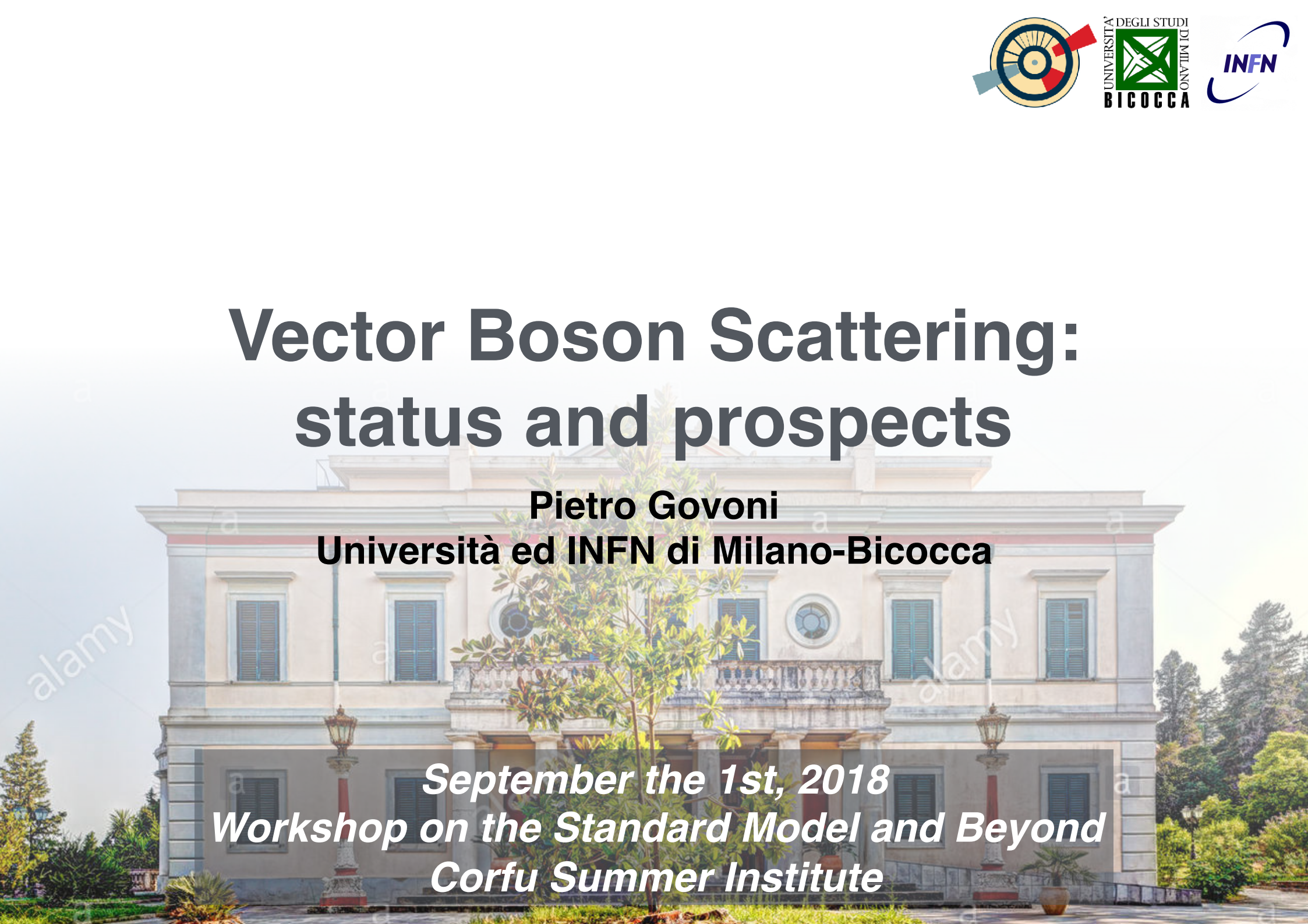
Vector Boson Scattering: status and prospects

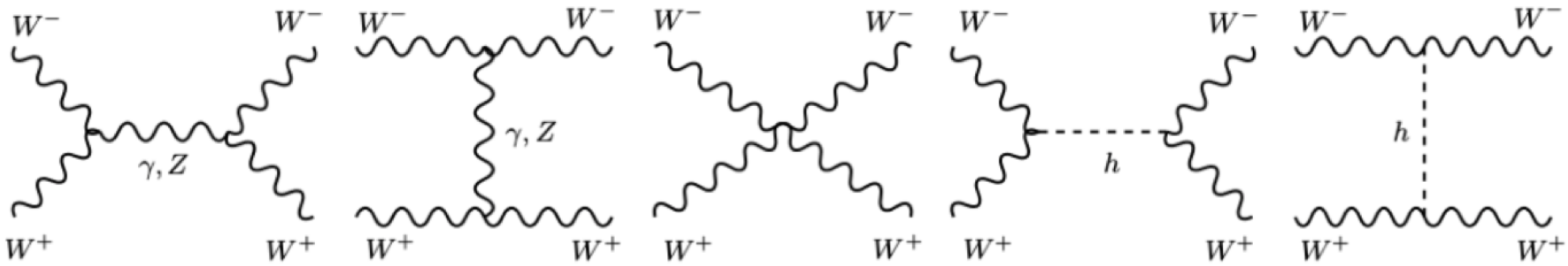
Pietro Govoni
Università ed INFN di Milano-Bicocca



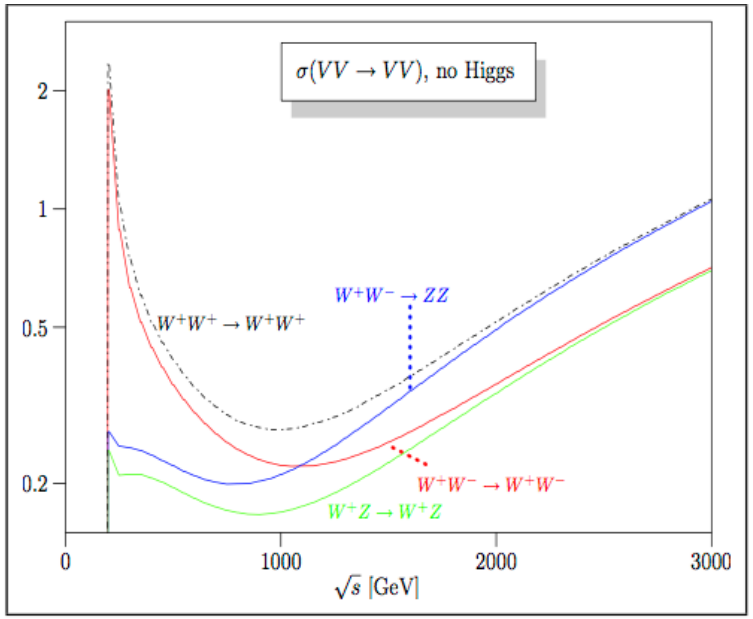
September the 1st, 2018
Workshop on the Standard Model and Beyond
Corfu Summer Institute

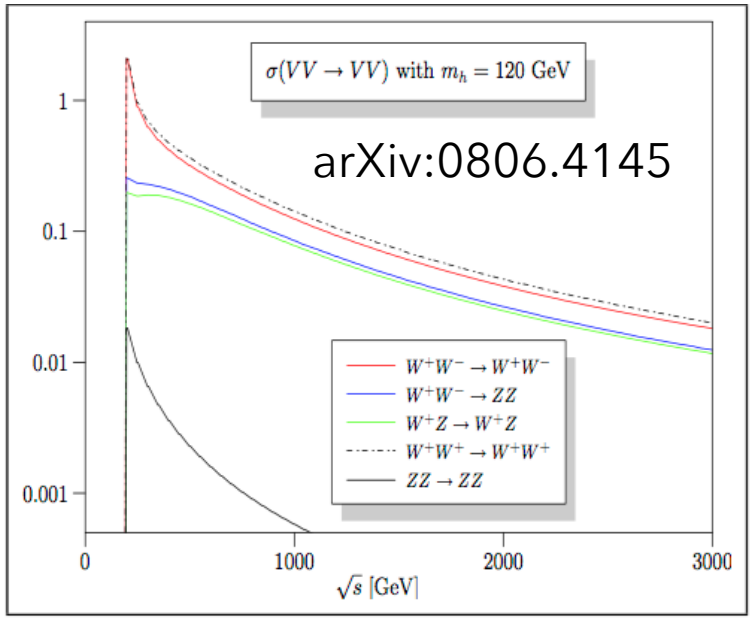
Vector Boson Scattering

- Unitary process in the Standard Model, thanks to the Higgs mechanism



$$\mathcal{M}_{gauge} \simeq i\frac{g^2}{4M_W^2}[s+t]\,, \quad \mathcal{M}_{Higgs} \simeq -i\frac{g^2}{4M_W^2}[s+t]$$



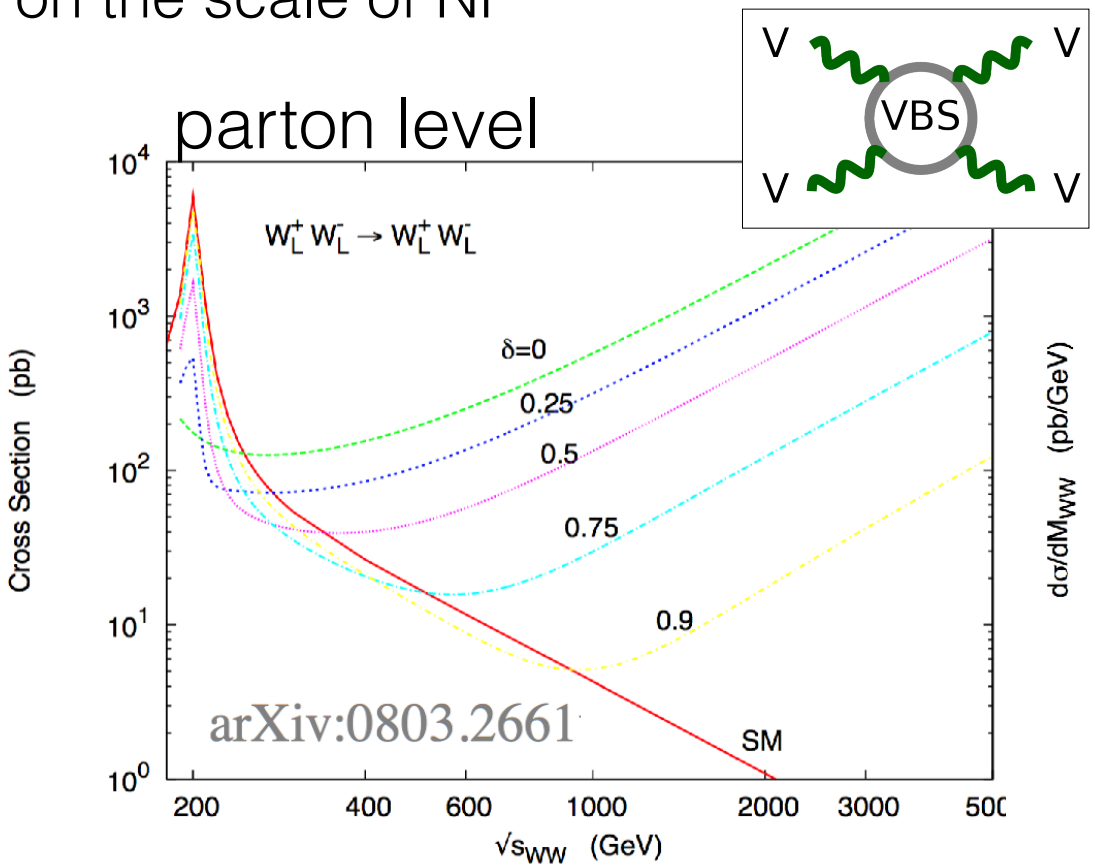


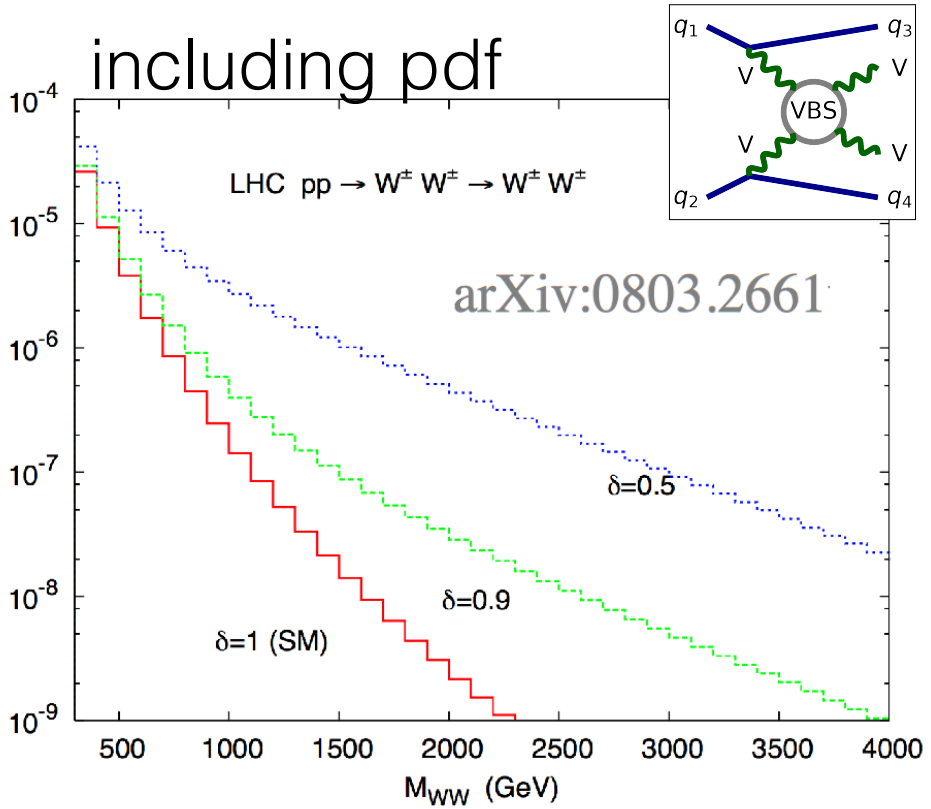
in case of anomalies

- if the delicate equilibrium is perturbed:

$$\mathcal{M}_{gauge} \simeq i\frac{g^2}{4M_W^2}[s+t]\,, \quad \mathcal{M}_{Higgs} \simeq -i\frac{g^2}{4M_W^2}[s+t] \ (\delta)$$

- any deviations signal **new physics in a model-independent way** and hints on the scale of NP





effective field theory

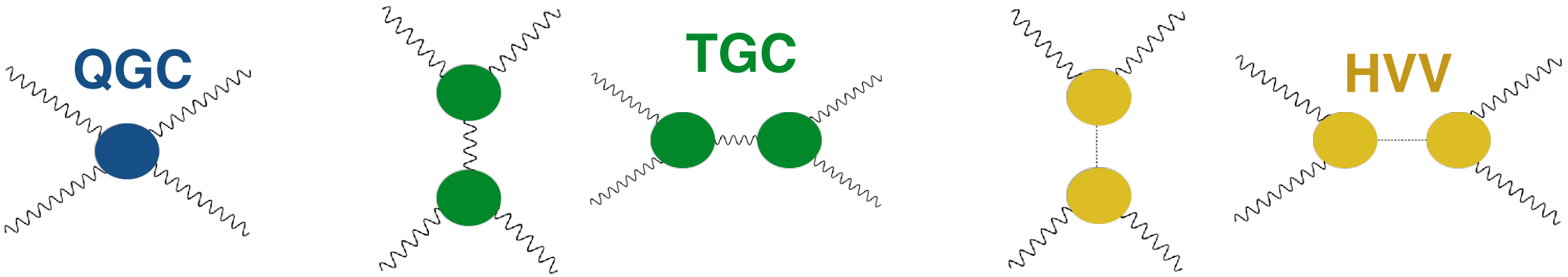
- add to the SM Lagrangian additional BSM terms
- generic **low-energy parameterisation of an unknown model** that would become apparent at (too) high energies

Dim 6 **Dim 8**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

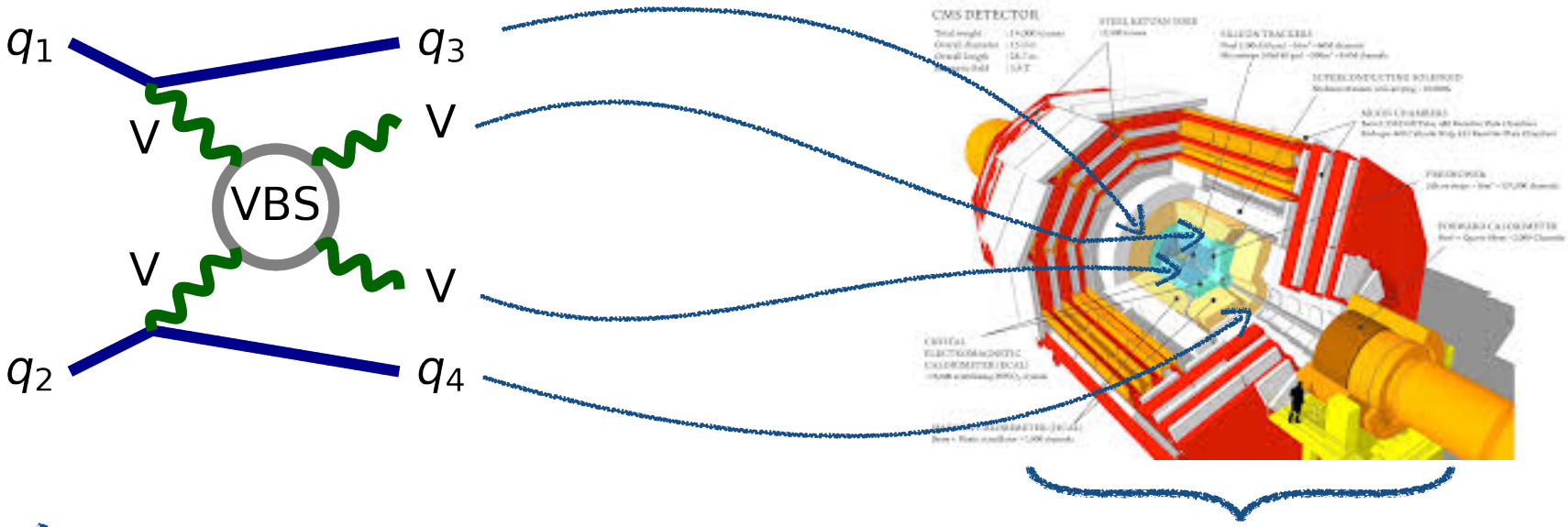
Pure Higgs field | **Pure Field-strength tensor** | **Mixed Higgs-field-strength**

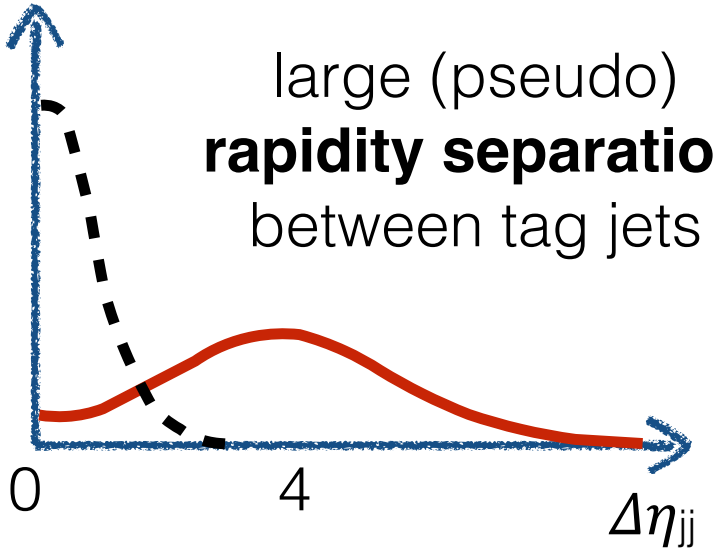
- simplistic realisation: choose a basis and associate operators to vertices in form of anomalous couplings



the VBS signature at LHC

- **signal**: six fermions final state at leading order $\mathcal{O}(\alpha^6)$





large (pseudo)
rapidity separation
between tag jets

low QCD activity
between tag jets,
since there's no color
flow between the two
protons

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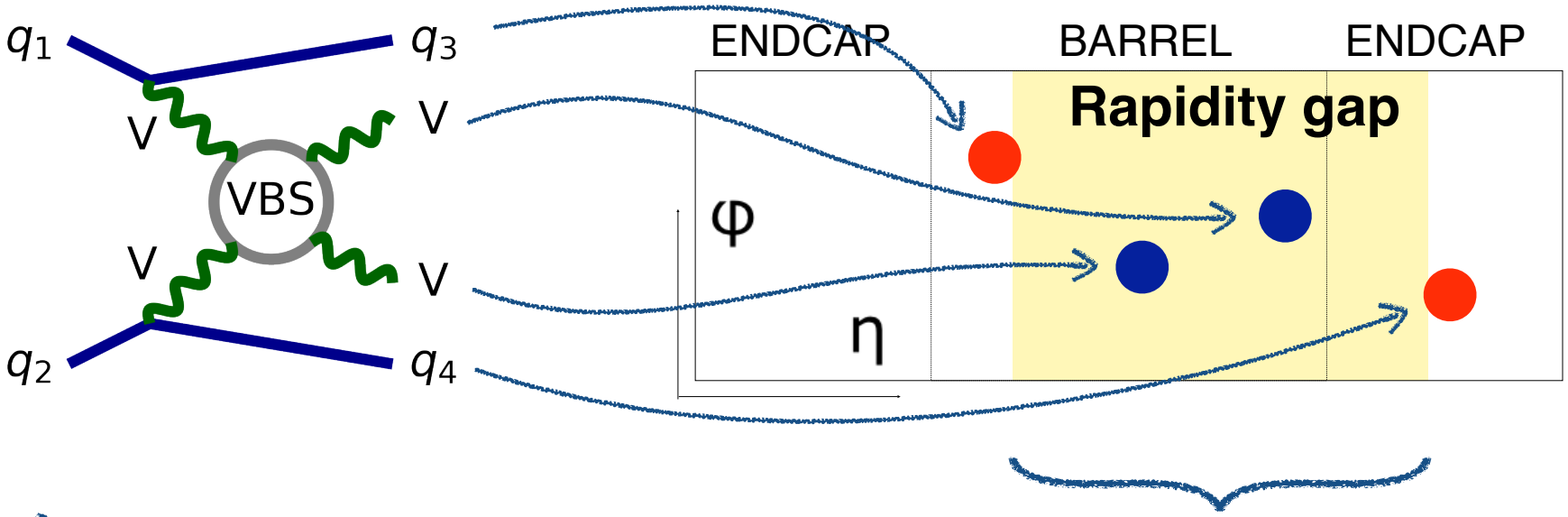

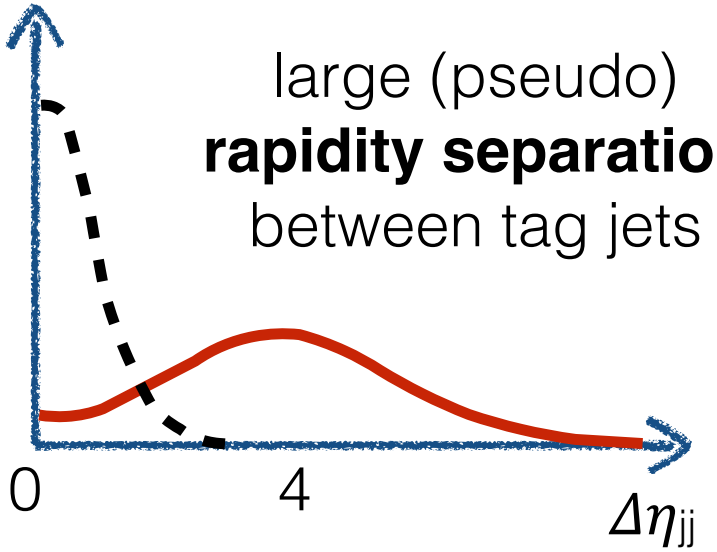

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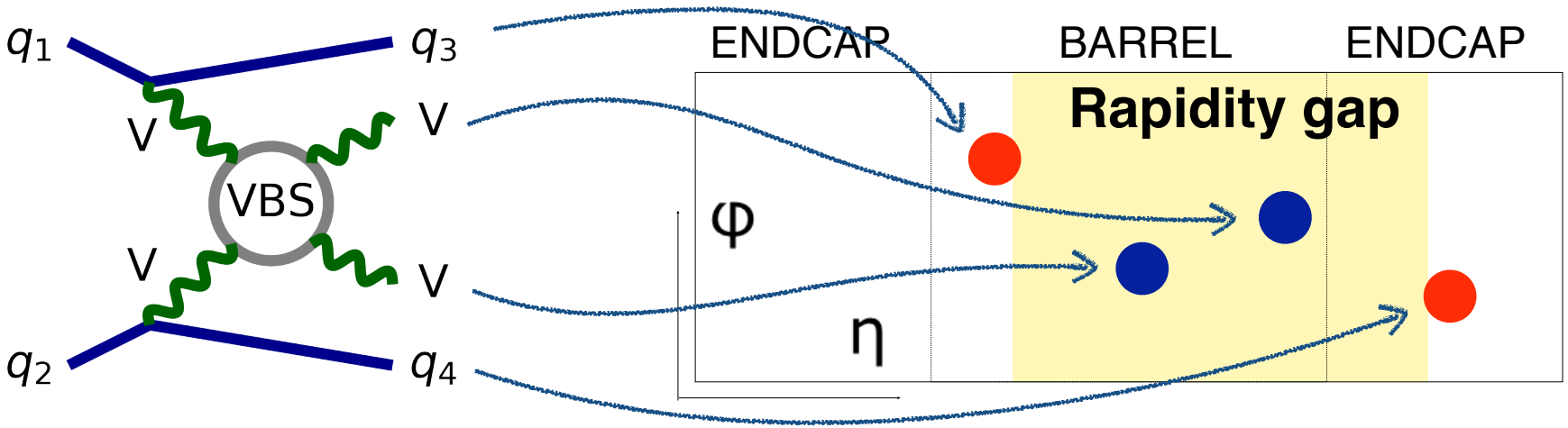
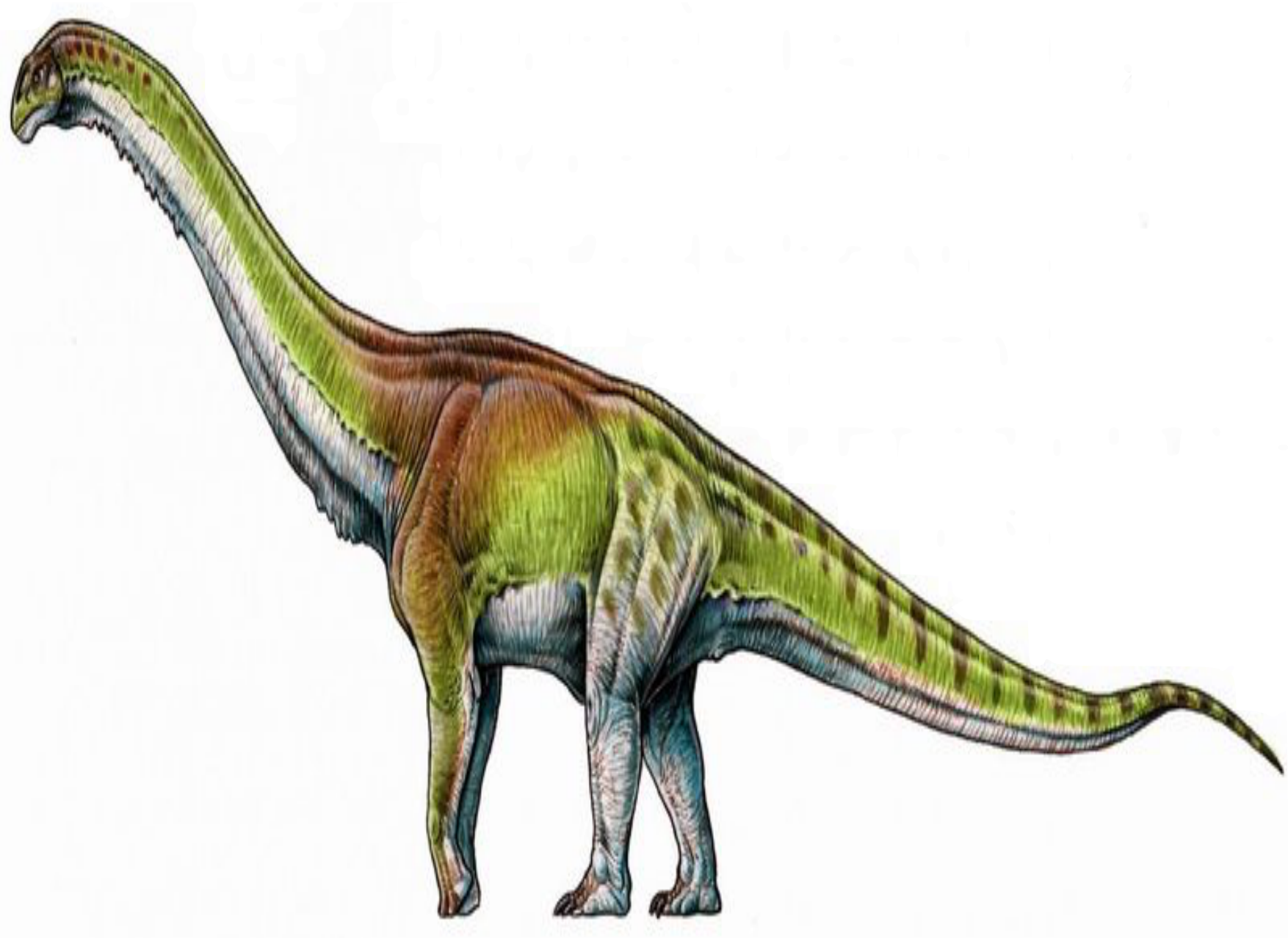
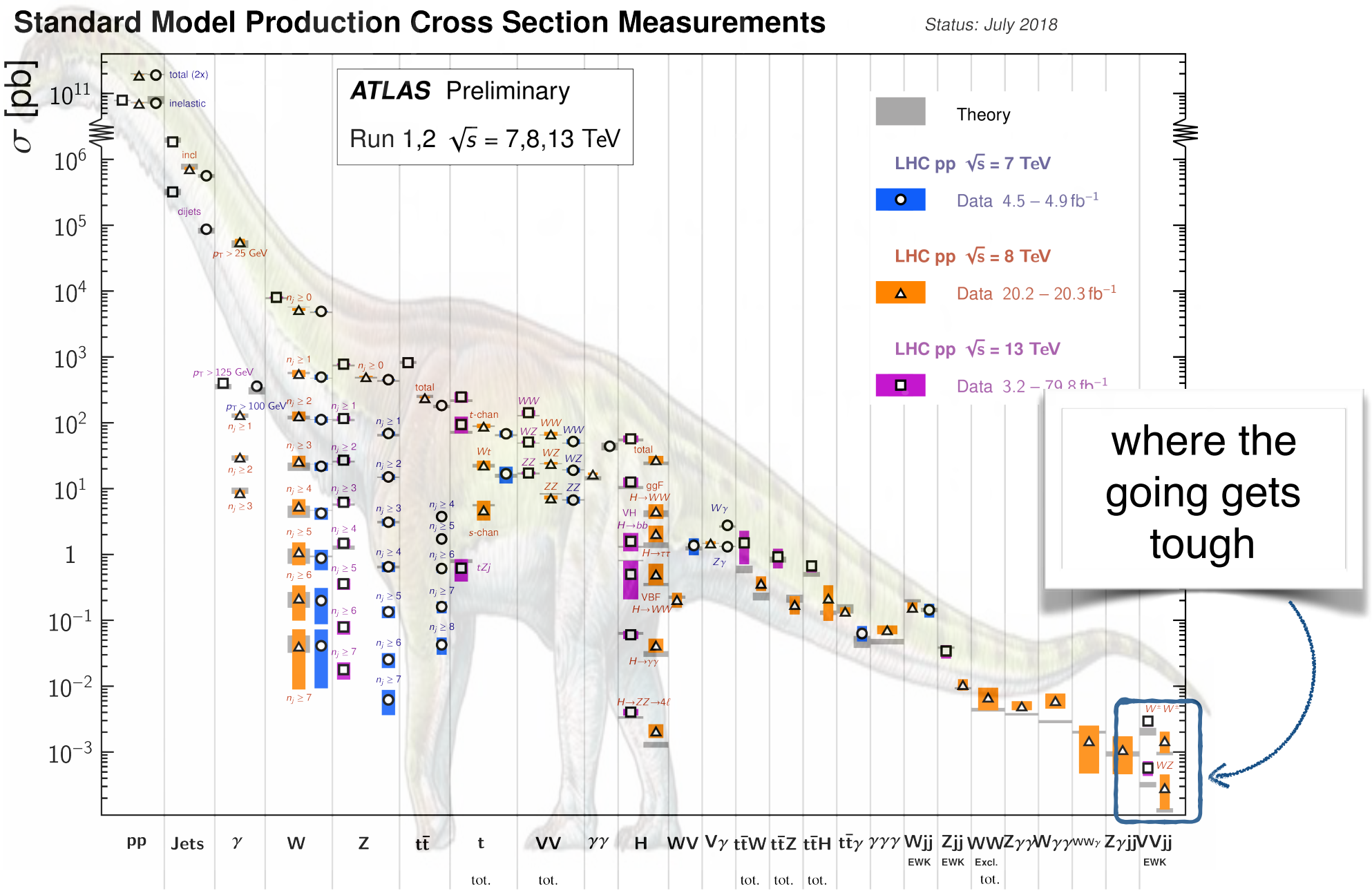


- irreducible **background**: at LO $\mathcal{O}(\alpha^4\alpha_S^2)$
- already at LO interferes with signal: $\mathcal{O}(\alpha^5\alpha_S)$
  - at first approximation evaluate it with MC and quote an uncertainty
  - provide a **combined EW+QCD** measurement
- **reducible** bkg due to mis-ID of final state particles (e.g. $\mathcal{O}(\alpha^2\alpha_S^4)$)
- significant systematic uncertainties from **jet energy reconstruction and background modelling**

the statistics challenge



the statistics challenge

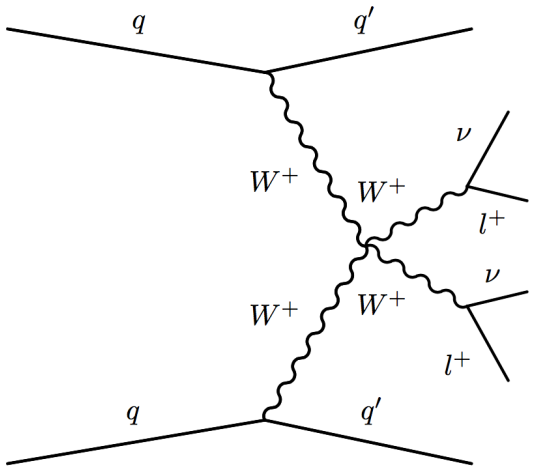


same-sign WW

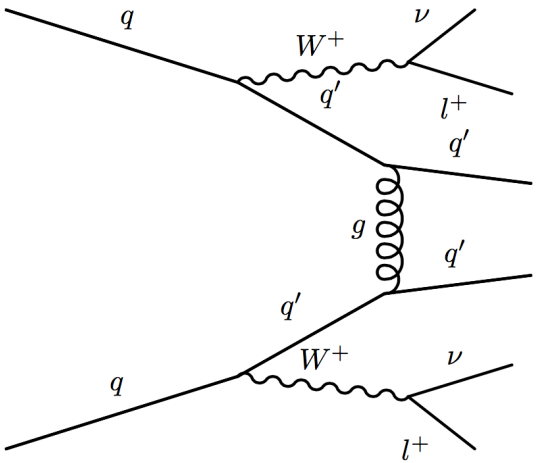
see Stefanie Todt's talk for ATLAS results

- **EW production** of two same-sign charged leptons
  - $\sigma_{(\text{fid})} < 5$ fb @ 13 TeV with $e^{\pm}$ or $\mu^{\pm}$ in final state
- **low cross-section, low background**
- **backgrounds**
  - non-prompt: jet identified as charged leptons, and leptons from hadron decays (data-driven)
  - ≥2 prompt SS charged leptons

	ATLAS	CMS
third lepton veto	applied	applied
B-tagging veto	applied	applied
$E_T^{miss} >$ [GeV]	30	40
$m_{\ell\ell} >$ [GeV]	20	20
$p_T^j >$ [GeV]	65-35	30-30
$m_{jj} >$ [GeV]	500	500
$\Delta\eta_{jj} >$	2.0	2.5
$\max(z_\ell^*) <$	-	0.75
$m_{ee} - m_Z >$ [GeV]	15	15



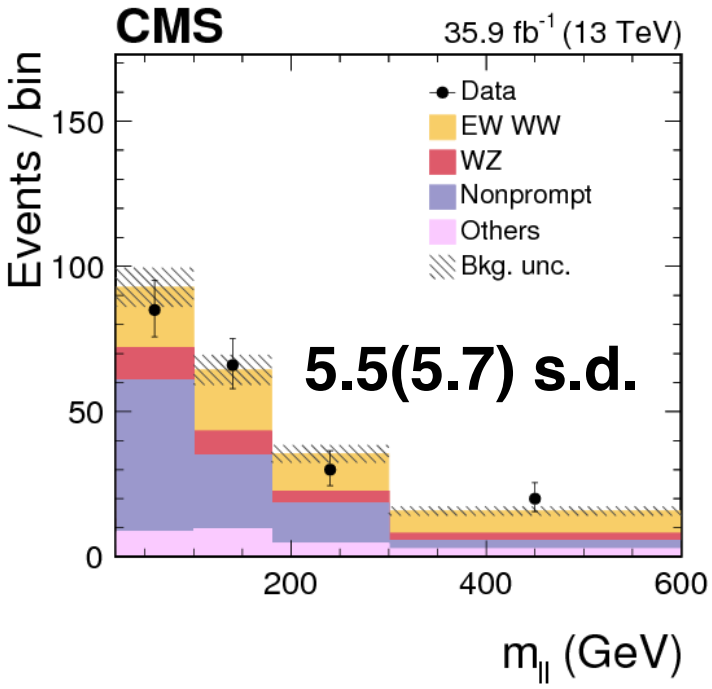
signal example

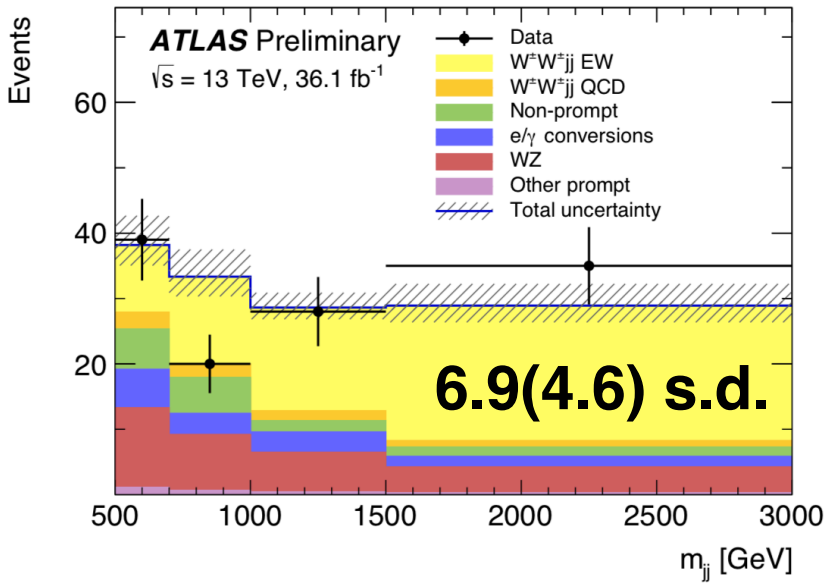


irreducible background

SSWW scattering results

- **observation** in CMS and ATLAS with 36/fb of data at 13 TeV





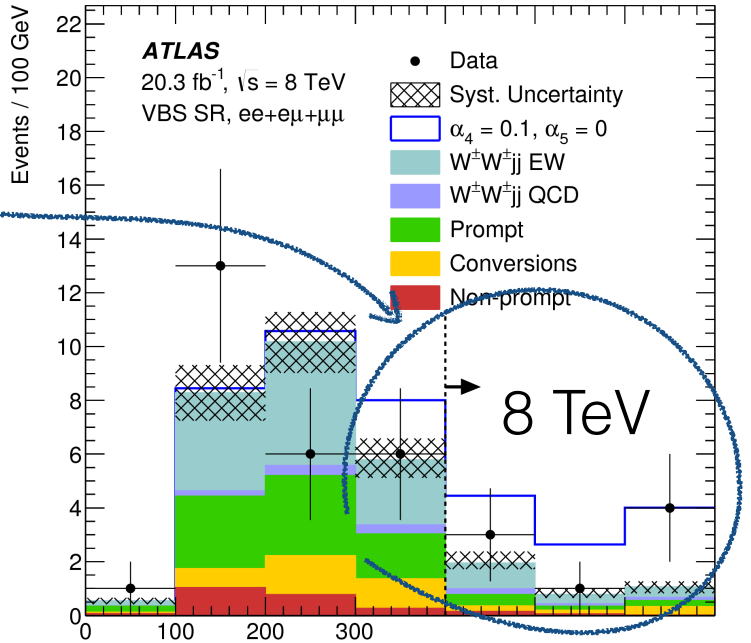
CMS	σ_{fid} = 3.83 ± 0.66 (stat) ± 0.35 (syst) fb
ATLAS	σ_{fid} = 2.95 ± 0.49 (stat) ± 0.23 (syst) fb

fiducial regions are not the same for the two collaborations

- **statistically-dominated**, waiting for updated results!

WWSS anomalous couplings

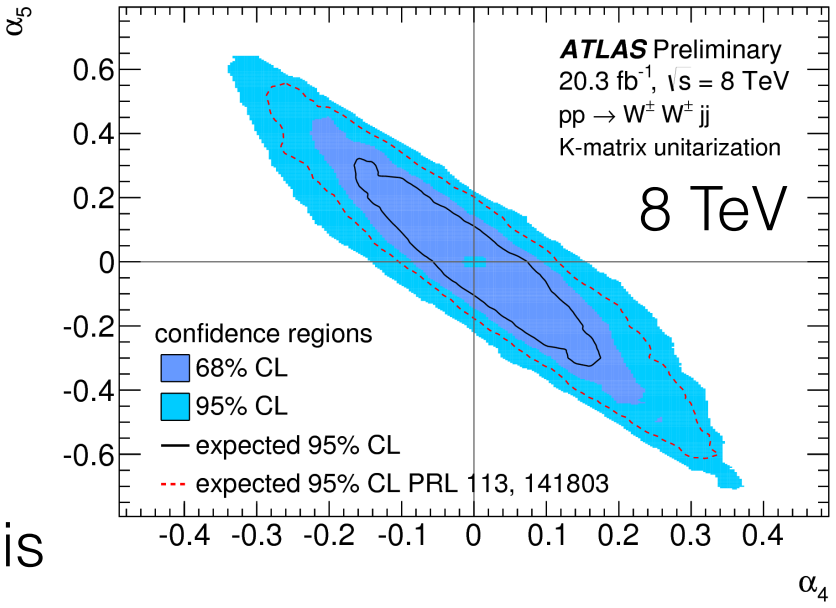
- deviations with respect to the standard model are expected at **high energy**



CMS 13 TeV

	Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$
f_{M6}/Λ^4	$[-11.9, 11.8]$	$[-11.1, 11.0]$
f_{M7}/Λ^4	$[-13.3, 12.9]$	$[-12.4, 11.8]$
f_{T0}/Λ^4	$[-0.62, 0.65]$	$[-0.58, 0.61]$
f_{T1}/Λ^4	$[-0.28, 0.31]$	$[-0.26, 0.29]$
f_{T2}/Λ^4	$[-0.89, 1.02]$	$[-0.80, 0.95]$

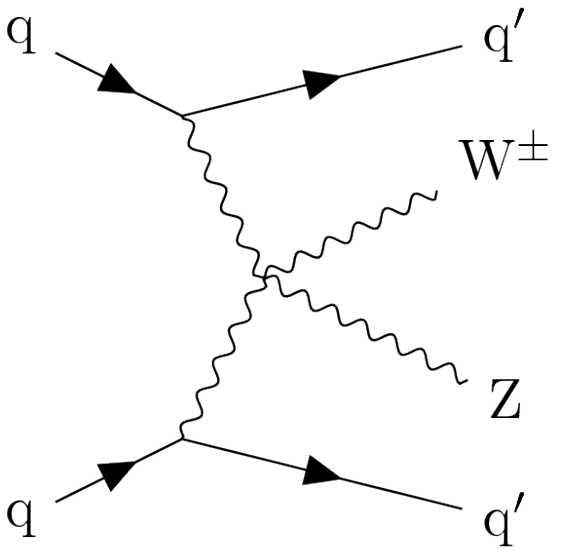
hep-ph/0606118 basis



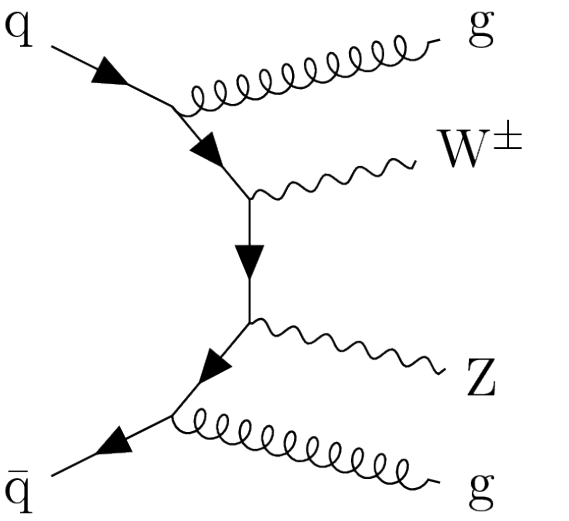
arXiv:0806.4145 basis

WZ scattering

- **three leptons** final state
- Less clean signature than W±W±, but cross section accessible with large dataset
- **backgrounds**
- QCD production of WZjj is the dominant background
- non-prompt component estimated from data
- analysis strategies
  - **CMS, conservative approach**, use features of EW vs. QCD processes that are well-understood and robust against limitations of theoretical predictions
  - **ATLAS, aggressive approach**: train BDT for EW vs QCD discrimination on 15 variables (selected from 33 studied)

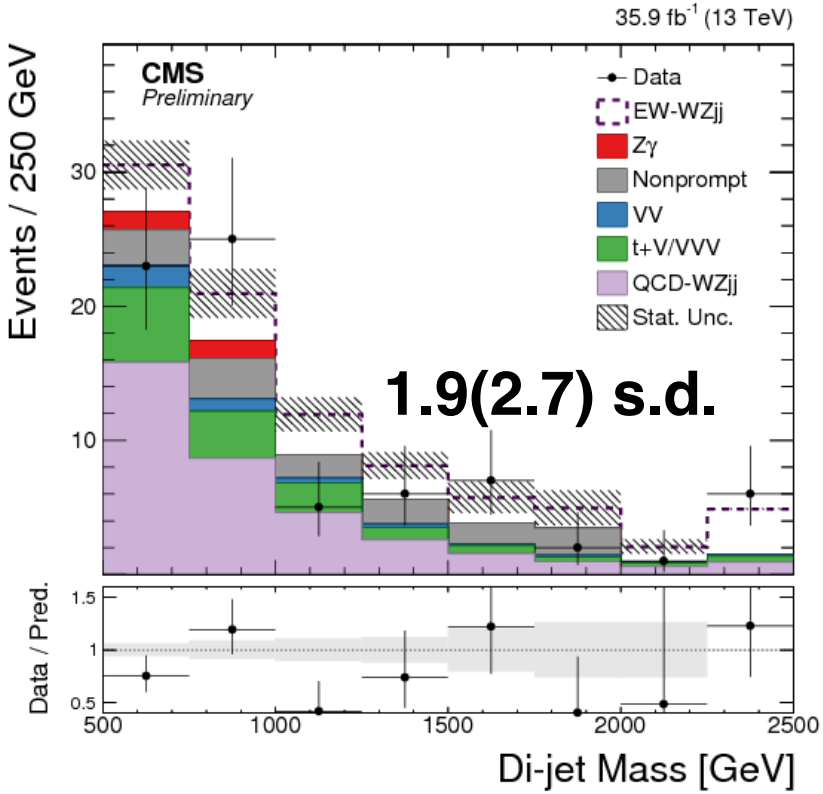


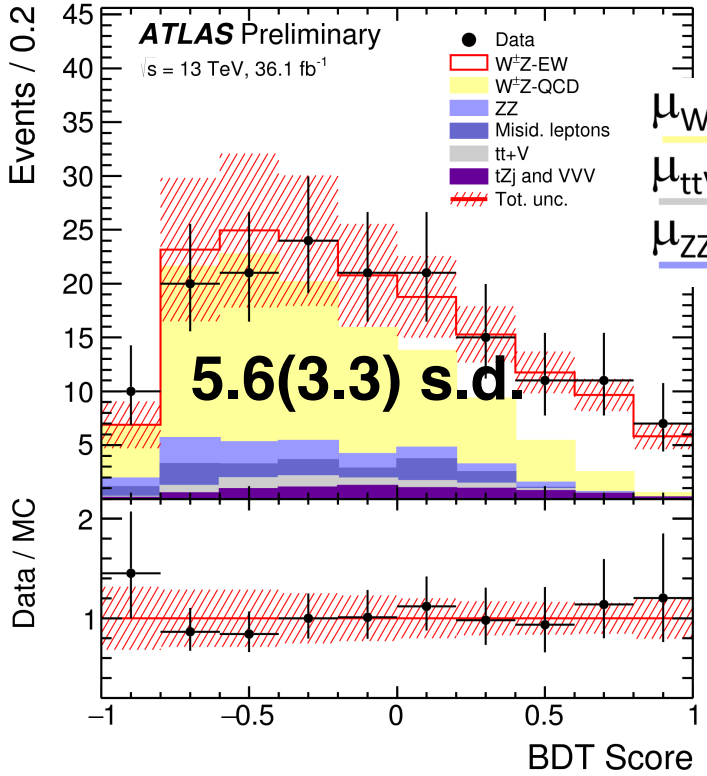
signal example



irreducible background

WZ scattering results





$\mu_{WZ\text{-}QCD} = 0.60 \pm 0.25$

$\mu_{ttV} = 1.18 \pm 0.19$

$\mu_{ZZ} = 1.34 \pm 0.29$

observation with 36/fb at 13 TeV

ATLAS $\sigma_{fid} = 0.57^{+0.14}_{-0.13}(\text{stat})\ ^{+0.04}_{-0.03}(\text{syst})$ fb **EW**

CMS $\sigma^{tight}_{fid} = 2.91^{+0.53}_{-0.49}(\text{stat})\ ^{+0.41}_{-0.34}(\text{syst})$ fb **EW+QCD**

CMS $\sigma^{loose}_{fid} = 4.01^{+0.72}_{-0.68}(\text{stat})\ ^{+0.57}_{-0.47}(\text{syst})$ fb **EW+QCD**

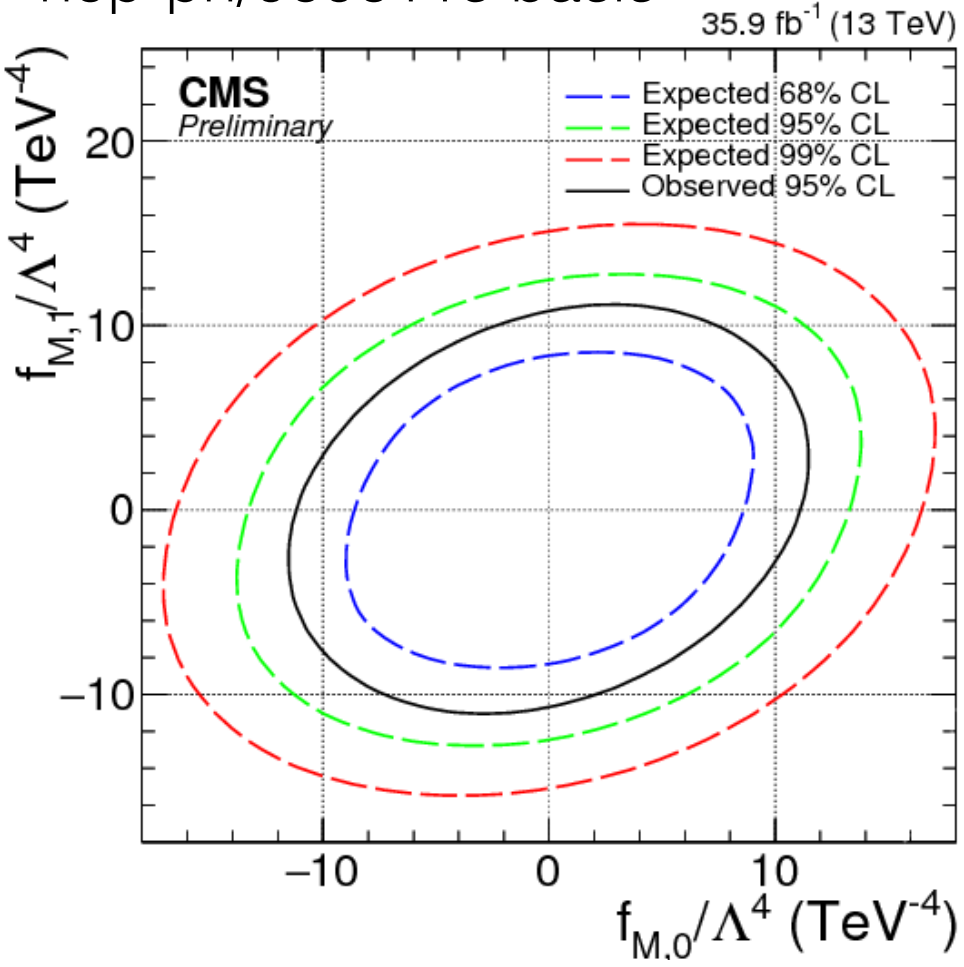
fiducial regions are not the same

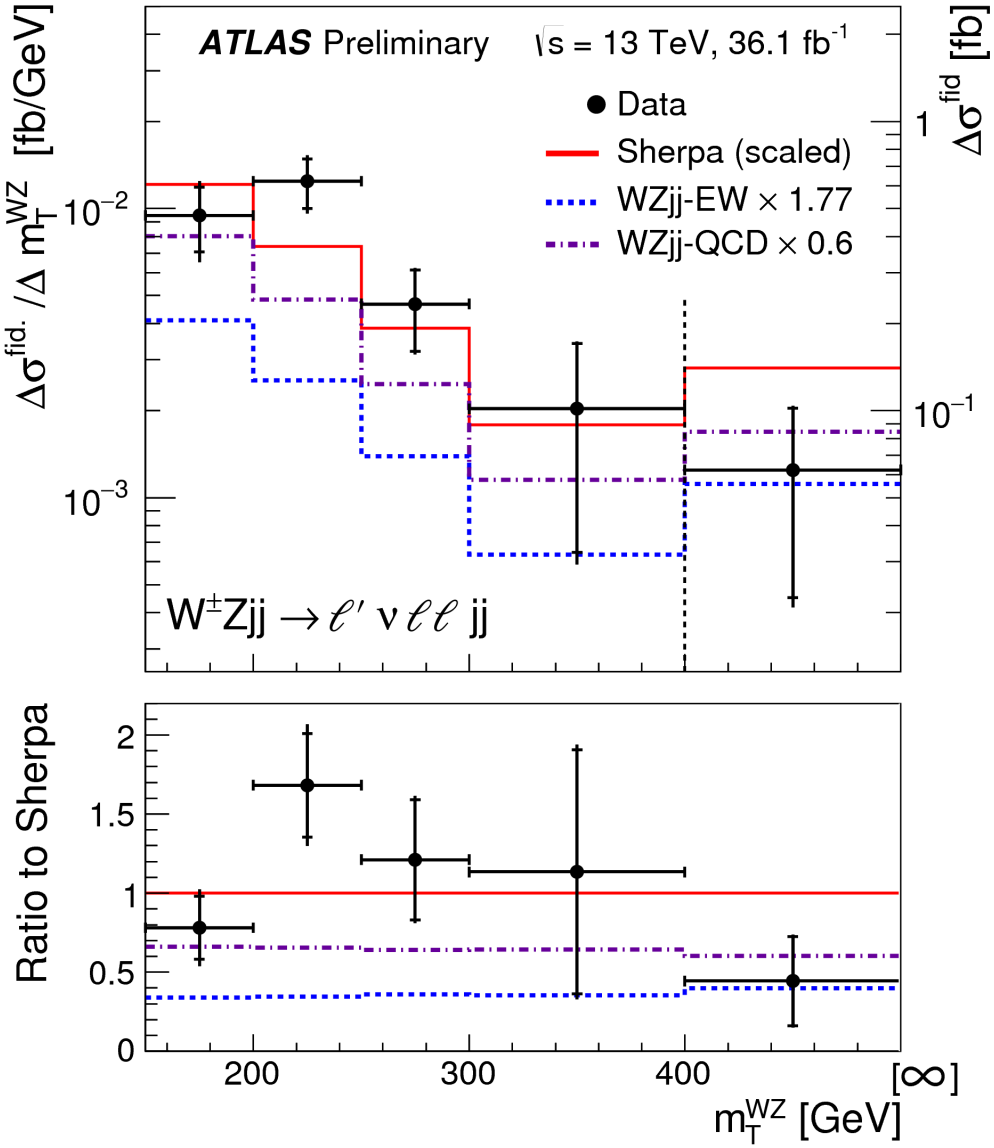
WZ anomalous couplings

see Stefanie Todt's talk for ATLAS results

- ATLAS publishes directly (a lot! of) **differential distributions**

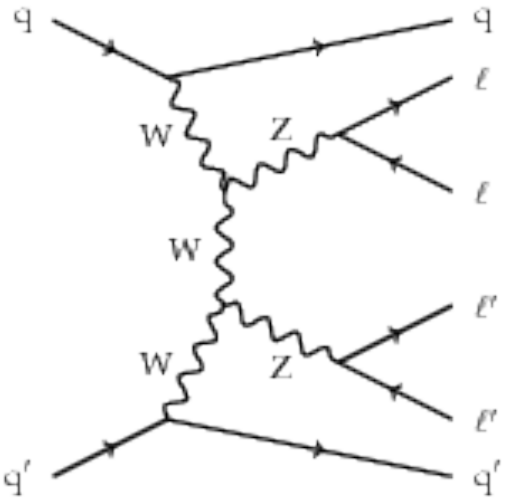
hep-ph/0606118 basis



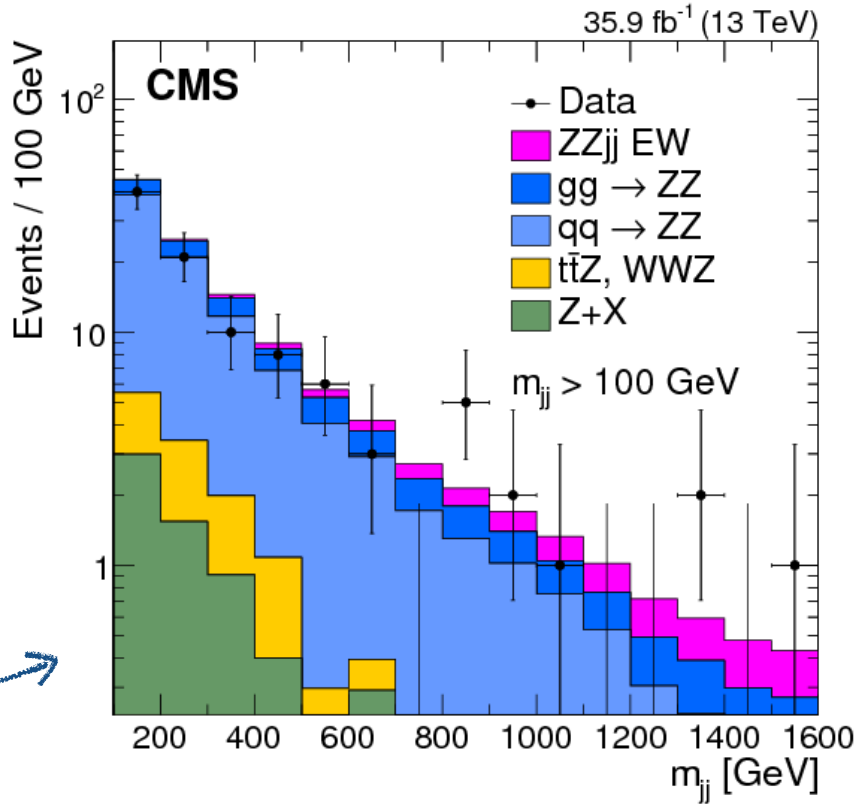


ZZ fully leptonic

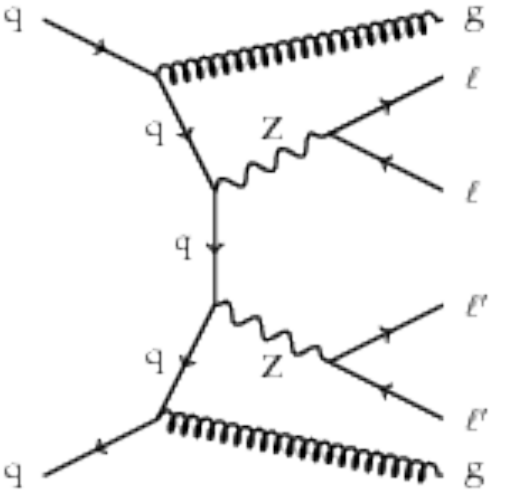
- four charged leptons ($e^{\pm}$ or $\mu^{\pm}$) in the final state
- **extremely clean** four-lepton signal (l = e, μ)
  - fully reconstructed final state (Z polarisation)
  - sensitive to resonances
- $\sigma_{(fid)}$ **< 0.5 fb @ 13 TeV** (1/10 of SSWW)
- **train BDT** with 7 variables for EW vs. QCD discrimination
- cross-checked w/ matrix-element method



signal example

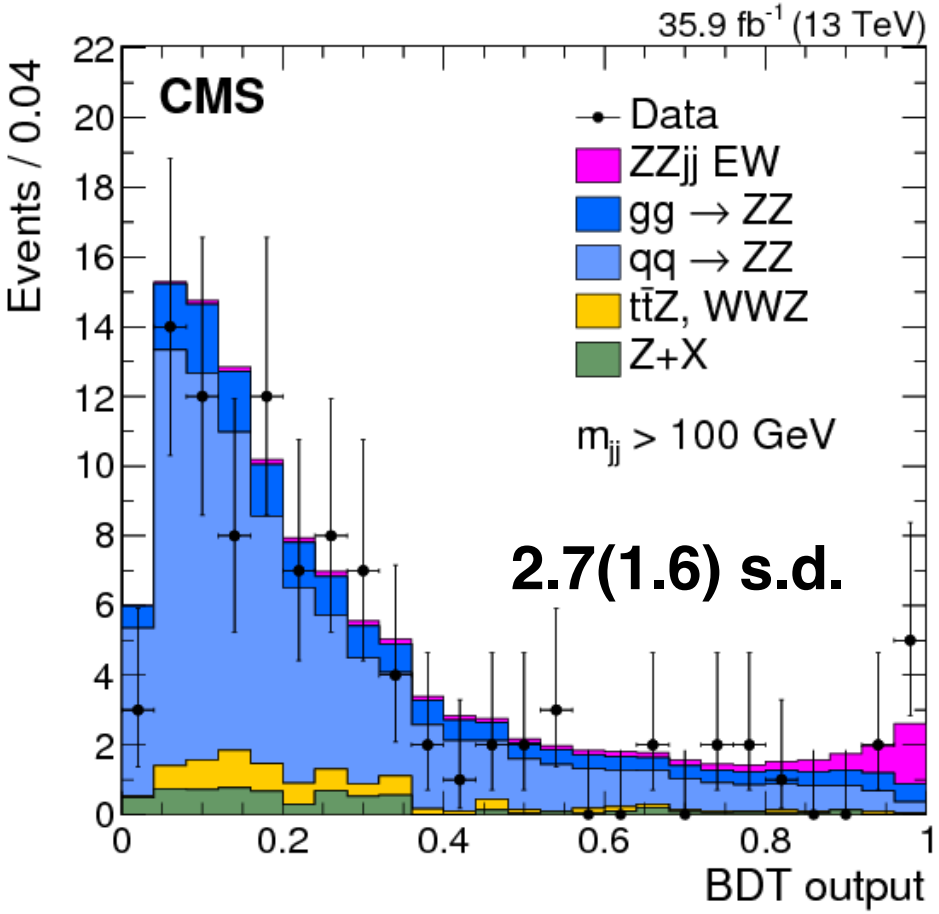


Very low non-prompt (fake) background



irreducible background

ZZ results



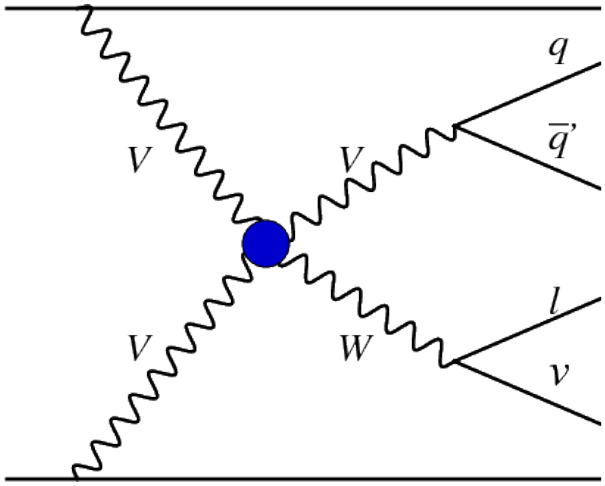
$$-0.46 < f_{T0}/\Lambda^4 < 0.44$$
$$-0.61 < f_{T1}/\Lambda^4 < 0.61$$
$$-1.2 < f_{T2}/\Lambda^4 < 1.2$$
$$-0.84 < f_{T8}/\Lambda^4 < 0.84$$
$$-1.8 < f_{T9}/\Lambda^4 < 1.8 \ .$$

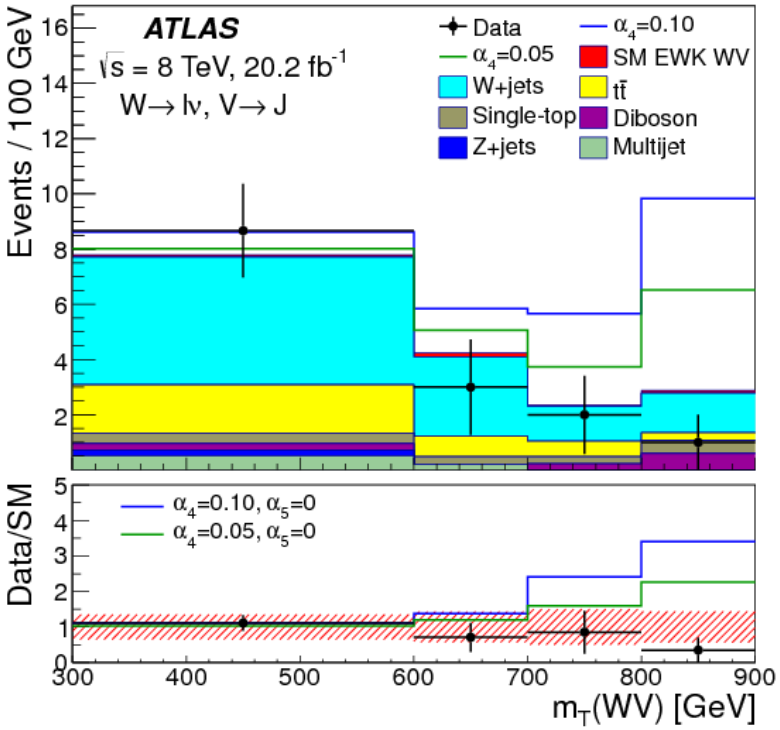
the **most stringent limits** on the T0, T1, T2, T8, and T9 anomalous quartic gauge couplings to date

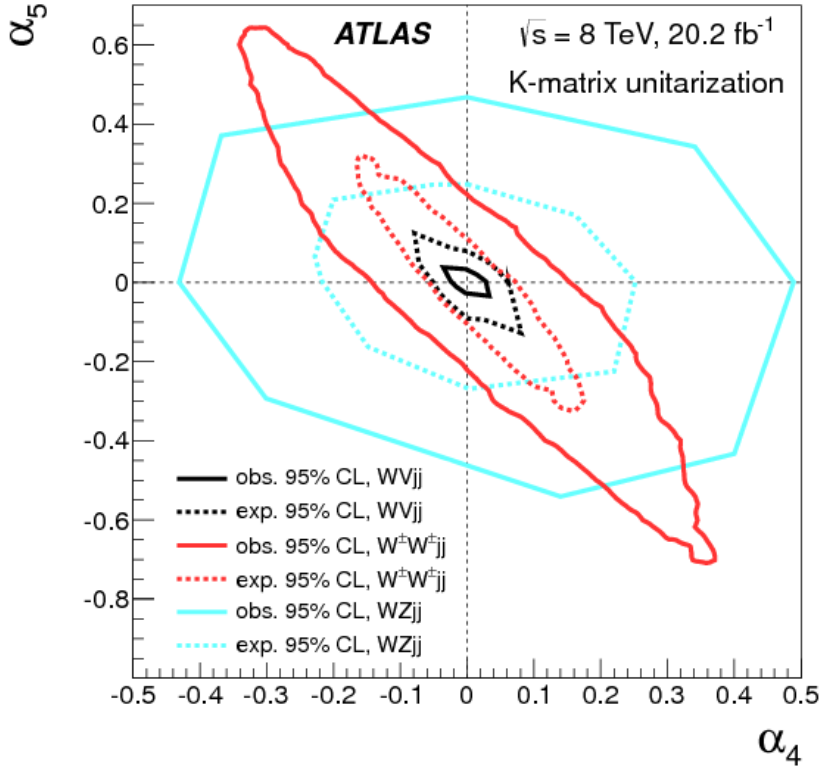
$$\sigma^{EW}_{(fid)} = 0.40^{+0.21}_{-0.16}(\text{stat})\ ^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

semi-leptonic final state

- WV with W⟶$\ell\nu$ and V⟶jj
- very large QCD bkg ($\mathcal{O}(\alpha^4\alpha_S^2)$ and $\mathcal{O}(\alpha^2\alpha_S^4)$)
- large sensitivity to BSM physics
- **boosted V reconstruction** at high energy scale





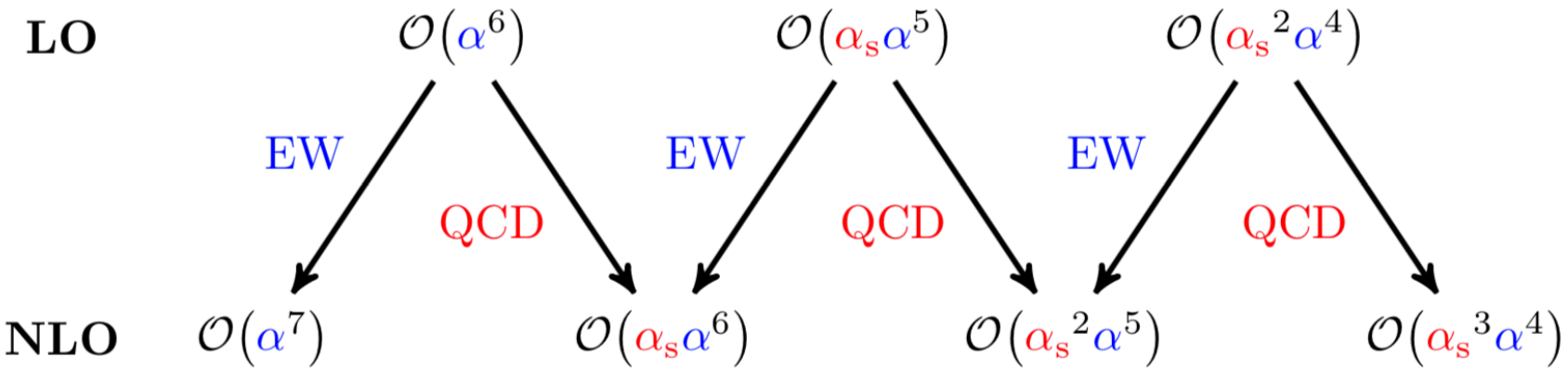


existing results

	ATLAS		CMS	
$W^{\pm}W^{\pm}$	8,13 TeV	6.9 (4.6) σ	8,13 TeV	5.5 (5.7) σ
WZ	8,13 TeV	5.7 (3.3) σ	13 TeV	1.9 (2.7) σ
$Z\gamma$	8 TeV	2.0 (1.8) σ	8 TeV	3.0 (2.1) σ
$W\gamma$	-	-	8 TeV	2.7 (1.5) σ
ZZ fully leptonic	-	-	13 TeV	2.7 (1.6) σ
WV semi-leptonic	8 TeV	anomalous couplings	-	-

theory developments

- very low statistics where EW contribution is dominating
- need for **reliable theoretical predictions**: higher orders, parton shower, estimate of approximations, ...
- at NLO: meaningless distinction between EW signal and QCD background
  ⇒ **provide combined measurement**



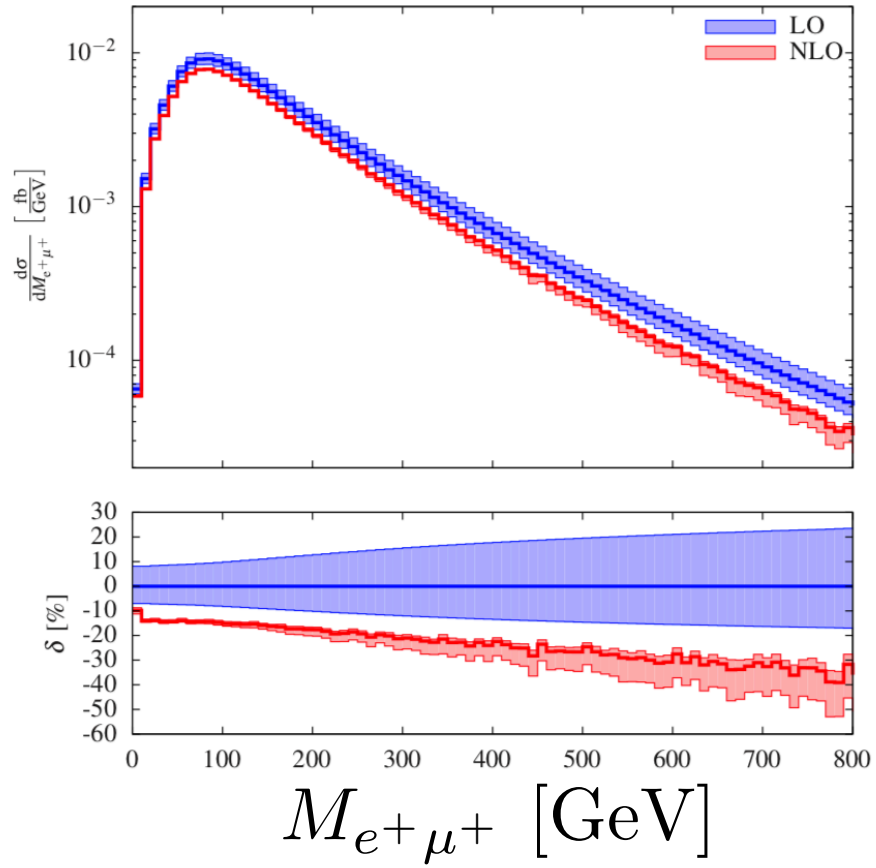
- All processes known at NLO QCD accuracy matched to parton shower, in VBS approximation for both QCD-/EW-induced processes
- **only for W±W±** the full NLO QCD computation and the NLO EWK are known as well

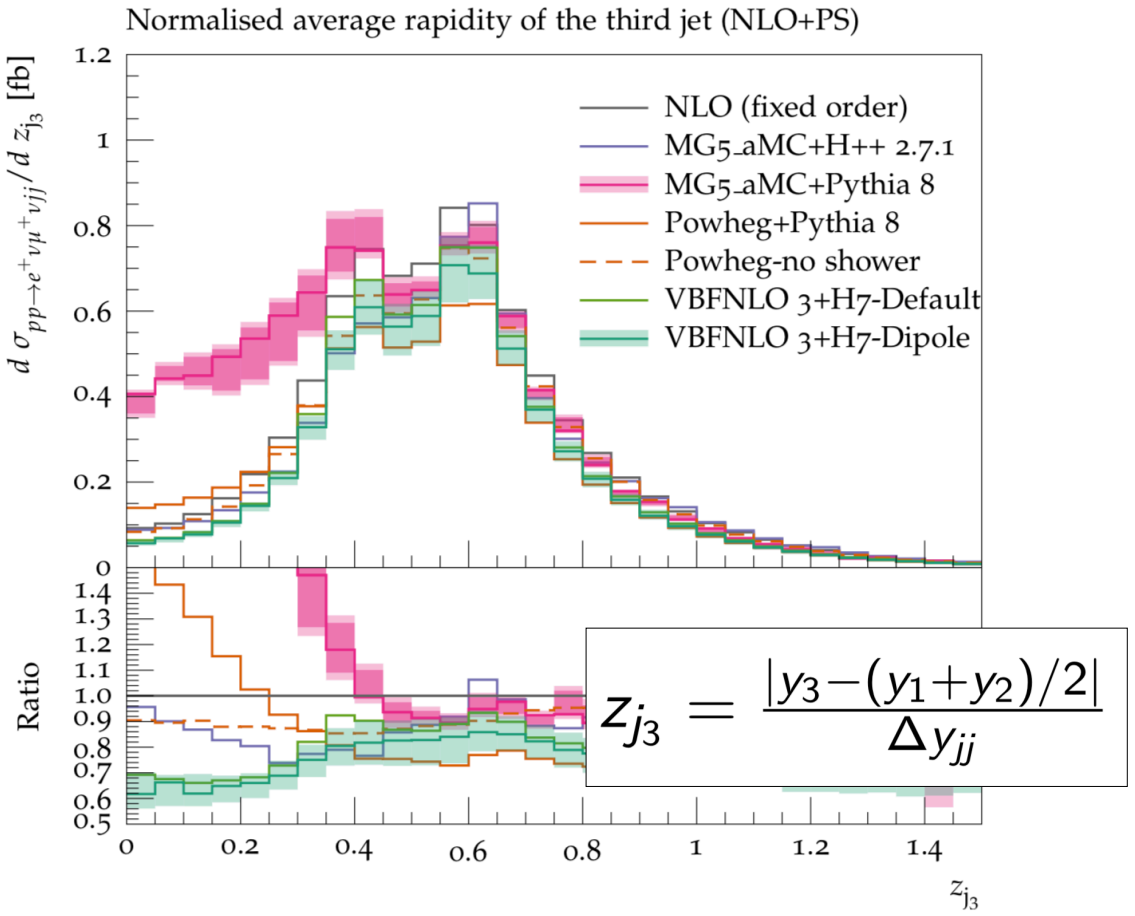
NLO fiducial XS for $e^+\mu^+jj$

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

Large NLO EW corrections: Intrinsic for VBS at the LHC

Very large differences for the third jet (only defined at NLO)

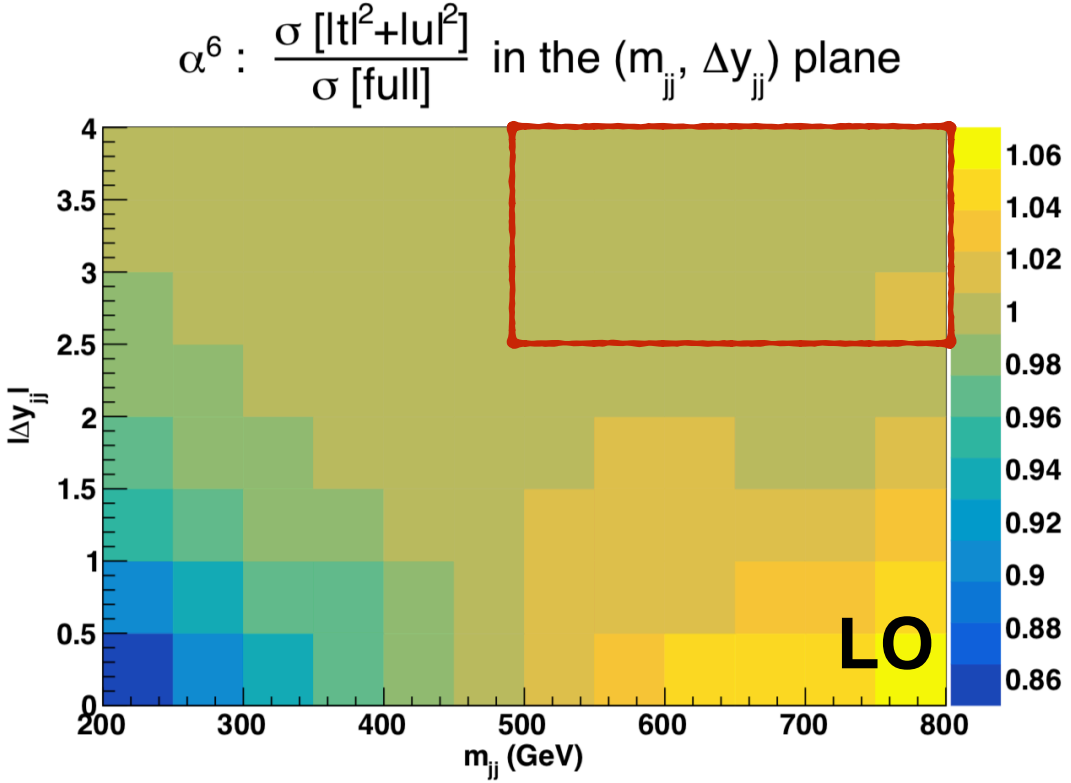


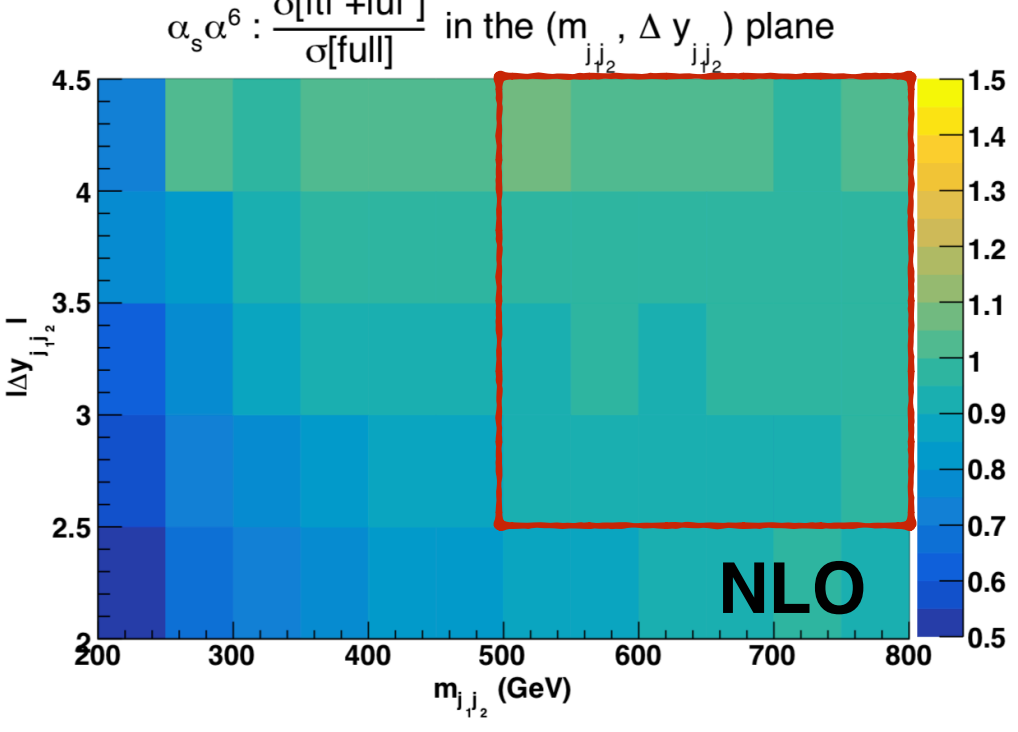


$$z_{j_3} = \frac{|y_3 - (y_1+y_2)/2|}{\Delta y_{jj}}$$

VBS approximation

- Neglecting s-channel contributions and t/u interferences
  - implemented in POWHEG and VBFNLO (including s-channel)
- **Good approximation at LO** in fiducial region for W^+W^+
- gets **worse at NLO**
- OK for current experimental precision, might be important in the future

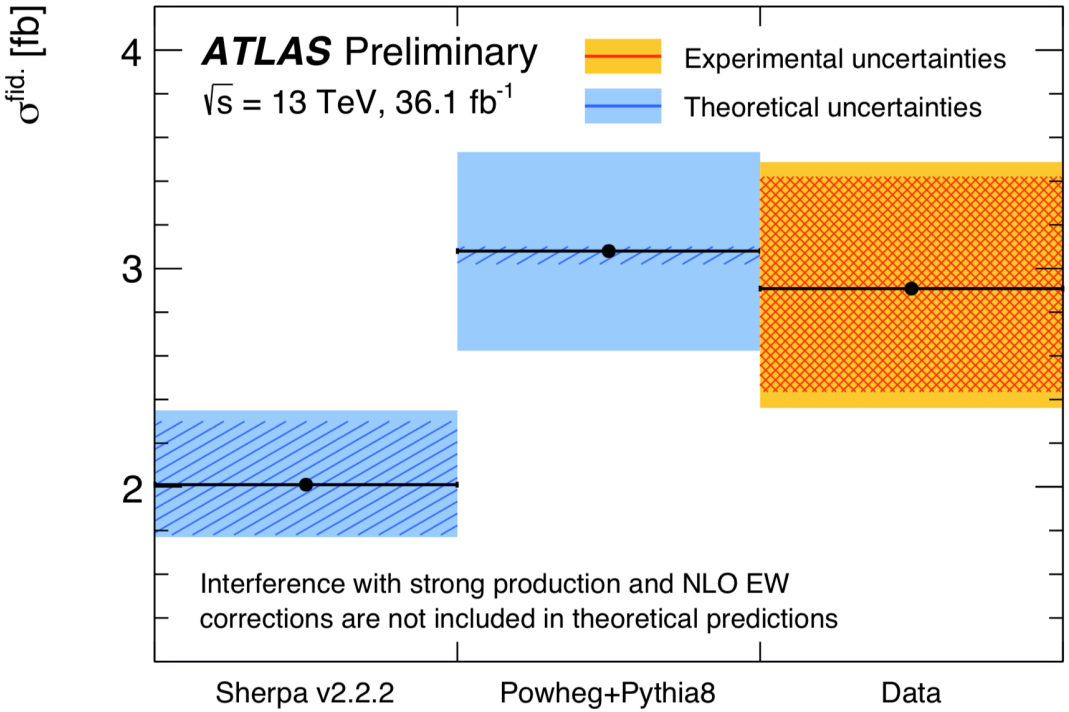


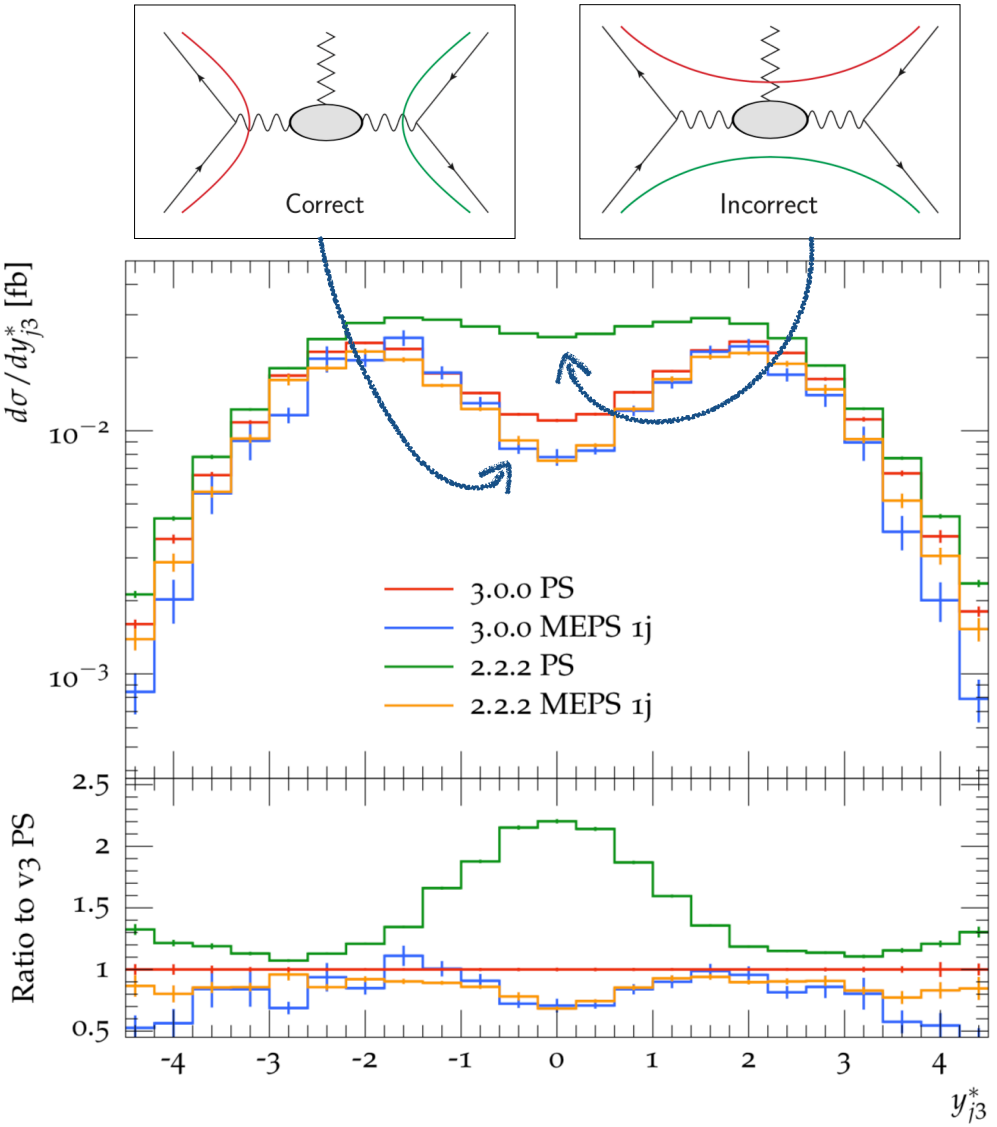


colour flow simulation

latest news from MBI

- ATLAS identified **large differences between Sherpa and Powheg (and data)** in the W±W± analysis
- Sherpa 3.0.0 predicts ~20% larger cross section after cuts as a result of **correct color flow and PS starting scales**





MC generators used

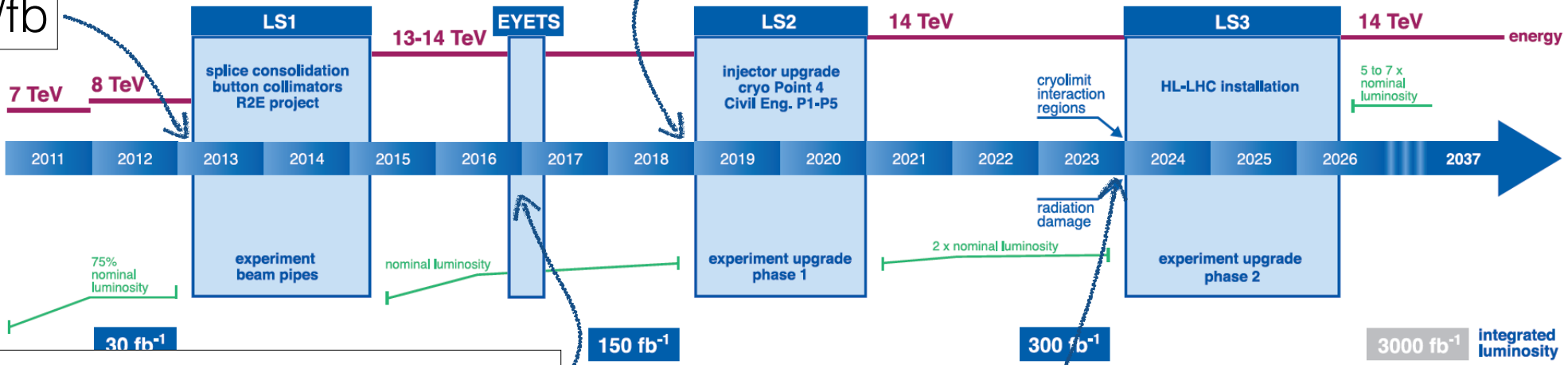
	Wγ CMS	ZZ CMS	WZ ATLAS	WZ CMS	WV ATLAS
EW	MG5 LO k_F=1.2 VBFNLO	MG5 LO	Sherpa NLO +jets	MG5 LO	Whizard LO
QCD	MG5 LO + MLM	MG5 NLO + FxFx	Sherpa NLO +jets	MG5 LO + MLM	Whizard LO
aQGC	MG5 LO	MG5 LO + ME reweigh		MG5 LO + ME reweigh	Sherpa LO + NLO XS
interf.	Neglected	Neglected	syst. (2%)	negligible	Neglected

	ssWW ATLAS	ssWW CMS	Zγ ATLAS	Zγ CMS
EW	Sherpa LO +MEPS	MG5 LO	Sherpa LO NLO XS VBFNLO	MG5 LO kFactor 1.1
QCD	Sherpa LO +MEPS	MG5 LO	Sherpa LO	MG5 LO + MLM
aQGC		MG5 LO	MG5 LO	MG5 LO
interf.	syst. (6%)	syst. (few %)	syst. (~10%)	syst. (~11%)

next steps

20/fb

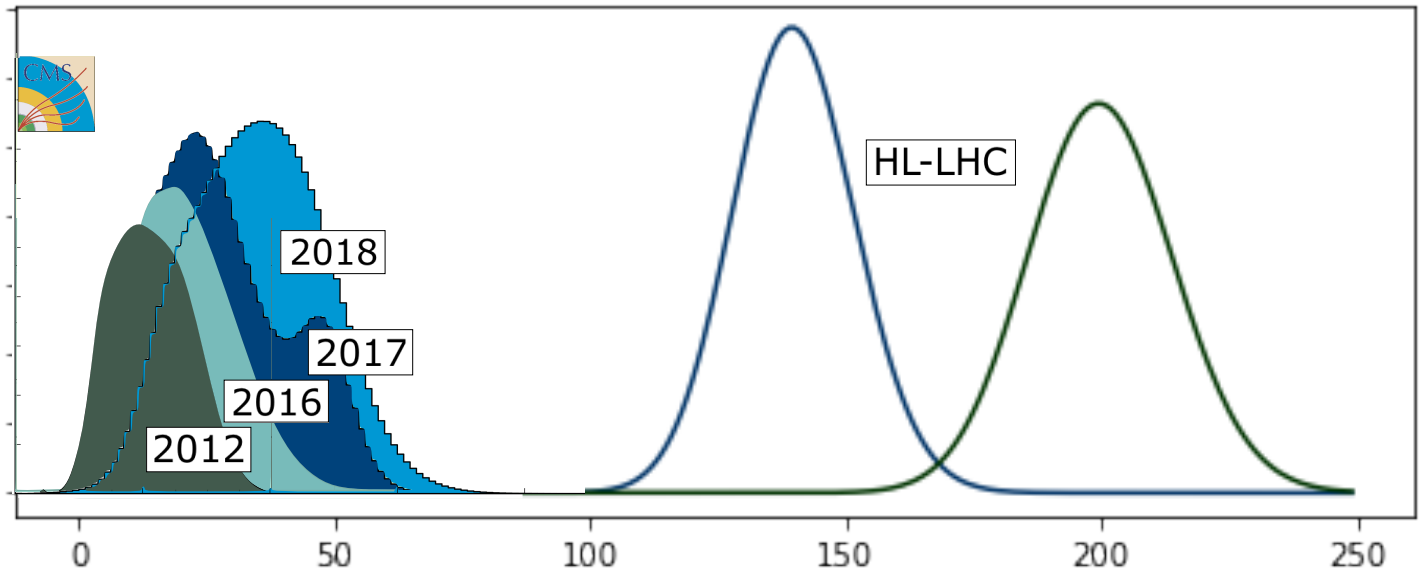
150/fb



data analysed **so far**: 35/fb

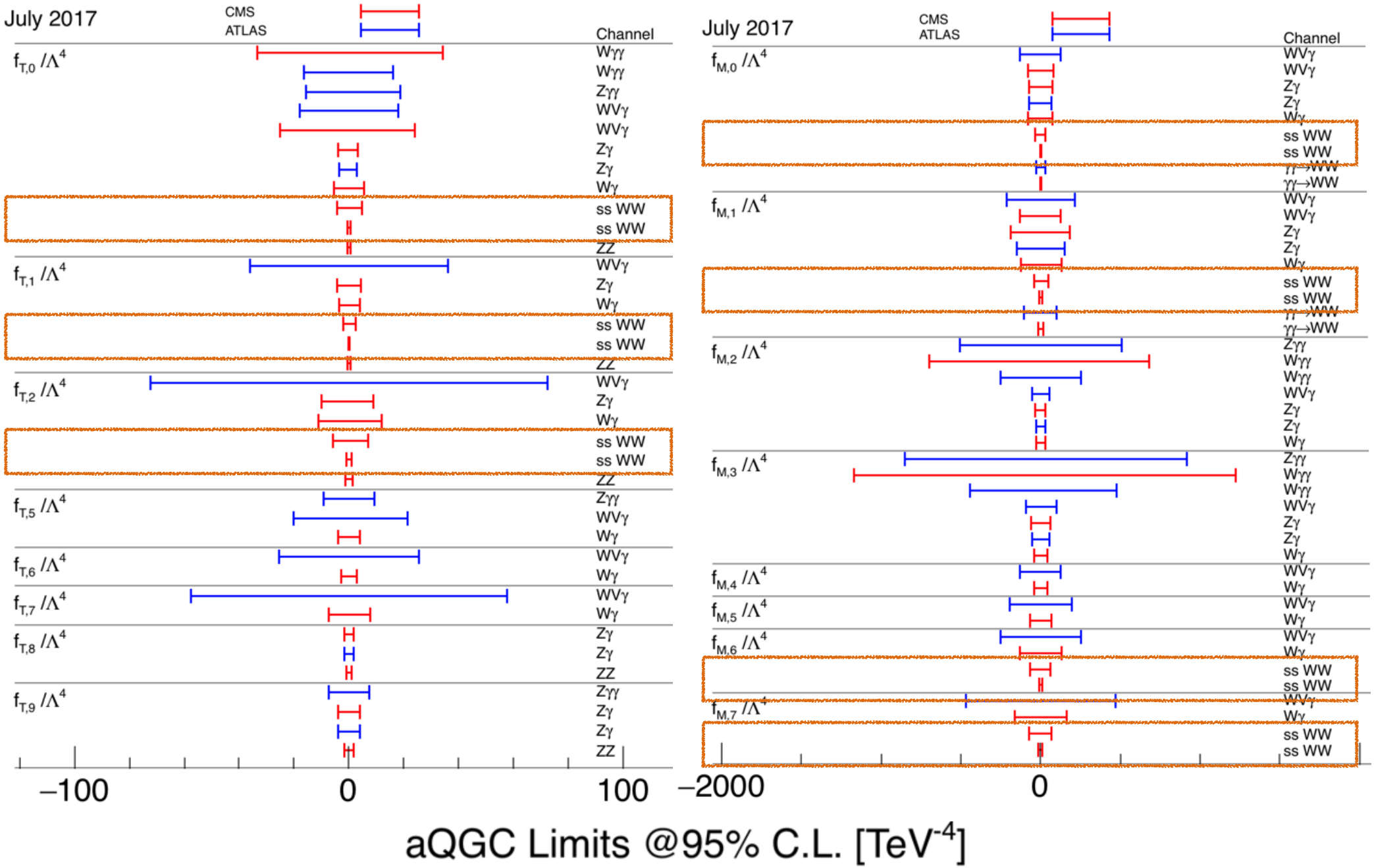
in **five years**: 10x statistics

HL-LHC: 100x statistics

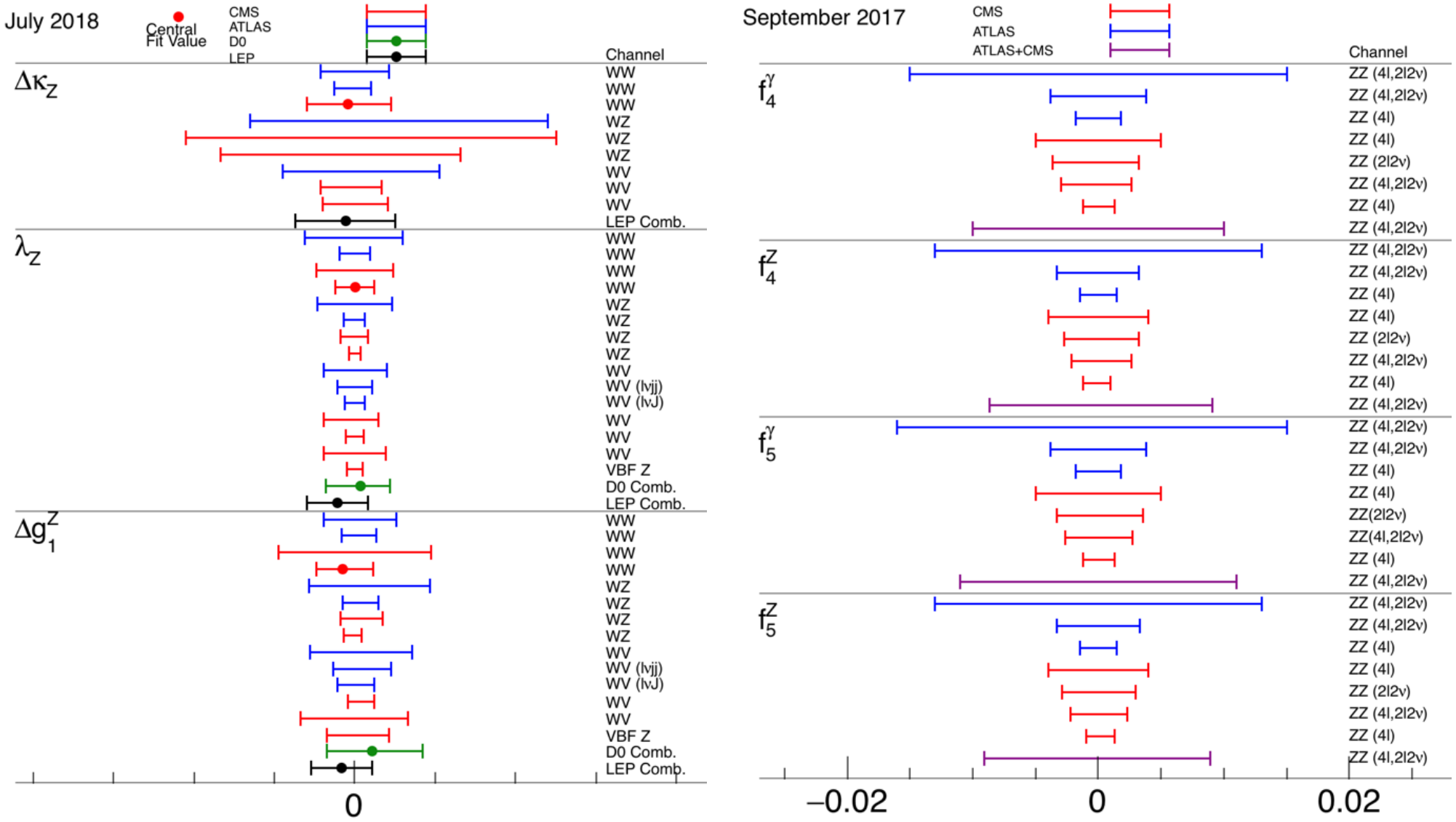


LHC and detector conditions will change in the HL scenario

anomalous quartic couplings



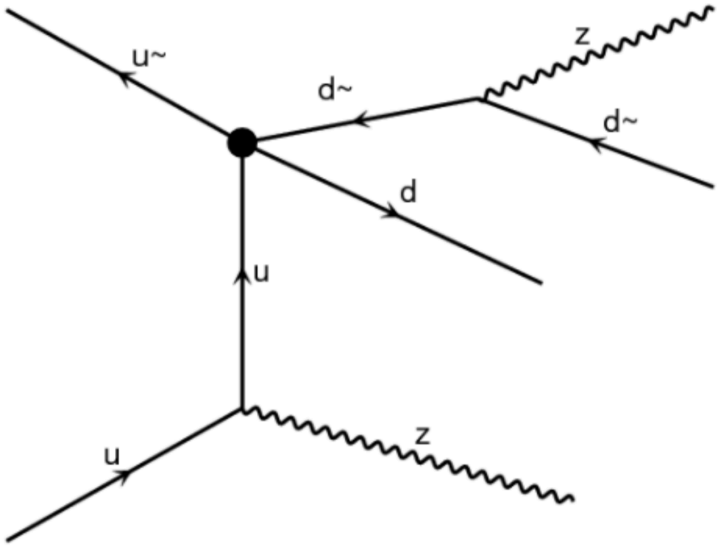
anomalous triple couplings



aTGC Limits @95% C.L.

search for BSM physics

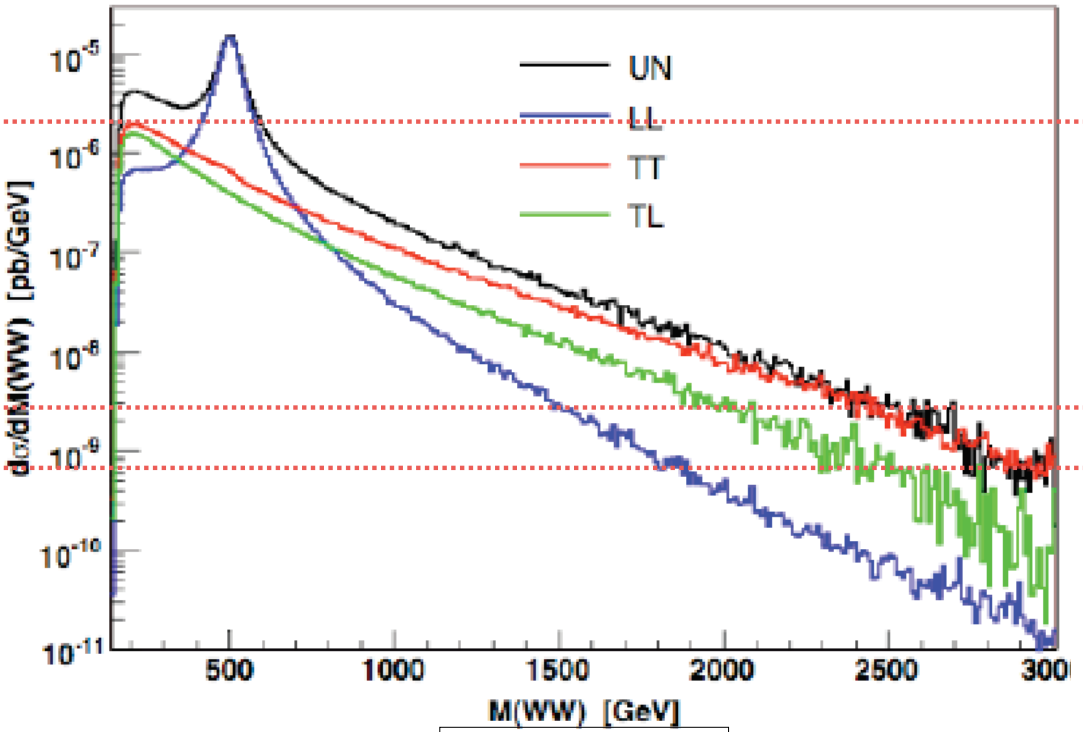
- due to the vast number of diagrams, **VBS very sensitive** to EFT operators
- existing searches constrain single (vertex) operators, sometimes pairs of them
- VBS studies address only quartic gauge couplings, while:
  - we are skipping the calculation of certain perturbative orders and include only higher ones: **dimension-6 effects should be introduced** in global fits, besides the dim. 8 ones
  - a study of VBS processes must allow for **EFT deviations in all the diagrams** (e.g. 4-fermi operators)
- find a **common base for CMS and ATLAS combinations**
- measurements of **differential distributions** wil key for the EFT effects



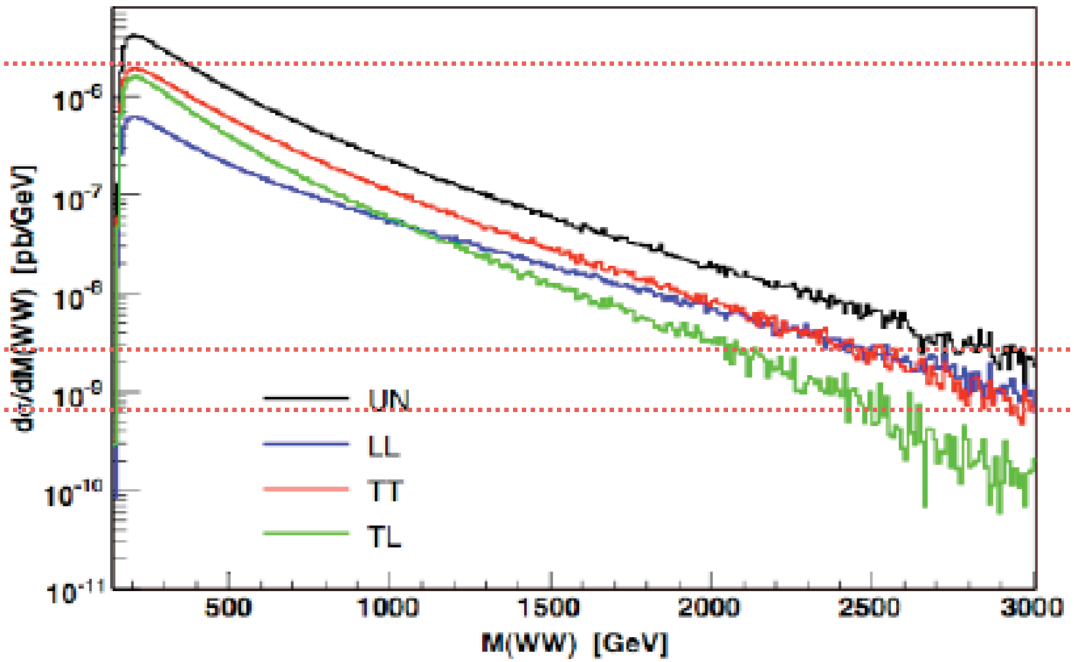
the longitudinal component

- $\mathbf{V_L V_L}$ is where the electroweak symmetry breaking plays its role
- At large M(VV) the $V_L V_L$ cross-section would be of the same order as the $V_T V_T$ one in the no-Higgs case
- If there is a new resonance at a scale Λ, **the $\mathbf{V_L V_L}$ cross-section will be anomalous until Λ**

Accomando et al: hep-ph/0512219



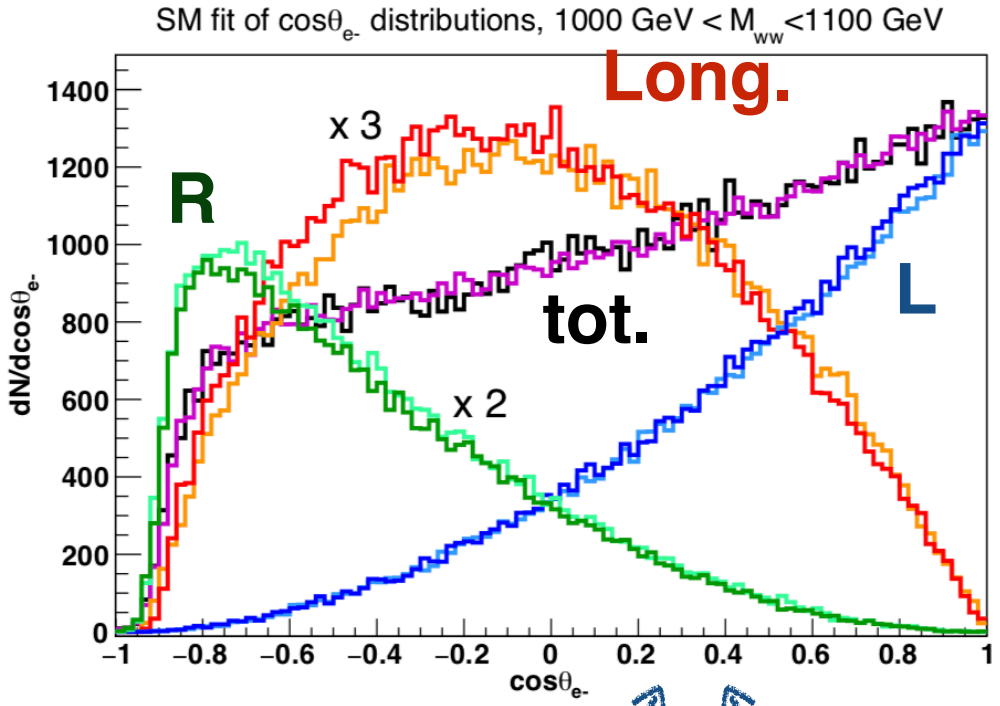
SM Higgs

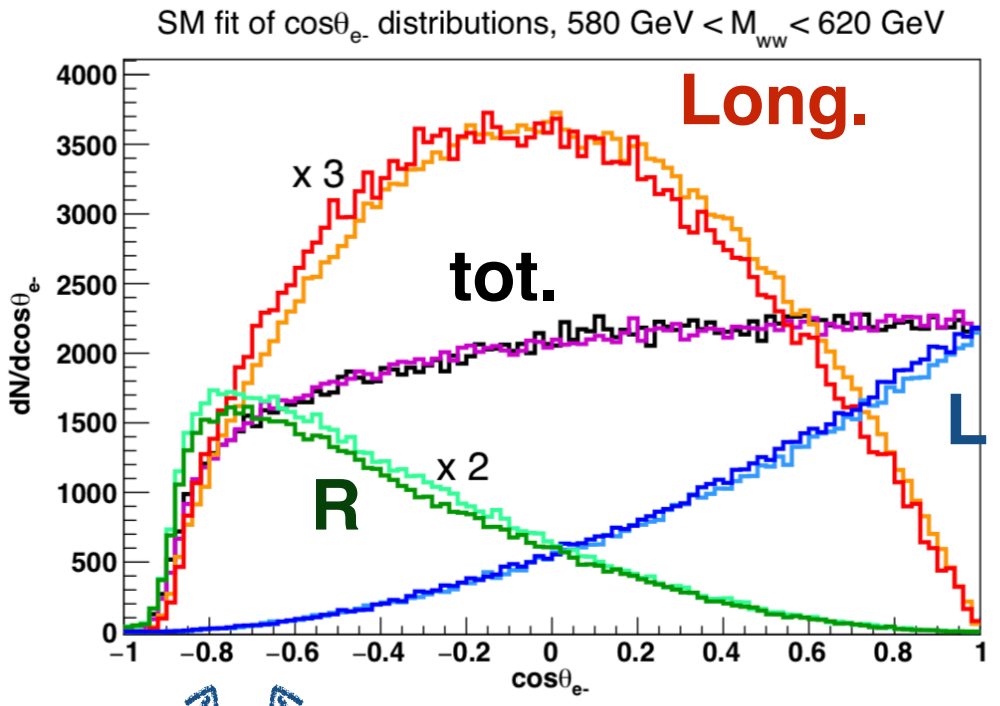


no Higgs

polarised VBS

- **extract polarization fractions for BSM models** fitting distributions with polarised SM shapes → model (in)dependence
- **V polarisation tagged** with the decay angle of charged lepton wrt the V direction, in the V reference frame
- compare the SM to EW-singlet model or to No Higgs





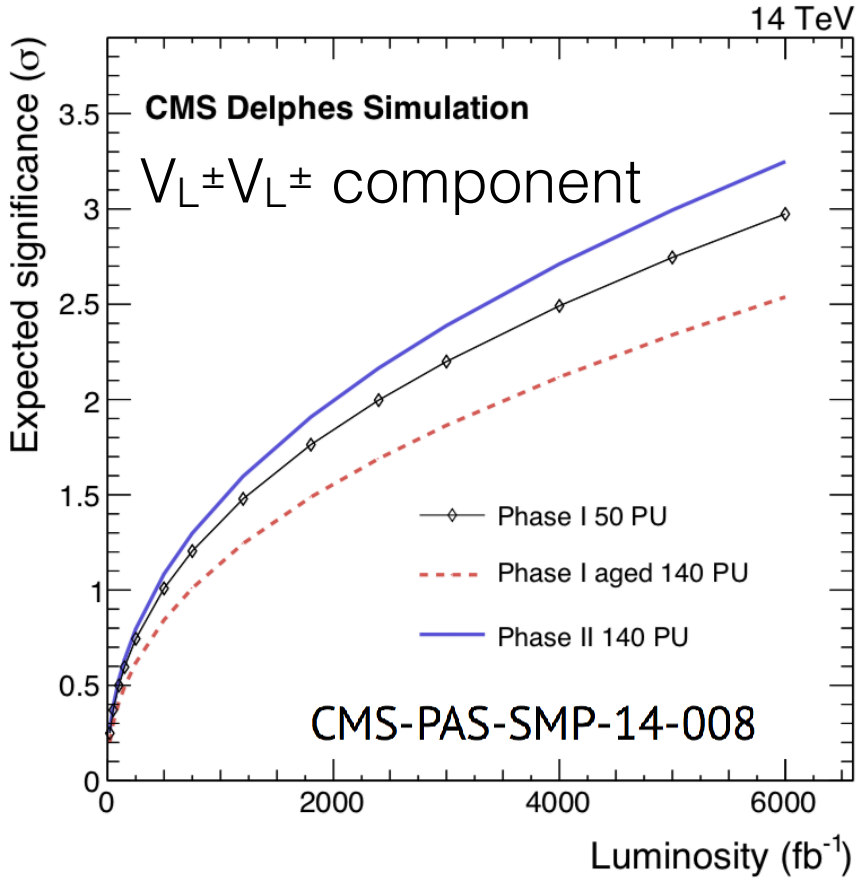
light lines:no Higgs

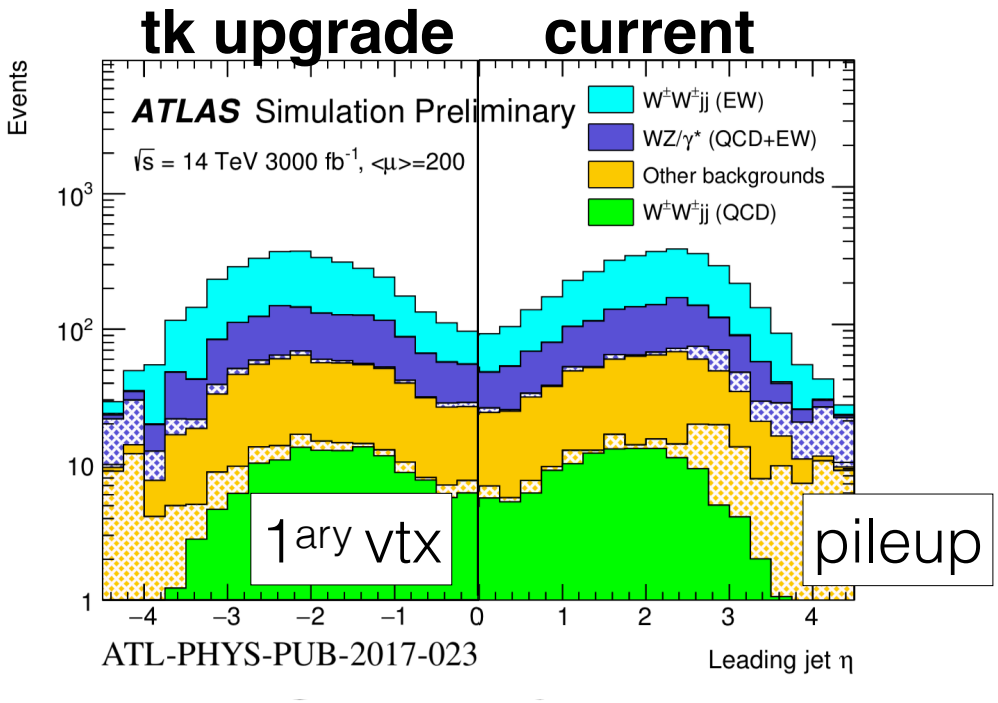
dark lines: SM

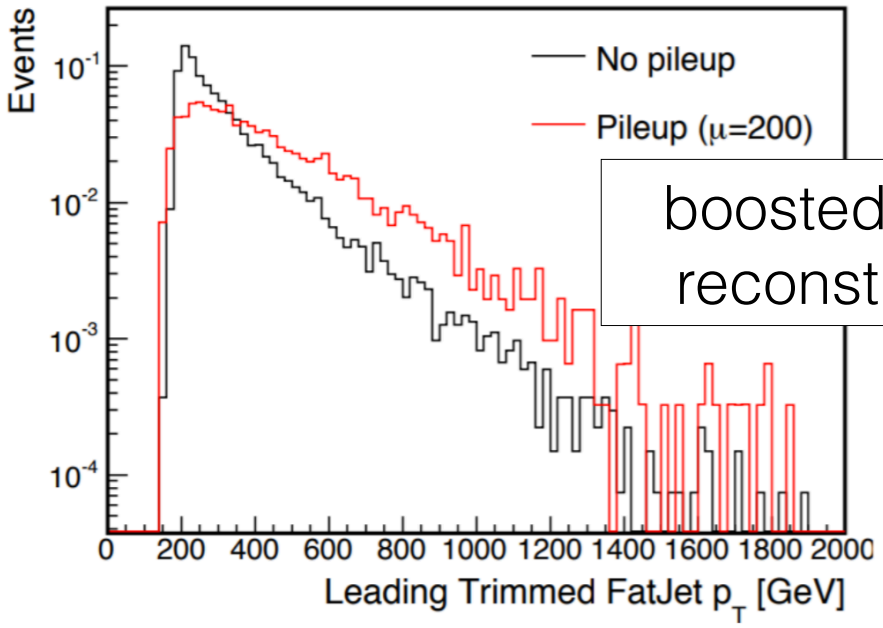
light lines: EW singlet

projections for HL-LHC

- main focus: **impact of detector upgrades** on analysis performances
- room for improvement in the absolute performances







boosted V→qq reconstruction

the list goes on…

- BSM physics in VBS can be searched for also with **explicit models:**
  - those who predict resonances within reach at the LHC,
  - and those who provide a UV-complete theory the has low energy effects
- the **final state particle reconstruction** at hadron colliders could be specialised to VBS: boosted vector bosons, central rapidity vetoes, high-energy leptons, forward jets, quark/gluon discrimination…
- the sophisticated VBS final state, together with absence of resonances, calls for the **use of machine learning algorithms**, to maximise the analysis performances

VBSCan

- COST Action targeting VBS studies
- involves more than 20 EU countries and a few extra-EU partners

> ***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***

- **Theory**: experts of Effective Field Theory, members from the communities of the major multi-purpose generators, authors of generators dedicated to VBS, VBF, vector bosons (Phantom, VBFNLO, Recola, Bonsay M5@NLO, Whizard, VBFNNLO, Sherpa)
- **CMS Experiment**: main authors of VBS and VBF analyses
- **ATLAS Experiment**: main authors of VBS and VBF analyses
- **data mining**: experts from Politecnico di Milano

VBSCan

- COST Action targeting VBS studies
- E a-
- **Th** nbers f of th generators, authors of gener S, VB antom, VBFNLO, Recola, Bonsay M5@NLO, Whizard, VBFNNLO, Sherpa)
- ain a
- main authors of VBS and VB
- **data mining**: experts from Politecnico di Milano

N(N)LO QCD and EWK predictions

high-energy leptons reconstruction

machine learning

background estimates

EFT fits

quark-gluon discrimination

EFT unitarisation

signal isolation

PU mitigation

polarised-V tagging

results combination

boosted jets reconstruction

signal definition

BSM models

topic events organisation

- **yearly meetings** at the end of June (**first** and **second** already took place)
- **PhD** schools
- **topic meetings** — followed by publications (on the VBS results combination, on EFT basis definition, on MC comparisons, on ATLAS and CMS results comparisons)
- **next events**:
  - workshop on on **longitudinal polarisation studies**, 10-12 October, in École Polytechnique
  - workshop on **physics objects reconstruction**, 22-24 October, in Krakow

Everybody is welcome to join our activities, just drop me an email (pietro.govoni@unimib.it) and visit our website:

https://vbscanaction.web.cern.ch

conclusions

- We discovered a Higgs boson, yet the comprehension of the **Electroweak Symmetry Breaking** is far from being complete
- **Vector Boson Scattering is one key** to access it at a different energy scale, with a completely different process
- it's time for **precision physics**: the first VBS observations have been published, paving the way for a systematic study of the process
- extremely interesting studies from several points of view, which require a coordinated **effort of the whole community** to face all its issues…
- … but **the race just started**: when the going get tough, the tough get going

references

- CMS SSWW 13 TeV https://arxiv.org/abs/1709.05822
- CMS SSWW 8 TeV https://arxiv.org/abs/1410.6315
- ATLAS SSWW 13 TeV https://cds.cern.ch/record/2629411
- ATLAS SSWW 8 TeV https://arxiv.org/abs/1611.02428
- CMS WZ 13 TeV http://inspirehep.net/record/1681230
- ATLAS WZ 13 TeV https://cds.cern.ch/record/2630183
- ATLAS WZ 8 TeV https://arxiv.org/abs/1603.02151
- CMS ZZ 13 TeV https://arxiv.org/abs/1708.02812
- ATLAS ZY 8 TeV https://arxiv.org/abs/1705.01966
- CMS ZY 8 TeV https://arxiv.org/abs/1702.03025
- CMS WY 8 TeV https://arxiv.org/abs/1612.09256
- ATLAS VW 8 TeV https://arxiv.org/abs/1609.05122
- CMS QCD ZZ+2jet https://arxiv.org/abs/1806.11073
- ATLAS QCD ZZ + jets http://cds.cern.ch/record/2285386

references

- *Éboli, Gonzalez-Garcia, Mizukoshi,* p p -> j j e+/- mu+/- nu nu and j j e+/- mu-/+ nu nu at O(α_{em}^6) and O(α_{em}^4 α_s^2) for the Study of the Quartic Electroweak Gauge Boson Vertex at LHC, https://arxiv.org/abs/hep-ph/0606118
- *Alboteanu, Kilian, Reuter,* Resonances and Unitarity in Weak Boson Scattering at the LHC, https://arxiv.org/abs/0806.4145
- *R. Gomez-Ambrosio*, talk: Effective field theory approach to Vector Boson Scattering, https://indico.cern.ch/event/681549/contributions/2945849/
- *Biedermann, Denner, Pellen*, Complete NLO corrections to W^+W^+ scattering and its irreducible background at the LHC, https://arxiv.org/abs/1708.00268
- *Ballestrero et al.*, Precise predictions for same-sign W-boson scattering at the LHC, https://arxiv.org/abs/1803.07943
- *Ballestrero, Maina, Pelliccioli*, W boson polarization in vector boson scattering at the LHC, https://arxiv.org/abs/1710.09339
- *ATLAS Collaboration*: Studies on the impact of an extended Inner Detector tracker and a forward muon tagger on W±W± scattering in pp collisions at the High-Luminosity LHC with the ATLAS experiment, https://cds.cern.ch/record/2298958
- *CMS Collaboration*: Prospects for the study of vector boson scattering in same sign WW and WZ interactions at the HL-LHC with the upgraded CMS detector, http://cds.cern.ch/record/2220831?ln=en
- anomalous coupling limits summary plots: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC
- latest news on Sherpa: *S. Höche's* talk at Multi-Boson Interactions 2018