Vector Boson Scattering @ LHC

and VBSCan

Joany Manjarrés

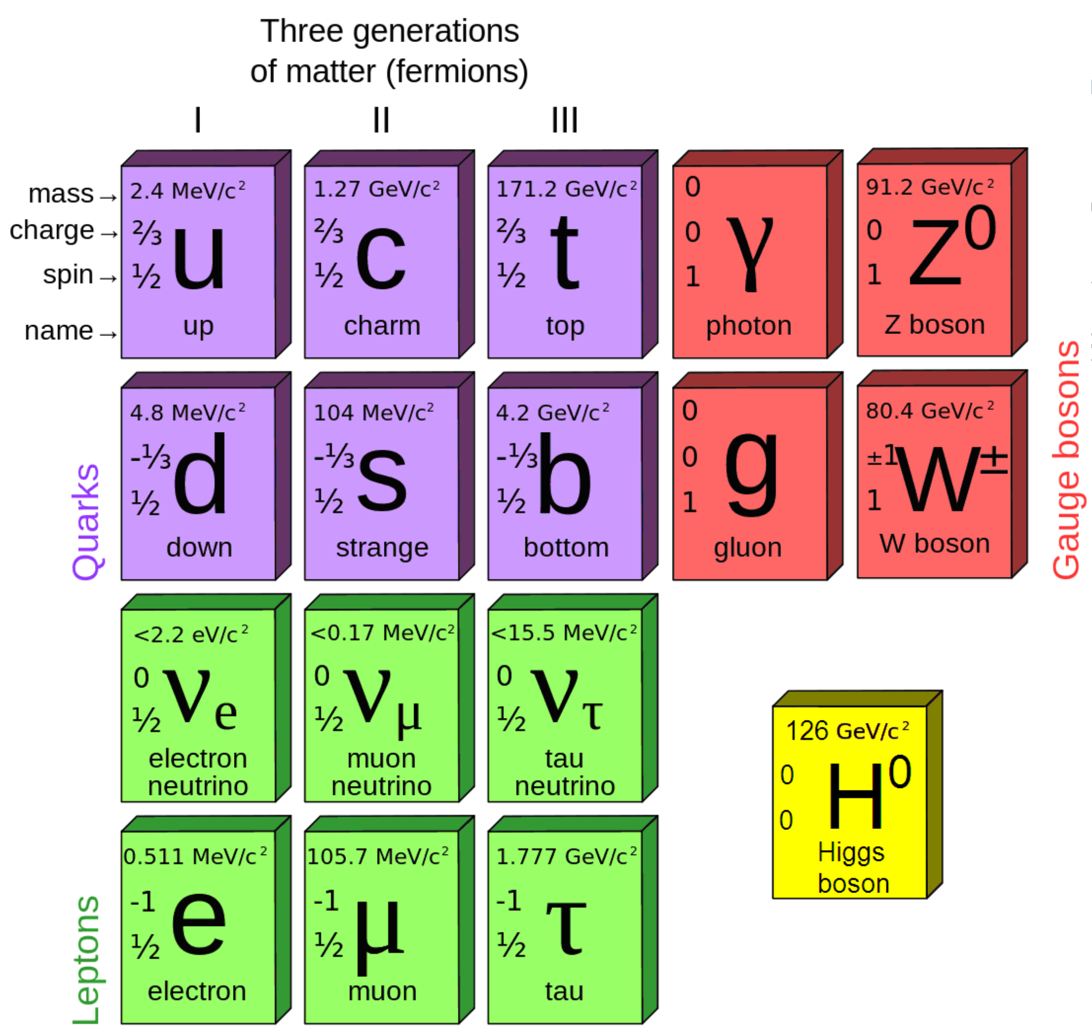
on behalf of the TU Dresden VBS group
and the VBSCan community

September 1st, 2018

TECHNISCHE UNIVERSITÄT DRESDEN

Vector Boson Scattering @ LHC

/BSCan

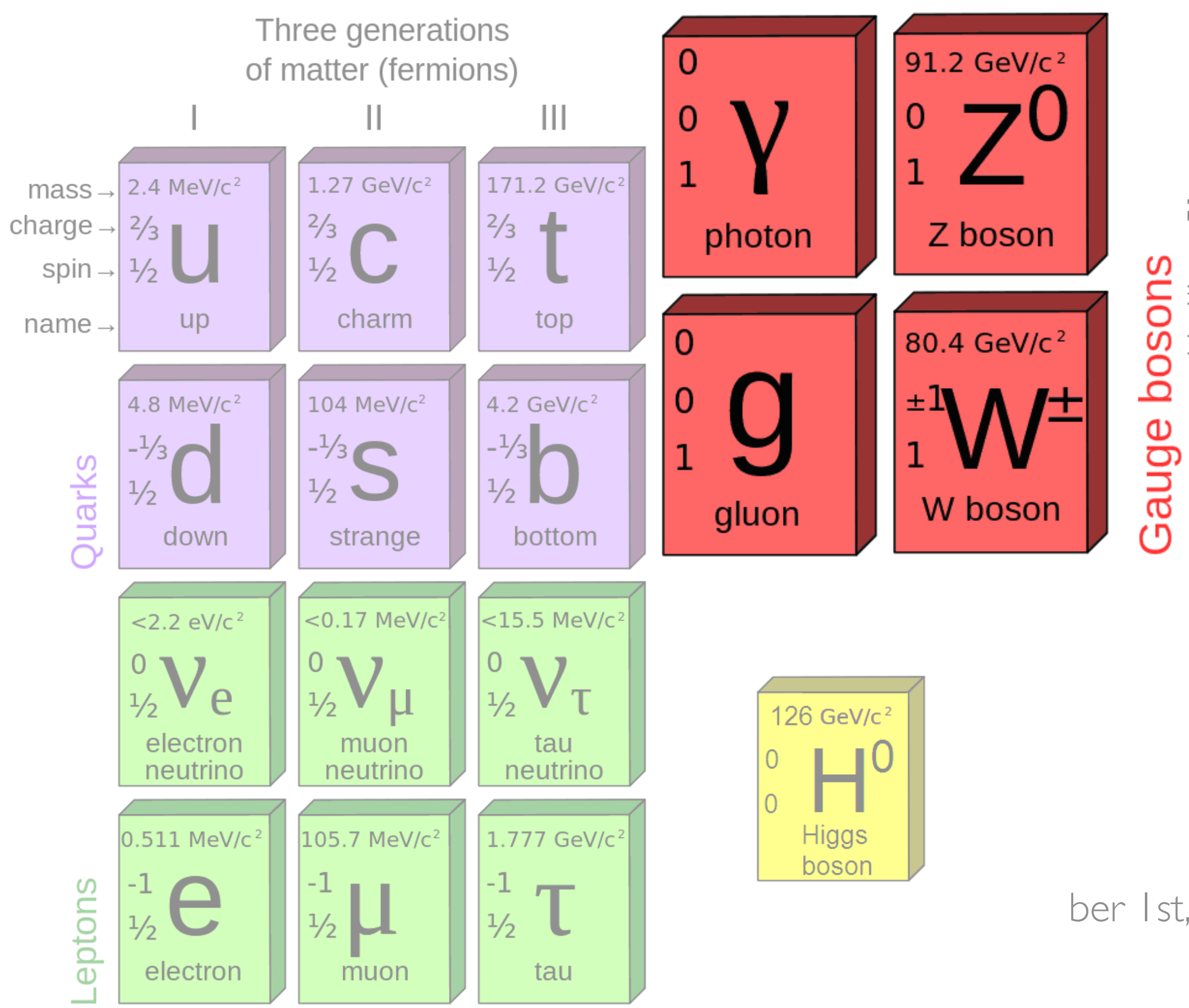


' Manjarrés
TU Dresden VBS group
3SCan community

ber 1st, 2018

TECHNISCHE UNIVERSITÄT DRESDEN

Vector Boson Scattering @ LHC



SCan

arrés

esden VBS group
community

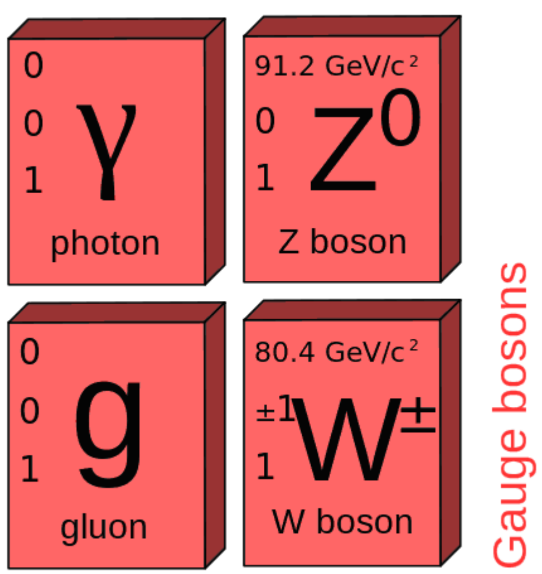
ber 1st, 2018

Vector Boson Scattering @ LHC

and VBSCan

Joany Manjarrés

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



September 1st, 2018

TECHNISCHE UNIVERSITÄT DRESDEN

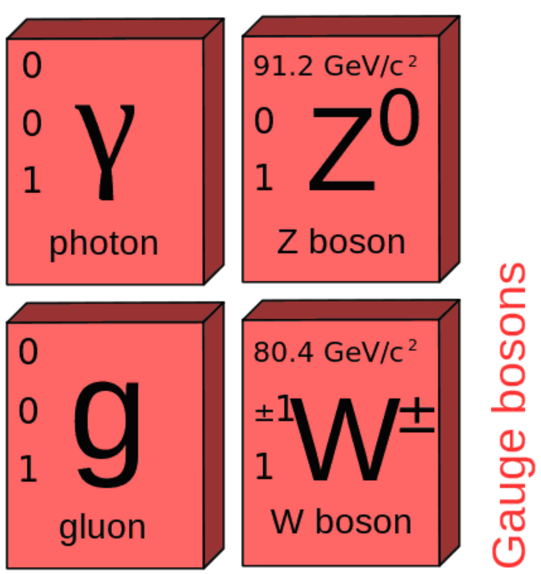
Vector Boson Scattering @ LHC

and VBSCan

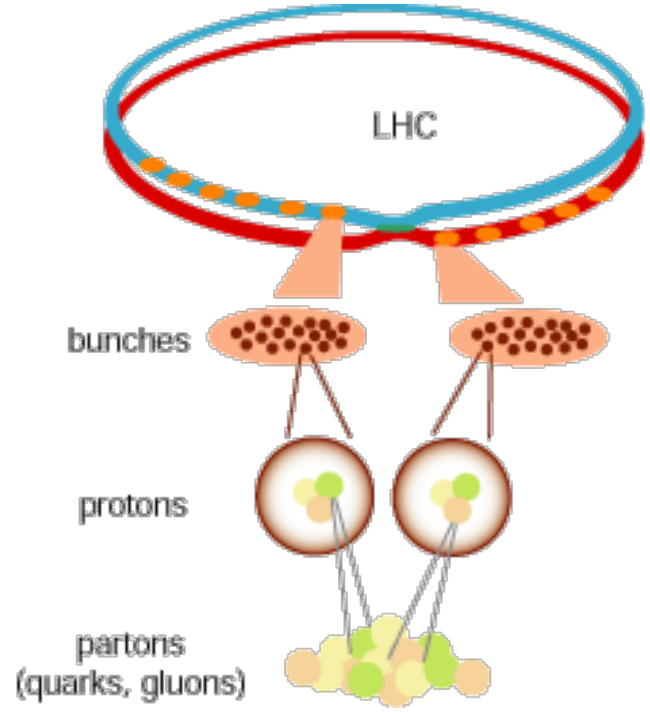
Large
Hadron
Collider

Joany Manjarrés

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

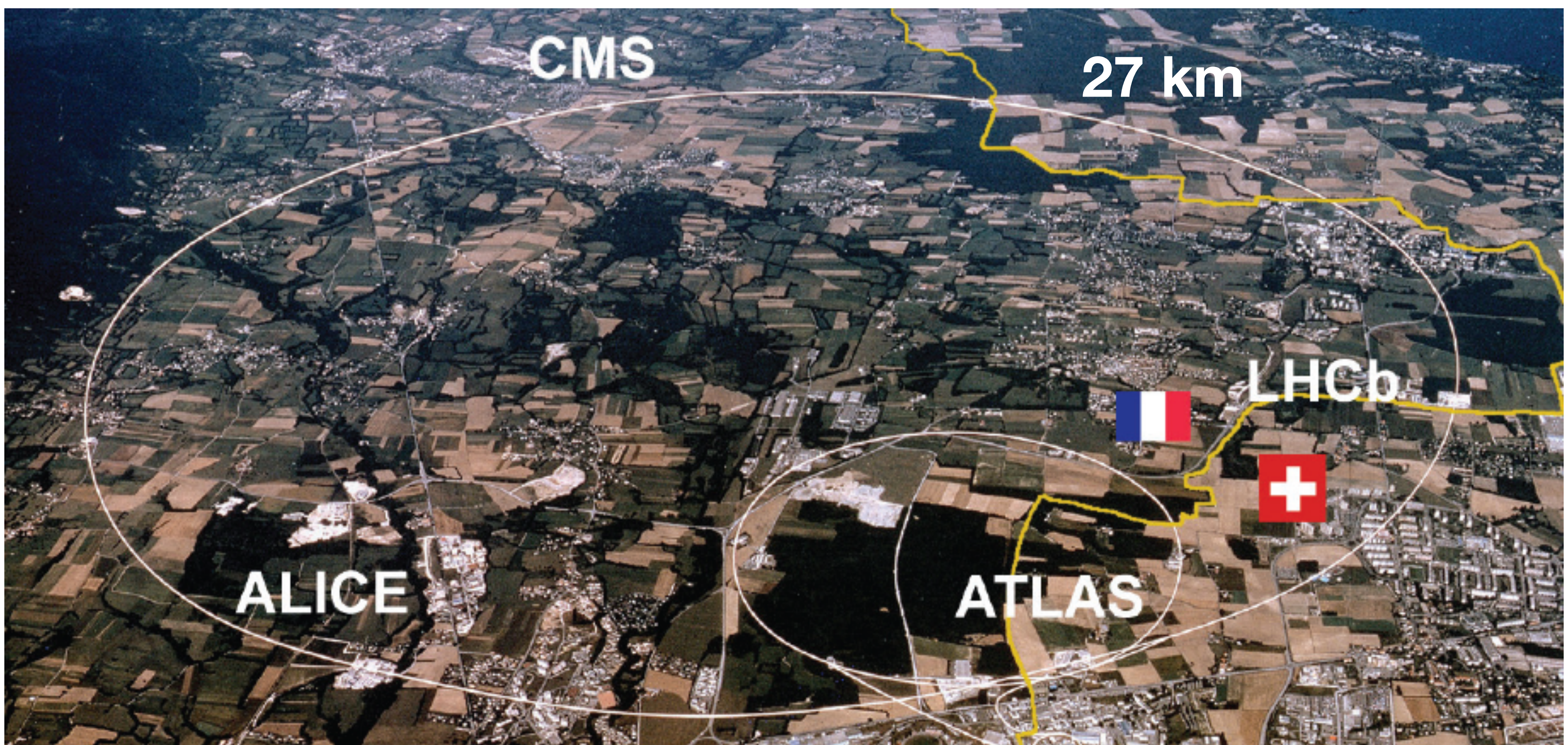


September 1st, 2018



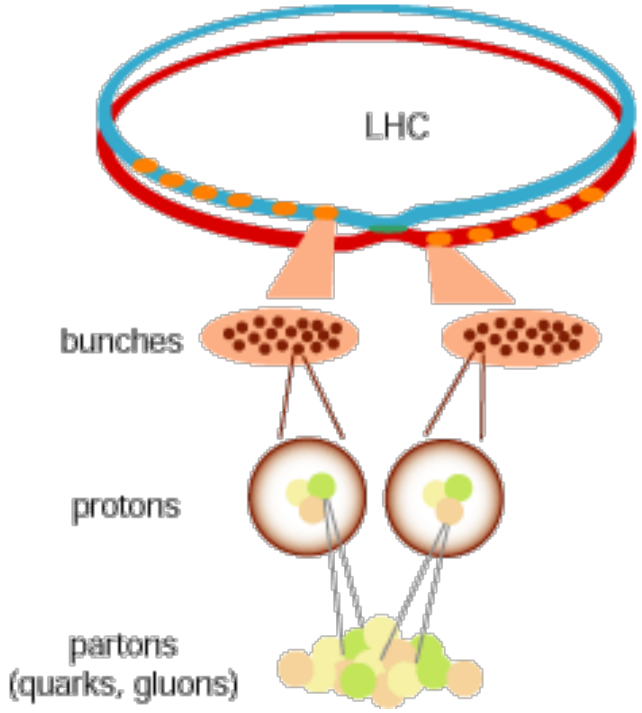
TECHNISCHE UNIVERSITÄT DRESDEN

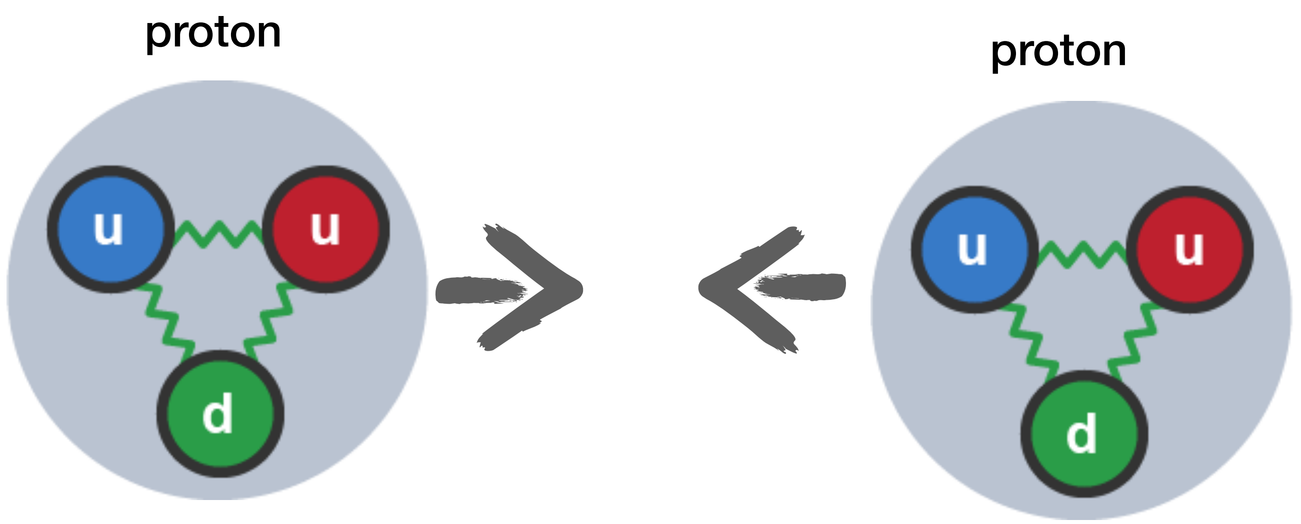
Vector Boson Scattering @ LHC



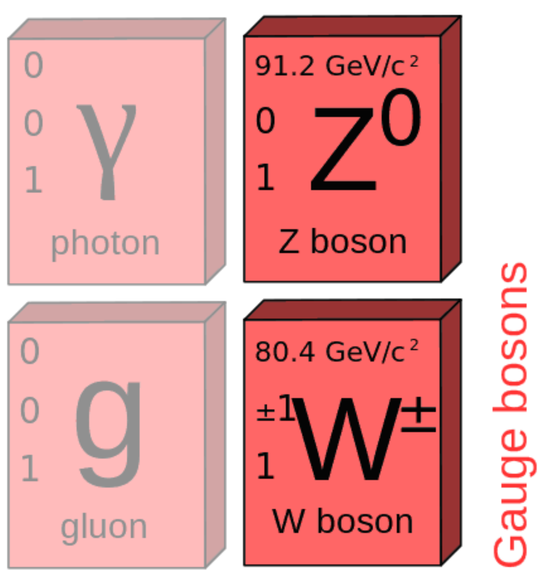
Large
Hadron
Collider

CERN

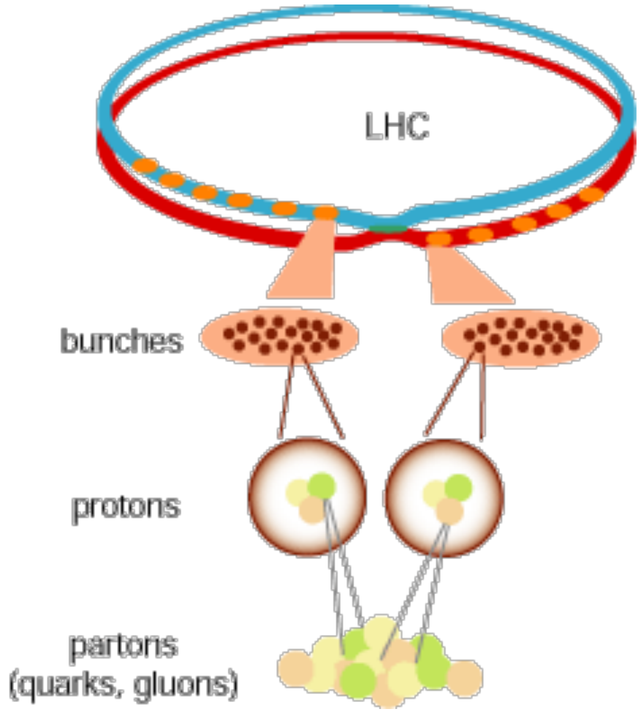


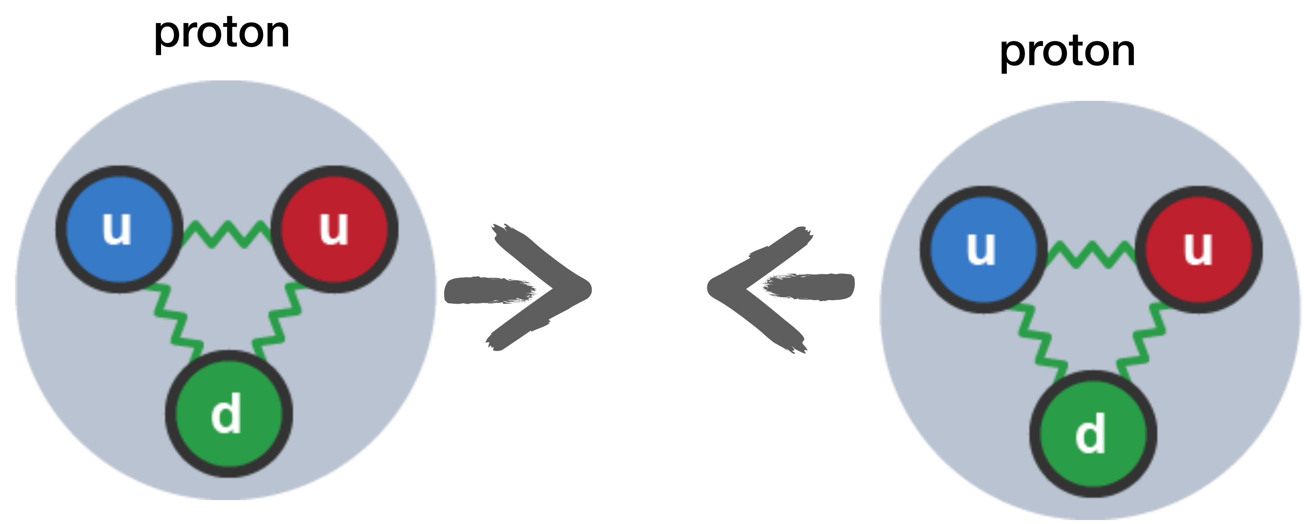


Vector Boson Scattering @ LHC

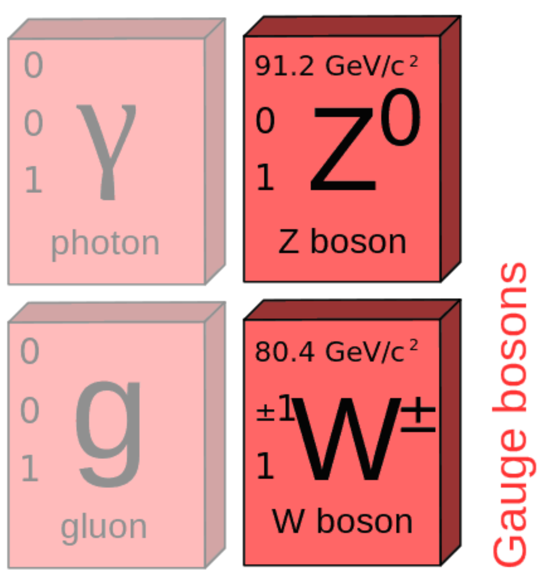


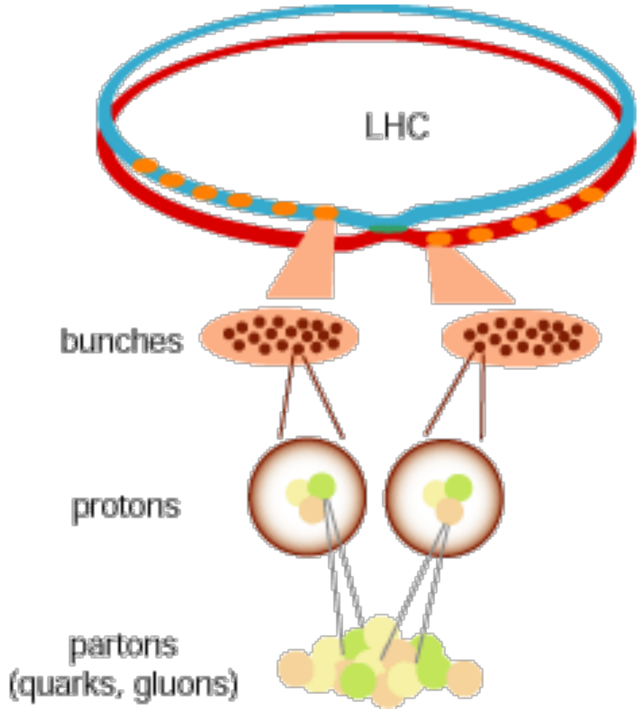
TECHNISCHE UNIVERSITÄT DRESDEN

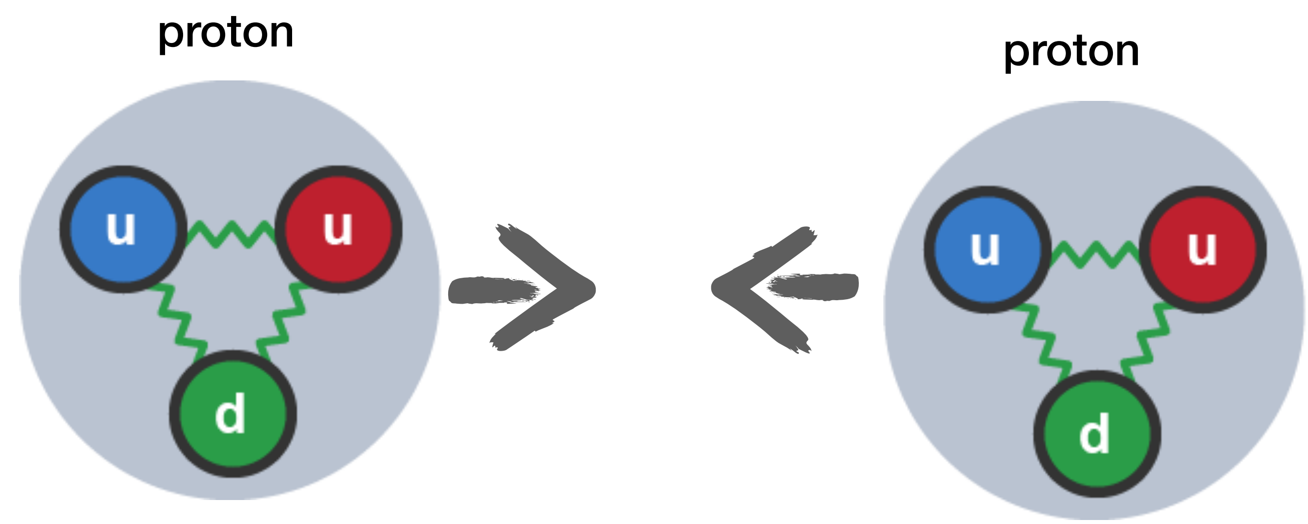




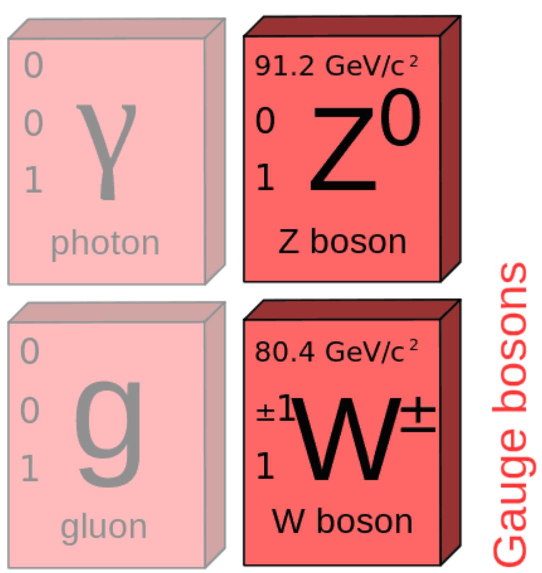
Vector Boson Scattering @ LHC

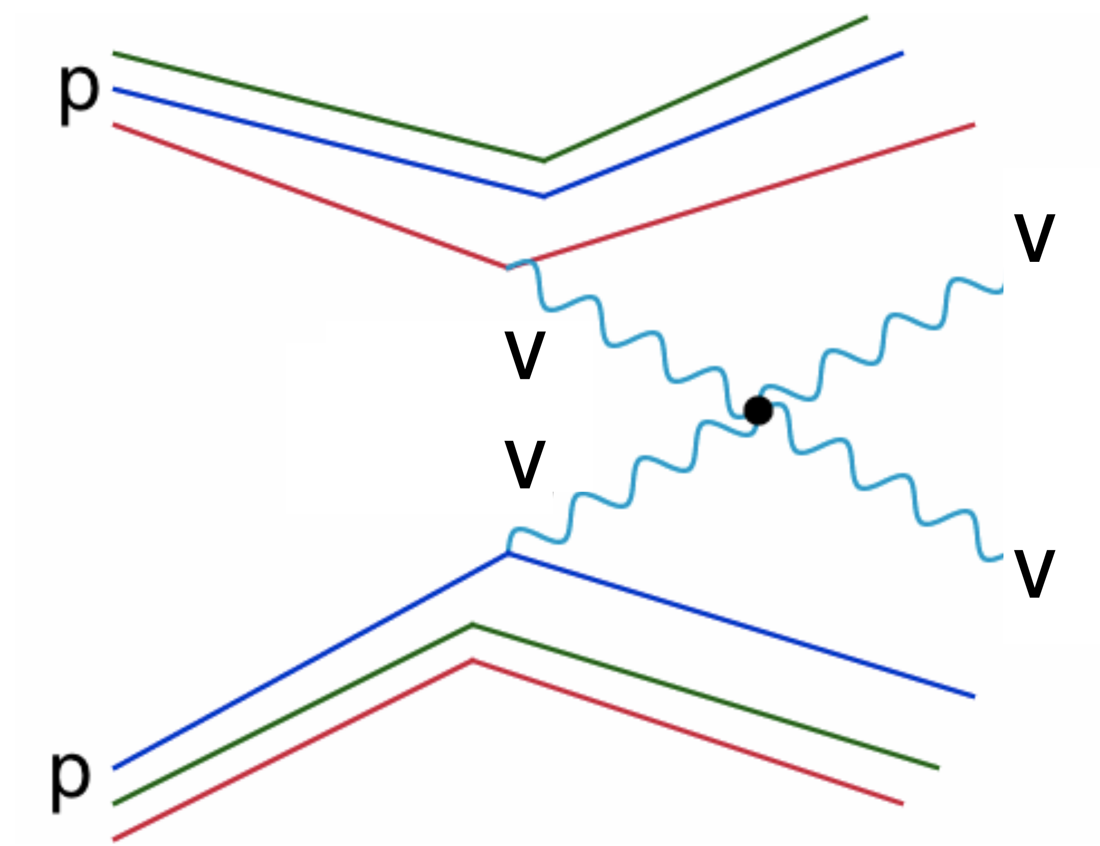






Vector Boson Scattering @ LHC





Vector Boson Scattering @ LHC

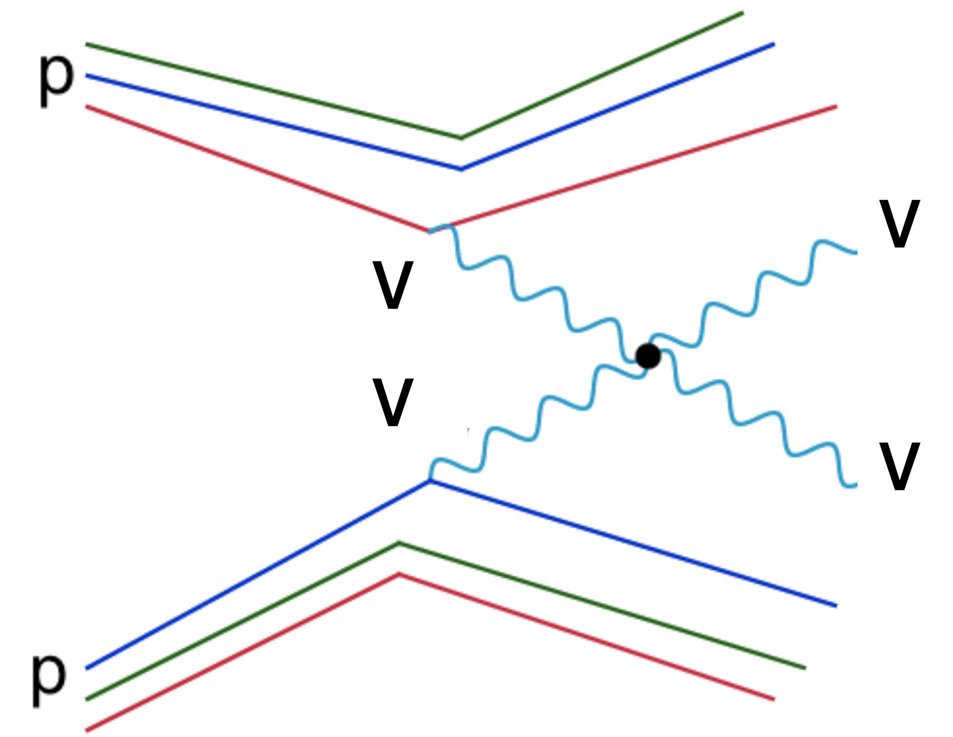
TECHNISCHE UNIVERSITÄT DRESDEN

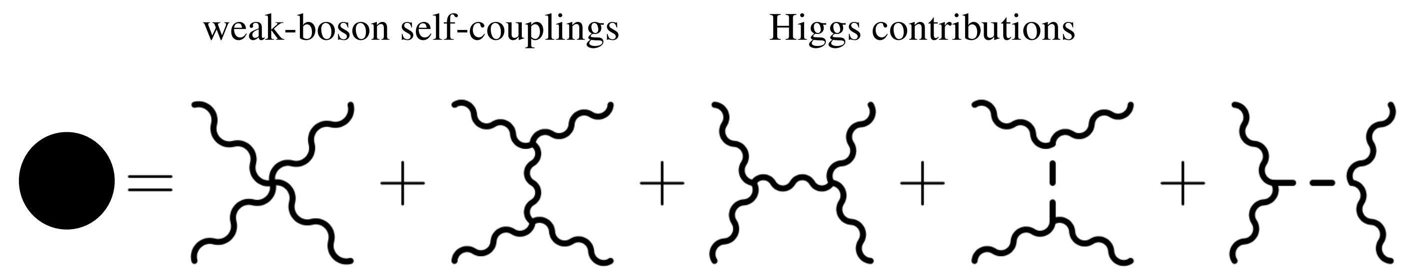
Why is interesting to look at VBS

~~Vector Boson Scattering~~ @ LHC ?

Why VBS @ LHC ?

1) Important process for the Standard Model



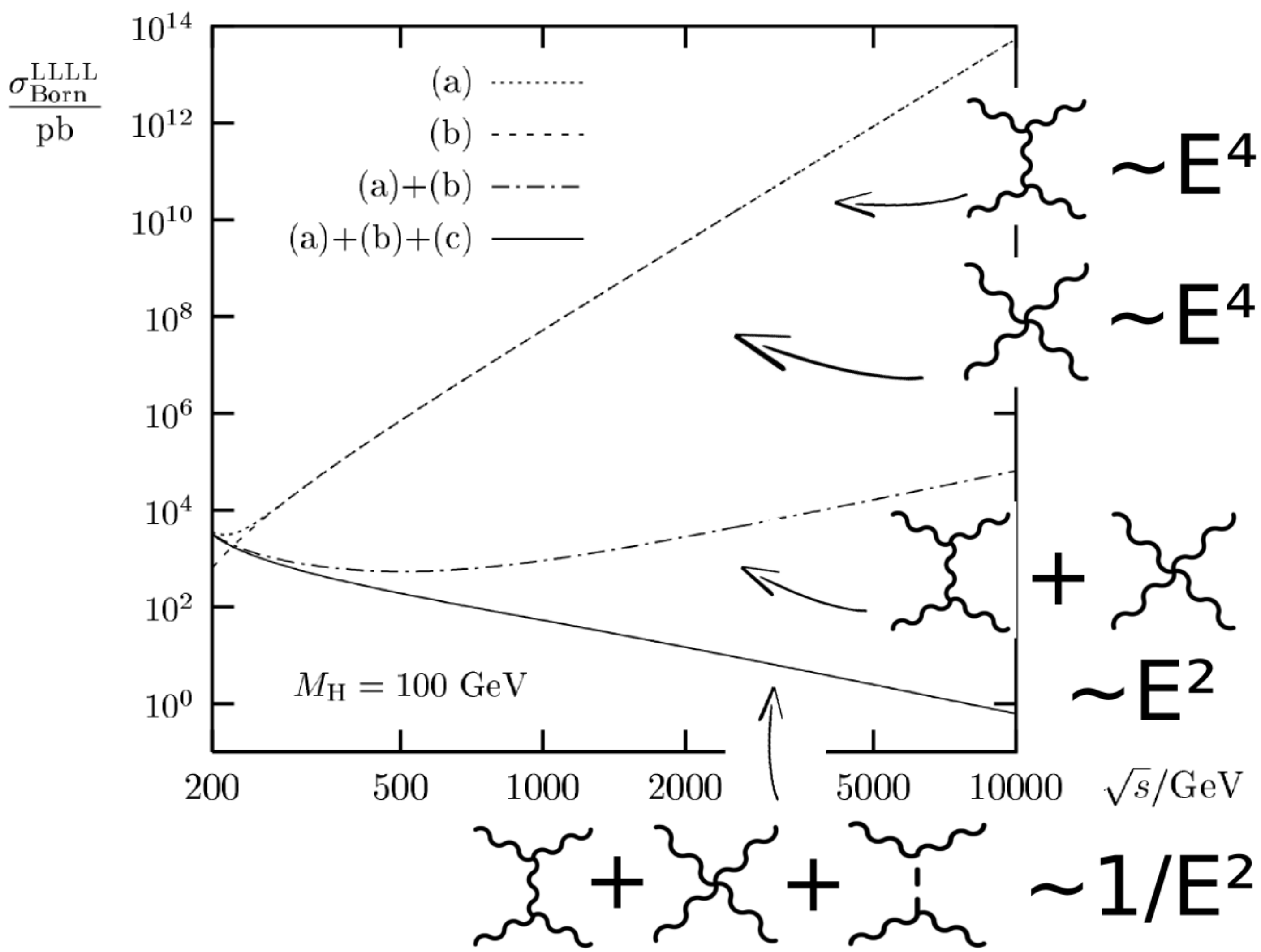


Why VBS @ LHC ?

TECHNISCHE UNIVERSITÄT DRESDEN

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]



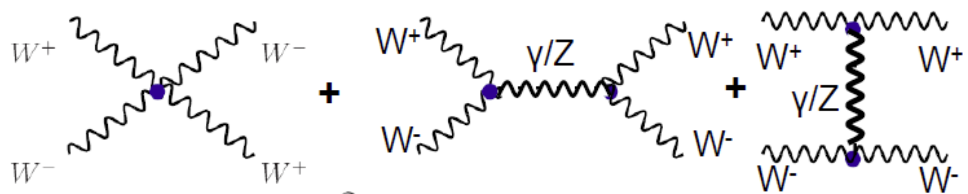
* cross-section (σ), a quantity expressing the likelihood of an interaction event between two particles. Wikipedia

Why VBS @ LHC ?

TECHNISCHE UNIVERSITÄT DRESDEN

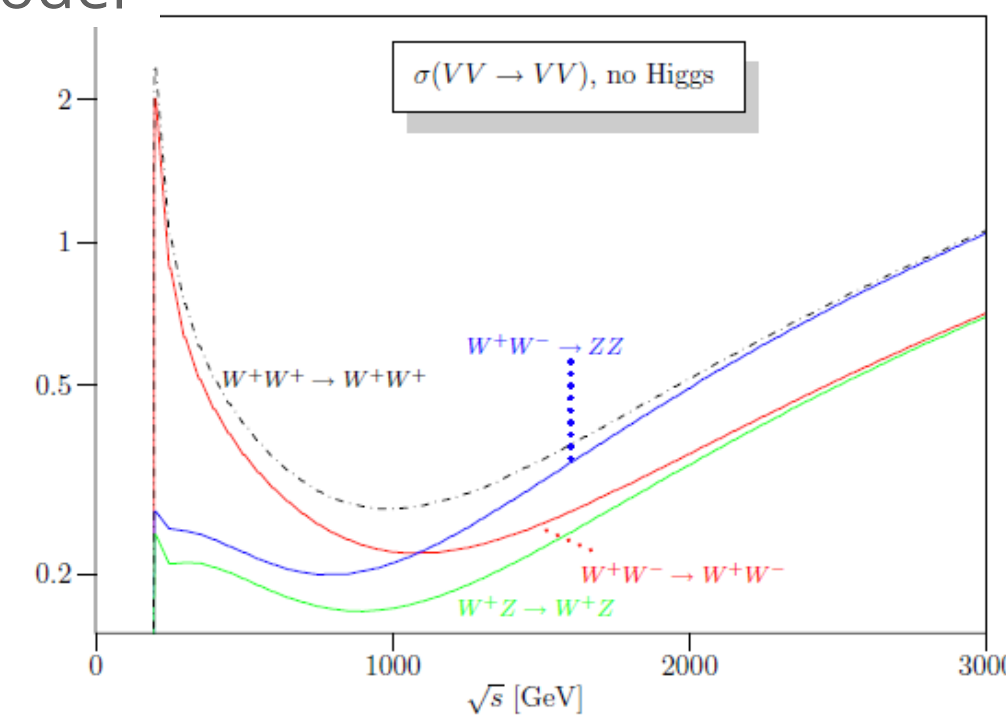
1) Important process for the Standard Model

- VBS Without Higgs contribution:

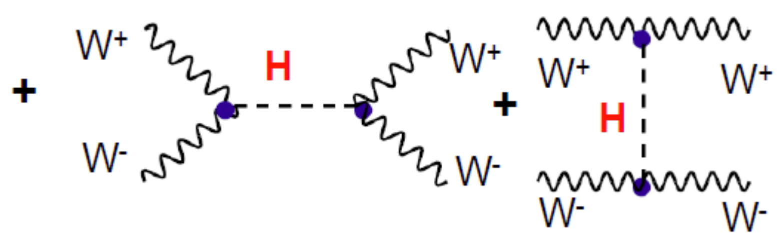


$$\sigma_{WW} \propto s^2 \to \infty \quad \text{wenn } s \to \infty$$

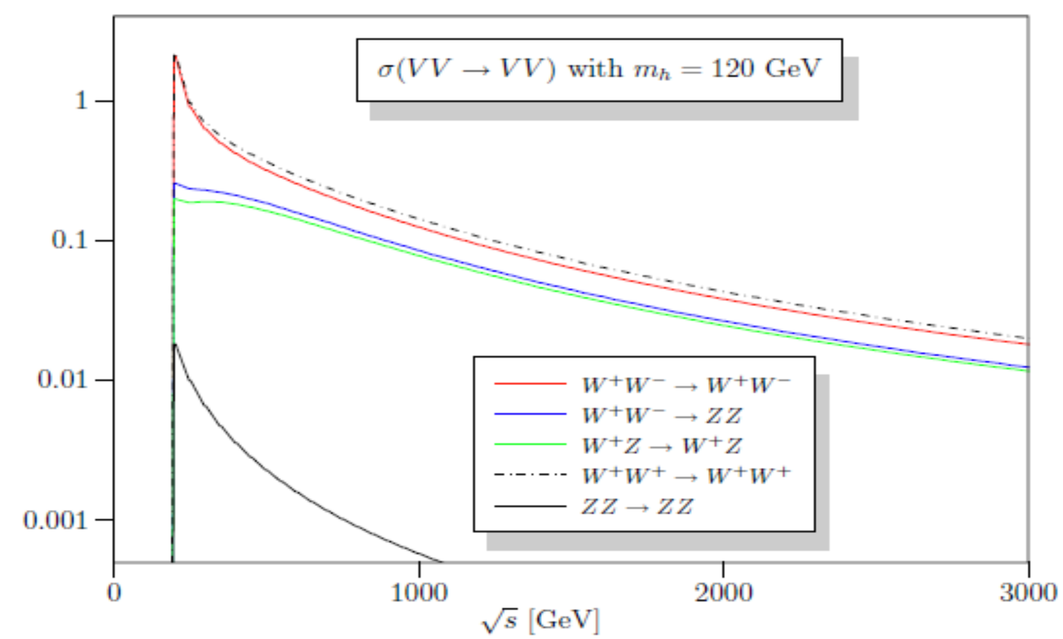
Violates "unitarity" (probability>1) at ~2 TeV



- 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

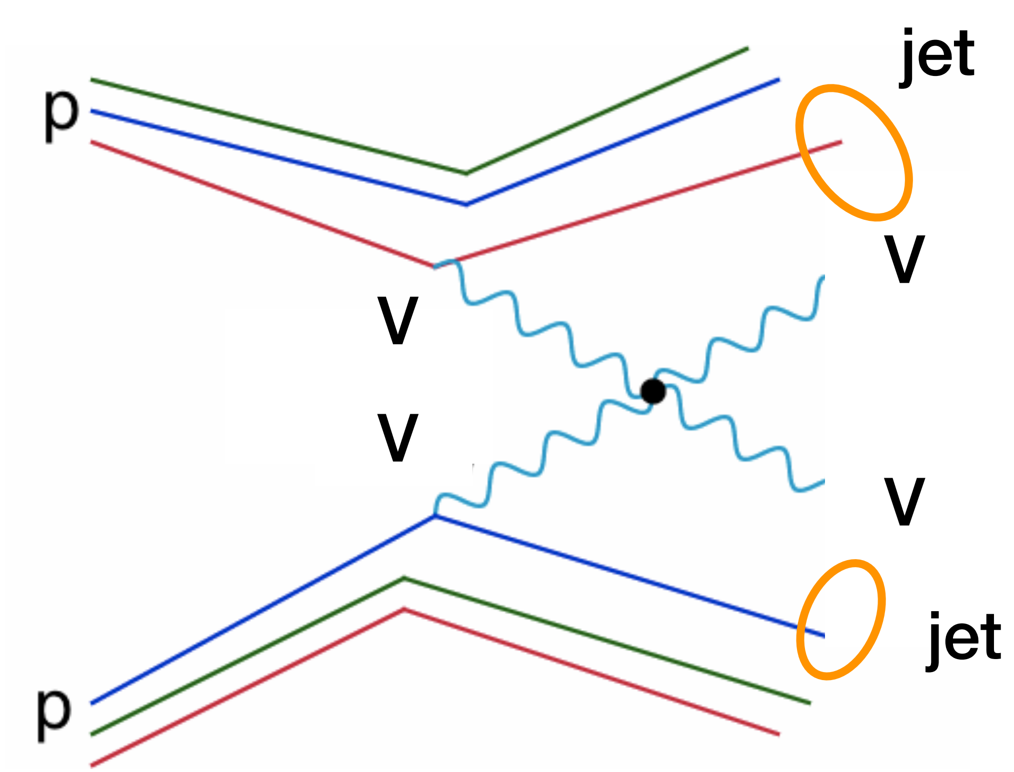
Why VBS @ LHC ?

TECHNISCHE UNIVERSITÄT DRESDEN

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 $0.1x10^{-15}$m before transforming into other particles, and their interaction with other particles is limited to a range of $0.002x10^{-15}$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**

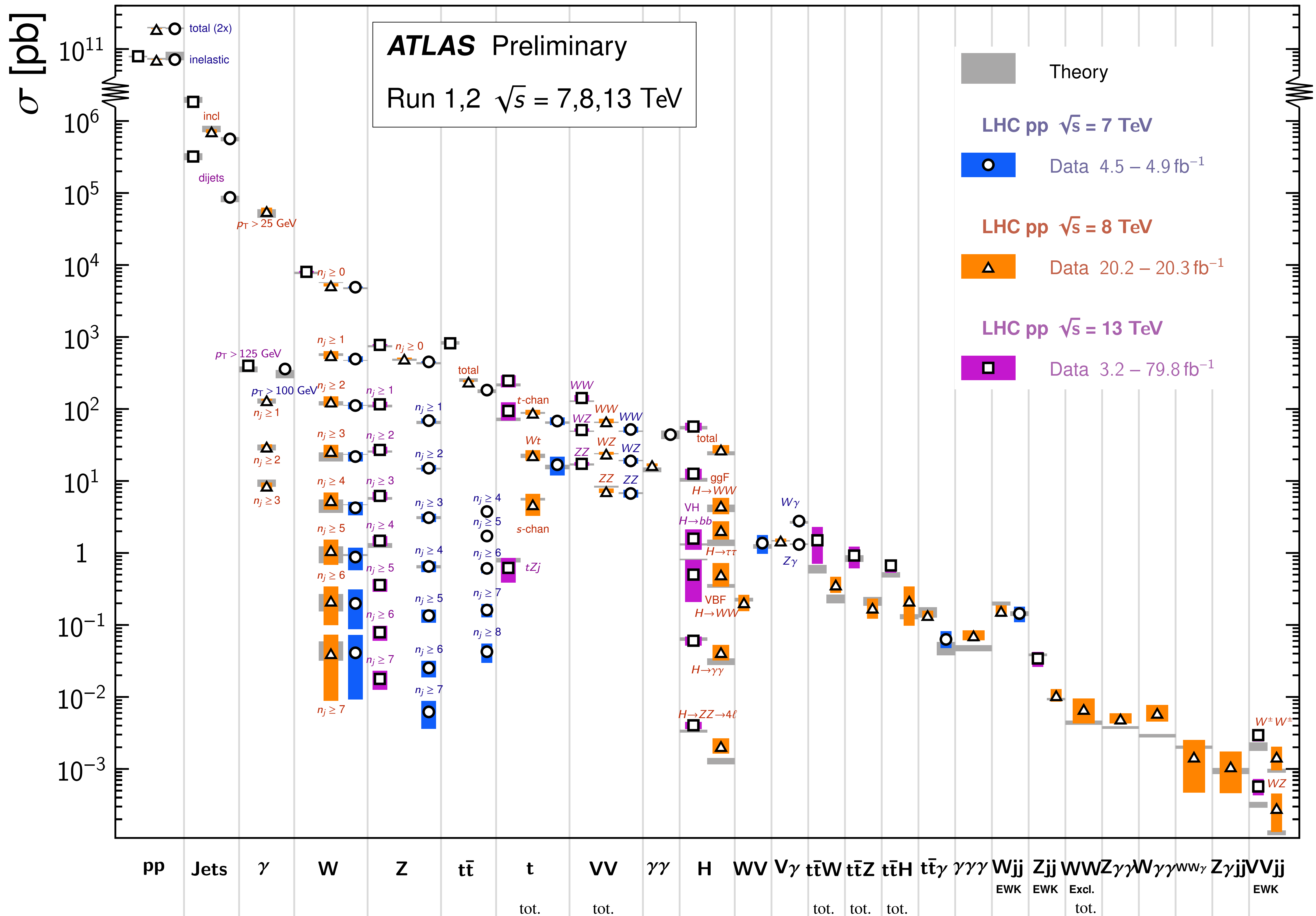
from ATLAS briefing



qq → VVjj

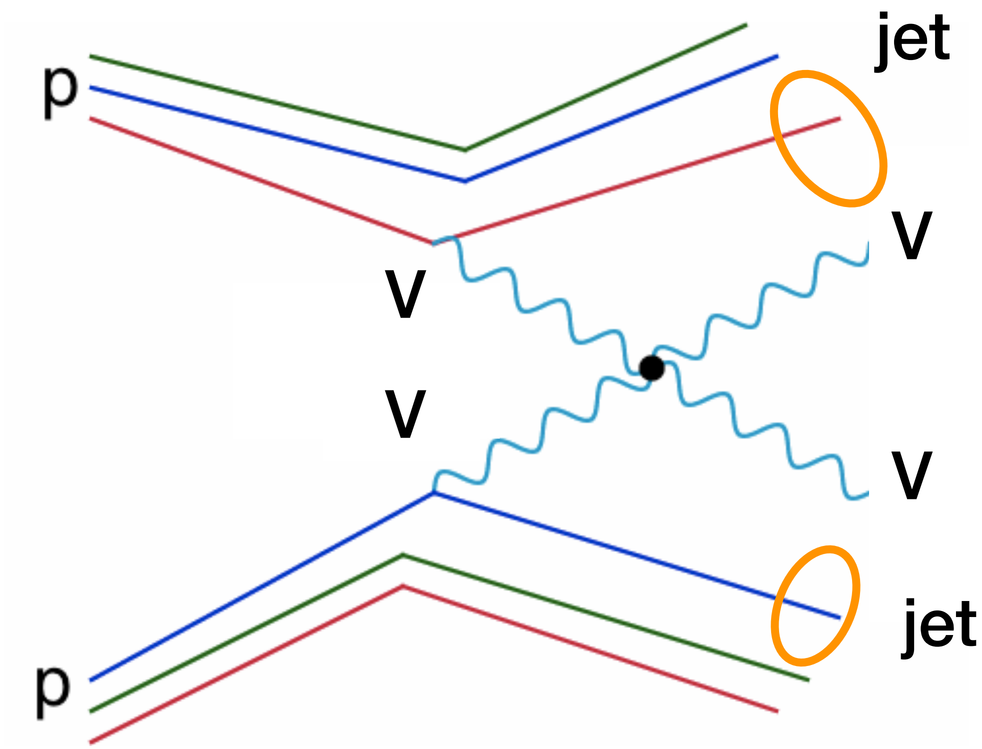
Standard Model Production Cross Section Measurements

Status: July 2018



Experimental work at the LHC

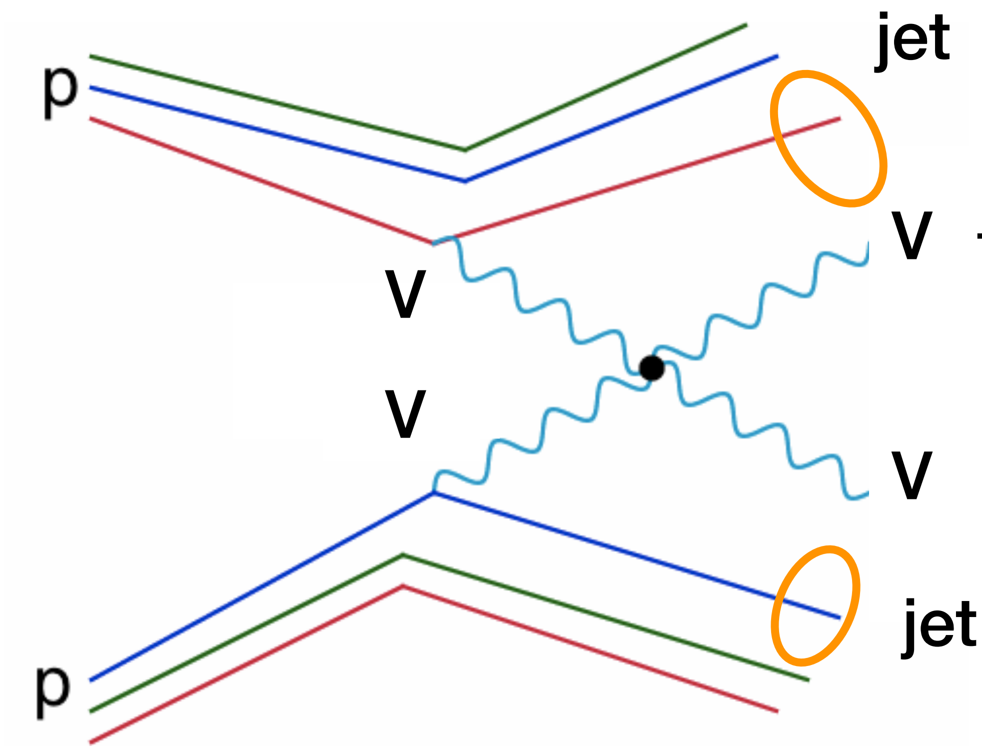
TECHNISCHE UNIVERSITÄT DRESDEN



Today: Latest LHC results

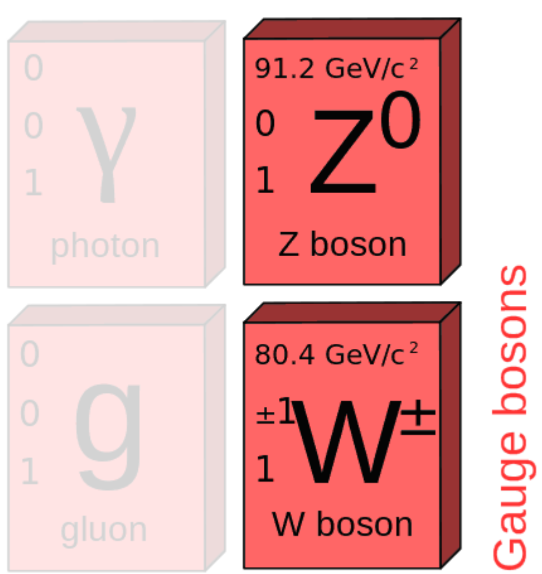
Experimental work at the LHC

TECHNISCHE UNIVERSITÄT DRESDEN



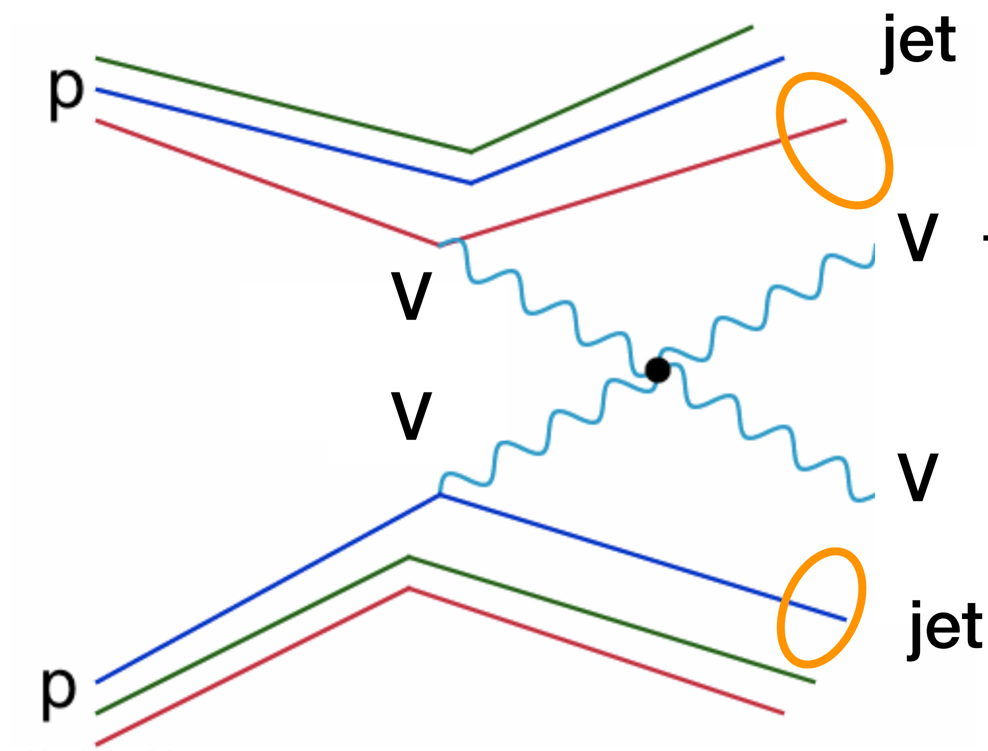
Today: Latest LHC results

→ V = $W^{\pm}$, Z



Experimental work at the LHC

TECHNISCHE UNIVERSITÄT DRESDEN



Today: **Latest LHC results**

V = W±, 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 × 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.

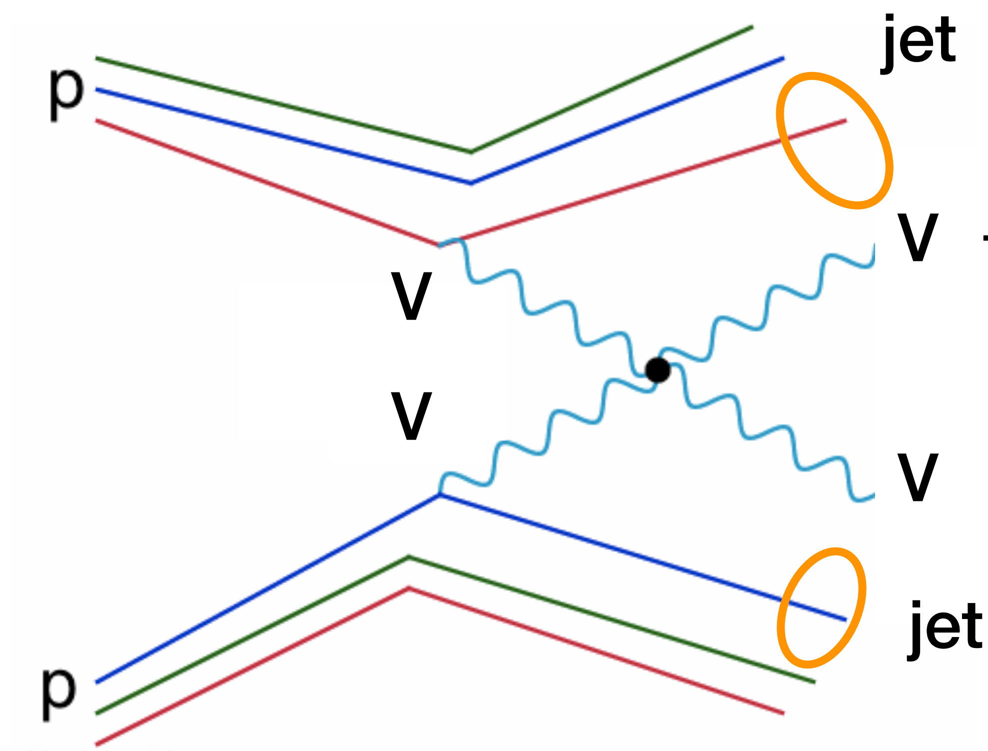
Z DECAY MODES

	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 pdg http://pdg.lbl.gov/

Experimental work at the LHC

TECHNISCHE UNIVERSITÄT DRESDEN



Today: Latest LHC results

V = W±, Z

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) %	

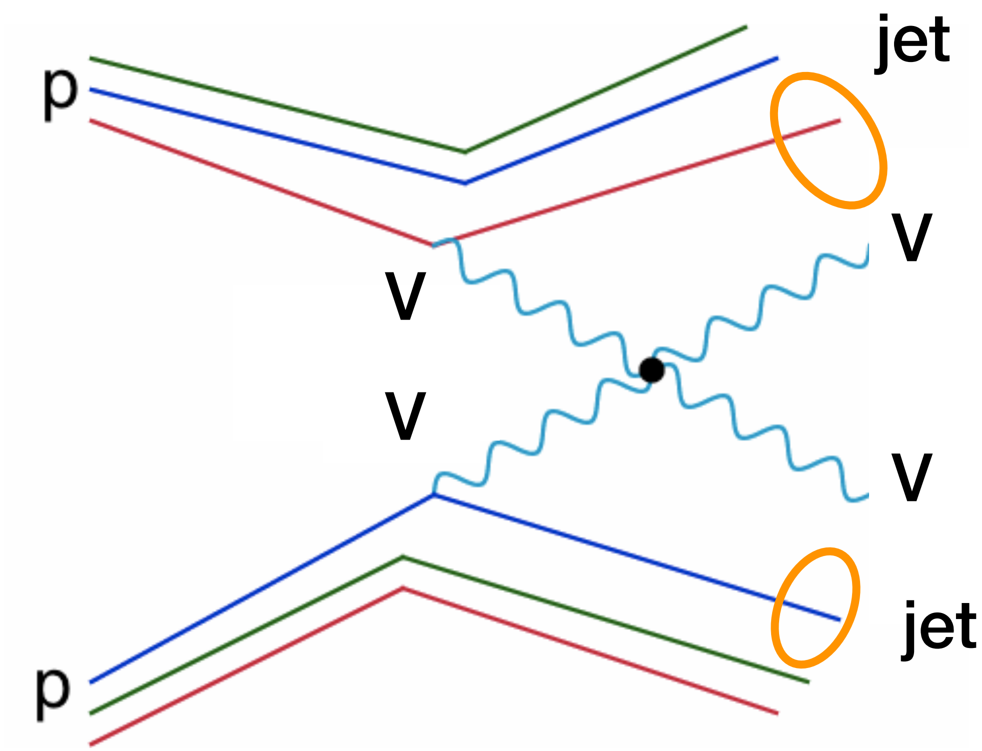
W^+ DECAY MODES

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) %	

Focus on electron and muons decays

Experimental work at the LHC

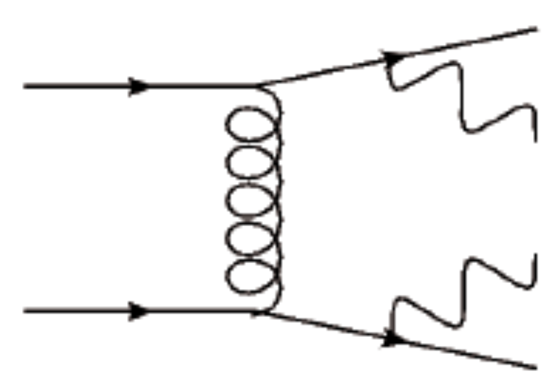


Today: **Latest LHC results**

- $W^{\pm}W^{\pm}$ 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

TECHNISCHE UNIVERSITÄT DRESDEN



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

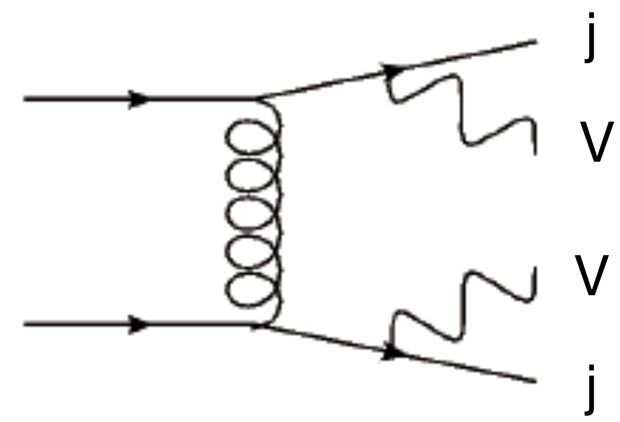
- **W±W±jj-EW**:= O(α_W^6)
  - contains VBS part (t-channel +QGC)
  - interf(QCD-EW)~10% included

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

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

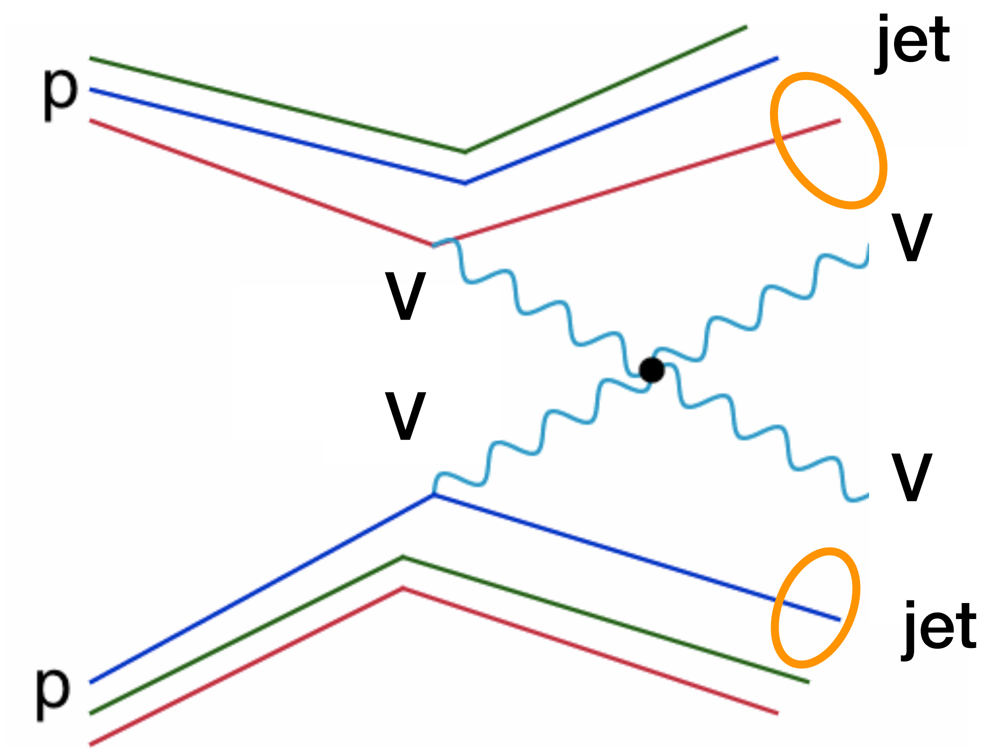


- **W±W±jj-EW**:= O(α_W^6)
  - contains VBS part (t-channel +QGC)
  - interf(QCD-EW)~10% included

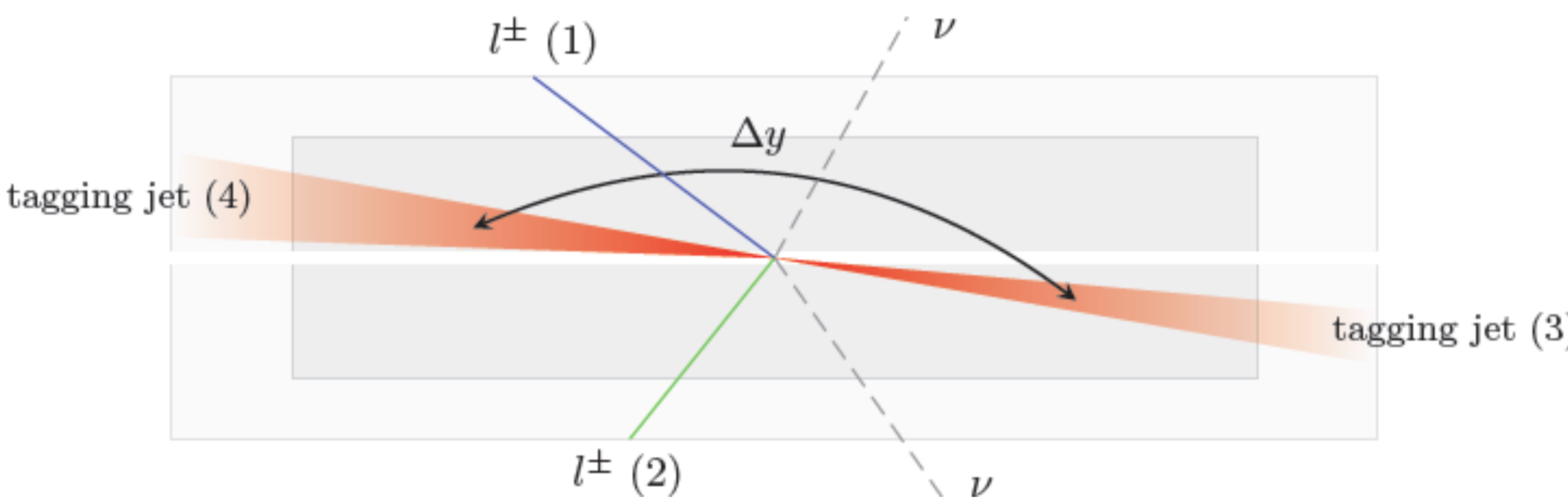
Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^\pm\nu\ell'^\pm\nu' jj$	$W^\pm W^\pm$	19.5 fb	18.8 fb	1:1
$\ell^\pm\nu\ell^\mp\nu jj$	$W^\pm W^\mp + ZZ$	93.7 fb	3192 fb	1:30
$\ell^\pm\ell^\mp\ell'^\pm\nu' jj$	$W^\pm Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

Experimental work at the LHC

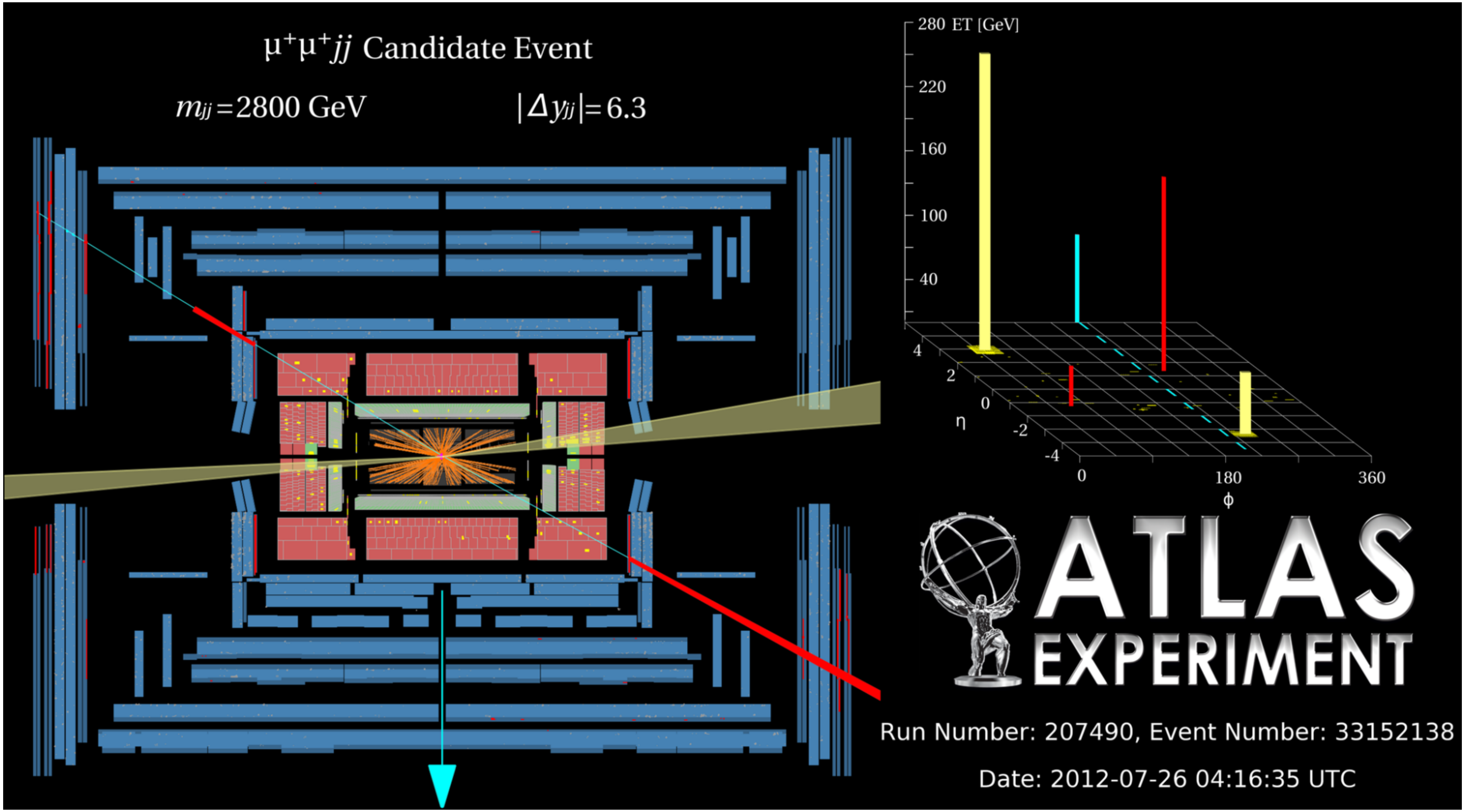
TECHNISCHE UNIVERSITÄT DRESDEN



- 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,

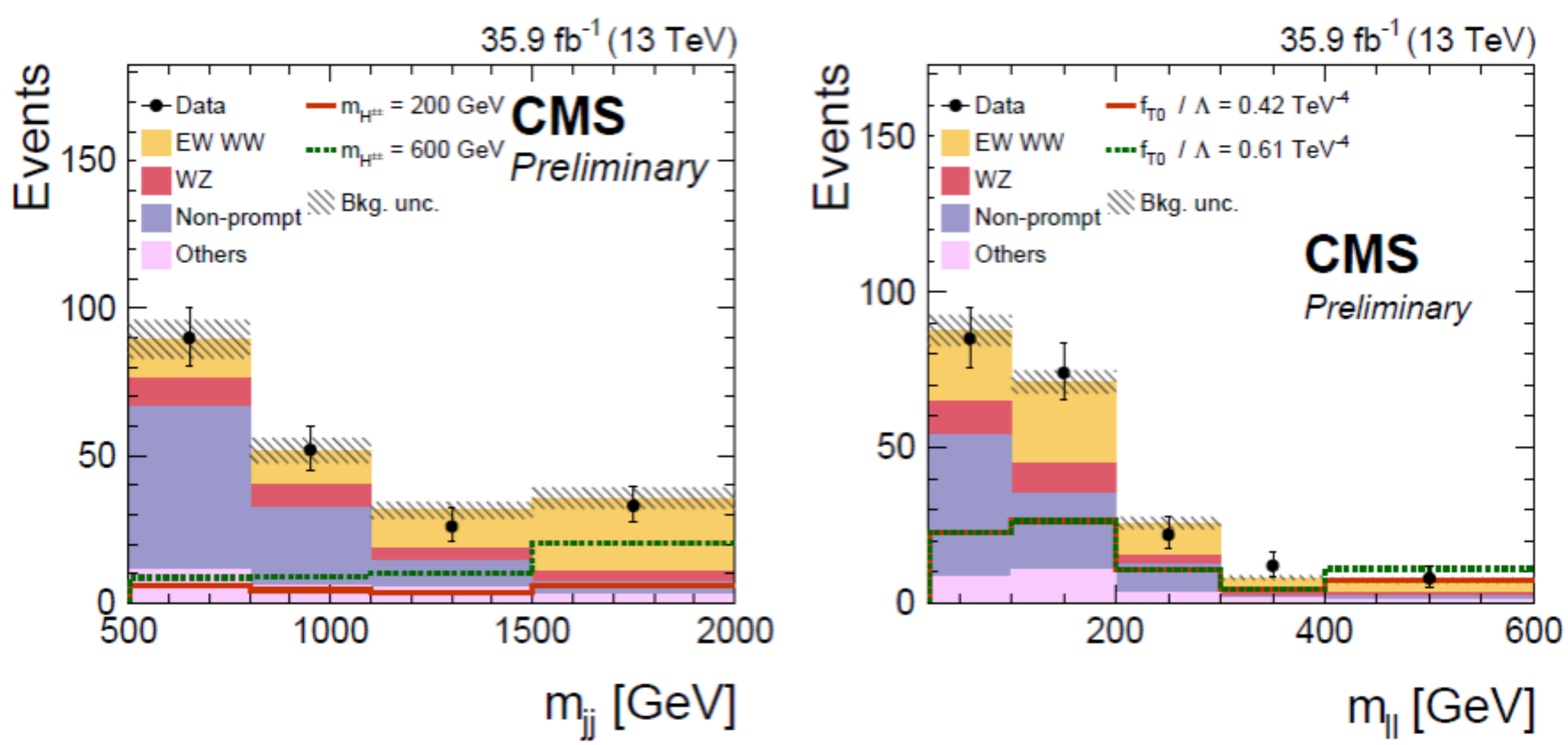
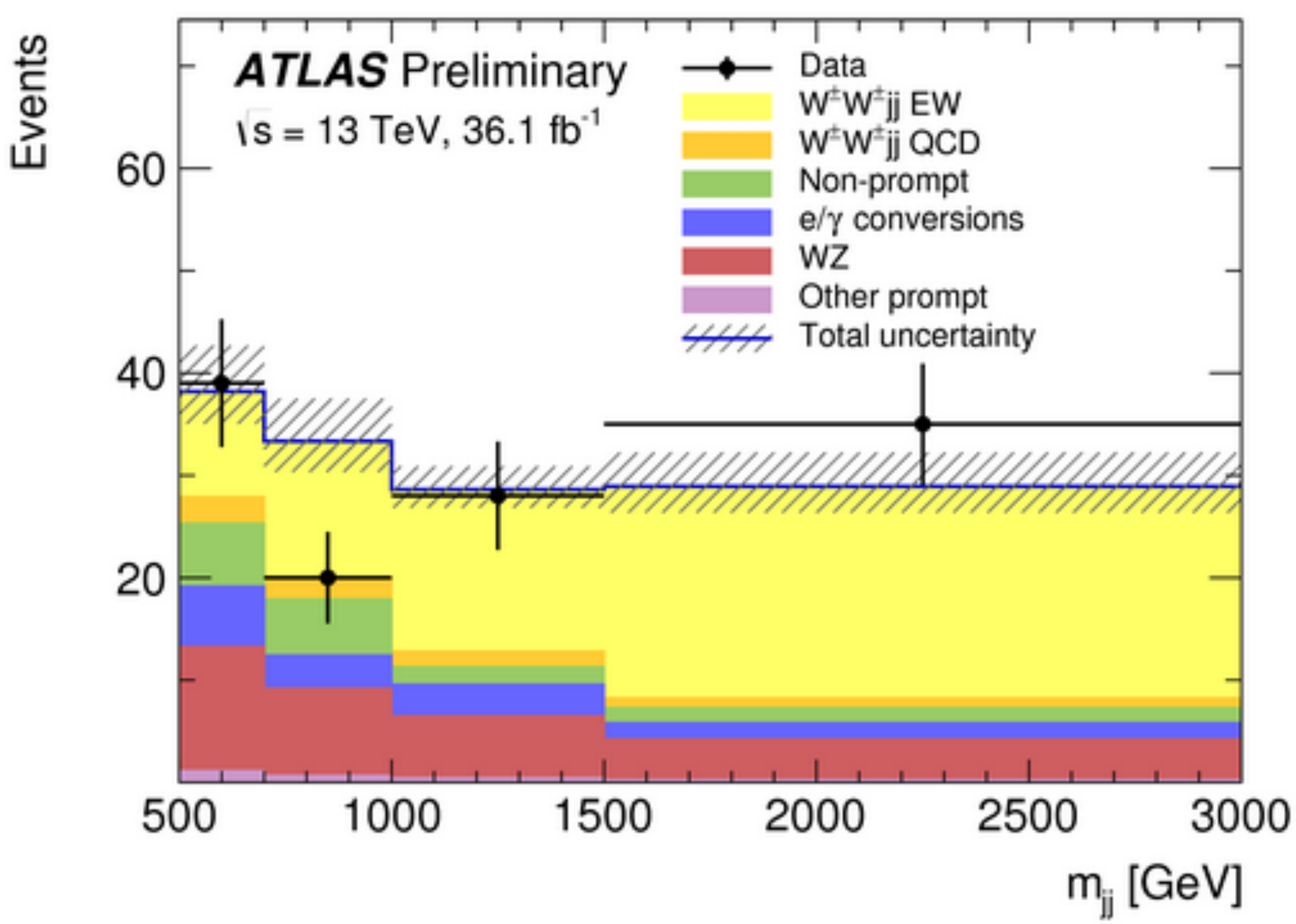


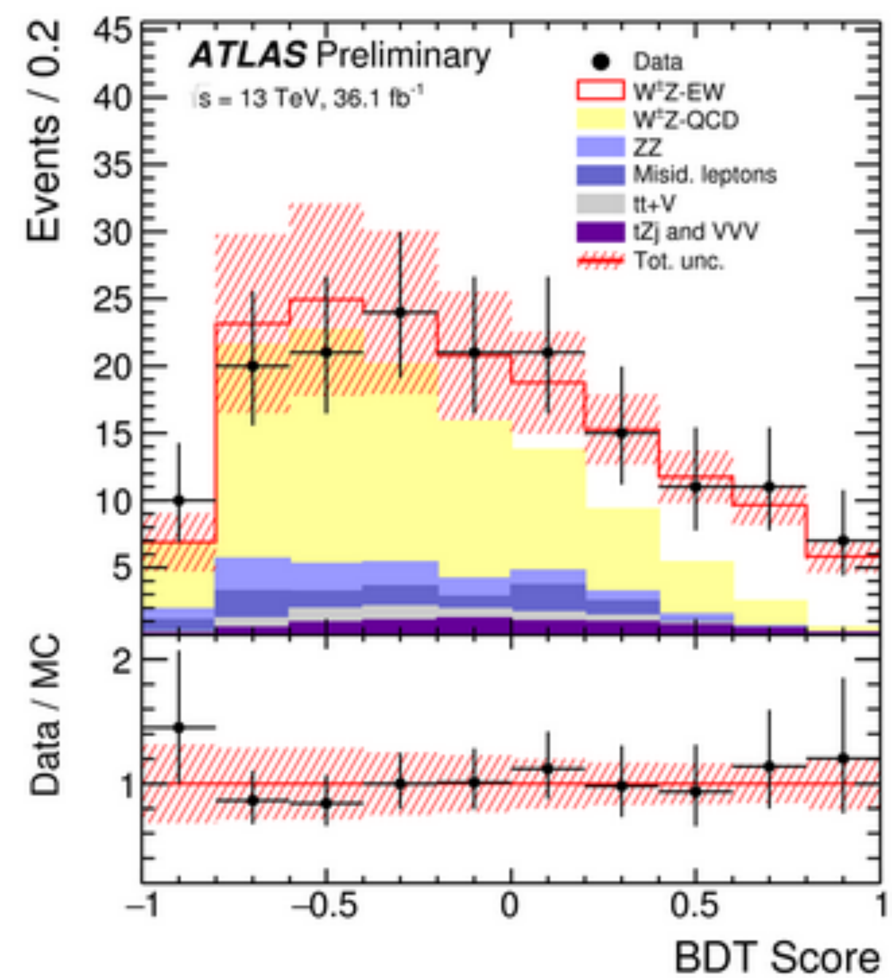
Figure 2: Distributions of m_{jj} (left) and $m_{\ell\ell}$ (right) in the signal region. The normalization of the predicted signal and background distributions corresponds to the result of the fit. The hatched bars include statistical and systematic uncertainties. For illustration, the doubly charged 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

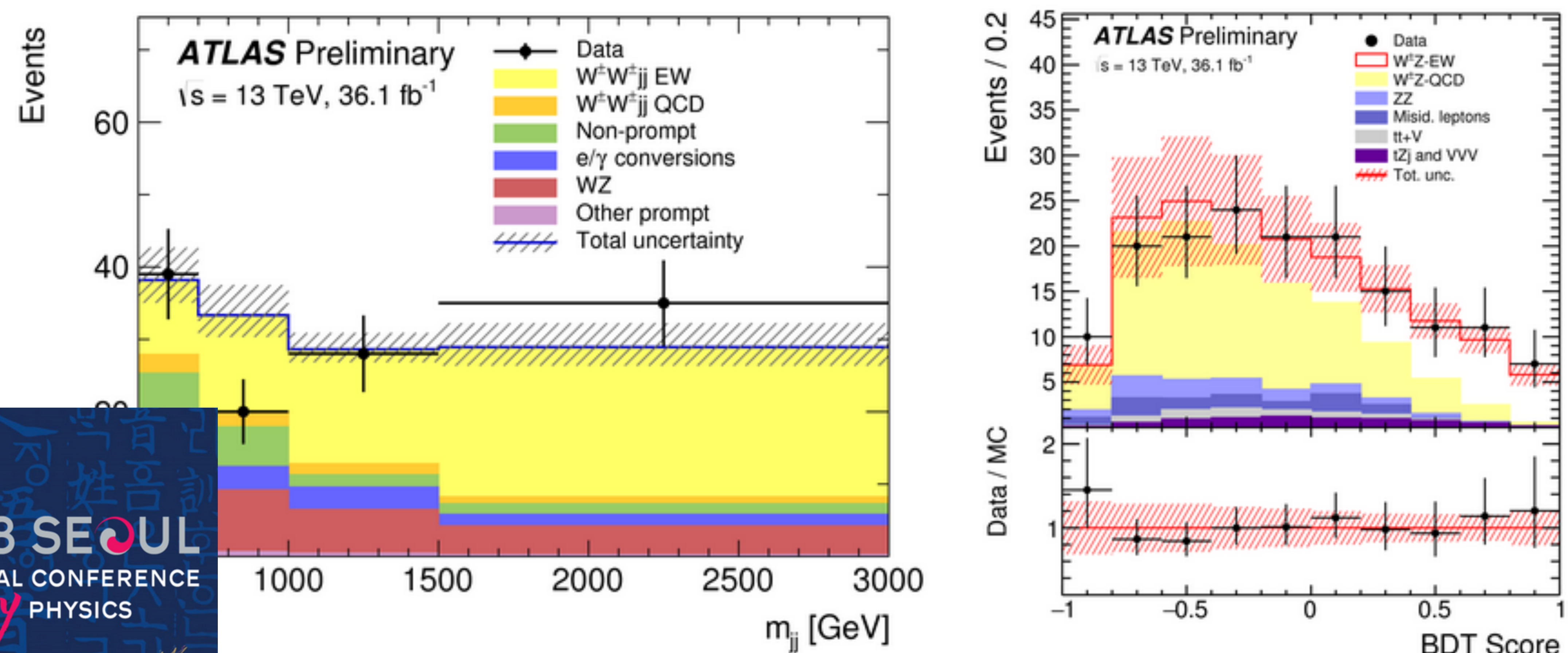
https://atlas.cern/updates/physics-briefing/weak-lightsabers

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.

Vector Boson Scattering @ LHC

and VBSCan

TECHNISCHE UNIVERSITÄT DRESDEN

Vector Boson Scattering @ LHC

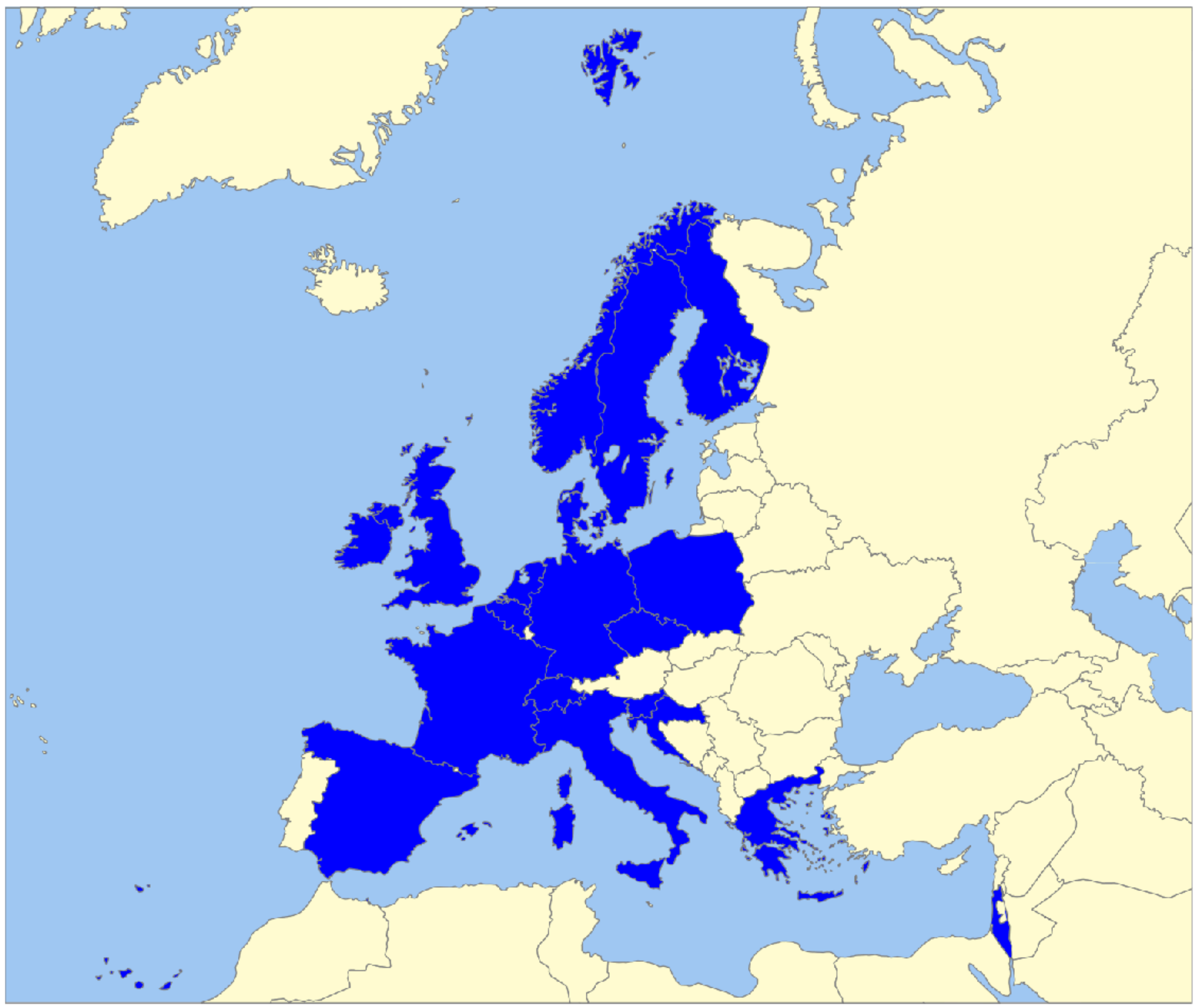
and VBSCan COST Network

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

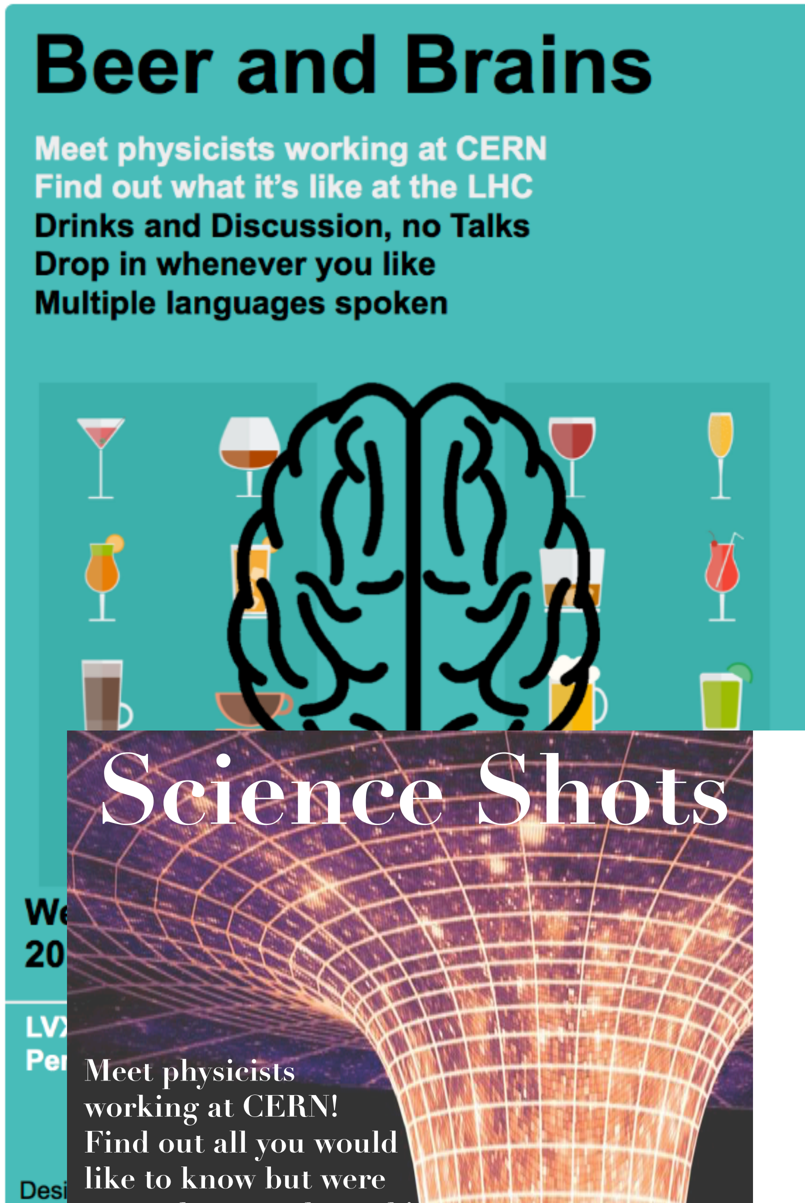


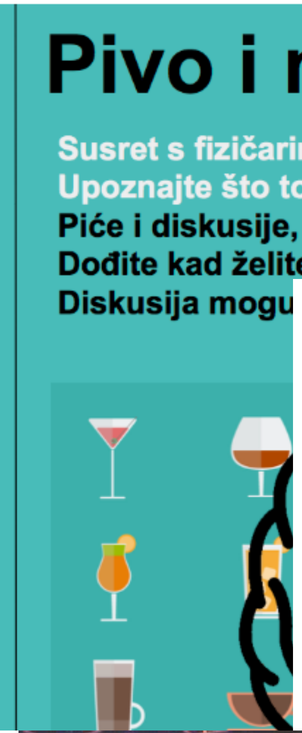
Country	Date	Status
Belgium	25/01/2017	Confirmed
Croatia	06/12/2016	Confirmed
Czech Republic	21/02/2017	Confirmed
Finland	03/02/2017	Confirmed
France	17/11/2016	Confirmed
Germany	28/11/2016	Confirmed
Greece	01/03/2017	Confirmed
Ireland	24/03/2017	Confirmed
Israel	07/03/2017	Confirmed
Italy	10/01/2017	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		

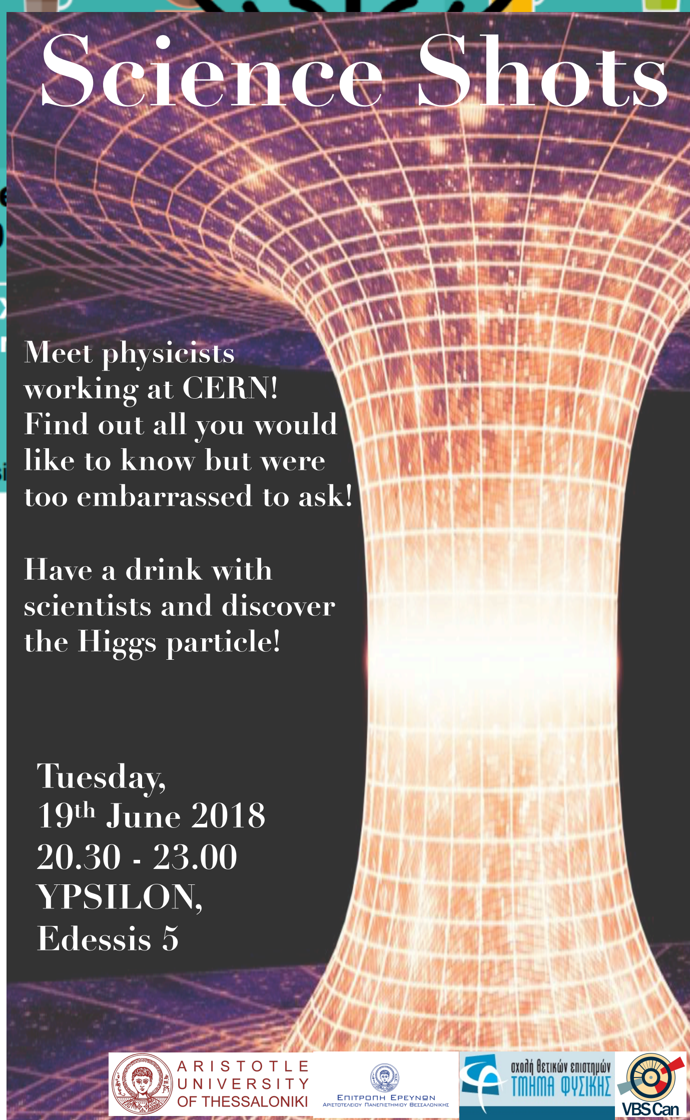
We are now 21 countries !

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
Diskusija mogu
Sreda, 28. lipn
20.00 - 23.00
Kavana LVXOR
Peristil, Split
Designed by Freepik

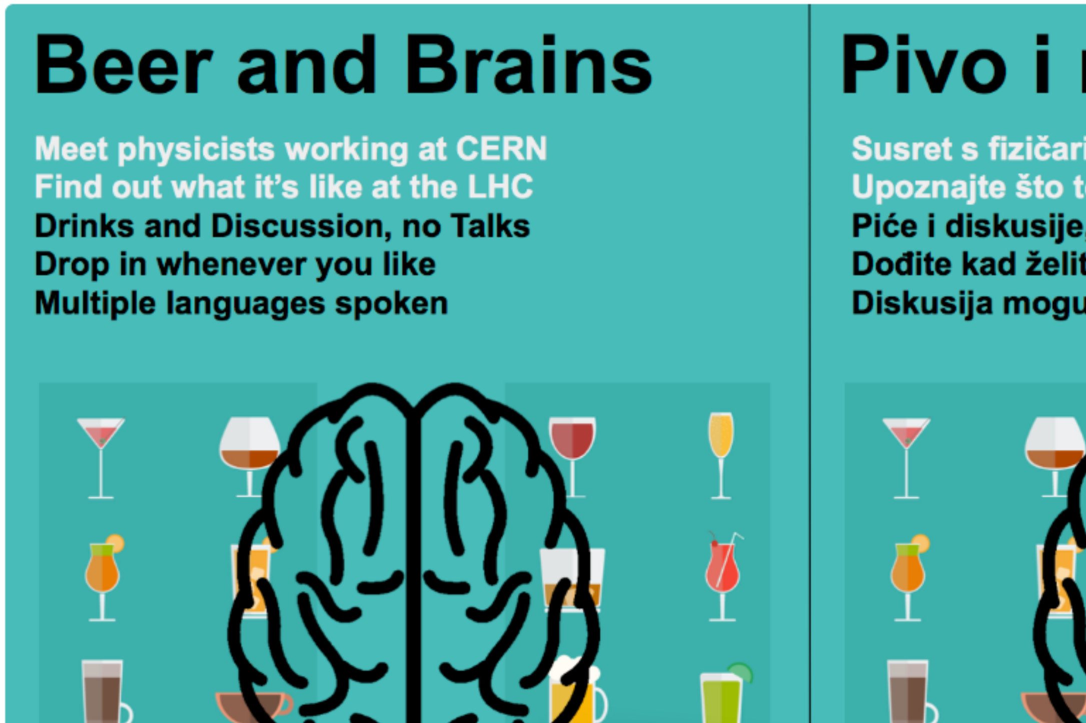






TECHNISCHE UNIVERSITÄT DRESDEN

TECHNISCHE UNIVERSITÄT DRESDEN



And now you!

TECHNISCHE UNIVERSITÄT DRESDEN

Vector Boson Scattering @ LHC

and

VBSCan COST Network

This is not the end!

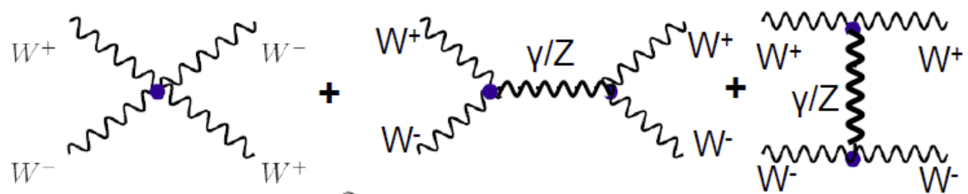
Why VBS

Remember this slide?

TECHNISCHE UNIVERSITÄT DRESDEN

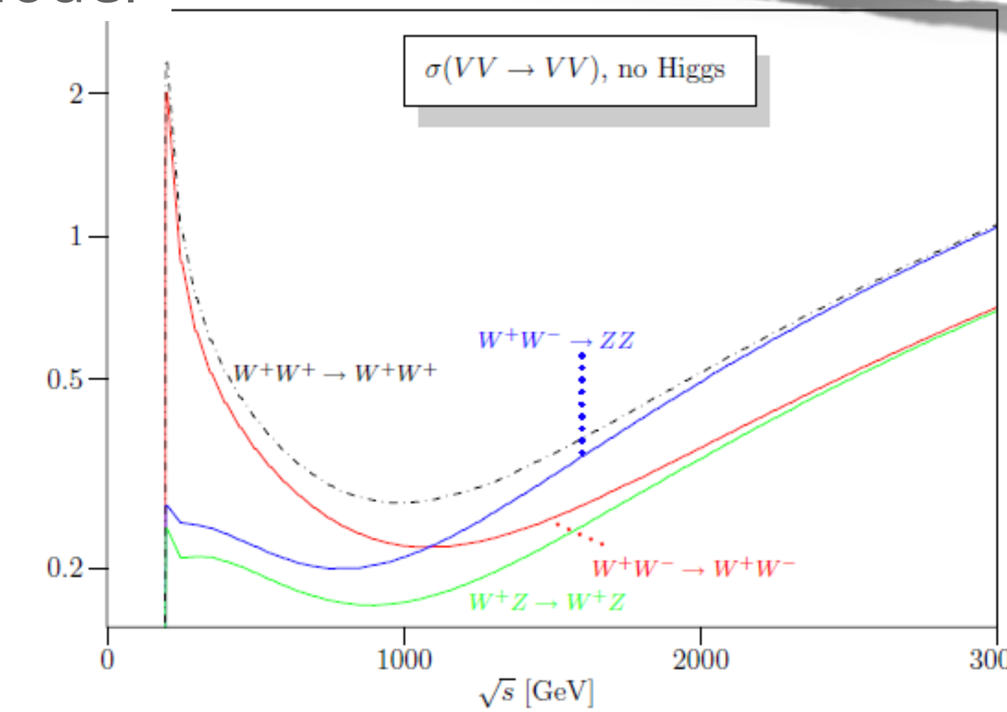
1) Important process for the Standard Model

- VBS Without Higgs contribution:

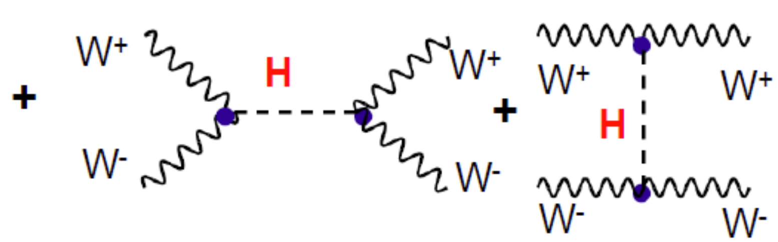


$$\sigma_{WW} \propto s^2 \to \infty \quad \text{wenn } s \to \infty$$

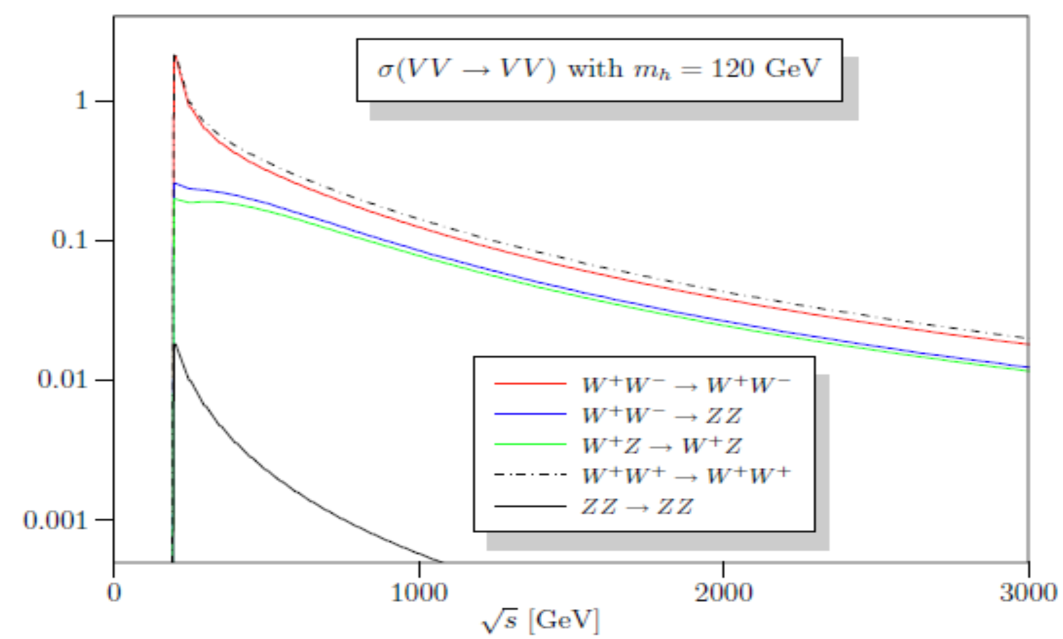
Violates “unitarity” (probability>1) at ~2 TeV



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



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



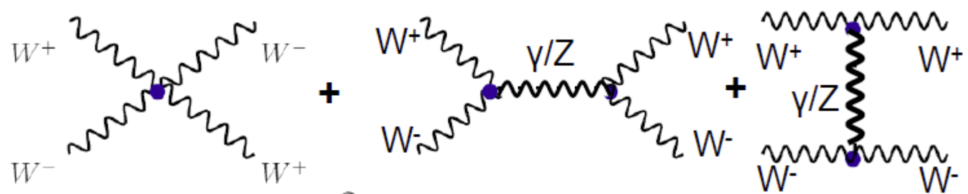
A. Alboteanu, W. Kilian, J. Reuter: http://arxiv.org/abs/0806.4145v1

Why VBS

Remember this slide?

1) Important process for the Standard Model

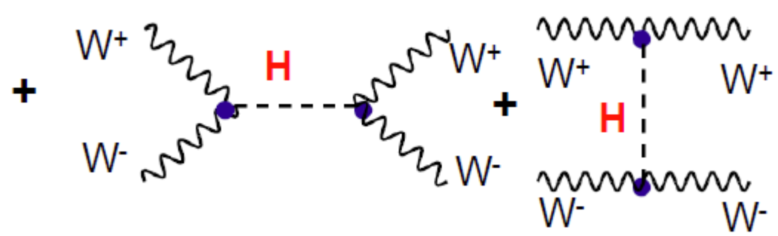
- VBS Without Higgs contribution:



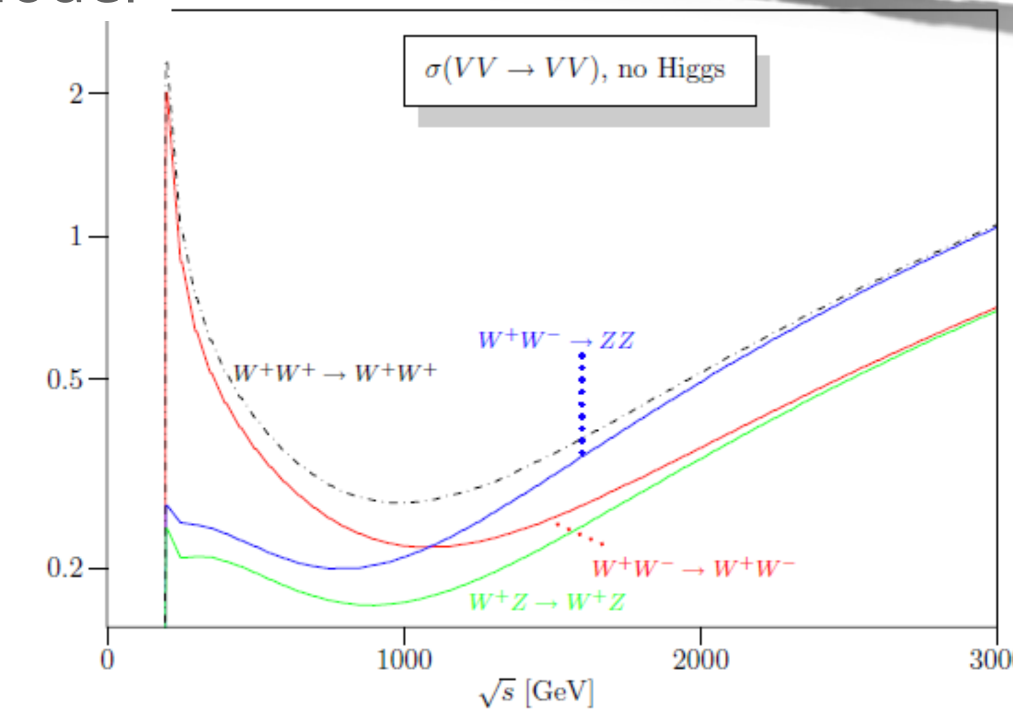
$$\sigma_{WW} \propto s^2 \to \infty \quad \text{wenn } s \to \infty$$

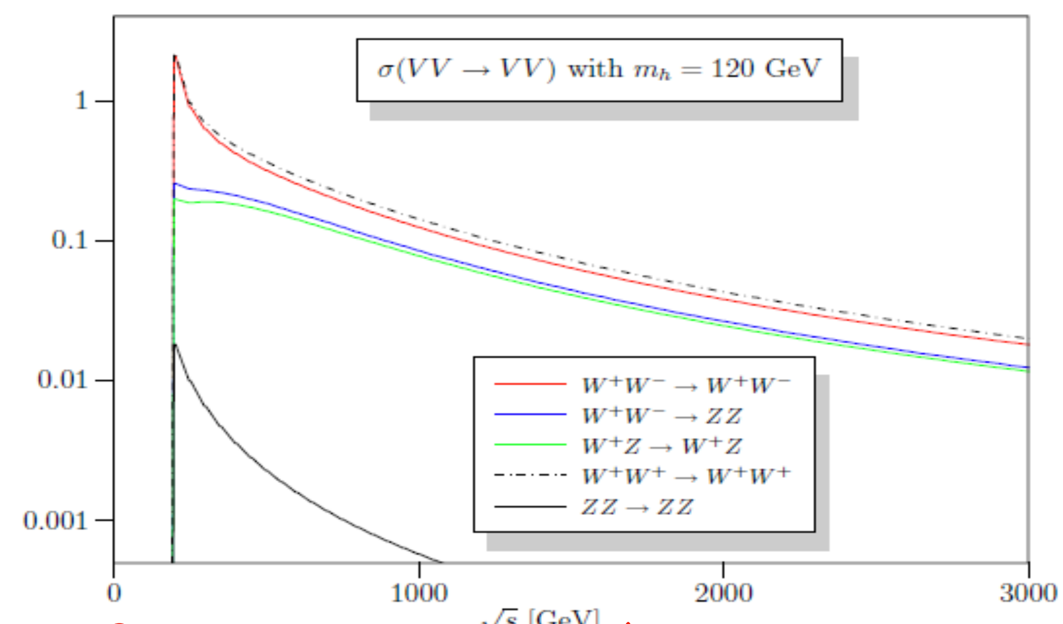
Violates "unitarity" (probability>1) at ~2 TeV

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



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

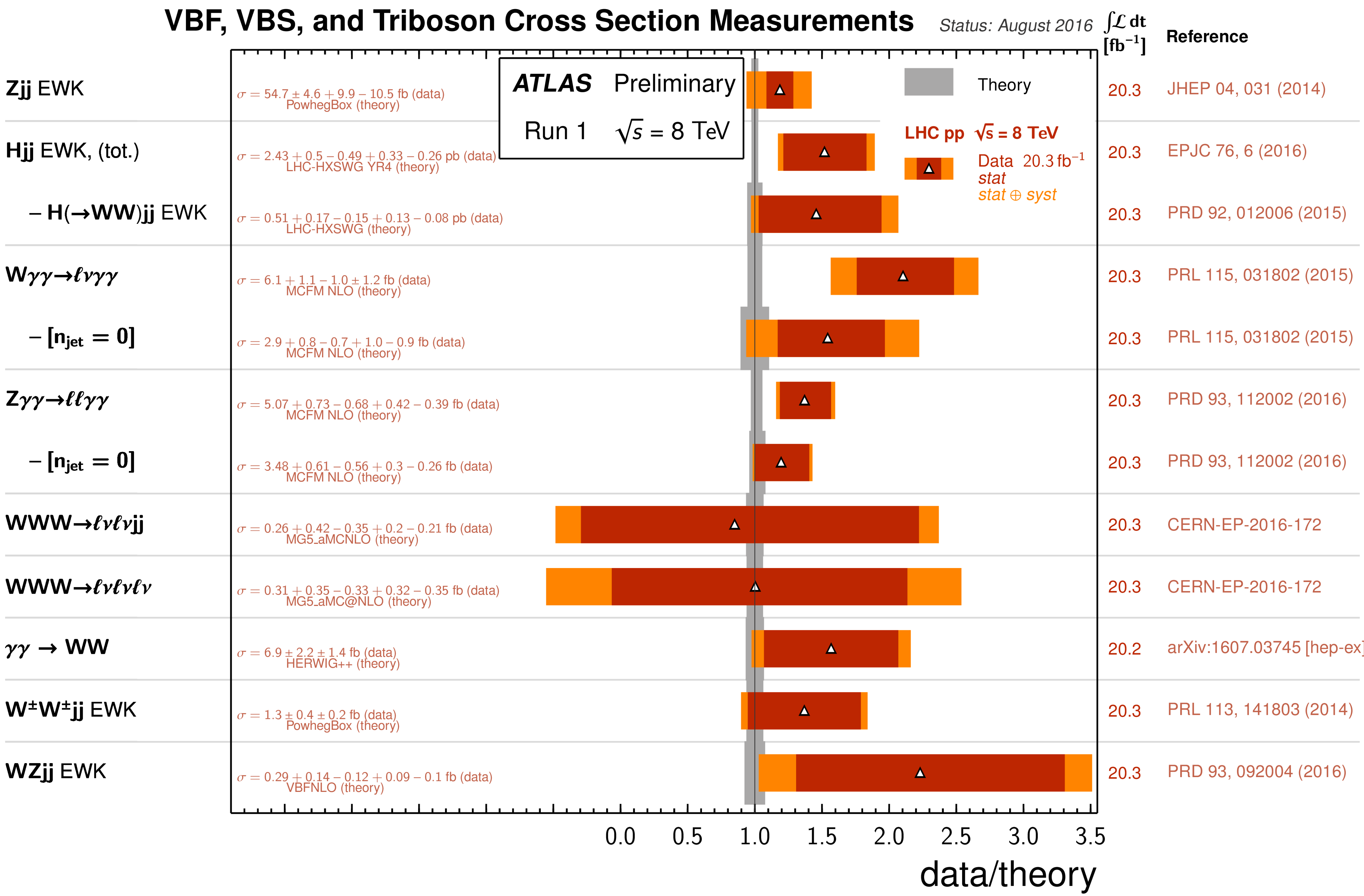




Why if the SM is an effective theory of a more complex one ?

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

VBF, VBS and Triboson



Look at beyond the SM physics

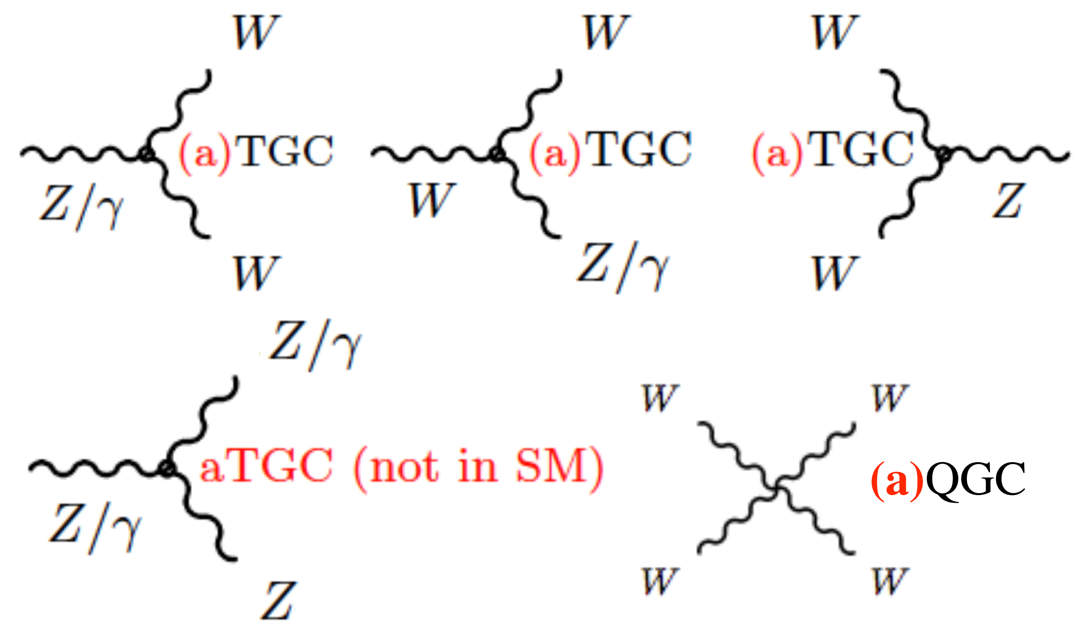
- The presence of new Physics in EWK sector modify gauge boson self-interactions
- Anomalous coupling approach: effective Lagrangian with anomalous triple or quartic gauge couplings (aTGC, aQGC)
  - Low energy effect from beyond SM physics can be modeled by effective theories (SM+higher dimension operators)

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

dimension d

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

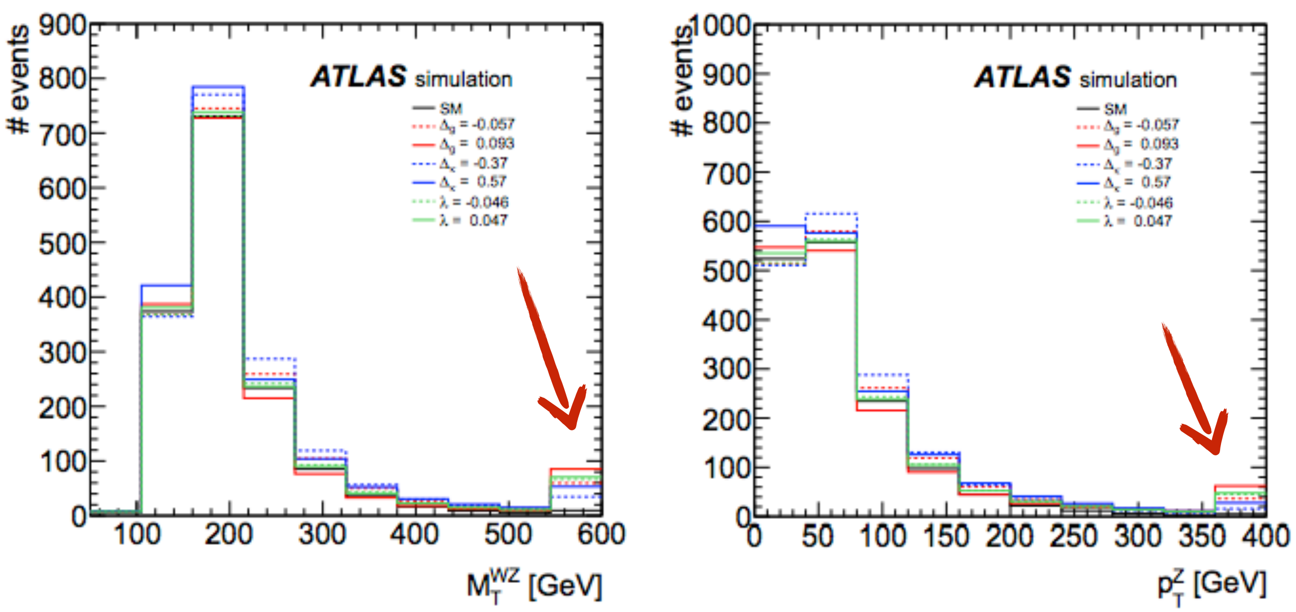


coupling	aTGC parameters (All = 0 in SM)	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ

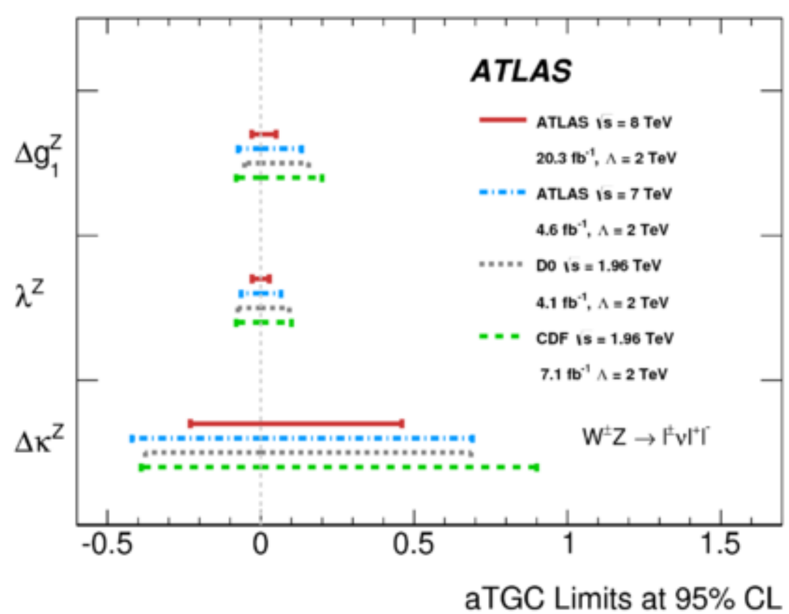
coupling	aQGC parameters (All = 0 in SM)	channel
$WWWW$, $WWZZ$	α_4, α_5	WW, WZ

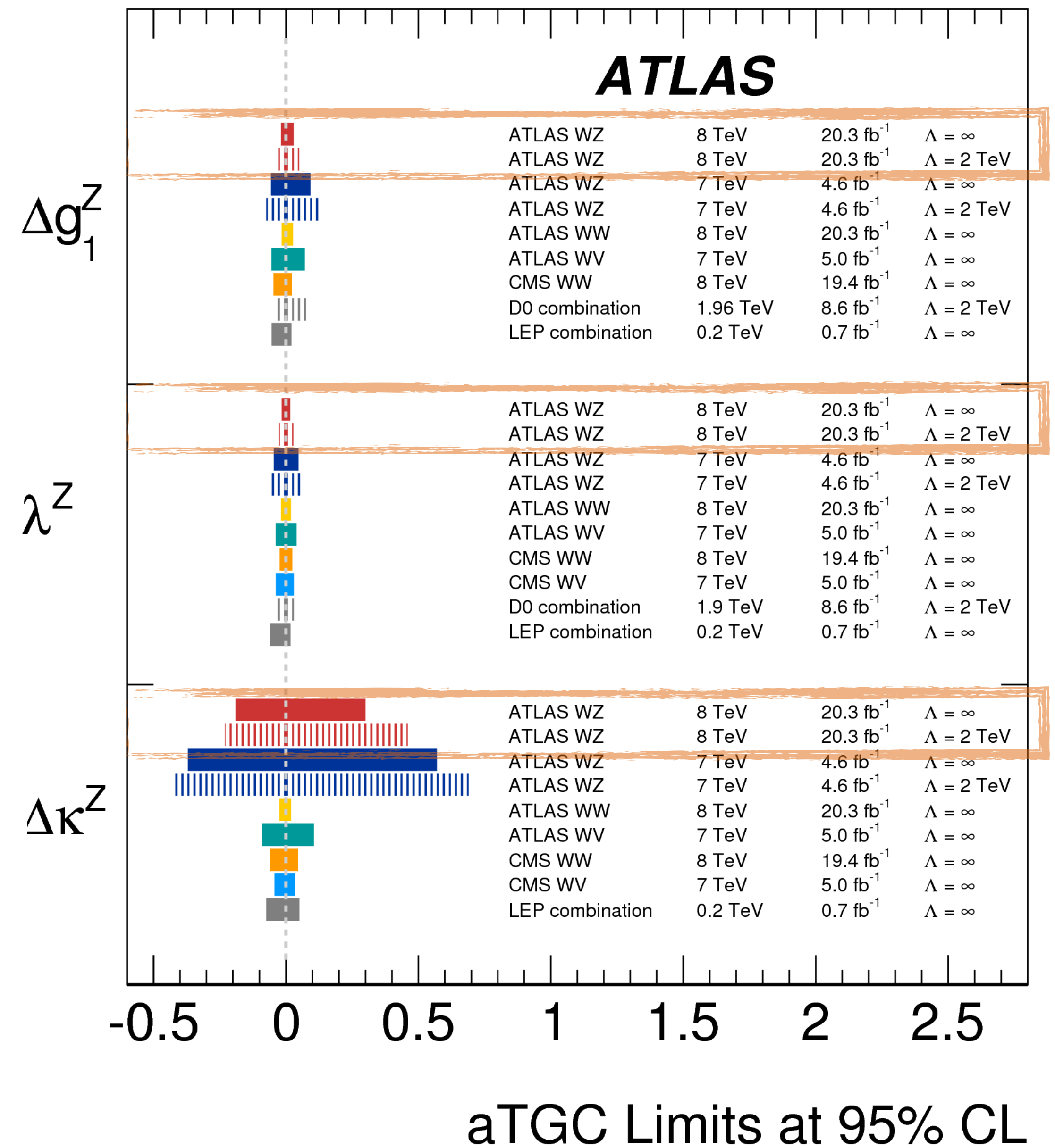
aTGC limits results

- 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

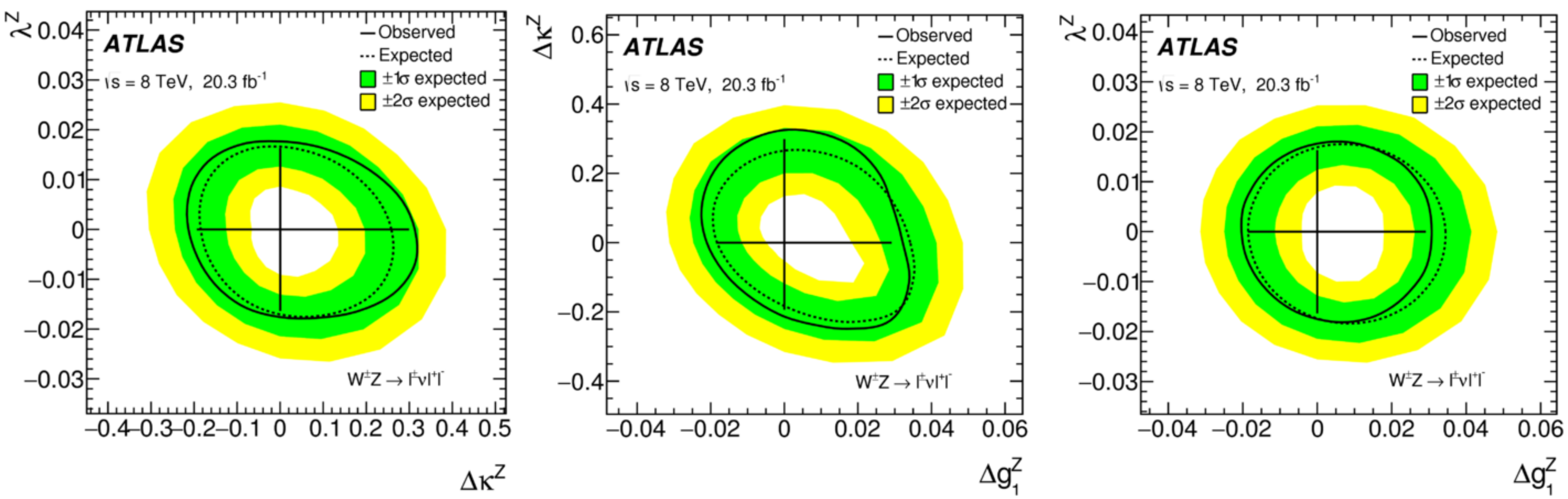




Observed 1D aTGC limits compared with previous measurements

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]

Vector Boson Scattering @ LHC

and VBSCan COST Network

Backup

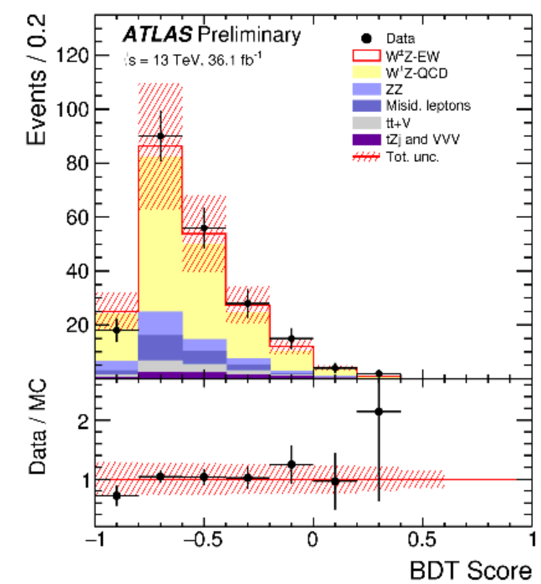
Originalveröffentlichungen

- Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at sqrt(s)=13 TeV with the ATLAS detector
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-030/
- Observation of electroweak W± Z boson pair production in association with two jets in pp collisions at √s = 13TeV with the ATLAS Detector
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-033/

7 Signal extraction procedure

Given the low purity in $WZjj$-EW processes in the signal region, a multivariate discriminant is therefore used to separate the signal and the backgrounds. A boosted decision tree (BDT), as implemented in the TMVA package [53], is used to exploit the kinematic differences between the $WZjj$-EW signal and the $WZjj$-QCD and other backgrounds. The BDT is trained and optimised on simulated events to separate $WZjj$-EW events from all other background processes.

A total of 15 variables are combined into one discriminant, the BDT score output value ranging onto the interval $[-1,+1]$. The variables can be classified into three categories. The variables related to the kinematic properties of the two tagging jets are the invariant mass of the two tagging jets, m_{jj}, the transverse momenta of the two jets, the difference in pseudorapidity and azimuthal angle of the two jets, $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$, respectively, the rapidity of the leading jet and the jet multiplicity. Variables related to the kinematic properties of the vector bosons are the transverse momenta of the W and Z bosons, the pseudorapidity of the W boson, the absolute difference between the rapidities of the Z boson and the lepton from the decay of the W boson, $|y_Z - y_{\ell,W}|$, and the transverse mass of the $W^{\pm}Z$ system m_{T}^{WZ}. The pseudorapidity of the W boson is reconstructed using an estimation of the longitudinal momentum of the neutrino obtained using the W mass constraint as detailed in Ref. [54]. The m_{T}^{WZ} observable is reconstructed following Ref. [11]. Variables that relate the kinematic properties of jets and leptons are the distance in the pseudorapidity-azimuth plane between the Z boson and the leading jet, $\Delta R(j_1, Z)$, the event balance $R_{p_{\mathrm{T}}}^{\mathrm{hard}}$, defined as the transverse component of the vector sum of the WZ bosons and tagging jets momenta, normalized to their scalar p_{T} sum, and, finally the centrality of the WZ system with respect to the tagging jets, defined as $\zeta_{\mathrm{lep.}} = min(\Delta\eta_-, \Delta\eta_+)$, with $\Delta\eta_- = min(\eta_\ell^W, \eta_{\ell_2}^Z, \eta_{\ell_1}^Z) - min(\eta_{j_1}, \eta_{j_2})$ and $\Delta\eta_+ = max(\eta_{j_1}, \eta_{j_2}) - max(\eta_\ell^W, \eta_{\ell_2}^Z, \eta_{\ell_1}^Z)$. A larger set of discriminant observables was studied and only variables improving the area under the signal-versus-background efficiency curve were retained.

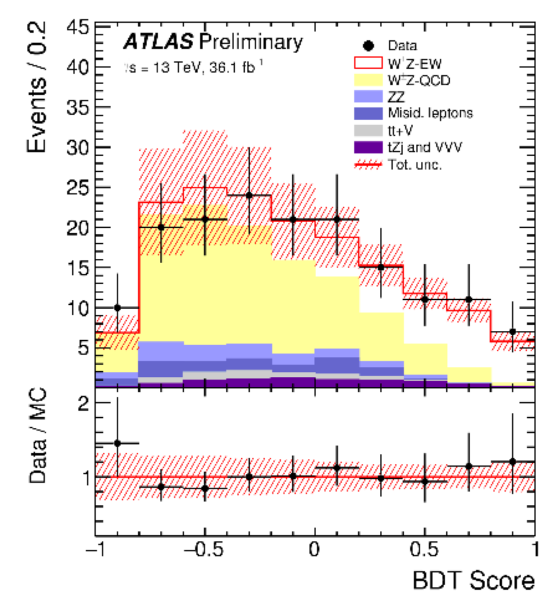


Distribution of BDT score

Control Region:

no white Signal

Background described well



Signal Region:

White signal visible at large BDT scores

(21 / 28 events above 0.4 are signal , 7 background)