New Physics / Resonances in Vector Boson Scattering at the LHC

25th Anniversary of the Rencontres du Vietnam Aug 5 – 11

ICISE

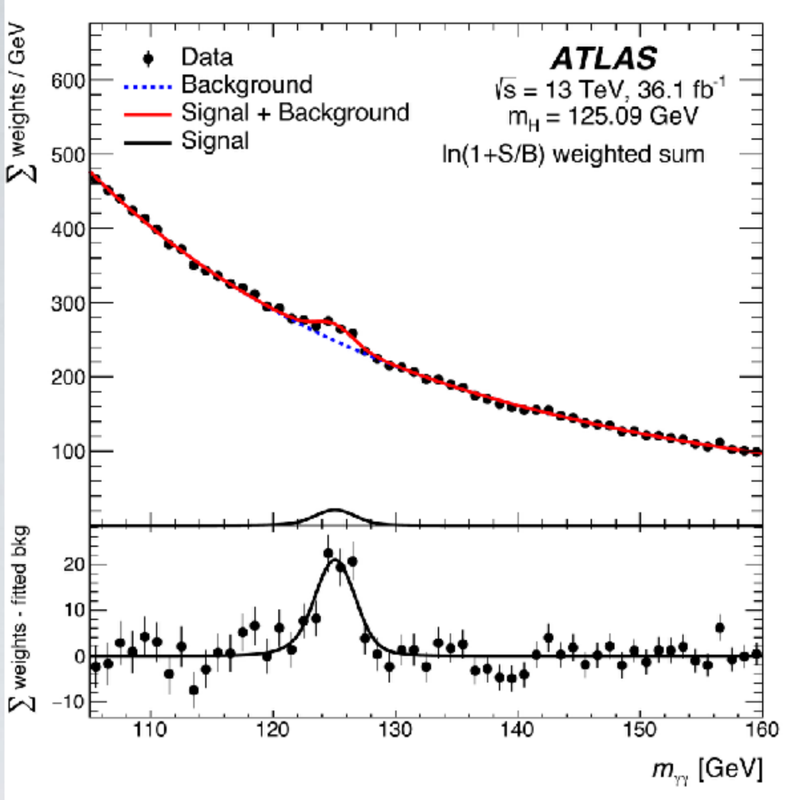
WINDOWS ON THE UNIVERSE 2018

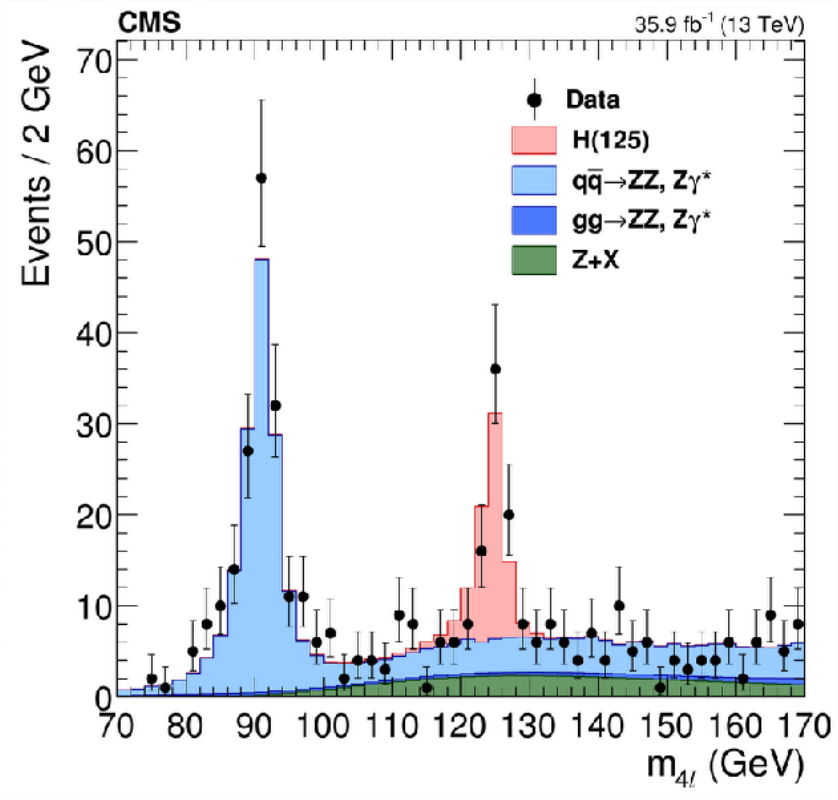
Jürgen R. Reuter, DESY

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



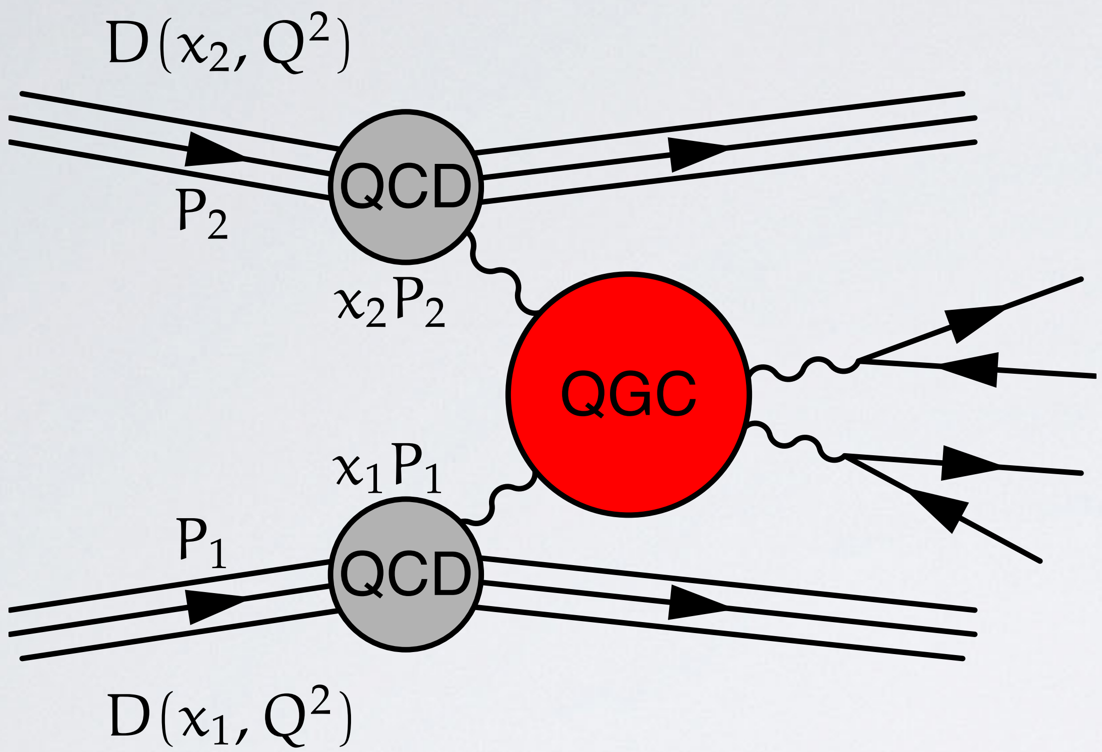


- Discovery of a light Higgs boson leaves still open questions:

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**

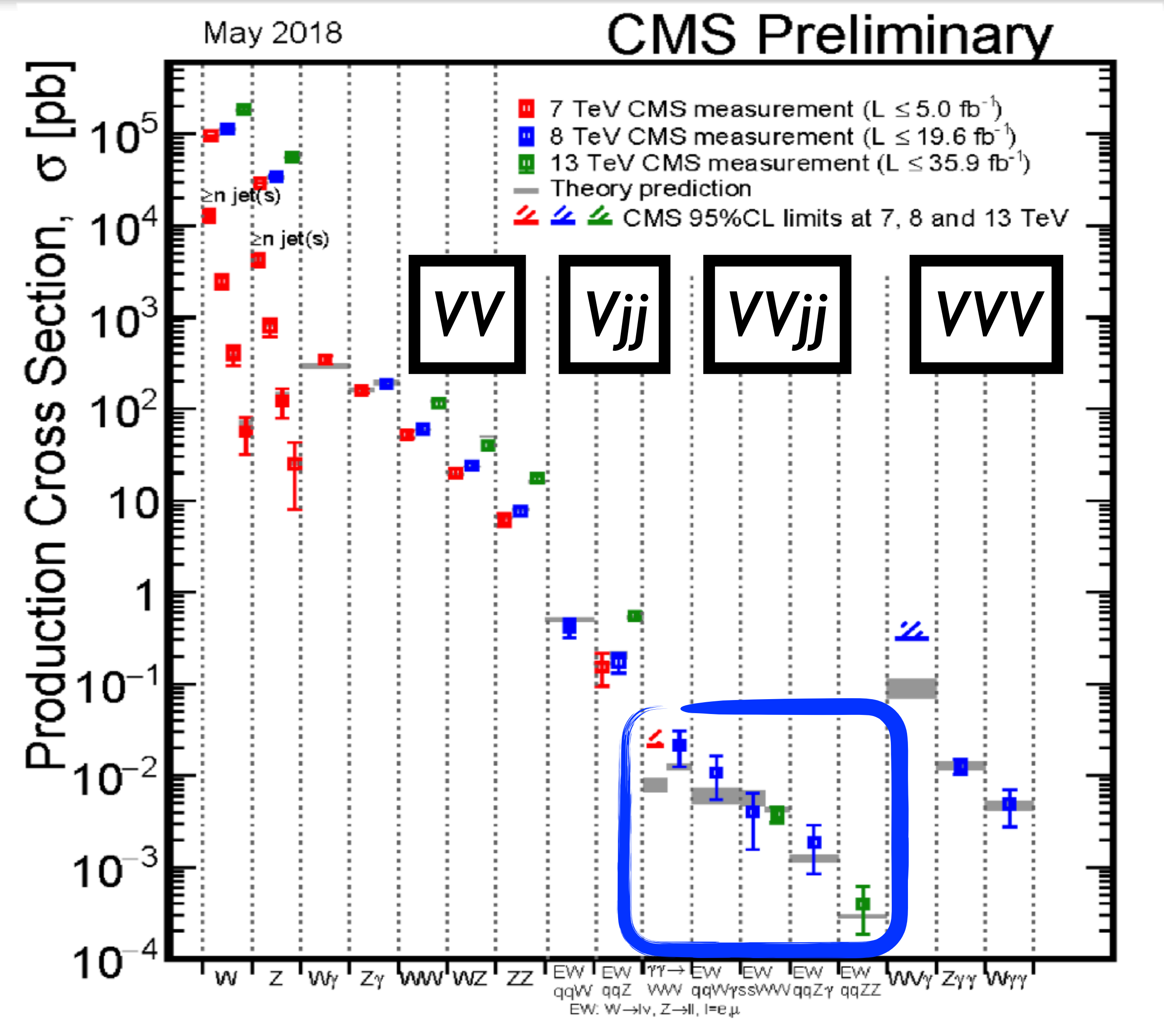
Anatomy of Vector Boson Scattering (VBS)

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



Backgrounds:

- *tt* → *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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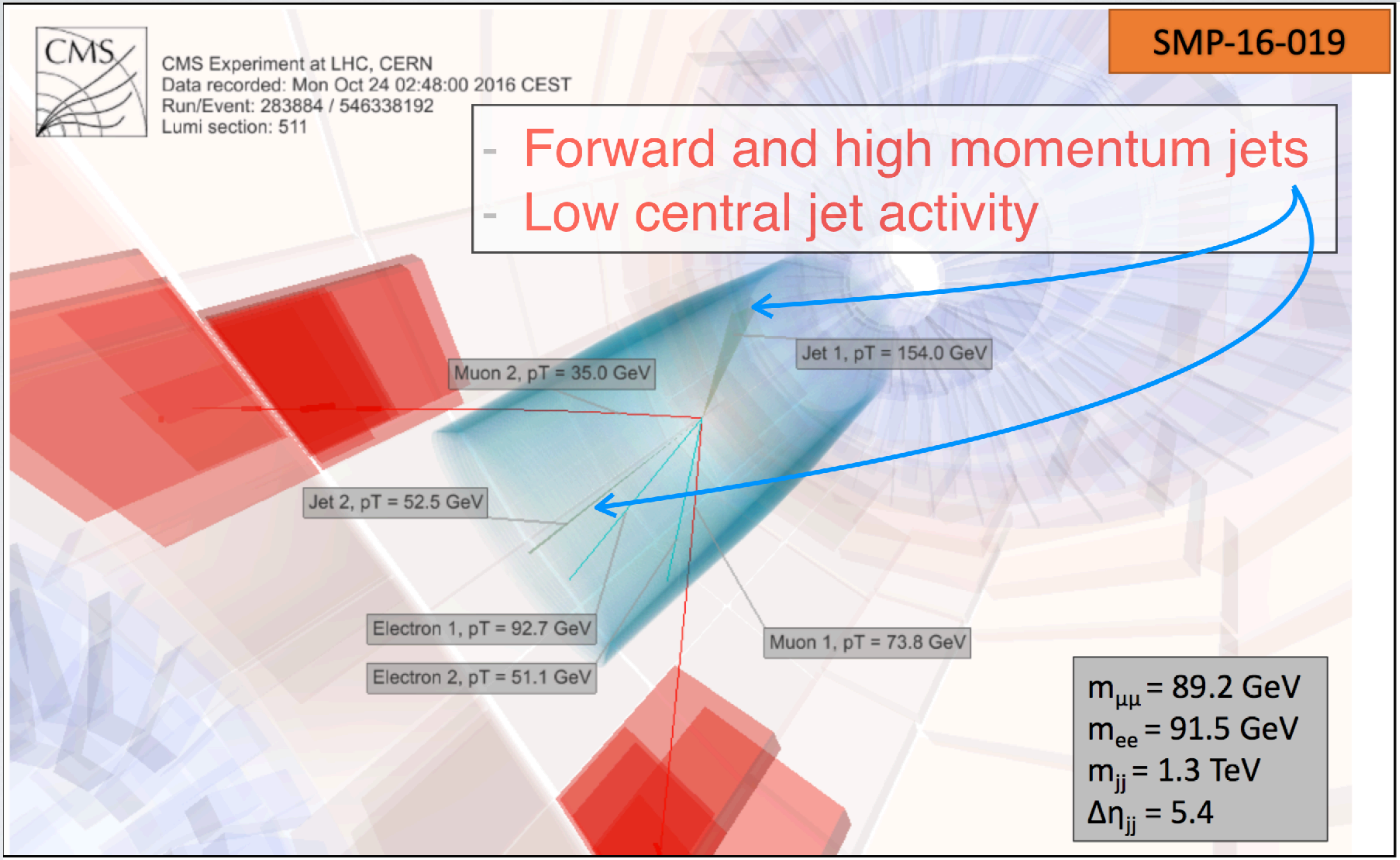

VBS ZZjj Candidate Event from PLB 774 (2017) 682

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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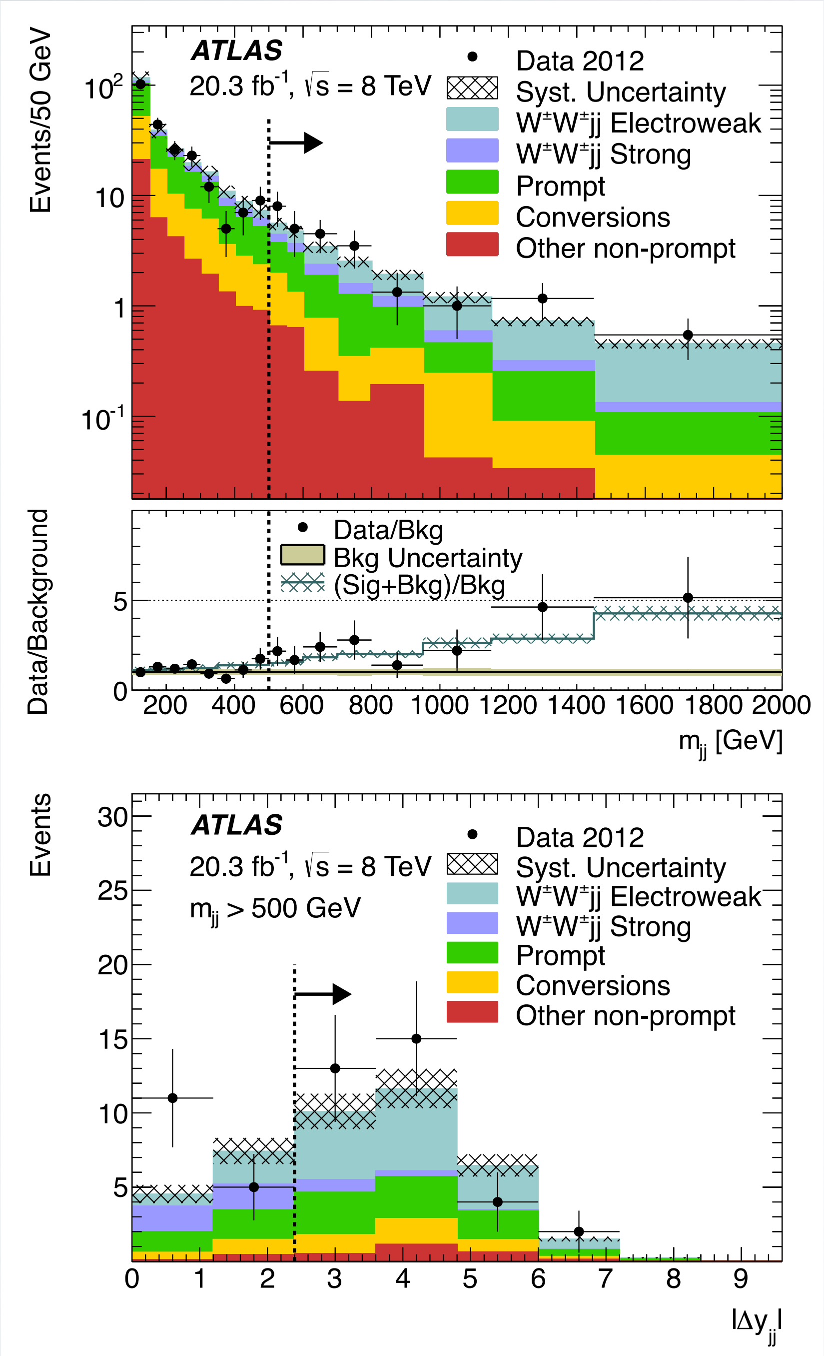

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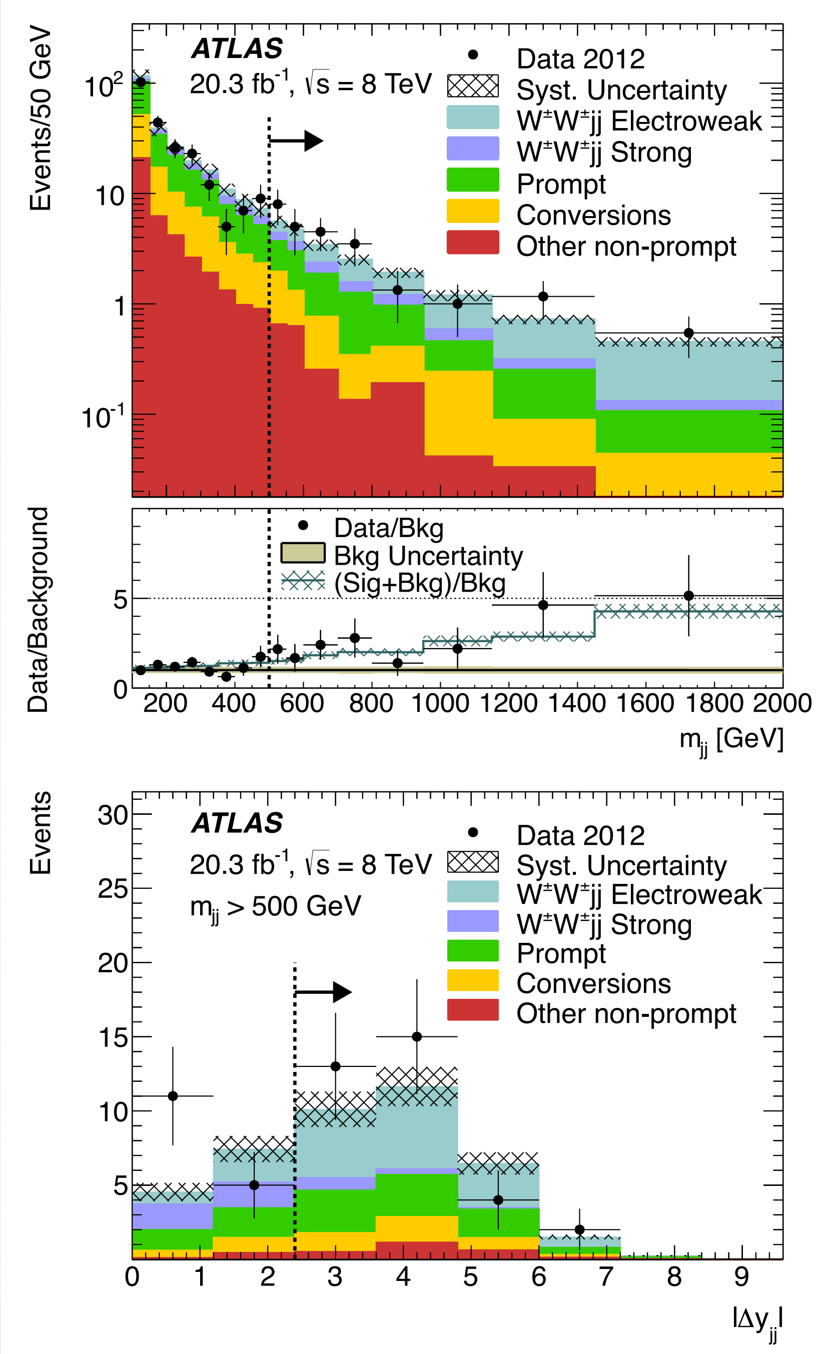

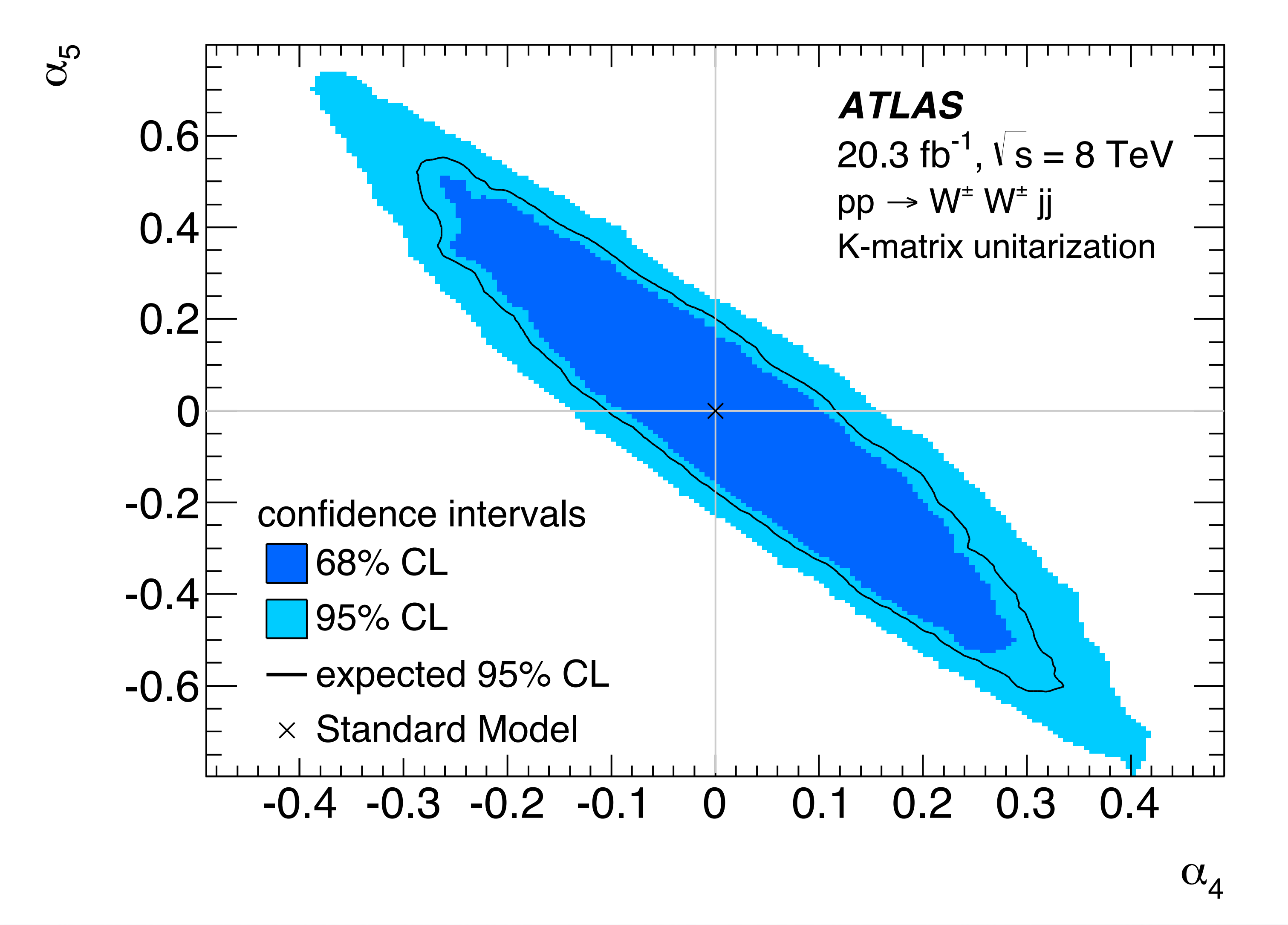

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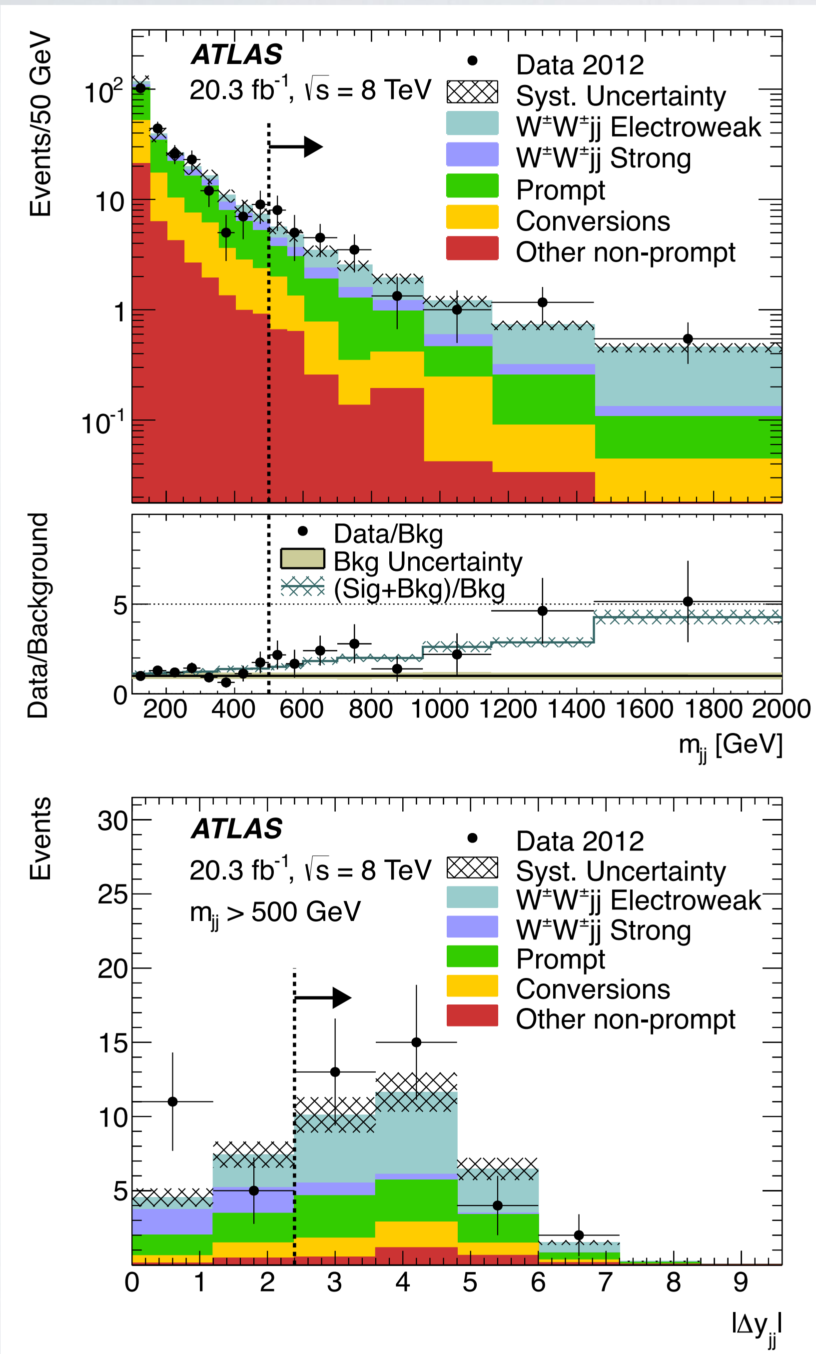
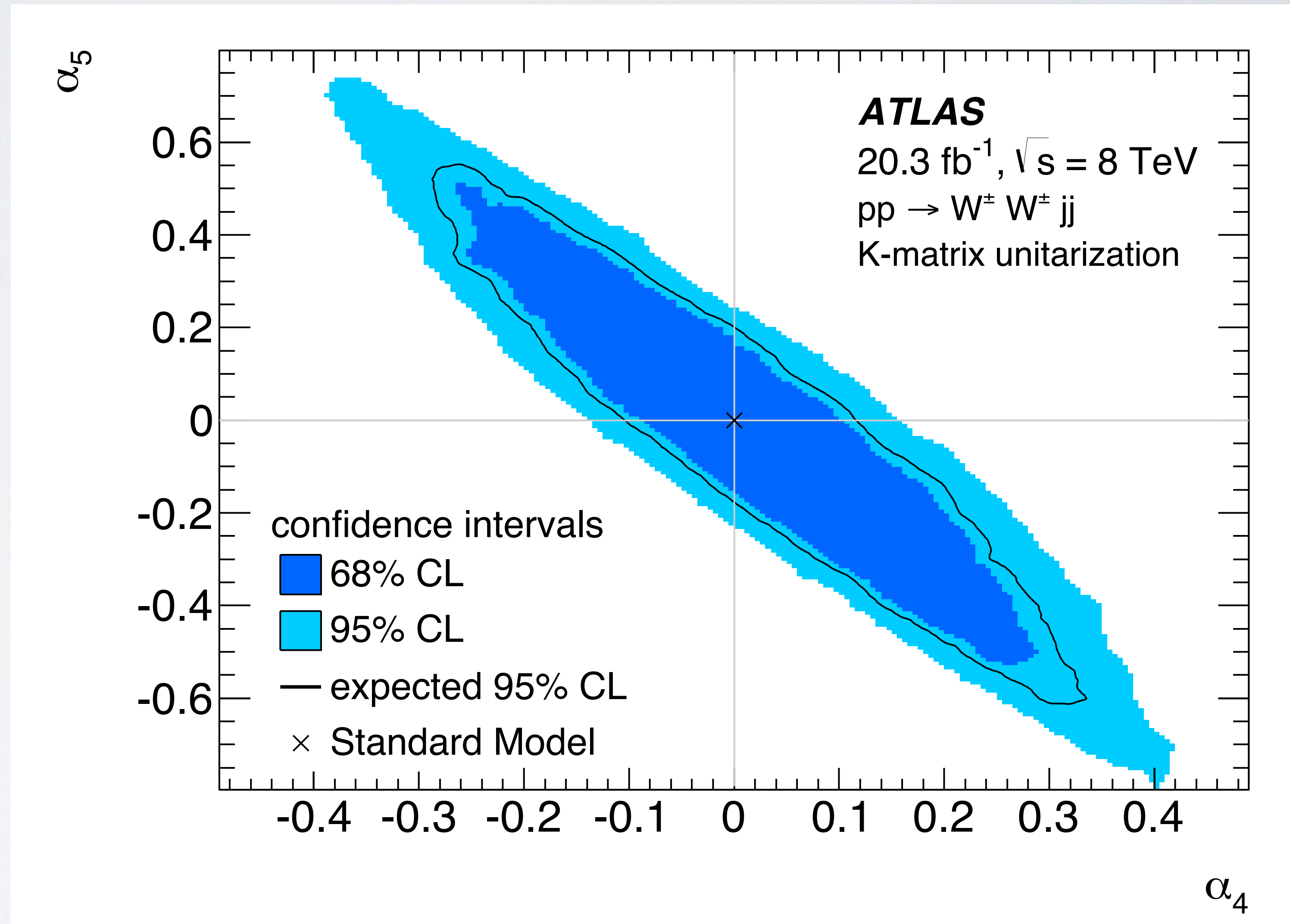
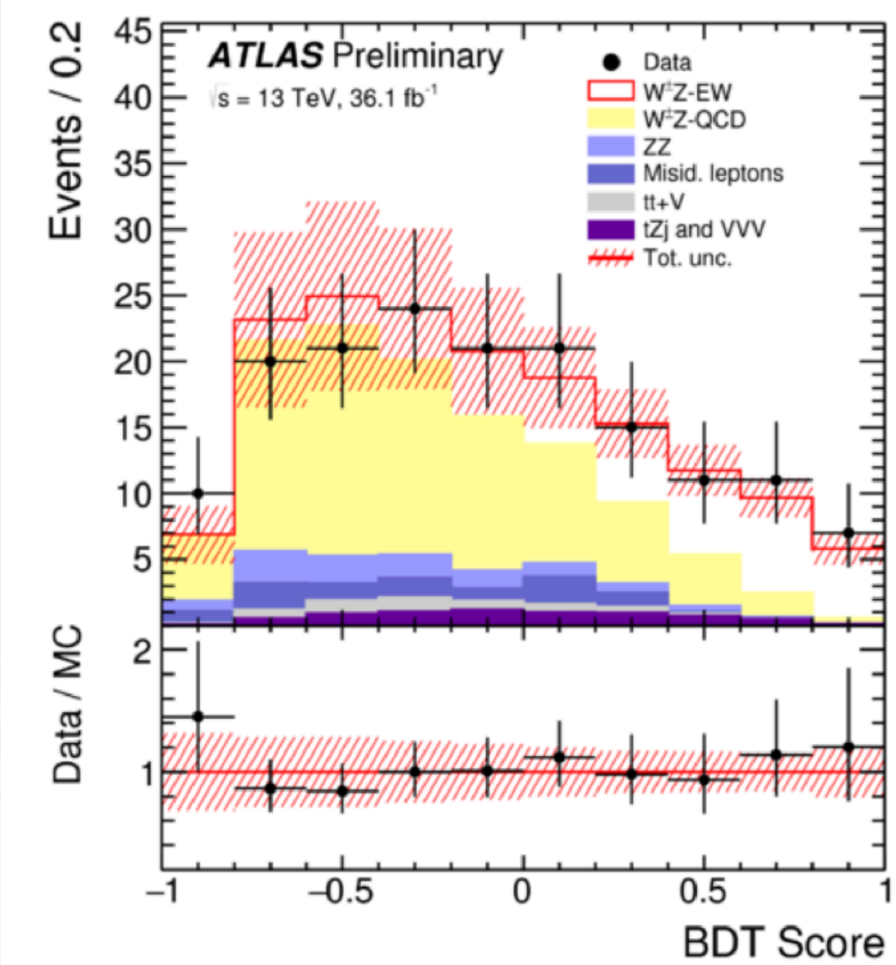




Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:
❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)

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

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

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

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

WZjj-EW measured signal strength:

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

Observed sign.: 5.6σ (3.3σ expected)

Corresponding fid. cross section:

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

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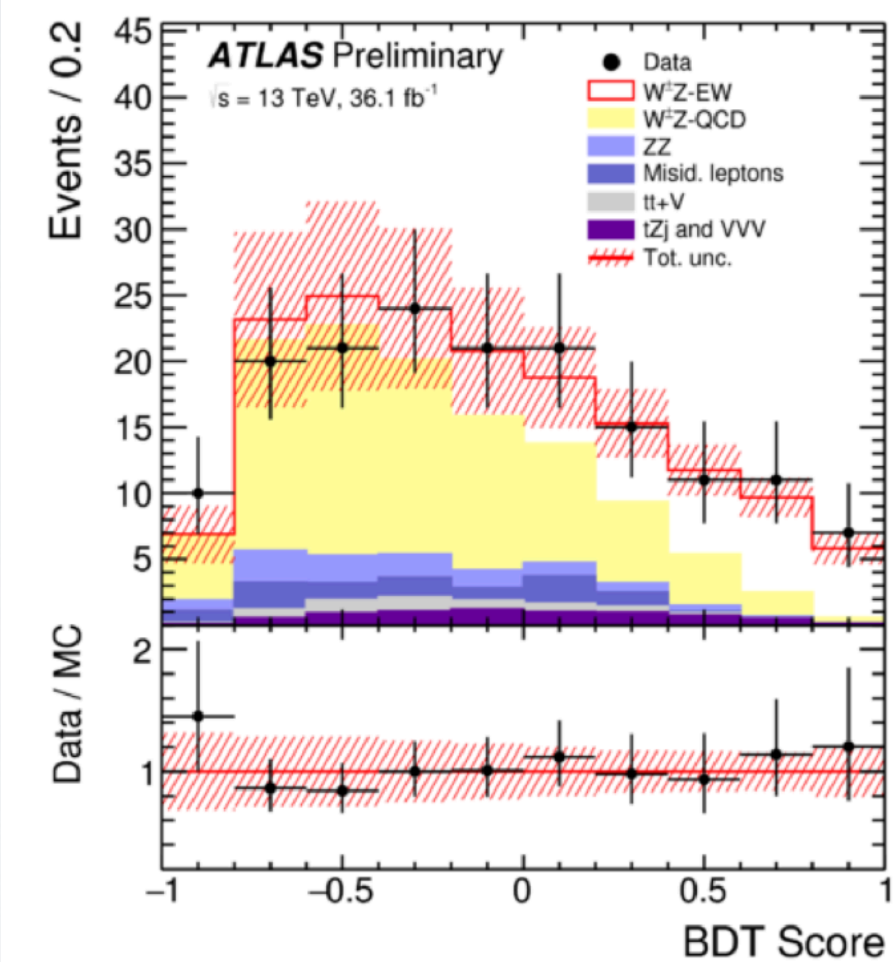

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$pp \to WZjj \to lljj + X$

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

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)

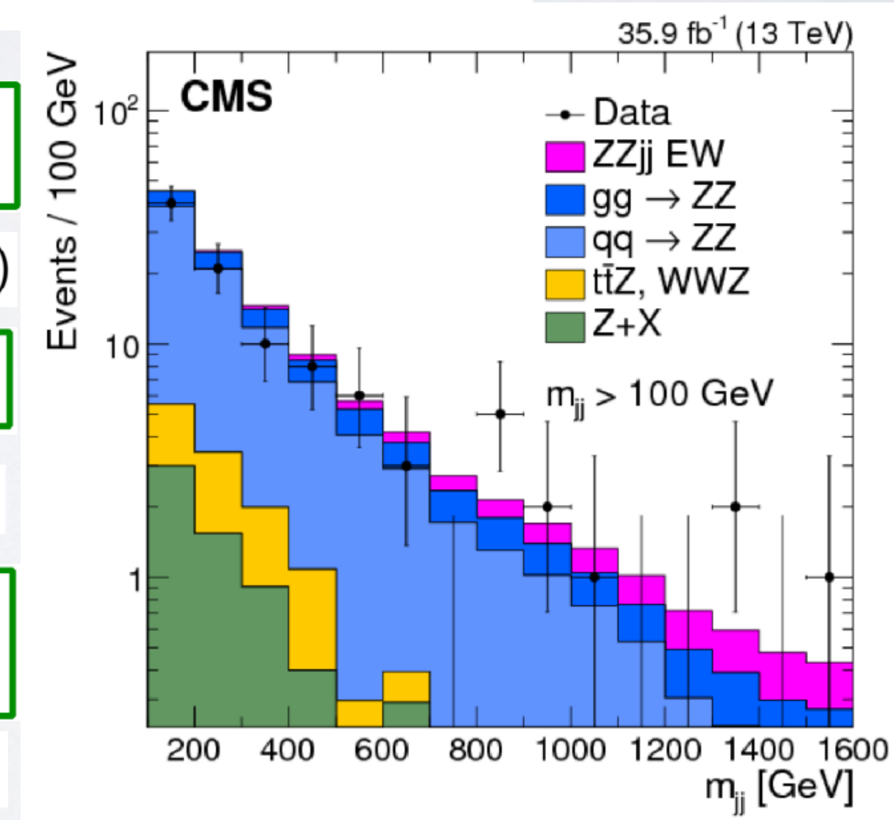
Observed (expected) of 5.5σ (5.7σ)

$pp \to ZZjj \to lllljj$

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

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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Eboli/Gonzalez-Garcia/Mizukoshi, 2006

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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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$$\mathcal{L}_{M,4} = -g g' F_{M_4} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\mu \mathbf{H}) \mathbf{B}^{\nu\rho}\right],$$
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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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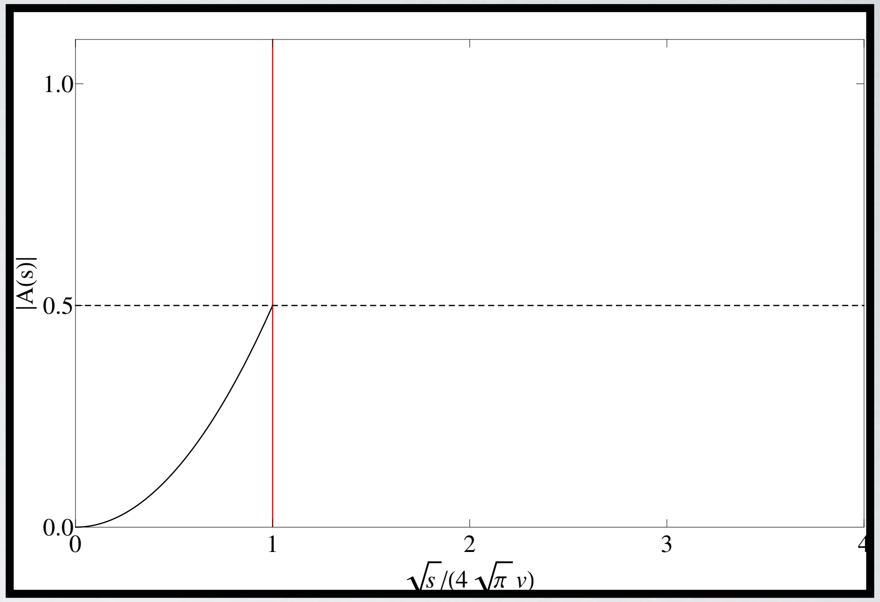
- Energy rise of operators lead to unitarity violation
- Unitarity violation between operators in UV-complete Theory

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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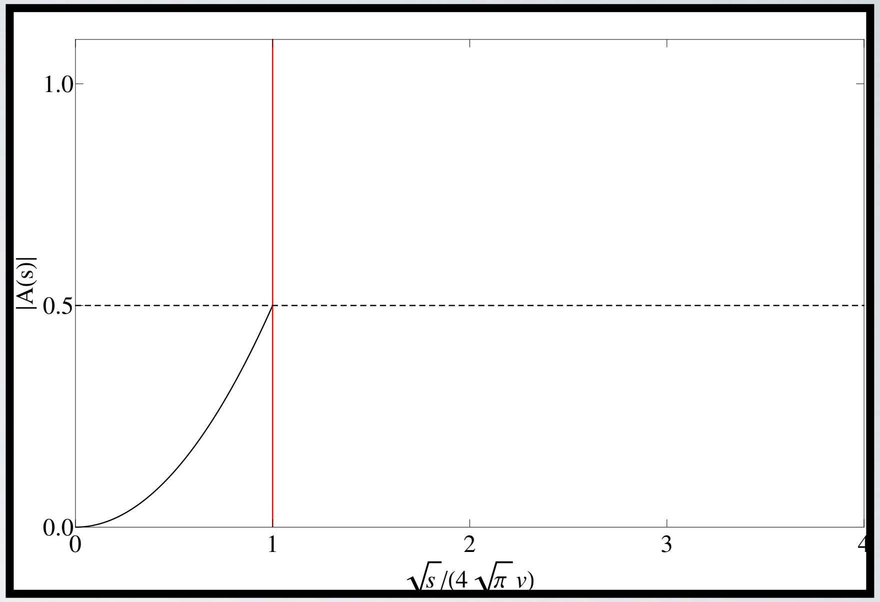
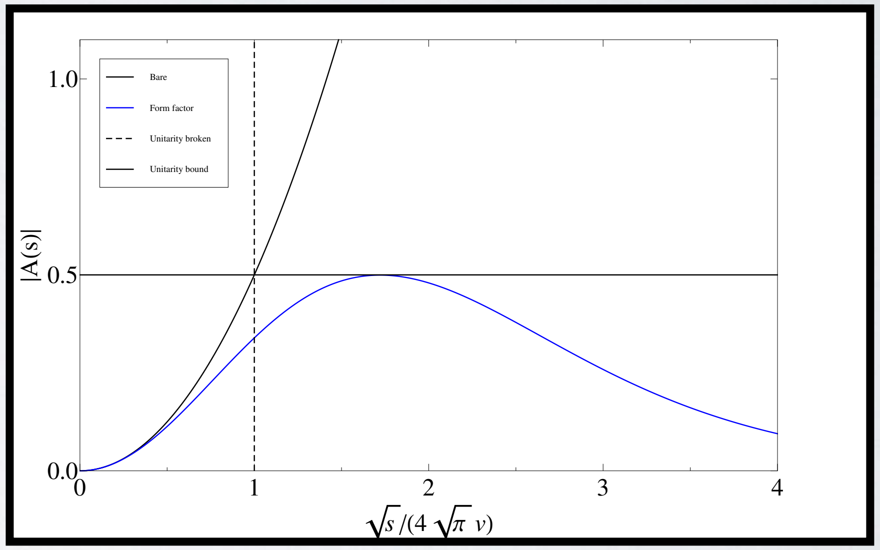


Form factor $\frac{1}{\left(1+\frac{s}{\Lambda_{FF}}\right)^n}$

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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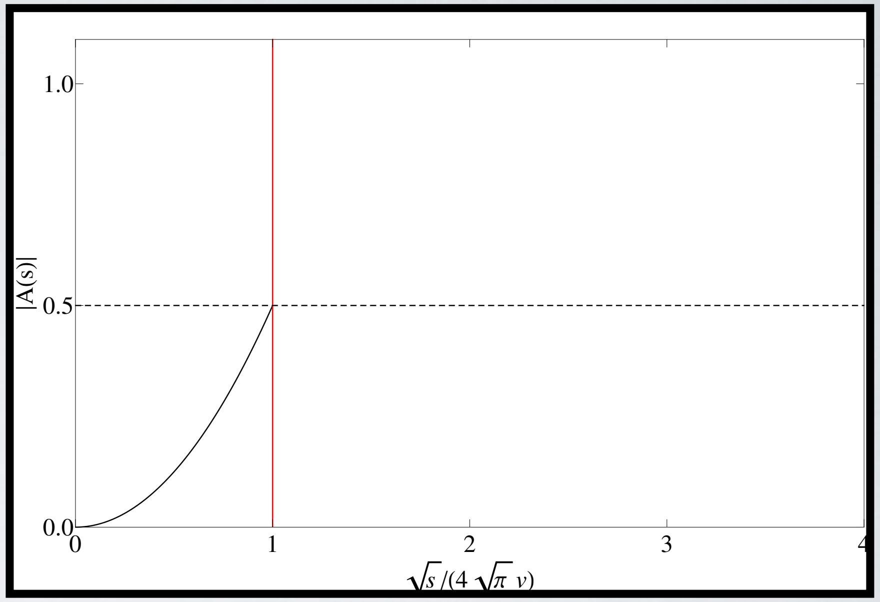

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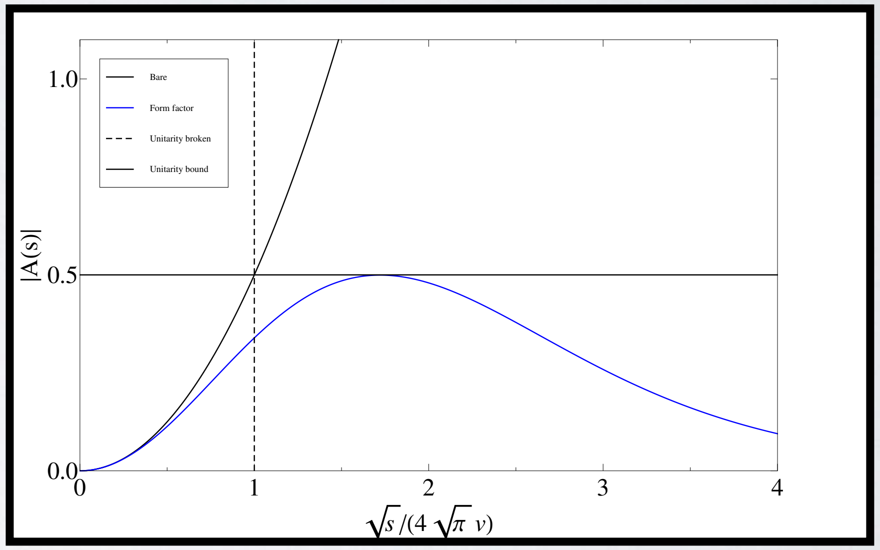
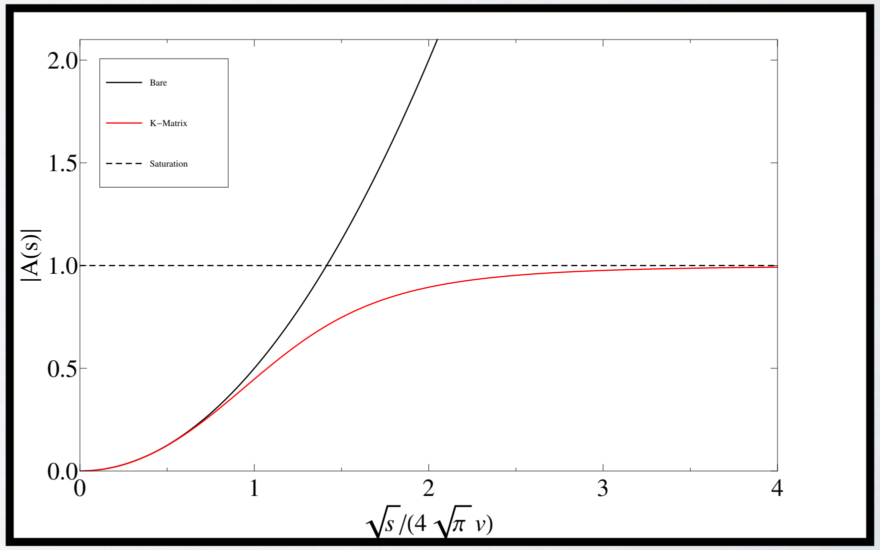


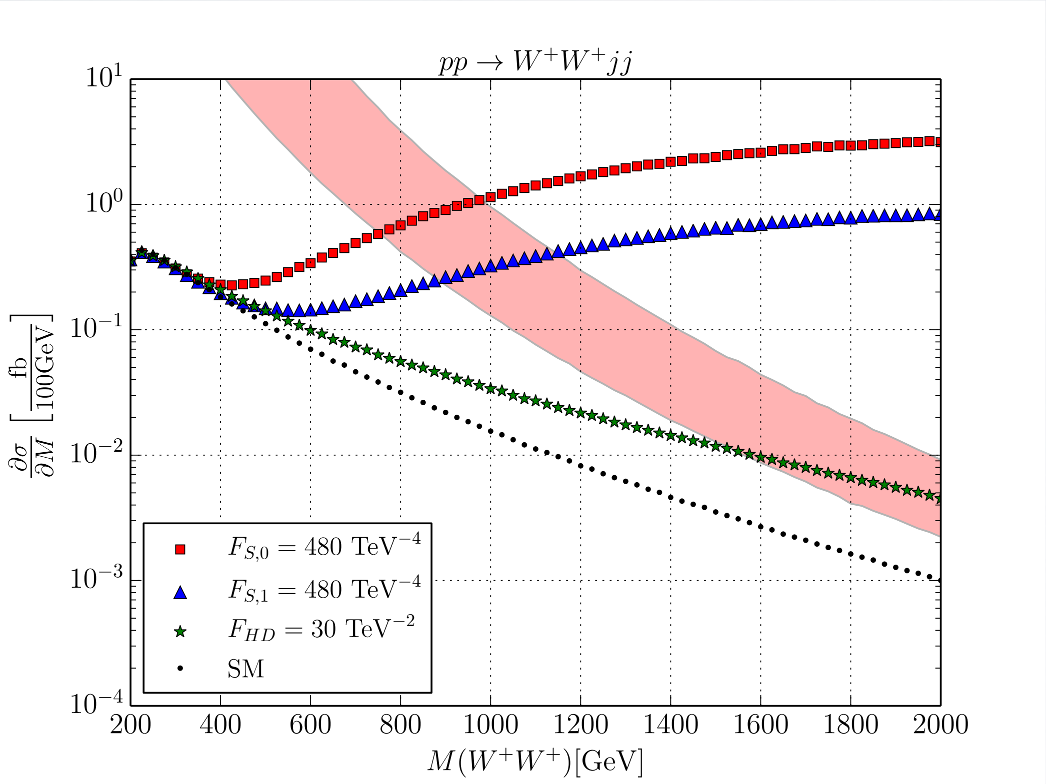
K-/*T*-matrix saturation $a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$

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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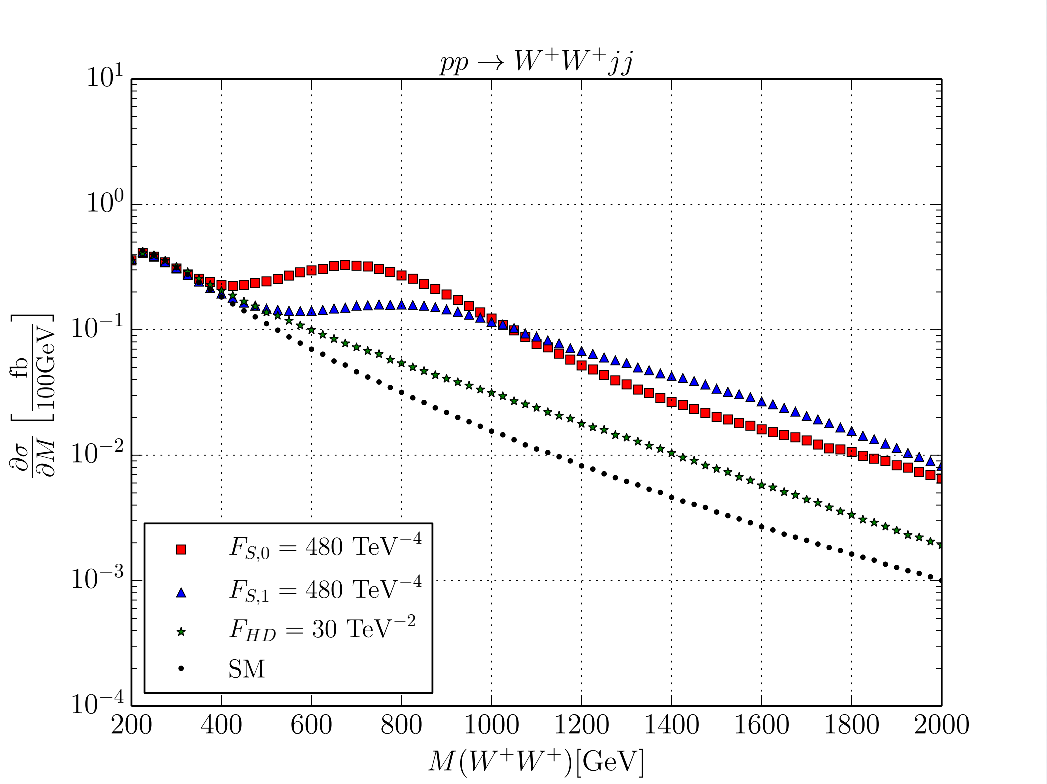

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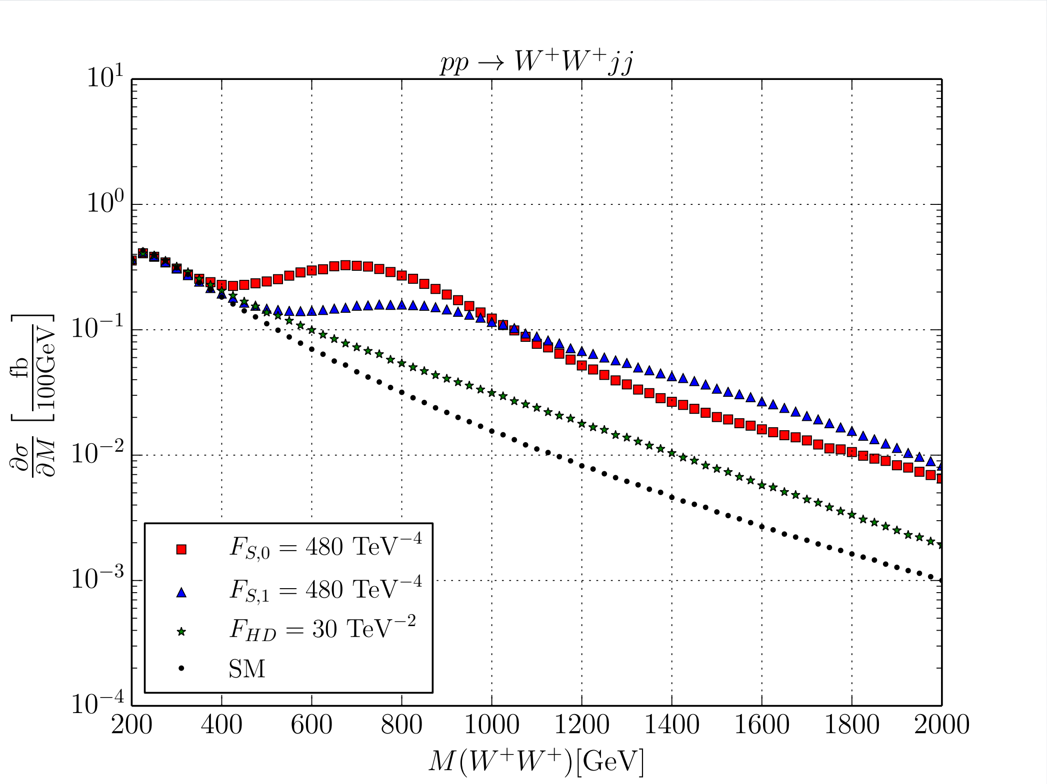

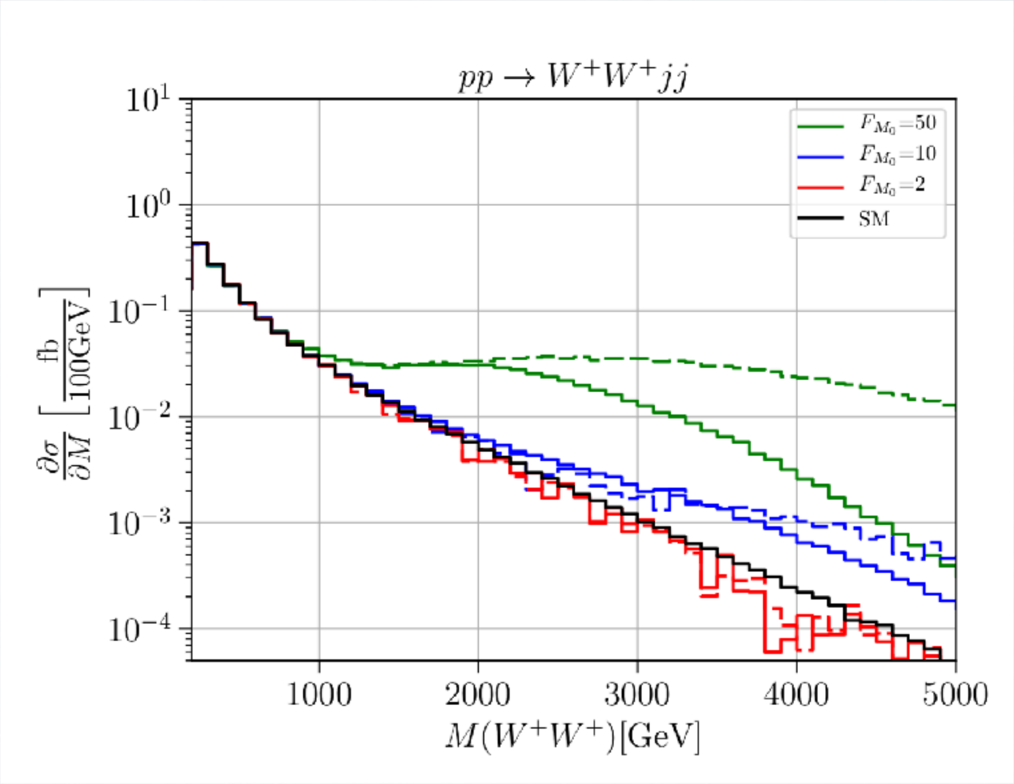

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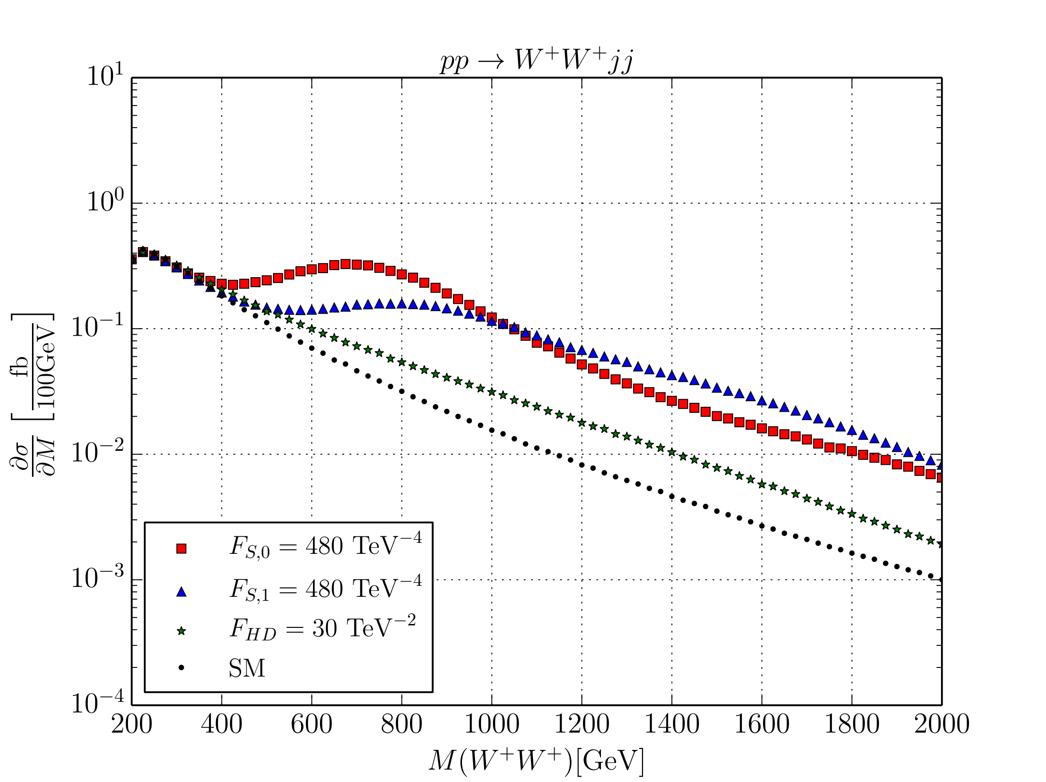

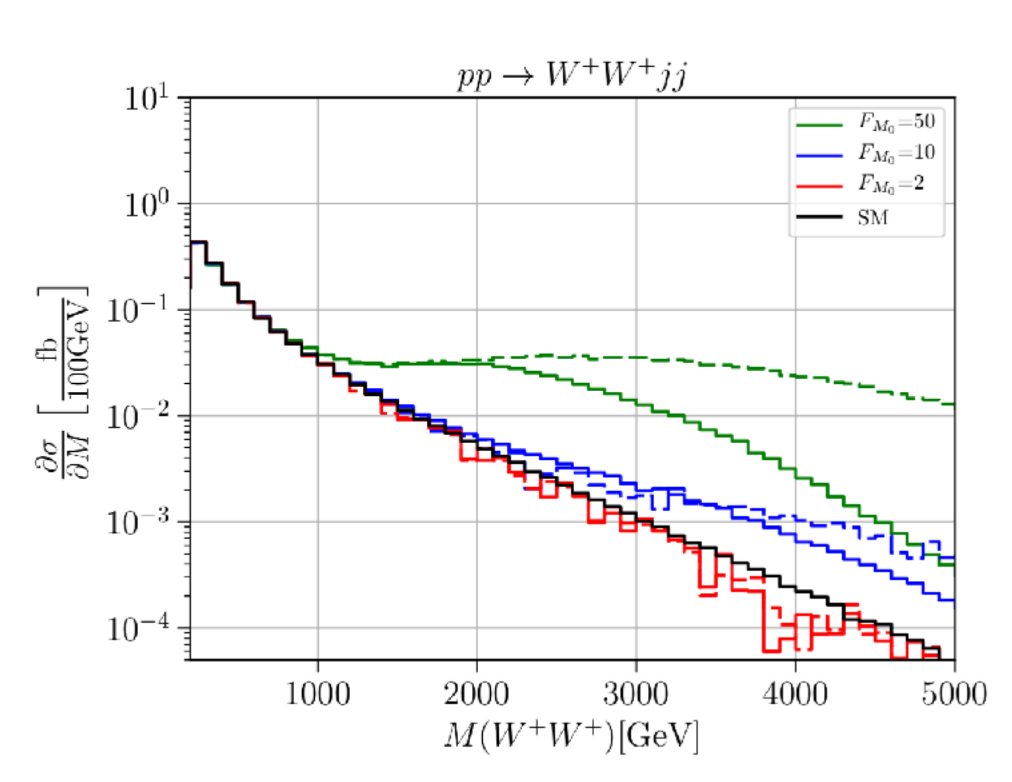

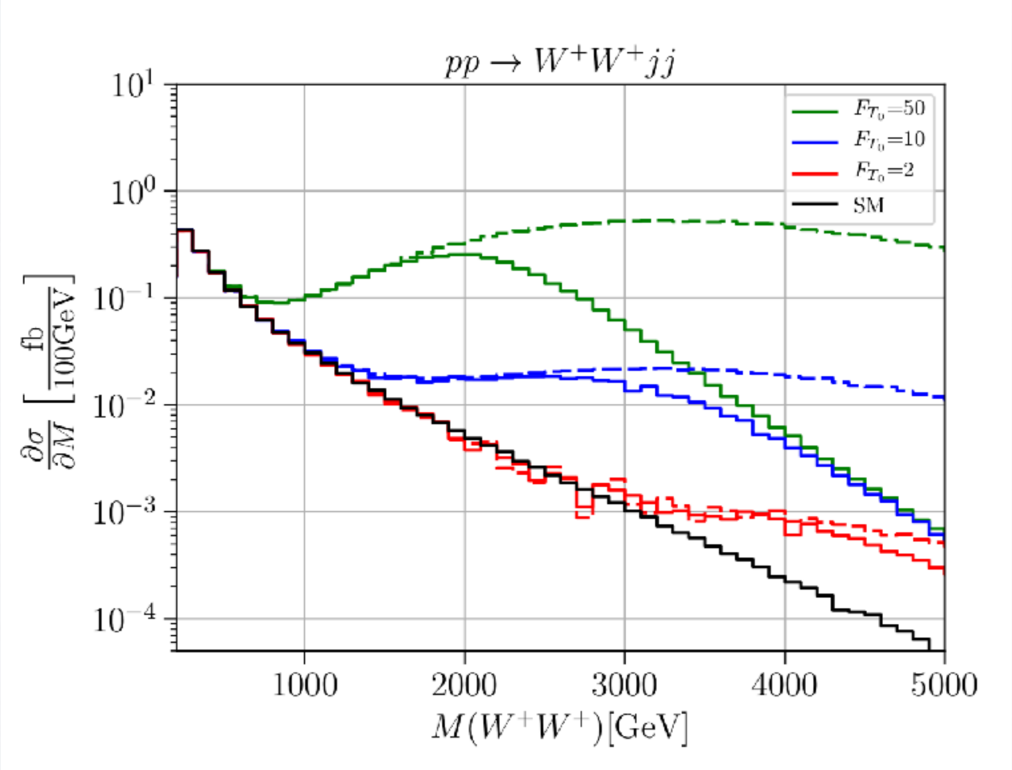

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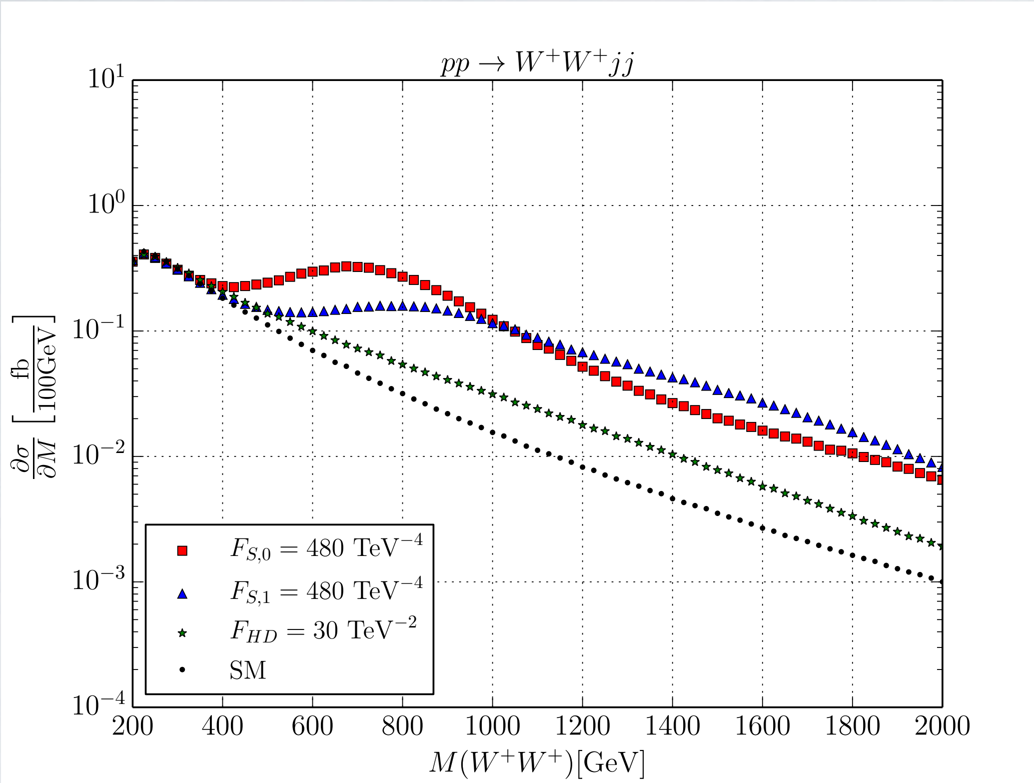

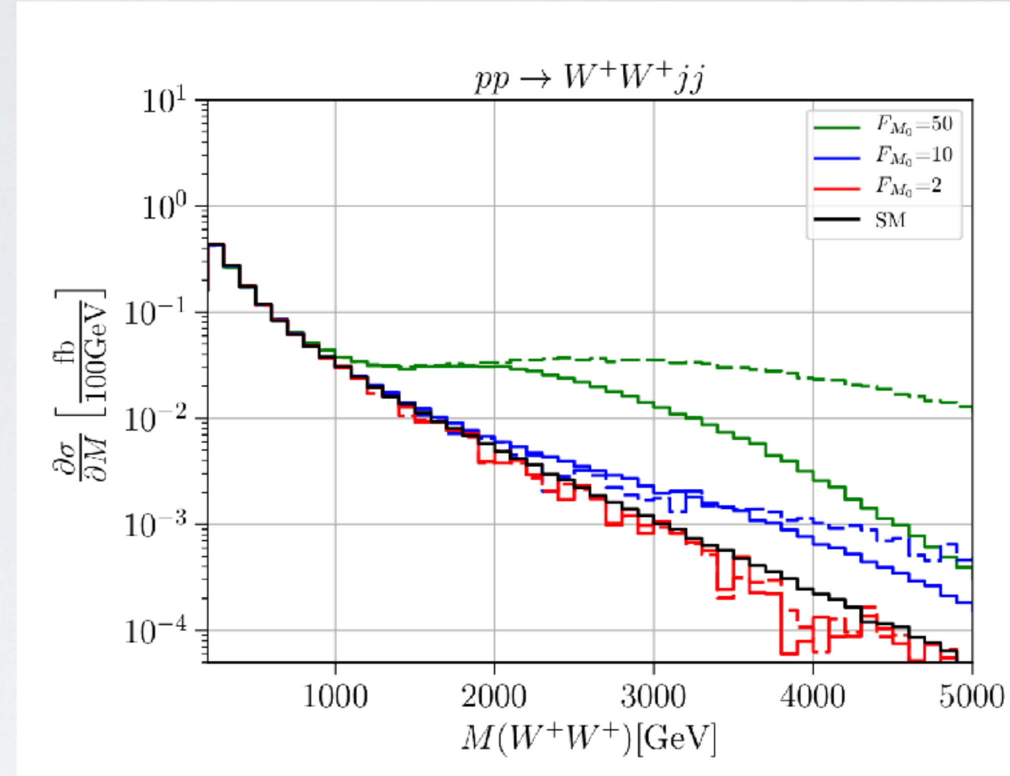

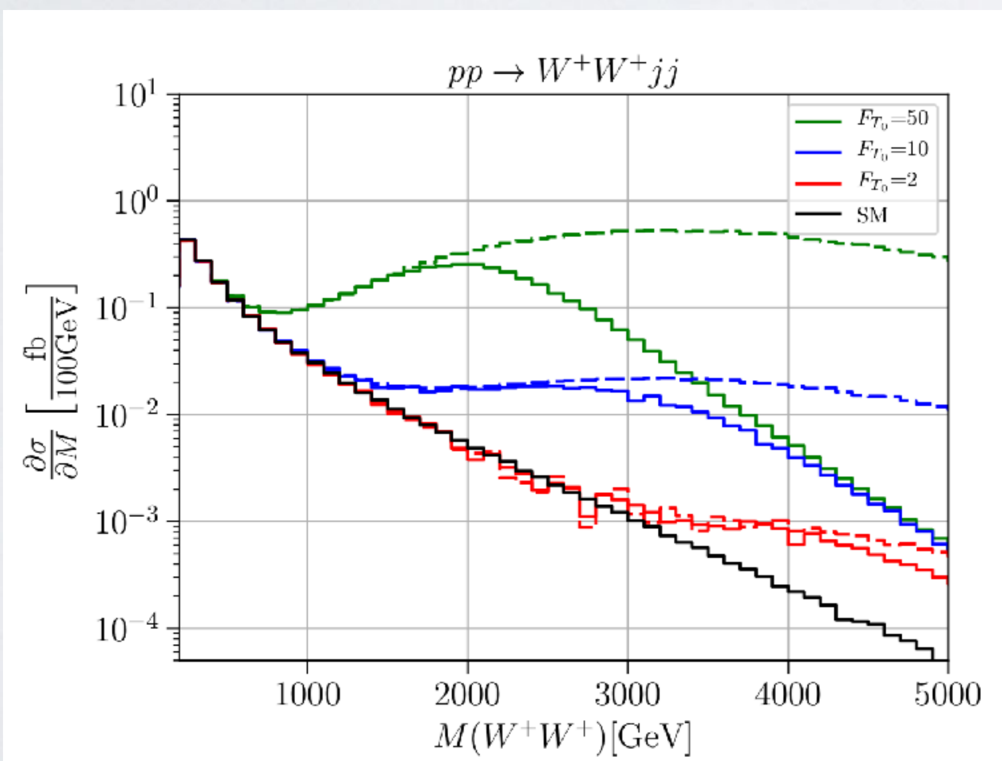

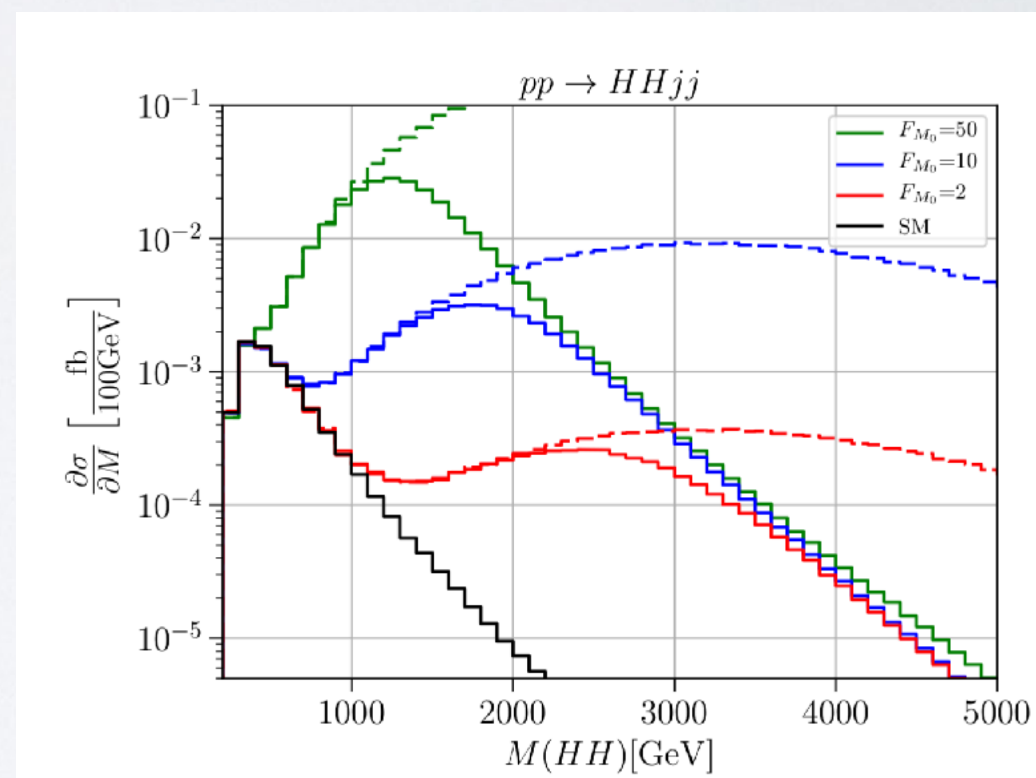

General cuts: $M_{jj} > 500\,\text{GeV};\ \Delta\eta_{jj} > 2.4;\ p_T^j > 20\,\text{GeV};\ |\Delta\eta_j| < 4.5$

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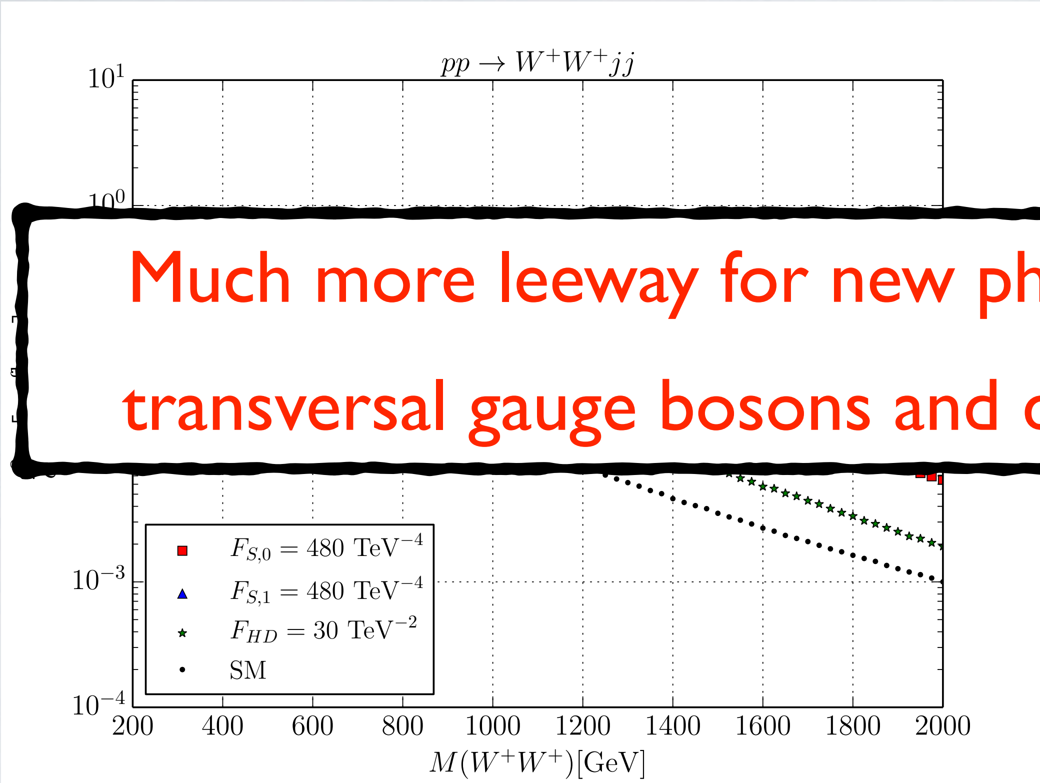
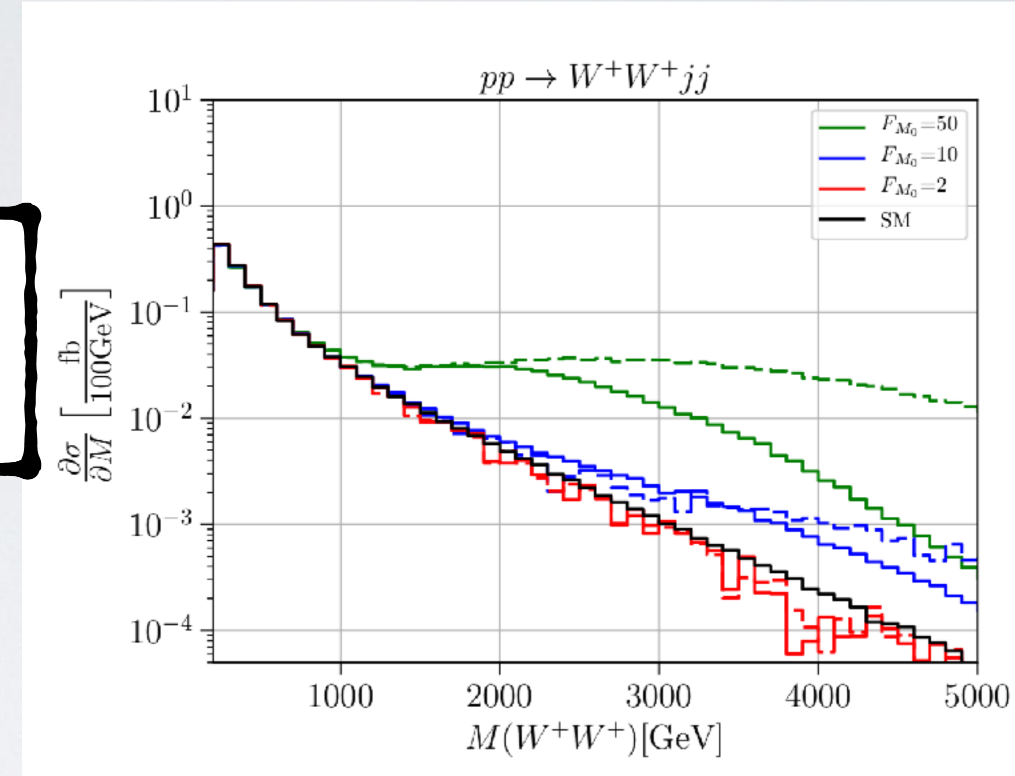
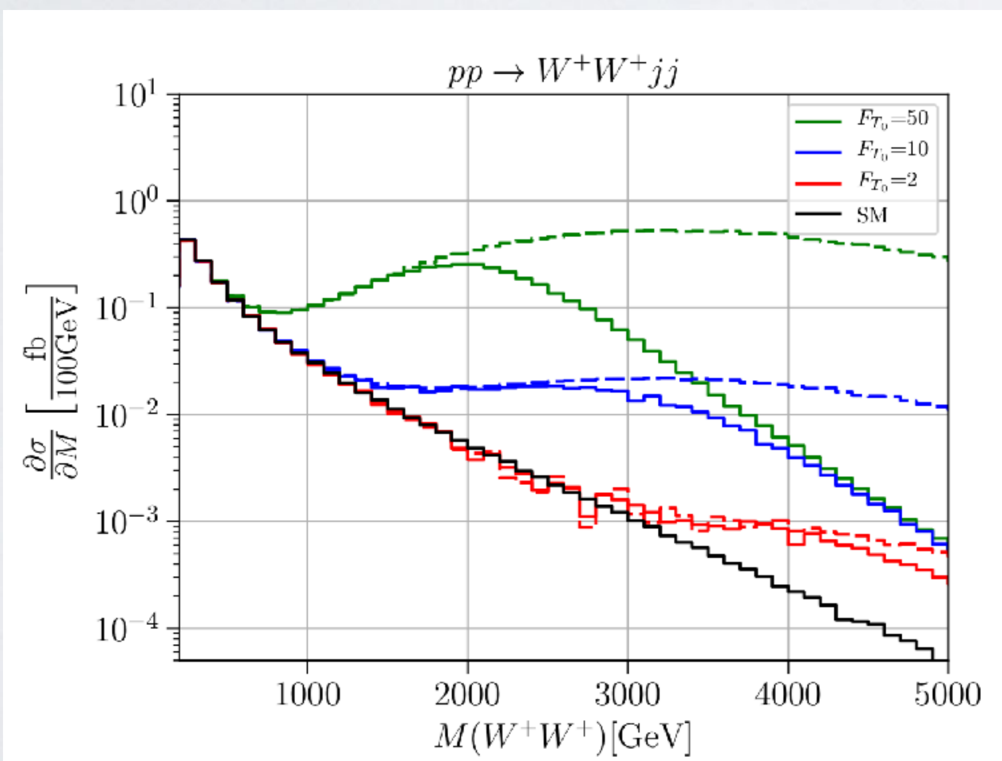
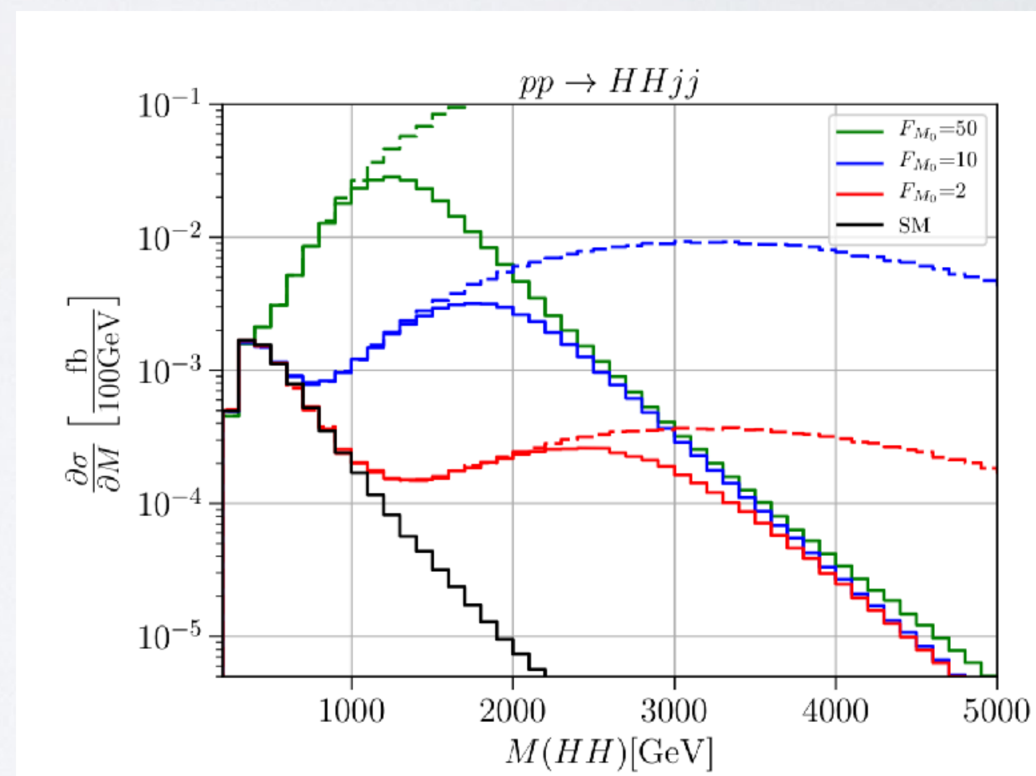


Much more leeway for new physics in transversal gauge bosons and di-Higgs







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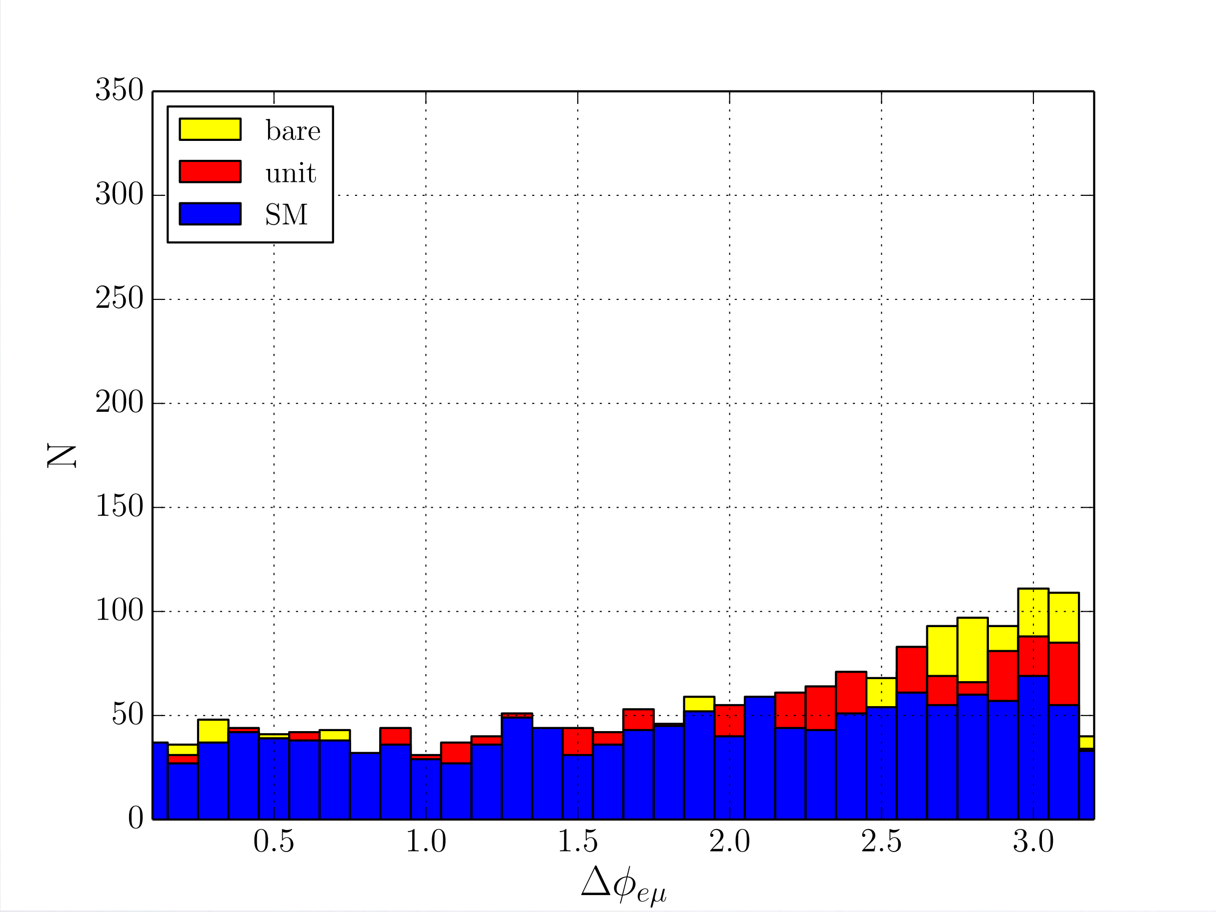
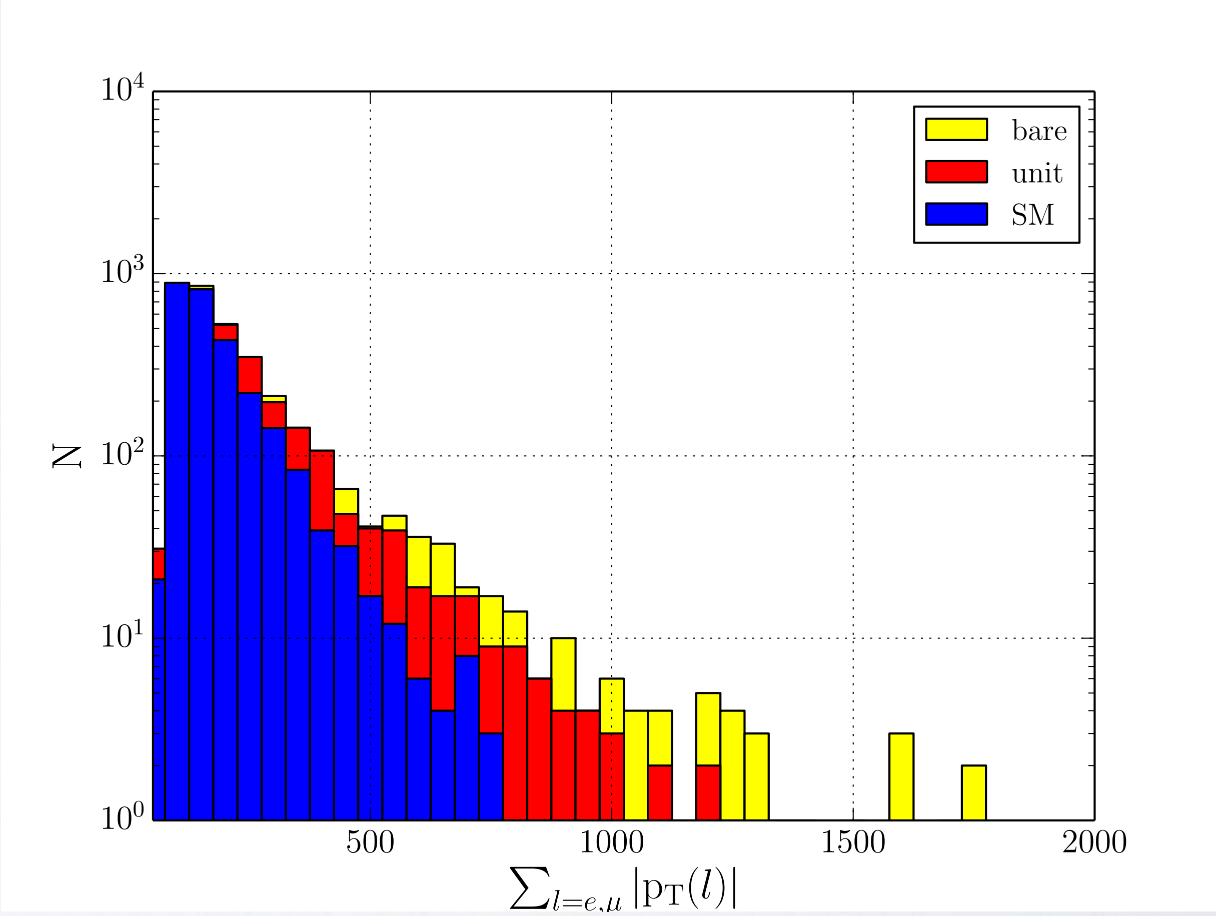
$$\mathcal{L}_{HD} = F_{HD}\,\text{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right] \cdot \text{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\,\mathbf{D}_\mu\mathbf{H}\right] \qquad F_{HD} = 30\ \text{TeV}^{-2}$$





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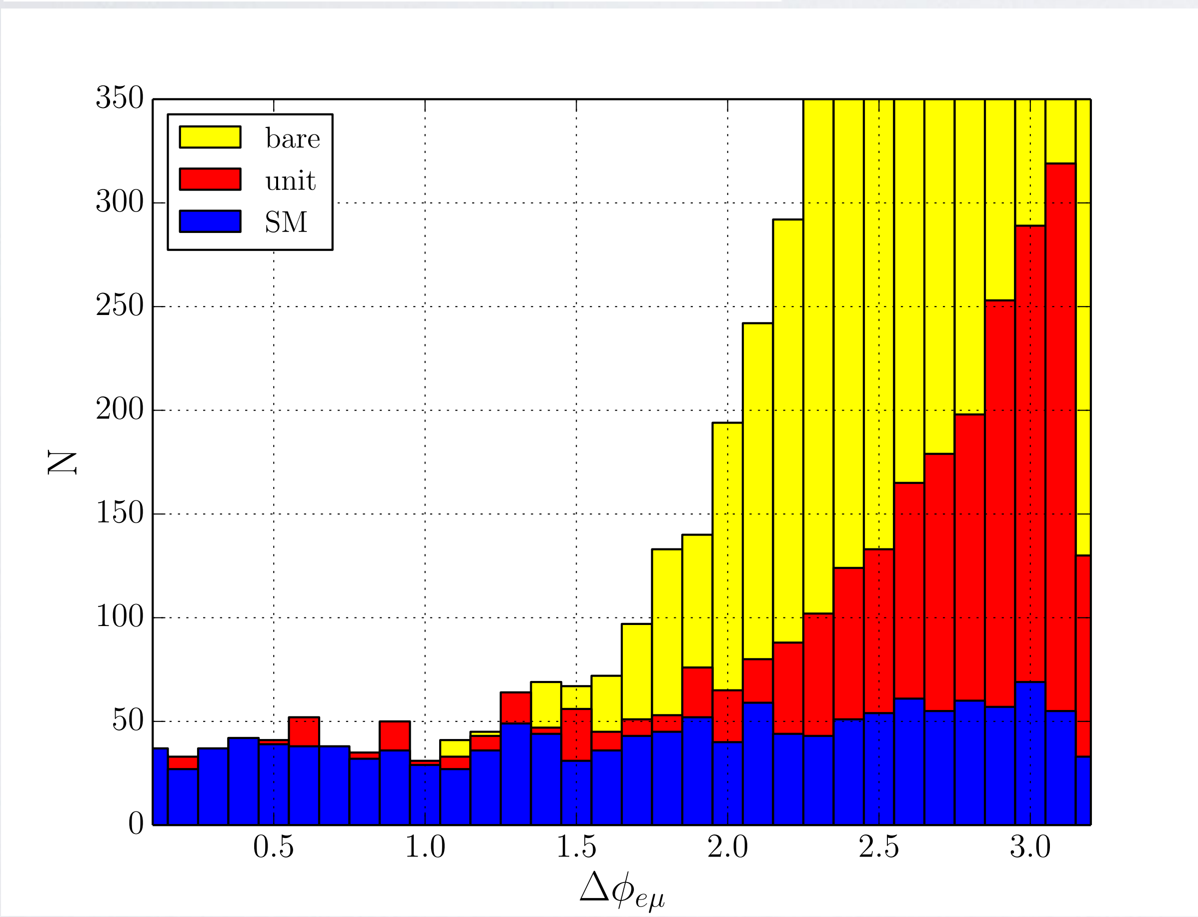
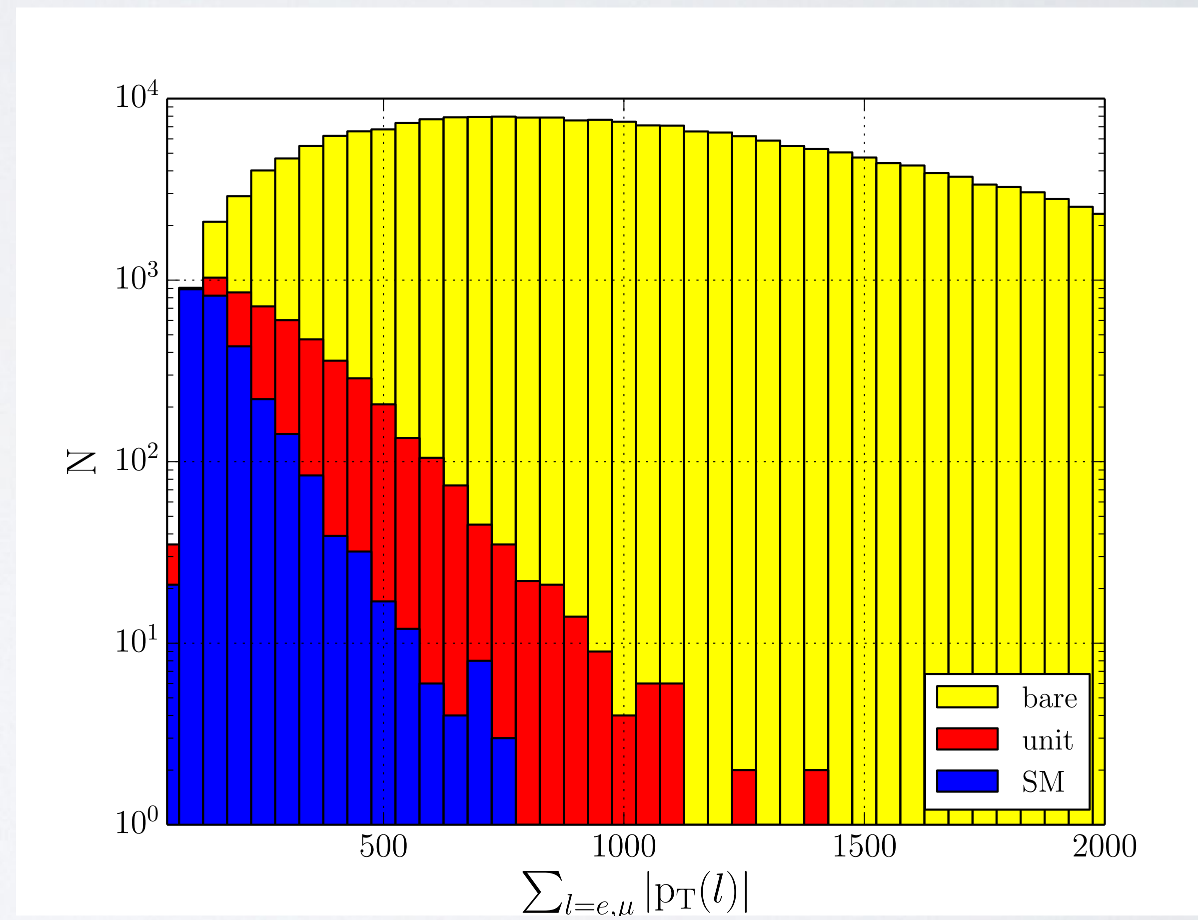
$$F_{S,0} = 480\ \text{TeV}^{-4}$$





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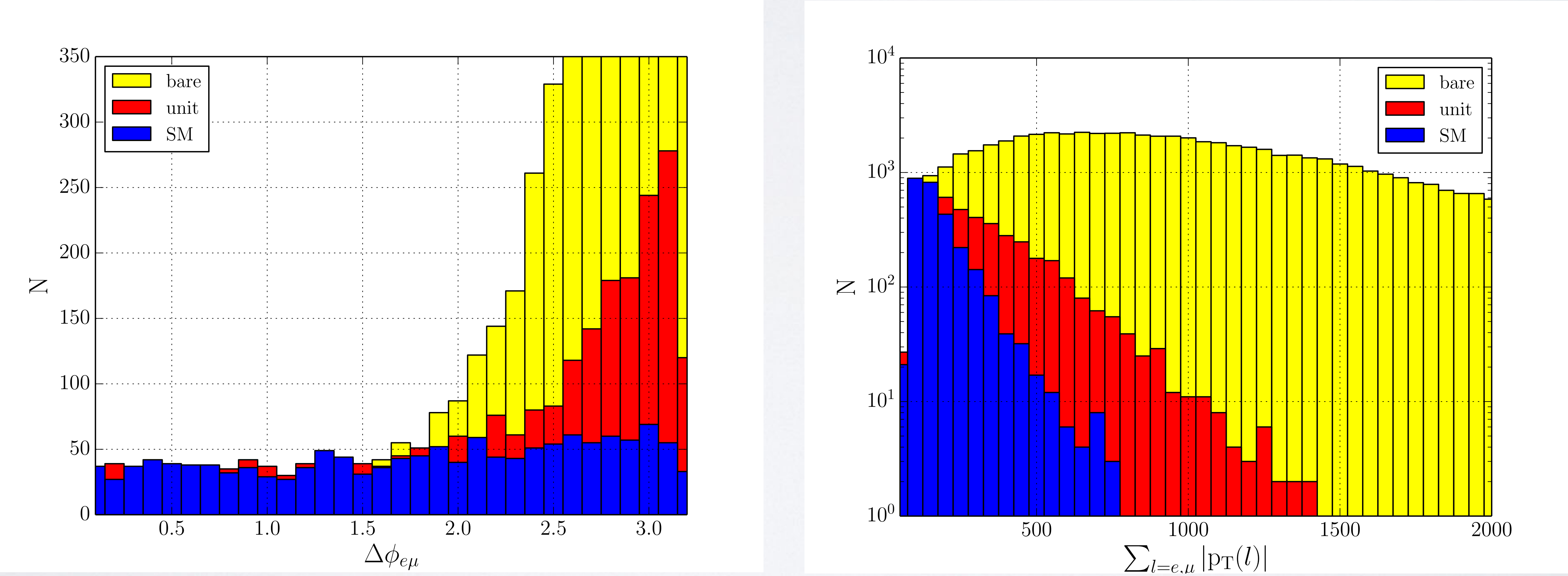

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Resonances: Quantum numbers & simplified models

- Rise of amplitude: is Taylor expansion below a resonance
- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: *SU(2)*$_L$ × *SU(2)*$_R$, *SU(2)*$_L$ × *U(1)*$_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

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

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

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

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

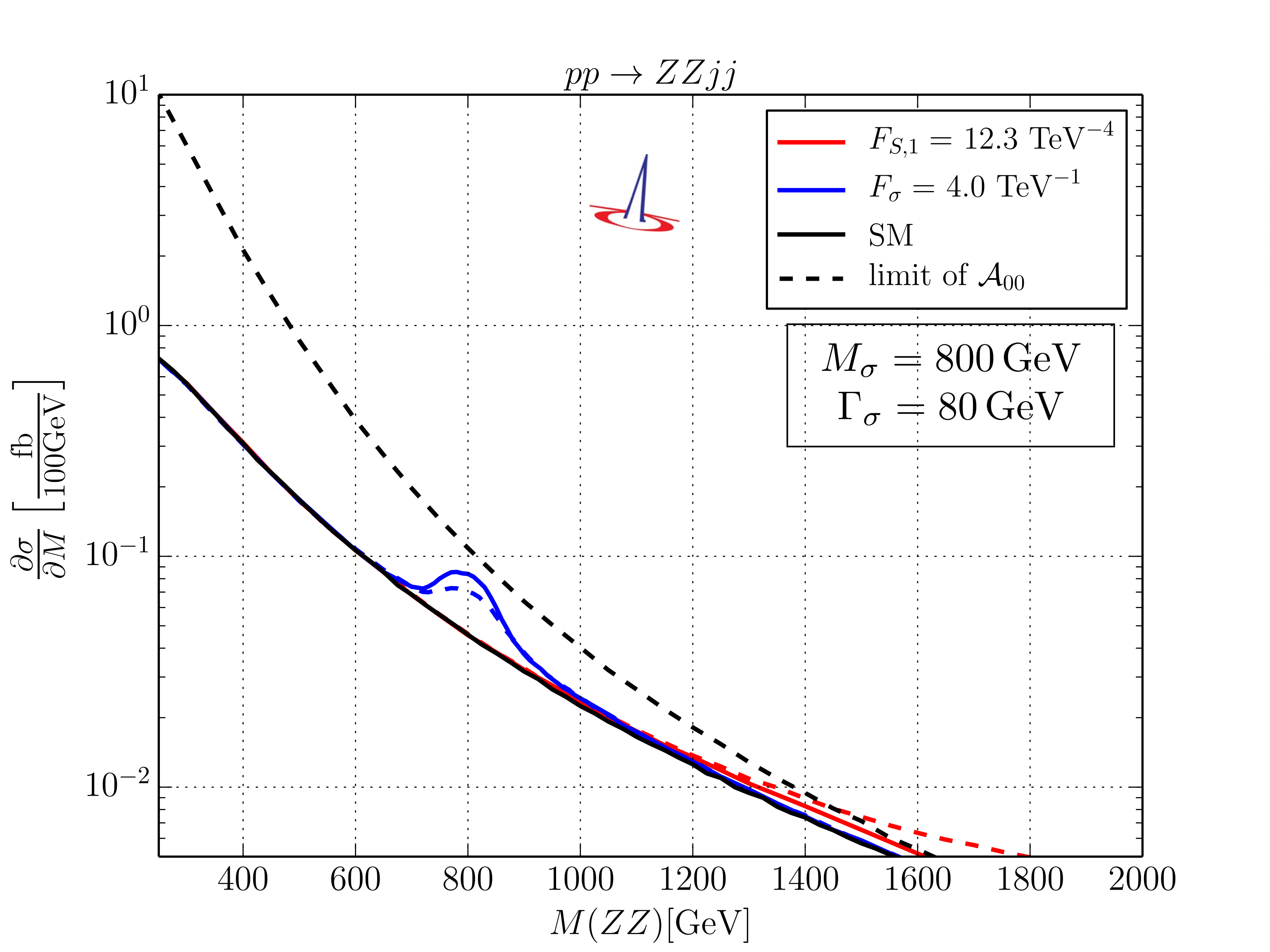
Translation into Wilson coefficients below resonance

Comparison: Simplified Models & EFT

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

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

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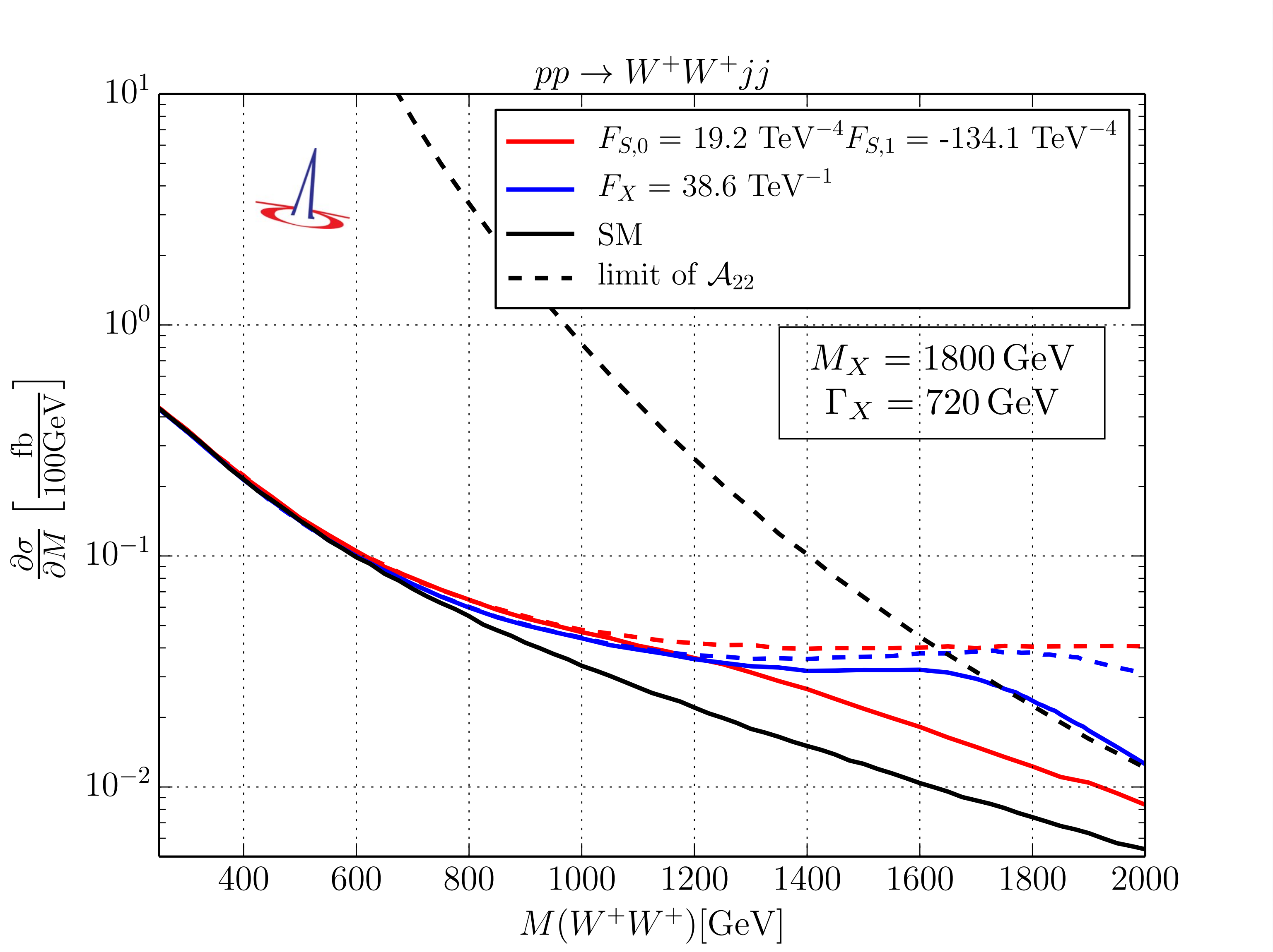

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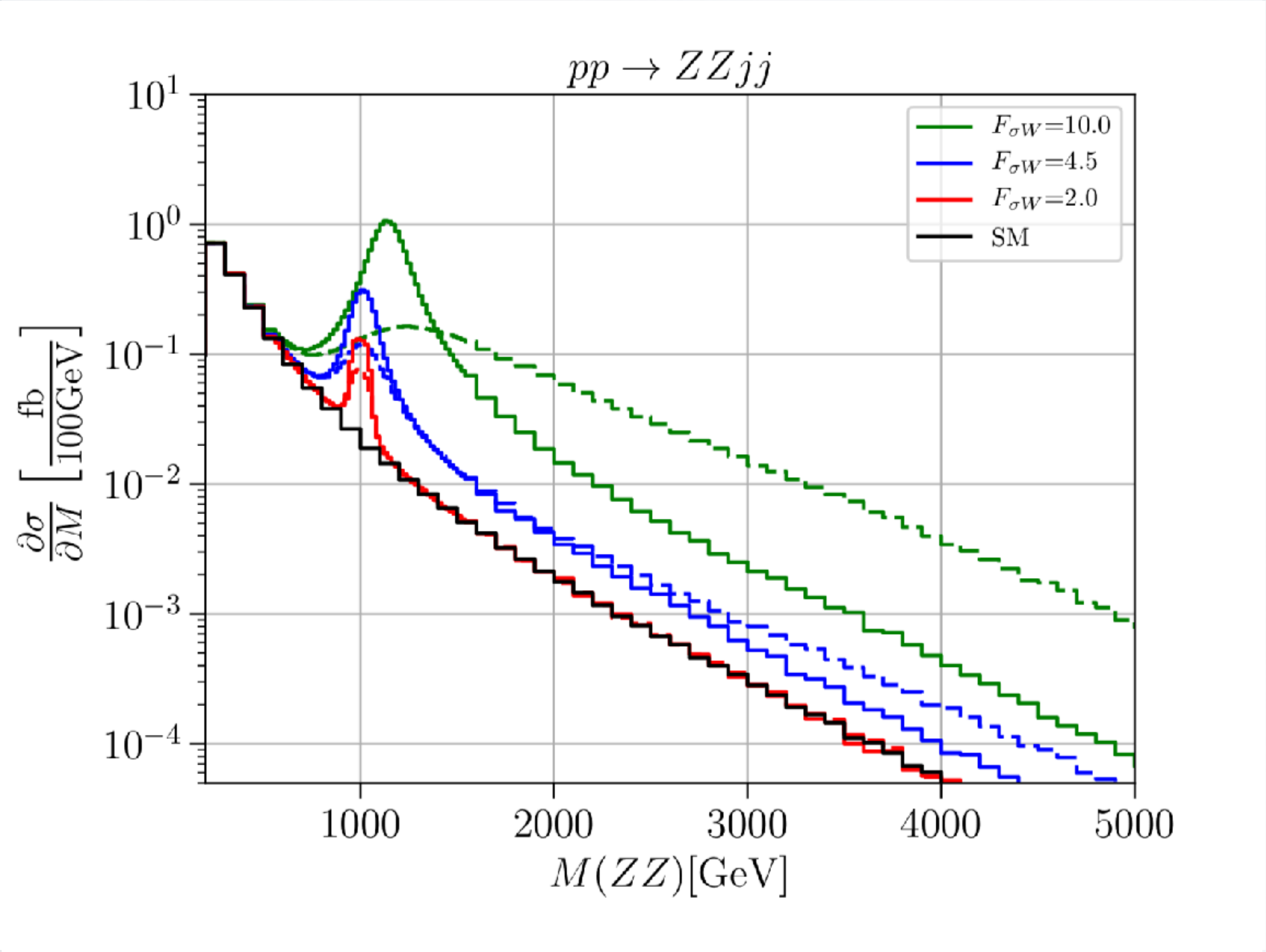

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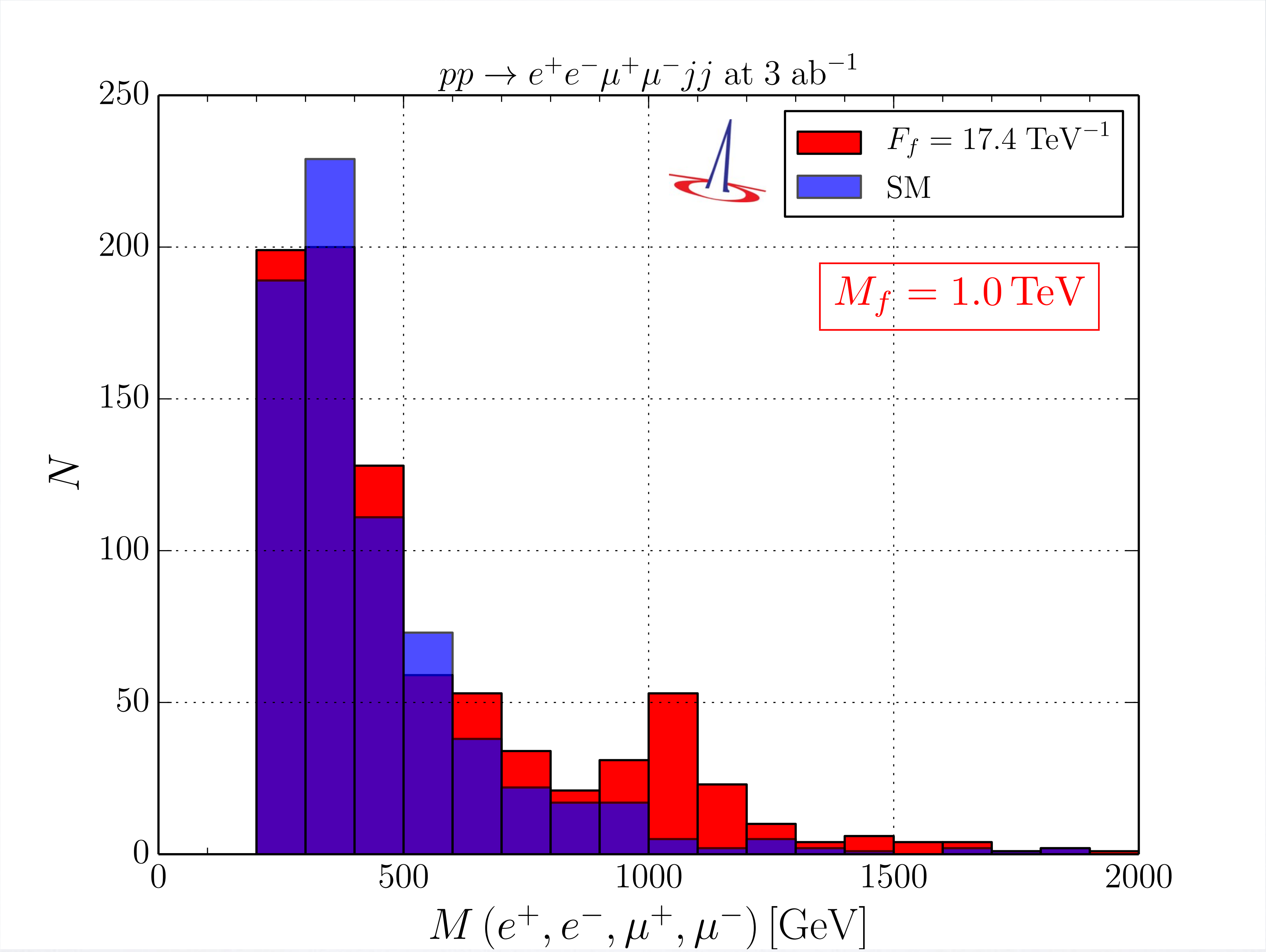
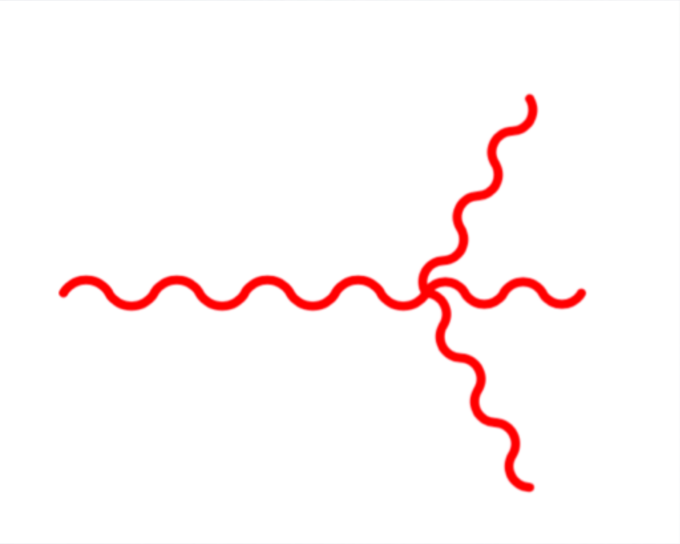
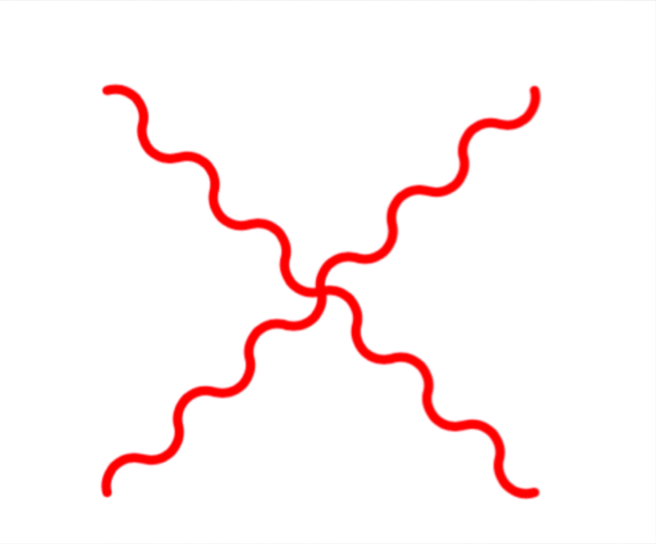
Complete LHC process at 14 TeV



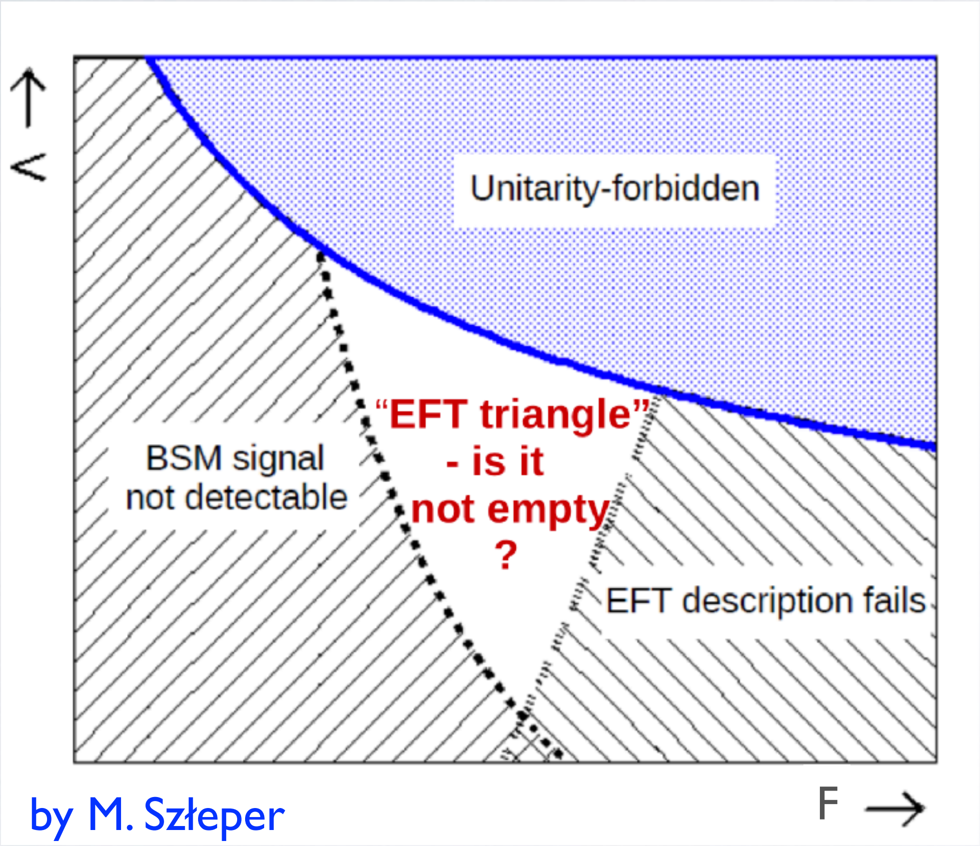
Triple [multiple] Vector Boson Production ?

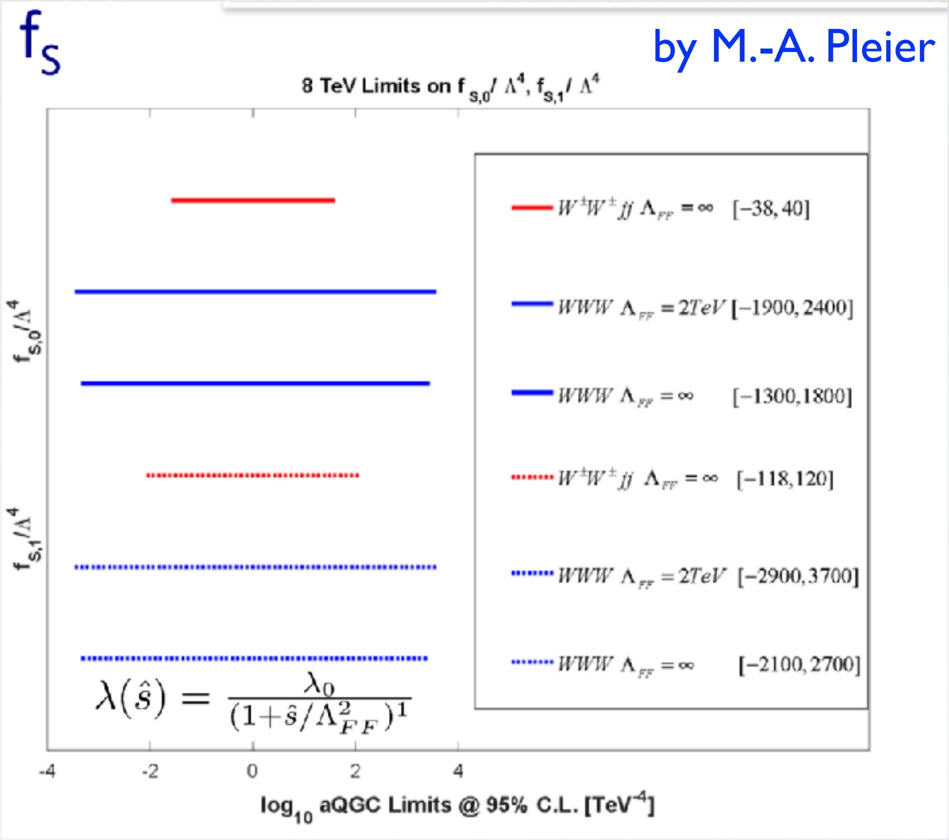
Relate  to  ?

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



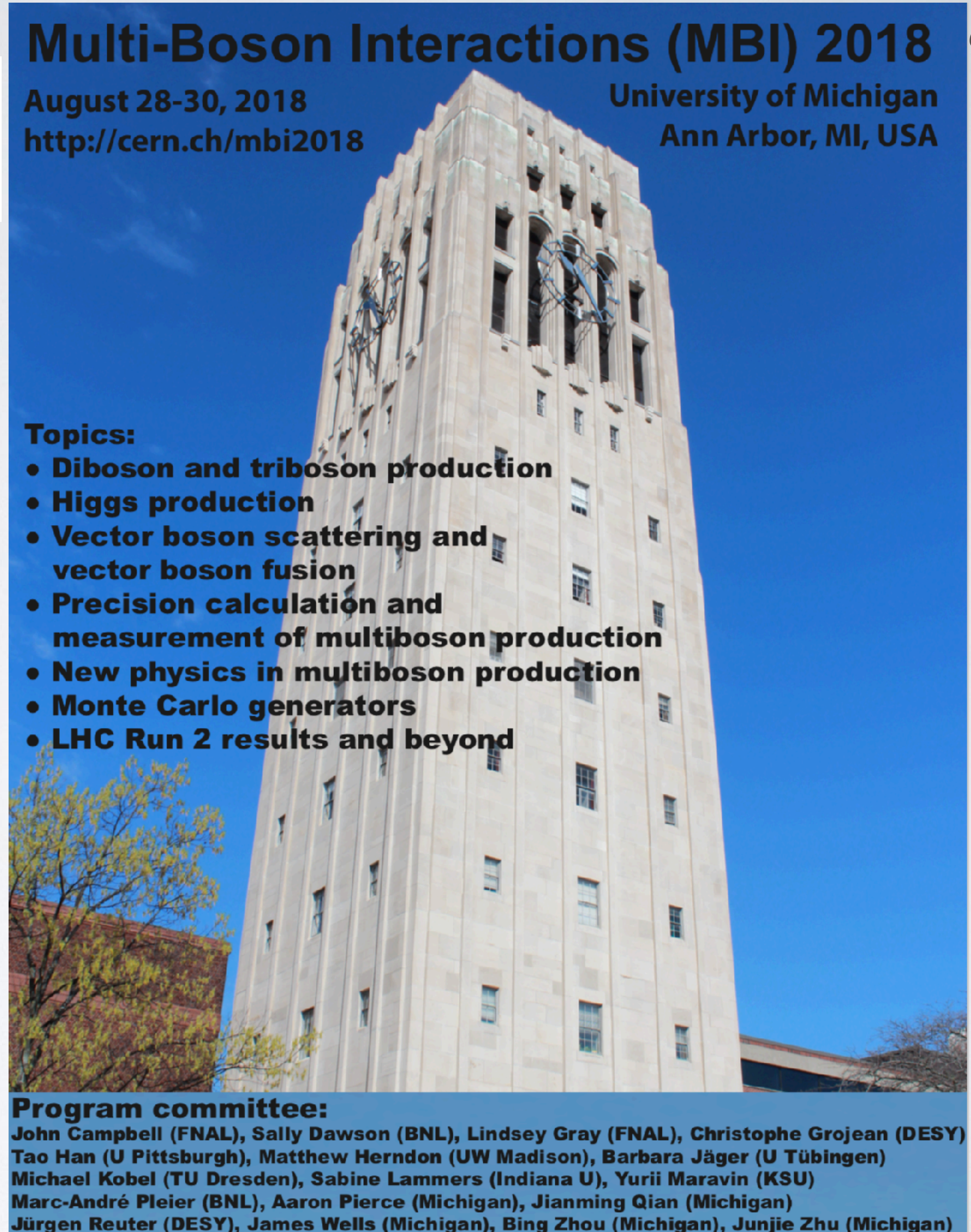


- There is not really a true model-independent parameterization!
- Unitarization for theoretically sane description (allows reliable BDT analysis)
- *T*-matrix unitarization universal scheme for EFT and resonances
- Simplified models: generic electroweak resonances
- Limits from LHC still quite limited: $\Lambda_{new\ physics} \sim$ 500-600 GeV

6th Workshop on Multi-Boson Interactions

August 28-30, 2018
U. Michigan, Ann Arbor

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



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

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

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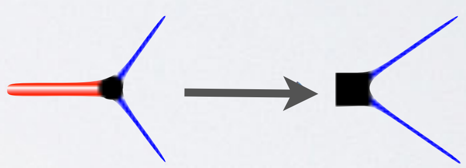
Completing the square (Gaussian integration)

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



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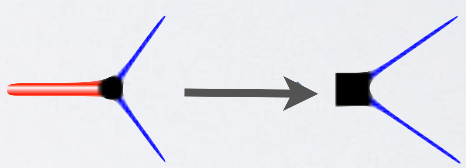


In the Lagrangian remove the high-scale d.o.f.s:

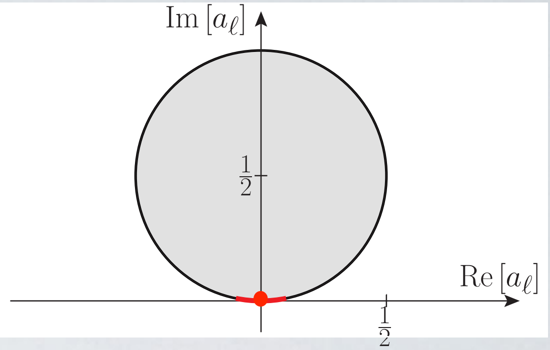
$$\frac{1}{2}(\partial\Phi)^2 - \frac{1}{2}M^2\Phi^2 - \lambda\varphi^2\Phi \quad = \quad \underbrace{-\frac{1}{2}\Phi'(M^2+\partial^2)\Phi'}_{\text{Irrelevant normalization of the path integral}} + \underbrace{\frac{\lambda^2}{2M^2}\varphi^2\left(1+\frac{\partial^2}{M^2}\right)^{-1}\varphi^2}_{\text{Tower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

Irrelevant normalization of the path integral

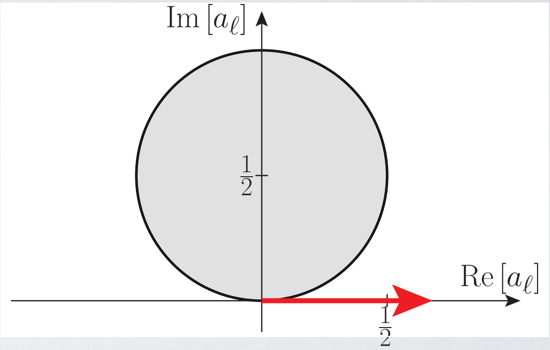
Tower of higher and higher-dim. operators of light fields

Scenarios for New Physics in VBS

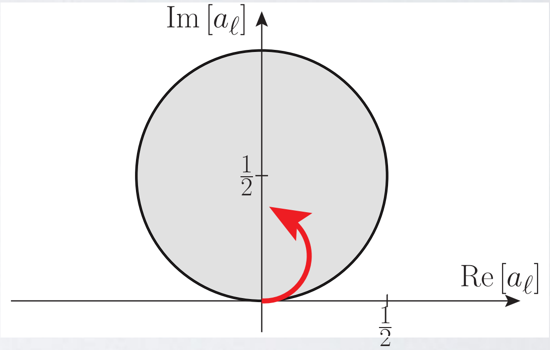
1. SM or weakly coupled physics (e.g. 2HDM):
   amplitude remains close to origin



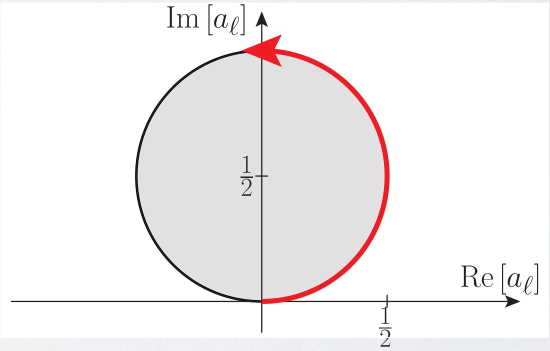
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.], strongly interacting regime



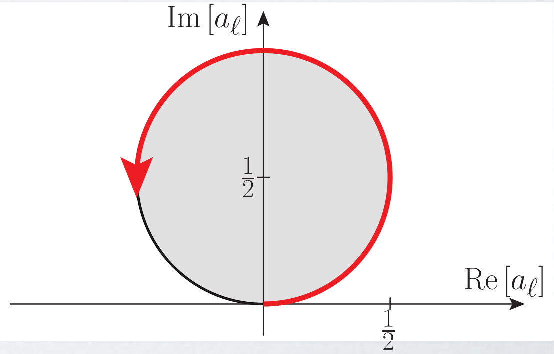
3. Inelastic channel opens (form-factor description): new channels open out, multi-boson final states



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



5. New resonance: amplitude turns over



Unitarity in vector boson scattering

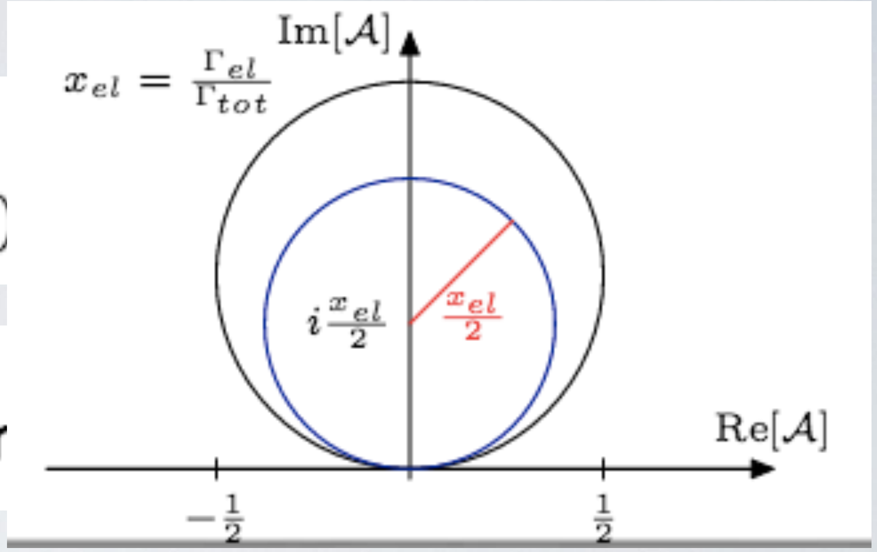
Optical Theorem (Unitarity of the S(cattering) Matrix):

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

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")

Unitarity in vector boson scattering



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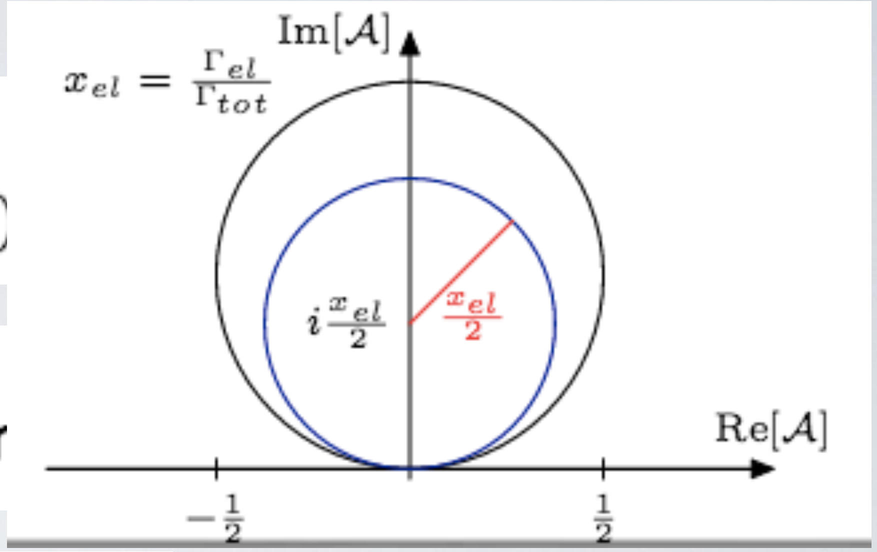

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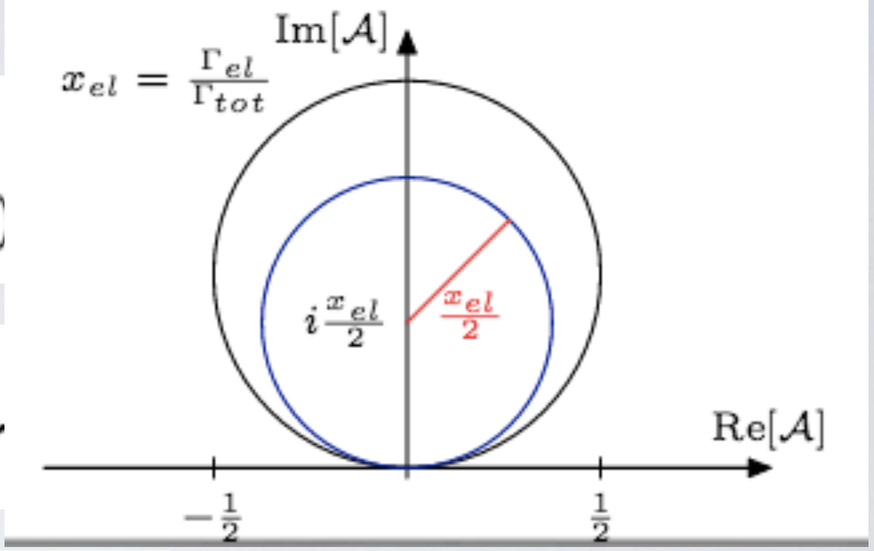

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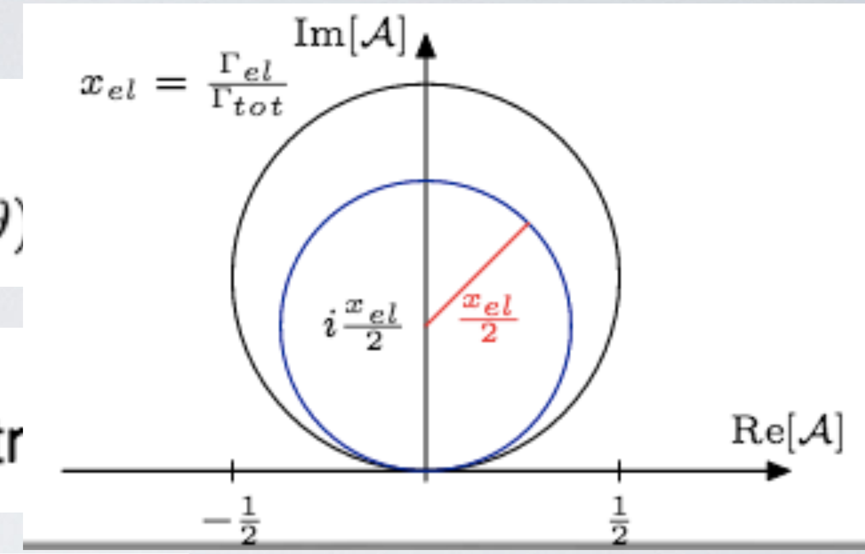

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Lee/Quigg/Thacker, 1973

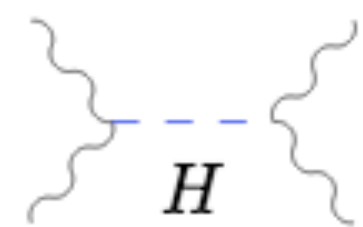
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

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

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- Stereographic projection to Argand circle

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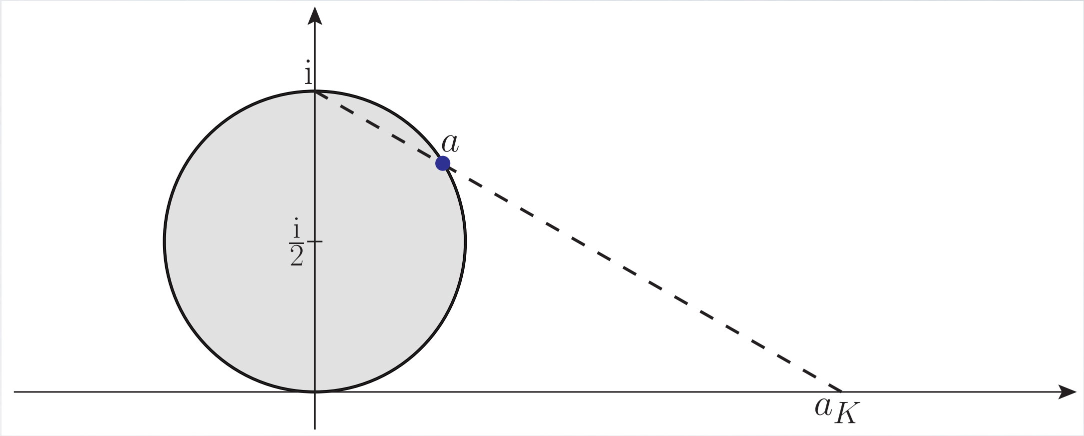

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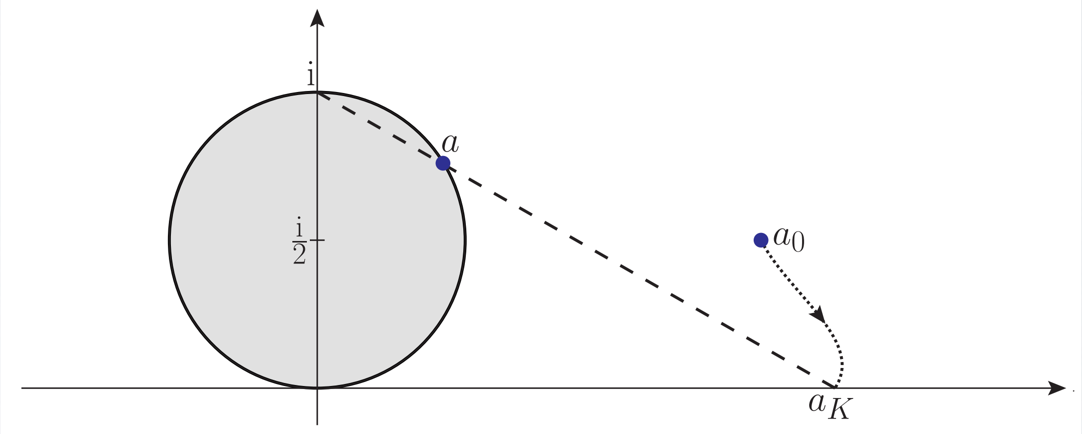

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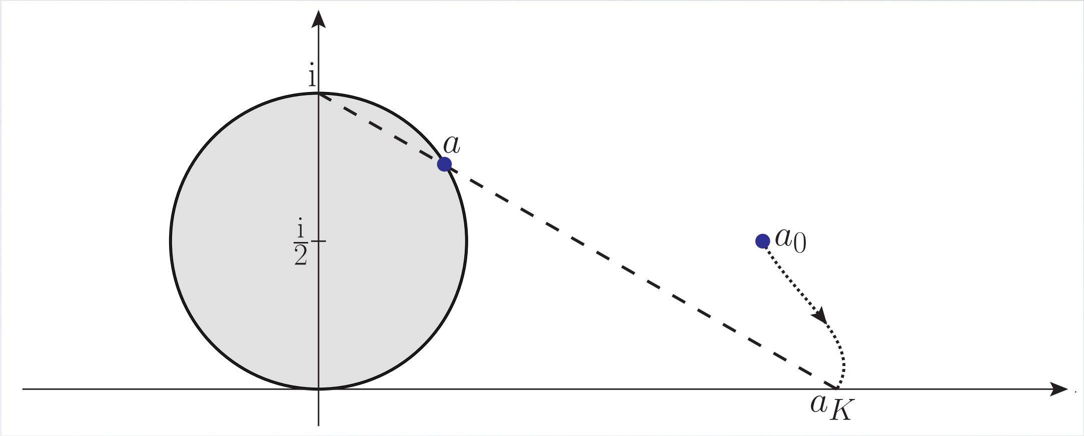

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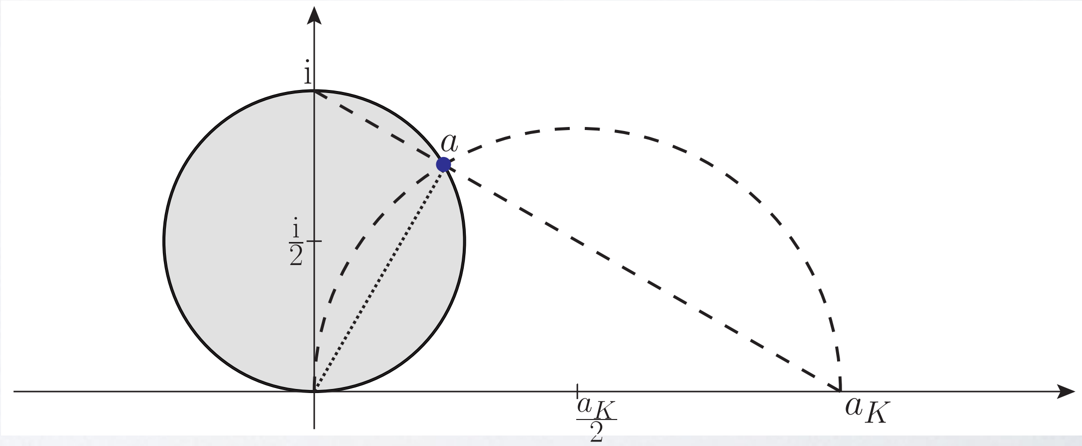

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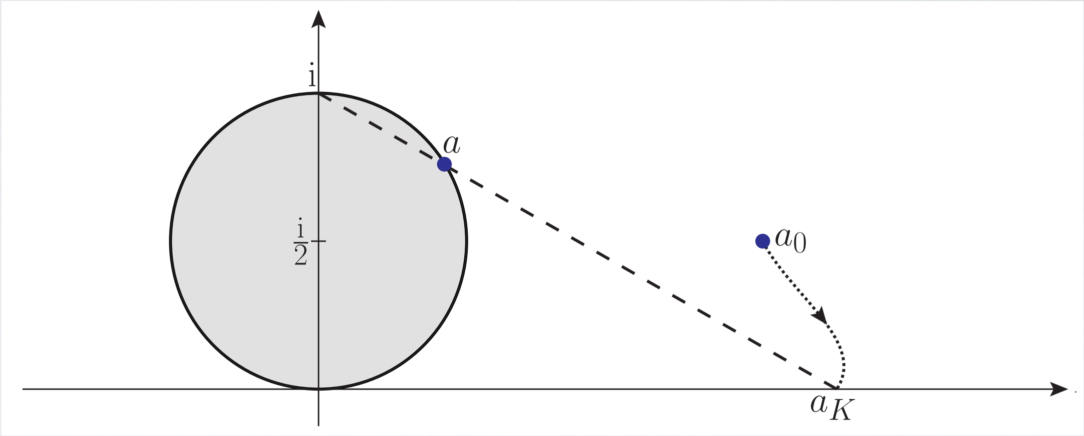

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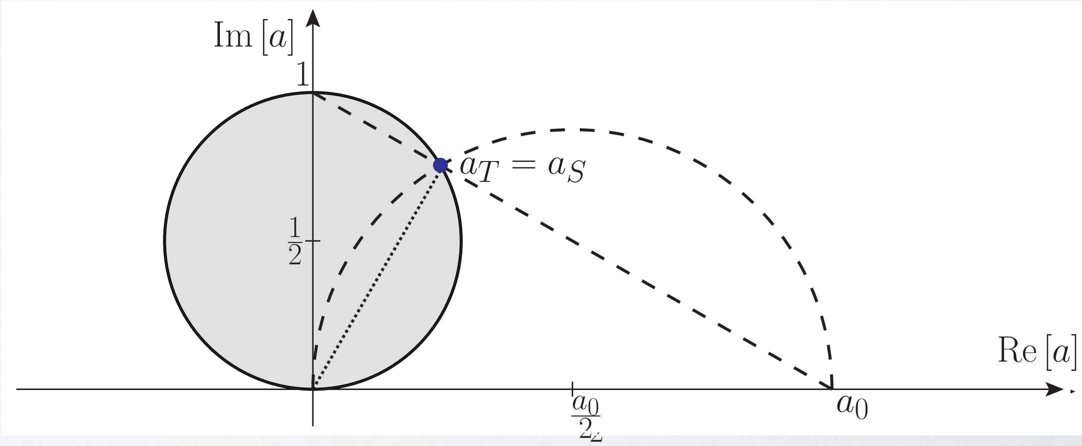

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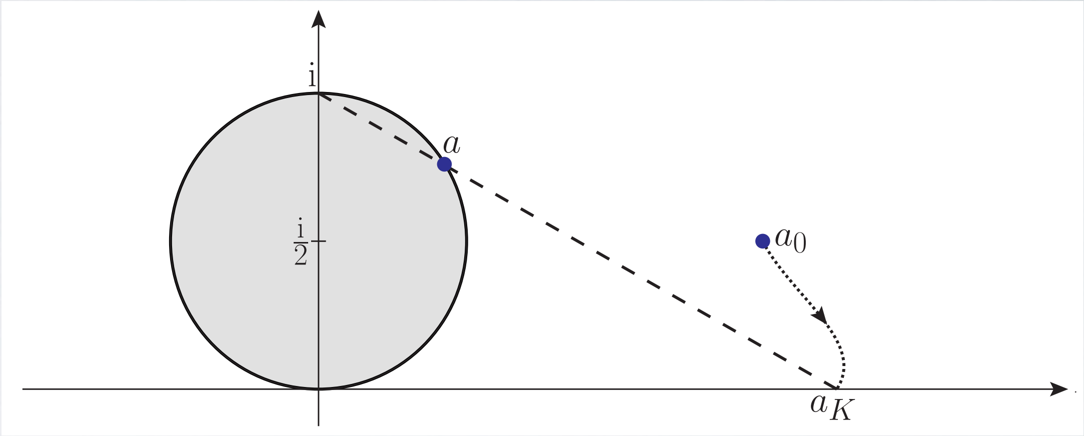

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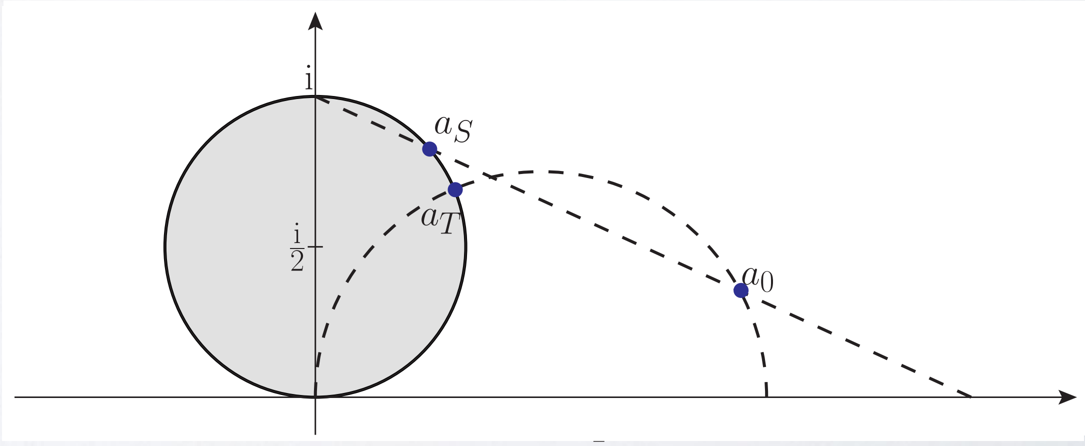

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