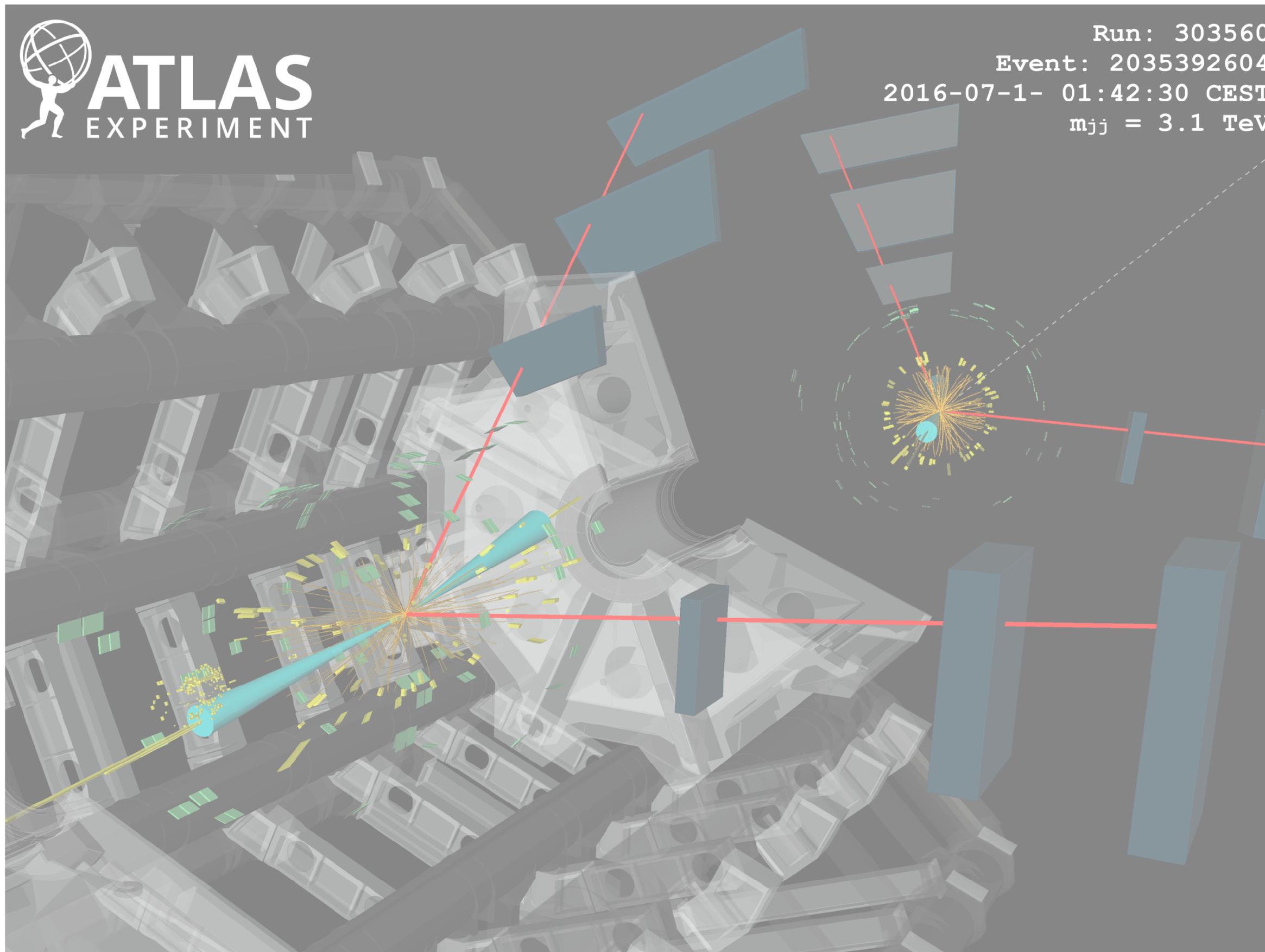


# Vector Boson Scattering at the LHC – Precision, Polarization & New Physics Searches



HELMHOLTZ



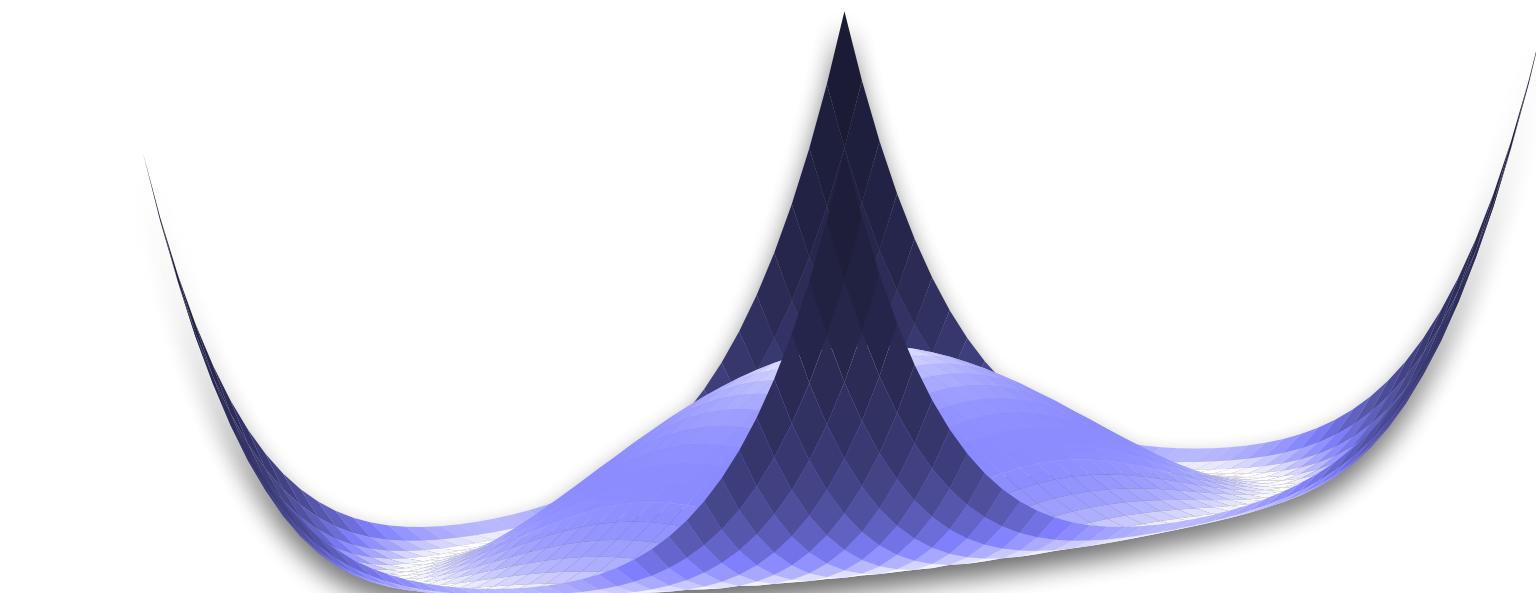
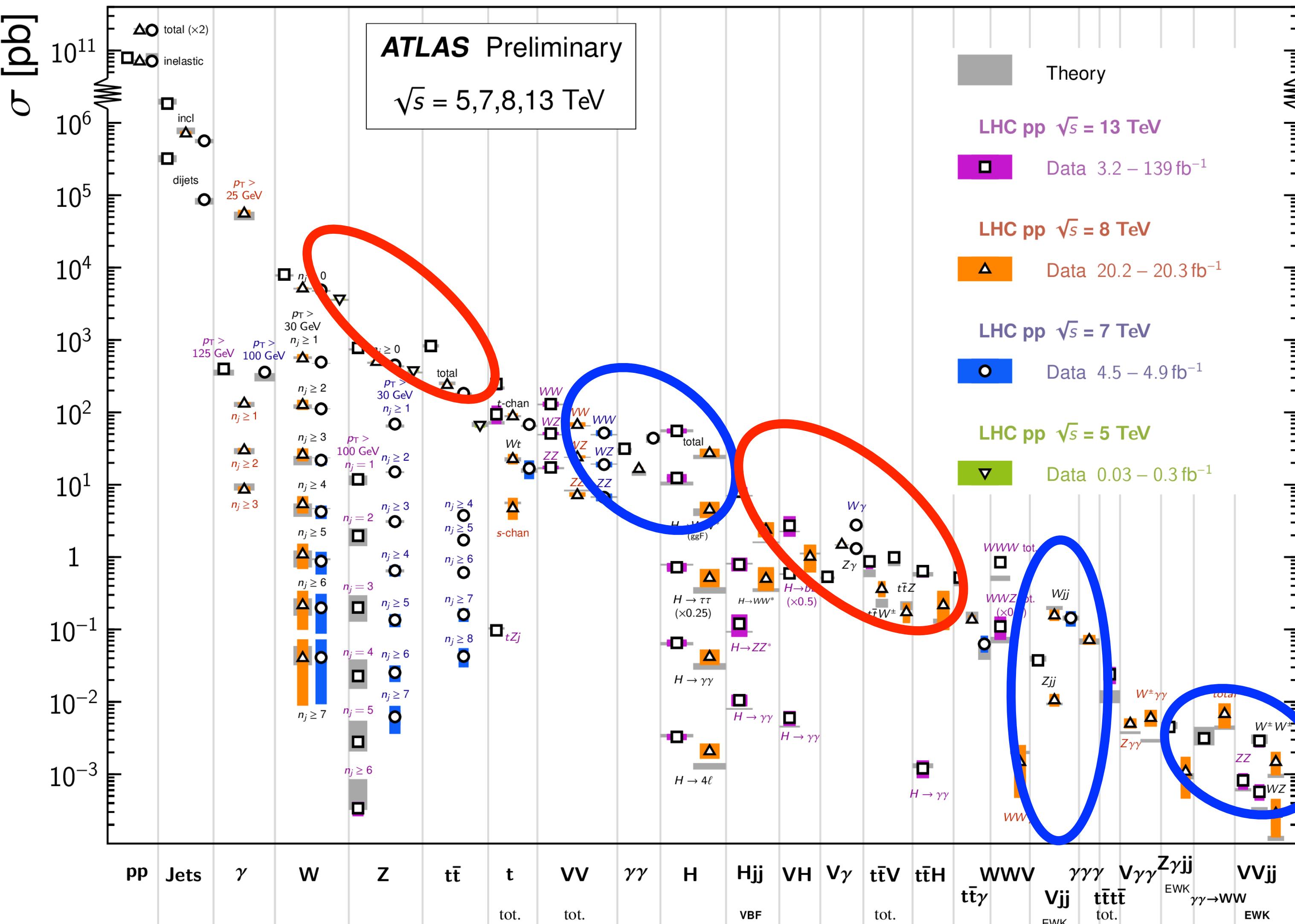
CLUSTER OF EXCELLENCE  
QUANTUM UNIVERSE

Jürgen R. Reuter

# The mystery of electroweak interactions

# Standard Model Production Cross Section Measurements

*Status: July 202*



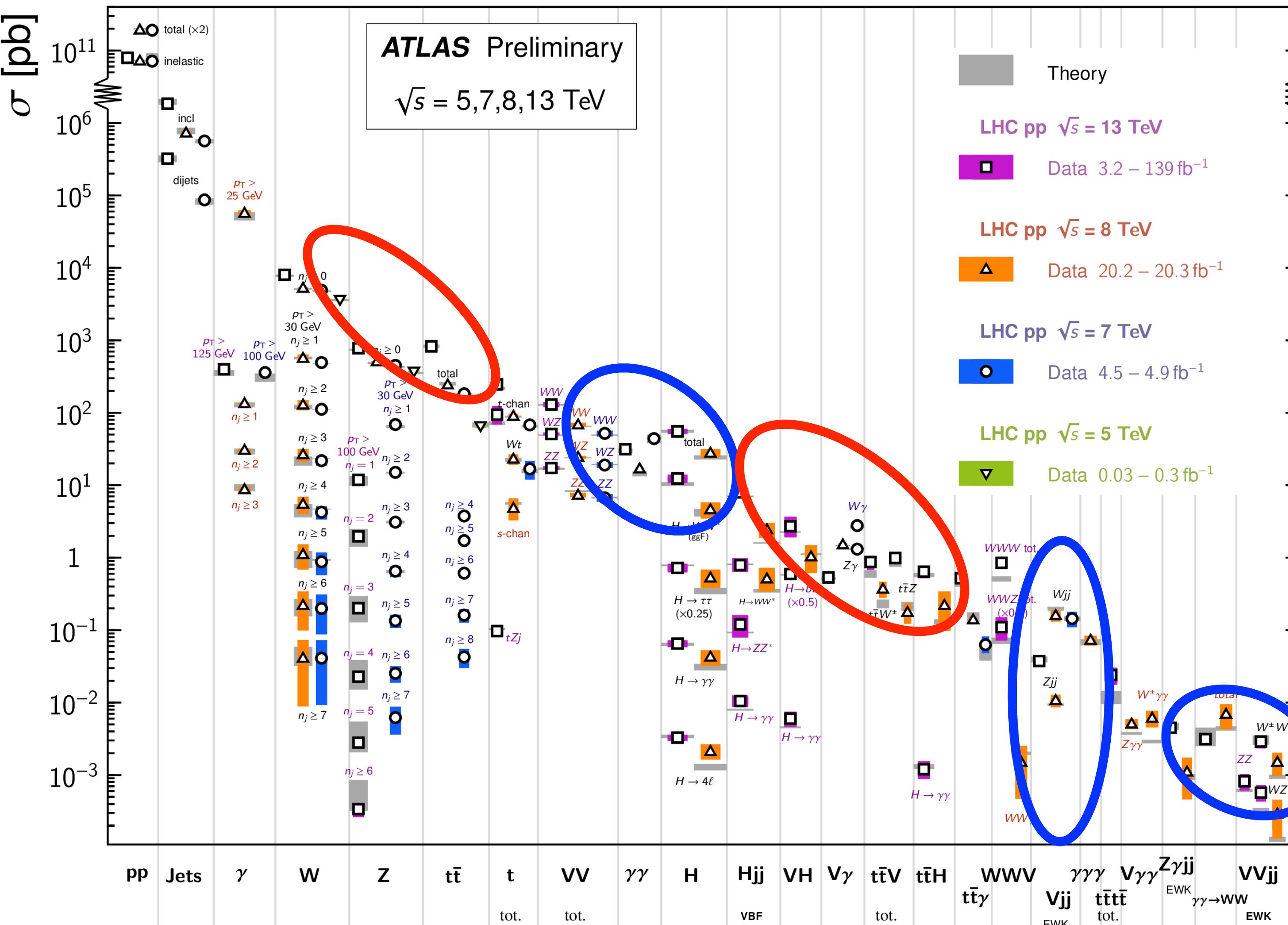
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  - Missing: **microscopic origin of EWSB**
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2 / 31

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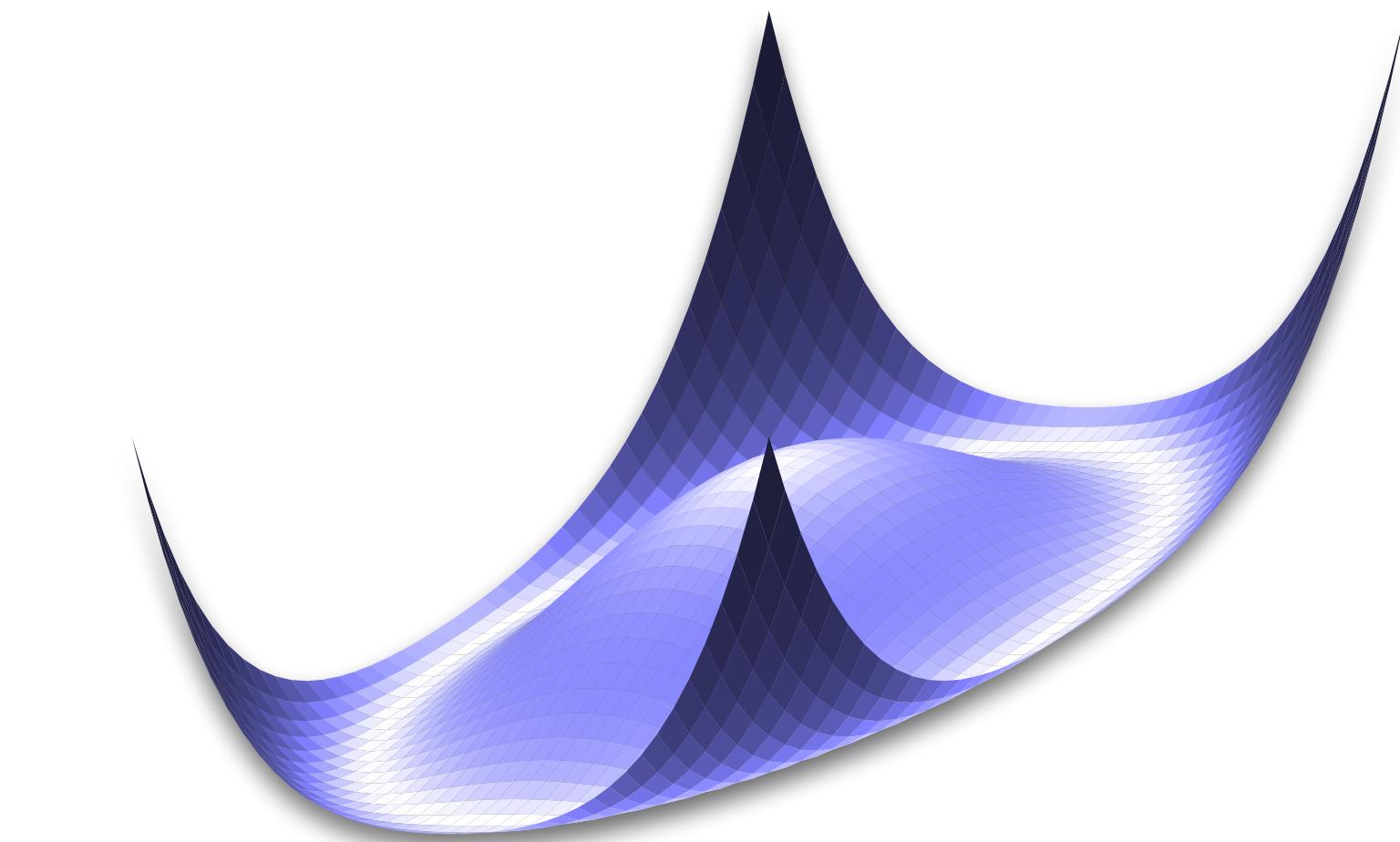
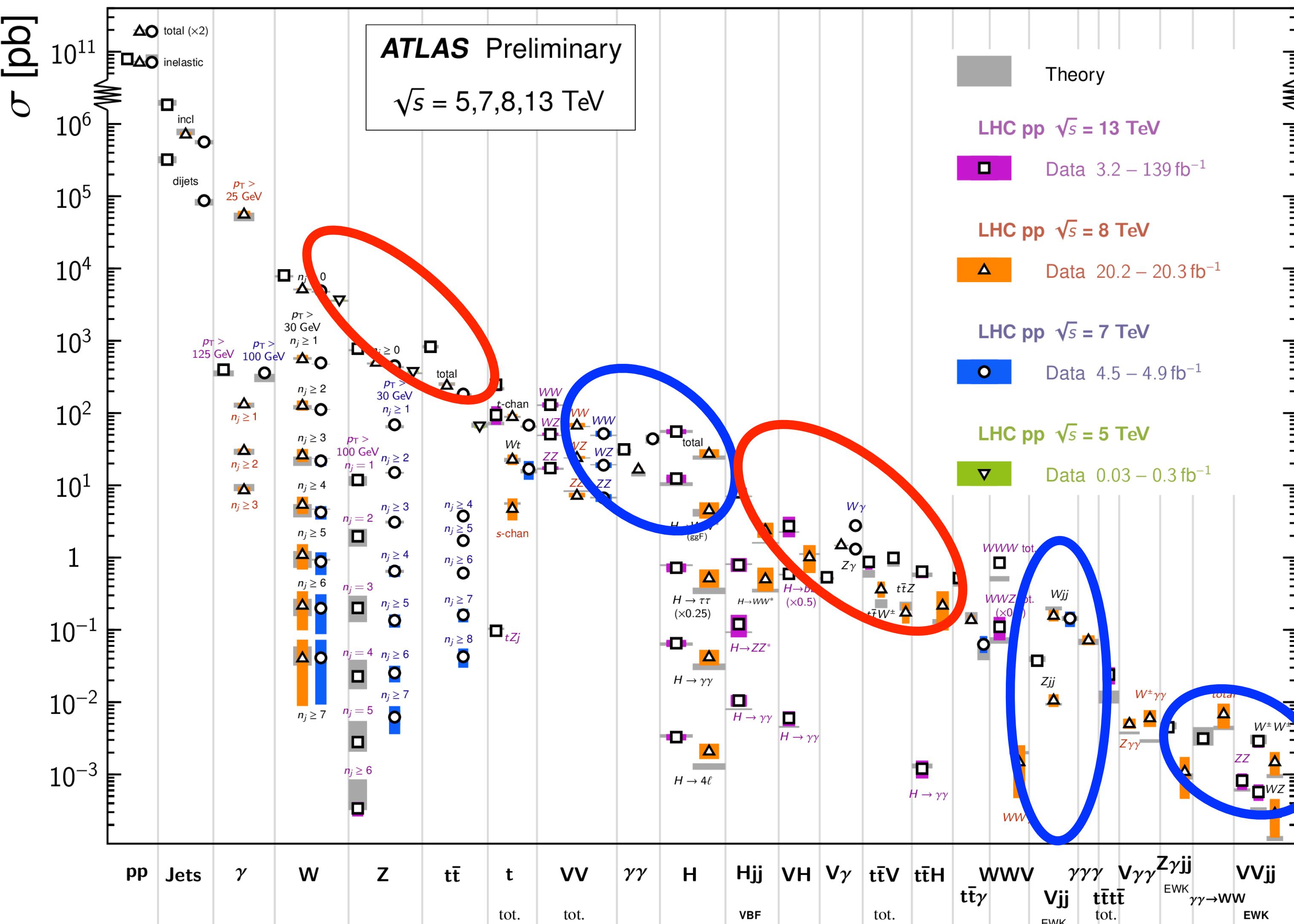
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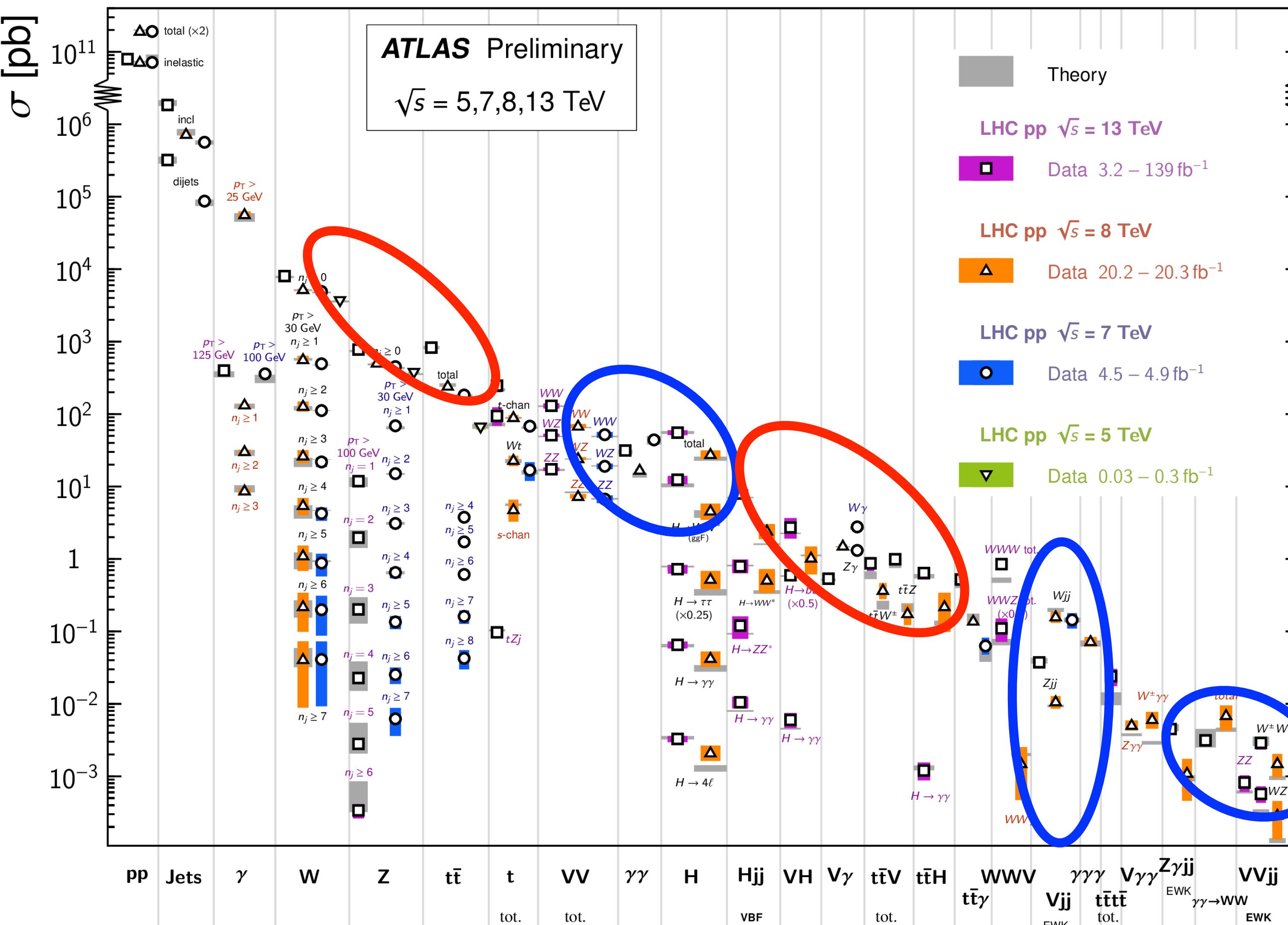
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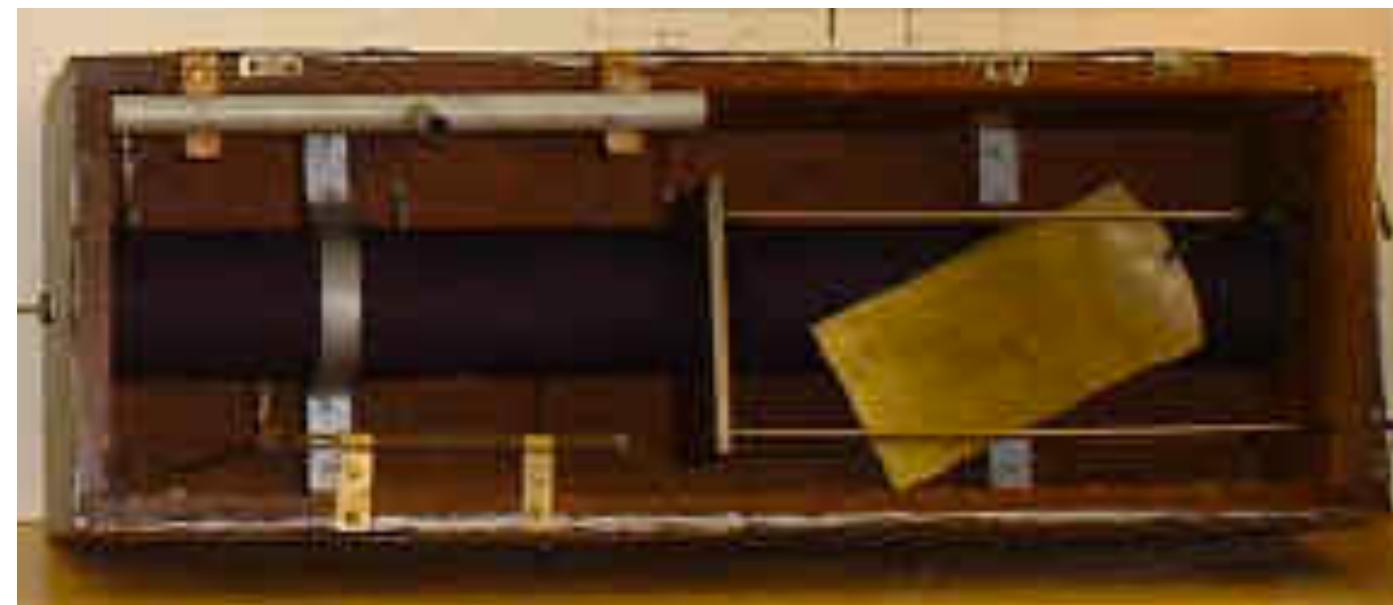
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# From the past via present to the future

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- 1898: Weak interactions known since 1898 (beta decay; virtual W exchange  
[used a new particle discovery, the electron !] )



VIII. *Uranium Radiation and the Electrical Conduction produced by it.* By E. RUTHERFORD, M.A., B.Sc., formerly 1851 Science Scholar, Coutts Trotter Student, Trinity College, Cambridge; McDonald Professor of Physics, McGill University, Montreal\*.

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The results of Becquerel showed that Röntgen and uranium radiations were very similar in their power of penetrating solid bodies and producing conduction in a gas exposed to them; but there was an essential difference between the two types of radiation. He found that uranium radiation could be refracted and polarized, while no definite results showing

\* Communicated by Prof. J. J. Thomson, F.R.S.

† C. R. 1896, pp. 420, 501, 559, 689, 762, 1086; 1897, pp. 438, 800.

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charged current weak processes  
(points to high scale ✓)

$$\mathcal{L}_{FEFT} = \frac{c_F}{v^2} (\bar{\Psi}_{e,L} \gamma^\mu \Psi_{\nu,L}) (\bar{\Psi}_{\nu,L} \gamma_\mu \Psi_{e,L})$$



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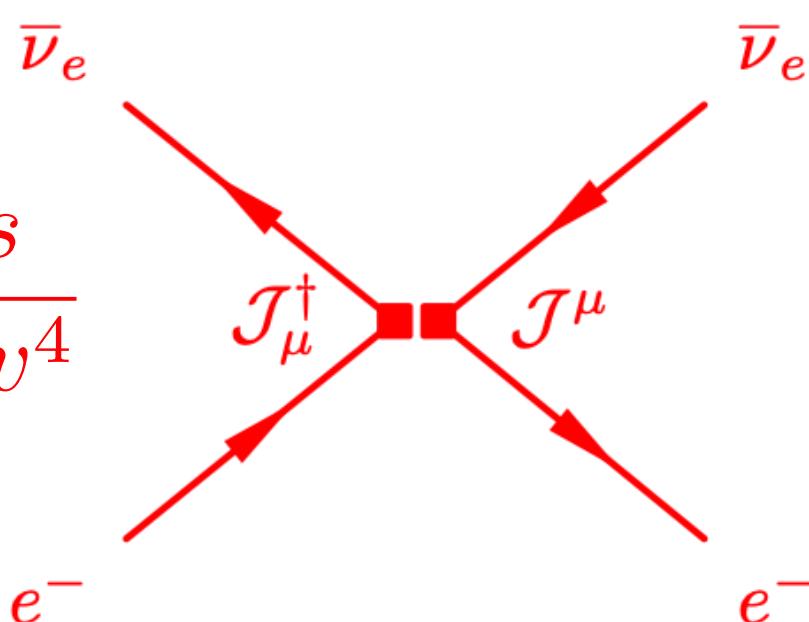
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- ◆ Contains known degrees of freedom
- ◆ Describes the measured interactions
- ◆ Includes a high new physics scale  $v$
- ◆ Contains coefficients parameterizing (unknown) new interactions

$$\sigma(e^- \nu_e \rightarrow e^- \nu_e) \rightarrow \sim \frac{s}{\pi v^4}$$



Effective theory leads to invalidity / unitarity violation at higher energies

S-wave unitarity demands:  $\sqrt{s} \lesssim 500 \text{ GeV}$

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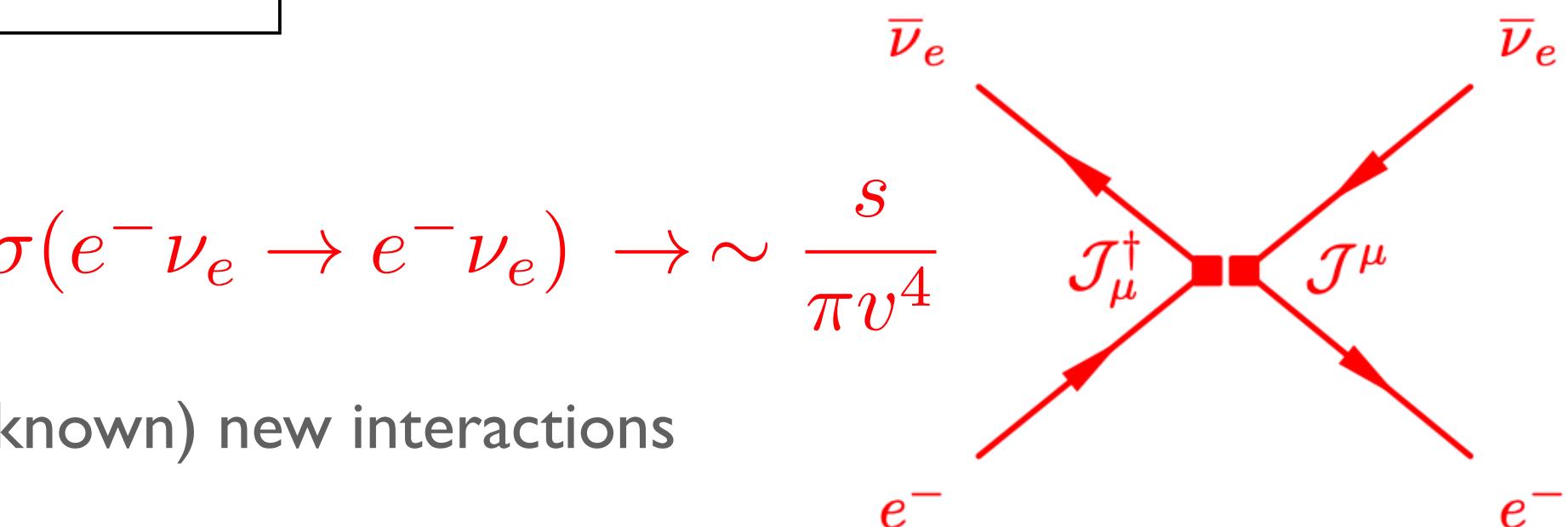
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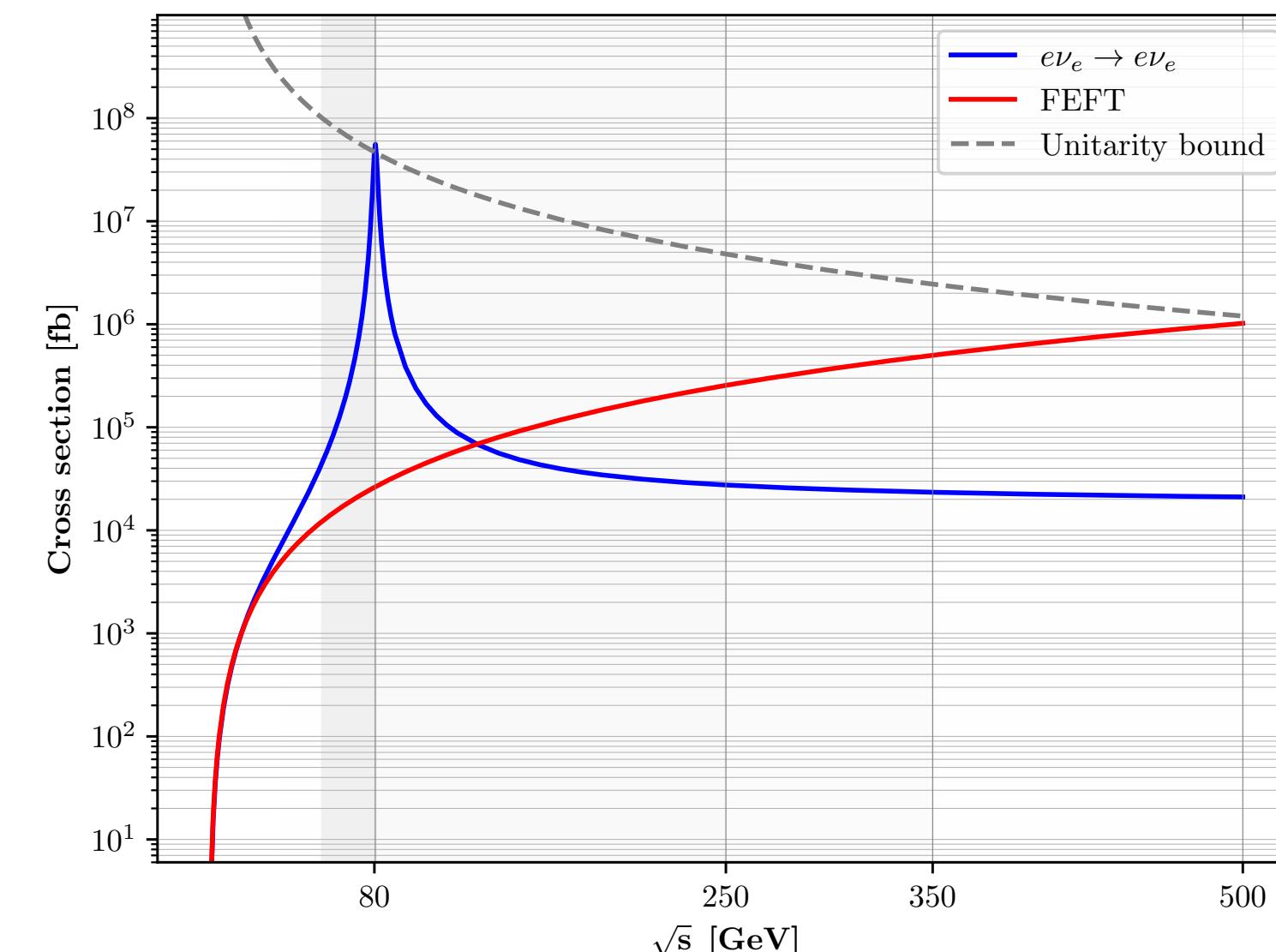
- 1964-1967: Renormalizable spontaneously broken “UV-complete”  $SU(2)$
- Discovery of  $W/Z$  at LHC



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# The rationale of Effective Field Theories

- SM contains all dim 2- and dim 4-operators “relevant” for low-energy physics:  $\mathcal{L}_{EW} = -\frac{1}{2}\text{tr}[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$  (no fermions or QCD here)

- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

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

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

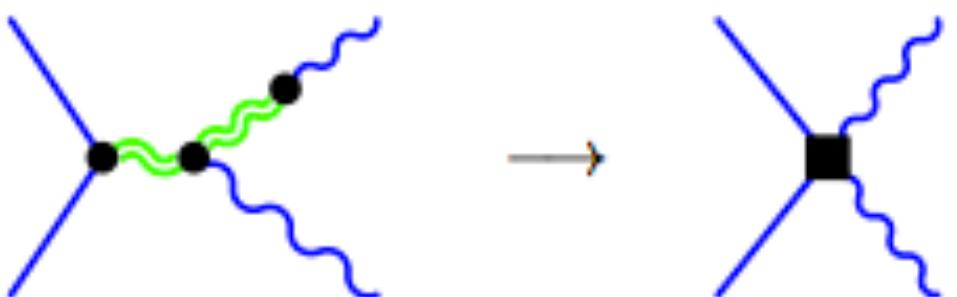
$$\mathcal{O}'_{\Phi,1} = \frac{1}{\Lambda^2} ((D\Phi)^\dagger\Phi) \cdot (\Phi^\dagger(D\Phi)) - \frac{v^2}{2}|D\Phi|^2$$



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

, such a general Lagrangian has no specific dynamical content beyond the general principles of analyticity, unitarity, cluster decomposition, Lorentz invariance, and chirality, so that when it is used to calculate S-matrix elements, it yields the most general matrix elements consistent with these general principles, provided that all terms of all orders in all couplings are included. One does not need the methods of current algebra for justification

S. Weinberg, 1979



Truncation introduces model dependence again

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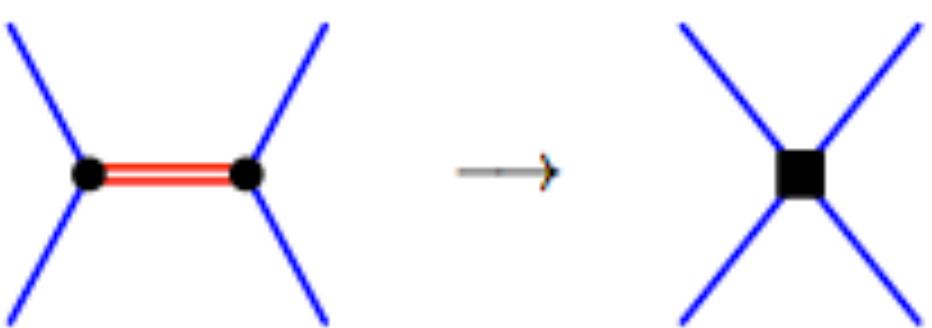
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$B^0$

$\Lambda_{\text{low}} = m_B$

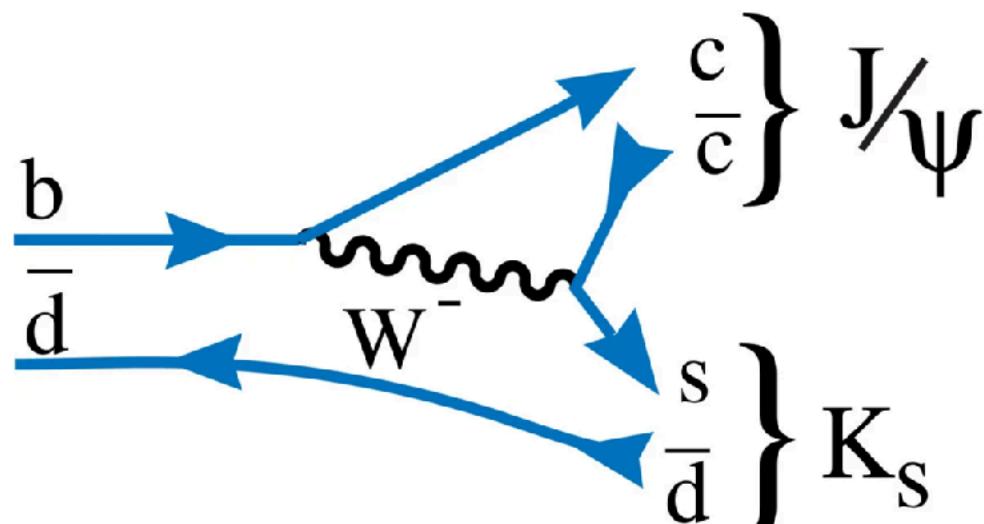
$I, J, P$  need confirmation. Quantum numbers predictions

Mass  $m_{B^0} = 5279.66 \pm 0.12$  MeV

$m_{B^0} - m_{B^\pm} = 0.52 \pm 0.05$  MeV

Mean life  $\tau_{B^0} = (1.519 \pm 0.004) \times 1$

$c\tau = 455.4$   $\mu$ m



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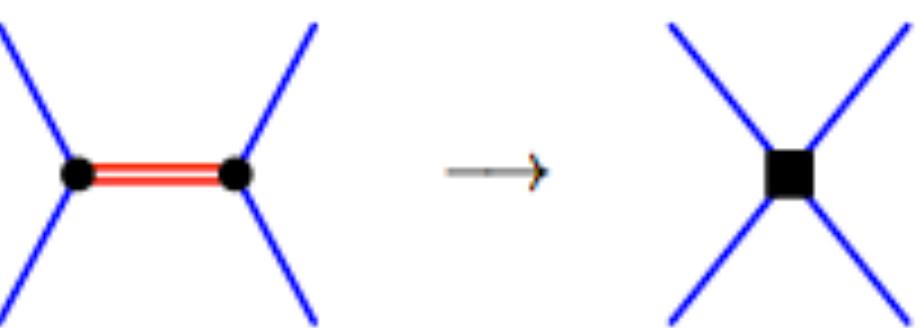
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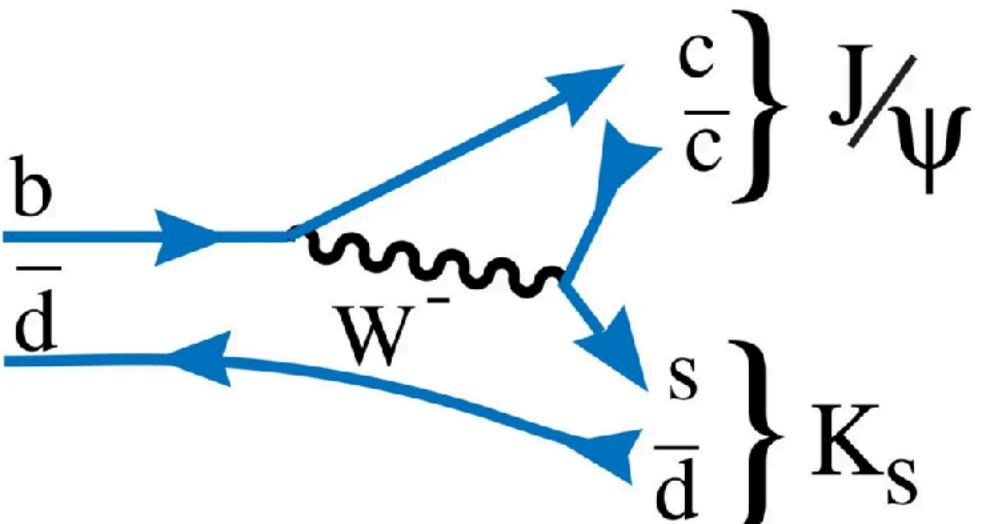
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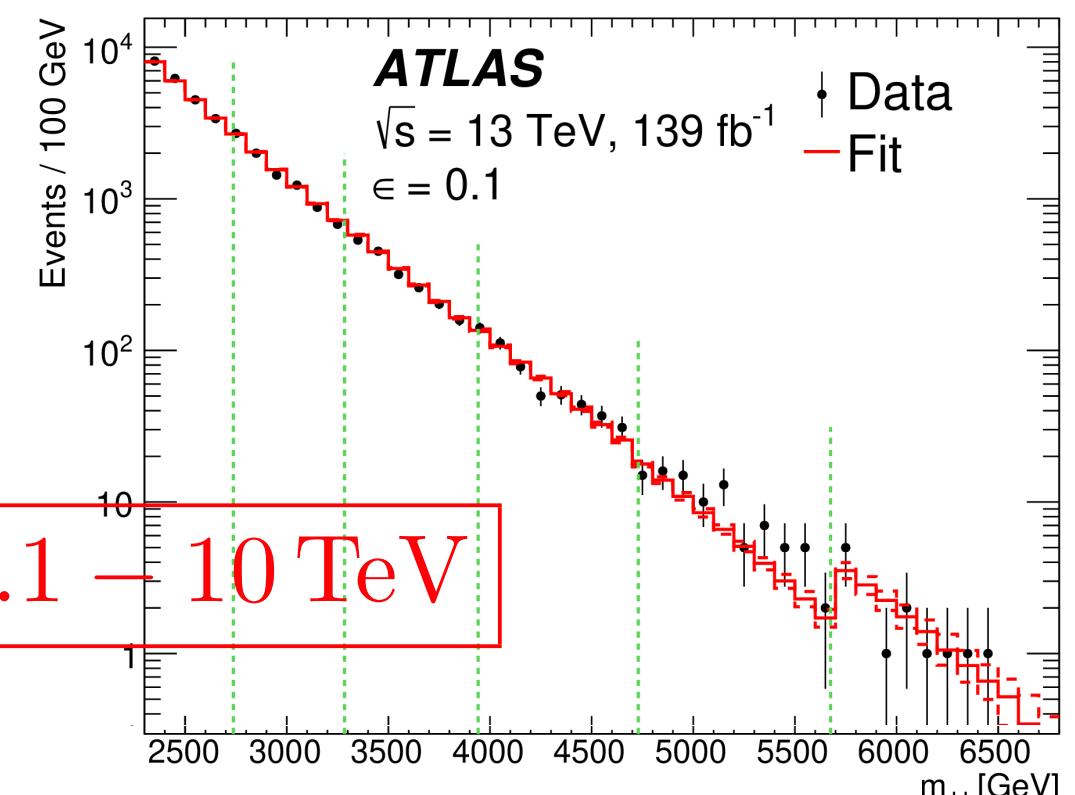
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$\Lambda_{\text{low}} \sim .1 - 10$  TeV



# EFT Operators in Multi-Boson Physics @ Dim-6

Dimension-6 operators for Multiboson physics (CP-conserving)

$$\begin{aligned}\mathcal{O}_{WWW} &= \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^\mu] & \mathcal{O}_{\partial\Phi} &= \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \\ \mathcal{O}_W &= (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) & \mathcal{O}_{\Phi W} &= (\Phi^\dagger \Phi) \text{Tr}[W^{\mu\nu} W_{\mu\nu}] \\ \mathcal{O}_B &= (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) & \mathcal{O}_{\Phi B} &= (\Phi^\dagger \Phi) B^{\mu\nu} B_{\mu\nu}\end{aligned}$$

Dimension-6 operators for Multiboson physics (CP-violating)

$$\begin{aligned}\mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi & \mathcal{O}_{\widetilde{W}WW} &= \text{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^\mu] \\ \mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu} \Phi & \mathcal{O}_{\widetilde{W}} &= (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi)\end{aligned}$$

All operators can change  
differential rates &  
polarization fractions!

	ZWW	AWW	HWZ	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓			
$\mathcal{O}_W$	✓	✓		✓	✓		✓			
$\mathcal{O}_B$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓	✓					
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$			✓	✓	✓	✓				
$\mathcal{O}_{\widetilde{W}WW}$	✓	✓					✓			
$\mathcal{O}_{\widetilde{W}}$	✓	✓		✓	✓			✓		
$\mathcal{O}_{\widetilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\widetilde{B}B}$			✓	✓	✓	✓				

- ▶ “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/Martin/Sanz/Setford, 1808.00442, Li et al., 2005.00008
- ▶ “EChL” basis: Dobado/Espriu/Pich et al.; Buchalla/Cata; Kilian/JRR et al.

connected to Higgs physics



# EFT Operators in Multi-Boson Physics @ Dim-8

## Longitudinal operators

$$\begin{aligned}\mathcal{O}_{S,0} &= \left[ (D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[ (D^\mu \Phi)^\dagger D^\nu \Phi \right] \\ \mathcal{O}_{S,1} &= \left[ (D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[ (D_\nu \Phi)^\dagger D^\nu \Phi \right]\end{aligned}$$

All operators can change differential rates & polarization fractions!

## Transversal operators

$$\begin{aligned}\mathcal{O}_{T,0} &= \text{Tr} [W_{\mu\nu} W^{\mu\nu}] \cdot \text{Tr} [W_{\alpha\beta} W^{\alpha\beta}] \\ \mathcal{O}_{T,1} &= \text{Tr} [W_{\alpha\nu} W^{\mu\beta}] \cdot \text{Tr} [W_{\mu\beta} W^{\alpha\nu}] \\ \mathcal{O}_{T,2} &= \text{Tr} [W_{\alpha\mu} W^{\mu\beta}] \cdot \text{Tr} [W_{\beta\nu} W^{\nu\alpha}] \\ \mathcal{O}_{T,5} &= \text{Tr} [W_{\mu\nu} W^{\mu\nu}] \cdot B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{O}_{T,6} &= \text{Tr} [W_{\alpha\nu} W^{\mu\beta}] \cdot B_{\mu\beta} B^{\alpha\nu} \\ \mathcal{O}_{T,7} &= \text{Tr} [W_{\alpha\mu} W^{\mu\beta}] \cdot B_{\beta\nu} B^{\nu\alpha} \\ \mathcal{O}_{T,8} &= B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \\ \mathcal{O}_{T,9} &= B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}\end{aligned}$$

## Mixed operators

$$\begin{aligned}\mathcal{O}_{M,0} &= \text{Tr} [W_{\mu\nu} W^{\mu\nu}] \cdot [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{O}_{M,1} &= \text{Tr} [W_{\mu\nu} W^{\nu\beta}] \cdot [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{O}_{M,2} &= [B_{\mu\nu} B^{\mu\nu}] \cdot [(D_\beta \Phi)^\dagger D^\beta \Phi] \\ \mathcal{O}_{M,3} &= [B_{\mu\nu} B^{\nu\beta}] \cdot [(D_\beta \Phi)^\dagger D^\mu \Phi] \\ \mathcal{O}_{M,4} &= [(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi] \cdot B^{\beta\nu} \\ \mathcal{O}_{M,5} &= [(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi] \cdot B^{\beta\mu} \\ \mathcal{O}_{M,6} &= [(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi] \\ \mathcal{O}_{M,7} &= [(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi]\end{aligned}$$

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



# The importance of multi-bosons

- Di-(multi-) boson seem to have much less statistical power than Drell-Yan
- (Almost) fully inclusive cross sections:  $\sigma(WW)/\sigma(DY) \sim 10^{-3}$
- This changes for looking at the high-energy region:

$$\sigma[pp \rightarrow W^+W^- \rightarrow e^+e^-\nu\nu] \sim 1.5 \text{ pb}$$

$$\sigma[pp \rightarrow Z^0 \rightarrow e^+e^-] \sim 2 \text{ nb}$$

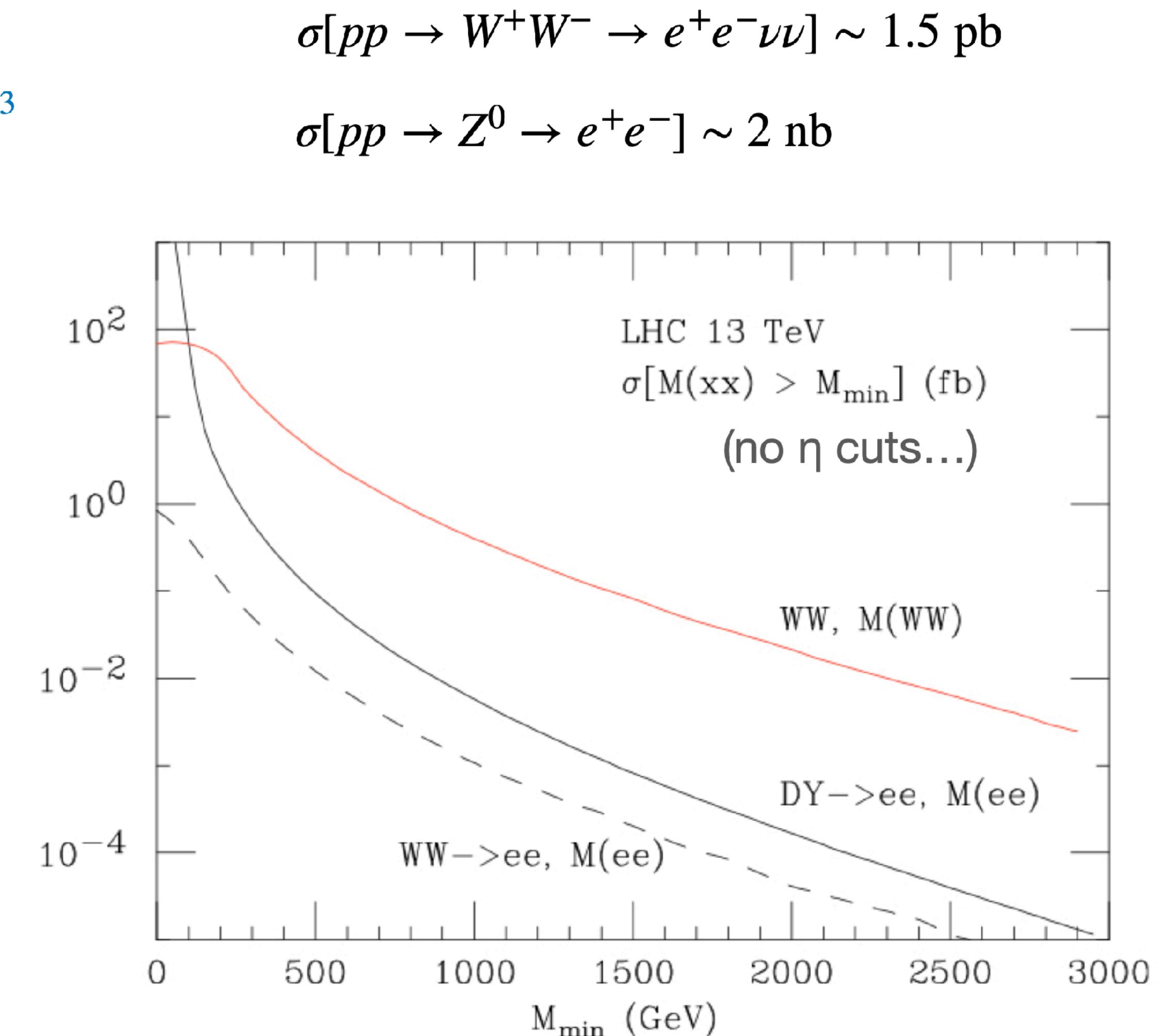


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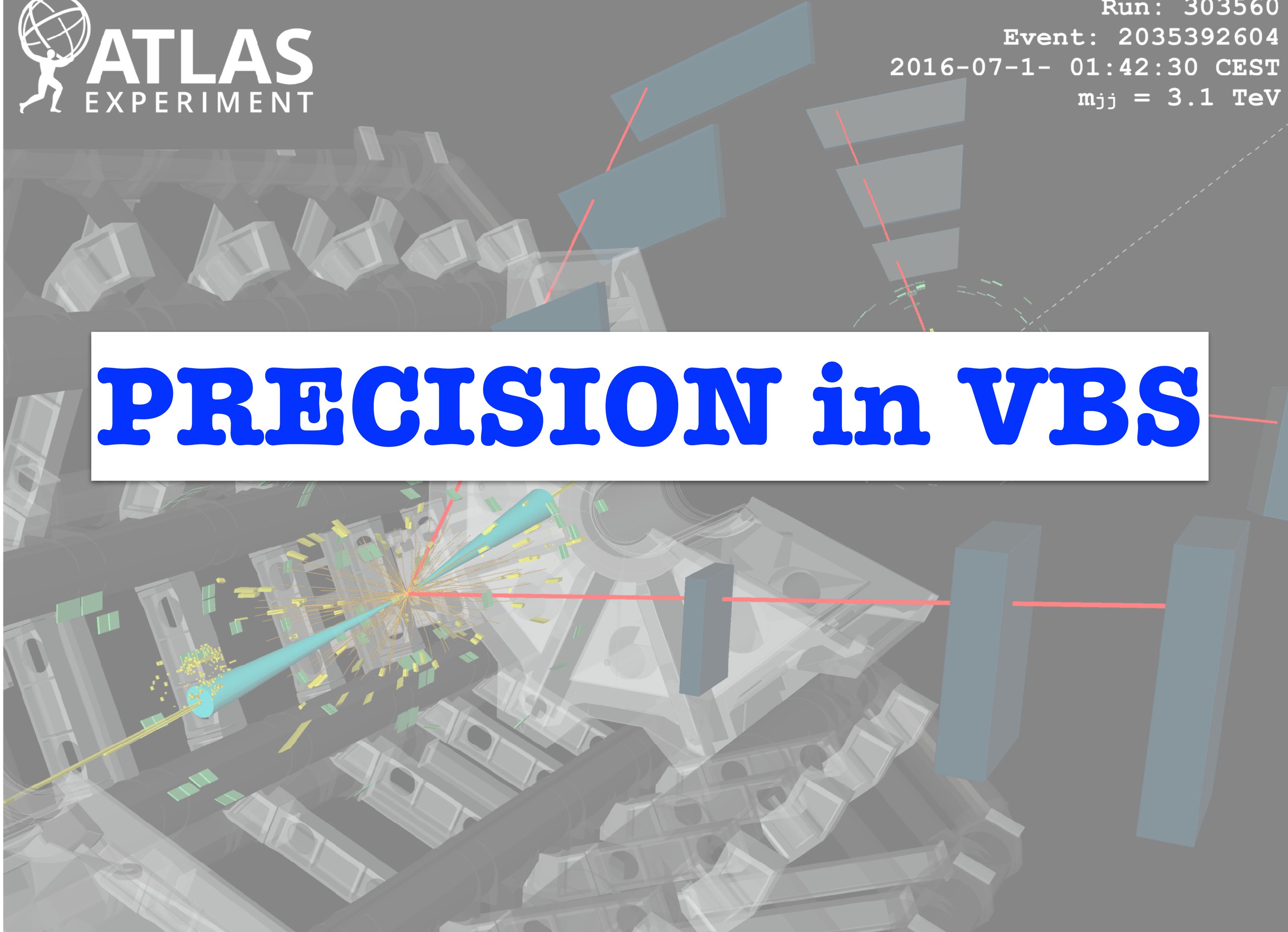
**Multibosons are the most sensitive probe of EW interactions in the high-Q<sub>2</sub> region**

- Di-(multi-) boson supersede DY: s- vs. t-channel
- Tri- [multi-] bosons usually higher BSM sensitivity
- BSM sensitivity vs. total cross sections
- HL/HE-LHC, MuC, ILC1000, CLIC: tribosons optimal
- Vector Boson Scattering (VBS): pay the price for double weak radiation twice, then universal behavior

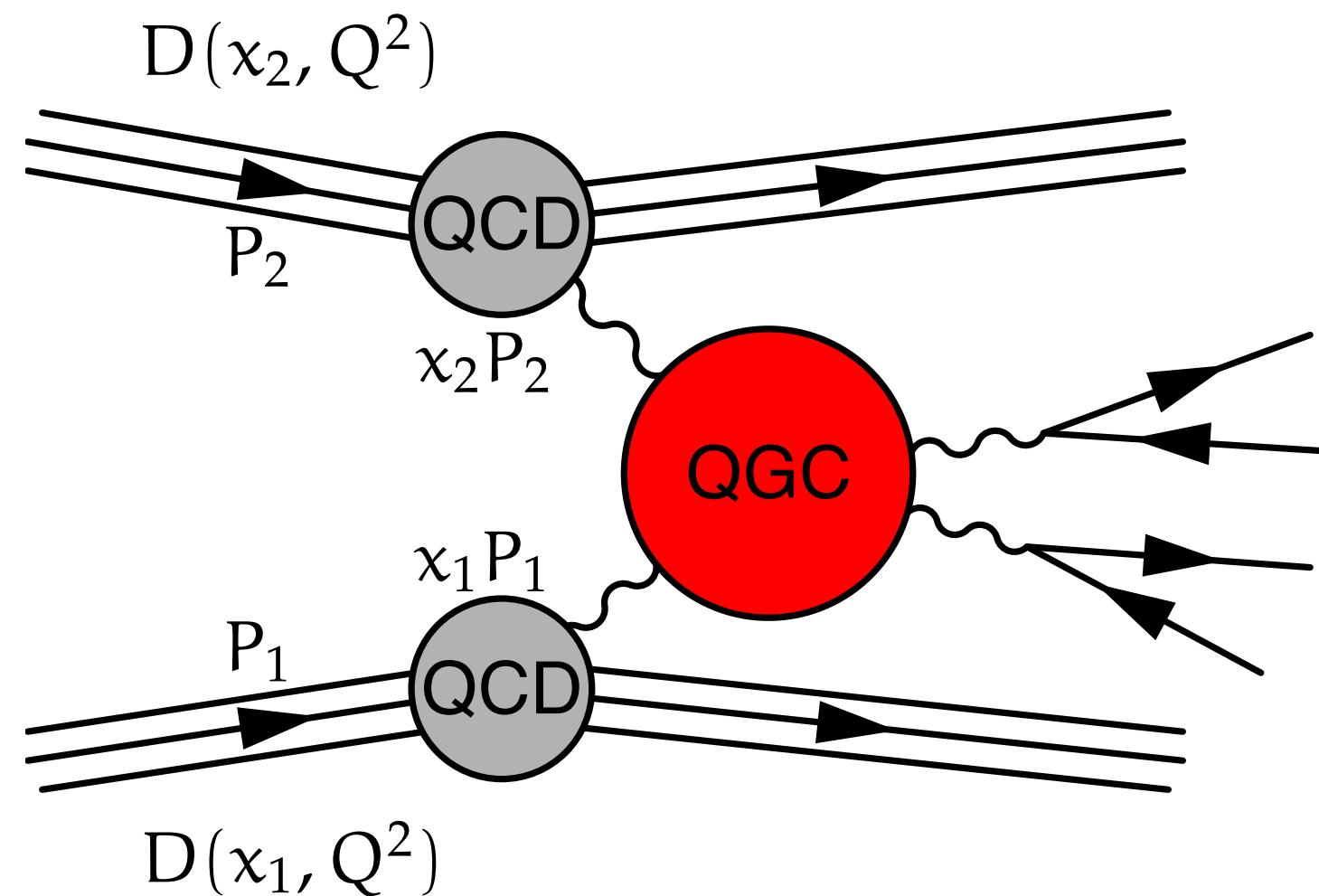


M. Mangano, MBI 22 Summary Talk

# PRECISION in VBS



# Vector boson scattering

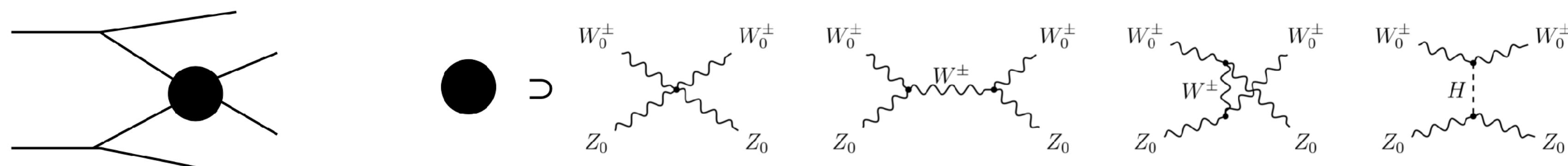


Fiducial phase space volume:

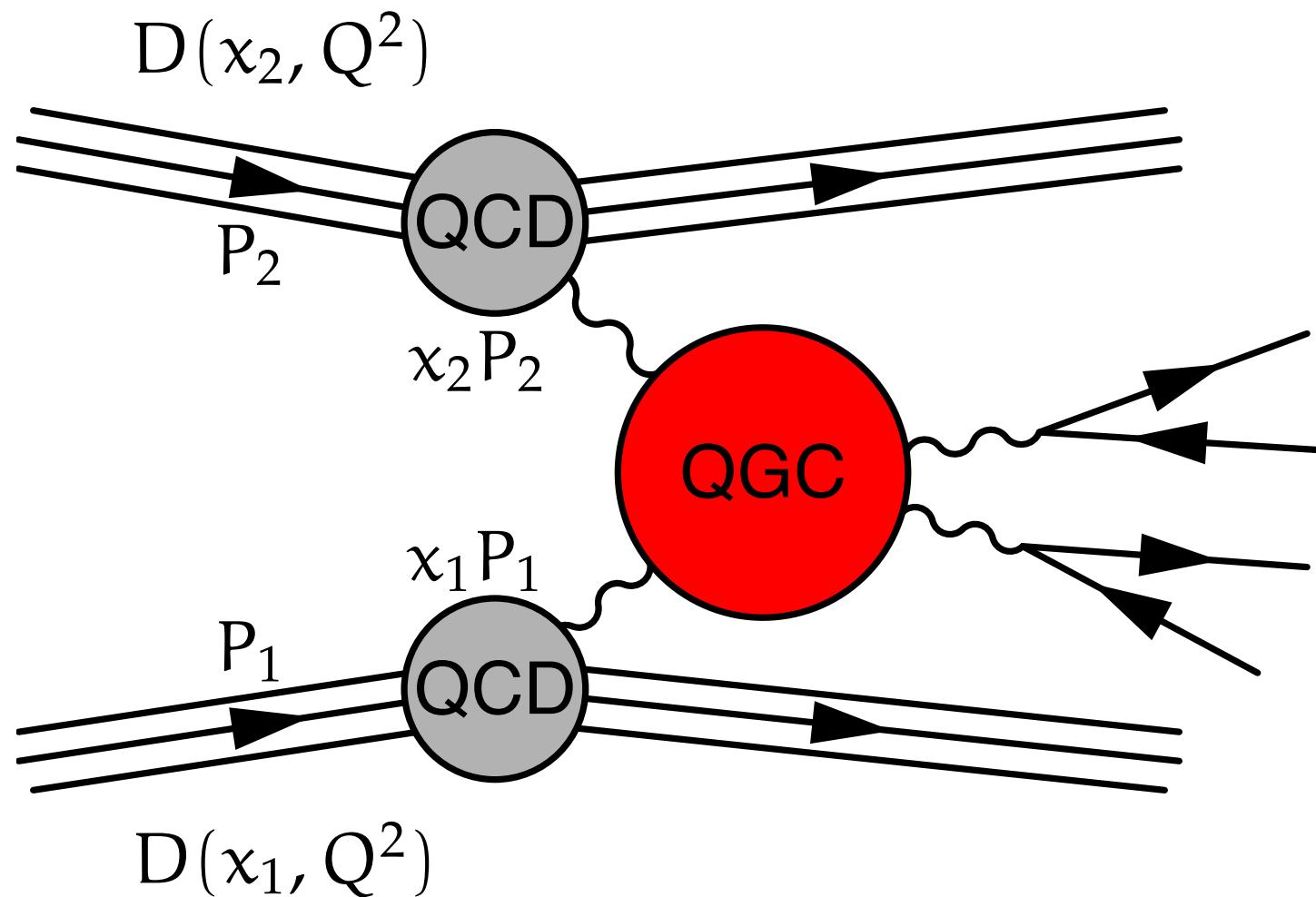
- $|lljj$  tag
- $m_{jj} > 500 \text{ GeV}$  (“jet recoil”)
- $|\Delta y_{jj}| > 2.4$  (“rapidity distance”)
- Cuts on  $E_j$ ,  $\rho_T^j$
- No / little central jet activity

## Importance of VBS

- VBS gives access to pure EW sector
- No dependence of fermion sector, flavor mixing etc. (almost)
- Goal: proof relation between Goldstones ( $W_L$ ,  $Z_L$ ) and Higgs  $H$
- Problem: longitudinal modes suppressed compared to transversal (~10%)



# Vector boson scattering

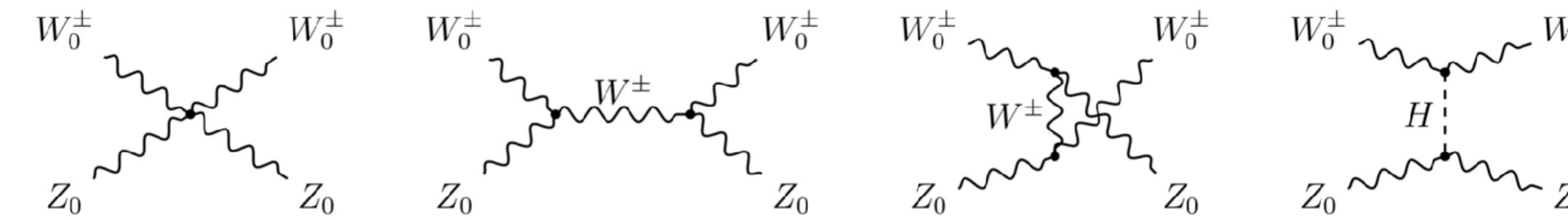
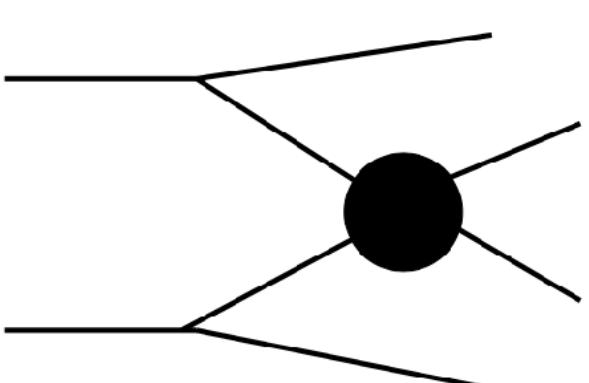


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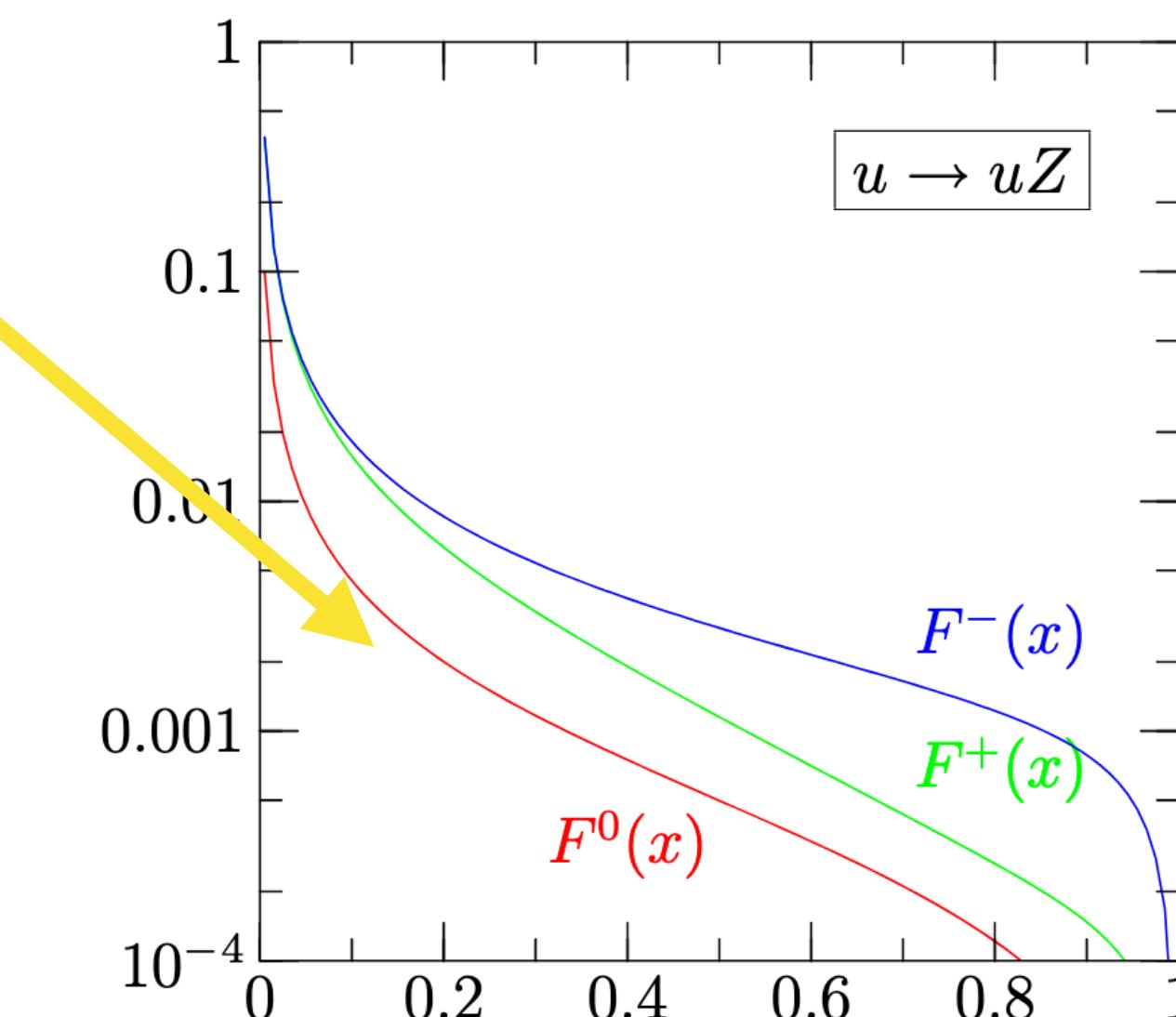
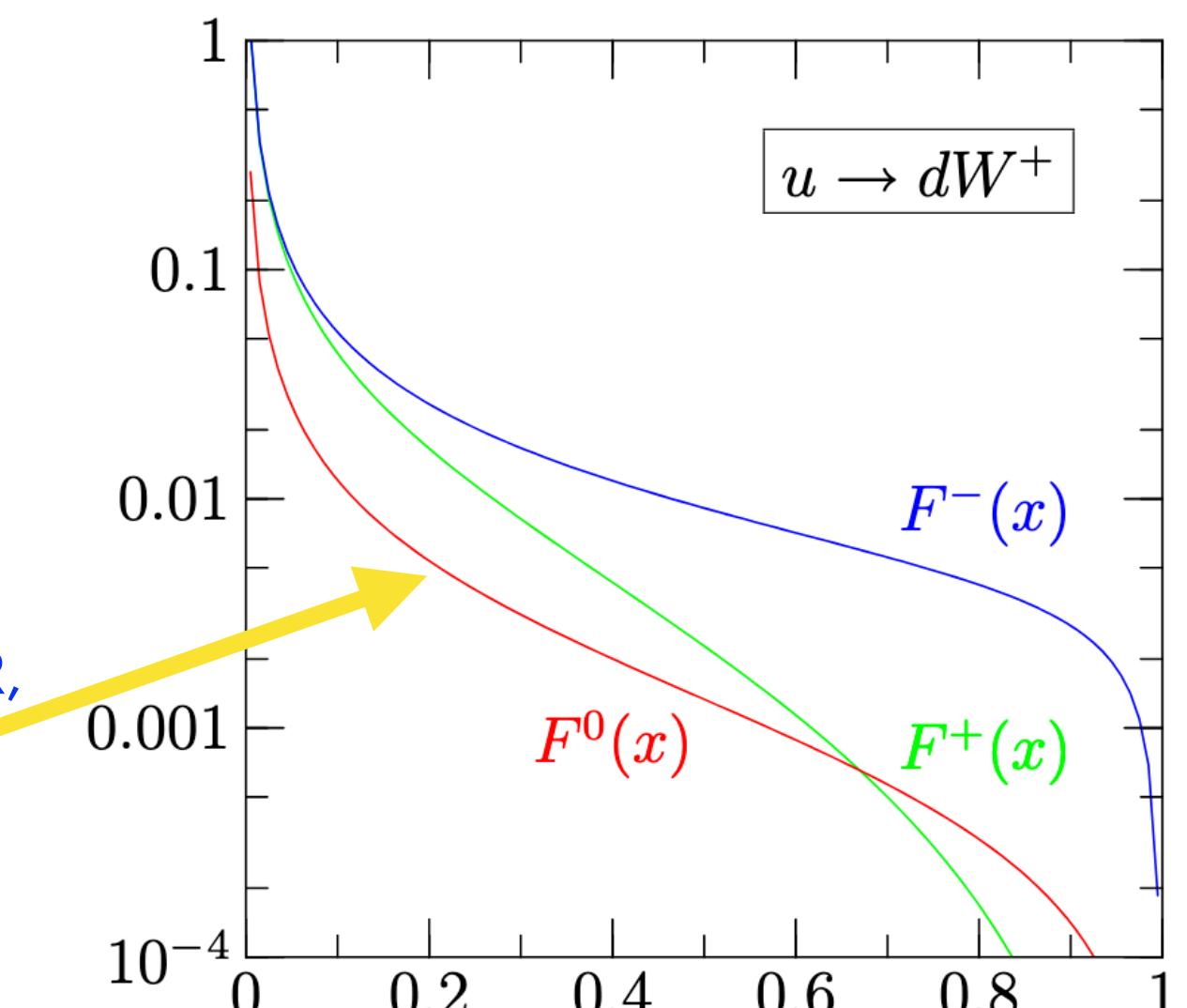
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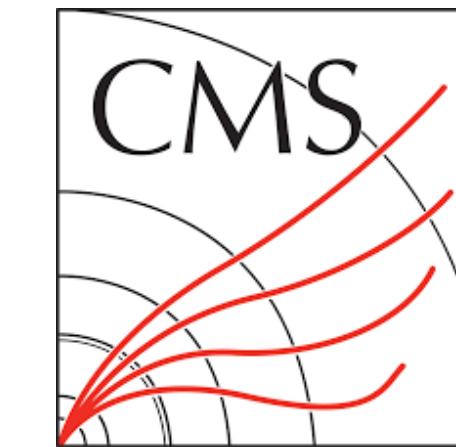
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from:  
Alboteanu/Kilian/JRR,  
0806.4145

EW PDF / Splitting function picture





Experimental results from CMS and ATLAS

$pp \rightarrow jjW^\pm W^\pm \rightarrow jj\ell\nu\ell\nu$

PRL 120, 081801 (2018)

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

5.5 $\sigma$

$pp \rightarrow jjZZ \rightarrow jj\ell\ell(\ell\ell/\nu\nu)$

PLB 774 (2017) 682

$$\sigma_{fid} = 2.91^{+0.16}_{-0.14} \text{ (stat)} \pm 0.35 \text{ (syst)} \text{ fb}$$

6.5 $\sigma$

$pp \rightarrow jjWZ \rightarrow jj\ell\ell\ell\nu$

PLB 809 (2020) 135710

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

2.7 $\sigma$

$pp \rightarrow jjZ\gamma \rightarrow jj\ell\ell\gamma$

CERN-EP-2019-206

$$\mu_{EW} = \sigma_{obs}/\sigma_{LO, MG} = 0.82^{+0.51}_{-0.43}$$

6.8 $\sigma$

$pp \rightarrow jjVV \rightarrow jjjj(\ell\ell/\ell\nu)$

PRD 100, 032007 (2019)

$$\sigma_{EW}^{fid} = 0.57^{+0.16}_{-0.14} \text{ fb}$$

5.3 $\sigma$

$pp \rightarrow jjWV \rightarrow jj\ell\nu jj$

PLB 809 (2020) 135710

$$\mu_{EW} = \sigma_{obs}/\sigma_{th.} = 0.64^{+0.23}_{-0.21}$$

4.7 $\sigma$

$$\mu_{Z\gamma jj-EW} = 1.00 \pm 0.19 \text{ (stat.)} \pm 0.13 \text{ (syst.)}$$

4.1 $\sigma$

$$\mu_{EW VV jj}^{\text{obs}} = 1.05 \pm 0.20 \text{ (stat.)}^{+0.37}_{-0.34} \text{ (syst.)}$$

2.7 $\sigma$

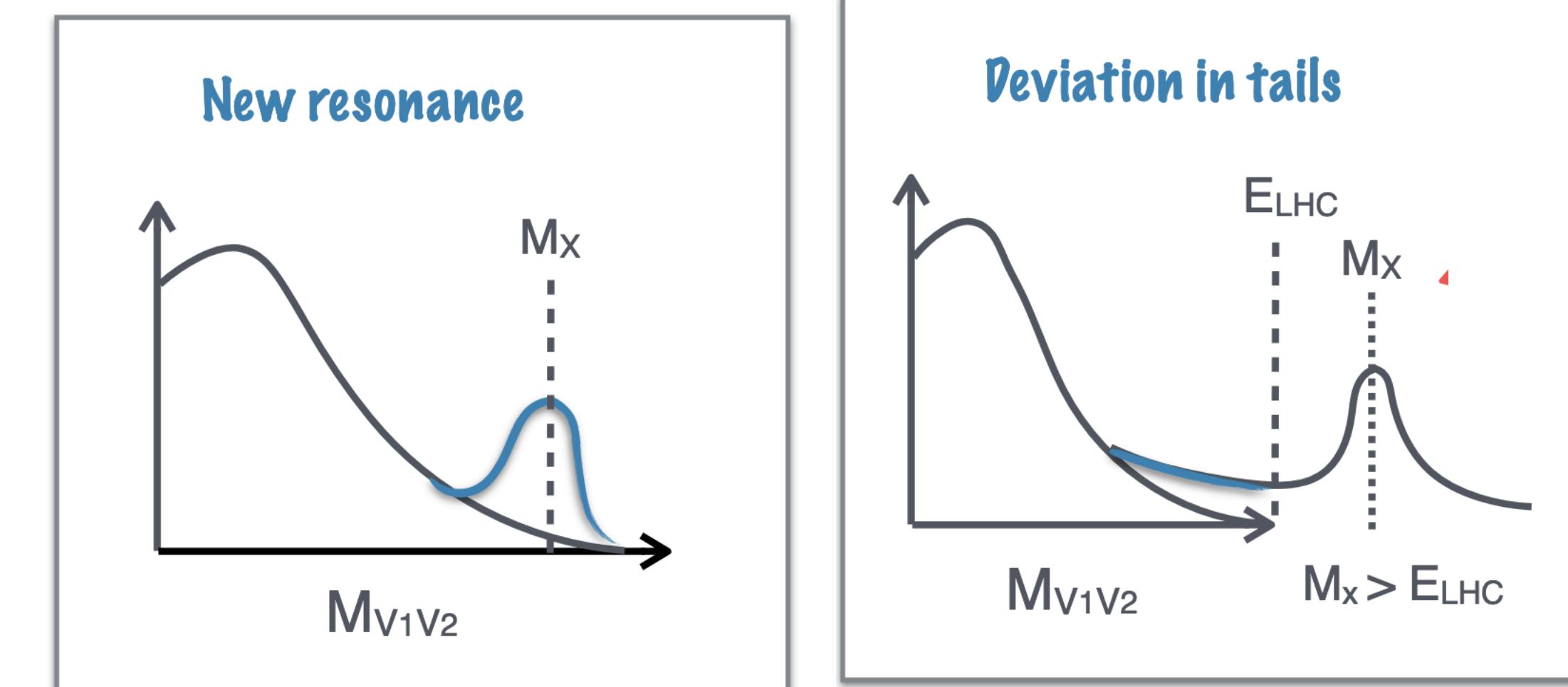
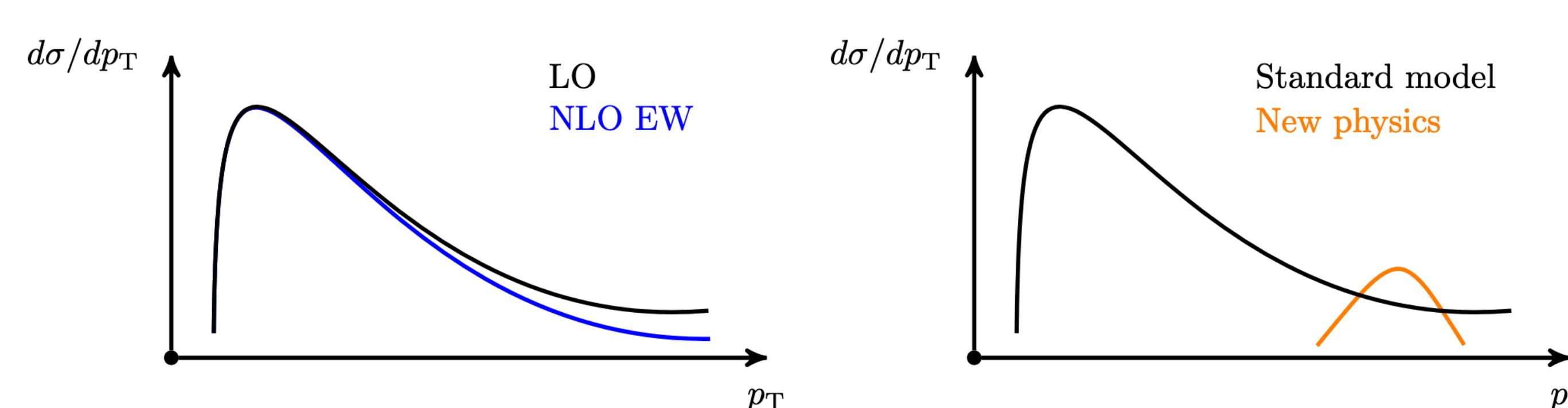
4.4 $\sigma$

- Fiducial regions difficult to compare
- Large differences in MC predictions
- Mostly very complicated DNNs very hard to unfold

# Precision in Vector Boson Scattering

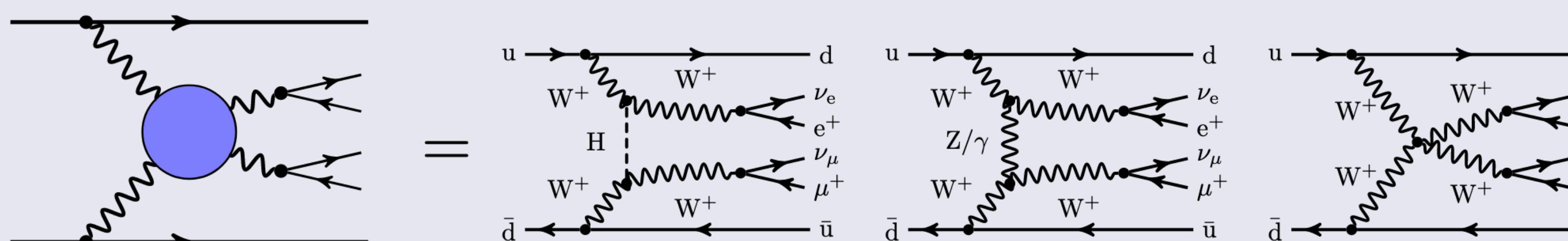
11 / 31

- Search for New Physics in tails: onset of resonances
- NLO EW(+QCD) corrections important for those tails



adapted from M. Pellen, MBI 2022

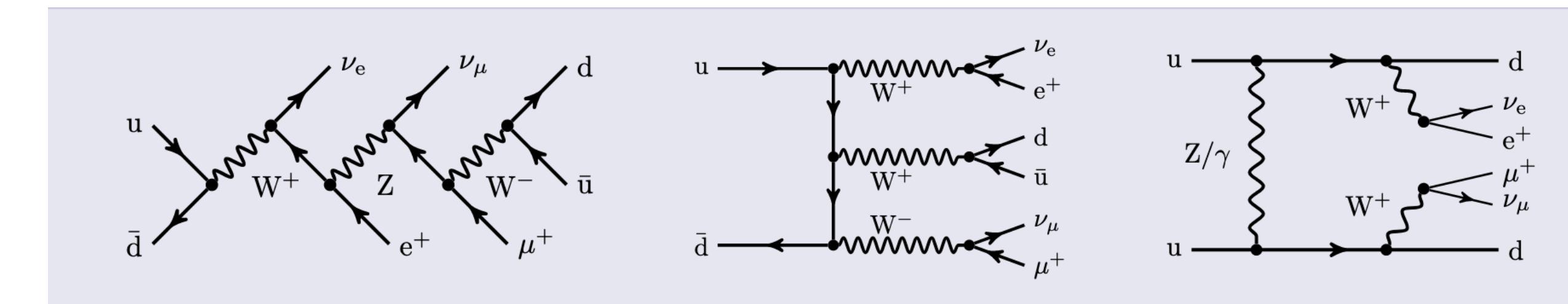
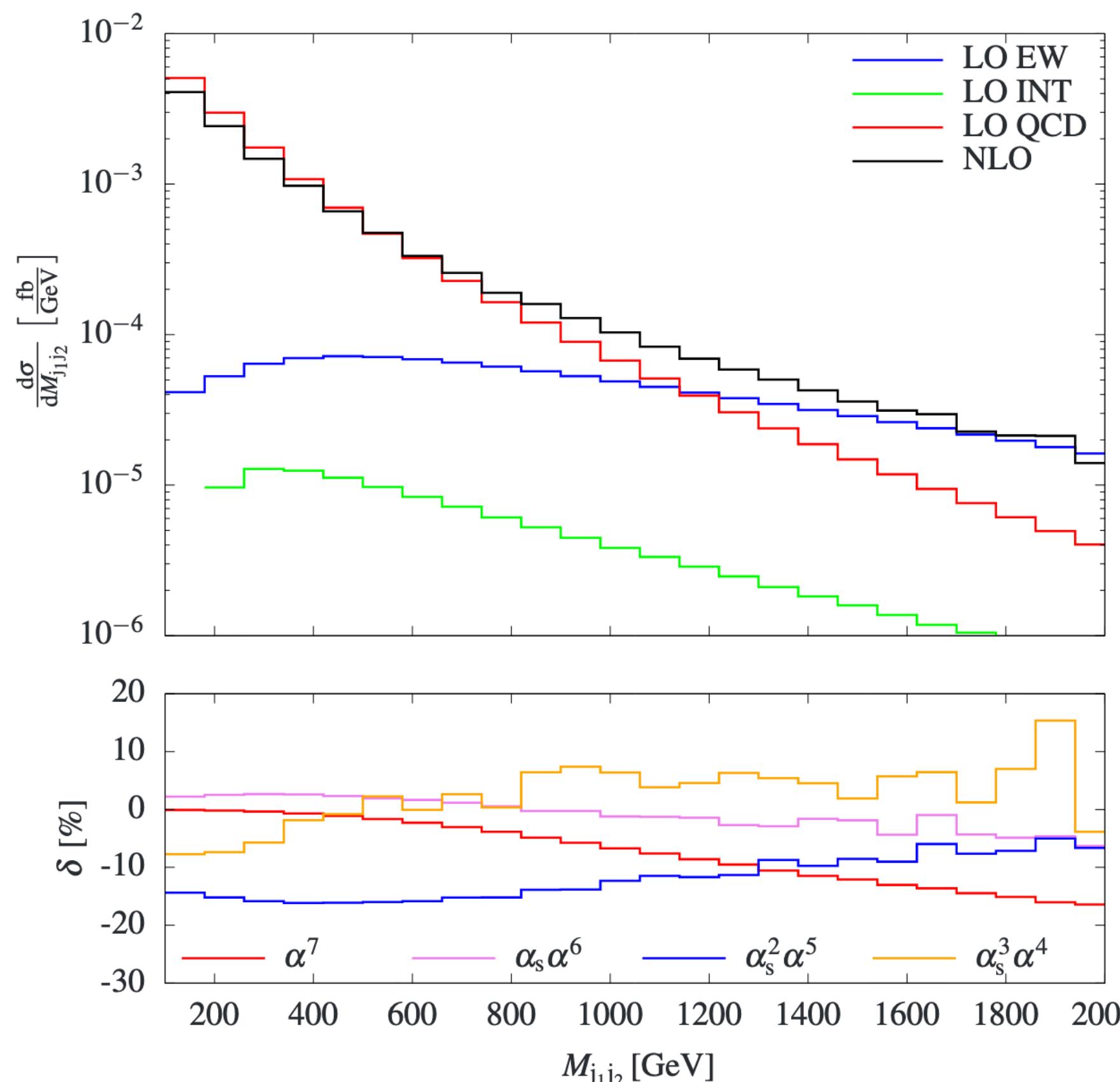
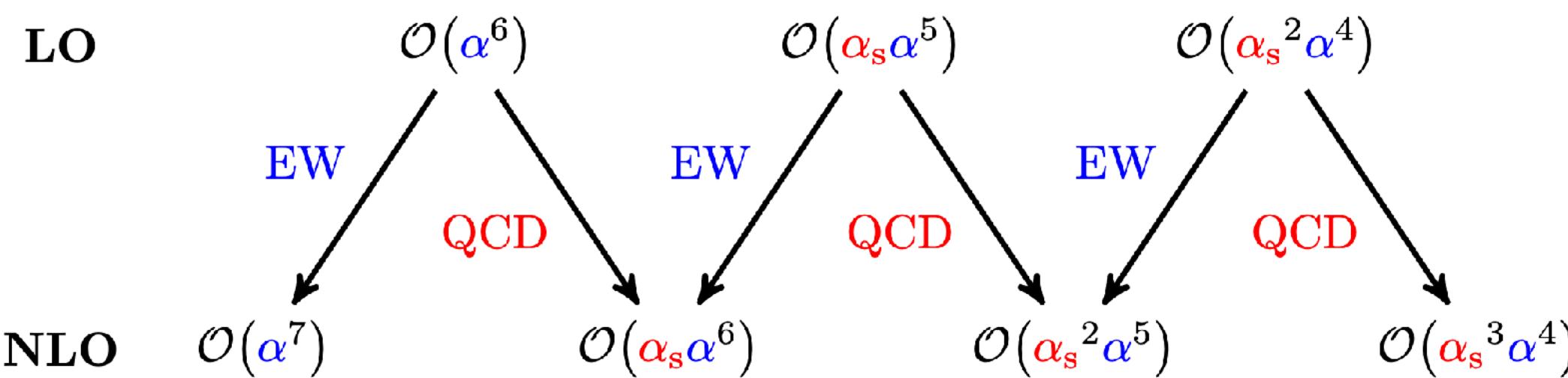
## VBS diagrams



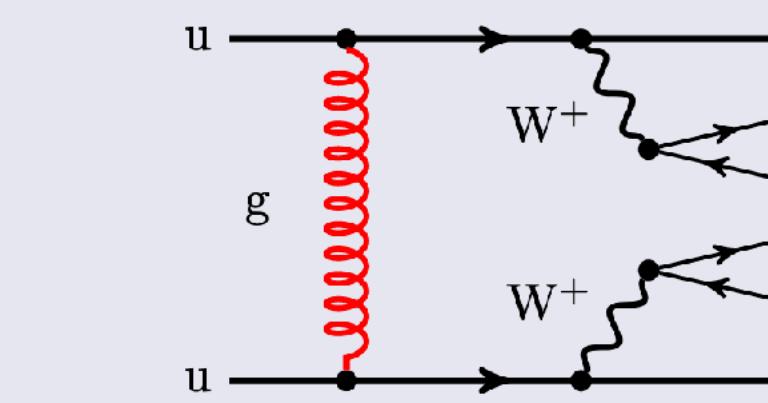
VBS LO+NLO:  
Biedermann, Denner, Pellen,  
1708.00268 ; Denner, Dittmaier,  
Maierhöfer, Pellen, Schwan,  
1611.02951; Ballestrero et al.,  
1803.07943; Denner, Franken, Pellen,  
Schmidt, 2107.10688;

# Precision in Vector Boson Scattering

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Even more (QCD) diagrams ...



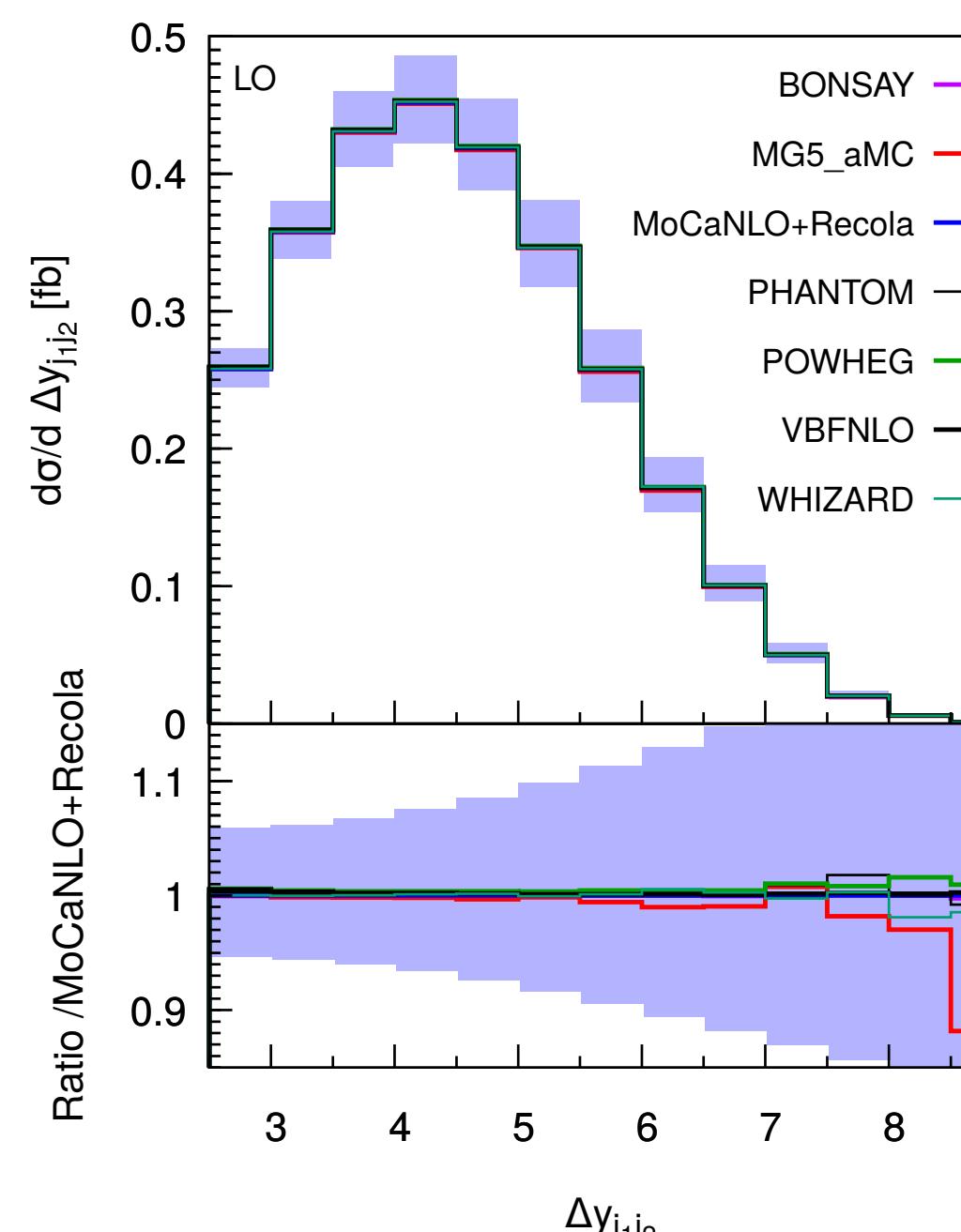
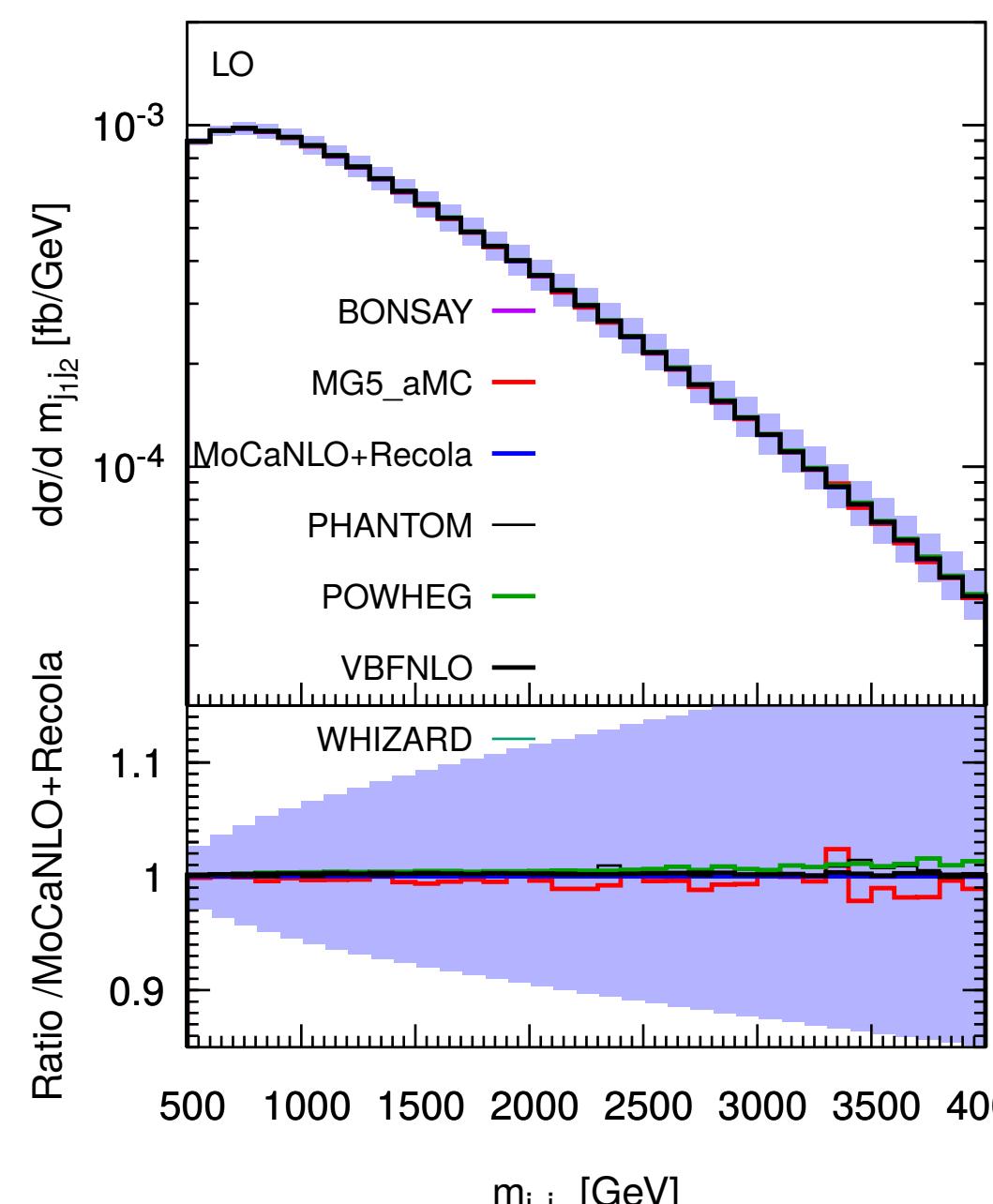
Process	$W^+ W^+$	$W^+ Z$	$ZZ$	$W^+ W^-$ (VBS setup)	$W^+ W^-$ (Higgs setup)
$\Delta\sigma_{\text{NLO}}^{\alpha^7} [\text{fb}]$	-0.2169(3)	-0.04091(2)	-0.015573(5)	-0.307(1)	-0.103(1)
$\sigma_{\text{LO}}^{\alpha^6} [\text{fb}]$	1.4178(2)	0.25511(1)	0.097683(2)	2.6988(3)	1.5322(2)
$\delta^{\alpha^7} [\%]$	-15.3	-16.0	-15.9	-11.4	-6.7

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s \alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^5)$	$\mathcal{O}(\alpha_s^3 \alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	X	✓

# Precision in Vector Boson Scattering

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s^2 \alpha^4)$	$\mathcal{O}(\alpha_s \alpha^5)$	
$\sigma[\text{fb}]$	$2.292 \pm 0.002$	$1.477 \pm 0.001$	$0.223 \pm 0.003$	
Code		$\sigma[\text{fb}]$		
BONSAY		$1.43636 \pm 0.00002$		
MG5_aMC		$1.4304 \pm 0.0007$		
MoCaNLO+RECOLA		$1.43476 \pm 0.00009$		
PHANTOM		$1.4374 \pm 0.0006$		
POWHEG-Box		$1.44092 \pm 0.00009$		
VBFNLO		$1.43796 \pm 0.00005$		
WHIZARD		$1.4381 \pm 0.0002$		

LO



$p_T, \ell > 20 \text{ GeV}$	$ y_\ell  < 2.5$	$\Delta R_{\ell\ell} > 0.3$
$p_{T,\text{miss}} > 40 \text{ GeV}$		
	Anti- $k_T$ jets with $R = 0.4$ :	
	$p_{T,j} > 30 \text{ GeV}$	$ y_j  < 4.5$
		$\Delta R_{\ell j} > 0.3$
	$m_{jj} > 500 \text{ GeV}$	$ \Delta y_{jj}  > 2.5$

LO+PS

Ballestrero et al., 1803.07943

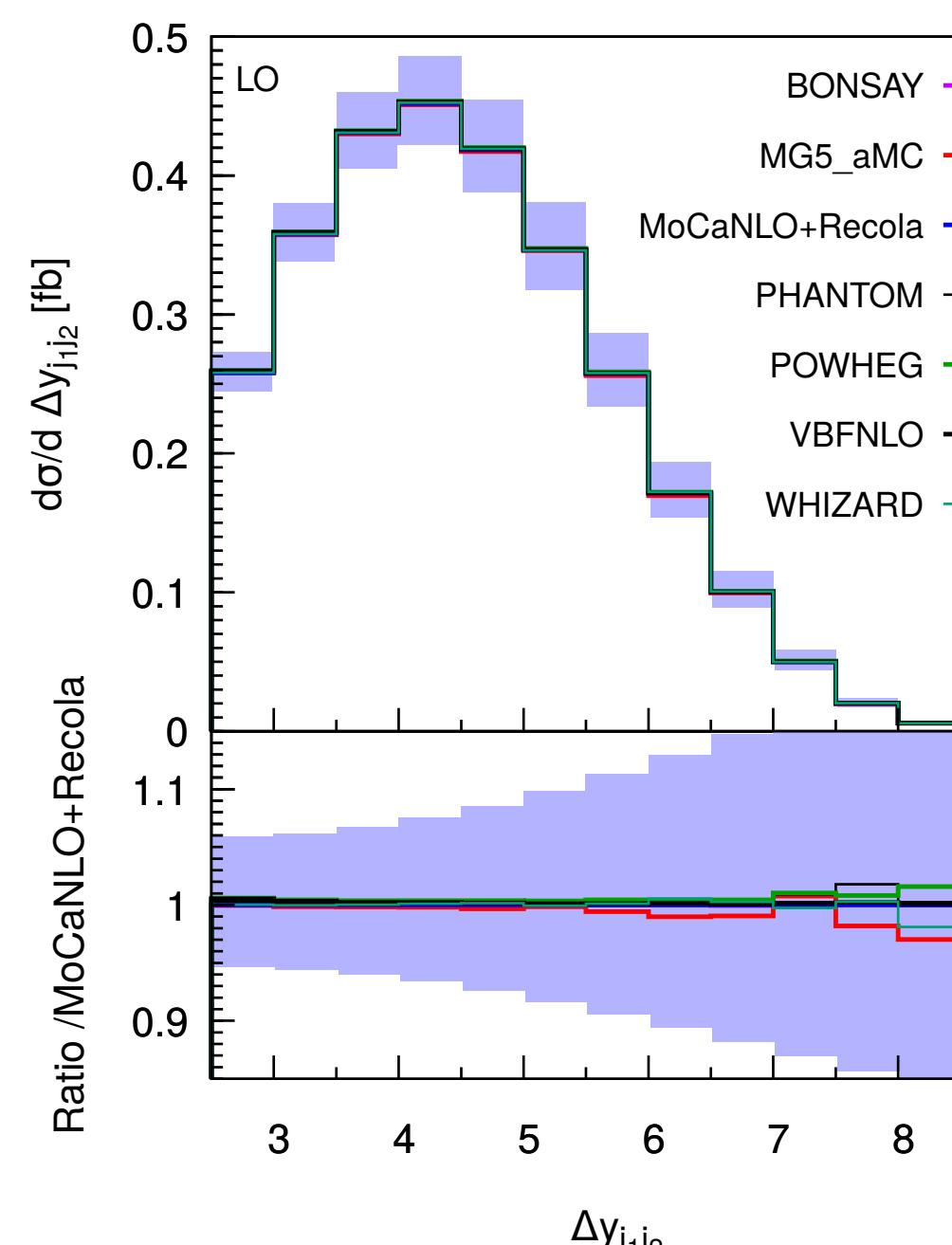
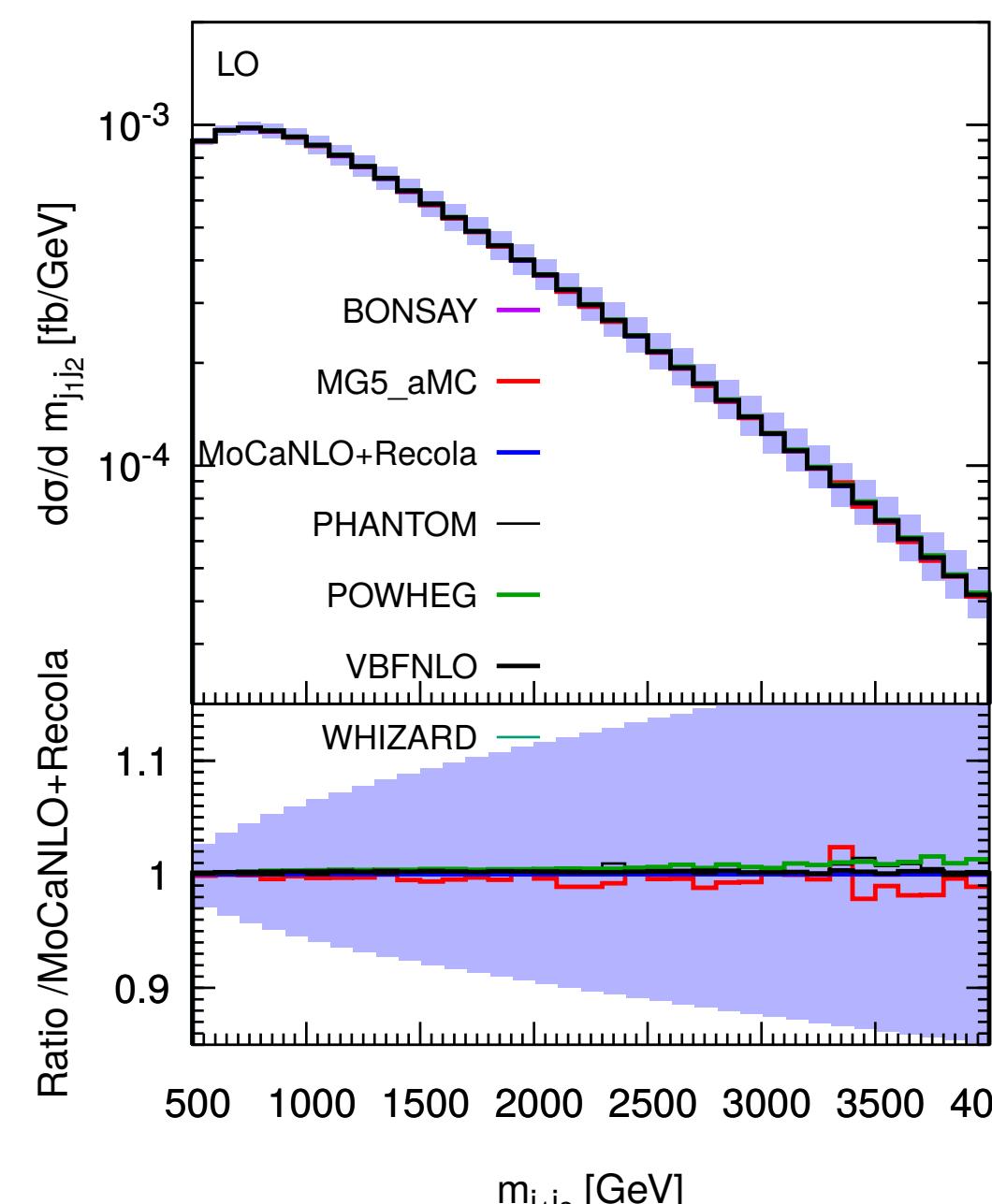
Code	$\sigma[\text{fb}]$
MG5_AMC+PYTHIA8	$1.352 \pm 0.003$
MG5_AMC+HERWIG7	$1.342 \pm 0.003$
MG5_AMC+PYTHIA8, $\Gamma_{\text{resc}}$	$1.275 \pm 0.003$
MG5_AMC+HERWIG7, $\Gamma_{\text{resc}}$	$1.266 \pm 0.003$
PHANTOM+PYTHIA8	$1.235 \pm 0.001$
PHANTOM+HERWIG7	$1.258 \pm 0.001$
VBFNLO+HERWIG7-DIPOLE	$1.3001 \pm 0.0002$
WHIZARD+PYTHIA8	$1.229 \pm 0.001$

# Precision in Vector Boson Scattering

13 / 31

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LO



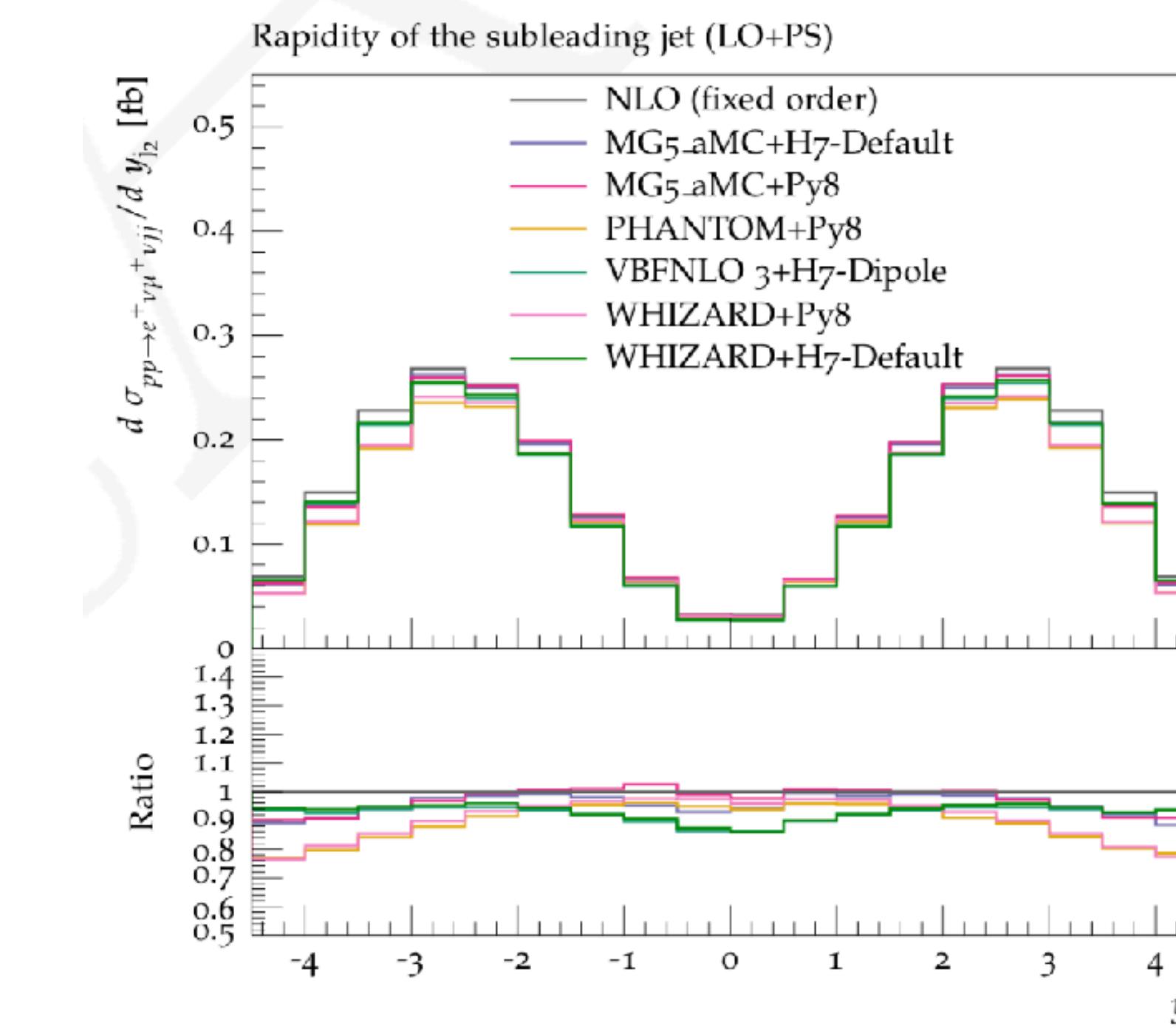
J. R. Reuter, DESY

$p_{T,\ell} > 20 \text{ GeV}$     $|y_\ell| < 2.5$     $\Delta R_{\ell\ell} > 0.3$   
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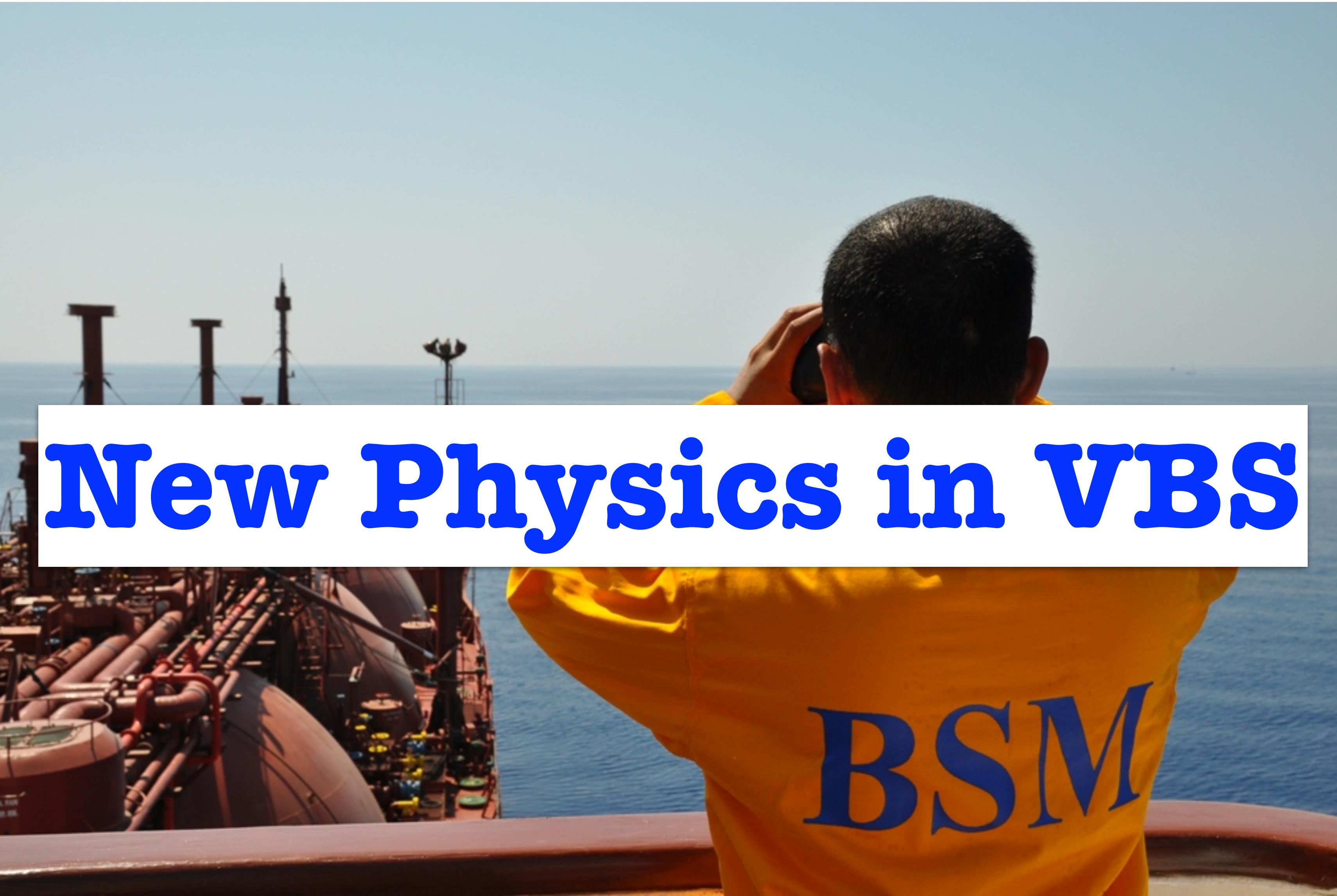
Ballestrero et al., 1803.07943

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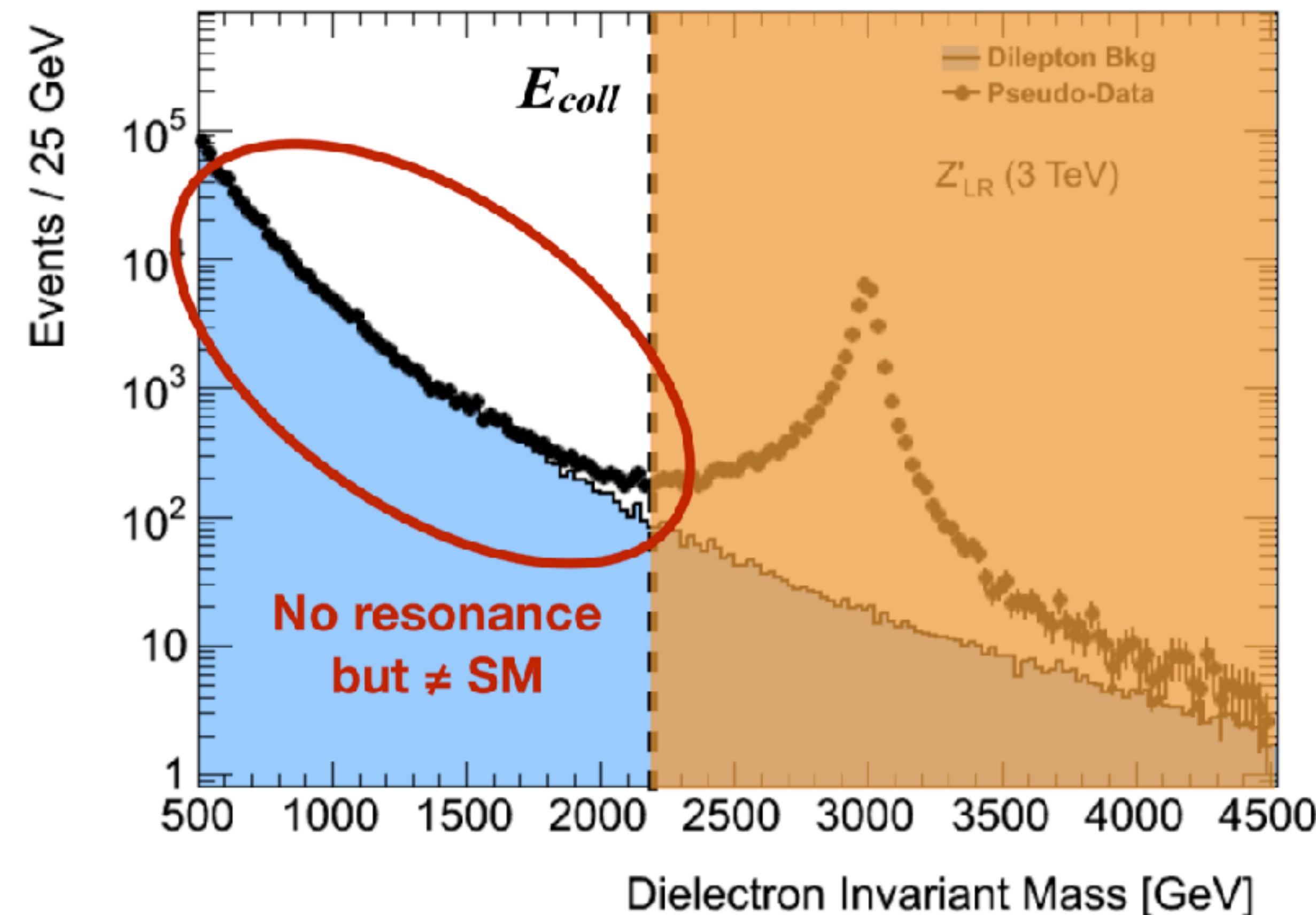


Seminar, University of Warsaw, 7.2.2023



# Signal models for VBS

1. “Parameterize deviations”: EFT description (HEFT, SMEFT)
  2. Resonances might be in direct reach of LHC: simplified models
  3. Specific physics models that predict diboson resonances  
(even still SUSY 
- 
- Rise of amplitude: is Taylor expansion below a resonance
  - EFT framework EW-restored regime:  
 $SU(2)_L \times SU(2)_R$ ,  $SU(2)_L \times U(1)_Y$  gauged
  - EFT is model-dependent: truncation, size of coefficients etc..  
need to consider unitarity etc. constraints
  - Simplified models: Include EFT operators in addition (more resonances, continuum contribution)
  - Simplified models: unitarity constraints (“UV-incomplete” model)



Courtesy: Jorge de Blas

# Unitarity in (VBS) Scattering Amplitudes

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

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

Partial wave amplitudes:

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



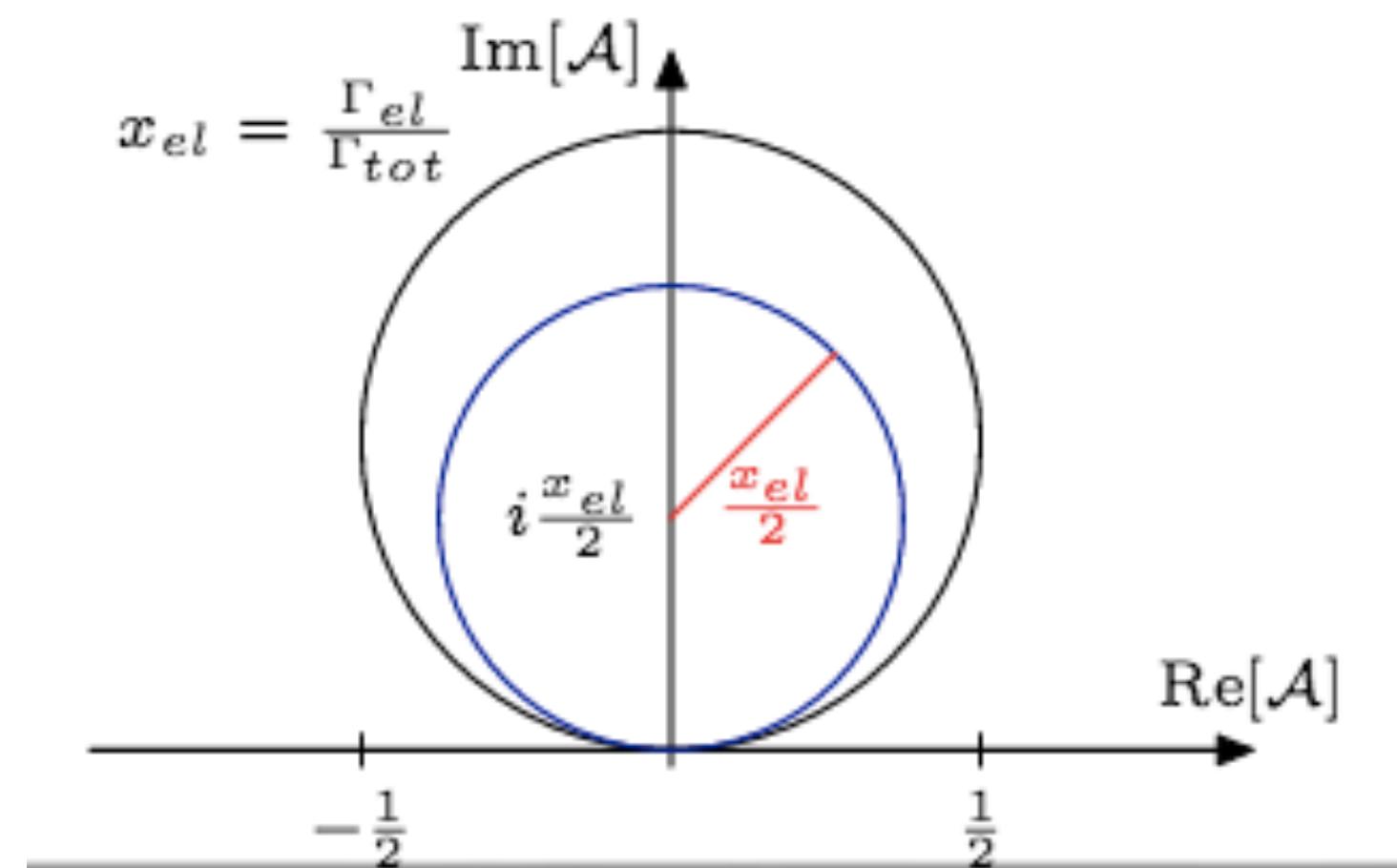
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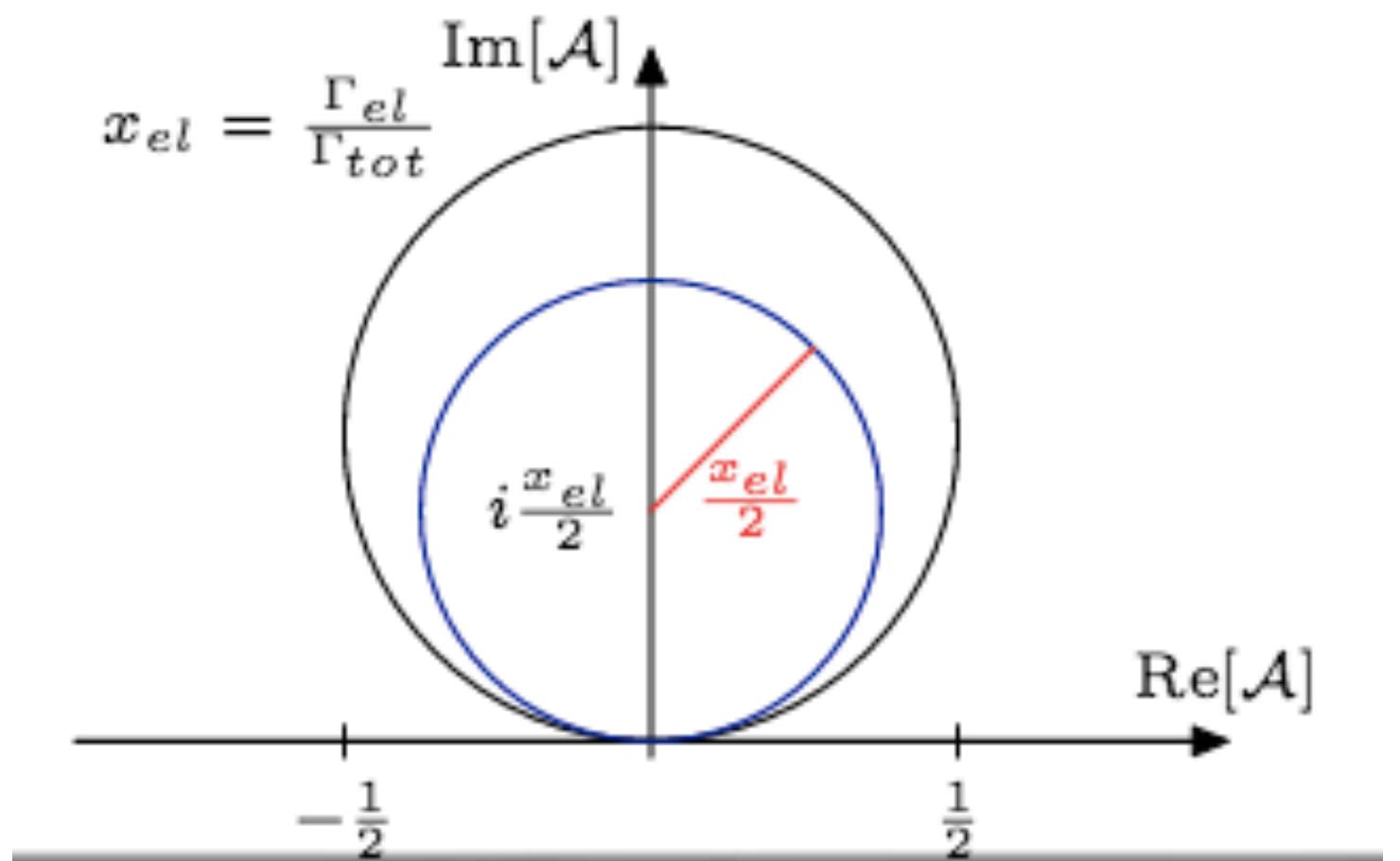
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Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_{\ell} \frac{32\pi(2\ell+1)}{s} |\mathcal{A}_{\ell}|^2 \stackrel{!}{=} \sum_{\ell} \frac{32\pi(2\ell+1)}{s} \text{Im} [\mathcal{A}_{\ell}] \quad \Rightarrow \quad |\mathcal{A}_{\ell}|^2 = \text{Im} [\mathcal{A}_{\ell}]$$



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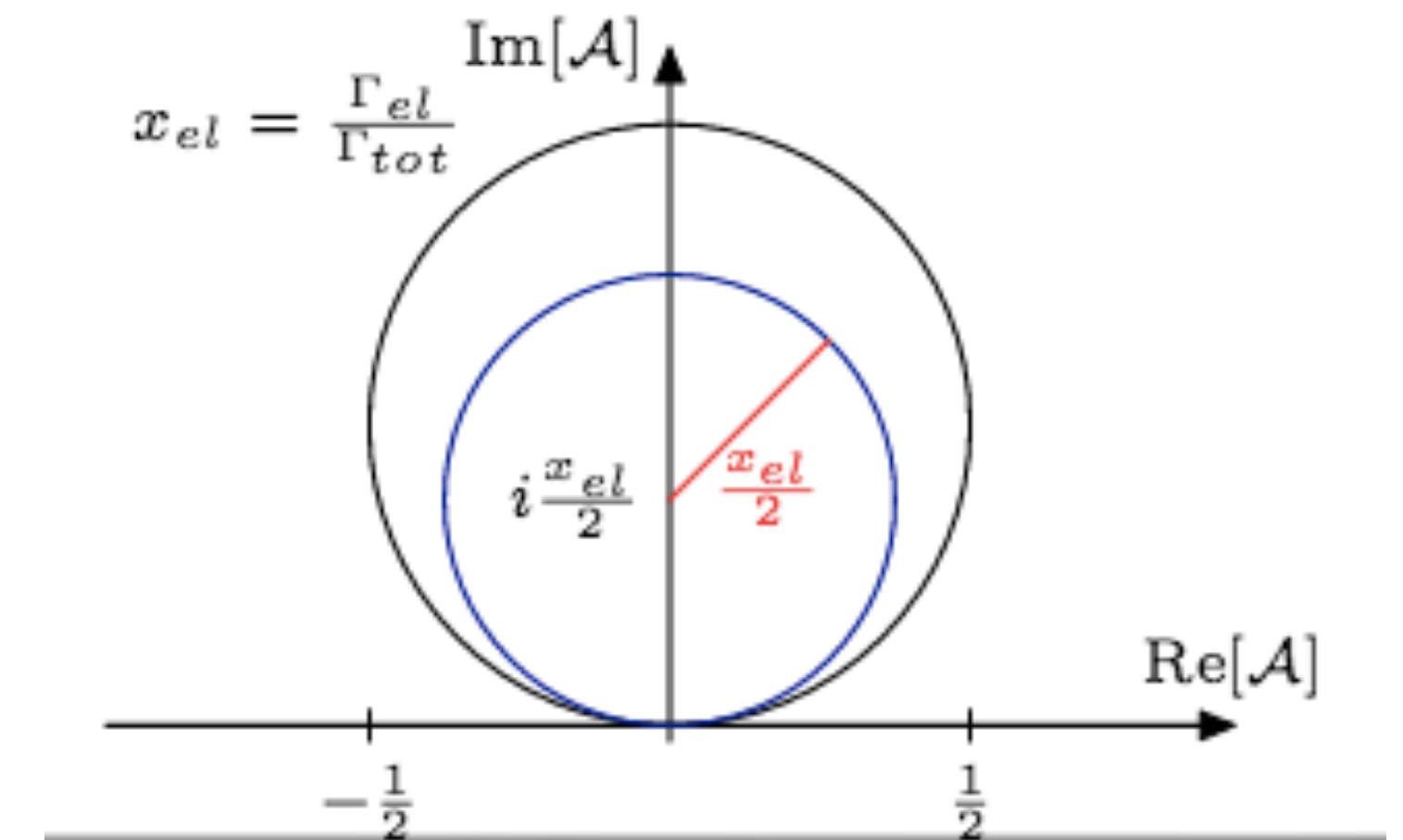
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Lee/Quigg/Thacker, 1973

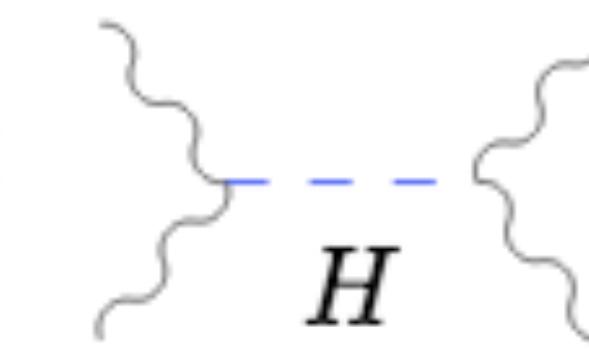
exceeds unitarity bound  $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$  at:

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

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

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

Higgs exchange:

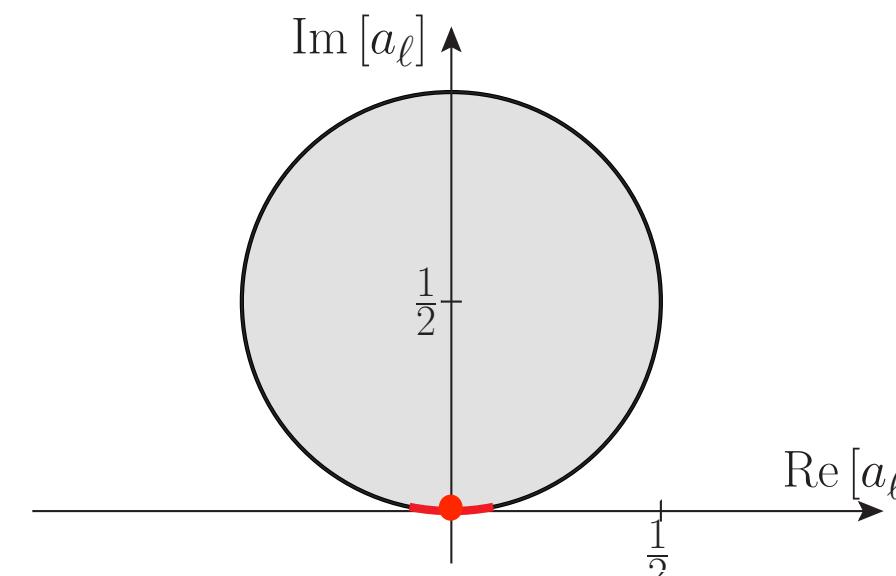


$$\mathcal{A}(s, t, u) = -\frac{M_H^2}{v^2} \frac{s}{s - M_H^2}$$

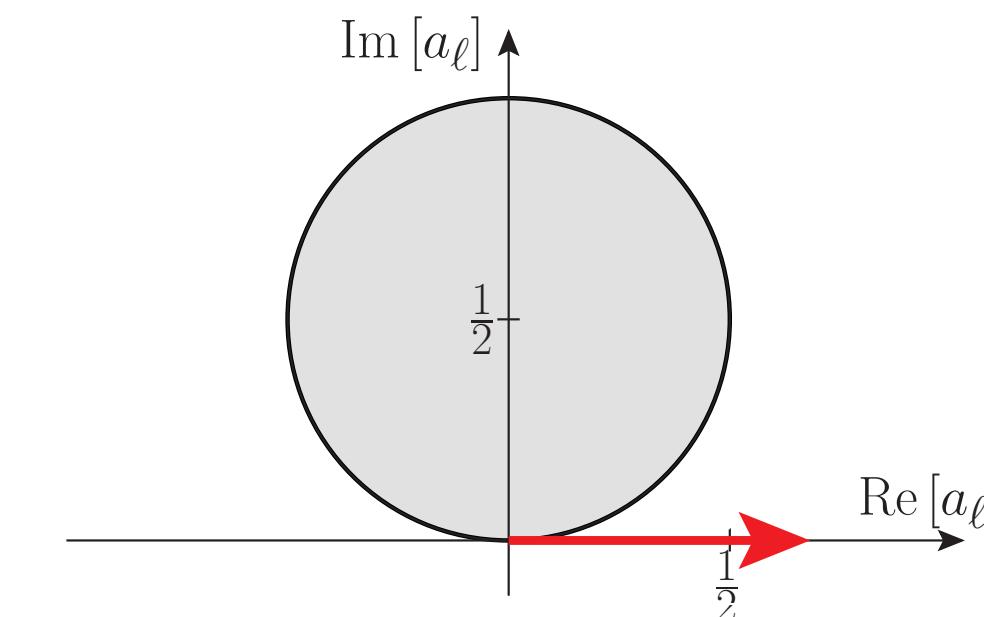
Unitarity:  $M_H \lesssim \sqrt{8\pi}v \sim 1.2 \text{ TeV}$

# Scenarios for New Physics in VBS

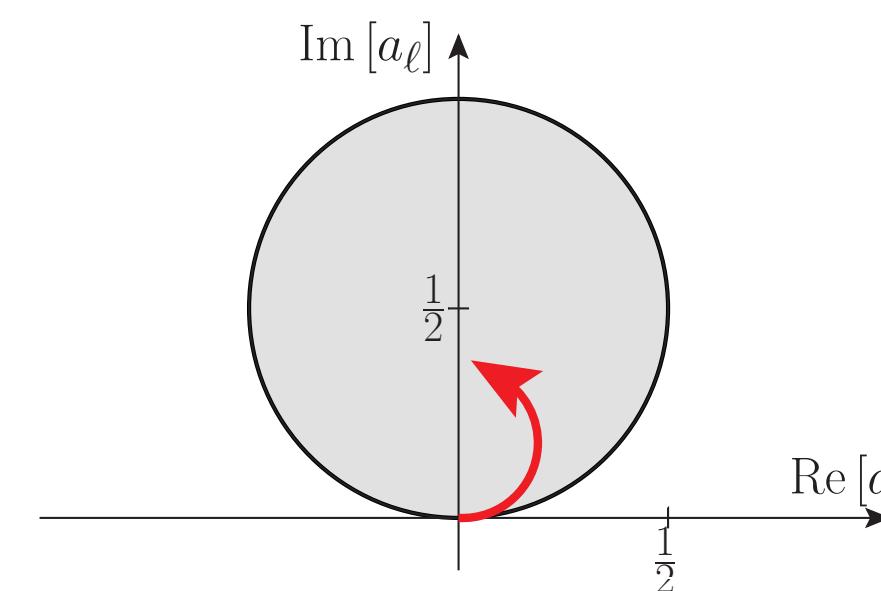
- I. SM or weakly coupled physics (e.g. 2HDM):  
amplitude remains close to origin



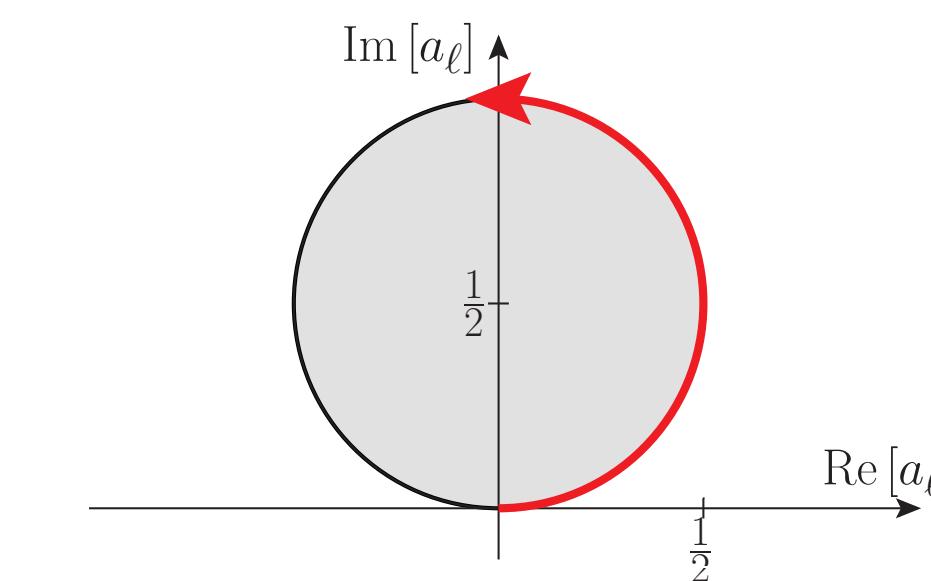
2. Rising amplitude (at least one dim-8 operator): rise beyond unitarity circle [unphys.],  
strongly interacting regime



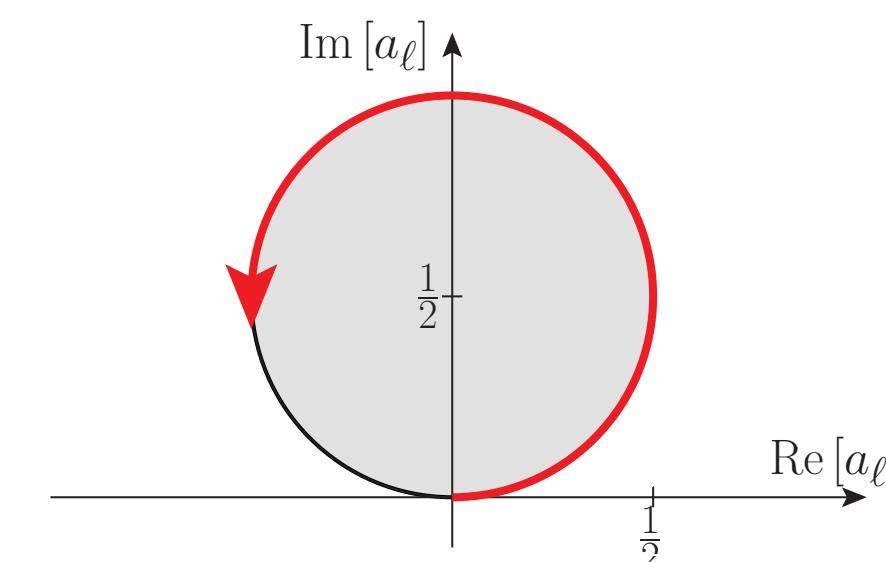
3. Inelastic channel opens (form-factor description):  
new channels open out, multi-boson final states



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



5. New resonance: amplitude turns over



# New Physics Searches in VBS - Struggling EFT description

- **Resonances in direct reach** (not clear: strongly interacting models [e.g.  $\sigma$  resonance])

- **Estimate of operator coefficients** (difficult for strongly coupled models)

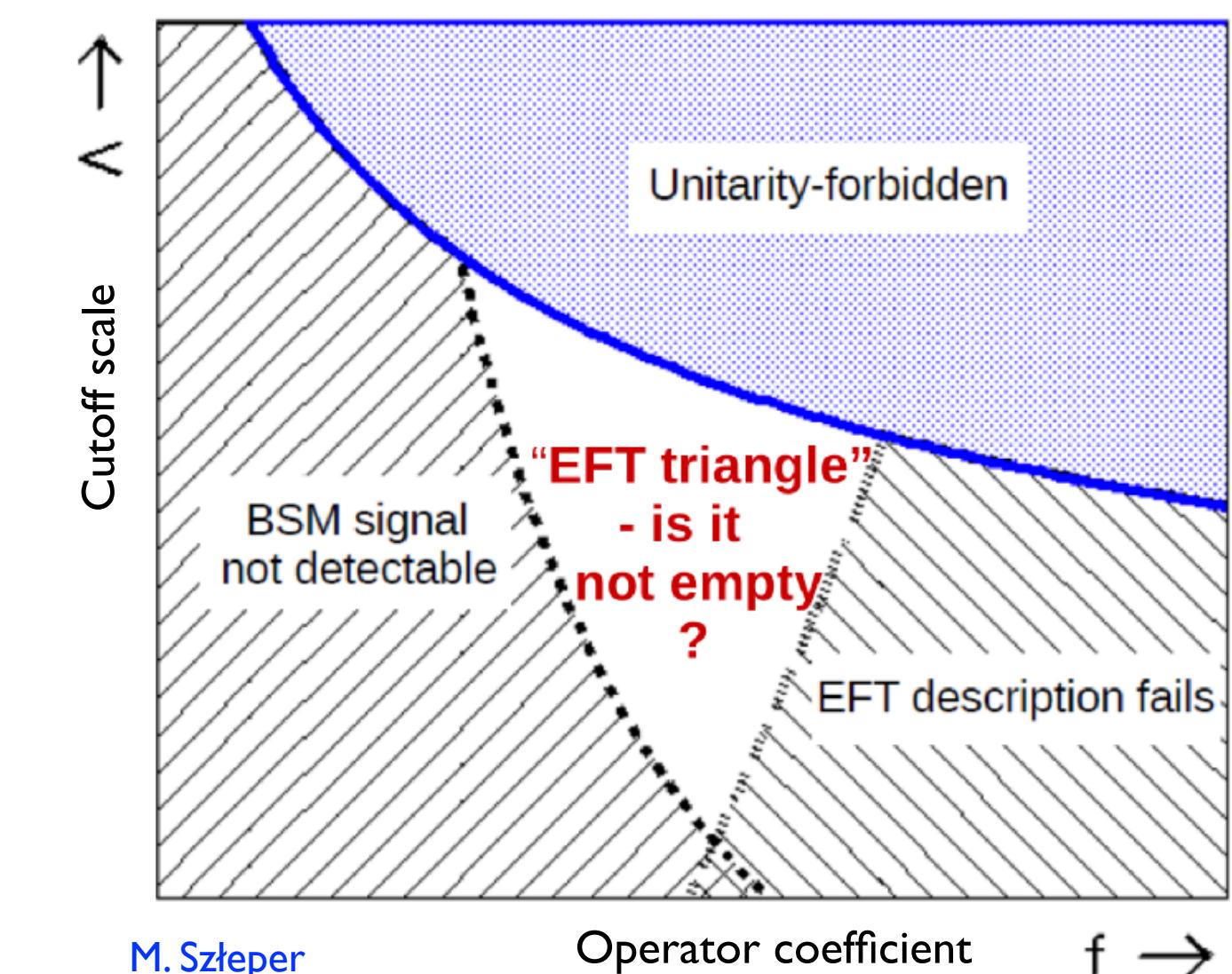
$$\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim |\mathcal{A}_{\text{dim-6}}|^2 \quad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}} \gtrsim |\mathcal{A}_{\text{dim-8}}|^2 \quad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim \mathcal{A}_{\text{SM}} \times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

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

- **Positivity constraints on operator coefficients (Analyticity: UV-complete or “swampland”)**

- **Size of coefficients:** dichotomy between validity and detectability (cf. also next slide)

- **EFT better/best[?] suited in intensity frontier** [example: Higgs / W / Z decays @  $\mathcal{O}(100 \text{ GeV})$ ]



M. Szleper

Operator coefficient

 $f \rightarrow$

# Plethora of unitarization procedures

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

unitarity bound (0th partial wave) at  $\Lambda_C$

no continuous transition beyond

might influence BDT/DNN training

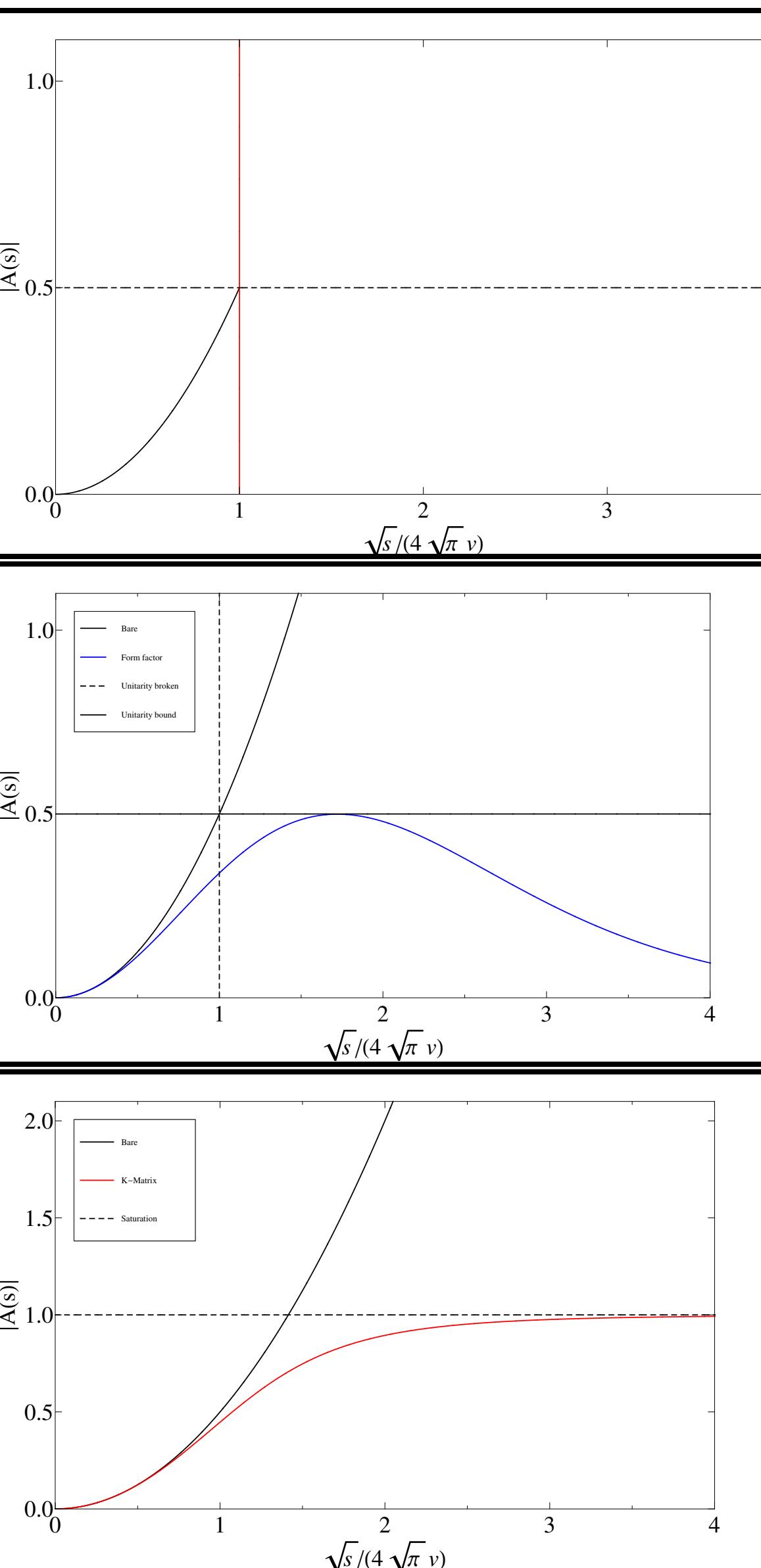
Form factor  $\frac{1}{\left(1 + \frac{s}{\Lambda_{FF}}\right)^n}$

Motivated from strong interactions

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

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

Saturation of unitarity: maximal event count, works also for complex ampl., no additional parameters



- Independent Amplitude Method (IAM)  
[Truong, 1988; Dobado/Herrero/Truong, 1990]
- Padé Method  
[Padé, 1890; Basdevant/Lee, 1970]
- N/D method  
[Chew/Mandelstam, 1960]
- Focus on correct descriptions of certain explicit (known) resonance channels
- Tied to chiral perturbation theory and QCD  $\Rightarrow$  more model-dependence
- Unitarization is not a tool to predict resonances



Never clip data!!!

# Unitarization: technicalities in a Monte Carlo

- Clebsch-Gordan decomposition into spin-isospin eigenamplitudes

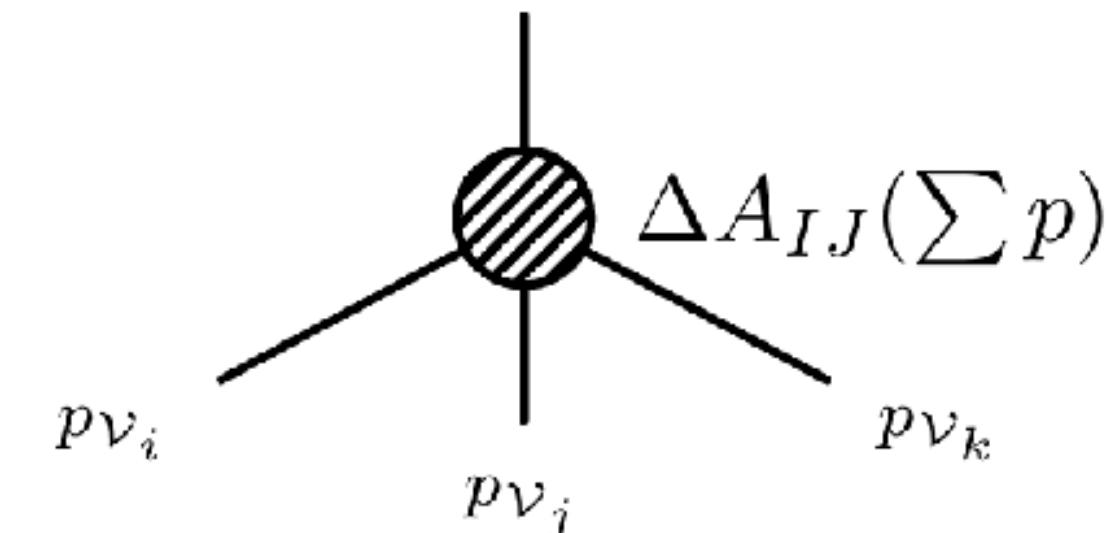
$$-p\nu_i - p\nu_i - p\nu_i$$

- Amplitudes should be modified only in s-channel configurations

$$\mathcal{A}(I = 0) = 3\mathcal{A}(s, t, u) + \mathcal{A}(t, s, u) + \mathcal{A}(u, s, t)$$

$$\mathcal{A}(I = 1) = \mathcal{A}(t, s, u) - \mathcal{A}(u, s, t)$$

$$\mathcal{A}(I = 2) = \mathcal{A}(t, s, u) + \mathcal{A}(u, s, t)$$



- Evaluate modified Feynman rules off-shell

- Scale that is used for the diboson system in s-channel setups:  $\sqrt{\hat{s}_{VV}}$

# Unitarization: technicalities in a Monte Carlo

• Clebsch-Gordan decomposition into spin-isospin eigenamplitudes

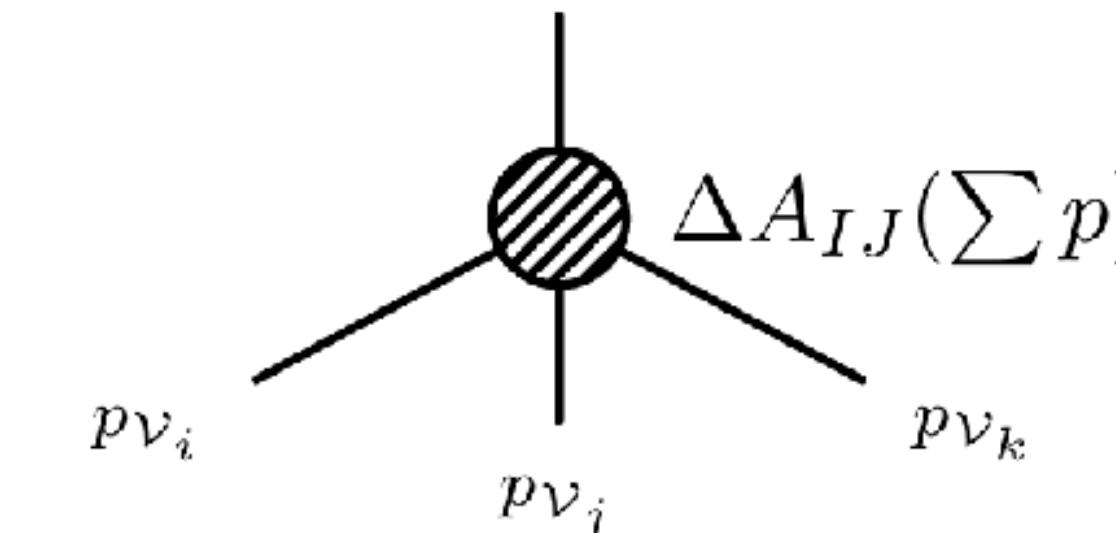
$$-p\nu_i - p\nu_i - p\nu_i$$

• Amplitudes should be modified only in s-channel configurations

$$\mathcal{A}(I=0) = 3\mathcal{A}(s,t,u) + \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)$$

$$\mathcal{A}(I=1) = \mathcal{A}(t,s,u) - \mathcal{A}(u,s,t)$$

$$\mathcal{A}(I=2) = \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)$$



• Evaluate modified Feynman rules off-shell

• Scale that is used for the diboson system in s-channel setups:  $\sqrt{\hat{s}_{VV}}$

Use spin-isospin eigenamplitudes **exclusive in helicities**:  $\mathcal{A}_0(s,t,u; \lambda)$

Can be obtained by using **Wigner's d-functions** [Wigner, 1931]  $\lambda = (\lambda_1, \lambda_2, \lambda_3, \lambda_4)$

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

Extract all partial waves:

$$A_{ij}(s; \lambda) / (g^4 s^2) =$$

$$(c_0 F_{T_0} + c_1 F_{T_1} + c_2 F_{T_2})$$

Corrections for off-shell vectors: important [Perez/Sekulla/Zeppenfeld, 1807.02707]

Implementation in WHIZARD takes leading corrections into account

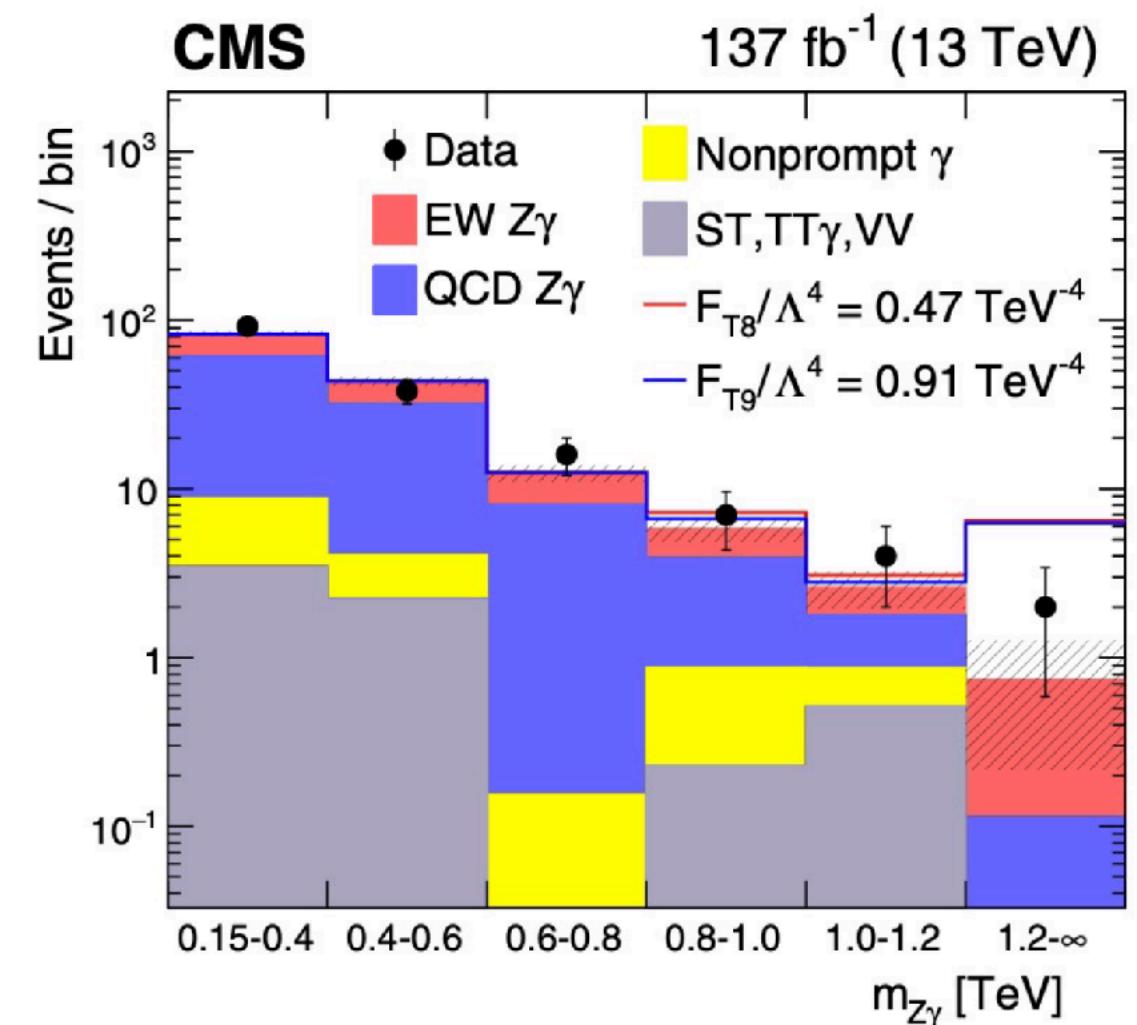
$$\lambda = \lambda_1 - \lambda_2 \quad \lambda' = \lambda_3 - \lambda_4$$

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

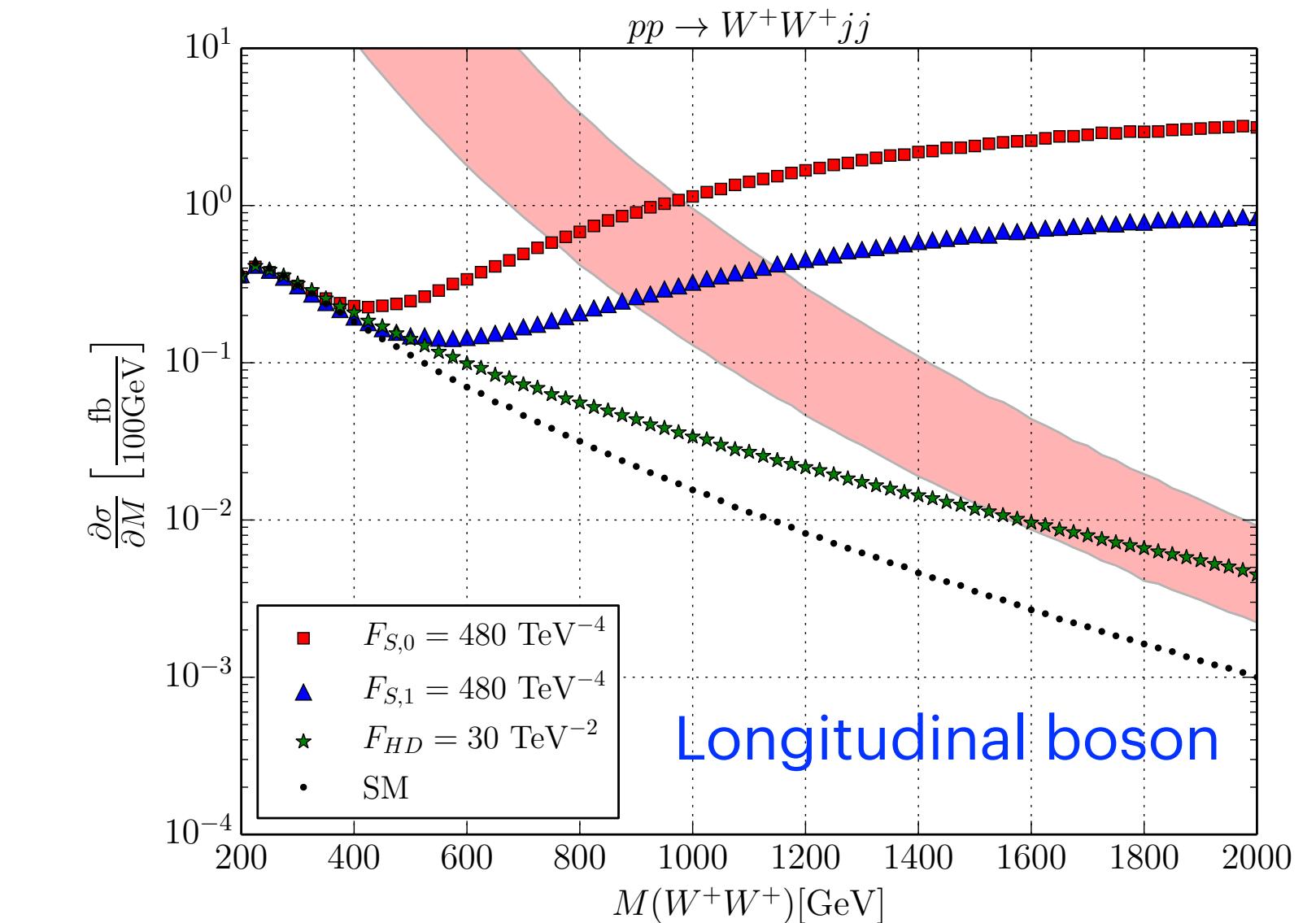
Braß/Fleper/Kilian/JRR/Sekulla, 1807.02512

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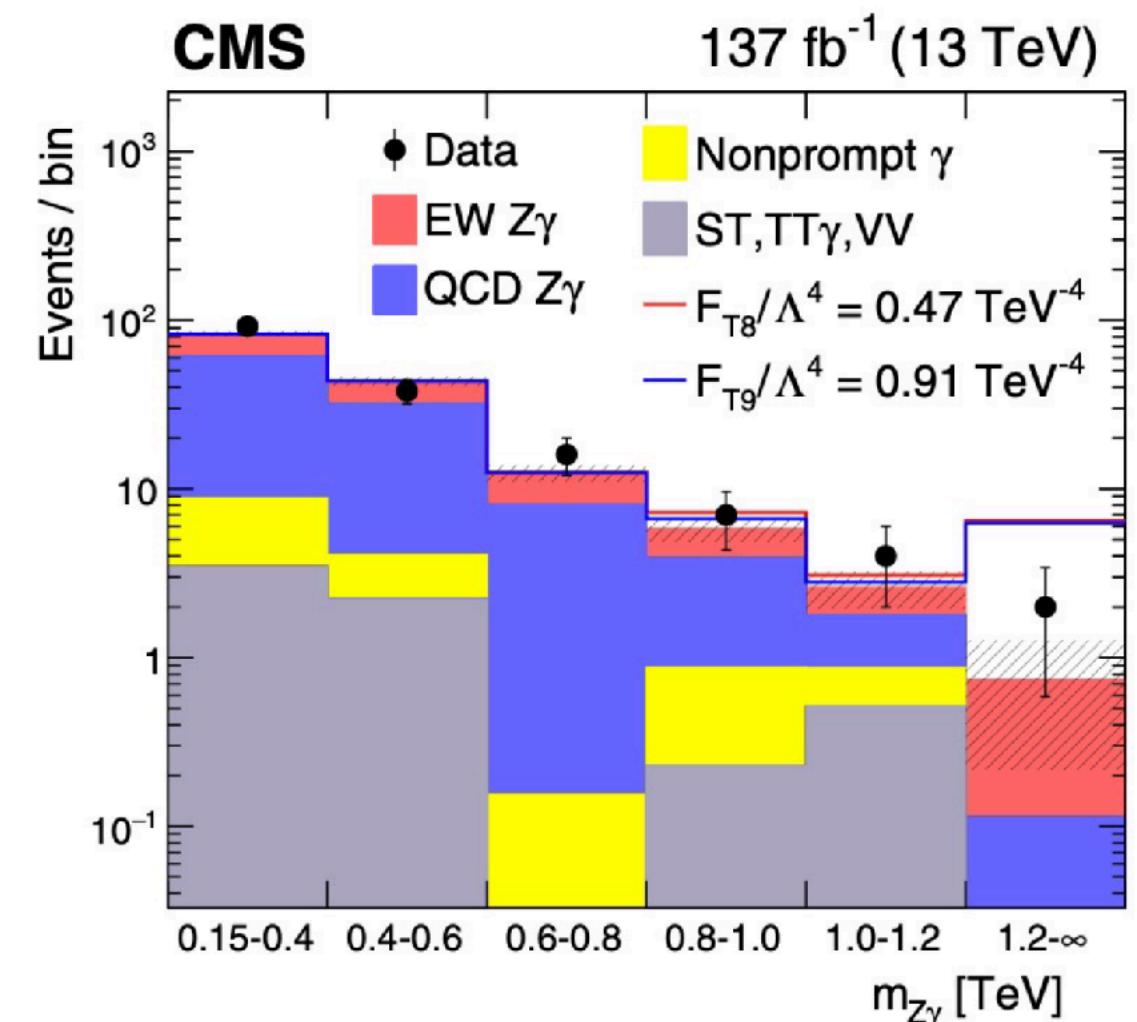


General cuts:

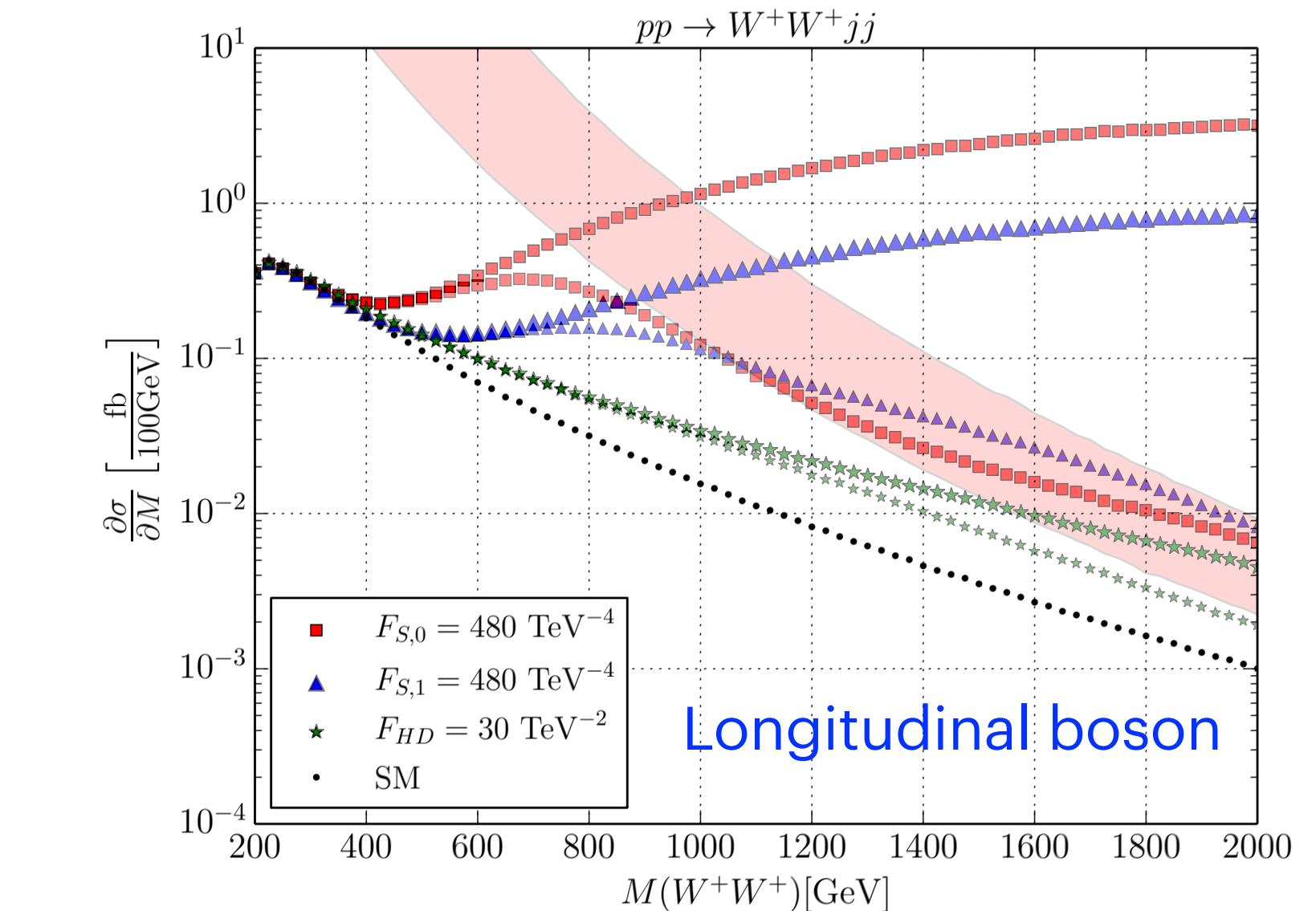
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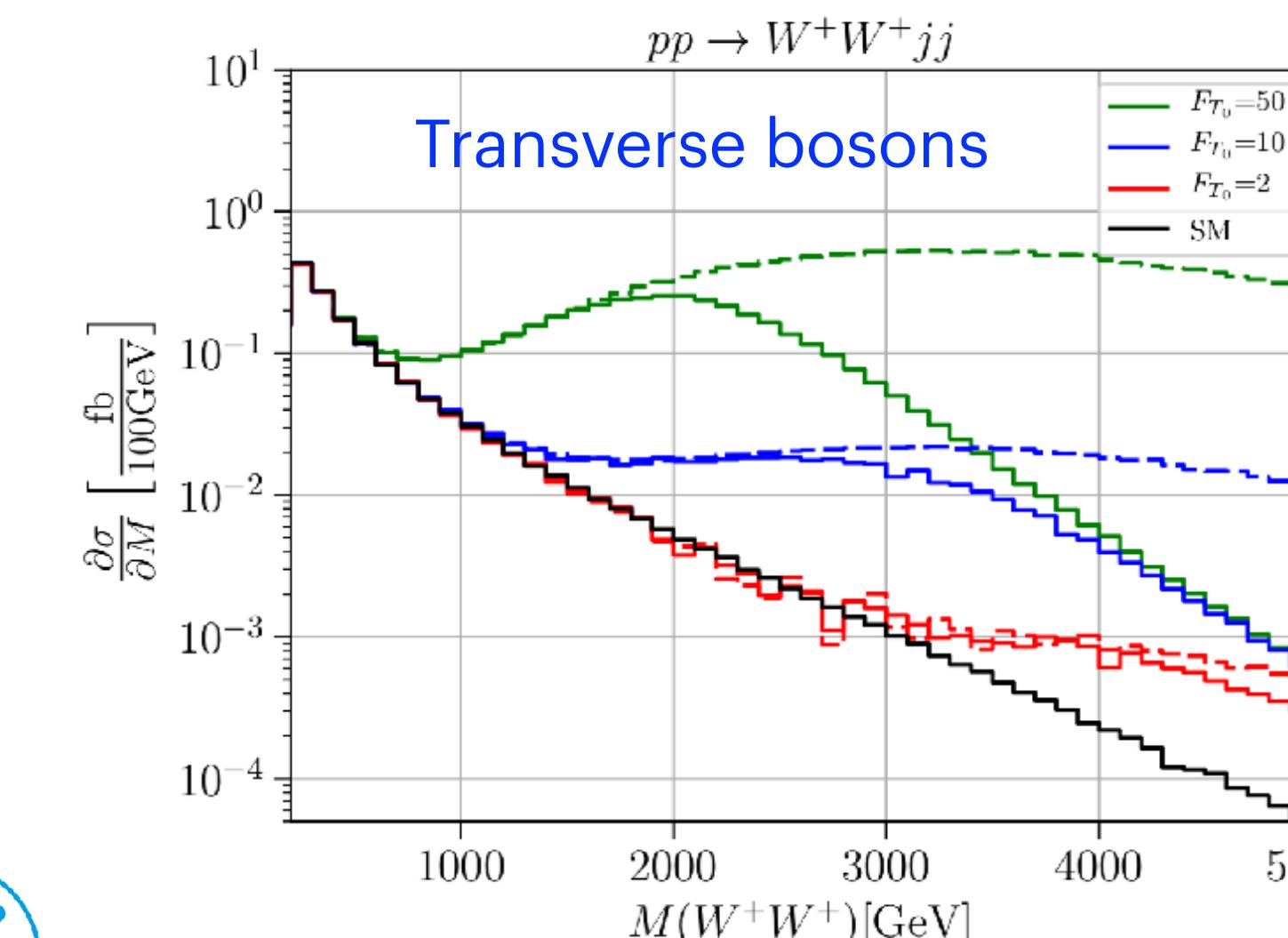
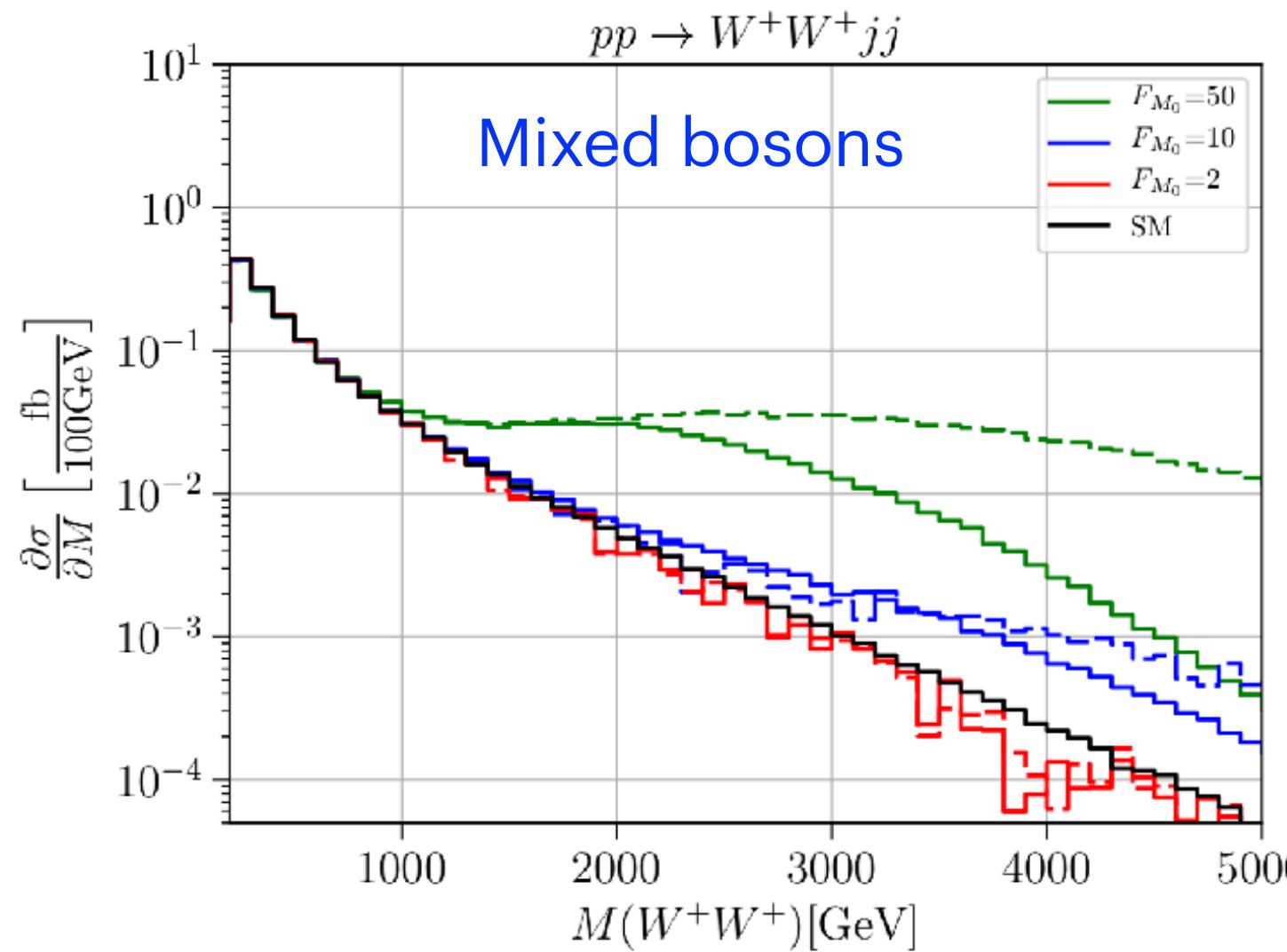


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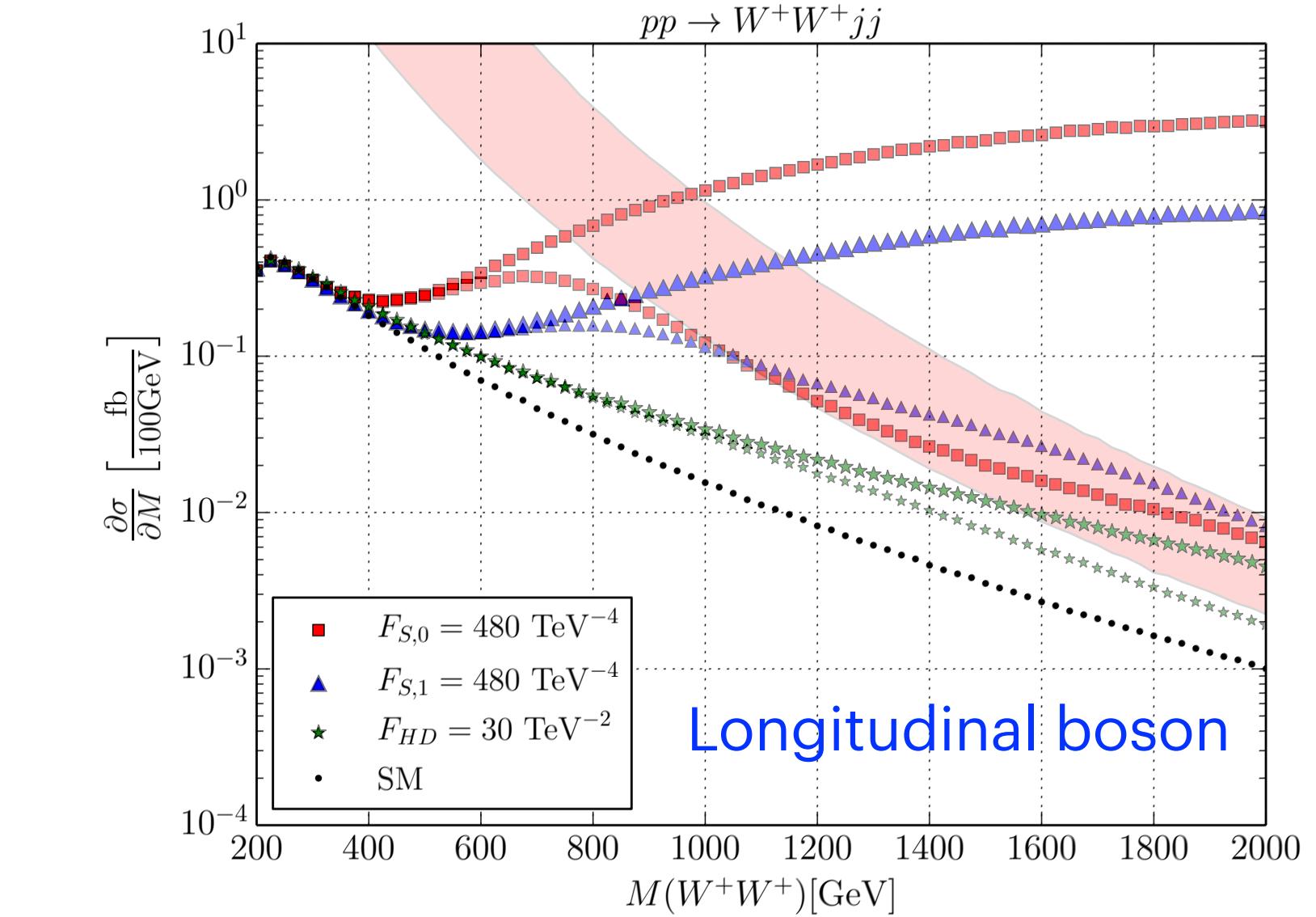
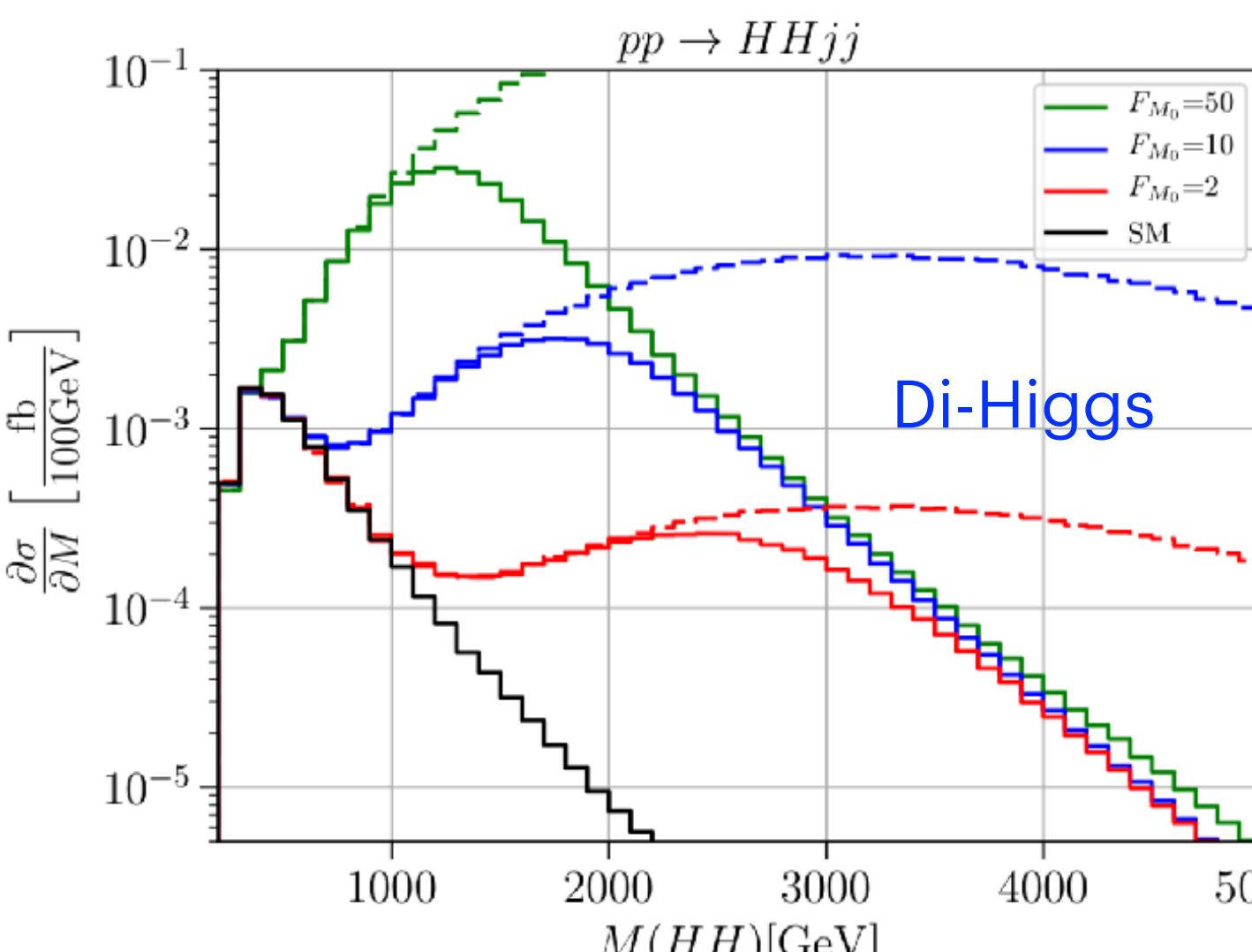
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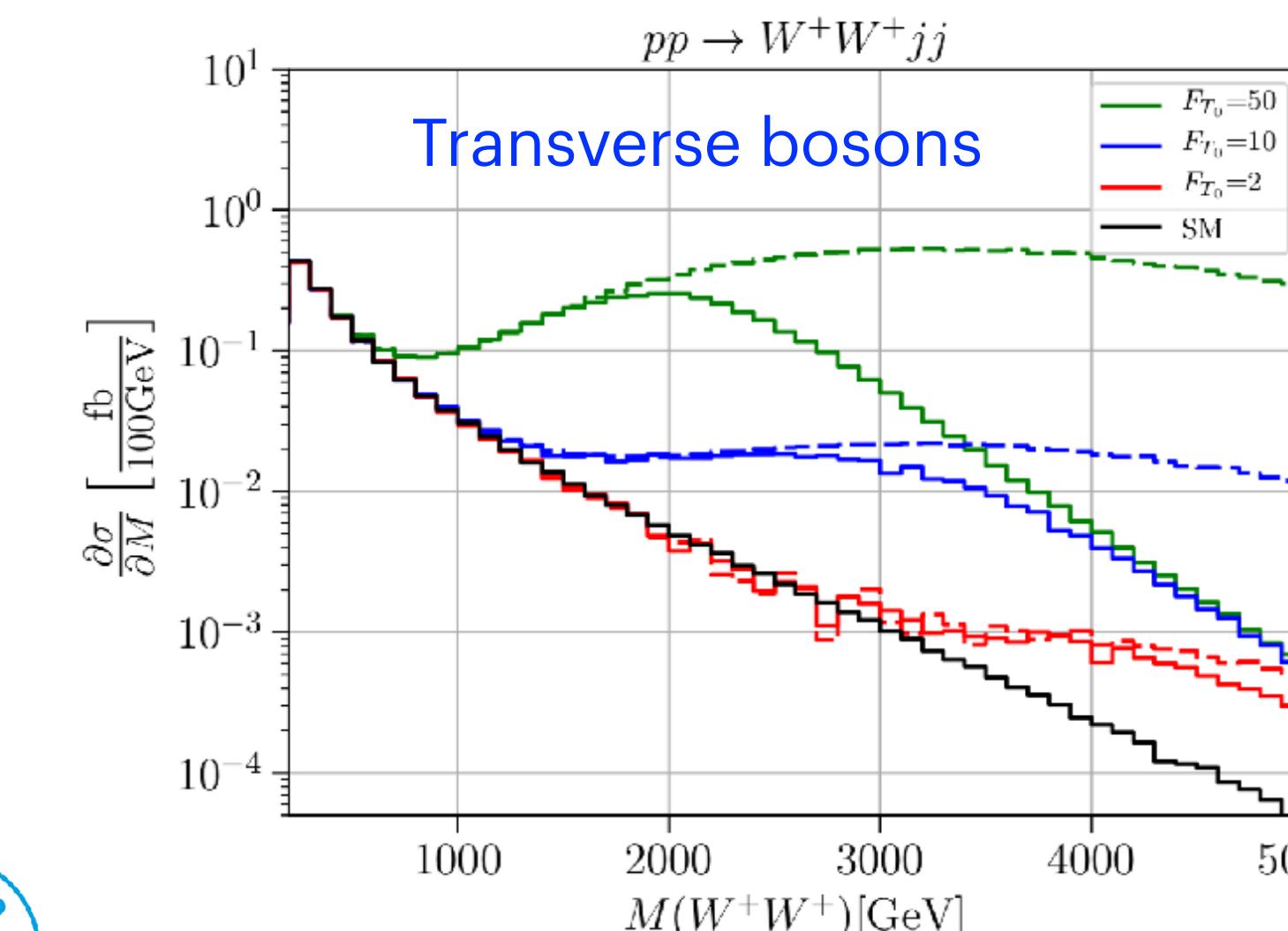
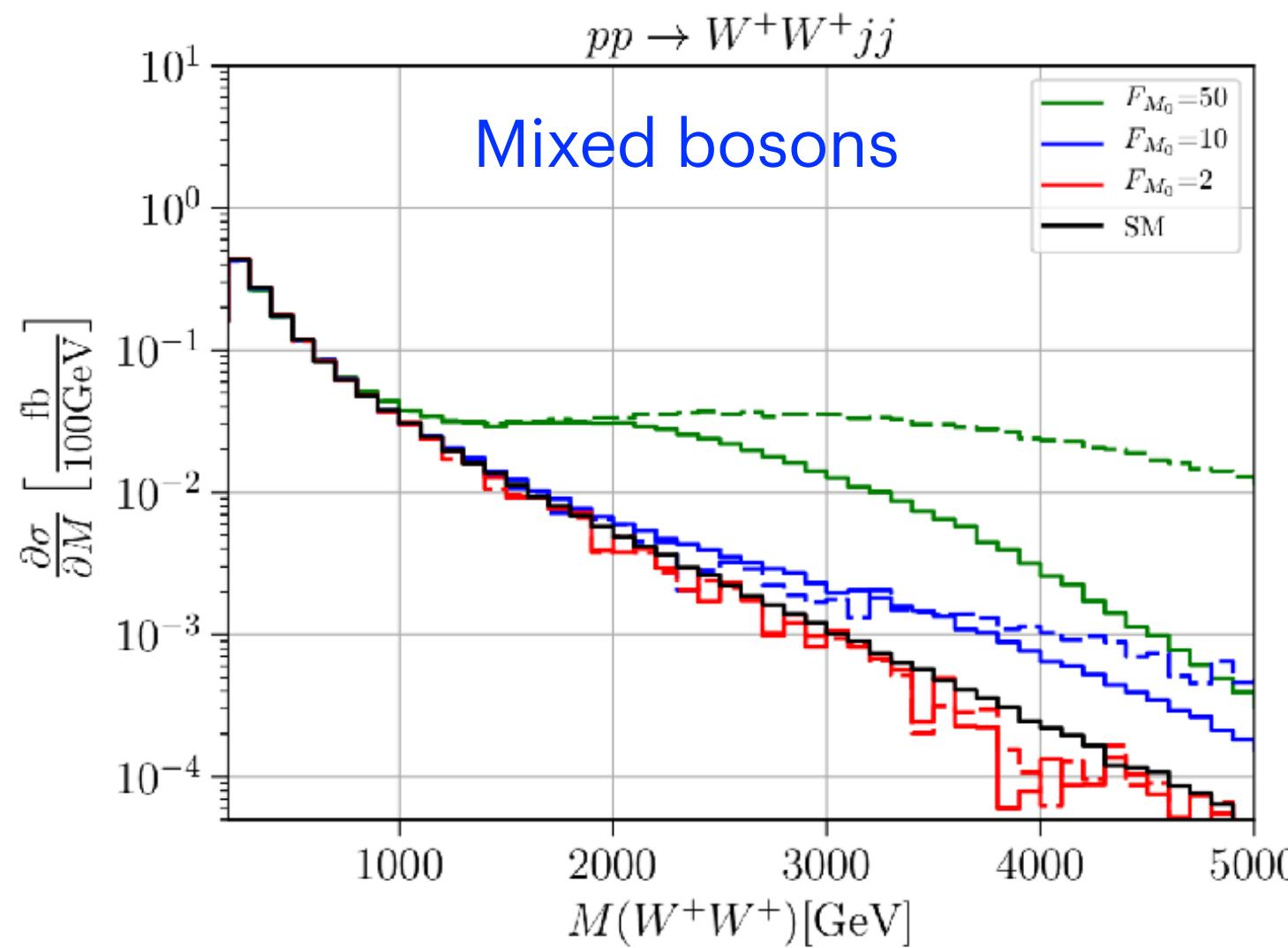
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Kilian/Ohl/JRR/Sekulla, 1511.00022

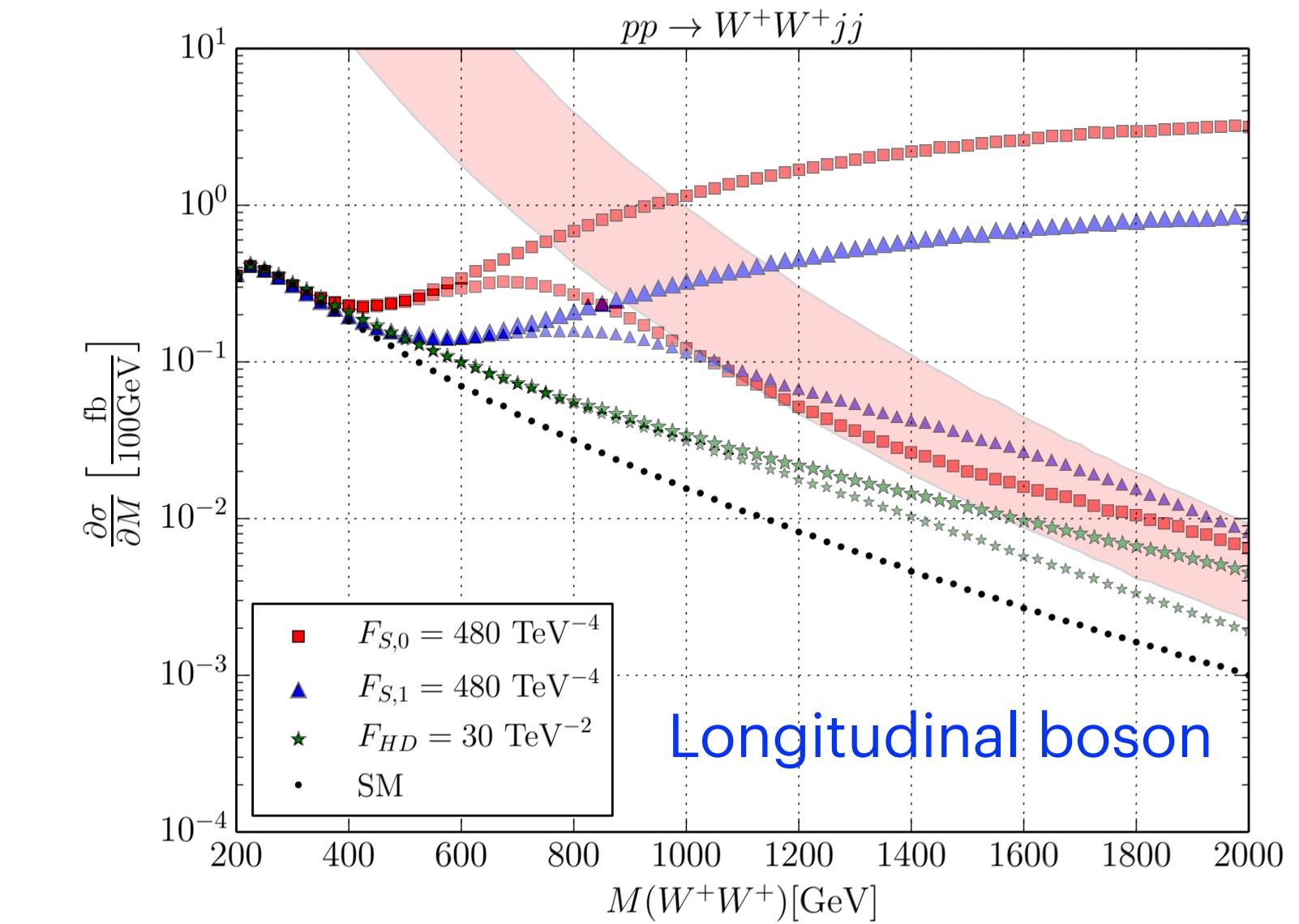
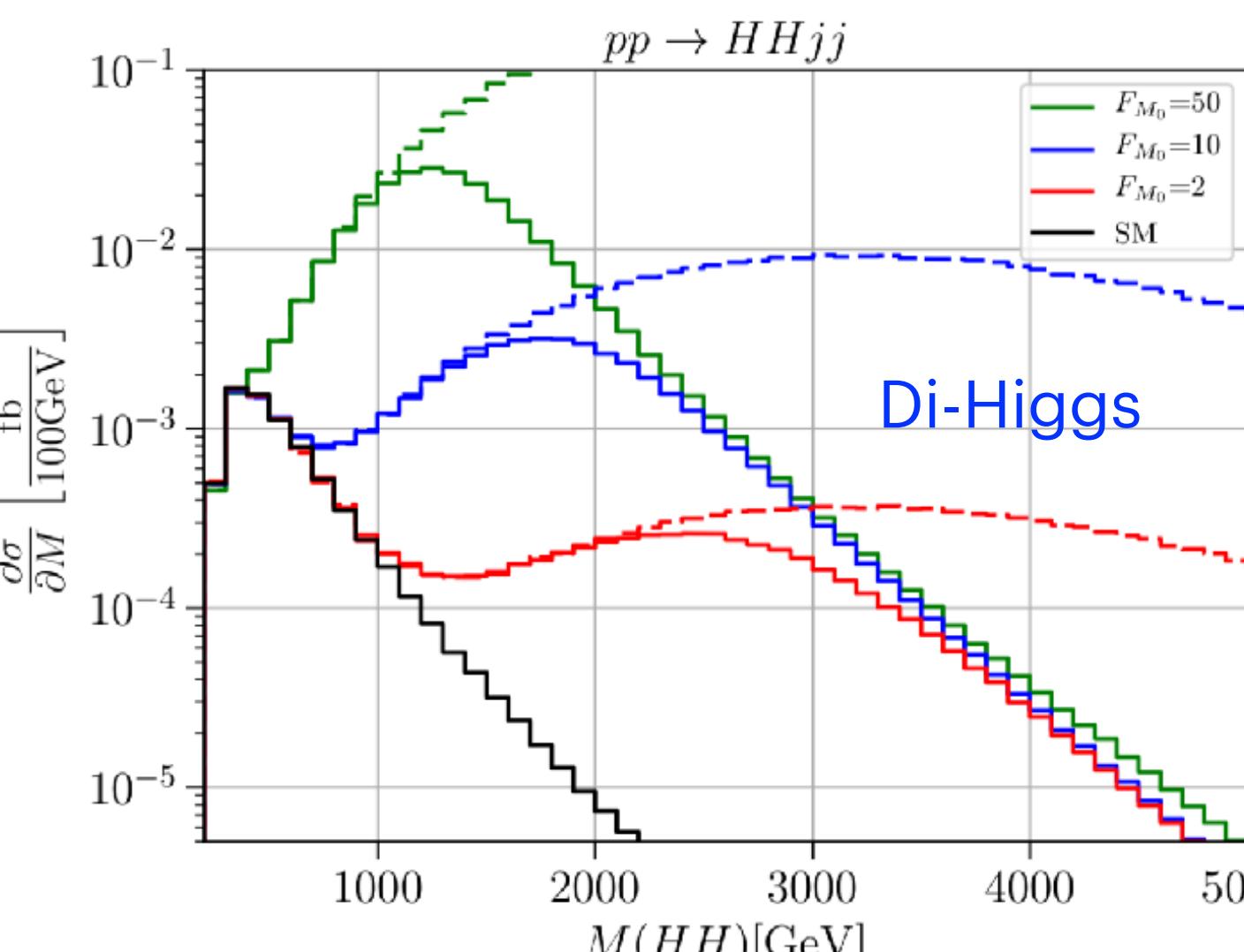
Seminar, University of Warsaw, 7.2.2023

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Much more leeway for new physics in transversal gauge bosons and di-Higgs ; longitudinal bosons much closer to unitarity limit

Kilian/Ohl/JRR/Sekulla, 1511.00022

Seminar, University of Warsaw, 7.2.2023

# Simplified New Physics Models for VBS

- Semi-model-independent: simplified models
- Consider all possible EW diboson resonances
- Very few parameters:  $(M_V, g_{VV})$ ,  $(M_V, \Gamma_{[VV]})$
- Distinguish weakly/strongly-coupled models

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

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	$\sigma^0$ (Higgs singlet?)	$\omega^0$ ( $\gamma'/Z'$ ?)	$f^0$ (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ ( $W'/Z'$ ?)	$a^\pm, a^0$
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...	...	...

Translation into Wilson coefficient below resonance

	$\sigma$	$\phi$	$f$	$X$
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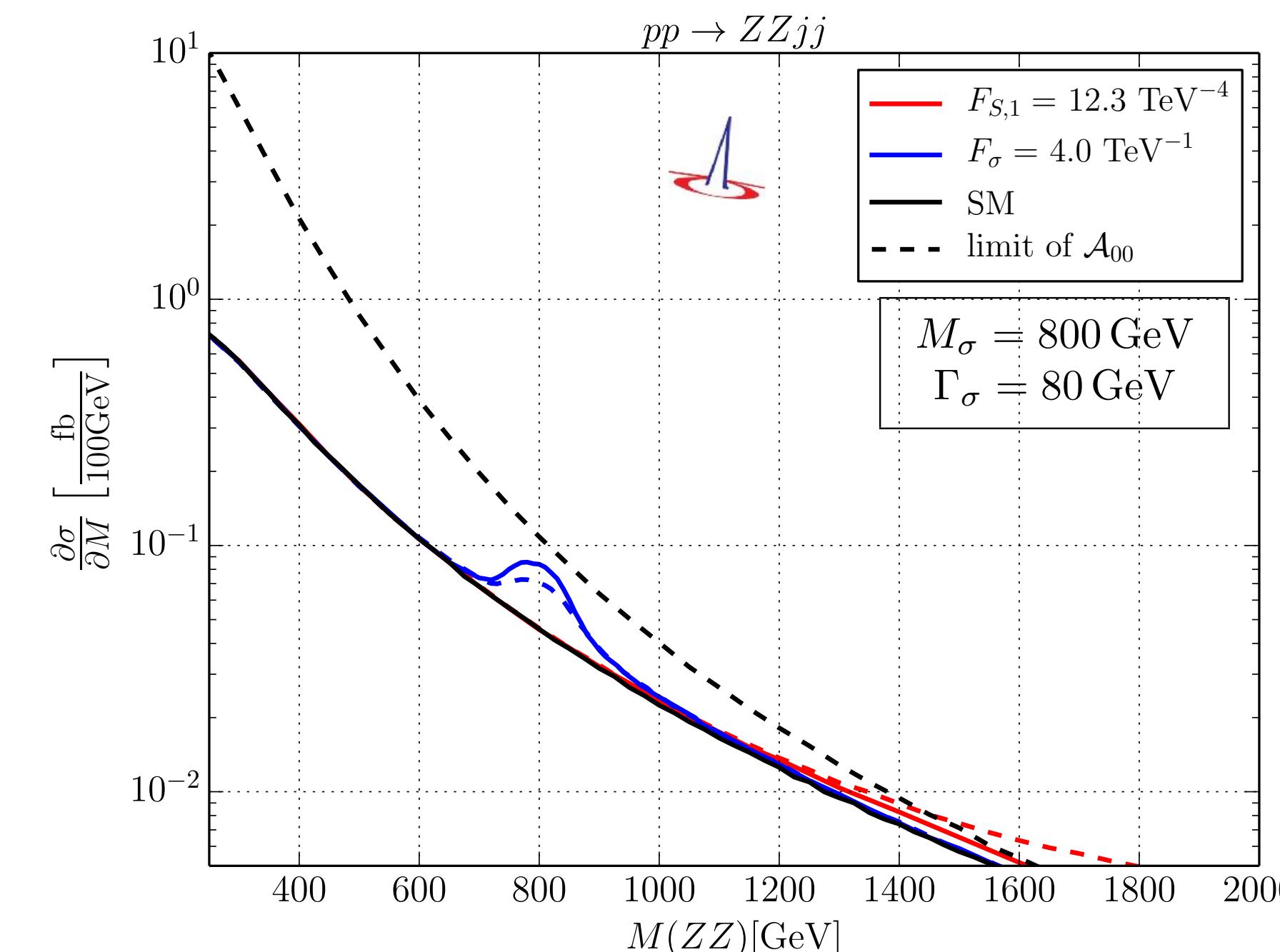
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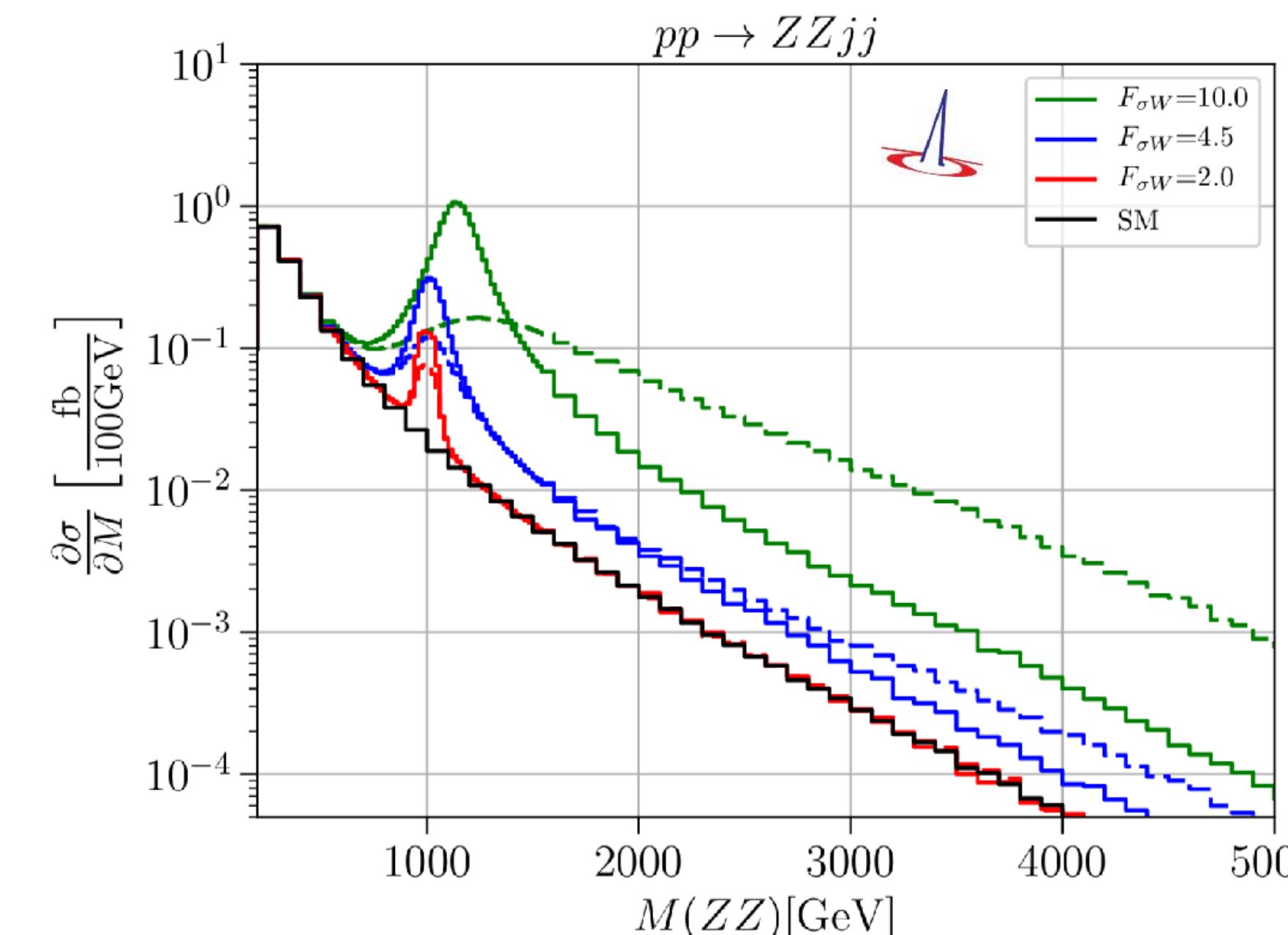
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- EFT fails at resonance
- EFT describes rise of resonance
- Unitarization applied
- Tensor resonances better visible than scalars

## Tensor resonances

# Tensor Resonances (in VBS)

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

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

💡 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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- 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

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

- $f^{\mu\nu}$ : on-shell  $f^{\mu\nu}$
- $\phi$ :  $\partial_\mu \partial_\nu f^{\mu\nu}$
- $A^\mu$ :  $\partial_\nu f^{\mu\nu}$
- $\sigma$ :  $f_\mu{}^\mu$

Gauge fixing:  $\sigma = -\phi$

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

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$$\begin{aligned}\mathcal{L}_{FP} = & \frac{1}{2} \partial_\alpha f_{\mu\nu} \partial^\alpha f^{\mu\nu} - \frac{1}{2} m^2 f_{\mu\nu} f^{\mu\nu} - \frac{1}{2} \partial_\alpha f_\mu^\mu \partial^\alpha f_\nu^\nu + \frac{1}{2} m^2 f_\mu^\mu f_\nu^\nu \\ & - \partial^\alpha f_{\alpha\mu} \partial_\beta f^{\beta\mu} - f_\alpha^\alpha \partial^\mu \partial^\nu f_{\mu\nu} + f_{\mu\nu} J_f^{\mu\nu}\end{aligned}$$

- 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 (in VBS)

## Tensor resonances

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

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

- $f^{\mu\nu}$ : on-shell  $f^{\mu\nu}$
- $\phi$ :  $\partial_\mu \partial_\nu f^{\mu\nu}$
- $A^\mu$ :  $\partial_\nu f^{\mu\nu}$
- $\sigma$ :  $f_\mu^\mu$

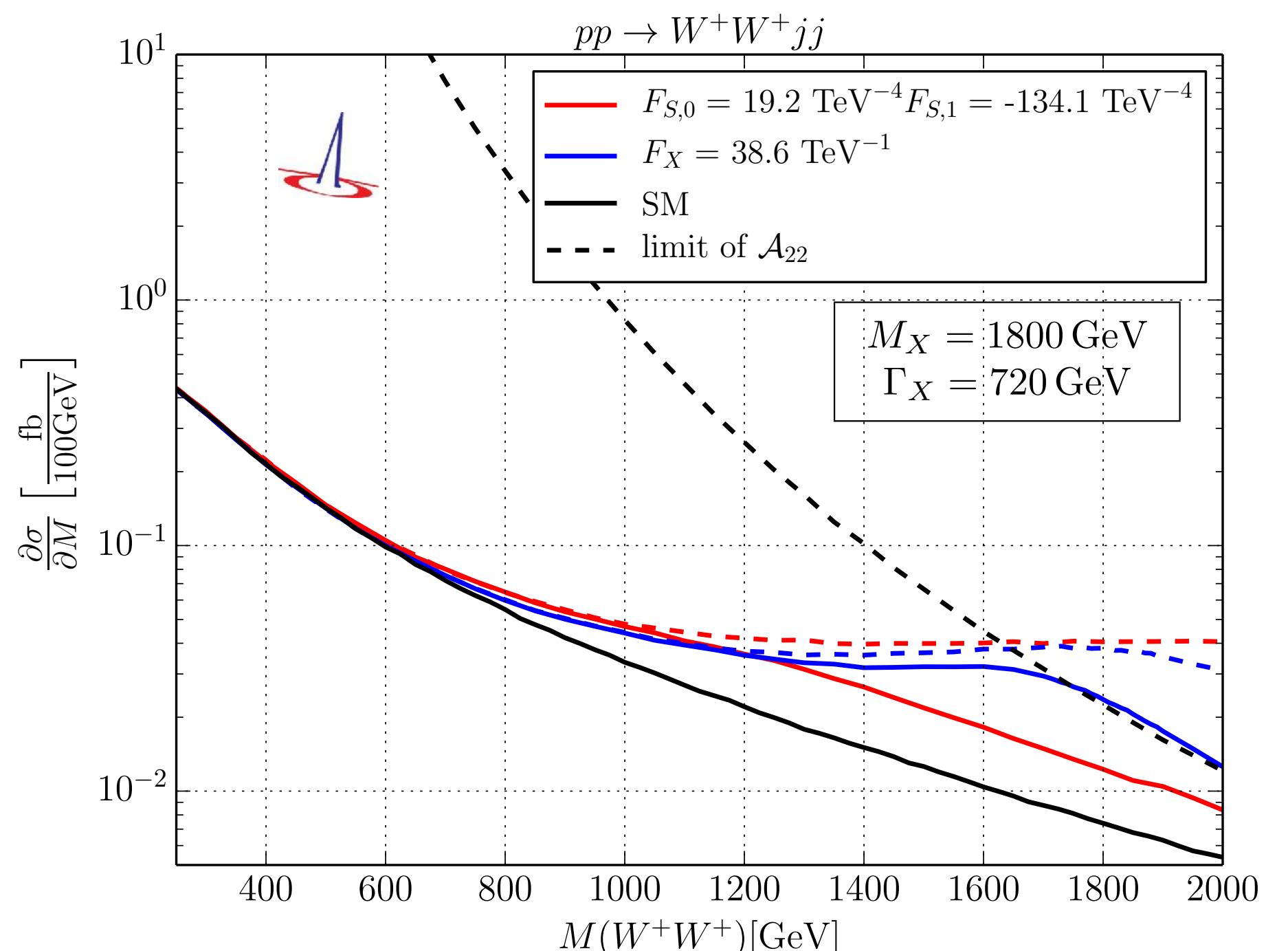
Gauge fixing:  $\sigma = -\phi$

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

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# Differential Spectra in VBS

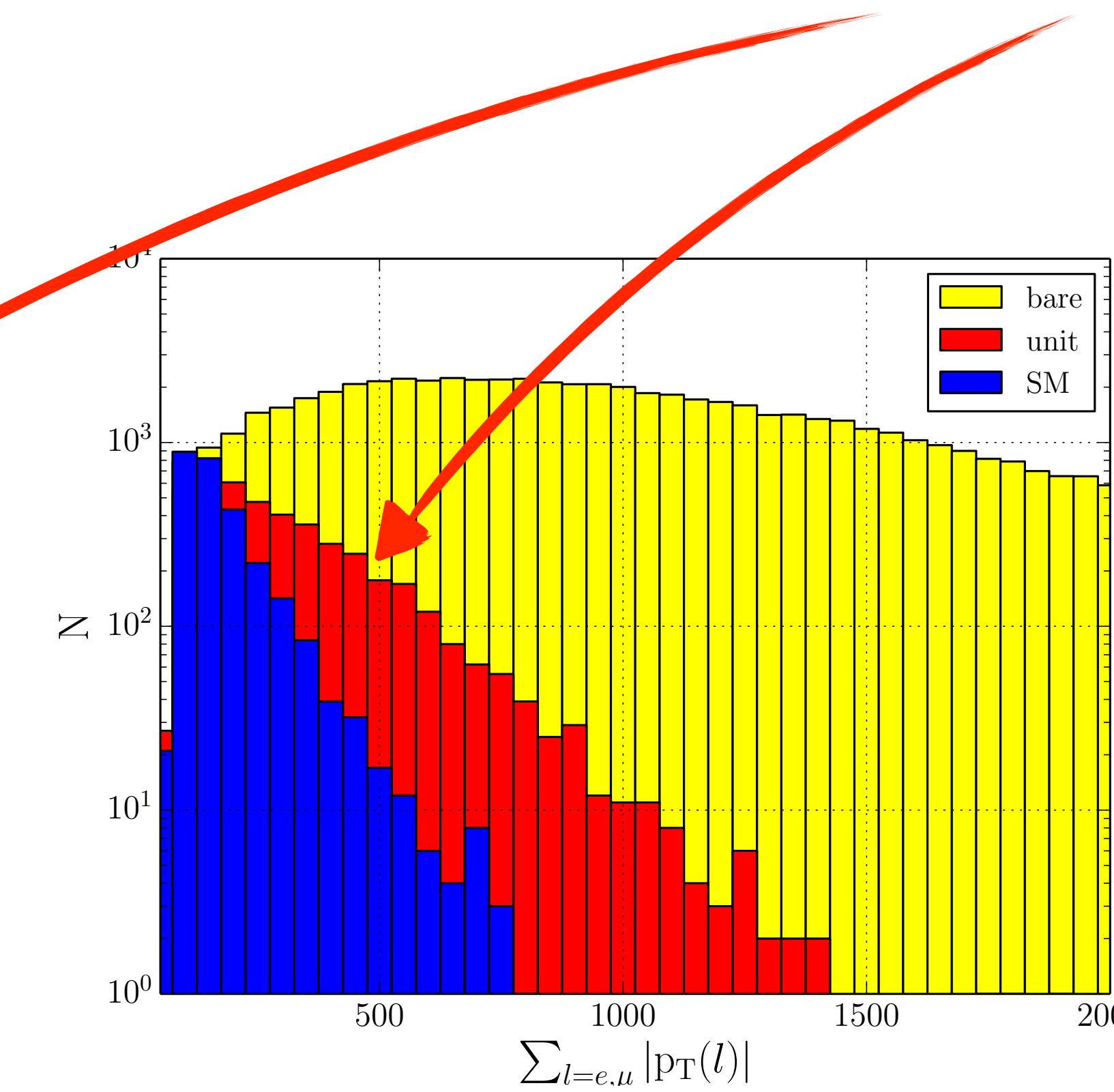
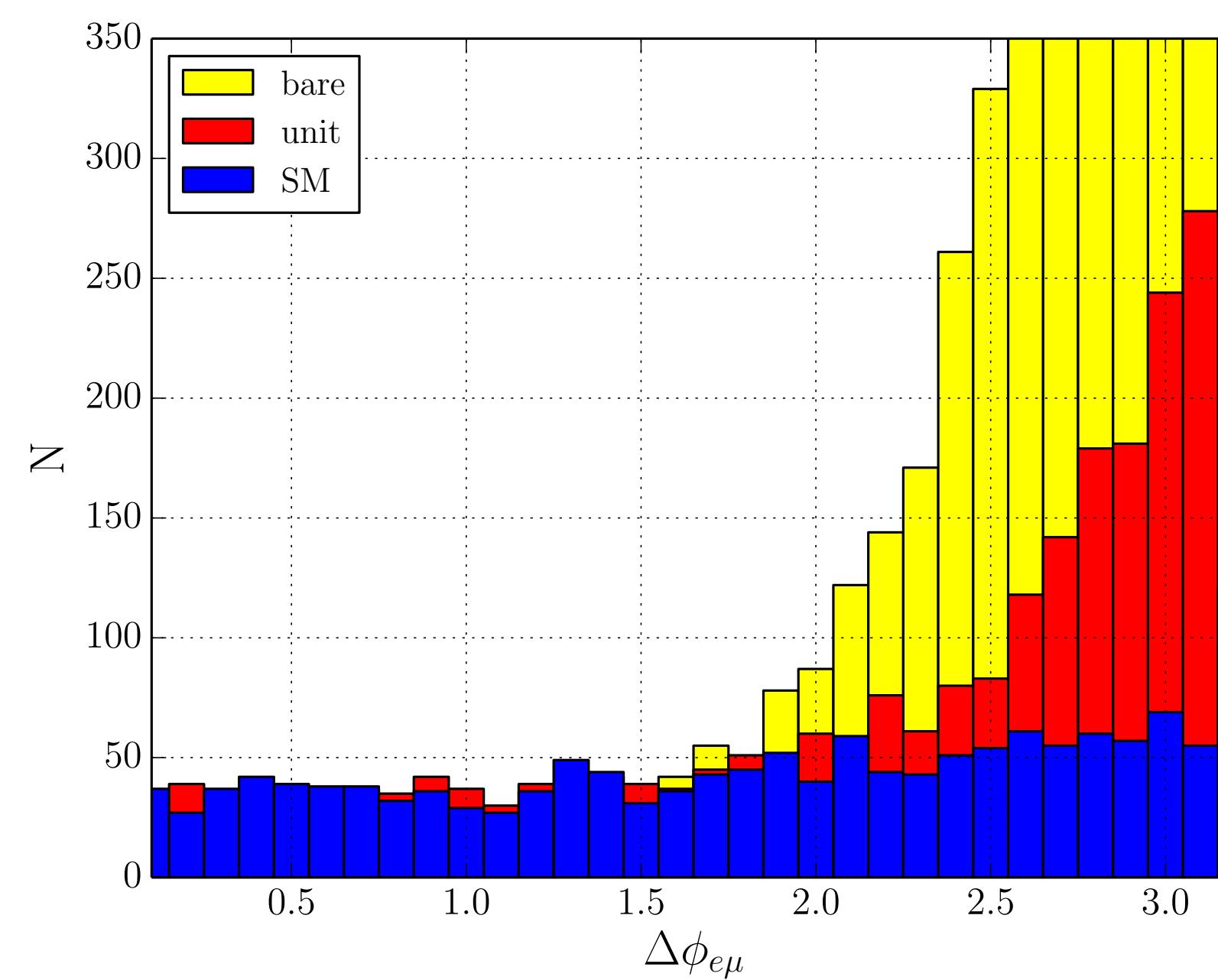
24 / 31

$pp \rightarrow e^+ \mu^+ \nu_e \nu_\mu jj$      $\sqrt{s} = 14 \text{ TeV}$      $\mathcal{L} = 1 \text{ ab}^{-1}$

Kilian/Ohl/JRR/Sekulla, 1408.6207

$$F_{S,1} = 480 \text{ TeV}^{-4}$$

distribution maximally possible in any QFT



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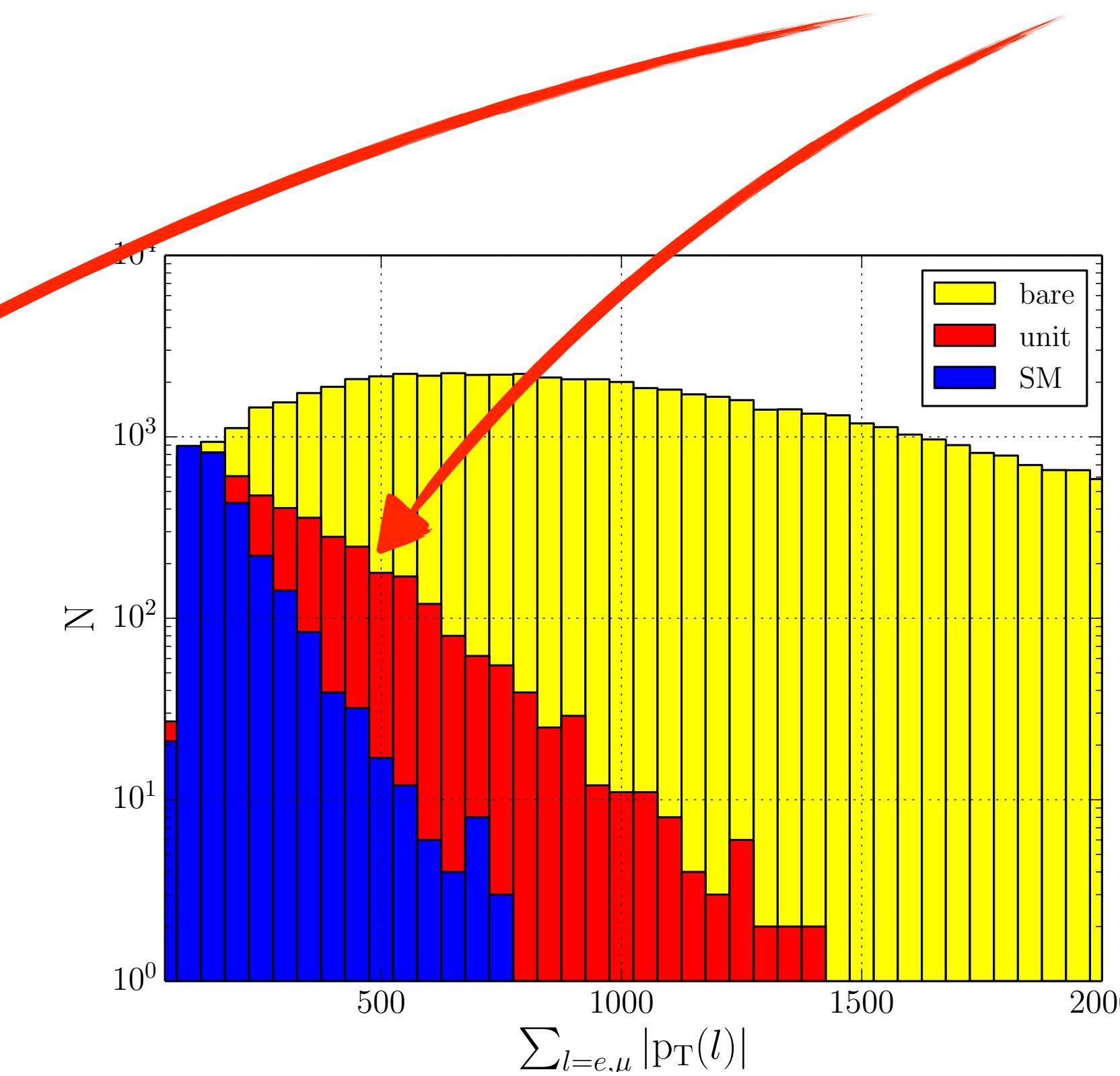
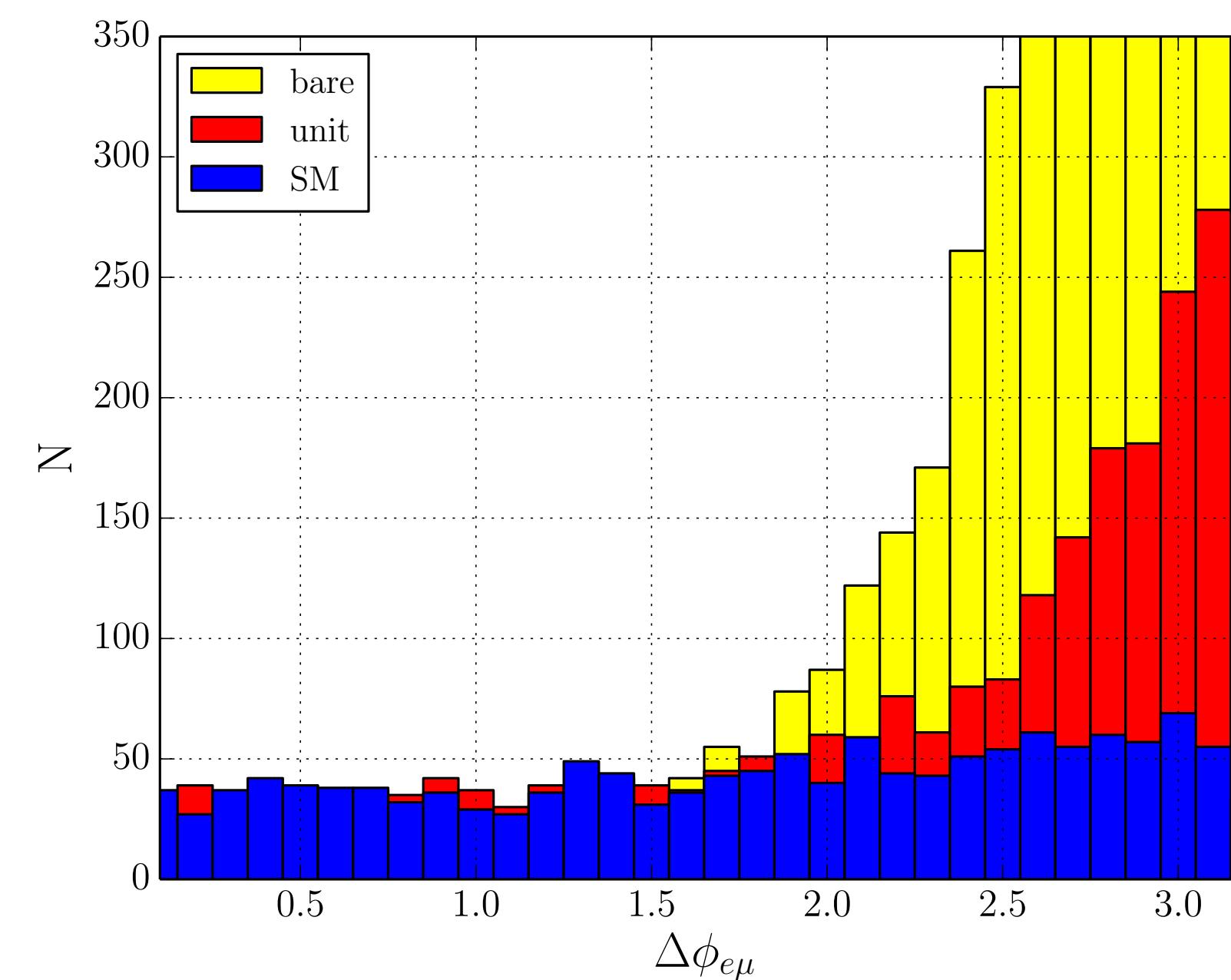
Kilian/Ohl/JRR/Sekulla, 1408.6207

$$\mathcal{L}_{S,0} = F_{S,0} \frac{v^4}{16} \text{Tr} [\mathbf{V}_\mu \mathbf{V}_\nu] \text{Tr} [\mathbf{V}^\mu \mathbf{V}^\nu]$$

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

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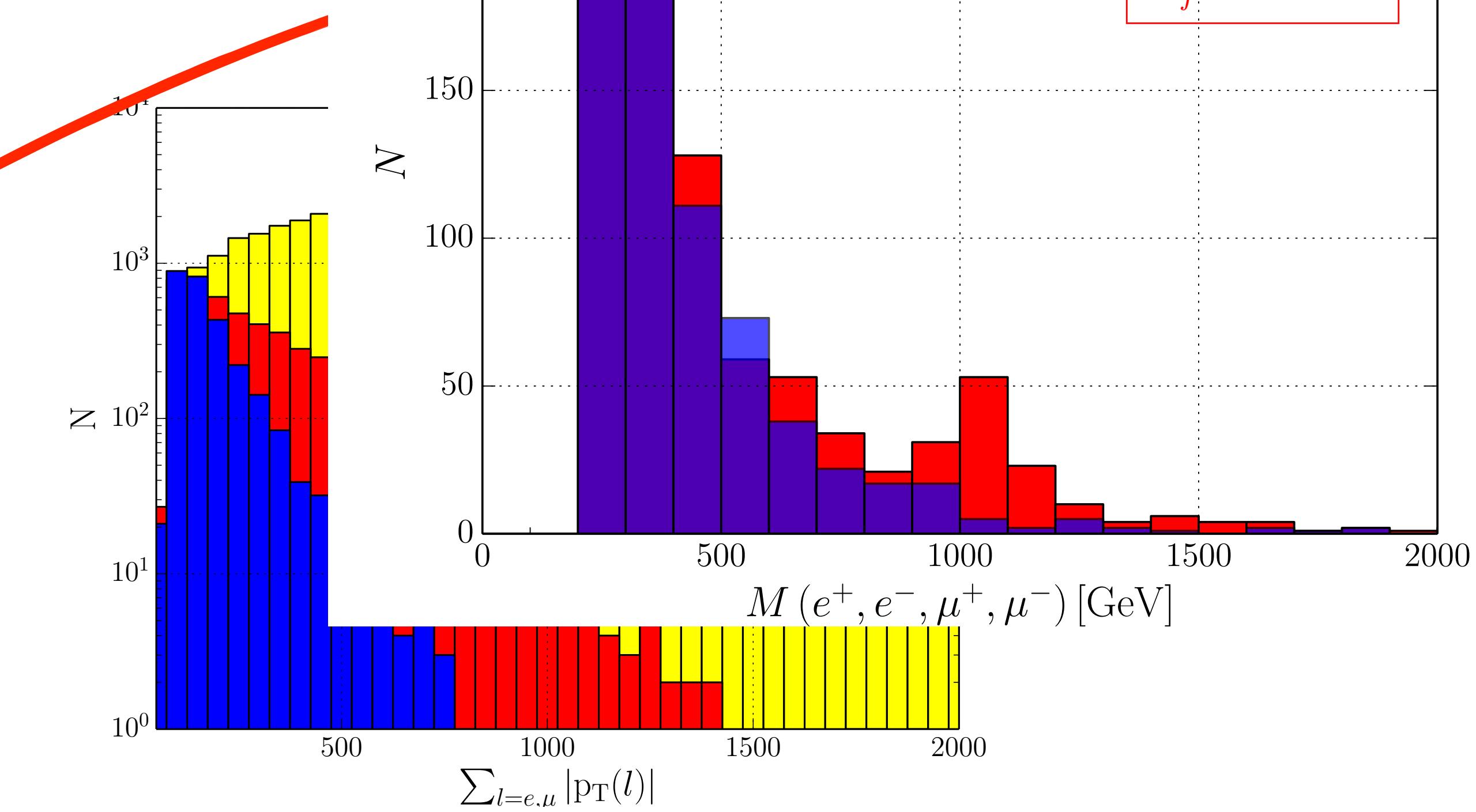
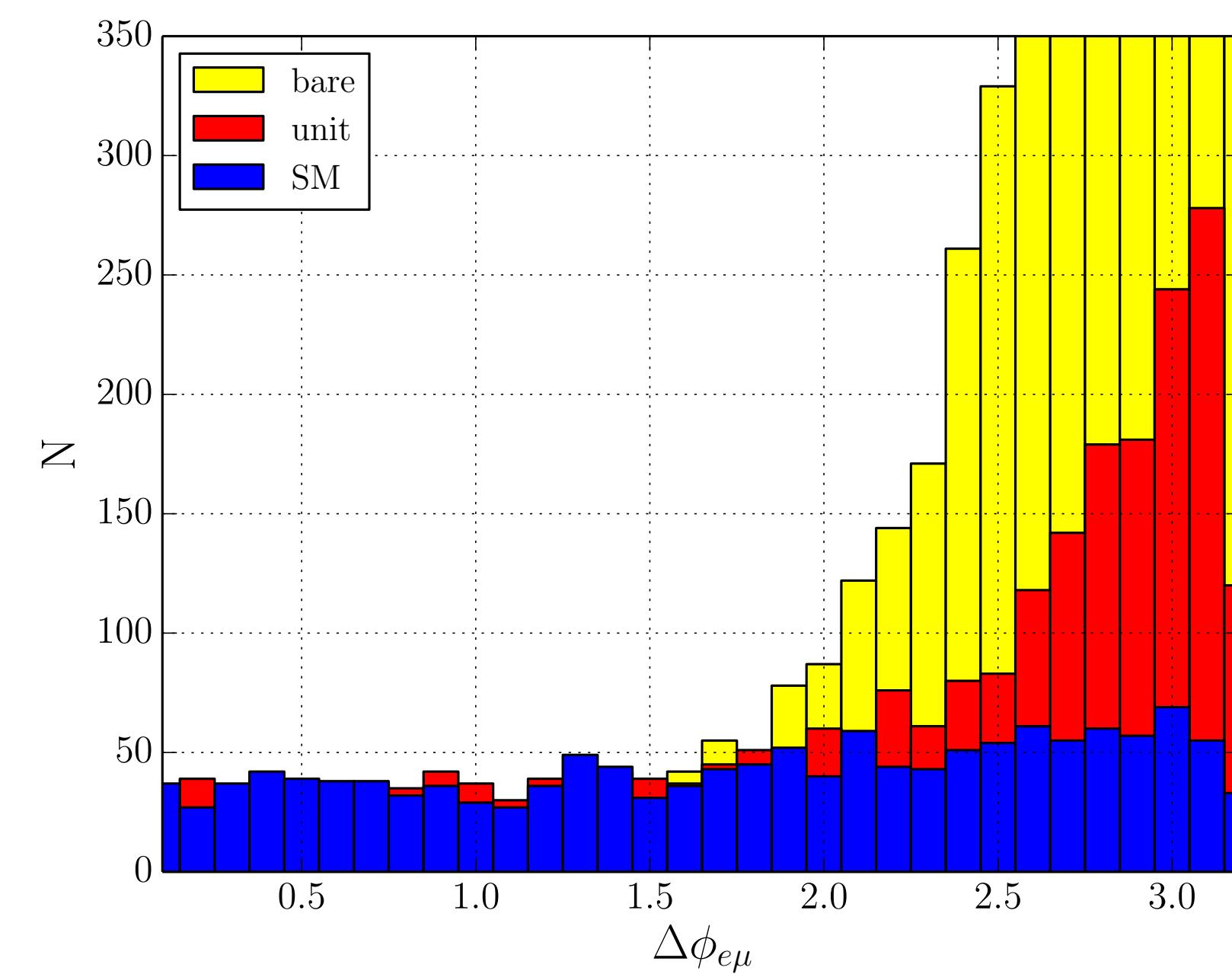
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- New physics models: “fermiophobic” resonances, visible in multi-bosons, but not in Drell-Yan
- Prime examples: 2HDM, Inert Doublet Model, Georgi-Machacek, Heavy Vector Triplet (HVT), MSSM-decoupl. limit, Little Higgs models, some Composite Higgs models, Higgs portals, Gegenbauer models, etc.
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$$\begin{aligned}\mathcal{L}_{HVT} = & \mathcal{L}_{SM} - \frac{1}{4} \tilde{V}^{\mu\nu A} \tilde{V}^A_{\mu\nu} + \frac{\tilde{m}_V^2}{2} \tilde{V}^{\mu A} \tilde{V}^A_\mu - \frac{\tilde{g}_M}{2} \tilde{V}^{\mu\nu A} \tilde{W}^A_{\mu\nu} \\ & + \tilde{g}_H \tilde{V}^{\mu A} J^A_{H\mu} + \tilde{g}_I \tilde{V}^{\mu A} J^A_{I\mu} + \tilde{g}_q \tilde{V}^{\mu A} J^A_{q\mu} + \frac{\tilde{g}_{VH}}{2} |H|^2 \tilde{V}^{\mu A} \tilde{V}^A_\mu\end{aligned}$$

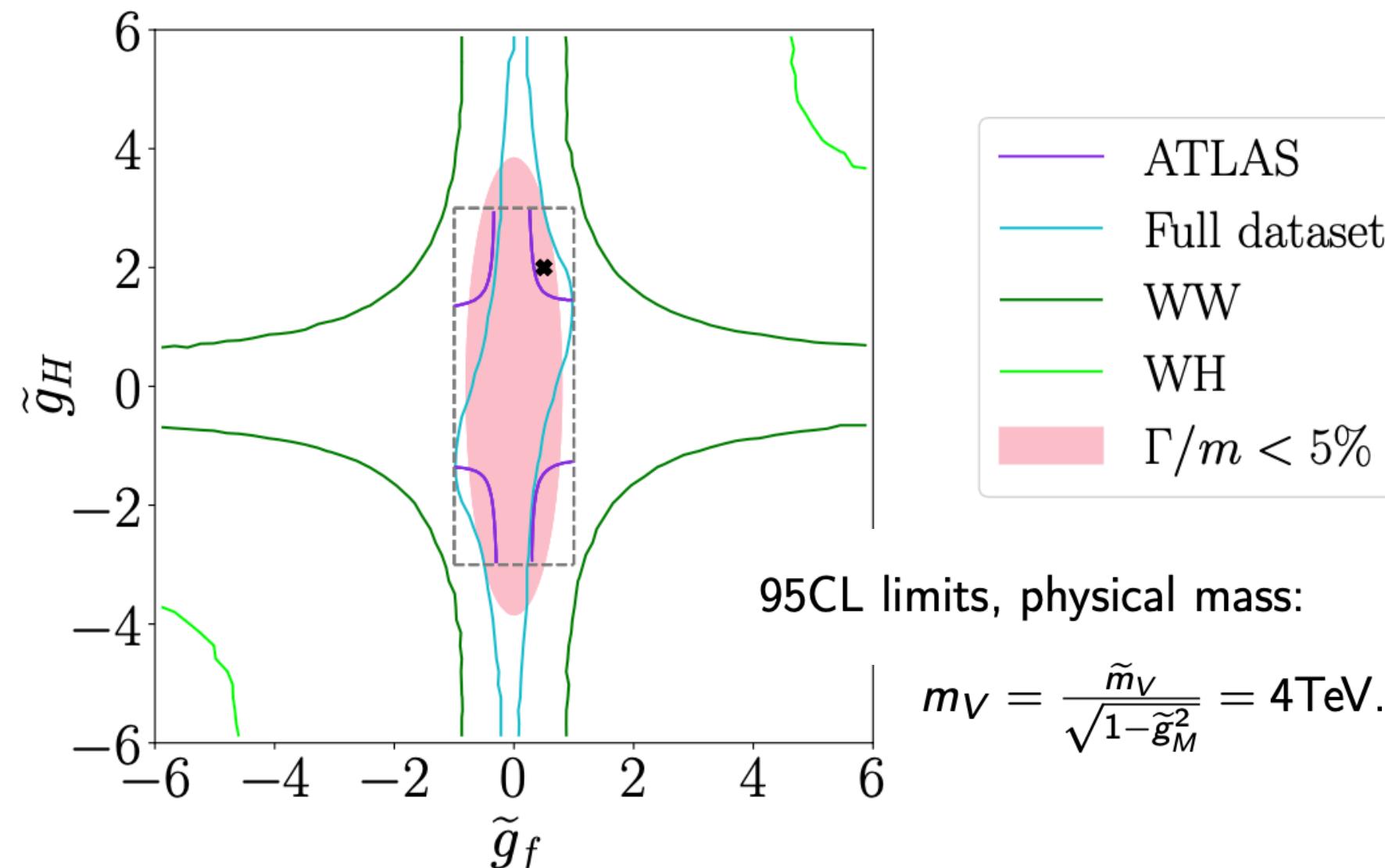
- 5 UV parameters, 1 matching scale Q
- 1-loop matching to 17 dim-6 operators:  $\frac{c_i}{\Lambda^2} (\tilde{g}_M, \tilde{g}_H, \tilde{g}_I, \tilde{g}_q, \tilde{g}_{VH}, \tilde{m}_V, Q)$
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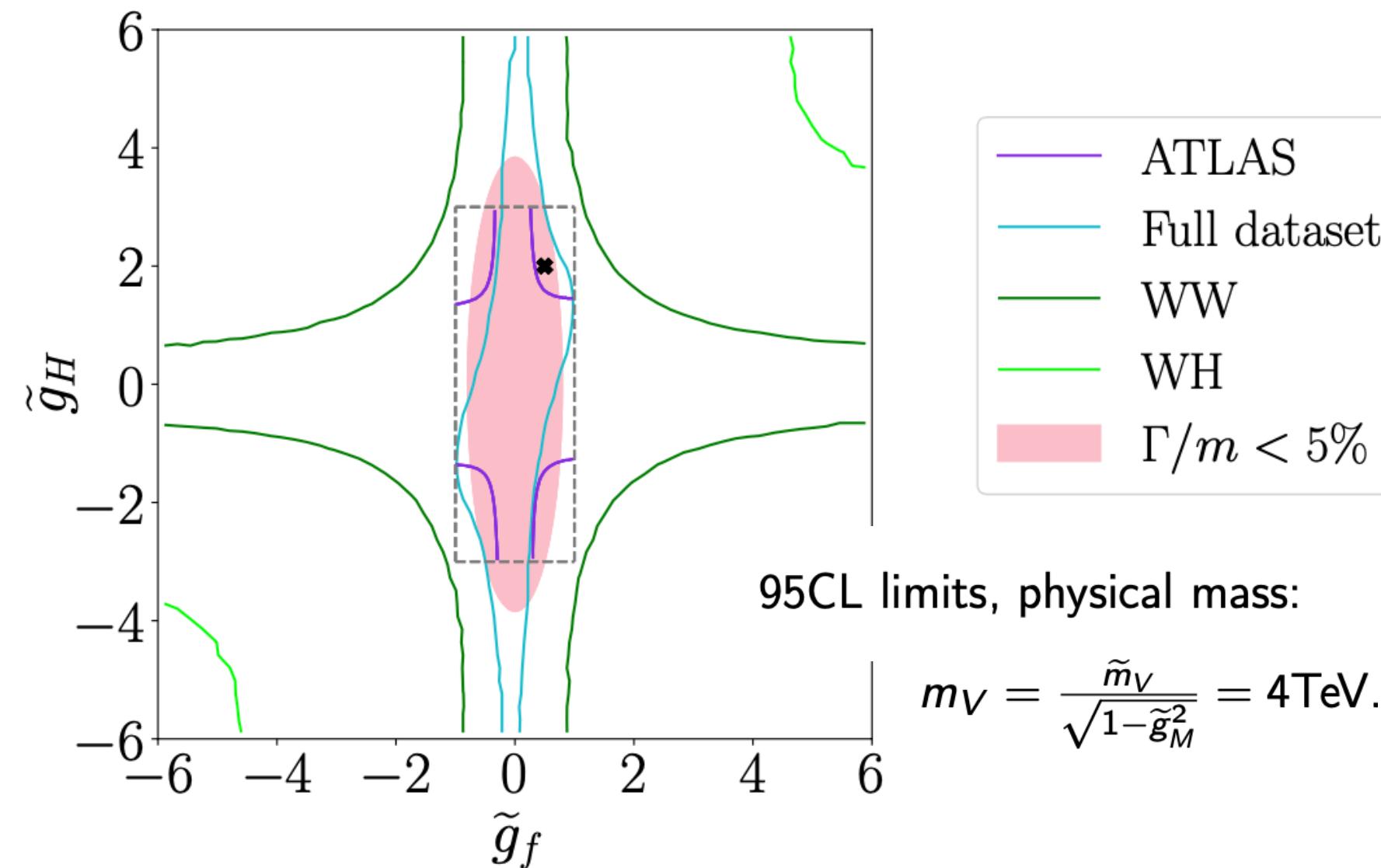
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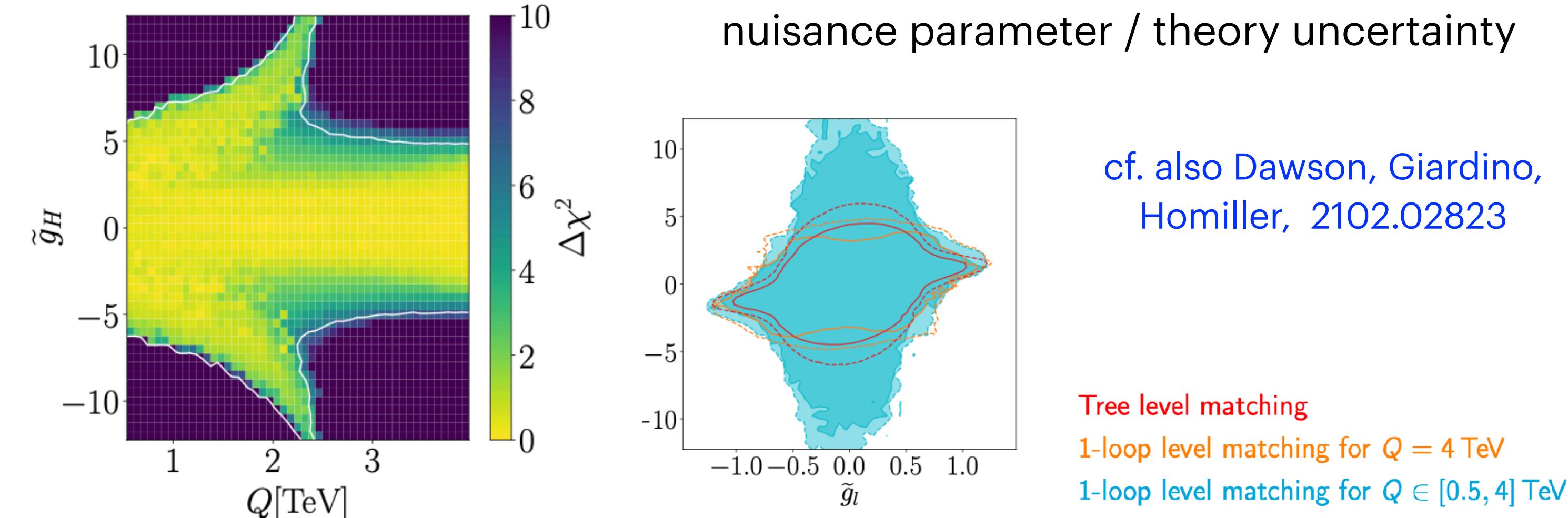
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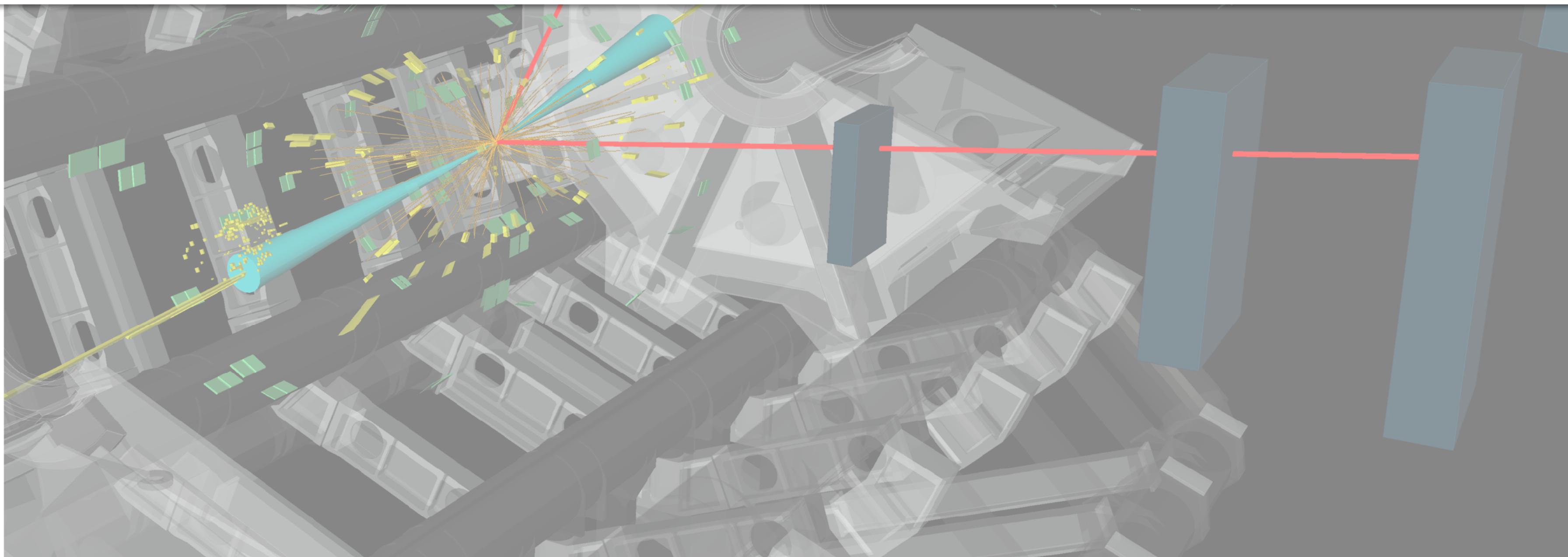
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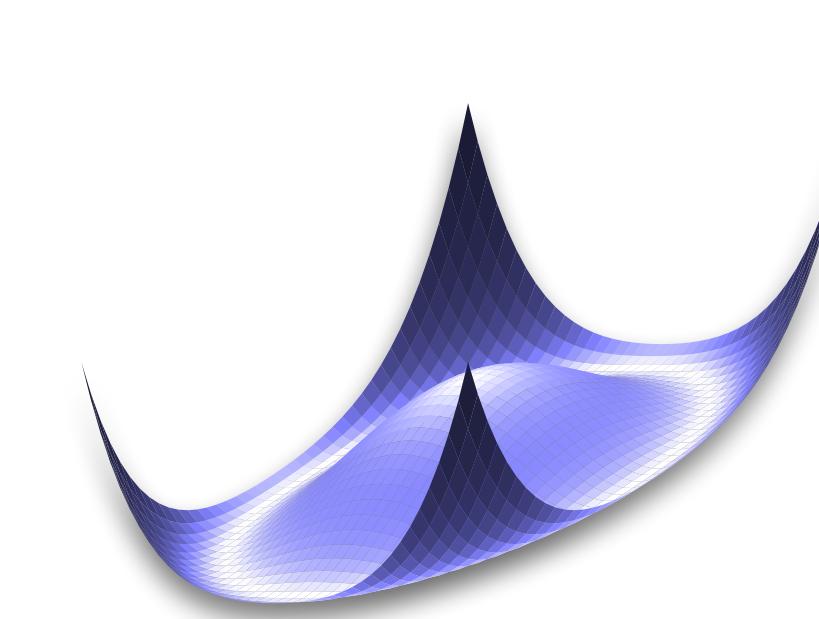
# POLARIZATION in VBS



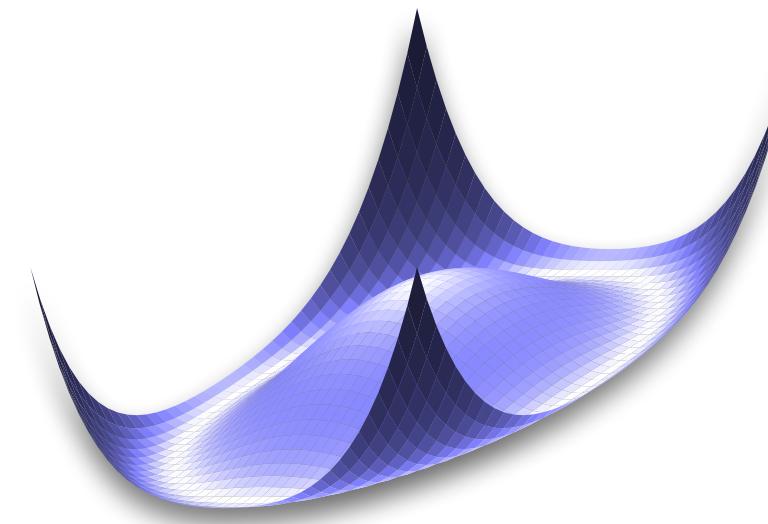
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Courtesy to René Poncelet for many polarization figures/plots

Polarized bosons discriminate between “gauge” and “Goldstone” modes: “Yang-Mills vs. EWSB”



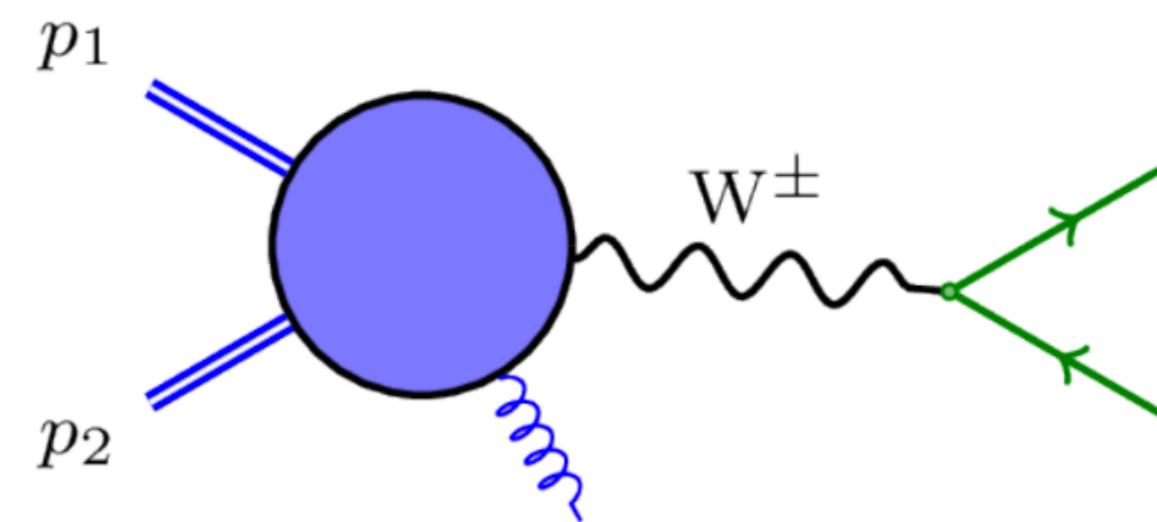
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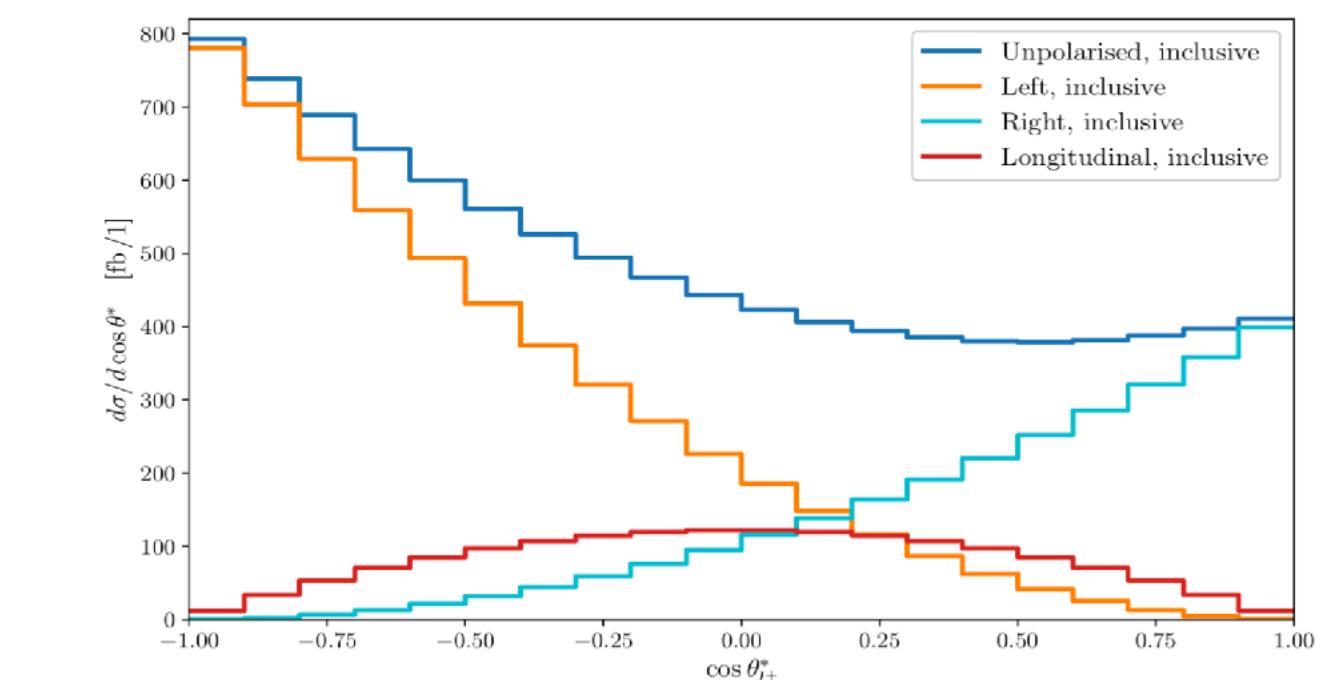
Polarization only accessible via decay products; definition of polarizations “as on-shell as possible”



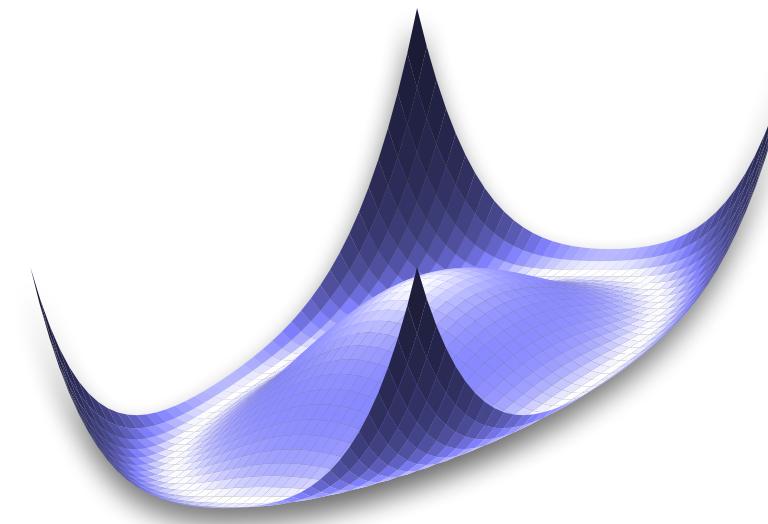
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$$-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2} \rightarrow \sum_\lambda \epsilon_\lambda^\mu * \epsilon_\lambda^\nu$$

On-shell vector bosons (NWA or DPA)



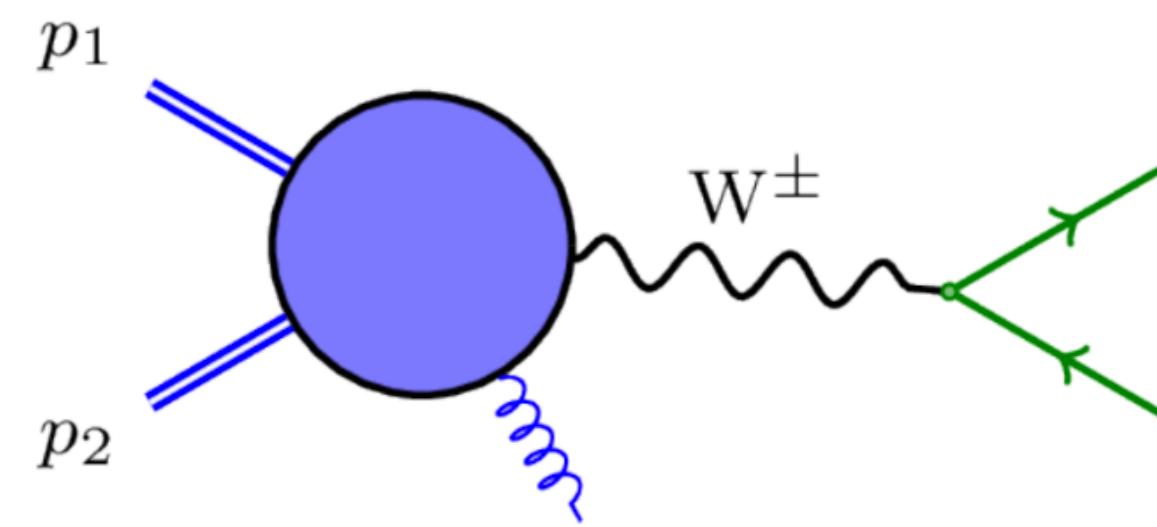
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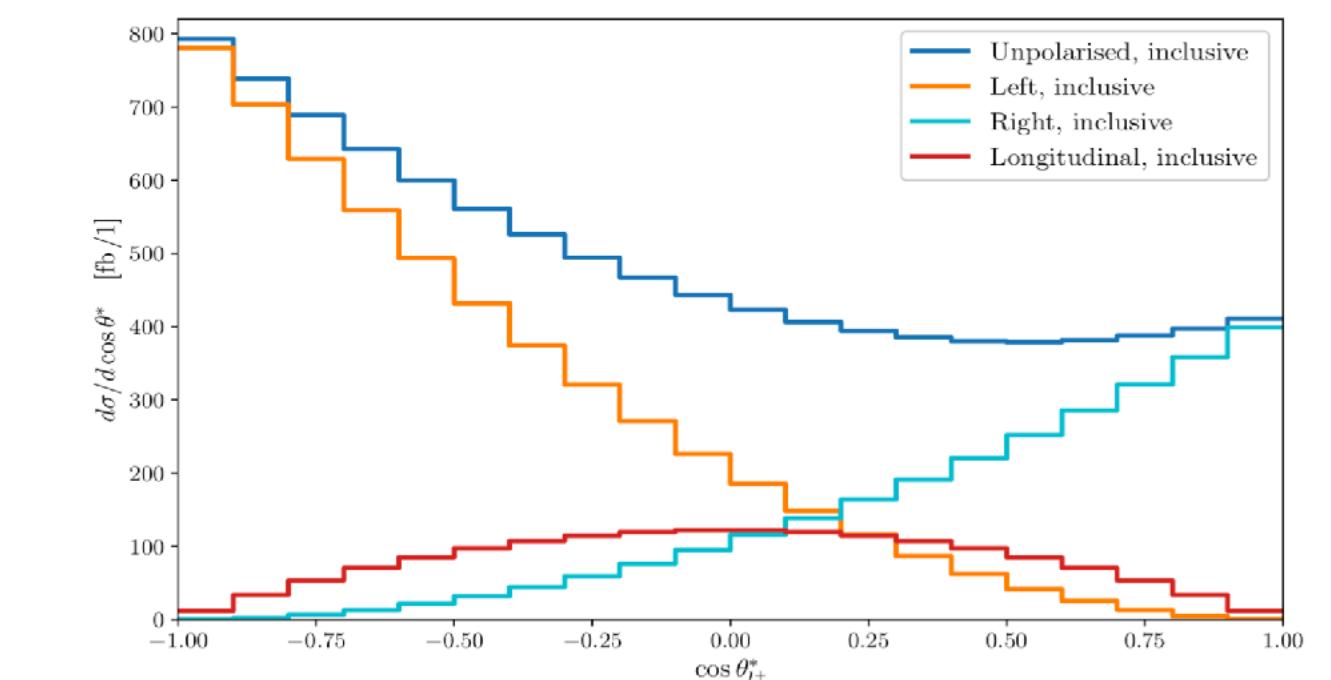


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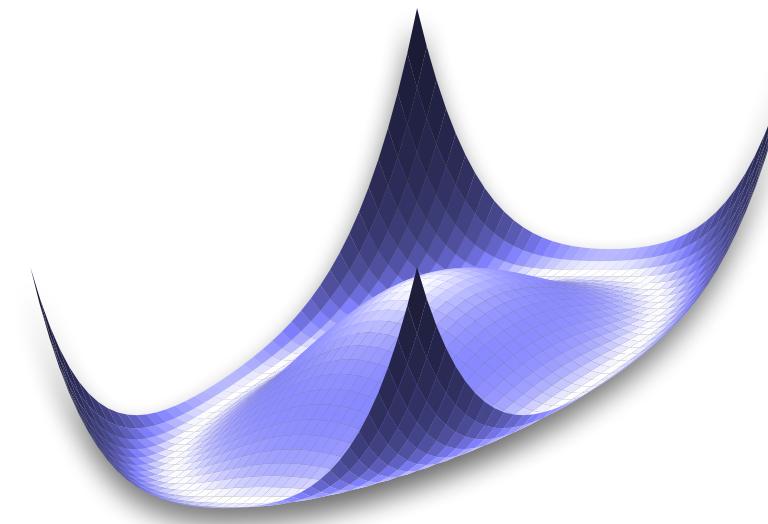
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Extract polarization fractions via projections and/or fits

Decay angle in vector boson rest frame  $\cos \theta^*$

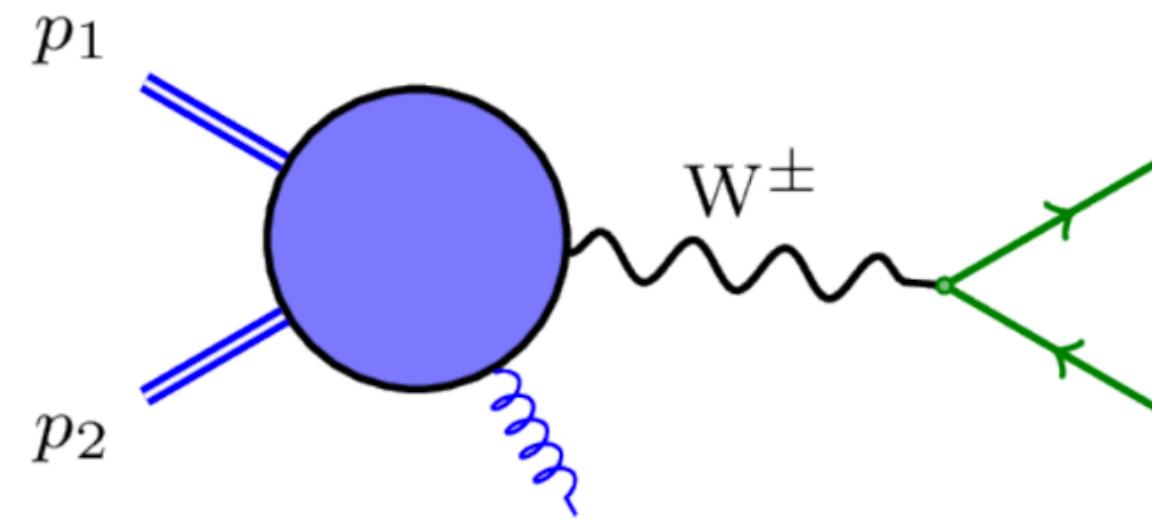
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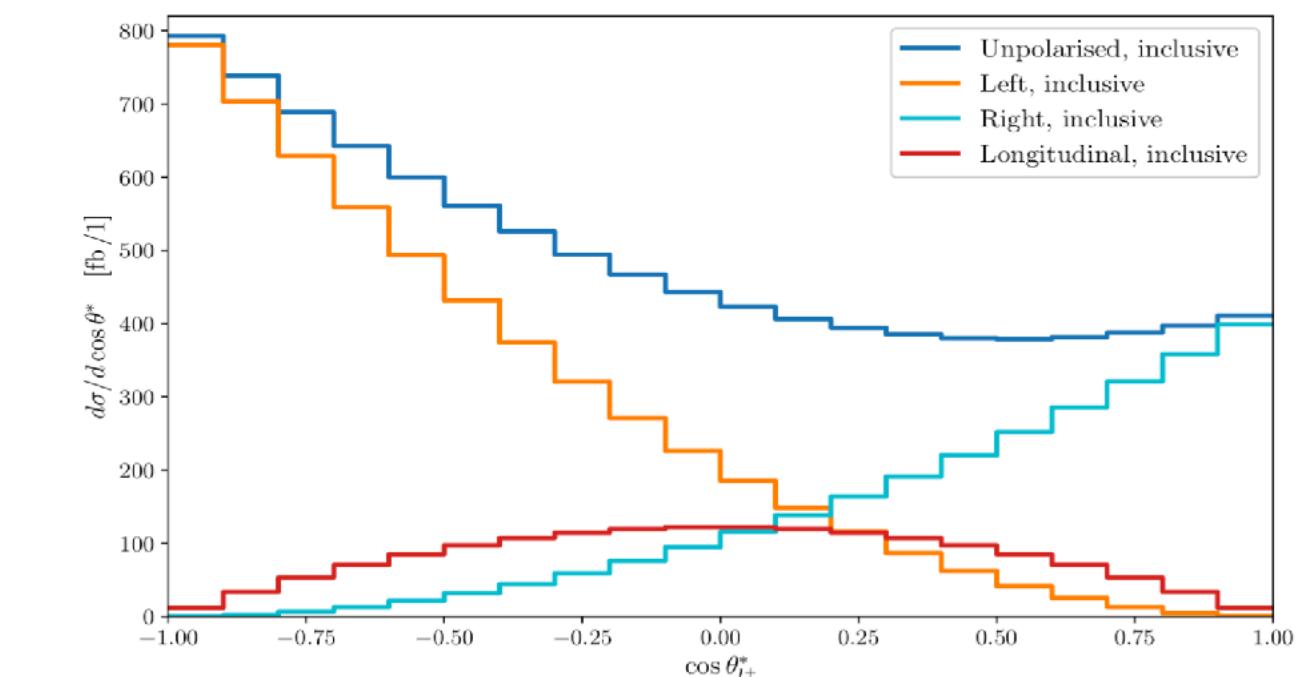
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## Problems

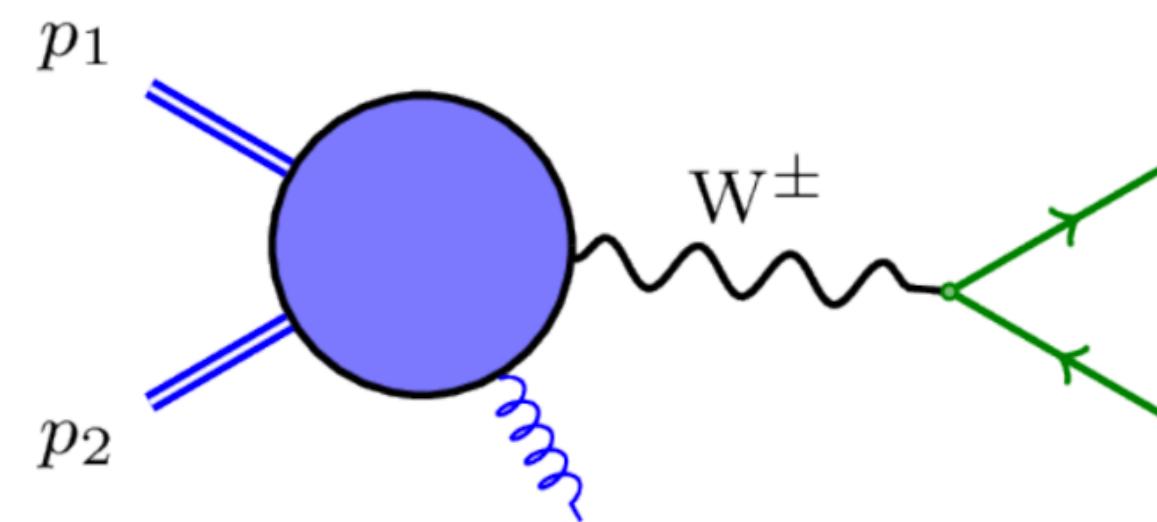
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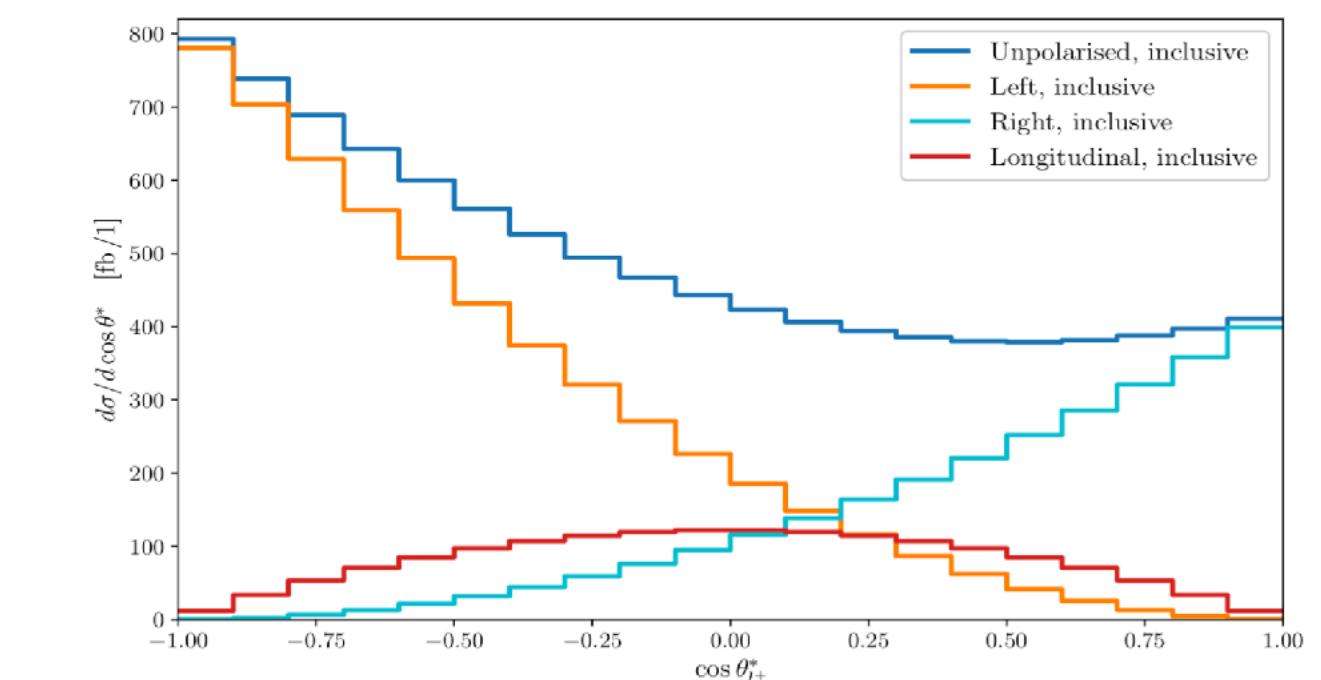


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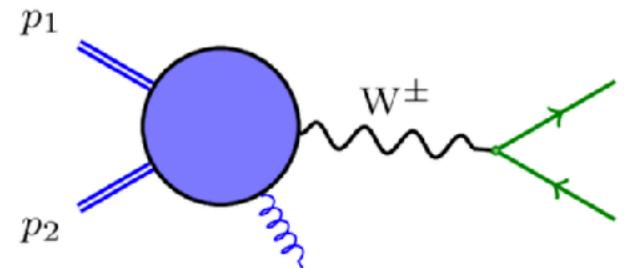
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Better: use signal model with polarized events

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# Definition of polarized vector bosons



$$|M|^2 = \underbrace{\sum_{\lambda} |M_{\lambda}|^2}_{\text{Polarized cross section/ squared matrix element}} + \underbrace{\sum_{\lambda \neq \lambda'} M_{\lambda}^* M_{\lambda'}}_{\text{Spin correlations/ interferences}}$$

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Polarized cross section/  
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Spin correlations/  
interferences

$$\frac{d\sigma}{d\mathcal{O}} = f_L \frac{d\sigma_L}{d\mathcal{O}} + f_R \frac{d\sigma_R}{d\mathcal{O}} + f_0 \frac{d\sigma_0}{d\mathcal{O}} \quad [+ f_{corr.} \frac{d\sigma_{corr.}}{d\mathcal{O}}]$$

Again: fit to the measurement the fractions  $f_L$ ,  $f_R$ ,  $f_0$

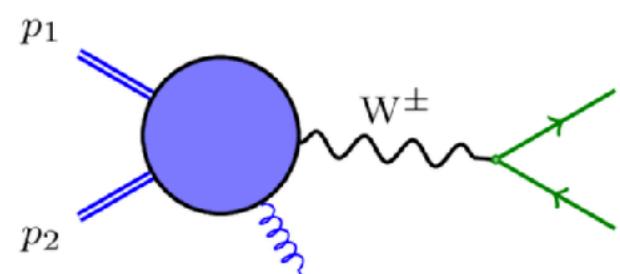
**Impact of higher order/spin correlations ?**

- Spin correlations can be included
- Any observable  $\mathcal{O}$  can be used (lab frame!)
- $d\sigma / d\mathcal{O}$  can be systematically improved (N[N]LO etc.)

$$\frac{d\sigma}{d\mathcal{O}} = f_{\perp} \frac{d\sigma_{\perp}}{d\mathcal{O}} + f_{\parallel} \frac{d\sigma_{\parallel}}{d\mathcal{O}} \quad [+ f_{corr.} \frac{d\sigma_{corr.}}{d\mathcal{O}}]$$

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select regions with small/tiny interferences

$pp \rightarrow ZZ \rightarrow llll + X$

polarized; NLO QCD / EW

[Denner, Pelliccioli, 2107.06579](#)

$pp \rightarrow W^+W^- \rightarrow e^-\bar{\nu}_e \mu^+\nu_{\mu} + X$

polarized; NNLO QCD

[Poncelet, Popescu, 2102.13583](#)

$pp \rightarrow W^+Z \rightarrow e^+\nu_e \mu^+\mu^- + X$

polarized; NLO QCD / EW

[Duc, Baglio, 2203.01470](#)

$pp \rightarrow Wj \rightarrow \ell\nu_{\ell} j + X$

polarized; NNLO QCD

[Pellen, Poncelet, Popescu, 2109.14336](#)

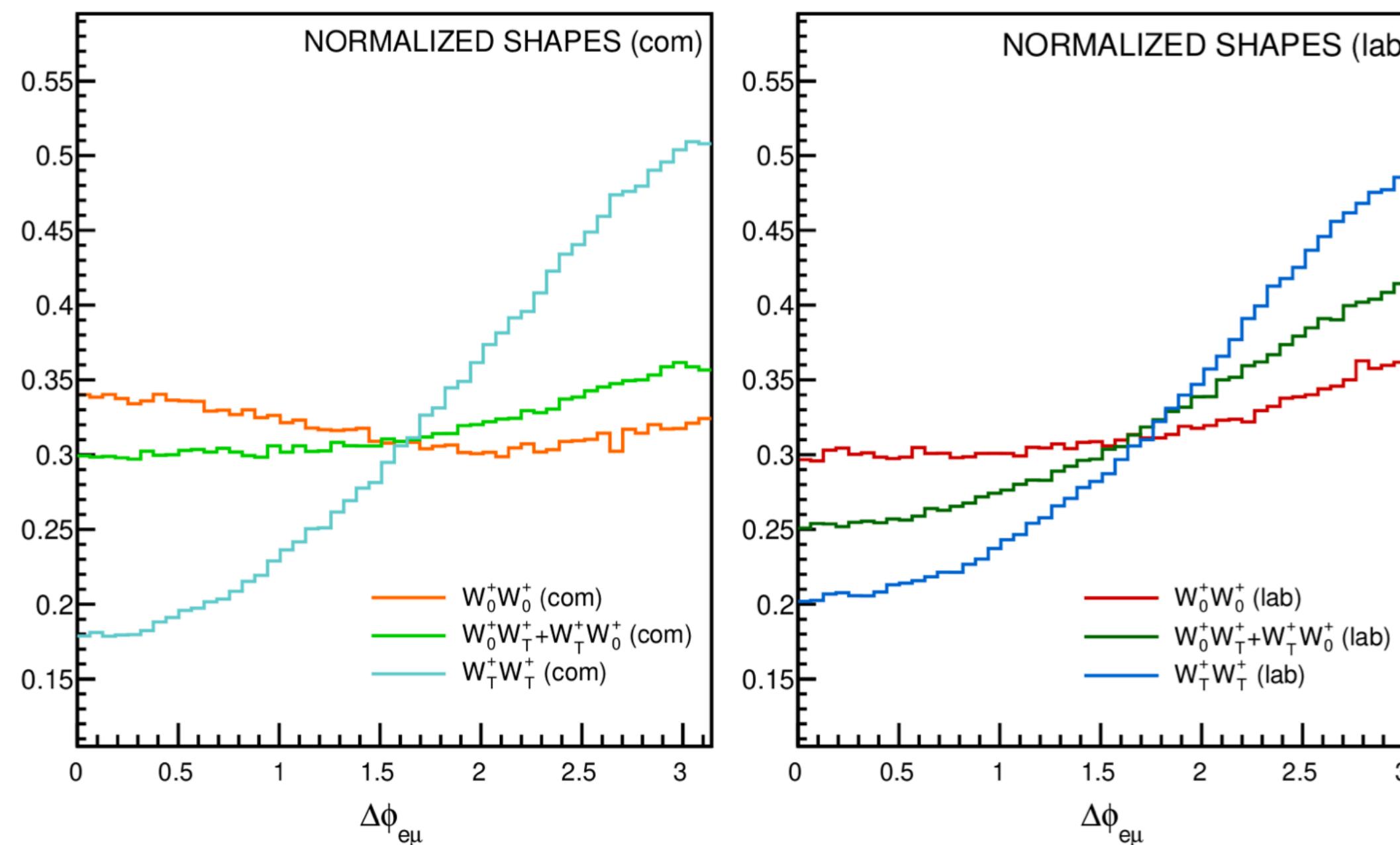
$pp \rightarrow e^+\nu_e \mu^-\bar{\nu}_{\mu} jj + X$

polarized; LO

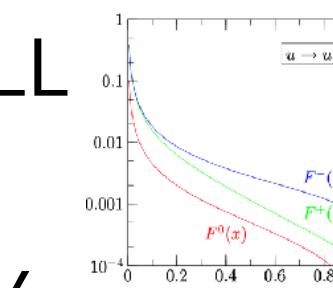
[Ballestrero, Maina, Pelliccioli, 2007.07133](#)

# Polarized Vector boson scattering

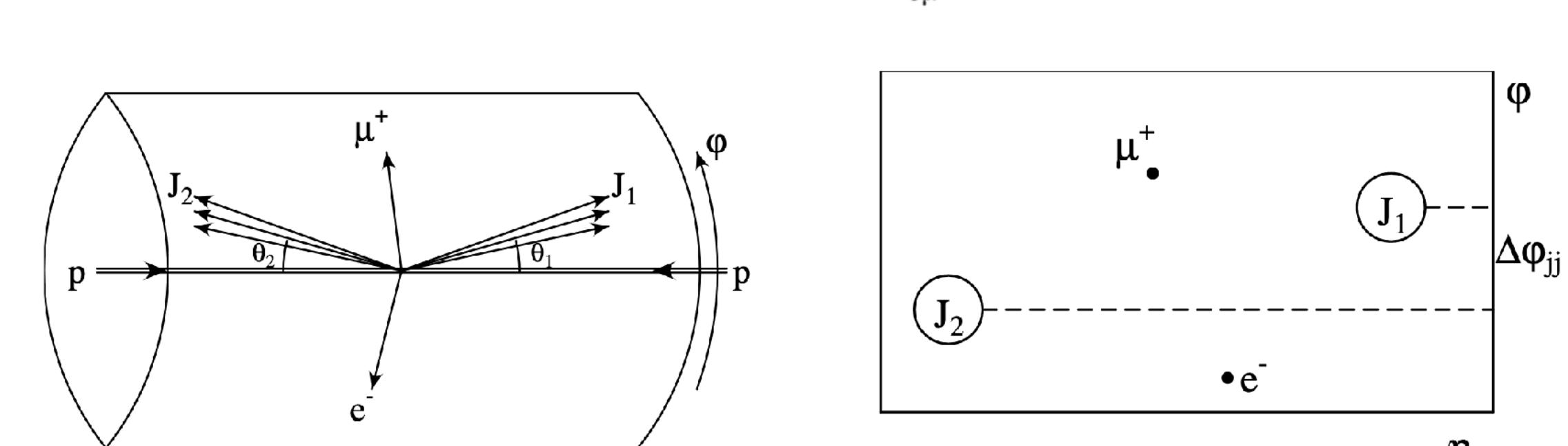
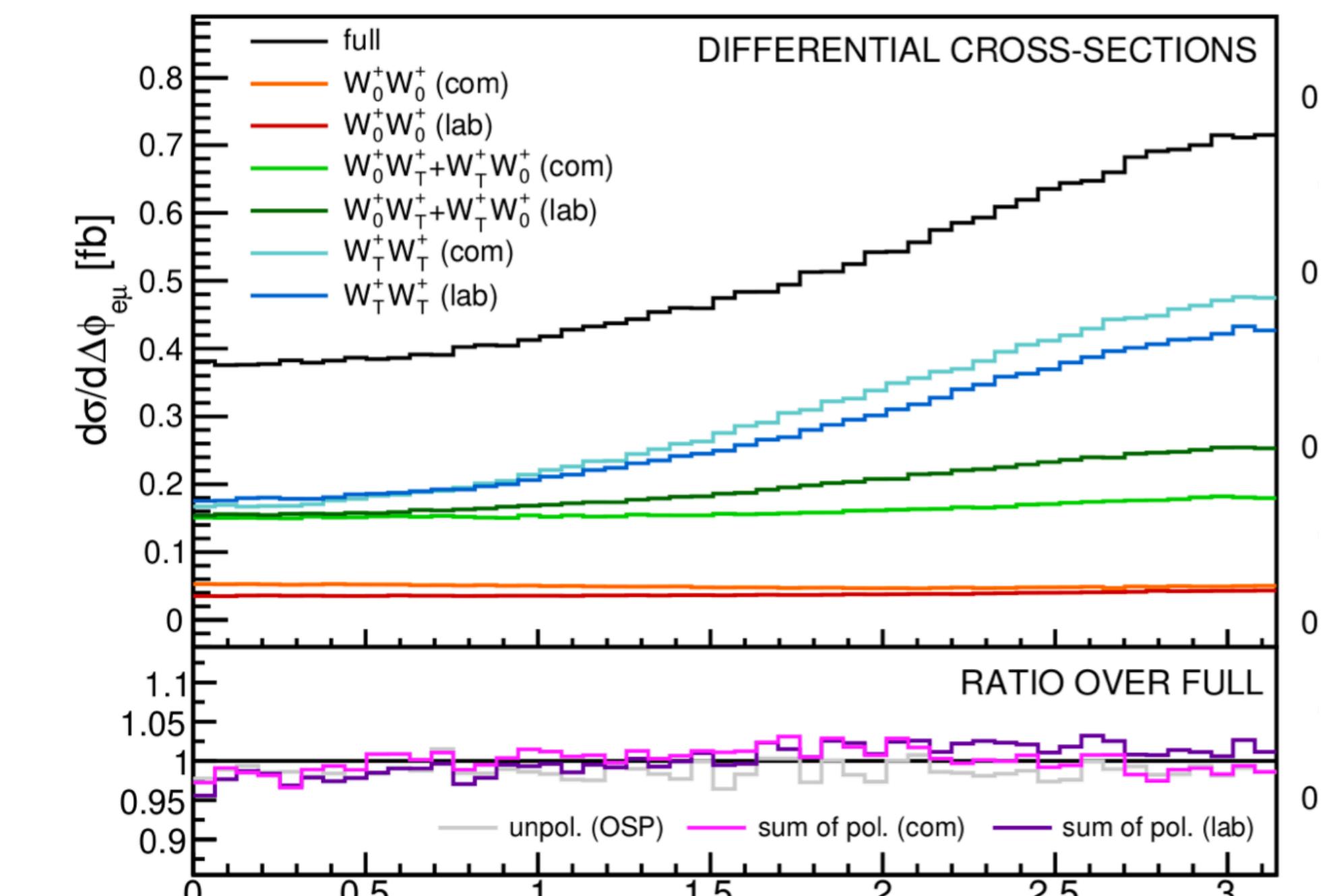
- Many LO tools available: MG5\_aMC@NLO, PHANTOM, WHIZARD
- Singly-/doubly-polarized VBS studied at LO
- Frame of polarization definition
- Impact of fiducial selection criteria
- Study of off-shell effects / spin correlations ("interferences")



- Small total double-longitudinal (LL) contribution (~10%)
- Drastically different angular correlations ( $\Delta\phi_{e\mu}$ ) for LL



Ballestrero, Maina, Pelliccioli, 2007.07133



# Polarized Vector boson scattering

- Many LO tools available: MG5\_aMC@NLO, PHANTOM, WHIZARD
- Singly /doubly polarized VBS studied at LO

Ballestrero, Maina, Pelliccioli, 2007.07.13

W+W+

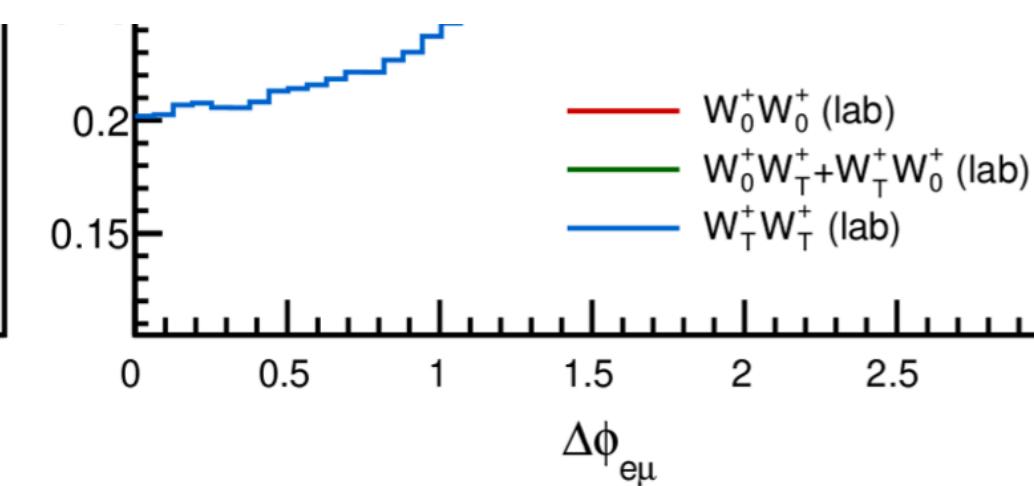
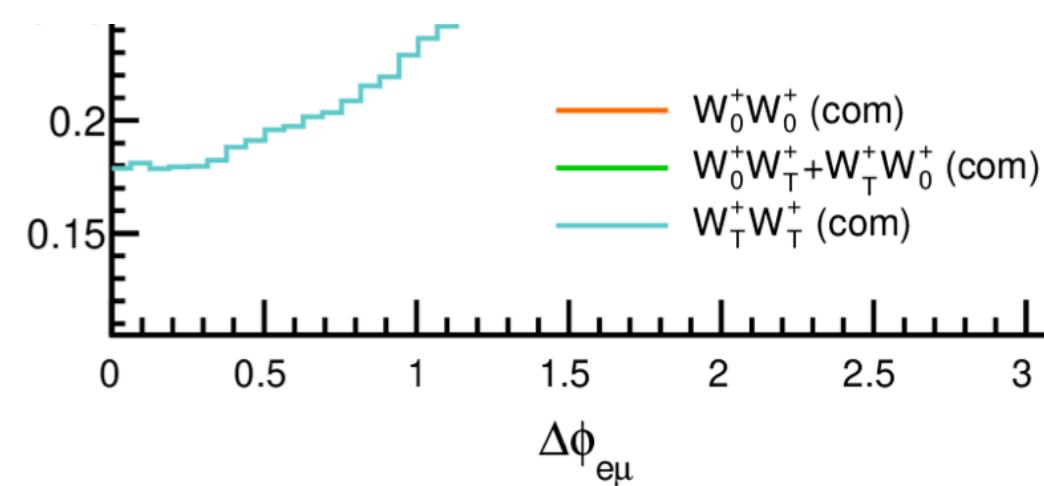
	Lab	WW CoM	ratio
full	3.185(3)		-
unpol	3.167(2)		-
0-unpol	0.8772(8)	0.8374(9)	0.95
T-unpol	2.287(2)	2.329(2)	1.02
0-0	0.2573(3)	0.3275(4)	1.27
0-T,T-0	0.6199(6)	0.5081(5)	0.82
T-T	1.666(1)	1.820(1)	1.09

W+W-

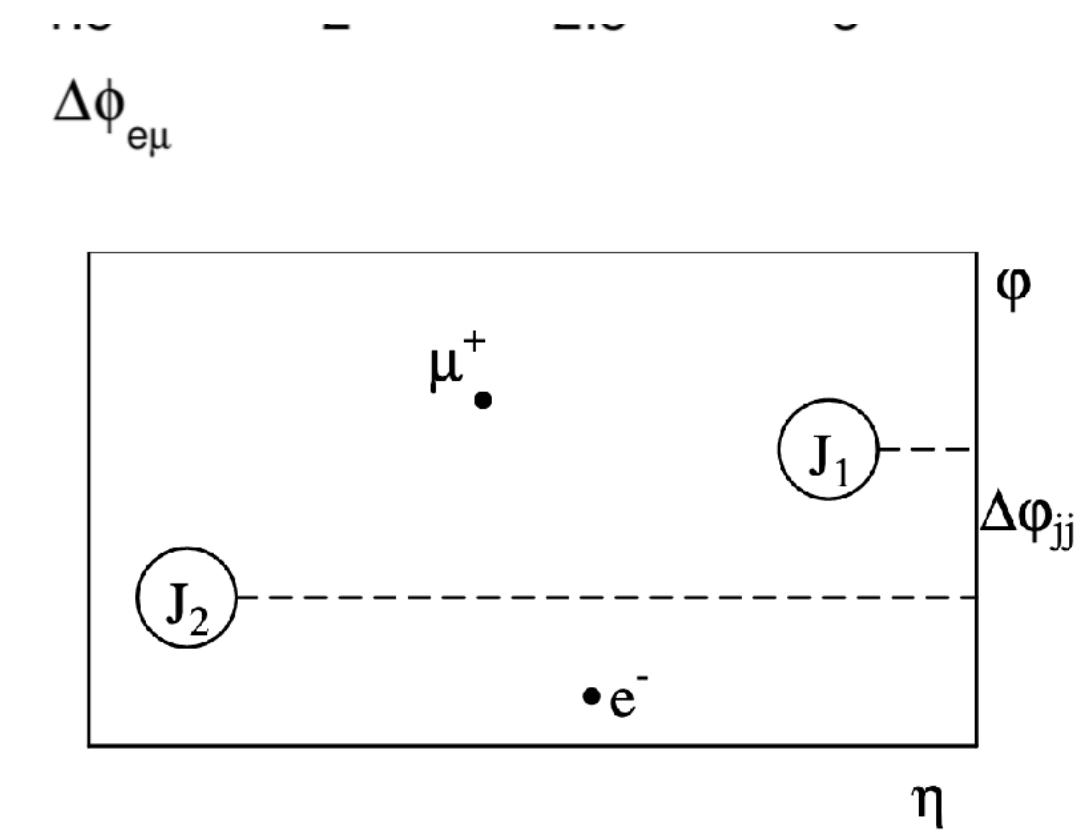
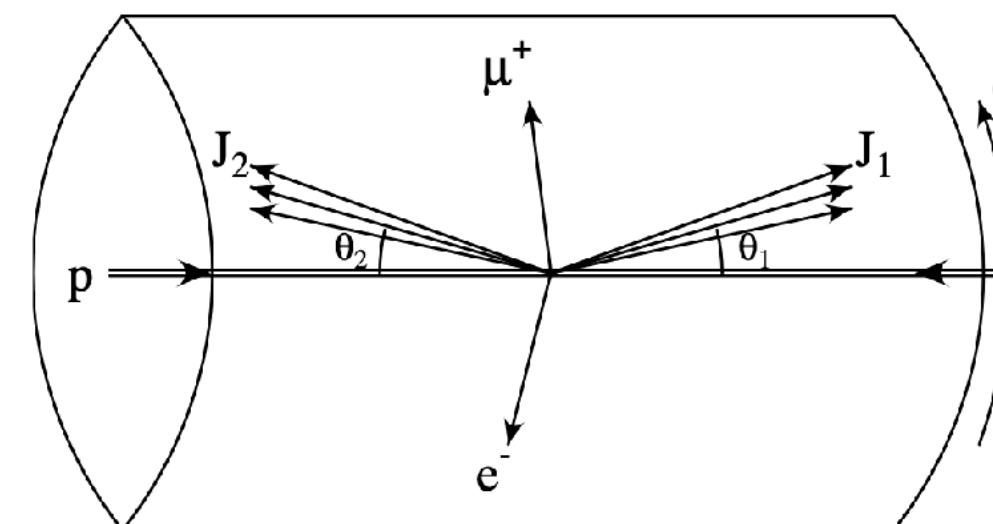
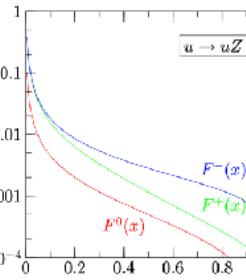
	Lab	WW CoM	ratio
full	4.651(2)		-
unpol	4.641(2)		-
0-unpol	1.186(1)	1.146(1)	0.97
T-unpol	3.456(2)	3.494(2)	1.01
unpol-0	1.2226(4)	1.1905(5)	0.97
unpol-T	3.418(1)	3.450(1)	1.01
0-0	0.3314(2)	0.3786(3)	1.14
0-T	0.8545(4)	0.7669(3)	0.90
T-0	0.8912(4)	0.8119(4)	0.91
T-T	2.563(1)	2.683(1)	1.05

WZ

	Lab	WZ CoM	ratio
full	0.5253(3)		-
unpol	0.5210(3)		-
0-unpol	0.1216(1)	0.1292(1)	1.06
T-unpol	0.3992(2)	0.3918(3)	0.98
unpol-0	0.1370(1)	0.1436(1)	1.05
unpol-T	0.3839(2)	0.3773(2)	0.98
0-0	0.03236(3)	0.03993(5)	1.23
0-T	0.08923(8)	0.08926(8)	1.00
T-0	0.1045(1)	0.1039(1)	0.99
T-T	0.2948(2)	0.2876(2)	0.98



- Small total double-longitudinal (LL) contribution (~10%)
- Drastically different angular correlations ( $\Delta\phi_{e\mu}$ ) for LL



# Conclusions & Outlook

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- Multi-boson + Higgs final states: multi-messenger detectors for electroweak sector **will shine in Run 3**
- Vector Boson Scattering: rare processes, potential to direct access to EWSB
- EFT interpretation difficult; model-dependence through truncation and assumptions
- Comparison with explicit models not very promising for EFT interpretation
- Alternative: simplified models with specific resonances
- Access to fully-hadronic channels (?)
- For theory interpretation: provide as much unfolded distributions as possible **Never clip data!!!**
- Look at (almost-)optimal observables: cross section ratios, ratios of angular correlations
- Combination of  $V$ ,  $VH$ ,  $VV$ ,  $VVV$ ,  $VVjj$  processes: lots of correlations, lots of power !!
- Polarization only defined on-shell: NLO QCD correction lead to huge corrections
- Great care is needed in interpreting polarization observables (at NLO / NNLO)
- Run 3 might have enough power to push EW processes into the Sudakov (precision) regime

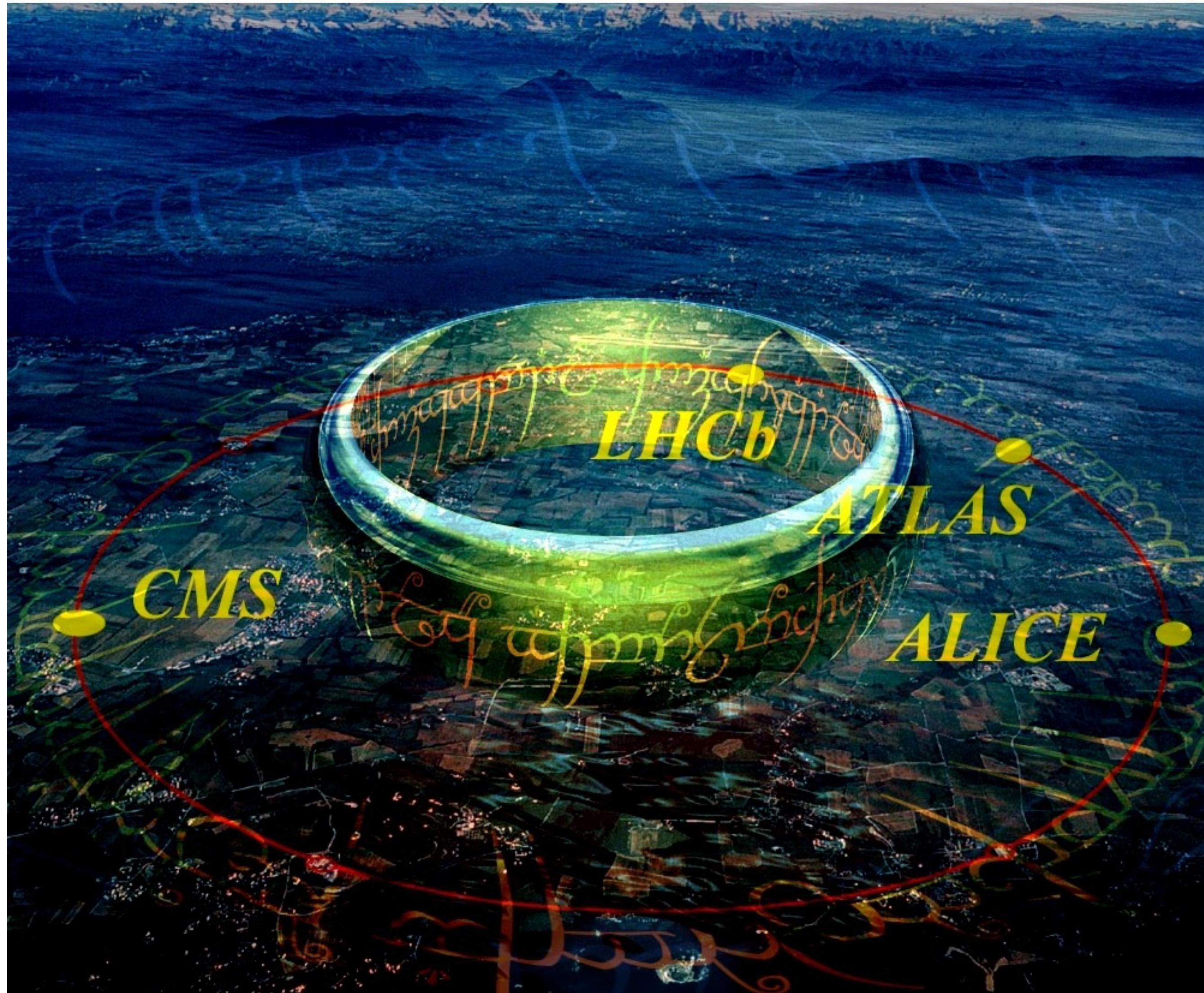


# One Ring, 3 Runs



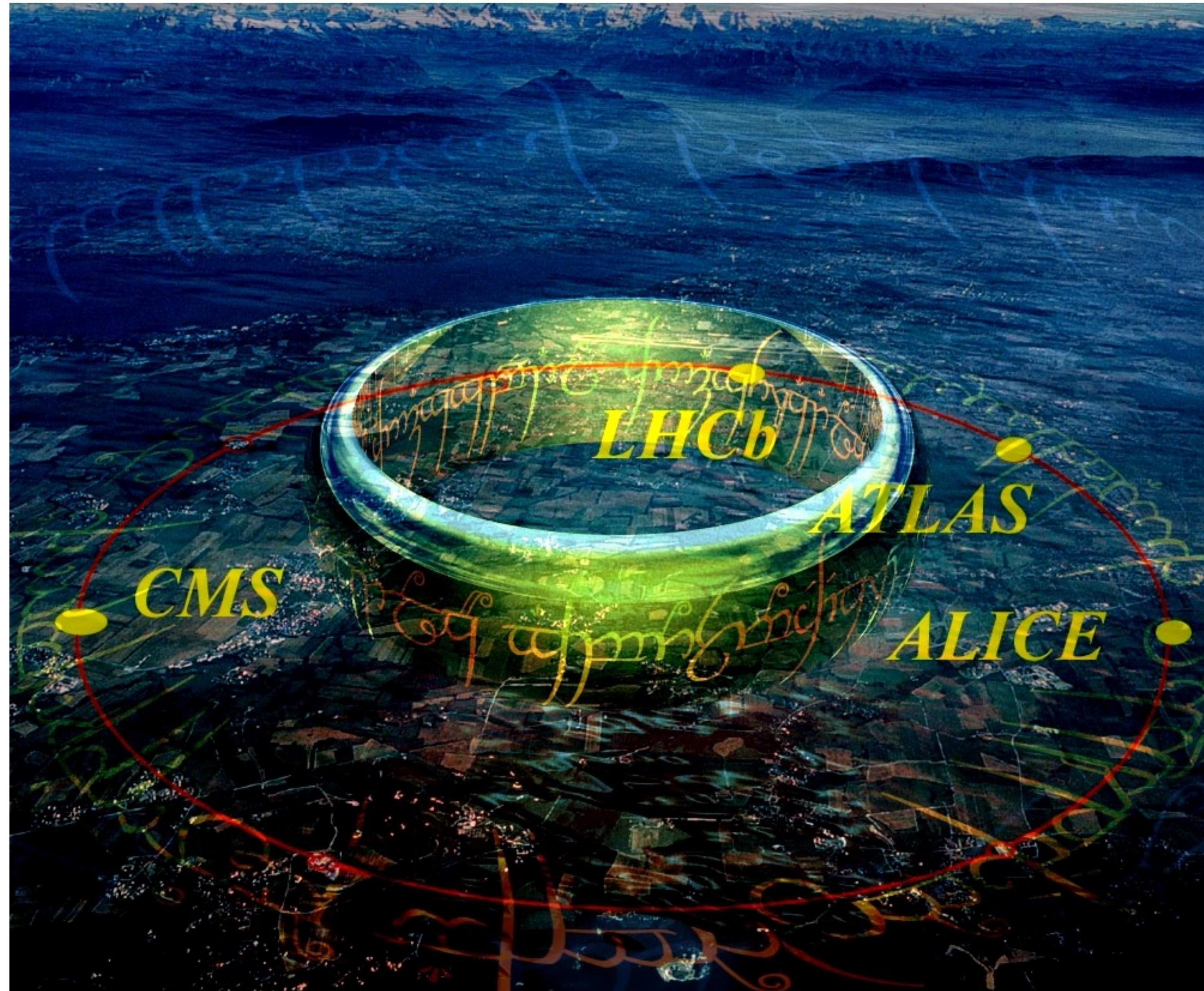
# One Ring To Find Them,

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# One Ring To Rule Them Out

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# One Ring To Rule Them Out

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# BACKUP

# Quick excursion to Higgsstrahlung

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Higgsstrahlung (a.k.a. Higgs associated production) is also “dibosons”

Subset of a wider scope of “standard search processes”:  $pp \rightarrow V^m H^n$  ,  $m, n \in 0, 1, 2, \dots$  e.g. [2205.15959](#)

Bernhard Mistlberger, MBI 2022



# Quick excursion to Higgsstrahlung

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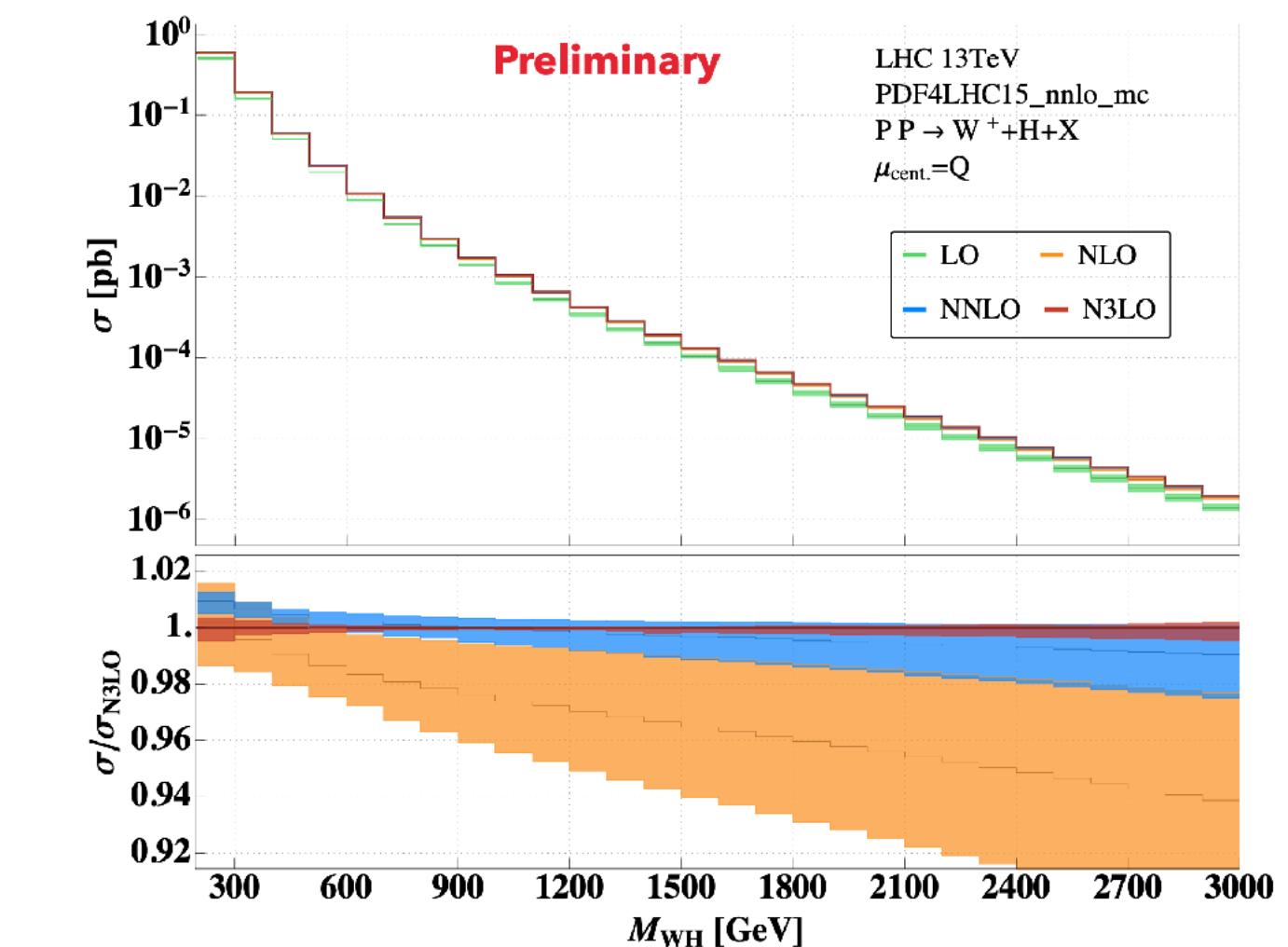
Higgsstrahlung (a.k.a. Higgs associated production) is also “dibosons”

Subset of a wider scope of “standard search processes”:  $pp \rightarrow V^m H^n$  ,  $m, n \in 0, 1, 2, \dots$  e.g. [2205.15959](#)

- NNNLO soon available
- Behaves very similar to charged-current Drell-Yan
- Lowest bin has no overlap of scale variations

Bernhard Mistlberger, MBI 2022

Process	Preliminary						
	$\sigma^{\text{LO}}$ [pb]	$\sigma^{\text{NLO}}$ [pb]	$K^{\text{NLO}}$	$\sigma^{\text{NNLO}}$ [pb]	$K^{\text{NNLO}}$	$\sigma^{\text{N}^3\text{LO}}$ [pb]	$K^{\text{N}^3\text{LO}}$
$W^+ H$	$0.758^{+2.43\%}_{-3.13\%}$	$0.873^{+1.28\%}_{-1.06\%}$	1.16	$0.891^{+0.27\%}_{-0.34\%}$	1.18	$0.884^{+0.28\%}_{-0.31\%}$	1.17
$W^- H$	$0.484^{+2.50\%}_{-3.26\%}$	$0.556^{+1.27\%}_{-1.14\%}$	1.15	$0.564^{+0.27\%}_{-0.34\%}$	1.17	$0.559^{+0.30\%}_{-0.32\%}$	1.16
$Z H$	$0.678^{+2.40\%}_{-3.11\%}$	$0.780^{+1.26\%}_{-1.05\%}$	1.16	$0.793^{+0.26\%}_{-0.30\%}$	1.16	$0.786^{+0.29\%}_{-0.31\%}$	1.16



# Quick excursion to Higgsstrahlung

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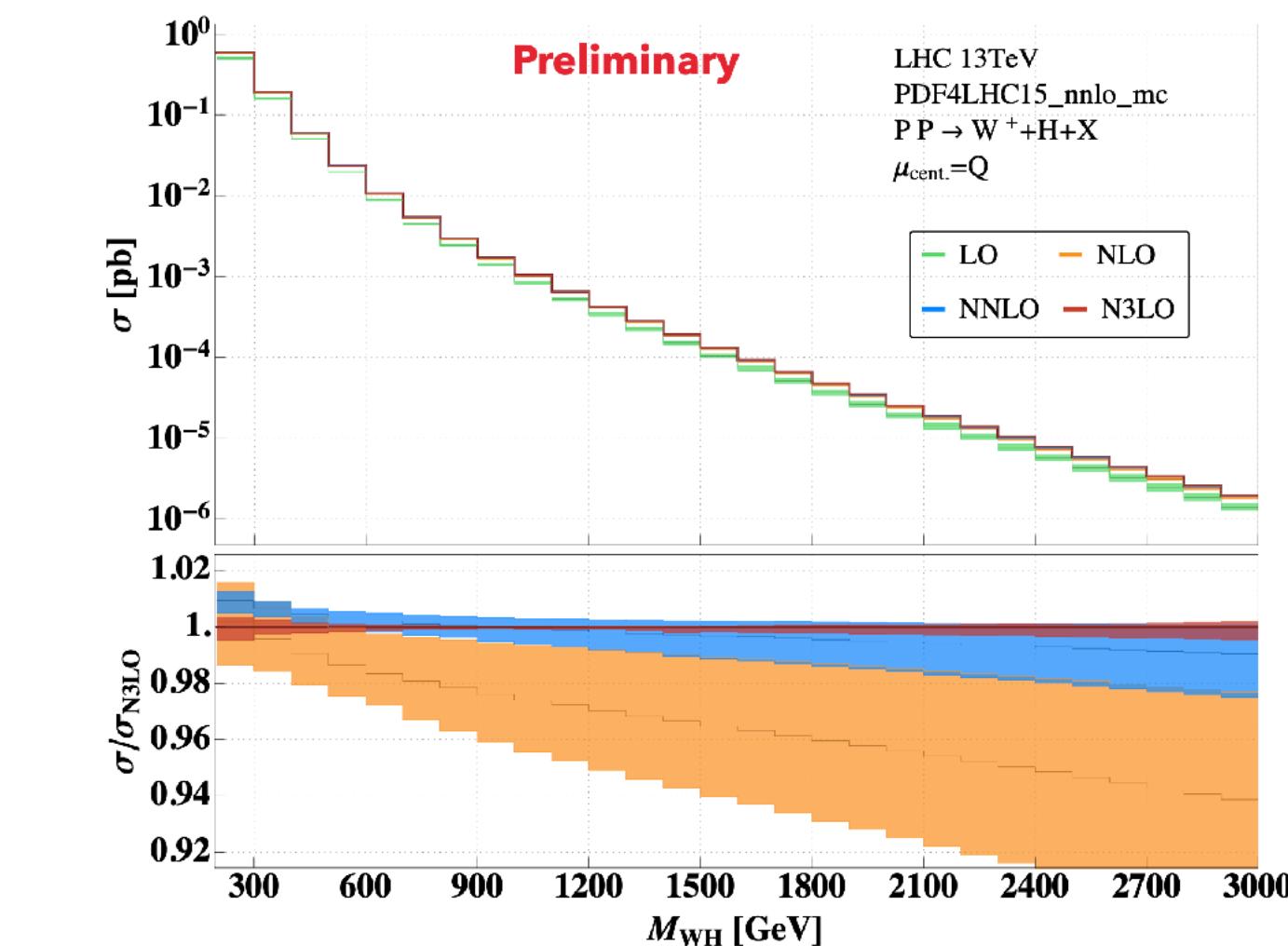
Higgsstrahlung (a.k.a. Higgs associated production) is also “dibosons”

Subset of a wider scope of “standard search processes”:  $pp \rightarrow V^m H^n$  ,  $m, n \in 0, 1, 2, \dots$  e.g. 2205.15959

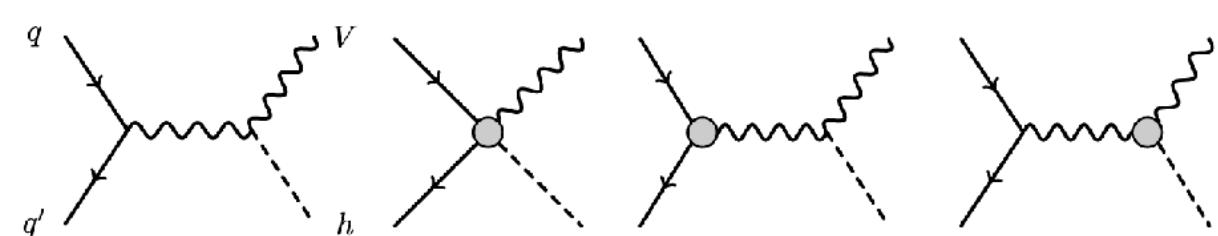
- NNNLO soon available
- Behaves very similar to charged-current Drell-Yan
- Lowest bin has no overlap of scale variations

Bernhard Mistlberger, MBI 2022

Process	$\sigma^{\text{LO}}$ [pb]	$\sigma^{\text{NLO}}$ [pb]	$K^{\text{NLO}}$	$\sigma^{\text{NNLO}}$ [pb]	$K^{\text{NNLO}}$	$\sigma^{\text{N}^3\text{LO}}$ [pb]	$K^{\text{N}^3\text{LO}}$
$W^+H$	$0.758^{+2.43\%}_{-3.13\%}$	$0.873^{+1.28\%}_{-1.06\%}$	1.16	$0.891^{+0.27\%}_{-0.34\%}$	1.18	$0.884^{+0.28\%}_{-0.31\%}$	1.17
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Bishara, P. Englert, Grojean, Panico, Rossia, 2208.11134

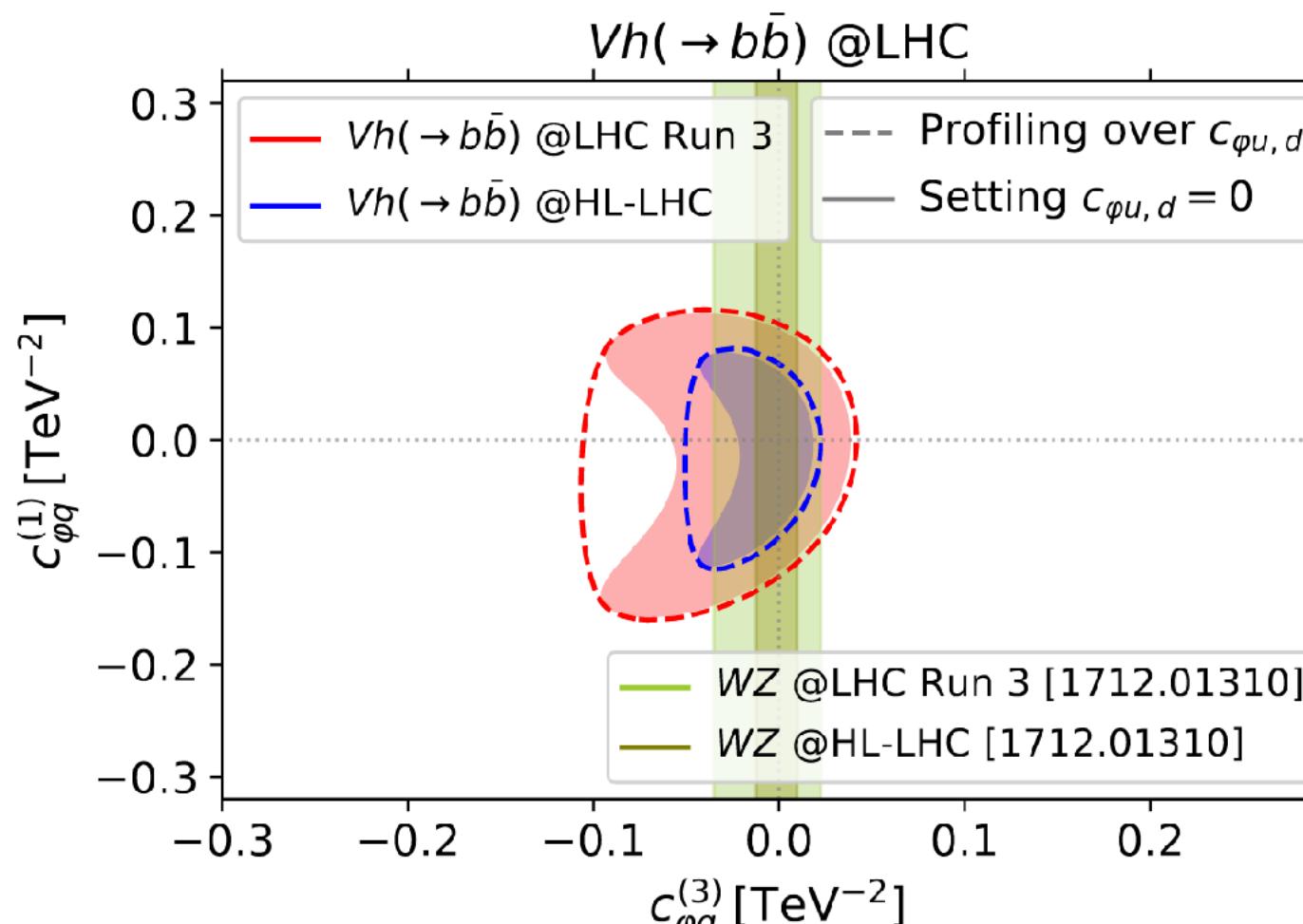


$$\mathcal{O}_{\varphi q}^{(1)} = (\bar{Q}_L \gamma^\mu Q_L) \left( iH^\dagger \overset{\leftrightarrow}{D}_\mu H \right),$$

$$\mathcal{O}_{\varphi q}^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L) \left( iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H \right)$$

$$\mathcal{O}_{\varphi u} = (\bar{u}_R \gamma^\mu u_R) \left( iH^\dagger \overset{\leftrightarrow}{D}_\mu H \right),$$

$$\mathcal{O}_{\varphi d} = (\bar{d}_R \gamma^\mu d_R) \left( iH^\dagger \overset{\leftrightarrow}{D}_\mu H \right),$$



Coefficient	Profiled Fit	One-Operator Fit
$c_{\varphi q}^{(3)} [\text{TeV}^{-2}]$	$[-7.9, 3.5] \times 10^{-2}$ LHC Run 3 $[-3.9, 1.9] \times 10^{-2}$ HL-LHC	$[-4.3, 3.2] \times 10^{-2}$ LHC Run 3 $[-1.7, 1.5] \times 10^{-2}$ HL-LHC
$c_{\varphi q}^{(1)} [\text{TeV}^{-2}]$	$[-1.2, 1.2] \times 10^{-1}$ LHC Run 3 $[-0.9, 0.8] \times 10^{-1}$ HL-LHC	$[-1.06, 0.87] \times 10^{-1}$ LHC Run 3 $[-0.72, 0.54] \times 10^{-1}$ HL-LHC
$c_{\varphi u} [\text{TeV}^{-2}]$	$[-1.9, 1.2] \times 10^{-1}$ LHC Run 3 $[-1.35, 0.82] \times 10^{-1}$ HL-LHC	$[-1.68, 0.9] \times 10^{-1}$ LHC Run 3 $[-1.24, 0.49] \times 10^{-1}$ HL-LHC
$c_{\varphi d} [\text{TeV}^{-2}]$	$[-1.8, 2.1] \times 10^{-1}$ LHC Run 3 $[-1.3, 1.5] \times 10^{-1}$ HL-LHC	$[-1.3, 1.7] \times 10^{-1}$ LHC Run 3 $[-0.8, 1.2] \times 10^{-1}$ HL-LHC

# $pp \rightarrow WW \rightarrow l\bar{v}l\bar{v} + X$ NNLO QCD

Poncelet, Popescu, 2102.13583

	NLO	NNLO	$K_{NNLO}$	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
unpol. (dpa)	$214.55(7)^{+1.8\%}_{-2.3\%}$	$219.4(4)^{+0.6\%}_{-0.6\%}$	1.023	$13.28(3)^{+25.5\%}_{-18.7\%}$	$232.7(4)^{+1.4\%}_{-1.1\%}$
$W_L^+$ (dpa)	$57.48(3)^{+1.9\%}_{-2.6\%}$	$59.3(2)^{+0.7\%}_{-0.7\%}$	1.032	$2.478(6)^{+25.5\%}_{-18.3\%}$	$61.8(2)^{+1.0\%}_{-0.8\%}$
$W_L^-$ (dpa)	$63.69(5)^{+1.9\%}_{-2.6\%}$	$65.4(3)^{+0.8\%}_{-0.8\%}$	1.026	$2.488(6)^{+25.5\%}_{-18.3\%}$	$67.9(3)^{+0.9\%}_{-0.8\%}$
$W_T^+$ (dpa)	$152.58(9)^{+1.7\%}_{-2.1\%}$	$155.7(6)^{+0.7\%}_{-0.6\%}$	1.020	$11.19(2)^{+25.5\%}_{-18.8\%}$	$166.9(6)^{+1.6\%}_{-1.3\%}$
$W_T^-$ (dpa)	$156.41(7)^{+1.7\%}_{-2.1\%}$	$159.7(6)^{+0.5\%}_{-0.6\%}$	1.021	$11.19(2)^{+25.5\%}_{-18.8\%}$	$170.9(6)^{+1.7\%}_{-1.3\%}$
$W_L^+ W_L^-$ (dpa)	$9.064(6)^{+3.0\%}_{-3.0\%}$	$9.88(3)^{+1.3\%}_{-1.3\%}$	1.090	$0.695(2)^{+25.5\%}_{-18.8\%}$	$10.57(3)^{+2.9\%}_{-2.4\%}$
$W_L^+ W_T^-$ (dpa)	$48.34(3)^{+1.9\%}_{-2.5\%}$	$49.4(2)^{+0.9\%}_{-0.7\%}$	1.021	$1.790(5)^{+25.5\%}_{-18.3\%}$	$51.2(2)^{+0.6\%}_{-0.8\%}$
$W_T^+ W_L^-$ (dpa)	$54.11(5)^{+1.9\%}_{-2.5\%}$	$55.5(4)^{+0.6\%}_{-0.7\%}$	1.025	$1.774(5)^{+25.5\%}_{-18.3\%}$	$57.2(4)^{+0.7\%}_{-0.7\%}$
$W_T^+ W_T^-$ (dpa)	$106.26(4)^{+1.6\%}_{-1.9\%}$	$108.3(3)^{+0.5\%}_{-0.5\%}$	1.019	$9.58(2)^{+25.5\%}_{-18.9\%}$	$117.9(3)^{+2.1\%}_{-1.6\%}$



# $pp \rightarrow WW \rightarrow l\bar{v}l\bar{v} + X$ NNLO QCD

Poncelet, Popescu, 2102.13583

	NLO	NNLO	$K_{NNLO}$	LI	NNLO+LI
off-shell	$220.06(5)^{+1.8\%}_{-2.3\%}$	$225.4(4)^{+0.6\%}_{-0.6\%}$	1.024	$13.8(2)^{+25.5\%}_{-18.7\%}$	$239.1(4)^{+1.5\%}_{-1.2\%}$
unpol. (nwa)	$221.85(8)^{+1.8\%}_{-2.3\%}$	$227.3(6)^{+0.6\%}_{-0.6\%}$	1.025	$13.68(3)^{+25.5\%}_{-18.7\%}$	$241.0(6)^{+1.5\%}_{-1.1\%}$
unpol. (dpa)	$214.55(7)^{+1.8\%}_{-2.3\%}$	$219.4(4)^{+0.6\%}_{-0.6\%}$	1.023	$13.28(3)^{+25.5\%}_{-18.7\%}$	$232.7(4)^{+1.4\%}_{-1.1\%}$
$W_L^+$ (dpa)	$57.48(3)^{+1.9\%}_{-2.6\%}$	$59.3(2)^{+0.7\%}_{-0.7\%}$	1.032	$2.478(6)^{+25.5\%}_{-18.3\%}$	$61.8(2)^{+1.0\%}_{-0.8\%}$
$W_L^-$ (dpa)	$63.69(5)^{+1.9\%}_{-2.6\%}$	$65.4(3)^{+0.8\%}_{-0.8\%}$	1.026	$2.488(6)^{+25.5\%}_{-18.3\%}$	$67.9(3)^{+0.9\%}_{-0.8\%}$
$W_T^+$ (dpa)	$152.58(9)^{+1.7\%}_{-2.1\%}$	$155.7(6)^{+0.7\%}_{-0.6\%}$	1.020	$11.19(2)^{+25.5\%}_{-18.8\%}$	$166.9(6)^{+1.6\%}_{-1.3\%}$
$W_T^-$ (dpa)	$156.41(7)^{+1.7\%}_{-2.1\%}$	$159.7(6)^{+0.5\%}_{-0.6\%}$	1.021	$11.19(2)^{+25.5\%}_{-18.8\%}$	$170.9(6)^{+1.7\%}_{-1.3\%}$
$W_L^+ W_L^-$ (dpa)	$9.064(6)^{+3.0\%}_{-3.0\%}$	$9.88(3)^{+1.3\%}_{-1.3\%}$	1.090	$0.695(2)^{+25.5\%}_{-18.8\%}$	$10.57(3)^{+2.9\%}_{-2.4\%}$
$W_L^+ W_T^-$ (dpa)	$48.34(3)^{+1.9\%}_{-2.5\%}$	$49.4(2)^{+0.9\%}_{-0.7\%}$	1.021	$1.790(5)^{+25.5\%}_{-18.3\%}$	$51.2(2)^{+0.6\%}_{-0.8\%}$
$W_T^+ W_L^-$ (dpa)	$54.11(5)^{+1.9\%}_{-2.5\%}$	$55.5(4)^{+0.6\%}_{-0.7\%}$	1.025	$1.774(5)^{+25.5\%}_{-18.3\%}$	$57.2(4)^{+0.7\%}_{-0.7\%}$
$W_T^+ W_T^-$ (dpa)	$106.26(4)^{+1.6\%}_{-1.9\%}$	$108.3(3)^{+0.5\%}_{-0.5\%}$	1.019	$9.58(2)^{+25.5\%}_{-18.9\%}$	$117.9(3)^{+2.1\%}_{-1.6\%}$

- LL pol. gets largest NNLO QCD correction
- Loop-induced contribution (LI):  
*large corrections, enhanced scale dep.*



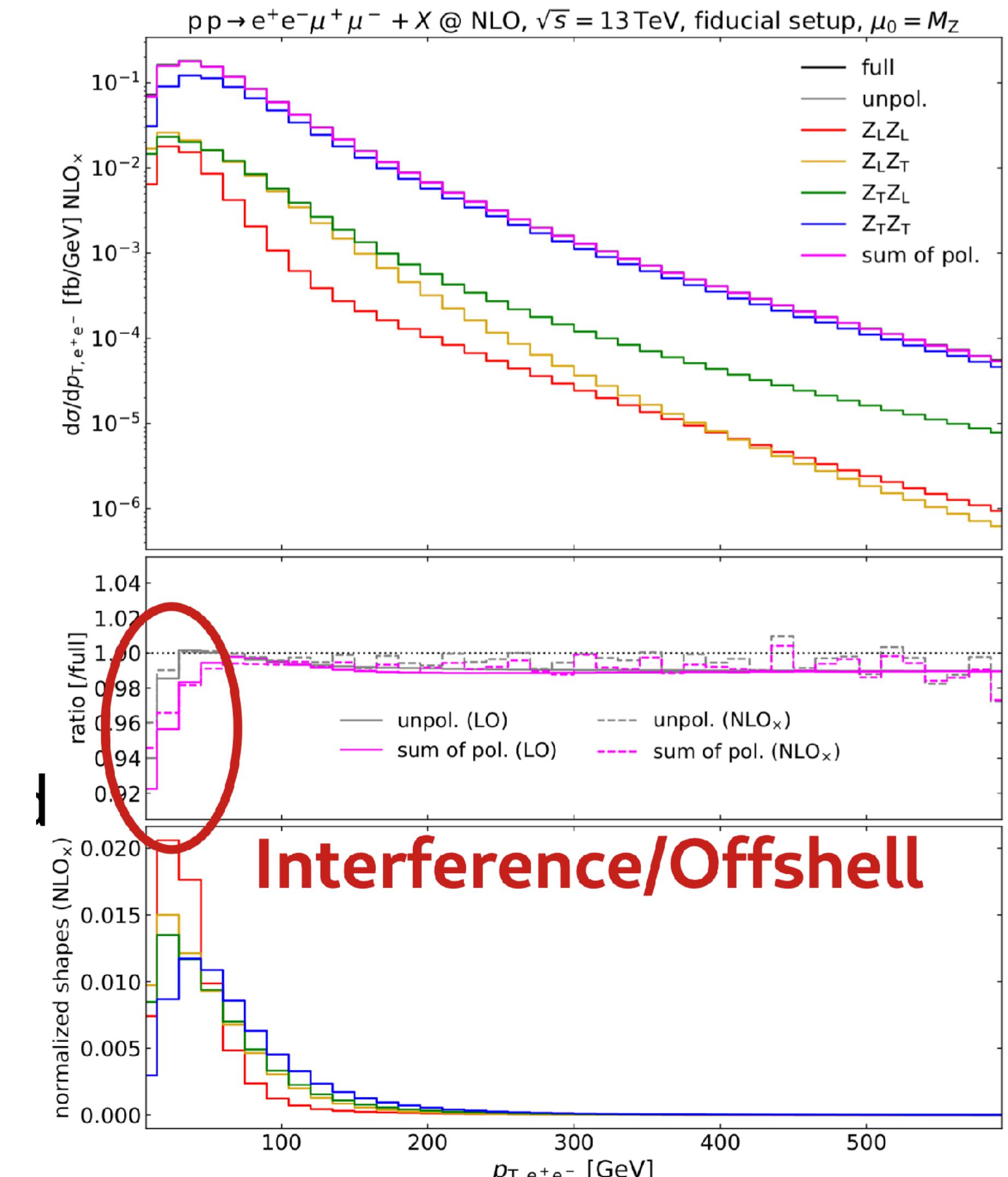
# $pp \rightarrow ZZ \rightarrow 4l + X$ NLO QCD + EW

Denner, Pelliccioli, 2107.06579

mode	$\sigma_{\text{LO}}$ [fb]	$\delta_{\text{QCD}}$	$\delta_{\text{EW}}$	$\delta_{\text{gg}}$	$\sigma_{\text{NLO}_+}$ [fb]	$\sigma_{\text{NLO}_x}$ [fb]
full	11.1143(5) <sup>+5.6%</sup> <sub>-6.8%</sub>	+34.9%	-11.0%	+15.6%	15.505(6) <sup>+5.7%</sup> <sub>-4.4%</sub>	15.076(5) <sup>+5.5%</sup> <sub>-4.2%</sub>
unpol.	11.0214(5) <sup>+5.6%</sup> <sub>-6.8%</sub>	+35.0%	-10.9%	+15.7%	15.416(5) <sup>+5.7%</sup> <sub>-4.4%</sub>	14.997(4) <sup>+5.5%</sup> <sub>-4.2%</sub>
$Z_L Z_L$	0.64302(5) <sup>+6.8%</sup> <sub>-8.1%</sub>	+35.7%	-10.2%	+14.5%	0.9002(6) <sup>+5.5%</sup> <sub>-4.3%</sub>	0.8769(5) <sup>+5.4%</sup> <sub>-4.1%</sub>
$Z_L Z_T$	1.30468(9) <sup>+6.5%</sup> <sub>-7.7%</sub>	+45.3%	-9.9%	+2.8%	1.8016(9) <sup>+4.3%</sup> <sub>-3.5%</sub>	1.7426(8) <sup>+4.1%</sup> <sub>-3.3%</sub>
$Z_T Z_L$	1.30854(9) <sup>+6.5%</sup> <sub>-7.7%</sub>	+44.3%	-9.9%	+2.8%	1.7933(9) <sup>+4.3%</sup> <sub>-3.4%</sub>	1.7355(8) <sup>+4.0%</sup> <sub>-3.2%</sub>
$Z_T Z_T$	7.6425(3) <sup>+5.2%</sup> <sub>-6.4%</sub>	+31.2%	-11.2%	+20.5%	10.739(4) <sup>+6.2%</sup> <sub>-4.7%</sub>	10.471(3) <sup>+6.1%</sup> <sub>-4.6%</sub>

## Total cross sections

- Small LL contribution, TT dominates
- Quite sizable NLO and EW corrections
- Large gg-loop induced (LI) contribution
- Pol. fractions preserved from LO to NLO
- Similar for NLO QCD/EW for  $WZ$ ,  $WW$



Interference/Offshell

# $pp \rightarrow ZZ \rightarrow 4l + X$ NLO QCD + EW

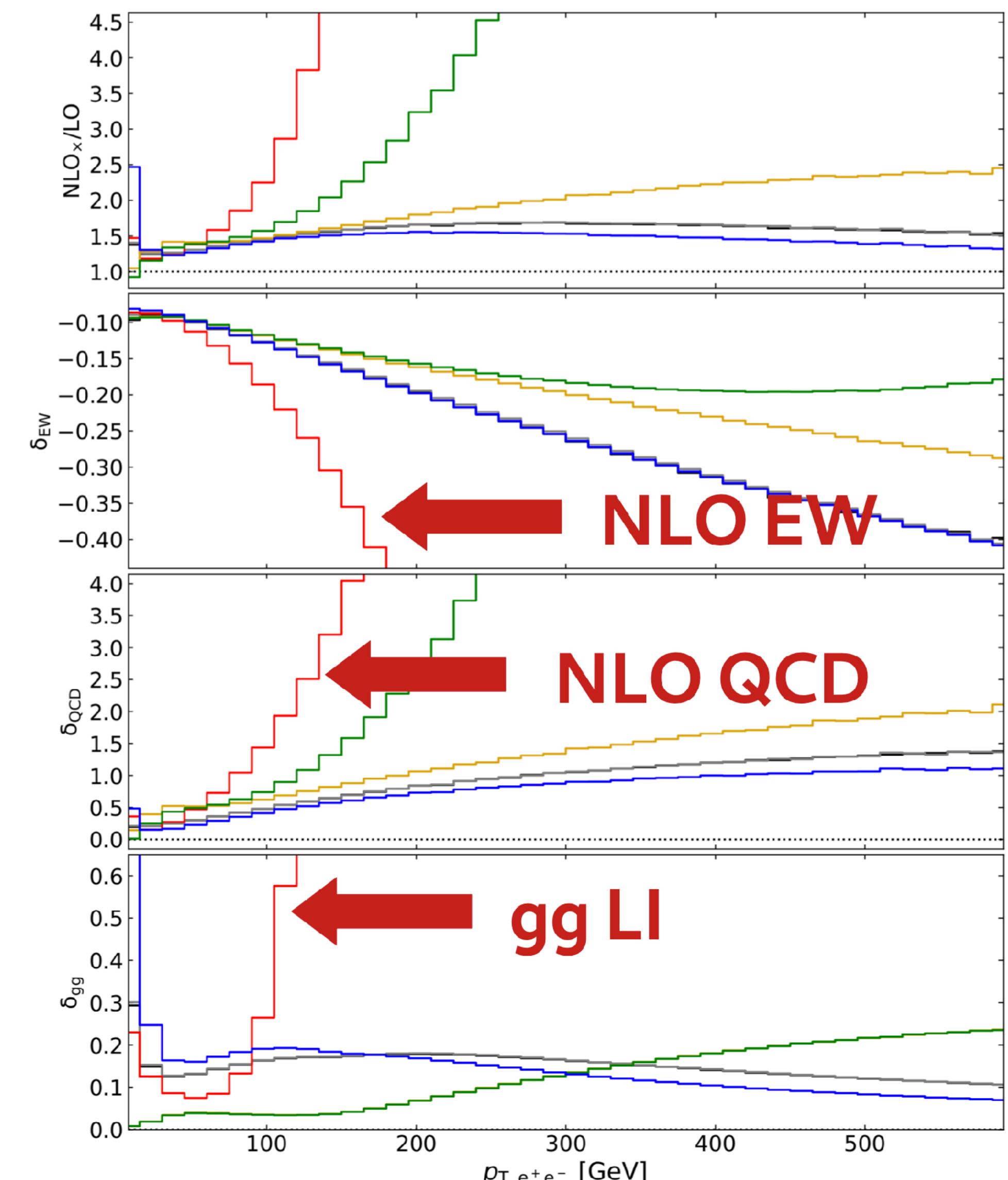
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Denner, Pelliccioli, 2107.06579

mode	$\sigma_{\text{LO}}$ [fb]	$\delta_{\text{QCD}}$	$\delta_{\text{EW}}$	$\delta_{\text{gg}}$	$\sigma_{\text{NLO}_+}$ [fb]	$\sigma_{\text{NLO}_x}$ [fb]
full	11.1143(5) <sup>+5.6%</sup> <sub>-6.8%</sub>	+34.9%	-11.0%	+15.6%	15.505(6) <sup>+5.7%</sup> <sub>-4.4%</sub>	15.076(5) <sup>+5.5%</sup> <sub>-4.2%</sub>
unpol.	11.0214(5) <sup>+5.6%</sup> <sub>-6.8%</sub>	+35.0%	-10.9%	+15.7%	15.416(5) <sup>+5.7%</sup> <sub>-4.4%</sub>	14.997(4) <sup>+5.5%</sup> <sub>-4.2%</sub>
$Z_L Z_L$	0.64302(5) <sup>+6.8%</sup> <sub>-8.1%</sub>	+35.7%	-10.2%	+14.5%	0.9002(6) <sup>+5.5%</sup> <sub>-4.3%</sub>	0.8769(5) <sup>+5.4%</sup> <sub>-4.1%</sub>
$Z_L Z_T$	1.30468(9) <sup>+6.5%</sup> <sub>-7.7%</sub>	+45.3%	-9.9%	+2.8%	1.8016(9) <sup>+4.3%</sup> <sub>-3.5%</sub>	1.7426(8) <sup>+4.1%</sup> <sub>-3.3%</sub>
$Z_T Z_L$	1.30854(9) <sup>+6.5%</sup> <sub>-7.7%</sub>	+44.3%	-9.9%	+2.8%	1.7933(9) <sup>+4.3%</sup> <sub>-3.4%</sub>	1.7355(8) <sup>+4.0%</sup> <sub>-3.2%</sub>
$Z_T Z_T$	7.6425(3) <sup>+5.2%</sup> <sub>-6.4%</sub>	+31.2%	-11.2%	+20.5%	10.739(4) <sup>+6.2%</sup> <sub>-4.7%</sub>	10.471(3) <sup>+6.1%</sup> <sub>-4.6%</sub>

## Differential distributions

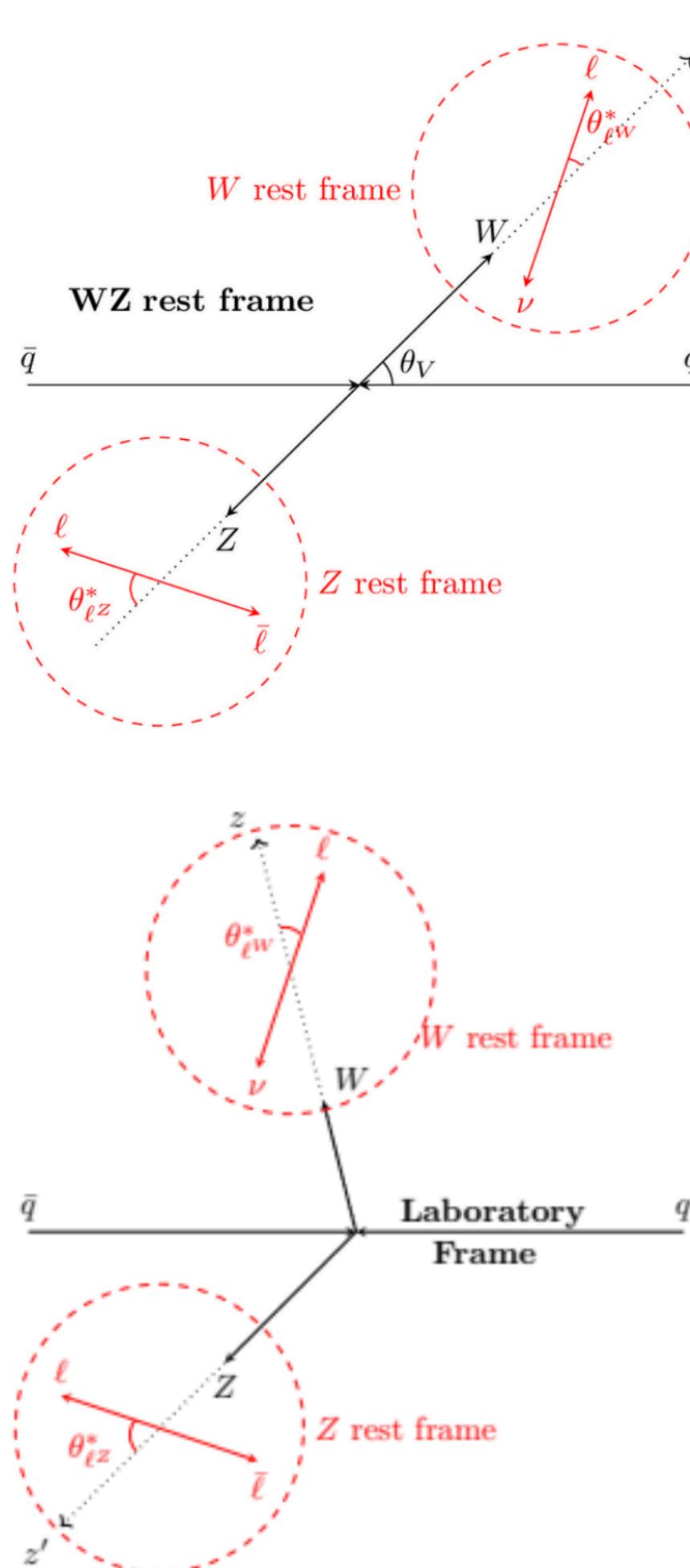
- Low region: off-shell effects and spin correlations
- Very large NLO QCD corrections
- New polarization from e.g.  $gq \rightarrow ZZq$
- Great care with such observables, e.g. in fits
- Never use without prescription from local theorist!



# $pp \rightarrow WZ \rightarrow lll\nu + X$ @ATLAS

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$$\mathbb{P}(V_1(v_1) \cap H = h_0) = \mathbb{P}(H = h_0 | V_1(v_1)) \mathbb{P}(V_1(v_1))$$



Distribution of variable  $V_1$ ,  
for a boson with  
polarisation  $H=h_0$

Polarisation fraction  $f_{h_0}(v_1)$  in  
bin around  $v_1$  for variable  $V_1$ ,  
= applied weight !

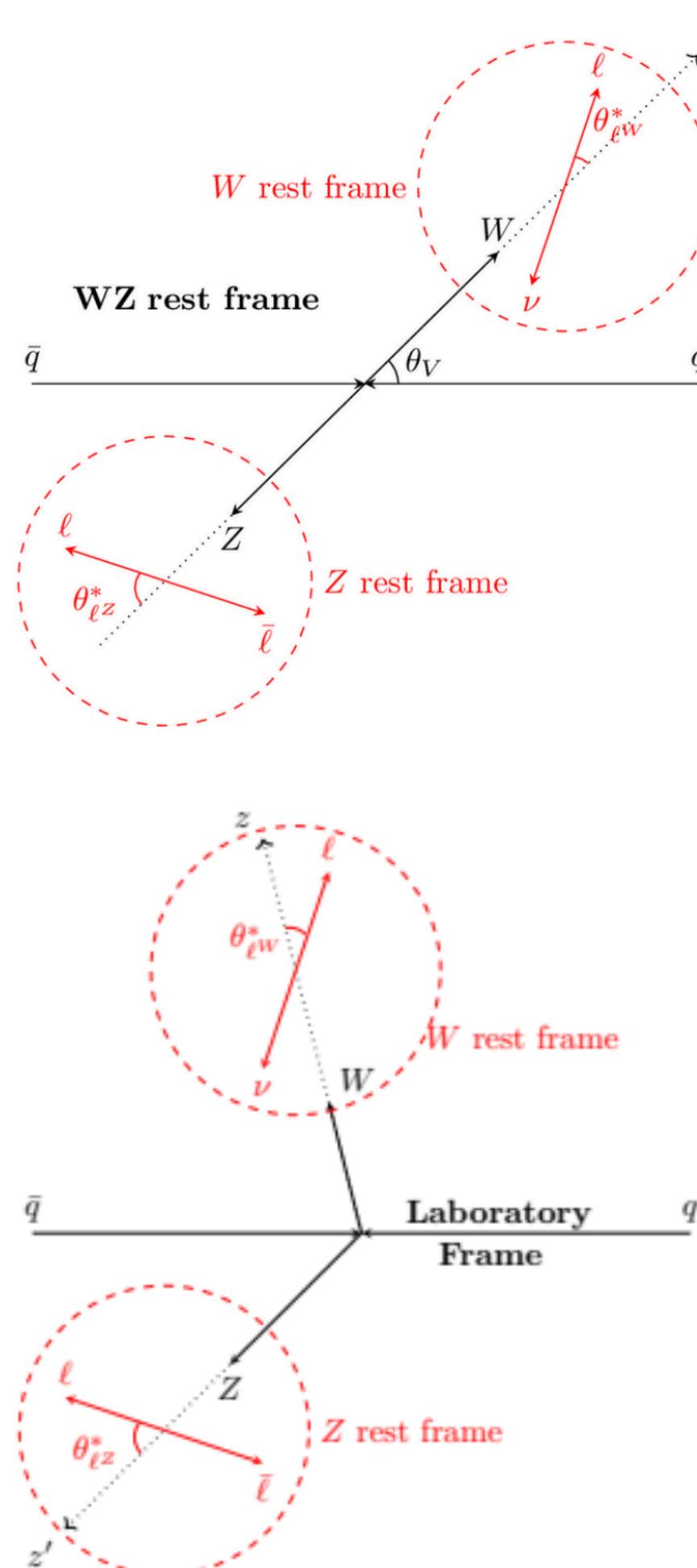
Distribution of  
variable  $V_1$  for an  
unpolarised boson

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} F_{\lambda'_W \lambda'_Z}^{(\mu_q \mu_{\bar{q}})*} \quad C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} \right|^2$$

$$\begin{aligned} f_{00} &= \rho_{0000} , \\ f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++} , \\ f_{0T} &= \rho_{00--} + \rho_{00++} , \\ f_{T0} &= \rho_{--00} + \rho_{++00} . \end{aligned}$$

# $pp \rightarrow WZ \rightarrow lll\nu + X$ @ATLAS

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$$\mathbb{P}(V_1(v_1) \cap H = h_0) = \mathbb{P}(H = h_0 | V_1(v_1)) \mathbb{P}(V_1(v_1))$$

*Distribution of variable  $V_1$ ,  
for a boson with  
polarisation  $H=h_0$*

*Polarisation fraction  $f_{h0}(v_1)$  in  
bin around  $v_1$  for variable  $V_1$ ,  
= applied weight !*

*Distribution of  
variable  $V_1$  for an  
unpolarised boson*

- DNN reweighted NLO joint-polarization template fit
- Independent fit of  $f_{TT}$ ,  $f_{0T}$ ,  $f_{00}$ ,  $N_{tot}$
- Decouple polarization fraction shapes from overall normalization
- Iterative Bayesian unfolding of polarization-sensitive variables:

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} F_{\lambda'_W \lambda'_Z}^{(\mu_q \mu_{\bar{q}})*} \quad C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F_{\lambda_W \lambda_Z}^{(\mu_q \mu_{\bar{q}})} \right|^2$$

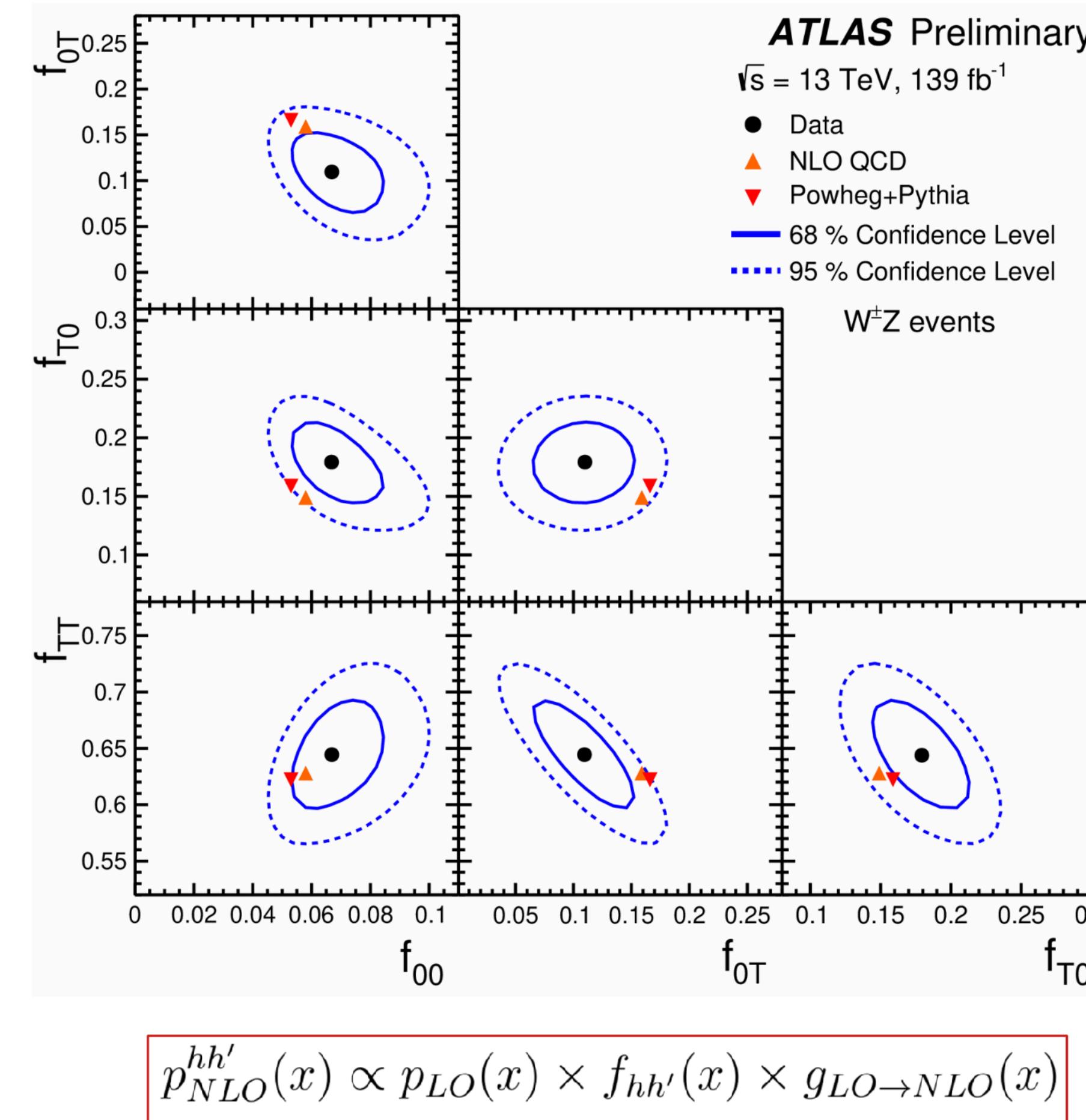
$$\begin{aligned} f_{00} &= \rho_{0000}, \\ f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}, \\ f_{0T} &= \rho_{00--} + \rho_{00++}, \\ f_{T0} &= \rho_{--00} + \rho_{++00}. \end{aligned}$$

# $pp \rightarrow WZ \rightarrow lll\nu + X$ @ATLAS

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$$\mathbb{P}(V_1(v_1) \cap H = h_0) = \mathbb{P}(H = h_0 | V_1(v_1)) \mathbb{P}(V_1(v_1))$$



Distribution of variable  $V_1$ ,  
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Polarisation fraction  $f_{h_0}(v_1)$  in  
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Distribution of  
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