Vector Boson Scattering at Electron Colliders

VBSCan COST Network

SnowMass2021

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Motivation for Vector Boson Scattering

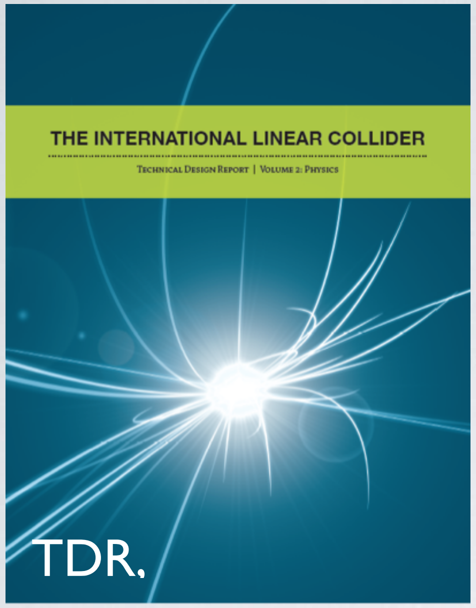
Physics potential of Vector Boson Scattering:

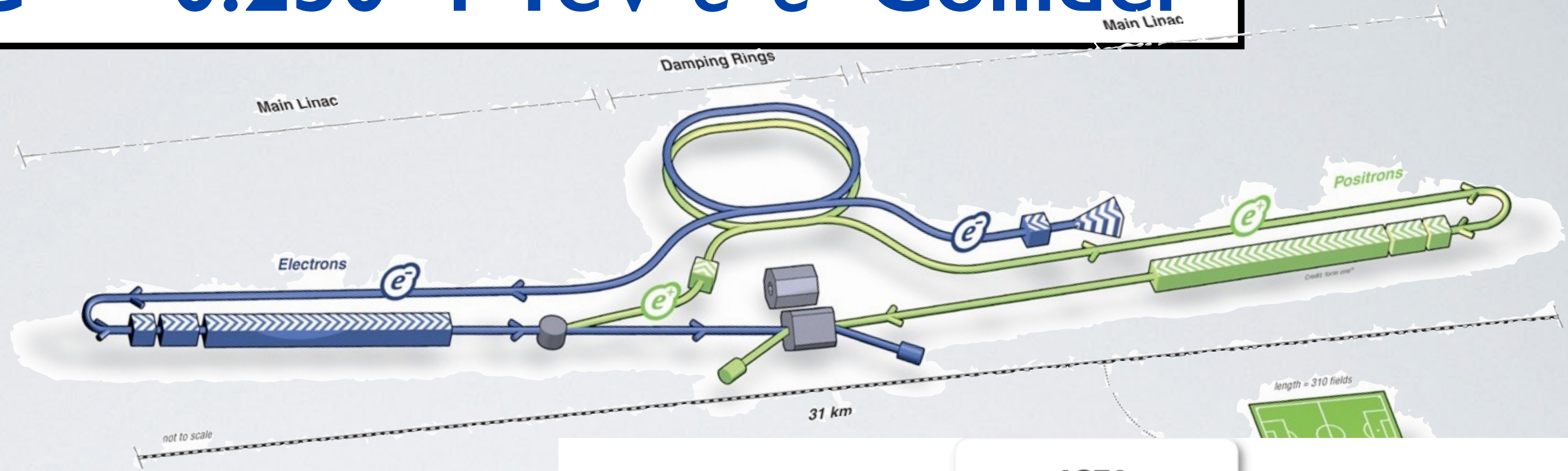
1. Precision test of the electroweak SM at high energies
2. The Higgs Mechanism at work
3. Non-standard Higgs couplings
4. New Higgs-sector physics: the Higgs Portal
    - Extra Higgses
    - Resonances excited by VBF
    - Strong interactions, continuum, compositeness, top quarks
    - New final states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

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

1. High energy: $s \gtrsim 1$ 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

ILC — 0.250–1 TeV e^+e^- Collider

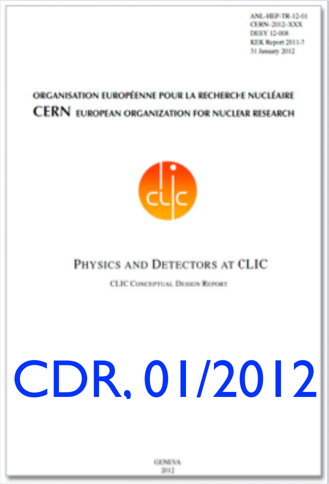




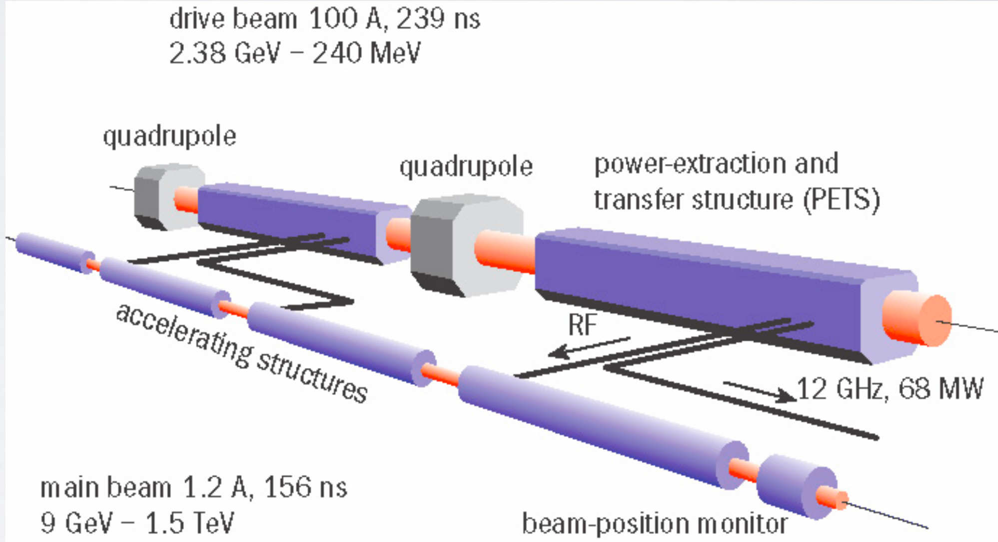
- e^+e^- collider, 20.5–31 km length, c.m. energy: 250–500 GeV (tunable) [Upgrade: 1 TeV]
- Based on superconducting RF cavities (31.5 MV/m design, 35 MV/m goal, 41–45 MV/m max.)
- Two detectors/experiments ILD & SiD (shared interaction point)
- Japan to start pre-lab phase 2022
- Deliverable: Engineering Design Report (EDR)

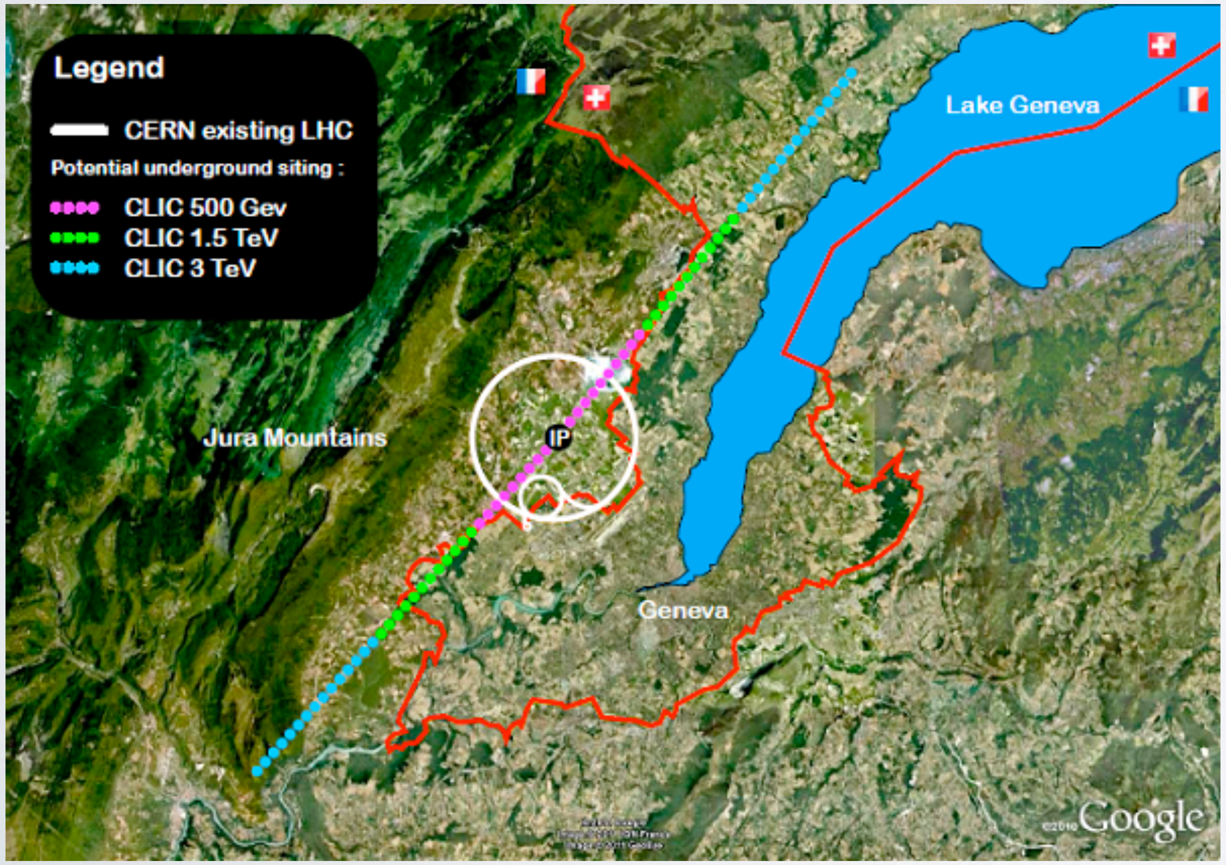
CLIC — 1.5–3 TeV e^+e^- Collider

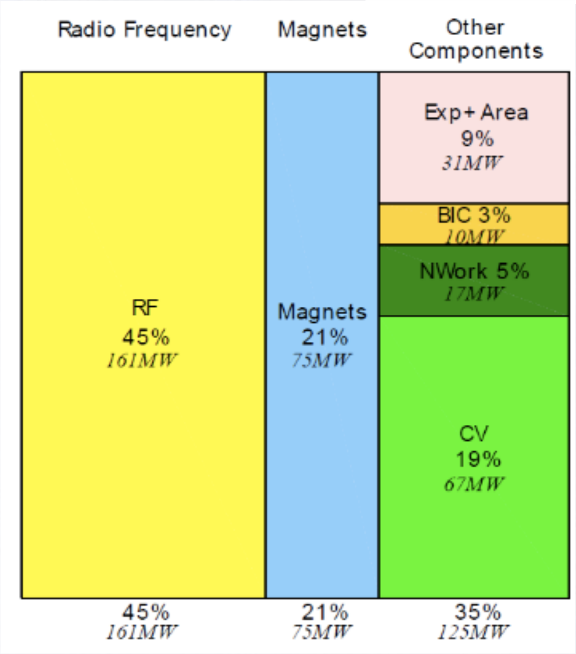
- Normalconducting RF cavities: drive beam with ca. 100 MV/m
- Conceptual Design Report (CDR): [01/2012]
- Linear tunnel of ca. 30-50 km at CERN
- staged approach: .38, 1.5, 3 TeV
- Main challenge I: large scale test facility → CLEAR 0.22 GeV
- Main challenge II: power consumption (590 MW @ 3 TeV)
- Only presently feasible multi-TeV option for e+e-

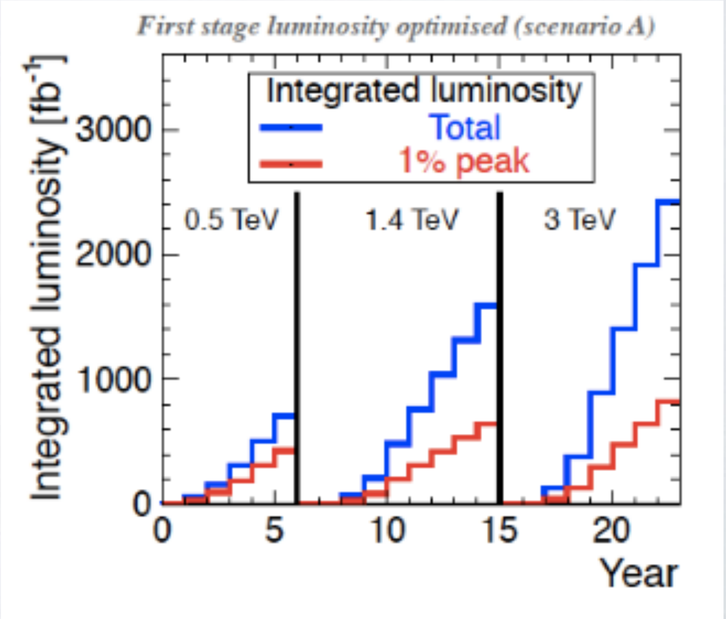


CDR. 01/2012









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, $\mathscr{L}_{\text{int}}$ = 5,000 fb^{-1}

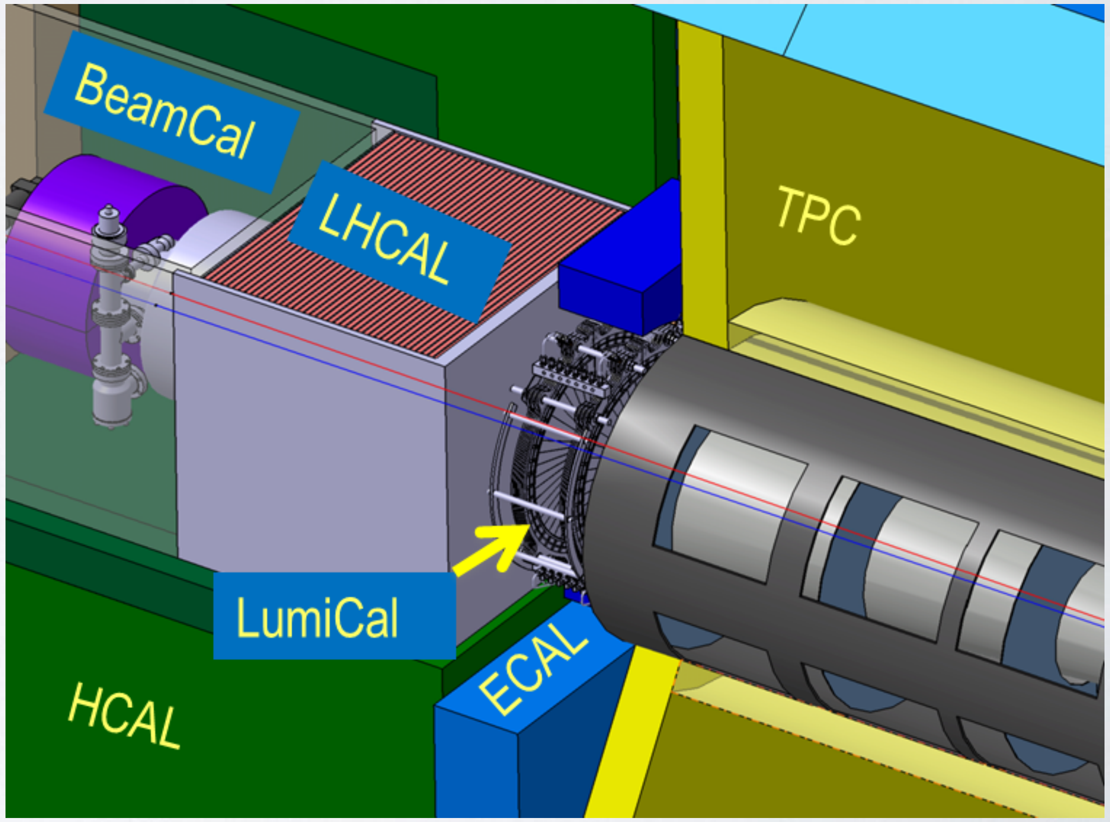
Initial state polarization: 80% e^-, 0% e^+

Low angle coverage

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

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

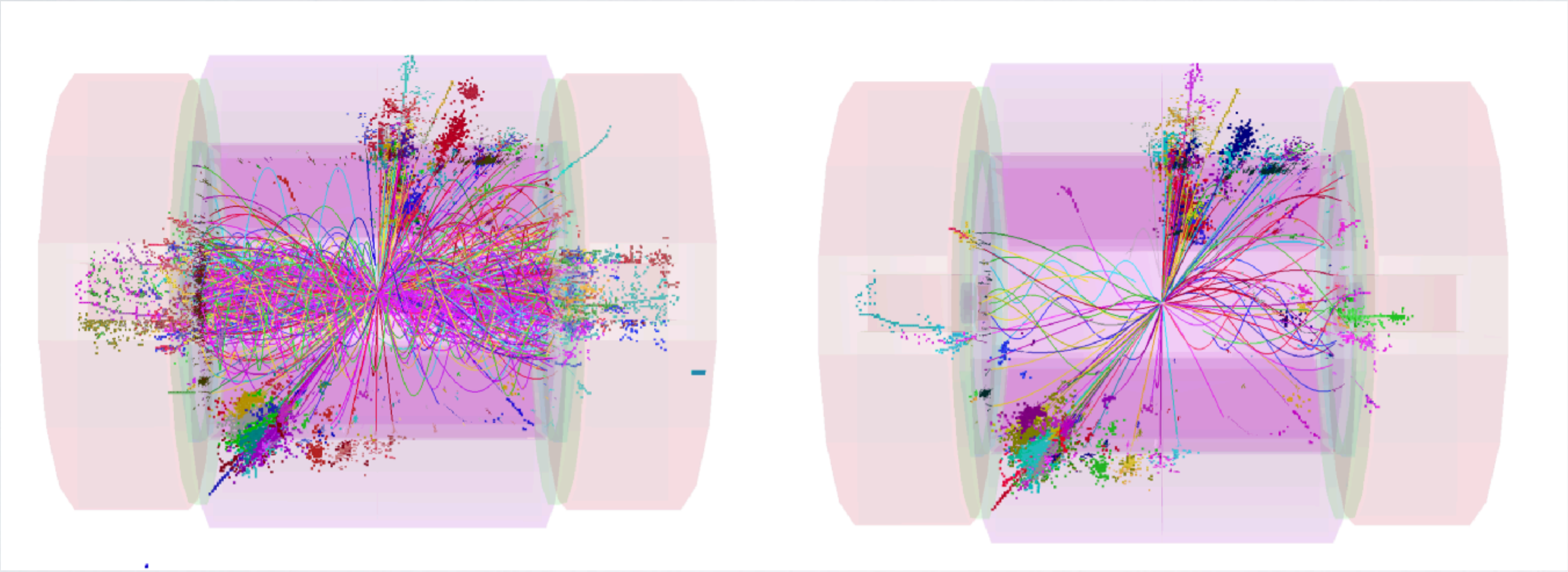
can go down to 15 mrad, i.e. $\eta \approx 4.9$



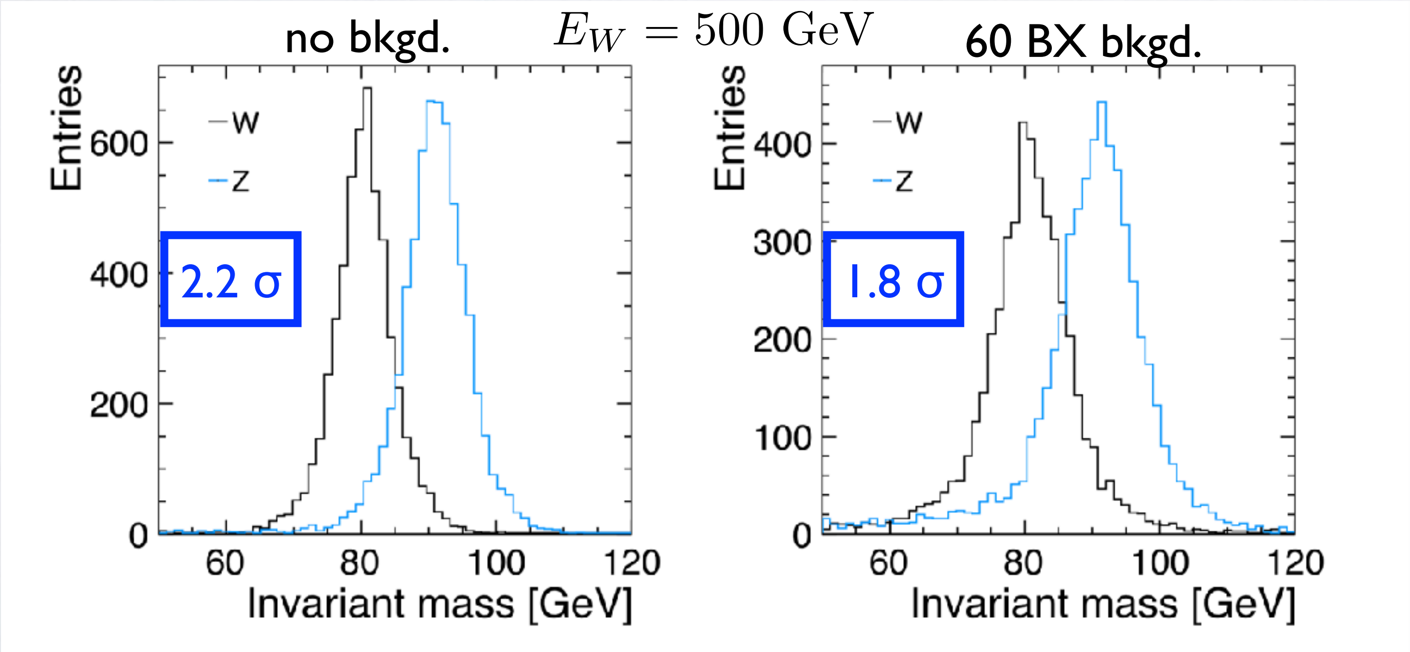
Identification of hadronic *W* / *Z*

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

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



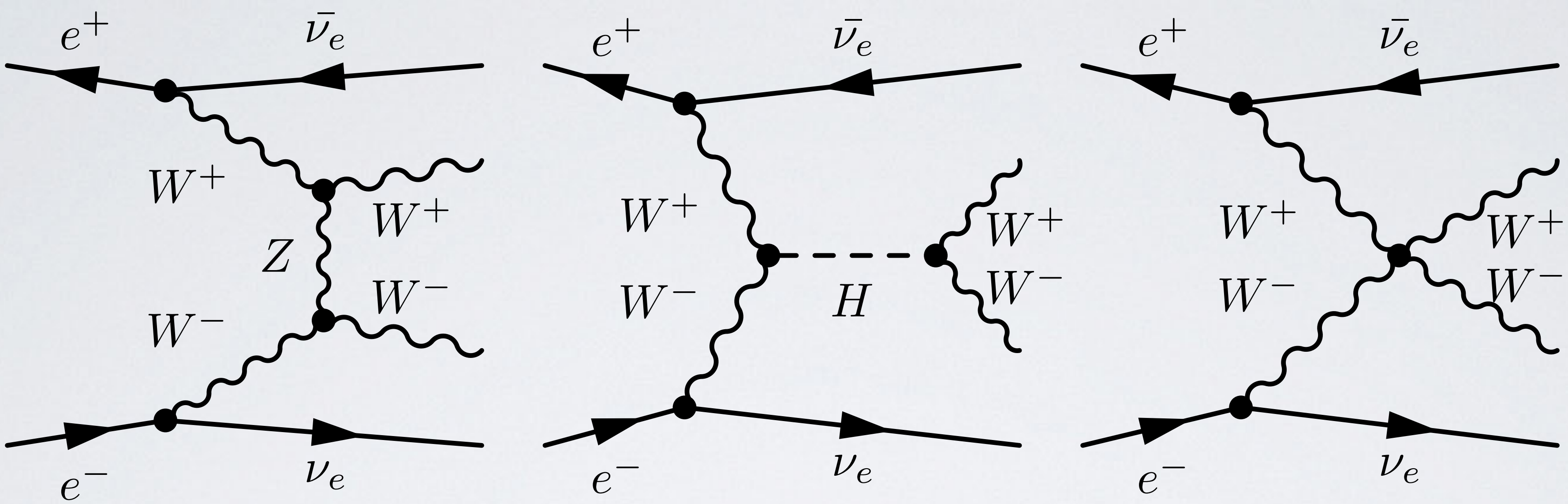
`Tight PFO` removes photon-induced background from 1.2 TeV to 100 GeV



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

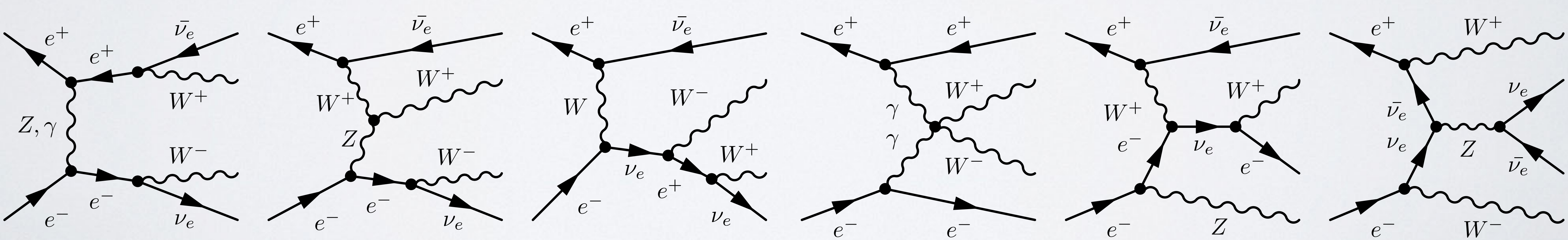
Vector Boson Scattering in $e^+ e^-$

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* →*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]:

- Vector-Boson Scattering
- Triboson Production
- Vector-Boson Scattering / Radiative Bhabha
- Top [pair] production
- Diboson Production
- Single W Production
- Radiative Z Production
- QCD Di-/Multijets

Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to W^+W^-$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$W^+W^- \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	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.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	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
$W^\pm Z e^\mp \nu$	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
$W^\pm Z e^\mp \nu$	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]

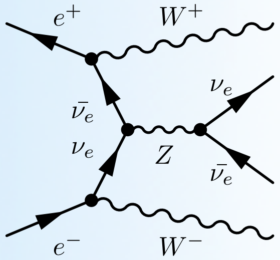
Fleper/Kilian/JRR/Sekulla: 1607.03030

- ☑ 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

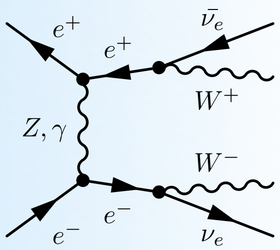
Cuts for 1 TeV ILC — 1.4 TeV CLIC — 3 TeV CLIC

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



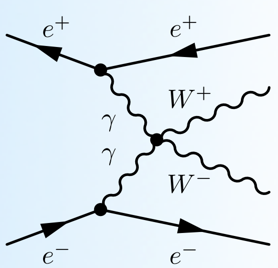
1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$M_{inv}(\bar\nu\nu) > 150\,\text{GeV}$	$M_{inv}(\bar\nu\nu) > 175\,\text{GeV}$	$M_{inv}(\bar\nu\nu) > 230\,\text{GeV}$

- Suppression of background from t–channel exchange in subprocess



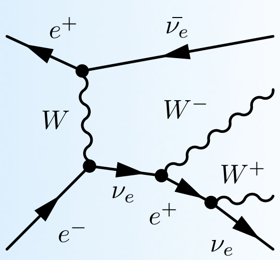
1 TeV ILC	1.4 TeV CLIC	3 TeV CLIC
$p_{\perp,W/Z} > 150\,\text{GeV}$	$p_{\perp,W/Z} > 180\,\text{GeV}$	$p_{\perp,W/Z} > 300\,\text{GeV}$
$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$	$\lvert\cos\theta(W/Z)\rvert < 0.8$

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



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

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



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

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

$$\mathcal{L}_{S,0} = F_{S,0} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}_\nu \mathbf{H})\right] \mathrm{tr}\left[(\mathbf{D}^\mu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})\right]$$
$$\mathcal{L}_{S,1} = F_{S,1} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[(\mathbf{D}_\nu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})\right]$$

Mixed operators

$$\mathcal{L}_{M,0} = -g^2 F_{M_0} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\rho}\right]$$
$$\mathcal{L}_{M,1} = -g^2 F_{M_1} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \mathrm{tr}\left[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu}\right]$$
$$\mathcal{L}_{M,2} = -g'^2 F_{M_2} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[\mathbf{B}_{\nu\rho} \mathbf{B}^{\nu\rho}\right]$$
$$\mathcal{L}_{M,3} = -g'^2 F_{M_3} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \mathrm{tr}\left[\mathbf{B}_{\nu\rho} \mathbf{B}^{\nu\mu}\right]$$
$$\mathcal{L}_{M,4} = -g g' F_{M_4} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\mu \mathbf{H}) \mathbf{B}^{\nu\rho}\right],$$
$$\mathcal{L}_{M,5} = -g g' F_{M_5} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\rho \mathbf{H}) \mathbf{B}^{\nu\mu}\right],$$
$$\mathcal{L}_{M,7} = -g^2 F_{M_7} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu} (\mathbf{D}^\rho \mathbf{H})\right];$$

Transversal operators

$$\mathcal{L}_{T,0} = g^4 F_{T_0} \mathrm{tr}\left[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{W}_{\alpha\beta} \mathbf{W}^{\alpha\beta}\right],$$
$$\mathcal{L}_{T,1} = g^4 F_{T_1} \mathrm{tr}\left[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{W}_{\mu\beta} \mathbf{W}^{\alpha\nu}\right],$$
$$\mathcal{L}_{T,2} = g^4 F_{T_2} \mathrm{tr}\left[\mathbf{W}_{\alpha\mu} \mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{W}_{\beta\nu} \mathbf{W}^{\nu\alpha}\right],$$
$$\mathcal{L}_{T,5} = g^2 g'^2 F_{T_5} \mathrm{tr}\left[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{B}_{\alpha\beta} \mathbf{B}^{\alpha\beta}\right],$$
$$\mathcal{L}_{T,6} = g^2 g'^2 F_{T_6} \mathrm{tr}\left[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\mu\beta} \mathbf{B}^{\alpha\nu}\right],$$
$$\mathcal{L}_{T,7} = g^2 g'^2 F_{T_7} \mathrm{tr}\left[\mathbf{W}_{\alpha\mu} \mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\beta\nu} \mathbf{B}^{\nu\alpha}\right],$$
$$\mathcal{L}_{T,8} = g'^4 F_{T_8} \mathrm{tr}\left[\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{B}_{\alpha\beta} \mathbf{B}^{\alpha\beta}\right],$$
$$\mathcal{L}_{T,9} = g'^4 F_{T_9} \mathrm{tr}\left[\mathbf{B}_{\alpha\mu} \mathbf{B}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\beta\nu} \mathbf{B}^{\nu\alpha}\right].$$

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

Mixed operators

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

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

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

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

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

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

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

Transversal operators

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

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

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

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

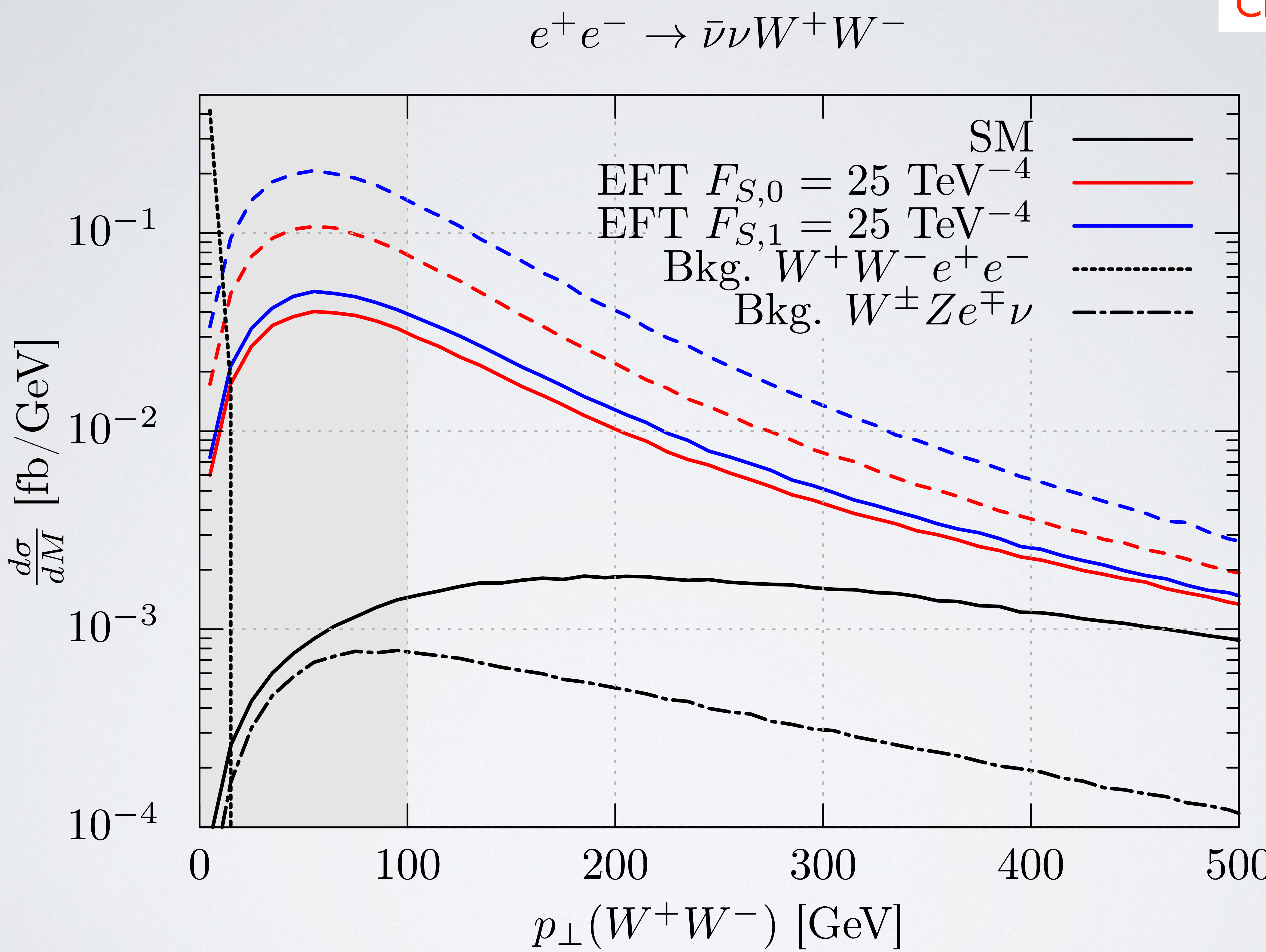
$$\mathcal{L}_{T,6} = g^2 g'^2 F_{T_6} \mathrm{tr}\left[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta} \right] \mathrm{tr}\left[\mathbf{B}_{\mu\beta} \mathbf{B}^{\alpha\nu} \right] ,$$

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

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

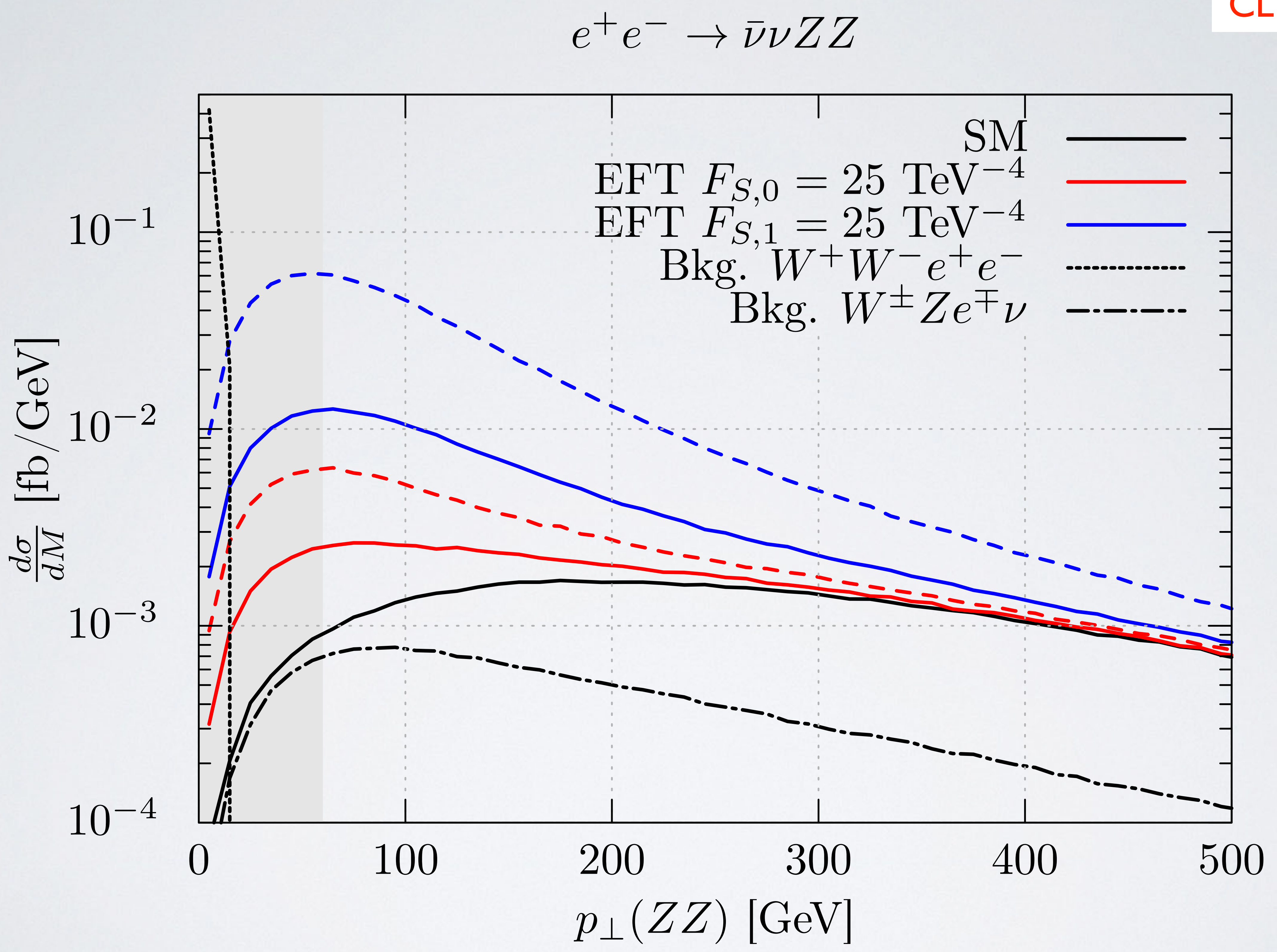
Longitudinal Vector Boson Scattering in e⁺ e⁻

CLIC 3 TeV

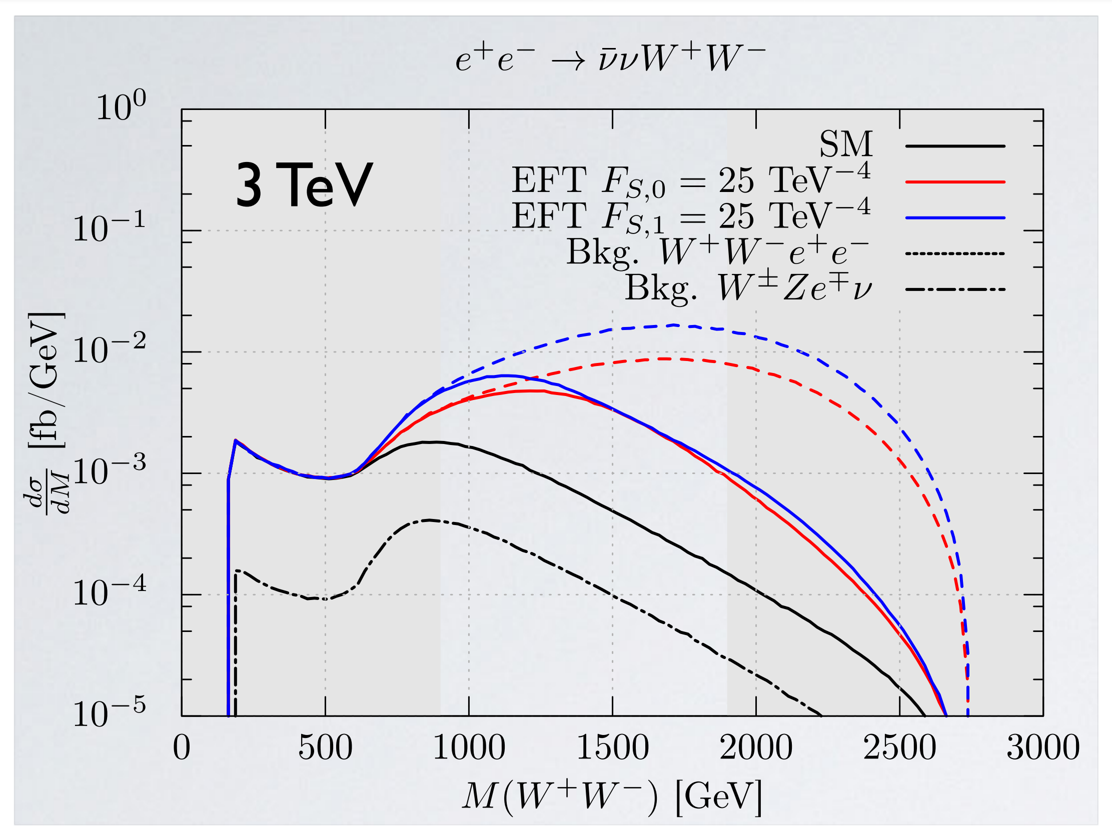


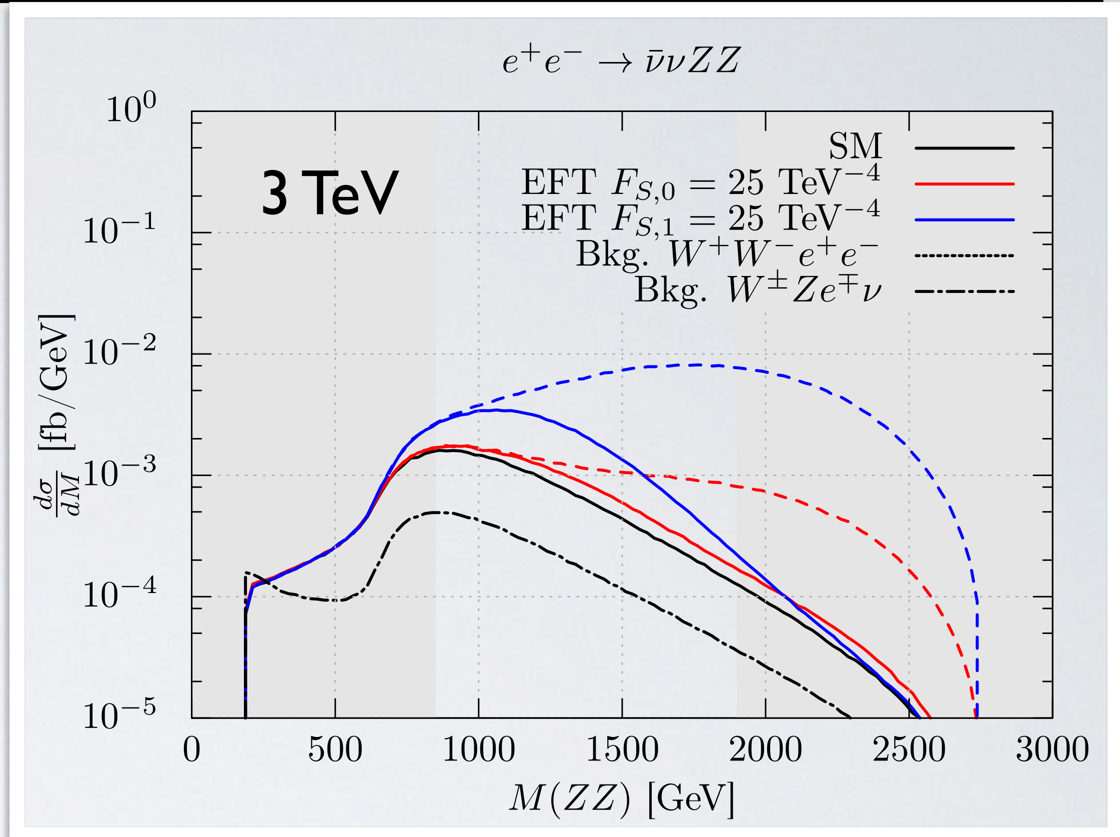
Longitudinal Vector Boson Scattering in $e^+ e^-$

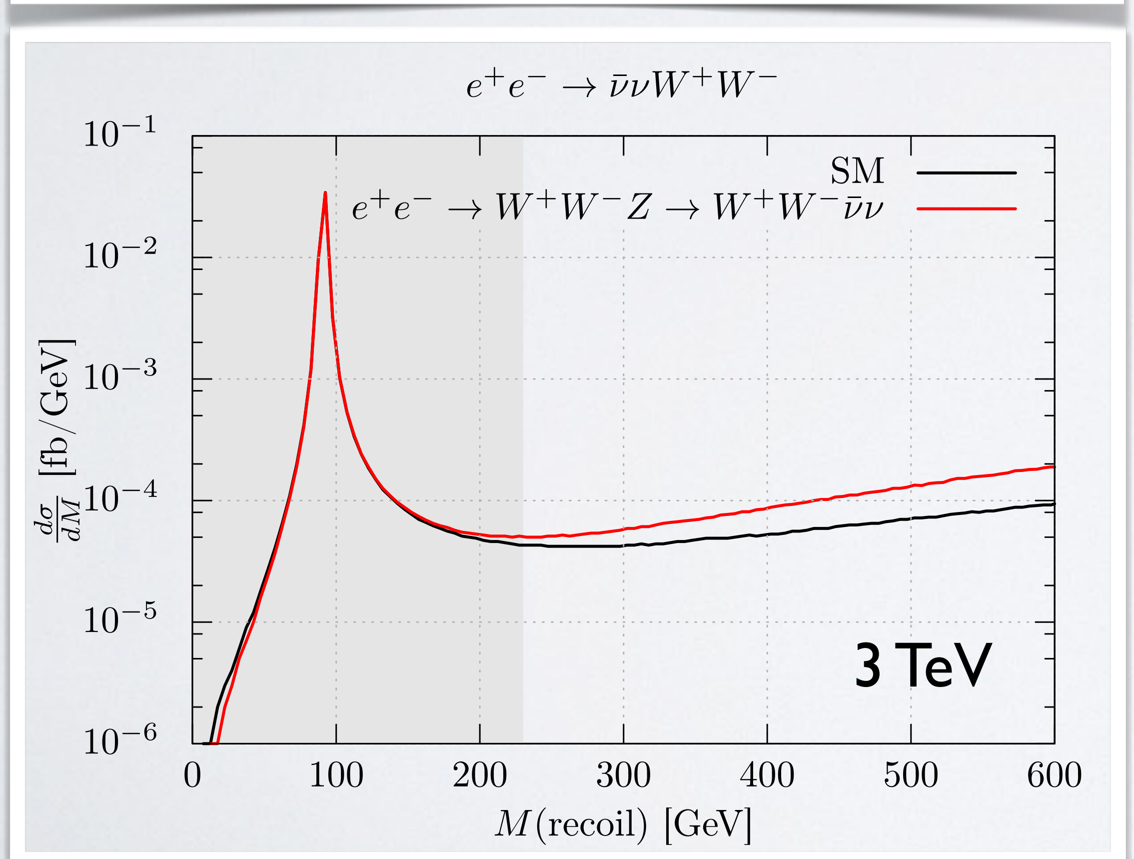
CLIC 3 TeV

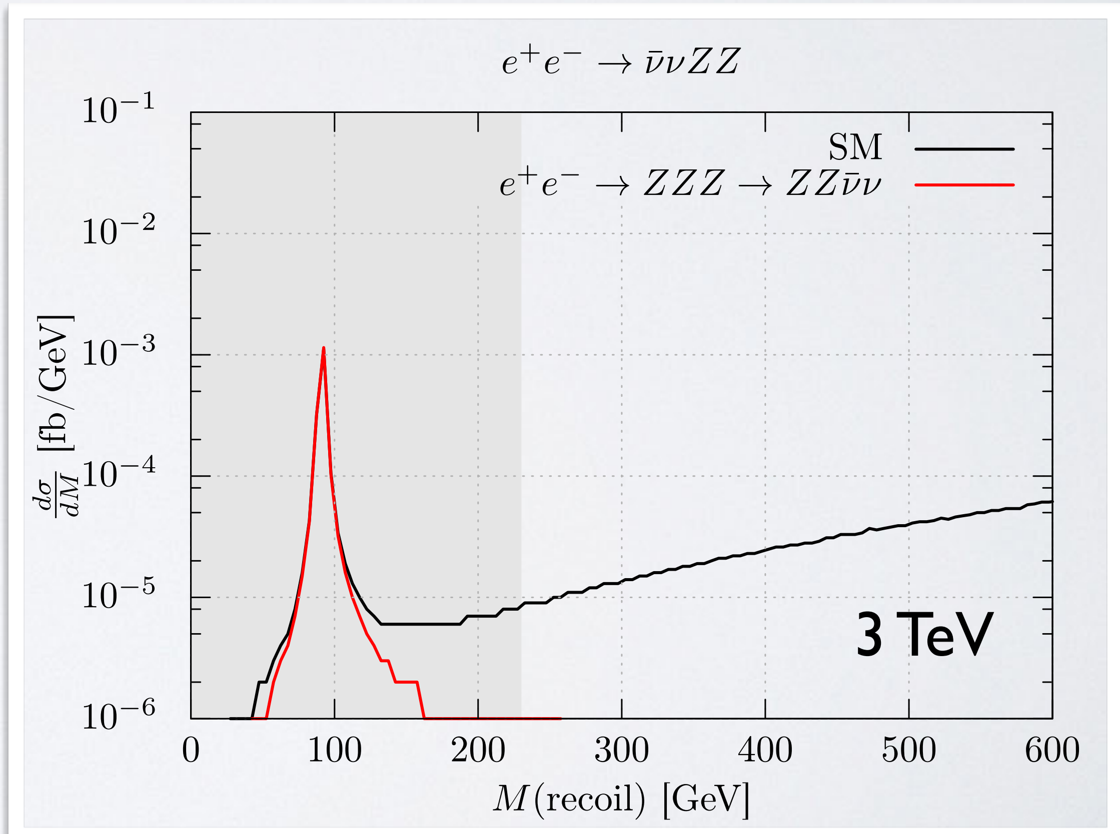


Separability of signal and triboson backgrounds









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
$W^\pm Ze^\mp\nu$	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
$W^\pm Ze^\mp\nu$	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

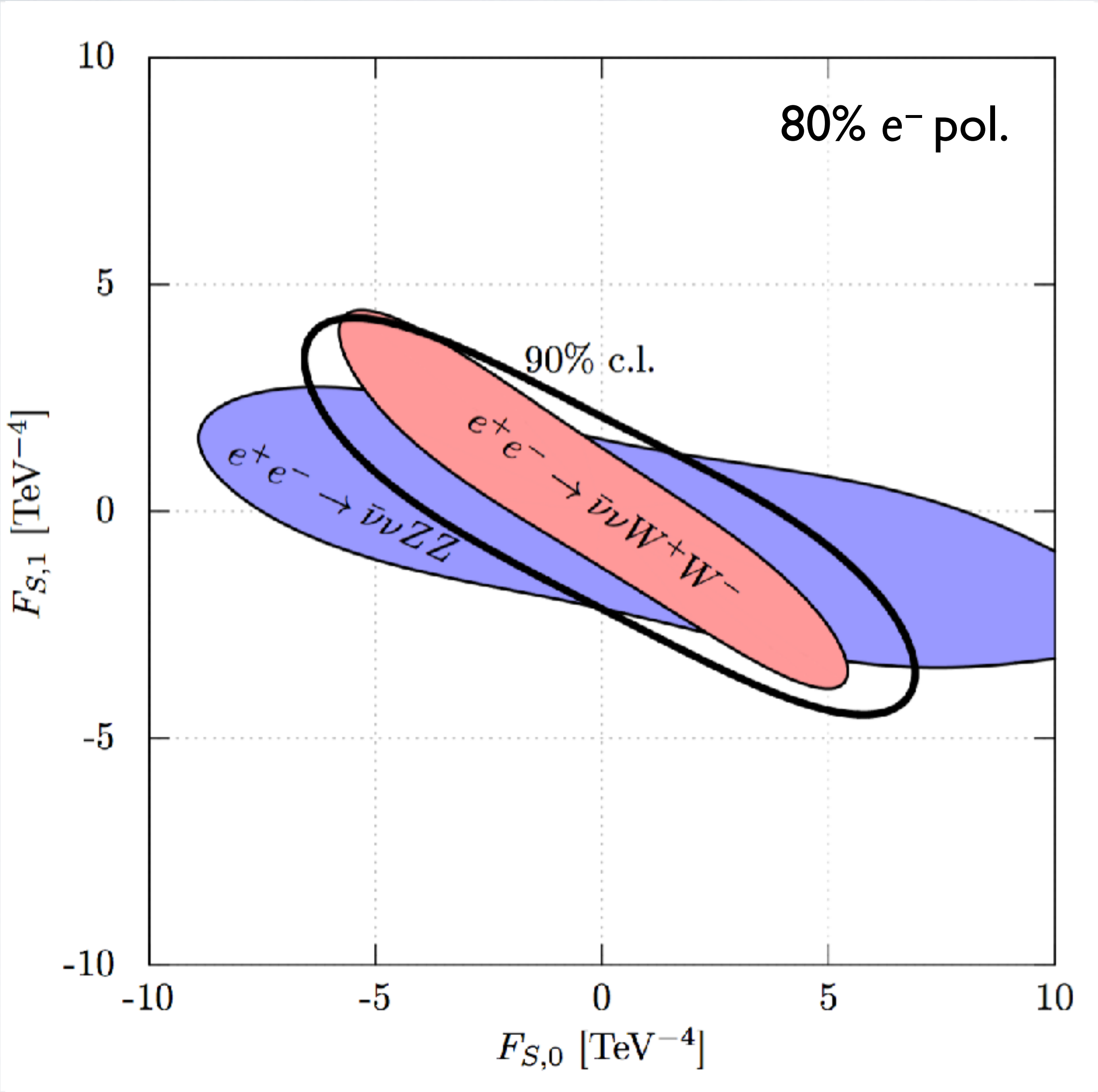
Total cross sections [fb], all cuts

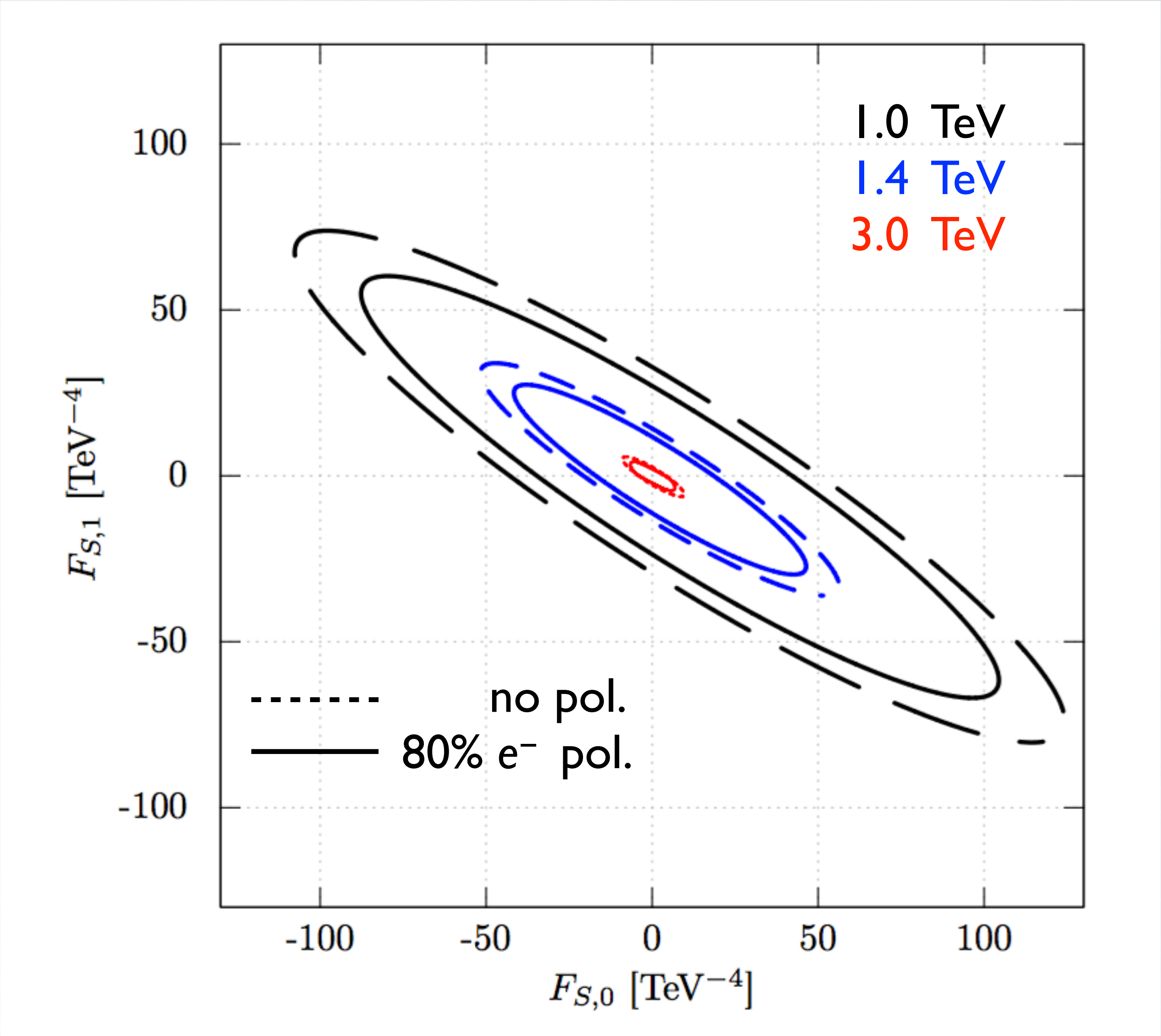
MC error are $\approx$ 1% on average

Exclusion sensitivities

5 ab^{-1} ⟸

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





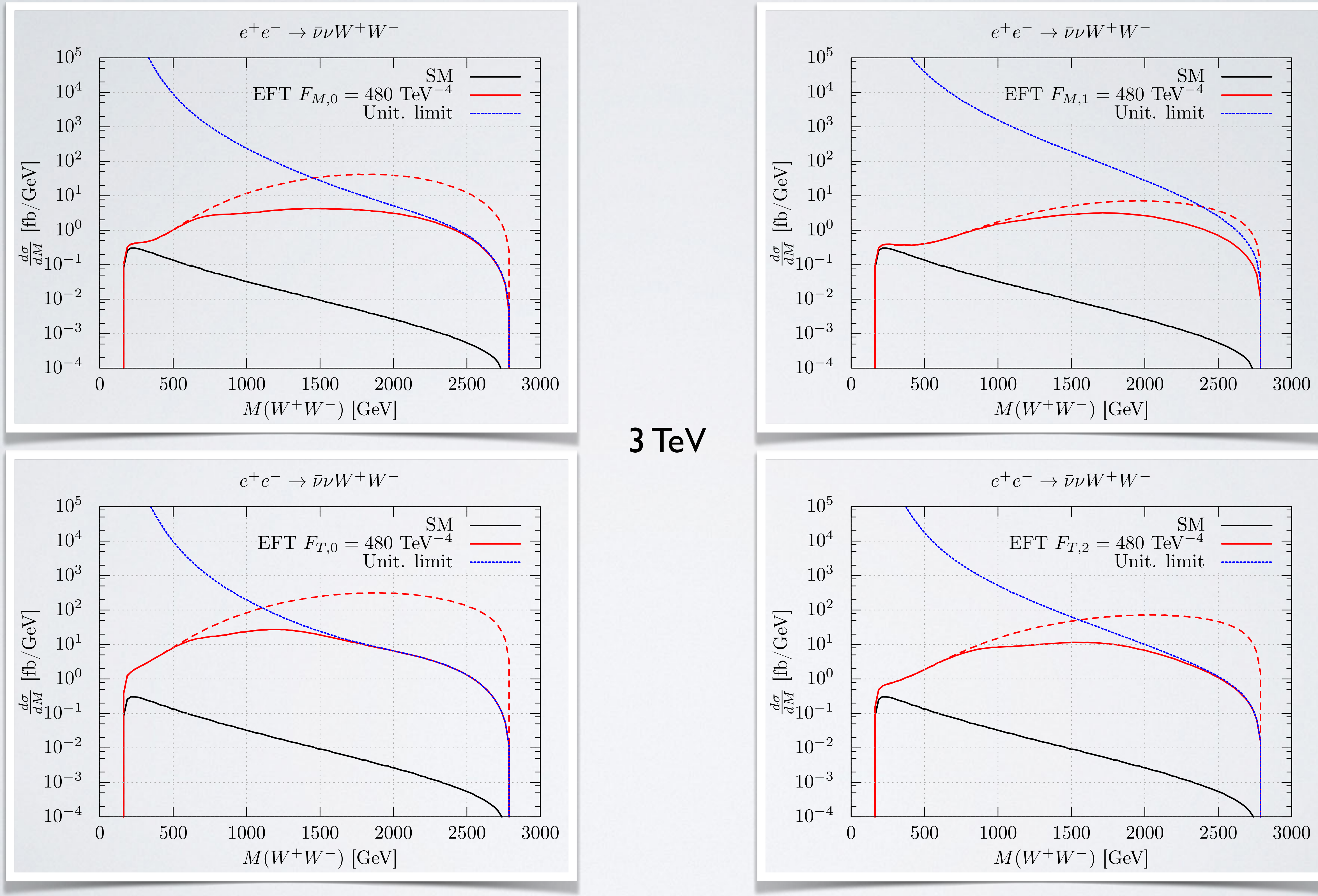
- All cuts have been applied
- Detector efficiencies are included
- All cross sections use *T*-matrix unitarization

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



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)

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

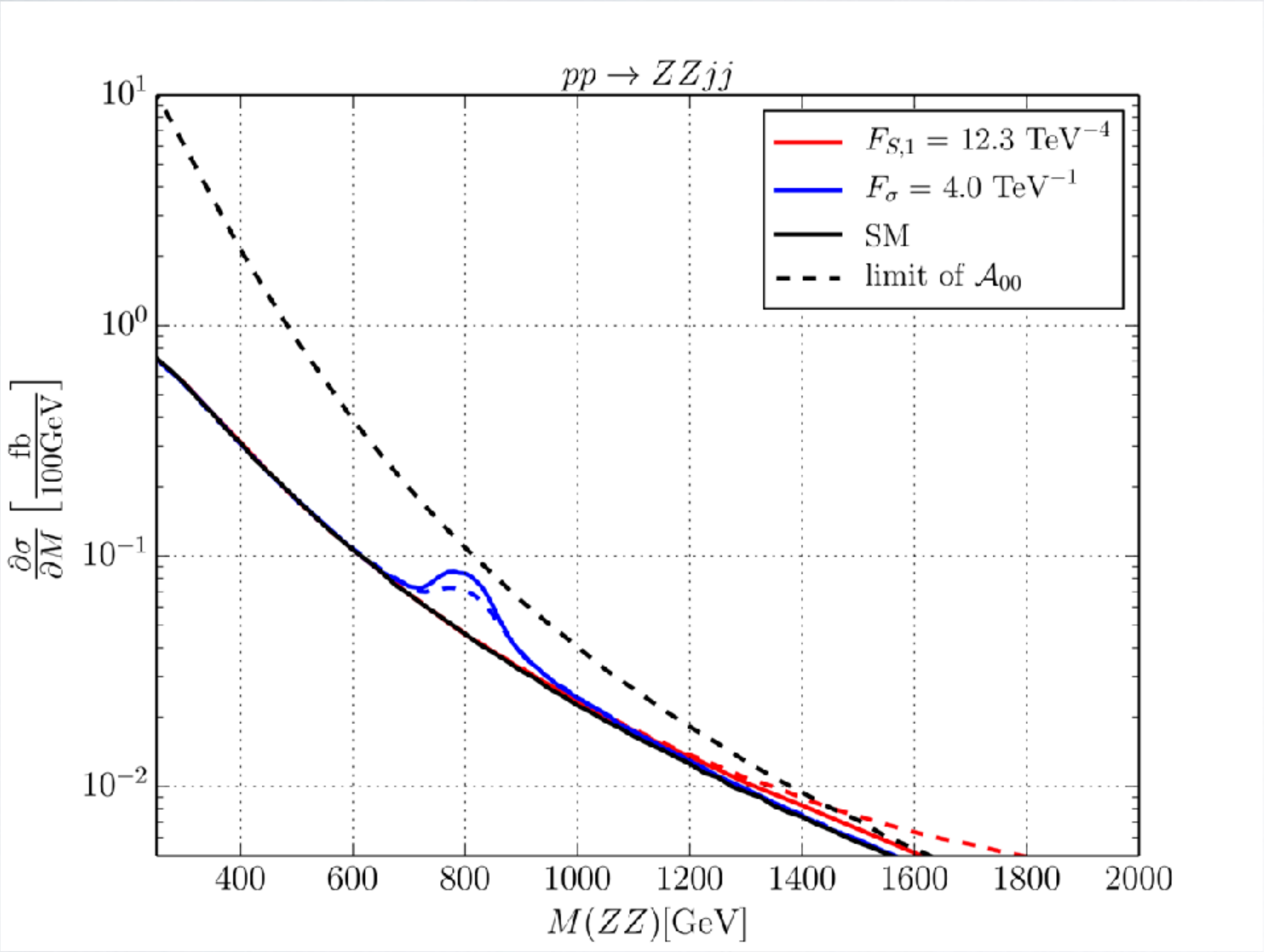
	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^{-}, \phi_t^{0}, \phi_t^{+}, \phi_t^{++}$ $\phi_v^{-}, \phi_v^{0}, \phi_v^{+}$ ϕ_s^{0}
tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^{-}, X_t^{0}, X_t^{+}, X_t^{++} \\ X_v^{-}, X_v^{0}, X_v^{+} \\ X_s^{0} \end{pmatrix}$
…	…	…

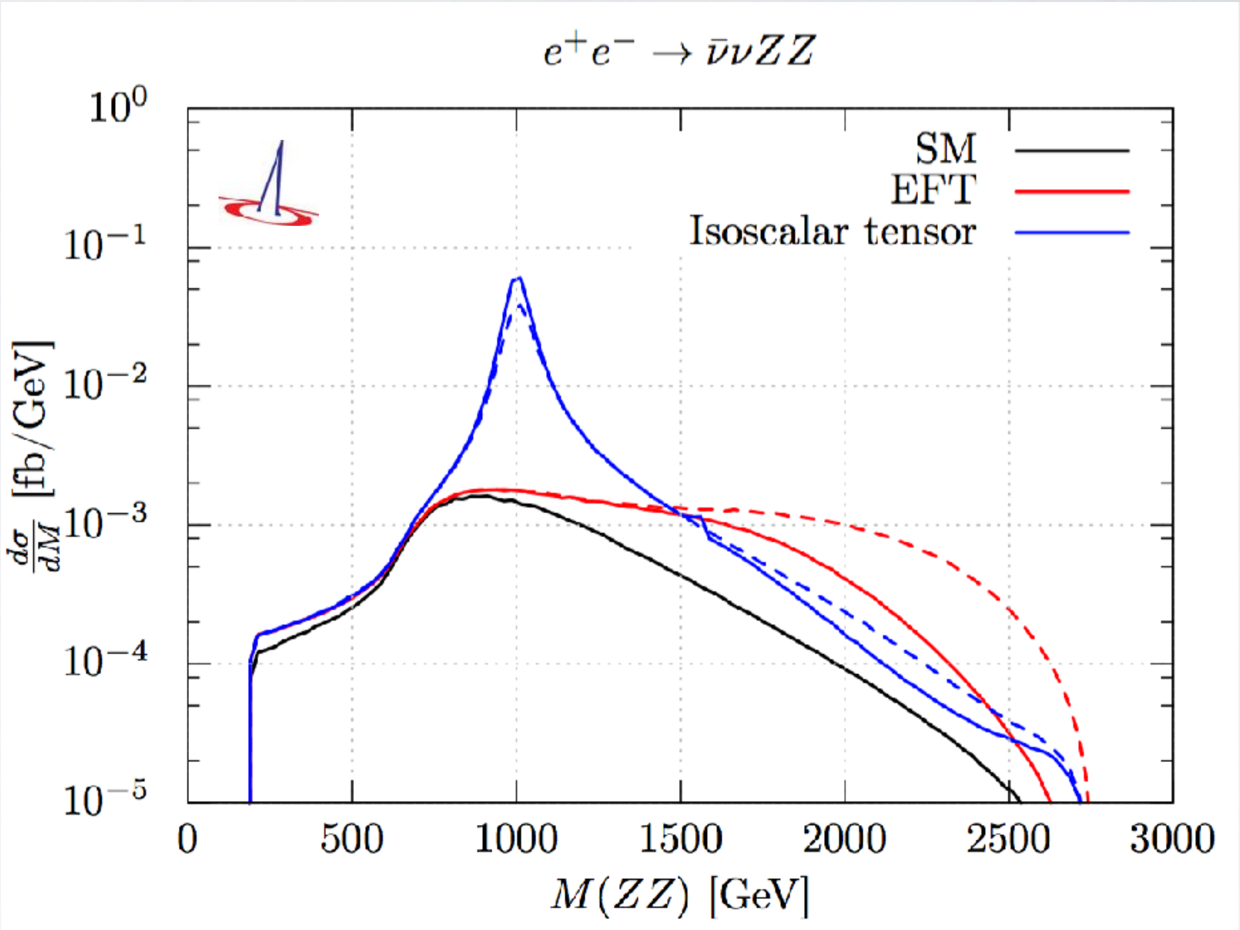
$$32\pi\Gamma/M^5$$

	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)

ILC Study Questions document

DESY 20-112,
KEK Preprint 2020-8,
IFIC/20-34, LCTP-20-14
SLAC-PUB-17543
July, 2020

ILC Study Questions for Snowmass 2021

LCC Physics Working Group

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ABSTRACT

To aid contributions to the Snowmass 2021 US Community Study on physics at the International Linear Collider and other proposed e^+e^- colliders, we present a list of study questions that could be the basis of

arXiv: 2007.03650v3

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: ≈ 1 x 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

Perspectives & Study Questions for Snowmass

- Precision discovery reach in VBS for high-energy e^+e^- colliders
- Fully hadronic final states available in VBS in e^+e^- colliders
- Hence: invariant mass of diboson system is fully reconstructable
- Gauge invariance: VBS and tribosons cannot be disentangled in signal model

Theory challenges, tasks, study questions

- Precision predictions: EW corrections, Sudakov logarithms, EW showers
- Connections to BSM models, access to *CP*-odd operators
- Importance of e^-e^- for VBS ?

Experimental challenges, tasks, study questions

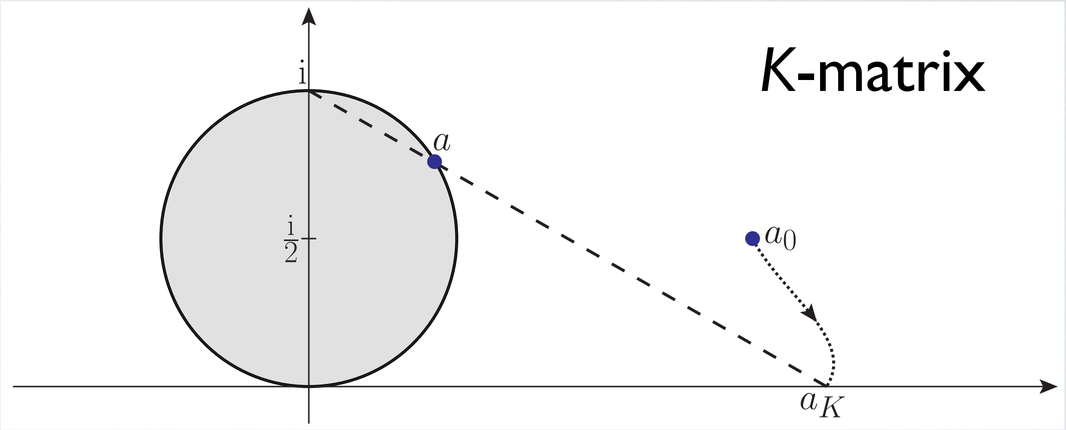
- Hadronic *W*/*Z* discrimination in TeV regime
- BDT-based separation of VBS vs. multi-bosons
- Improvement on forward-lepton tagging and vetoes
- Ultimate VBS measurement might be in plasma-driven 10-50 TeV e^+e^-

BACKUP

Quick remark on validity and unitarization

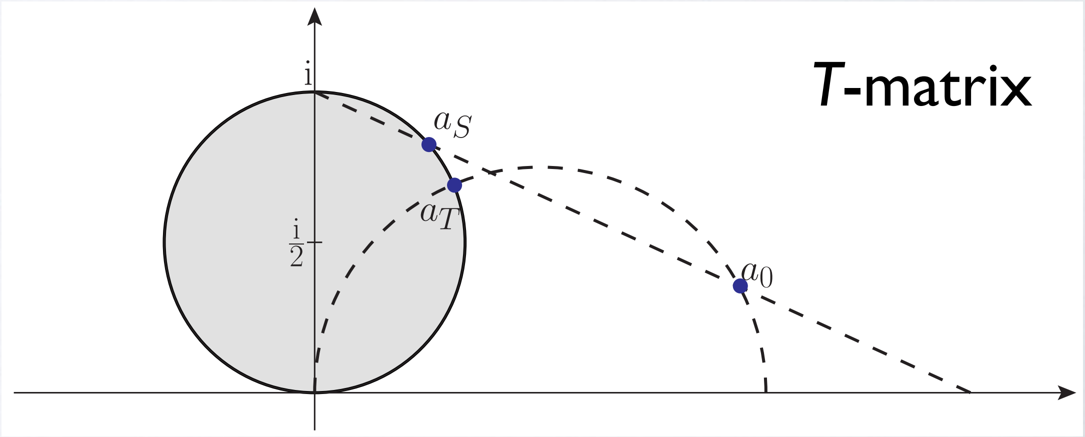
- EFT only valid for energy scales well below new degrees of freedom
- Higher-dimensional operators: amplitudes rise with energy
- High-energy regime could lead to unphysical results
  - Truncate reach ("event clipping")
  - Measurement only in low-energy bins
  - Unitarization procedure

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

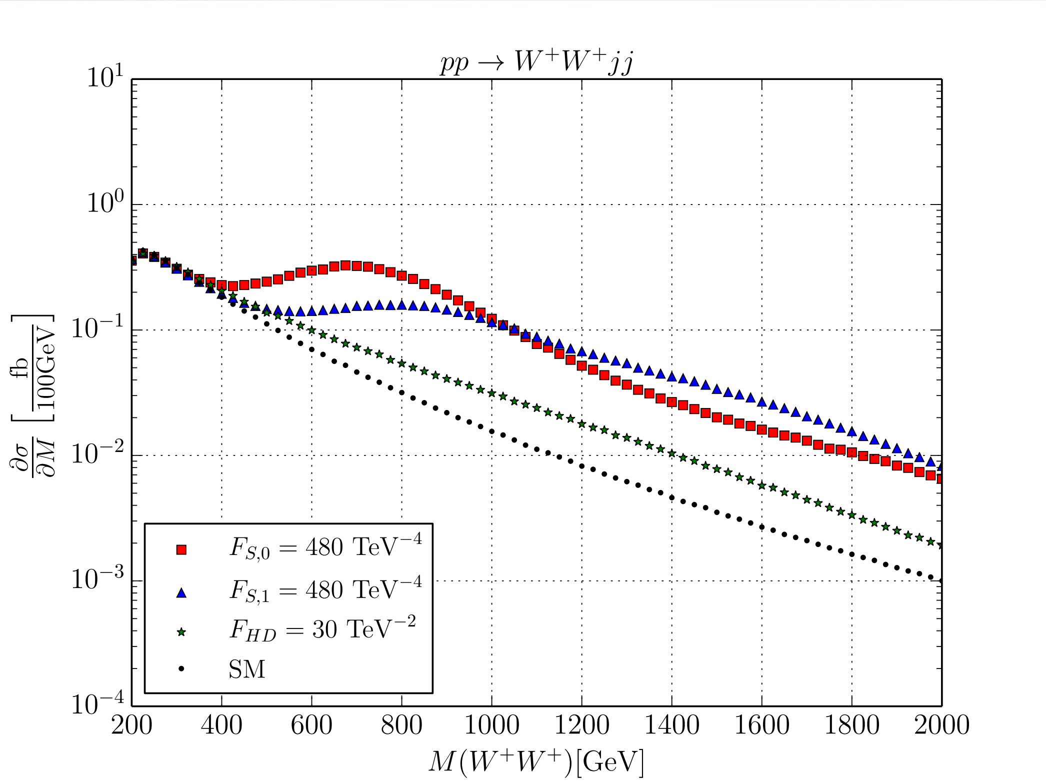


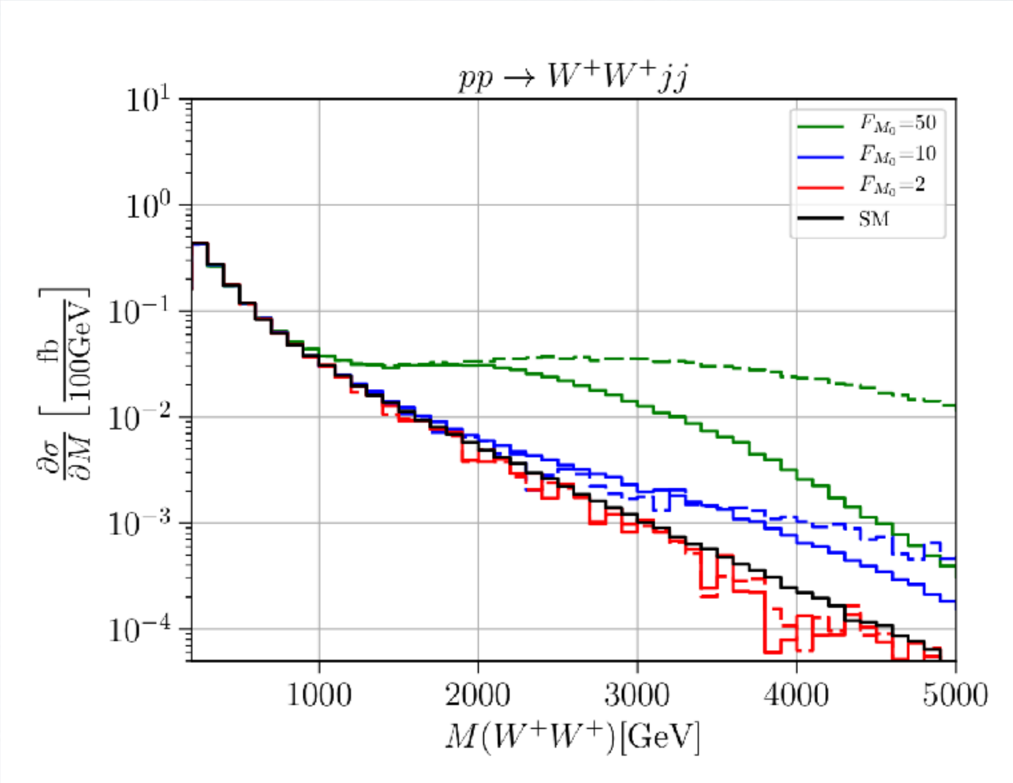
- *K*-matrix: Stereographic projection to Argand circle
- … is partial resummation of perturbative series
- Gives bin-wise highest event yield compatible with QFT
- Problem for amplitudes with intrinsic imaginary part (e.g. resonances)
- *T*-matrix: Thales circle construction [Kilian/Ohl/JRR/Sekulla 2014]
- Identical to *K*-matrix for real amplitudes
- Does not rely on perturbative description

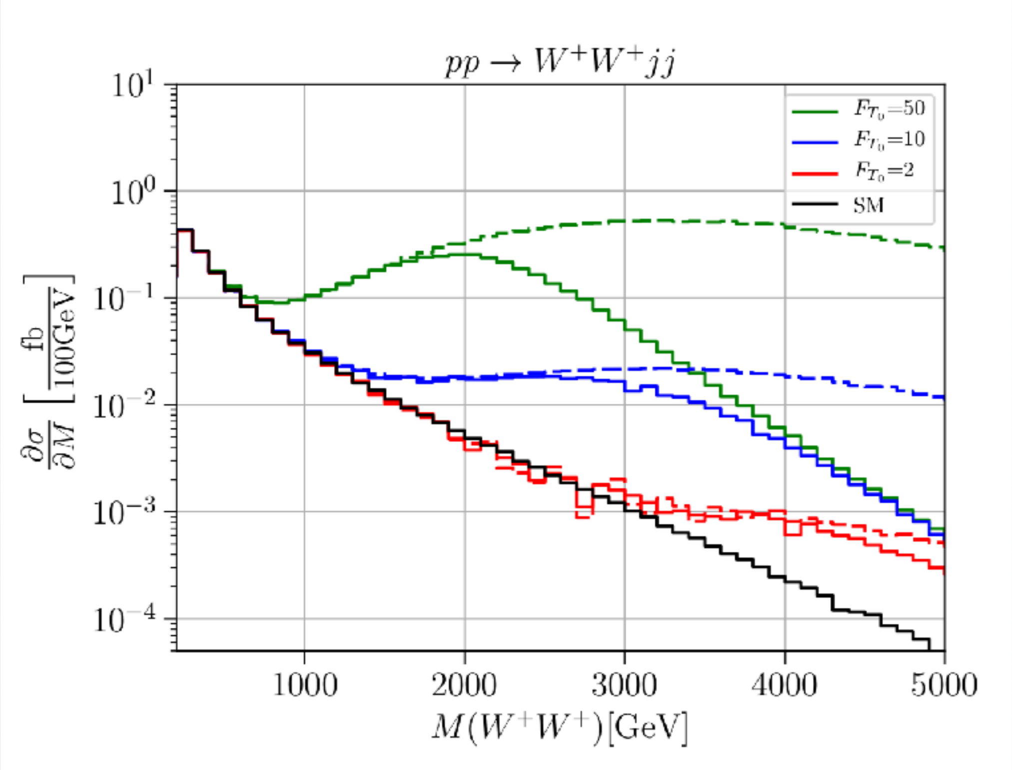
$$\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$$

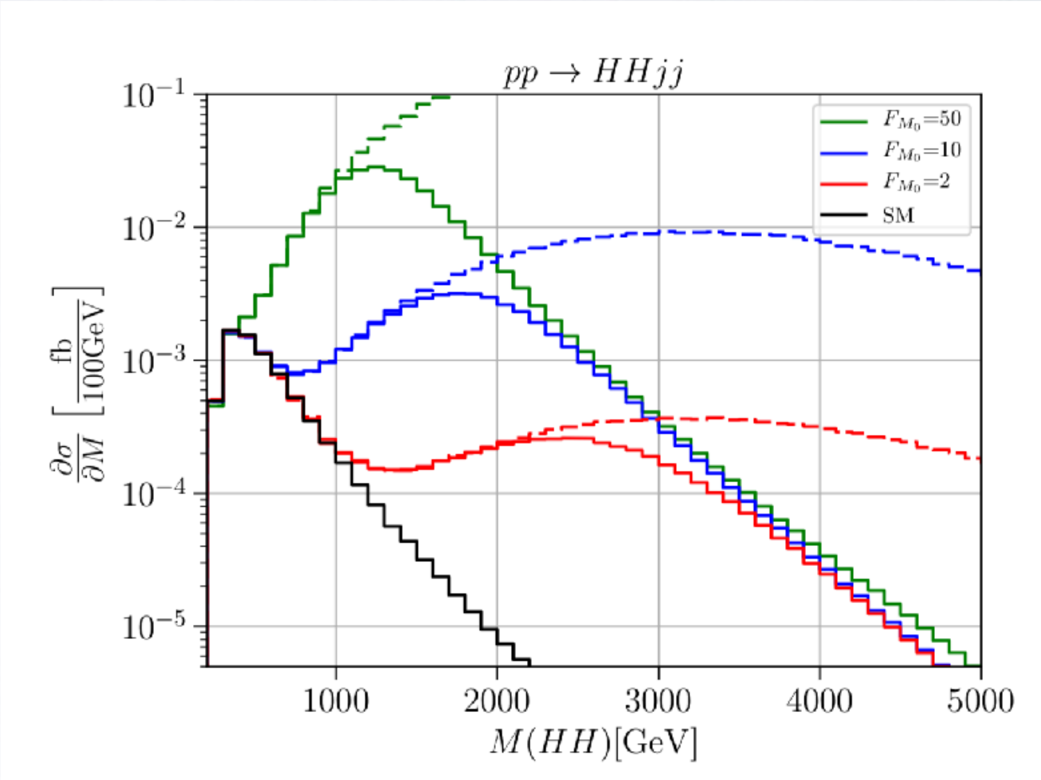


VBS diboson spectra



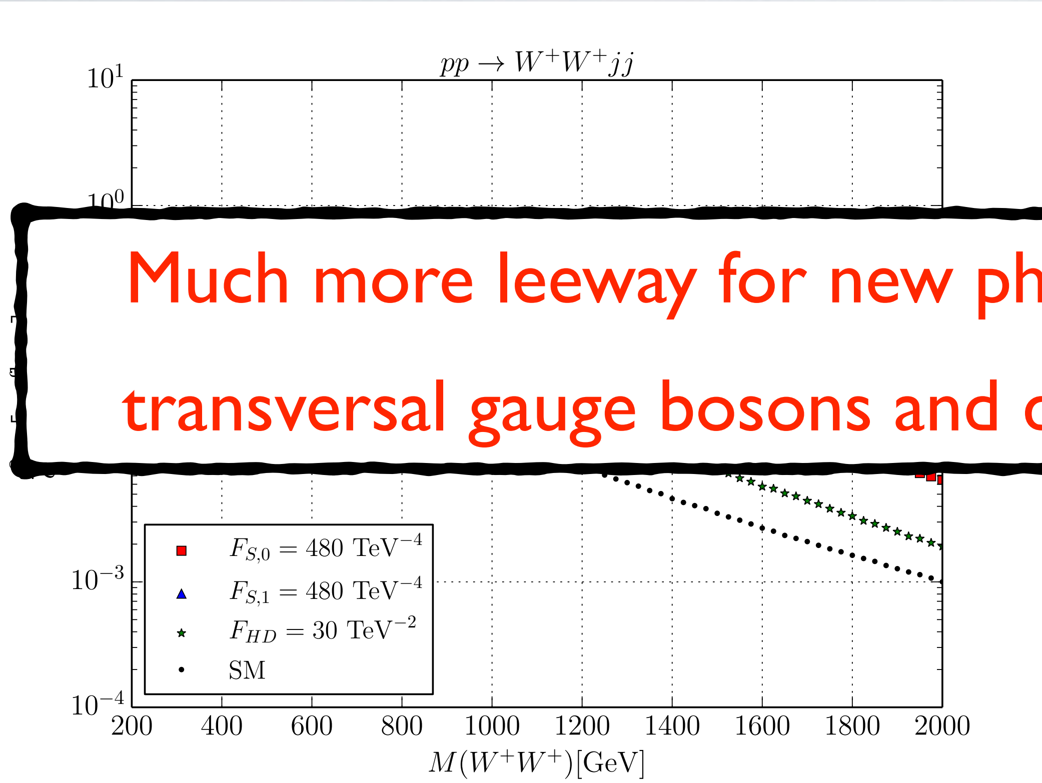




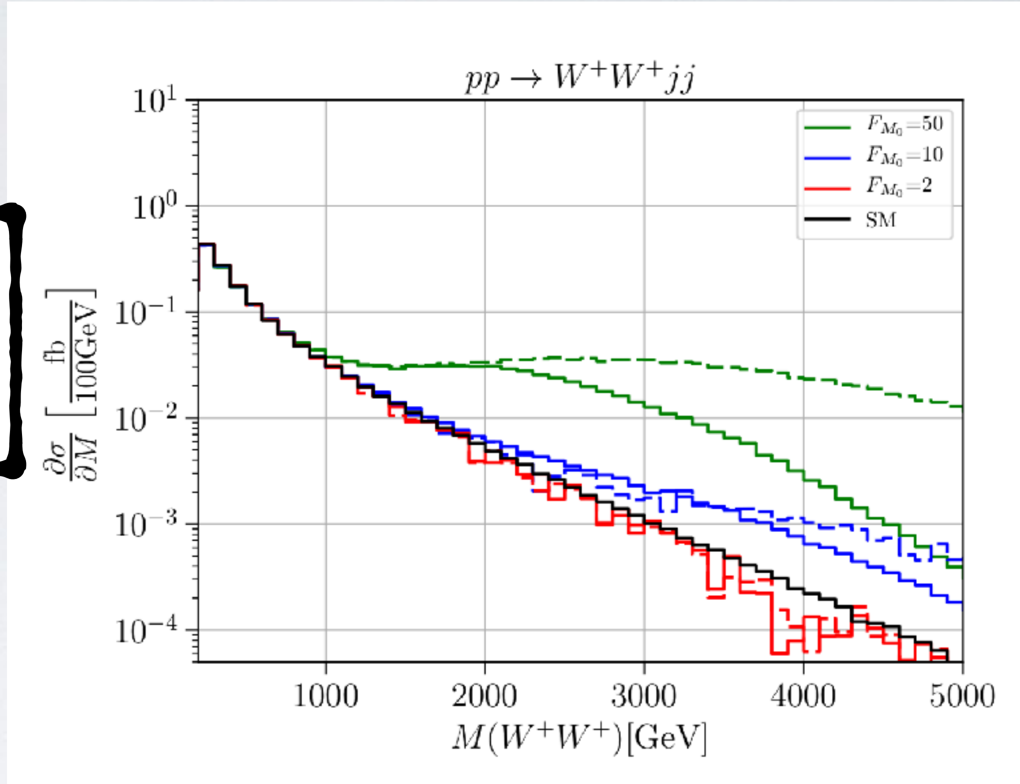


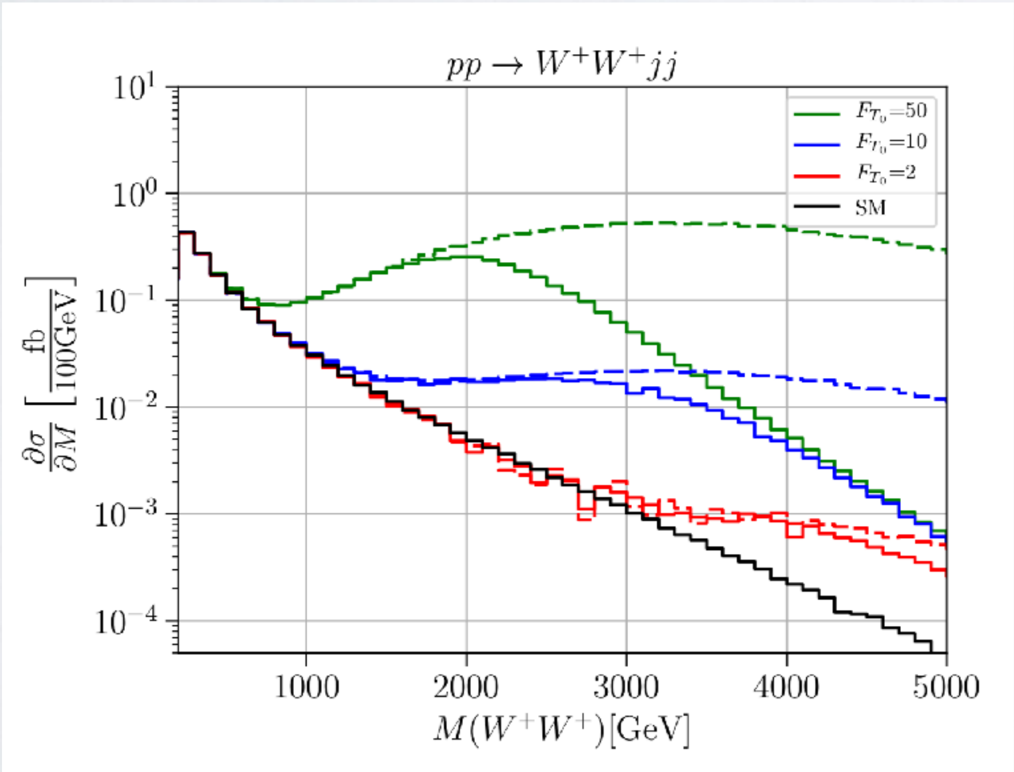
General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

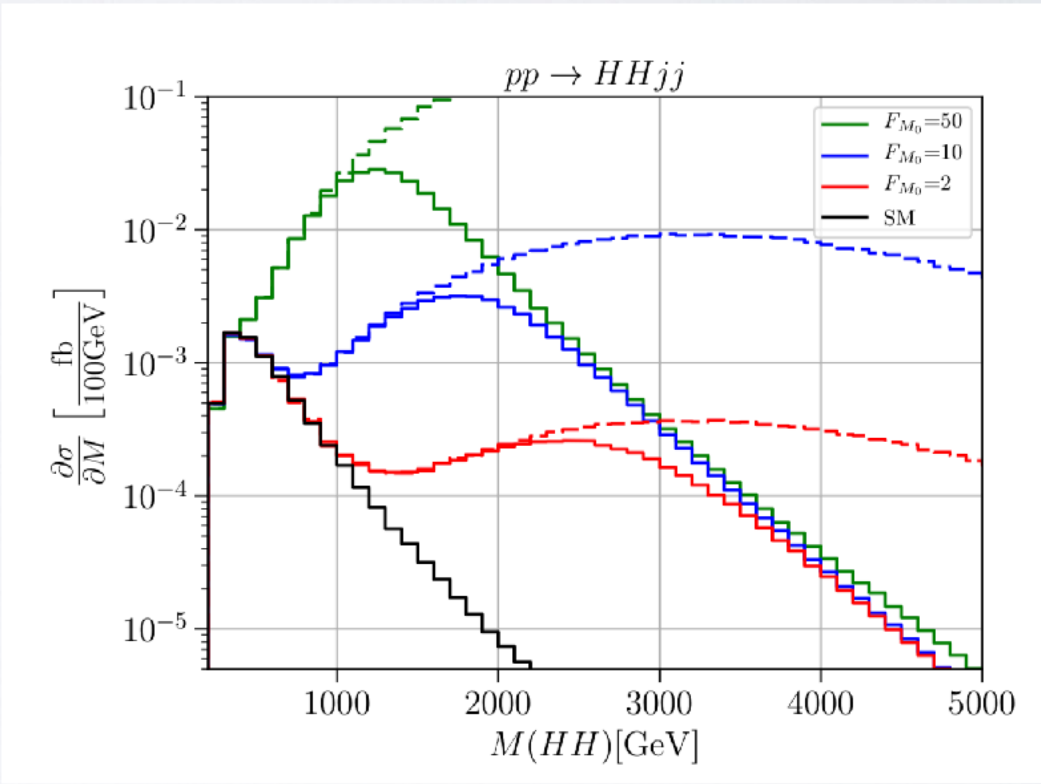
VBS diboson spectra



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







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