New Physics in Vector Boson Scattering at the LHC

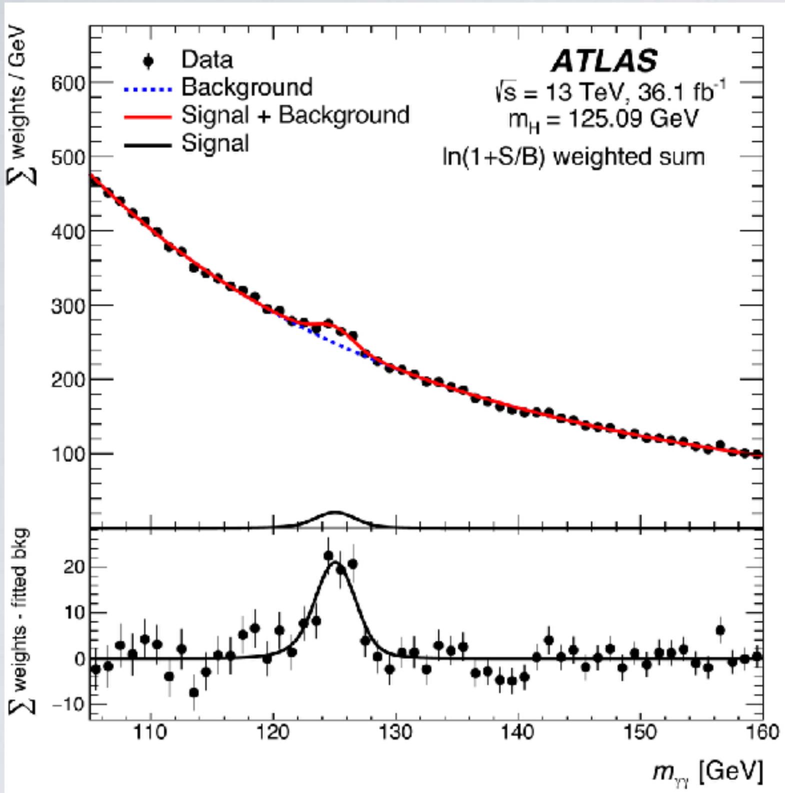
Jürgen R. Reuter, DESY

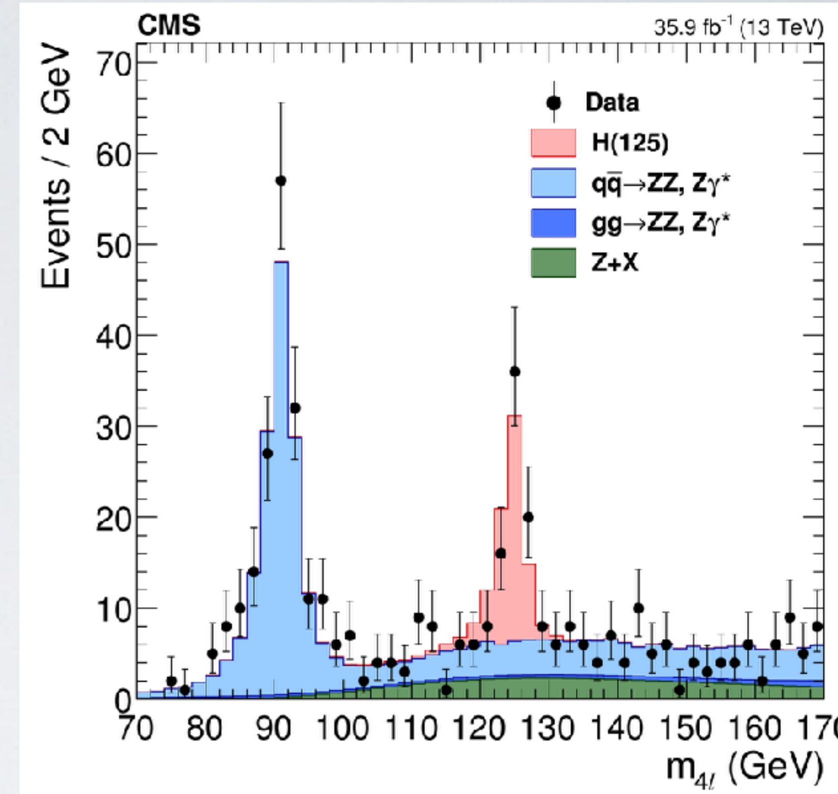
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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

w. EPJC [1807.02512] PRD93(16),3. 036004 [1511.00022],
PRD91(15) 096007 [1408.6207] JHEP 0811.010 [0806.4145]

VBS after the Higgs Discovery



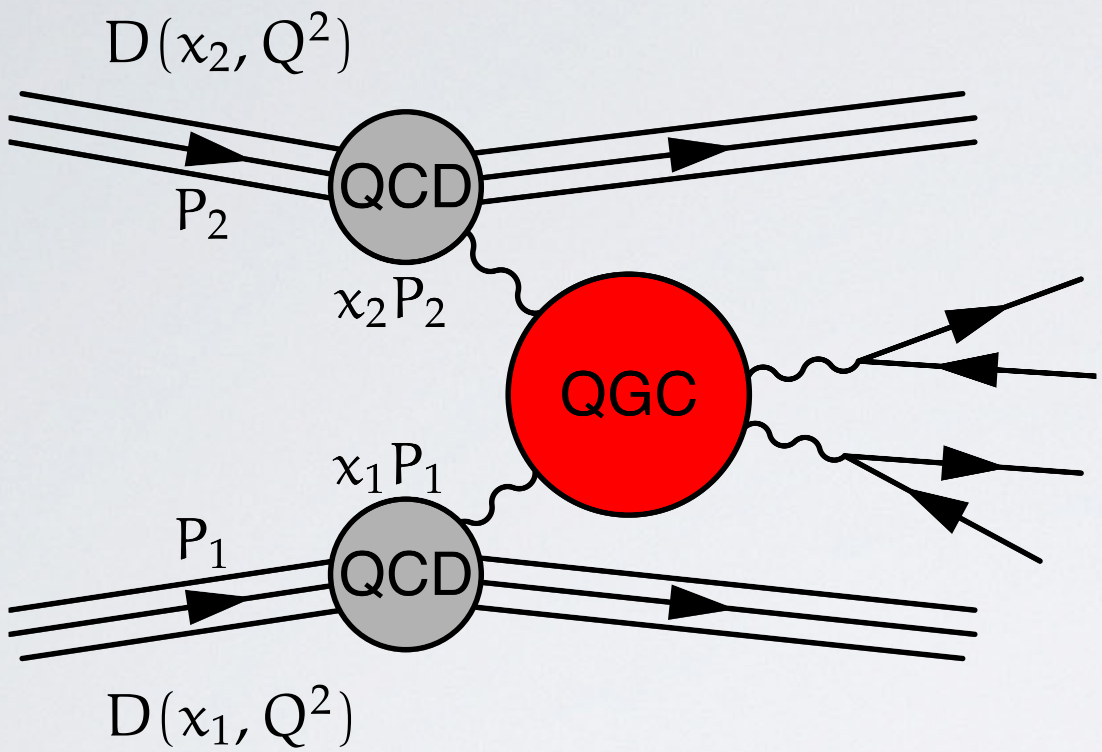


- Discovery of a light Higgs boson leaves still open questions:

  1. Nature of Electroweak Symmetry Breaking
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does "the Higgs" fulfill the US-fermion/Europe-boson rule?
  4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
  5. How do EW vector bosons scatter? (true heart of weak interactions)
  6. Is there something related to the Little Hierarchy problem (strong or weak)
  7. **Look for deviations in intricate cancellations of VBS amplitudes**

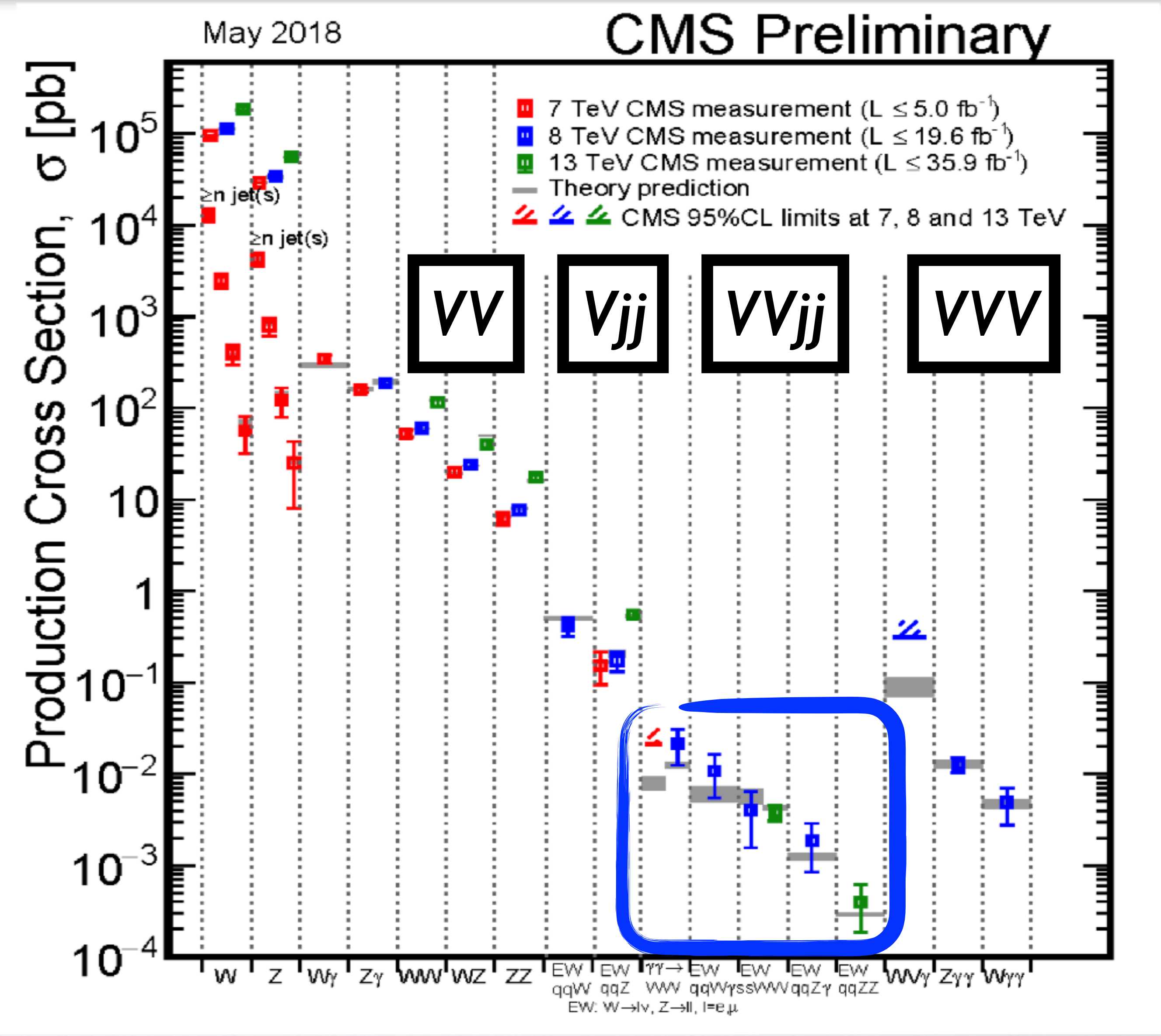
Anatomy of Vector Boson Scattering (VBS)

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



Backgrounds:

- $tt \to WbWb$
- W + *jets*
- single top, misreconstructed jet
- *WWjj* QCD production
- *ll* + X + Emiss ("prompt")



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 mini jet vetoes

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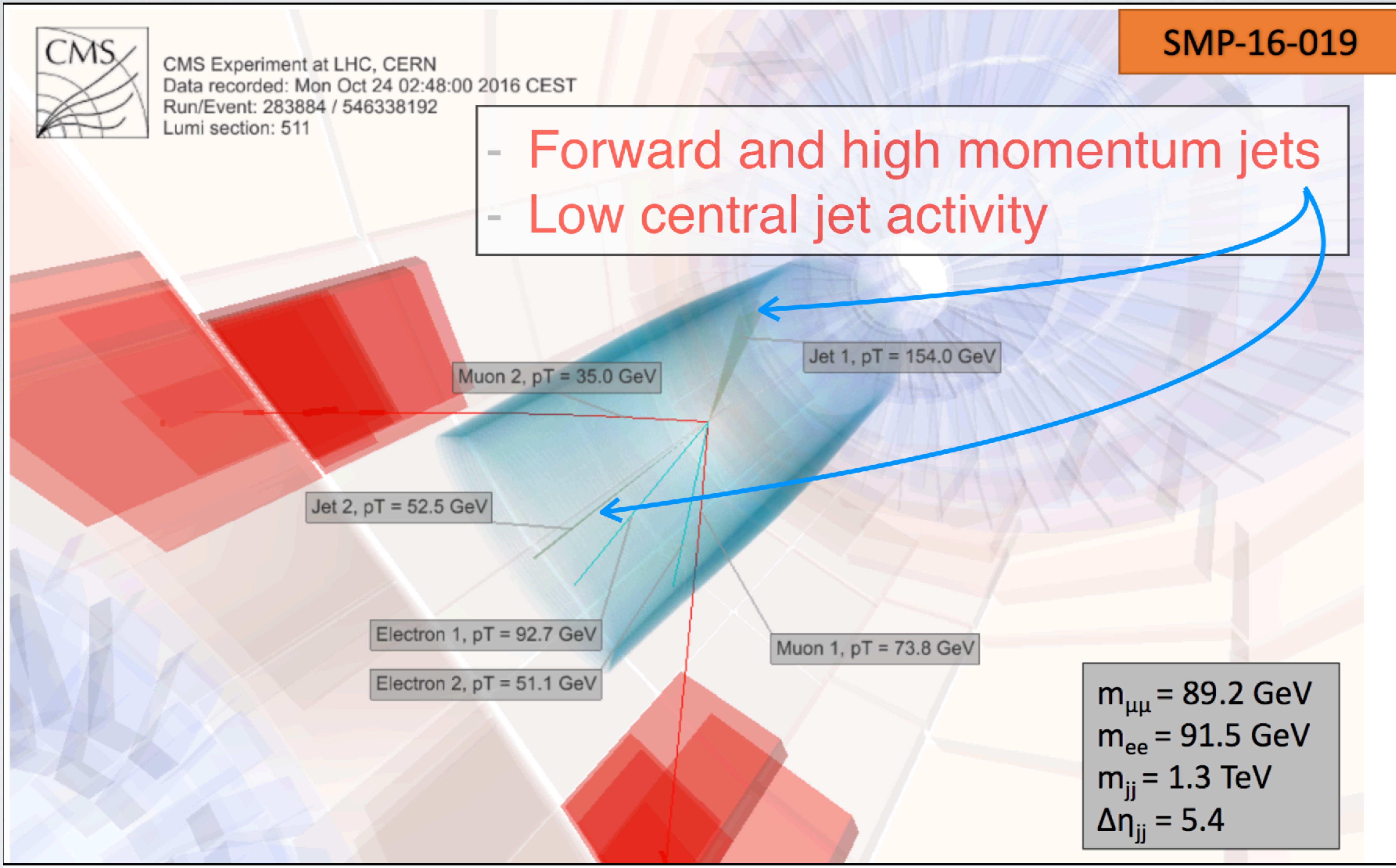

VBS ZZjj Candidate Event from PLB 774 (2017) 682

shown by Kenneth Long, Seoul, ICHEP 2018

The Holy Grail of Vector Boson Scattering

- Discovery for W^+W^+jj (electroweak production)

  ATLAS PRL 113(2014)14, 141803 [1405.6241] & 1611.02428; CMS PRL 114(2015), 051801 [1410.6315]

- First limits on New Physics in pure electroweak gauge/Goldstone sector

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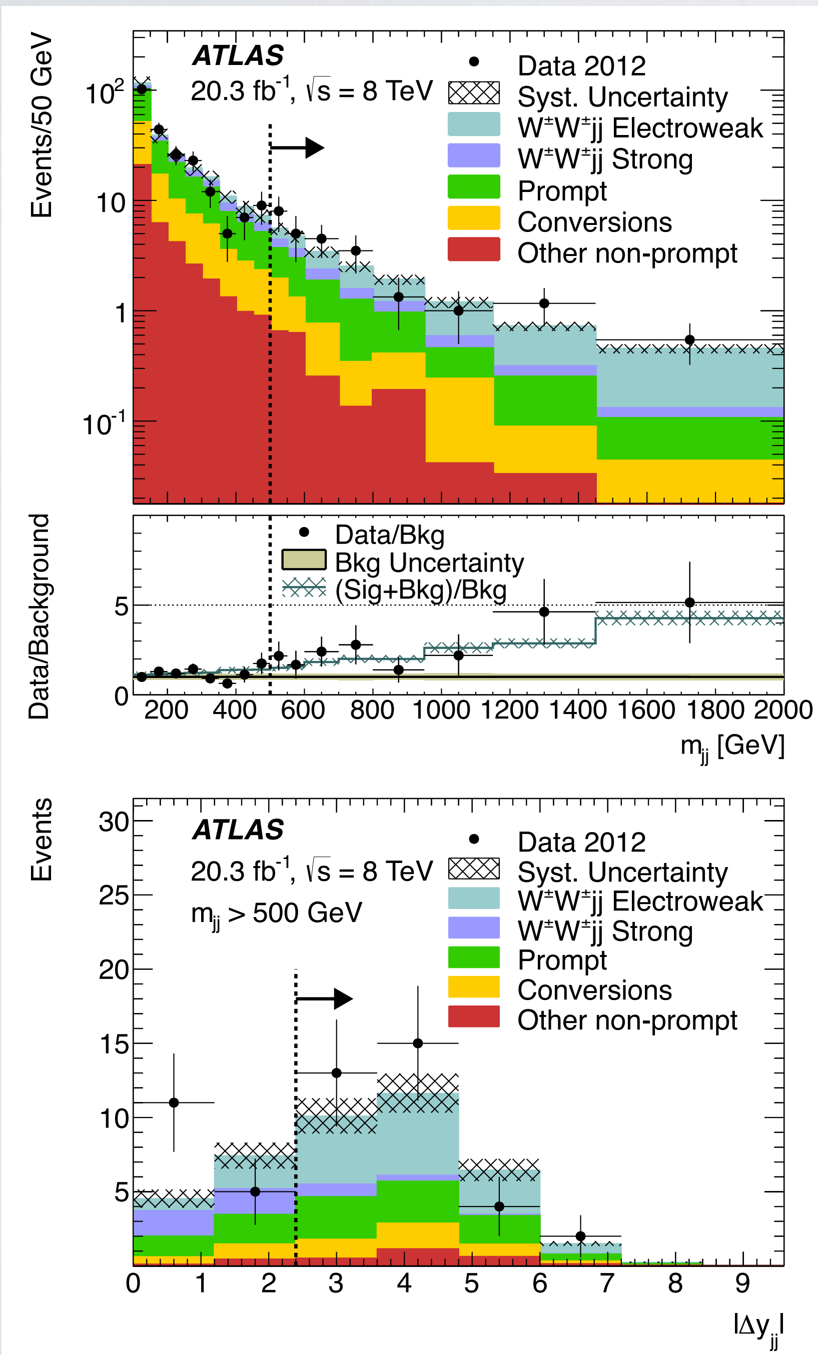

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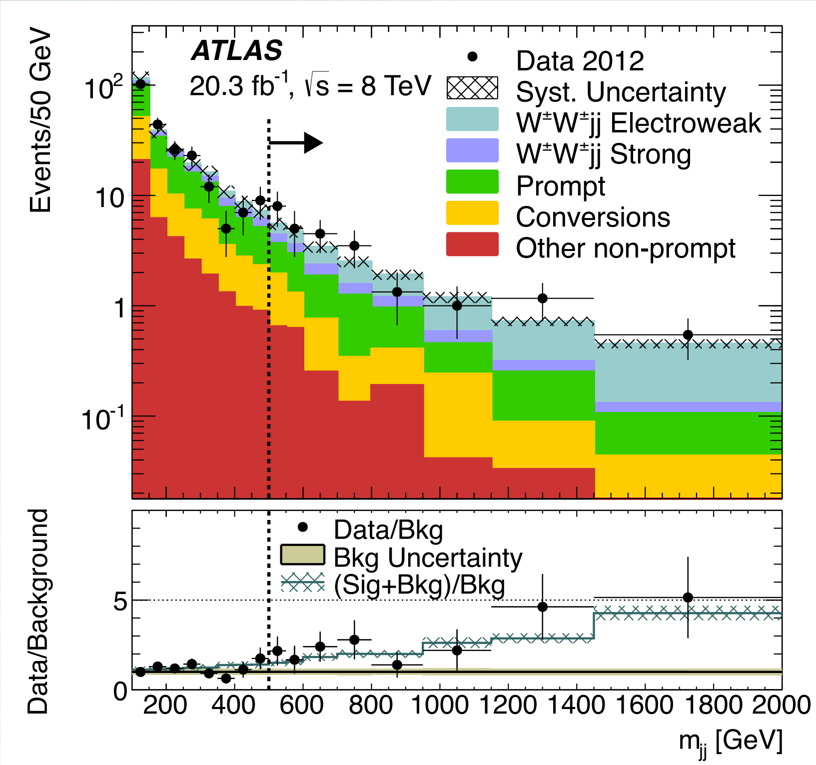

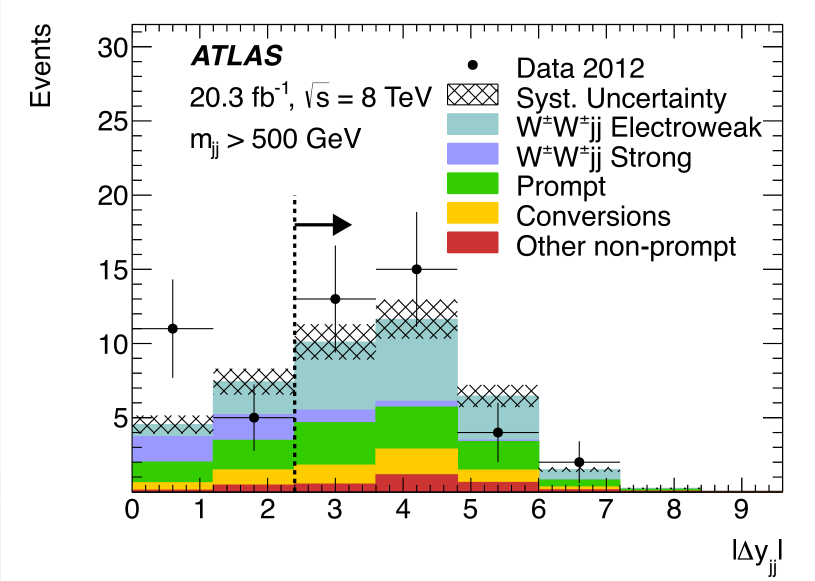

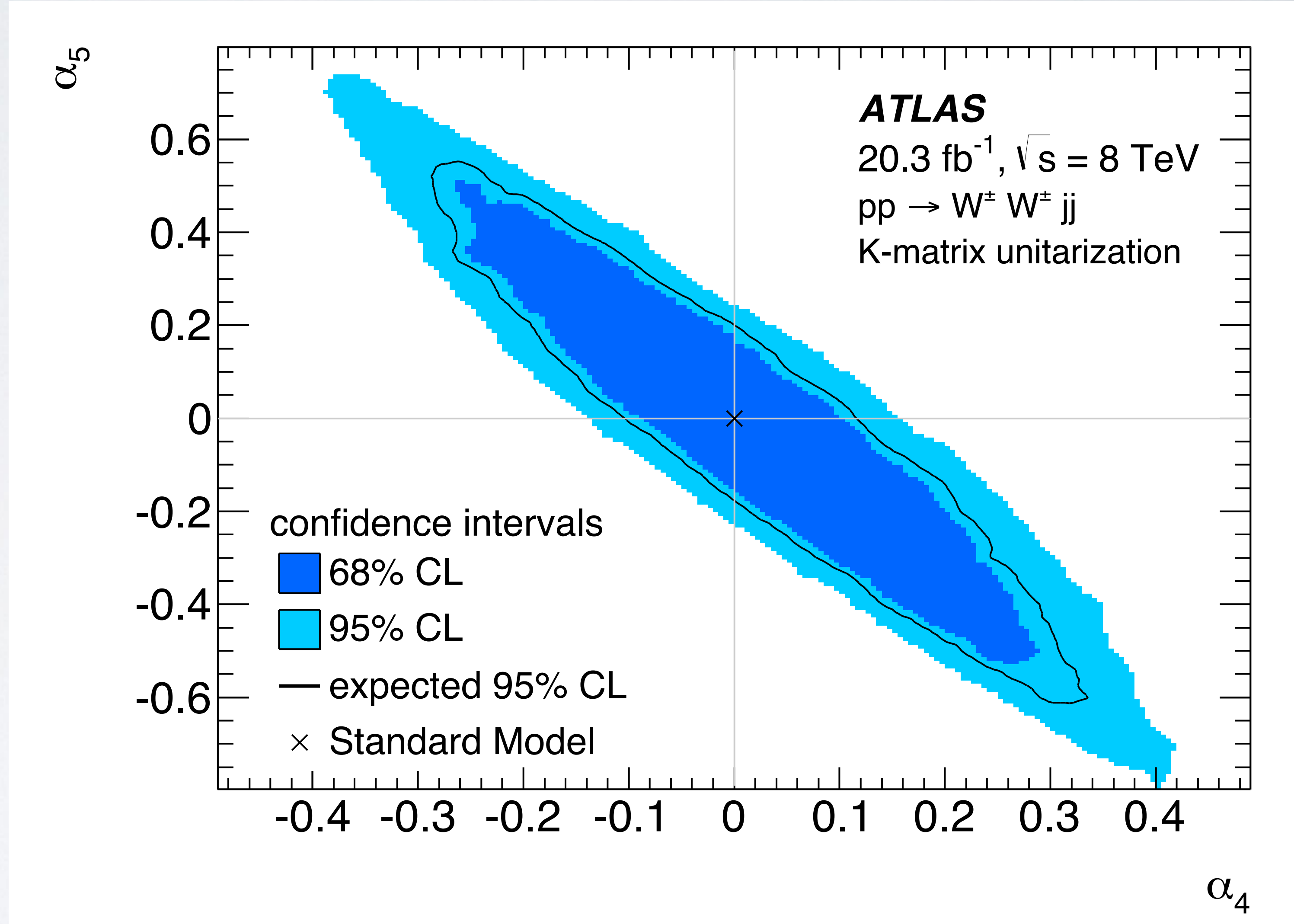

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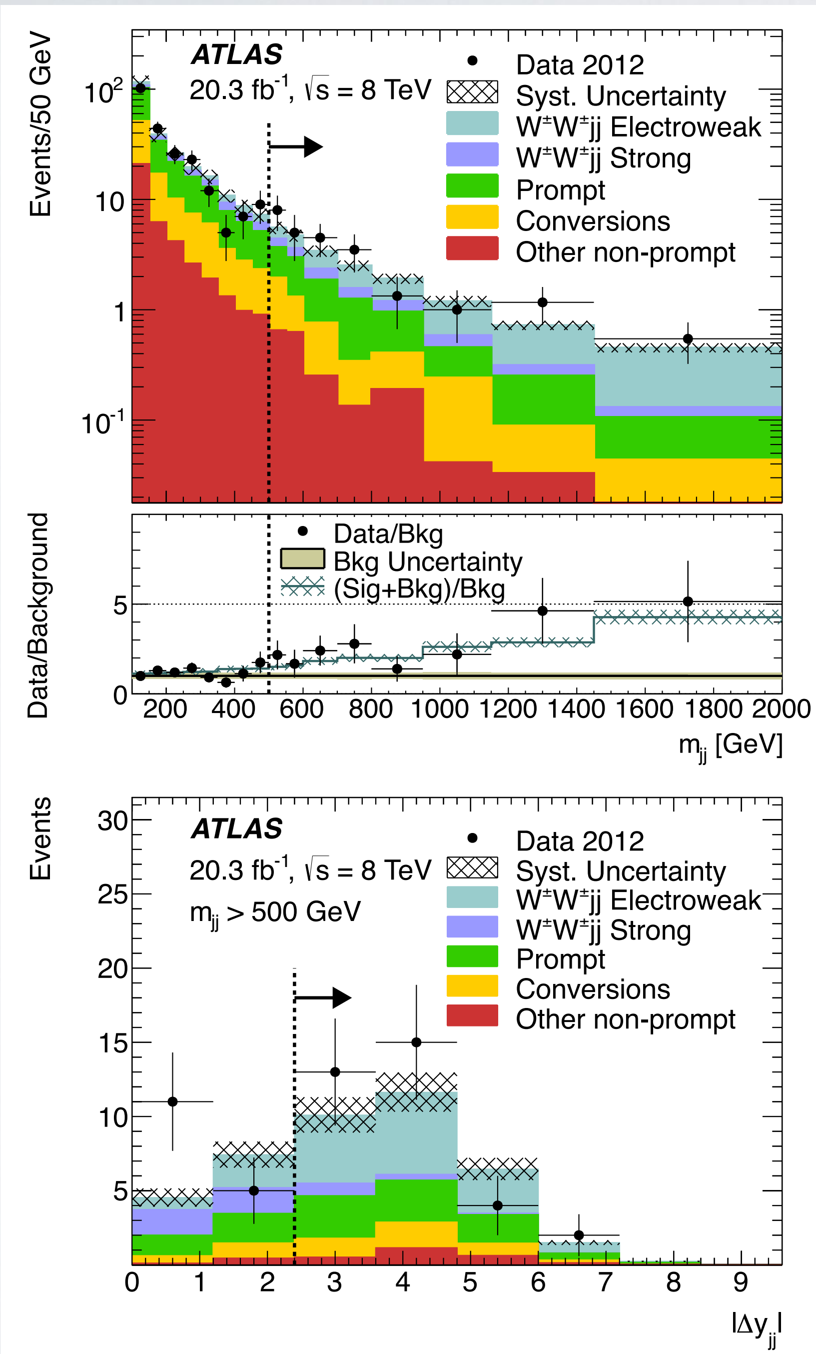
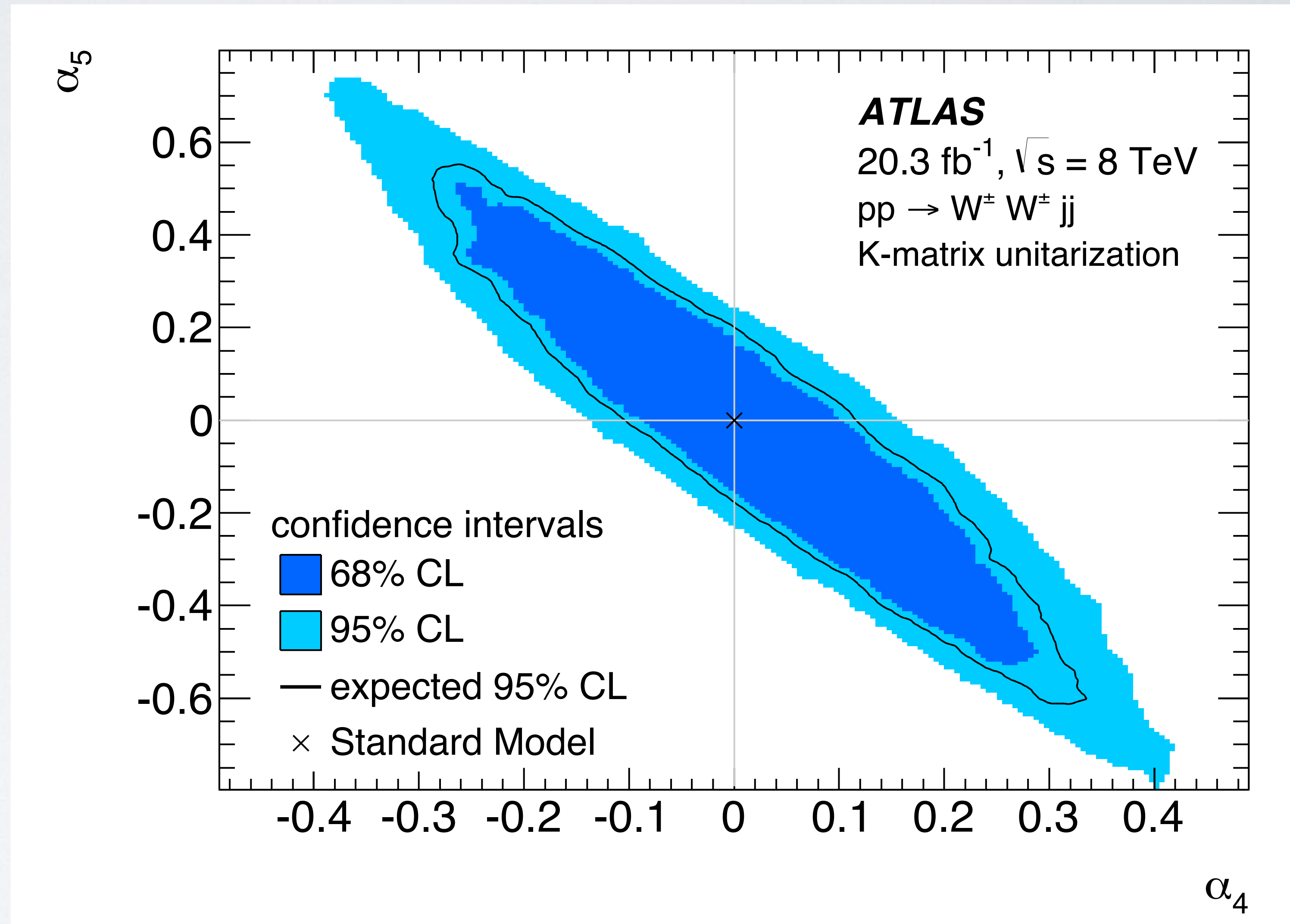
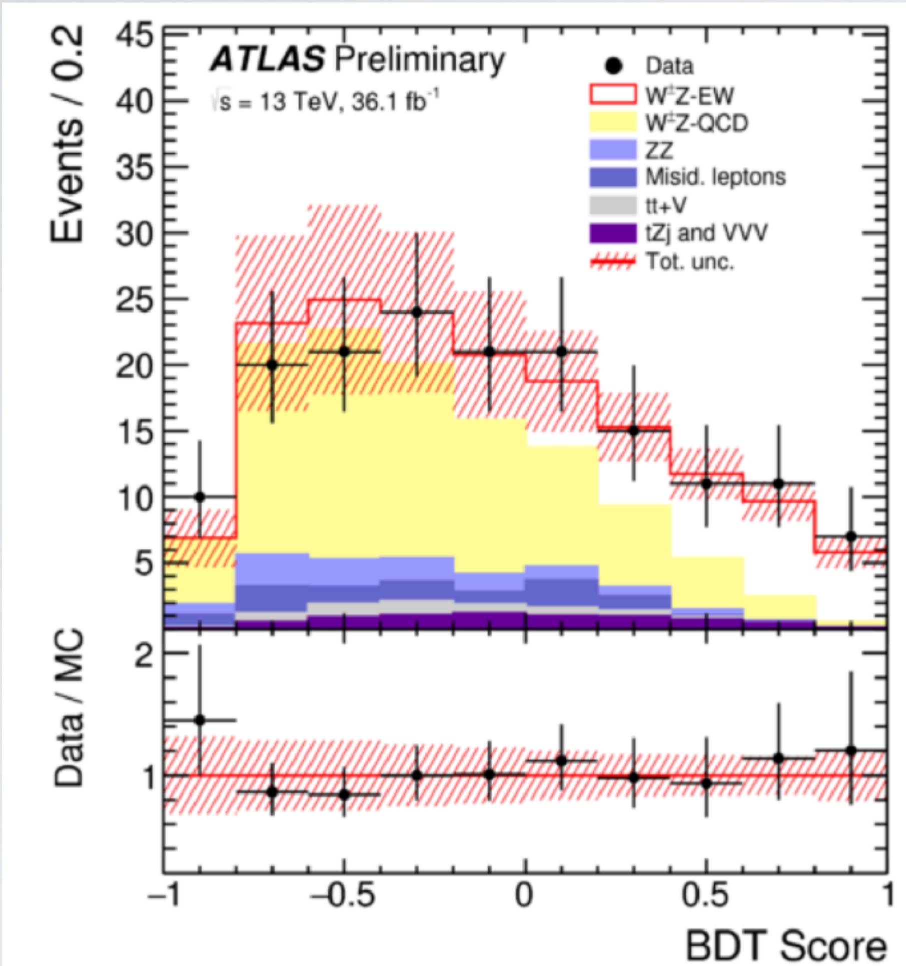




Exploration of E-frontier →look for heavy objects, including high-mass V_LV_L scattering:
❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

F. Gianotti, 01/2014

More channels coming up …



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

ATLAS-CONF-2018-033
M.-A. Pleier, Seoul, ICHEP 2018

Post-fit background normalisations

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

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

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

WZjj-EW measured signal strength:

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

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

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

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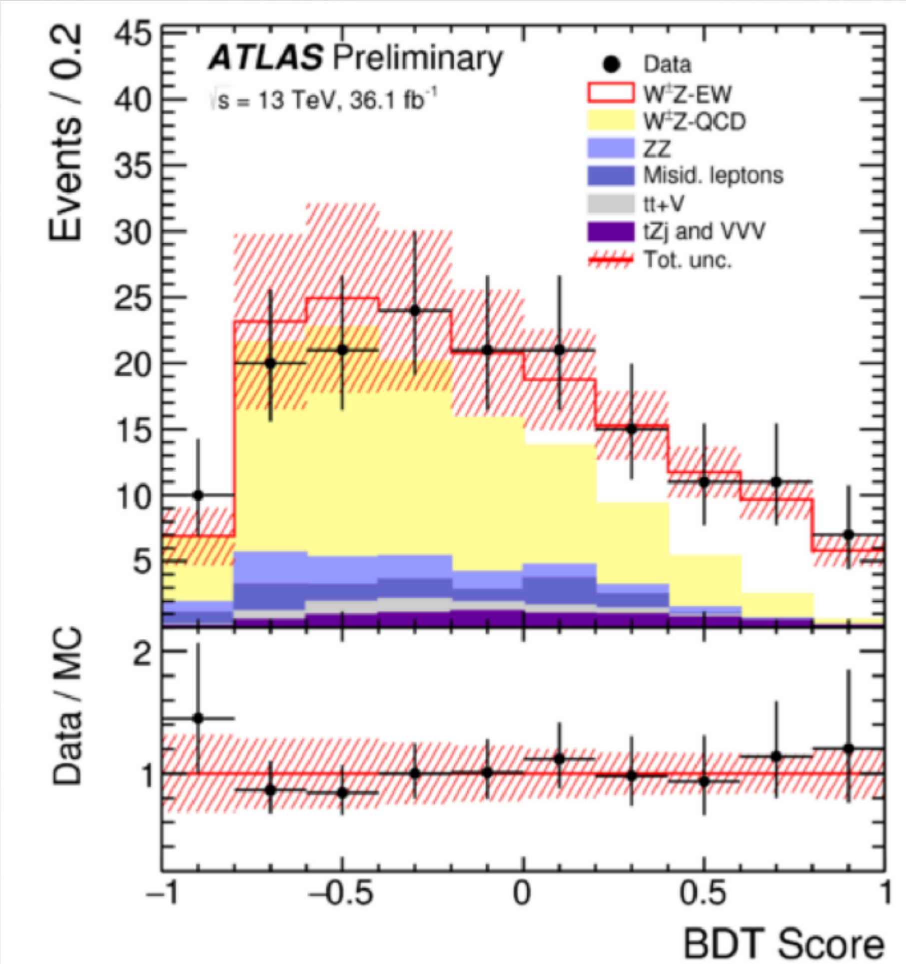

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$pp \to WZjj \to lljj + X$

$$\sigma^{\text{fid}}_{\text{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\text{stat})\ ^{+0.41}_{-0.34}\,(\text{syst})$$

CMS-SMP-18-001

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

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

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

PRL 120, 081801(2018)

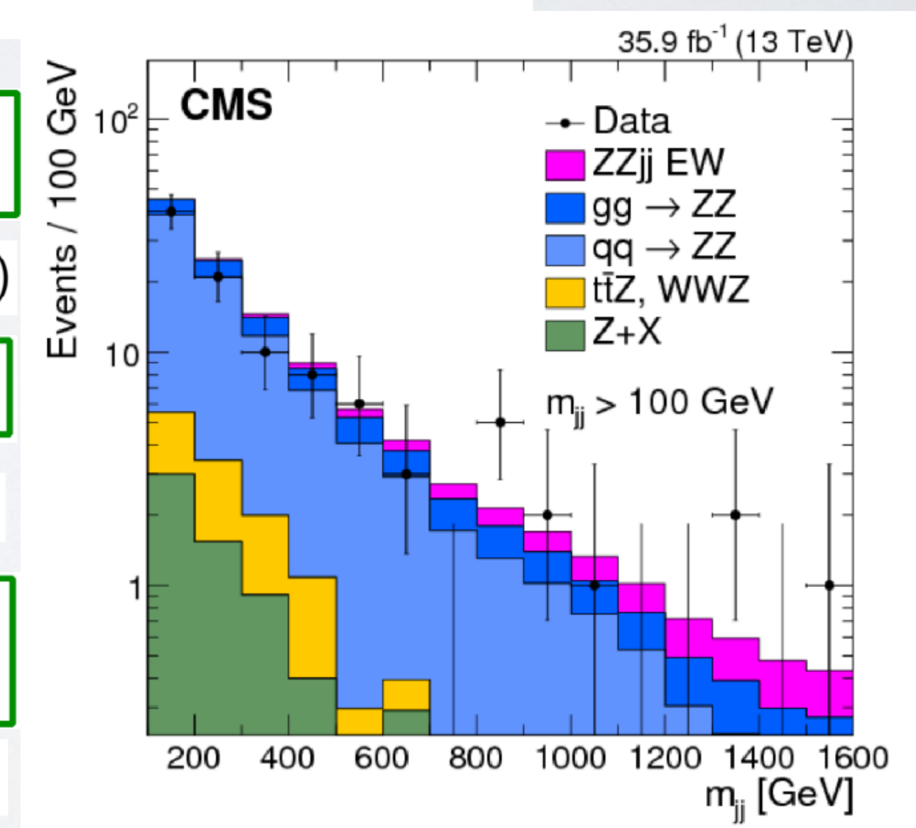
Observed (expected) of 5.5σ (5.7σ)

$pp \to ZZjj \to lllljj$

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

PLB 774(2017) 682

Observed (expected) of 2.7σ (1.6σ)



Deviations as EFT — Dim 8 Operators

Motivated by SMEFT:

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

S. Weinberg, 1979 — Buchmüller/Wyler, 1986

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

Longitudinal operators

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

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

Mixed operators

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

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

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Transversal operators

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

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

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")

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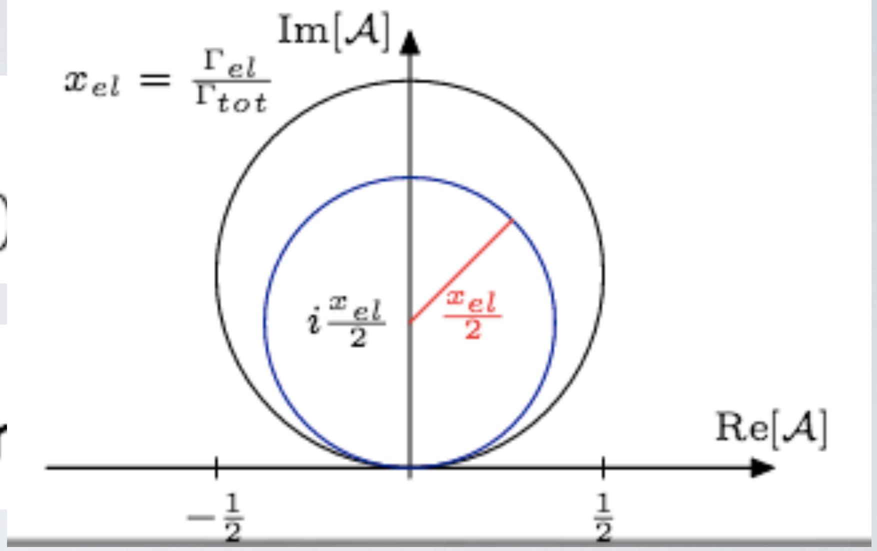

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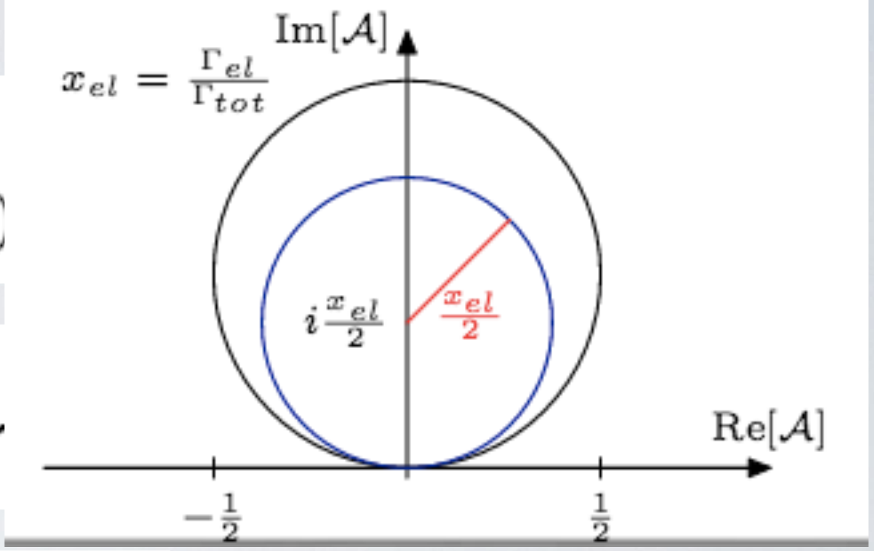

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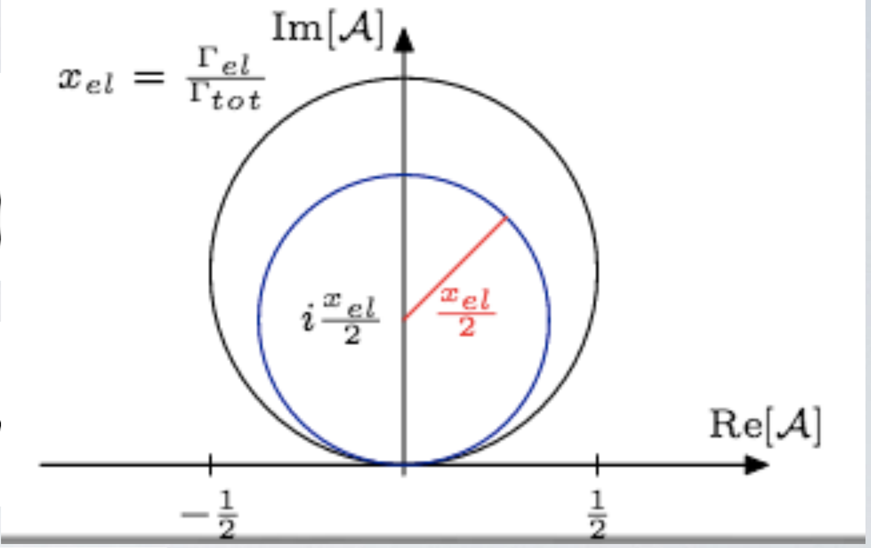

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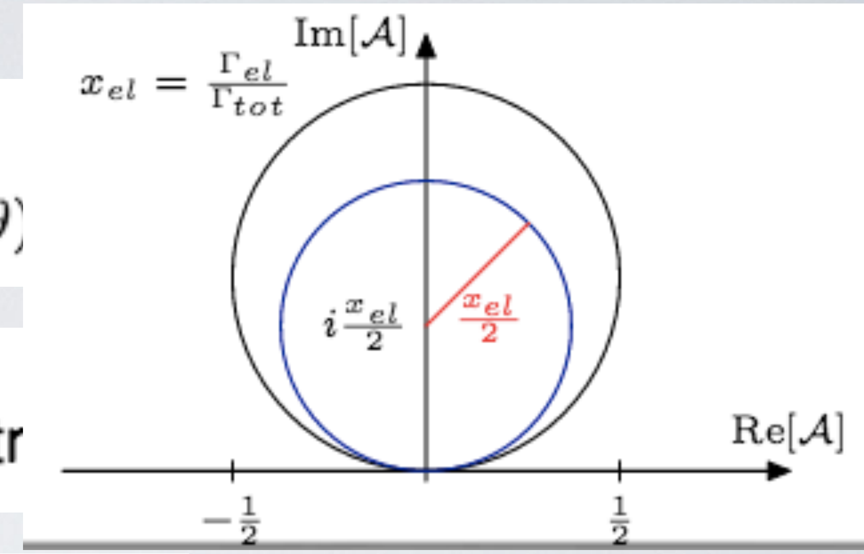
Unitarity in vector boson scattering



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Lee/Quigg/Thacker, 1973

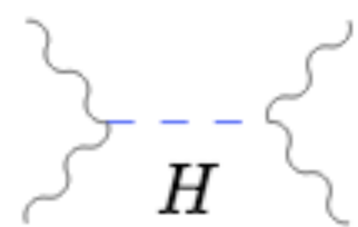
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

Higgs exchange:

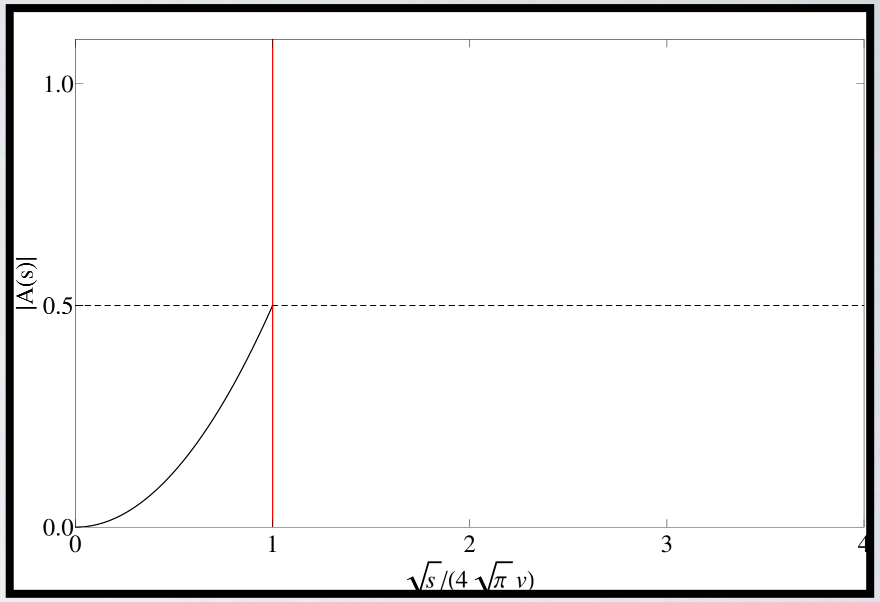


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

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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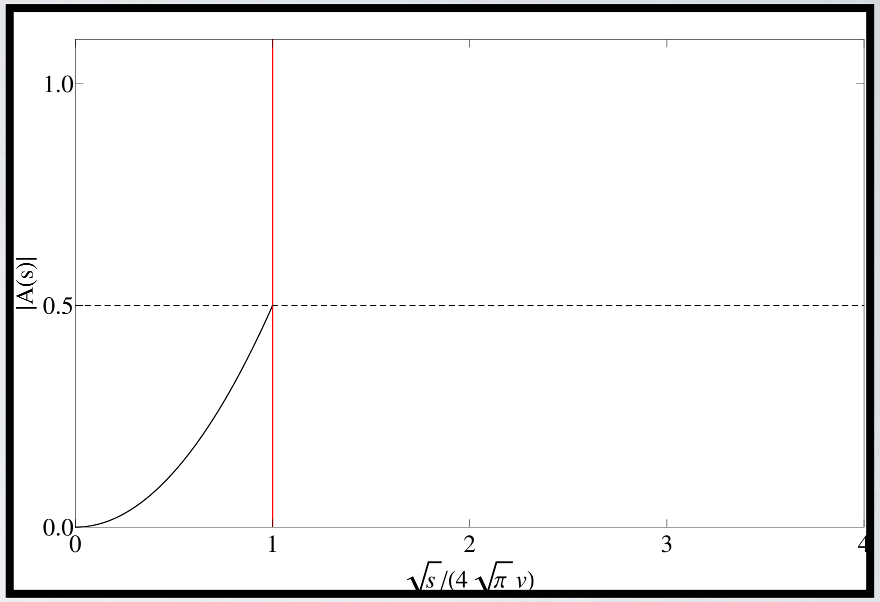
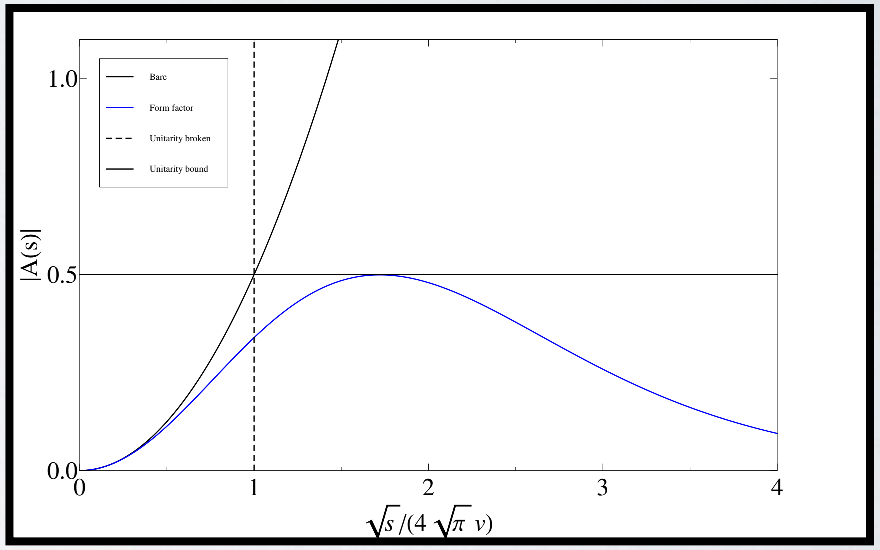


Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

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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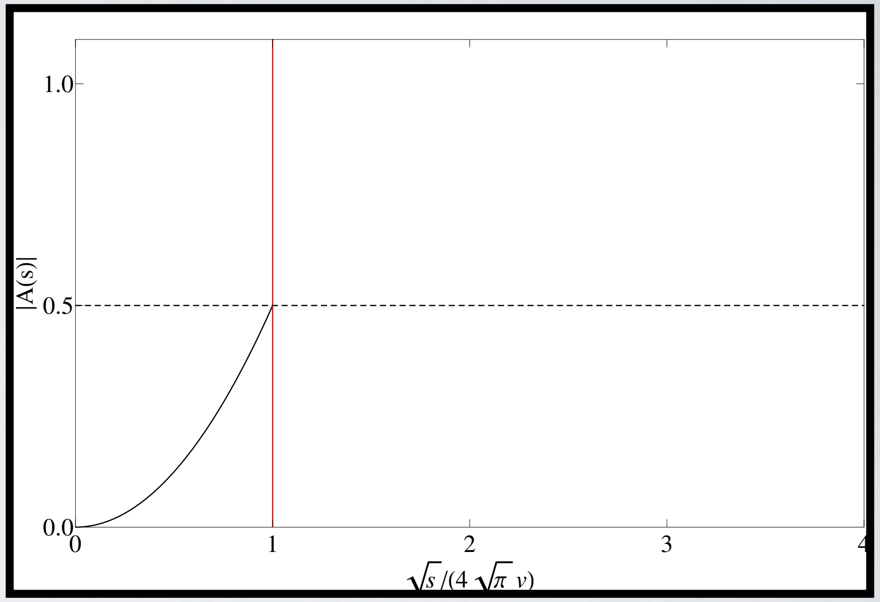

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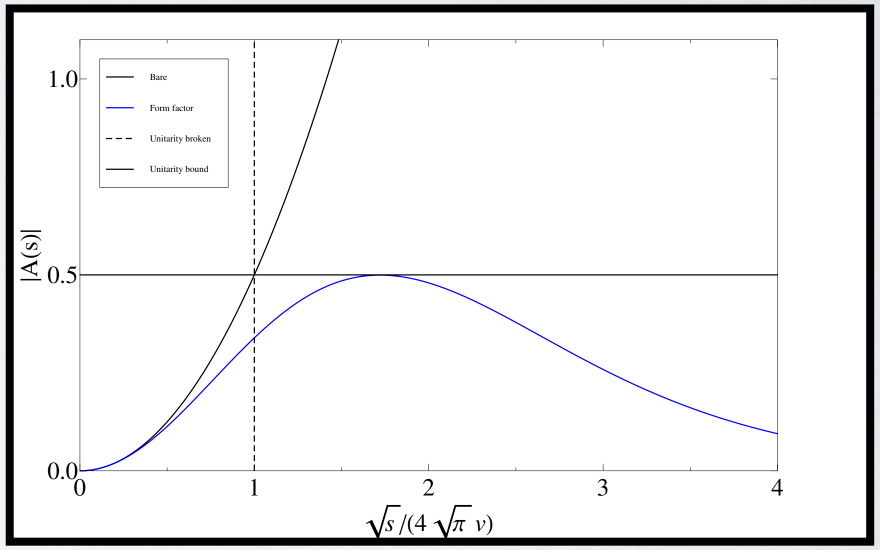

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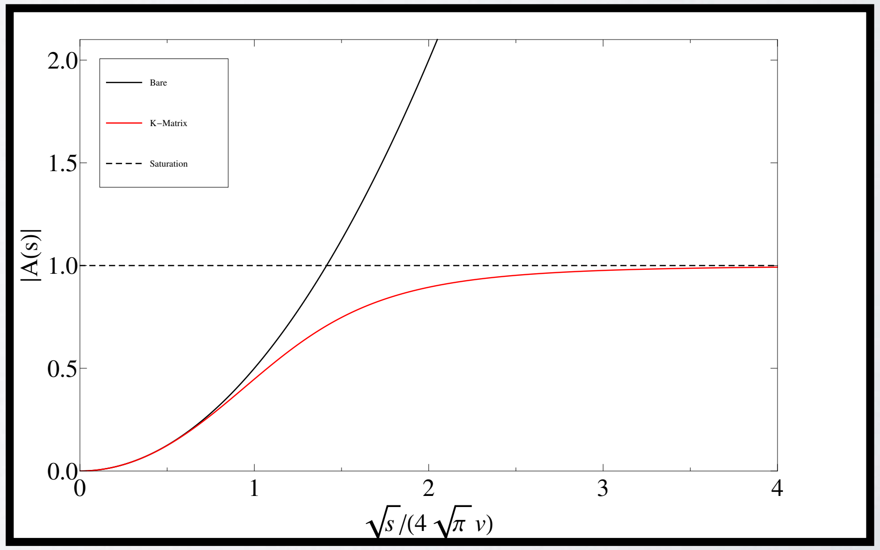
K-/*T*-matrix saturation $a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$



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

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

Different unitarity projections

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

Heitler, 1941; Schwinger, 1949; Gupta, 1950

- Stereographic projection to Argand circle

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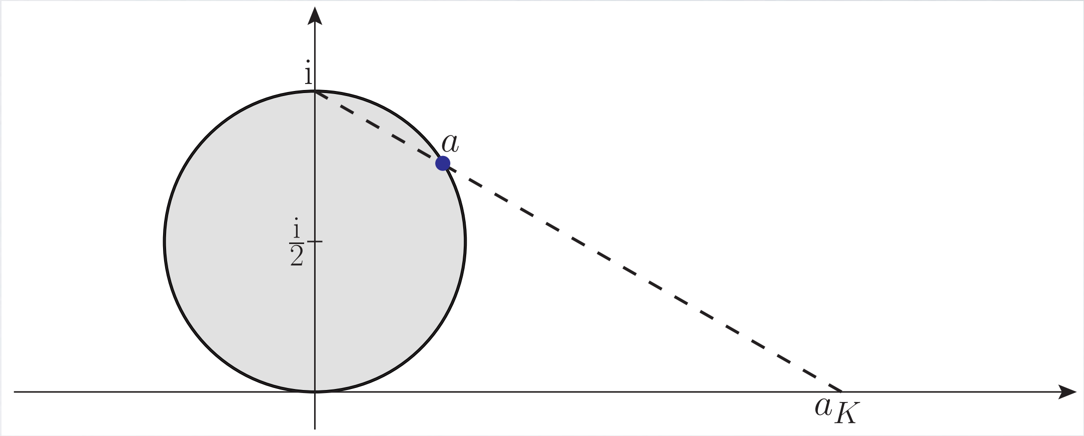

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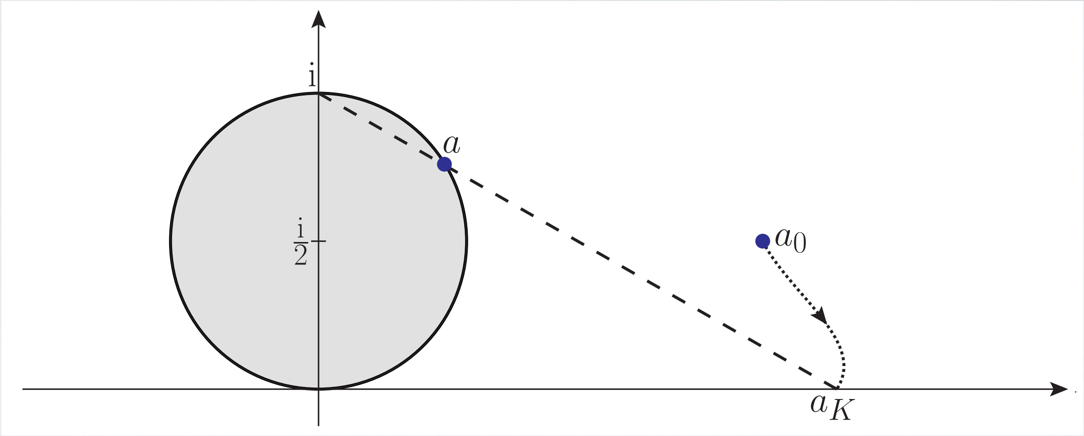

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- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator

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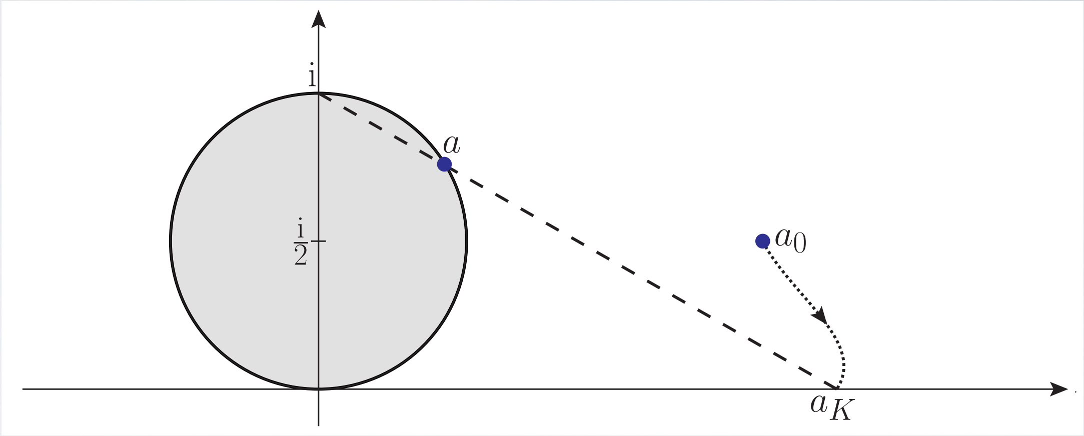

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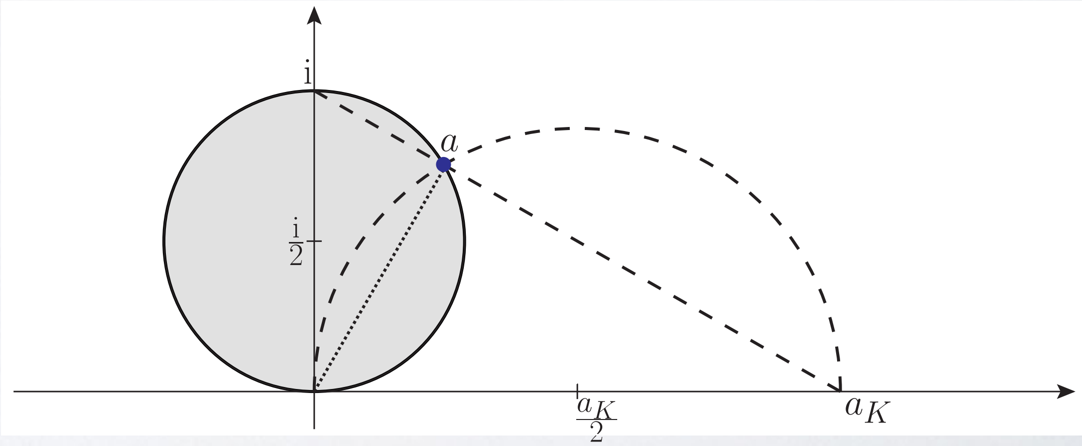

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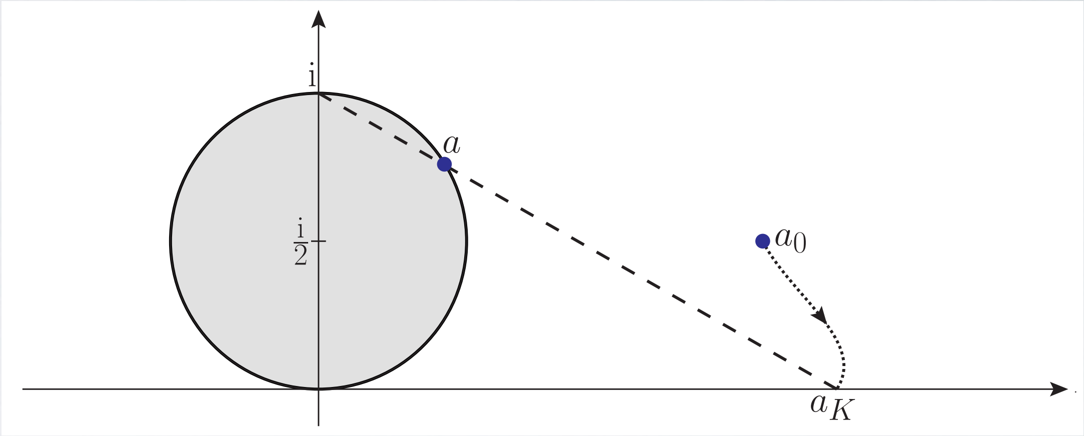

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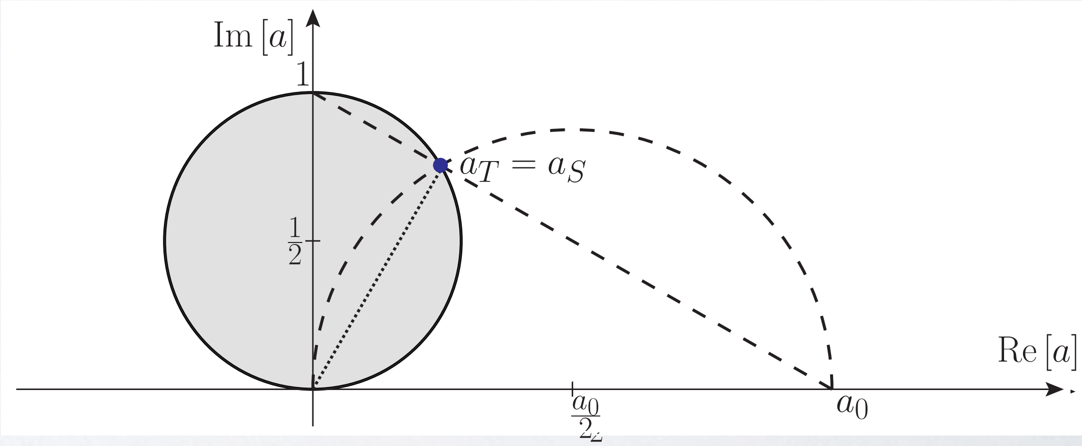

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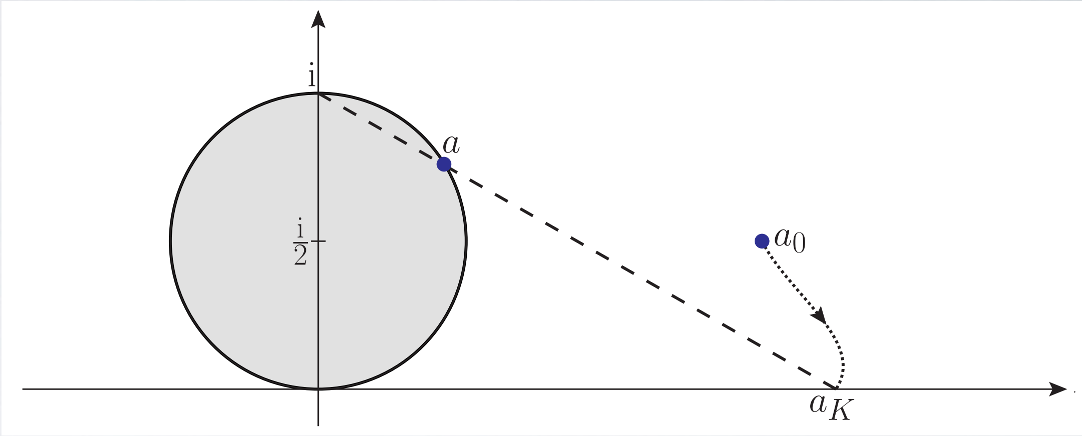

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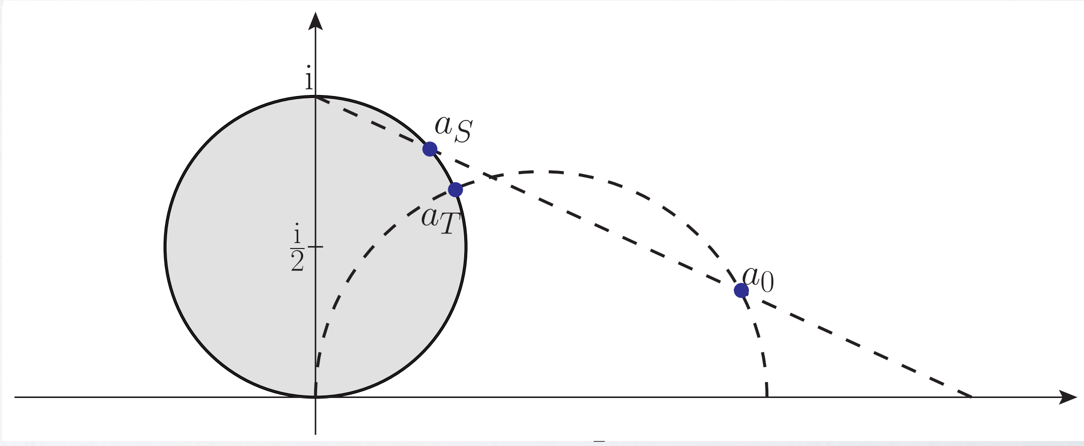

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- Independent Amplitude Method (IAM) [Truong, 1988; Dobado/Herrero/Truong, 1990], Padé [Padé, 1890; Basdevant/Lee, 1970], N/D method [Chew/Mandelstam, 1960]
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Unitarization of transverse operators

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

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

> Extract all partial waves:

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

Braß/Fleper/Kilian/JRR/Sekulla, 1807.02512

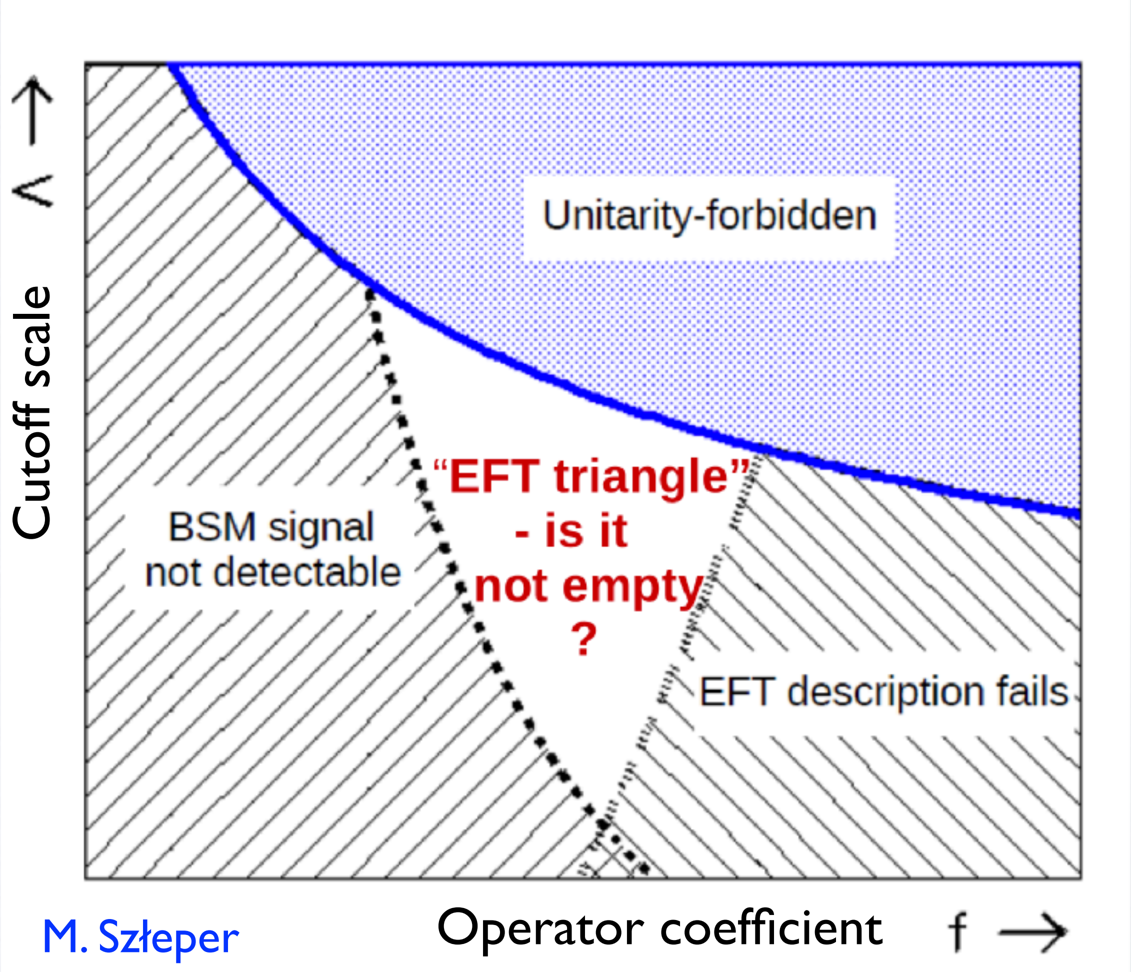
i \ j	0			1			2			$\boldsymbol{\lambda}$			
0	-6	-2	$-\frac{5}{2}$	0	0	0	0	0	0	+	+	+	+
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	−	+	−
	0	0	0	0	0	0	$-\frac{2}{5}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	−	−	+
	$-\frac{22}{3}$	$-\frac{14}{3}$	$-\frac{11}{6}$	0	0	0	$-\frac{2}{15}$	$-\frac{4}{15}$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

(In)Validity of (In)Effective Field Theories

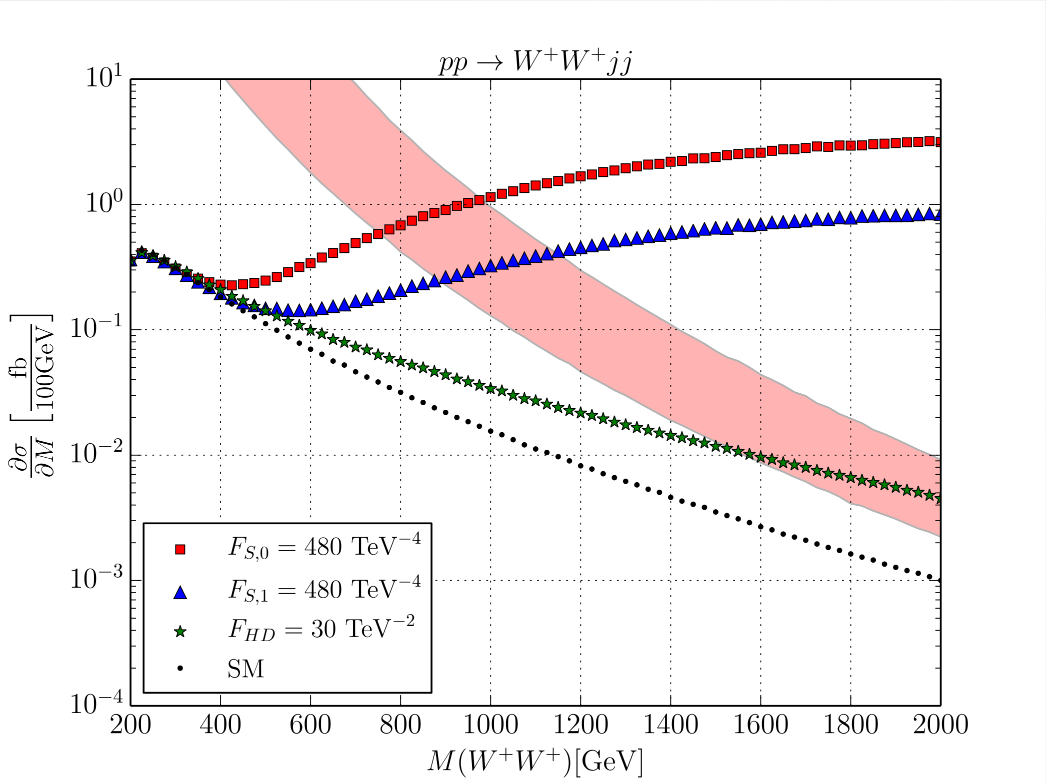
- **Resonances in direct reach** (not clear: strongly interacting models [e.g. σ resonance]
- **Estimate of operatDors coefficients** (difficult for strongly coupled models)

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

- **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**



VBS diboson spectra



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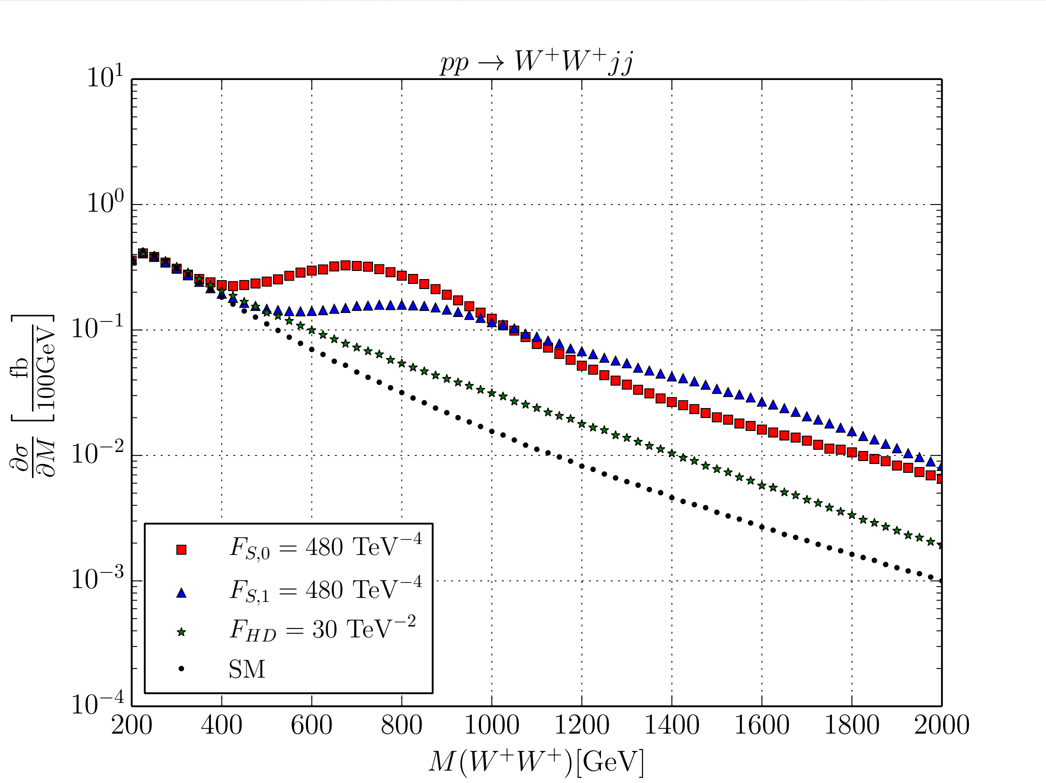

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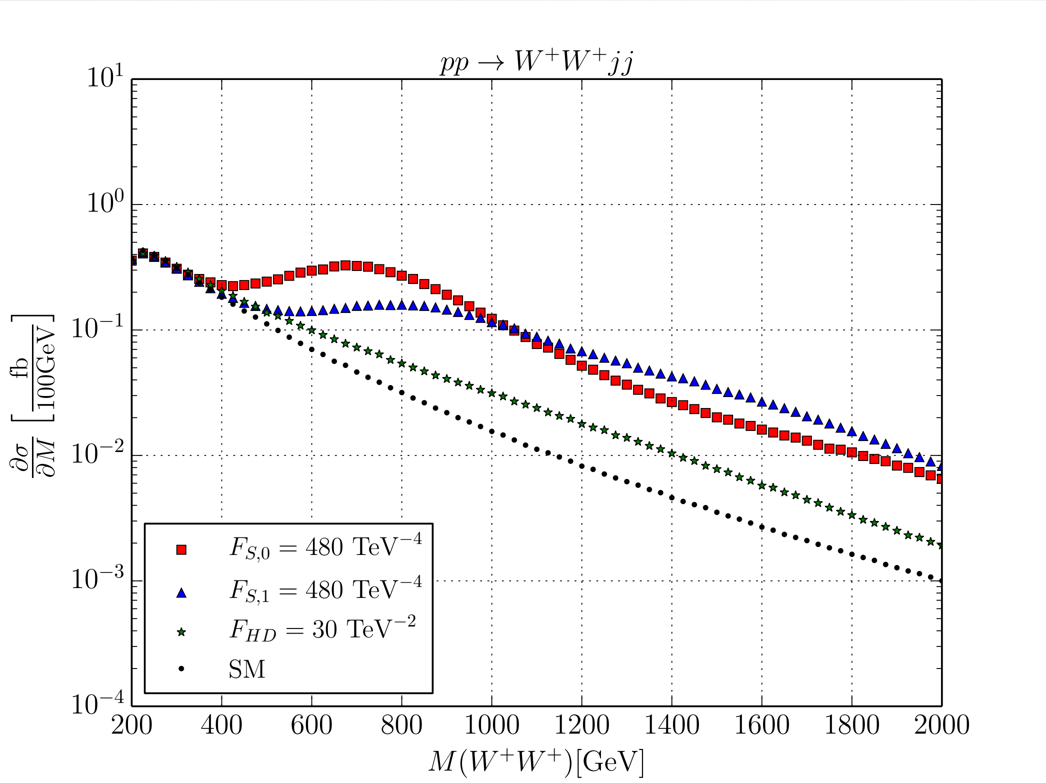

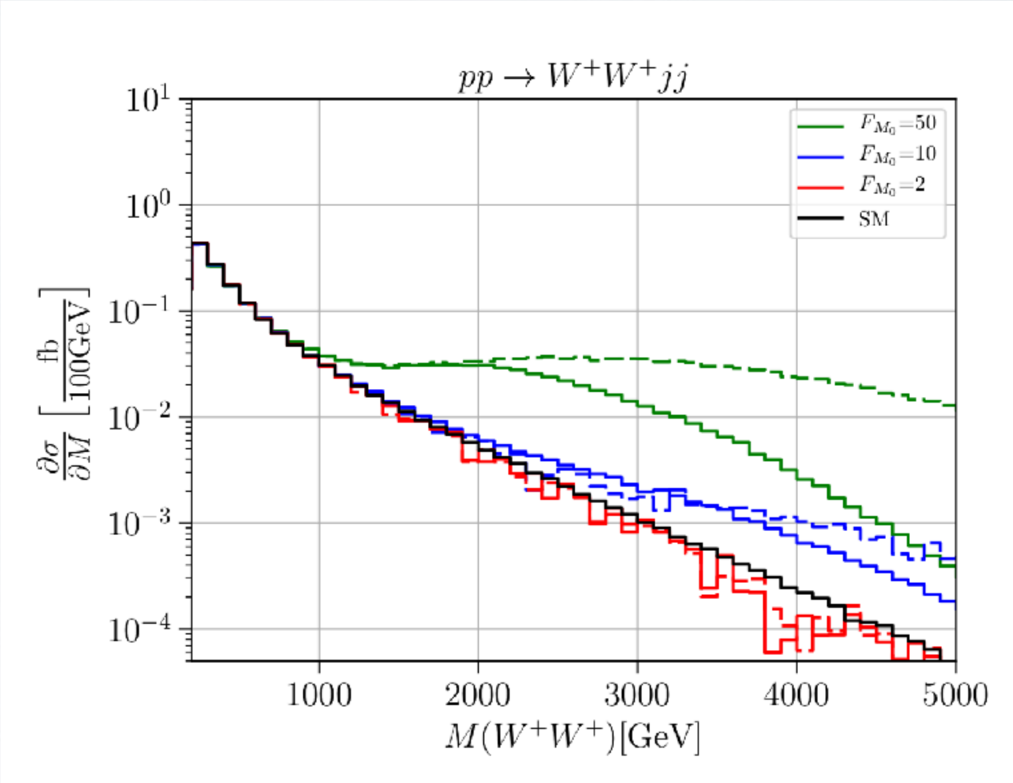

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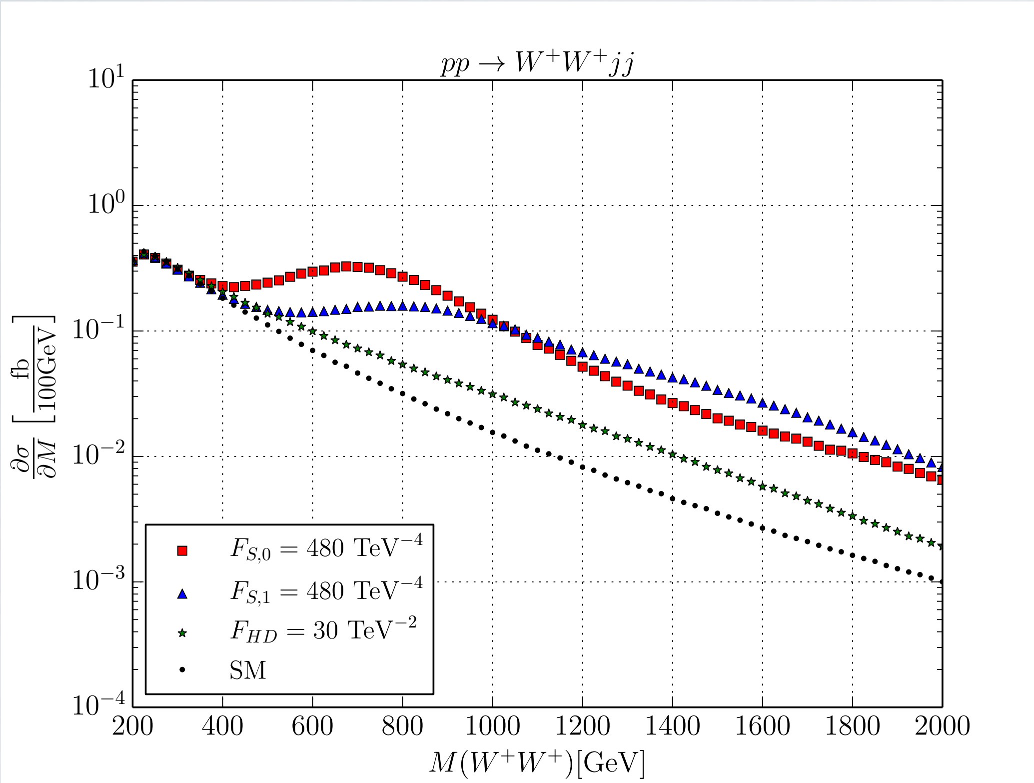

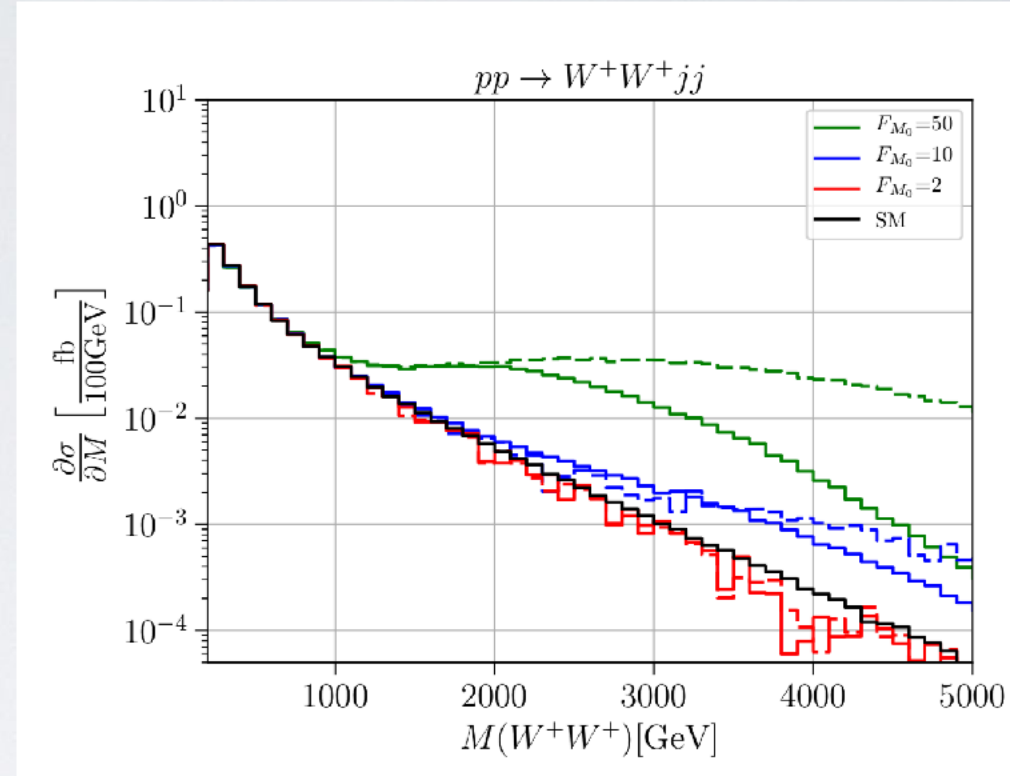

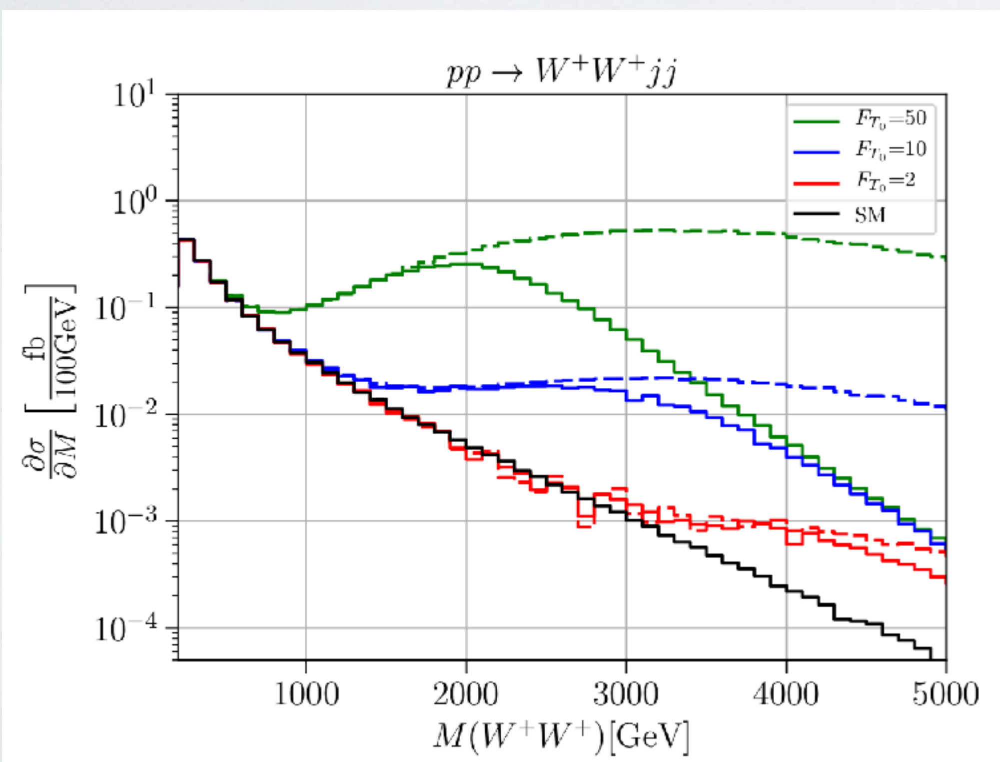

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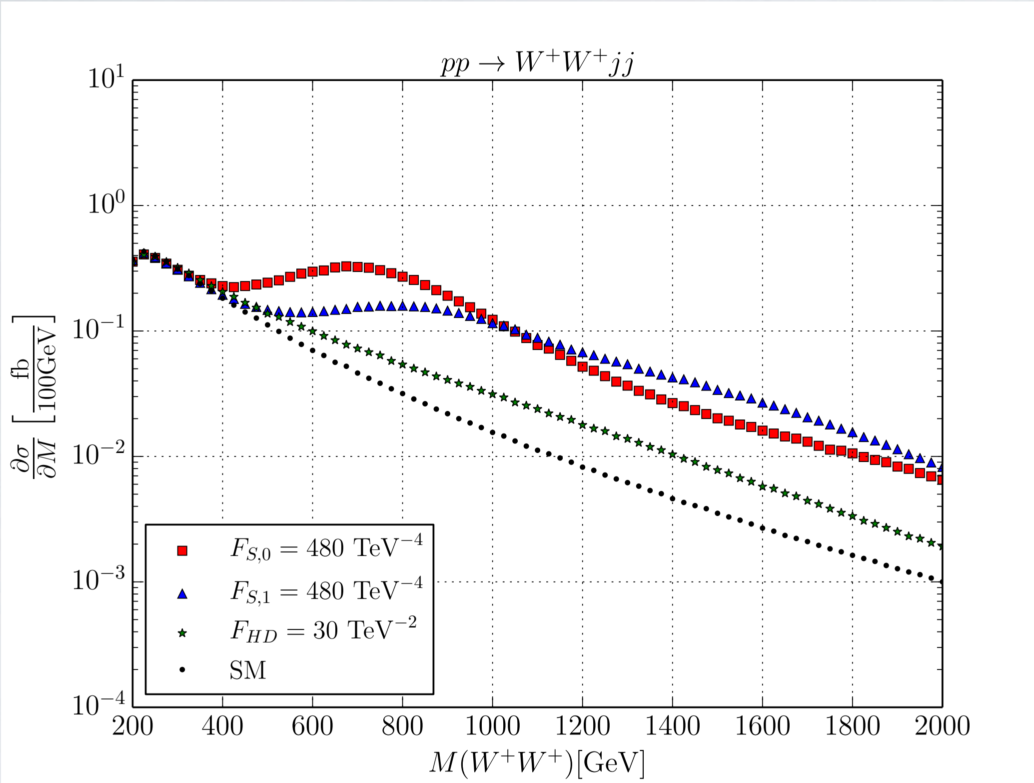

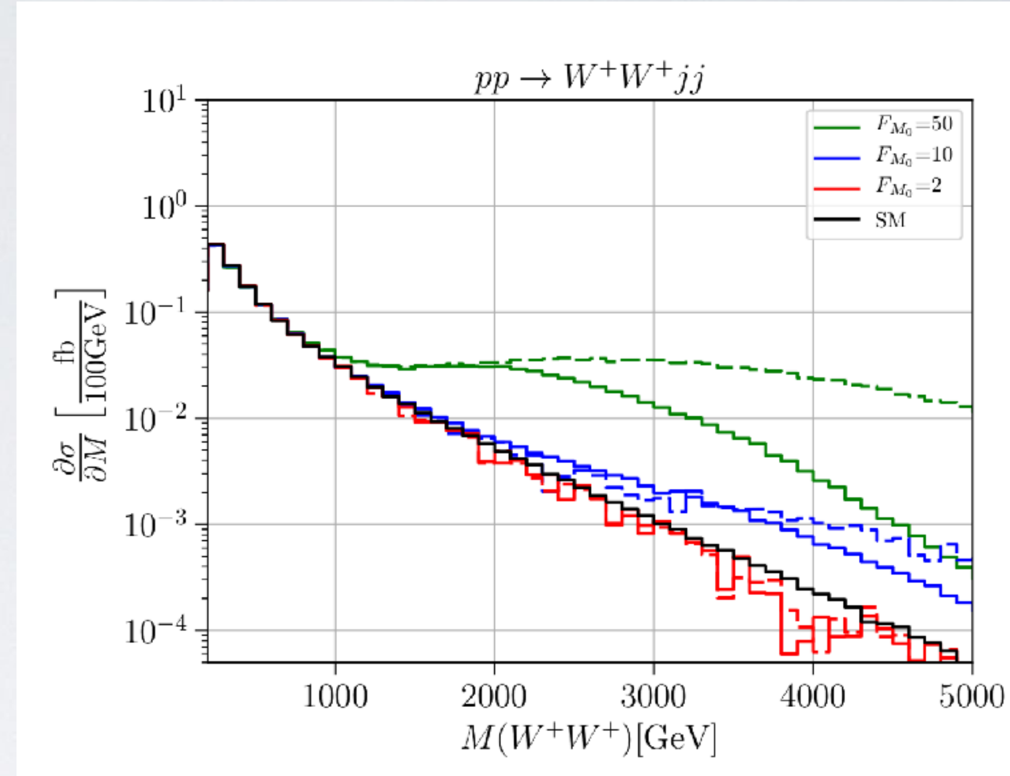

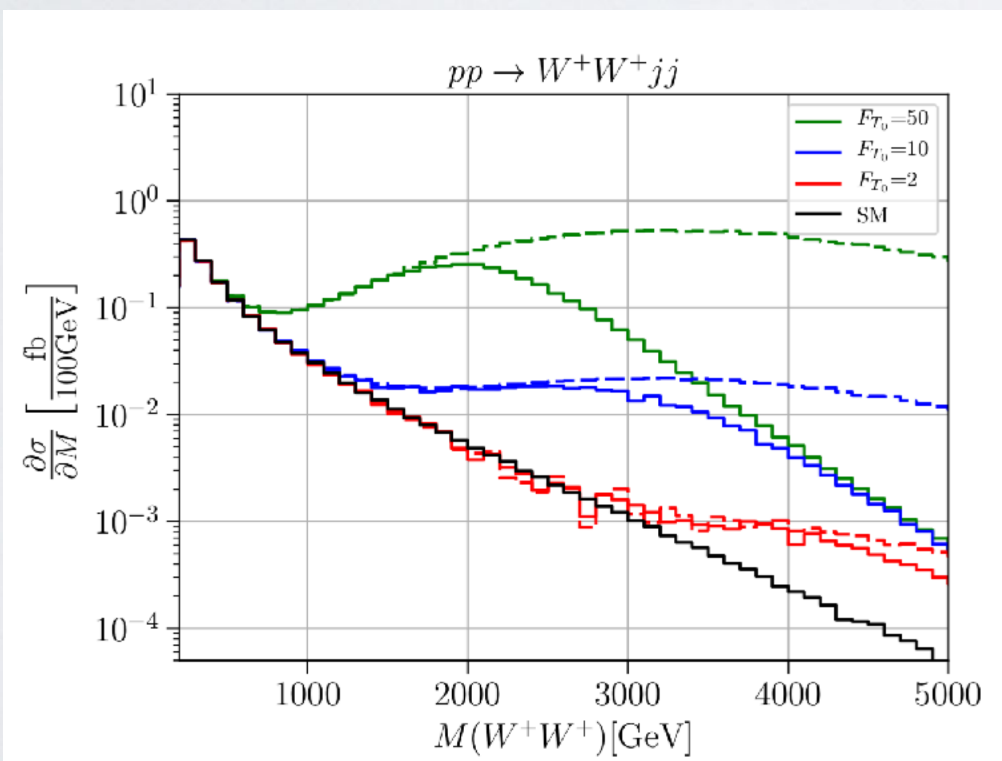

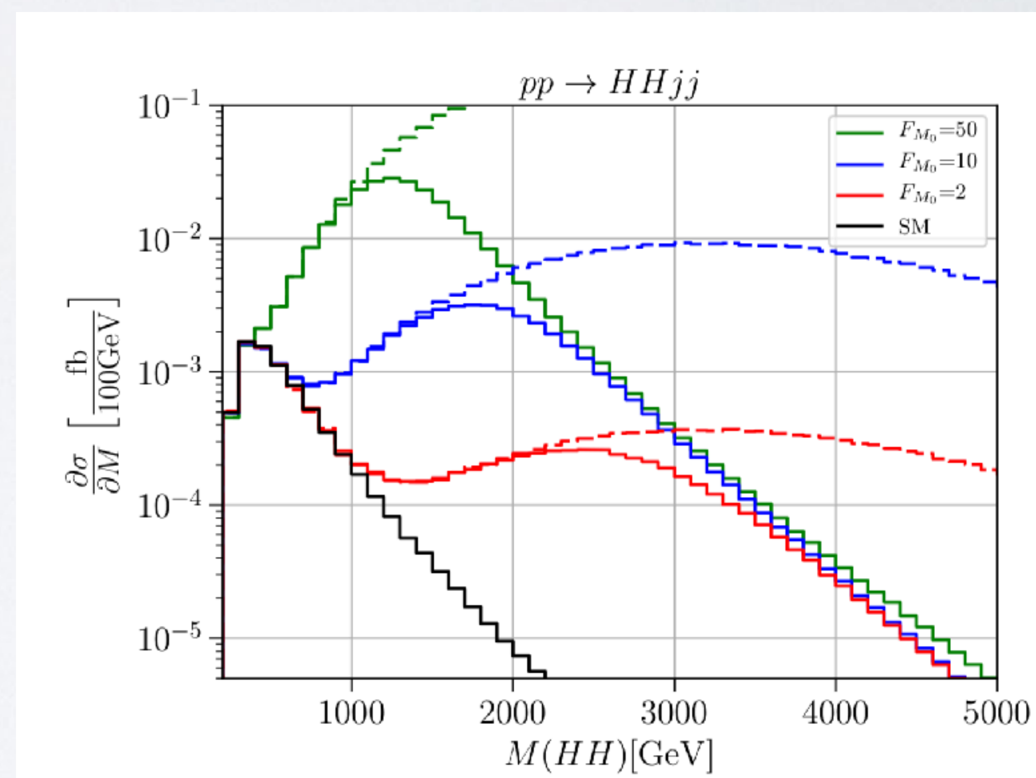

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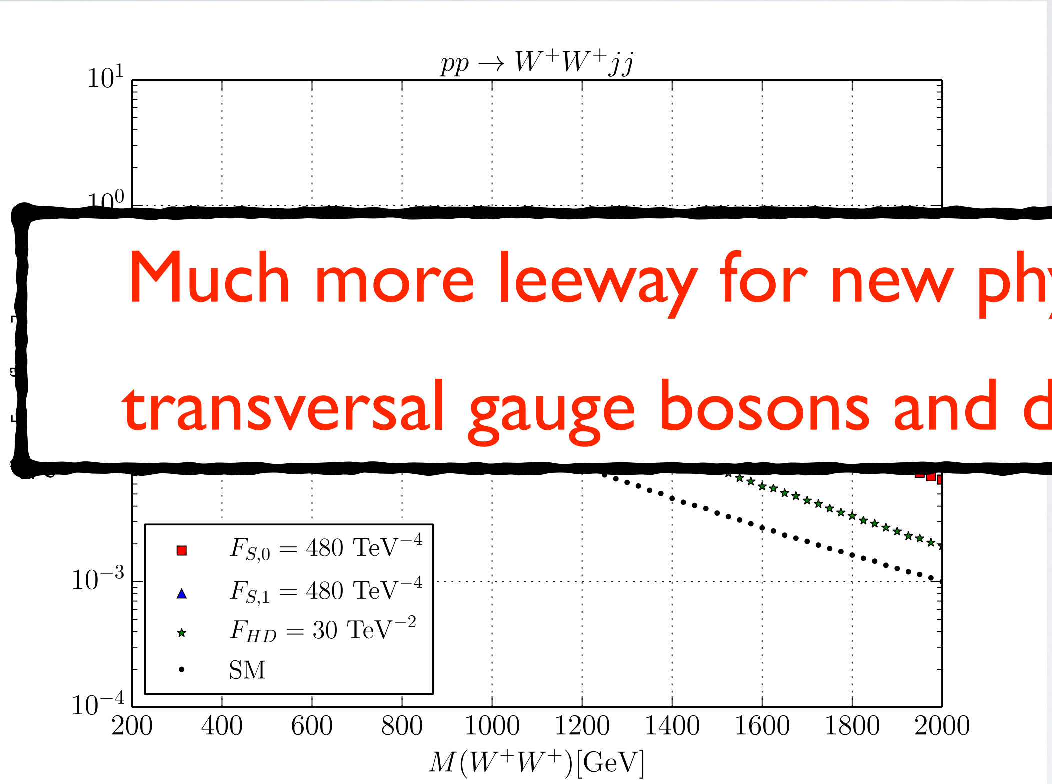
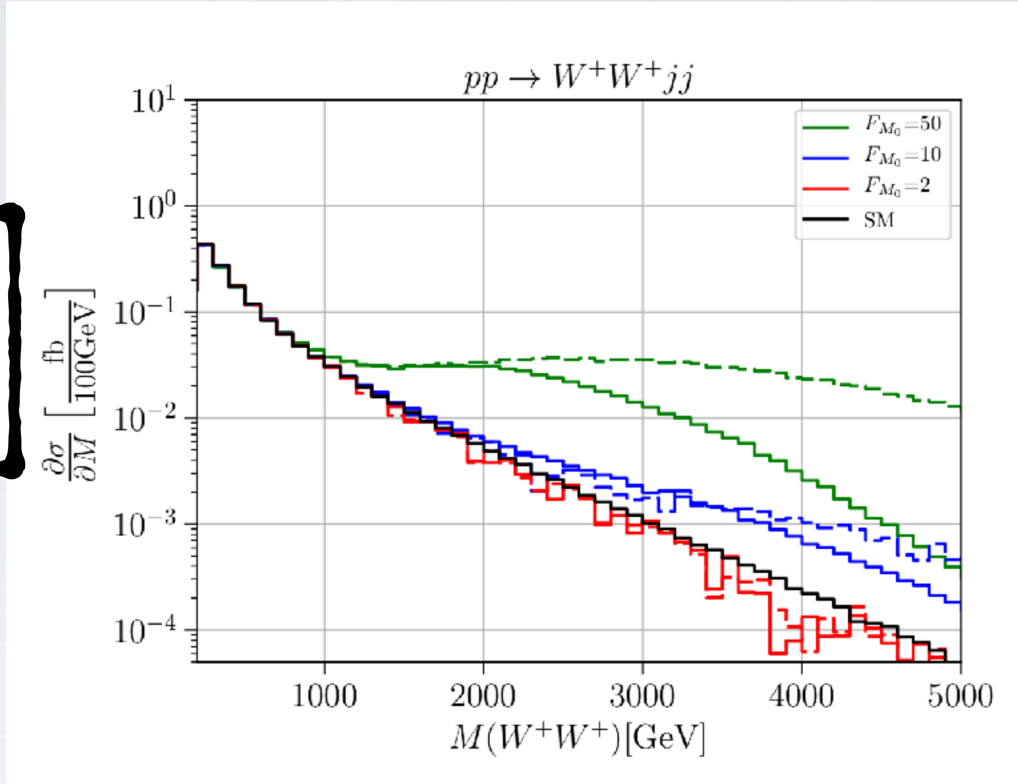
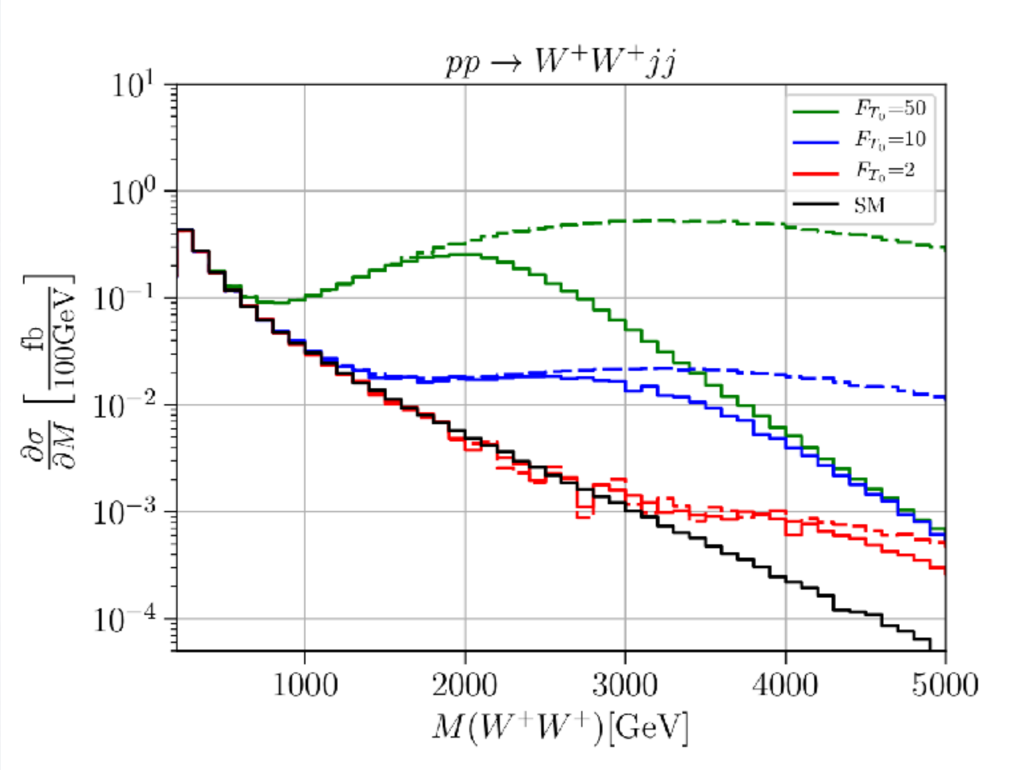
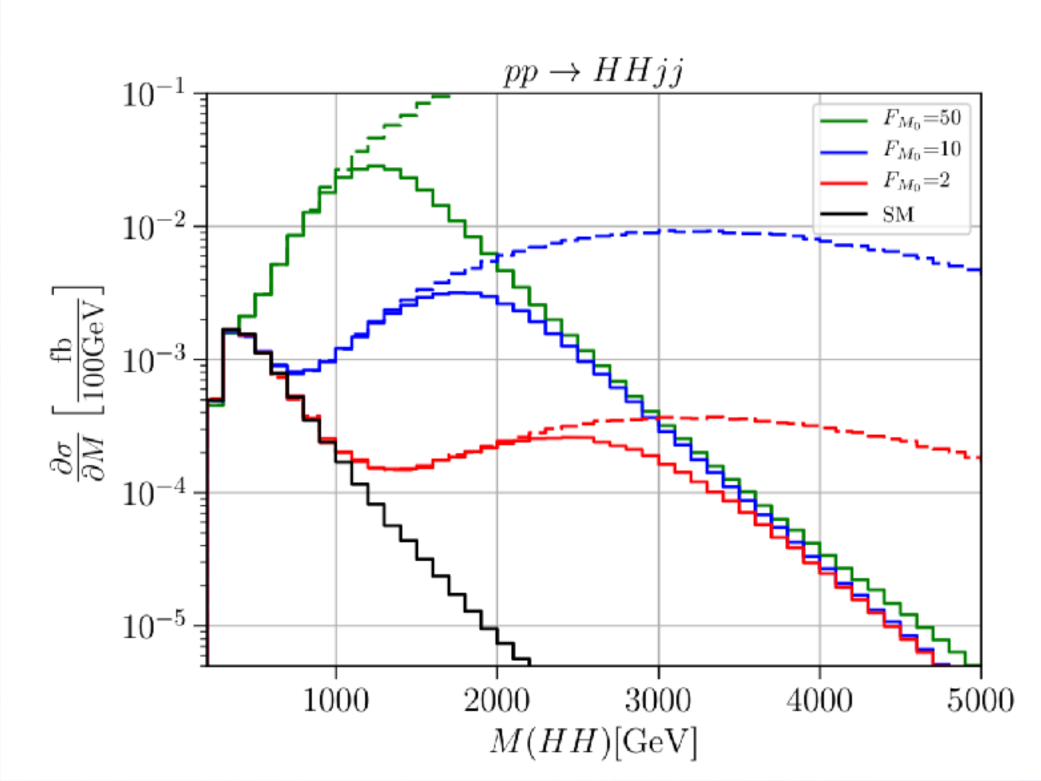


Much more leeway for new physics in transversal gauge bosons and di-Higgs







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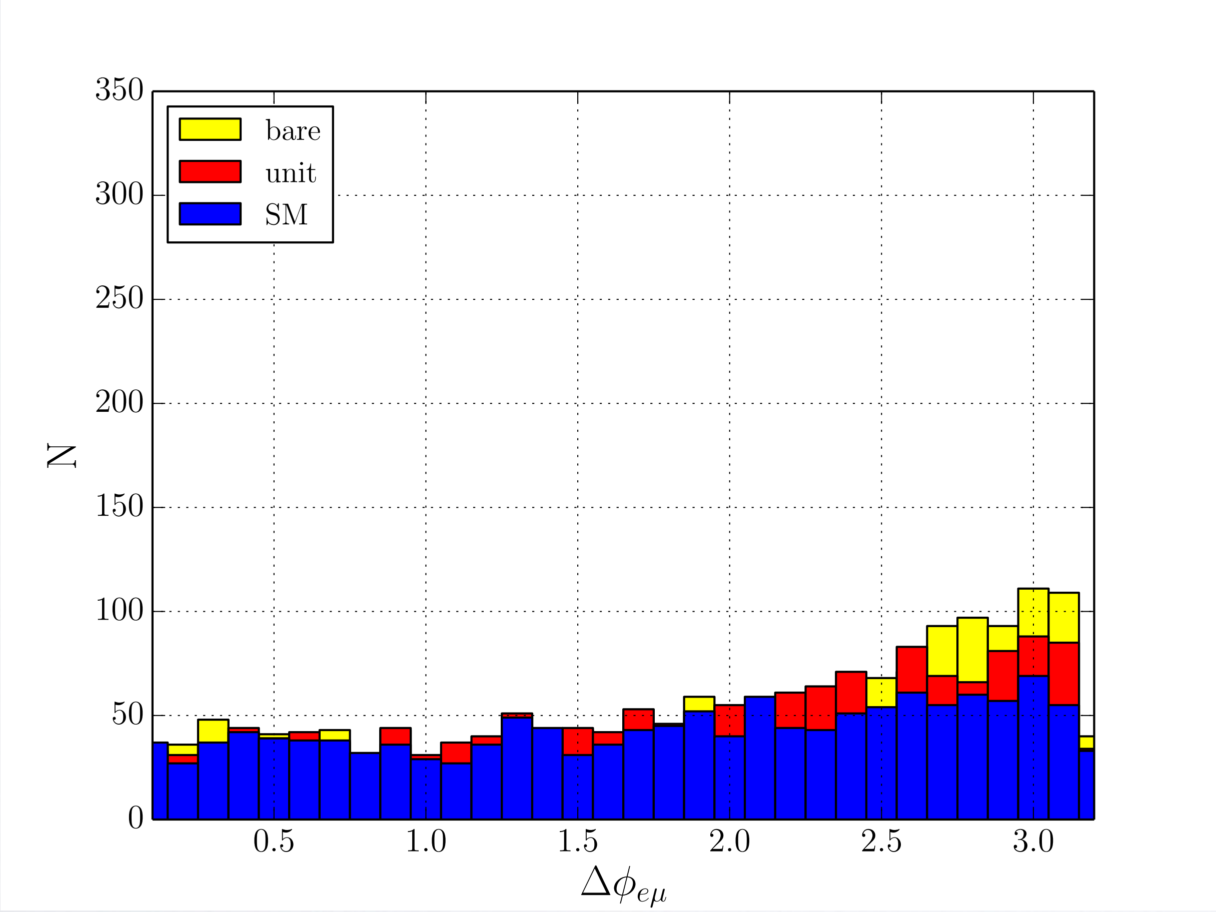
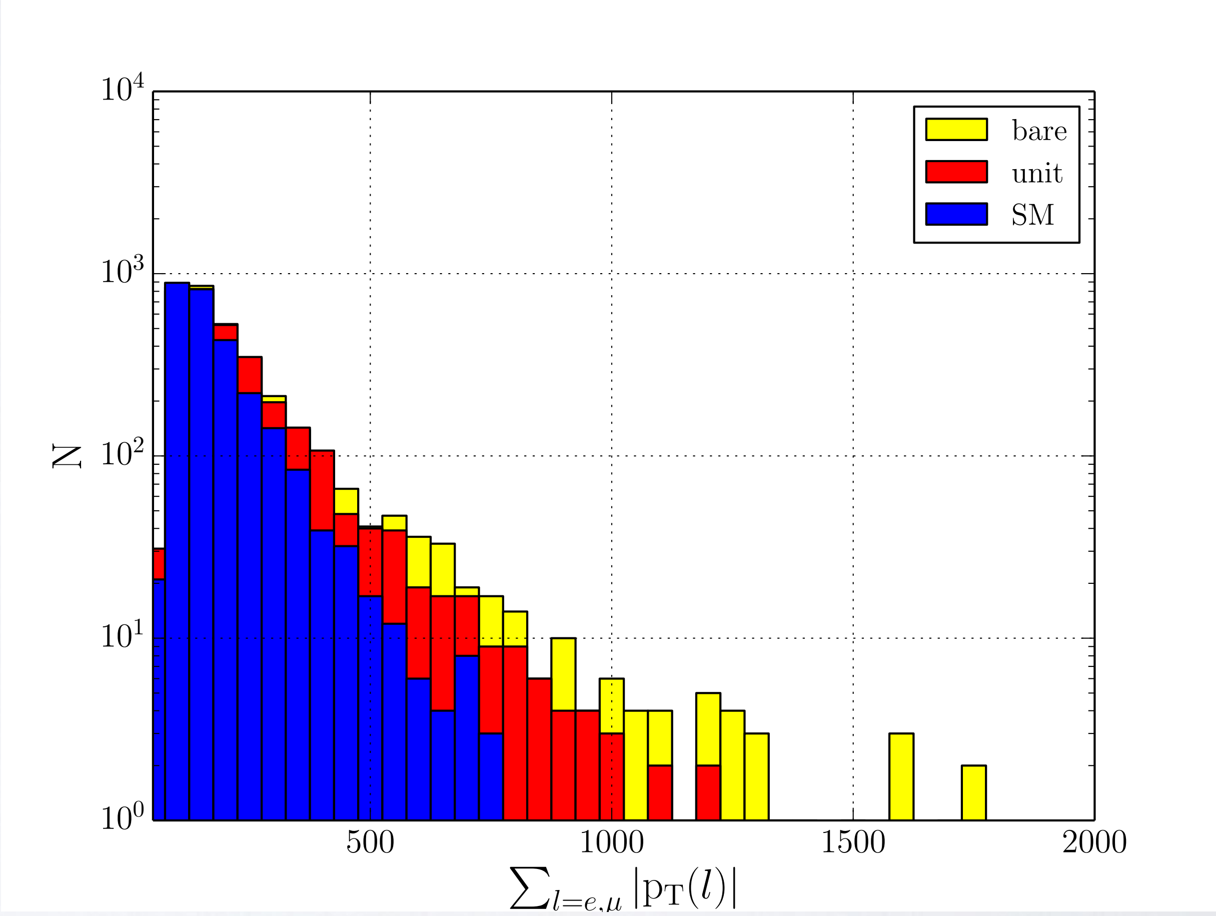
$$\mathcal{L}_{HD} = F_{HD}\,\text{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right]\cdot \text{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\,\mathbf{D}_\mu\mathbf{H}\right] \qquad F_{HD} = 30\,\text{TeV}^{-2}$$





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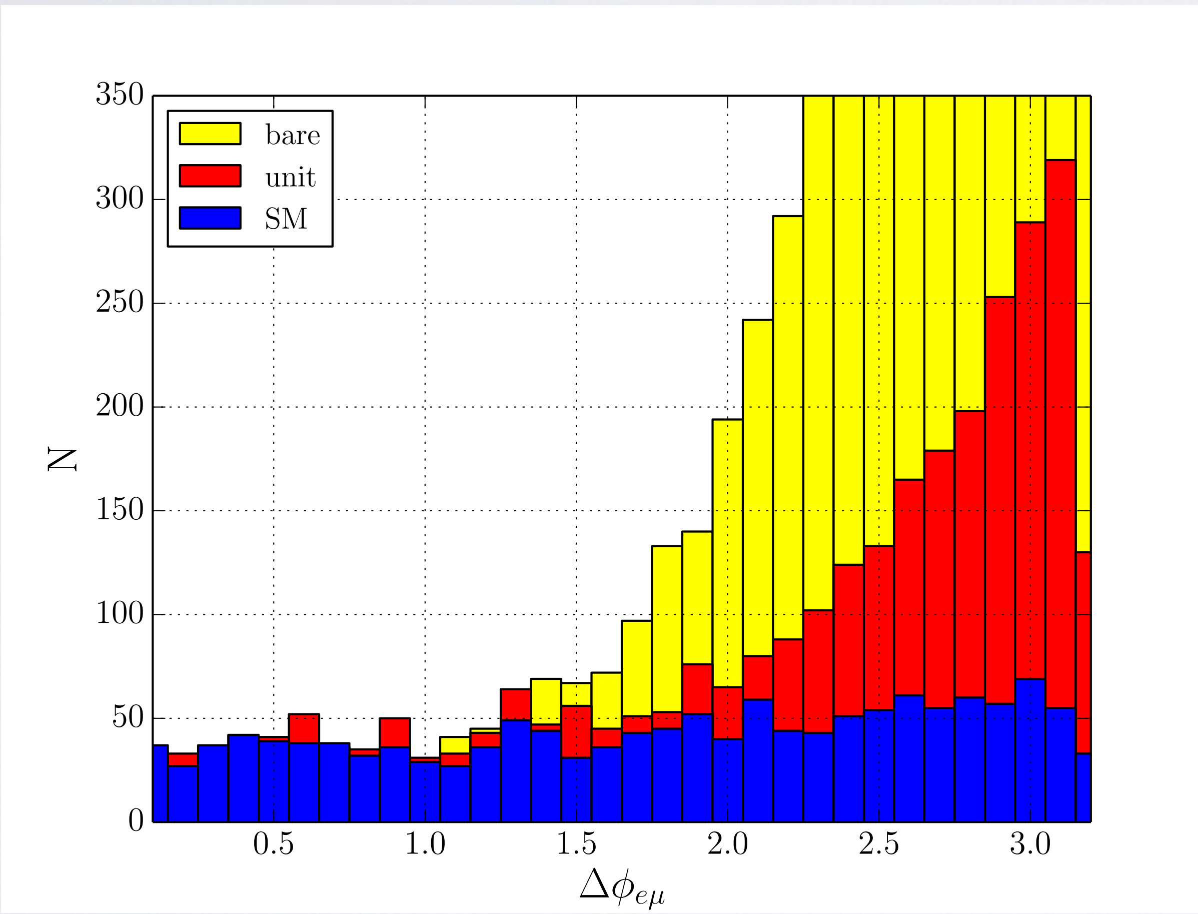

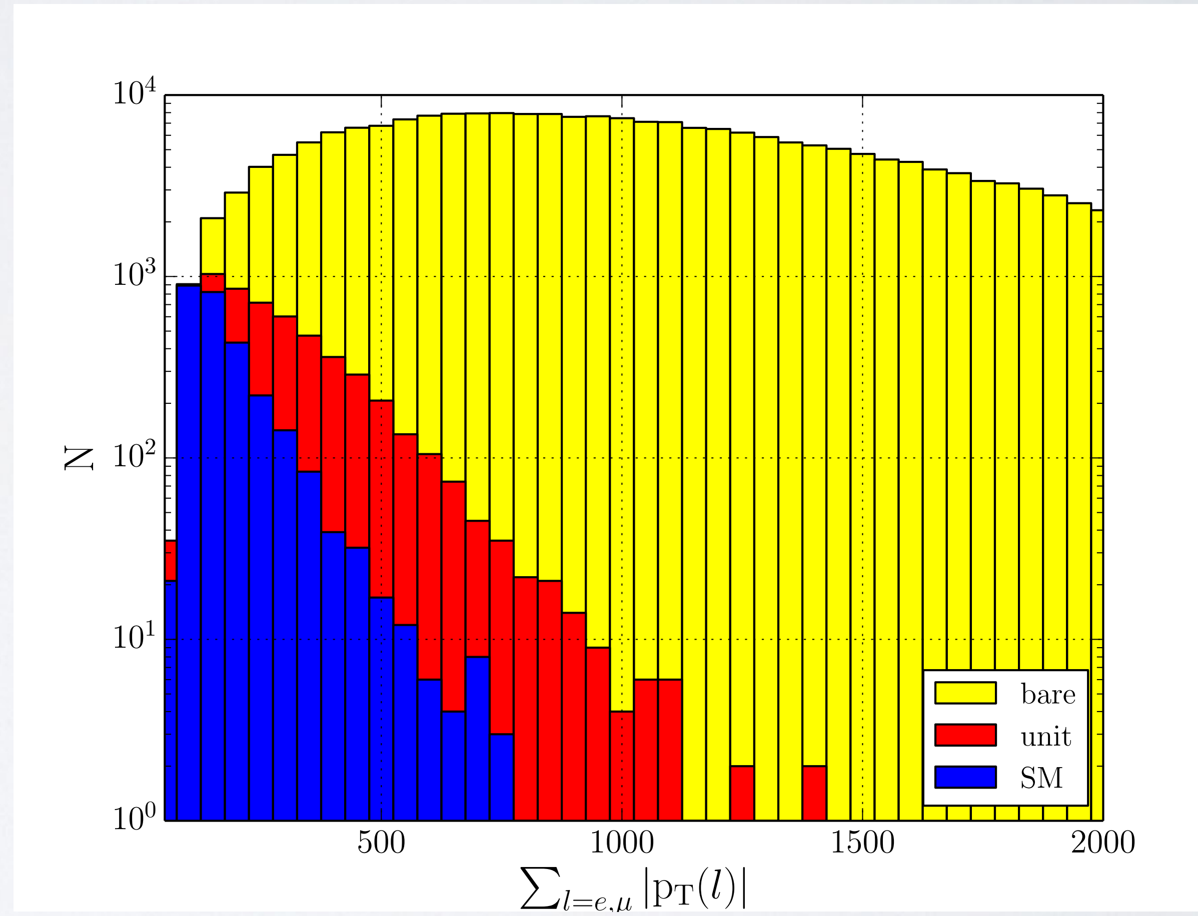

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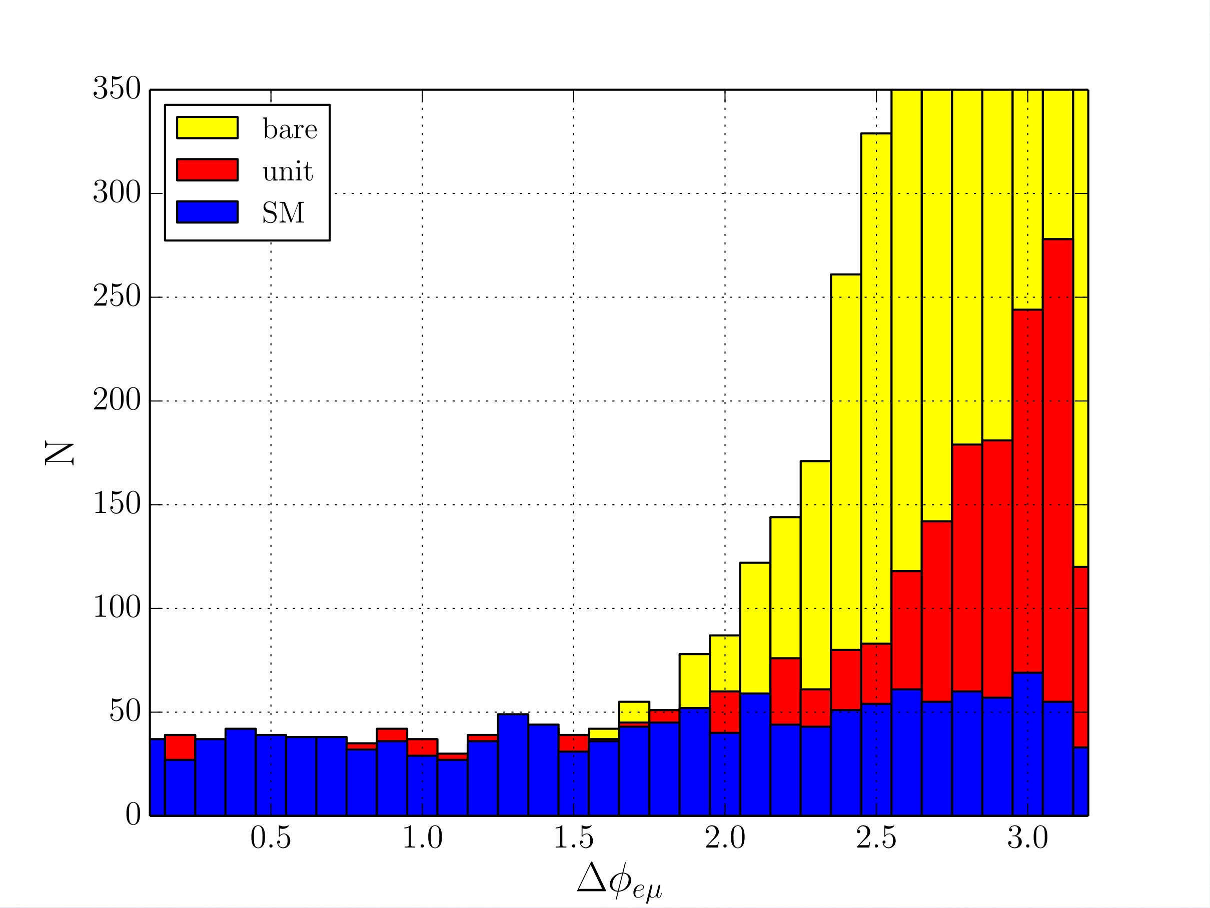

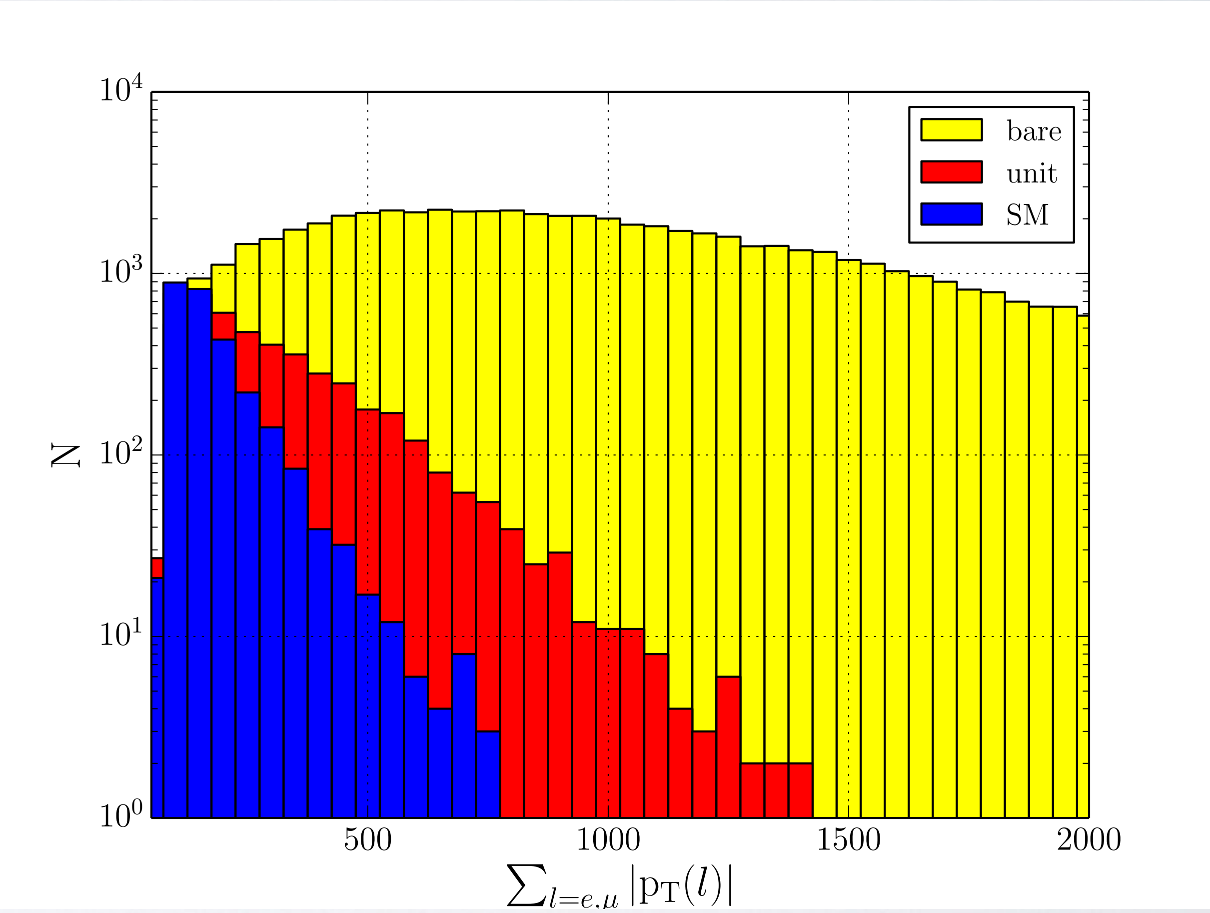

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Beyond the EFT: Simplified models

- Rise of amplitude: is Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
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- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

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

	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

Beyond the EFT: Simplified models

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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

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

Kilian/Ohl/JRR/Sekulla, 1511.00022

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- Fierz-Pauli conditions not valid off-shell

Kilian/Ohl/JRR/Sekulla, 1511.00022

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- Use Stückelberg formalism to make off-shell high-energy behavior explicit
- Introduce compensator fields $\Rightarrow$ no propagators with momentum factors
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$$\mathcal{L} = \frac{1}{2}f_{f\,\mu\nu}\left(-\partial^2 - m_f^2\right)f_f^{\mu\nu} + \frac{1}{2}f_{f\ \mu}^{\mu}\left(-\frac{1}{2}\left(-\partial^2 - m_f^2\right)\right)f_{f\ \nu}^{\nu}$$
$$+ \frac{1}{2}A_{f\mu}\left(\partial^2 + m_f^2\right)A_f^\mu + \frac{1}{2}\sigma_f\left(-\partial^2 - m_f^2\right)\sigma_f$$
$$+ \left(f_{\mu\nu} - \frac{1}{\sqrt{6}}\sigma_f g_{\mu\nu}\right)J_f^{\mu\nu}$$
$$- \left(\frac{1}{\sqrt{2}m_f}\left(A_{f\mu}\partial_\nu + A_{f\nu}\partial_\mu\right) - \frac{\sqrt{2}}{\sqrt{3}m_f^2}\sigma_f\partial_\mu\partial_\nu\right)J_f^{\mu\nu}$$

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

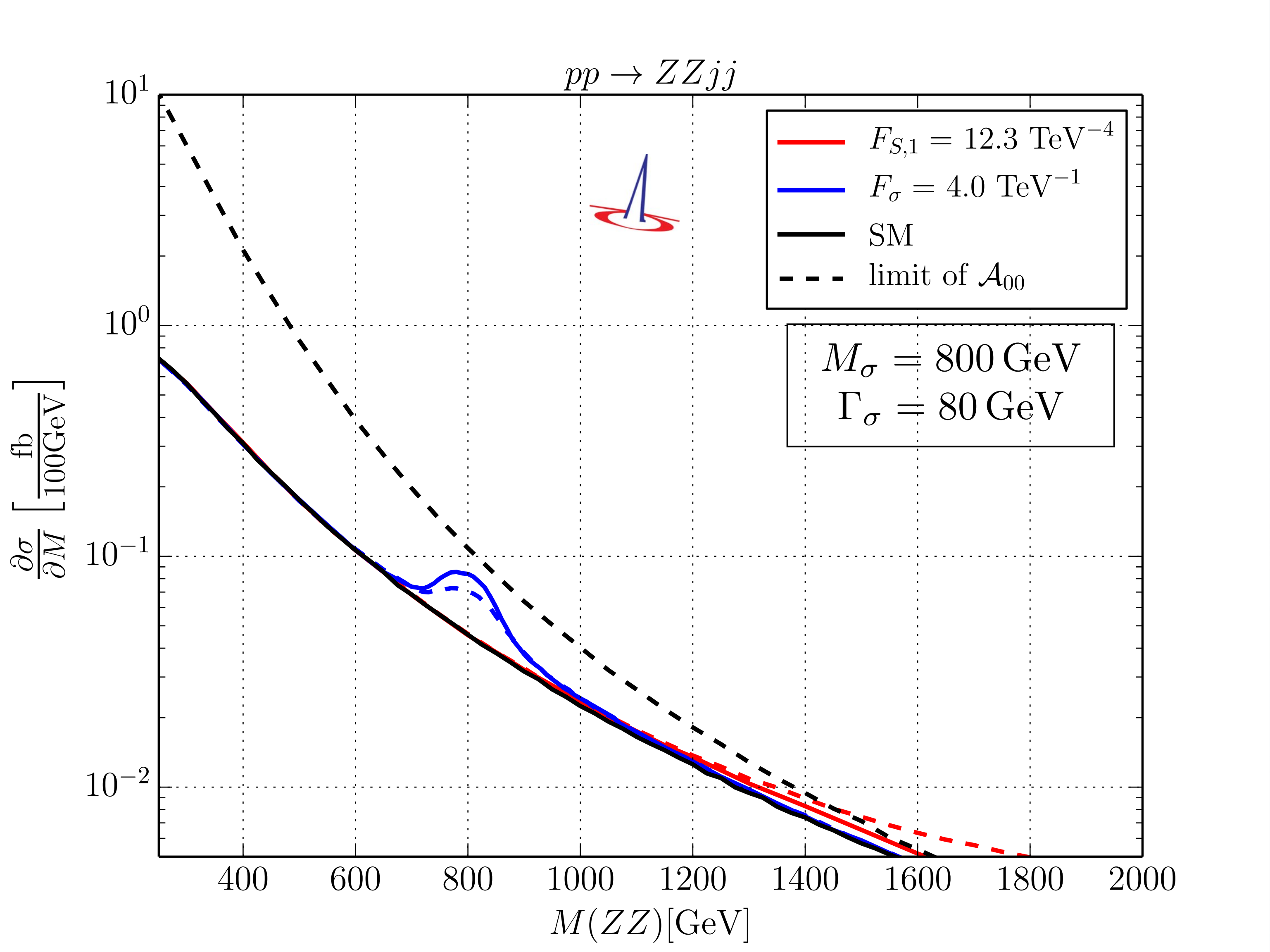
Gauge fixing: $\sigma = -\phi$

Comparison: Simplified Models & EFT

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

Brass/Fleper/Kilian/JRR/Sekulla: w. EPJC [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

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

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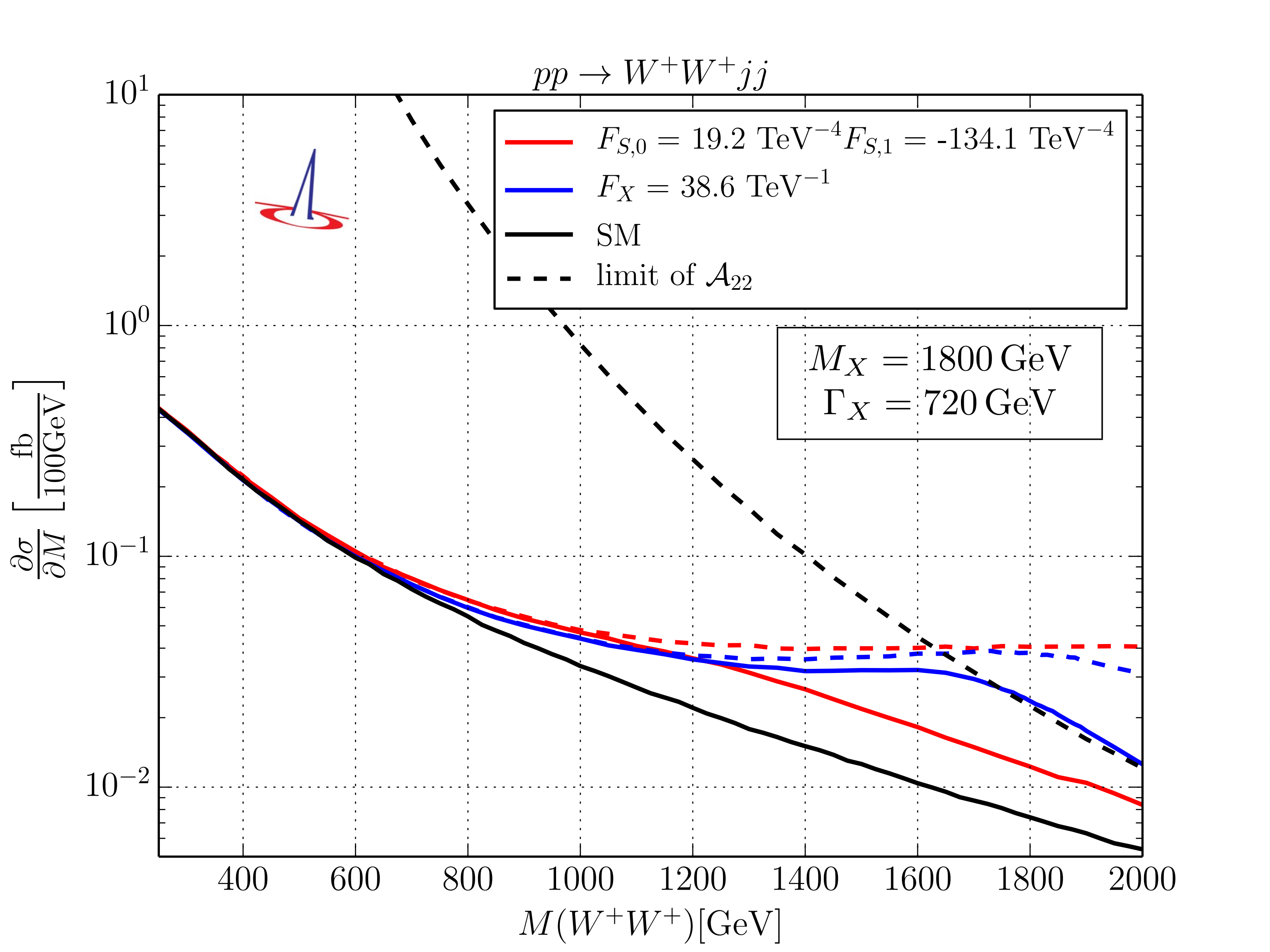

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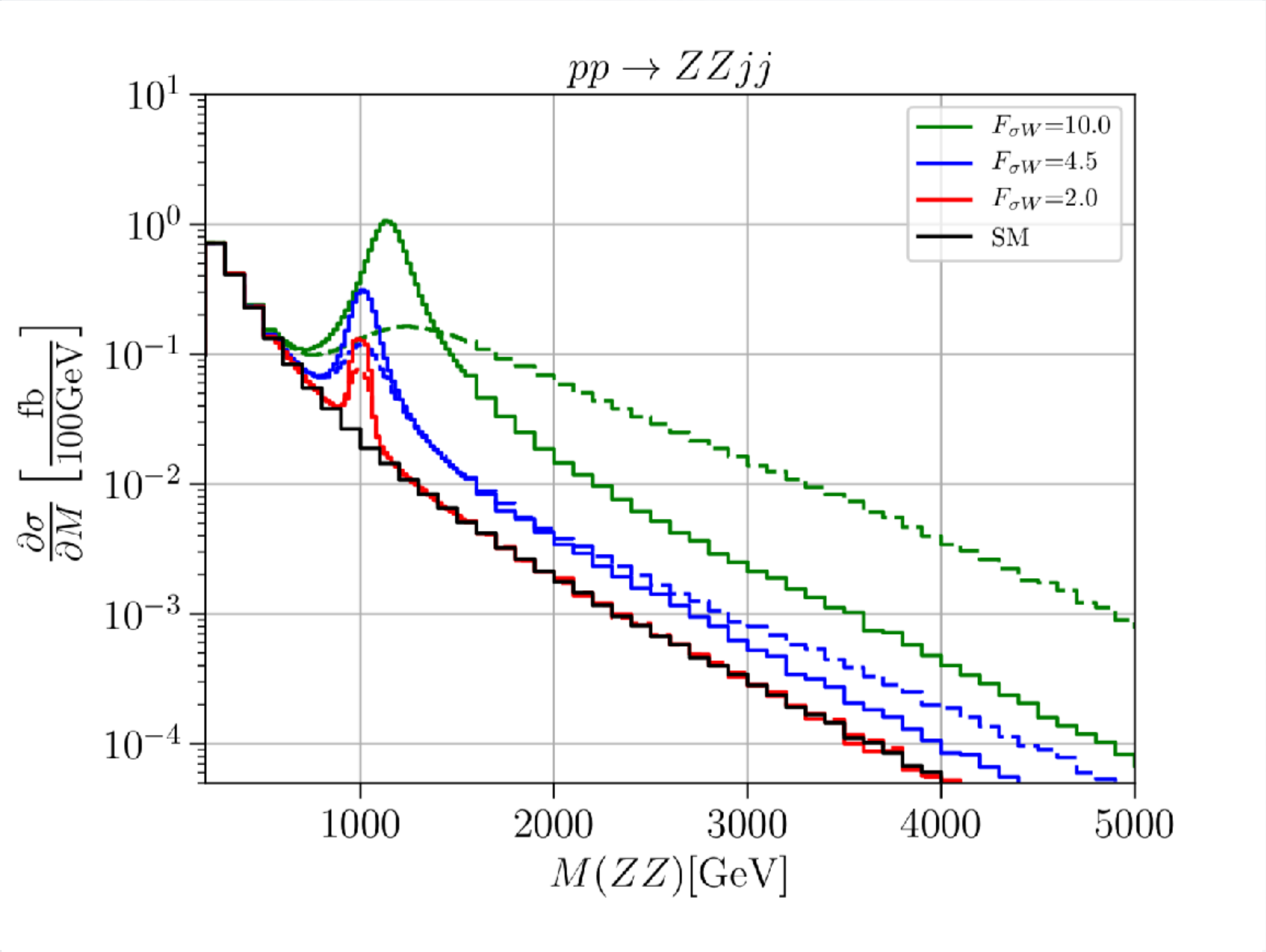

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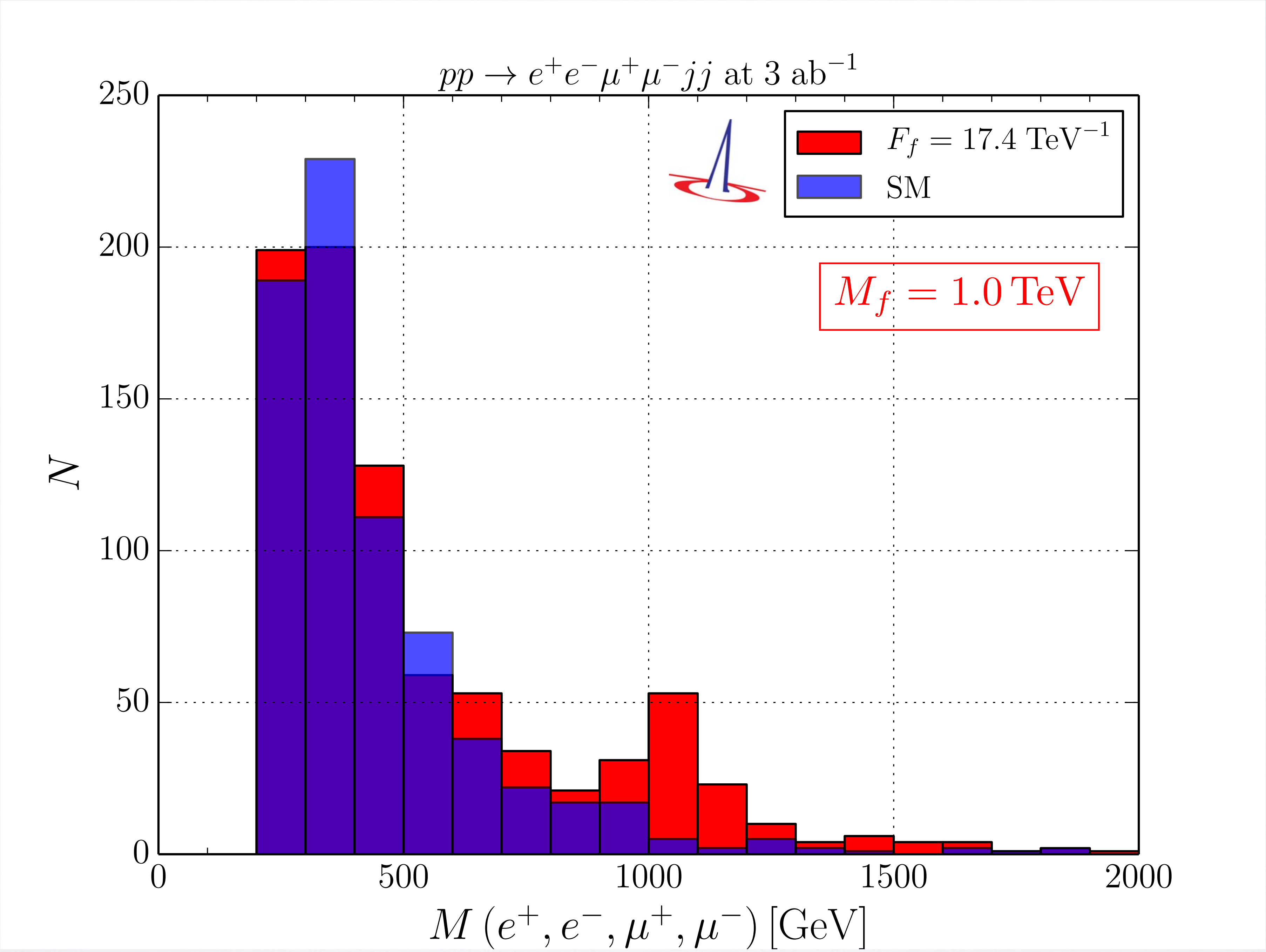
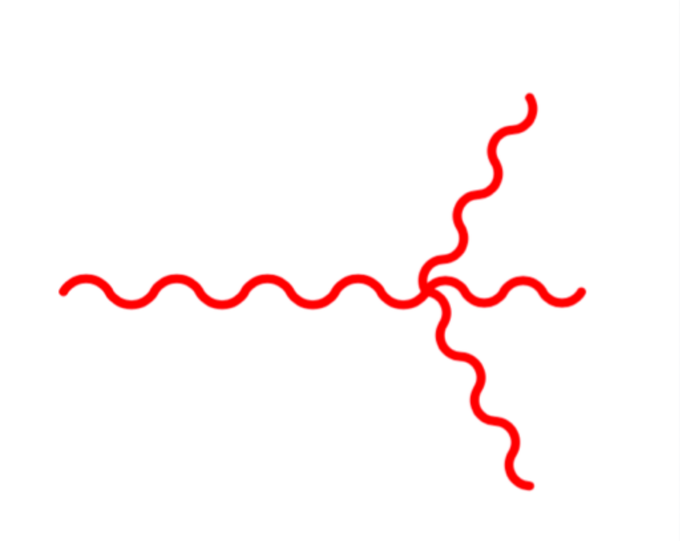
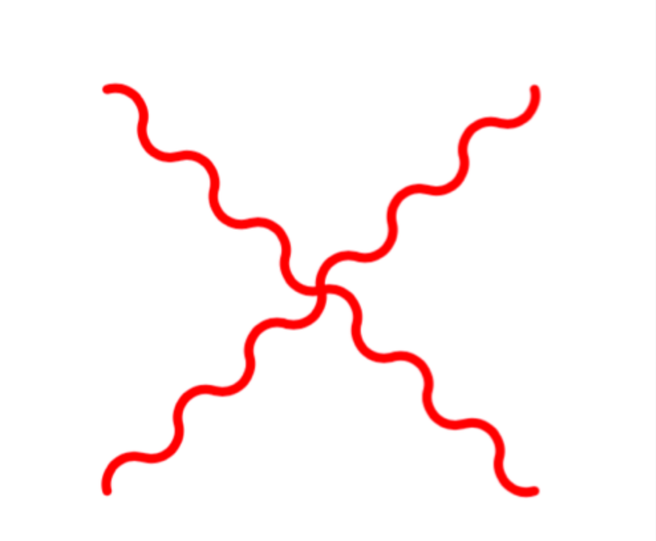
Complete LHC process at 14 TeV



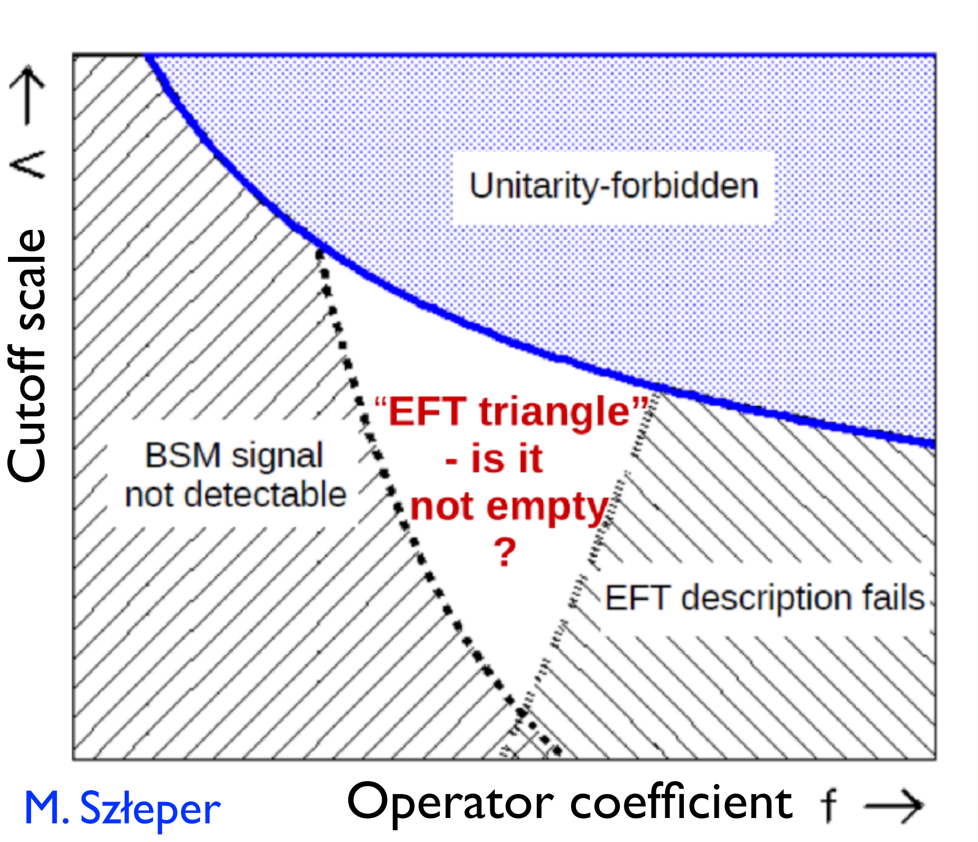
Triple [multiple] Vector Boson Production ?

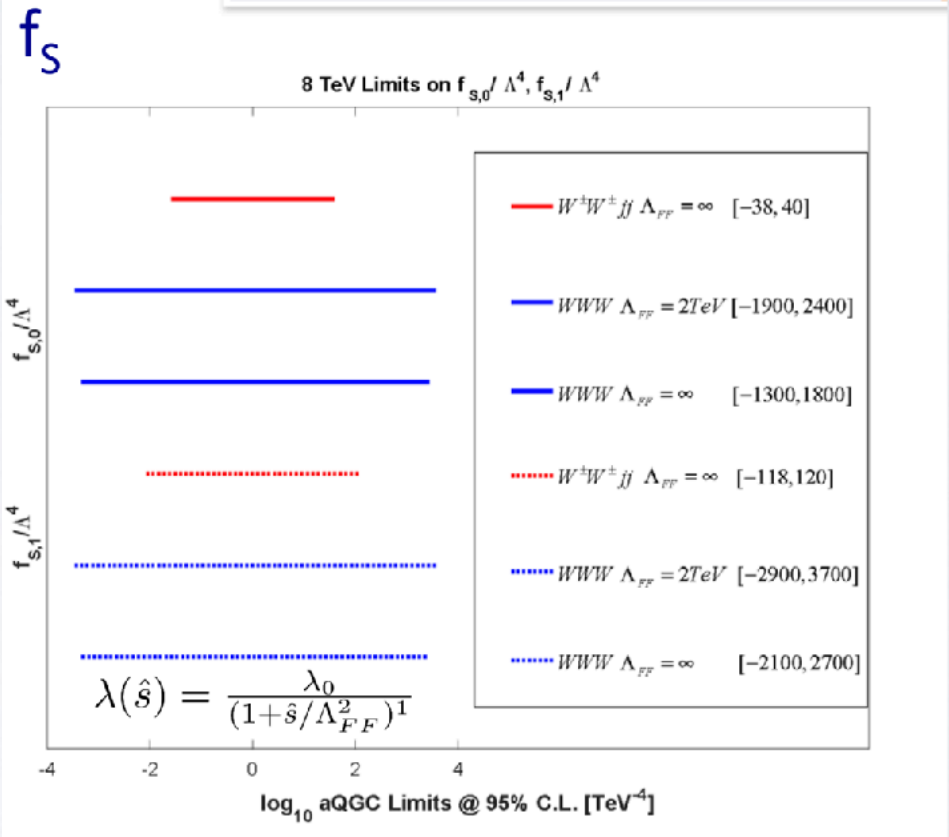
Relate  to  ?

- 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.”)

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
- ✦ Generation of (subsets of) complete dim-8 operator basis possible





- ✦ 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
- ✦ Simplified models: generic electroweak resonances

7th Workshop on Multi-Boson Interactions

MBI 2019

Summer 2019

Chair: Chara Petridou

Aristotle-U. Thessaloniki

1. TU Dresden
2. BNL (Brookhaven Ntl. Lab)
3. DESY
4. U. of Wisconsin — Madison
5. KIT Karlsruhe
6. U. of Michigan — Ann Arbor
7. Aristotle-U. of Thessaloniki

BACKUP SLIDES

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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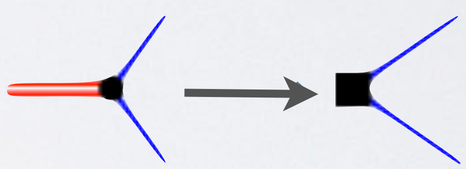
Completing the square (Gaussian integration)

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



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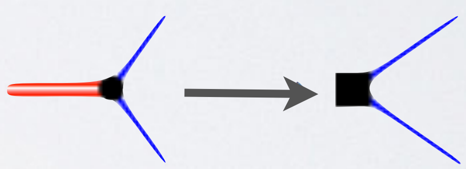
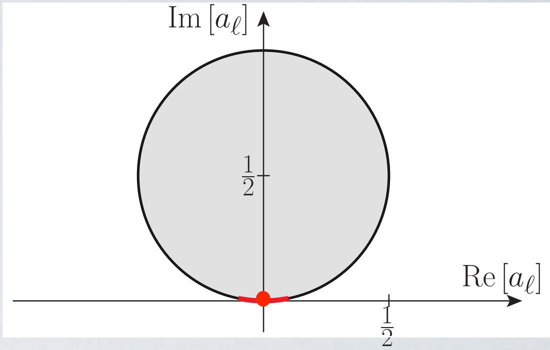


In the Lagrangian remove the high-scale d.o.f.s:

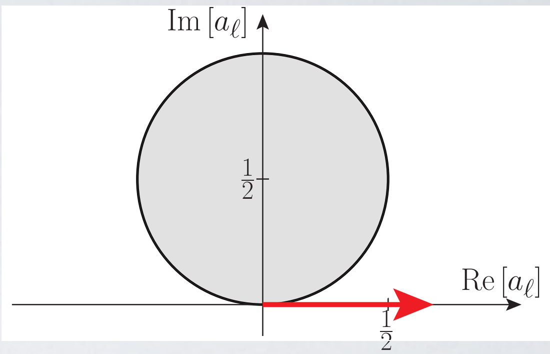
$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2 + \partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1 + \frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower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

Scenarios for New Physics in VBS

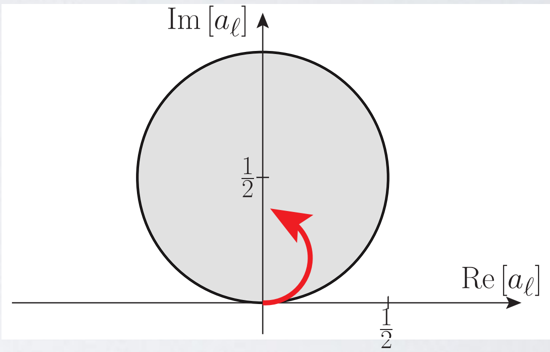
1. SM or weakly coupled physics (e.g. 2HDM): amplitude remains close to origin



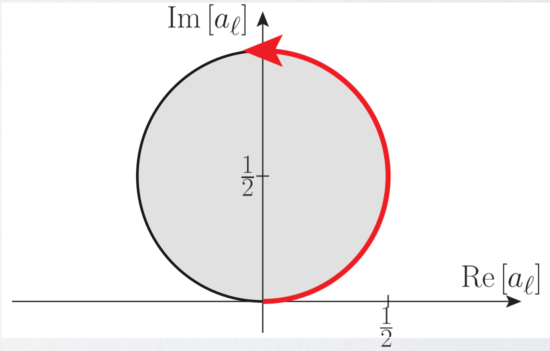
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



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