Unitarization in VBS and Tribosons

Jürgen R. Reuter, DESY

work together with
S. Braß, C. Fleper, W. Kilian, T. Ohl, M. Sekulla

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

WHIZARD: Multi-boson processes / Unitarization

WHIZARD v2.6.3 (10.02.2018) http://whizard.hepforge.org <whizard@desy.de>

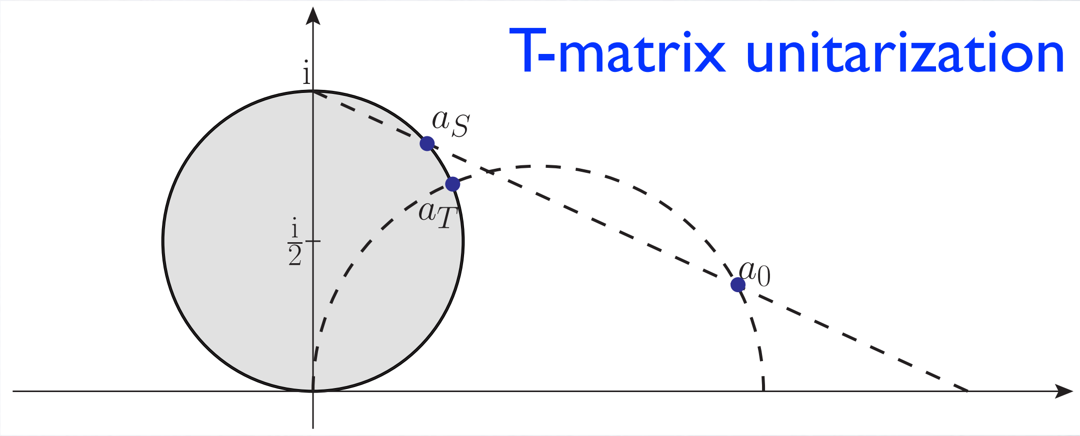
Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Vincent Rothe/Christian Schwinn/Marco Sekulla/So Young Shim/Pascal Stienemeier/Manuel Utsch/Zhijie Zhao + 2 Master

- Multi-purpose MC for *pp* and ee physics
- Final validation phase for NLO (QCD) automation; first test results for NLO EW
- UFO interface for SM-like models
- Completely general UFO interface: final validation phase [5-,6-pt vertices etc., MC4BSM2018?]
- Dim. 8 operators for VBS / Simplified Models for VBS / Unitarization:

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

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

Longitudinal dim-8 operators



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

Dim 8 operators and their Unitarization:

$$\mathcal{L}_{M,0} = -g^2 F_{M_0} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\rho}\right]$$
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Transversal dim-8 operators

Mixed dim-8 operators

Braß/Kilian/JRR/Sekulla, 03/18

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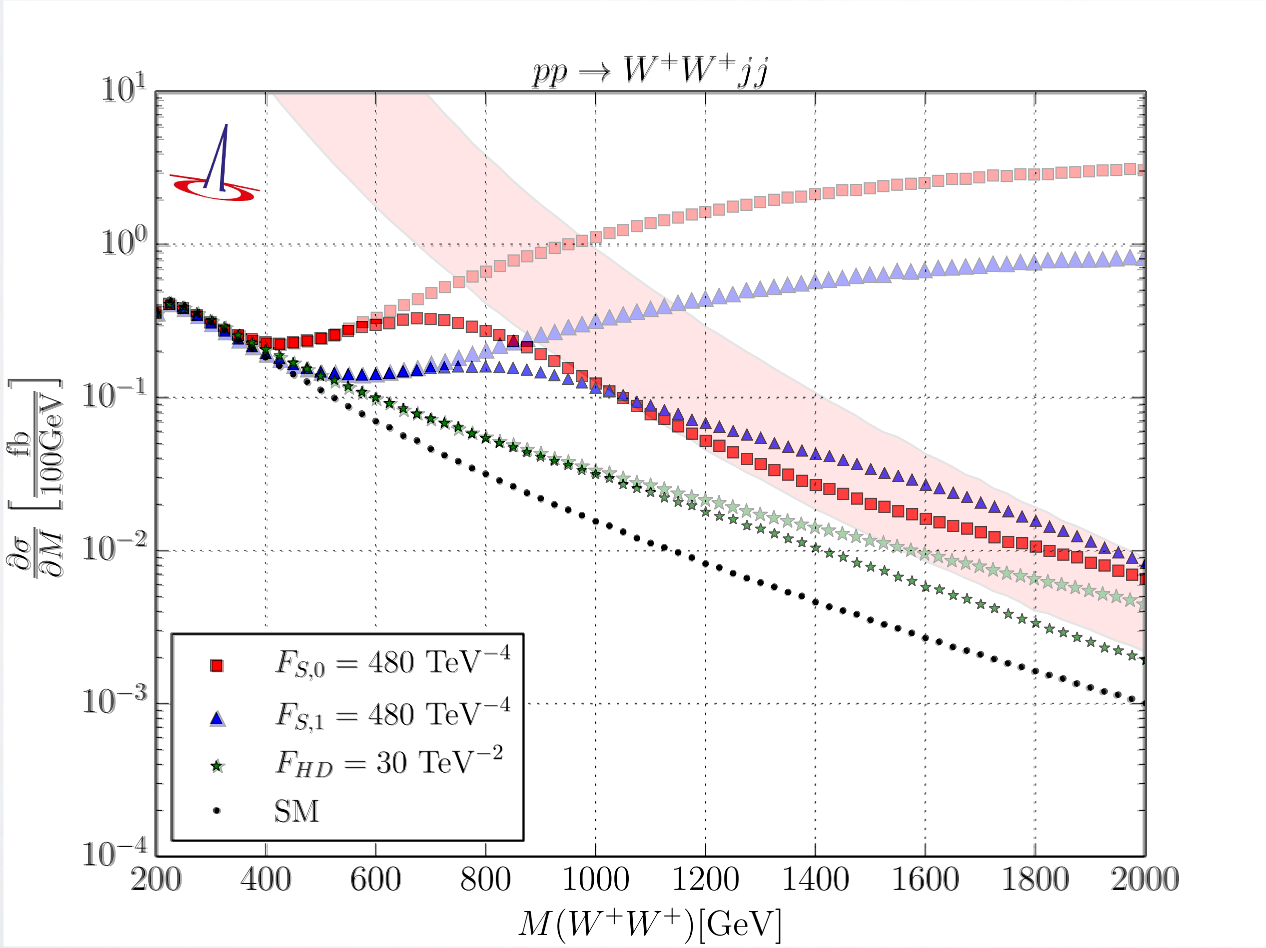

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Transversal dim-8 operators

Mixed dim-8 operators

Braß/Kilian/JRR/Sekulla, 03/18

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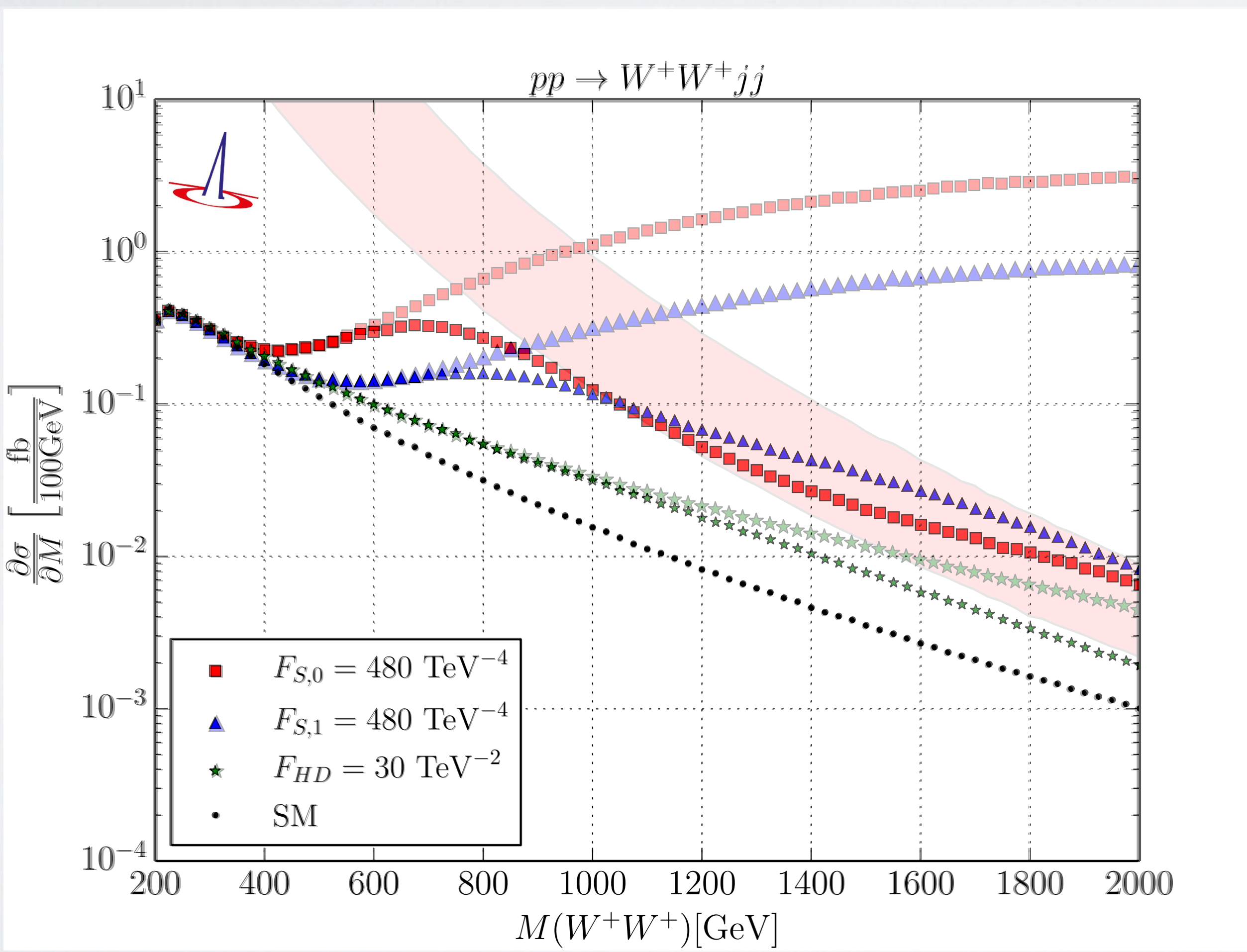

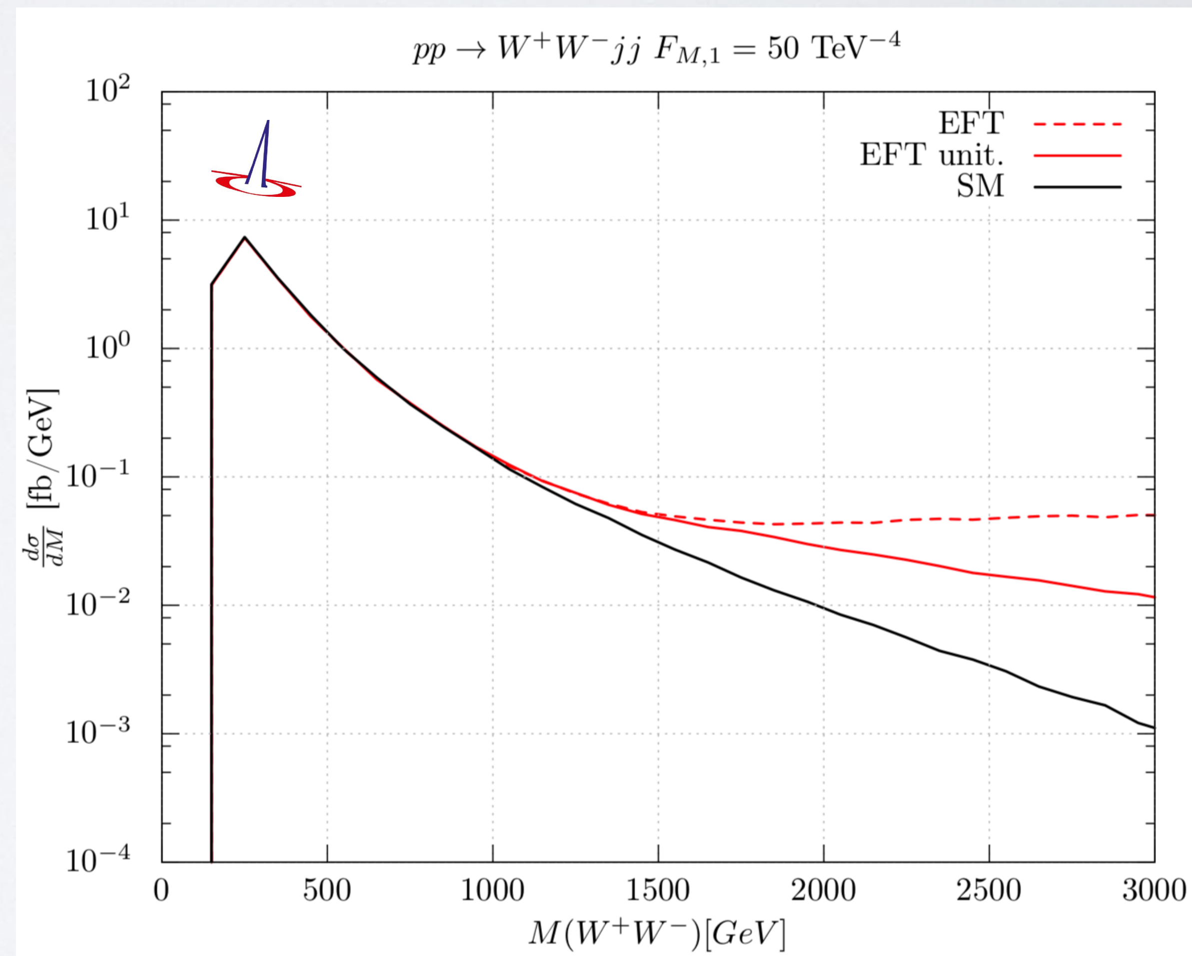

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Mixed dim-8 operators

Transversal dim-8 operators

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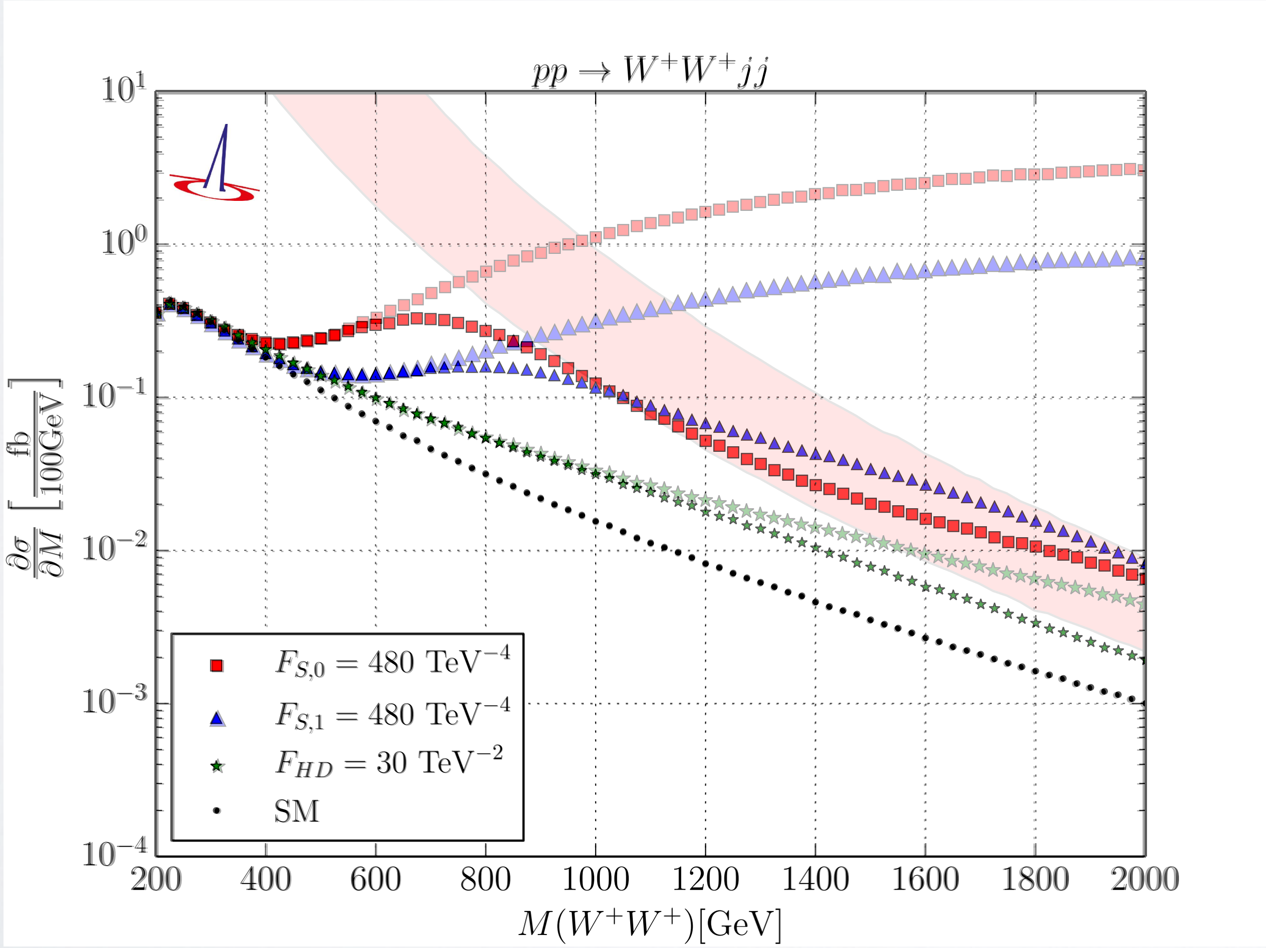
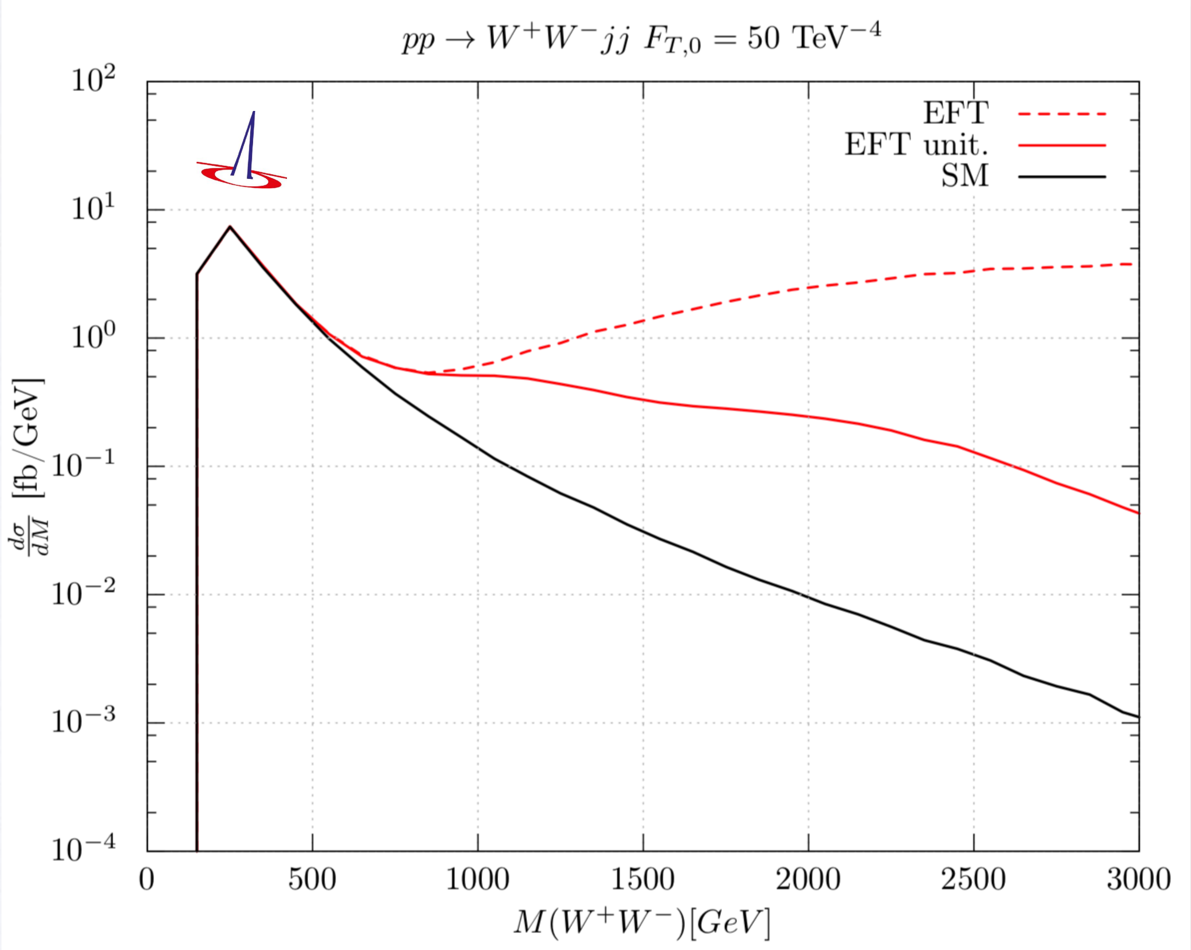
Braß/Kilian/JRR/Sekulla, 03/18





Dim 8 operators and their Unitarization:

Transversal (&mixed) operators:

Much more room for new physics

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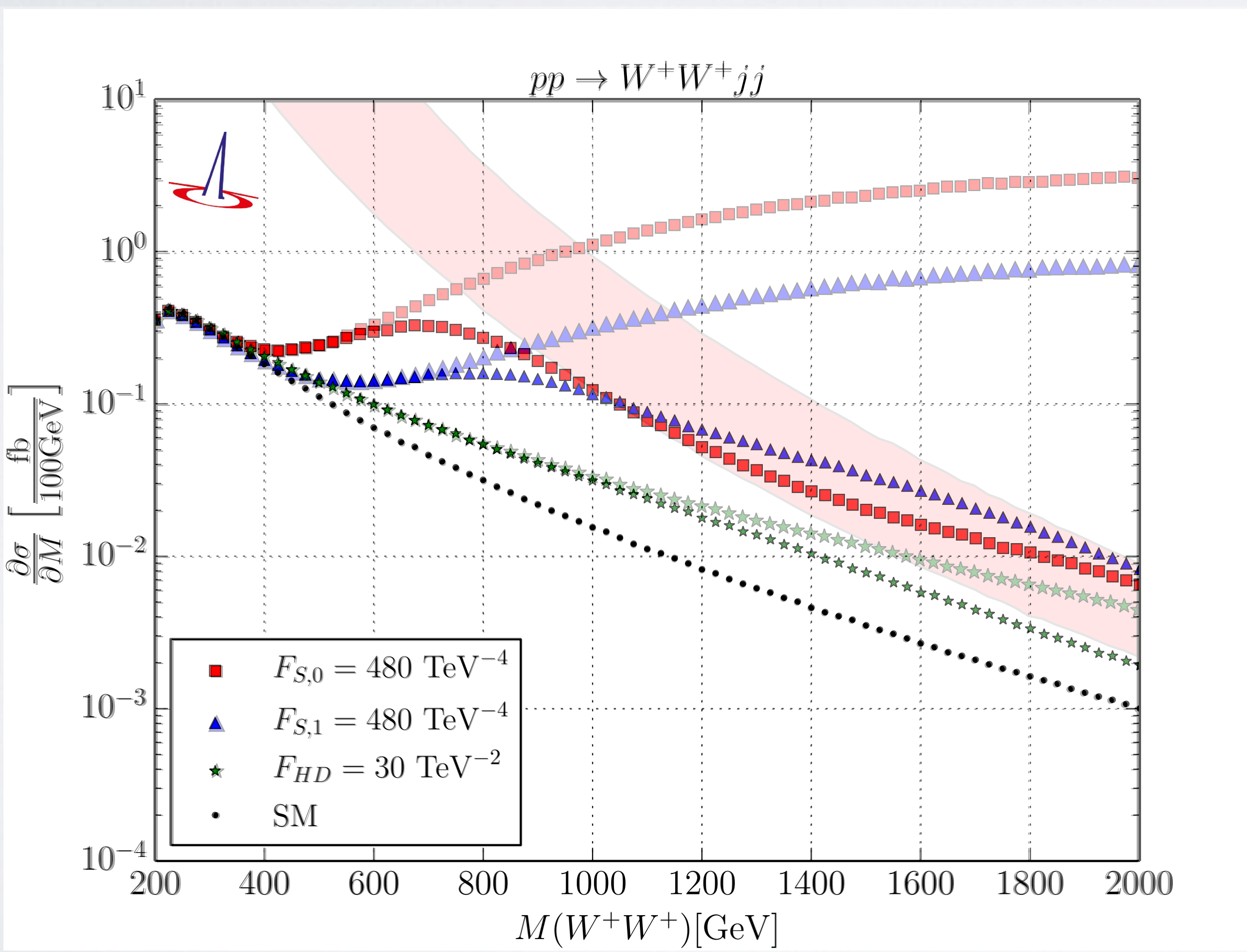
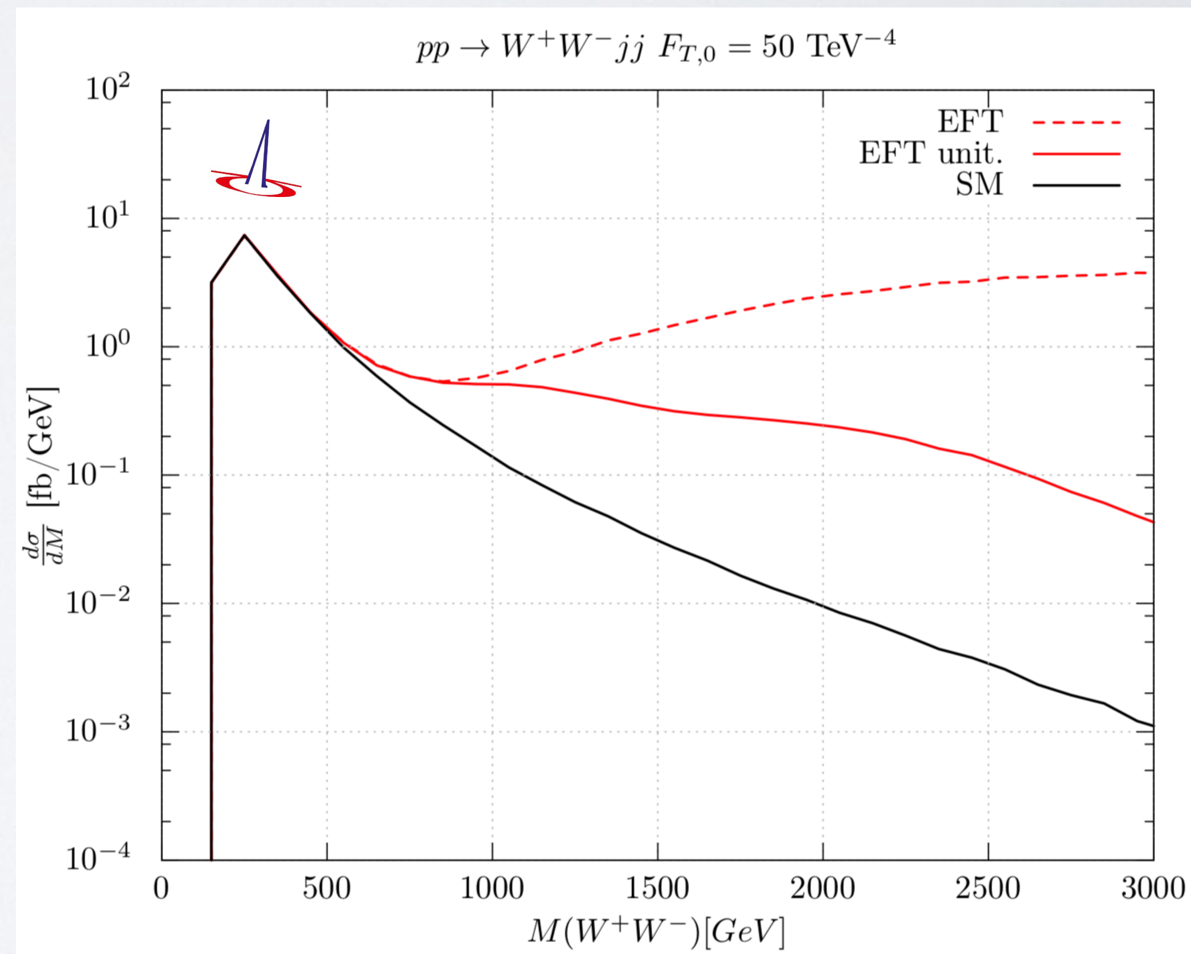
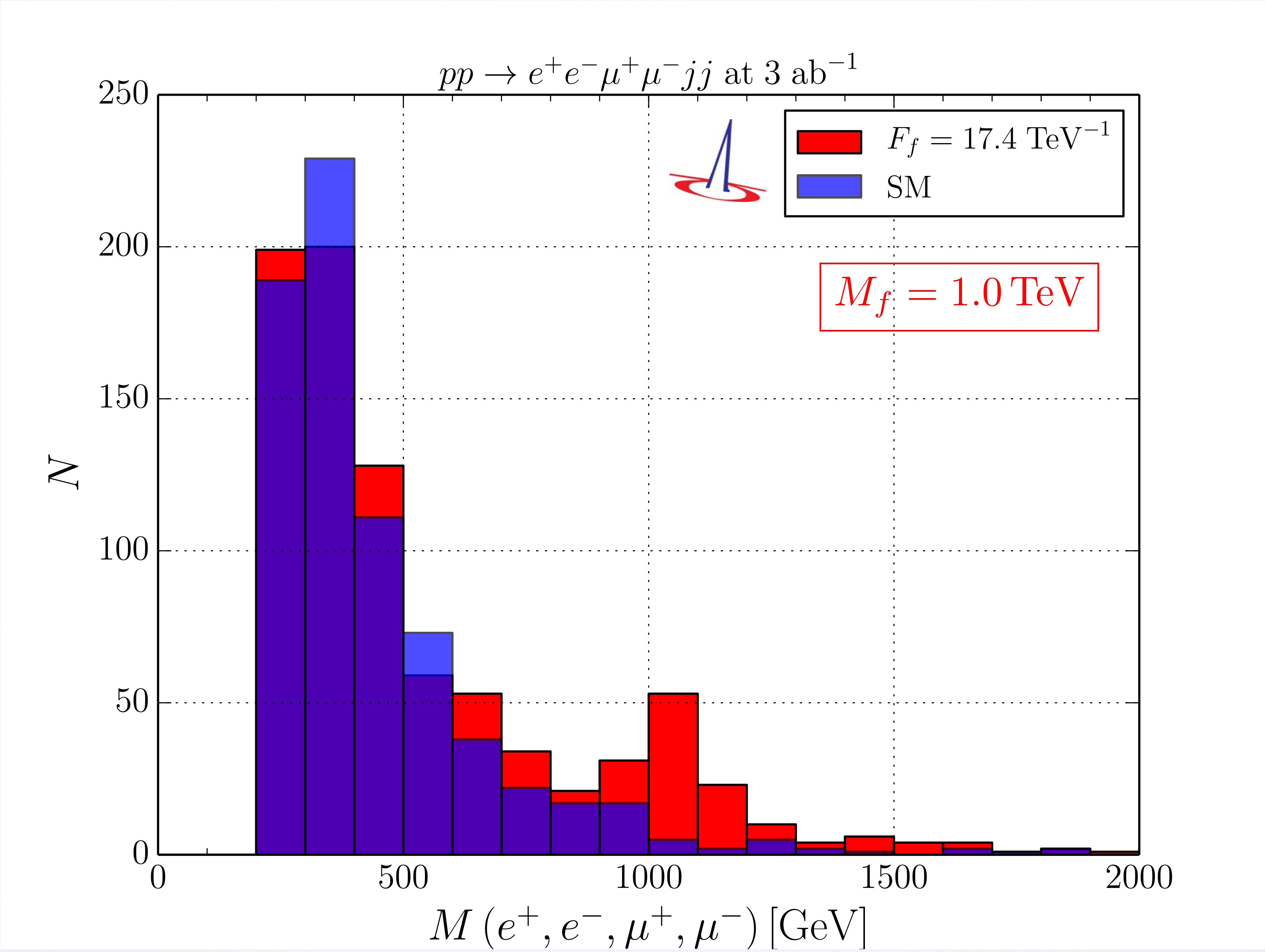
Braß/Kilian/JRR/Sekulla, 03/18





Complete LHC process at 14 TeV



EFT, Unitarization, and Simplified Models

- Rise of amplitude: 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)

Spins 0, 2 considered, 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	$\begin{pmatrix} X_t^{--}, X_t^{-}, X_t^0, X_t^+, X_t^{++} \\ X_v^-, X_v^0, X_v^+ \\ X_s^0 \end{pmatrix}$
...	...	...

$32\pi\Gamma/M^5$

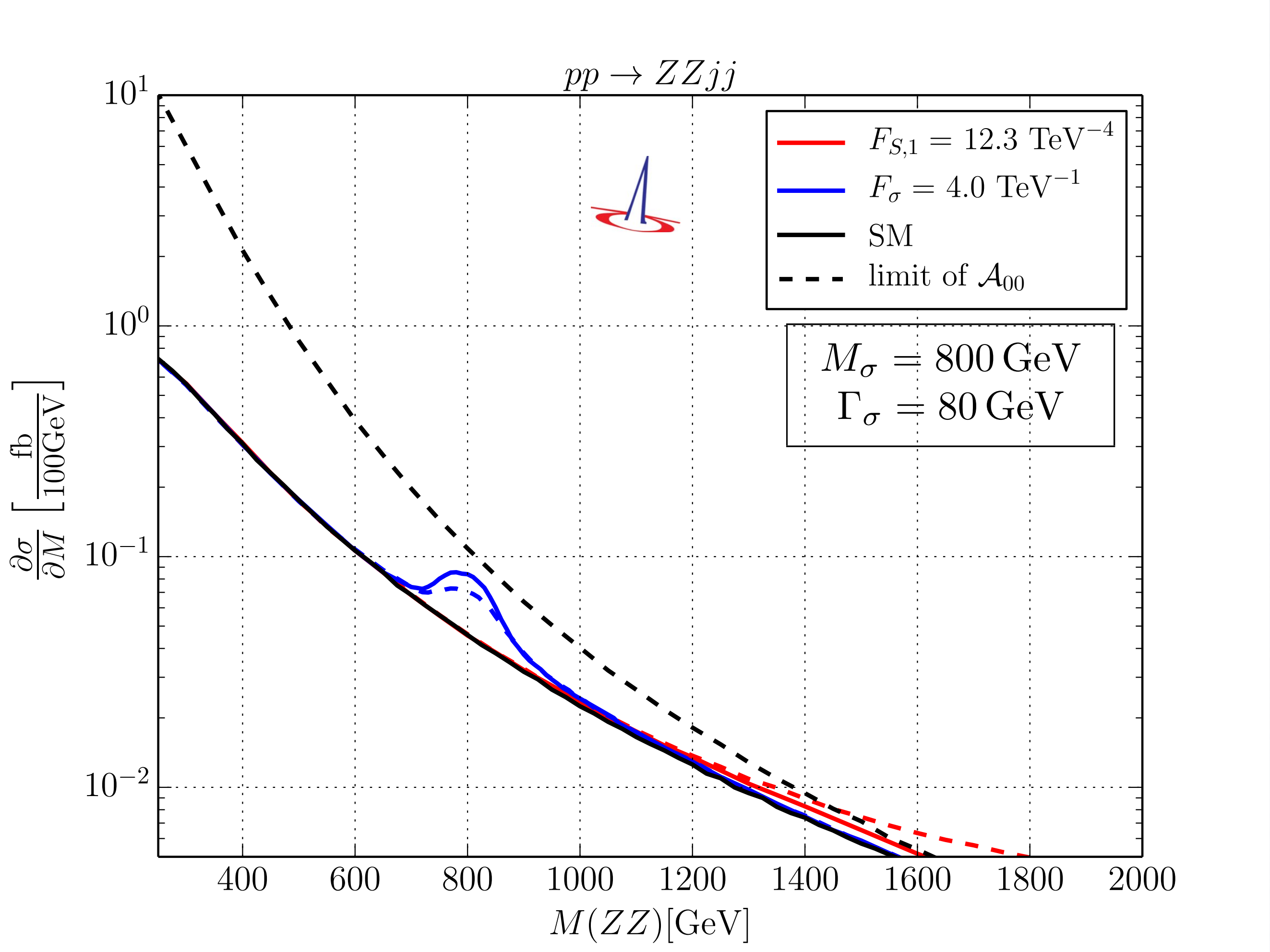
	σ	ϕ	f	X
$F_{S,0}$	$\frac{1}{2}$	2	15	5
$F_{S,1}$	–	-$\frac{1}{2}$	-5	-35

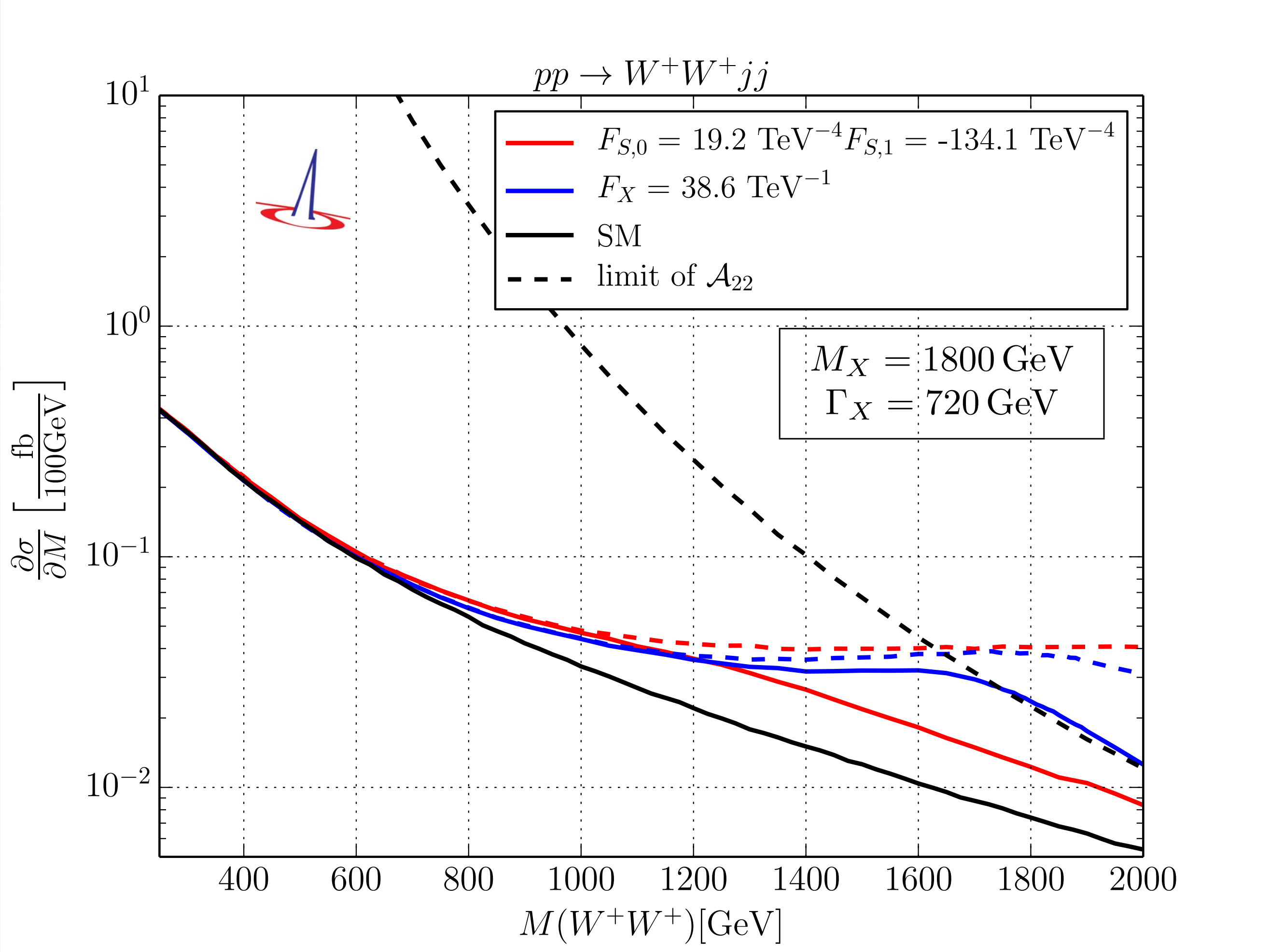
Translation into Wilson coefficients below resonance

Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: PRD93(16),3. 036004 [1511.00022]

Black dashed line:
saturation of $\mathcal{A}_{22}(W^+W^+)/\mathcal{A}_{00}(ZZ)$

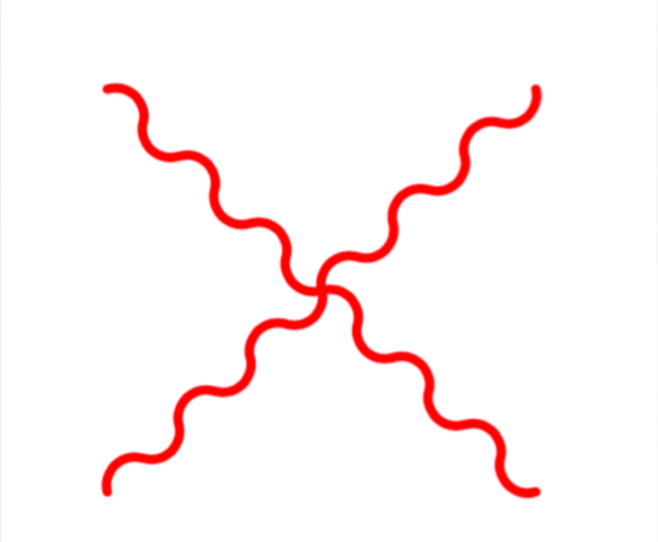




$$M_{jj} > 500\,\text{GeV};\ \ \Delta\eta_{jj} > 2.4;\ \ p_T^j > 20\,\text{GeV};\ \ |\Delta\eta_j| < 4.5$$

Resonances with transversal operators: *in preparation* Braß/Kilian/JRR/Sekulla, 03/18

Triple [multiple] Vector Boson Production ?

Relate  to  ?

- Yes, same Feynman rule as in VBS, but …
- one external *W/Z/γ* always far off-shell
- Unitarization formalism: work in progress (needs $2 \to 3$ unitarizations)

  (using scattering matrix with elastic & inelastic channels Kilian/JRR/Sekulla *in prep.*)
- Different Wilson coefficients dominate (particularly for resonances)
- Important physics (partially) independent from VBS ("different fiducial vol.")

Open Questions / Further projects

- Better treatment of on-/off-resonance transitions at kinematic edge
- How much do luminosity and energy buy us?
- Investigate other potentially strongly coupled channels like: $pp \to jjVV \to jj\,tt$
- Study connections of Wilson coefficient dependence between VBS and tribosons
- Sensitivity of triboson channels & unitarity bounds
- Relations between $pp \to VVV$ […] and $pp \to HHH$ […]
- Importance of QCD (+ EW) corrections on signal for limit setting

MBI 2018 [6th Multi-Boson Interactions]
University of Michigan, Ann Arbor, Aug. 28-30 2018

https://indico.cern.ch/event/700961/

BACKUP SLIDES