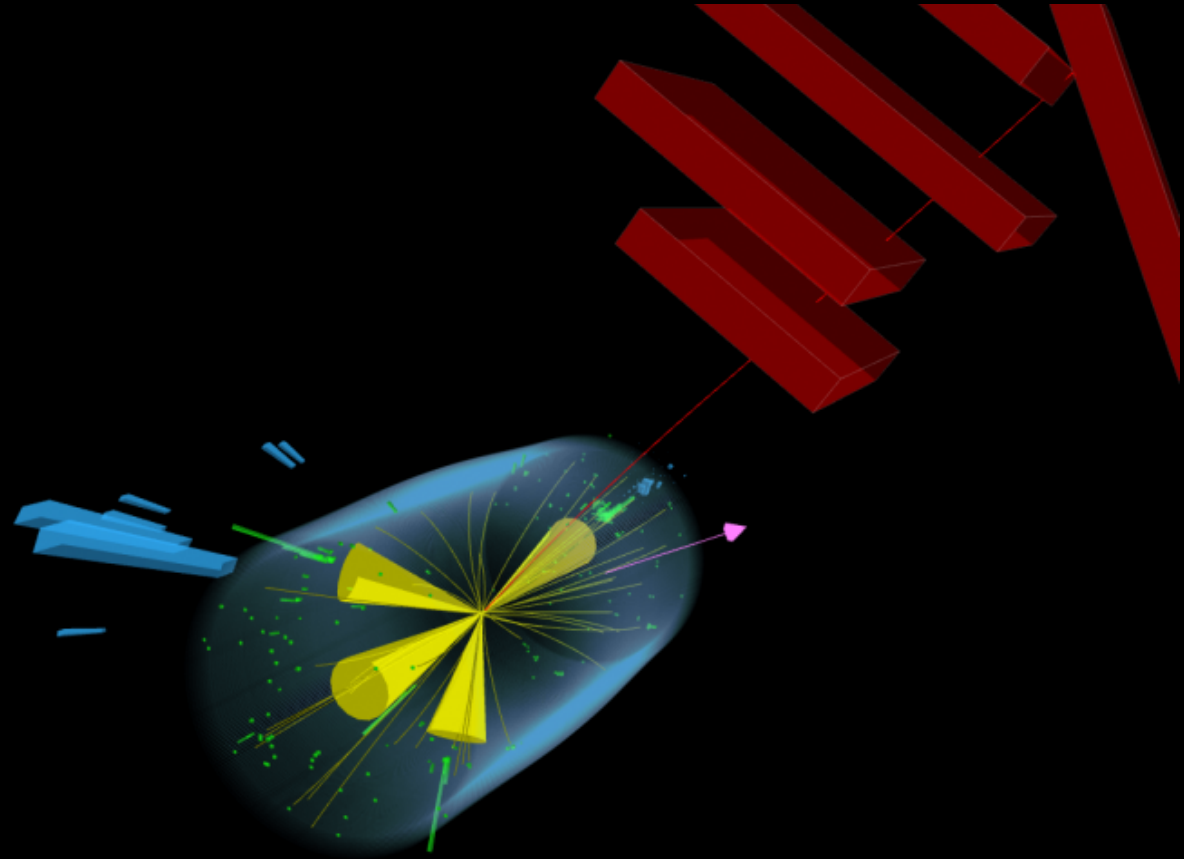
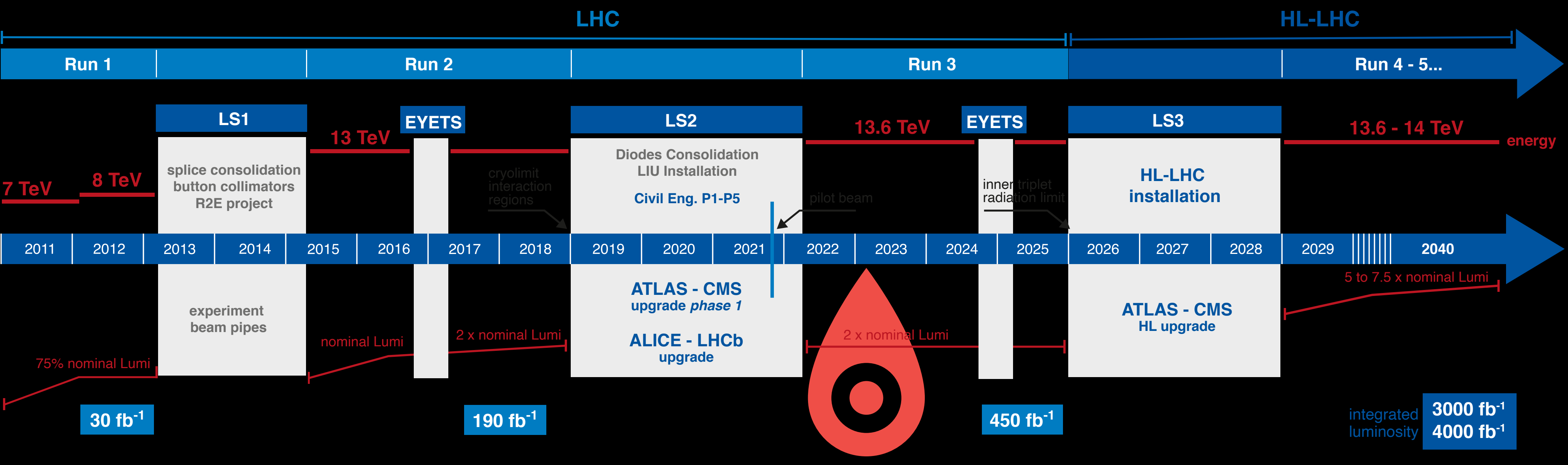


Recent results in CMS on Vector Boson Scattering and the Effective Field Theory approach

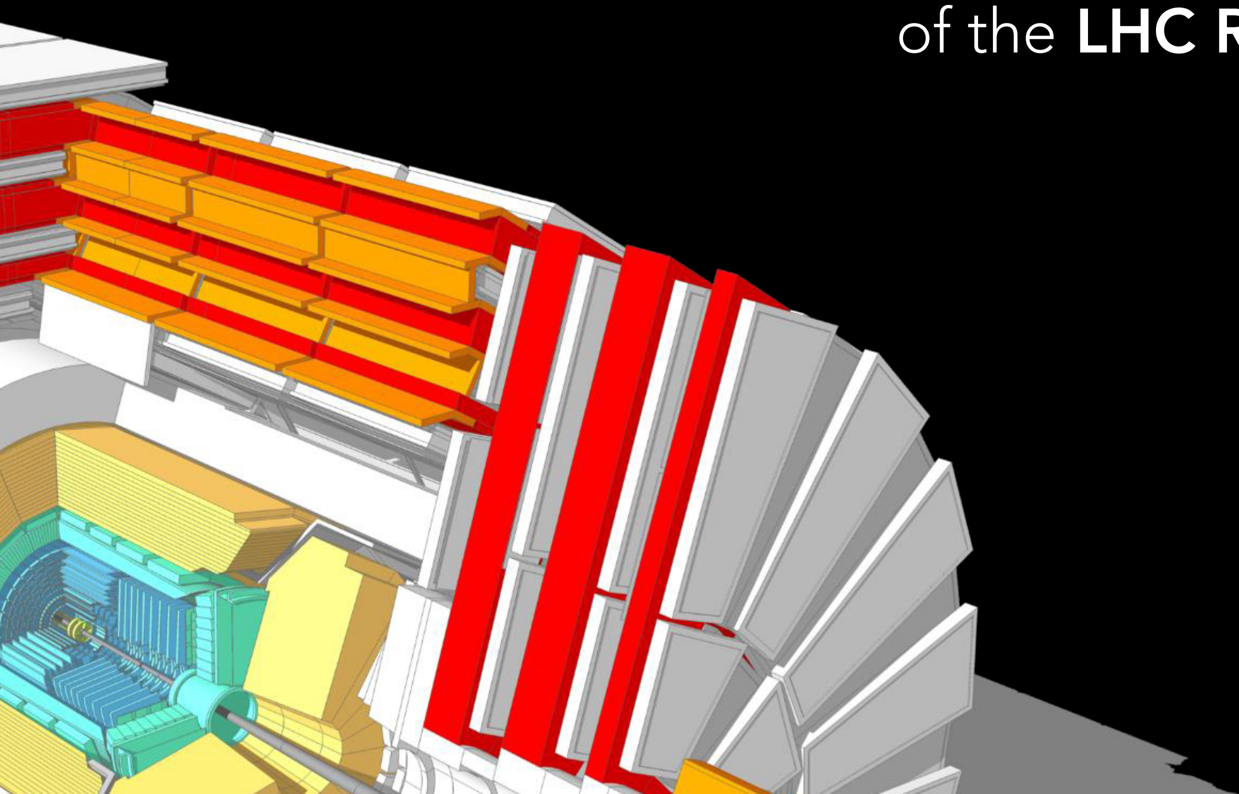
Matteo Presilla - INFN, Perugia

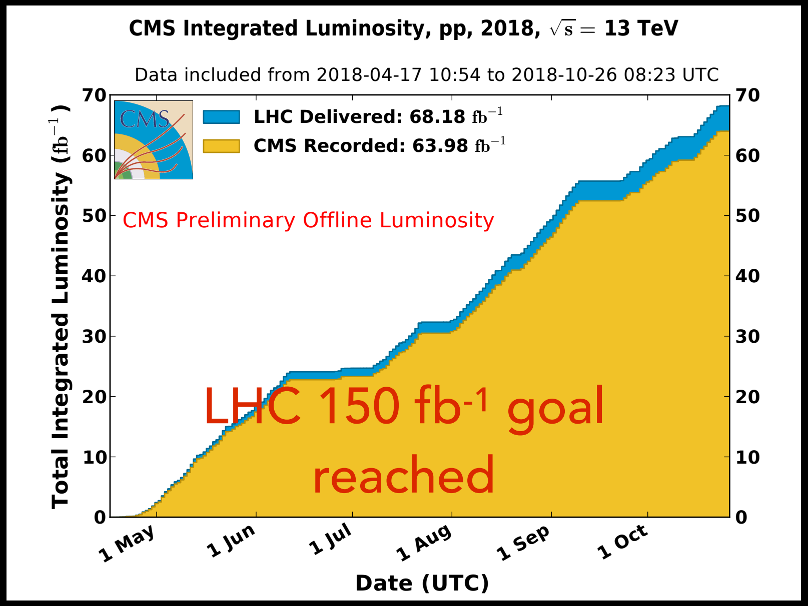
KIT, 10 JANUARY 2023

LHC / HL-LHC Plan

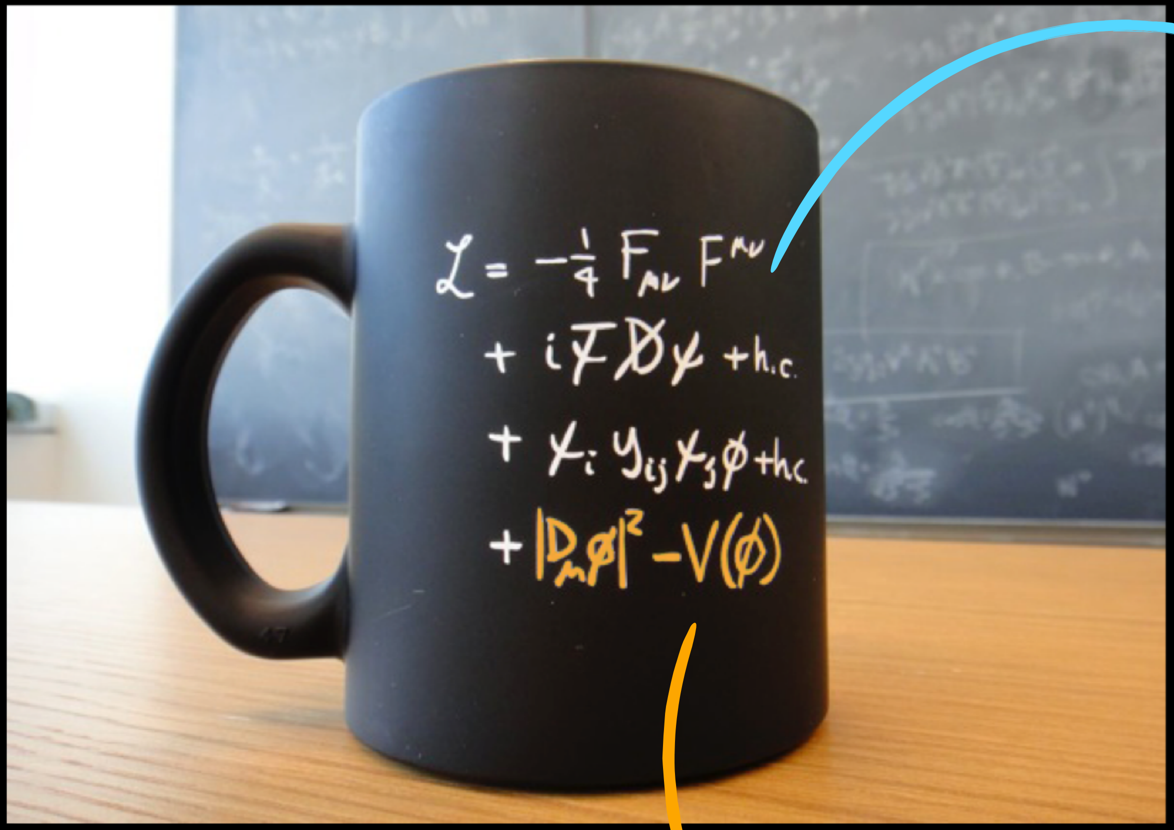


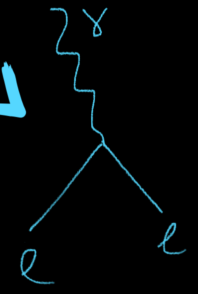
- Almost 10 years from Higgs boson discovery
- Quality and amount of measurements beyond expectations:
  it started with Higgs detection, we target di-Higgs production
- Excellent performance of **LHC** and **CMS detector** at the end of the **LHC Run 2 data taking**



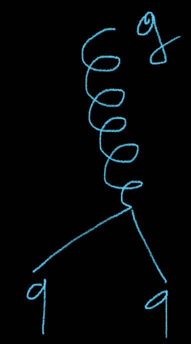


“The” laws of physics look extremely compact

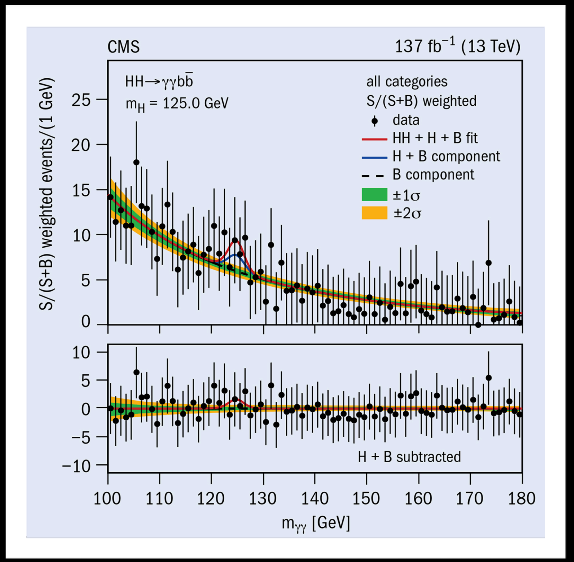




EW INTERACTIONS



STRONG INTERACTIONS



Targeting di-Higgs measurements
ArXiv.2011.12373

However, Standard Model is observationally unfit…

What is the dark matter in the Universe?

Why QCD does not violate CP?

How have baryons originated in the early Universe?

What originates flavor mixing and fermions masses?

What gives mass to neutrinos?

Why gravity and weak interactions are so different?

What fixes the cosmological constant?

Each of these issues one day will teach us a lesson!

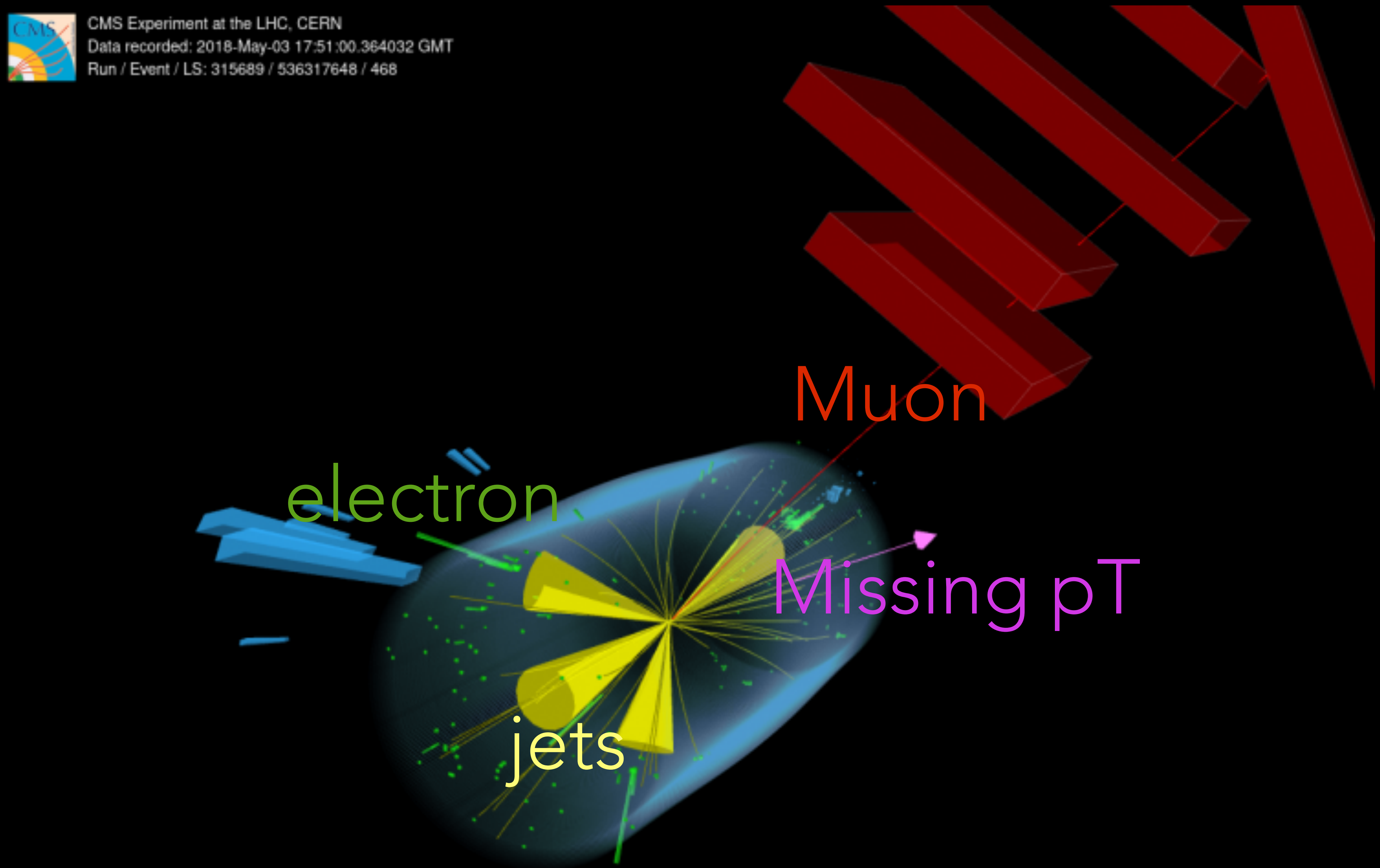
However, Standard Model is observationally unfit…

	EW INTERACTIONS	STRONG INTERACTIONS
What is the dark matter in the Universe?	X	
Why QCD does not violate CP?	X	X
How have baryons originated in the early Universe?	X	
What originates flavor mixing and fermions masses?	X	
What gives mass to neutrinos?	X	
Why gravity and weak interactions are so different?	X	
What fixes the cosmological constant?	X	

Each of these issues one day will teach us a lesson!

EWK FROM THE OUTSIDE

Accelerators are still excellent probes for ewk physics, but…



- Production cross-sections among the smallest ever measured
- Challenging experimental signatures (high-multiplicity jets final states, missing pT, …)
- Theoretical uncertainties and experimental uncertainties both quite relevant

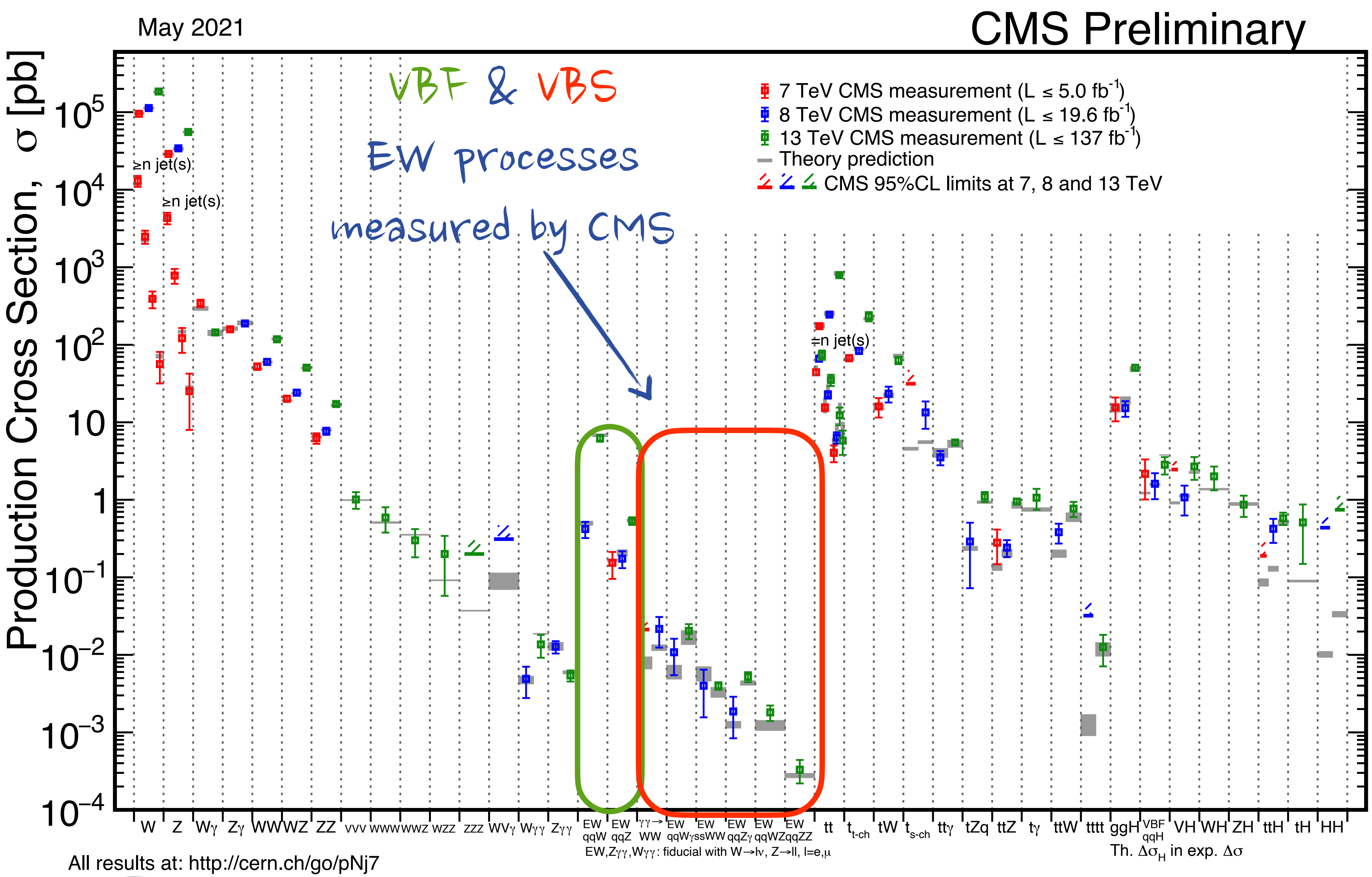
FOCUS OF THE SEMINAR

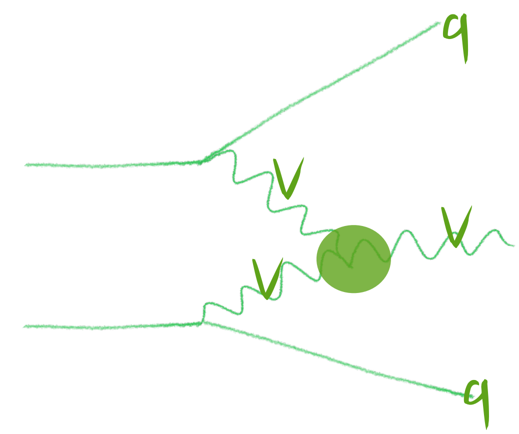
- Vector Boson Scattering physics at hadron colliders
- Challenging signatures:
  first evidence for semi-leptonic VBS
- Recent anomalous couplings bounds and SMEFT
- Towards a global EFT

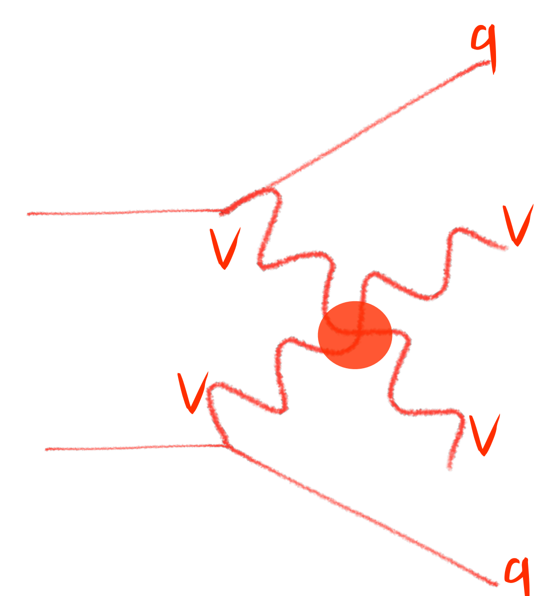
PRECISION ERA

SM keeps resisting with reasonable **agreement** across 10 orders of magnitudes of cross-sections!

LHC was proven to be a powerful **precision** machine: diagrams in which two Vector Boson interacts, giving either one or two Vector Bosons in the final state, are among the rarest processed measured







LHC AS THE VECTOR BOSON COLLIDER

Major effort undertaken to investigate VBS processes in CMS with full Run 2 dataset

PROCESS	LUMI [fb^{-1}]	RESULTS	REFERENCE
VBF Z	2016 data (36/fb)	Inclusive XS+ dim-6 EFT limits	EPJC 78 (2018) 589
VBF W	2016 data (36/fb)	Inclusive XS+ dim-6 EFT limits	EPJC 80 (2020) 43
VBS in ssWW + WZ	Full Run 2 (137/fb)	Observation & XS+ dim-8 EFT limits	PLB 809 (2020) 135710
polarized **VBS** ssWW	Full Run 2 (137/fb)	$W_L W_L$ measurement	PLB 812 (2020) 136018
VBS ZZ	Full Run 2 (137/fb)	4.0 σ + dim-8 EFT limits	PLB 812 (2021) 135992
VBS OSWW	Full Run 2 (137/fb)	Observation & XS	CMS-SMP-21-001
VBS VV	Full Run 2 (137/fb) 2016 data (36/fb)	Evidence with full Run2 + Dim-8 EFT limits with 2016 data	PLB 834 (2022) 137438 PLB 798 (2019)134985
VBS Wγ	Full Run 2 (137/fb)	Observation, differential XS + dim-8 EFT limits	PLB 811 (2020) 135988
VBS Zγ	Full Run 2 (137/fb)	Observation	JHEP 06 (2020) 076
VBS PPS γγWW	Full Run 2 PPS (100/fb)	Dim-6	CMS-SMP-21-014

LHC AS THE VECTOR BOSON COLLIDER

Major effort undertaken to investigate VBS processes in CMS with full Run 2 dataset

PROCESS	LUMI [fb^{-1}]	RESULTS	REFERENCE
VBF Z	2016 data (36/fb)	Inclusive XS+ dim-6 EFT limits	EPJC 78 (2018) 589
VBF W	2016 data (36/fb)	Inclusive XS+ dim-6 EFT limits	EPJC 80 (2020) 43
VBS in ssWW + WZ	Full Run 2 (137/fb)	Observation & XS+ dim-8 EFT limits	PLB 809 (2020) 135710
polarized **VBS** ssWW	Full Run 2 (137/fb)	$W_L W_L$ measurement	PLB 812 (2020) 136018
VBS ZZ	Full Run 2 (137/fb)	4.0 σ + dim-8 EFT limits	PLB 812 (2021) 135992
VBS OSWW	Full Run 2 (137/fb)	Observation & XS	CMS-SMP-21-001
VBS VV	Full Run 2 (137/fb) 2016 data (36/fb)	Evidence with full Run2 + Dim-8 EFT limits with 2016 data	PLB 834 (2022) 137438 PLB 798 (2019)134985
VBS Wγ	Full Run 2 (137/fb)	Observation, differential XS + dim-8 EFT limits	PLB 811 (2020) 135988
VBS Zγ	Full Run 2 (137/fb)	Observation	JHEP 06 (2020) 076
VBS PPS γγWW	Full Run 2 PPS (100/fb)	Dim-6	CMS-SMP-21-014

Fully-leptonic VBS (2jets+4leptons)

Semi-leptonic VBS (4jets+2leptons)

No public fully-hadronic (all jets) so far

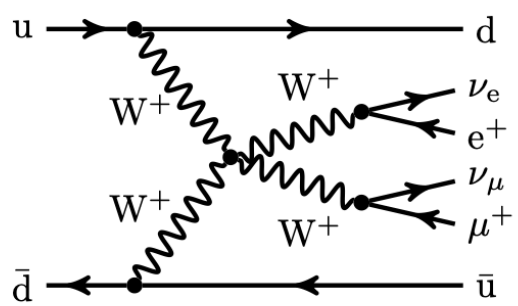
OVERVIEW

PHYSICS OF THE VBS

HOW VBS LOOKS LIKE

THEORY PERSPECTIVE (BORN LEVEL)

exemplary case of ssWWjj

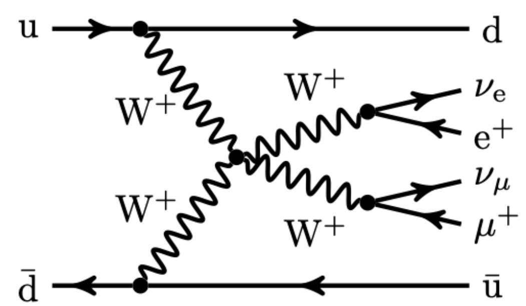


$\mathcal{O}(\alpha_{ew}^6)$

HOW VBS LOOKS LIKE

THEORY PERSPECTIVE (BORN LEVEL)

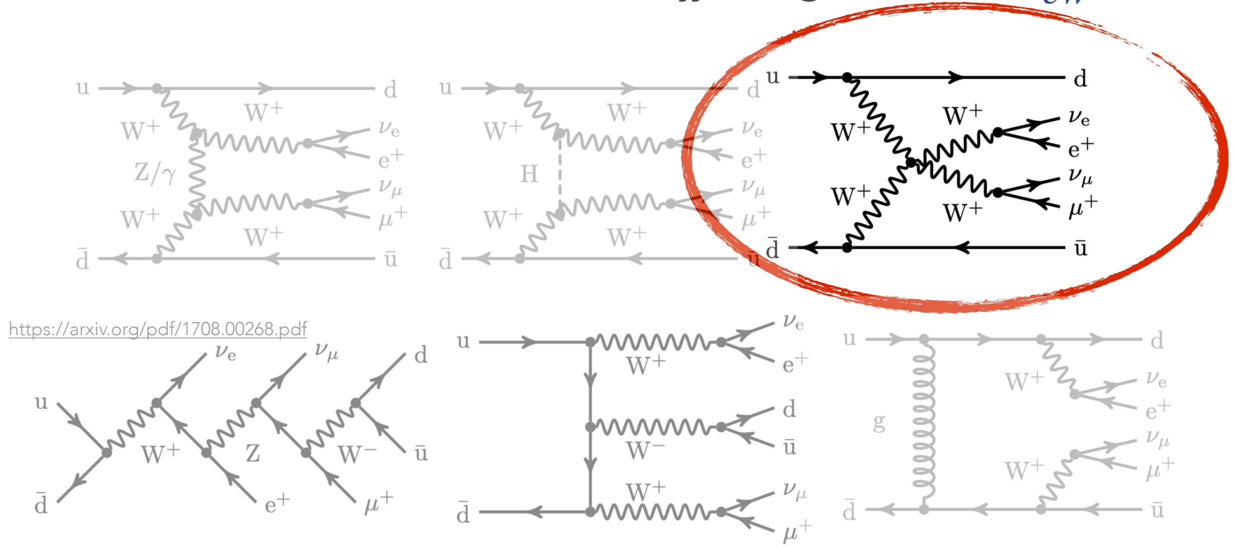
exemplary case of ssWWjj



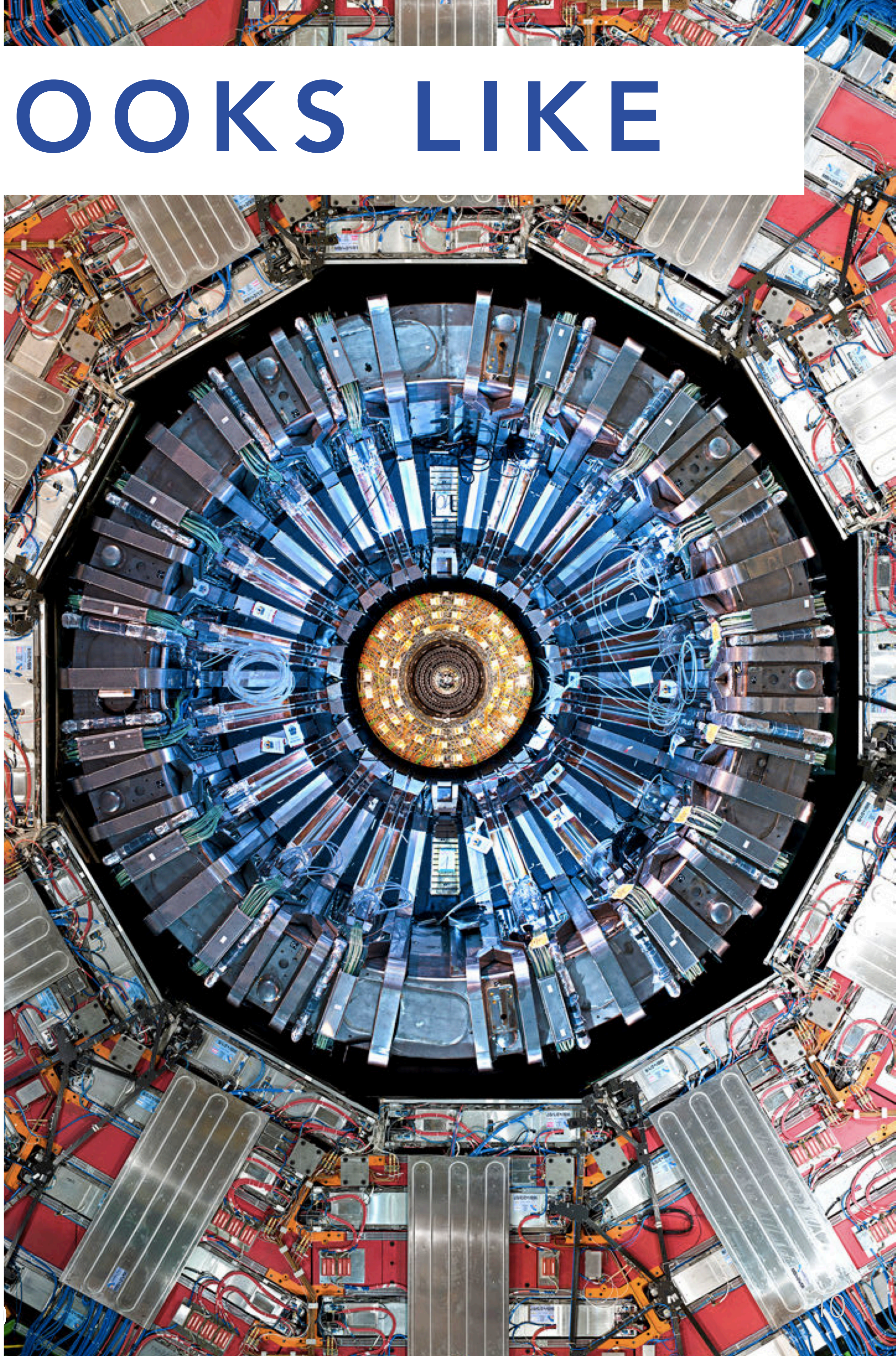
$\mathcal{O}(\alpha_{ew}^6)$

Gauge invariance complicates the picture…

set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$



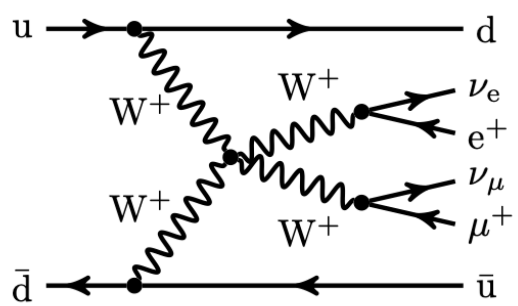
https://arxiv.org/pdf/1708.00268.pdf



HOW VBS LOOKS LIKE

THEORY PERSPECTIVE (BORN LEVEL)

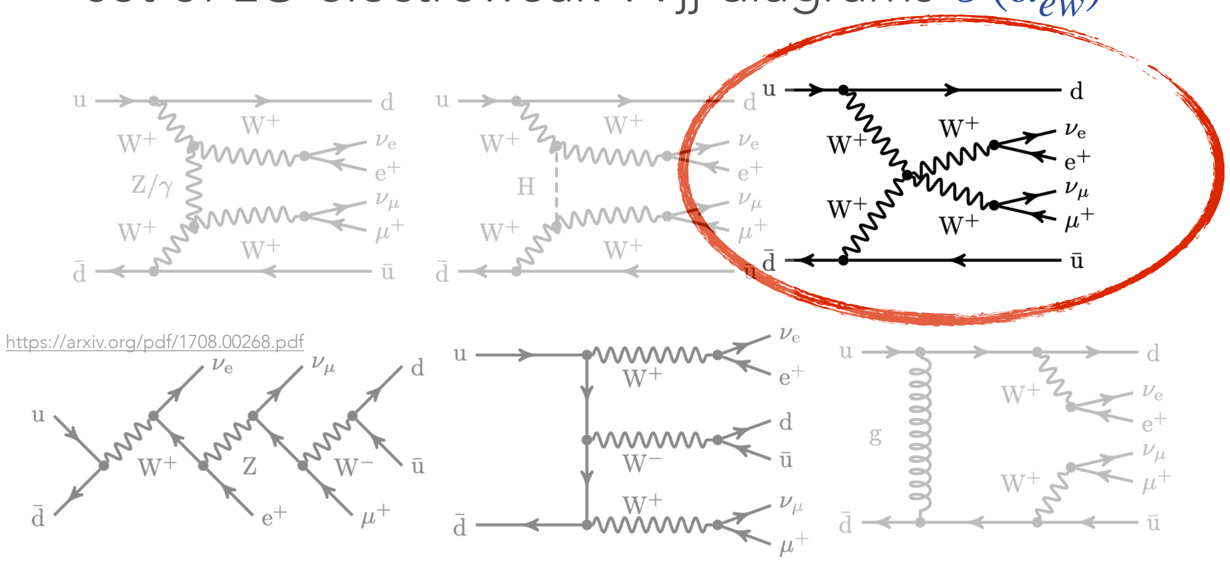
exemplary case of ssWWjj



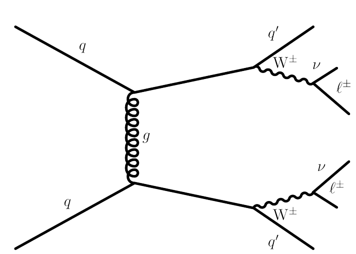
$\mathcal{O}(\alpha_{ew}^6)$

Gauge invariance complicates the picture…

set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$



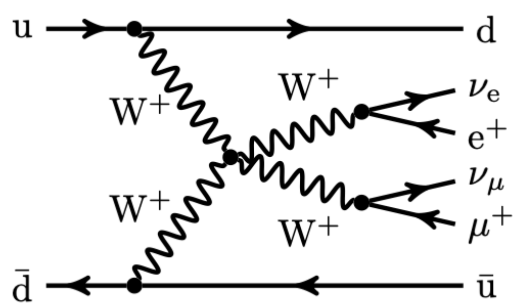
+ **QCD induced processes** $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$…



HOW VBS LOOKS LIKE

THEORY PERSPECTIVE (BORN LEVEL)

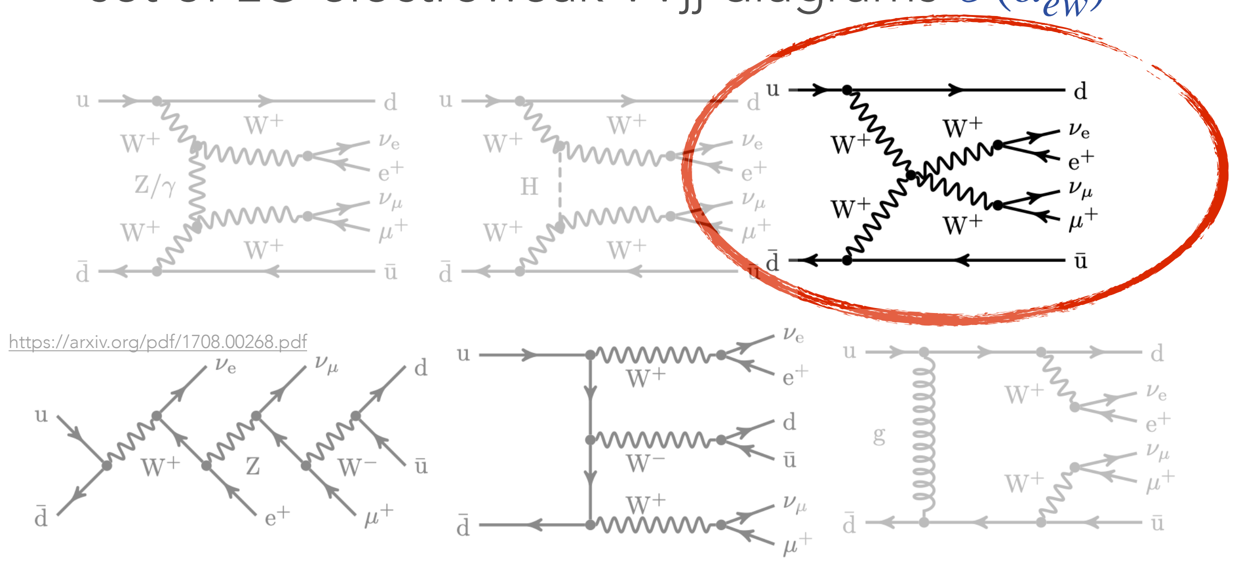
exemplary case of ssWWjj



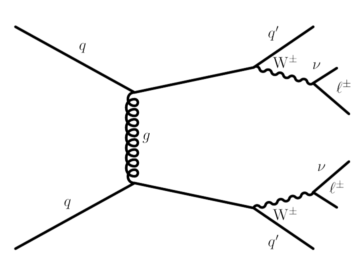
$\mathcal{O}(\alpha_{ew}^6)$

Gauge invariance complicates the picture…

set of LO electroweak VVjj diagrams $\mathcal{O}(\alpha_{ew}^6)$

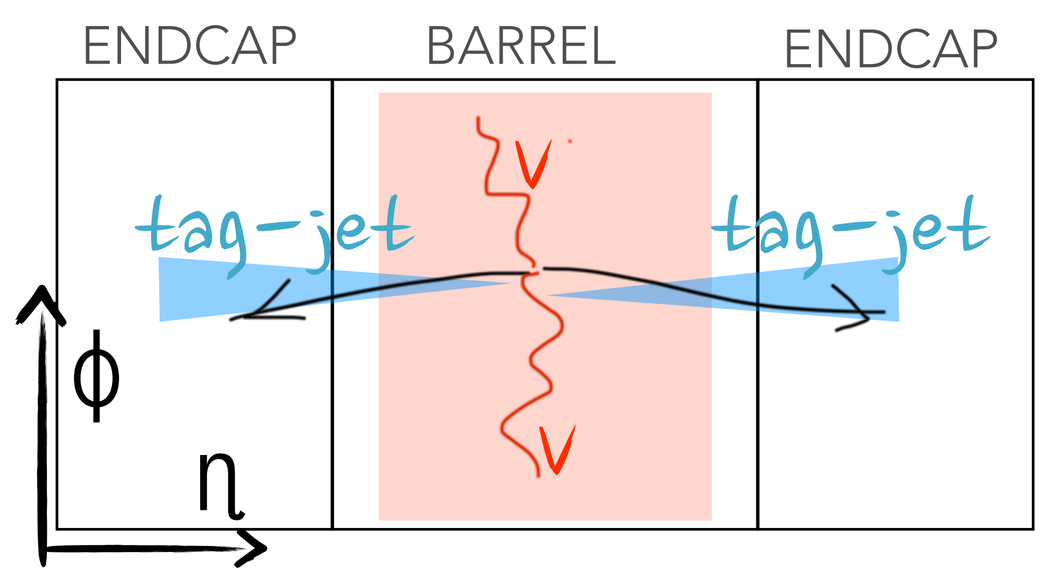


+ QCD induced processes $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$…



CMS PERSPECTIVE

- Vector Bosons produced in the central part of the detector
- VBS "**tag-jets**" in **forward** detector region: highest invariant-mass in the event
- **Large pseudorapidity separation between the VBS-jets** - for the low QCD activity btw partons (no color flow at LO arXiv. 1805.09335)



VBS EVENT TOPOLOGY

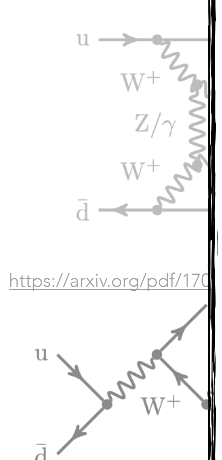
HOW VBS LOOKS LIKE

THEORY PERSPECTIVE (BORN LEVEL)

exemplary case of ssWWjj

Gauge set o

https://arxiv.org/pdf/170



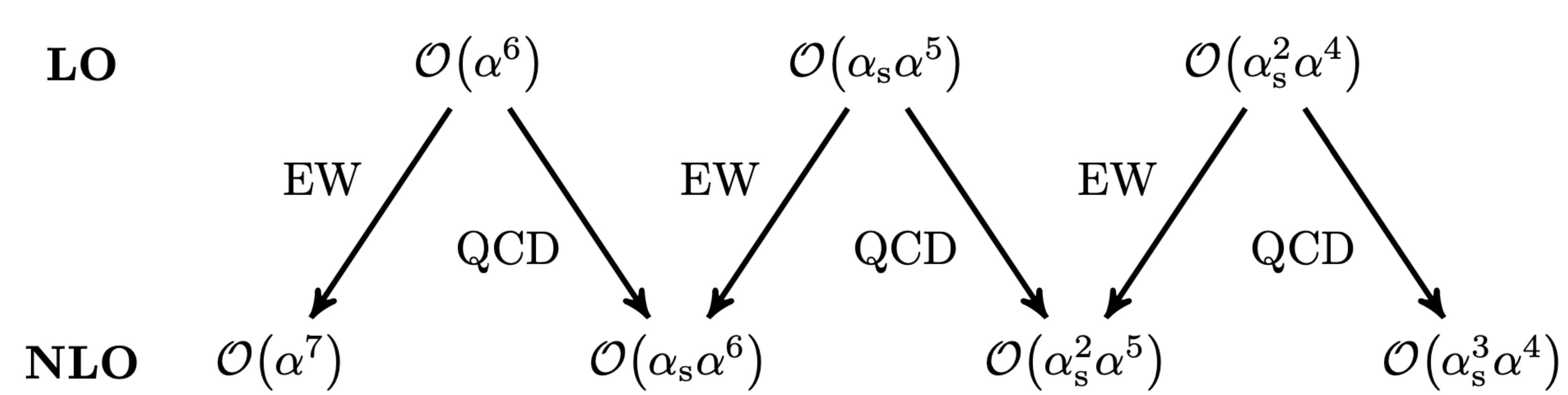
CMS PERSPECTIVE

- Vector Bosons produced in the central part

on:

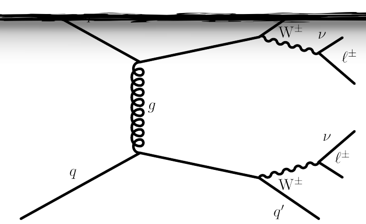
THEORY PERSPECTIVE (INCLUDING CORRECTIONS)

All contributing orders at both LO and NLO for VBS processes at the LHC (arXiv:1708.00268)



It is not possible to define an NLO signal or background without making assumptions.

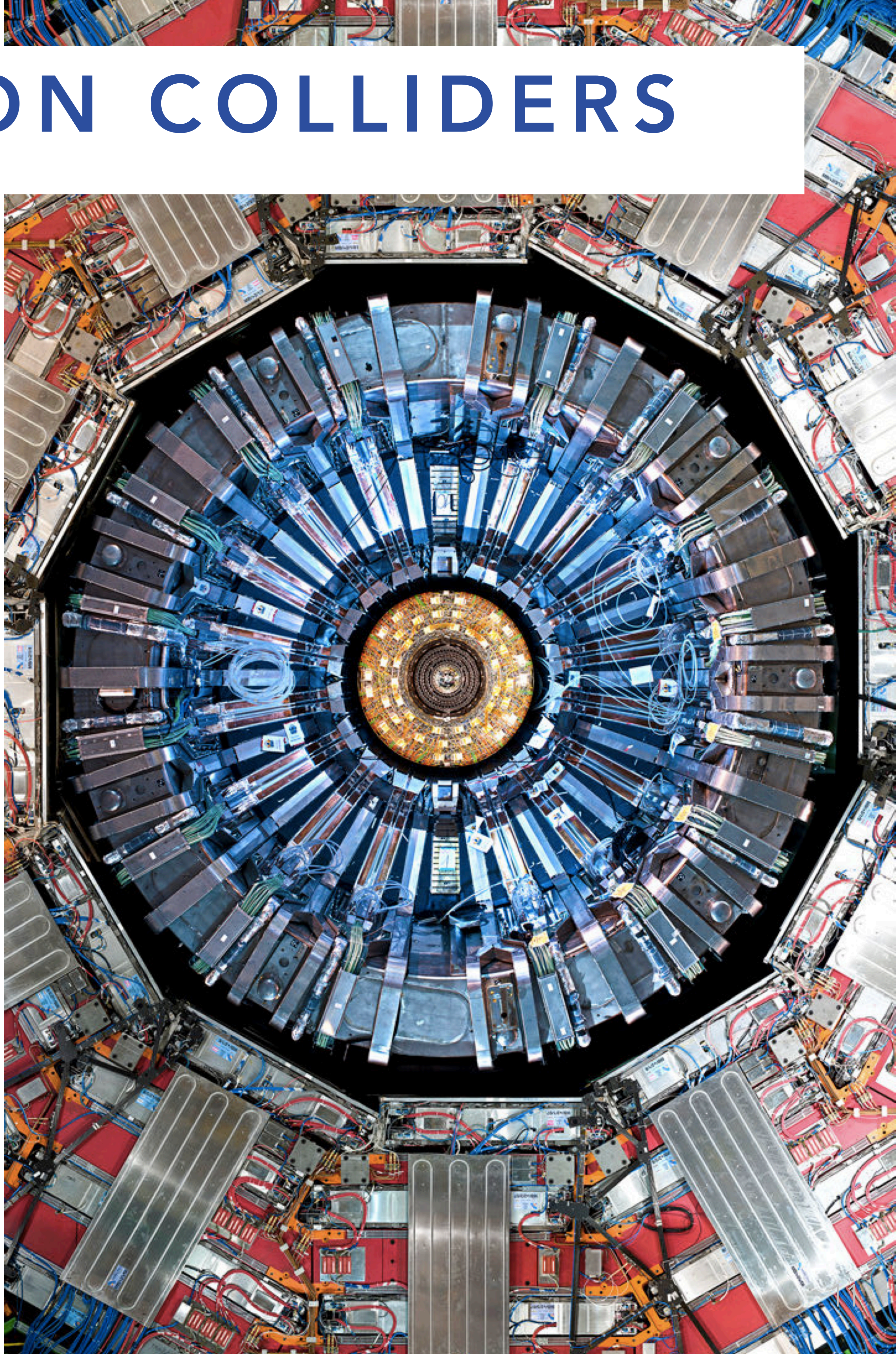
+ **QCD induced processes** $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$...



VBS EVENT TOPOLOGY

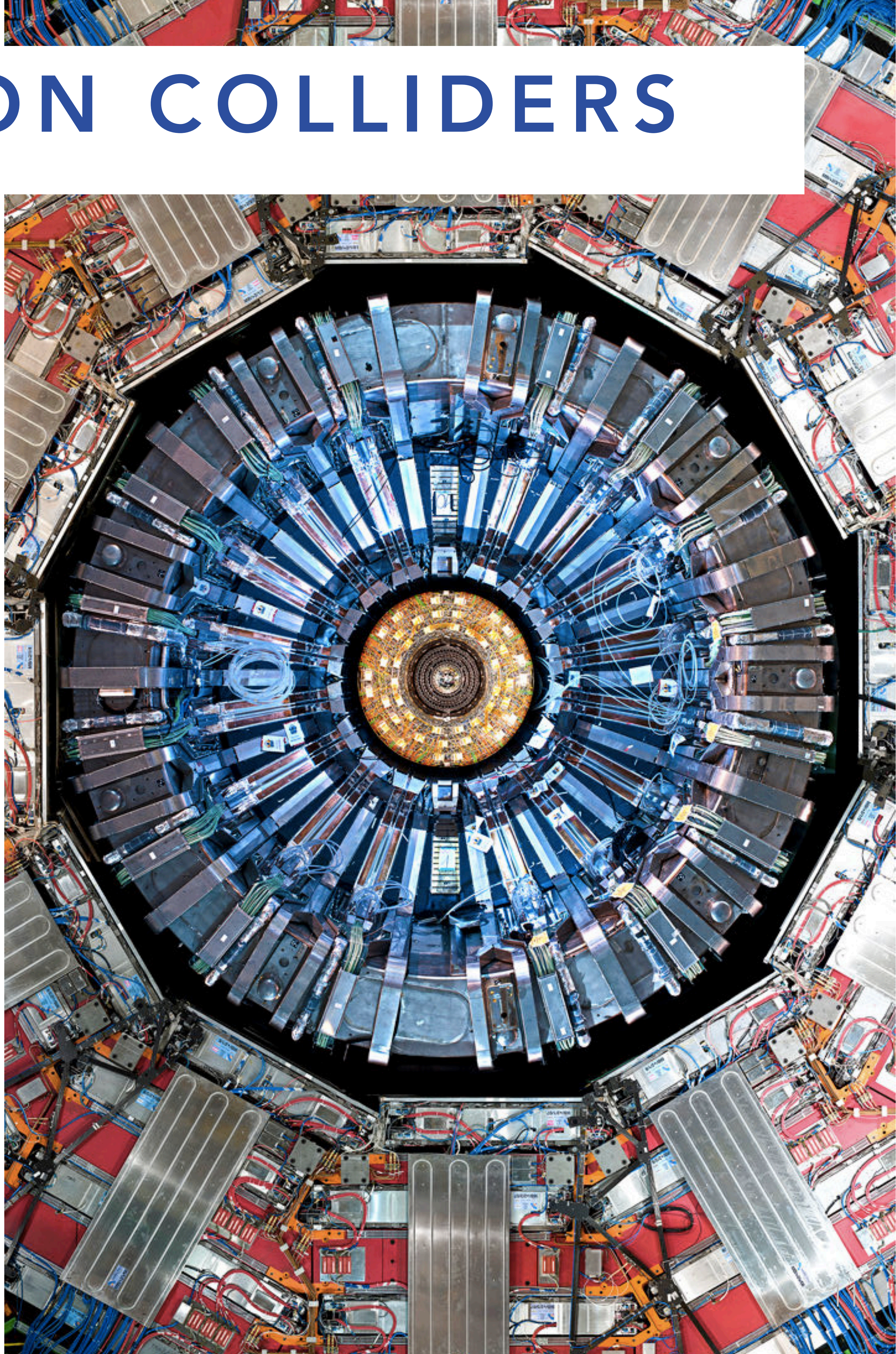
VBS IN HADRON COLLIDERS

- **At the heart of EWSB, probing non-abelian structure of the SM:** triple and quartic gauge couplings



VBS IN HADRON COLLIDERS

- **At the heart of EWSB, probing non-abelian structure of the SM:** triple and quartic gauge couplings
- **Studies of gauge invariance of the SM**: this process is gauge invariant thanks to very delicate cancellations between diagrams

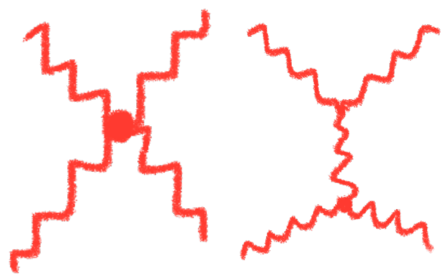


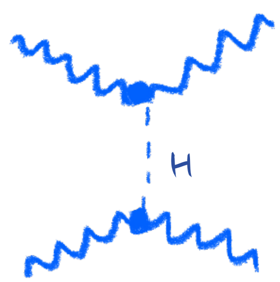
VBS IN HADRON COLLIDERS

- **At the heart of EWSB, probing non-abelian structure of the SM:** triple and quartic gauge couplings
- **Studies of gauge invariance of the SM**: this process is gauge invariant thanks to very delicate cancellations between diagrams
- **Unitarity of the SM:** VBS amplitude explodes with energy, without H mediation!

Undergrad typical QFT exercise:

SCATTERING $W_L W_L \Longleftrightarrow W_L W_L$



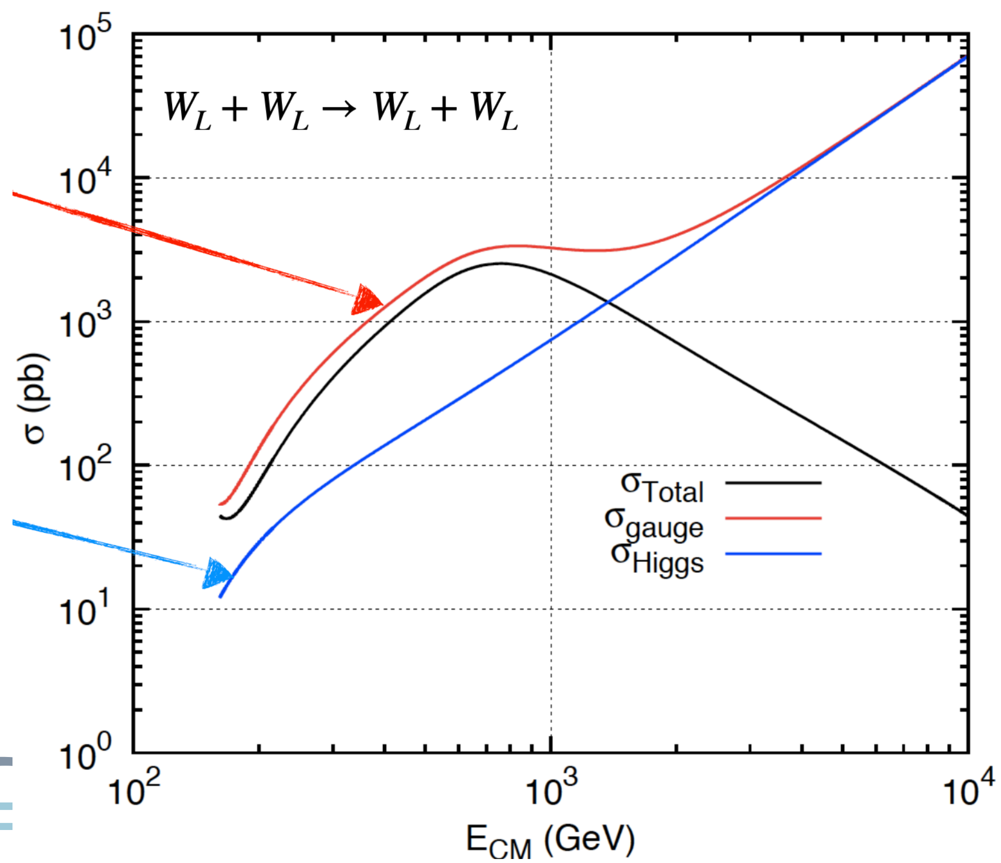


$$iM_{gauge} \simeq -i\frac{g^2}{4m_W^2}[s+t]$$

$$iM_{Higgs} \simeq i\frac{g^2}{4m_W^2}[s+t]$$

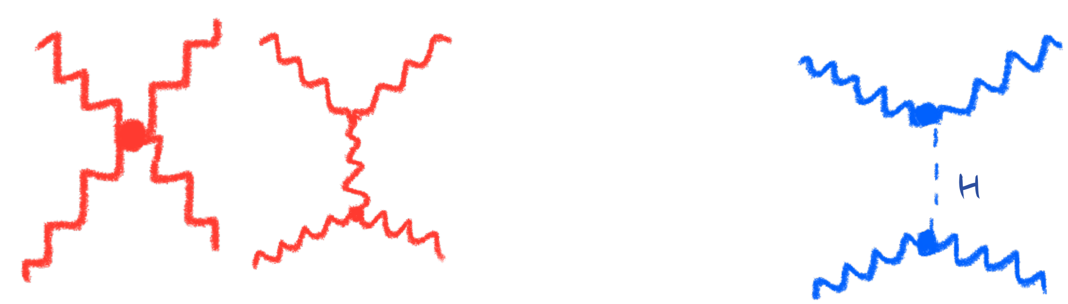
VBS IN HADRON COLLIDERS

- **At the heart of EWSB, probing non-abelian structure of the SM:** triple and quartic gauge couplings
- **Studies of gauge invariance of the SM**: this process is gauge invariant thanks to very delicate cancellations between diagrams
- **Unitarity of the SM:** VBS amplitude explodes with energy, without H mediation!



Undergrad typical QFT exercise:

SCATTERING $W_L W_L \Longleftrightarrow W_L W_L$



$$iM_{gauge} \simeq -i\frac{g^2}{4m_W^2}[s+t]$$

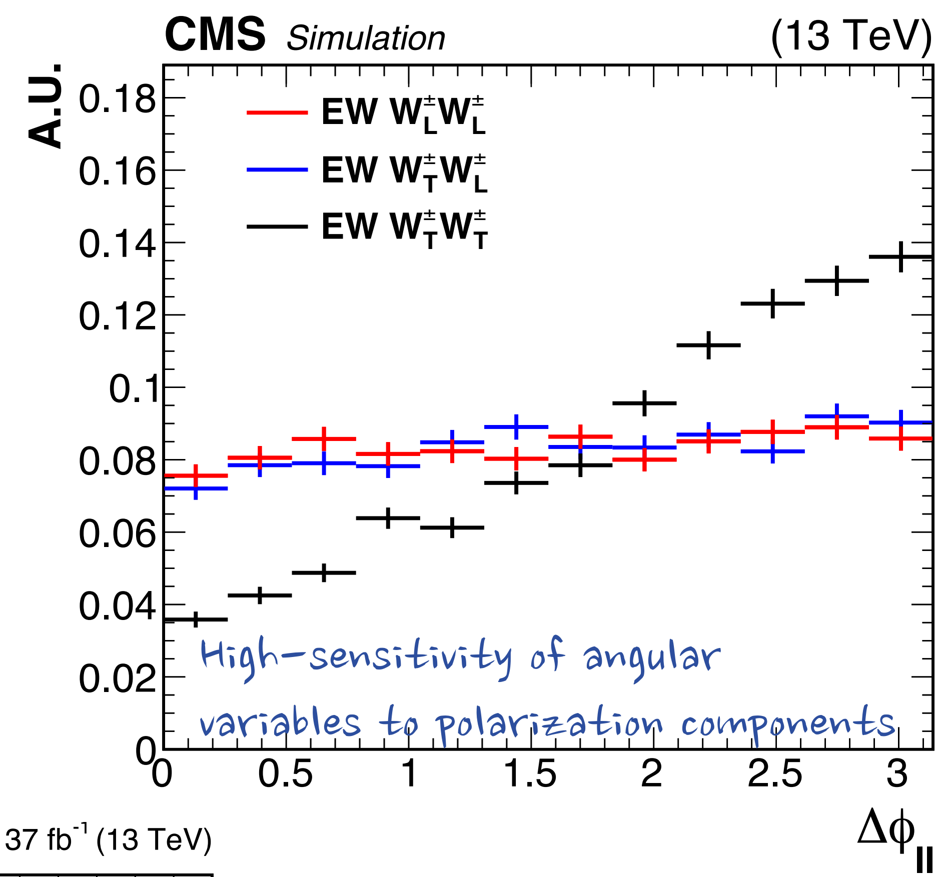
$$iM_{Higgs} \simeq i\frac{g^2}{4m_W^2}[s+t]$$

Higgs exchange exactly cancels high-energy (E^2) growth if its couplings are SM-like, matrix element is unitary for $m_H \lesssim 1\text{TeV}$

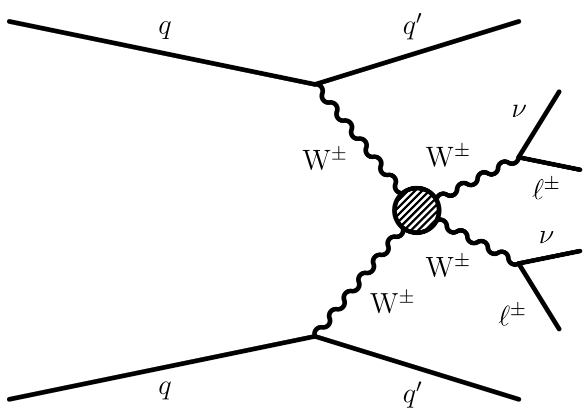
(Lee, Quigg, Thacker bound)

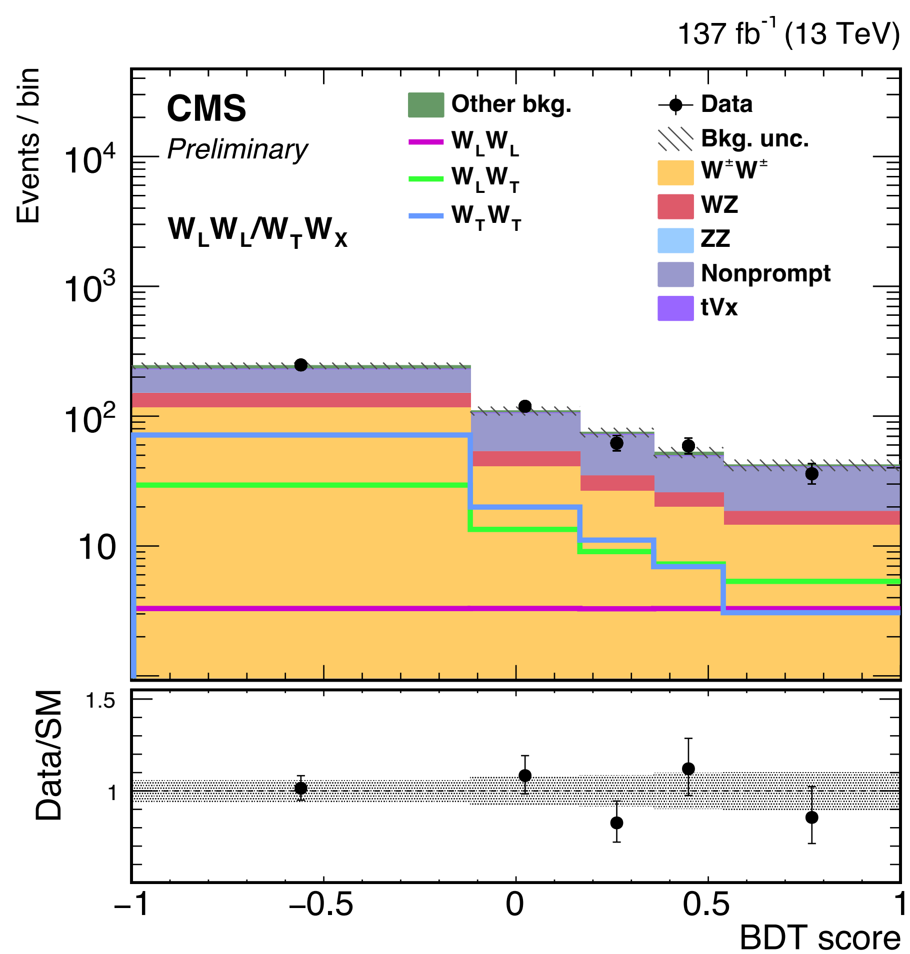
Polarization measurements

CMS-SMP-20-006, arXiv:2009.09429



- **Extremely challenging at the LHC as V_LV_L->V_LV_L is ~10% of the total EW WW scattering cross section**
- **Possibility to access different polarization states already with Run 2 data, with the Golden channel of VBS ssWW**
  - Measurement of **WLWL**, **WLWT** and **WTWT** processes (**reference-frame-dependent:** parton-parton and WW CoM reference frames)
  - Significance of ~1 (3) standard deviations for WLWL (WLWX)





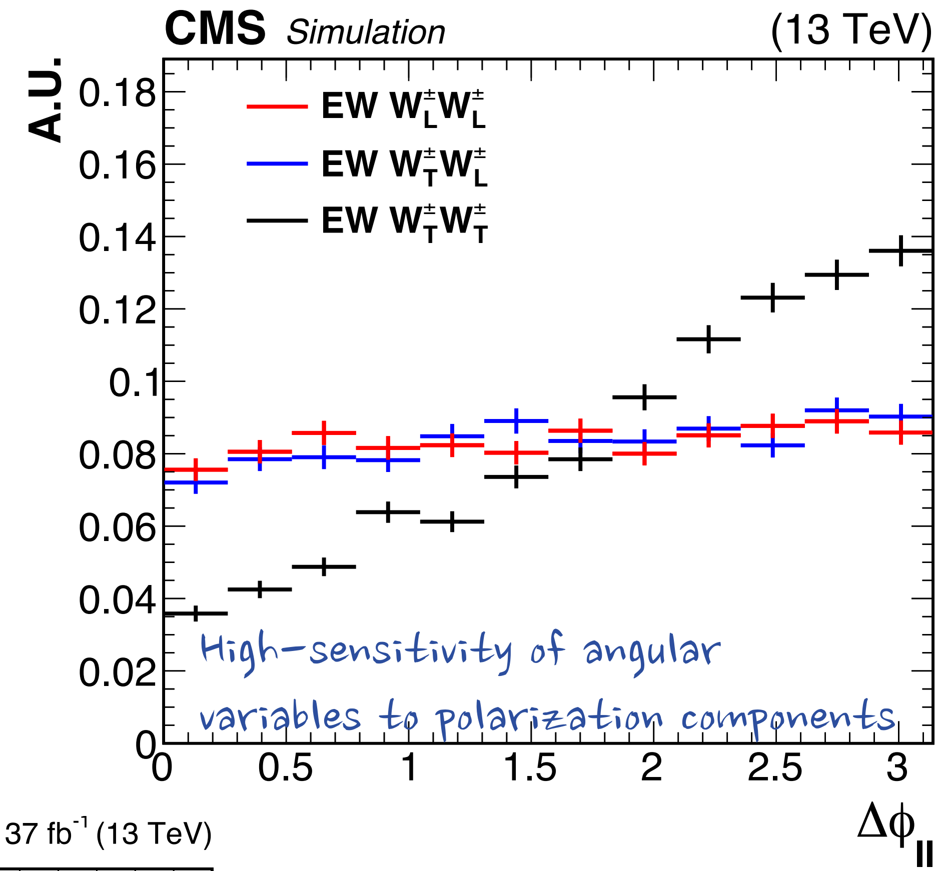
specific signal BDT for (**WLWL vs WXWT**) and (WTWT vs WXWL) and separate likelihood fits

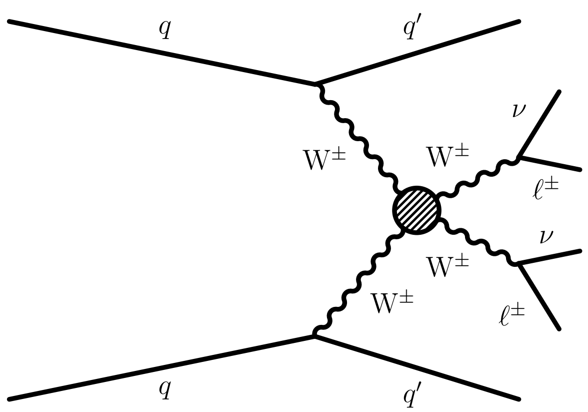
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

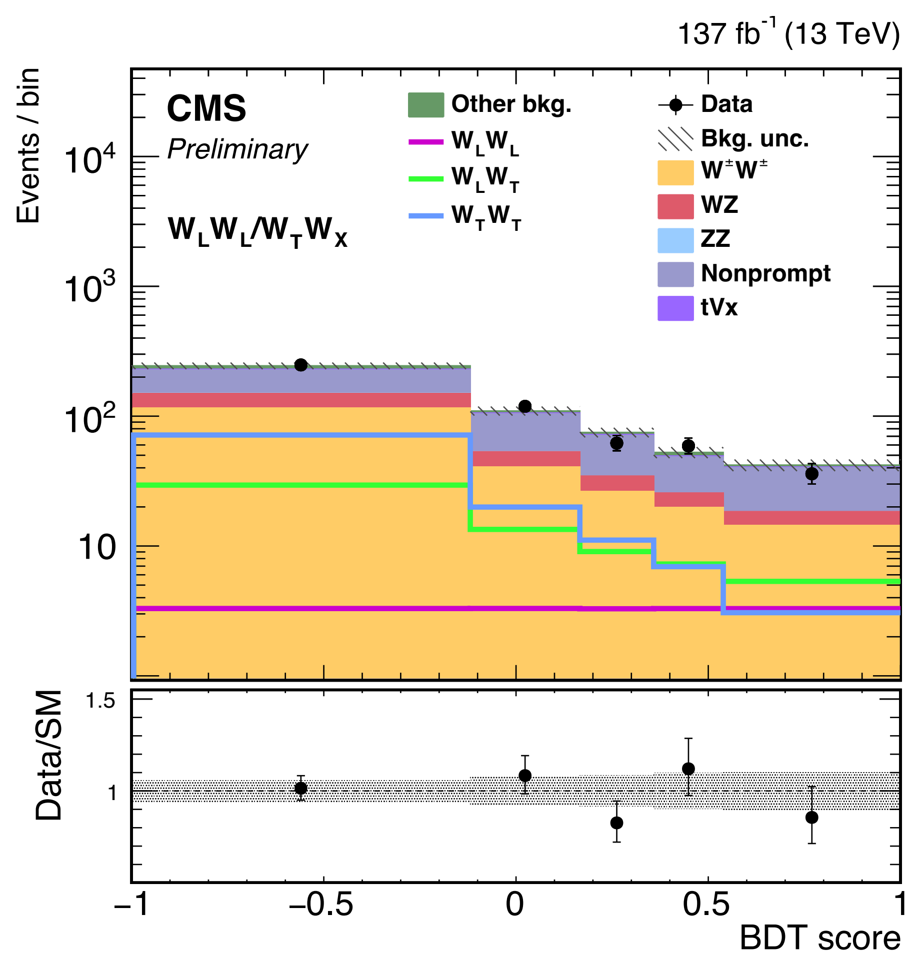
Polarization measurements

CMS-SMP-20-006, arXiv:2009.09429

- **Extremely challenging at the LHC as V_LV_L->V_LV_L is ~10% of the total EW WW scattering cross section**
- **Possibility to access different polarization states already with Run 2 data, with the Golden channel of VBS ssWW**
  - Measurement of **WLWL**, **WLWT** and **WTWT** processes (**reference-frame-dependent:** parton-parton and WW CoM reference frames)
  - Significance of ~1 (3) standard deviations for WLWL (WLWX)







spe
(W
(W
sep

Proc
$W^\pm_L$
$W^\pm_X$
$W^\pm_L$
$W^\pm_T$

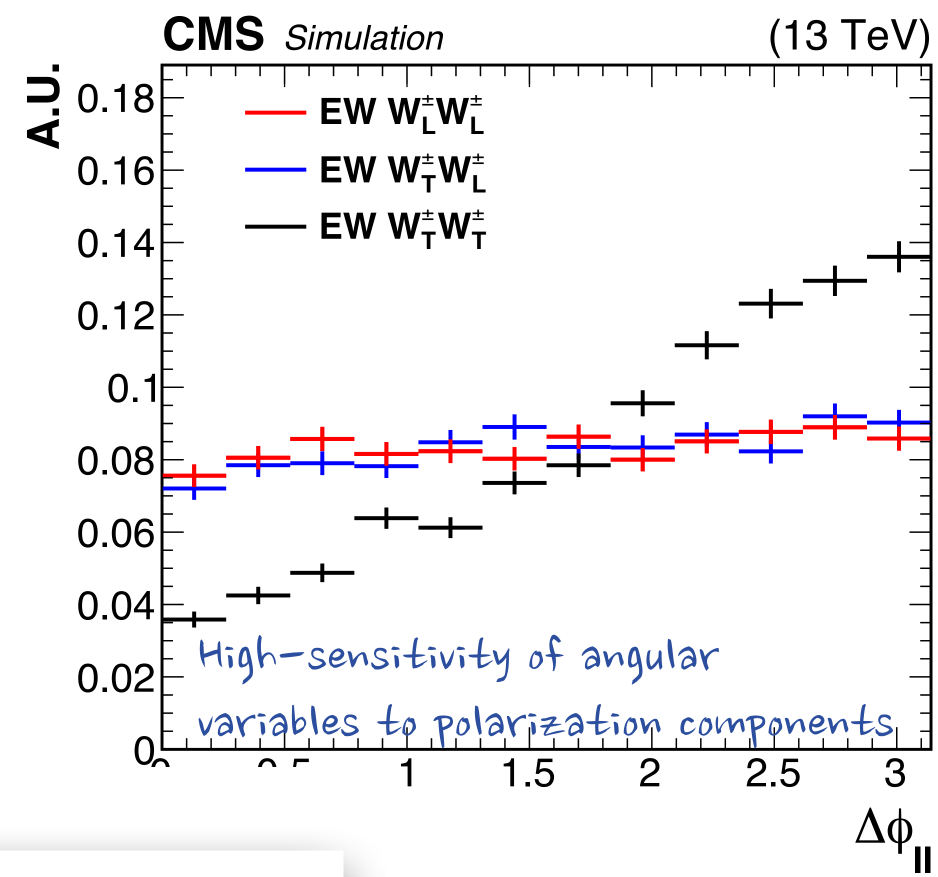
Studies of same-sign WW, WZ, and ZZ processes at HL-LHC and HE-LHC (CERN-LPCC-2018-03)

Access to longitudinal scattering=>unitarity of the SM

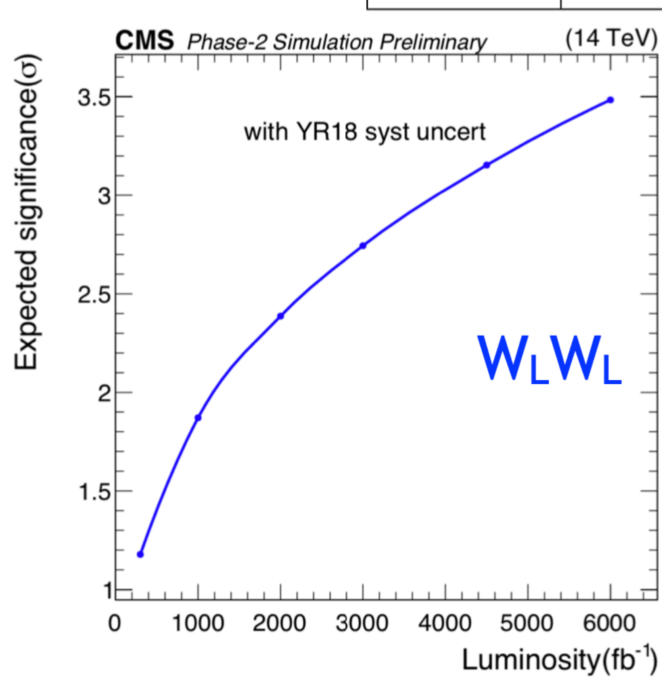
Polarization measurements

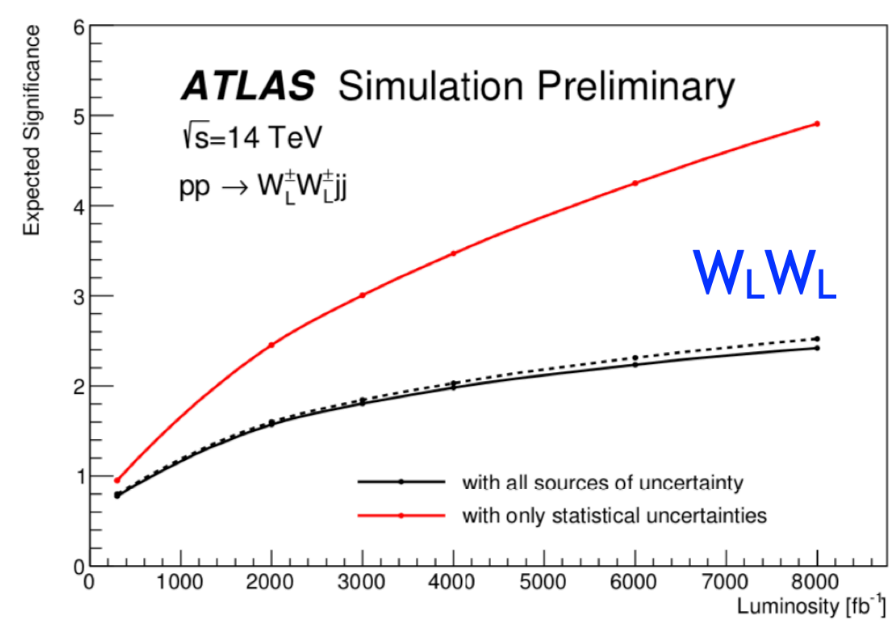
CMS-SMP-20-006, arXiv:2009.09429

- **Extremely challenging at the LHC as V_LV_L->V_LV_L is ~10% of the total EW WW scattering cross section**
- **Possibility to access different polarization states already with Run 2 data, with the Golden channel of VBS ssWW**
    - Measurement of **WLWL**, **WLWT** and **WTWT** processes (**reference-frame-dependent:** parton-parton and WW CoM reference frames)
    - Significance of ~1 (3) standard deviations for WLWL (WLWX)



Z_LZ_L	significance	
	w/ syst. uncert.	w/o syst. uncert.
HL-LHC	1.4σ	1.4σ
HE-LHC	5.2σ	5.7σ





Studies of same-sign WW, WZ, and ZZ processes at HL-LHC and HE-LHC (CERN-LPCC-2018-03)

Access to longitudinal scattering=>unitarity of the SM

ZOOM ON CMS ANALYSIS, PHYS. LETT. B 834 (2022) 137438

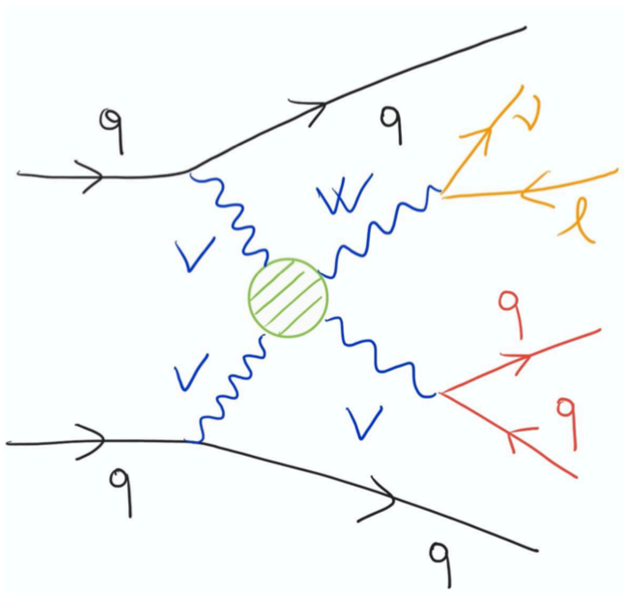
FIRST EVIDENCE FOR VBS IN SEMI-LEPTONIC FINAL STATE

SEMI-LEPTONIC VBS

Good balance between:

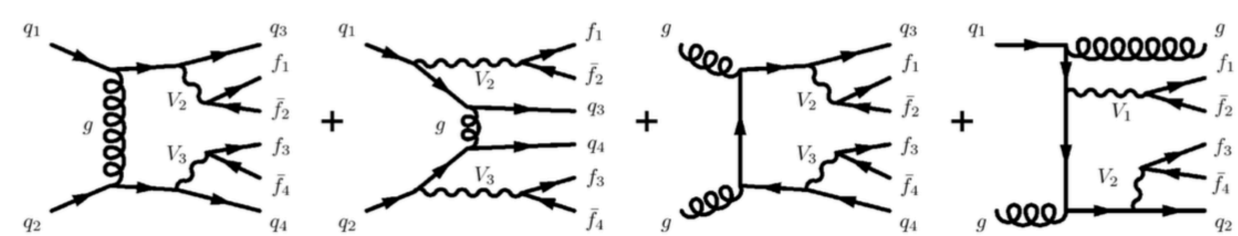
- ✓ Benefit from the large hadronic branching fraction of W or Z boson
- ✳ Larger irreducible backgrounds

SIGNAL

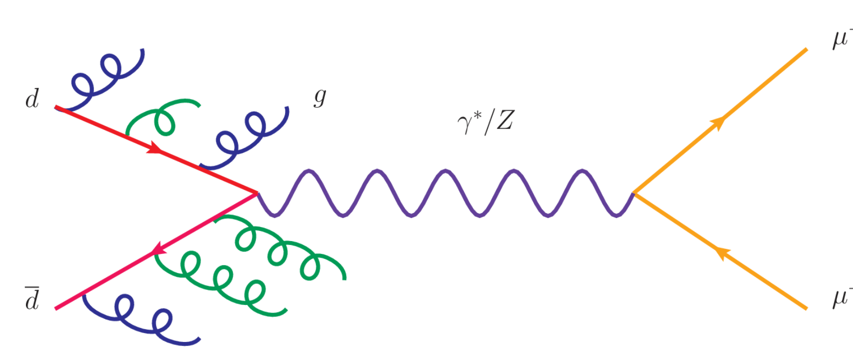


$\mathcal{O}(\alpha_{EW}^6)$

IRREDUCIBLE BACKGROUNDS



$\mathcal{O}(\alpha_{EW}^4\alpha_S^2)$ QCD-VV production
(negligible interference with the signal)

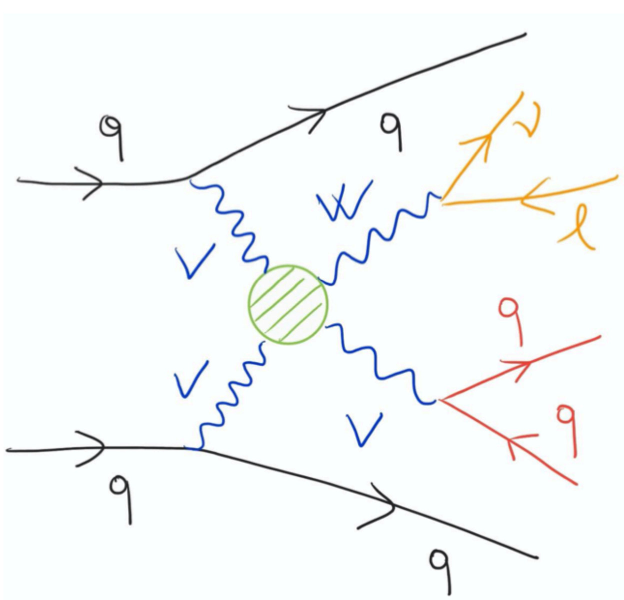


$\mathcal{O}(\alpha_{EW}^2\alpha_S^4)$ V+jets

CMS-SMP-20-013, arXiv:2112.05259

SEMI-LEPTONIC VBS

SIGNAL

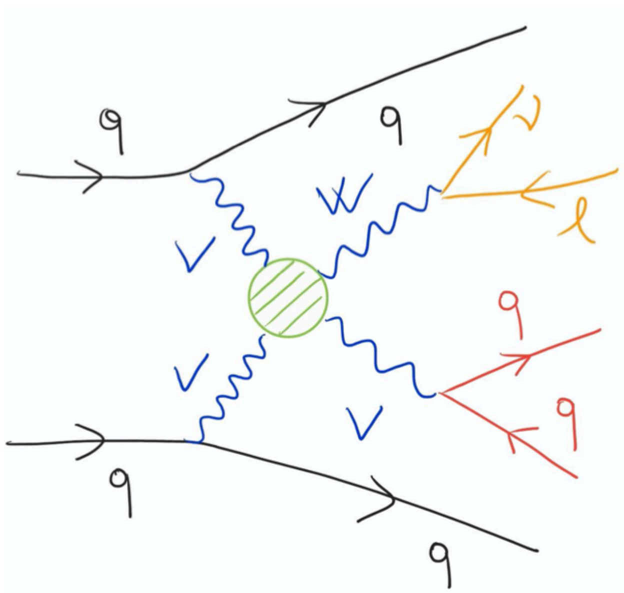


$\mathcal{O}(\alpha_{EW}^6)$

CMS-SMP-20-013, arXiv:2112.05259

SEMI-LEPTONIC VBS

SIGNAL



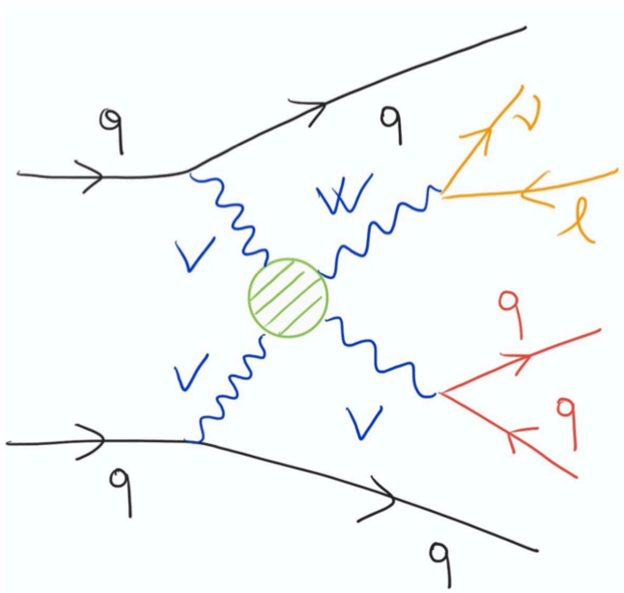
$\mathcal{O}(\alpha_{EW}^6)$

- Both ATLAS and CMS have reported studies of semileptonic VBS final states in the 2016 subset of the 13-TeV LHC data, including W±V and ZV .
- Thanks to advanced techniques for background estimation and signal extraction, CMS got extremely close to observation of WV process with Run 2 data!
- There are no public predictions beyond LO accuracy for any of the semileptonic signatures
- Advances in signal modeling of parton-shower effects (Dipole recoil scheme arXiv:1710.00391 used for first time)

CMS-SMP-20-013, arXiv:2112.05259

SEMI-LEPTONIC VBS

SIGNAL



$\mathcal{O}(\alpha_{EW}^6)$

- Both ATLAS and CMS have reported studies of semileptonic VBS final states in the 2016 subset of the 13-TeV LHC data, including W±V and ZV .
- Thanks to advanced techniques for background estimation and signal extraction, CMS got extremely close to observation of WV process with Run 2 data!
- There are no public predictions beyond LO accuracy for any of the semileptonic signatures
- Advances in signal modeling of parton-shower effects (Dipole recoil scheme arXiv:1710.00391 used for first time)

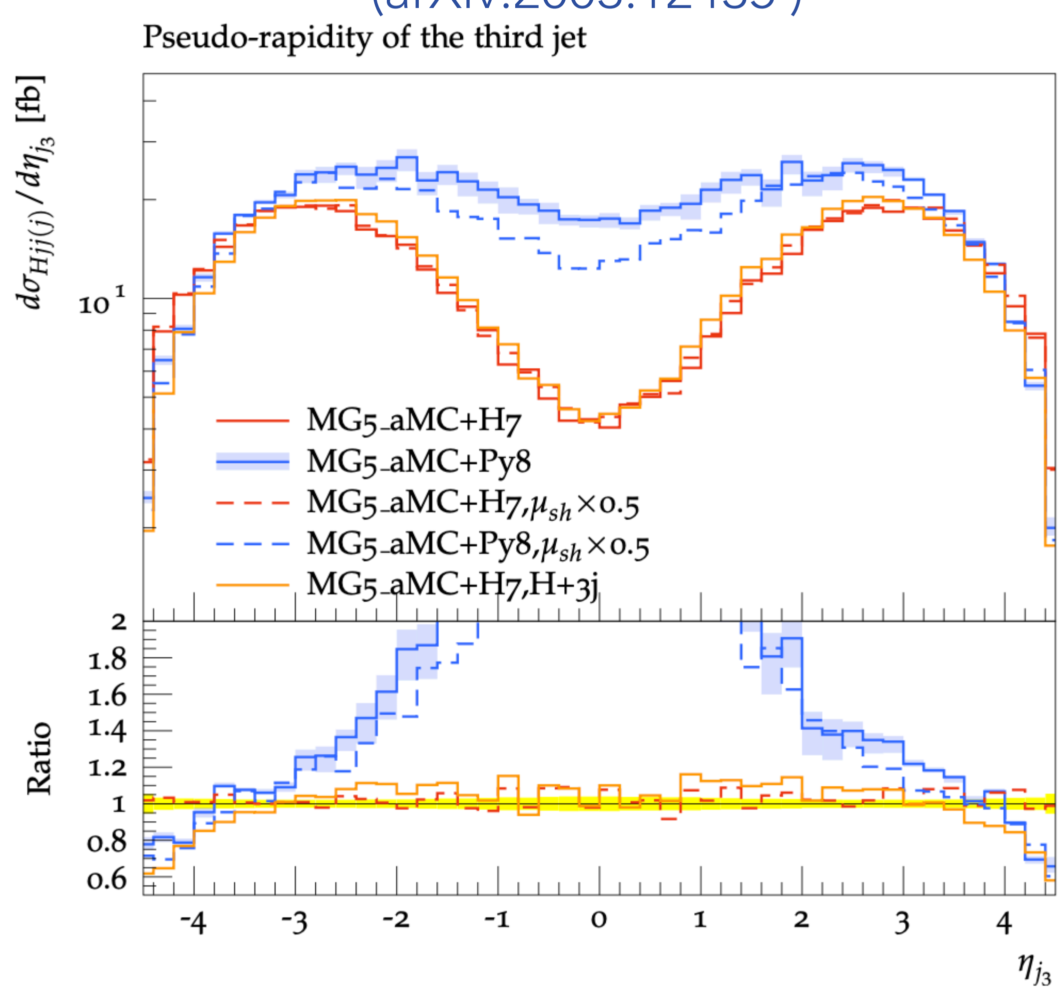
> A relevant exception, worth to be discussed, is related to the modelling of the third-jet kinematics. It has been observed that, for predictions matched with PYTHIA8 [83, 84], the global-recoil scheme leads to a large unphysical enhancement of the third-jet activity in the mid-rapidity region, related to a wrong assignment of the phase-space boundaries for processes with initial-final color connections. Such an enhancement, absent in predictions obtained with

Arxiv 2102.10991

CMS-SMP-20-013, arXiv:2112.05259

SEMI-LEPTONIC VBS

Central-rapidity enhancement observed for predictions matched with Pythia8 is unphysical (arXiv:2003.12435)



- Both ATLAS and CMS have reported studies of semileptonic VBS final states in the 2016 subset of the 13-TeV LHC data, including W±V and ZV .
- Thanks to advanced techniques for background estimation and signal extraction, CMS got extremely close to observation of WV process with Run 2 data!
- There are no public predictions beyond LO accuracy for any of the semileptonic signatures
- Advances in signal modeling of parton-shower effects (Dipole recoil scheme arXiv:1710.00391 used for first time)

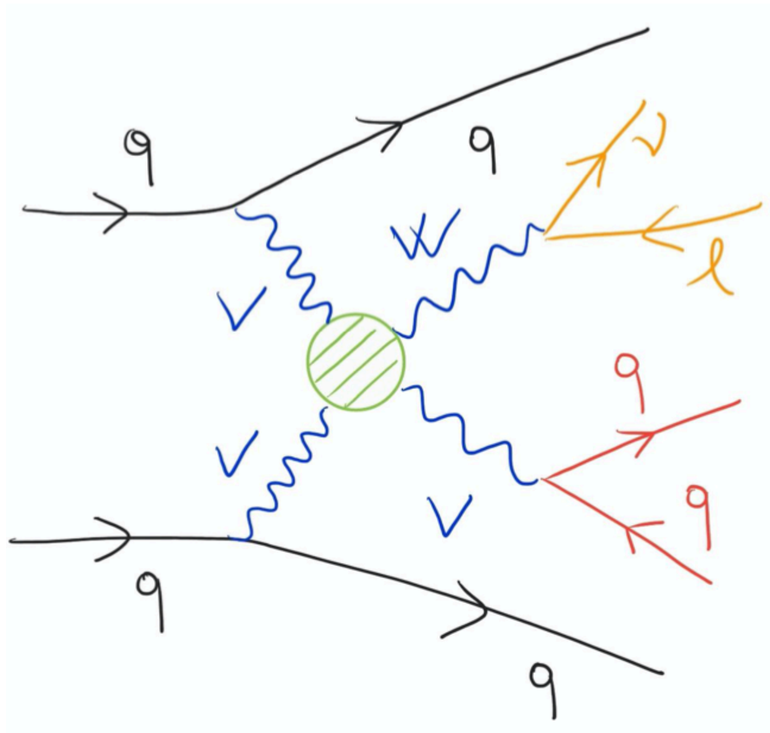
A relevant exception, worth to be discussed, is related to the modelling of the third-jet kinematics. It has been observed that, for predictions matched with PYTHIA8 [83, 84], the global-recoil scheme leads to a large unphysical enhancement of the third-jet activity in the mid-rapidity region, related to a wrong assignment of the phase-space boundaries for processes with initial-final color connections. Such an enhancement, absent in predictions obtained with

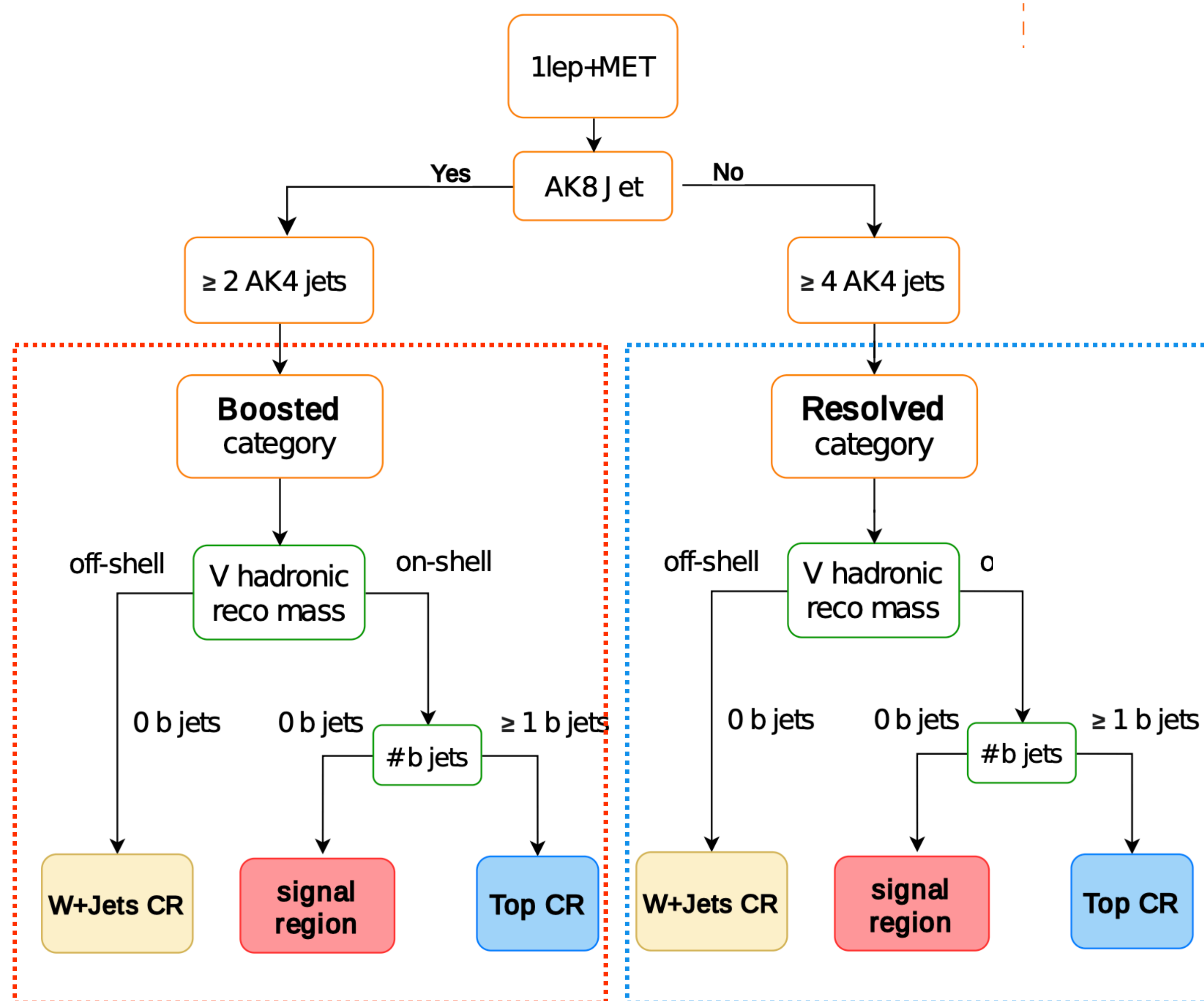
Arxiv 2102.10991

CMS-SMP-20-013, arXiv:2112.05259

CATEGORIES AND BACKGROUND ESTIMATION

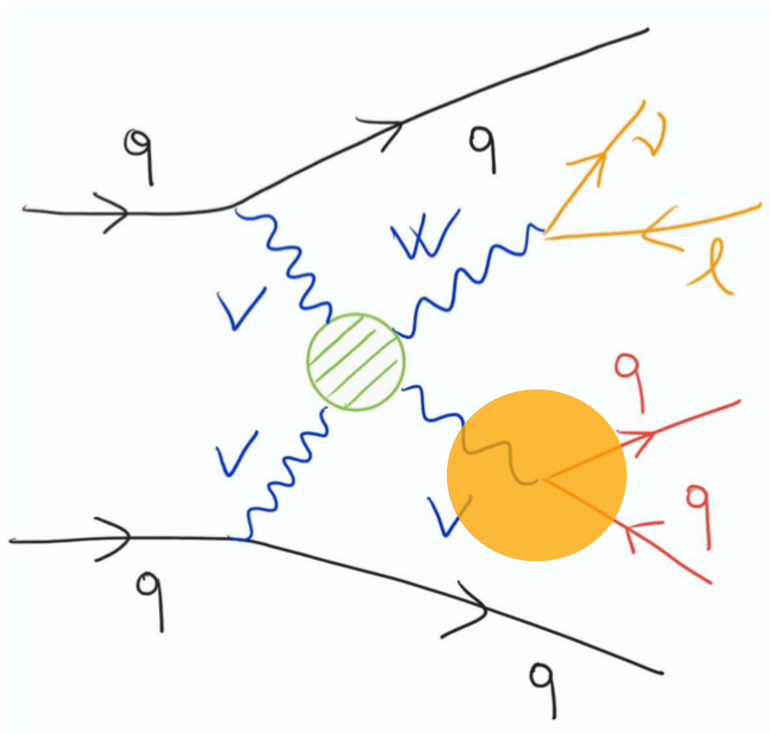
High jet-multiplicity at the reconstructed level

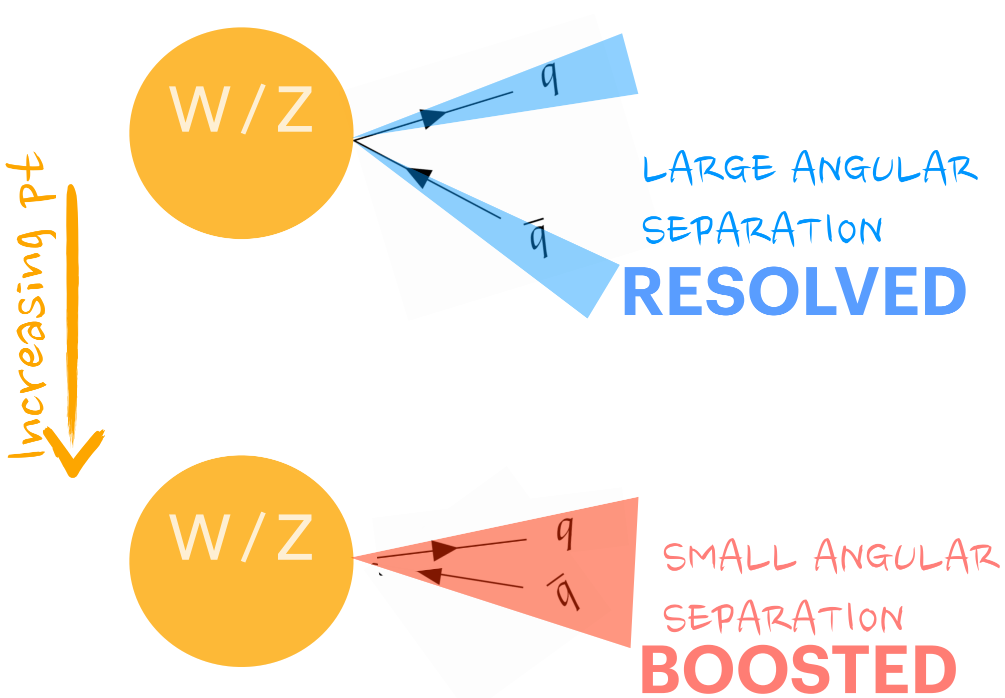


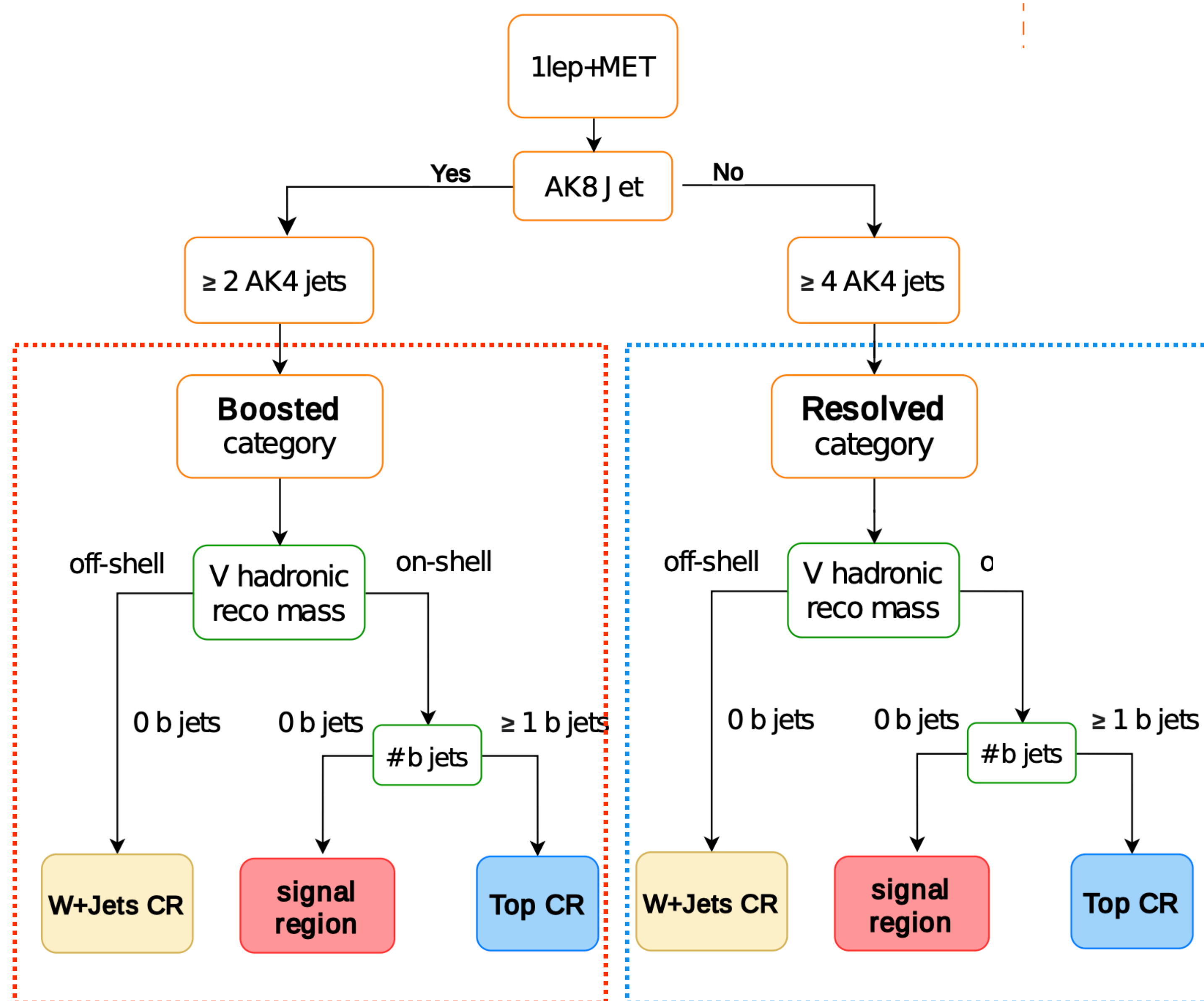


CATEGORIES AND BACKGROUND ESTIMATION

High jet-multiplicity at the reconstructed level

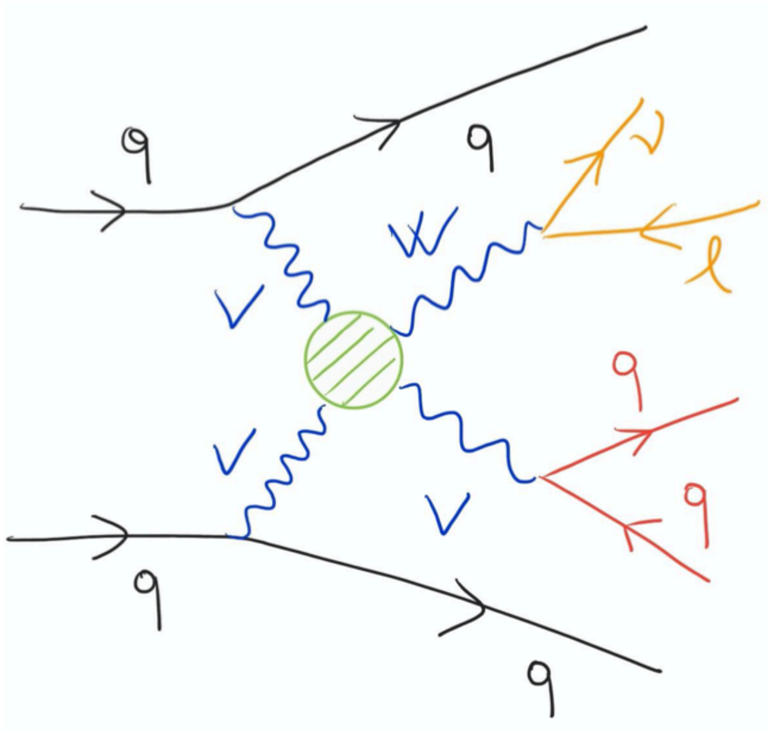


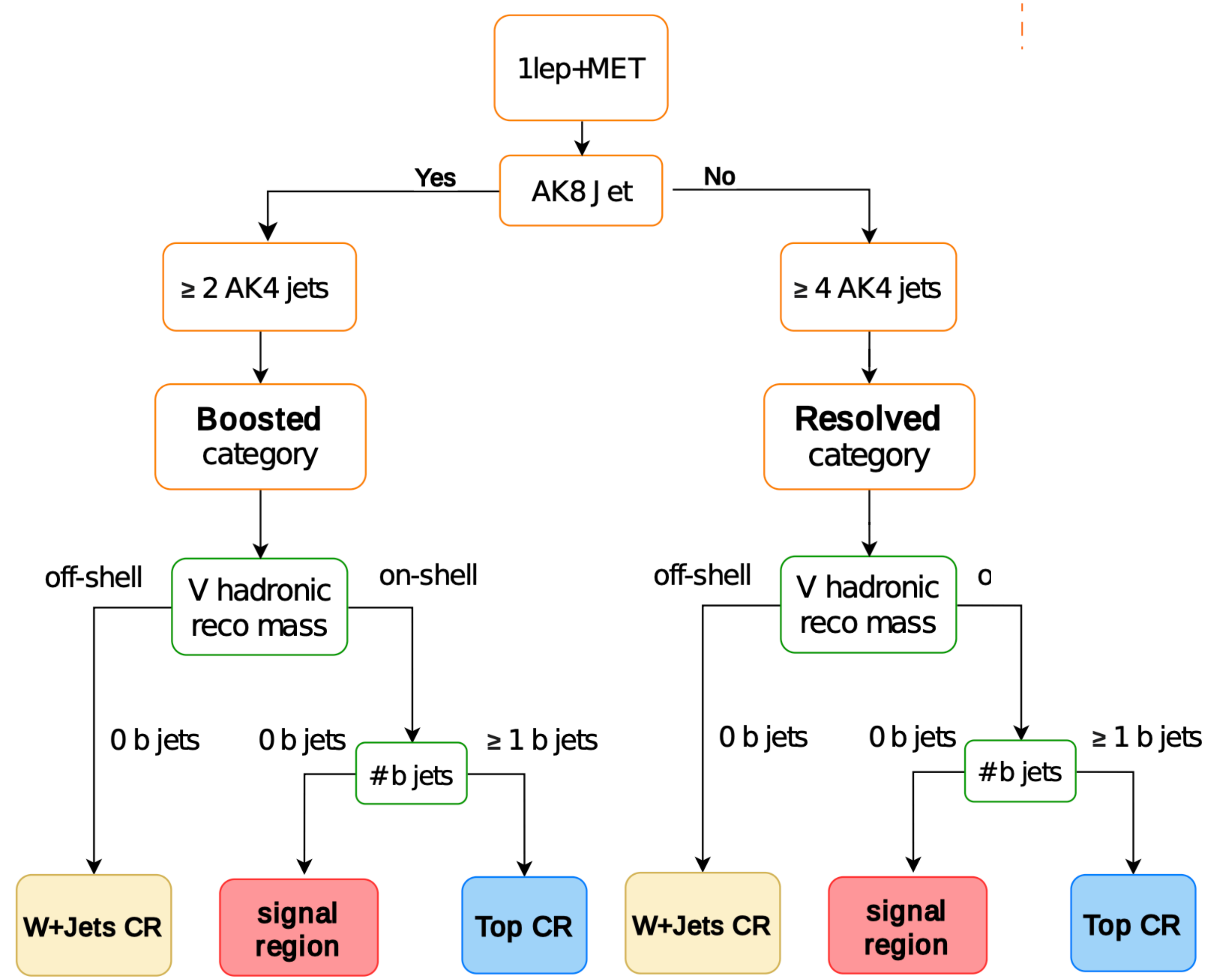




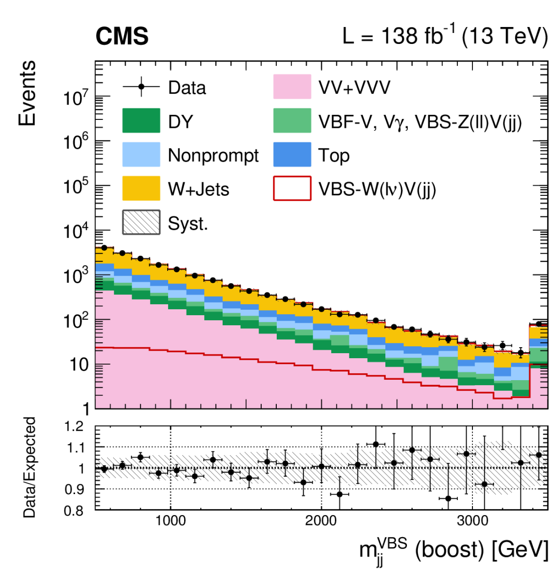
CATEGORIES AND BACKGROUND ESTIMATION

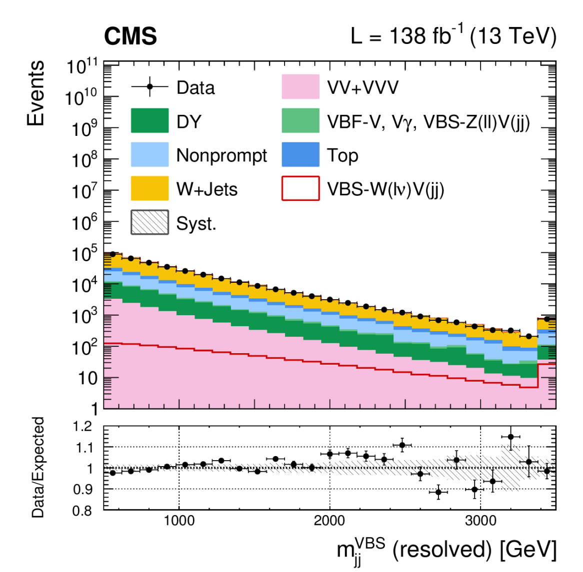
High jet-multiplicity at the reconstructed level





- Good description of the data by MC thanks to the data-driven strategy applied to improve the modeling of the Top and W+jets backgrounds
- Top: **one free floating parameter** per category in the ML fit
- Wjets: several free floating parameters per category in the ML fit, to perfect the **modeling of VBS-jets momenta**.





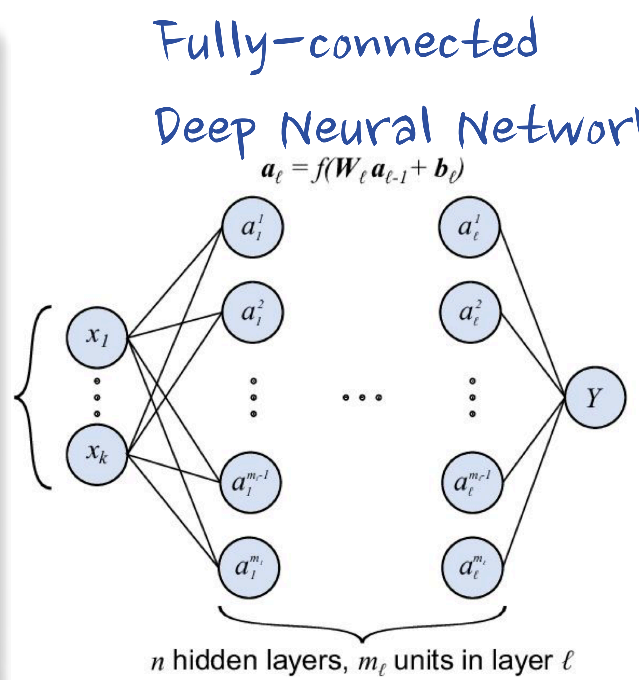
A PLAYGROUND FOR DNN

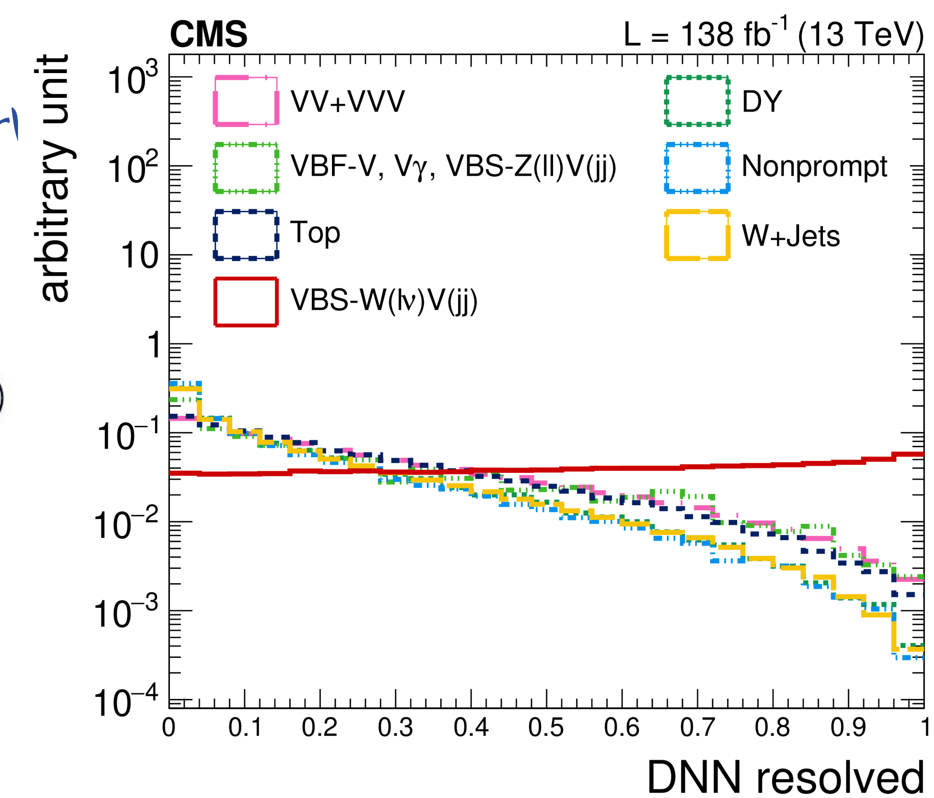
Exploit multi-variate techniques to optimize the sensitivity to the EW Vector Boson Scattering process.

14 INPUT VARIABLES

BINARY

Variable	Resolved	Boosted	SHAP ranking Resolved	SHAP ranking Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30\,\mathrm{GeV}$	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13





- Basic approach: all Backgrounds vs Signal
- DNN models trained for the resolved and boosted category to separate the VBS signal from the large backgrounds
- DNN architecture: 4 layers of 64 (32) nodes for resolved (boosted) category models.

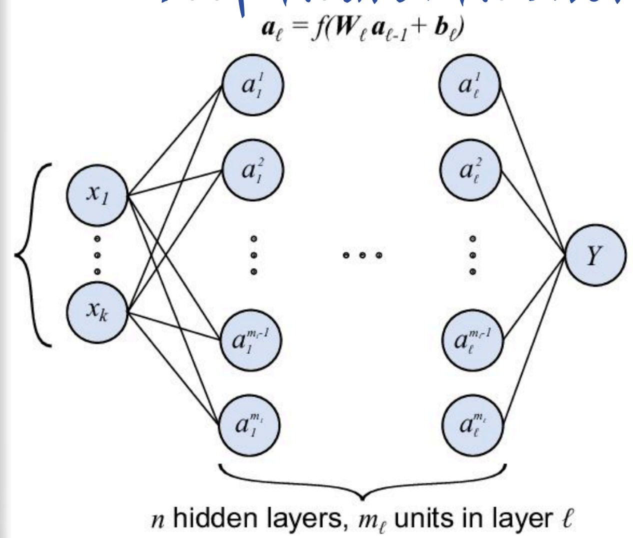
A PLAYGROUND FOR DNN

Exploit multi-variate techniques to optimize the sensitivity to the EW Vector Boson Scattering process.

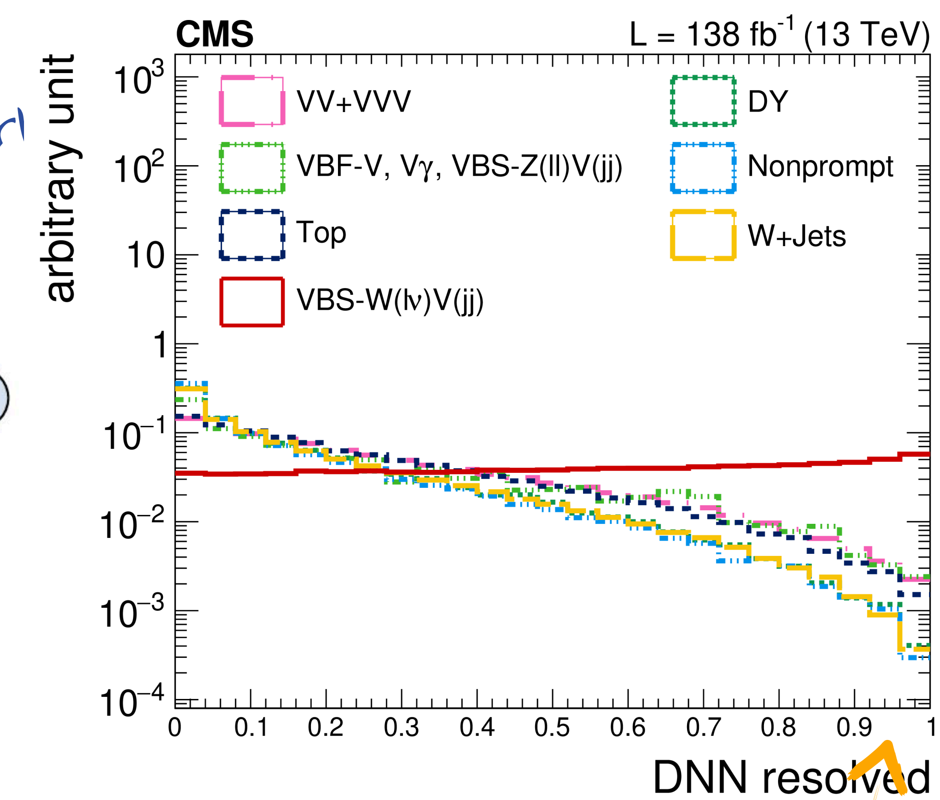
14 INPUT VARIABLES

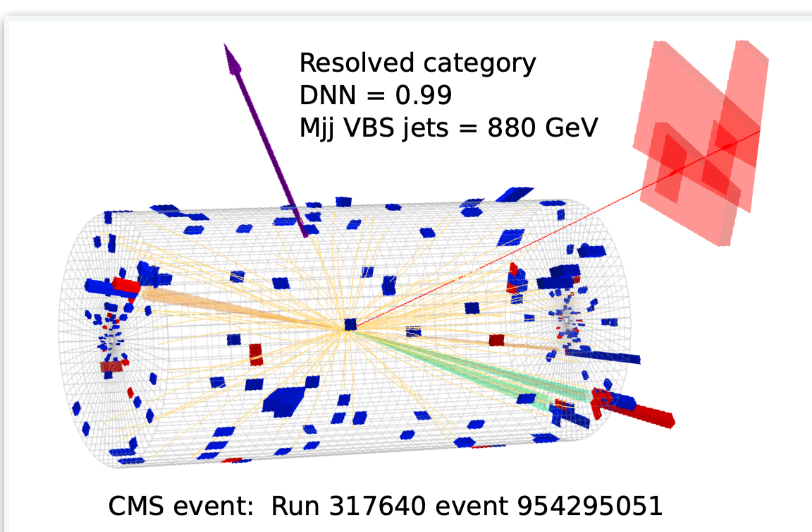
Variable	Resolved	Boosted	SHAP ranking Resolved	SHAP ranking Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30\,GeV$	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13

Fully-connected Deep Neural Network



BINARY





FIRST EVIDENCE OF SEMI-LEPTONIC VBS

Three different measurements from the same data

FIRST EVIDENCE OF SEMI-LEPTONIC VBS

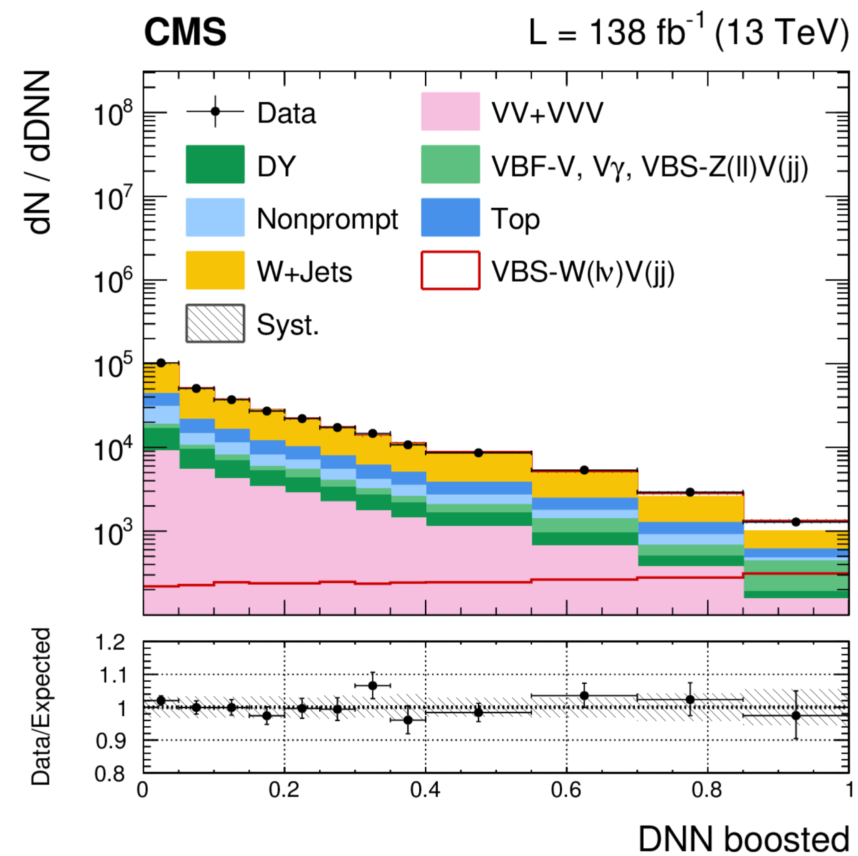
Three different measurements from the same data

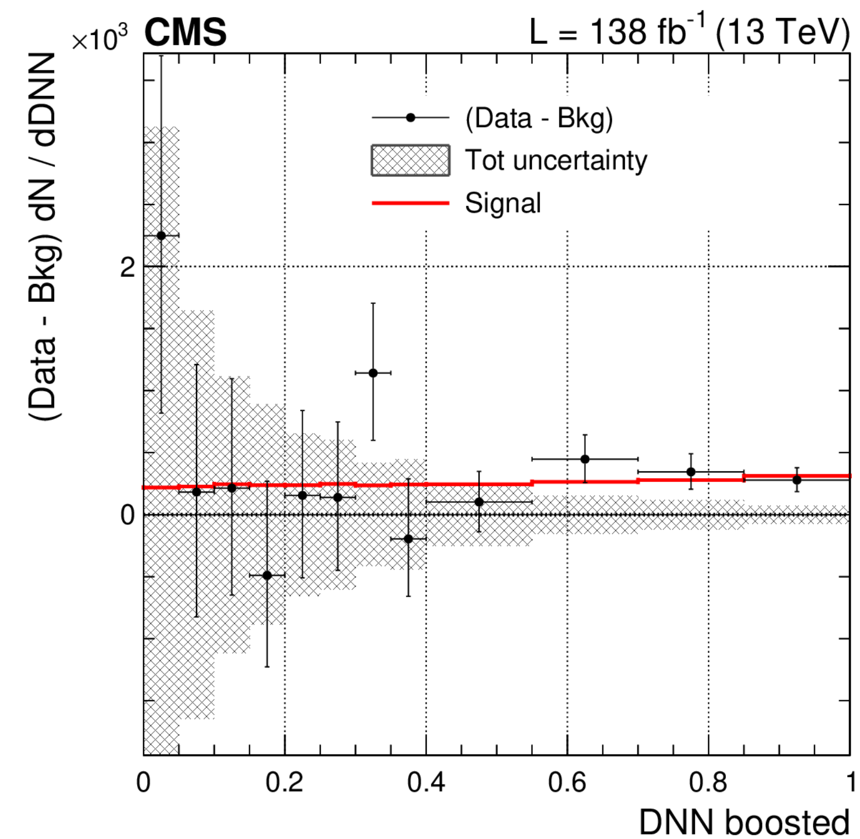
- SM electroweak signal strength:

FIRST EVIDENCE OF SEMI-LEPTONIC VBS

Three different measurements from the same data

- SM electroweak signal strength:
  - $\mu_{EW} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.85^{+0.24}_{-0.20} = ^{+0.21}_{-0.17}(\text{ syst })^{+0.12}_{-0.12}(\text{ stat })$
  - **signal significance of 4.4 standard deviations** (5.1 expected).
  - Observed fiducial cross-section (mqq>100 GeV, ptq >10 GeV) of 1.9 +- 0.5 pb
- **Considering EW and QCD WV production as signal**, the signal strength is measured as:

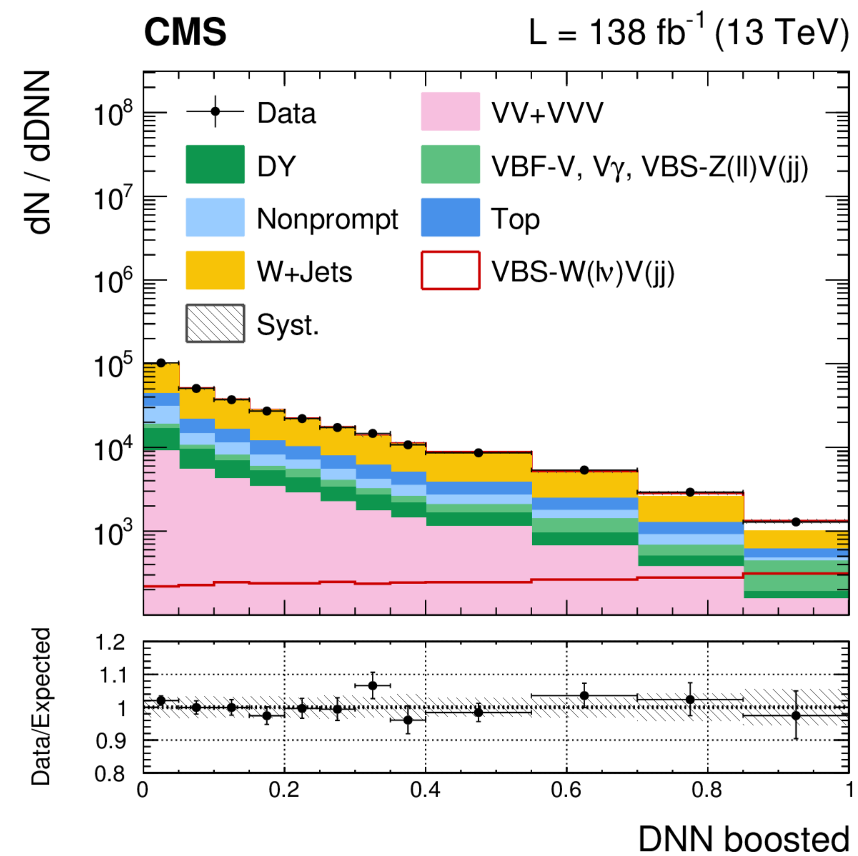


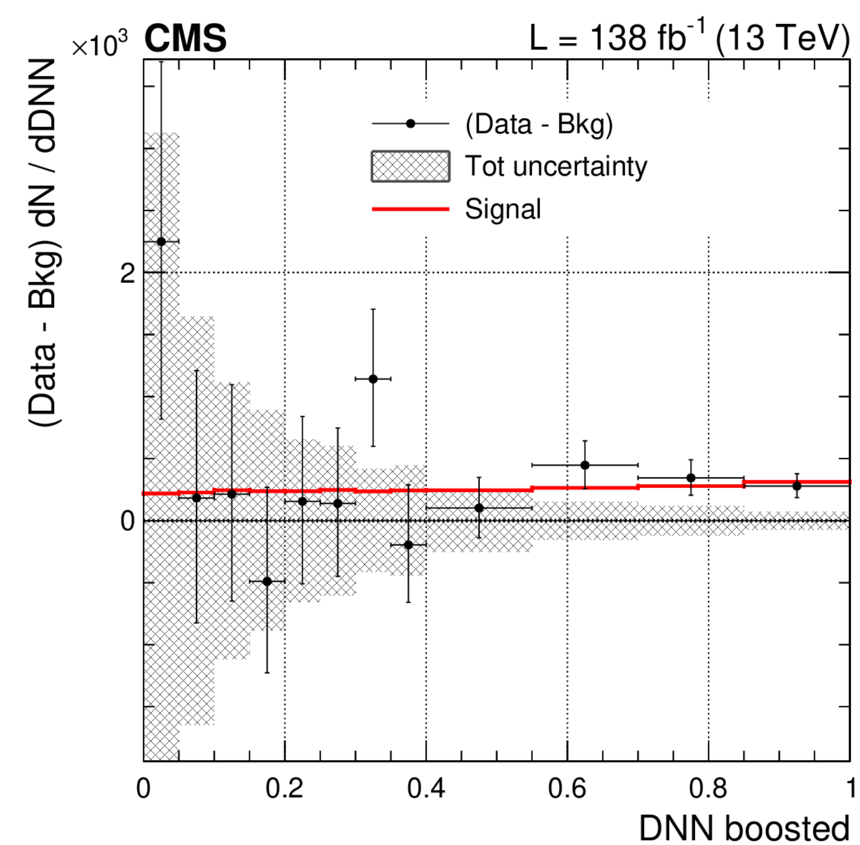


FIRST EVIDENCE OF SEMI-LEPTONIC VBS

Three different measurements from the same data

- SM electroweak signal strength:
    - $\mu_{EW} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.85^{+0.24}_{-0.20} = {}^{+0.21}_{-0.17}(\text{ syst })^{+0.12}_{-0.12}(\text{ stat })$
    - **signal significance of 4.4 standard deviations** (5.1 expected).
    - Observed fiducial cross-section (mqq>100 GeV, ptq >10 GeV) of 1.9 +- 0.5 pb
- **Considering EW and QCD WV production as signal**, the signal strength is measured as:
    - $\mu_{EW+QCD} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.98^{+0.20}_{-0.17} = {}^{+0.19}_{-0.16}(\text{ syst })^{+0.07}_{-0.07}(\text{ stat })$
    - and the total EW+QCD measured cross-section is: $16.6^{+3.4}_{-2.9}$ pb

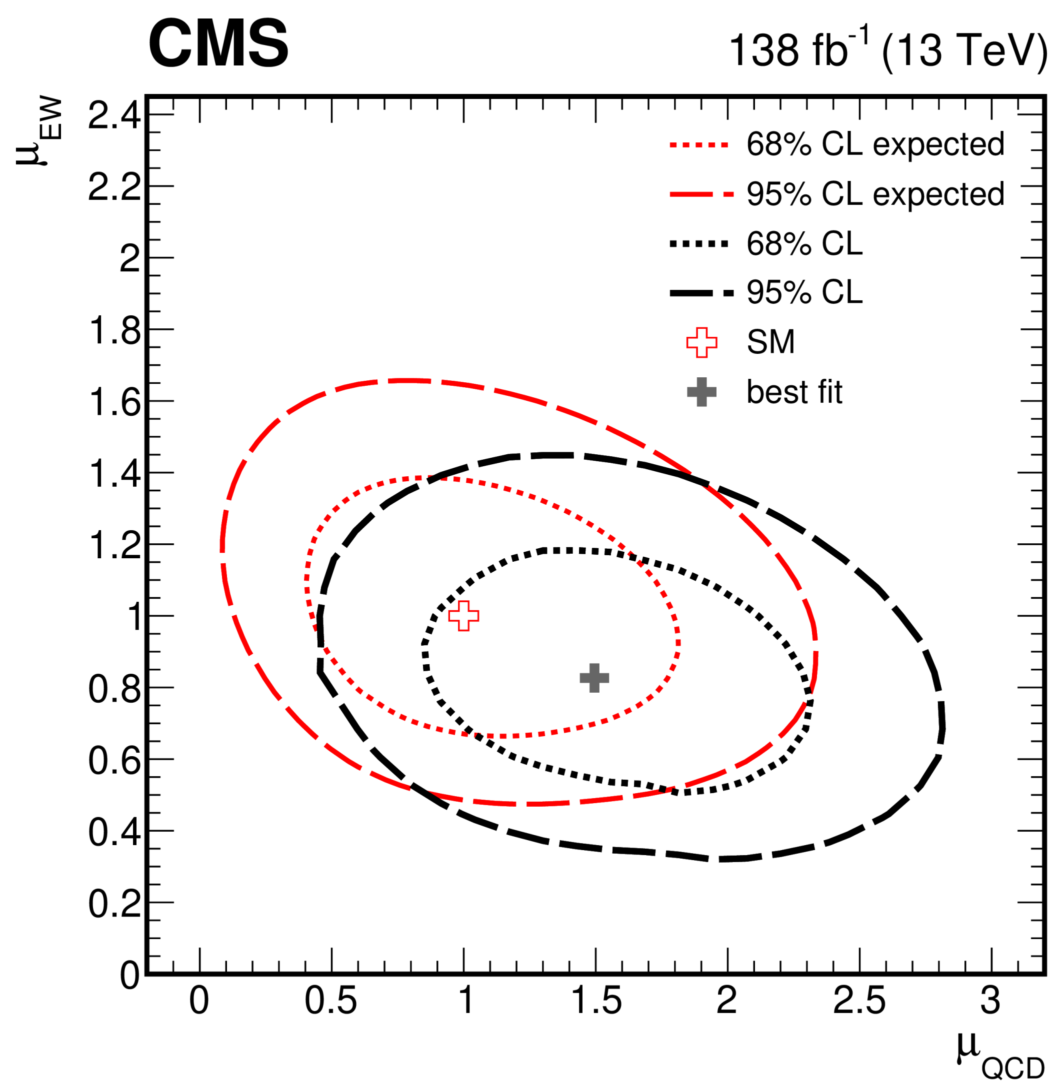




FIRST EVIDENCE OF SEMI-LEPTONIC VBS

Three different measurements from the same data

- SM electroweak signal strength:
  - $\mu_{EW} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.85^{+0.24}_{-0.20} = {}^{+0.21}_{-0.17}(\text{ syst })^{+0.12}_{-0.12}(\text{ stat })$
  - **signal significance of 4.4 standard deviations** (5.1 expected).
  - Observed fiducial cross-section (mqq>100 GeV, ptq >10 GeV) of 1.9 +- 0.5 pb
- **Considering EW and QCD WV production as signal**, the signal strength is measured as:
  - $\mu_{EW+QCD} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.98^{+0.20}_{-0.17} = {}^{+0.19}_{-0.16}(\text{ syst })^{+0.07}_{-0.07}(\text{ stat}$
  - and the total EW+QCD measured cross-section is: 16.6 $^{+3.4}_{-2.9}$ pb
- **Simultaneous 2D fit of the EW and QCD WV signal strengths**



FIRST EVIDENCE OF SEMI-LEPTONIC VBS

Three different measurements from the same data

- SM electroweak signal strength:
  - $\mu_{EW} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.85^{+0.24}_{-0.20} = {}^{+0.21}_{-0.17}(\text{ syst })^{+0.12}_{-0.12}(\text{ stat })$
  - signal significance of 4.4 standard deviations (5.1 expected).
  - Observed fiducial cross-section (mqq>100 GeV, ptq >10 GeV) of 1.9 +- 0.5 pb
- **Considering EW and QCD WV production as signal**, the signal strength is measured as:
  - $\mu_{EW+QCD} = \sigma^{\text{obs}}/\sigma^{\text{SM}} = 0.98^{+0.20}_{-0.17} = {}^{+0.19}_{-0.16}(\text{ syst })^{+0.07}_{-0.07}(\text{ stat })$
  - and the total EW+QCD measured cross-section is: $16.6\ ^{+3.4}_{-2.9}$ pb
- **Simultaneous 2D fit of the EW and QCD WV signal strengths**
- Main sources of systematic uncertainties from signal modeling, background estimation and statistics of data

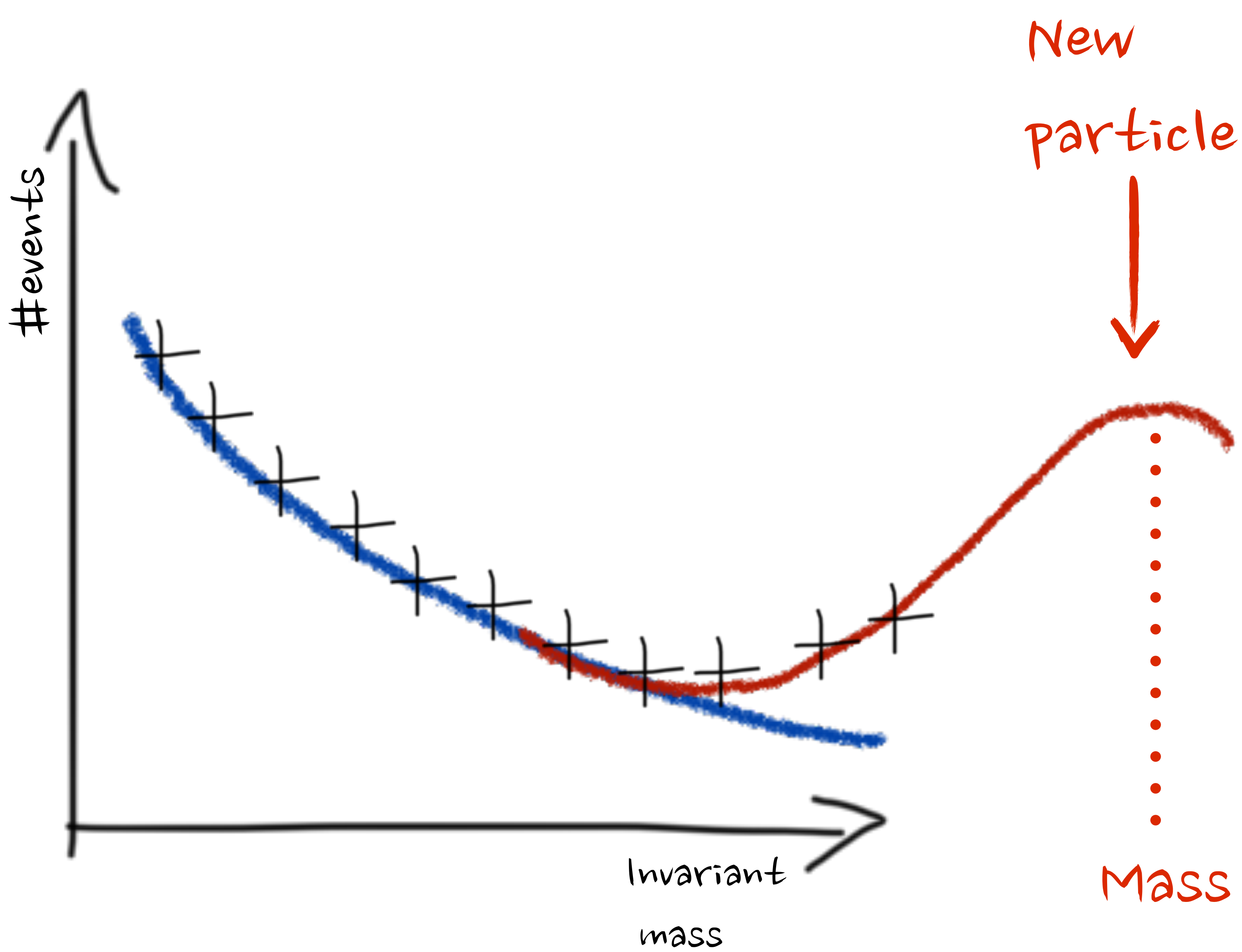
Uncertainty source	$\Delta\mu_{\text{EW}}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	
b-tagging	0.05
Jet energy scale and resolution	0.04
Integrated luminosity	0.01
Lepton identification	0.01
Boosted V boson identification	0.01
Total	0.06
Theory	
Signal modeling	0.09
Background modeling	0.08
Total	0.12
Total	0.22

EFT

IMPACT ON BEYOND-THE-STANDARD-MODEL THEORIES

VBS AND NEW PHYSICS

Powerful portal to access BSM in a model-independent approach, usually parametrizing deviations from SM as Effective Field Theory (EFT) expansion.



BSM physics with mass scales beyond the LHC direct reach.

We can invoke some UV theory that we are still not able to catch

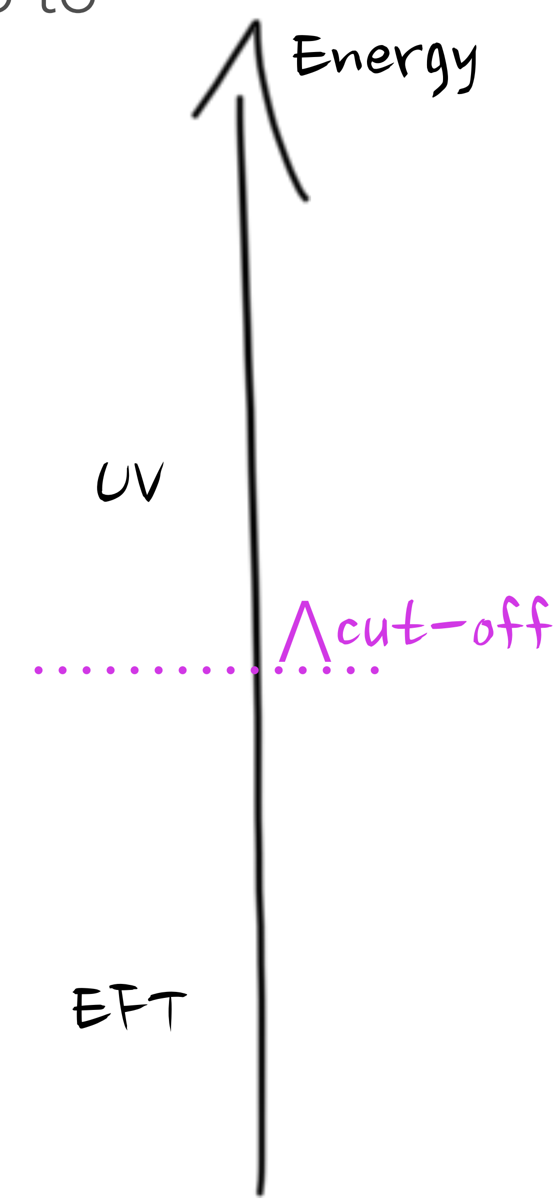
Bottom-up approach: build a Taylor expansion, truncated up to some order, with a well defined validity domain

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \mathscr{L}_8 + \cdots$$

$$\sum_i c_i \frac{\mathcal{O}_i}{\Lambda^2}$$

New BSM couplings (Wilson coefficients)

BSM scale

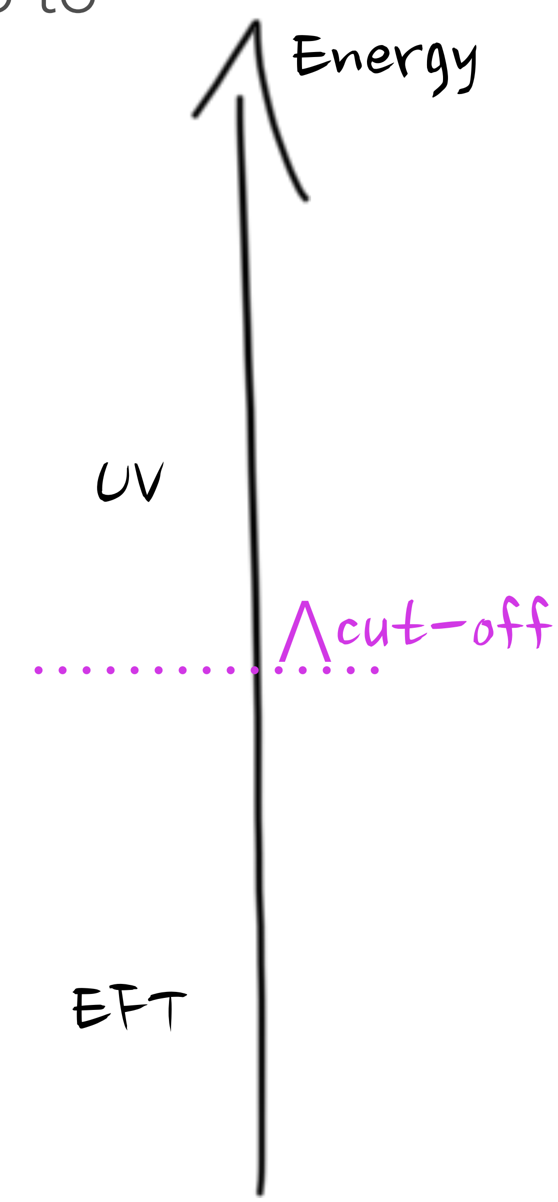


EFFECTIVE FIELD THEORY AND VBS

We can invoke some UV theory that we are still not able to catch

Bottom-up approach: build a Taylor expansion, truncated up to some order, with a well defined validity domain

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \mathscr{L}_8 + \cdots$$



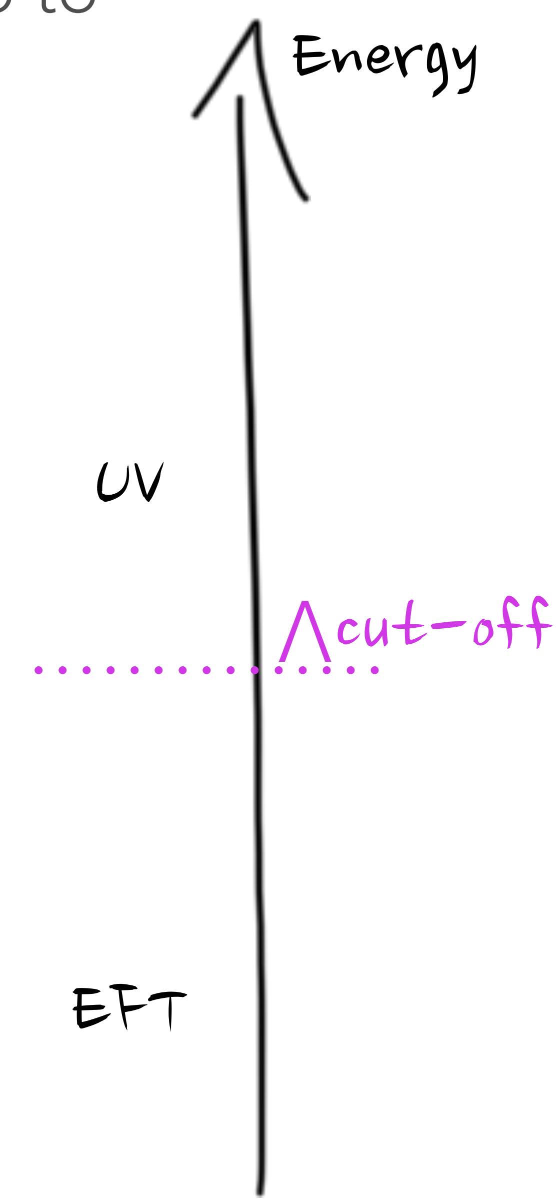
EFFECTIVE FIELD THEORY AND VBS

We can invoke some UV theory that we are still not able to catch

Bottom-up approach: build a Taylor expansion, truncated up to some order, with a well defined validity domain

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \cancel{\mathscr{L}_5} + \mathscr{L}_6 + \cancel{\mathscr{L}_7} + \mathscr{L}_8 + \cdots$$

Lepton Number
Violating terms



EFFECTIVE FIELD THEORY AND VBS

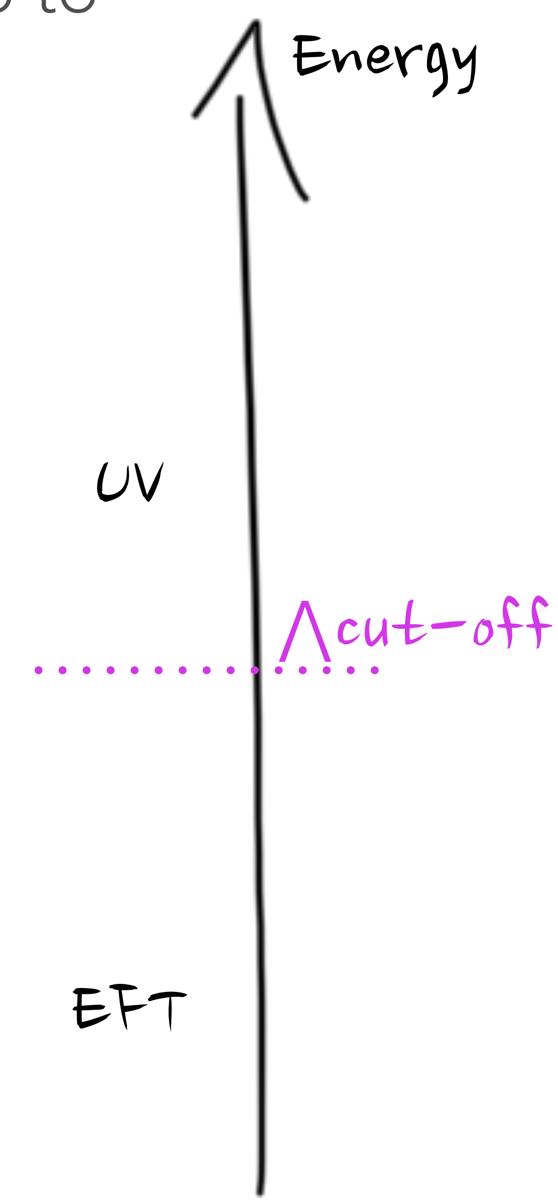
We can invoke some UV theory that we are still not able to catch

Bottom-up approach: build a Taylor expansion, truncated up to some order, with a well defined validity domain

$$\mathscr{L}_{BSM} \xrightarrow[(E\ll M)]{} \mathscr{L}_{\mathrm{eft}} \simeq \mathscr{L}_4 + \cancel{\mathscr{L}_5} + \cancel{\mathscr{L}_6} + \cancel{\mathscr{L}_7} + \mathscr{L}_8 + \cdots$$

Lepton Number Violating terms

Historically "negligible" for VBS processes

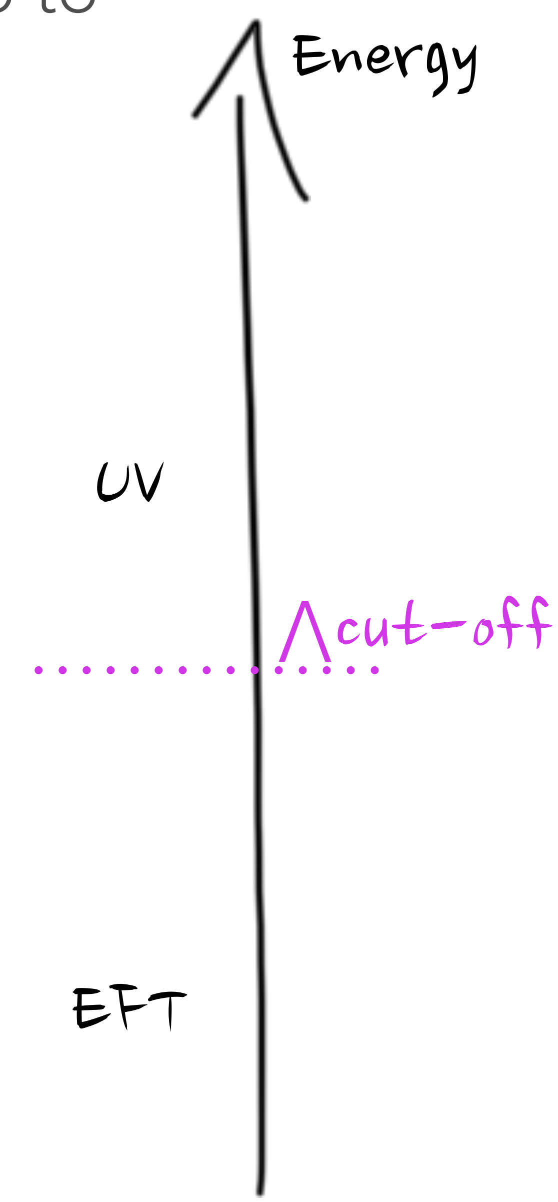


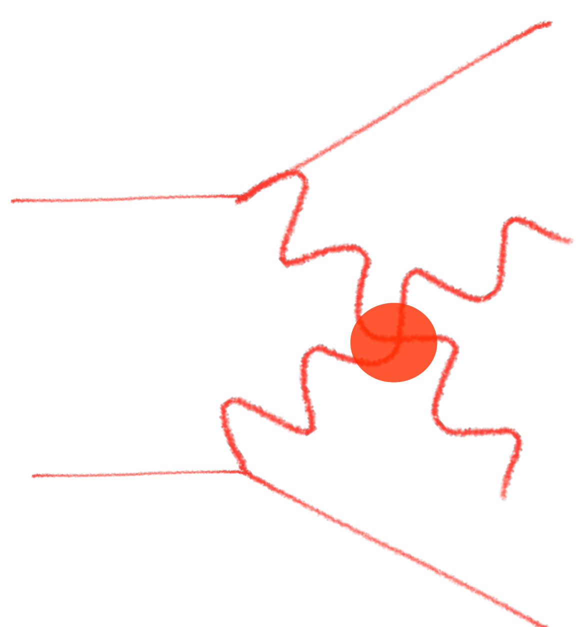
EFFECTIVE FIELD THEORY AND VBS

We can invoke some UV theory that we are still not able to catch

Bottom-up approach: build a Taylor expansion, truncated up to some order, with a well defined validity domain

$$\mathscr{L}_{BSM} \xrightarrow[(E \ll M)]{} \mathscr{L}_{\text{eft}} \simeq \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \mathscr{L}_8 + \cdots$$



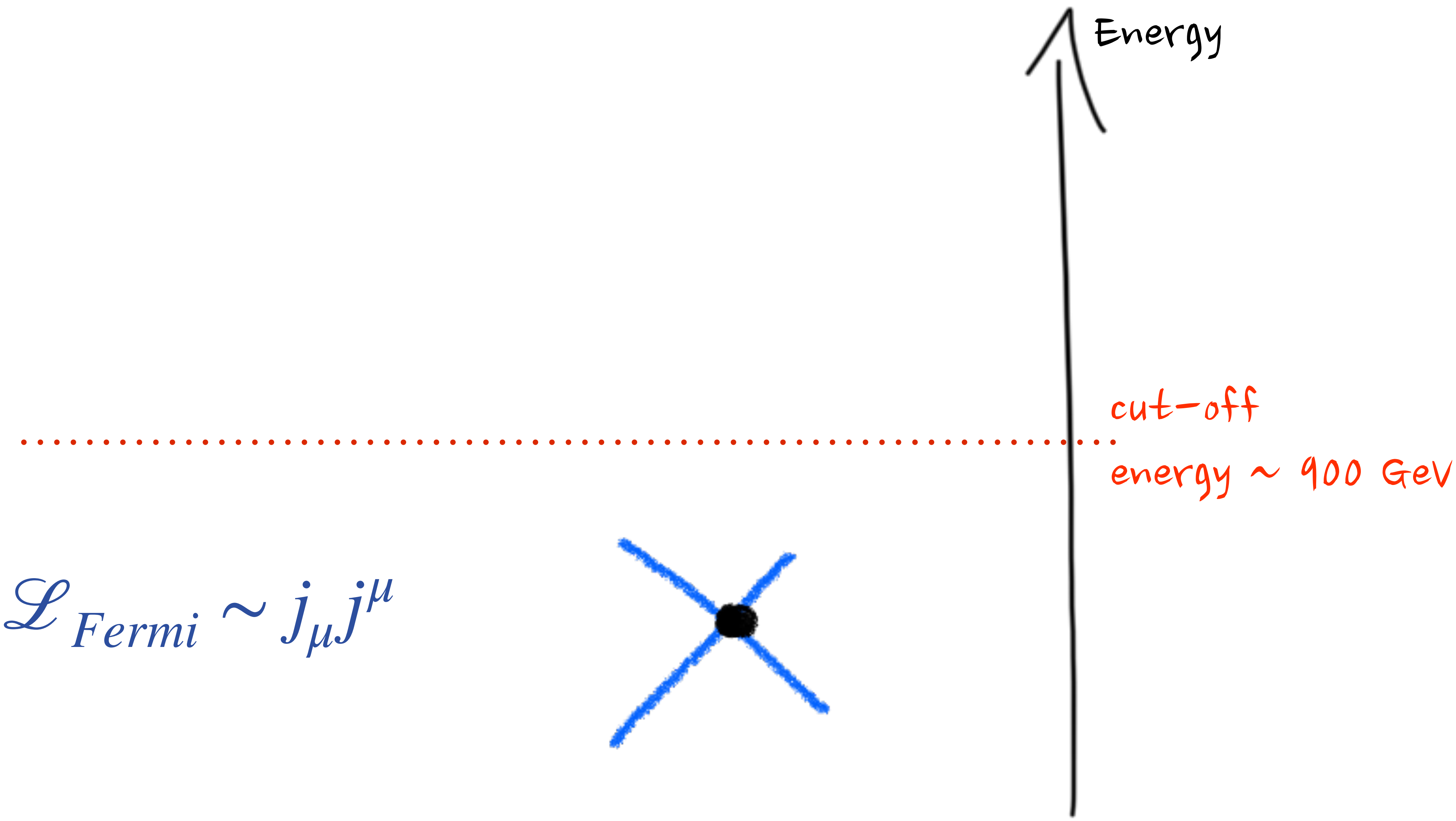


Anomalous quartic gauge couplings
(dim-8 EFT)

VALIDITY OF THE EFFECTIVE FIELD THEORY

Well-known example:

Fermi theory for beta decay domain

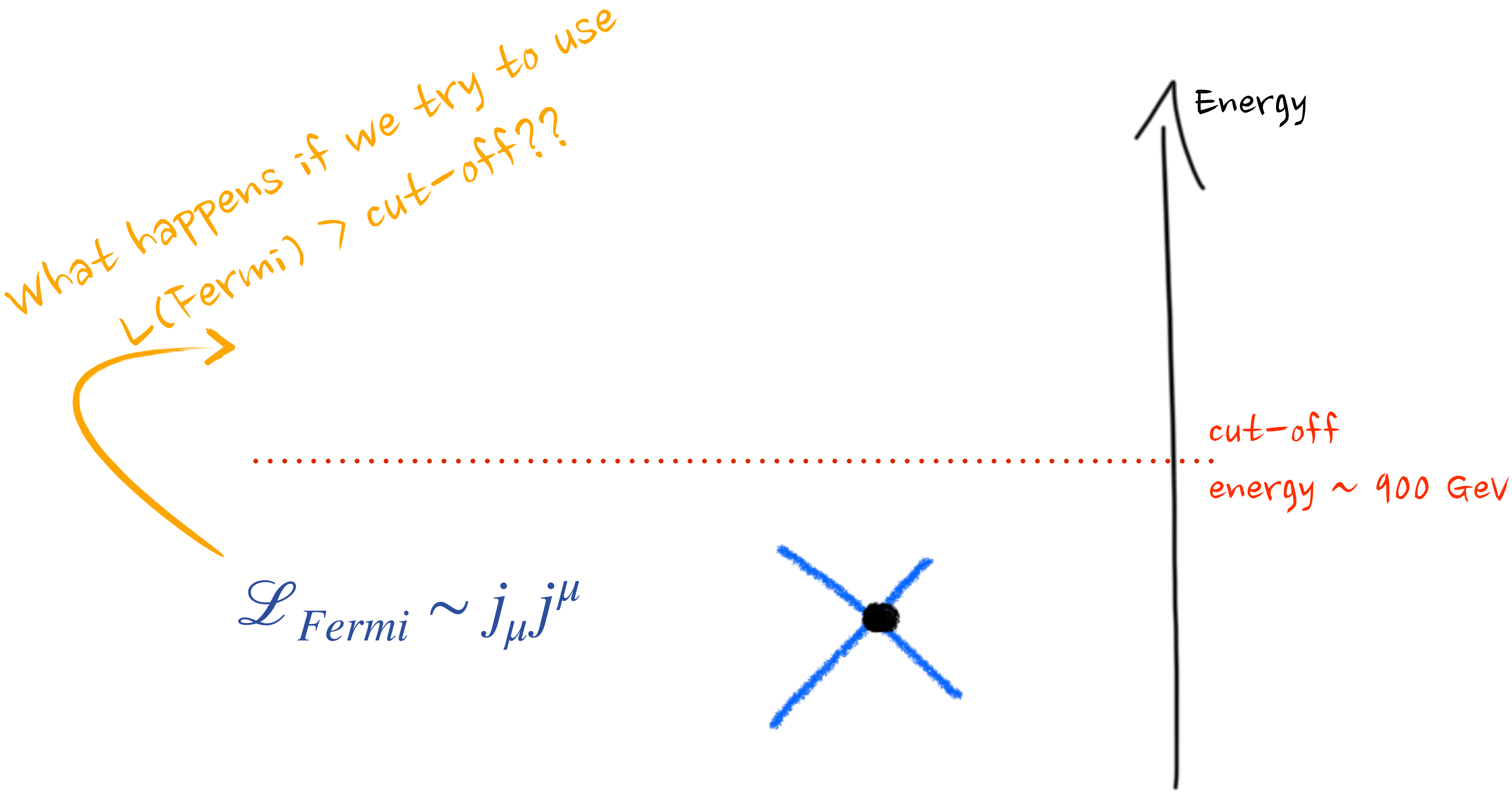


$$\mathscr{L}_{Fermi} \sim j_\mu j^\mu$$

VALIDITY OF THE EFFECTIVE FIELD THEORY

Well-known example:

Fermi theory for beta decay domain

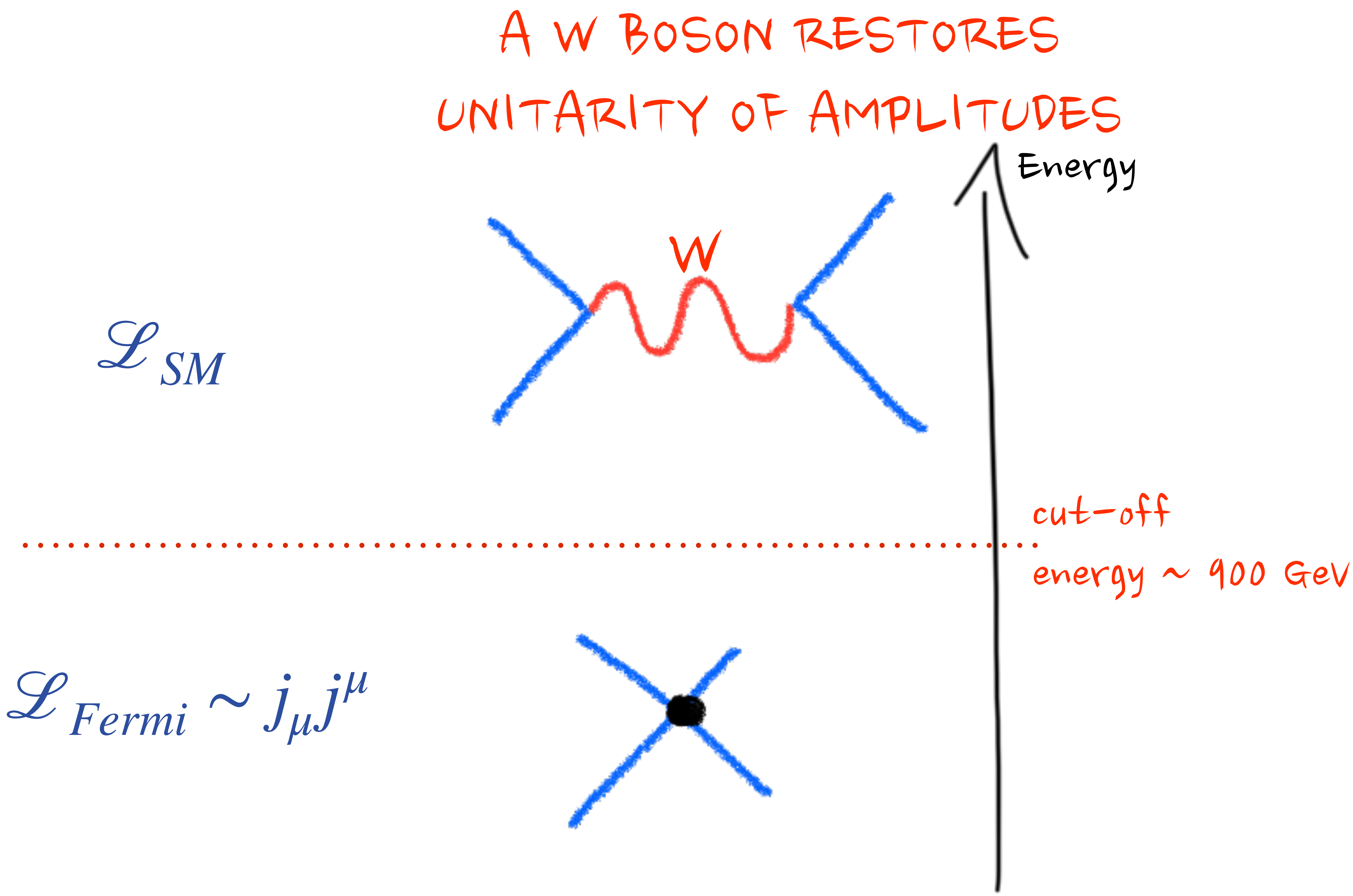


$$\mathcal{L}_{Fermi} \sim j_\mu j^\mu$$

VALIDITY OF THE EFFECTIVE FIELD THEORY

Well-known example:

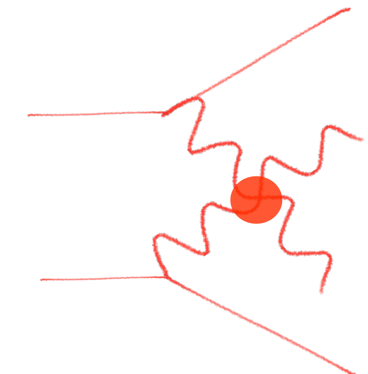
Fermi theory for beta decay domain



VBS AND ANOMALOUS COUPLINGS APPROACH

- Experimentally-simplified EFT: historically, experimental VBS studies targeted dimension-8 EFT couplings as if like dimension-6 didn't exist
- Longitudinal, transverse, and mix operators:

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$



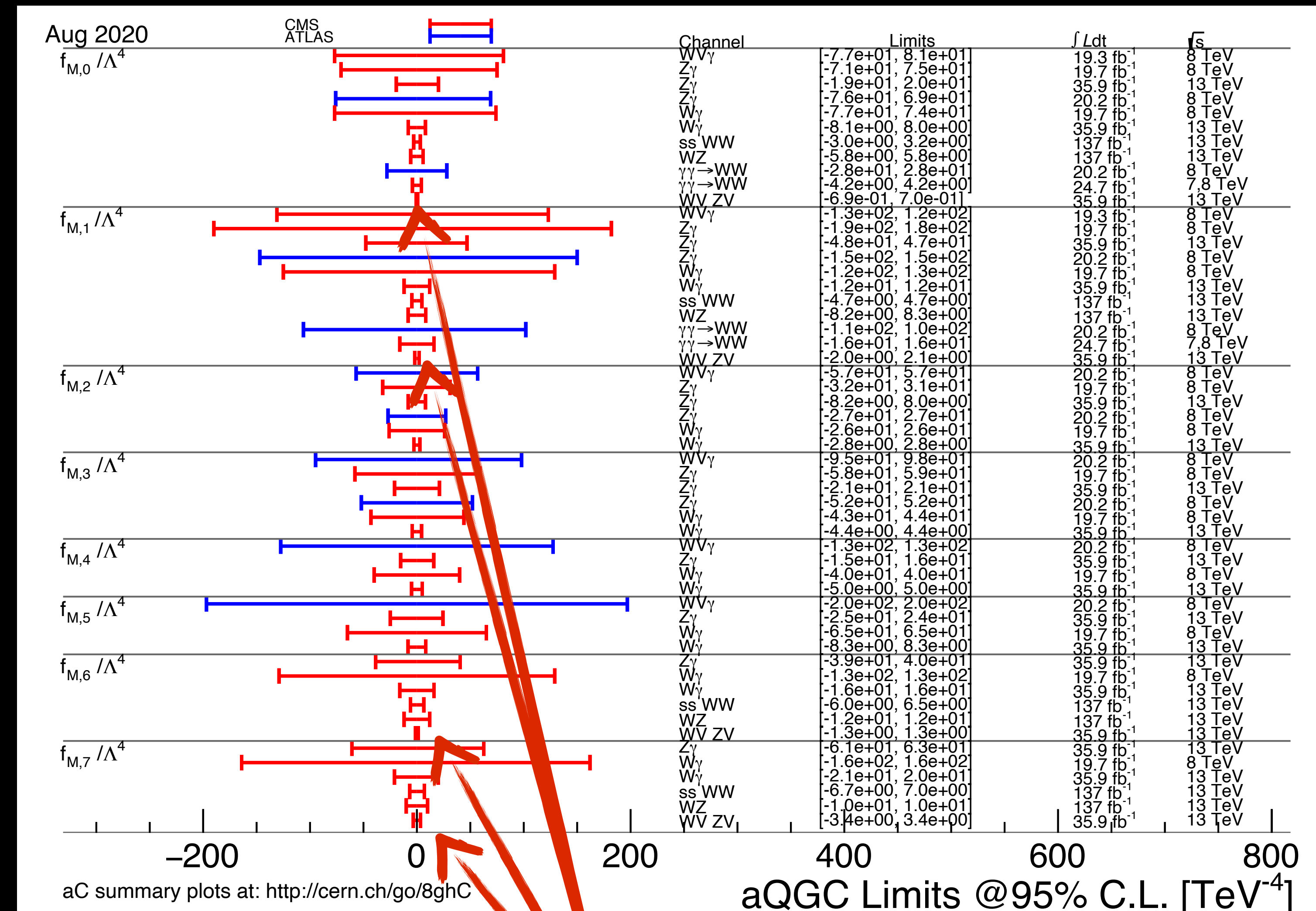
$$\mathcal{O}_{S_0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S_1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S_2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$
$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}\,,$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}\,,$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}\,,$$
$$\mathcal{O}_{T_8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}\,,$$
$$\mathcal{O}_{T_9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}\,.$$

$$\mathcal{O}_{M_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]\,,$$
$$\mathcal{O}_{M_1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]\,,$$
$$\mathcal{O}_{M_2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]\,,$$
$$\mathcal{O}_{M_3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]\,,$$
$$\mathcal{O}_{M_4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}\,,$$
$$\mathcal{O}_{M_5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}\,,$$
$$\mathcal{O}_{M_7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right]\,.$$

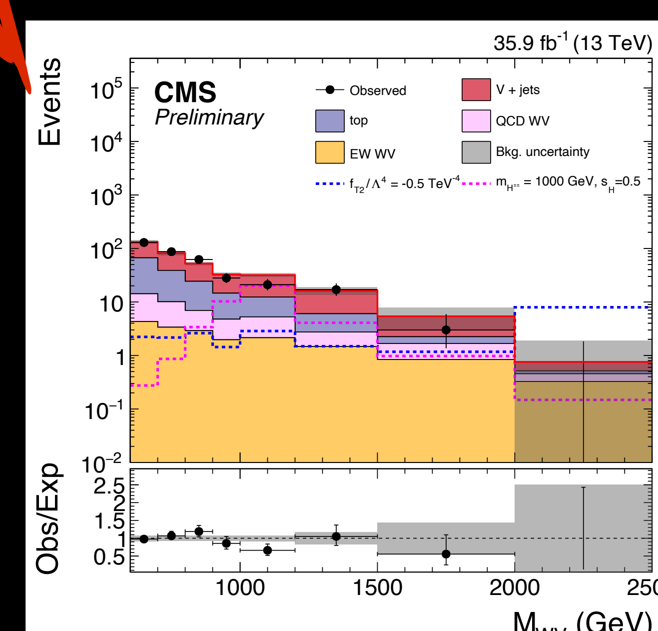
NOT A COMPLETE BASIS FOR THE EFT (NOT LIKE SMEFT DIM-6), BUT ACCOUNTS FOR ALL POSSIBLE ANOMALOUS VVVV INTERACTIONS

DIM-8 EFT, AND UNITARITY BOUNDS



- Enhancement of cross section at large diboson pT and invariant masses
- Focus on boosted topology
  - Semi-leptonic decays set better limits, even with a smaller fraction of Run 2 data!
- All explored aQGC parameters limits compatible with the Standard Model
- Both ATLAS & CMS experiments have set constraints, but often adopting different unitarization schemes!

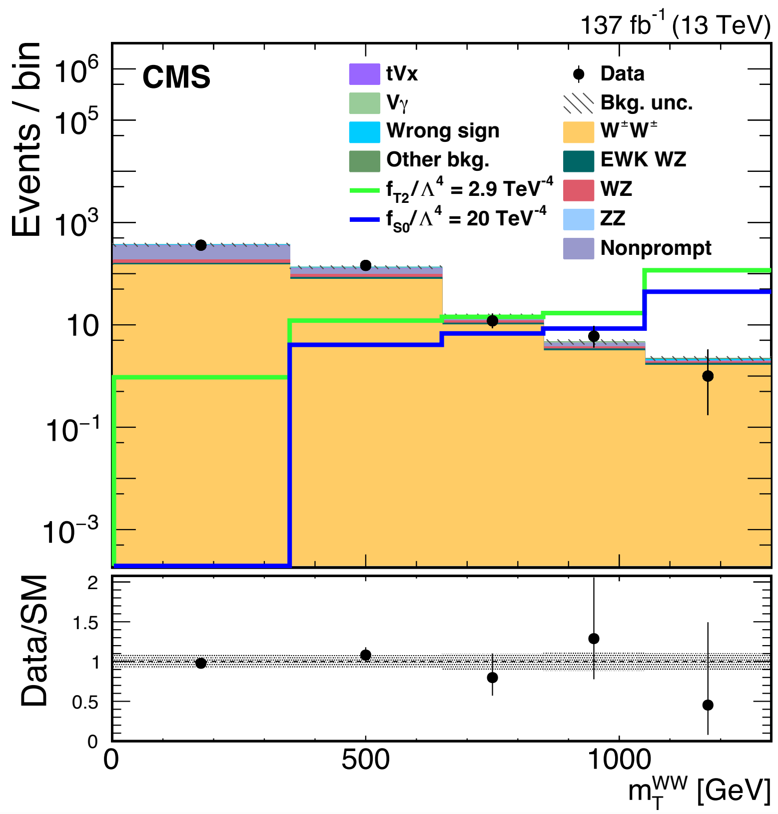
No trivial comparison possible right now



CMS-SMP-18-006, arXiv:1905.07445

AQGC IN SSWW VBS, AND EFT VALIDITY

CMS-SMP-19-012

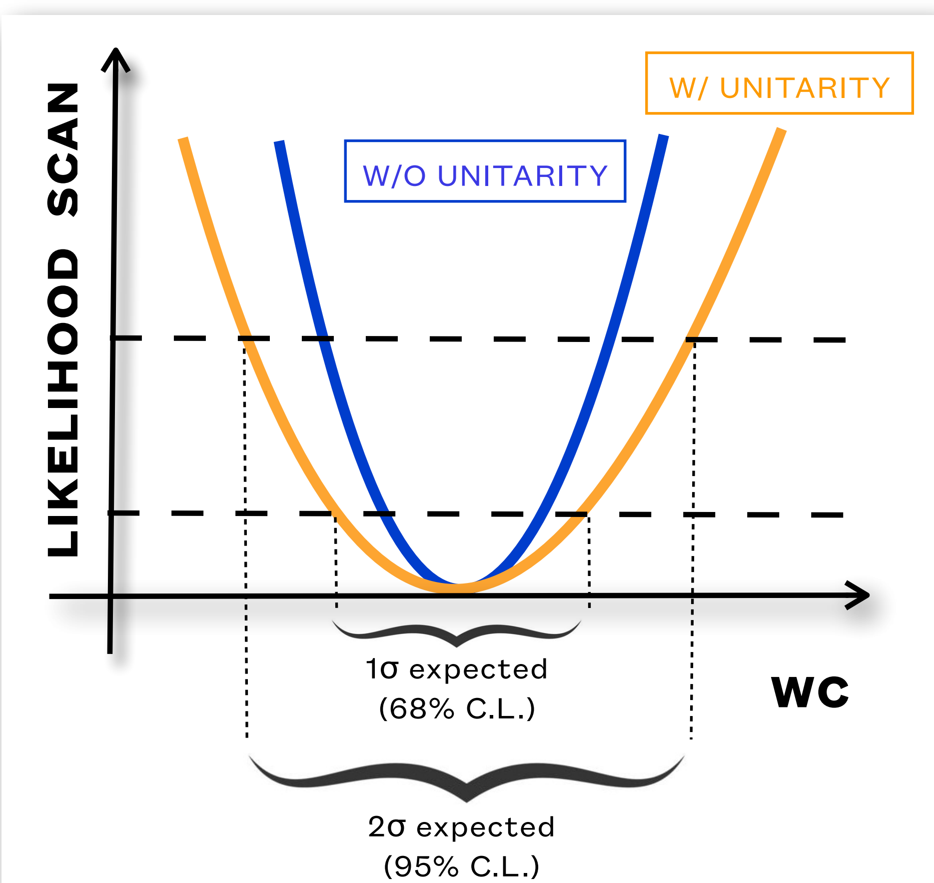


- Transverse masses show high-sensitivity to NP scenarios in EFT approach
- Limits on aQGCs cited **with**, and **without** unitarity bounds

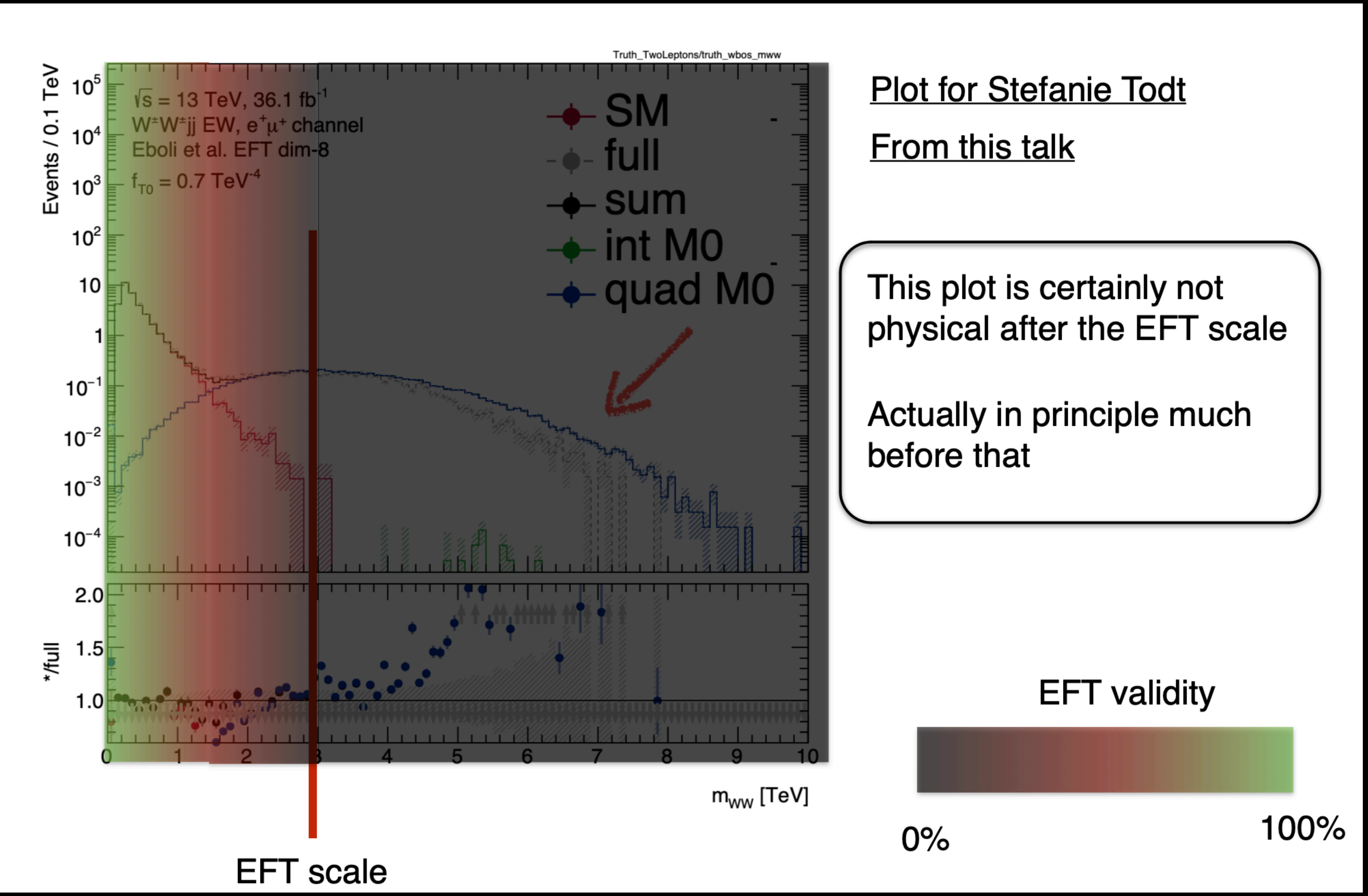
	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

Same limits, but cutting on unitarity violating phase

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]



Events violating unitarity are rejected ~ 80%(WW) & 50%(WZ)



Stolen from Olivier Mattelaer

UNITARITY VIOLATION

HOW ARE WE DEALING WITH THIS?

Experimental approach

We do not consider unitarity violation

We monitore the issue and report how unitarity affects measurement
(based on unitarization schemes)

We apply unitarization schemes
(ATLAS)

Unitarization procedure

Cut-off

limits the theory up to the unitarity violation

K-matrix unitarization

Effectively somewhat like a very broad resonance

unitarity imposed at partial wave level

Form Factors

smoother suppression with a continuous

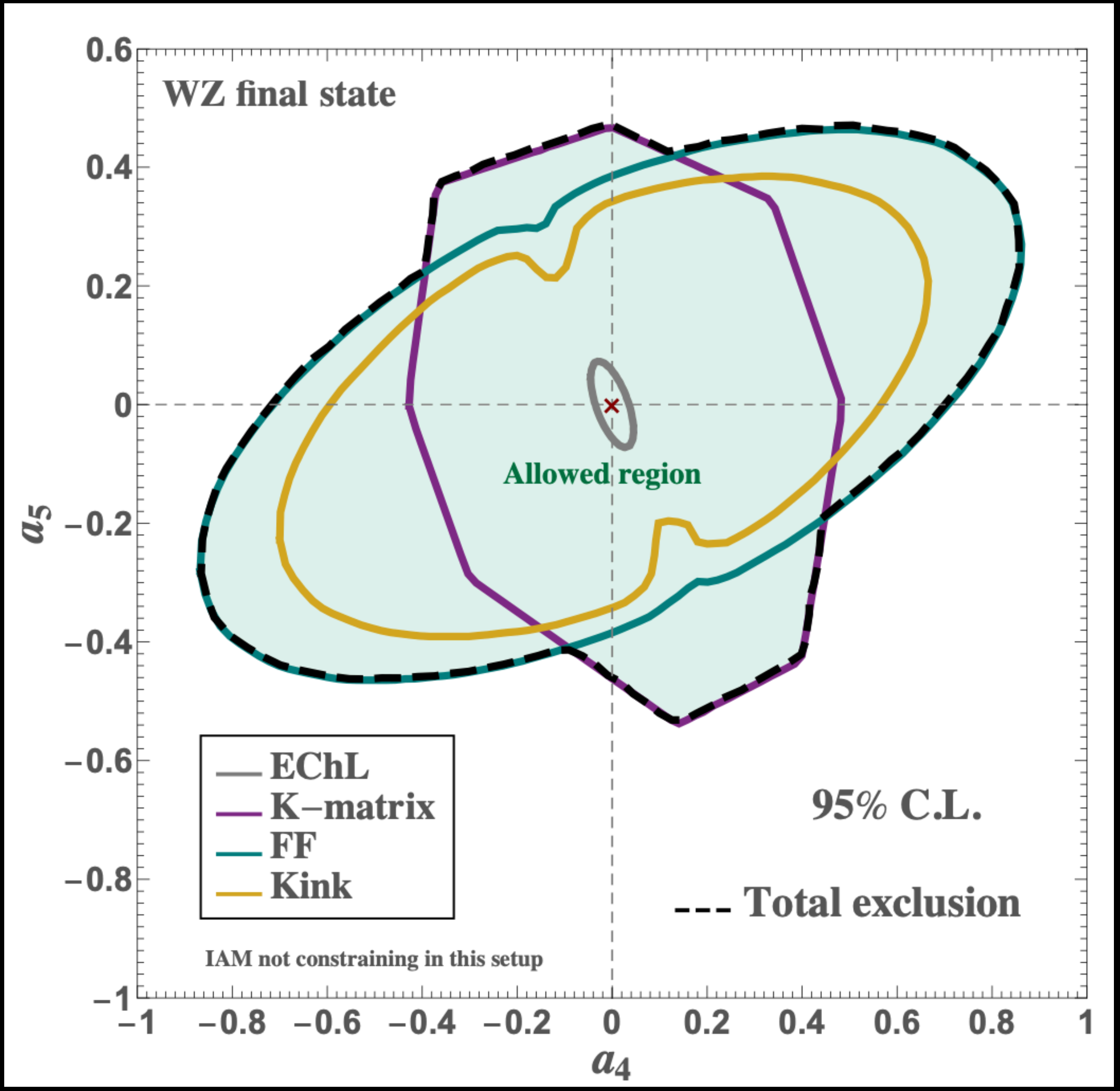
+ many other (not really used): T-matrix, Kink, …

UNITARITY VIOLATION

Different unitarization procedures lead to different predictions:

Bounds on non-unitary theory can over-constrain (& viceversa)

$\sigma_{\text{EChL}} > \sigma_{\text{K-matrix}} > \sigma_{\text{Kink}} > \sigma_{\text{FF}}$



[Garcia-Garcia, Herrero, Morales arXiv:1907.06668]

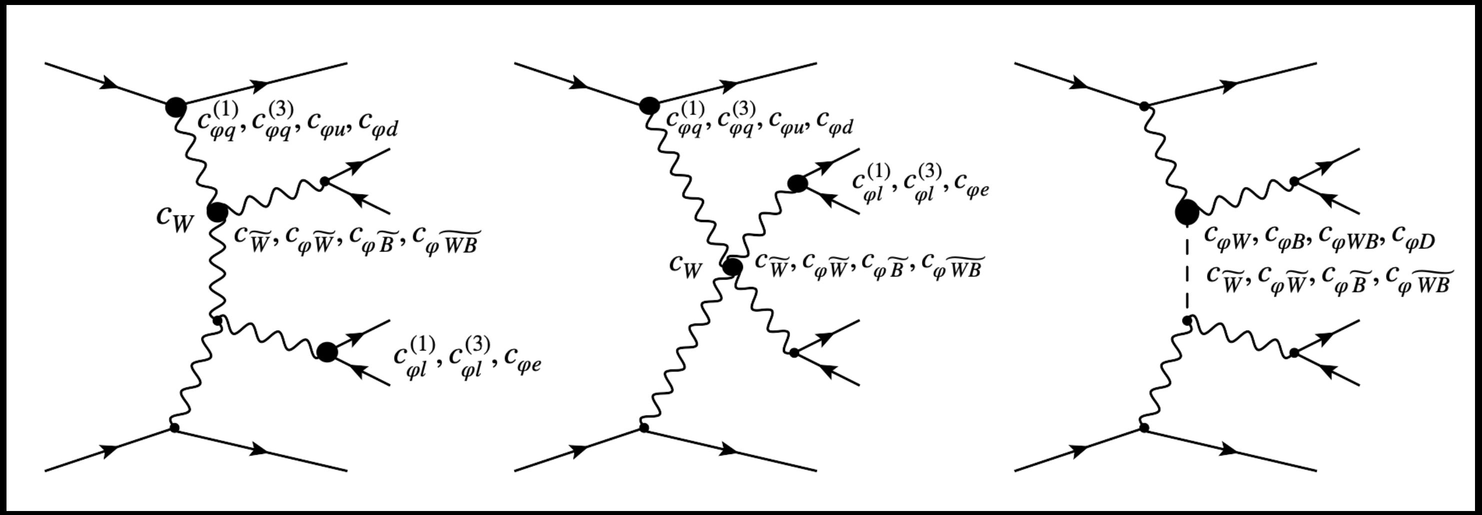
FINAL REMARKS

TOWARDS A GLOBAL EFT

VBS SENSITIVITY TO DIMENSION-6 EFT

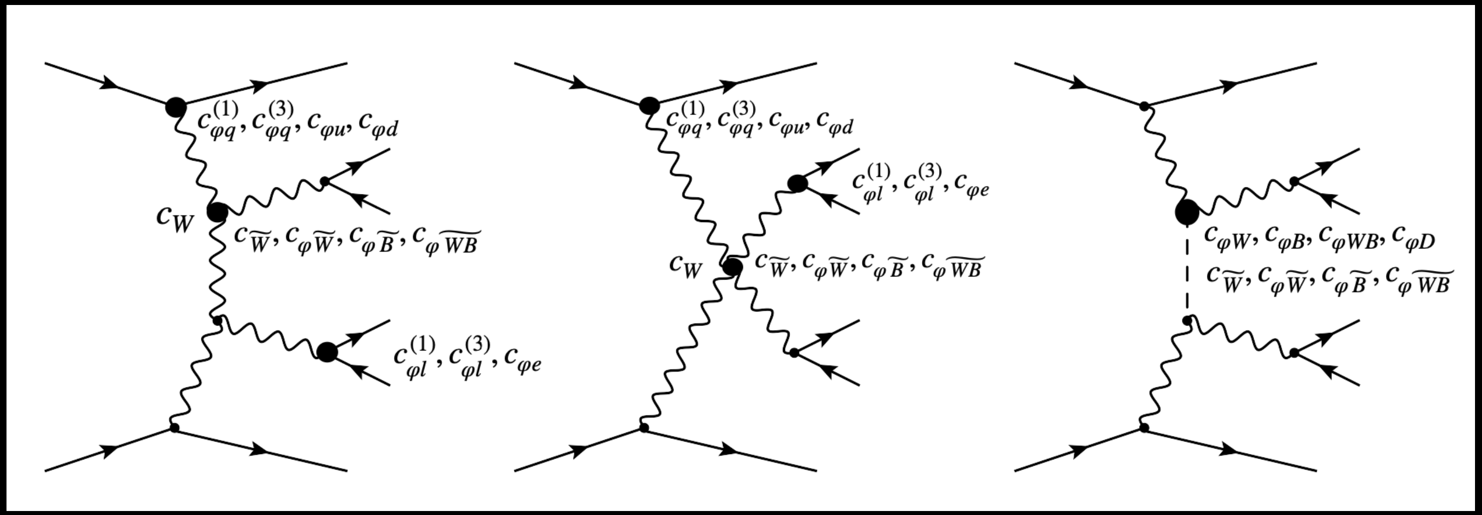
VBS SENSITIVITY TO DIMENSION-6 EFT

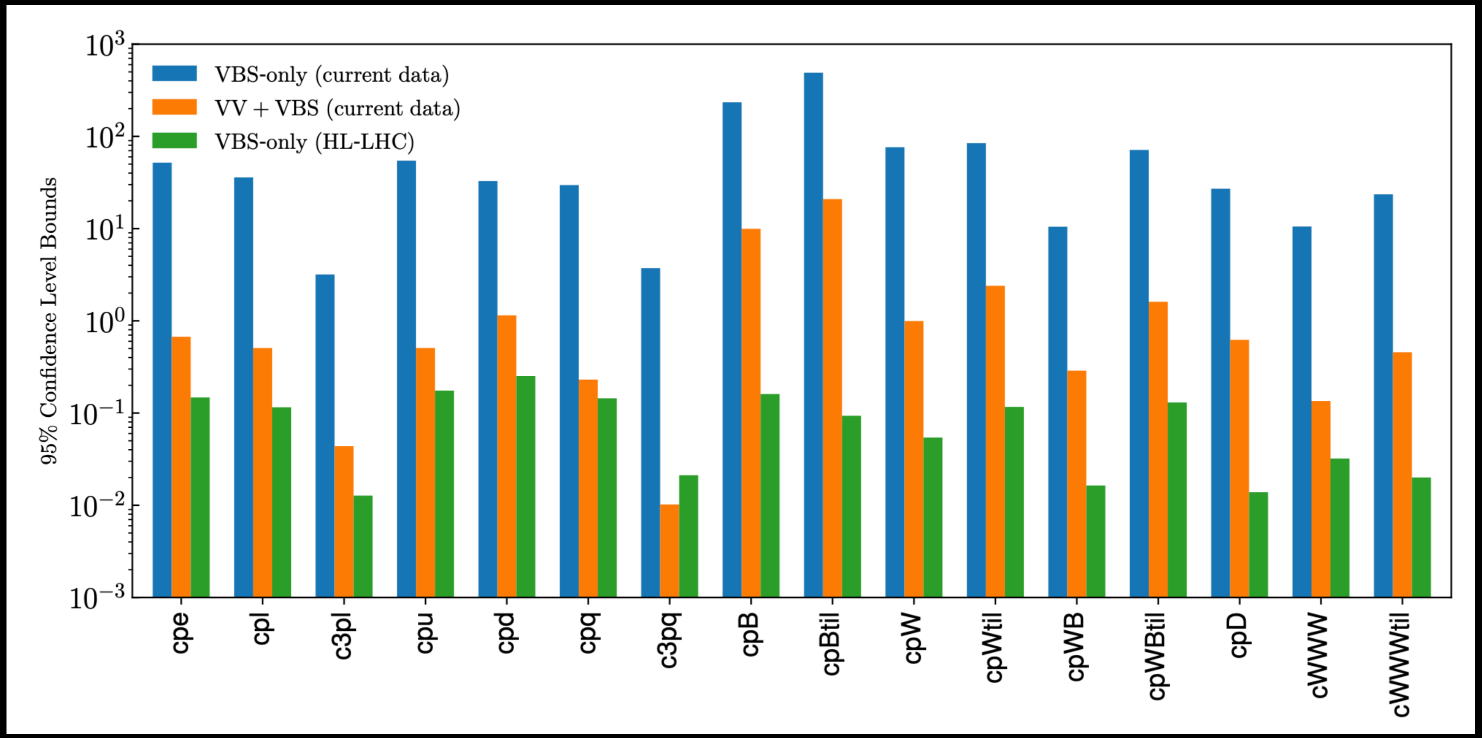
- Only recently dimension-6 EFT sensitivity was tested in VBS processes (arxiv.2101.03180 , arxiv.2108.03199)



VBS SENSITIVITY TO DIMENSION-6 EFT

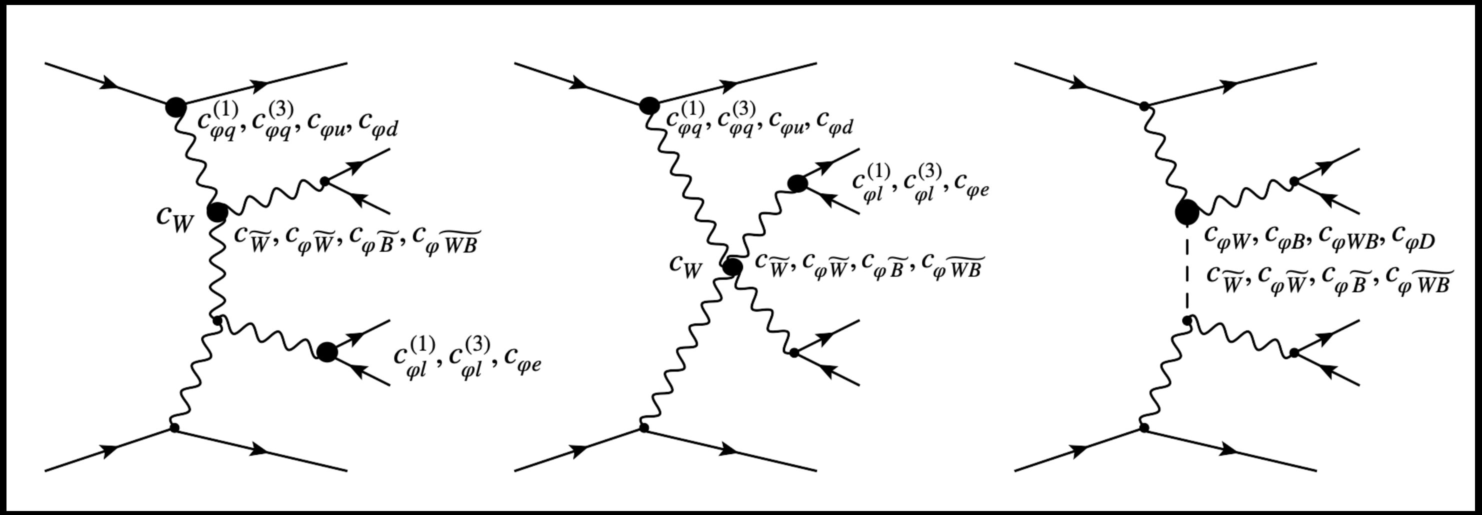
- Only recently dimension-6 EFT sensitivity was tested in VBS processes (arxiv.2101.03180 , arxiv.2108.03199)
- VBS can improve sensitivity to several dim-6 SMEFT coefficients

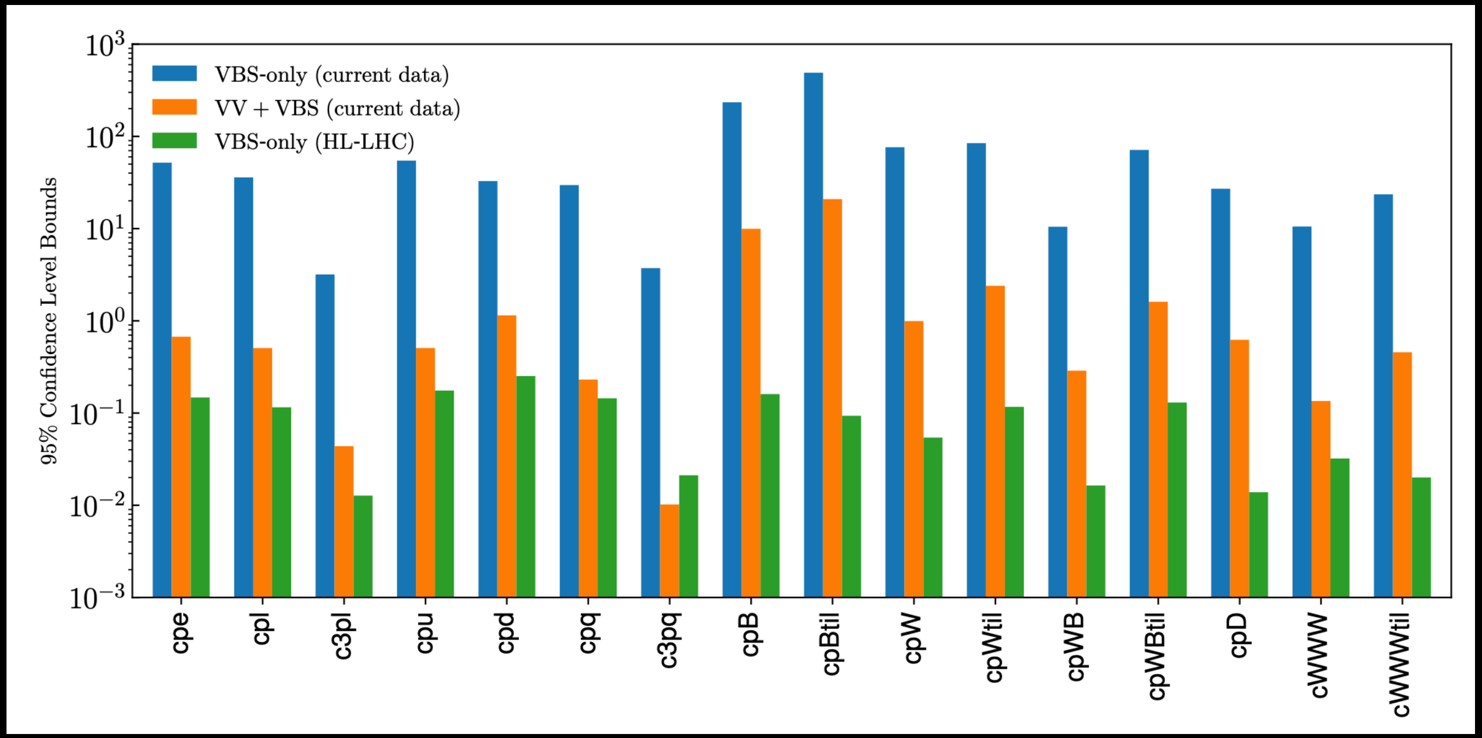




VBS SENSITIVITY TO DIMENSION-6 EFT

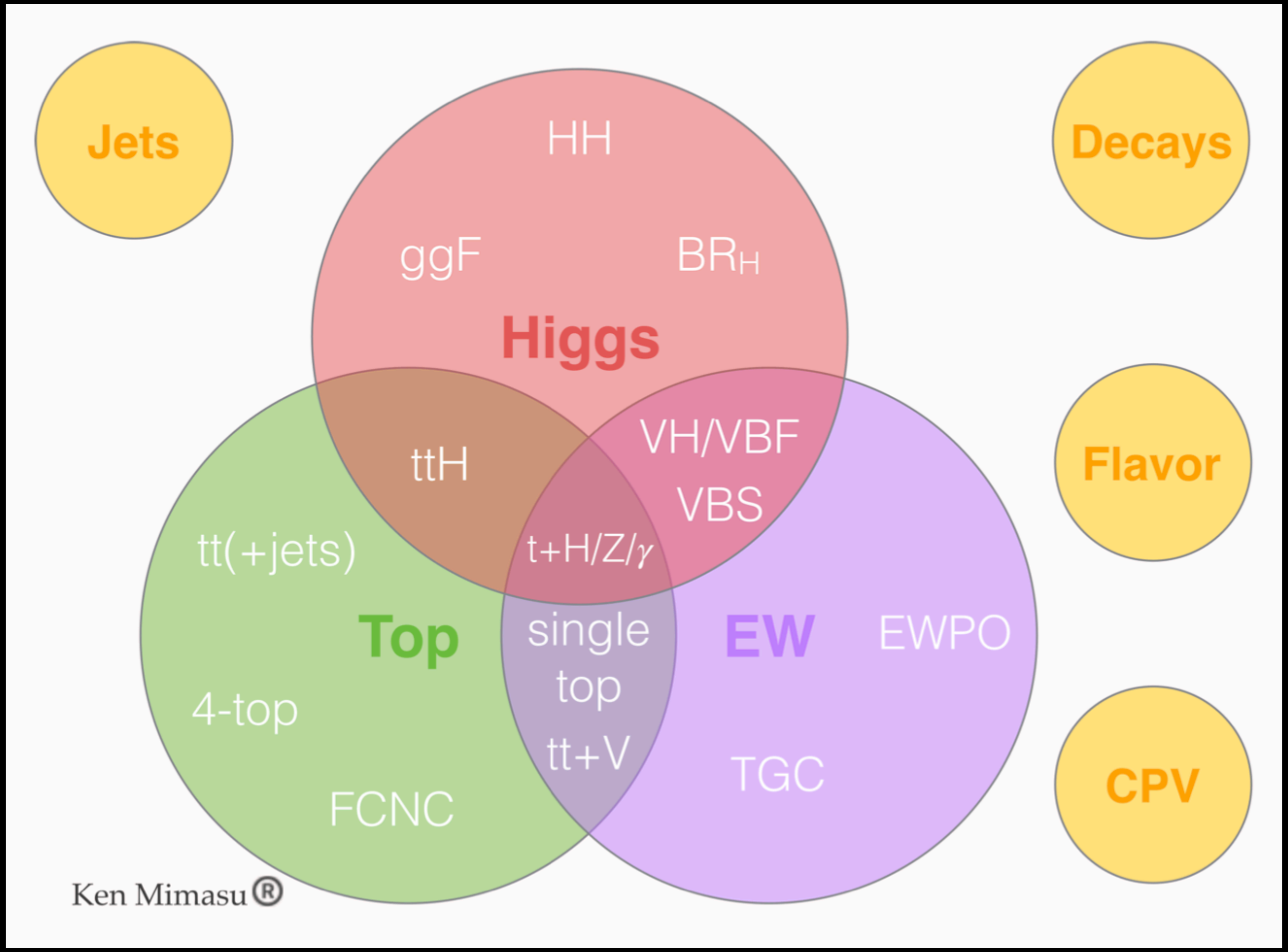
- Only recently dimension-6 EFT sensitivity was tested in VBS processes (arxiv.2101.03180 , arxiv.2108.03199)
- VBS can improve sensitivity to several dim-6 SMEFT coefficients
- EFT can be plugged in all vertices! Complexity increases!
- SMEFT dim-6 basis extremely solid and well developed !
- Unitarity bounds almost not relevant





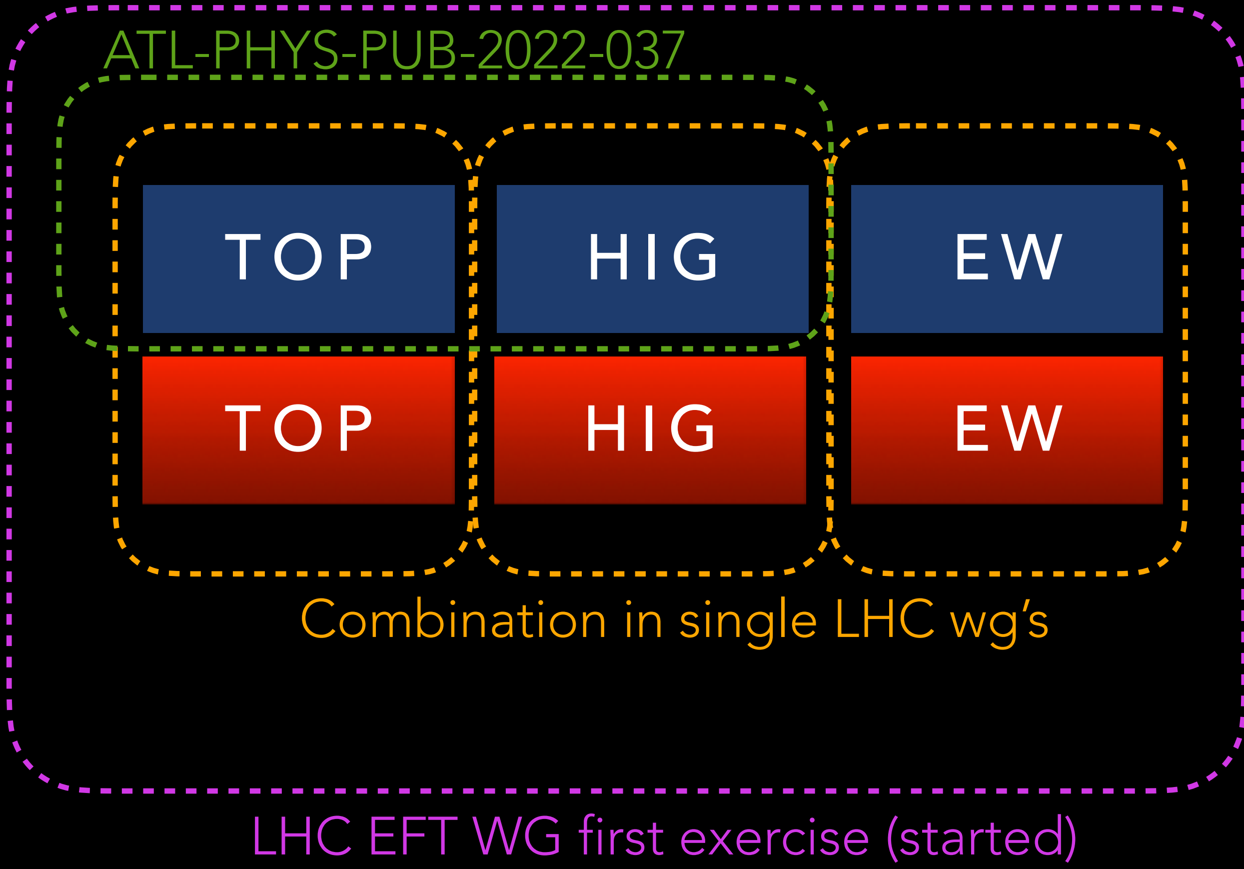
VBS SENSITIVITY TO DIMENSION-6 EFT

- Only recently dimension-6 EFT sensitivity was tested in VBS processes (arxiv.2101.03180 , arxiv.2108.03199)
- VBS can improve sensitivity to several dim-6 SMEFT coefficients
- EFT can be plugged in all vertices! Complexity increases!
- SMEFT dim-6 basis extremely solid and well developed !
- Unitarity bounds almost not relevant
- Complementary to direct searches. Will become more relevant in next Runs.



- key idea: implement a comprehensive, agnostic program
- Allow combination with non-LHC measurements. "global likelihood"

TOWARDS A GLOBAL ANALYSIS FROM LHC EXPERIMENTS

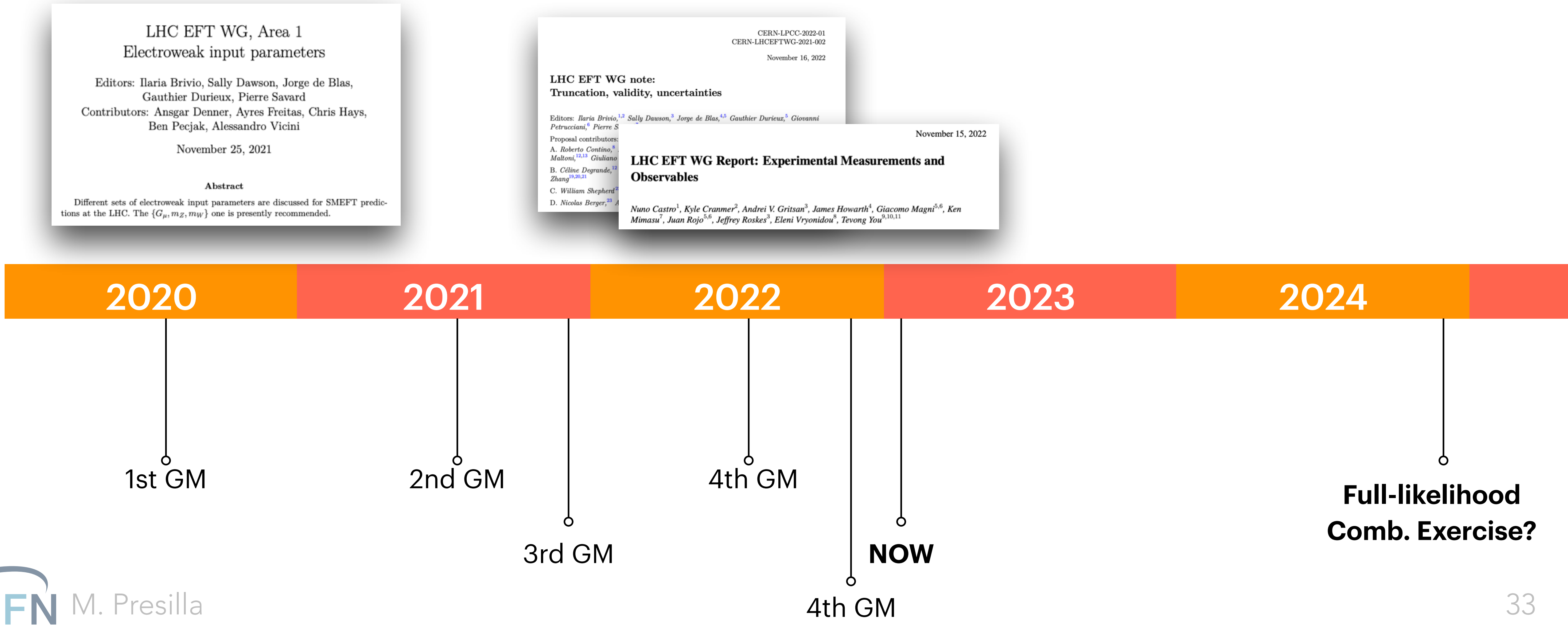


Common assumptions:
Warsaw basis, dim-6, common input scheme (mW), U3l flavour assumption arXiv:2111.12515...

- Formation of LHC EFT WG
- Coordination between existing LHC WGs: Higgs, Top and Electroweak
- Ultimate goal: global EFT analyses
- 6 areas of activity
    1. EFT formalism
    2. predictions and tools
    3. experimental measurements and observables
    4. fits and related systematic uncertainties
    5. benchmark scenarios from UV models
    6. flavor physics

FUTURE PLANS AND INTERMEDIATE STEPS

- 4 write-ups public from the wg, addressing several open issues in EFT measurements
- Incredibly fast ramp-up of Area 4 techniques, thanks also to developments of tools and interaction with other Areas for conventions and studies
- Full-experimental vs. χ2-simplified fits and assess the feasibility for a subset of processes



SUMMARY

- **Future speaks about statistics and precision, open issues of fundamental physics can be addressed there… lots of interest and activities**
- Highlights from CMS measurements in VBS: consistency tests of the EW sector of SM at the LHC
- **Many new analyses under implementation**
  - Leptonic decays of V bosons involved much powerful tool for SM EW measurements
  - Semi-leptonic targeted mostly to BSM, now also possible to measure EW
- VBS powerful enough to infer on the presence of **new physics in a "UV-agnostic" way**
- Huge theoretical & experimental progress behind all these measurements
  - Fine control of background sources in control regions
  - Exploit machine learning techniques
  - Importance of NLO calculations (up to ~15% effect on XS!)
- Run3/4 are ahead, plus **many interesting results from Run 2 are yet to come!**

Backup.

-THANK YOU FOR LISTENING!