Simplified Models for New Physics in VBS

Jürgen R. Reuter, DESY

based on work with:
S. Brass, W. Kilian, T. Ohl, M. Sekulla

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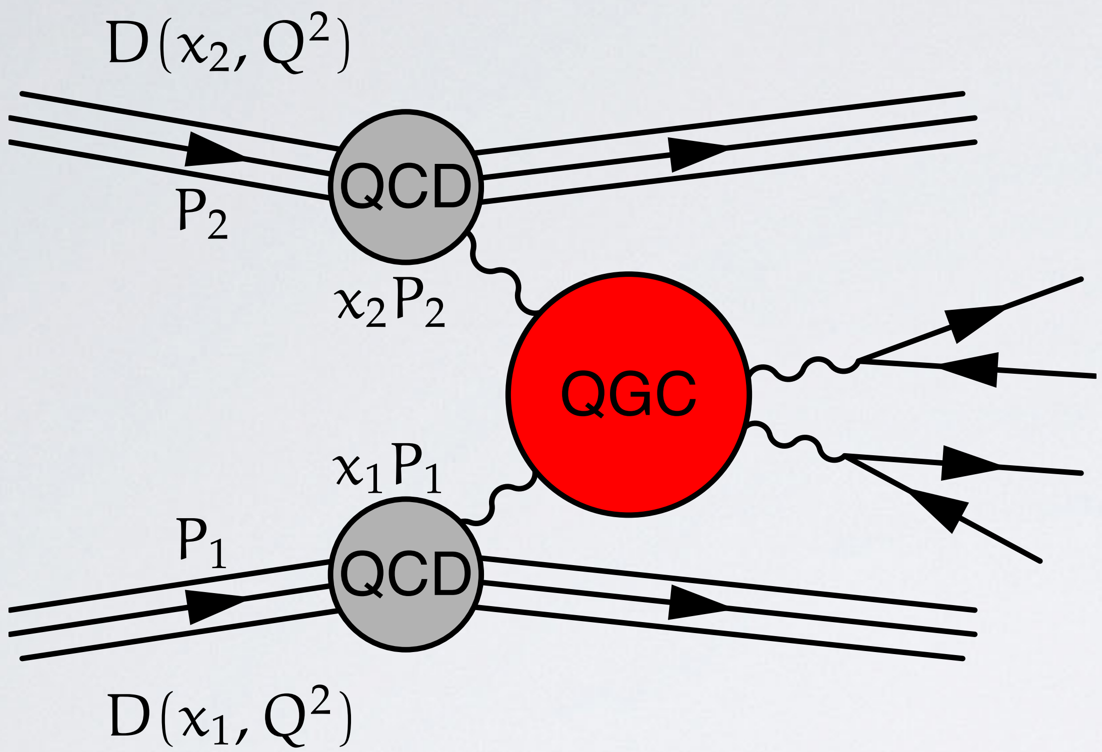
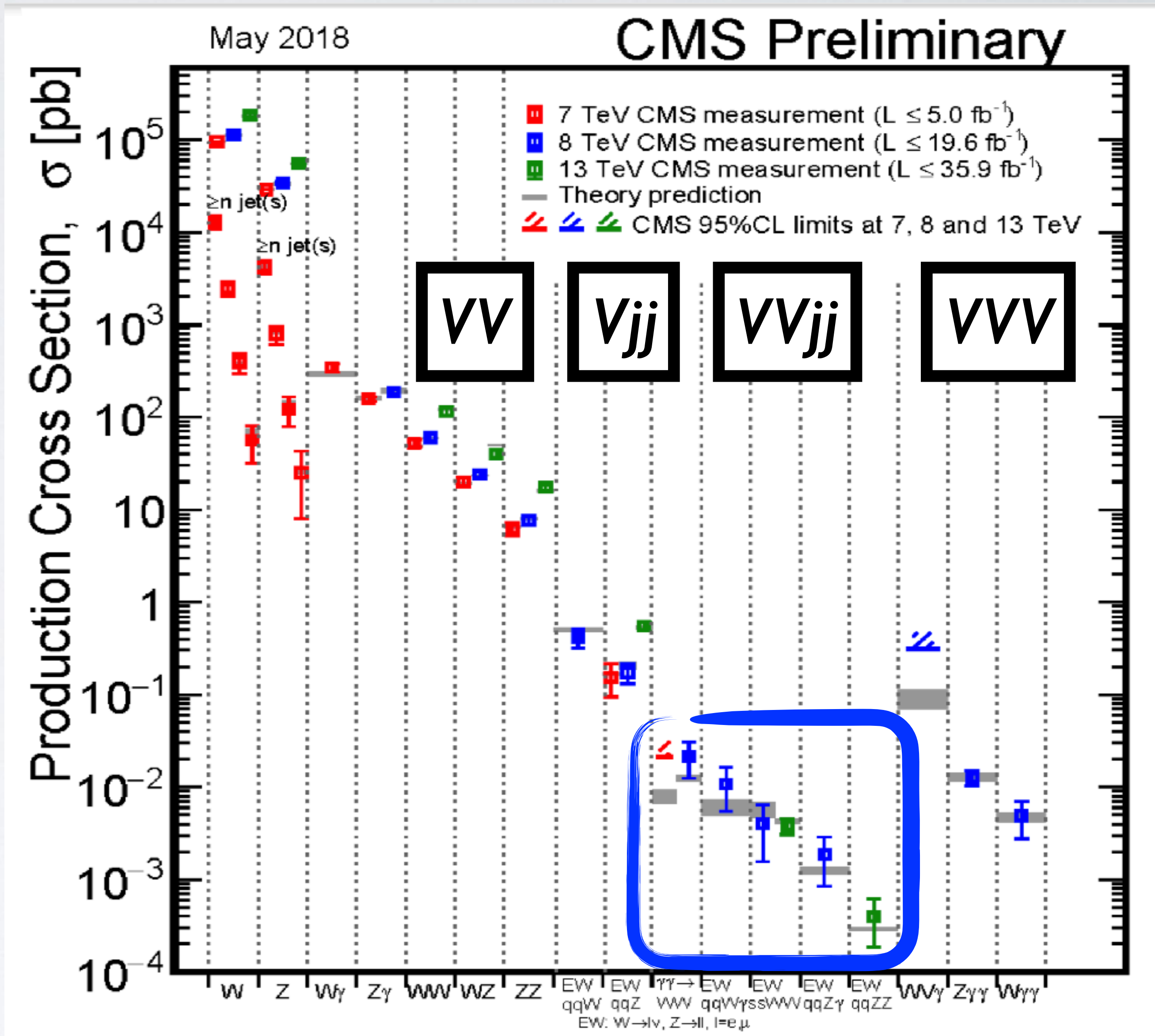
PRD93(16),3. 036004 [1511.00022]
PRD91(15) 096007 [1408.6207]

Anatomy of Vector Boson Scattering (VBS)

$pp \to WWjj \to \ell\ell\nu\nu jj$



Smallest accessible SM cross sections



Fiducial phase space volume:

- $lljj$ tag
- m_{jj} > 500 GeV (“jet recoil”)
- $|\Delta y_{jj}|$ > 2.4 (“rapidity distance”)
- Cuts on E_j , $p_T{}^j$
- No / little central jet activity

Subtle cancellation of amplitudes in SM

Dim-8 operators in MBI physics

Dim-8 operators for MBI physics

Longitudinal operators

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

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

Mixed operators

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

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Transversal operators

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \mathrm{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right]$$

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$$\mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

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	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

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- Energy rise of operators lead to unitarity violation
- Unitarity violation cancels between operators in UV-complete Theory

									A
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$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
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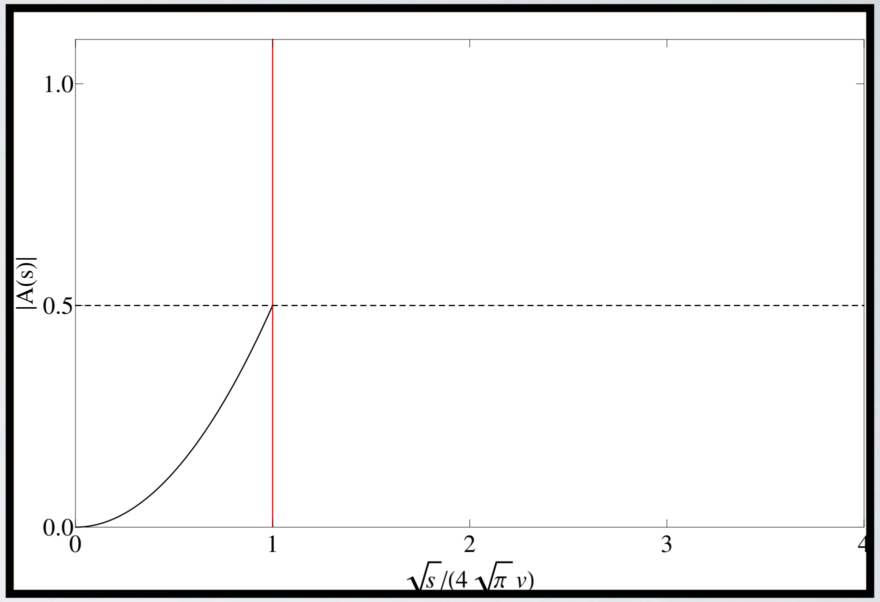
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

Procedures to treat unitarity violations

Cut-off (a.k.a. "Event clipping") $\theta(\Lambda_C^2 - s)$

unitarity bound (0th partial wave) at Λ_C
no continuous transition beyond
Effect on BDT training not clear



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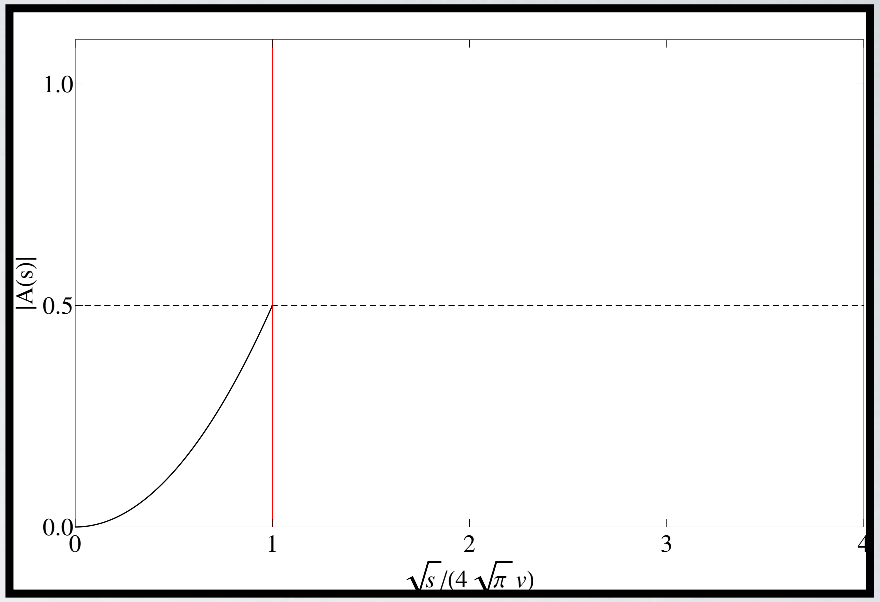

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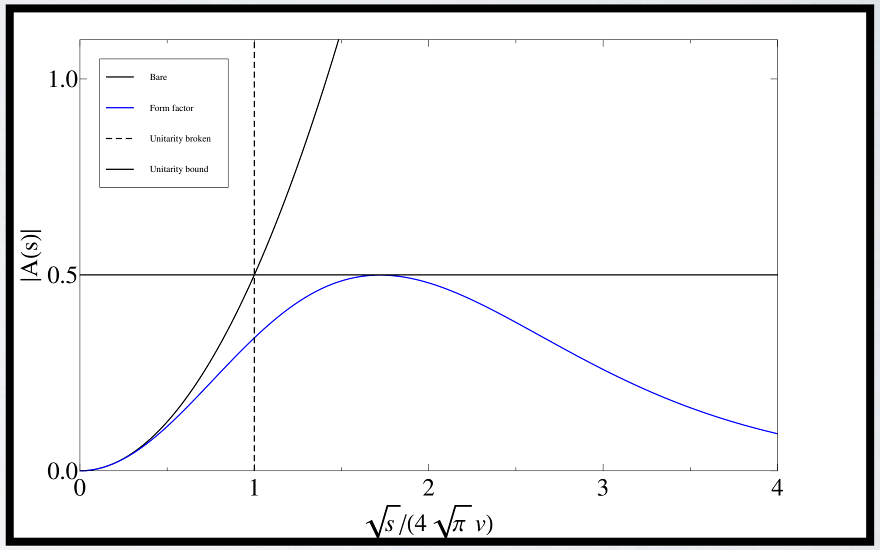
Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$



Applicable for arbitrary operators, tuning in 2 parameters: *n* damps unitarity violation, Λ_{FF} highest value to satisfy 0th partial wave

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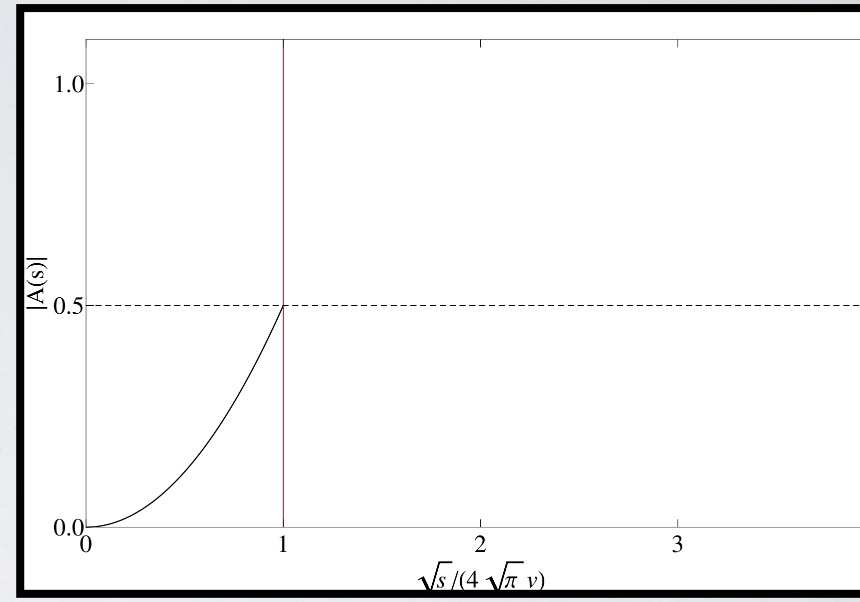

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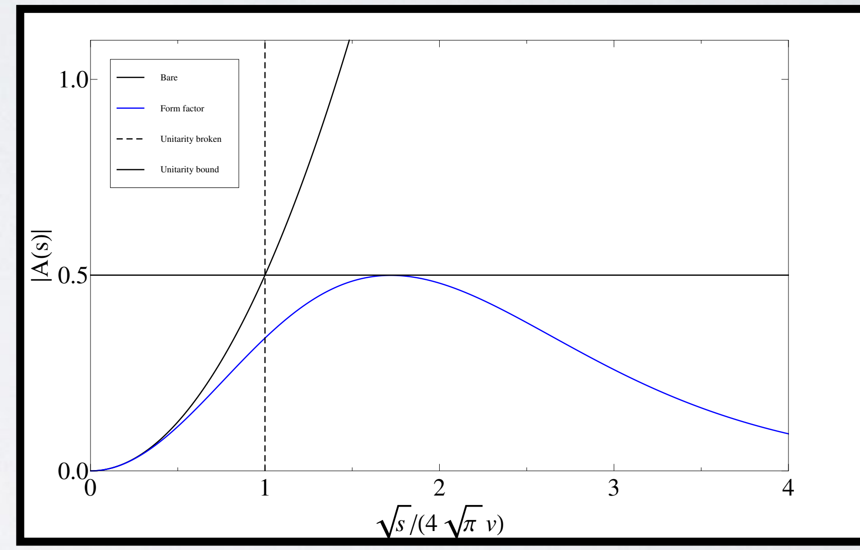
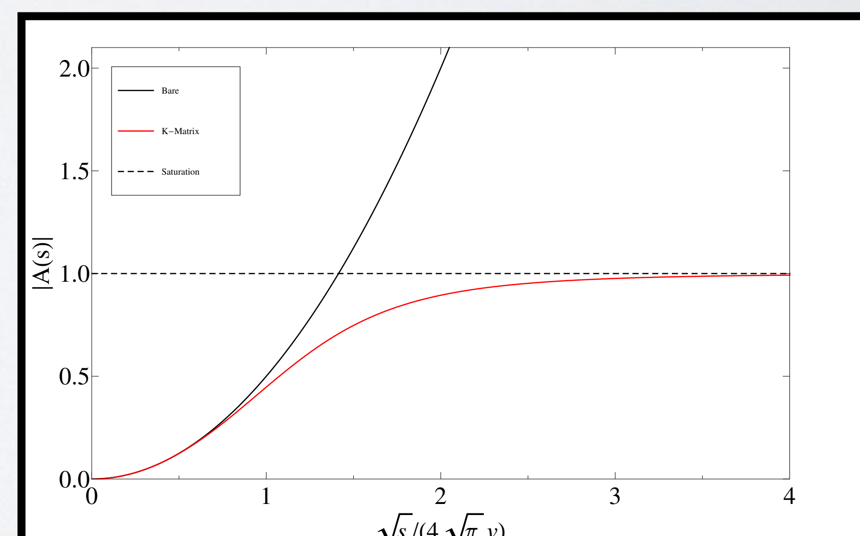


K-/T-matrix saturation $a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$

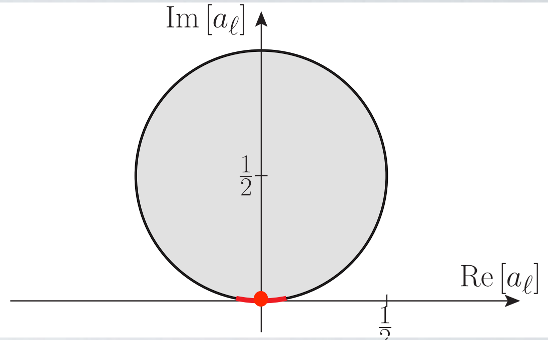
saturates amplitude [projection to unitarity circle], also for complex ampl., no additional parameters



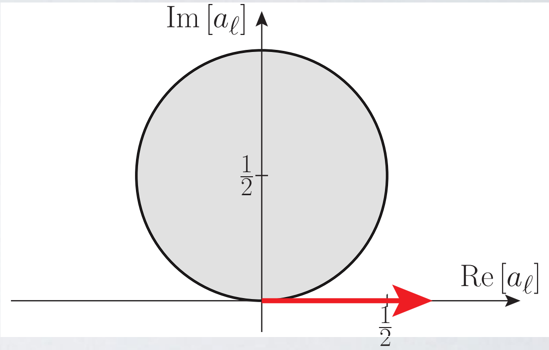
Alboteanu/Kilian/JRR, 0806.4145 Kilian/Ohl/JRR/Sekulla, 1408.6207

Scenarios for New Physics in VBS

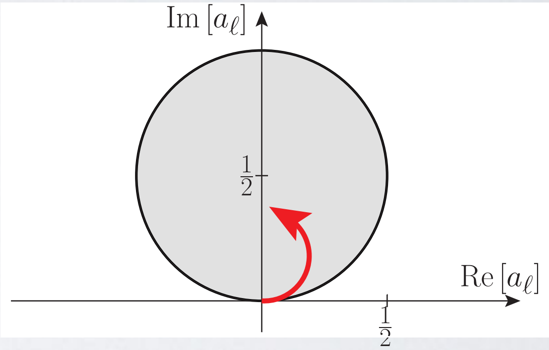
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



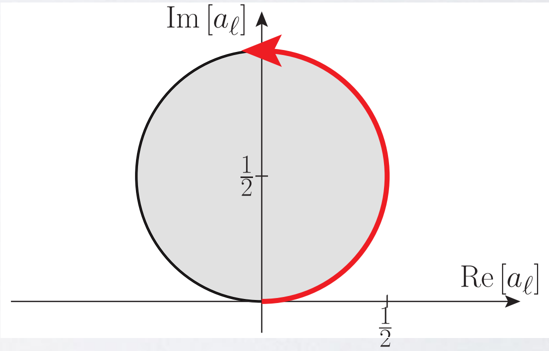
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



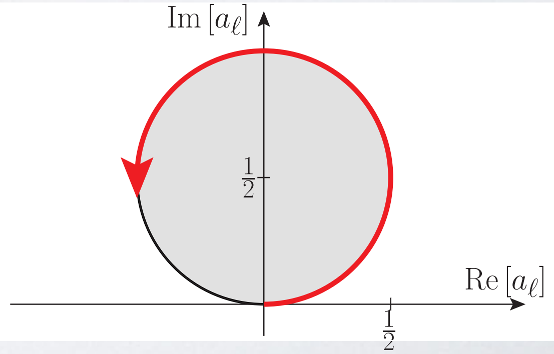
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



4. Saturation of amplitude: maximal amplitude, strongly interacting continuum, K-/T-matrix unitarization



5. New resonance: amplitude turns over



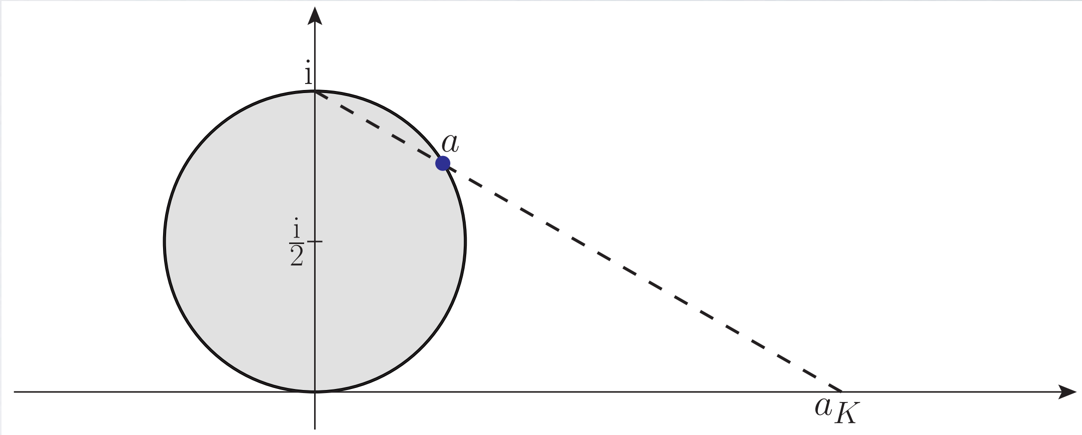
Different unitarity projections

- *K*-matrix: Cayley transform of *S*-matrix

Heitler, 1941; Schwinger, 1949; Gupta, 1950

- Stereographic projection to Argand circle

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



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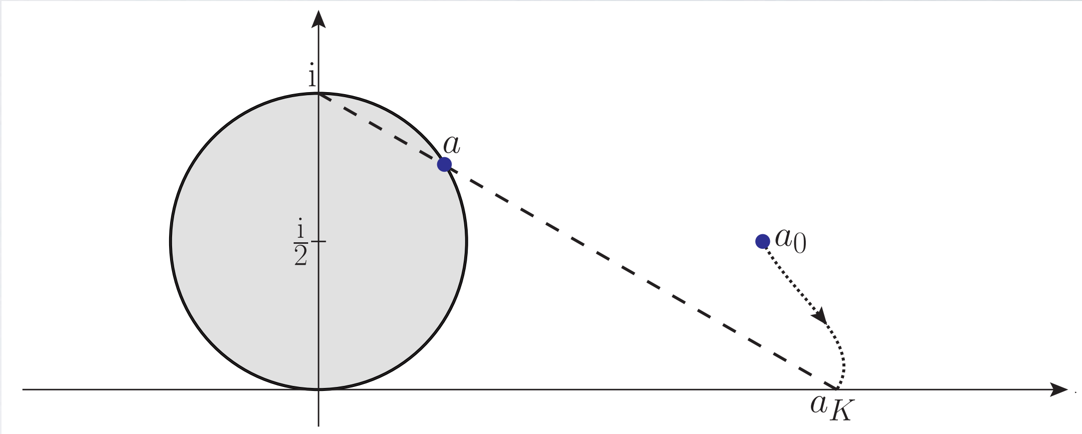

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator
  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

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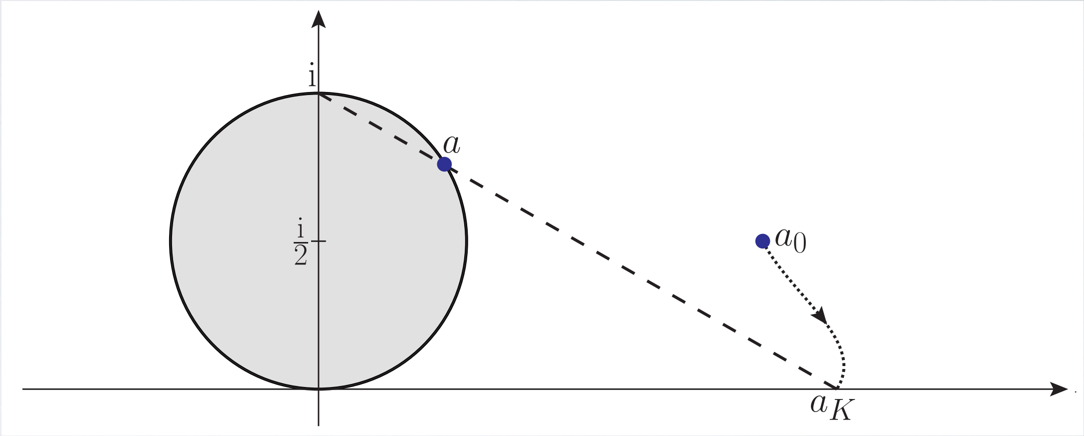

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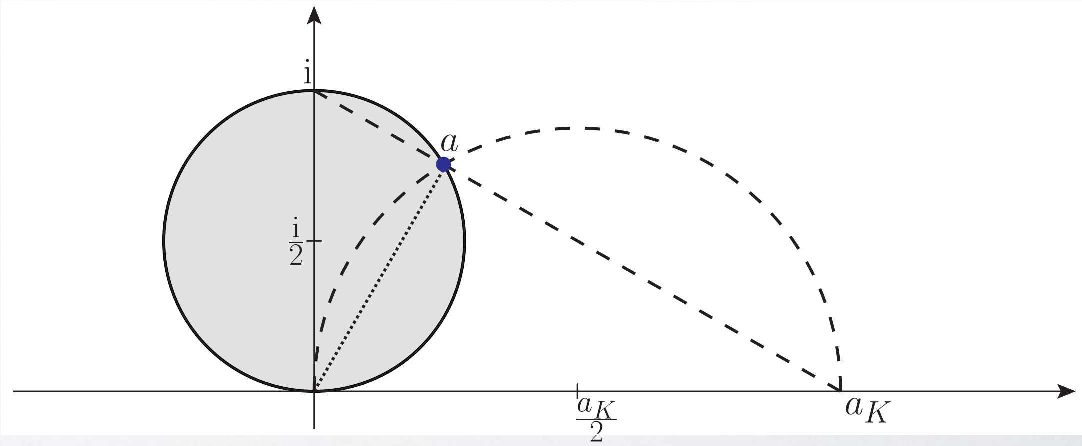
- Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \quad \Rightarrow \quad a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



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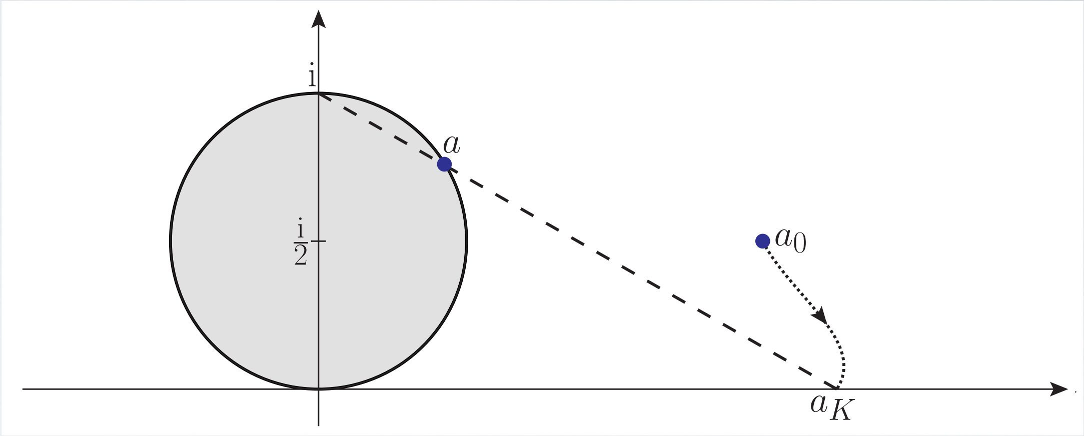

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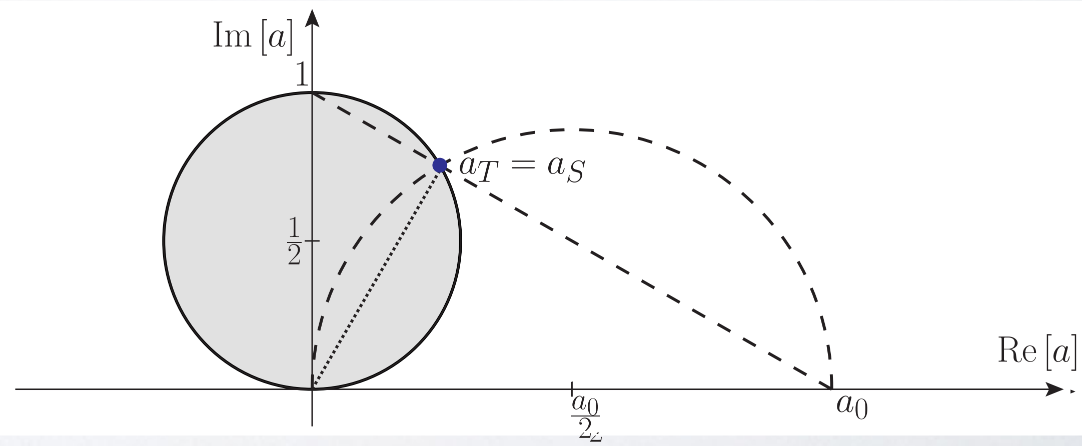

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- Points on Argand circle left invariant
- Does not rely on perturbation theory
- Applicable for amplitudes with imaginary parts (models with resonances)

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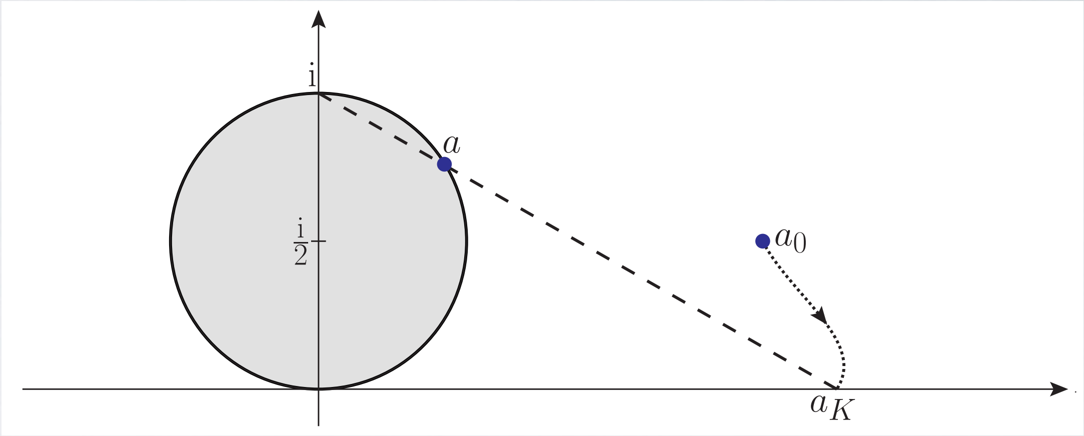

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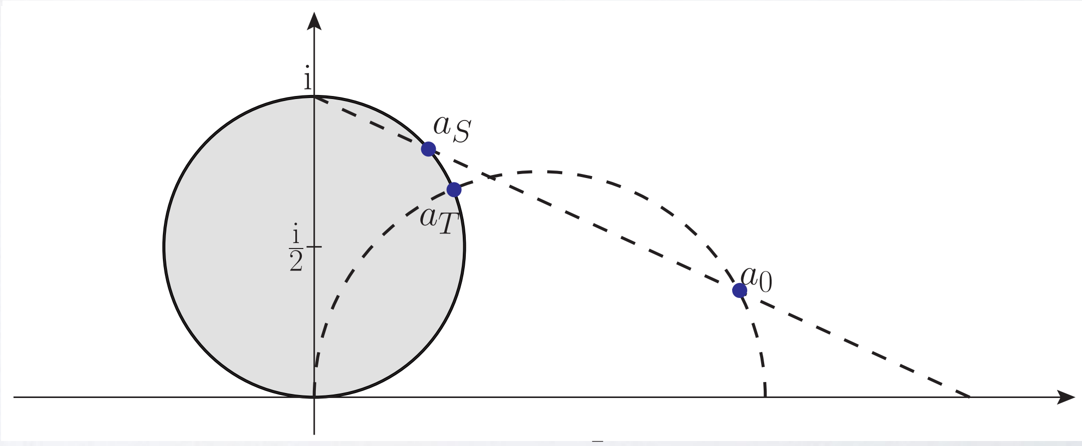

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Remark on alternative unitarizations

- Independent Amplitude Method (IAM) [Truong, 1988; Dobado/Herrero/Truong, 1990]
- Padé Method [Padé, 1890; Basdevant/Lee, 1970]
- N/D method [Chew/Mandelstam, 1960]
- Focus on correct descriptions of certain explicit (known) resonance channels
- Tied to chiral perturbation theory and QCD $\Rightarrow$ more model-dependence
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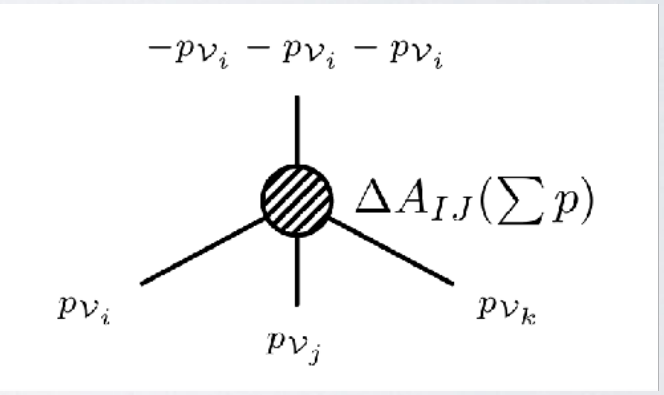
Unitarization of operators

- Clebsch-Gordan decomposition into spin–isospin eigenamplitudes
- Amplitudes should be modified only in *s*–channel configurations

$$
\begin{aligned}
\mathcal{A}(I=0) &= 3\mathcal{A}(s,t,u) + \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t) \\
\mathcal{A}(I=1) &= \mathcal{A}(t,s,u) - \mathcal{A}(u,s,t) \\
\mathcal{A}(I=2) &= \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)
\end{aligned}
$$



- Evaluate modified Feynman rules off-shell
- Scale that is used for the diboson system in *s*-channel setups: $\sqrt{\hat{s}_{VV}}$

Unitarization of [transverse] operators

- Use spin-isospin eigenamplitudes exclusive in helicities: $\mathcal{A}_0(s,t,u;\boldsymbol{\lambda})$
- Can be obtained by using Wigner's *d*-functions [Wigner, 1931] $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)$

$$\mathcal{A}_{IJ}(s;\boldsymbol{\lambda}) = \int_{-s}^{0} \frac{dt}{s} \mathcal{A}_I(s,t,u;\boldsymbol{\lambda}) \cdot d^J_{\lambda,\lambda'}\left[\arccos\left(1 + 2\frac{t}{s}\right)\right] \qquad \lambda = \lambda_1 - \lambda_2 \qquad \lambda' = \lambda_3 - \lambda_4$$

- Extract all partial waves:

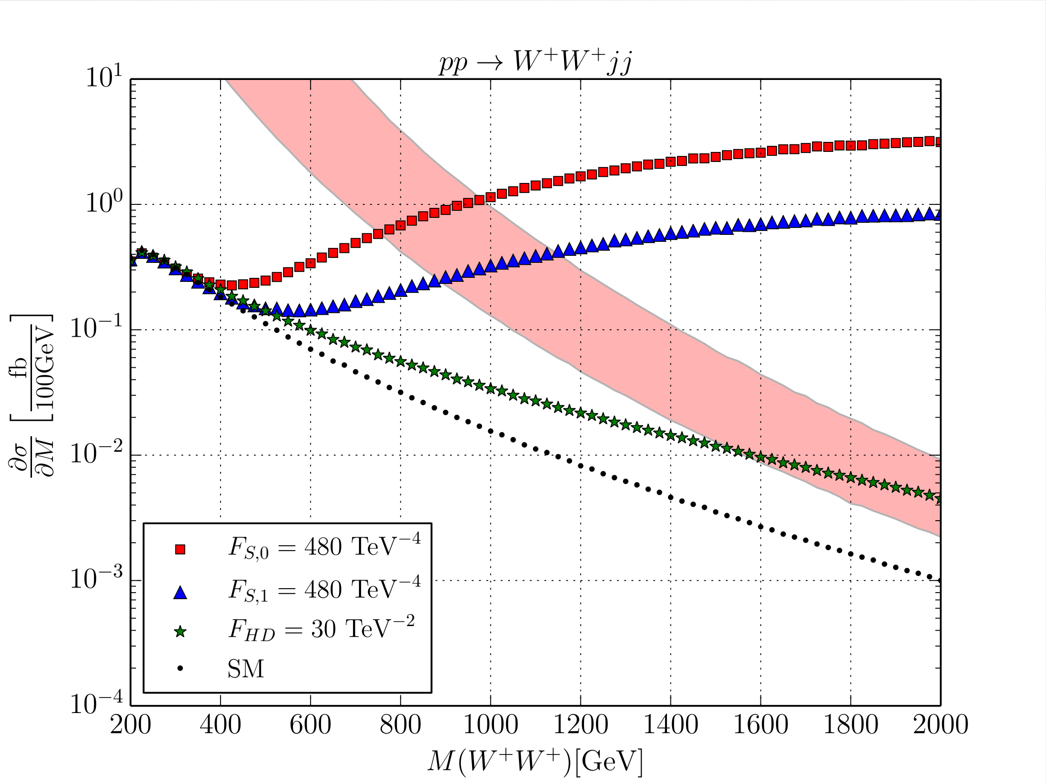
$$\mathcal{A}_{ij}(s;\boldsymbol{\lambda})/(g^4 s^2) = (c_0 F_{T_0} + c_1 F_{T_1} + c_2 F_{T_2})$$

Braß/Fleper/Kilian/JRR/Sekulla, 1807.02512

i \ j	0			1			2			$\boldsymbol{\lambda}$			
0	-6	-2	$-\frac{5}{2}$	0	0	0	0	0	0	+	+	+	+
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	−	+	−
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	−	−	+
	$-\frac{22}{3}$	$-\frac{14}{3}$	$-\frac{11}{6}$	0	0	0	$-\frac{2}{15}$	$-\frac{4}{15}$	$-\frac{1}{30}$	+	+	−	−
1	0	0	0	0	0	0	0	0	0	+	+	+	+
	0	0	0	0	0	0	$\frac{2}{5}$	$-\frac{1}{5}$	0	+	−	+	−
	0	0	0	0	0	0	$-\frac{2}{5}$	$\frac{1}{5}$	0	+	−	−	+
	0	0	0	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	0	0	0	+	+	−	−
2	0	-2	-1	0	0	0	0	0	0	+	+	+	+
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{1}{5}$	$-\frac{1}{5}$	+	−	+	−
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{1}{5}$	$-\frac{1}{5}$	+	−	−	+
	$-\frac{4}{3}$	$-\frac{8}{3}$	$-\frac{1}{3}$	0	0	0	$-\frac{2}{15}$	$-\frac{1}{15}$	$-\frac{1}{30}$	+	+	−	−
	c_0	c_1	c_2	c_0	c_1	c_2	c_0	c_1	c_2				

- Corrections for off-shell vectors: important [Perez/Sekulla/Zeppenfeld, 1807.02707]
- Implementation in `WHIZARD` takes leading corrections into account

VBS diboson spectra



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

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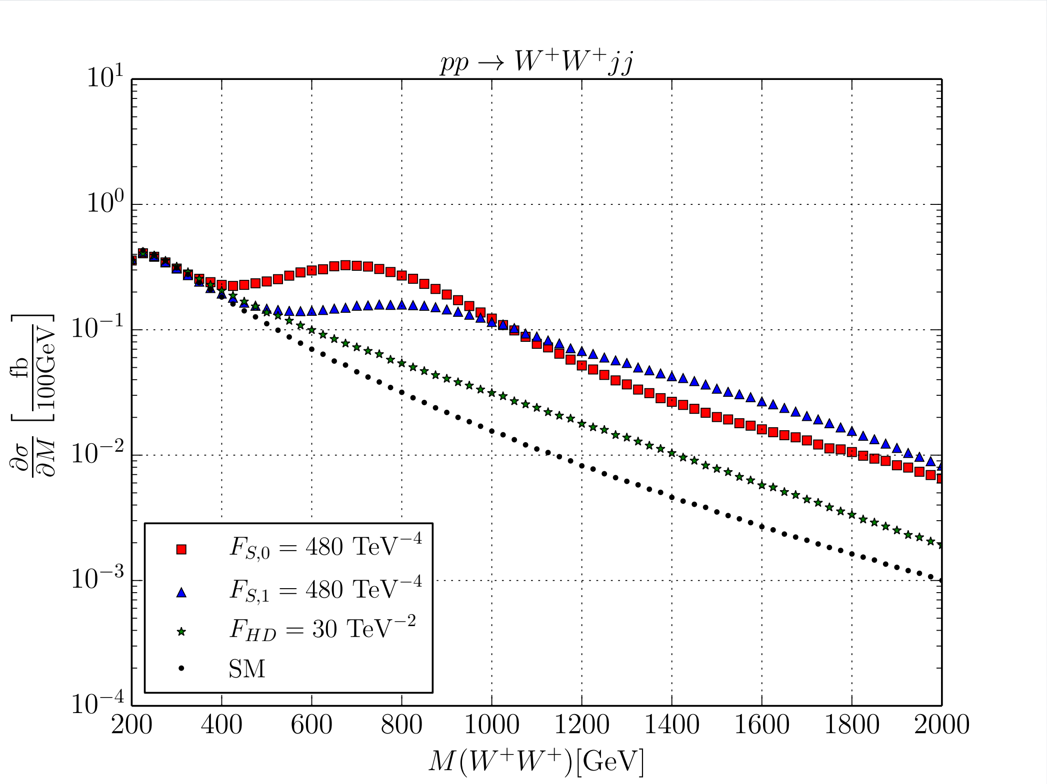

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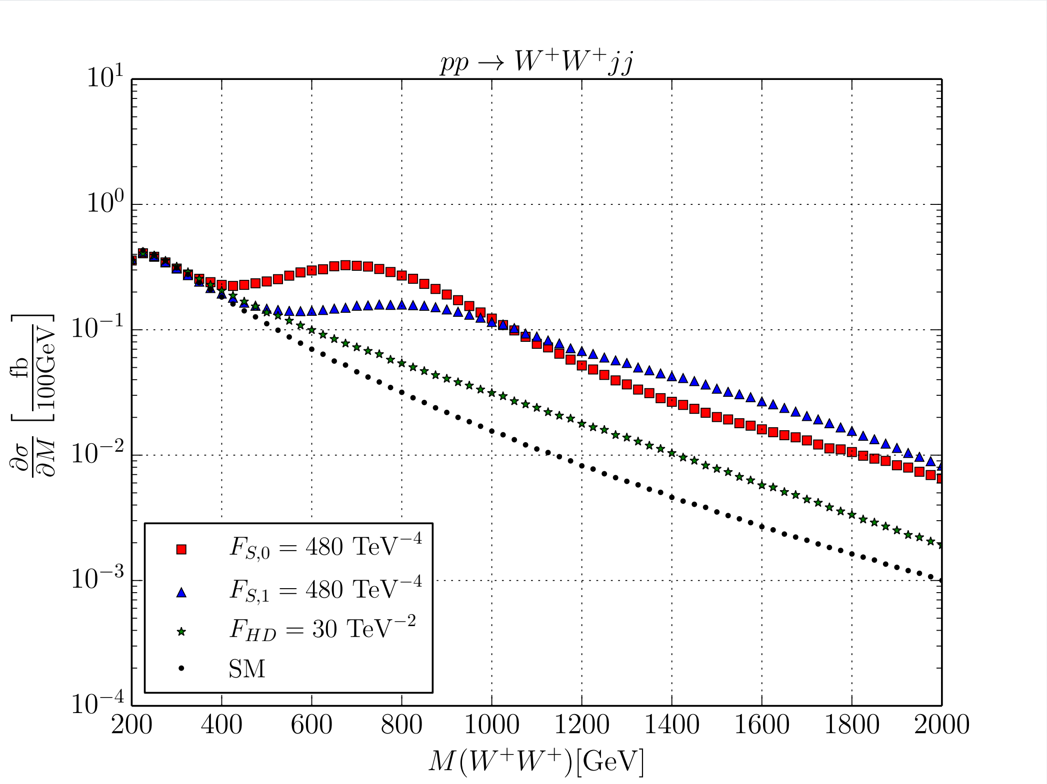

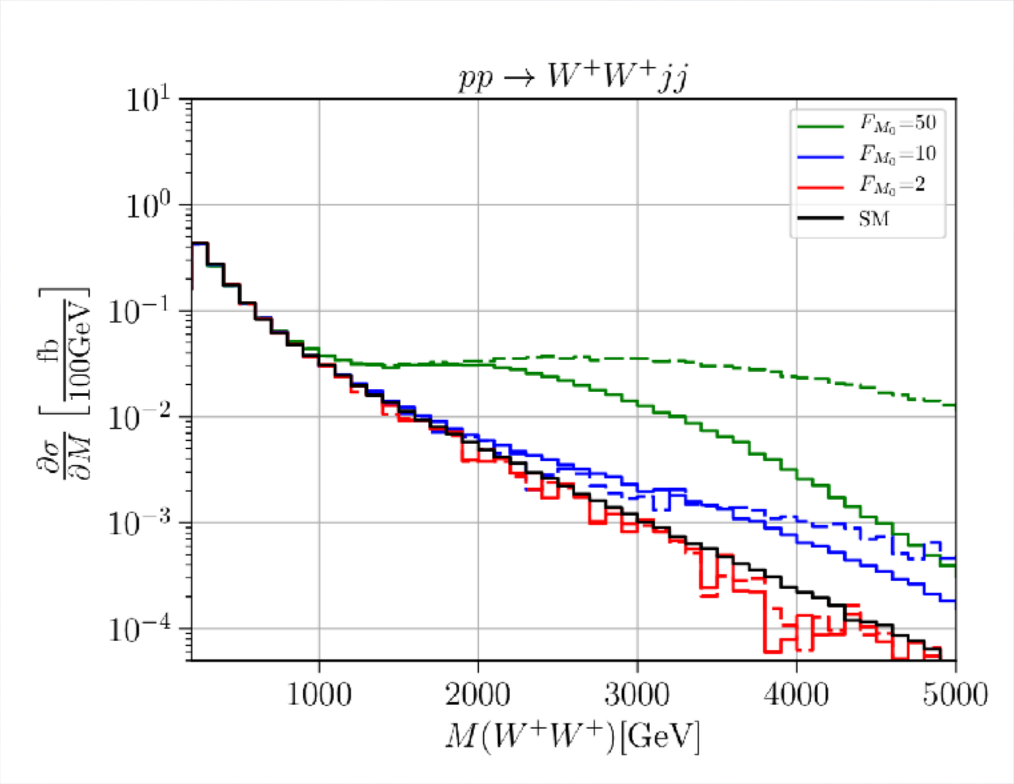

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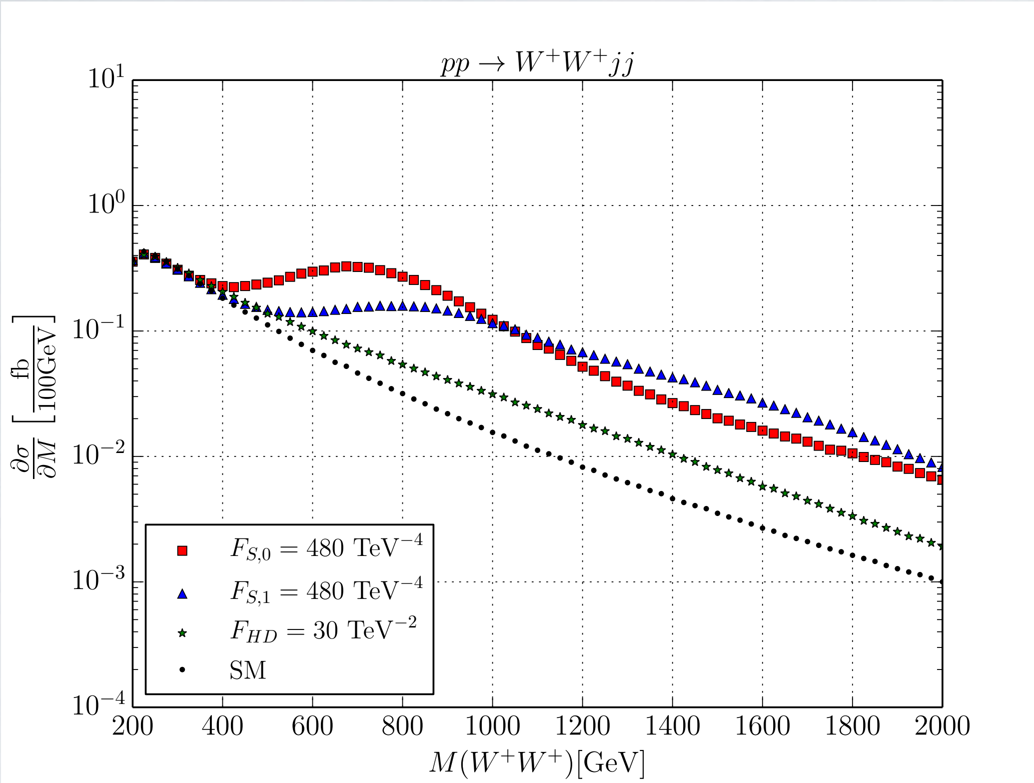

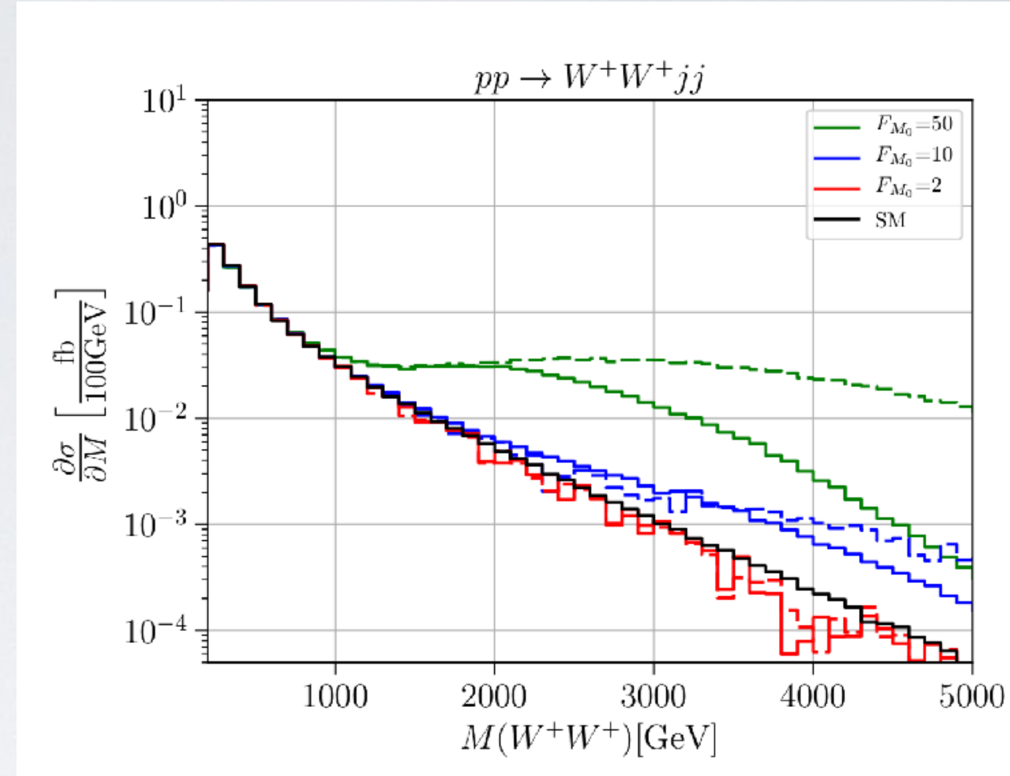

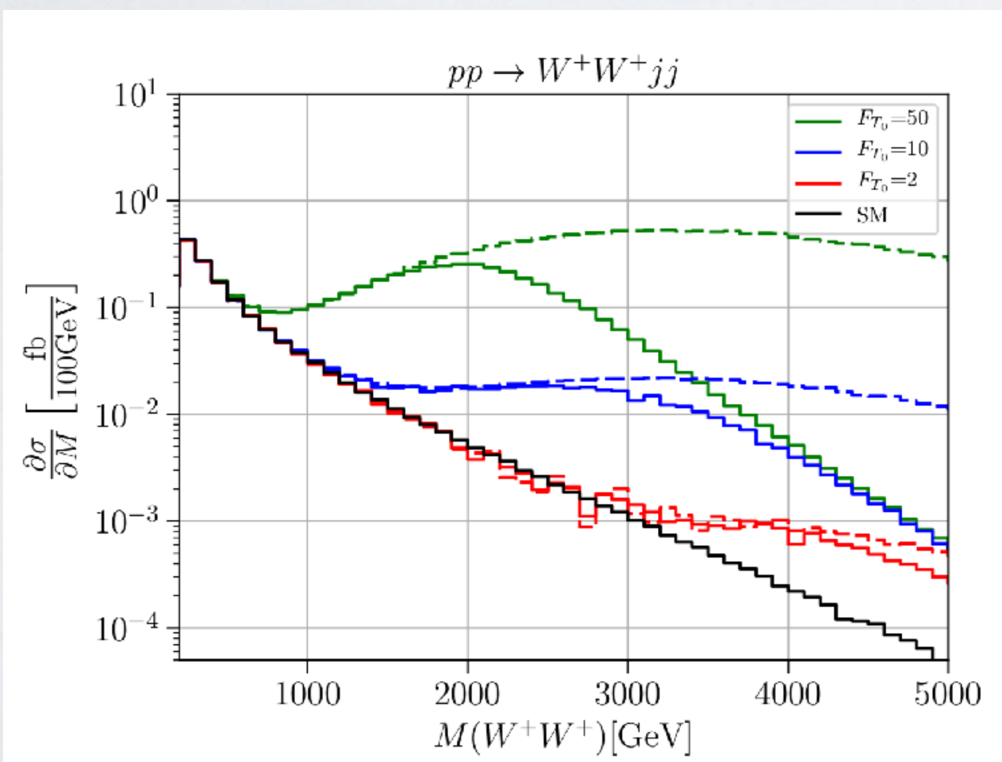

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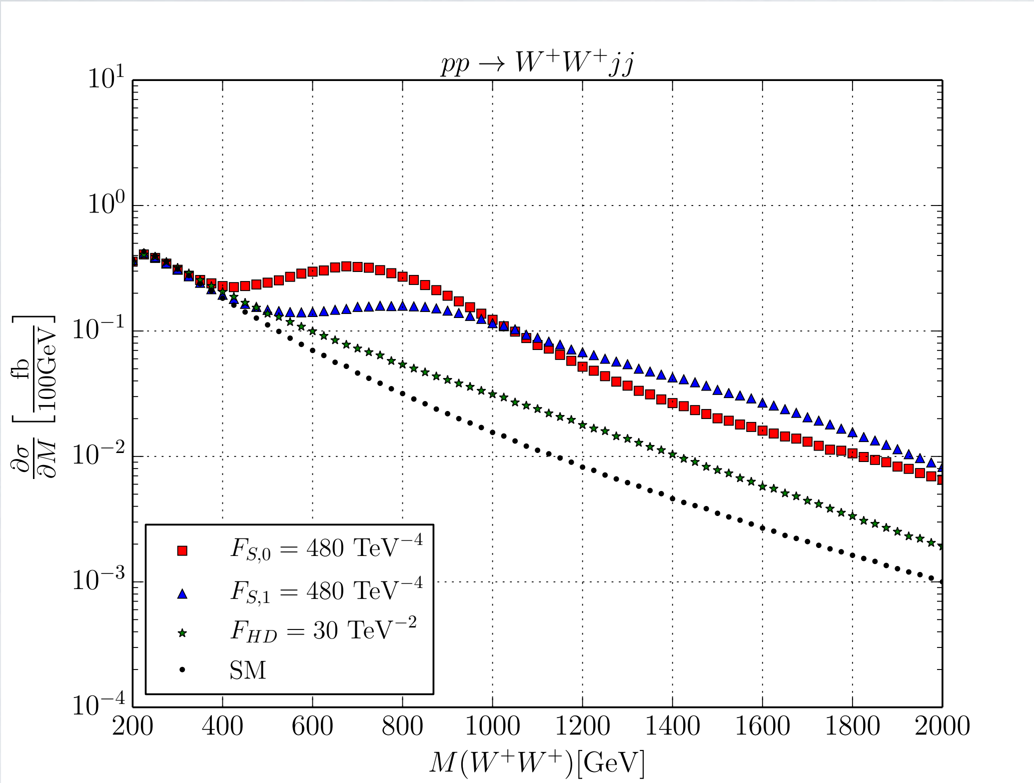

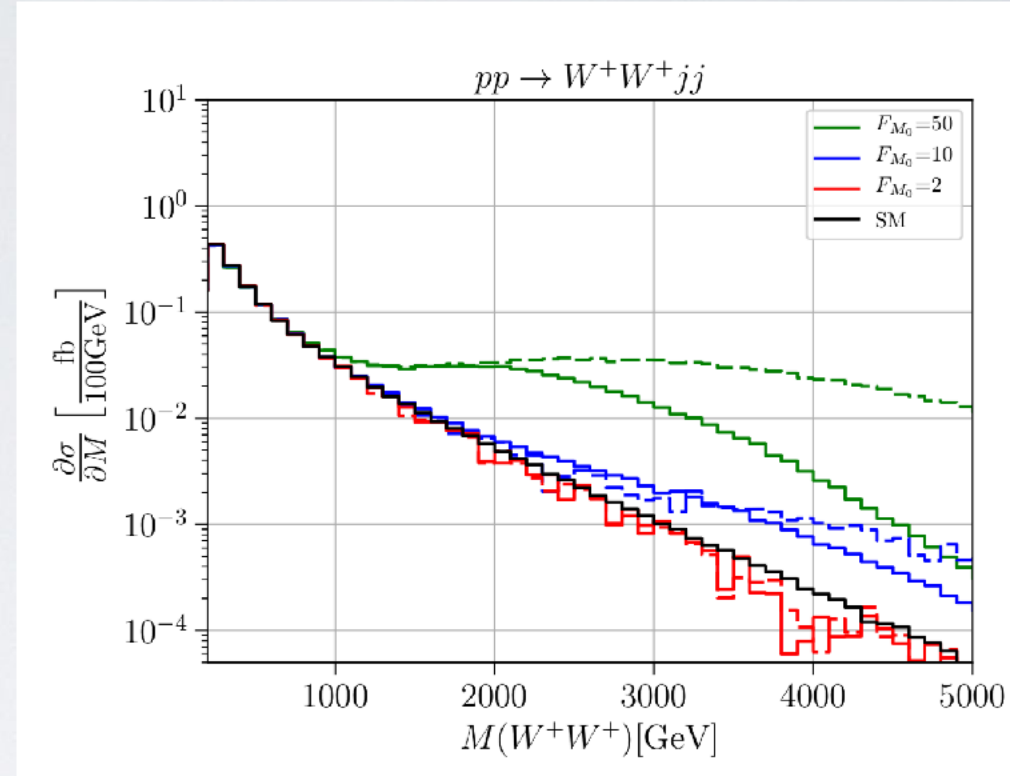

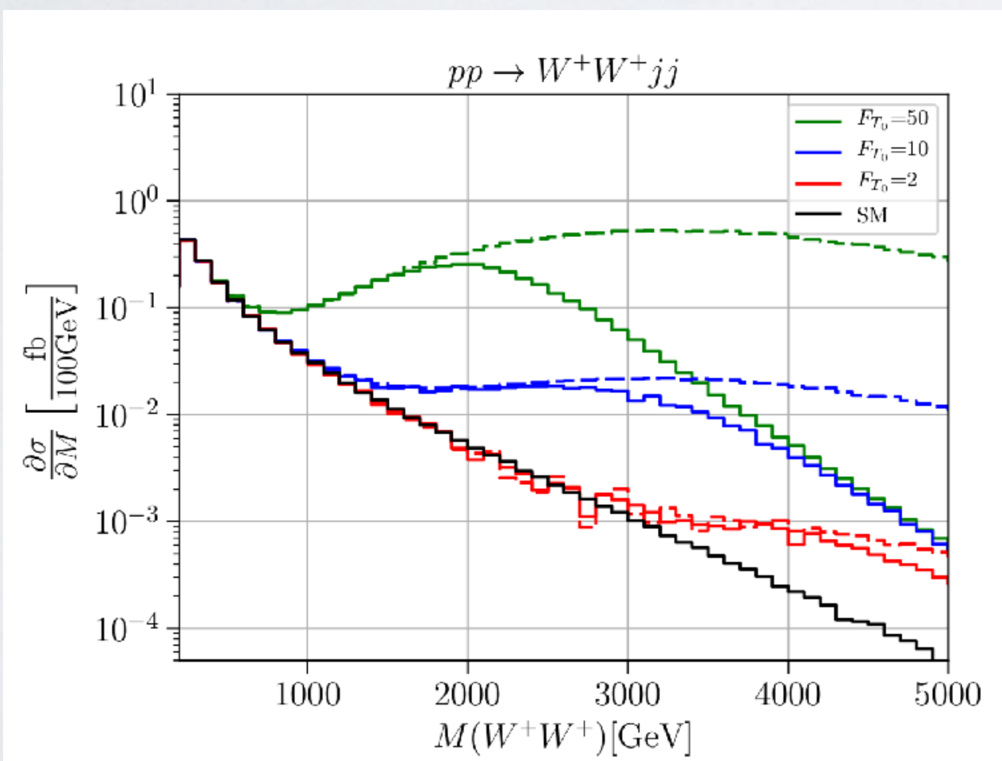

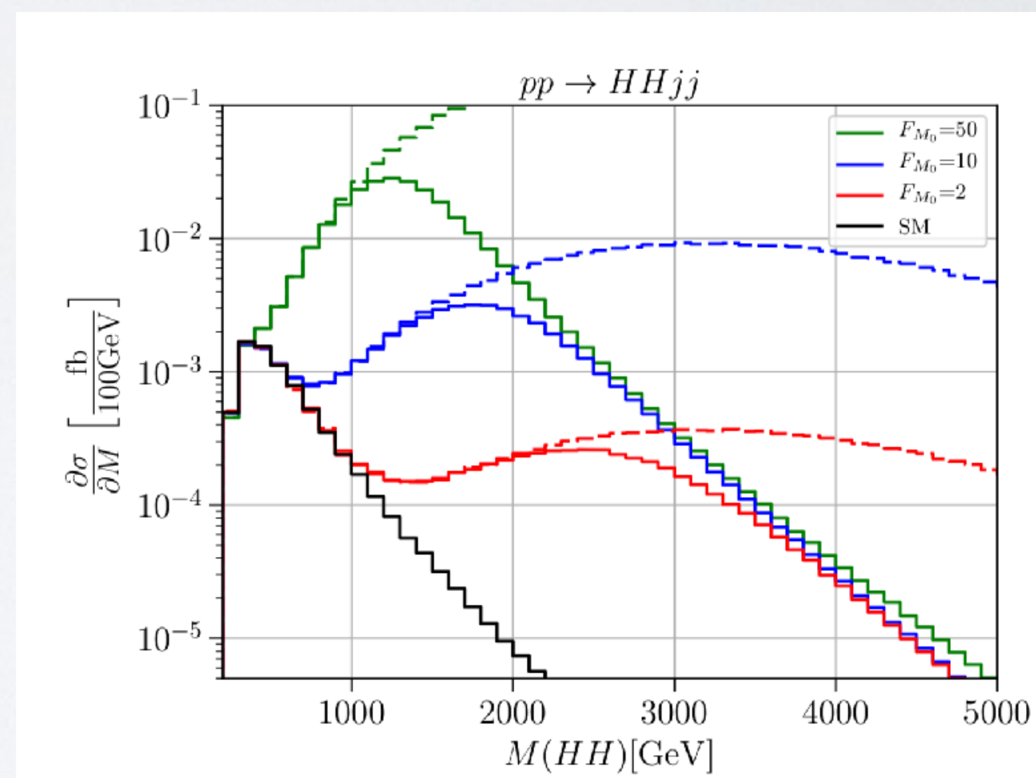

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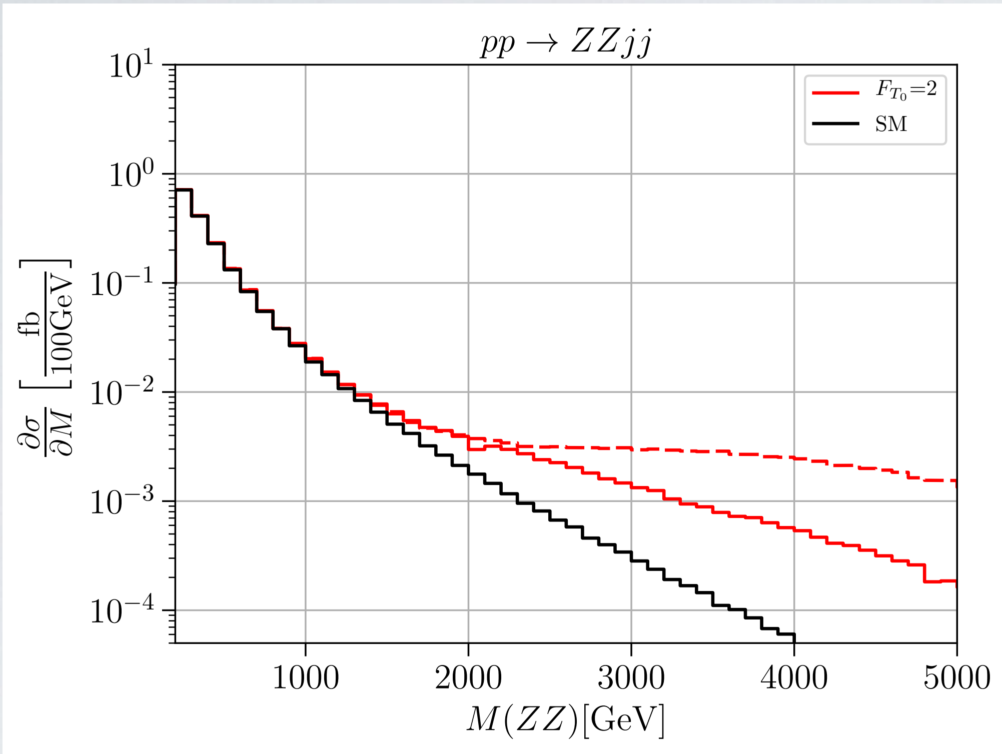

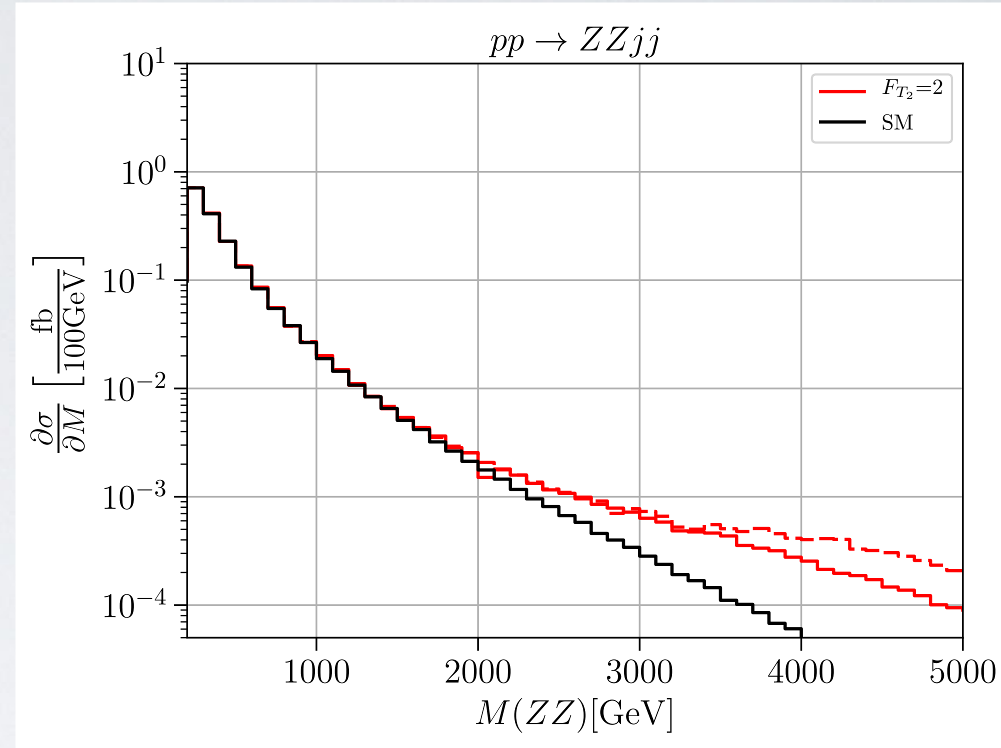

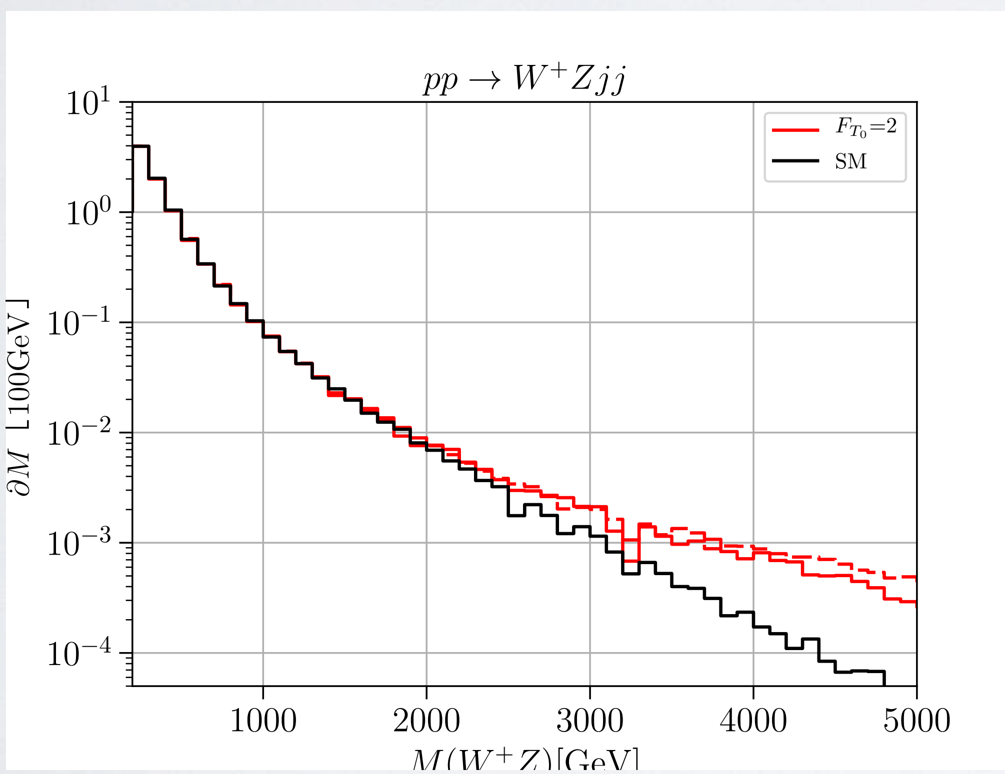

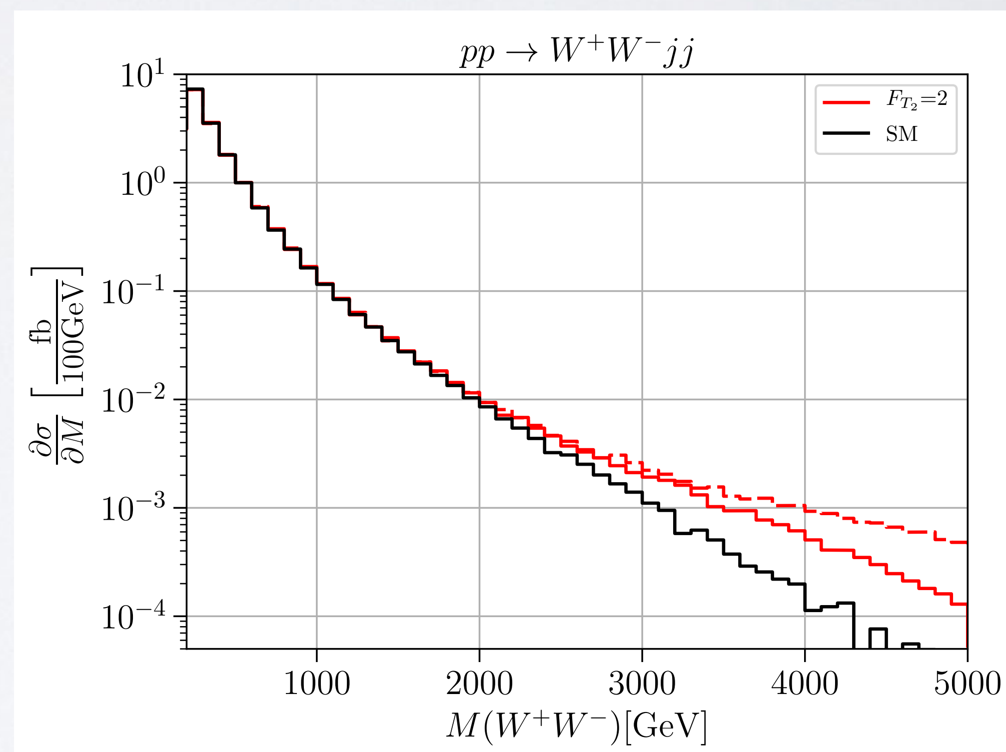

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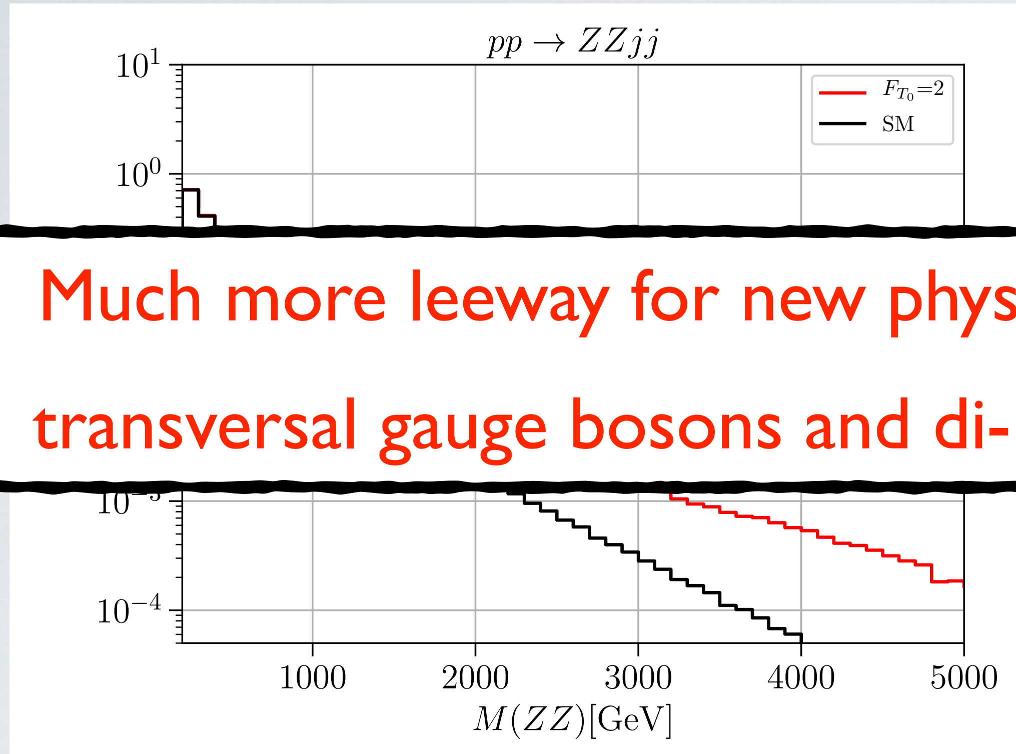
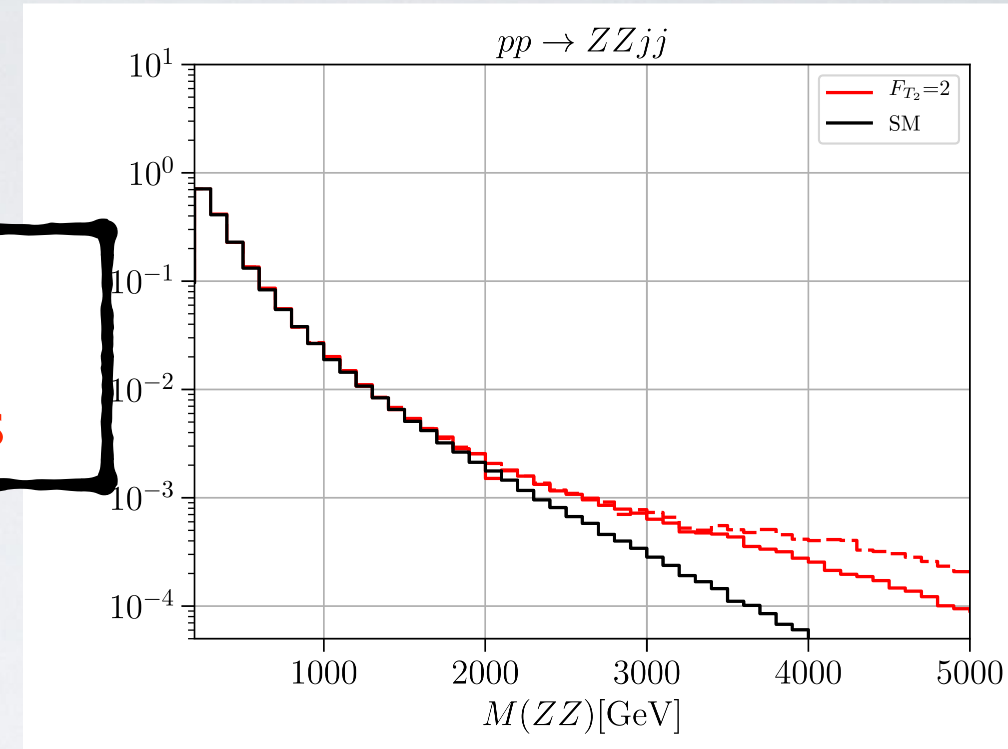
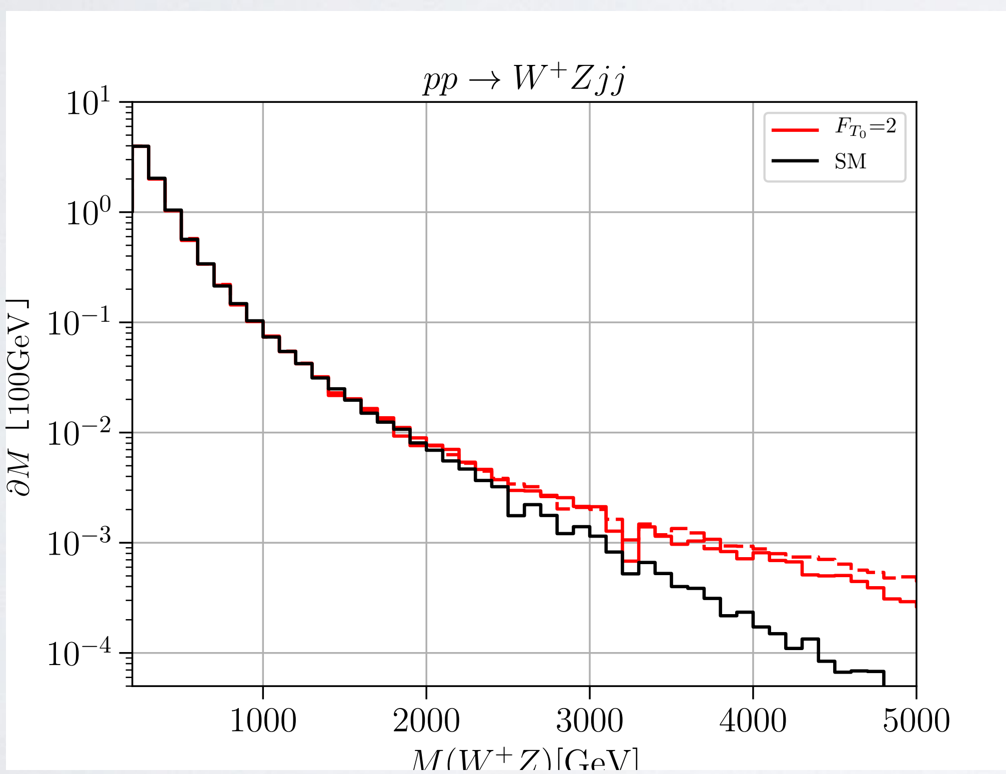
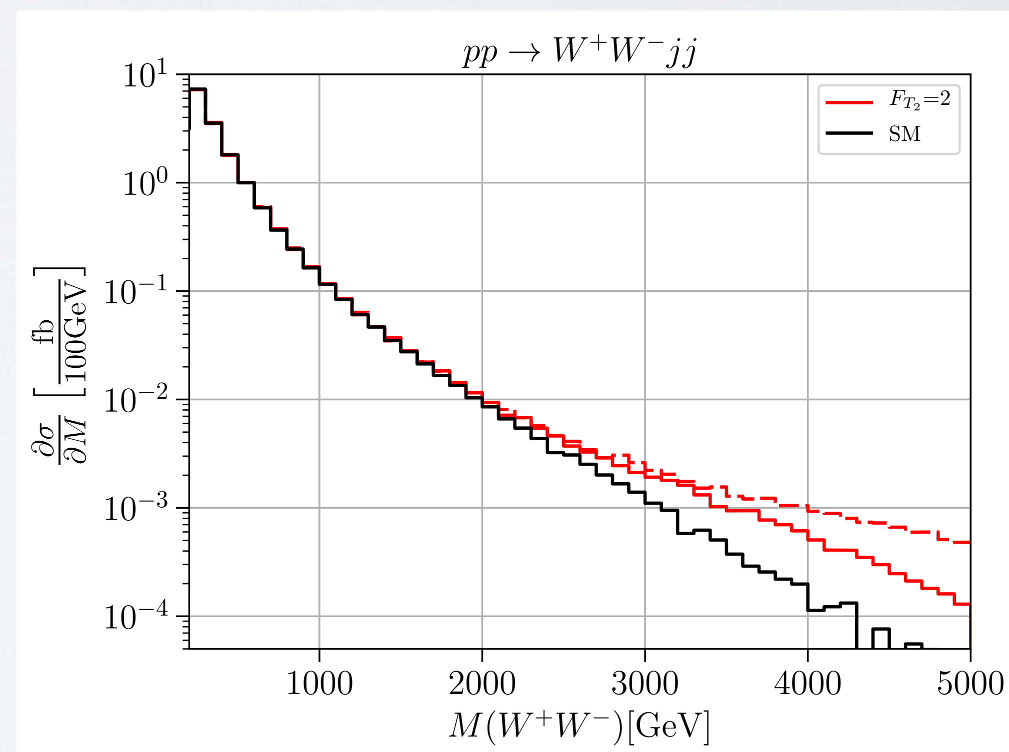




Much more leeway for new physics in transversal gauge bosons and di-Higgs





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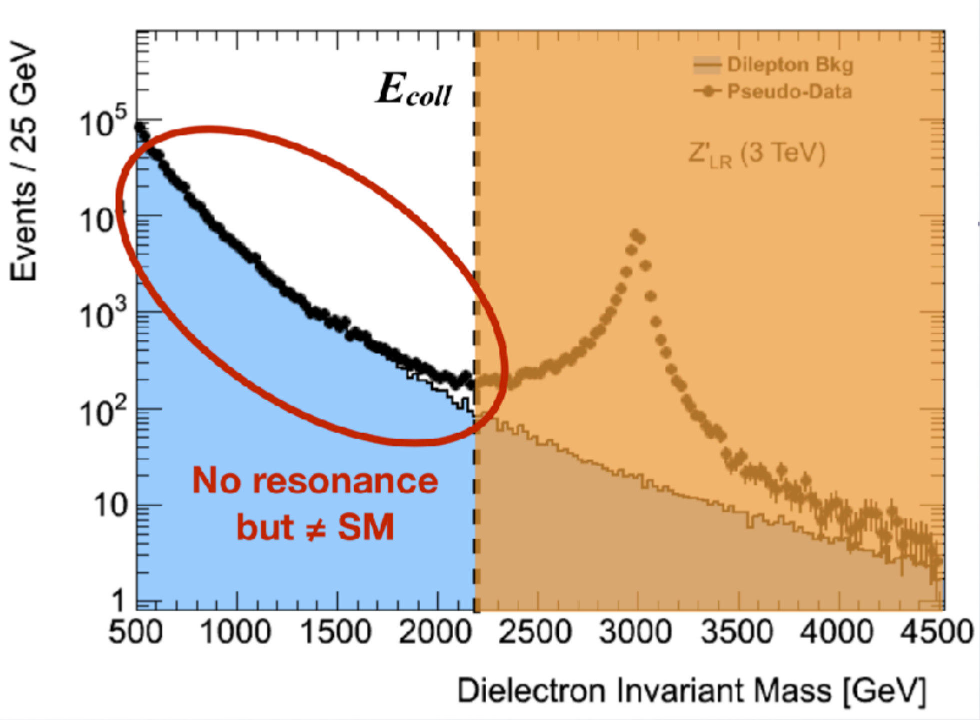
Simplified signal models: generic resonances

- Rise of amplitude: is 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)

Courtesy: Jorge de Blas



Spins 0, 2 considered, Spin 1 has (partially) different physics (mixing with W/Z)

$SU(2)_L \times SU(2)_R$	$\rightarrow$	$SU(2)_C$
$(0,0)$	$\rightarrow$	0
$(1,1)$	$\rightarrow$	$2+1+0$

	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

Tensor resonances: Fierz-Pauli vs. Stückelberg

- Start with Fierz-Pauli Lagrangian for symmetric tensor

$$\mathcal{L}_{\text{FP}} = \frac{1}{2}\partial_\alpha f_{\mu\nu}\partial^\alpha f^{\mu\nu} - \frac{1}{2}m^2 f_{\mu\nu}f^{\mu\nu} - \frac{1}{2}\partial_\alpha f^\mu_\mu \partial^\alpha f^\nu_\nu + \frac{1}{2}m^2 f^\mu_\mu f^\nu_\nu - \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_\alpha \partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J^{\mu\nu}_f$$

- Symmetric tensor $f_{\mu\nu}$
- On-shell conditions: 10 → 5 components
- Tracelessness: $f_\mu{}^\mu = 0$
- Transversality: $\partial_\mu f^{\mu\nu} = 0$

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- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
- Crucial for MCs

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- $f^{\mu\nu}$: on-shell $f^{\mu\nu}$
- ϕ: $\partial_\mu\partial_\nu f^{\mu\nu}$
- A^μ: $\partial_\nu f^{\mu\nu}$
- σ: $f^\mu_{\ \mu}$

Gauge fixing: $\sigma = -\phi$

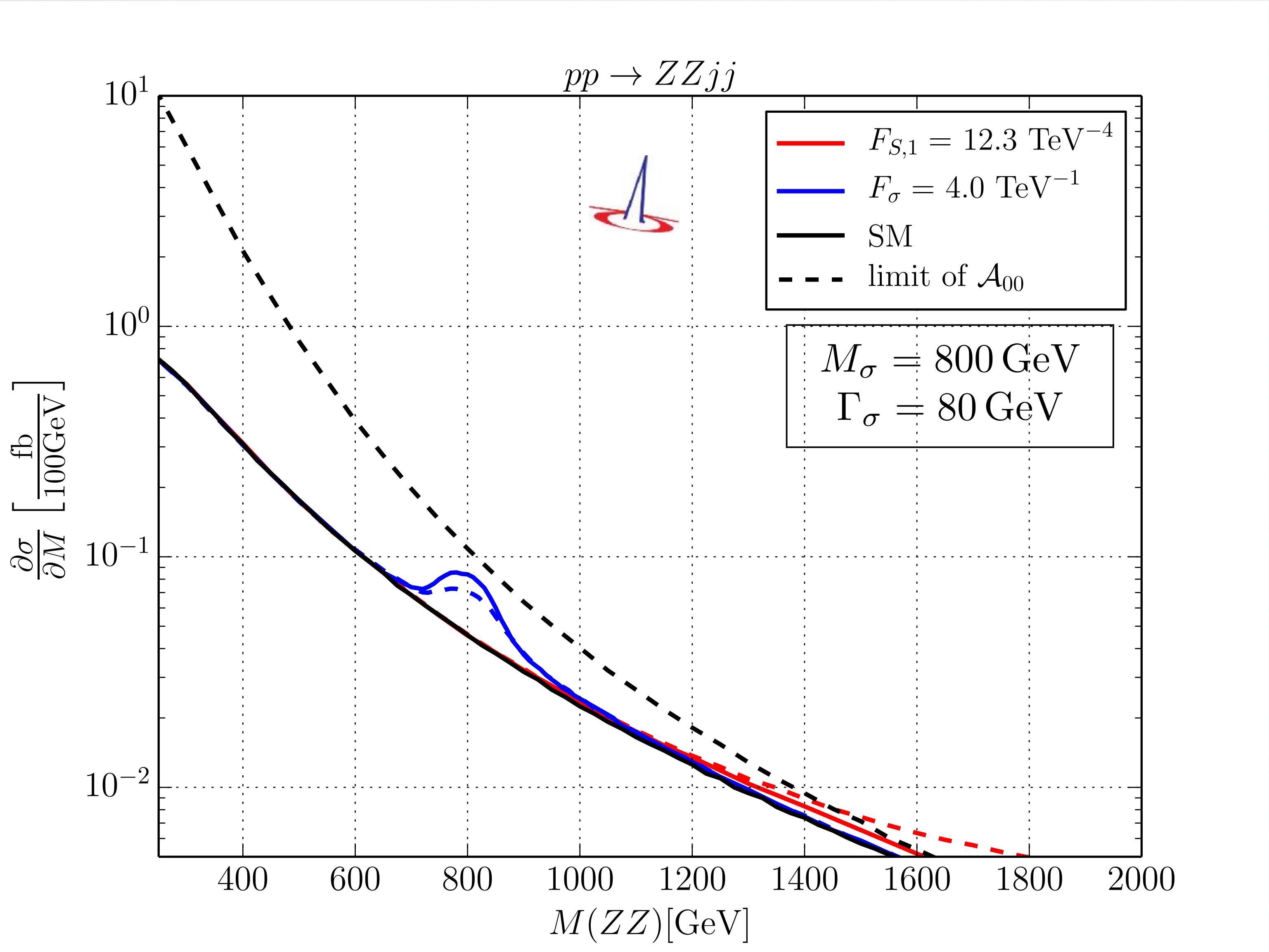
$$\begin{aligned}\mathcal{L} = &\frac{1}{2}f_{f\,\mu\nu}\left(-\partial^2 - m_f^2\right)f_f^{\mu\nu} + \frac{1}{2}f^\mu_{f\ \mu}\left(-\frac{1}{2}\left(-\partial^2 - m_f^2\right)\right)f^\nu_{f\ \nu} \\ &+ \frac{1}{2}A_{f\mu}\left(\partial^2 + m_f^2\right)A_f^\mu + \frac{1}{2}\sigma_f\left(-\partial^2 - m_f^2\right)\sigma_f \\ &+ \left(f_{\mu\nu} - \frac{1}{\sqrt{6}}\sigma_f g_{\mu\nu}\right)J_f^{\mu\nu} \\ &- \left(\frac{1}{\sqrt{2}m_f}\left(A_{f\mu}\partial_\nu + A_{f\nu}\partial_\mu\right) - \frac{\sqrt{2}}{\sqrt{3}m_f^2}\sigma_f\partial_\mu\partial_\nu\right)J_f^{\mu\nu}\end{aligned}$$

Comparison: Simplified Models & SMEFT

Kilian/Ohl/JRR/Sekulla: 1511.00022

Brass/Fleper/Kilian/JRR/Sekulla: 1807.02512

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



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- aQGC describe rise of resonance
- Unitarization applied
- Tensor resonances better visible than scalars

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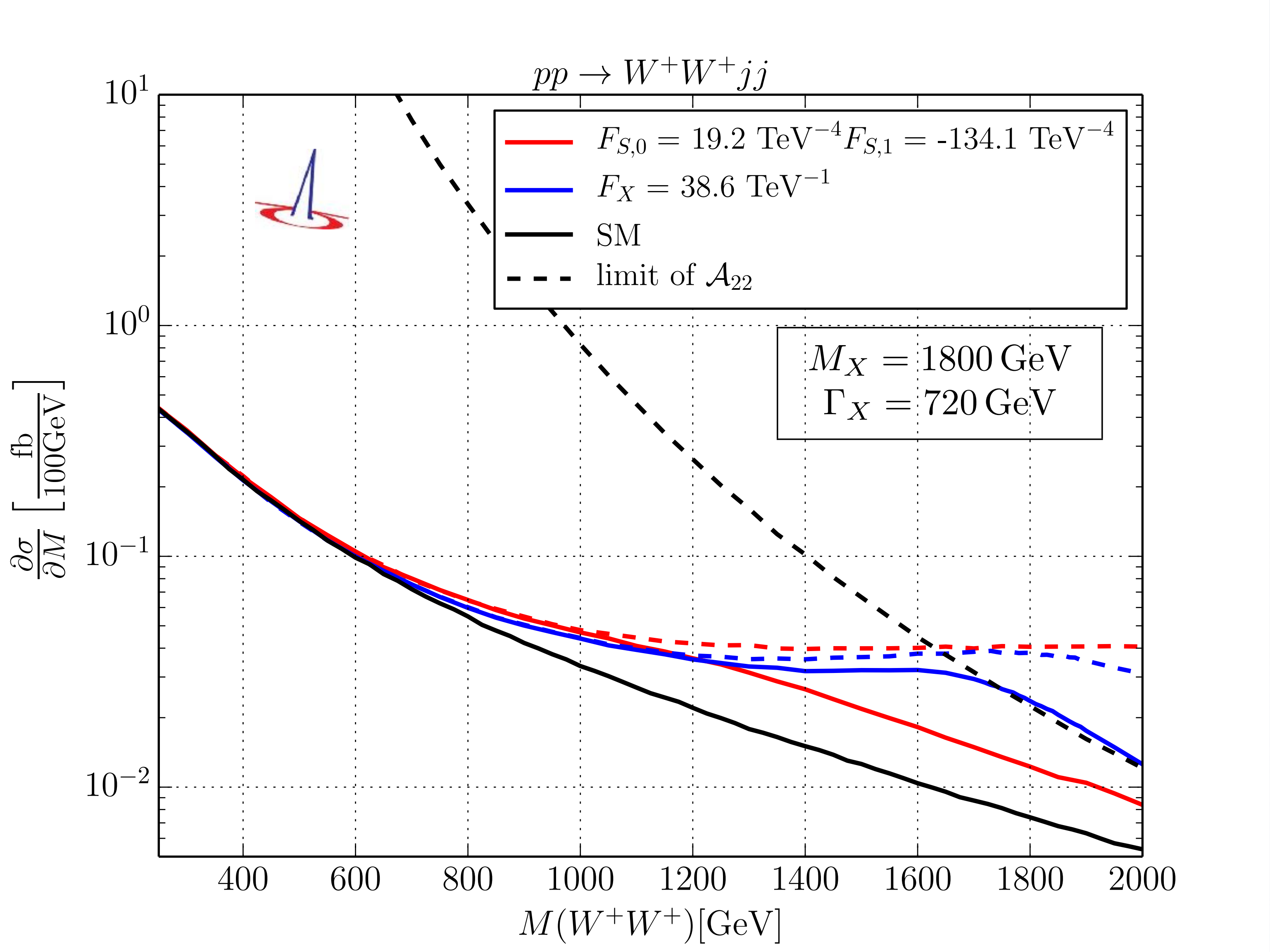

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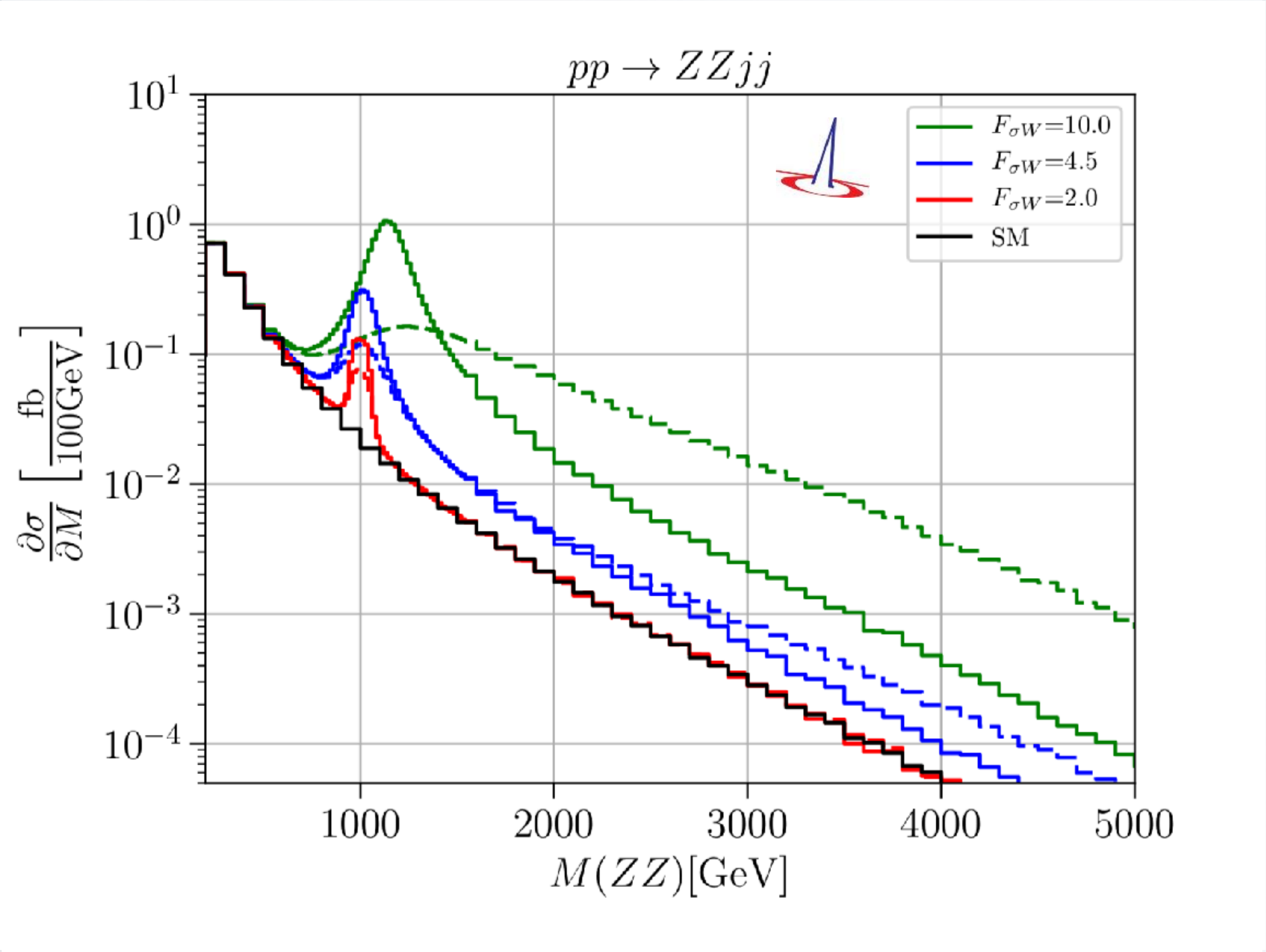

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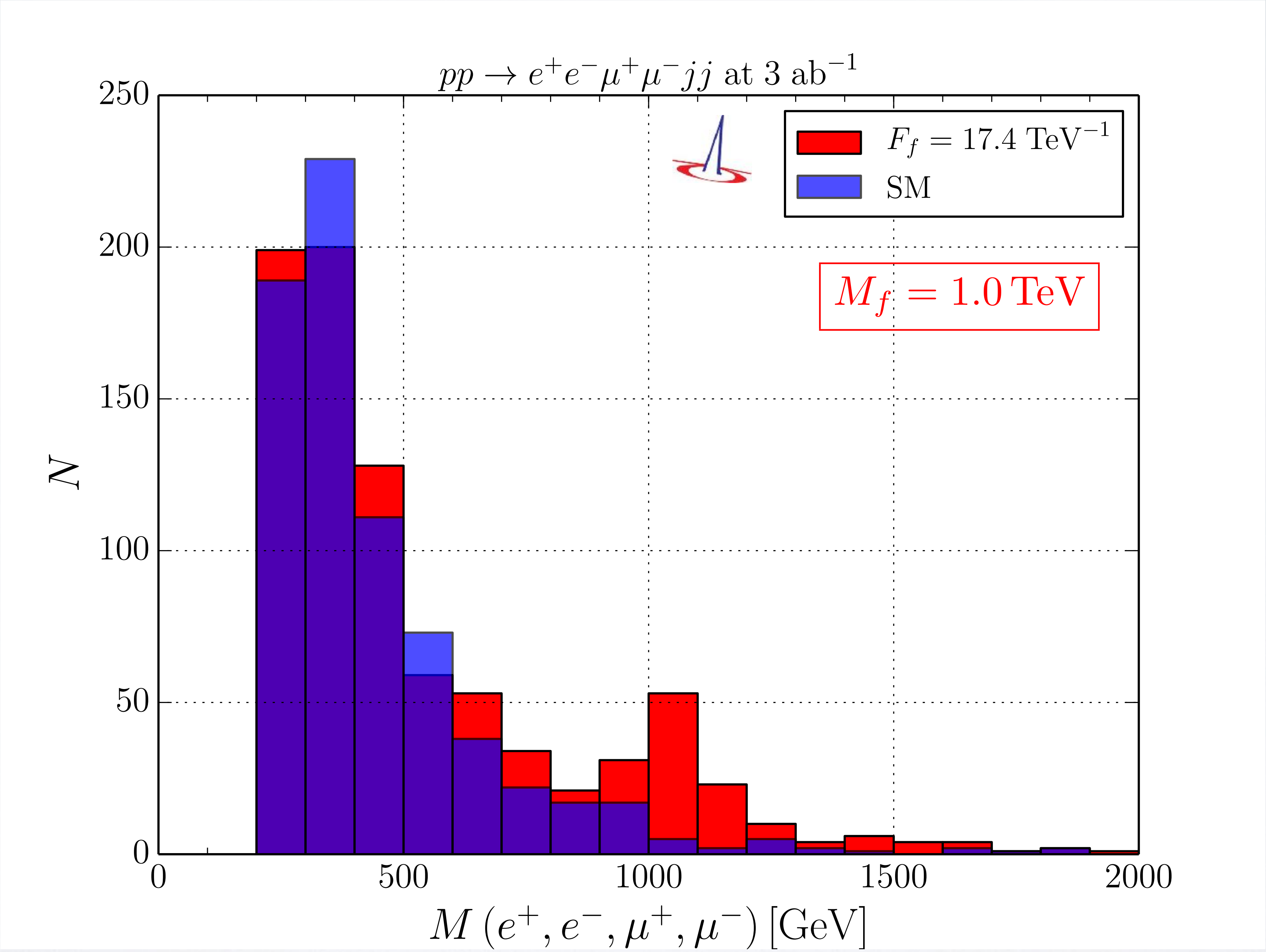
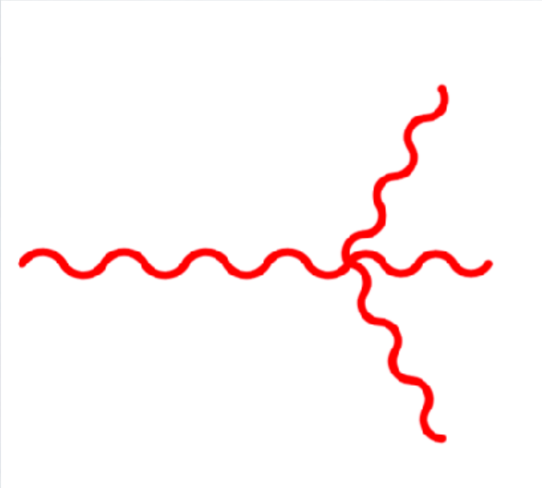
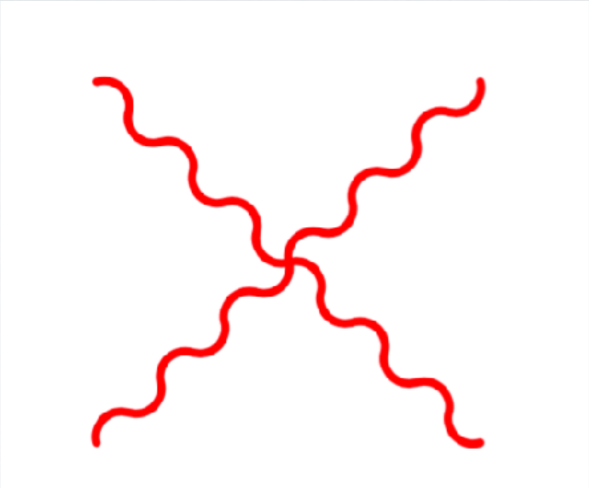
Complete LHC process at 14 TeV



Triple [multiple] Vector Boson Production ?

Relate  to  ?

ATLAS data: 1903.10415

Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ

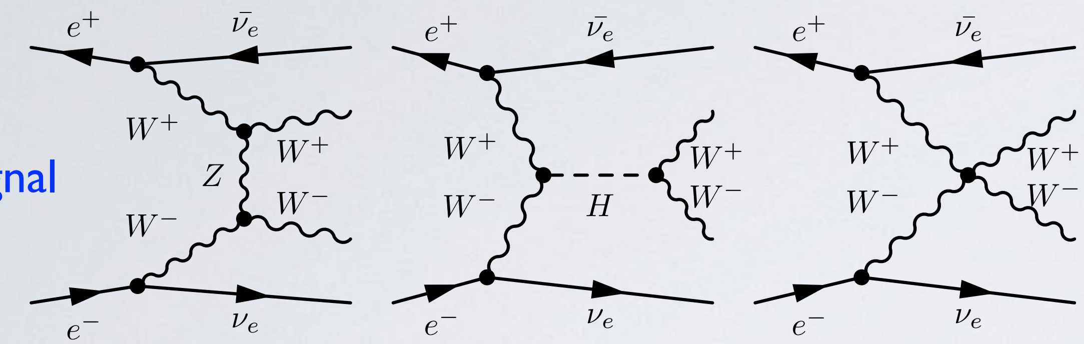
[CMS: downward fluctuation]

- Yes, same Feynman rule as in VBS, but …
- one external $W/Z/\gamma$ always far off-shell
- Unitarization: work in progress (needs $2 \to 3$ unitarizations, inelastic channels) [Bahl/Braß/Kilian/Kreher/JRR, *w.i.p.*]
- Different Wilson coefficients dominate (particularly for resonances)
- Important physics (partially) independent from VBS ("different fiducial vol.")

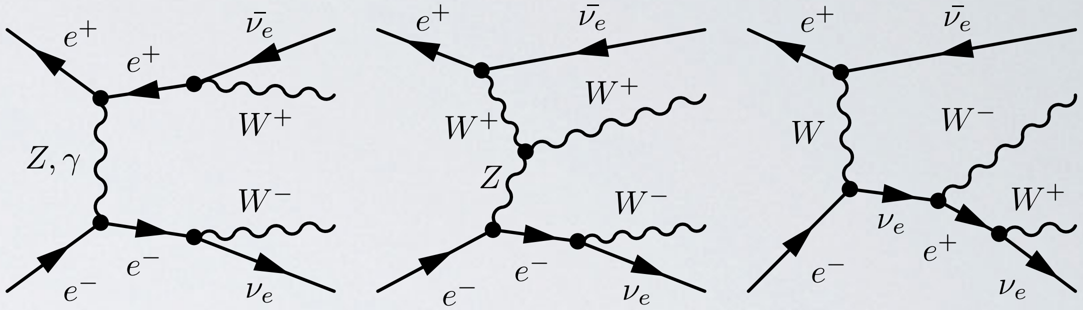
New Physics in VBS at Lepton Colliders

Fleper/Kilian/JRR/Sekulla: Eur.Phys.J. C77 (2017) no.2, 120

Signal



Bkgd.



$$\mathcal{L}_{HD} = F_{HD} \;\text{tr}\left[\mathbf{H}^\dagger \mathbf{H} - \frac{v^2}{4}\right] \cdot \text{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right]$$

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Unitarization necessary for sane high-energy description 1607.03030

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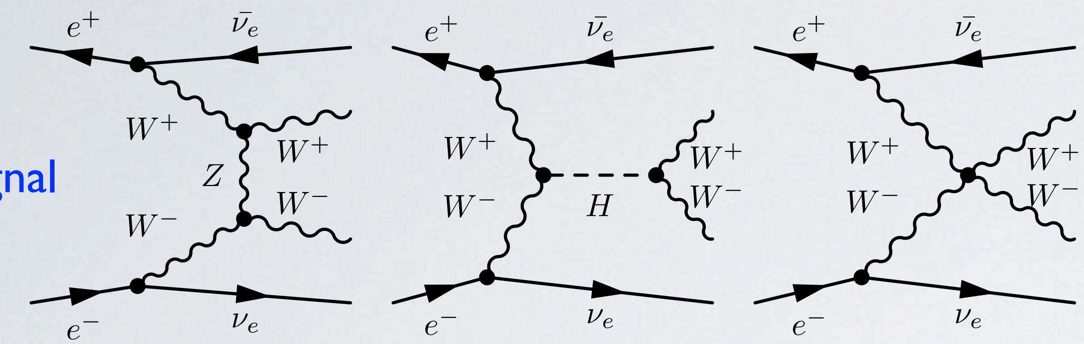

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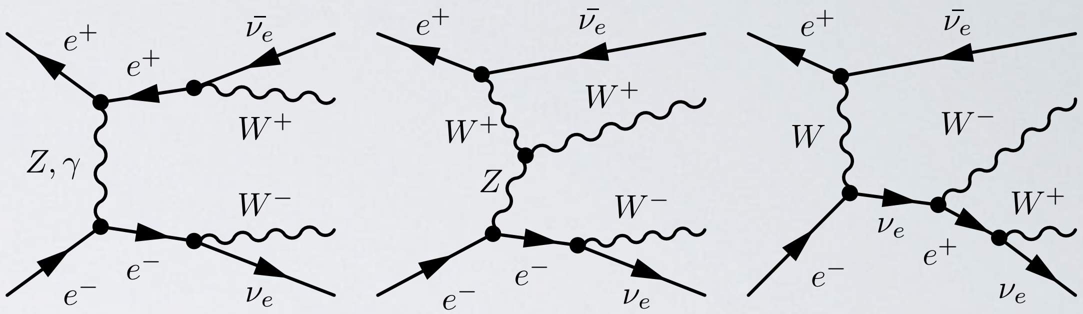

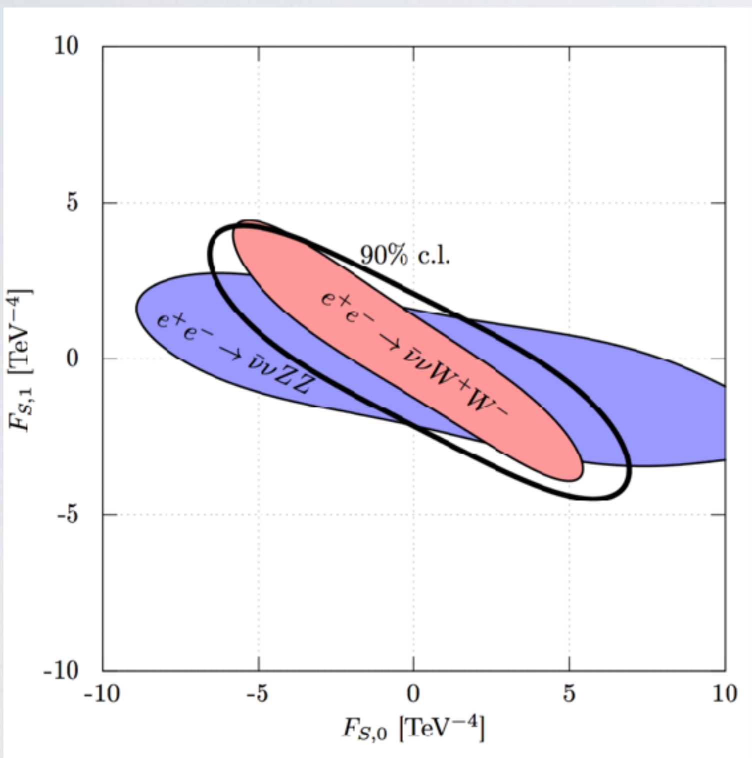

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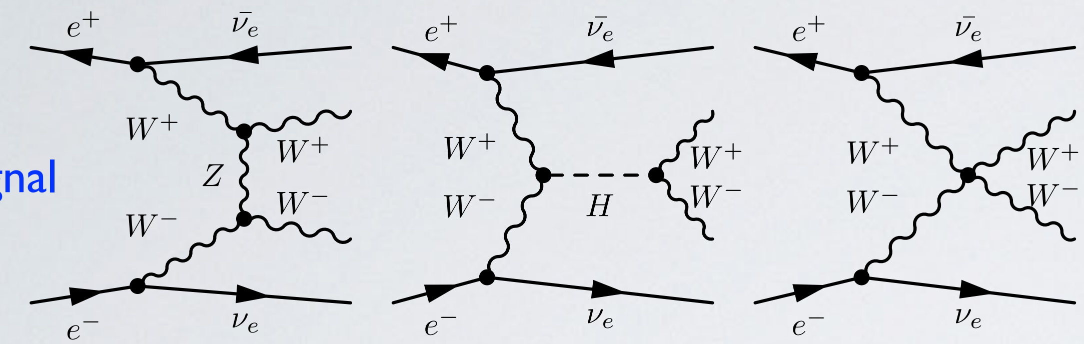

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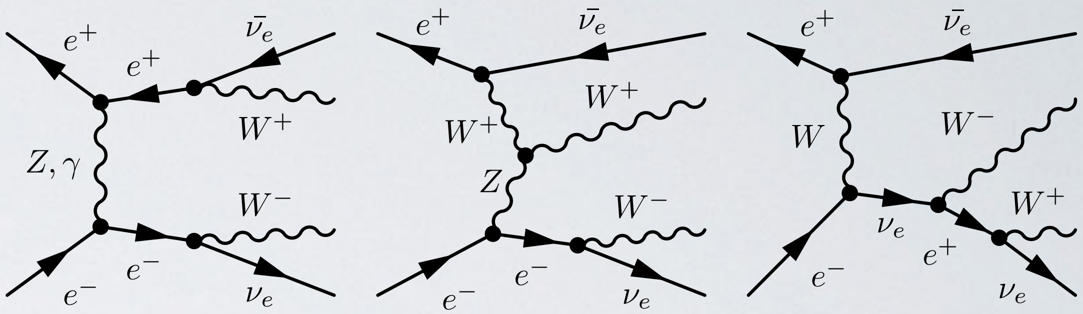

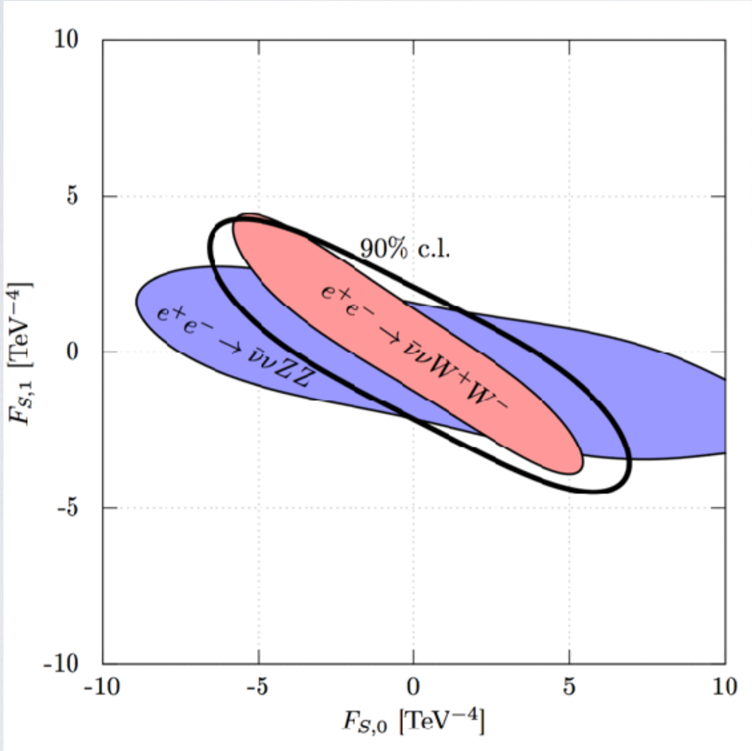

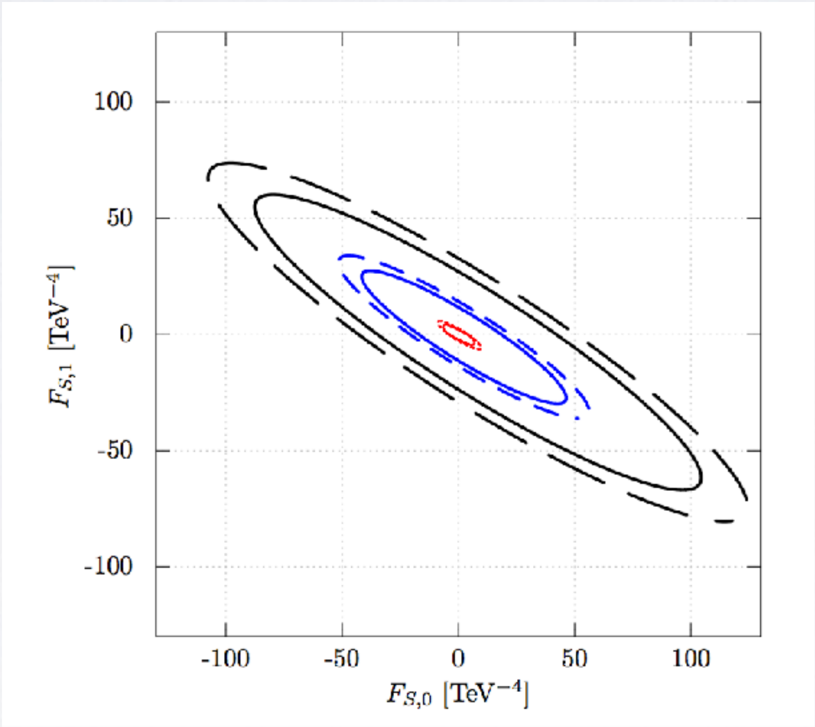

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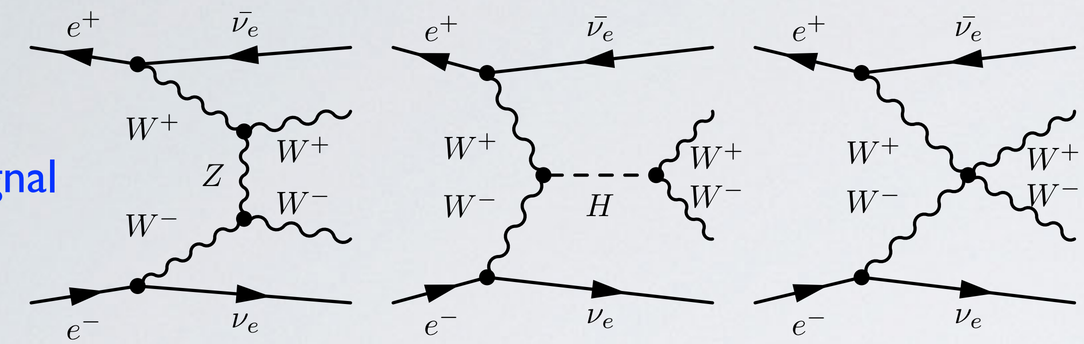
Unitarization necessary for sane high-energy description 1607.03030

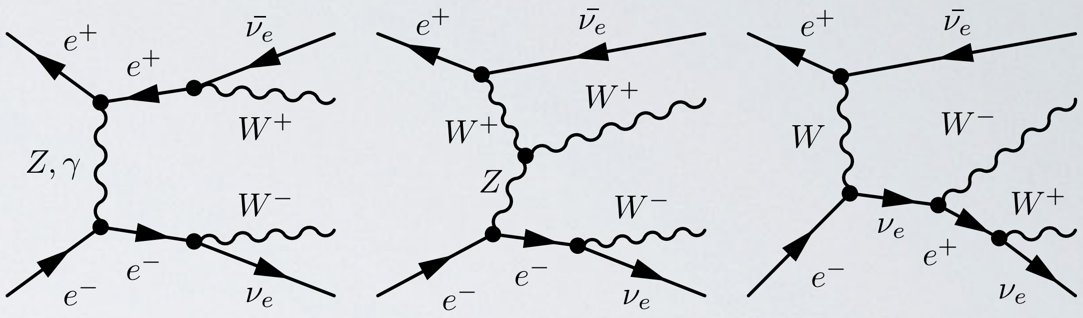
New Physics in VBS at Lepton Colliders

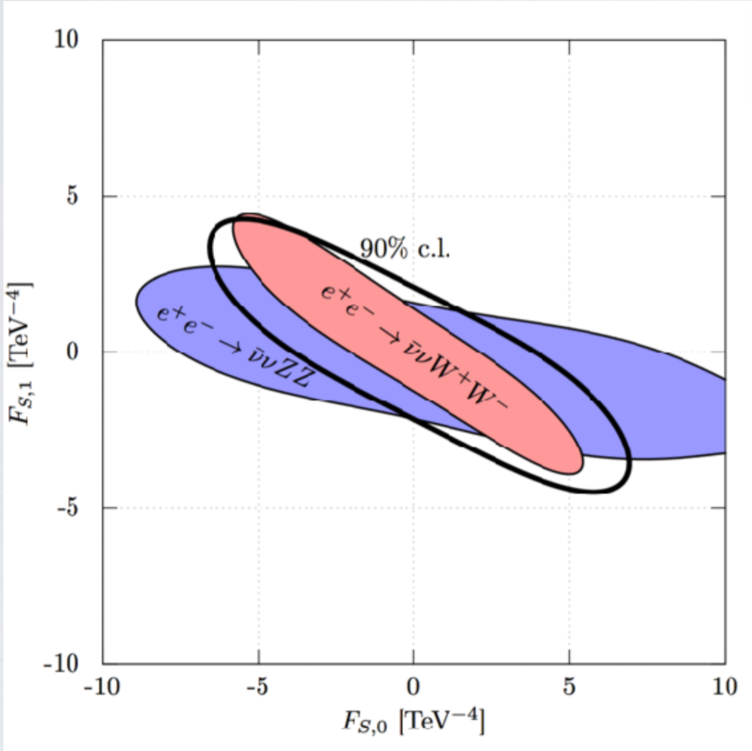
Fleper/Kilian/JRR/Sekulla: Eur.Phys.J. C77 (2017) no.2, 120

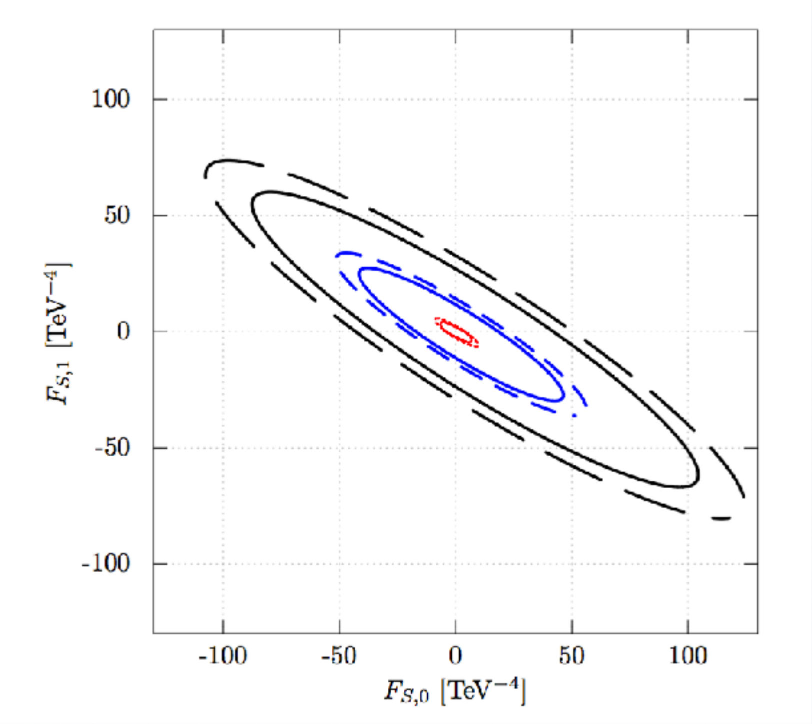
Signal

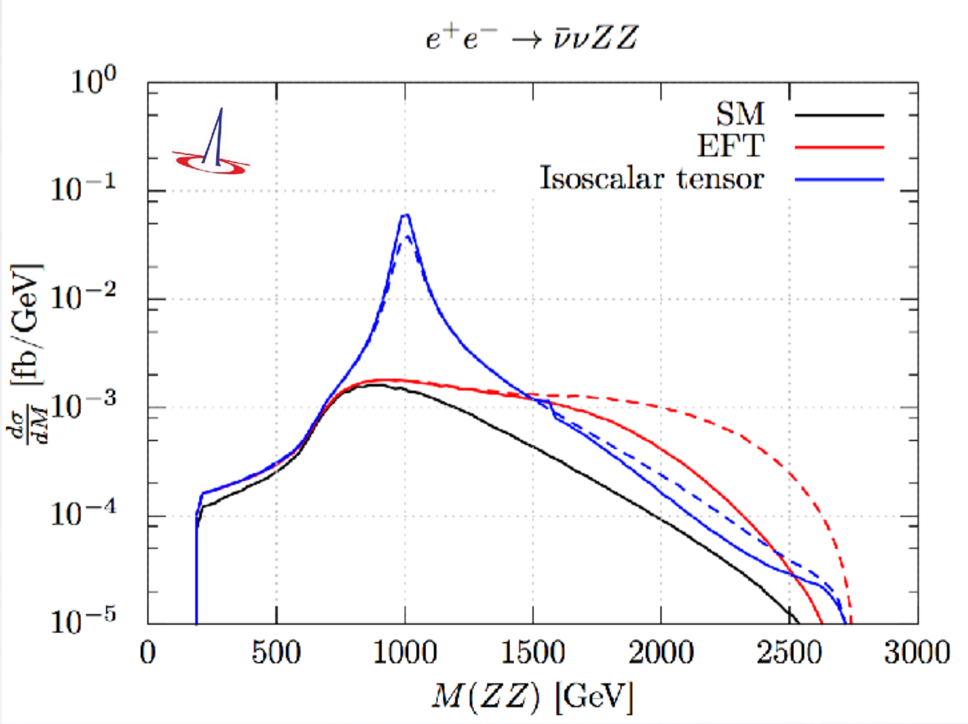


Bkgd.









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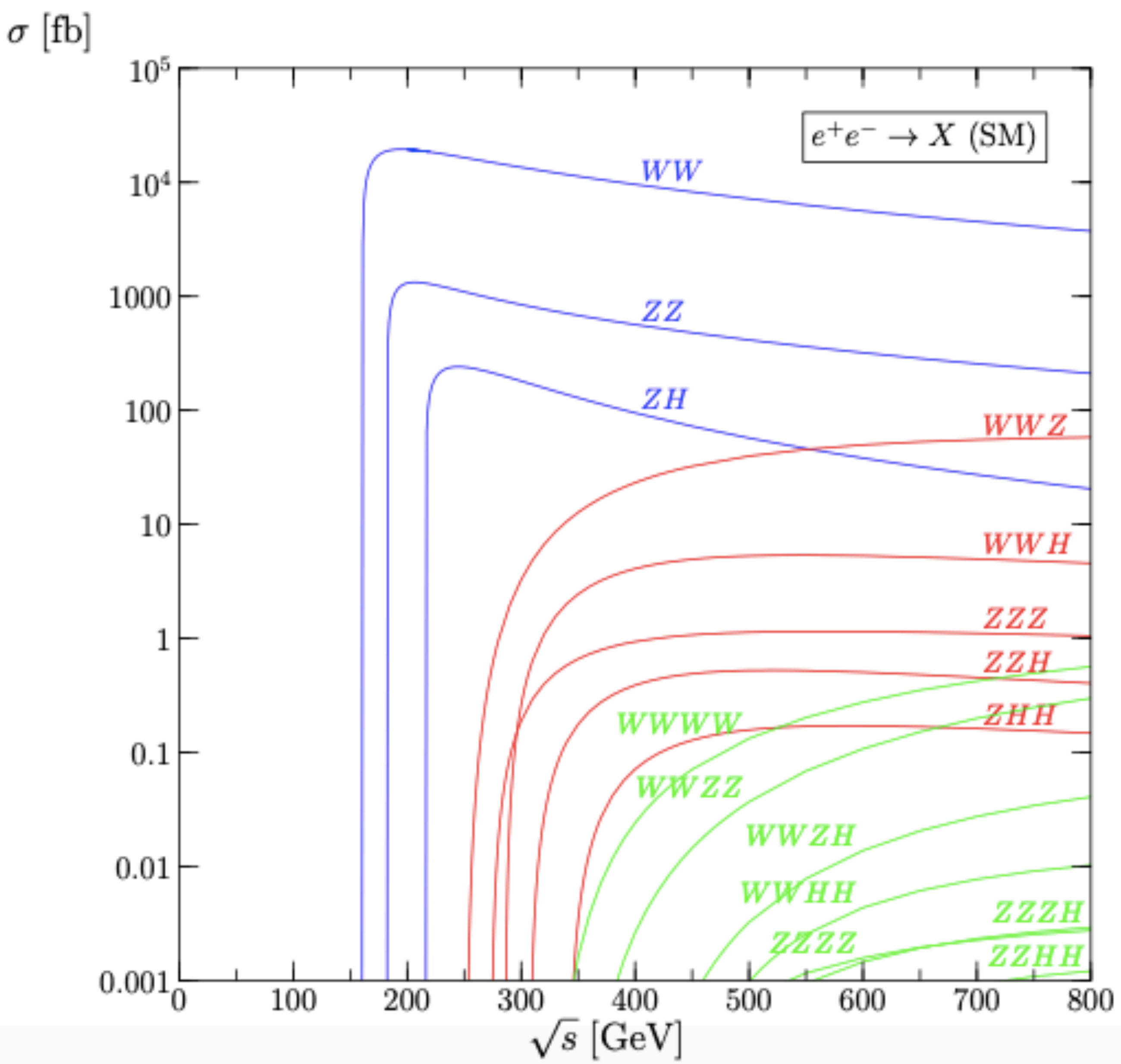
New Physics in VBS at Lepton Colliders

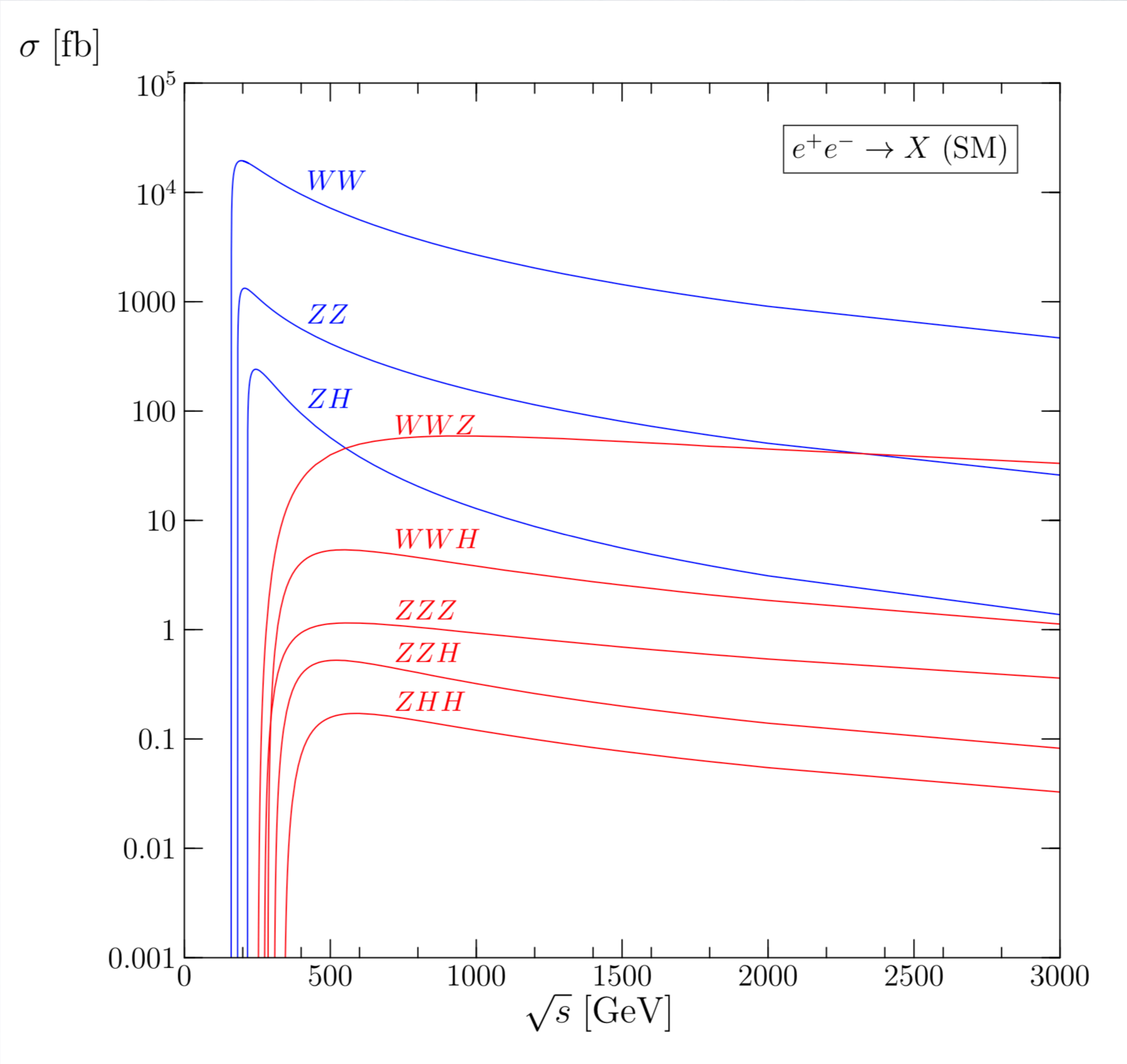
- 6-, 8-, 10-fermion final states studied trigger-less and fully exclusive in all observables
- Main issues: hadronic separation of W, Z, H; jet charge ($W^{\pm}$) ; combinatorics
- Low rates in clean environments: statistics dominated



	thr [GeV]	max [GeV]
WW	160.8	195
ZZ	182.4	200
ZH	216.3	240
WWZ	252.0	950
ZZZ	273.6	550
WWH	285.9	550
ZZH	307.5	520
ZHH	341.4	590
$WWWW$	321.5	3000
$WWZZ$	343.1	4000
$WWZH$	377.0	2000
$WWHH$	410.9	1400

New Physics in VBS at Lepton Colliders

- *WWZ* important process
- compare *WWH* vs. *ZH*
- Pure neutral states suppressed



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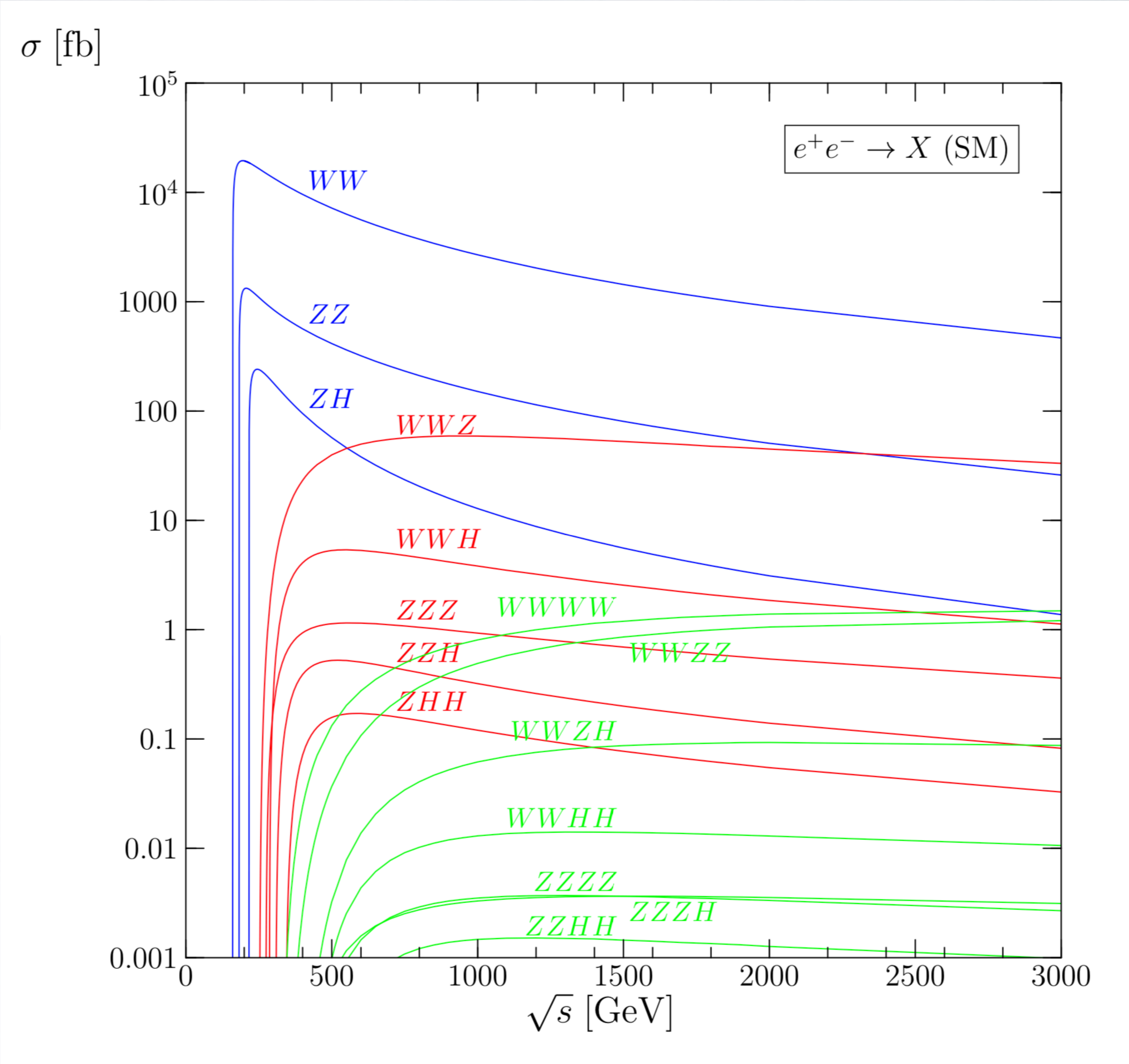
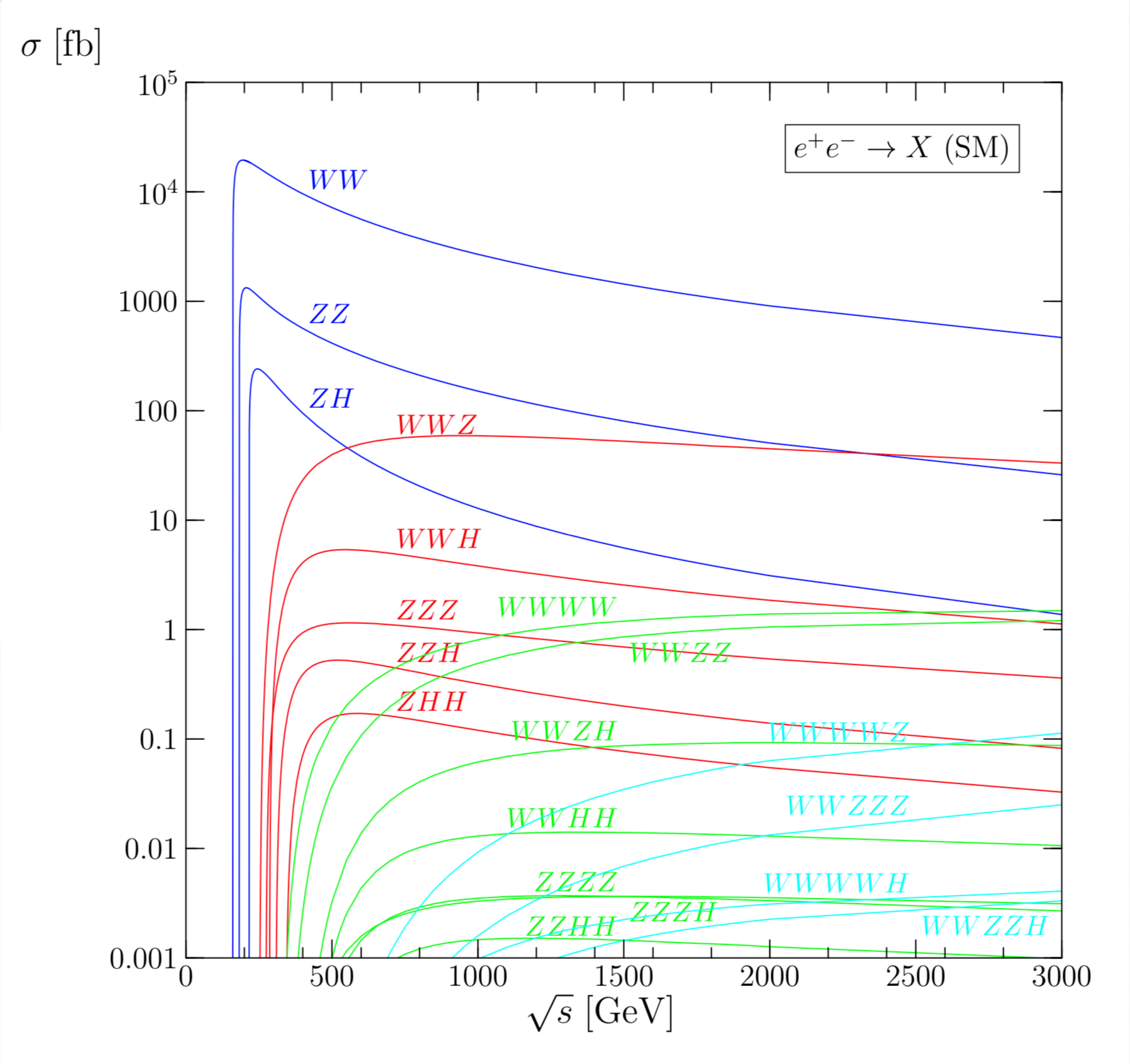


New Physics in VBS at Lepton Colliders

- *WWZ* important process
- compare *WWH* vs. *ZH*
- Pure neutral states suppressed
- Quartic boson production
- 6j, 8j, 10j: signal & background



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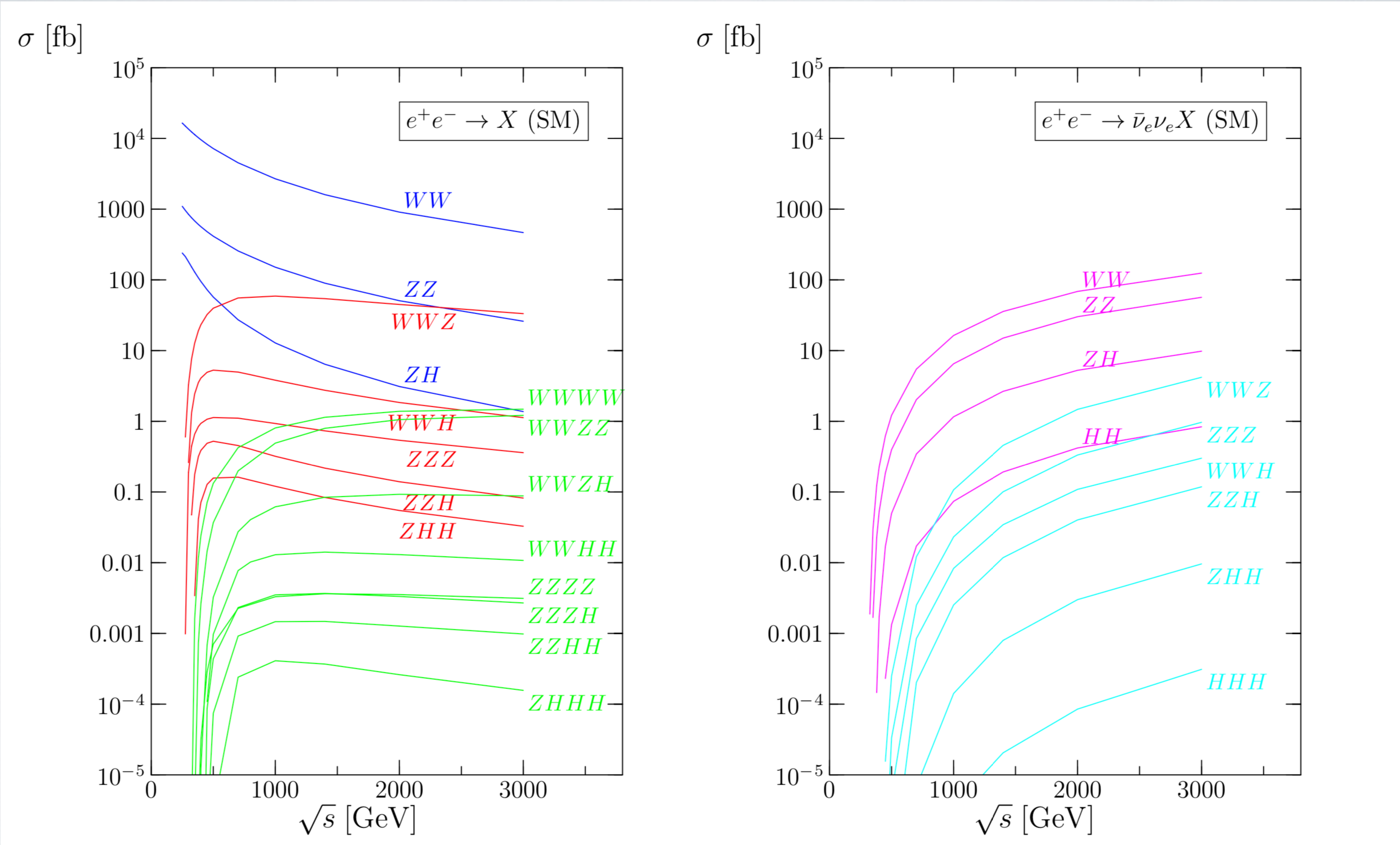


VBS beats multi-boson at high energies

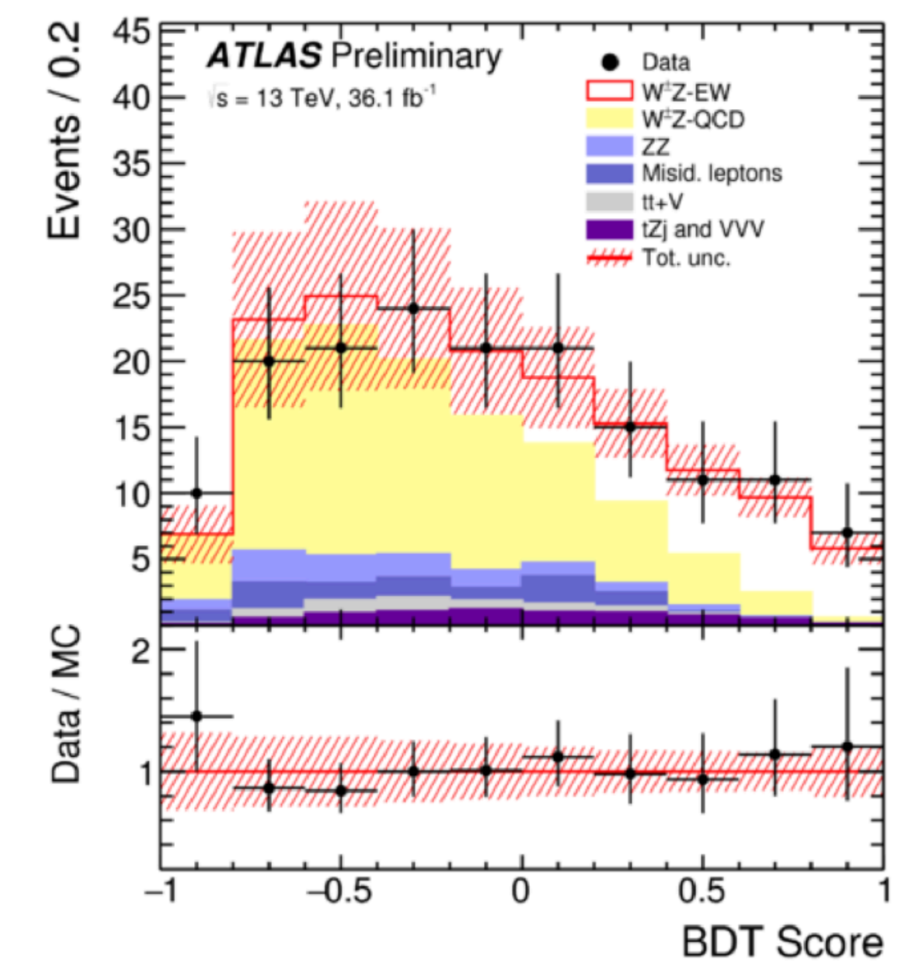
1812.02093; Brass/Kilian/Kreher/JRR, *in prep.*

Conclusions / Summary

- Vector boson scattering one of the flagship measurements of LHC Runs III/IV
- EFT provides well-defined (and very limited) framework for SM deviations
- *T*-matrix unitarization: no new parameters, yields maximal (bin-wise) event counts
- Unitarization bounds: more space for new physics in di-Higgs / transverse op.
- Simplified models: generic electroweak resonances
- Classification according to spin / isospin quantum numbers
- Covers both strongly and weakly coupled models
- Technically non-trivial signal models for vector and even more tensor resonances
- Interesting kinematically different constraints from tri-boson production
- Huge discovery potential for high-energy lepton colliders [energy frontier]

BACKUP SLIDES

VBS measured in many different channels



Post-fit background normalisations

$\mu_{WZ\text{-}QCD} = 0.60 \pm 0.25$

$\mu_{ttV} = 1.18 \pm 0.19$

$\mu_{ZZ} = 1.34 \pm 0.29$

$pp \to WZjj \to l\nu lljj$

1812.09740

$pp \to WZjj \to (l/\nu)(l/\nu)jjjj$

1905.07714

WZjj-EW measured signal strength:

$$\mu_{EW} = 1.77 \pm 0.41(\text{stat.}) \pm 0.17(\text{syst.}) = 1.77 \pm 0.45$$

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

$$\sigma^{\text{fid., EW}}_{WZ^\pm jj \to \ell\nu\ell\ell jj} = 0.57 \,^{+0.15}_{-0.14}\,\text{fb} = 0.57 \,^{+0.14}_{-0.13}\,(\text{stat.}) \,^{+0.05}_{-0.04}\,(\text{sys.}) \,^{+0.04}_{-0.03}\,(\text{th.})\,\text{fb}$$

Philip Chang, plenary; Usama Hussain, parallel 24.5.

$pp \to WZjj \to lljj + X$

$$\sigma^{\text{fid}}_{WZjj} = 3.18^{+0.57}_{-0.52}\,(\text{stat})^{+0.43}_{-0.36}\,(\text{syst})\,\text{fb} = 3.18^{+0.71}_{-0.63}\,\text{fb}$$

1901.04060

Observed (expected) of EW WZ 1.9σ (2.7σ)

$pp \to W^+W^+jj \to l\nu l\nu jj$

$\sigma_{fid} = 3.83 \pm 0.66\,(\text{stat}) \pm 0.35\,(\text{syst})\,\text{fb}$

PRL 120, 081801(2018)

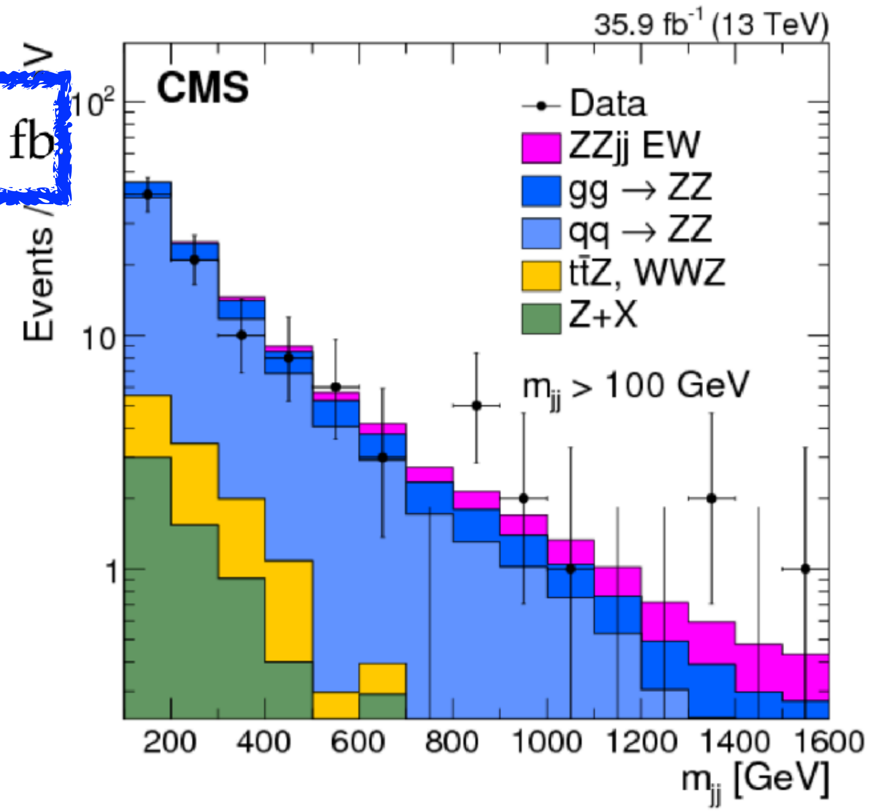
Observed (expected) of 5.5σ (5.7σ)

$pp \to ZZjj \to lllljj$

$\mu = \sigma_{obs}/\sigma_{th.} = 1.39 \,^{+0.72}_{-0.57}\,(\text{stat}) \,^{+0.46}_{-0.31}\,(\text{syst.})$

PLB 774(2017) 682

Observed (expected) of 2.7σ (1.6σ)



Unitarity in vector boson scattering

Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

Partial wave amplitudes:

$$\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta) \qquad \text{(“Power spectrum”)}$$

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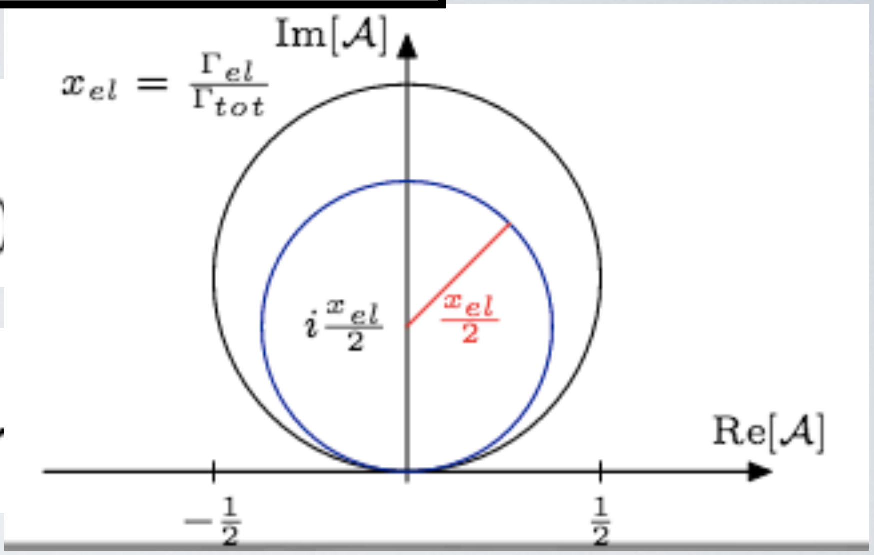

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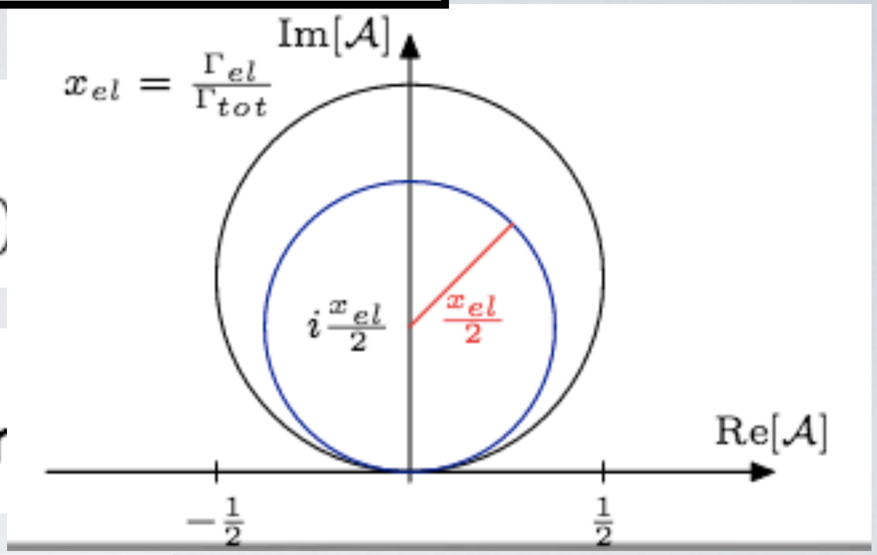

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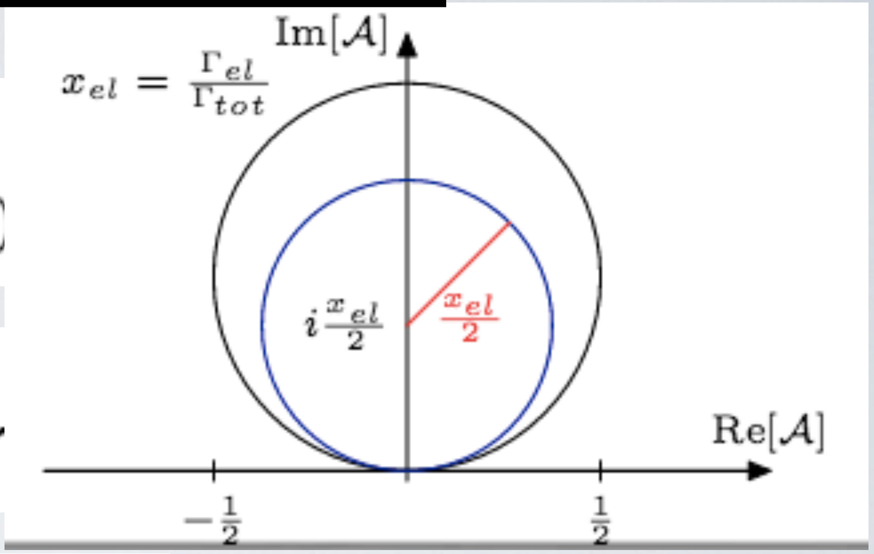

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SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

$$\mathcal{A}_{I=0} = 2\frac{s}{v^2}P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2}P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2}P_0(s)$$

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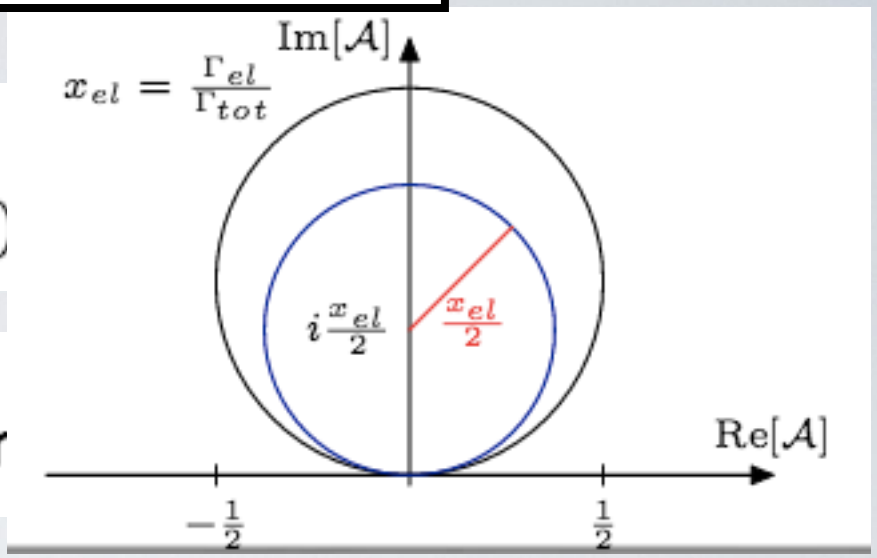

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Lee/Quigg/Thacker, 1973

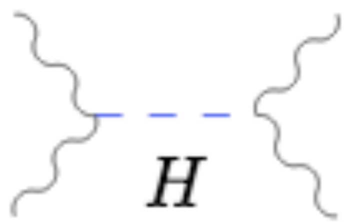
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

Higgs exchange:



$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

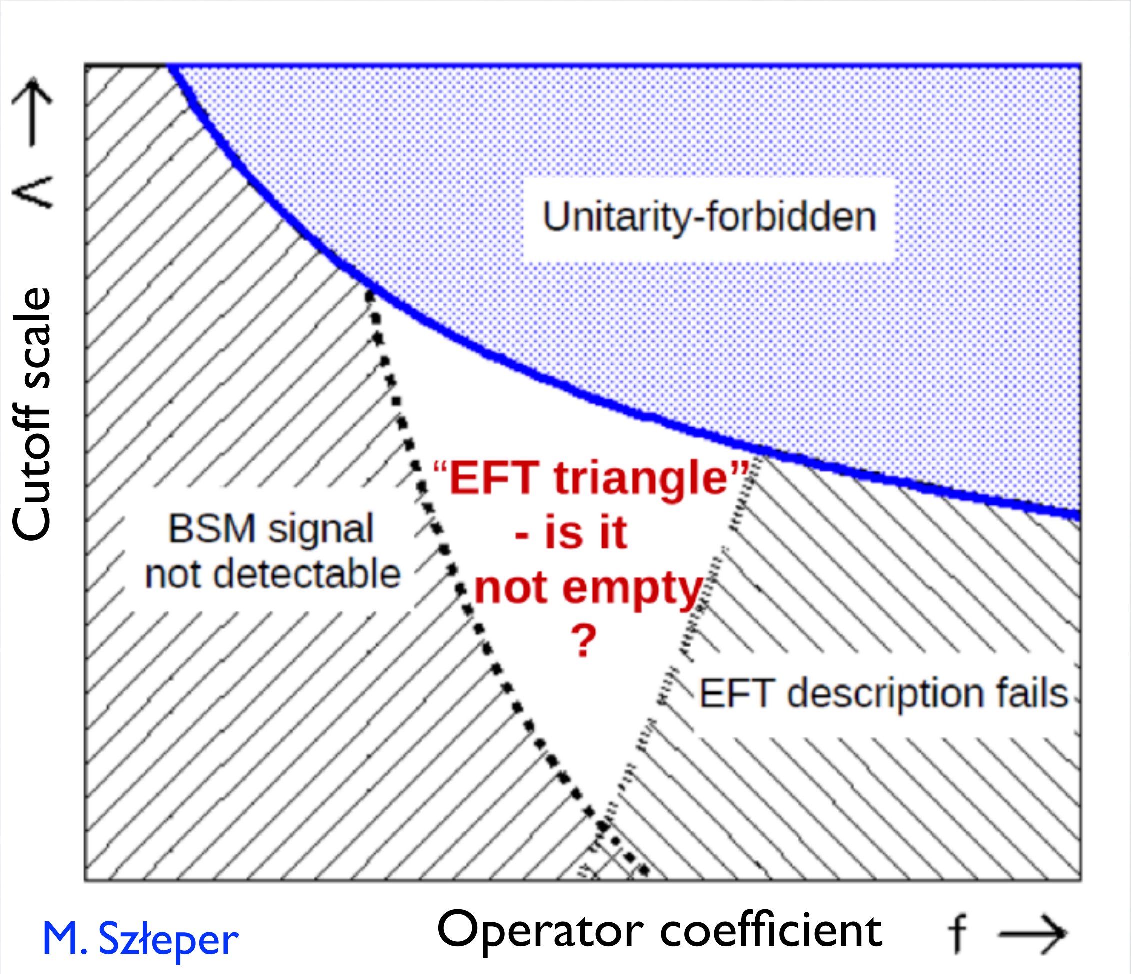
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

(In)Validity of (In)Effective Field Theories

- **Resonances in direct reach** (not clear: strongly interacting models [e.g. σ resonance]
- **Estimate of operator coefficients** (difficult for strongly coupled models)

$$\mathcal{A}_{\rm SM} \times \mathcal{A}_{\rm dim\text{-}6} \gtrsim |\mathcal{A}_{\rm dim\text{-}6}|^2 \qquad \mathcal{A}_{\rm SM} \times \mathcal{A}_{\rm dim\text{-}8} \gtrsim |\mathcal{A}_{\rm dim\text{-}8}|^2 \qquad \mathcal{A}_{\rm SM} \times \mathcal{A}_{\rm dim\text{-}6} \gtrsim \mathcal{A}_{\rm SM} \times \mathcal{A}_{\rm dim\text{-}8}$$

- **Partial wave unitarity:** gives guidance on maximally possible event numbers
- **Positivity constraints on operator coefficients**
- **Size of coefficients:** dichotomy between validity and detectability
- **EFT better/best[?] suited in intensity frontier** [example: HEFT @ $\mathcal{O}$(100 GeV)]
- **EFT borderline in energy frontier physics**



Differential spectra in VBS

$$pp \to e^+\mu^+\nu_e\nu_\mu jj \qquad \sqrt{s} = 14\,\mathrm{TeV} \qquad \mathcal{L} = 1\,\mathrm{ab}^{-1}$$

using K-matrix unitarization

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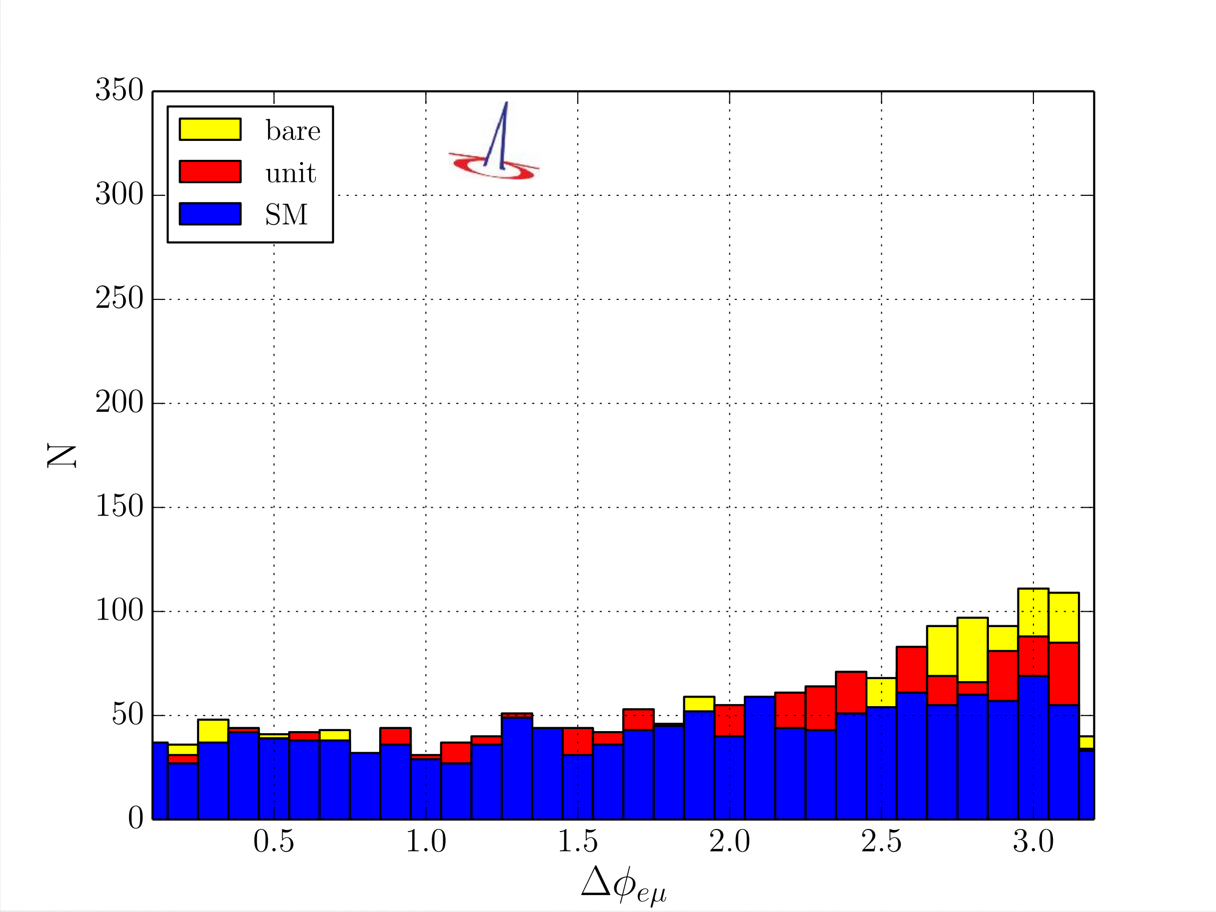

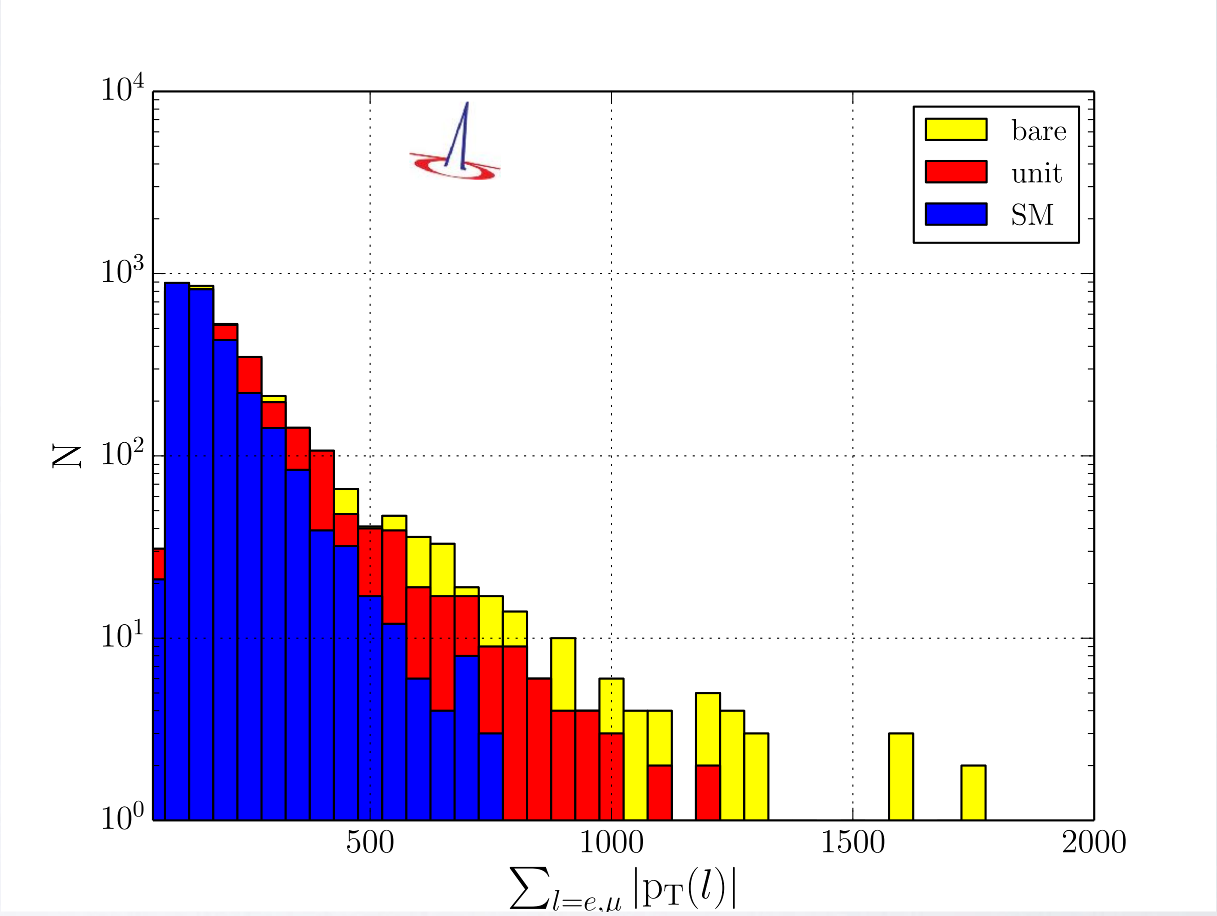

(now) exaggerated Wilson coefficients

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

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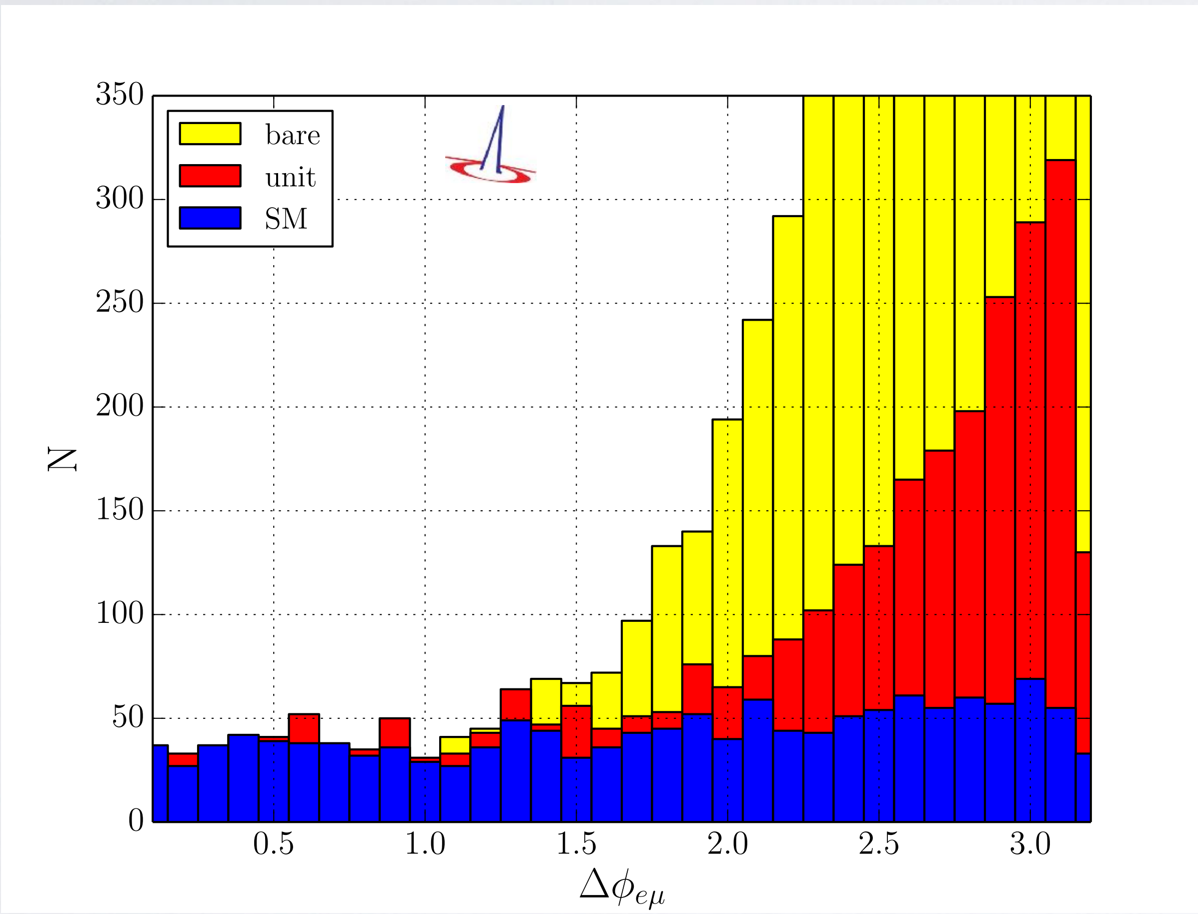
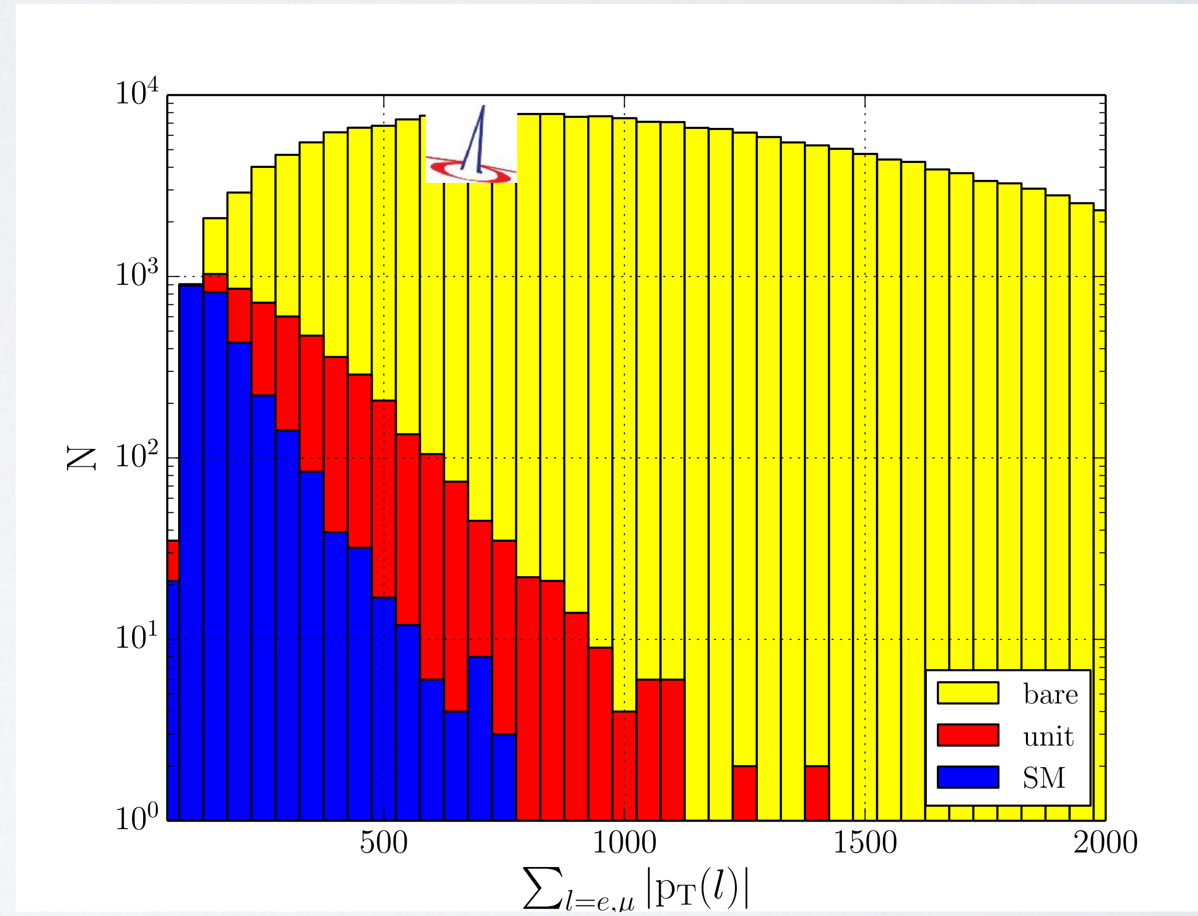
$$F_{S,0} = 480\ \text{TeV}^{-4}$$





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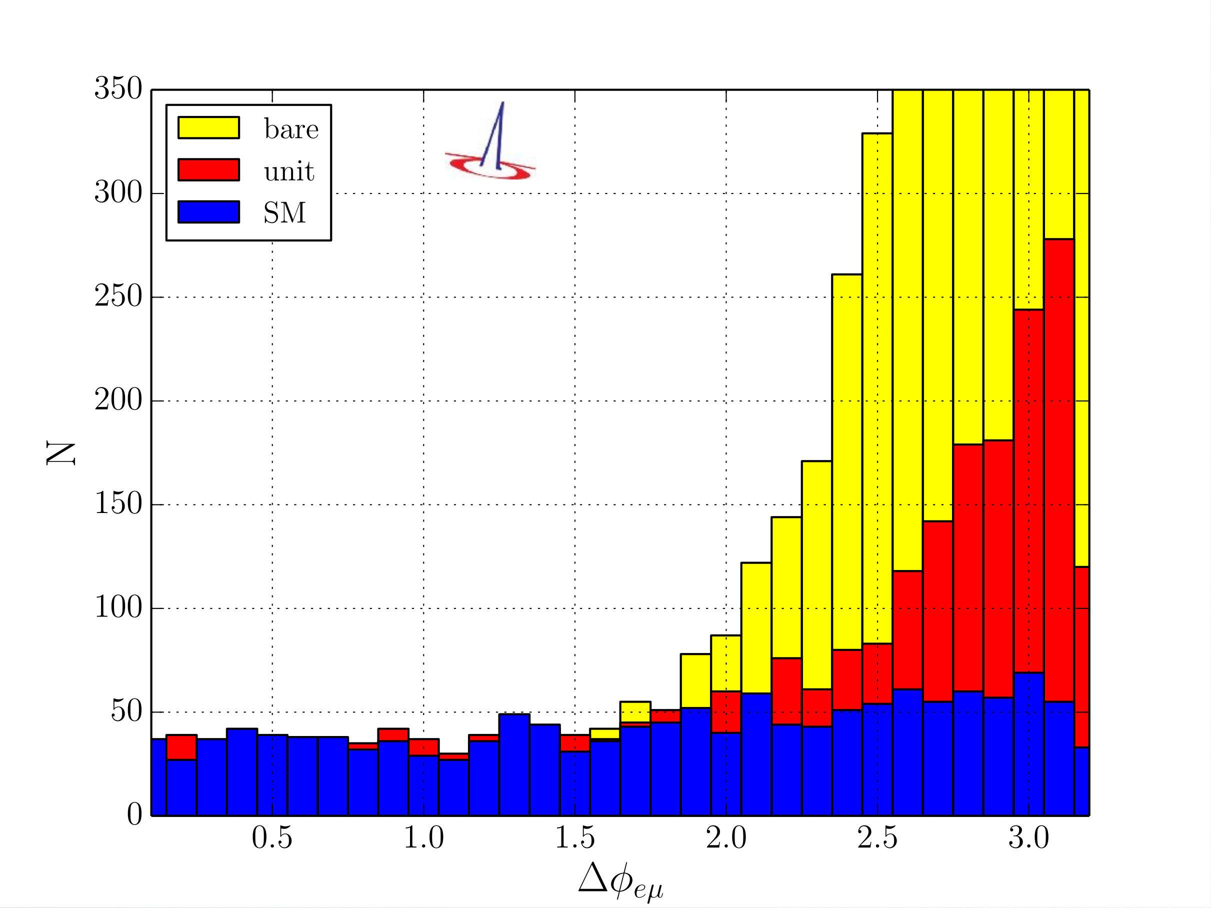

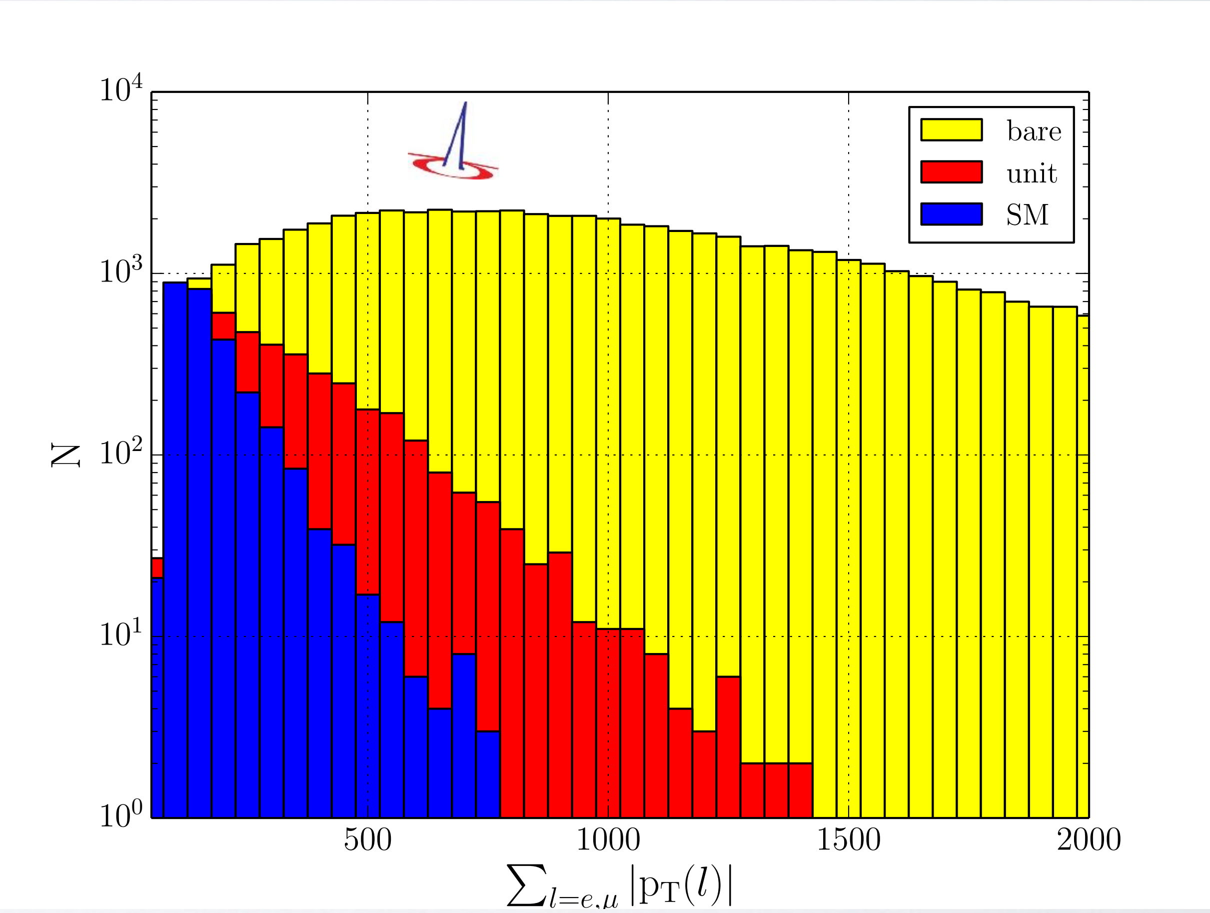

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