Electroweak physics at the HL(E)-LHC

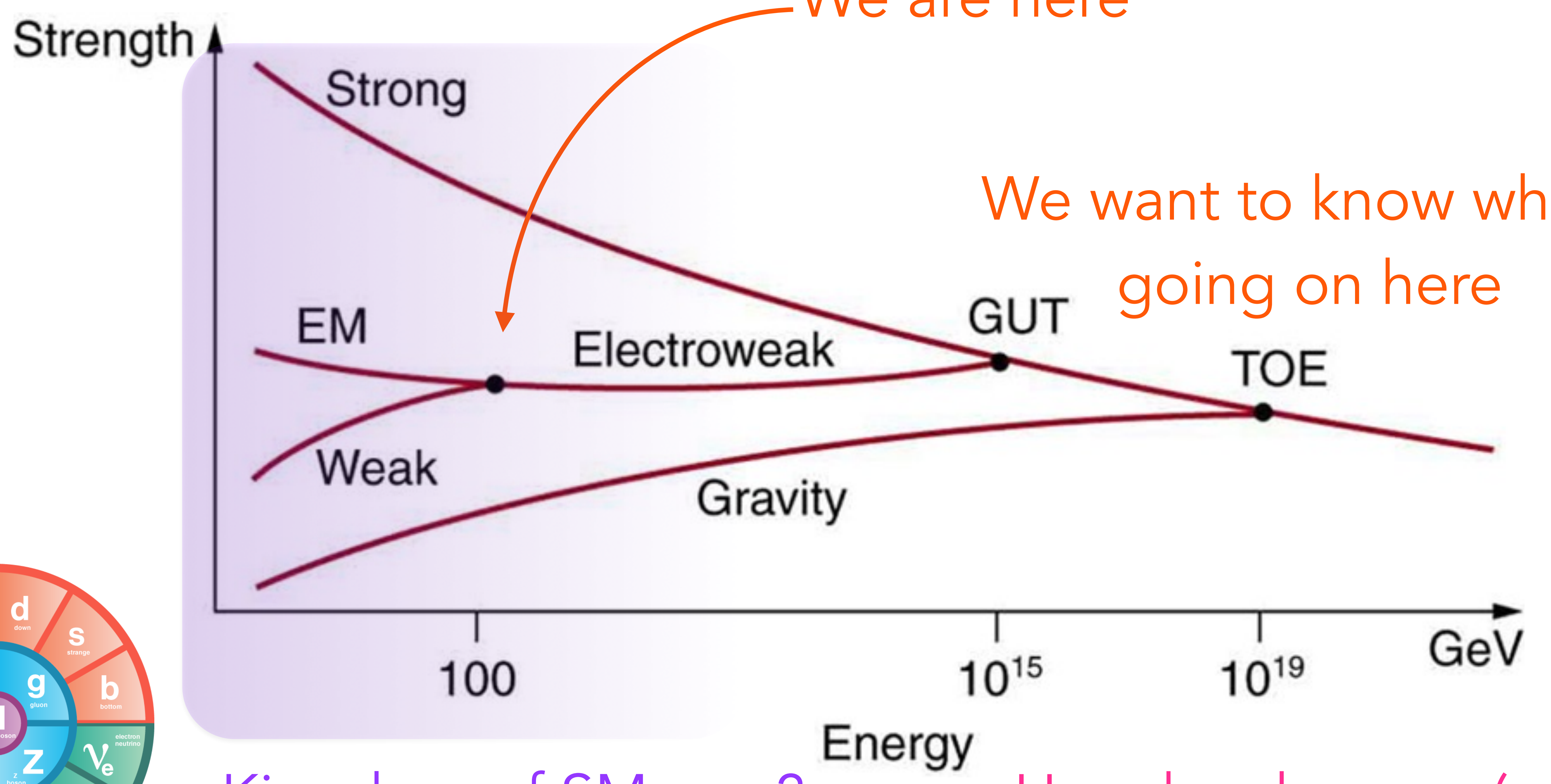
Di-bosons, multi-bosons, VBF and VBS

Claire Lee (Brookhaven National Laboratory) on behalf of ATLAS & CMS
HL/HE-LHC2017: Workshop on the physics of HL-LHC, and perspectives at HE-LHC
CERN, 30 October - 1 November 2017

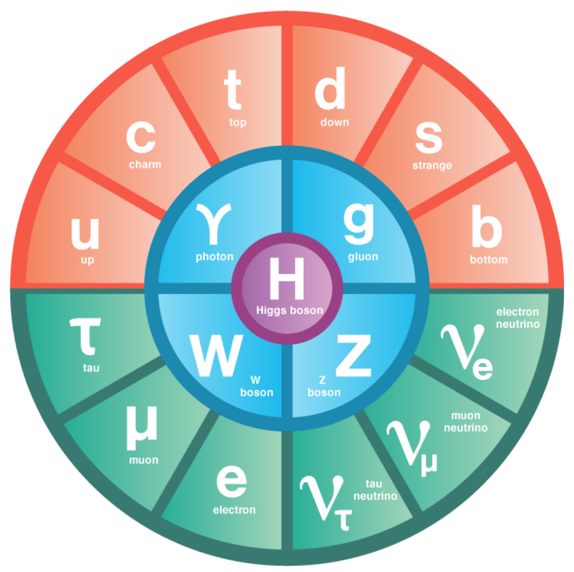
Where are we now & what can we do with 3000 fb^{-1} of 14 TeV data?

Despite the (frustratingly) ongoing success of the SM, it is a natural theory only up to ~1TeV or so…

We are here



We want to know what's going on here



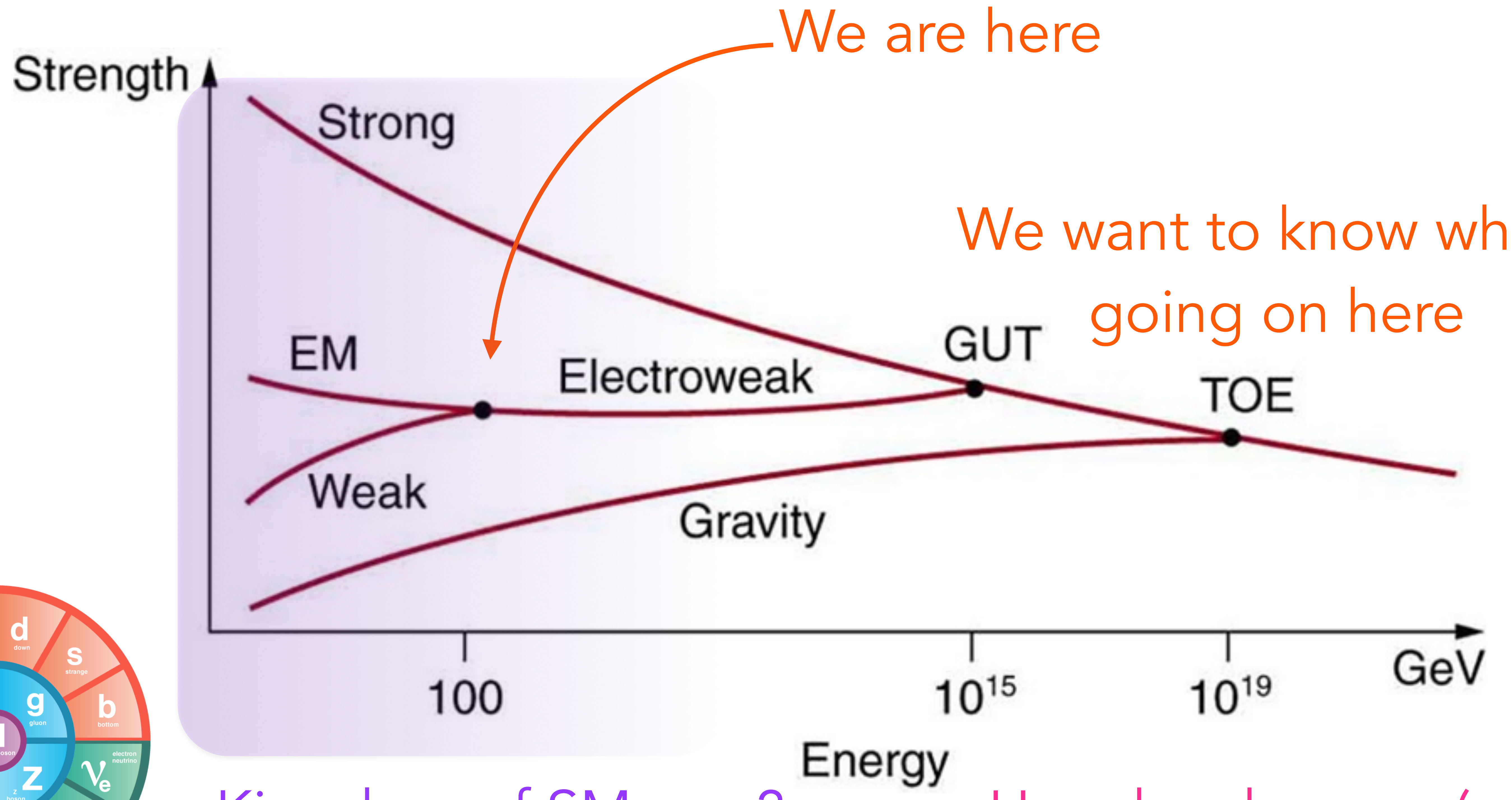
Kingdom of SM ⟶ ?

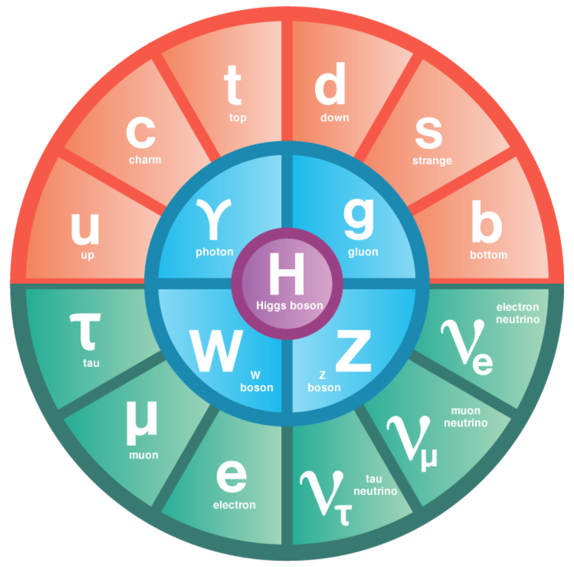
Here be dragons (new physics)?

Where are we now & what can we do with 3000 fb^{-1} of 14 TeV data?

Probe the nature of Electroweak Symmetry Breaking

Keep searching for New Physics beyond the SM





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Precision electroweak sector measurements at our energy scale may give insight into new physics at higher (not-directly-accessible) scales.

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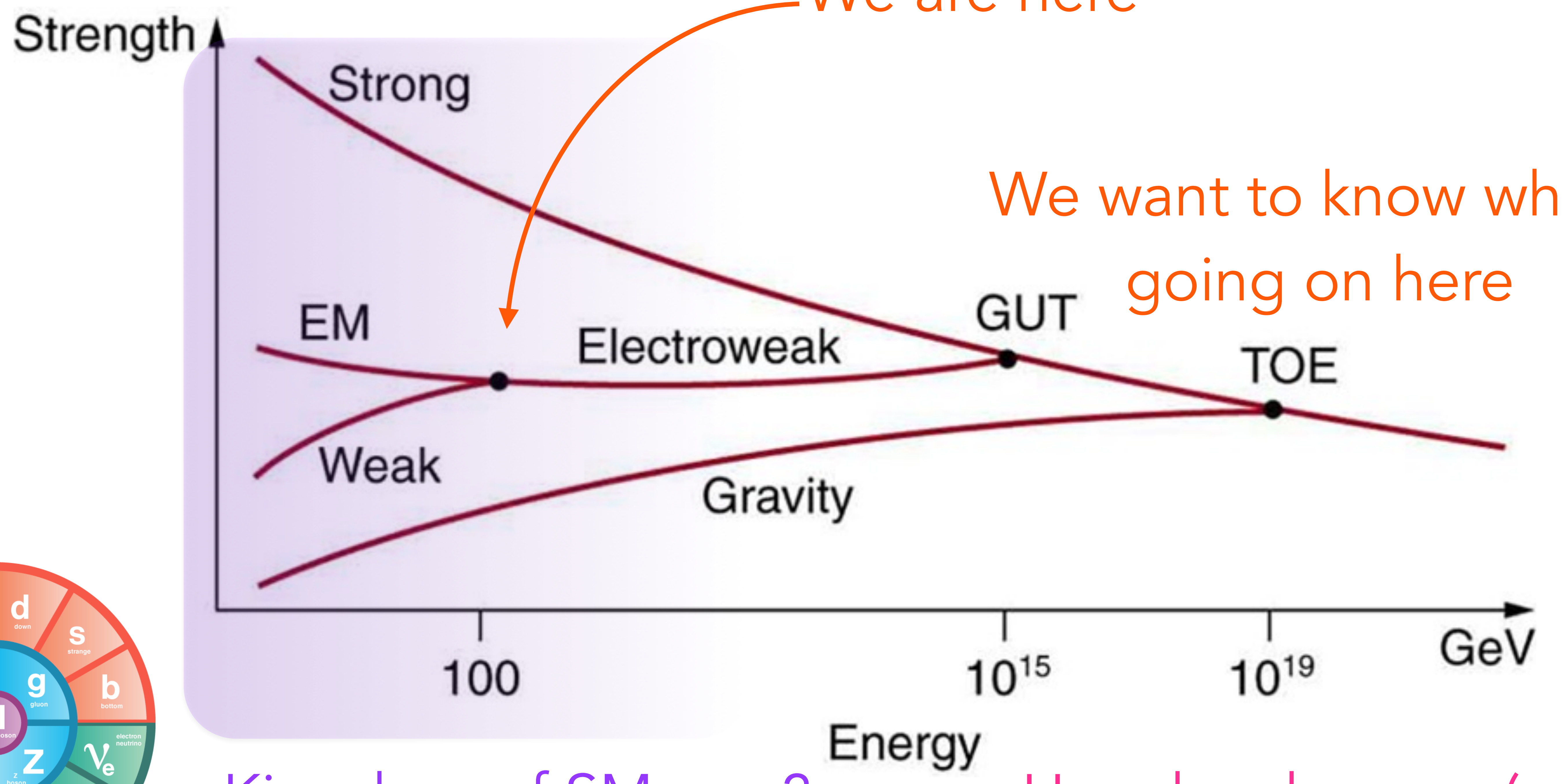

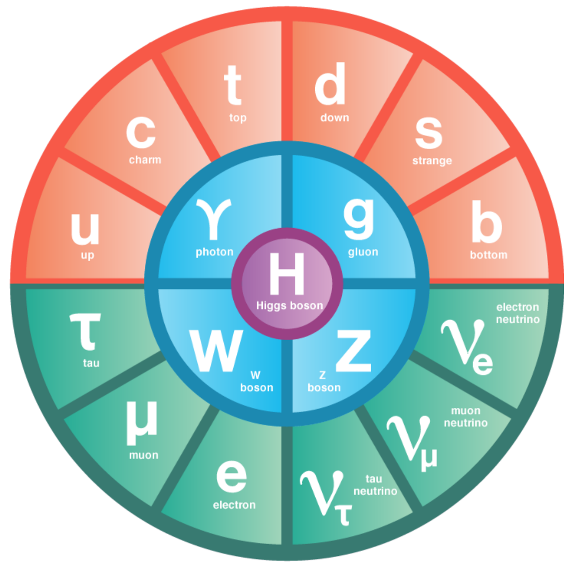

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Where are we now & what can we do with 3000 fb^{-1} of 14 TeV data?

Probe the nature of Electroweak Symmetry Breaking

Precision studies of Higgs couplings

Probe (anomalous) Vector Boson couplings

Observe as many Higgs production & decay modes as possible

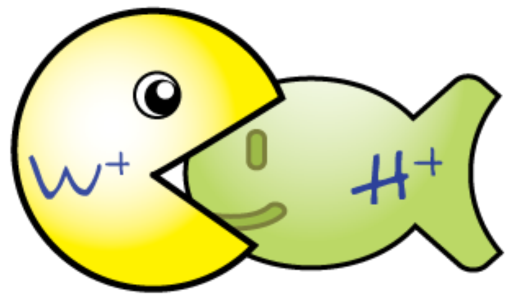
Measure the Higgs self-coupling

Precision electroweak sector measurements at our energy scale may give insight into new physics at higher (not-directly-accessible) scales.

The study of triple, quartic, and Higgs couplings are an important test of the SM.

QGCs are additionally connected to the EWSB sector, with the Higgs, to ensure unitarity at high energies for longitudinally-polarised scattering processes.

Dibosons & VBF:	**aTGC**
Tribosons & VBS:	**aQGC**



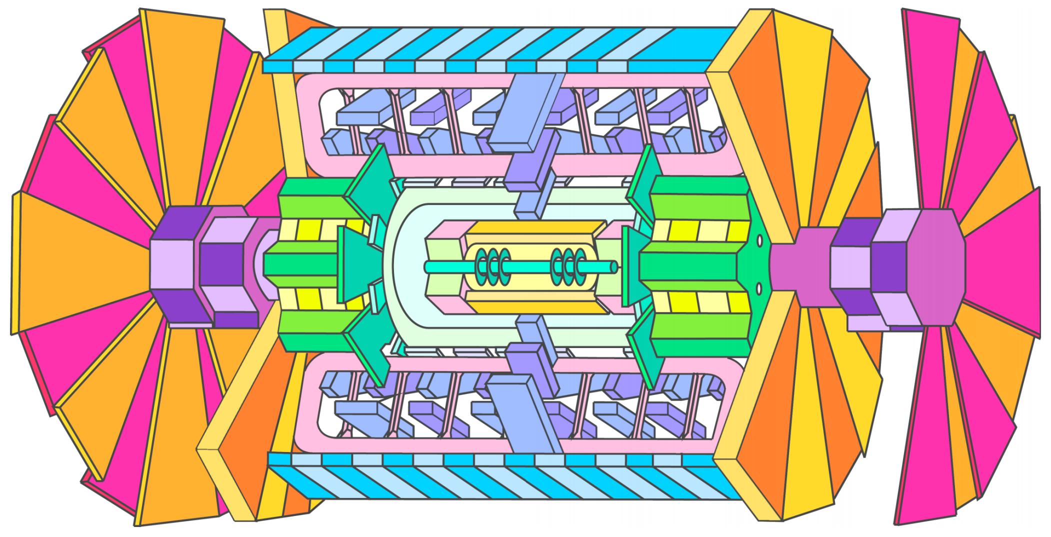
Where are we now & what can we do with 3000 fb^{-1} of 14 TeV data?

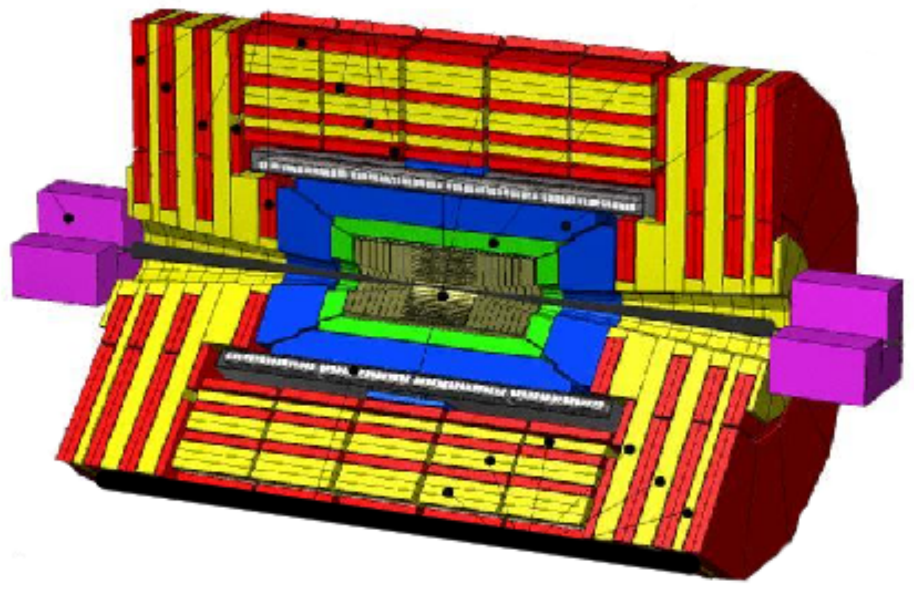
Probe the nature of Electroweak Symmetry Breaking

studies already done in the context of HL-LHC

VBF H→WW
VBF H→ZZ
VBF H→$\tau\tau$
VBF H→γγ

VBF W/Z
VBS W$^{\pm}$W$^{\pm}$, WZ, ZZ, and WW
Zγγ





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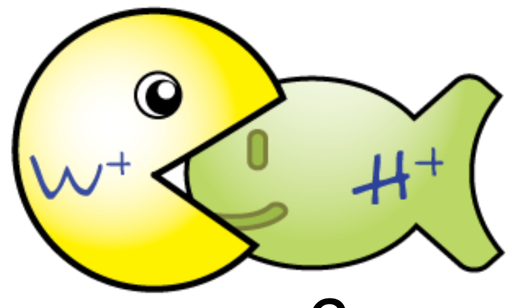
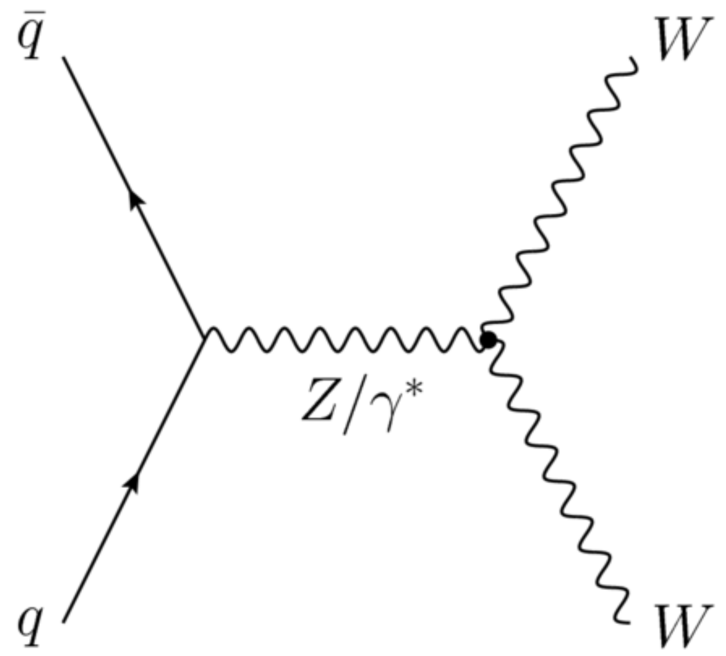
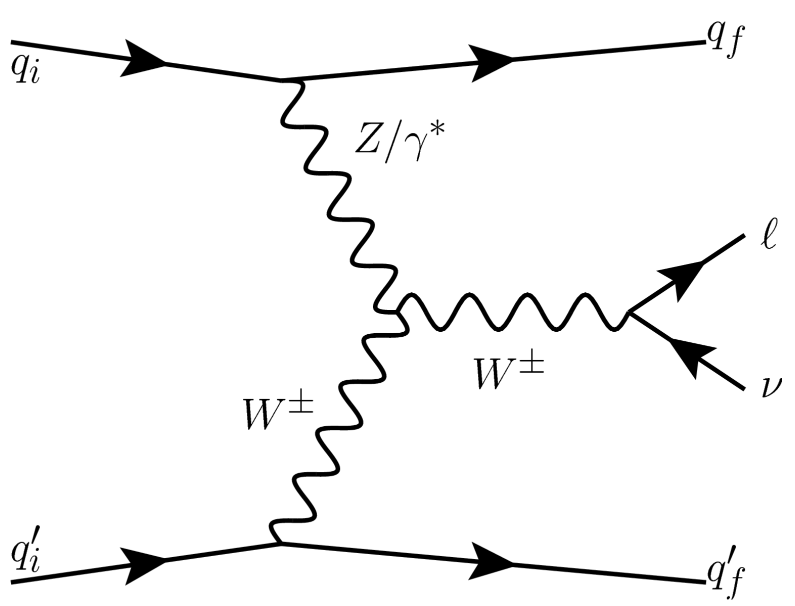
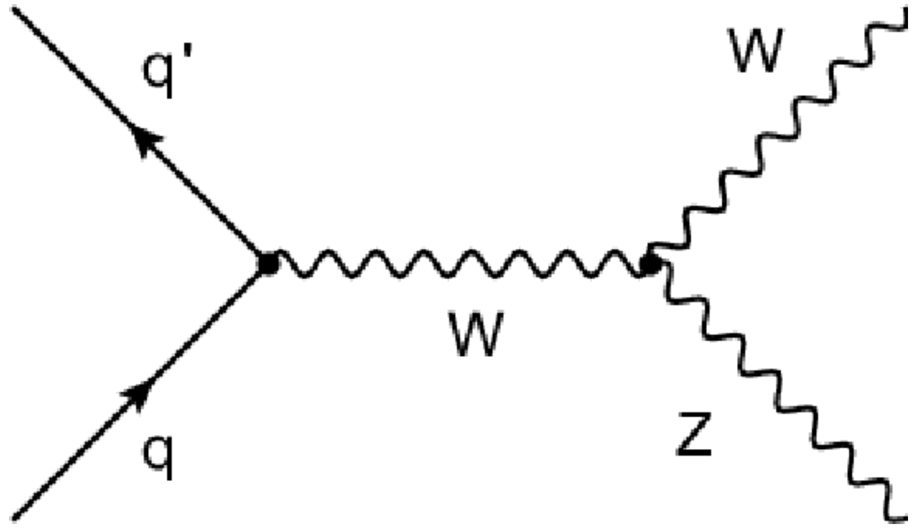


TGCs and QGCs

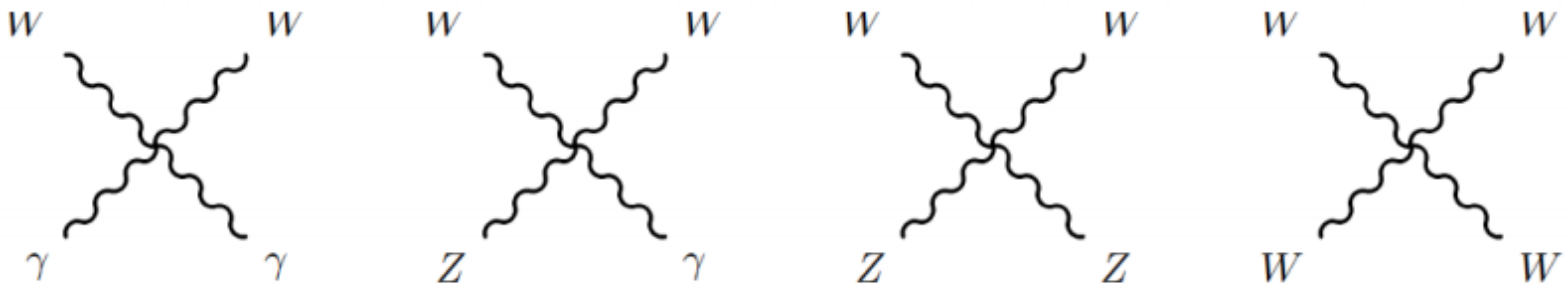
- Trilinear and Quartic Gauge boson couplings are precisely determined by the non-Abelian nature of the SU(2) x U(1) gauge symmetry group that governs the Electroweak theory.
  - Neutral couplings are forbidden at tree-level
    - allowed TGCs: WWɣ and WWZ
    - allowed QGCs: WWWW, WWɣɣ, WWZɣ, WWZZ

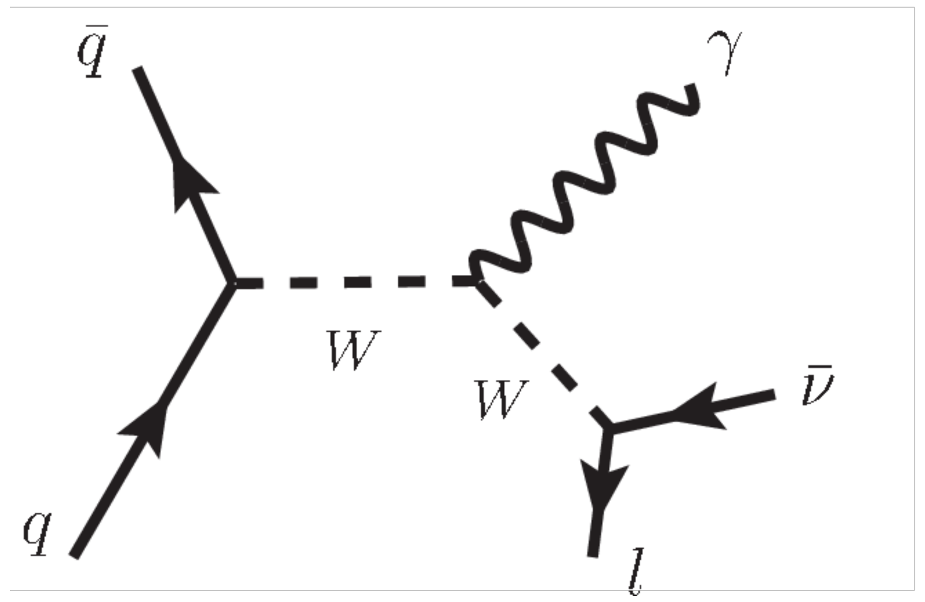


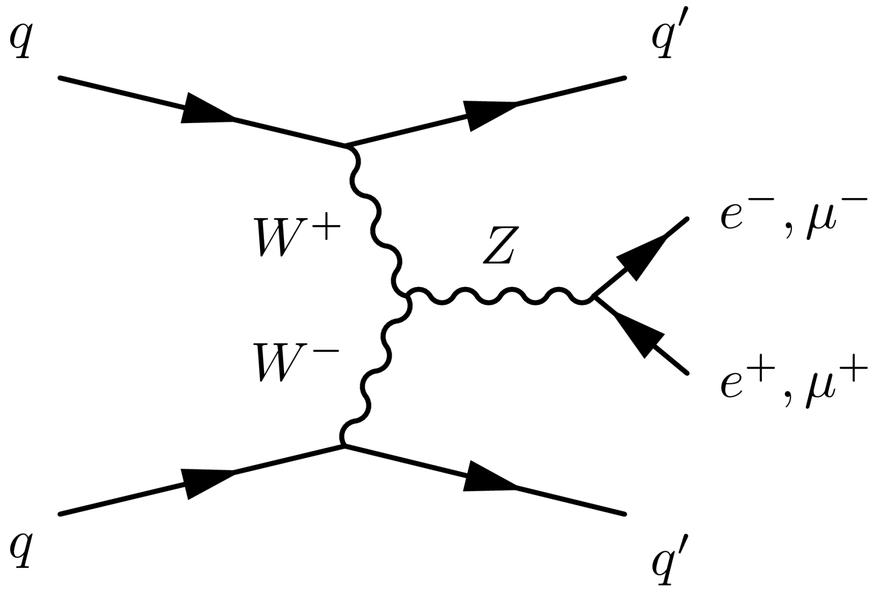




Any couplings that deviate from these are considered new physics







EFT Approach

- A useful way to look for the effects of new physics in a model-independent framework is to use an EFT description of the SM
  - Define a scale of new physics $\boldsymbol{\Lambda}$, and add higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \ldots$$

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- There are three CP-conserving dimension-6 operators (with coefficients that are zero in the SM) and are related to the LEP-constrained aTGC parameters:

$$\begin{aligned} \mathcal{O}_W &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,, \\ \mathcal{O}_{WWW} &= Tr[W_{\mu\nu}W^{\nu\rho}W^\mu_\rho]\,. \end{aligned}$$

$$\begin{aligned} \frac{c_W}{\Lambda^2} &= \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_B}{\Lambda^2} &= \frac{2}{m_W^2}\Delta\kappa_\gamma - \frac{2}{m_Z^2}\Delta g_1^Z\,, \\ \frac{c_{WWW}}{\Lambda^2} &= \frac{2}{3g^2m_W^2}\lambda\,. \end{aligned}$$

EFT Approach

http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

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- Dimension-8 operators are the lowest-dimension operators inducing only QGCs without TGC vertices: 18 independent C,P conserving aQGC (dim 8) operators:

S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

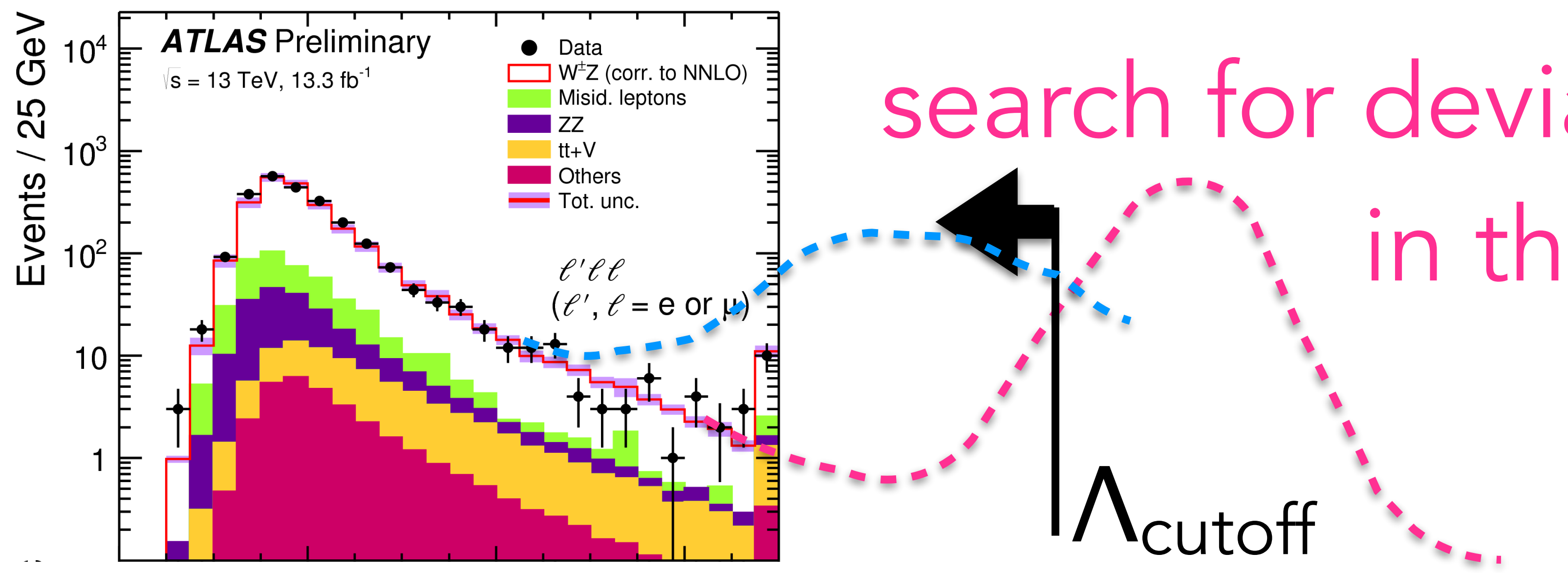
	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Allowed by SM

Anomalous coupling signatures

- Anomalous couplings result in an enhancement of vector boson cross sections at high energy scales
- Best observables are those that carry the energy of the system
  - e.g. invariant mass or transverse momentum
  - Sensitivity mostly in the highest bin
  - Couplings are measured (or limits set) by performing a binned fit in a single sensitive observable
- Challenges:
  - Statistics in the tail
  - Systematic (& statistical) uncertainties

The sensitivity of the result depends on background size, size of the anomalous coupling signal, and uncertainties

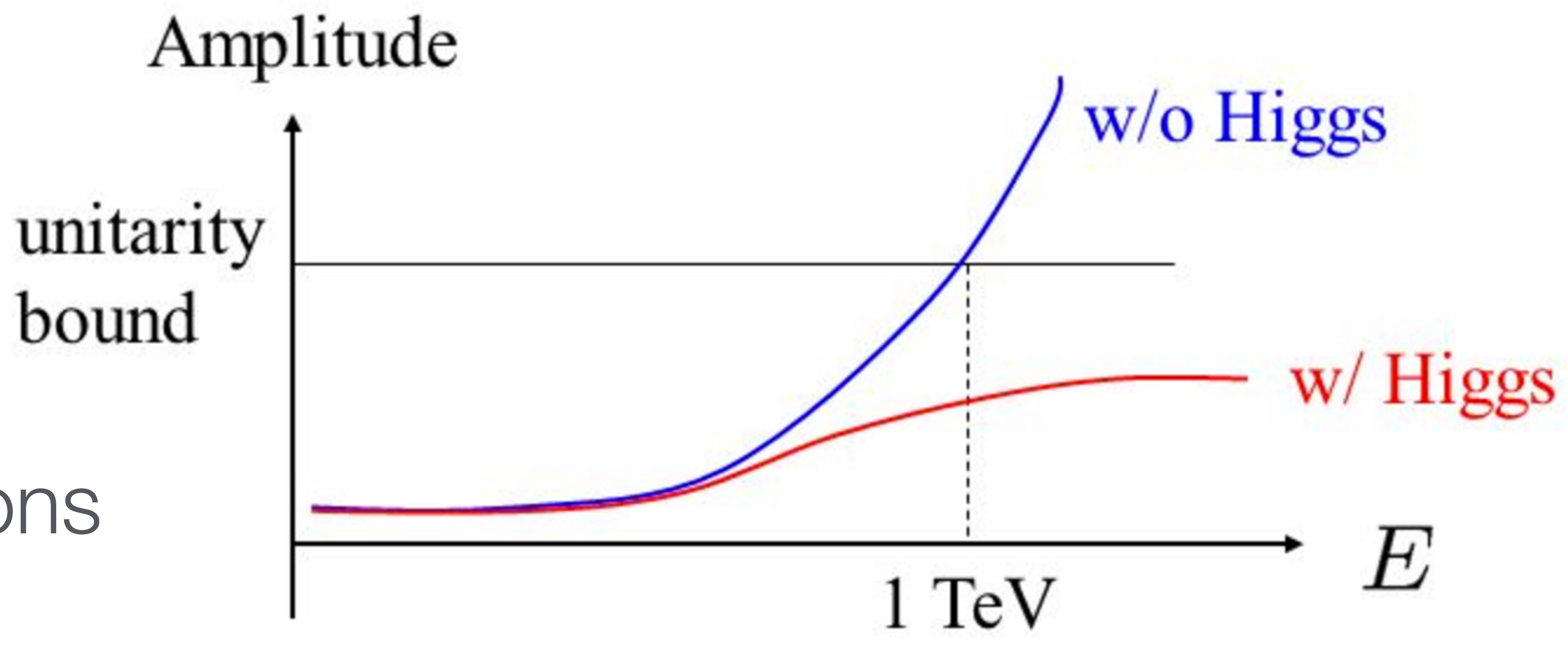


search for deviations in the tails

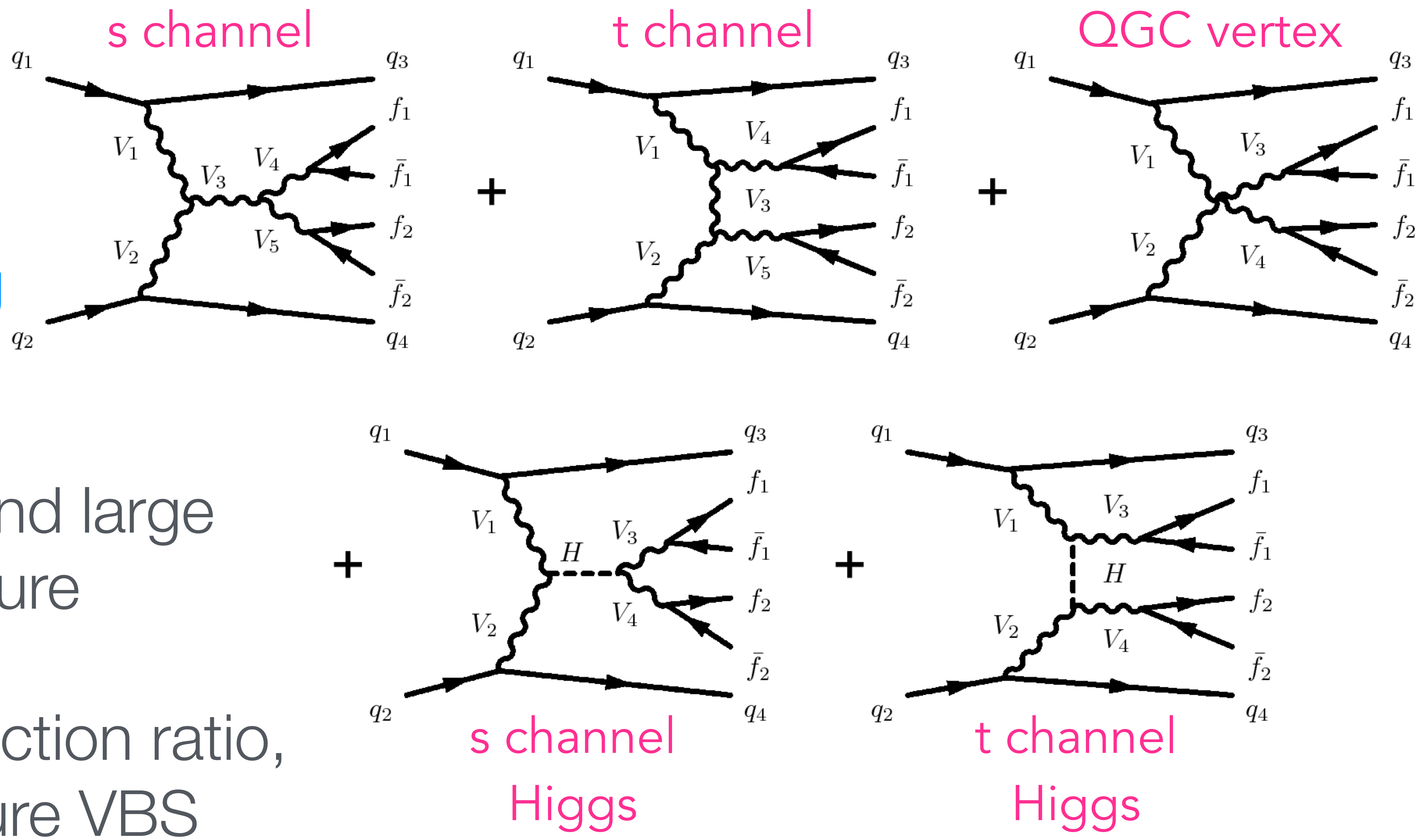
$M_T(WZ)$

Vector Boson Scattering

VBS W±W±, WZ, ZZ, and WW



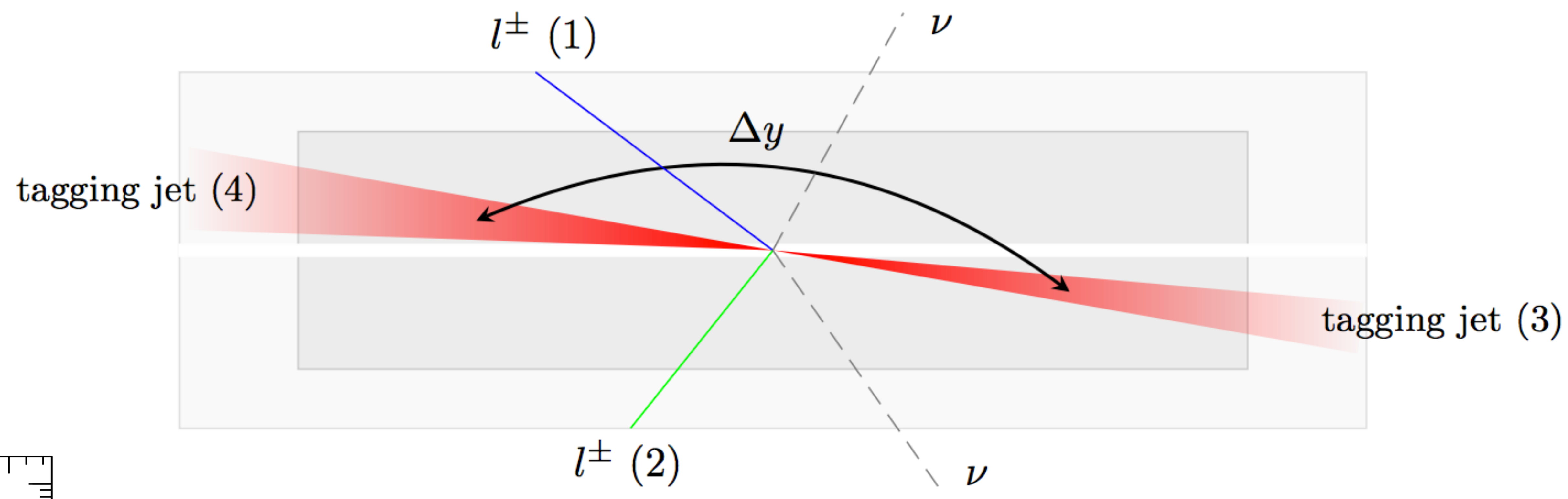
- In the VBS topology, two incoming quarks radiate bosons which interact - final state of two jets and two massive bosons decaying to fermions
- This final state can be the result of EW production with and without a scattering topology, or of processes involving the strong interaction.
- Two "tag" jets with large rapidity separation and large invariant mass give good experimental signature
- $W^{\pm}W^{\pm}jj$ has the largest EW to strong cross section ratio, and is one of the best opportunities to measure VBS



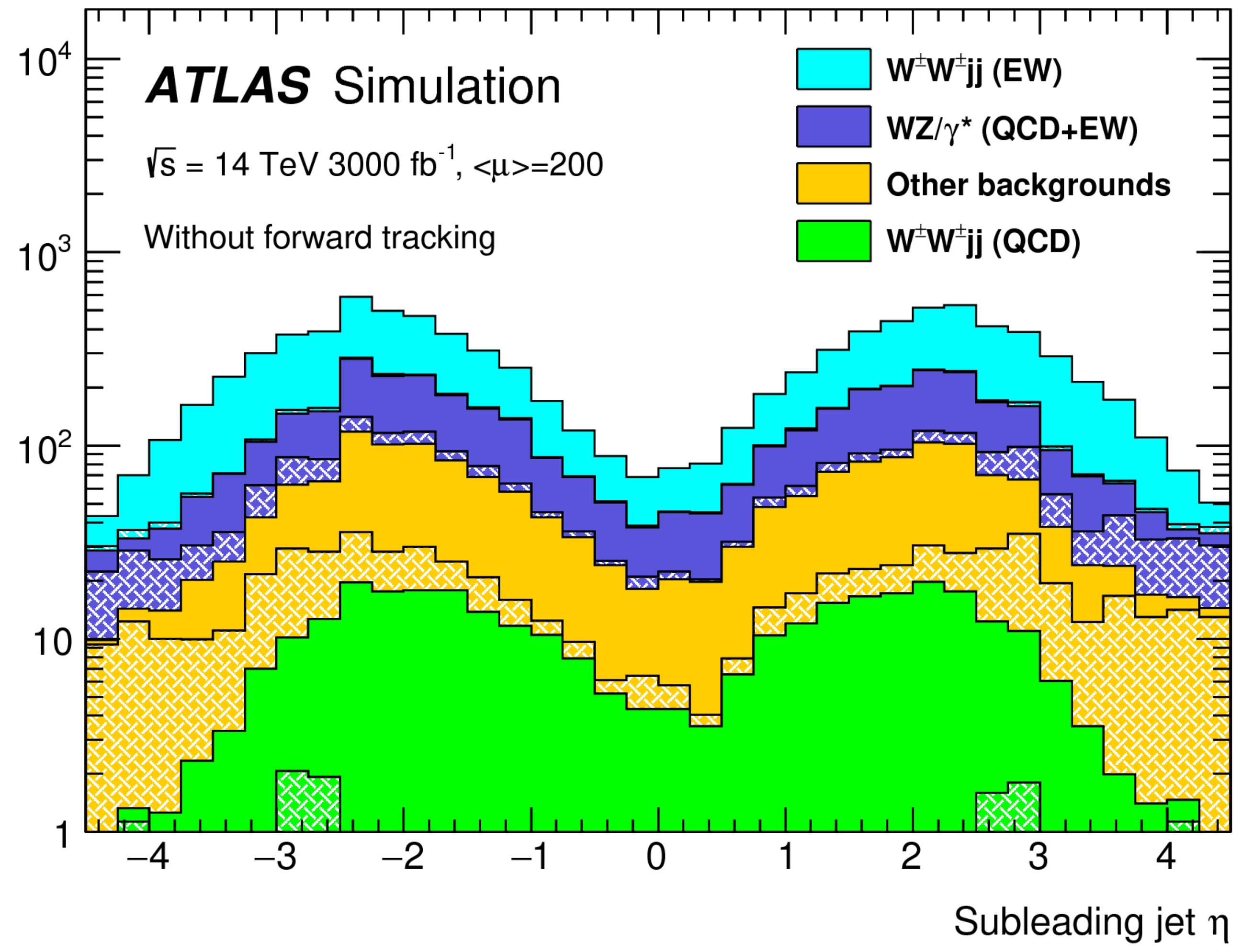
VBS W±W±→ℓνℓν

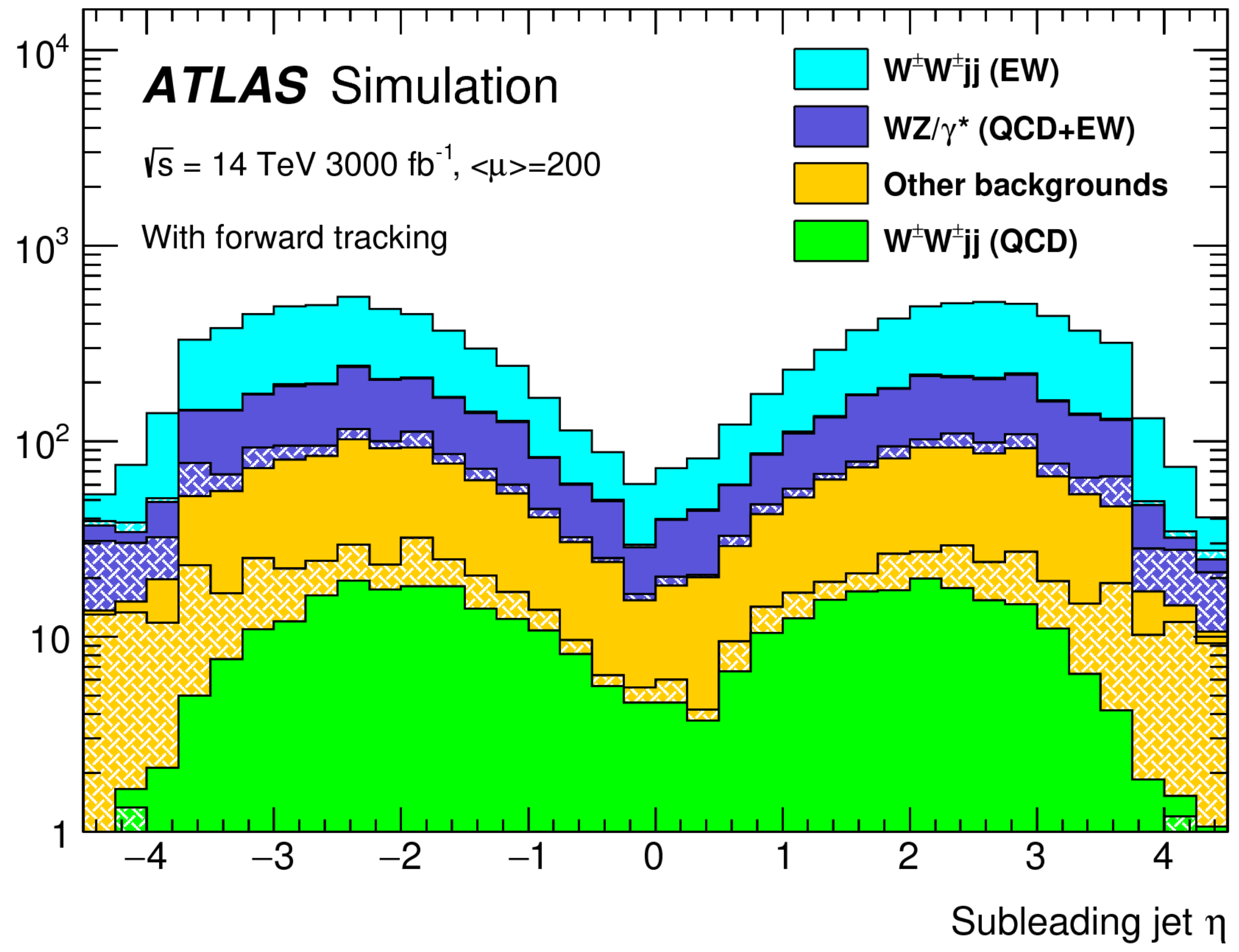
CERN-LHCC-2017-005

- Studies improvement on measurement precision with ITk & a forward muon tagger
  - Improves signal acceptance and (WZ) background rejection



	Signal variation	Background variation	$\frac{\Delta\sigma}{\sigma}$ variation
Pile-up rejection	+12%	+15%	+2.0%
Additional lepton veto	+2.8%	-8.5%	-13%
Combined	+14%	+7.3%	-13%





	$\frac{\Delta\sigma}{\sigma}$
Without forward tracking	4.5%
With forward tracking	3.9%

- **ssWW Event Selections**
  - Two forward jets well separated in rapidity
  - Two same-sign leptons & ETmiss
  - Dominant backgrounds: WZ & ssWW QCD
  - Background systematics ~15%

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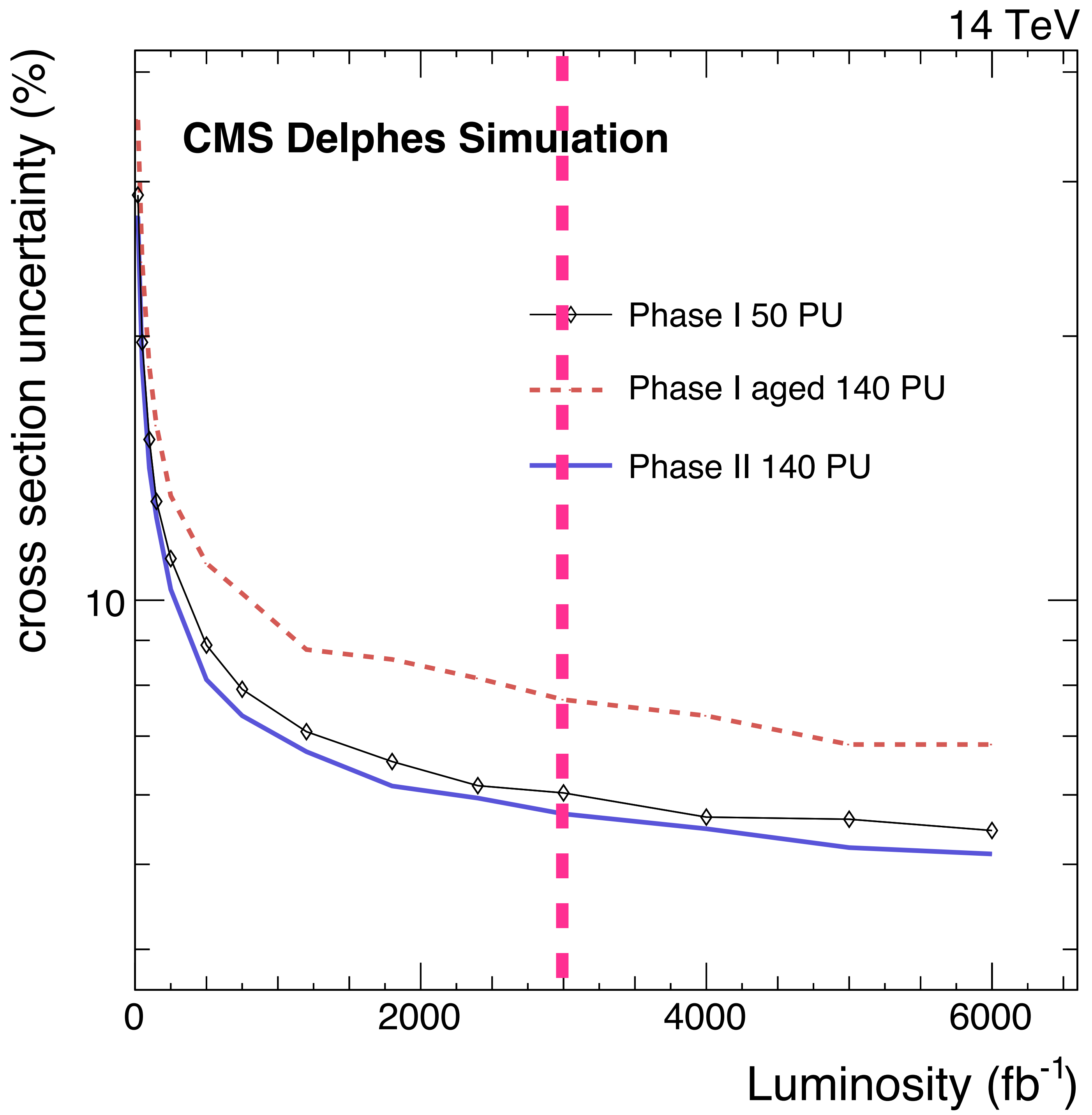
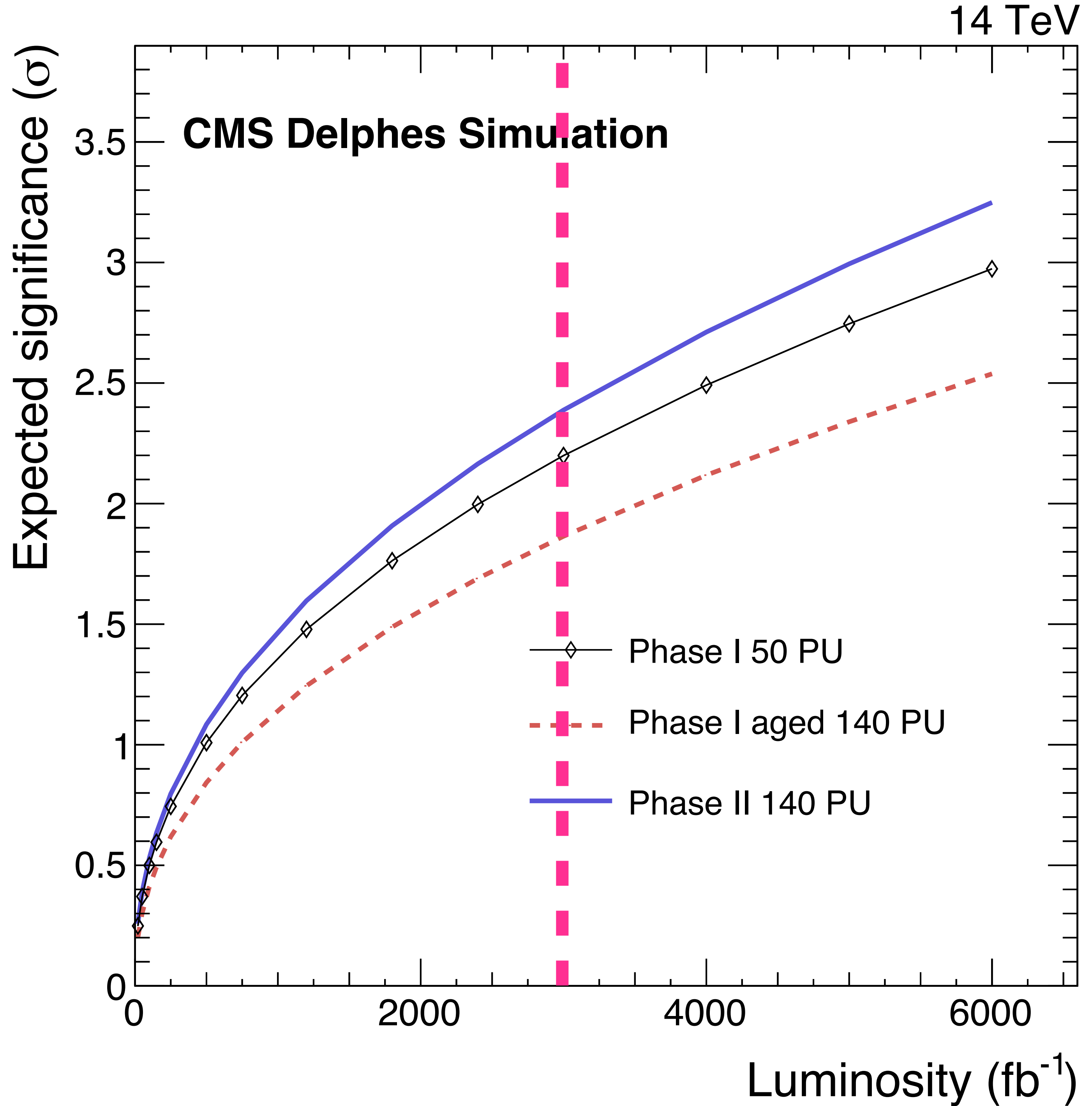
VBS $W^{\pm}W^{\pm} \rightarrow \ell\nu\ell\nu$

SMP-14-008

- Inclusive EW cross section determined from a 2D template fit of lepton-related variables - uncertainty of ~6% (taking into account 30% fake rate and <5% individual experimental systematics - see slide on WZ)
- The total vector boson scattering is composed of three components, depending on the polarisation of the final-state vector bosons:
  - Both longitudinal (LL), both transverse (TT), one of each (LT)
  - ($\Delta\phi$jj, leading lepton pT) chosen for the 2D fit to extract the LL component
  - Expected significance for the LL component of up to 2.4 sigma
- Expected 95% CL limits on the coefficients for dimension-8 operators in the EFT Lagrangian for 3 ab–1 of data show large improvement over Run 1 results

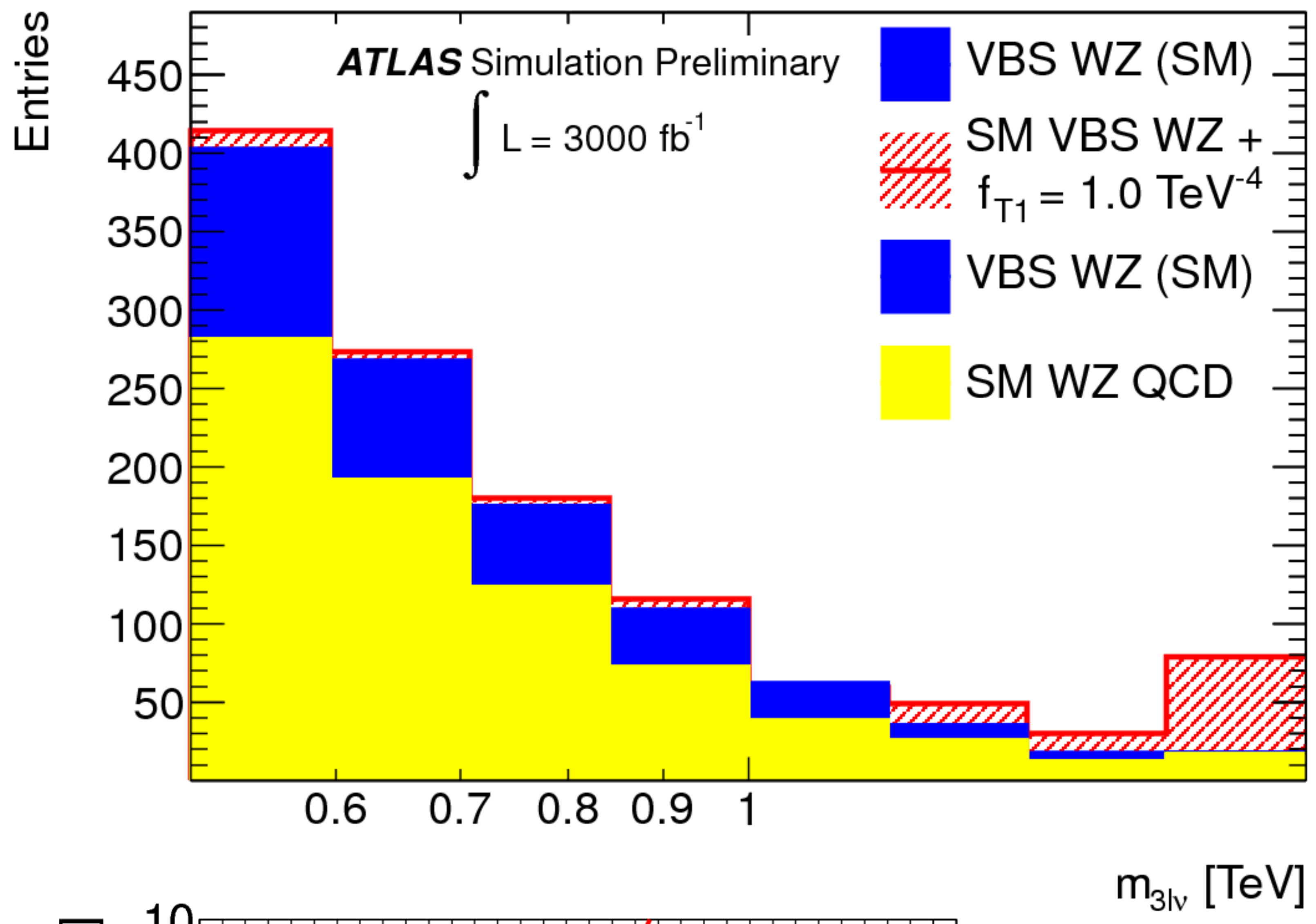


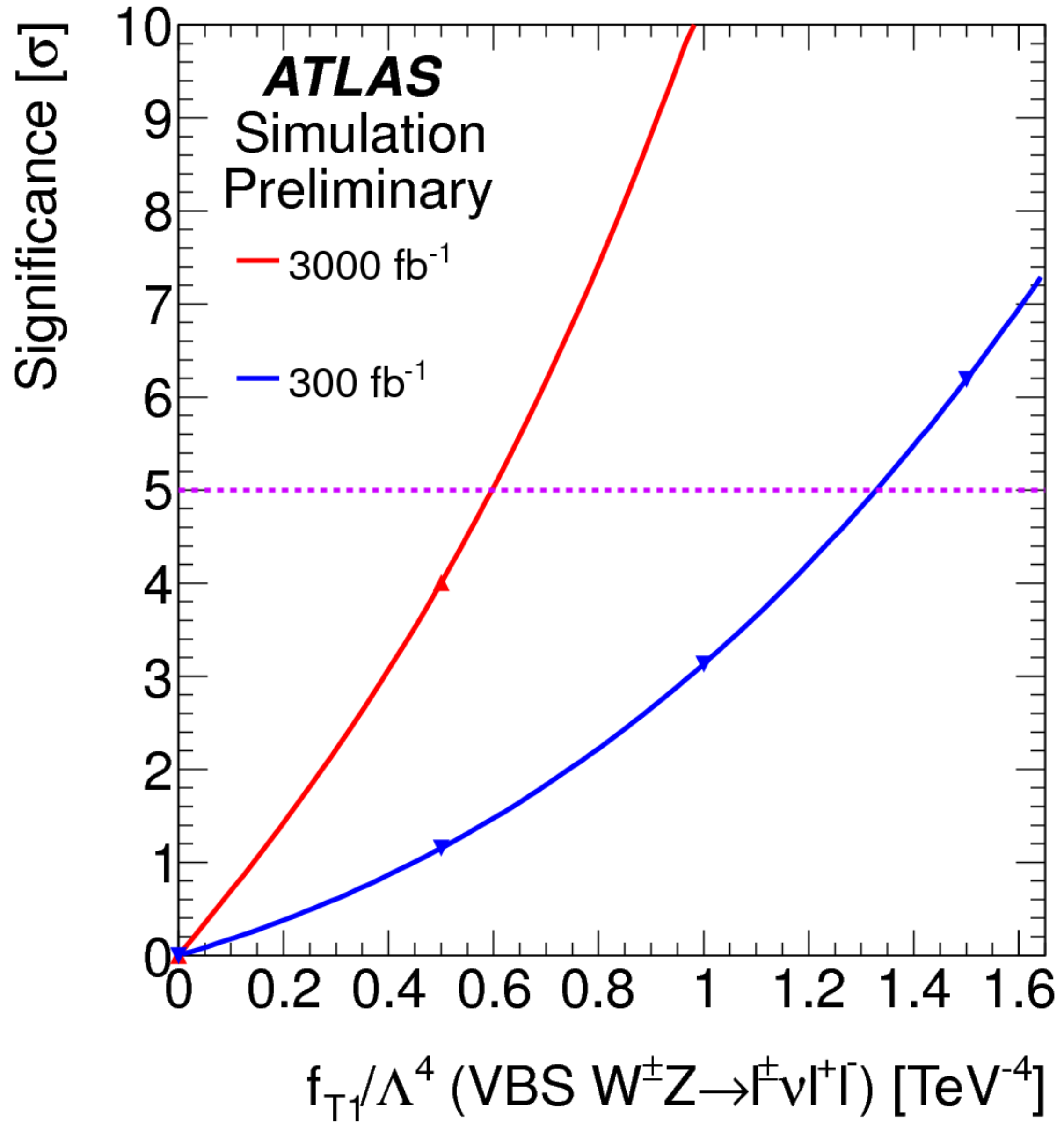


VBS WZ→ℓνℓℓ

[ATL-PHYS-PUB-2013-006]

- The fully leptonic WZjj channel has a larger cross section than ZZjj and can still be reconstructed using the W boson mass constraint for the neutrino.
  - Lepton pT > 25 GeV
  - Leptons from Z decay determined by same-flavour opposite-sign pair (and dilepton mass if needed)
  - m_{jj} > 1 TeV with jet pT > 50 GeV
- Consider only SM WZjj-QCD production as background
- Mass distribution used for extraction of anomalous coupling coefficients



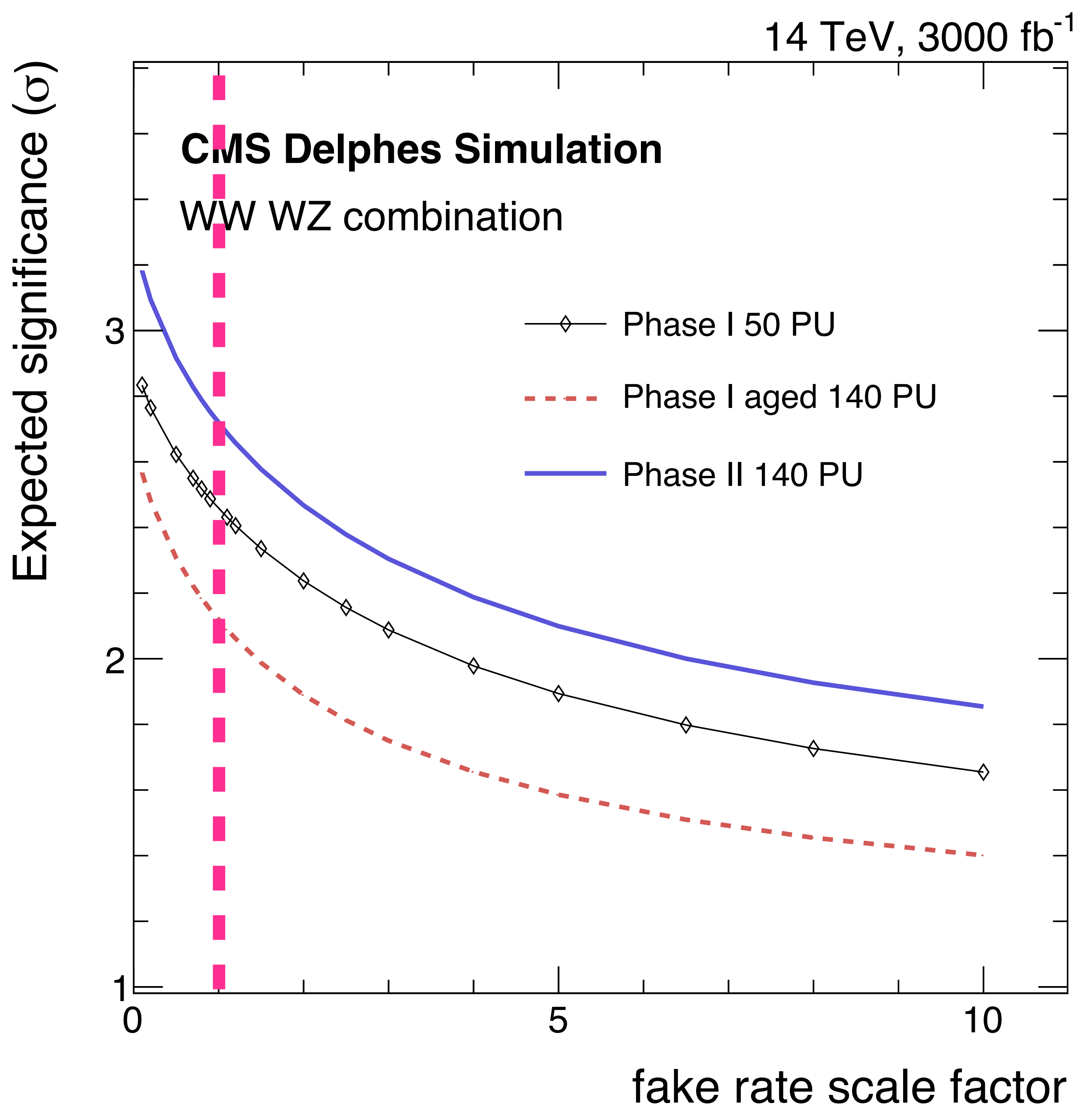


VBS WZ→ℓνℓℓ

[SMP-14-008]

Systematic sources	Analysis		Detector scenarios		
	$W^{\pm}W^{\pm}$	WZ	Phase I	Phase I aged	Phase II
jet energy scale	X	X	1–3%	1.5–4%	1–3%
jet energy resol.	X	X	5%	6.5%	5%
muon energy scale	X	X	1%	2%	1%
muon energy resol.	X	X	1%	2%	1%
electron energy scale	X	X	2%	4%	2%
electron energy resol.	X	X	2%	4%	2%
lepton efficiency	X	X	2%	2%	2%
lepton fake rate	X		30%	30%	30%
lepton wrong charge	X		30%	30%	30%
b-tag efficiency	X		4%	5.5%	4%
signal acceptance	X	X	2%	2%	2%
QCD scale choice	X	X	3%	3%	3%
parton densities	X	X	7%	7%	7%
LHC luminosity	X	X	2.6%	2.6%	2.6%

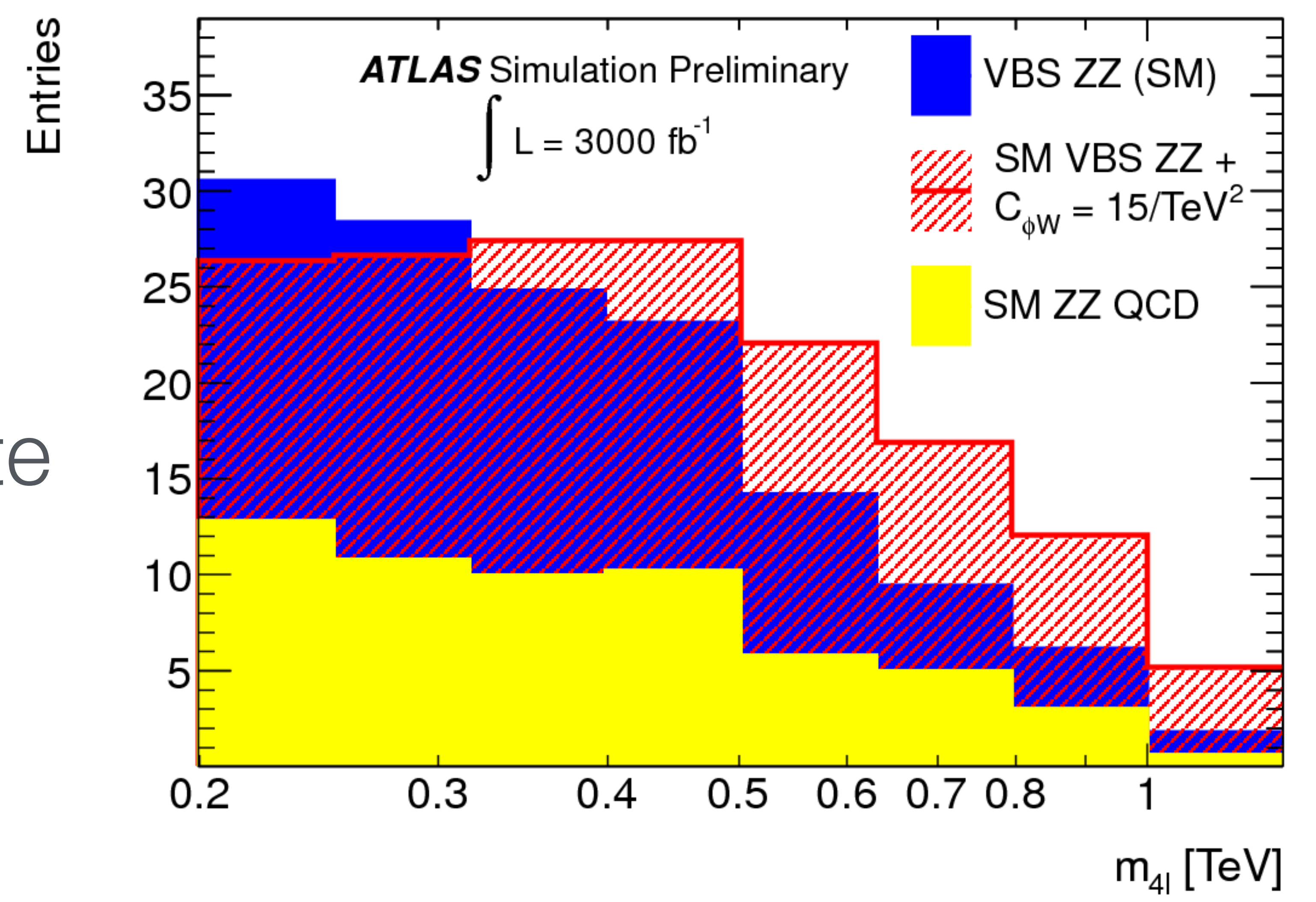
- Lepton pT > 20 GeV
- Main backgrounds from QCD production of ZZ and WZ, and EW production of ZZ boson pairs
- Results depend on global fake rate scale factor (fake rate depends on detector geometry)
- Inclusive EWK cross-section is determined by fitting the 2D distribution of (pT_{jj}, $\Delta\eta_{ll}^{SS}$)
- Same longitudinal extraction done as for $W^{\pm}W^{\pm}$
- Combination with $W^{\pm}W^{\pm}$ (taking into account correlations):
  - LL scattering discovery significance: 2.75 (fake rate SF of 1)

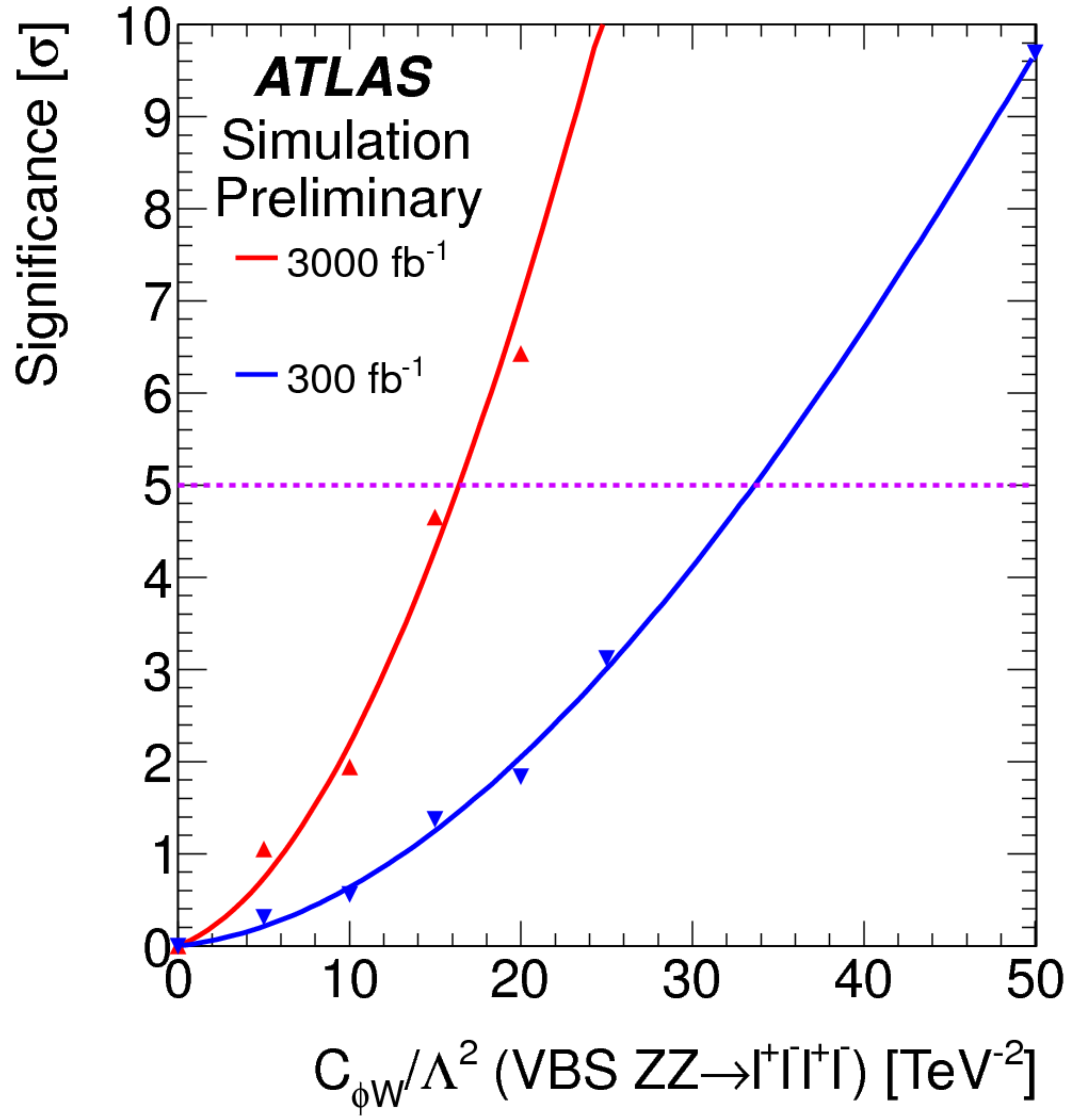


VBS ZZ→4ℓ

ATL-PHYS-PUB-2013-006

- Small cross section but provides a clean, fully reconstructible ZZ final state
  - SM ZZjj-QCD production considered as background
- Jet pT > 50 GeV, and dijet mass requirement of 1 TeV reduces the contribution from jets accompanying non-VBS diboson production
- Exactly four selected leptons (each with pT > 25 GeV) which can be separated into two opposite sign, same flavour pairs (No Z mass window requirement)
- Background-only p0-value expected is calculated using the $m_{4\ell}$ spectrum
- Since the 4–lepton mass is the process √s, the study of its distribution directly probes the energy-dependence of the new physics



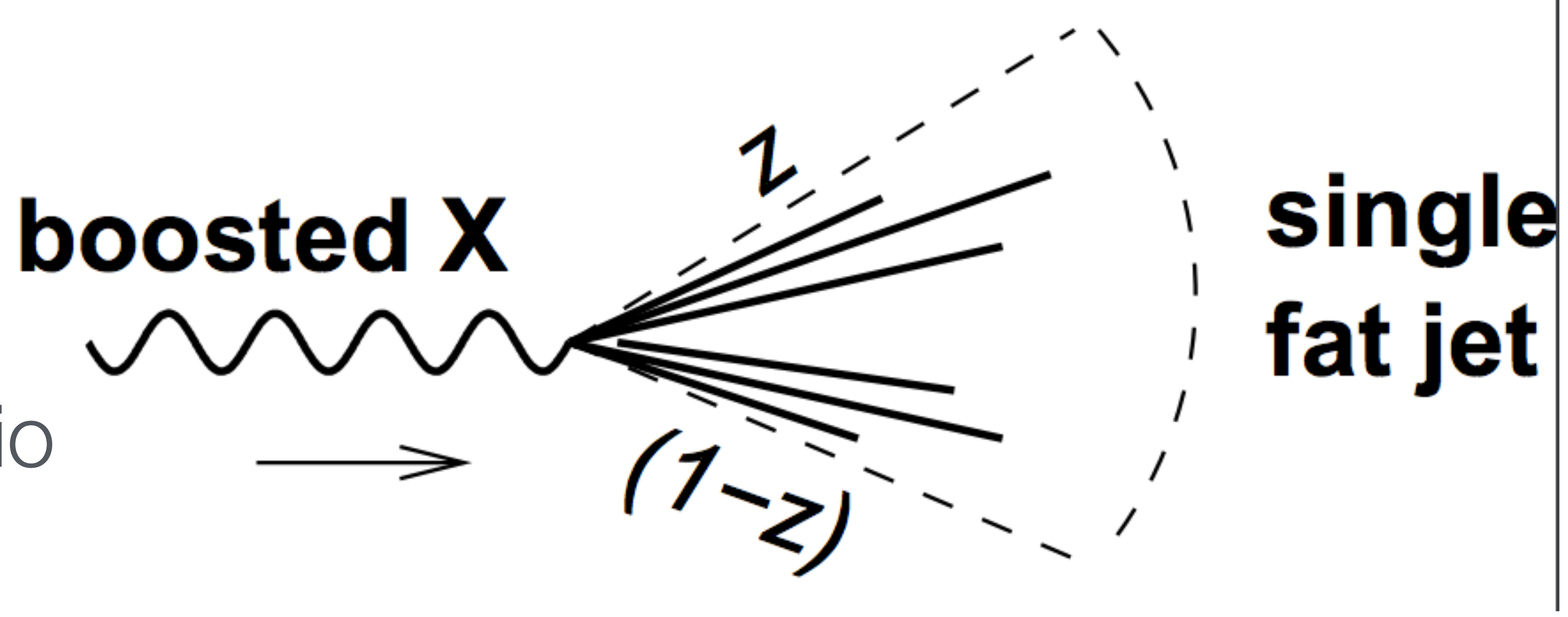


VBS WW→ℓvJ

ATL-PHYS-PUB-2012-005

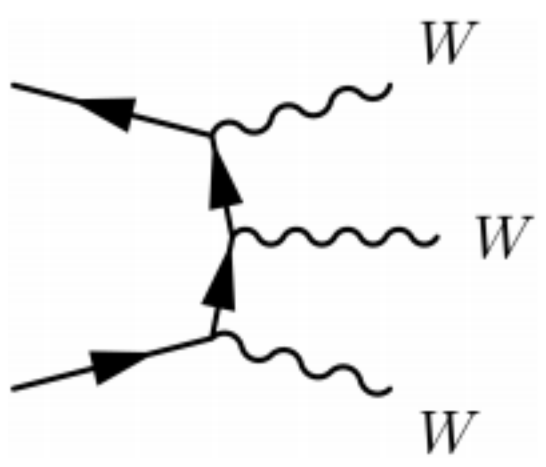
- WW with one W boson decaying to ev or μv and one W boson decaying hadronically
  - The presence of jets and the large background from W+jets and ttbar production limit the experimental precision, but ~6 times greater branching ratio
  - Also, for WW case the ℓvqq kinematics can be better reconstructed
  - Large R jet has increased reconstruction efficiency at high p_T
- Lepton pT > 60 GeV , ETMiss > 25 GeV
- Two anti-kt R = 0.4 jets with pT > 40 GeV, mjj > 250 GeV, and Δη > 5 (tag jets)
- W-jet: one anti-kt R = 0.6 jet with pT > 300 GeV and 60 GeV<m<110 GeV. Veto on top quark mass to reduce background

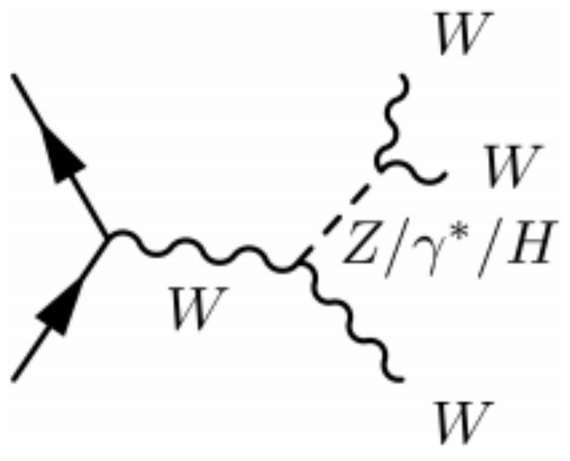
diagram credit: G Salam

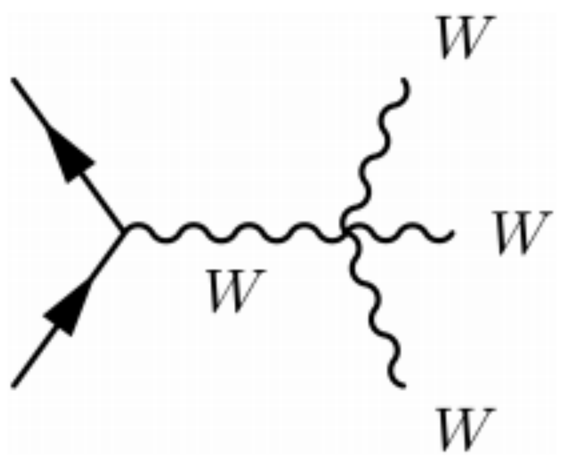


model	SM
(a_4, a_5)	(0, 0)
S/B	$(3.3 \pm 0.3)\%$
$S/\sqrt{B}$ ($L = 300\text{fb}^{-1}$)	2.3 ± 0.3
$S/\sqrt{B}$ ($L = 3000\,\text{fb}^{-1}$)	7.2 ± 0.1

Tribosons



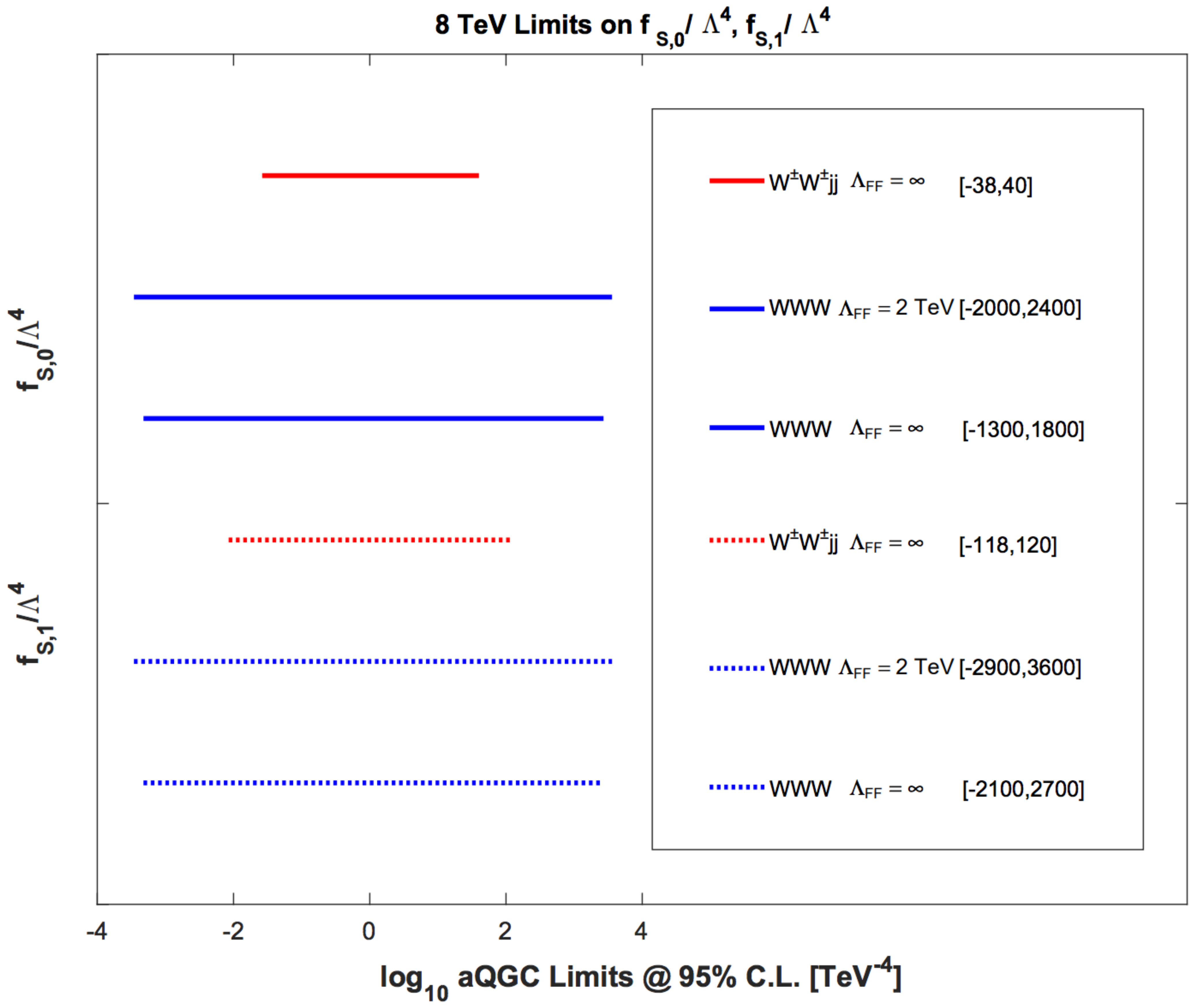




- Finally sensitive to triboson production at hadron colliders!
  - Important to constrain these processes from data as they form the background to many direct new physics searches.
- Triboson measurements are complementary to those from VBS analyses (aQGCs…)
  - For limit setting of dimension-8 operators, tribosons don't achieve the sensitivity of VBS, but are a nice cross check.

$W\gamma\gamma$: >3σ
$Z\gamma\gamma$: >5σ

arxiv:1610.07572

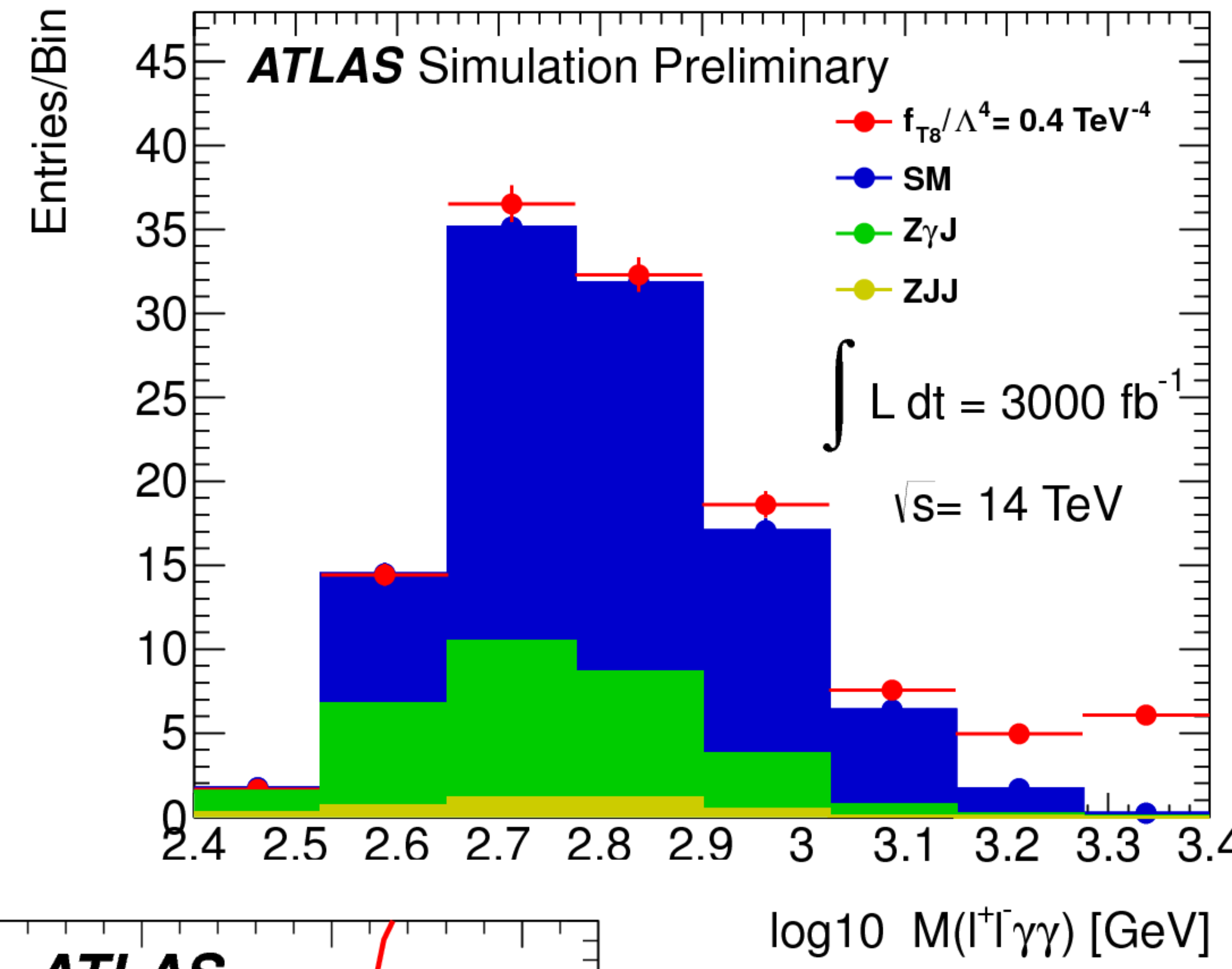


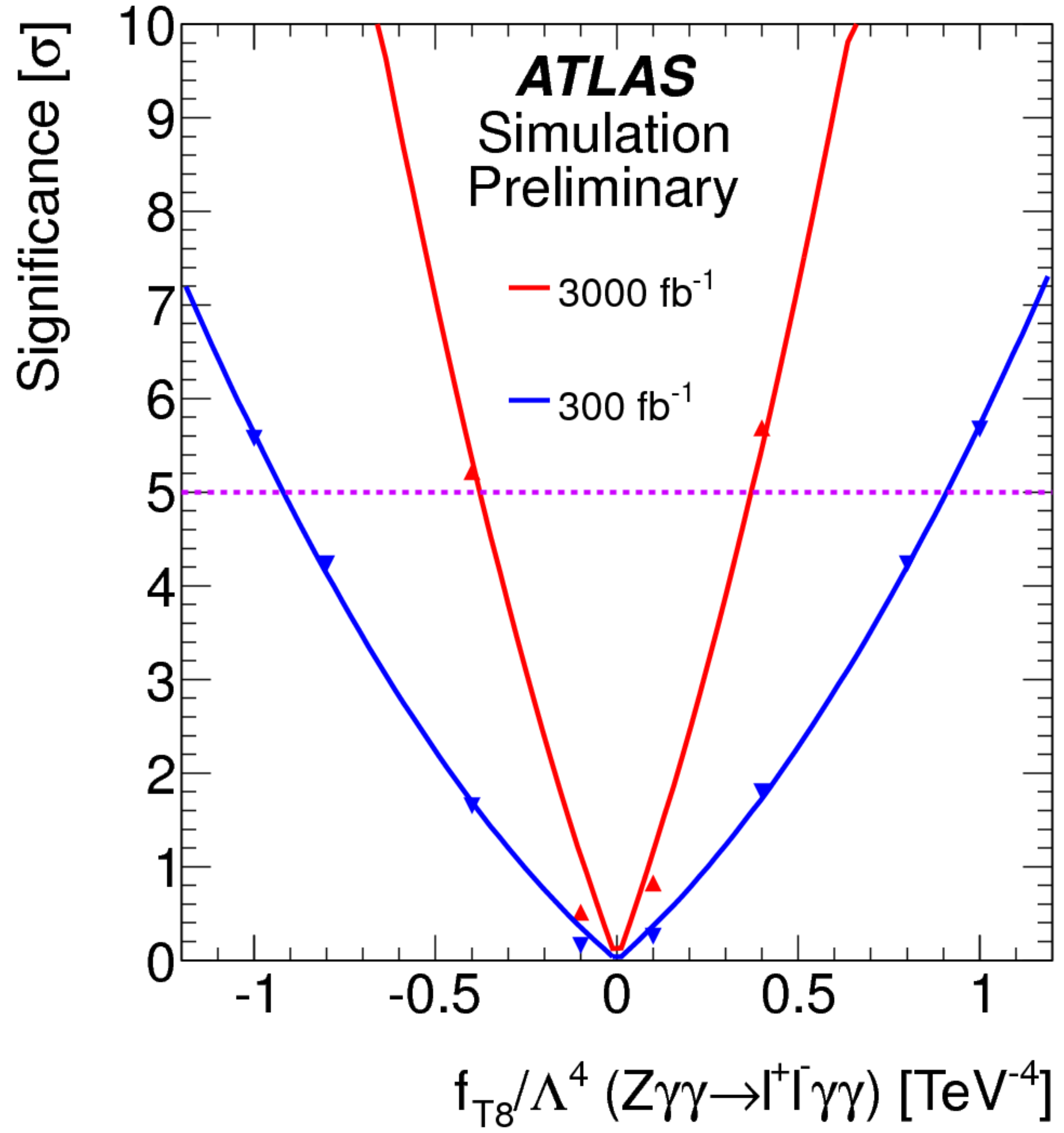
[Total production cross sections at 14 TeV at NLO in QCD]

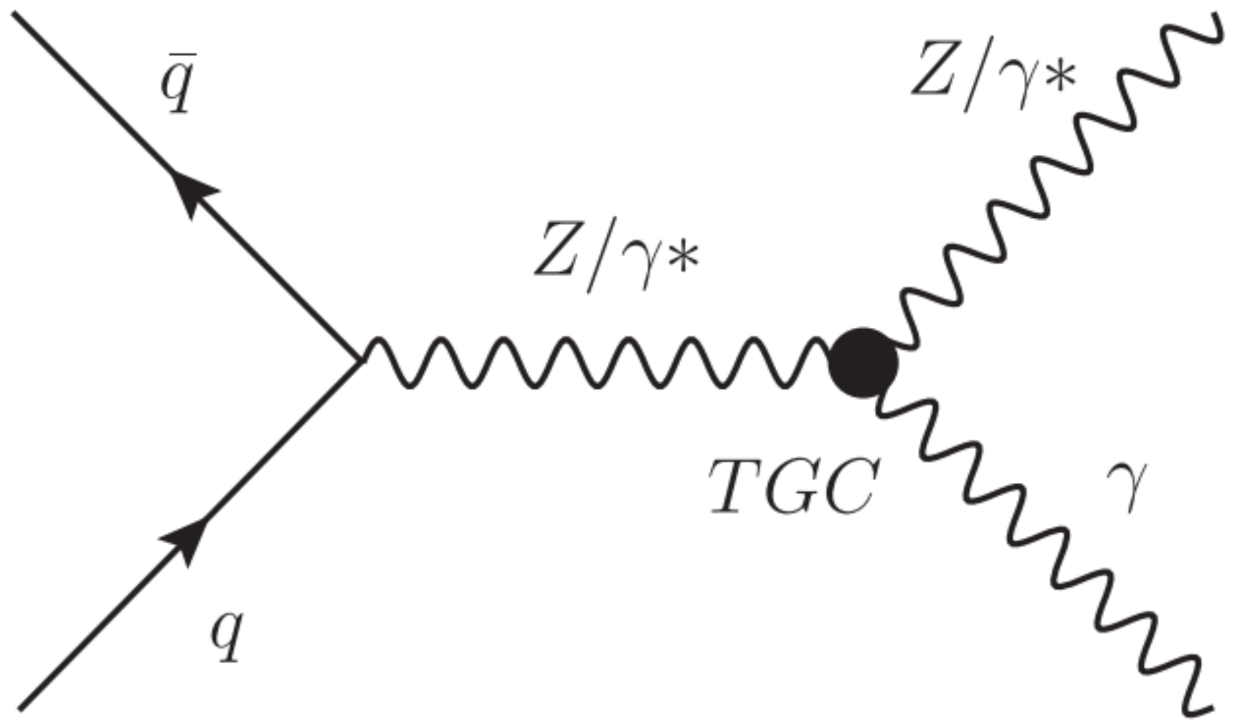
Process	scale μ	Born cross section [fb]	NLO cross section [fb]
ZZZ	$3M_Z$	9.7(1)	15.3(1)
WZZ	$2M_Z + M_W$	20.2(1)	40.4(2)
WWZ	$M_Z + 2M_W$	96.8(6)	181.7(8)
WWW	$3M_W$	82.5(5)	146.2(6)

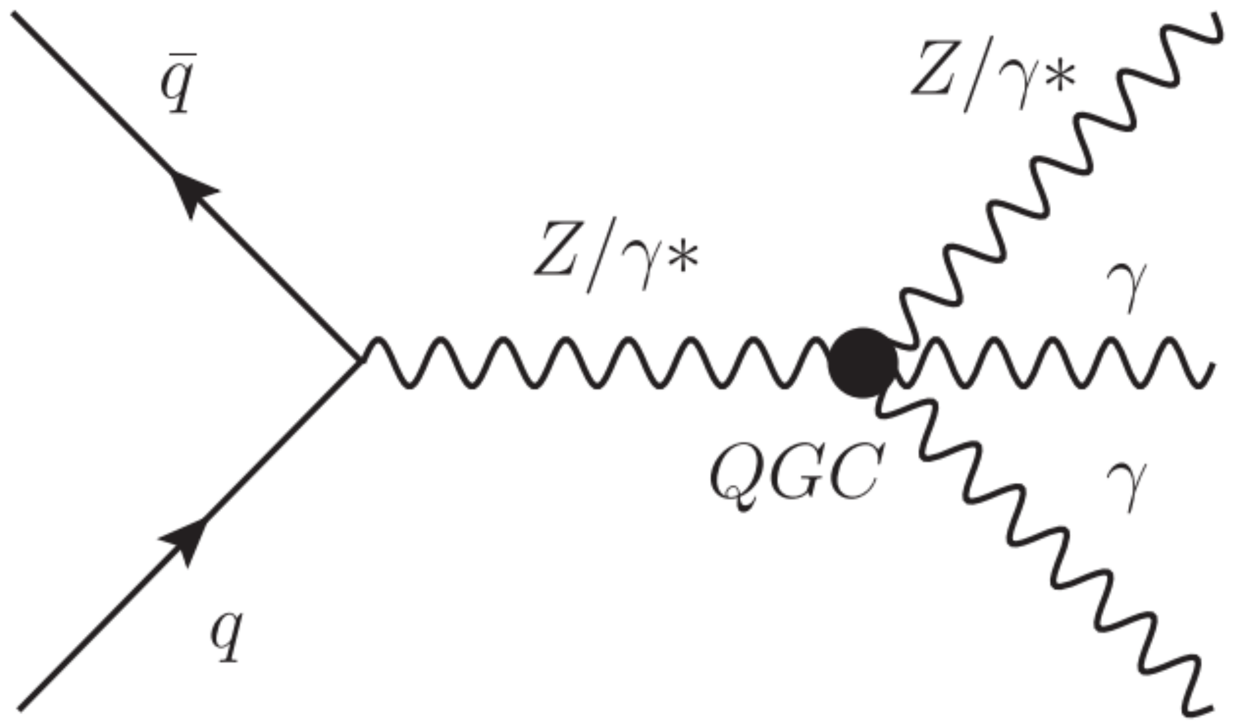
Triboson HL-LHC thoughts

- By the end of Run 2 we should have the first evidence for more massive triboson final states (WWW, WWɣ, WZɣ).
  - In WWW, the signal and almost all other important background processes have cross sections increased by a factor of ~2 compared to 8 TeV
  - At HL-LHC the high pile-up may cause problems in terms of fake leptons, jets from other interactions and MET resolution









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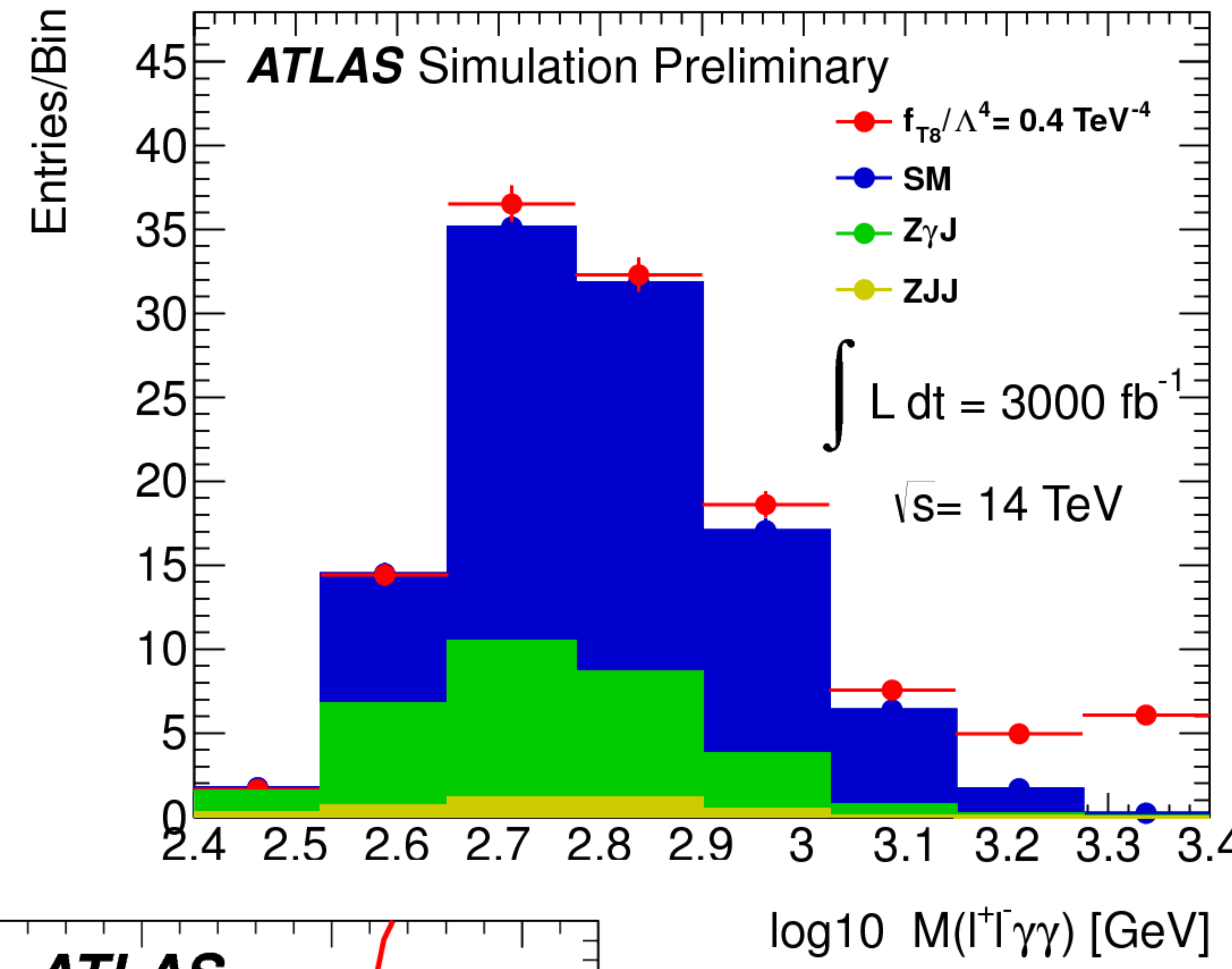
[ATL-PHYS-PUB-2013-006]

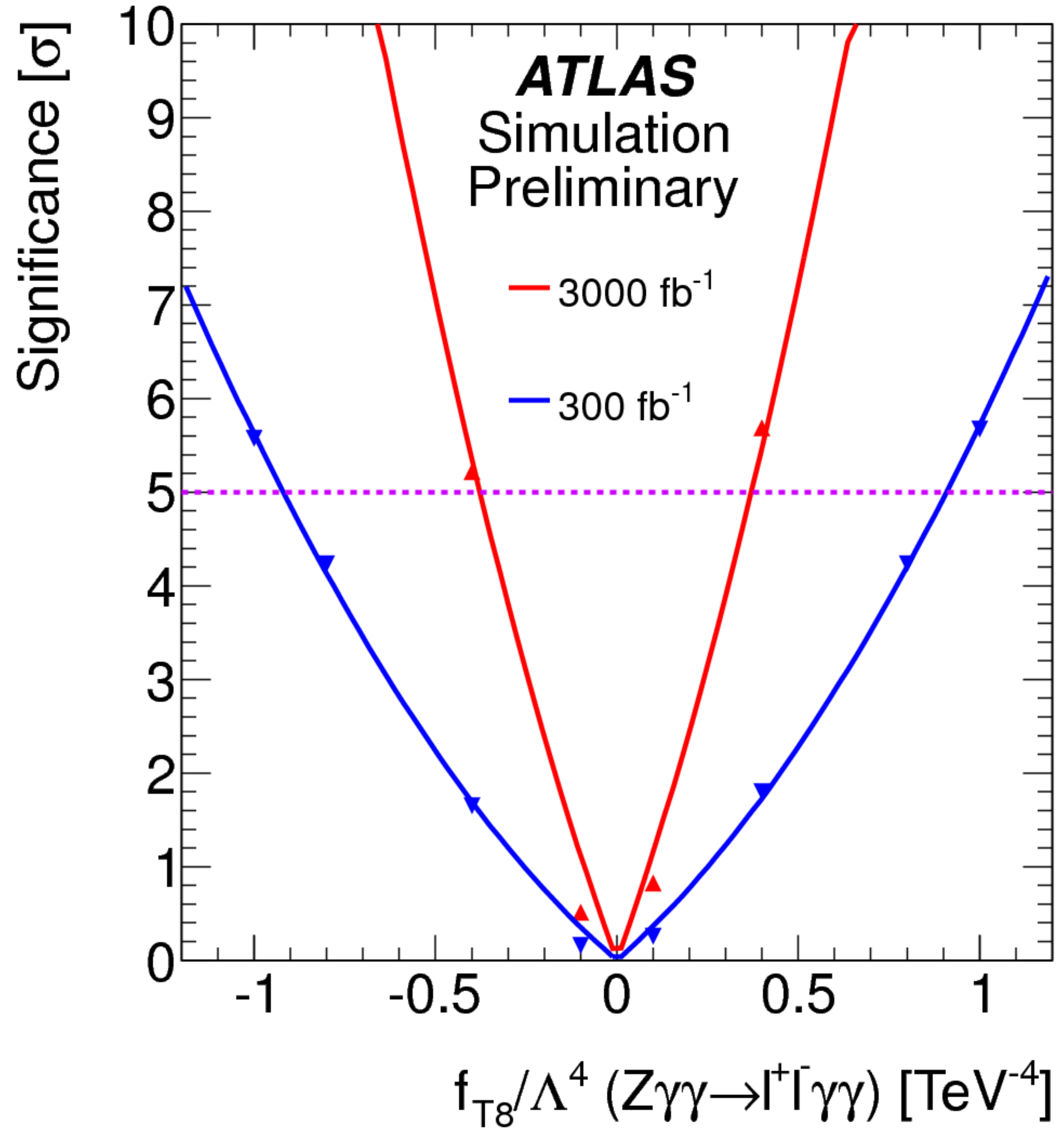
[Total production cross sections at 14 TeV at NLO in QCD]

Triboson HL-LHC thoughts

Process	scale μ	Born cross section [fb]	NLO cross section [fb]
ZZZ	$3M_Z$	9.7(1)	15.3(1)
WZZ	$2M_Z + M_W$	20.2(1)	40.4(2)
WWZ	$M_Z + 2M_W$	96.8(6)	181.7(8)
WWW	$3M_W$	82.5(5)	146.2(6)

- By the end of Run 2 we should have the first evidence for more massive triboson final states (WWW, WWɣ, WZɣ).
  - In WWW, the signal and almost all other important background processes have cross sections increased by a factor of ~2 compared to 8 TeV
  - At HL-LHC the high pile-up may cause problems in terms of fake leptons, jets from other interactions and MET resolution
- Seeing ZZZ in any state will be challenging (taking total cross section as ~15fb)





ZZZ xsec*BR not including selection efficiencies, etc:
(4l+2j): 46 ab
(4l+2nu): 13 ab
(6l): 4.3 ab

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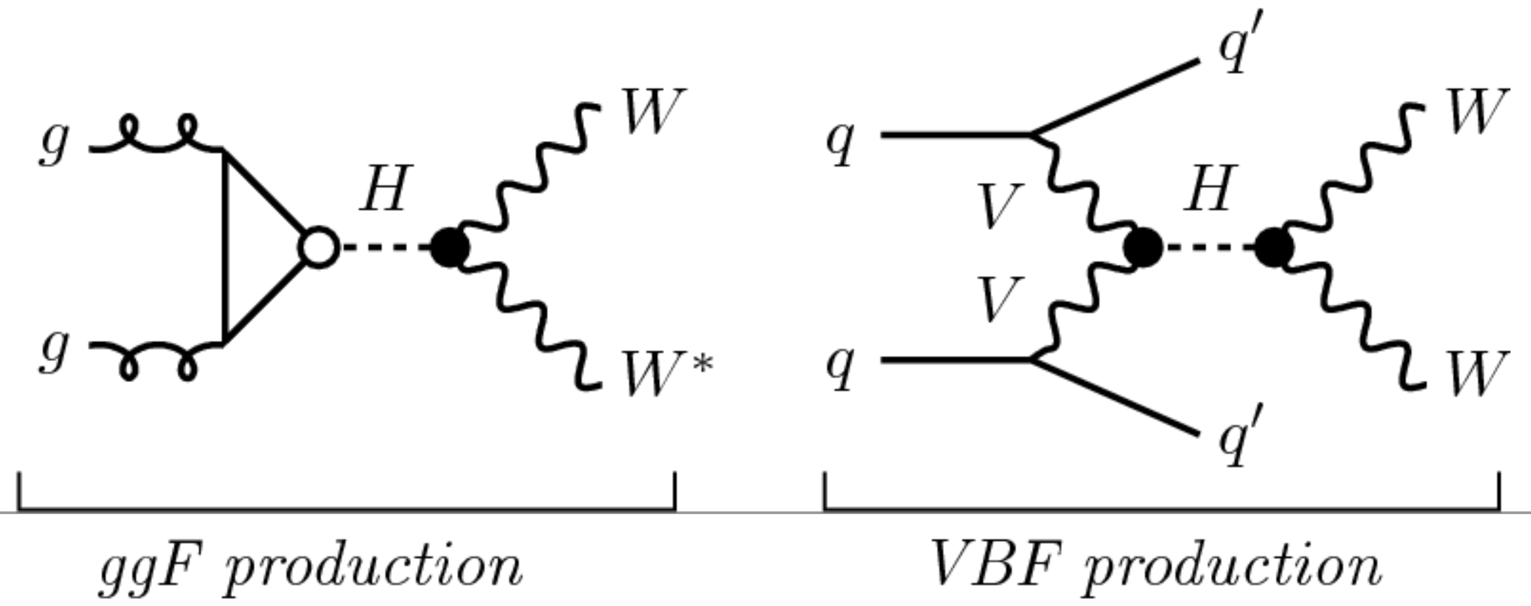
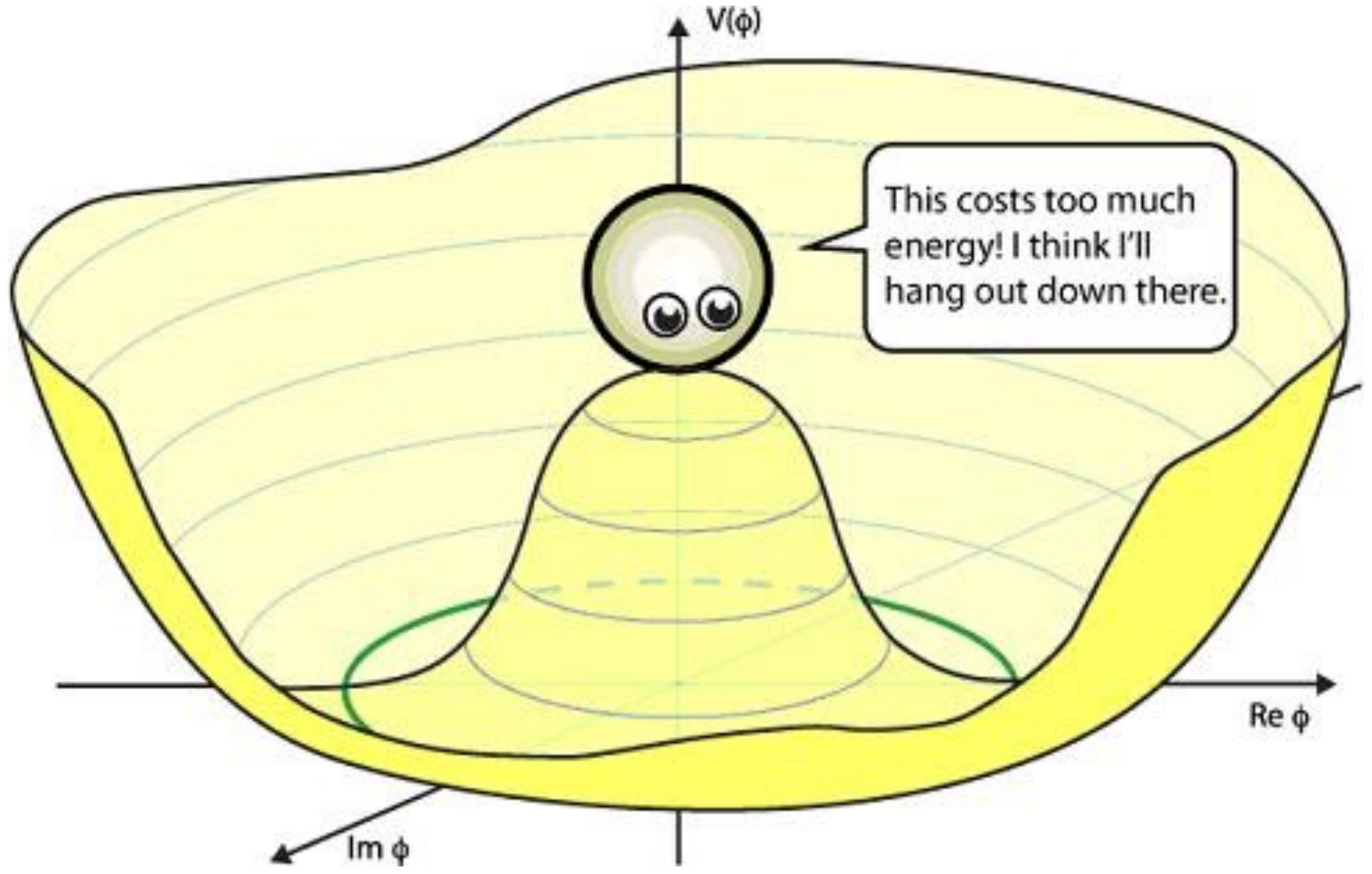
VBF Higgs



VBF H→WW

- In the SM, all the properties of the Higgs are defined once its mass is known. However, the many possible BSM theories give different predictions for the properties of the SM (and possibly other) Higgses
- VBF Higgs production is a good channel for precision measurements at the HL(E)-LHC
  - VBF has the 2nd largest cross section of all Higgs production mechanisms (factor ~10 less than ggF at 14 TeV)
  - Owing to the direct coupling to EW vector bosons, VBF has smaller theoretical uncertainties compared to ggF
  - Again, experimentally, the tag jets give a good signature
- Focus in these studies is on the measurement & uncertainty on the Higgs boson signal strength (Δμ)



Syst. unc.	ggF (%)	VBF (%)
QCD N_{jet} cross-section	43	1
QCD acceptance	4	4
PDF	8	3
UE/PS	9	3
Total	44	6

ATL-PHYS-PUB-2016-018

more VBF Higgs results here…

- VBF H→ZZ and VBF H→ττ (ATLAS)
- H→ZZ , H→γγ, HH & BSM H→ττ and H→invisible (CMS)

VBF H→WW

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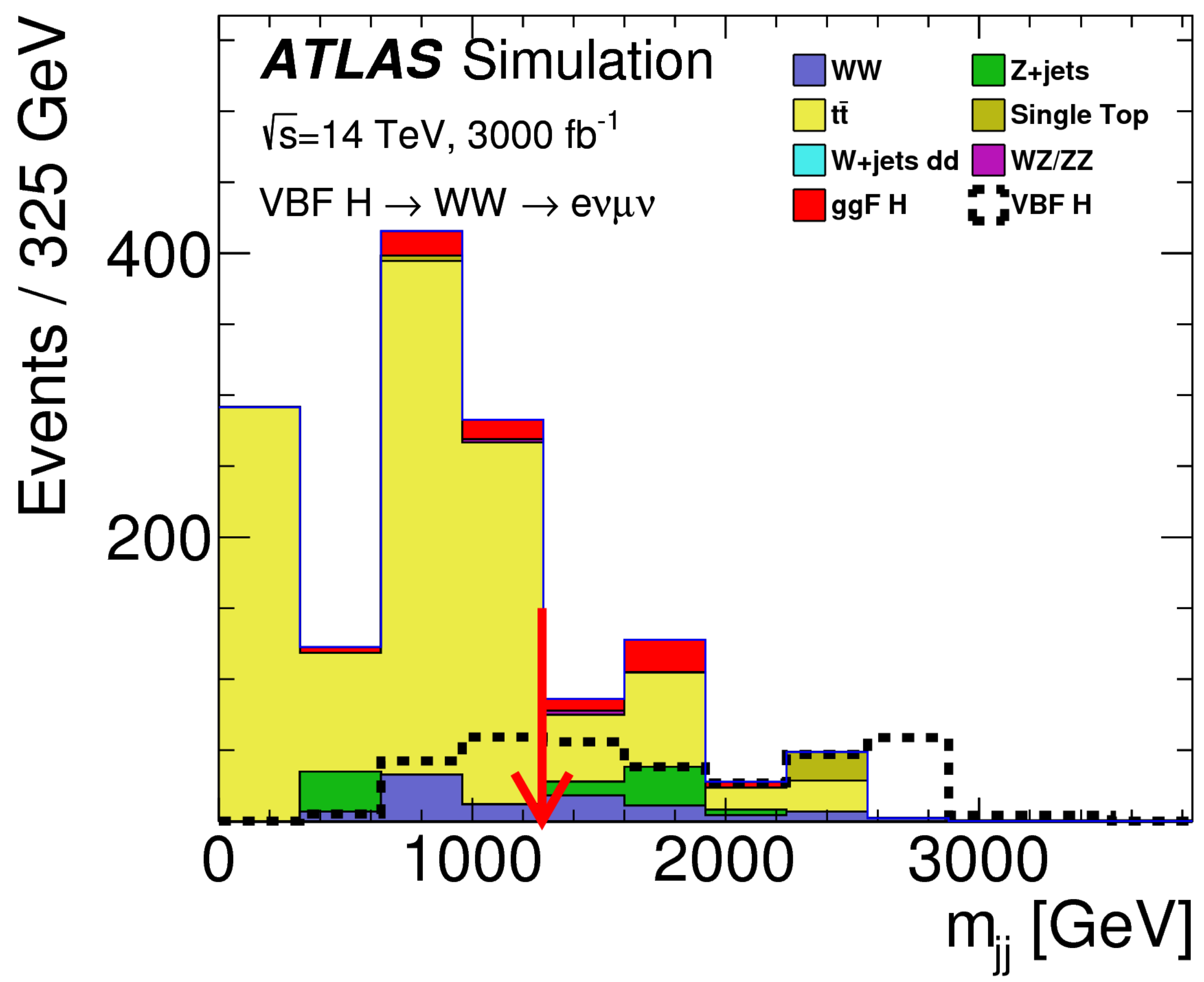
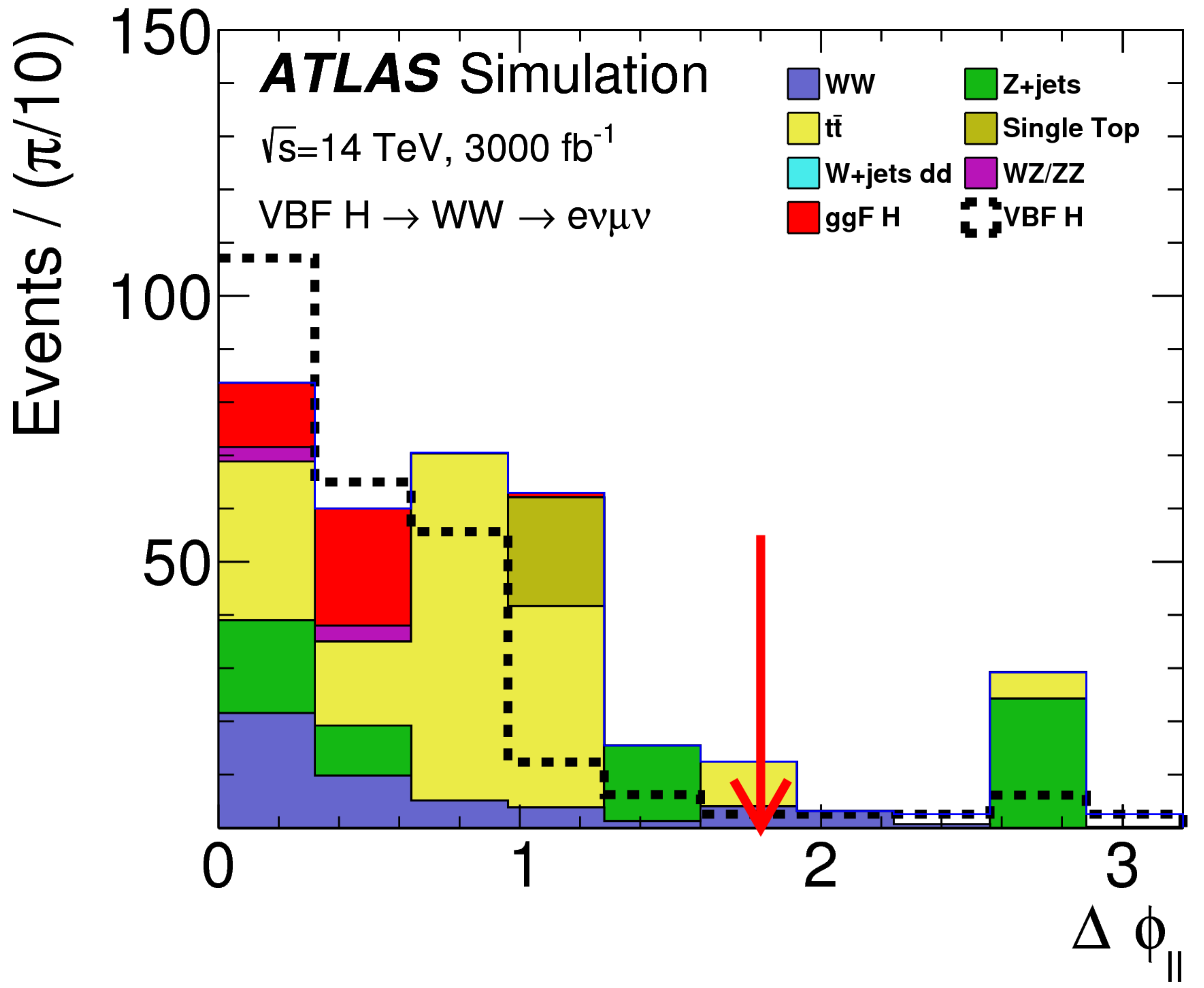
- **VBF HWW Event Selections**
  - Two forward jets well separated in rapidity
  - Two opposite-sign leptons & ETmiss
  - Dominant backgrounds: ggF, SM ttbar, diboson, and V+jets

VBF topology	$m_{jj} > 1250$ GeV and $\lvert\eta_j\rvert > 2.0$, opposite hemisphere No jets ($p_T > 30$ GeV) in rapidity gap (CJV) Require both ℓ in rapidity gap
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 60$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_T < 1.07 \times m_H$





Bkg. process	$N_{\rm jet} \geq 2$ 14 TeV (%)	Run-1 (%)
WW	10	30
VV	10	20
$t\bar{t}$	10	33
$tW/tb/tqb$	10	33
Z+jets	10	20
W+jets	20	30

Scoping scenario	Δ_μ			Significance (σ)		
Signal unc.	Full	1/2	None	Full	1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0

Summary 1: Experimental Challenges & Potential Enhancements

- VBF and VBS signatures will form a key part of the HL-LHC programme, but will face a number of challenges:
  - Rely on the presence of tag jets
    - Largely affected by pileup
    - Jet-related uncertainties are dominant systematics
  - Strong production is a dominant background
  - Low(ish) lepton pT, affected by single lepton trigger, fakes
  - aGCs sensitivity shows up in tails of distributions

Reduced systematics

Boosted boson tagging

Forward tracking

Jet tagging (q/g)

Topological triggers

Forward lepton tagging

Additional pileup rejection

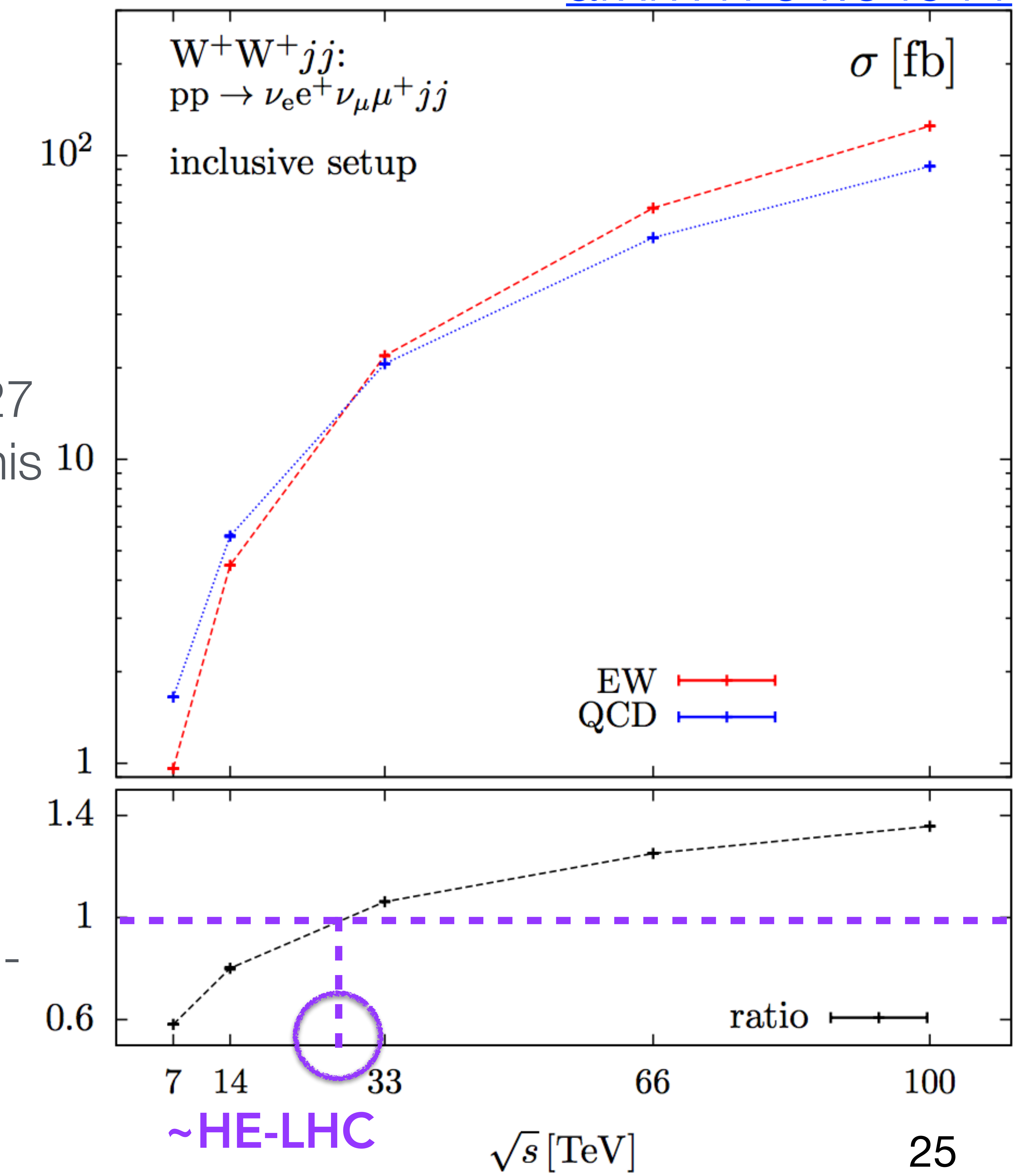
Improved lepton efficiencies

…and more!

Summary 2: VBF/VBS-specific HE-LHC thoughts…

- HE-LHC will allow us to probe new physics at higher scales and set stronger limits due to higher statistics
    - Ratios at different sqrt(s) allow for increased sensitivity to thanks to cancellations of correlated systematics
- For searches it is relatively easy to extrapolate sensitivities from 14 to 27 TeV. For precision SM measurements, however, it is not obvious that this approach is ideal (new diagrams, backgrounds scale differently, etc…)
- Practicalities of the studies:
    - Pileup of ~800 will play a major role in the backgrounds, as well as tag jet selection - what do we do about pileup modelling?
    - Many backgrounds are data-driven (fakes, charge flip, conversions - how can we do this in a realistic way?

arxiv:1704.04911

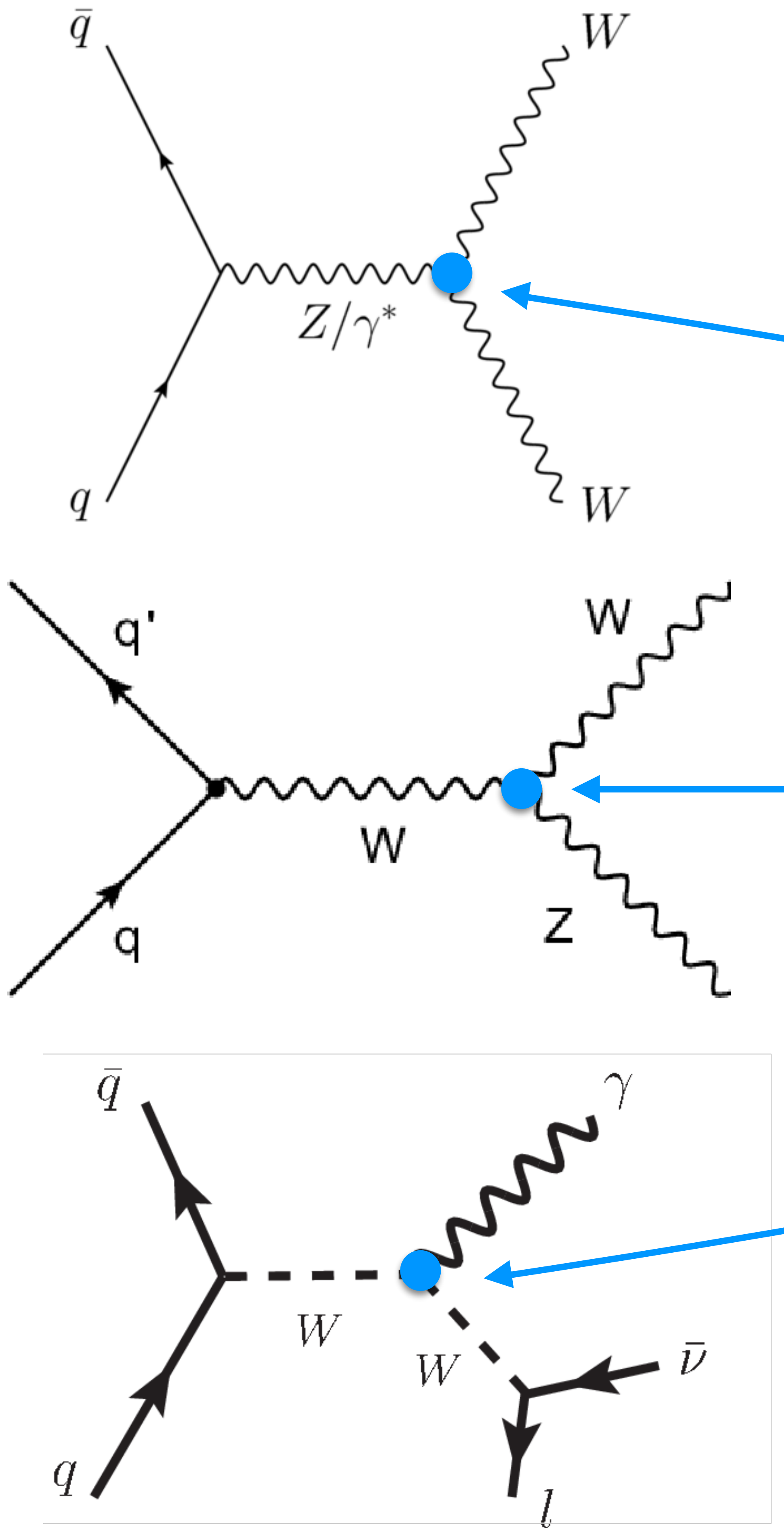


backup

Charged TGCs and $\mathscr{L}_{WWV}$

- Can write a parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or γ)

$$
\begin{aligned}
\mathcal{L}_{WWV} &= i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) \\
&+ \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) \\
&+ g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial} W_\nu \right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\
&+ \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},
\end{aligned}
$$



only Wγ and WWZ allowed in SM

gives final states WW, WZ, Wγ

Charged TGCs and $\mathscr{L}_{WWV}$

- Can write a parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or γ)

Terms violating C and/or P

$$\mathcal{L}_{WWV} = ig_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu \right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},$$

Charged TGCs and $\mathscr{L}_{WWV}$

- Can write a parameterisation of possible charged TGCs that is Lorentz invariant and obeys charge conservation: (V = Z or ɣ)

$$\mathcal{L}_{WWV} = ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + \frac{i\lambda_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) + g_5^V \epsilon^{\mu\nu\rho\sigma}\left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right)V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu \tilde{V}^{\nu\lambda} + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu},$$

Terms violating C and/or P

$g_1^\gamma = 1$ from EM gauge invariance

- $g_1^Z - 1$
- $\kappa_\gamma - 1$
- $\kappa_Z - 1$
- λ_γ
- λ_Z

remaining independent parameters, all = 0 in SM

ATLAS ssWW Event Selection

Selection requirement	Selection value
Number of leptons	2 leptons with $p_{\mathrm{T}} > 25$ GeV
Dilepton separation and charge	$\Delta R_{\ell,\ell} \geq 0.3$, $q_{\ell_1} \cdot q_{\ell_2} > 0$
Dilepton mass	$m_{\ell\ell} > 20$ GeV
Z_{ee} veto	$\lvert m_{ee} - m_Z \rvert > 10$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
Jet selection and separation	at least two jets with $\Delta R_{\ell,j} > 0.3$
Dijet rapidity separation	$\Delta \eta_{j,j} > 2.4$
Number of additional preselected leptons	0
Dijet mass	$m_{jj} > 500$ GeV
Lepton centrality	$\zeta > 0$

CMS ssWW Event Selection

- two well identified and isolated tight same-charge leptons, with p_T larger than 20 GeV, have to be found in the event
- no additional loose leptons found in the event
- the two leptons invariant mass ($m_{\ell\ell}$) has to be larger than 40 GeV
- exclude events with $m_{\ell\ell}$ within 20 GeV of the Z boson mass
- the pseudorapidity difference between the two leptons ($\Delta\eta_{\ell\ell}$) has to be smaller than 2 units
- at least 40 GeV of missing energy should be present in the event
- at least two jets with p_{T} larger than 30 GeV have to be present and the first two highest p_{T} ones are identified as the "tag" jets from the VBS process
- the pseudorapidity difference between the two tag jets ($\Delta\eta_{jj}$) has to be larger than 2.5
- the invariant mass of the the two tag jets (m_{jj}) has to be larger than 850 GeV
- no jet with $p_{\mathrm{T}} > 30$ GeV should be identified as a b quark jet by the CSV algorithm
- events are discarded if a soft muon with $p_T > 5$ GeV is found inside a jet with $p_T > 20$ GeV
- the two leading leptons are required to be within the tag jets along the η direction
- the distance between the di-jet and the di-lepton systems $\Delta R(ll, jj)$ has to be smaller than 6 units
- the scalar sum of the transverse momentum of all the tracks originating from the primary vertex not being associated to the leptons and located between the two tag jets in pseudorapidity, with p_{T} above 0.5 GeV, has to be lower than 125 GeV for Phase I scenario and 150 GeV for the Phase 2 scenario, the difference of selection coming from the extended tracker pseudorapidity coverage of the Phase II detector.

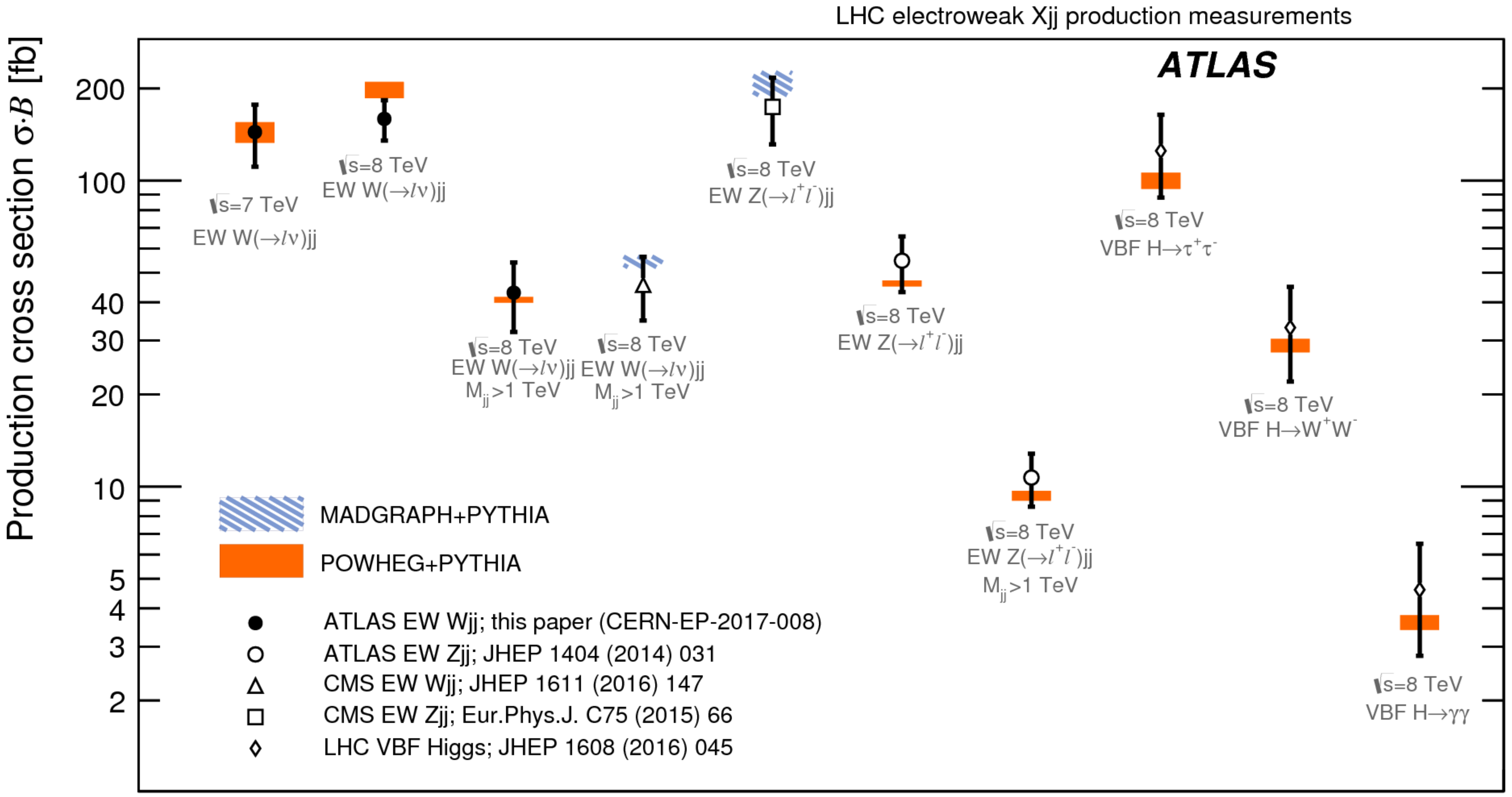
CMS ssWW limits on aQGCs

	Phase I (TeV^{-4})	Phase II (TeV^{-4})	Phase I aged (TeV^{-4})	Run-I results (TeV^{-4})
S_0	2.47	2.49	2.85	43 [12]
S_1	8.19	8.25	9.45	131 [12]
M_0	1.88	1.76	2.03	4.6 [38]
M_1	2.54	2.38	2.72	1.7 [38]
M_6	3.78	3.54	4.05	69 [12]
M_7	3.42	3.24	3.75	73 [12]
T_0	0.17	0.17	0.19	3.4 [39]
T_1	0.078	0.070	0.080	2.4 [12]
T_2	0.25	0.23	0.25	7.1 [12]

VBF Wjj at 7 and 8 TeV

[STDM-2014-11]

Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV Lepton $\lvert\eta\rvert < 2.5$ $E_T^{miss} > 20$ GeV $m_T > 40$ GeV $p_T^{j_1} > 80$ GeV $p_T^{j_2} > 60$ GeV Jet $\lvert y\rvert < 4.4$ $M_{jj} > 500$ GeV $\Delta y(j_1, j_2) > 2$ $\Delta R(j, \ell) > 0.3$
Fiducial and differential measurements	
Signal region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Forward-lepton control region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} = 0$
Central-jet validation region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} \geq 1$
Differential measurements only	
Inclusive regions	$M_{jj} > 0.5$ TeV, 1 TeV, 1.5 TeV, or 2 TeV
Forward-lepton/central-jet region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} \geq 1$
High-mass signal region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Anomalous coupling measurements only	
High-q^2 region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0, p_T^{j_1} > 600$ GeV



Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$\frac{c_W}{\Lambda^2}$	$[-39, 37]$	$[-33, 30]$
$\frac{c_B}{\Lambda^2}$	$[-200, 190]$	$[-170, 160]$
$\frac{c_{WWW}}{\Lambda^2}$	$[-16, 13]$	$[-13, 9]$
$\frac{c_{\tilde{W}}}{\Lambda^2}$	$[-720, 720]$	$[-580, 580]$
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	$[-14, 14]$	$[-11, 11]$

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