TeV Physics Workshop, GuangZhou, China 2014.05.16

Multi-boson production and anomalous quartic gauge boson coupling at the LHC

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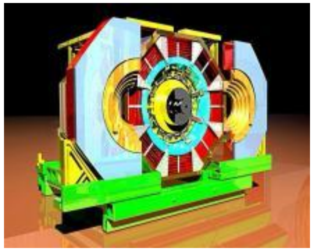
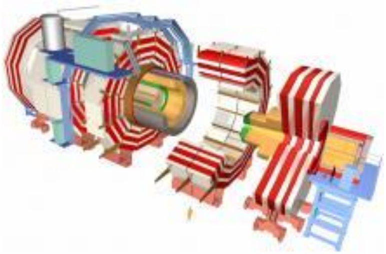
http://hepfarm02.phy.pku.edu.cn/drupal/





hermes

Belle II

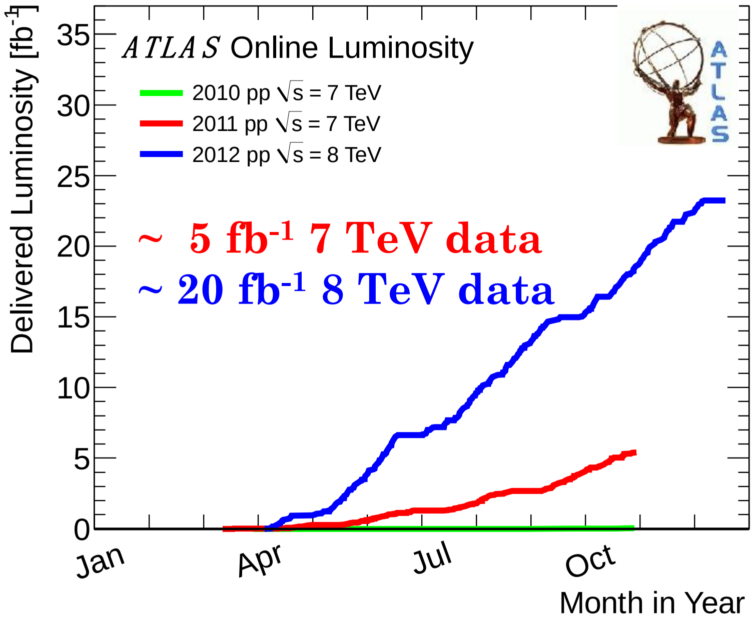
Daya Bay
θ_{13}

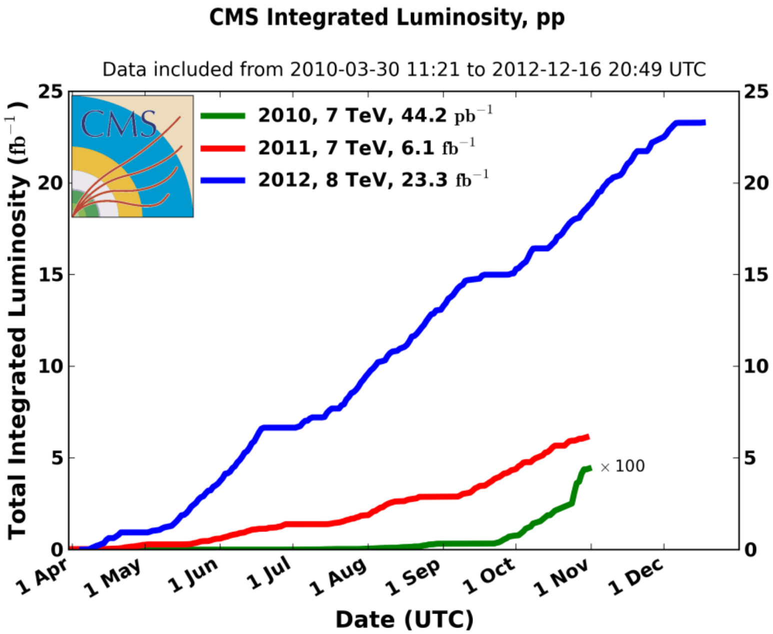
Outline

- LHC Status and Future Plan
- Anomalous Quartic Gauge Couplings
- ATLAS and CMS Results
- MC Studies
- Summary

- LHC Status and Future Plan

LHC Run - 1





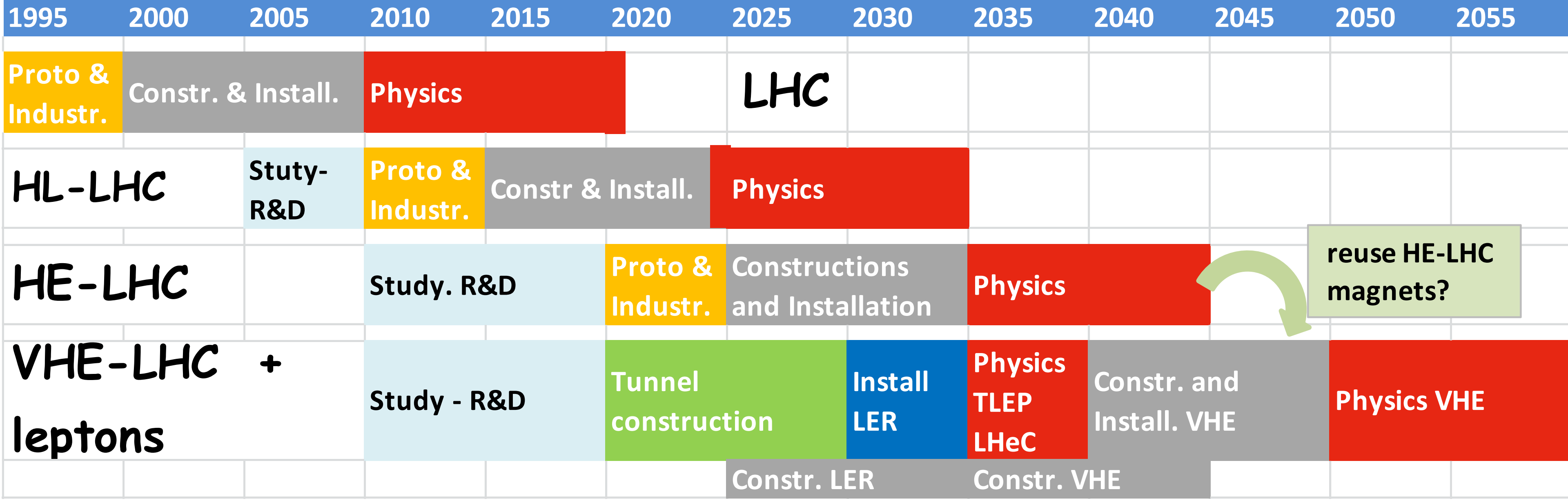
- ☐ **Successful LHC run in 2010-2012**
- ☐ **Similar for ATLAS & CMS:**
  ~ 5 fb^{-1} 7 TeV data
  ~ 20 fb^{-1} 8 TeV data
- ☐ **Peak luminosity at 2012:**
  - **7.7 * 10 33 cm-2s-1 (~30 pileup events)**
  - **<μ> ~ 21 @ 8TeV**
- ☐ **Data quality (2012):**
  - **93.7% ready for physics**

LHC schedule beyond LS1

🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
⬛ Technical stop

HL-LHC
3’ 000 fb^{-1}

(Extended) Year End Technical Stop: (E)YETS



1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Proto & Industr.	Constr. & Install.		Physics			LHC						
HL-LHC		Stuty-R&D	Proto & Industr.	Constr & Install.	Physics							
HE-LHC			Study. R&D		Proto & Industr.	Constructions and Installation		Physics			reuse HE-LHC magnets?	
VHE-LHC + leptons			Study - R&D		Tunnel construction		Install LER	Physics TLEP LHeC	Constr. and Install. VHE		Physics VHE	
						Constr. LER		Constr. VHE				

HL-LHC (~2022-2030)

$E_{CoM}=14$ TeV, $\hat{\mathcal{L}}\sim 5\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

with luminosity leveling

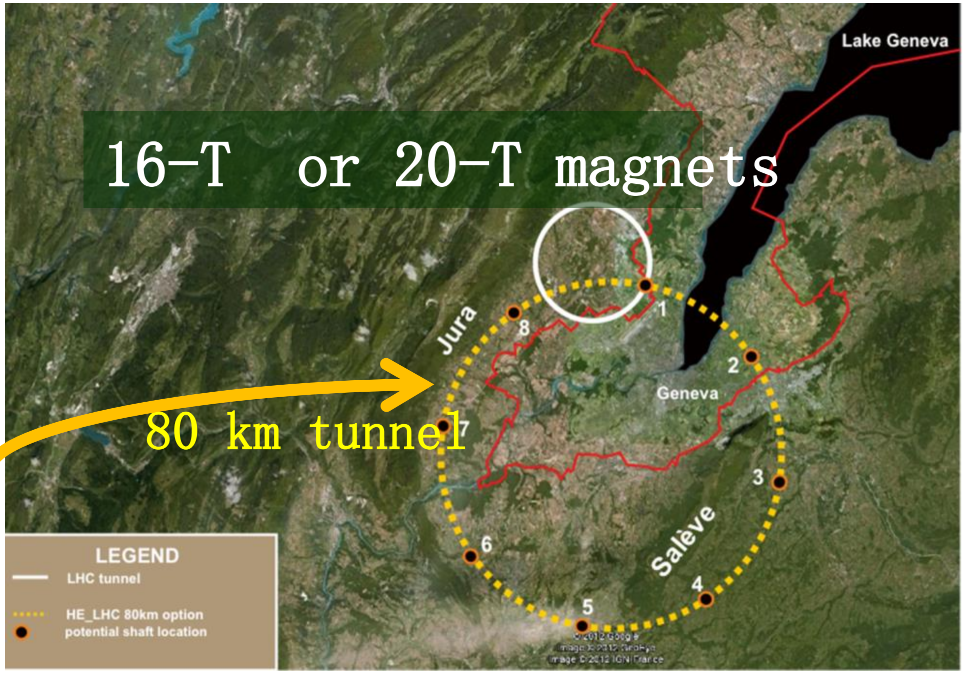
HE-LHC: in LHC tunnel (2035-)

$E_{CoM}=33$ TeV, $\hat{\mathcal{L}} = 5\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

VHE-LHC/FCC: new 80 km tunnel

$E_{CoM}=84\text{–}104$ TeV, $\hat{\mathcal{L}} = 5\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

Frank Zimmermann



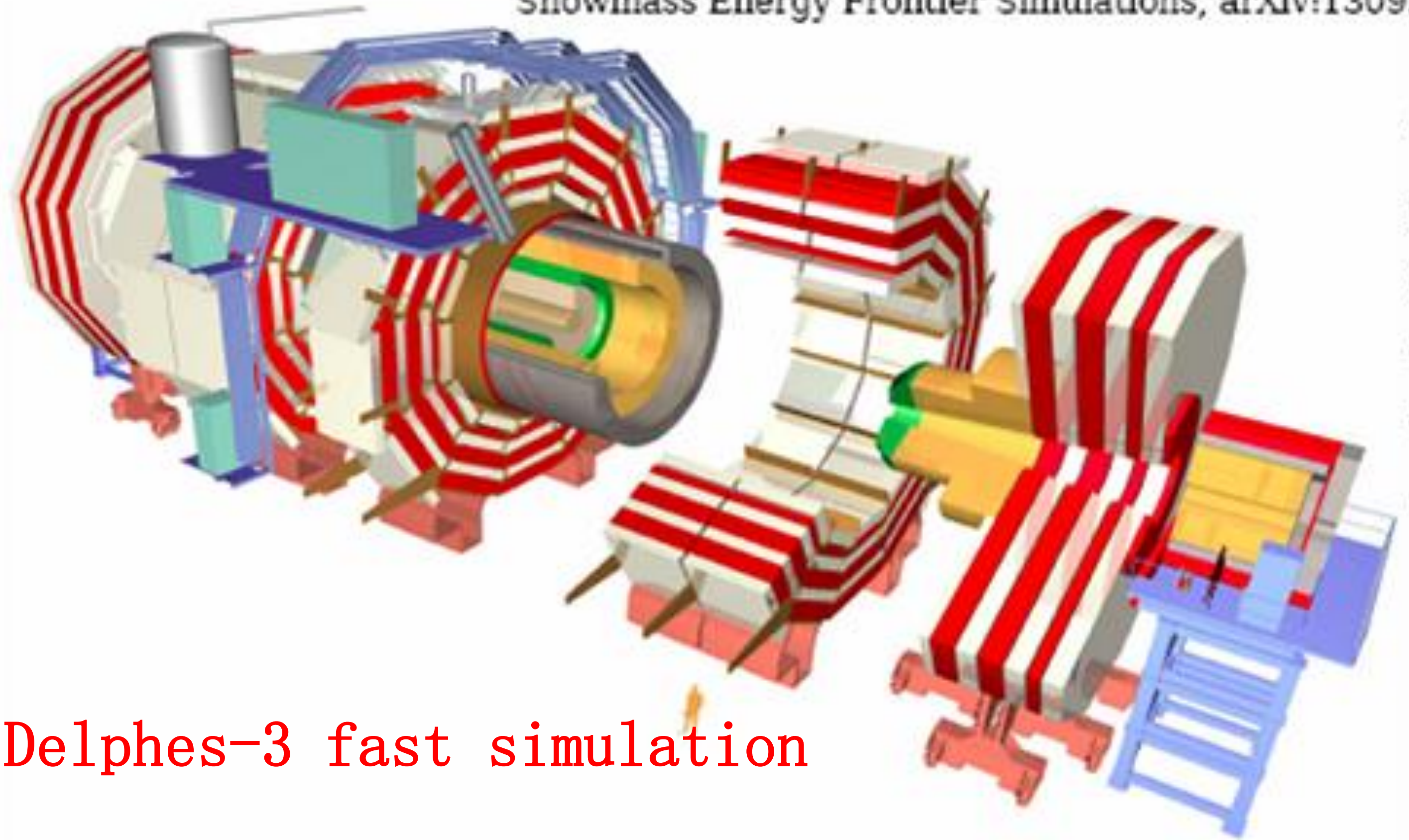
Snowmass Studies

For long range physics planning at Snowmass, we wanted to make a physics case

- with high luminosity running, higher energy, etc.

It was decided to use parameterized detector, called Snowmass Combined LHC detector

Snowmass Energy Frontier Simulations, arXiv:1309.1057, Sept. 2013



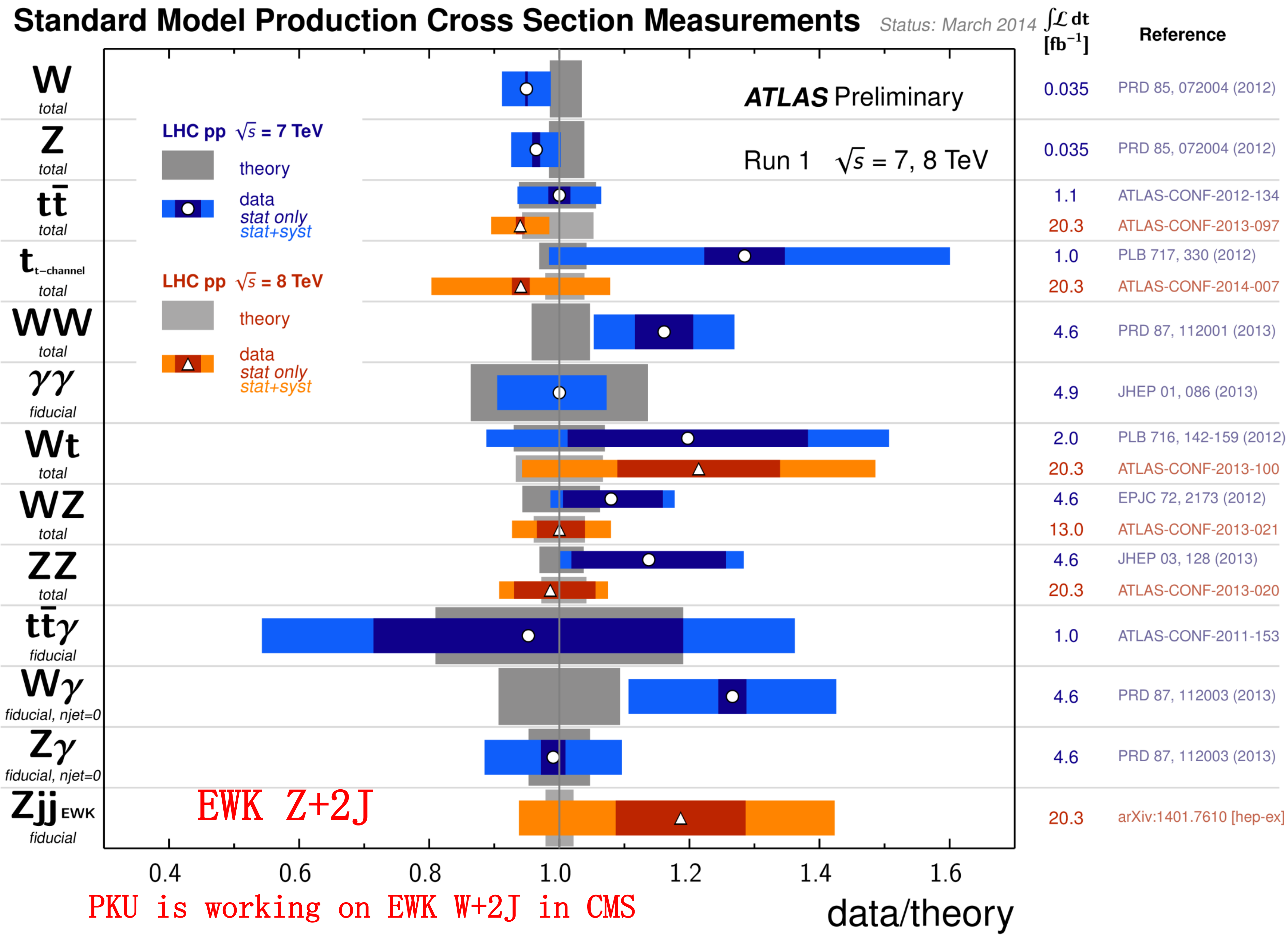
"Components" from the ATLAS and CMS detectors:

- CMS tracker
- ATLAS Calorimeter
- CMS B-Field, etc

Delphes-3 fast simulation

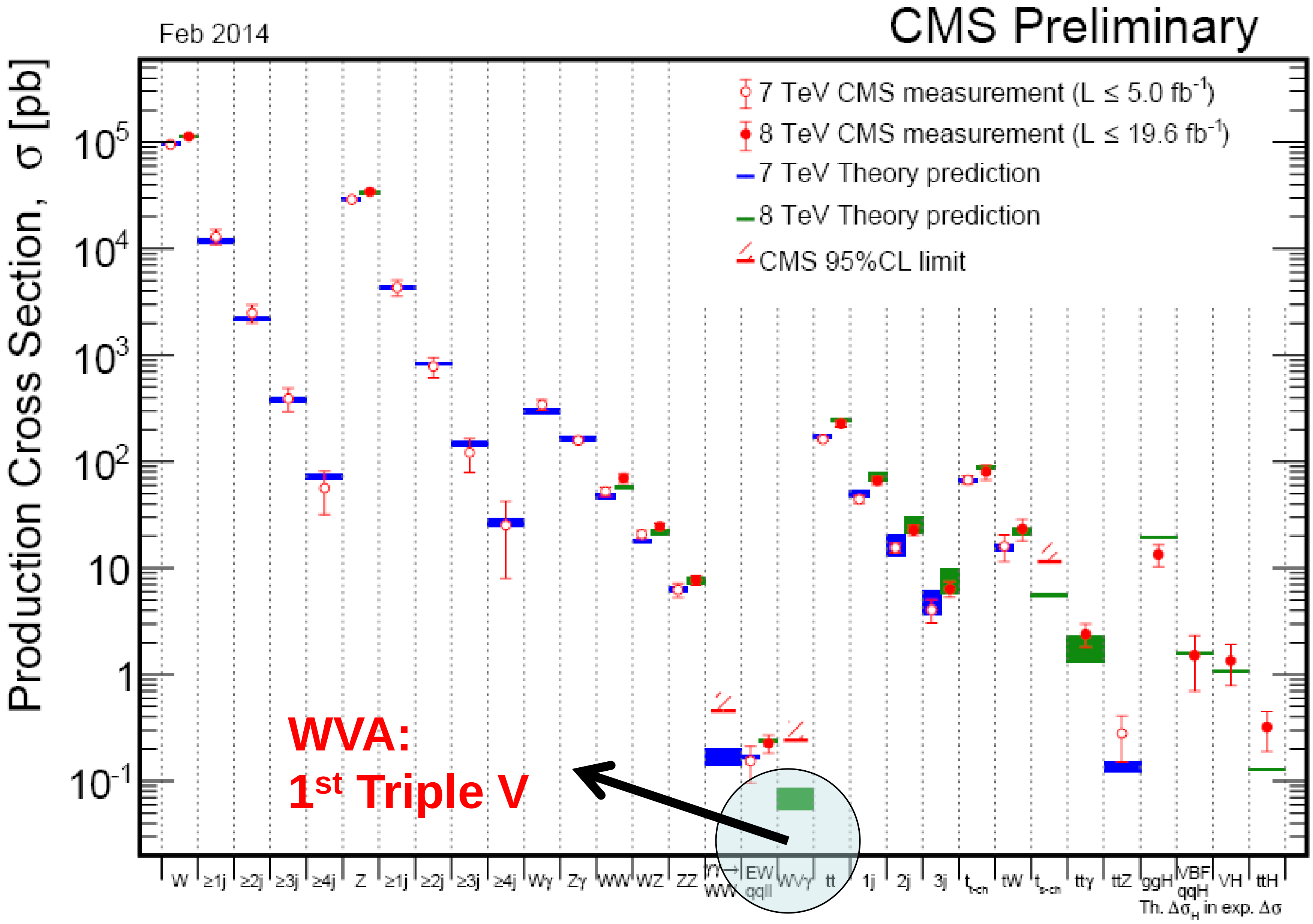
Chinese CEPC 100TeV R&D in collaboration with snowmass/FCC group:
Qi-Shu Yan, Manqi Ruan, Bin Zhang, Qiang Li + M. Narain, S. Padhi, TaoHan+…..

- Anomalous Quartic Gauge Couplings



EWK Z+2J

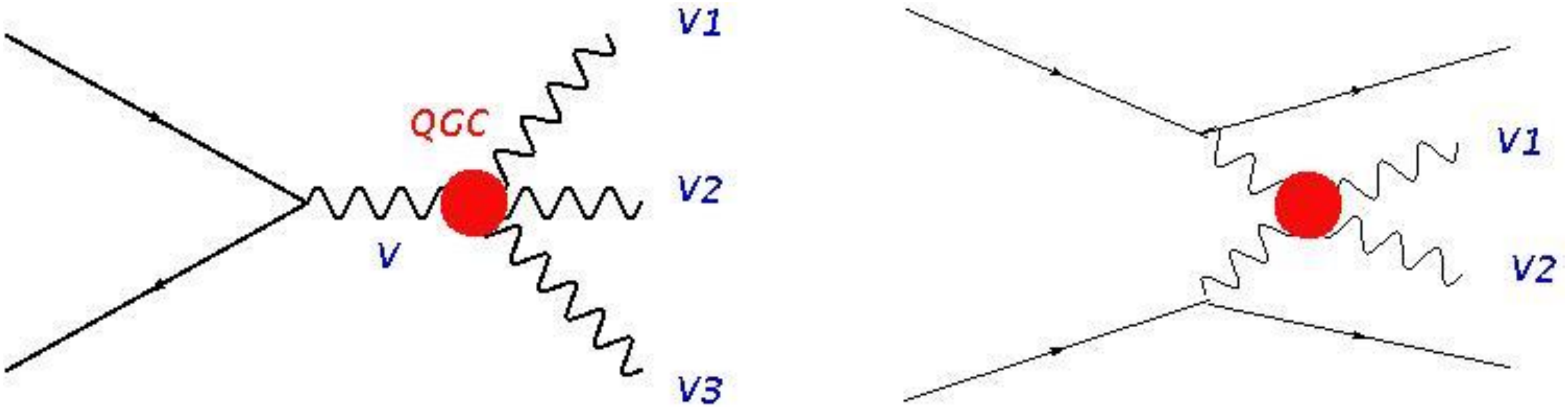
PKU is working on EWK W+2J in CMS



WVA: 1st Triple V

Daneng Yang (PKU) gave the approval talk

Physics Motivations

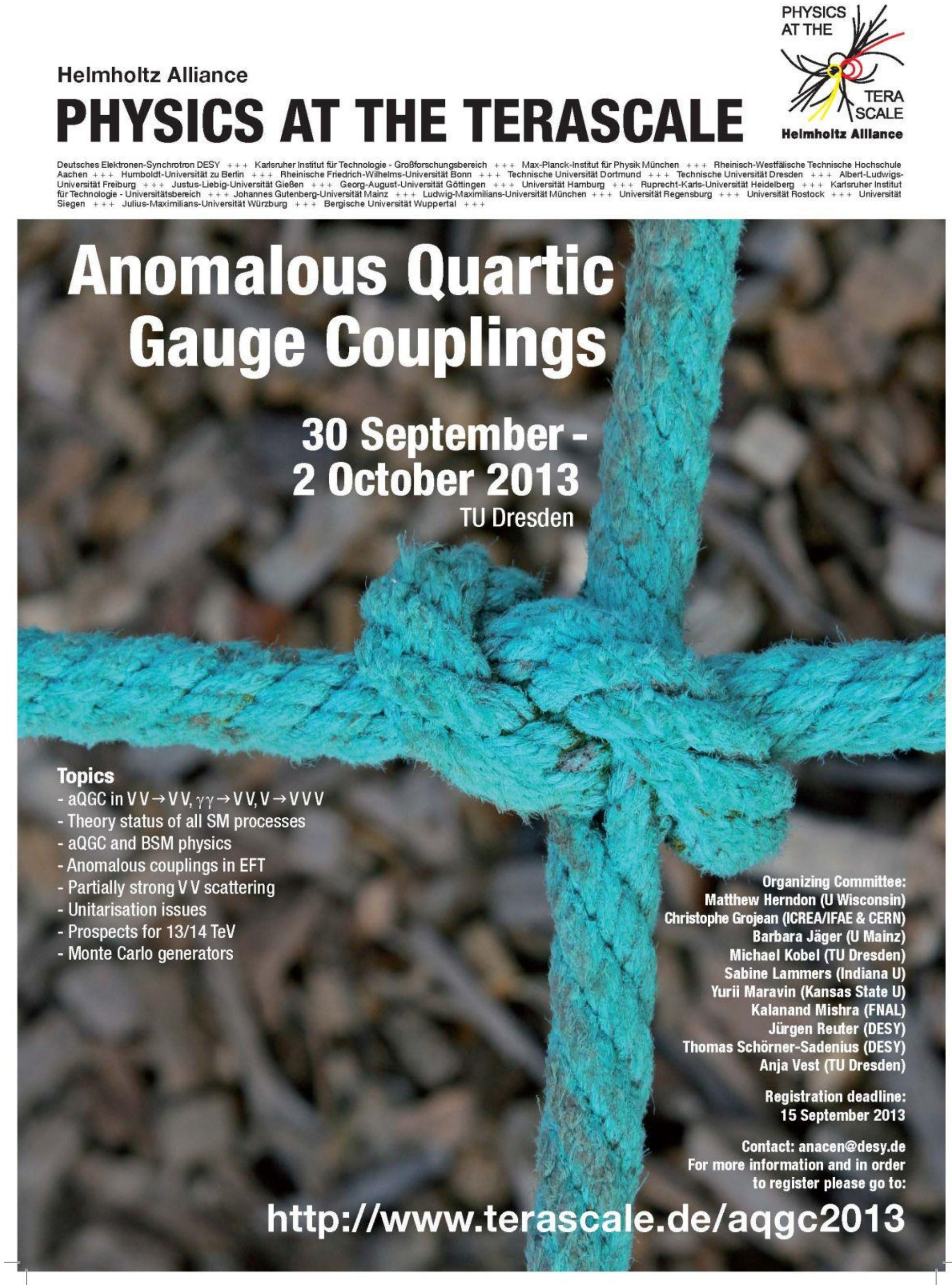


~O(1-10)fb

- *Rare* processes, Crucial test of the SM:
  e.g. on the non-Abelian gauge symmetry part of the SM

- Important backgrounds to Higgs and new physics searches

- Sensitive to anomalous Quartic Gauge Couplings
  Indirect probe on new physics
  Much less studied compared with aTGC



Helmholtz Alliance

PHYSICS AT THE TERASCALE

Deutsches Elektronen-Synchrotron DESY +++ Karlsruher Institut für Technologie - Großforschungsbereich +++ Max-Planck-Institut für Physik München +++ Rheinisch-Westfälische Technische Hochschule Aachen +++ Humboldt-Universität zu Berlin +++ Rheinische Friedrich-Wilhelms-Universität Bonn +++ Technische Universität Dortmund +++ Technische Universität Dresden +++ Albert-Ludwigs-Universität Freiburg +++ Justus-Liebig-Universität Gießen +++ Georg-August-Universität Göttingen +++ Universität Hamburg +++ Ruprecht-Karls-Universität Heidelberg +++ Karlsruher Institut für Technologie - Universitätsbereich +++ Johannes Gutenberg-Universität Mainz +++ Ludwig-Maximilians-Universität München +++ Universität Regensburg +++ Universität Rostock +++ Universität Siegen +++ Julius-Maximilians-Universität Würzburg +++ Bergische Universität Wuppertal +++

Anomalous Quartic Gauge Couplings

30 September -
2 October 2013
TU Dresden

Topics
- aQGC in $VV \to VV$, $\gamma\gamma \to VV$, $V \to VVV$
- Theory status of all SM processes
- aQGC and BSM physics
- Anomalous couplings in EFT
- Partially strong VV scattering
- Unitarisation issues
- Prospects for 13/14 TeV
- Monte Carlo generators

Organizing Committee:
Matthew Herndon (U Wisconsin)
Christophe Grojean (ICREA/IFAE & CERN)
Barbara Jäger (U Mainz)
Michael Kobel (TU Dresden)
Sabine Lammers (Indiana U)
Yurii Maravin (Kansas State U)
Kalanand Mishra (FNAL)
Jürgen Reuter (DESY)
Thomas Schörner-Sadenius (DESY)
Anja Vest (TU Dresden)

Registration deadline:
15 September 2013

Contact: anacen@desy.de
For more information and in order
to register please go to:

http://www.terascale.de/aqgc2013

The aims are to bring together theorists and experimentalists to discuss theoretical and experimental status of all processes sensitive to aQGC,

models for parametrizing aQGC and (partially) strong VV scattering.

issues of unitarization prescriptions,

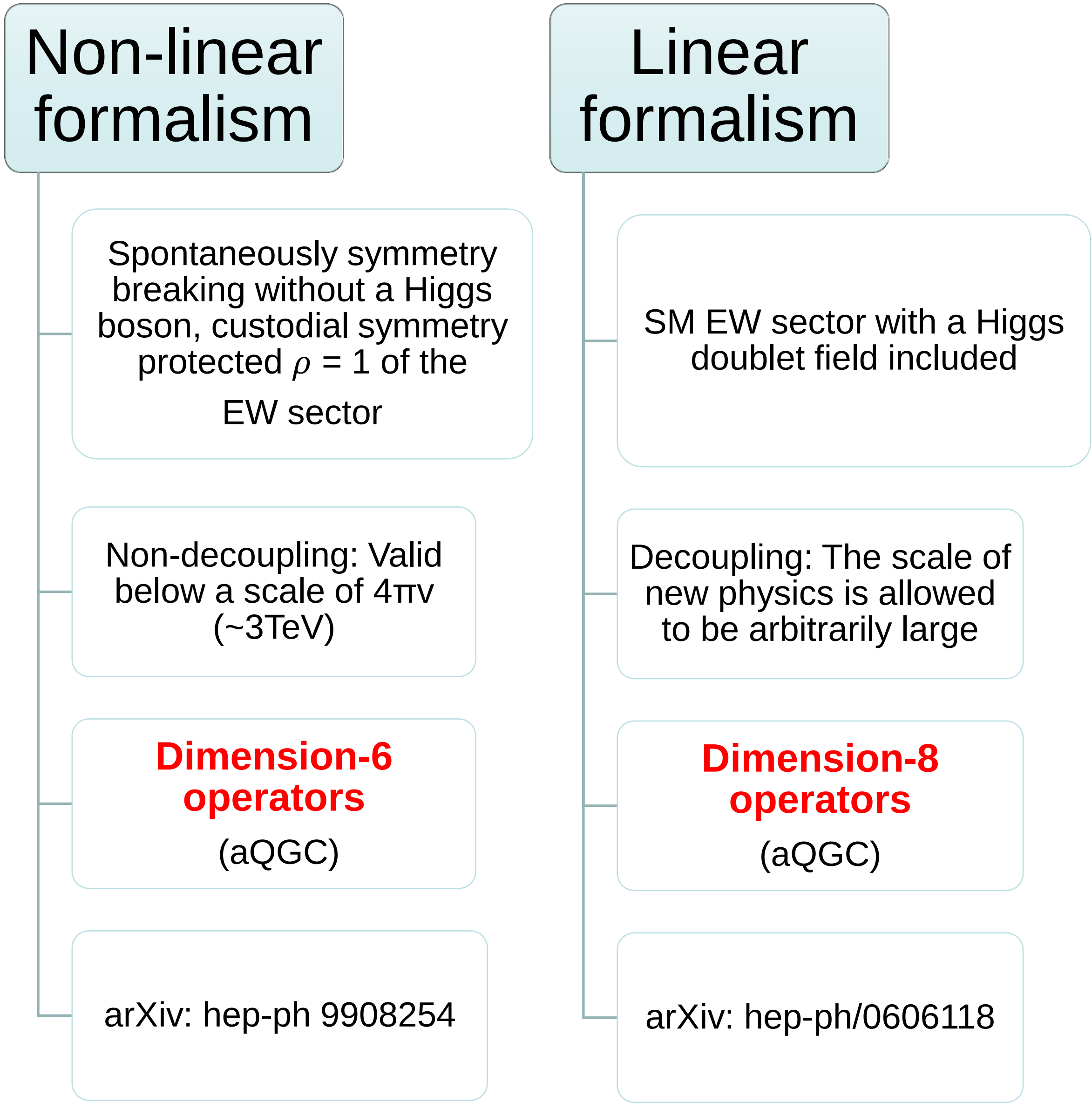
available Monte Carlo Generators and validation procedures,

experimental prospects for the 13-14 TeV runs at LHC,

Wish lists of experimentalists and theorists: WAA, ZAA, WWA,…., EWK WW, WZ, ZZ, WA, ZA….

aQGC

Request SU(2)⊗U(1) gauge symmetry and independently conserved C, P



Non-linear formalism

- Spontaneously symmetry breaking without a Higgs boson, custodial symmetry protected $\rho = 1$ of the EW sector
- Non-decoupling: Valid below a scale of 4πv (~3TeV)
- **Dimension-6 operators** (aQGC)
- arXiv: hep-ph 9908254

Linear formalism

- SM EW sector with a Higgs doublet field included
- Decoupling: The scale of new physics is allowed to be arbitrarily large
- **Dimension-8 operators** (aQGC)
- arXiv: hep-ph/0606118

Dim6-aQGC

$$\mathcal{L}_6 = \underbrace{\frac{k_0^{\gamma\gamma}}{\Lambda^2}\mathcal{W}_0^{\gamma} + \frac{k_c^{\gamma\gamma}}{\Lambda^2}\mathcal{W}_c^{\gamma}}_{\text{WW}\gamma\gamma} + \underbrace{\frac{k_0^{W}}{\Lambda^2}\mathcal{W}_0^{Z} + \frac{k_c^{W}}{\Lambda^2}\mathcal{W}_c^{Z} + \sum_{i=1,2,3}\frac{k_i^{W}}{\Lambda^2}\mathcal{W}_i^{Z}}_{\text{WWZ}\gamma}$$

$$\mathcal{W}_0^{\gamma} = -\frac{e^2g^2}{2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^{-}_{\alpha},$$

$$\mathcal{W}_c^{\gamma} = -\frac{e^2g^2}{4}F_{\mu\nu}F^{\mu\alpha}(W^{+\nu}W^{-}_{\alpha} + W^{-\nu}W^{+}_{\alpha})$$

LEP Parametrization

$$\mathcal{W}_0^{Z} = -e^2g^2F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^{-}_{\alpha}$$

$$\mathcal{W}_c^{Z} = -\frac{e^2g^2}{2}F_{\mu\nu}Z^{\mu\alpha}(W^{+\nu}W^{-}_{\alpha} + W^{-\nu}W^{+}_{\alpha})$$

$$\mathcal{W}_1^{Z} = -\frac{e^2g^2}{2c_ws_w}F^{\mu\nu}(W^{+}_{\mu\nu}W^{-}_{\alpha}Z^{\alpha} + W^{-}_{\mu\nu}W^{+}_{\alpha}Z^{\alpha})$$

$$\mathcal{W}_2^{Z} = -\frac{e^2g^2}{2c_ws_w}F^{\mu\nu}(W^{+}_{\mu\alpha}W^{-\alpha}Z_{\nu} + W^{-}_{\mu\alpha}W^{+\alpha}Z_{\nu})$$

$$\mathcal{W}_3^{Z} = -\frac{e^2g^2}{2c_ws_w}F^{\mu\nu}(W^{+}_{\mu\alpha}W^{-}_{\nu}Z^{\alpha} + W^{-}_{\mu\alpha}W^{+}_{\nu}Z^{\alpha})$$

Dim8-aQGC Relatively new

http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling#no1

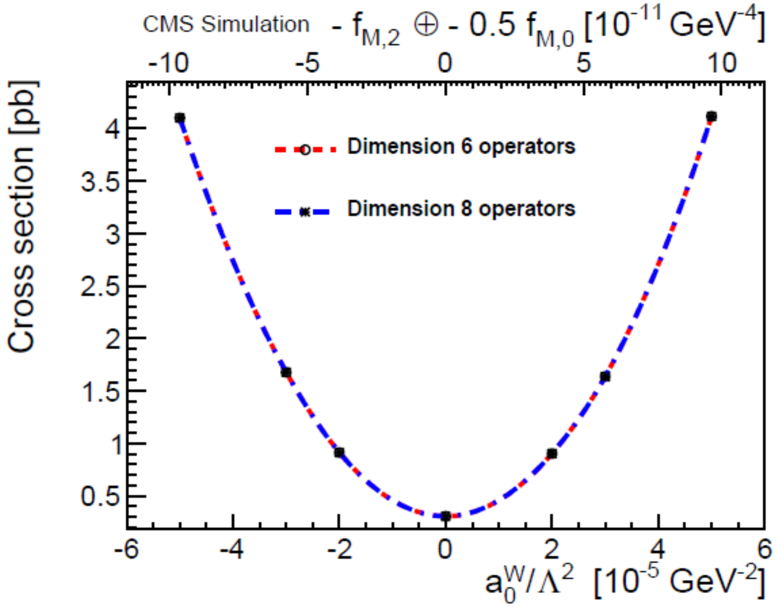
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \qquad \mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

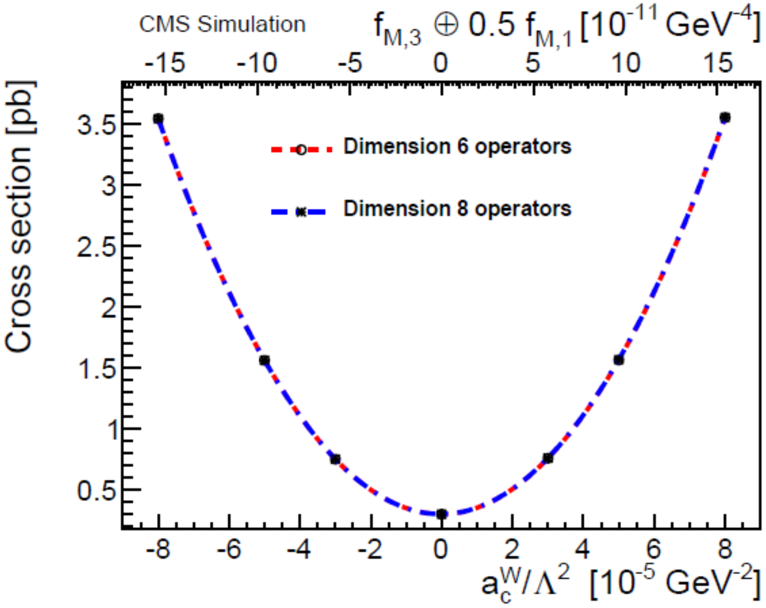
$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

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

Dim6 ↔ Dim8





MG/ME
FeynRules

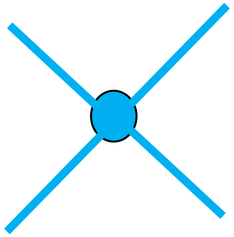
$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda'^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda'^4},$$

$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda'^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda'^4}.$$

CMS aQGC Parameterization

Eg.

$$\mathcal{L}_{aQGC} = \frac{a_0^W}{4g^2}\mathcal{W}_0^\gamma + \frac{a_C^W}{4g^2}\mathcal{W}_c^\gamma + \sum_i \kappa_i^W \mathcal{W}_i^Z + \mathcal{L}_{T,0} + \mathcal{L}_{T,1} + \mathcal{L}_{T,2}.$$



- *CLs and profile likelihood methods used to set the upper limit*

aQGC implemented in aMC@NLO
http://hepfarm02.phy.pku.edu.cn/foswiki/CMS/AQGCs

Unitarity can be checked with VBFNLO
https://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=overview

- ATLAS and CMS Results

Central Exclusive γγ →WW

7 TeV CMS

JHEP 1307 (2013) 116

Events selections:

① Forward scattered protons escaping detection

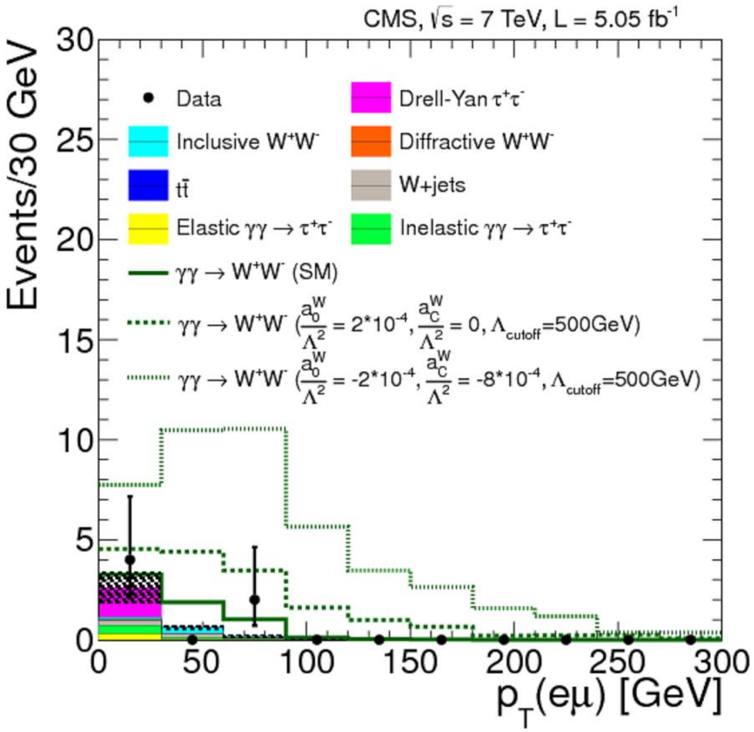
② μe vertex with no additional charged tracks

③ $P_T^{(e\mu)}$>35GeV

Main backgrounds

- ➢ Inclusive WW, W + jets, ττ + jets, DY + jets

Cross checked within μμ and τ τ , and also extra track control regions



signal exp.	*background exp.*	*data*
2.2 ± 0.5	0.84 ± 0.13(stat.)	2

~1σ

$$\sigma\left(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}\right) = 2.2^{+3.3}_{-2.0}\,\text{fb},$$

Central Exclusive γγ →WW

7 TeV CMS

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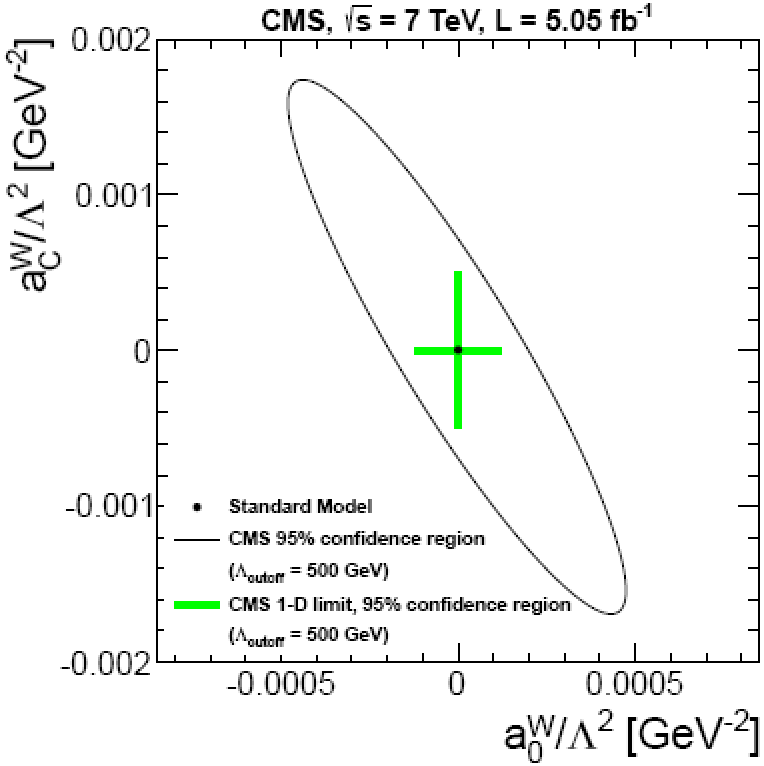
Use $P_T^{(e\mu)}$ tail (>100GeV) to set limit on Dim-6 aQGC

$$-0.00015 < a_0^W/\Lambda^2 < 0.00015\,\text{GeV}^{-2} \quad (a_C^W/\Lambda^2 = 0, \Lambda_\text{cutoff} = 500\,\text{GeV}),$$

$$-0.0005 < a_C^W/\Lambda^2 < 0.0005\,\text{GeV}^{-2} \quad (a_0^W/\Lambda^2 = 0, \Lambda_\text{cutoff} = 500\,\text{GeV}).$$

$$-4.0\times 10^{-6} < a_0^W/\Lambda^2 < 4.0\times 10^{-6}\,\text{GeV}^{-2} \quad (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$

$$-1.5\times 10^{-5} < a_C^W/\Lambda^2 < 1.5\times 10^{-5}\,\text{GeV}^{-2} \quad (a_0^W/\Lambda^2 = 0, \text{no form factor}).$$



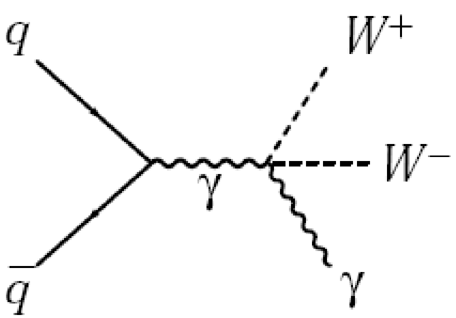
approximately two orders of magnitude more restrictive than limits obtained at the Tevatron without form factors

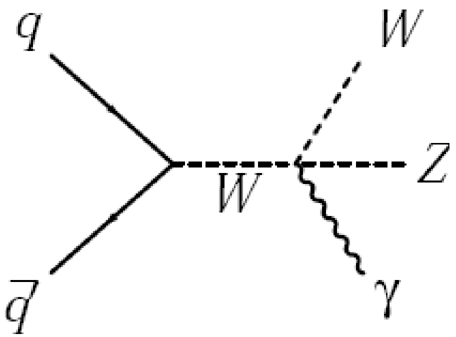
8 TeV CMS

WWγ+WZγ →lνjjγ

CMS-PAS-SMP-13-009; arXiv:1404.4619

Events selections:





① **Exactly one isolated lepton**:

Single Lepton trigger &

(P_T^e>35GeV & $|\eta^e|$<2.5) ||

(P_T^μ>25GeV & $|\eta^\mu|$<2.1)

② **Two PF AK5 Jets with b veto**:

P_T^j >30GeV & $|\eta^j|$<2.4

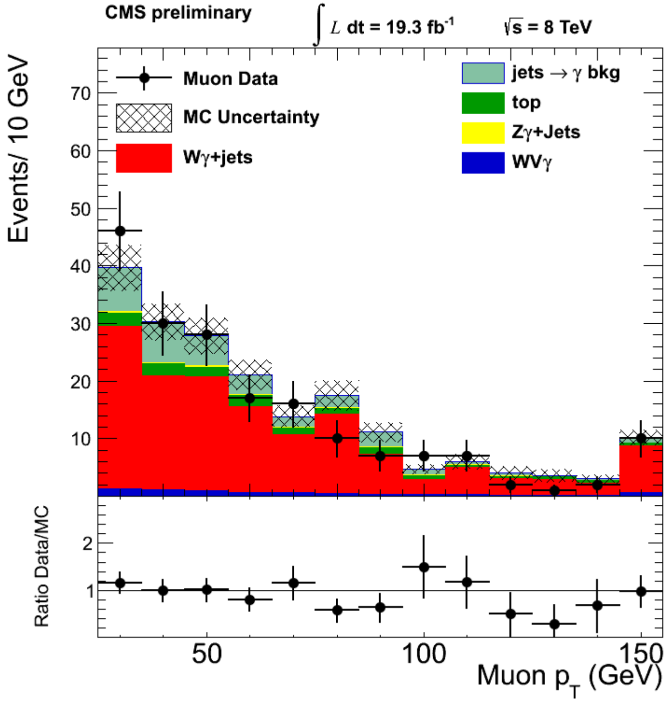
③ **MET>35 GeV**

④ **Δφ(MET,J1)>0.4, $R_{j\gamma}$>0.5, $R_{l\gamma}$>0.5**

⑤ **M_T^W>30 GeV**

⑥ **$|M_{\gamma e}-M_z|$>10GeV**

⑦ **$|\Delta\eta_{jj}|$<1.4, 70GeV<M_{jj}<110GeV**



Main Backgrounds from Data-Driven:

- **Wγ+Jets : sideband**
- **Fake Photon: ratio method**

σ(WV γ)< 241fb, 3.4 times SM (70.3fb)
E_T^γ >15GeV

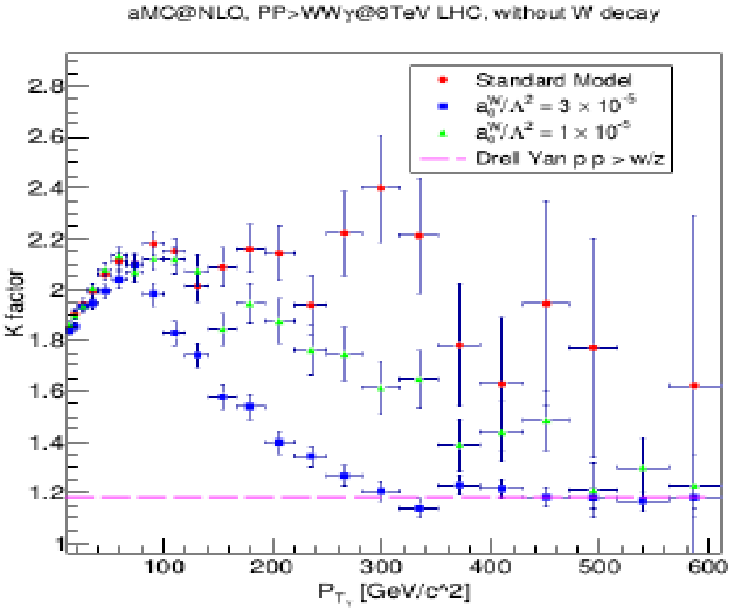
8 TeV CMS

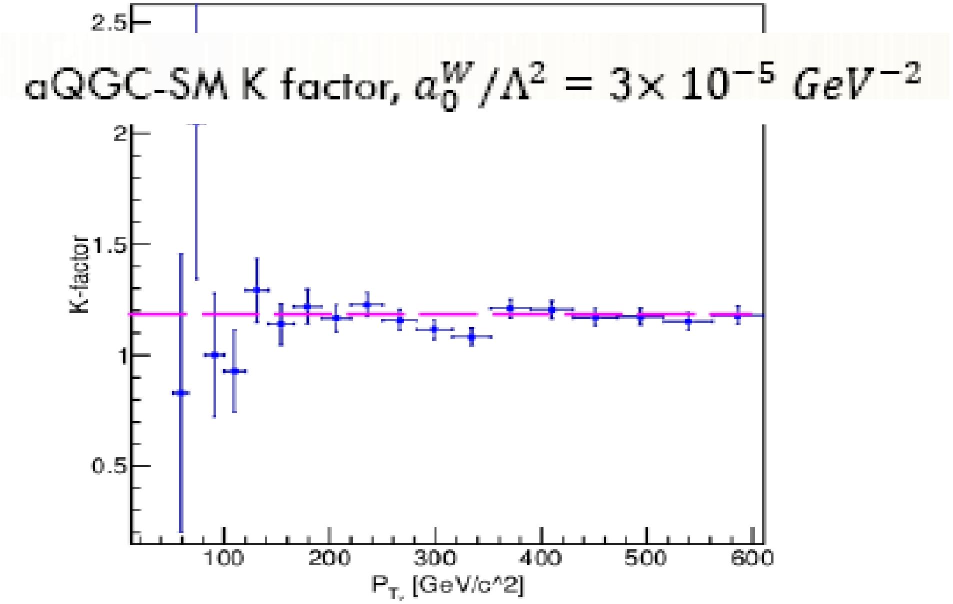
WWγ+WZγ →lνjjγ

CMS-PAS-SMP-13-009; arXiv:1404.4619

E_t^γ used to set limits on aQGC, binned over 30-450GeV. The last bin includes the overflow.

NLO K factors evaluated with aMC@NLO

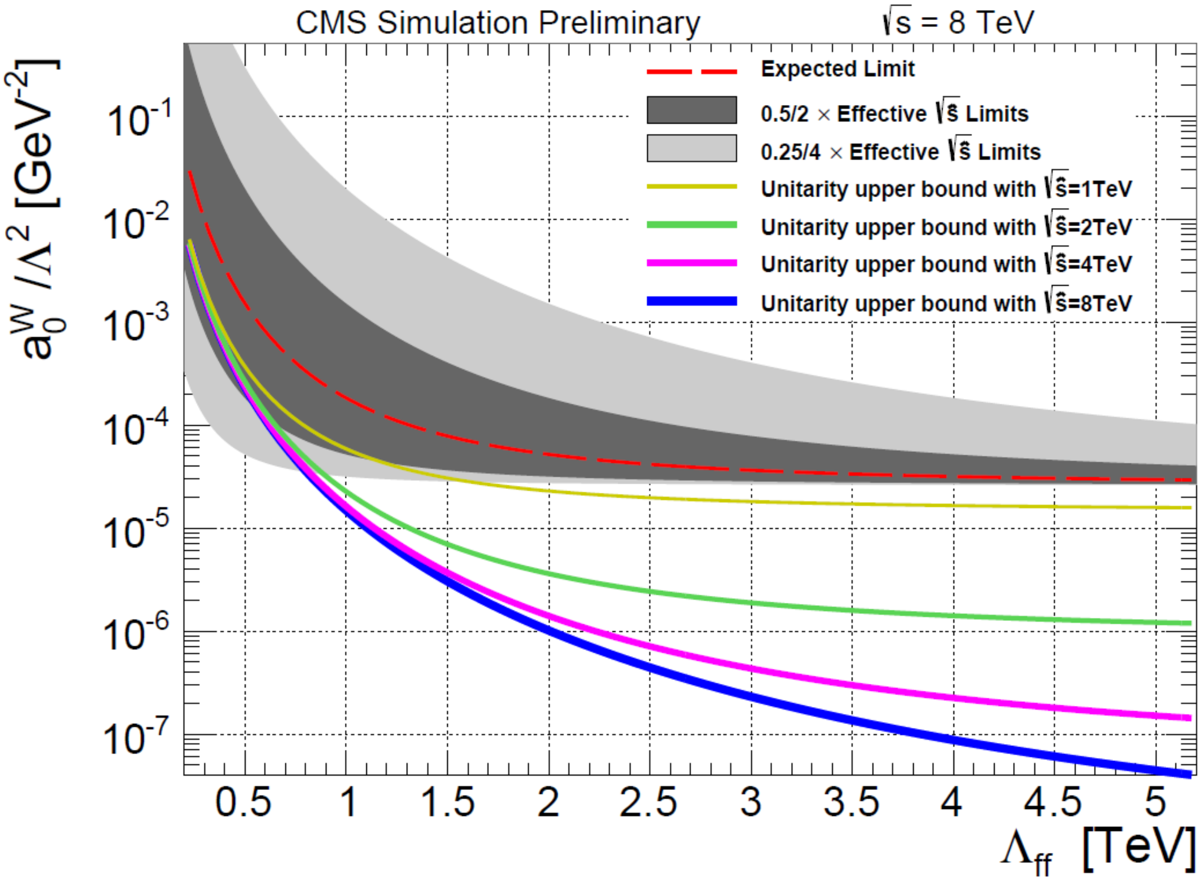



aQGC-SM K factor, $a_0^W/\Lambda^2 = 3\times 10^{-5}\ GeV^{-2}$

Find that the unitarity condition cannot be generally satisfied with a dipole form factor; More complex form factor is possible.

Choice is made to set limits without using a form factor.

Expected Limits with a Form Factor



$$ff = \frac{1}{(1+\hat{s}/\Lambda_{ff}^2)^2}$$

Unitarity bound calculated using Eq. 17 of Ref. arXiv: hep-ph/0009262

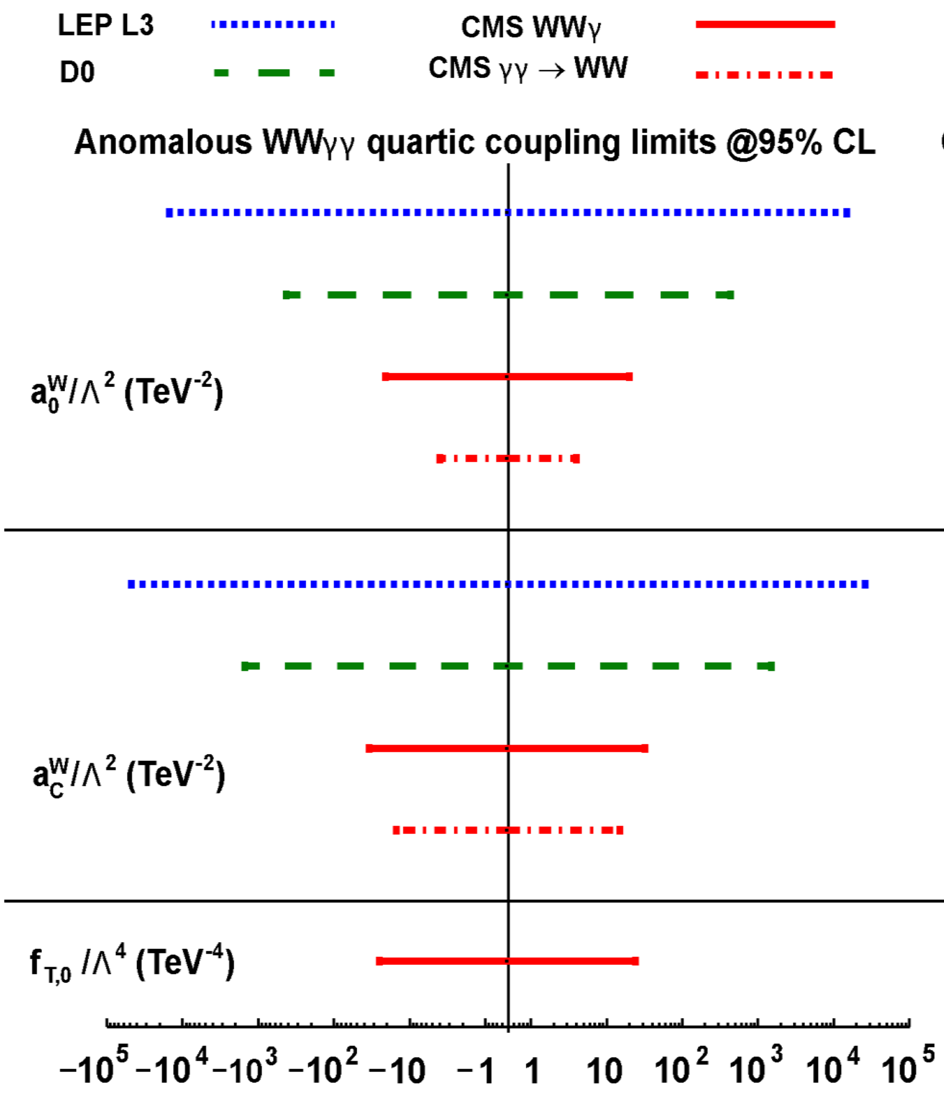
$$\frac{1}{N}\left(\frac{\alpha a s}{16}\right)^2\left(1-\frac{4M_W^2}{s}\right)^{1/2}\left(3-\frac{s}{M_W^2}+\frac{s^2}{4M_W^4}\right)\le 1 \text{ for } V=W$$

where $a = a_0/\Lambda^2$ or a_C/Λ^2 and $N = 1/4\ (4)$ for a_0/Λ^2 (a_C/Λ^2)

8 TeV CMS

WWγ+WZγ →lνjjγ

CMS-PAS-SMP-13-009; arXiv:1404.4619



	Channel	Limits	∫L	√s
a_0^W/Λ^2 (TeV^{-2})	WWγ	[- 15000, 15000]	0.4fb^{-1}	0.20 TeV
	γγ → WW	[- 430, 430]	9.7fb^{-1}	1.96 TeV
	WWγ	[- 21, 20]	19.3fb^{-1}	8.0 TeV
	γγ → WW	[- 4, 4]	5.1fb^{-1}	7.0 TeV
a_C^W/Λ^2 (TeV^{-2})	WWγ	[- 48000, 26000]	0.4fb^{-1}	0.20 TeV
	γγ → WW	[- 1500, 1500]	9.7fb^{-1}	1.96 TeV
	WWγ	[- 34, 32]	19.3fb^{-1}	8.0 TeV
	γγ→ WW	[- 15, 15]	5.1fb^{-1}	7.0 TeV
$f_{T,0}/\Lambda^4$ (TeV^{-4})	WWγ	[- 25, 24]	19.3fb^{-1}	8.0 TeV

$$\begin{aligned}\mathcal{L}_{\mathrm{AQGC}} = &-\frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\nu}F^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)\\ &- e^2g^2\frac{\kappa_0^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2g^2}{2}\frac{\kappa_C^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha)\\ &+ \frac{f_{T,0}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \mathrm{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}].\end{aligned}$$

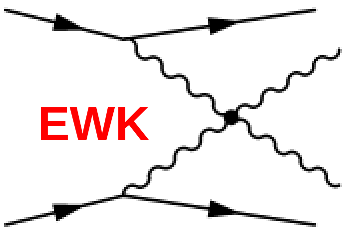
Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20\ \mathrm{TeV}^{-2}$	$-24 < a_0^W/\Lambda^2 < 23\ \mathrm{TeV}^{-2}$
$-34 < a_C^W/\Lambda^2 < 32\ \mathrm{TeV}^{-2}$	$-37 < a_C^W/\Lambda^2 < 34\ \mathrm{TeV}^{-2}$
$-25 < f_{T,0}/\Lambda^4 < 24\ \mathrm{TeV}^{-4}$	$-27 < f_{T,0}/\Lambda^4 < 27\ \mathrm{TeV}^{-4}$
$-12 < \kappa_0^W/\Lambda^2 < 10\ \mathrm{TeV}^{-2}$	$-12 < \kappa_0^W/\Lambda^2 < 12\ \mathrm{TeV}^{-2}$
$-18 < \kappa_C^W/\Lambda^2 < 17\ \mathrm{TeV}^{-2}$	$-19 < \kappa_C^W/\Lambda^2 < 18\ \mathrm{TeV}^{-2}$

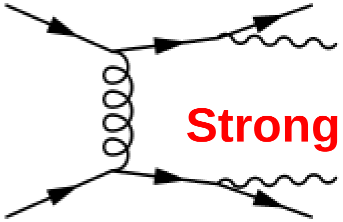
Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 81$	$-89 < f_{M,0}/\Lambda^4 < 93$
$-131 < f_{M,1}/\Lambda^4 < 123$	$-143 < f_{M,1}/\Lambda^4 < 131$
$-39 < f_{M,2}/\Lambda^4 < 40$	$-44 < f_{M,2}/\Lambda^4 < 46$
$-66 < f_{M,3}/\Lambda^4 < 62$	$-71 < f_{M,3}/\Lambda^4 < 66$

8 TeV ATLAS **See more in Prof. Liu's Talk**

Same Sign WW

ATLAS-CONF-2014-013





Mjj>500GeV EWK+Strong

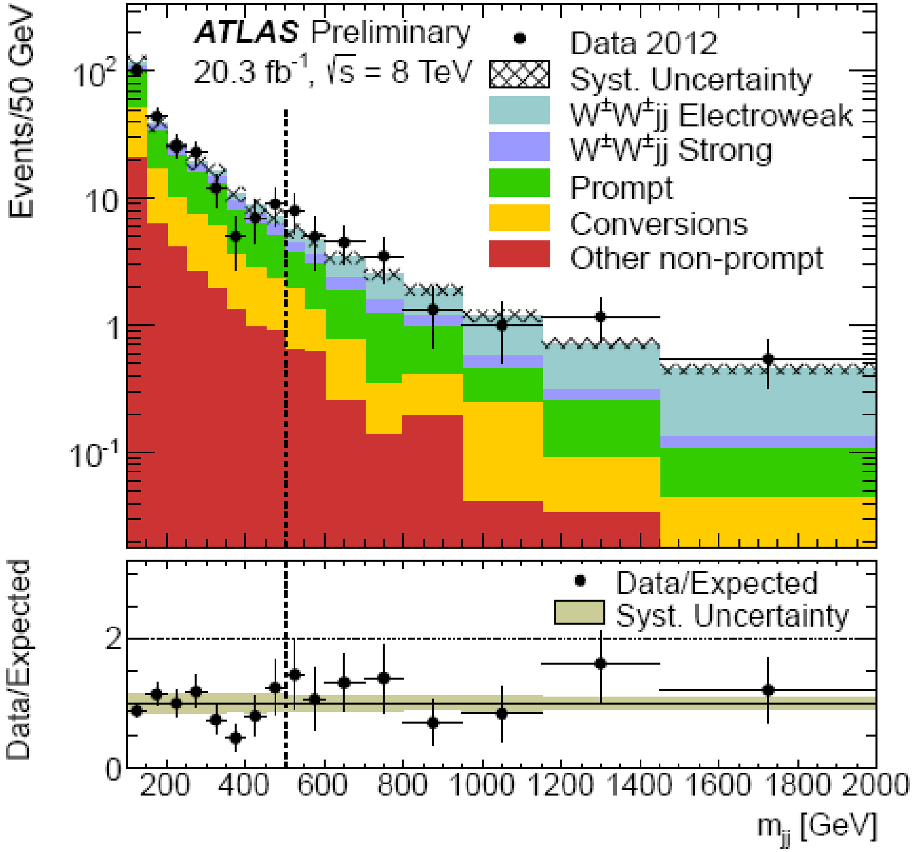
$$\sigma^{\text{fid}} = 2.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})\ \text{fb}.$$

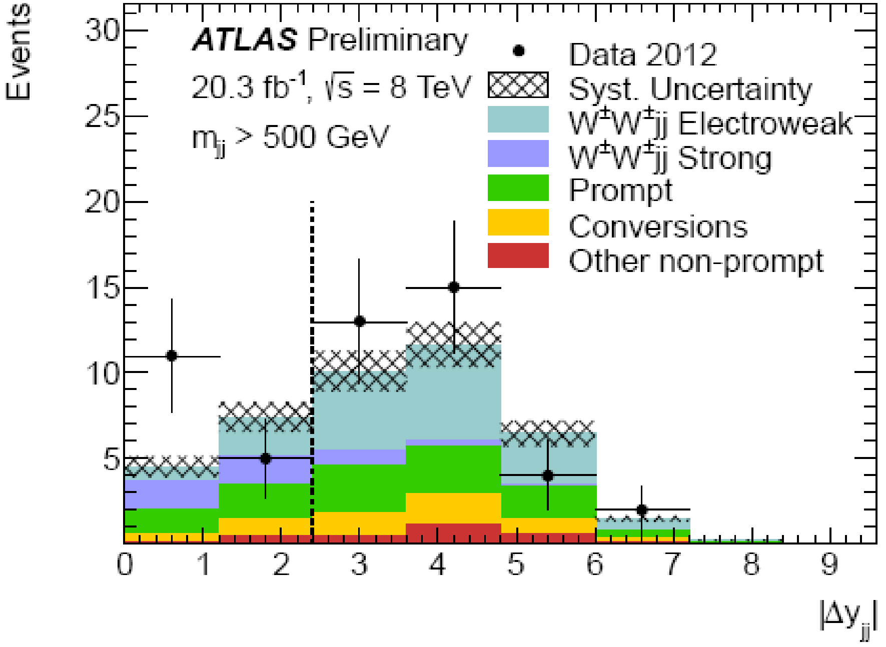
$\boxed{1.52 \pm 0.11\ \text{fb}}$ **4.5σ**

Mjj>500GeV $|\Delta y_{jj}|$>2.4 EWK

$$\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{fb}.$$

$\boxed{0.95 \pm 0.06\ \text{fb}}$ **3.6σ**

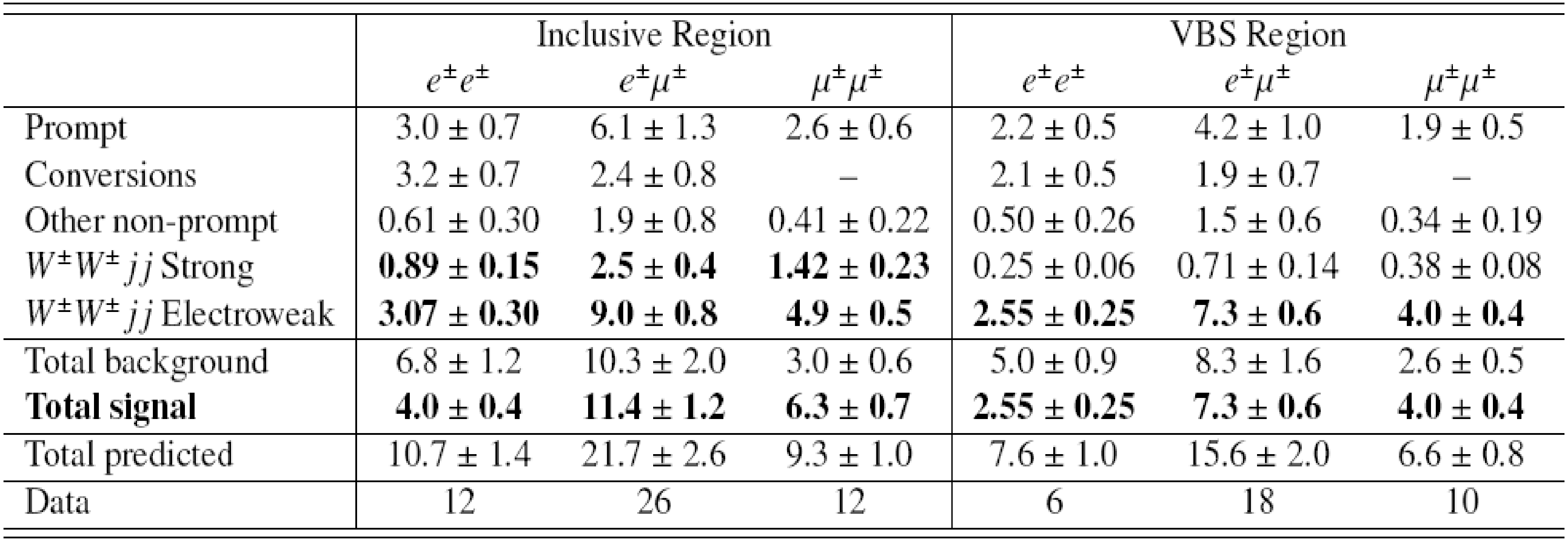




8 TeV ATLAS

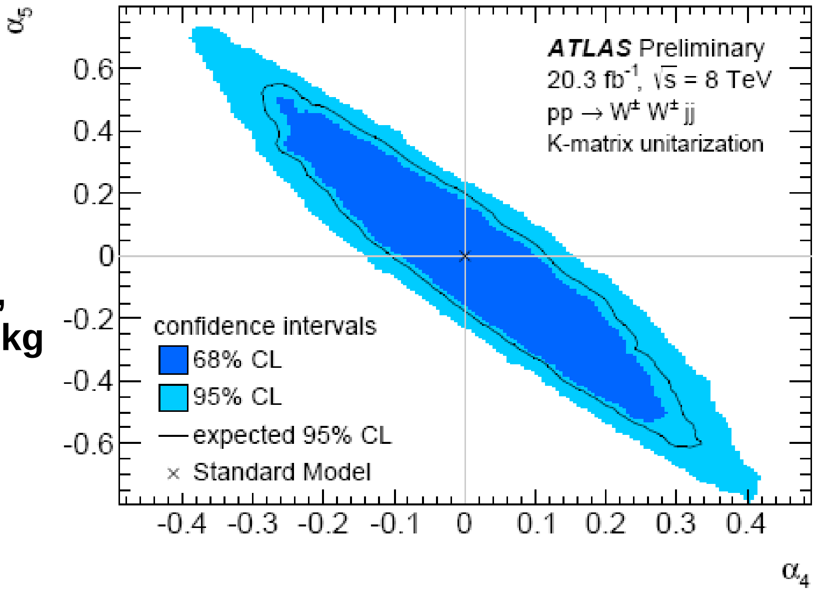
Same Sign WW

ATLAS-CONF-2014-013



	Inclusive Region			VBS Region		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^\pm W^\pm jj$ Strong	**0.89 ± 0.15**	**2.5 ± 0.4**	**1.42 ± 0.23**	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^\pm W^\pm jj$ Electroweak	**3.07 ± 0.30**	**9.0 ± 0.8**	**4.9 ± 0.5**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total signal	**4.0 ± 0.4**	**11.4 ± 1.2**	**6.3 ± 0.7**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

Tri-lepton Control Region
Jet fake lepton
Charge Misidentification
ALPGEN+HERWIG/JIMMY,
SHERPA for Conversion bkg



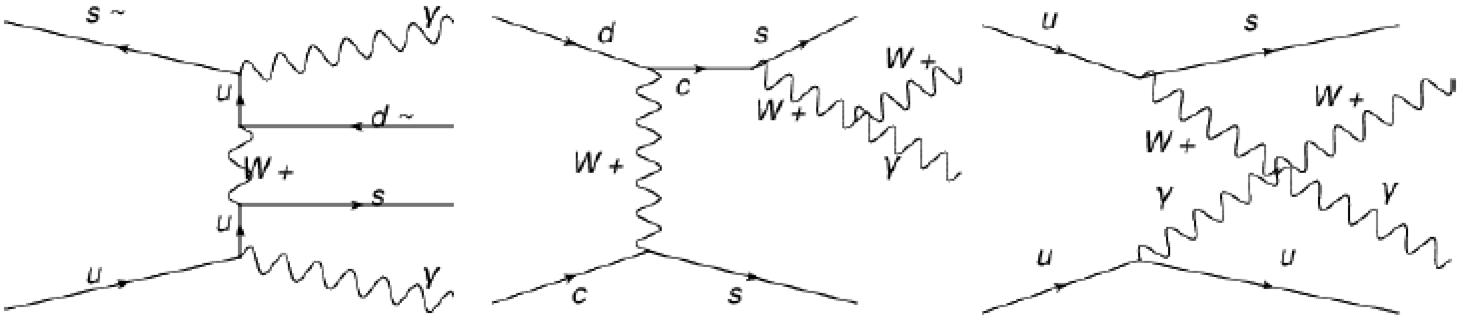
WHIZARD event-generator

K-matrix unitarization method

$$\mathcal{L}_4 = \alpha_4(\mathrm{tr}\,[\mathrm{V}_\mu \mathrm{V}_\nu])^2,$$
$$\mathcal{L}_5 = \alpha_5(\mathrm{tr}\,[\mathrm{V}_\mu \mathrm{V}^\mu])^2.$$

EWK WA,ZA

In collaboration with Prof. DongHee Kim's team at KNU, Korea



Use Mjj, Zeppenfeld Variable $(|\eta_{W\gamma}-(\eta_{j1}+\eta_{j2})/2|)$ and $|\Delta\eta_{jj}|$ to discriminate signal from bkg

Tried also TMVA

Main Bkg: QCD W/ZA+Jets, Jet Fake photon, estimated from Data-Driven

Based on MC estimation, we anticipate to achieve one-order better limits on fM0-4, fT0,1,2,8,9 than CMS WVA 8TeV analysis

|pTj|>40GeV, |etaj|<4.7, |pTa|>20GeV,

|etaa|<2.4, DeltaR jj>0.5, Deltall>0.5,

DeltaR aj>0.5, DeltaEta jj>3.0,

Mjj>600GeV, |etal|<2.4, DeltaR jl>0.5,

Anomalous Quadruple Gauge Coupling

Significance	|pta|>100GeV	|pta|>120GeV
KOG = 0.5e-5	0.7sigma	0.7sigma
KOG = 0.8e-5	1.7sigma	2.0sigma
KOG = 1.0e-5	2.8sigma	2.8sigma
KOG = 1.2e-5	3.7sigma	4.1sigma
KOG = 1.5e-5	5.6sigma	6.5sigma

CMS-PAS-SMP-13-009 arXiv:1404.4619

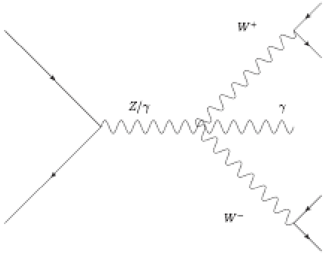
$-12 < \kappa_0^W / \Lambda^2 < 10\,\mathrm{TeV}^{-2}$ $-12 < \kappa_0^W / \Lambda^2 < 12\,\mathrm{TeV}^{-2}$

- MC Studies

WWγ → llνγ

JHEP 1304 (2013) 108
Daneng Yang, Qiang Li, et.al.

Signal: Two OS leptons + One photon + MET $|m_{ll} - M_Z| > 10\text{GeV}$
Bkg: Zγ, TTbar+γ, TWγ, ZZγ, WZγ … .
Tool: MG/ME, Delphes v2 (**PU not included at that time**)



at 14 TeV LHC with an integrated luminosity of 100 (30) fb−1, one can reach a significance of 9 (5) to observe the SM W+W− production

Processes	Cross section [fb]	K-factor [Ref.]	Events		
			$(A^*)\ P_{T\,j}^{Up} = 60$ GeV	$(B^*)\ P_{T\,\gamma}^{cut} = 80$ GeV	$(C^*)\ n_j = 0, 1,\ P_{T\,j} > 25$ GeV
$W^+W^-\gamma$	18.286	2.0 [41]	95.818	58.880	114.84
I(F)SR WW	3114.1	1.5 [42]	35.812	4.6712	54.498
$Z\gamma$	4107.2	1.5 [43]	61.608	47.232	57.501
$ZZ\gamma$	45.818	1.3 [41]	0.2779	0.1985	0.2780
$W^\pm Z\gamma$	1.3698	1.5 [44]	0.8903	0.5739	1.0068
$t\bar{t}\gamma$	170.22	1.9 [45]	88.830	73.738	60.801
$tW^\pm\gamma$	26.858	1.0 [42]	17.905	11.442	16.527

$WW\gamma \to ll\nu\gamma$

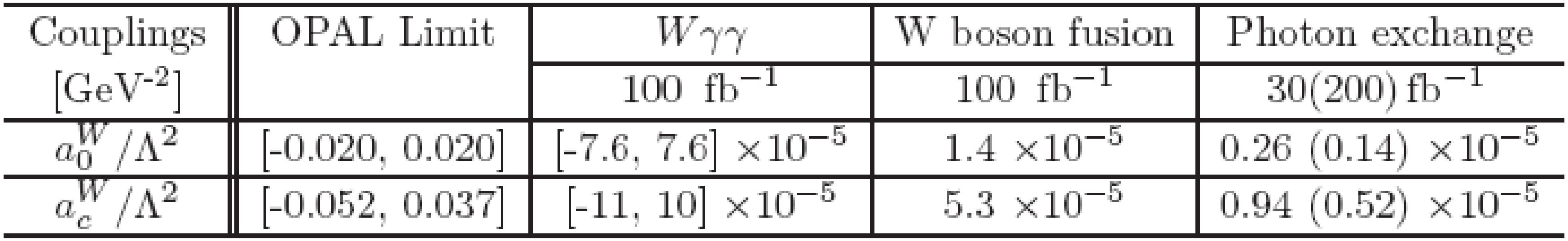
JHEP 1304 (2013) 108
Daneng Yang, Qiang Li, et.al.

- (a) $P_{T\gamma} > 250$ GeV.
- (b) The leading lepton $P_T > 200$ GeV

can constrain at the 95% CL the anomalous WW coupling parameters, e.g., $a^W_{0,c}/\Lambda^2$ at $1 \times 10^{-5}\mathrm{GeV}^{-2}$

w/o form factors

Comparing with Previous LEP and MC results



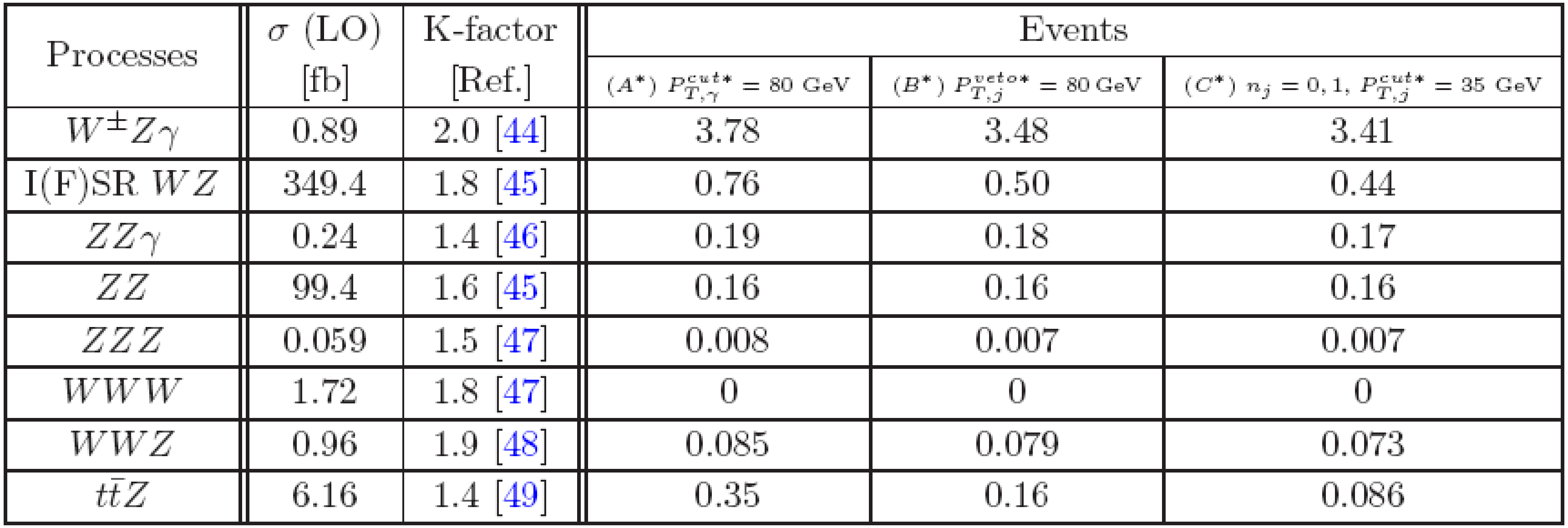
Couplings [GeV^{-2}]	OPAL Limit	$W\gamma\gamma$	W boson fusion	Photon exchange
		100 fb^{-1}	100 fb^{-1}	30(200) fb^{-1}
a_0^W/Λ^2	[-0.020, 0.020]	[-7.6, 7.6] $\times 10^{-5}$	1.4 $\times 10^{-5}$	0.26 (0.14) $\times 10^{-5}$
a_c^W/Λ^2	[-0.052, 0.037]	[-11, 10] $\times 10^{-5}$	5.3 $\times 10^{-5}$	0.94 (0.52) $\times 10^{-5}$

See refs in JHEP 1304 (2013) 108

$WZ\gamma \rightarrow ll l\nu\gamma$

PRD88 (2013) 015023
Ke Ye, Daneng Yang, Q.Li

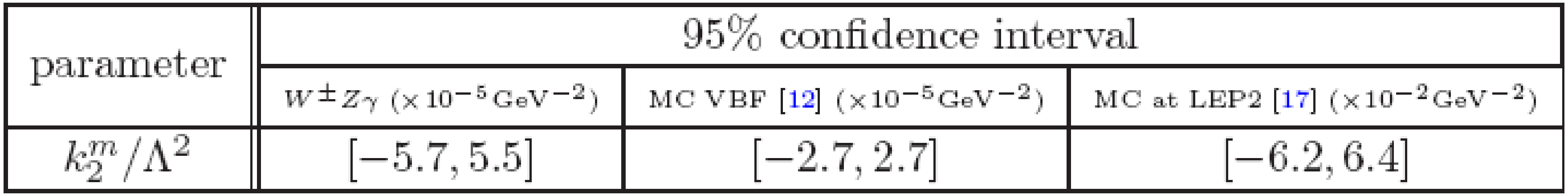
Signal: Three leptons + One photon + MET



Processes	σ (LO) [fb]	K-factor [Ref.]	Events		
			$(A^*)\ P_{T,\gamma}^{cut*} = 80$ GeV	$(B^*)\ P_{T,j}^{veto*} = 80$ GeV	$(C^*)\ n_j = 0, 1,\ P_{T,j}^{cut*} = 35$ GeV
$W^{\pm}Z\gamma$	0.89	2.0 [44]	3.78	3.48	3.41
I(F)SR WZ	349.4	1.8 [45]	0.76	0.50	0.44
$ZZ\gamma$	0.24	1.4 [46]	0.19	0.18	0.17
ZZ	99.4	1.6 [45]	0.16	0.16	0.16
ZZZ	0.059	1.5 [47]	0.008	0.007	0.007
WWW	1.72	1.8 [47]	0	0	0
WWZ	0.96	1.9 [48]	0.085	0.079	0.073
$t\bar{t}Z$	6.16	1.4 [49]	0.35	0.16	0.086

Table 1. Cut flow at the LHC with $\sqrt{s} = 14$ TeV and integrated luminosity of $100\,\mathrm{fb}^{-1}$.

$$P_{T,\gamma} \geqslant 200 \text{ GeV}, \qquad P_{T,l} \geqslant 120 \text{ GeV}.$$



parameter	95% confidence interval		
	$W^{\pm}Z\gamma$ $(\times 10^{-5}\,\mathrm{GeV}^{-2})$	MC VBF [12] $(\times 10^{-5}\,\mathrm{GeV}^{-2})$	MC at LEP2 [17] $(\times 10^{-2}\,\mathrm{GeV}^{-2})$
k_2^m/Λ^2	$[-5.7, 5.5]$	$[-2.7, 2.7]$	$[-6.2, 6.4]$

WWW

Snowmass: arXiv:1309.7452
Ongoing:
Yiwen Wen, Daneng Yang, Huilin Qu, Qishu Yan, Q.Li

1. Pure leptonic $W^{\pm}W^{\pm}W^{\mp} \rightarrow 3l$+MET **Checked with Snomass**

2 categories: $e^{\pm}e^{\pm}\mu^{\mp}, \mu^{\pm}\mu^{\pm}e^{\mp};$ *and others*

Bkg: WZ,ttW,ZZ,ttZ,WWZ

14/100TeV LHC **Delphes V3, PU added**

cutbased or MVA

2. Same-sign dileptons + 2 jets: $W^{\pm}W^{\pm}W^{\mp} \rightarrow l^{\pm}l^{\pm}jj$+MET **First study**

BKg: QCD/EWK same sign WW

14/100TeV LHC **Delphes V3, PU added**

cutbased or MVA

Delphes Card

In detector simulation, for 14 TeV, we use default CMS setup. As to 100 TeV, we use Snowmass setup.

Snowmass

1. **PileUp Merger**:Mean PileUp 140
2. **Electron efficiency**: $P_T \leq 10$ 0%
   in $|\eta| \leq 1.5$, $P_T > 10$ 98%
   in $1.5 \leq |\eta| \leq 2.5$, $P_T > 10$ 90%
   in $|\eta| \geq 2.5$, $P_T > 10$ 0%
3. **Muon efficiency**: $P_T \leq 10$ 0%
   in $|\eta| \leq 1.5$, $P_T > 10$ 99%
   in $1.5 \leq |\eta| \leq 2.4$, $P_T > 10$ 97%
   in $|\eta| \geq 2.4$, $P_T > 10$ 0%
4. **b-tagging**:efficiency formula as function of η and P_t

WWW

Snowmass: arXiv:1309.7452
Ongoing:
Yiwen Wen, Daneng Yang, Huilin Qu, Qishu Yan, Q.Li

$W^{\pm}W^{\pm}W^{\mp} \rightarrow 3l$+MET 14TeV LHC

	XS[fb]	Events						
		cut-based						BDT
		Pileup 0		Pileup 50		Pileup 140		Pileup 0
		s1	s2	s1	s2	s1	s2	s1
WWW	2.1	20.9	6.2	19	5.8	17	5.1	20
WZ	411	421	6.8	428	6.7	397	6.5	337
$t\bar{t}W$	9.8	33	10.3	38	11	38	11	56
ZZ	272	40	1.0	98	1.6	106	2.7	32
$t\bar{t}Z$	6.3	10	2.7	12	3.4	13	3.6	18
WWZ	0.8	3.7	1.0	3.0	1.0	3.5	0.94	3.2
significance		0.92	1.2	0.82	1.1	0.75	0.98	0.94

Table: Cut flow at the LHC with $\sqrt{s} = 14$ TeV and integrated luminosity of 100 fb^{-1}.

WWW

Snowmass: arXiv:1309.7452
Ongoing:
Yiwen Wen, Daneng Yang, Huilin Qu, Qishu Yan, Q.Li

$W^{\pm}W^{\pm}W^{\mp} \rightarrow 3l$+MET 14TeV LHC

	WWW	VBF by Eboli†	Snowmass $WWW^{\ddagger}$
$\frac{f_{S0}}{\Lambda^4}$ [GeV^{-4}]	1.8×10^{-10}	2.4×10^{-11}	-
$\frac{f_{S1}}{\Lambda^4}$ [GeV^{-4}]	2.7×10^{-10}	2.5×10^{-11}	-
$\frac{f_{T0}}{\Lambda^4}$ [GeV^{-4}]	5.8×10^{-13} §	-	1.2×10^{-12}

Our results are presented at 95%CL with 100 fb^{-1}

§8×10^{-13} in 5 σ with 100 fb^{-1}

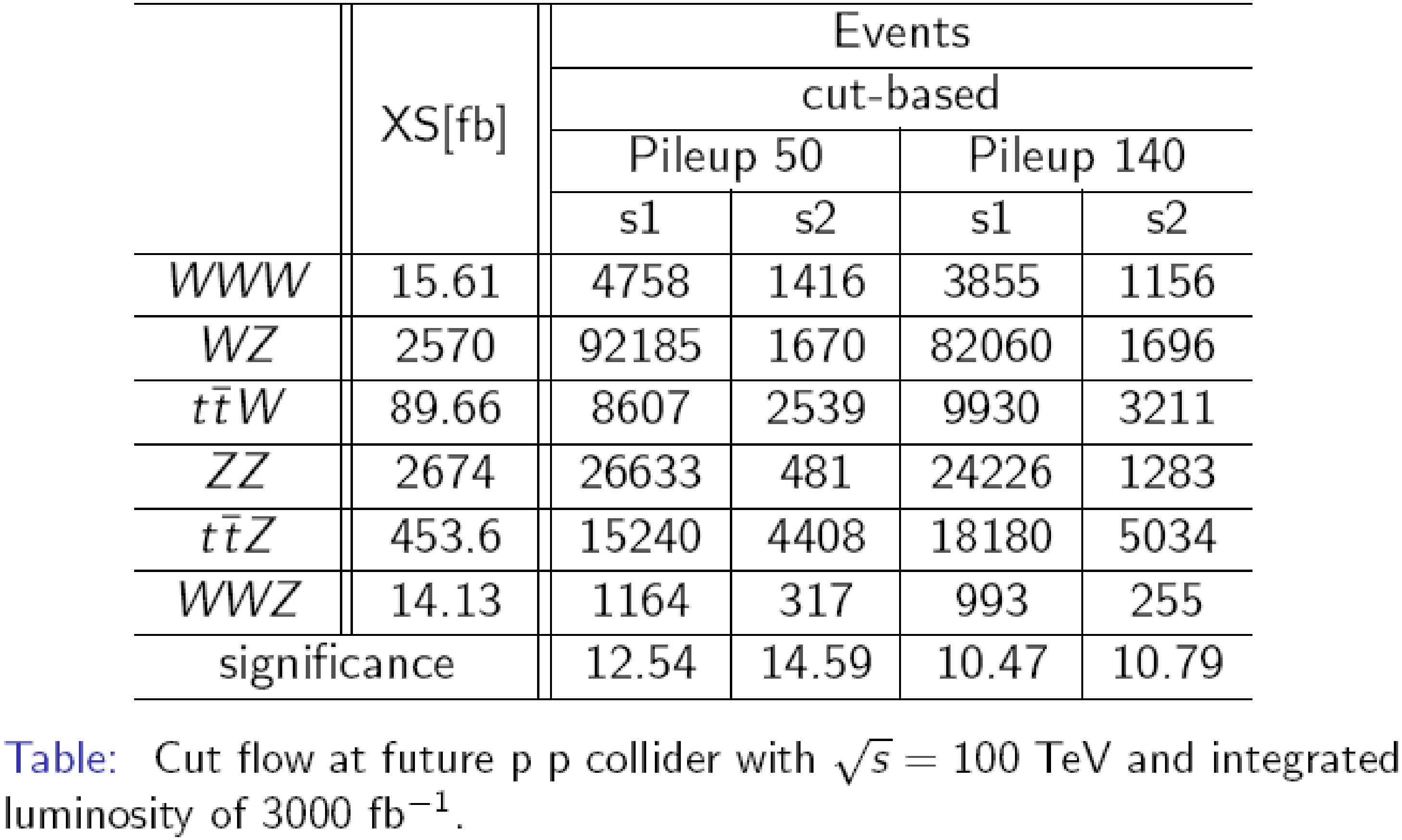
† arXiv:hep-ph/0606118 results are presented at 99% CL

‡ arXiv:1309.1475 results are at 5σ with 300 fb^{-1}

WWW

Snowmass: arXiv:1309.7452
Ongoing:
Yiwen Wen, Daneng Yang, Huilin Qu, Qishu Yan, Q.Li

$W^{\pm}W^{\pm}W^{\mp} \to 3l$+MET 100TeV LHC



	XS[fb]	Events			
		cut-based			
		Pileup 50		Pileup 140	
		s1	s2	s1	s2
WWW	15.61	4758	1416	3855	1156
WZ	2570	92185	1670	82060	1696
$t\bar{t}W$	89.66	8607	2539	9930	3211
ZZ	2674	26633	481	24226	1283
$t\bar{t}Z$	453.6	15240	4408	18180	5034
WWZ	14.13	1164	317	993	255
significance		12.54	14.59	10.47	10.79

Table: Cut flow at future p p collider with $\sqrt{s} = 100$ TeV and integrated luminosity of 3000 fb^{-1}.

$W^{\pm}W^{\pm}W^{\mp} \rightarrow l^{\pm}l^{\pm}jj$+MET

Pileup	**0**	**50**	**140**
Two and only two same-sign leptons with $p_T \geq 20$ GeV, $\lvert\eta\rvert \leq 2.4$. No extra lepton with $p_T \geq 10$ GeV, $\lvert\eta\rvert \leq 2.4$			
N_j (Number of jet with $p_T \geq 30$ GeV, $\lvert\eta\rvert \leq 5$)	$= 2$	$2 \sim 3, (\geq 2^*)$	≥ 2
E_T^{miss}	$\geq 30\text{GeV}$		
$\lvert m_{jj} - m_W \rvert$	$\leq 15\text{GeV}$	$\leq 20\text{GeV}$	$\leq 30\text{GeV}$
$\lvert m_{jj} - m_W \rvert$	$\leq 15\text{GeV}$	$\leq 20\text{GeV}$	$\leq 30\text{GeV}$

p_T^{j1}	p_T^{j2}	η^{j1}	η^{j2}	m^{j1}	m^{j2}	N_j	p_T^{l1}	E_T^{miss}
m_{jj}	ΔR_{jj}	$\Delta\phi_{jj}$	p_T^{ll}	ΔR_{ll}	$\Delta\phi_{ll}$	ΔR_{jl}^{min}	$\Delta\phi_{ll,E_T^{miss}}$	$\Delta\phi_{l,E_T^{miss}}^{min}$

	14TeV, 100fb^{-1}			**100TeV, 100fb^{-1}**		
Pileup	**0**	**50**	**140**	**0**	**50**	**140**
cut-based	**1.7**	**1.2**	**0.9**	**3.8**	**2.0**	**1.2**
BDT	**1.8**	**1.4**	**1.3**	**4.4**	**3.0**	**2.6**

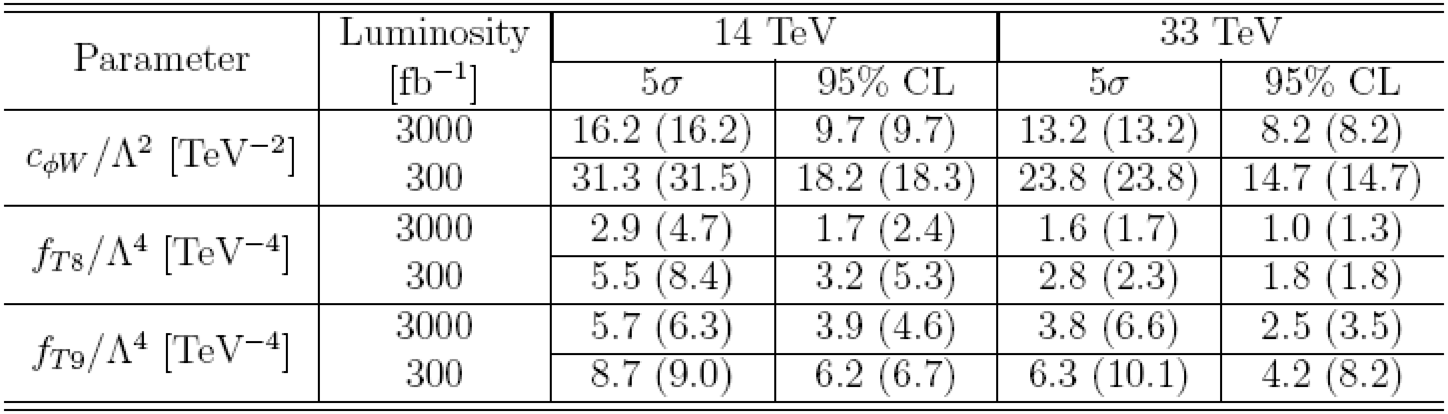
95% CL (14TeV, 100fb^{-1}): $1.16\ \text{TeV}^{-4} \leq f_{T0} \leq 1.26\ \text{TeV}^{-4}$

Snowmass VBS / VVV

arXiv:1309.7452

VBF ZZ

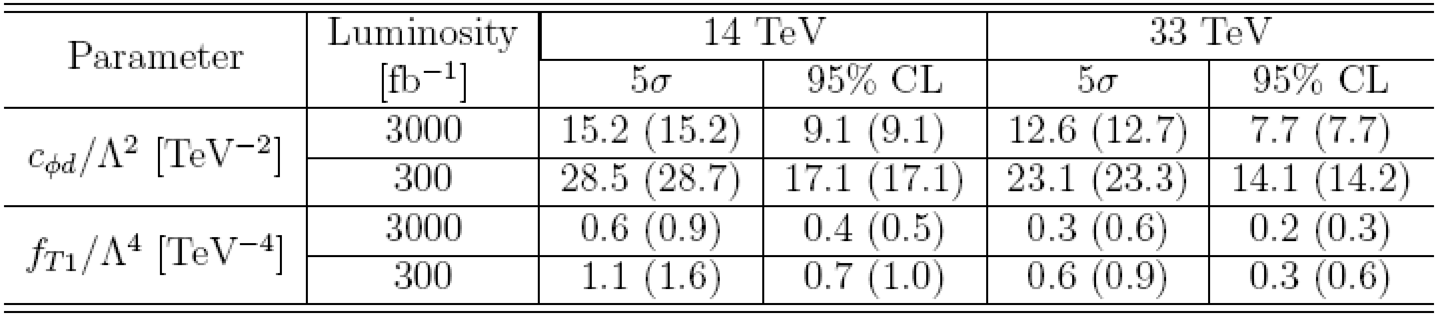
$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$



Parameter	Luminosity [fb^{-1}]	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$ [TeV^{-2}]	3000	16.2 (16.2)	9.7 (9.7)	13.2 (13.2)	8.2 (8.2)
	300	31.3 (31.5)	18.2 (18.3)	23.8 (23.8)	14.7 (14.7)
f_{T8}/Λ^4 [TeV^{-4}]	3000	2.9 (4.7)	1.7 (2.4)	1.6 (1.7)	1.0 (1.3)
	300	5.5 (8.4)	3.2 (5.3)	2.8 (2.3)	1.8 (1.8)
f_{T9}/Λ^4 [TeV^{-4}]	3000	5.7 (6.3)	3.9 (4.6)	3.8 (6.6)	2.5 (3.5)
	300	8.7 (9.0)	6.2 (6.7)	6.3 (10.1)	4.2 (8.2)

VBF WZ

$$\mathcal{L}_{\phi d} = \frac{c_{\phi d}}{\Lambda^2}\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$$



Parameter	Luminosity [fb^{-1}]	14 TeV		33 TeV	
		5σ	95% CL	5σ	95% CL
$c_{\phi d}/\Lambda^2$ [TeV^{-2}]	3000	15.2 (15.2)	9.1 (9.1)	12.6 (12.7)	7.7 (7.7)
	300	28.5 (28.7)	17.1 (17.1)	23.1 (23.3)	14.1 (14.2)
f_{T1}/Λ^4 [TeV^{-4}]	3000	0.6 (0.9)	0.4 (0.5)	0.3 (0.6)	0.2 (0.3)
	300	1.1 (1.6)	0.7 (1.0)	0.6 (0.9)	0.3 (0.6)

Snowmass VBS/ VVV

arXiv:1309.7452

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

Parameter	$\sqrt{s}$ [TeV]	Luminosity [fb^{-1}]	pileup	5σ [TeV^{-4}]	95% CL [TeV^{-4}]
f_{T1}/Λ^4	14	300	50	0.2 (0.4)	0.1 (0.2)
f_{T1}/Λ^4	14	3000	140	0.1 (0.2)	0.06 (0.1)
f_{T1}/Λ^4	14	3000	0	0.1 (0.2)	0.06 (0.1)
f_{T1}/Λ^4	100	1000	40	0.001 (0.001)	0.0004 (0.0004)
f_{T1}/Λ^4	100	3000	263	0.001 (0.001)	0.0008 (0.0008)
f_{T1}/Λ^4	100	3000	0	0.001 (0.001)	0.0008 (0.0008)

$Z\gamma\gamma \to l^+l^-\gamma\gamma$

Parameter	$\sqrt{s}$	14 TeV	14 TeV	33 TeV	100 TeV
	Lum.	300 fb^{-1}	3000 fb^{-1}		
f_{M0}/Λ^4 [TeV^{-4}]	5σ	7300 (830)	3600 (310)	1900 (190)	750 (120)
	95% CL	4200 (360)	1200 (160)	660 (120)	71 (59)
f_{M1}/Λ^4 [TeV^{-4}]	5σ	7600 (1600)	3600 (680)	2100 (340)	1000 (220)
	95% CL	4500 (800)	1200 (290)	770 (160)	240 (126)
f_{M2}/Λ^4 [TeV^{-4}]	5σ	3300 (130)	510 (48)	310 (26)	120 (16)
	95% CL	670 (56)	160 (21)	110 (13)	25 (10)
f_{M3}/Λ^4 [TeV^{-4}]	5σ	2400 (250)	720 (120)	320 (66)	180 (34)
	95% CL	820 (133)	210 (52)	130 (23)	38 (15)

Summary

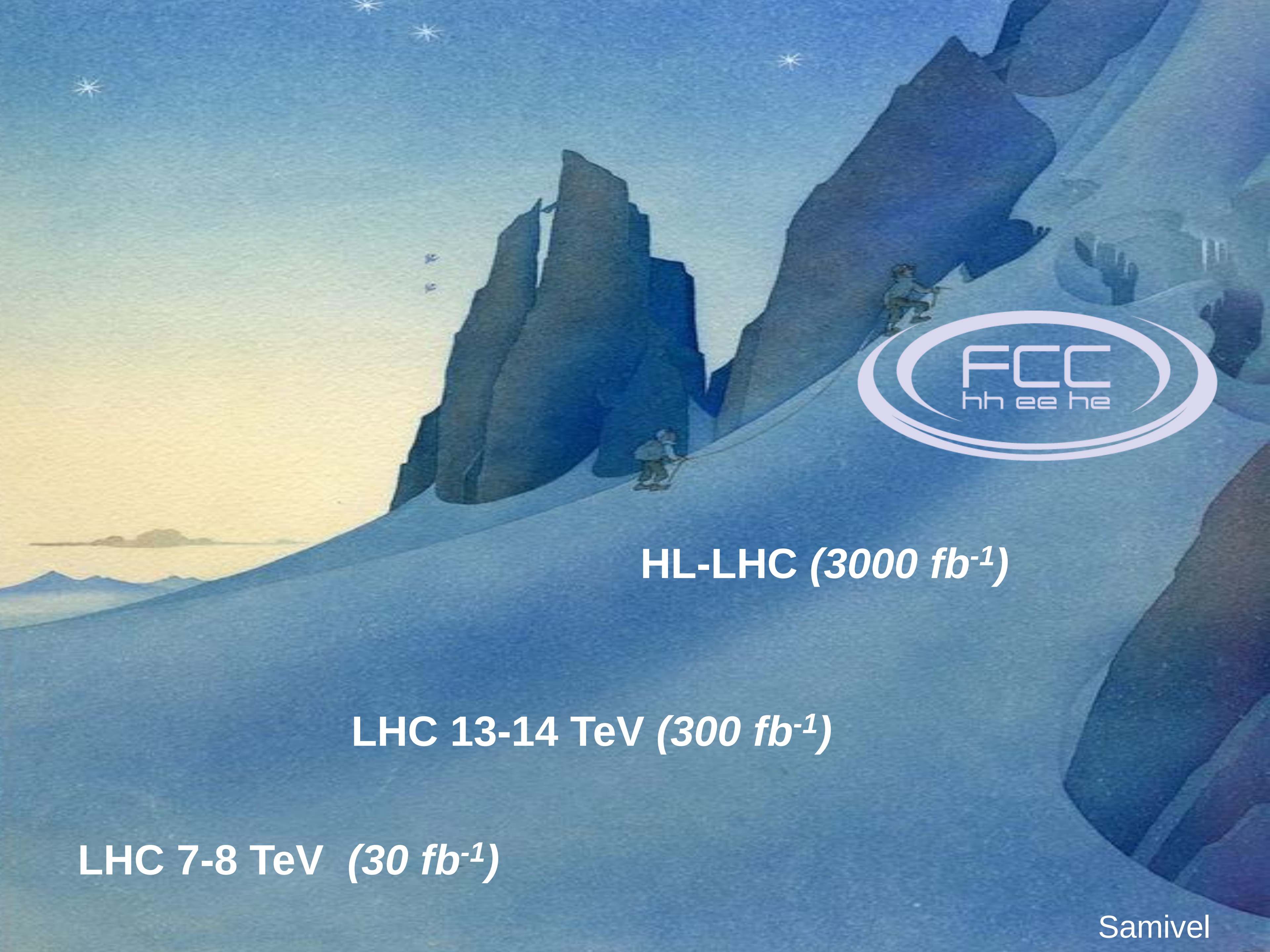
- **First measurement on aQGC at the LHC from 3 channels**

  First ever limits on **f^{0}_{T}**, K_0^w, K_c^w **, 4W coupling**

- **Triple V and EWK VV+2Jets Processes will serve as further test on the SM, and will be much sensitive to aQGC**

- **TGC and QGC will enter precision measurement era!!**

- **At harder tail, we may explore aQGC with Jet subtructure (PKU Group contributed much on W-tagging and EXO VV resonance search at CMS, see more in Shuai Liu's talk)**



HL-LHC *(3000 fb^{-1})*

LHC 13-14 TeV *(300 fb^{-1})*

LHC 7-8 TeV *(30 fb^{-1})*

Samivel

Backup