Measuring Multi-Boson Production with the ATLAS Detector

Marc-André Pleier

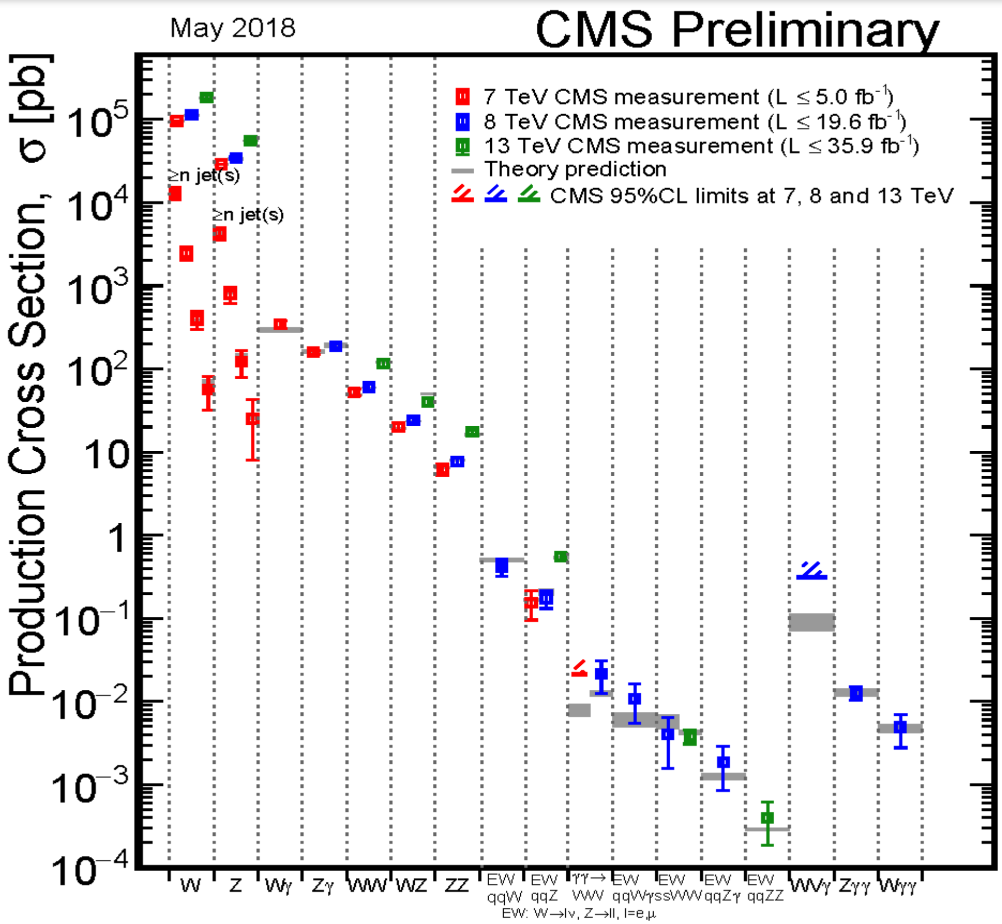
ATLAS EXPERIMENT

BROOKHAVEN NATIONAL LABORATORY

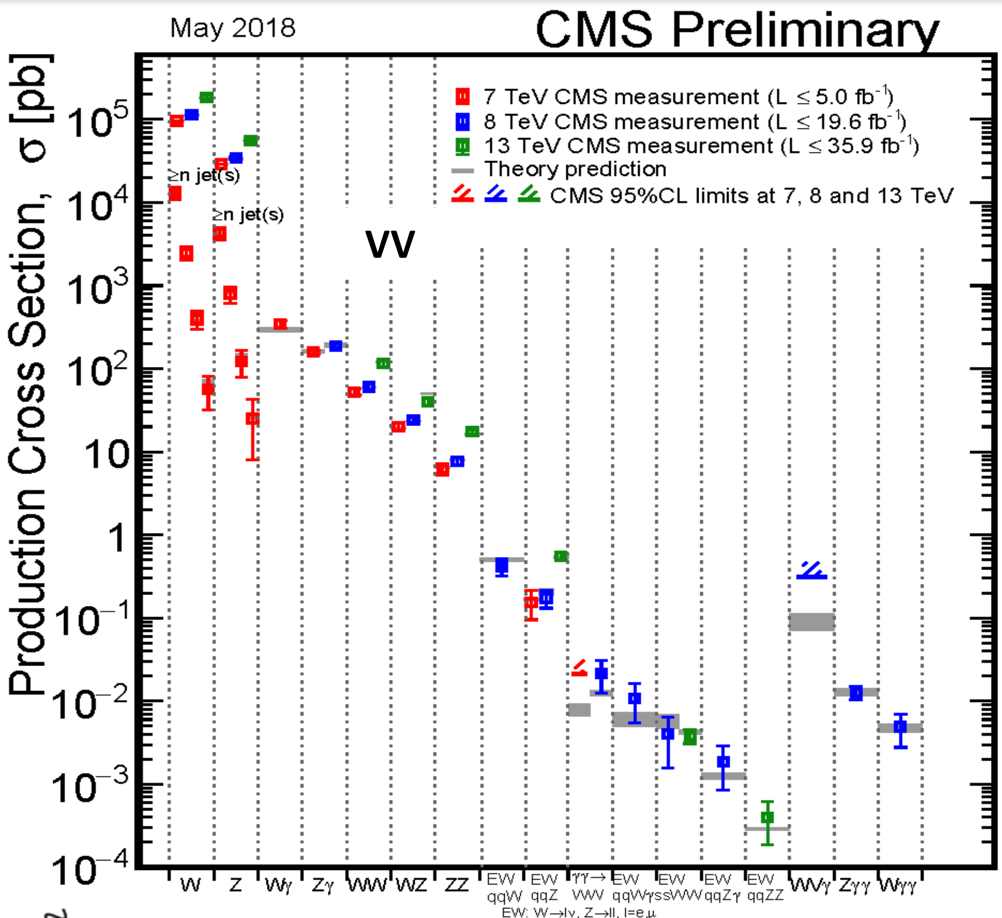
CERN

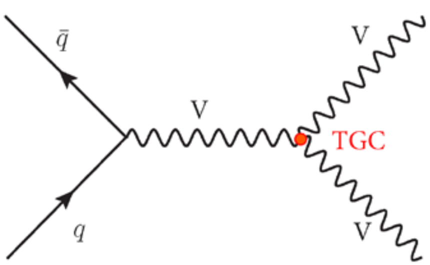
CEA Saclay, October 8 2018

(Multi-) V Production



(Multi-) V Production





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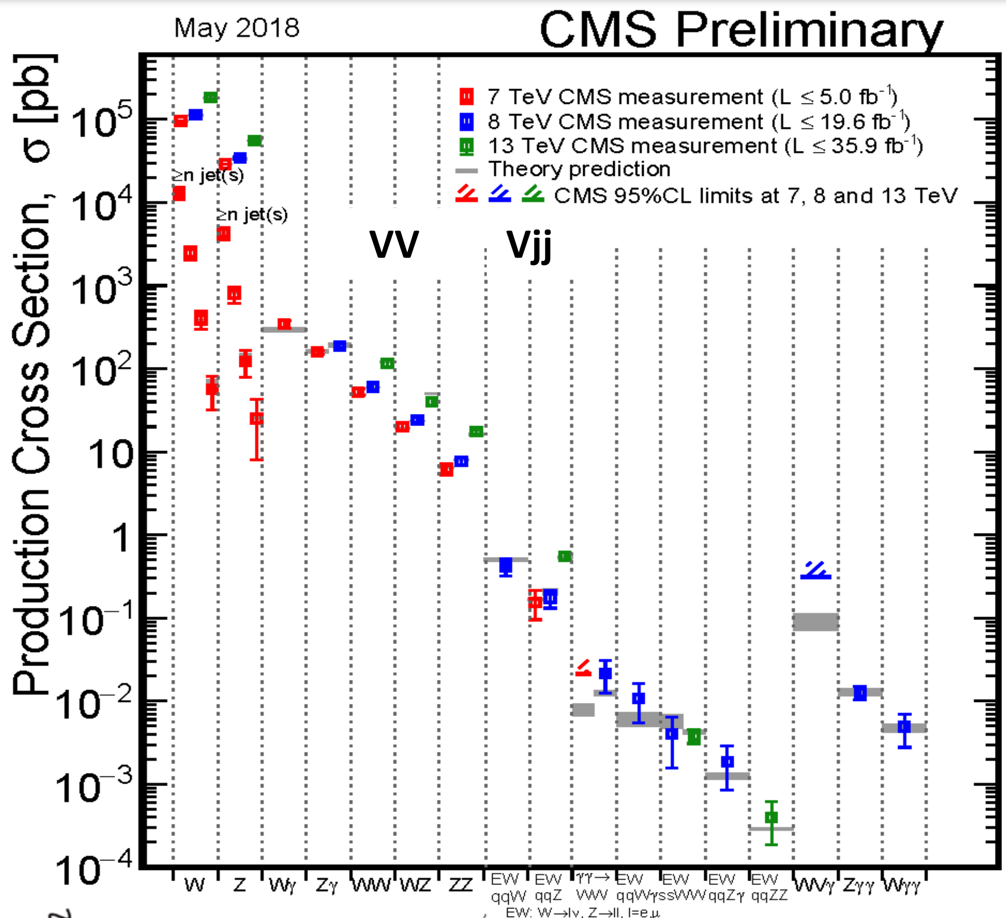

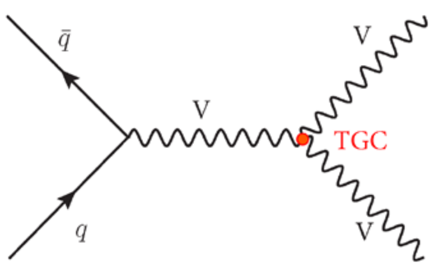

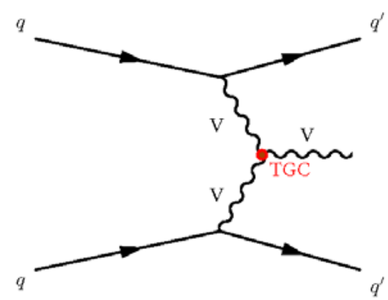

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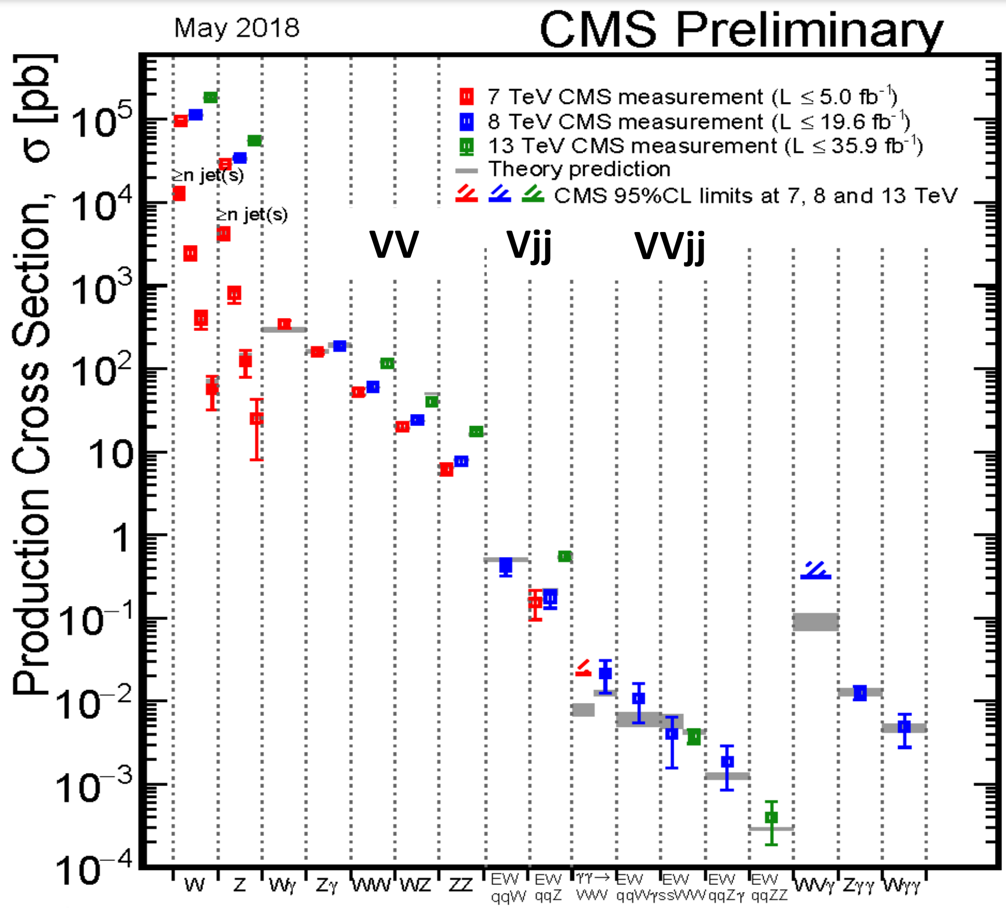
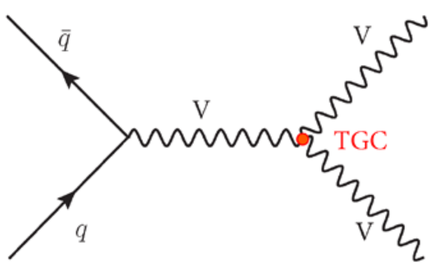
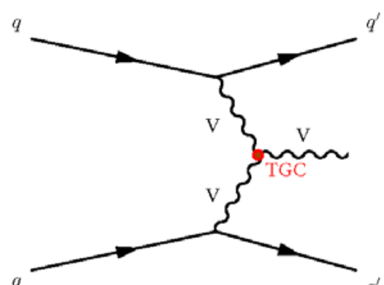
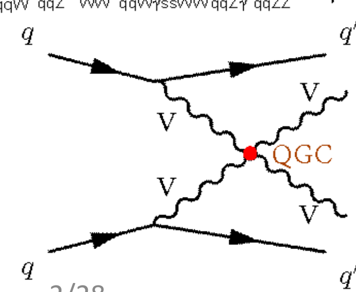
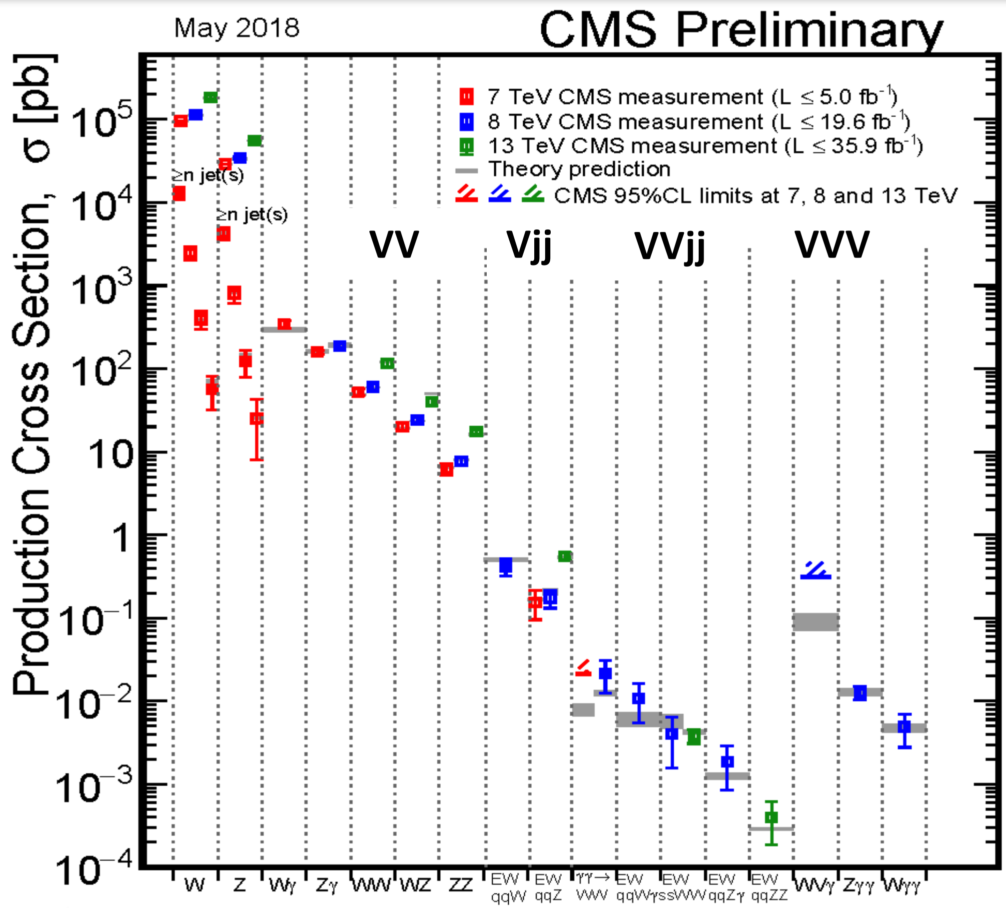


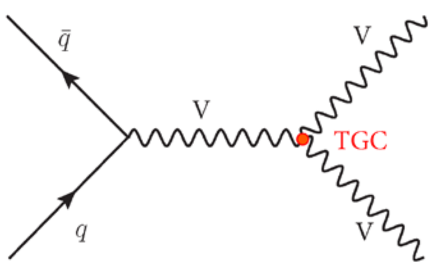


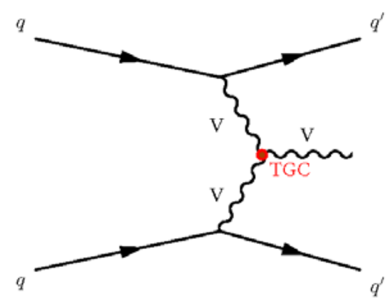


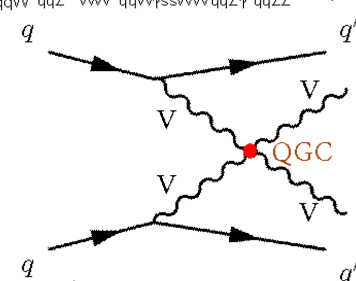


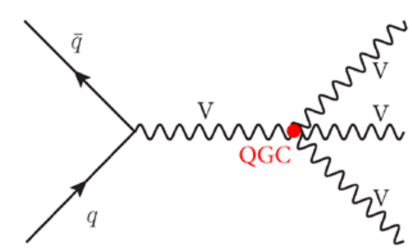
(Multi-) V Production











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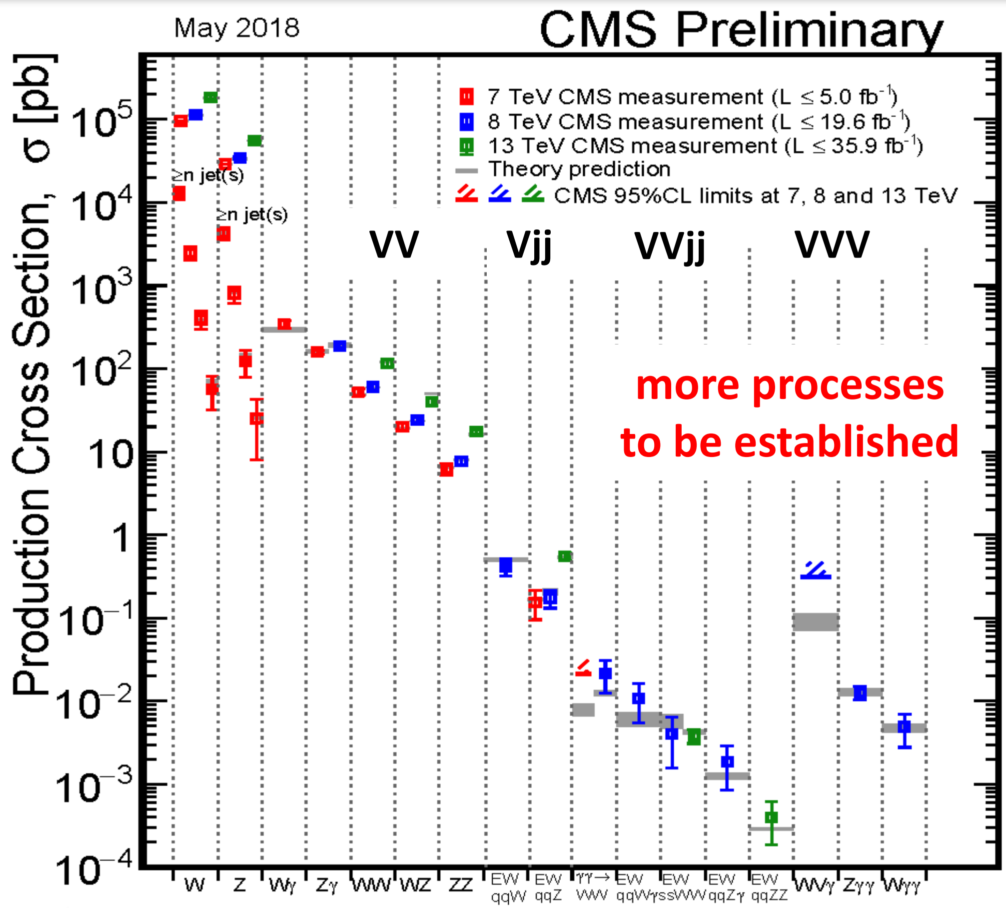
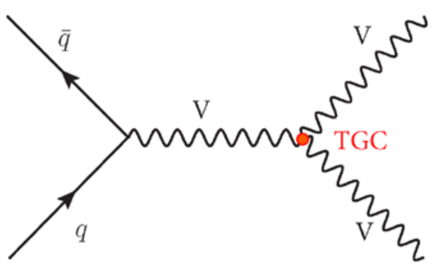
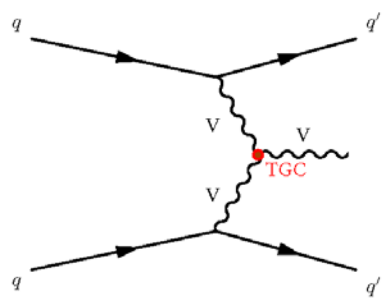
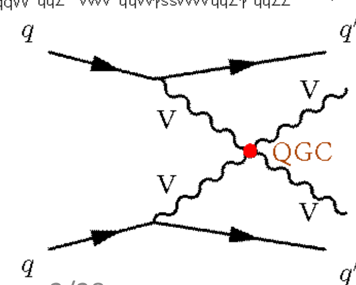
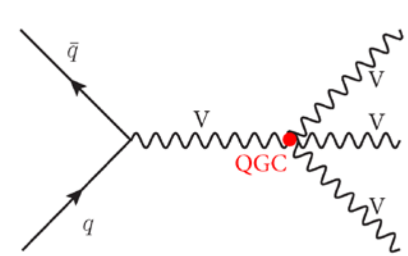


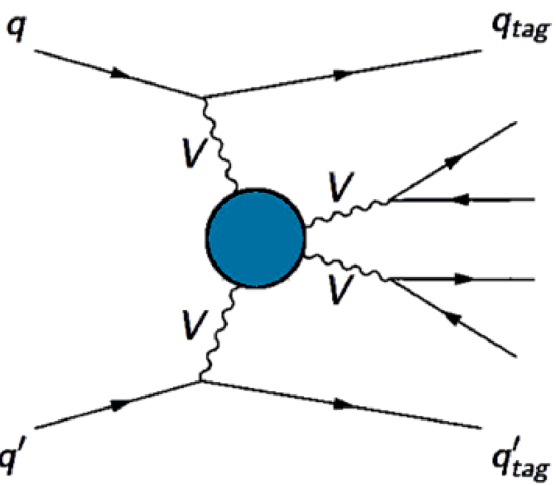








Vector Boson Scattering



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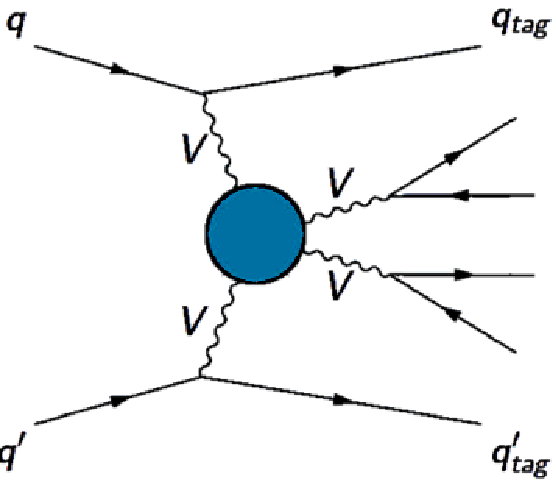

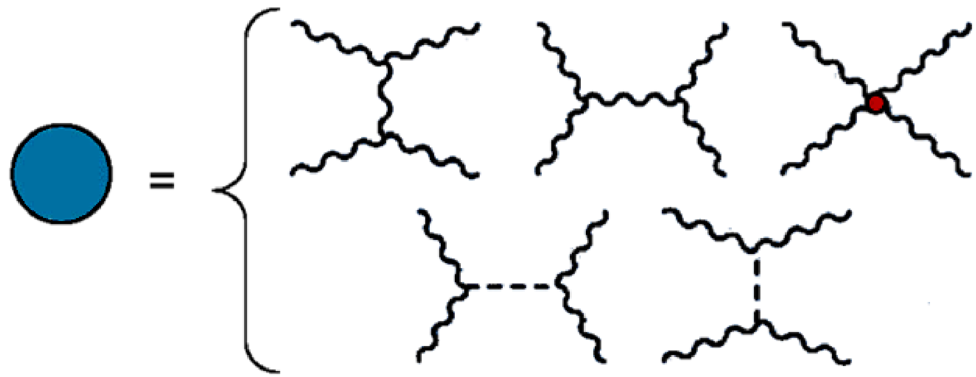

V=W/Z self-interactions

V-Higgs interactions

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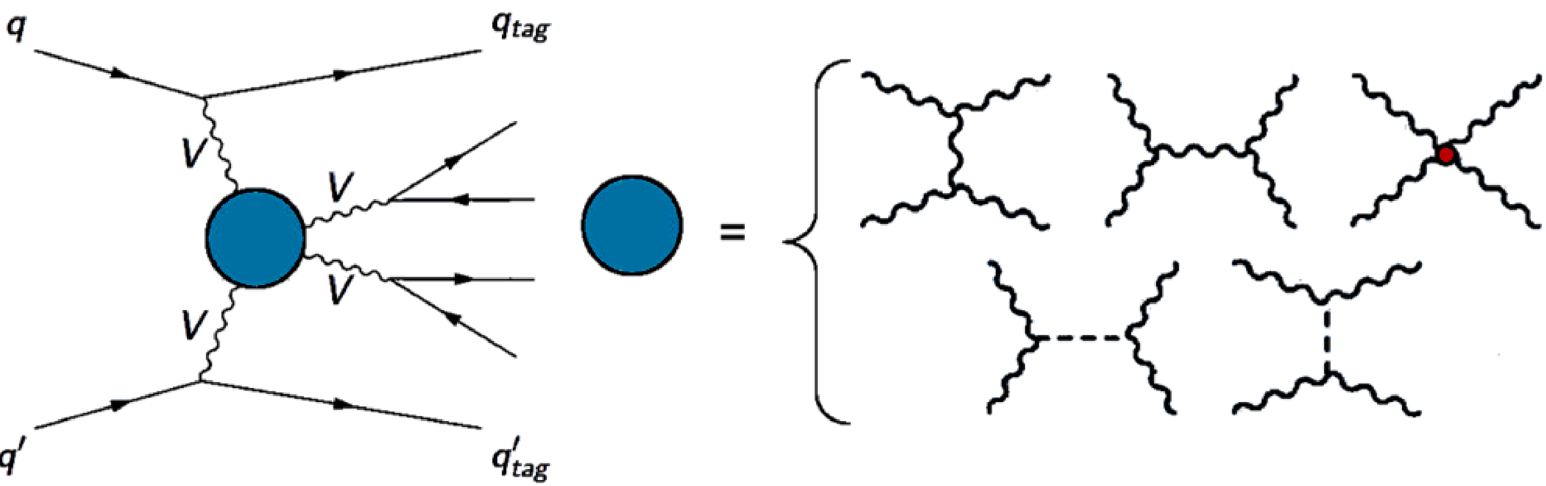
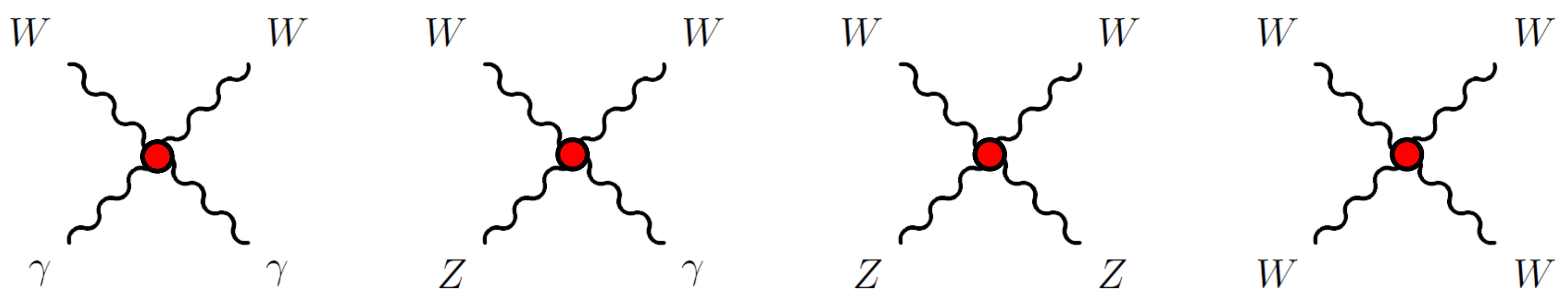


V=W/Z self-interactions

V-Higgs interactions

- **Quartic self-interactions of W/Z never observed before LHC era – untested territory!**



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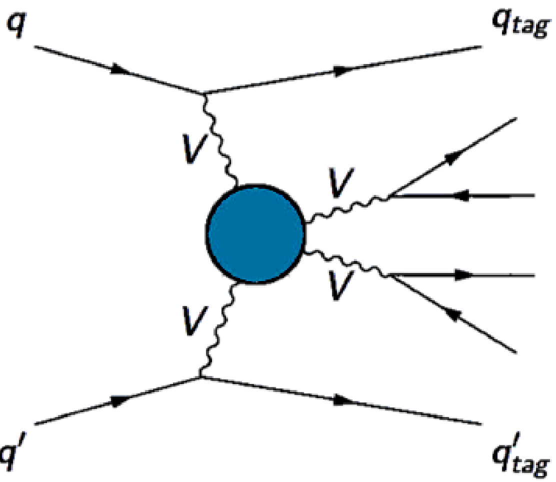

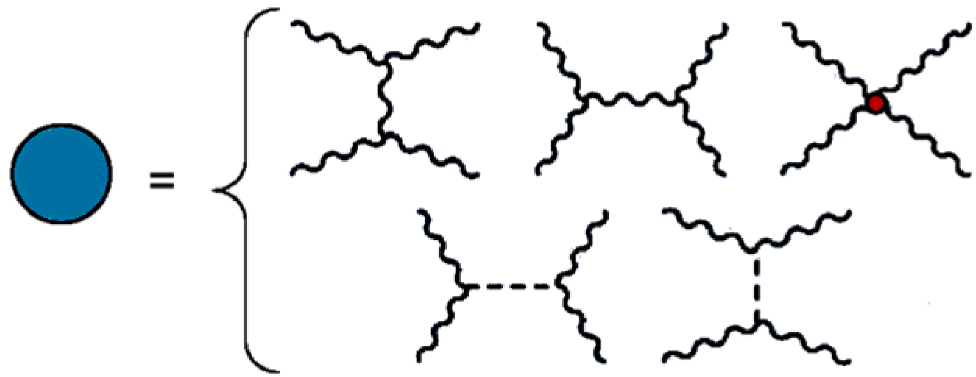

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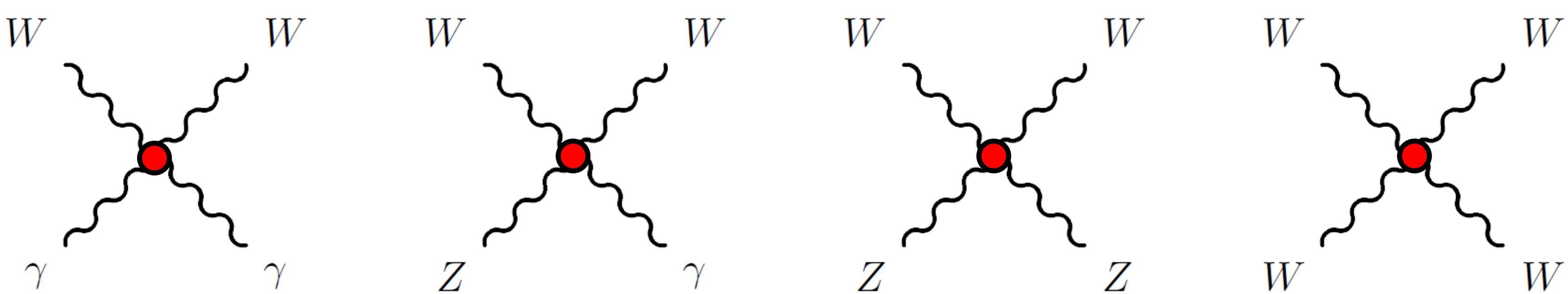
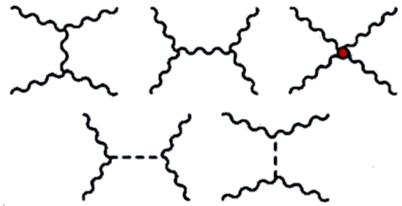


- Quartic self interactions just involving γ/Z forbidden…

Why the Higgs part matters

- No Higgs:



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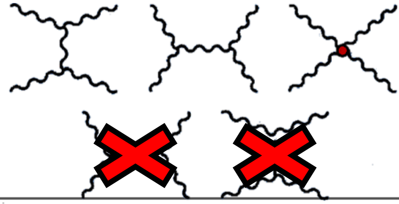

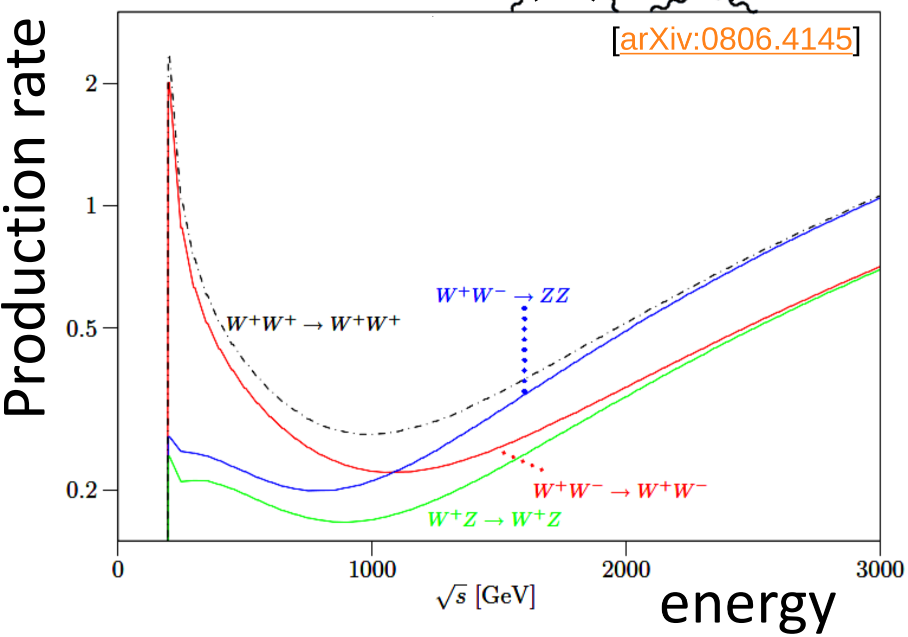

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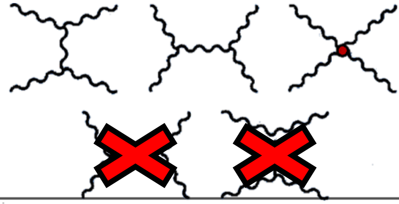

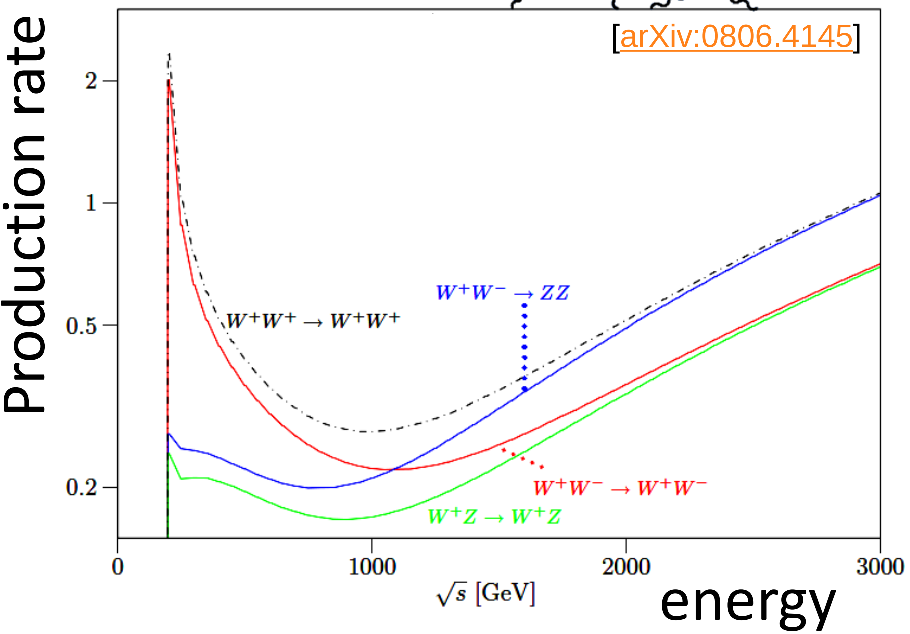

- Production rate **in**creases with energy

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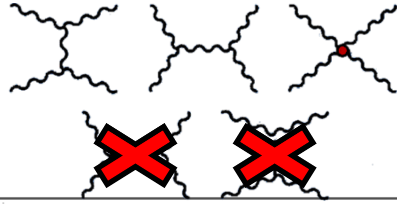

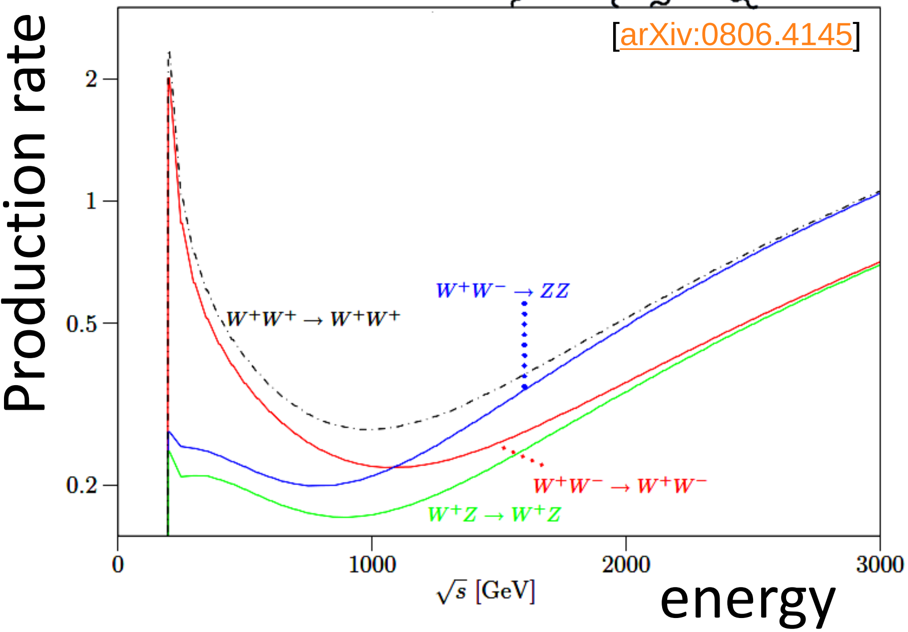

- Production rate **in**creases with energy
- Probabilities > 1 at high energies

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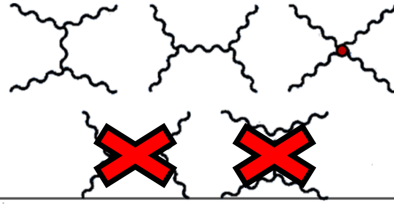

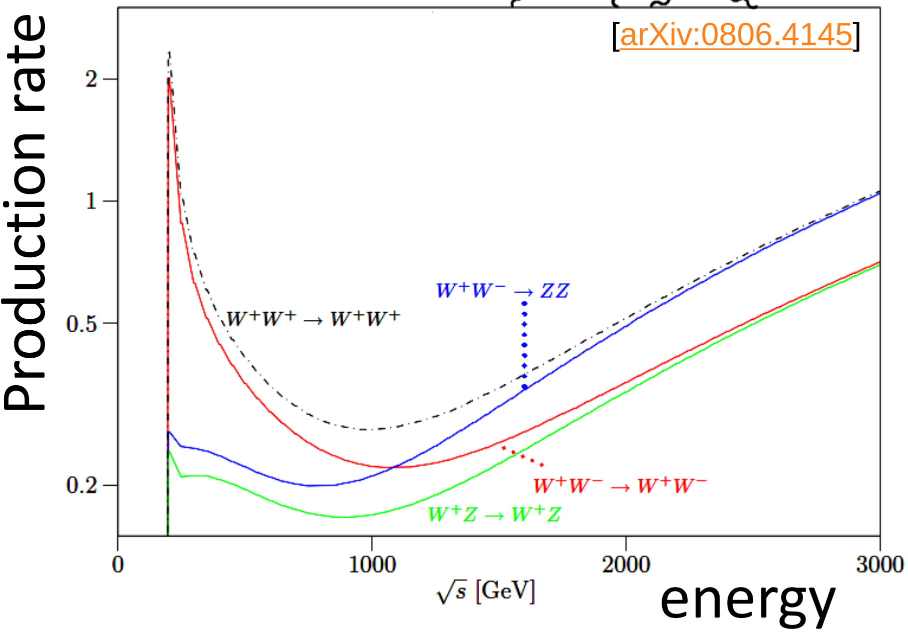

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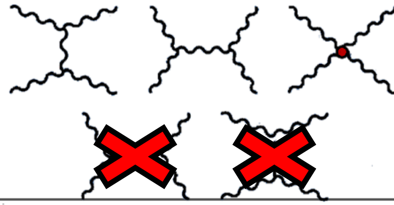

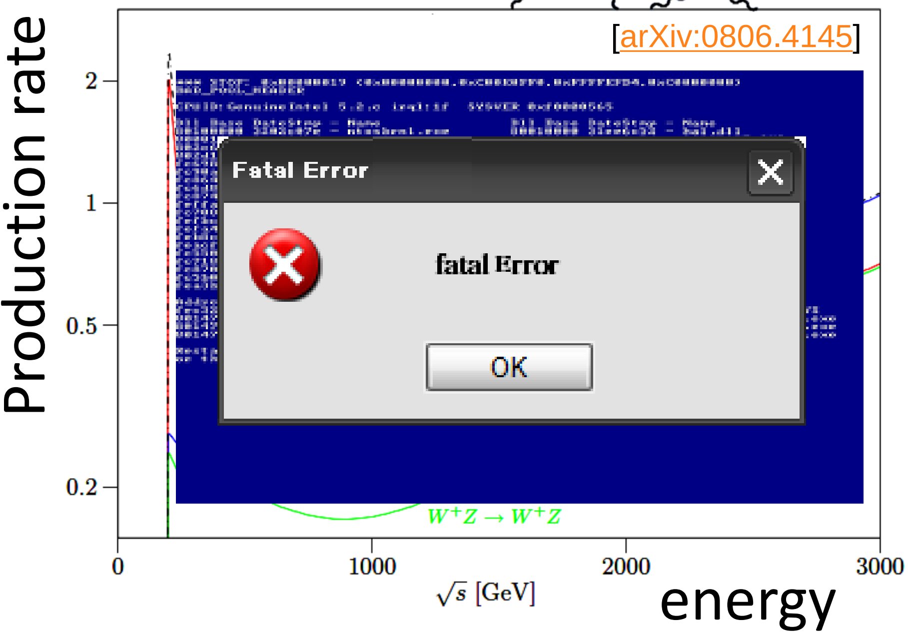

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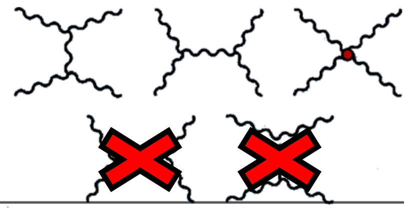

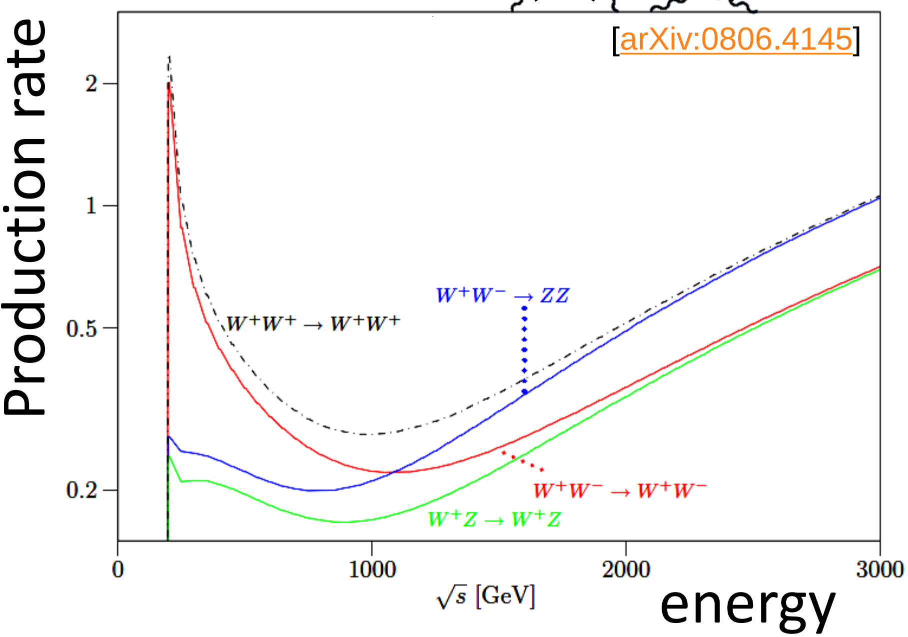

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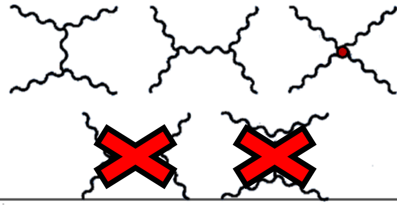
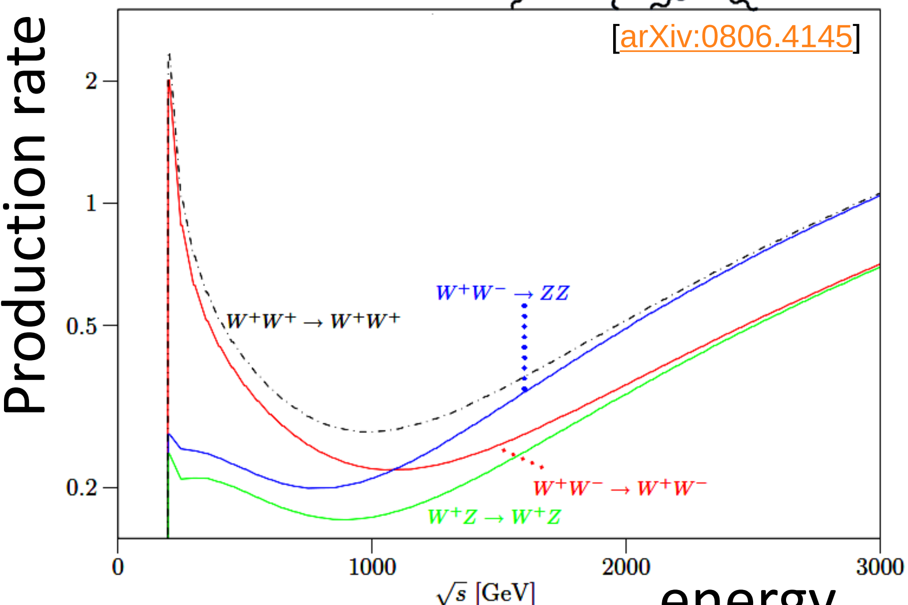
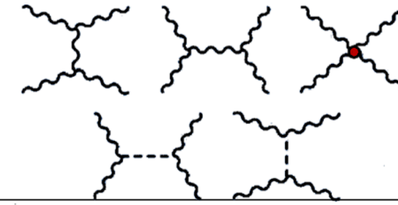
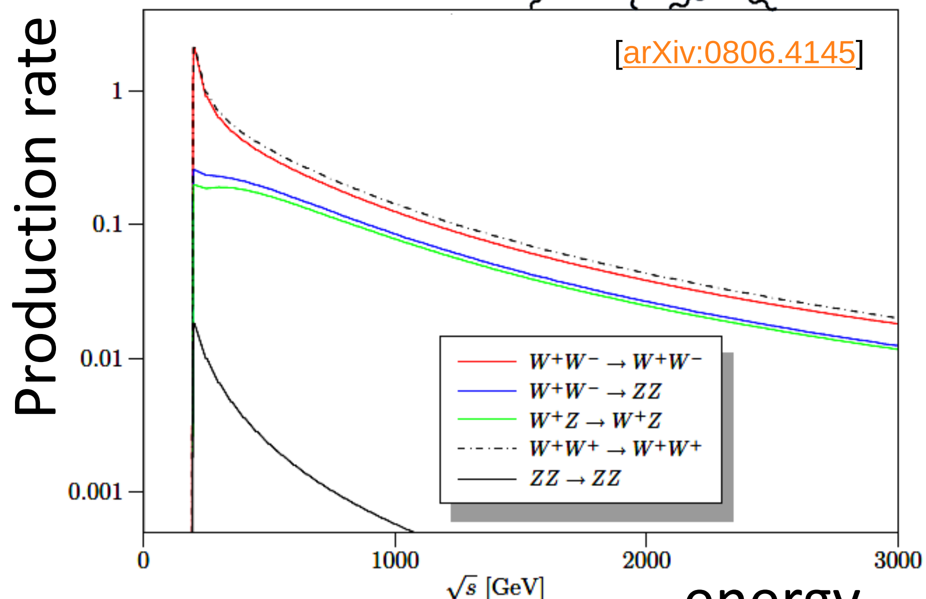




energy

- With Higgs:





energy

- Production rate **in**creases with energy
- Probabilities > 1 at high energies
- Standard Model breaks down!

- Production rate **de**creases with energy
- Probabilities < 1 for all energies
- Standard Model alive & kicking!

Why the Higgs part matters

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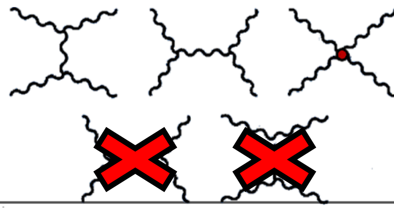

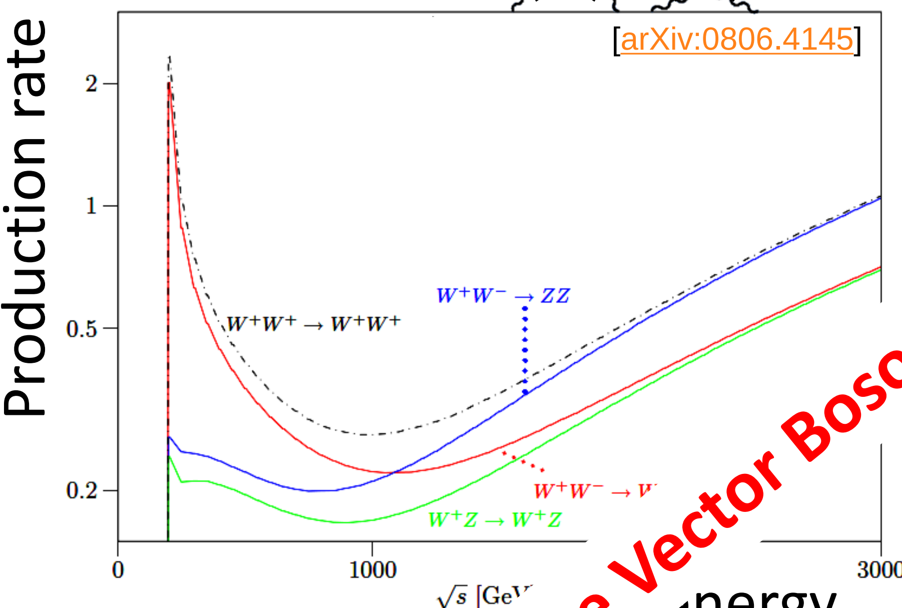

energy

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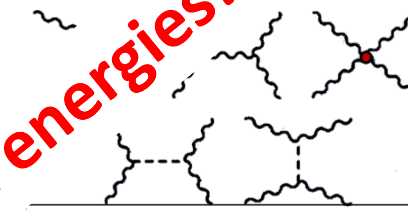

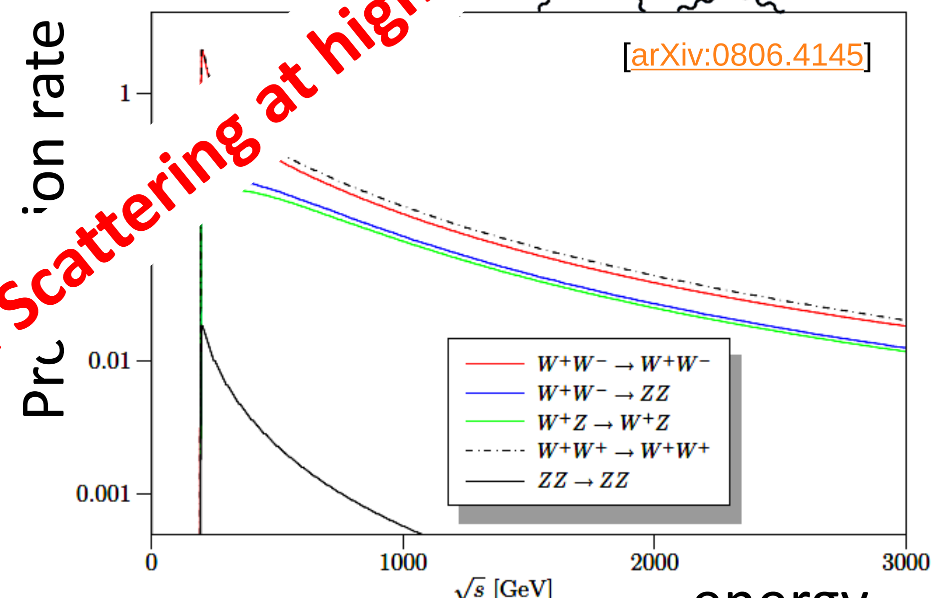

energy

Need to measure Vector Boson Scattering at high energies!

- Production r creases with energy
- Prob es > 1 at high energies
- St ard Model breaks down!

- Production rate **de**creases with energy
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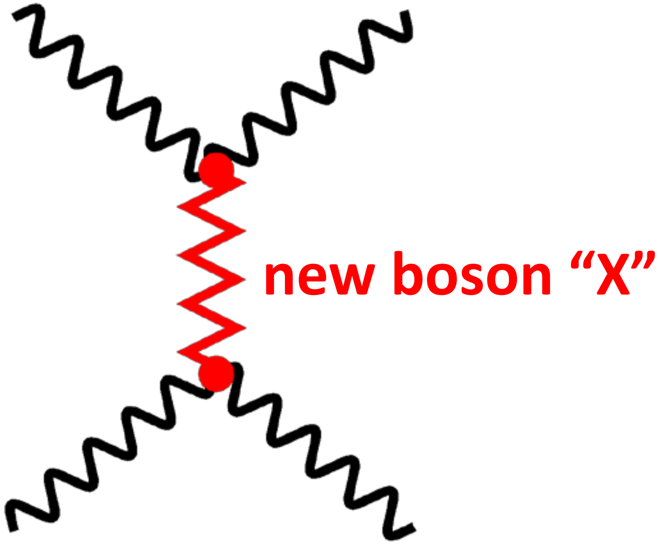
Exploring the unknown

- Wealth of models propose extensions to Standard Model (which is known to be incomplete):



- Can search for specific models (full theory), simplified models (benchmark), or do a “model-independent” search for modifications from the SM: “Effective Field Theory”
- “New Physics” will modify production rate and kinematics of decay products

VBS/VVV Production and aQGCs

- Overview of studied aQGCs:

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓	✓						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			✓			✓	✓	✓	✓

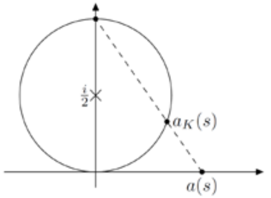
Vertex-specific conversions from WHIZARD α_4, α_5 exist, e.g. for WWWW:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}, \alpha_4 + 2 \cdot \alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

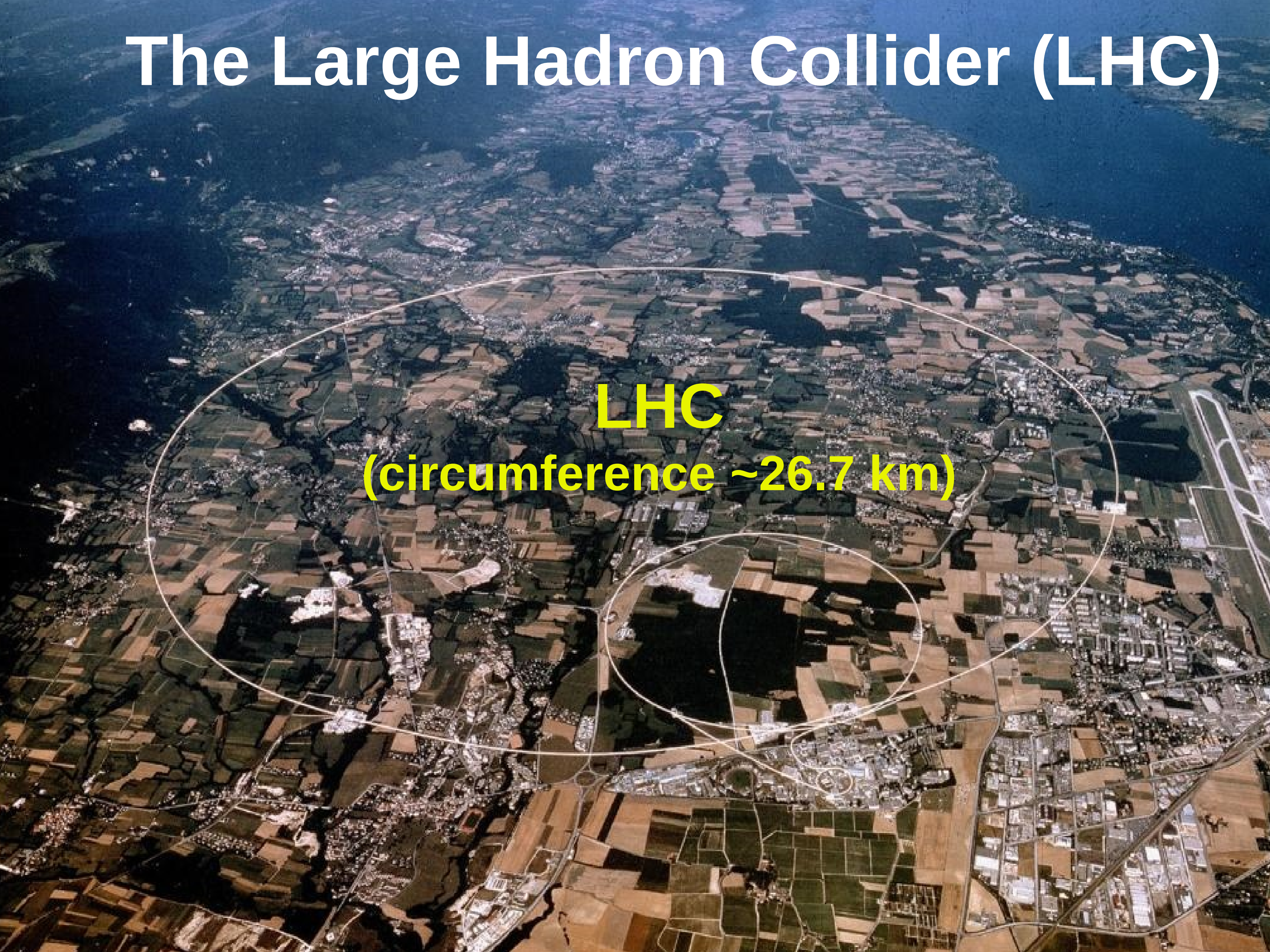
- Experimental access: aQGCs modify total production rate as well as event kinematics
  - Use cross-section measurement or kinematics to constrain aQGCs
- Unitarisation methods:
  - Form factor

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^n}$$

  - K-matrix unitarisation



The Large Hadron Collider (LHC)



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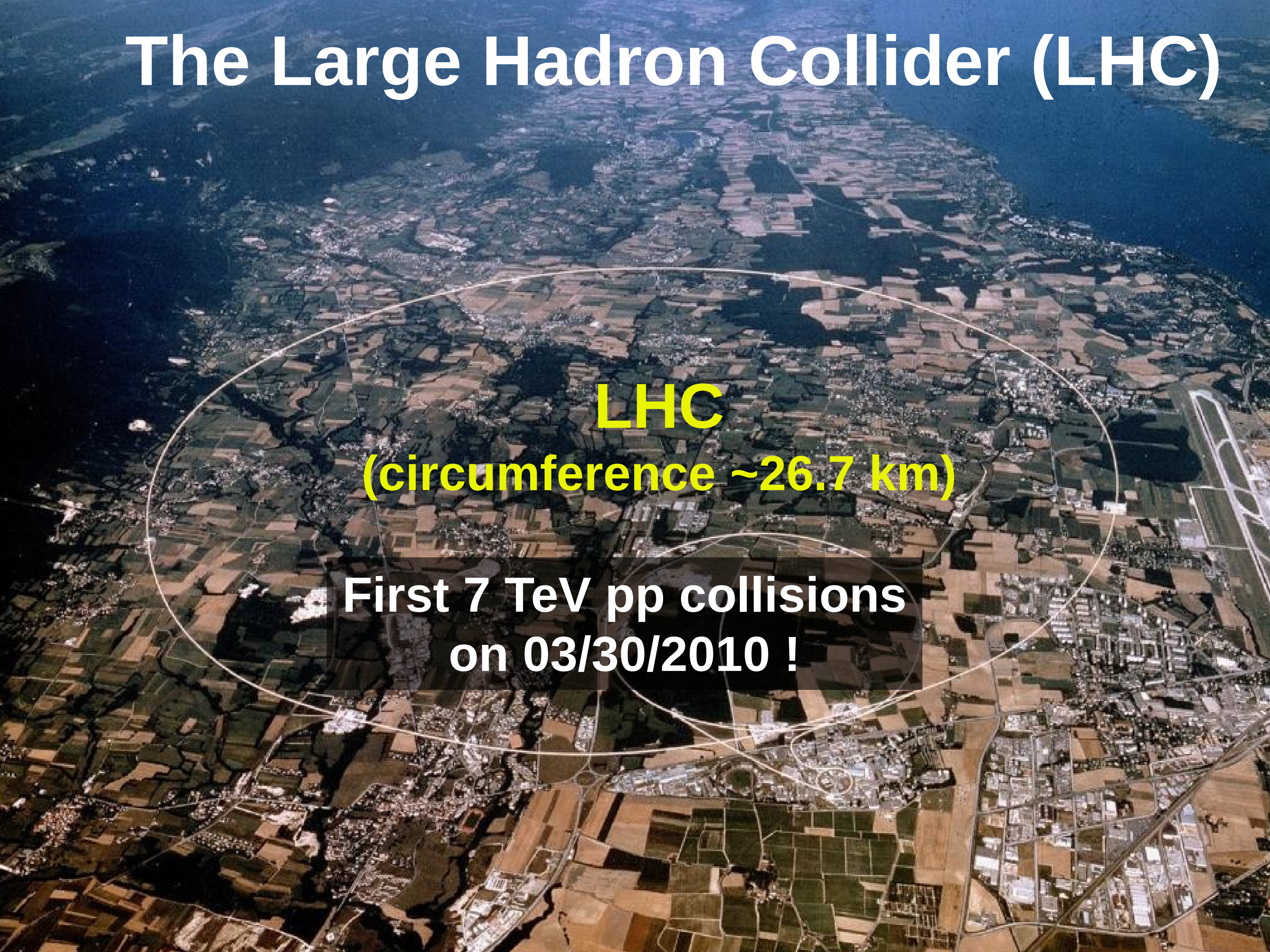
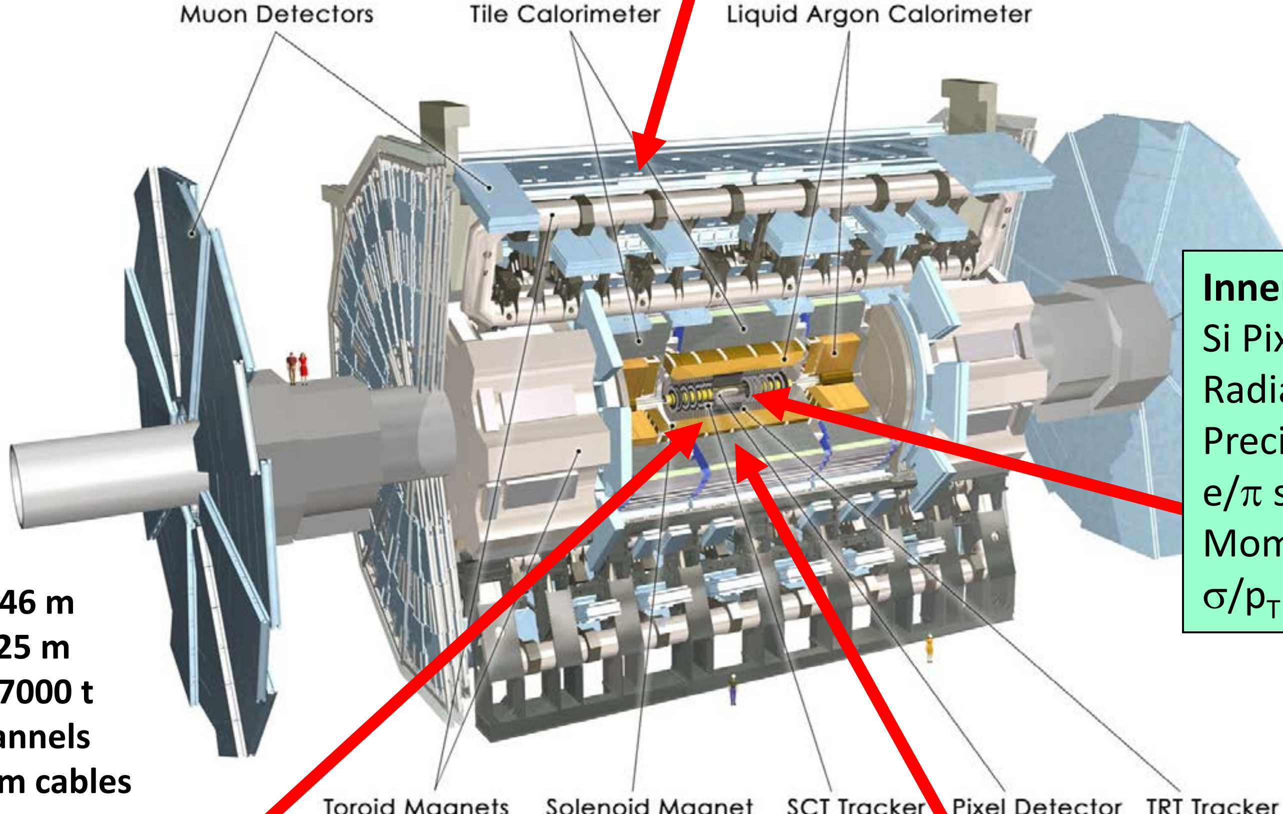


The ATLAS-Detector

(A Toroidal LHC ApparatuS)

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_{μ} ~ 1 TeV

Trigger: 2-levels reducing the rate from 40 MHz to ~1 kHz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T\,(\text{GeV}) \oplus 0.015$

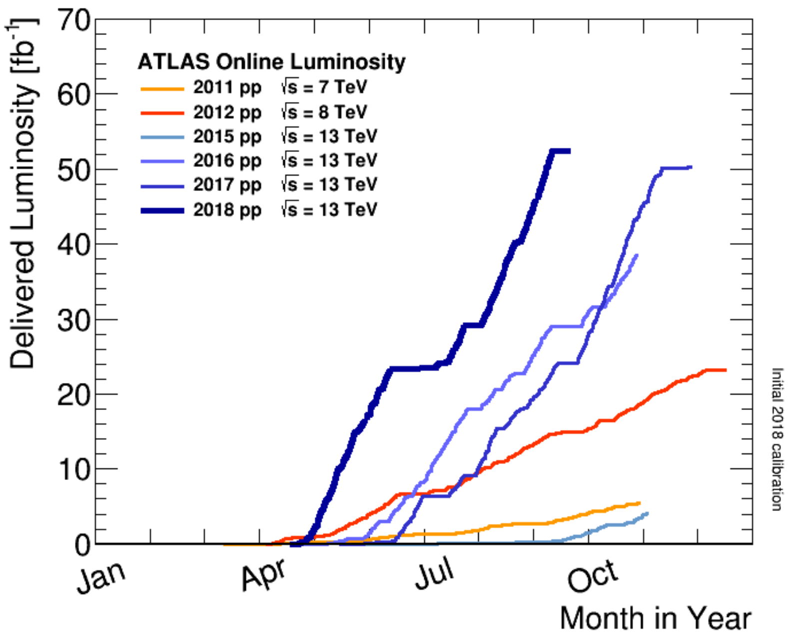
Length: 46 m
Diam. : 25 m
Weight:7000 t
~10^8 channels
~3000 km cables

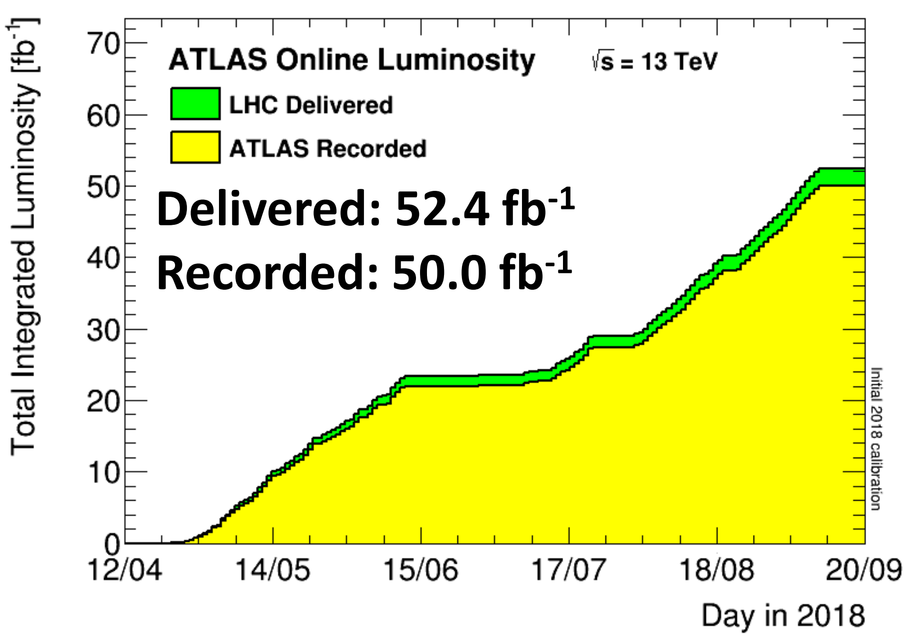
EM calorimetry: Pb-LAr Accordion
e/γ trigger, ID and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

LHC Run 2 as seen by ATLAS

PDG 2010: So to achieve high luminosity, **all one has to do** is make high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible.



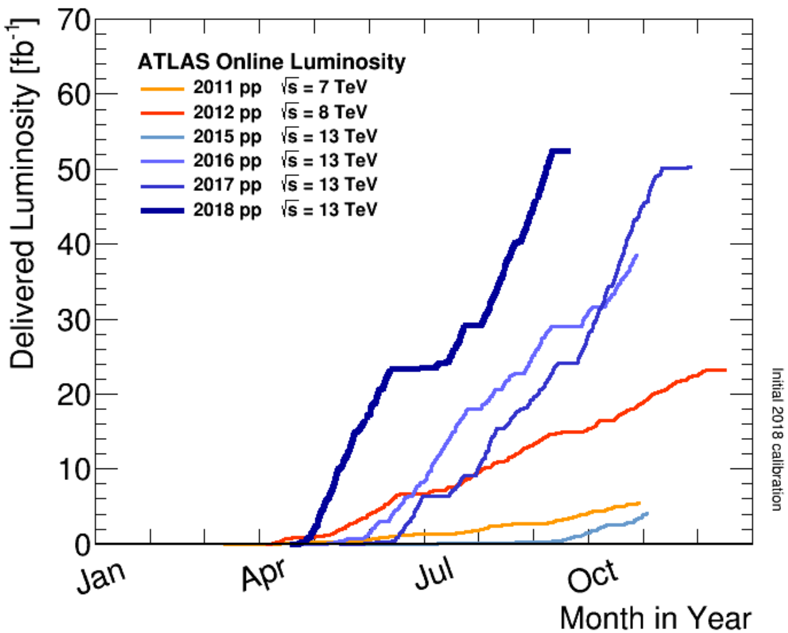


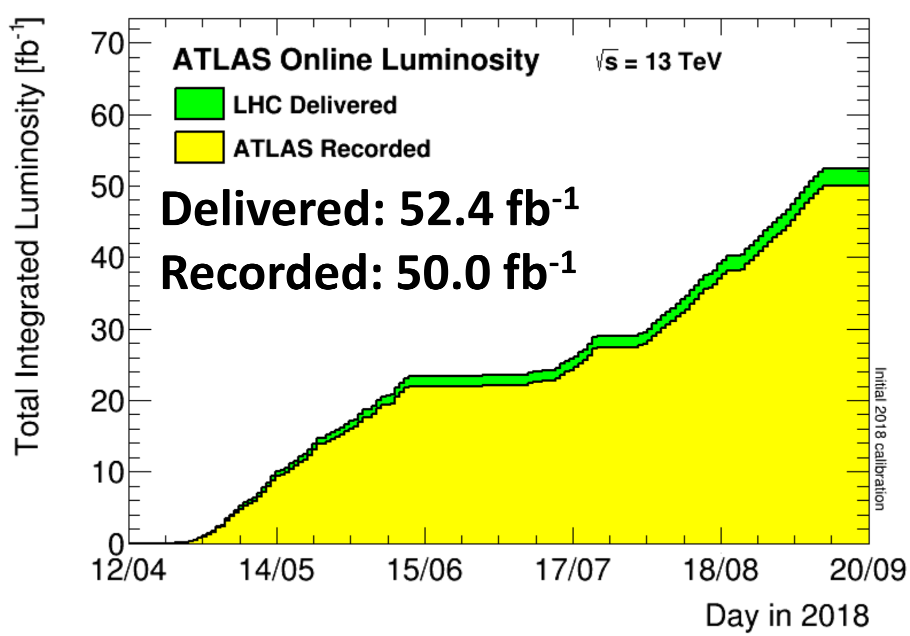
Total 13 TeV pp integrated luminosity in Run 2: 136 fb^{-1}.

LHC Run 2 as seen by ATLAS

ATLAS luminosity in 2018

Peak Stable Luminosity Delivered:	2.14×10^{34} $cm^{-2}s^{-1}$
Max average interactions per bunch crossing:	64
Max Luminosity in fill/day/week:	739.4 pb^{-1} /926.2 pb^{-1} /5.371 fb^{-1}
2016 Luminosity uncertainty:	2.2%
2017 Luminosity uncertainty:	2.4% (prelim.)





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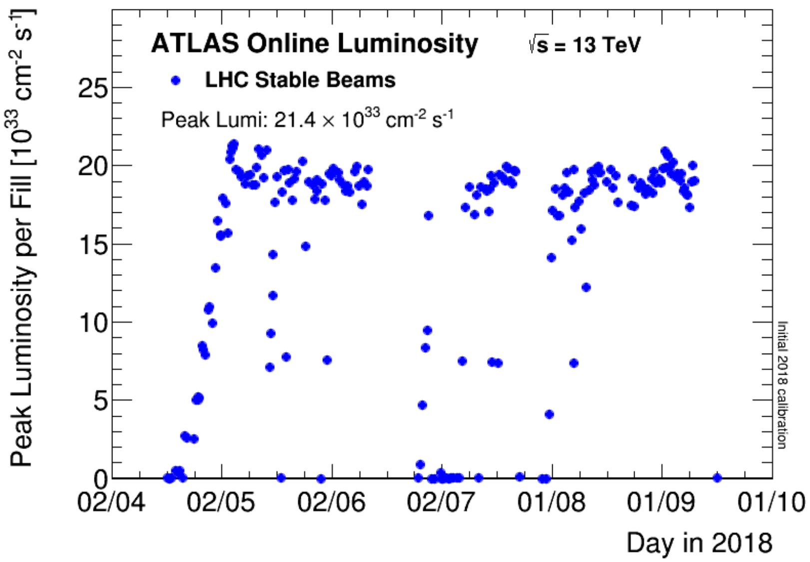
ATLAS Detector Performance

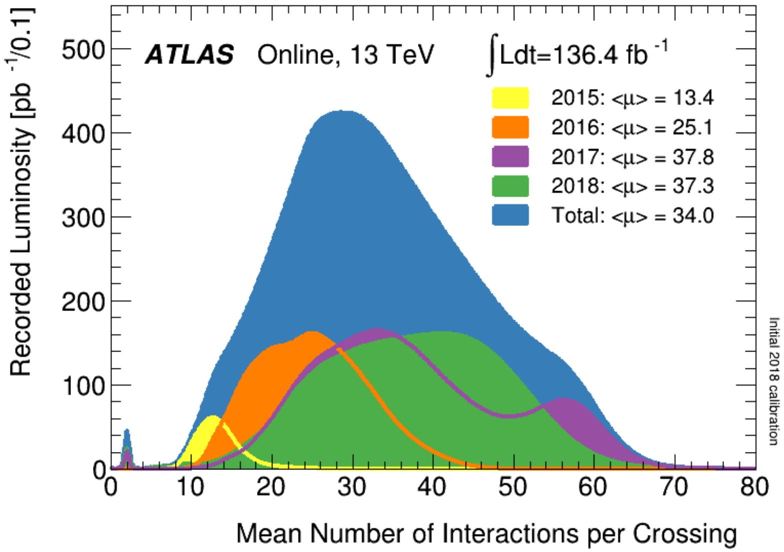
ATLAS pp data: April 25-August 20 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.7	99.6	100	99.6	100	99.7	99.6	100	100	100	99.3
Good for physics: 96.5% (36.4 fb^{-1})										

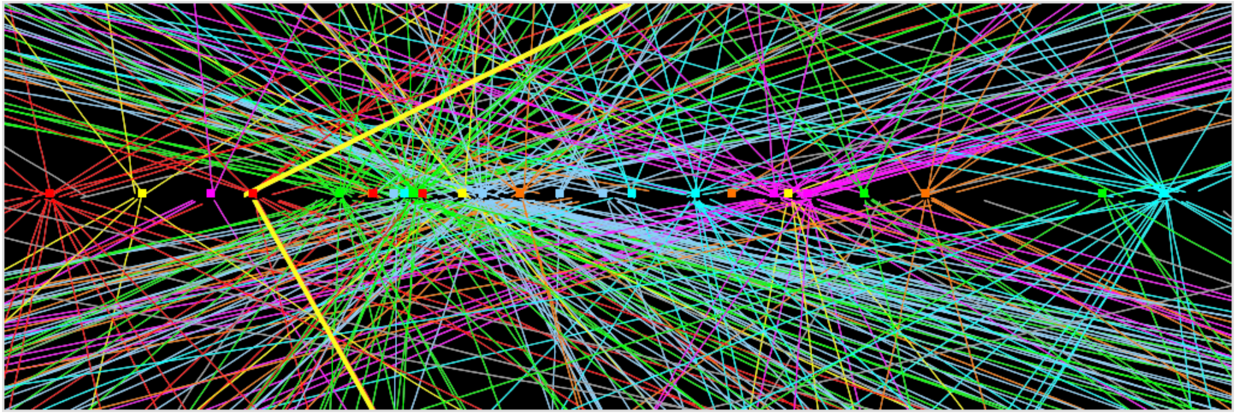
Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions at $\sqrt{s}$=13 TeV between April 25 – August 20 2018, corresponding to a delivered integrated luminosity of 39.2 fb^{-1} and a recorded integrated luminosity of 37.7 fb^{-1}. Dedicated luminosity calibration activities during LHC fills used 0.7% of recorded data and are included in the inefficiency. The luminosity includes 193 pb^{-1} of good data taken at an average pileup of μ=2.

- Data-taking efficiency for above period: 96.2%
- **~93% of delivered luminosity can be used for physics analysis**

The price of high lumi…



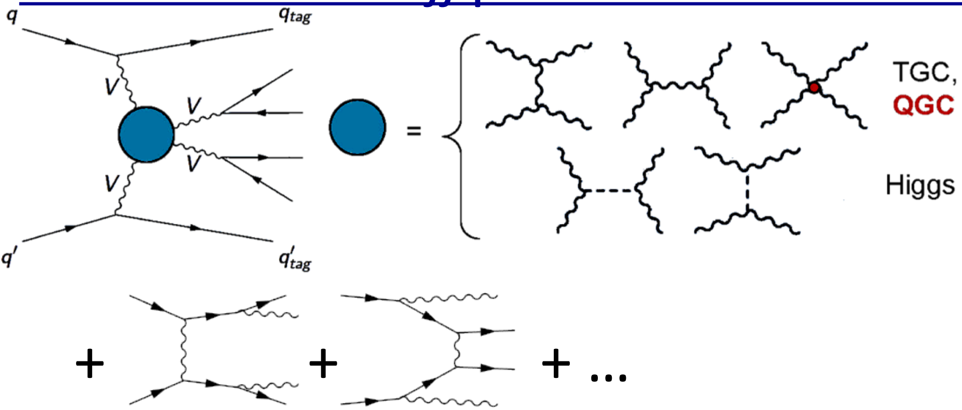




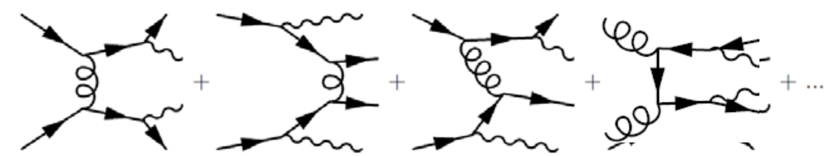
Z→ μμ candidate event, with 25 reconstructed vertices.

Vector Boson Scattering

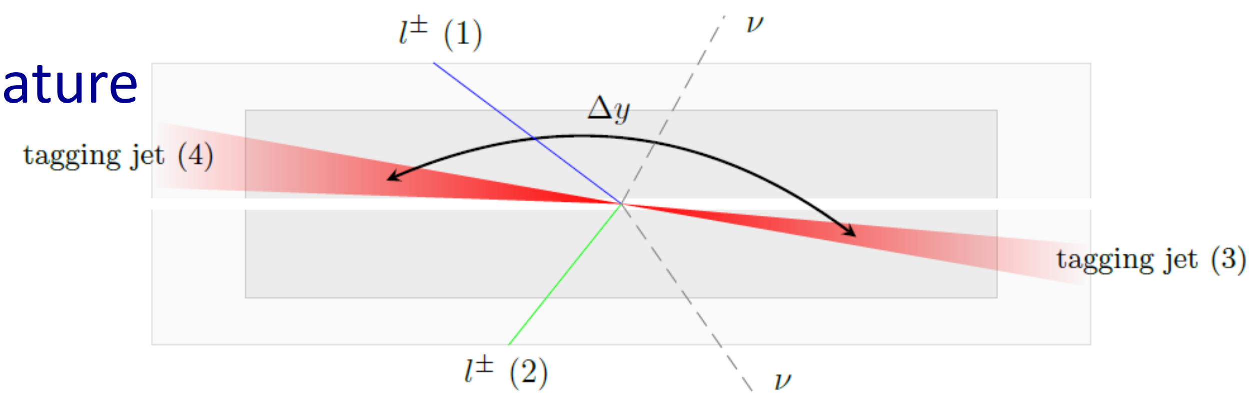
electroweak VVjj production includes:



strong VVjj production includes:



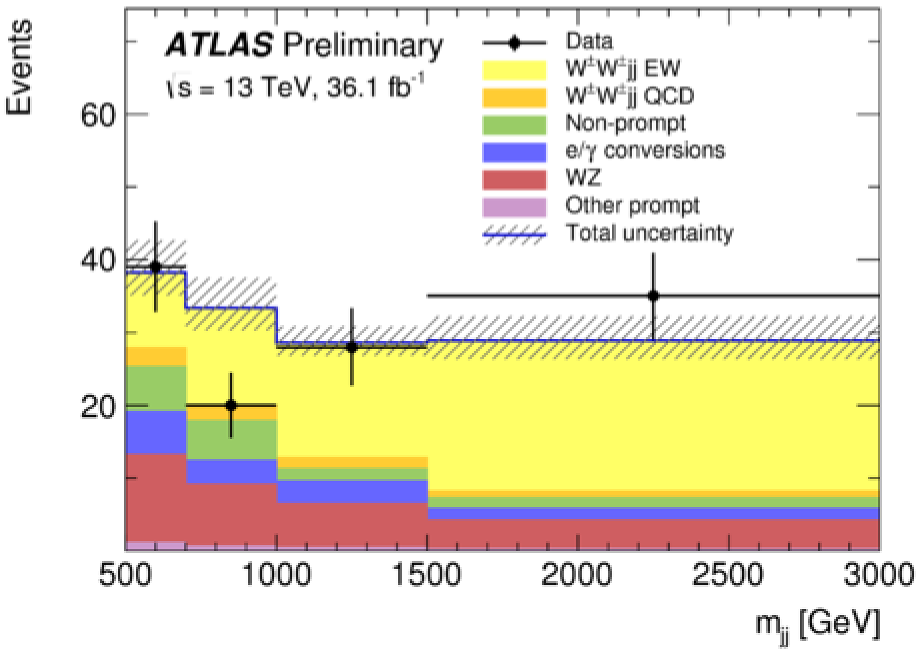
- Experimental signature ($W^{\pm}W^{\pm}$ example):



  - 1,2 = Central, high-p_T charged leptons from V decays
  - 3,4 = Forward/backward tagging jets (large m_{jj} and well separated in y)

$W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$

- Exactly 2 *same charge* isolated leptons (e or μ), MET > 30 GeV
- VBS signal region: ≥ 2 jets, $|\Delta y_{jj}| > 2$, $m_{jj} > 500$ GeV, b-jet veto
- Likelihood fit in 6 channels (charge/lepton combis), 4 m_{jj} bins



Expected fiducial cross section:

POWHEGBOX:

$$\sigma^{\text{fid}}_{\text{EWK}} = 3.08^{+0.45}_{-0.46}\ (\text{syst.+stat.})\ \text{fb}$$

SHERPA:

$$\sigma^{\text{fid}}_{\text{EWK}} = 2.01^{+0.33}_{-0.23}\ (\text{sys.+stat.})\ \text{fb}$$

Observed sign.: 6.9σ (4.6σ expected)

Measured fiducial cross section:

$$\sigma^{\text{fid}} = 2.91^{+0.51}_{-0.47}\ (\text{stat.}) \pm 0.27\ (\text{sys.})\ \text{fb}$$

$W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$

- Exactly 2 *same charge* isolated leptons (e or μ), MET > 30 GeV
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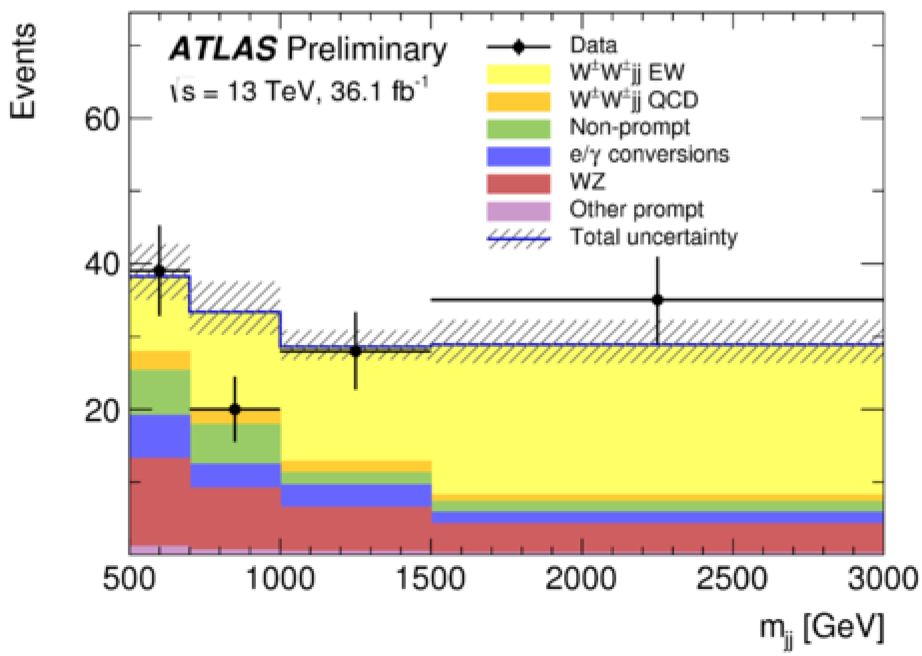

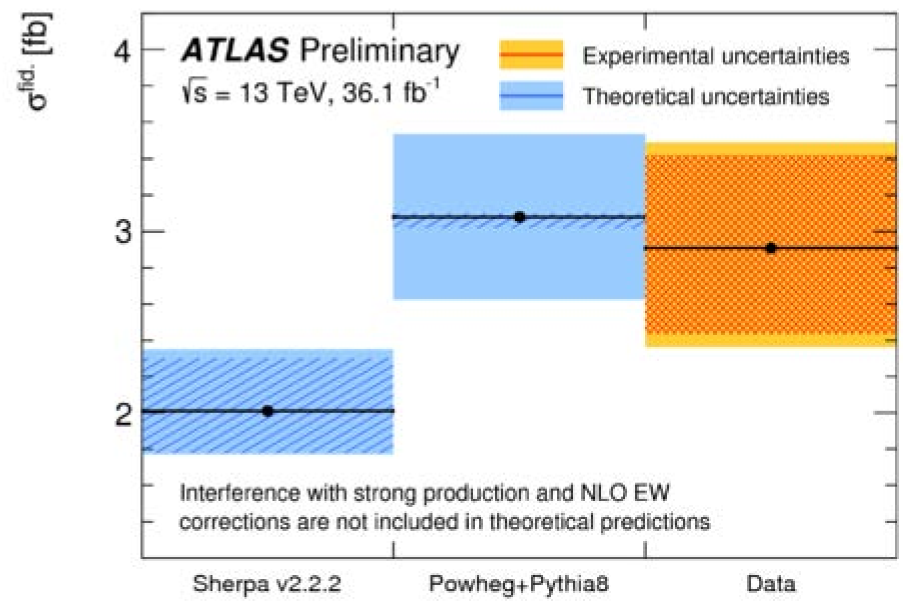

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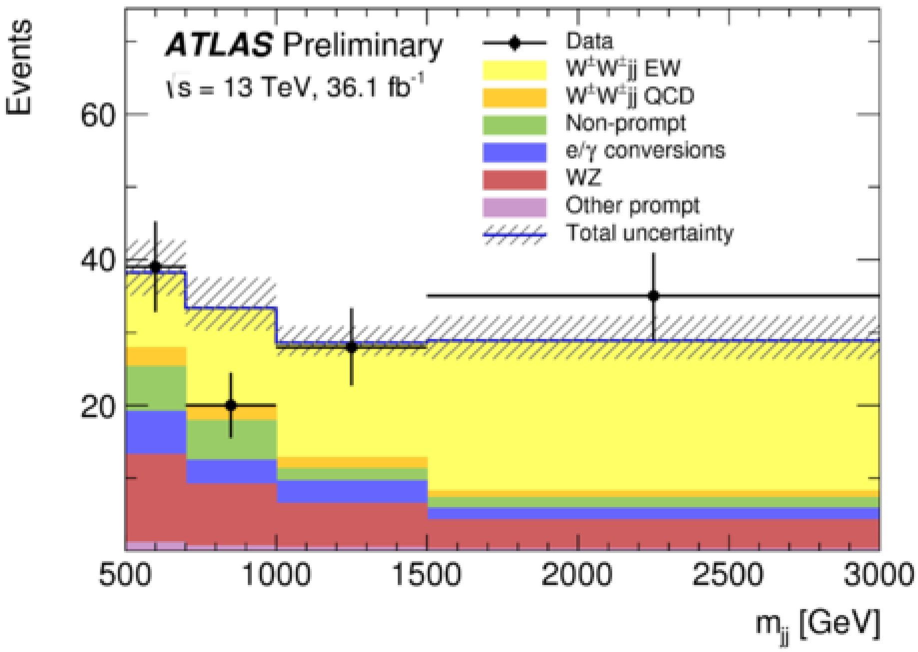
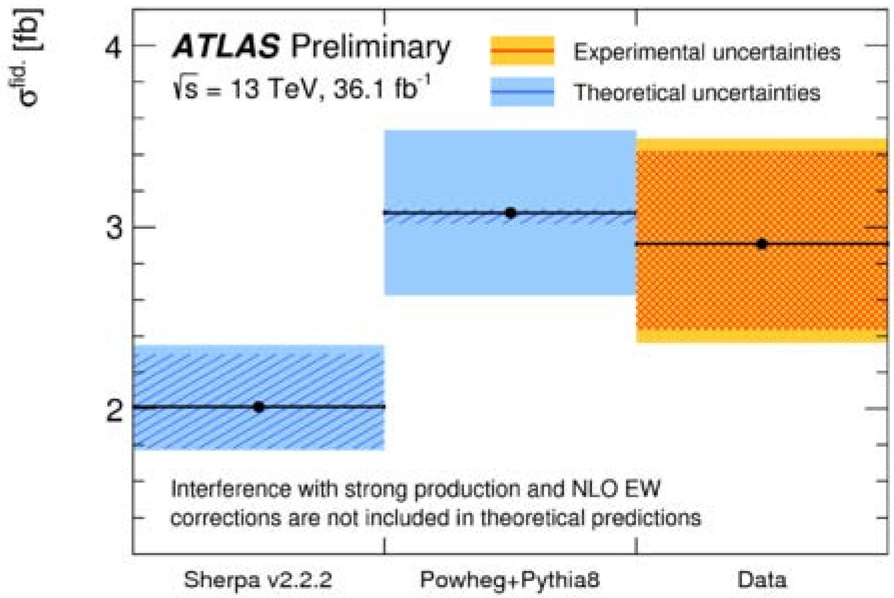
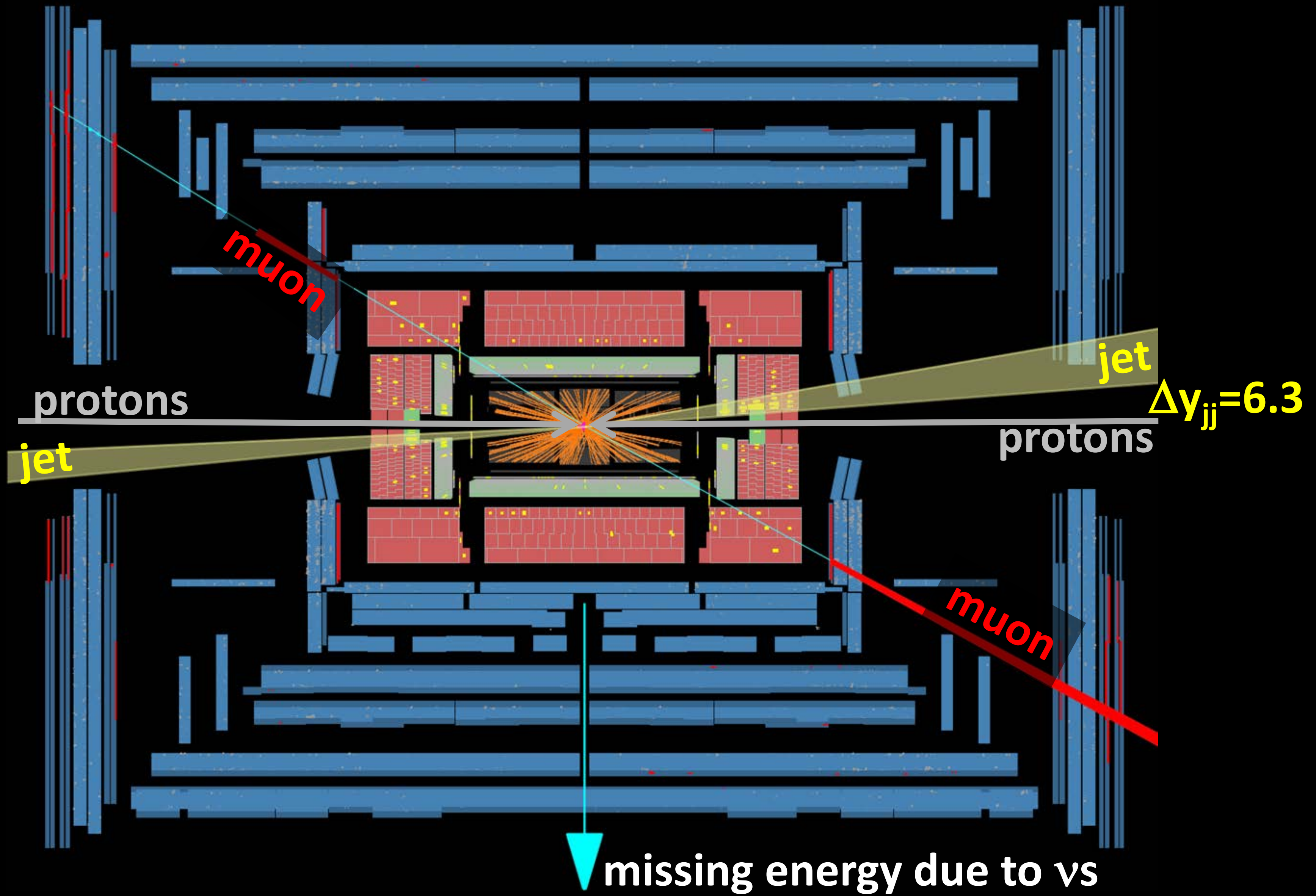




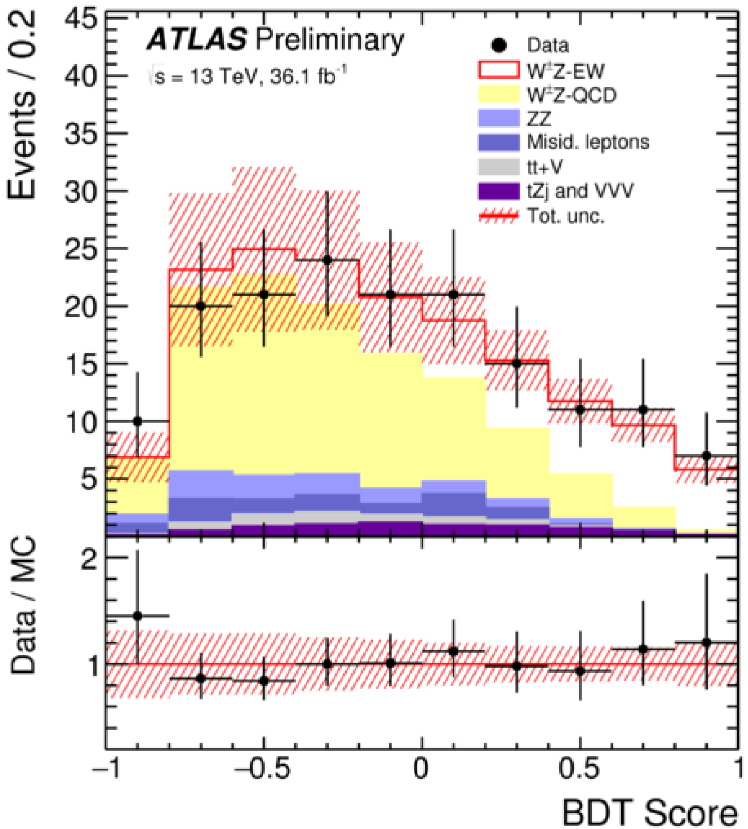
- Updated Sherpa predicts 20% larger xsec (corrected color flow)

$W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu jj$ candidate event



$W^{\pm}Zjj \longrightarrow \ell\nu\ell\ell jj$ ATLAS-CONF-2018-033

- 3 isolated leptons (e or μ), MET (via m_T) as WZ inclusive
- VBS signal region (SR): ≥ 2 jets, p_T > 40 GeV , m_{jj} > 500 GeV, b-jet veto
- BDT discriminant based on 15 variables reflecting VBS kinematics



Post-fit background normalisations

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

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

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

WZjj-EW measured signal strength:

$$\mu_{EW} = 1.77 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.}) = 1.77 \pm 0.45$$

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

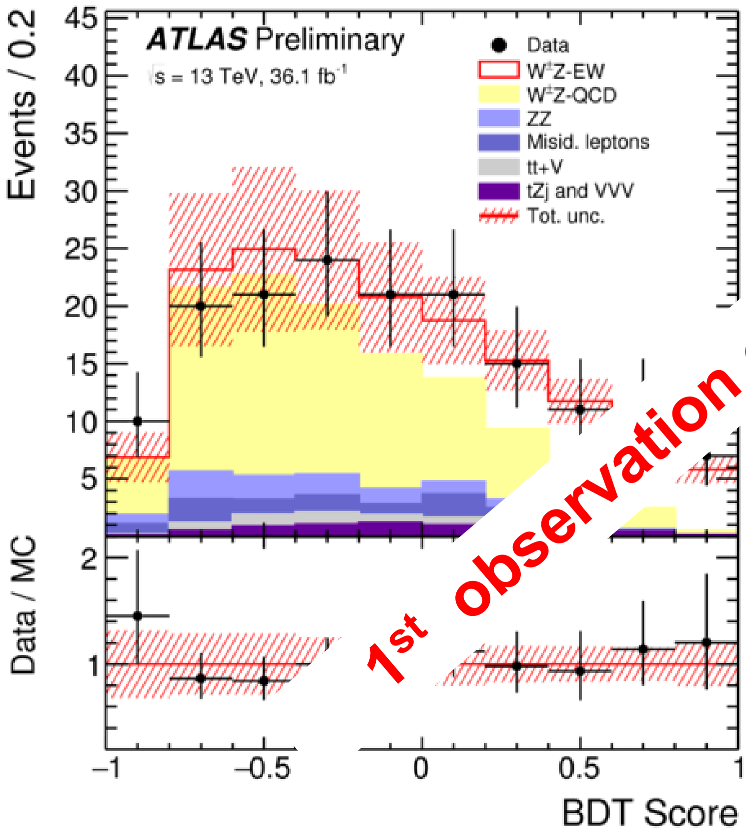
$$\sigma^{\text{fid., EW}}_{WZ^{\pm}jj\to\ell\nu\ell\ell jj} = 0.57\,^{+0.15}_{-0.14}\ \text{fb} = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{sys.})\,^{+0.04}_{-0.03}\,(\text{th.})\ \text{fb}\,.$$

- Background estimate constrained via 3 control regions fitted w/ SR

$W^{\pm}Zjj \longrightarrow \ell\nu\ell\ell jj$ ATLAS-CONF-2018-033

- 3 isolated leptons (e or μ), MET (via m_T) as WZ inclusive
- VBS signal region (SR): ≥ 2 jets, p_T > 40 GeV , m… GeV, b-jet veto
- BDT discriminant based on 15 variables refl… VBS kinematics

1st observation of EW W±Zjj production!



Post-fit backg… …rmalisations

$\mu_{WZ-QC…}$ … ± 0.25

$\mu_{tt…}$ 1.18 ± 0.19

… = 1.34 ± 0.29

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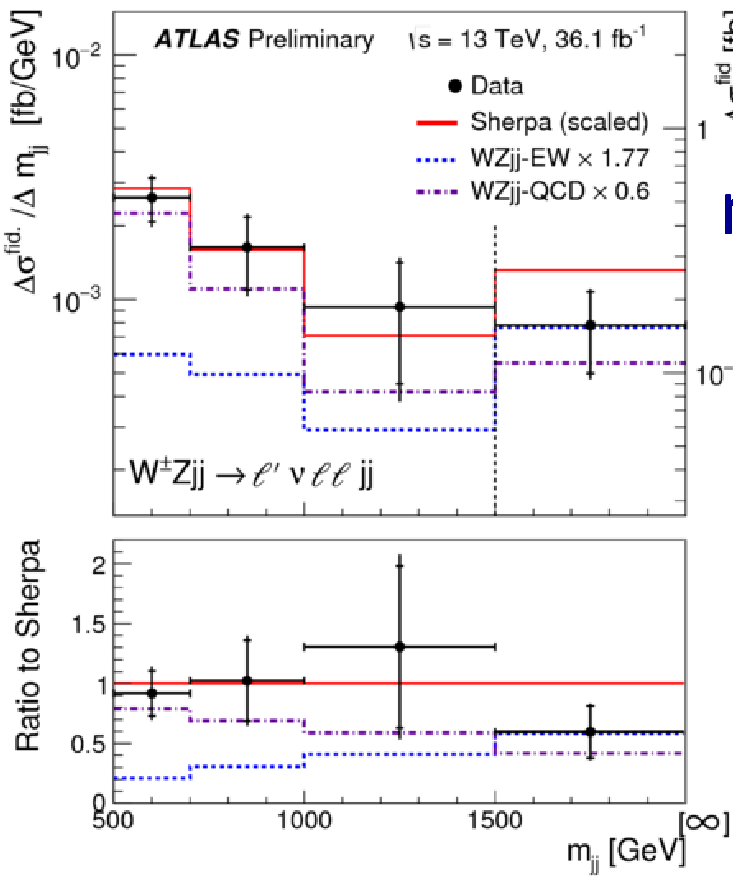
- Background estimate constrained via 3 control regions fitted w/ SR

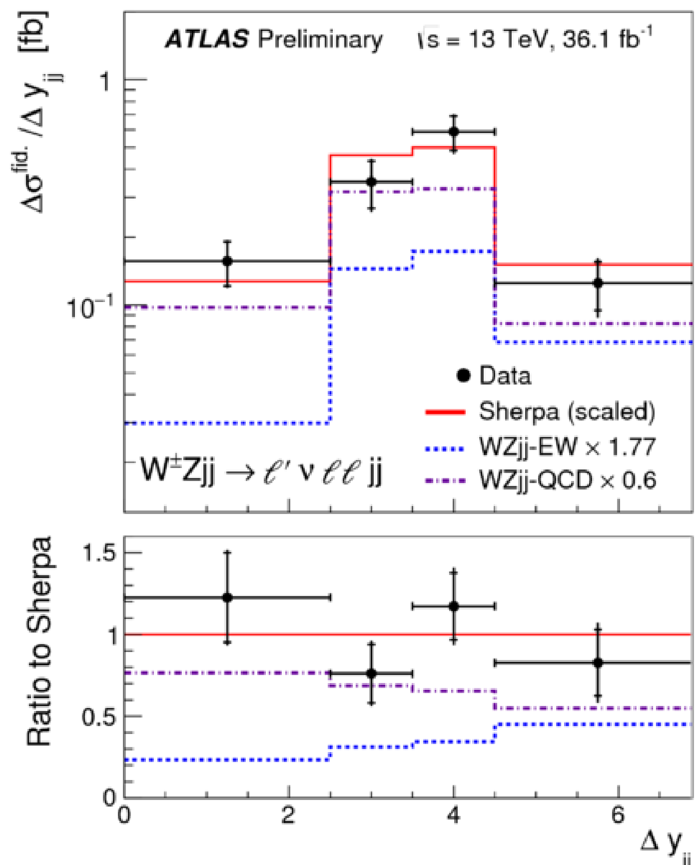
$W^{\pm}Zjj \longrightarrow \ell\nu\ell\ell jj$

ATLAS-CONF-2018-033

- Differential cross-sections extracted in SR (mjj > 500 GeV)
- Compared to normalized Sherpa predictions for WZjj (QCD + EW)



m_{jj}



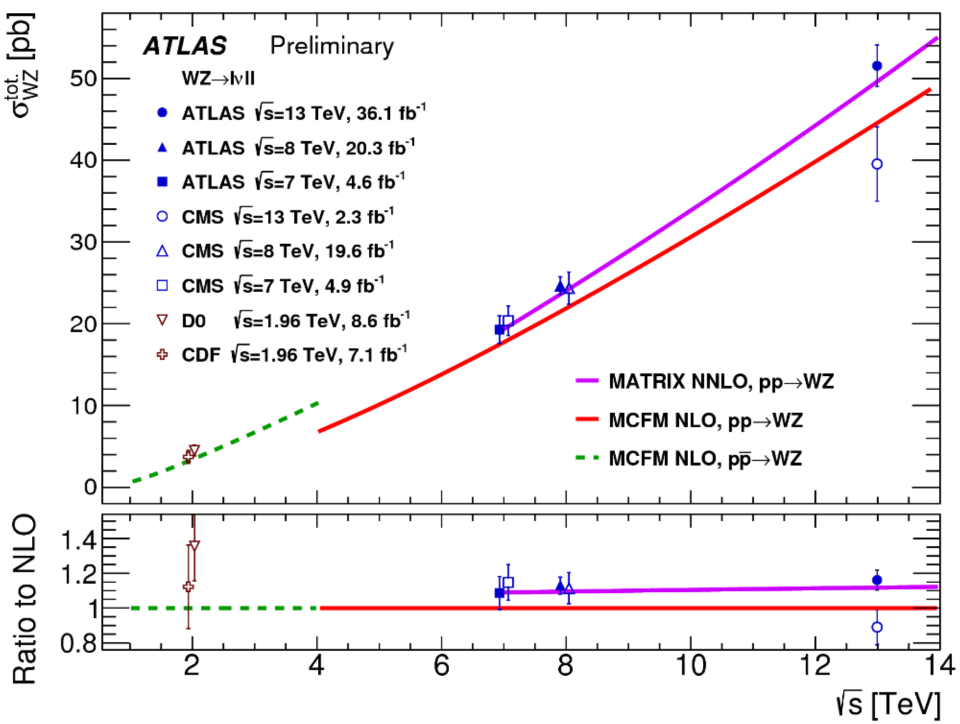
Δy_{jj}

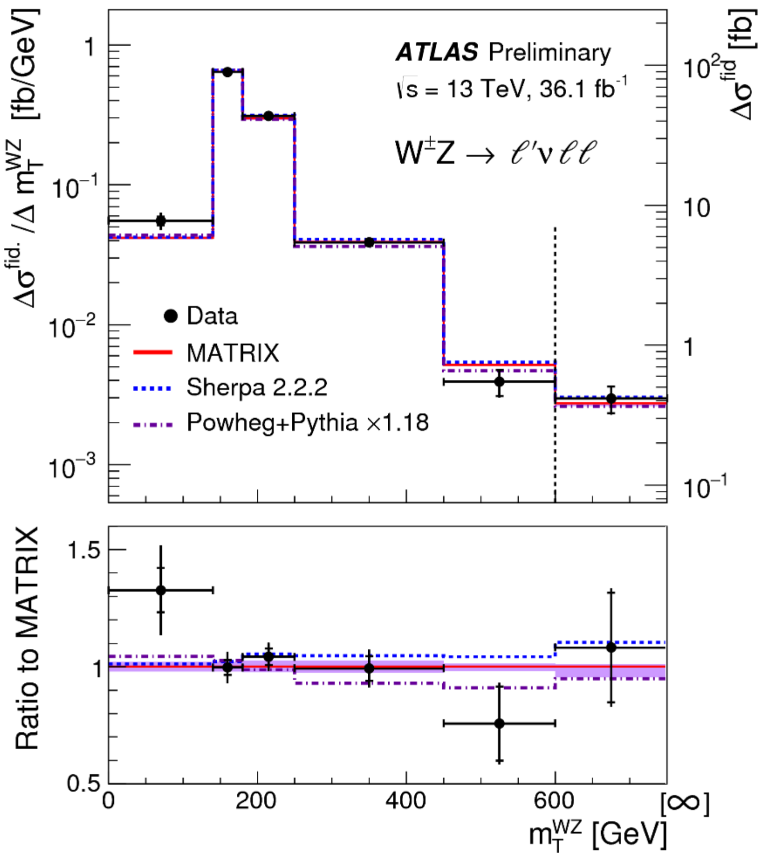
- More distributions available: N_{jets}, Σp_T^l, m_T^{WZ}, $\Delta\phi_{jj}$, $\Delta\phi(W,Z)$, N_{jets}^{gap}

$W^{\pm}Z \longrightarrow \ell\nu\ell\ell$

ATLAS-CONF-2018-034

- 3 isolated leptons (e or μ), MET (via m_T), **no VBS selection!**
- Precision test of NNLO QCD, unfolded single differential xsecs
- W and Z polarisation measurements – test bed for VBS!

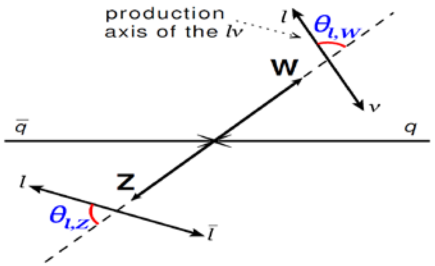


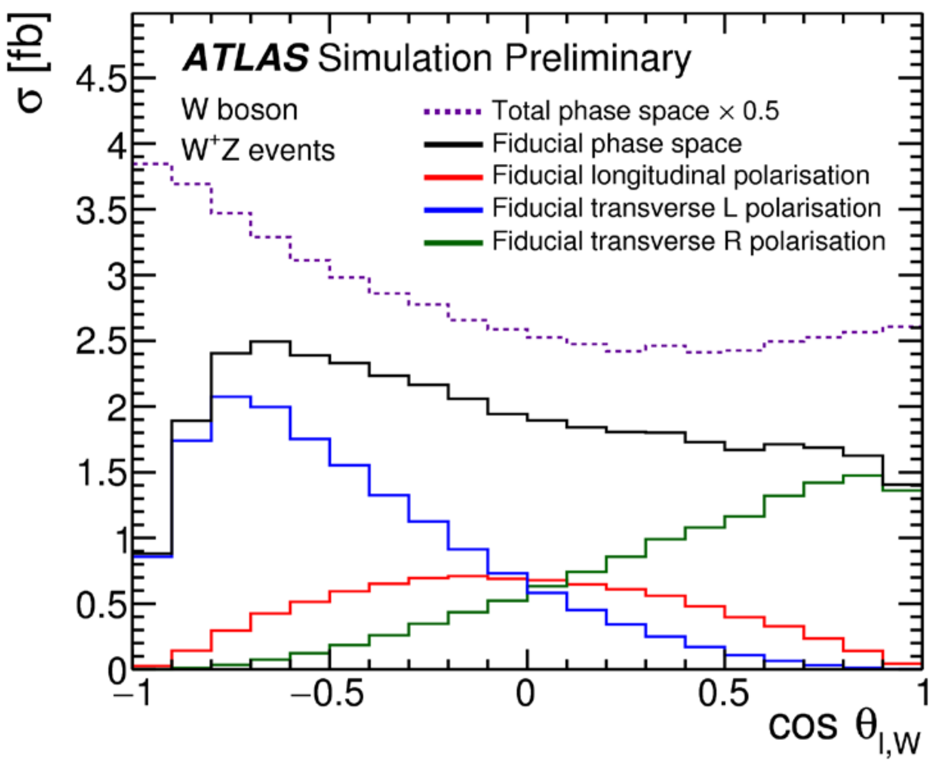


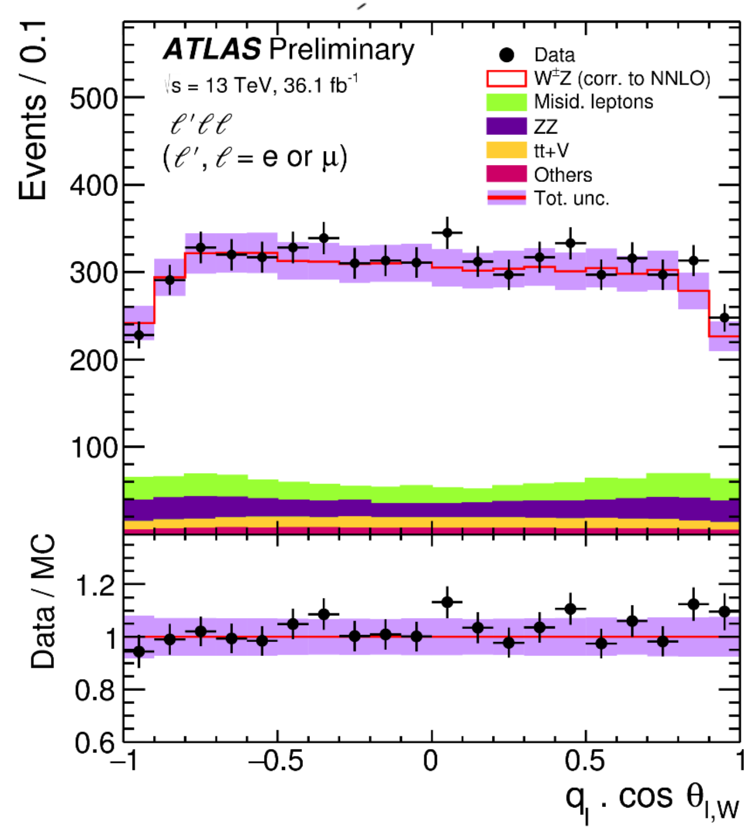
$W^{\pm}Z \rightarrow \ell\nu\ell\ell$ Polarisation

ATLAS-CONF-2018-034

- V polarisation determined from angular distribution decay products
- f_0, f_L,f_R: longitudinal, transverse-left & -right handed helicity fractions; $f_0 + f_L + f_R = 1$
- Fit $q_\ell \cdot \cos\theta_{\ell,W}$ and $\cos\theta_{\ell,Z}$ distribution templates



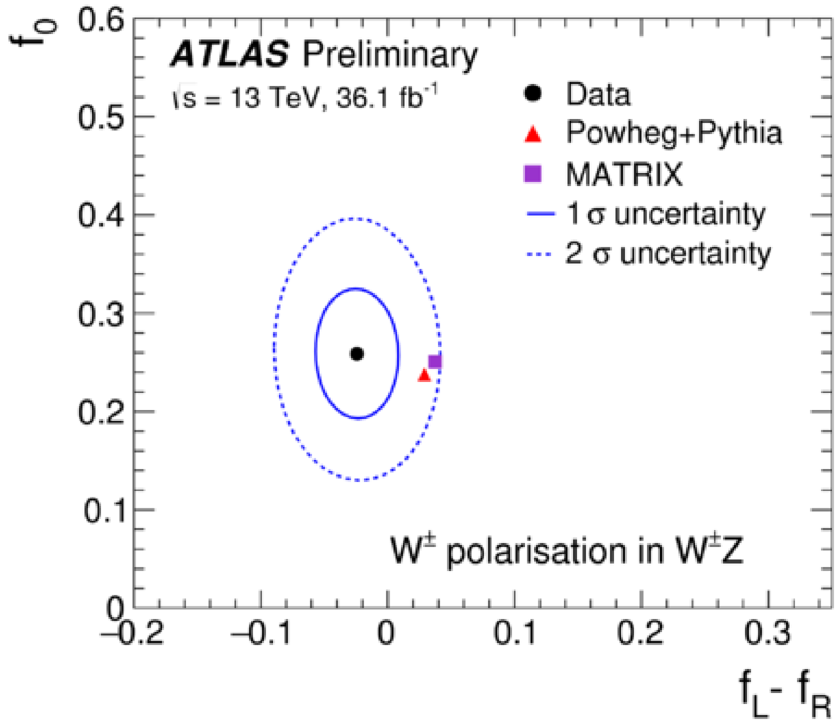


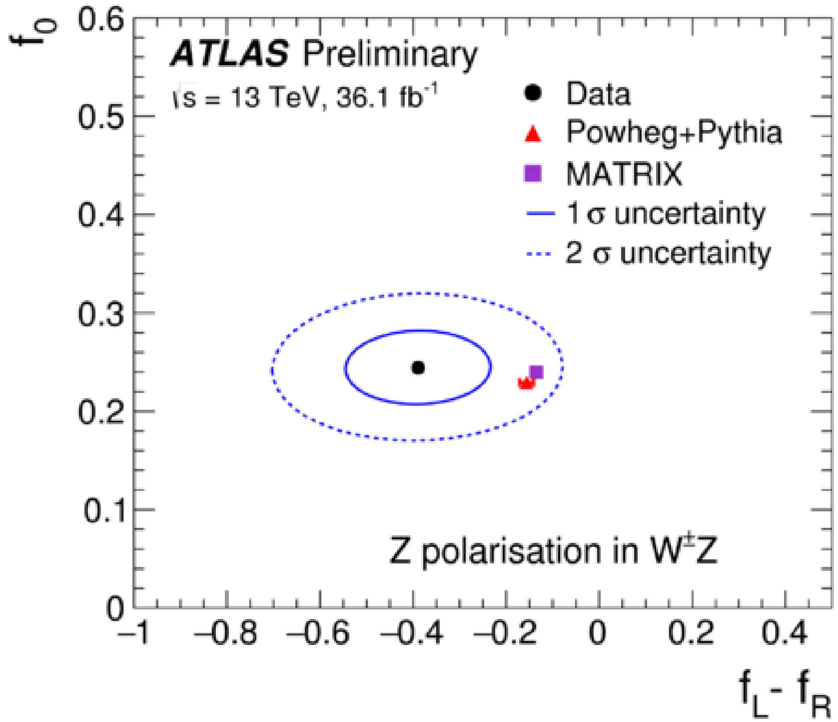


$W^{\pm}Z \longrightarrow \ell\nu\ell\ell$ Polarisation

ATLAS-CONF-2018-034

- 1^{st} measurement of longitudinal V boson polarisation in hadron-hadron collisions!
  - Measured: $f_0(W) = 0.26 \pm 0.06$; predicted: $f_0(W) = 0.238 \pm 0.003$
  - Measured: $f_0(Z) = 0.24 \pm 0.04$; predicted: $f_0(Z) = 0.230 \pm 0.003$
- SM agreement within 2 standard deviations.

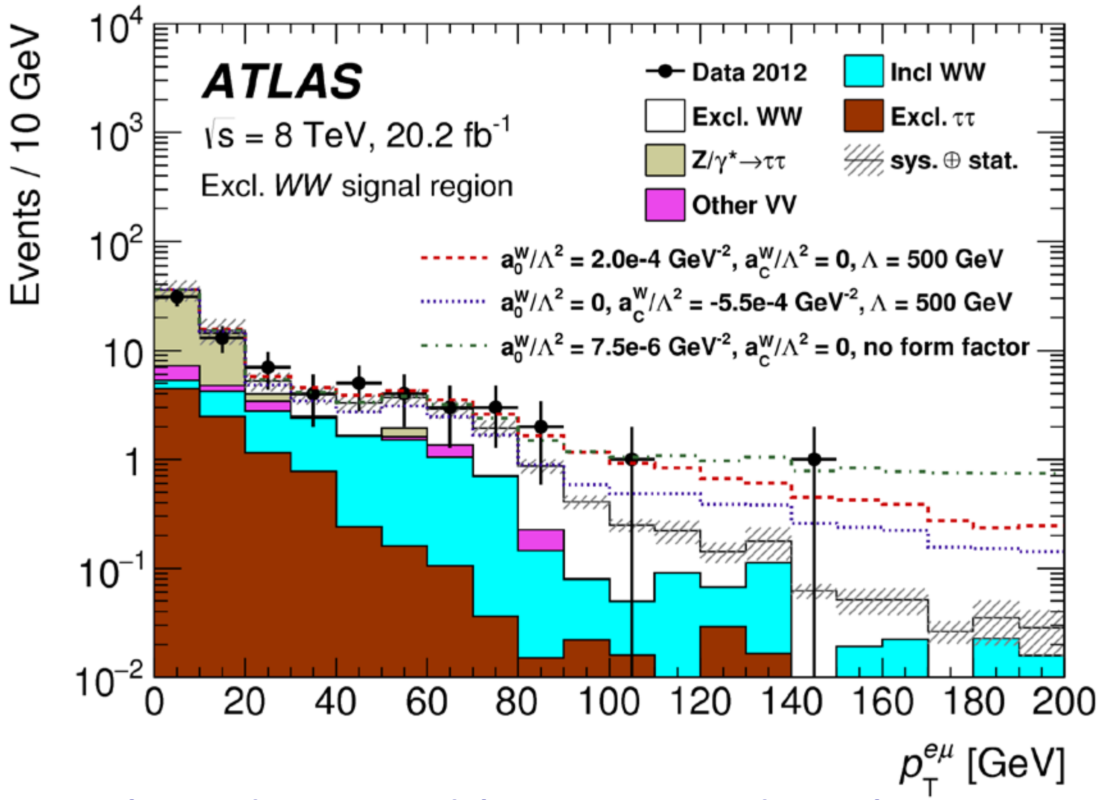




$\gamma\gamma \longrightarrow$ WW @ 8 TeV

PRD 94, 032011 (2016)

- eμ pair with large pT, no other charged particles @ vertex
- 1st *SM signal* evidence: ATLAS: 3.0σ (8TeV)

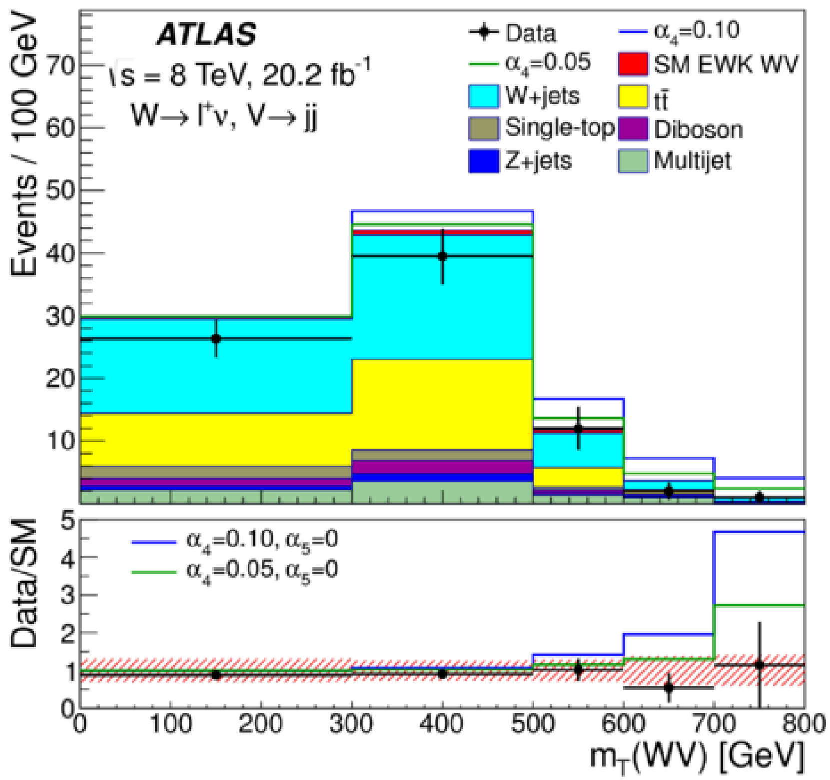


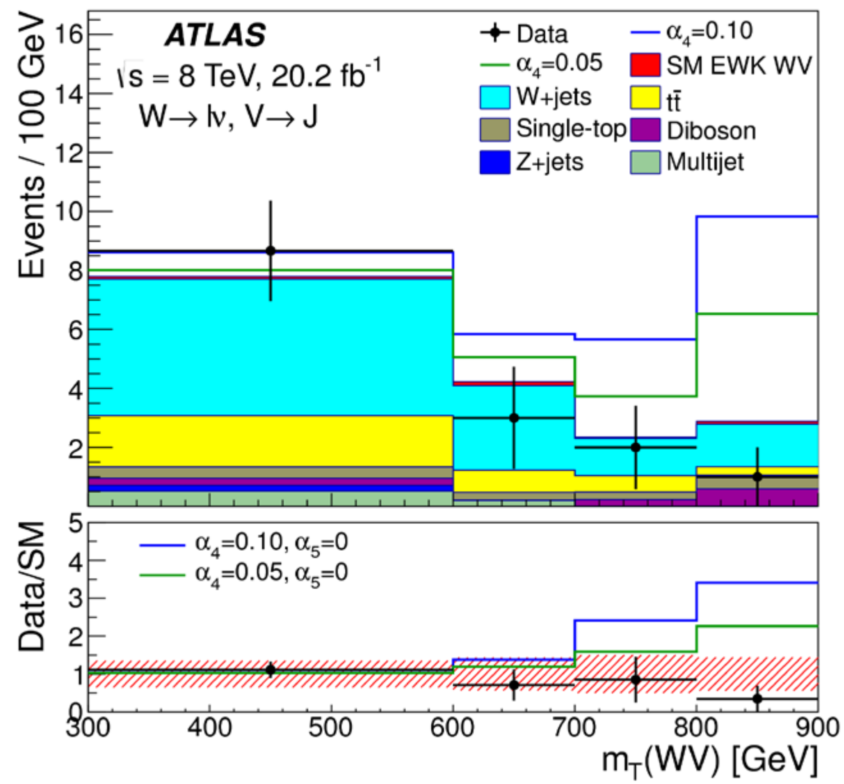
- aQGC limits placed using dilepton pT distribution
- No (tag) jets -> suppressed WWWW, WWZZ, WWZγ contributions

WVjj → ℓν(jj/J) jj @ 8 TeV

PRD 95, 032001 (2017)

- 1 isolated lepton (e or μ), MET, jj/J **hadronic** V, two tagging jets
- Not sensitive to SM xsec yet, but optimized for aQGC $\alpha_{4,5}$



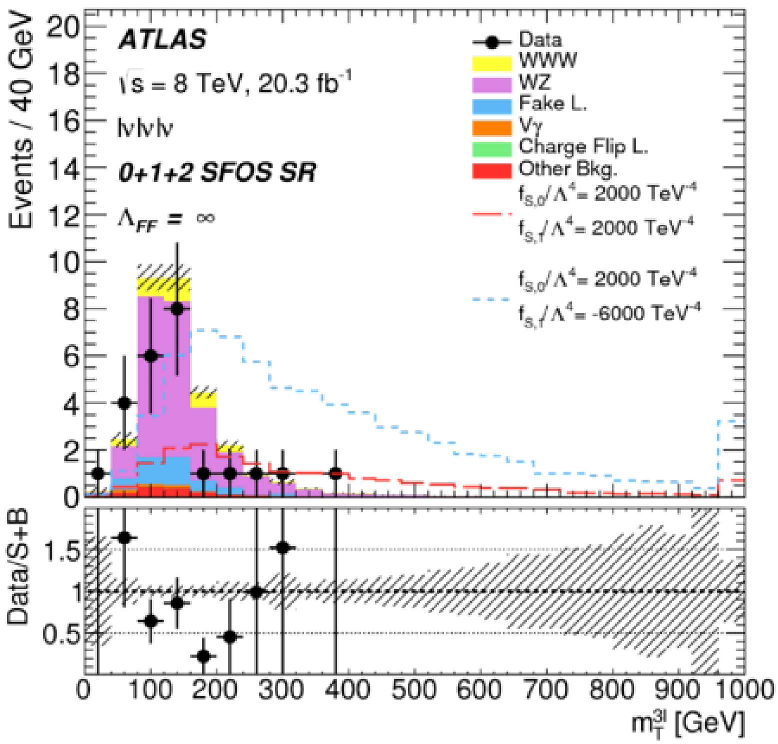


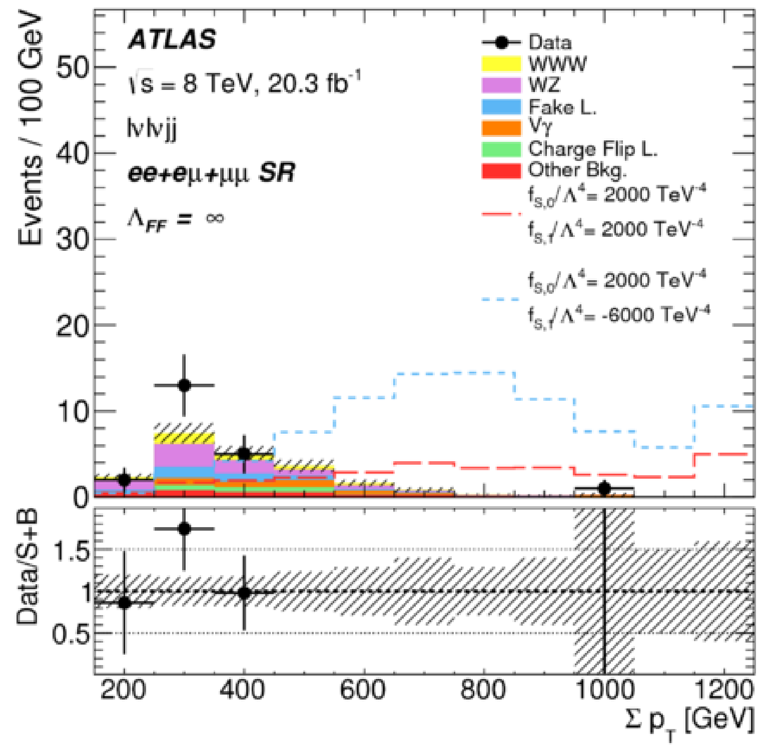
- Merged (J) category improves expected sensitivity by 40%
- No conversion $\alpha_{4,5}$ to $f_{s0,1}$ since WWjj *and* WZjj contribute

$WWW \longrightarrow 3\ell 3\nu/\ell^{\pm}\nu\ell^{\pm}\nu jj$ @ 8 TeV

EPJC 77 (2017) 141

- 3 isolated leptons (e or μ), MET – very clean, low statistics
- 2 isolated leptons (e or μ), MET, 2 jets ($W^{\pm} W^{\pm}jj$ VBS "spin-off")
- combined signal significance is ~1σ => place upper limits on xsec



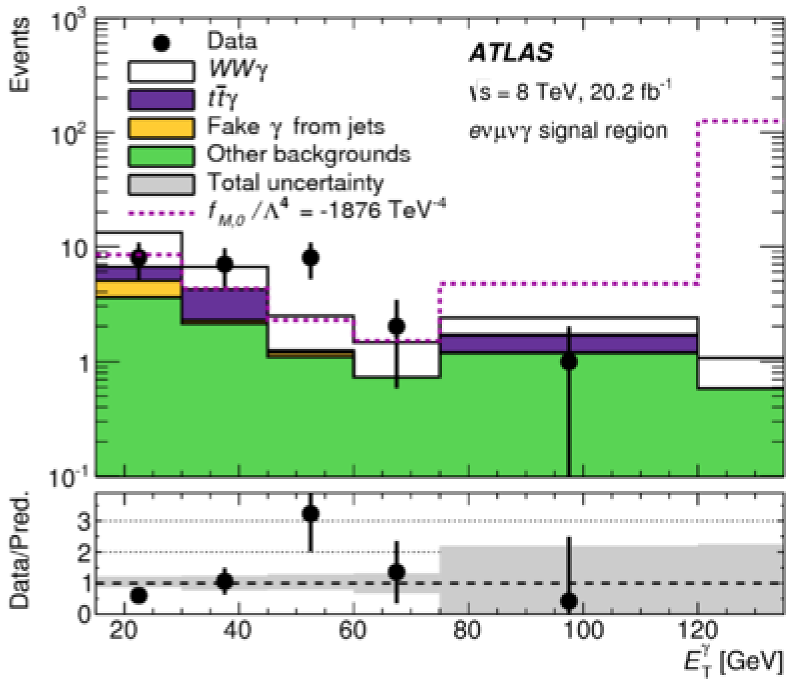


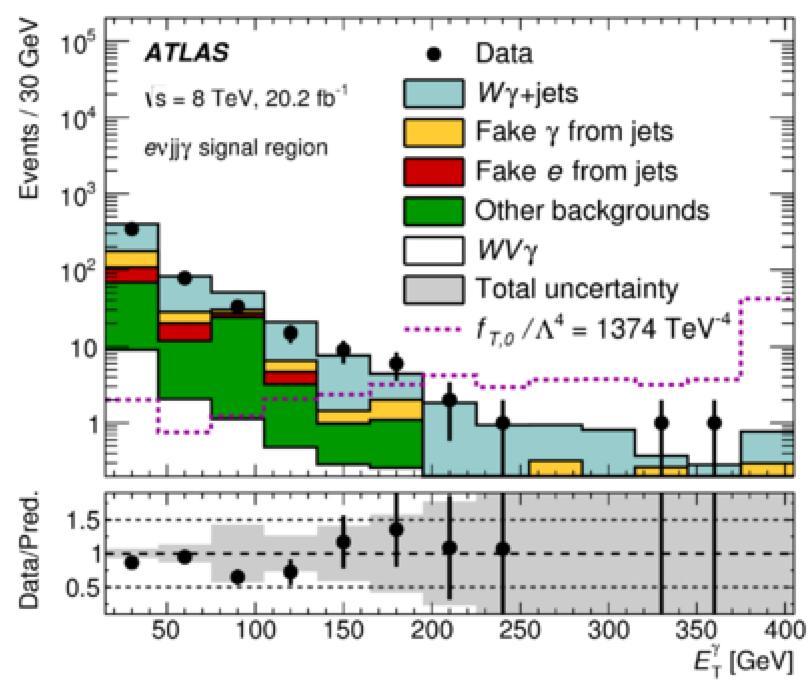
- Limits on dim-8 operators with couplings $f_{S0,1}$ set based on above distributions (combined final states)

WVγ @ 8 TeV

EPJC 77 (2017) 646

- 1 isolated lepton (e or μ), MET, ≥2 jets plus isolated photon(s): WVγ
- 1 isolated e, 1 isolated μ, MET plus isolated photon(s) : WWγ
- place upper limits on xsec in agreement with SM expectation



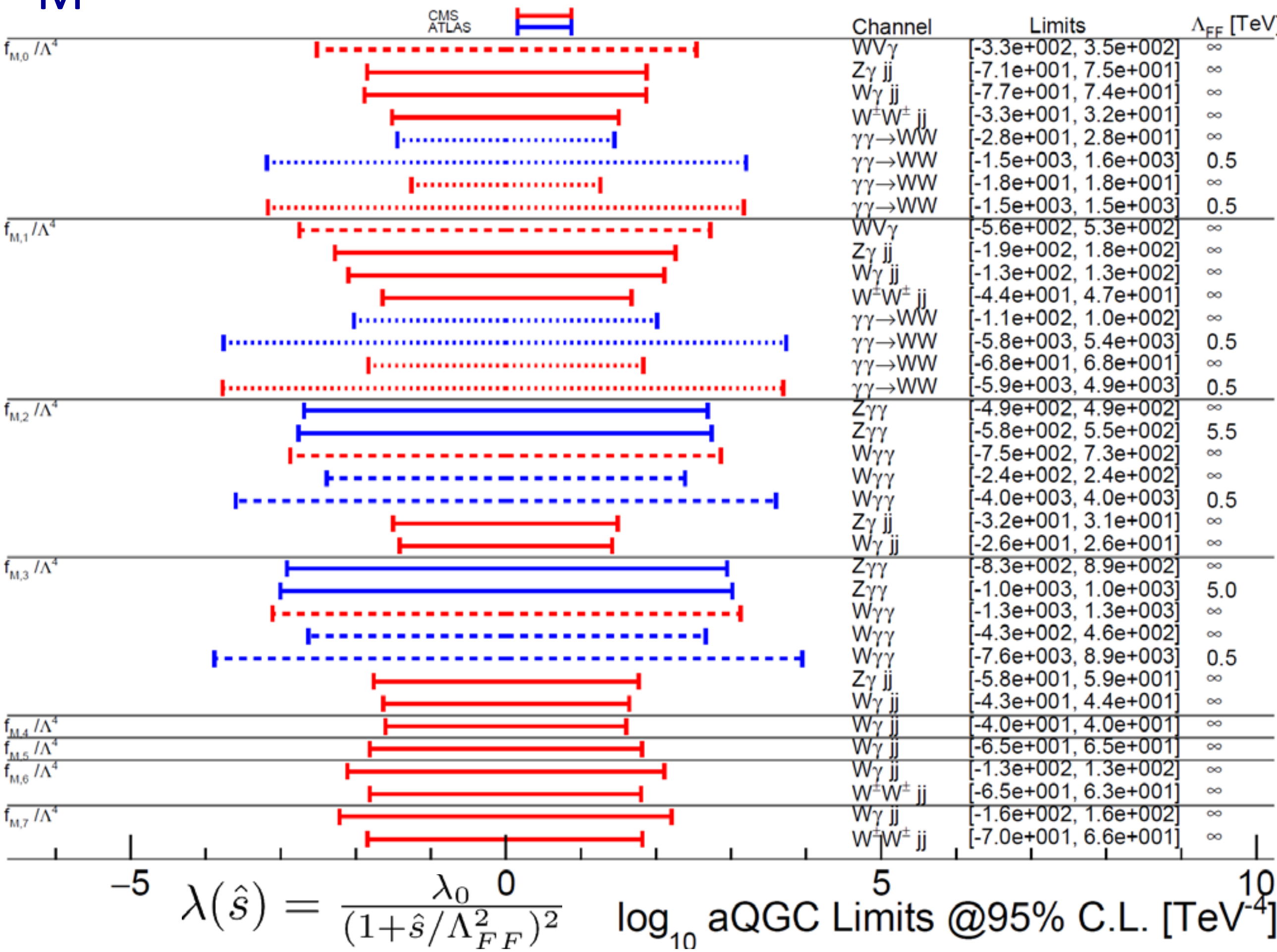


- Limits on 14 dim-8 operators with couplings $f_{Ti,}$ f_{Mi} set based on above distributions (combined final states).

aQGC status @ 8 TeV

RMP 89 (2017) no.3, 035008

f_M

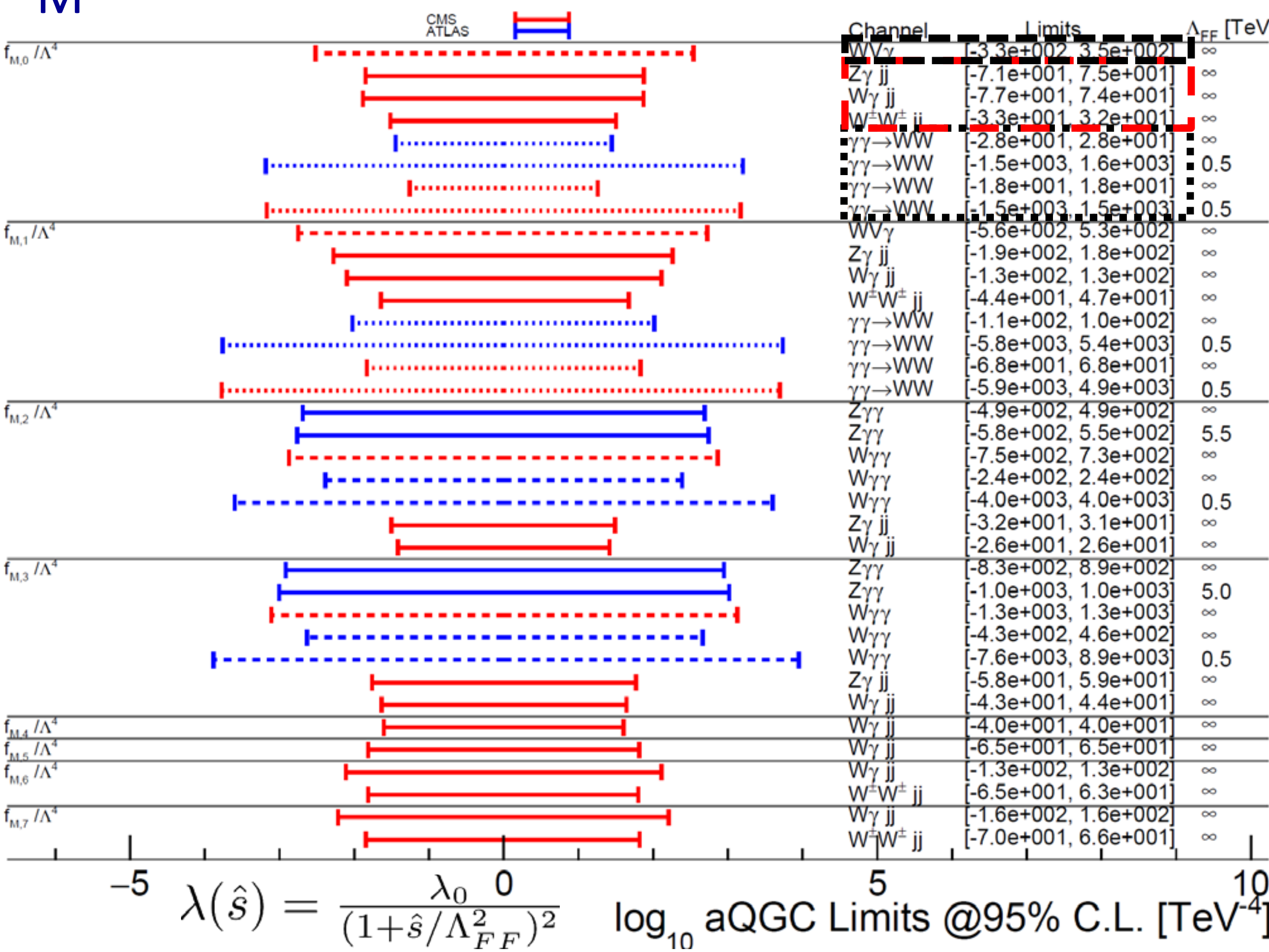


- All results use full 8 TeV datasets
- Trend that exclusive outperforms VBS, which is better than VVV
- Note **strong** impact of unitarisation
- Fair comparison requires some work

aQGC status @ 8 TeV

RMP 89 (2017) no.3, 035008

f_M



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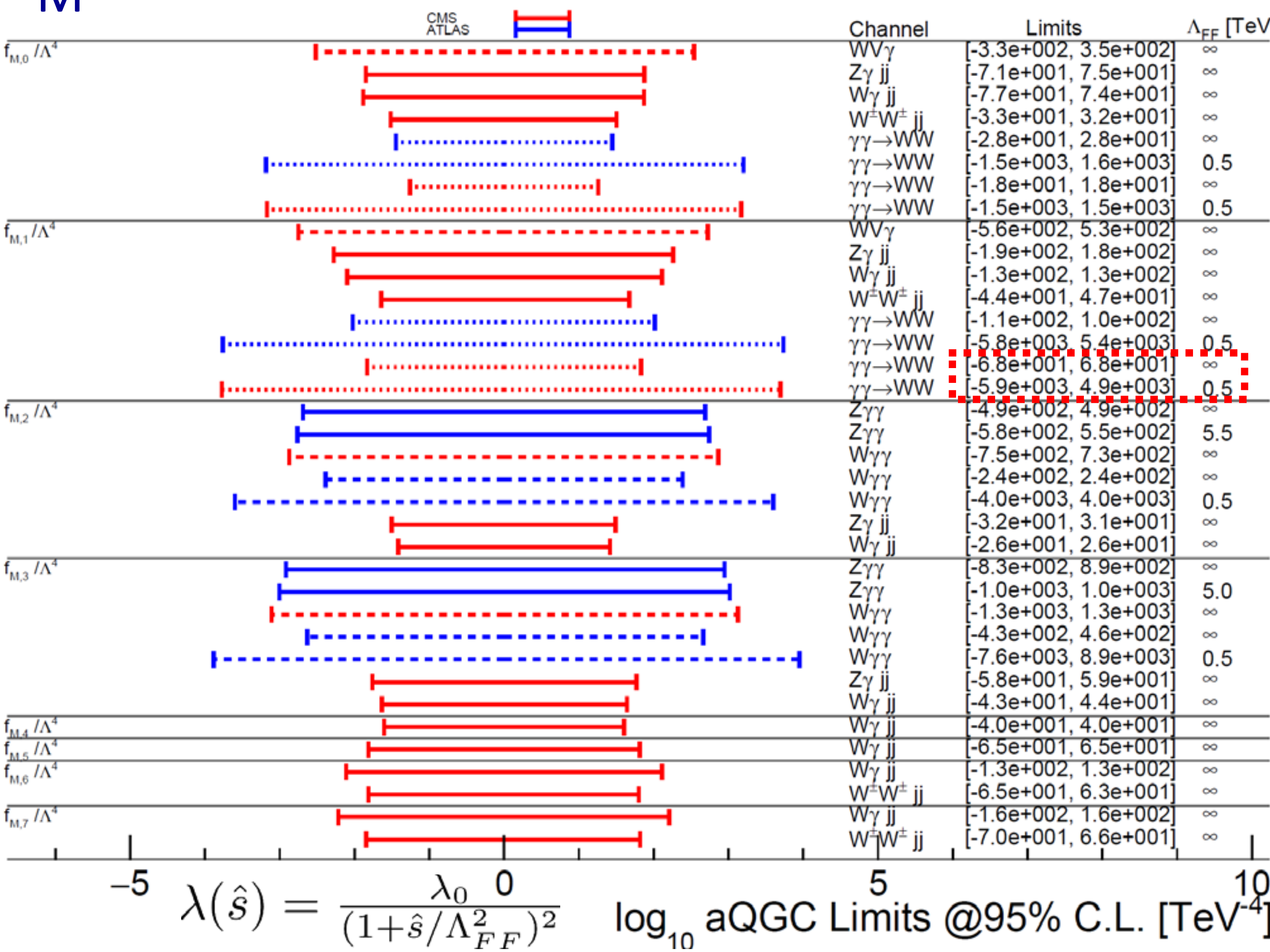
f_M



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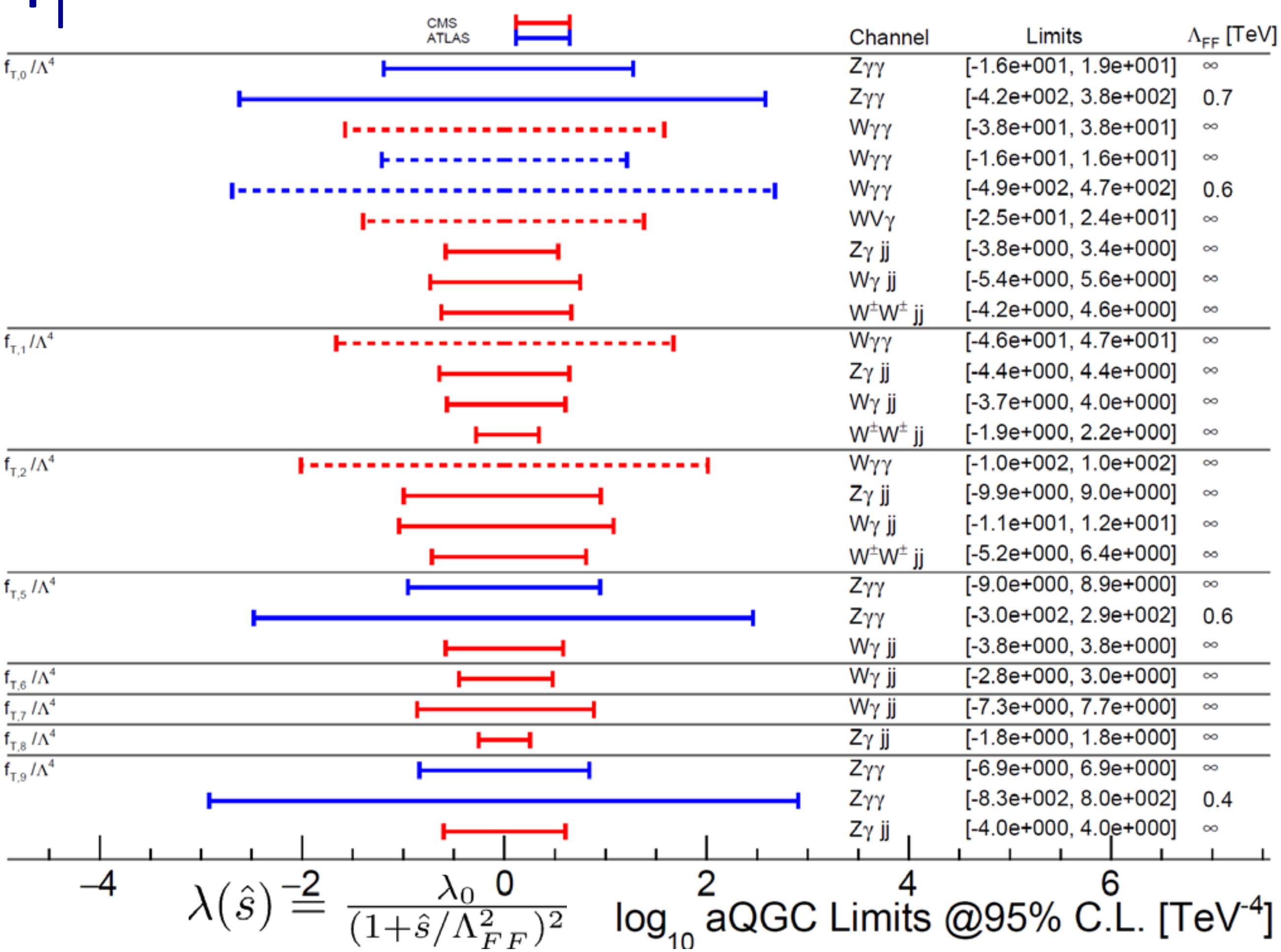
RMP 89 (2017) no.3, 035008

f_T



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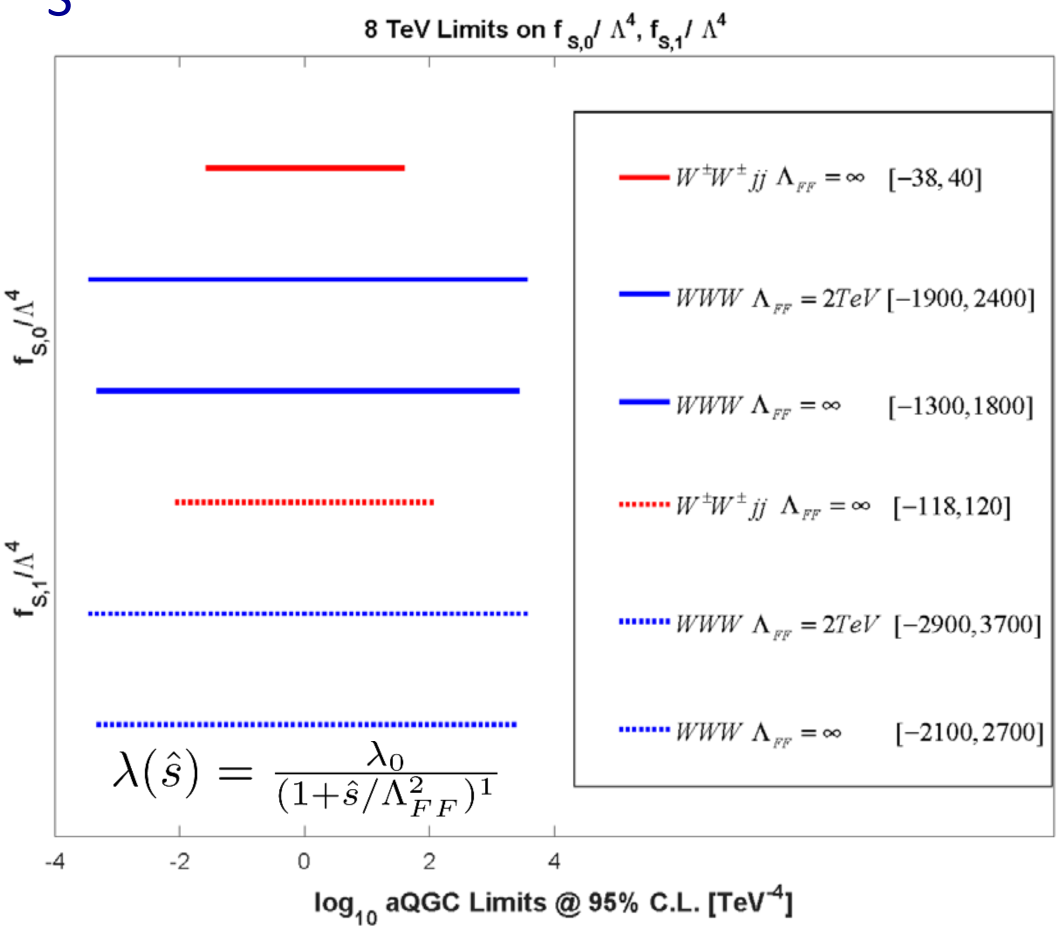
aQGC status @ 8 TeV

RMP 89 (2017) no.3, 035008

f_S



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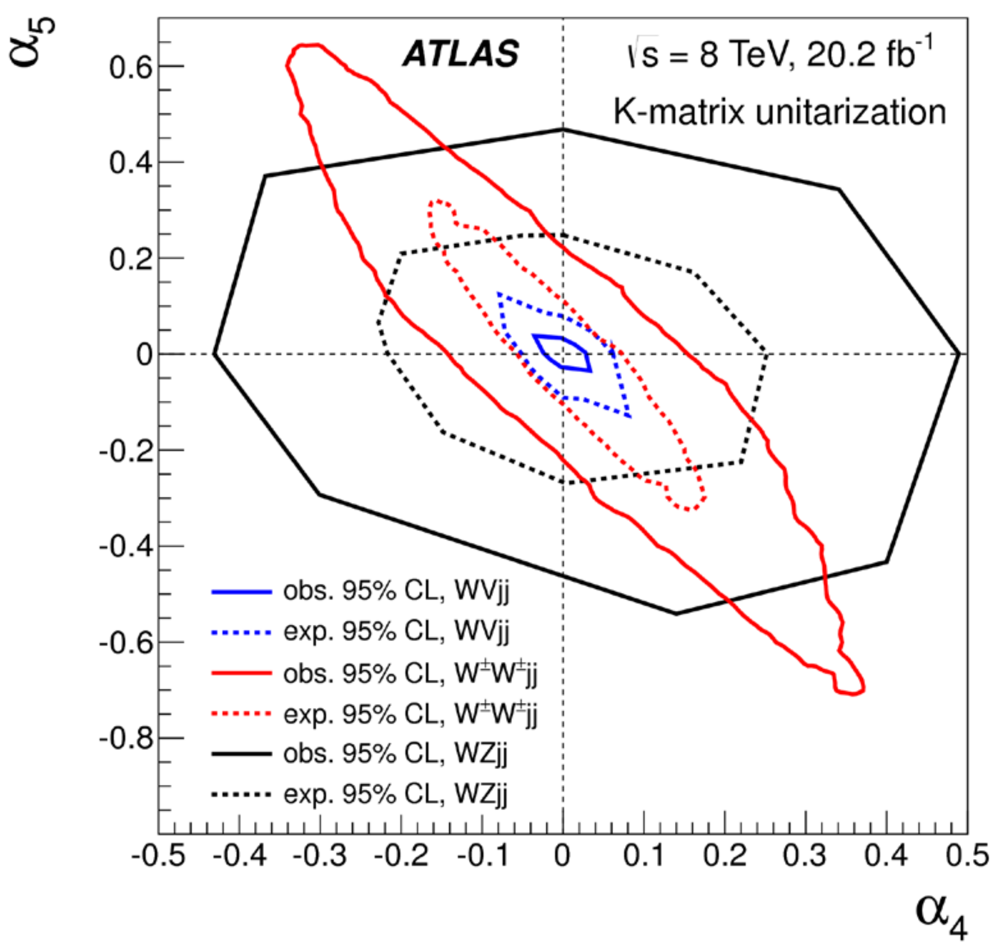
aQGC status @ 8 TeV

RMP 89 (2017) no.3, 035008



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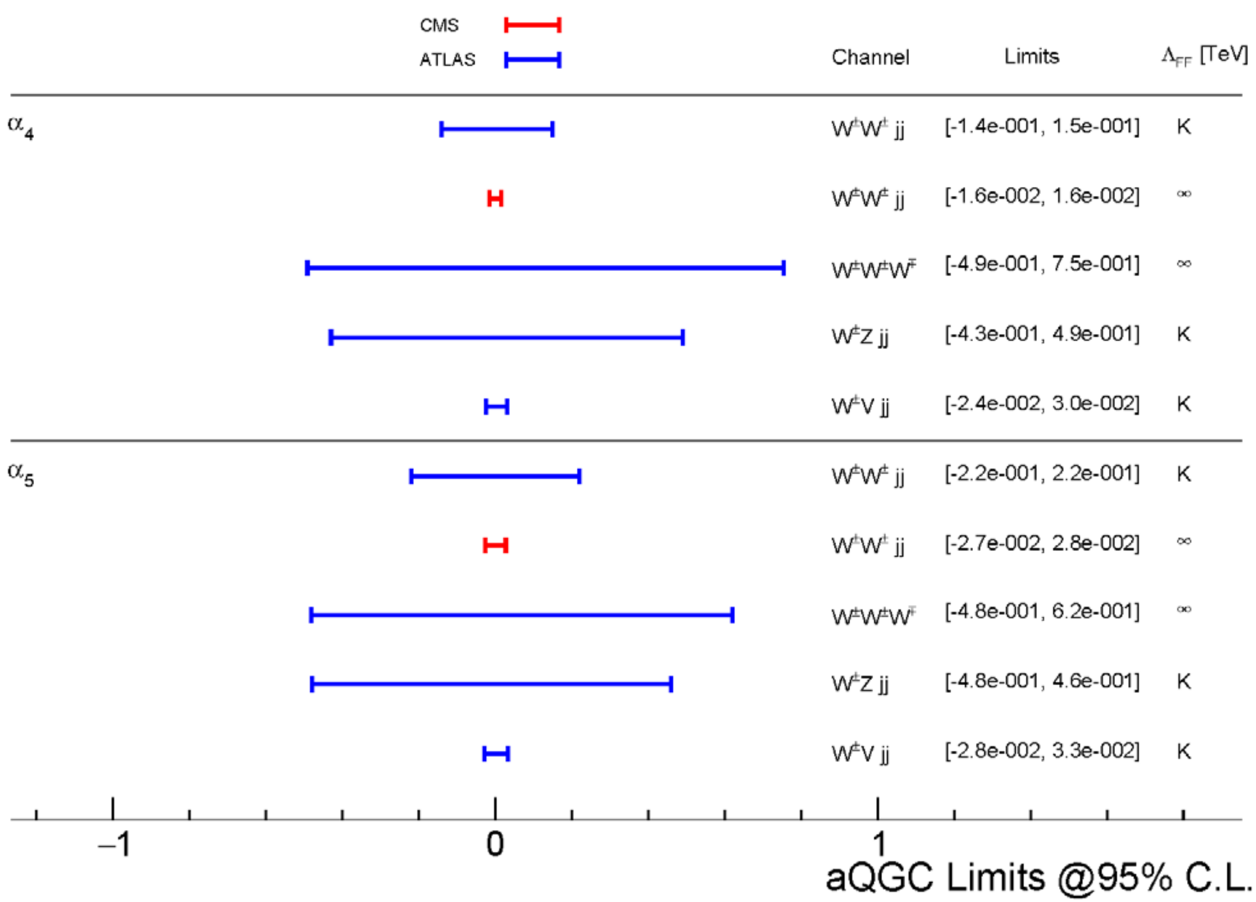
- Semileptonic VBS analysis **very** sensitive!

aQGC status @ 8 TeV

RMP 89 (2017) no.3, 035008



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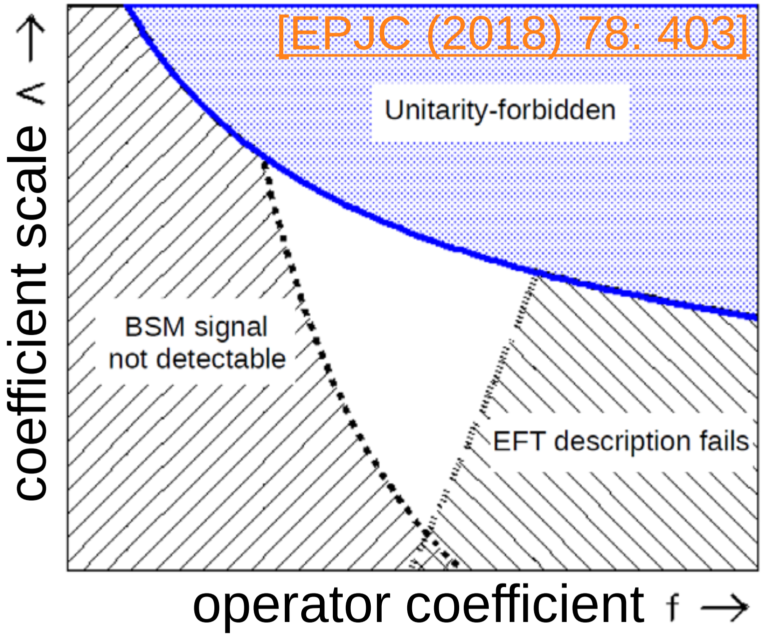
EFT validity and model independence

- EFT is a well-defined framework for BSM physics
- Ongoing efforts for combined fits, e.g. with Higgs measurements
- Need unitarisation to avoid unphysical parameter regions => *loss of model-independence*
- Simplified models (generic EWK resonances) provide benchmarks



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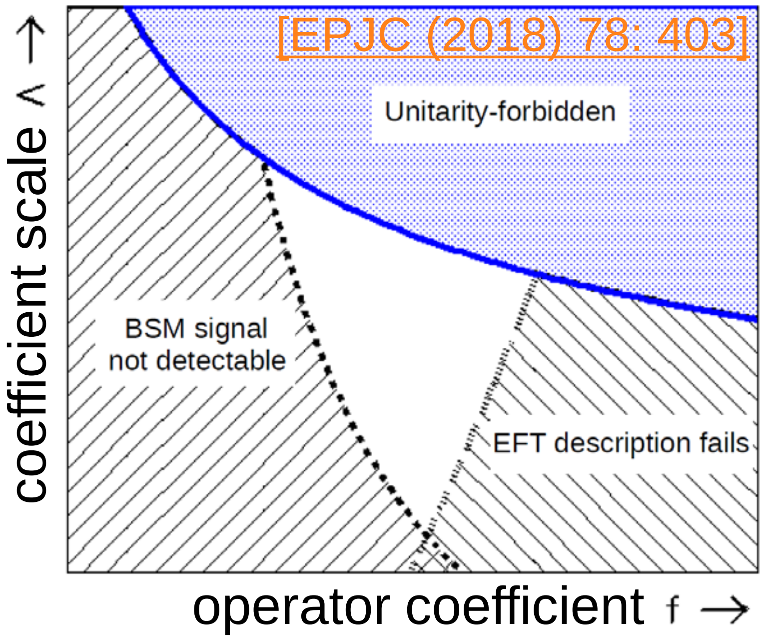


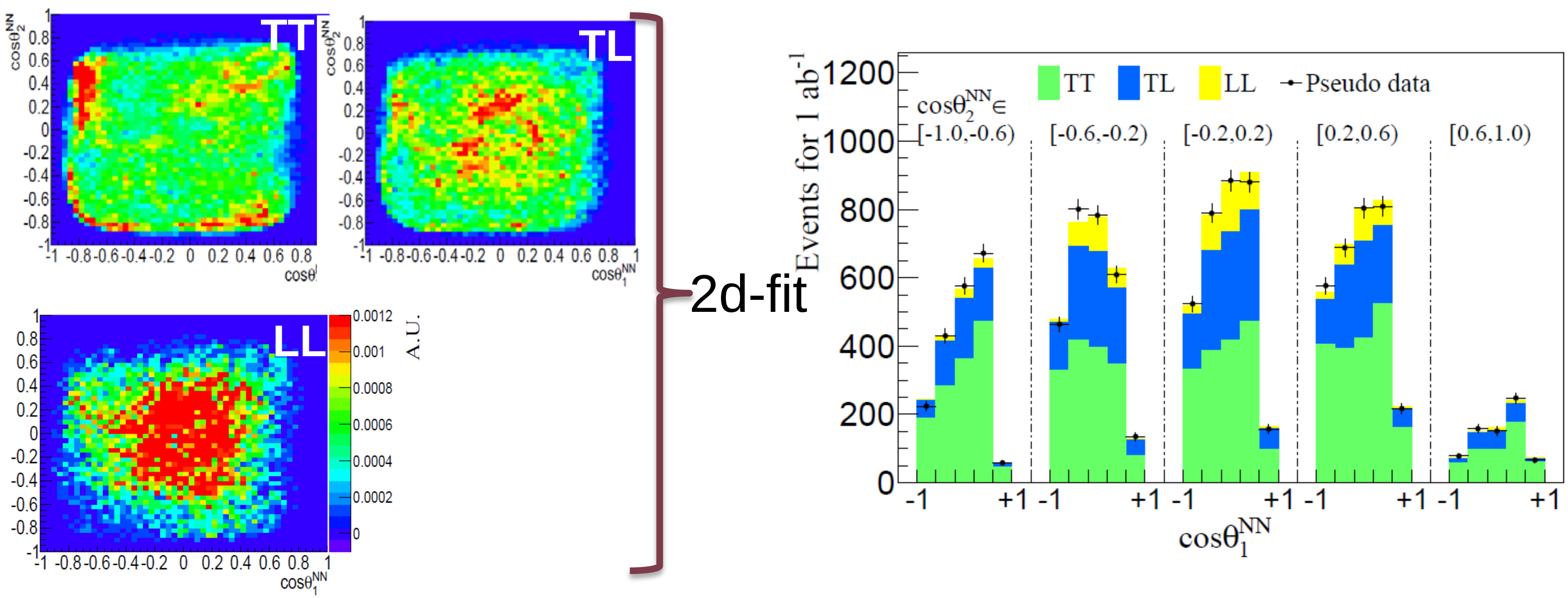
- **Always a good idea: provide**
  - *upper limits on fiducial cross sections* as an alternative to EFT interpretations and/or
  - *unfolded differential cross-section distributions* in sensitive variables

=> can be confronted with any new physics model of interest.

$W^\pm W^\pm jj \rightarrow \ell^\pm \nu \ell^\pm \nu jj$ Polarisation

PRD 93, 094033 (2016)

- Test unitarization of the longitudinal vector boson scattering by H
- Same-sign WW promising S/B, but νν final state (⚡ $\cos\theta_{\ell,W}$ access)
- Use deep machine learning to recover angular distributions from measurable event kinematics



- **2x** expected sensitivity compared to $R_{pT} = (p_T^{\ell 1} \times p_T^{\ell 2})/(p_T^{j_1} \times p_T^{j_2})$ [PRD 86, 036011]

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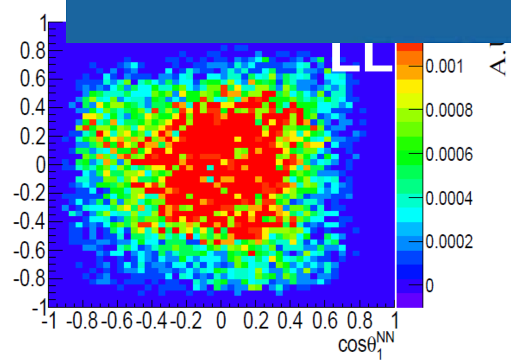

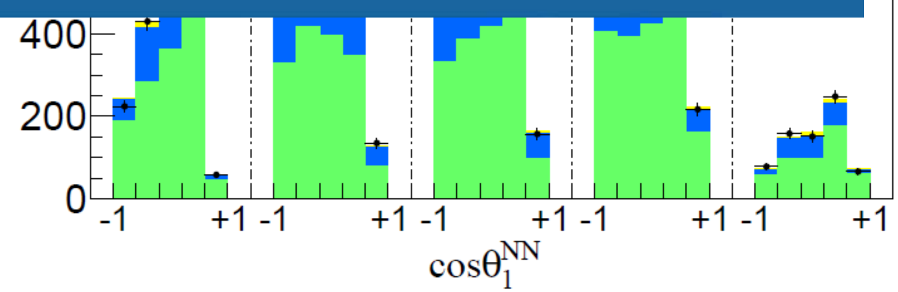

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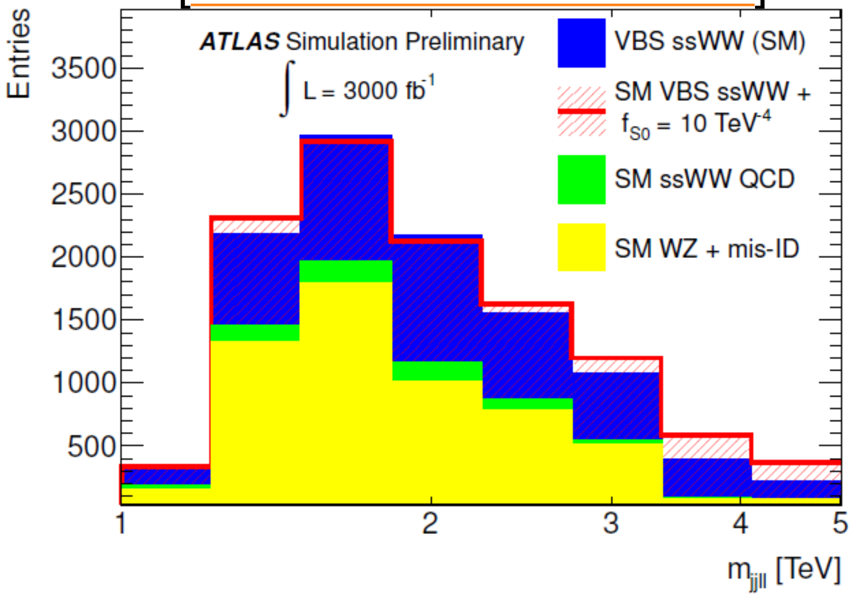
Looking forward

- What could we see w/ 6 vs. 60 times the current dataset?

[ATL-PHYS-PUB-2013-006]



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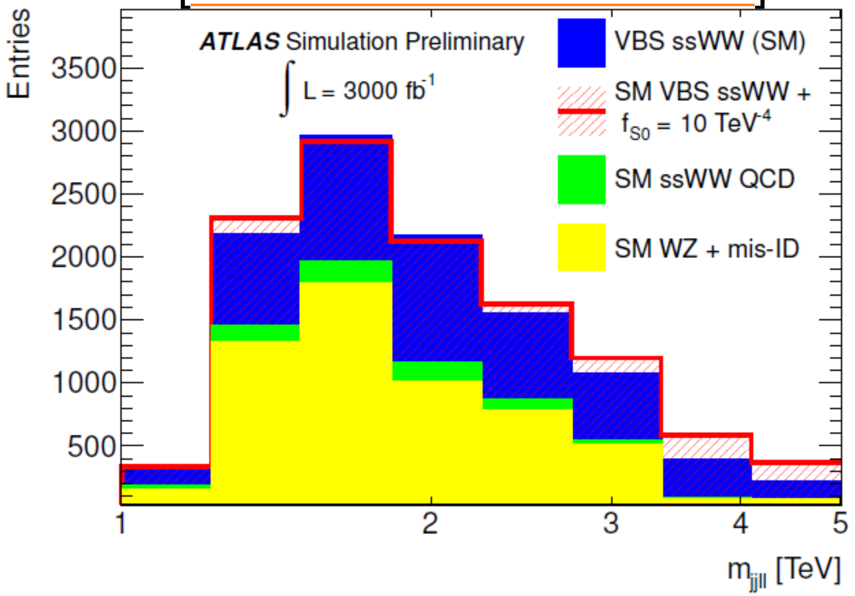
[ATL-PHYS-PUB-2013-006]

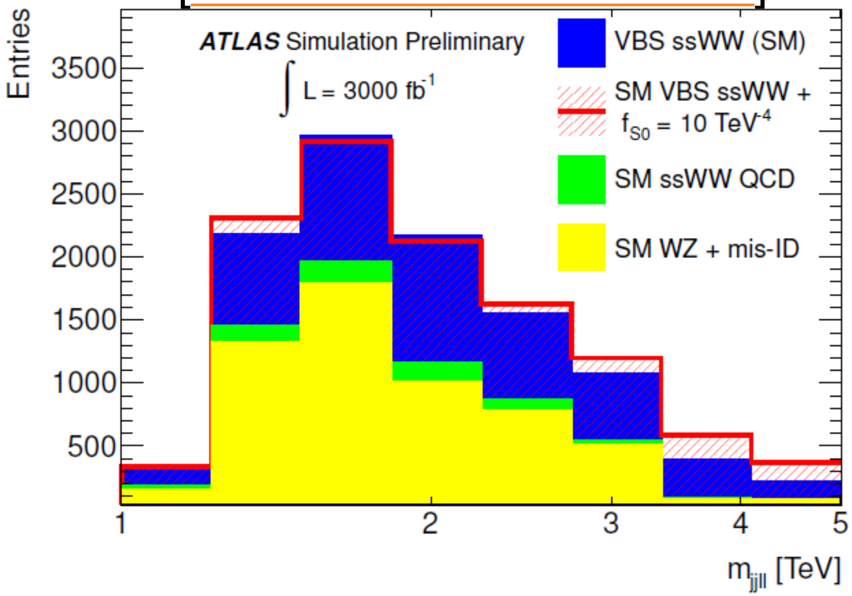


- Gain in sensitivity (5σ aQGC discovery) for HL-LHC: **factor of two.**

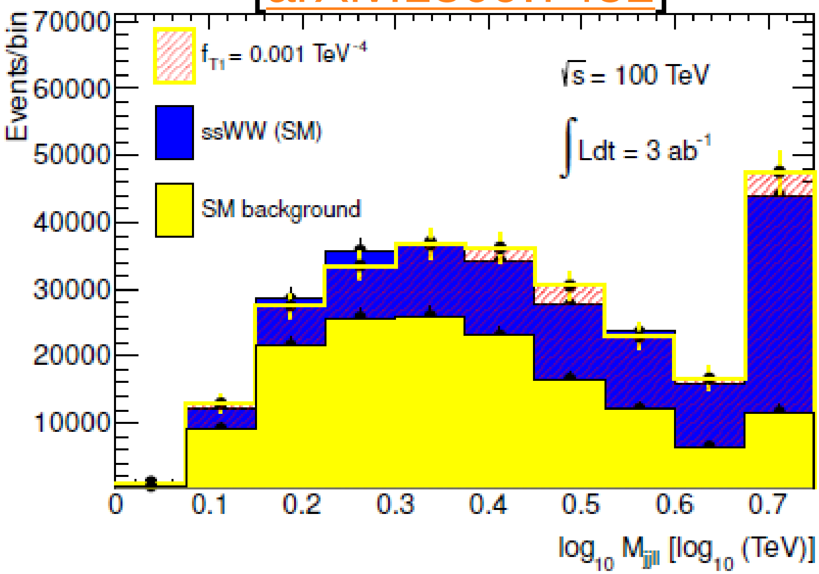
Looking forward

- What could we see w/ 6 vs. 60 times the current dataset?
- What could we gain running at 100 TeV rather than 14 TeV?

[ATL-PHYS-PUB-2013-006]



[arXiv:1309.7452]



- Gain in sensitivity (5σ aQGC discovery) for HL-LHC: **factor of two.**
- Gain in sensitivity (5σ aQGC discovery) for 14 $\rightarrow$ 100 TeV: **factor of one hundred.**

Summary

- Run II providing access to more processes (VBS, VVV), and better BSM sensitivity!
  - First observation of EW $W^{\pm}Zjj$ production!
- Time to prepare for V_LV_L scattering studies…
  - First V_L measurement in inclusive $W^{\pm}Z$ performed, exploring MVA
- The Standard model is a tough nut to crack!

Summary

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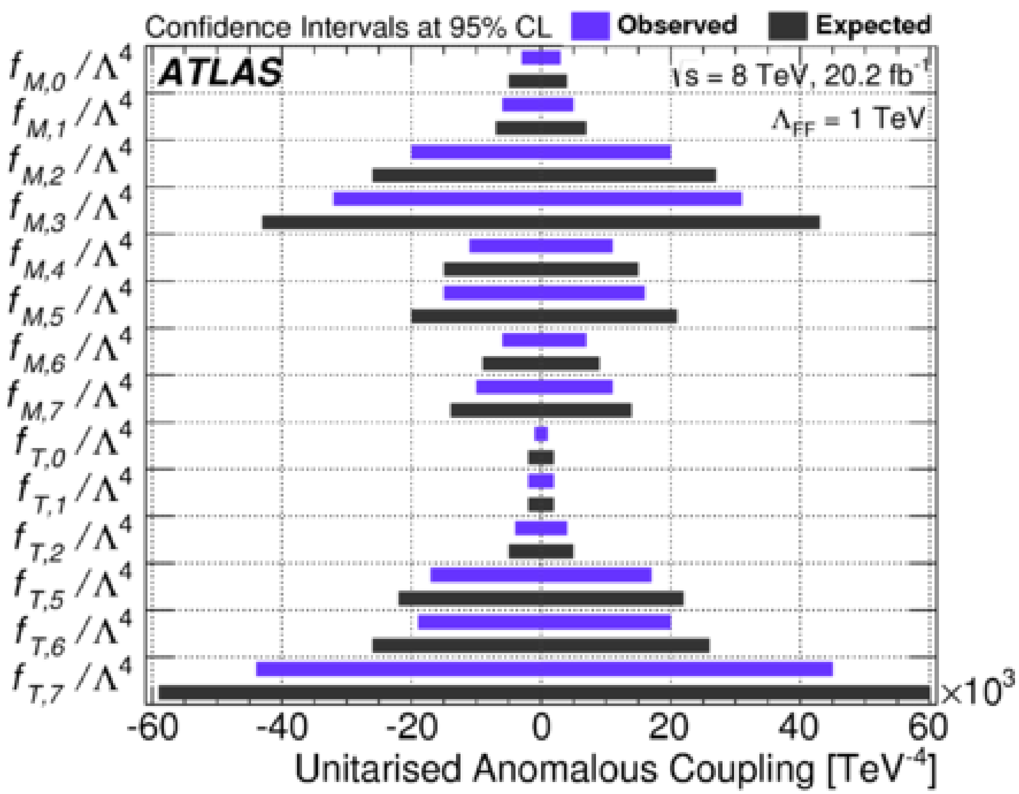
Dessert

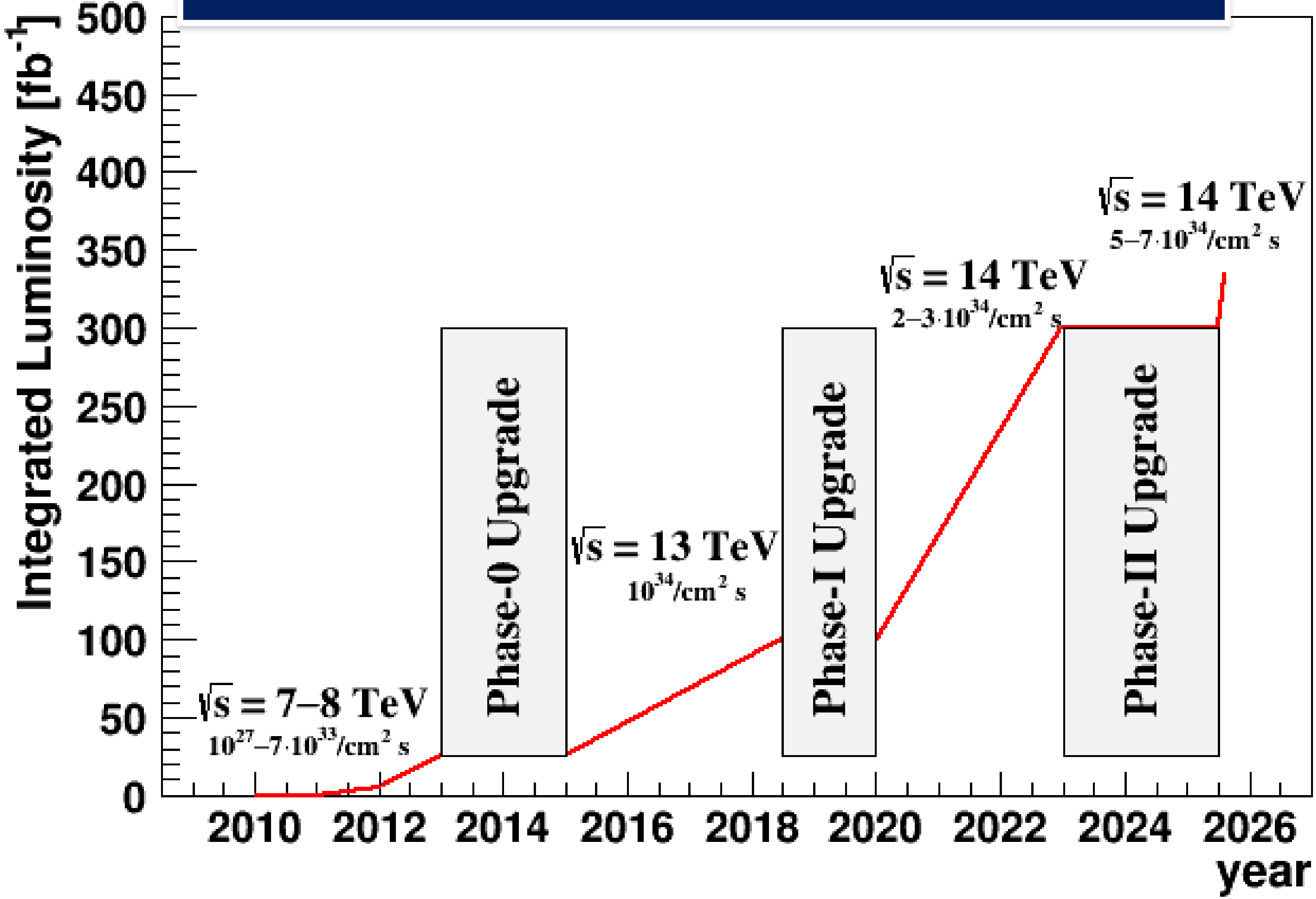
WVγ aQGC limits @ 8 TeV

EPJC 77 (2017) 646

- Observed and expected 95% CL intervals on anomalous quartic gauge couplings for the combined WVγ analysis.
- Couplings are unitarised using a dipole form factor with a form factor energy scale of Λ_{FF} = 1 TeV.



LHC Run Plan



Integrated Luminosity [fb^{-1}]
500
450
400
350
300
250
200
150
100
50
0
2010
2012
2014
2016
2018
2020
2022
2024
2026
year
$\sqrt{s}$ = 7–8 TeV
10^{27}–$7\cdot10^{33}$/cm^2 s
Phase-0 Upgrade
$\sqrt{s}$ = 13 TeV
10^{34}/cm^2 s
Phase-I Upgrade
$\sqrt{s}$ = 14 TeV
2–$3\cdot10^{34}$/cm^2 s
Phase-II Upgrade
$\sqrt{s}$ = 14 TeV
5–$7\cdot10^{34}$/cm^2 s