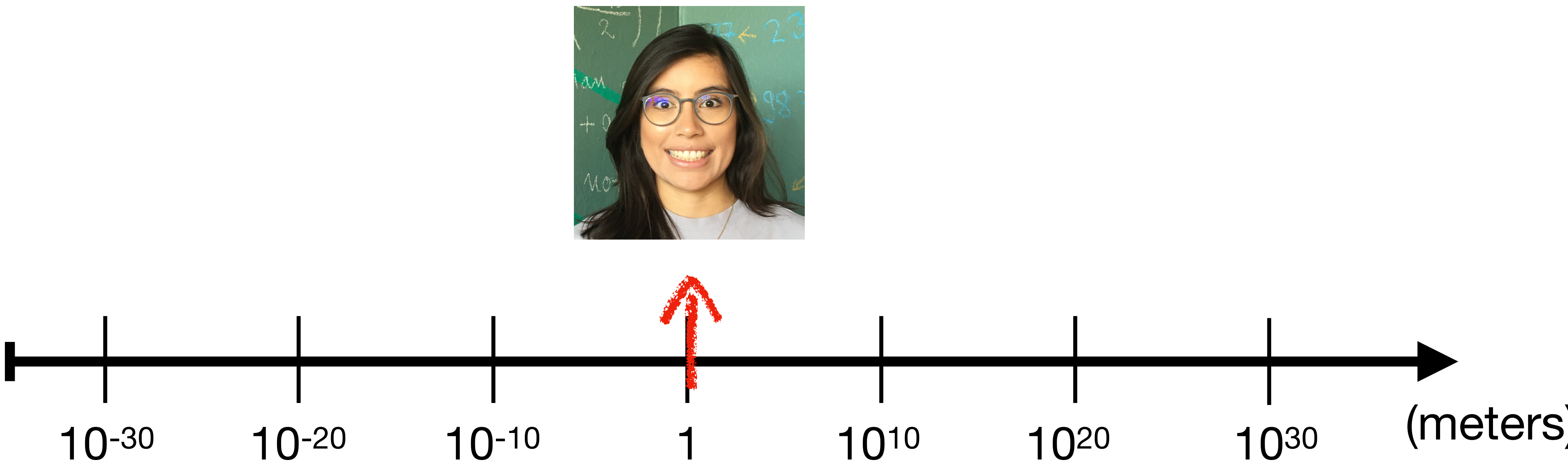
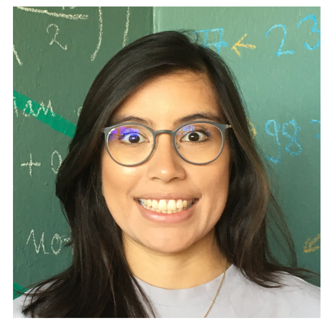
Modèle standard : Comprendre l'univers avec l'aide des bosons

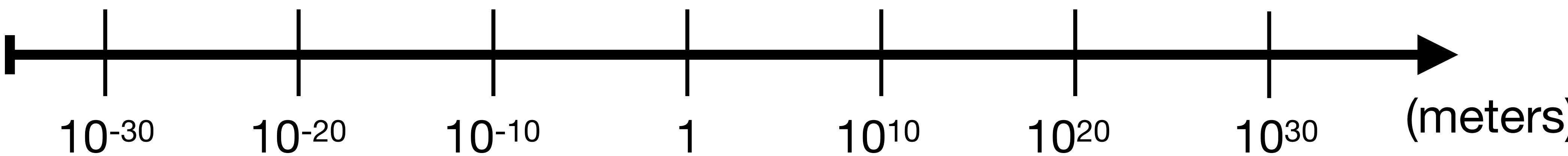
21 Octobre 2022

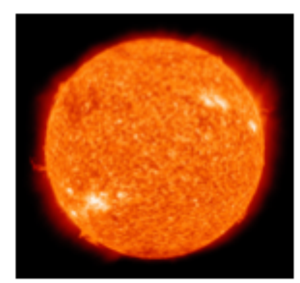
A reference point



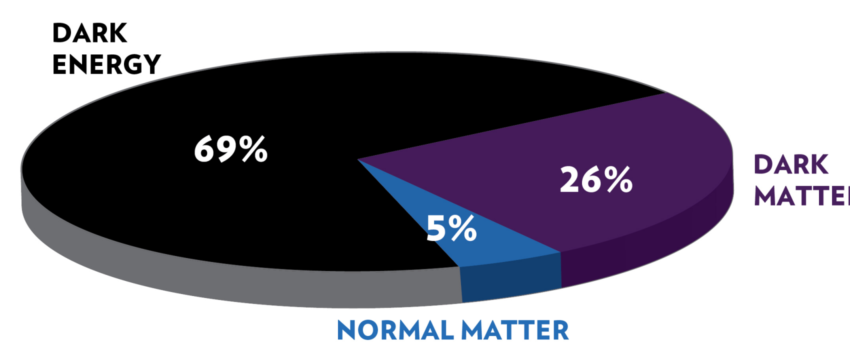
Zooming out



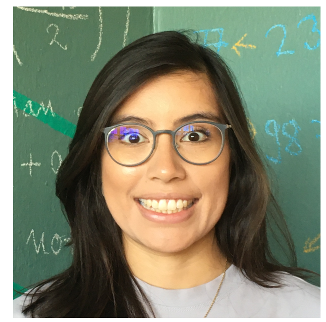


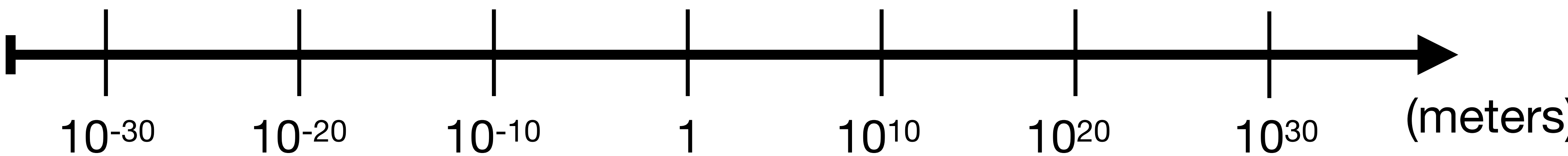


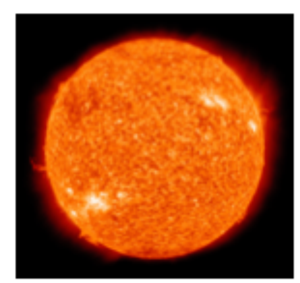
ENERGY DISTRIBUTION
OF THE UNIVERSE

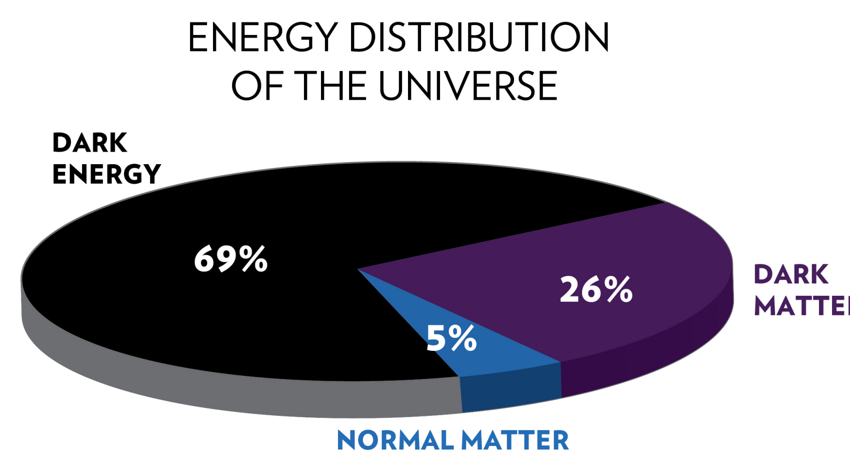


Zooming out





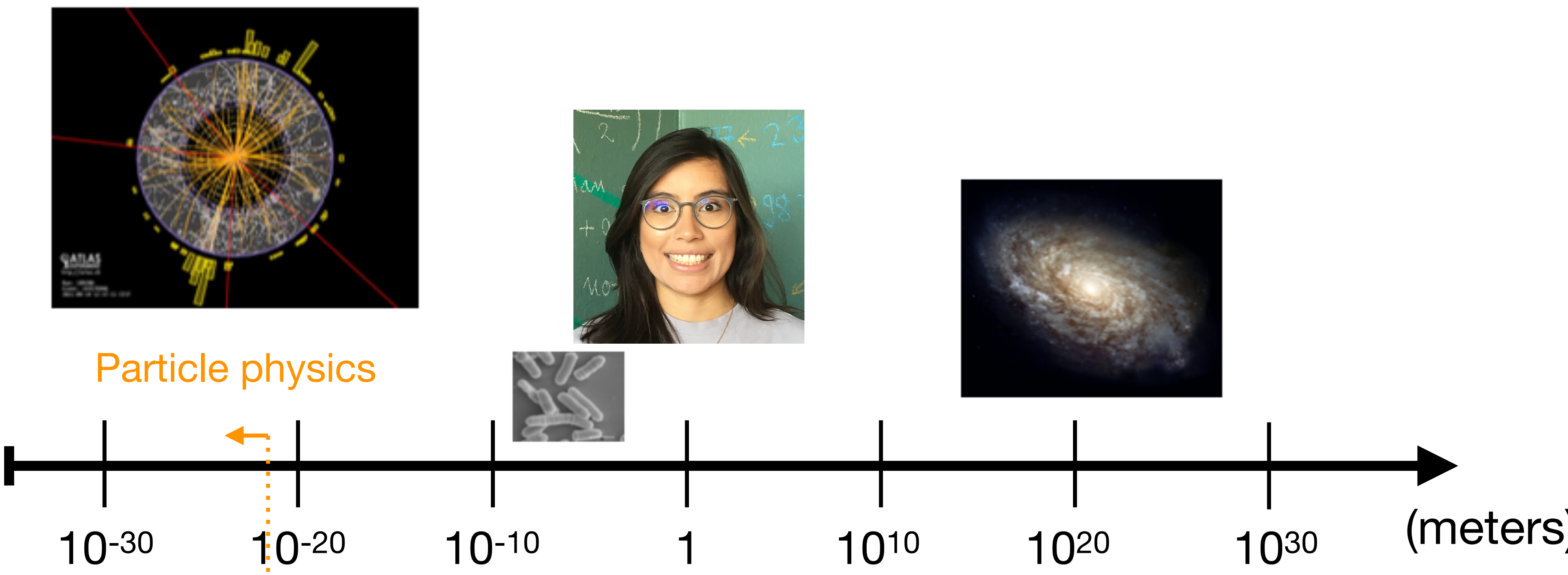


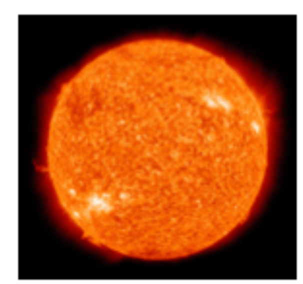


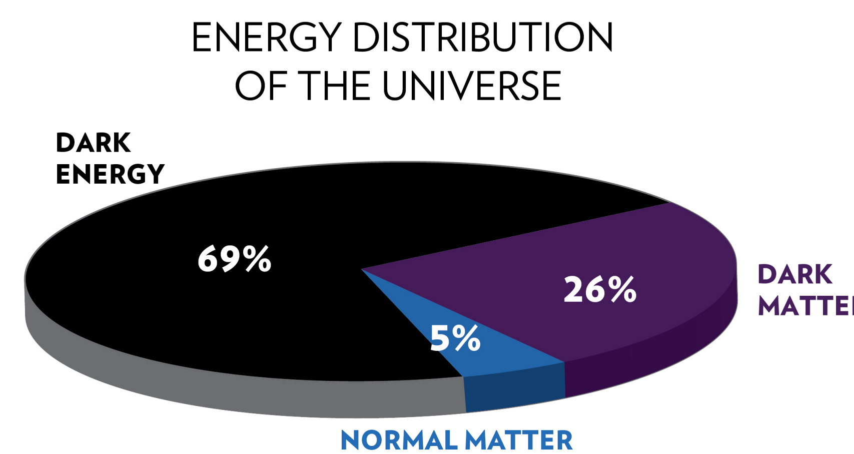
know unknown

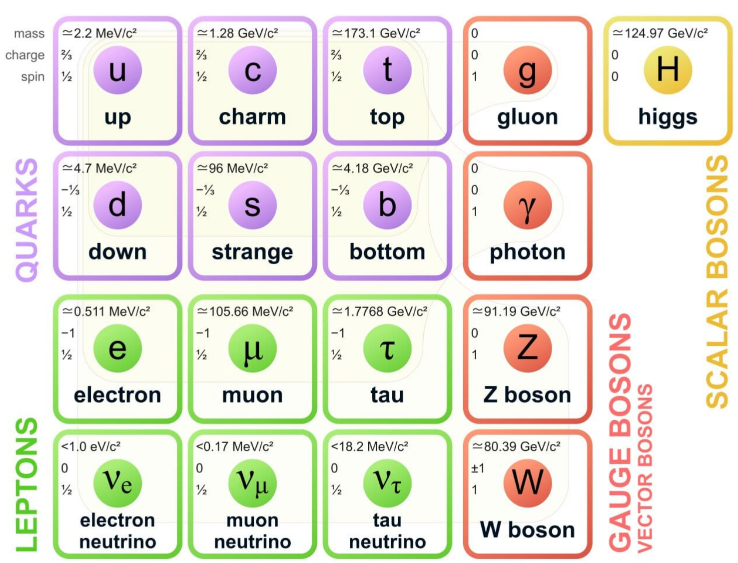
(Dark matter, dark energy, CP asymmetry)

Zooming in





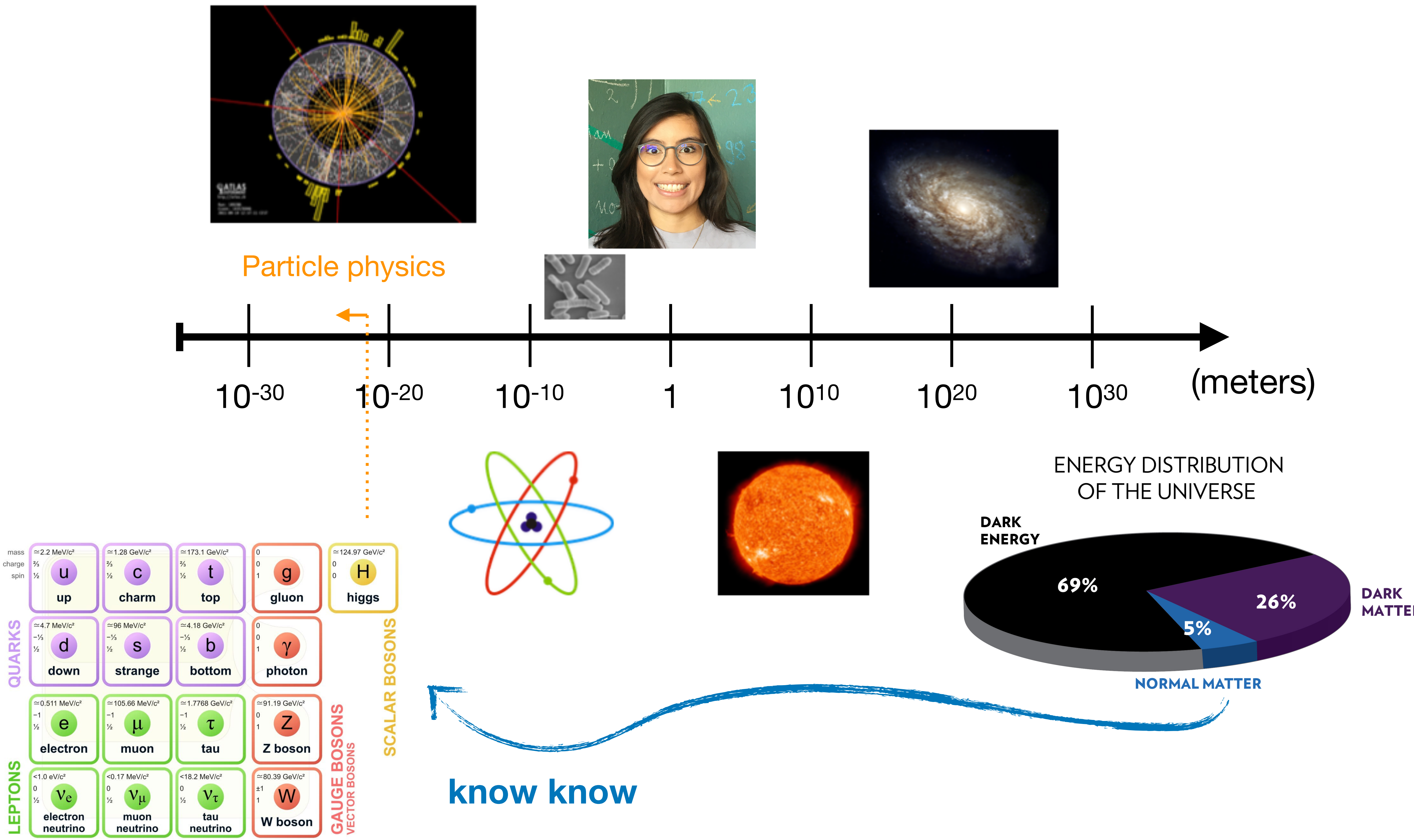




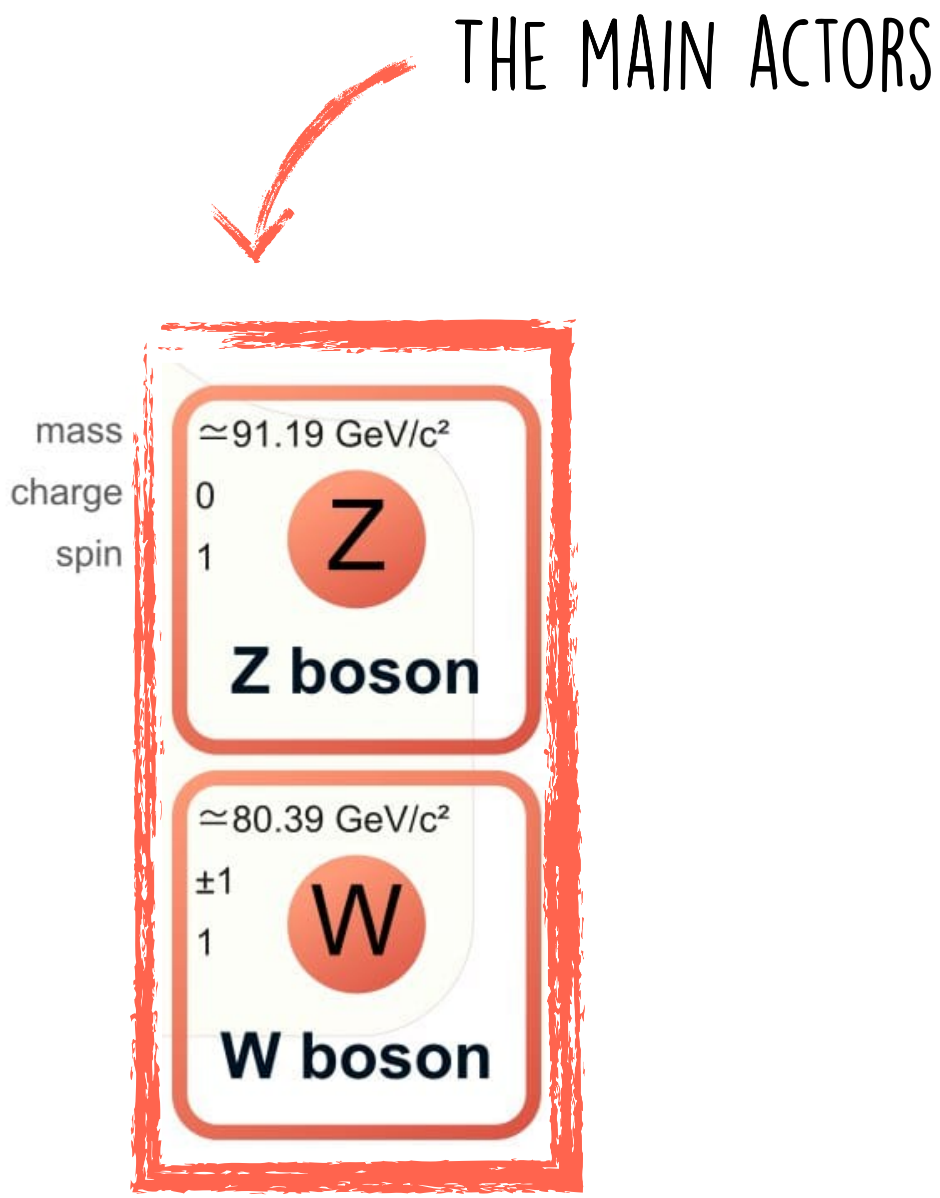
know unknown

(Dark matter, dark energy, CP asymmetry)

Zooming in


Particle physics
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
10^{30}
(meters)
mass
charge
spin
u up
c charm
t top
g gluon
H higgs
d down
s strange
b bottom
γ photon
e electron
μ muon
τ tau
Z boson
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS
ENERGY DISTRIBUTION OF THE UNIVERSE
DARK ENERGY
69%
26%
DARK MATTER
5%
NORMAL MATTER
know know

In this talk



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

The Large Hadron Collider ring:

Matrix of knowledge*

know know *things we know we know* The Standard Model	**know unknown** *things we know we don’t know* Dark matter, dark energy, CP asymmetry, quantum gravity, muon g-2 anomaly
unknown know *things we think we know* Higher order calculations	**unknown unknown** *things we don't know we don't know* Surprises!

* Rumsfeld’s Matrix of Knowledge

Matrix of knowledge*

MY WORK

know know
things we know we know

The Standard Model

know unknown
things we know we don't know

Dark matter, dark energy, CP asymmetry, quantum gravity

unknown know
things we think we know

Higher order calculations

unknown unknown
things we don't know we don't know

Surprises!

MY WORK

* Rumsfeld's Matrix of Knowledge

How well do we know Standard Model?

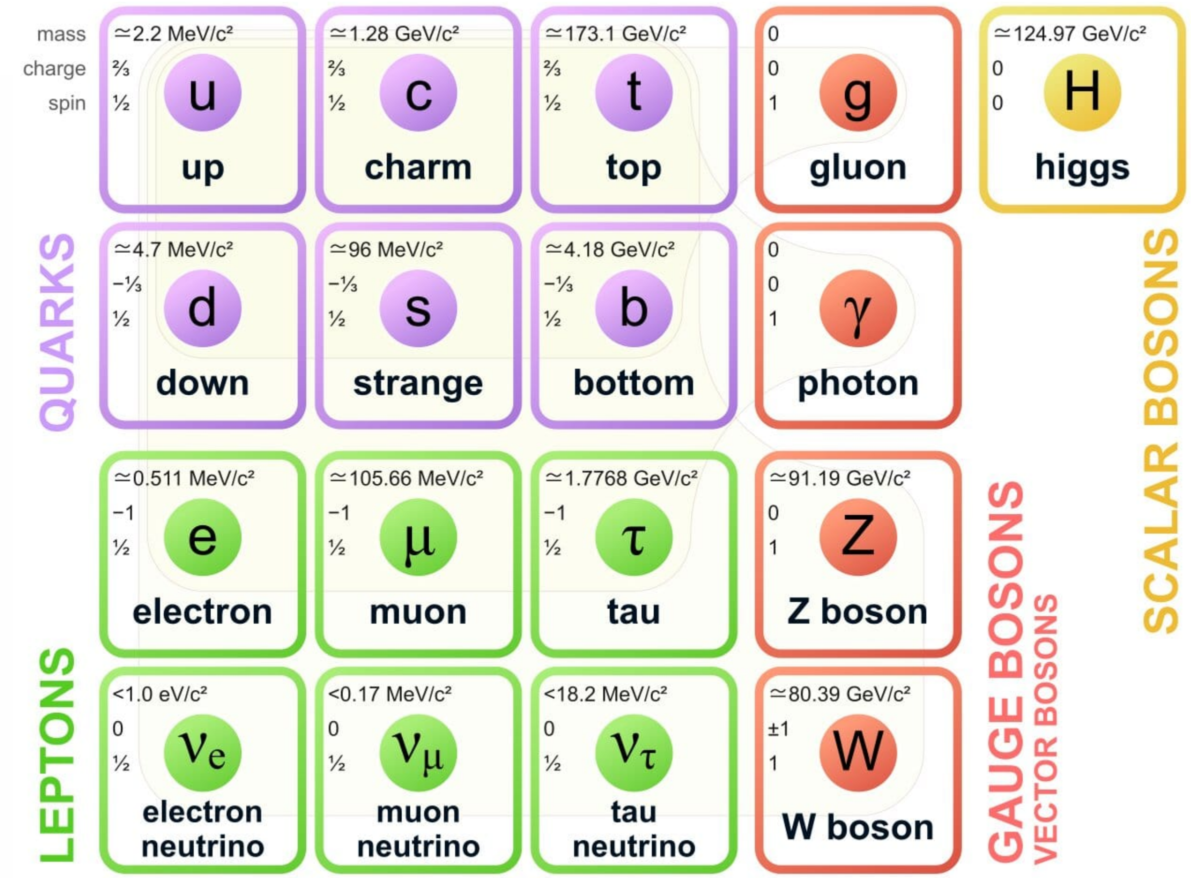
The Standard Model of particle physics

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

The Standard Model predicts

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

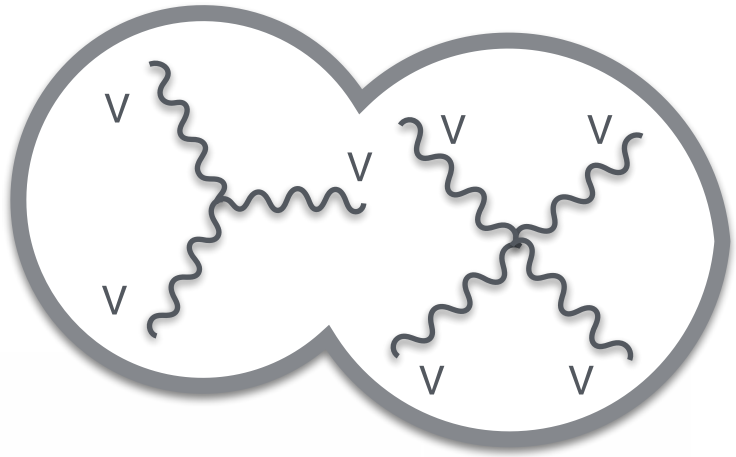
- Particle content



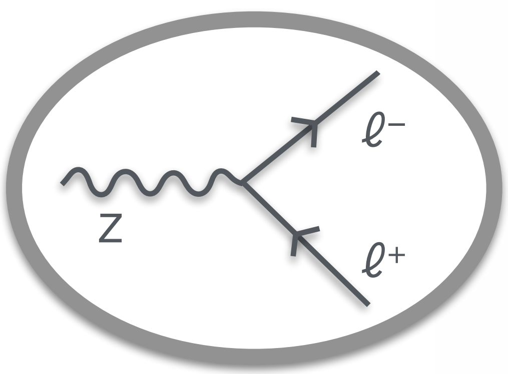
The Higgs boson observed 10 years ago!

DO WE KNOW KNOW IT ALL?

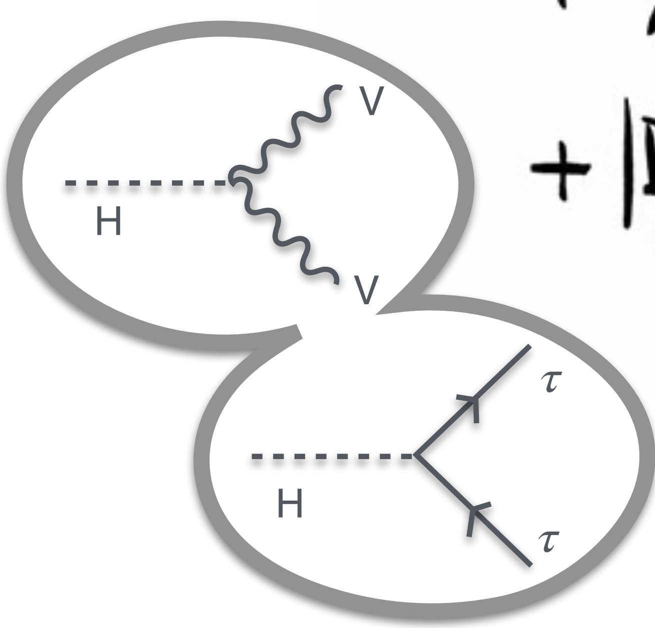
The Standard Model predicts

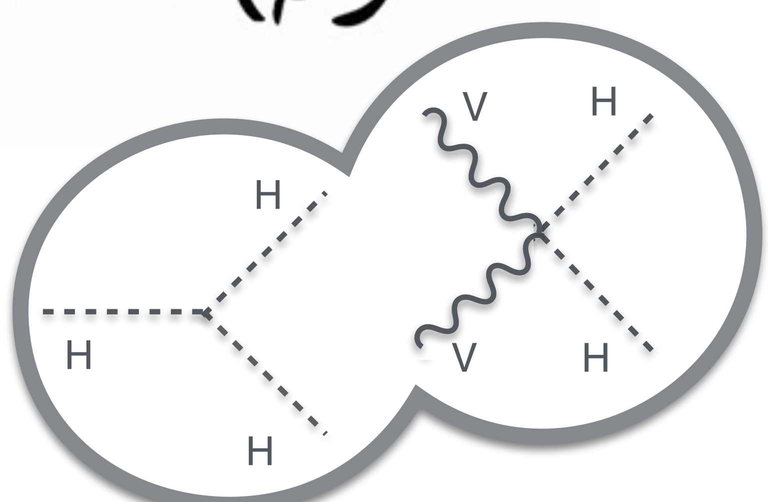


- Particle content
- Particle interactions



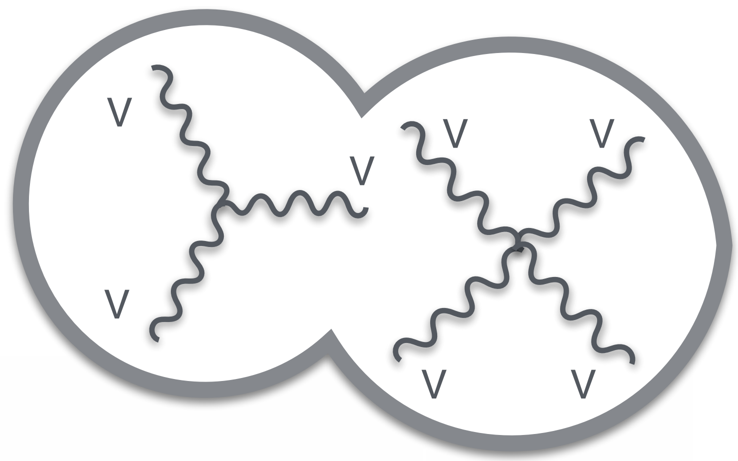
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

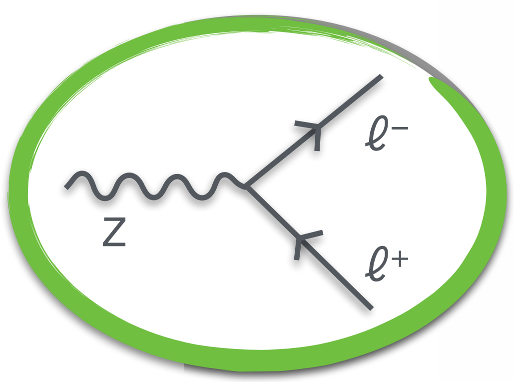




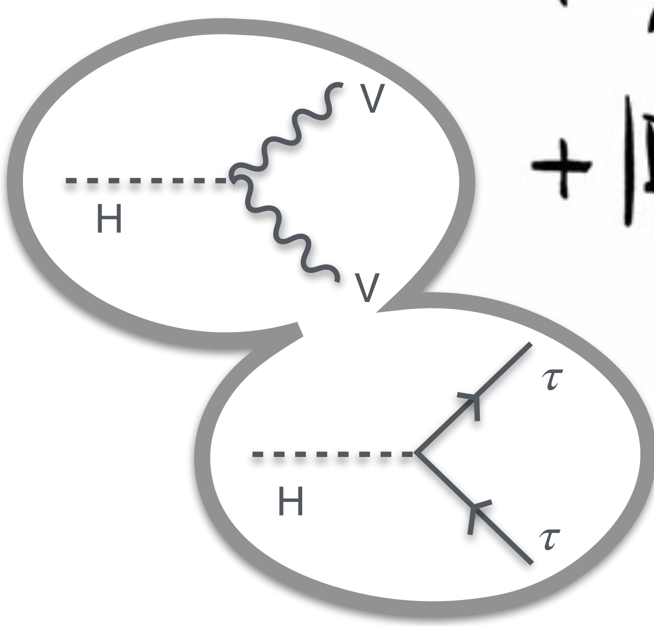
The Standard Model predicts

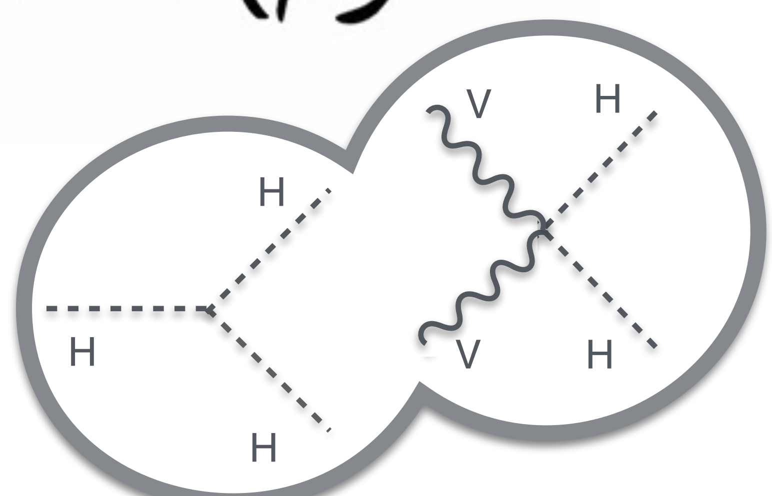
- Particle content
- Particle interactions
  - ✔ γ/Z → ℓℓ, W → ℓν very well understood



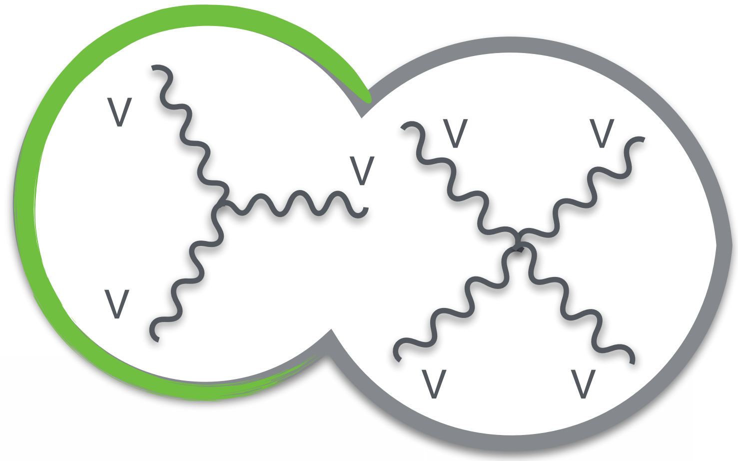


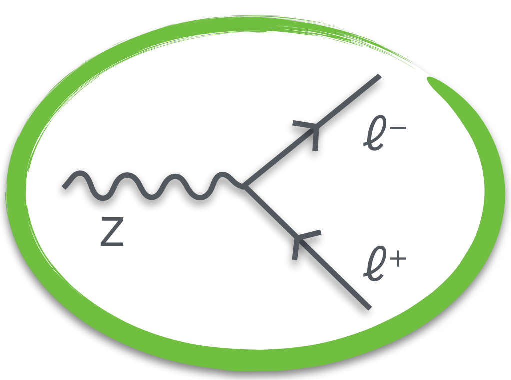
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



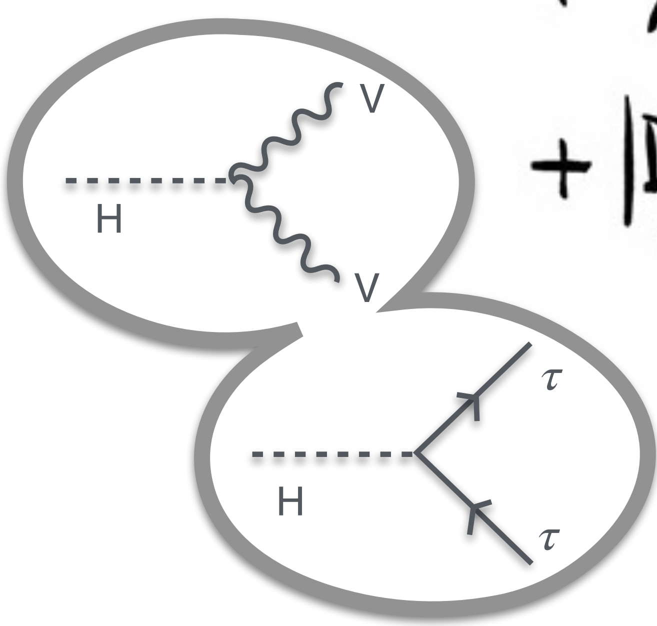


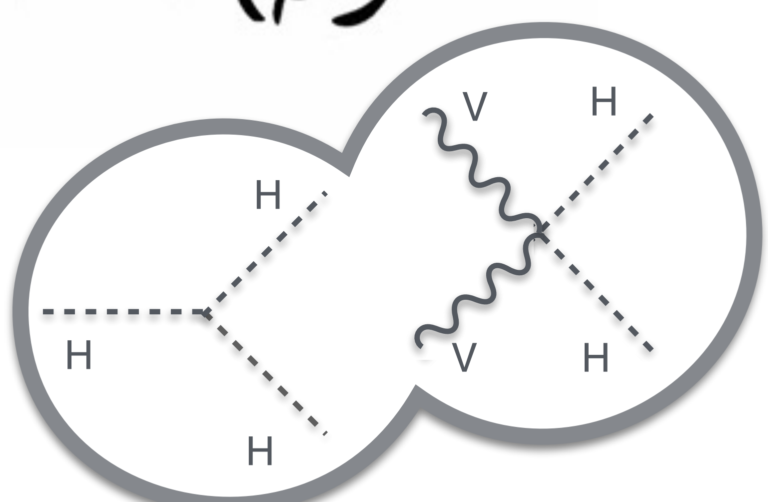
The Standard Model predicts





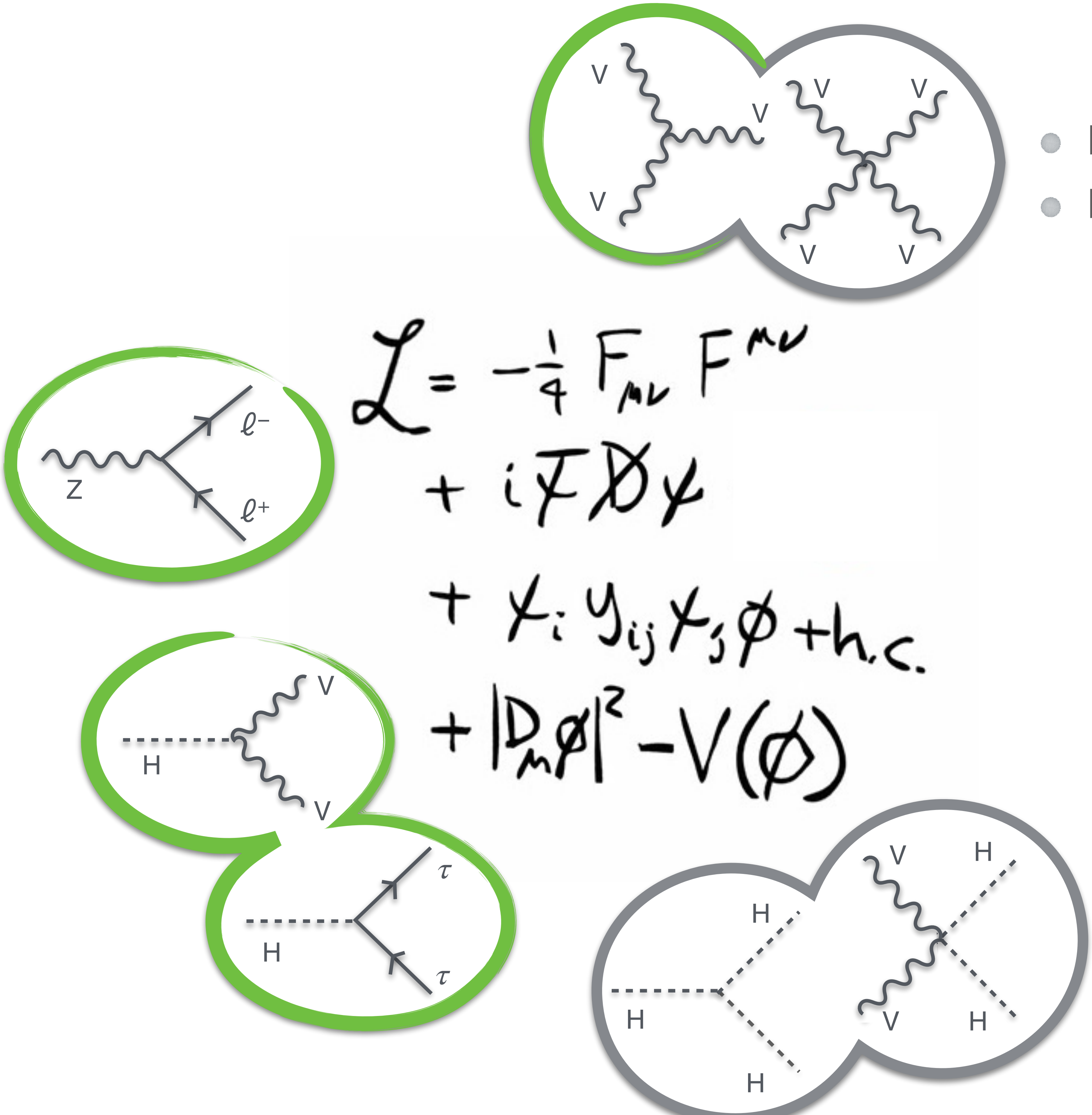
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$





- Particle content
- Particle interactions
  - ✔ γ/Z → ℓℓ, W → ℓv very well understood
  - ✔ WWV (V = Z, W) seen at LEP and LHC

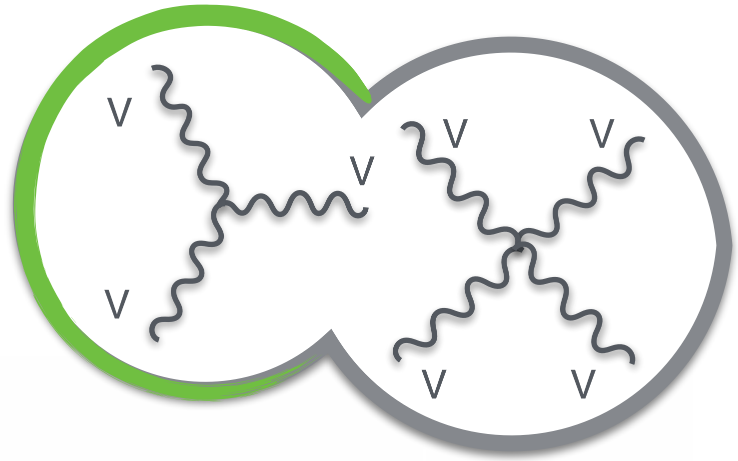
The Standard Model predicts

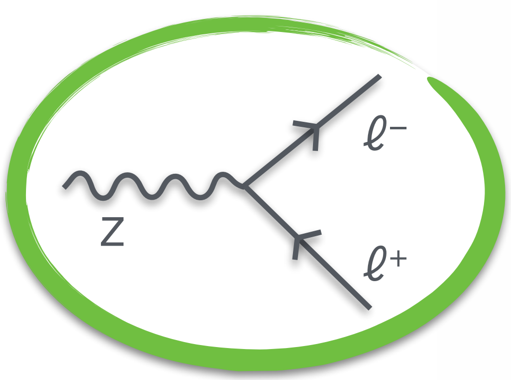


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

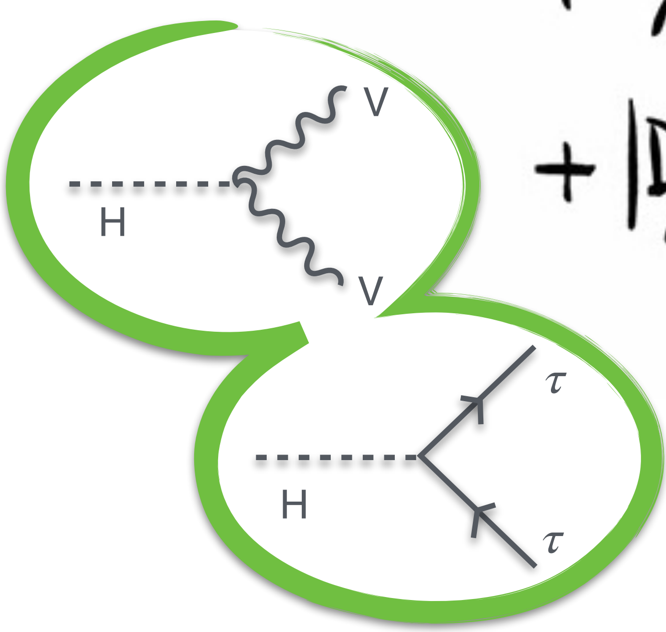
- Particle content
- Particle interactions
  - ✔ γ/Z → ℓℓ, W → ℓν very well understood
  - ✔ WWV (V = Z, W) seen at LEP and LHC
  - ✔ Higgs coupling to fermions and vector bosons observed at LHC

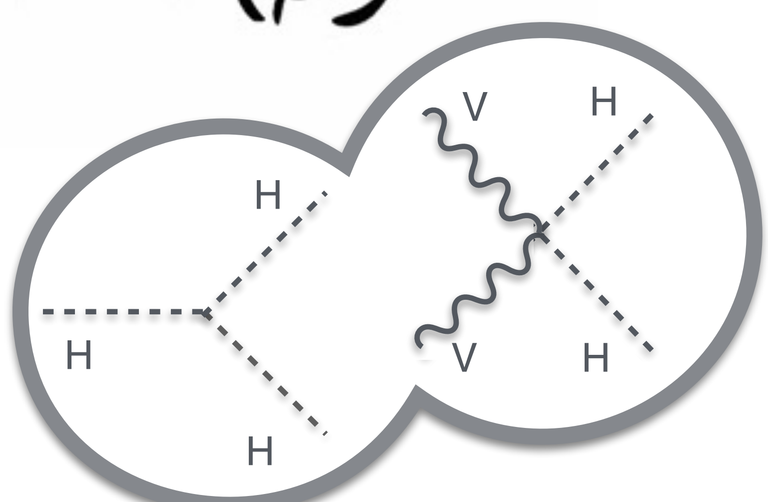
The Standard Model predicts





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





DO WE KNOW KNOW IT ALL?

- Particle content
- Particle interactions

- [x] γ/Z → ℓℓ, W → ℓν very well understood
- [x] WWV (V = Z, W) seen at LEP and LHC
- [x] Higgs coupling to fermions and vector bosons observed at LHC
- [ ] Coupling of 4 gauge bosons → only accessible now!
- [ ] Higgs self couplings not yet seen → HL-LHC?

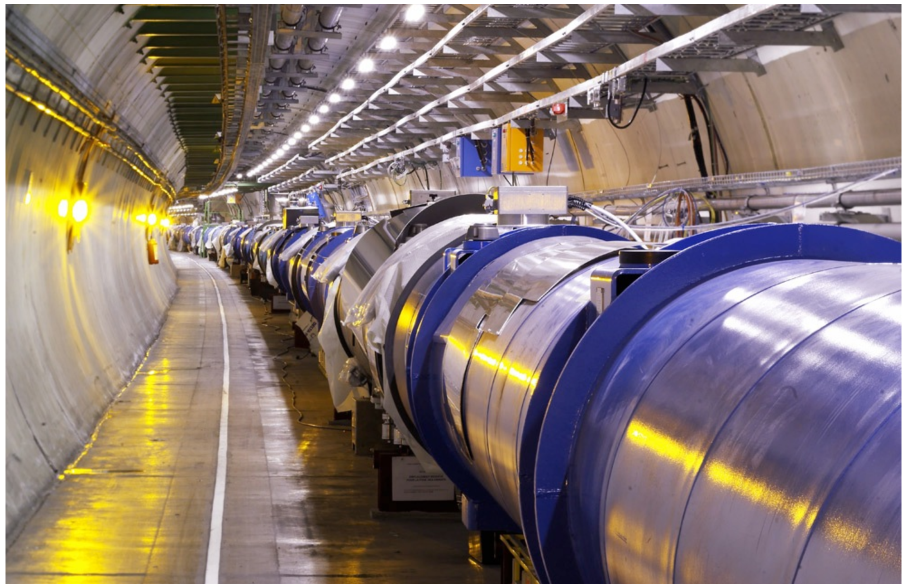
How do we explore those regions of the SM?

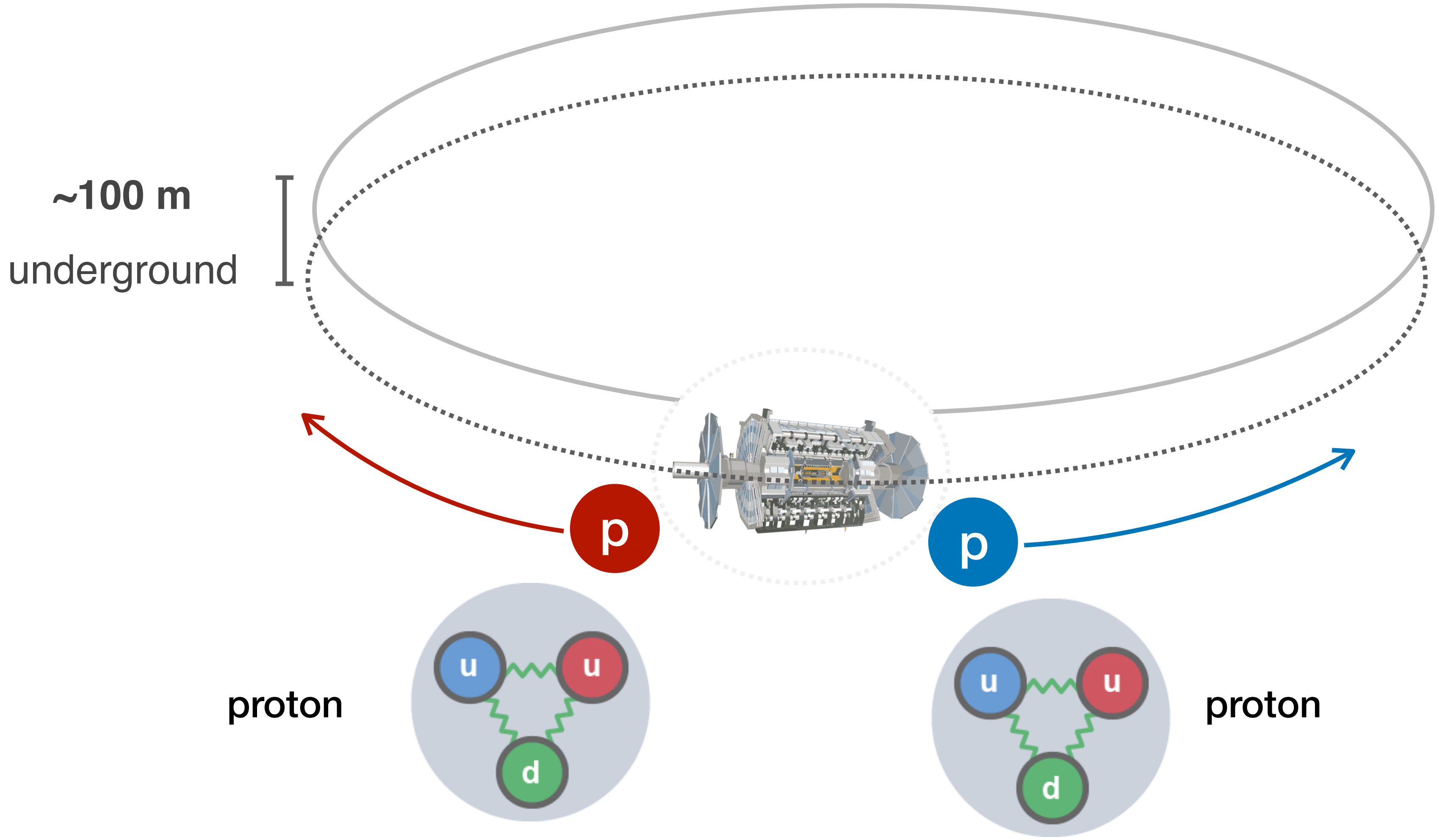
1. Get the vector bosons pairs
2. Compare with the Standard Model theory predictions

How do we explore those regions of the SM?

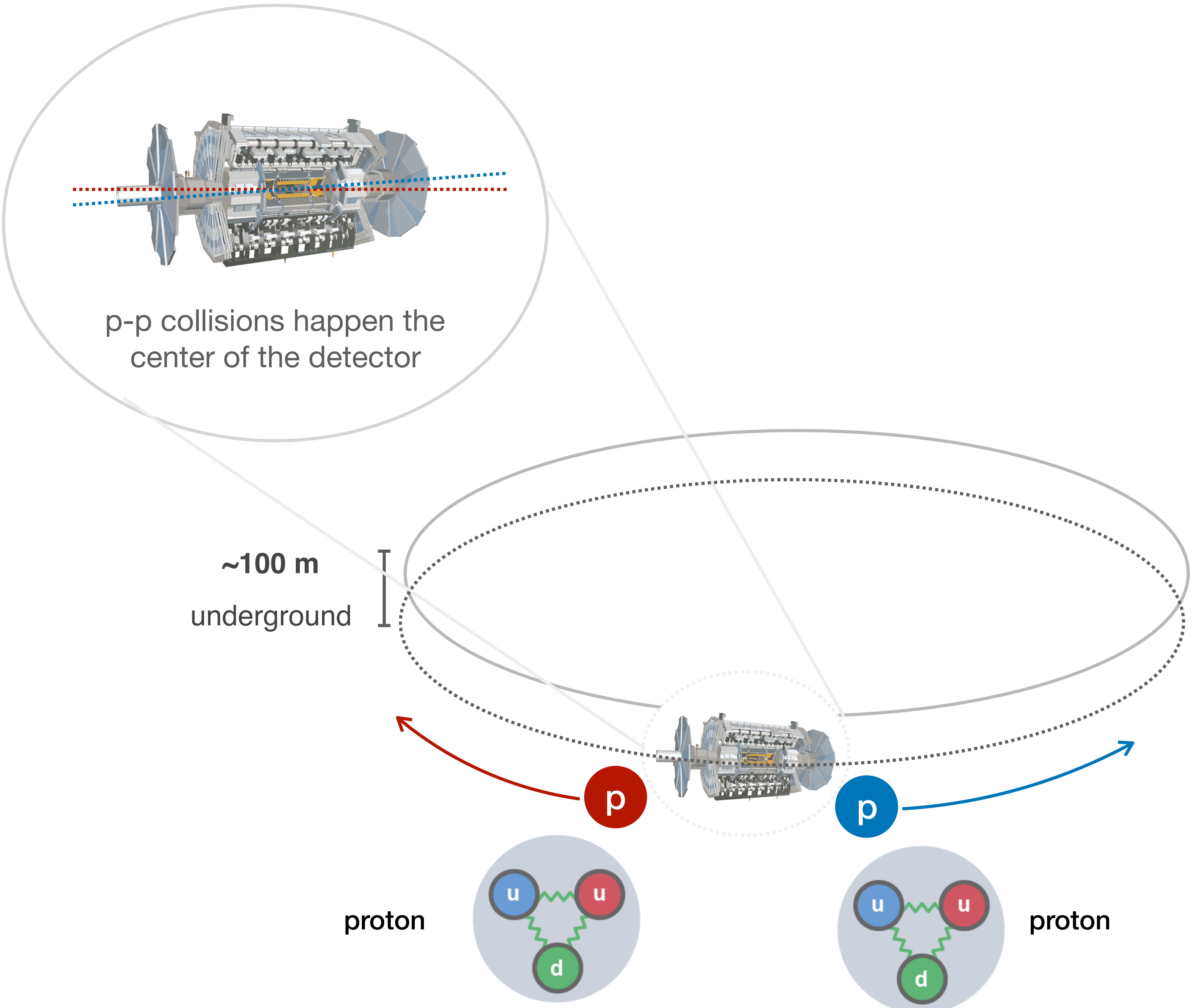
1. Get the vector bosons pairs
2. Compare with the Standard Model theory predictions

The Large Hadron Collider

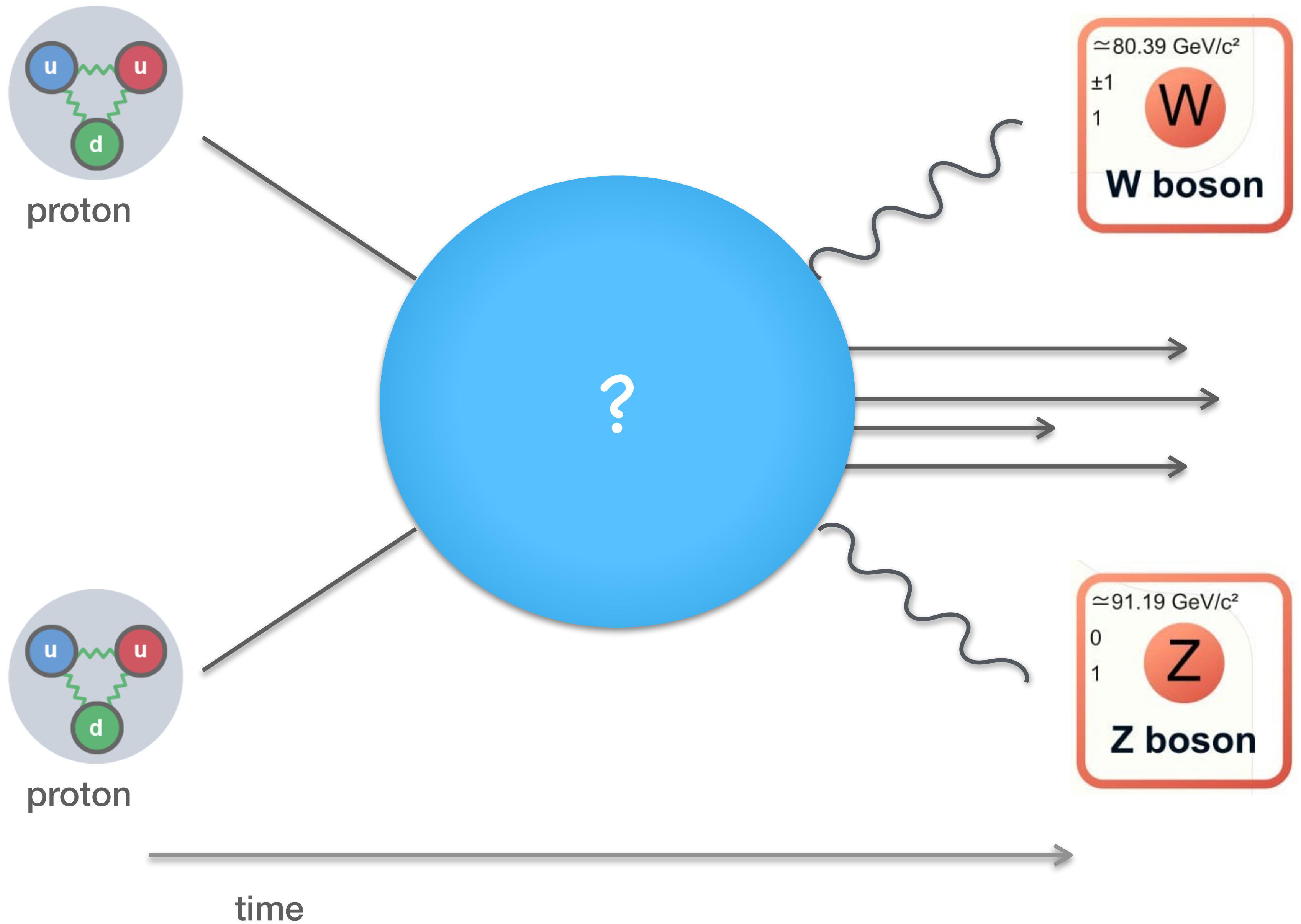




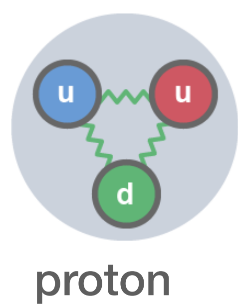
The Large Hadron Collider and ATLAS

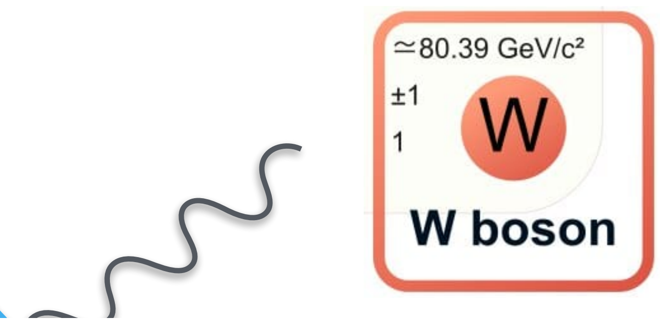


From proton collisions to vector boson pairs



From proton collisions to vector boson pairs





W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.80± 0.09) %	
Γ_2	$e^+\nu$		(10.75± 0.13) %	
Γ_3	$\mu^+\nu$		(10.57± 0.15) %	
Γ_4	$\tau^+\nu$		(11.25± 0.20) %	
Γ_5	hadrons		(67.60± 0.27) %	
Γ_6	$\pi^+\gamma$		< 8 × 10^{-5}	95%
Γ_7	$D_s^+\gamma$		< 1.3 × 10^{-3}	95%
Γ_8	cX		(33.4 ± 2.6) %	
Γ_9	$c\overline{s}$		(31 $^{+13}_{-11}$) %	
Γ_{10}	invisible	[b]	(1.4 ± 2.9) %	

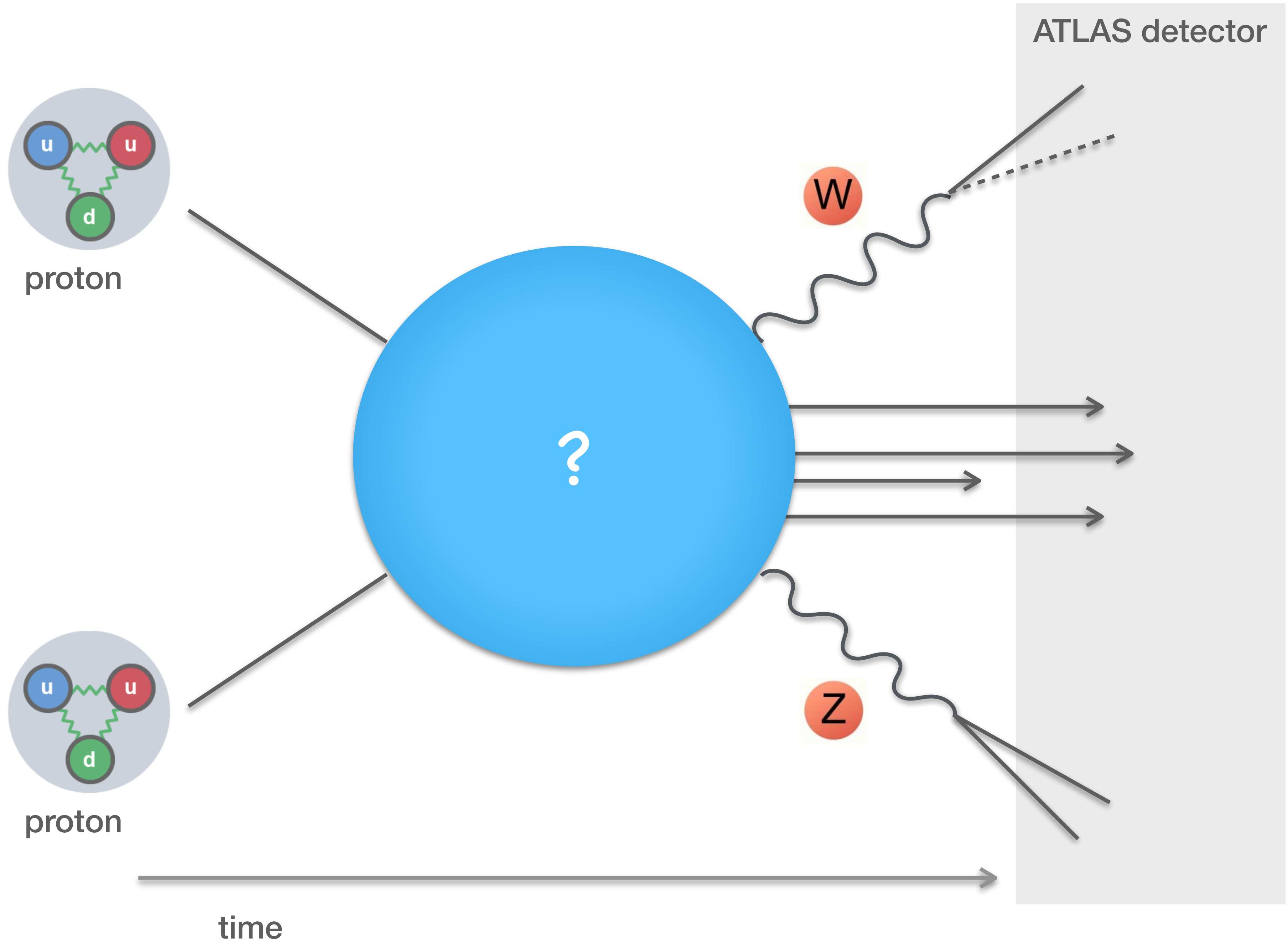
[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

[b] This represents the width for the decay of the W boson into a charged particle with momentum below detectability, p< 200 MeV.

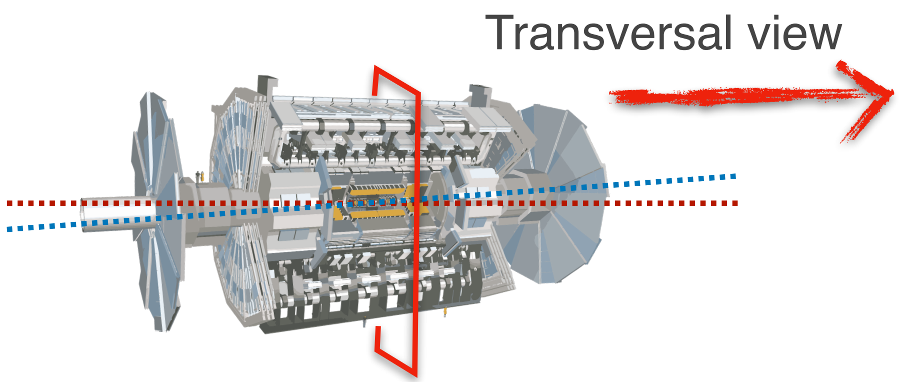
Z DECAY MODES

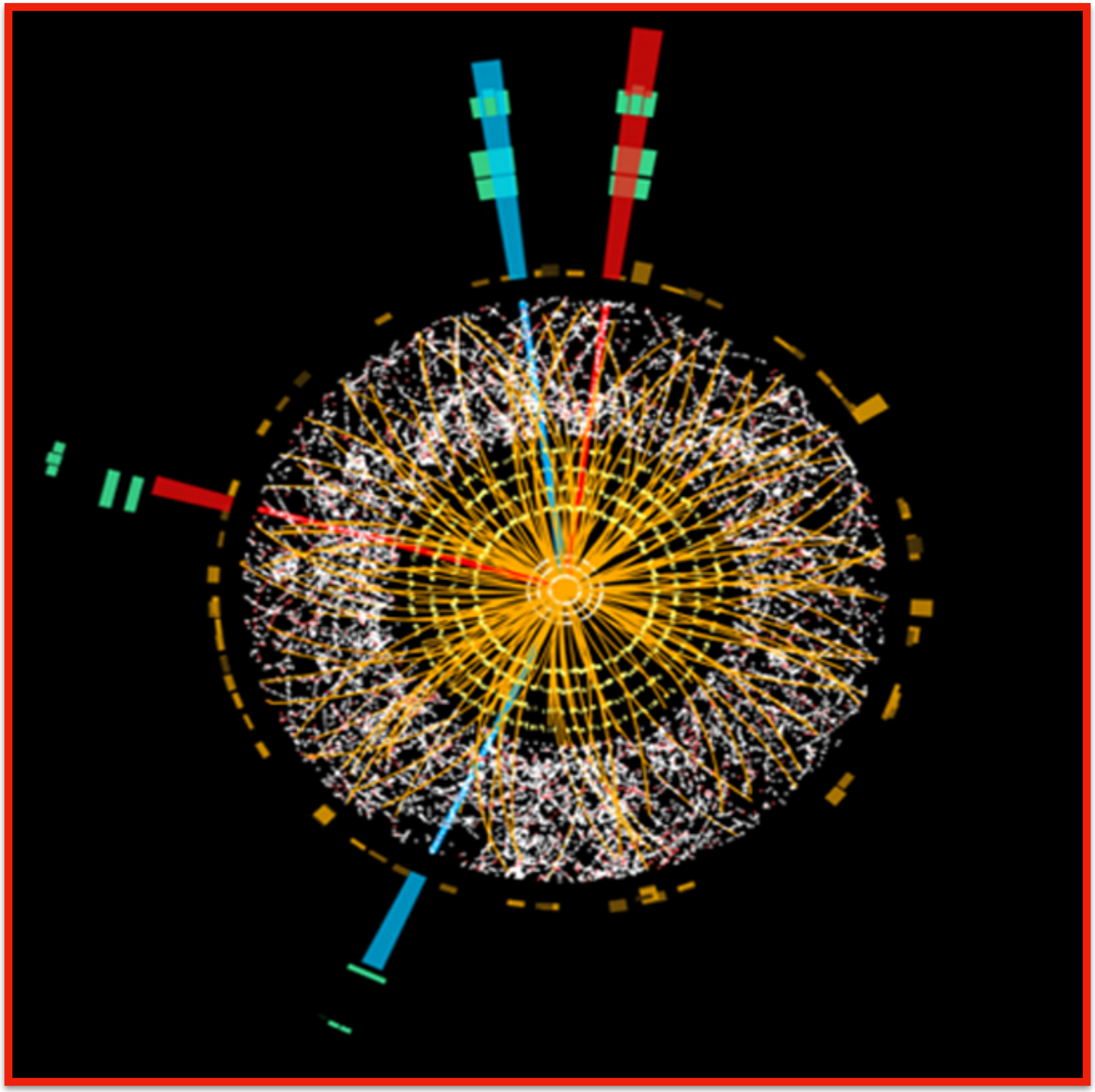
	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-		(3.363 ±0.004) %	
Γ_2	$\mu^+\mu^-$		(3.366 ±0.007) %	
Γ_3	$\tau^+\tau^-$		(3.370 ±0.008) %	
Γ_4	$\ell^+\ell^-$	[a]	(3.3658±0.0023) %	
Γ_5	invisible		(20.00 ±0.06) %	
Γ_6	hadrons		(69.91 ±0.06) %	
Γ_7	$(u\overline{u}+c\overline{c})/2$		(11.6 ±0.6) %	
Γ_8	$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ±0.4) %	
Γ_9	$c\overline{c}$		(12.03 ±0.21) %	
Γ_{10}	$b\overline{b}$		(15.12 ±0.05) %	
Γ_{11}	$b\overline{b}b\overline{b}$		(3.6 ±1.3) × 10^{-4}	
Γ_{12}	ggg		< 1.1 %	CL=95%
Γ_{13}	$\pi^0\gamma$		< 5.2 × 10^{-5}	CL=95%
Γ_{14}	$\eta\gamma$		< 5.1 × 10^{-5}	CL=95%
Γ_{15}	$\omega\gamma$		< 6.5 × 10^{-4}	CL=95%
Γ_{16}	$\eta'(958)\gamma$		< 4.2 × 10^{-5}	CL=95%
Γ_{17}	$\gamma\gamma$		< 5.2 × 10^{-5}	CL=95%
Γ_{18}	$\gamma\gamma\gamma$		< 1.0 × 10^{-5}	CL=95%
Γ_{19}	$\pi^\pm W^\mp$	[b]	< 7 × 10^{-5}	CL=95%

From proton collisions to vector boson pairs



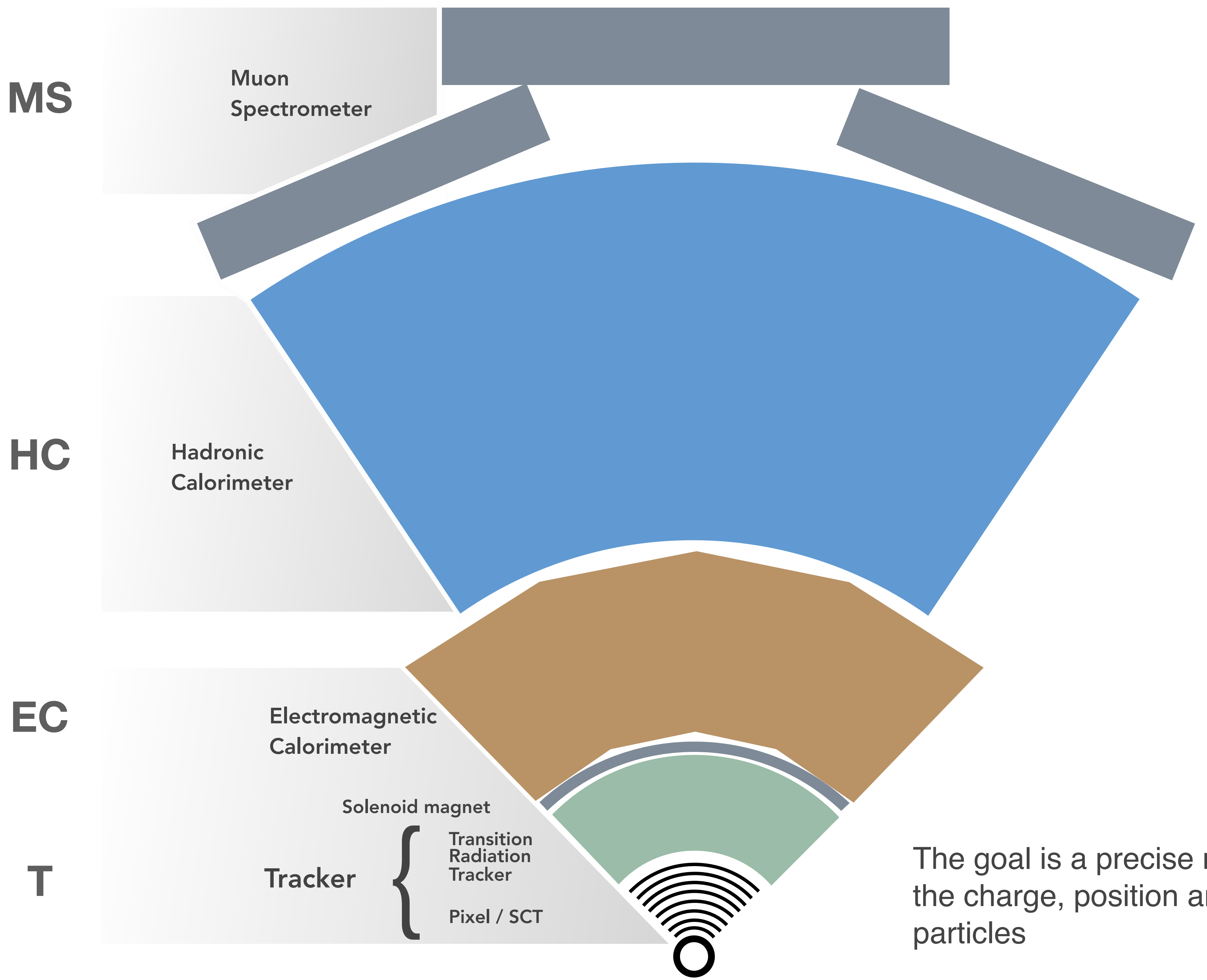
How an ATLAS event look like?





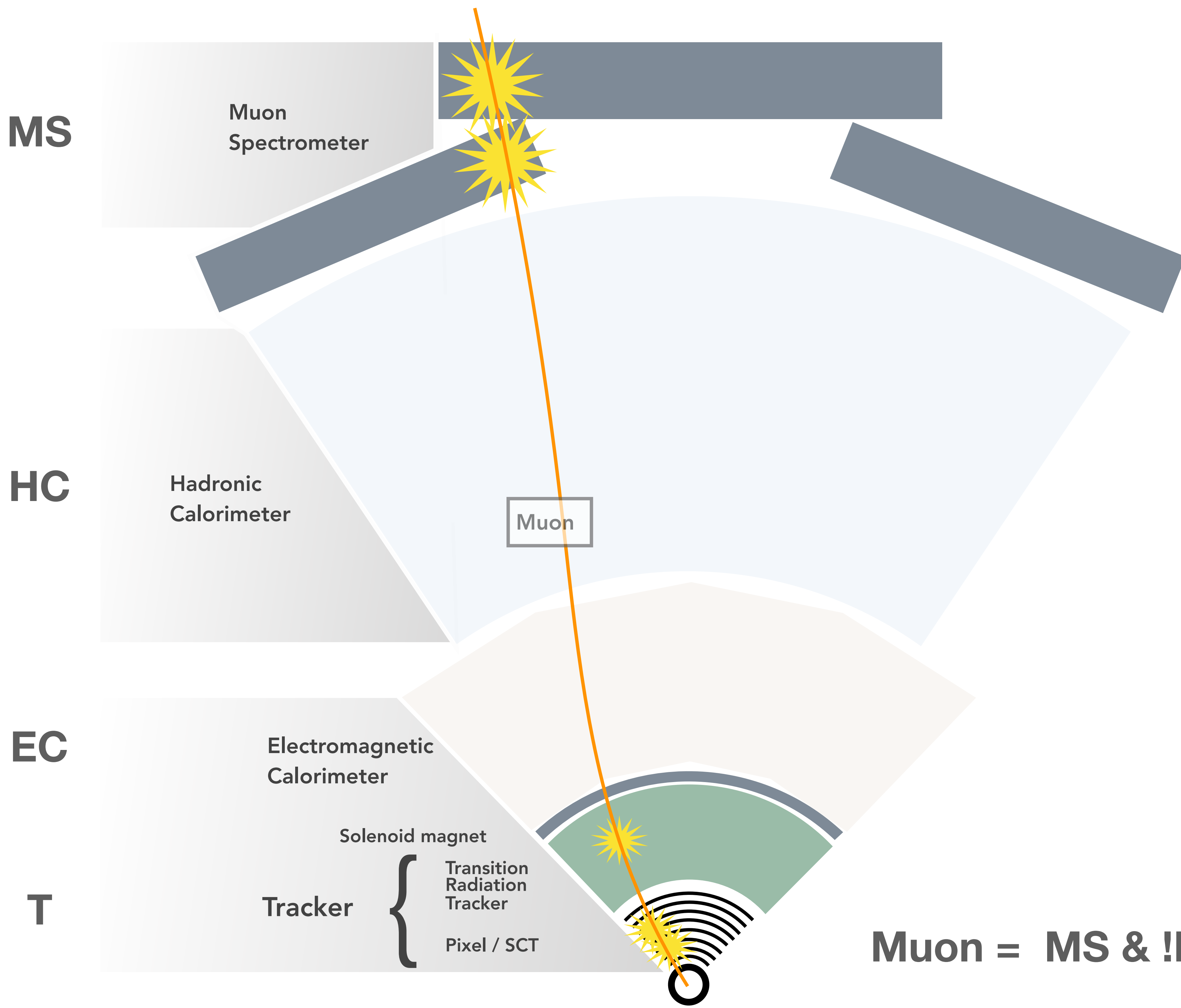
VECTOR BOSONS ARE YOU THERE?

The ATLAS detector



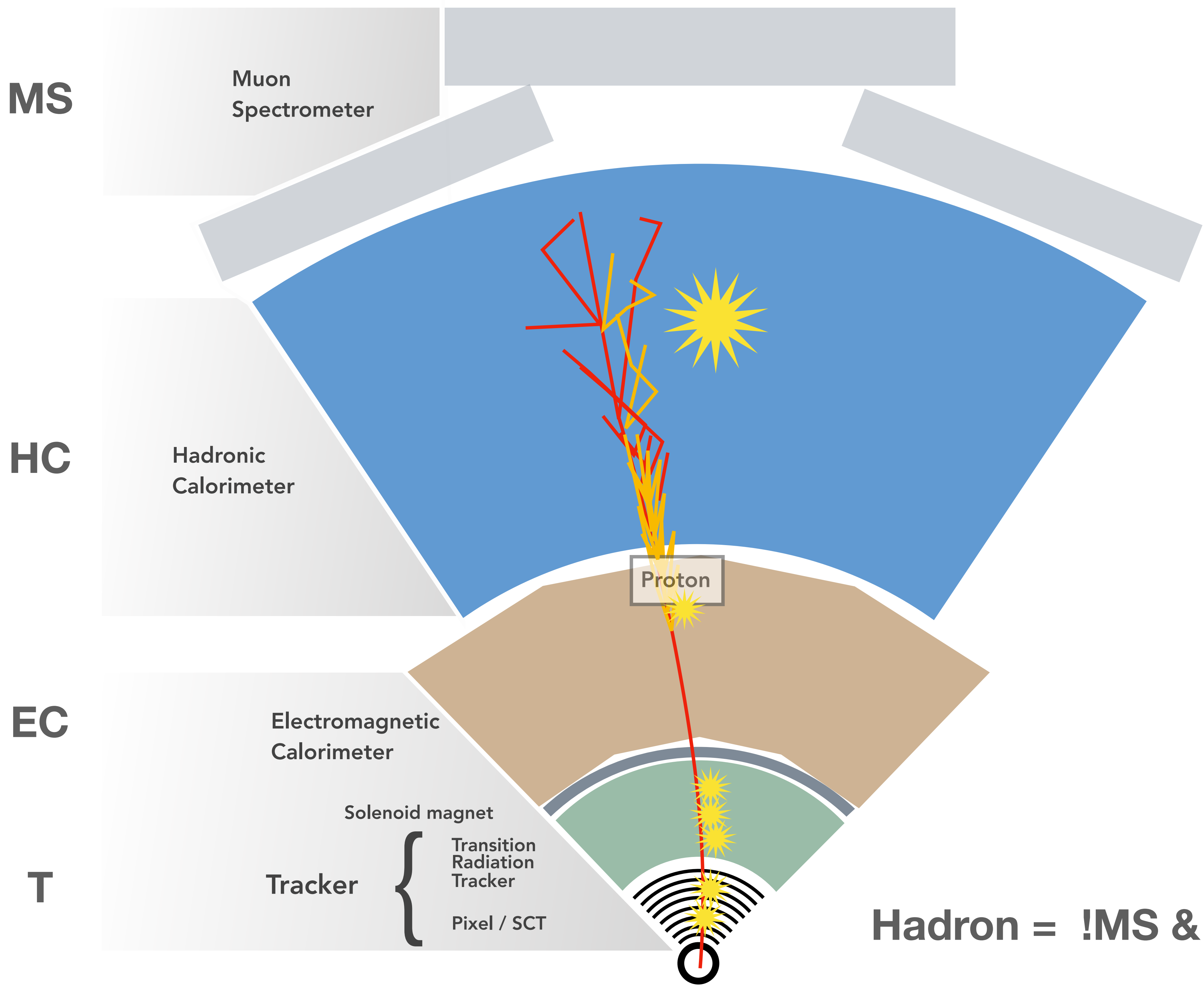
The goal is a precise measurement of the charge, position and energy of the particles

A muon in ATLAS



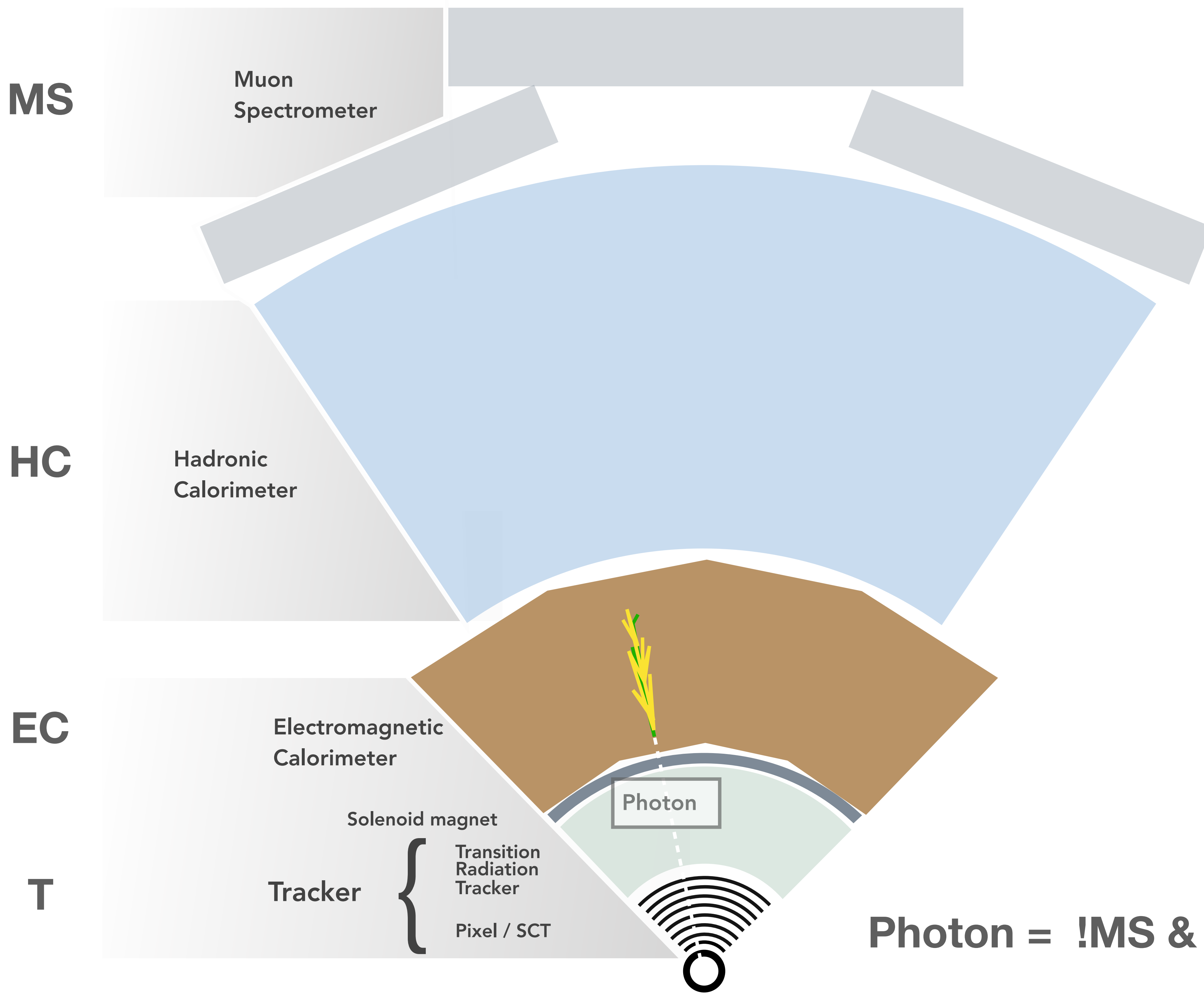
Muon = MS & !HC & !EC & T

An hadron in ATLAS



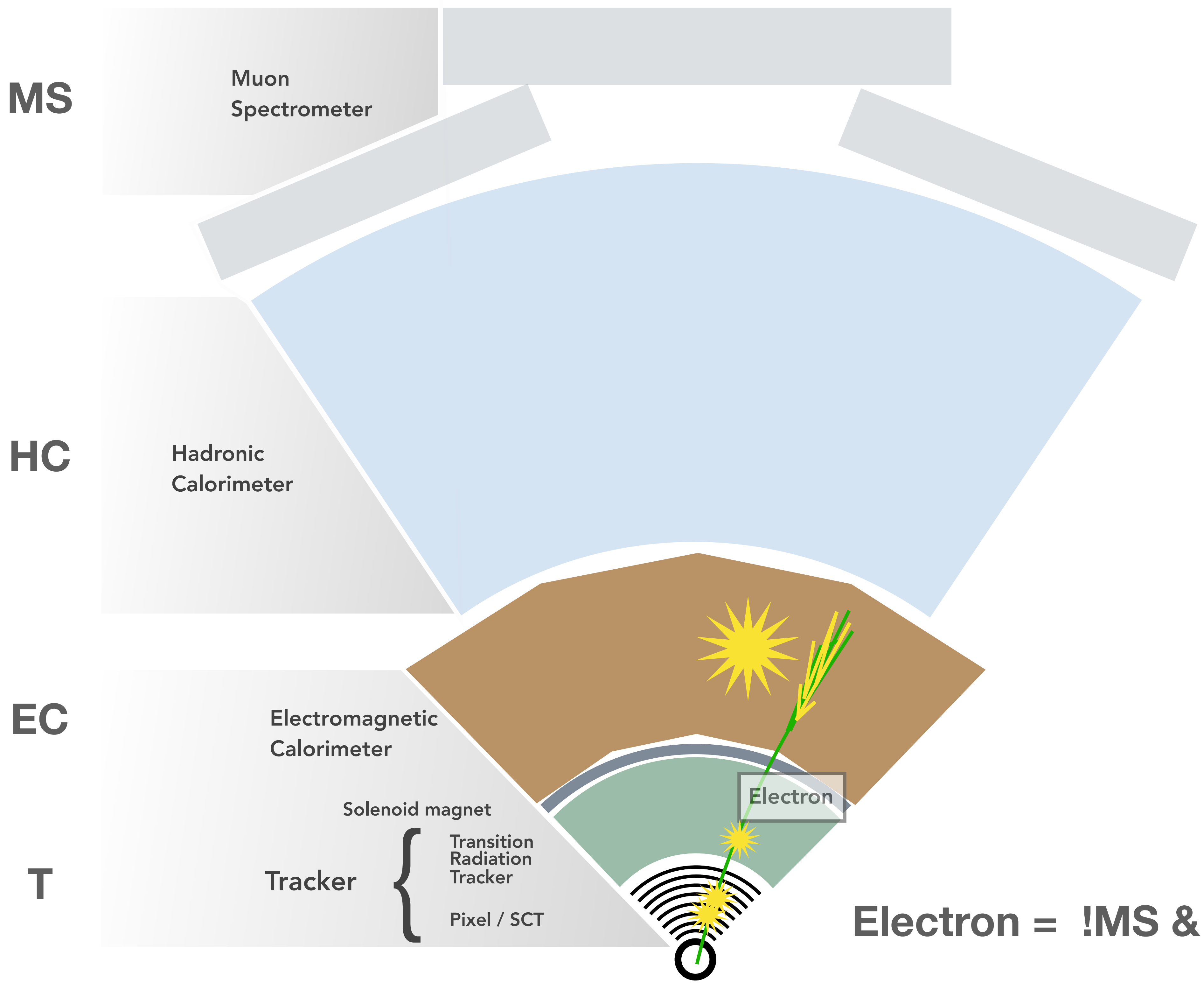
Hadron = !MS & HC & EC & T

A photon in ATLAS



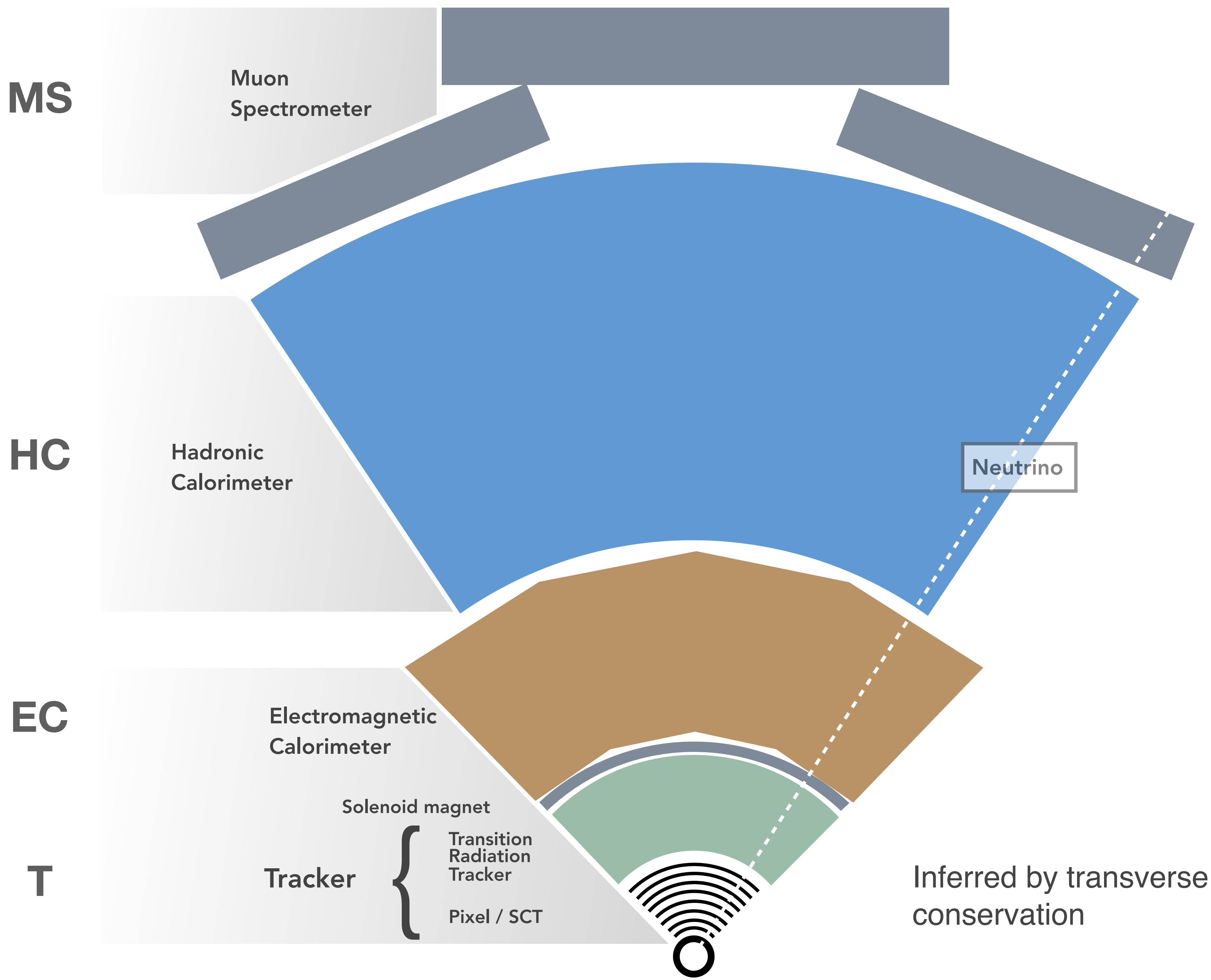
Photon = !MS & !HC & EC & !T

An electron in ATLAS



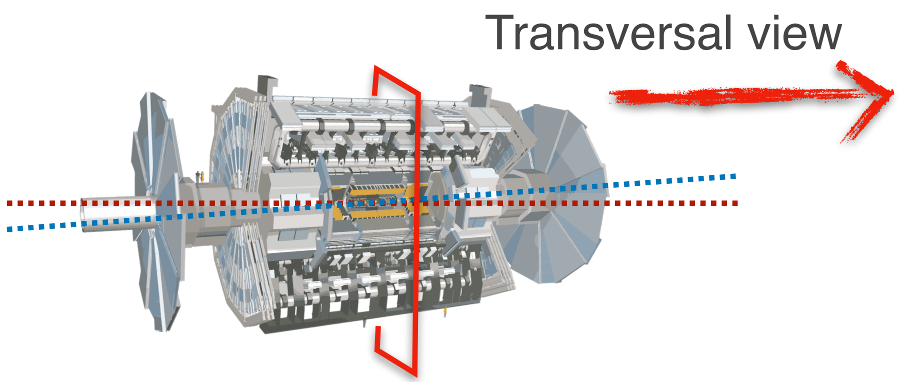
Electron = !MS & !HC & EC & T

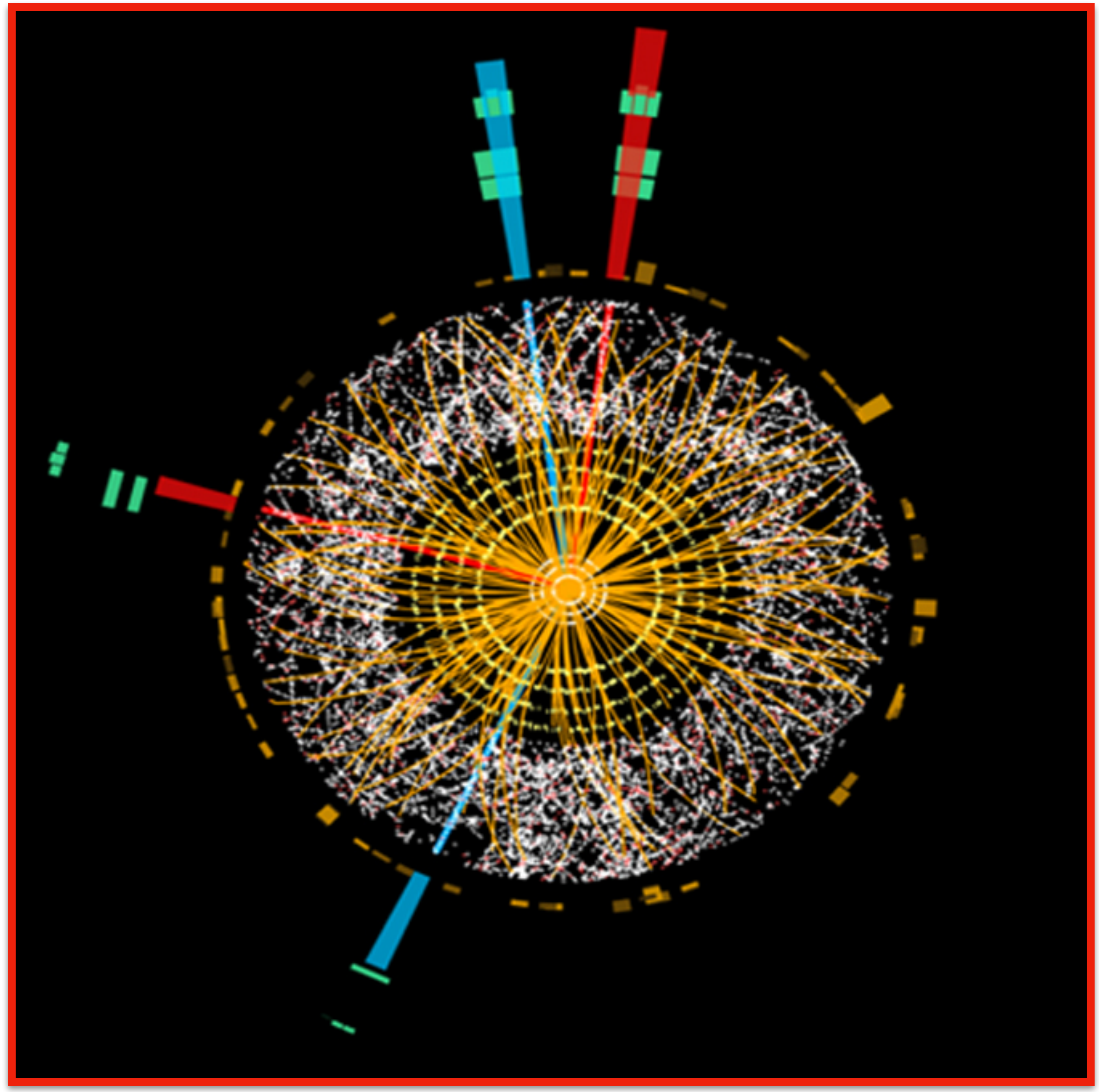
A neutrino in ATLAS



Inferred by transverse momentum conservation

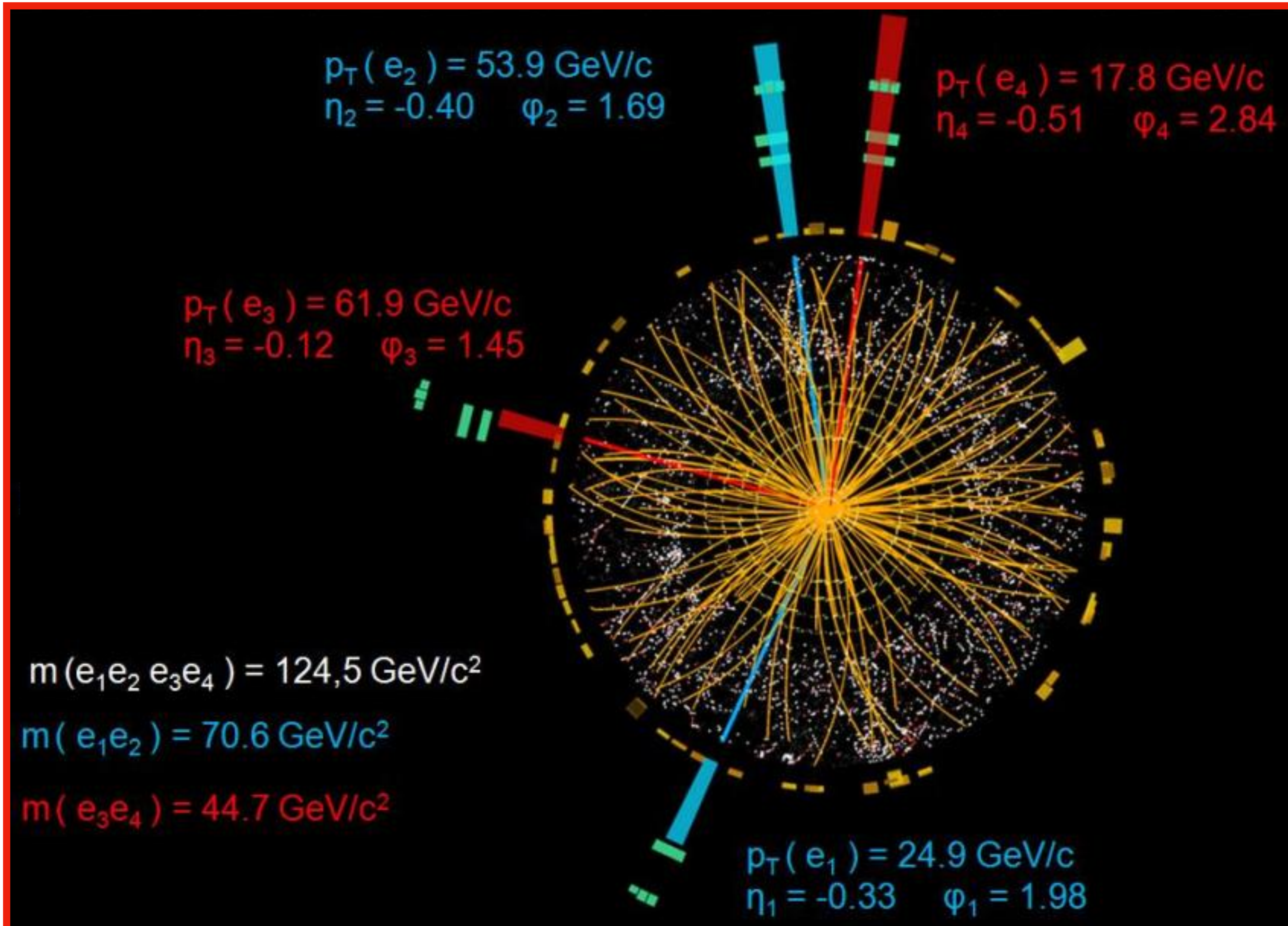
How an ATLAS event look like?





VECTOR BOSONS ARE YOU THERE?

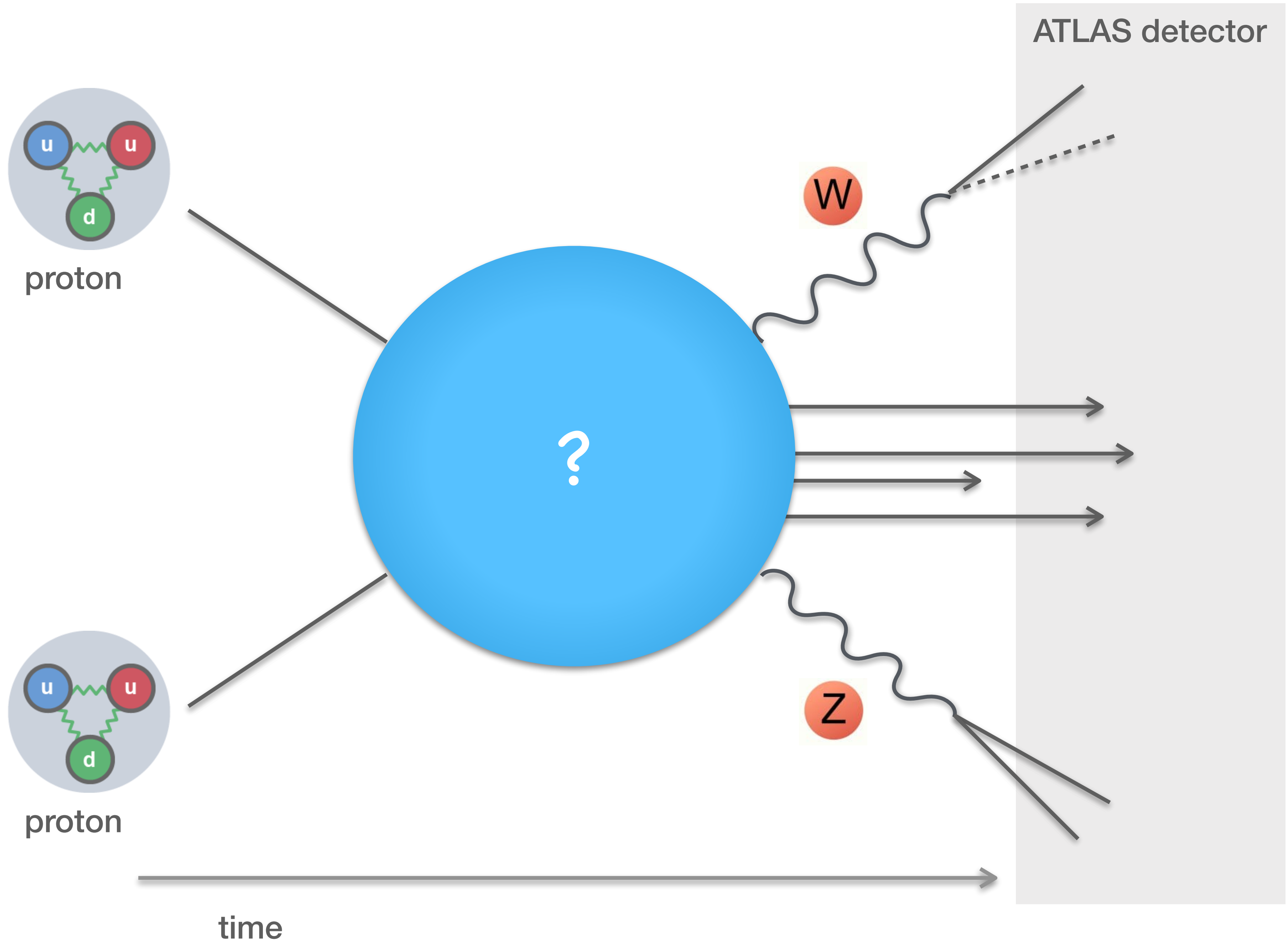
Here we have a $H \to ZZ^* \to e^+e^- e^+e^-$ candidate!



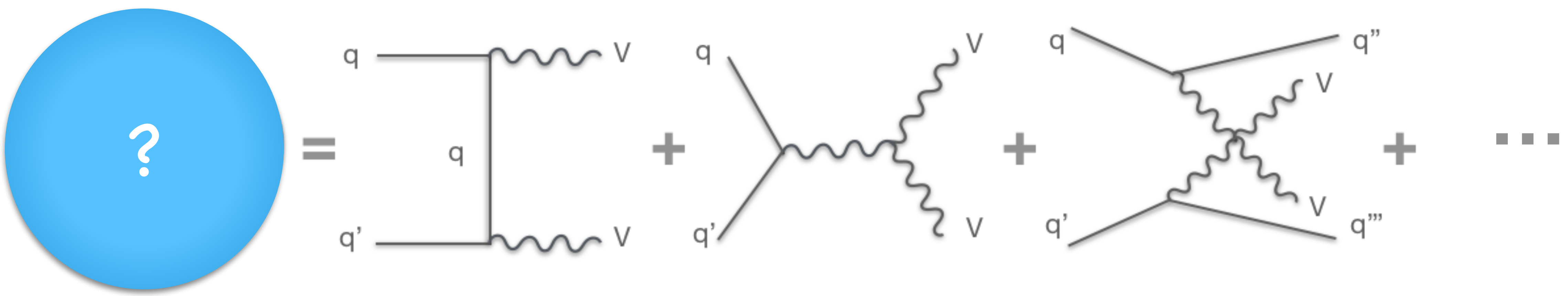
How do we explore those regions of the SM?

1. Get the vector bosons pairs
2. Compare with the Standard Model theory predictions

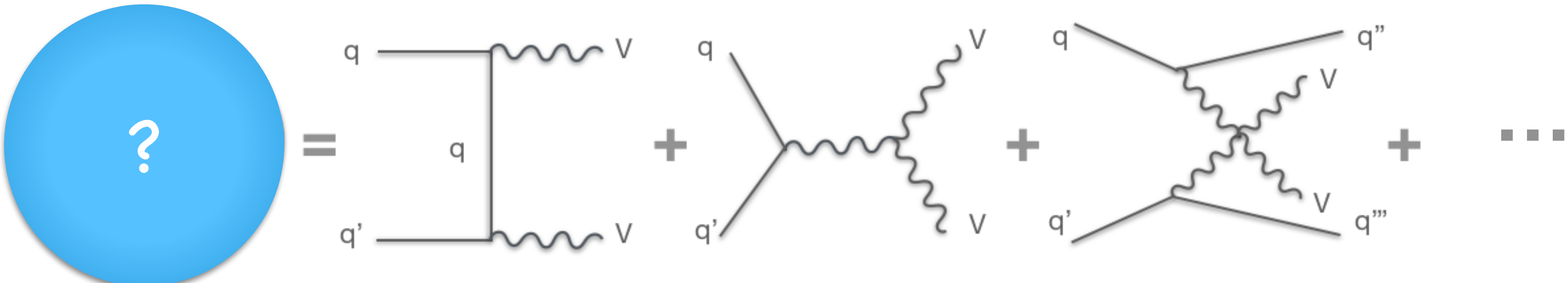
Vector boson pairs



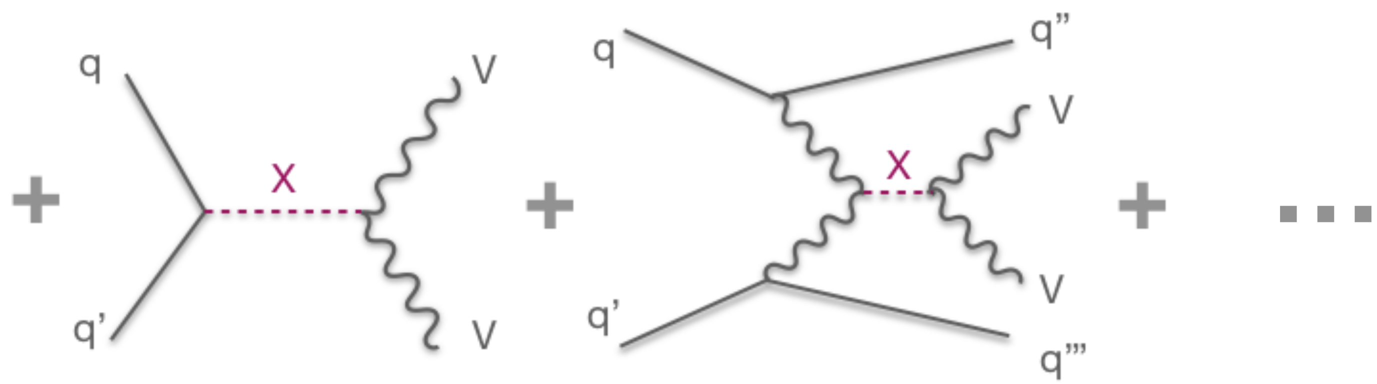
Vector boson pairs **to test the SM**



Vector boson pairs to go beyond the SM

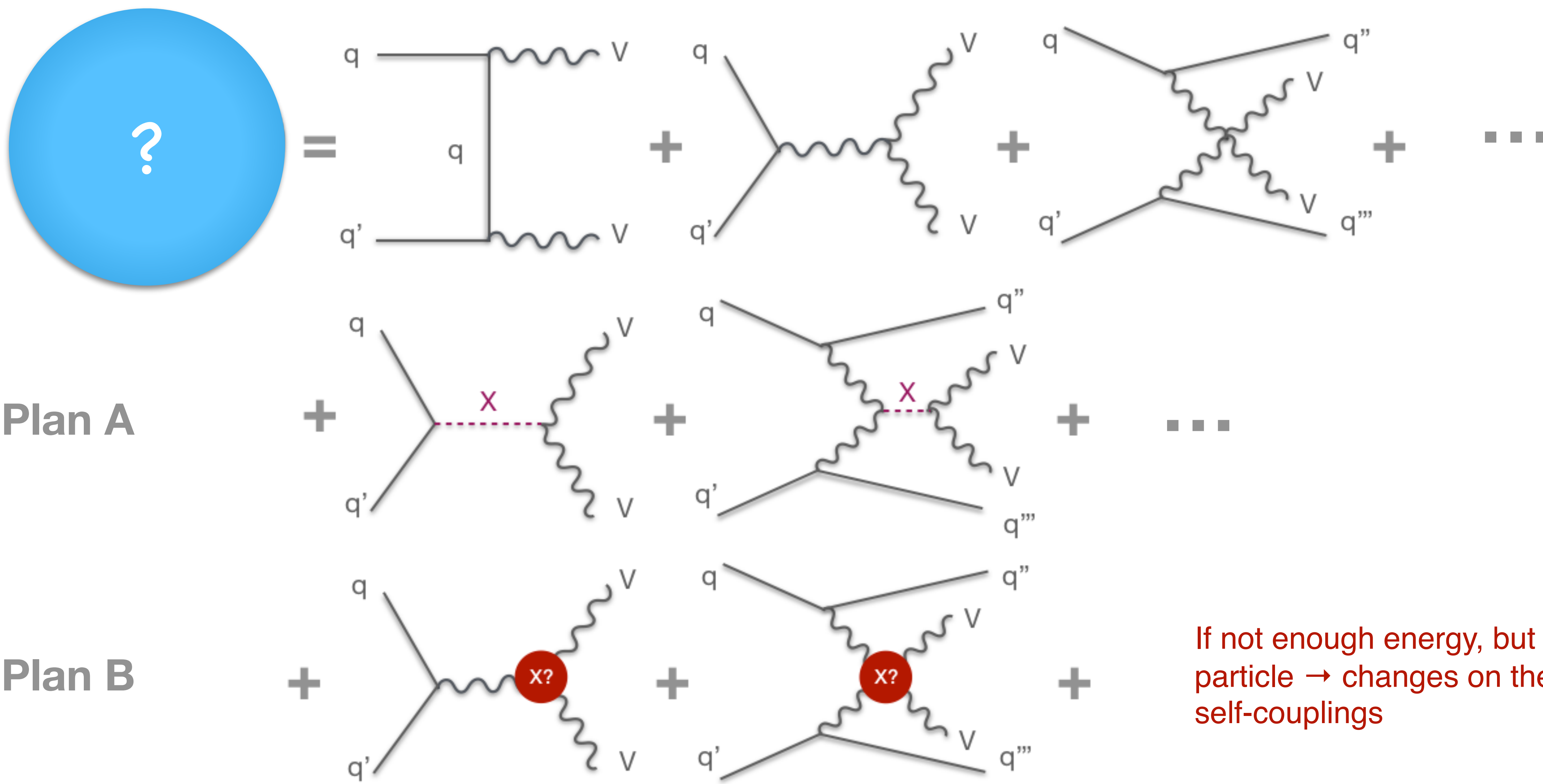


Plan A



If we are lucky we have enough energy to produce a new **unknown** particle on-shell

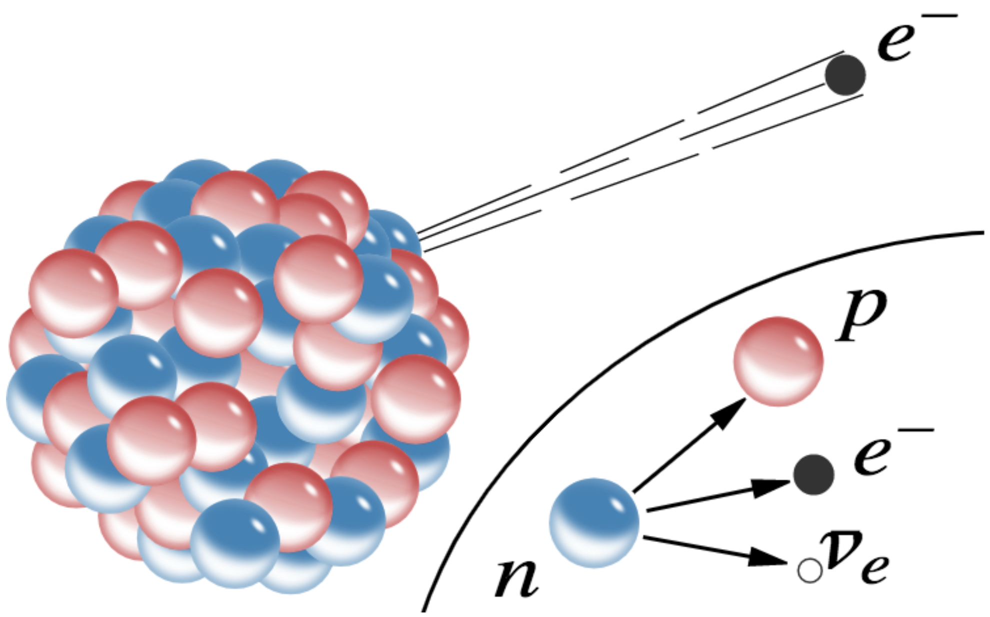
Vector boson pairs to go **beyond the SM**



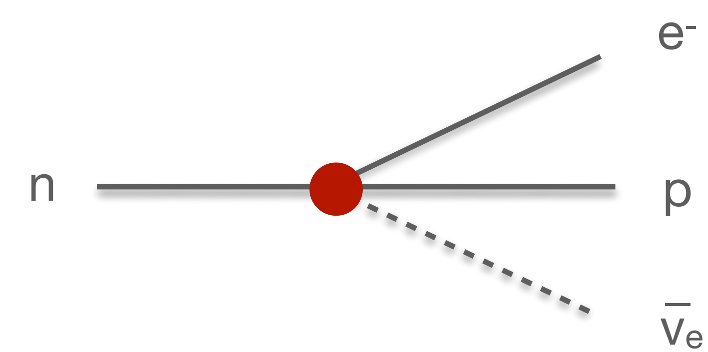
If not enough energy, but new particle → changes on the bosons self-couplings

And this won't be the first time!

Fermi Theory of β decay

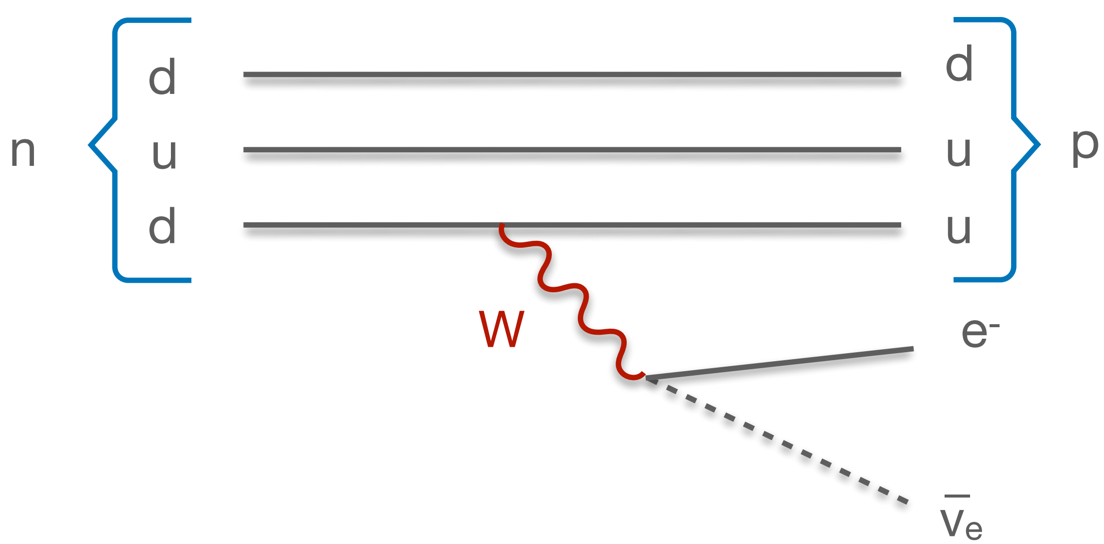


Fermi theory (1933) originally predicted a 4-fermion point like interaction



Excellent giving predictions at low energy, but….

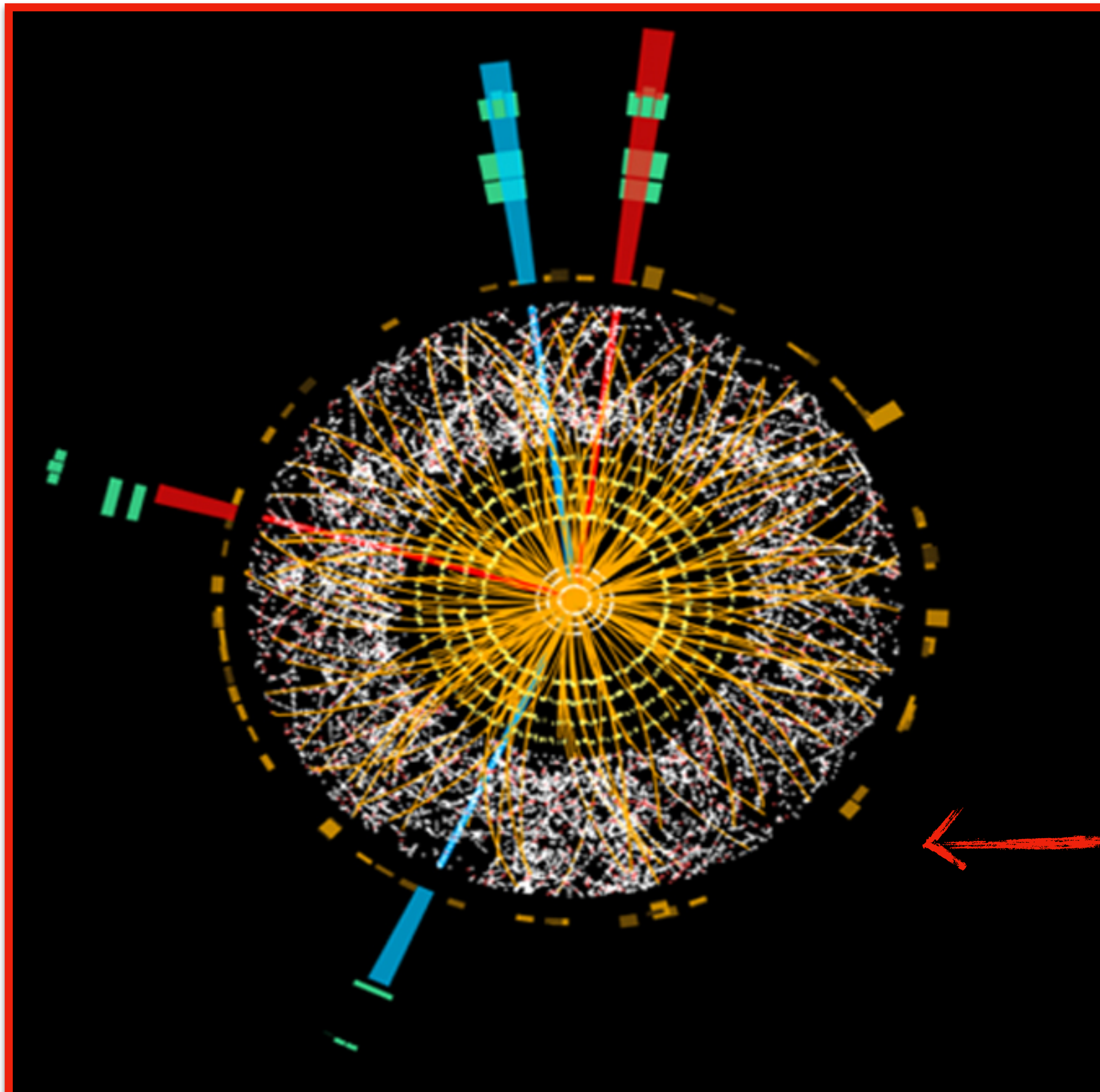
Nowadays we know that we need a W boson exchange!



The Fermi theory is an Effective Field Theory

Comparing with theory

Detector measurement



Theory

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

How?

Measuring and calculating **Cross-sections!**

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

A cross section measurement

Number of events
[Measured]

$$\sigma = \frac{N}{L}$$

Cross Section
[Your measurement]

Integrated Luminosity
[Provided by LHC]

A cross section measurement

Number of observed events (just count …)

Number of background events (measured from data or predicted by theory)

$$\sigma = \frac{N_{obs} - N_{bkg}}{L \cdot \varepsilon \cdot A}$$

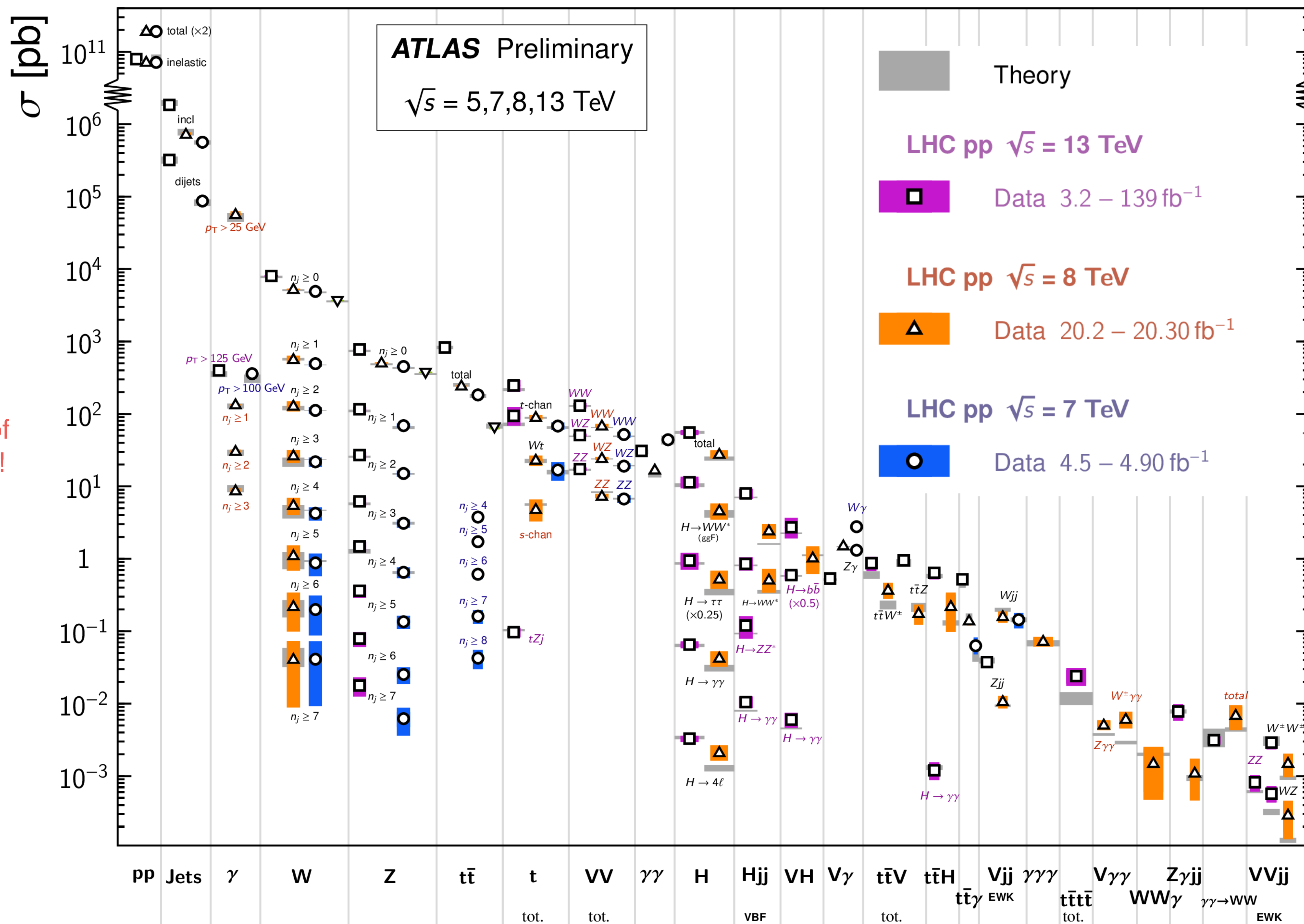
Acceptance
[Your detector volume]

Efficiency
[Your detector characteristics]

The Standard Model testing status

Events per month*

14 orders of magnitude!

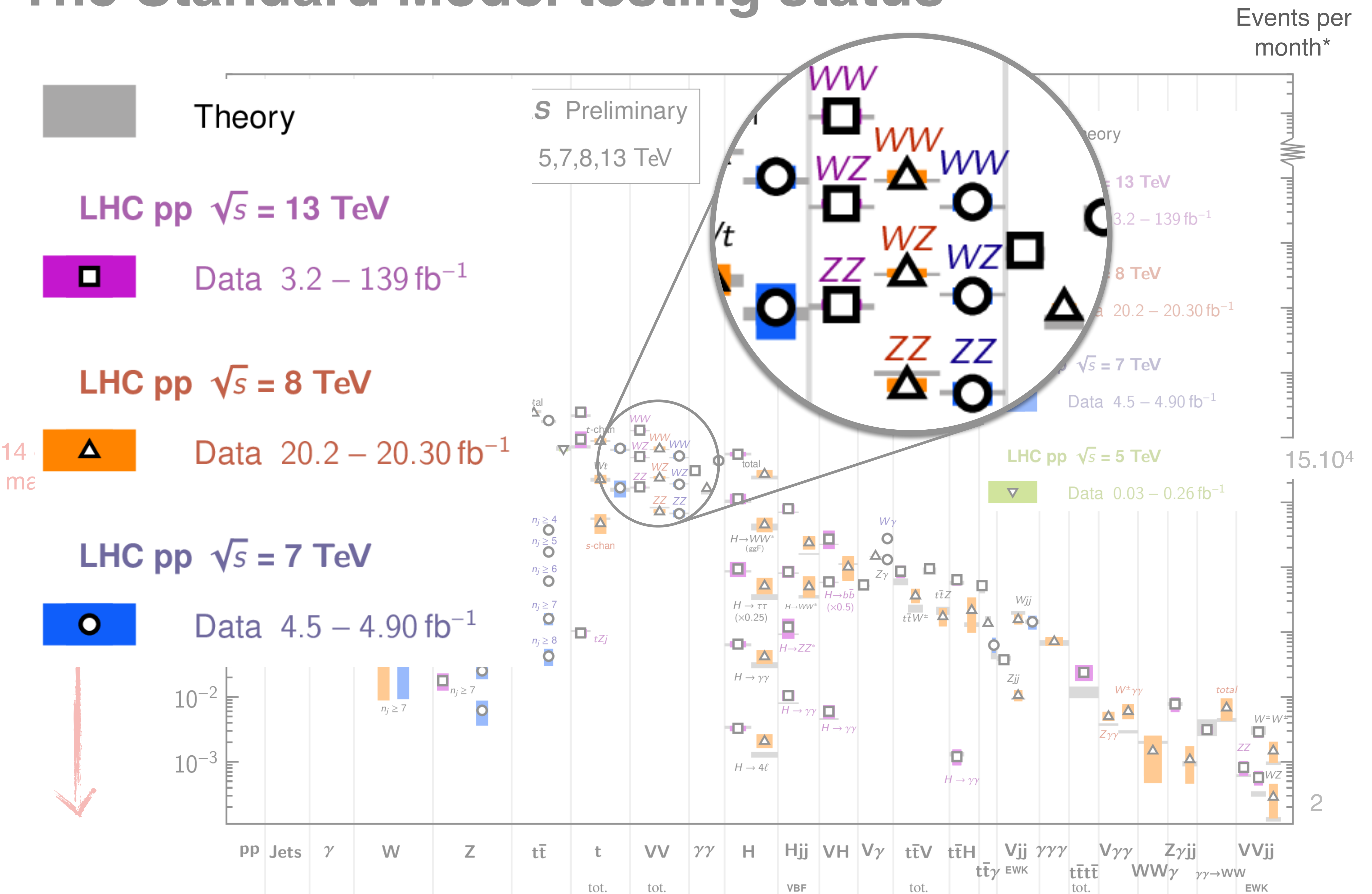


15.10^4

2

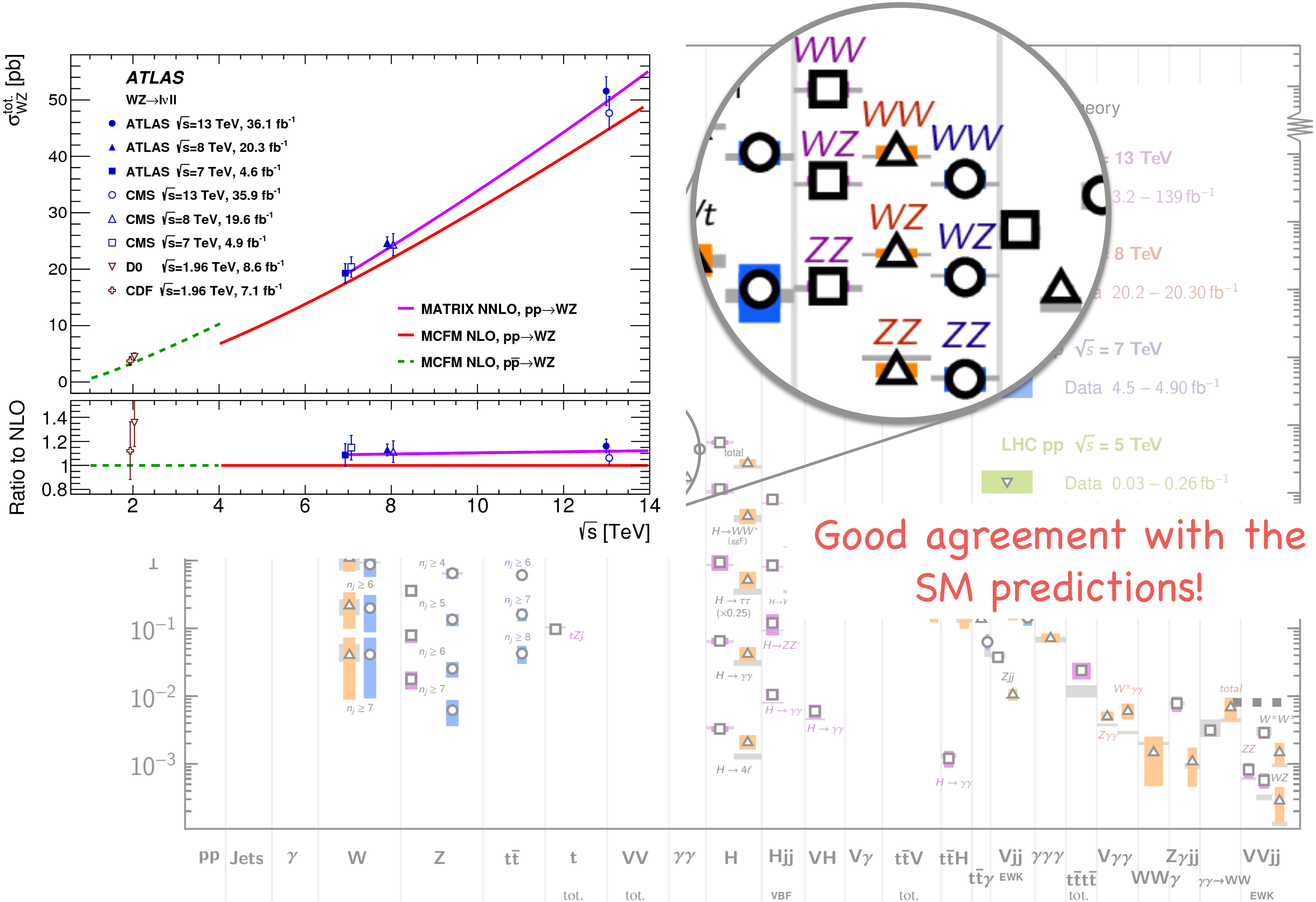
* at 13 TeV assuming 3fb^{-1} are collected per month

The Standard Model testing status



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

The Standard Model testing status



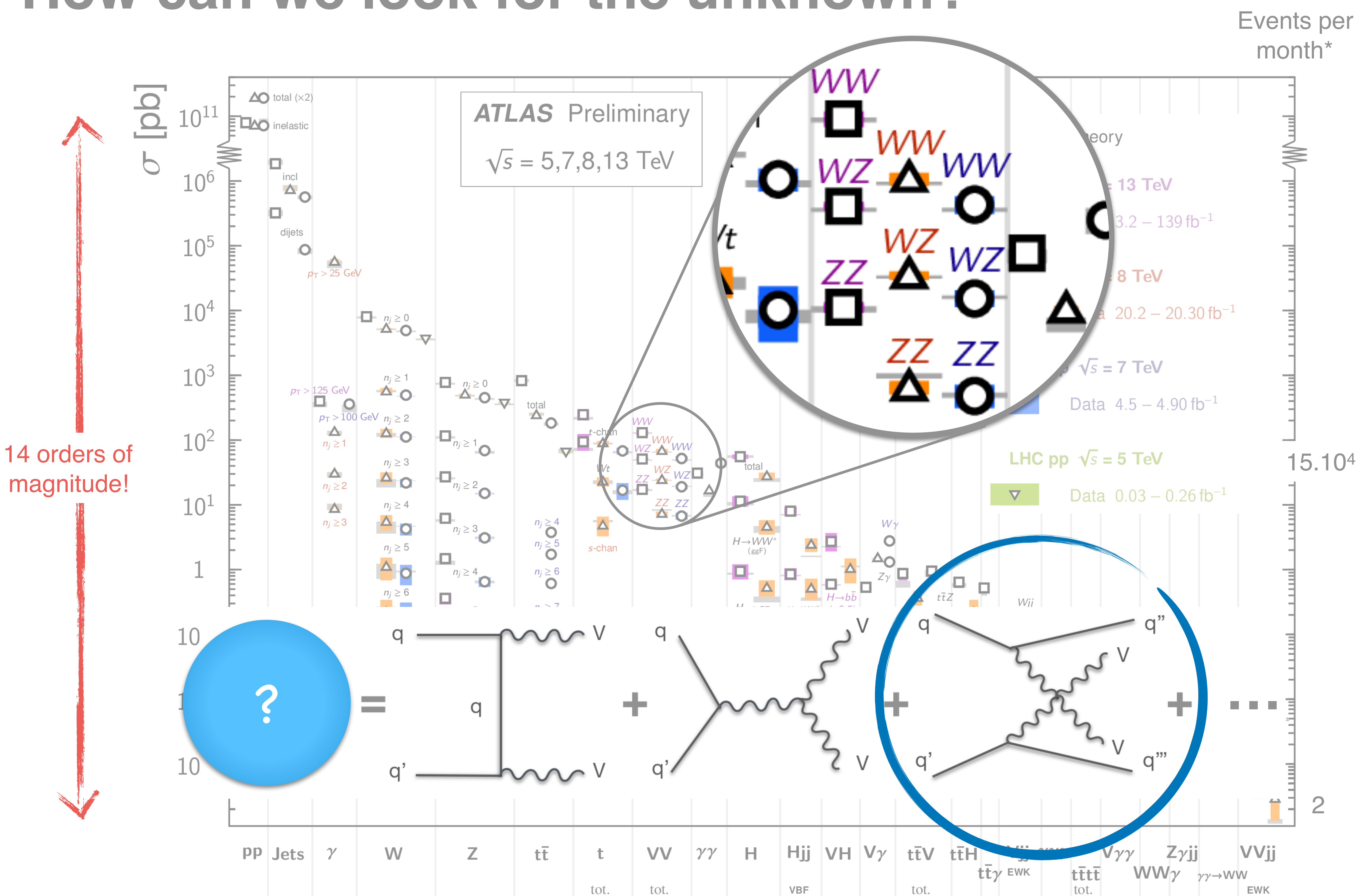
Good agreement with the SM predictions!

How do we explore those regions of the SM?

1. Get the vector bosons pairs
2. Compare with the Standard Model theory predictions

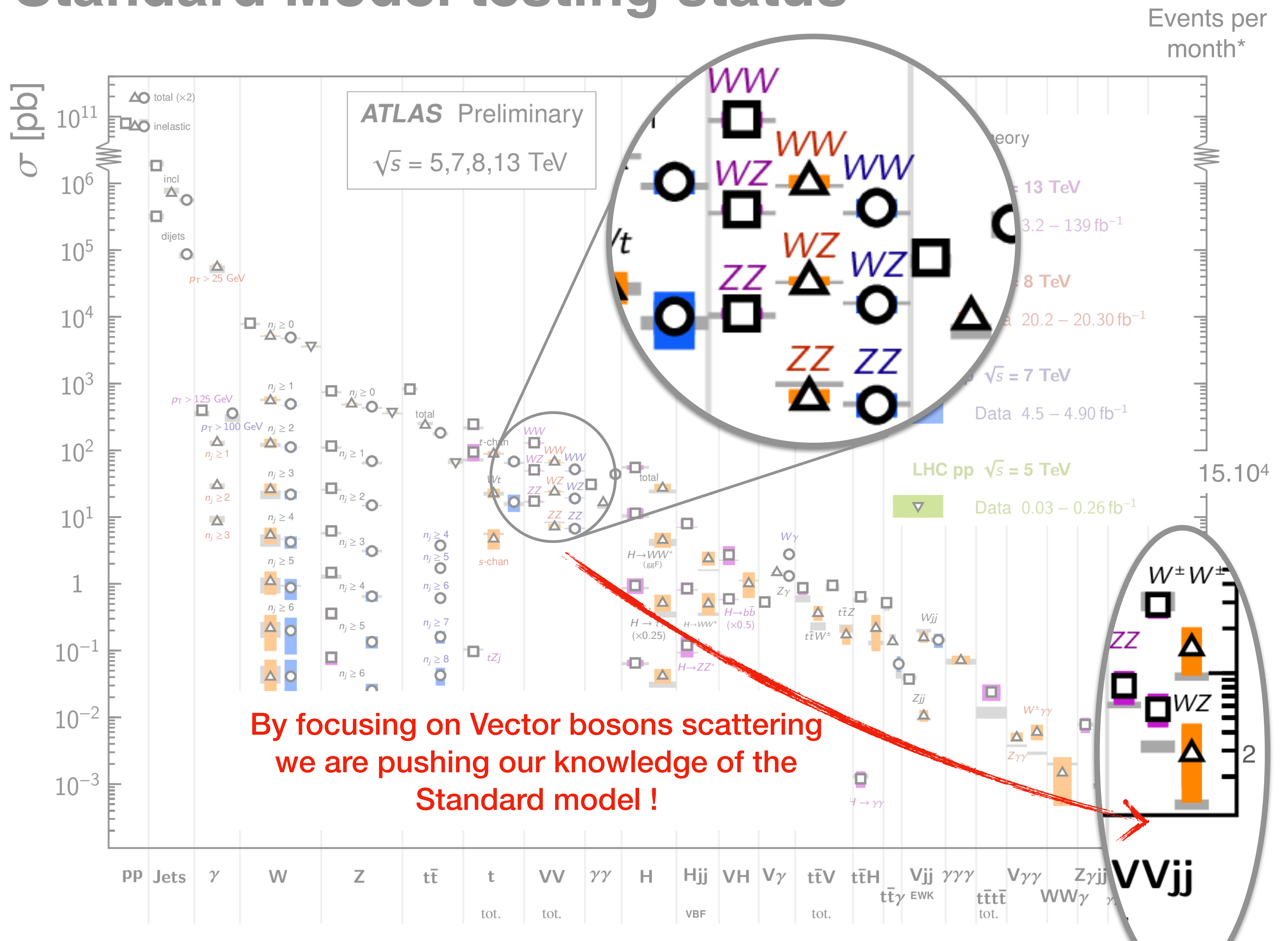
lets push harder!

How can we look for the unknown?



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

The Standard Model testing status

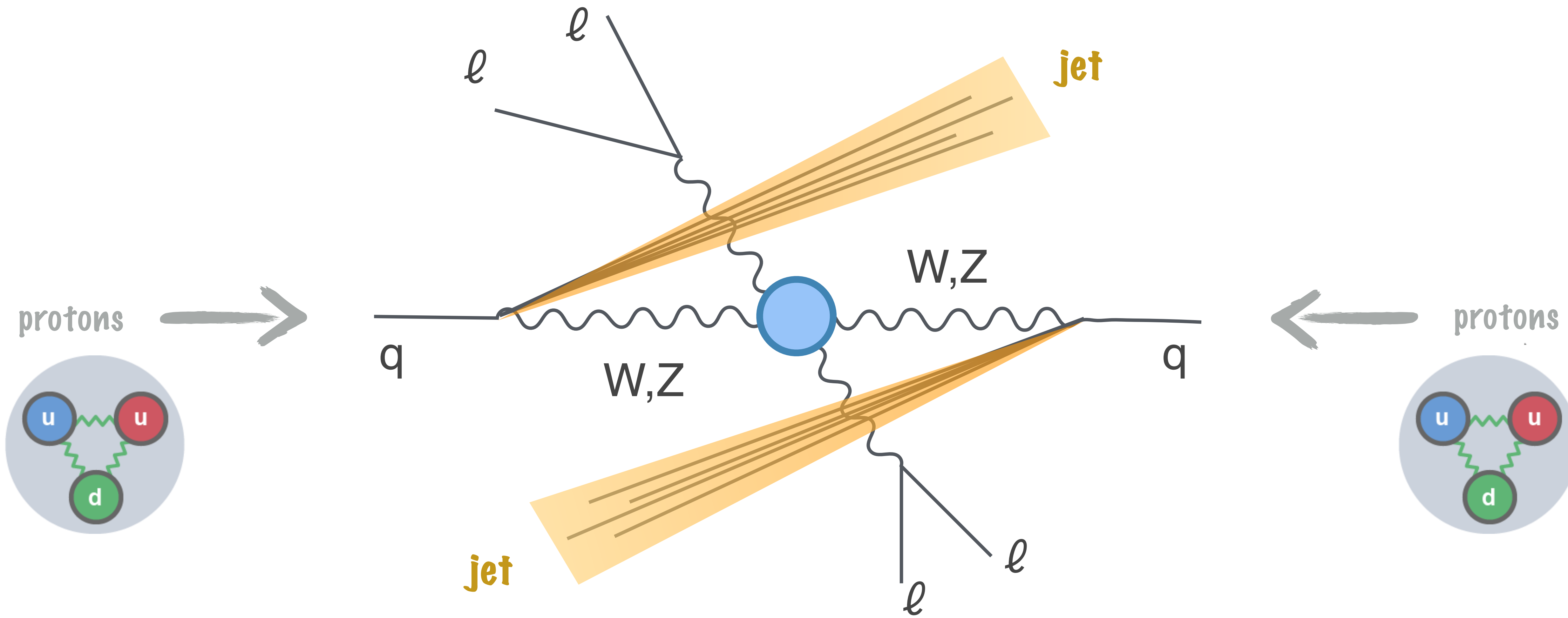


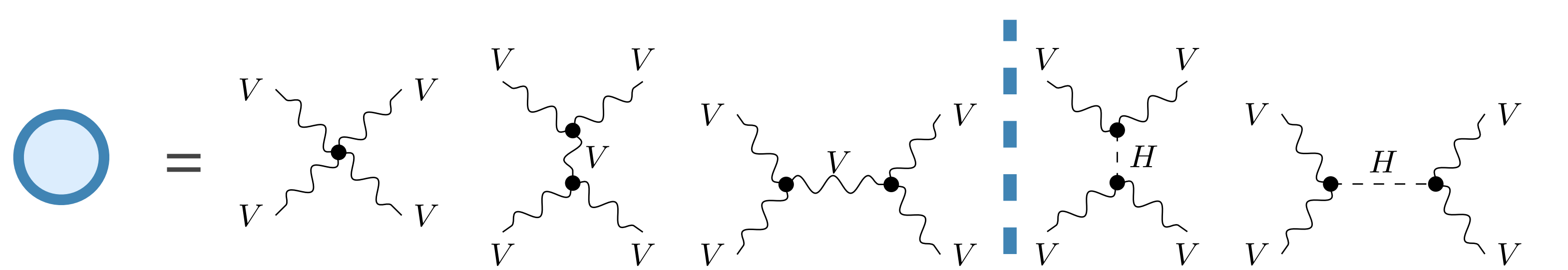
By focusing on Vector bosons scattering we are pushing our knowledge of the Standard model !

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

Vector Boson Scattering at the LHC

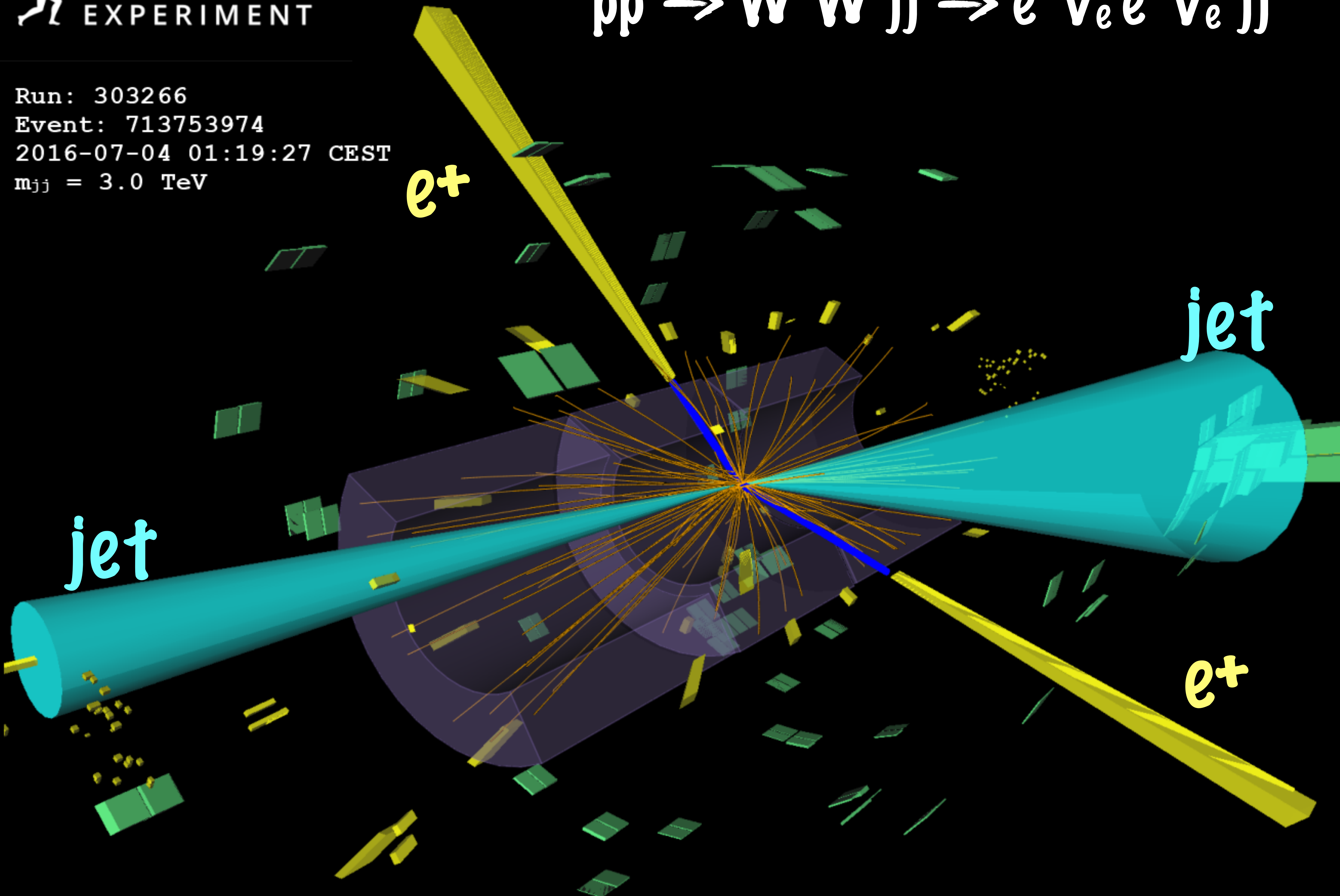
Protons in LHC serve as source of vector boson beams.

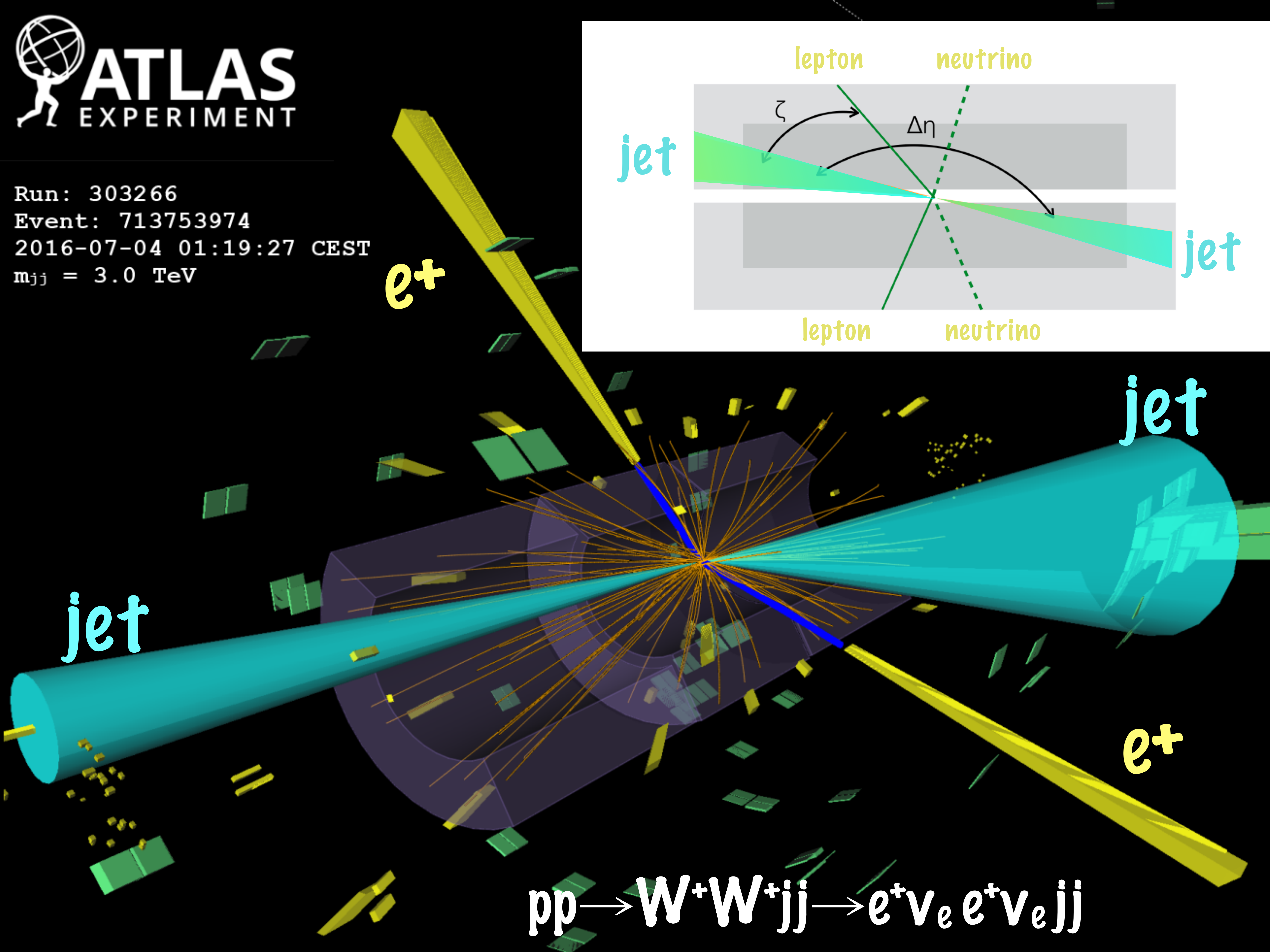




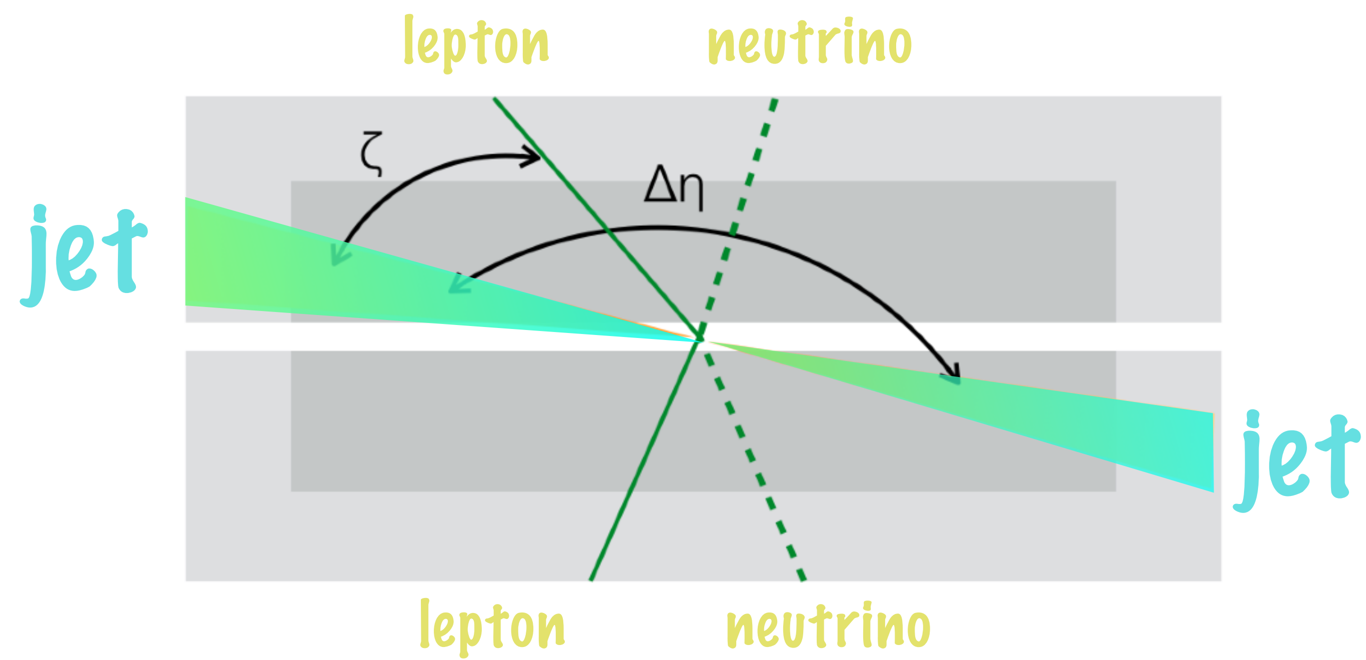
ATLAS EXPERIMENT

$pp \rightarrow W^+W^+jj \rightarrow e^+\nu_e e^+\nu_e jj$

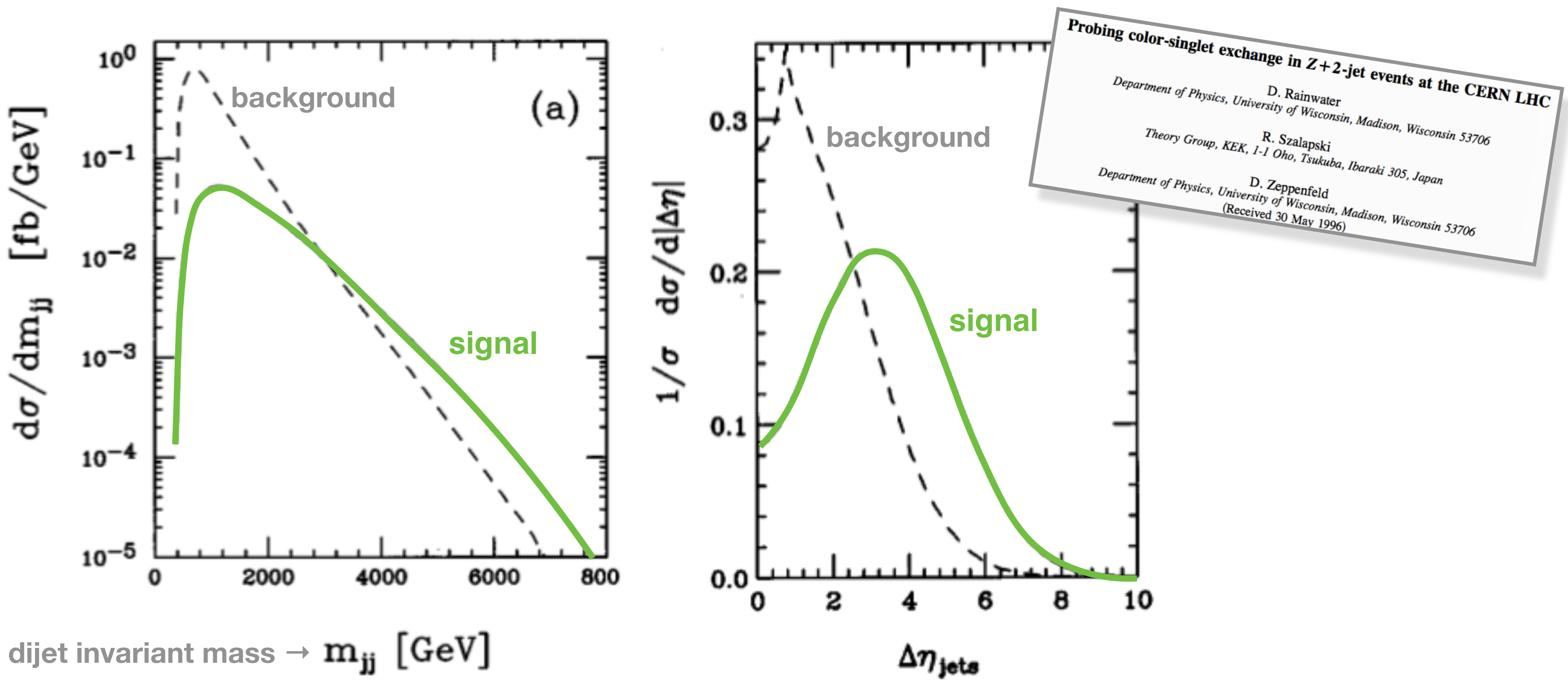



ATLAS EXPERIMENT
Run: 303266
Event: 713753974
2016-07-04 01:19:27 CEST
m_{jj} = 3.0 TeV
lepton
neutrino
ζ
Δη
jet
jet
lepton
neutrino
e+
jet
jet
e+
$pp \rightarrow W^+W^+jj \rightarrow e^+\nu_e e^+\nu_e jj$

The VBS topology



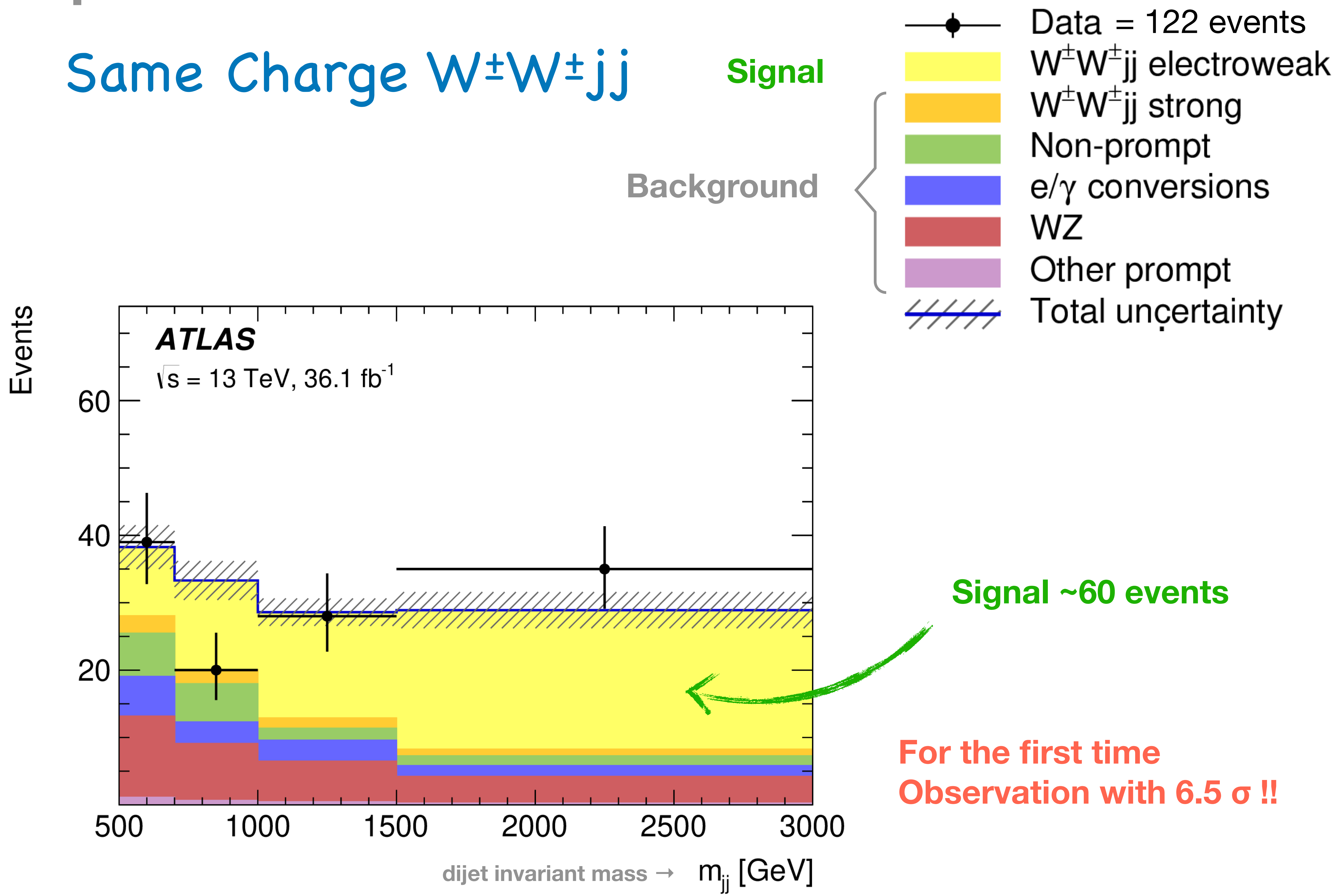
Theory calculations can provide us with differential cross sections



Knowing how the signal and backgrounds will look like allow us to push the discrimination (i.e using machine learning algorithms)

Experimental results

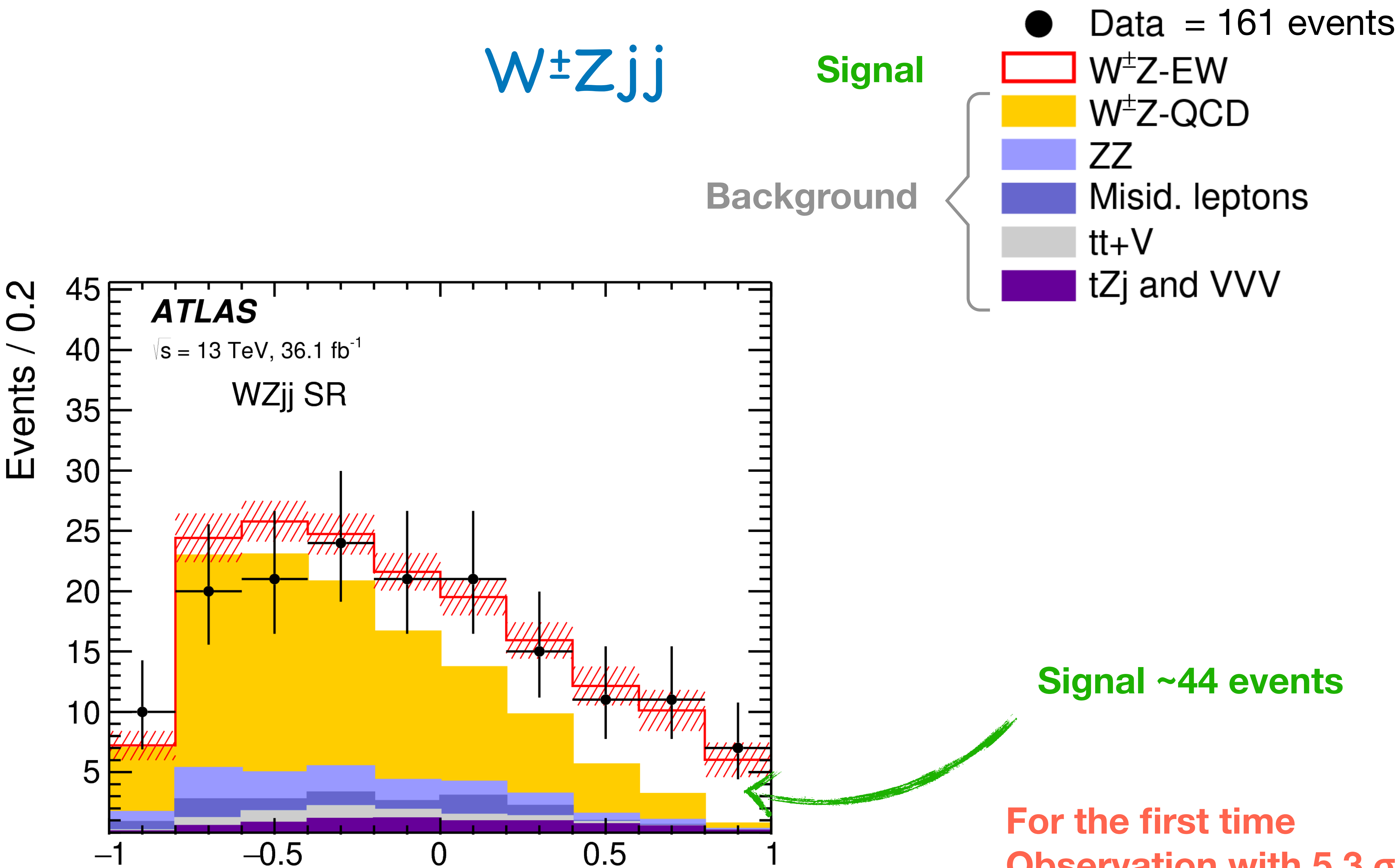
Same Charge $W^{\pm}W^{\pm}jj$



For the first time
Observation with 6.5 σ !!

Experimental results

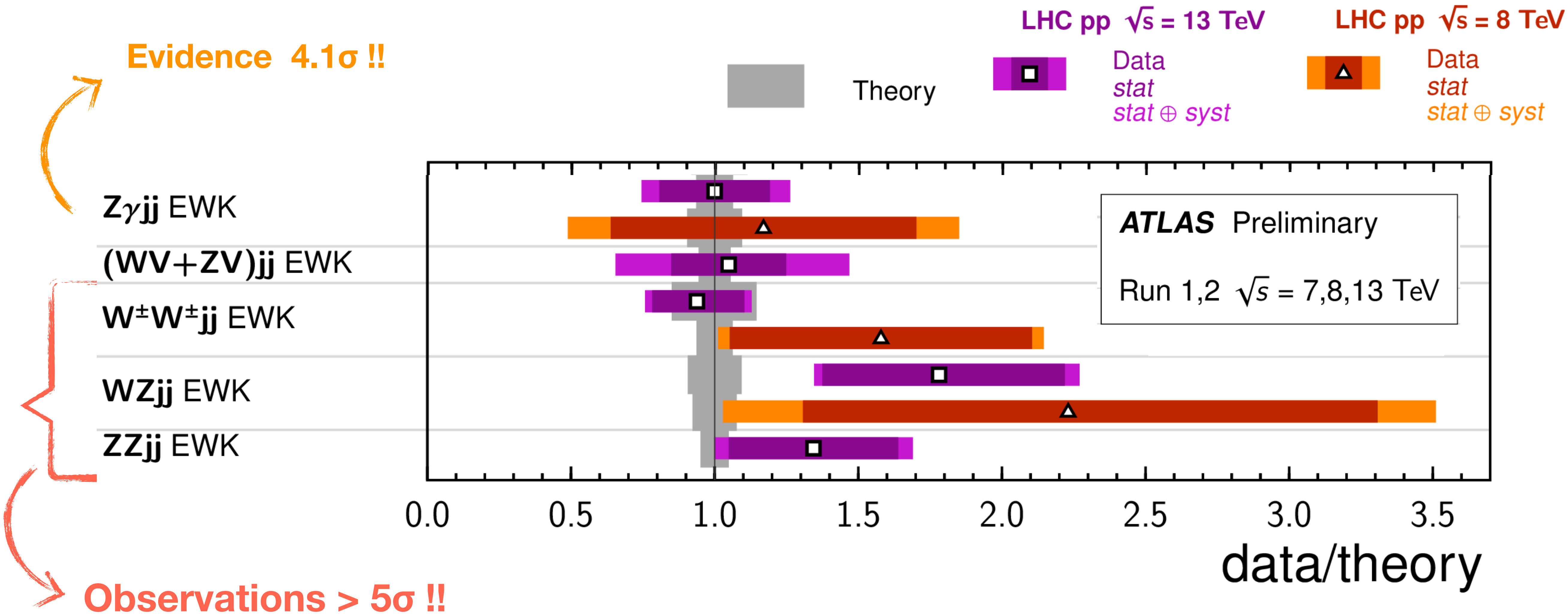
W±Zjj



Machine Learning discriminant output → BDT Score

For the first time
Observation with 5.3 σ !!

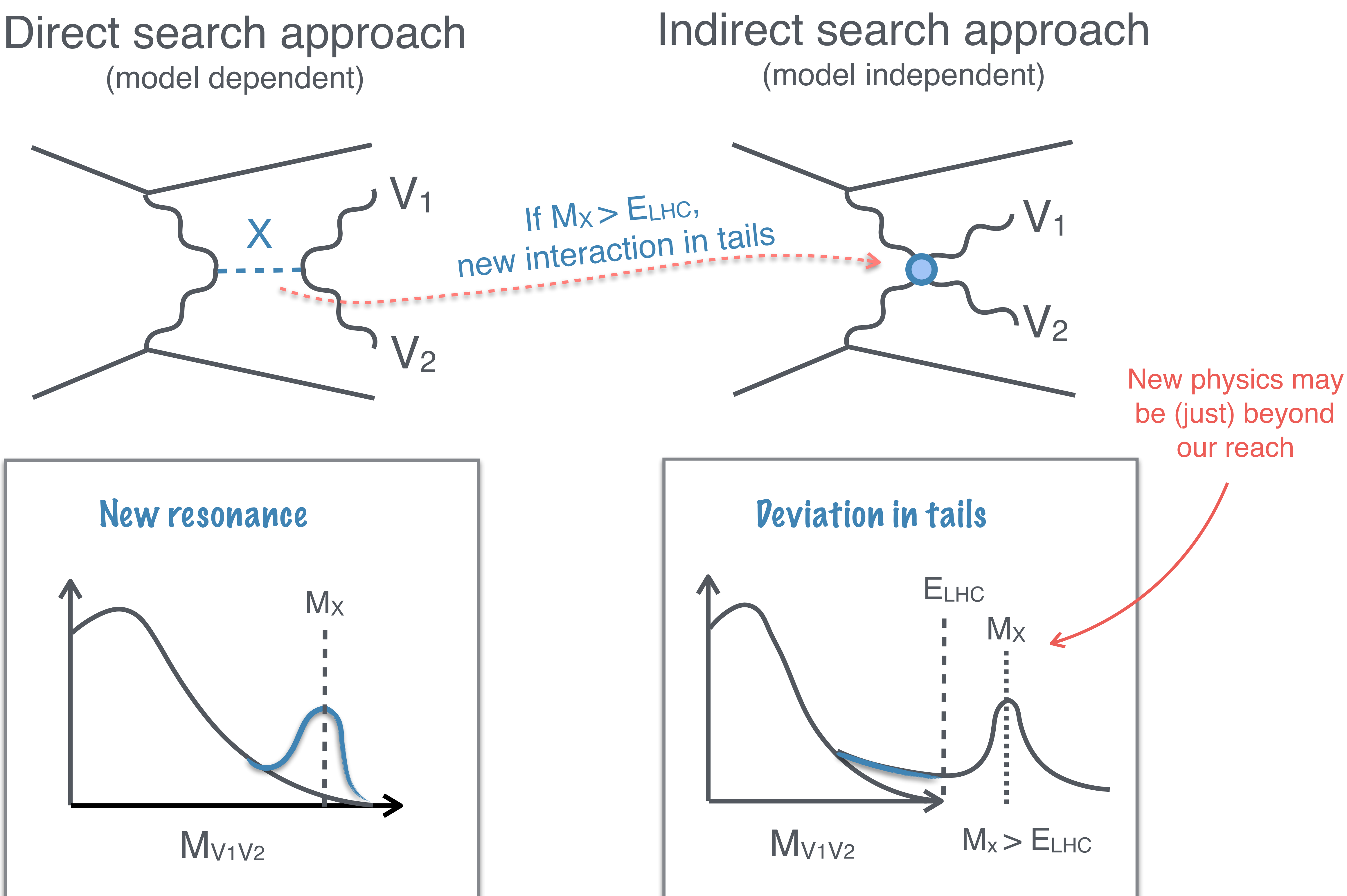
The cross sections measurements



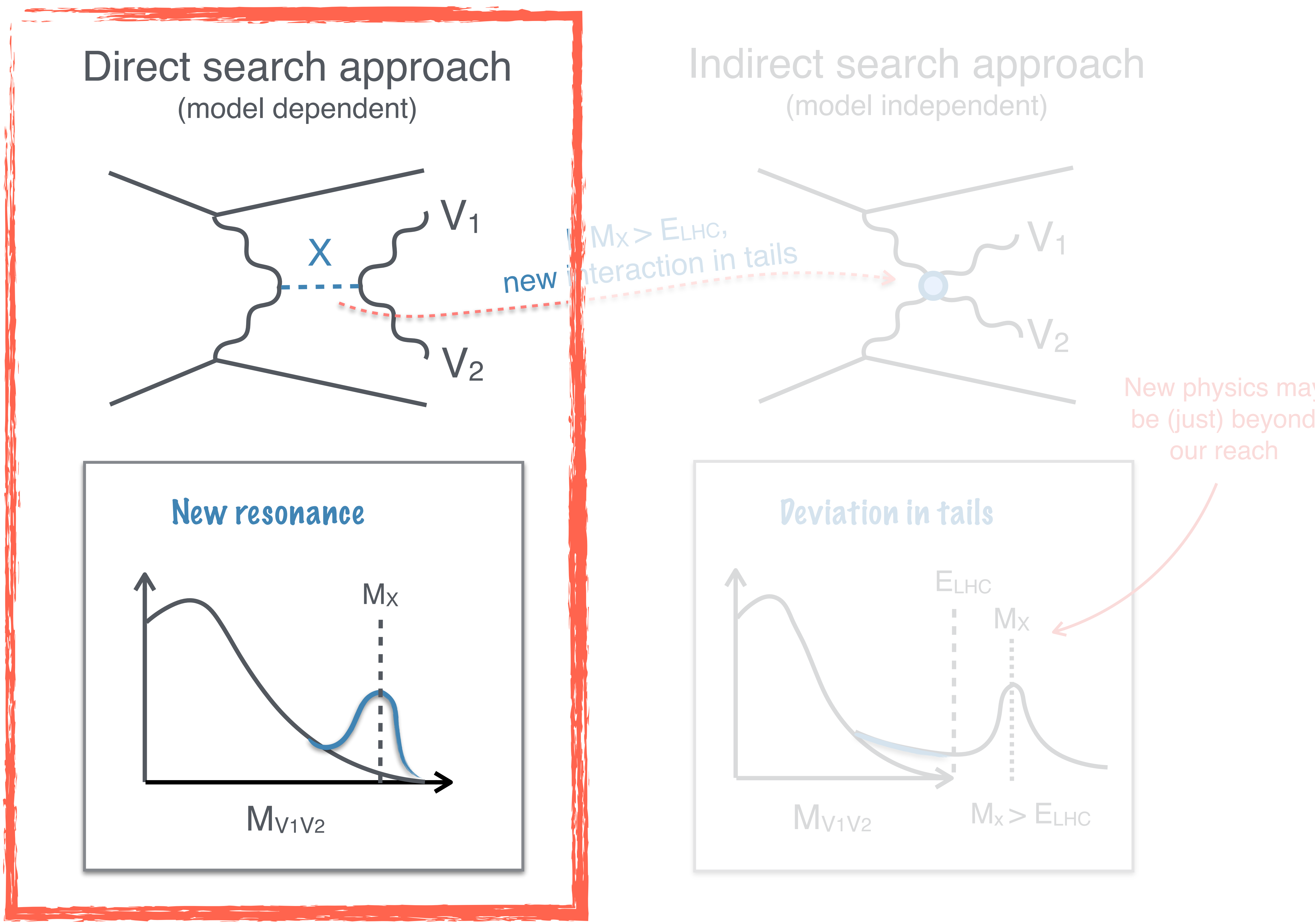
First results still dominated by statistical uncertainty but the full Run-2 data is still being processed and Run-3 is approaching!

How to look for the unknown?

New physics in bumps and tails



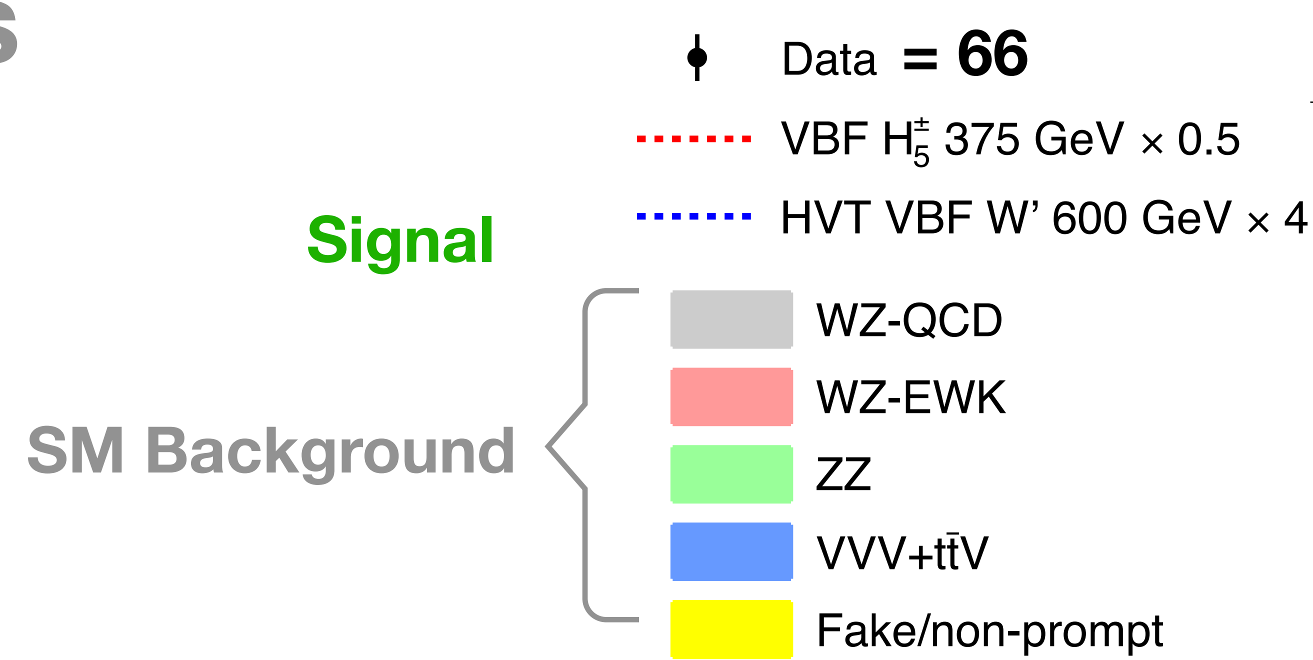
New physics in bumps and tails

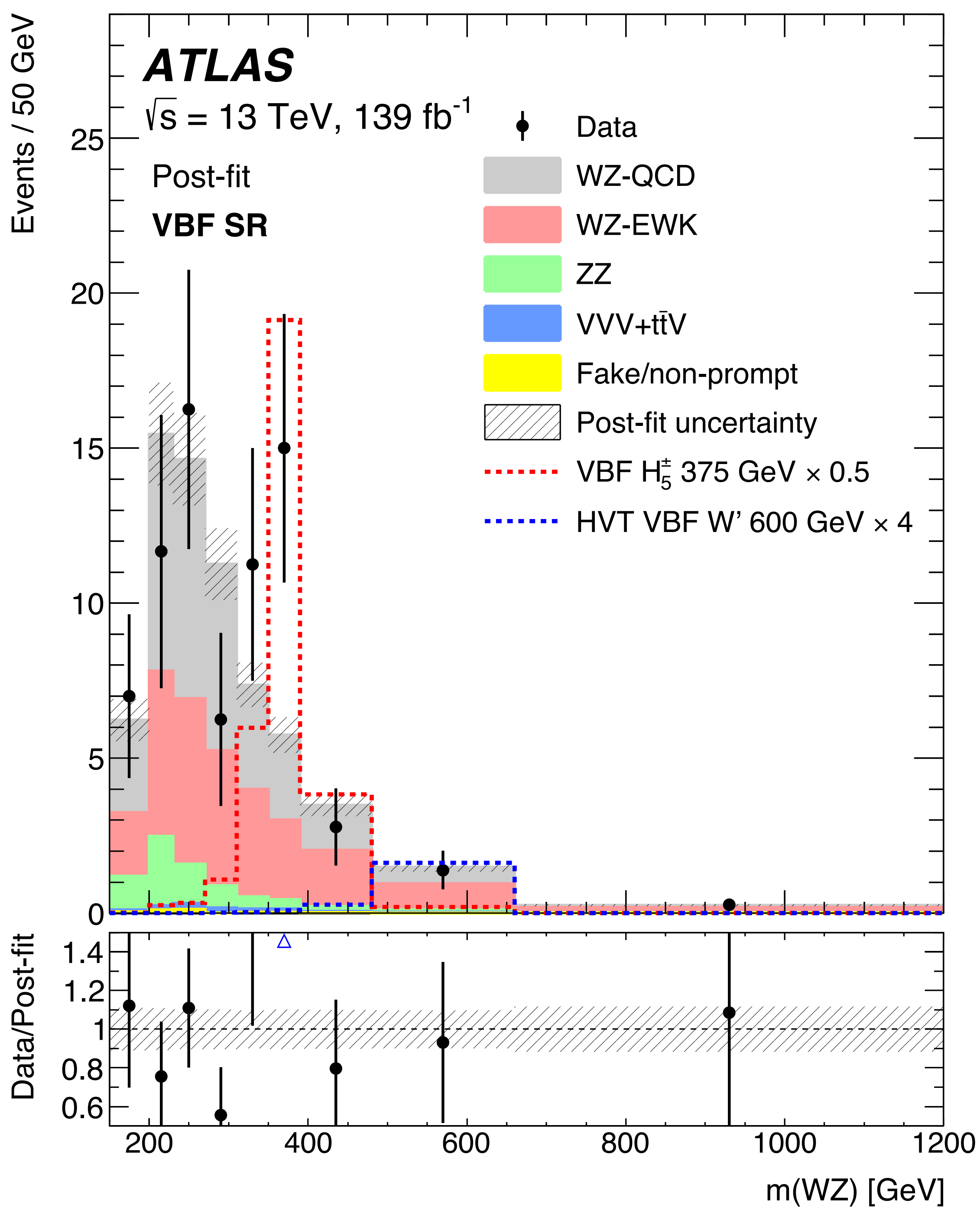


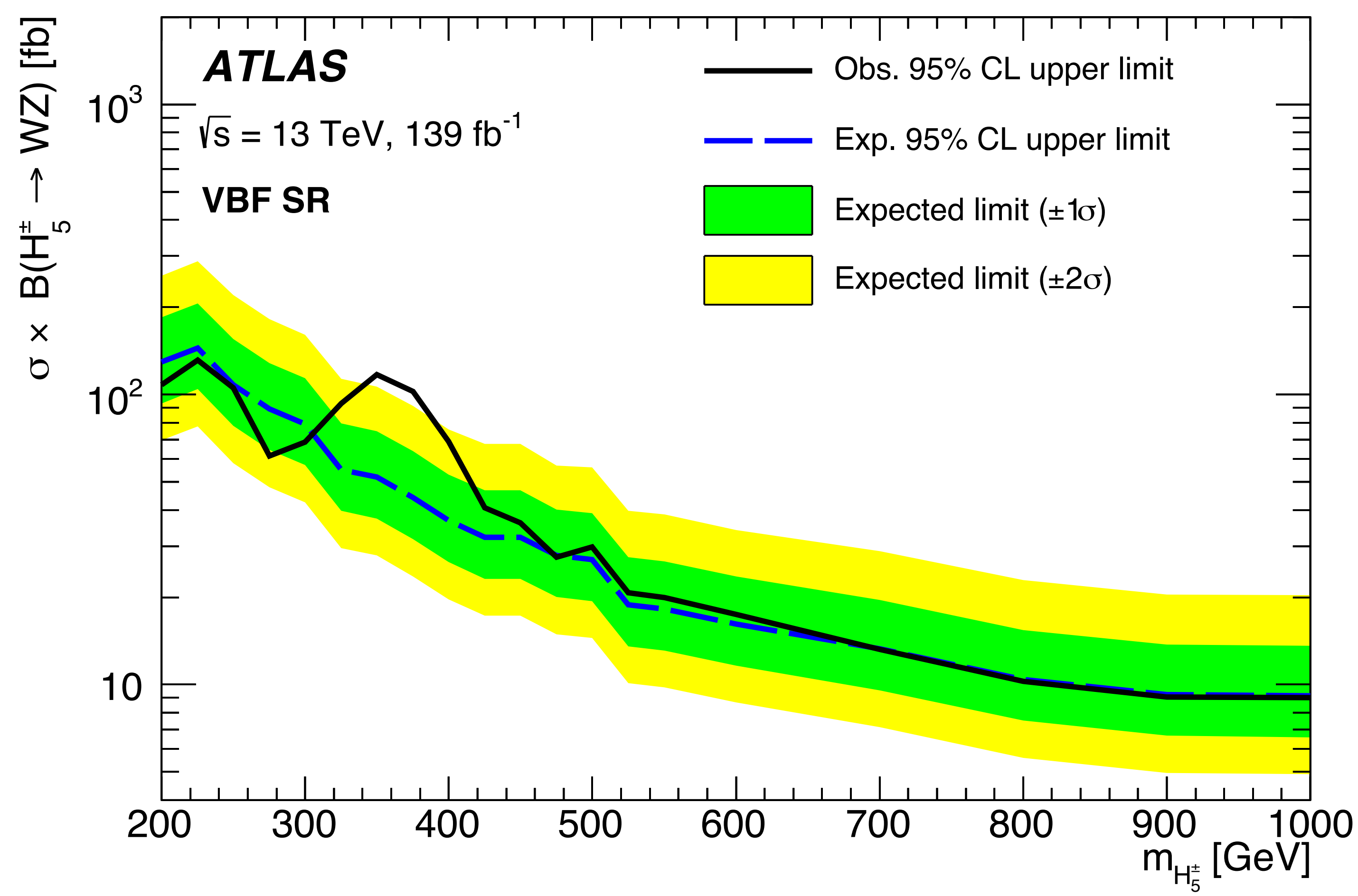
Looking for resonances

$pp \rightarrow H^{\pm}jj \rightarrow W^{\pm}Zjj$

The benchmark: The Georgi-Machacheck model predicts a charged Higgs boson





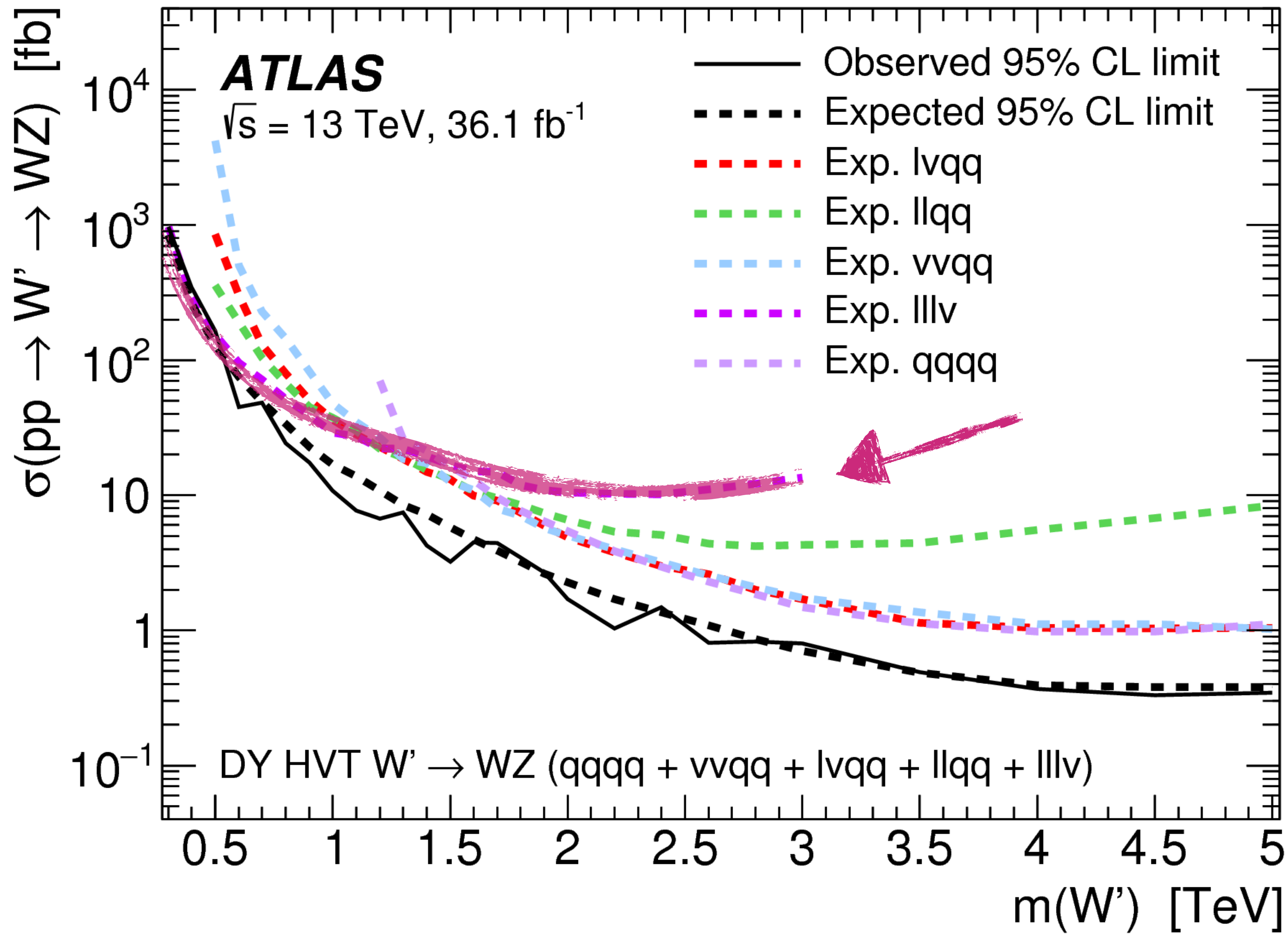


Observed limit: compare data to models
Expected limit: compare background only to models

Combined search for resonances

$pp \rightarrow W'^{\pm} \rightarrow W^{\pm}Z$

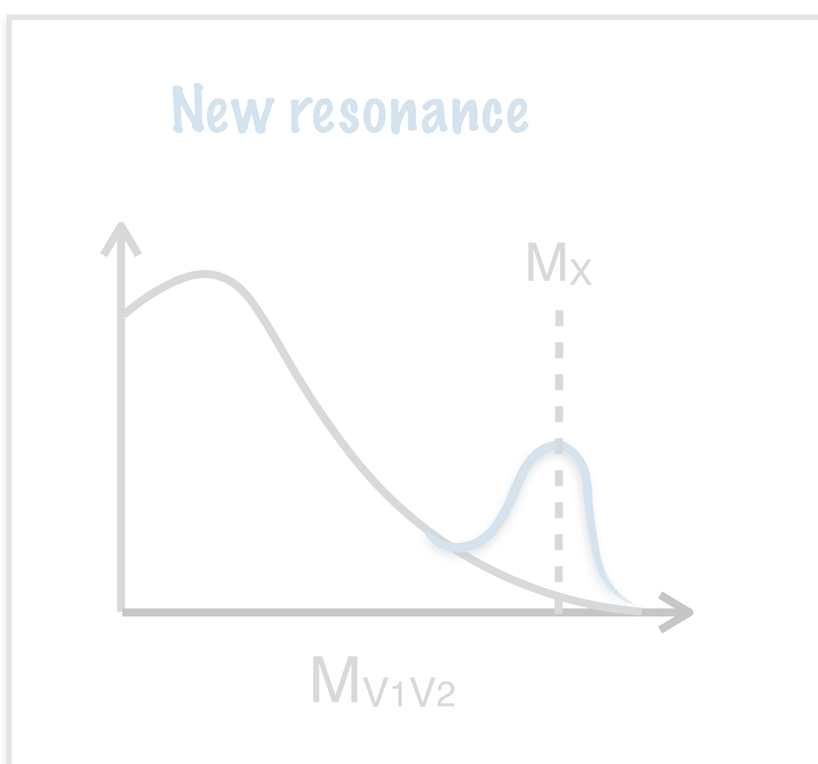
The benchmark: The Heavy Vector Triplet Lagrangian parametrization that predicts a W'



New physics in bumps and tails

Direct search approach

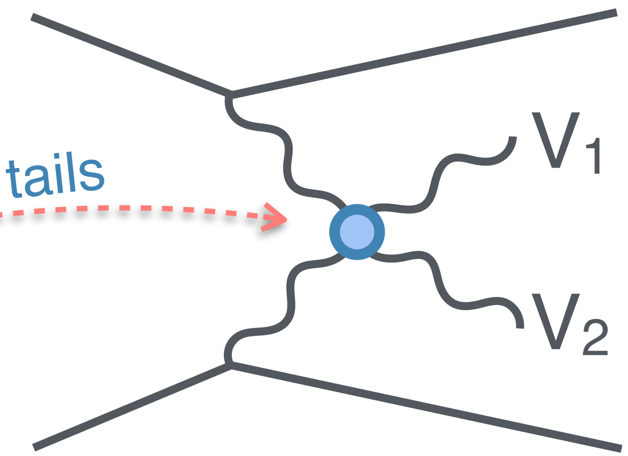
(model dependent)



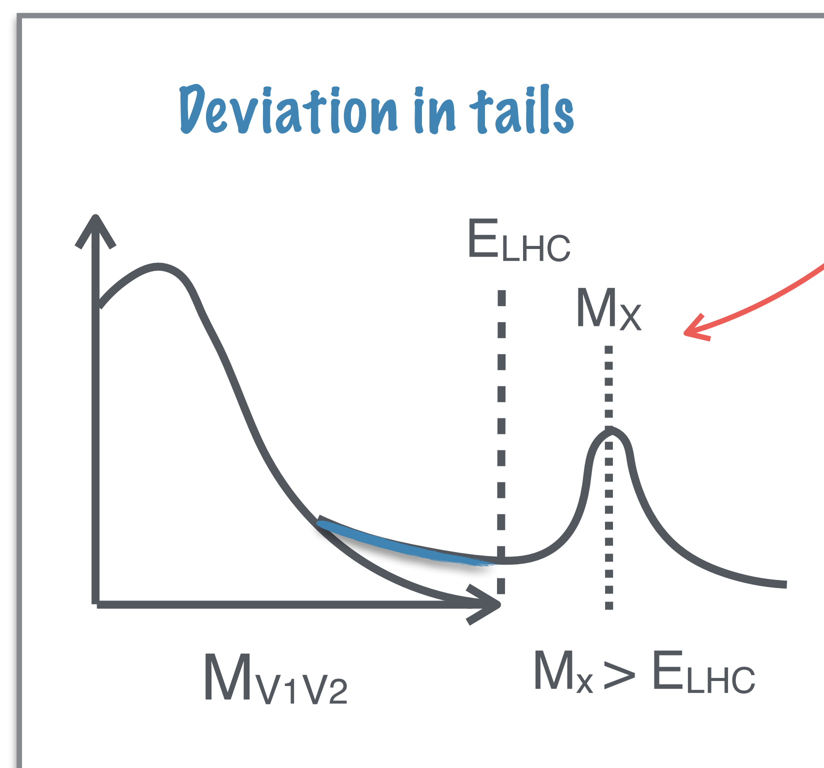
If $M_X > E_{LHC}$,
new interaction in tails

Indirect search approach

(model independent)



New physics may be (just) beyond our reach

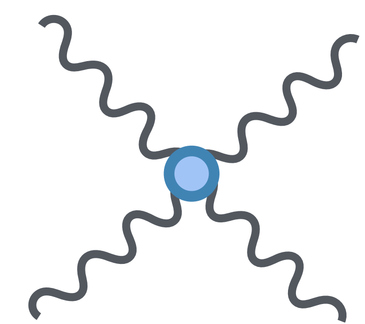


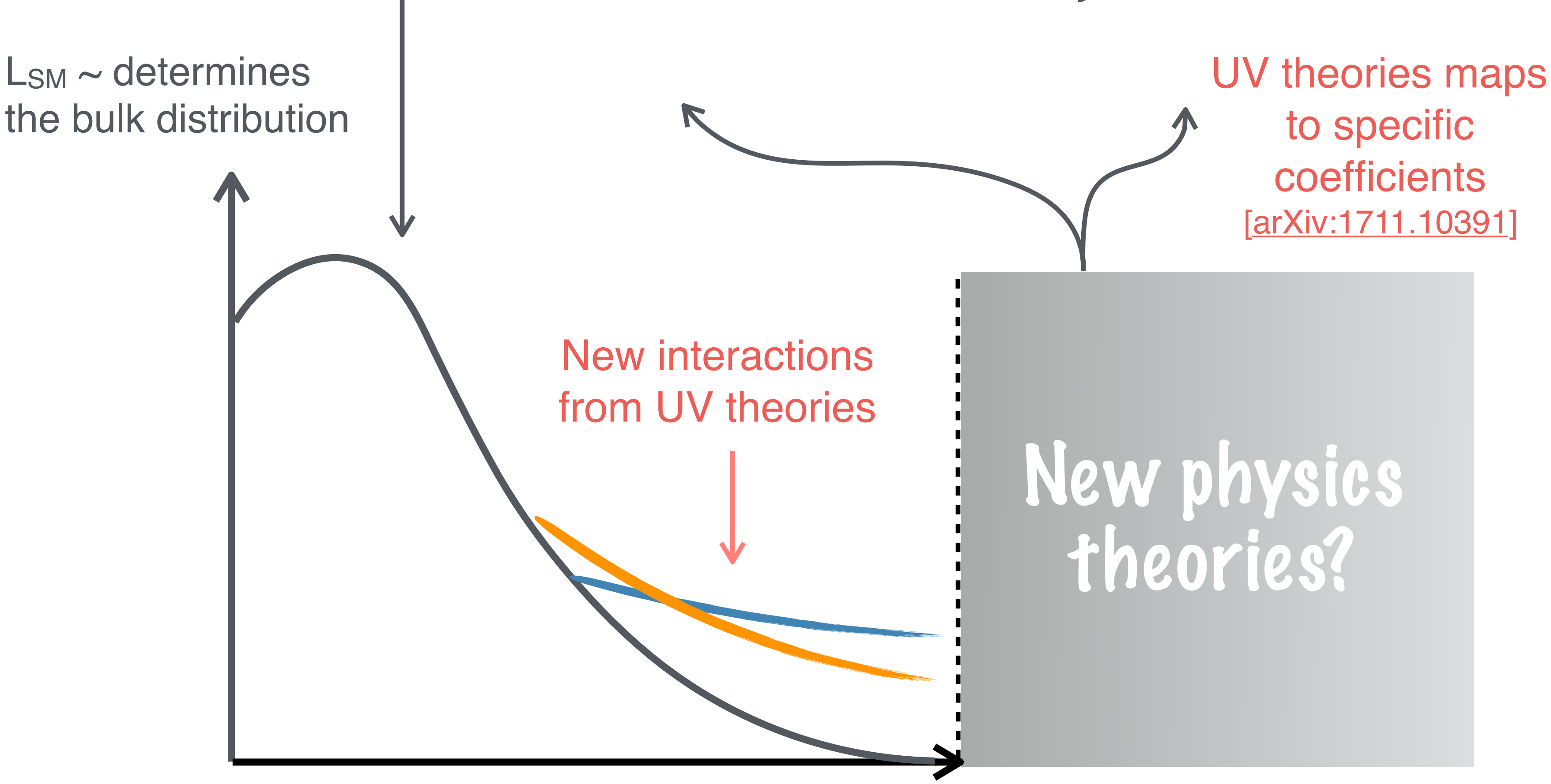
The SM Effective Field Theory

- Deviations are parametrized by higher order operators from SM fields

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

dim-8 operators can
affect VBS at tree level





- EFT are model independent and self consistent framework for parametrizing deviations from the SM

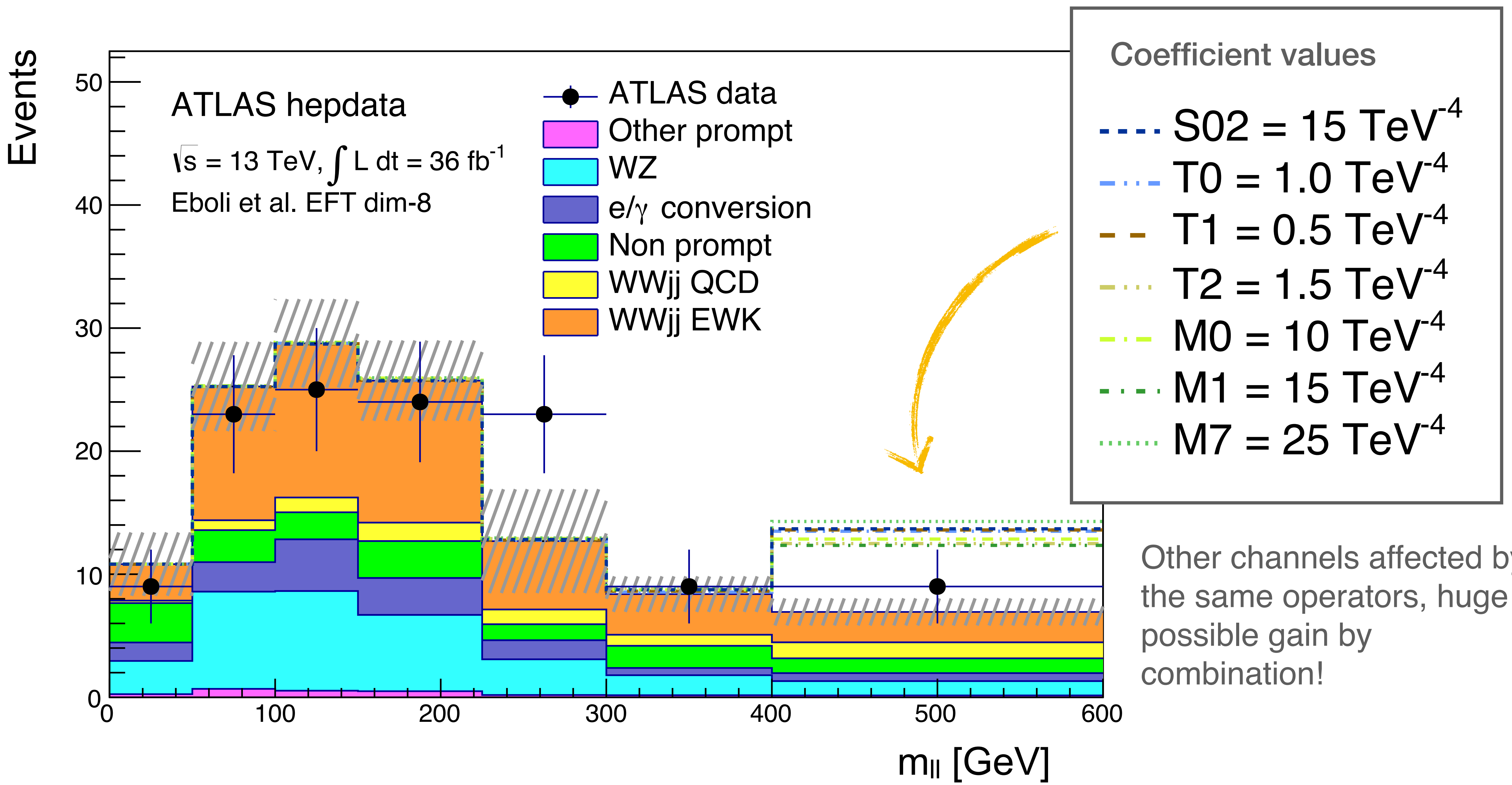
The SM Effective Field Theory

Same Charge $W^{\pm}W^{\pm}jj$

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

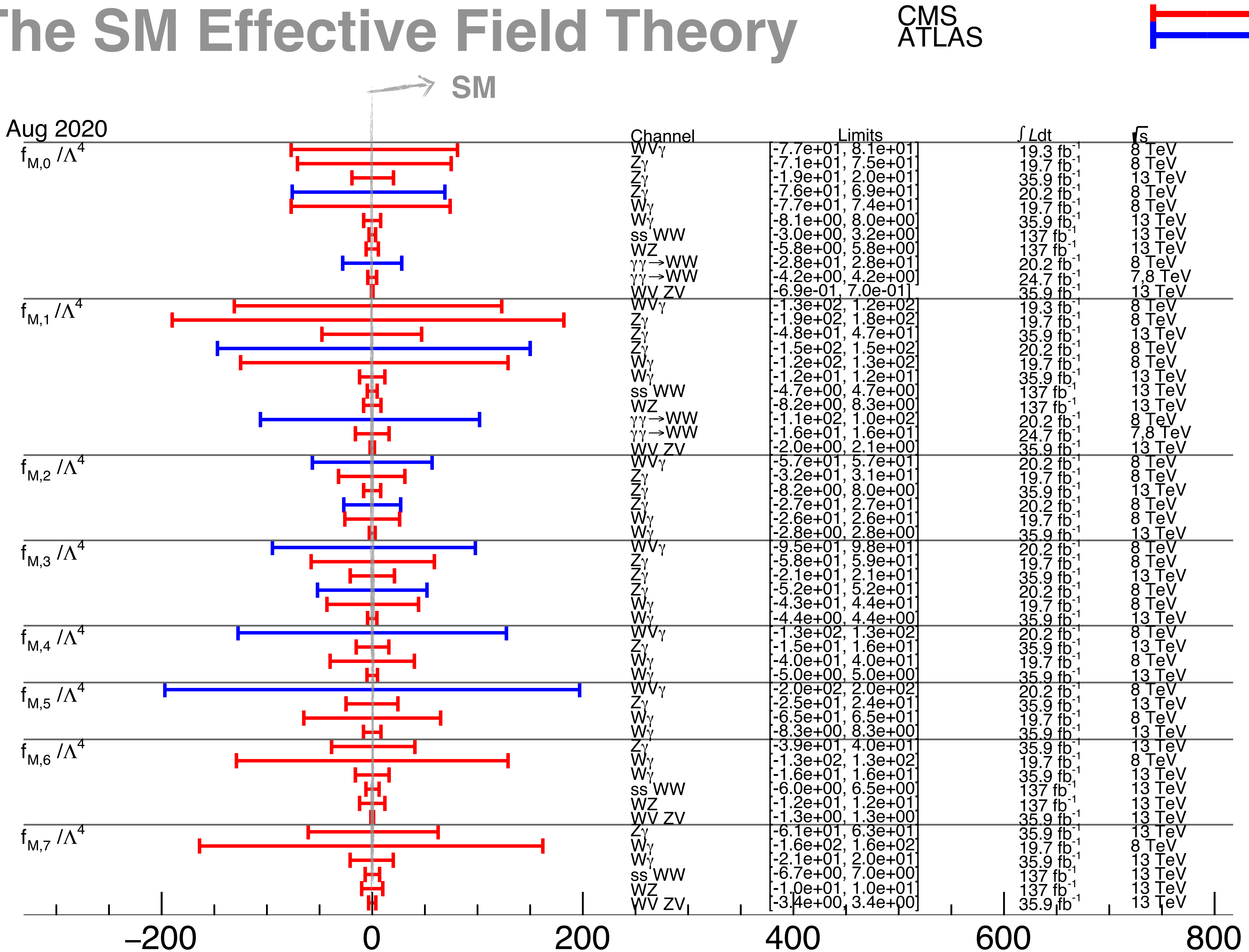
BSM interactions of SM particles (O_{T2})

Coefficient (F_{T2})



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

The SM Effective Field Theory



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.9e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.1e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-3.0e+00, 3.2e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.9e-01, 7.0e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.8e+01, 4.7e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.7e+00, 4.7e+00]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-8.2e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.1e+01, 2.1e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.4e+00, 4.4e+00]	35.9 fb^{-1}	13 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-1.5e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.0e+00, 5.0e+00]	35.9 fb^{-1}	13 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-2.5e+01, 2.4e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.3e+00, 8.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,6}/\Lambda^4$	Zγ	[-3.9e+01, 4.0e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.6e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.0e+00, 6.5e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.2e+01, 1.2e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Zγ	[-6.1e+01, 6.3e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.1e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.7e+00, 7.0e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+01, 1.0e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

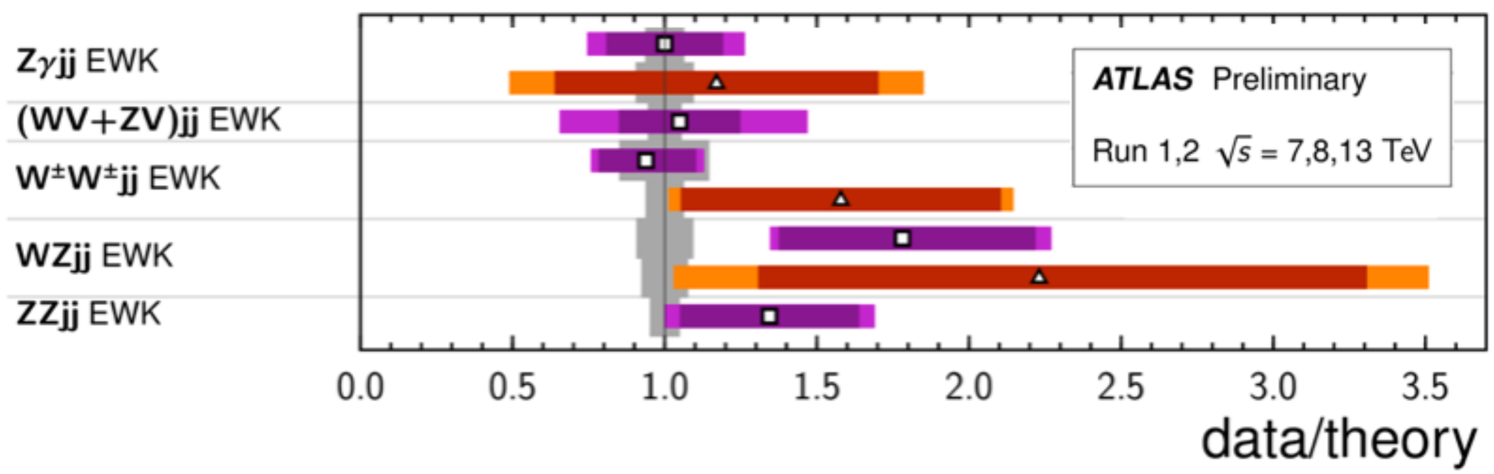
Take away

know know

things we know we know

The Standard Model stands strong!

- We have observed one of the most rare processes predicted by the SM!



- We can push harder by looking at polarized vector bosons self interactions

unknown unknown

things we don't know we don't know

We are actively looking for them, nothing so far but there is still room for **Surprises!**

* Rumsfeld's Matrix of Knowledge