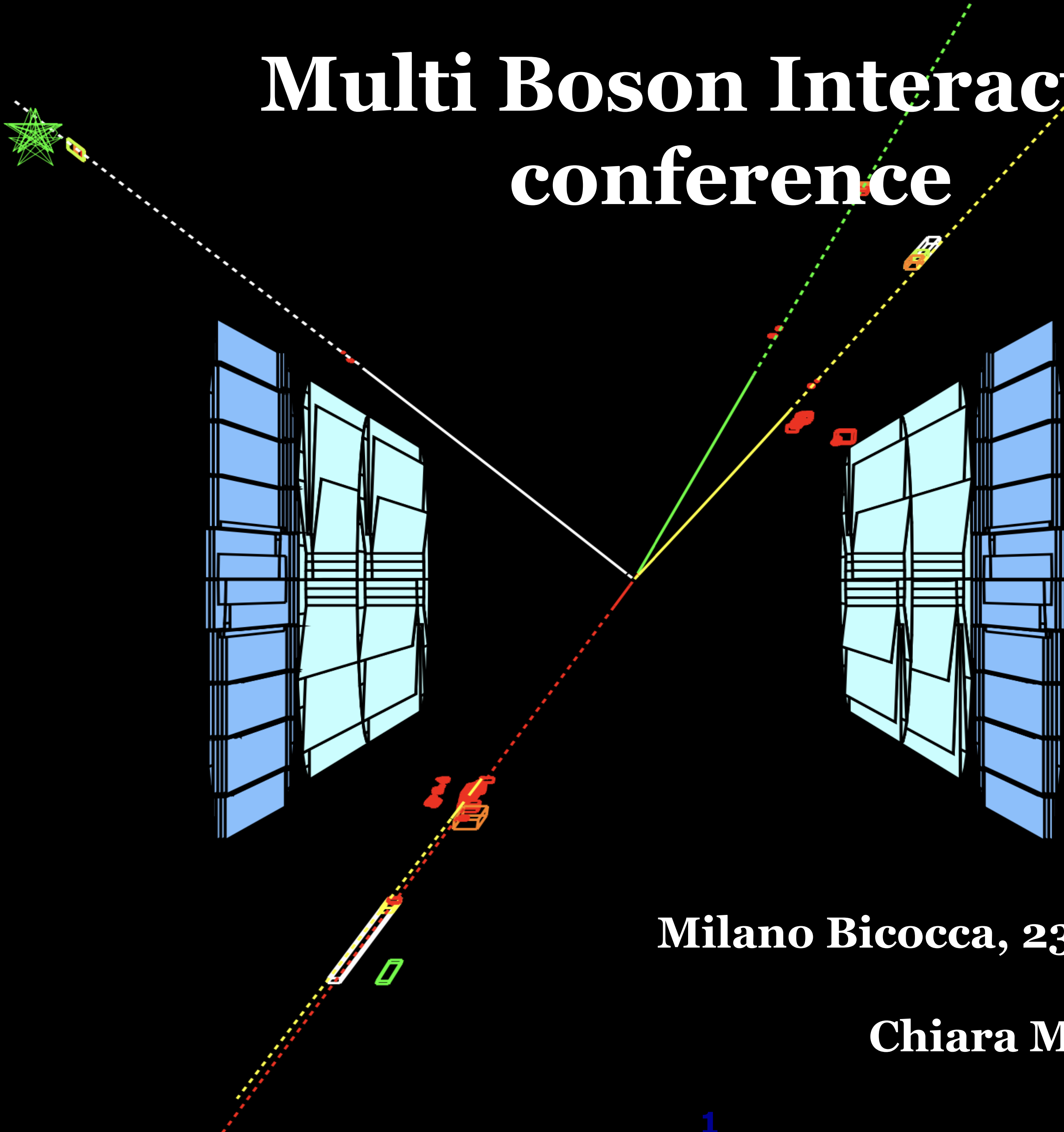
Multi Boson Interaction conference



Milano Bicocca, 23-27 August 2021

Chiara Mariotti

Thanks !

Thanks to Pietro Govoni and the organising commettee for this amazing invitation !

With Pietro we did start the VBF/S adventure in CMS ~15-20 years ago :

VBF Z : arXiv:1001.4357

VBS W+W+ : Eur. Phys. J. C71: 1514, 2011.

.... and many more

today he is one of the leader of the field.

Congratulations !

To all the speakers for the very nice talks, the very interesting results and discussions → I will try to report your main message

Apologies for mistakes and oversights …

Precision physics and new physics at LHC via MBI

- The first production of di-bosons at LEP !
- Why MBI ?
- Theory progress
- Experimental results
- The future

The SM: a long journey

54 Yang & Mills

61 Glashow

64 Brout, Englert, Higgs et al

67-68 Glashow, Weinberg and Salam

70 't Hooft et Veltman

73 Gargamelle : discovery of the week neutral current

83 Ua1 & UA2: W and Z discovery

89-2000: LEP and HERA: the triumph of the SM

95 Tevatron: top quark discovery

2012 LHC: discovery the Higgs boson

The SM: a long journey

54 Yang & Mills

61 Glashow

As Gödel's incompleteness theorems say:
you cannot get an ultimate answer, since every answer creates automatically a new question.
Yariv Friedman (Geneva film director) rephrased it :
"the act of discovery is basically what creates the unknown"

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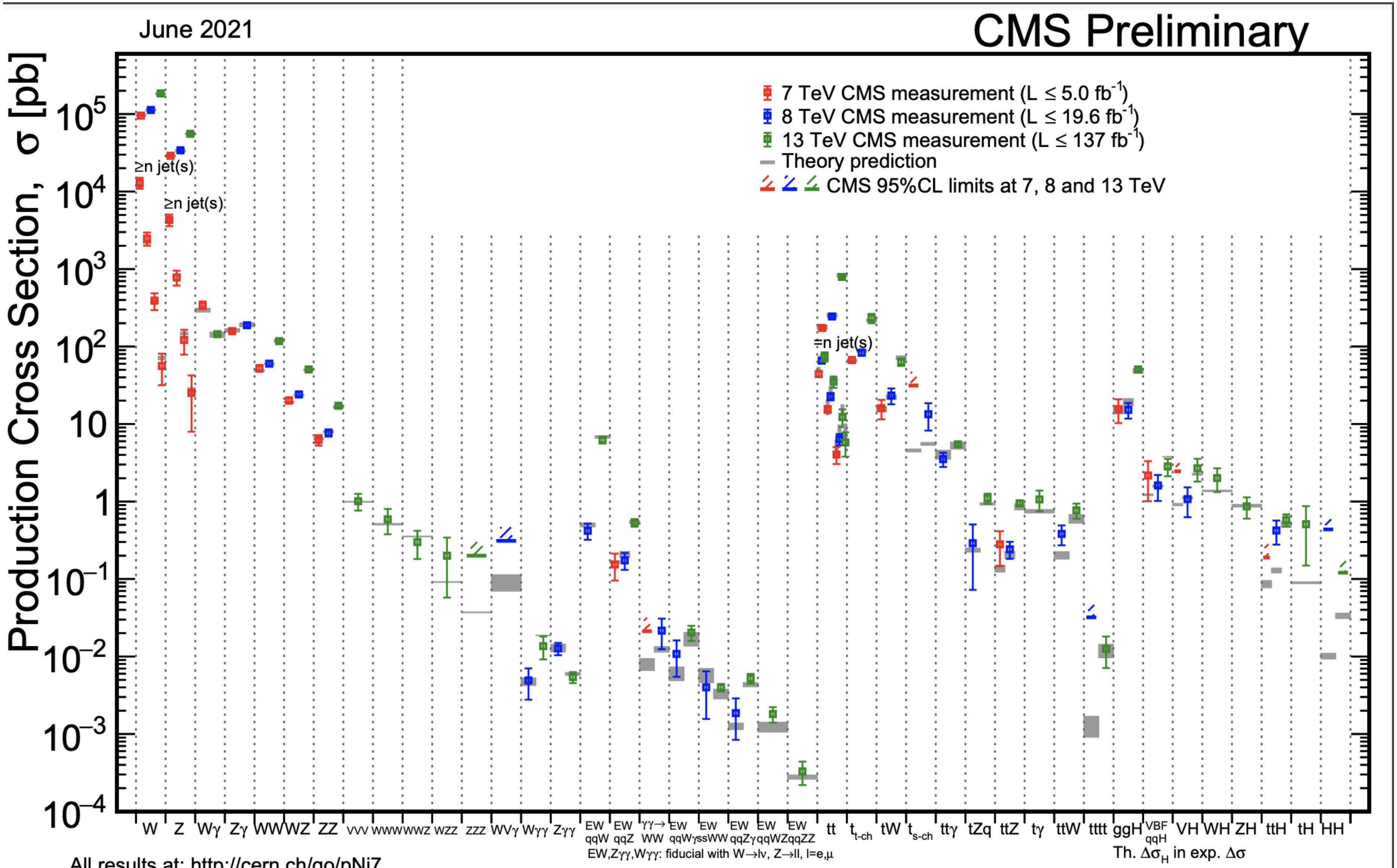
2012 LHC: discovery the Higgs boson

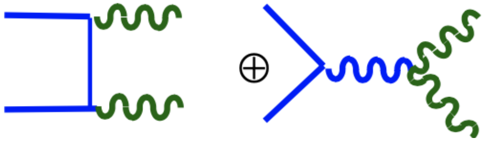
→ precision measurements, search for new physics

The SM as of today at LHC

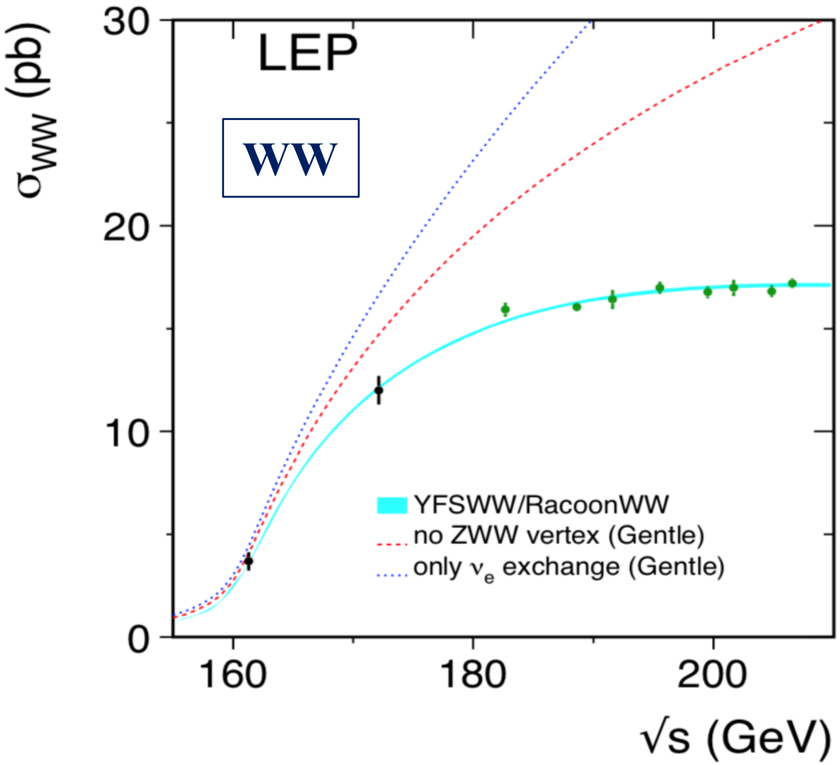
Measurements and theoretical predictions over 10 orders of magnitude

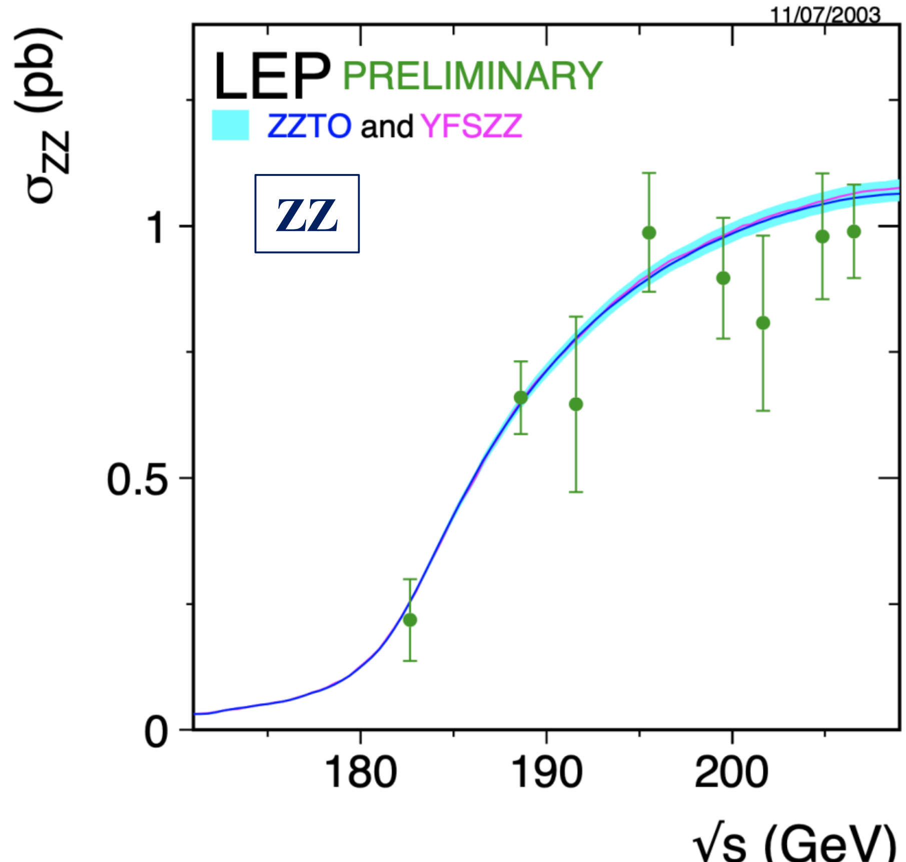


Going back to the beginning of MBI



4 fermions cross sections





~40000 WW events at LEP

MANY theoretical progress on O(α).

Rad.Corr. modify the kinem. distributions (mass,boost…) and give a global -1.5% shift in σ(WW)

All 5 final states are measured:

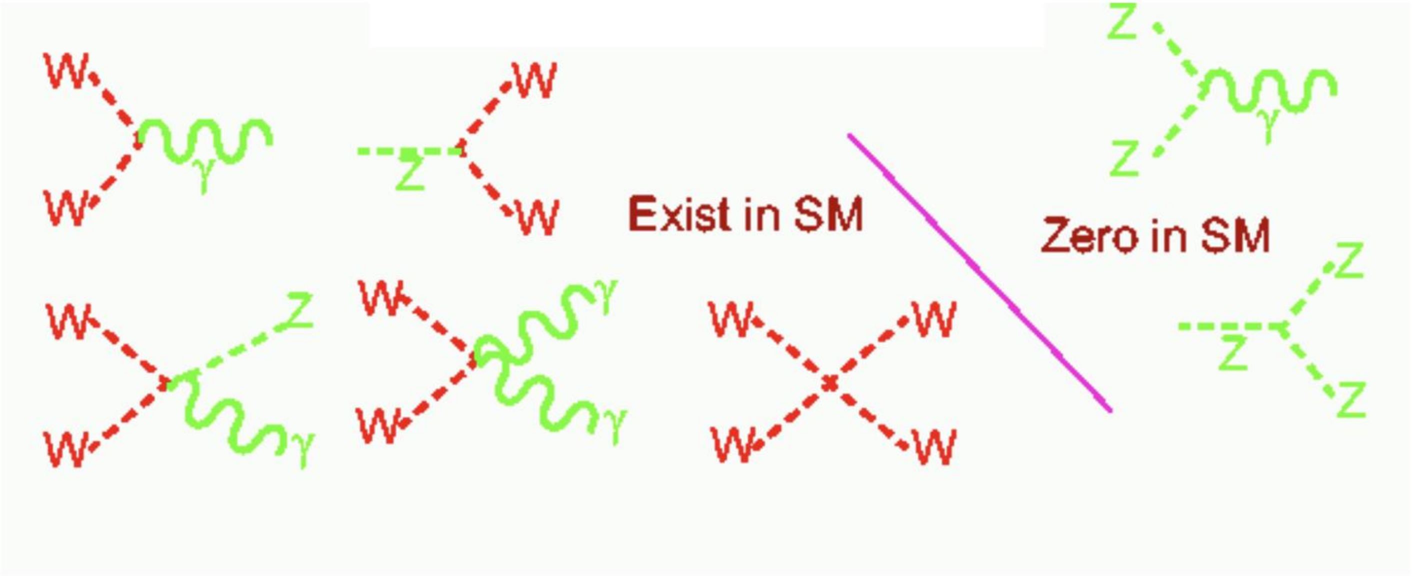
qqqq,qqll,qqnn,llvv,llll

DELPHI measures also

Zγ* cross section.

Going back to the beginning of MBI at LEP

Triple and quartic gauge couplings



TGC AND QGC are determined by the gauge structure of the theory:
SU(2) is a NON abelian theory: the gauge bosons interact between them
U(1) is abelian: photons do not have TGC.

Many measurements, no deviations observed within the large uncertainties

Why multiboson interaction?

Validation of perturbative calculations

Test of the non-abelian structure of Electroweak Theory

→ TGC and QGC

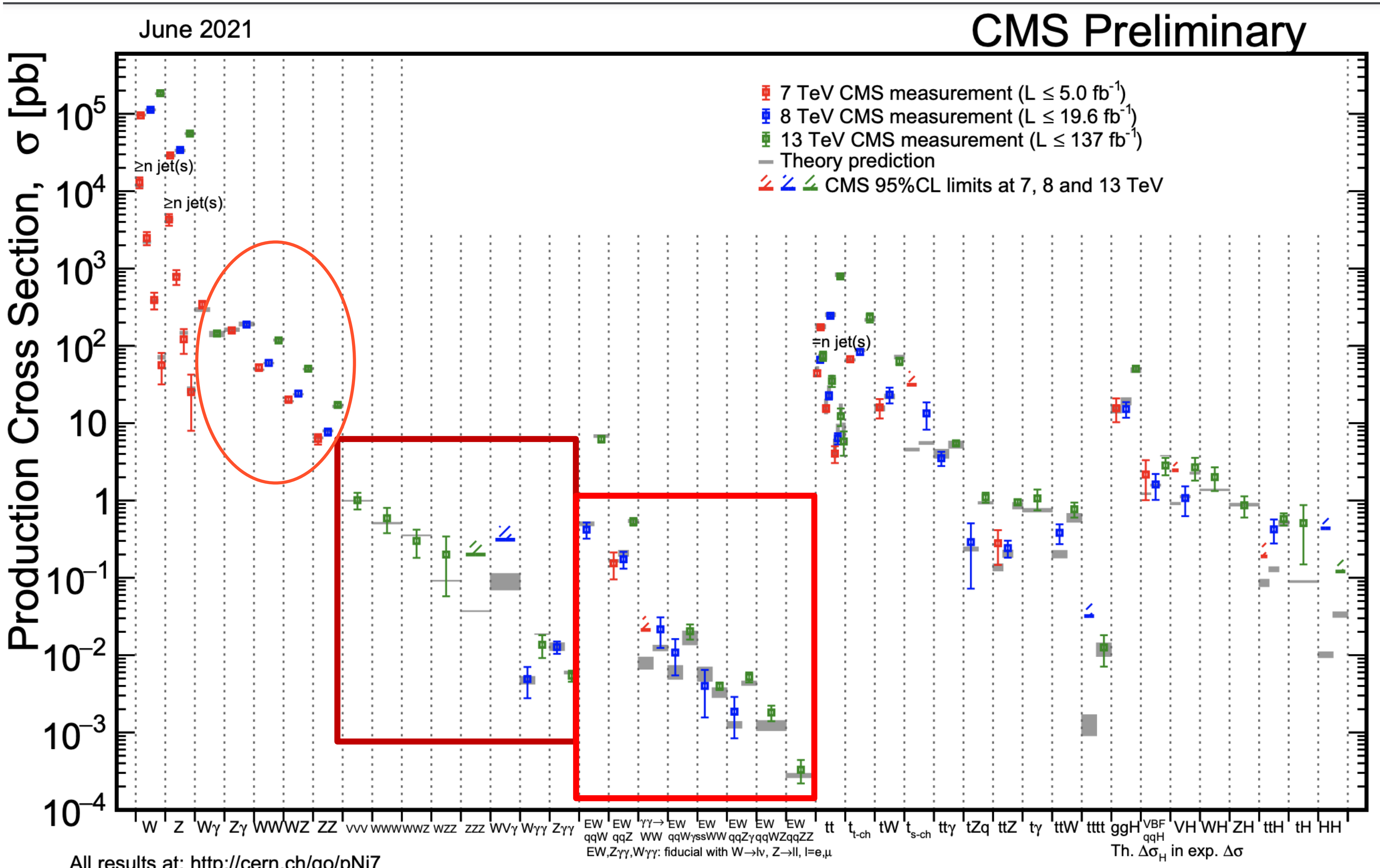
Vector Boson Scattering :

- unitarity preserved via Higgs contributions (if not rise of $V_L V_L$)
- test gauge structure of EW interactions, having tree-level sensitivity to quartic gauge couplings (QGC). Moreover the quartic interactions and their interplay with trilinear couplings lead to potentially large gauge cancellations
- couplings between the Higgs and gauge bosons at the same time, at energy scales which sensibly differ from the Higgs mass

Searches for new resonances/gauge bosons (via the rise of $V_L V_L$)

Search for new physics with EFT

Experimentally very challengy



Di-Bosons

Progress in theory

→Theory precision is key to harness full potential of LHC data!

Jonas Lindert

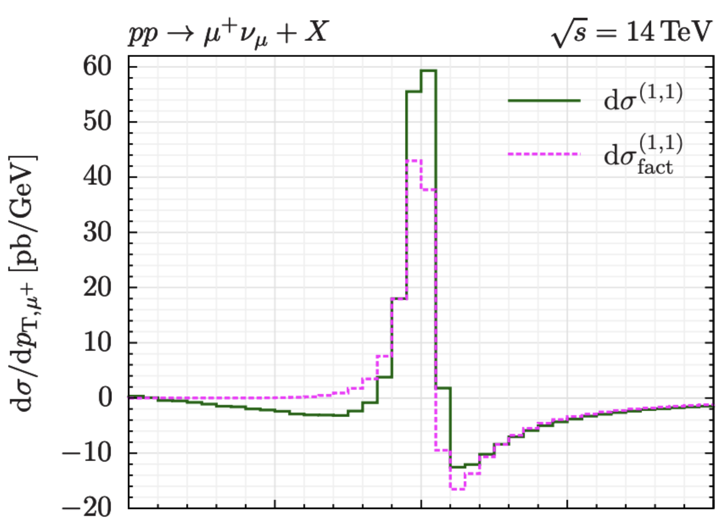
QCD and EW corrections to V, VV

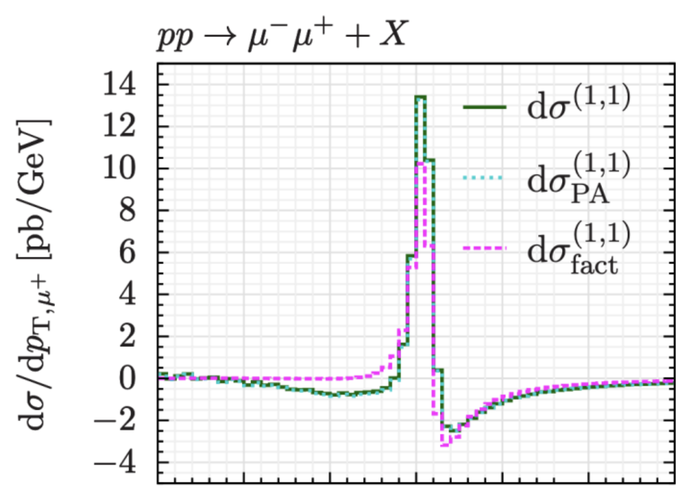
Massimiliano Grazzini

Drell –Yan: NNLO QCD + NLO EW

- mixed EW+QCD $\mathcal{O}(\alpha_s\alpha)$ correction complete for neutral current and complete for charged current except for bottleneck 2 loop virtual amplitude ->Pole Approximation used

- The mixed corrections to the muon p_T distribution are negative and at $p_T = 500$ GeV they amount to -20% (-15%) in the charged current (neutral current) case
- Neutral current: the impact of the mixed corrections up to invariant masses of 1 TeV is about -1.5% with respect to the NLO QCD result

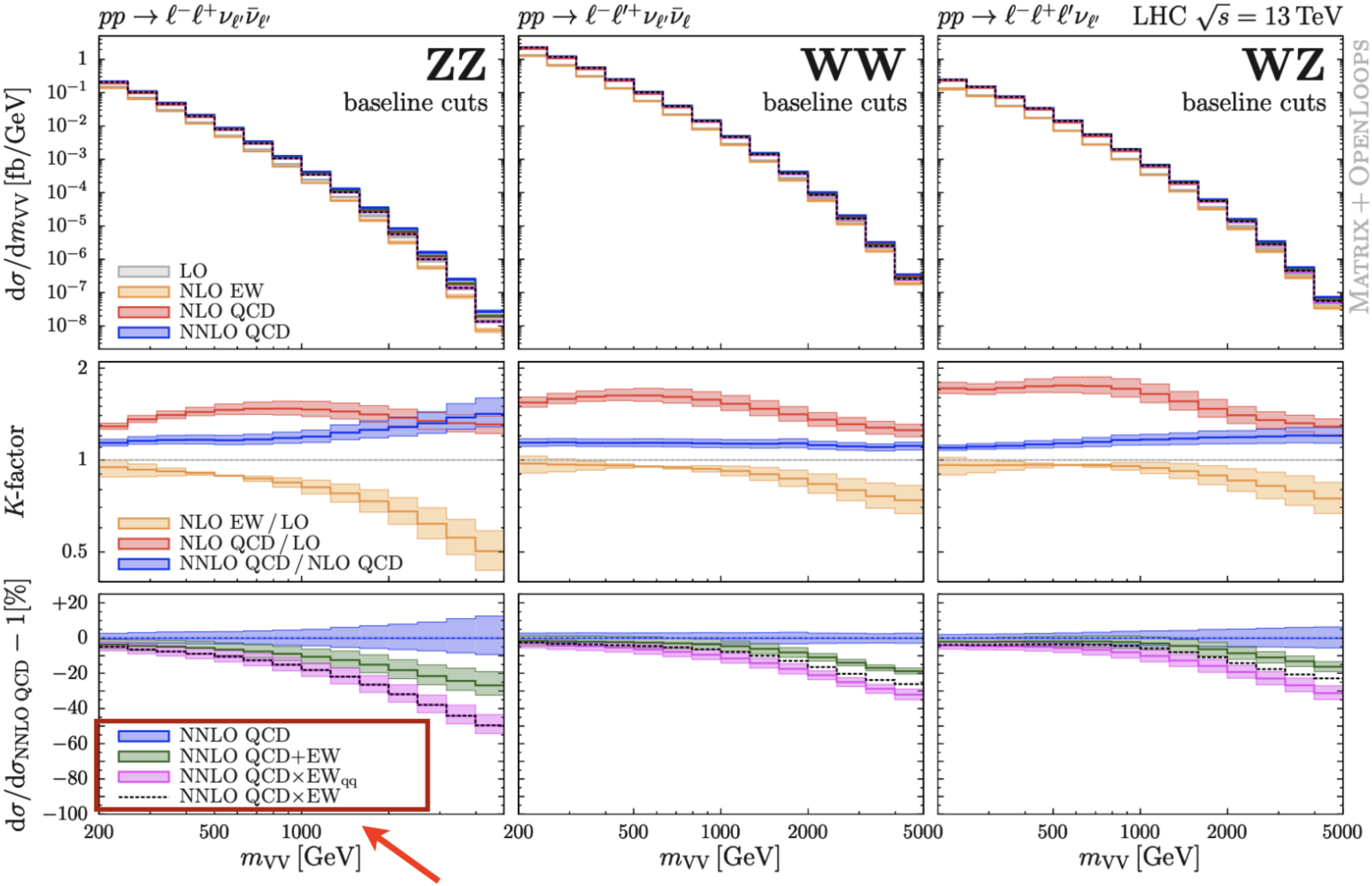




Massimiliano Grazzini

NNLO QCD+NLO EW for dibosons

Kallweit, Lindert, Pozzorini, Wiesemann, MG (2019)



Different combination prescriptions

Massimiliano Grazzini

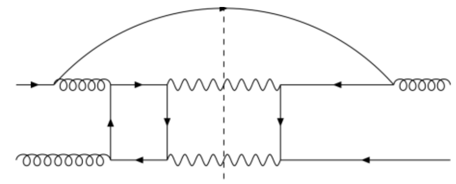
MATRIX V2.0

process	description
$pp/p\bar{p} \to H$	on-shell Higgs-boson production
$pp/p\bar{p} \to Z$	on-shell Z production (EW)
$pp/p\bar{p} \to W^-$	on-shell W^- production with CKM
$pp/p\bar{p} \to W^+$	on-shell W^+ production with CKM
$pp/p\bar{p} \to e^-e^+$	Z production with decay (EW)
$pp/p\bar{p} \to \nu_e\bar{\nu}_e$	Z production with decay (EW)
$pp/p\bar{p} \to e^-\bar{\nu}_e$	W^- production with decay and CKM (EW)
$pp/p\bar{p} \to e^+\nu_e$	W^+ production with decay and CKM (EW)
$pp/p\bar{p} \to \gamma\gamma$	$\gamma\gamma$ production
$pp/p\bar{p} \to e^-e^+\gamma$	$Z\gamma$ production with decay
$pp/p\bar{p} \to \nu_e\bar{\nu}_e\gamma$	$Z\gamma$ production with decay
$pp/p\bar{p} \to e^-\bar{\nu}_e\gamma$	$W^-\gamma$ with decay
$pp/p\bar{p} \to e^+\nu_e\gamma$	$W^+\gamma$ with decay
$pp/p\bar{p} \to ZZ$	on-shell ZZ production
$pp/p\bar{p} \to W^+W^-$	on-shell W^+W^- production
$pp/p\bar{p} \to e^-\mu^-e^+\mu^+$	ZZ production with decay (ggNLO, EW)
$pp/p\bar{p} \to e^-e^-e^+e^+$	ZZ production with decay (ggNLO, EW)
$pp/p\bar{p} \to e^-e^+\nu_\mu\bar{\nu}_\mu$	ZZ production with decay (ggNLO, EW)
$pp/p\bar{p} \to e^-\mu^+\nu_\mu\bar{\nu}_e$	W^+W^- production with decay (ggNLO, EW)
$pp/p\bar{p} \to e^-e^+\nu_e\bar{\nu}_e$	ZZ / W^+W^- production with decay (ggNLO, EW
$pp/p\bar{p} \to e^-\mu^-e^+\bar{\nu}_\mu$	W^-Z production with decay (EW)
$pp/p\bar{p} \to e^-e^-e^+\bar{\nu}_e$	W^-Z production with decay (EW)
$pp/p\bar{p} \to e^-e^+\mu^+\nu_\mu$	W^+Z production with decay (EW)
$pp/p\bar{p} \to e^-e^+e^+\nu_e$	W^+Z production with decay (EW)

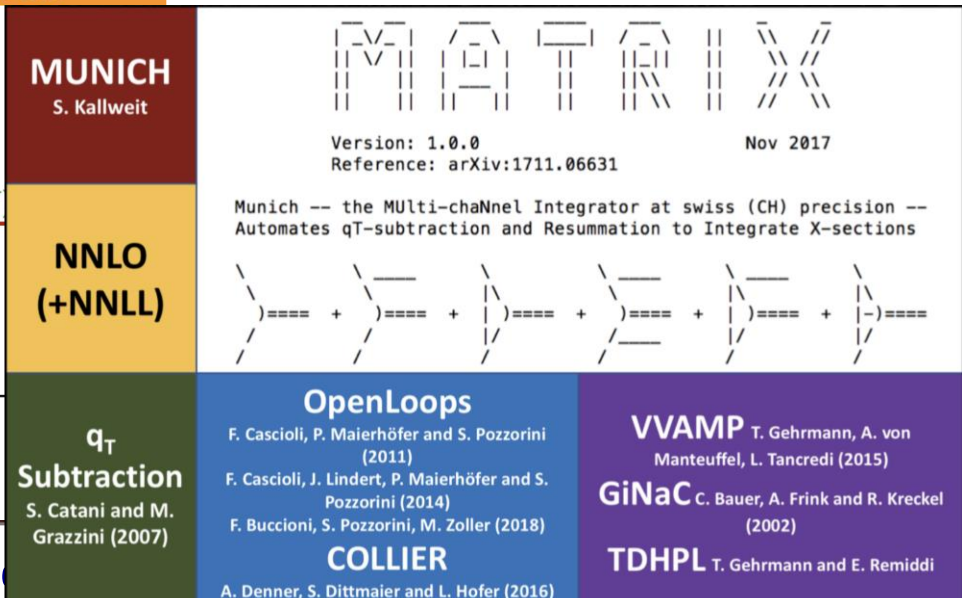
NNLO QCD + NLO EW for all the single and massive diboson processes

NLO QCD for loop induced gg contribution for WW and ZZ

Already at NNLO the two production channels mix



We combine both calculations in MATRIX



EW corrections to V, VV

Jonas Lindert

- Many exciting new results for EW corrections to MBI processes pushing theory precision to the O(1-10%) level

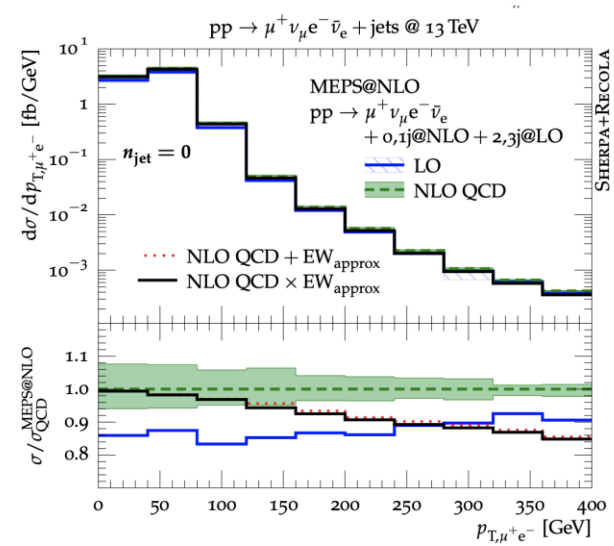
In MC : aMC@NLO, POWHEG, Sherpa, MATRIX, …

VV

- NNLO QCD + NLO EW available in MATRIX+OpenLoops for all massive VV processes: largest uncertainty at large energies from NNLO QCD-EW
- NLO QCD + EW for polarised VV: at inclusive level universal correction, but non-universalities at differential level
- NLO (QCD + EW) + PS (QCD + QED) for VV available in POWHEG: resonance-aware matching available at NLO EW.

V+jets / VV+jets

- QCD and EW processes formally overlap at NLO
- very rich phenomenology
- EW corrections become dominant in VBF/VBS phase-space



Simone Alioli

GENEVA MC at NNLL

Introduction

GENEVA combines the 3 theoretical tools we use for QCD predictions into a single framework:

1) Fully differential fixed-order calculations

- up to NNLO via *N*-jettiness or q_T-subtraction

2) Higher-logarithmic resummation

- up to NNLL′ or N3LL via SCET or RadISH

3) Parton showering, hadronization and MPI

- recycling standard SMC. Using PYTHIA8 now, any SMC supporting LHEF and user-hook vetoes is OK

COMPARISON with **MATRIX**

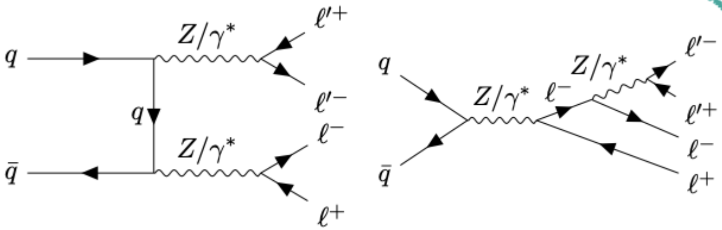
Resulting Monte Carlo event generator has many advantages:

- consistently improves perturbative accuracy away from FO regions
- provides event-by-event systematic estimate of theoretical perturbative uncertainties and correlations
- gives a direct interface to SMC hadronization, MPI modeling and detector simulations.

Gabriel Koole

MiNNLO$_{PS}$

$q\bar{q}$

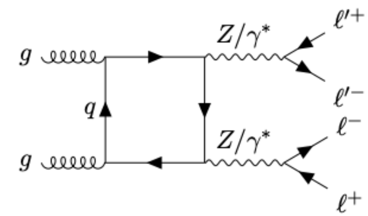


16%

NNLO+PS with MiNNLO$_{PS}$

μ_R, μ_F from MiNNLO$_{PS}$

gg



100%

NLO+PS with POWHEG

$\mu_R = \mu_F = m_{T,4\ell}$

$$pp \to \ell^+\ell^-\ell^{(\prime)+}\ell^{(\prime)-}$$

nNNLO+PS

5%

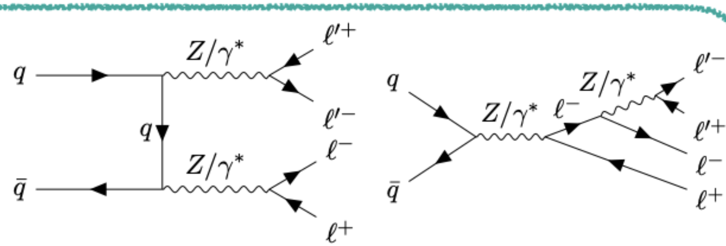
- all (non-)resonant topologies included
  spin correlations, interferences and off-shell effects accounted for

- implementation in POWHEG-BOX-RES & interface to MATRIX [Lombardi, Wiesemann, Zanderighi '20]

MiNNLO$_{PS}$

Gabriel Koole

$q\bar{q}$



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μ_R, μ_F from MiNNLO$_{PS}$

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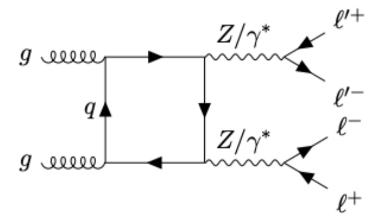

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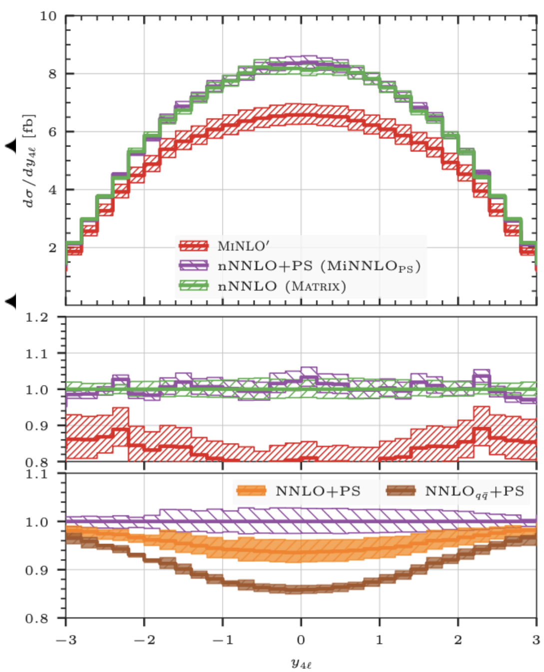
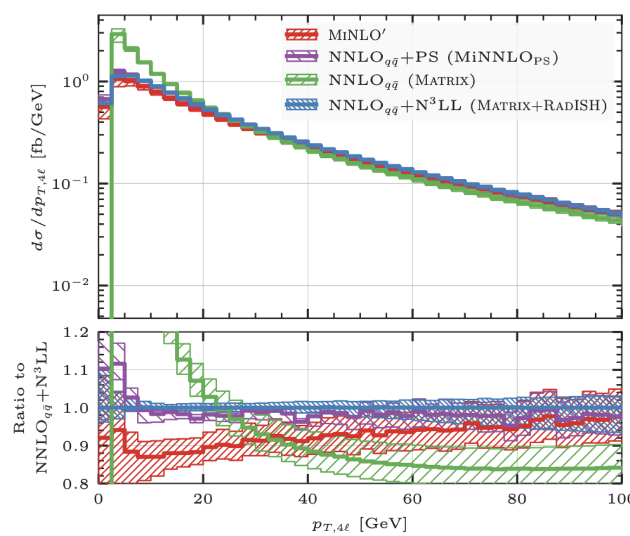
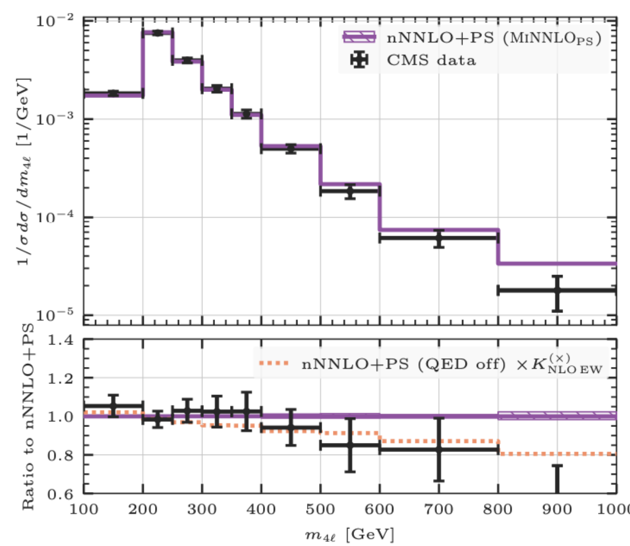


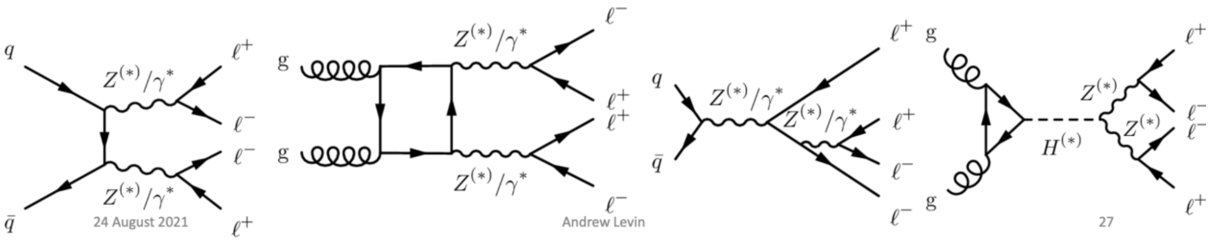


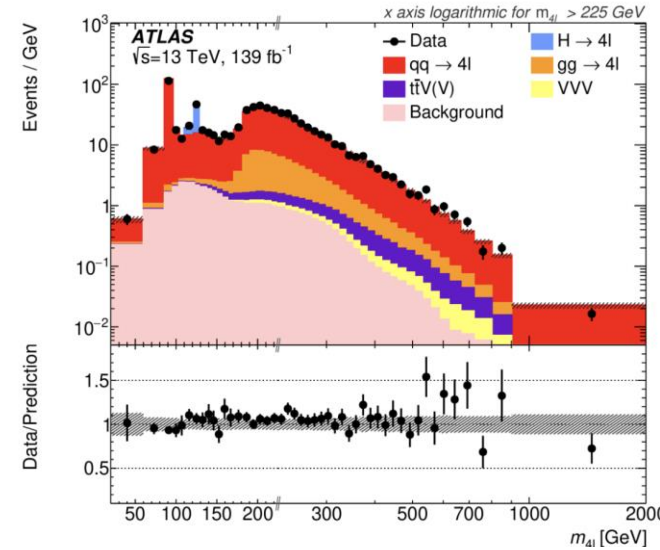


4l final state

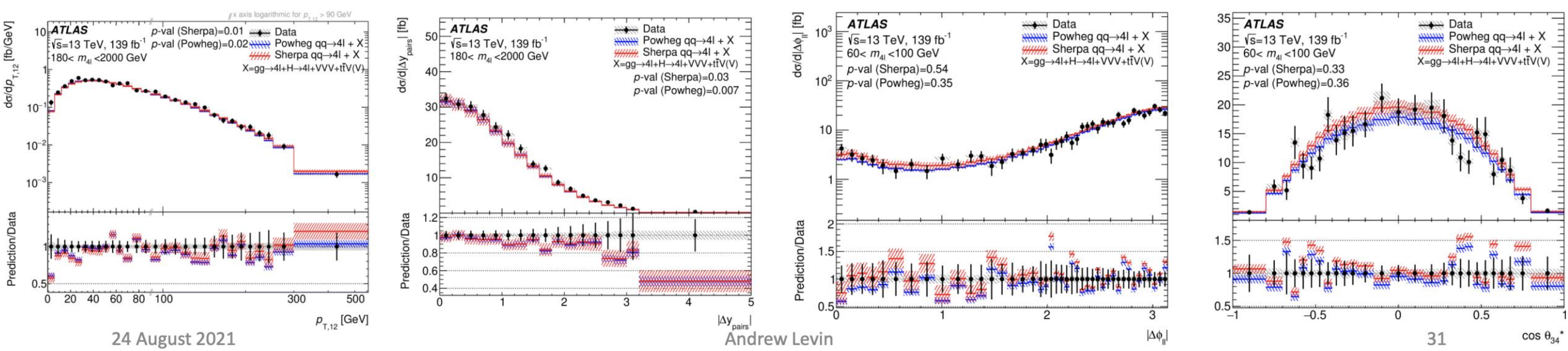
Andrew Levin

ZZ / 4leptons differential cross section



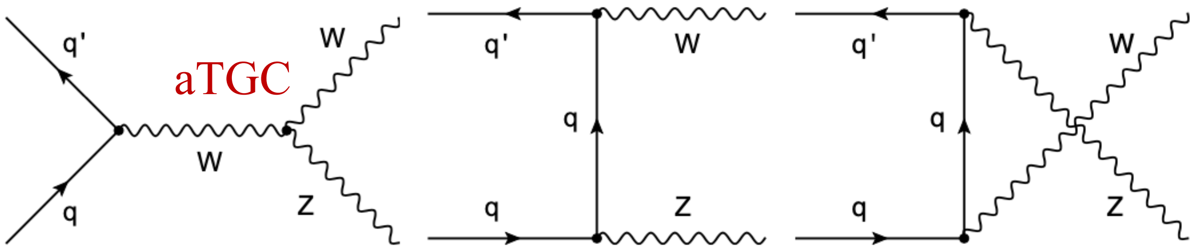


- Generally good agreement found for all observables, except $|\Delta y_{pairs}|$, where Powheg and Sherpa badly underpredict the yield in the highest bin



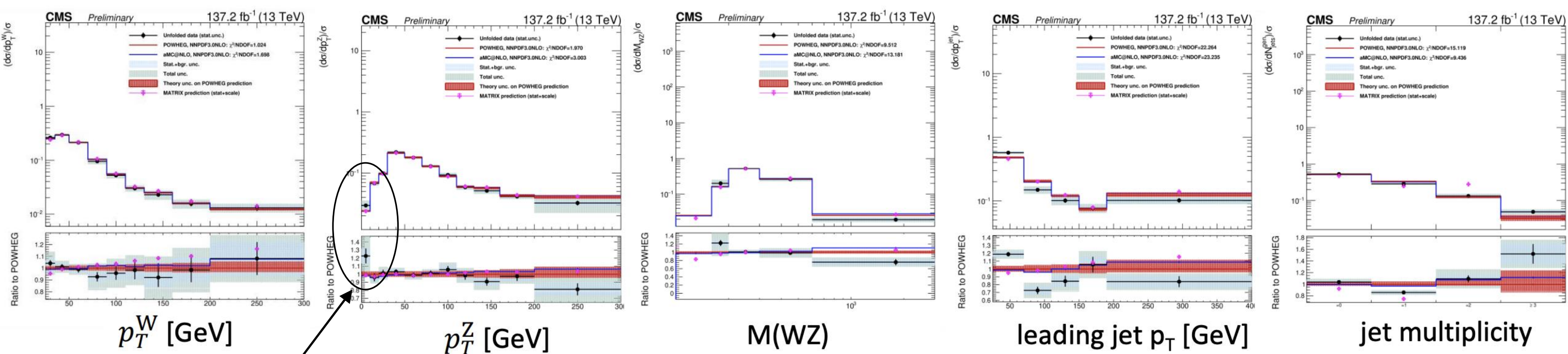
WZ cross section

Andrew Levin



TOTAL XS: agreement with Matrix at NNLO QCD + NLO EW

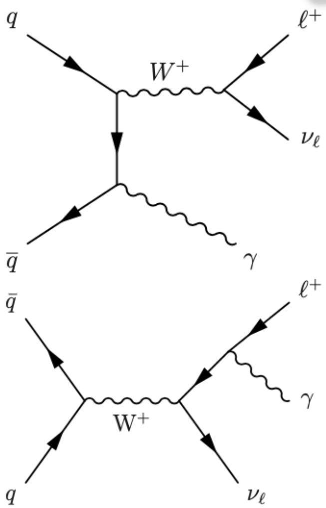
- Generally good agreement for p_T^W, p_T^Z, and M(WZ)

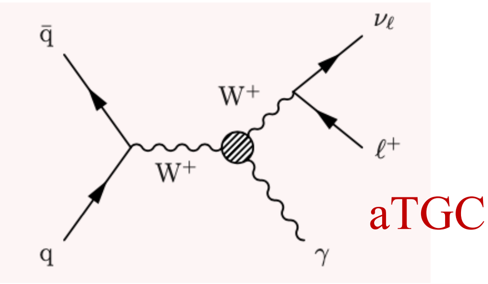


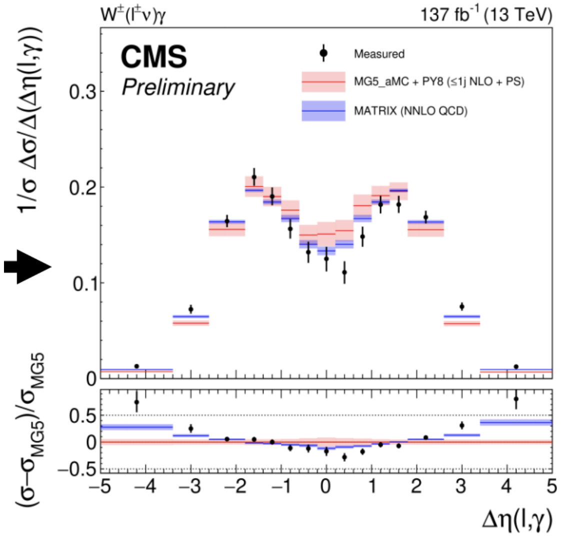
Suggestion: try to compare with Matrix+Radish to see if the discrepancy at low pT is understandable by resummation effects.

Wγ

Andrew Levin





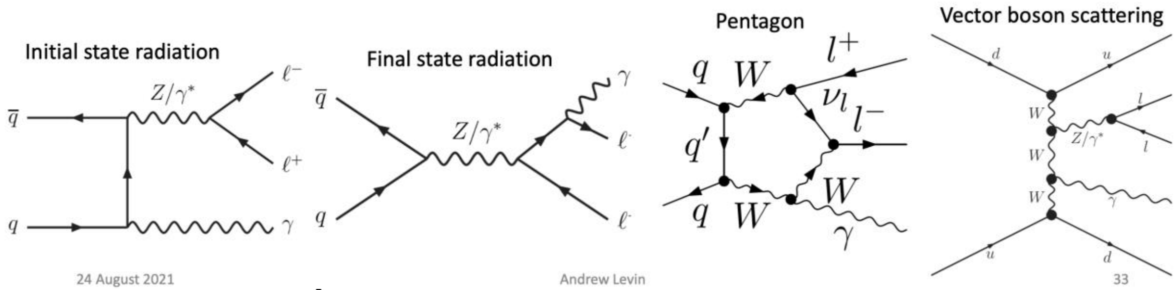


- Phenomenon called radiation amplitude zero: a 0 in the LO cross section at $\Delta\eta(l,\gamma) = 0$

- Clear preference for MATRIX at higher photon p_T and higher $\Delta R(l,\gamma)$
- Neither MATRIX nor MG5_aMC predicts well the jet multiplicity distribution
- Slight mismodeling of peak in m_T^{cluster} (transverse mass of the lνγ) distribution

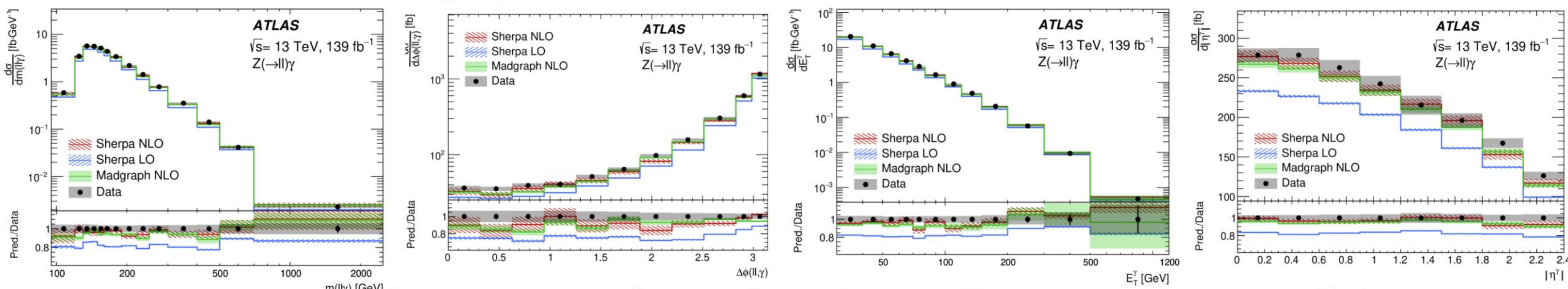
Zγ

Andrew Levin

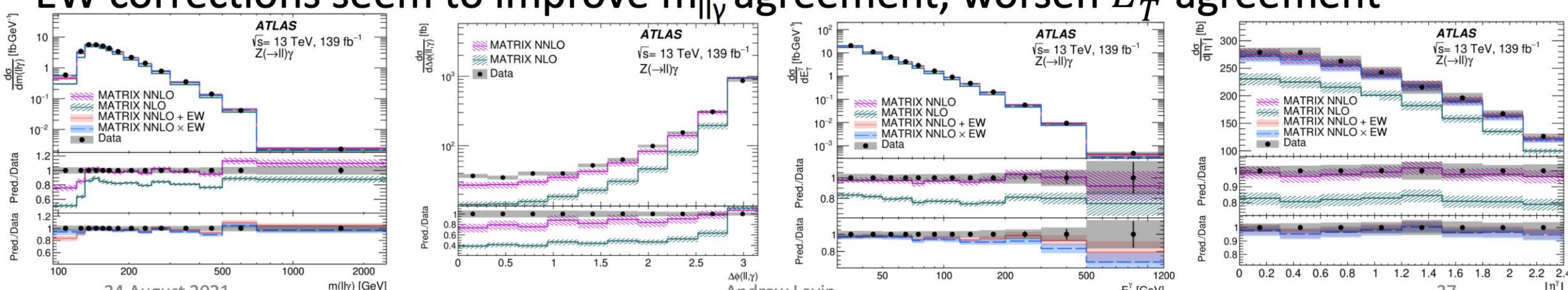


Total XS in good agreement with MATRIX

- Sherpa NLO and Madgraph NLO reproduce results within statistical uncertainties



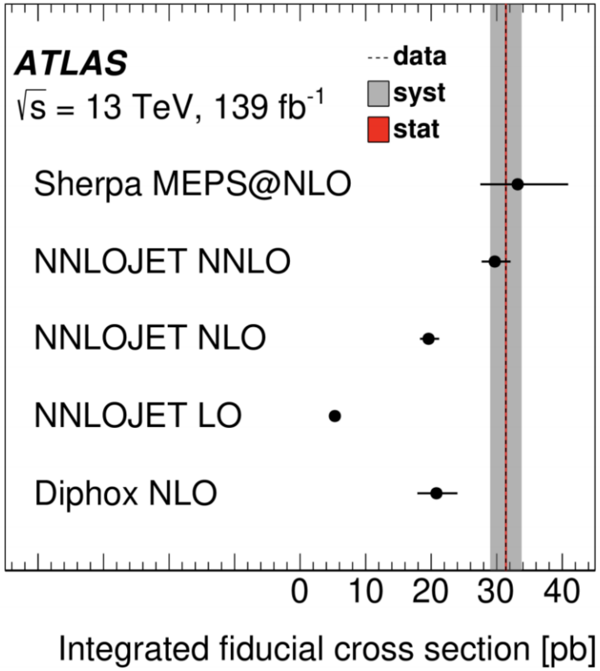
- MATRIX NNLO prediction reproduces the photon E_T and η shape well, but is somewhat off for other variables
- EW corrections seem to improve $m_{ll\gamma}$ agreement, worsen E_T^{γ} agreement



Andrew Levin

ATLAS: γγ cross section (VI)

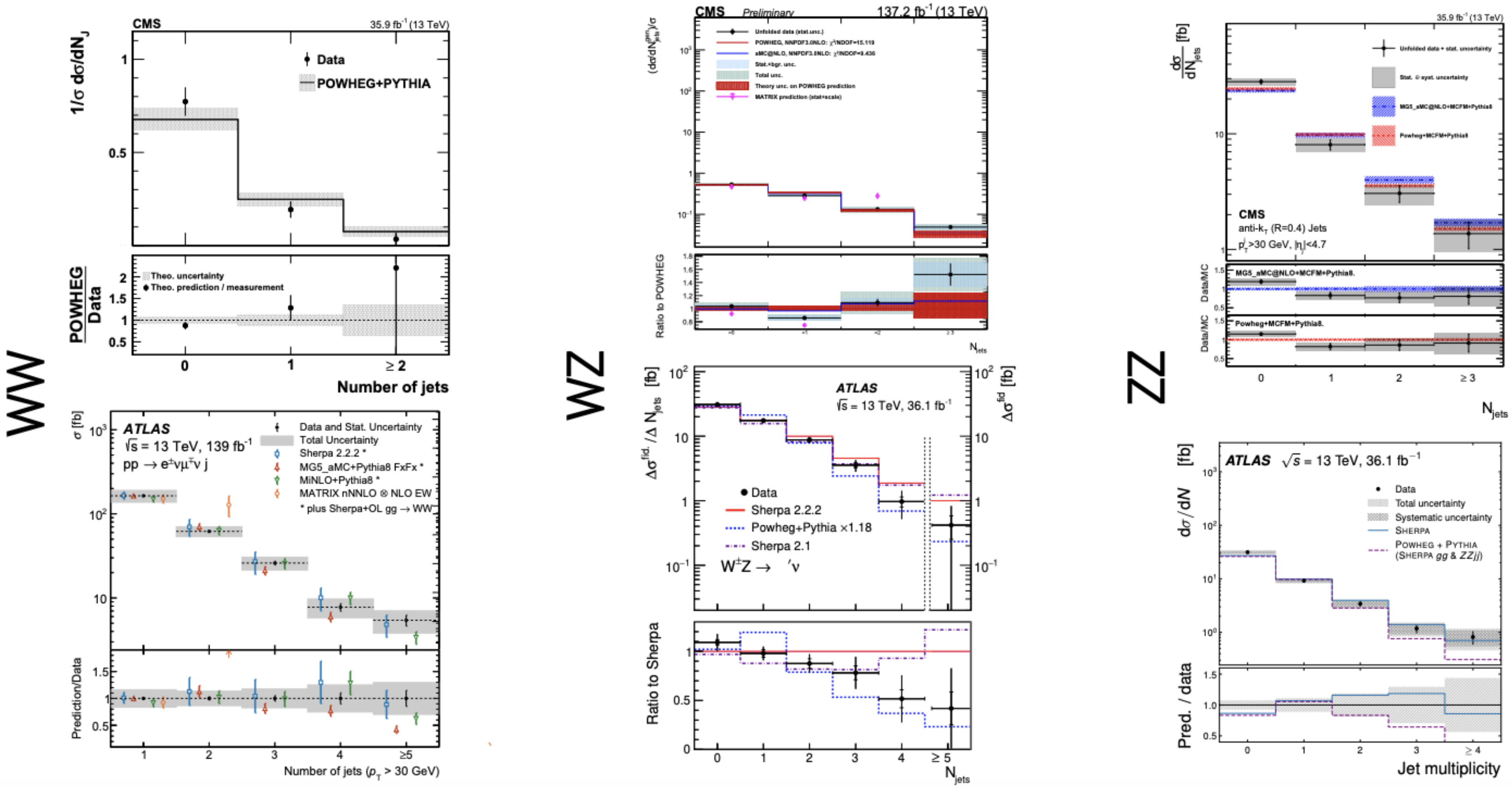
- Inclusive cross section based on integral of p_{T,γ_2} differential cross section (consistent if other variables are used instead of p_{T,γ_2})
- NNLOJET NNLO and Sherpa MEPS@NLO both predict inclusive cross section well
- LO cross section is almost a factor of 6 too low!
- Statistical component of uncertainty almost negligible



VV+jets

Hannes Mildner

- Large Run 2 dataset, advanced analysis techniques, and precise theoretical prediction enable precision studies of *VV*+jets
- CMS and ATLAS both published measurements of jets in *WW*, *WZ*, and *ZZ* production
- Good agreement with NLO QCD predictions of *VV*+jet production



Studies on polarized VV

Giovanni Pelliccioli

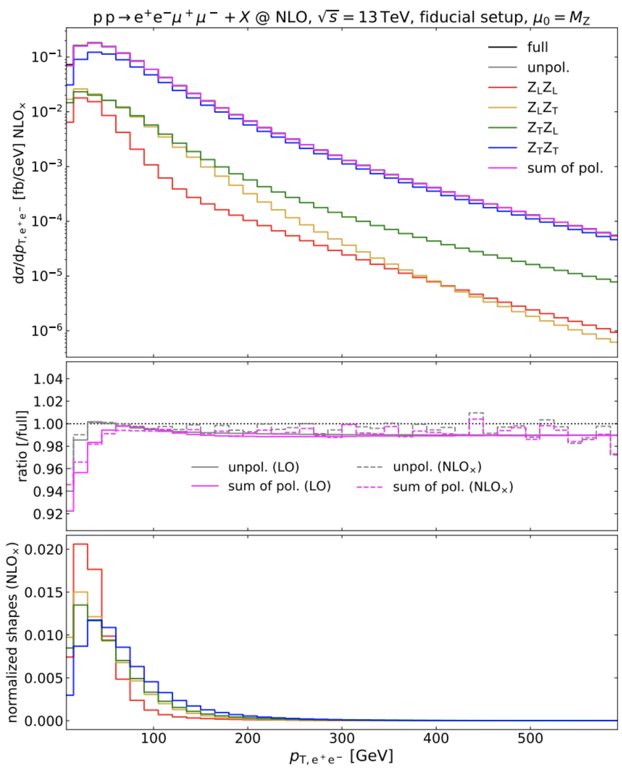
Important: the definition of the frame. Best is the VV Center-of-Mass

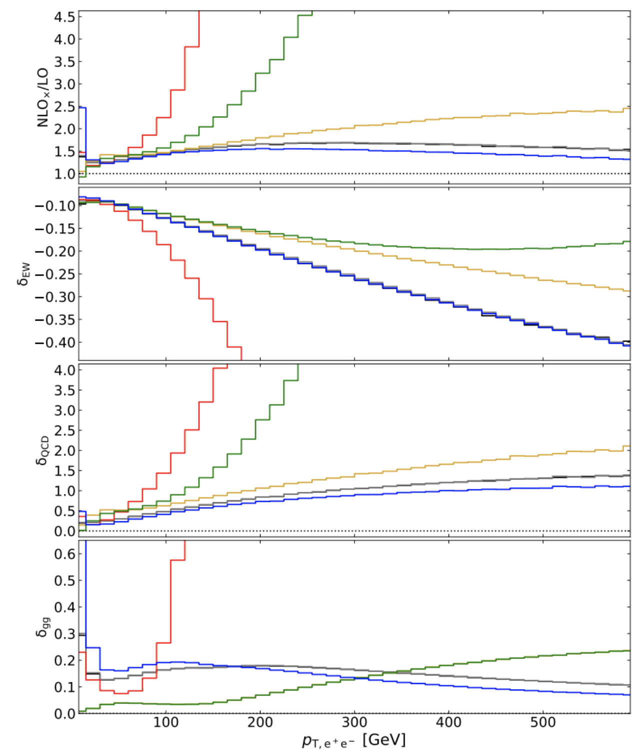
the V boson are on-shell

the cuts on the leptons affect the interference terms

NLO to VV : large effect (+45% QCD, -11 % EW ...)

expecially on Longitudinal polarization, with kinematic dependence





NNLO for polarized VV production

Calculation for on-shell W

Andrei Popescu

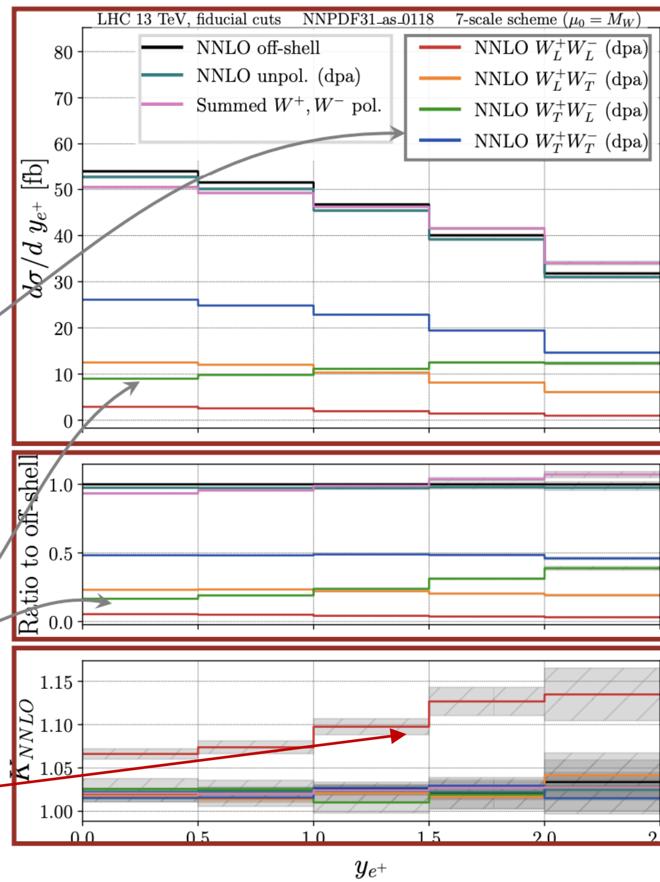
- **NNLO corrections** are important to reduce theory uncertainty, and are **well-behaved**.
- QCD corrections are polarisation dependent and are particularly strong for $W_L^+ W_L^-$ setup.
- Loop-induced channel has a significant effect on both on results and scale uncertainty.

Unpolarised setups:

- DPA vs off-shell shows non-resonant background
- Polarisation sum vs DPA shows interference effects

Doubly-polarised setups:

- Individual polarisation setup shape
- Relative contribution of each setup



Absolute values

Relative to off-shell

$\sigma_{\text{NNLO}}/\sigma_{\text{NLO}}$

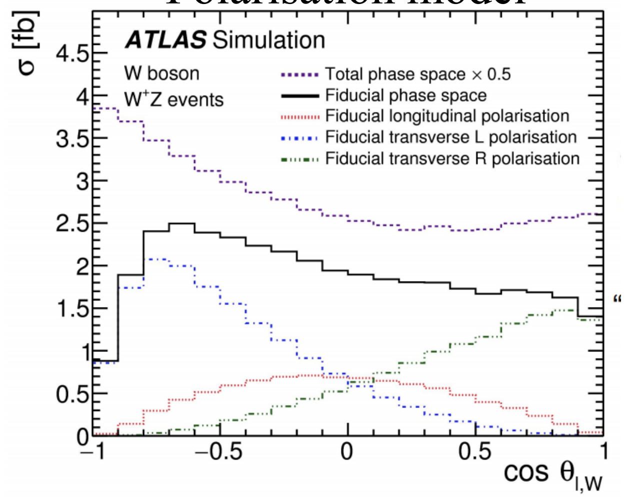
- Rising K-factor for LL setup corrections – different from other polarisations

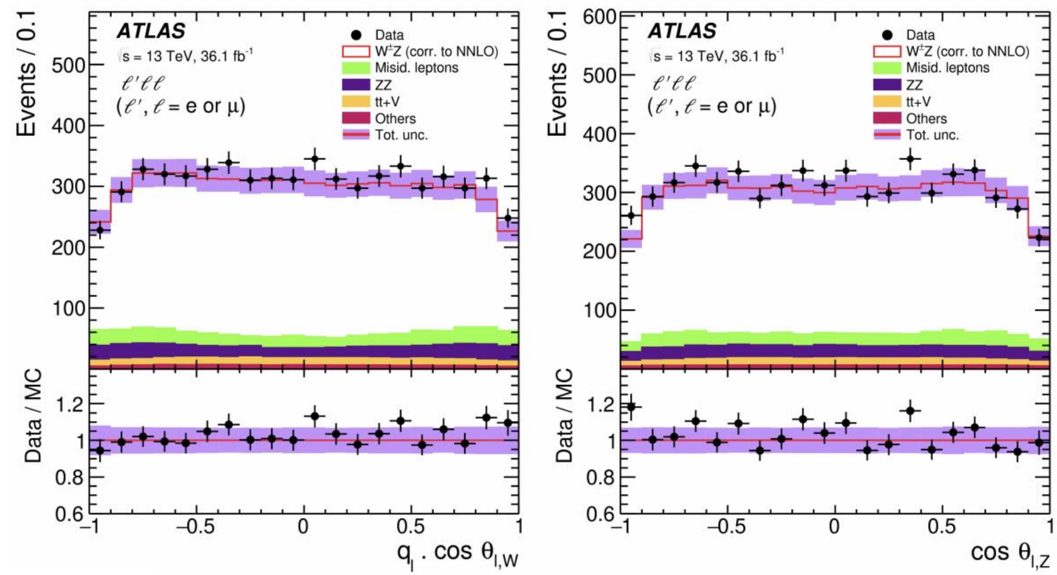
First observation of V Polarization in WZ

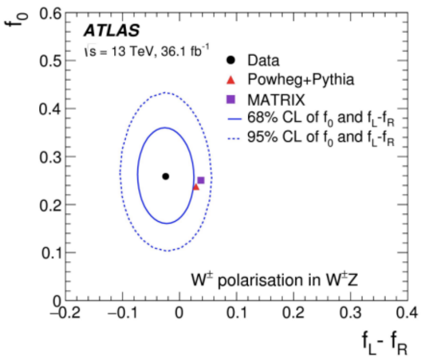
Carlo Francisco Erice Cid

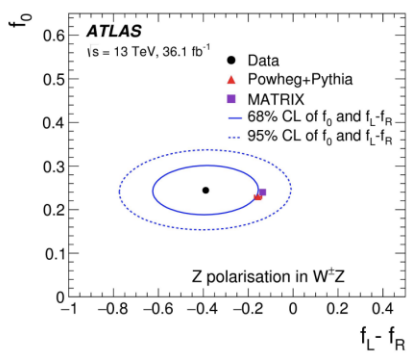
Reference frame to be defined - not the same in Atlas and CMS

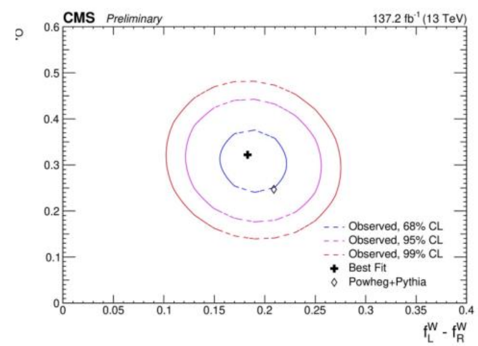
Polarisation model

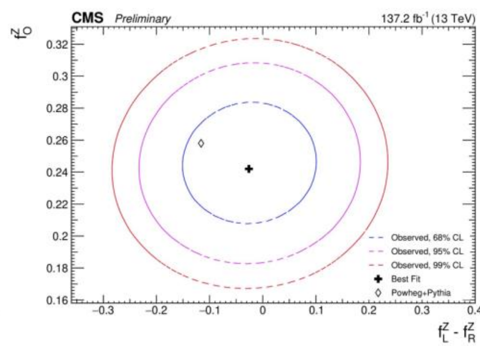












Very first results at >5 sigma (or more) significance !

But statistically limited at Run2 and it will be as well for the Run3…

Dominik Duka

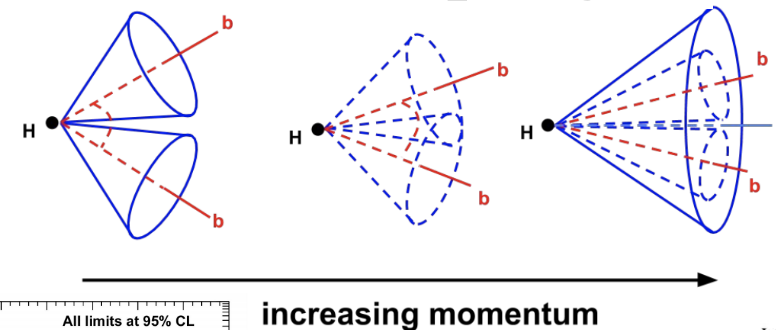
Search for resonances in VV,VH

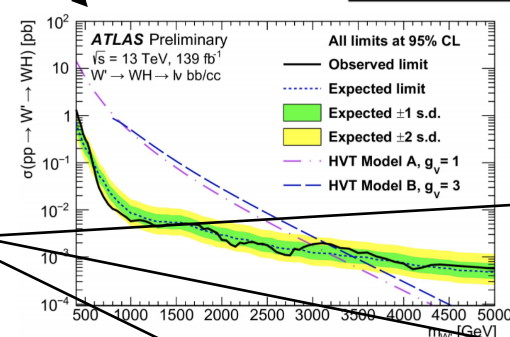
Many analyses in ATLAS and CMS:

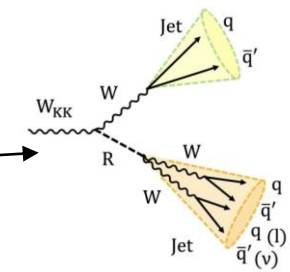
- atlas W' → Wh → lν bb
- Z' → Zh → llbb
- cms W' → WW, WZ, Wh
- Z' → ZZ, ZW, Zh
- atlas X → γV
- cms H+ → fermiophobic
- cms X → aa → 4b
- atlas X → hh --> 4b, 2b2tau
- cms Wkk → W+Radion → WWW
- atlas H++ search

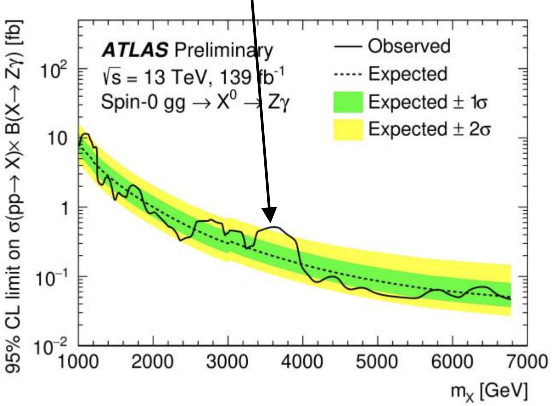
.....

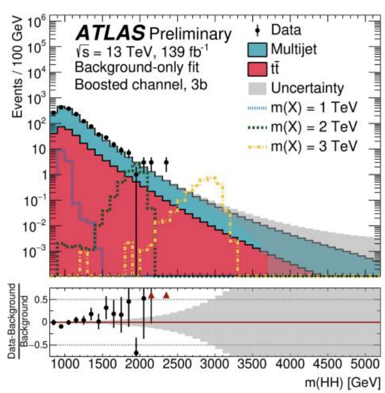
Boosted topologies:

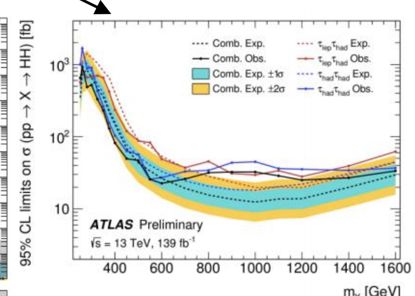


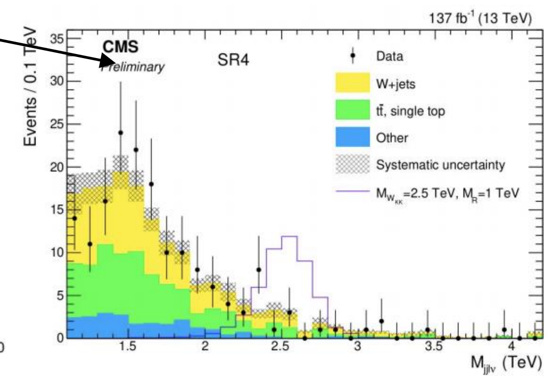












HH search

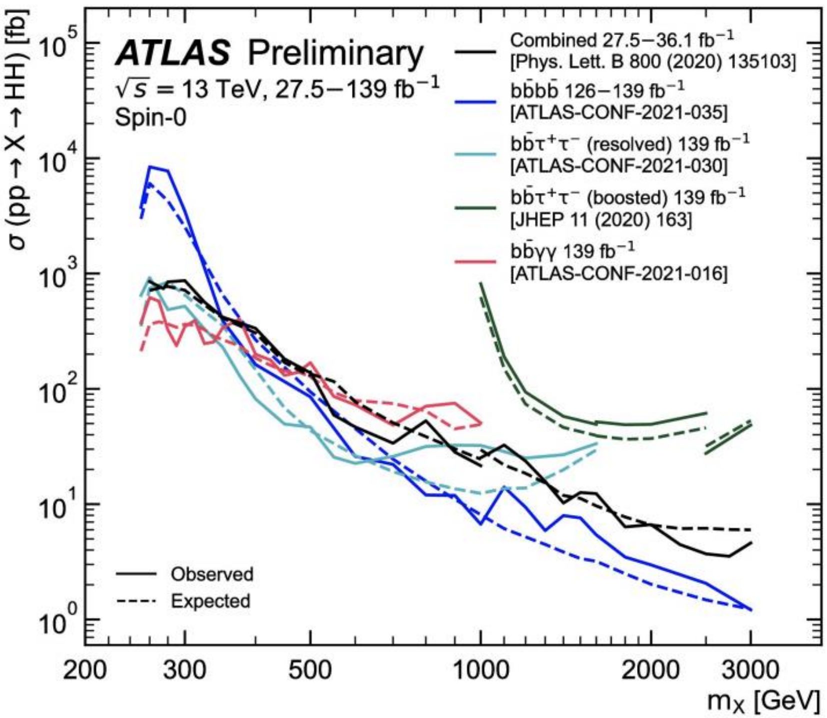
Dominik Duka

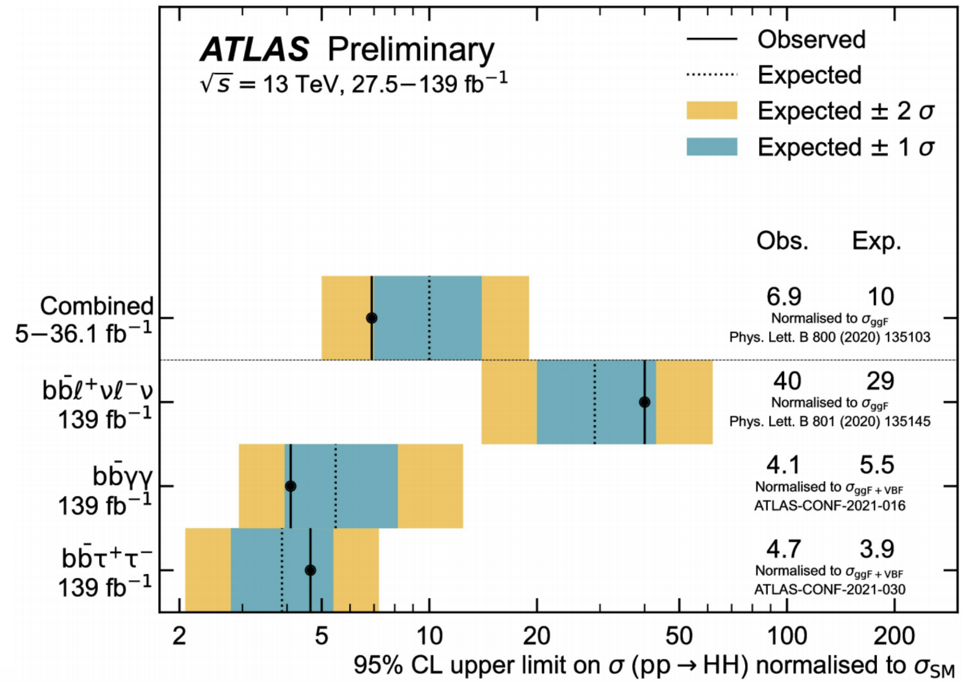
Viviana Cavaliere

Resonant and non resonant

Targeted *HH* decays

	bb
bb	33%
WW	25%
ττ	7.4%
ZZ	3.1%
γγ	0.26%



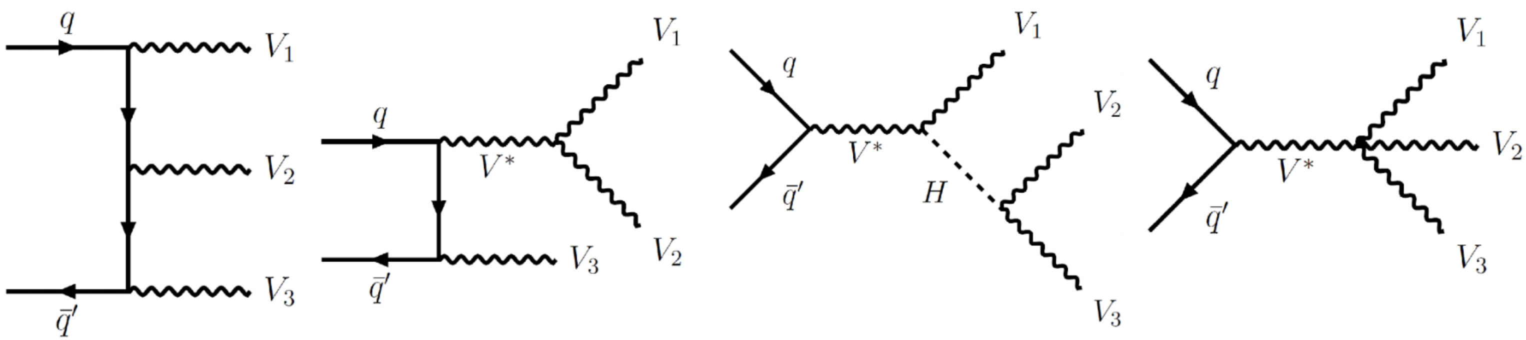


Analyses with Run2 data have sensitivity expected with HL-LHC !

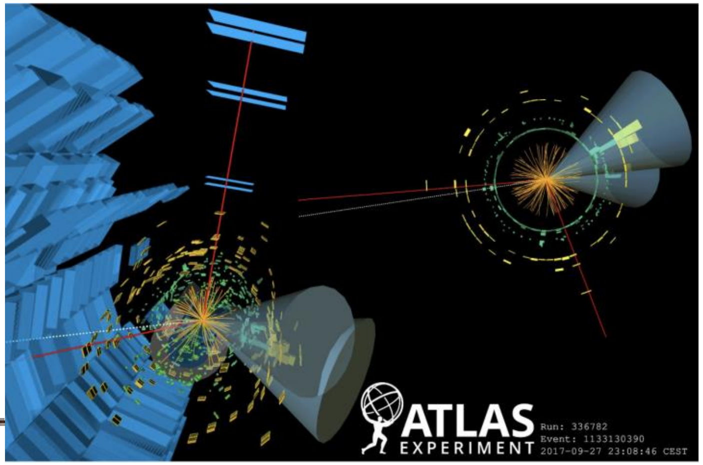
VVV: Tri-boson production

Siyuan Sun
Alberto Mecca

- Direct measurement of gauge boson self-coupling and precision test of SM



- Finely balanced cancellations between QGC, TGC, Higgs amplitudes is needed to preserve unitarity at high CM energies.
- Any anomalous HVV, QGC and TGC coupling can disturb the balance and create large cross-sections at high energies.



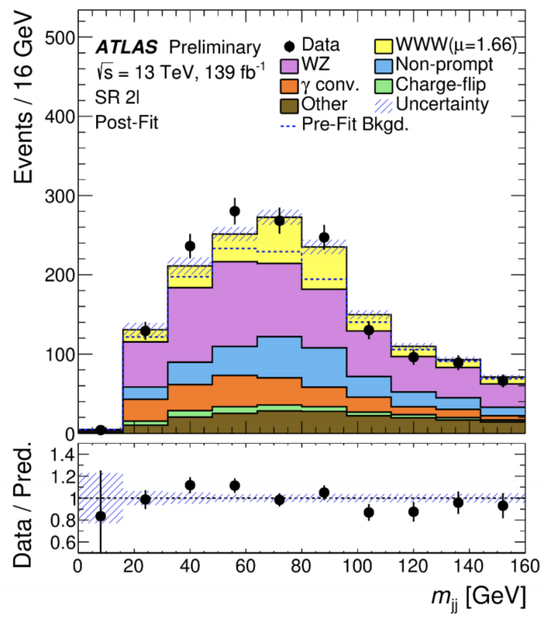
Siyuan Sun

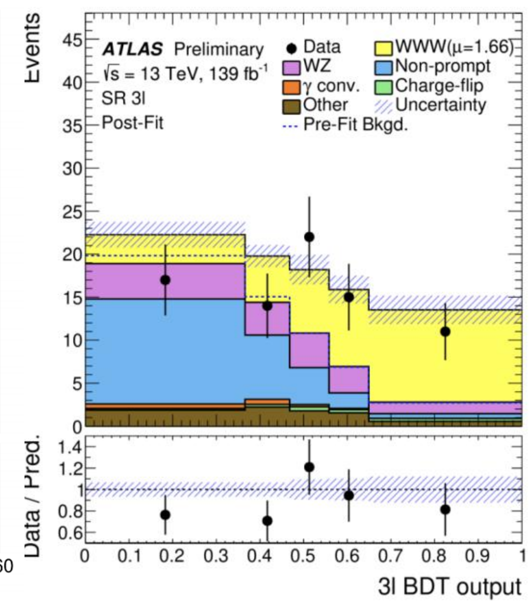
WWW Atlas

- Avoids SM processes that pair produce oppositely charged leptons

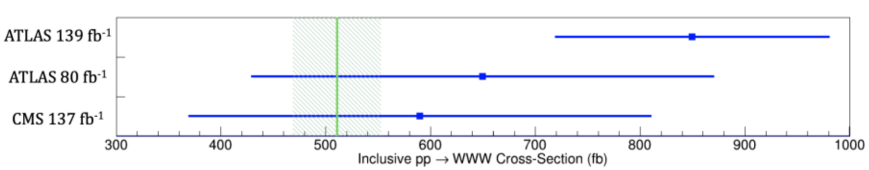
	Detector Signatures		
$W^{\pm}W^{\pm}W^{\mp} \to 2l2\nu 2j$	$e^{\pm}e^{\pm}jj + E_T^{miss}$	$e^{\pm}\mu^{\pm}jj + E_T^{miss}$	$\mu^{\pm}\mu^{\pm}jj + E_T^{miss}$
$W^{\pm}W^{\pm}W^{\mp} \to 3l3\nu$	$e^{\pm}e^{\pm}\mu^{\mp} + E_T^{miss}$		$\mu^{\pm}\mu^{\pm}e^{\mp} + E_T^{miss}$

	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
WZ	80.6 ± 5.7	344 ± 22	171 ± 10	16.4 ± 1.4
Charge-flip	30.3 ± 7.2	18.8 ± 4.5	–	1.7 ± 0.4
γ conversions	62.1 ± 8.7	142 ± 15	–	1.5 ± 0.1
Non-prompt	16.6 ± 4.1	138 ± 24	98 ± 21	26.3 ± 2.9
Other	22.8 ± 3.7	102 ± 15	59.7 ± 9.0	8.0 ± 0.9
Total predicted	242 ± 11	872 ± 22	414 ± 17	89.7 ± 5.4
Data	242	885	418	79





Analysis	μ	σ[pb]	Reference
ATLAS @ 139fb^{-1}	1.66 ± 0.28	0.85 ± 0.13	CDS
ATLAS @ 80fb^{-1}	1.29 ± 0.44	0.65 ± 0.22	Physics Let. B. 2019
CMS @ 137fb^{-1}	1.15 ± 0.45	0.59 ± 0.22	Physics Rev. L. 2020

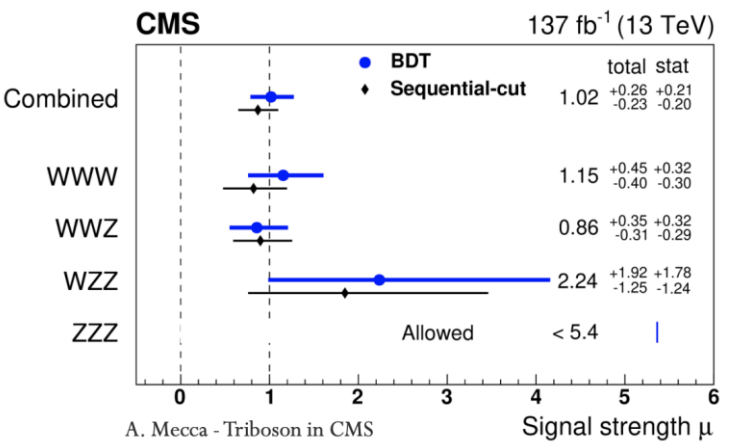


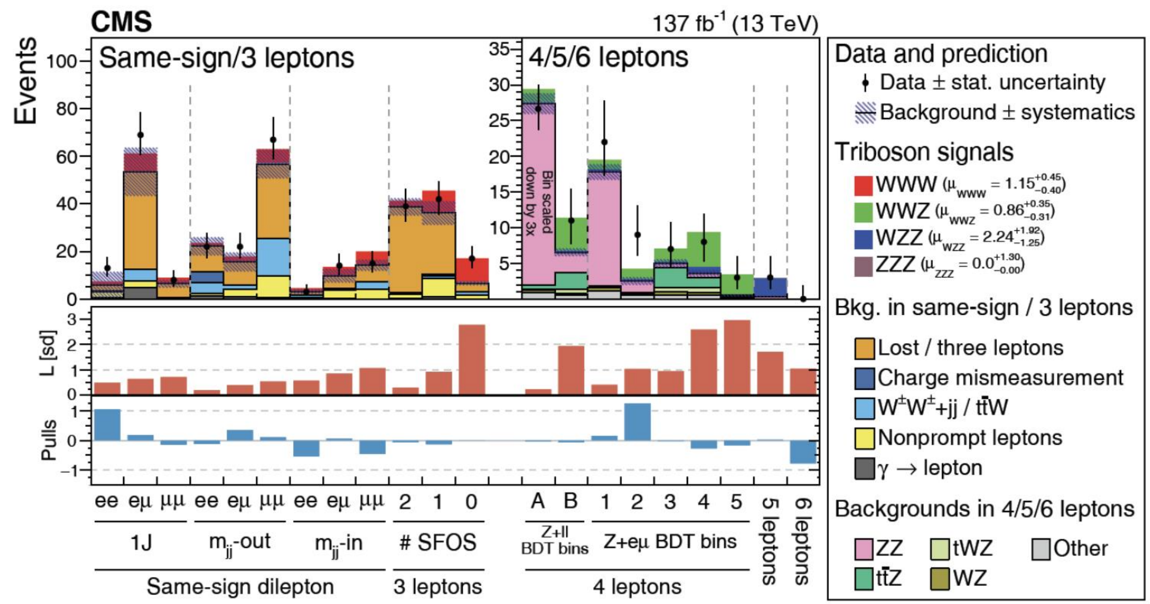
VVV in CMS

Alberto Mecca

Process	Theoretical cross section (NLO)	σ_{TOT} x BR	Expected events for 137 fb^{-1}
WWW	509 fb	54.0 fb *	7 400
WWZ	354 fb	4.12 fb	560
WZZ	91.6 fb	0.36 fb	50
ZZZ	37.1 fb	0.05 fb	6.9

- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\ell^{\pm}\, 2\nu\, q\bar{q}'$ **2 charged leptons**
- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\ell^{\pm}\ell^{\mp}\, 3\nu$ **3 charged leptons**
- $W^{\pm}W^{\mp}Z \rightarrow \ell^{\pm}\ell^{\mp}\, 2\nu\, \ell^{\pm}\ell^{\mp}$ **4 charged leptons**
- $W^{\pm}Z\,Z \rightarrow \ell^{\pm}\, \nu\, 2(\ell^{\pm}\ell^{\mp})$ **5 charged leptons**
- $Z\,Z\,Z \rightarrow 3(\ell^{\pm}\ell^{\mp})$ **6 charged leptons**



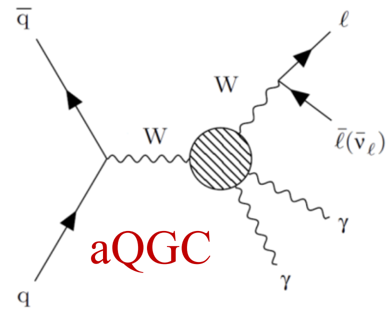


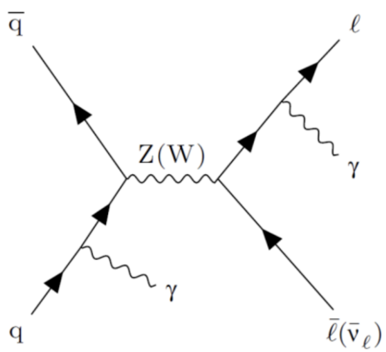
Alberto Mecca

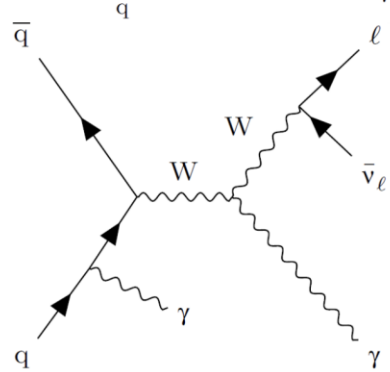
Vγγ in CMS

Wγγ and Zγγ at 13 TeV

Process	Theo. Cross section (NLO)
Wγγ	2 000 fb
Zγγ	680 fb



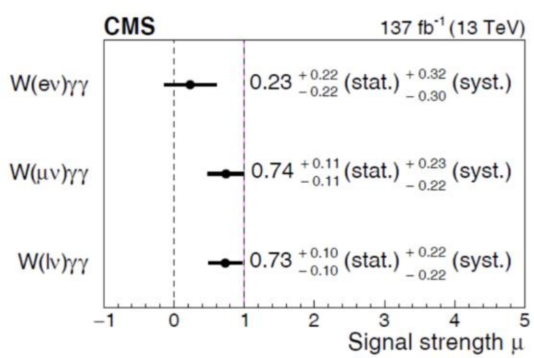


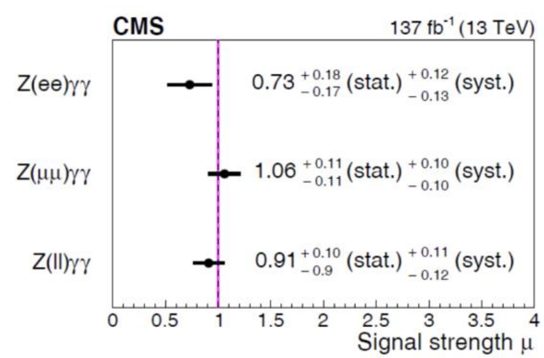


aQGC Limits

Parameter	Wγγ (TeV⁻⁴) Expected	Wγγ (TeV⁻⁴) Observed	Zγγ (TeV⁻⁴) Expected	Zγγ (TeV⁻⁴) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

- $\sigma(W\gamma\gamma)_{SR} = \mathbf{13.6}^{+1.9}_{-1.9}$ (stat) $^{+4.0}_{-4.0}$(syst) ± 0.08 (PDF+scale) fb
- $\sigma(Z\gamma\gamma)_{SR} = \mathbf{5.41}^{+0.58}_{-0.55}$ (stat) $^{+0.64}_{-0.70}$(syst) ± 0.06 (PDF+scale) fb





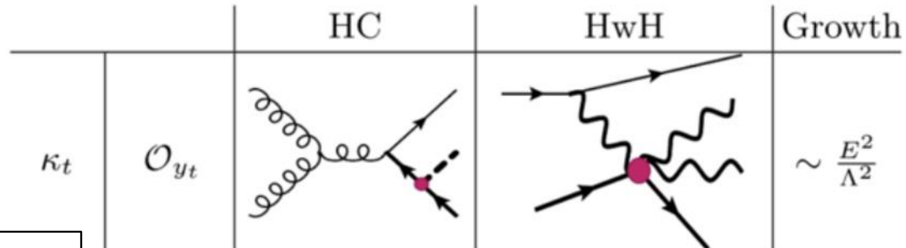
Tribosons to constrain light-Yukawa

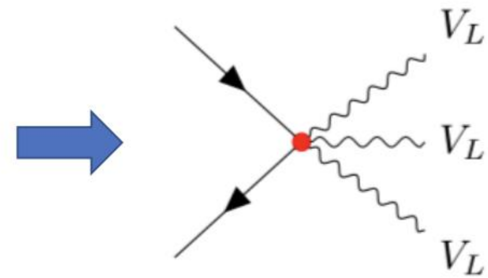
Tevong You

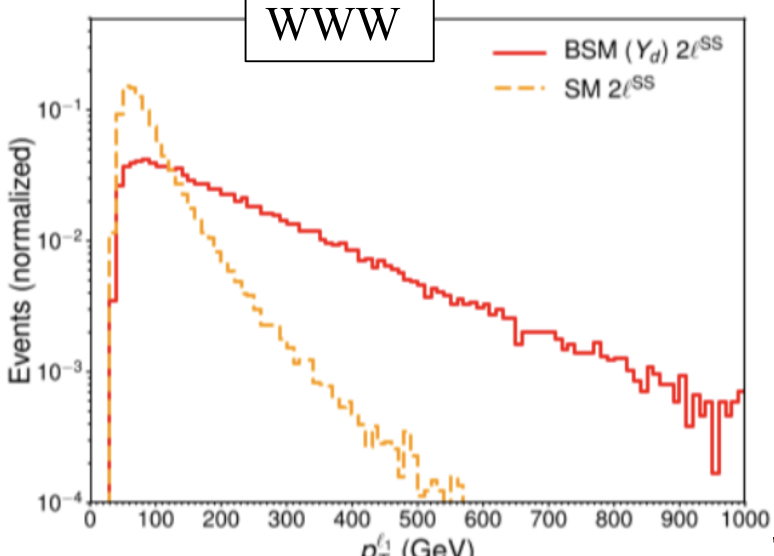
- **Triboson** final state for Yukawa couplings

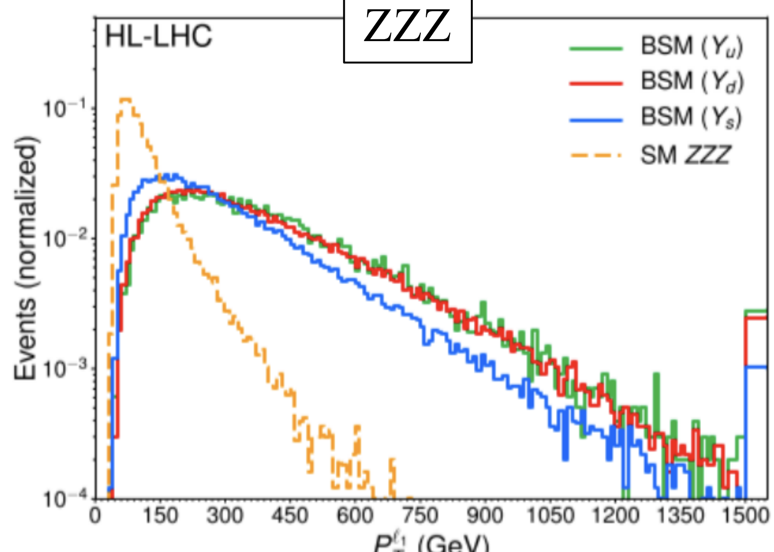
$$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R$$

D6 operator

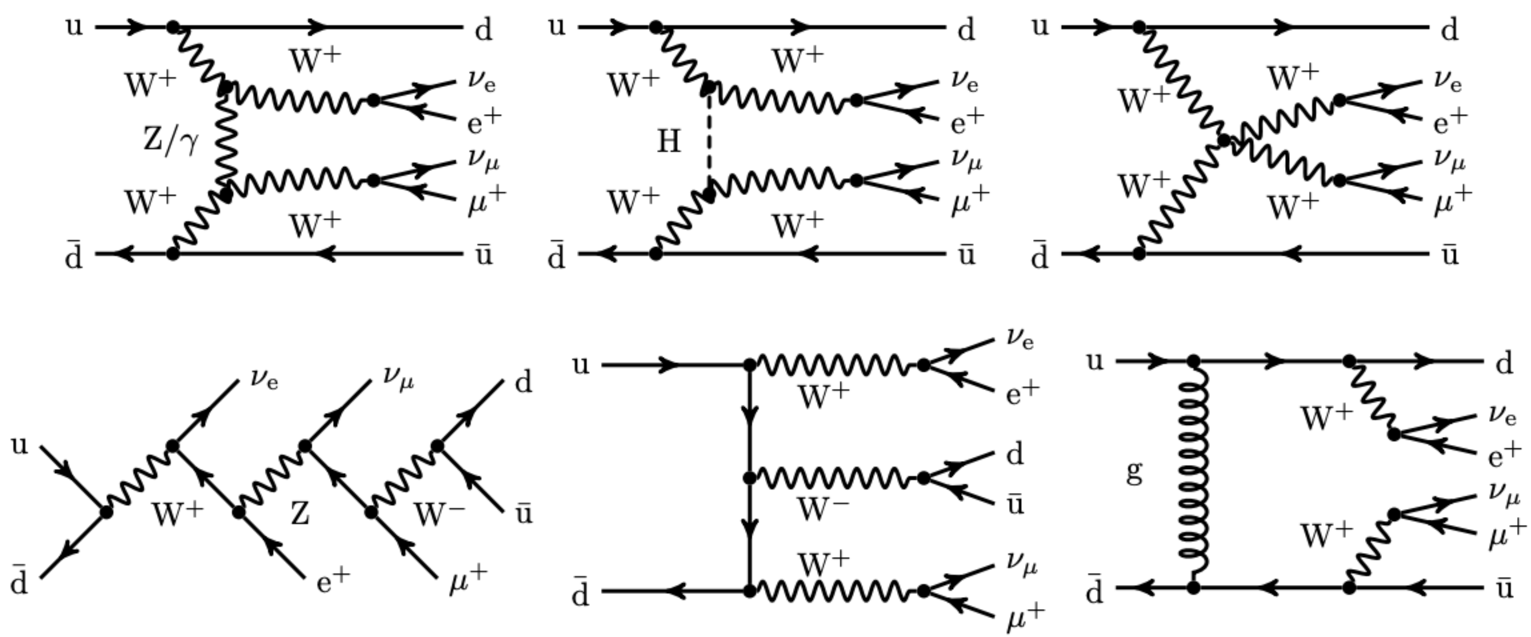








VBS

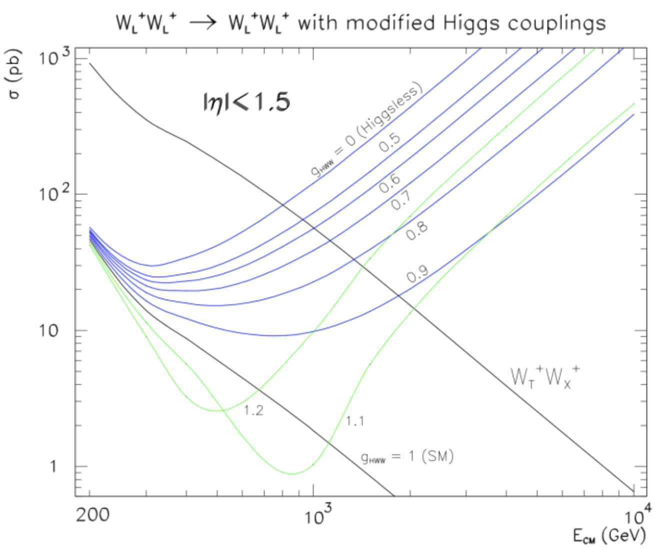


These diagrams must be computed all together, since the "VBS" alone are not gauge invariant and the interference with the other diagrams is huge and negative.

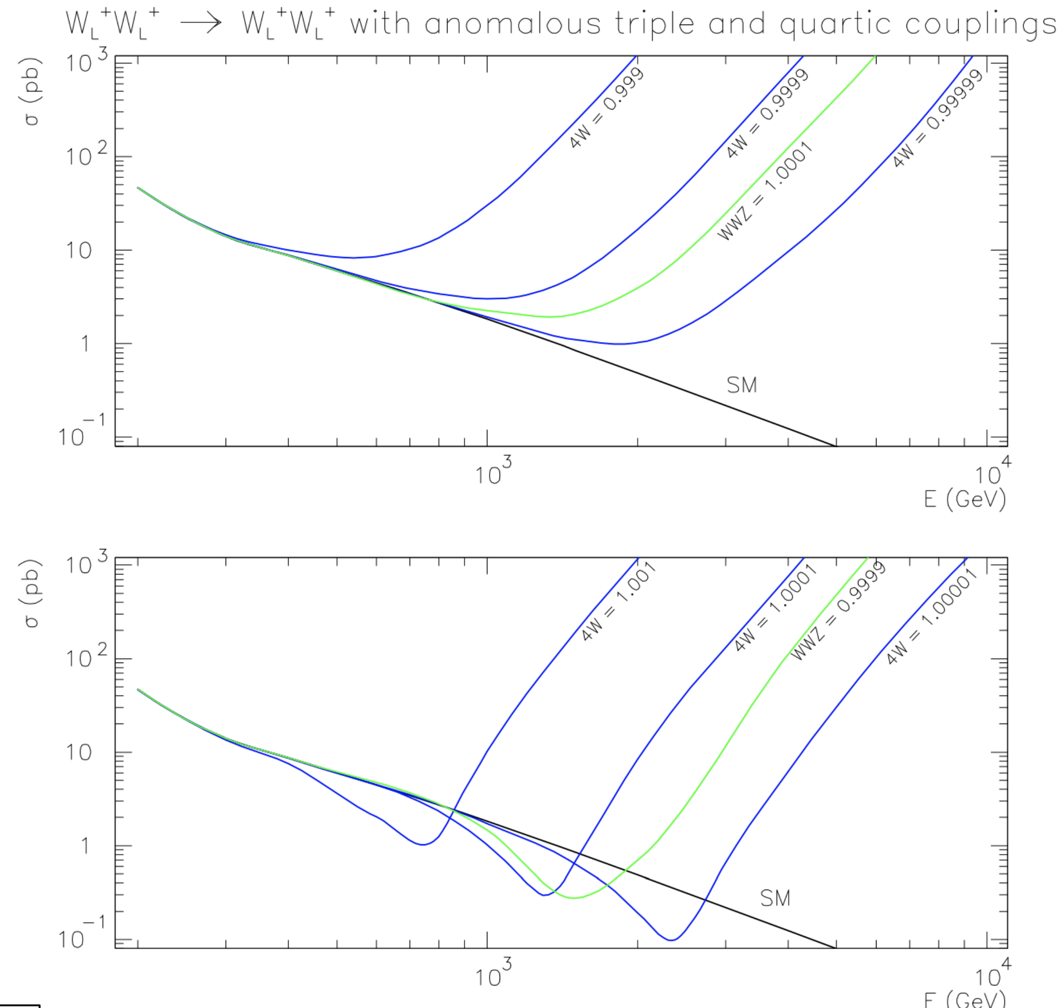
→ very small cross section for the EW process.

VBS

If the cancellation of the Higgs diagrams is not complete, then we expect a g_{hWW} coupling smaller than the SM. The $W_L W_L$ will keep growing with $\sqrt{s}$, up to the the new resonance, or more generaly to the new physics scale Λ.



Anomanlous triple and quartic couplings



Michael Szleper
https://arxiv.org/pdf/1412.8367.pdf

NLO QCD and EW in VBF

NLO QCD for leptonic final states ->VBFNLO, Madgraph

NLO –EW recently calculated for W+W+, WZ, ZZ

(on going for W+W-) ~ - 16%

All diagrams - on going (done for W+W+)

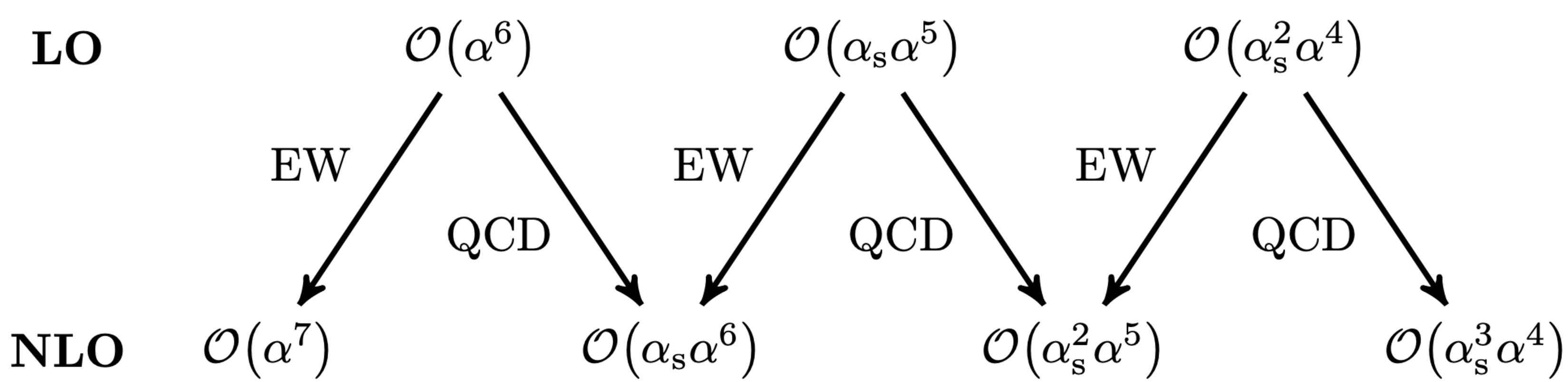


Fig. 3. All contributing orders at both LO and NLO for the VBS processes at the LHC. This figure is taken from Ref.[24]

QCD studies in VBS

Simon Plätzer
Christian Preuss

VBS and VBF processes provide unique challenges for QCD description.

Fixed order and parton showers established, uncertainties and interplay with non-perturbative contributions needs careful understanding.

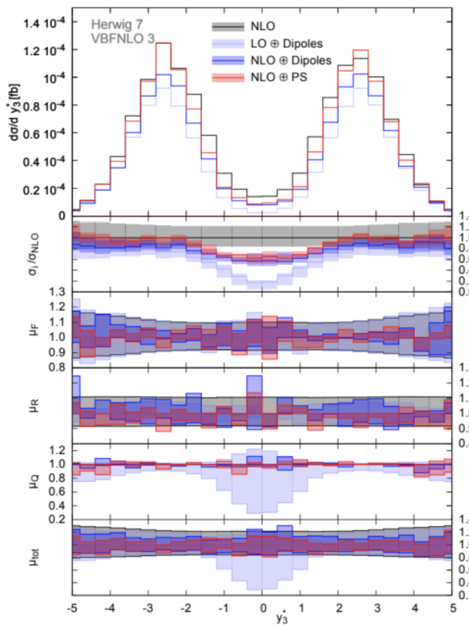
Standard event generators not capable of reproducing all relevant effects, specifically mixing of colour structures and beyond leading-N contributions to non-global jet vetos.

Many studies on PS and the matching
+2, 3, 4 jets distributions
Comparison between generators
Color reconnection effects
Soft gluon effects

- PYTHIA's (default) DGLAP shower **unable** to describe QCD radiation in VBF/VBS **even after NLO matching** if not done carefully (!)

Since PYTHIA 8.304, VINCIA **ready to use** in "real-life" VBF/VBS setups! (using **sector showers**, including CKKW-L merging & POWHEG hooks).

Vincia can handle the merging in VBF/VBS

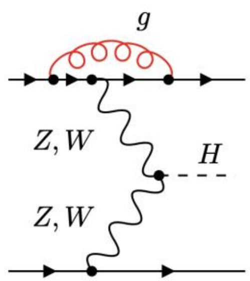


[Rauch, Plätzer – EPJ C77 (2017) 293]

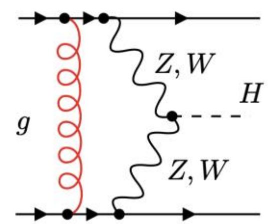
Non-factorizable QCD corrections to VBS

Kiril Menlikov

Known at NN(N)LO
- In PDF approach
- Fully differential
 (VBF cuts enhance them)



Factorizable QCD effects



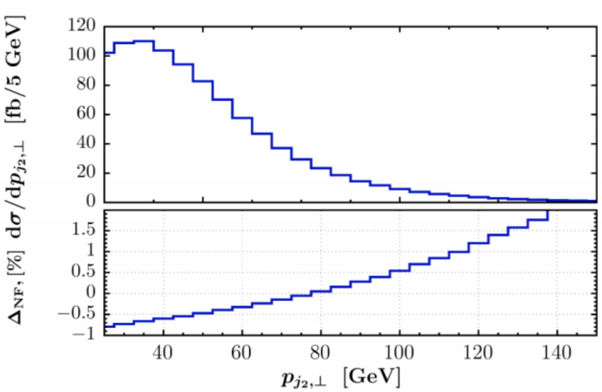
Non-factorizable QCD effects

Given the high precision of the Fact. QCD corr to VBF/S → need to compute the nonfactorizable (non present in PS)

Technicaly complicated + "extreme" situation due to the VBF/S cuts

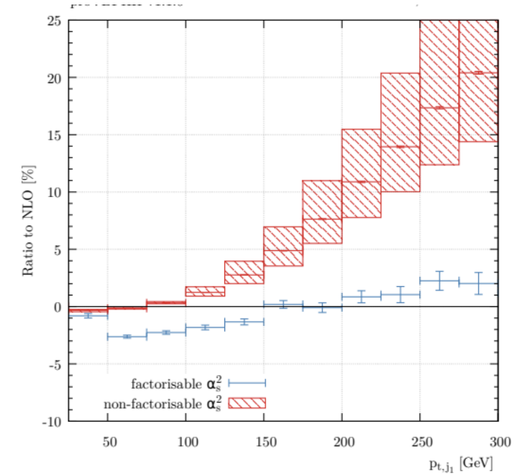
RESULTS:

They amount to ~ -4%
but with some kinematic dependence



di-HIGGS WBF production

Very strong cancellations occurs:
Non-factorizable ~ factorizable

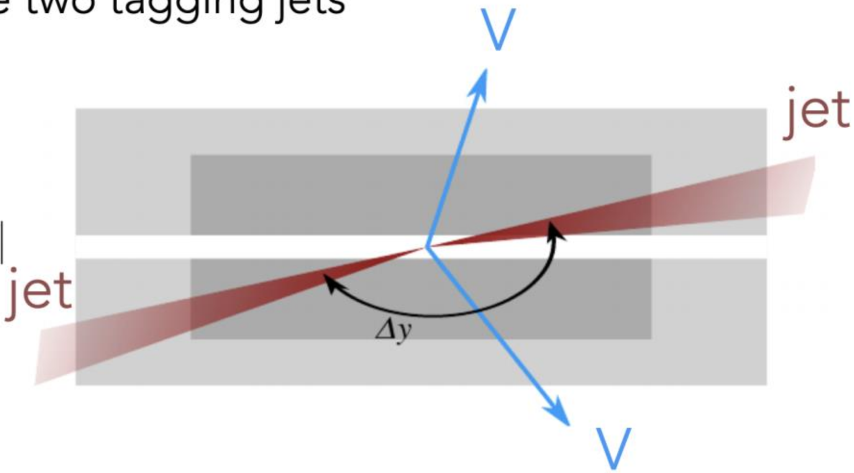


VBF topology

Yee Chinn Yap
Geetanjali Chaudhary

- Typical topology:
  - 2 high energy jets with wide rapidity separation and large invariant mass.
- Hadronic activity suppressed between the two jets.
- Boson pair more central than in non-EW processes.

- ζ: centrality of the diboson system relative to the two tagging jets
  - $\zeta = \left| \frac{y_{VV} - (y_{j1} + y_{j2})/2}{y_{j1} - y_{j2}} \right|$
  - Zeppenfeld variable $\eta^* = | y_{VV} - (y_{j1} + y_{j2})/2 |$



- m_{jj}: dijet invariant mass
- $|\Delta y_{jj}|$ or $|\Delta\eta_{jj}|$: (pseudo-)rapidity difference
- N^{gap}_{jets}: number of jets within the rapidity gap between the two tagging jets
- $|\Delta\phi(VV, jj)|$: azimuthal angle difference between diboson and dijet

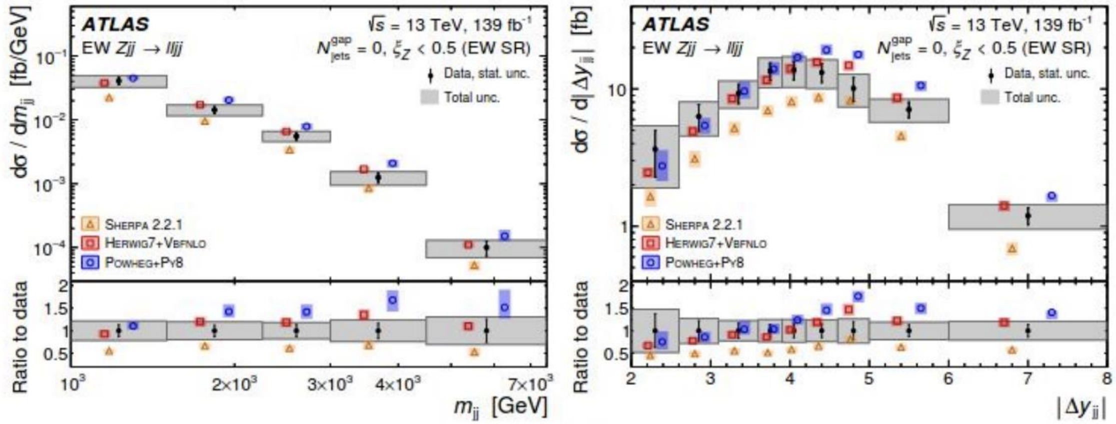
VBF V and VV, leptonic f.s.

Geetanjali Chaudhary
Bianca Sofia Pinolini

Z+jj (cms +atlas)

Herwig7 +VBFNLO

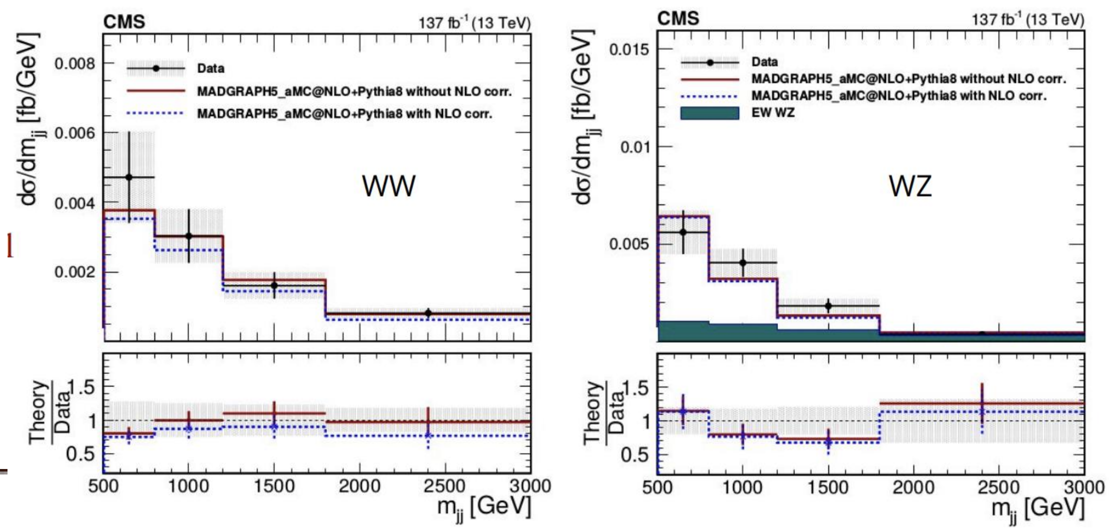
Differential cross-sections for EW Zjj production



W⁺W⁺jj +WZ jj (cms, atlas separately)

EW production dominant over QCD-induced

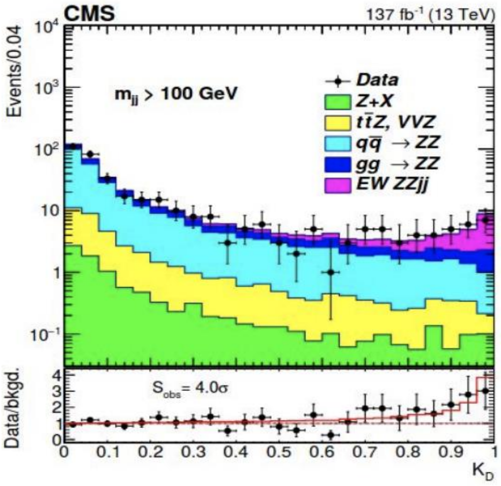
First observation of EW-WZ VBS ! (~7 sigma)



VBF V and VV, leptonic f.s.

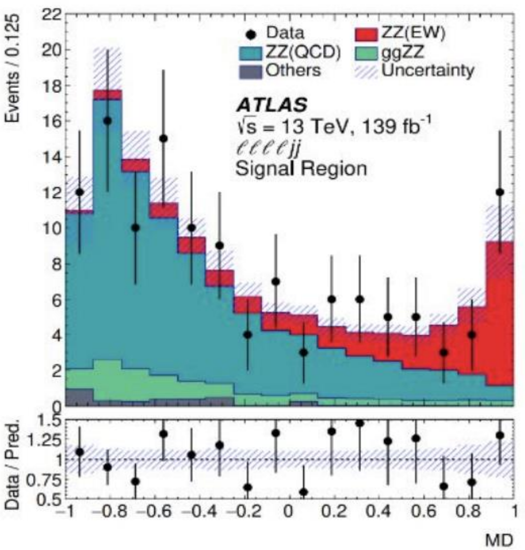
Geetanjali Chaudhary

ZZ+jj (cms)



Large QCD ZZ+jj bckg ($gg \to ZZ$ process)

ZZ+jj → llll +jj + llvv + jj (atlas)



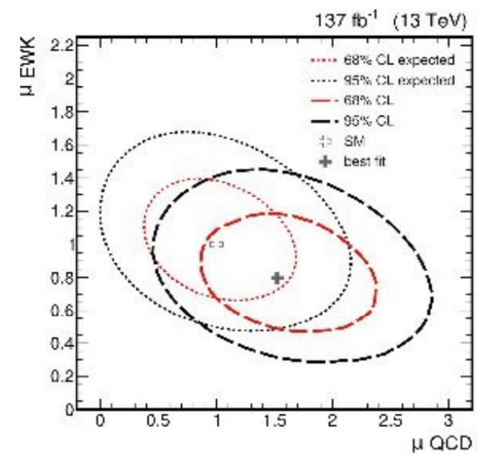
Reaching more than 5 sigma

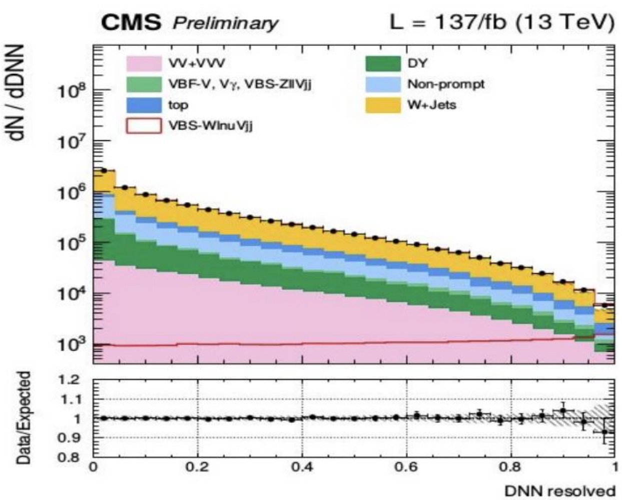
VBF V and VV: semileptonic fs

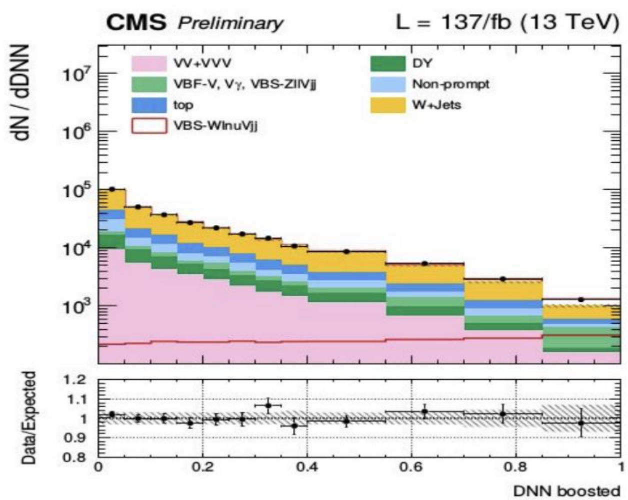
Geetanjali Chaudhary
Bianca Sofia Pinolini

WZ+jj → lv jj +jj (atlas)

ZV/WV/ZV +jj → vv/lv/vv qq +jj (cms)





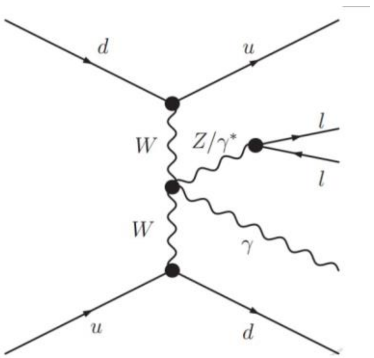


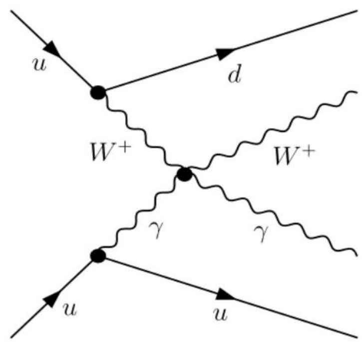
4.4 sigma

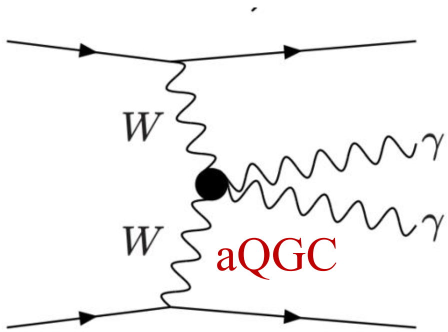
Even though the opposite-sign $W+W-jj \rightarrow$ l+l−νν jj process has the largest production rate, it has not been observed yet, due to the huge tt background.

Zγ,Wγ, γγ VBS

Yee Chinn Yap





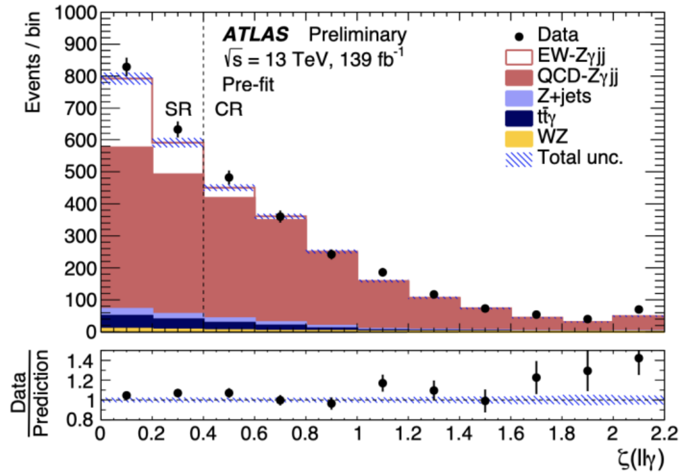


Zγ + jj (atlas +cms)

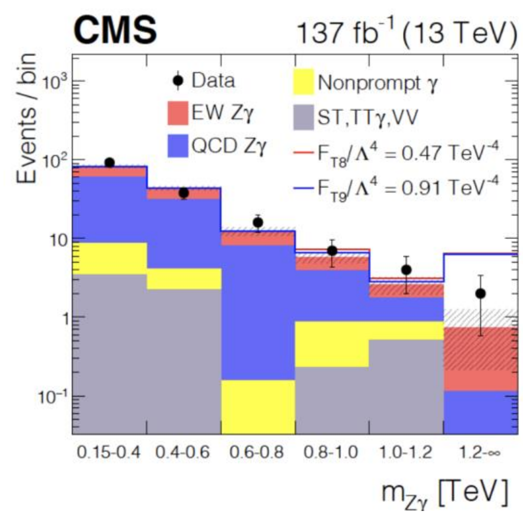
Qcd largest bckg

FSR and VVV as bckg

More than 10 sigma



Limits on DIM8 EFT

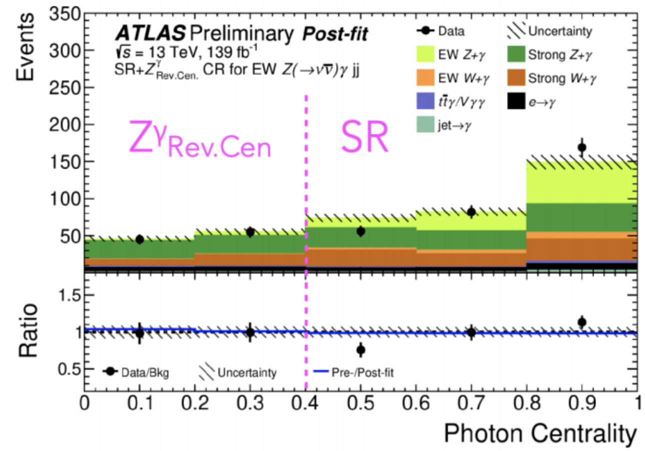


- Most stringent limit to date on T9.

Zγ,Wγ, γγ VBS

Yee Chinn Yap

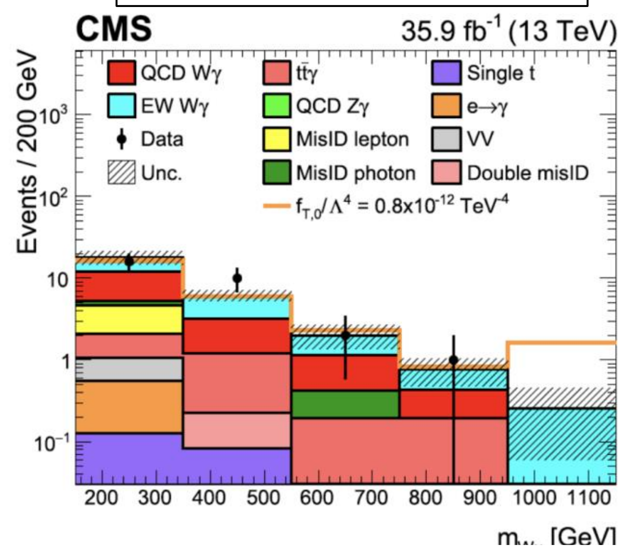
Zγ + jj → νν γ + jj (atlas)



5 sigma

Limits on DIM-8 EFT

Wγ + jj ->lν +jj (cms)



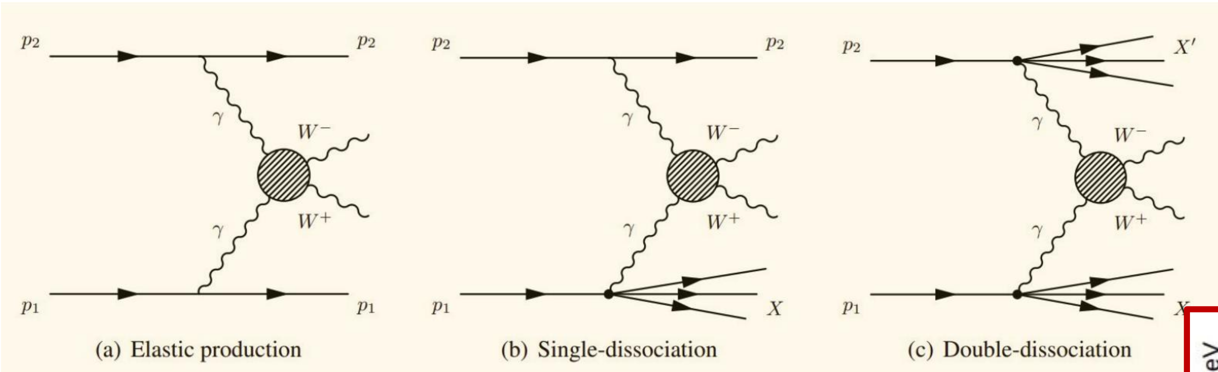
5 sigma

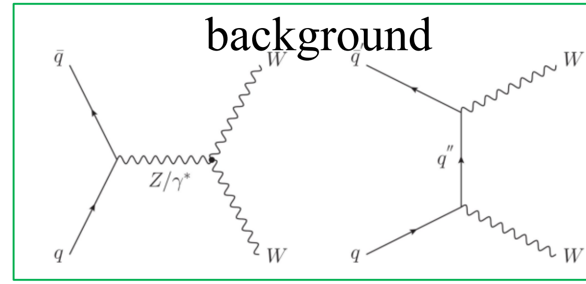
- Limits on operators M0 to M7, T0 to T2, T5 to T7. Very stringent.

γγ → WW

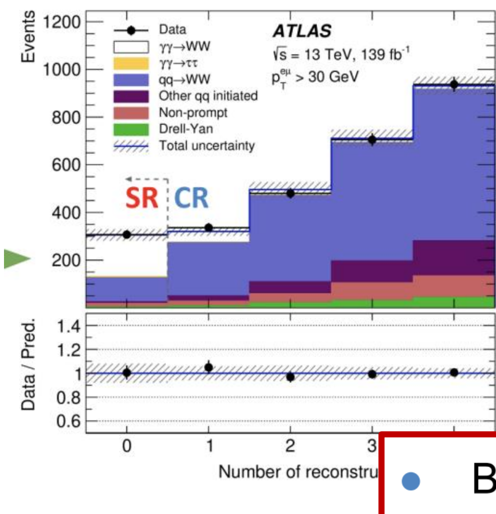
Savanna Clawson

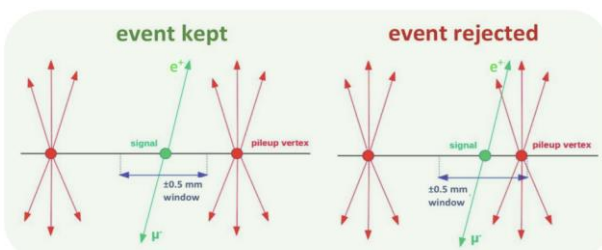
First observation of photon-photon collision → WW

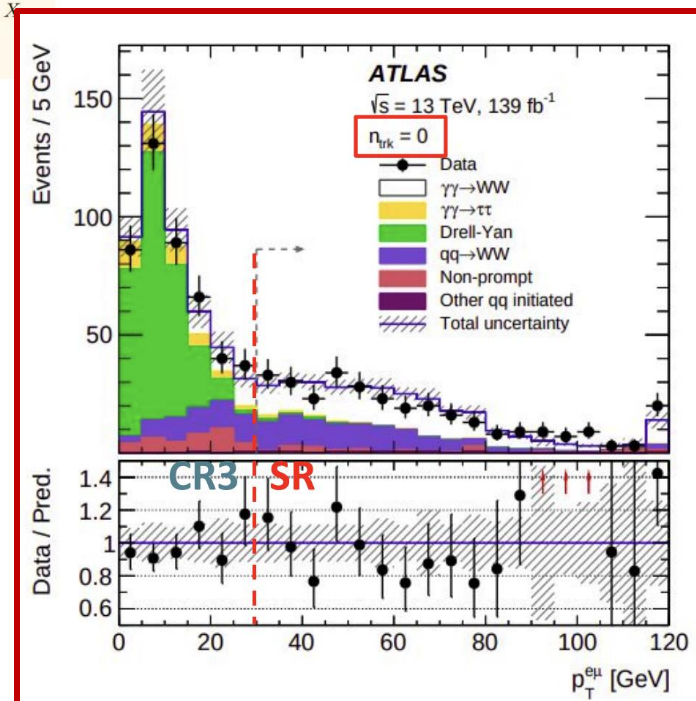




Very delicate analysis: no additional charged tracks, bckg from pileup…



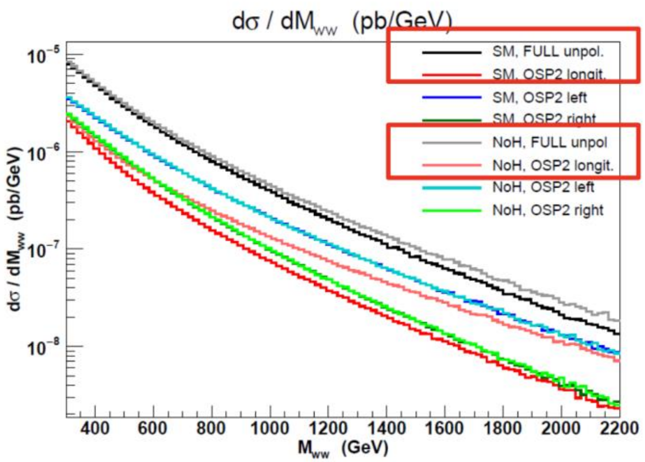




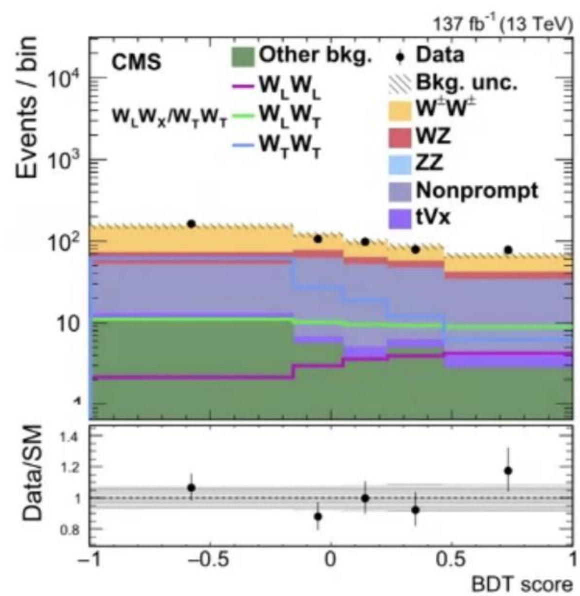
- Background hypothesis rejected with a significance of **8.4σ**
- Measured fiducial cross-section of **3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb**

POLARISATION in VBS

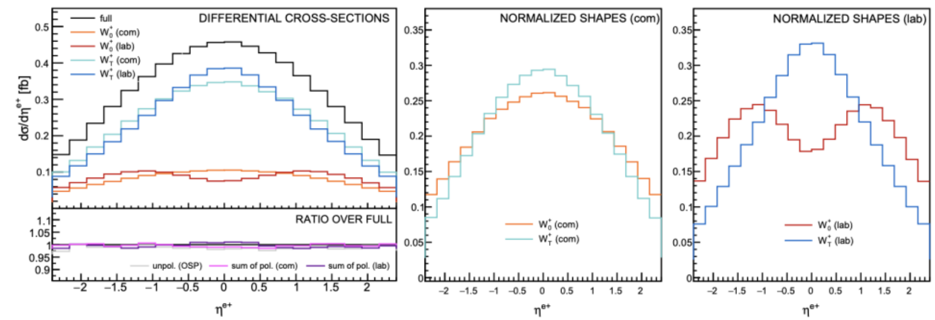
Giovanni Pellicciolі
Carlo F. Erice Cid
Bianca Sofia Pinolini



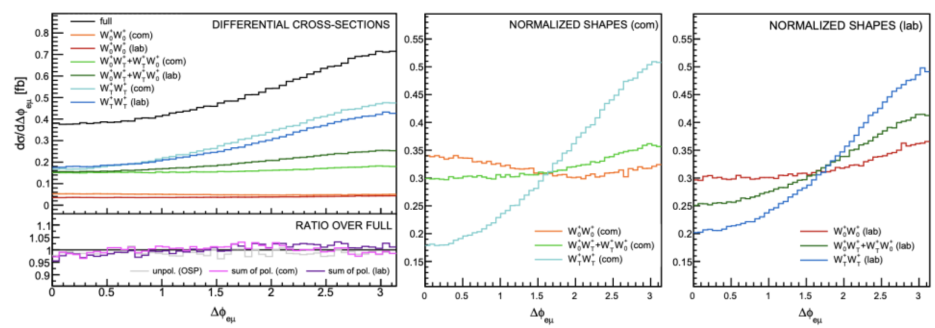
Ballestrero, Maina, Pellicciolі, JHEP 03, 170 (2018)



Differential results [Ballestrero Maina GP 2007.07133]:



η_{e^+}: strong shape differences in the transverse mode between two definitions.



$\Delta\phi_{\ell\ell'}$: noticeable shape differences among polarized modes, mostly in the CM.

Results do not favor either of the two definitions, CM better motivated.

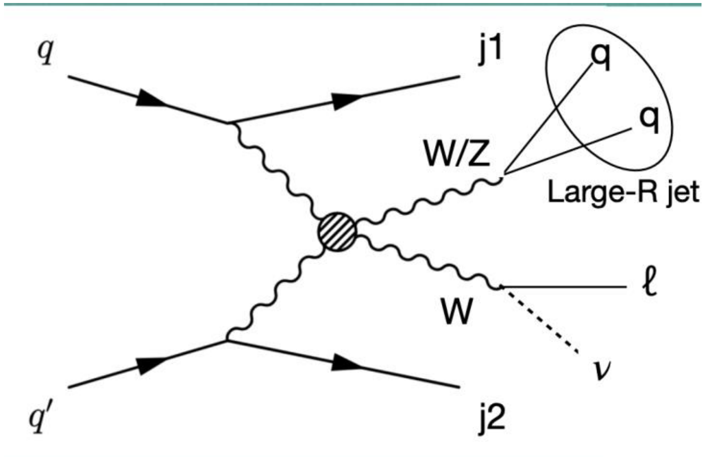
Significance for LX production at 2.3σ (3.1σ expected)

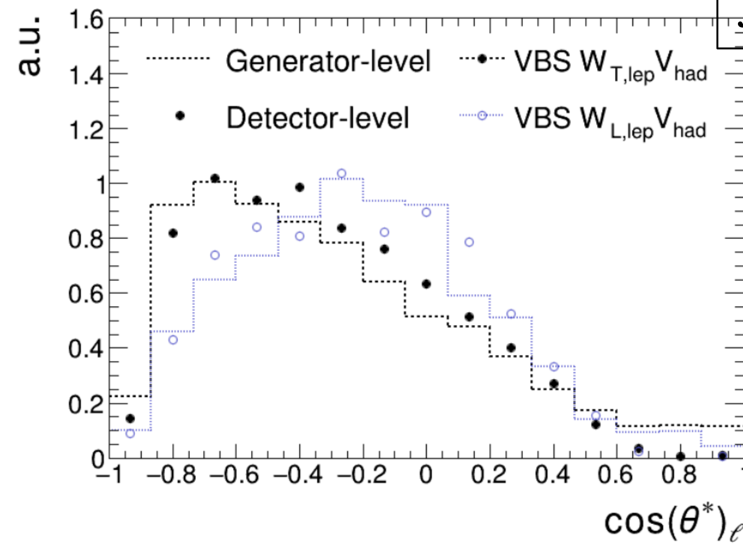
In the WW ref Frame

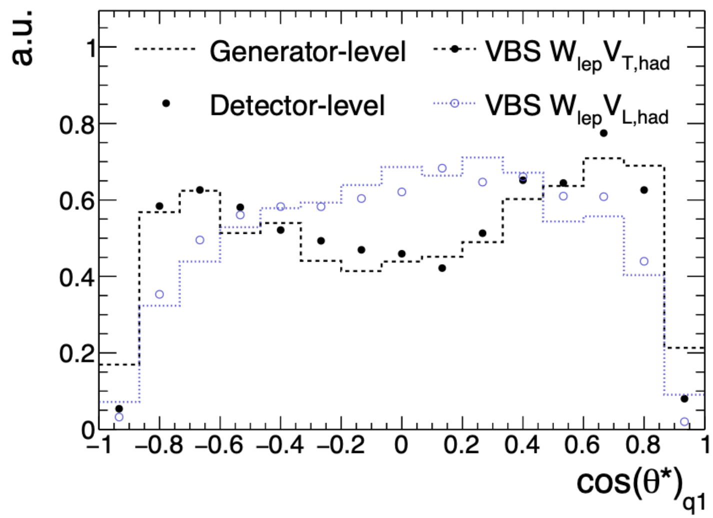
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

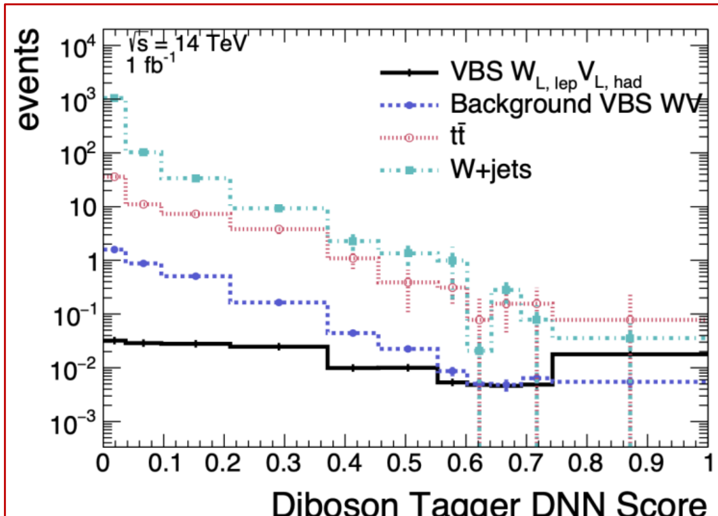
Study of $W_L V_L$ semileptonic fs

Jennifer Roloff









3 sigma with L=3ab-1

SMEFT

Effective Field Theory reveals high energy physics through precise measurements at low energy. The validity is for E<<Λ

from Lagrangian ...

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{n=1}^{N_8} \frac{b_j}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

SM — **EFT$_{\mathbf{d6}}$** — **EFT$_{\mathbf{d8}}$**

Linear EFT cross-sections: interference SM-EFT$_{d6}$

Quadratic EFT cross-sections: squares EFT$_{d6}$

to cross-sections ....

$$\sigma_{\mathrm{SMEFT}}\left(c, \Lambda\right) \simeq \sigma_{\mathrm{SM}} \times \left(1 + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \sigma_m^{(\mathrm{eft})} + \sum_{m,n=1}^{N_6} \frac{c_m c_n}{\Lambda^4} \sigma_{m,n}^{(\mathrm{eft})} \right)$$

evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD with **SMEFT@NLO**

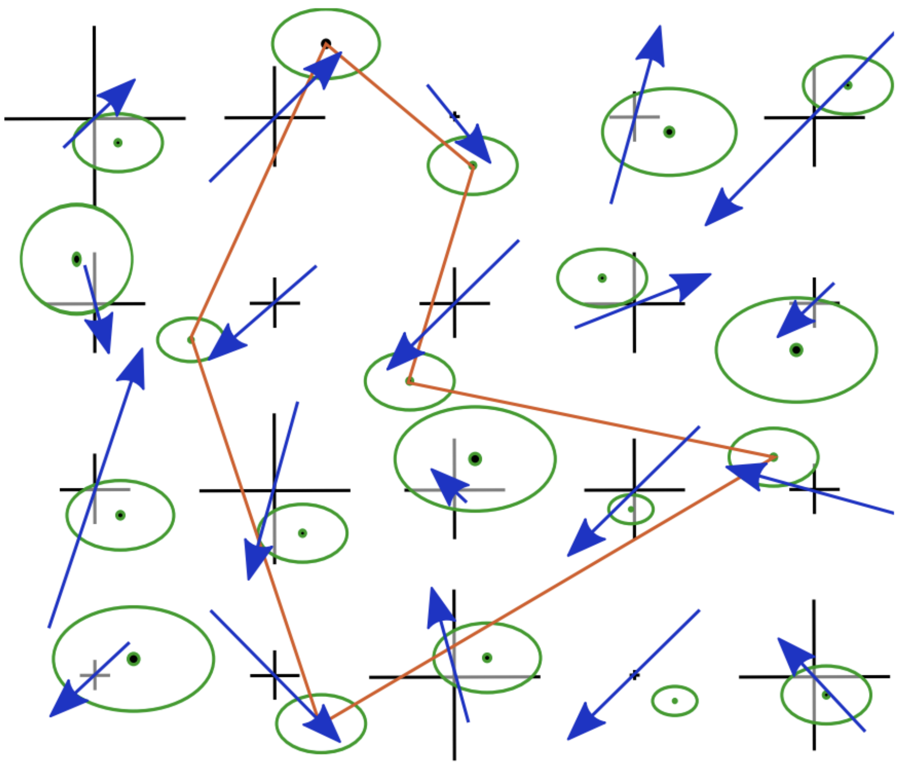
d5 → maiorana neutrino. The Weinberg operator can be probed at the LHC through the same-sign *WW VBS* channel, with W_1-> *e*,μ,τ, but W_2-> μ,τ

Richard Ruiz

EFT a way to

Gautier Durieux

Identifying patterns of new physics



design sensitive observables

- precise SM predictions
- precise SMEFT predictions
- precise measurements

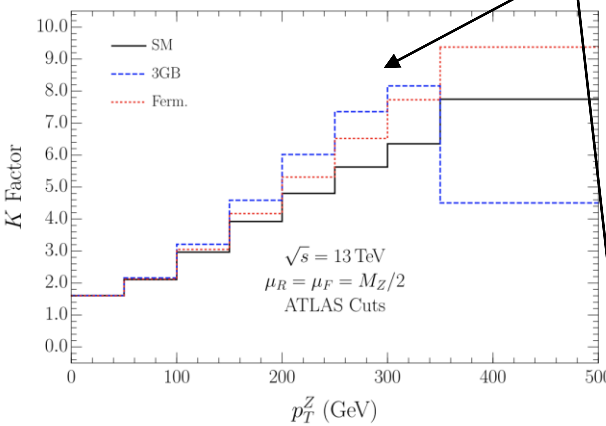
→ leverage correlations

NLO in SMEFT

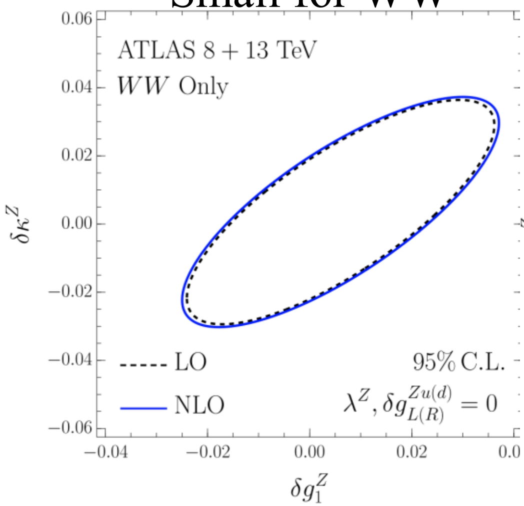
Samuel Homiller

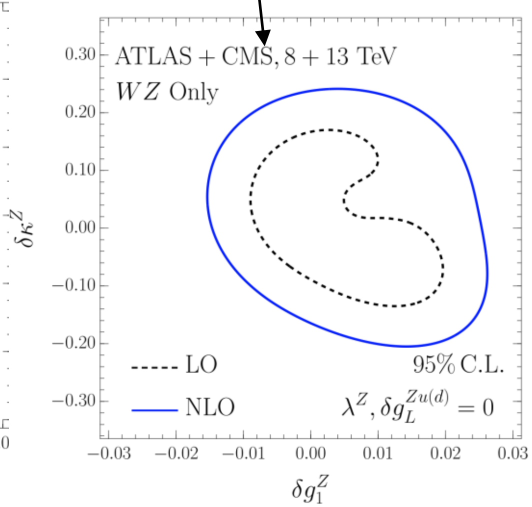
Gautier Durieux

Large effect of NLO in WZ production

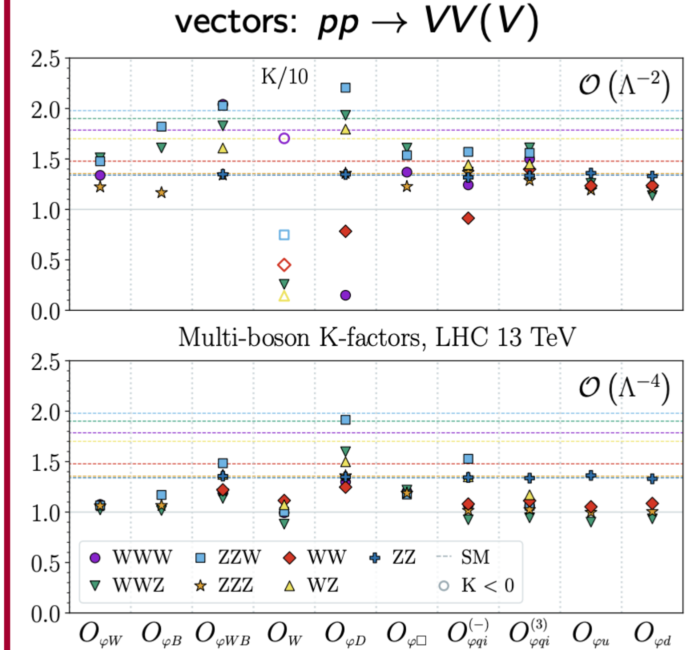


Small for WW





SMEFT@NLO



widely varying K-factors across operators and processes

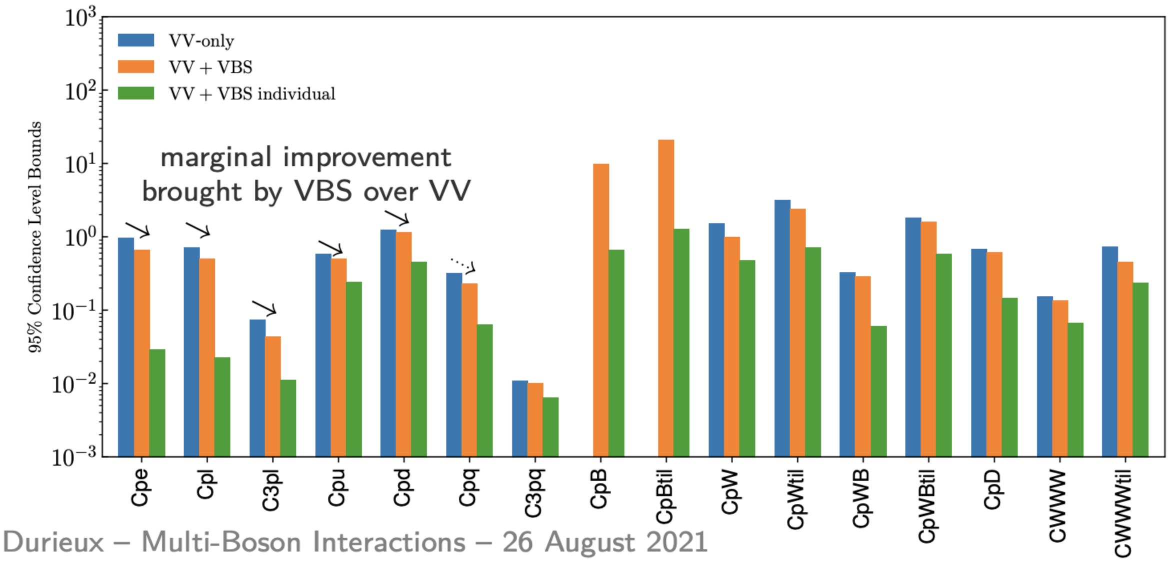
Large impact on the fit

VV+VBS SMEFT fit

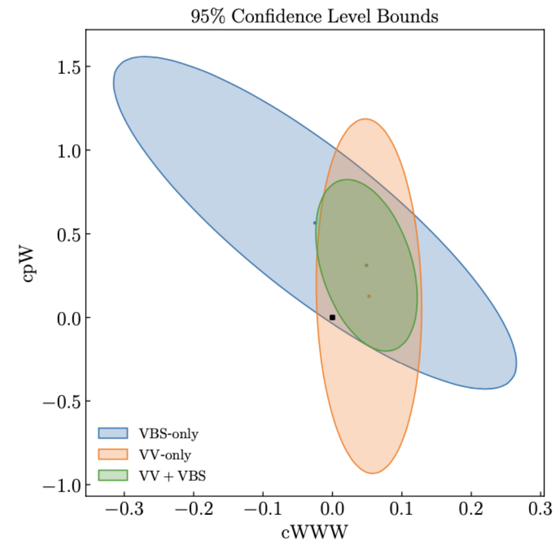
Giacomo Magni

DIM-6 - linear contribution @ LO

16 operators



Durieux – Multi-Boson Interactions – 26 August 2021



Complementarity between

VBS and VV data

when looking at dim6 EFT effects !

VV+VBS SMEFT fit

Giacomo Boldrini

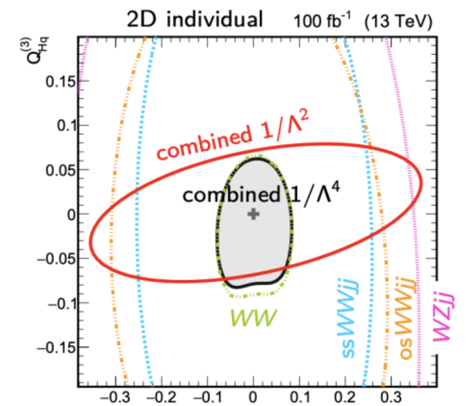
Dim 6, Linear and quadratic terms

$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM}} + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^{\dagger}_{Q_\alpha})}_{\text{Lin}} + \frac{c^2_\alpha}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\text{Quad}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\mathrm{Re}(\mathcal{A}_{Q_\alpha}\mathcal{A}^{\dagger}_{Q_\beta})}_{\text{Mix}}$$

VV, EW VVjj + QCD VVjj

- **Strong impact of fits including** $O(\Lambda^{-4})$ **terms** for $\frac{1}{2}$ operators. For the remaining, no difference observed.
- **including the background QCD dependence improves the sensitivity** reach of all analyses.

2D FIT →: complementarity of VBS and VV



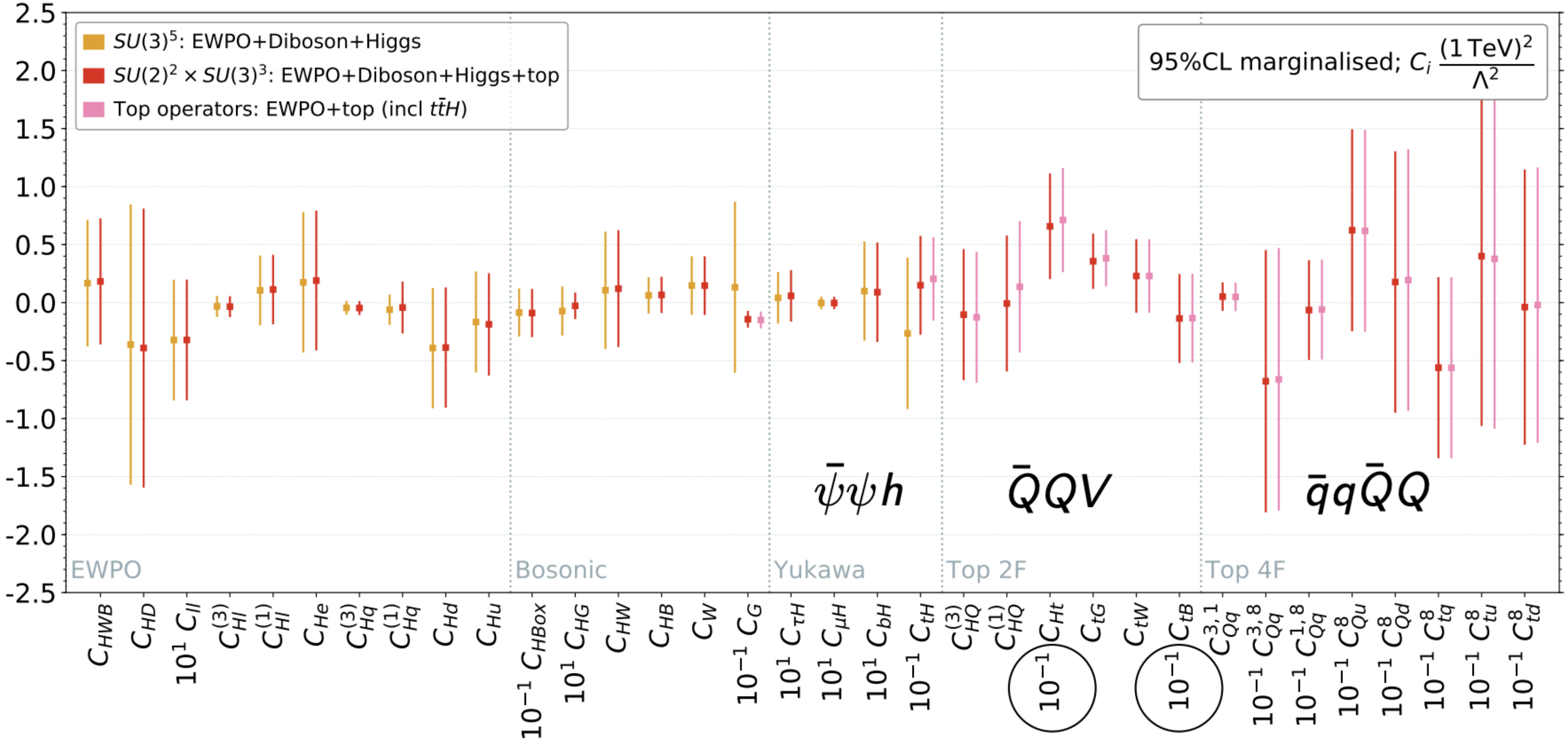
Impact of $O(\Lambda^{-4})$ **terms non negligible:**

- Distorts the linear elliptic c.l. in a non-trivial way
- Linear-only sometimes better (differently from 1D): Mixed interference between dim-6 amplitudes can mitigate deviations

Adding top and Higgs

Gautier Durieux

Fitmaker: EW+Higgs+top



- tension in various top observables (ttW, m_{tt}&y_{tt}, $p_T^{\text{t-chan}}$: $\chi^2/n \sim 2,\ 1.5,\ 5$) but no deviation consistent overall

Saptaparna Bhattacharya

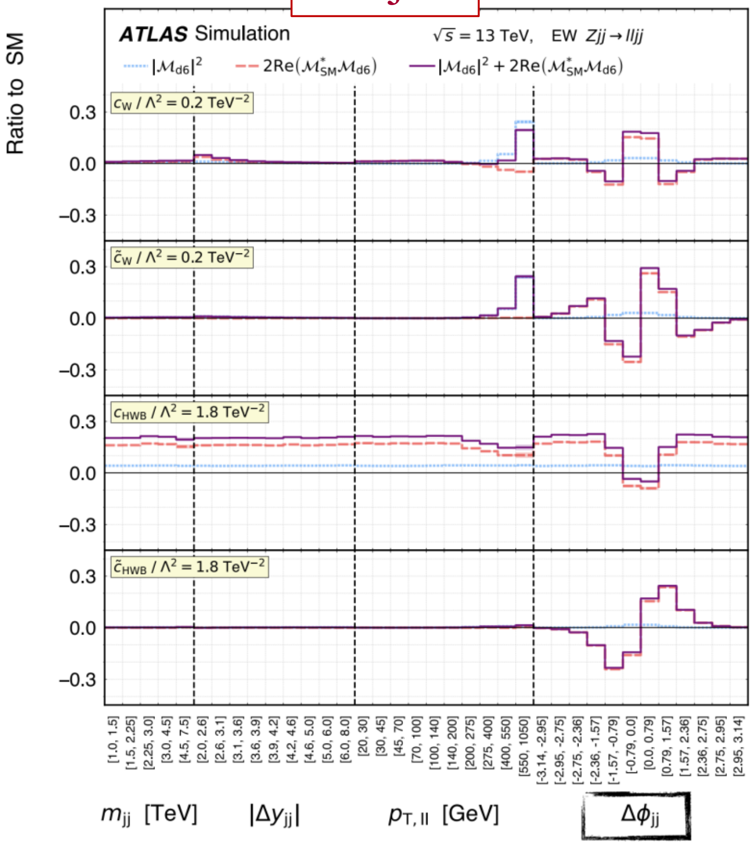
Search for new physis with EFT

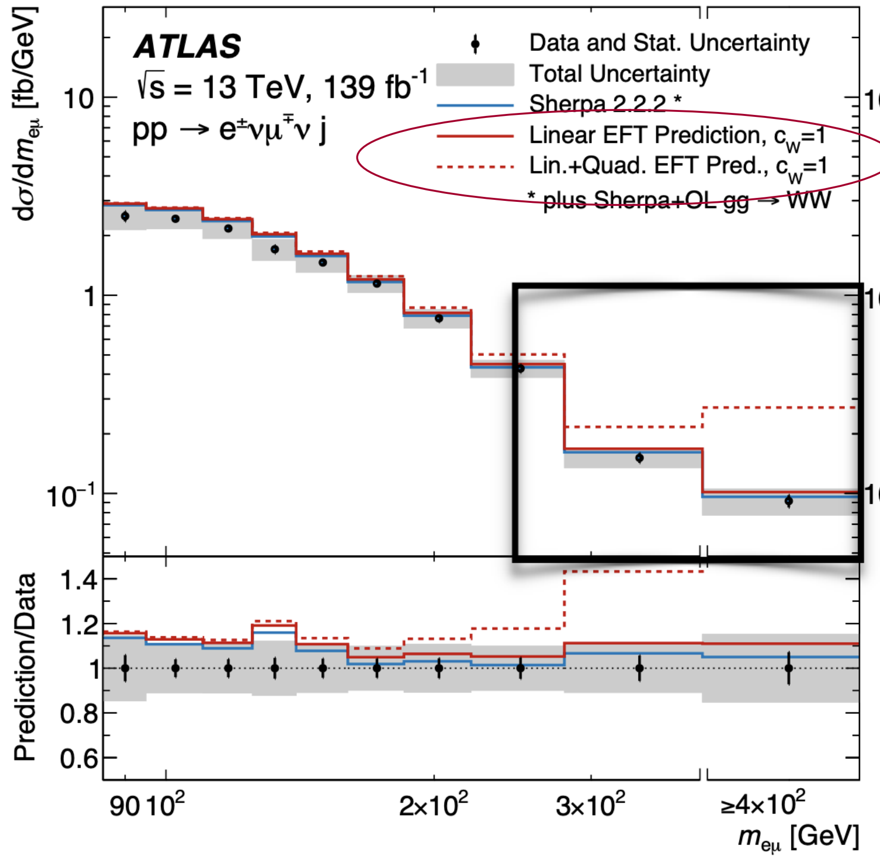
Study of both terms

$$\sigma(C_{3W}) = \sigma_{SM} + C_{3W}\sigma_{int} + C_{3W}^2\sigma_{BSM}$$

Linear Quadratic

Z+2jets





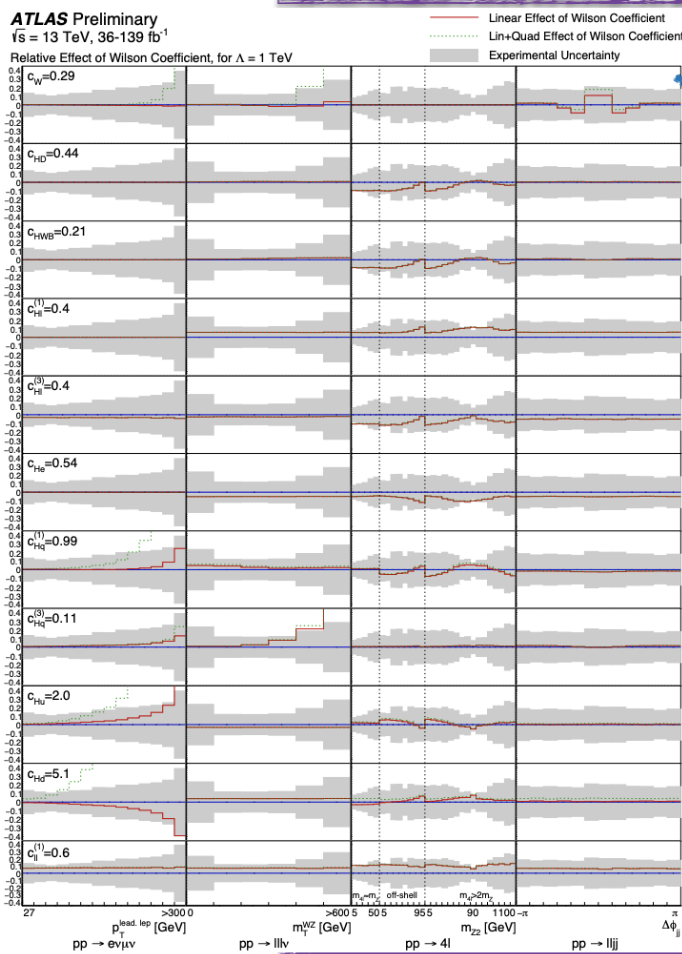
- Limits driven by linear term
- Allows test of missing higher order contributions

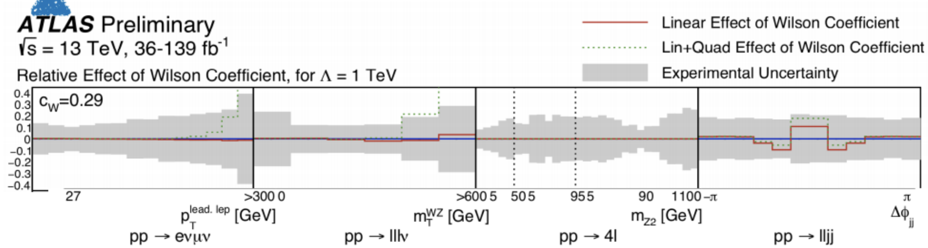
p_T of leading-jet > 30 GeV

Search for new physis with EFT

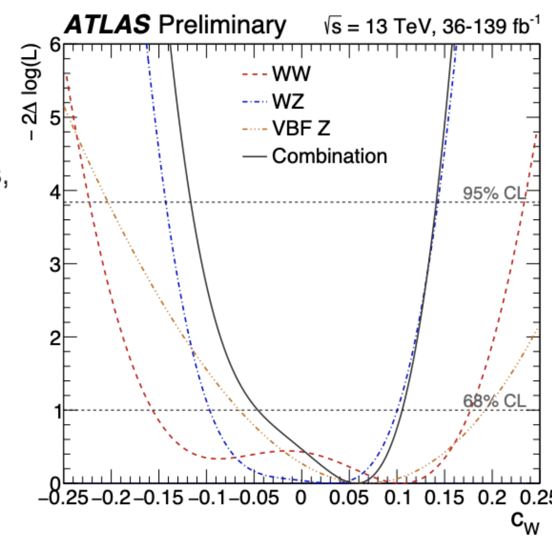
Saptaparna Bhattacharya

Combined effective field theory interpretation of differential cross-sections measurements of WW, WZ, 4l, and Z-plus-two-jets production using ATLAS data





- Impact of the Wilson coefficients on the differential cross sections, relative to the SM cross section
- Value of the Wilson coefficient obtained from 2σ sensitivity of the SMEFT model including only linear terms



Multiboson Interactions, 2021

EFT to DY: Lorenzo Ricci

Fully differential measurements improve sensitivity and reduce the impact of quadratic terms

GeoSMEFT

Michael Trott

SMEFT has to many operators, and all have to be considered to be “bases independent”.

geoSMEFT: “the physics of the SMEFT near resonances is interacting fields in a curved Higgs field space. Using this idea the theory is drammatically simplified”.

An instant pay off of this approach

- Growth in operator forms in connections *Always* saturate to fixed number, this is just the simplest organization exploiting this

Field space connection	Mass Dimension 6	8	10	12	14
$h_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J$	2	2	2	2	2
$g_{AB}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu}$	3	4	4	4	4
$k_{IJA}(\phi)(D^\mu\phi)^I(D^\nu\phi)^J\mathcal{W}^A_{\mu\nu}$	0	3	4	4	4
$f_{ABC}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\nu\rho}\mathcal{W}^{C,\mu}_{\rho}$	1	2	2	2	2
$Y^u_{pr}(\phi)\bar{Q}u+$ h.c.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$Y^d_{pr}(\phi)\bar{Q}d+$ h.c.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$Y^e_{pr}(\phi)\bar{L}e+$ h.c.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$d^{e,pr}_A(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$d^{u,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$d^{d,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$L^{\psi_R}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2	N_f^2	N_f^2
$L^{\psi_L}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$	$2\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$

2001.01453 Helset, Martin, Trott

- Once we have things to dim eight it is sufficient in many observables

Mases
Couplings and mixing angles
TGC, Higgs to ZZ,WW
QGC,TGC + Higgs

Yukawas

Dipoles

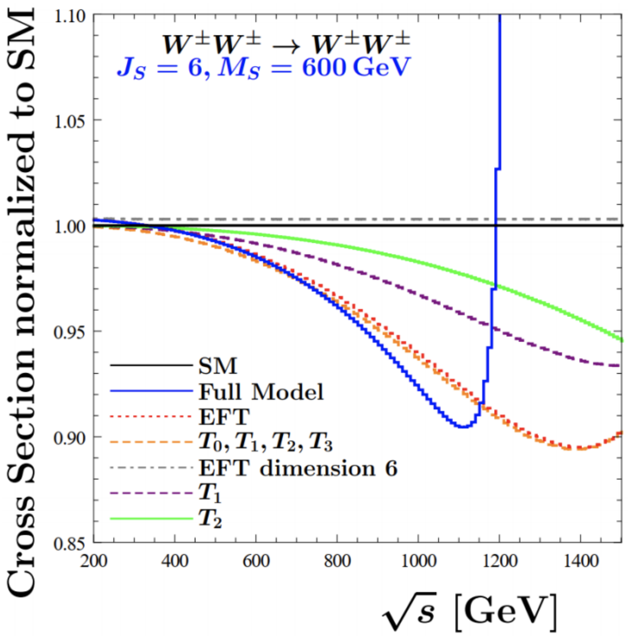
W,Z couplings to fermions +higgs

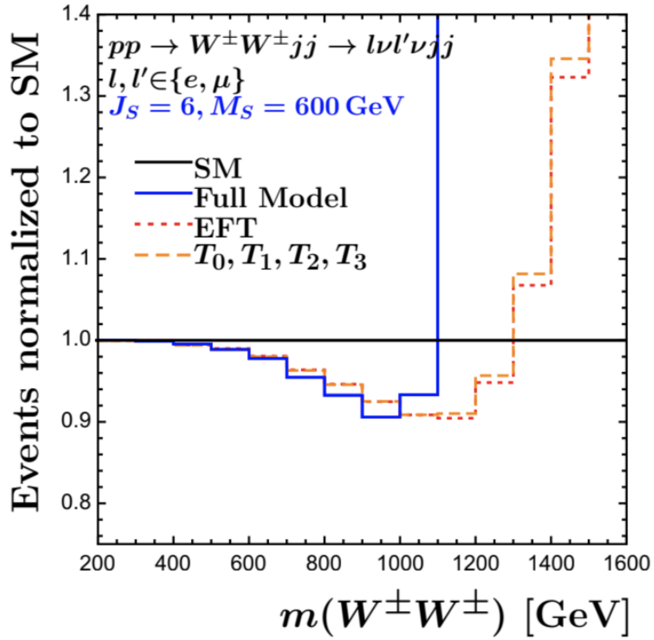
- Basis choice changes entries in these geometric structures, but geometric organization exist in any basis. The trend of saturation of effects at dimension eight is a general feature.

EFT vs UV-complete models in VBS

EFT validity range

Dieter Zeppenfeld





A benchmark model with extra scalar or fermion multiplets

- EFT is valid only well below threshold at $2M_S$ =1200 GeV (as expected)
- Deviations from SM barely reach 10% within EFT validity range, even for J_S= 6
- Because of J_R^5 vs J_R^3 growth, dim-8 terms are much more important than dim-6

- EFT as tool for describing BSM effects is of only limited use in describing processes with vast dynamic range such as VBS at the LHC

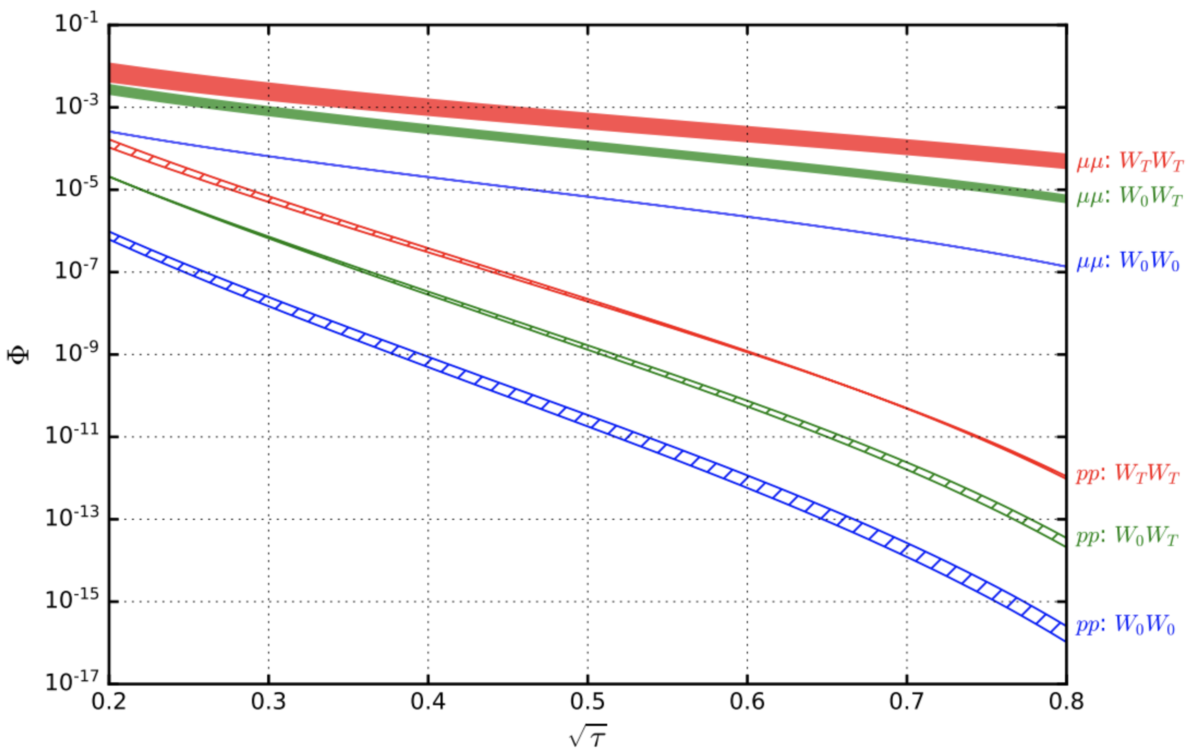
VBS at future collider

VBS at muon collider

Richard Ruiz

Noteworthy that $W^+_\lambda W^-_{\lambda'}$ parton luminosites (Φ) in $\mu^+\mu^-$ collisions can exceed those at a pp collider (holds for other VV', too!)

$$\Phi_i j(\tau, Q) = \int_\tau^1 \frac{d\xi}{\xi} f_{i/\mu}(\xi, Q) f_{j/\mu}\left(\frac{\tau}{\xi}, Q\right), \quad \tau = \frac{Q^2}{s}$$

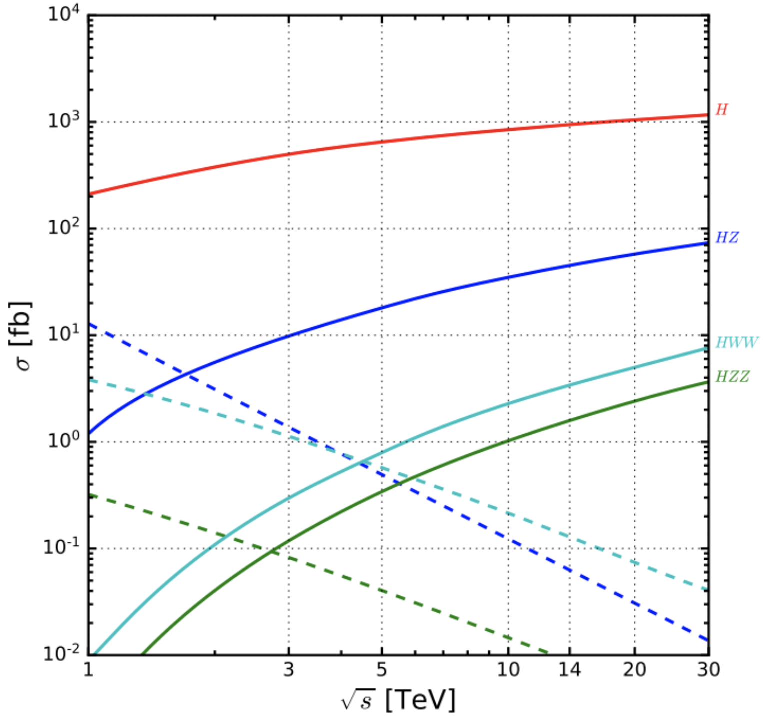


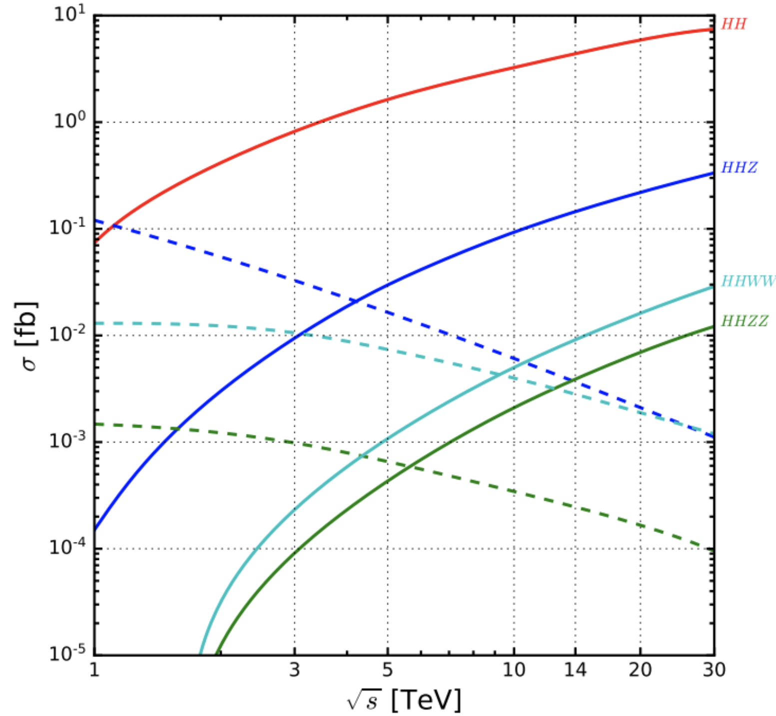
Costantini, RR, et al [2005.10289]

Muon collider

Richard Ruiz

cross sections (σ) vs $\sqrt{s}$ for
s-channel annihilation (dash) vs VBF (solid)





- $\sigma^{VBF} > \sigma^{s-channel}$ since
  - $\sigma^{s-channel} \sim 1/s$
  - $\sigma^{VBF} \sim \log^2(M_{VV}^2/M_V^2)/M_{VV}^2$ due to forward emission of $V = W/Z$

The same for top, Susy, BSM…

By the end of LHC

Many more and much more precise measurements and precise theory prediction of VV and VBS

Boson Polarization

EFT fits (or GeoSMEFT ?): dim6 + dim8 +…

as ~100 years ago!

Maybe New Physics:

- a new "global picture" thanks to the all precision measurements,
- or because of discovery of new particles

And much mo

SLIDE AT A CONFERENCE IN Jan – 2014
“Vector Boson Scattering” at the Royal Society

More channels to

redone with the full detector simulation, + WW→ lv4j etc…)

From the experience we have reached so far, even if it will be very challenging and it will take few years:

→ “it could work”

Frankestein Junior

Interesting also to add also more final state:

p.e.: Double Higgs Production → can be easier to be seen than VBS in case of composite Higgs (see for example Contino et al: arxiv:1309.7038)

And much mo

SLIDE AT A CONFERENCE IN Jan – 2014
"Vector Boson Scattering" at the Royal Society

More channels to

redone with the full detector simulation, + WW→ lv4j etc…)

From the experience we have reached so far, even if it will be very challenging and it will take few years:

→ "it could work"

Frankestein Junior

IT DID WORK !!!

Interesting

p.e.: Double … n than VBS in case of

composi … 038)