New Physics / Resonances in Vector Boson Scattering at the LHC

HELMHOLTZ GEMEINSCHAFT

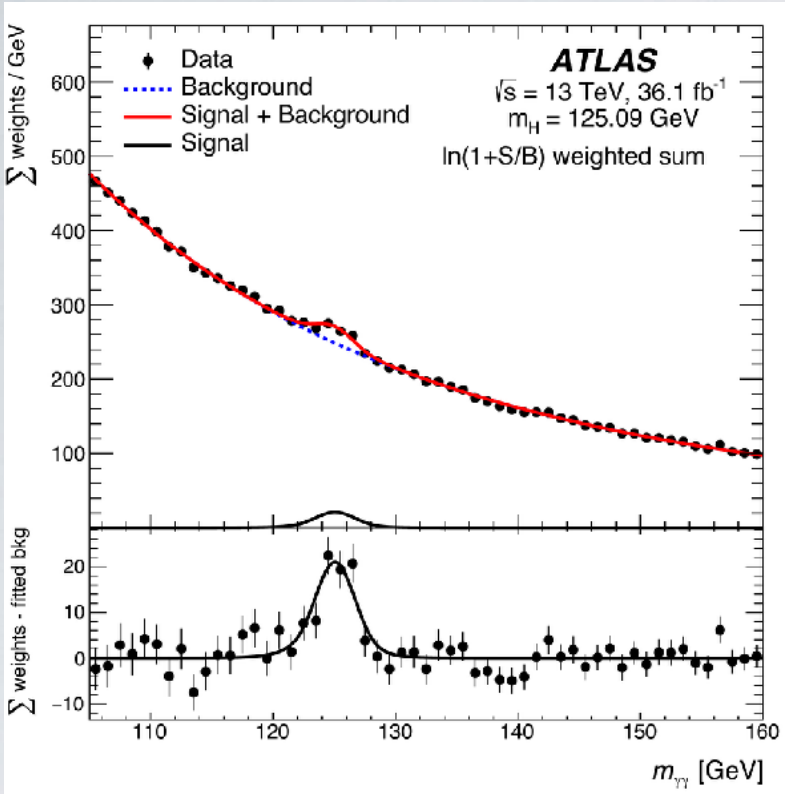
Jürgen R. Reuter, DESY

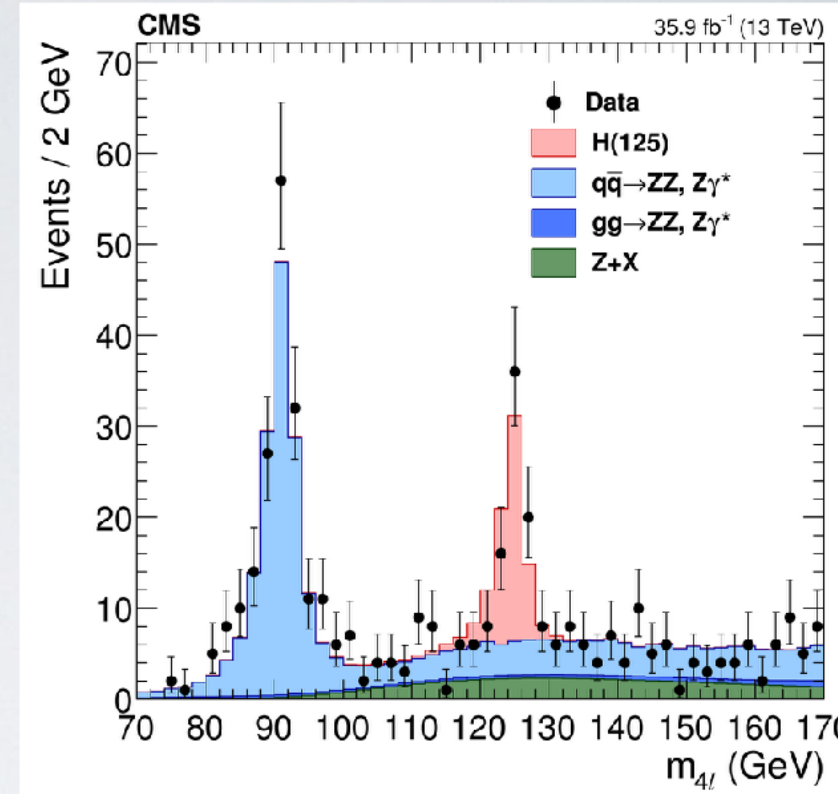
DESY.

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]

Vector Boson Scattering after the Higgs Discovery



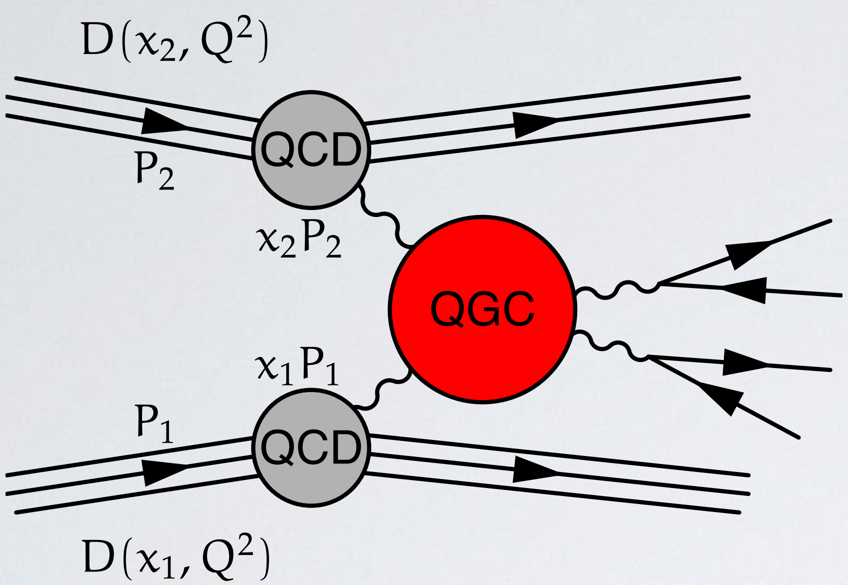


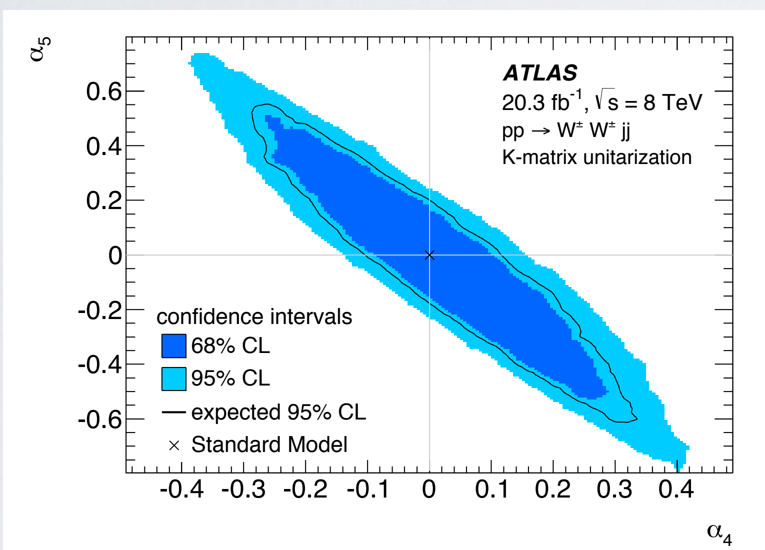
- **Discovery of a light Higgs boson leaves still open questions:**

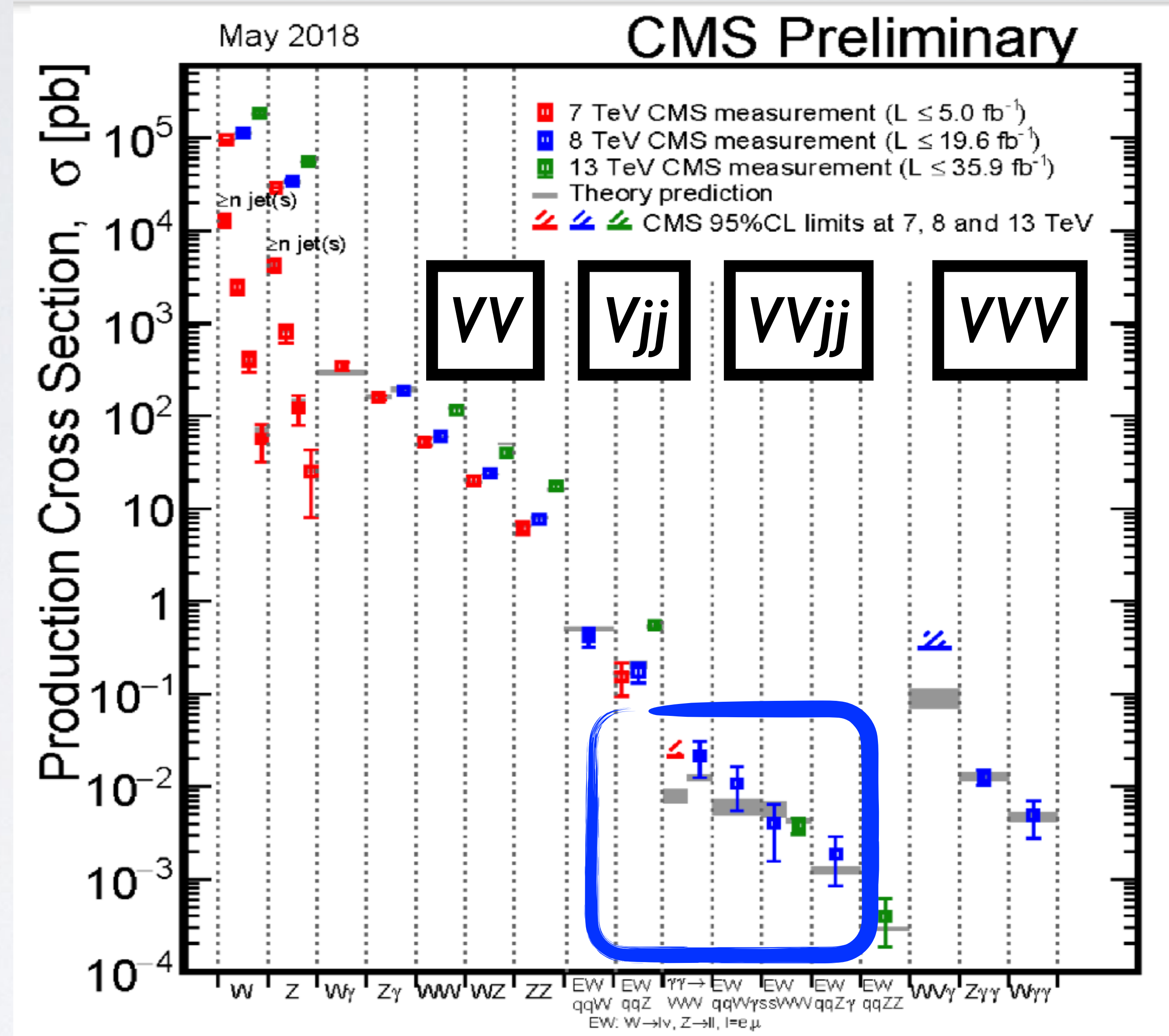
1. Nature of Electroweak Symmetry Breaking
2. Higgs boson potential, all the way like the Standard Model!?
3. Does "the Higgs" fulfill the US-fermion/Europe-boson rule?
4. Is the 125 GeV state the only resonance in the system of EW vector bosons?
5. How do EW vector bosons scatter? (true heart of weak 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)

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





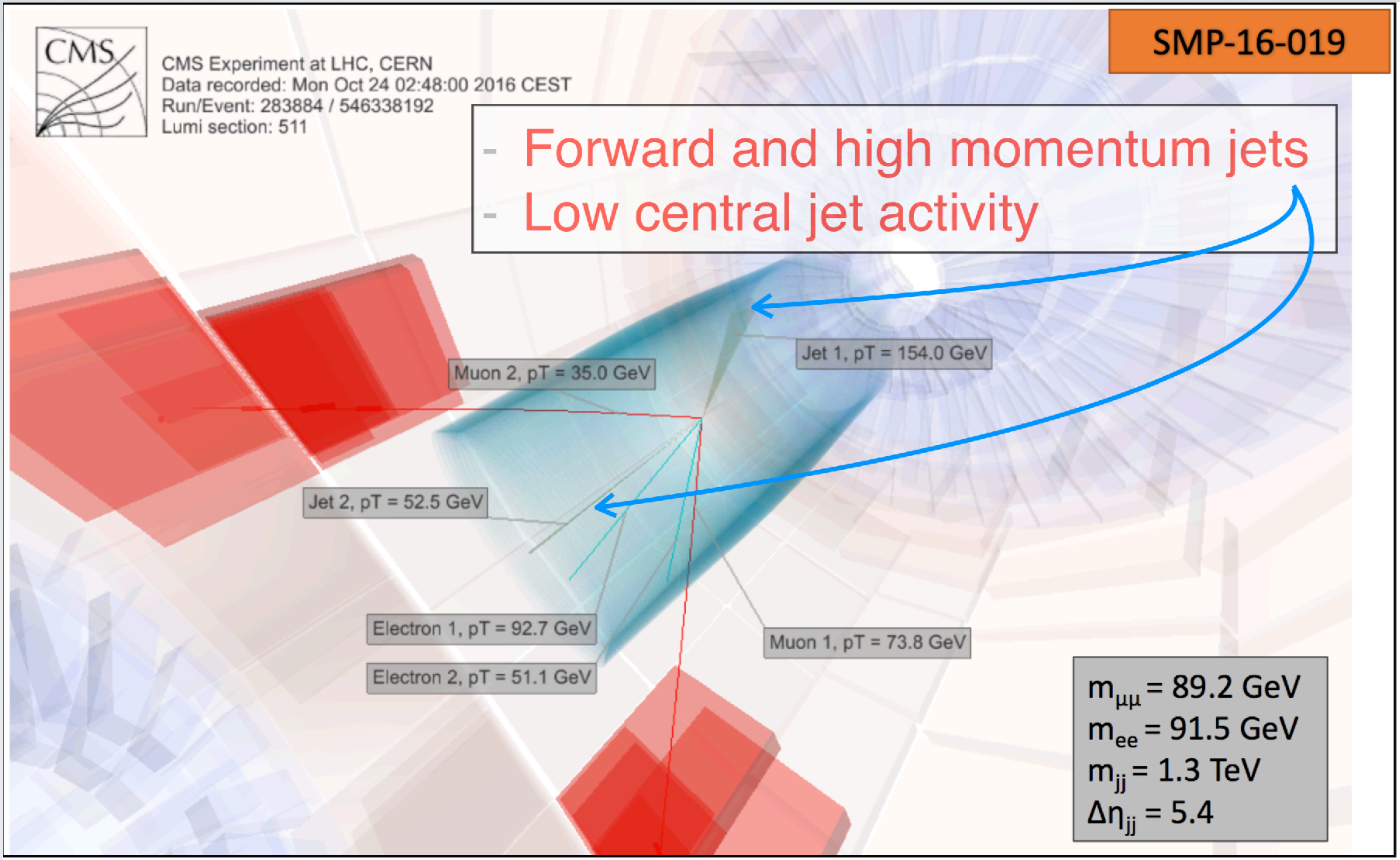


- Discovery for W^+W^+jj (electroweak production)

  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

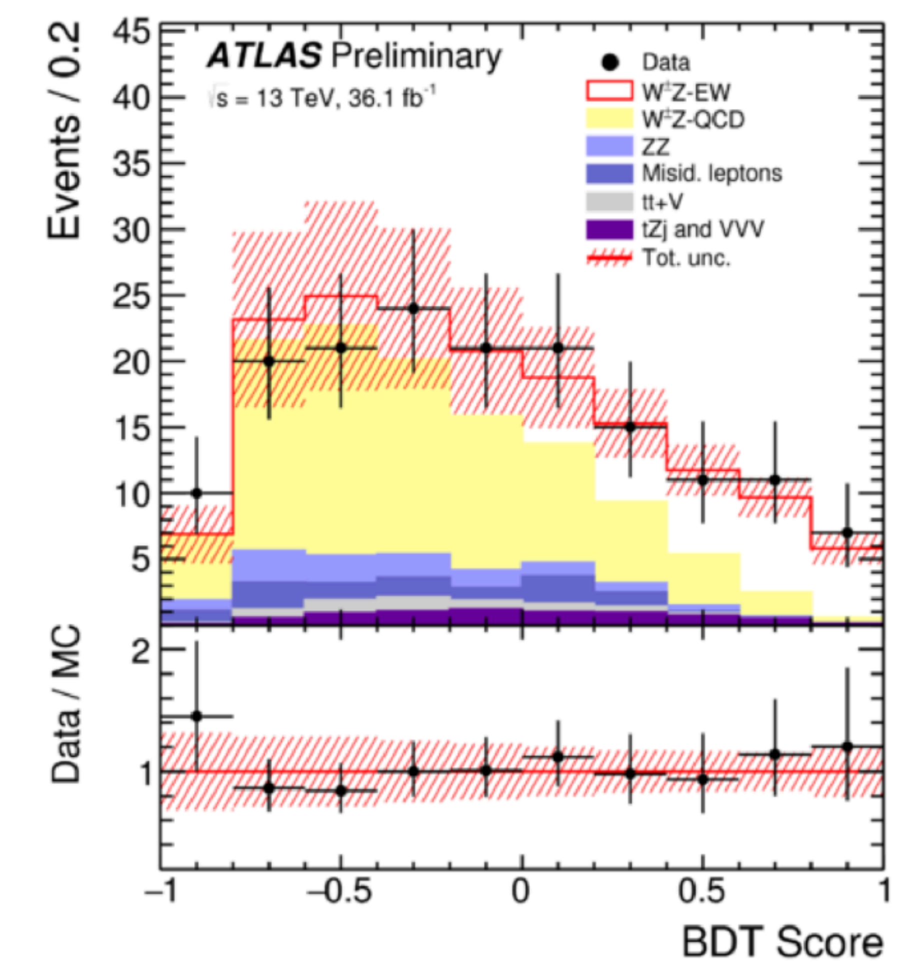
Anatomy of Vector Boson Scattering (VBS)



VBS ZZjj Candidate Event from PLB 774 (2017) 682

shown by Kenneth Long, Seoul, ICHEP 2018

More channels came/coming up …



Post-fit background normalisations

$\mu_{WZ\text{-}QCD}$ = 0.60 ± 0.25

μ_{ttV} = 1.18 ± 0.19

μ_{ZZ} = 1.34 ± 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:

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

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

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

Philip Chang, plenary; Usama Hussain, parallel 24.5.

$pp \to WZjj \to lljj + X$

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

1901.04060

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

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

σ_{fid} = 3.83 ± 0.66 (stat) ± 0.35 (syst) fb

PRL 120, 081801(2018)

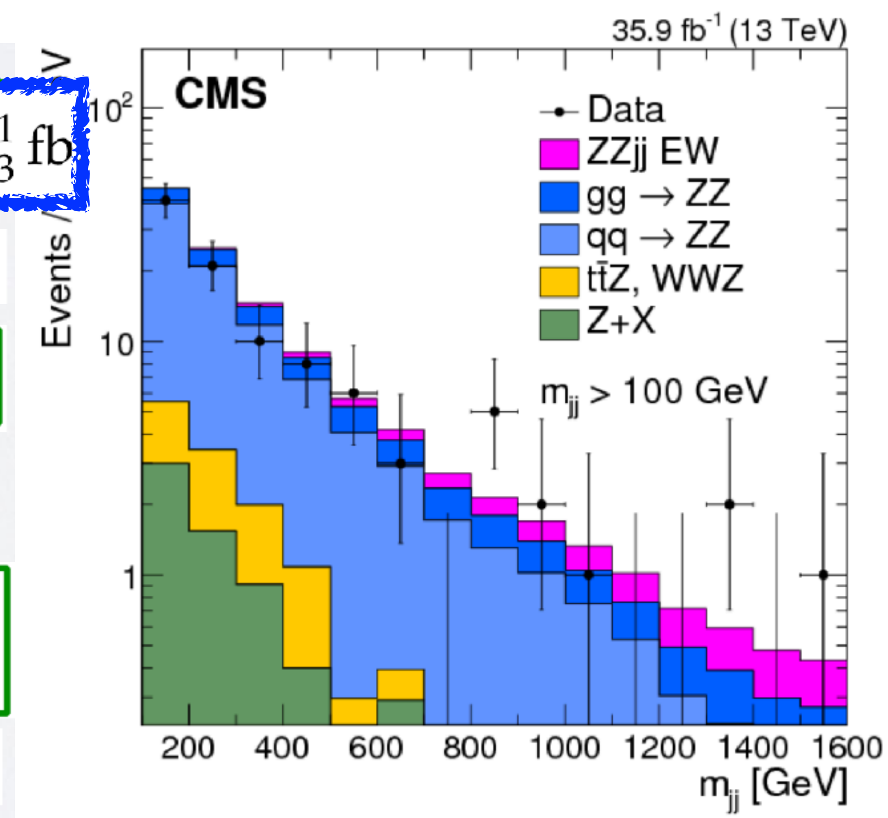
Observed (expected) of 5.5σ (5.7σ)

$pp \to ZZjj \to lllljj$

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

PLB 774(2017) 682

Observed (expected) of 2.7σ (1.6σ)



Deviations as EFT — Dim 8 Operators

Motivated by SMEFT:

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

S.Weinberg, 1979 Buchmüller/Wyler, 1986

Grzadkowski/Iskrzysnki/Misiak/Rosiek, 2010

Eboli/Gonzalez-Garcia/Mizukoshi, 2006

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

Longitudinal operators

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

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

Mixed operators

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

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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 cancels between operators in UV-complete Theory

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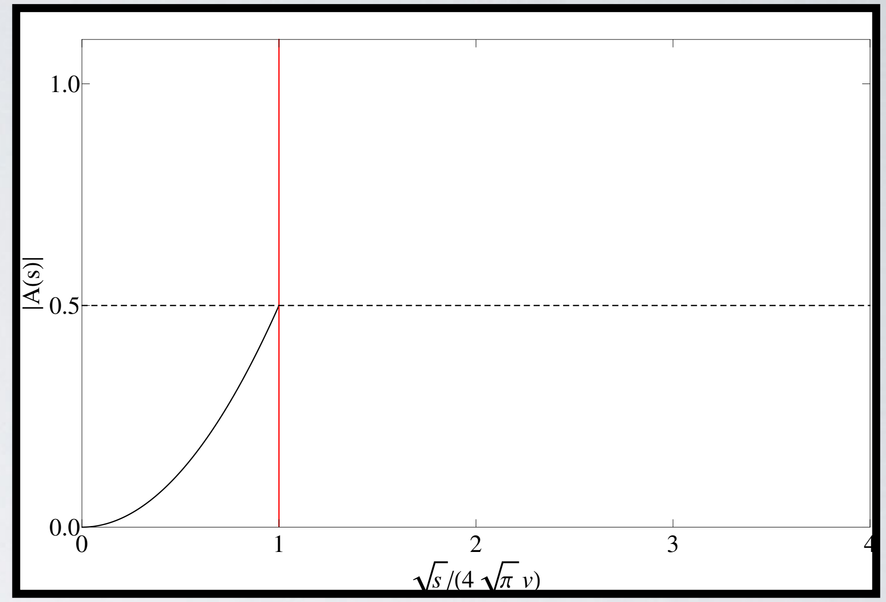
Procedures to treat unitarity violations



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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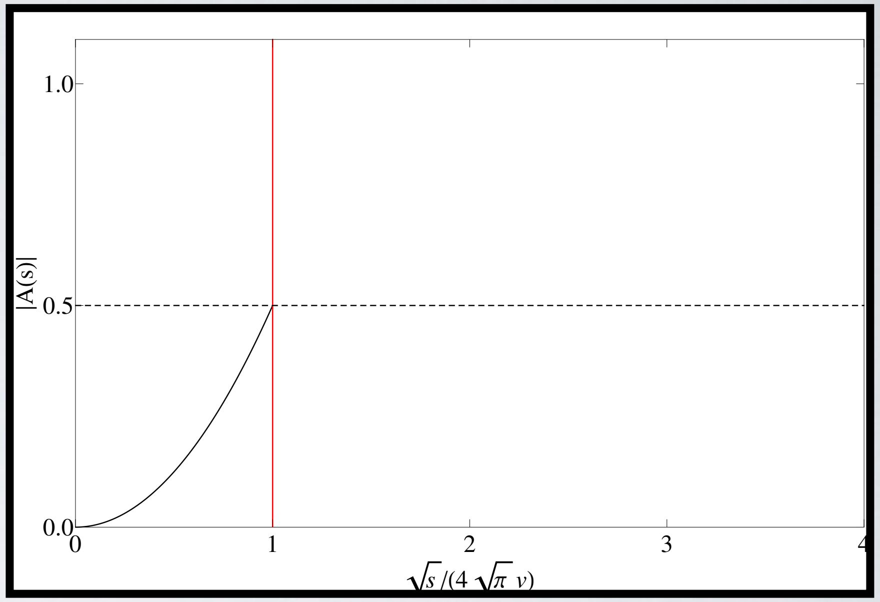
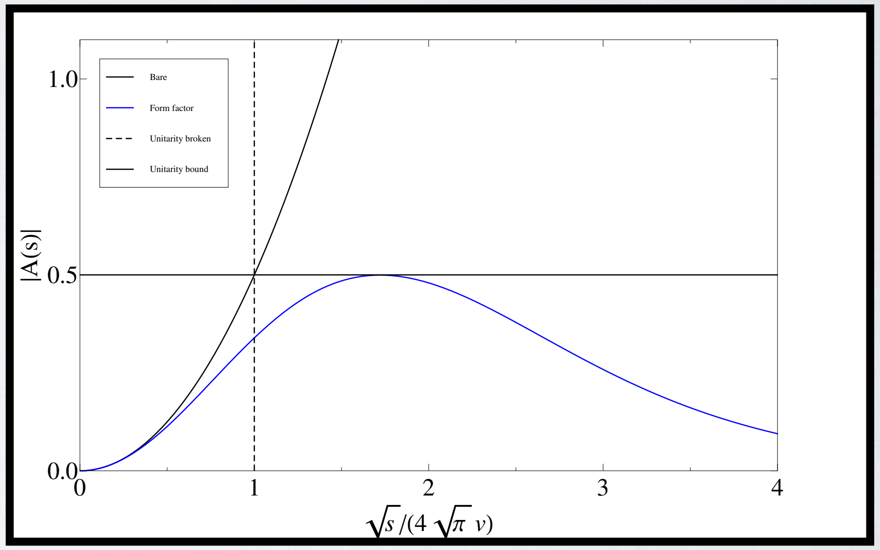


Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

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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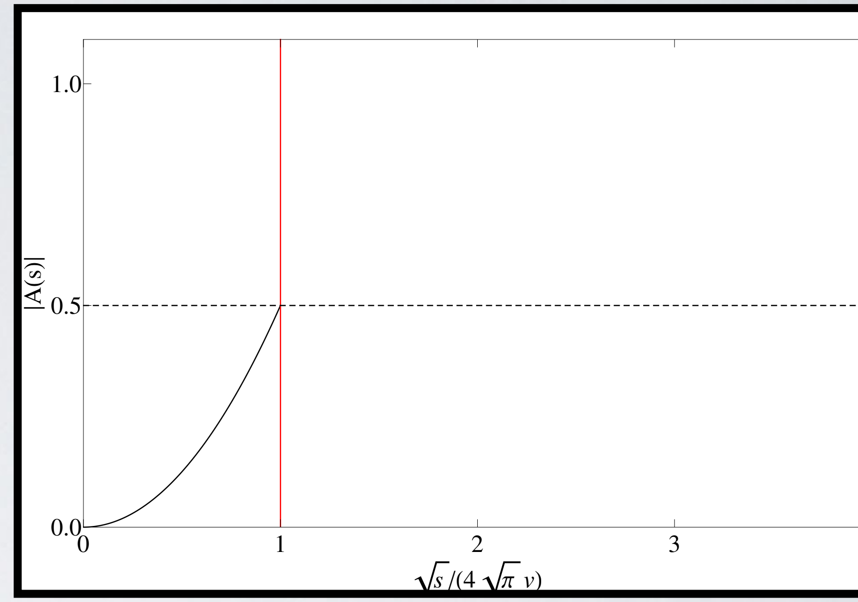

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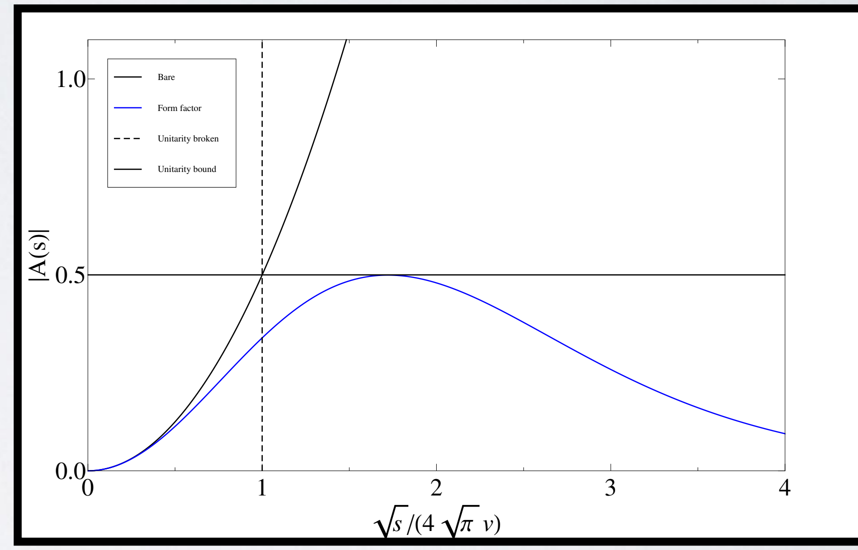
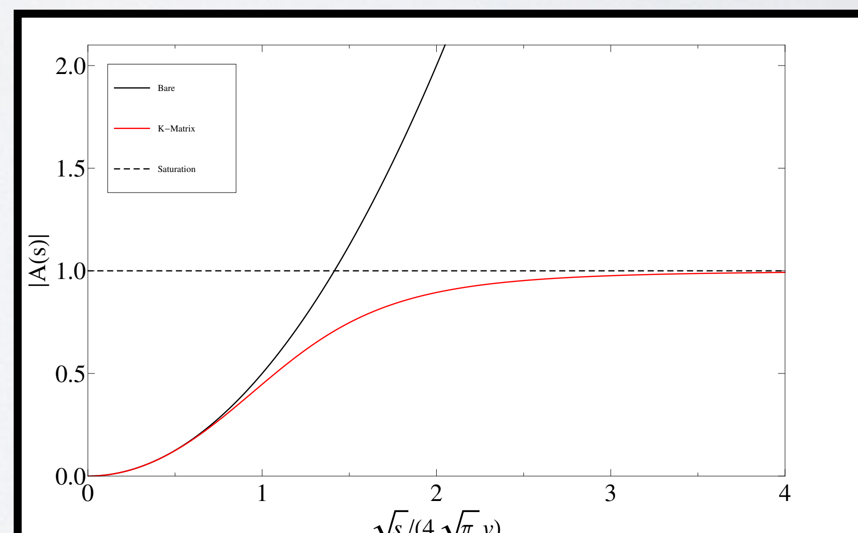


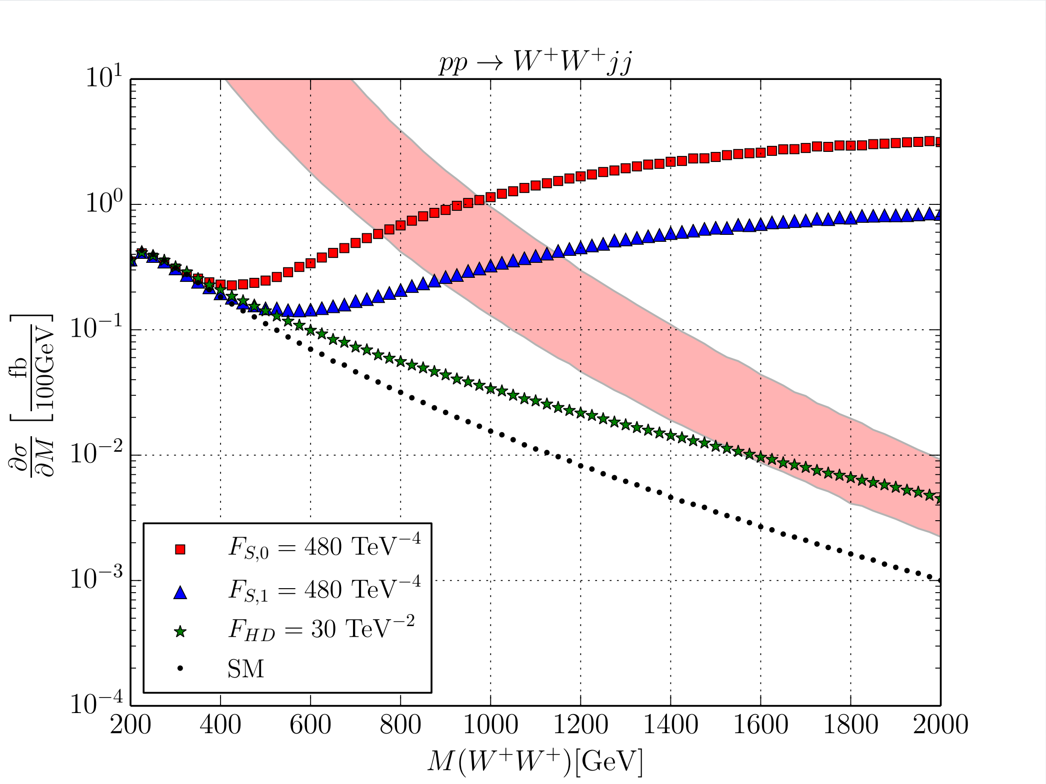
K-/T-matrix saturation $a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$

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



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

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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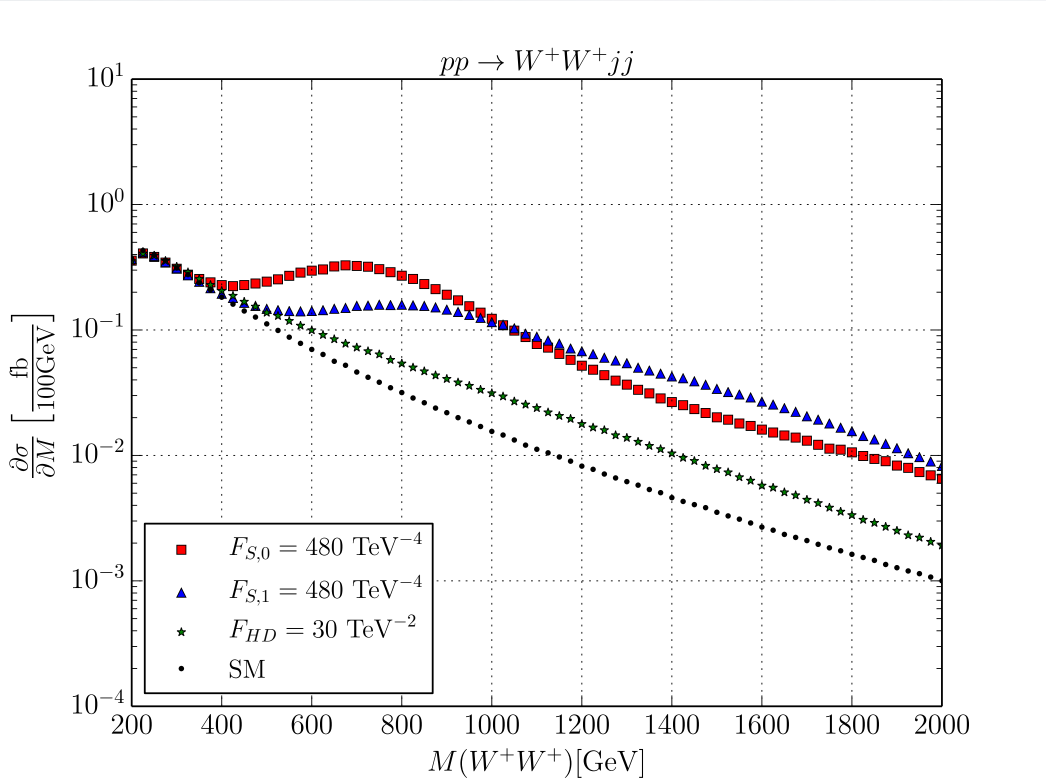

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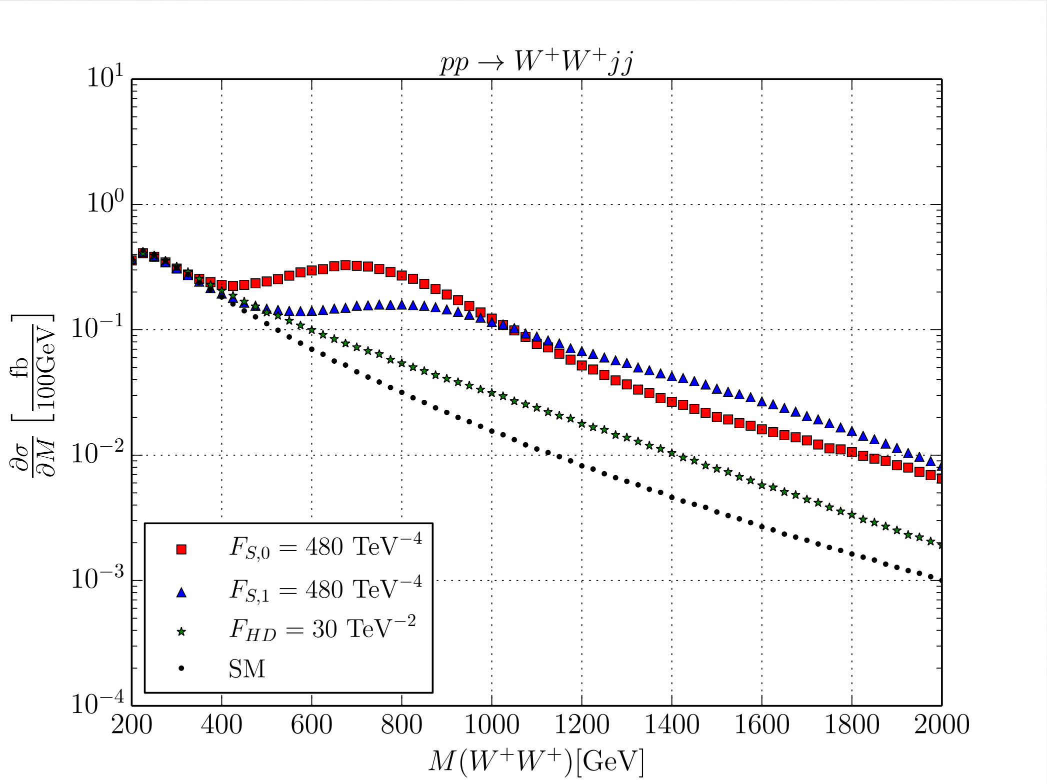

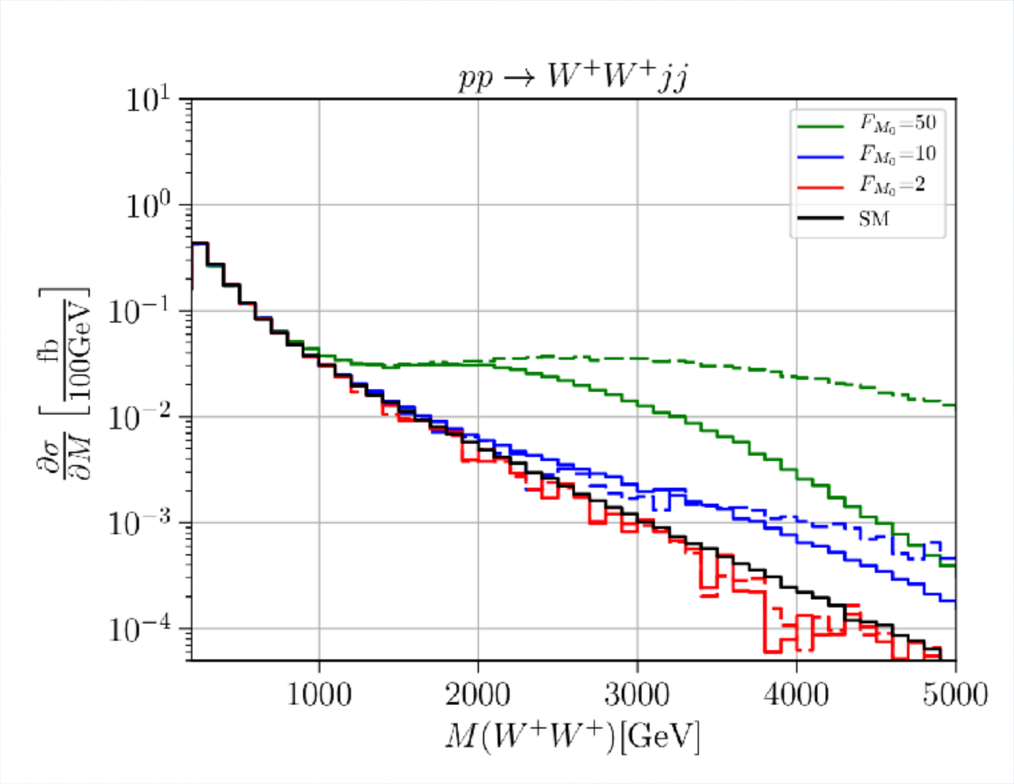

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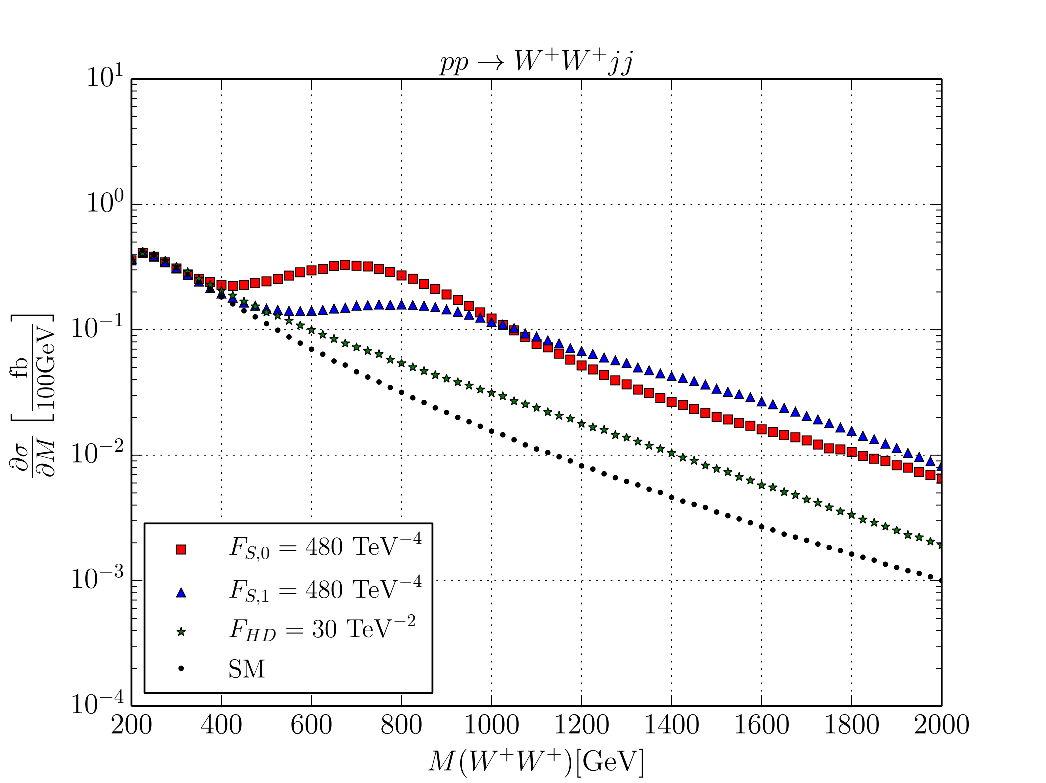

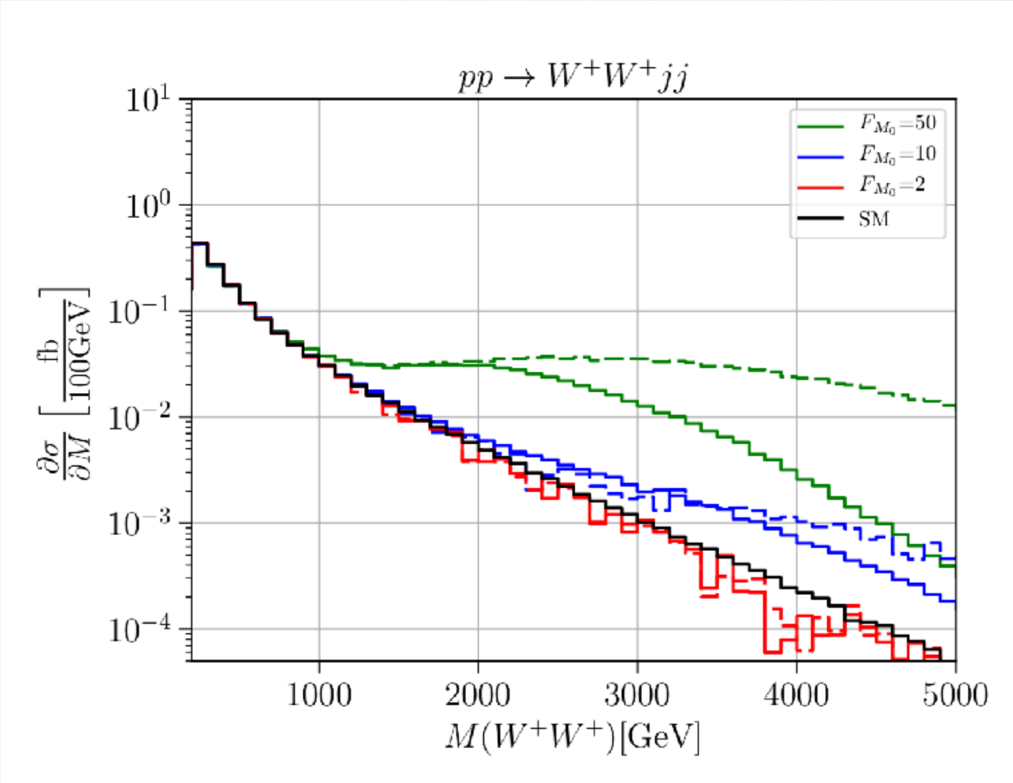

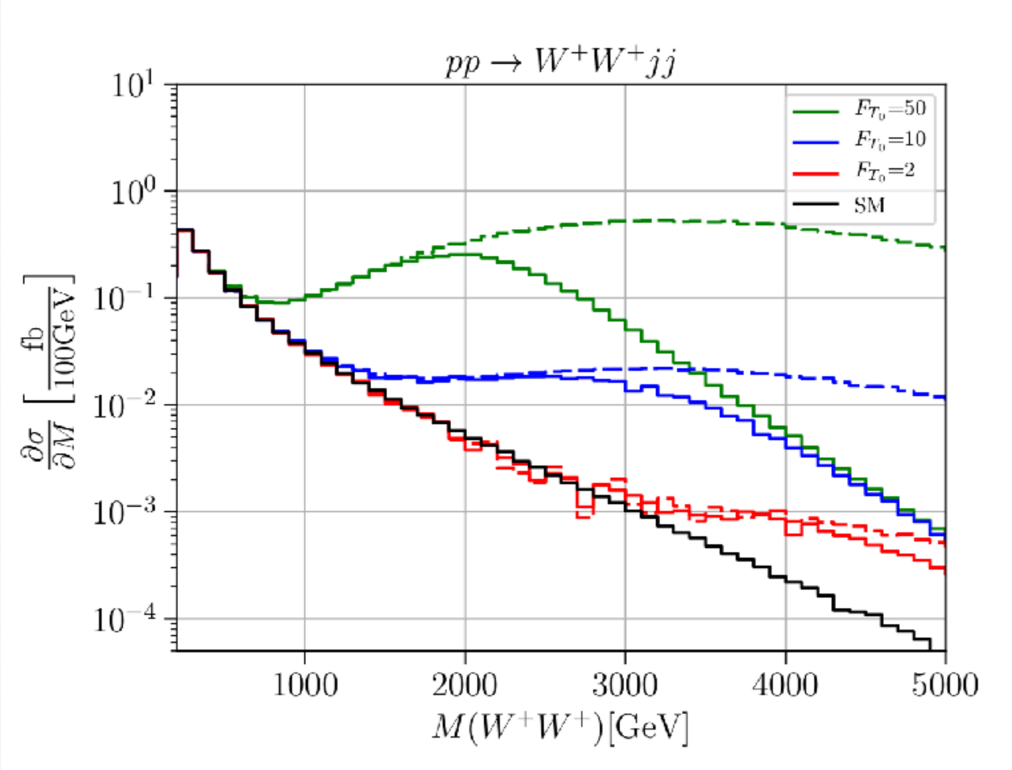

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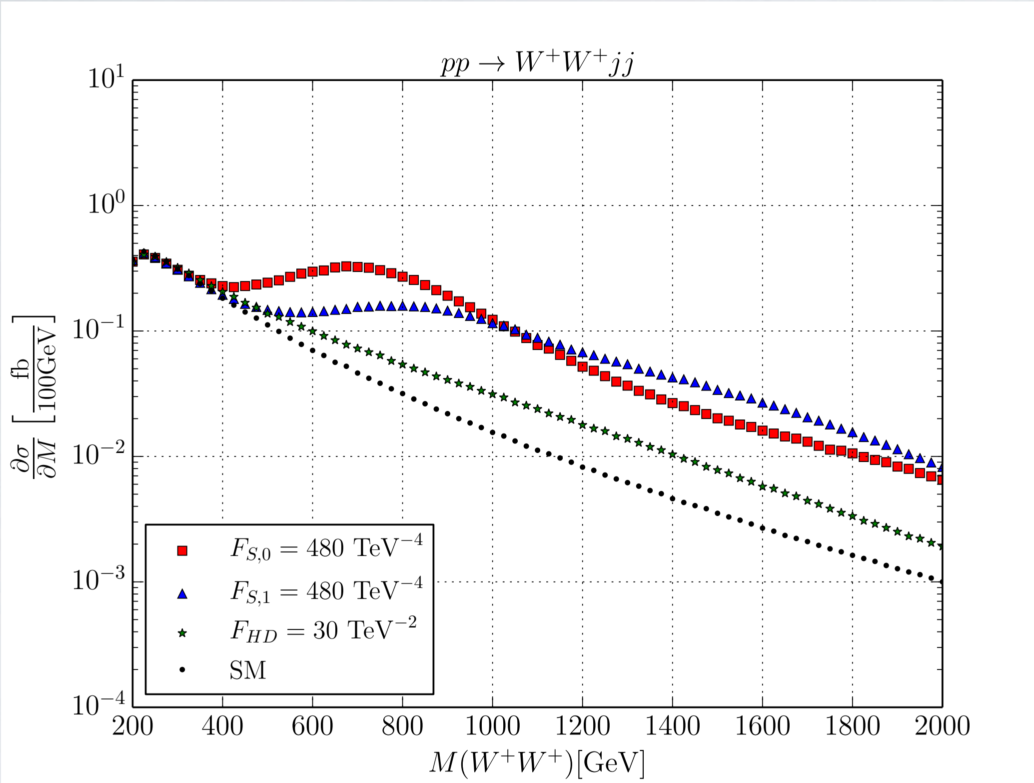

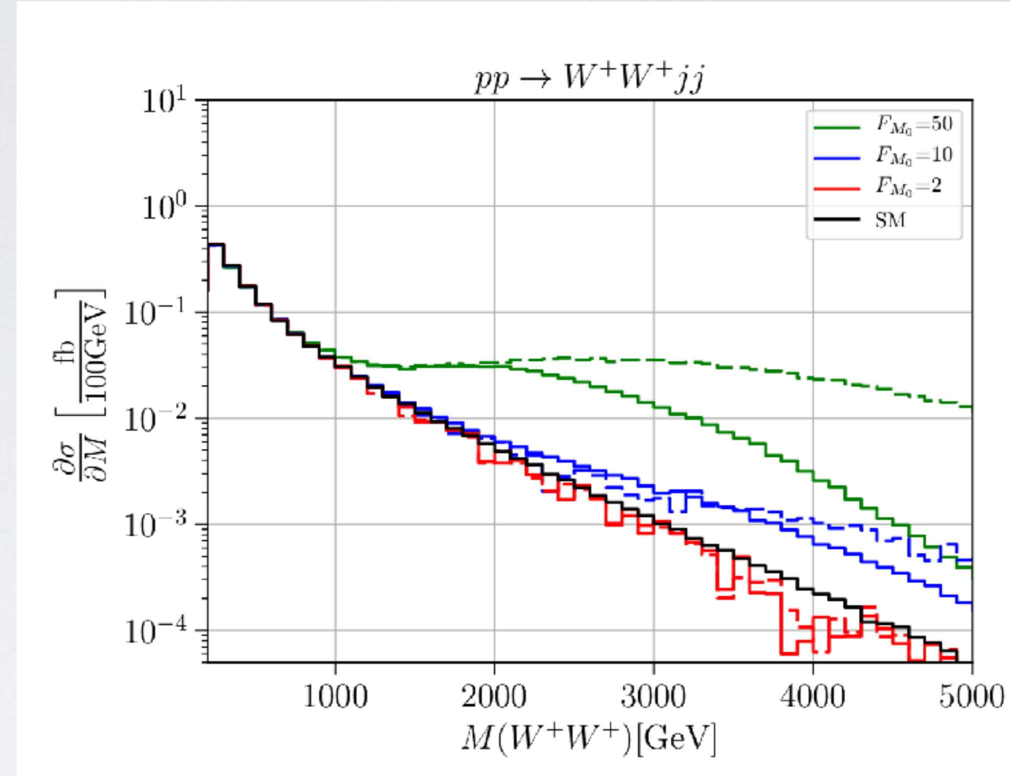

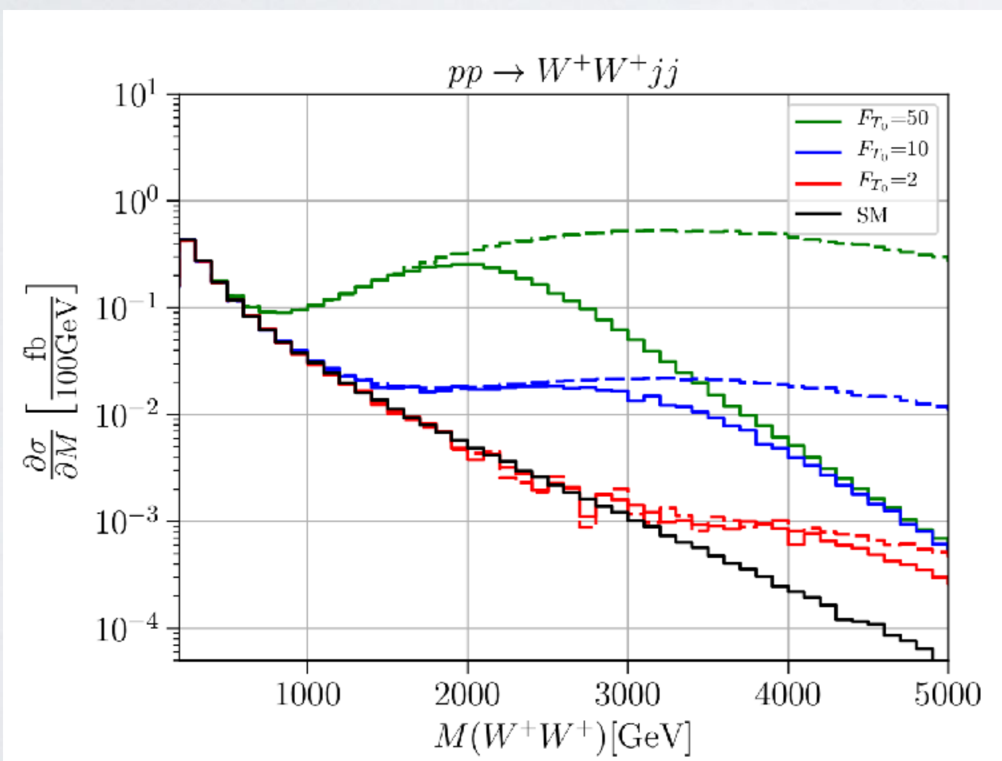

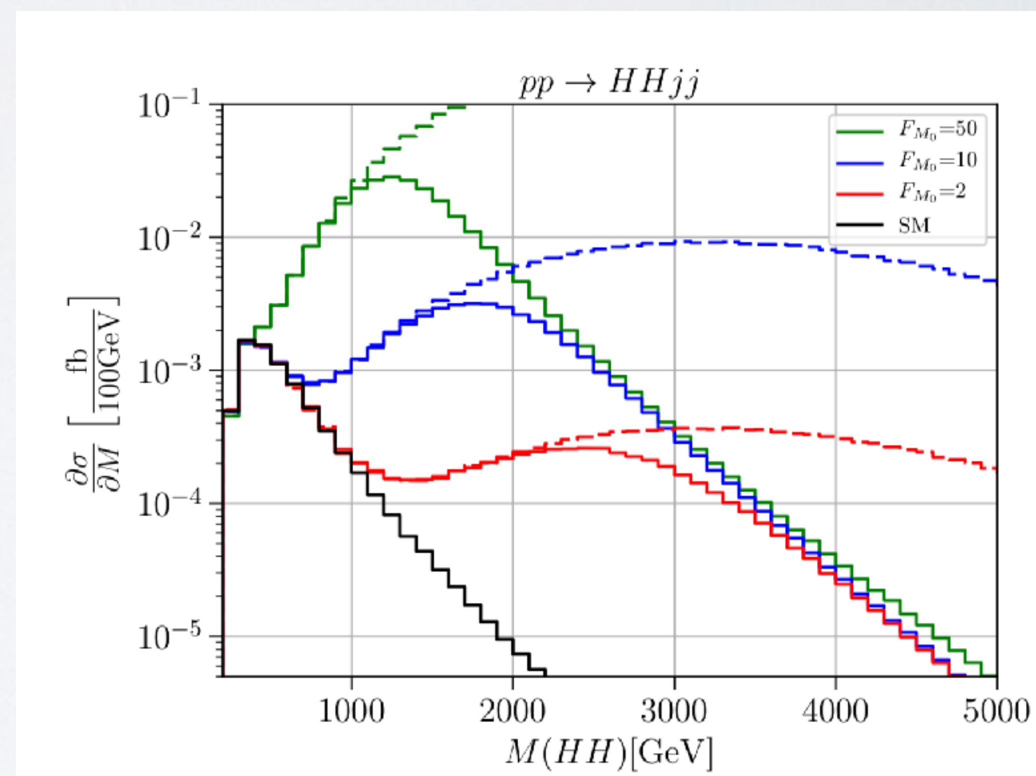

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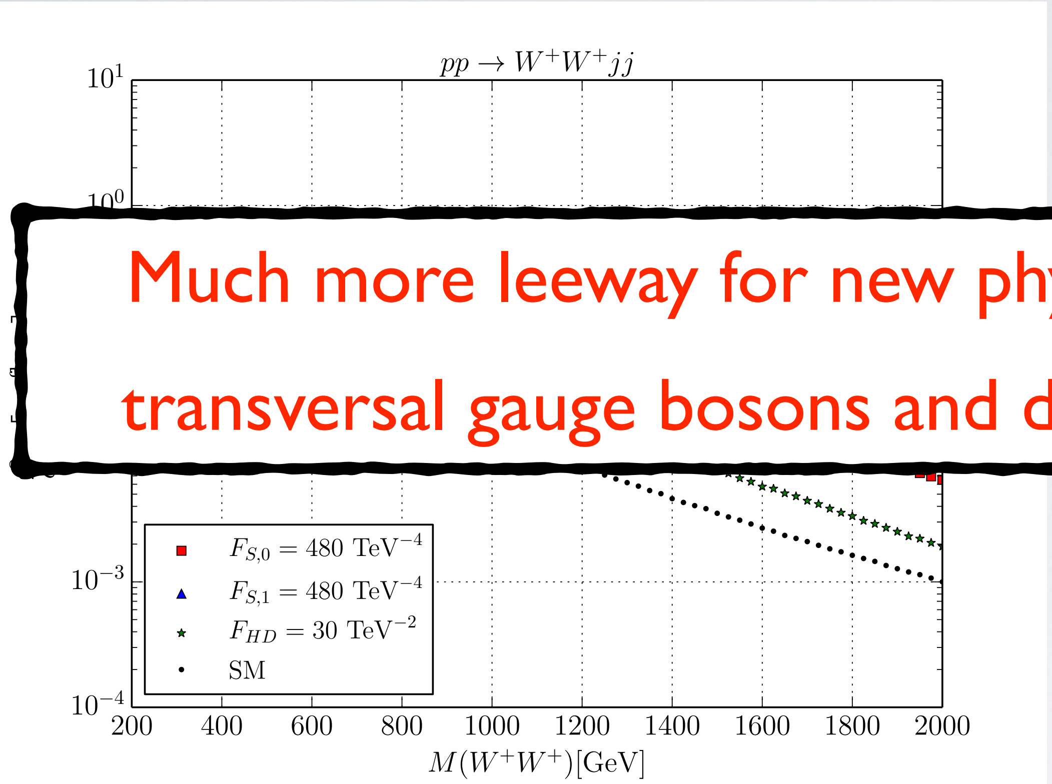
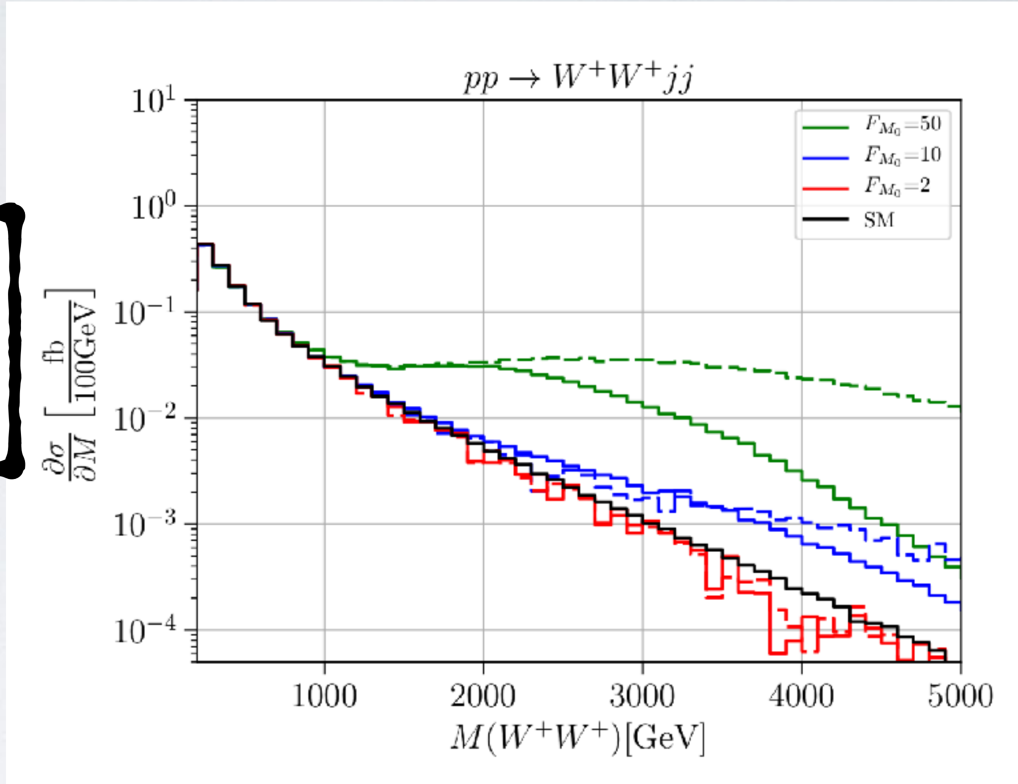
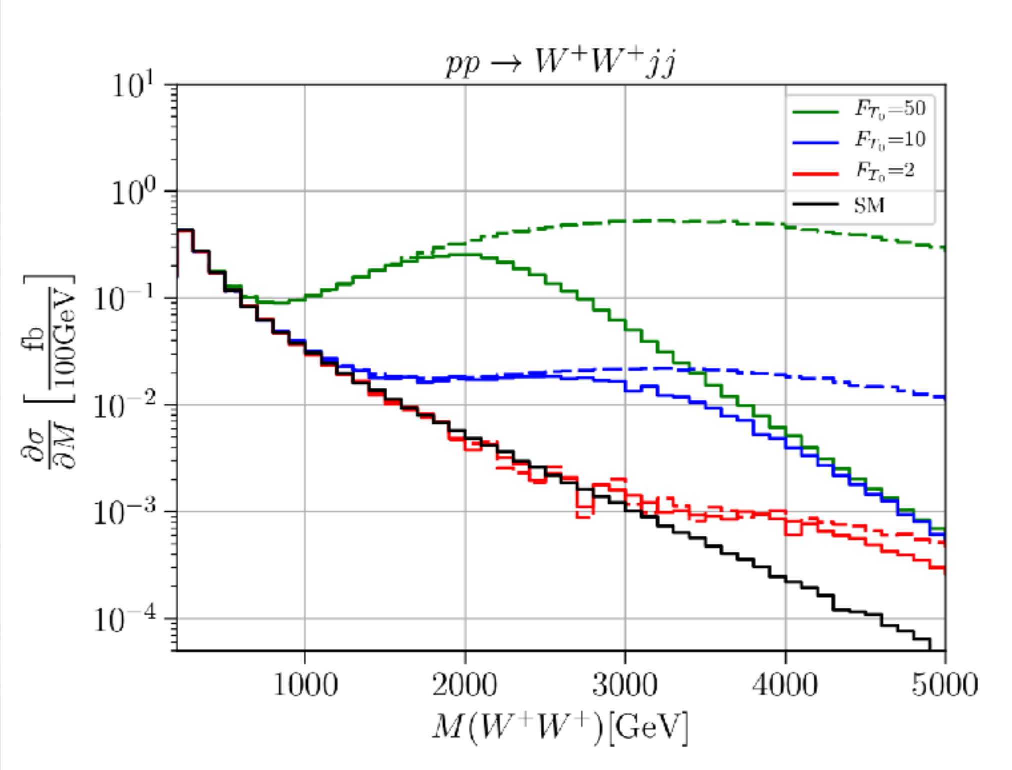
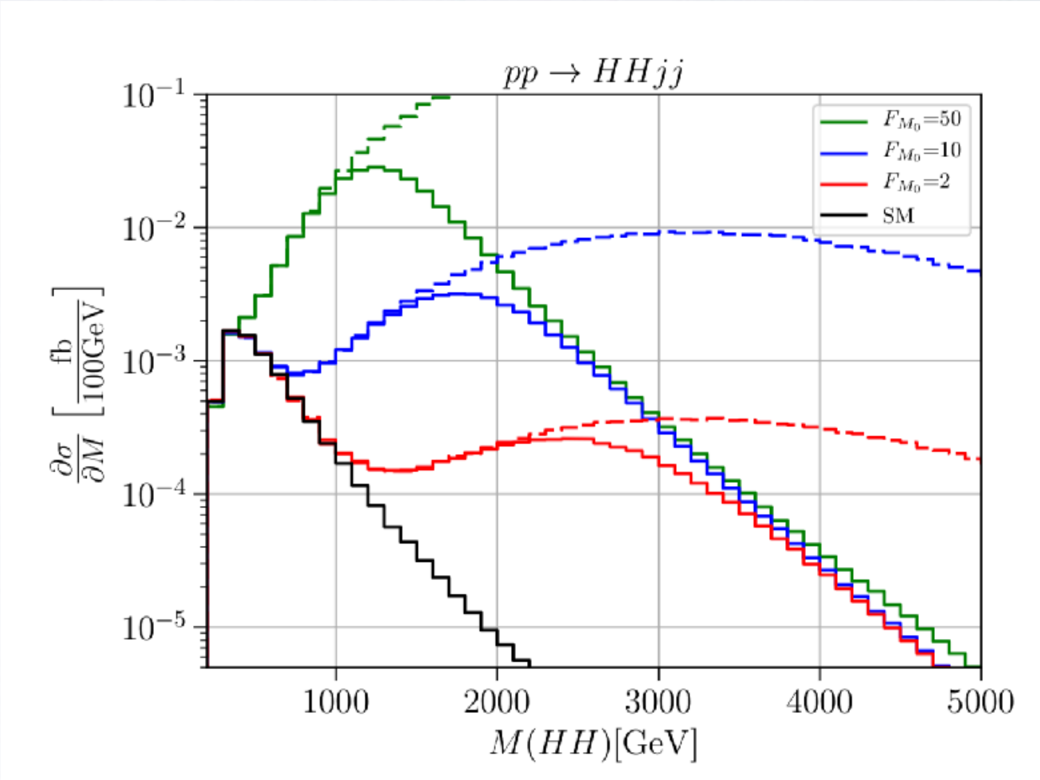


Much more leeway for new physics in transversal gauge bosons and di-Higgs







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(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)

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

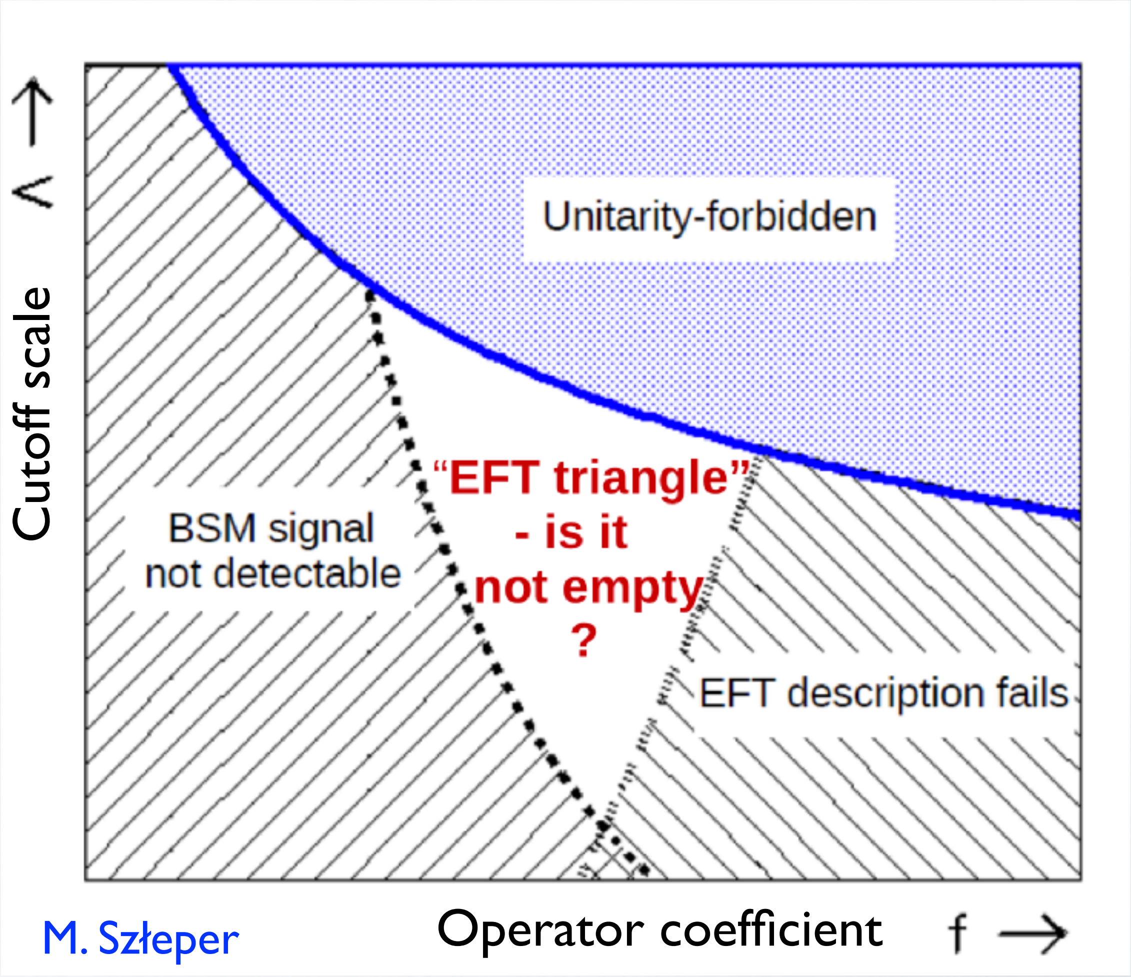
- **Partial wave unitarity:** gives guidance on maximally possible event numbers

- **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 VBS/energy frontier physics**



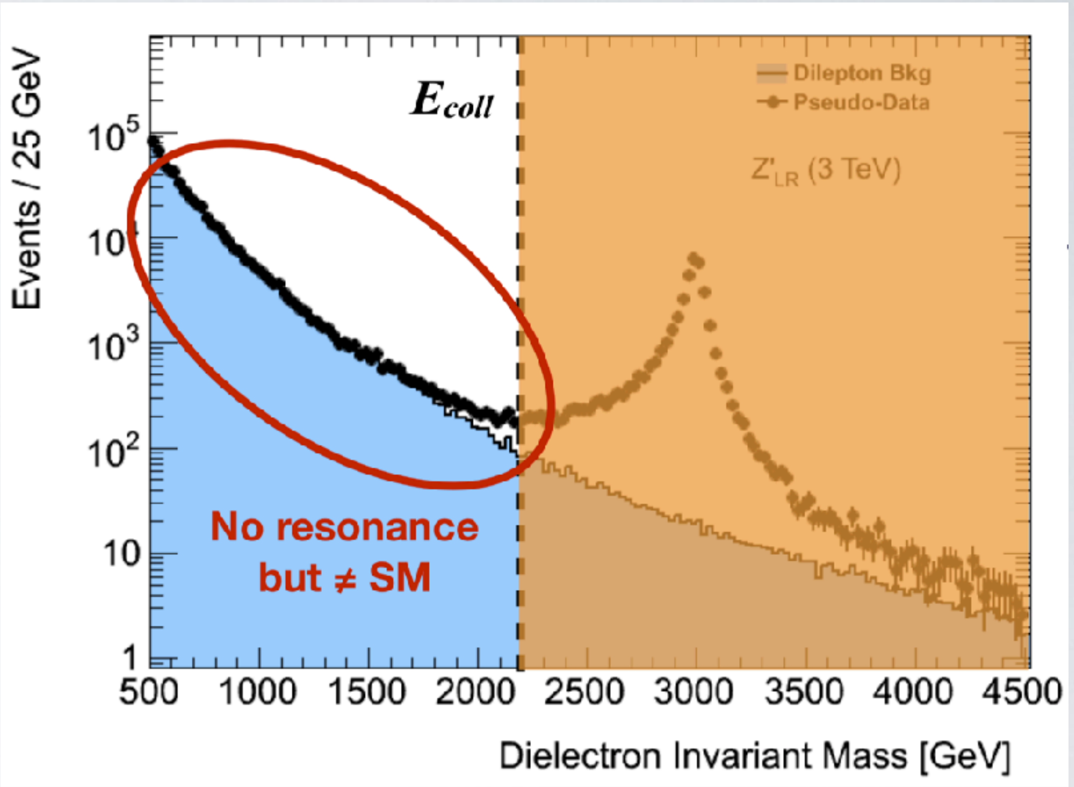
M. Szłeper

Bumps vs. Tails

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)

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

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

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

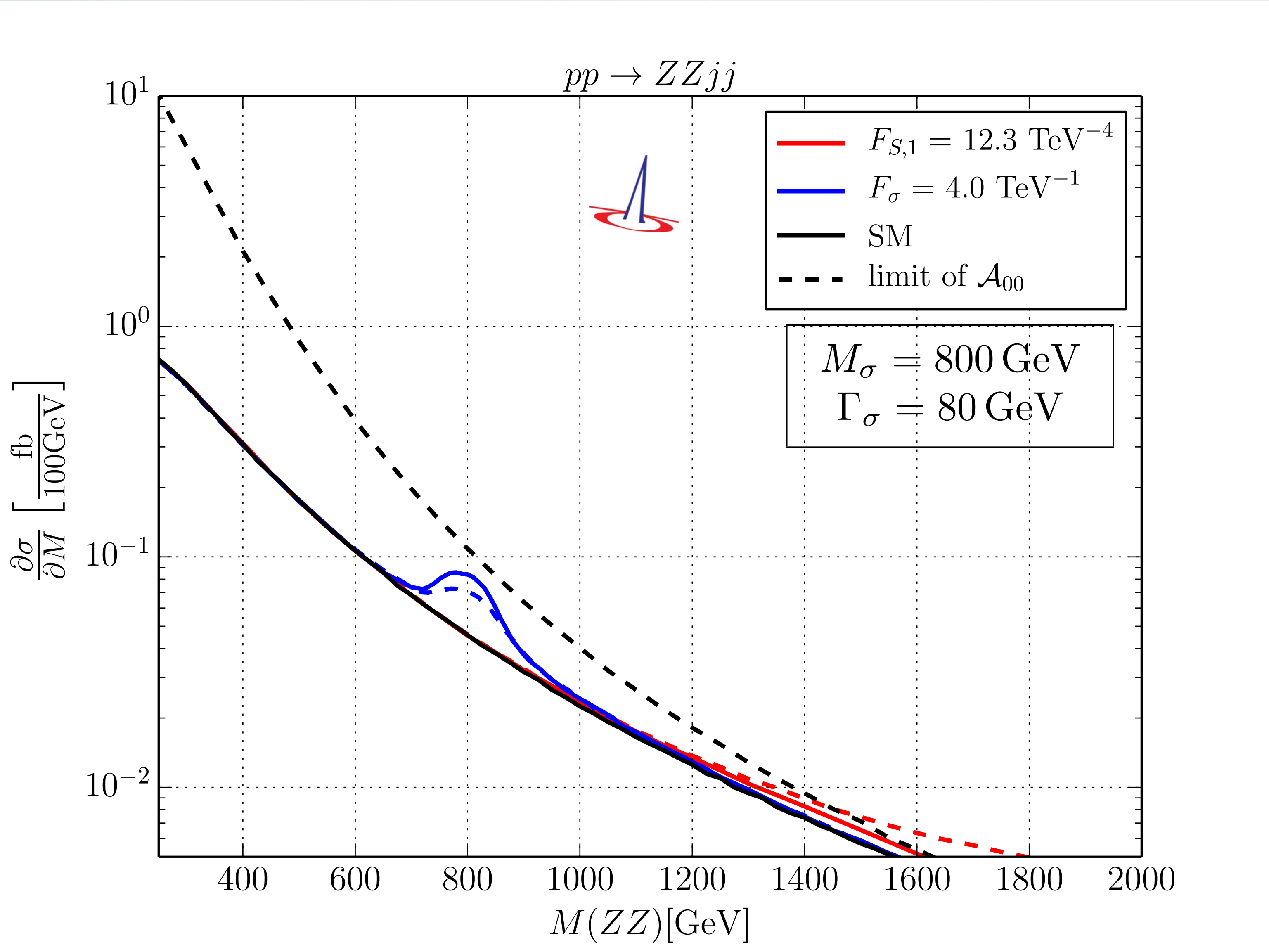
Translation into Wilson coefficients below resonance

Comparison: Simplified Models & EFT

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

Brass/Fleper/Kilian/JRR/Sekulla: w. EPJC [1807.02512]

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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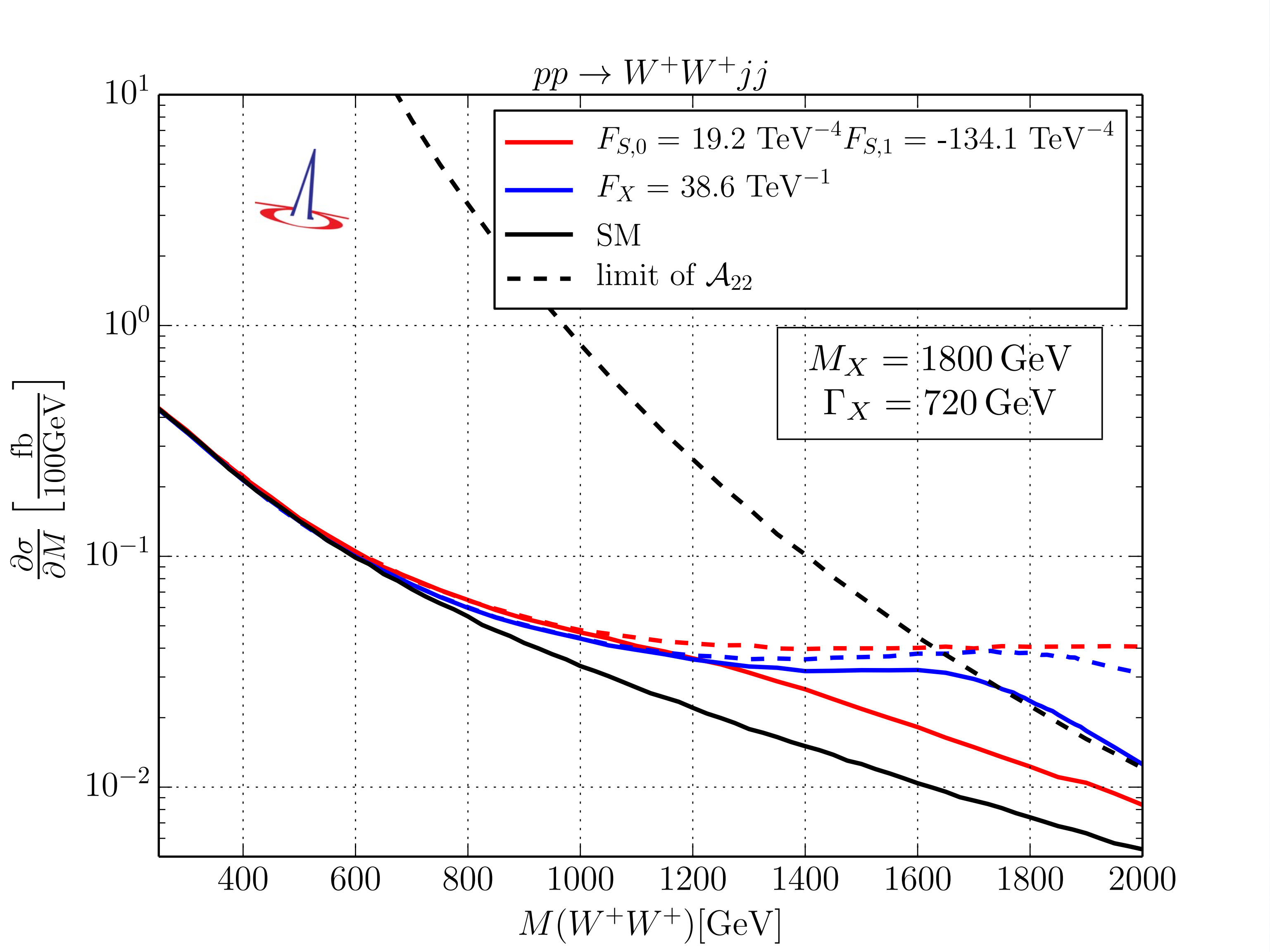

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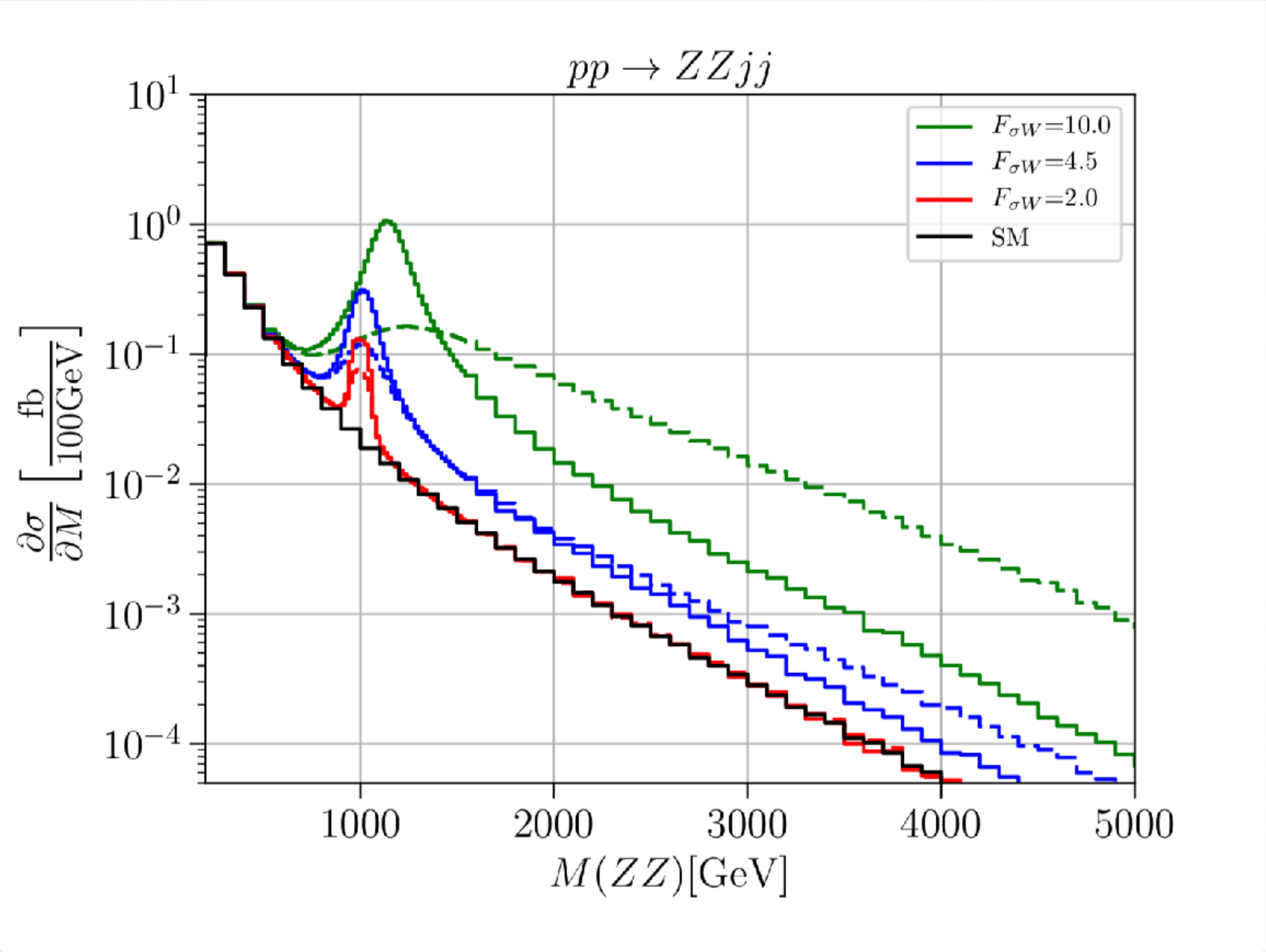

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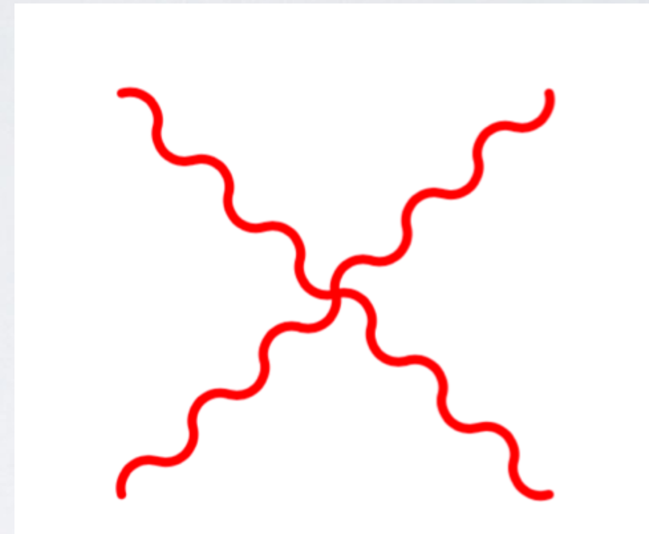
Triple [multiple] Vector Boson Production ?

Evidence at ATLAS at 4σ level: smallest SM cross section

→ Philip Chang, plenary session, 24.05.
Usama Hussain, parallel session, 24.05.
Markus Cristianziani, parallel/poster, 21./24.05.

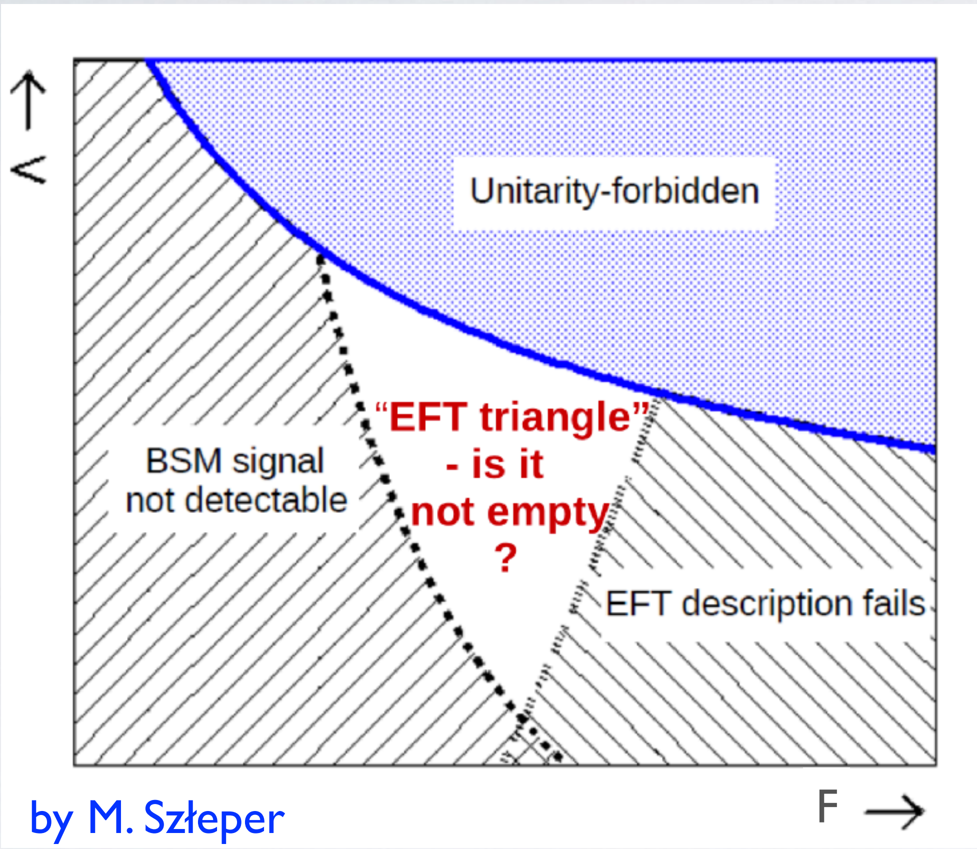
1903.10415

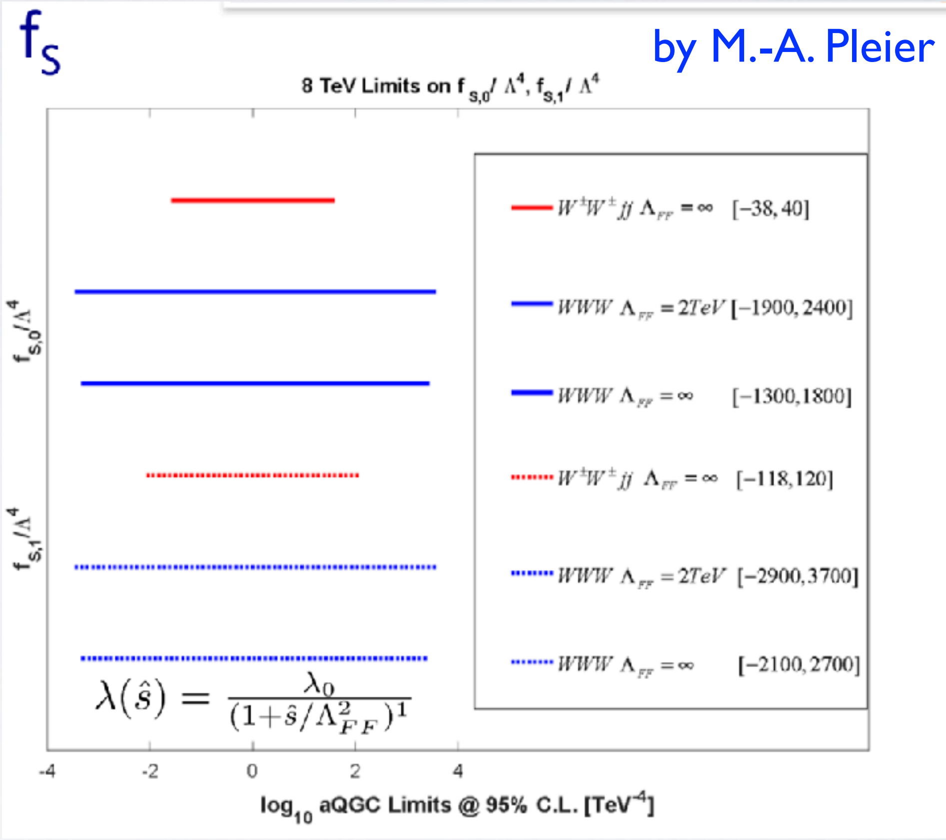
Relate  to  ?

- 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 a flagship measurement of Runs II/III (and FCC-hh !)
- EFT provides well-defined (and very limited) framework for SM deviations





- There is not really a true model-independent parameterization!
- Unitarization for theoretically sane description (allows reliable BDT analysis)
- *T*-matrix unitarization universal scheme for EFT and resonances
- Simplified models: generic electroweak resonances
- Limits from LHC still quite limited: $\Lambda_{new\ physics} \sim$ 700–800 GeV

7th Workshop on Multi-Boson Interactions

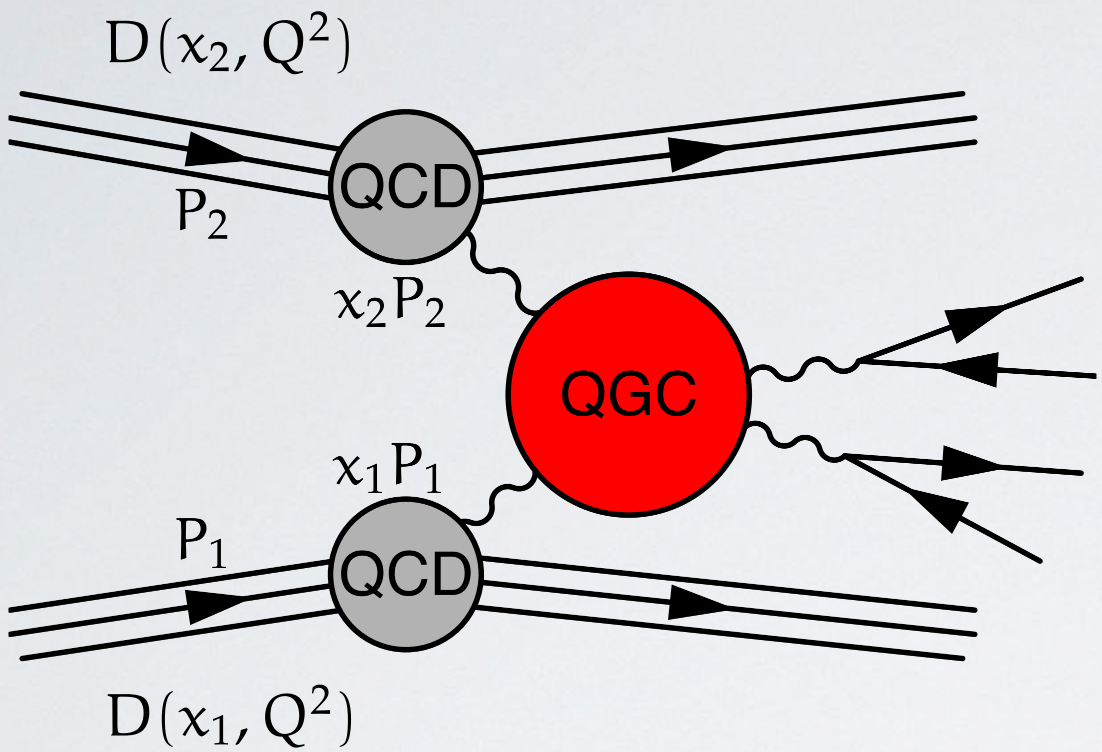
August 26-28, 2019
Aristotle U., Thessaloniki

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. Thessaloniki**

BACKUP SLIDES

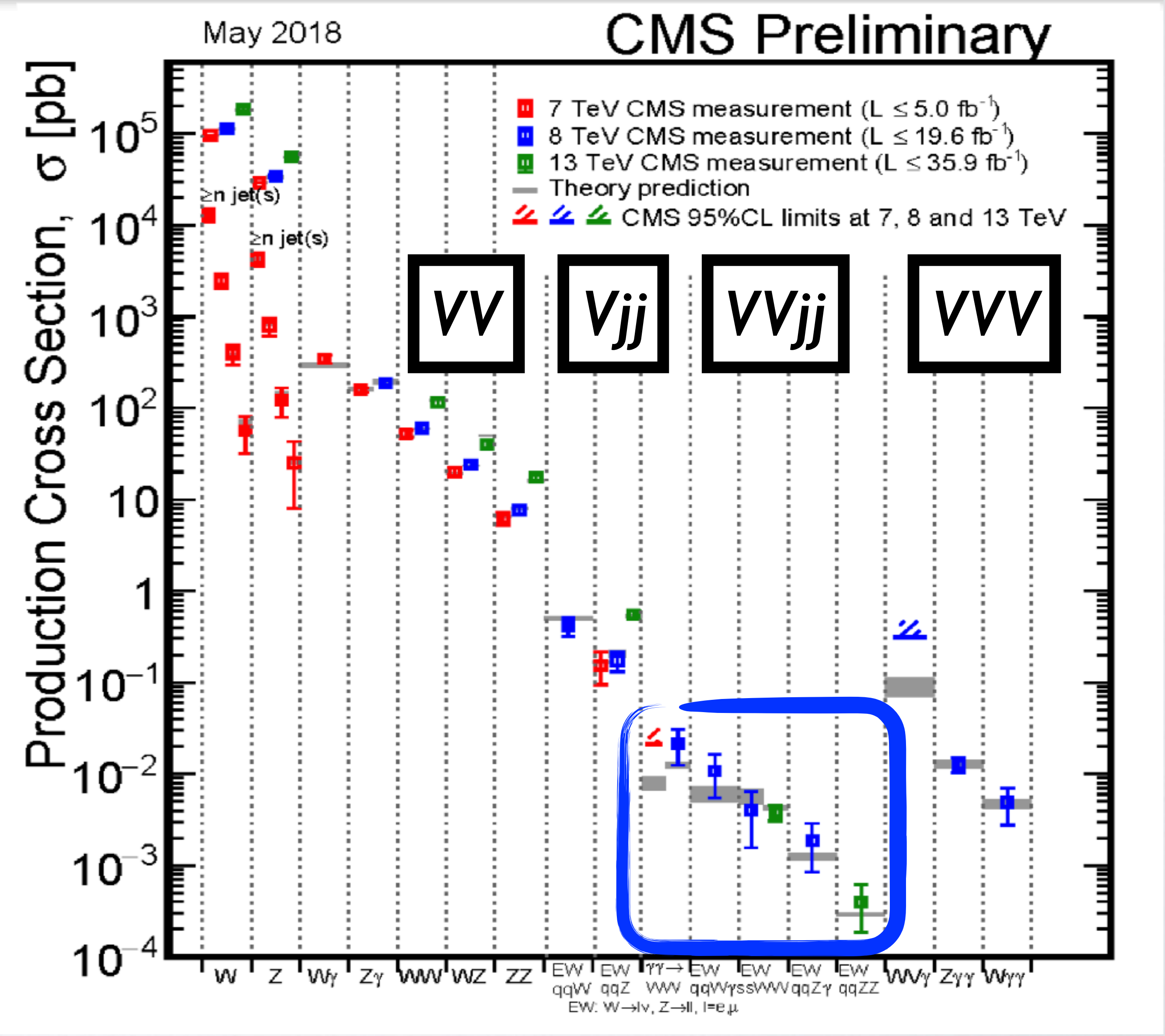
Anatomy of Vector Boson Scattering (VBS)

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



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

Differential spectra in VBS

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

Simulations with `WHIZARD` [http://whizard.hepforge.org, Kilian/Ohl/JRR]

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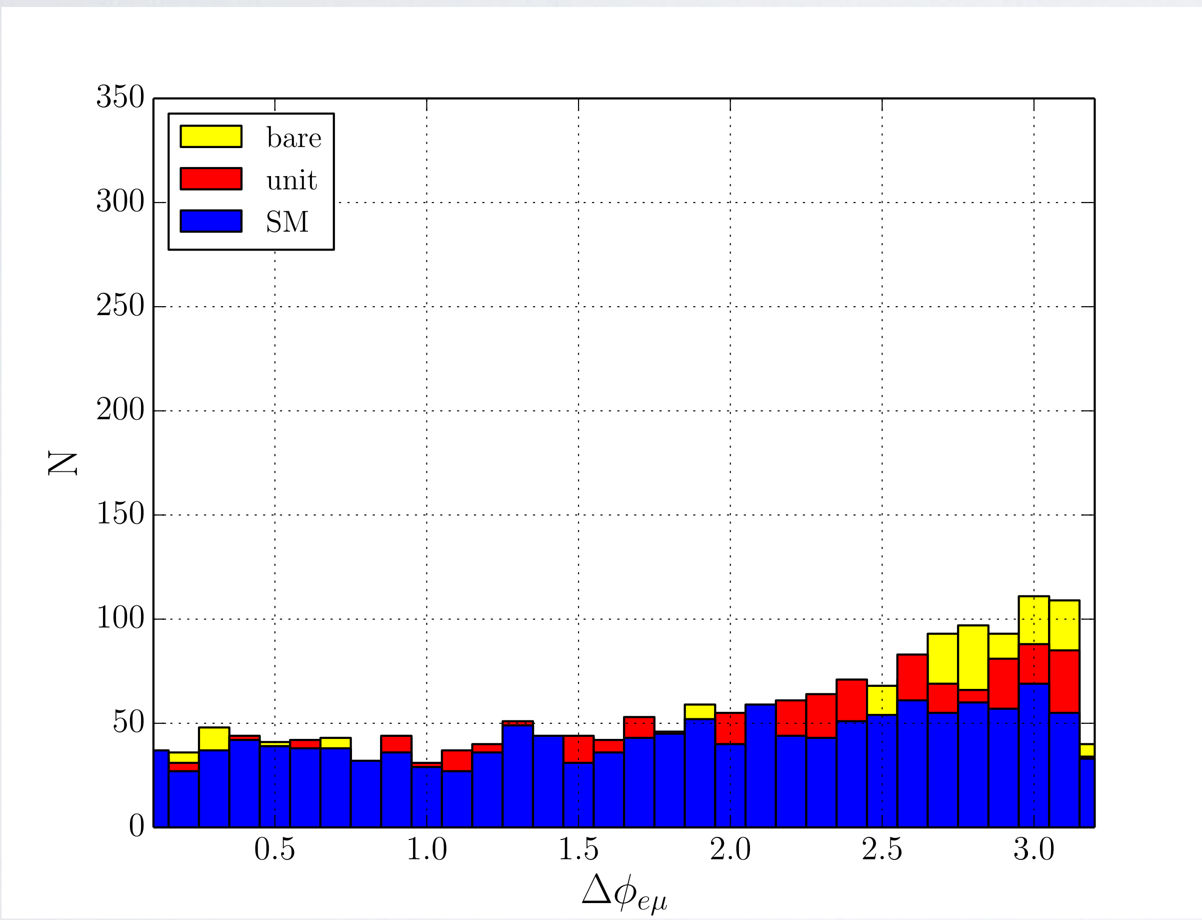
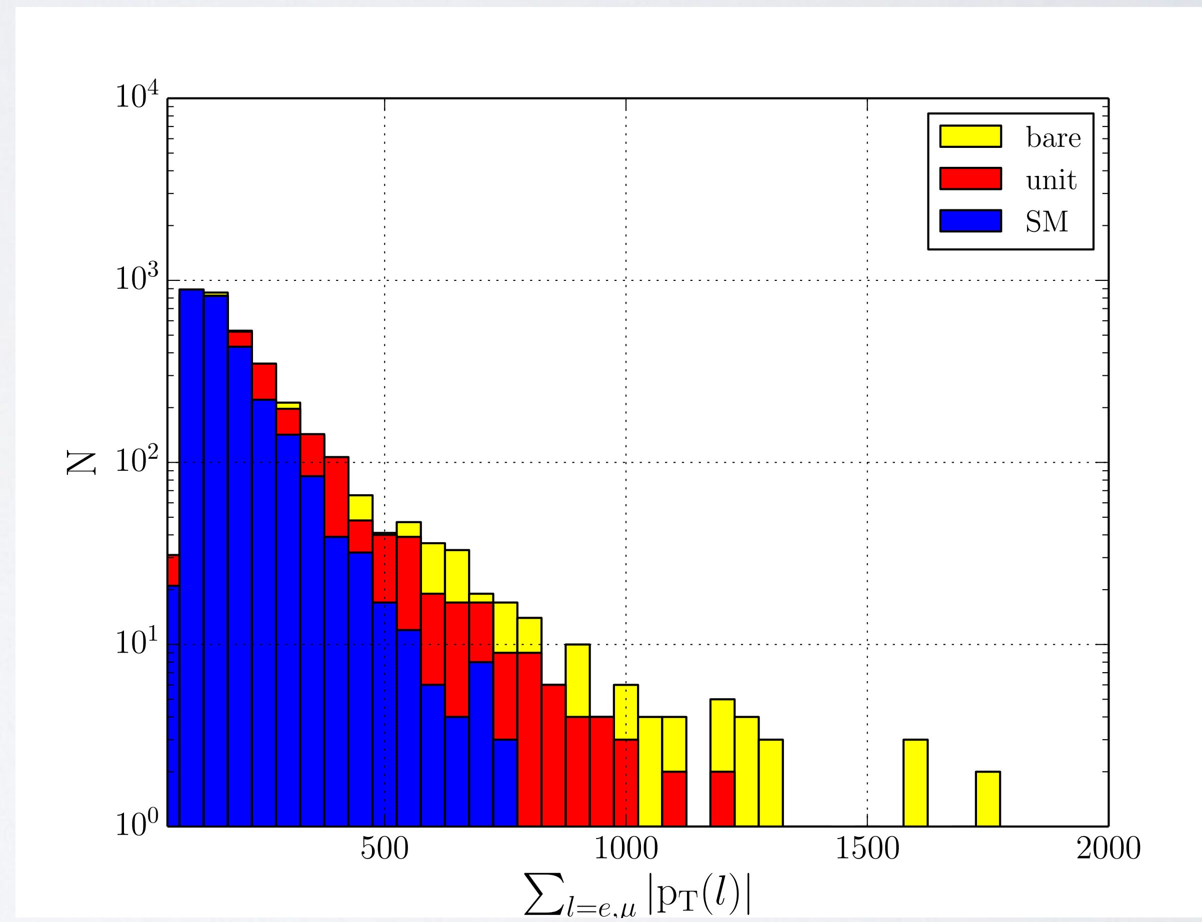
$$\mathcal{L}_{HD} = F_{HD}\,\mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right] \cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\,\mathbf{D}_\mu\mathbf{H}\right] \qquad F_{HD} = 30\ \mathrm{TeV}^{-2}$$





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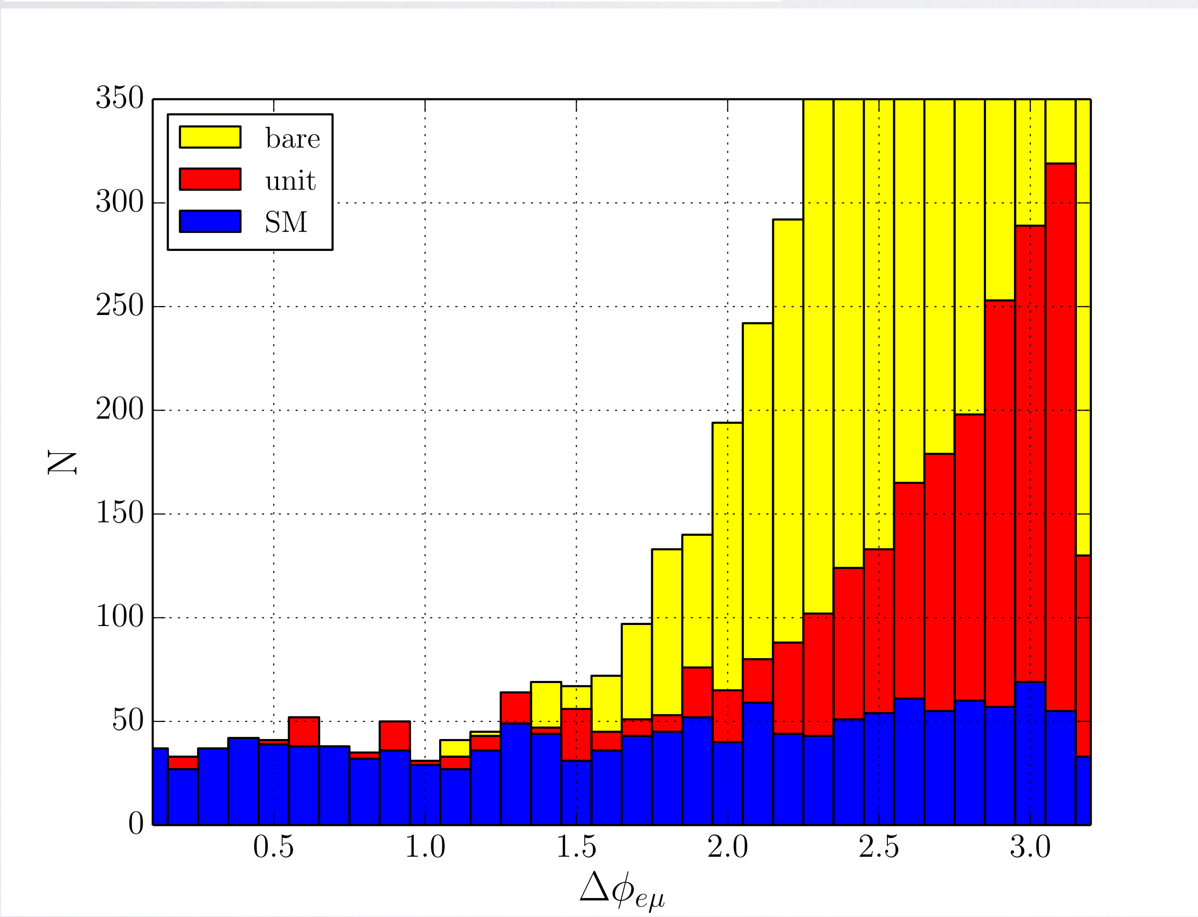

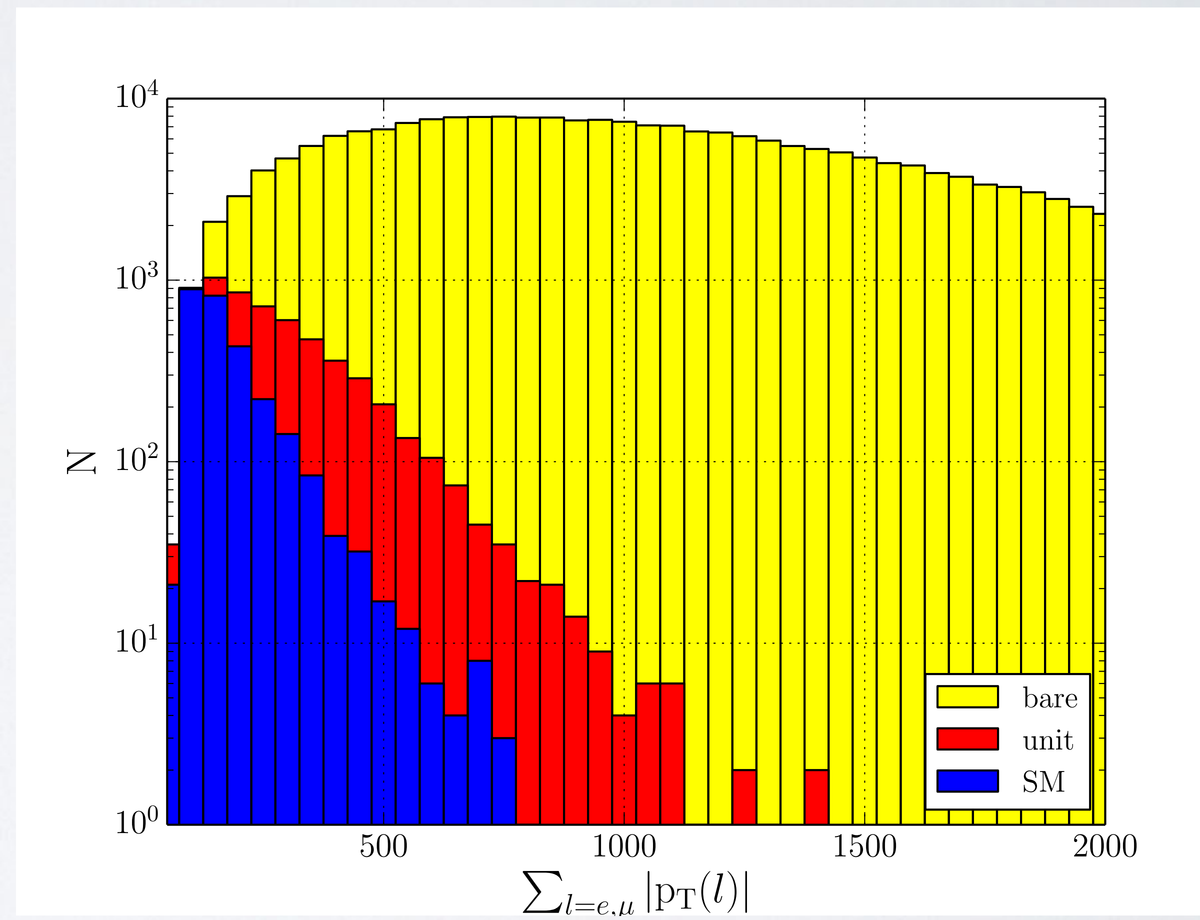

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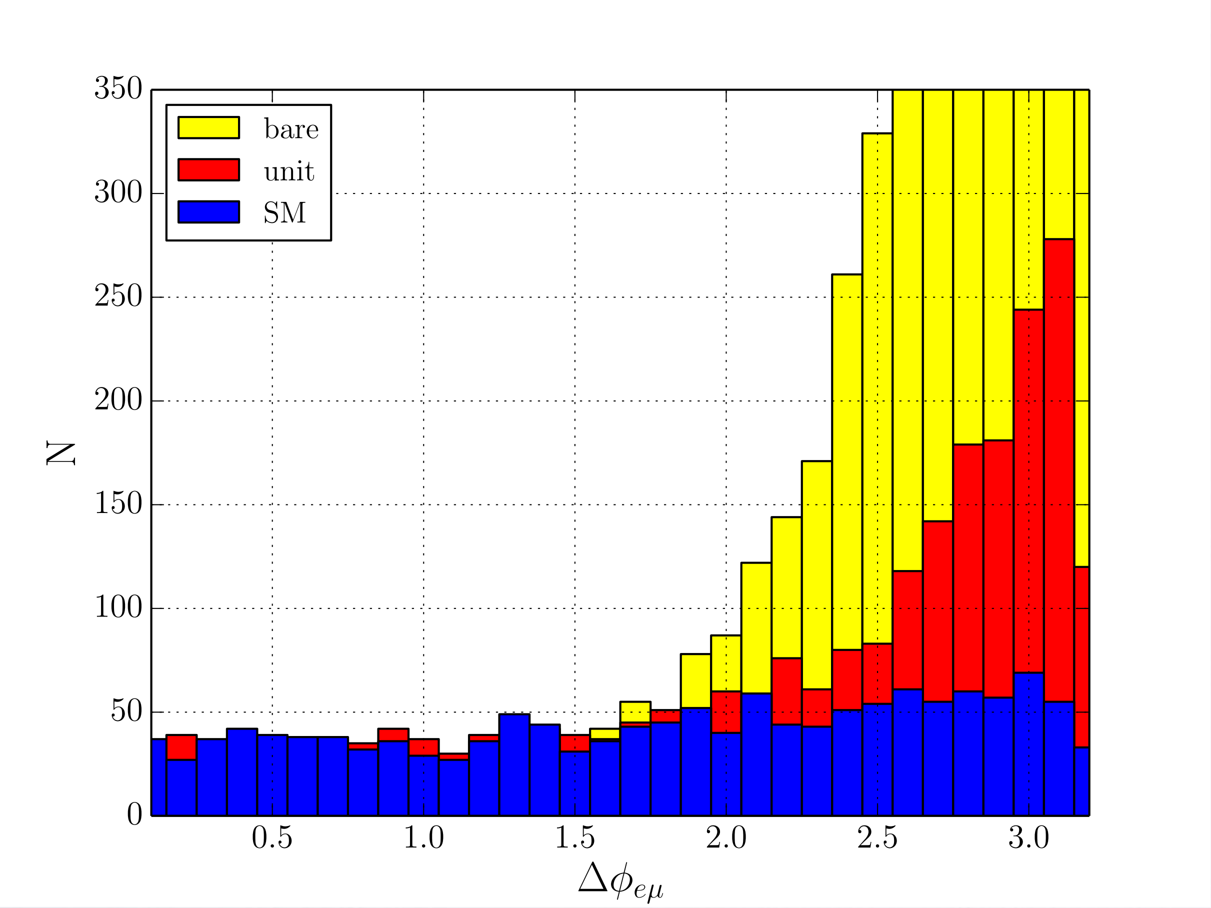

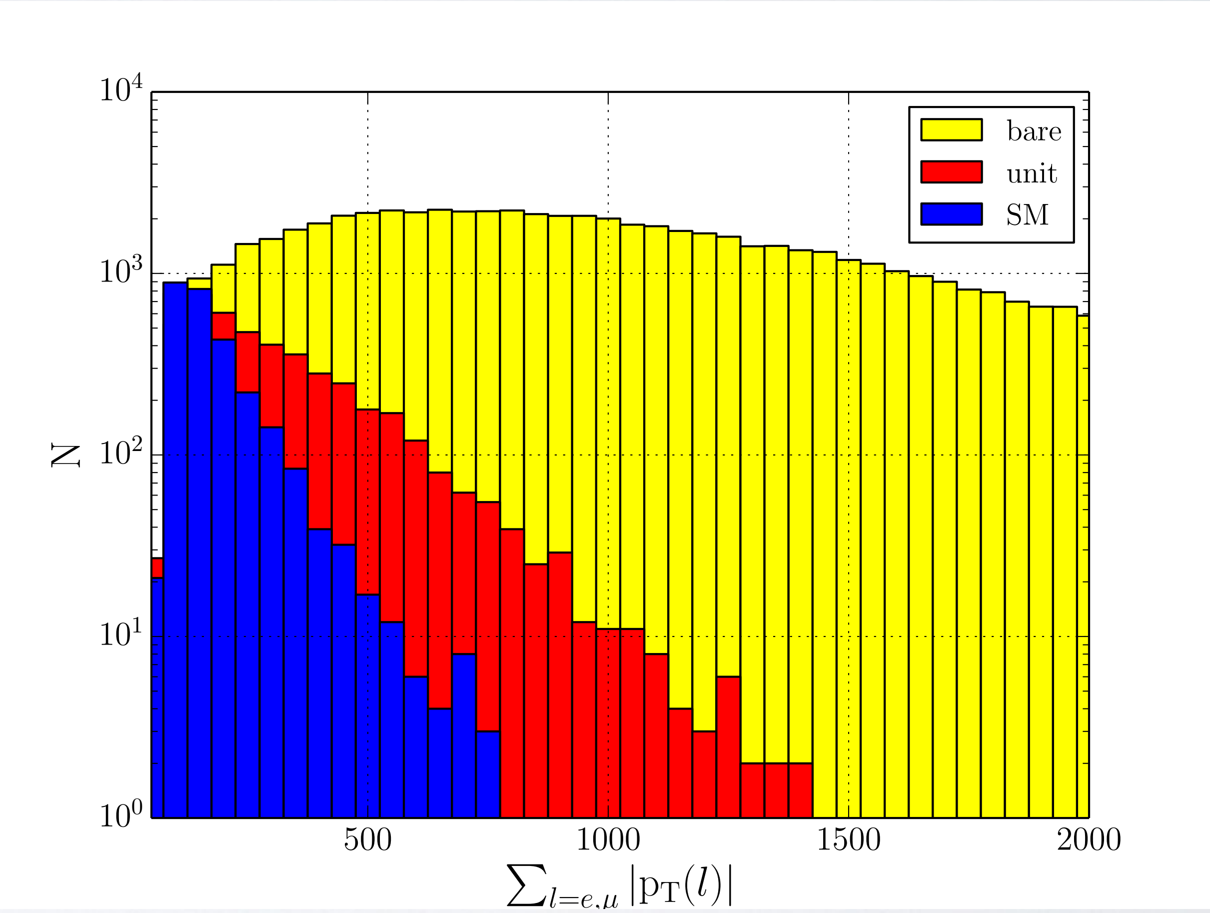

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How to get EFTs from New Physics

- 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

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

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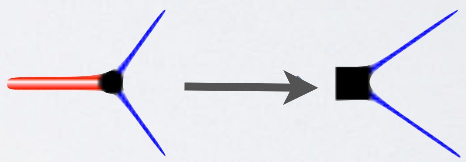
Completing the square (Gaussian integration)

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



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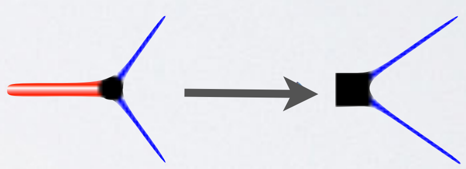
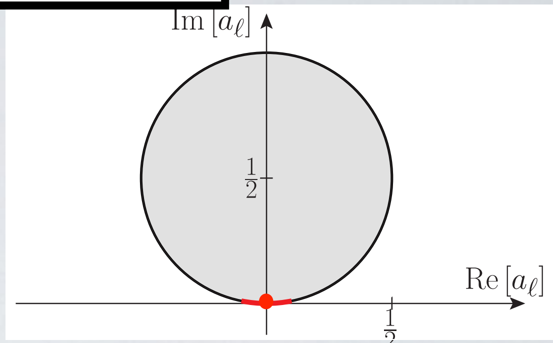


In the Lagrangian remove the high-scale d.o.f.s:

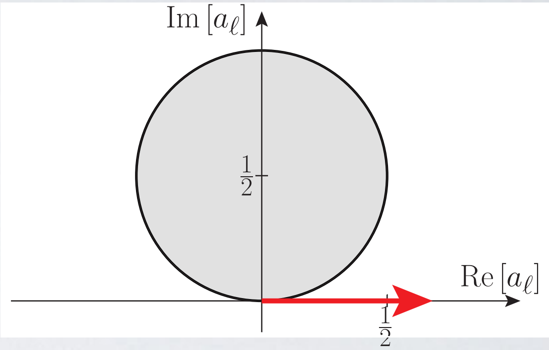
$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2+\partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1+\frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower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

Scenarios for New Physics in VBS

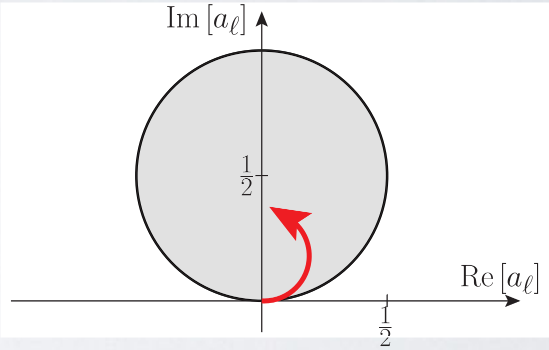
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



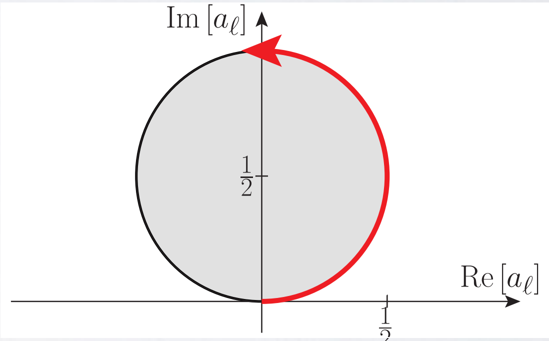
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



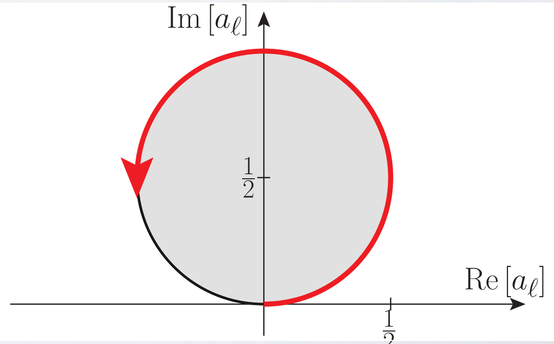
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



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



5. New resonance: amplitude turns over



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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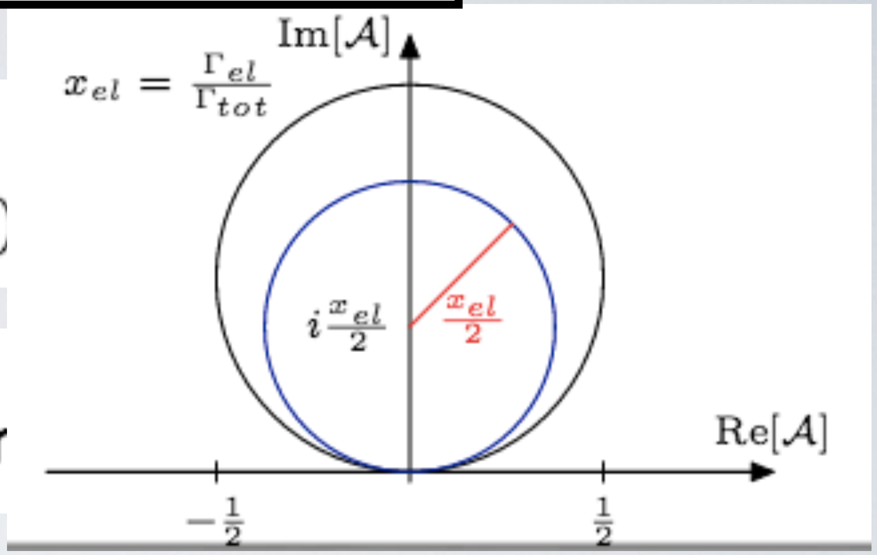

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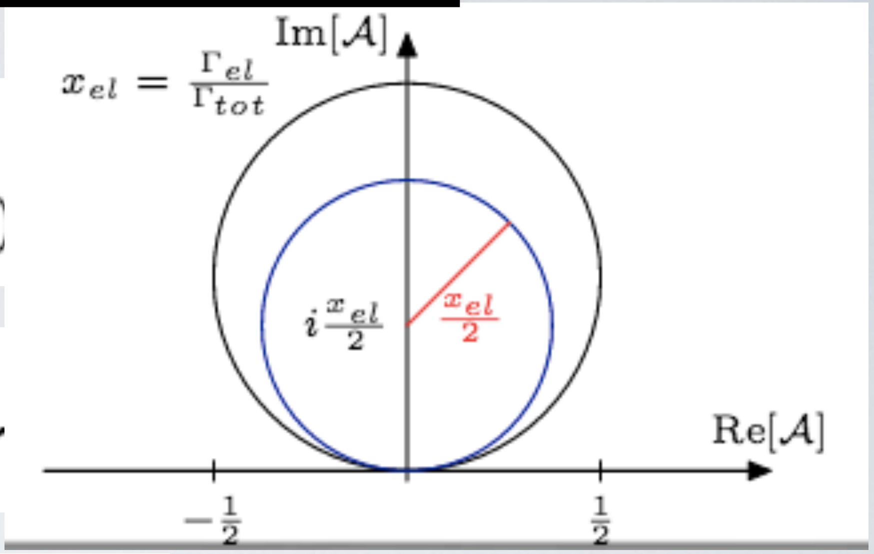

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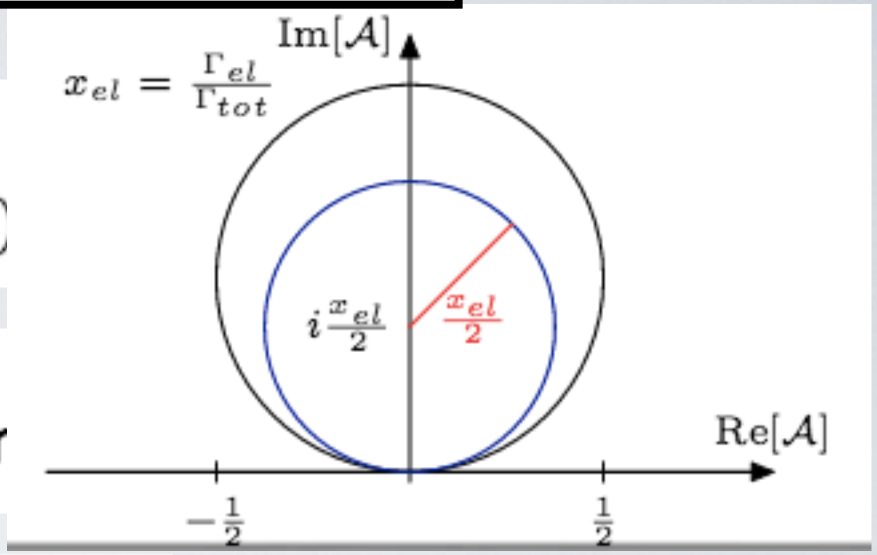

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$$\mathcal{A}_{I=0} = 2\frac{s}{v^2}P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2}P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2}P_0(s)$$

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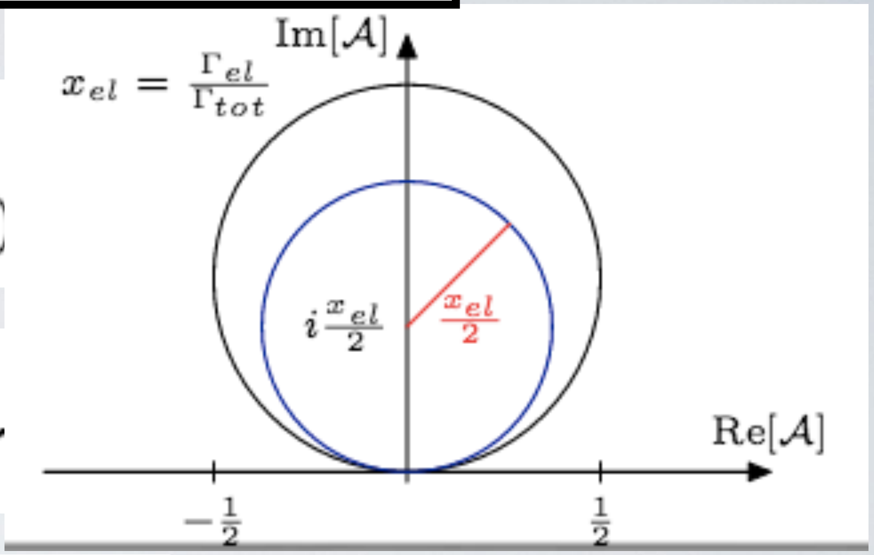

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Lee/Quigg/Thacker, 1973

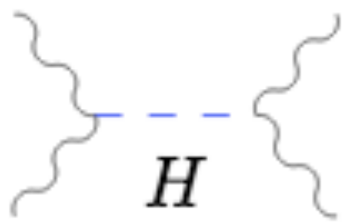
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

Higgs exchange:

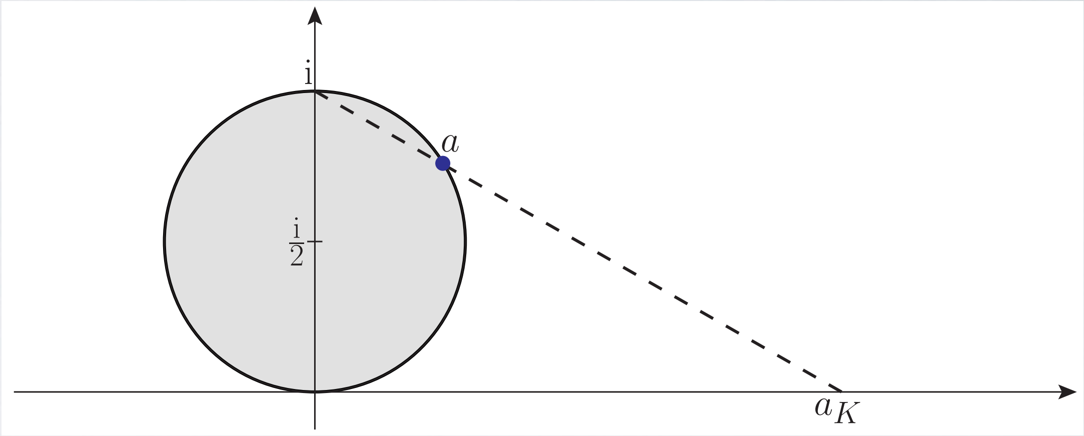


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

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

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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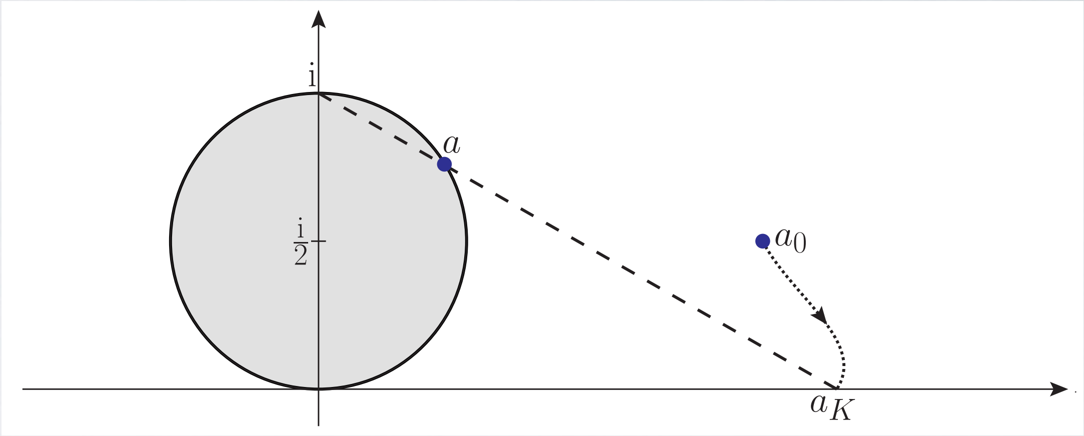

- Stereographic projection to Argand circle
- Formalism does a partial resummation of perturbative series
- need to construct (orig.) *K*-matrix as self-adjoint intermediate operator
  Problems, if *S*-matrix non-diagonal, presence of non-perturbative contrib.

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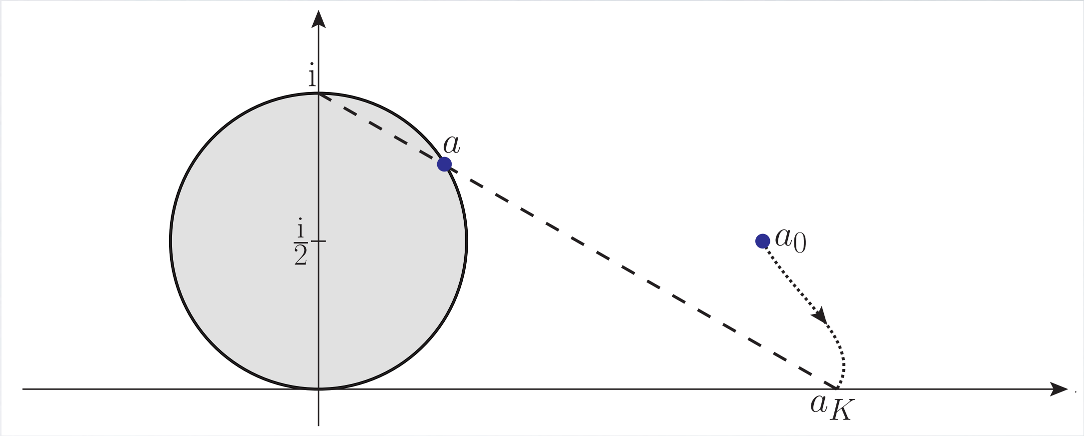

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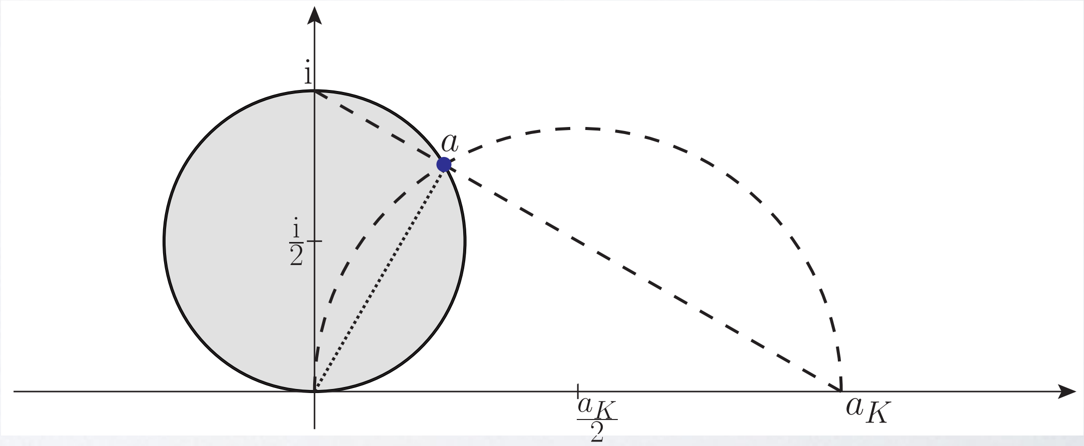

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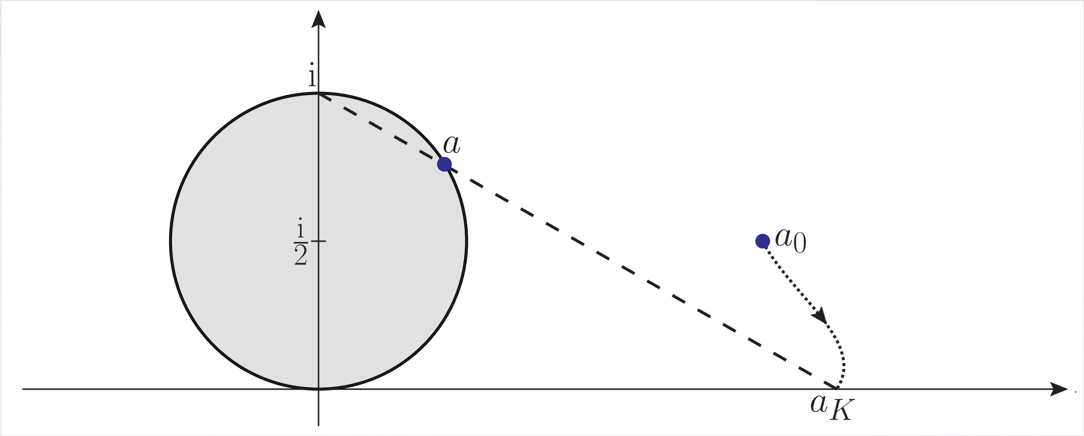

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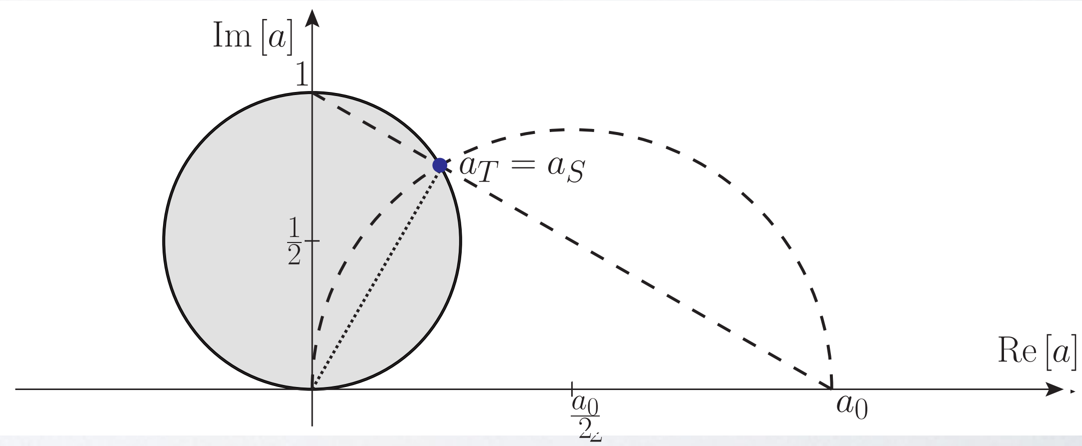

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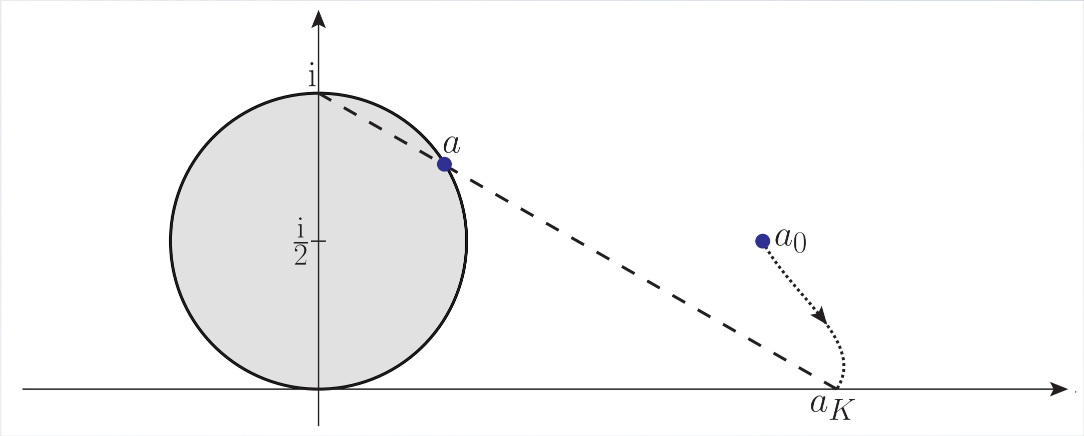

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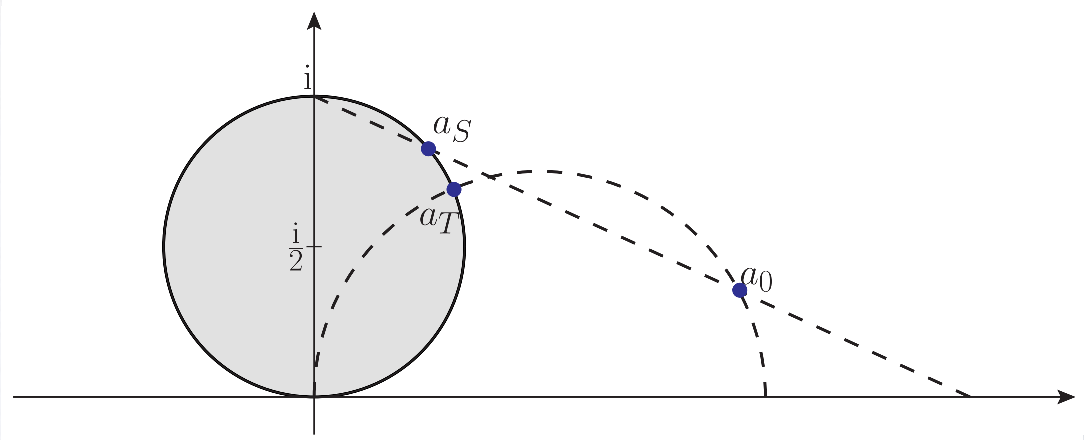

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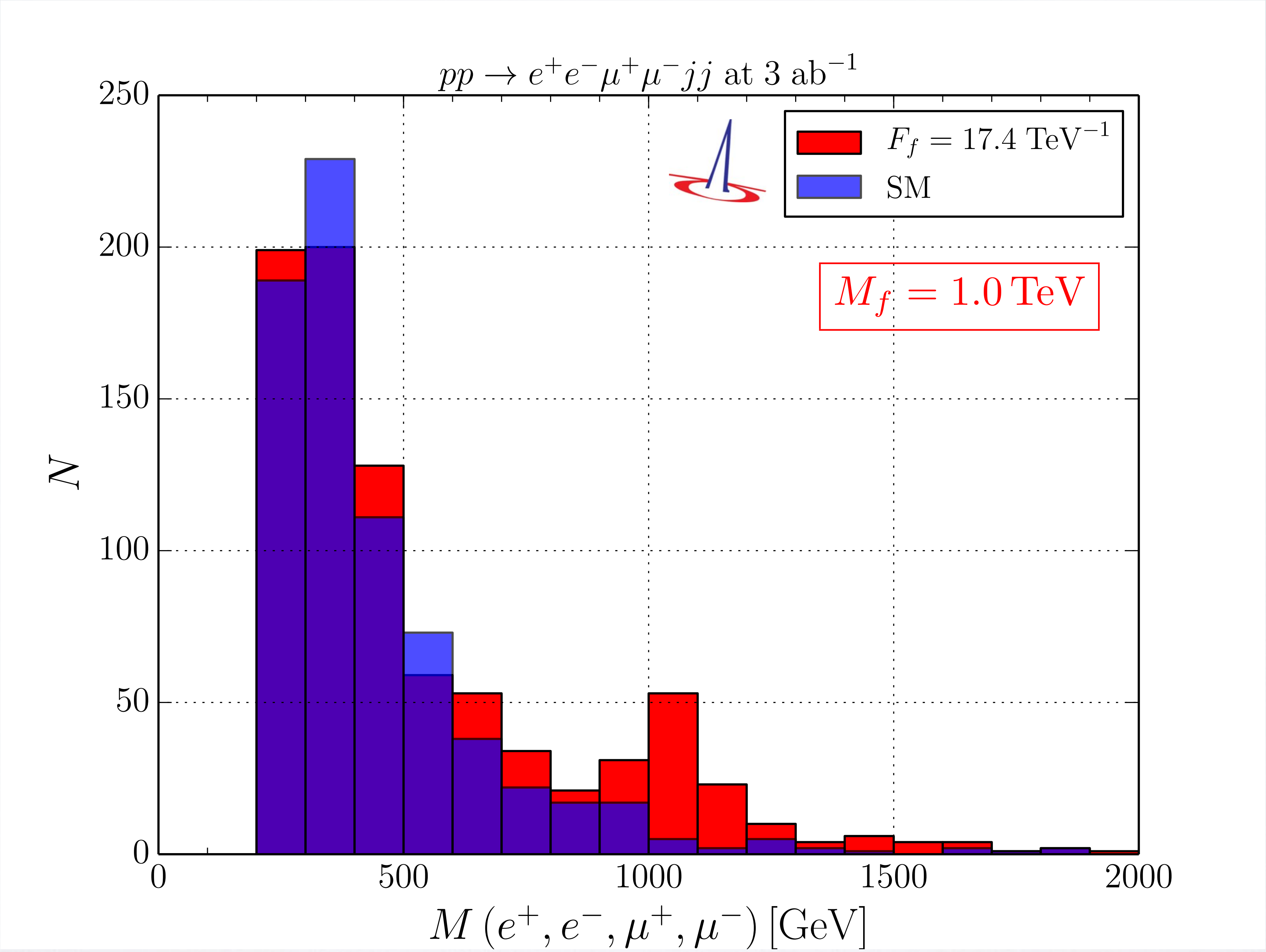
Complete LHC process at 14 TeV



Remark on alternative unitarizations

- Independent Amplitude Method (IAM) [Truong, 1988; Dobado/Herrero/Truong, 1990]
- Padé Method [Padé, 1890; Basdevant/Lee, 1970]
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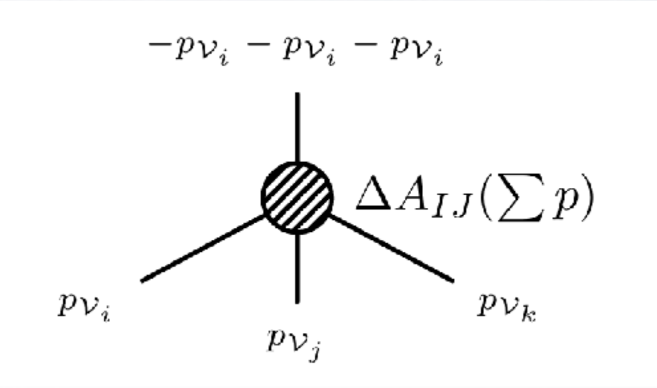
Unitarization of operators

- 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:

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

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				