Transversal Operators and Polarized *V*s in WHIZARD

DESY.

Jürgen R. Reuter, DESY

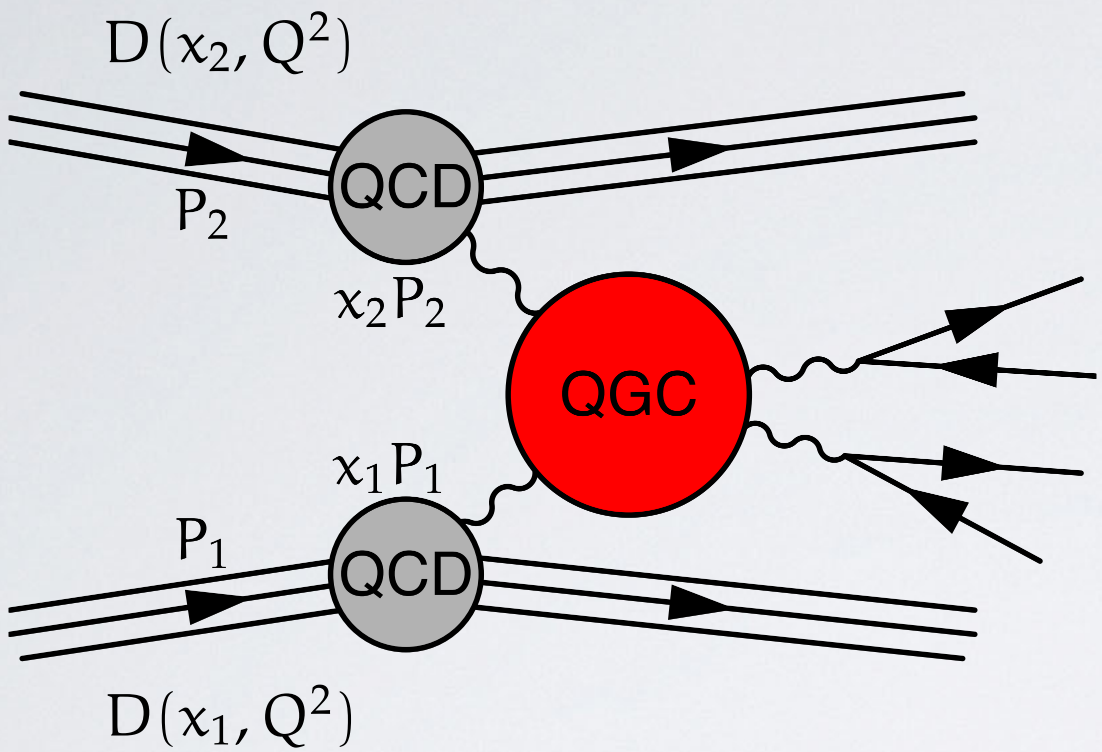
based on work with
S. Brass, C. Fleper, W. Kilian, T. Ohl, M. Sekulla

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

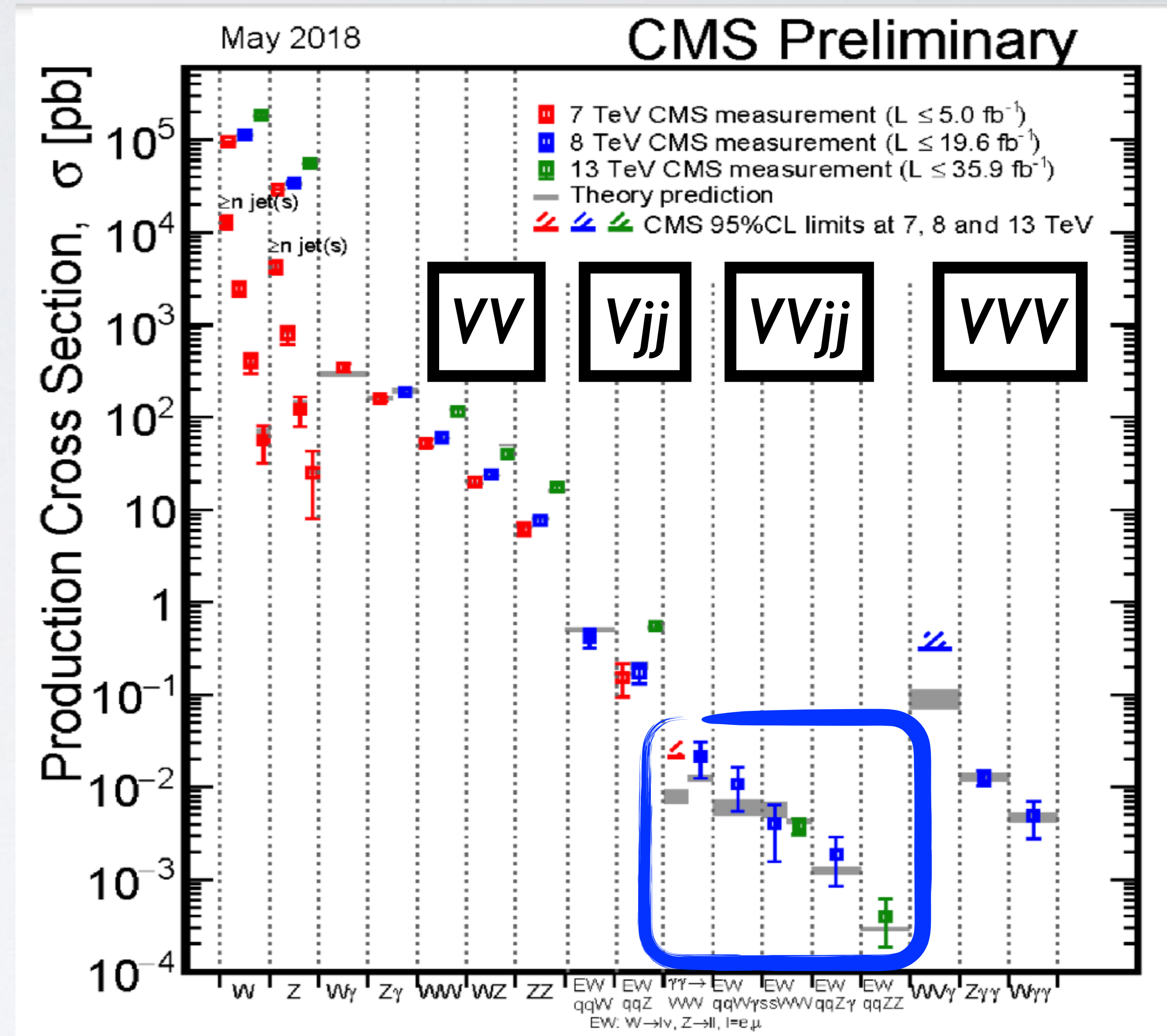
w. EPJC [1807.02512]; PRD93(16),3. 036004 [1511.00022]; PRD91(15) 096007 [1408.6207]

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

How to encode deviations from the SM?

The Rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators "relevant" for low-energy physics:
  (no fermions or QCD here) $\mathcal{L}_{EW} = -\frac{1}{2}\text{tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$
- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

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

S. Weinberg, 1979

- $v \ll \Lambda$: new physics scale; $c_i^{(d)}$: dimensionless Wilson coefficient
- Odd operators involve fermions, all dim-5 & dim-7 violate *B* and/or *L*

No unique basis exists

- Validity of EFT assumes $E \ll \Lambda$
  - "HISZ" basis: no fermionic operators — Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993
  - "GIMR" basis: first minimal complete basis — Grzadkowski/Iskrzyński/Misiak/Rosiek, 2010
  - "SILH" basis: complete basis — Giudice/Grojean/Pomarol/Ratazzi, 2007; Elias-Miró et al, 2013
  - Dim. 8 operators: — Eboli et al., 2006; Kilian/JRR/Ohl/Sekulla, 2014+2015; Hays et al.
  - "EChL" basis: — Dobado/Espriu/Pich et al.; Buchalla/Cata; Kilian/JRR et al.

Dim-6 operators for Multiboson physics

$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger\Phi\right)\text{Tr}[W^{\mu\nu}W_{\mu\nu}]$$
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Dim-6 operators for Multiboson physics

- Only at loop-level from (weakly coupled) models

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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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- Dim. 8 generate aQGCs independently
- Energy dependence: rise of cross sections
- [possibility to construct full dim-8 $\Longrightarrow$ backup slides]

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
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Unitarity in vector boson scattering

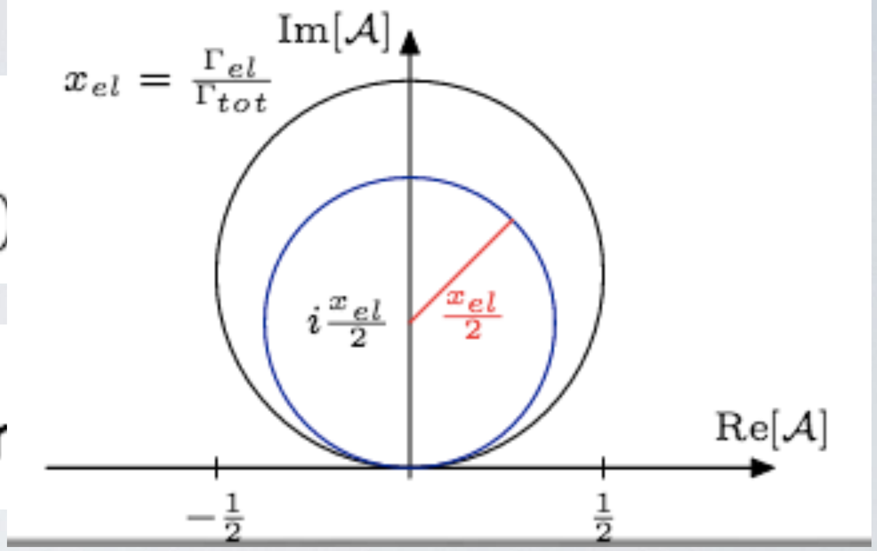
Optical Theorem (Unitarity of the S(cattering) Matrix):

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

Partial wave amplitudes:

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

Unitarity in vector boson scattering



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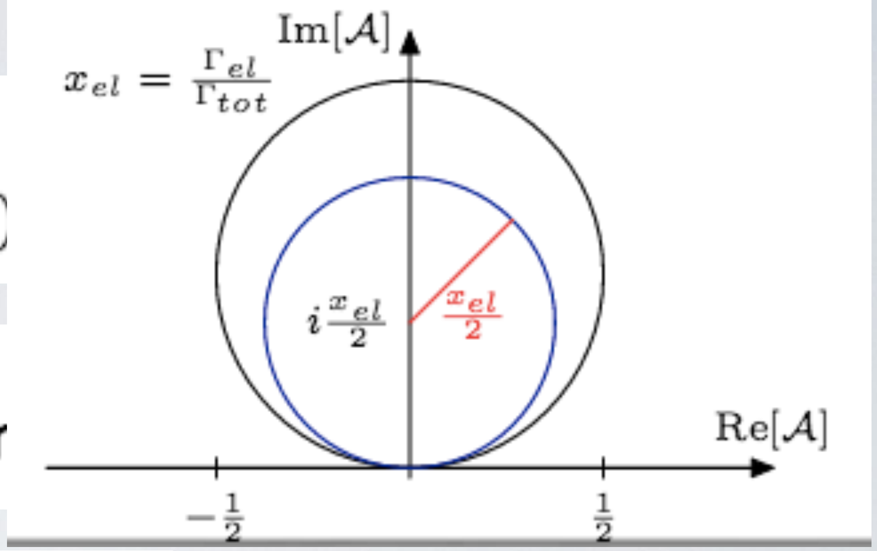

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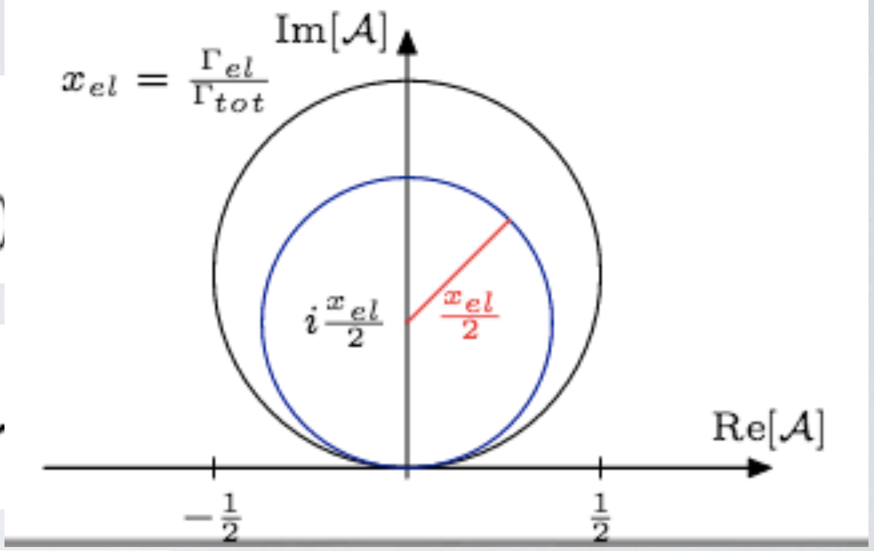

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SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

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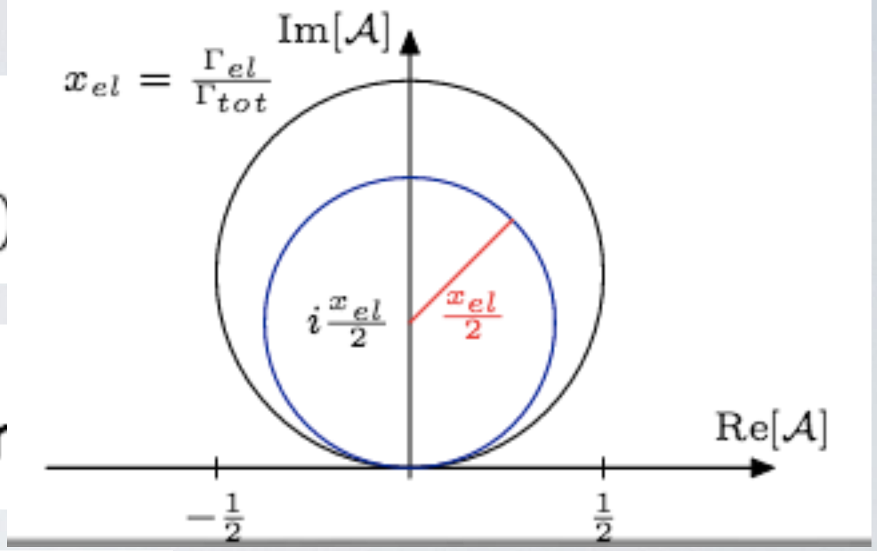

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Lee/Quigg/Thacker, 1973

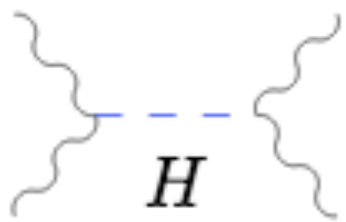
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

Higgs exchange:

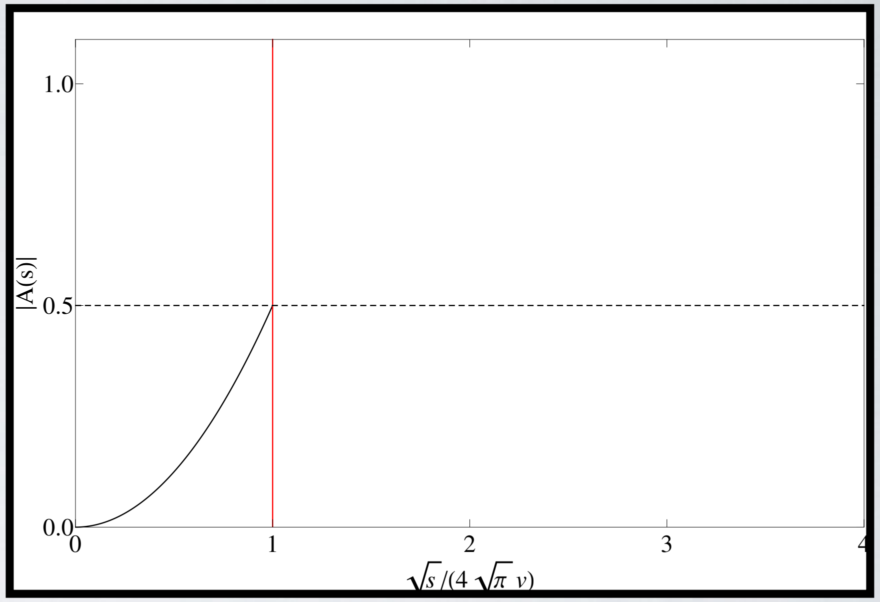


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

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

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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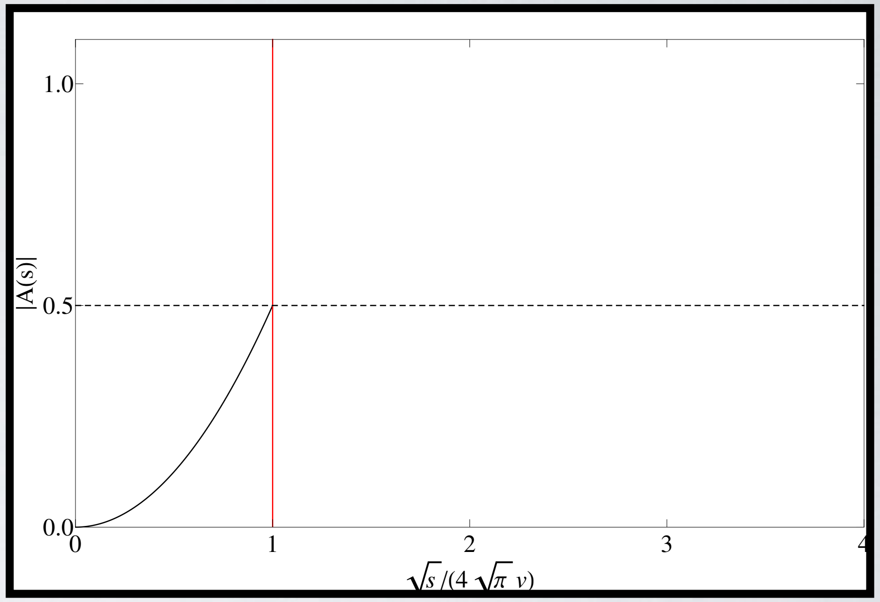
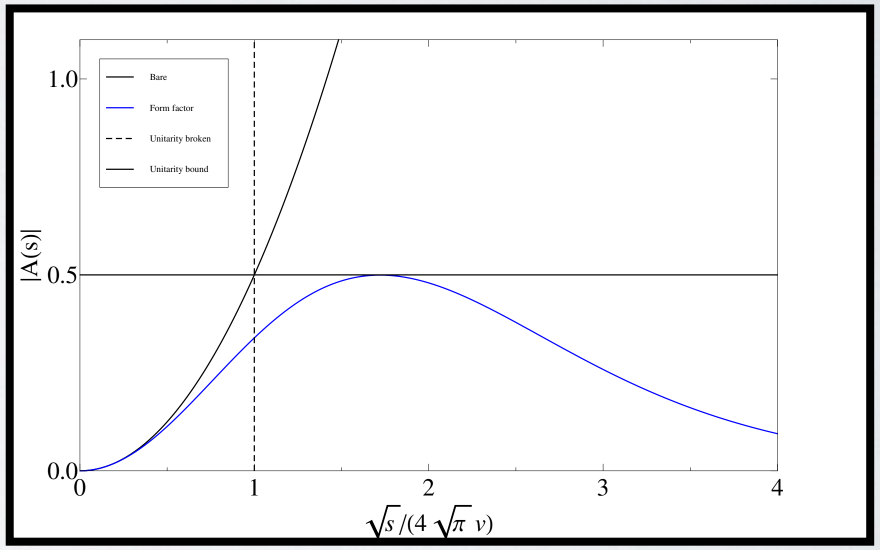


Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

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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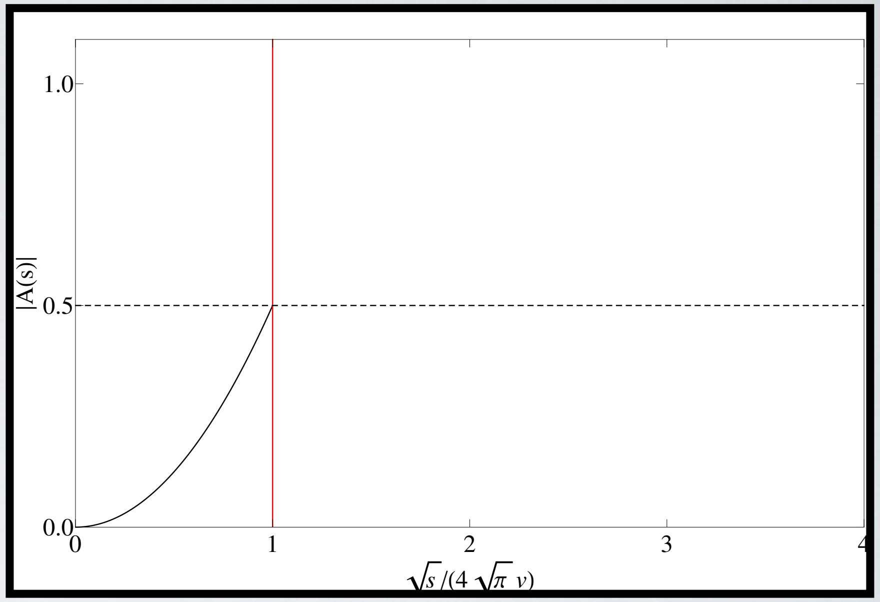

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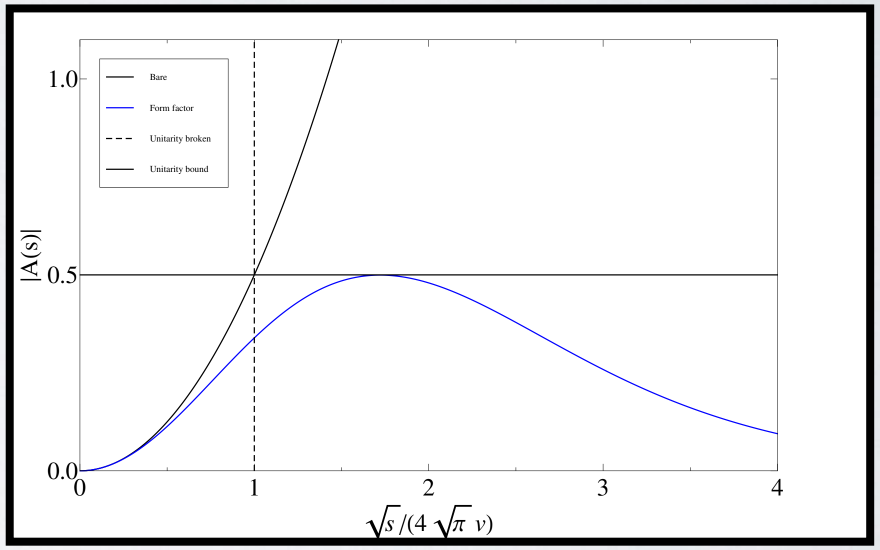

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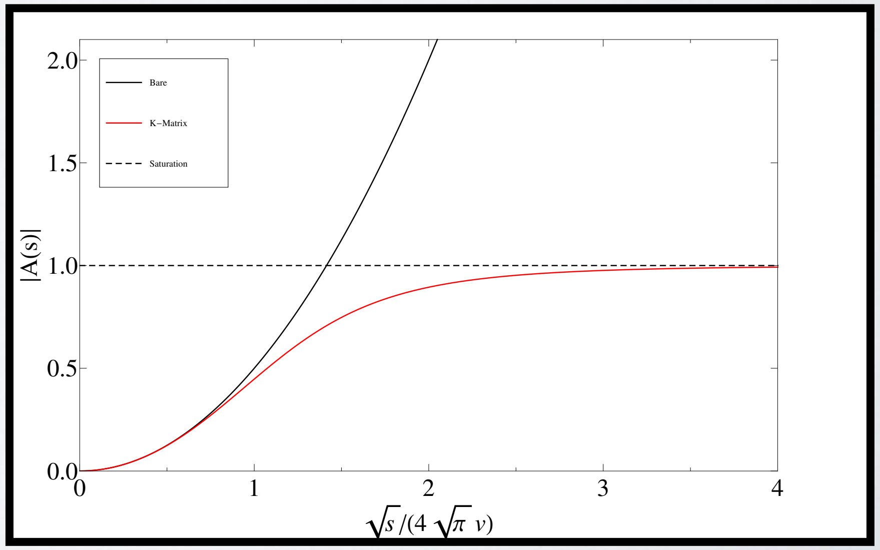
K-/*T*-matrix saturation $a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



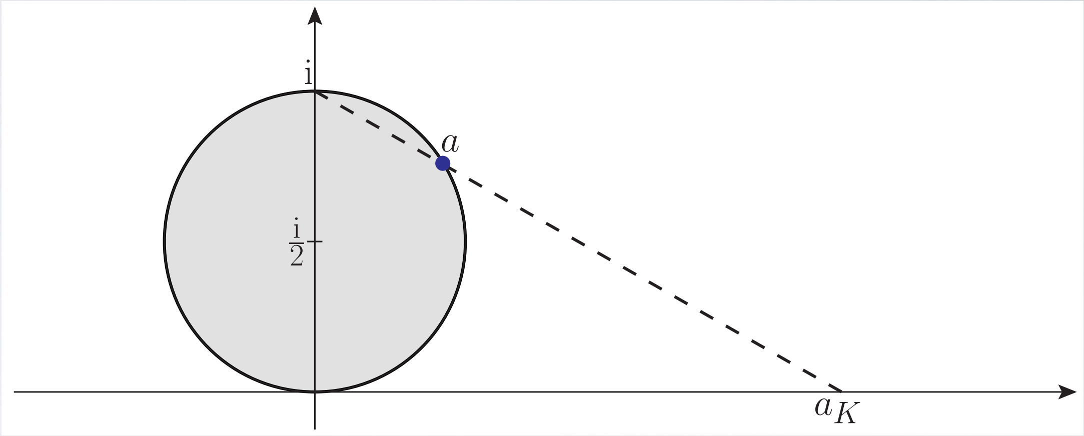
saturates amplitude [projection to unitarity circle], also for complex ampl., no additional parameters

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

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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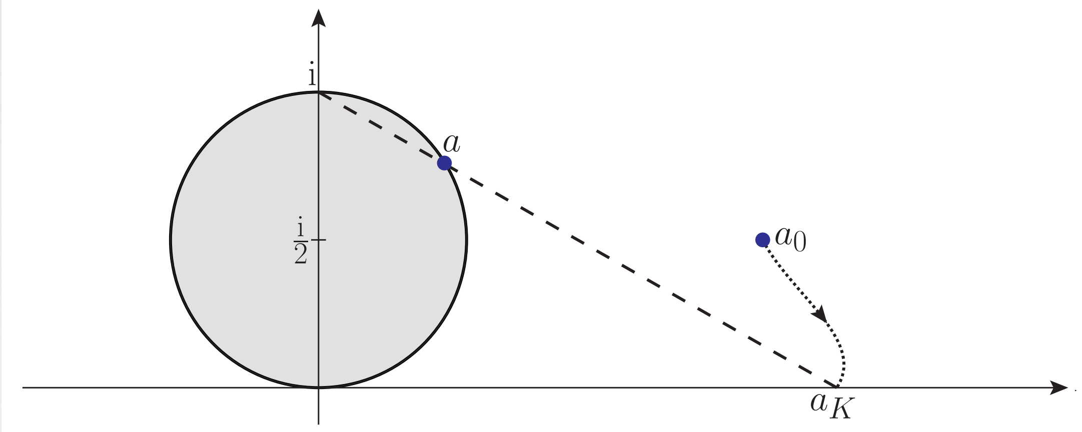

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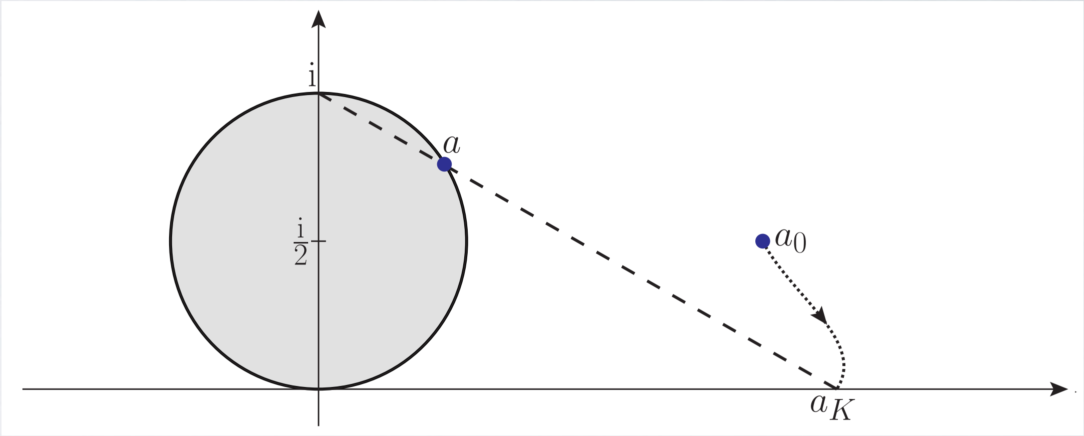

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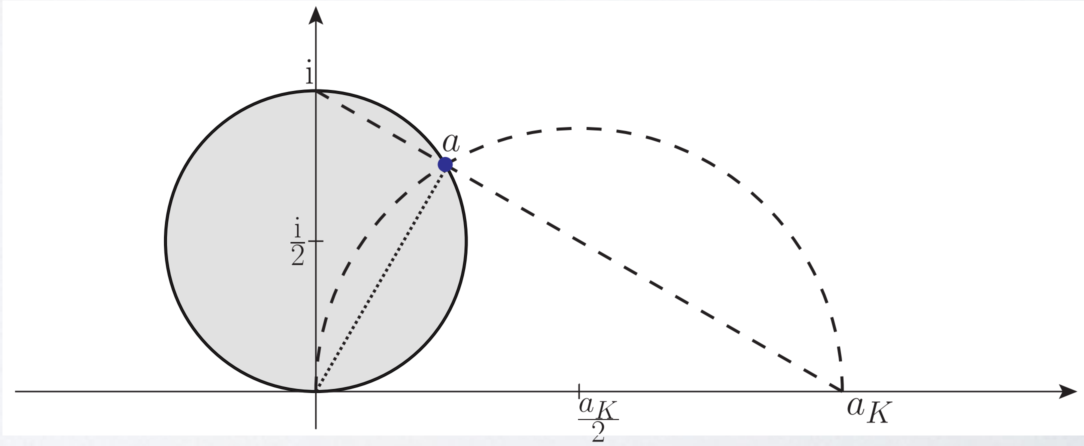

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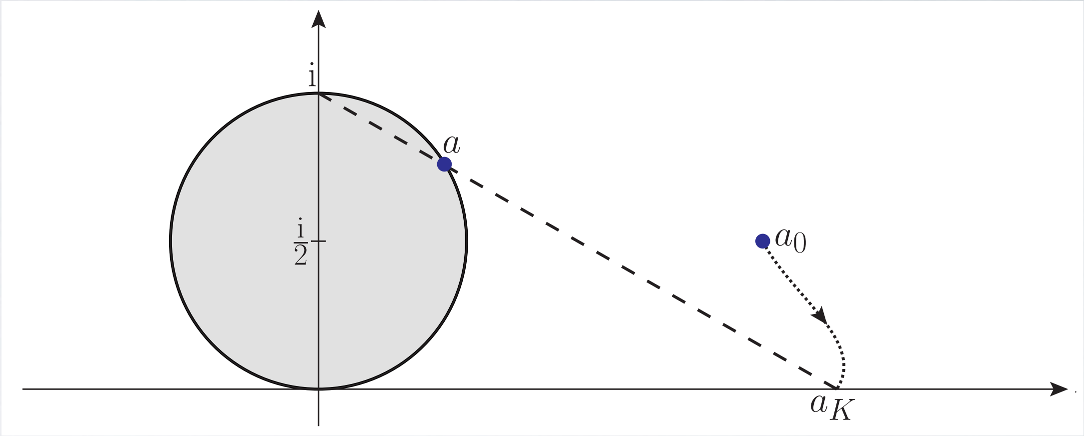

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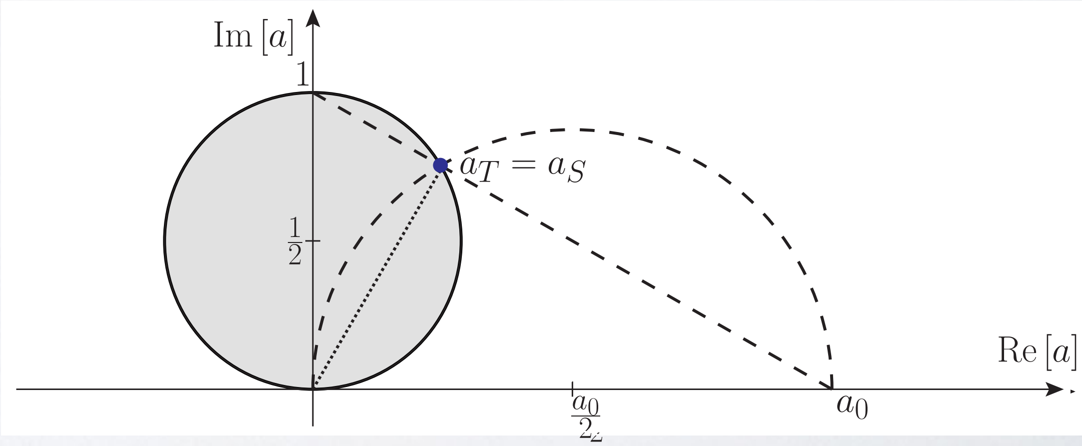

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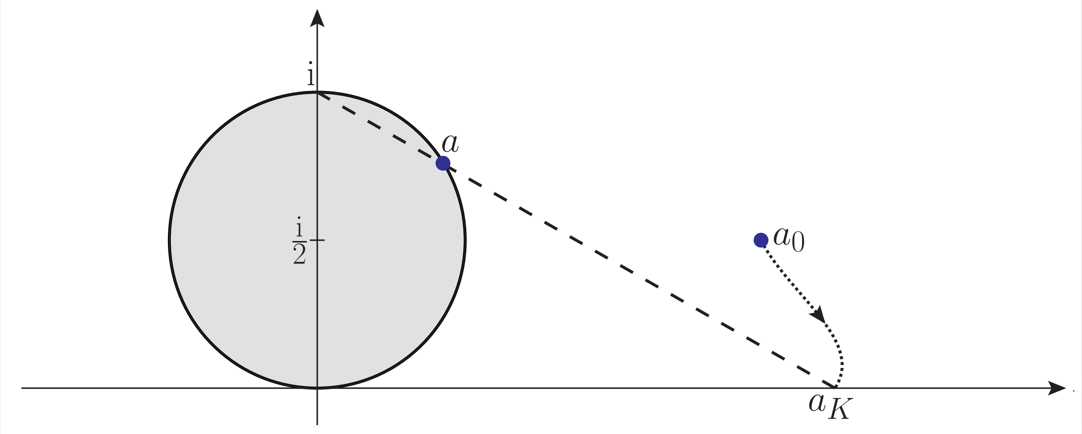

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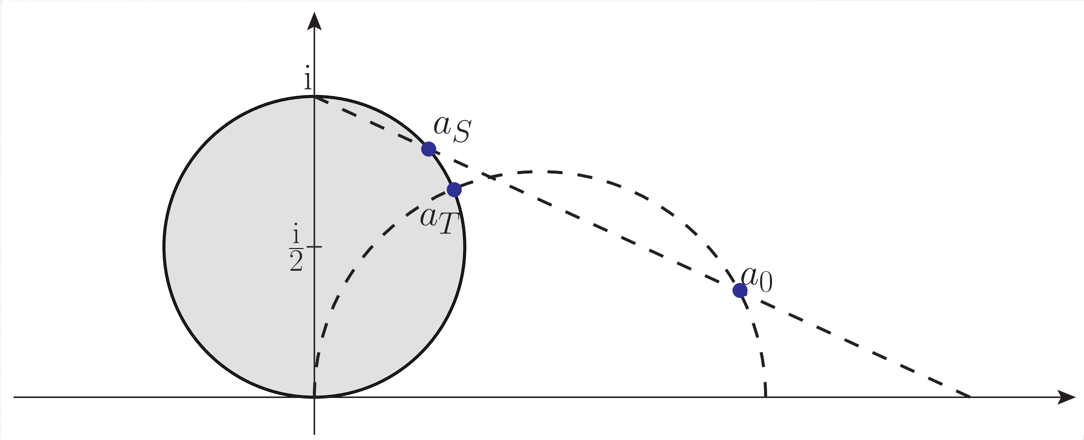

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Unitarization of transverse operators

- 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] $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)$

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

$$\lambda = \lambda_1 - \lambda_2 \qquad \lambda' = \lambda_3 - \lambda_4$$

- Extract all partial waves:

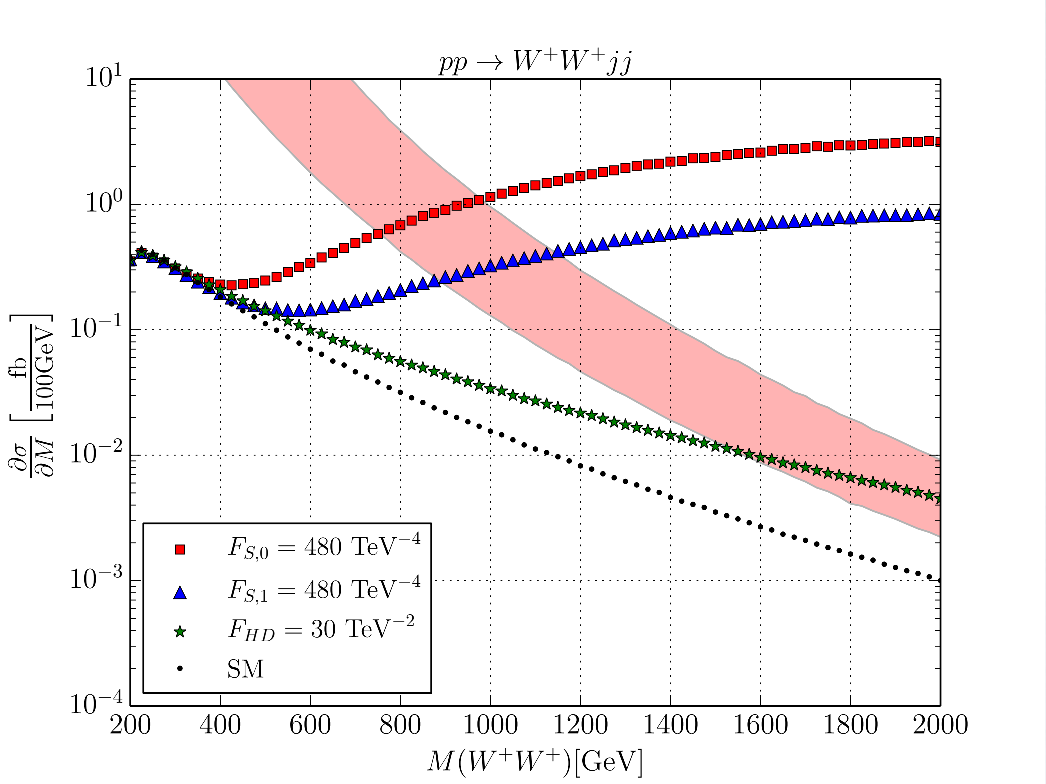
$$A_{ij}(s;\boldsymbol{\lambda})/(g^4 s^2) = (c_0 F_{T_0} + c_1 F_{T_1} + c_2 F_{T_2})$$

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				

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

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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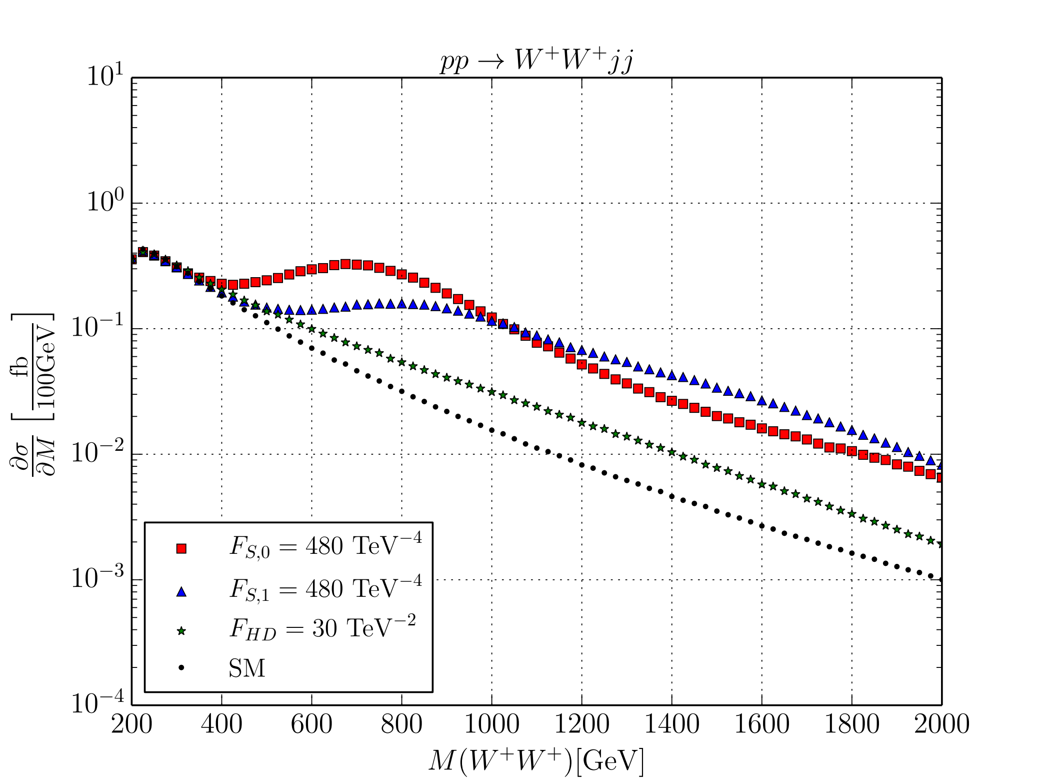

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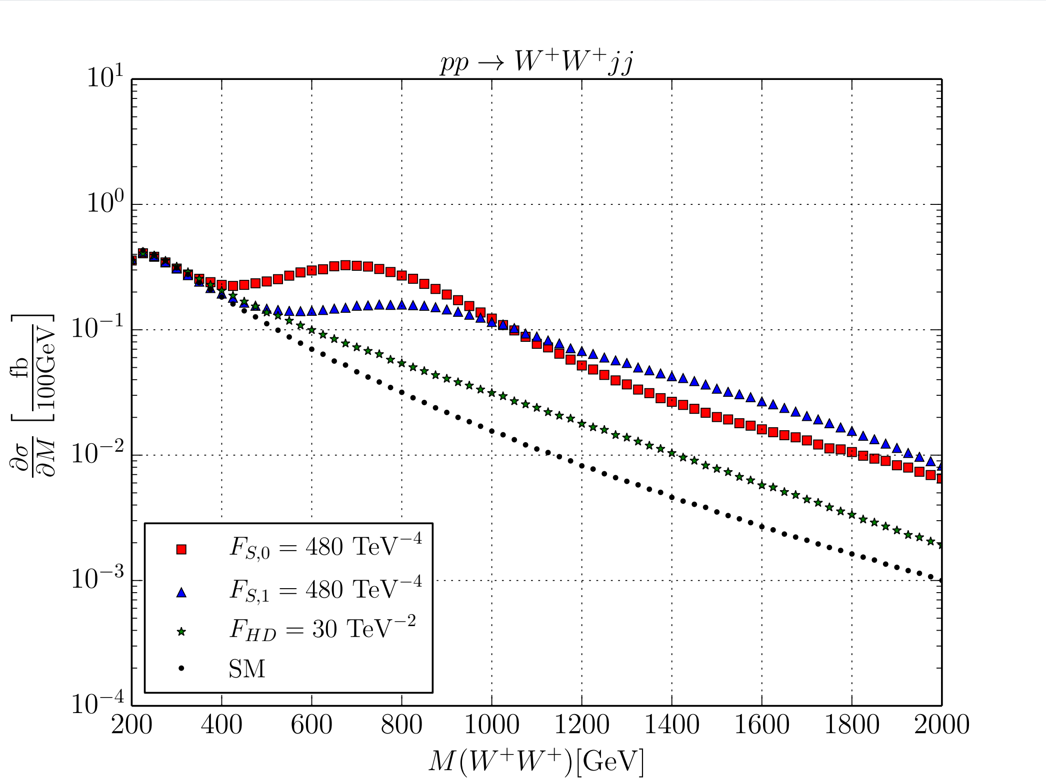

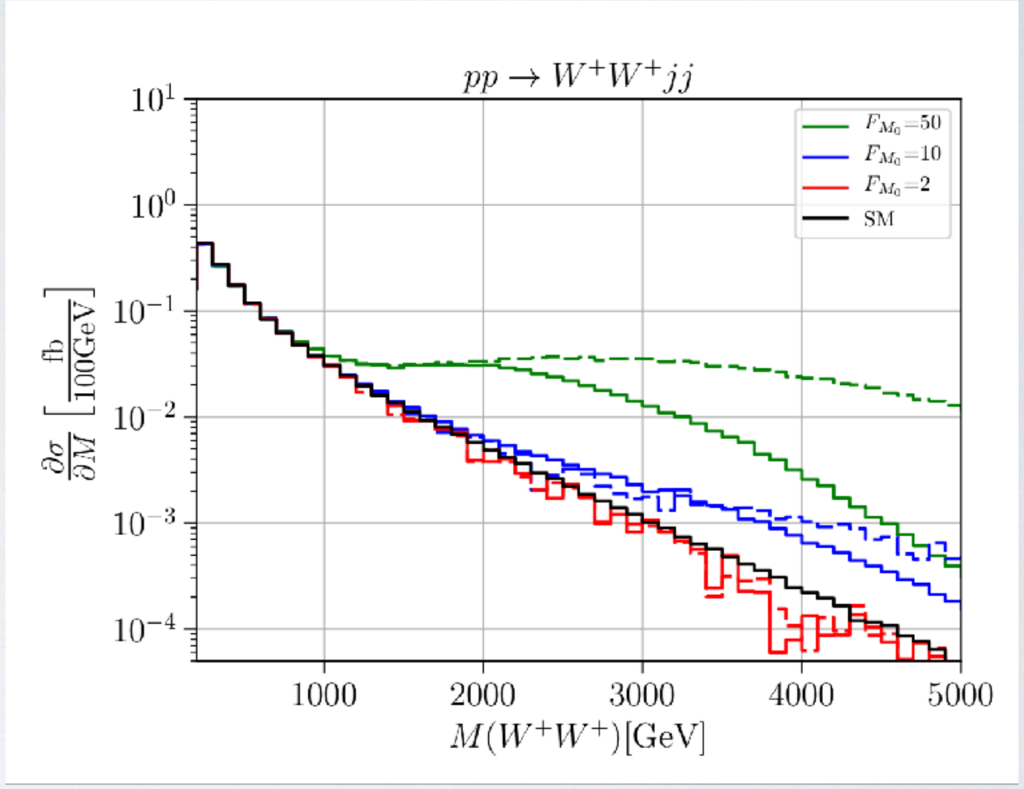

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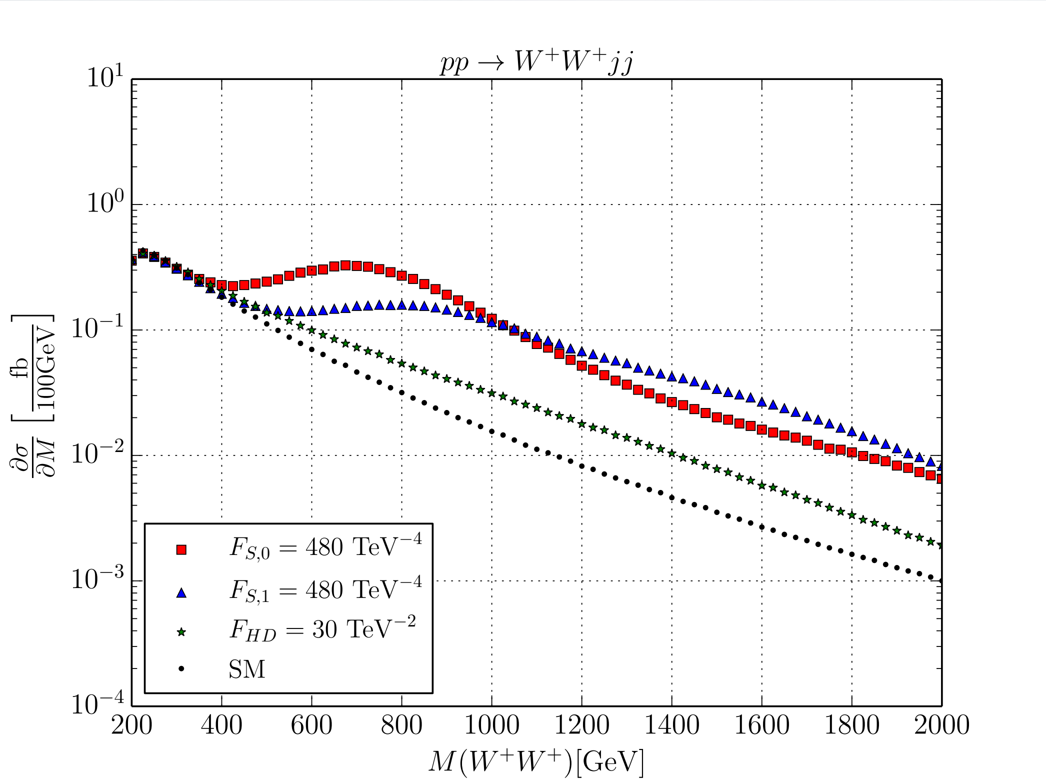

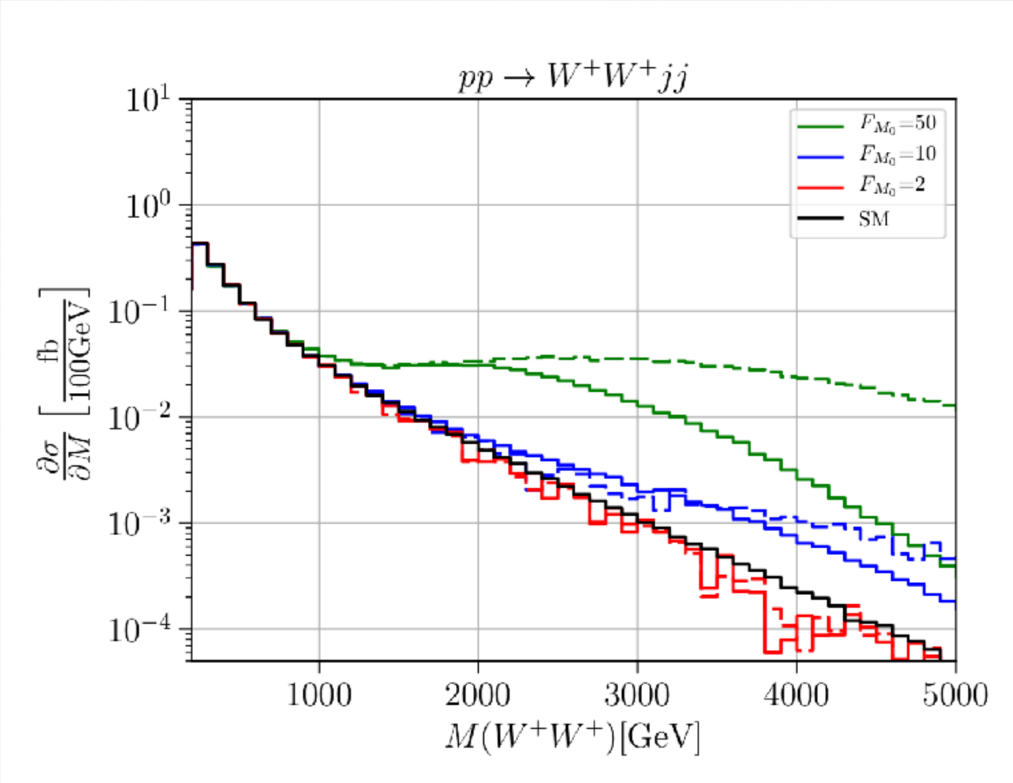

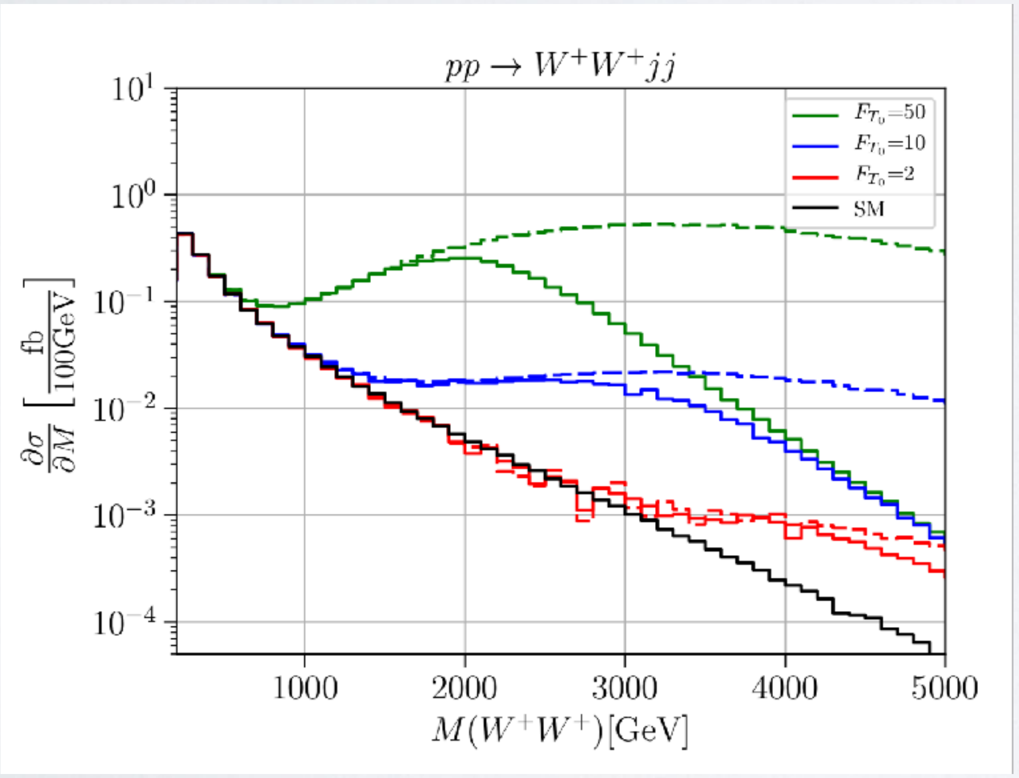

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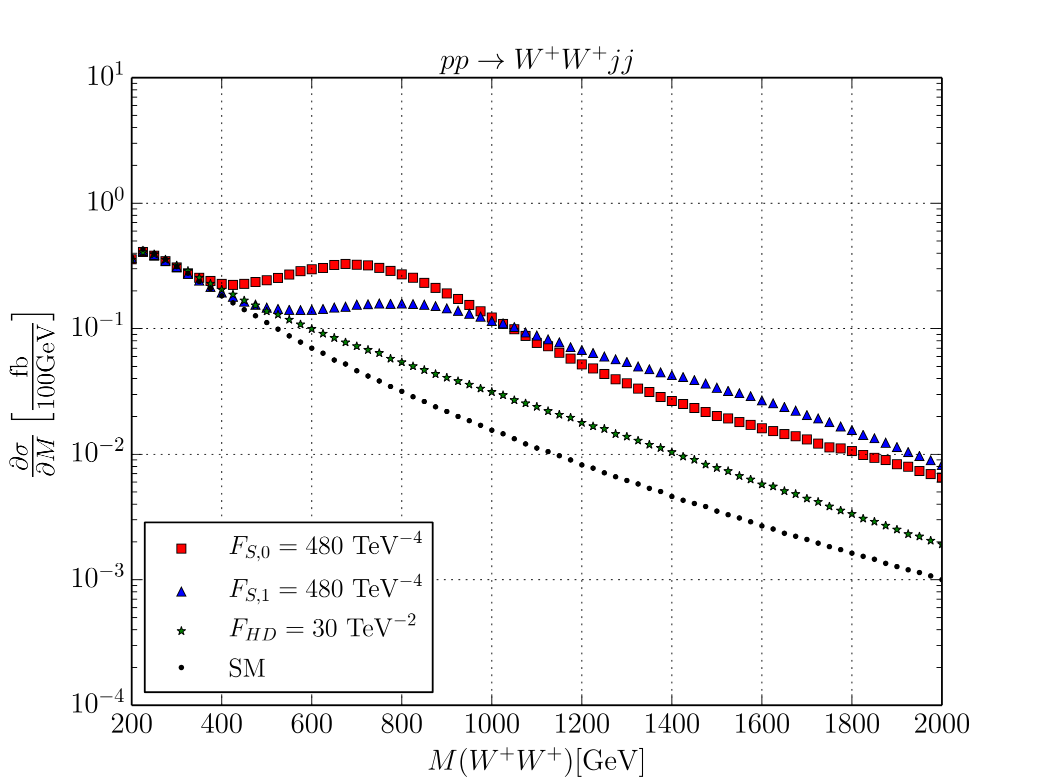

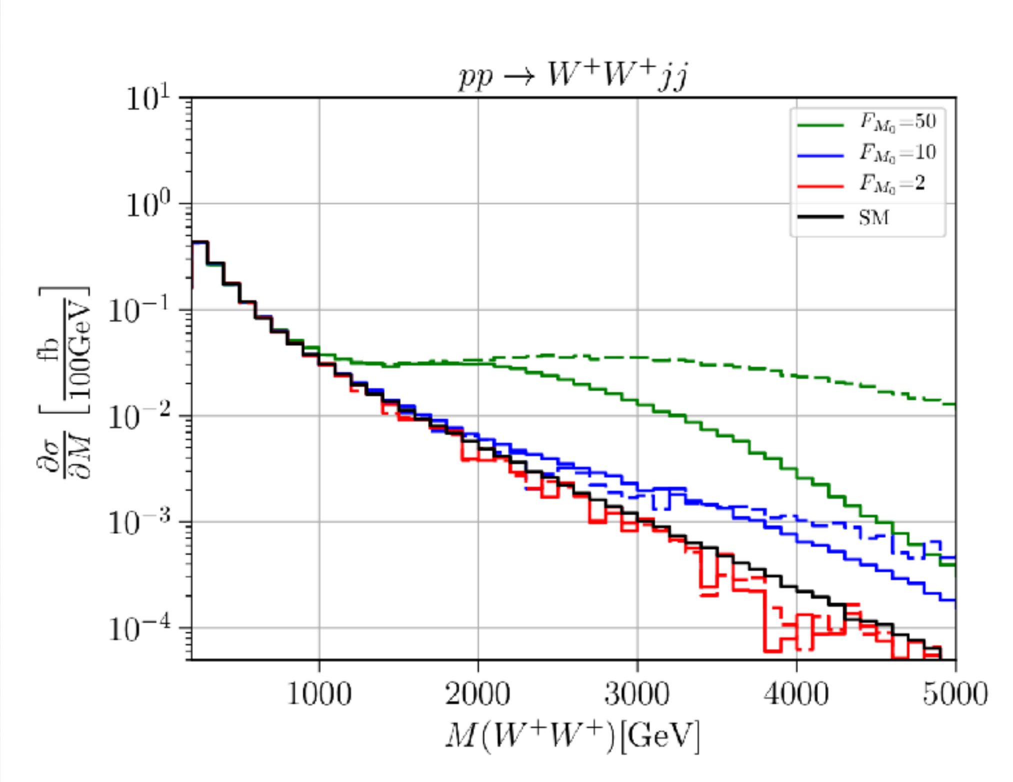

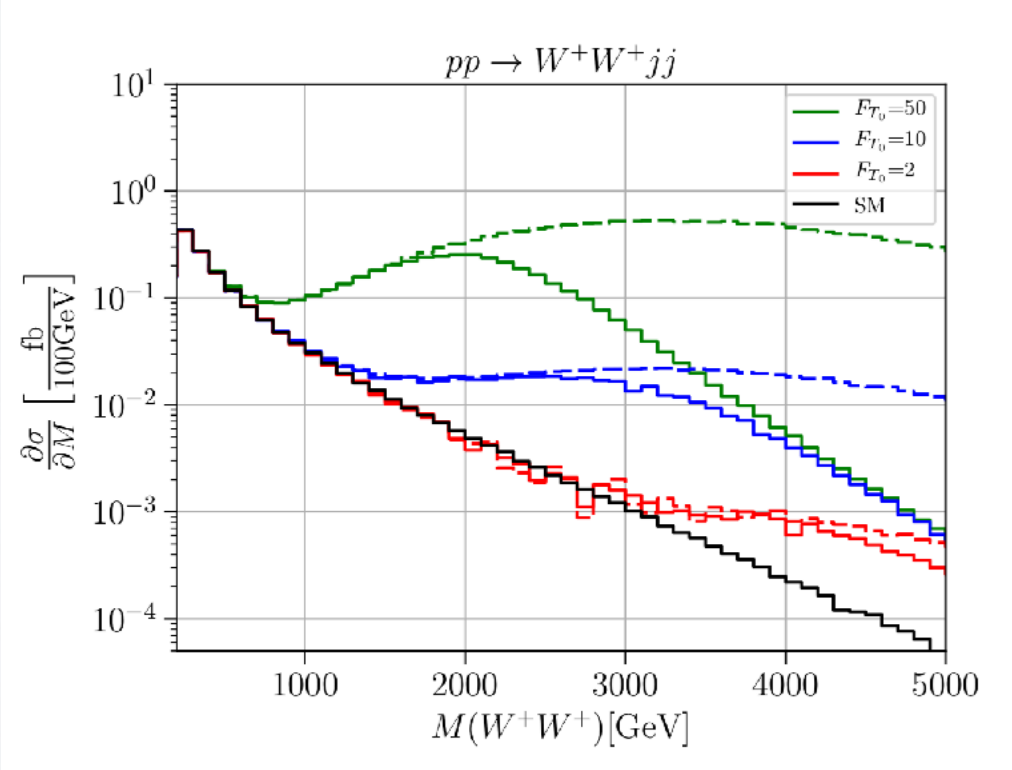

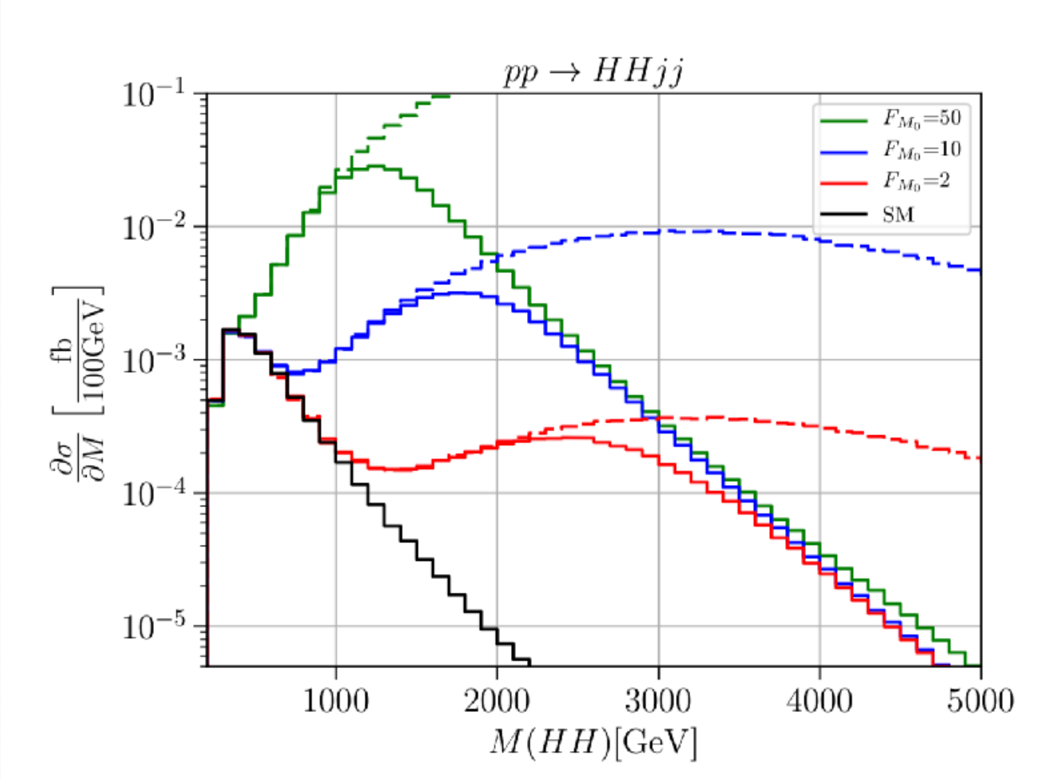

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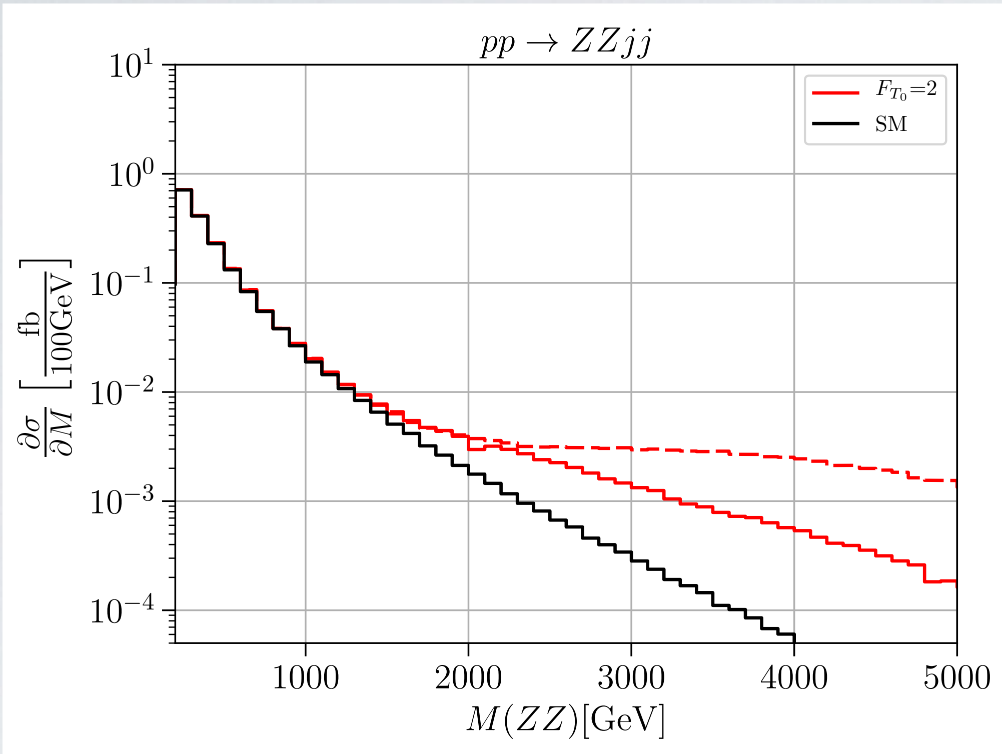

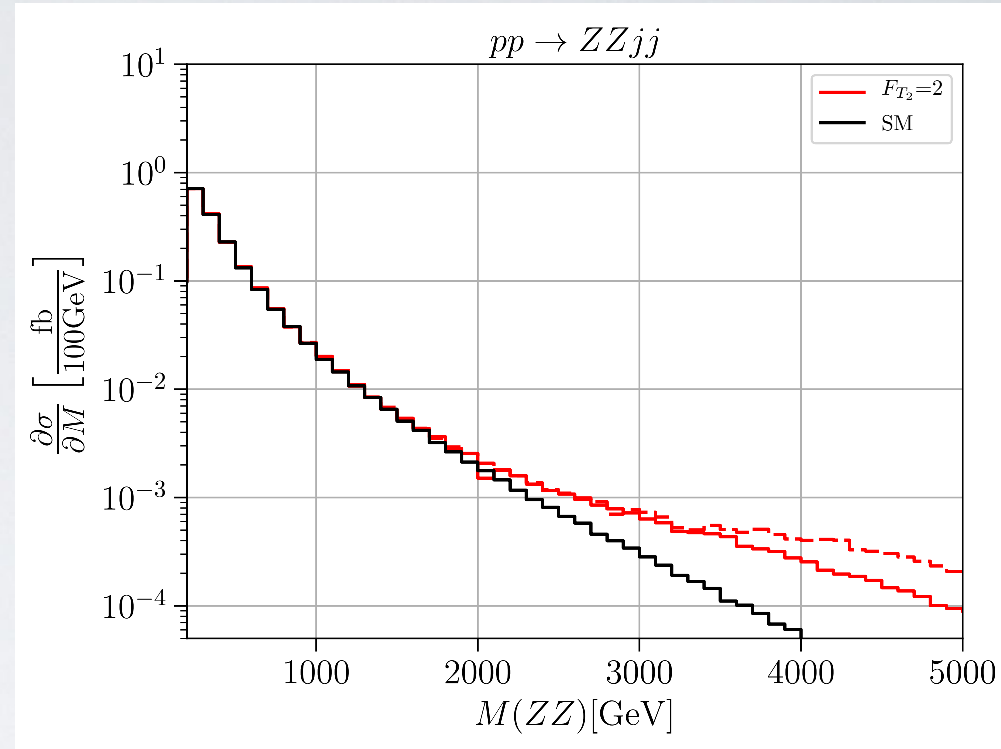

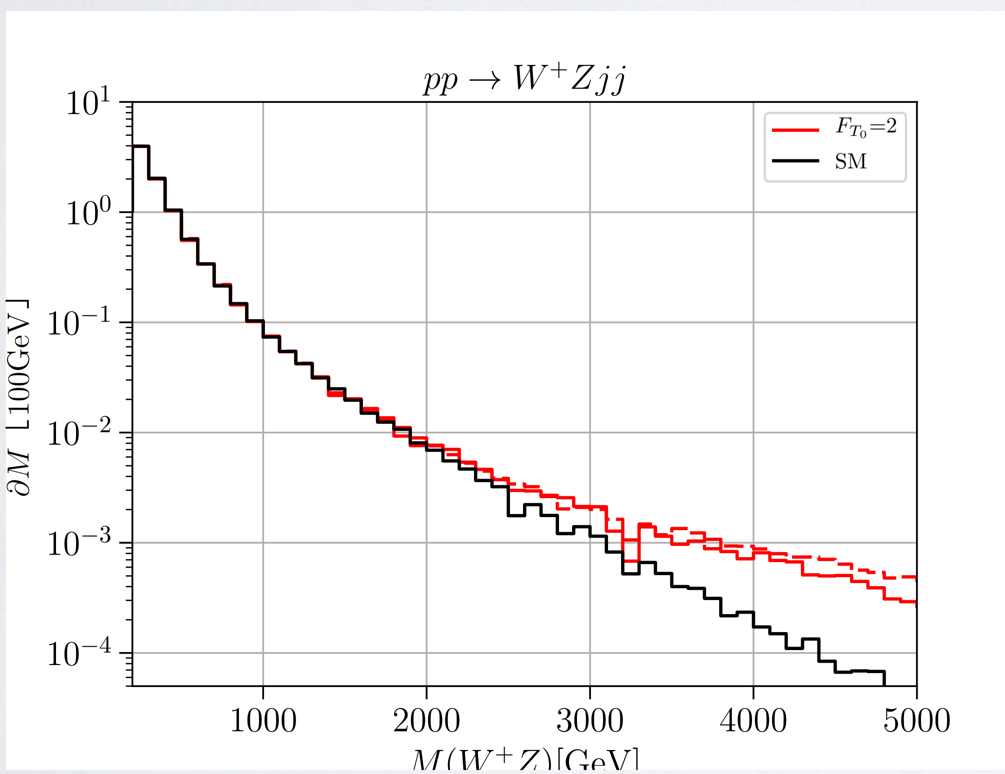

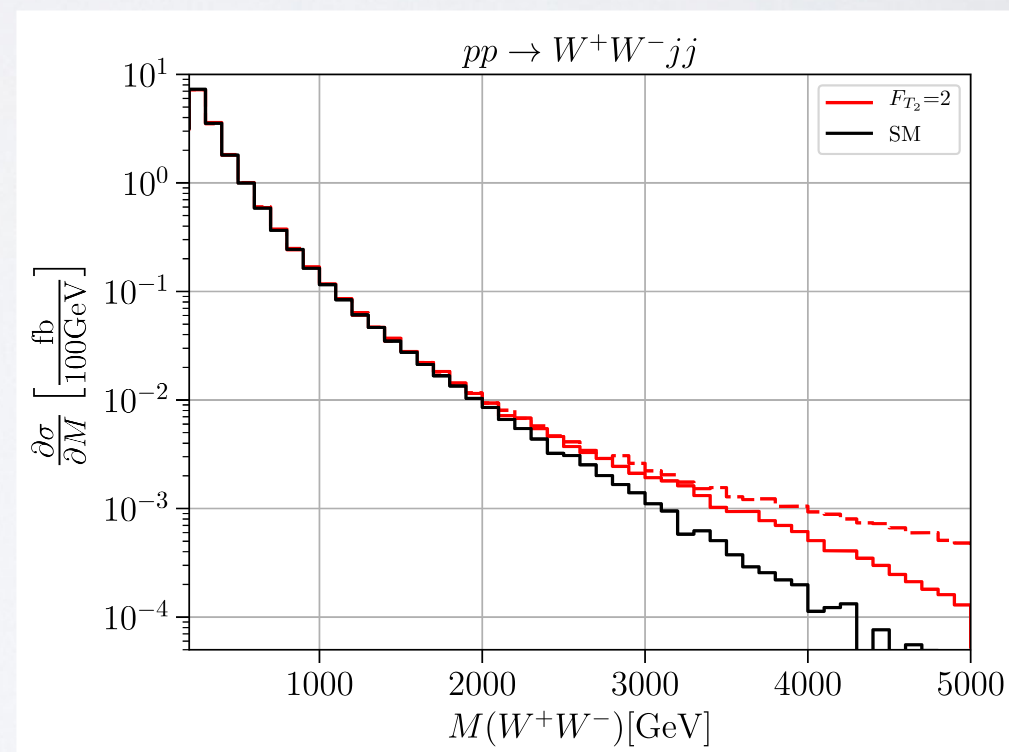

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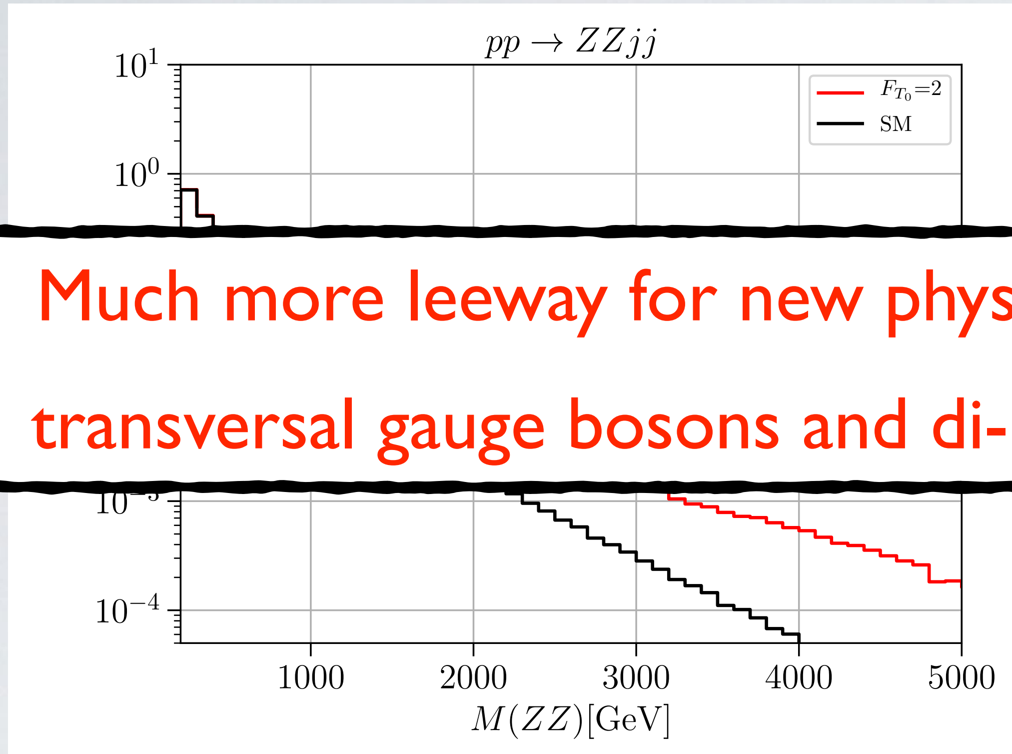
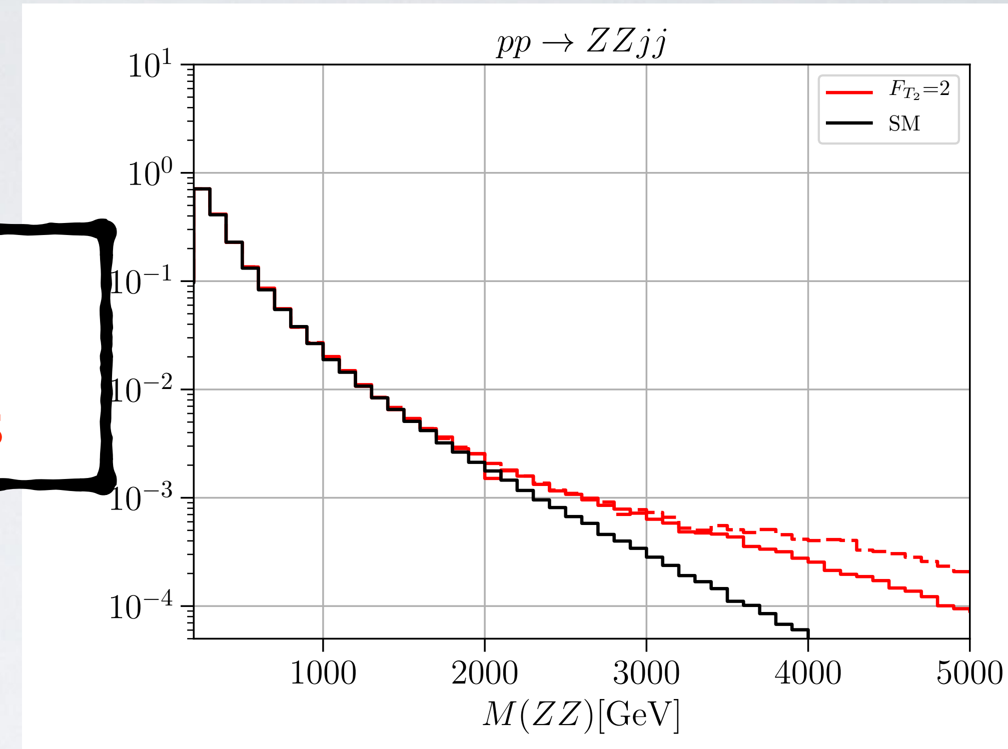
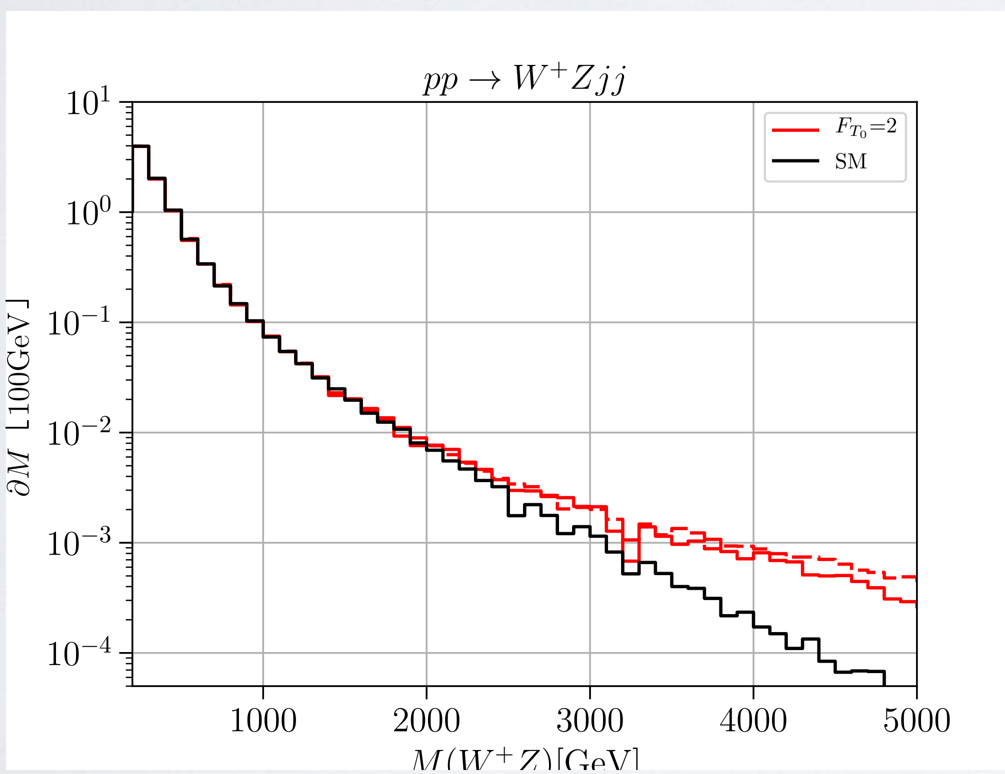
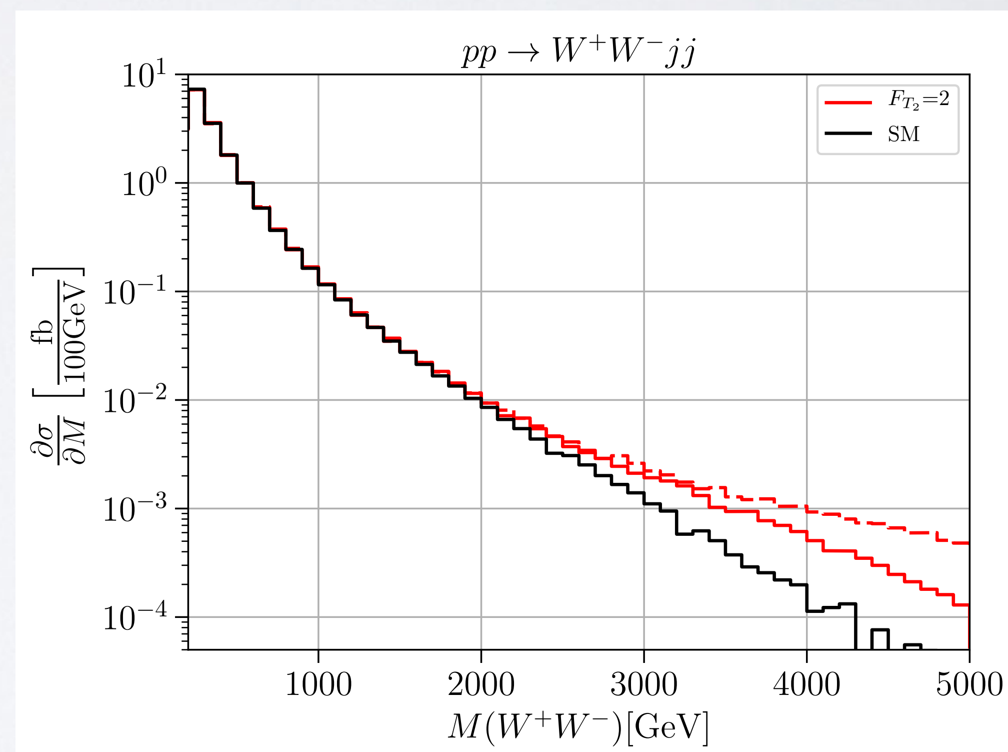




Much more leeway for new physics in transversal gauge bosons and di-Higgs





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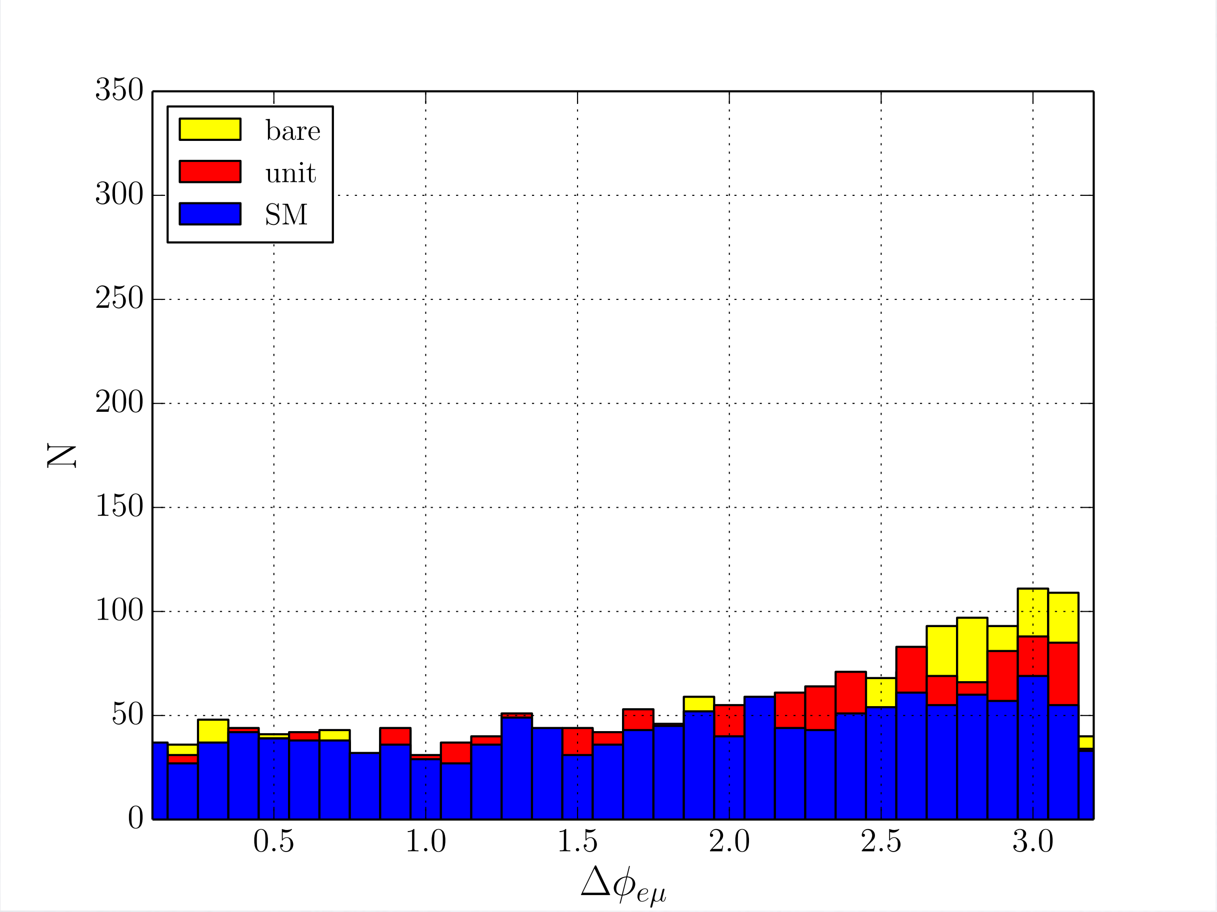

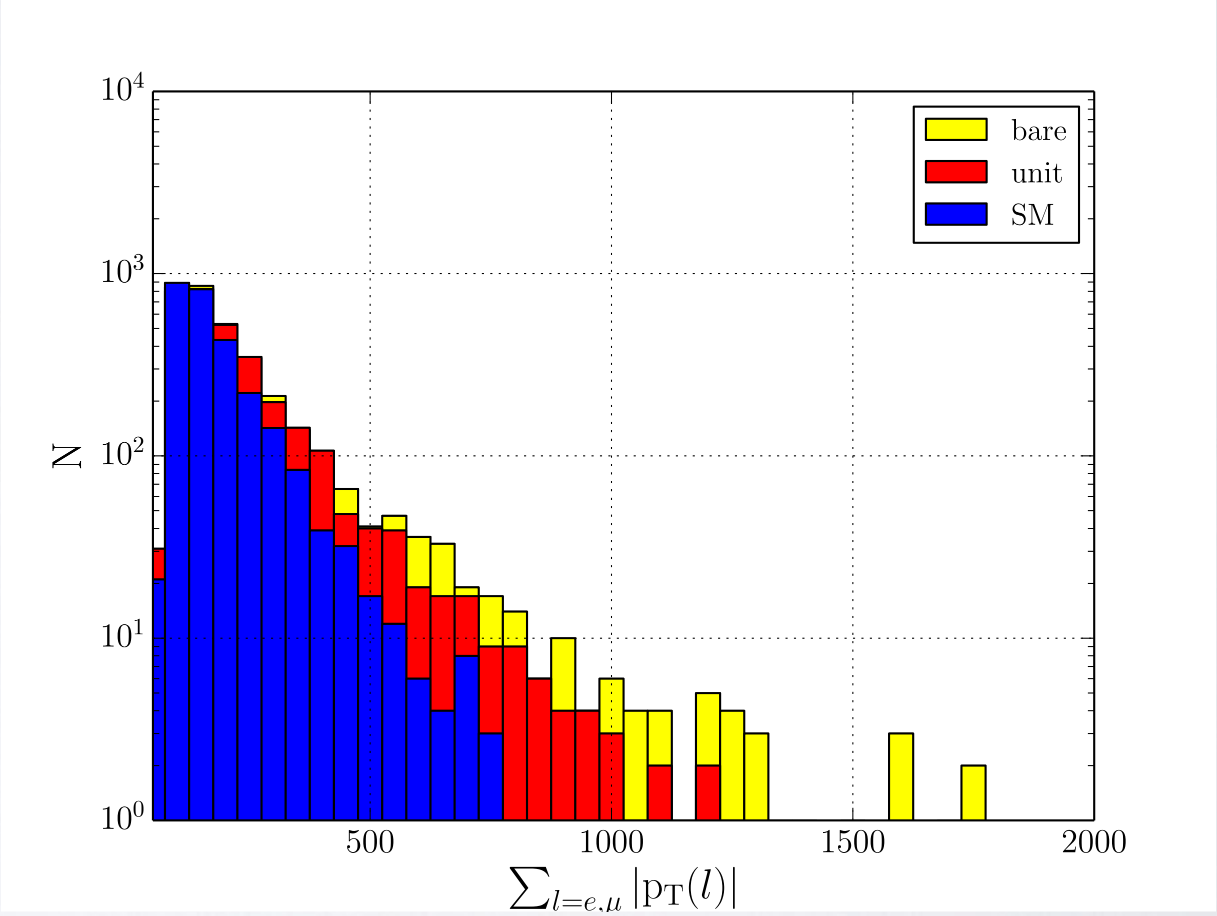

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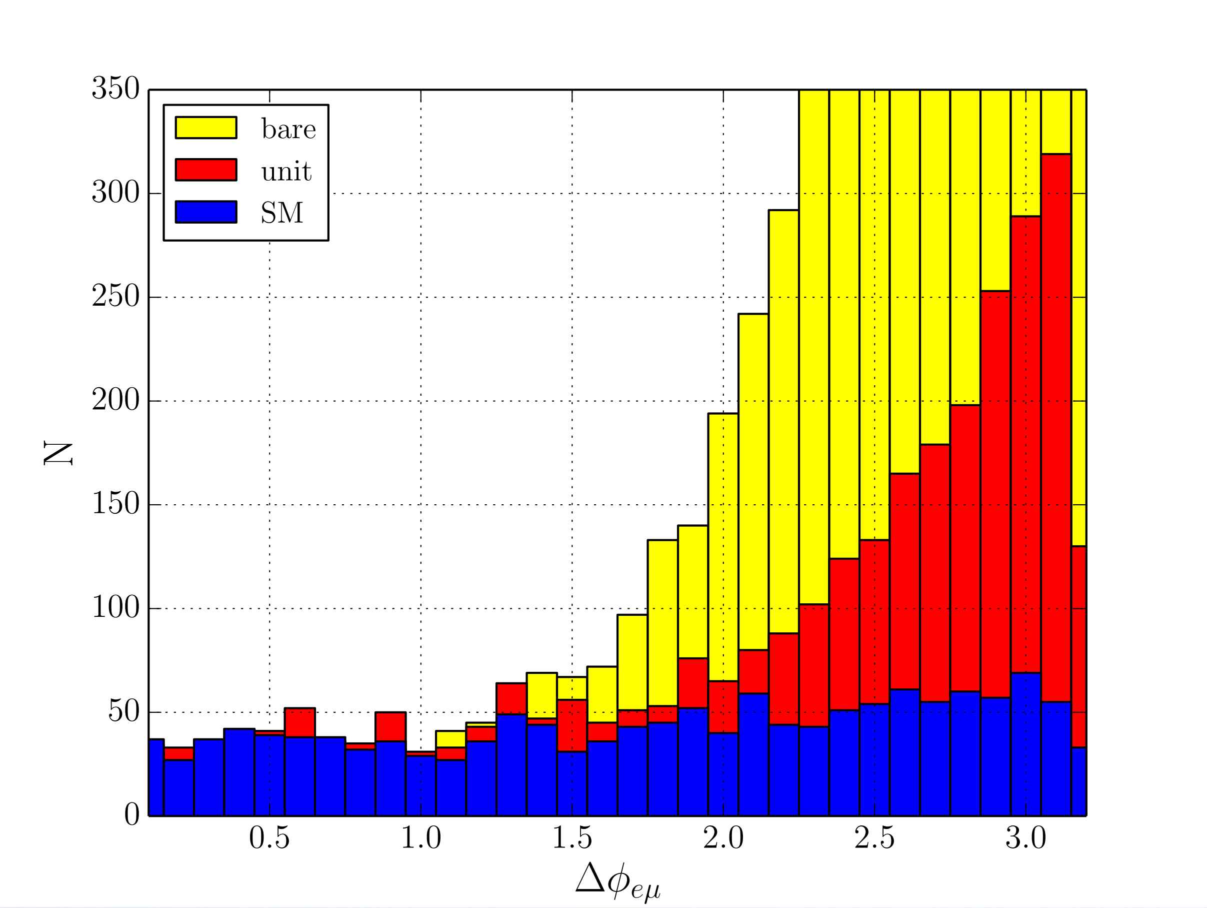

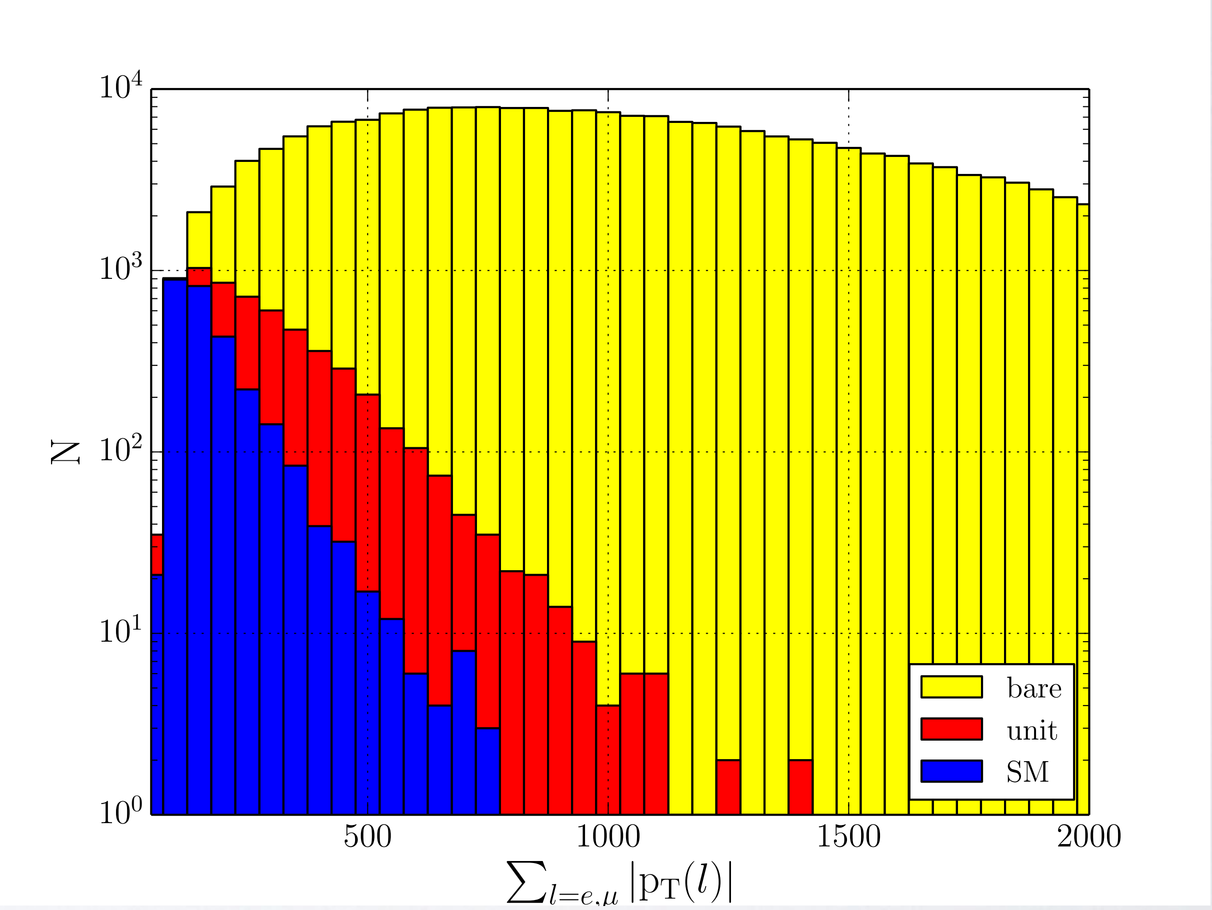

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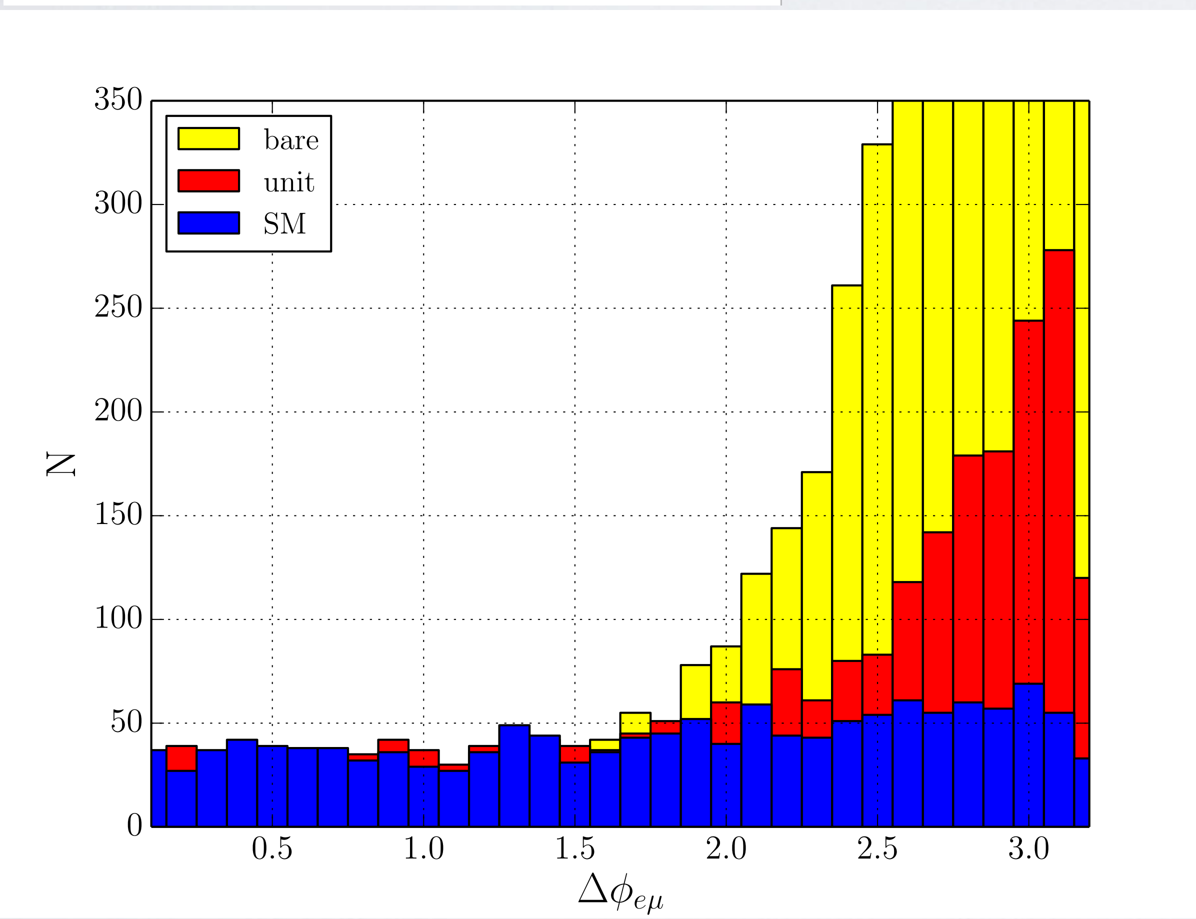

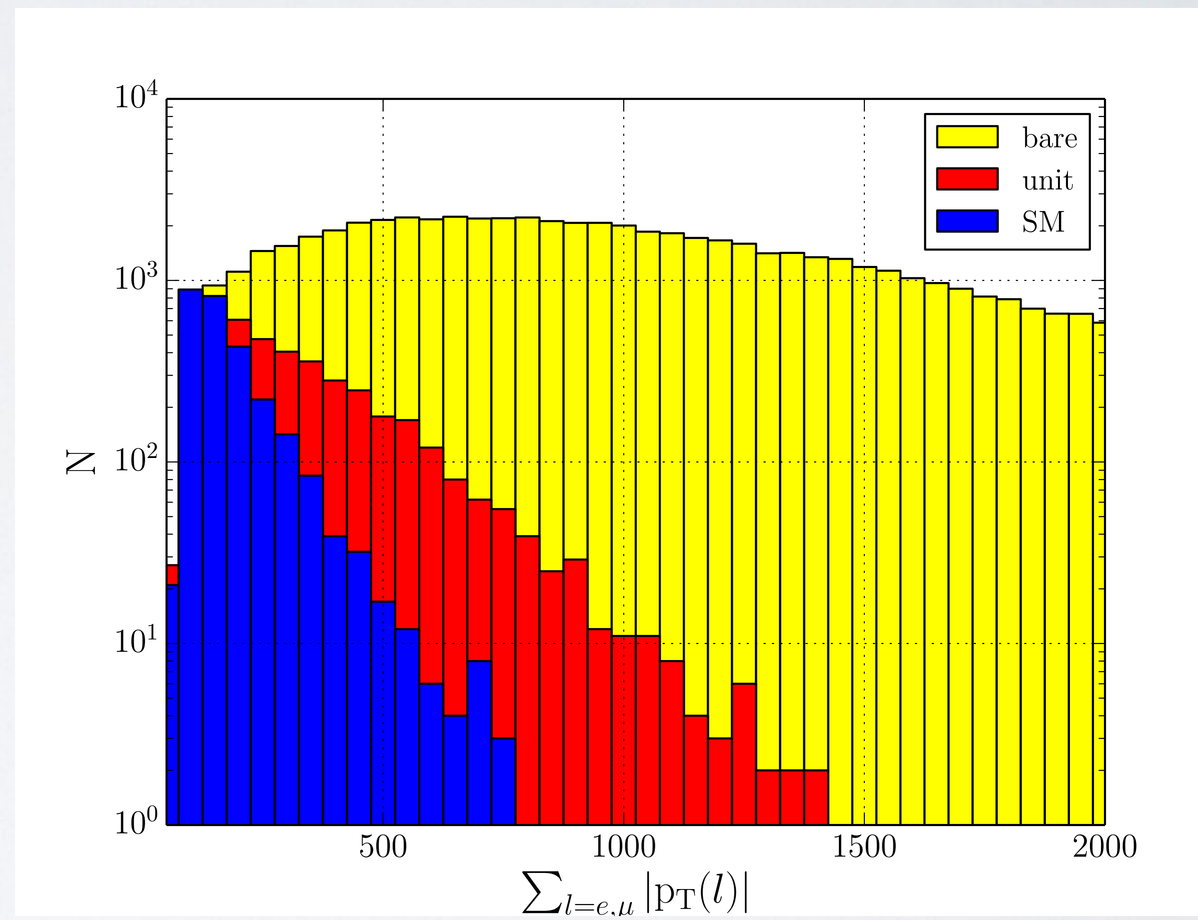

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- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
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Spins 0, 2 considered

Spin 1 different physics (mixing w. *W*/*Z*) [Delgado et al, 2018]

Kilian/Ohl/JRR/Sekulla, 1511.00022

	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	$\begin{pmatrix} X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++} \\ X_v^-, X_v^0, X_v^+ \\ X_s^0 \end{pmatrix}$
$\cdots$	$\cdots$	$32\pi\Gamma/M^5$ $\cdots$

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Translation into Wilson coefficients below resonance

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Translation into Wilson coefficients below resonance

Tensor resonances

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

How to deal with *off-shell* tensor in realistic processes?

Tensor resonances: Fierz-Pauli vs. Stückelberg

- Start with Fierz-Pauli Lagrangian for symmetric tensor

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

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$$- \partial^\alpha f_{\alpha\mu}\partial_\beta f^{\beta\mu} - f^\alpha_\alpha \partial^\mu\partial^\nu f_{\mu\nu} + f_{\mu\nu}J_f^{\mu\nu}$$

- Fierz-Pauli conditions not valid off-shell
- Fierz-Pauli propagator has bad high-energy behavior
- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
- Crucial for MCs

Tensor resonances: Fierz-Pauli vs. Stückelberg

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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: $\sigma = -\phi$

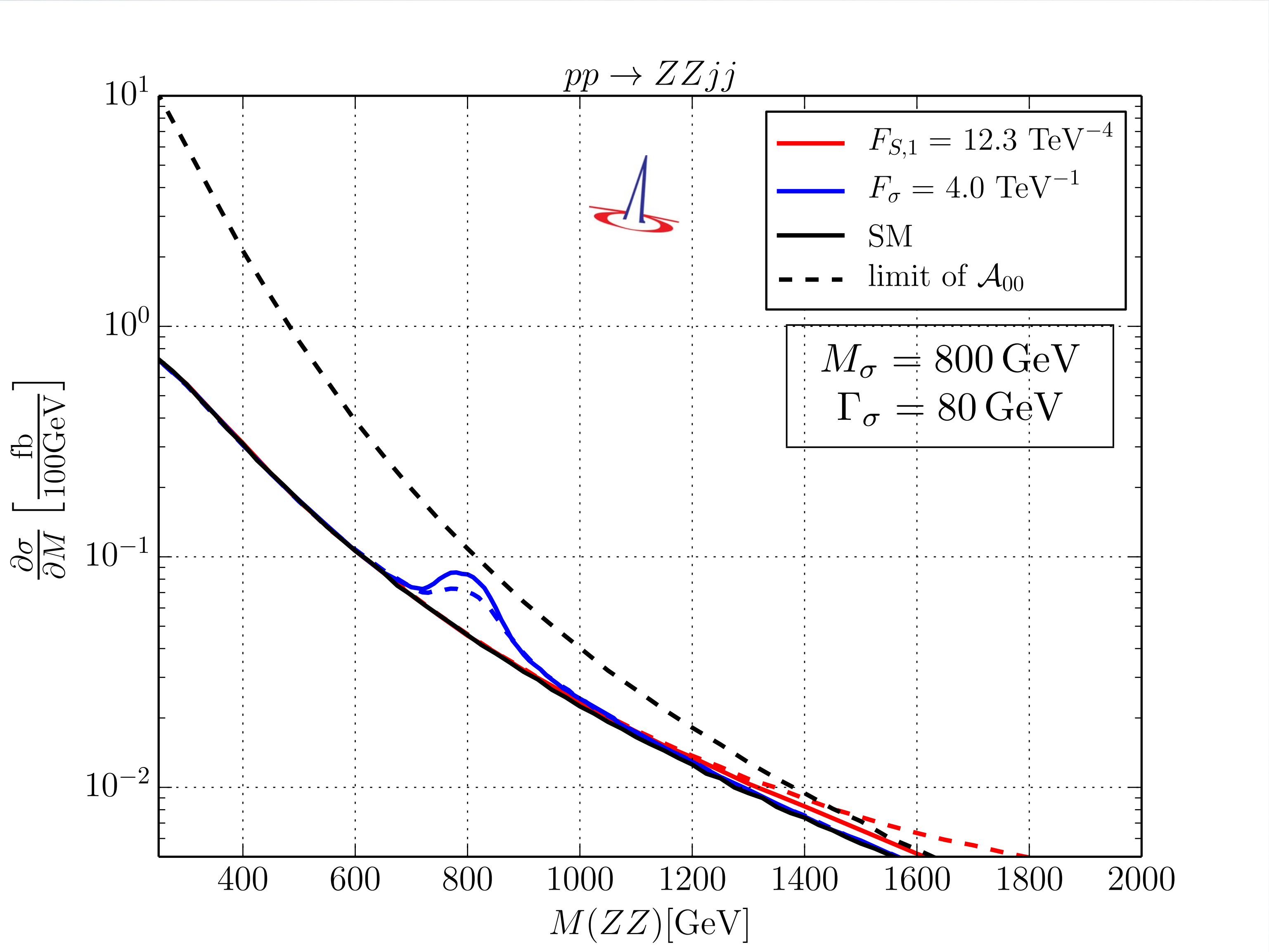
$$\mathcal{L} = \frac{1}{2}f_{f\,\mu\nu}\left(-\partial^2 - m_f^2\right)f_f^{\mu\nu} + \frac{1}{2}f^\mu_{f\ \mu}\left(-\frac{1}{2}\left(-\partial^2 - m_f^2\right)\right)f^\nu_{f\ \nu}$$
$$+ \frac{1}{2}A_{f\mu}\left(\partial^2 + m_f^2\right)A_f^\mu + \frac{1}{2}\sigma_f\left(-\partial^2 - m_f^2\right)\sigma_f$$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

Comparison: Simplified Models & EFT

Kilian/Ohl/JRR/Sekulla: 1511.00022 [longitudinal coupl.]

Brass/Fleper/Kilian/JRR/Sekulla: 1807.02512 [transversal coupl.]

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



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

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

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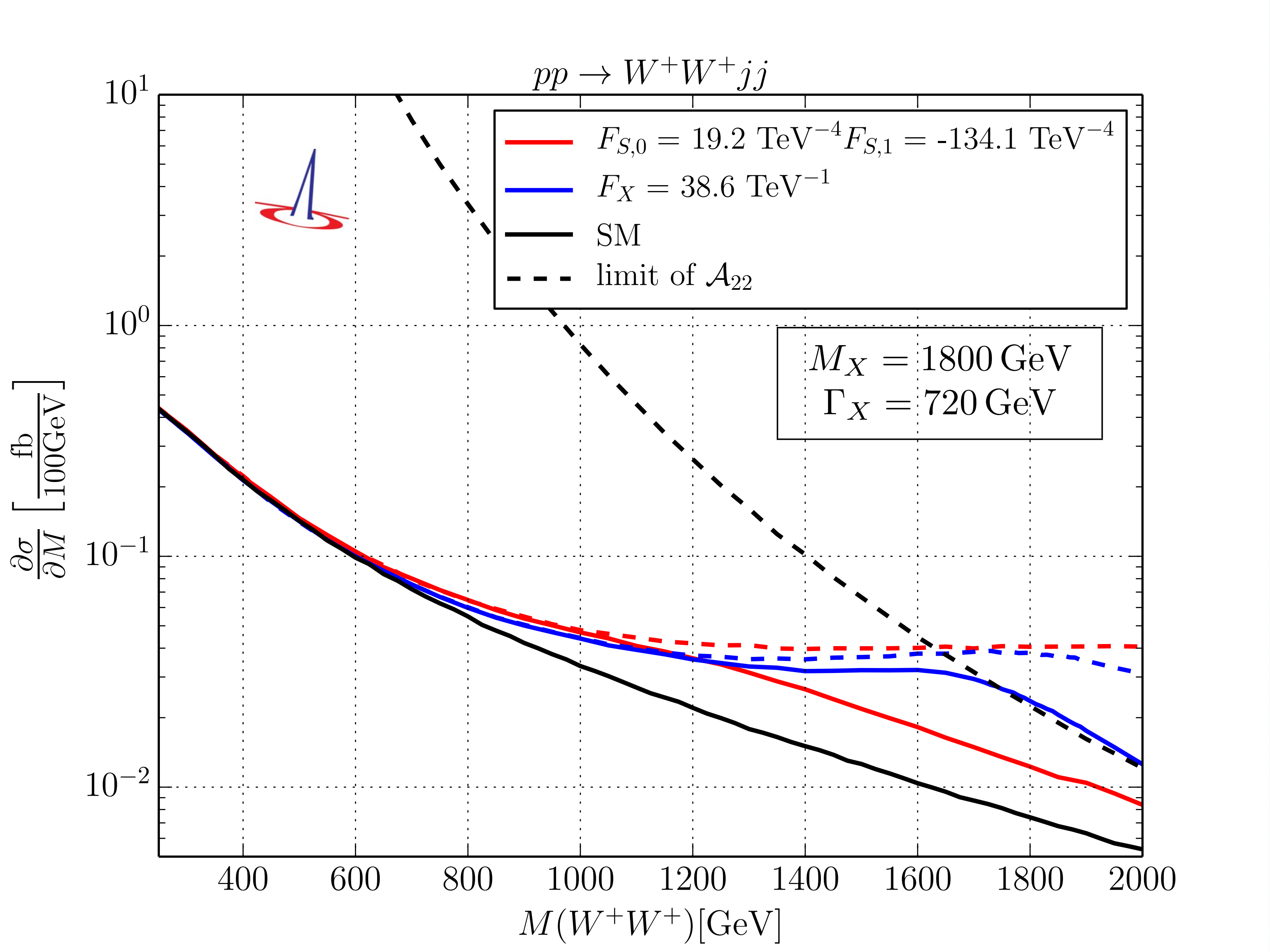

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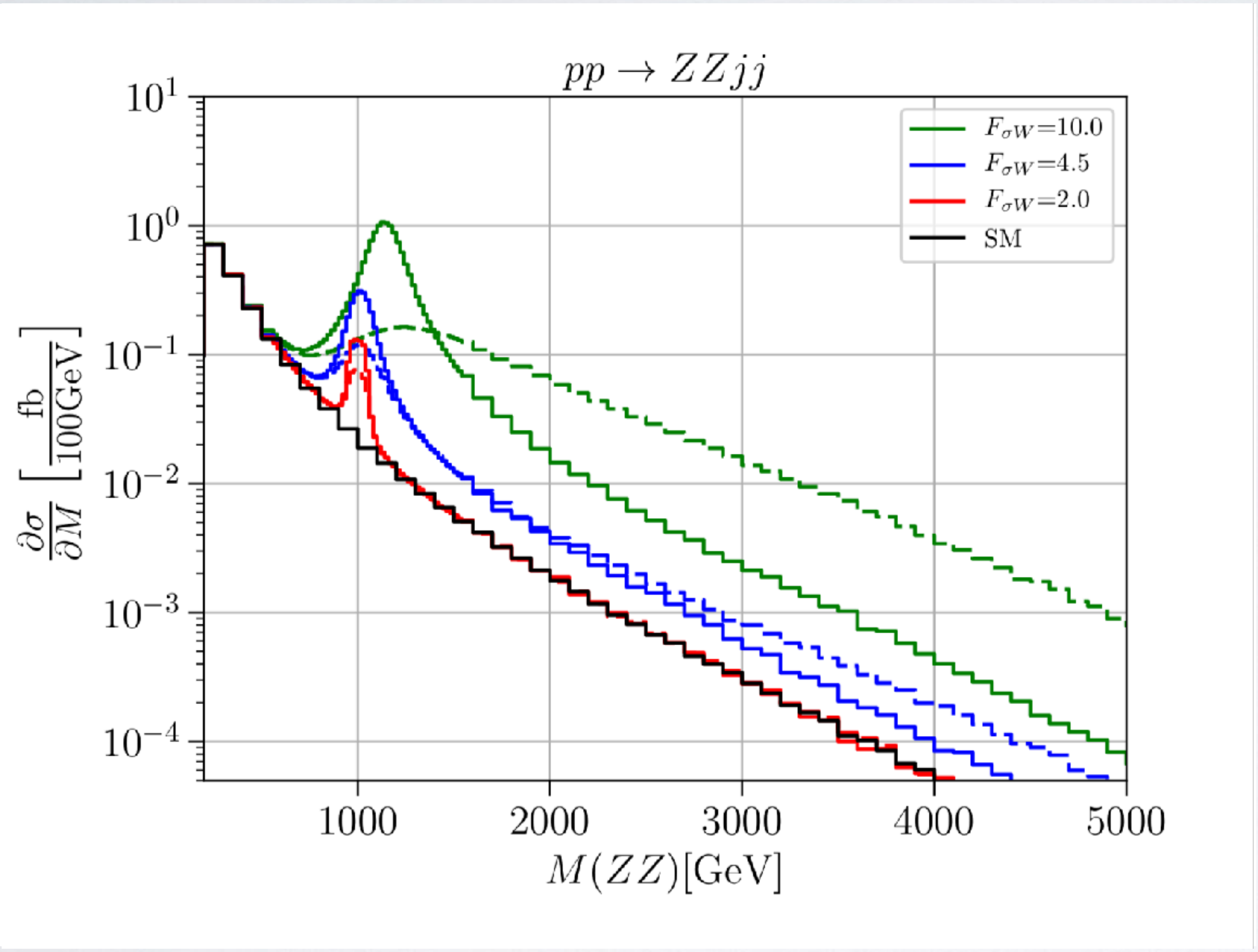

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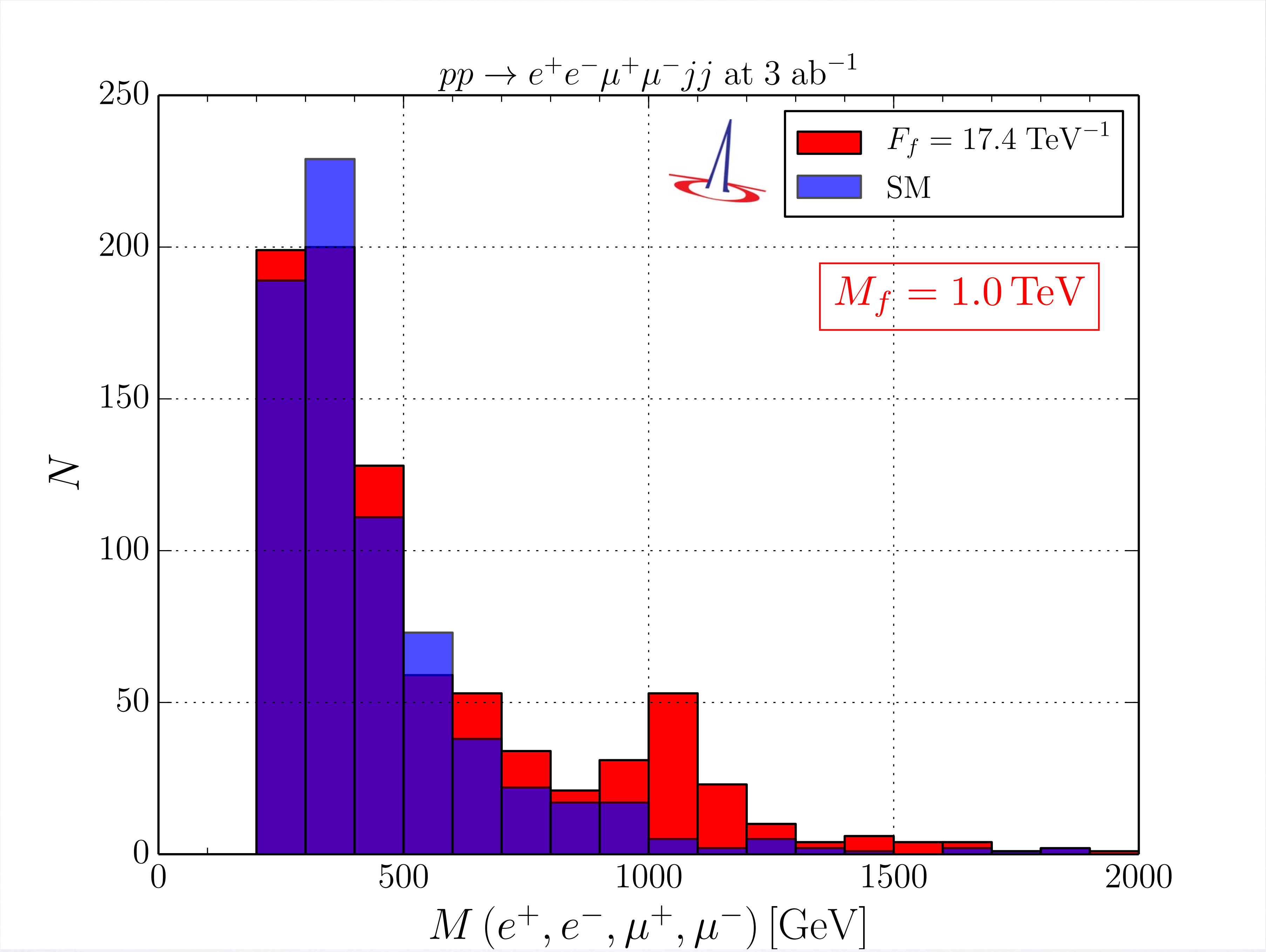
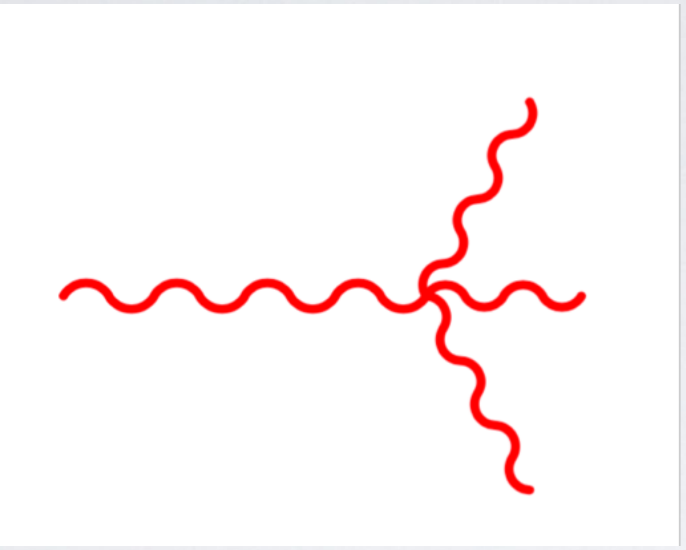
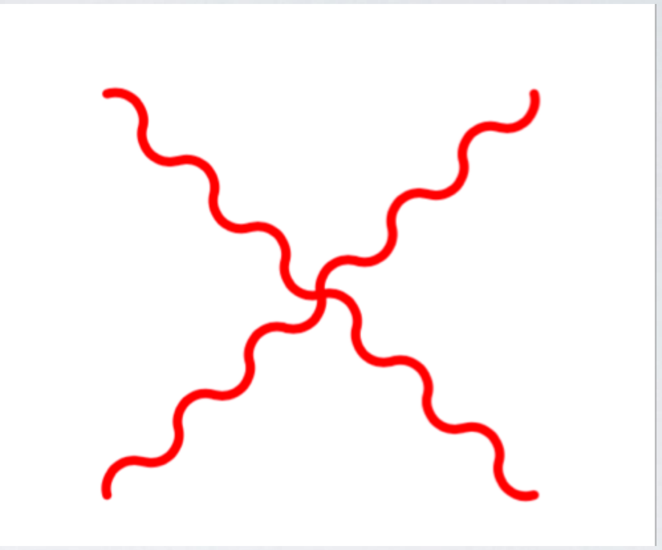
Complete LHC process at 14 TeV



Triple [multiple] Vector Boson Production ?

Relate  to  ?

- 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) [Kilian/Kreher/JRR, *w.i.p.*]
- Different Wilson coefficients dominate (particularly for resonances)
- Important physics (partially) independent from VBS ("different fiducial vol.")

WHIZARD: Overview

WHIZARD v2.6.4 (23.08.2018) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR*

Simon Braß/Vincent Rothe/Christian Schwinn/So Young Shim/Pascal Stienemeier/Zhijie Zhao + *2 Master*

- Programming Languanges: `Fortran2008 (gfortran ≥4.8.4), OCaml (≥3.12.0)`
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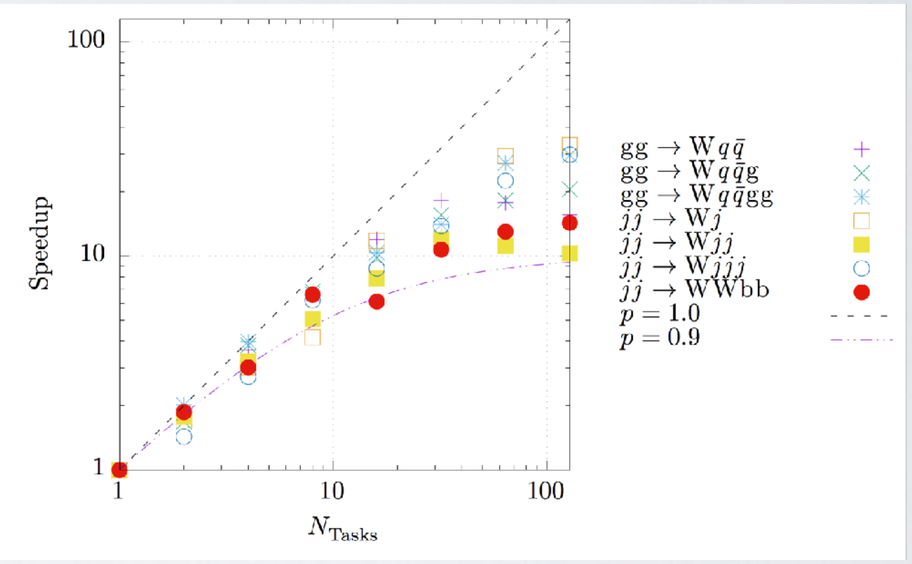

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- QCD NLO automation close to completeion
- New: parallelized (MPI) phase space integration
- Full spin density matrix of hard process available
- `SINDARIN` scripting language for input
- SMEFT (Dim.-6 bosonic), Dim.-8 and Unitarization, Simplified Models in official version since v2.6.2

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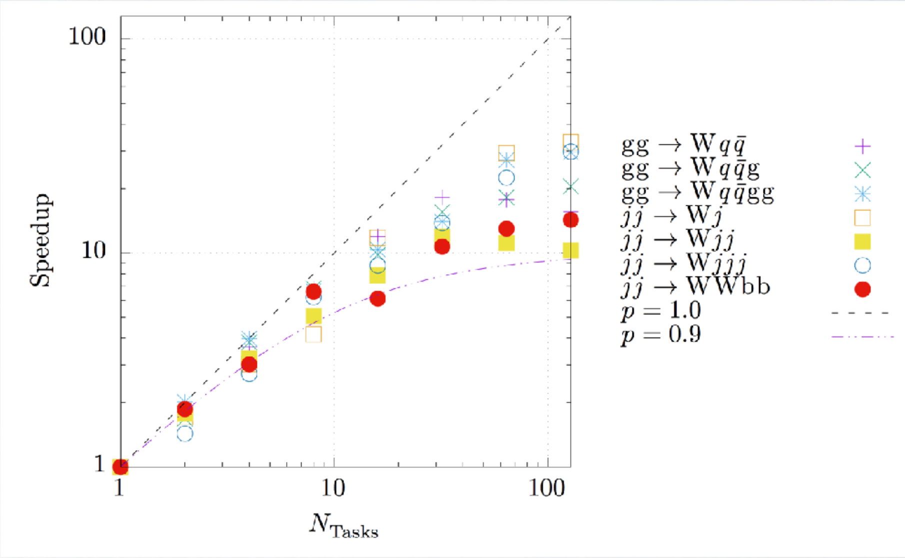

Polarized event simulation

```
?polarized_events = true
polarized “W+” “W-“
```

Extensively used for ILC/CLIC

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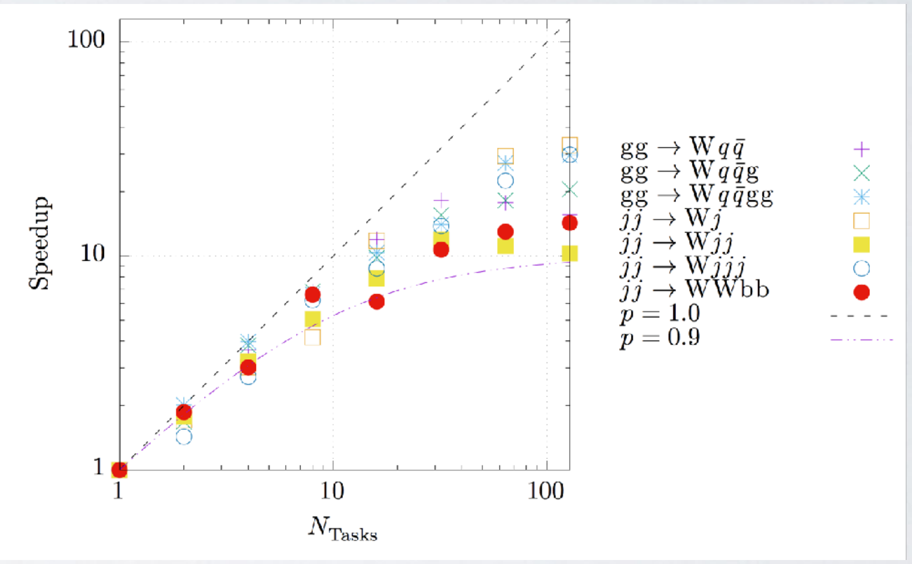

Polarized event simulation

```
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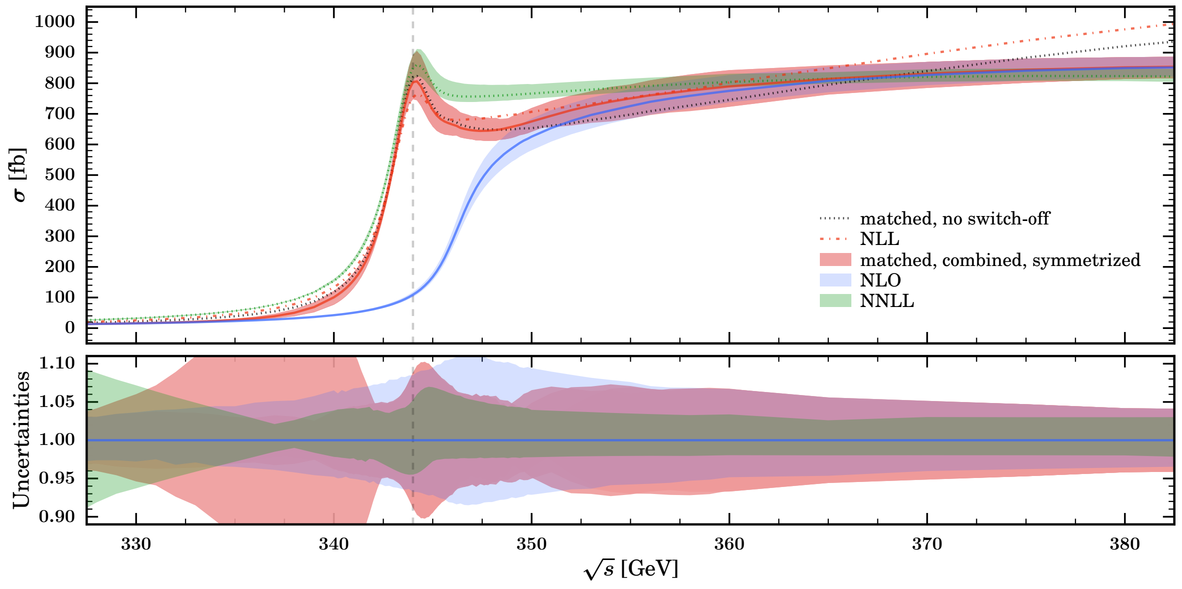
Extensively used for ILC/CLIC

On-shell projection with full spin correlations:

Thresholds: *t*, *W* (*wip*)



Beam structure: beam polarization

Beam polarization

```
beams_pol_density = @([<spin entries>]), @([<spin entries>])
beams_pol_fraction = <degree beam 1>, <degree beam 2>
```

Spin j	Particle type	possible m values
0	Scalar boson	0
1/2	Spinor	+1, -1
1	(Massive) Vector boson	+1, (0), -1
3/2	(Massive) Vectorspinor	+2, (+1), (-1), -2
2	(Massive) Tensor	+2, (+1), (0), (-1), -2

Different density matrices

$|m| = 2$ massless

$|m| = 2j+1$ massive

```
beams_pol_density = @()
```

Unpolarized beams $\rho = \frac{1}{|m|}\mathbb{I}$

```
beams_pol_density = @(±j)
beams_pol_fraction = f
```

Circular polarization $\rho = \mathrm{diag}\left(\frac{1\pm f}{2}, 0, \ldots, 0, \frac{1\mp f}{2}\right)$

```
beams_pol_density = @(0)
beams_pol_fraction = f
```

Longitudinal polarization (massive) $\rho = \mathrm{diag}\left(\frac{1-f}{|m|}, \ldots, \frac{1-f}{|m|}, \frac{1+f\,(|m|-1)}{|m|}, \frac{1-f}{|m|}, \ldots, \frac{1-f}{|m|}\right)$

```
beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
beams_pol_fraction = f
```

Transversal polarization (along an axis)

$$\rho = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \frac{f}{2}\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ \frac{f}{2}\,e^{i\phi} & \cdots & \cdots & 0 & 1 \end{pmatrix}$$

```
beams_pol_density = @(j:j:1-cos(theta),
          j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))
beams_pol_fraction = f
```

Polarization along arbitrary axis (θ,Φ)

$$\rho = \frac{1}{2}\cdot\begin{pmatrix} 1-f\cos\theta & 0 & \cdots & \cdots & f\sin\theta\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ f\sin\theta\,e^{i\phi} & \cdots & \cdots & 0 & 1+f\cos\theta \end{pmatrix}$$

```
beams_pol_density = @(j:j:hj, j-1:j-1:hj-1, …, -j:-j:h-j)
```

```
beams_pol_density = @({m:m':xm,m'})
```

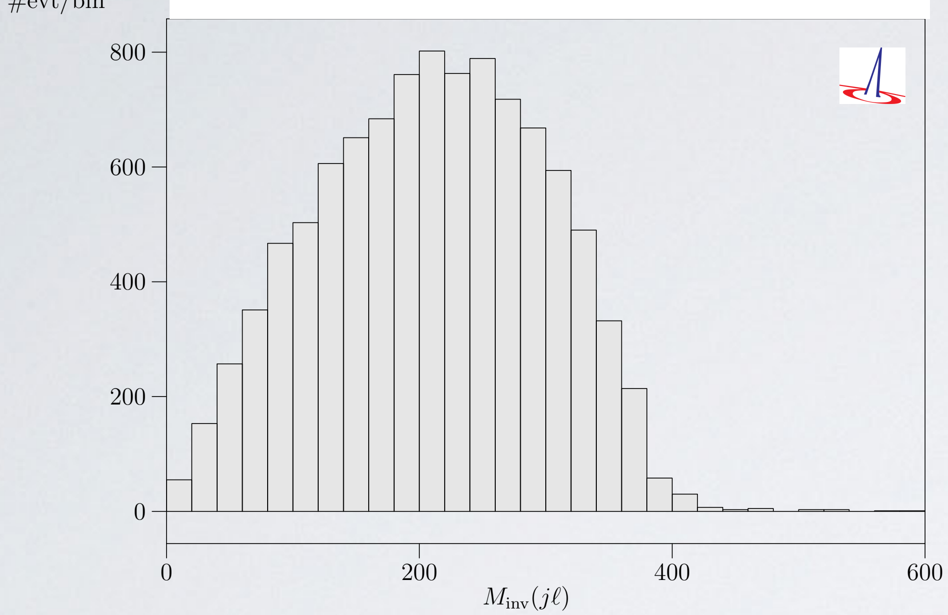
Diagonal / arbitrary density matrices

Spin Correlation and Polarization in Cascades

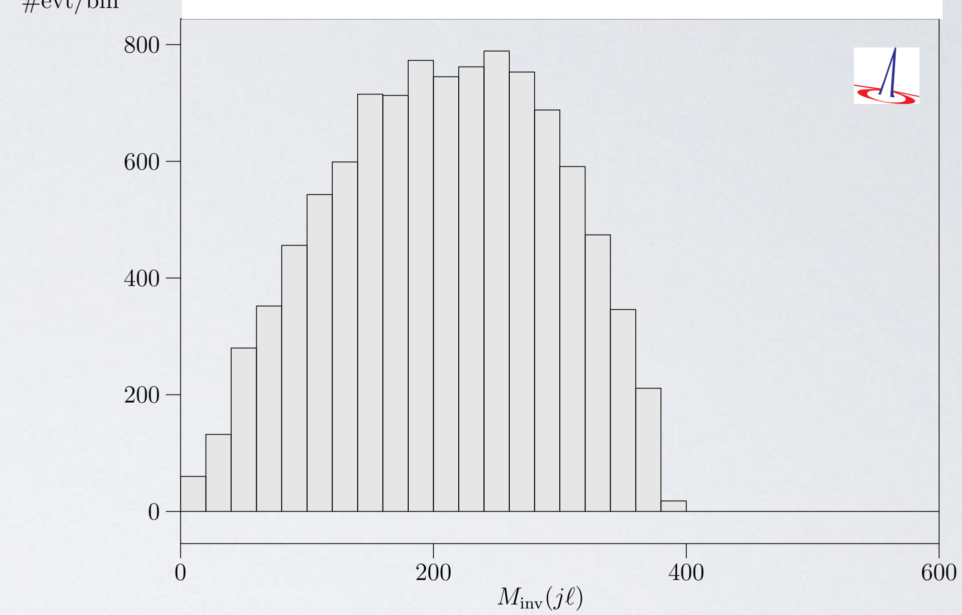
Cascade decay, factorize production and decay

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

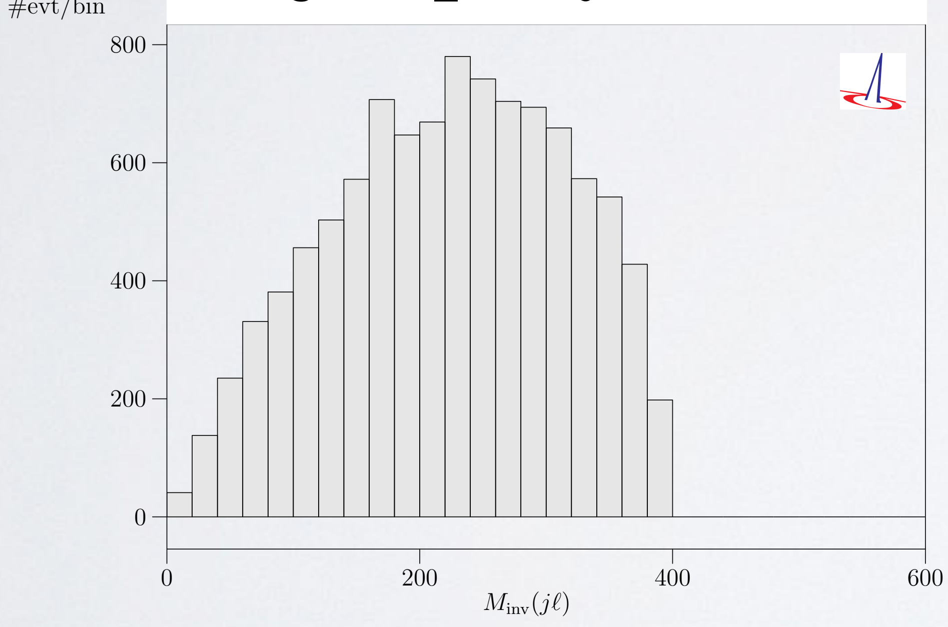
`simulate (fullproc)`



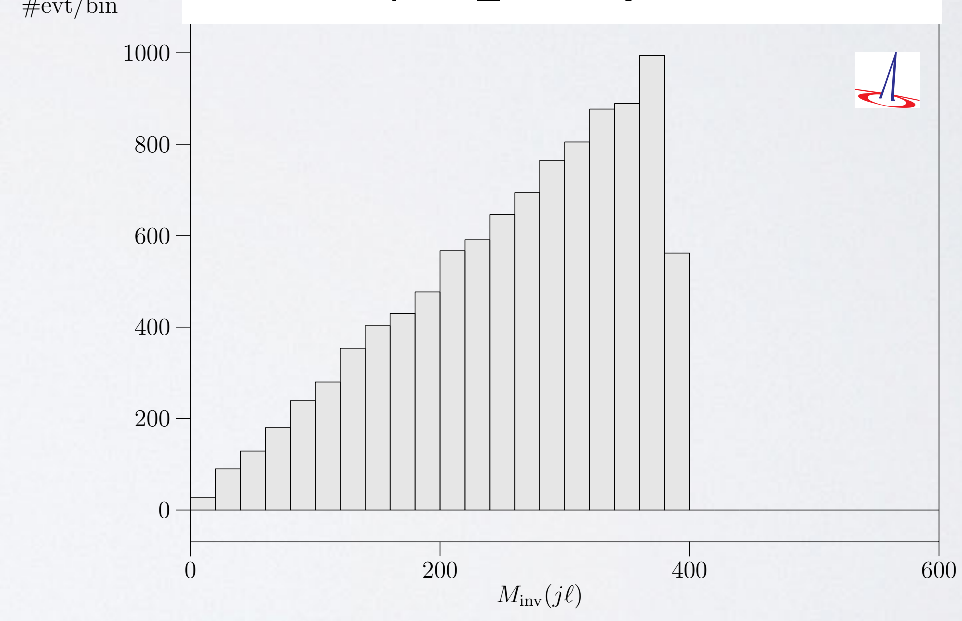
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



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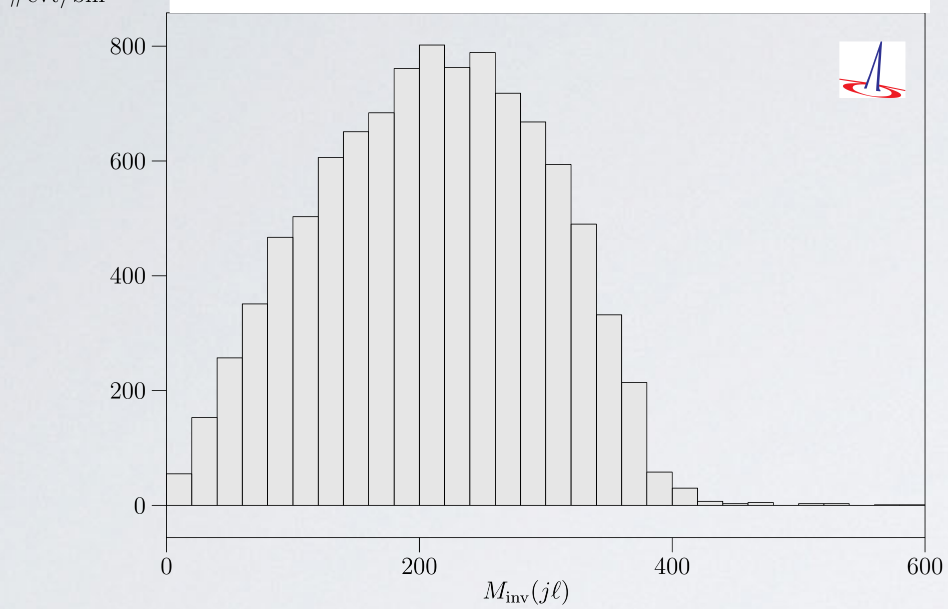

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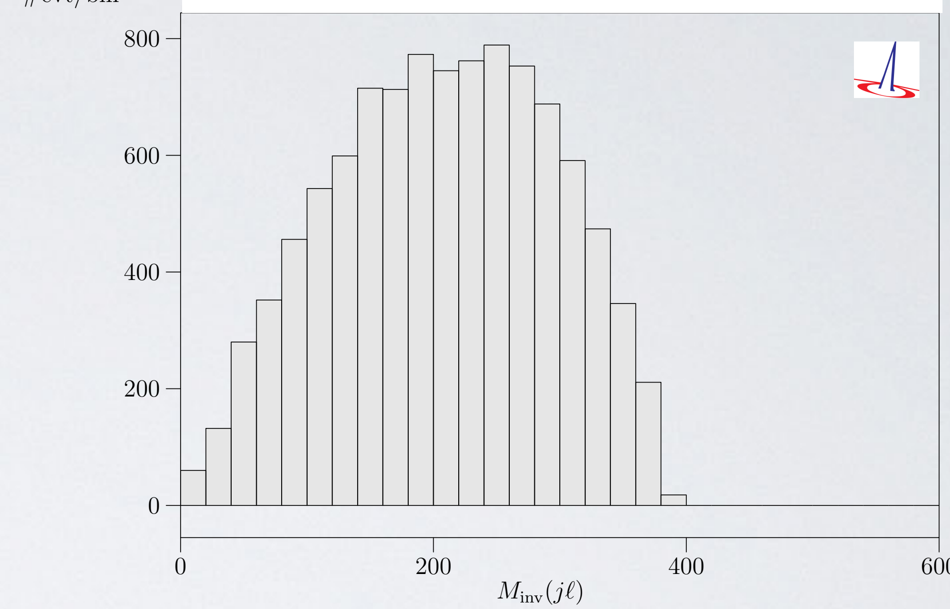

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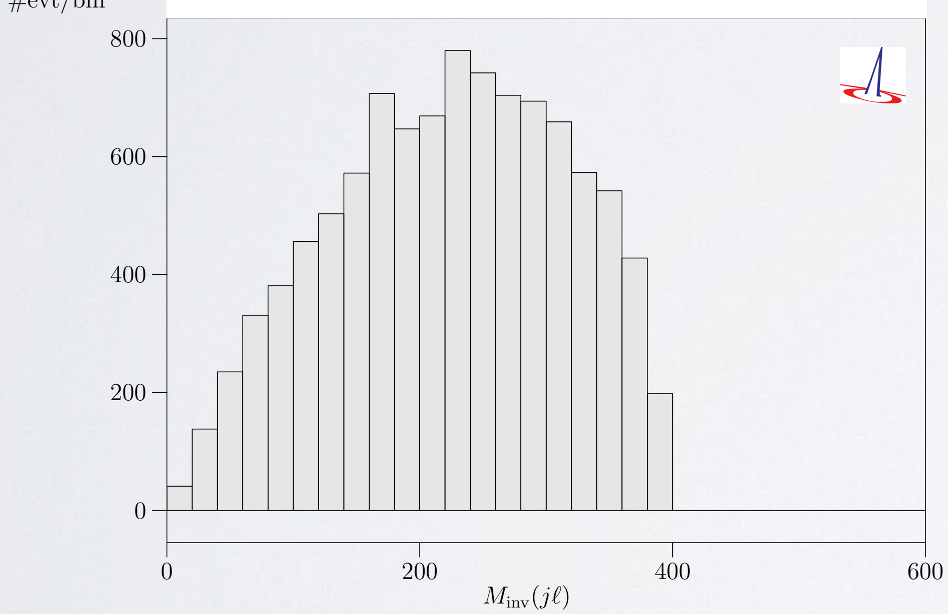

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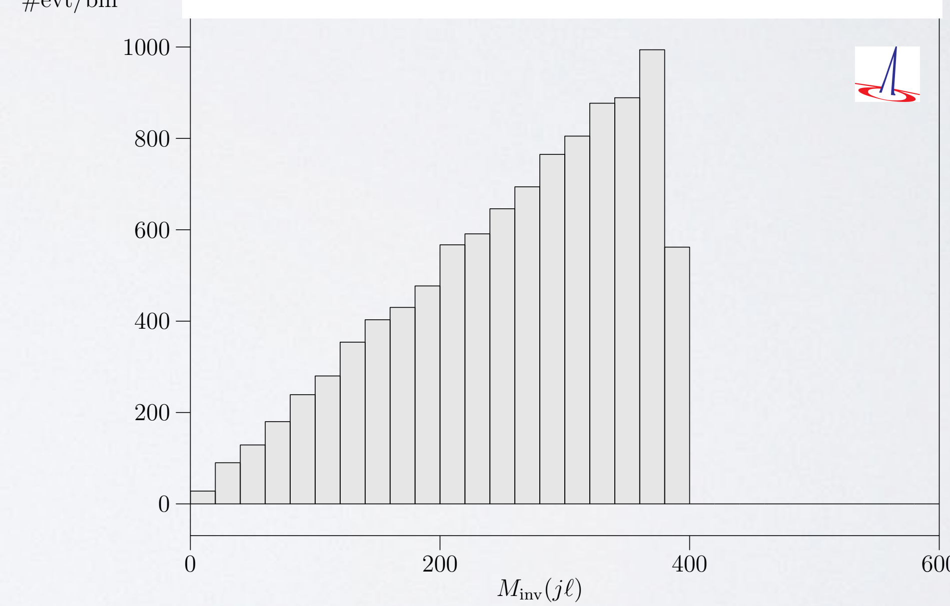

Possibility to select specific helicity in decays:

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unstable “W+” { decay_helicity = 0 }
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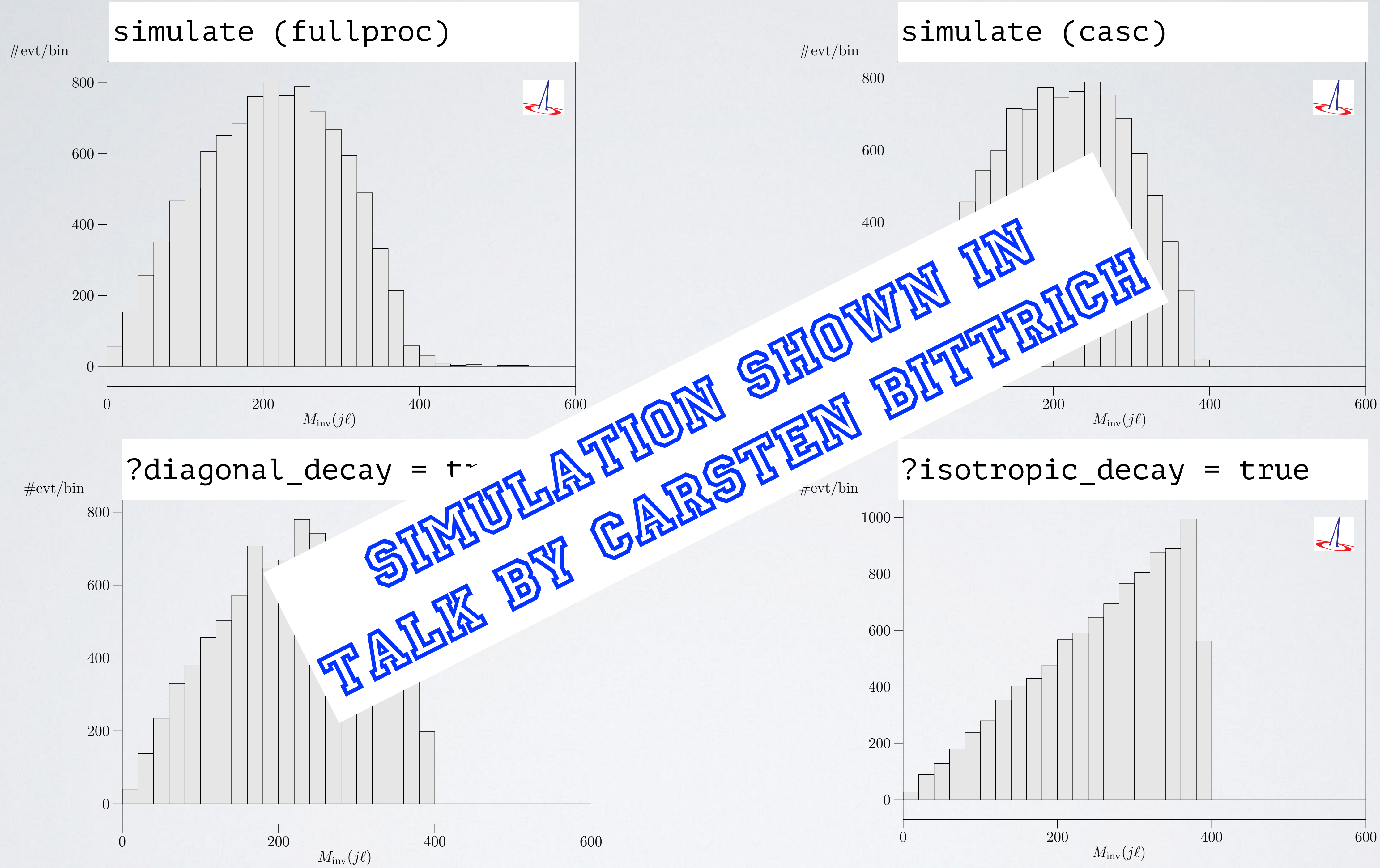

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Conclusions / Summary

- Vector boson scattering one of the flagship measurements of Runs II/III
- EFT provides well-defined (and very limited) framework for SM deviations
- Longitudinal vs. mixed vs. transversal operators

trans/versal
CONSULTING

- There is not really a true model-independent parameterization!
- Unitarization for theoretically sane description
- *T*-matrix unitarization: no new parameters, yields maximal (bin-wise) event counts
- Much more room for new physics in transversal modes than longitudinal ones
- Simplified models: generic electroweak resonances
- `WHIZARD` offers possibility to choose helicity of intermediate on-shell states

BACKUP SLIDES

Towards a Complete Dim-8 Basis?

- Hilbert series techniques use characters of group representations
- Groups are $SU(3)_C \times SU(2)_L \times U(1)_Y$ and the Lorentz [conformal] group
- Conformal group resolves redundancies from integration by parts (IBP)
- Using short multiplets of conformal group resolves redundancies from EOM
- Delivers # invariants / mass dimension and field content of invariants
- E.g. $2 \cdot D^2 \left(H^\dagger H\right)$: 2 existing operators with 2 derivatives and 4 Higgs fields
- Higher derivatives eliminated in favor of more fields: leads to Warsaw basis
- Lorentz invariants automatic extraction DEFT package: Gripaios/Sutherland, 1807.07546

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- SMEFT dim. 8: 993 operators (1 generation) — 44807 operators (3 generations)

Lehman/Martin, 1503.07537; Henning/Lu/Melia/Murayama, 1512.03433

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Effects of Dim-8 (and Dim-6) Operators

- **New vertices** (field combinations, tensor structure, 5-,6-,7-,8-point vertices
- **Field redefinitions** (shift of Higgs vev [dim. 8 + dim. 6 squared]), redefined gauge fields
  - $\Rightarrow$ at dim. 8 weak mixing angle in mass diagonalization and covariant derivative differ
- **Modified relations between couplings and experimental observables**

Towards a Complete Dim-8 Basis?

Example: Classification of Dim. 8 that affect $pp \to Wh$ — Hays/Martin/Sanz/Setford, 1808.00442

No derivatives

$\mathcal{O}_{8,1}$	$(H^\dagger H)^4$	$\mathcal{O}_{8,11}$	$\epsilon_{IJK}\,(H^\dagger\tau^I H)\left(\widetilde{B}^{\mu\nu}W^J_{\nu\rho}W^{\rho,K}_\mu + B^{\mu\nu}W^J_{\nu\rho}\widetilde{W}^{\rho,K}_\mu\right)$
$\mathcal{O}_{8,2}$	$(H^\dagger H)^2 B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{8,12}$	$\epsilon_{IJK}\,(H^\dagger H)W^{\mu\nu,I}W^J_{\nu\rho}W^{\rho,K}_\mu$
$\mathcal{O}_{8,3}$	$(H^\dagger H)^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}$	$\mathcal{O}_{8,13}$	$\epsilon_{IJK}\,(H^\dagger H)W^{\mu\nu,I}\widetilde{W}^J_{\nu\rho}W^{\rho,K}_\mu$
$\mathcal{O}_{8,4}$	$\delta_{IJ}\,(H^\dagger H)(H^\dagger\tau^I H)B_{\mu\nu}W^{\mu\nu,J}$	$\mathcal{O}_{8,14}$	$\delta_{AB}\,(H^\dagger H)^2 G^A_{\mu\nu}G^{\mu\ nu,B}$
$\mathcal{O}_{8,5}$	$\delta_{IJ}\,(H^\dagger H)(H^\dagger\tau^I H)B_{\mu\nu}\widetilde{W}^{\mu\nu,J}$	$\mathcal{O}_{8,15}$	$\delta_{AB}\,(H^\dagger H)^2 G^A_{\mu\nu}\widetilde{G}^{\mu\nu,B}$
$\mathcal{O}_{8,6}$	$\delta_{IJ}(H^\dagger H)^2 W^I_{\mu\nu}W^{\mu\nu,J}$	$\mathcal{O}_{16}$	$f_{ABC}\,(H^\dagger H)G^{\mu\nu,A}G^B_{\nu\rho}G^{\rho,C}_\mu$
$\mathcal{O}_{8,7}$	$\delta_{IJ}(H^\dagger H)^2 W^I_{\mu\nu}\widetilde{W}^{\mu\nu,J}$	$\mathcal{O}_{8,17}$	$f_{ABC}\,(H^\dagger H)G^{\mu\nu,A}\widetilde{G}^B_{\nu\rho}G^{\rho,C}_\mu$
$\mathcal{O}_{8,8}$	$\delta_{IK}\delta_{JM}(H^\dagger\tau^I H)(H^\dagger\tau^J H)W^K_{\mu\nu}W^{\mu\nu,M}$		
$\mathcal{O}_{8,9}$	$\delta_{IK}\delta_{JM}(H^\dagger\tau^I H)(H^\dagger\tau^J H)W^K_{\mu\nu}\widetilde{W}^M_{\mu\nu}$		
$\mathcal{O}_{8,10}$	$\epsilon_{IJK}\,(H^\dagger\tau^I H)B^\nu_\mu W^J_{\nu\rho}W^{\mu\rho,K}$		

4 derivatives

$\mathcal{O}_{8,4D1}$	$(D_\mu H^\dagger D_\nu H)(D^\nu H^\dagger D^\mu H)$
$\mathcal{O}_{8,4D2}$	$(D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$
$\mathcal{O}_{8,4D3}$	$(D^\mu H^\dagger D_\mu H)(D^\nu H^\dagger D_\nu H)$

Towards a Complete Dim-8 Basis?

Example: Classification of Dim. 8 that affect $pp \to Wh$

Hays/Martin/Sanz/Setford, 1808.00442

2 derivatives

$\mathcal{O}_{8,2D1}$	$(H^\dagger H)^2 (D_\mu H^\dagger D^\mu H)$	$\mathcal{O}_{8,2D14}$	$\epsilon_{IJK} (D^\mu H^\dagger \tau^I D^\nu H)(W^J_{\mu\rho} \widetilde{W}^{\rho,K}_\nu + \widetilde{W}^J_{\mu\rho} W^{\rho,K}_\nu)$
$\mathcal{O}_{8,2D2}$	$\delta_{IJ} (H^\dagger H)(H^\dagger \tau^I H)(D^\mu H^\dagger \tau^J D_\mu H)$	$\mathcal{O}_{8,2D15}$	$\delta_{IJ} (D^\mu H^\dagger \tau^I D_\mu H) B^{\rho\sigma} W^J_{\rho\sigma}$
$\mathcal{O}_{8,2D3}$	$(D^\mu H^\dagger D^\nu H) B_{\mu\rho} B^\rho_\nu$	$\mathcal{O}_{8,2D16}$	$\delta_{IJ} (D^\mu H^\dagger \tau^I D_\mu H) B^{\rho\sigma} \widetilde{W}^J_{\rho\sigma}$
$\mathcal{O}_{8,2D4}$	$(D^\mu H^\dagger D_\mu H) B^{\rho\sigma} B_{\rho\sigma}$	$\mathcal{O}_{8,2D17}$	$i\,\delta_{IJ} (D^\mu H^\dagger \tau^I D^\nu H)(B_{\mu\rho} W^{\rho,J}_\nu - B_{\nu\rho} W^{\rho,J}_\mu)$
$\mathcal{O}_{8,2D5}$	$(D^\mu H^\dagger D_\mu H) B^{\rho\sigma} \widetilde{B}_{\rho\sigma}$	$\mathcal{O}_{8,2D18}$	$\delta_{IJ} (D^\mu H^\dagger \tau^I D^\nu H)(B_{\mu\rho} W^{\rho,J}_\nu + B_{\nu\rho} W^{\rho,J}_\mu)$
$\mathcal{O}_{8,2D6}$	$\delta_{AB} (D^\mu H^\dagger D^\nu H) G^A_{\mu\rho} G^{\rho,B}_\nu$	$\mathcal{O}_{8,2D19}$	$\delta_{IJ} (D^\mu H^\dagger \tau^I D^\nu H)(B^\rho_{[\mu} \widetilde{W}^J_{\nu]\rho} - \widetilde{B}^\rho_{[\mu} W^J_{\nu]\rho})$
$\mathcal{O}_{8,2D7}$	$\delta_{AB} (D^\mu H^\dagger D_\mu H) G^{\rho\sigma,A} G^B_{\rho\sigma}$	$\mathcal{O}_{8,2D20}$	$\delta_{IJ} (D^\mu H^\dagger \tau^I D^\nu H)(B^\rho_{\{\mu} \widetilde{W}^J_{\nu\}\rho} + \widetilde{B}^\rho_{\{\mu} W^J_{\nu\}\rho})$
$\mathcal{O}_{8,2D8}$	$\delta_{AB} (D^\mu H^\dagger D_\mu H) G^{\rho\sigma,A} \widetilde{G}^B_{\rho\sigma}$	$\mathcal{O}_{8,2D21}$	$i\,(H^\dagger H)(D_\mu H^\dagger D_\nu H) B^{\mu\nu}$
$\mathcal{O}_{8,2D9}$	$\delta_{IJ} (D^\mu H^\dagger D^\nu H) W^I_{\mu\rho} W^{\rho,J}_\nu$	$\mathcal{O}_{8,2D22}$	$i\,(H^\dagger H)(D_\mu H^\dagger D_\nu H) \widetilde{B}^{\mu\nu}$
$\mathcal{O}_{8,2D10}$	$\delta_{IJ} (D^\mu H^\dagger D_\mu H) W^{\rho\sigma,I} W^J_{\rho\sigma}$	$\mathcal{O}_{8,2D23}$	$i\,\delta_{IJ} (H^\dagger H)(D^\mu H^\dagger \tau^I D^\nu H) W^J_{\mu\nu}$
$\mathcal{O}_{8,2D11}$	$\delta_{IJ} (D^\mu H^\dagger D_\mu H) W^{\rho\sigma,I} \widetilde{W}^J_{\rho\sigma}$	$\mathcal{O}_{8,2D24}$	$i\,\delta_{IJ} (H^\dagger H)(D^\mu H^\dagger \tau^I D^\nu H) \widetilde{W}^J_{\mu\nu}$
$\mathcal{O}_{8,2D12}$	$\epsilon_{IJK} (D^\mu H^\dagger \tau^I D^\nu H) W^J_{\mu\rho} W^{\rho,K}_\nu$	$\mathcal{O}_{8,2D25}$	$i\,\epsilon_{IJK} (H^\dagger \tau^I H)(D^\mu H^\dagger \tau^J D^\nu H) W^K_{\mu\nu}$
$\mathcal{O}_{8,2D13}$	$\epsilon_{IJK} (D^\mu H^\dagger \tau^I D^\nu H)(W^J_{\mu\rho} \widetilde{W}^{\rho,K}_\nu - \widetilde{W}^J_{\mu\rho} W^{\rho,K}_\nu)$	$\mathcal{O}_{8,2D26}$	$i\,\epsilon_{IJK} (H^\dagger \tau^I H)(D^\mu H^\dagger \tau^J D^\nu H) \widetilde{W}^K_{\mu\nu}$

Towards a Complete Dim-8 Basis?

Example: Classification of Dim. 8 that affect $pp \to Wh$

Hays/Martin/Sanz/Setford, 1808.00442

Quark operators

$\mathcal{O}_{QW1}$	$\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu Q)\,D^\mu(H^\dagger\tau^I H)\,W^J_{\mu\nu}$
$\mathcal{O}_{Q\tilde W1}$	$\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu Q)\,D^\mu(H^\dagger\tau^I H)\,\tilde W^J_{\mu\nu}$
$\mathcal{O}_{QW2}$	$i\,\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu Q)(H^\dagger \overleftrightarrow{D}^\mu\tau^I H)\,W^J_{\mu\nu}$
$\mathcal{O}_{Q\tilde W2}$	$i\,\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu Q)(H^\dagger \overleftrightarrow{D}^\mu\tau^I H)\,\tilde W^J_{\mu\nu}$
$\mathcal{O}_{QW3}$	$\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu\tau^I\,Q)\,D^\mu(H^\dagger H)\,W^J_{\mu\nu}$
$\mathcal{O}_{Q\tilde W3}$	$\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu\tau^I\,Q)\,D^\mu(H^\dagger H)\,\tilde W^J_{\mu\nu}$
$\mathcal{O}_{QW4}$	$i\,\delta_{IJ}\,(Q^\dagger\bar\sigma^\nu\tau^I\,Q)(H^\dagger \overleftrightarrow{D}^\mu H)\,W^J_{\mu\nu}$
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$\mathcal{O}_{QW5}$	$\epsilon_{ABC}\,(Q^\dagger\bar\sigma^\nu\tau^A\,Q)\,D^\mu(H^\dagger\tau^B H)\,W^C_{\mu\nu}$
$\mathcal{O}_{Q\tilde W5}$	$\epsilon_{ABC}\,(Q^\dagger\bar\sigma^\nu\tau^A\,Q)\,D^\mu(H^\dagger\tau^B H)\,\tilde W^C_{\mu\nu}$
$\mathcal{O}_{QW6}$	$i\,\epsilon_{ABC}\,(Q^\dagger\bar\sigma^\nu\tau^A Q)(H^\dagger \overleftrightarrow{D}^\mu\tau^B H)\,W^C_{\mu\nu}$
$\mathcal{O}_{Q\tilde W6}$	$i\,\epsilon_{ABC}\,(Q^\dagger\bar\sigma^\nu\tau^A Q)(H^\dagger \overleftrightarrow{D}^\mu\tau^B H)\,\tilde W^C_{\mu\nu}$

$\mathcal{O}_{Q1}$	$i(Q^\dagger\bar\sigma^\mu Q)(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger H)$
$\mathcal{O}_{Q2}$	$i\,\delta_{IJ}\,(Q^\dagger\bar\sigma^\mu\tau^I\,Q)\Big((\overleftrightarrow{D}_\mu H^\dagger\tau^J H)(H^\dagger H)+(\overleftrightarrow{D}_\mu H^\dagger\,H)(H^\dagger\tau^J\,H)\Big)$
$\mathcal{O}_{Q3}$	$\epsilon_{IJK}(Q^\dagger\bar\sigma^\mu\tau^I\,Q)(H^\dagger \overleftrightarrow{D}^\mu\tau^J H)(H^\dagger\tau^K\,H)$
$\mathcal{O}_{Q4}$	$\epsilon_{IJK}(Q^\dagger\bar\sigma^\mu\tau^I\,Q)(H^\dagger\tau^J H)\,D_\mu(H^\dagger\tau^K\,H)$
$\mathcal{O}_{3Q1}$	$i\,(Q^\dagger\bar\sigma^\mu D^\nu Q)(D^2_{(\mu\nu)}H^\dagger H)$
$\mathcal{O}_{3Q2}$	$i\,\delta_{IJ}(Q^\dagger\bar\sigma^\mu\tau^I D^\nu Q)(D^2_{(\mu\nu)}H^\dagger\tau^J H)$
$\mathcal{O}_{3Q3}$	$i\,(Q^\dagger\bar\sigma^\mu D^\nu Q)(H^\dagger D^2_{(\mu\nu)}H)$
$\mathcal{O}_{3Q4}$	$i\,\delta_{IJ}(Q^\dagger\bar\sigma^\mu\tau^I D^\nu Q)(H^\dagger\tau^J D^2_{(\mu\nu)}H)$

How to get EFTs from New Physics

- Consider effects from heavy states by using (known) low-energy d.o.f.s

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy.

H. Georgi, 1993

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- Integrating out heavy d.o.f.s marginalizes over details of short-distance interactions
- Toy Example: two interacting scalar fields φ, Φ

Path integral

$$\mathcal{Z}[j,J] = \int \mathcal{D}[\Phi]\,\mathcal{D}[\varphi]\;\exp\left[i\int dx\left(\frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}\Phi(\Box + M^2)\Phi - \lambda\varphi^2\Phi - \ldots + J\Phi + j\varphi\right)\right]$$

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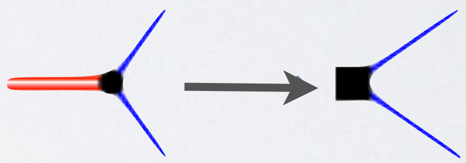
Completing the square (Gaussian integration)

$$\Phi' = \Phi + \frac{\lambda}{M^2}\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2 \qquad \Longrightarrow$$



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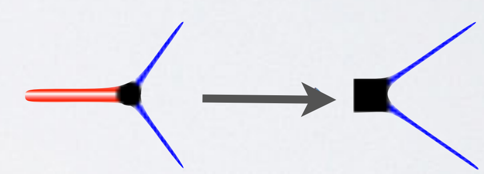
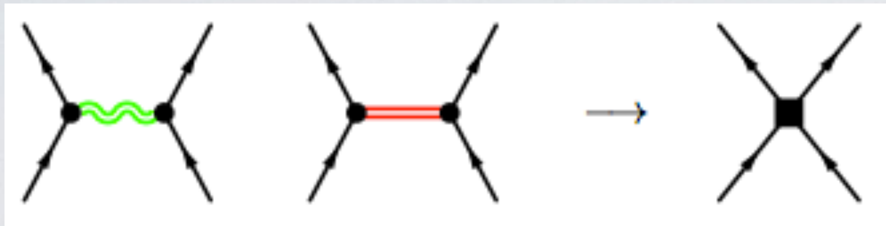


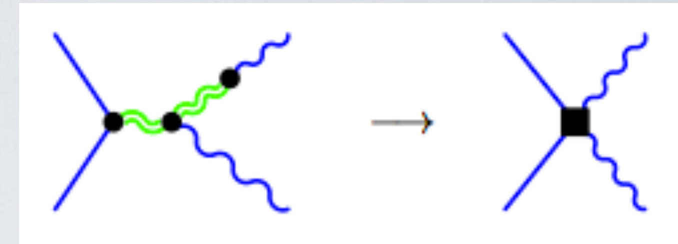
In the Lagrangian remove the high-scale d.o.f.s:

$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower of higher and higher-dim. operators of light fields}}$$

Generation of Higher-dimensional Operators

$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2}\text{tr}\left[J^{(I)} \cdot J^{(I)}\right]$$





$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\text{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

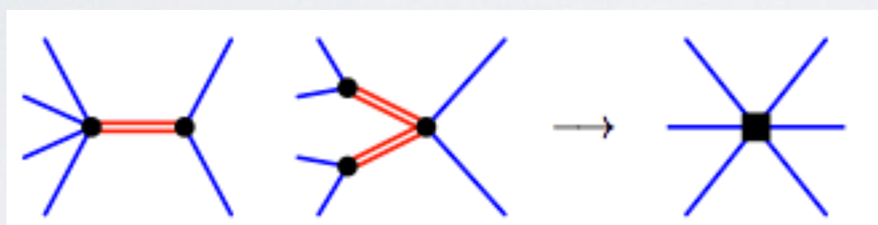
$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger(D_\nu\Phi)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$

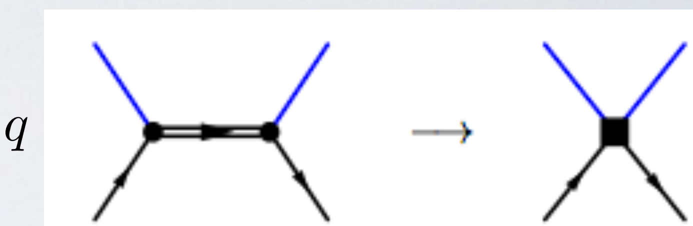
$$\mathcal{O}'_{\Phi,1} = \frac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(\Phi^\dagger(D\Phi)\right) - \frac{v^2}{2}|D\Phi|^2$$

$$\mathcal{O}'_{\Phi\Phi} = \frac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

$$\mathcal{O}'_{\Phi,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}\Phi(\not{D}\Phi)q$$



Couplings of new states to the longitudinal / transversal diboson system

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
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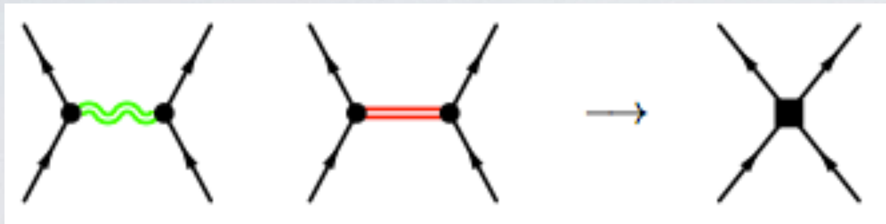

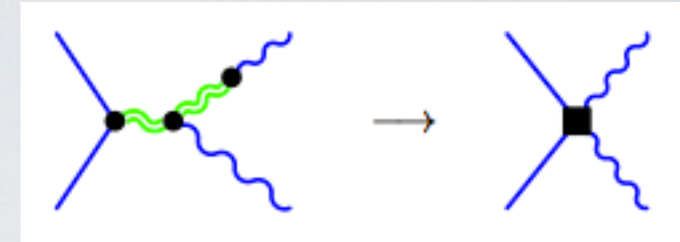

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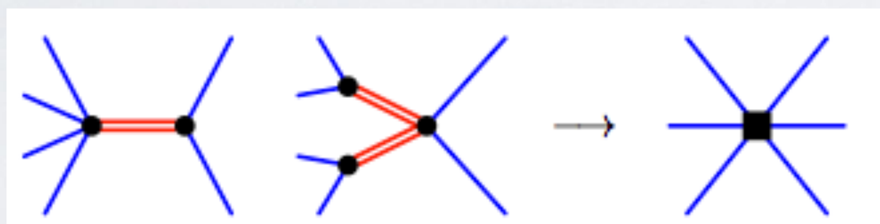

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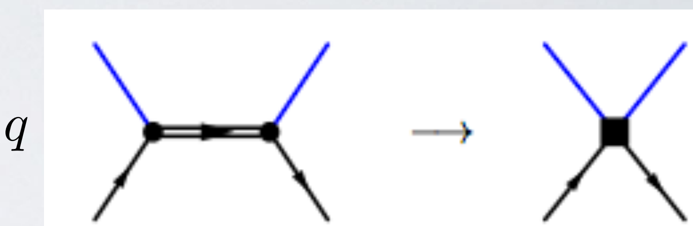

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$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Different power counting for weakly and strongly interacting theories

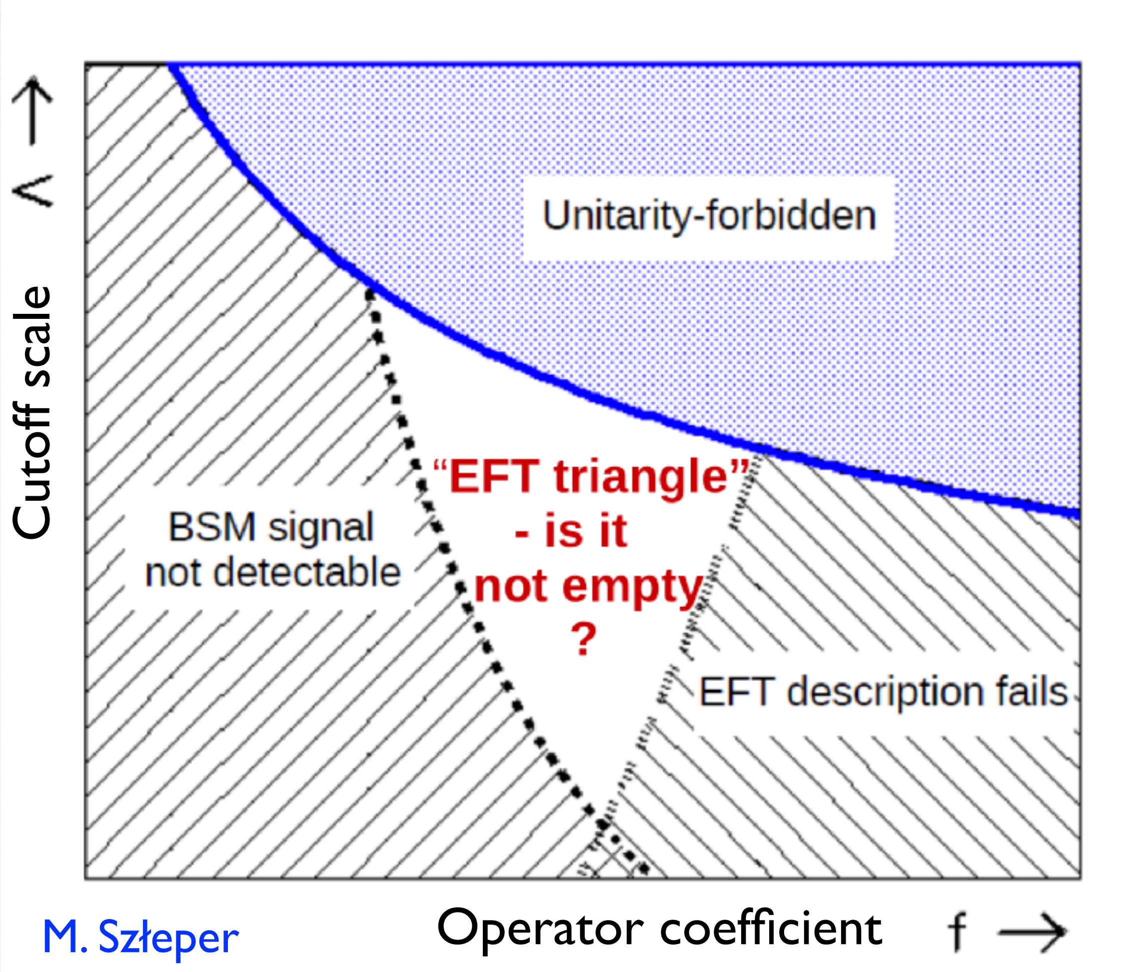
$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$

(In)Validity of (In)Effective Field Theories

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

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

- **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**



Vast literature (non-exhaustive) from 2000+

Omissions are my fault !!

Dimension-6 operators / EWPT / HEFT/ SMEFT

Han/Skiba, hep-ph/0412166; Giudice/Grojean/Pomarol/Ratazzi, hep-ph/0703164; Grzadkowski/Iskrzynski/Misiak/Rosiek, 1008.4884; Corbett/Eboli/Gonzalez-Fraile/Gonzalez-Garcia, 1211.4580 + 1304.1151; Contino/Ghezzi/Grojean/Mühlleitner/Spira, 1303.3876; Dumont/Fichet/von Gersdorff. 1304.3359; Buchalla/Cata/Krause, 1307.5017; Pomarol/Riva, 1308.2803; Alloul/Fuks/Sanz, 1310.5150; Ellis/Sanz/You, 1404.3667; Gupta/Pomarol/Riva, 1405.0181; E. Masso, 1406.6376; Ellis/Sanz/You, 1410.7703; Falkowski/Riva, 1411.0669; Berthier/Trott, 1502.02570; Corbett/Eboli/Goncalves/Gonzalez-Fraile/Plehn/Rauch, 1505.05516; Falkowski/Gonzalez-Alonso/Greljo/Marzocca, 1508.00581; Falkowski/Fuks/Mawatari/Mimasu/Riva/Sanz, 1508.05895; Buchalla/Cata/Celis/Krause, 1511.00988; Butter/Eboli/Gonzalez-Fraile/Gonzalez-Garcia/Plehn/Rauch, 1604.03105; Berthier/Björn/Trott, 1606.06693; Degrande/Fuks/Mawatari/Mimasu/Sanz, 1609.04833; Falkowski/Gonzalez-Alonso/Greljo/Marzocca/Son, 1609.06312; Farina/Panico/Pappadopulo/Ruderman/Torre/Wulzer, 1609.08157; Brivio/Trott, 1701.06424; Falkowski/Gonzalez-Alonso/Mimouni, 1706.03783; Murphy, 1710.02008; Franceschini/Panico/Pomarol/Riva/Wulzer, 1712.01310; Aebischer, 1712.05298; Ellis/Murphy/Sanz/You, 1803.03252; Banerjee/Englert/Gupta/Spannowsky, 1807.01796; Hays/Martin/Sanz/Setford, 1808.00442

Dimension-8 operators

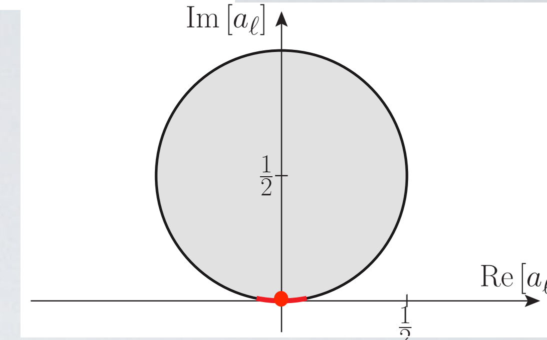
Beyer/Kilian/Krstonosic/Mönig/JRR/Schmidt/Schröder, hep-ph/0604048; Eboli/Gonzalez-Garcia/Mizukoshi, hep-ph/0606118; Alboteanu/Kilian/JRR, 0806.4145; C. Degrande, 1398.6323; Kilian/JRR/Ohl/Sekulla, 1408.6207 + 1511.00022; Liu/Pomarol/Ratazzi/Riva, 1603.03064; Fleper/Kilian/JRR/Sekulla, 1607.03030; Delgado/Dobado/Espriu/Garcia-Garcia/Herrero/Marcano/Sanz-Cillero, 1707.04580; Liu/Wang, 1804.08688; Brass/Fleper/Kilian/JRR/Sekulla, 1807.02512; Perez/Sekulla/Zeppenfeld, 1807.02707; Gripaios/Sutherland, 1807.07546; Kilian/Sun/Yan/Zhao/Zhao, 1808.05534

General formalism / arbitrary dimensions

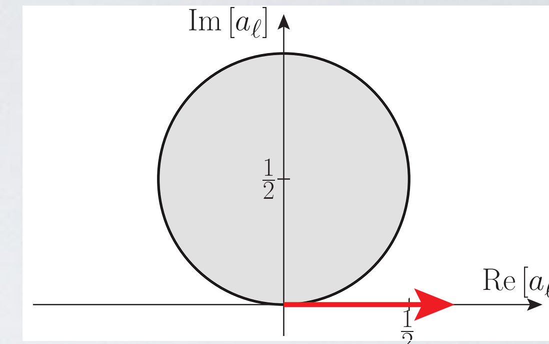
Adams/Arkani-Hamed/Dubovsky/Nicolis/Ratazzi, hep-th/0602178; Bellazzini/Martucci/Torre, 1405.2960; Lehman/Martin, 1503.07537 + 1510.00372; Henning/Lu/Melia/Murayama, 1507.07240 + 1512.03433

Scenarios for New Physics in VBS

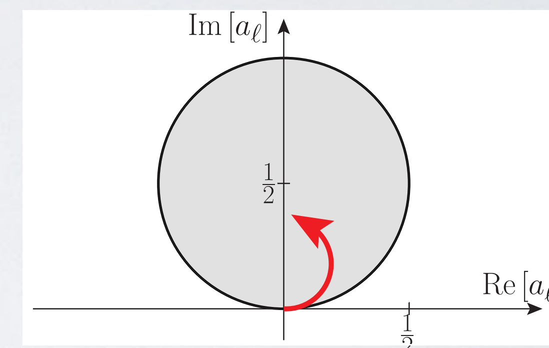
1. SM or weakly coupled physics (e.g. 2HDM): amplitude remains close to origin



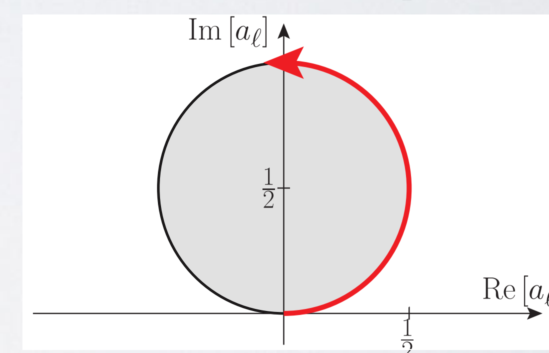
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



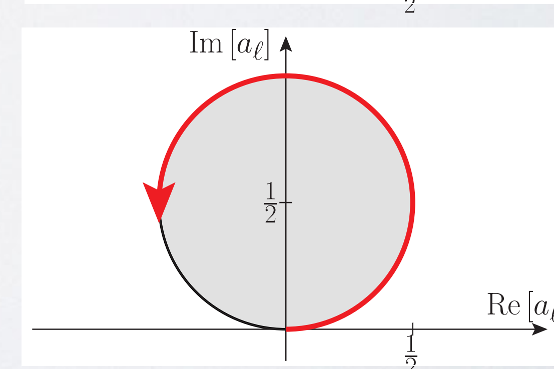
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



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



5. New resonance: amplitude turns over



Decay processes / auto decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

histogram e_e1 (0, 60 MeV, 1 MeV)
analysis = record e_e1 (eval E [e1])

n_events = 100000

simulate (mudec)

compile_analysis { $out_file = “test.dat” }
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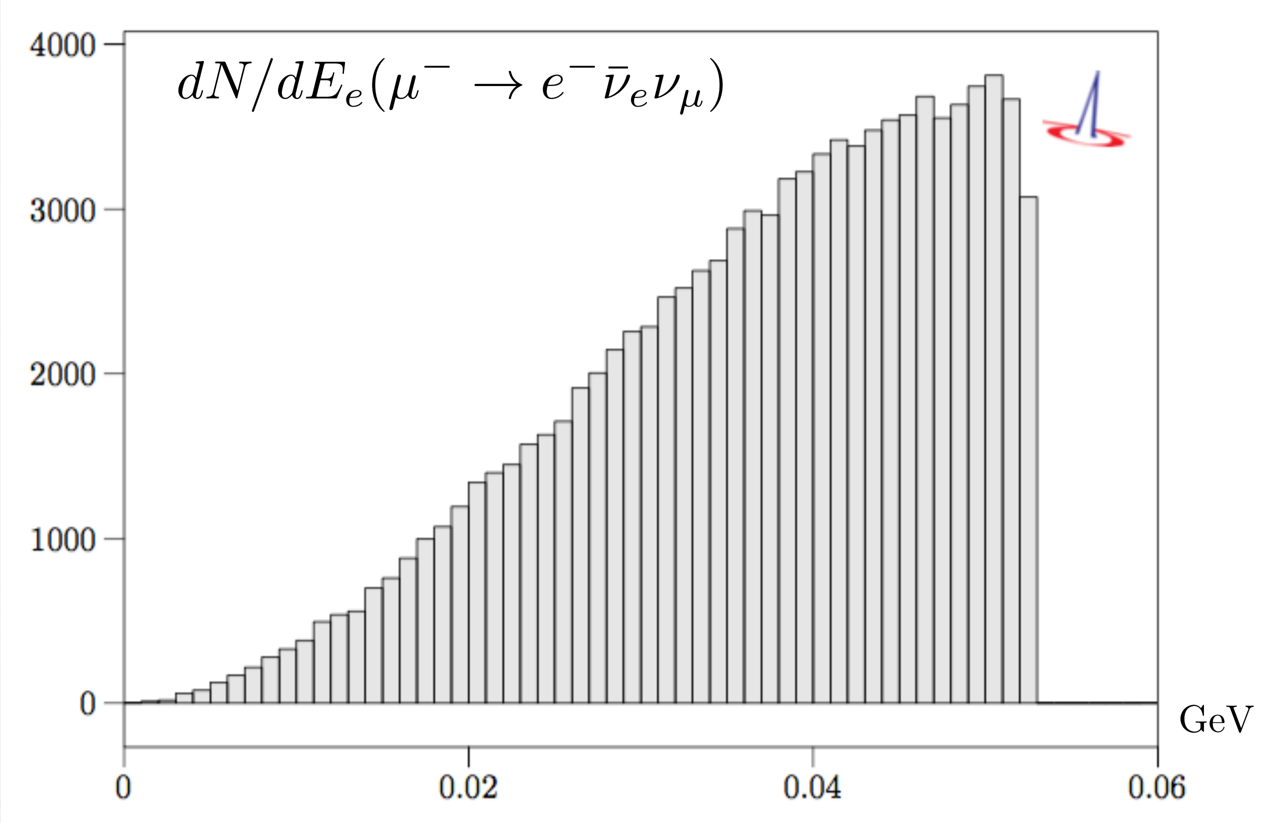

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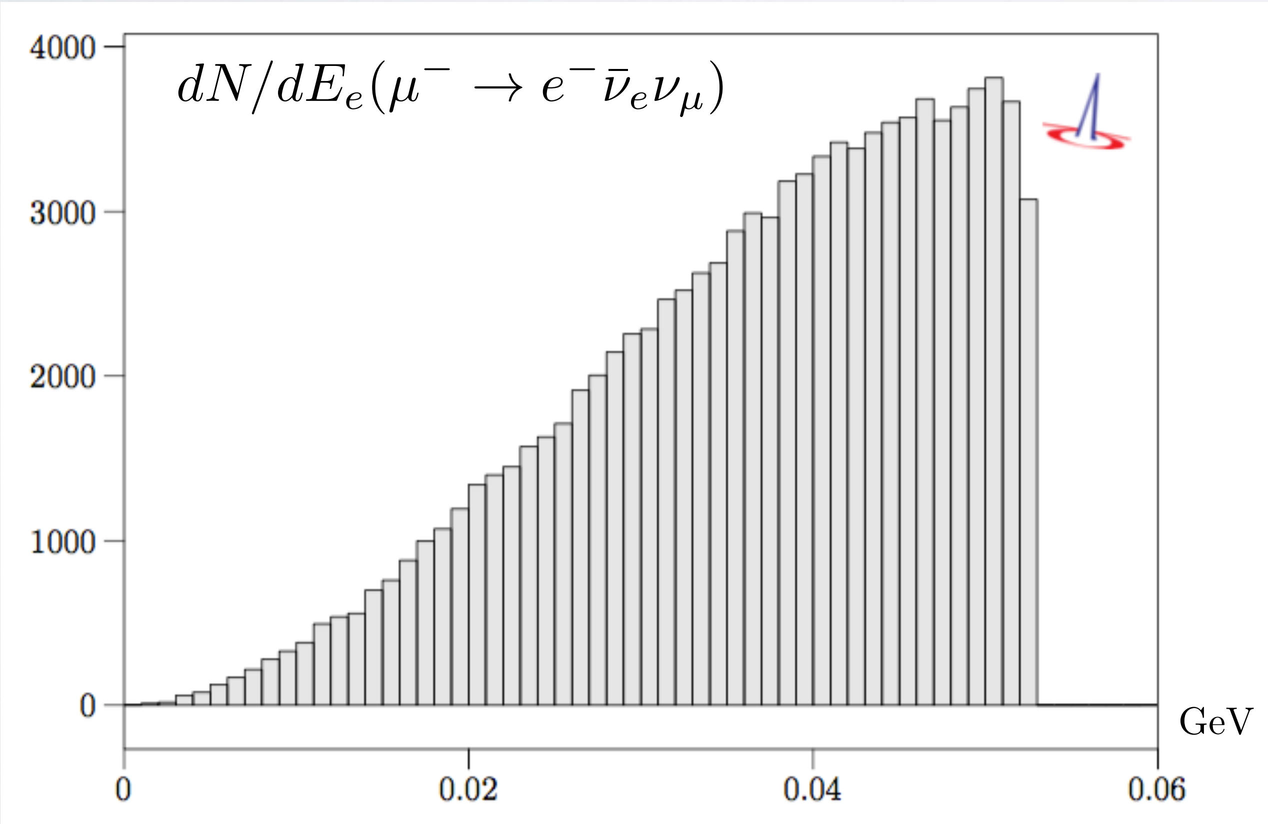

Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

unstable Wp () { ?auto_decays = true }
```

```
|==================================================================
| It      Calls  Integral[GeV]  Error[GeV]  Err[%]    Acc
|==================================================================
   1       100   2.2756406E-01  0.00E+00    0.00    0.00*
|------------------------------------------------------------------
   1       100   2.2756406E-01  0.00E+00    0.00    0.00
|==================================================================
| Unstable particle W+: computed branching ratios:
|   decay_p24_1: 3.3337068E-01   dbar, u
|   decay_p24_2: 3.3325864E-01   sbar, c
|   decay_p24_3: 1.1112356E-01   e+, nue
|   decay_p24_4: 1.1112356E-01   mu+, numu
|   decay_p24_5: 1.1112356E-01   tau+, nutau
|   Total width = 2.0478471E+00 GeV (computed)
|               = 2.0490000E+00 GeV (preset)
|   Decay options: helicity treated exactly
```