TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften, Fachrichtung Physik

WG2: Analysis Techniques Prospects

Michael Kobel
TU Dresden

VBSCAN COST Kickoff Meeting, Split, 29.06.2017

SPONSORED BY THE
Federal Ministry of Education and Research

DRESDEN concept

Disclaimer

- Several studies for High Lumi LHC VBS
  - *Prospects for VBS in same sign WW/WZ with High Luminosity LHC*
    CMS-PAS-SMP-14-008: https://cds.cern.ch/record/2220831
  - *Projection of VV Scattering Measurements for ECFA*
    CMS-PAS-FTR-13-006: https://cds.cern.ch/record/1606835
  - *Studies of Vector Boson Scattering And Triboson Production with an Upgraded ATLAS Detector at a High-Luminosity LHC*
    ATL-PHYS-PUB-2013-006: https://cds.cern.ch/record/1558703
  - *Physics at a High-Luminosity LHC with ATLAS*
    https://arxiv.org/abs/1307.7292
- Hard to find public material for shorter term prospects
- Thus, I address several topics I came across in last years
  - Heavily biased to ATLAS
  - Even more heavily biased to work of Dresden students: Bachelor, Master, Ph.D.

TECHNISCHE UNIVERSITÄT DRESDEN

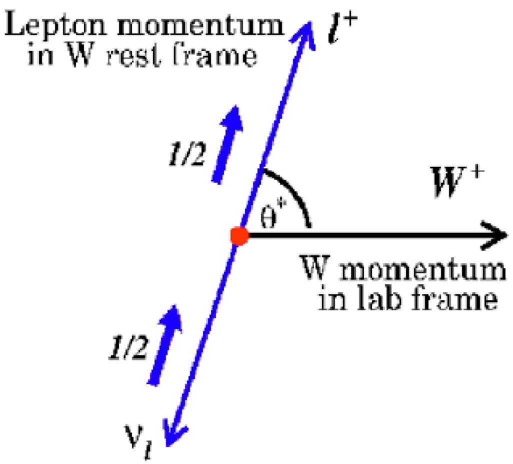
List of (unordered) topics

- Polarisation measurements (see also Ezio‘s talk)
  - Especially $V_L V_L \rightarrow V_L V_L$
- Charge ratios W+/W-
  - Examples, and influence of pdfs
- BSM (see also Ilaria‘s talk)
  - Validity of EFT tails, Explicit or Simplified Models?
- Best way to interpretation
  - Fit to complete distributions vs. extreme phase space regions ?
- Extend the reach (not in my talk)
  - Scattering channels, decay channels (see Narei‘s talk, WG2)
  - boosted topologies (see Christoph‘s and Andreas‘ talk, WG3)

POLARIZATION
(SEE ALSO EZIO'S TALK)

Especially $V_L\ V_L \rightarrow V_L\ V_L$

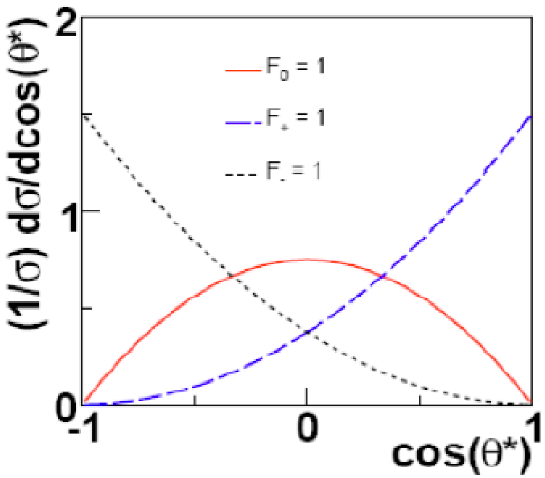
- Lepton decay angle (→ pt !) depends on W helicity (below for W^+)



- Measurement makes use of the cos θ^* distributions in the decay $W \rightarrow l + \nu$
- Cross section can be expressed in three terms of the polarisation fractions, with $F_+ \equiv 1 - F_- - F_0$

$$\frac{d\sigma_W}{d\cos\theta^*} \propto (1 - F_- - F_0) \cdot \frac{3}{8}(1 + \cos\theta^*)^2 \quad \text{left}$$
$$+ F_0 \cdot \frac{3}{4}(1 - \cos^2\theta^*) \quad \text{longitudinal}$$
$$+ F_- \cdot \frac{3}{8}(1 - \cos\theta^*)^2 . \quad \text{right}$$

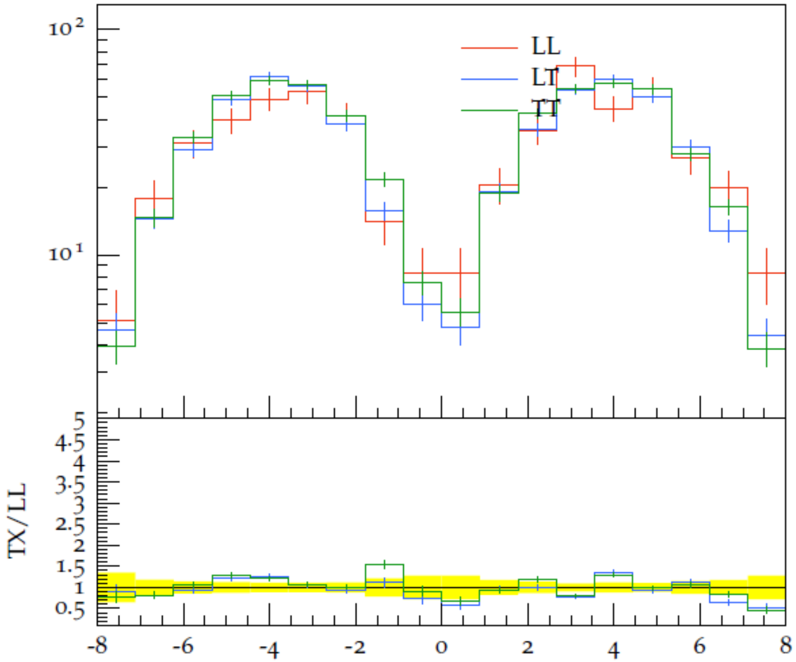
(for W^+)



David South (H1/TU Dortmund), Photons@LHC 2008 Page 20

What variables to use?

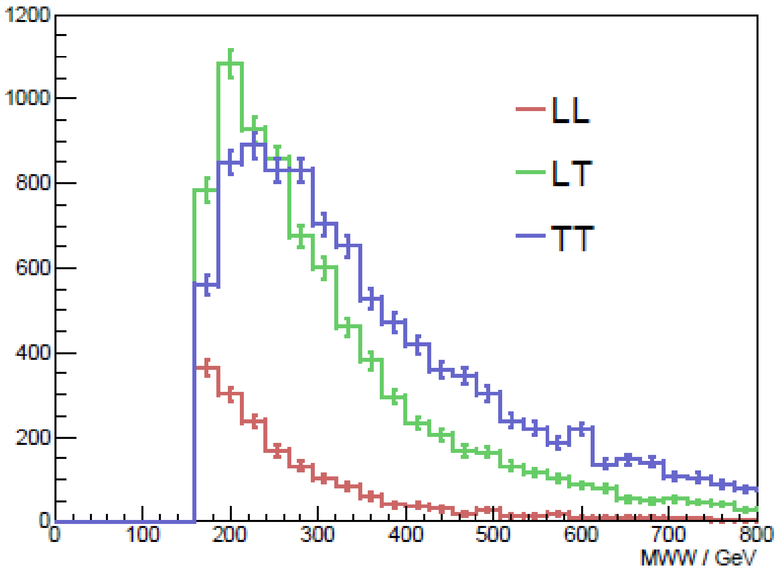
- Ulrike Schnoor, talk at MBI workshop 2015, Hamburg
  https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=11808
  - Polarisation in $W^\pm W^\pm \to W^\pm W^\pm$



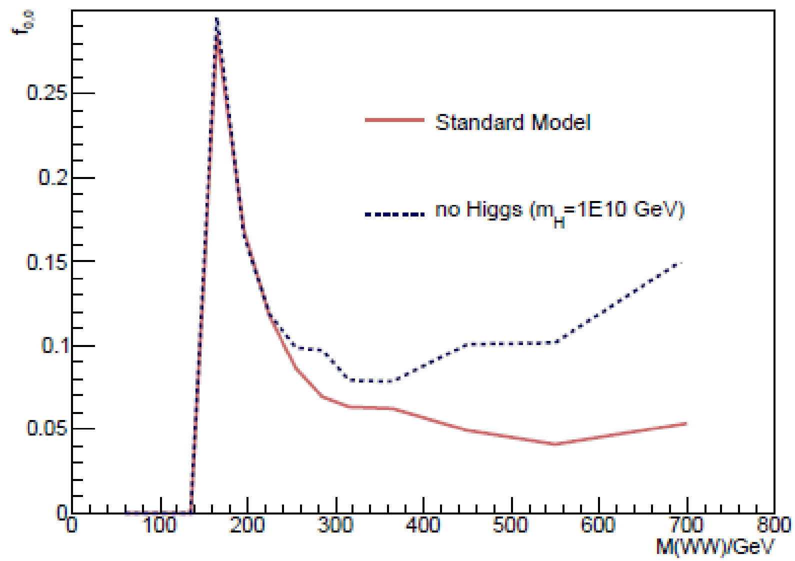
$|\Delta\eta(jj)|$

- "Typical" VBS cut variables do not favor $W_L W_L$ over $W_L W_T$ and $W_T W_T$ scattering: e.g. $M(jj)$, $|\Delta\eta|$, and lepton centrality give no separation power
- Look for variables suitable to distinguish between W polarizations

- M(WW) is sensitive to W polarizations
- M(WW) is sensitive to new physics in the electroweak sector



Contributions from the different polarizations in dependence of M(WW)



Fraction of longitudinal scattering in dependence of M(WW)

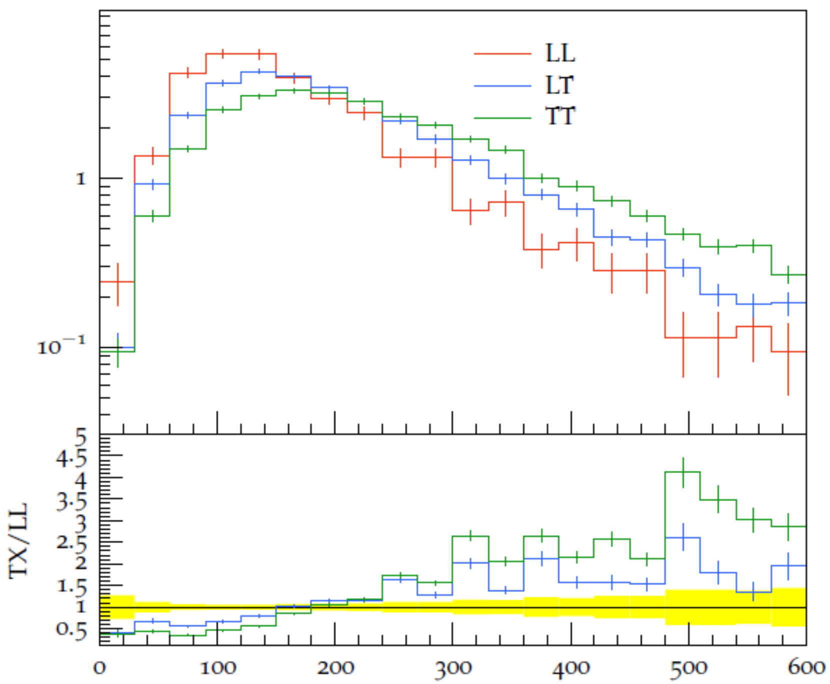
How to approximate M_{WW} best?

- Mo1 gives highest separation power of all investigated variables (e.g. m_{vis}, m_{eff}, m_{col}, mass bound,)

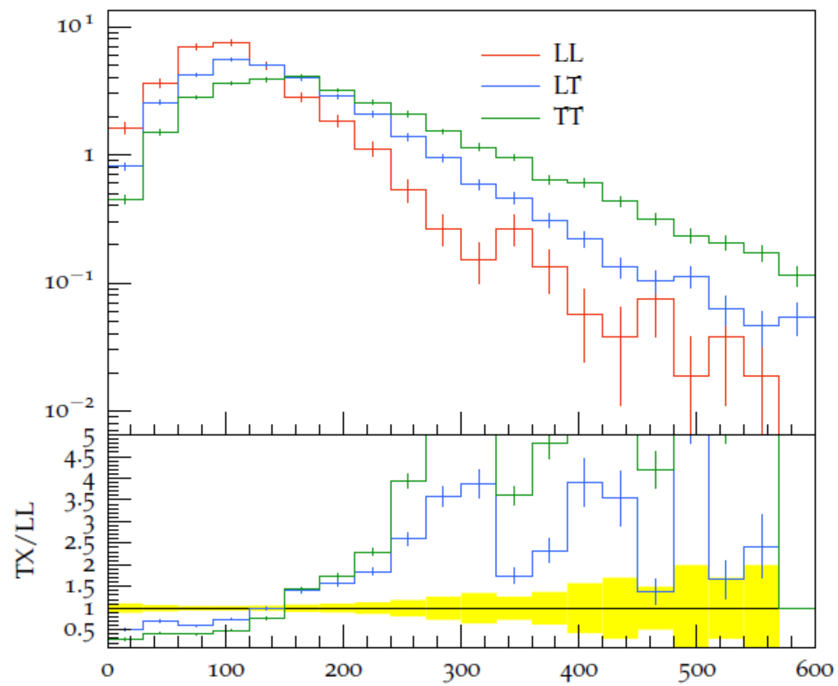
Mass bound variables

- $M_{o1} = (|\vec{p}_T(\ell_1)| + |\vec{p}_T(\ell_2)| + |\vec{p}_{Tmiss}|)^2 - (\vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) + \vec{p}_{Tmiss})^2$
- $M_{1T} = \left(\sqrt{M_{\ell\ell}^2 + \vec{p}(\ell_1) + \vec{p}(\ell_2)} + |\vec{p}_{Tmiss}|\right)^2 - (\vec{p}(\ell_1) + \vec{p}(\ell_2) + \vec{p}_{Tmiss})^2$

introduced in hep-ph/1105.2977



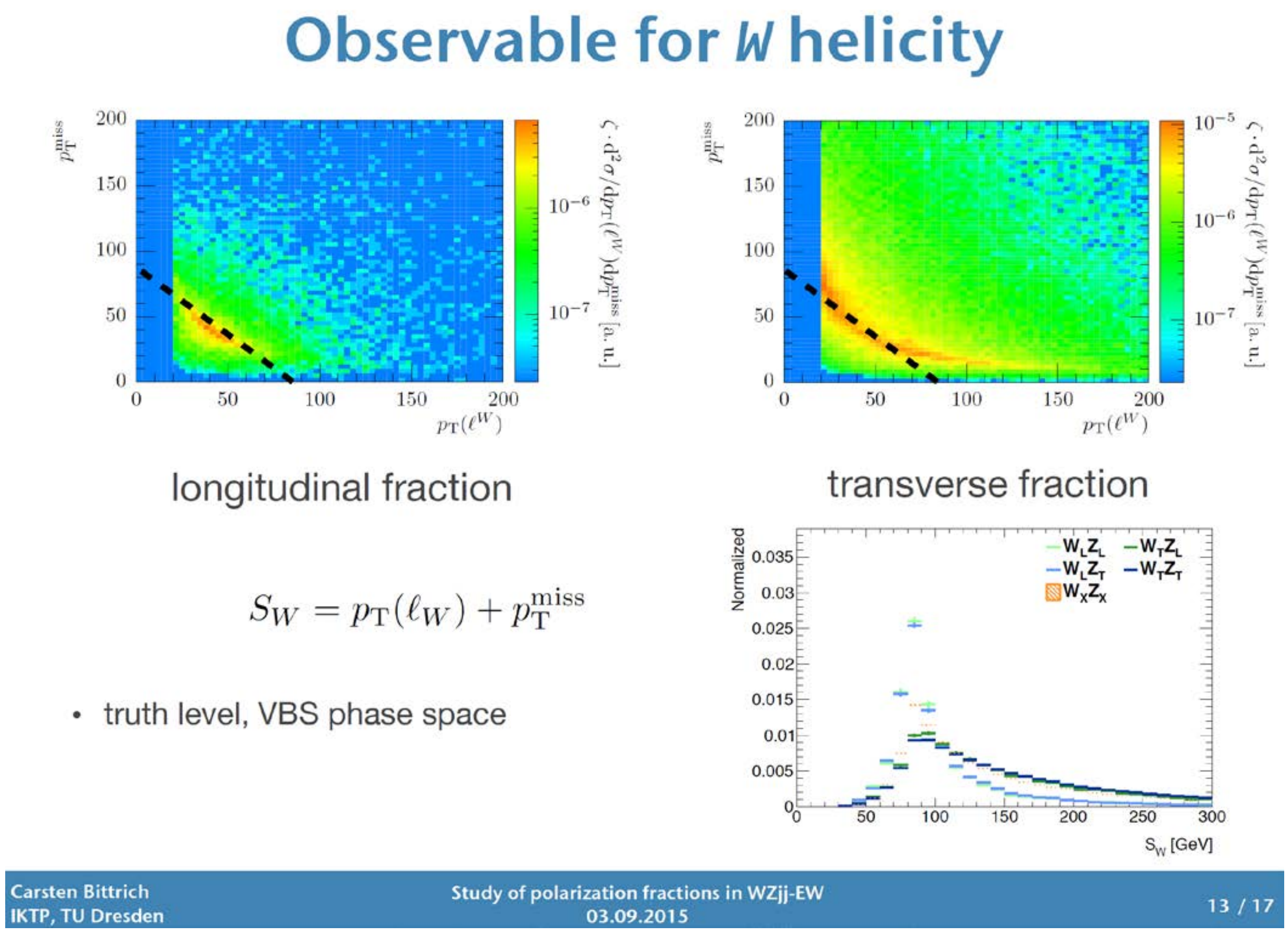
M_{1T}



M_{o1}

Template fit approach: $W^{\pm}W^{\pm}jj$

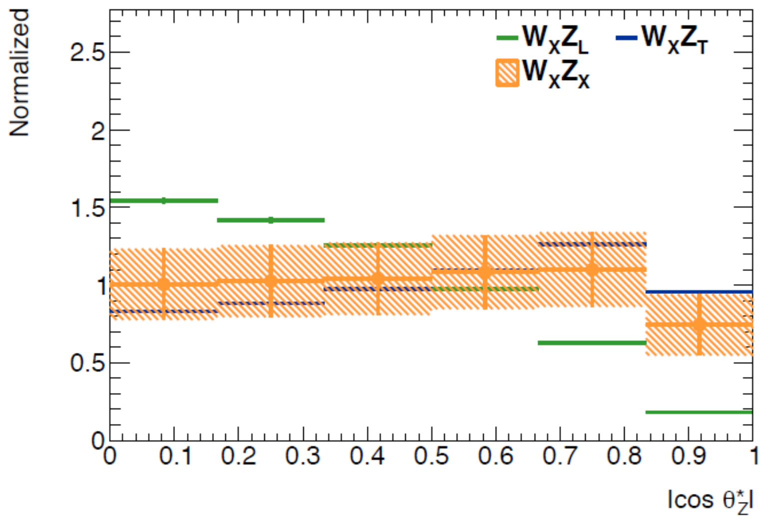
- Results from Master Thesis Carsten Bittrich, CERN-THESIS-2015-039
  see also his talk at MBI 2015 in Hamburg



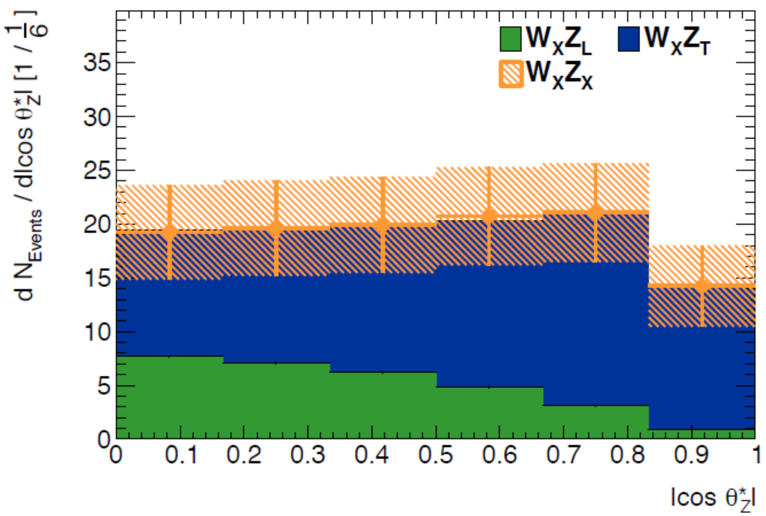
Template fit approach: $W^{\pm}Zjj$ for 100 fb^{-1} at 13 TeV (stat errors only)

- $|\cos\ \theta^*_Z|$, VBS phase space, scaled to $\mathcal{L}_{int} = 100 fb^{-1}$

normalized distributions



fit to mixed template



	fraction
$W_X Z_L$	0.260 ± 0.159
$W_X Z_T$	0.739 ± 0.170

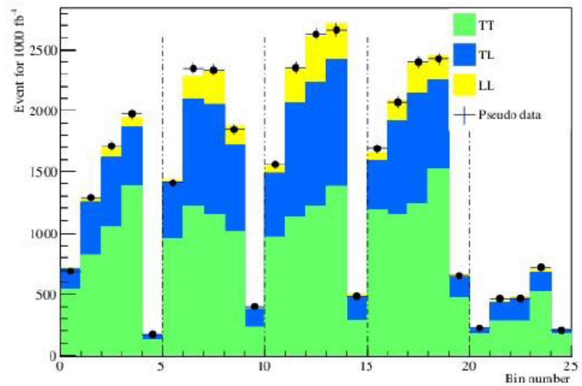
- listed uncertainties are purely statistical and should be considered as “lower limit on uncertainty”

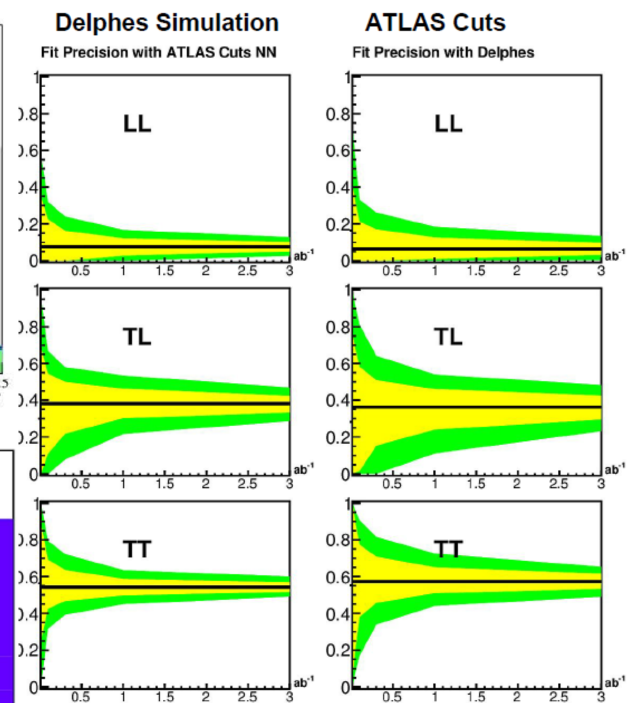
❖ Jake Searcy, talk at MBI 2015 Hamburg
https://indico.desy.de/conferenceOtherViews.py?view=standard&confId=11808

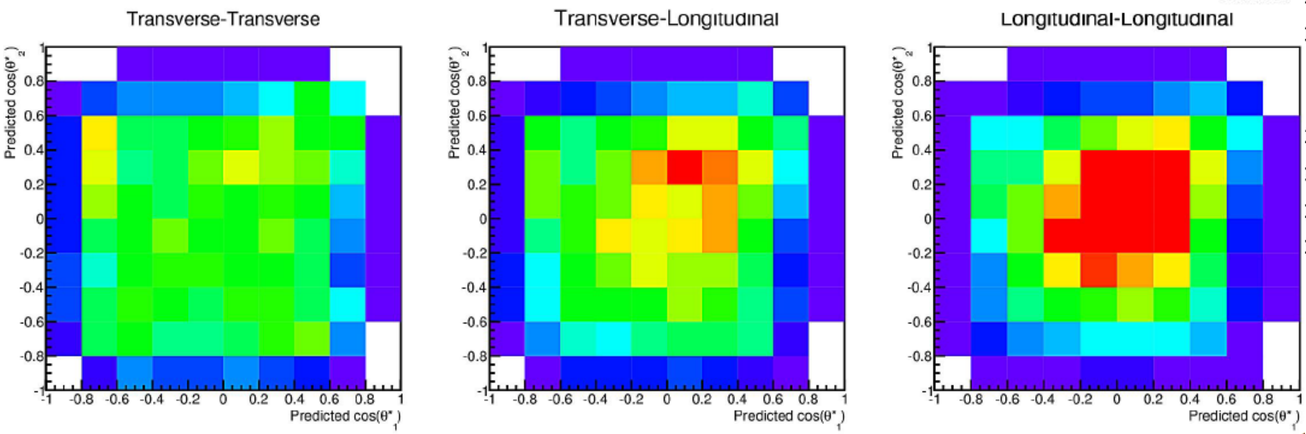
Fit Neural Network

- 6 templates
  - ++,--,+-.LL,+L,-L
- Combine into 3
  - Transverse-Transverse
  - Transverse-Longitudinal
  - Longitudinal-Longitudinal

1 ab^{-1} Fit





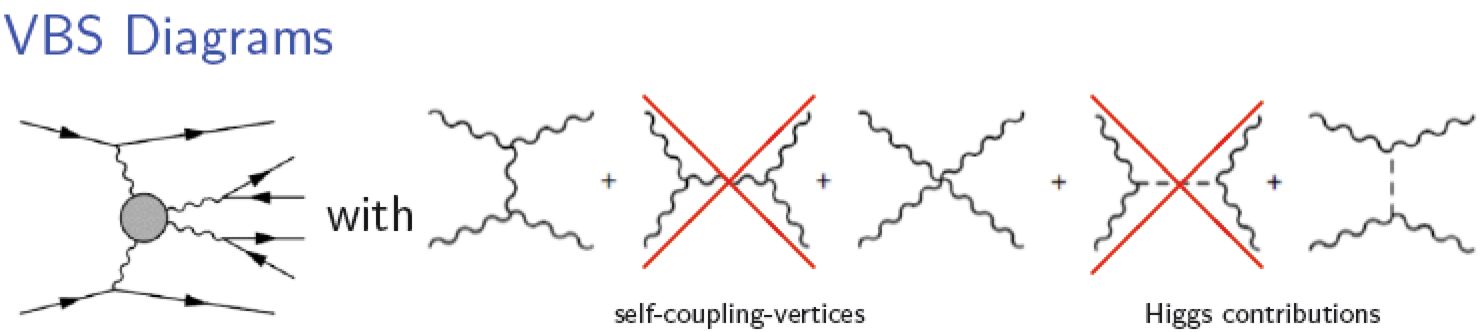


CHARGE RATIOS W+ / W-

Examples, and influence of pdfs

Exploit +/- differences in $W^{\pm}Vjj$-EW?

- VBS contribution in Standard Model ($W^{\pm}W^{\pm}jj$):



- Naively:
  - $\sigma(++)/\sigma(--)$ = 2($W^{\pm}Z$) or 4($W^{\pm}W^{\pm}$) due to proton quark content
  - Differential distributions dσ/d… identical
- In reality modified by several effects, e.g.
  - pdf: d/u << 0.5 at large x, linearly(?) decreasing
    - large x is important region for VBS and BSM-VBS
  - Parity violation of weak interactions -> eta-dependence
    - W helicity fractions $F_- > F_0 > F_+$ for W-radiation from quarks
      → differences in eta and thus lepton p_t from W^+ and W^-
    - F_0 (corresp. to W_LW_L scattering) strongly enhanced in aQGC/BSM
      → prefers large x, modifies differences in lepton p_t

Systematics on u/d large at large x

„Recent“ fits vom 2011:

- J. Arrington J. G. Rubin and W. Melnitchouk
  http://arxiv.org/pdf/1110.3362v1.pdf

At leading order in the strong coupling constant, the nucleon structure functions are given by the charge-squared weighted sum of the u and d quark distributions. In this approximation the extracted value of F_{2n}/F_{2p} is directly related to the ratio of d to u quark distributions,

$$\frac{d}{u} = \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}. \qquad (2)$$

The resulting d/u ratio is shown in Fig 6, along with the fractional uncertainty (inset), for the full range of models, as well as for the on-shell and off-shell models

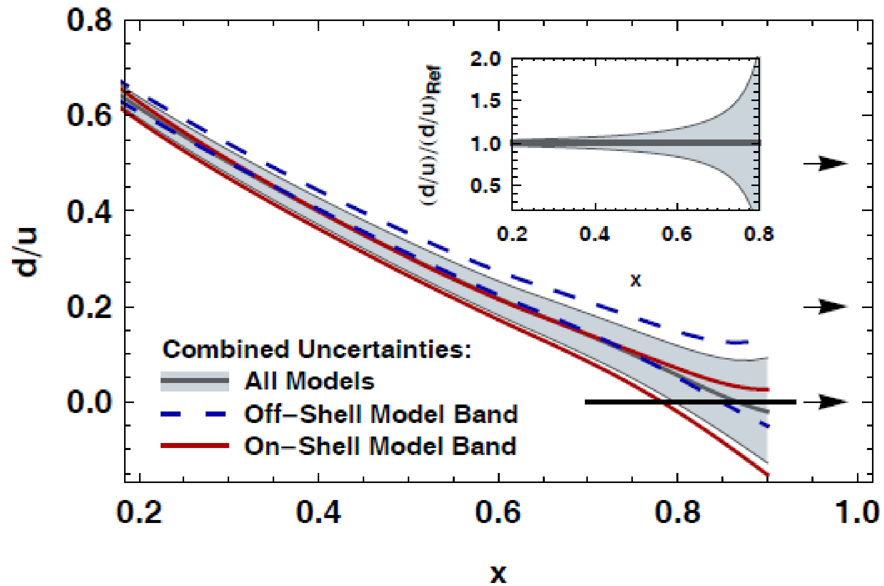
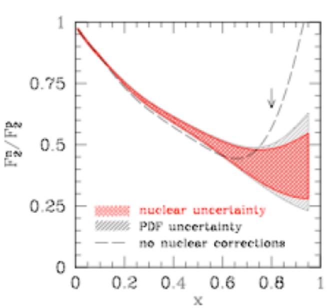
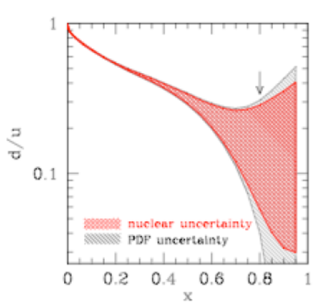


FIG. 6: Ratio d/u extracted from F_{2n}/F_{2p} at $Q^2 = 16\ \mathrm{GeV}^2$ using Eq. (2), with the gray band indicating the total uncertainties as shown in Fig. 4, with the dashed (solid) curves representing the on-shell (off-shell) nuclear model results. The inset shows the growing fractional uncertainty on d/u as the ratio becomes smaller for $x \to 1$.

F_2^n/F_2^p



d/u



- Resulting uncertainty bands for d/u and F_2^n/F_2^p
  - nuclear corrections dominant   Thia Keppel, PANIC 2011, CTEQ
- F_2^n/F_2^p ratio is bounded below at 1/4

Crucial pdf region for VBS

Bachelor Thesis Th.Kwasnitza, 09/14 Dresden

https://iktp.tu-dresden.de/IKTP/pub/14/Bachelorarbeit_Kwasnitza.pdf

- Relevant range for x-section
  0.05 < x < 0.5 (for SM)
  0.05 < x < 0.6... (aQGC)
- x- enhancement by aQGC:
  x> 0.25 more important
  ~ flat enhancement (here ~ 3)
- Since d/u falls with x
  +/- charge ratio
  will rise with aQGC

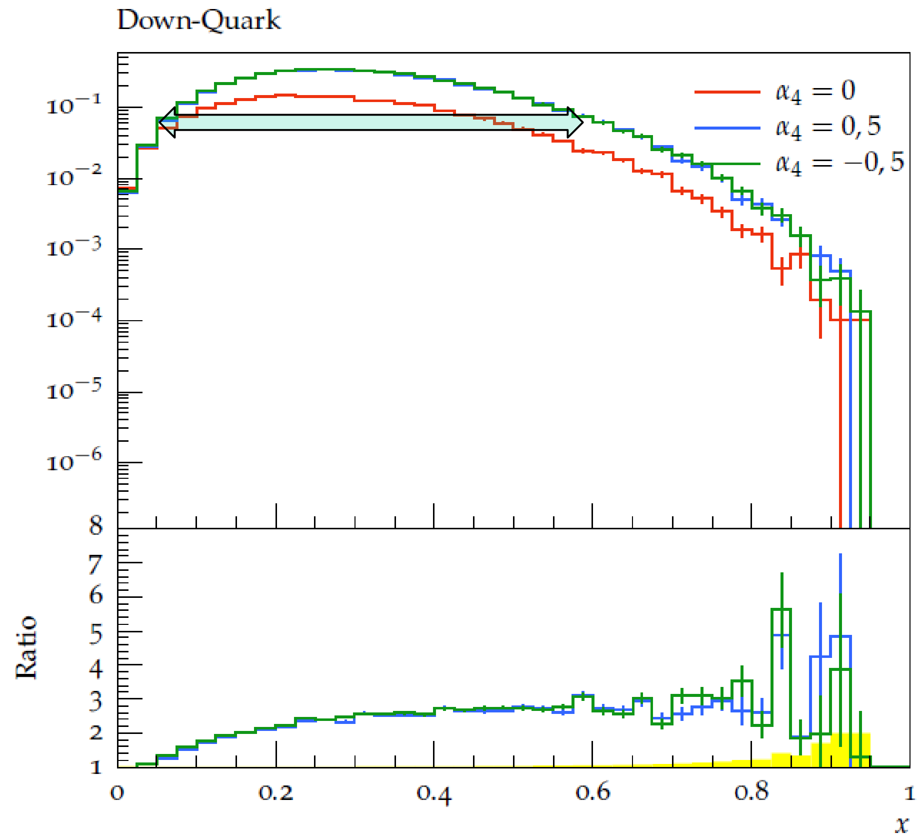


Abbildung 5.7: Oben ist die Verteilung der Bjorkenschen Skalenvariable $x \cdot f_{fiducial}(x)$ für das Down-Quark nach den Fiducial-Cuts. Unten ist das Verhältnis der Verteilungen für verschiedene Theorien im $W^{-}Zjj$-Endzustand dargestellt

++/-- ratio changes by aQGC

- **Saturation of VBS contribution with aQGC**
  (Philipp Anger, Ph.D. Thesis, Dresden, CERN-THESIS-2014-105)
  - Significant dependence of unitarization procedure

WZjj

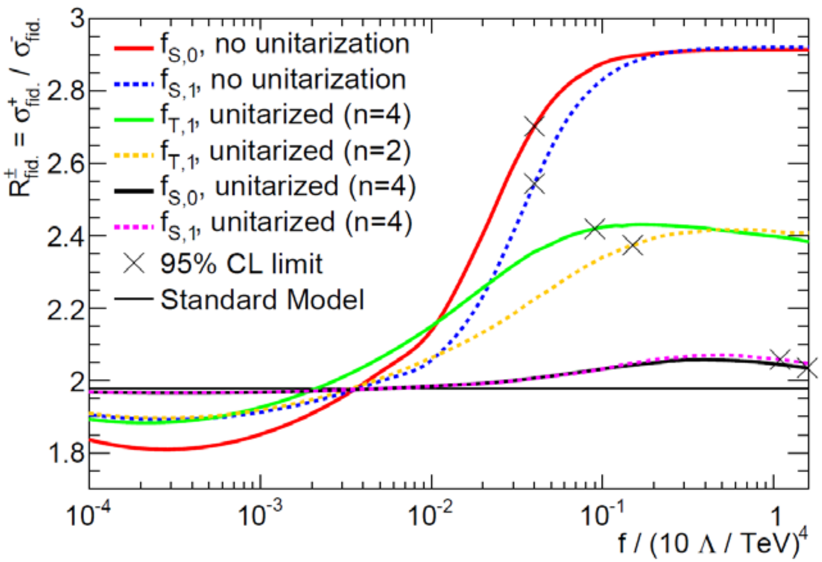
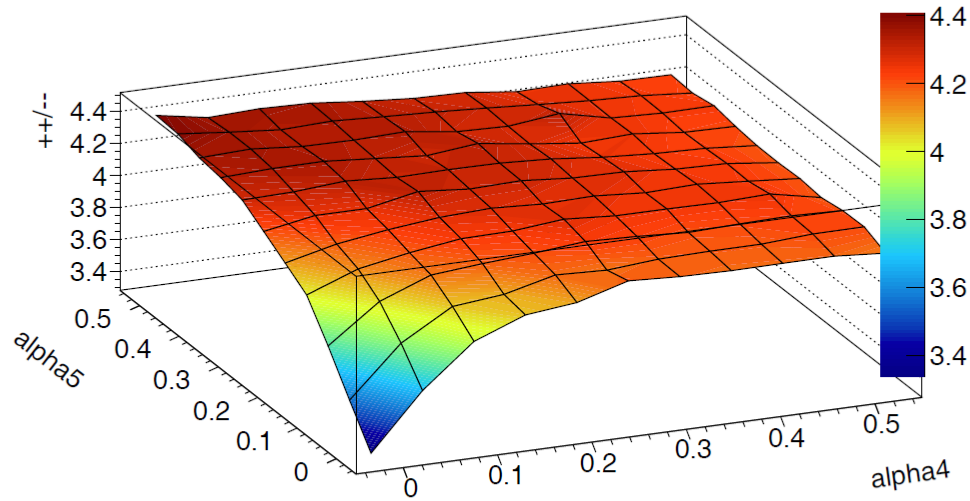


Figure 12.10: *Next-to-leading order fiducial cross section ratios of the electroweak W^+Zjj and W^-Zjj production in the electroweak WZjj fiducial phase space as a function of different aQGC parameters for different unitarization prescriptions based on form factors.*

$W^{\pm}W^{\pm}jj$

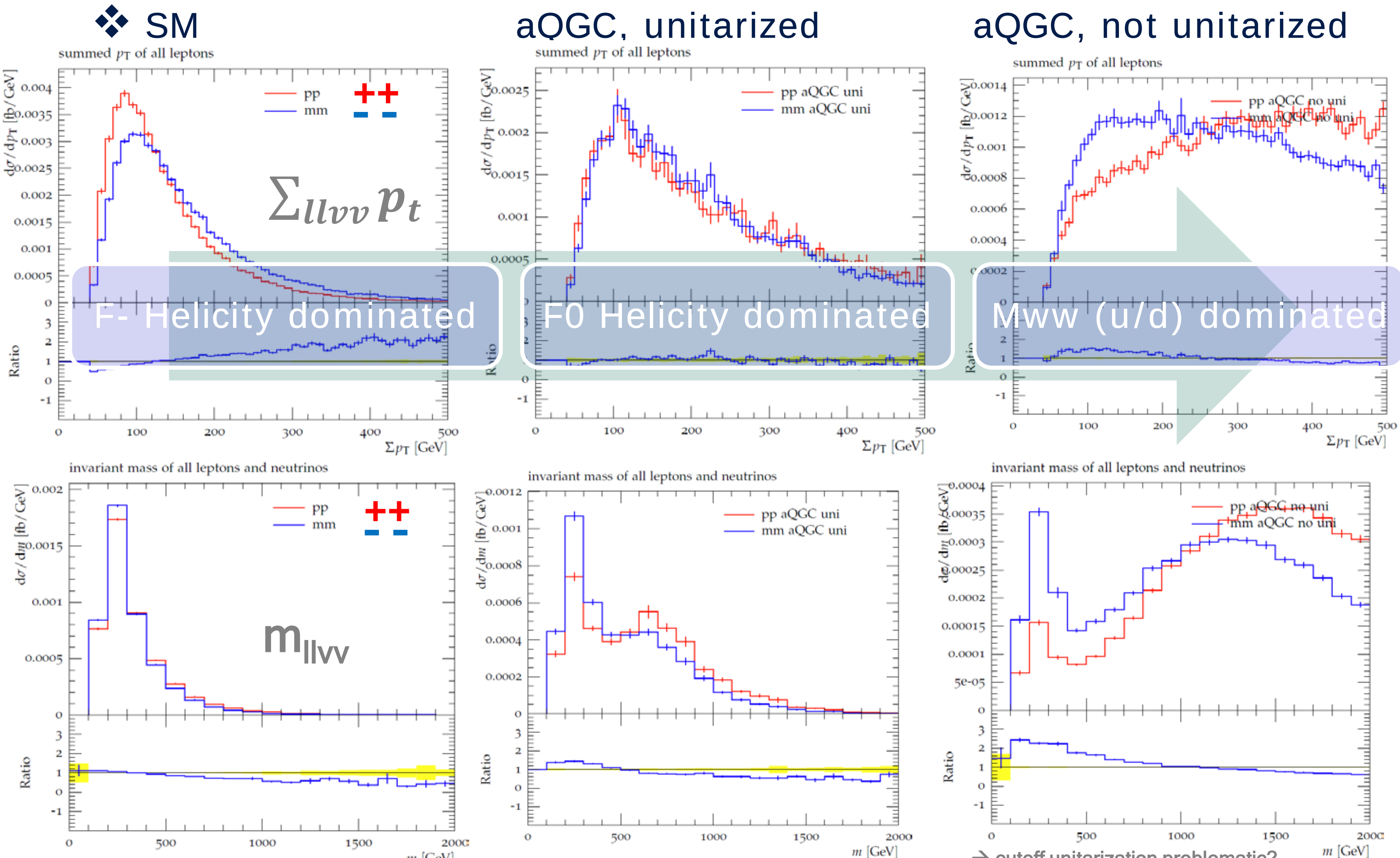


Lepton kinematics in W±W±jj influenced by helicity and pdfs

TECHNISCHE UNIVERSITÄT DRESDEN

ATLAS EXPERIMENT

CMS

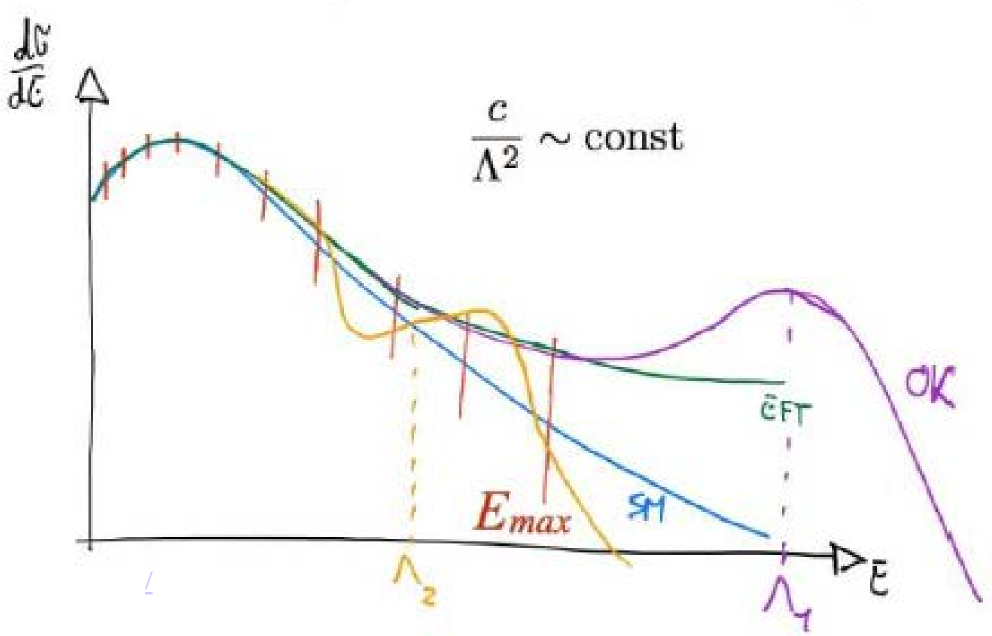


→ cutoff unitarization problematic?

BSM
(SEE ALSO ILARIA‘S TALK)

Validity of EFT tails, Explicit or Simplified Models?

❖ -> Discuss further on the basis of Ilaria's talk today and from the COST EFT Pre-Meting https://indico.cern.ch/event/647015



Both models generate the same dim-6 coefficient

Model 1 is clearly consistent with the EFT analysis.

Model 2 is not.

The EFT analysis can't be used to put consistent limits on Model 2.

Does EFT describe resonance tails?

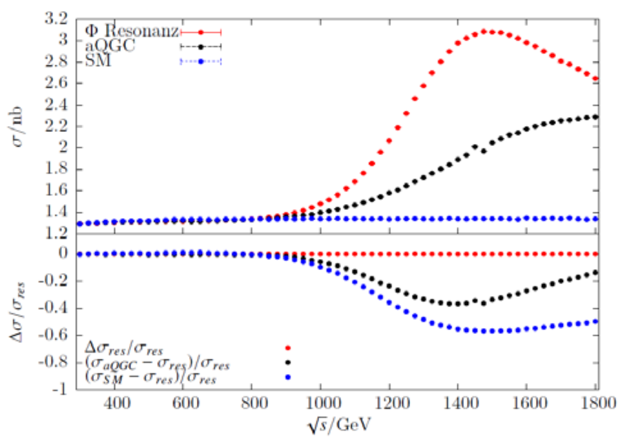
- [Bachelor Thesis](#) Daniel Reichelt, TU Dresden, May 2014
  - Conversion of resonance parameters into aQGC (Alboteanu, Kilian, Reuter, 0806.4145)

$$\alpha_i = \Delta\alpha_{i,j} \cdot \frac{16\pi\Gamma v^4}{M^5}$$

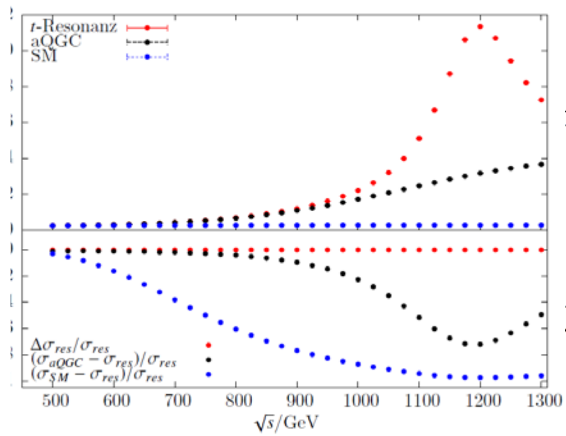
mit $i \in \{4,5\}$, $j \in \{\sigma, \Phi, \rho, f, t\}$,

Resonanz	σ	Φ	ρ	f	t
$\Delta\alpha_4$	0	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{2}$	$-\frac{5}{8}$
$\Delta\alpha_5$	$\frac{1}{12}$	$-\frac{1}{12}$	$-\frac{3}{4}$	$-\frac{5}{8}$	$\frac{35}{8}$

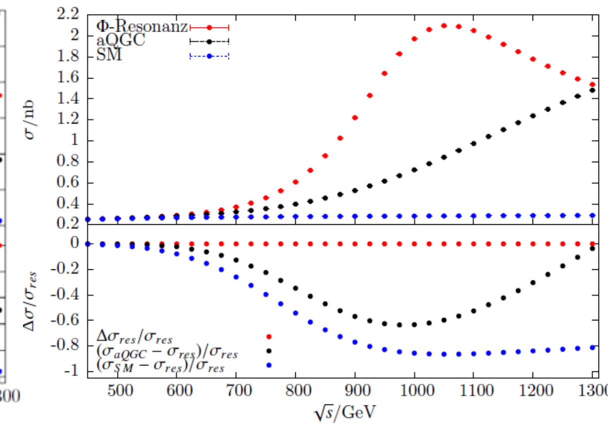
- $W^\pm W^\pm jj$ $W^\pm Zjj$



4: Φ_{1600}-Resonanz in $W^+W^+ \to W^+W^+$. Im unteren Bereich sind



irkunsquerschnitt des $W^+Z \to W^+Z$-Prozesses mit T



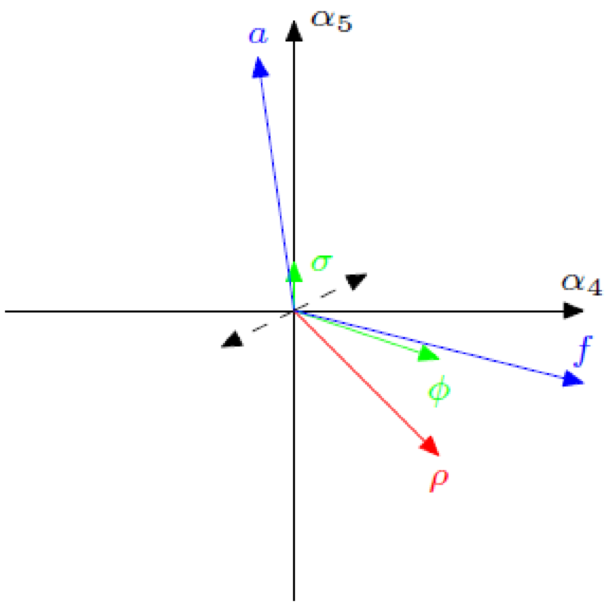
(a) $W^+Z \to W^+Z$

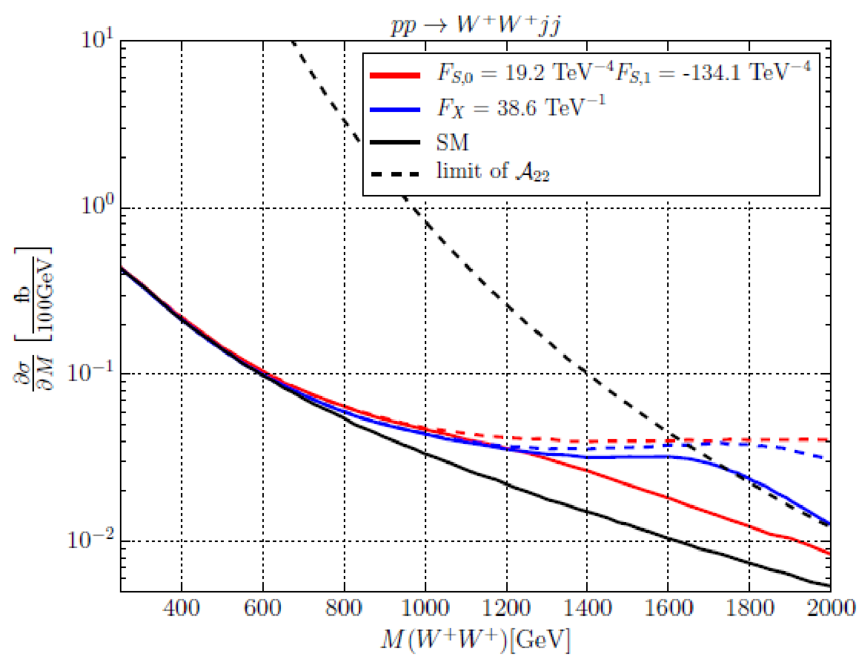
Abbildung 4.18: Skalar-Isotensor in W^+Z

- Only Tensor-Isotensor in WZjj has sizeable region with measurable effect(!) where aQGC describes the resonance tail

❖ Analogue results: M.Sekulla, talk at MBI Workshop 2016

- Simplified Models: Reuter, Kilian, Sekulla: arXiv:1307.8170v2
  how to deal with large parameter space (I,J,M,Γ)?
  → develop specialized analysis techniques for simplified models?





Shifts in the (α_4, α_5) plane through heavy resonances in diff
nd ϕ are scalar resonances with $I = 0, 2$, respectively, ρ is a
tensor resonances of $I = 0, 2$, respectively. The dashed line
ameters from higher orders in the SM perturbative series.

Calculation: WHIZARD

$$m_X = 1800\ \text{GeV},\ \Gamma_X / m_X = 0.4$$

$$F_{S,0} = \frac{1}{2}\frac{F_f^2}{m_f^2},\ F_{S,1} = -\frac{1}{6}\frac{F_f^2}{m_f^2}$$

Limits in Term of **explicit model** here: Georgi-Machacek

- Recent CMS limits from $W^{\pm}W^{\pm}jj$ (CMS-SMP-17-004)
  - Boils down to *1* parameter only (s_H or x-section*BR)
  - limits extracted from fitting m_{jj} and m_{ll} distribution (how optimise?)

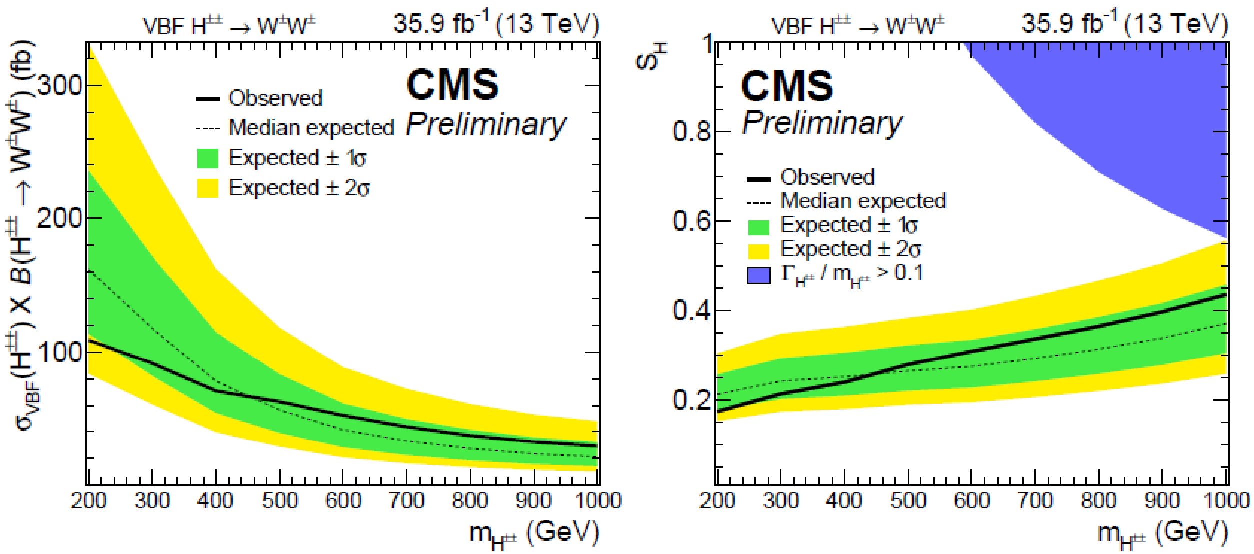


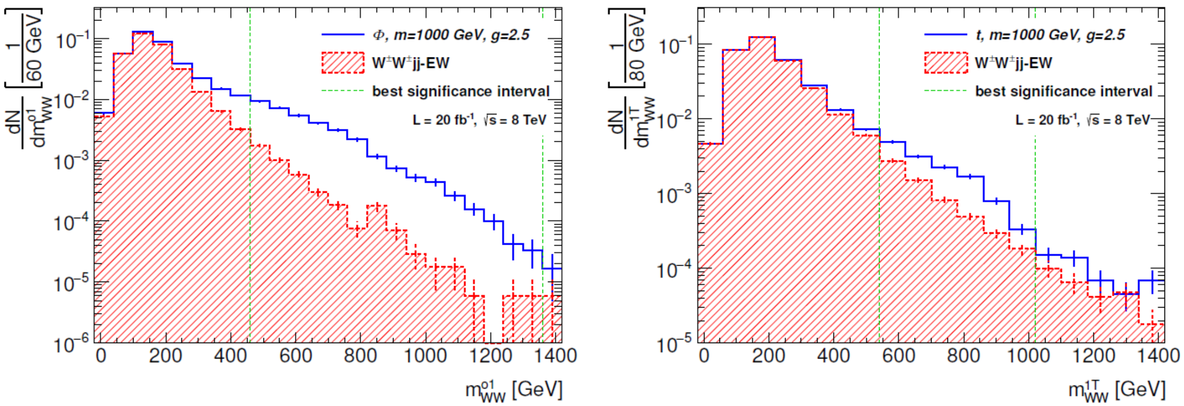
Figure 3: Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_{VBF}(H^{\pm\pm}) \times B(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm})$ (left) and on s_H in the Georgi–Machacek model (right) as a function of doubly charged Higgs boson mass. The blue area covers the theoretically not allowed parameter space [32].

Mass variables for finding resonances

- For channel with neutrinos, esp. The m_{1T} and m_{o1} seem to be best

Mass bound variables

- $M_{o1} = (|\vec{p}_T(\ell_1)| + |\vec{p}_T(\ell_2)| + |\vec{p}_{Tmiss}|)^2 - (\vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) + \vec{p}_{Tmiss})^2$
- $M_{1T} = \left(\sqrt{M_{\ell\ell}^2 + \vec{p}(\ell_1) + \vec{p}(\ell_2)} + |\vec{p}_{Tmiss}|\right)^2 - (\vec{p}(\ell_1) + \vec{p}(\ell_2) + \vec{p}_{Tmiss})^2$



(e) m_{o1}, ϕ resonance, $m = 1000\,\text{GeV}$, $g = 2.5$

(f) m_{1T}, t resonance, $m = 1000\,\text{GeV}$, $g = 2.5$

Figure 8.16: Reconstructed invariant diboson mass m_{WW}^{reco} for the determination of the discovery potential $S/\sqrt{B}$ for the ϕ (left) and t (right) resonance for masses $m \in \{500\,\text{GeV}, 750\,\text{GeV}, 1000\,\text{GeV}\}$ and coupling $g = 2.5$. For demonstration purposes, for each resonance parameter combination, the distribution of the mass variable is shown which gives the best discovery potential (compare Tables D.3 and D.4 in the appendix). The SM $W^\pm W^\pm$jj-EW distribution (red, filled) represents an estimate on the expected background. The $W^\pm W^\pm$jj contribution with resonances is shown in blue. The window comprising the bins with best discovery potential is marked (green, dashed). All distributions are normalised to the product of the corresponding parton level cross section (Table 5.3) and a luminosity of $20\,\text{fb}^{-1}$.

resonance	mass m [GeV]	coupling g	variable with best $S/\sqrt{B}$
ϕ	500	2.5	m_{o1}
	600		
	750		
	800		
	1000		
	1200		
t	500	2.5	m_{eff}
	600		$m_{1\text{T(bound)}}$
	750		$m_{1\text{T(bound)}}$
	800		m_{vec}, $m_{1\text{T(bound)}}$, m_{o1}
	1000		$m_{1\text{T}}$
	1200		$m_{1\text{Tbound}}$
ϕ	500	0.5	$m_{1\text{T}}$
		1.0	$m_{1\text{T(bound)}}$, m_{vis}
		1.5	$m_{1\text{T(bound)}}$
		2.0	m_{o1}
t	500	0.5	m_{vec}
		1.0	m_{vis}
		1.5	m_{eff}, $m_{1\text{T}}$
		2.0	$m_{1\text{T(bound)}}$

e 8.3: Best mass reconstruction variables with respect to th

- Diploma thesis, TU Dresden Steffi Todt, 01/2015, CERN-THESIS-2015-018

BEST WAY TO BSM INTERPRETATION?

Fit to complete distributions .vs.
extreme phase space regions

Limits on BSM from full distributions

- Recent CMS observation of W±W±jj (5.5. s.d., CMS-SMP-17-004)
  - large(-ish) statistics for limits, well verified via control regions,

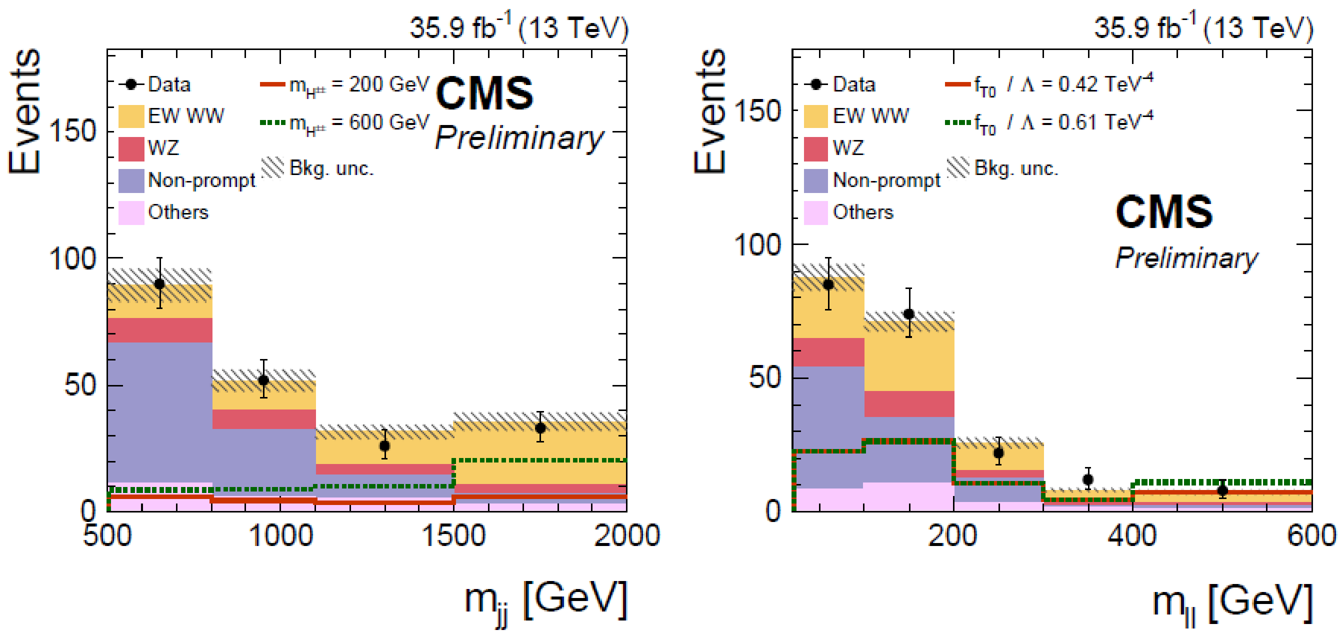
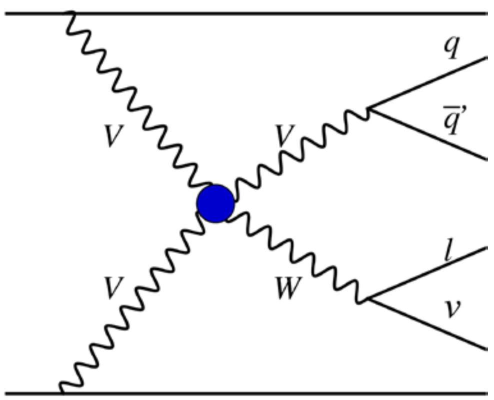


Figure 2: Distributions of m_{jj} (left) and $m_{\ell\ell}$ (right) in the signal region. The normalization of the predicted signal and background distributions corresponds to the result of the fit. The hatched bars include statistical and systematic uncertainties. For illustration, the doubly charged Higgs boson signal normalized to a cross section of 0.1 pb (left) and the distribution with aQGCs are shown. The histograms for other backgrounds include the contributions from QCD WW, Wγ, wrong-sign events, DPS, and VVV processes.

sensitivity of extreme phase space

- ATLAS VBS WV+jj semileptonic: http://arxiv.org/abs/1609.05122
- Advantages of semi-leptonic channel
  - Can reconstruct boson kinematics
  - Background falls as you move to higher pTs, -> ideal for aQGC measurements



- Signal from multiple sources
  - Opp.Sign WW, Same Sign WW, WZ
  - prevents translation between aQGC params
- higher background :
  - SM hard to see, but more sensitive for BSM **especially in merged V->J**
- Two main selection channels

Resolved V → jj	Merged V->J
$\geq$4 small-R jets	$\geq$2 small-R jets
W jet pairs: $64 < m_{jj} < 96$ GeV	W-Jet: $64 < m_J < 96$ GeV, closest to m_W
Tagging jets: max m_{jj} pair remaining	

Event Selection

- M(j,j) > 900 GeV (tag jets)
- MET > 30 GeV
- b-veto
- Boson centrality > 0.9

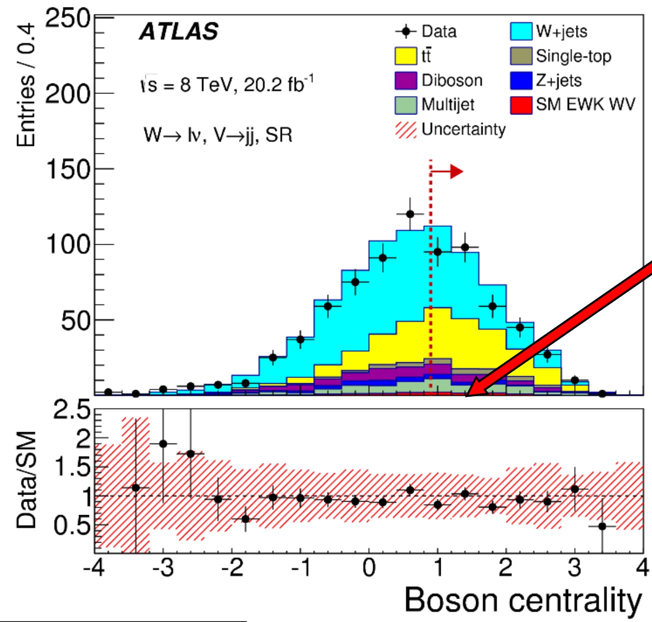
$$\zeta = min\{\Delta\eta_-, \Delta\eta_+\},$$

$$\Delta\eta_- = min\{\eta_i\} - min\{\eta_{j_{t1}}, \eta_{j_{t2}}\},$$

$$\Delta\eta_+ = max\{\eta_{j_{t1}}, \eta_{j_{t2}}\} - max\{\eta_i\}.$$

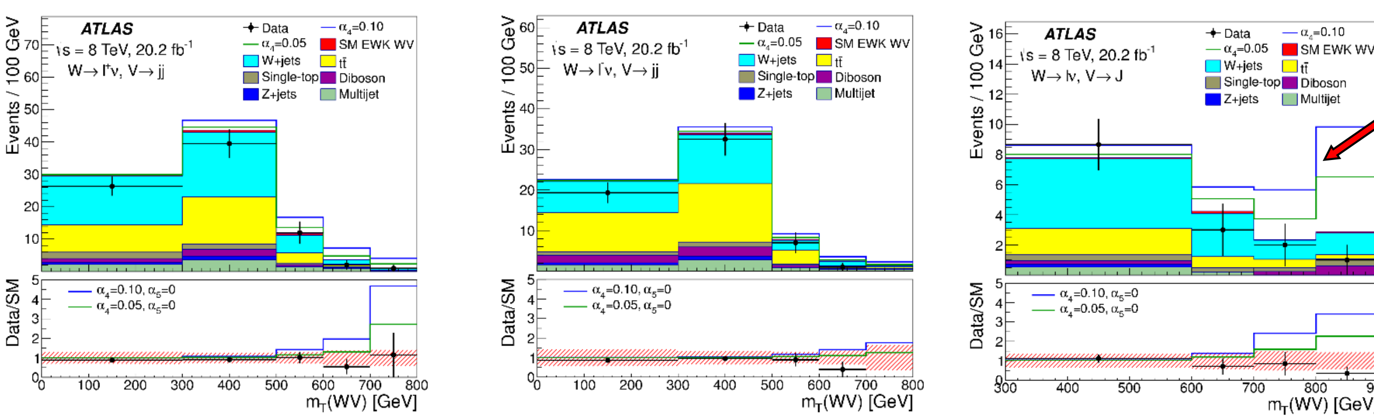
Dominant Background

- W+Jets, ttbar <- control regions



SM VBS Signal

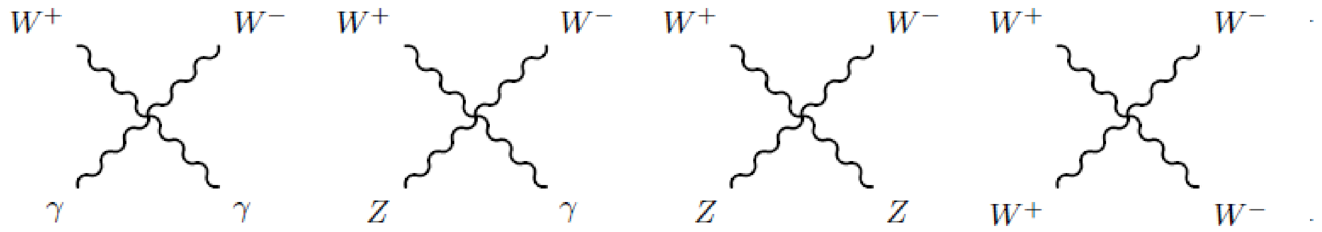
$$m_T(WV) = \sqrt{(E_T(V_{had}) + E_T(W_{lep}))^2 - (p_x(V_{had}) + p_x(W_{lep}))^2 - (p_y(V_{had}) + p_y(W_{lep}))^2}$$



aQGC Effect

Instead of a summary: Our aims

- Standard model:
  - $\mathcal{L}_{WWVV}$ contains the quartic gauge self-couplings (QGC)



$$\mathcal{L}_{WWVV} = -\frac{g^2}{4}\left\{[2W_\mu^+W^{-\mu} + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)^2]^2 - [W_\mu^+W_\nu^- + W_\nu^+W_\mu^- + (A_\mu \sin\theta_W - Z_\mu \cos\theta_W)(A_\nu \sin\theta_W - Z_\nu \cos\theta_W)]^2\right\}$$

  - no neutral self-couplings in the SM

1. **Observe all SM QGC Processes with these vertices**
2. **Constrain or find BSM physics (in EFT or full models)**
3. **Test Eweak Symmetry breaking and Higgs properties**
   - **One of the core reasons, why LHC has been built!**

BACKUP

2. Beyond the SM: aQGC

- **Assume SM is effective theory of a more complex one**, as e.g.
  - Low-E Fermi-Theorie with 4f Vertex → Weak Gauge Bosons in SU(2)
  - Low-E Chiral QCD langrangian → Composite qq condensate, hadrons

- **Consider effective electroweak Langrangian**

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_{\text{dimension } d} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

  - valid only, if new physics beyond kinematic reach ($\Lambda \gg \sqrt{\hat{s}}$)
  - model independent, complementary to direct searches
  - generally requires additional unitarization (re-introducing model dependence)

- **Relevant parameters for aQGC contributions**
  - Some d=8 parameters can be mapped to those for d=6 and d=4

d=4	d=6	d=8
WWWW, WWZZ	WWZγ, WW$\gamma\gamma$	all VVVV
Chiral Lagrangian non-linear representation		Effective Operators linear representation
α_4 , α_5	a_0 / Λ^2 , a_C / Λ^2	$f_{S,i} / \Lambda^4$, $f_{M,i} / \Lambda^4$, $f_{T,i} / \Lambda^4$
Appelquist et al. (1980)	Belanger et al. (1992)	Eboli et al. (2006)

Effective QGC in VBS

$$\mathcal{L}_4 = \alpha_4 \frac{g^2}{2} \left\{ \left[(w^+ w^+)(w^- w^-) + (w^+ w^-)^2 \right] + \frac{2}{c_W^2} (w^+ z)(w^- z) + \frac{1}{2 c_W^4} (zz)^2 \right\}$$

$$\mathcal{L}_5 = \alpha_5 \frac{g^2}{2} \left\{ (w^+ w^-)^2 + \frac{2}{c_W^2} (w^+ w^-)(zz) + \frac{1}{2 c_W^4} (zz)^2 \right\}$$

- = Effective parametrization of physics beyond kinematic reach
  - e.g. resonances at new physics scale $\Lambda = \upsilon / \sqrt{\alpha_i}$
    - Wide: → continuum
    - Narrow: → particles
  - α parametrize low-mass tail of these resonances, e.g. $\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8 M_\sigma^2} \right)$

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs ?)	ω^0 $(\gamma'/Z'\ ?)$	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'\ ?)$	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

- Unitarization only guaranteed for
  - Explicitly included resonance(s) at unique value(s) of *g*
  - effective parametrization always violates unitarity at some m_{VV}

Why is d/u << 0.5 at large x? Two Models on the market:

review: W.Melnitchouk, A.W.Thomas: http://arxiv.org/pdf/nucl-th/9602038.pdf

- *Close(1973), Carlitz(1975): Broken SU(6) symmetrie (from SU(3)$_{flavor}$ x SU(2)$_{spin}$)*

$$p\uparrow = \frac{1}{\sqrt{2}} u\uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u\uparrow \cancel{(ud)}_{S=1} - \frac{1}{3} u\downarrow \cancel{(ud)}_{S=1} - \frac{1}{3} d\uparrow \cancel{(uu)}_{S=1} - \frac{\sqrt{2}}{3} d\downarrow \cancel{(uu)}_{S=1},$$

- spin-induced mass splitting

$$(qq)_{S=0} \gg (qq)_{S=1}, \qquad x \to 1.$$

- Proton at x→1 dominated by single u-quark (carries spin)

$$\frac{F_2^n}{F_2^p} \to \frac{1}{4}, \qquad \frac{d}{u} \to 0 \qquad [S = 0 \text{ dominance}].$$

- *Farrar et al(1975), Brodsky et al(1995) perturbative QCD*
  large x-behaviour for quarks parallel ($\Delta S_z = 1$) or antiparallel ($\Delta S_z = 0$) to proton helicity:

$$q^{\uparrow\downarrow}(x) = (1 - x)^{2n-1+\Delta S_z}$$

- Di-quark spin *projection*

$$(qq)_{S_z=0} \gg (qq)_{S_z=1}, \qquad x \to 1.$$

- Proton at x→ 1 has non-zero d/u

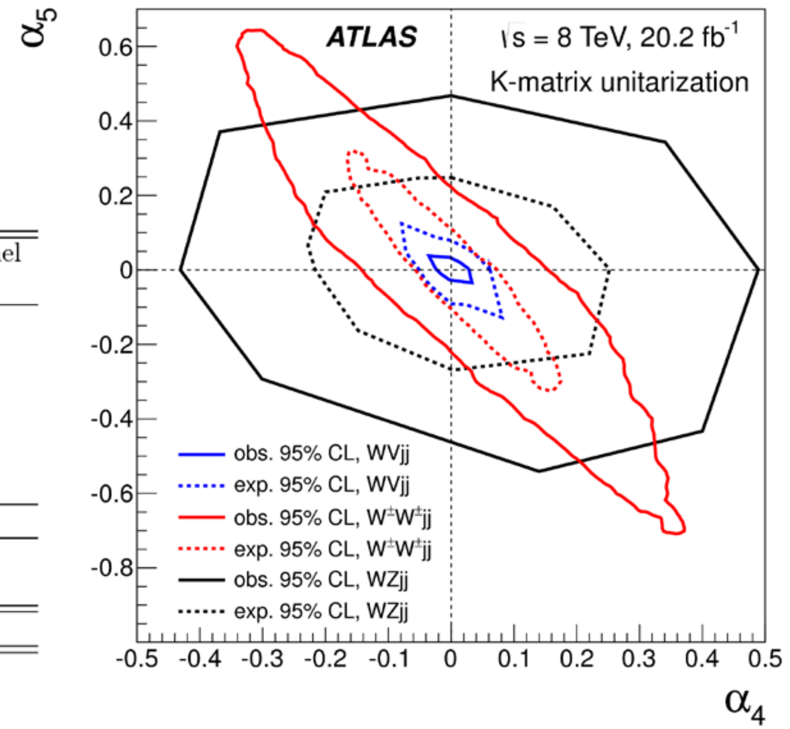
$$\frac{F_2^n}{F_2^p} \to \frac{3}{7}, \qquad \frac{d}{u} \to \frac{1}{5} \qquad [S_z = 0 \text{ dominance}].$$

Comparison of ATLAS aQGC limits

- Best sensitivity: semileptonic WVjj
  - Obs: Λ > 1500 GeV with Λ ~ v/√α

$$-0.024 < \alpha_4 < 0.030 \text{ and } -0.028 < \alpha_5 < 0.033$$

	Resolved channel		Merged channel
	e^+ and μ^+	e^- and μ^-	e and μ
$W+$jets	92 ± 37	51 ± 29	19.4 ± 9.9
$t\bar{t}$	59 ± 18	63 ± 35	6.8 ± 2.8
Single-top	10.0 ± 5.6	5.5 ± 3.2	2.2 ± 1.2
Diboson	8.6 ± 5.7	10.8 ± 6.4	1.6 ± 1.2
$Z+$jets	4.5 ± 1.5	3.4 ± 2.4	0.58 ± 0.64
Multijet	16 ± 16	12 ± 12	1.8 ± 1.9
Total background	190 ± 53	145 ± 54	32 ± 12
EWK WV (SM)	3.66 ± 0.82	2.34 ± 0.56	0.54 ± 0.22
EWK WV ($\alpha_4 = 0.1, \alpha_5 = 0$)	21.0 ± 4.2	9.2 ± 1.9	15.1 ± 4.4
Data	173	131	32



- Compare the *dashed* lines
  - Black : WZ (observed: excess)
  - Red: W±W± (observed: excess)
  - Blue: WV (observed: deficit)
- Low statistics gives broad band for expected limit, example:
  WZ VBS, compared to (old) W±W± VBS