Vector Boson Scattering at Electron Colliders

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Motivation for Vector Boson Scattering

Physics potential of Vector Boson Scattering:

1. Precision test of the electroweak SM at high energies
2. The Higgs Mechanism at work
3. Non-standard Higgs couplings
4. New Higgs-sector physics: the Higgs Portal
   - Extra Higgses
   - Resonances excited by VBF
   - Strong interactions, continuum, compositeness, top quarks
   - New final states (Dark Matter ?)

Requirements / Benefits at High-Energy Electron colliders $s \gtrsim 1\ \mathrm{TeV}^2$

1. High energy: $s \gtrsim 1\ \mathrm{TeV}^2$
2. Well-defined initial state: electroweak production (small theory errors)
3. High precision, triggerless operation: complete coverage of final states
4. Separation of spin, isospin, CP quantum number
5. Discriminating power even on (some) light quark flavors

Setup of ILC / CLIC

(HE-)ILC: energies & staging

- [E_1 = 0.25 TeV, $\mathscr{L}_{\text{int}}$ = 2,000 fb^{-1}]
- [E_2 = 0.35 TeV, $\mathscr{L}_{\text{int}}$ = 200 fb^{-1}]
- ⋮ E_3 = 0.5 TeV, $\mathscr{L}_{\text{int}}$ = 4,000 fb^{-1} ⋮
- E_4 = 1.0 TeV, $\mathscr{L}_{\text{int}}$ = 8,000 fb^{-1}

Initial state polarization: 80% e^- , ≳30% e^+

CLIC: energies & staging

- [E_1 = 0.35/0.38 TeV, $\mathscr{L}_{\text{int}}$ = 100+500 fb^{-1}]
- E_2 = 1.5 TeV, $\mathscr{L}_{\text{int}}$ = 1,500 fb^{-1}
- E_3 = 3.0 TeV, $\mathscr{L}_{\text{int}}$ = 3,000 fb^{-1}

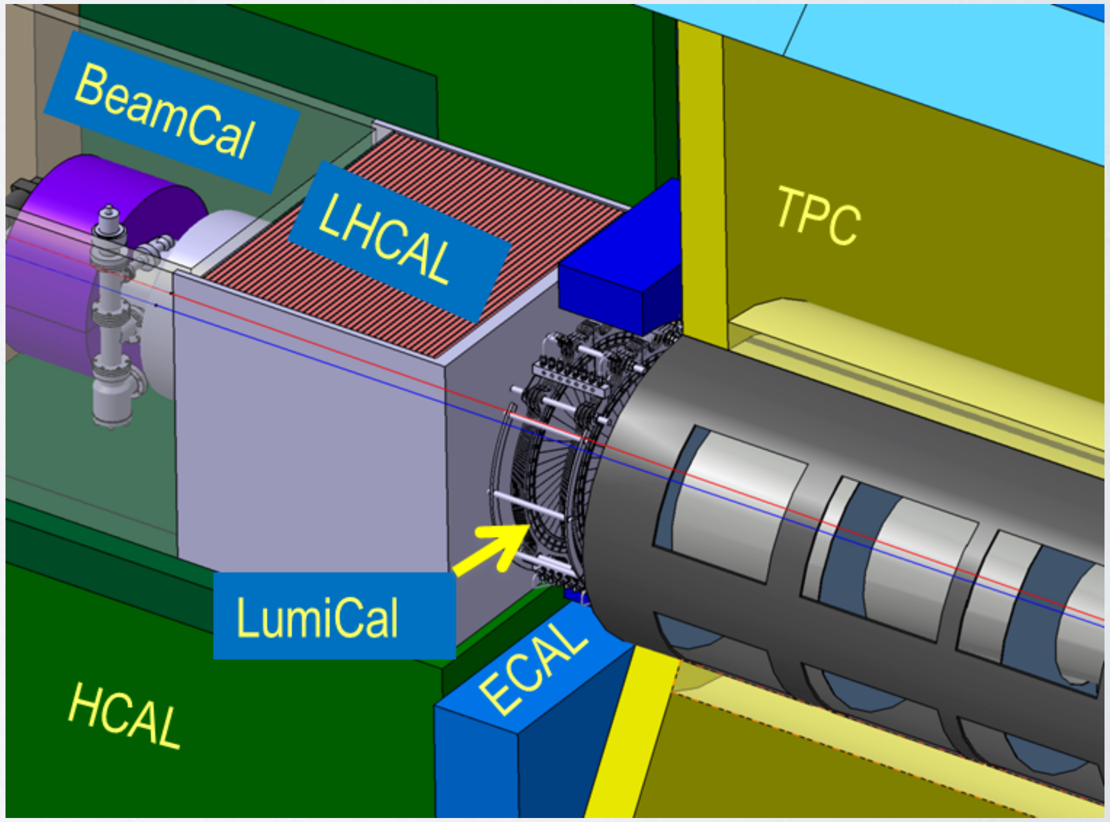
Initial state polarization: 80% e^- , 0% e^+

Low angle coverage

M. Idzik: A.Phys. Pol. B46 (2015) 1297

- LumiCal: 38 — 110 mrad
- BeamCal: 15 — 38 mrad

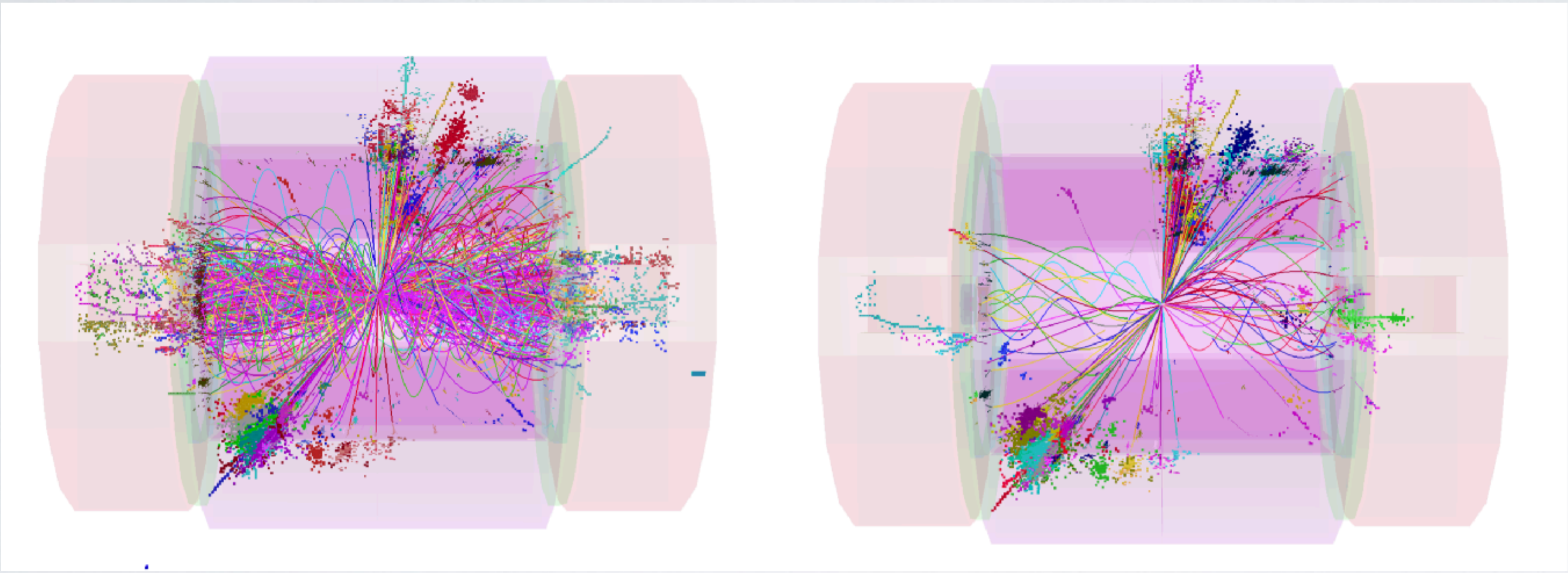
can go down to 15 mrad, i.e. $\eta \approx 4.9$



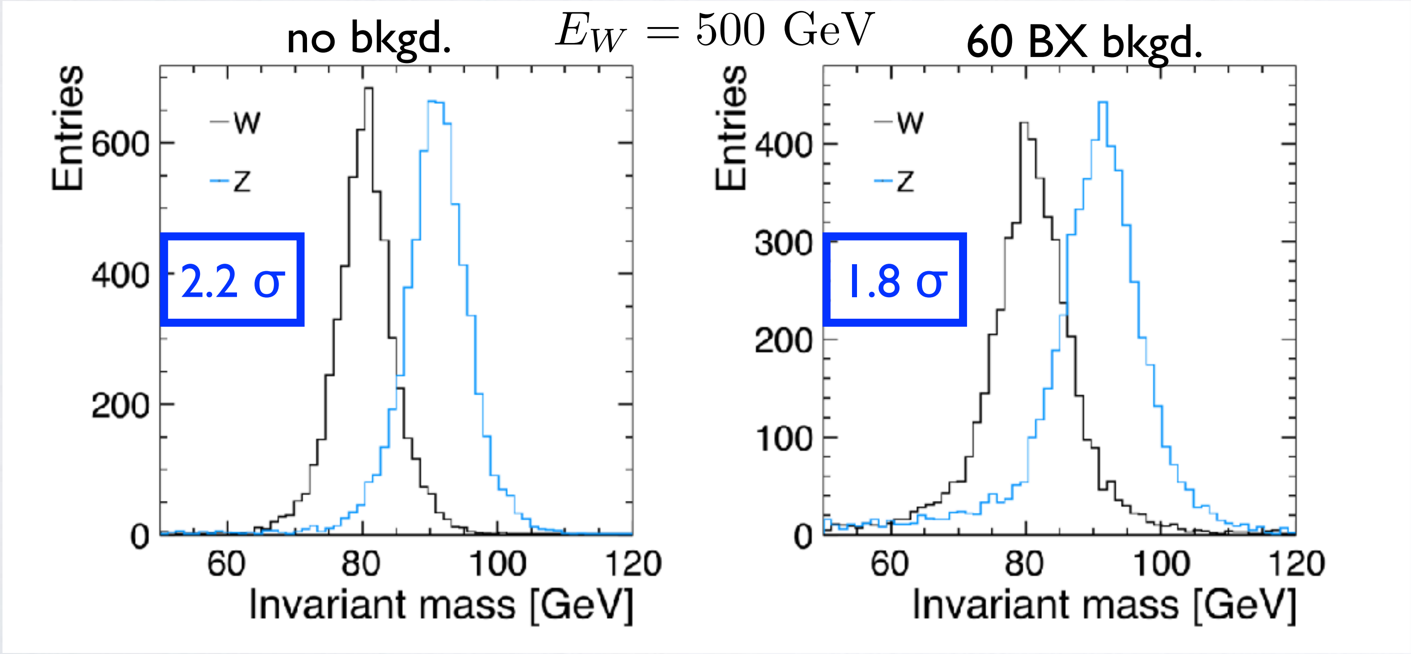
Identification of hadronic *W / Z*

J. S. Marshall / A. Münnich / M.A. Thomson , arXiv: 1209.4039

Particle Flow Algorithm (PFA) allows very good particle ID for ILD detector



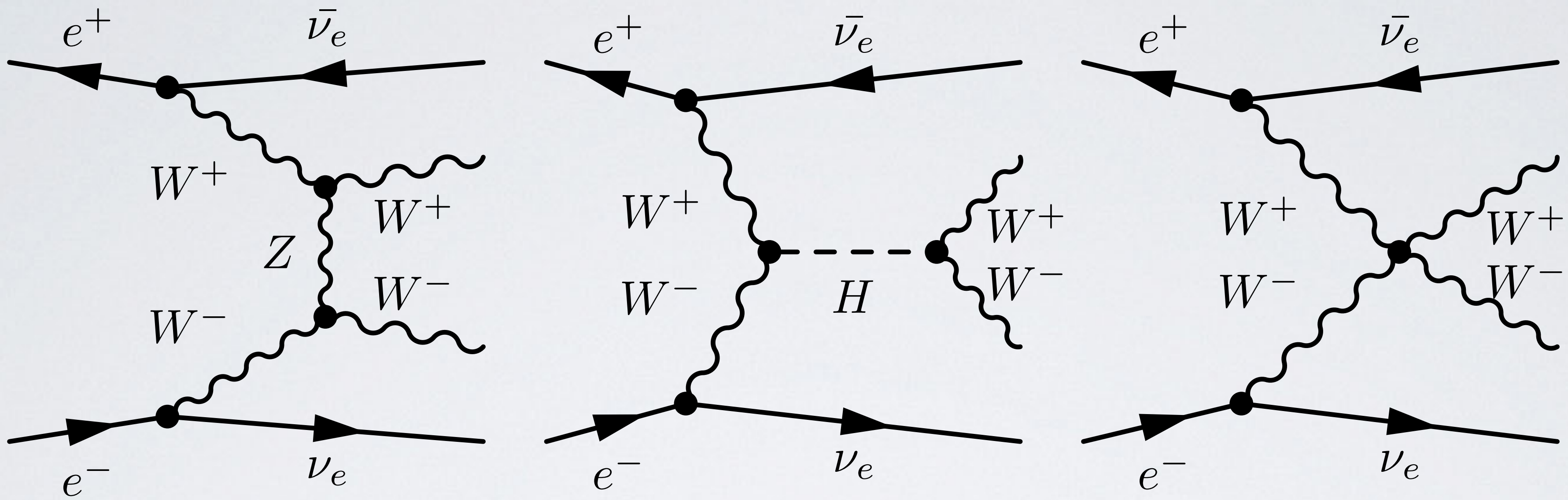
Tight PFO removes photon-induced background from 1.2 TeV to 100 GeV



- *W/Z* discrimination: 88% efficiency
- With γ-induced bkgd: 71 — 79 %

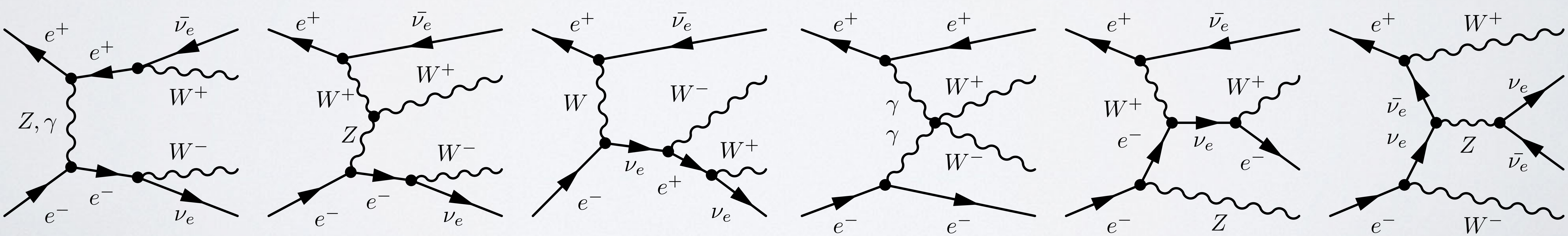
Vector Boson Scattering in $e^+ e^-$

Signal process: triple gauge couplings, Higgs-V-V couplings, quartic gauge couplings



same for WZ and ZZ , using all W/Z decays, particularly $W/Z \to jj$

Background: difermions with EW radiation, single W, tribosons, radiative dibosons etc.



(Non-exhaustive) Literatur: VBS in $e^+ e^-$ / $e^- e^-$

- Gunion/Tofighi-Niaki, PRD36 (1987) 2671: full MEs for VBS (*WW*) and heavy Higgs production [0.5, 1, 2 TeV]
- Gunion/Tofighi-Niaki, PRD38 (1988) 1433: same for *ZZ* final states [0.5, 1, 2 TeV]
- Barger/Cheung/Han/Phillips, PRD52 (1995) 3815: measurements of *WW*/*ZZ* ratios [1.5 – 2 TeV]
- Dominici, Riv.Nuo.Cim.20 (1997) 1: access to parameters of EW chiral Lagrangian in *WW* VBS [1.5 TeV]
- Denner/Dittmaier/Hahn, PRD56 (1997) 117: EW corrections to $ZZ \to ZZ$
- Denner/Hahn, NPB525 (1998) 27: EW corrections to $WW \to WW$
- Han/He/Yuan, PLB422 (1998) 294: interplay of *WW* VBS and *WWZ*/*ZZZ* production [0.5, 0.8, 1, 1.6 TeV]
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD57 (1998) 1553: EW chiral Lagrangian (strong EW) [1.6 TeV]
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD61 (2000) 077901: strong EW: ZZ/W^-W^- channels [1.6 TeV]
- Kilian, Int.J.Mod.Phys.A15 (2000) 2387: strong EW in e^-e^- [1 TeV]
- Linear Collider Physics Ressource Book 2001, Part 3: Studies of Exotic and SM Physics [hep-ex/0106057]
- Chierici/Rosati/Kobel, LC-PHSM-2001-038 : experimental study for strong EW [0.18–0.8 TeV]
- Rosati, CERN-THESIS-2002-083 : experimental study for strong EW [0.18–0.8 TeV]
- Beyer/Kilian/Krstonošić/Mönig/JRR/Schmidt/Schröder, EPJC48 (2006) 353: α parameters, VBS+VVV [1 TeV]
- Accomando/Denner/Pozzorini, JHEP 0703 (2007) 078: EW Sudakov logarithms in VBS [3 TeV]
- Liebler/Moortgat-Pick/Weiglein, JHEP 1506 (2015) 093: Off-shell Higgs effects in $ee \to \nu\nu VV$ [0.25 – 1 TeV]
- Fleper/Kilian/JRR/Sekulla, EPJC77.2 (2017) 120: VBS for SMEFT with dim 8 / simplified models [1, 1.4, 3 TeV]

VBS in $e^+ e^-$: SM rates and Backgrounds (I)

Experimentally: study all processes that lead to VBS–like signatures [1 TeV]:

	Process	Subprocess	σ [fb]
Vector-Boson Scattering	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to W^+W^-$	23.19
	$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to ZZ$	7.624
Triboson Production	$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
Vector-Boson Scattering / Radiative Bhabha	$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
	$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
	$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
Top [pair] production	$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
Diboson Production	$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
	$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
Single W Production	$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
Radiative Z Production	$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
QCD Di-/Multijets	$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

[80% e^-, 40% e^+ polarization]

[Beyer/Kilian/Krstonošić/Mönig/JRR/Schmidt/Schröder, EPJC48 (2006) 353]

VBS in $e^+ e^-$: SM rates and Backgrounds (II)

Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar{\nu}$	47.1	132	1
$W^+W^-e^+e^-$	1570	3820	1
$W^\pm Ze^\mp\nu$	138	408	0.136
ZZe^+e^-	3.78	4.70	0.019
$W^+W^-(Z \to \nu\bar{\nu})$	11.7	9.35	1
$ZZ\nu\bar{\nu}$	15.7	57.5	1
ZZe^+e^-	3.78	4.70	1
$W^\pm Ze^\mp\nu$	138	408	0.136
$W^+W^-e^+e^-$	1570	3820	0.019
$ZZ(Z \to \nu\bar{\nu})$	0.484	0.237	1

Total cross sections [fb], no cuts

Mismatched hadronic vector bosons

Triboson background

[80% e^-, 0% e^+ polarization]

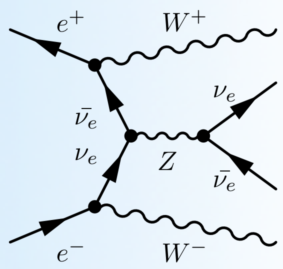
Fleper/Kilian/JRR/Sekulla: 1607.03030

- Signal cross sections rise factor 3–4 from 1.4 to 3 TeV
- Mistagging from *W/Z* conversions in hadronic bosons: severe for *WZ* scattering
- Irreducible backgrounds from tribosons (Gauge invariance connects full processes)

VBS in e⁺ e⁻ : Selection / isolation cuts

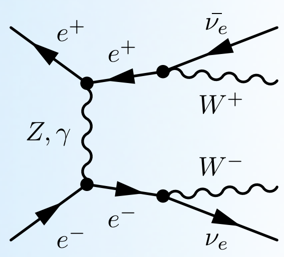
Cuts for 1 TeV ILC — 1.4 TeV CLIC — 3 TeV CLIC

- **Suppression of background from Z → $\nu\nu$, W⁺W⁻ , and QCD 4-jet production**



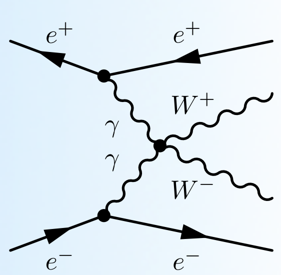
1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$M_{inv}(\bar\nu\nu) > 150\,\mathrm{GeV}$	$M_{inv}(\bar\nu\nu) > 175\,\mathrm{GeV}$	$M_{inv}(\bar\nu\nu) > 230\,\mathrm{GeV}$

- **Suppression of background from t–channel exchange in subprocess**



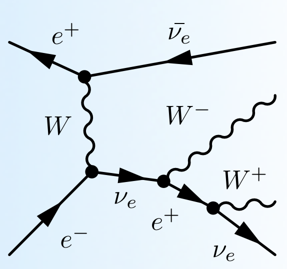
1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$p_{\perp,W/Z} > 150\,\mathrm{GeV}$	$p_{\perp,W/Z} > 180\,\mathrm{GeV}$	$p_{\perp,W/Z} > 300\,\mathrm{GeV}$
$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$

- **Suppression of $\gamma\gamma$–fusion induced backgrounds**



1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$p_\perp(WW) > 45\,\mathrm{GeV}$	$p_\perp(WW) > 50\,\mathrm{GeV}$	$p_\perp(WW) > 100\,\mathrm{GeV}$
$p_\perp(ZZ) > 40\,\mathrm{GeV}$	$p_\perp(ZZ) > 40\,\mathrm{GeV}$	$p_\perp(ZZ) > 60\,\mathrm{GeV}$
$\theta(e) > 15\,\mathrm{mrad}$	$\theta(e) > 15\,\mathrm{mrad}$	$\theta(e) > 15\,\mathrm{mrad}$

- **Suppression of non-scattering vector boson processes [i.e. massive EW radiation]**



1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$M_{inv}^{WW} \in [575, 800]\,\mathrm{GeV}$	$M_{inv}^{WW} \in [800, 1175]\,\mathrm{GeV}$	$M_{inv}^{WW} \in [900, 1900]\,\mathrm{GeV}$
$M_{inv}^{ZZ} \in [600, 800]\,\mathrm{GeV}$	$M_{inv}^{ZZ} \in [800, 1175]\,\mathrm{GeV}$	$M_{inv}^{ZZ} \in [850, 1900]\,\mathrm{GeV}$

Deviations as EFT — Dim 8 Operators

Motivated by SMEFT:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \right]$$

S. Weinberg, 1979 — Buchmüller/Wyler, 1986

Grzadkowski/Iskrzysnki/Misiak/Rosiek, 2010

Eboli/Gonzalez-Garcia/Mizukoshi, 2006

Alboteanu/Kilian/JRR, 2008 — Kilian/Ohl/JRR/Sekulla, 2014

Longitudinal operators

$$\mathcal{L}_{S,0} = F_{S,0} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}_\nu \mathbf{H})\right] \operatorname{tr}\left[(\mathbf{D}^\mu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})\right]$$

$$\mathcal{L}_{S,1} = F_{S,1} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \operatorname{tr}\left[(\mathbf{D}_\nu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})\right]$$

Mixed operators

$$\mathcal{L}_{M,0} = -g^2 F_{M_0} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \operatorname{tr}\left[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\rho}\right]$$

$$\mathcal{L}_{M,1} = -g^2 F_{M_1} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \operatorname{tr}\left[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu}\right]$$

$$\mathcal{L}_{M,2} = -g'^2 F_{M_2} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \operatorname{tr}\left[\mathbf{B}_{\nu\rho} \mathbf{B}^{\nu\rho}\right]$$

$$\mathcal{L}_{M,3} = -g'^2 F_{M_3} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \operatorname{tr}\left[\mathbf{B}_{\nu\rho} \mathbf{B}^{\nu\mu}\right]$$

$$\mathcal{L}_{M,4} = -g g' F_{M_4} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\mu \mathbf{H}) \mathbf{B}^{\nu\rho}\right],$$

$$\mathcal{L}_{M,5} = -g g' F_{M_5} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\rho \mathbf{H}) \mathbf{B}^{\nu\mu}\right],$$

$$\mathcal{L}_{M,7} = -g^2 F_{M_7} \operatorname{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu} (\mathbf{D}^\rho \mathbf{H})\right];$$

Transversal operators

$$\mathcal{L}_{T,0} = g^4 F_{T_0} \operatorname{tr}\left[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}\right] \operatorname{tr}\left[\mathbf{W}_{\alpha\beta} \mathbf{W}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T,1} = g^4 F_{T_1} \operatorname{tr}\left[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta}\right] \operatorname{tr}\left[\mathbf{W}_{\mu\beta} \mathbf{W}^{\alpha\nu}\right],$$

$$\mathcal{L}_{T,2} = g^4 F_{T_2} \operatorname{tr}\left[\mathbf{W}_{\alpha\mu} \mathbf{W}^{\mu\beta}\right] \operatorname{tr}\left[\mathbf{W}_{\beta\nu} \mathbf{W}^{\nu\alpha}\right],$$

$$\mathcal{L}_{T,5} = g^2 g'^2 F_{T_5} \operatorname{tr}\left[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}\right] \operatorname{tr}\left[\mathbf{B}_{\alpha\beta} \mathbf{B}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T,6} = g^2 g'^2 F_{T_6} \operatorname{tr}\left[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta}\right] \operatorname{tr}\left[\mathbf{B}_{\mu\beta} \mathbf{B}^{\alpha\nu}\right],$$

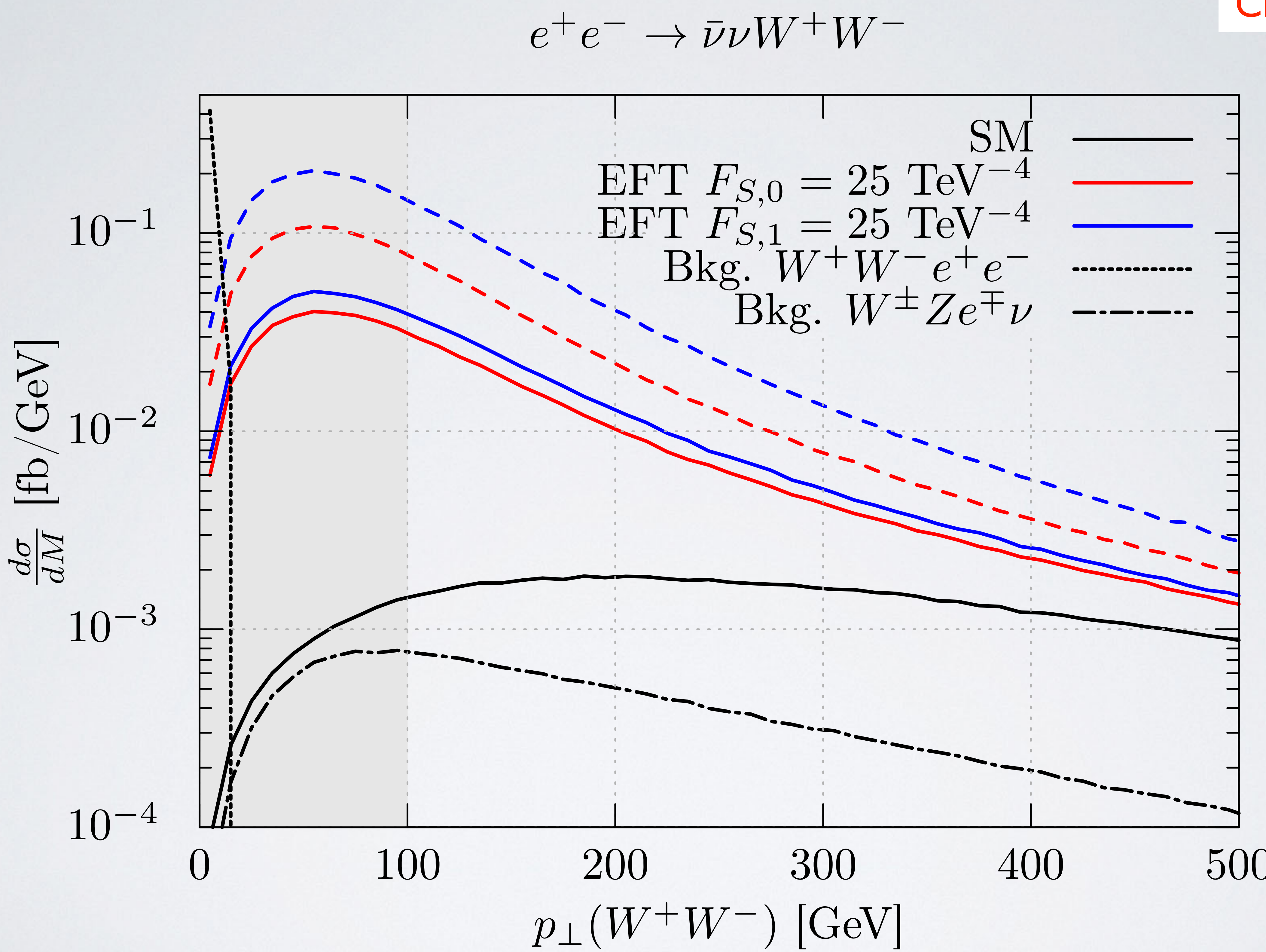
$$\mathcal{L}_{T,7} = g^2 g'^2 F_{T_7} \operatorname{tr}\left[\mathbf{W}_{\alpha\mu} \mathbf{W}^{\mu\beta}\right] \operatorname{tr}\left[\mathbf{B}_{\beta\nu} \mathbf{B}^{\nu\alpha}\right],$$

$$\mathcal{L}_{T,8} = g'^4 F_{T_8} \operatorname{tr}\left[\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}\right] \operatorname{tr}\left[\mathbf{B}_{\alpha\beta} \mathbf{B}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T,9} = g'^4 F_{T_9} \operatorname{tr}\left[\mathbf{B}_{\alpha\mu} \mathbf{B}^{\mu\beta}\right] \operatorname{tr}\left[\mathbf{B}_{\beta\nu} \mathbf{B}^{\nu\alpha}\right].$$

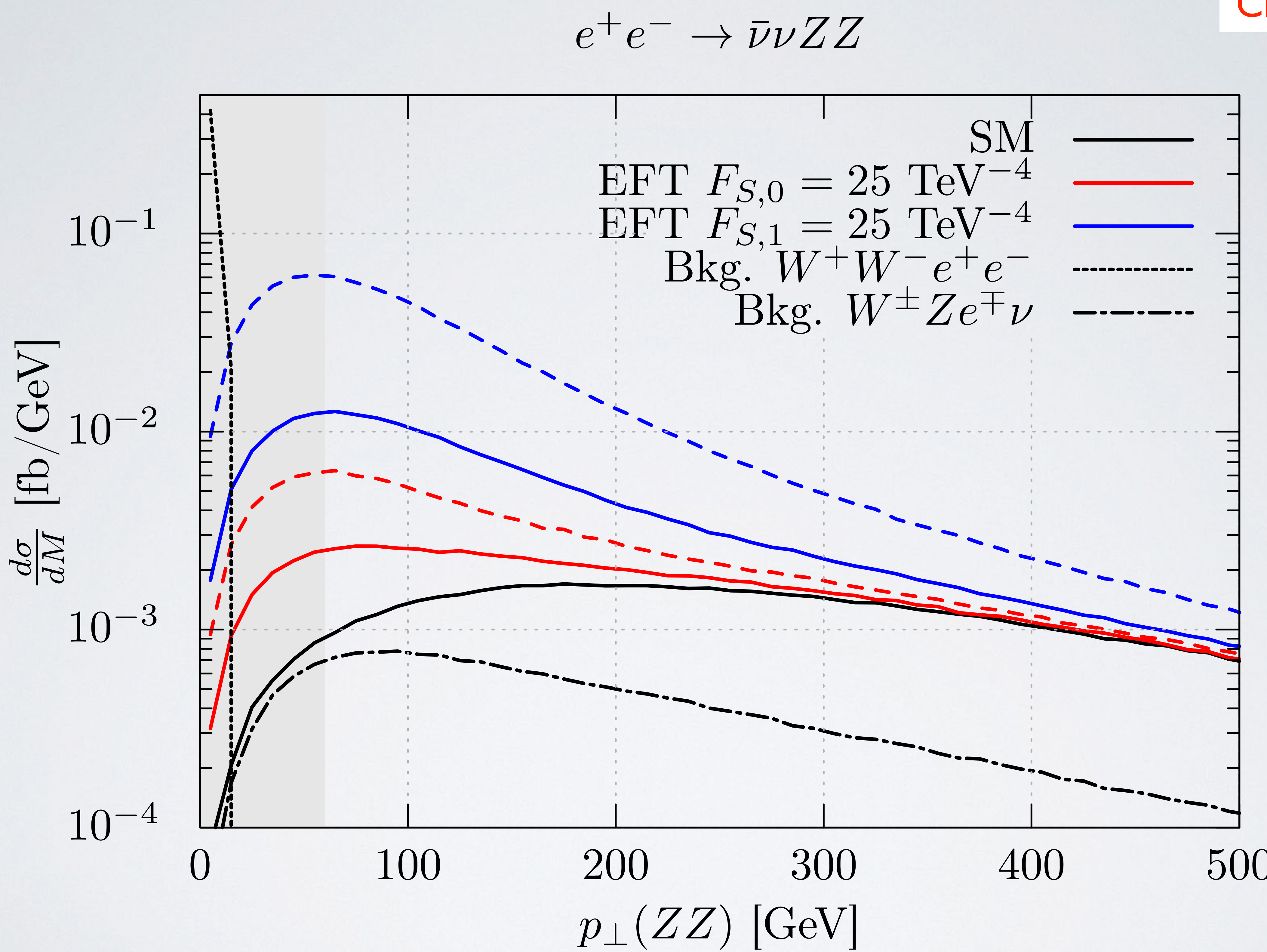
Longitudinal Vector Boson Scattering in $e^+ e^-$

CLIC 3 TeV

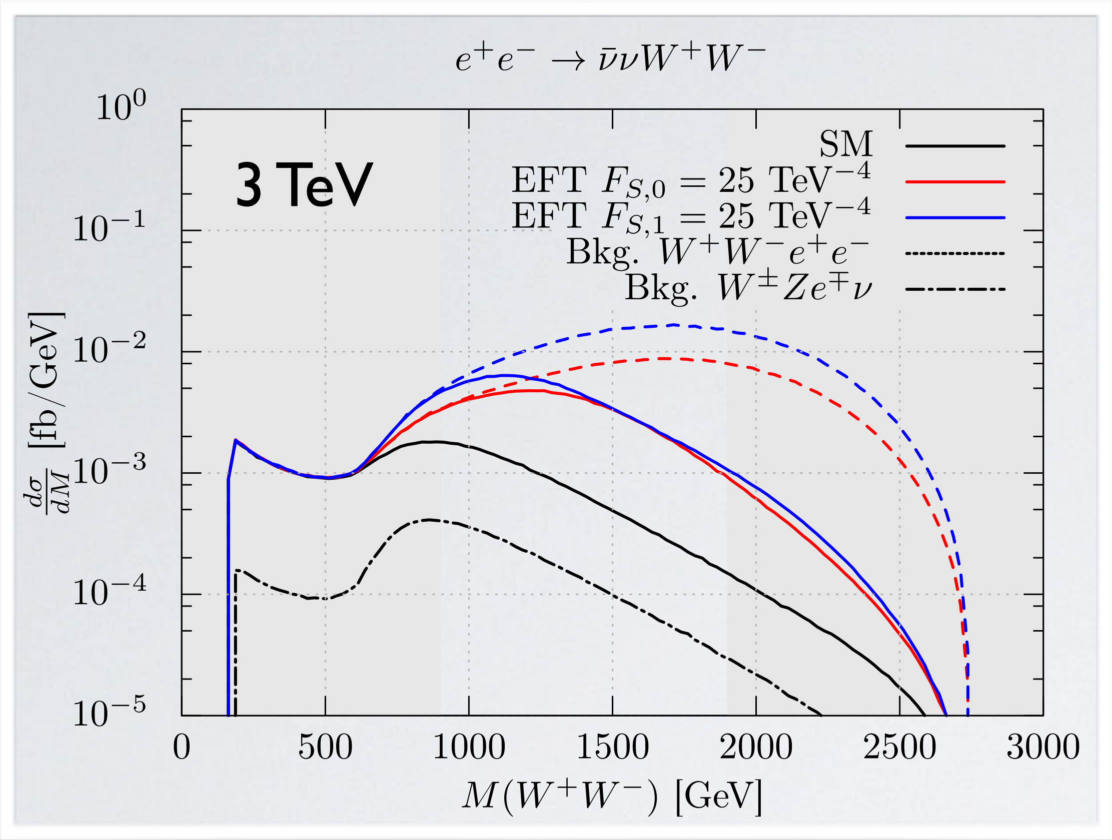


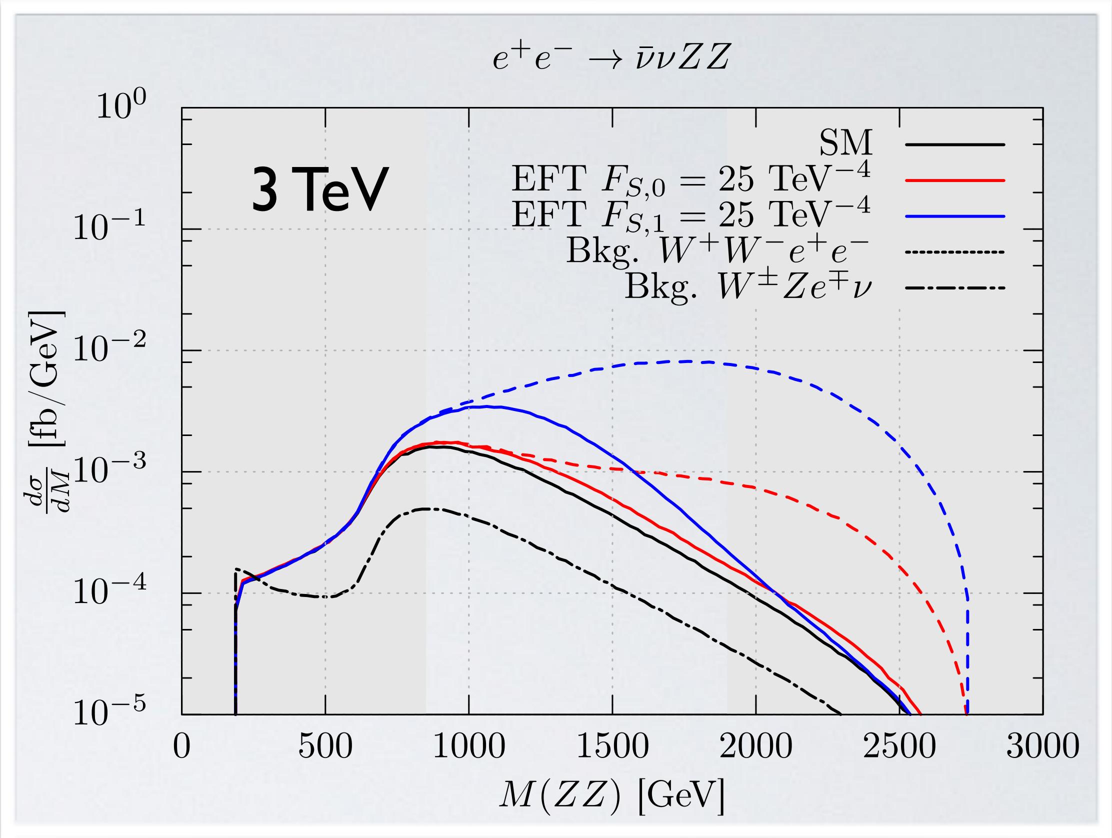
Longitudinal Vector Boson Scattering in e⁺ e⁻

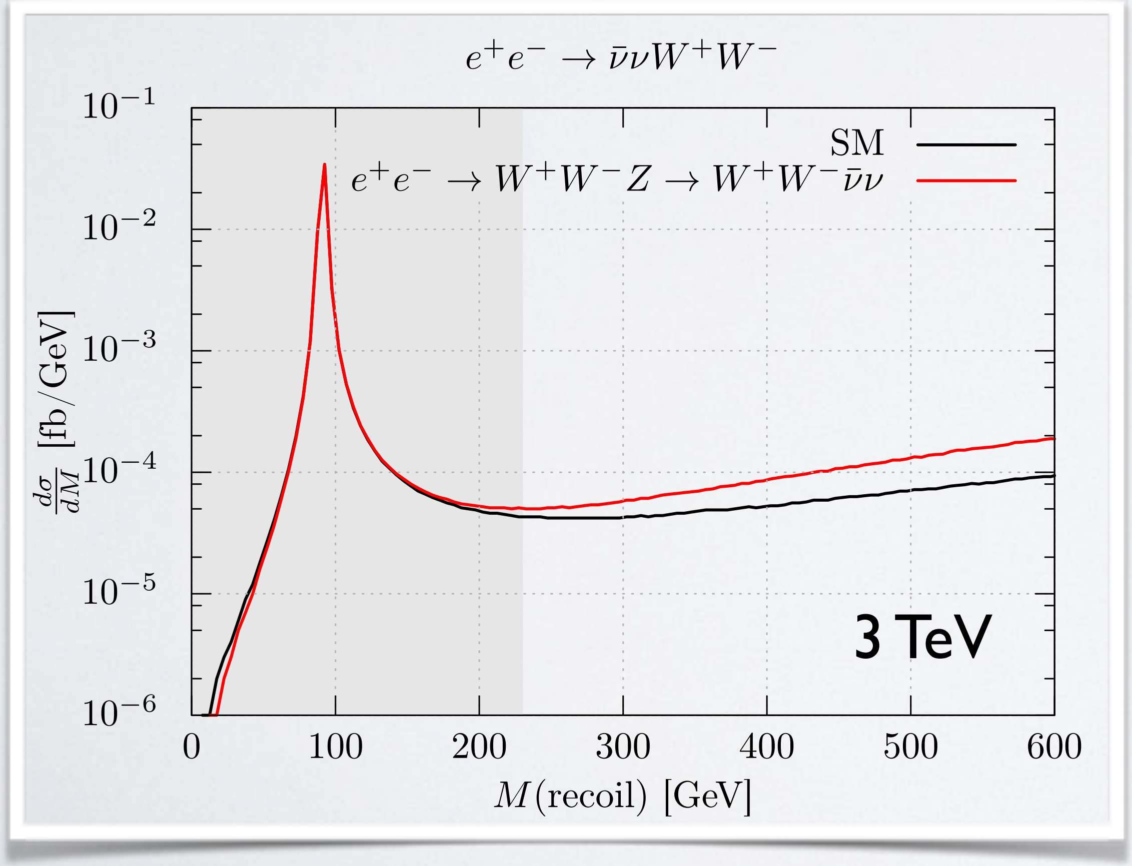
CLIC 3 TeV

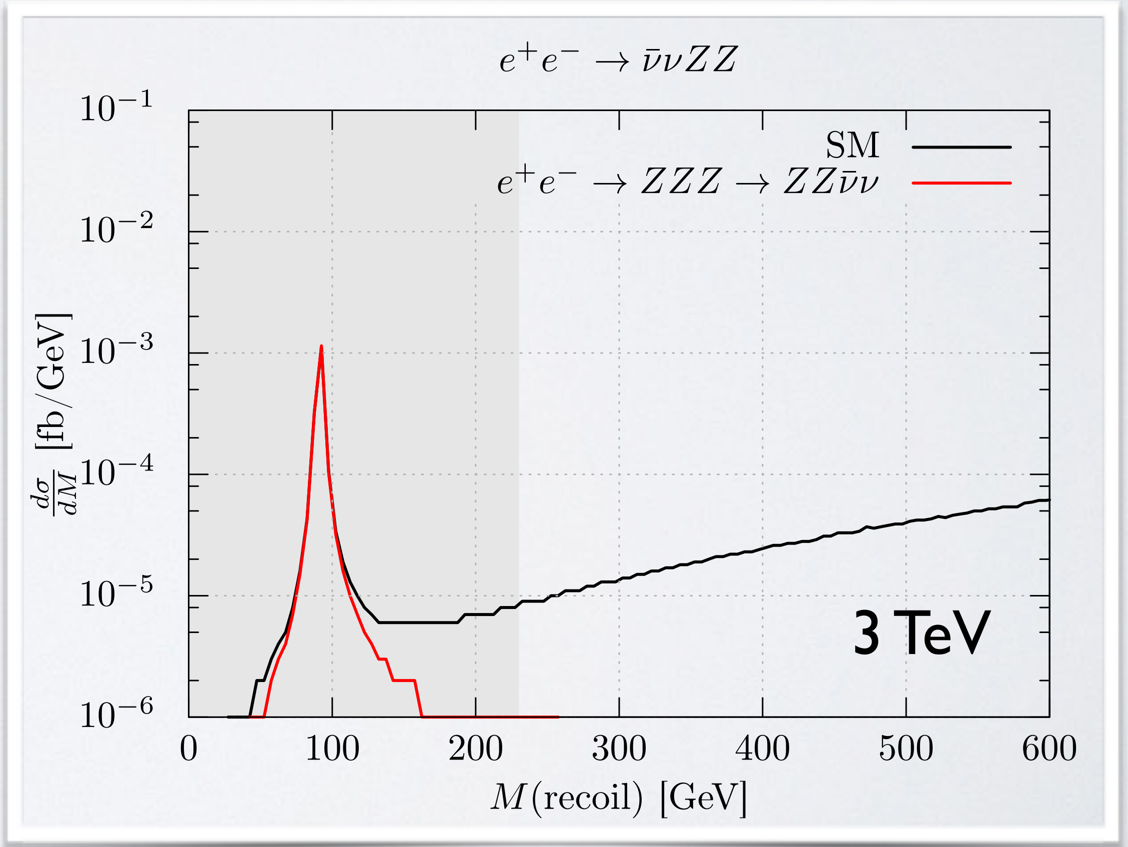


Separability of signal and triboson backgrounds









VBS in $e^+ e^-$: SM rates and Backgrounds (III)

Fleper/Kilian/JRR/Sekulla: 1607.03030

Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar{\nu}$	0.119	0.790	1
$W^+W^-e^+e^-$	0.000	0.000	1
$W^\pm Z e^\mp \nu$	0.269	1.200	0.136
ZZe^+e^-	0.000	0.000	0.019
$W^+W^-(Z \to \nu\bar{\nu})$	0.039	0.610	1
$ZZ\nu\bar{\nu}$	0.084	0.790	1
ZZe^+e^-	0.000	0.000	1
$W^\pm Z e^\mp \nu$	0.288	1.593	0.136
$W^+W^-e^+e^-$	0.000	0.000	0.019
$ZZ(Z \to \nu\bar{\nu})$	0.000	0.000	1

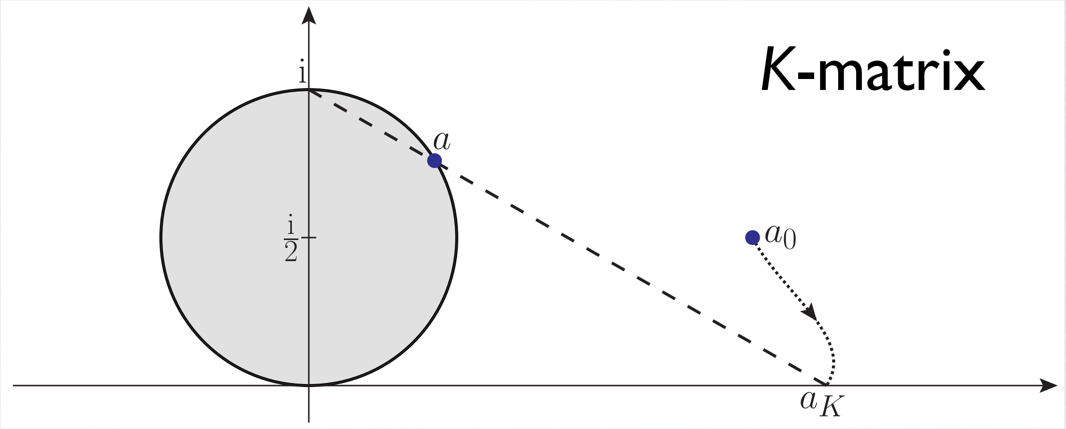
Total cross sections [fb], all cuts

MC error are $\approx$ 1% on average

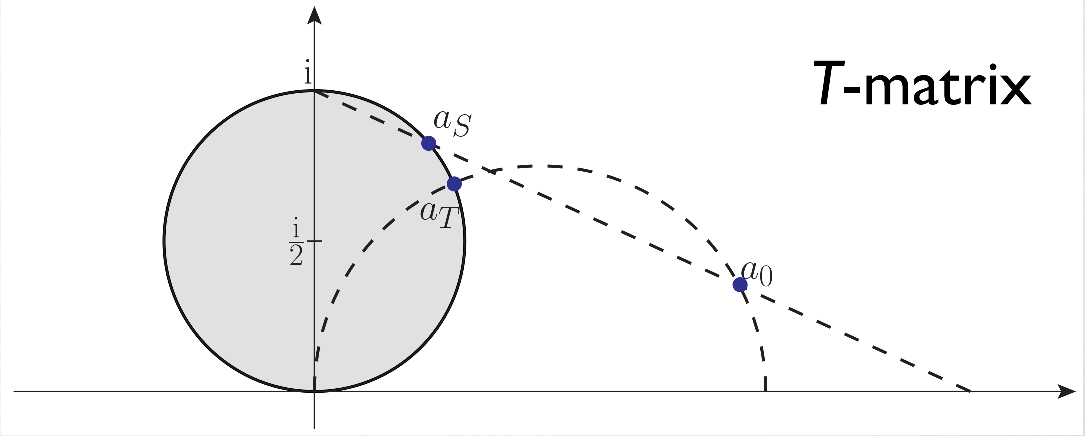
Quick remark on validity and unitarization

- EFT only valid for energy scales well below new degrees of freedom
- Higher-dimensional operators: amplitudes rise with energy
- High-energy regime could lead to unphysical results
  - Truncate reach ("event clipping")
  - Measurement only in low-energy bins
  - Unitarization procedure
- *K*-matrix: Stereographic projection to Argand circle
- … is partial resummation of perturbative series
- Gives bin-wise highest event yield compatible with QFT
- Problem for amplitudes with intrinsic imaginary part (e.g. resonances)
- *T*-matrix: Thales circle construction [Kilian/Ohl/JRR/Sekulla 2014]
- Identical to *K*-matrix for real amplitudes
- Does not rely on perturbative description

$$S = \frac{1+iK/2}{1-iK/2} \qquad a_K(s) = \frac{a(s)}{1-\mathrm{i}a(s)}$$

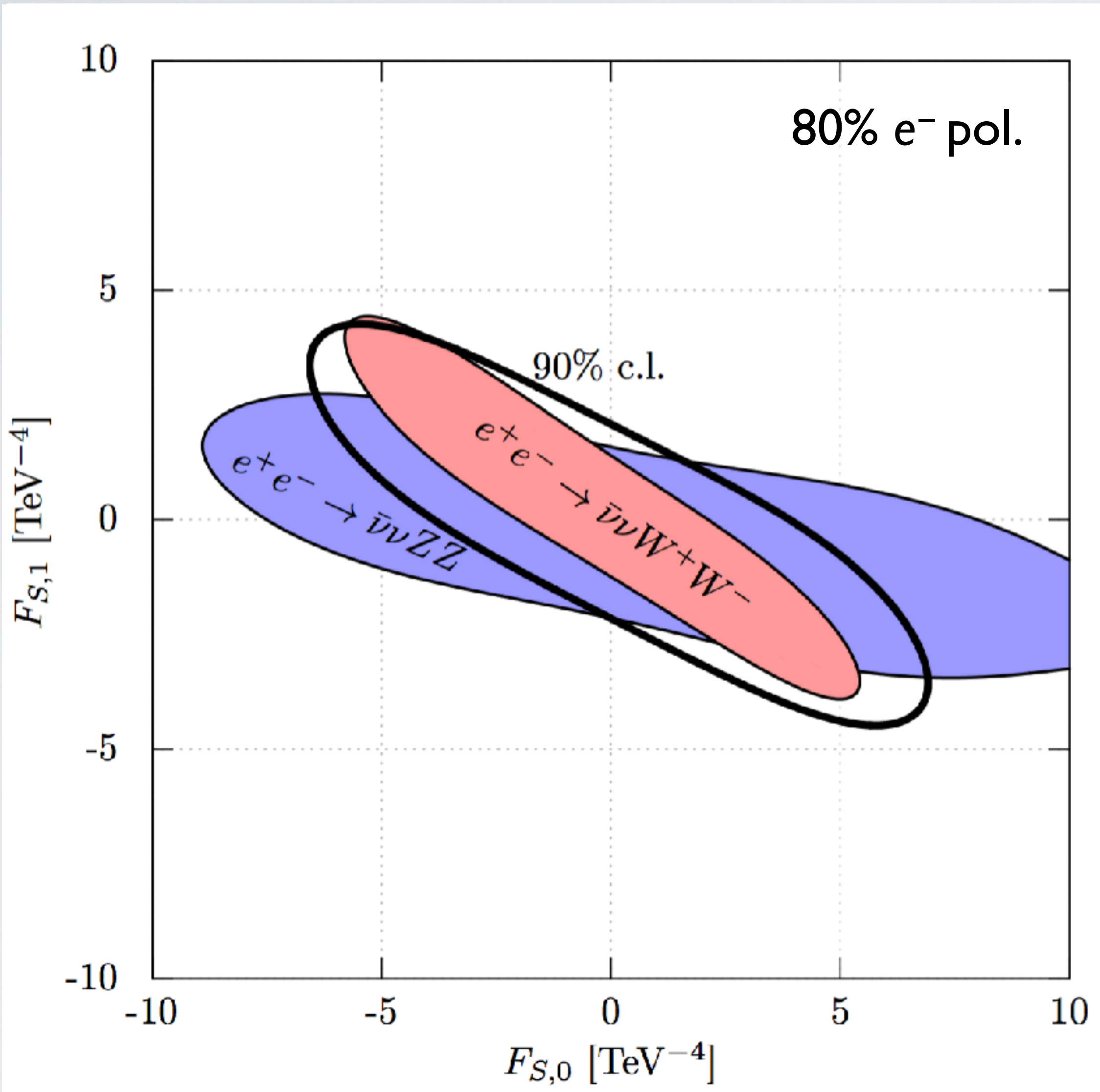


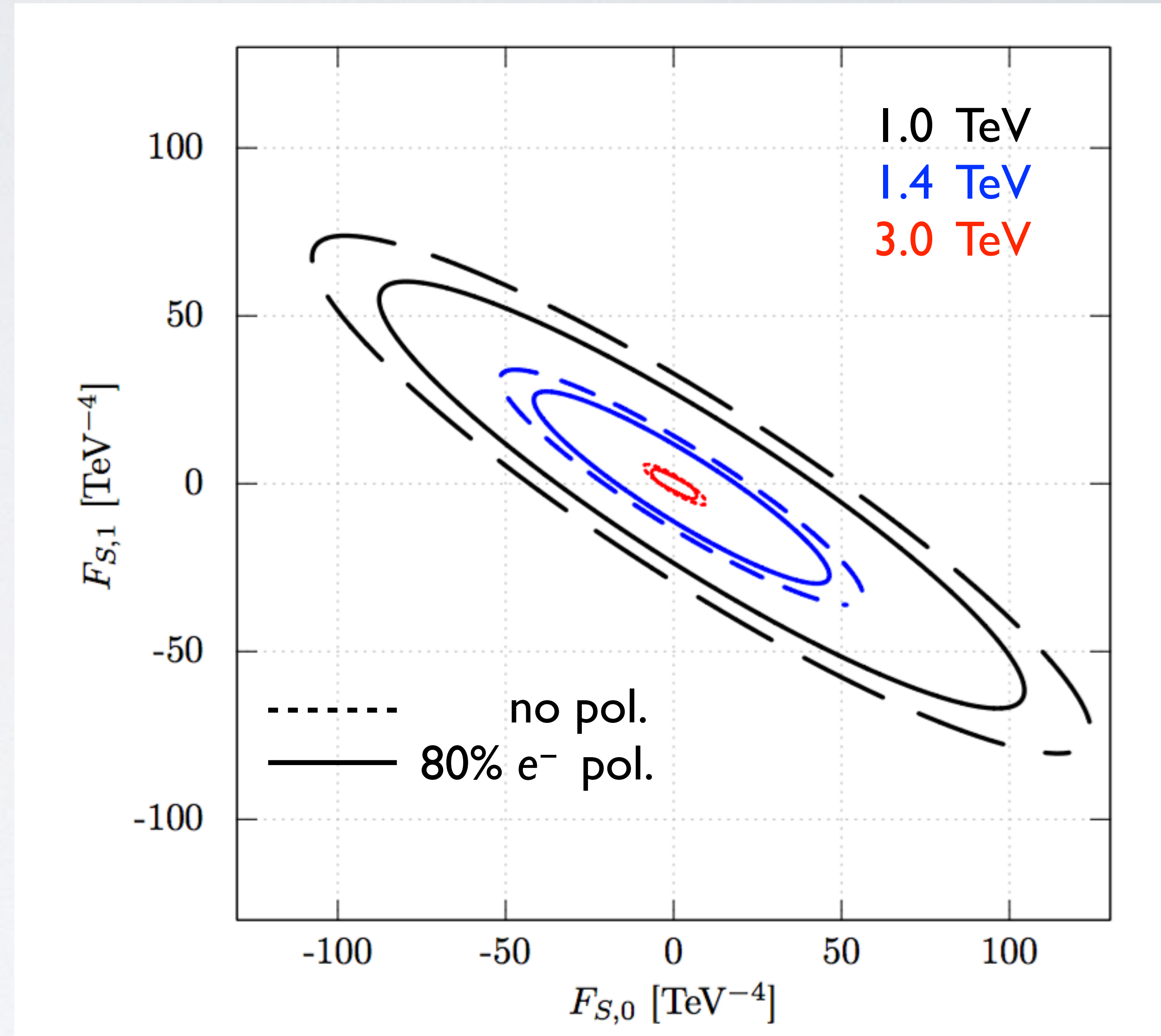
$$\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$$



Exclusion sensitivities

Continuum model matched to low-energy SMEFT with two Dim 8-coefficients at 3 TeV, 2 ab^{-1}





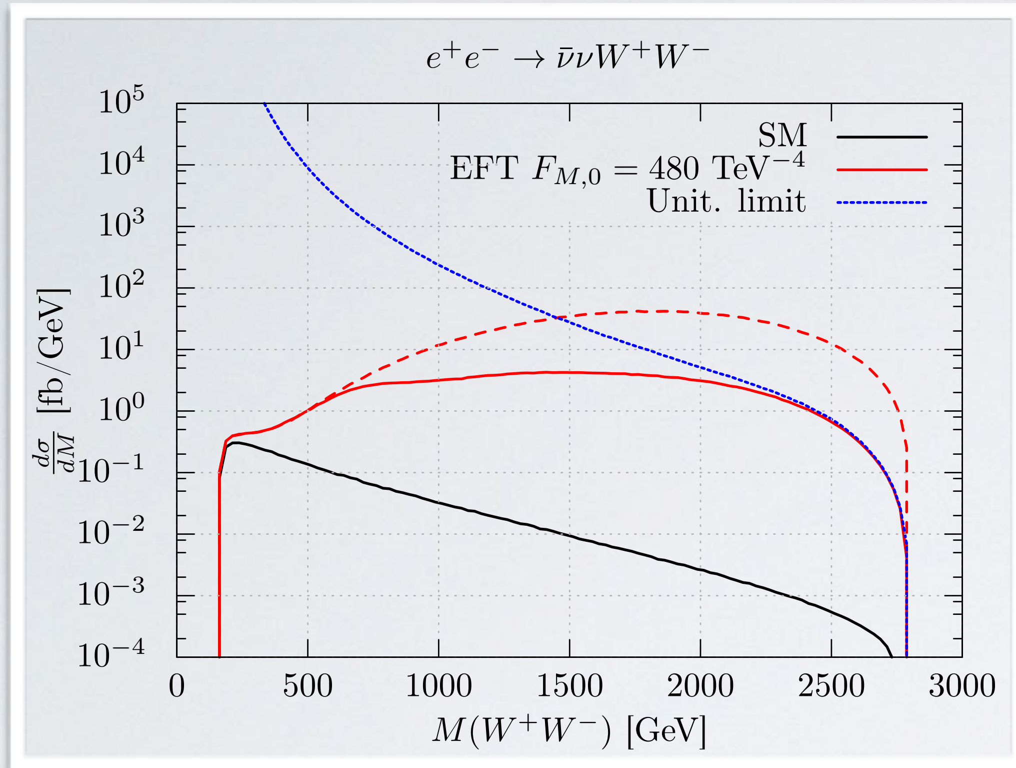
- All cuts have been applied
- Detector efficiencies are included
- All cross sections use *T*-matrix unitarization

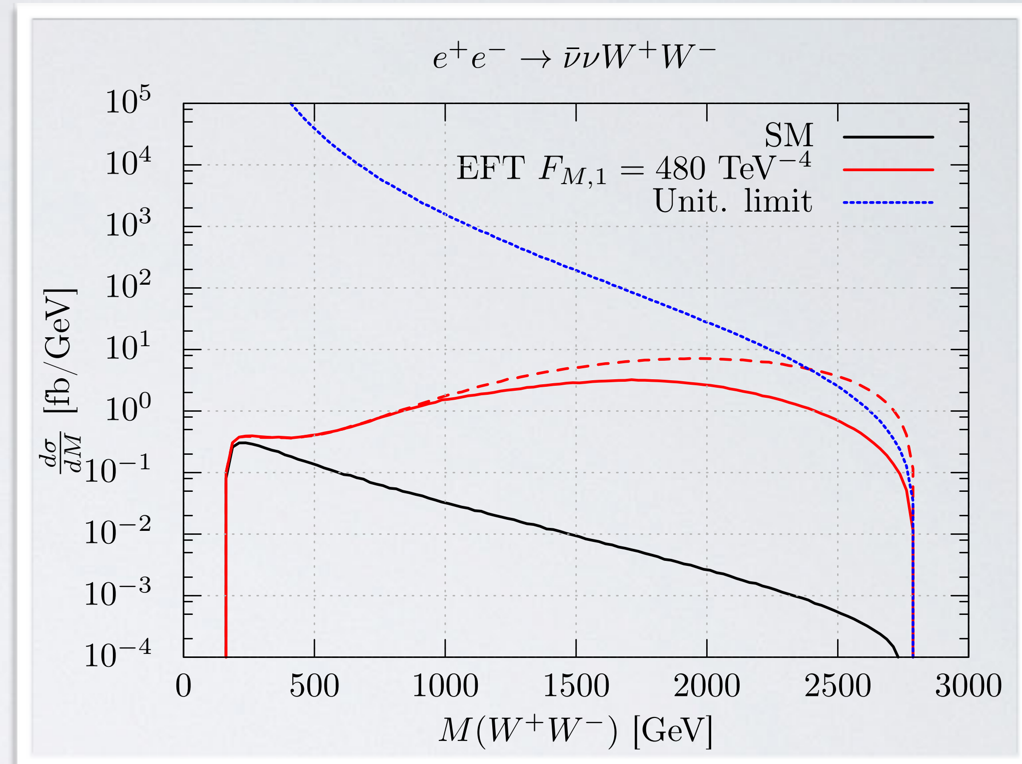
Fleper/Kilian/JRR/Sekulla: 1607.03030

- Confirmed by full simulation [CLICdp]

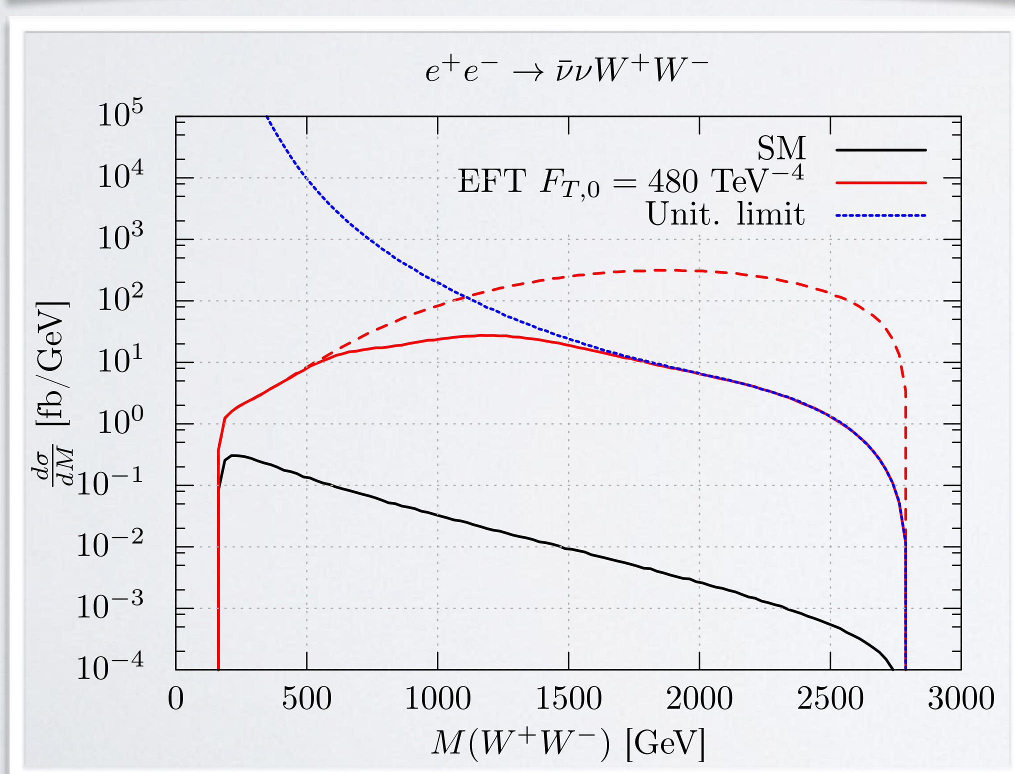
SMEFT dim. 8: longitudinal vs. mixed operators

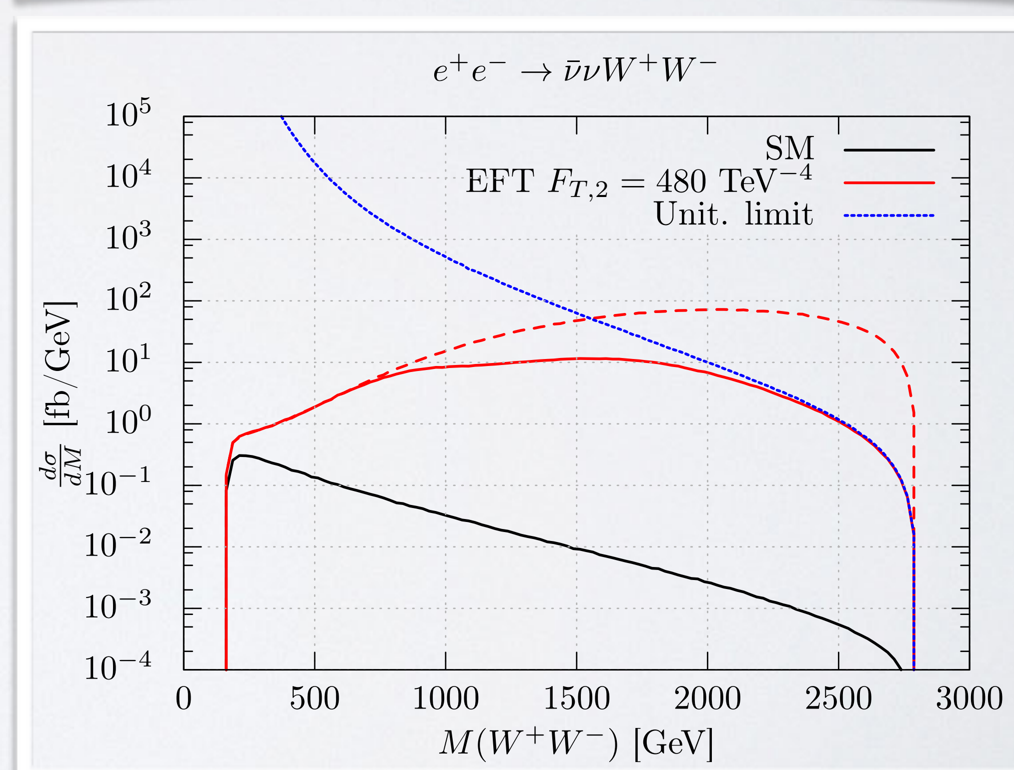
$e^+e^- \to \nu\bar{\nu}W^+W^-$ LT op. (upper panel), T operators (lower panel); continuum, no cuts



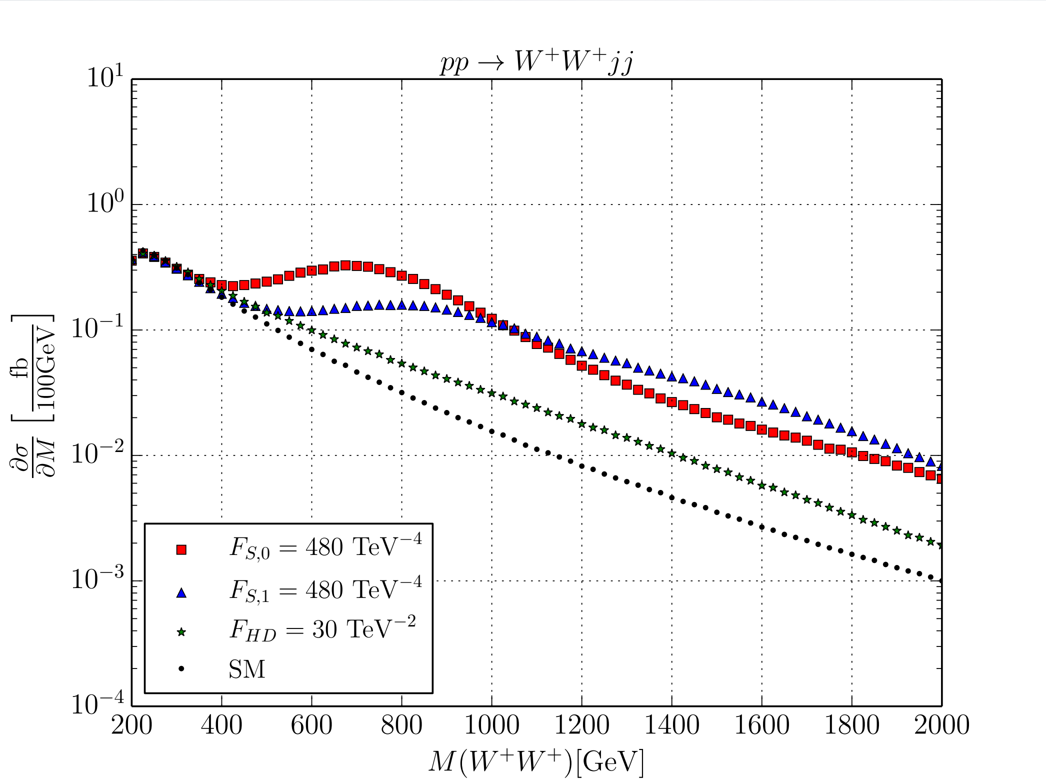


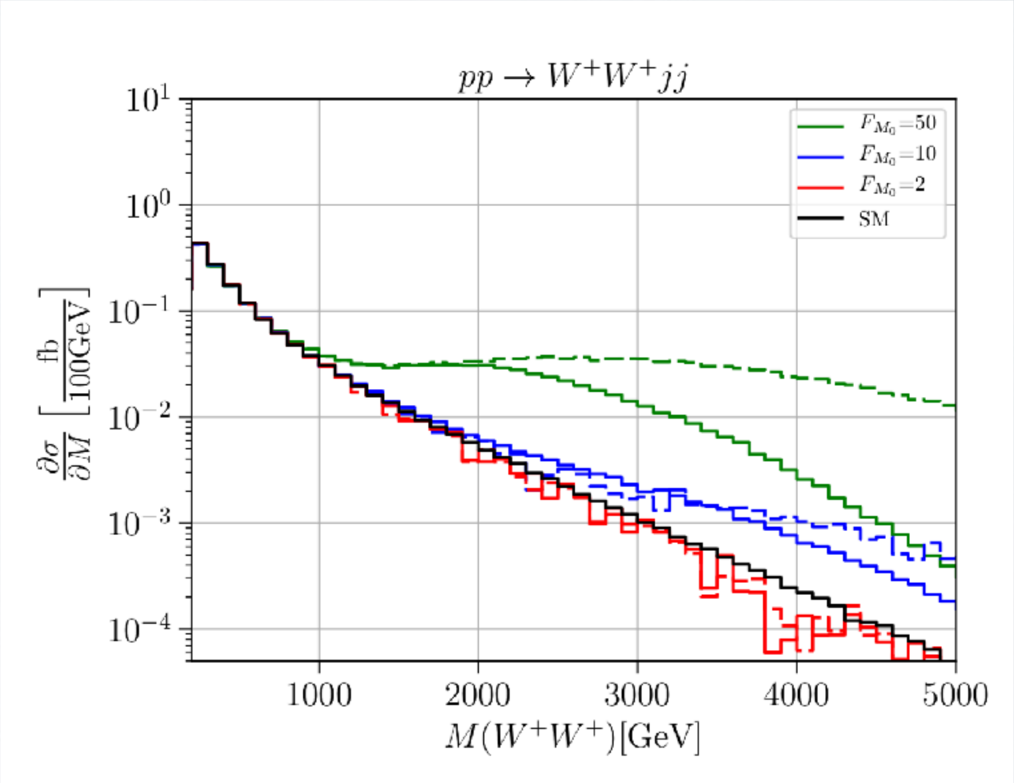
3 TeV

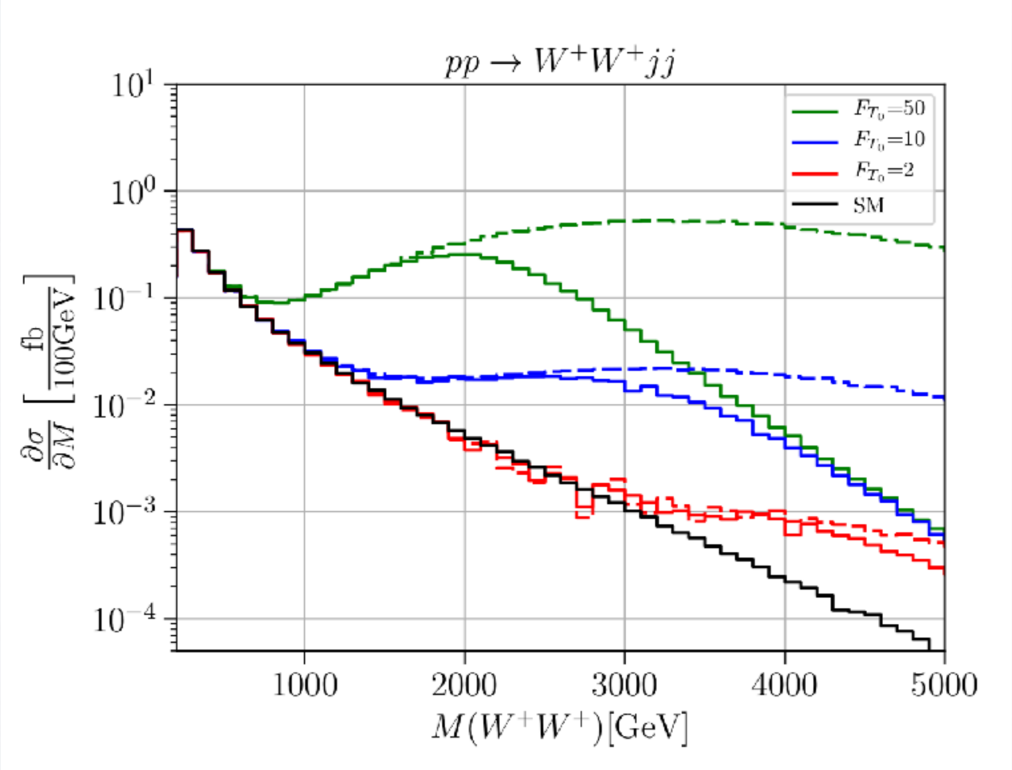


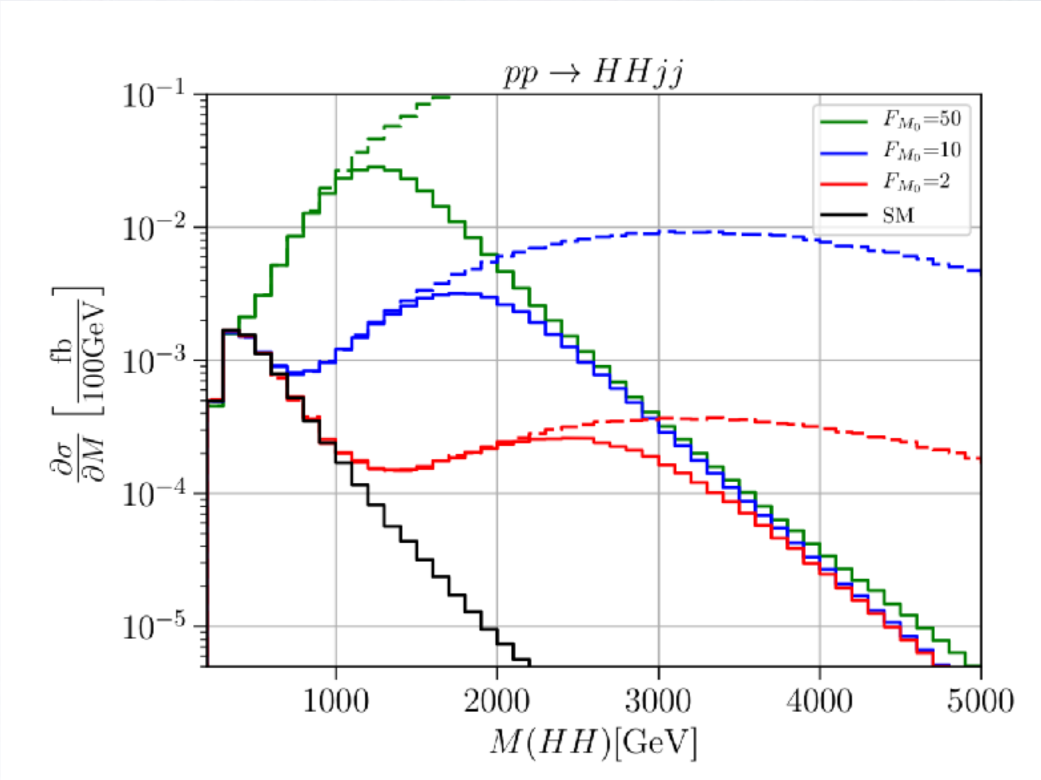


VBS diboson spectra



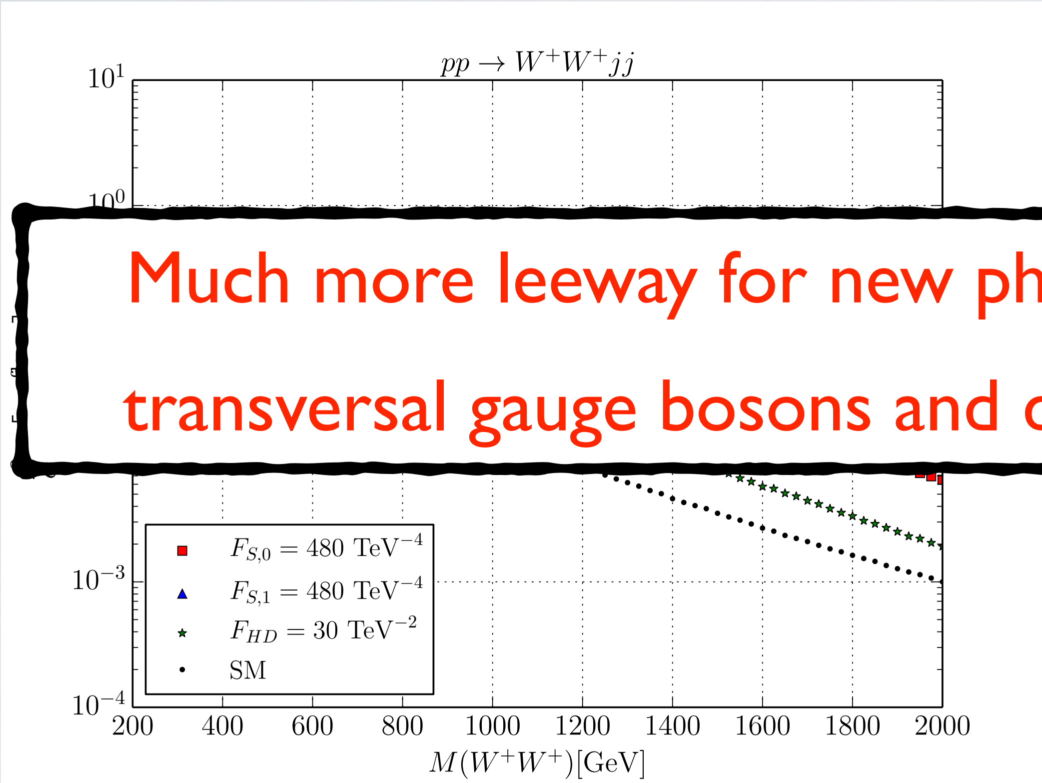




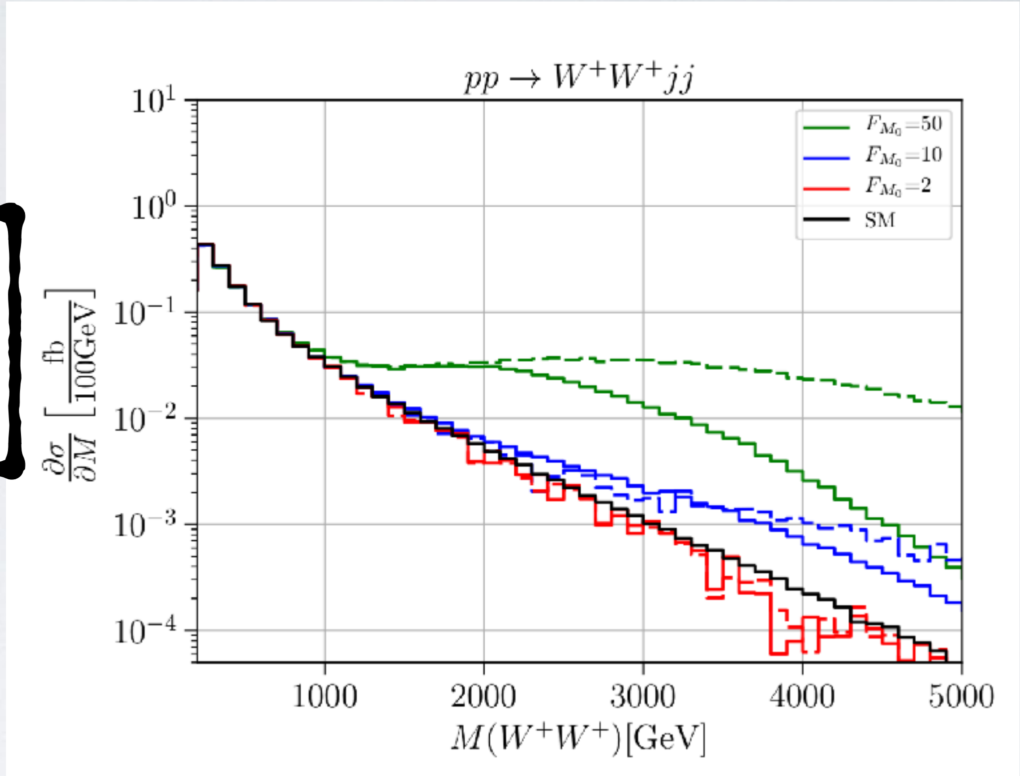


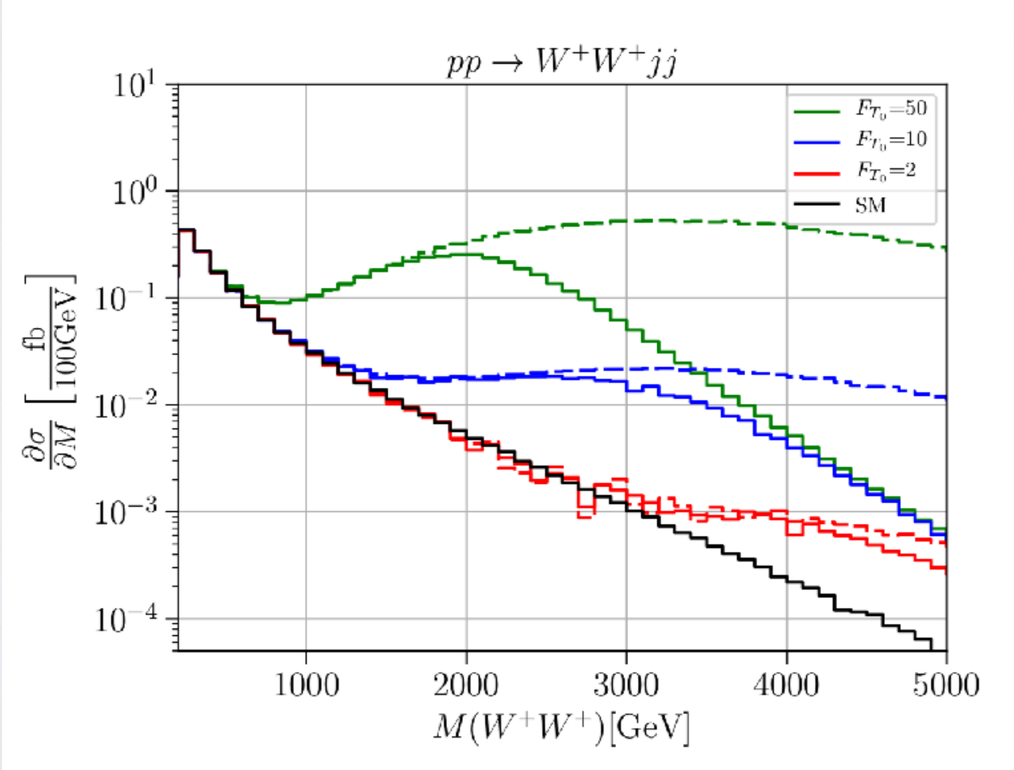
General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

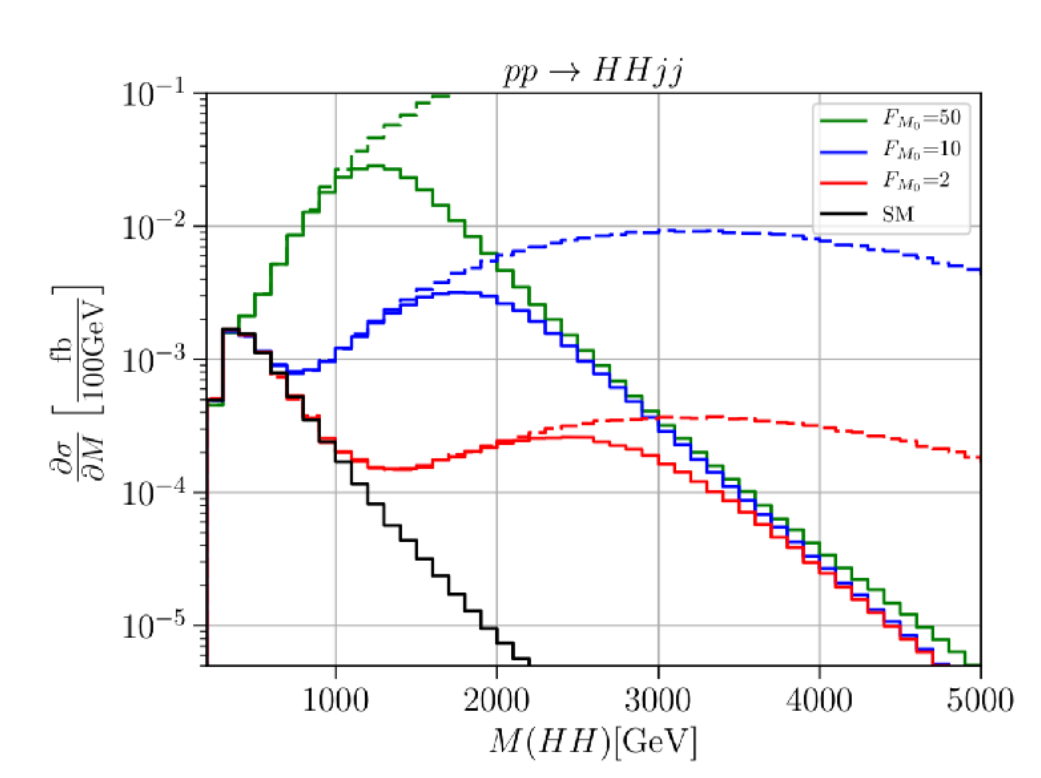
VBS diboson spectra



Much more leeway for new physics in transversal gauge bosons and di-Higgs







General cuts: $M_{jj} > 500\,\mathrm{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\mathrm{GeV};\ |\Delta\eta_j| < 4.5$

Simplified Models & New Resonances

- Rise of amplitude / anomalous coupling: Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

Consider four simple cases (resonances)

- Isoscalar scalar (neutral)
- Isotensor scalar (5 states: ++, +, 0, –, – –)
- Isoscalar tensor (neutral)
- Isotensor tensor (5 states)

	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^-, \phi_t^0, \phi_t^+, \phi_t^{++}$ $\phi_v^-, \phi_v^0, \phi_v^+$ ϕ_s^0
tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++} \\ X_v^-, X_v^0, X_v^+ \\ X_s^0 \end{pmatrix}$
…	…	…

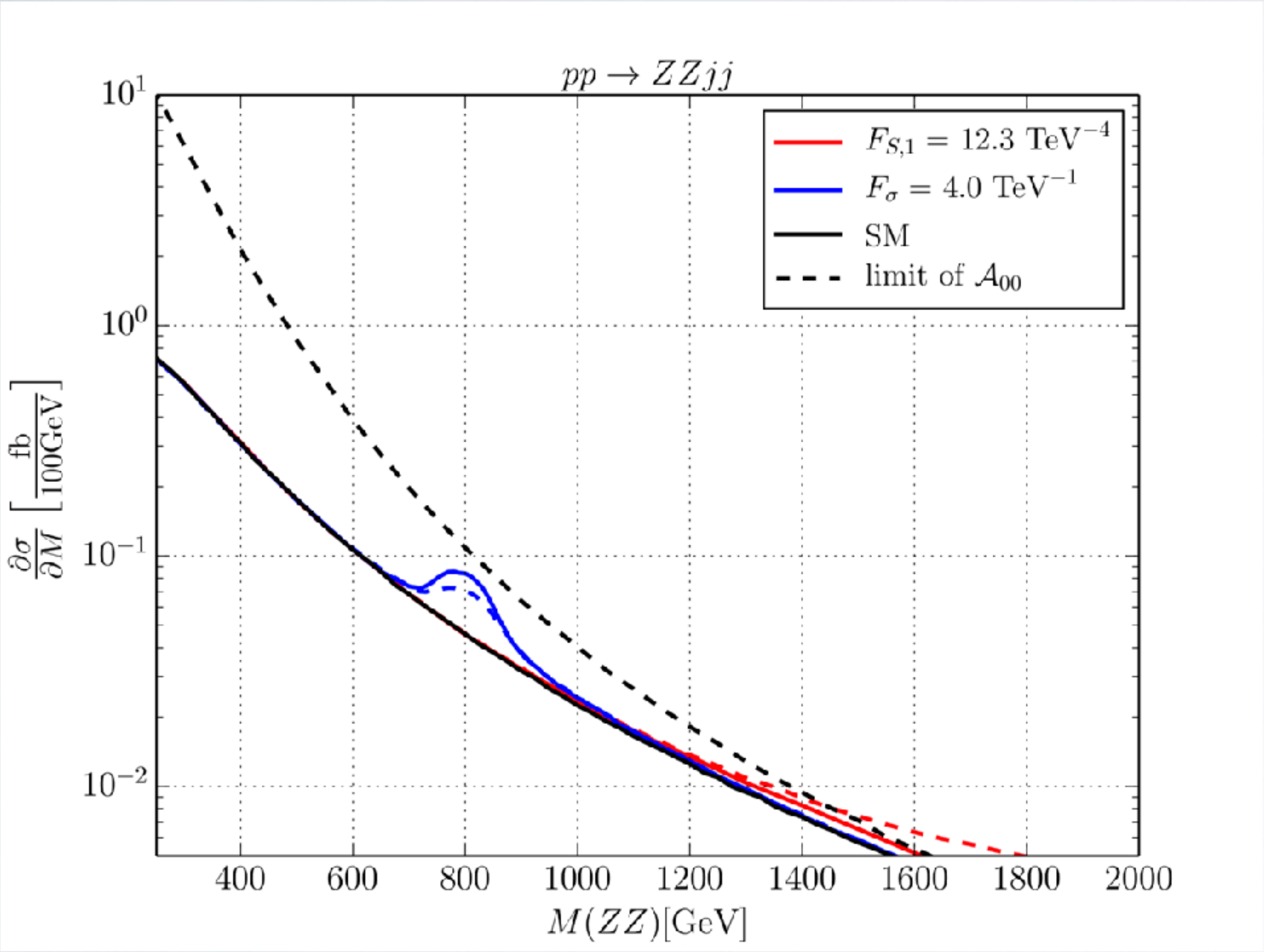
Spin 1 has different physics (mixing with *W*/*Z*)

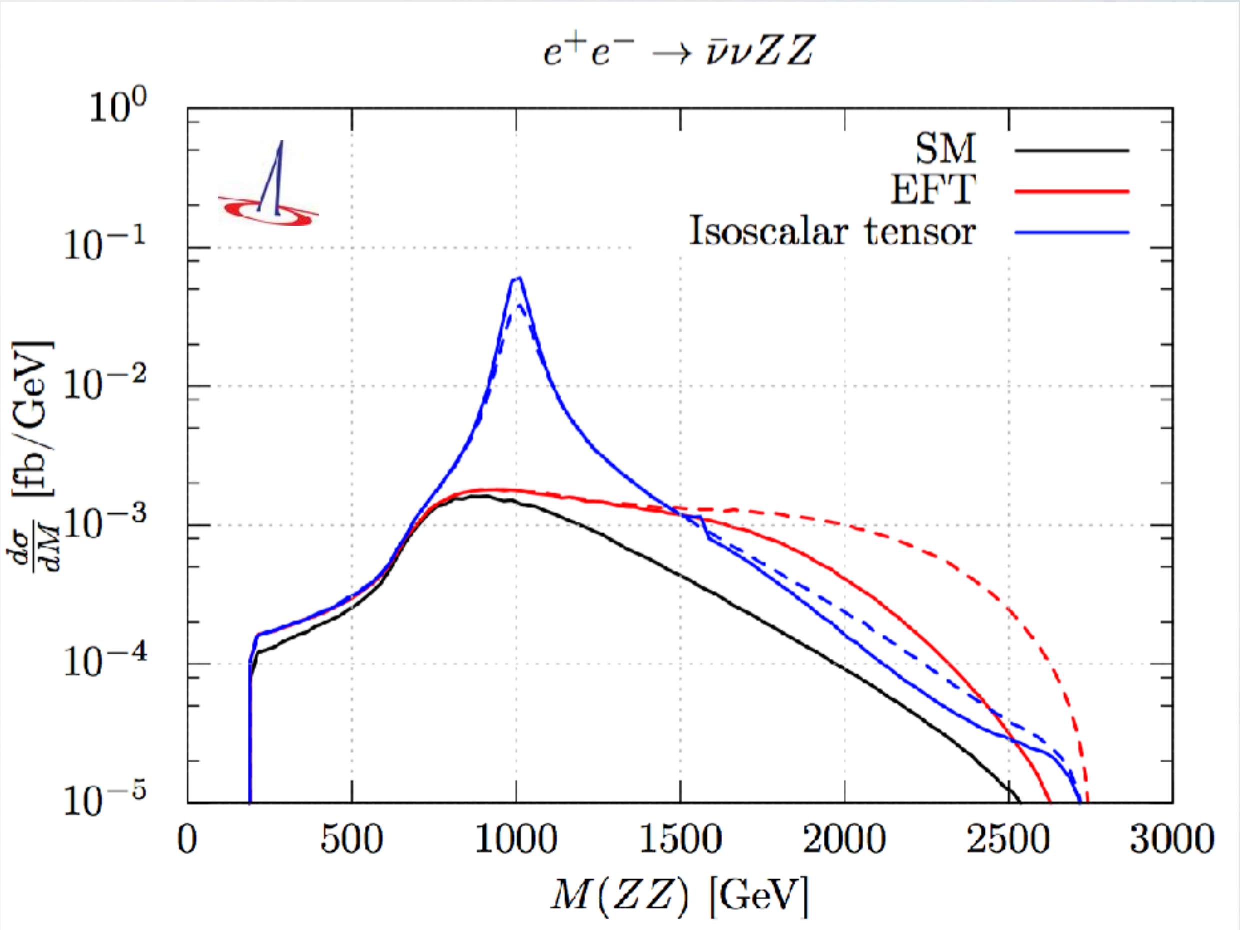
$$32\pi\Gamma/M^5$$

	σ	ϕ	f	X
$F_{S,0}$	$\frac{1}{2}$	2	15	5
$F_{S,1}$	–	$-\frac{1}{2}$	-5	-35

Simplified Models: New Resonances in VBS

Comparison: Isoscalar scalar resonance , with cuts



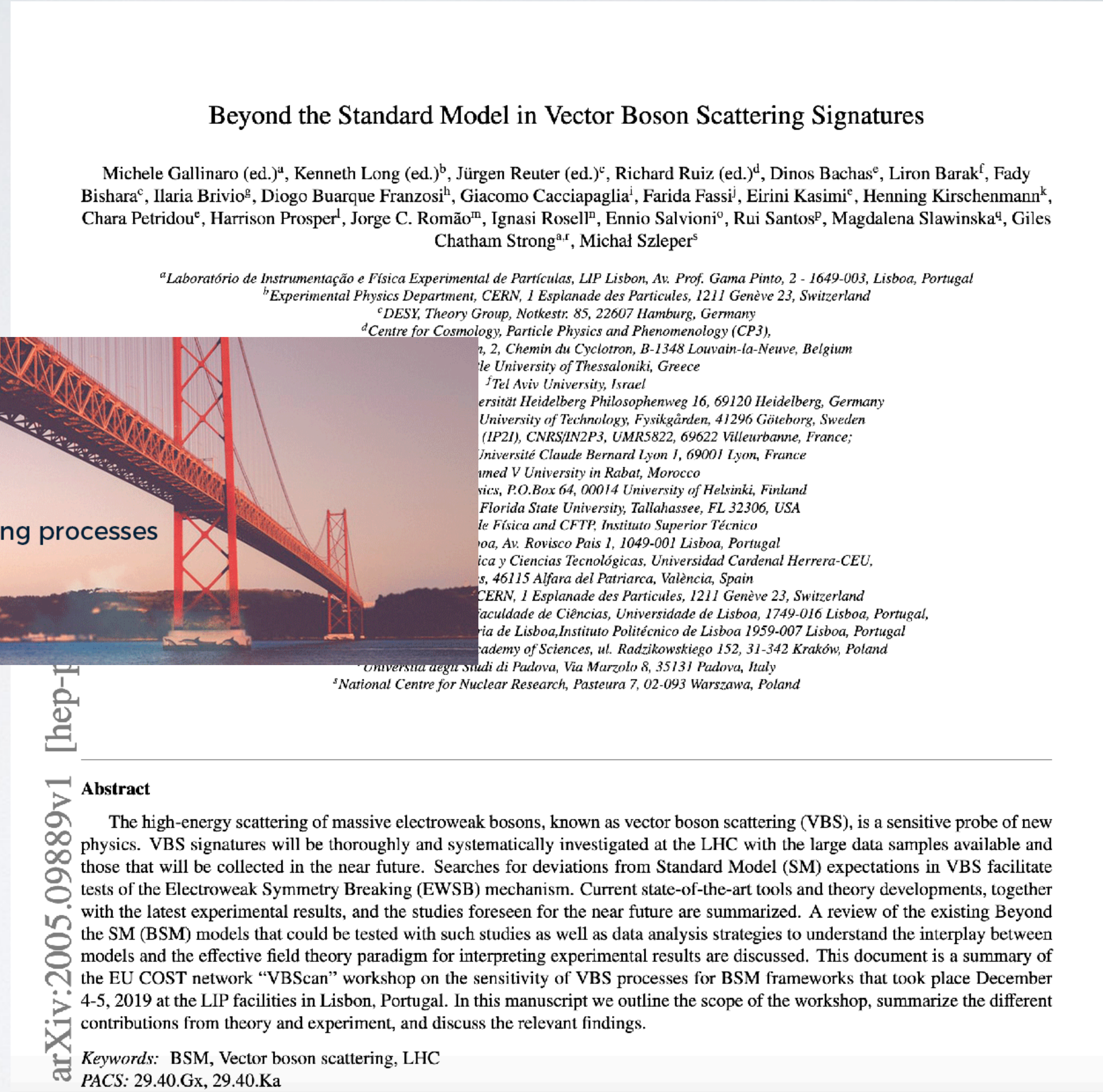


LHC (14 TeV)

CLIC (3 TeV)

Connection: VBS ⟷ BSM

- Cross connection EF04/EF08
- Not topic of this talk, but
- Great workshop in Lisbon 12/2019



Beyond the Standard Model in Vector Boson Scattering Signatures

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Abstract

The high-energy scattering of massive electroweak bosons, known as vector boson scattering (VBS), is a sensitive probe of new physics. VBS signatures will be thoroughly and systematically investigated at the LHC with the large data samples available and those that will be collected in the near future. Searches for deviations from Standard Model (SM) expectations in VBS facilitate tests of the Electroweak Symmetry Breaking (EWSB) mechanism. Current state-of-the-art tools and theory developments, together with the latest experimental results, and the studies foreseen for the near future are summarized. A review of the existing Beyond the SM (BSM) models that could be tested with such studies as well as data analysis strategies to understand the interplay between models and the effective field theory paradigm for interpreting experimental results are discussed. This document is a summary of the EU COST network "VBScan" workshop on the sensitivity of VBS processes for BSM frameworks that took place December 4-5, 2019 at the LIP facilities in Lisbon, Portugal. In this manuscript we outline the scope of the workshop, summarize the different contributions from theory and experiment, and discuss the relevant findings.

Keywords: BSM, Vector boson scattering, LHC
PACS: 29.40.Gx, 29.40.Ka

arXiv:2005.09889 , more than 180 references

The ultimate VBS measurement

- Ultimate machines: plasma-driven e^+e^- accelerators
- ALEGRO: Advanced LinEar collider study GROup
- RF cavities: 50 MV/m, Drive beam: 100-150 MV/m
- Dielectric Laser (DLA): 1 GV/m , Plasema Wakefield (PWFA): 10–100 GV/m
- Idea for linear ultra-high energy e^+e^- collider: 10 TeV / 30 TeV / 50 TeV
- Problem: needed peak luminosity: $10^{36}\ cm^{-2}\ s^{-1}$, beam power: 50 MW (?), size: $\approx 1 \times 1\ nm^2$
- Beam spectrum: only fraction will be in highest bin, non-linear regime
- Effectively becomes a photon collider: $\gamma\gamma \to W^+W^-$ quite favorable
- VBS cross sections tremendous: 0.8 pb [30 TeV] → 1.1 pb [50 TeV]
- Regime of EW radiation [VBS is just EW parton scattering]:

  W radiation probability: $$2 \times \frac{\alpha_w}{\pi} \log^2 \frac{\sqrt{s}}{m_W} \sim 0.44$$

- Very boosted objects: macroscopic lifetimes *b*: 40 cm c: 20 cm τ : 70 cm

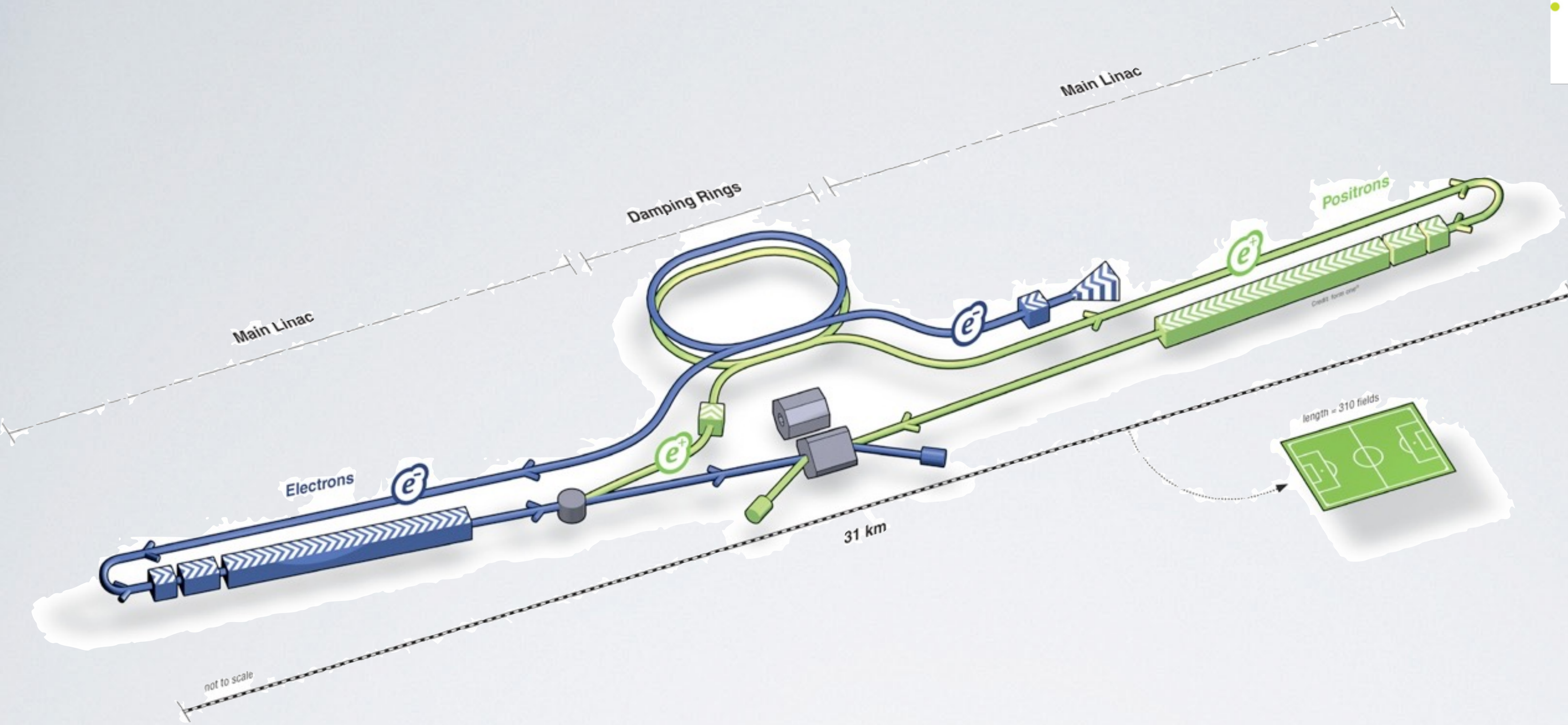
Conclusions & Outlook

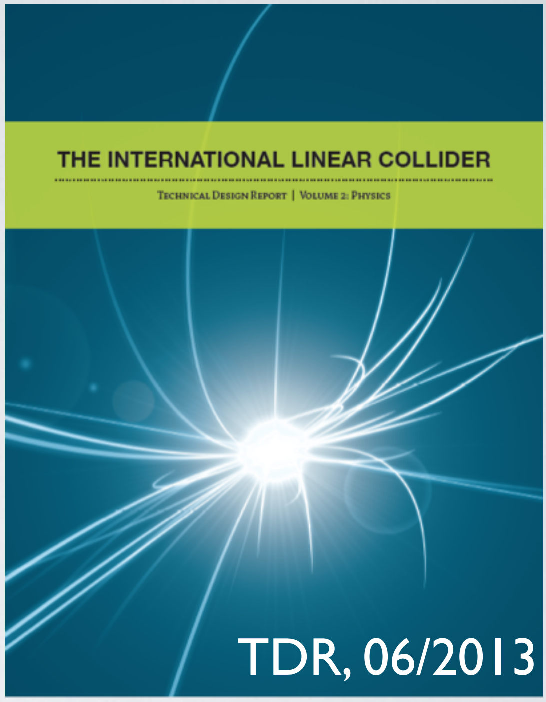
- Fully hadronic final states available in VBS in lepton colliders
- Hence: invariant mass of diboson system is fully reconstructable
- Gauge invariance: VBS and tribosons cannot be disentangled in signal model
- Fiducial volumes: cuts can massively enrich VBS component
- Theory challenges: precision predictions, EW corrections, Sudakov logarithms
- Experimental challenges: hadronic *W/Z* discrimination in TeV regime
- Studies of L, LT, T (longitudinal / mixed / transversal) [dim-8] operators
- Validity of EFT: energy range, violation of perturbative unitarity, unitarization
- Beyond SMEFT: simplified models with new resonances

- Ultimate VBS measurement might be in plasma-driven 10-50 TeV e^+e^-

BACKUP

ILC — 0.250–1 TeV e^+e^- Collider





- e^+e^- collider, 20.5–31 km length, c.m. energy: 250–500 GeV (tunable) [Upgrade: 1 TeV]
- Integrated Luminosity: 250/fb/yr [> 500/fb/yr]
- Based on superconducting RF cavities (31.5 MV/m design, 35 MV/m goal, 41–45 MV/m max.)
- Two detectors/experiments ILD & SiD (shared interaction point)
- Japan starts pre-lab phase this year (follow-up organization of Linear Collider Collaboration)

CLIC — 1.5–3 TeV e^+e^- Collider

- Normalconducting RF cavities: drive beam with ca. 100 MV/m
- Conceptual Design Report (CDR): [01/2012]
- Linear tunnel of ca. 30-50 km at CERN
- staged approach: .38, 1.4, 3 TeV
- Main challenge I: large scale test facility → CLEAR 0.22 GeV
- Main challenge II: power consumption (590 MW @ 3 TeV)
- Only presently feasible multi-TeV option for e+e-