Vector Boson Scattering @ LHC

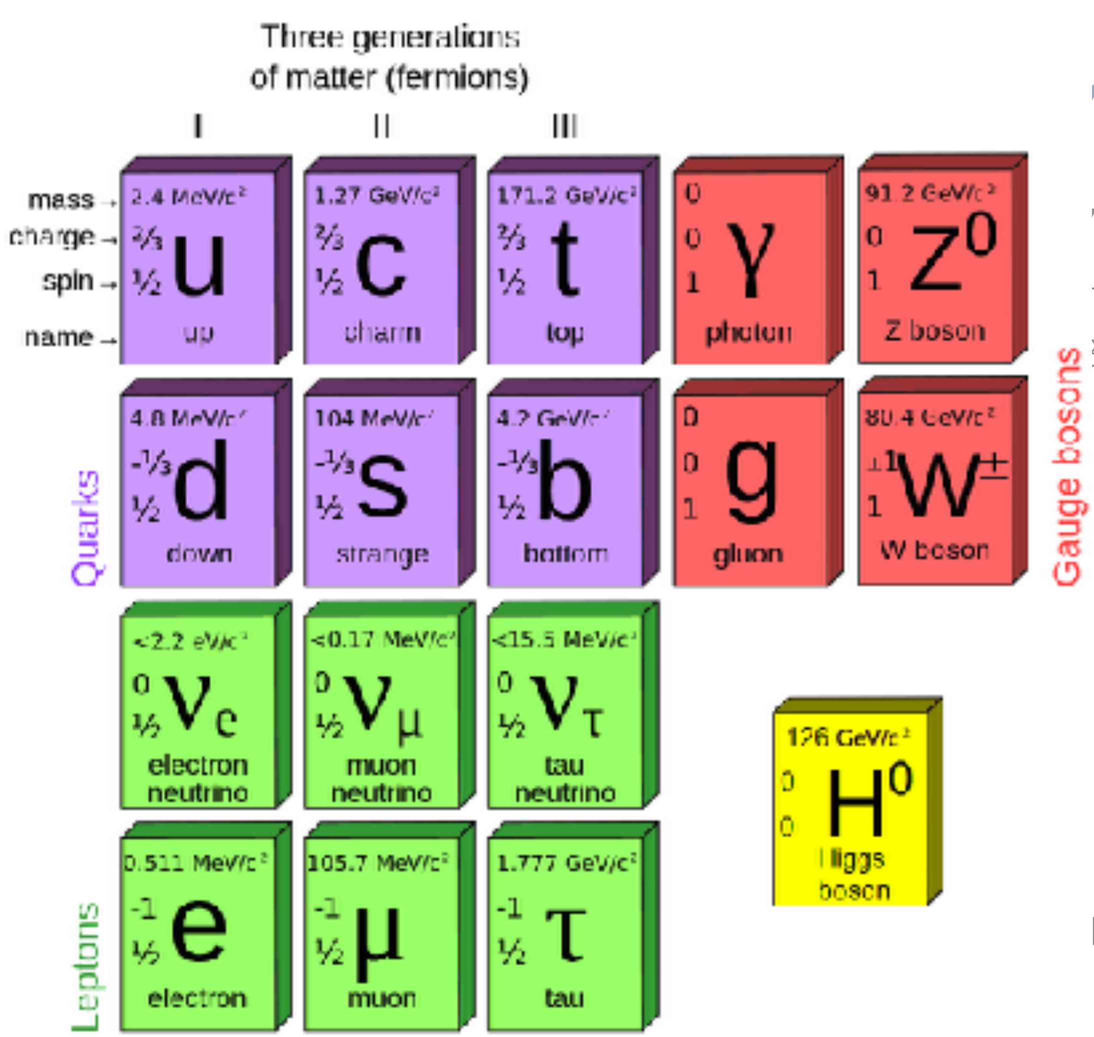
and VBSCan

Joany Manjarrés

on behalf of the TU Dresden VBS group
and the VBSCan community

September 1st, 2018

Vector Boson Scattering @ LHC



/BSCan

' Manjarrés

TU Dresden VBS group
3SCan community

ber 1st, 2018

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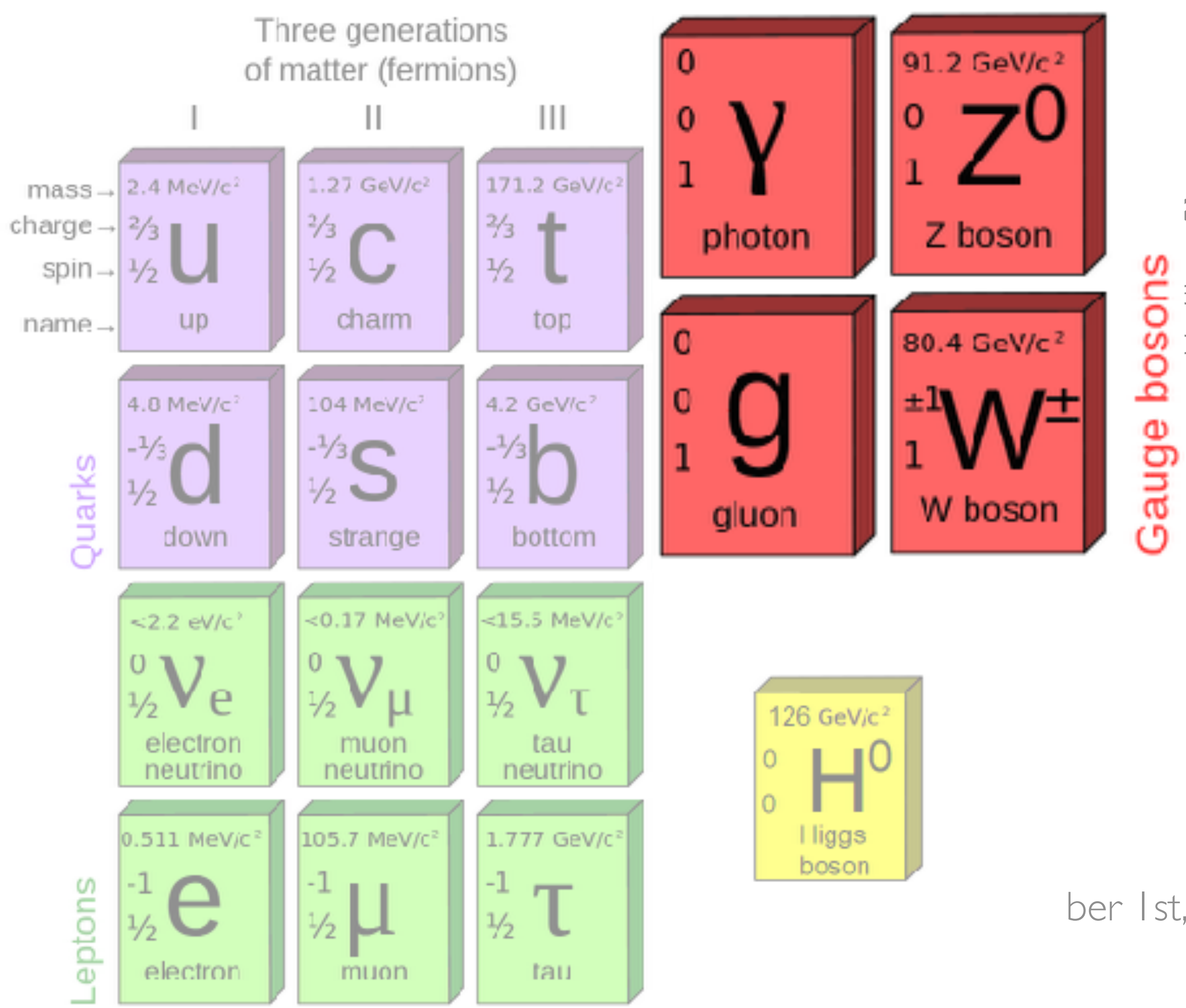
Vector Boson Scattering @ LHC



SCan

arrés

esden VBS group

community

ber 1st, 2018

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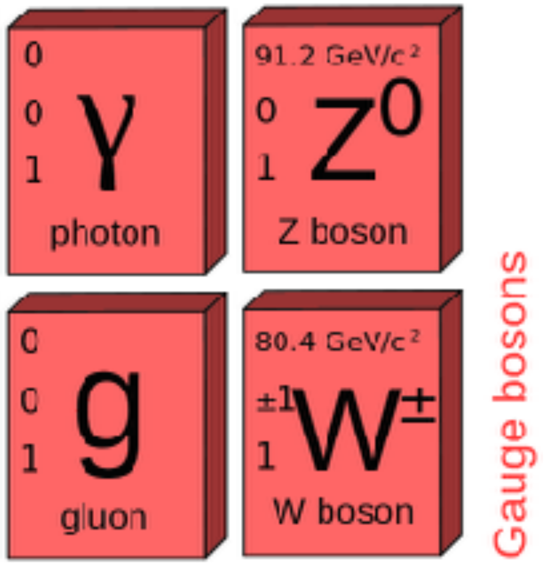

September 1st, 2018

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Vector Boson Scattering @ LHC

and VBSCan

Large
Hadron
Collider

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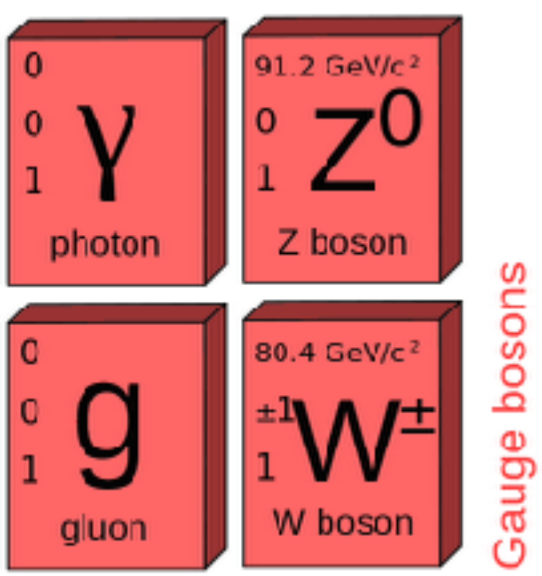

September 1st, 2018

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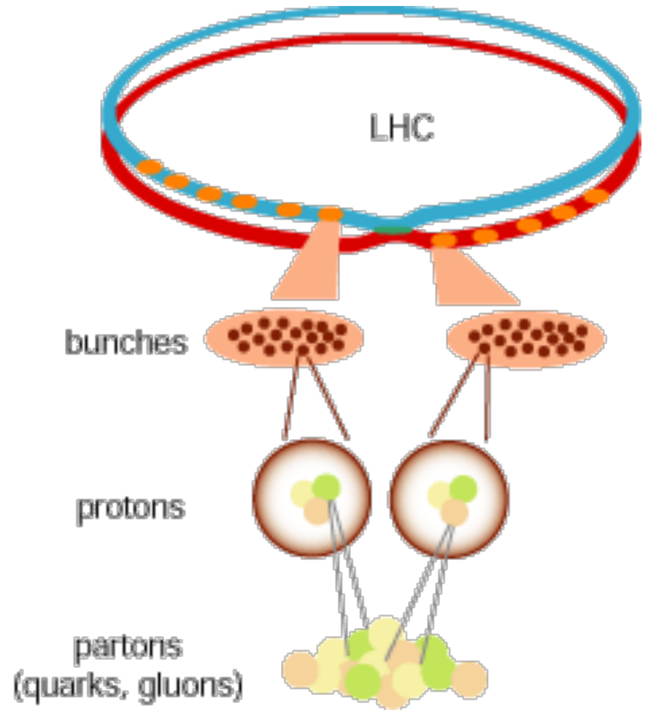
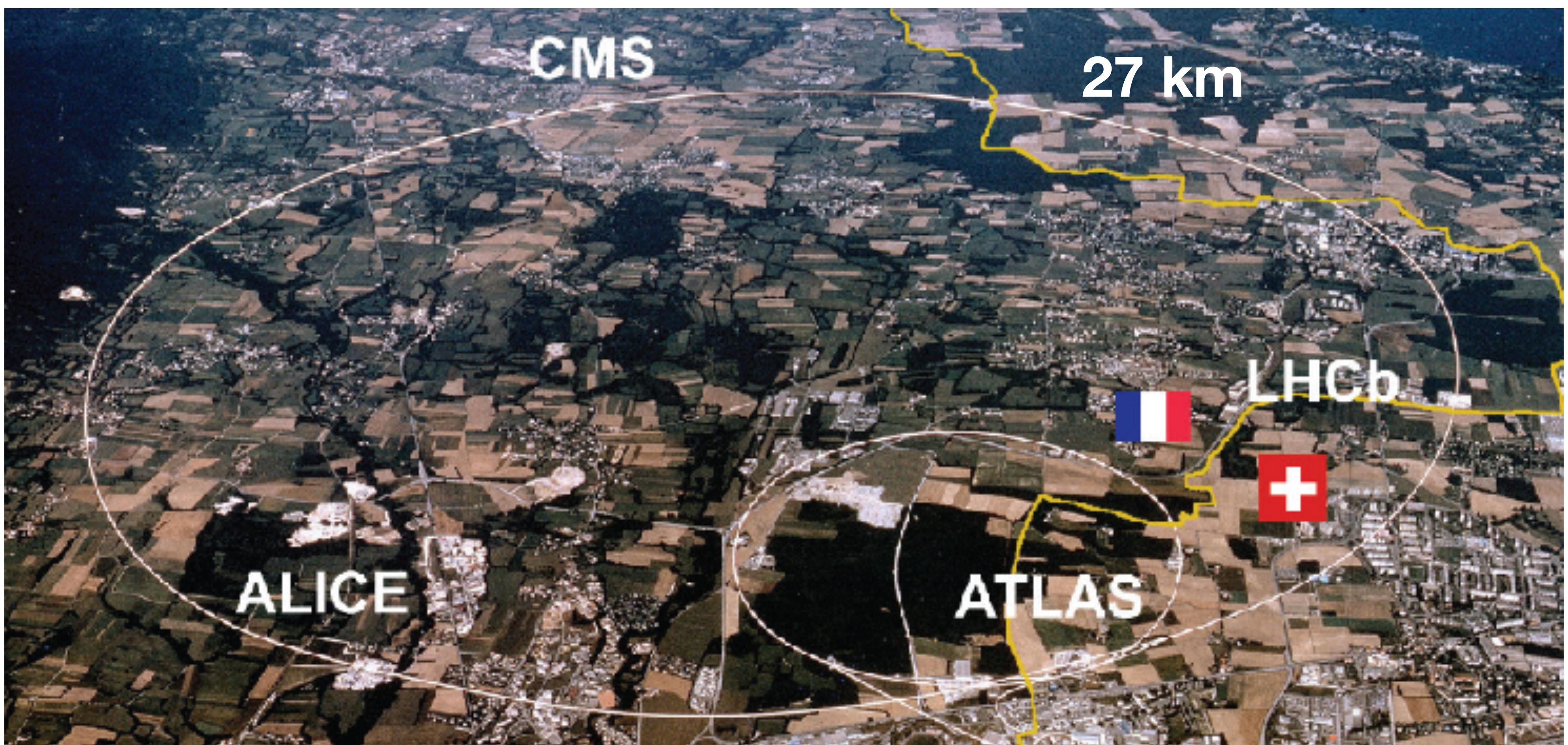
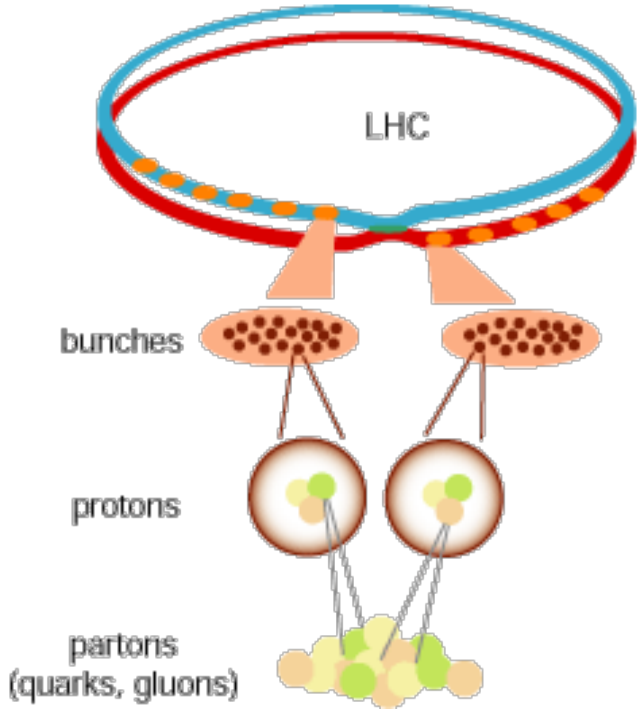


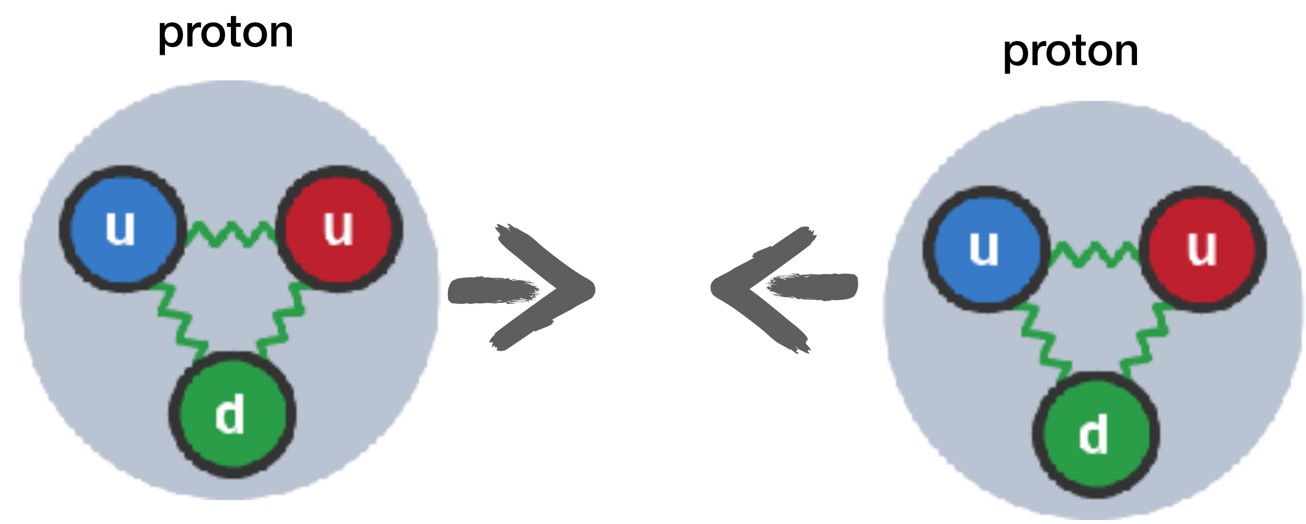
Vector Boson Scattering @ LHC



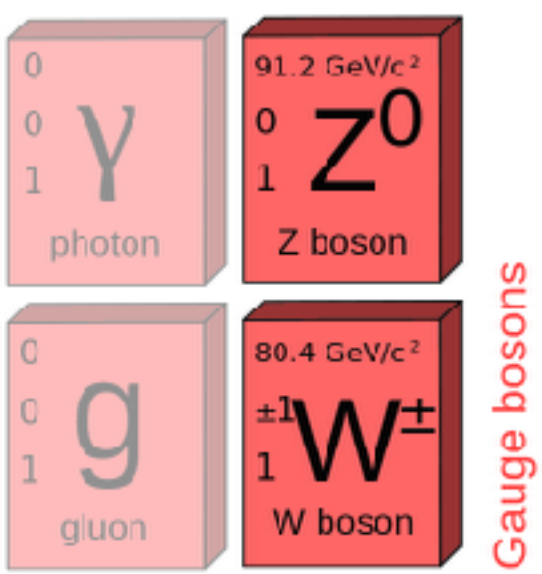
Large
Hadron
Collider

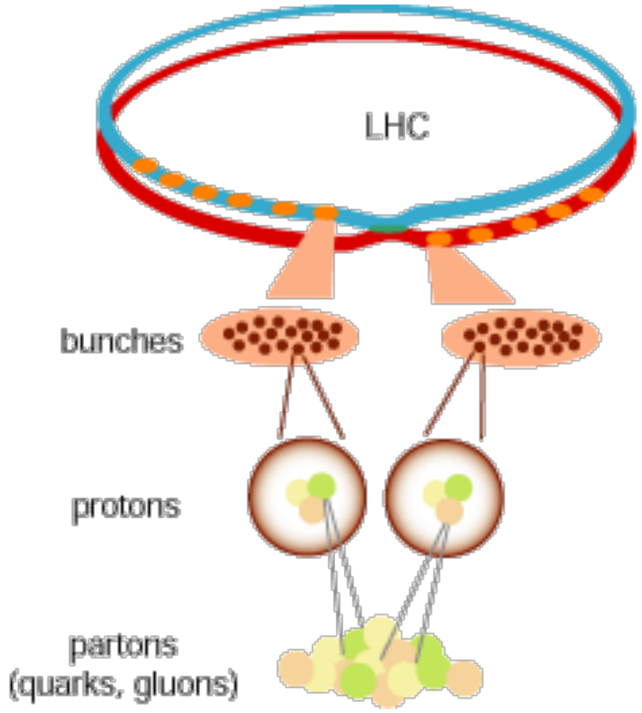
CERN

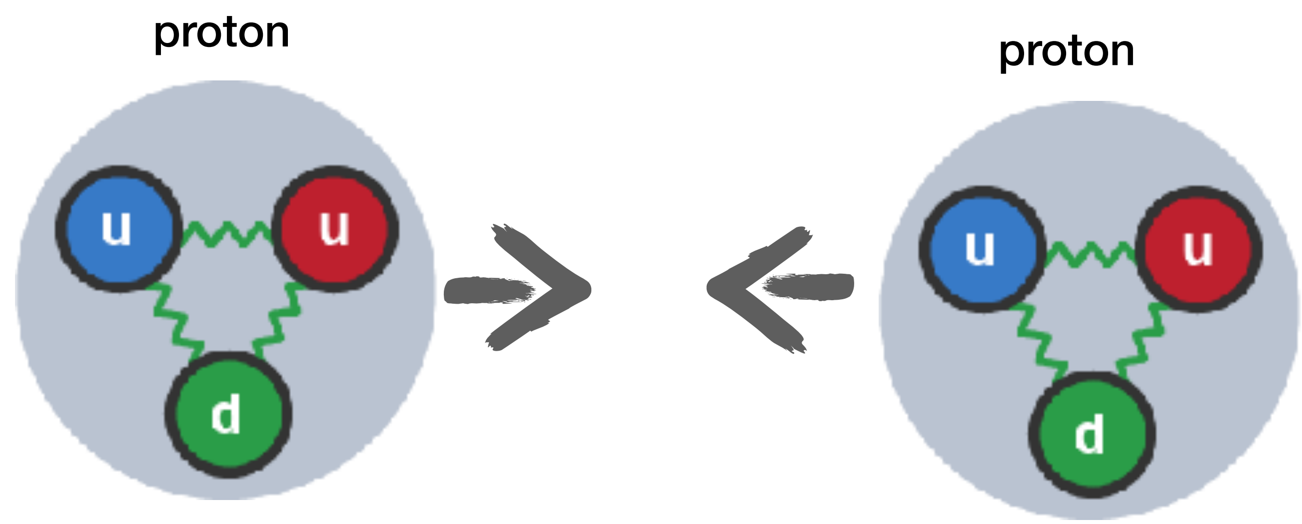




Vector Boson Scattering @ LHC







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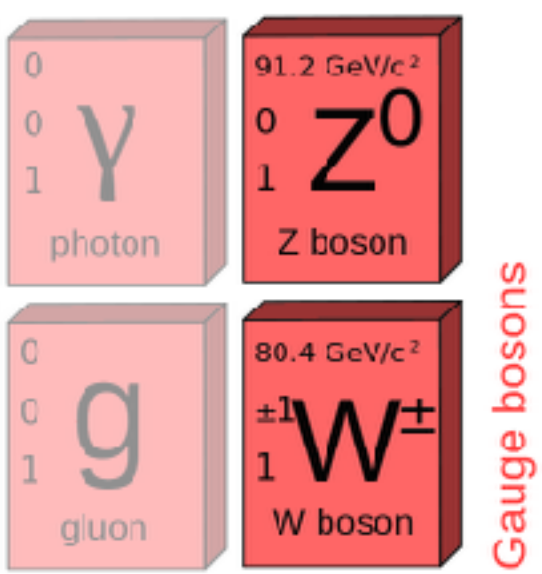
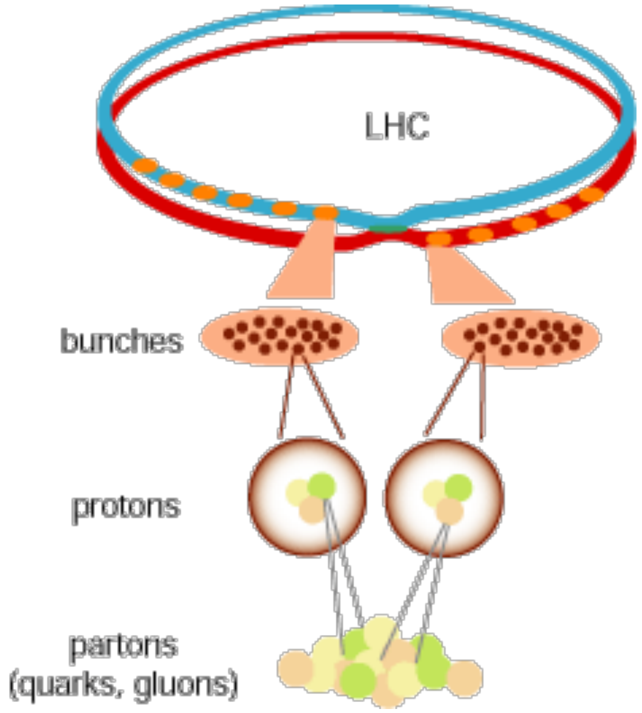
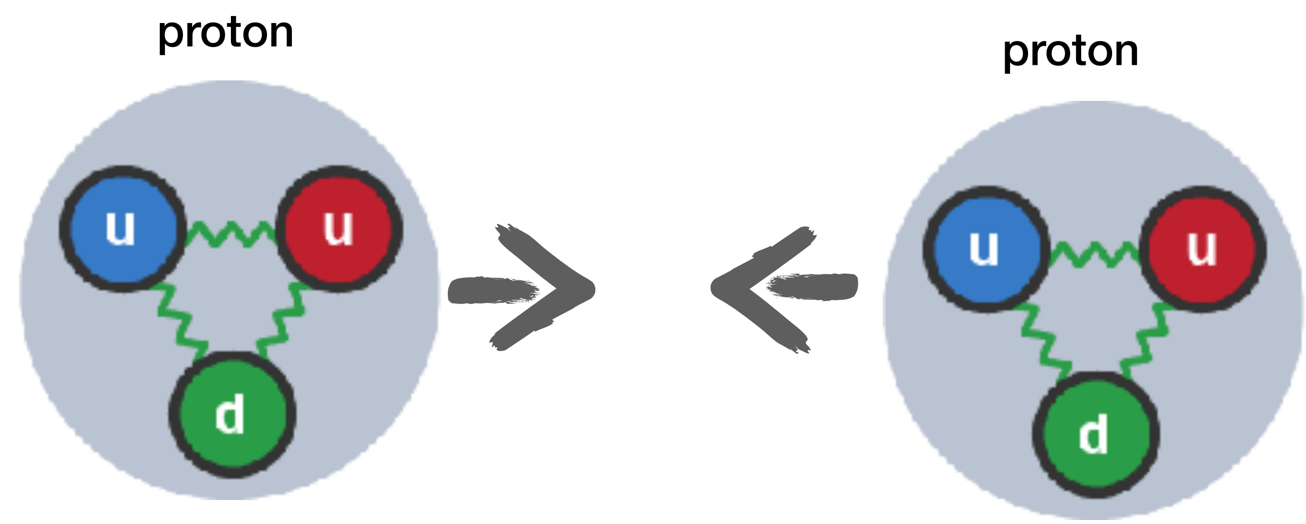
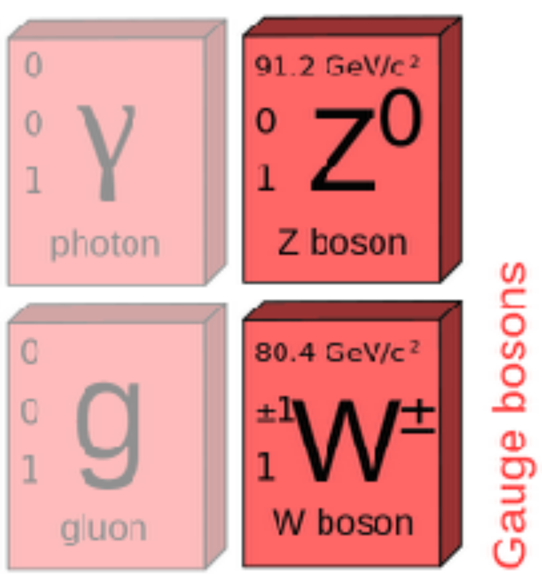
Vector Boson Scattering @ LHC

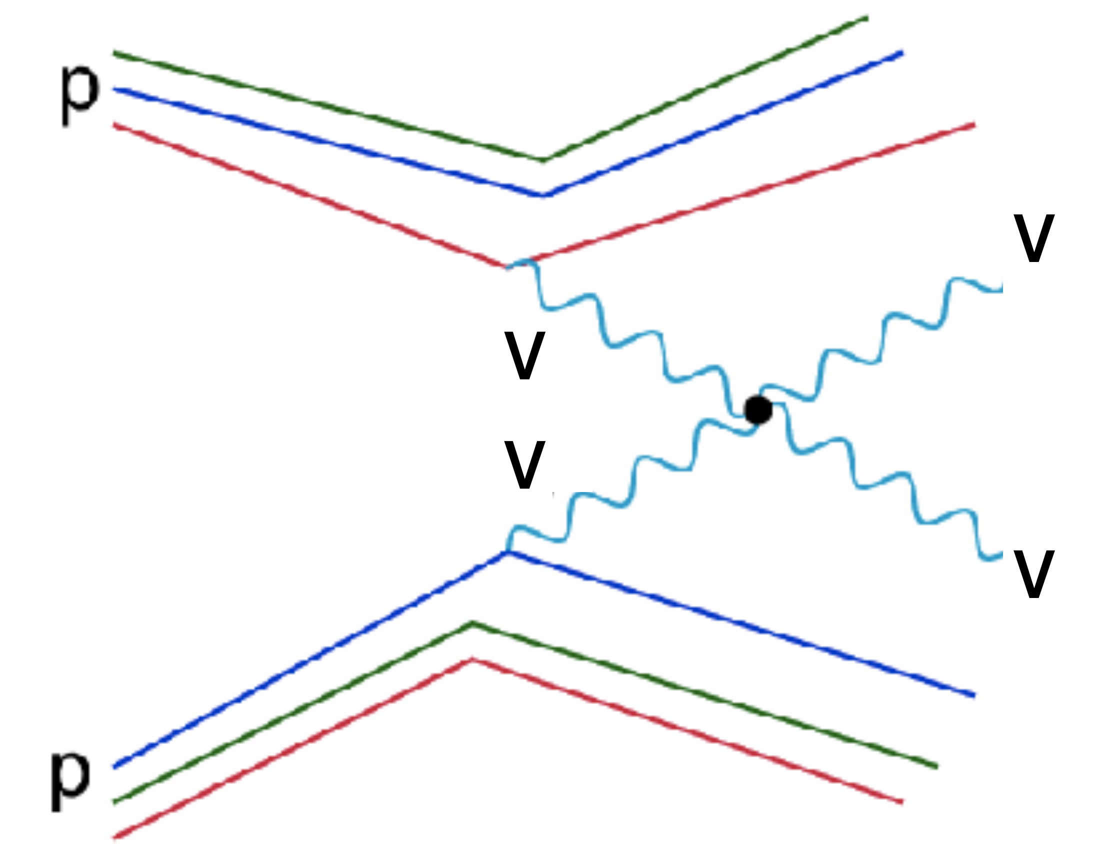






Vector Boson Scattering @ LHC





Vector Boson Scattering @ LHC

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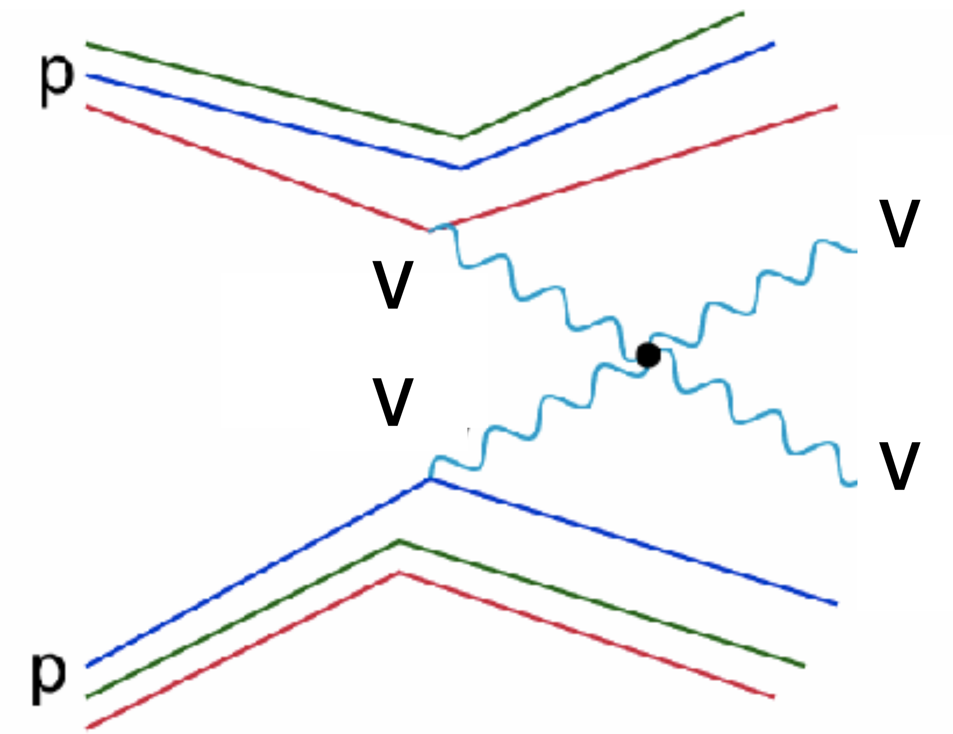
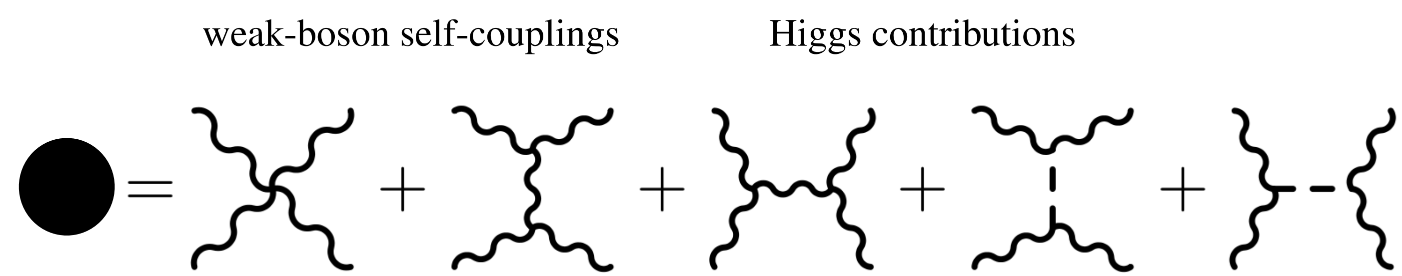
Why is interesting to look at VBS

~~Vector Boson Scattering~~ @ LHC ?

Why VBS @ LHC ?

1) Important process for the Standard Model





Why VBS @ LHC ?

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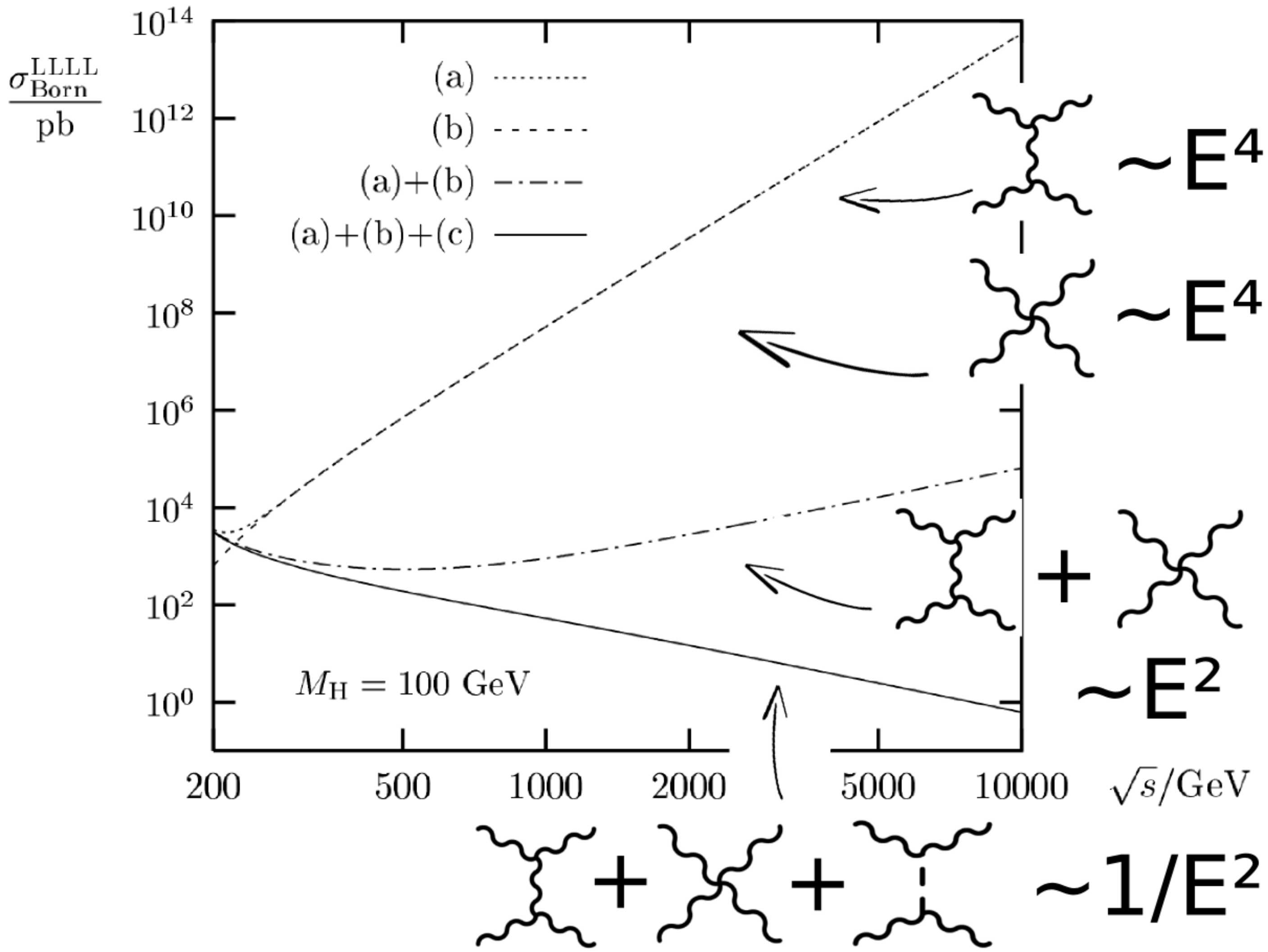
1) Important process for the Standard Model

From the theory the cross-section* for longitudinal $W_L^+W_L^- \rightarrow W_L^+W_L^-$ scattering: [Denner, Hahn, 1997]



* cross-section (σ), a quantity expressing the likelihood of an interaction event between two particles. Wikipedia

Why VBS @ LHC ?

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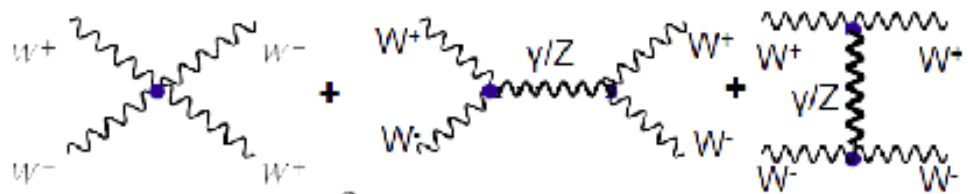
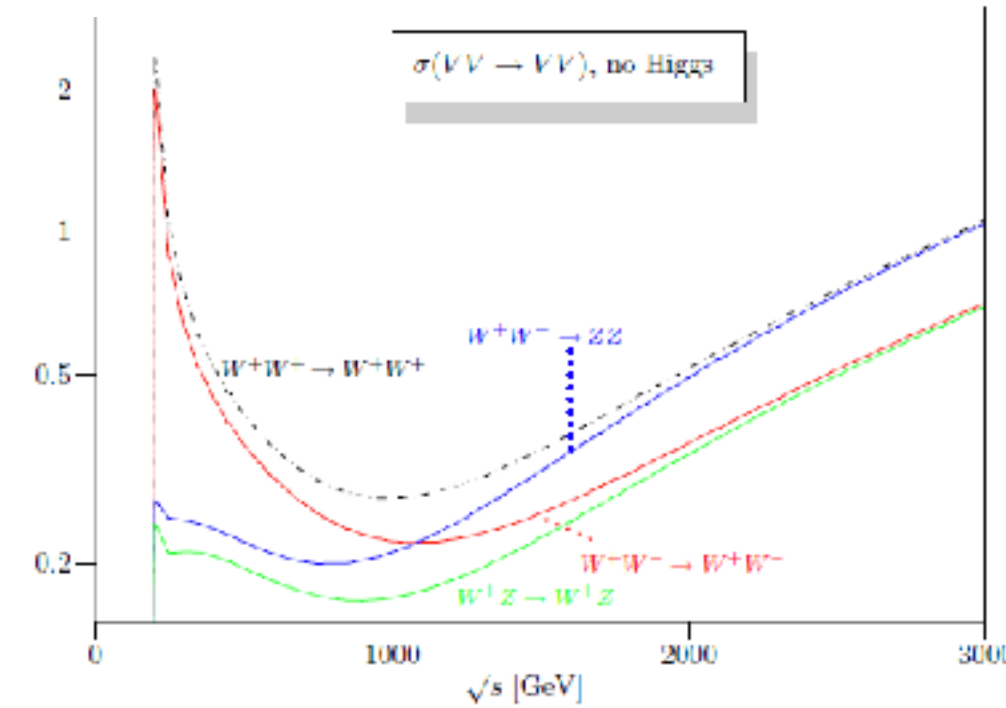
1) Important process for the Standard Model

- VBS Without Higgs contribution:

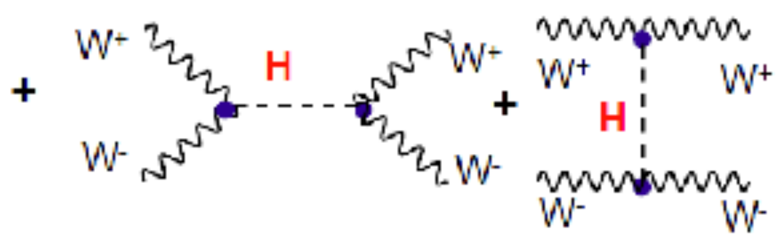


$$\sigma_{WW} \propto s^2 \to \infty \quad \text{wenn } s \to \infty$$

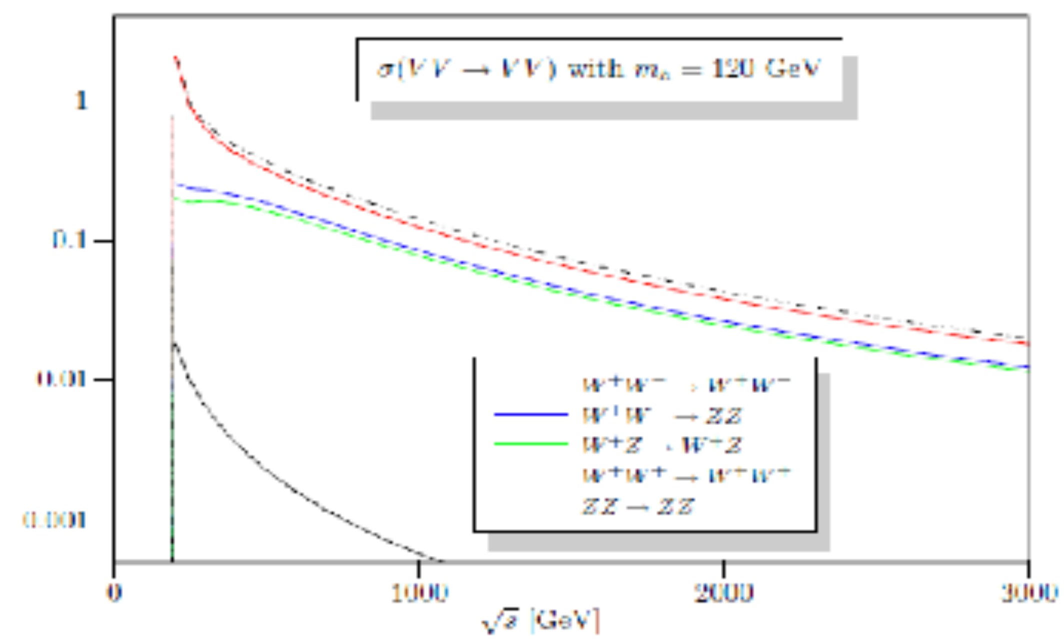
Violates "unitarity" (probability>1) at ~2 TeV



- Higgs contribution (or new physics, or both) needed



Higgs exactly cancels increase for large s
but *only* for SM H-WW coupling!



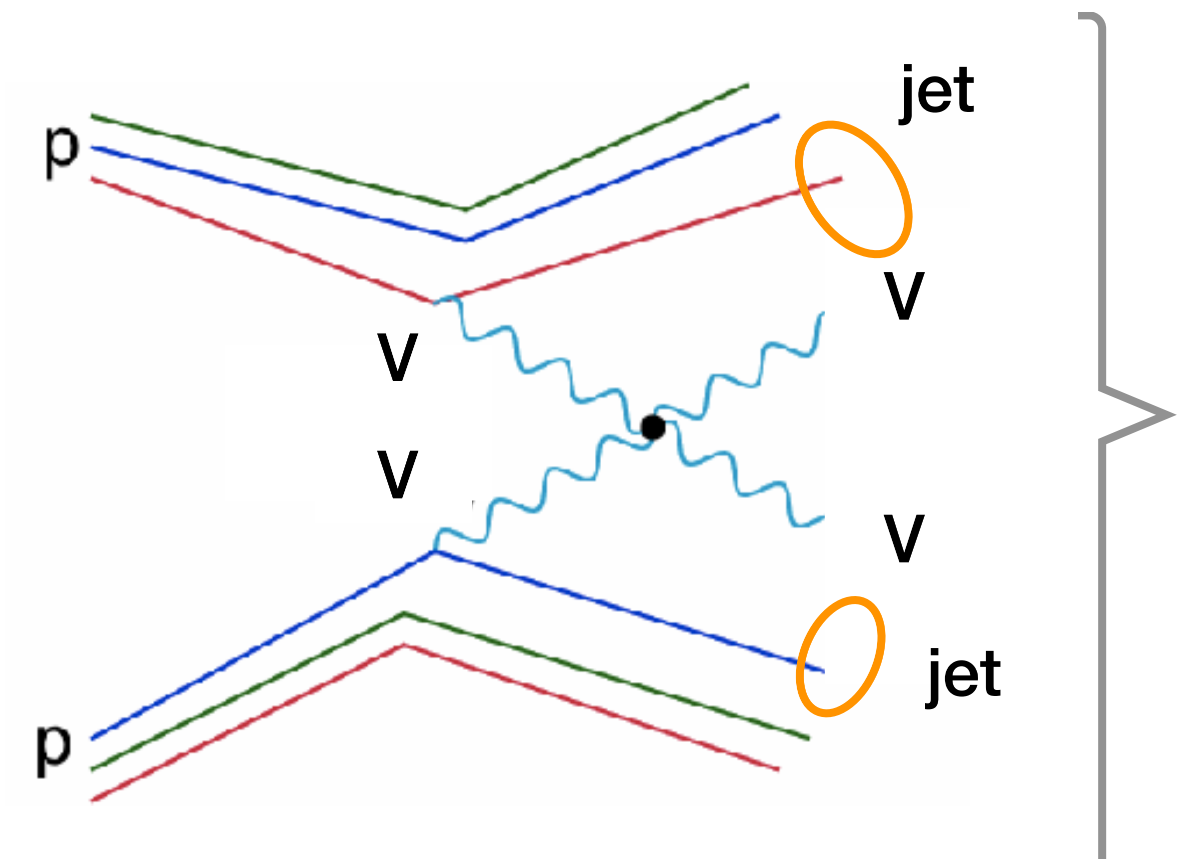
A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

Why VBS @ LHC ?

1) Important process for the Standard Model
2) Is a rare process that we can only observe now at the LHC

One quark in each of two colliding protons has to radiate a W or a Z boson. These extremely short-lived particles are only able to fly a distance of 0.1×10^{-15}m before transforming into other particles, and their interaction with other particles is limited to a range of 0.002×10^{-15}m. In other words, these extremely short "weak lightsabers" extend only about 1/10th of a proton's radius and have to approach each other by 1/500th of a proton's radius! **Such an extremely improbable coincidence happens only about once in 20,000 billion proton-proton interactions, recorded typically in one day of LHC operation**

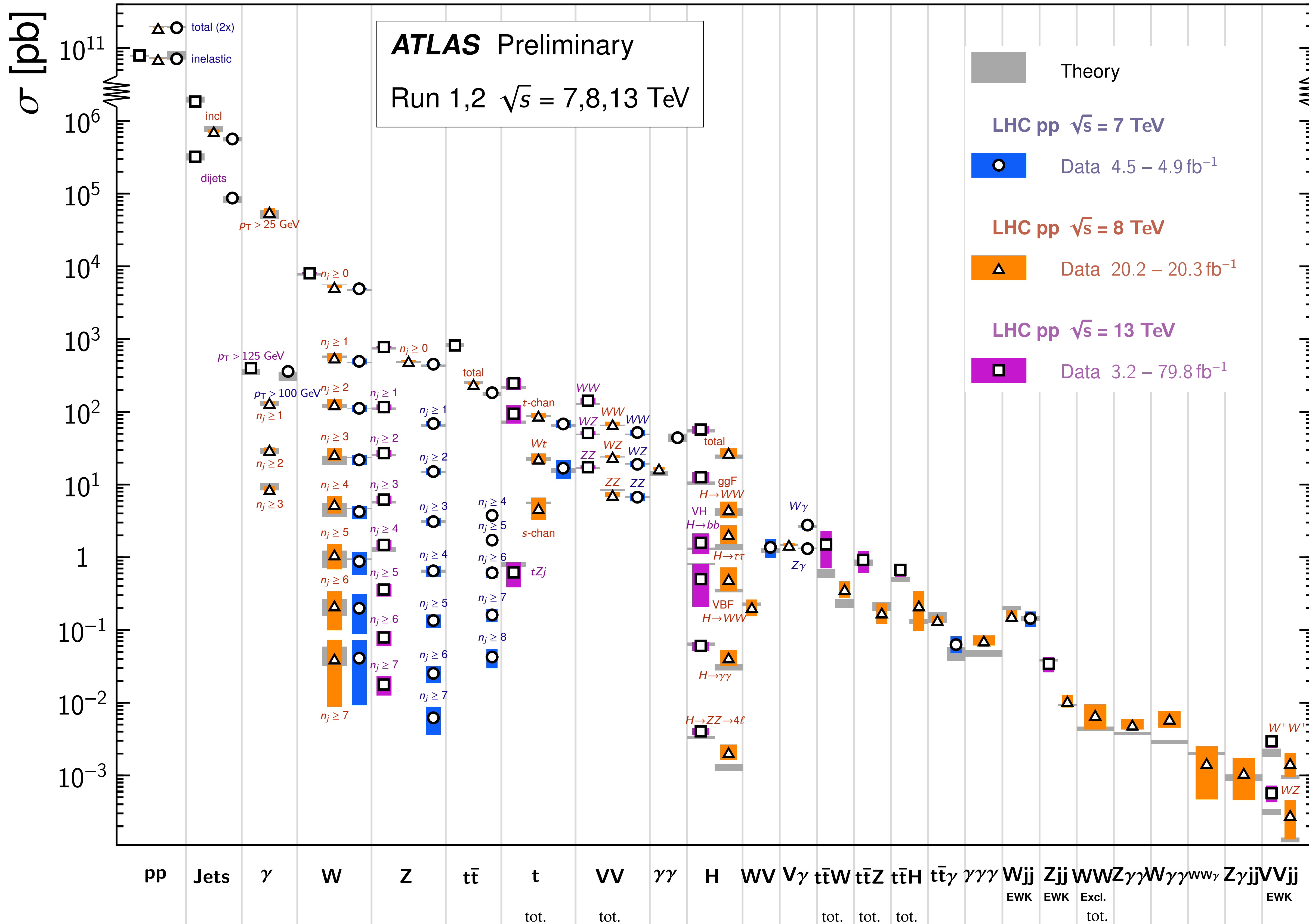
from ATLAS briefing



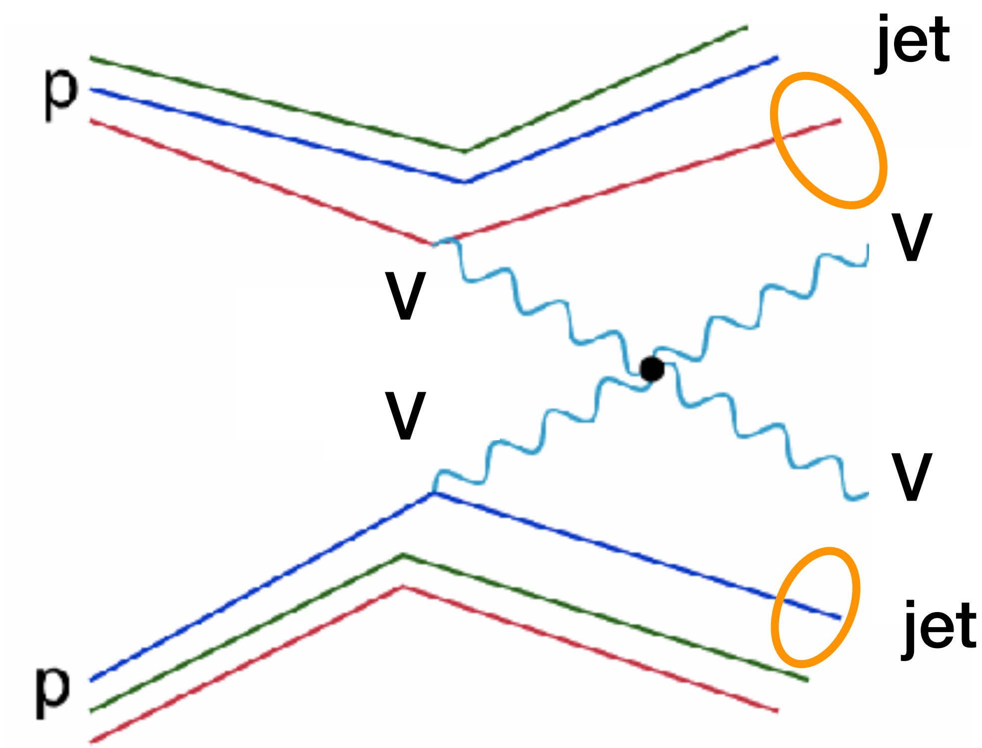
$qq \rightarrow VVjj$

Standard Model Production Cross Section Measurements

Status: July 2018

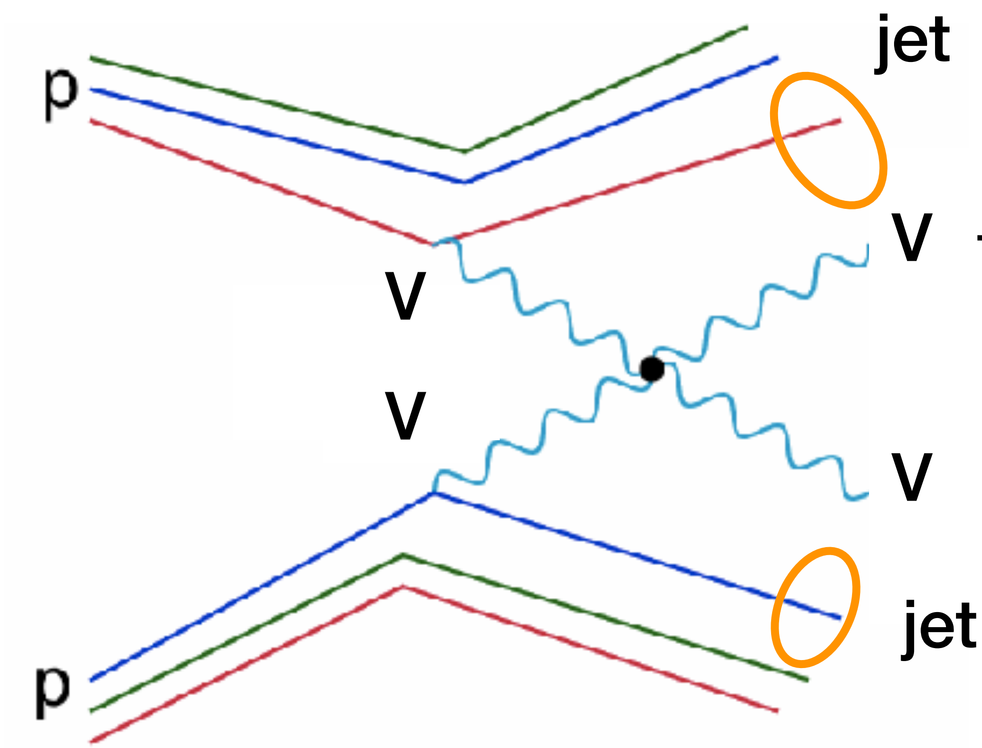


Experimental work at the LHC



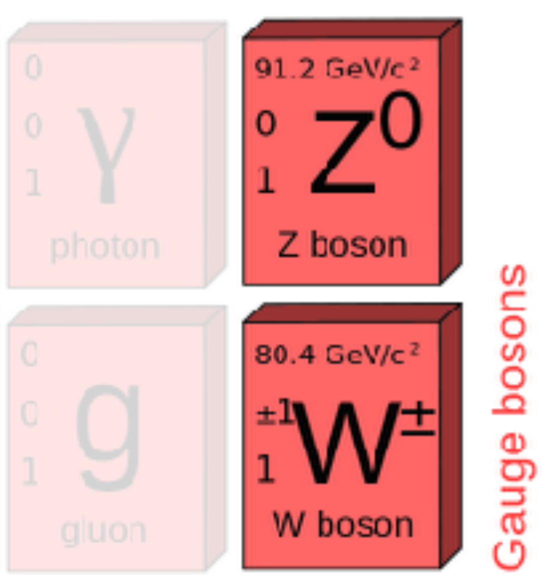
Today: Latest LHC results

Experimental work at the LHC



Today: Latest LHC results

→ V = $W^{\pm}$, Z



Experimental work at the LHC

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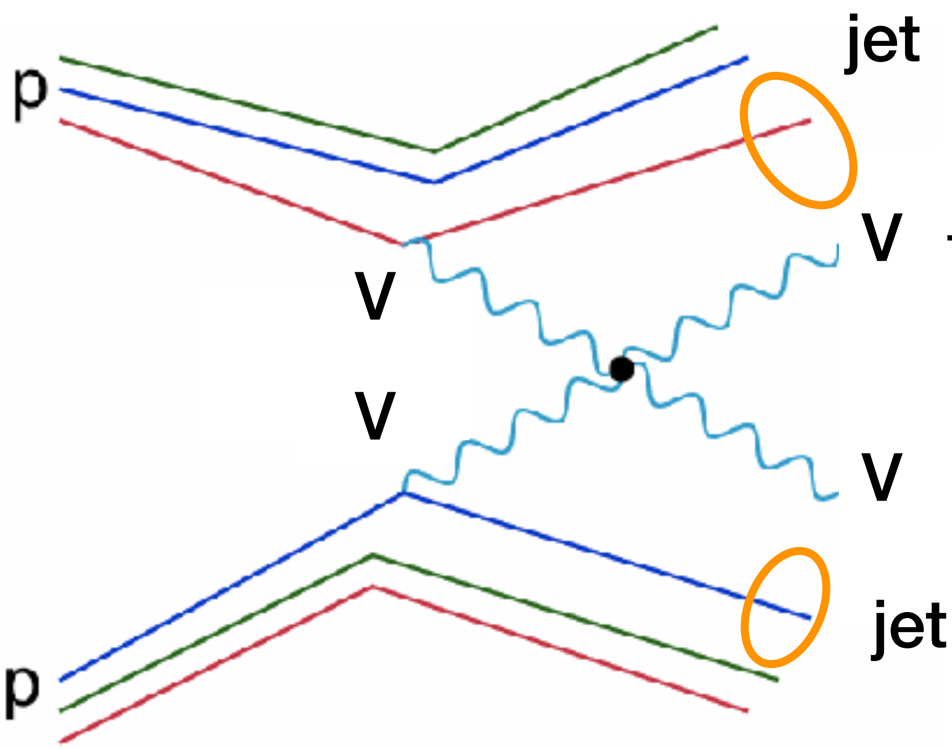

Today: **Latest LHC results**

→ $V = W^\pm, Z$

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	$\pi^+\gamma$		$< 8 \times 10^{-5}$	95%
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$	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}	$b\overline{b}b\overline{b}$		$(3.6 \pm 1.3) \times 10^{-4}$	
Γ_{12}	ggg		< 1.1 %	CL=95%
Γ_{13}	$\pi^0\gamma$		$< 5.2 \times 10^{-5}$	CL=95%
Γ_{14}	$\eta\gamma$		$< 5.1 \times 10^{-5}$	CL=95%
Γ_{15}	$\omega\gamma$		$< 6.5 \times 10^{-4}$	CL=95%
Γ_{16}	$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	CL=95%
Γ_{17}	$\gamma\gamma$		$< 5.2 \times 10^{-5}$	CL=95%
Γ_{18}	$\gamma\gamma\gamma$		$< 1.0 \times 10^{-5}$	CL=95%
Γ_{19}	$\pi^\pm W^\mp$	[b]	$< 7 \times 10^{-5}$	CL=95%

from pdg http://pdg.lbl.gov/

Experimental work at the LHC

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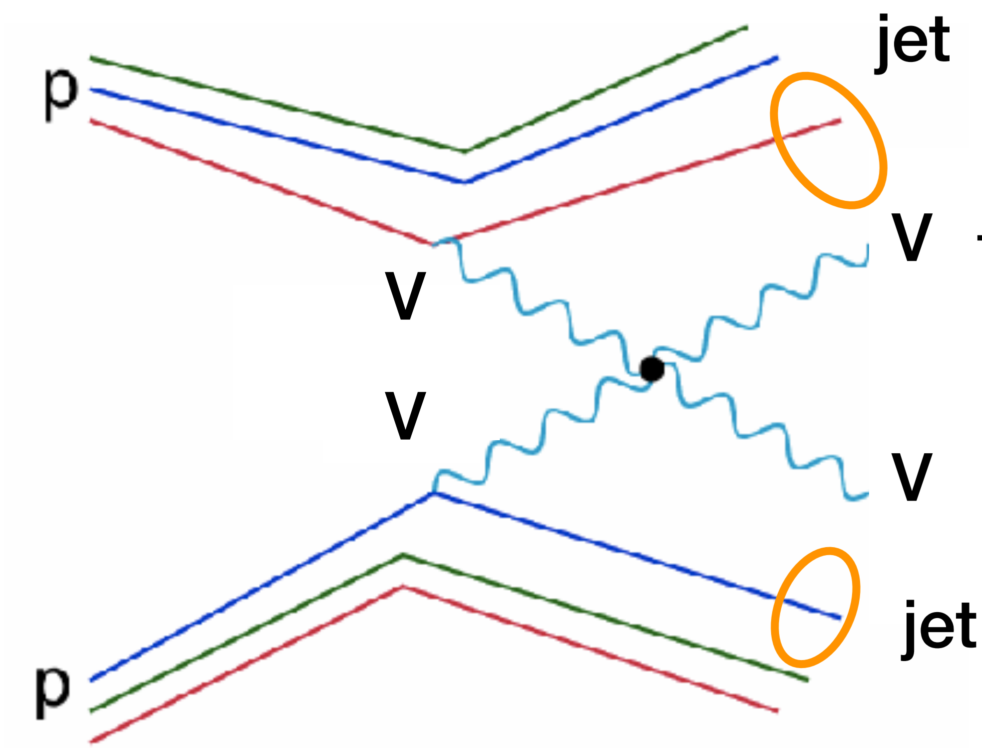
Today: **Latest LHC results**



$\rightarrow$ **V = W±, Z**

Z DECAY MODES

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Γ_2	$\mu^+\mu^-$	(3.366 ± 0.007) %	

W^+ DECAY MODES

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Γ_3	$\mu^+\nu$	(10.57 ± 0.15) %	

Focus on electron and muons decays

Experimental work at the LHC

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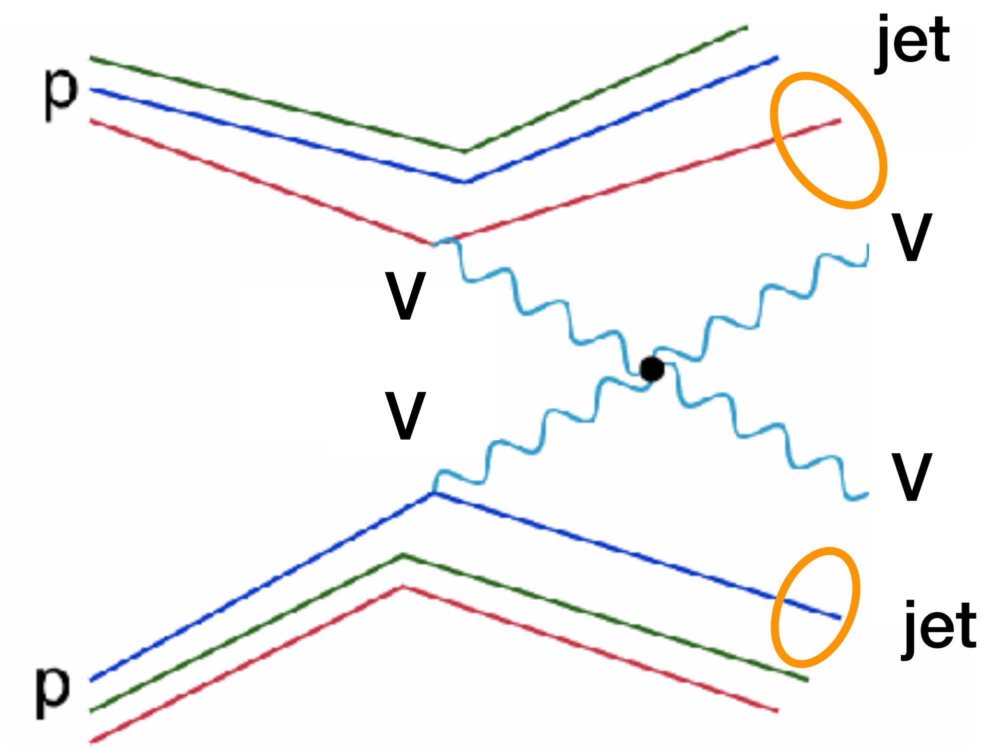
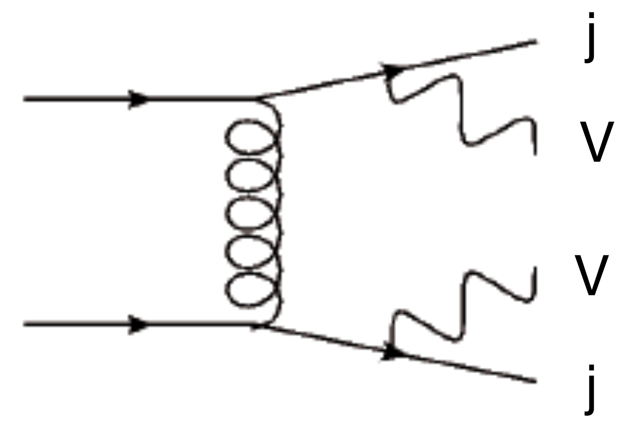


Today: Latest LHC results

- $W^{\pm}W^{\pm}$ jj→ $\ell^{\pm}\nu$ $\ell^{\pm}\nu$ jj
- $W^{\pm}Z$ jj→ $\ell^{\pm}\nu$ $\ell^{\pm}\ell^{\mp}$ jj

Experimental work at the LHC



VVjj has two process classes:

- **W±W±jj-QCD**:= O(α_s^2 x α_W^4)
  - Lowest order is pp → W±W±+ **2j**,
  - no gg initial state (special for W±W±) → low background

- **W±W±jj-EW**:= O(α_W^6)
  - contains VBS part (t-channel +QGC)
  - interf(QCD-EW)~10% included

Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^\pm \nu \ell'^\pm \nu' jj$	$W^\pm W^\pm$	19.5 fb	18.8 fb	1:1
$\ell^\pm \nu \ell^\mp \nu jj$	$W^\pm W^\mp + ZZ$	93.7 fb	3192 fb	1:30
$\ell^\pm \ell^\mp \ell'^\pm \nu' jj$	$W^\pm Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

Experimental work at the LHC

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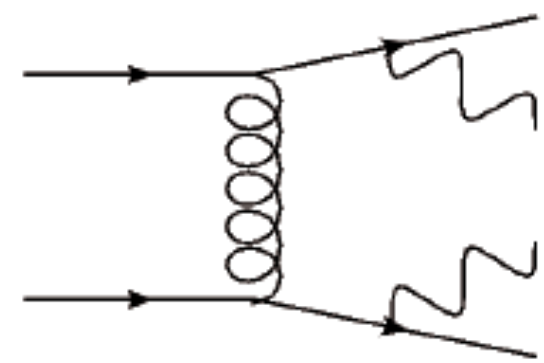

VVjj has two process classes:

- **$W^\pm W^\pm jj$-QCD**:= $O(\alpha_s^2 \times \alpha_W^4)$
  - Lowest order is pp → $W^\pm W^\pm$+ **2j**,
  - no gg initial state (special for $W^\pm W^\pm$) → low background

- **$W^\pm W^\pm jj$-EW**:= $O(\alpha_W^6)$
  - contains VBS part (t-channel +QGC)
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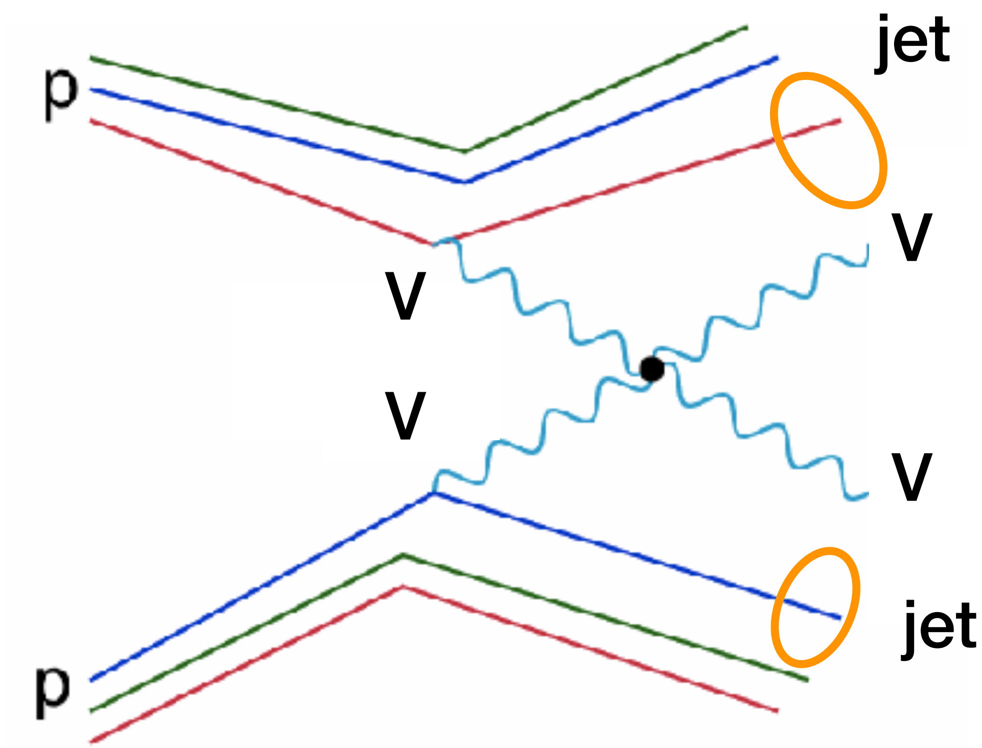
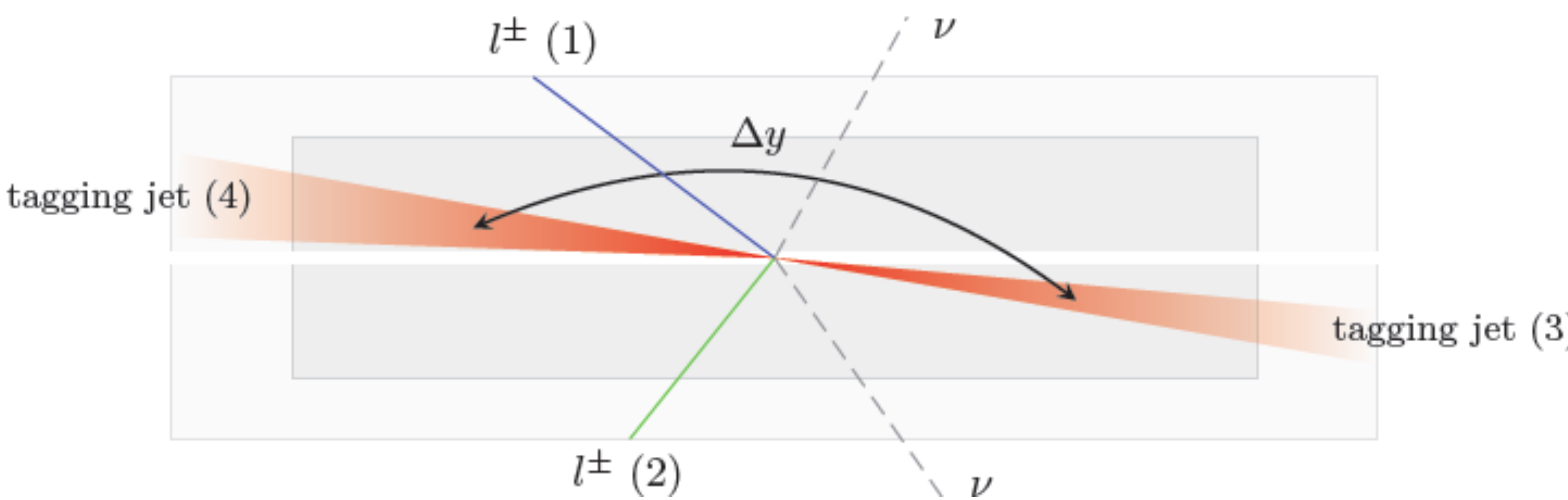
Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^\pm \nu \ell'^\pm \nu' jj$	$W^\pm W^\pm$	19.5 fb	18.8 fb	1:1
$\ell^\pm \nu \ell^\mp \nu jj$	$W^\pm W^\mp + ZZ$	93.7 fb	3192 fb	1:30
$\ell^\pm \ell^\mp \ell'^\pm \nu' jj$	$W^\pm Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

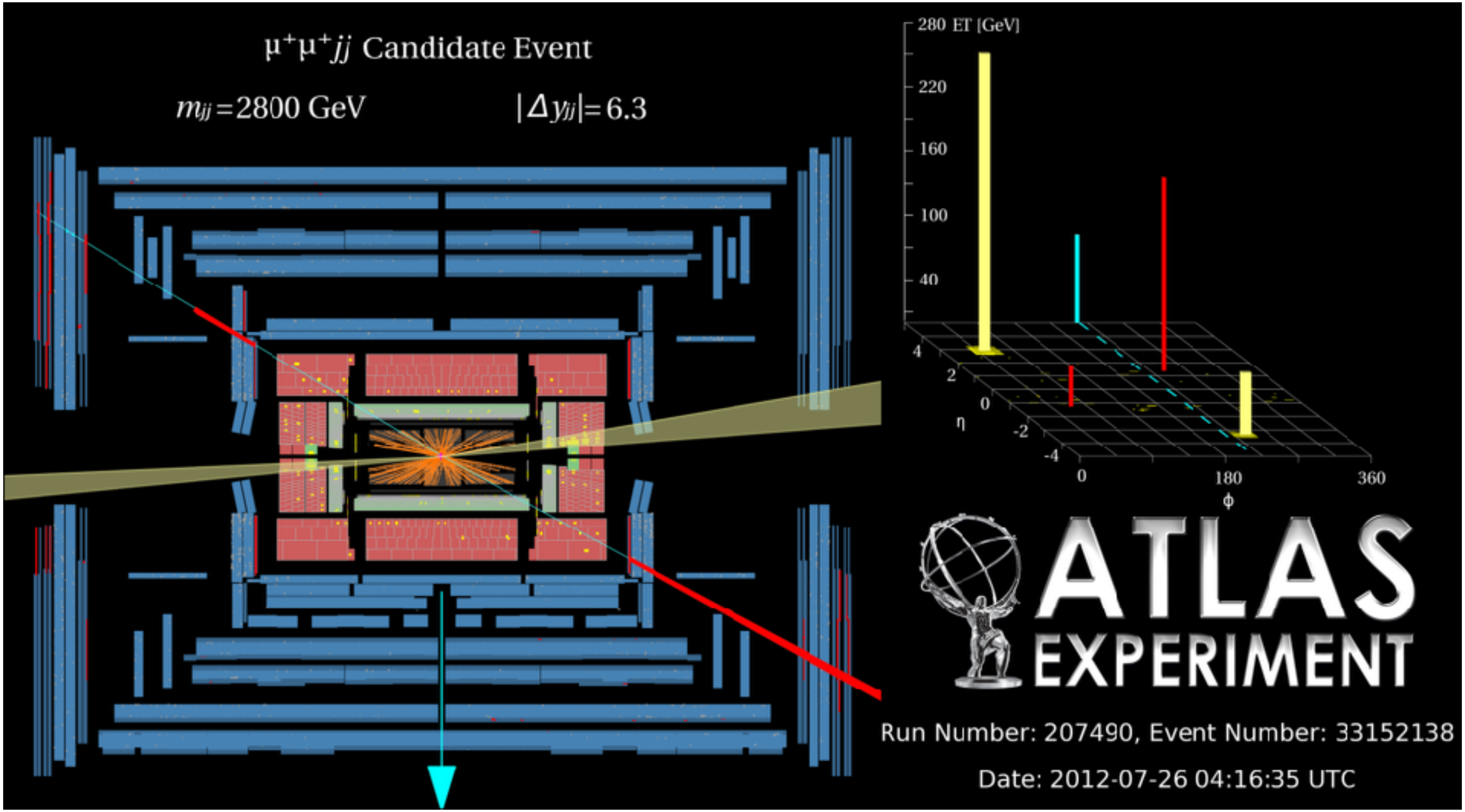
Experimental work at the LHC



- Distinct qq → VVjj topology:
  - tagging Jets with large Δy
  - leptons from VV → ℓν ℓν between jets



Candidate event in ATLAS



CMS observation of W±W±jj (5.5. s.d., CMS-SMP-17-004)

large statistics for limits, well verified via control regions,

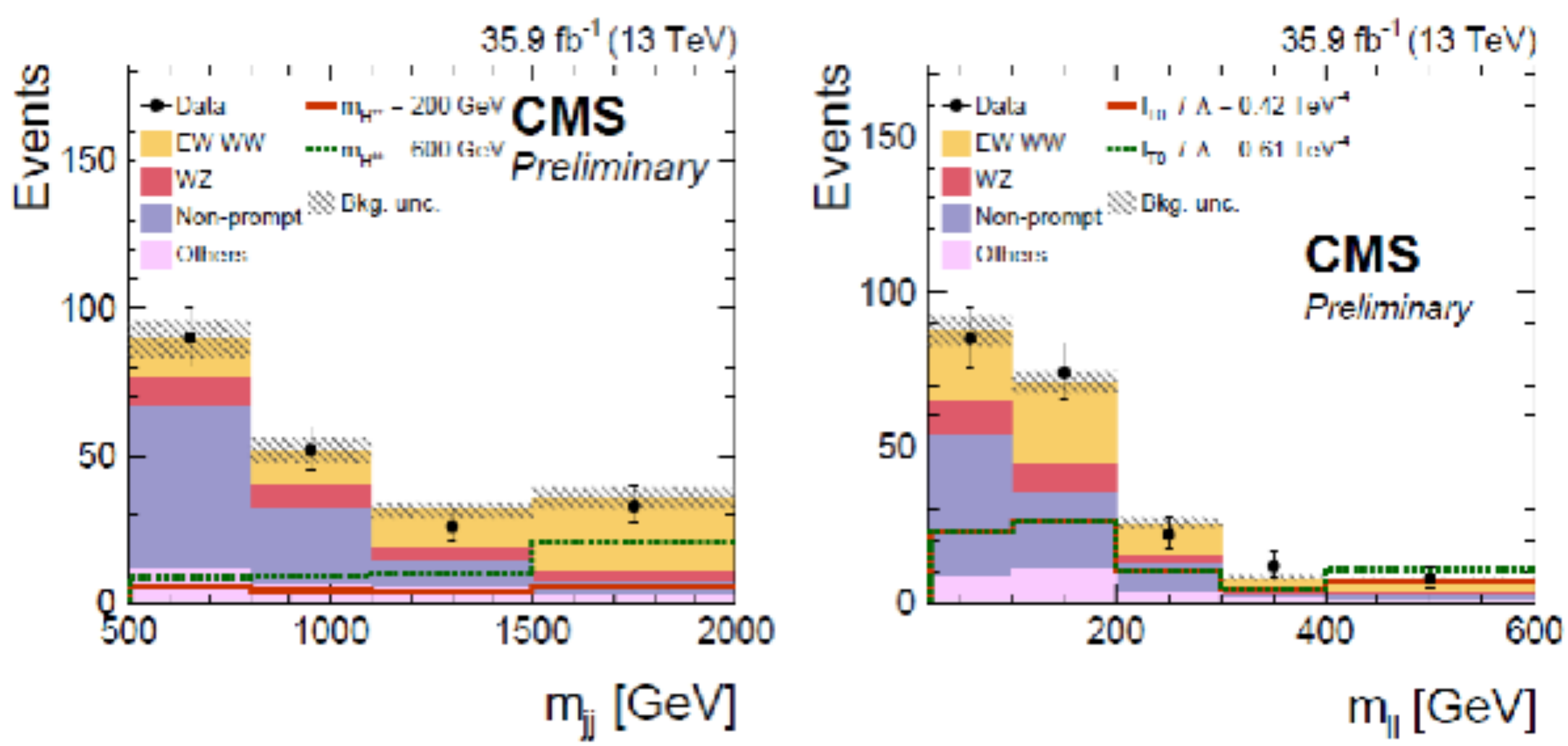
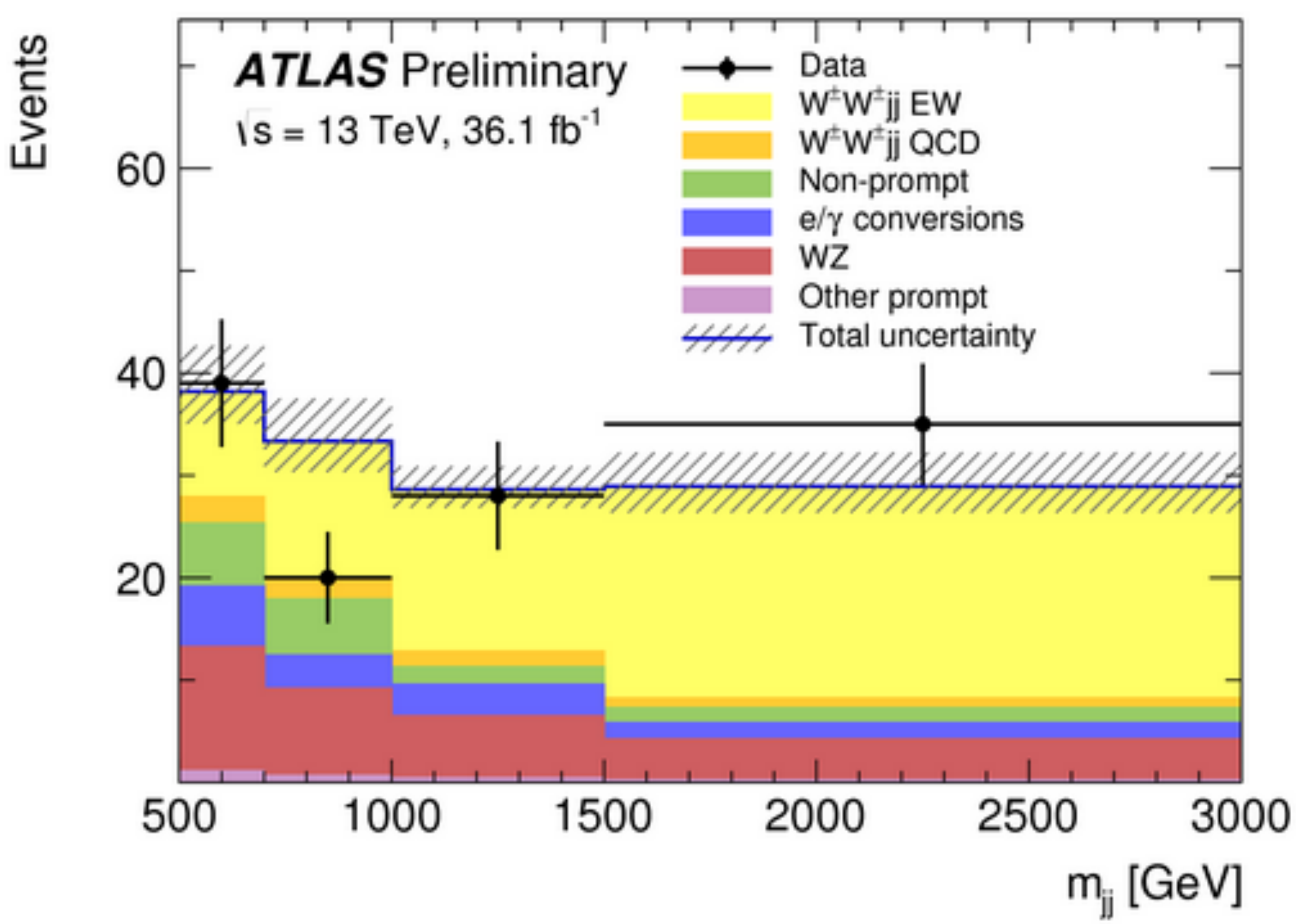


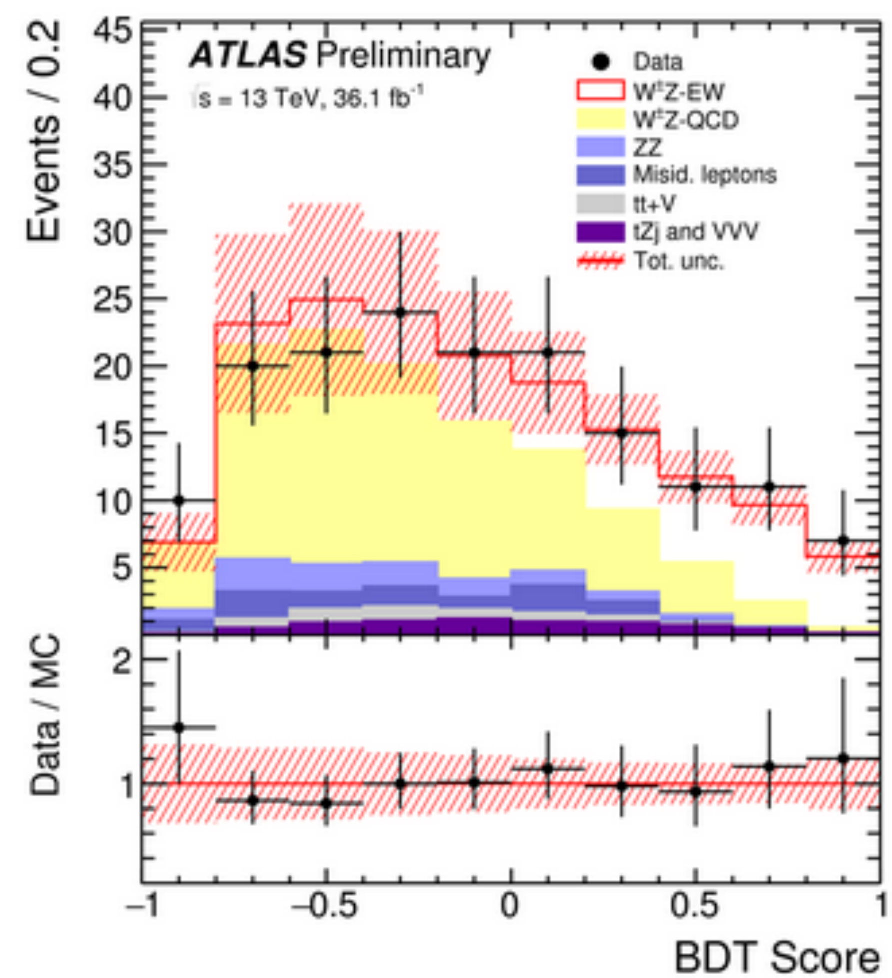
Figure 2: Distributions of m_{jj} (left) and $m_{\ell\ell}$ (right) in the signal region. The normalization of the predicted signal and background distributions corresponds to the result of the fit. The hatched bars include statistical and systematic uncertainties. For illustration, the doubly charged Higgs boson signal normalized to a cross section of 0.1 pb (left) and the distribution with aQGCs are shown. The histograms for other backgrounds include the contributions from QCD WW, Wγ, wrong-sign events, DPS, and VVV processes.

ATLAS observation of

$W^{\pm}W^{\pm}jj$ (6.9. s.d., ATLAS-CONF-2018-030)

$W^{\pm}Z$ jj (5.6. s.d., ATLAS-CONF-2018-033)





Updates

Latest News, Physics Briefings, Press Statements, Feature Articles, Collaboration Portraits and Blog Entries from ATLAS

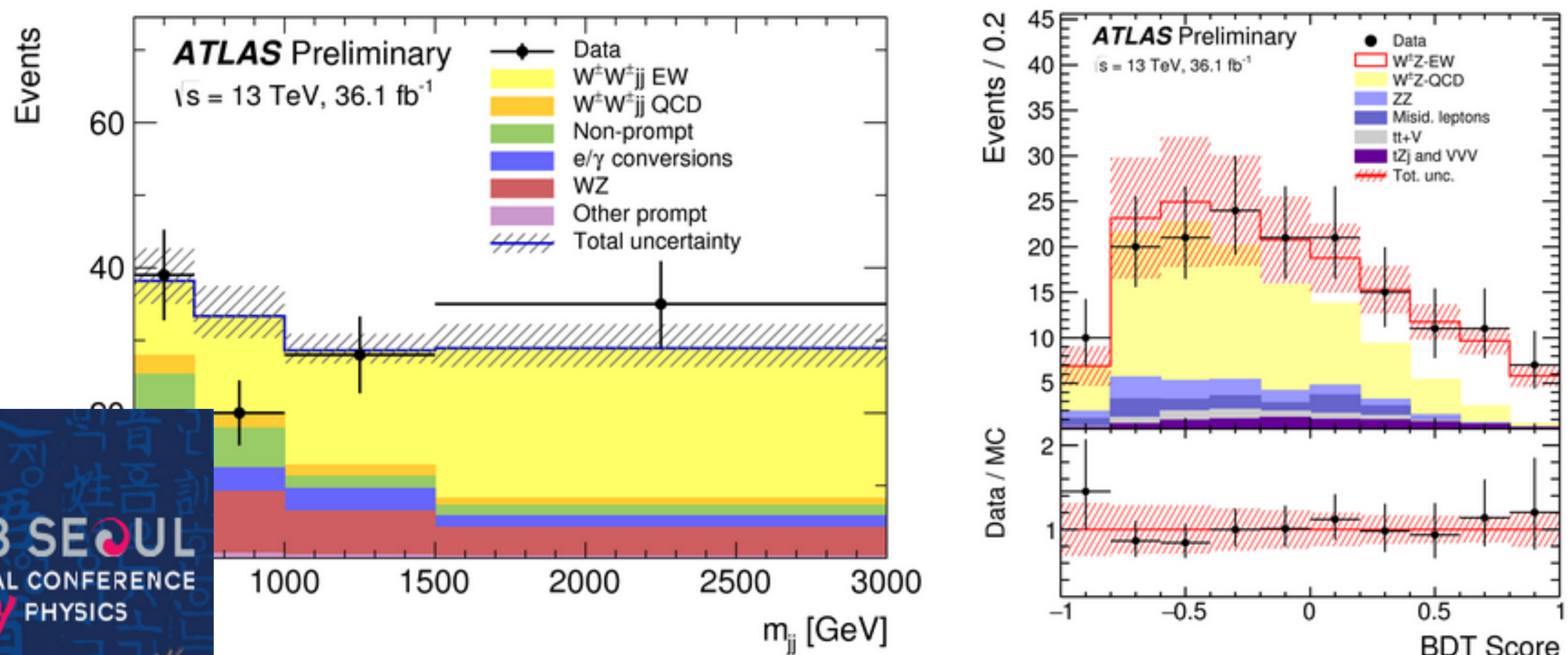
https://atlas.cern/updates/physics-briefing/weak-lightsabers

Physics Briefing

Tags: Physics Results, ICHEP2018

Quarks observed to interact via minuscule “weak lightsabers”

By ATLAS Collaboration, 5th July 2018



Left: Especially at invariant jet-jet masses, mjj, > 1000 GeV the yellow signal of W±W± W±W± scattering can be clearly seen above the background from other processes. Right: The orange signal of W±Z W±Z scattering is evident as the white contribution at large values of the score value of a multivariate boosted decision tree (BDT). (Image: ATLAS Collaboration/CERN)

Two among the rarest processes probed so far at the Large Hadron Collider (LHC), the scattering between W and Z bosons emitted by quarks in proton-proton collisions, have been established by the ATLAS experiment at CERN.

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Vector Boson Scattering @ LHC

and VBSCan

Vector Boson Scattering @ LHC

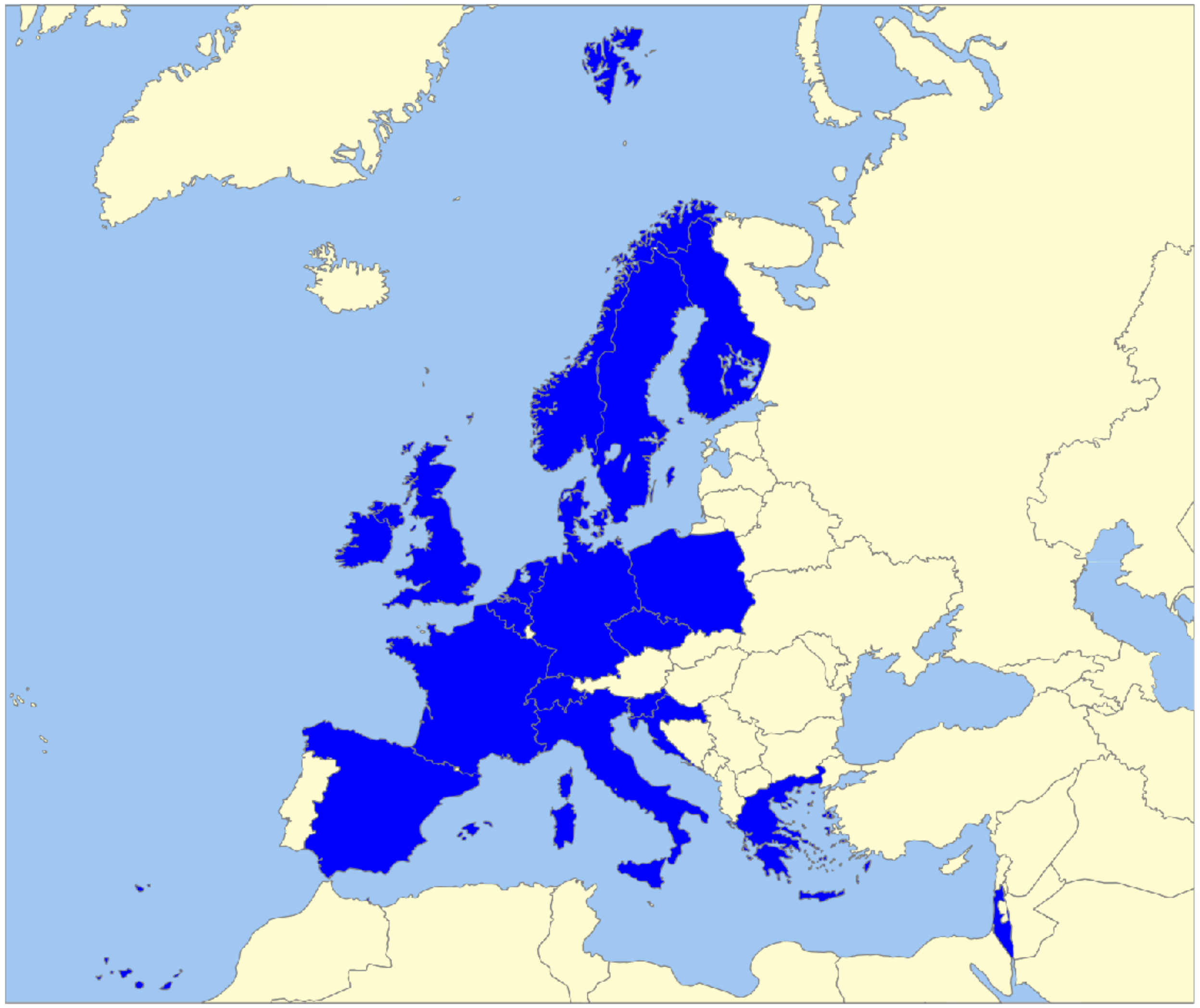
and VBSCan COST Network

investigate the Vector Boson Scattering (VBS) process and its implications for the Standard Model, by coordinating existing theoretical and experimental efforts in the area and by best exploiting hadron colliders data, thereby laying the groundwork for long-term studies of the subject and creating a solidly interconnected community of VBS experts

https://vbscanaction.web.cern.ch/

the VBSCan Action current shape

- **Norway** and **Denmark** will join soon as well



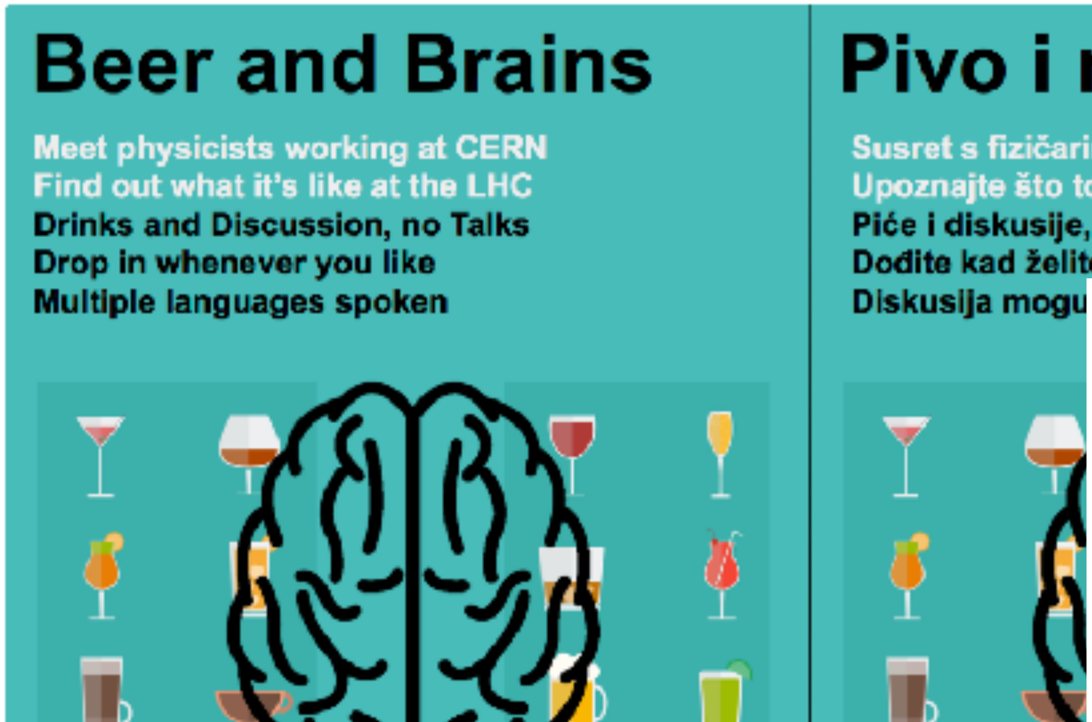
Country	Date	Status
Belgium	25/01/2017	Confirmed
Croatia	06/12/2016	Confirmed
Czech Republic	21/02/2017	Confirmed
Finland	03/02/2017	Confirmed
France	17/11/2016	Confirmed
Germany	28/11/2016	Confirmed
Greece	01/03/2017	Confirmed
Ireland	24/03/2017	Confirmed
Israel	07/03/2017	Confirmed
Italy	10/01/2017	Confirmed
Netherlands	21/02/2017	Confirmed
Poland	28/11/2016	Confirmed
Slovenia	17/11/2016	Confirmed
Spain	03/01/2017	Confirmed
Sweden	25/01/2017	Confirmed
Switzerland	20/02/2017	Confirmed
United Kingdom	08/12/2016	Confirmed
Total: 17		

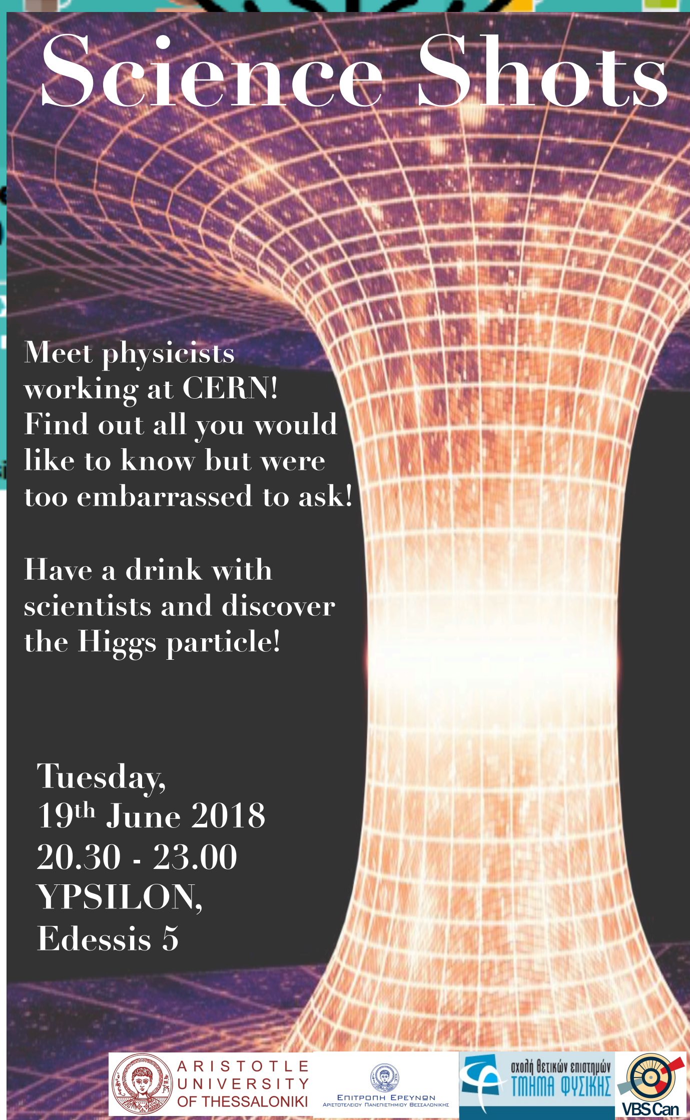
We are now 21 countries !

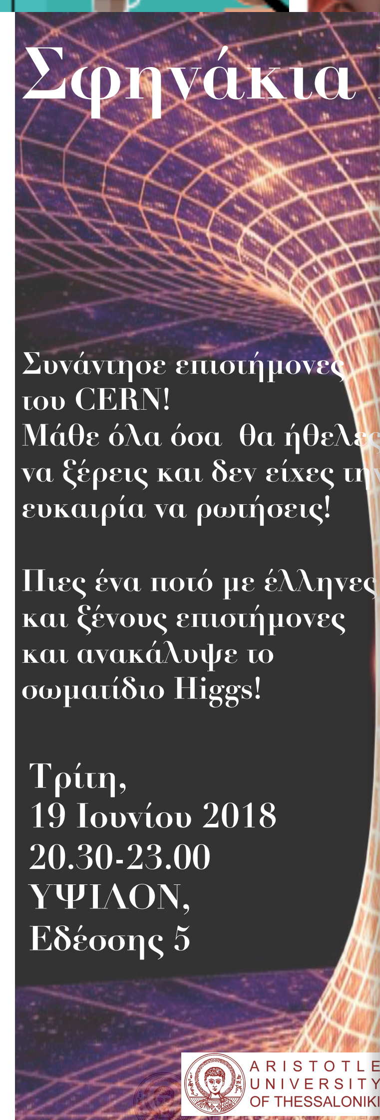
Not everybody is in the picture!


Beer and Brains
Meet physicists working at CERN
Find out what it's like at the LHC
Drinks and Discussion, no Talks
Drop in whenever you like
Multiple languages spoken
Wednesday, 28th June 2017
20.00 - 23.00
LVXOR Cafe
Peristil square, Split
Designed by Freepik
Pivo i mozgovi
Susret s fizičarima koji rade u CERN-u u Ženevi
Upoznajte što to znači raditi na LHC-u
Piće i diskusije, bez prezentacija
Dođite kad želite
20.00 - 23.00
Kavana LVXOR
Peristil, Split
Designed by Freepik


TECHNISCHE UNIVERSITÄT DRESDEN







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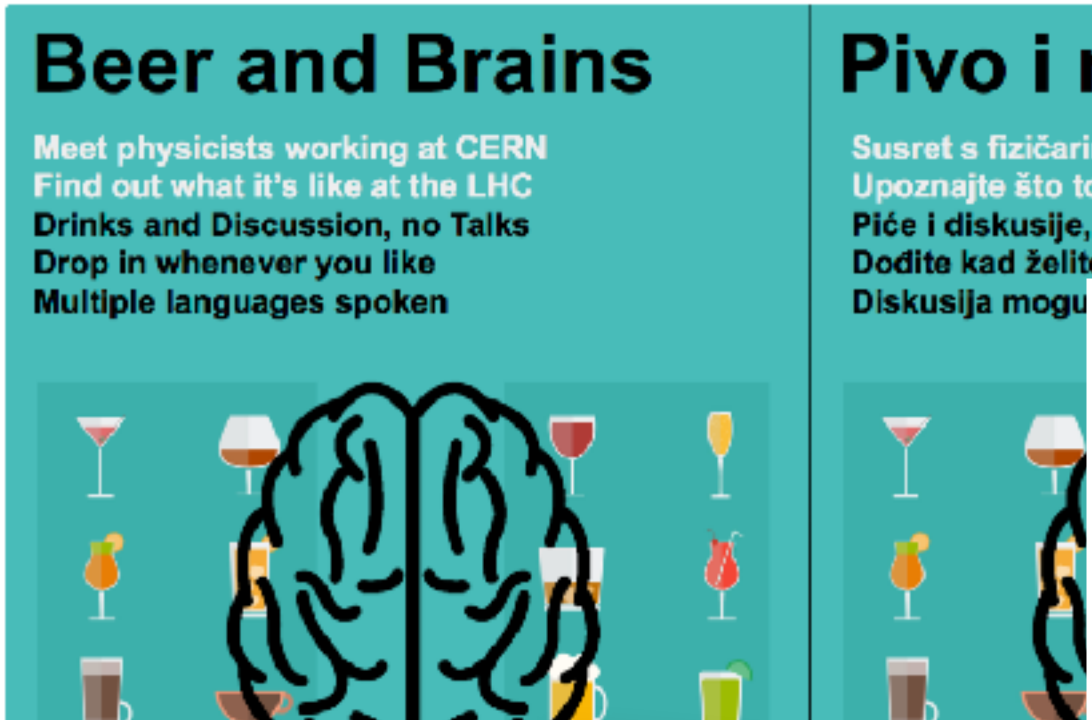


And now you!

TECHNISCHE UNIVERSITÄT DRESDEN

Vector Boson Scattering @ LHC

and VBSCan COST Network

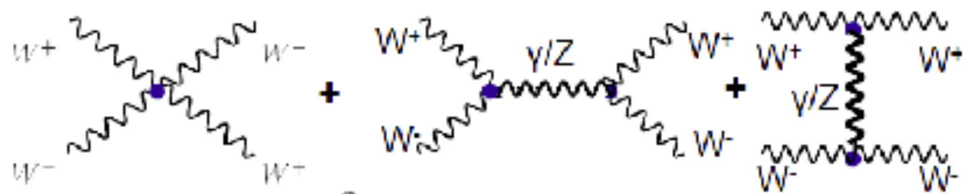
This is not the end!

Why VBS @LHC ?

Remember this slide?

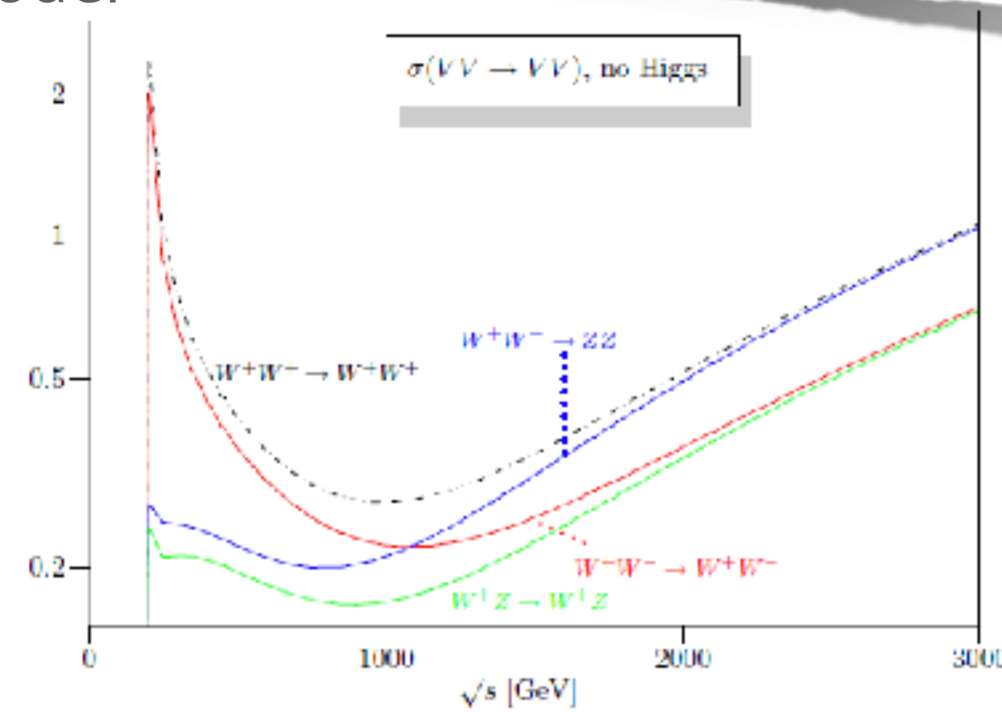
1) Important process for the Standard Model

- VBS Without Higgs contribution:

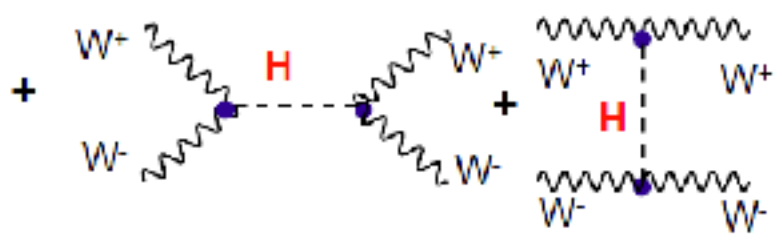


$\sigma_{WW} \propto s^2 \to \infty \quad \text{wenn } s \to \infty$

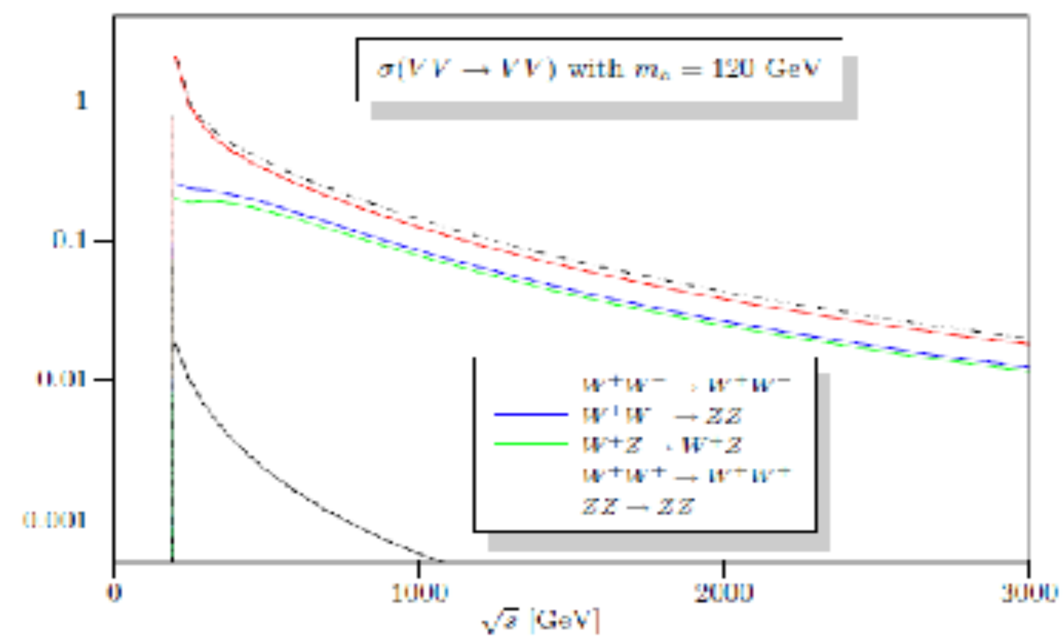
Violates “unitarity” (probability>1) at ~2 TeV



- Higgs contribution (or new physics, or both) needed



Higgs exactly cancels increase for large s
but *only* for SM H-WW coupling!



A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

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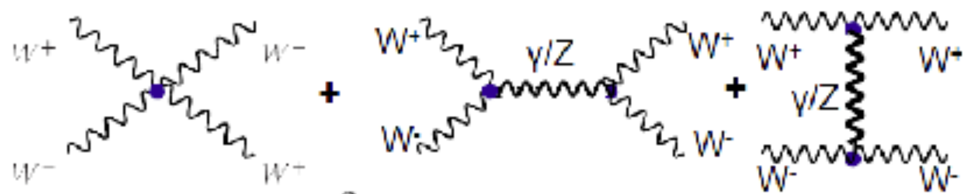

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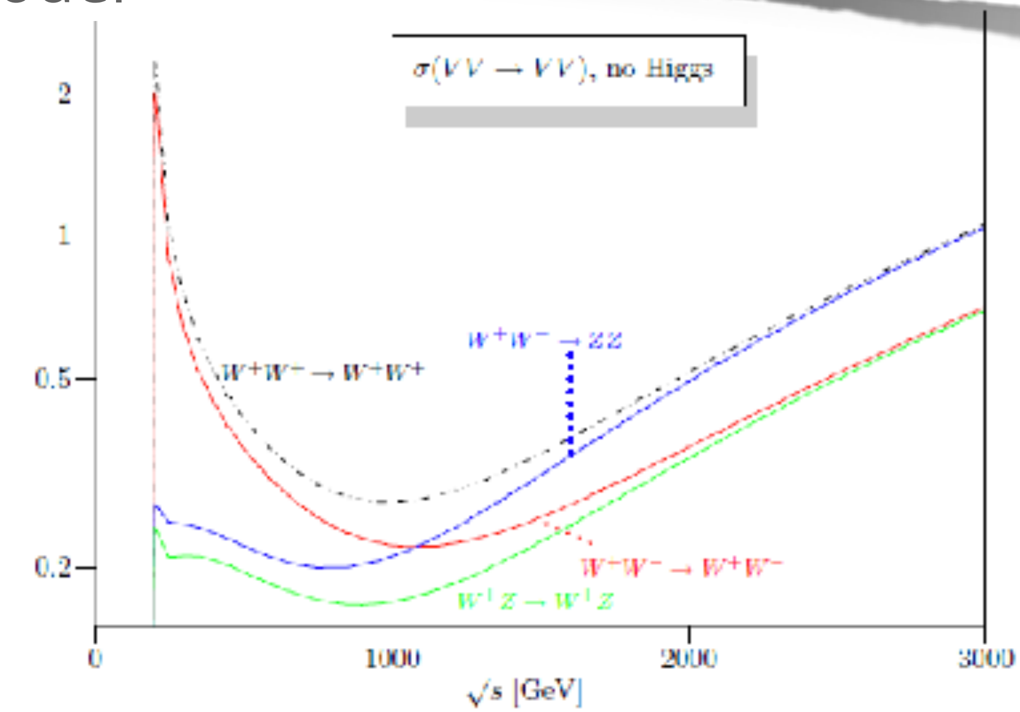

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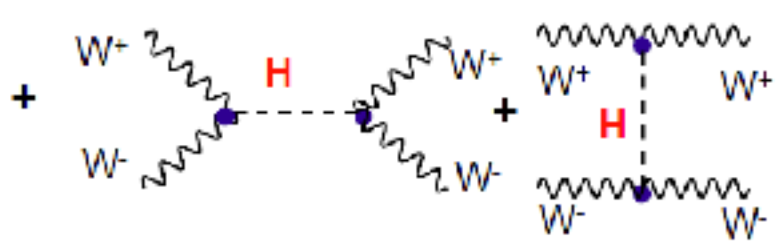

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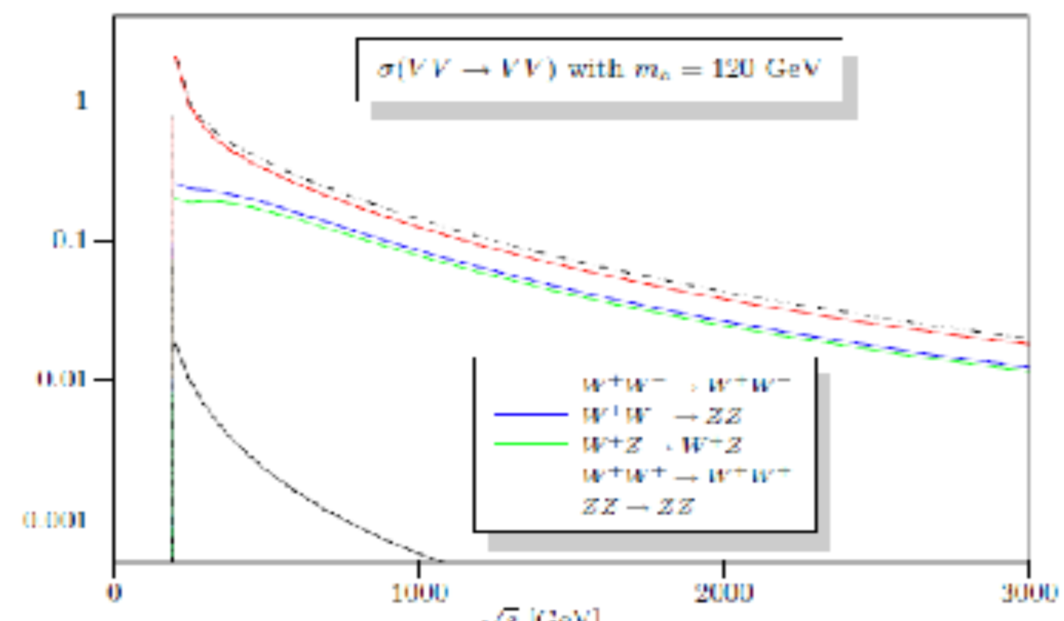
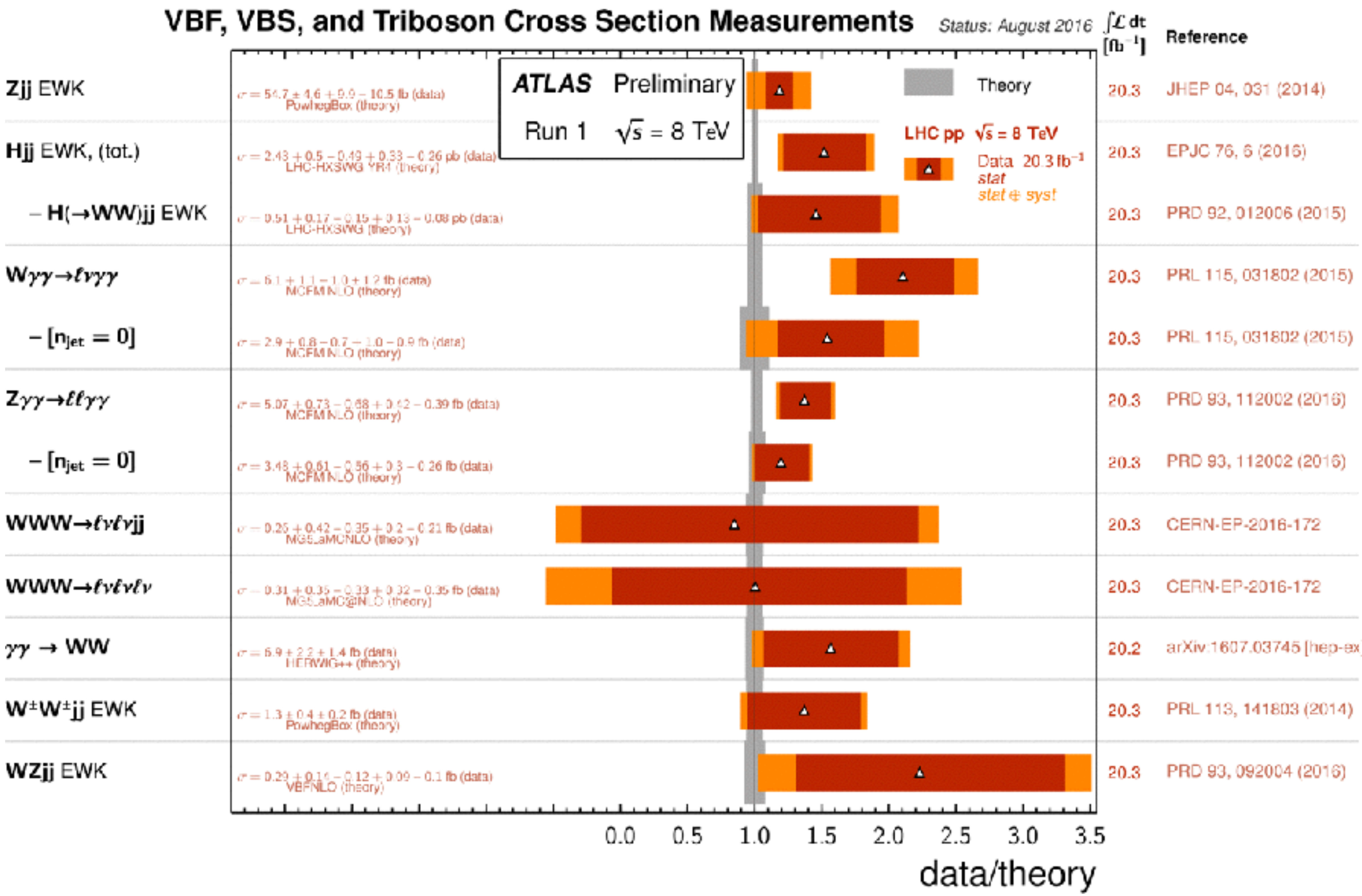


Why if the SM is an effective theory of a more complex one ?

A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

VBF, VBS and Triboson



Look at beyond the SM physics

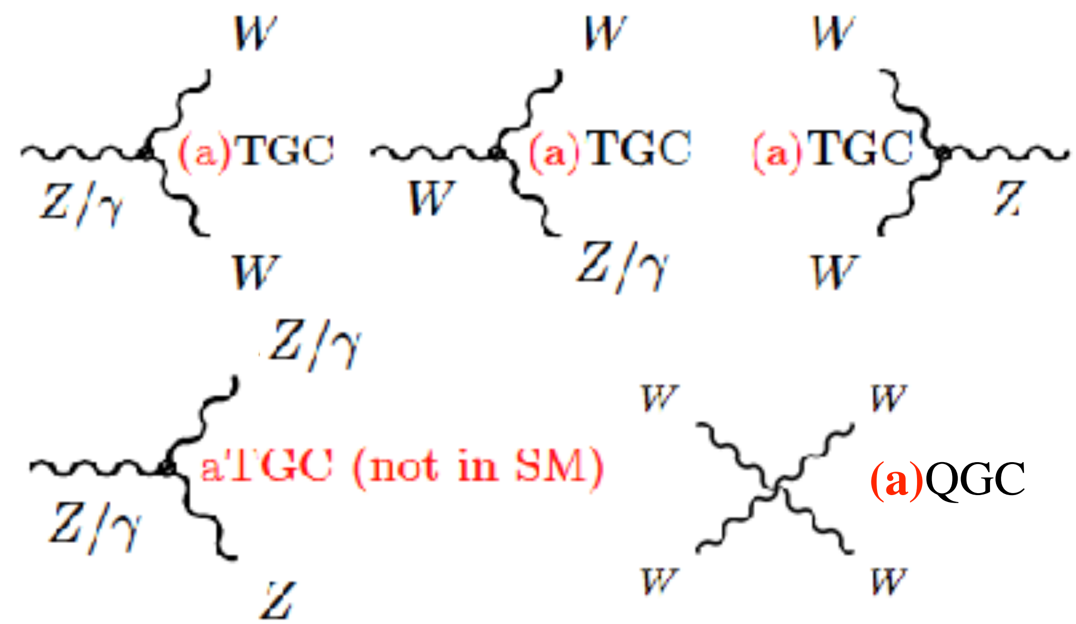
- The presence of new Physics in EWK sector modify gauge boson self-interactions
- Anomalous coupling approach: effective Lagrangian with anomalous triple or quartic gauge couplings (aTGC, aQGC)
  - Low energy effect from beyond SM physics can be modeled by effective theories (SM+higher dimension operators)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

dimension d i

Λ: scale of New Physics

  - anomalous triple or quartic coupling terms (aTGCs, aQGCs) are in the effective Lagrangian
- A single channel is not sensible to all the parameters
  - Need to study various processes to put constraints on all operators
- Anomalous couplings manifest themselves as :
  - Enhanced production cross section
  - Modified kinematics distributions

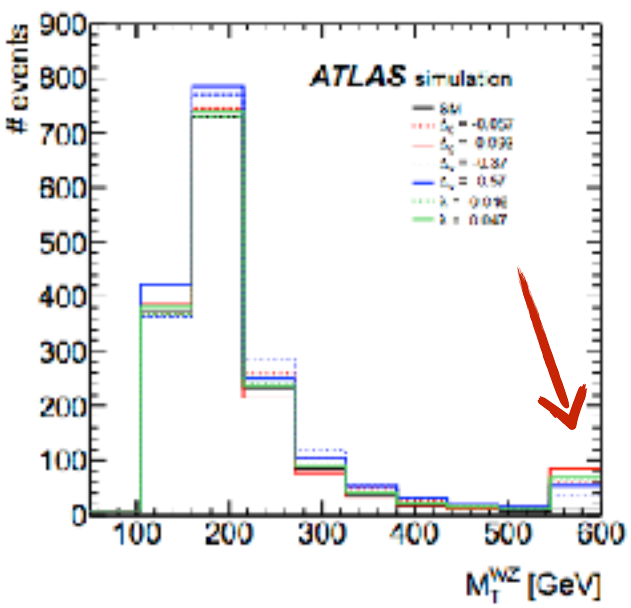


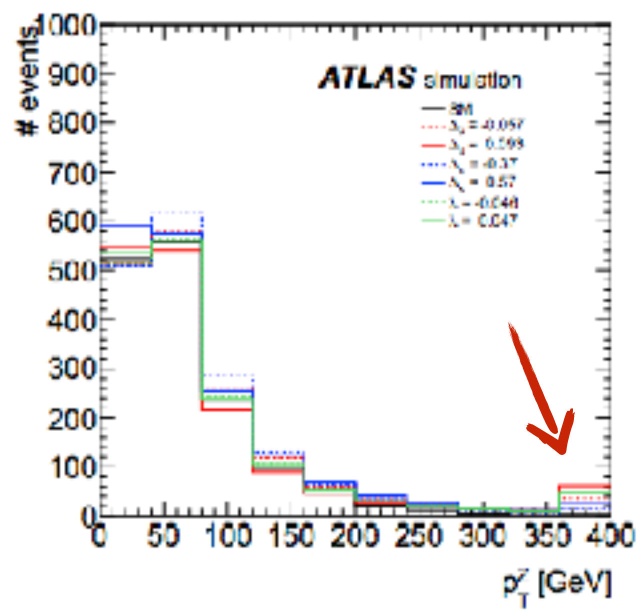
coupling	aTGC parameters (All = 0 in SM)	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ

coupling	aQGC parameters (All = 0 in SM)	channel
$WWWW$, $WWZZ$	α_4, α_5	WW, WZ

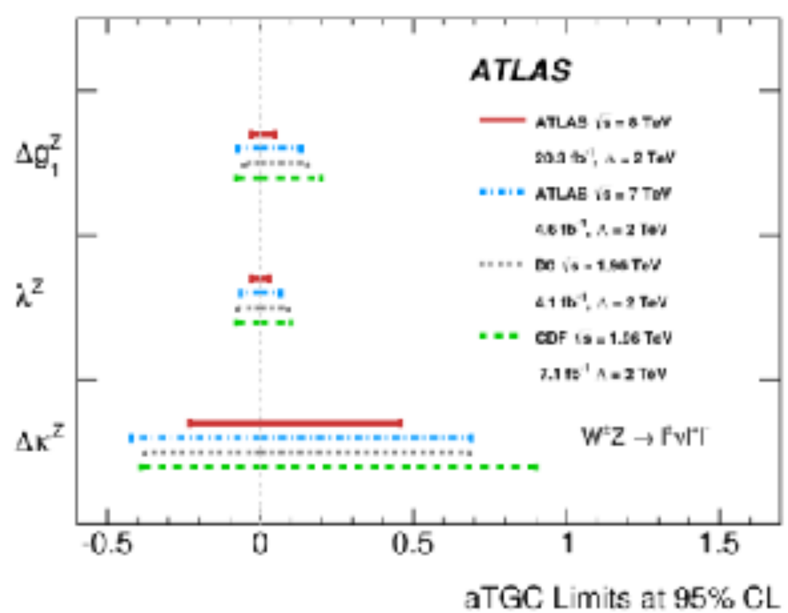
aTGC limits results

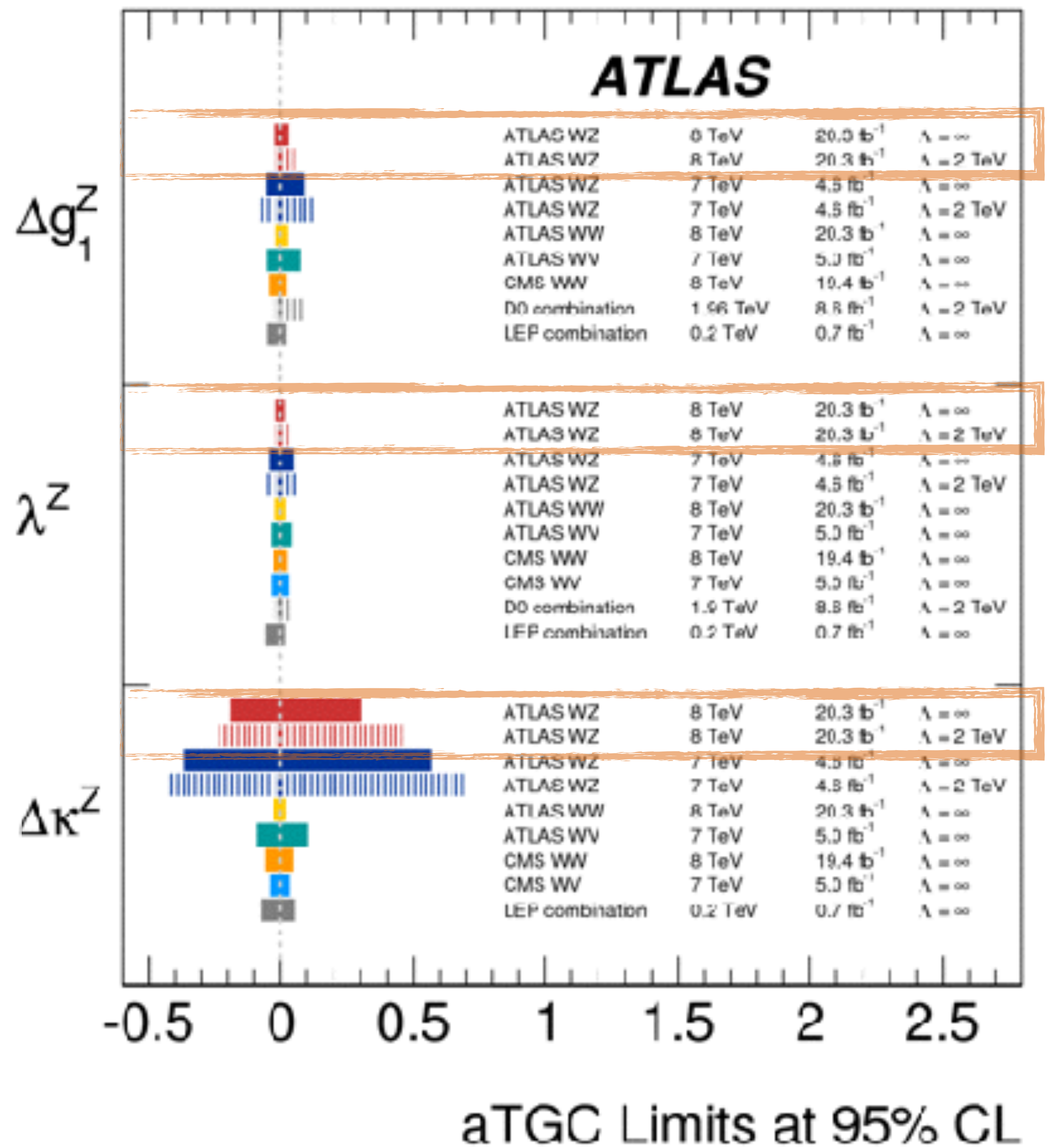
- Studied different kinematic distributions for limit extraction
  - WZ Transverse mass, Z p_T, leading lepton and WZ Mass
  - Use the inclusive binned WZ M_T distribution to extract limits → less sensitive to higher-order QCD and EW effects in perturbation theory





- The expected number of events is written as a function of the SM cross sections plus some other terms depending on the aTGC parameters
- 1D limits extracted using a likelihood fit, and fixing 2 of the parameters to the SM
- The limits are improved by a factor of ~2 large dataset → most stringent limits on WWZ anomalous couplings to date

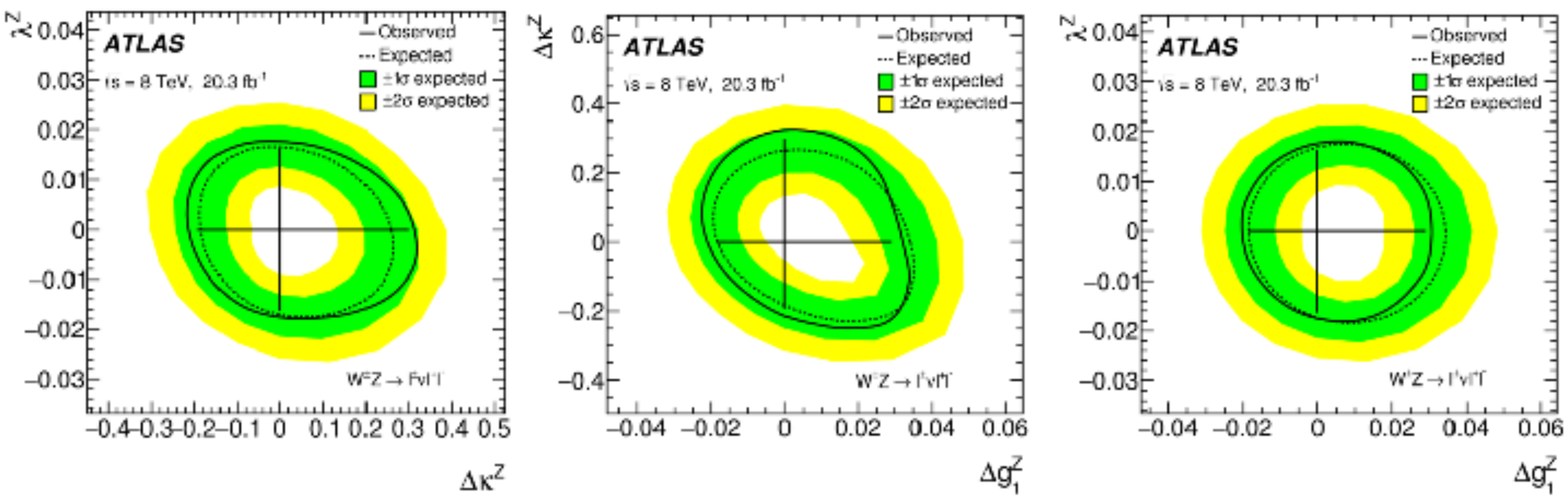




Observed 1D aTGC limits compared with previous measurements

aTGC limits results

- Limit contours for the different aTGC coupling combinations are calculated by fixing 1 aTGC parameter to the SM



- The anomalous couplings can be reinterpreted in terms of the EFT parameters c_i/Λ^2 (i = WWW, W, B)

EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]

There is still much more to do channels to explore and corners of the SM to look at!

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See you soon!