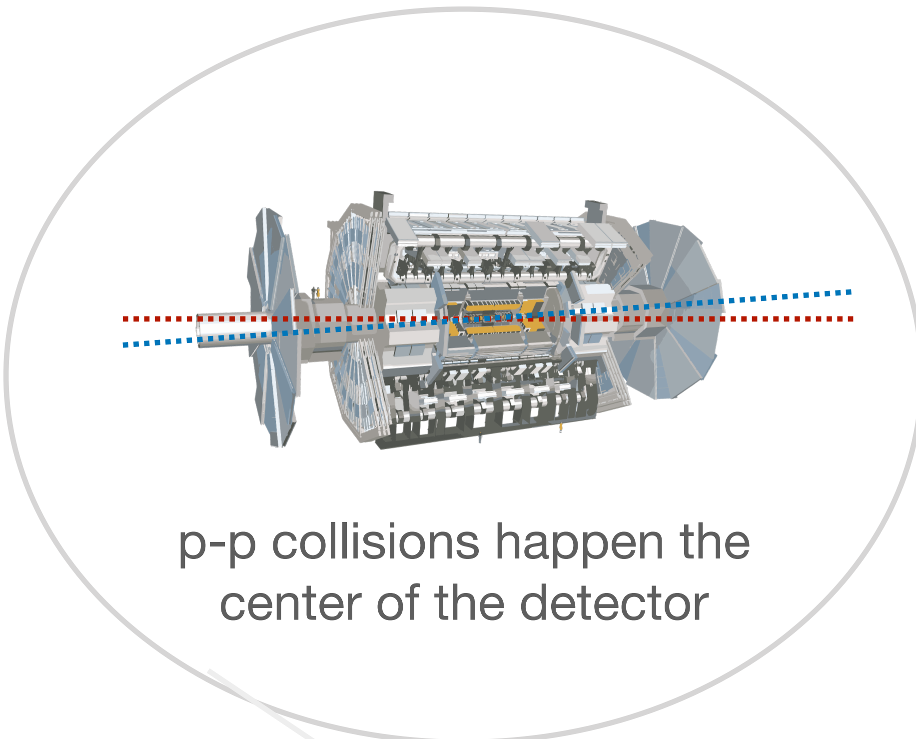
- New resonance
- Deviations on SM predictions

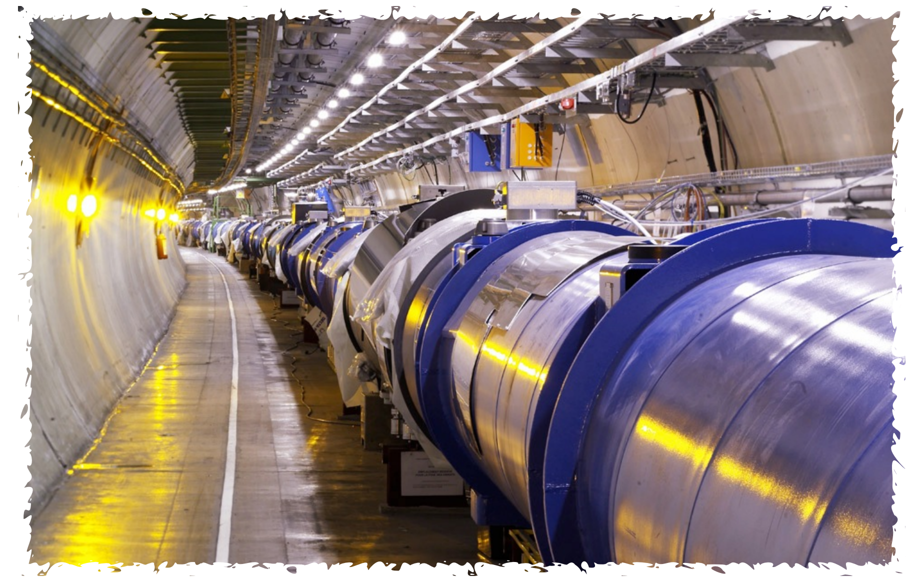


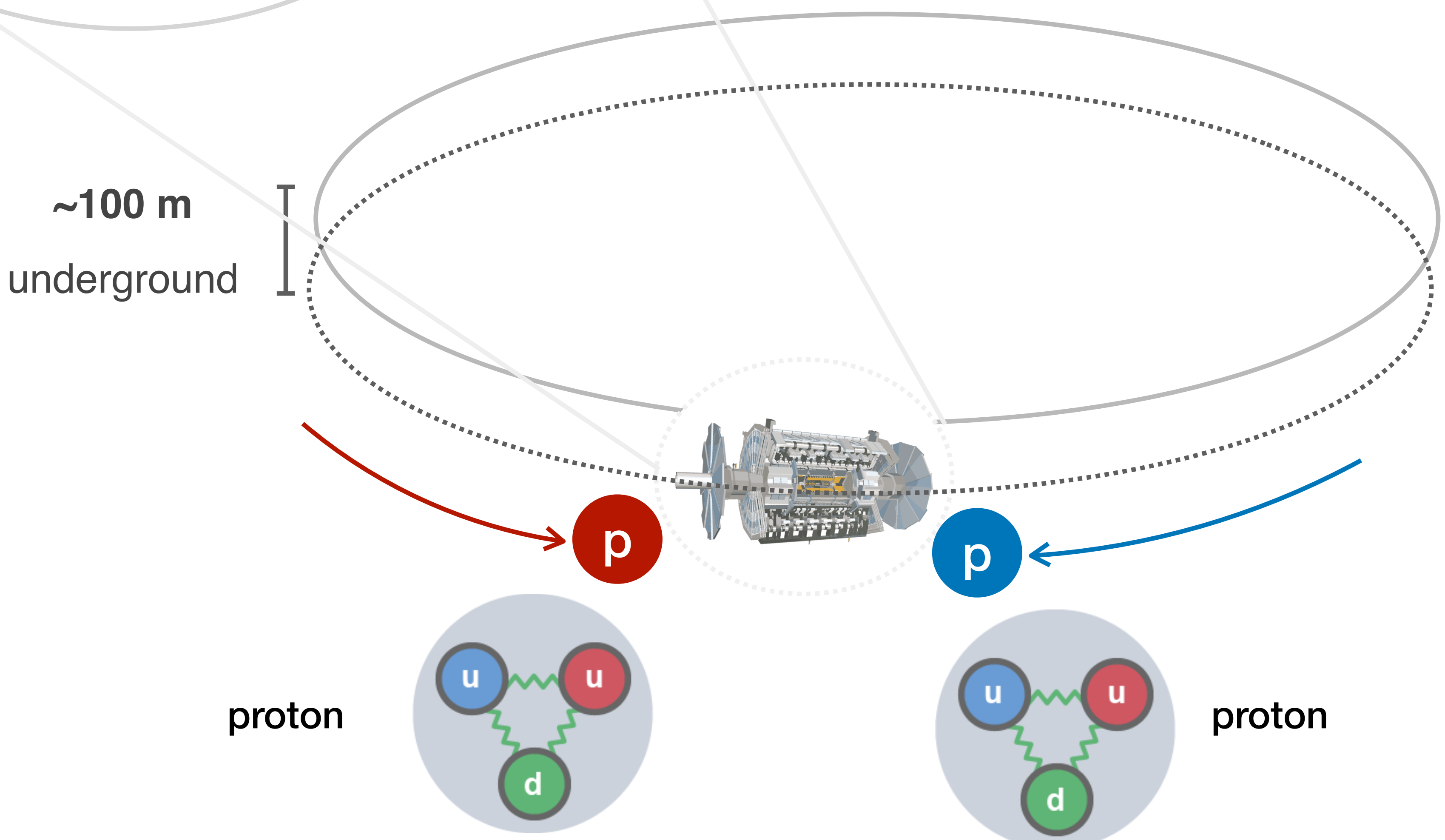
How do we explore those interactions?

1. Bosons collisions
2. Compare measurements with theory predictions

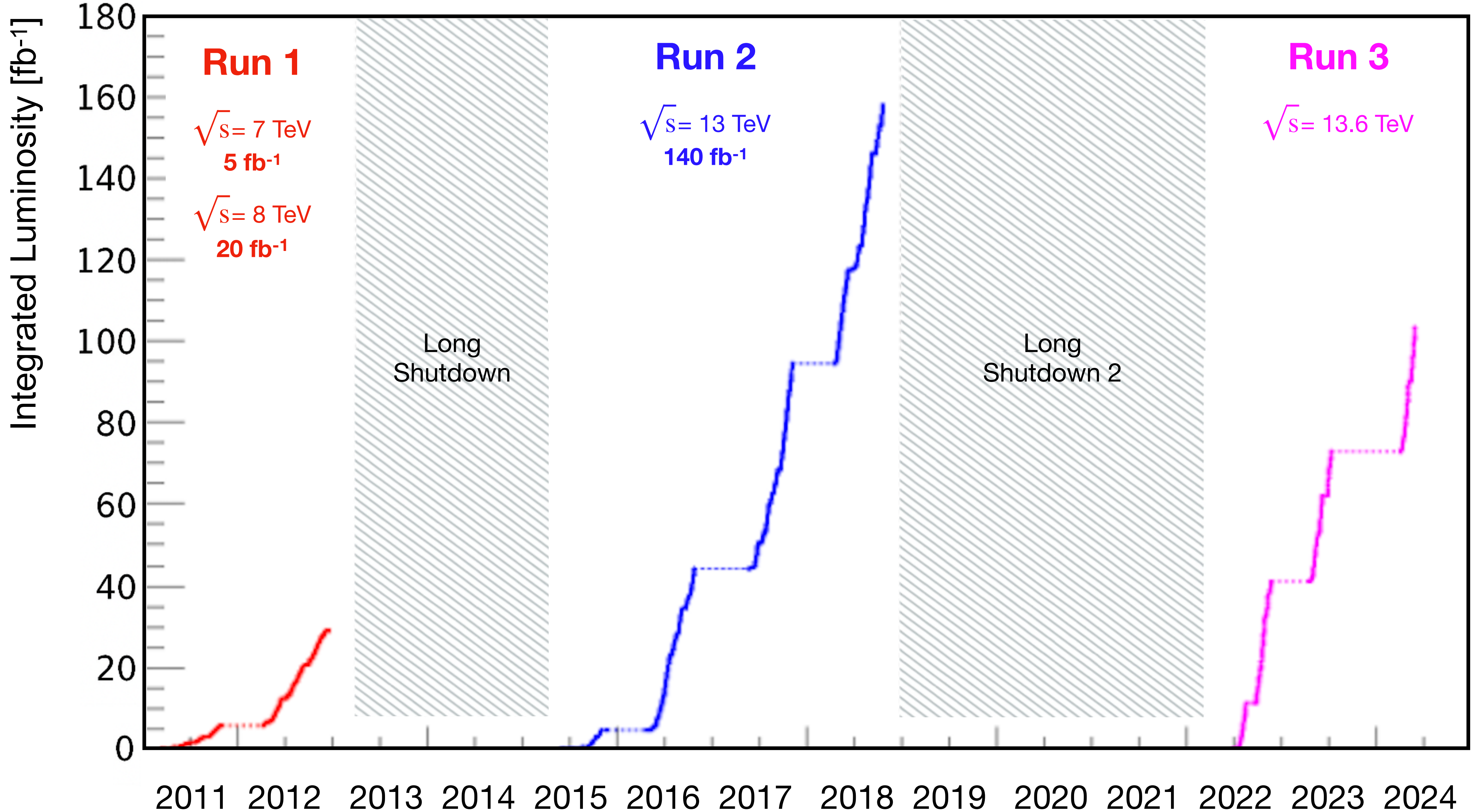
The Large Hadron Collider and ATLAS



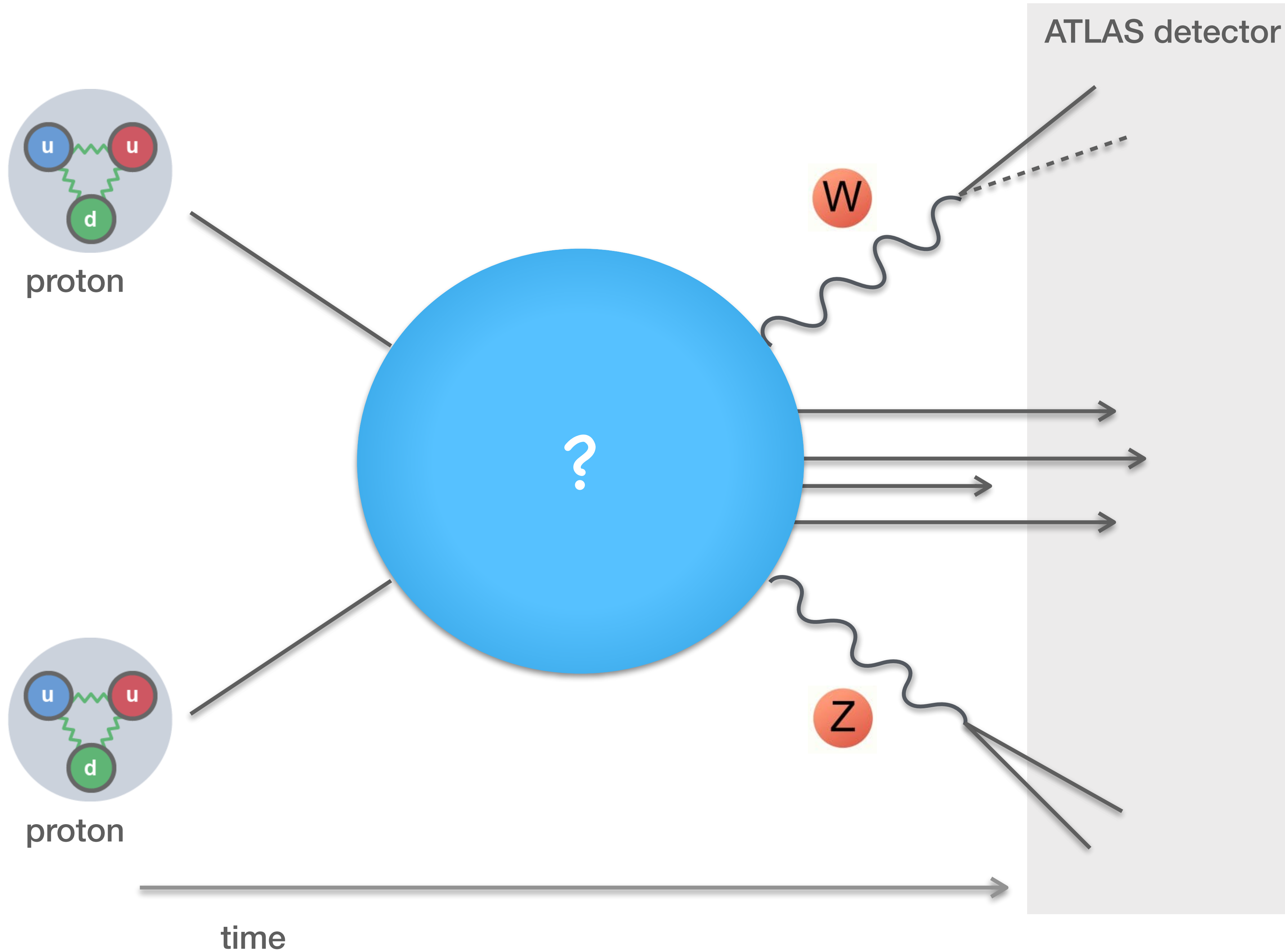




The Large Hadron Collider and ATLAS

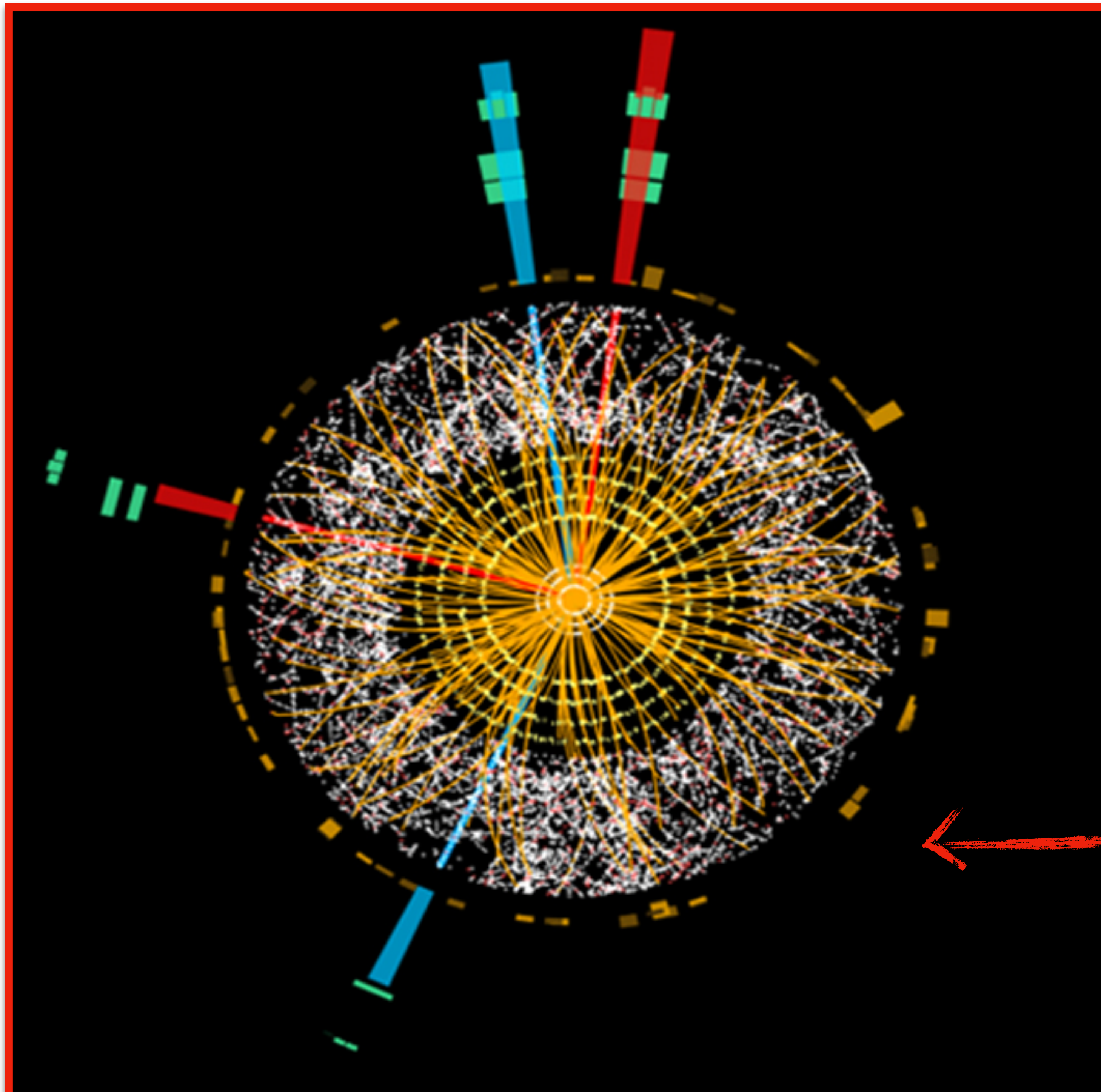


From proton collisions to vector boson pairs



Testing the Standard Model predictions

Detector measurement



Theory

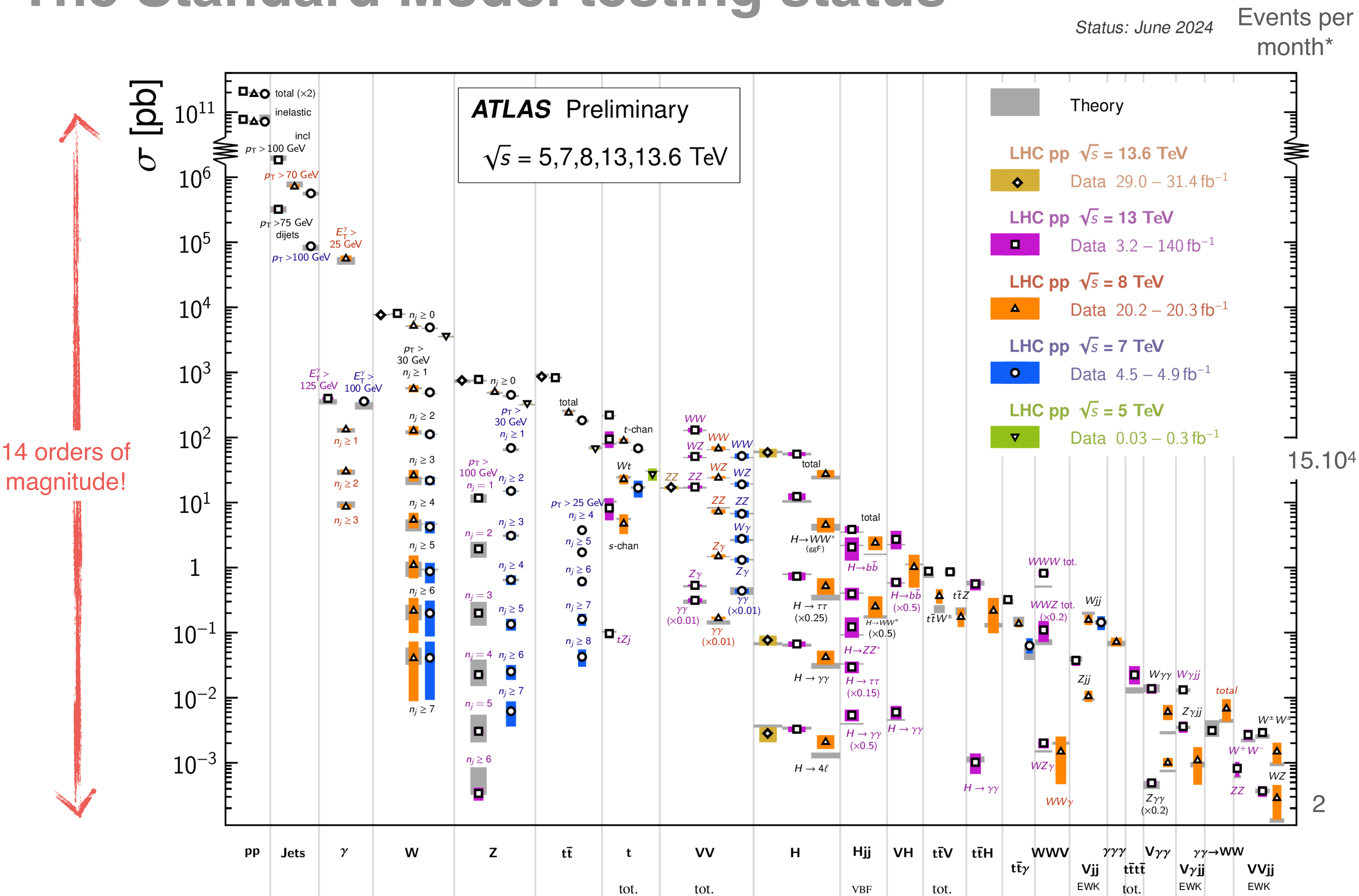
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i\bar{\psi} \not{D} \psi \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

How?

Measuring and calculating **Cross-sections!**

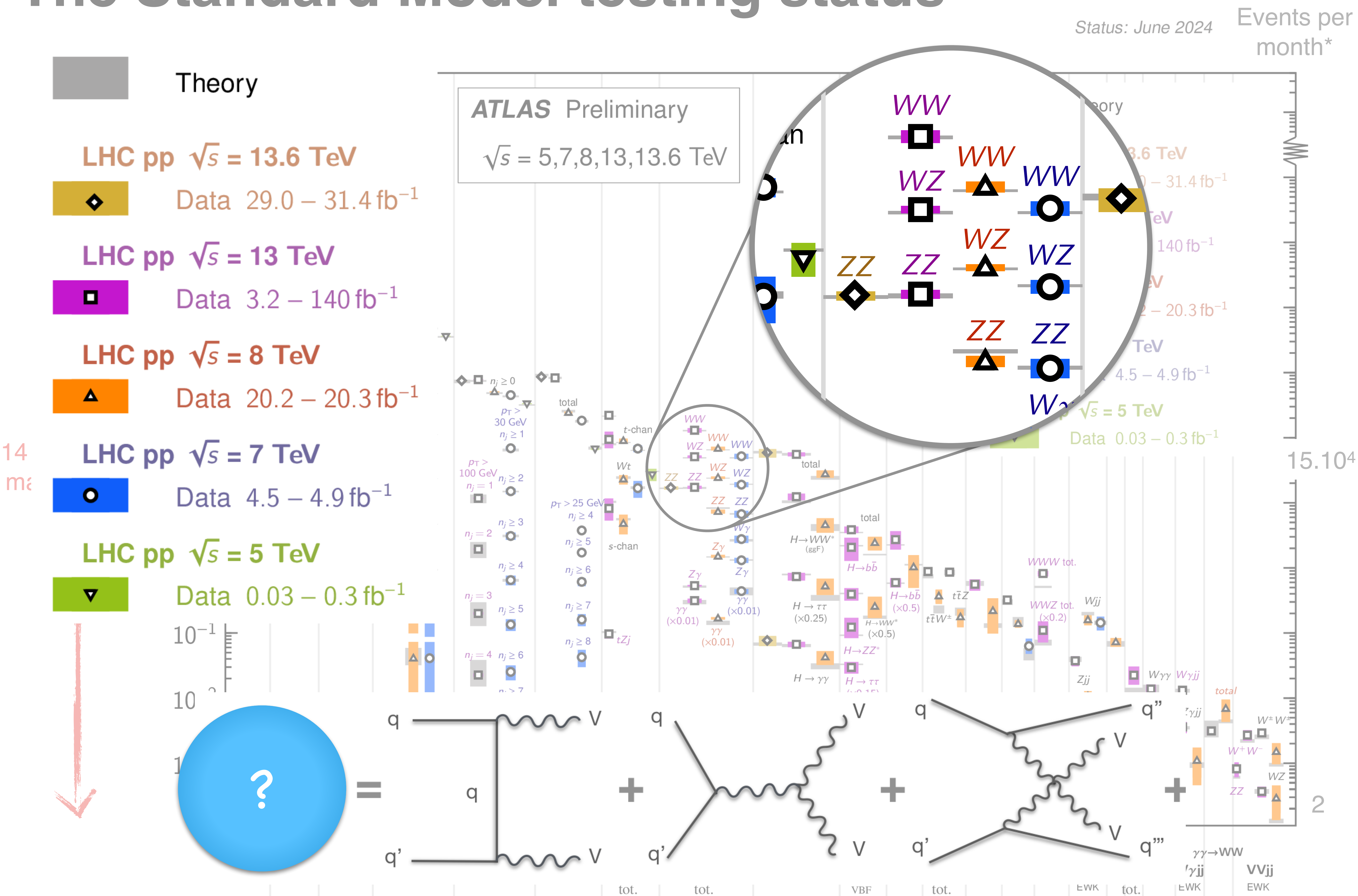
A cross section is a measure of the probability that a specific process will take place

The Standard Model testing status



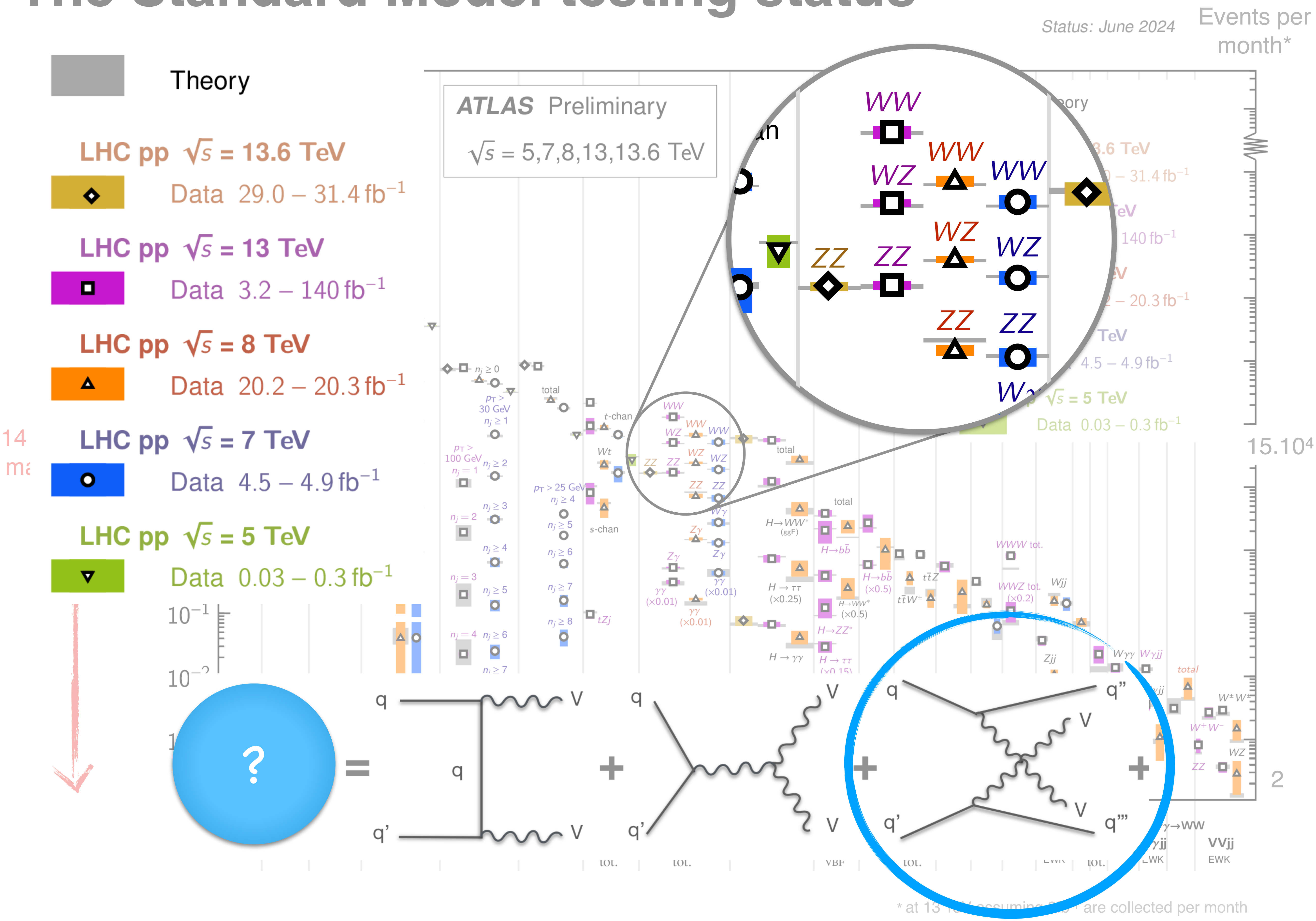
* at 13 TeV assuming 3fb^{-1} are collected per month

The Standard Model testing status

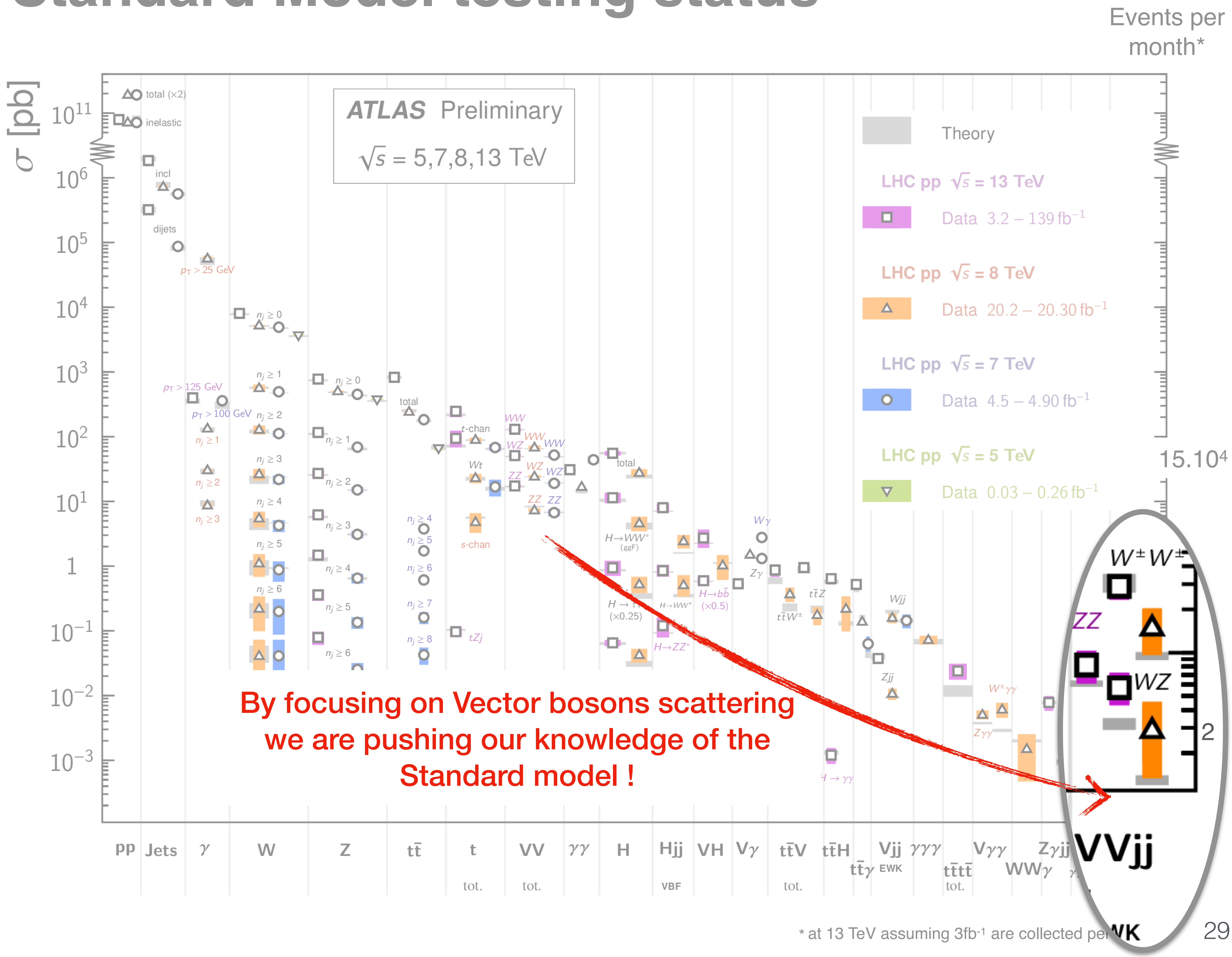


* at 13 TeV assuming 3fb⁻¹ are collected per month

The Standard Model testing status



The Standard Model testing status



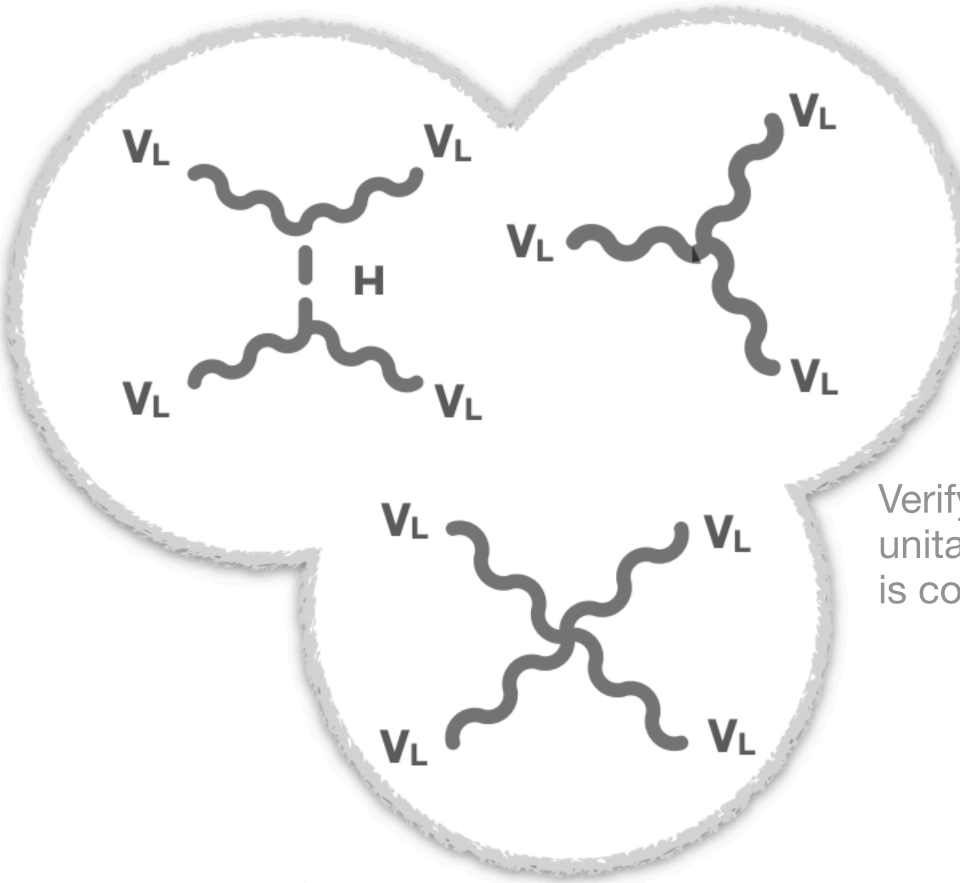
By focusing on Vector bosons scattering we are pushing our knowledge of the Standard model !

* at 13 TeV assuming 3fb^{-1} are collected per WK

1. Challenge the SM

Quartic Bosons interactions ○

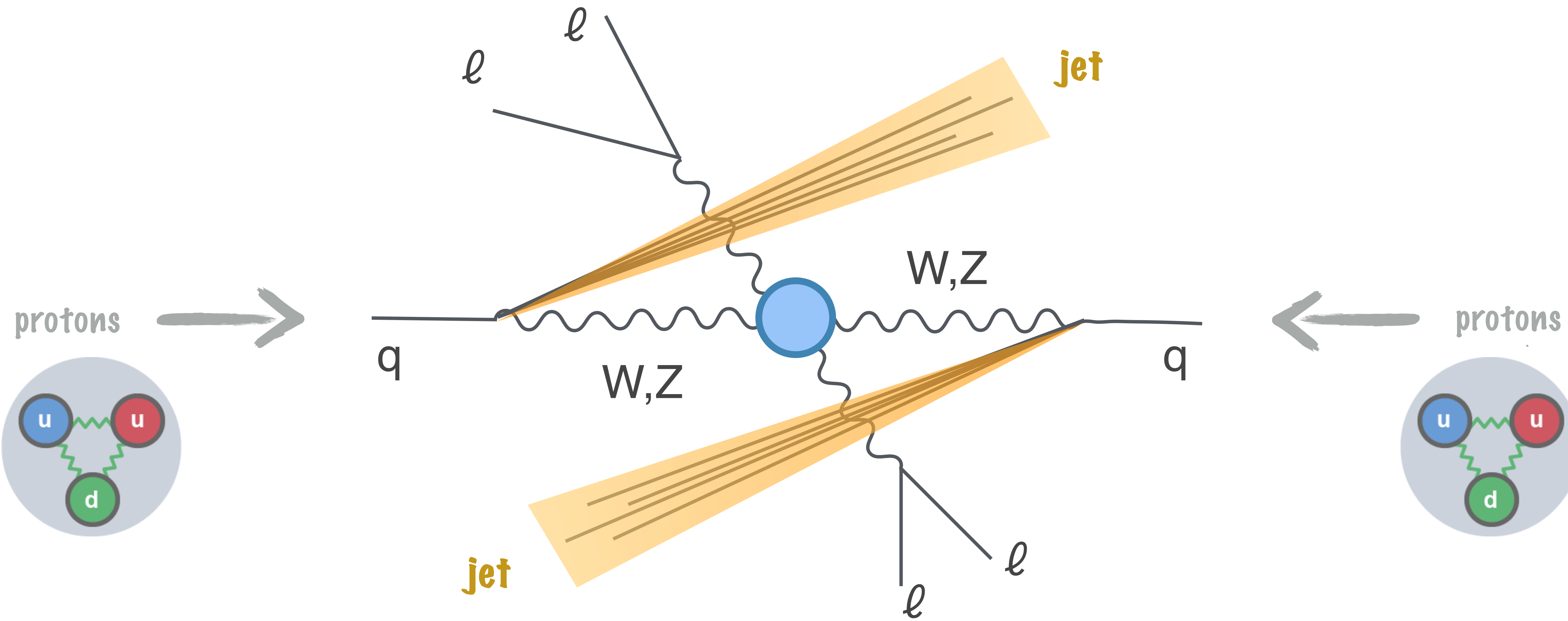
Longitudinal polarised bosons interactions ○

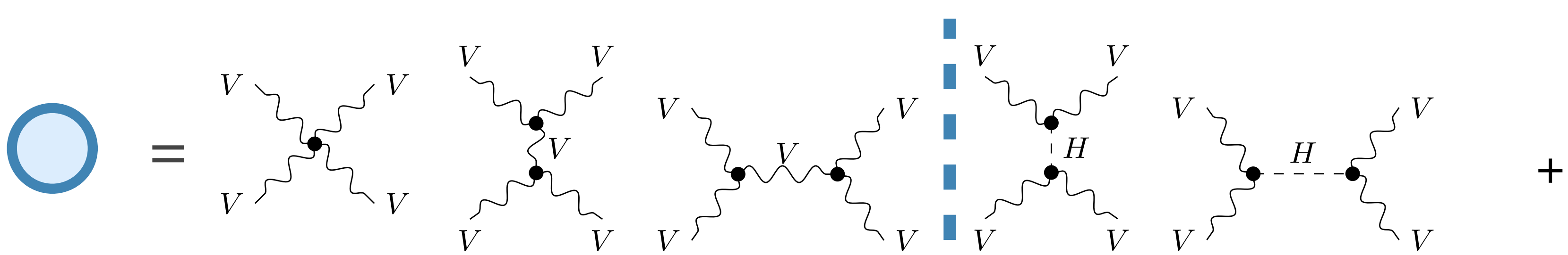


Verify if the unitarisation is complete

Vector Boson Scattering at the LHC

Protons in LHC serve as source of vector boson beams.



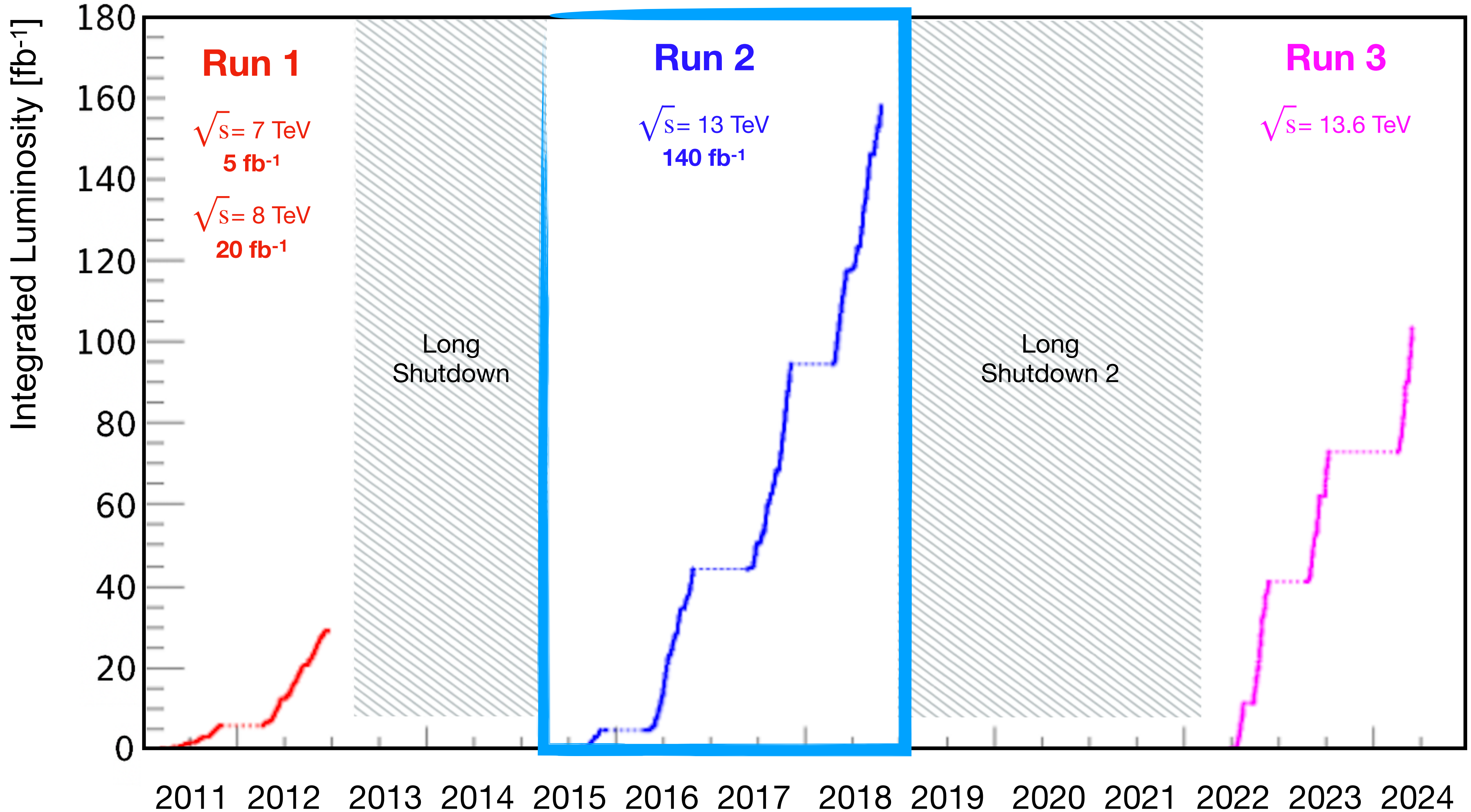


α_{EW} : order 6
α_s : order 0

gauge structure of the Standard Model

electroweak symmetry breaking

The Large Hadron Collider and ATLAS



Run 1: Vector Boson Scattering
a bit of perspective

- The 8 TeV dataset gave us first analyses and with them the first evidence !

PRL **113**, 141803 (2014) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2014

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad *et al.**
(ATLAS Collaboration)
(Received 23 May 2014; published 3 October 2014)

4.5 σ (3.6 σ)

PHYSICAL REVIEW D **93**, 092004 (2016)

Measurements of $W^{\pm}Z$ production cross sections in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector and limits on anomalous gauge boson self-couplings

G. Aad *et al.**
(ATLAS Collaboration)
(Received 8 March 2016; published 13 May 2016)

Only upper limit on the cross section reported

PRL **114**, 051801 (2015) PHYSICAL REVIEW LETTERS week ending 6 FEBRUARY 2015

Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets

V. Khachatryan *et al.**
(CMS Collaboration)
(Received 23 October 2014; revised manuscript received 11 December 2014; published 2 February 2015)

2.0 σ (3.1 σ)

Physics Letters B 770 (2017) 380–402

Measurement of the cross section for electroweak production of $Z\gamma$ in association with two jets and constraints on anomalous quartic gauge couplings in proton–proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

3.0 σ (2.1 σ)

Run 1: Vector Boson Scattering
a bit of perspective

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PRL **114,** 051801 (2015) PHYSICAL REVIEW LETTERS 6 FE

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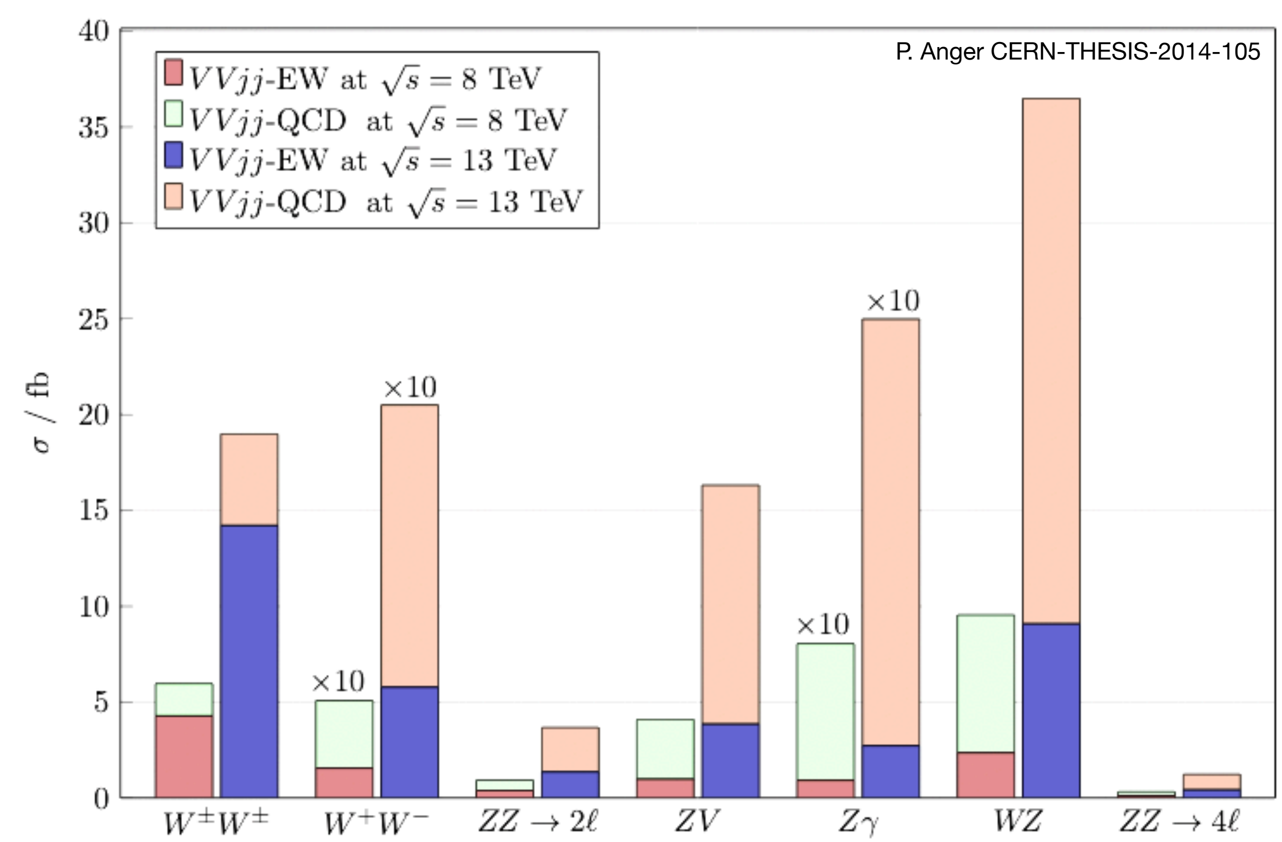
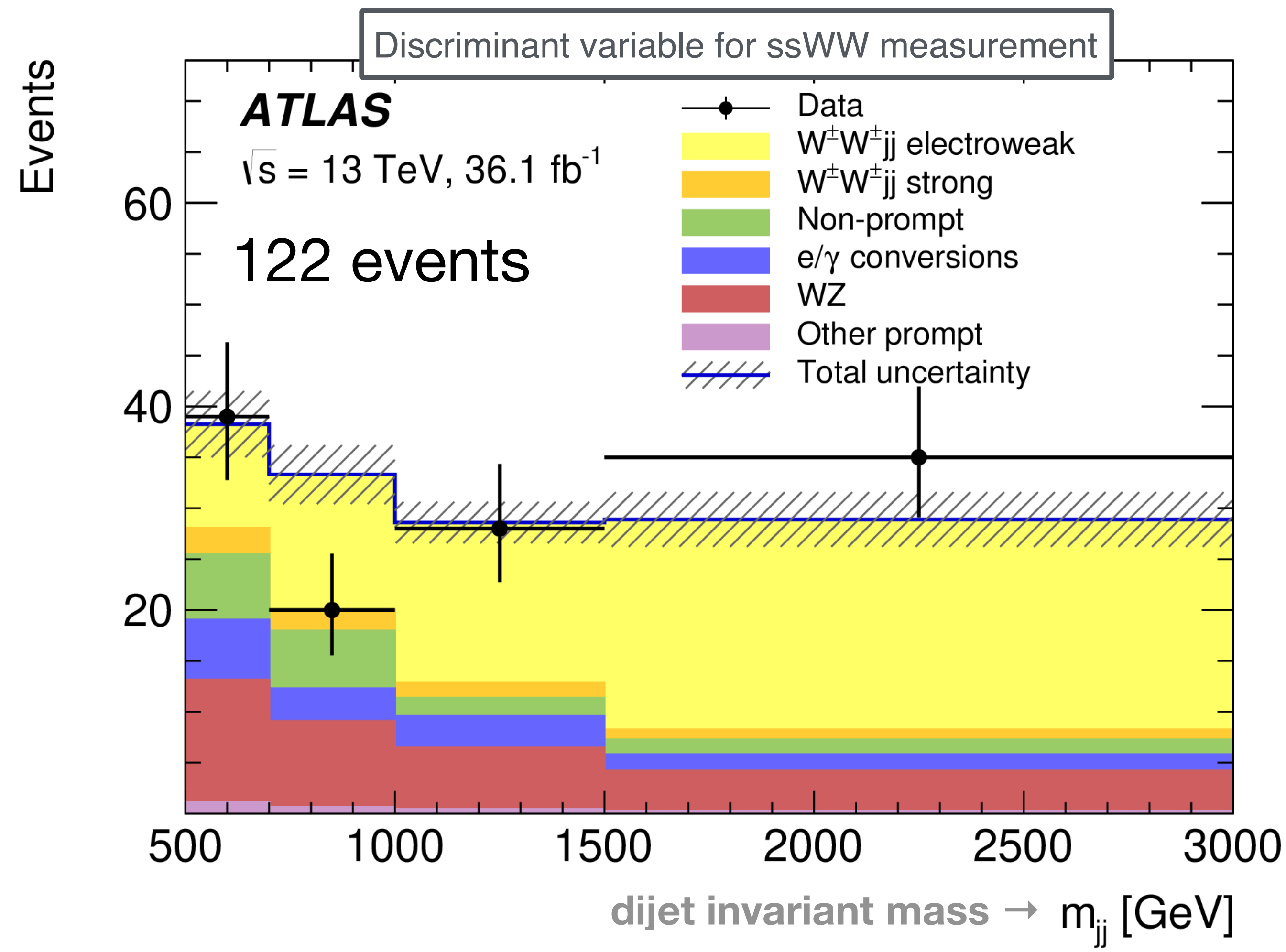


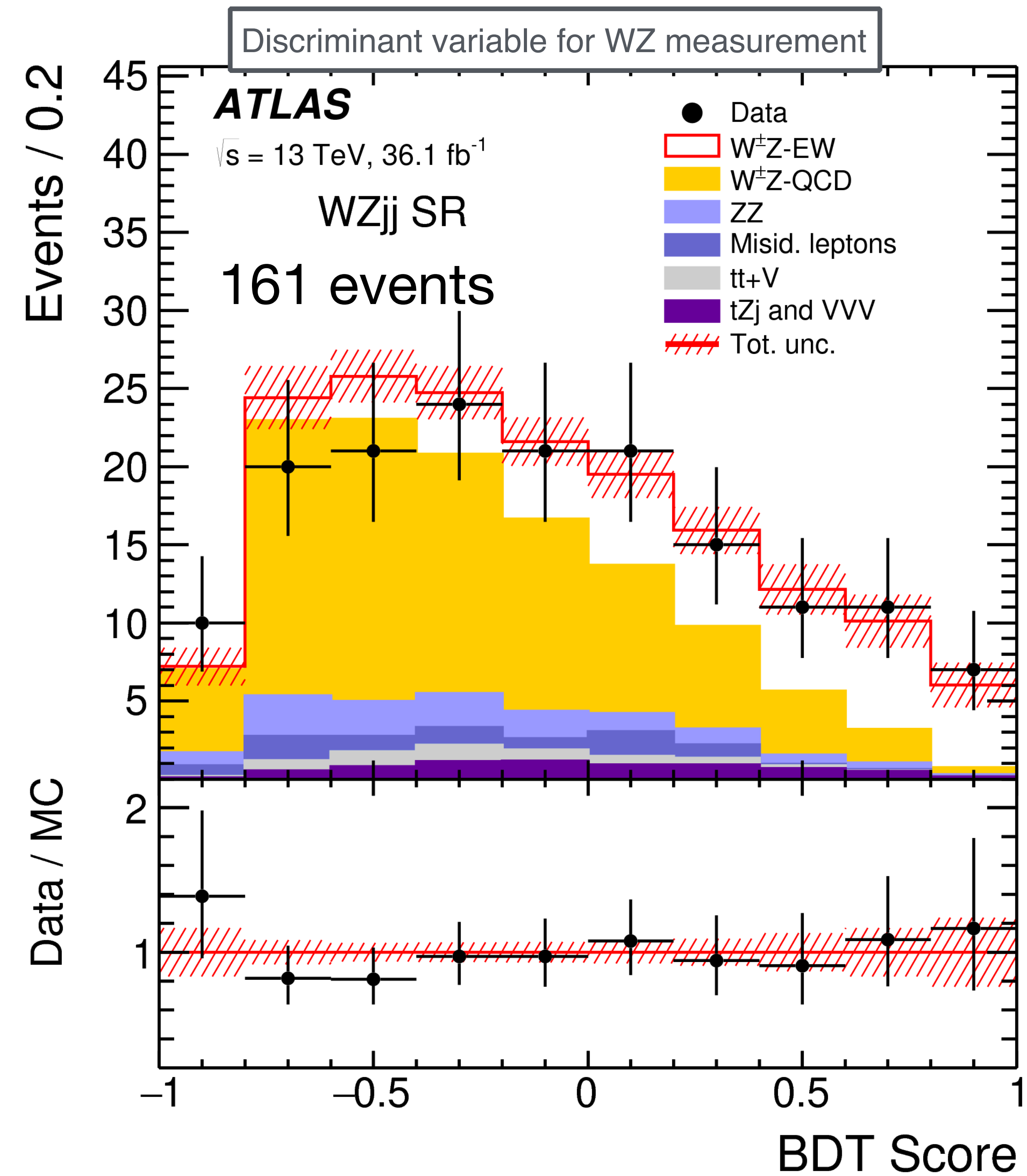
- **Run-2 data was coming:**
  - Increased energy → larger cross-sections (factor ~3)
  - But still a small signal/background ratio
  - Required analysis optimisations to reach observation
  - First observations were expected with the early Run-2 dataset !

C. Bittrich CERN-THESIS-2020-039
S. Todt CERN-THESIS-2022-268

Analysis strategies

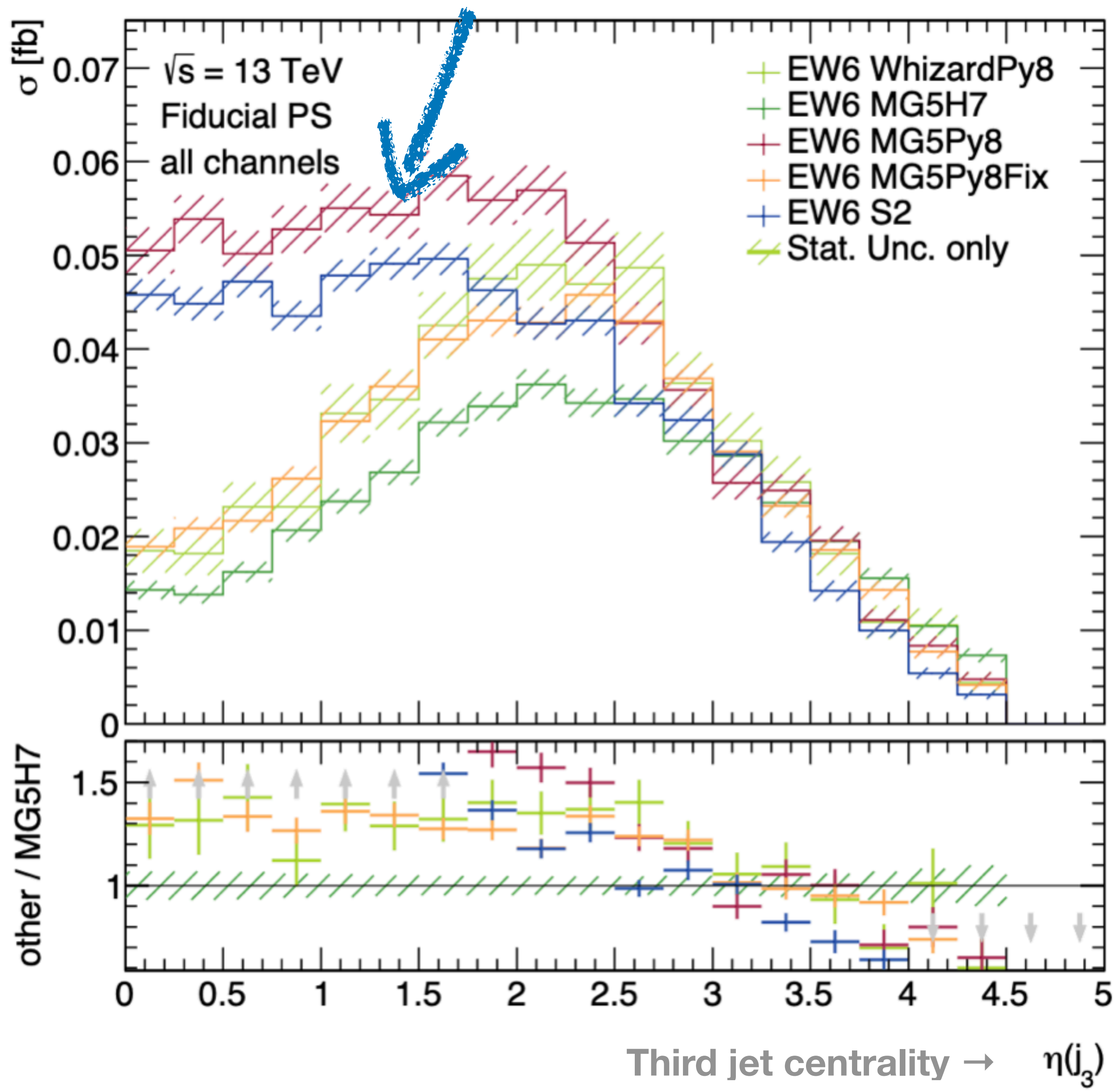
- Small signal over a large irreducible background
- Control regions to estimate from data the main backgrounds
- Use of discriminant variables or MVA to increase the signal and background sedation

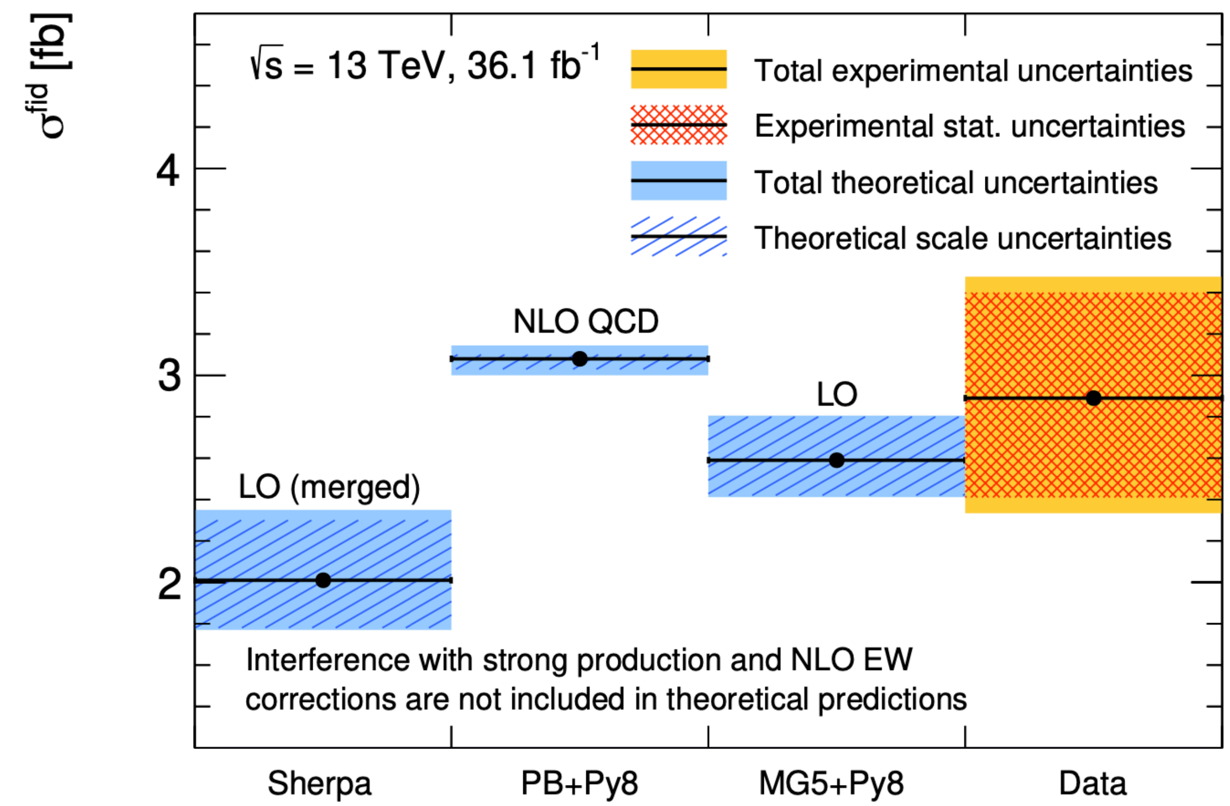




Some lessons learned

- ✓ Accurate MC modeling is essential — the shapes of the distributions are key!





Very different cross sections !

and shapes!

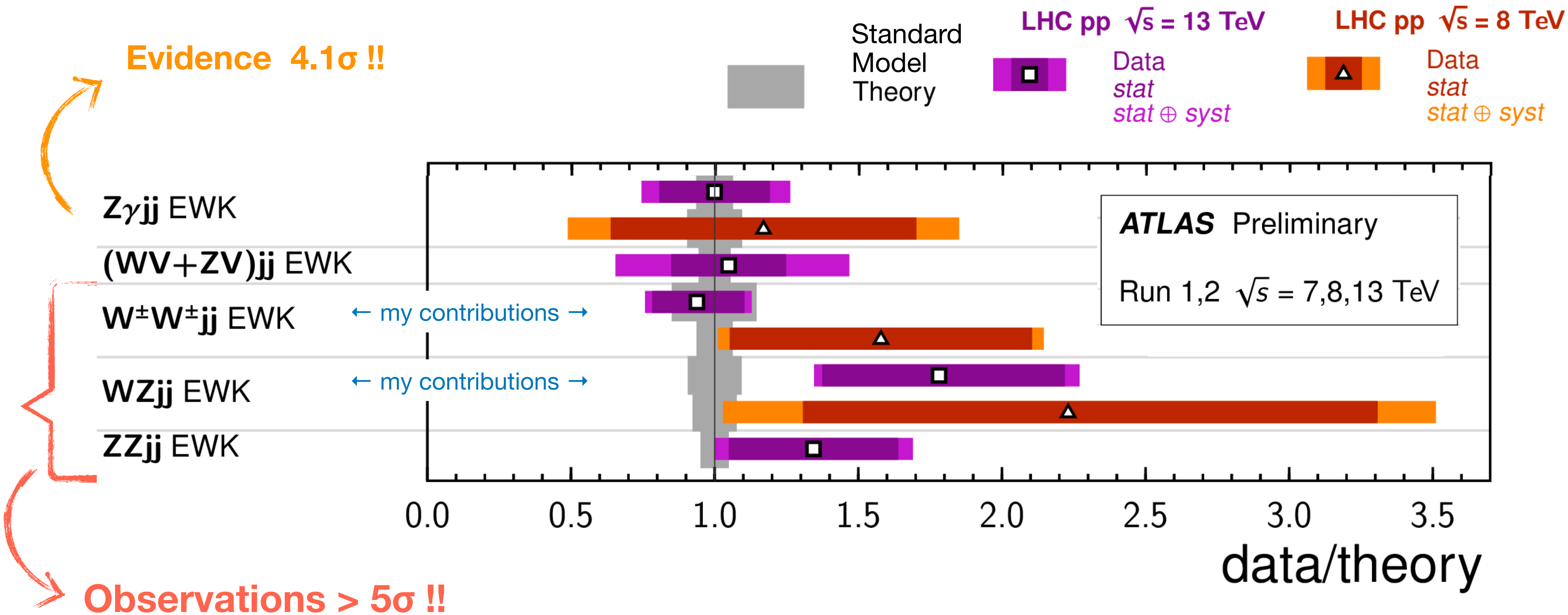
It is essential to get and provide feedback to theorists

VBSCan COST Action

First observations of VBS in 2019!

C. Bittrich CERN-THESIS-2020-039
S. Todt CERN-THESIS-2022-268

- I was the convener of the EWK physics group, overseeing VBS analyses during the first observations.



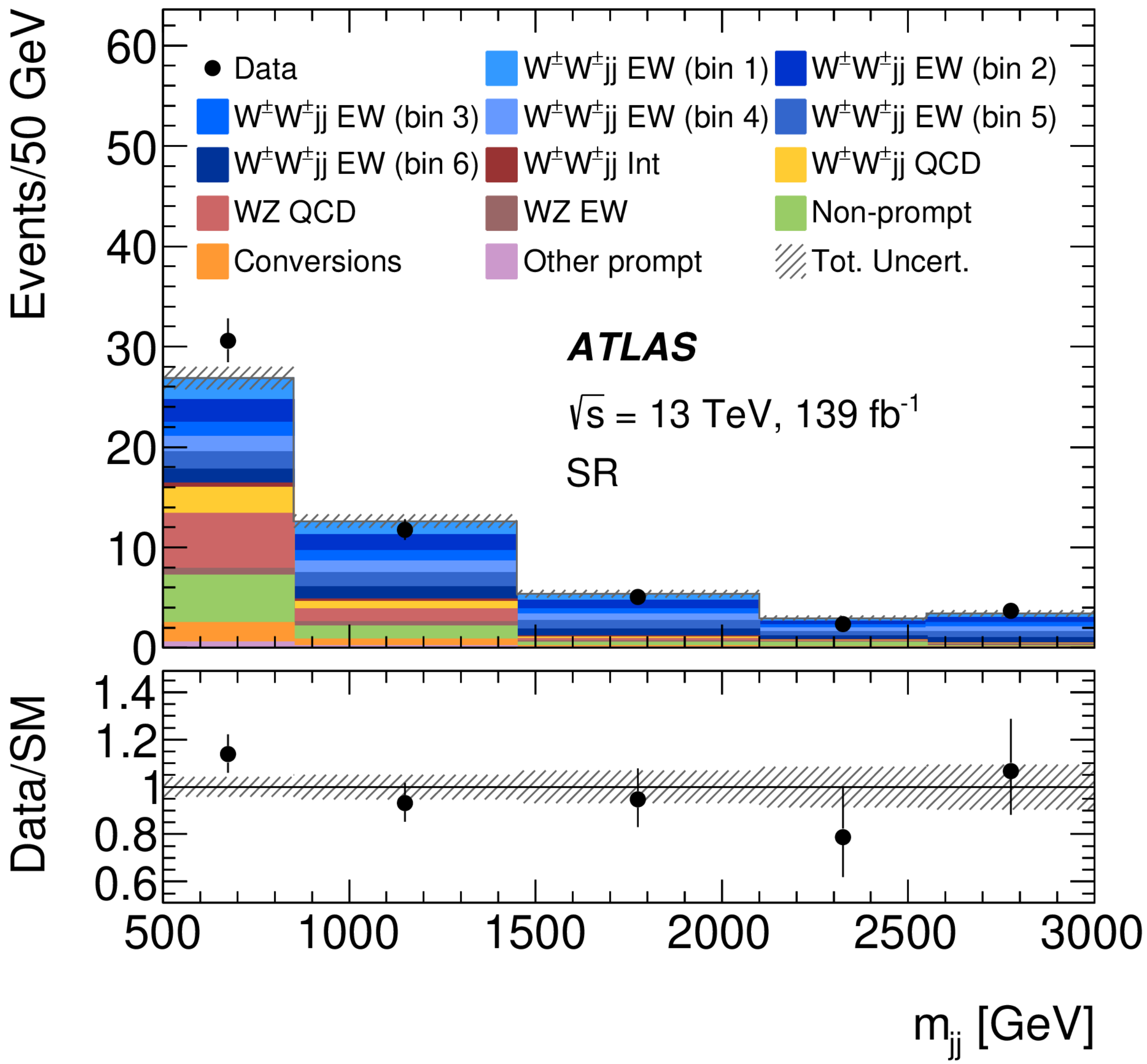
- With Full Run-2 observations for all diboson combinations even with semi-leptonic decays!

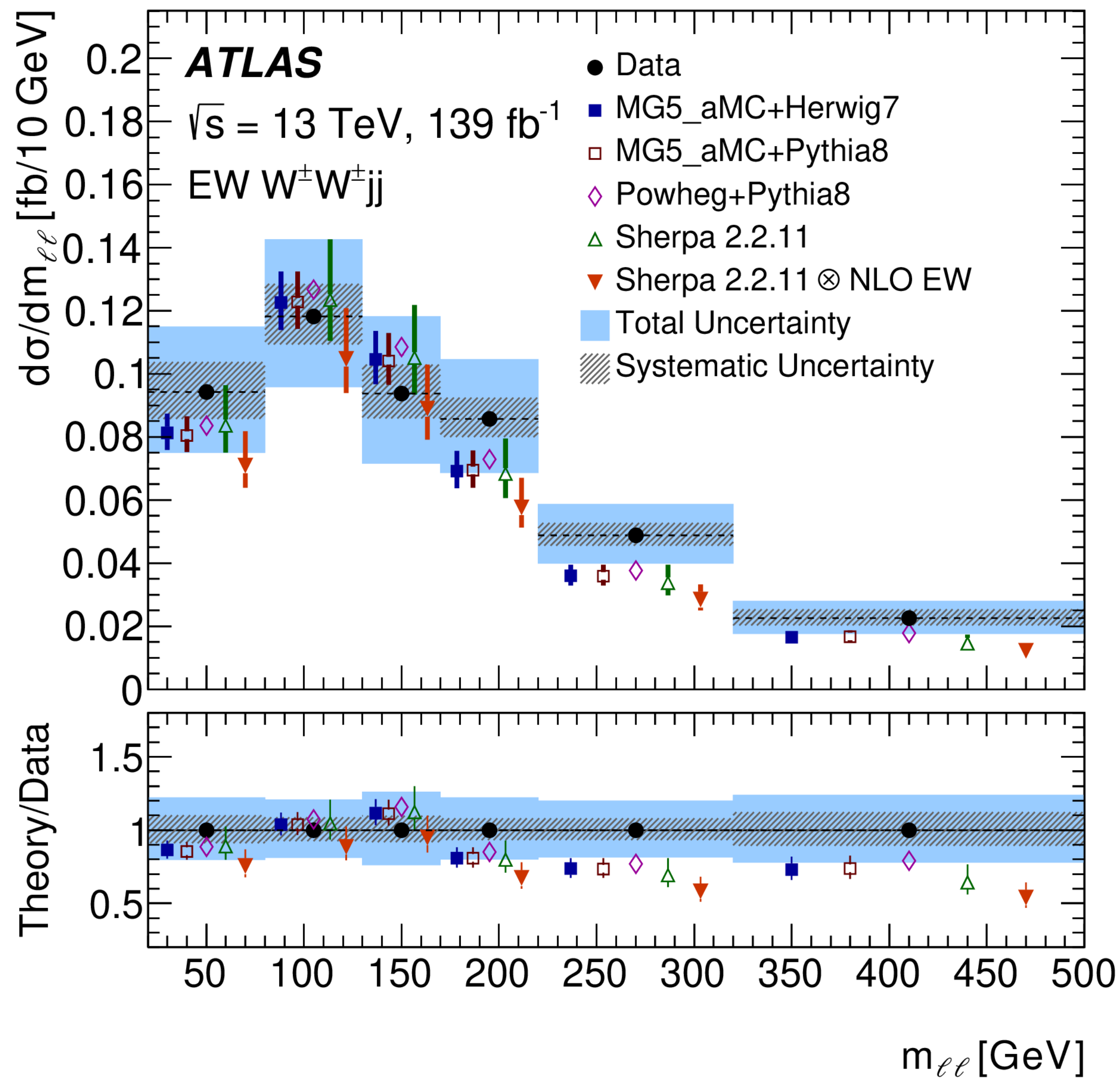
Now with full Run-2 !

T. Herrmann CERN-THESIS-2023-419

Let's have a closer look to our VBS golden channel

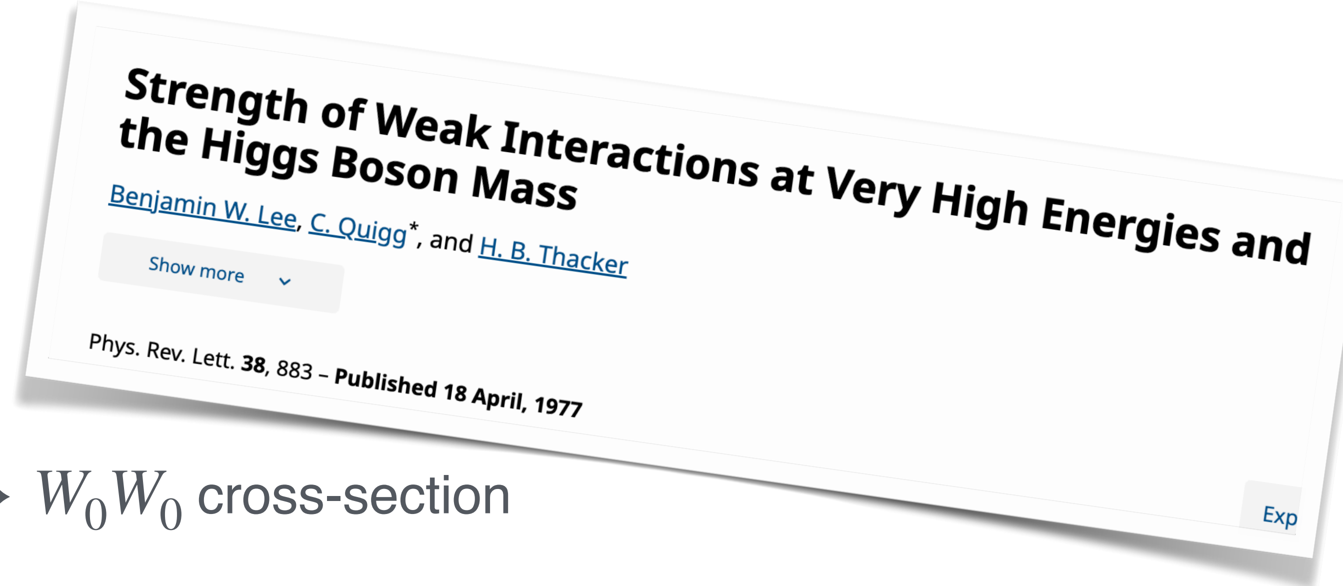
- We have with full run-2 ~500 events in this region (~250 ssWW signal)
- With this data we can now go differential !





Are we really testing quartic couplings and the EWSB?

A unitarity argument


Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass

Benjamin W. Lee, C. Quigg*, and H. B. Thacker

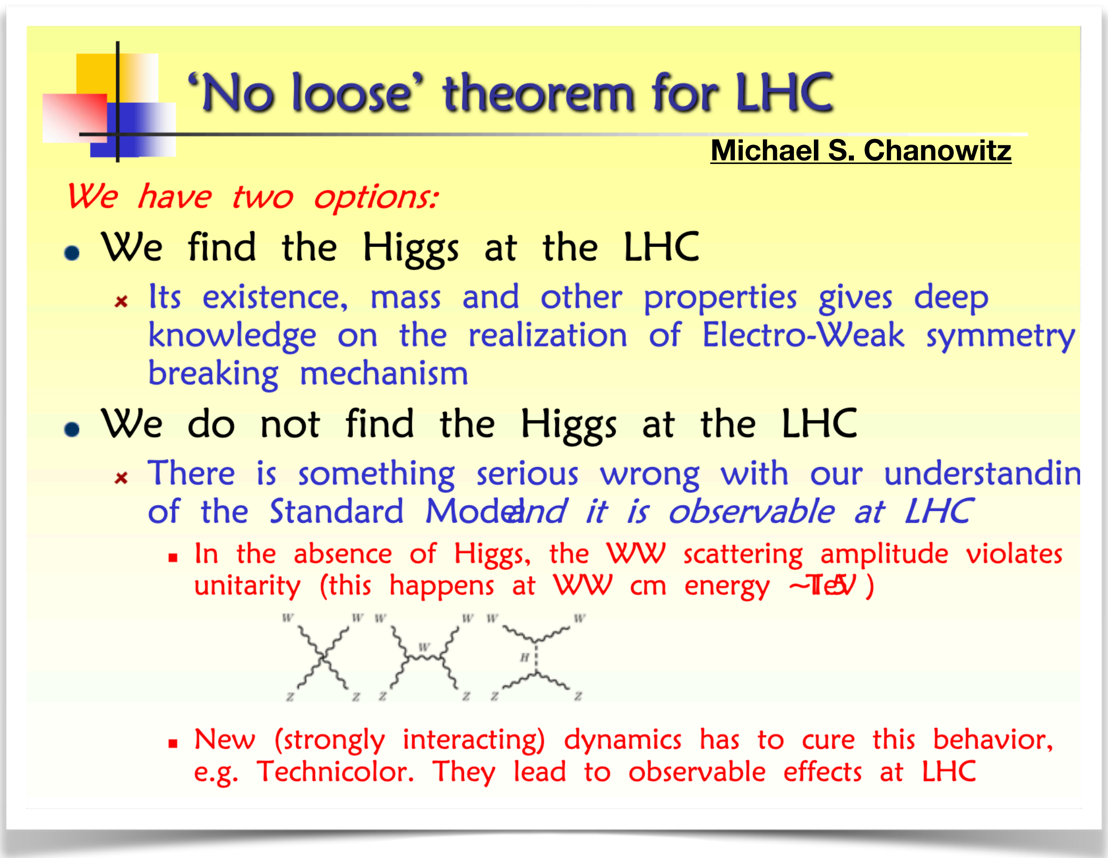
Show more

Phys. Rev. Lett. **38**, 883 – **Published 18 April, 1977**

Exp

"No-lose theorem" for LHC

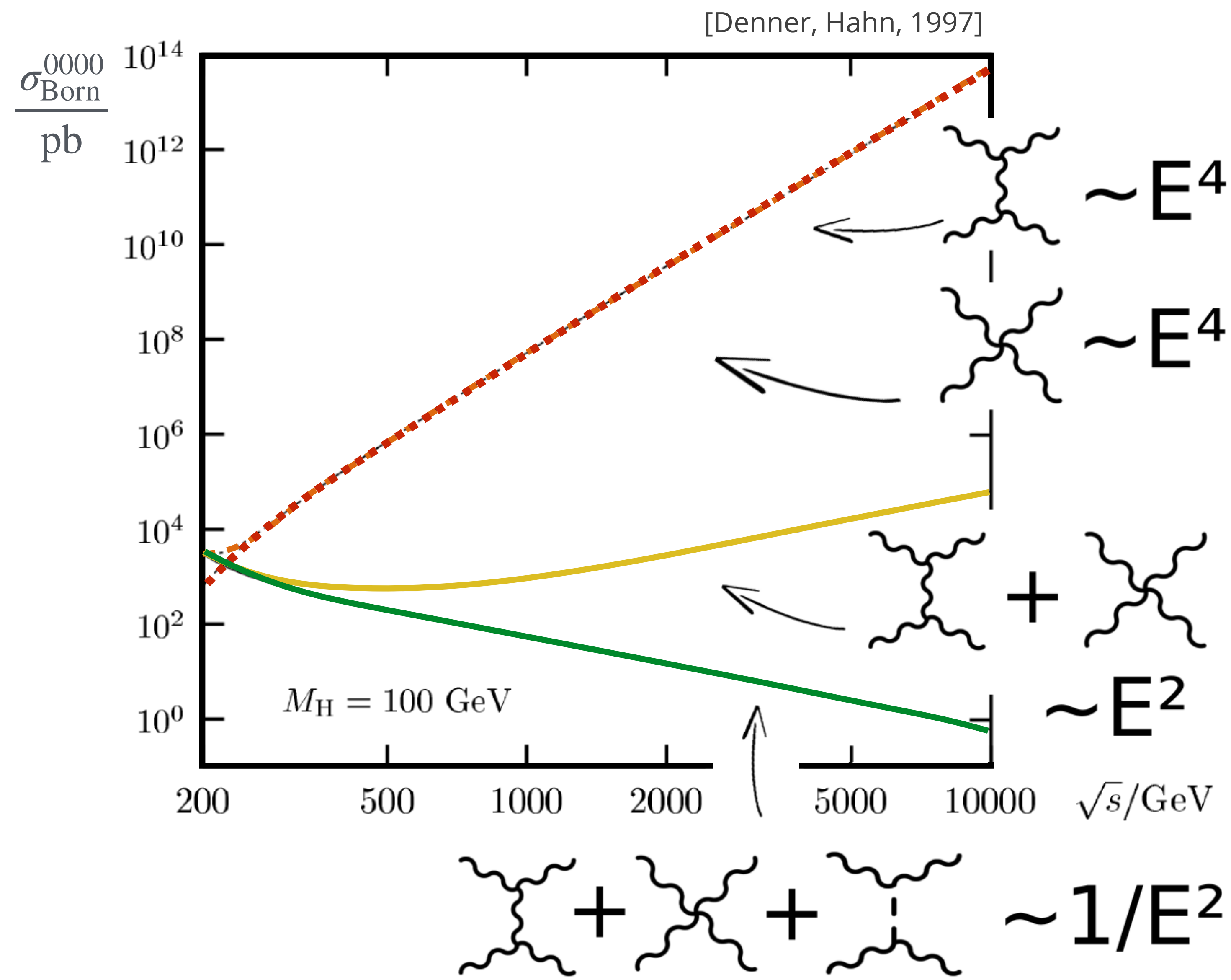
- We need something to regularise the $W_0 W_0 \to W_0 W_0$ cross-section


'No loose' theorem for LHC

Michael S. Chanowitz

We have two options:

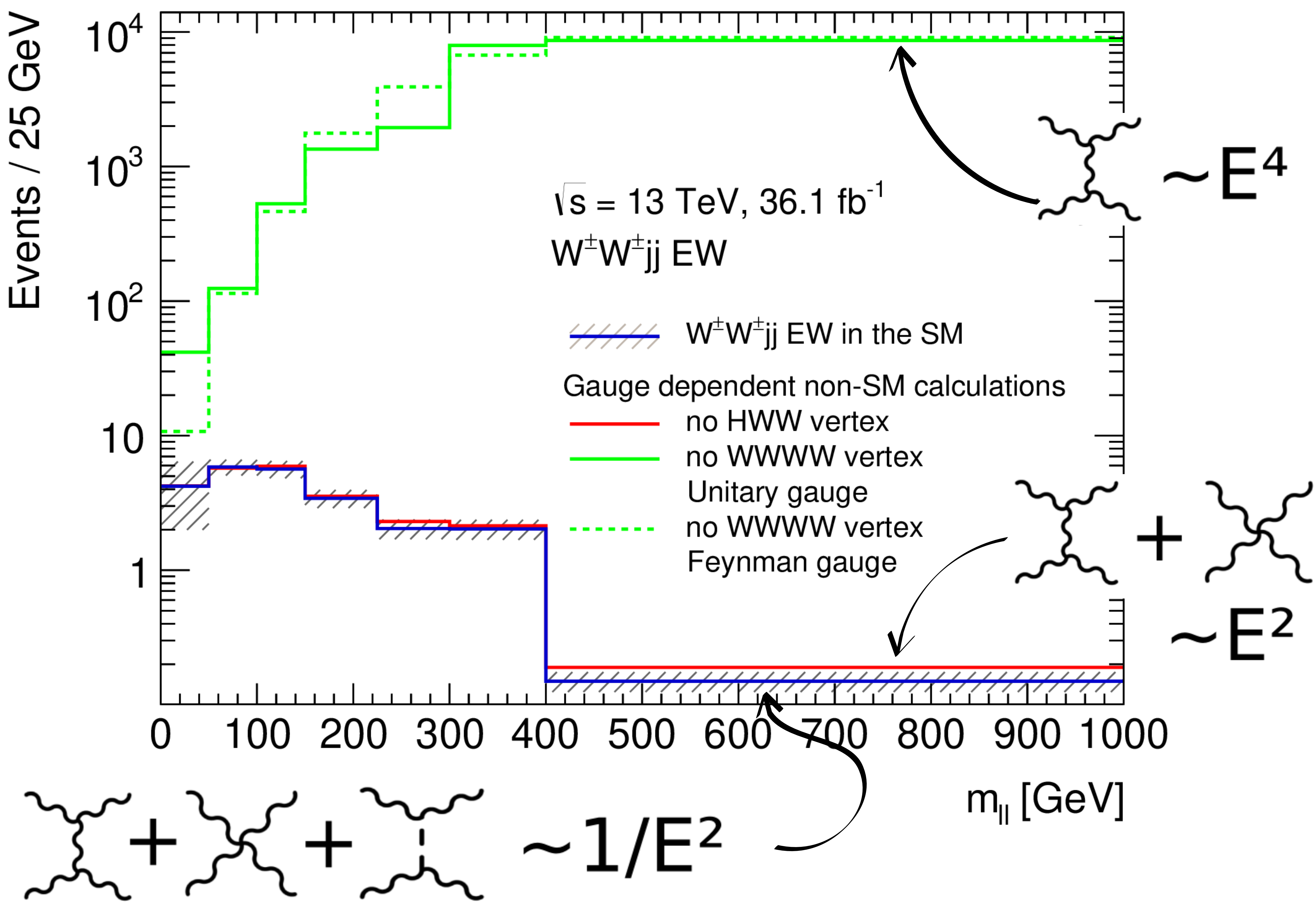
- We find the Higgs at the LHC
  - Its existence, mass and other properties gives deep knowledge on the realization of Electro-Weak symmetry breaking mechanism
- We do not find the Higgs at the LHC
  - There is something serious wrong with our understandin of the Standard Model *and it is observable at LHC*
    - In the absence of Higgs, the WW scattering amplitude violates unitarity (this happens at WW cm energy ~TeV)
    - New (strongly interacting) dynamics has to cure this behavior, e.g. Technicolor. They lead to observable effects at LHC



Now that we know the Higgs exist, we can still verify if he is doing the job

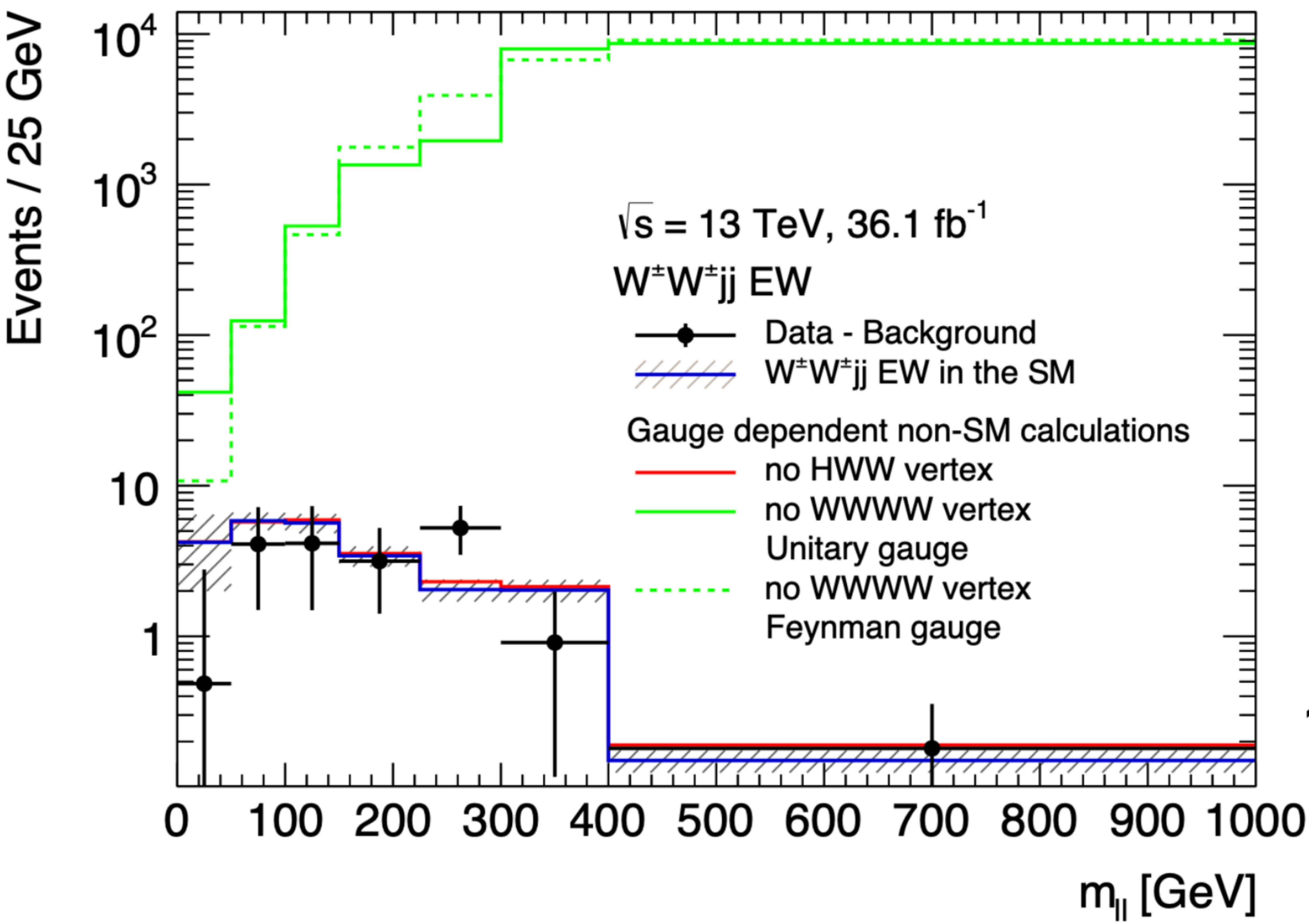
Challenge: Unitarisation

S. Todt CERN-THESIS-2022-268



Challenge: Unitarisation

S. Todt CERN-THESIS-2022-268



$\sim E^2$

Are we really testing quartic couplings and the EWSB?

A unitarity argument

“No **We need longitudinal bosons!**

- We need something to regularise the $W_0 W_0 \to W_0 W_0$ cross-section
- Either we find the Higgs Boson
- Or some new physics must be there.

'No loose' theorem for LHC

We have two options:

- We find the Higgs at the LHC
  - Its existence, mass and other properties gives deep knowledge on the realization of Electro-Weak symmetry breaking mechanism
- We do not find the Higgs at the LHC
  - There is something serious wrong with our understandin of the Standard Model *and it is observable at LHC*
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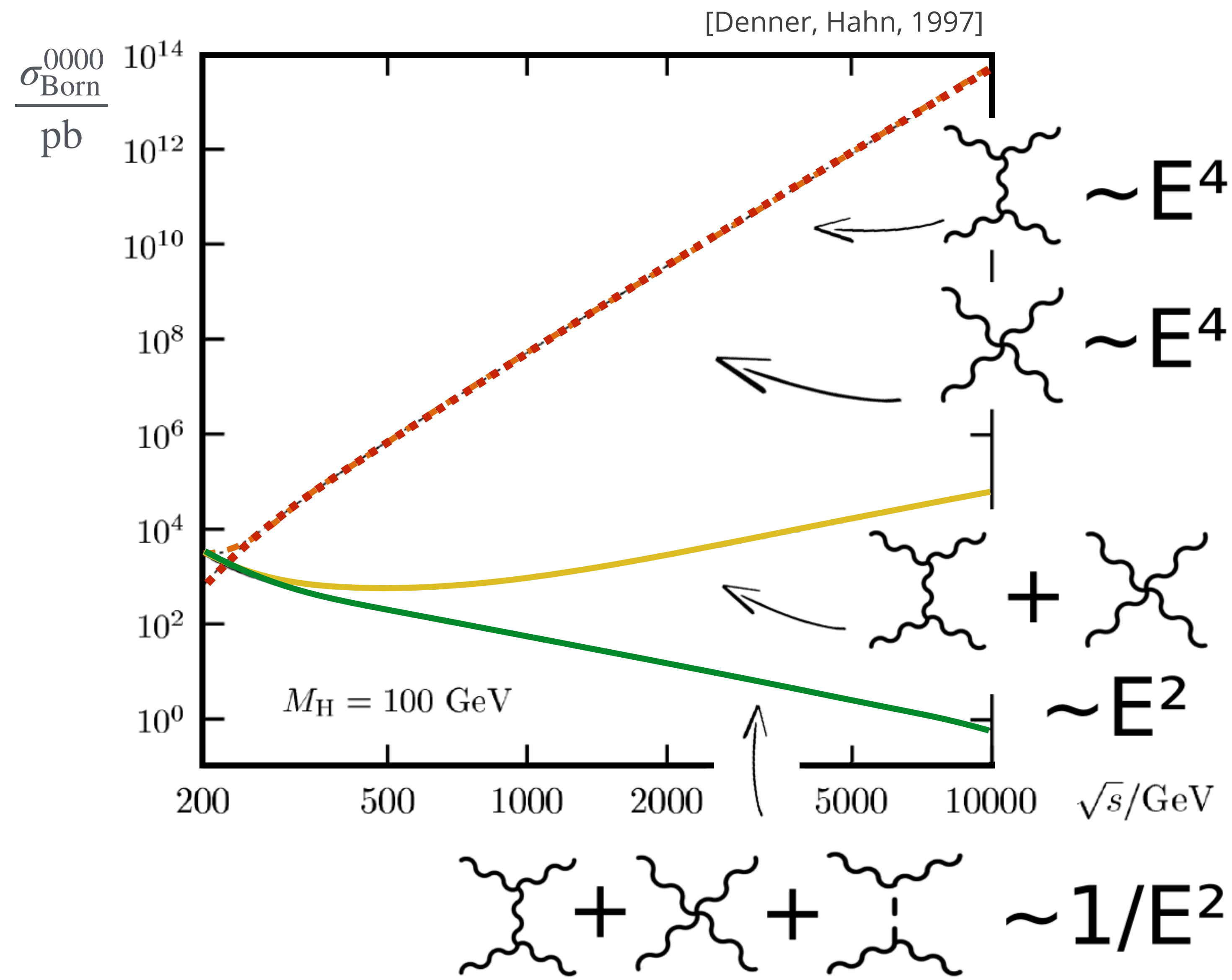
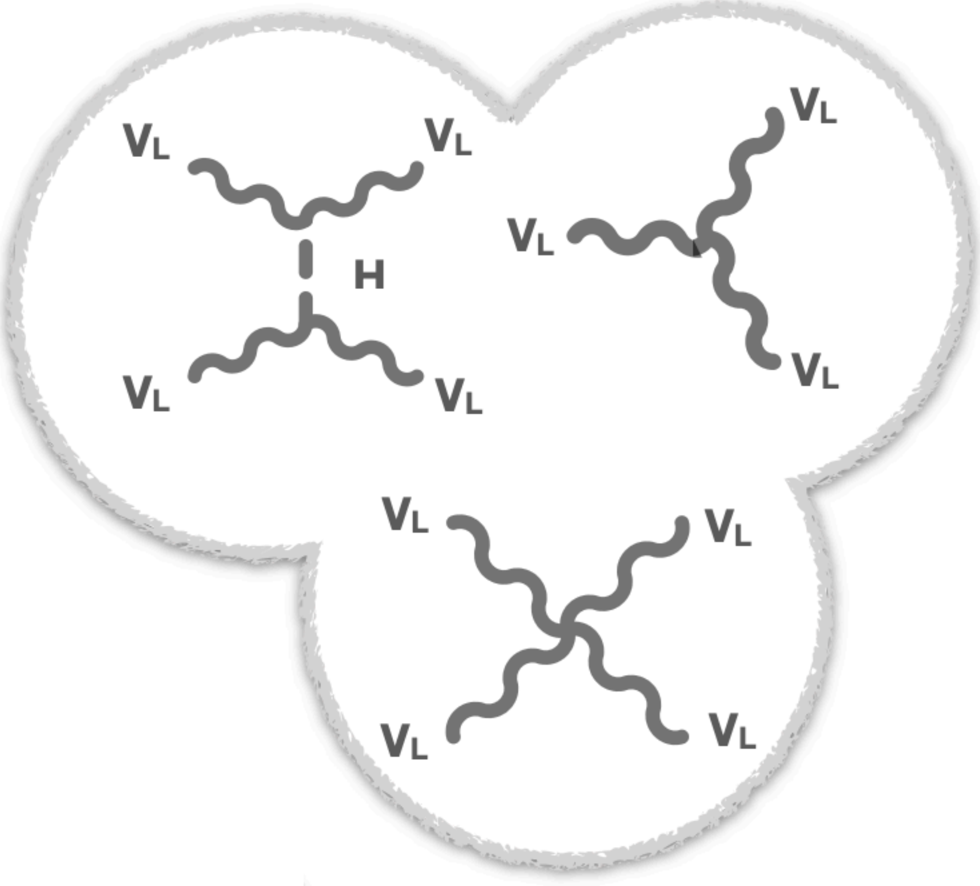


1. Challenge the SM

Quartic Bosons interactions ✔

Longitudinal polarised bosons interactions ○



The state-of-the-art

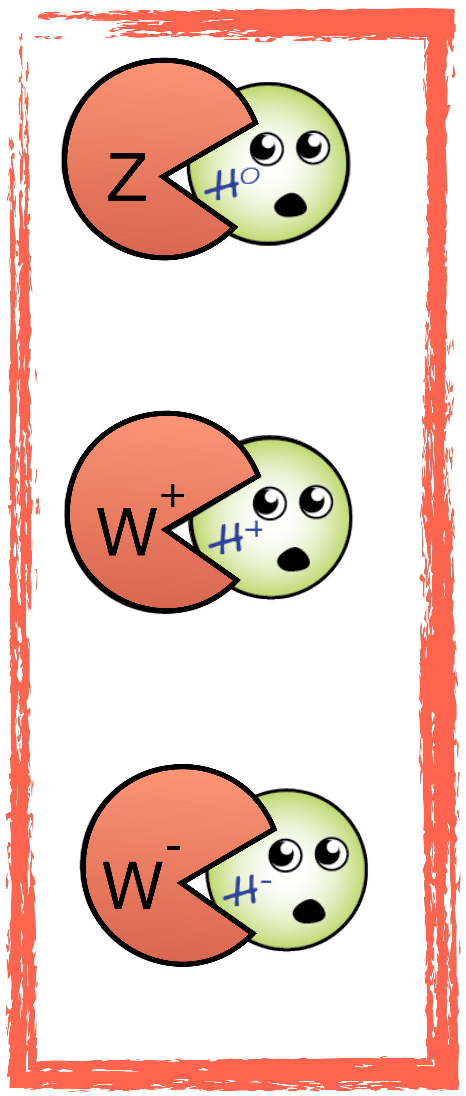
Measurements at LEP:

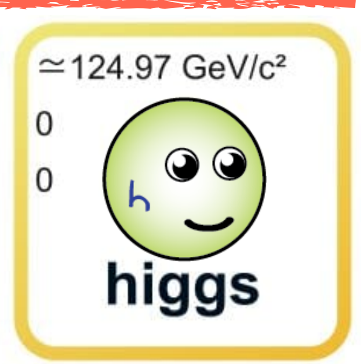
- Only diboson process accessible for such measurements $e^+e^- \to W^+W^-$
  - ***Single boson polarization measurements***: L3 [arXiv:0301027], OPAL [arXiv:0312047], DELPHI [arXiv:0801.1235]
  - ***Joint-polarization measurements***: OPAL [arXiv:0009021], DELPHI [arXiv:0908.1023]
- Never reached observation level sensitivity for longitudinal-longitudinal joint-polarization

Measurements at the LHC:

- Single and Joint- boson polarization measurements
- ***$pp \to W^{\pm}Z$***
  - CMS @13TeV 137 fb^{-1} (inclusive phase space) CMS-SMP-20-014
  - ATLAS @13TeV 139 fb^{-1} (inclusive phase space) Phys. Lett. B 843 (2023) 137895
  - ATLAS @13TeV 139 fb^{-1} (high p_T (Z) phase space) Phys. Rev. Lett. 133 (2024) 101802
- ***$pp \to ZZ$***
  - ATLAS @13TeV 140 fb-1 (inclusive phase space) JHEP 12 (2023) 107
- ***$pp \to W^{\pm}W^{\pm}jj$***
  - CMS @13TeV 137 fb^{-1} (VBS phase space) Phys. Lett. B 812 (2020) 136018
  - ATLAS@13TeV 140 fb^{-1} (VBS phase space) Accepted by PRL (2025)

Longitudinal polarised bosons interactions





The goal

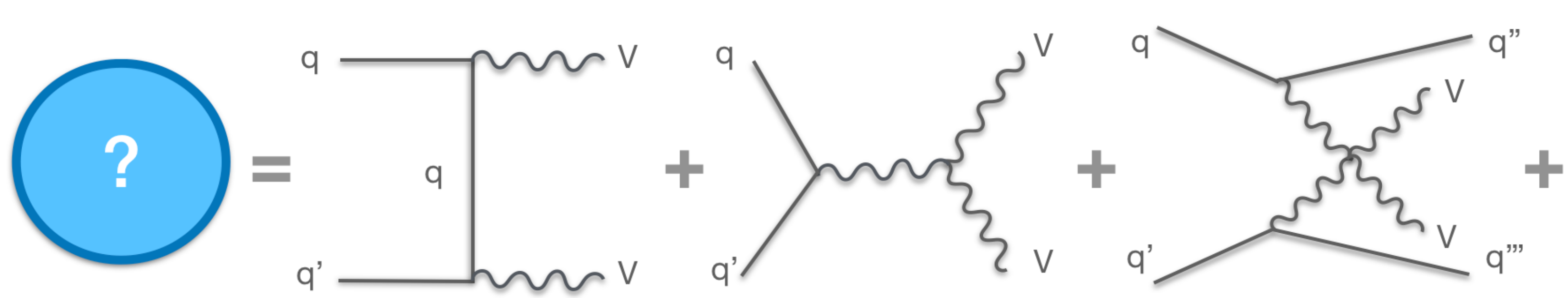
- Measure longitudinal bosons interactions → even better if it is a high energy

Goldstone boson Equivalence theorem

"At high energy, longitudinal vector bosons are analogous to goldstone bosons"

The challenges

- Simulation tools for polarised amplitudes → Madgraph [D. Buarque Franzosi et al. 2020]
- Vector Boson Scattering cross sections are tiny (~5% of it is V_0V_0)

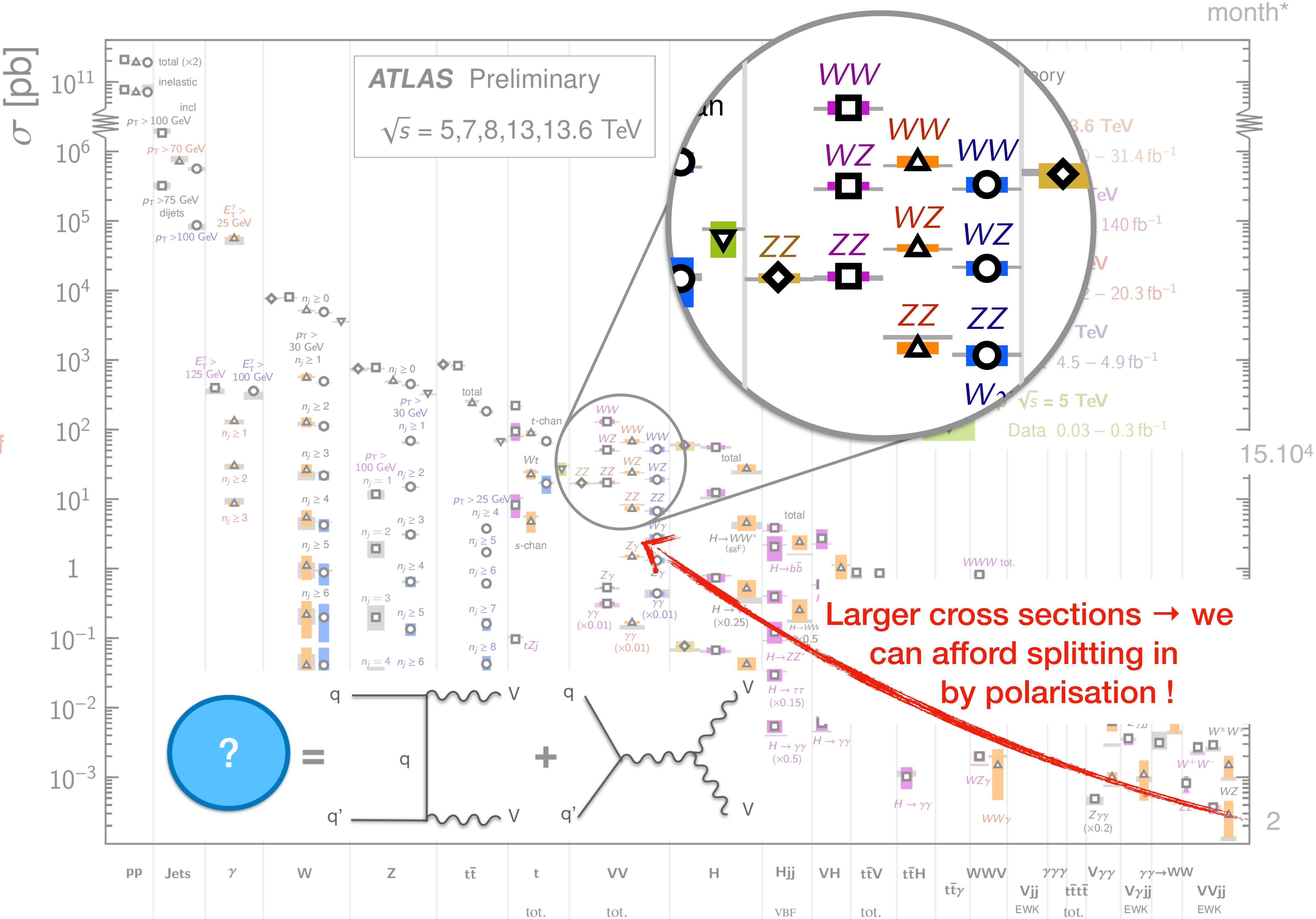


The Standard Model testing status

Status: June 2024

Events per month*

14 orders of magnitude!



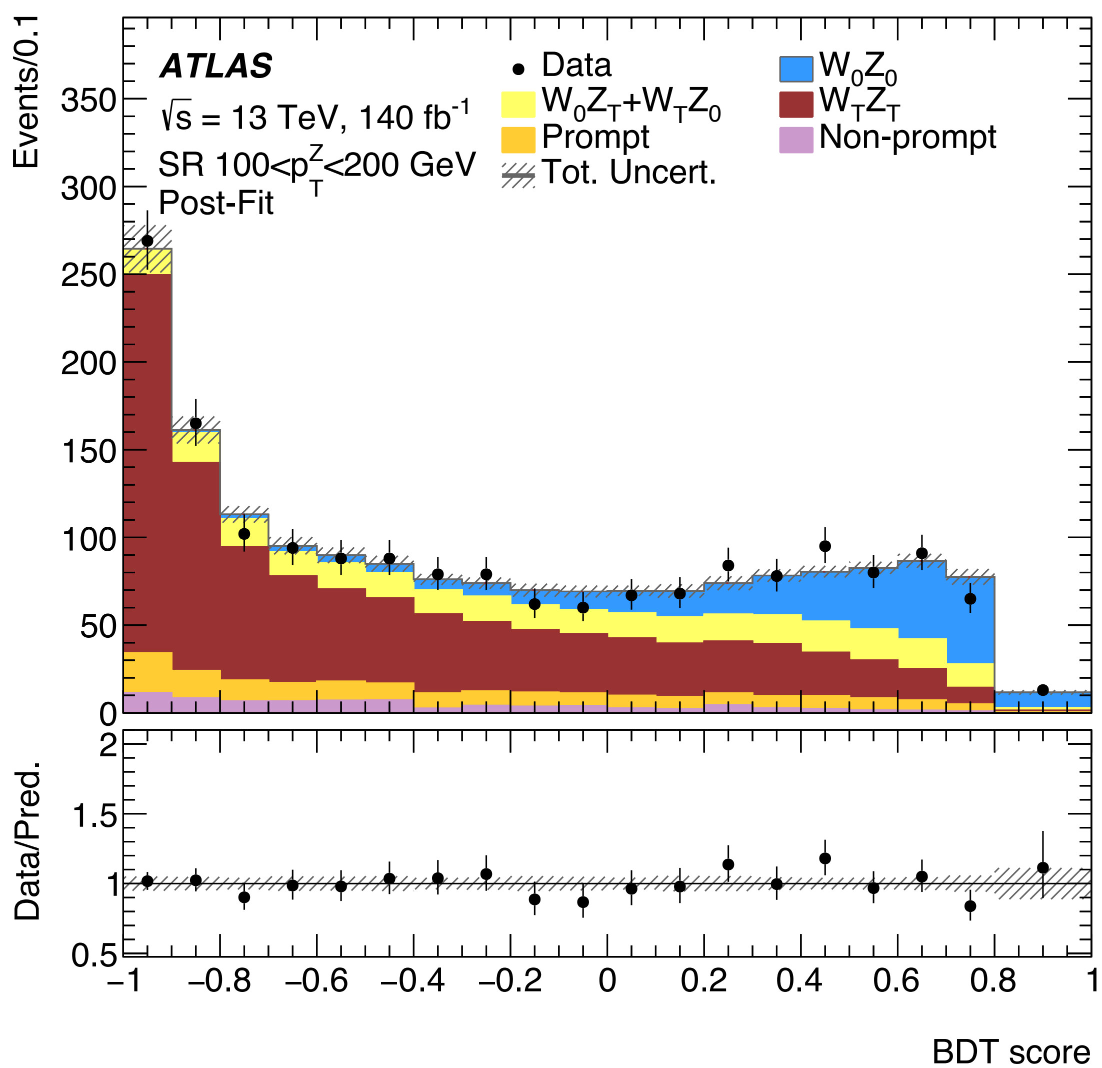
* at 13 TeV assuming 3fb⁻¹ are collected per month

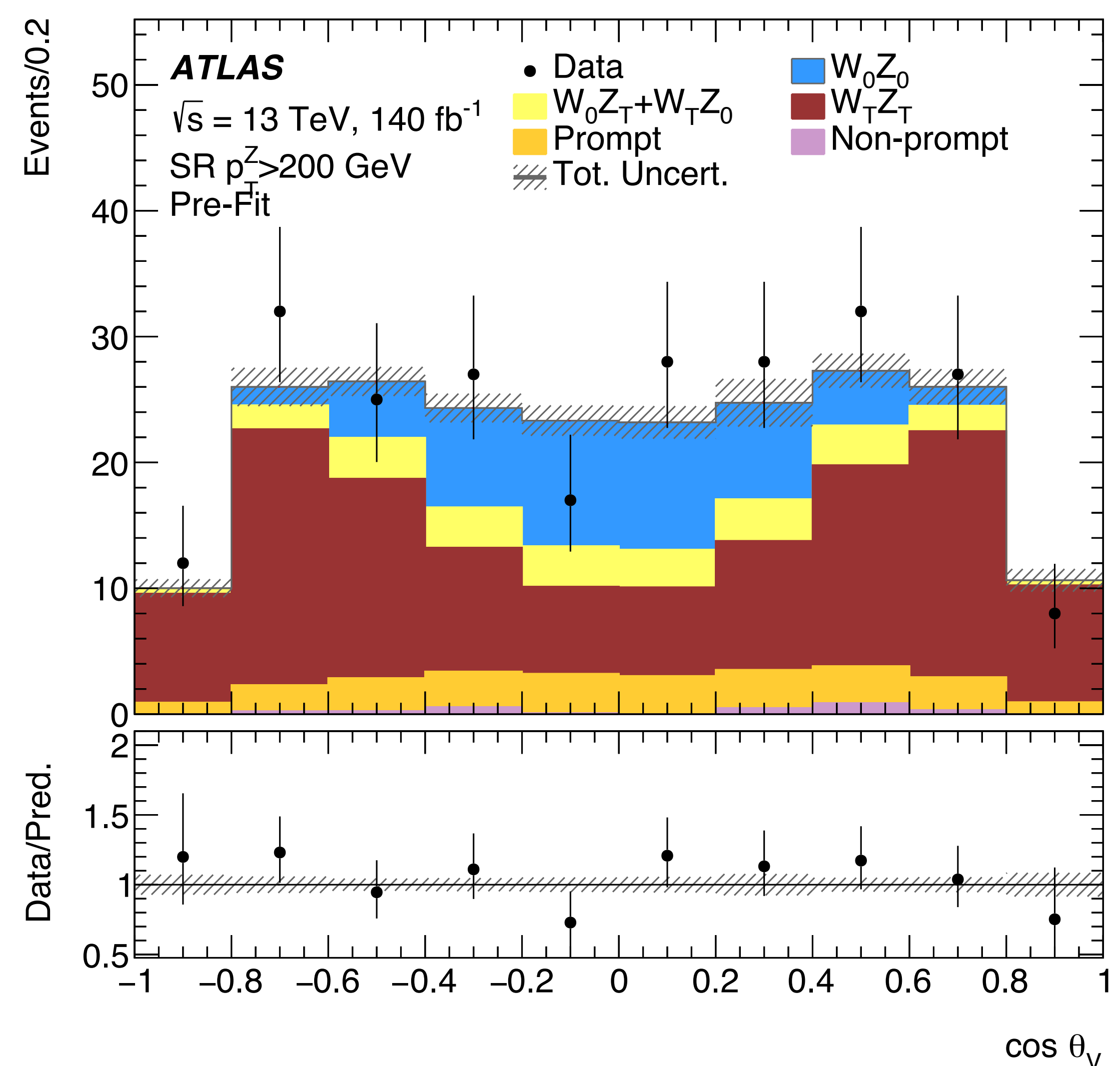
W_0Z_0 joint polarization - 00-enhaced region

- Increase the W_0Z_0 contribution → exploit the RAZ by $p_T(WZ)<70$ GeV
- Require high boson p_T → closer to the Goldstone boson behaviour

	Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008

Phys. Rev. Lett. 133 (2024) 101802





WZ joint polarization - 00-enhaced region

- **We are able to measure $W_0 Z_0$ bosons at high p_T (Z) !!**

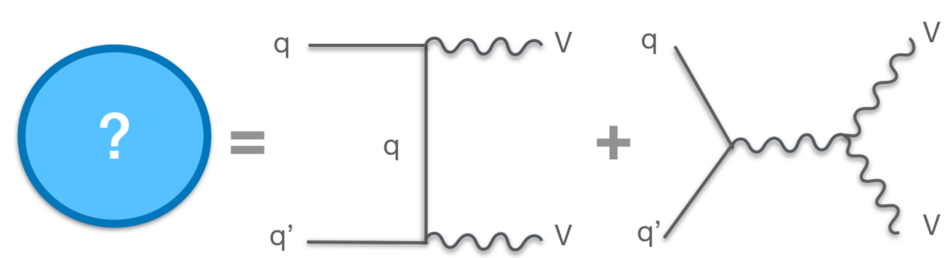
	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ

Observation

Evidence

Phys. Rev. Lett. 133 (2024) 101802

Are we really testing longitudinal bosons interactions?



- The spin correlations using $R_c = \dfrac{f_{00}}{f_0^W f_0^Z}$
  - $R_c = 1$ No correlation
  - $R_c = 2.1$ SM prediction
- Measured value $2.4^{+0.8}_{-0.6}$ excluding the no correlation hypothesis with $2.8(2.2)\sigma$

What can we do better?

Source	Impact on f_{00} [%]	
Experimental	**$100 < p_T^Z \leq 200$ GeV**	**$p_T^Z > 200$ GeV**
Luminosity	0.1	0.1
Electron calibration	1.0	0.9
Muon calibration	0.6	0.6
Jet energy scale and resolution	3.1	4.8
E_T^{miss} scale and resolution	0.3	0.3
Flavor-tagging inefficiency	0.0	0.0
Pileup modelling	1.0	0.7
Non-prompt background estimation	3.6	0.6
Modelling		
Background, other	0.9	0.9
Model statistical	1.6	2.2
NLO QCD effects	3.7	9.1
NLO EW effects	0.9	7.5
Effect of additive vs multiplicative QCD+EW combination	0.5	1.7
Interference impact	2.4	1.4
PDF, Scales, and shower settings	4.0	4.0
Experimental and modelling	8.1	13.9
Data statistical	11.4	31.4
Total	14.0	34.4

Phys. Rev. Lett. 133 (2024) 101802

Some nice work has started

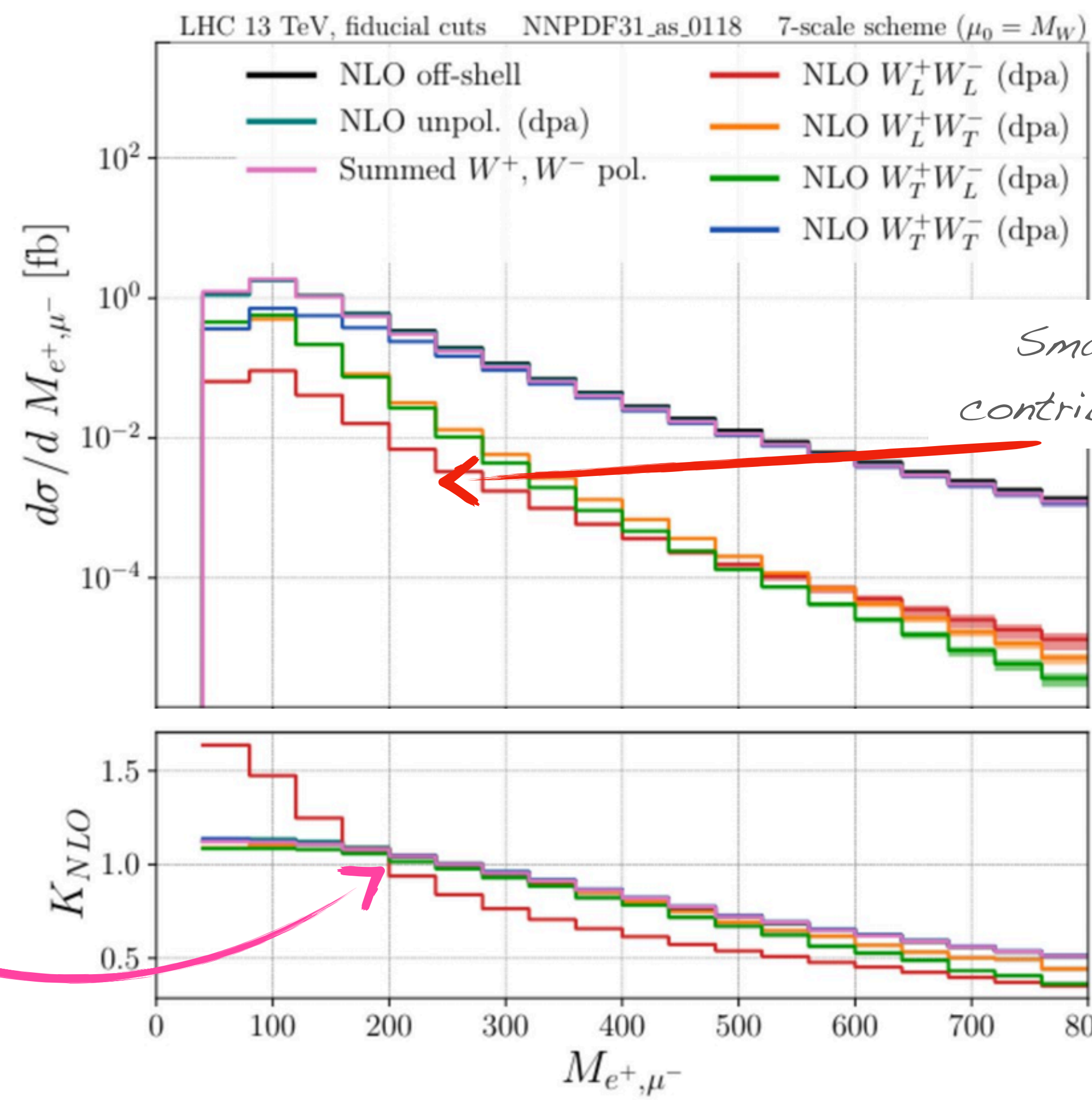
Monte Carlo generators

- Several generators in the market:
  - PHANTOM: 2 → 6 processes @ LO+PS [A. Ballestrero et al. 2008, 2017]
  - Madgraph: arbitrary processes @ LO, PS matching, multi-jet merging [D. Buarque Franzosi et al. 2020]
  - POWHEG-BOX-RES: diboson processes @NLO QCD+PS [G. Pelliccioli, G. Zanderighi 2023]
  - Sherpa: arbitrary processes @nLO QCD, PS matching, multi-jet merging [MH, M. Schönherr, F. Siegert 2023]
- Madgraph has been so far the one used by the collaborations

Fixed-order calculations

- Fixed-order calculations available for some processes (NNLO QCD, NLO QCD and EW) show large polarization depended corrections

R. Poncelet and A. Popescu



Small LL contribution !

NLO corrections are polarization aware and have different shape and size

Some nice work has started

Monte Carlo generators

- Several ge
  - PHANTO
  - Madgrapl
  - POWHEC
  - Sherpa: ar
- Madgraph h

2020]

F. Siegert 2023]

. Popescu

Fix order calcula

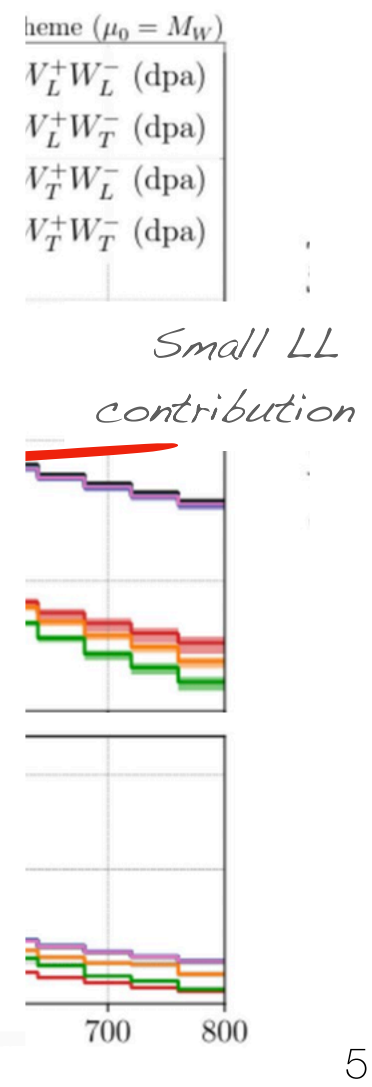
- Fix order calcu processes (NN show large pol

COMETA workshop on vector-boson polarisations

23–24 Sept 2024
Maison de la Recherche et de la Valorisation, Toulouse (France)
Europe/Paris timezone

and supported by

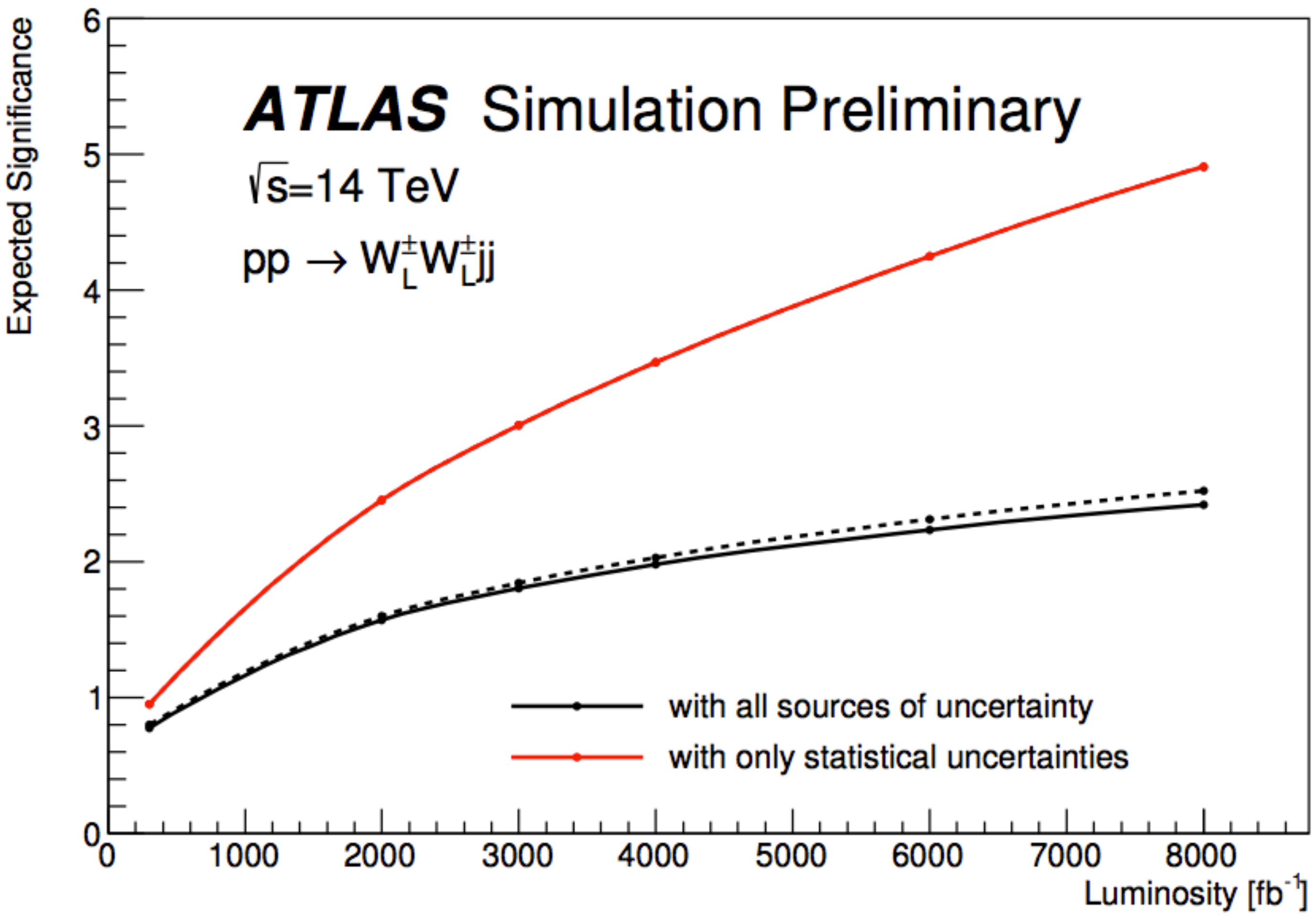
cnrs · Université de Toulouse · Université Toulouse III Paul Sabatier · L2IT

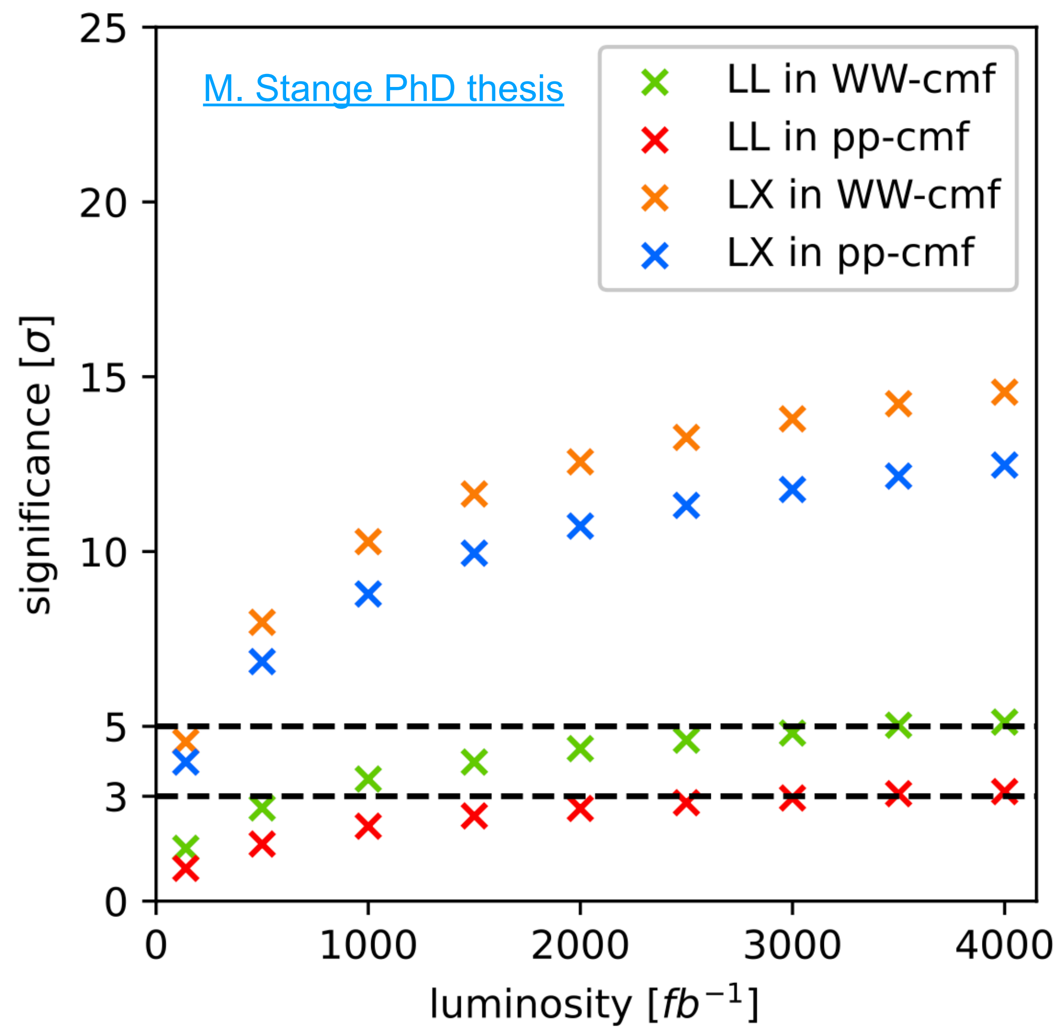


In the future

- **Now in 2025:** The same sign $W^{\pm}W^{\pm}jj$ team reached evidence 3.3σ of single boson polarization $W^{\pm}_{L}W^{\pm}jj$!!
- Some projection studies for polarization measurements in the HL-LHC were made back in 2018
- Updated projection results are more optimistic with evidence of $W^{\pm}_{L}W^{\pm}_{L}jj$ possible with 500 fb[-1] !

ATL-PHYS-PUB-2018-052





- Exploiting polarization in hadronic decays?

Polarised interactions will keep us busy

1. Challenge the SM

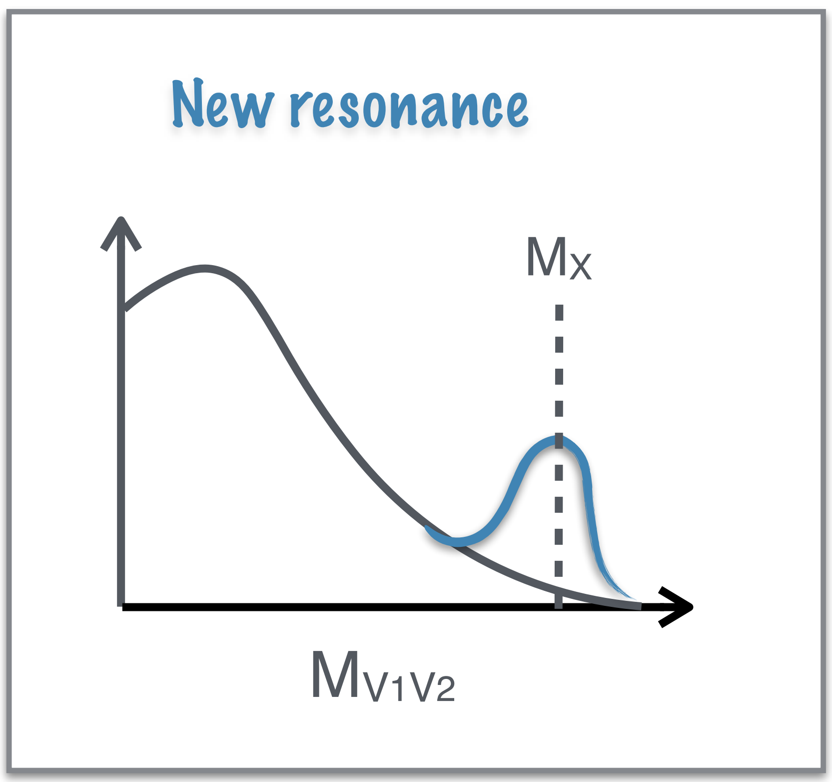
- Quartic Bosons interactions ✔
- Longitudinally polarized boson interactions ✔

2. Look for New physics

- New resonances
- Deviations on SM predictions

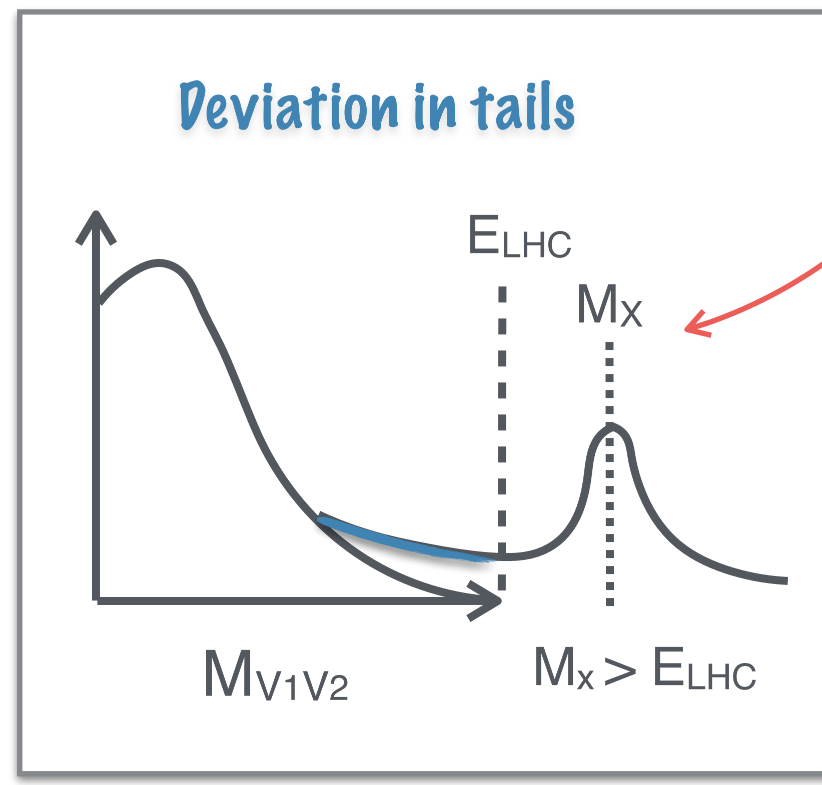
How to look for the unknown ?

Direct search approach
(model dependent)



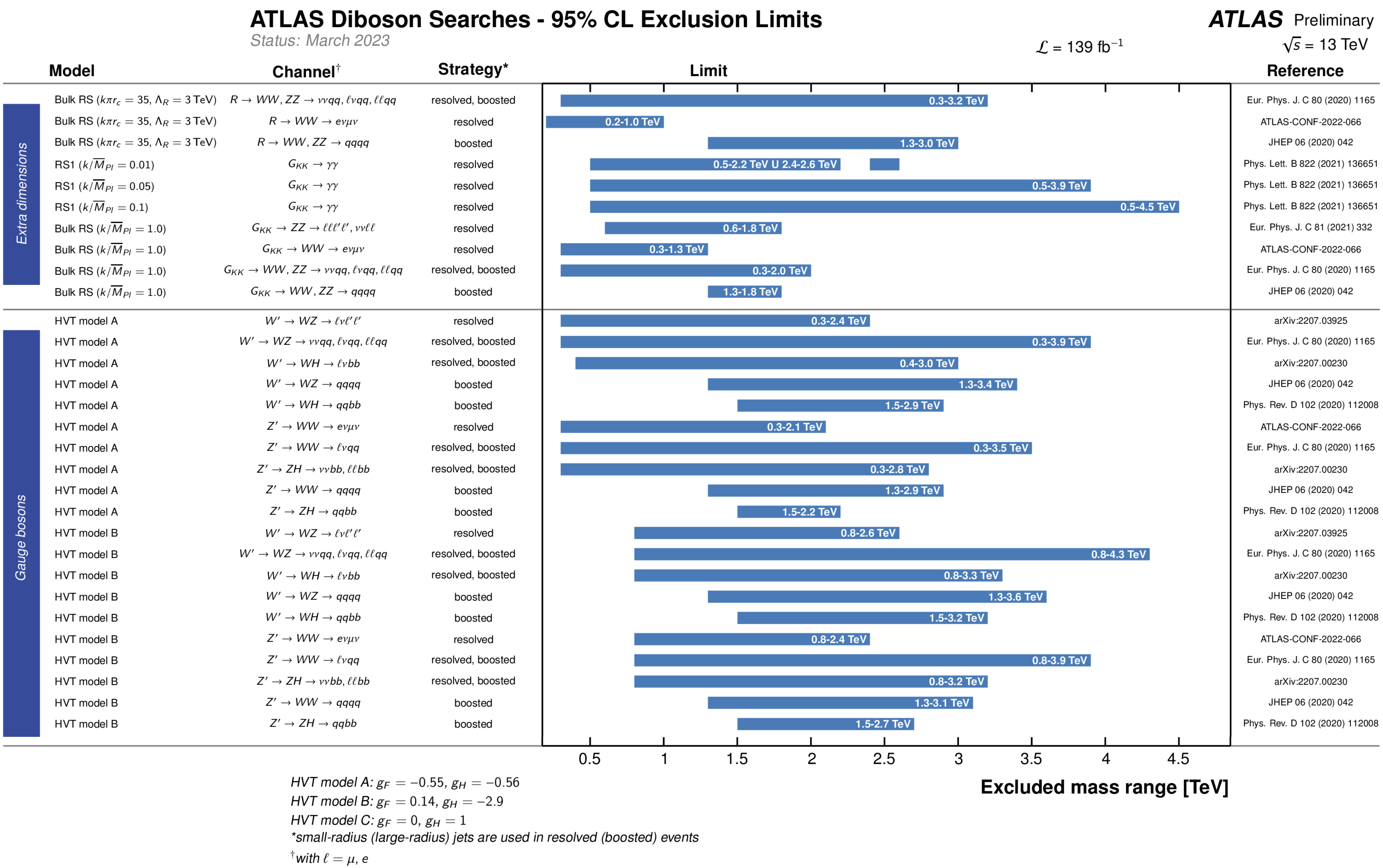
Indirect search approach
(model independent)

New physics may be beyond the energy reach of the LHC



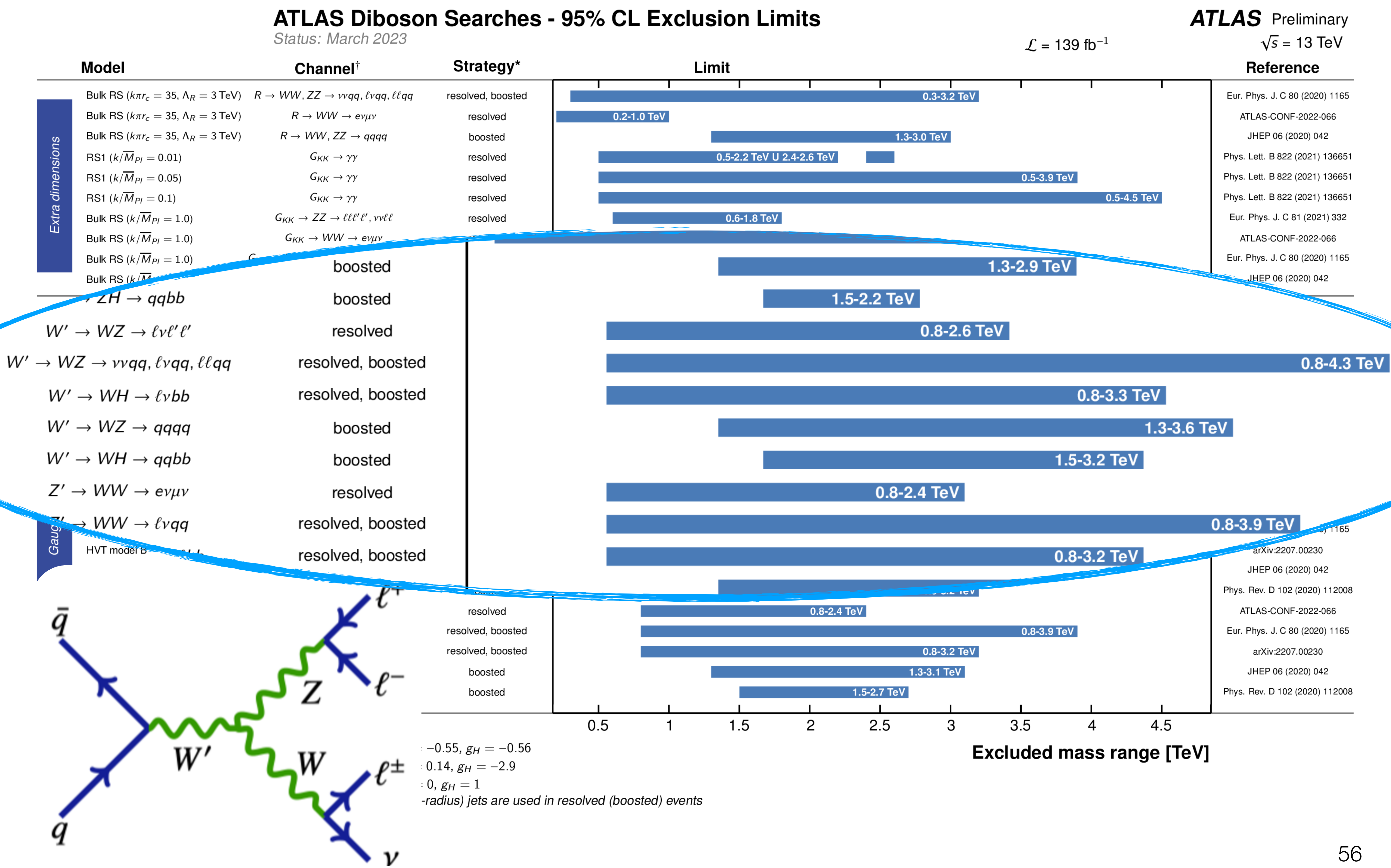
Diboson resonance searches in ATLAS

ATL-PHYS-PUB-2023-007



Diboson resonance searches in ATLAS

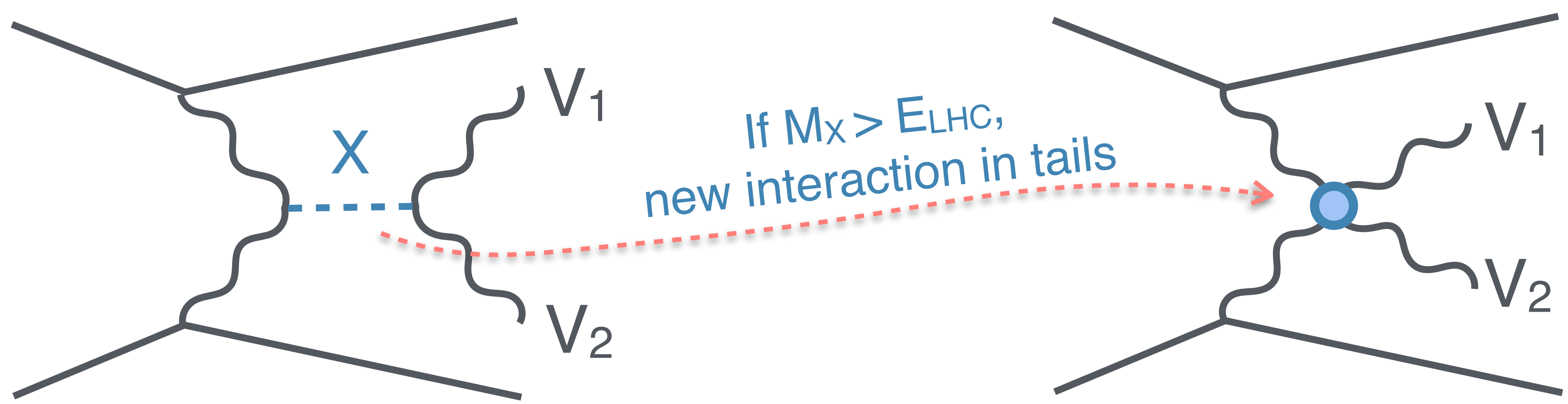
ATL-PHYS-PUB-2023-007



What if new physics is fermiophobic?

Direct search approach
(model dependent)

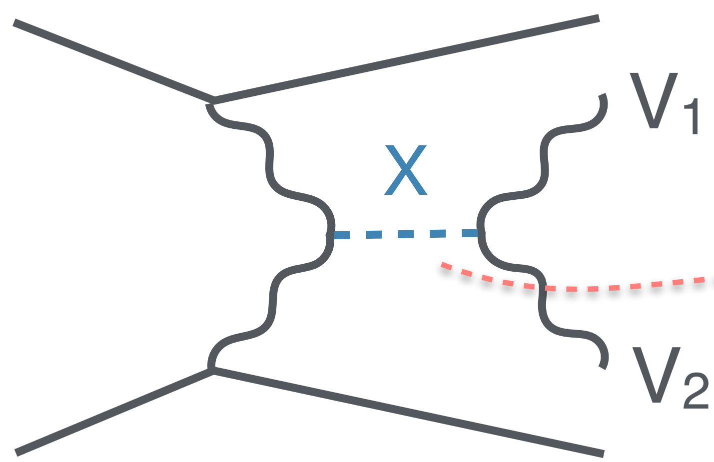
Indirect search approach
(model independent)



What if new physics is fermiofobic?

- The new particles couple bosons

Direct search approach
(model dependent)

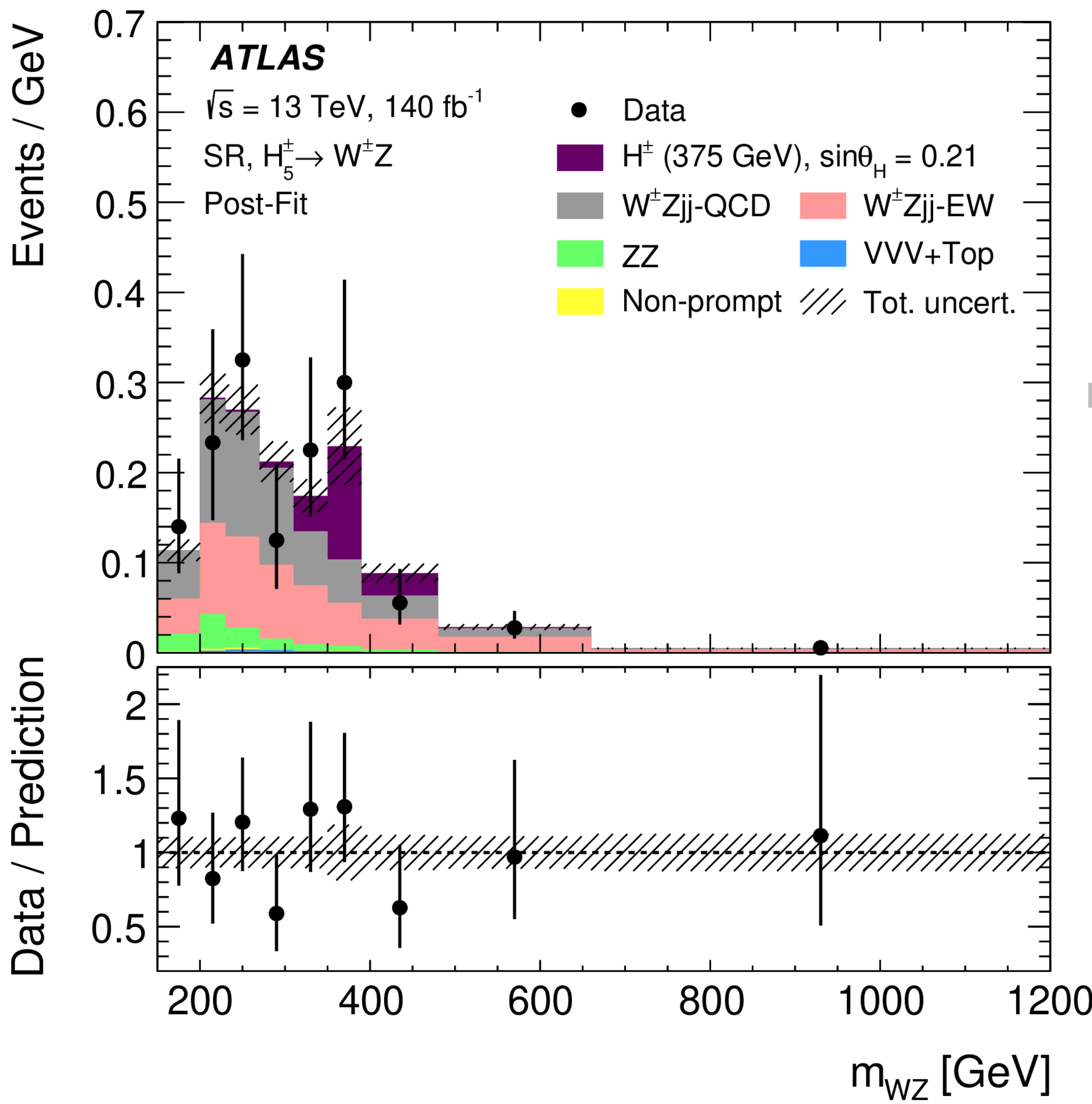


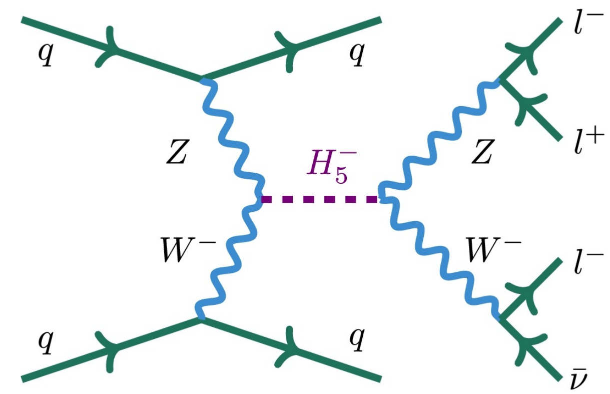
Georgi-Machacek (GM) model

- Extends SM Higgs sector with scalar triplets
- Keeps custodial symmetry → ρ = 1 at tree level
- Among the new scalars $H_5^{\pm}$, $H_5^{\pm\pm}$, H_5^0
- These couple directly to vector boson pairs

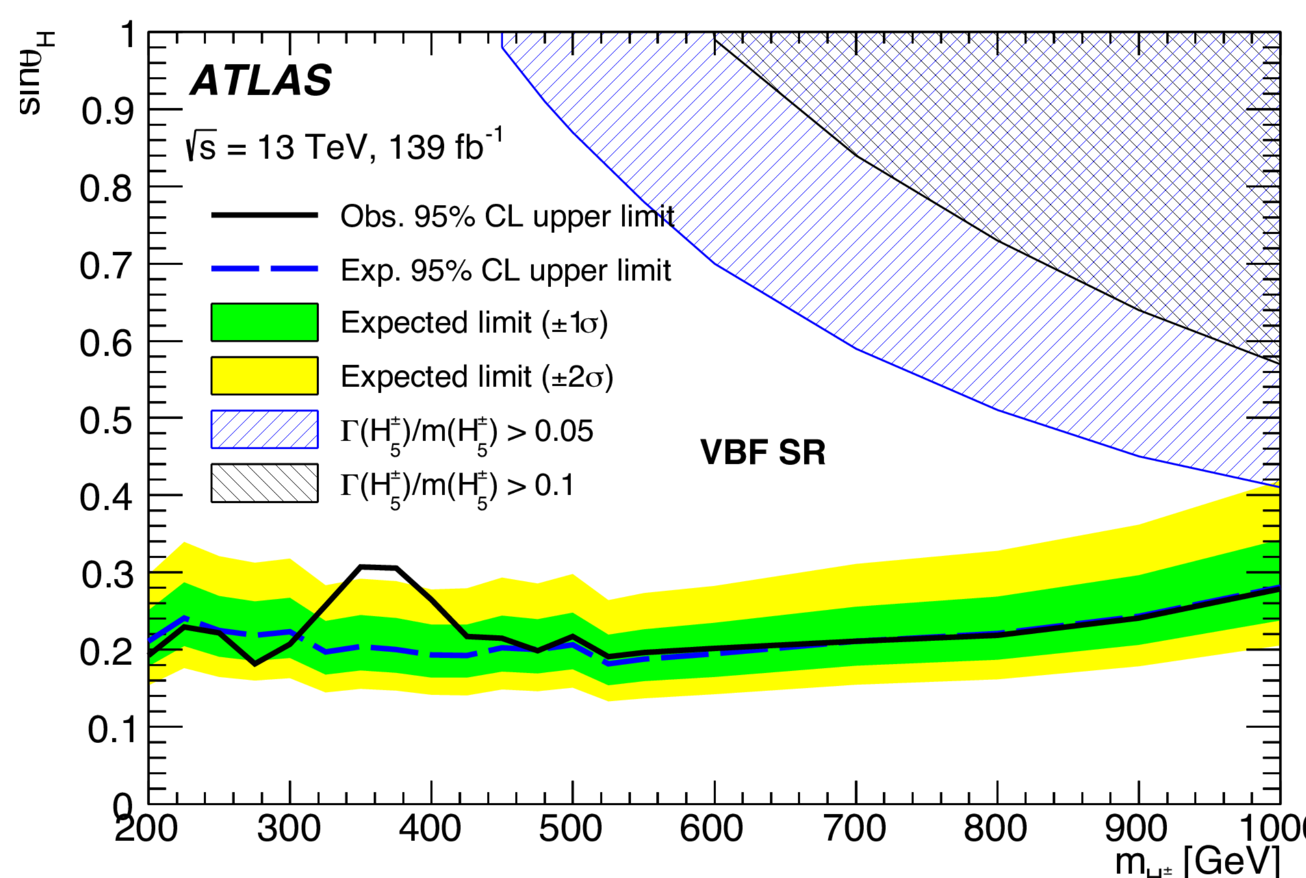
Charged Higgs resonance search

A. Nag CERN-THESIS-2022-115



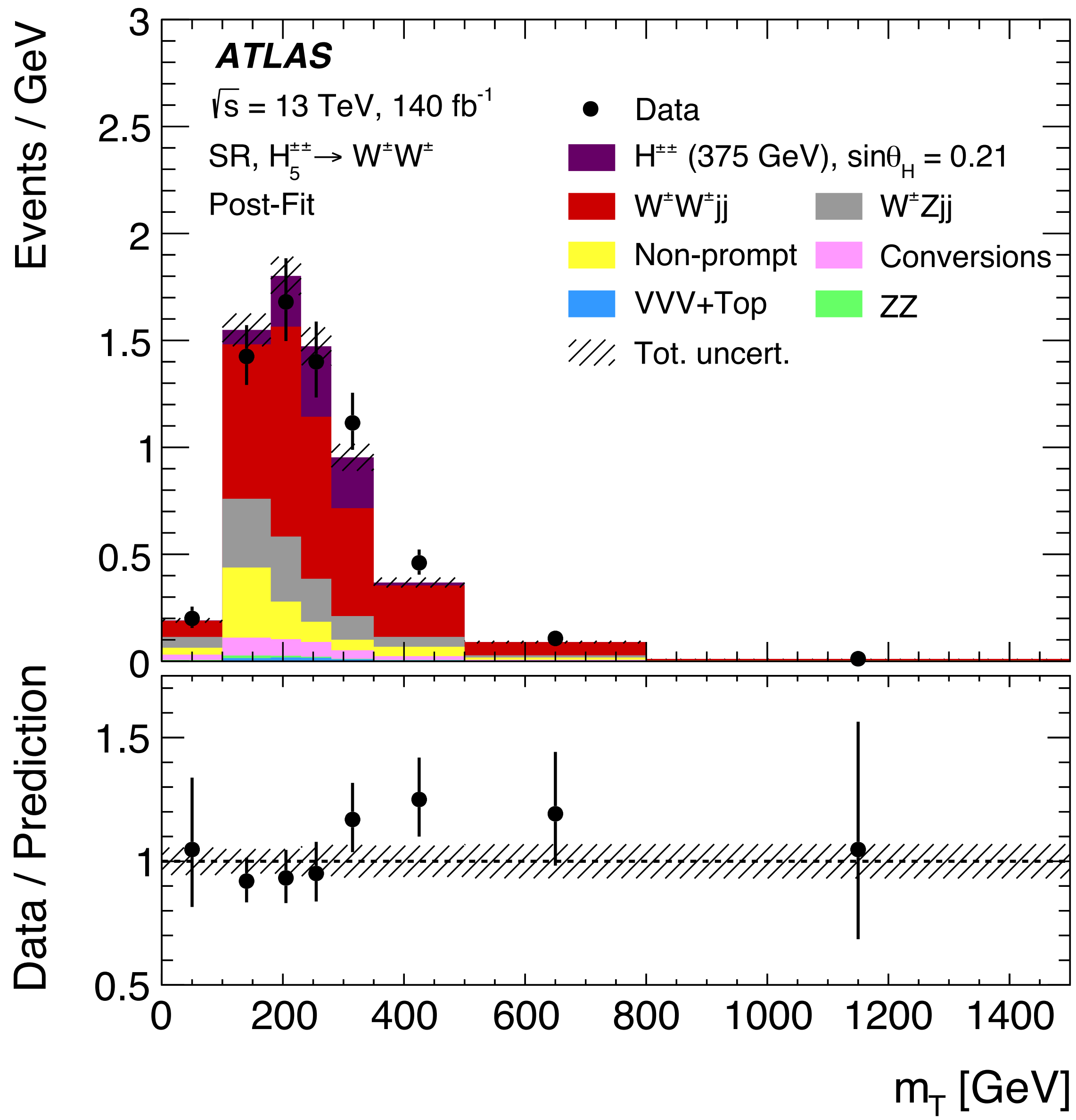


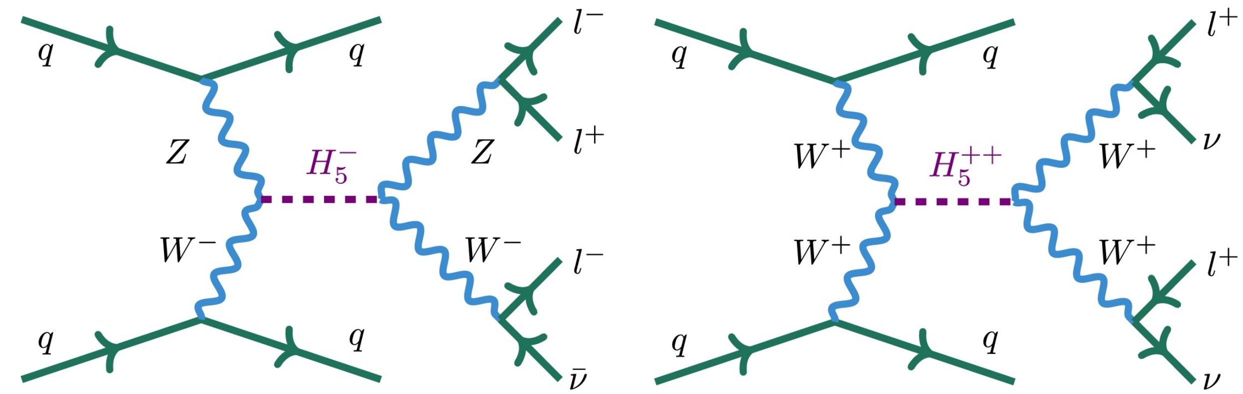
- Limits on $\sin\theta_H$ quantifies how much of EWSB is due to triplet fields
  - $\sin\theta_H \to 0$: triplet VEV $\to 0$, pure SM limit
  - $\sin\theta_H \to 1$: doublet VEV $\to 0$, triplet-dominated

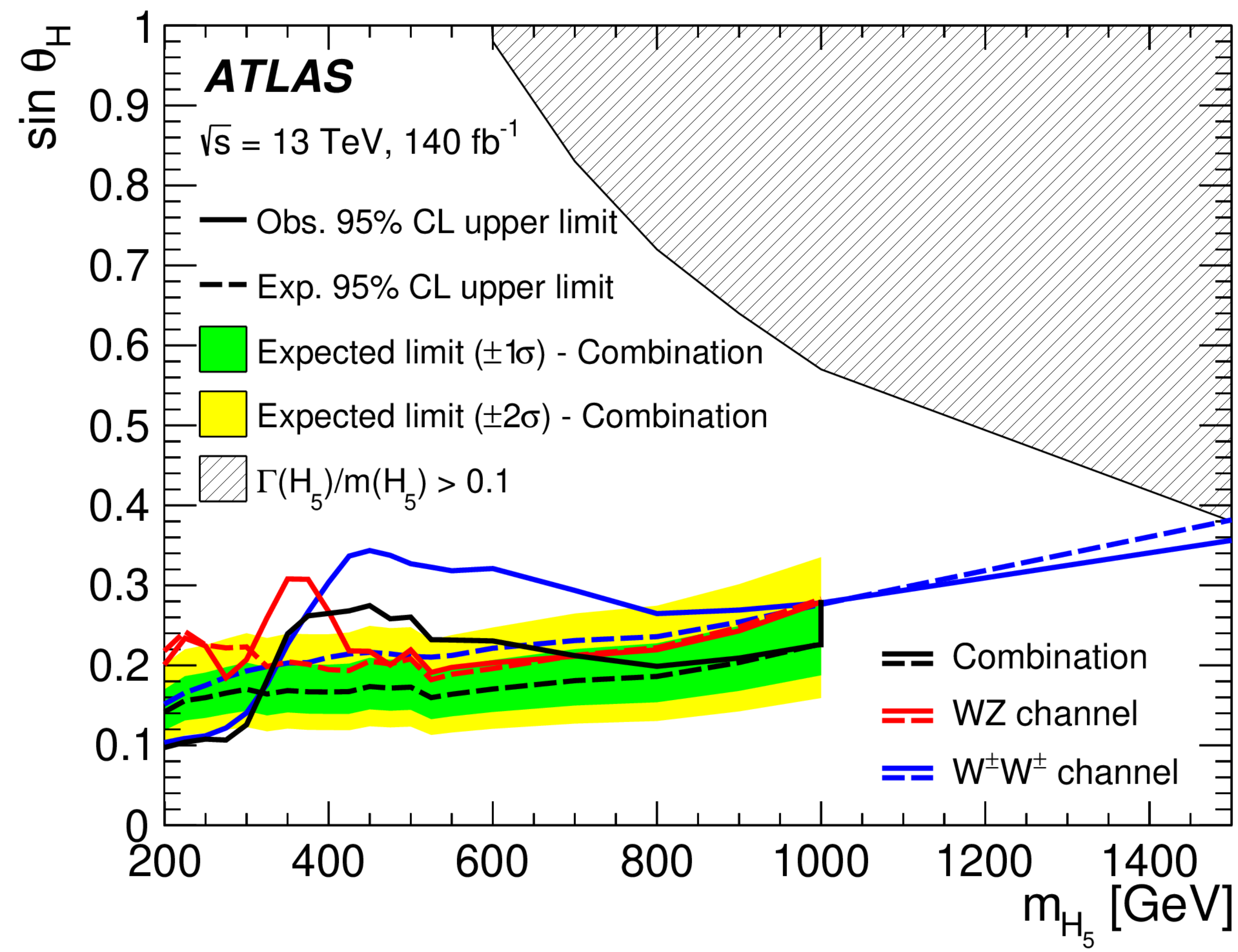


- An excess of 2.8σ local (1.6σ global) significance found at 375GeV

Charged Higgs resonance search

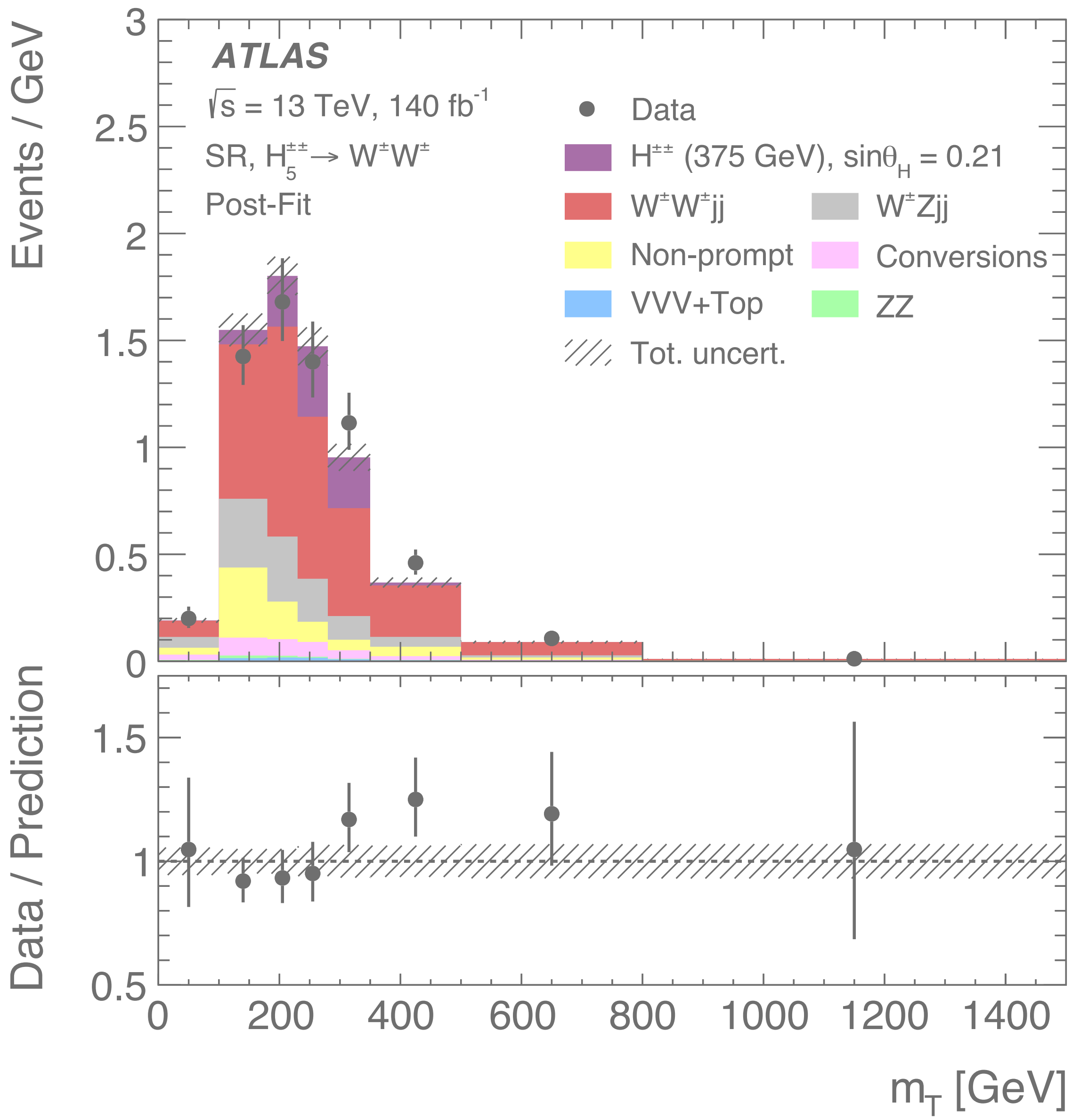


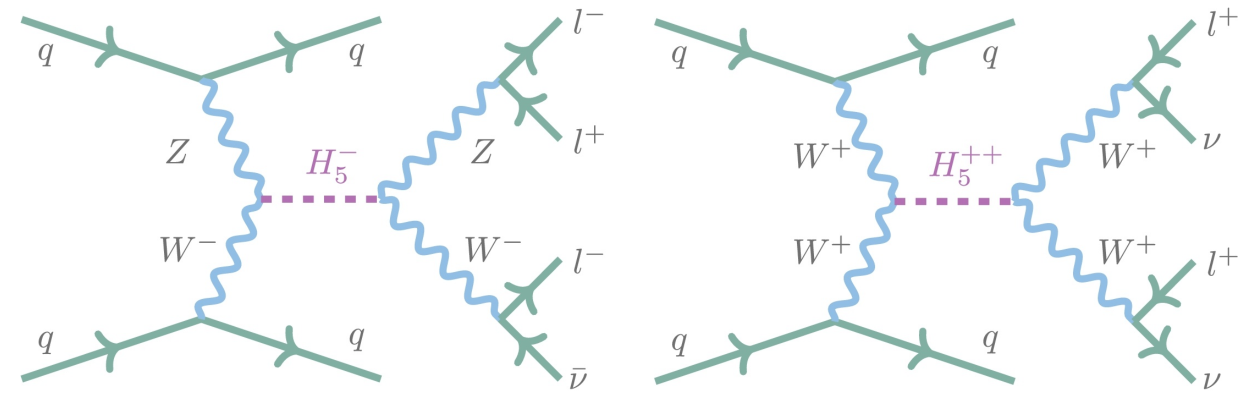


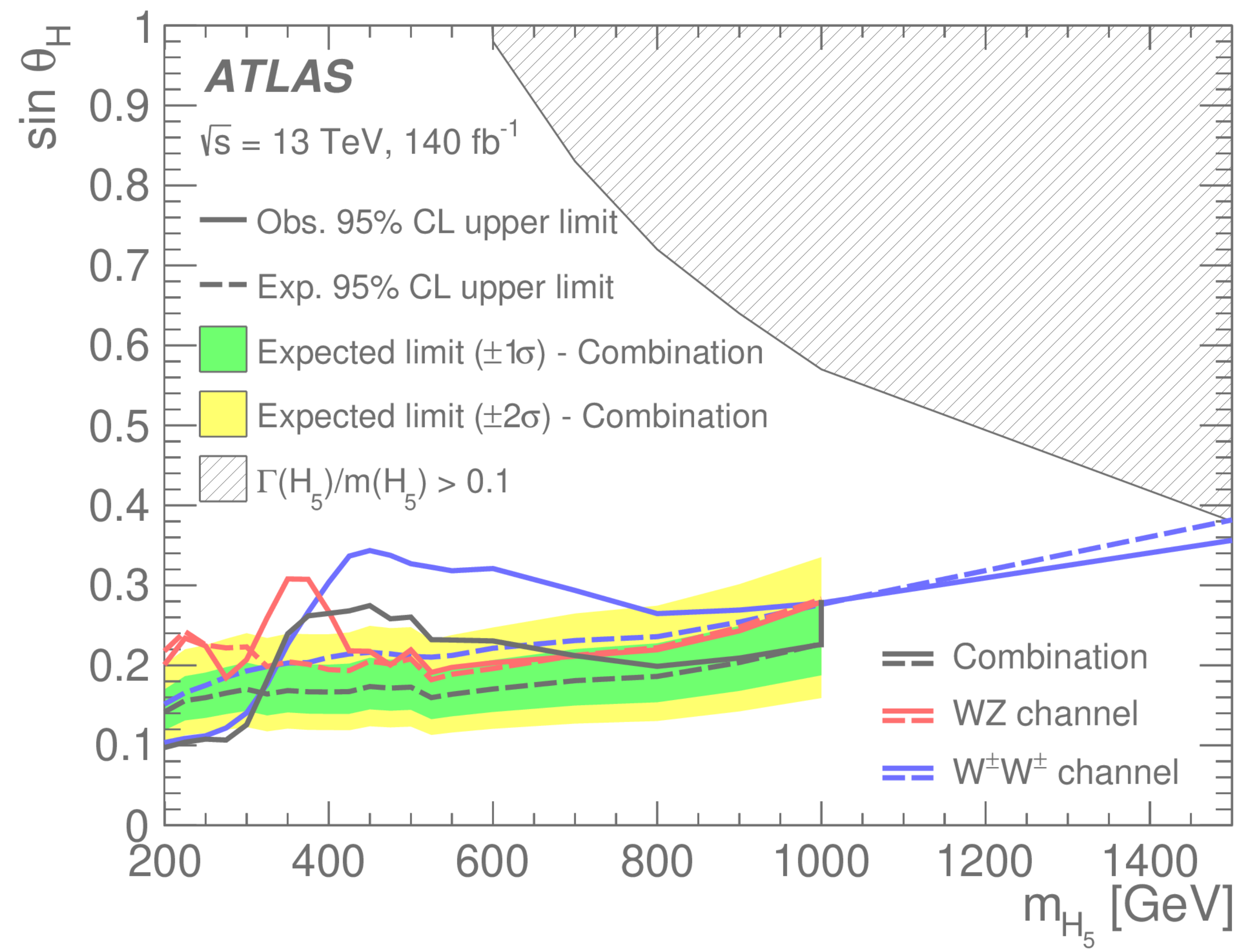


- An excess of 2.5σ global significance was found after combining $WZjj$ and $W^{\pm}W^{\pm}jj$ channels together

Charged Higgs resonance search





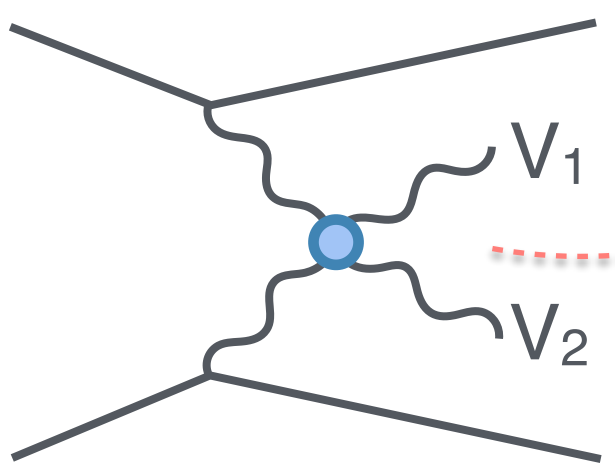


- An excess of 2.5σ global significance found after combining $WZjj$ and $W^{\pm}W^{\pm}jj$ channels together

A small excess to follow up, but so far no clear sign of a new physics….

How to look for the unknown ?

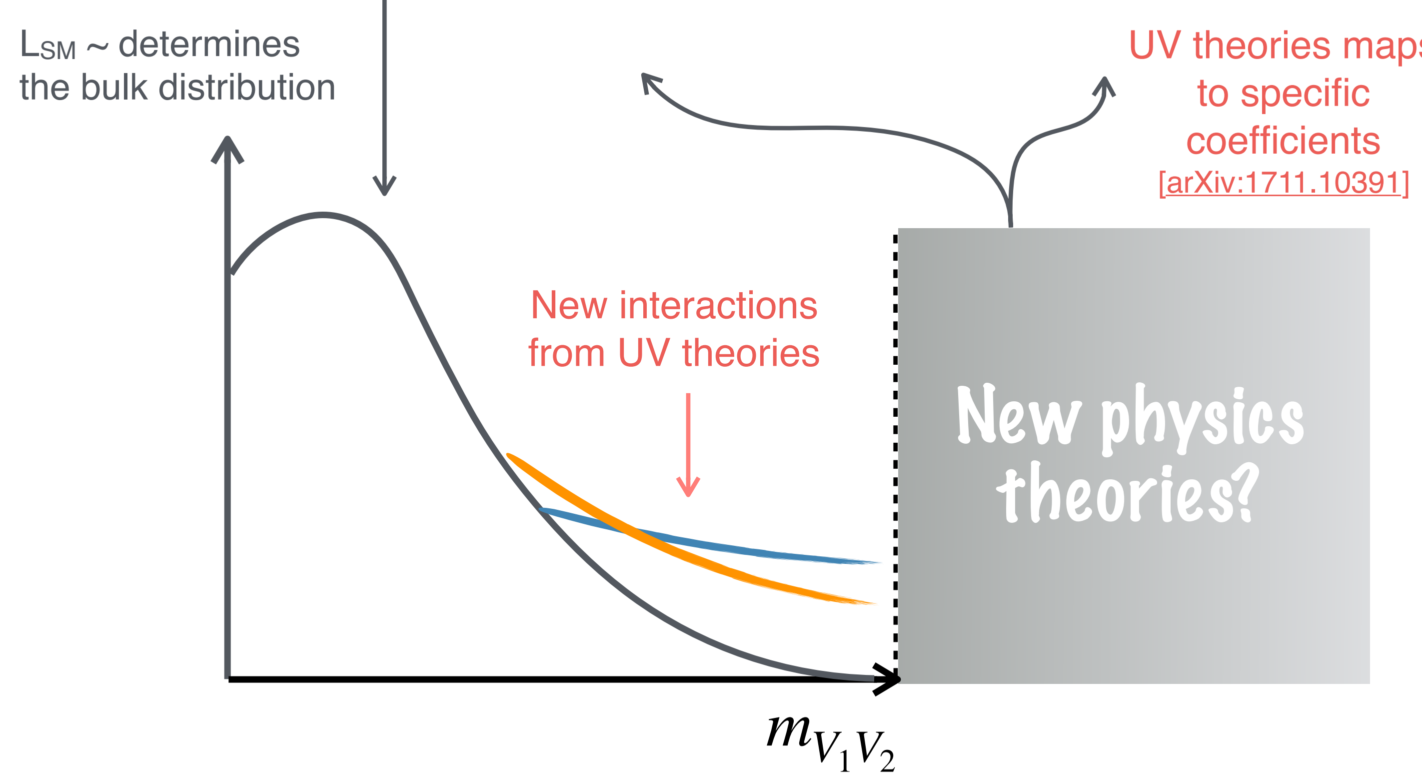
Indirect search approach
(model independent)



Effective Field Theory interpretation
Eboli model

- Extends SM using higher order operators
- Focus on genuine quartic couplings i.e dim-8

$$L_{EFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_{i,dim-6} + \sum_j \frac{c_j}{\Lambda^4} O_{j,dim-8}$$



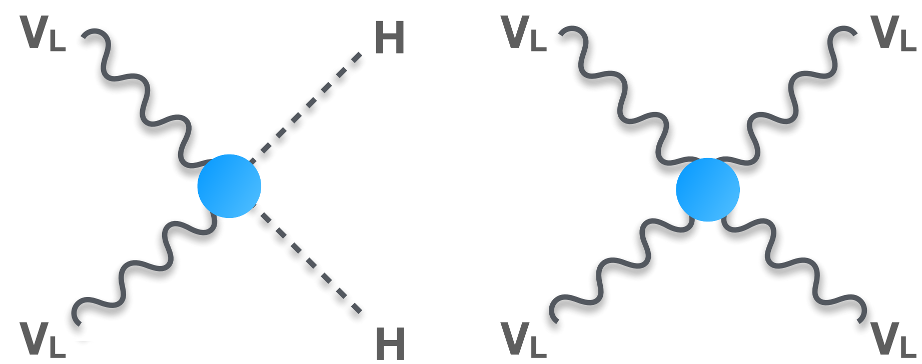
The dim-8 Operators

19 parameters*

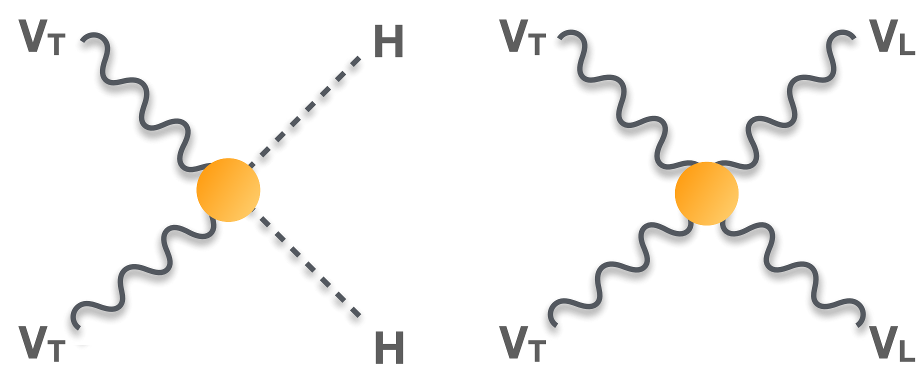
CP	Operator
++	$O_{S,0}, O_{S,1}, O_{S,2}$
	$O_{M,0}, O_{M,1}, O_{M,7}$
	$O_{M,2}, O_{M,3}, O_{M,4}, O_{M,5}$
	$O_{T,0}, O_{T,1}, O_{T,2}$
	$O_{T,5}, O_{T,6}, O_{T,7}$
	$O_{T,8}, O_{T,9}$

* 43 considering CP violating

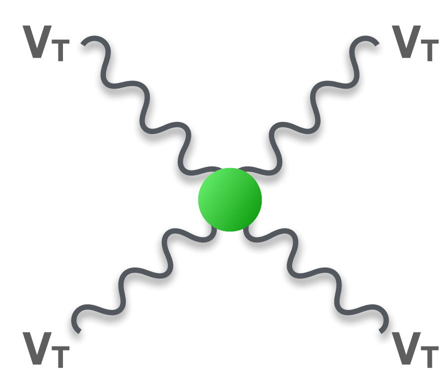
- S-Type: affecting Longitudinal polarised bosons and Higgs



- M-Type: involving Higgs and gauge Fields



- T-Type: involving transversally polarised gauge bosons



S. Todt CERN-THESIS-2022-268

The dim-8 Operators

- Many vertices affected by the same operator

CP	Operator	Vertices												
		$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
++	$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}, \mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
++	$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
++	$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
++	$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
++	$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
++	$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				

Effort so far by the ATLAS and CMS collaborations

First results HH !
A. Tegetmeier, T. Amezza

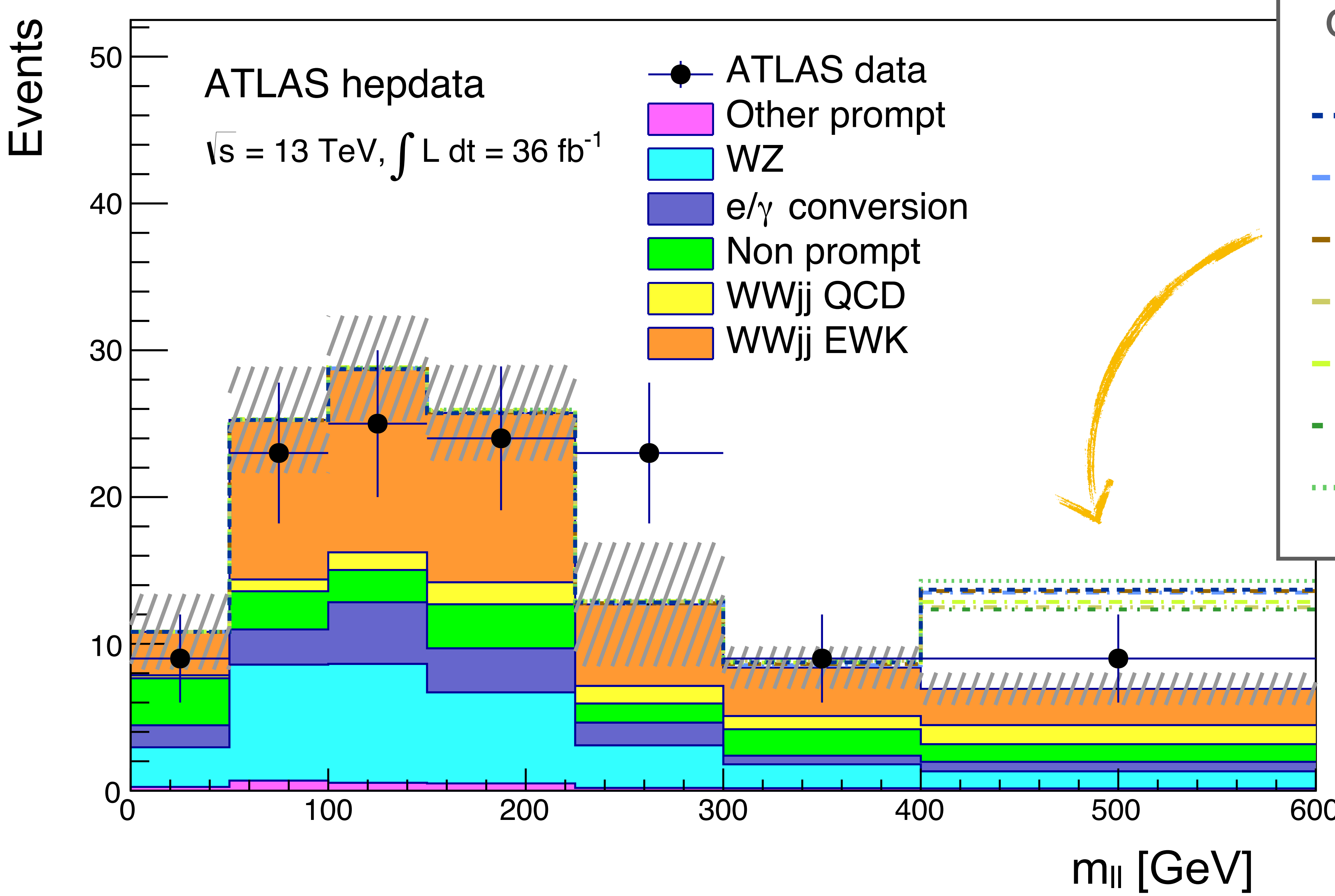
The effect of the EFT operators

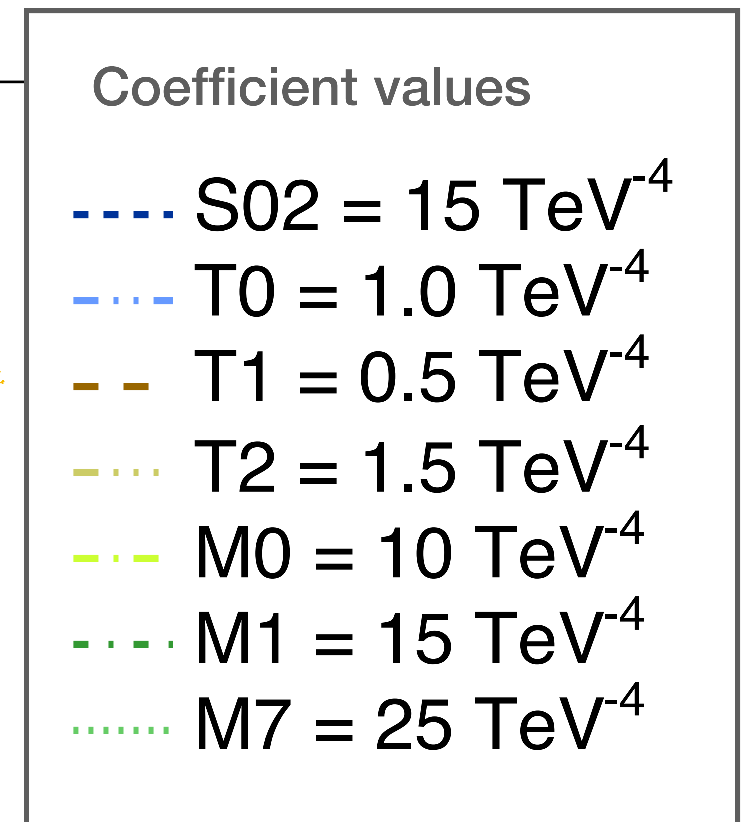
Same Charge W±W±jj

BSM interactions of SM particles

$$L_{EFT} = L_{SM} + F_{T2}\, O_{T2}$$

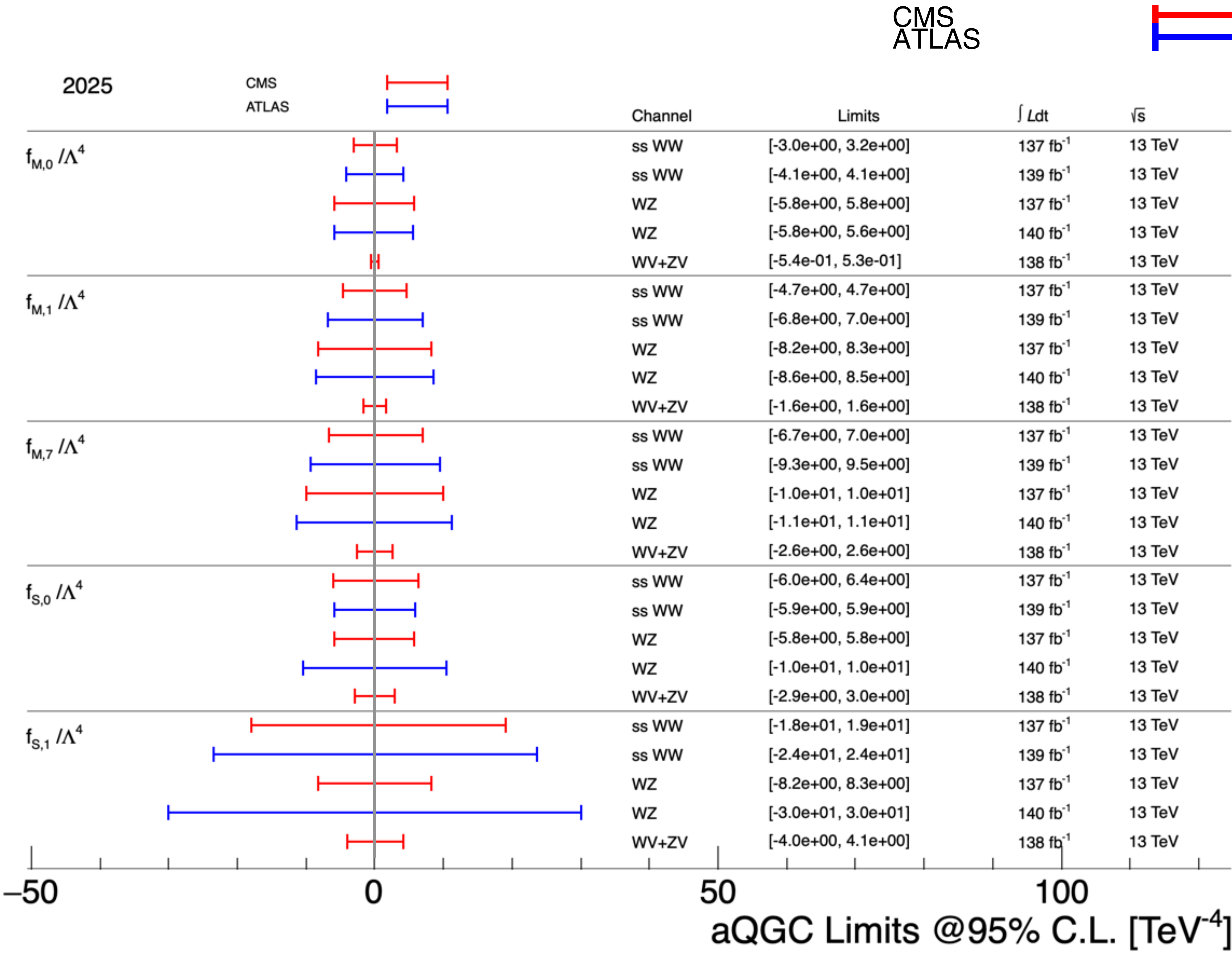
Coefficient





Other channels affected by the same operators, huge possible gain by combination!

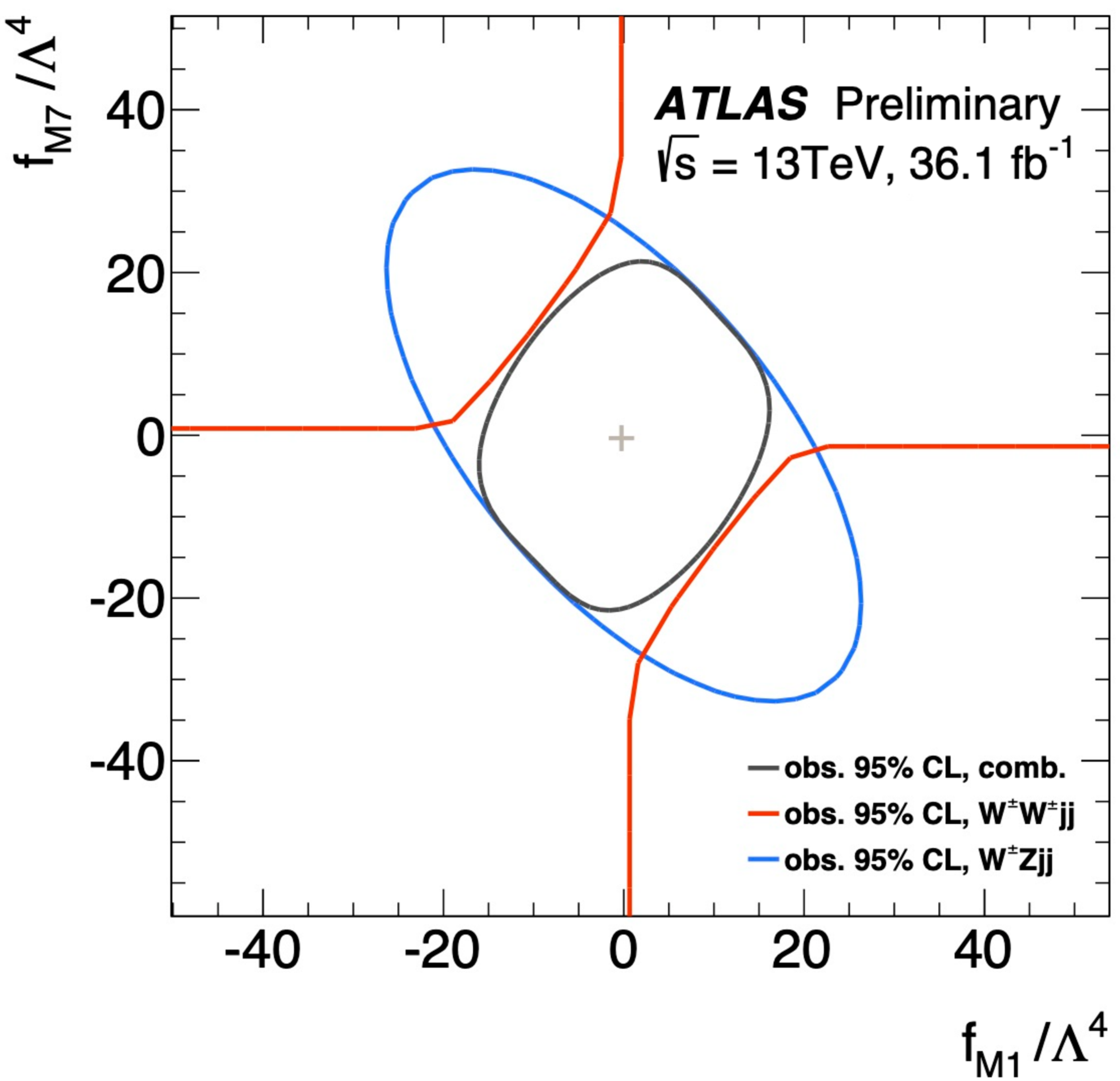
The SM Effective Field Theory

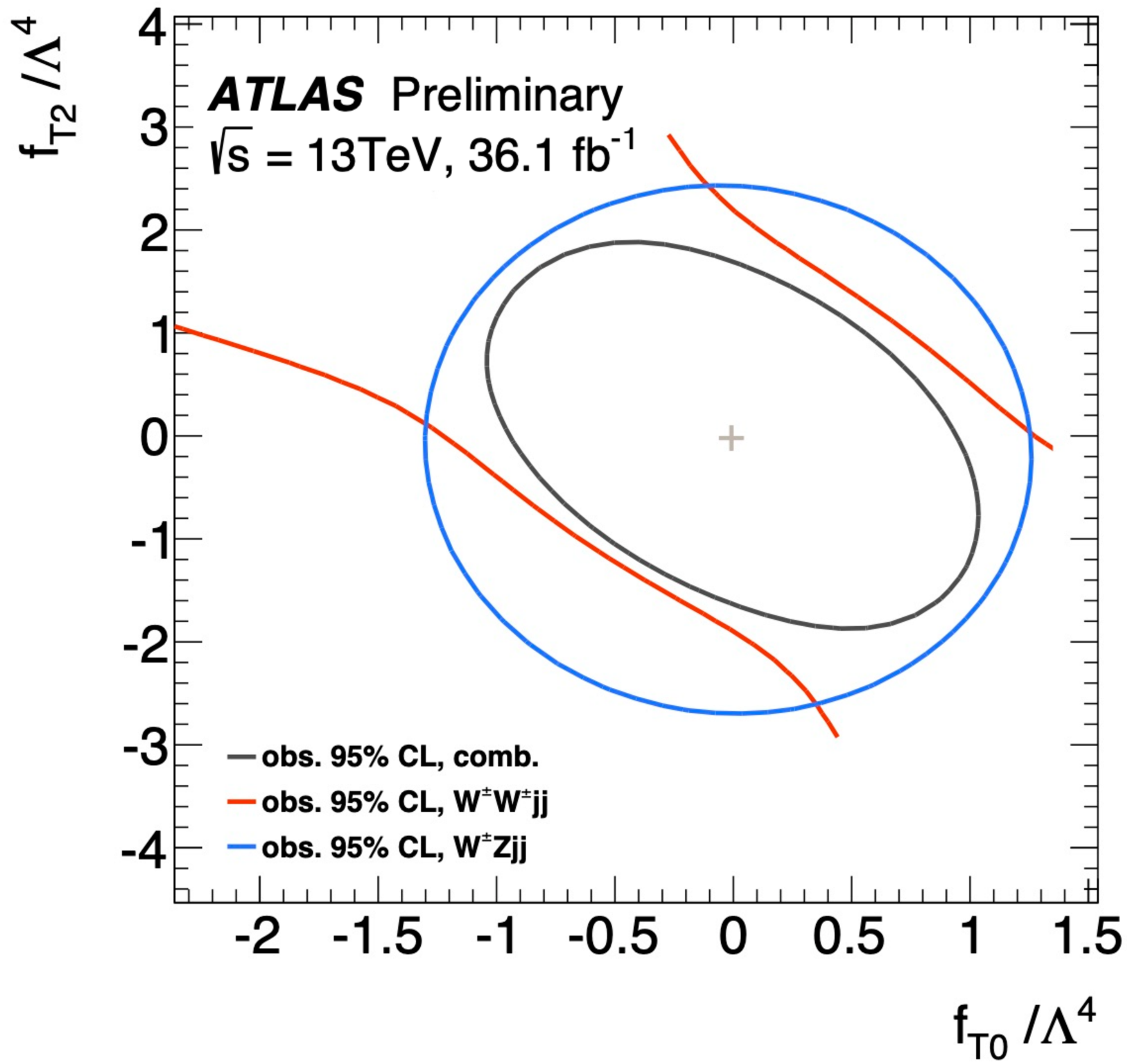


Huge gain by combining channels!

ATL-PHYS-PUB-2023-002

- First combination of dim-8 EFT operators !





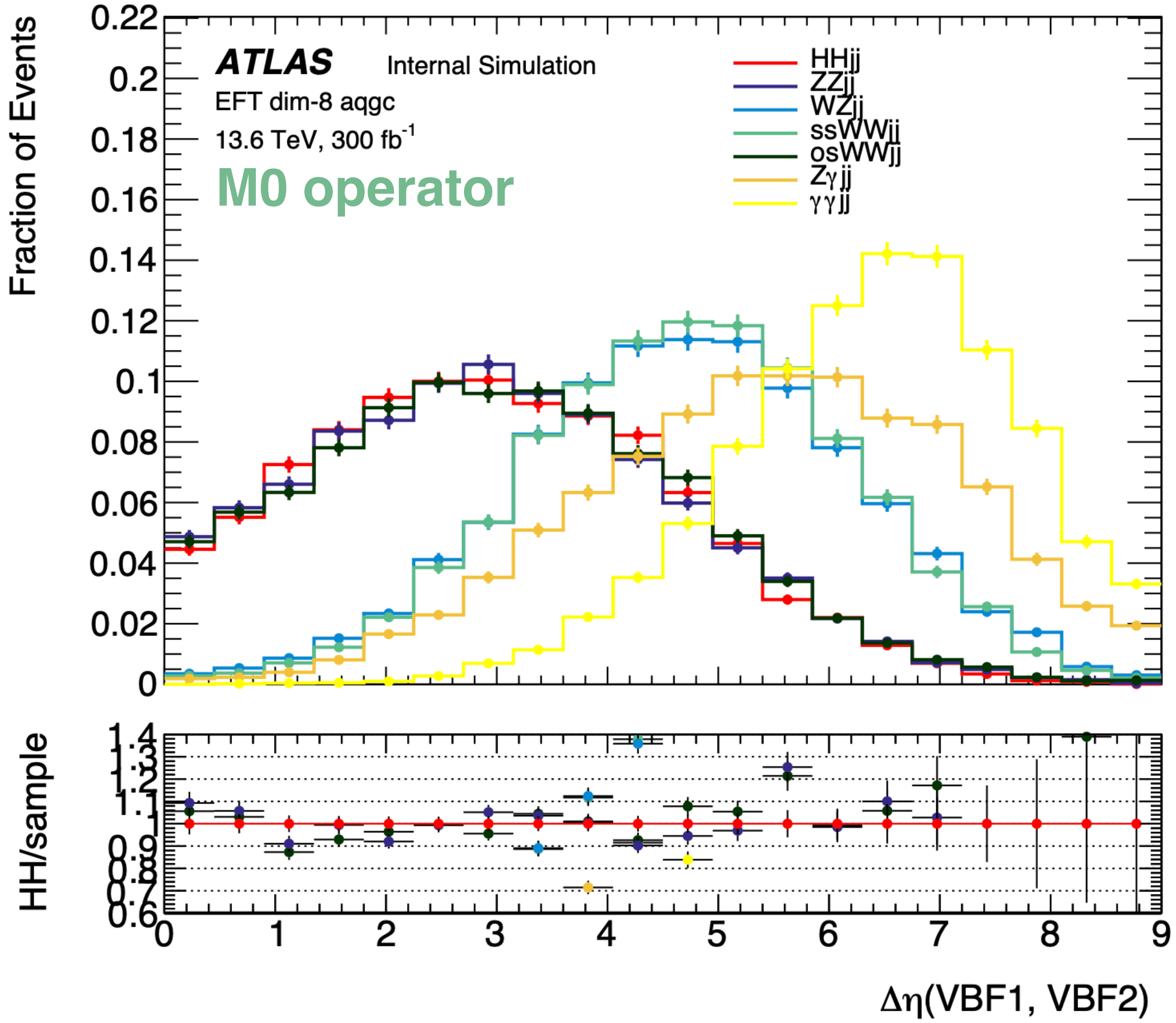
- Ongoing work in preparation for EFT dim-8 recommendations inside ATLAS

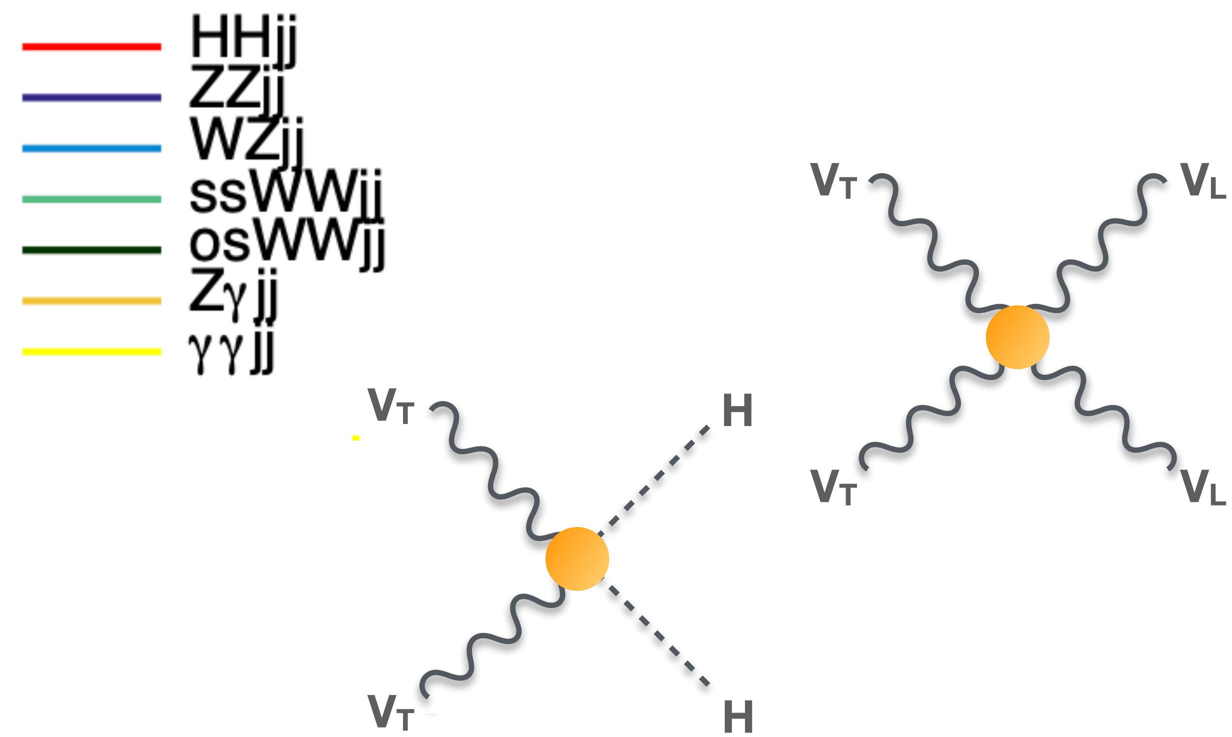
so far there is no clear sign of a new physics.... But many ideas to test !

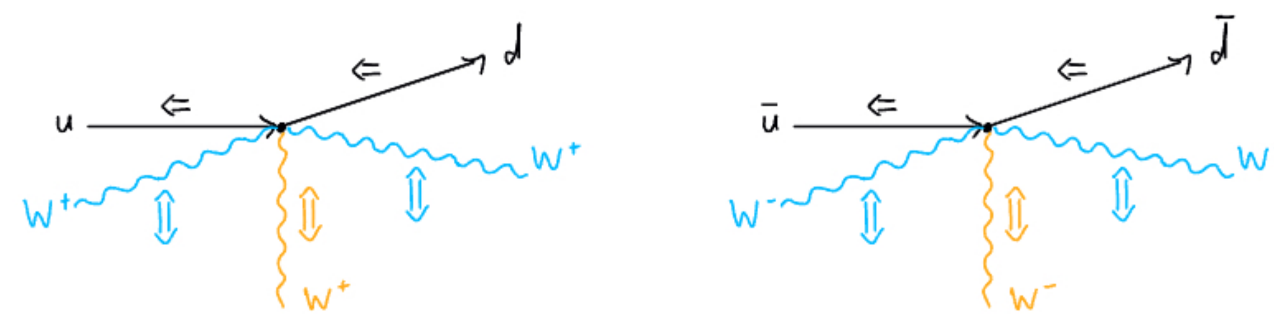
Polarised EFT dim-8

A. Tegetmeier PhD

- There is correspondence between each operator, the vertices it modifies, and its polarization.







Our current understanding

- The link between polarization and EFT still needs to be explored further, especially in the context of future analyses.

1. Challenge the SM

Quartic Bosons interactions ✓

Longitudinal polarised bosons interactions ✓

2. Look for New physics

New resonances ✓

Deviations on SM predictions ✓

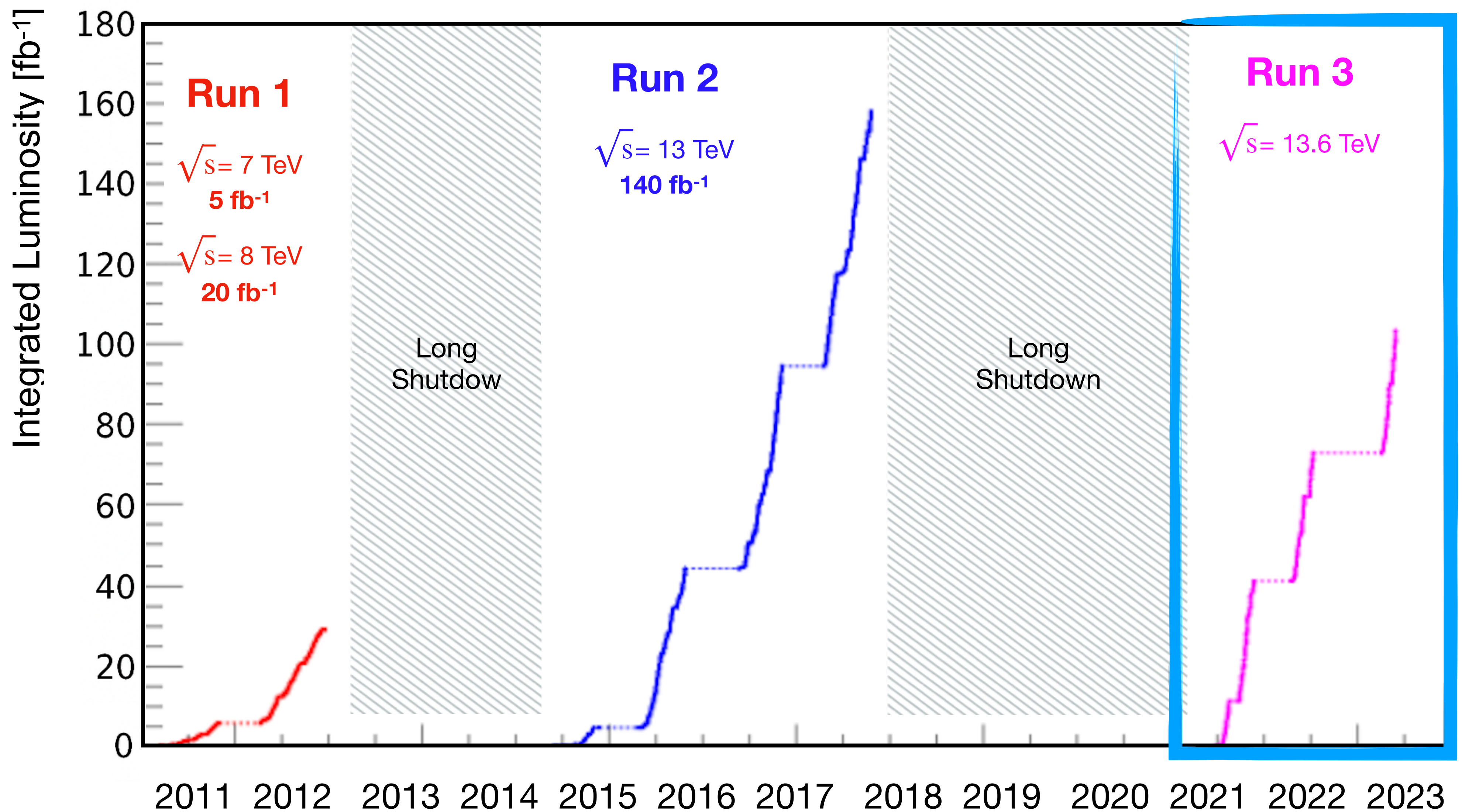
3. What is next?

Di-Higgs ○

Quartic gauge Higgs couplings ○

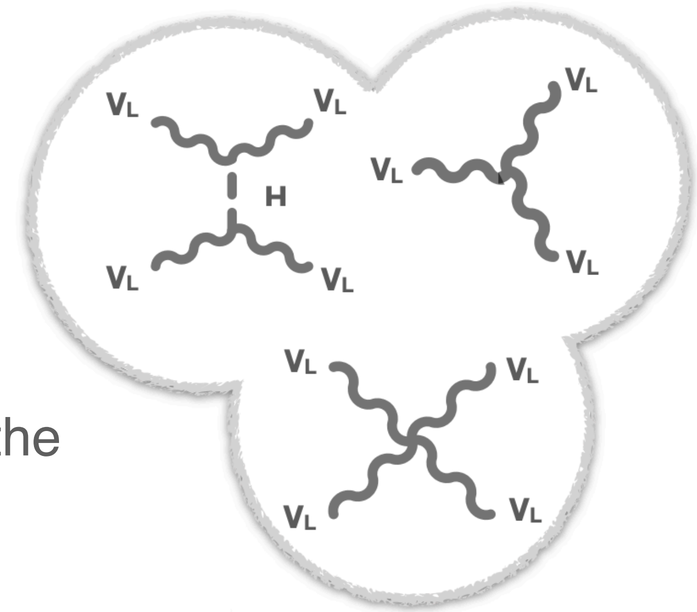
Polarised EFT ○

Outlook : More data



- Run 3 already has delivered 220 fb^{-1} of data, we might triple the Run-2 dataset by July 2026
- HL-LHC expected to deliver ~ 3000 fb^{-1} by 2041

Projection studies

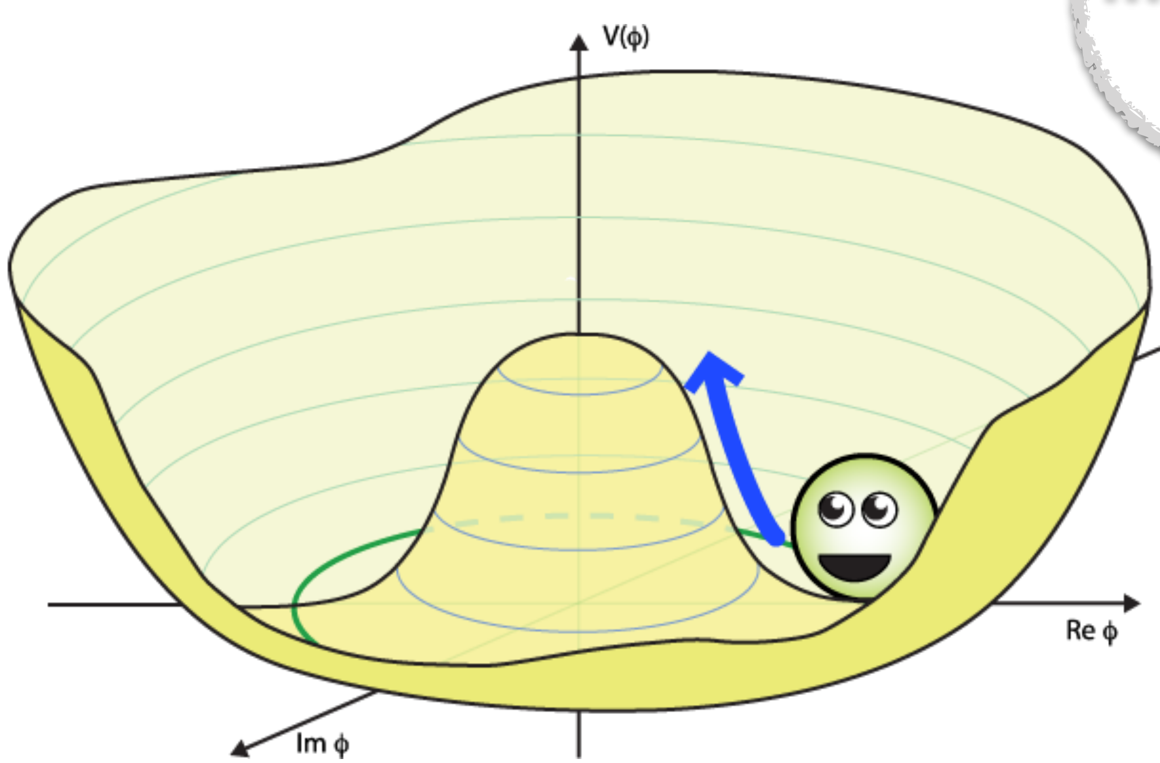


Polarisation

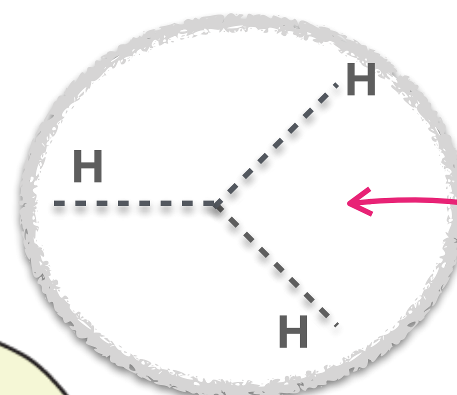
- Run-3 will probably confirm interactions $V_LV_LV_L$
- Double longitudinal interactions will probably have to wait for the HL-LHC statistics

Di-Higgs

- Crucial to describe the shape of the Higgs potential



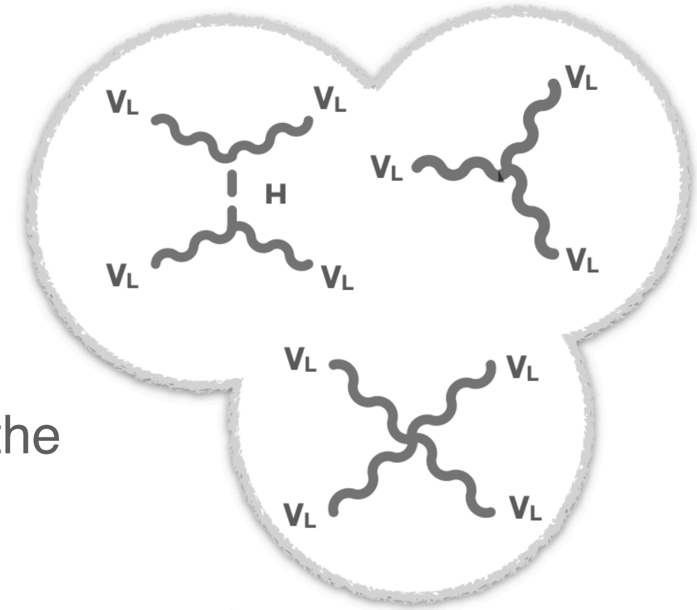
Di-Higgs



Direct access to λ_{HHH}

$$V(h) \simeq \frac{1}{2} m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$$

Projection studies

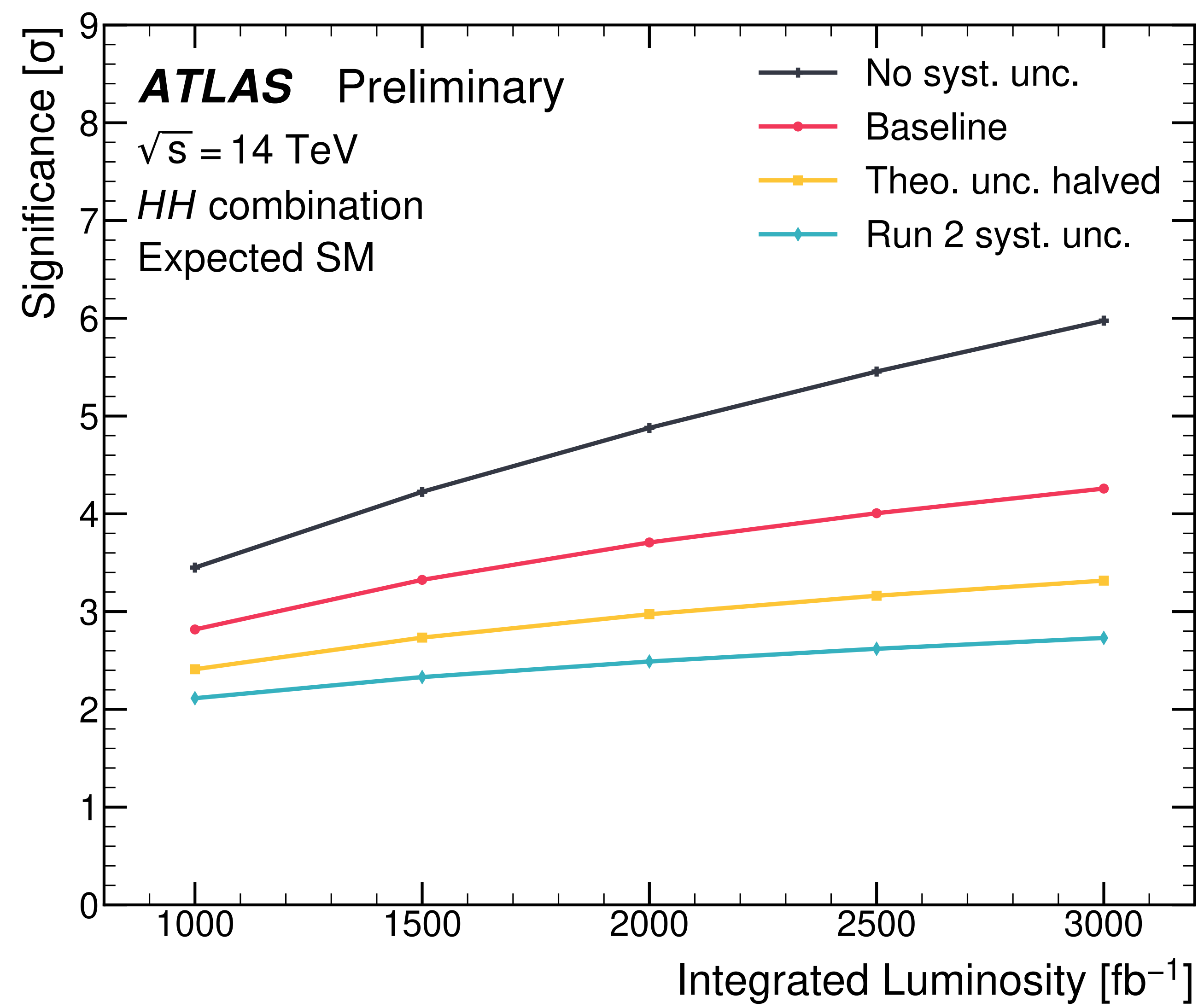


Polarisation

- Run-3 will probably confirm interactions $V_L V_L V_L$
- Double longitudinal interactions will probably have to wait for the HL-LHC

Di-Higgs

- Crucial to describe the shape of the Higgs potential
- HH signal significance of 4.5 per experiment, above 7 after ATLAS+CMS combination.
- Imagine what we can do in 20 years!

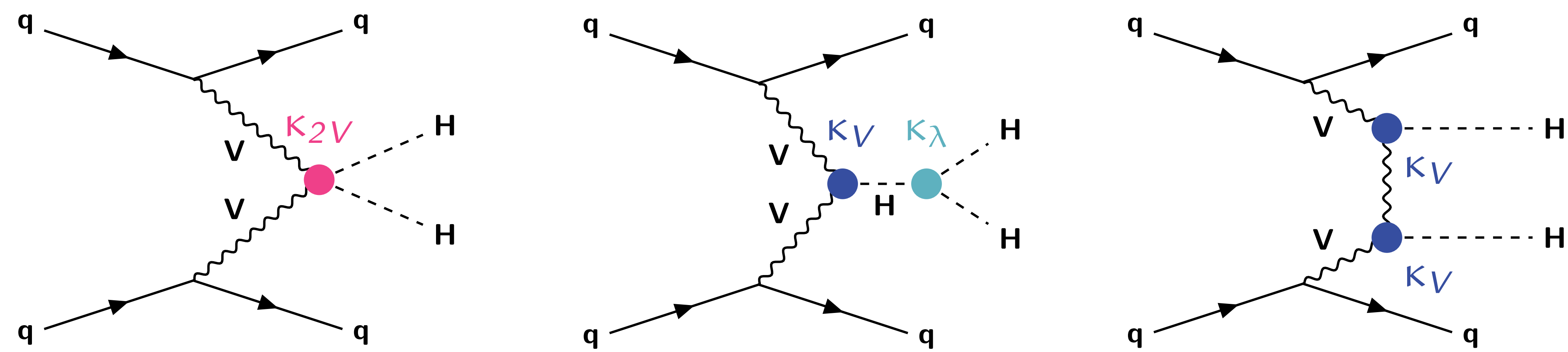


Outlook new analyses

- Look for rare processes with even smaller cross sections

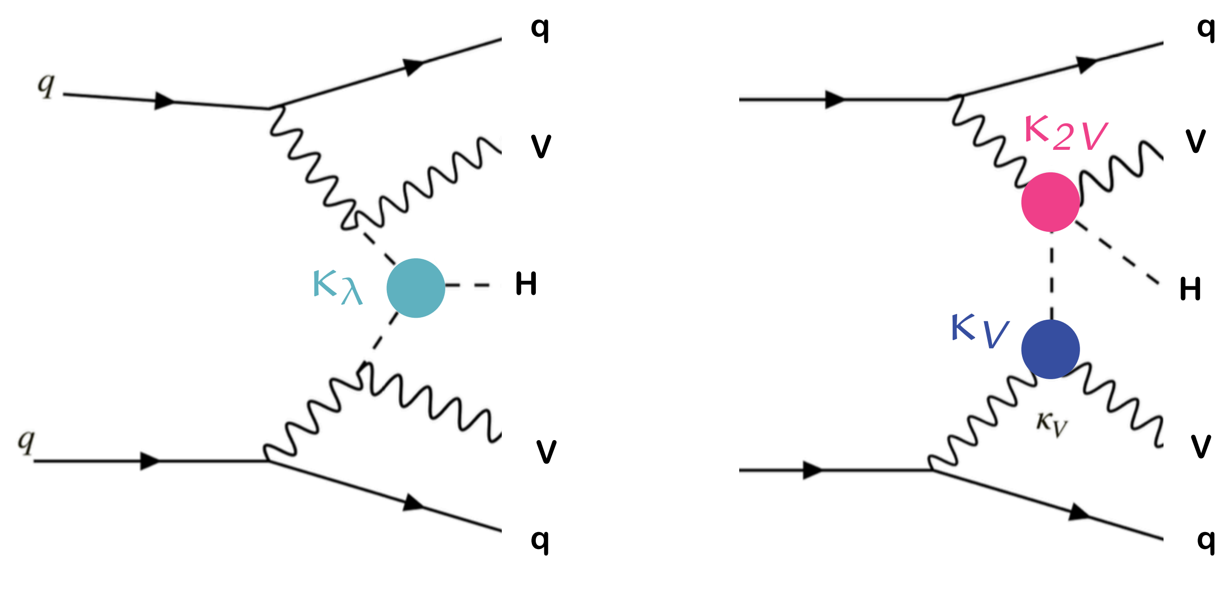
VBF di-Higgs

A. Tegetmeier
T. Amezza
S. Zhang



VBS Higgs

A. Martone



New in ATLAS !

Analysis in preparation, first sensitivity studies made by our group

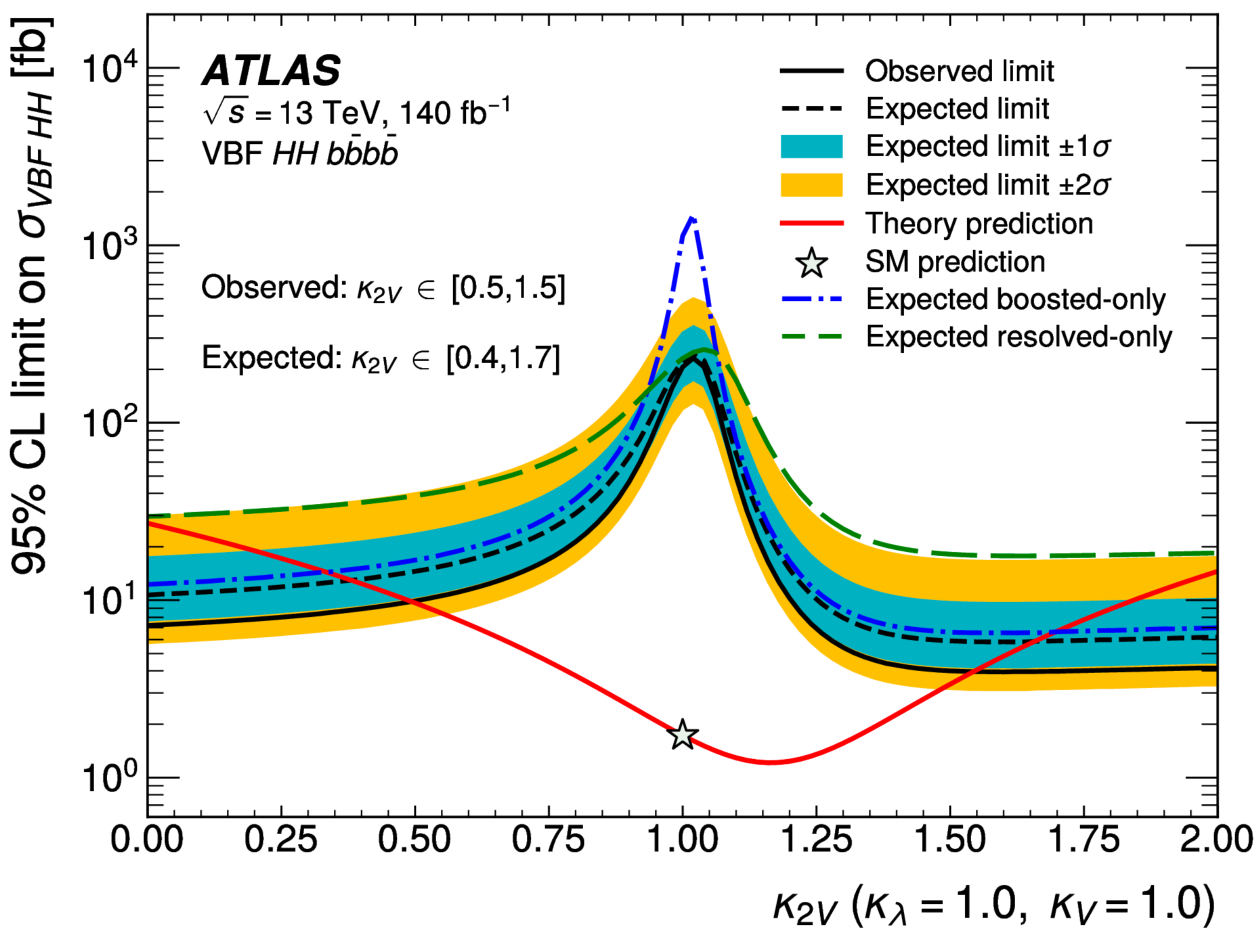
[CERN-THESIS-2024-105]
[ANA-HMBS-2024-57]

Quartic Gauge Higgs Couplings

- First ATLAS studies show excellent sensitivity!

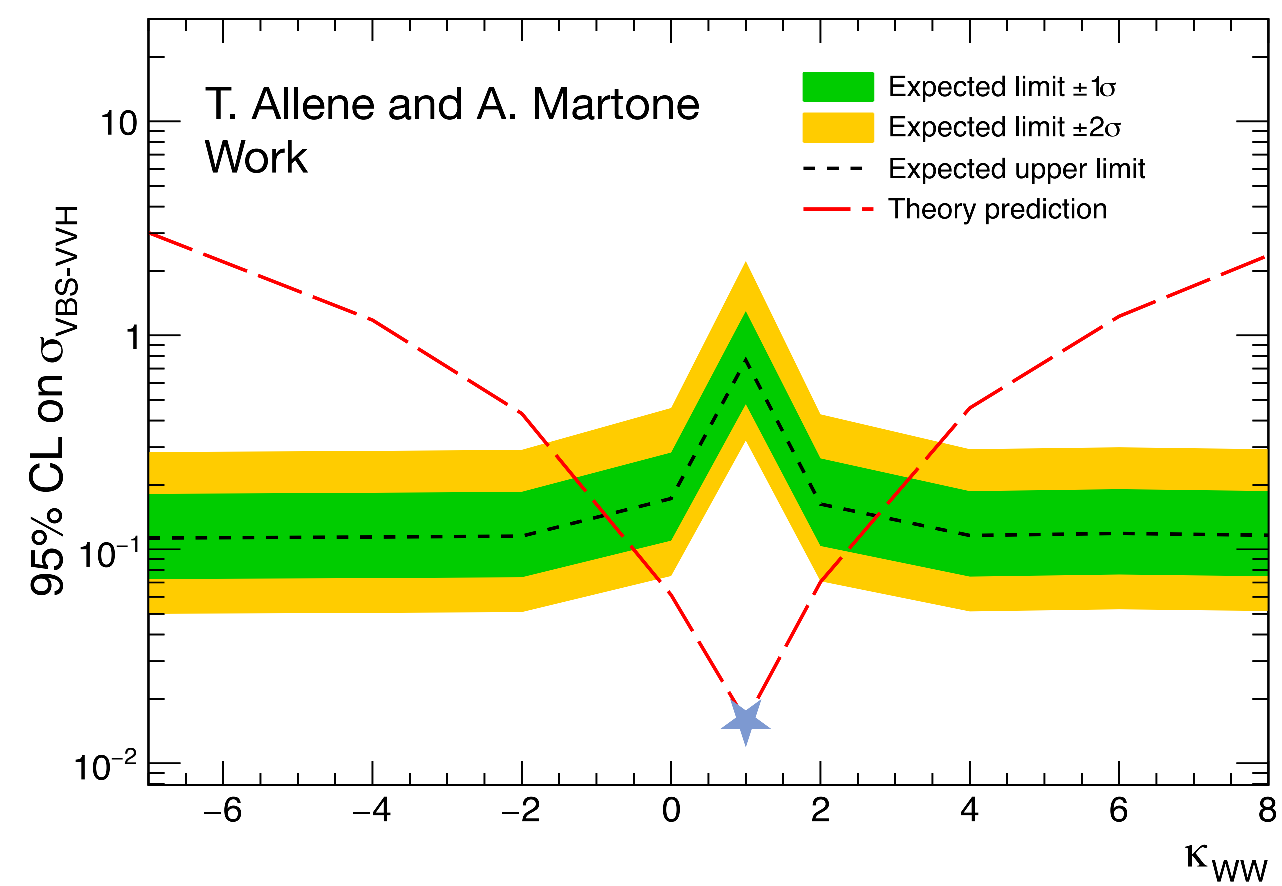
VBF di-Higgs

$\kappa_{2V} \in$ [0.4, 1.7]



VBS $W^\pm W^\pm h \to l\nu l\nu bb$

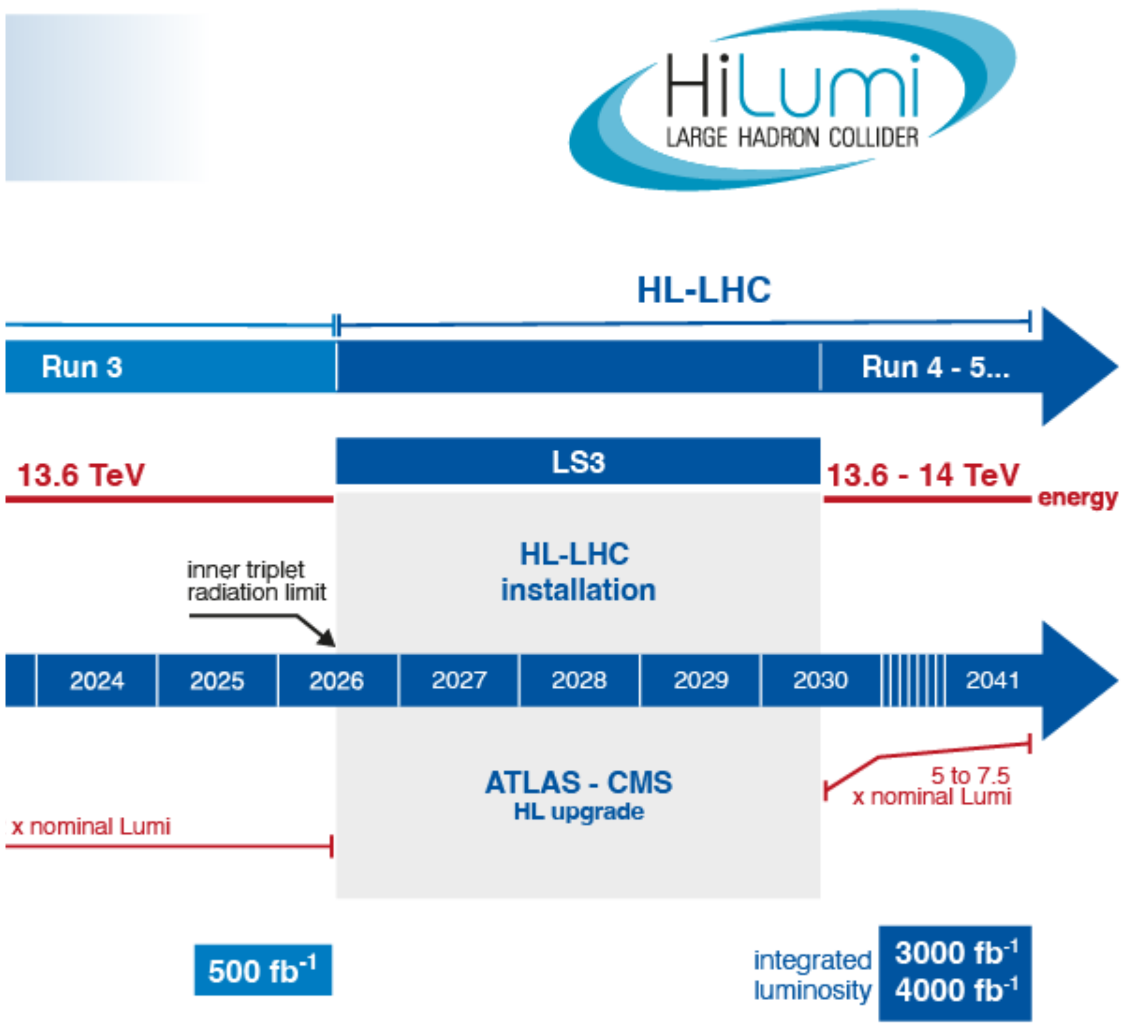
$\kappa_{2V} \in$ [-1.0, 2.7]

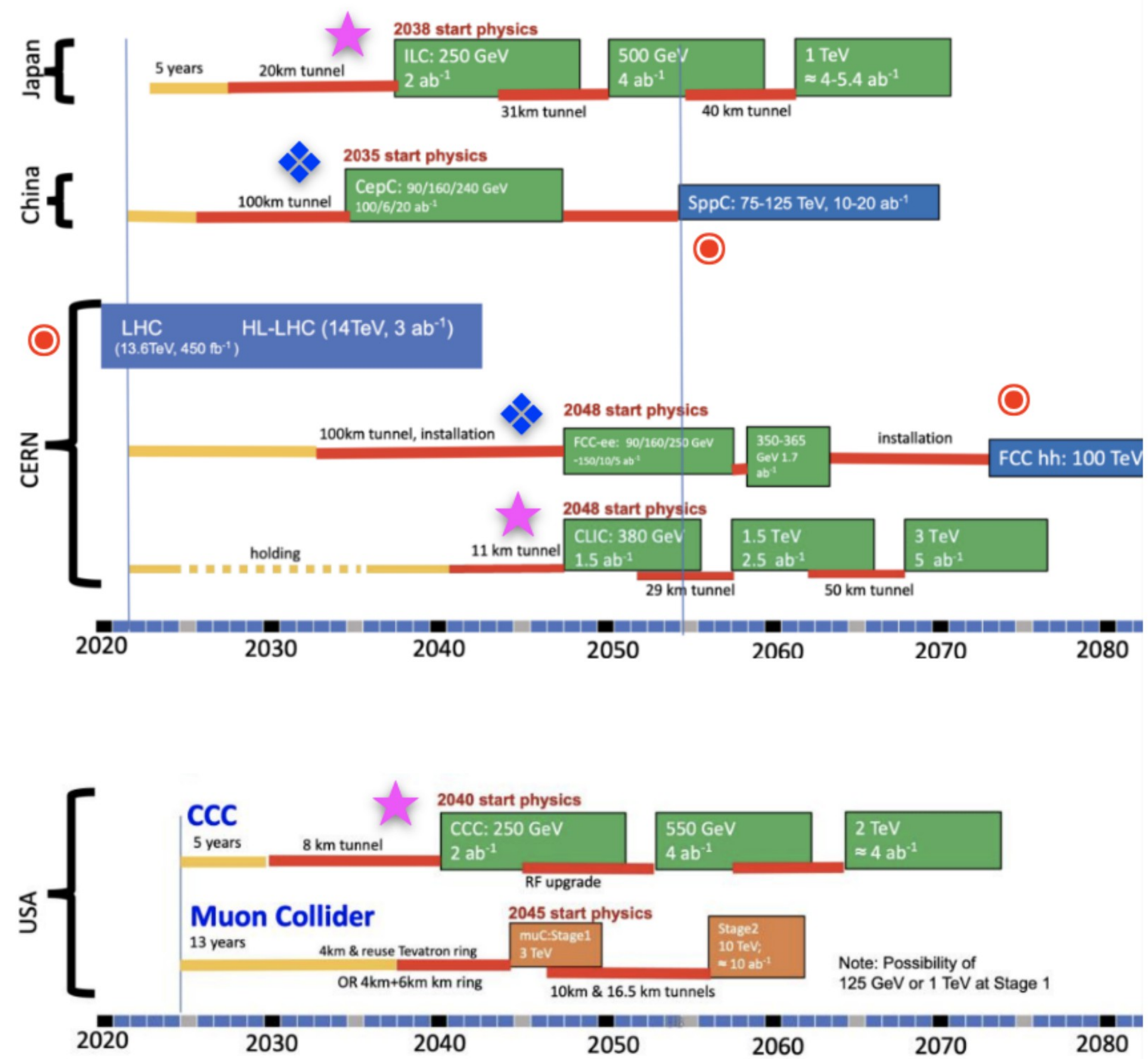


- CMS just presented in EPS this results using more decay channels with κ_{2V} observed (expected) range **[0.40, 1.60]** ([0.34, 1.66]) → best result on κ_{2V} !

Even further ahead

★ linear e+e-
❖ circular e+e-
◉ circular hh





And an amazing group of people