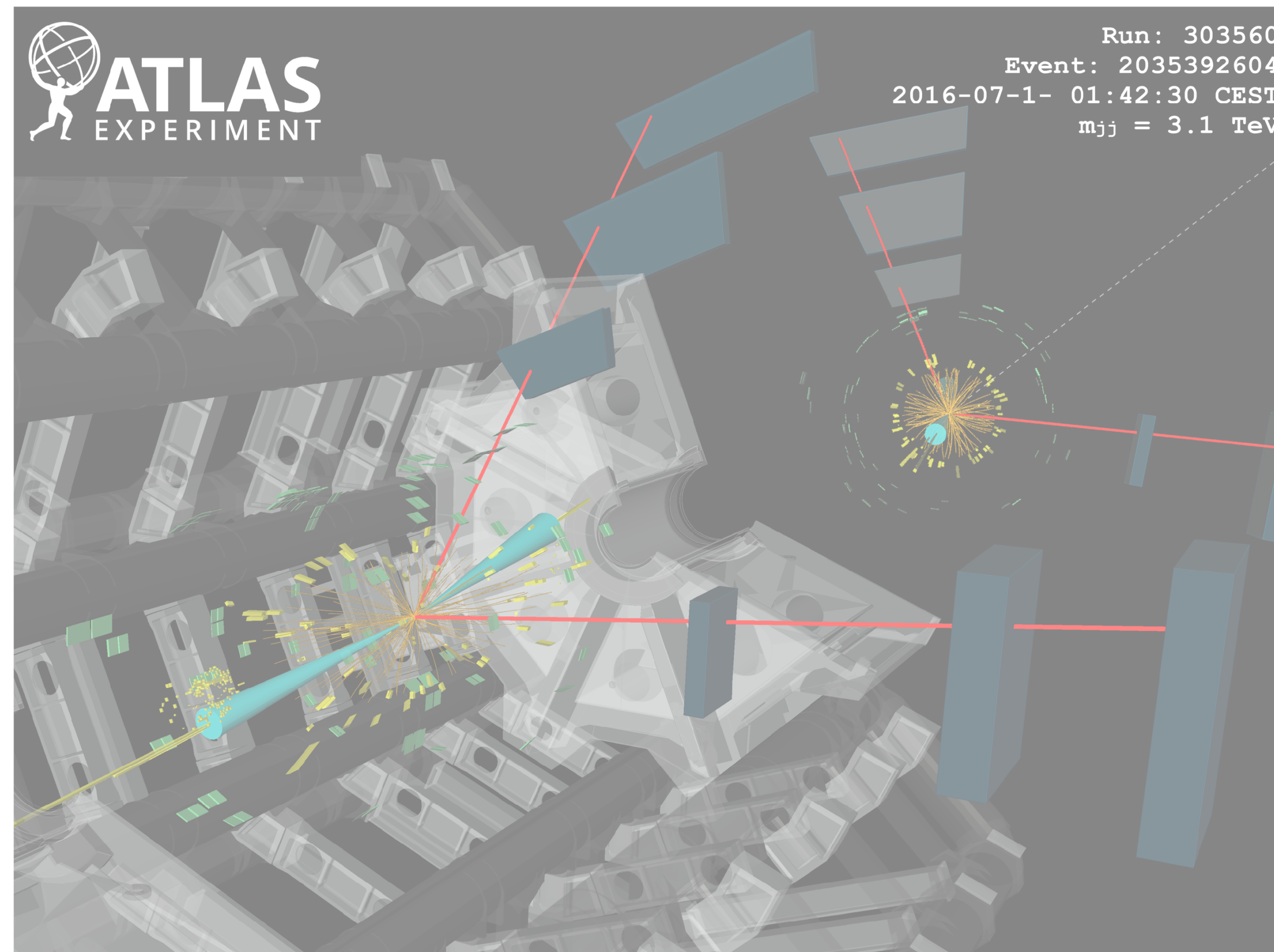


Vector Boson Scattering at the LHC — Precision, Polarization & New Physics Searches



HELMHOLTZ



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Jürgen R. Reuter

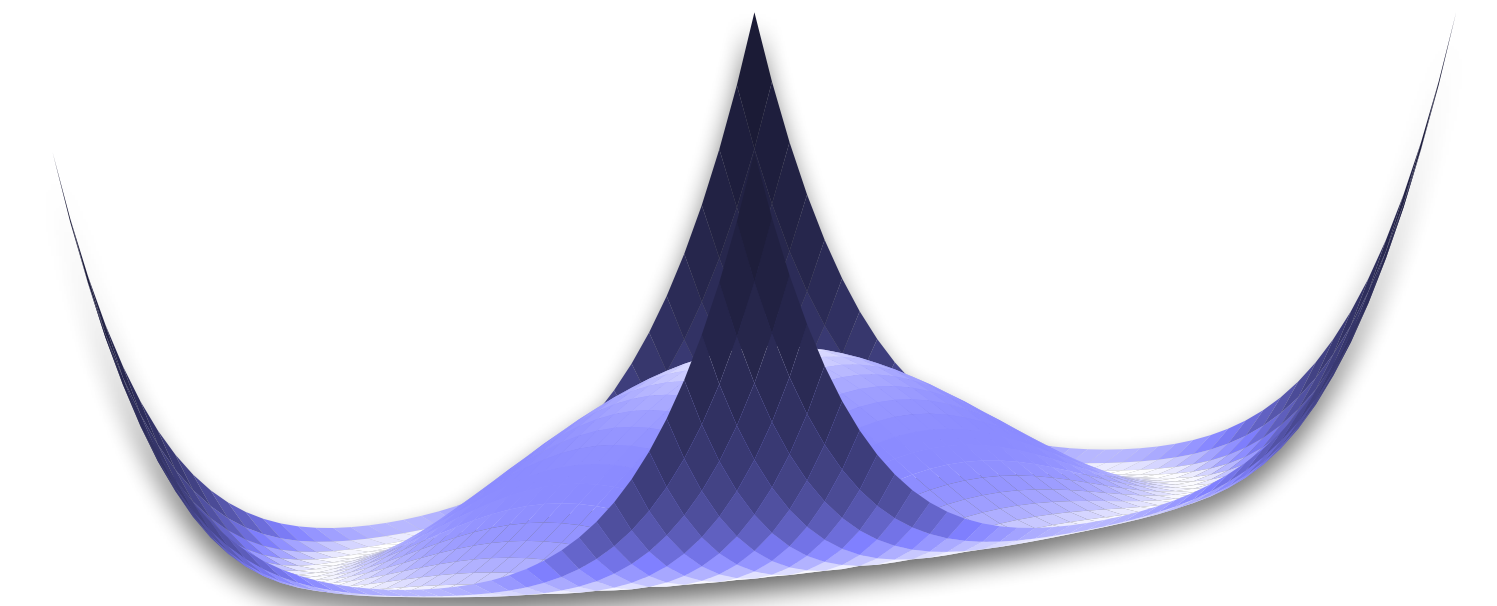
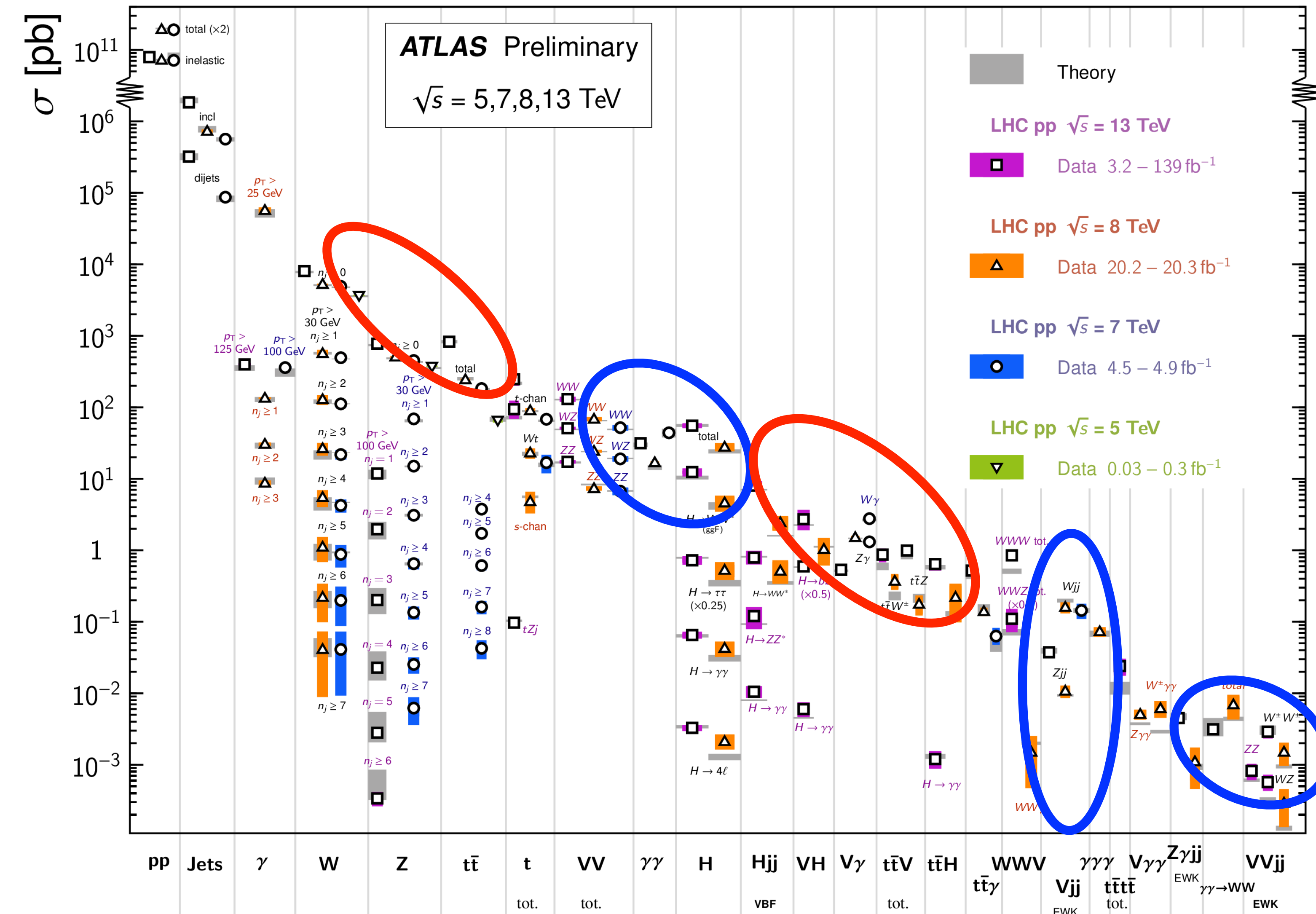


The mystery of electroweak interactions

2 / 31

Standard Model Production Cross Section Measurements

Status: July 2021



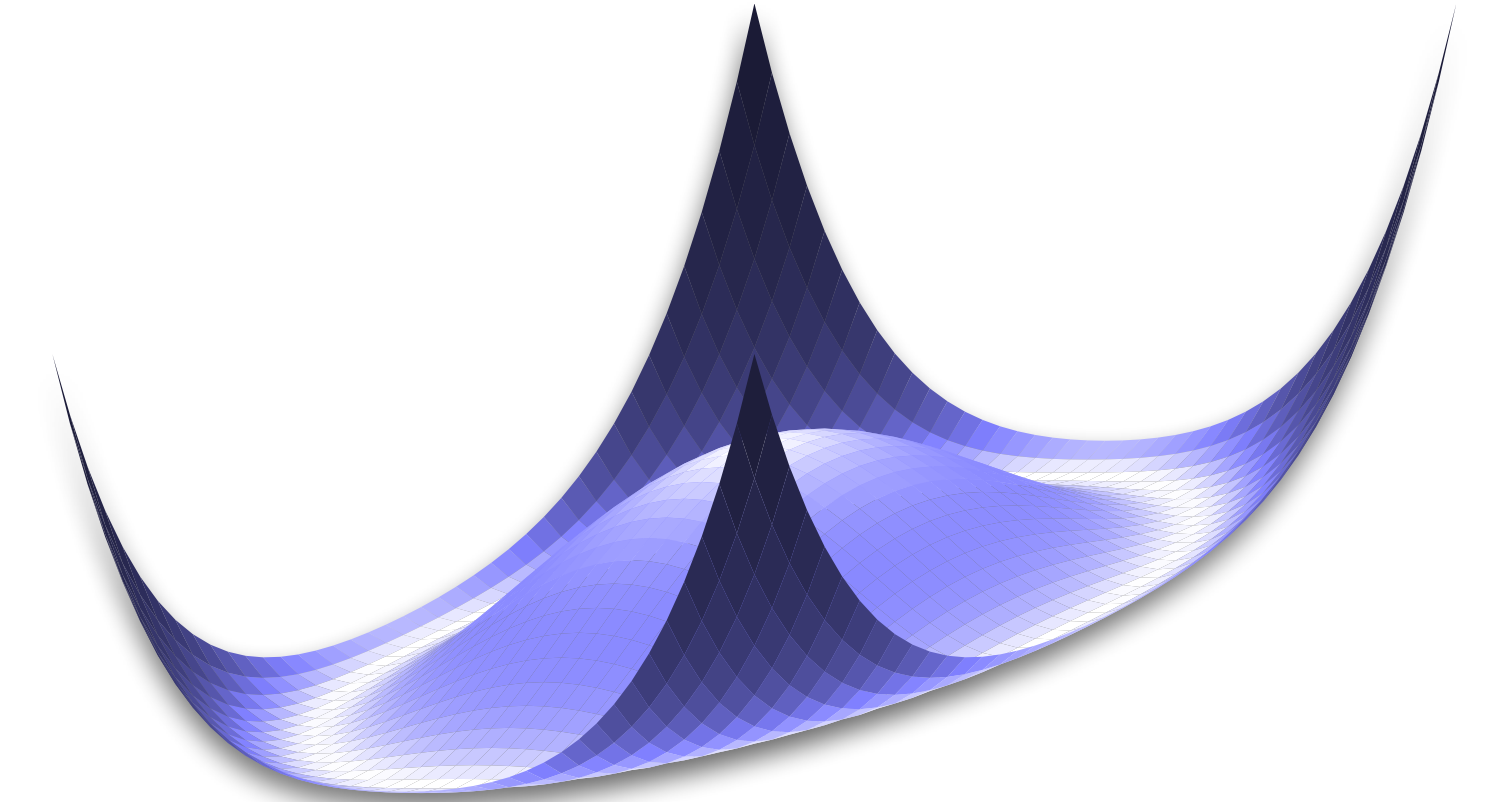
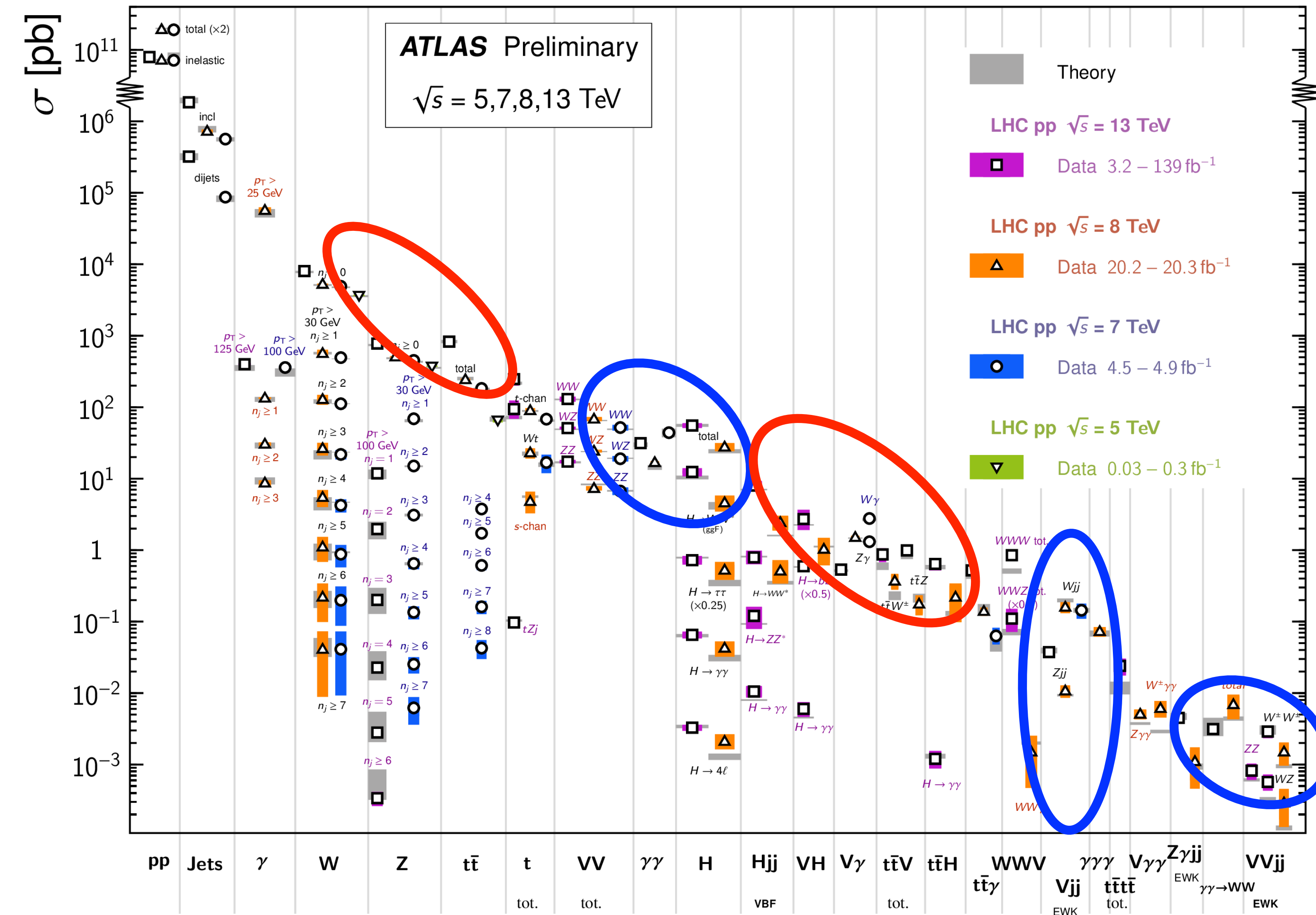
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- Missing: **microscopic origin of EWSB**
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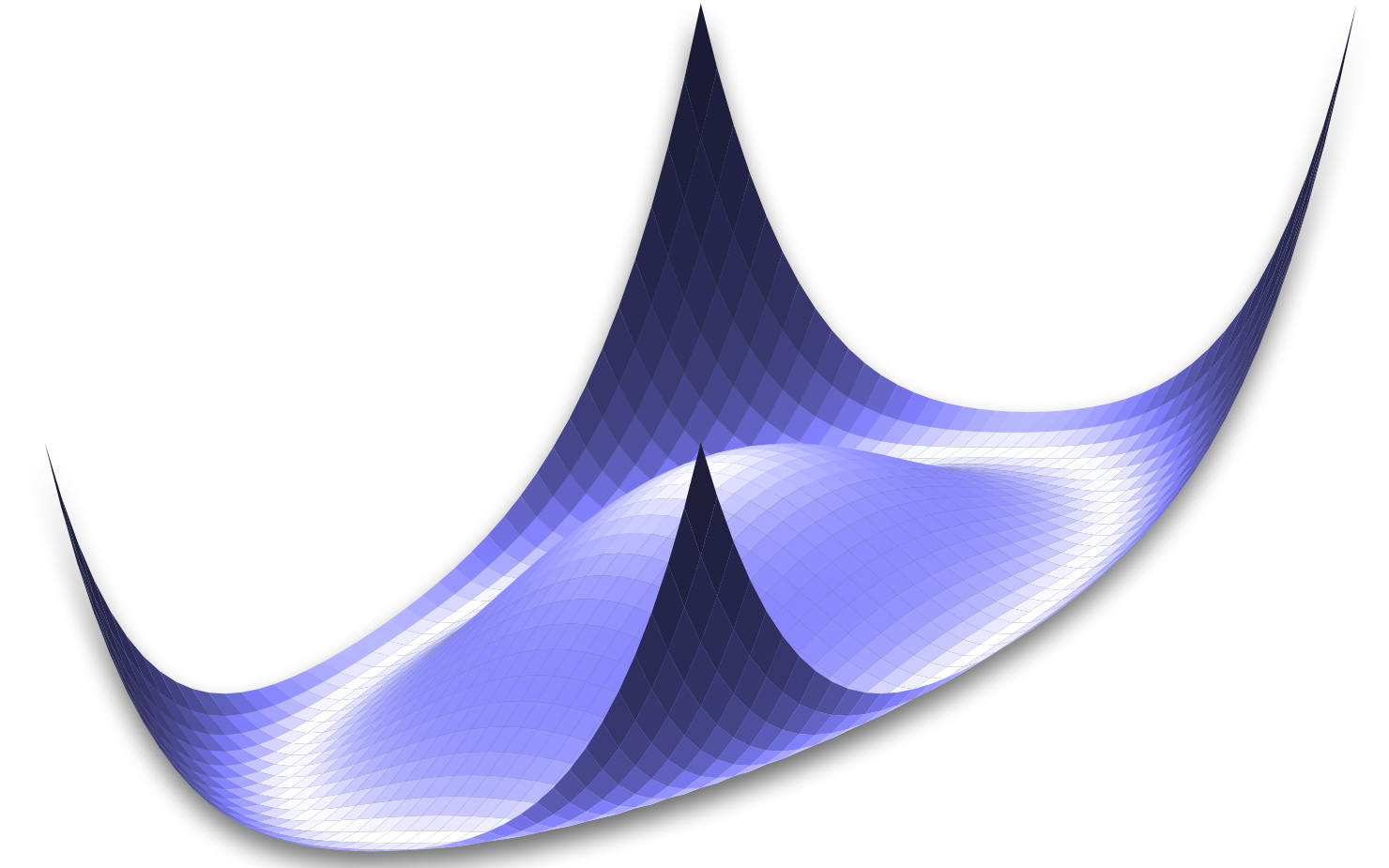
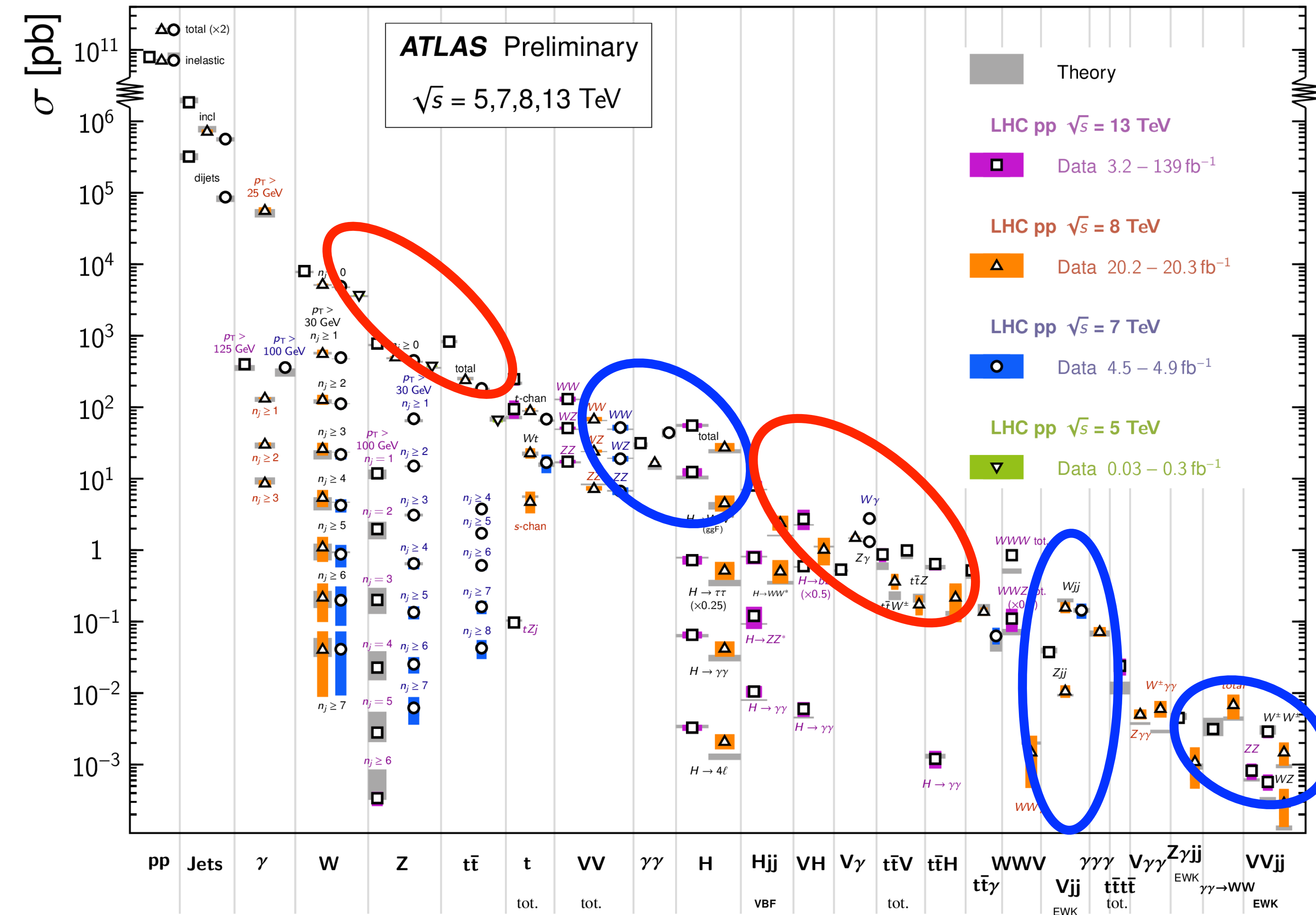
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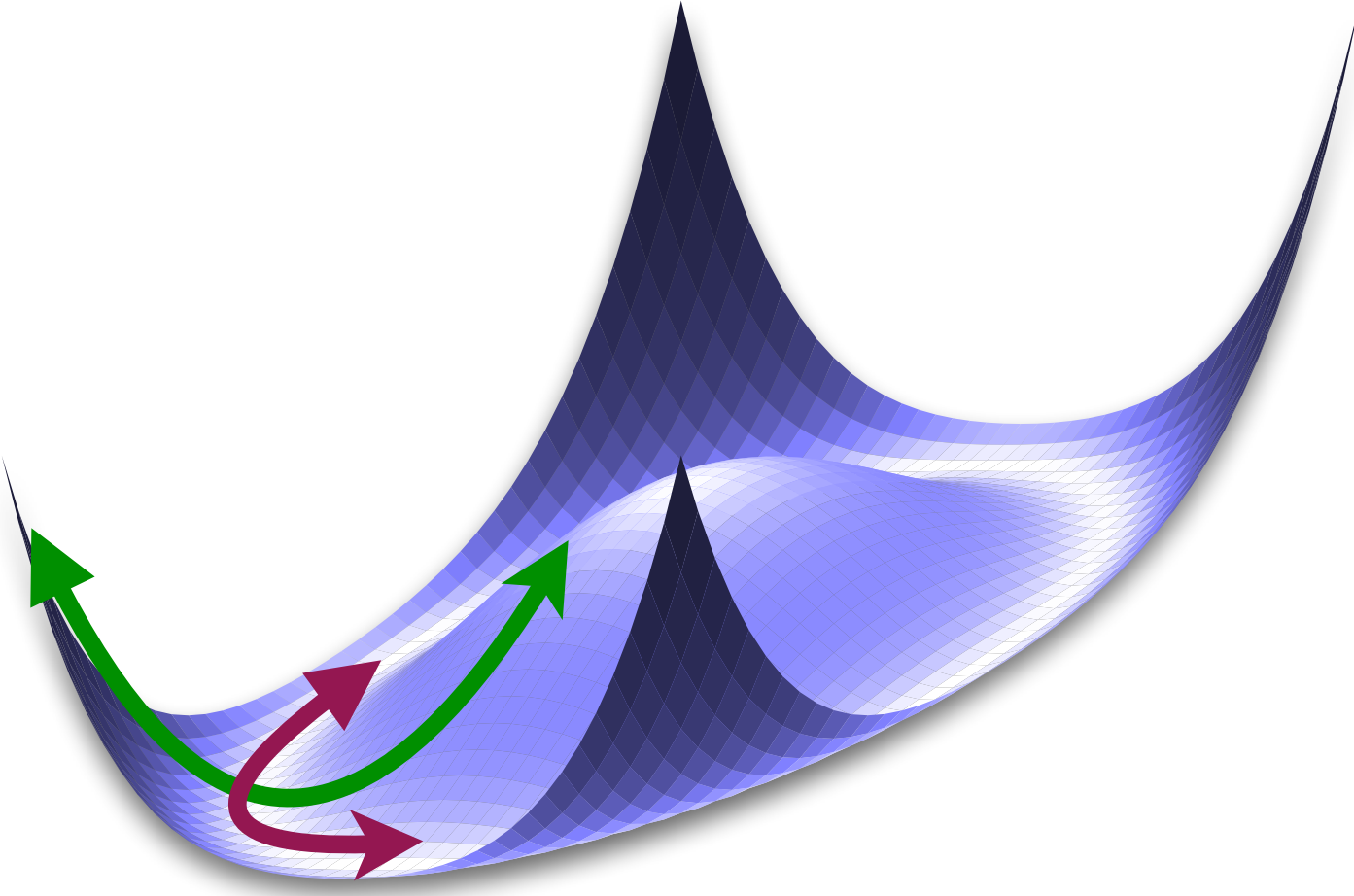
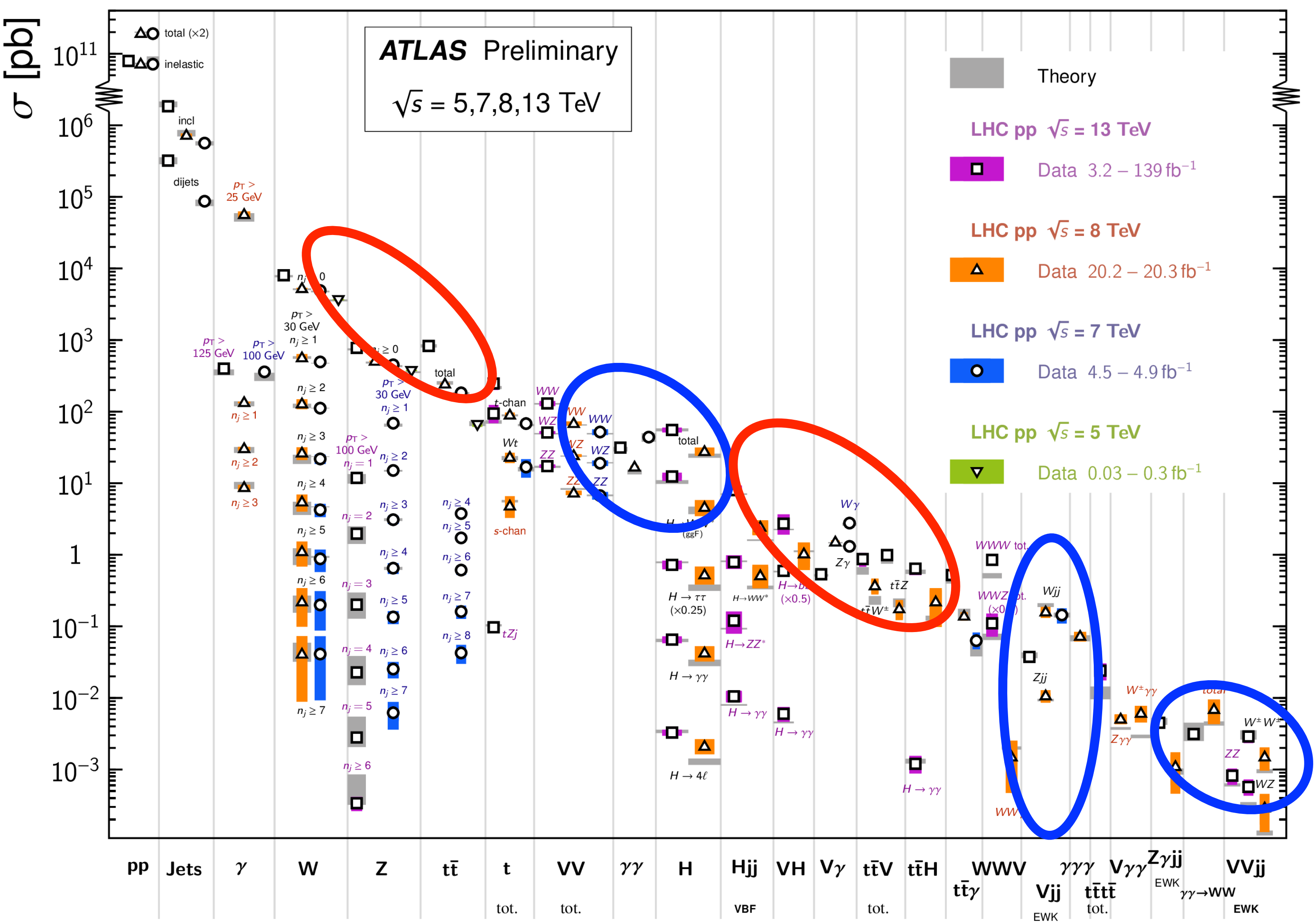


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From the past via present to the future

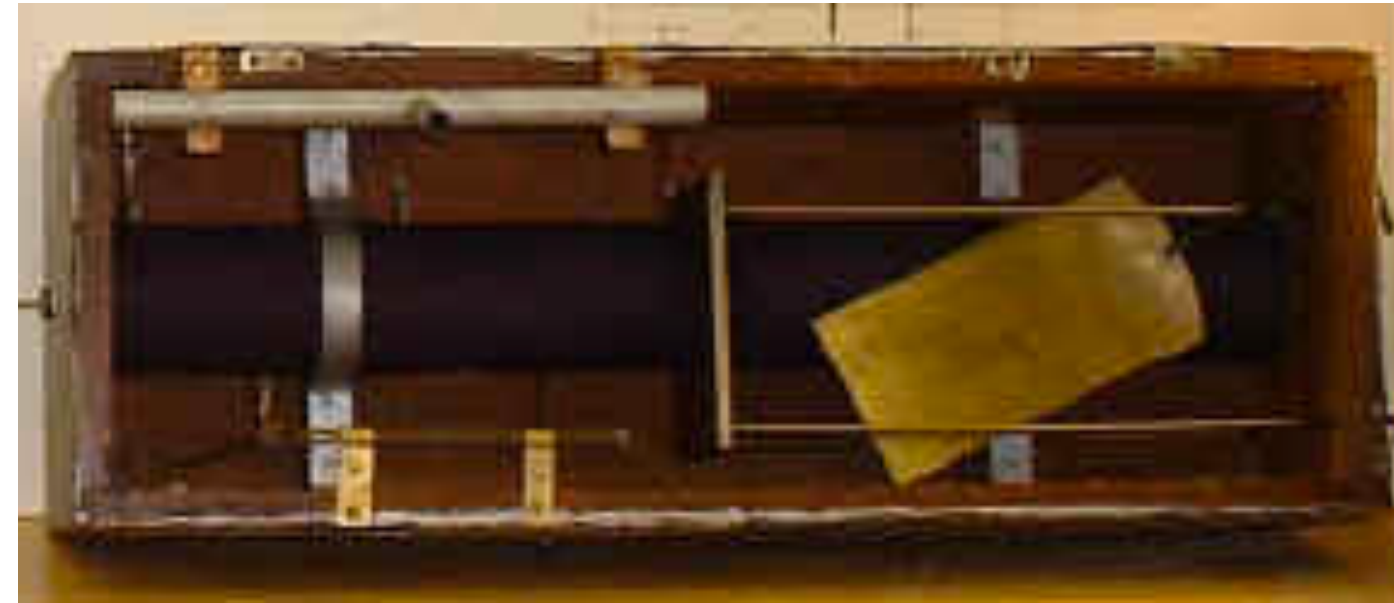
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From the past via present to the future

3 / 31

- 1898: Weak interactions known since 1898 (beta decay; virtual W exchange
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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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* 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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(points to high scale v)

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- ✦ Describes the measured interactions
- ✦ Includes a high new physics scale ν
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Effective theory leads to invalidity / unitarity violation at higher energies

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



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

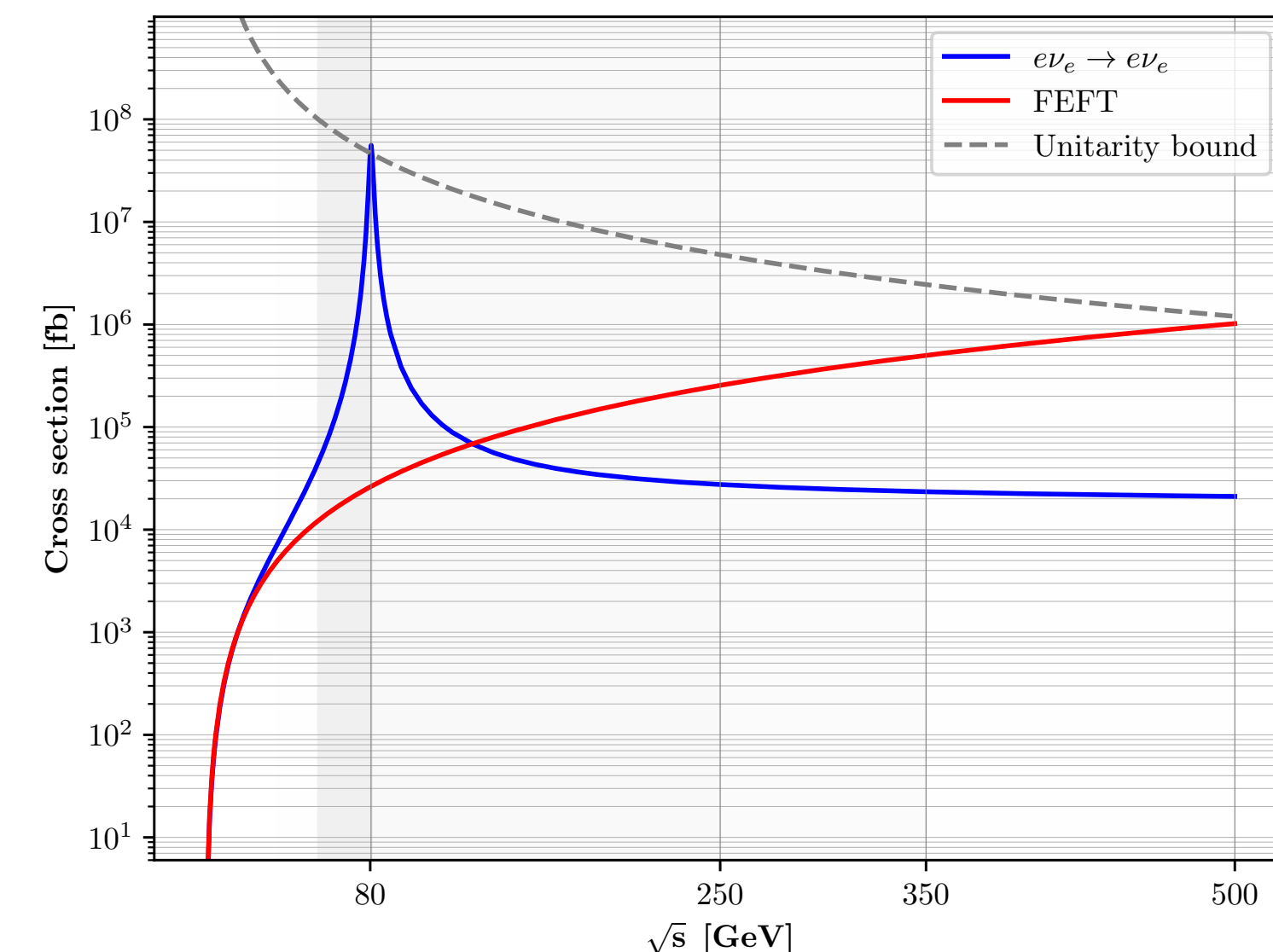
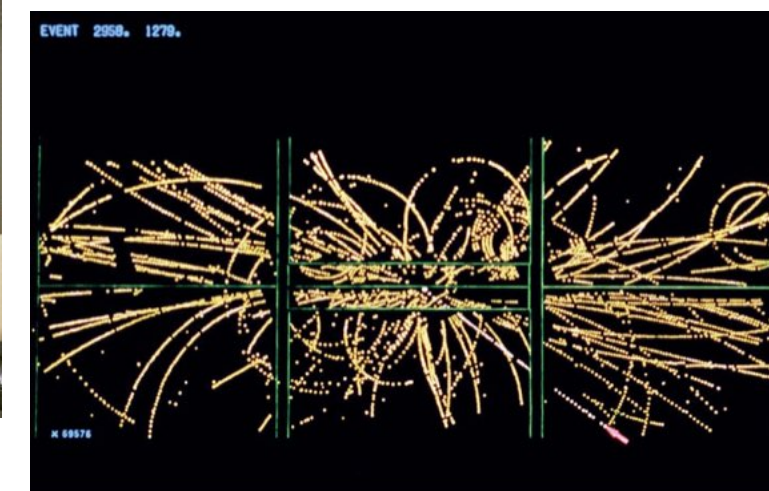
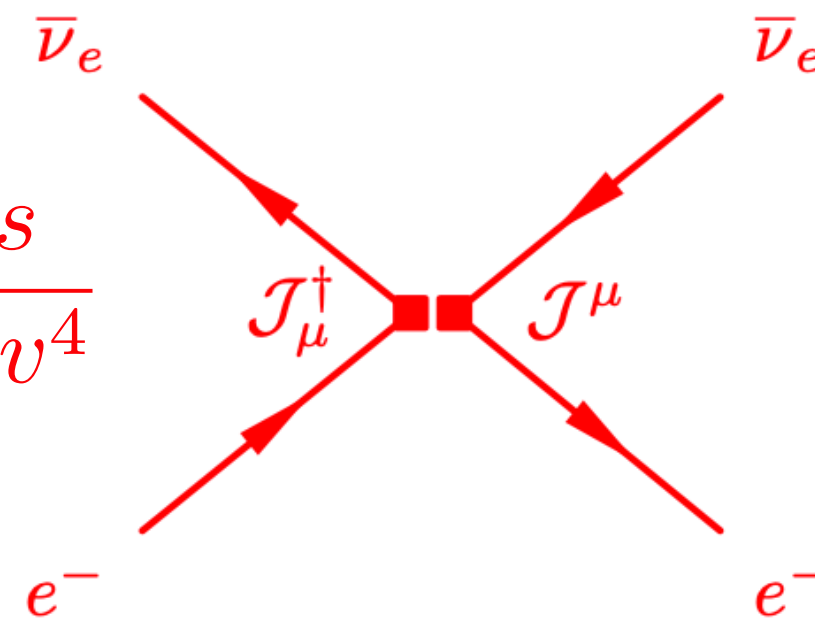


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The rationale of Effective Field Theories

4 / 31

- 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)

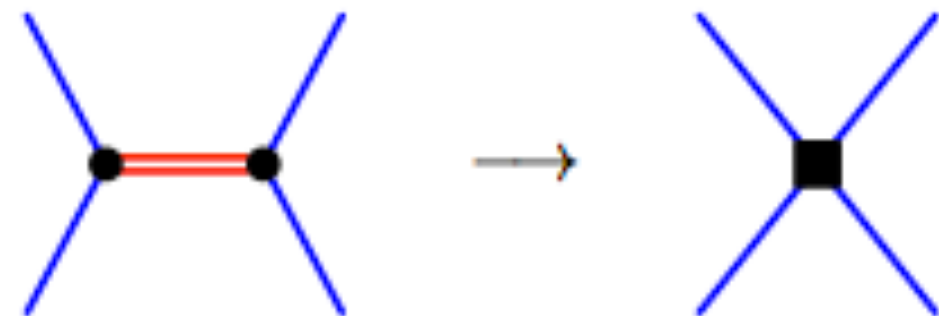
- Add all higher-dimensional operators consisting of SM fields/consistent with SM symmetries

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

- $v \ll \Lambda$: 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

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

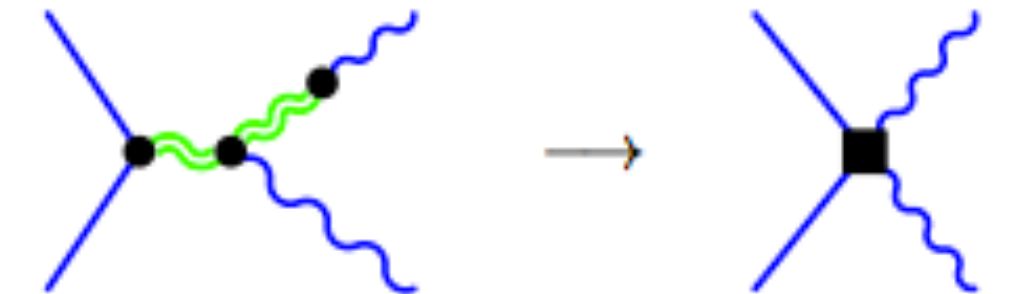
$$\mathcal{O}'_{\Phi\Phi} = \frac{1}{\Lambda^2} (\Phi^\dagger\Phi - v^2/2) (D\Phi)^\dagger \cdot (D\Phi)$$



Truncation introduces model dependence again

..., 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



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

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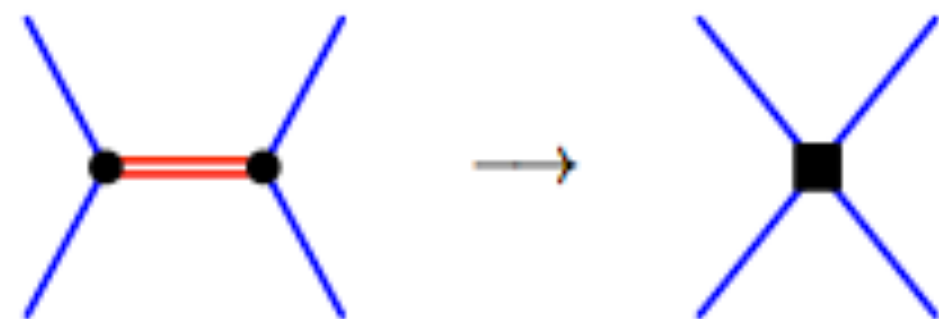
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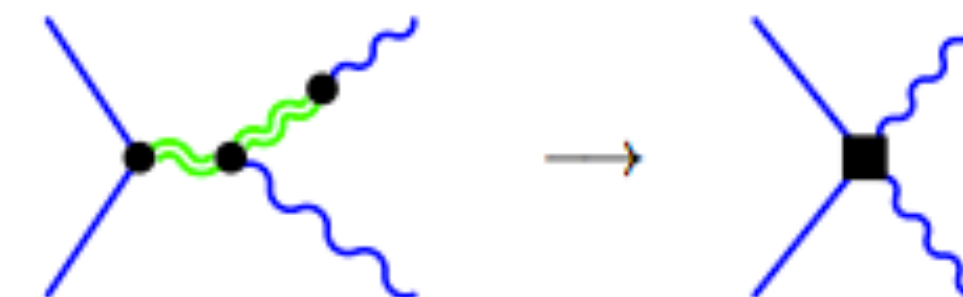
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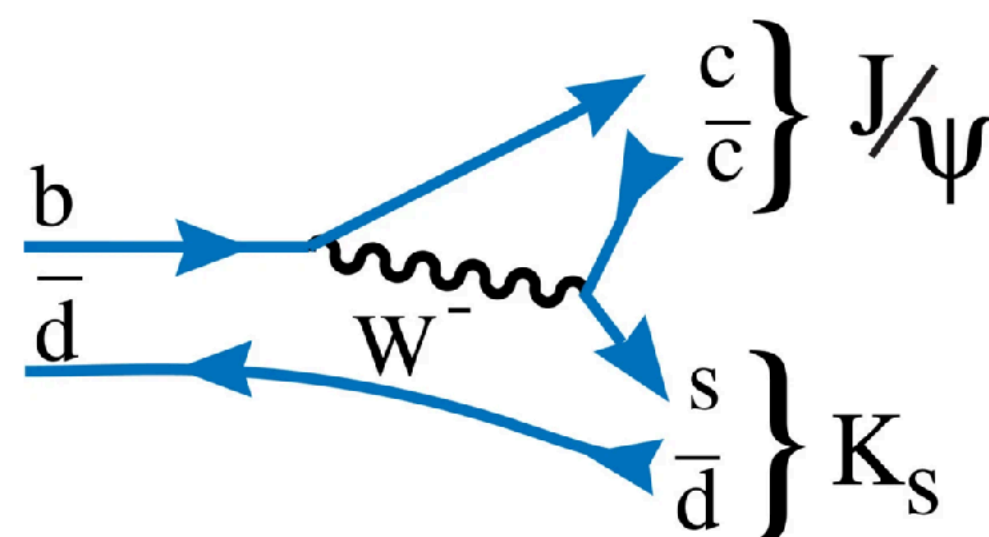
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$$\text{Mass } m_{B^0} = 5279.66 \pm 0.12 \text{ MeV}$$

$$m_{B^0} - m_{B^\pm} = 0.32 \pm 0.05 \text{ MeV}$$

$$\text{Mean life } \tau_{B^0} = (1.519 \pm 0.004) \times 10^{-12} \text{ s}$$

$$c\tau = 455.4 \text{ } \mu\text{m}$$



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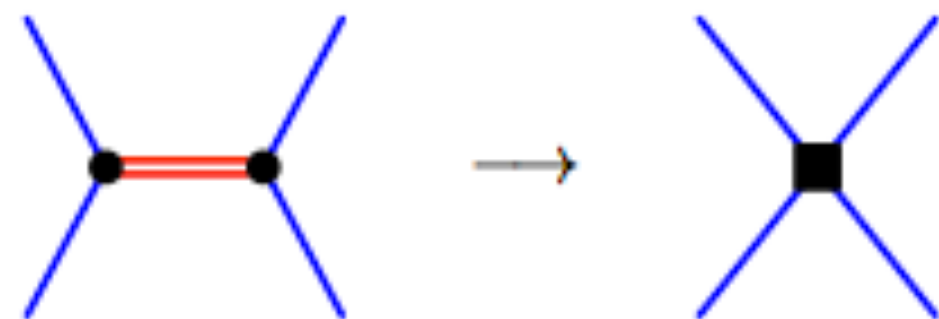
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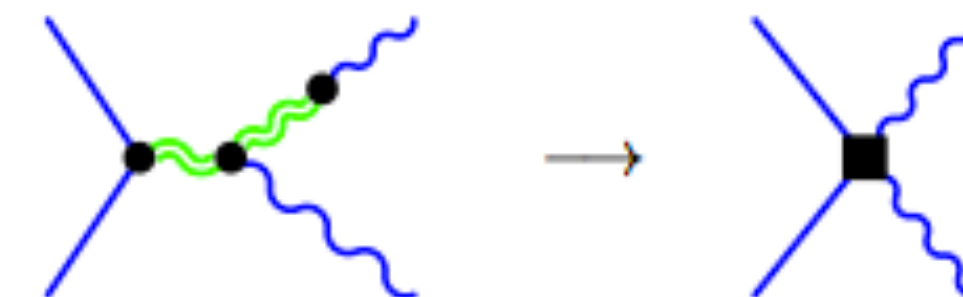
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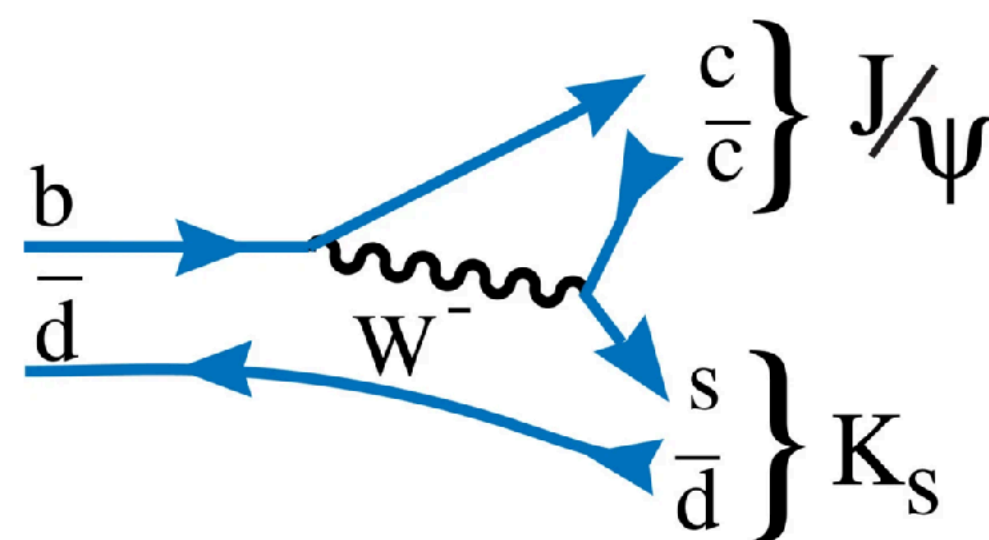
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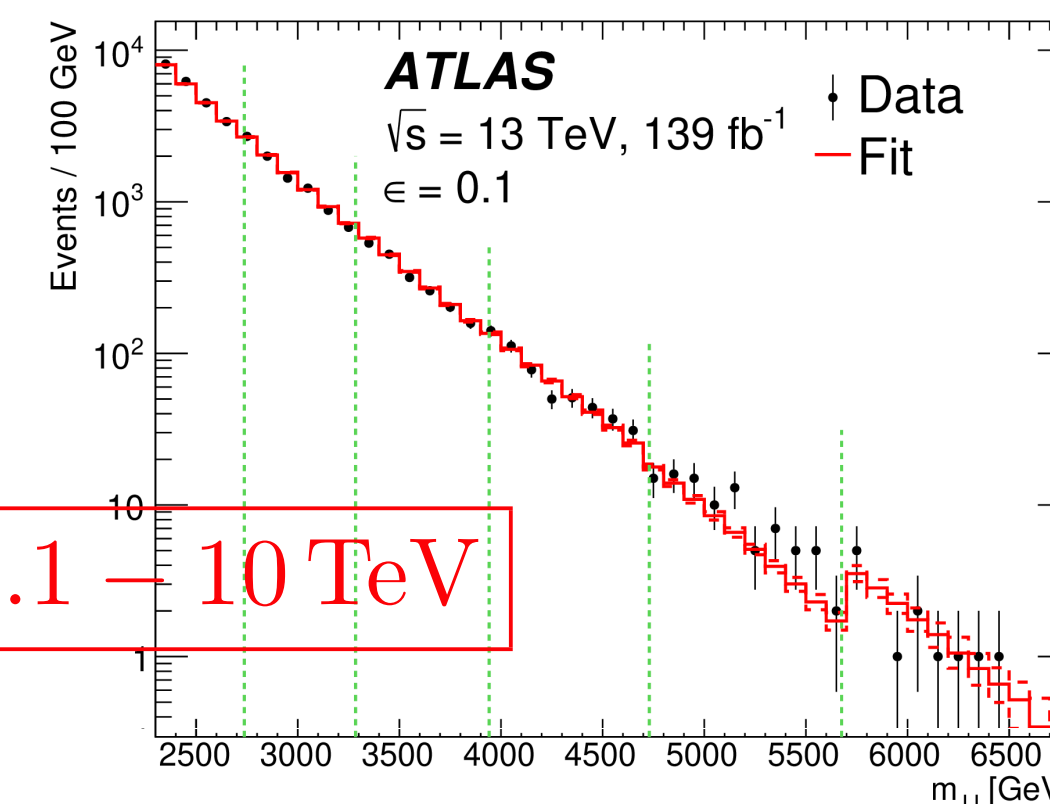
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$$\Lambda_{\text{low}} \sim .1 - 10 \text{ TeV}$$



EFT Operators in Multi-Boson Physics @ Dim-6

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

$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$

$$\mathcal{O}_W = (D_{\mu}\Phi)^{\dagger} W^{\mu\nu} (D_{\nu}\Phi)$$

$$\mathcal{O}_B = (D_{\mu}\Phi)^{\dagger} B^{\mu\nu} (D_{\nu}\Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_{\mu}(\Phi^{\dagger}\Phi) \partial^{\mu}(\Phi^{\dagger}\Phi)$$

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

$$\mathcal{O}_{\Phi B} = (\Phi^{\dagger}\Phi) B^{\mu\nu} B_{\mu\nu}$$

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

$$\mathcal{O}_{\tilde{W}W} = \Phi^{\dagger} \tilde{W}_{\mu\nu} W^{\mu\nu} \Phi \quad \mathcal{O}_{\tilde{W}WW} = \text{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$

$$\mathcal{O}_{\tilde{B}B} = \Phi^{\dagger} \tilde{B}_{\mu\nu} B^{\mu\nu} \Phi \quad \mathcal{O}_{\tilde{W}} = (D_{\mu}\Phi)^{\dagger} \tilde{W}^{\mu\nu} (D_{\nu}\Phi)$$

All operators can change
differential rates &
polarization fractions!

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

- “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

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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

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

	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

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- 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:

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

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

The importance of multi-bosons

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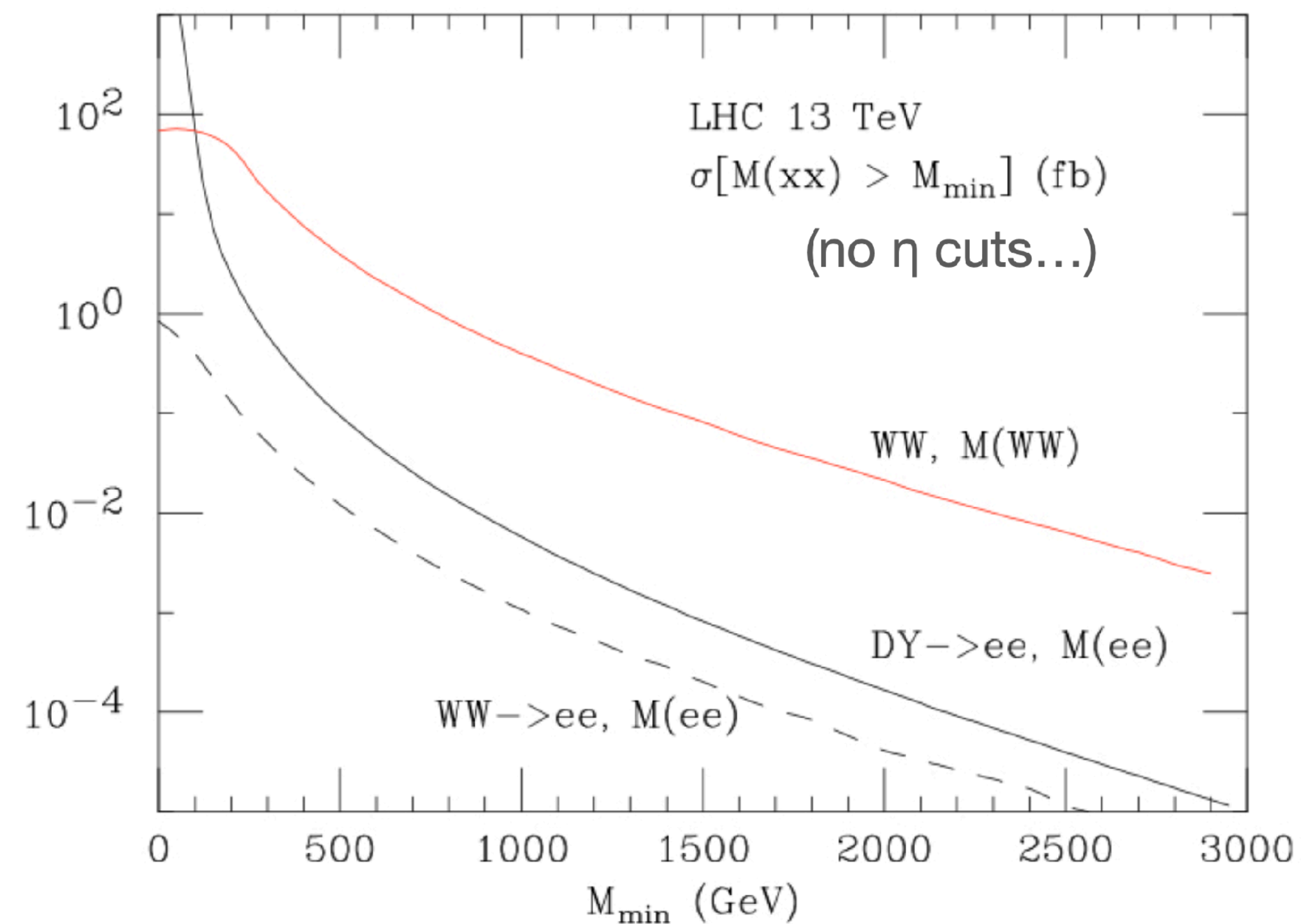
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- This changes for looking at the high-energy region:

Multibosons are the most sensitive probe of EW interactions in the high- Q^2 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

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

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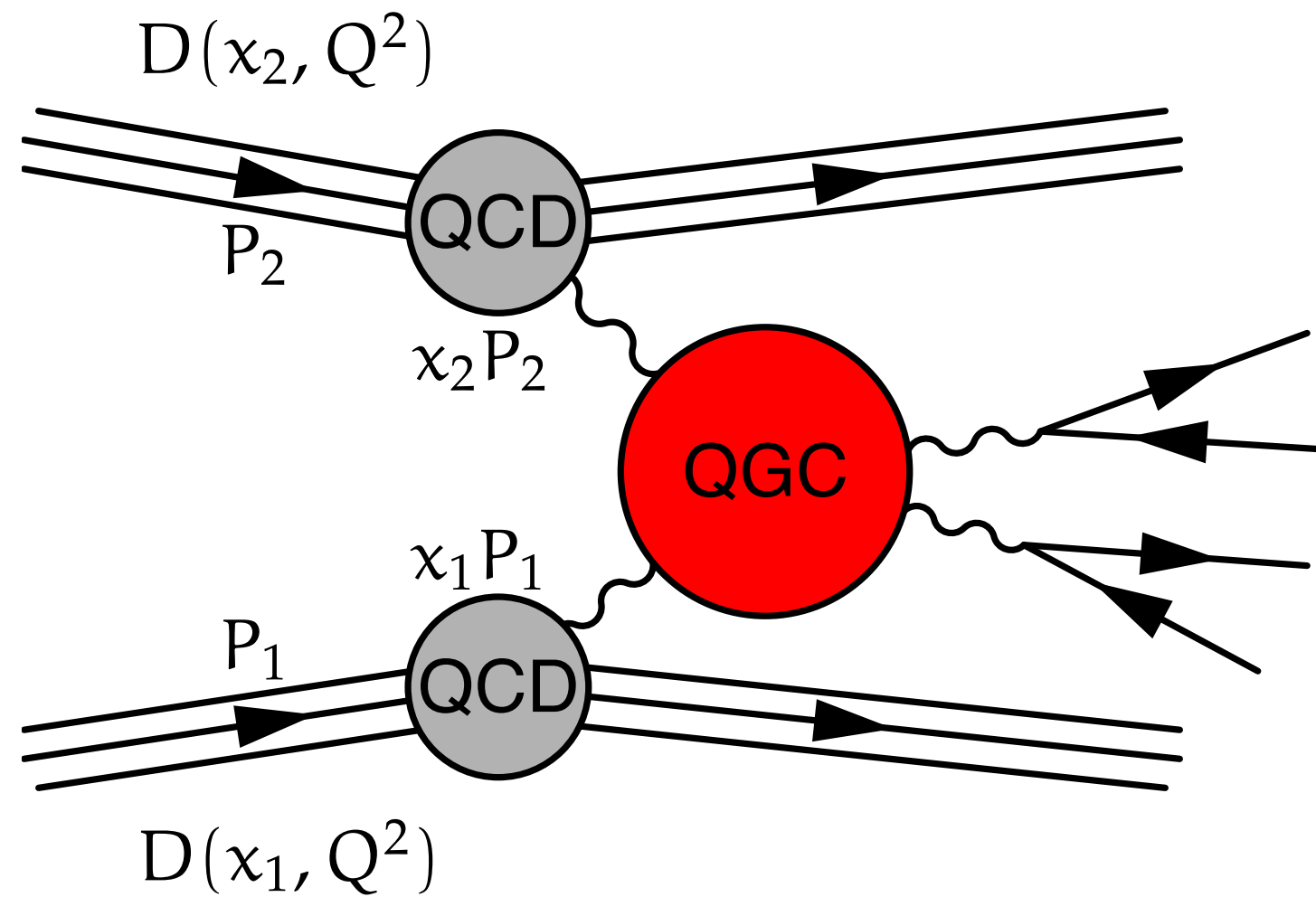


M. Mangano, MBI 22 Summary Talk

PRECISION in VBS

Vector boson scattering

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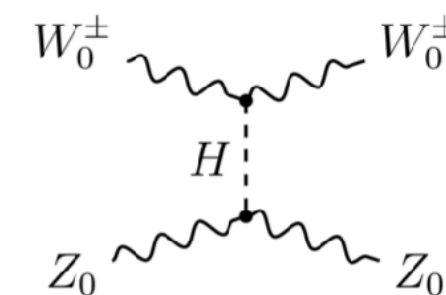
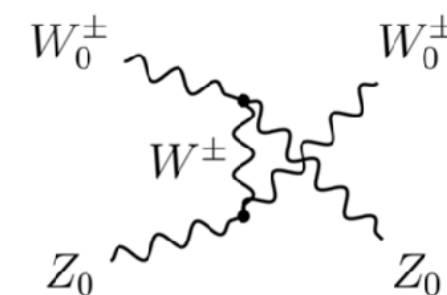
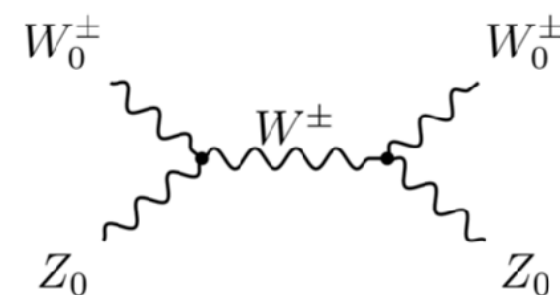
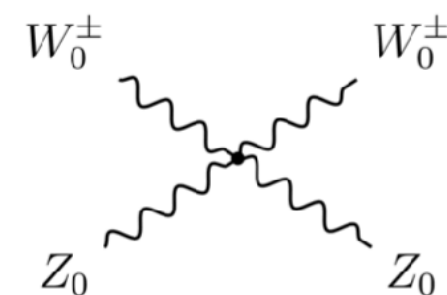
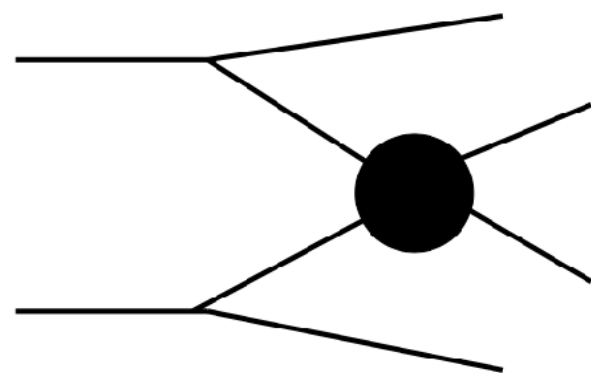


Fiducial phase space volume:

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

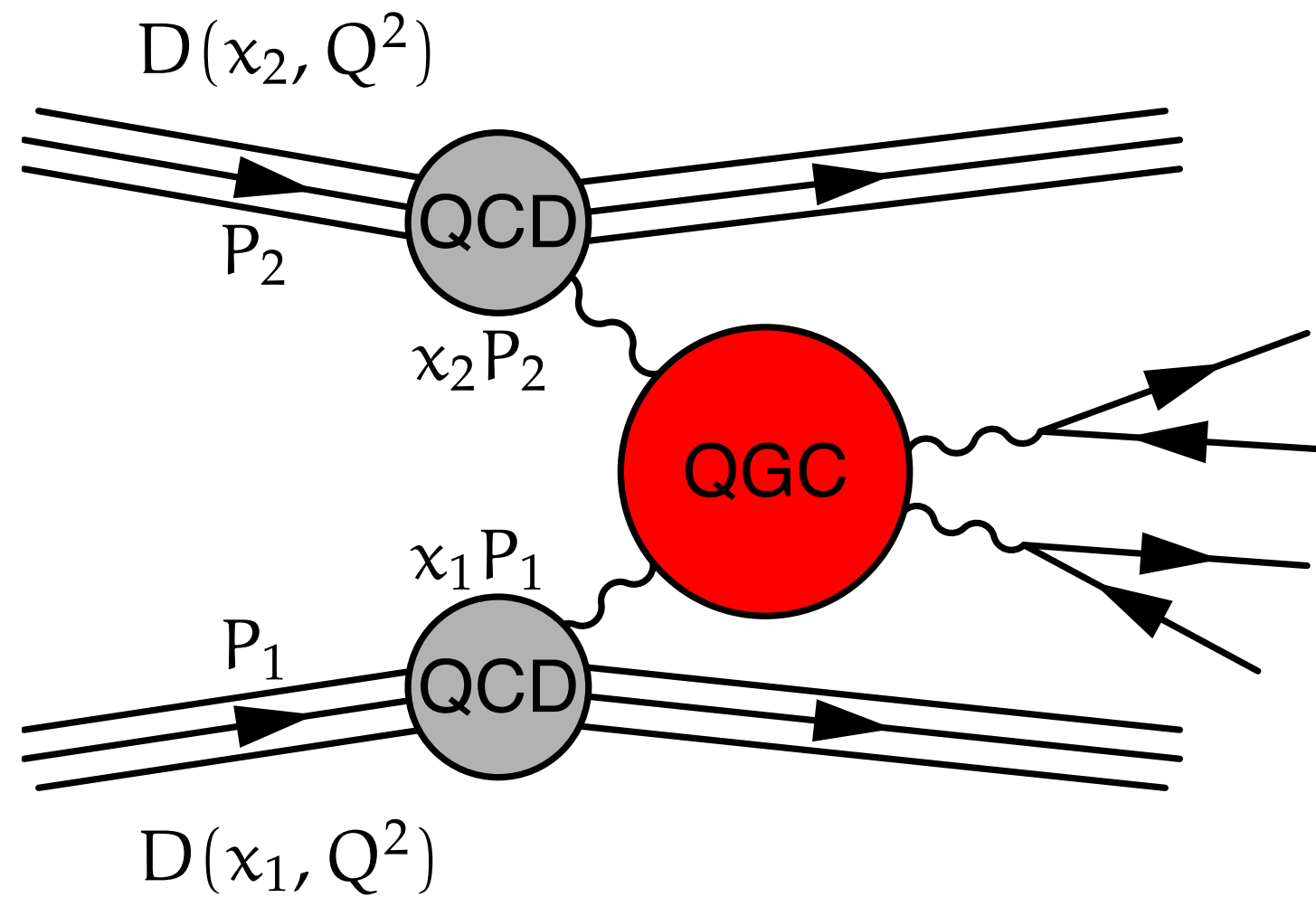
Importance of VBS

- 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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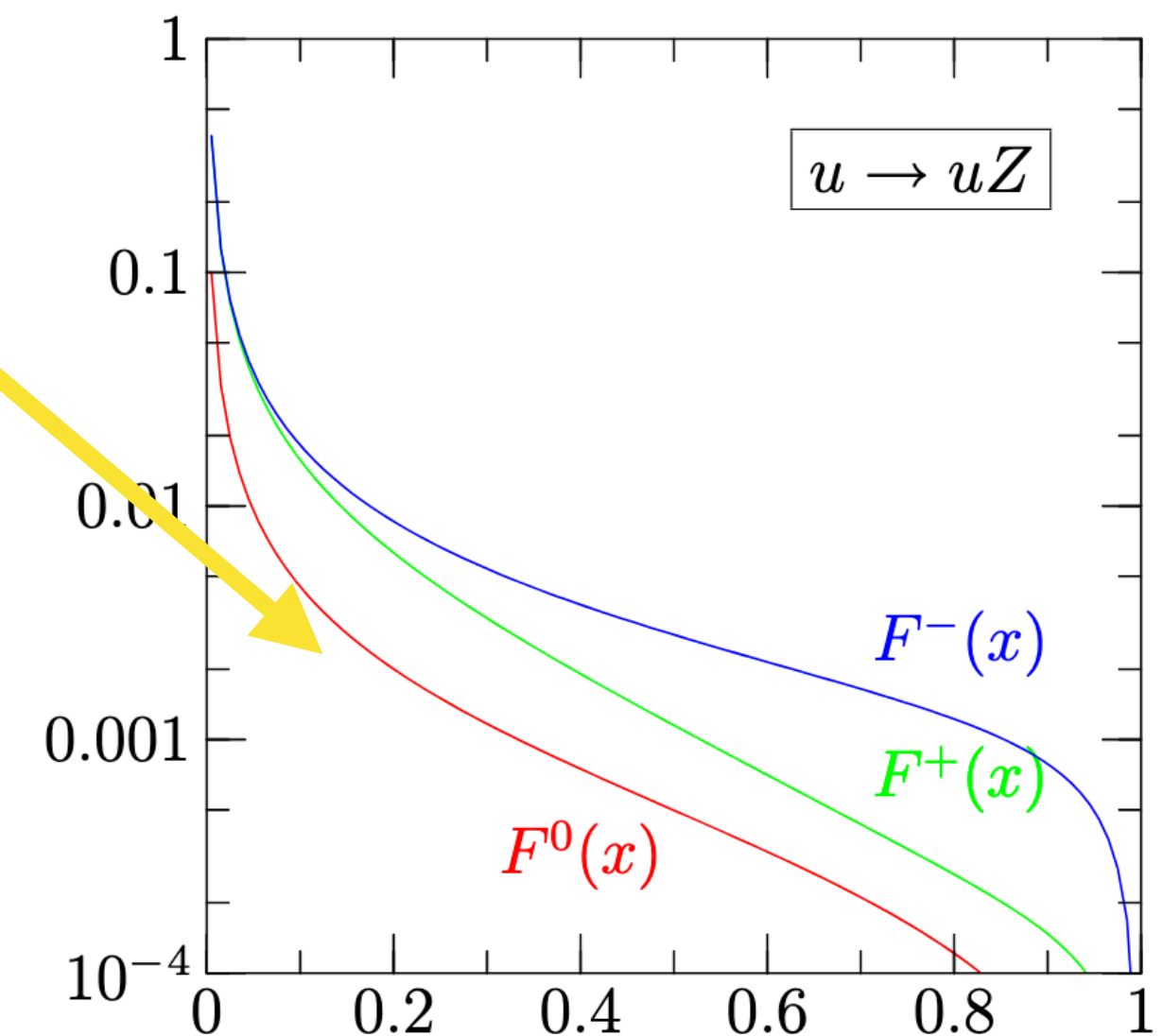
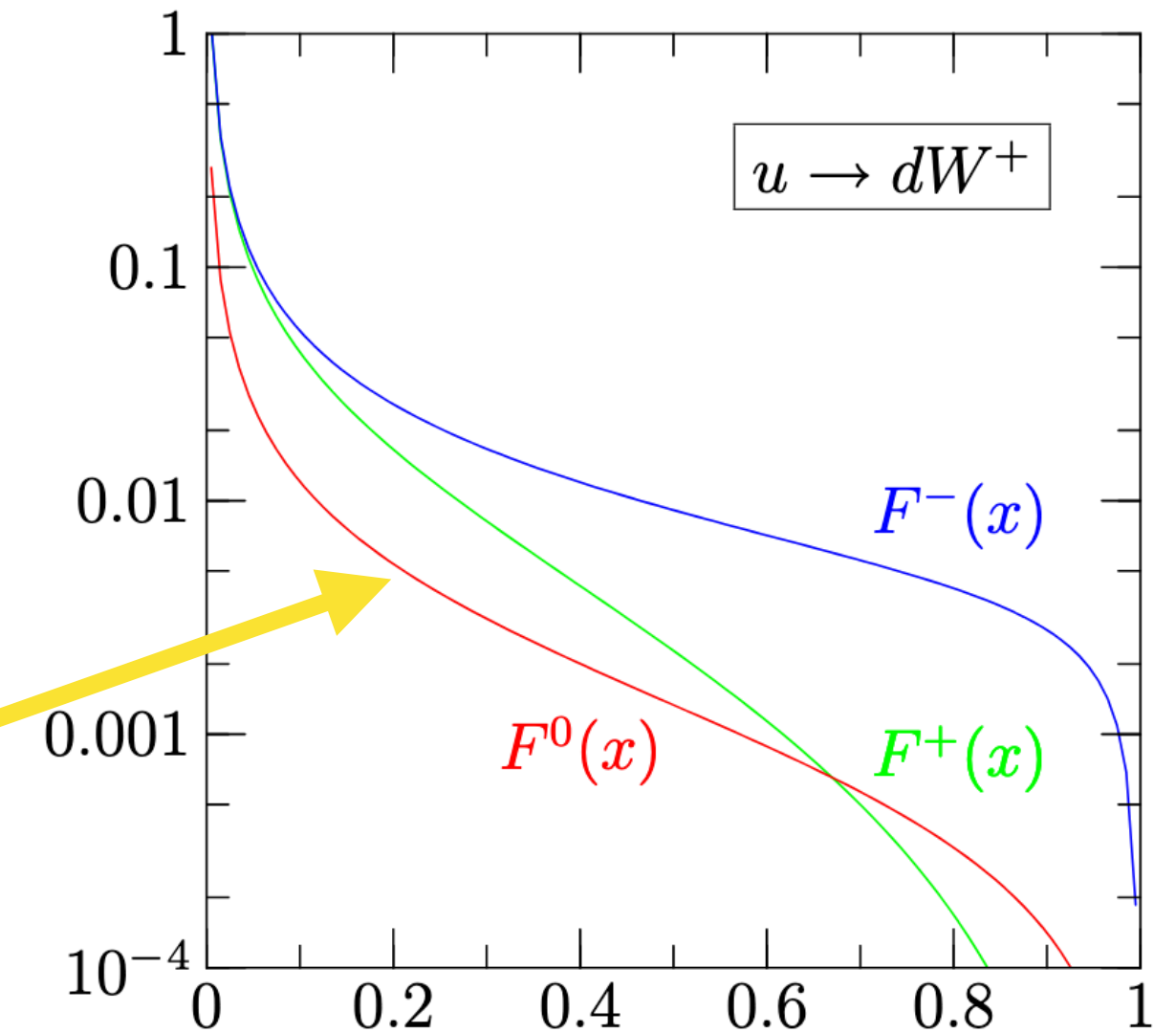


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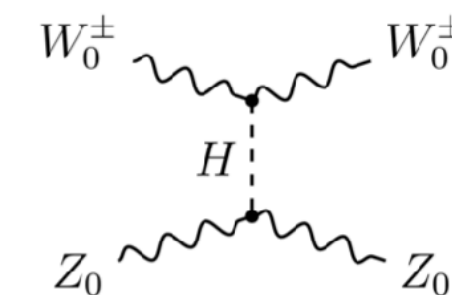
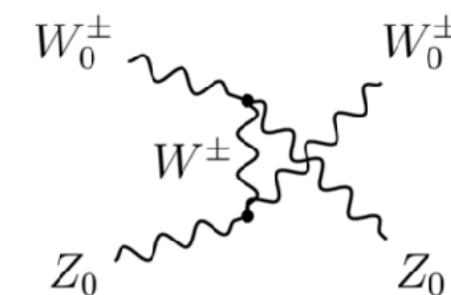
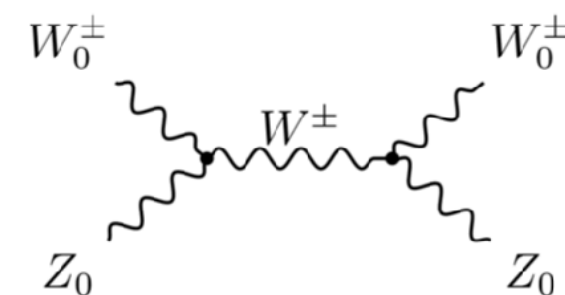
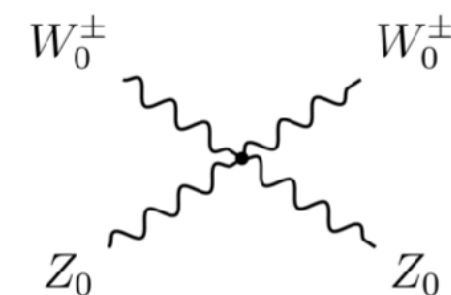
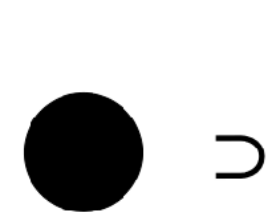
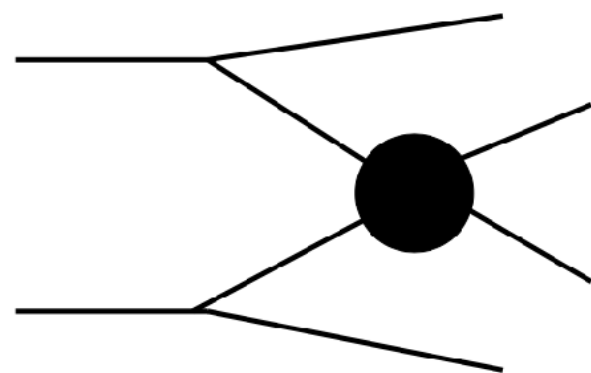
from:
Alboreanu/Kilian/JRR,
0806.4145

EW PDF / Splitting function picture



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Experimental results from CMS and ATLAS

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

PRL 120, 081801 (2018)

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

5.5 σ

PRL 123, 161801 (2019)

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

6.5 σ

PLB 774 (2017) 682

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

2.7 σ

ATLAS-CONF-2019-033

$$\mu_{\text{ZZ}} = \sigma_{\text{obs}}/\sigma_{\text{th.}} = 1.35 \pm 0.34$$

5.5 σ

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

PLB 809 (2020) 135710

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

6.8 σ

PLB 793 (2019) 469

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

5.3 σ

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

CERN-EP-2019-206
CMS-PAS-SMP-18-007

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

4.7 σ

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

4.1 σ

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

PRD 100, 032007 (2019)

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

2.7 σ

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

PLB 809 (2020) 135710

4.4 σ

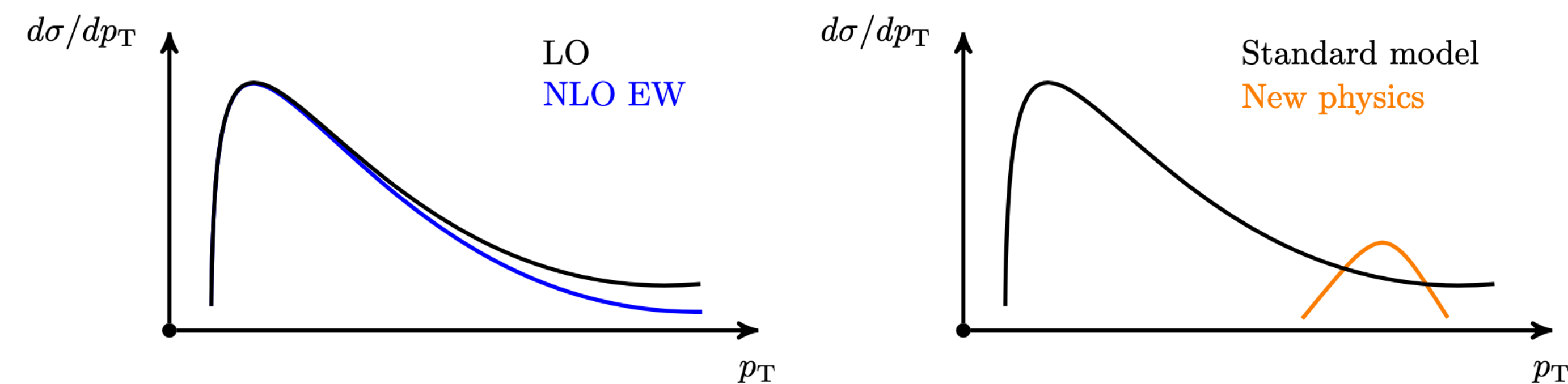
$$pp \rightarrow jjWV \rightarrow jj\ell\nu jj$$

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

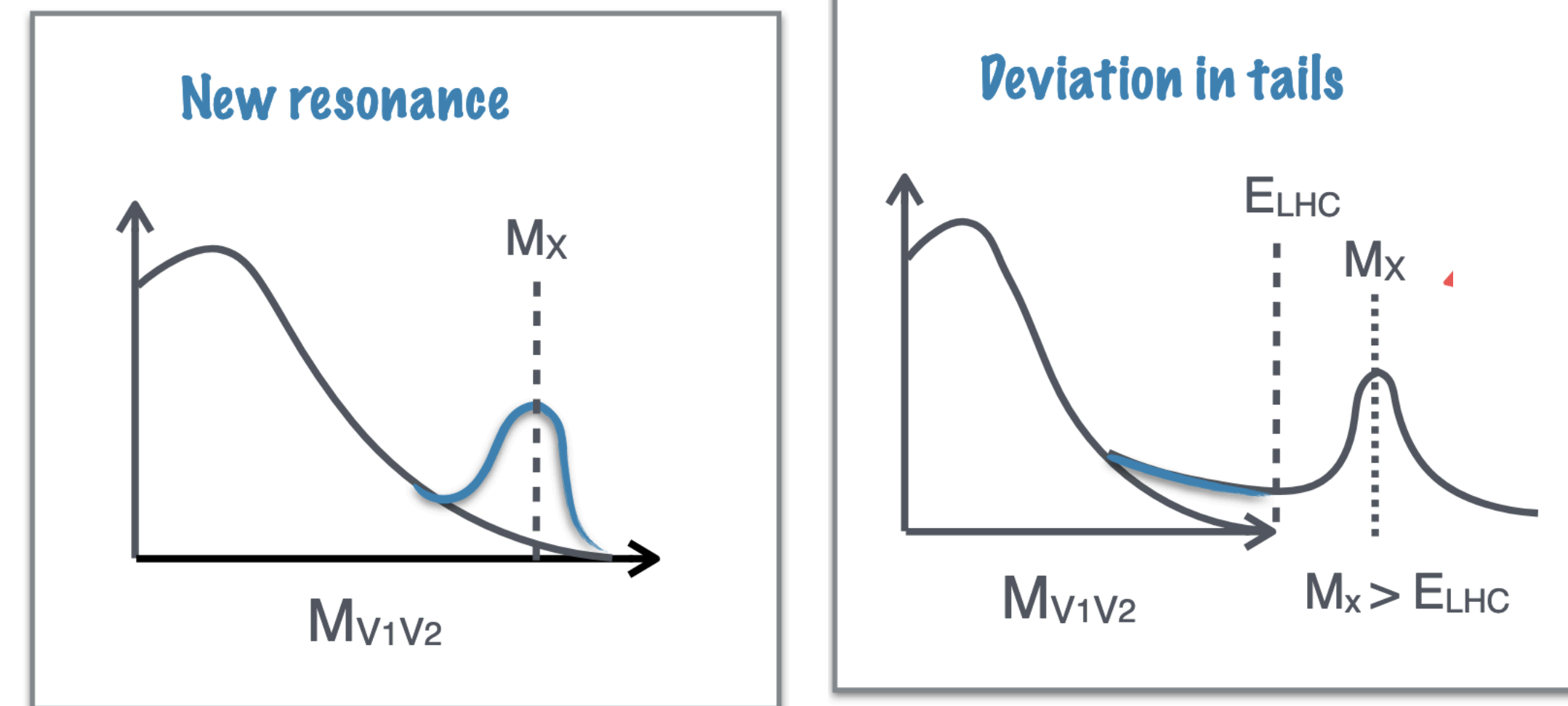
Precision in Vector Boson Scattering

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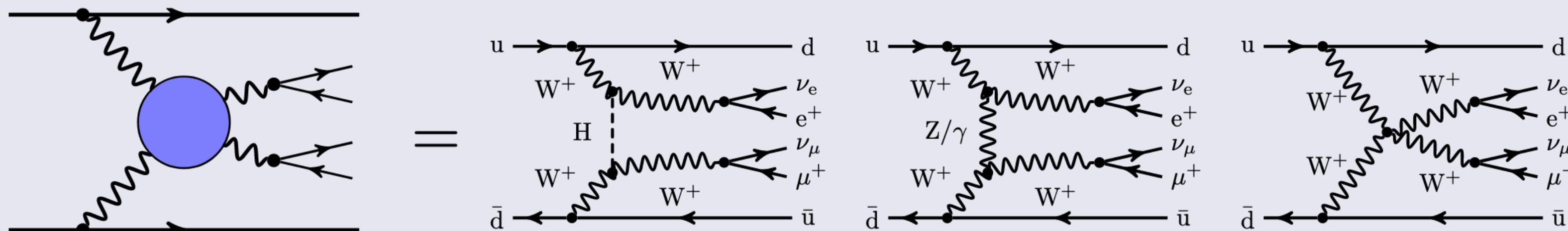
- Search for New Physics in tails: onset of resonances
- NLO EW(+QCD) corrections important for those tails



adapted from M. Pellen, MBI 2022



VBS diagrams

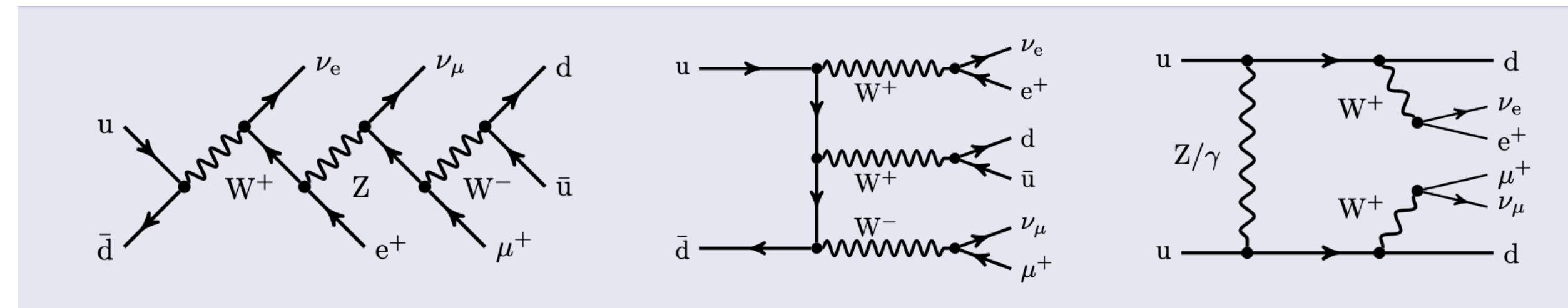
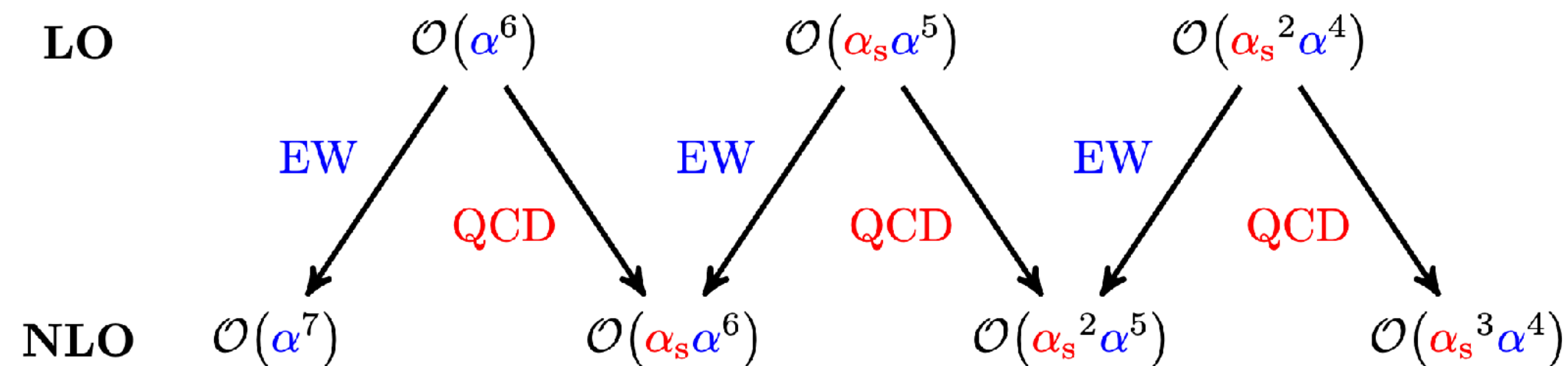


VBS LO+NLO:

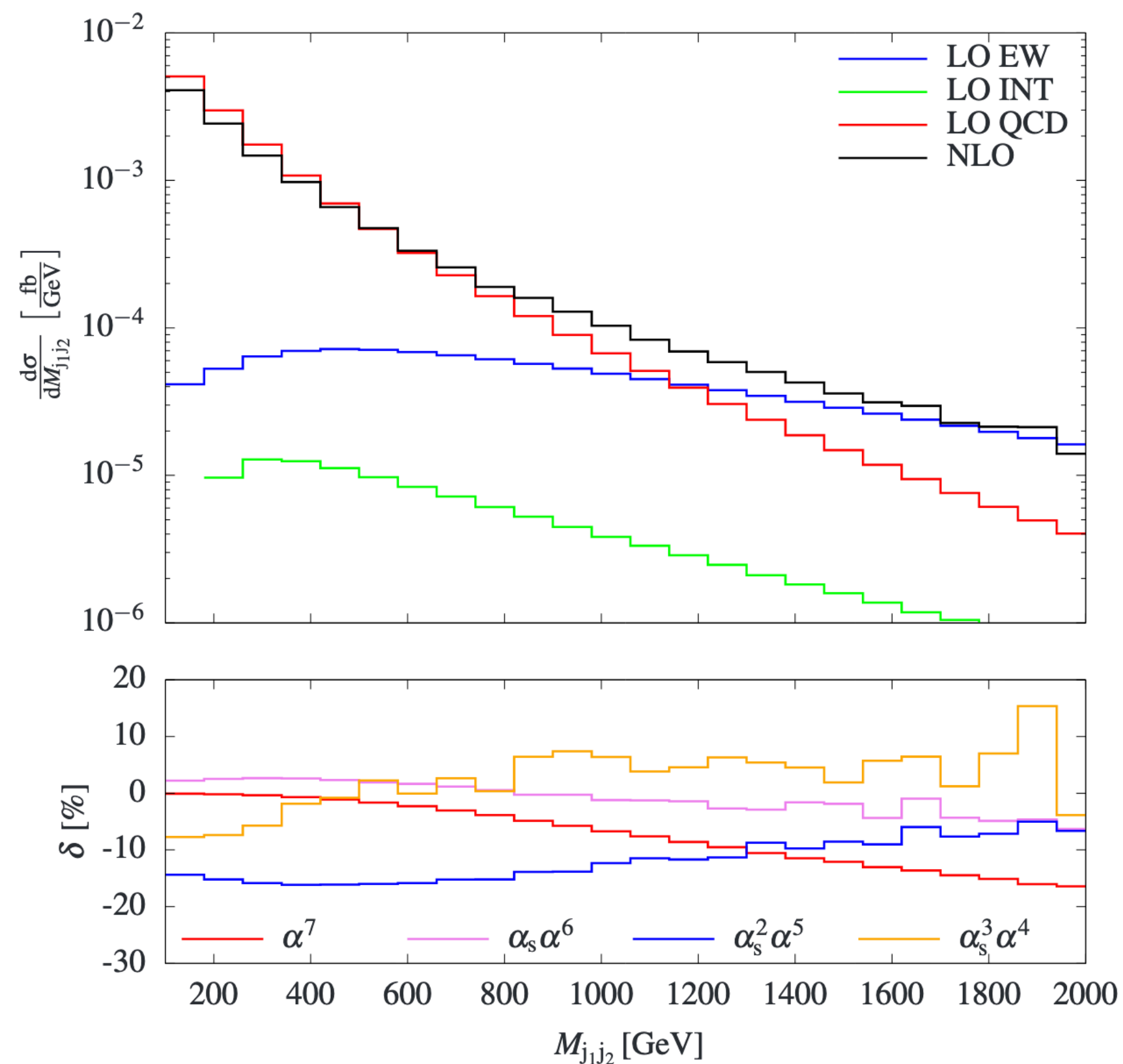
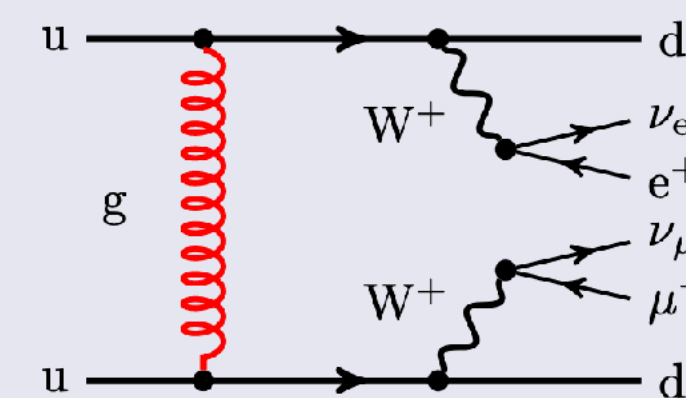
Biedermann, Denner, Pellen, 1708.00268 ; Denner, Dittmaier, Maierhöfer, Pellen, Schwan, 1611.02951; Ballestrero et al., 1803.07943; Denner, Franken, Pellen, Schmidt, 2107.10688;

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	✓	✓*	✗	✓

Precision in Vector Boson Scattering

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Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	$\mathcal{O}(\alpha_s\alpha^5)$
$\sigma[\text{fb}]$	2.292 ± 0.002	1.477 ± 0.001	0.223 ± 0.003

Code	$\sigma[\text{fb}]$
BONSAY	1.43636 ± 0.00002
MG5_AMC	1.4304 ± 0.0007
MoCaNLO+RECOLA	1.43476 ± 0.00009
PHANTOM	1.4374 ± 0.0006
POWHEG-BOX	1.44092 ± 0.00009
VBFNLO	1.43796 ± 0.00005
WHIZARD	1.4381 ± 0.0002

$$p_{T,\ell} > 20 \text{ GeV} \quad |y_\ell| < 2.5 \quad \Delta R_{\ell\ell} > 0.3$$

$$p_{T,\text{miss}} > 40 \text{ GeV}$$

Anti- k_T jets with $R = 0.4$:

$$p_{T,j} > 30 \text{ GeV} \quad |y_j| < 4.5 \quad \Delta R_{\ell j} > 0.3$$

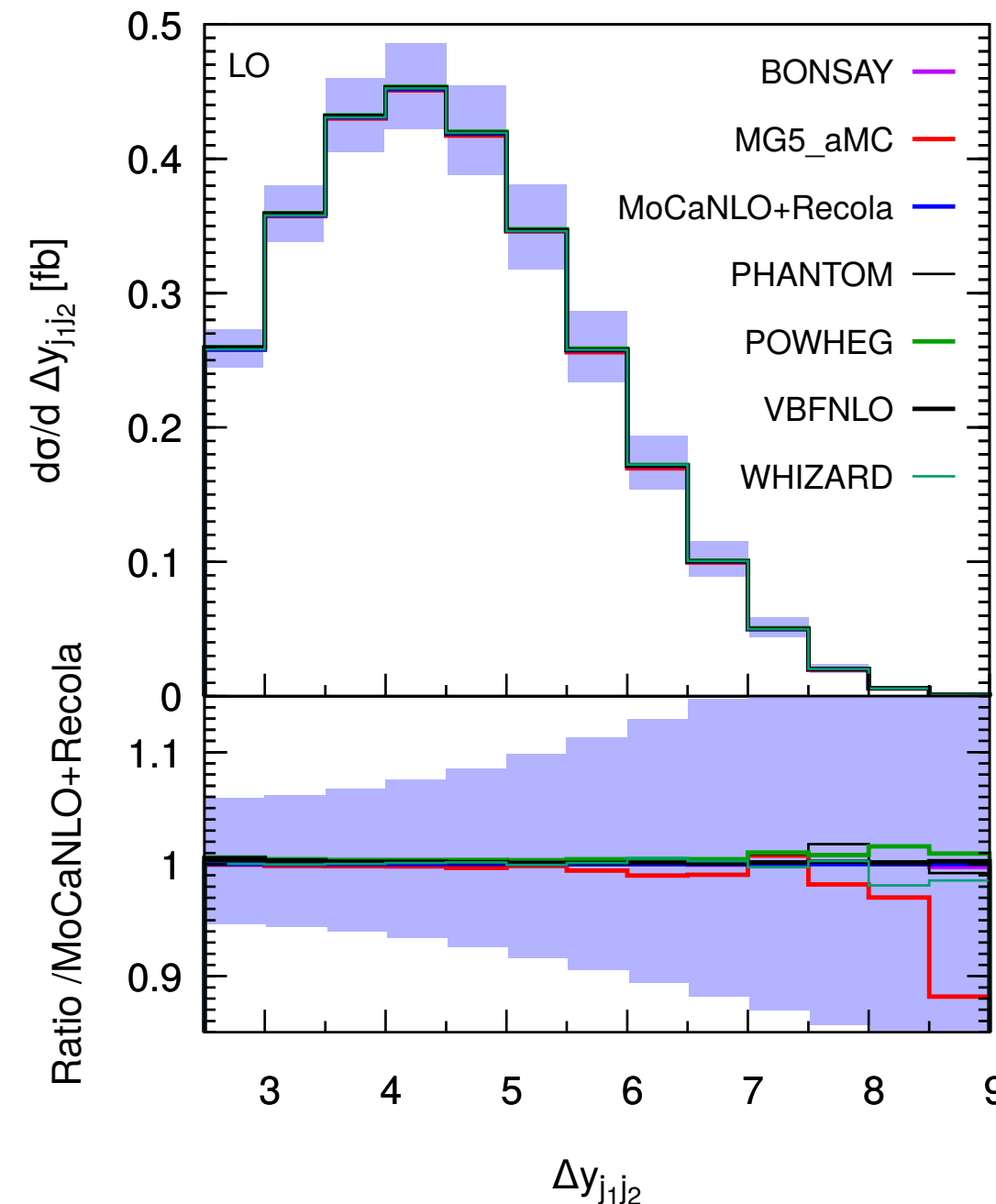
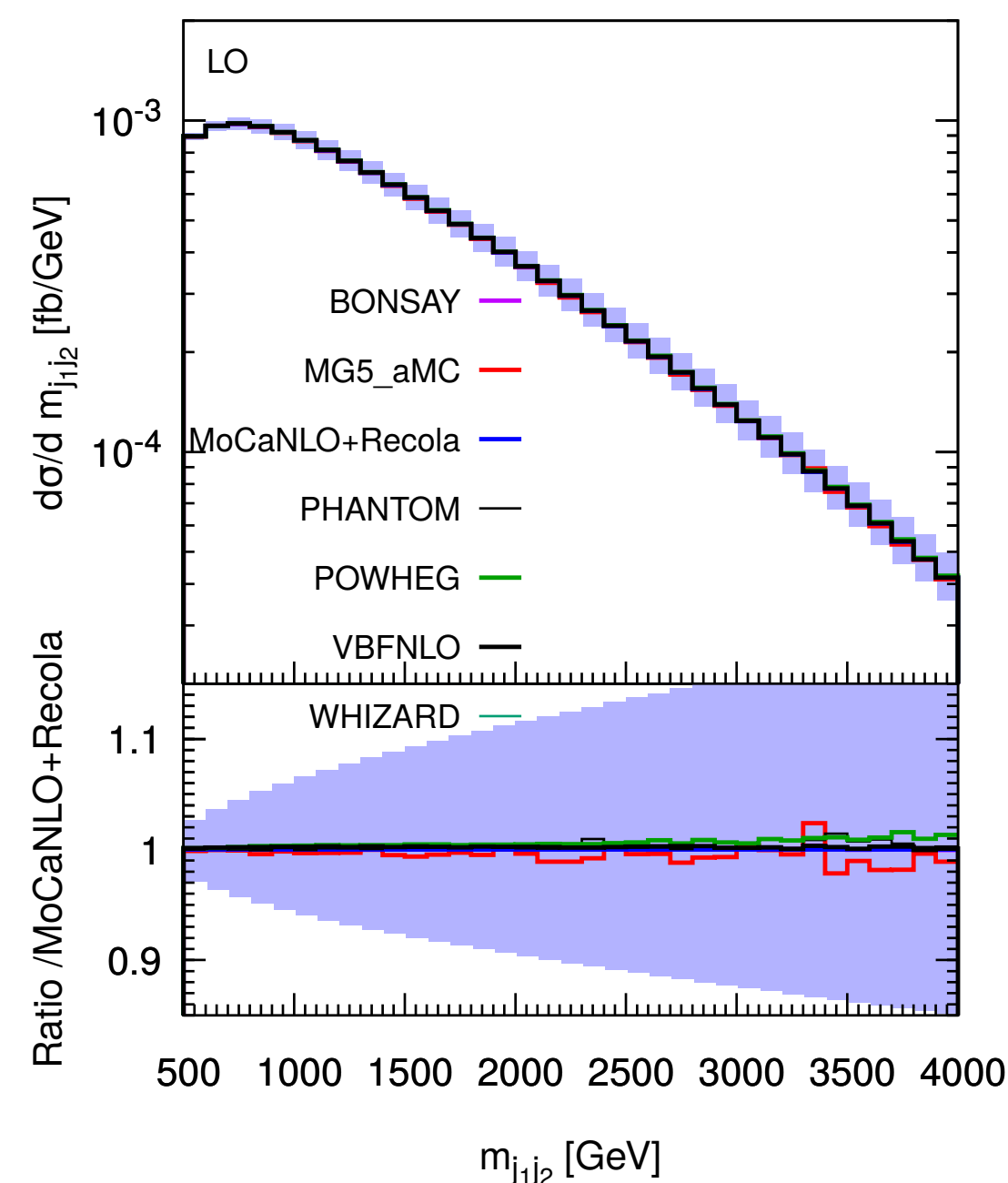
$$m_{jj} > 500 \text{ GeV} \quad |\Delta y_{jj}| > 2.5$$

Ballestrero et al., 1803.07943

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MG5_AMC+PYTHIA8, Γ_{resc}	1.275 ± 0.003
MG5_AMC+HERWIG7, Γ_{resc}	1.266 ± 0.003
PHANTOM+PYTHIA8	1.235 ± 0.001
PHANTOM+HERWIG7	1.258 ± 0.001
VBFNLO+HERWIG7-DIPOLE	1.3001 ± 0.0002
WHIZARD+PYTHIA8	1.229 ± 0.001

LO+PS

LO



Precision in Vector Boson Scattering

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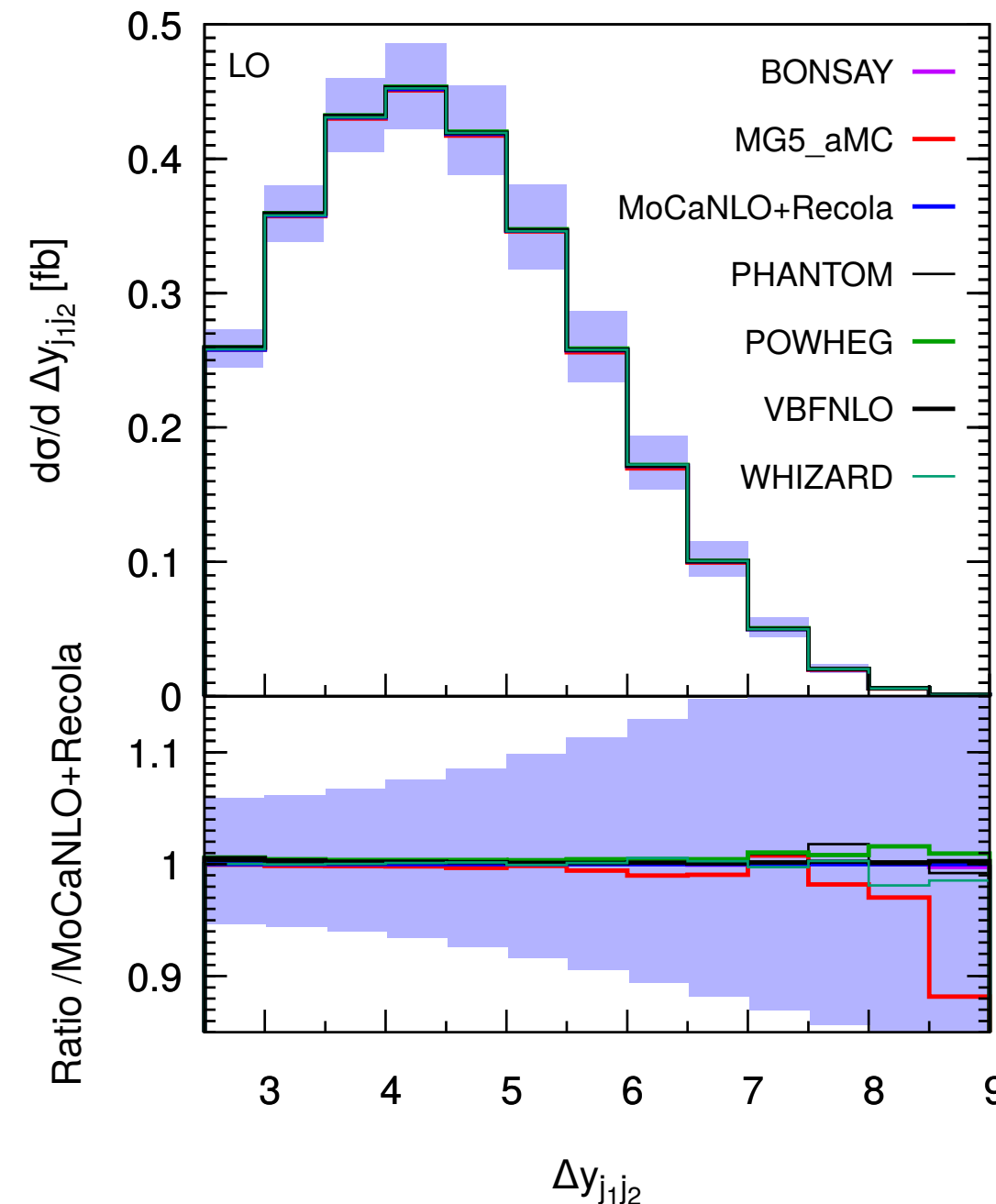
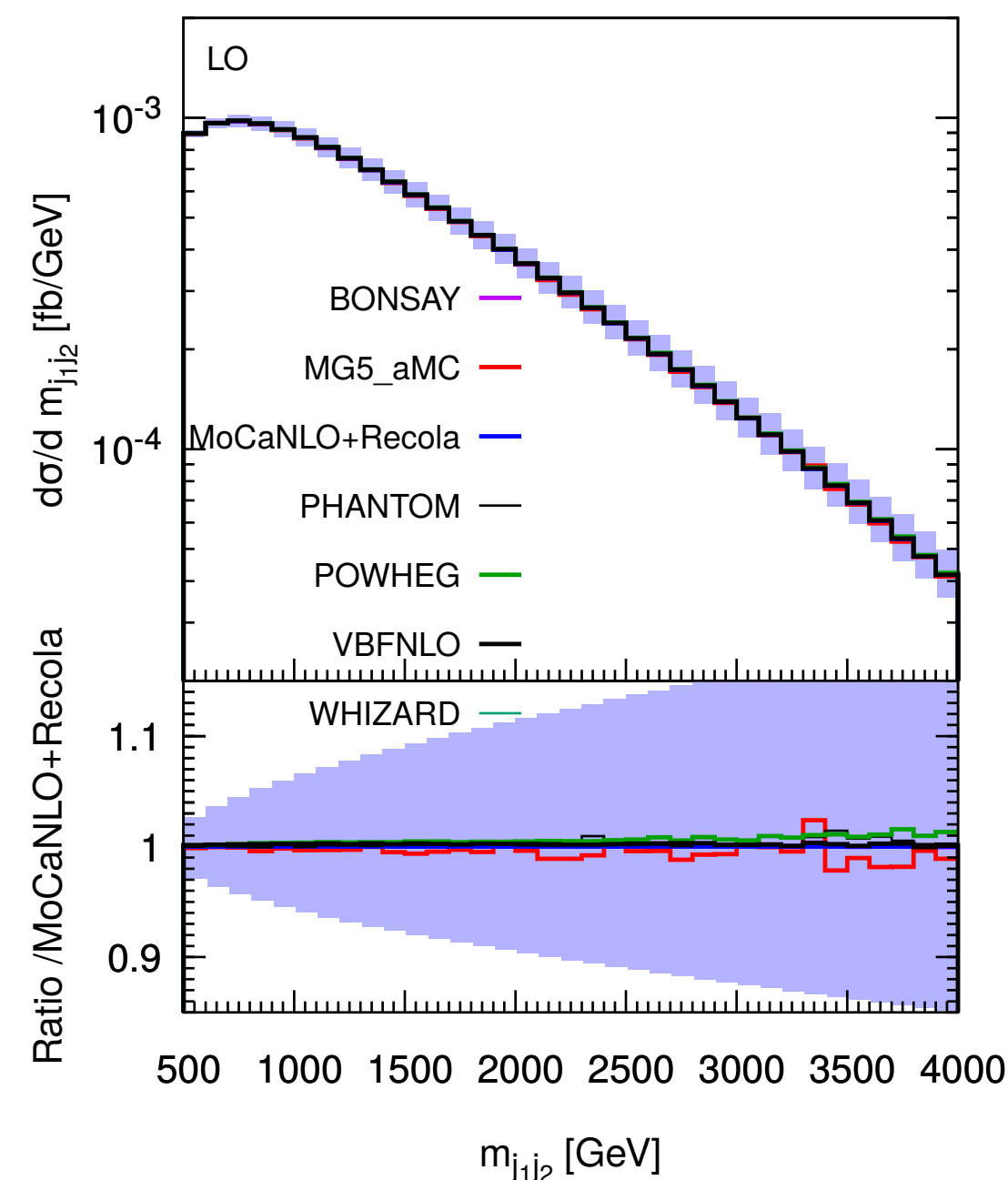
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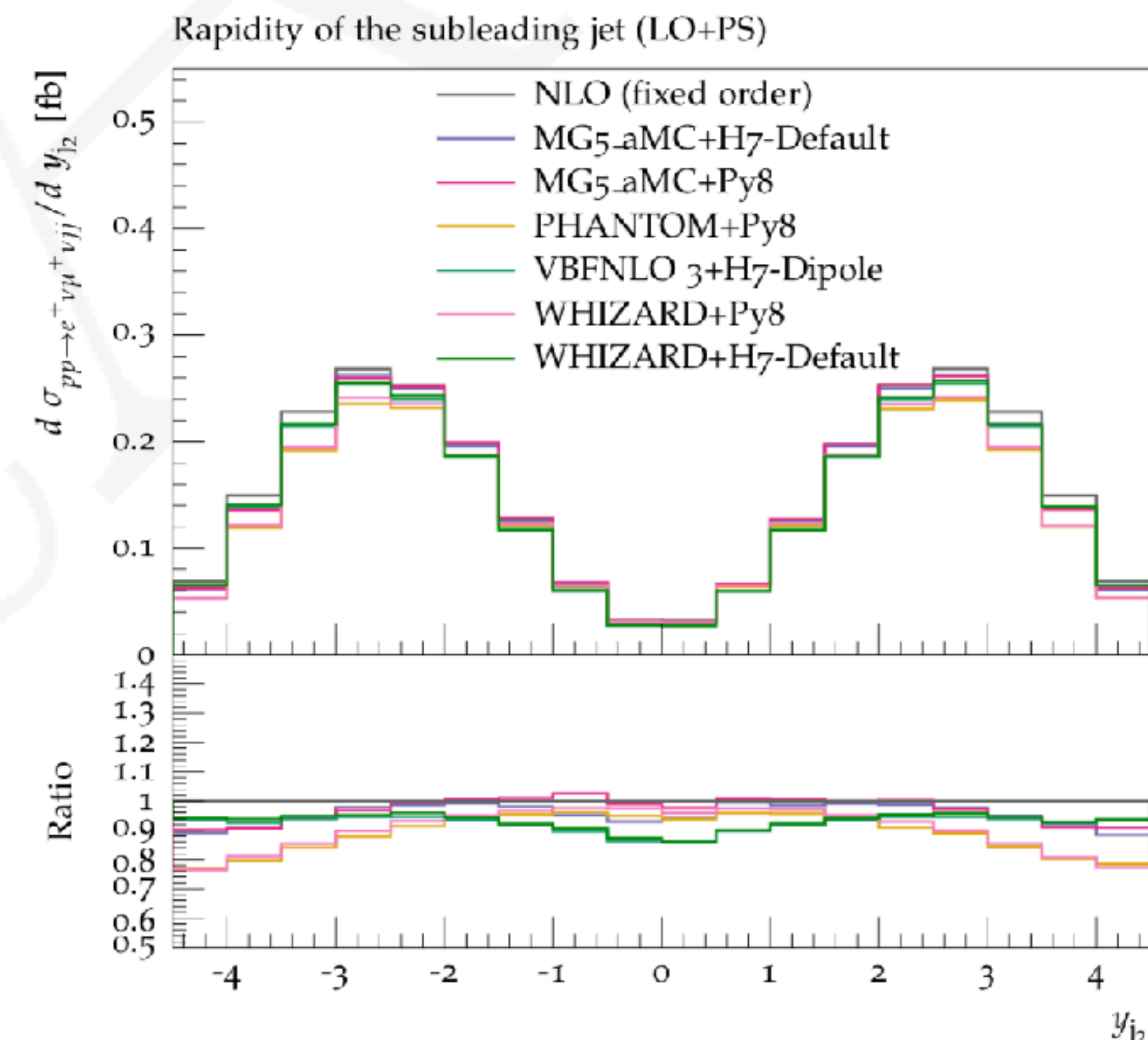
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LO



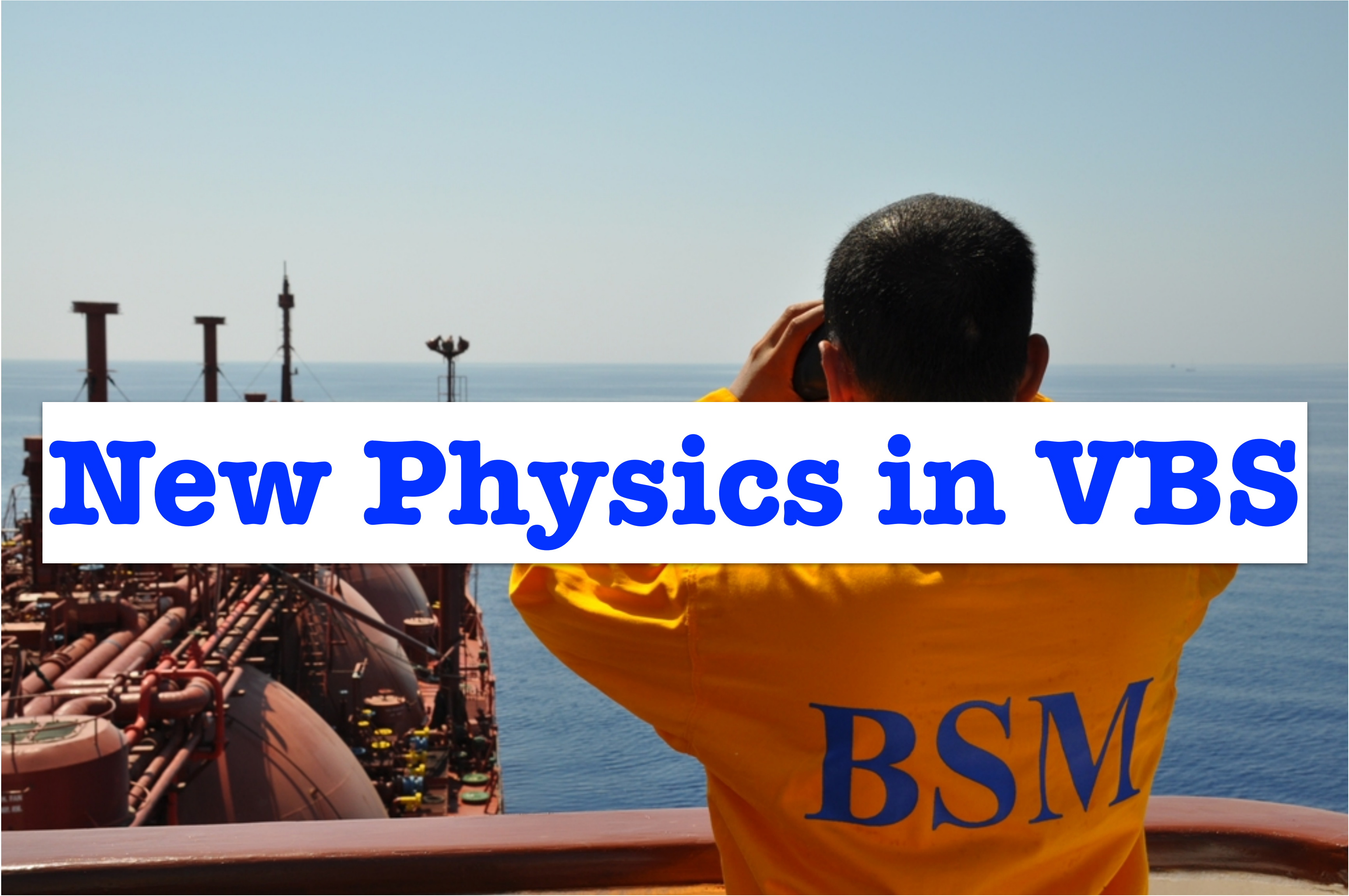
LO+PS



J. R. Reuter, DESY

Seminar, University of Pittsburgh, 22.9.2022

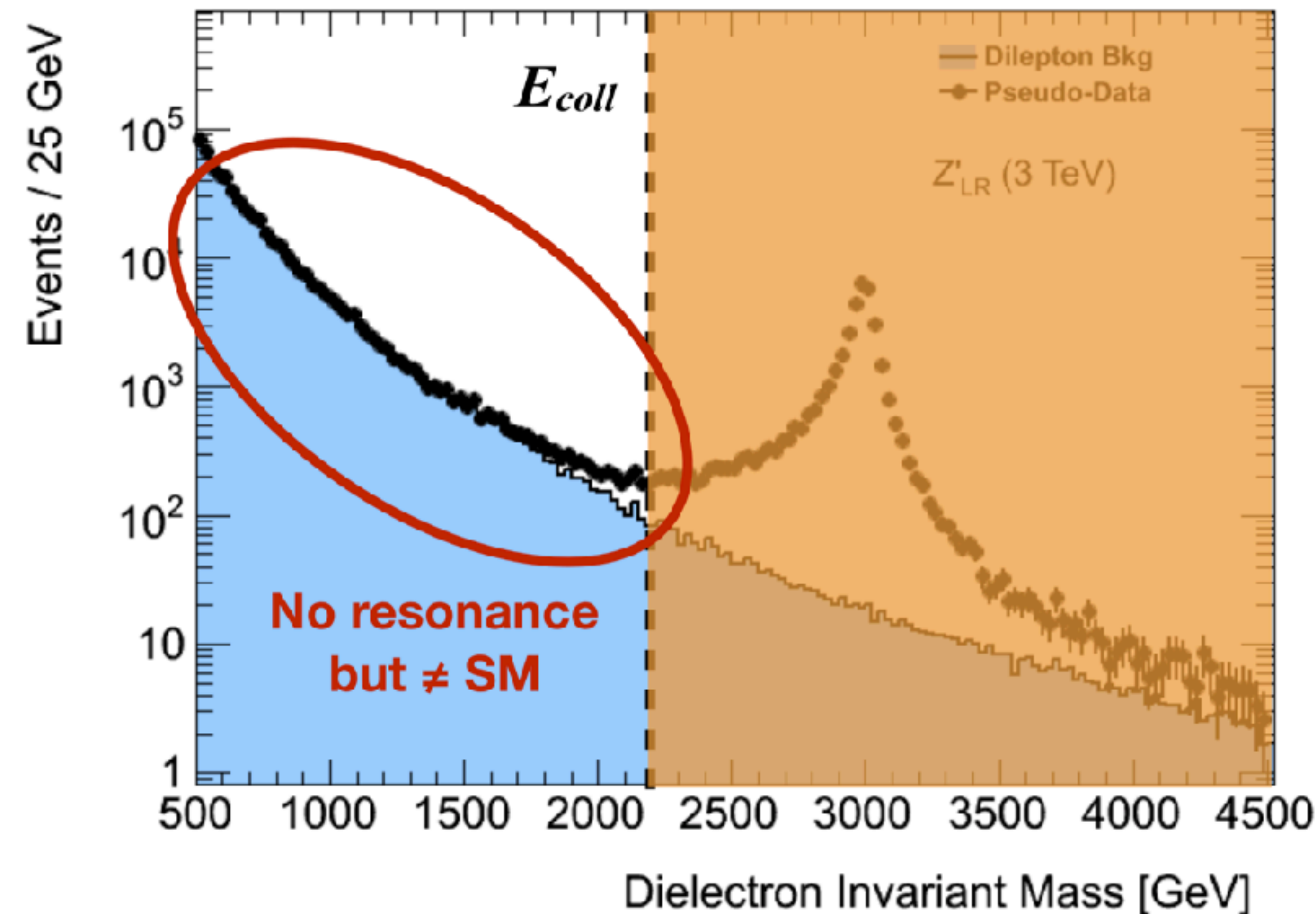


A photograph of a person from behind, wearing a bright yellow long-sleeved shirt with the letters 'BSM' printed in blue on the back. The person is holding a camera up to their eye, taking a picture of a large ship at sea. The ship has a complex structure with various masts and antennas. The background is a clear blue sky and a calm blue sea. A white rectangular box with blue text is overlaid on the center of the image.

New Physics in 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

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:

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

Unitarity in (VBS) Scattering Amplitudes

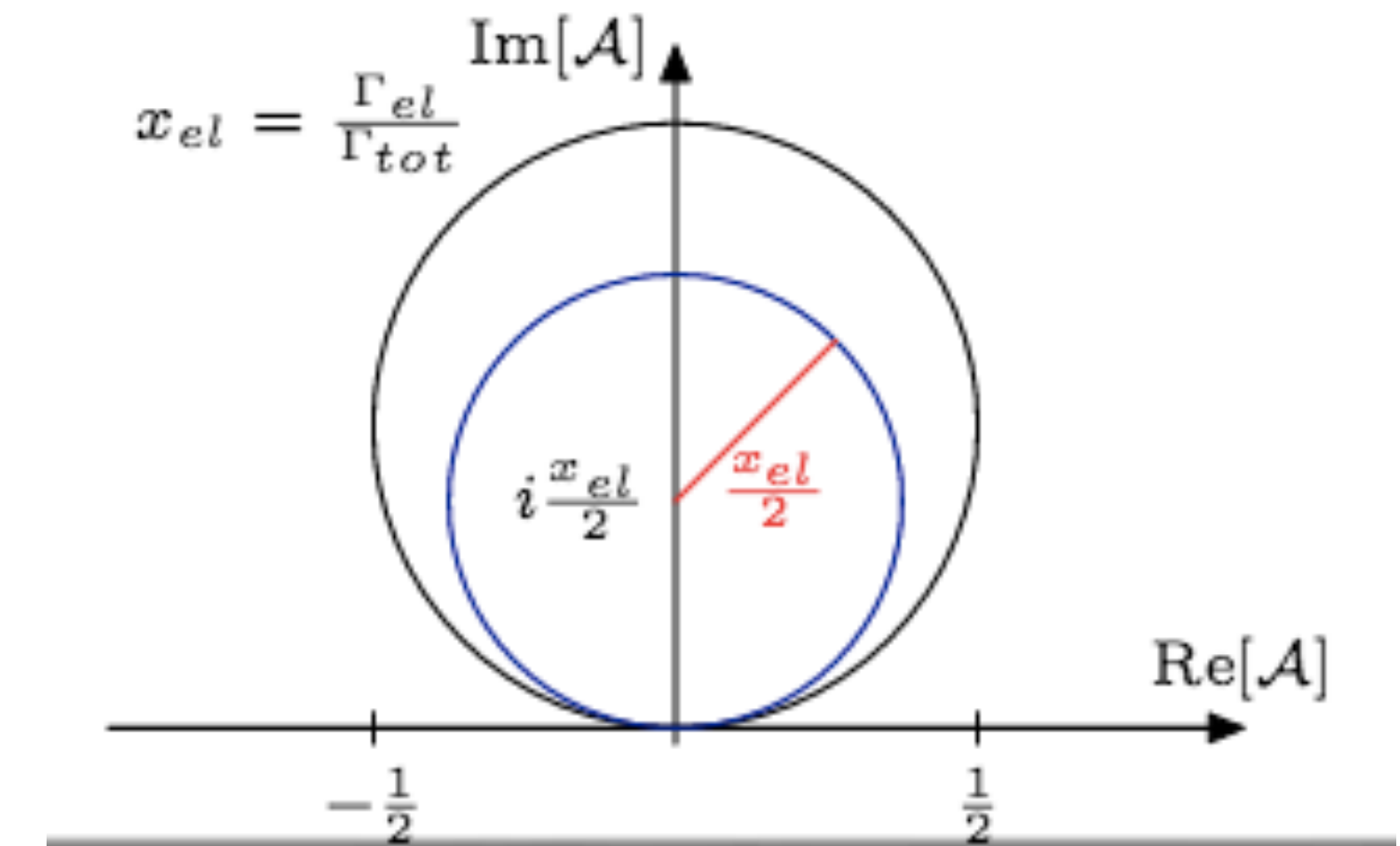
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Unitarity in (VBS) Scattering Amplitudes

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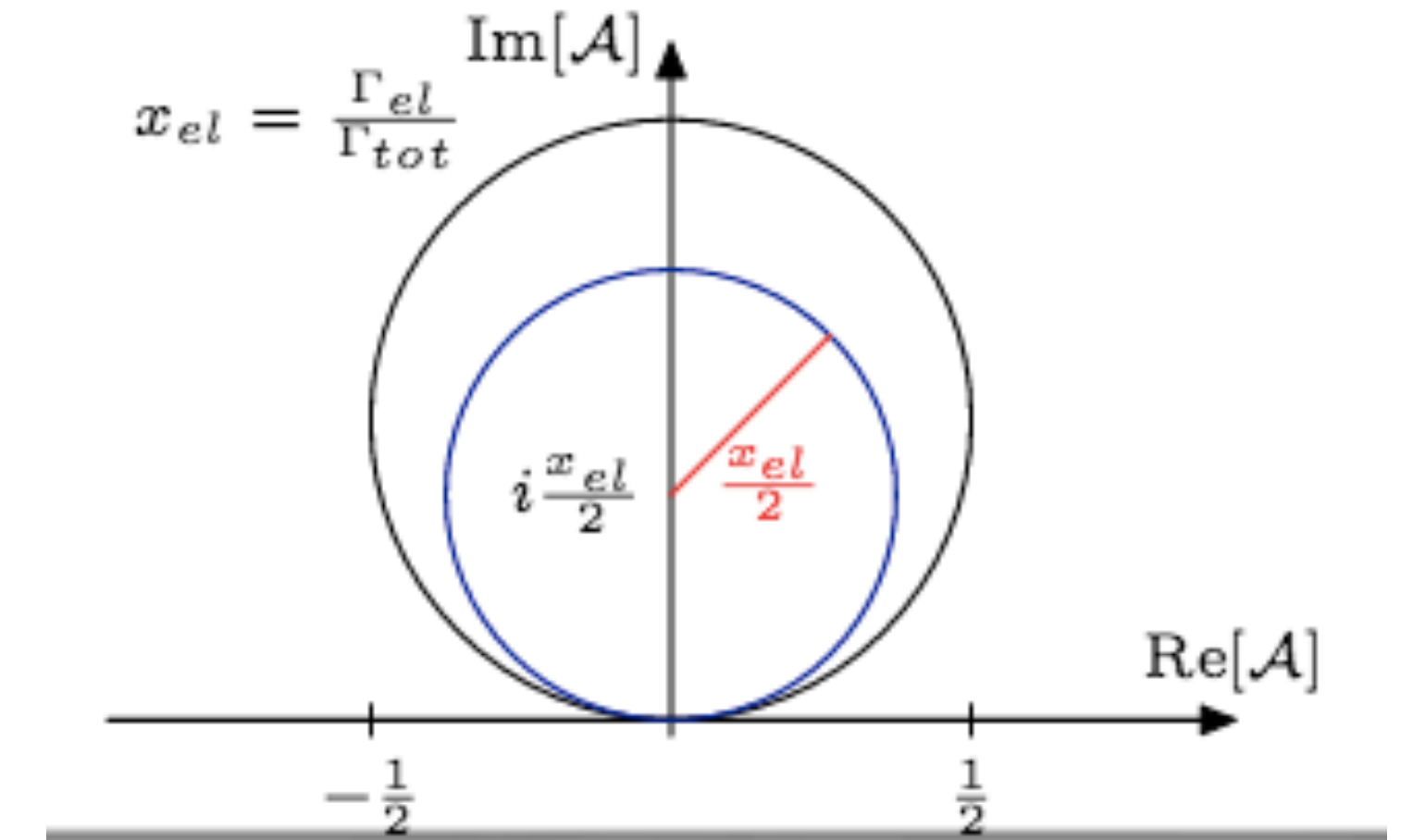
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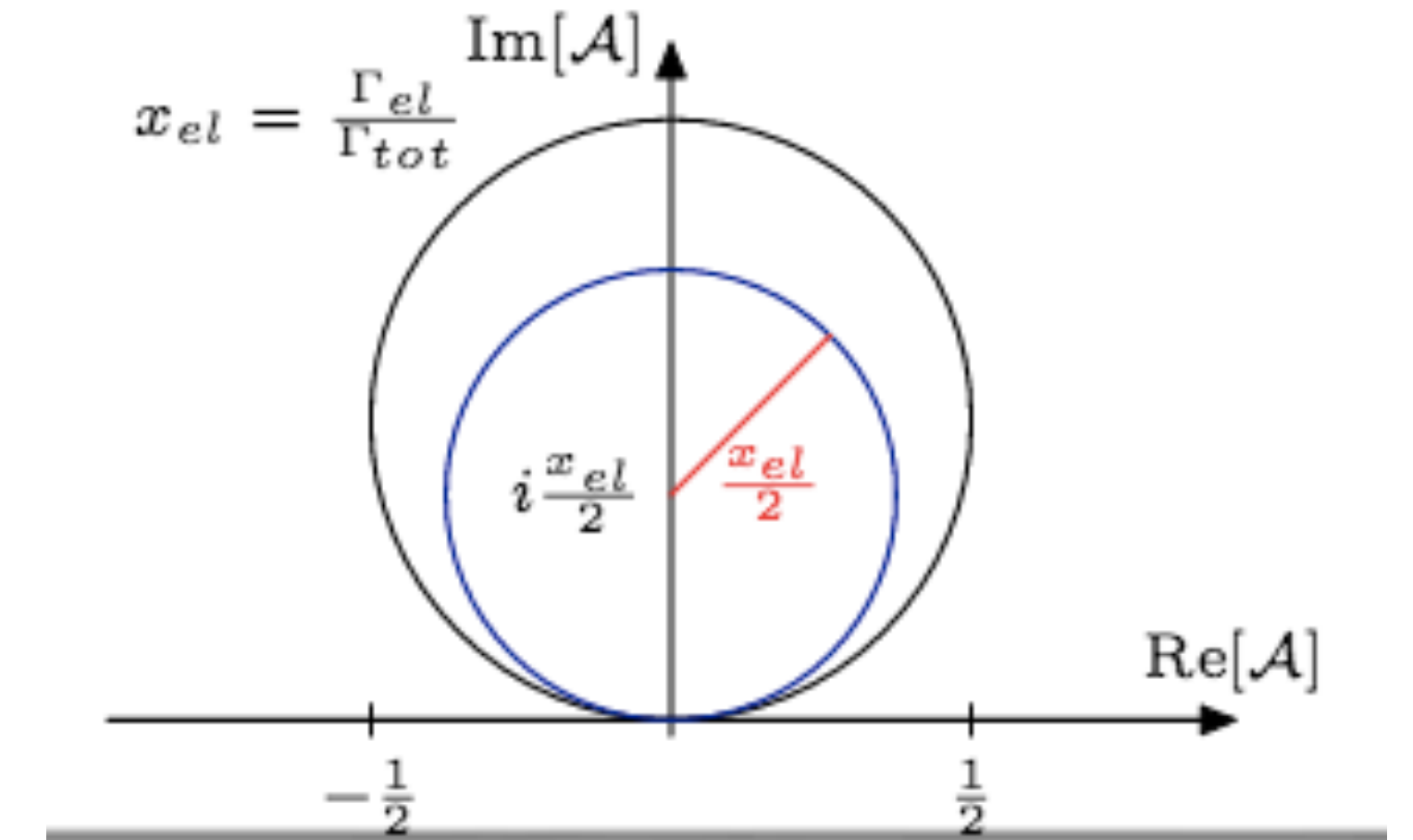
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Lee/Quigg/Thacker, 1973

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

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

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

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

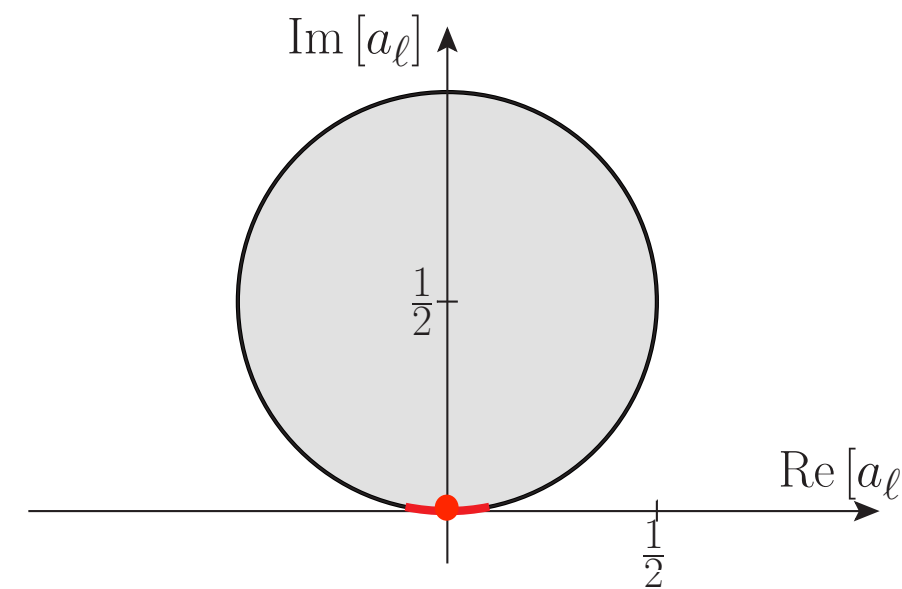
Higgs exchange:

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

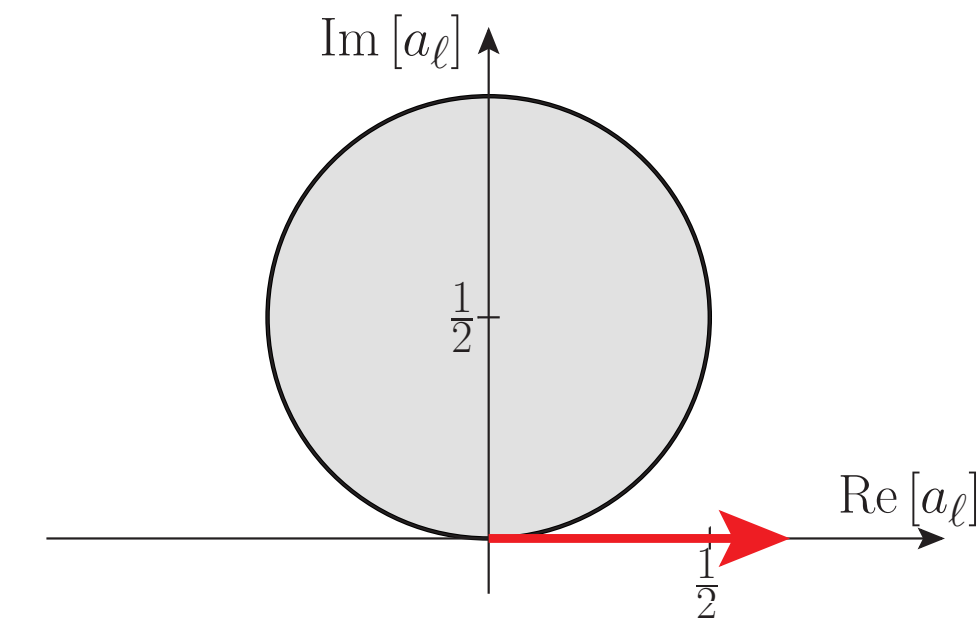
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2 \text{ TeV}$

1. **SM or weakly coupled physics (e.g. 2HDM):**

amplitude remains close to origin

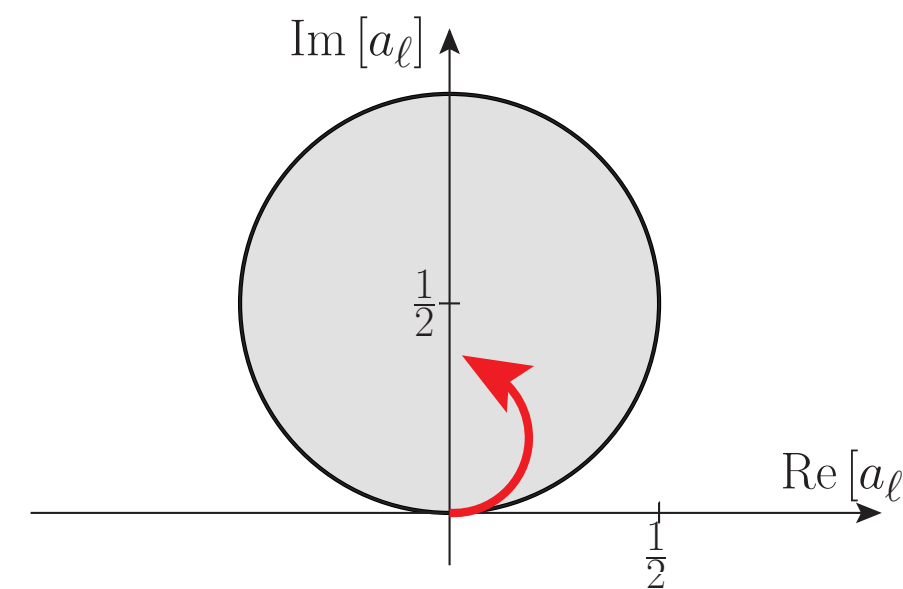


2. **Rising amplitude (at least one dim-8 operator):** rise beyond unitarity circle [unphys.], strongly interacting regime

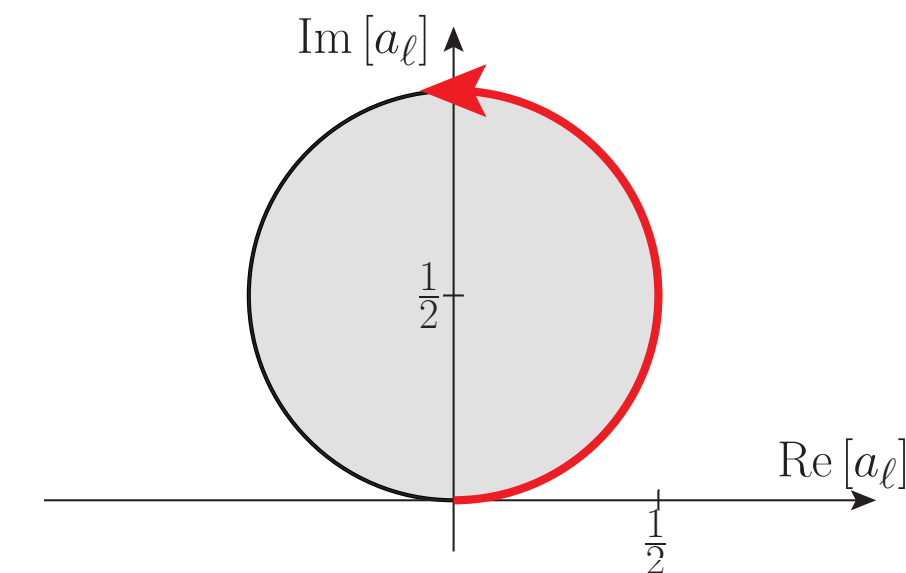


3. **Inelastic channel opens (form-factor description):**

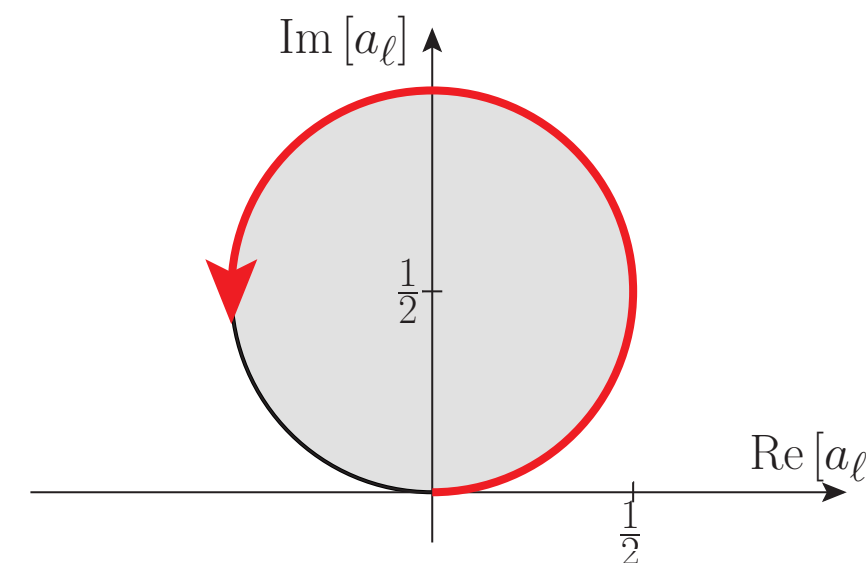
new channels open out, multi-boson final states



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



5. **New resonance:** amplitude turns over



❑ **Resonances in direct reach** (not clear: strongly interacting models [e.g. σ resonance])

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

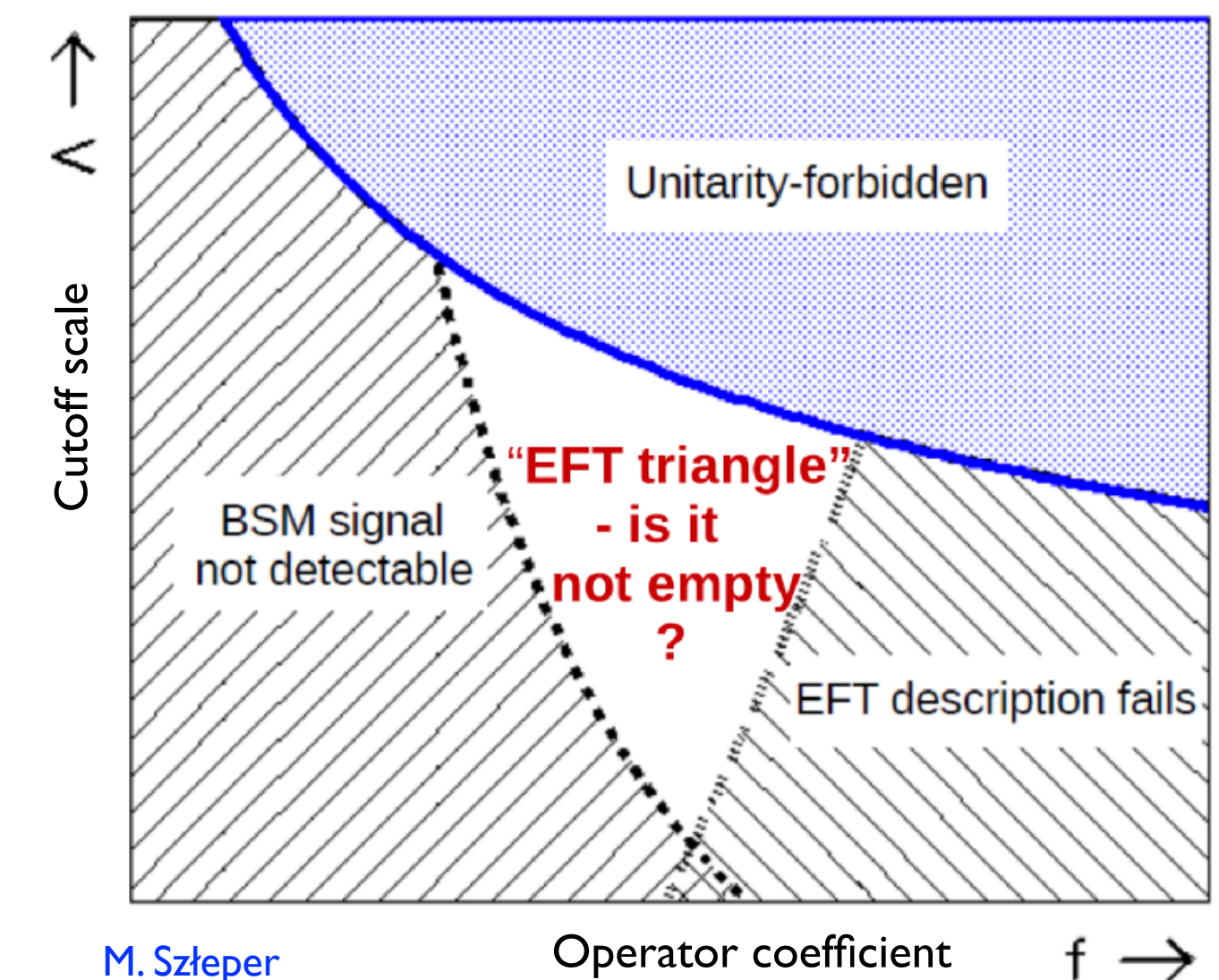
$$\mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim |\mathcal{A}_{\text{dim-6}}|^2 \quad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-8}} \gtrsim |\mathcal{A}_{\text{dim-8}}|^2 \quad \mathcal{A}_{\text{SM}} \times \mathcal{A}_{\text{dim-6}} \gtrsim \mathcal{A}_{\text{SM}} \times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

❑ **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 @ $\mathcal{O}(100 \text{ GeV})$]



Plethora of unitarization procedures

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

unitarity bound (0th partial wave) at Λ_C
no continuous transition beyond
might influence BDT/DNN training

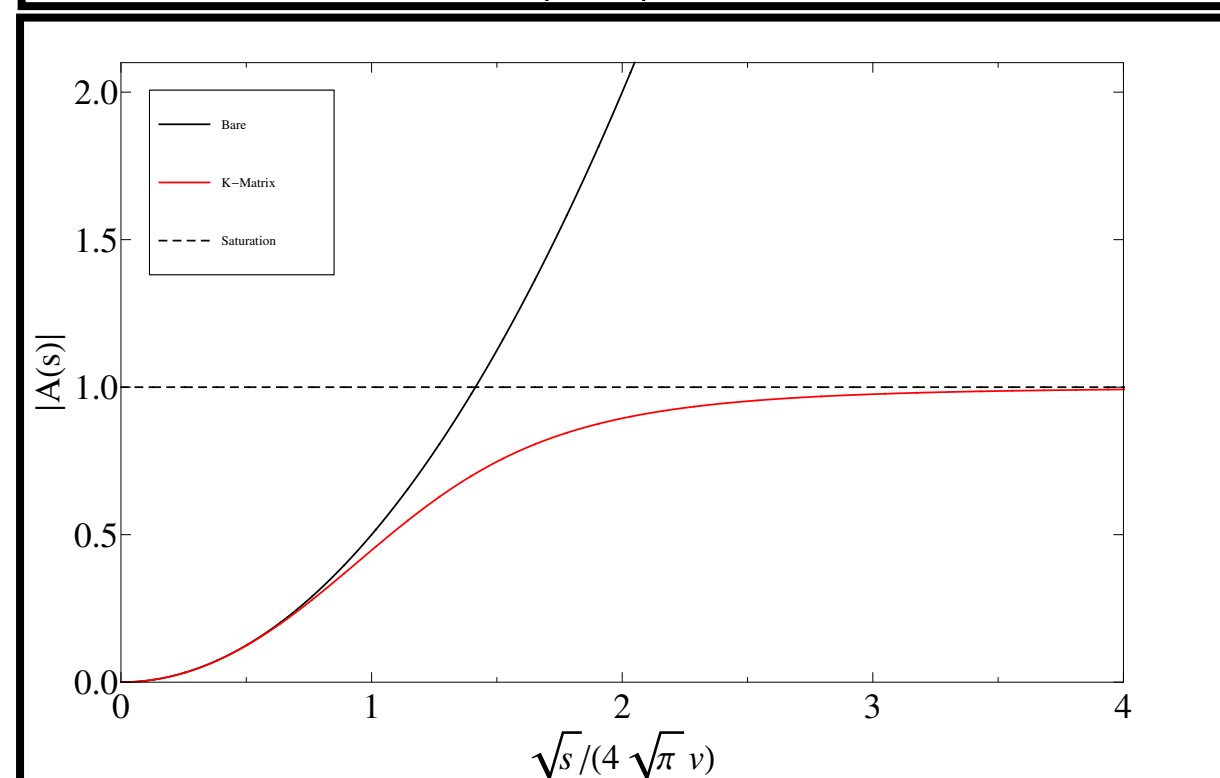
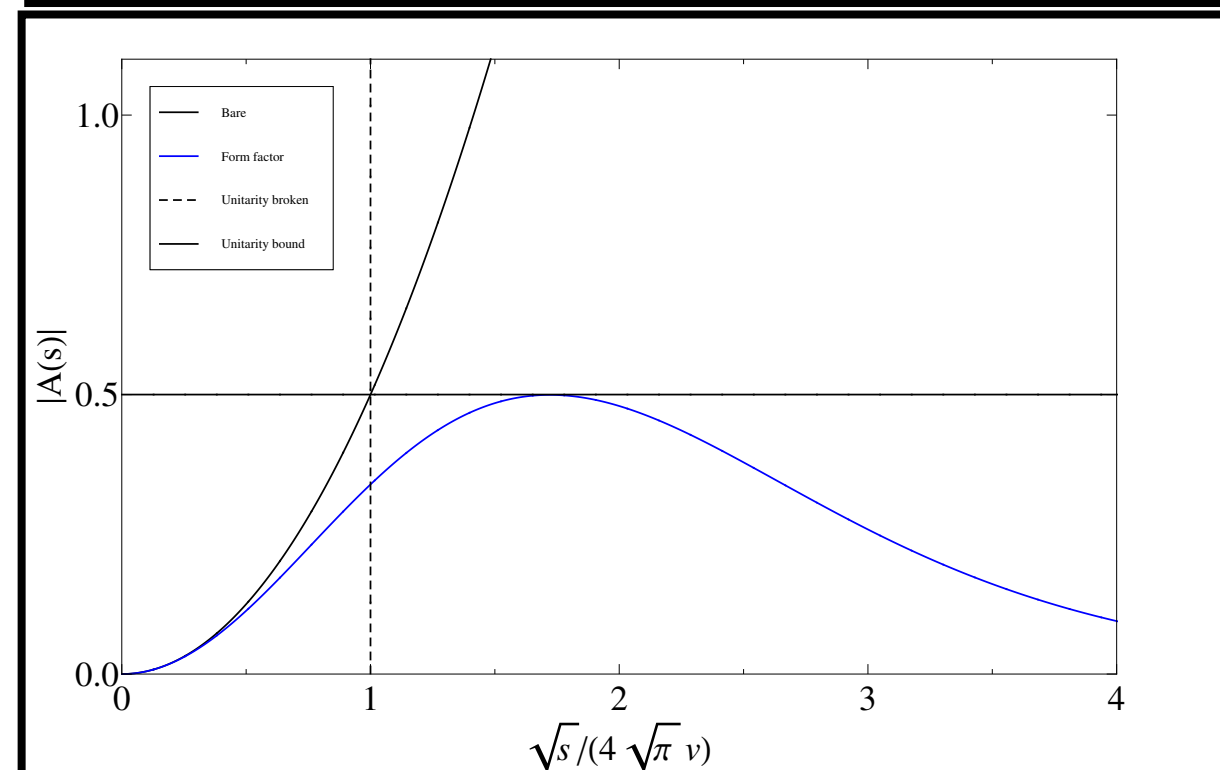
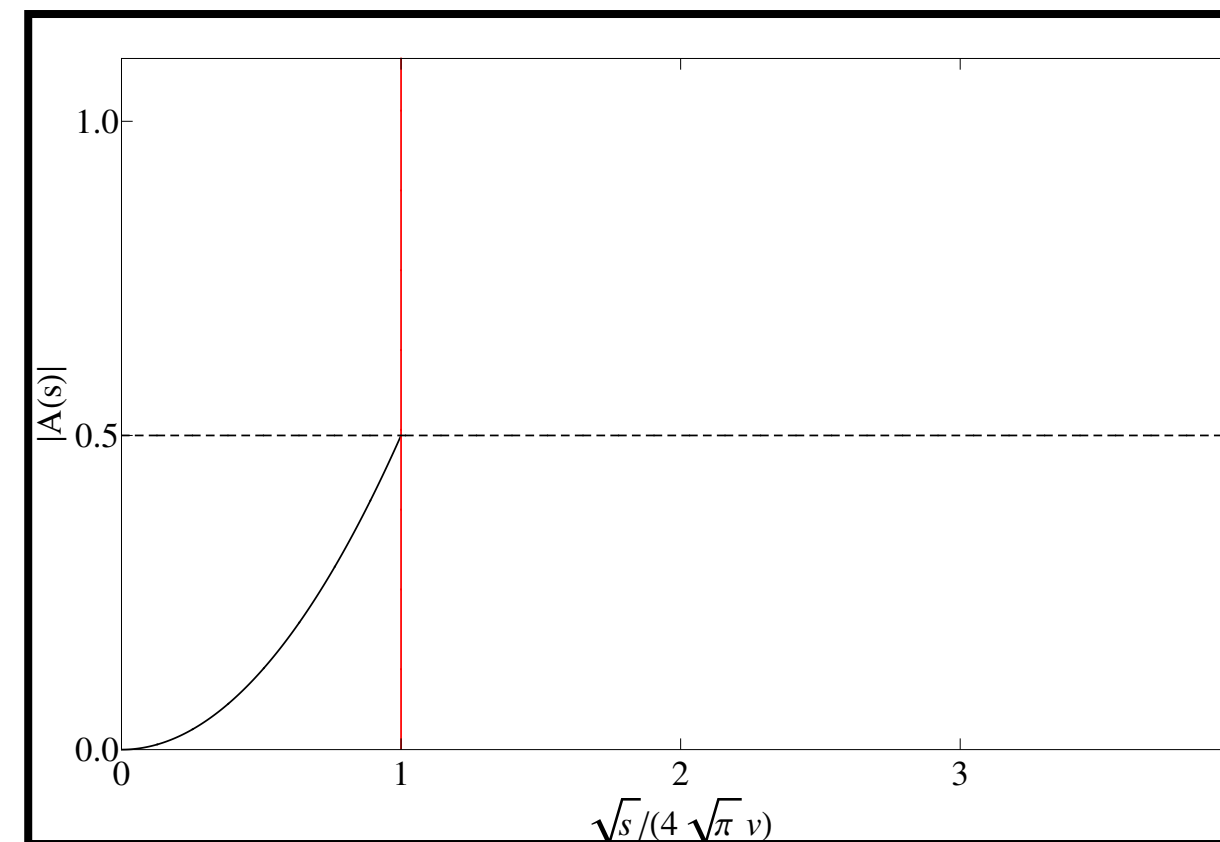
Form factor $\frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n}$

Motivated from strong interactions

Applicable for arbitrary operators, tuning in 2 parameters: n damps unitarity violation, Λ_{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!!!**

- Clebsch-Gordan decomposition into spin–isospin eigenamplitudes

- Amplitudes should be modified only in s–channel configurations

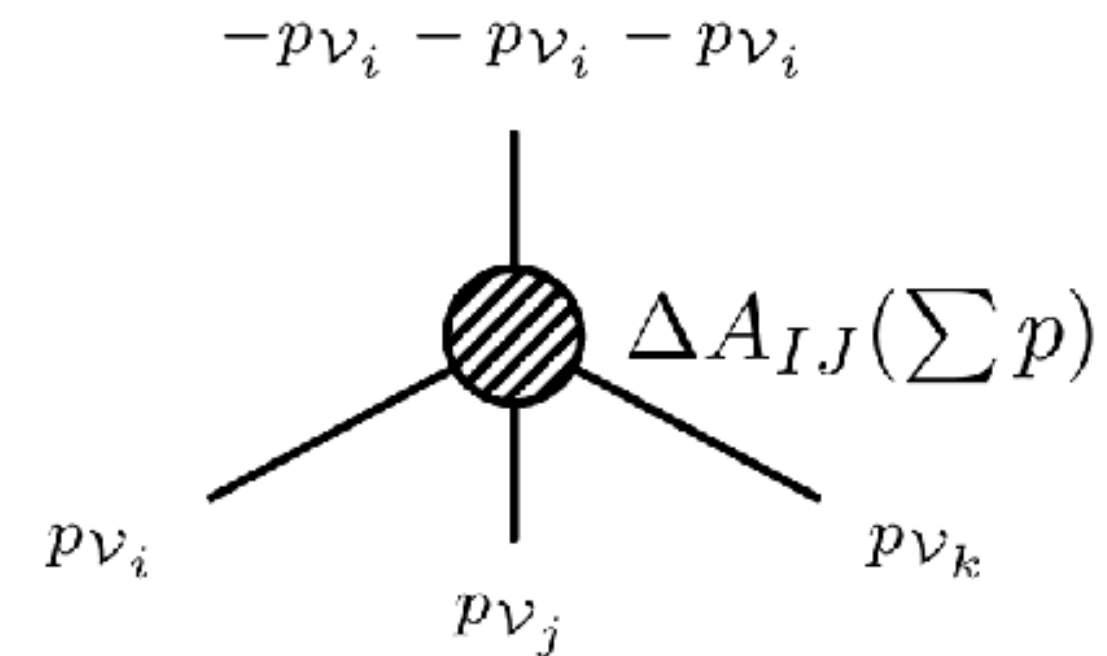
$$\mathcal{A}(I = 0) = 3\mathcal{A}(s, t, u) + \mathcal{A}(t, s, u) + \mathcal{A}(u, s, t)$$

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

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

- Evaluate modified Feynman rules off-shell

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



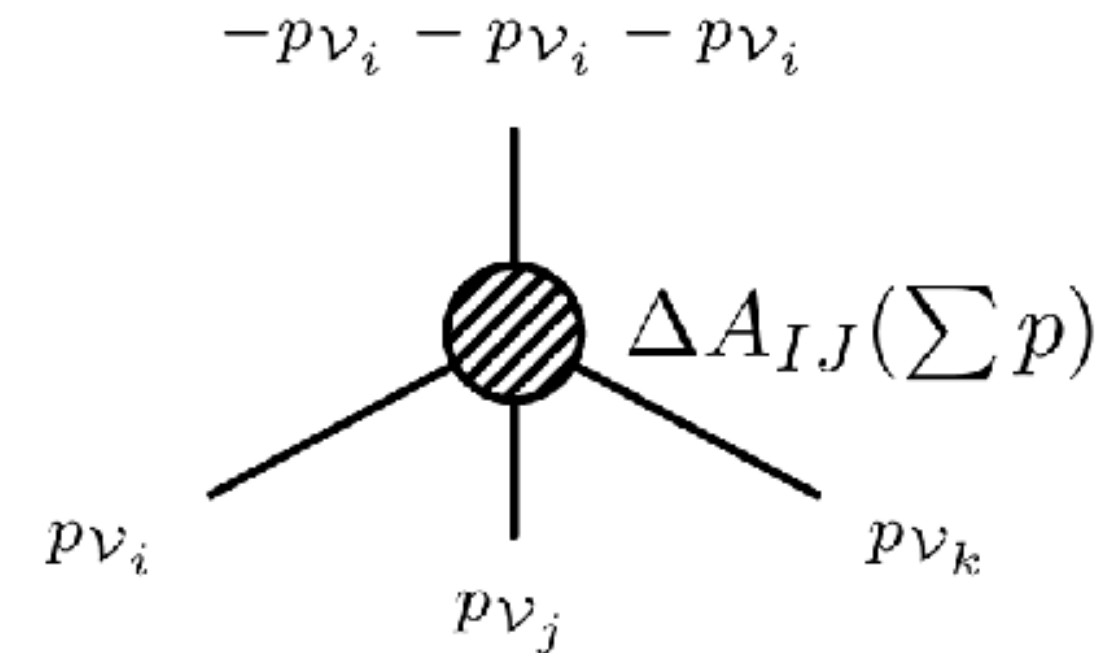
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• Evaluate modified Feynman rules off-shell

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

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

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

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

Extract all partial waves:

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

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

Implementation in WHIZARD takes leading corrections into account

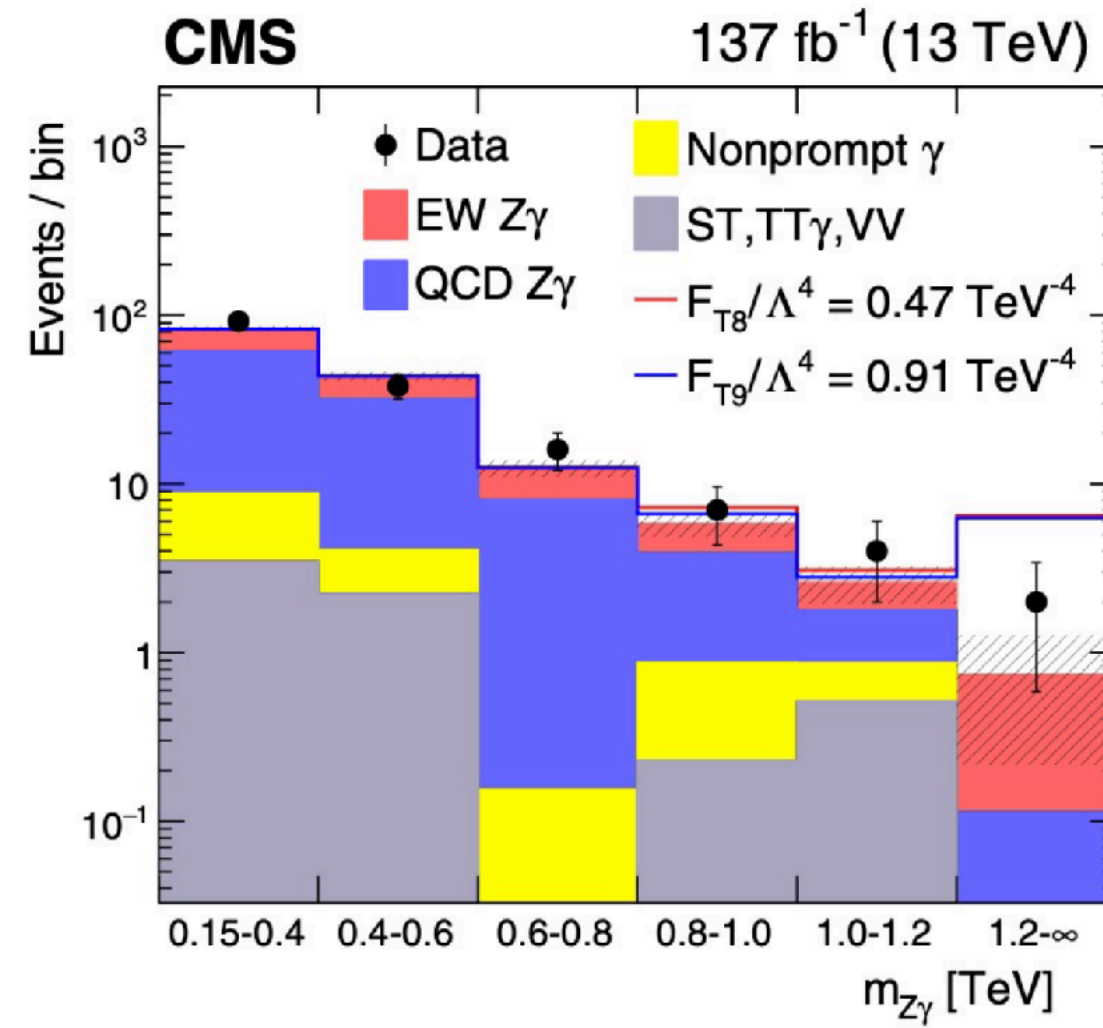
Braß/Fleper/Kilian/JRR/Sekulla, 1807.02512

$\lambda = \lambda_1 - \lambda_2 \qquad \lambda' = \lambda_3 - \lambda_4$														
i \ j	0			1			2			λ				
0	-6	-2	$-\frac{5}{2}$	0	0	0	0	0	0	+	+	+	+	
	0	0	0	0	0	0	$-\frac{2}{3}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	-	+	-	
	0	0	0	0	0	0	$-\frac{2}{3}$	$-\frac{4}{5}$	$-\frac{1}{2}$	+	-	-	+	
	$-\frac{22}{3}$	$-\frac{14}{3}$	$-\frac{11}{6}$	0	0	0	$-\frac{2}{15}$	$-\frac{4}{15}$	$-\frac{1}{30}$	+	+	-	-	
1	0	0	0	0	0	0	0	0	0	+	+	+	+	
	0	0	0	0	0	0	$\frac{2}{5}$	$-\frac{1}{5}$	0	+	-	+	-	
	0	0	0	0	0	0	$-\frac{2}{5}$	$\frac{1}{5}$	0	+	-	-	+	
	0	0	0	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	0	0	0	+	+	-	-	
2	0	-2	-1	0	0	0	0	0	0	+	+	+	+	
	0	0	0	0	0	0	$-\frac{2}{3}$	$-\frac{1}{5}$	$-\frac{1}{5}$	+	-	+	-	
	0	0	0	0	0	0	$-\frac{2}{3}$	$-\frac{1}{5}$	$-\frac{1}{5}$	+	-	-	+	
	$-\frac{4}{3}$	$-\frac{8}{3}$	$-\frac{1}{3}$	0	0	0	$-\frac{2}{15}$	$-\frac{1}{15}$	$-\frac{1}{30}$	+	+	-	-	
	c_0	c_1	c_2	c_0	c_1	c_2	c_0	c_1	c_2					

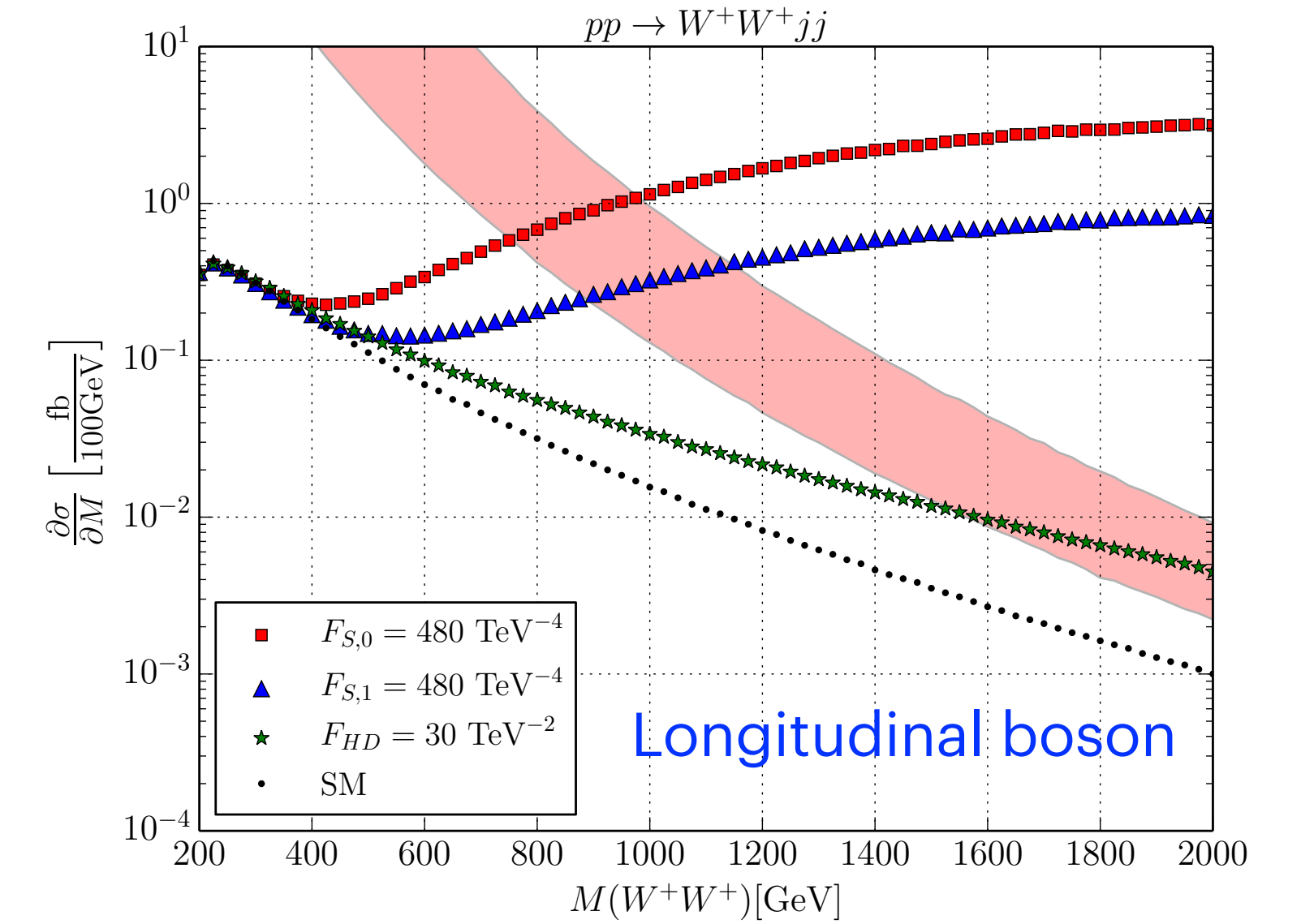
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F_{M7}/Λ^4	-44.7	45.0	-56.6	55.9	1.6
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General cuts:

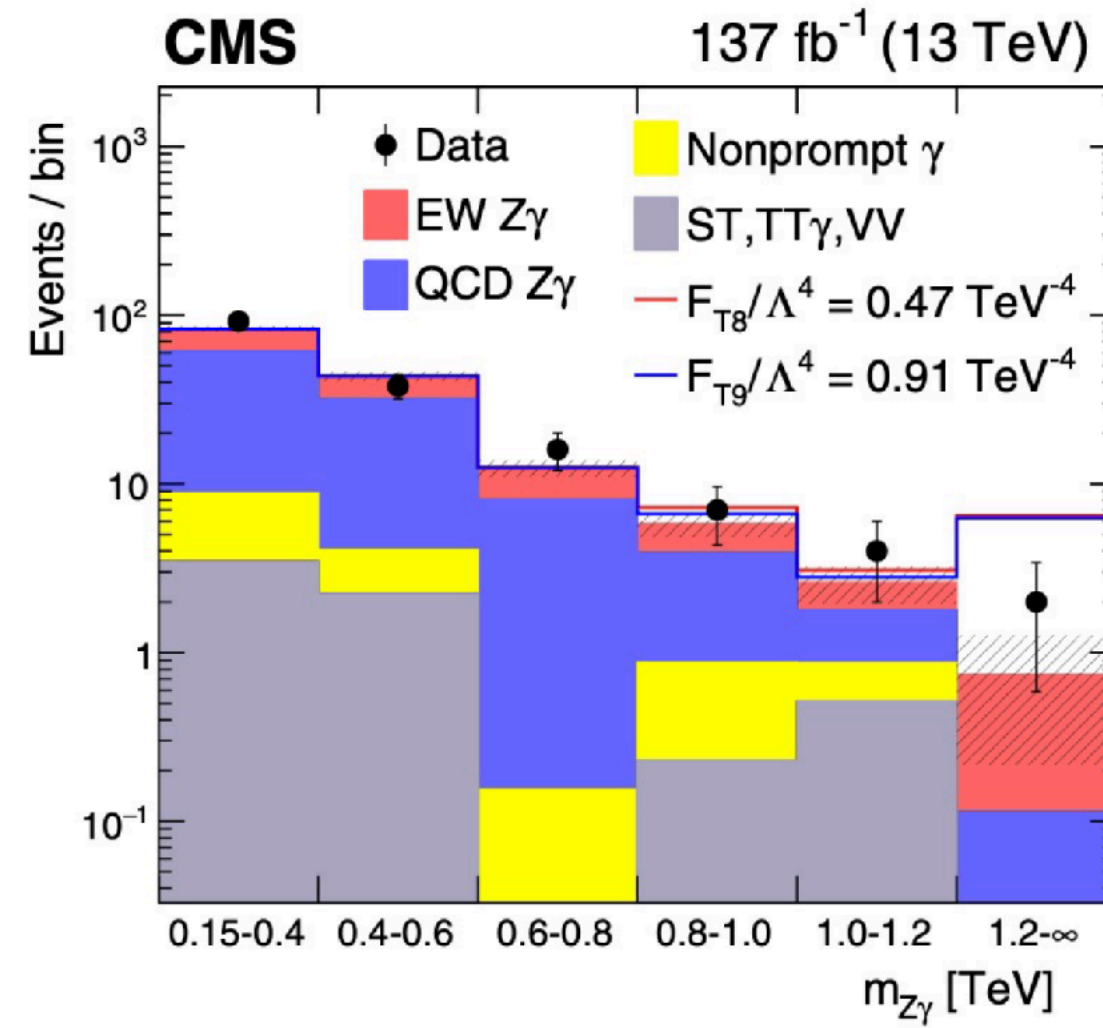
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Kilian/Ohl/JRR/Sekulla, 1511.00022

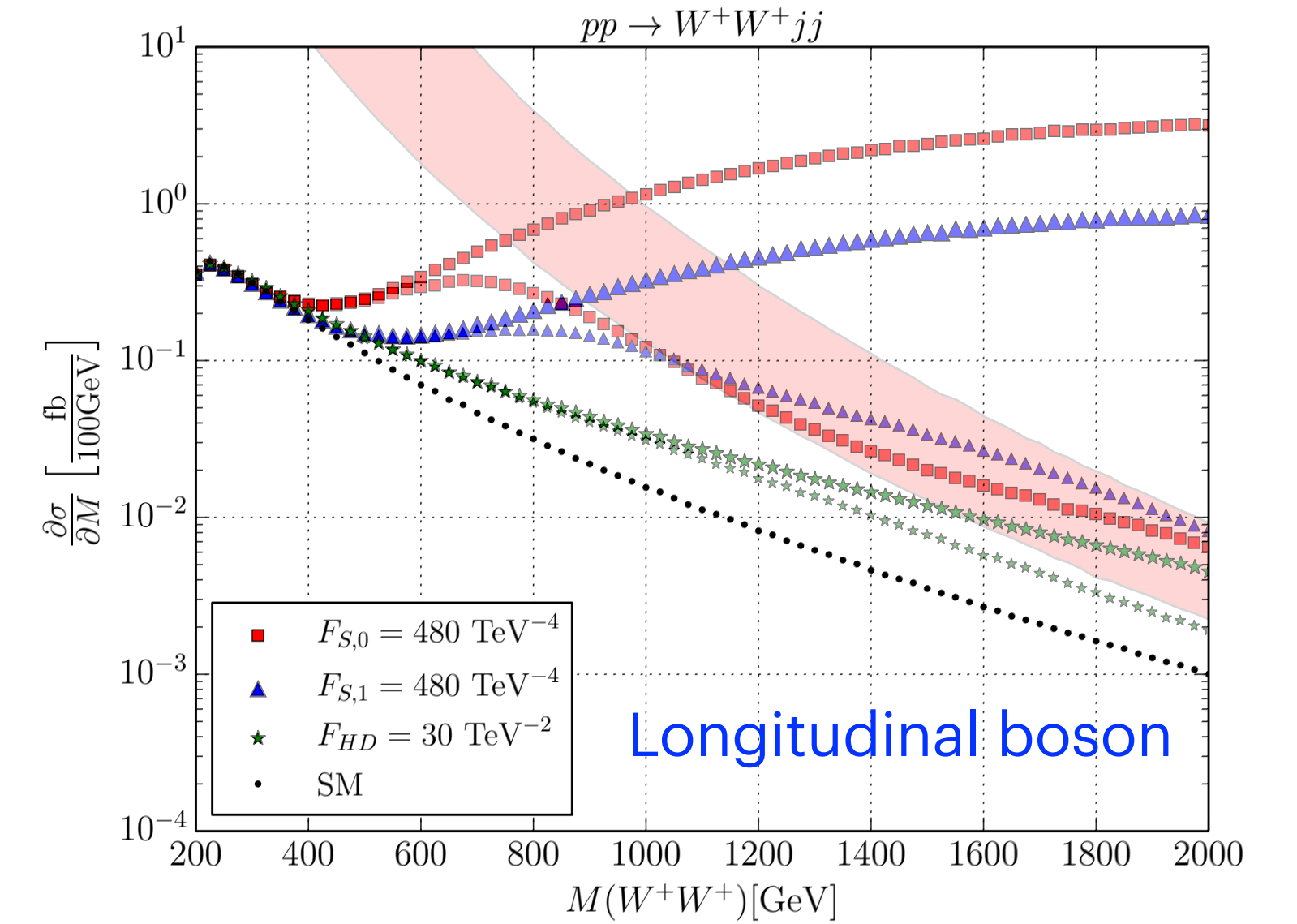
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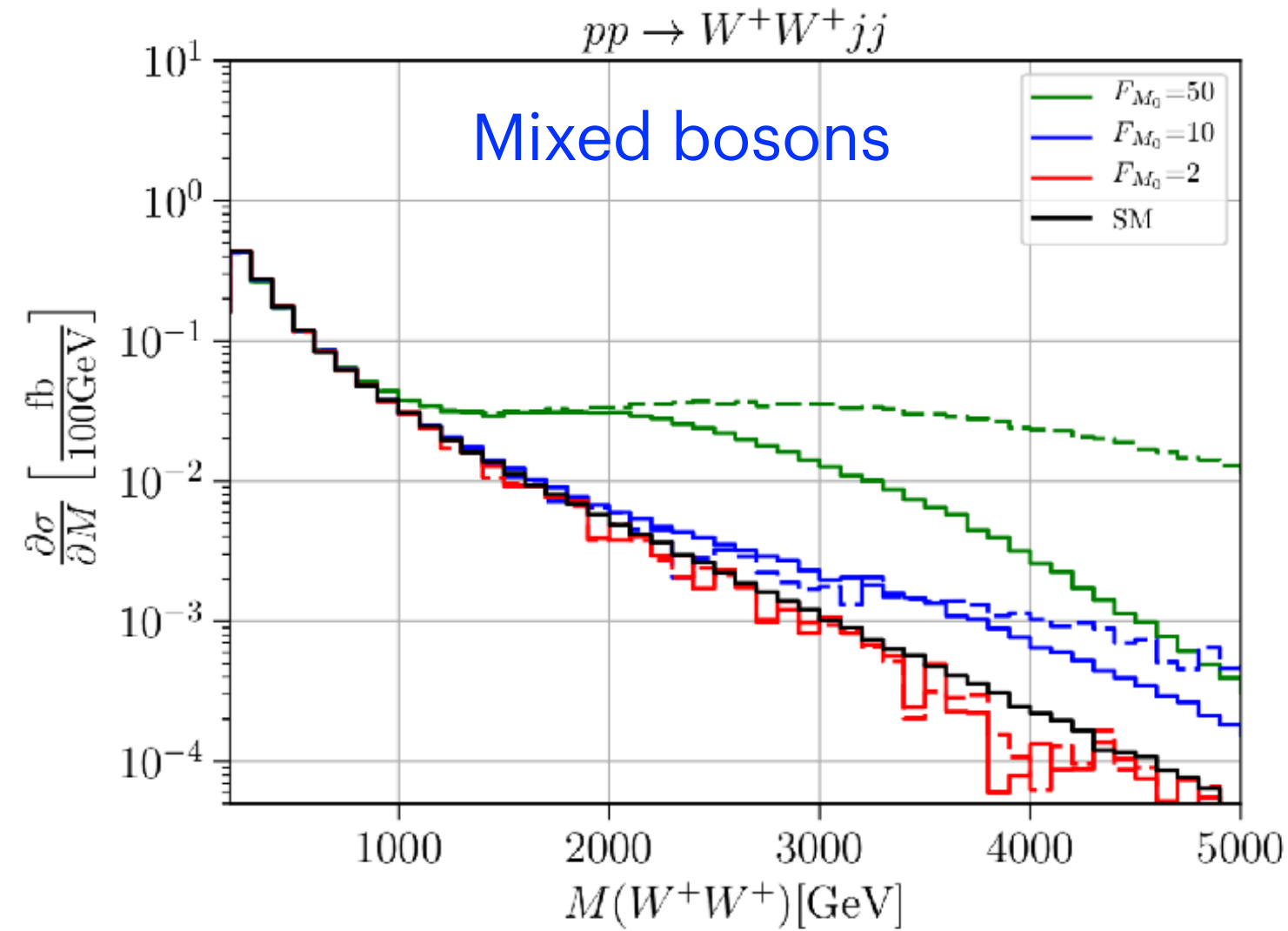
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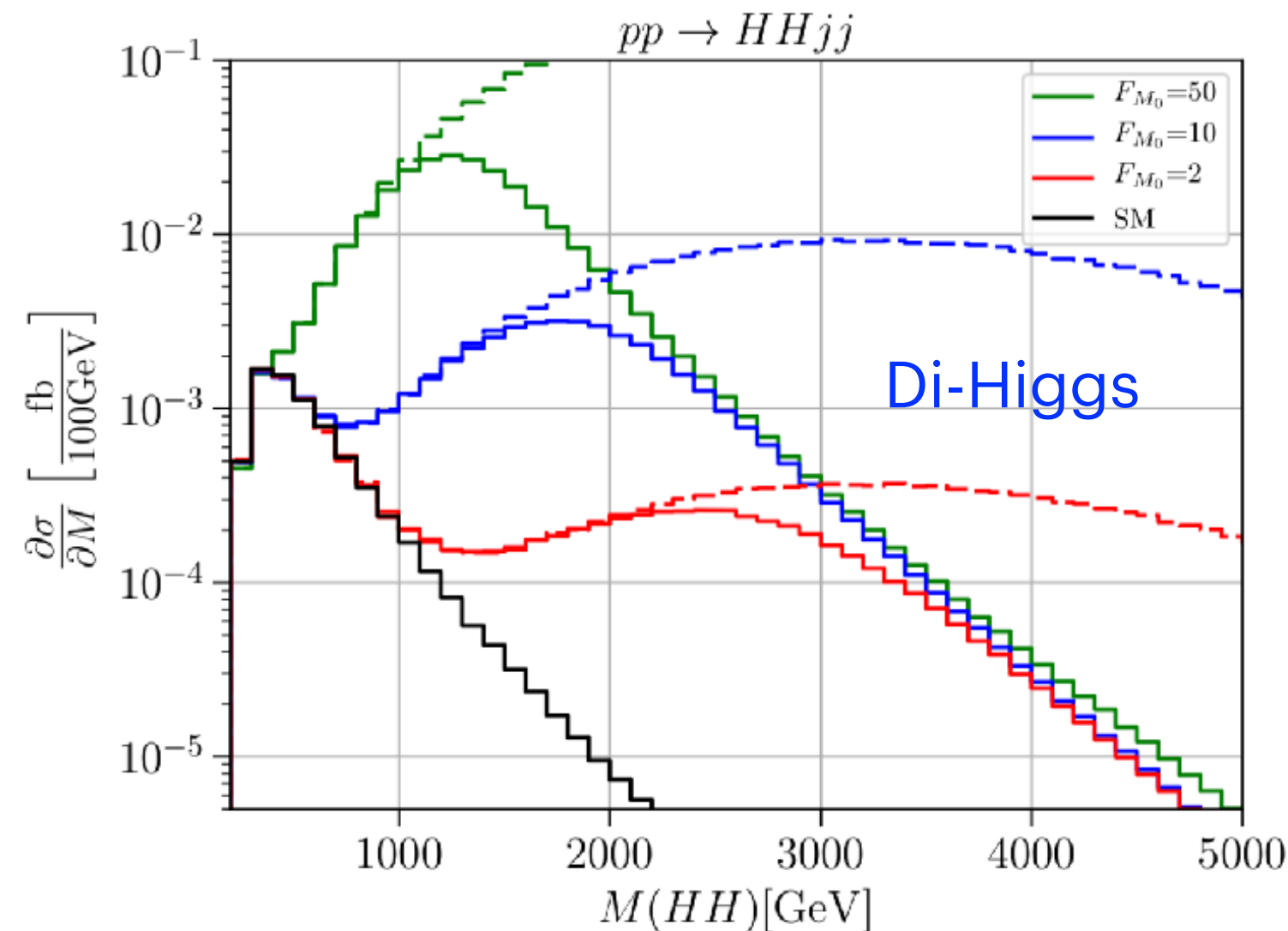
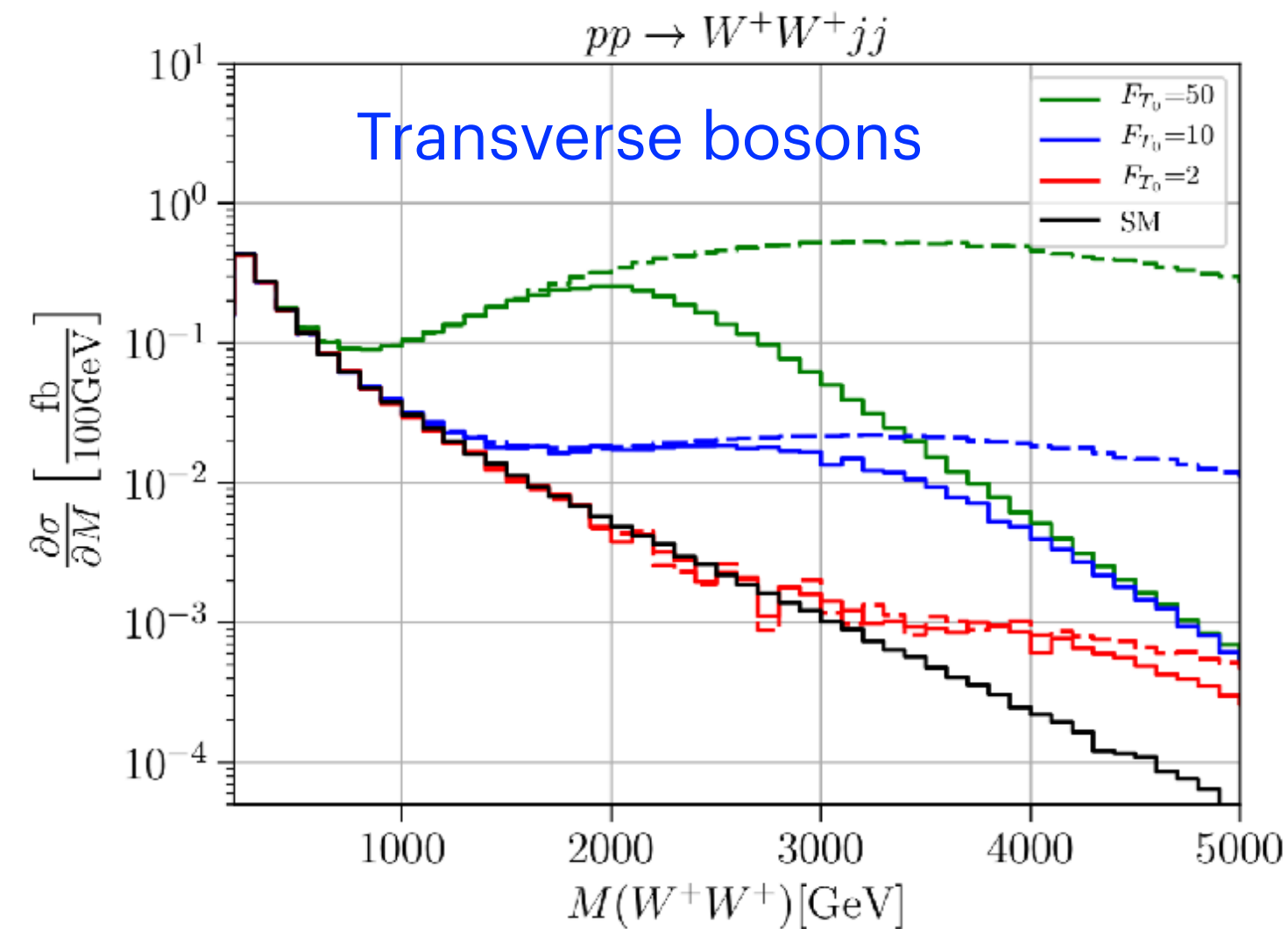
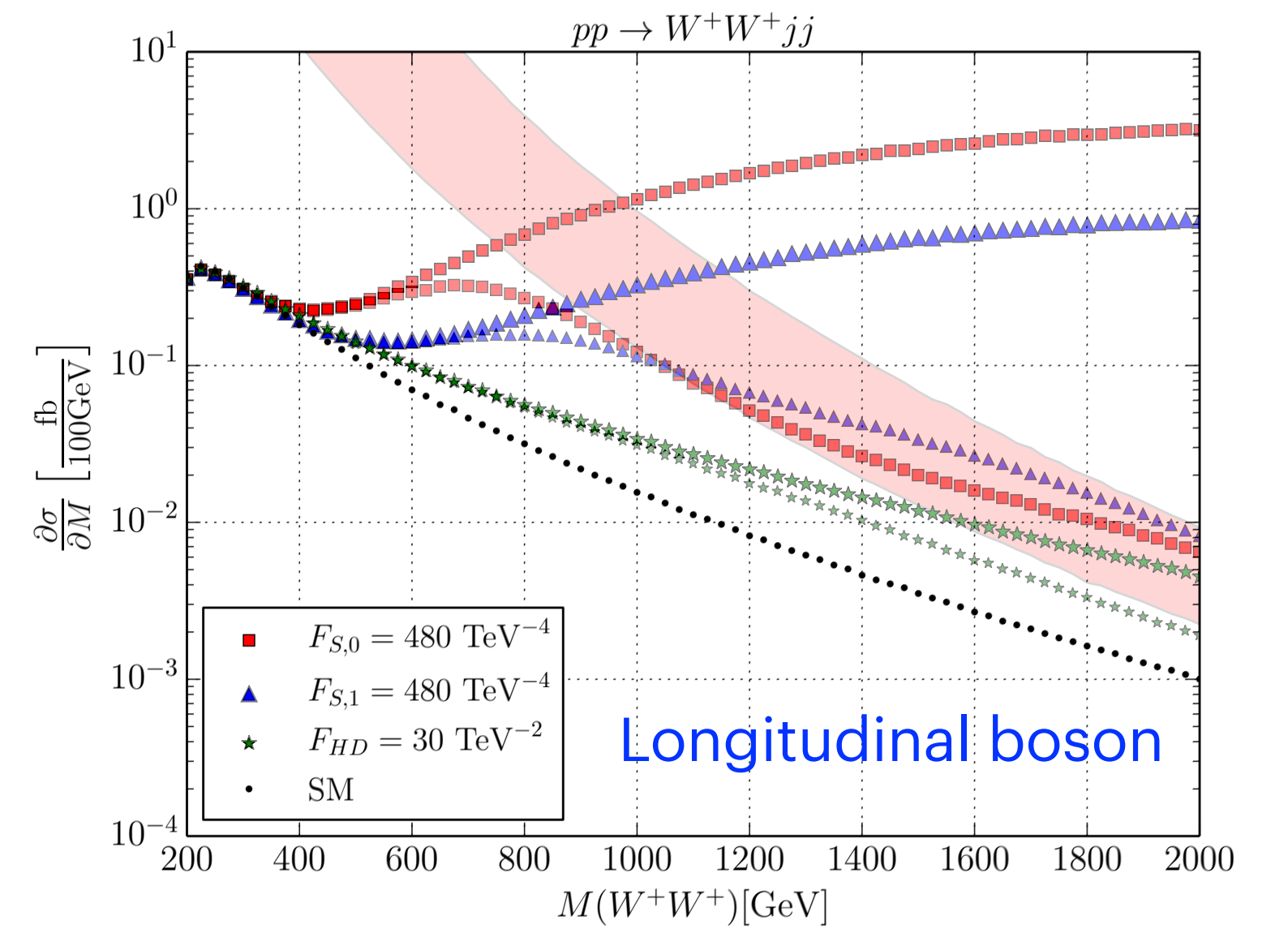
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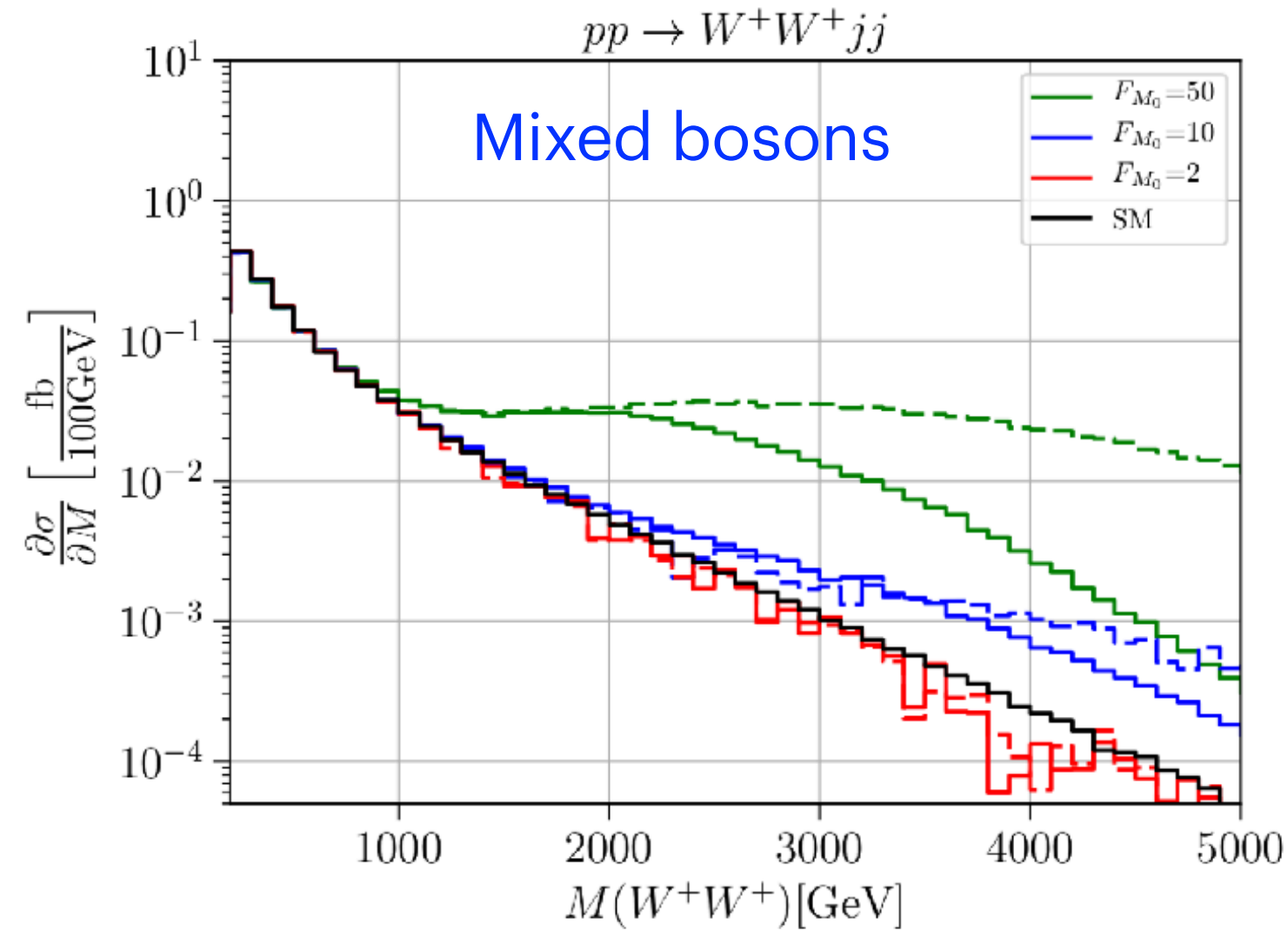
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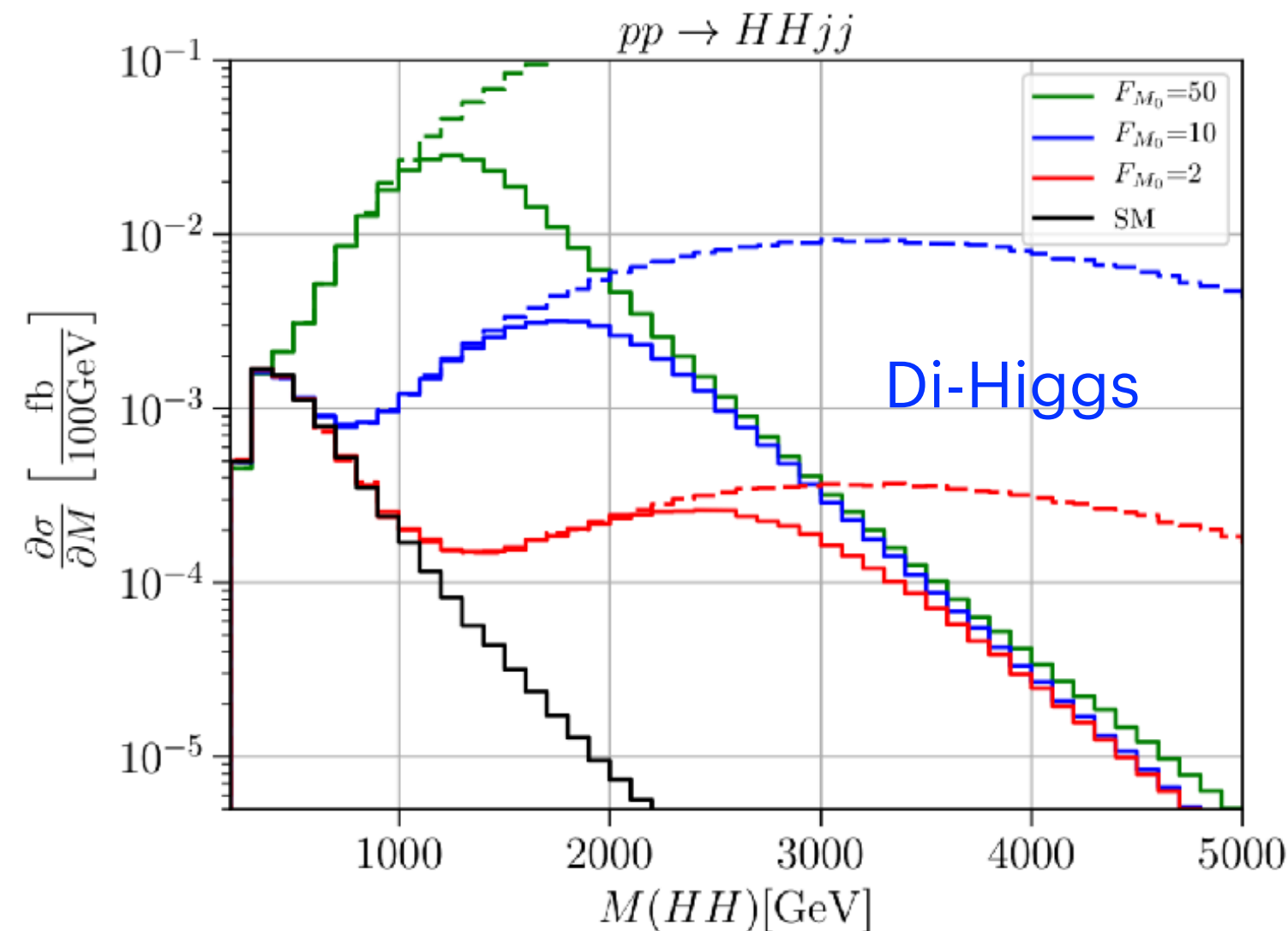
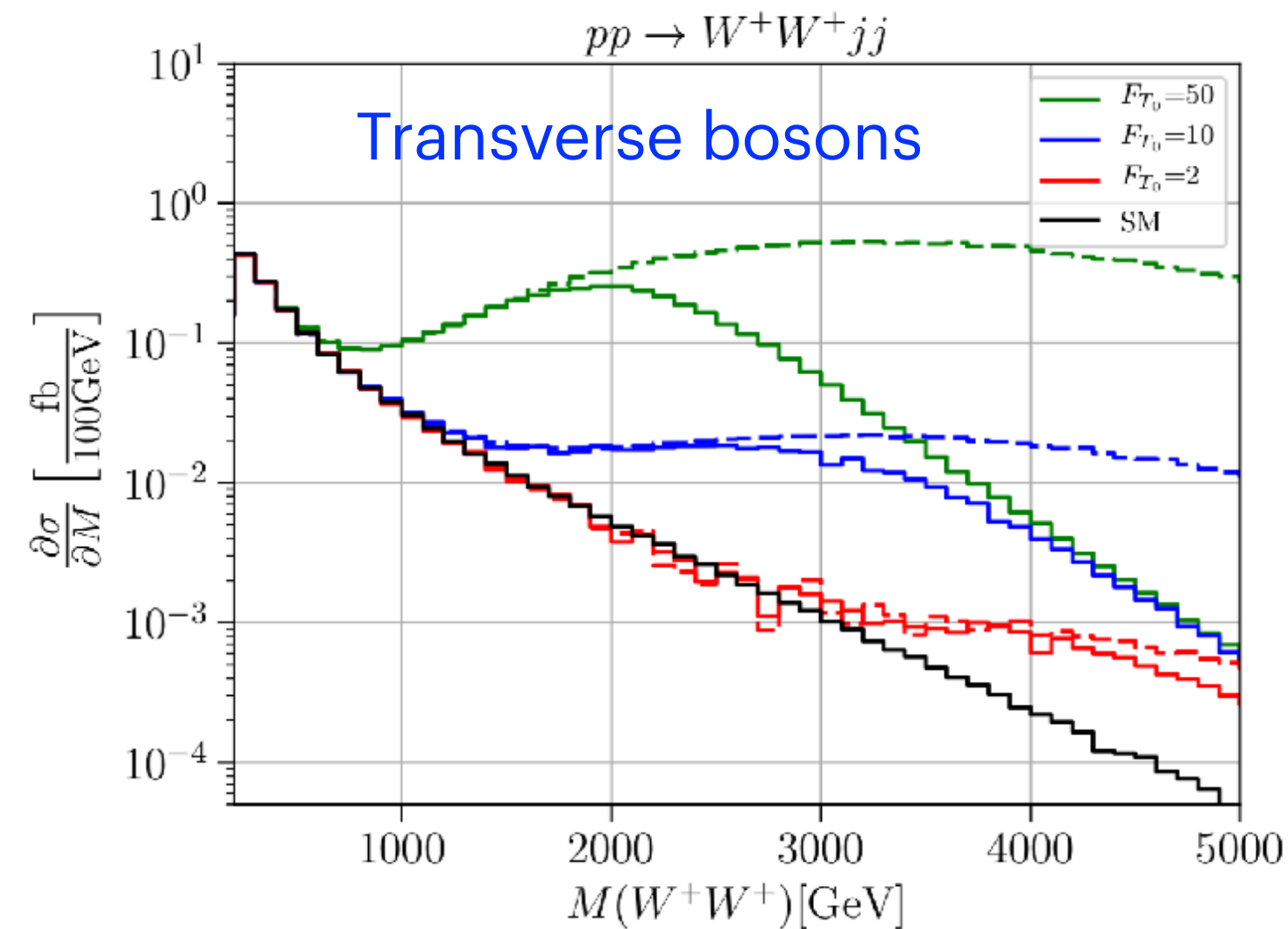
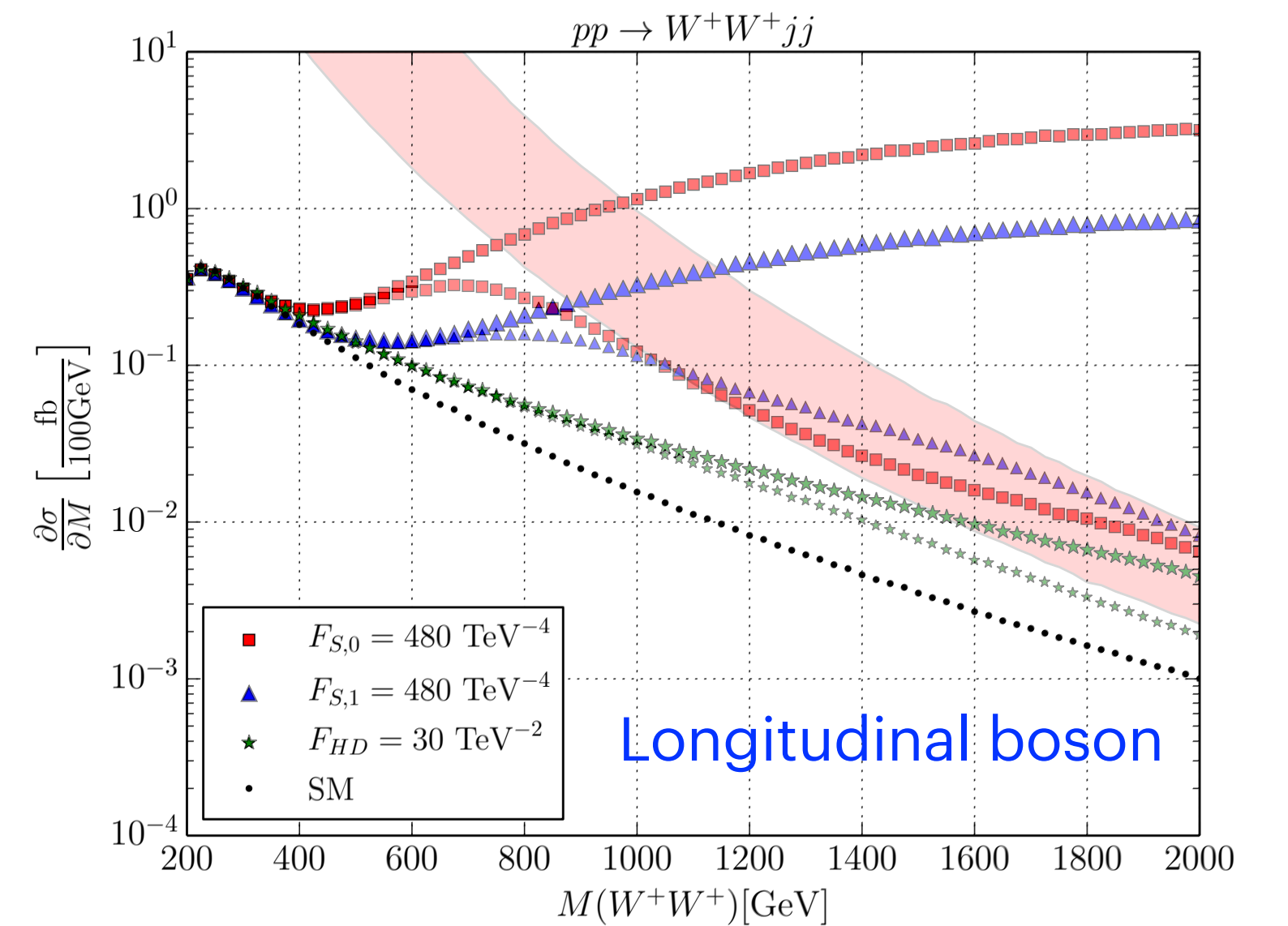
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Much more leeway for new physics in transversal gauge bosons and di-Higgs ; longitudinal bosons much closer to unitarity limit

Kilian/Ohl/JRR/Sekulla, 1511.00022

- 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

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

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs singlet?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
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$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Alboreanu/Kilian/JRR, 0806.4145; Kilian et al., 1511.00022; Braß et al. , 1807.02512
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tensor	f^0	$\left(X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++} \right)$ X_v^-, X_v^0, X_v^+ X_s^0
...	...	...

Translation into Wilson coefficient below resonance

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

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

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...	...	...

Translation into Wilson coefficient below resonance

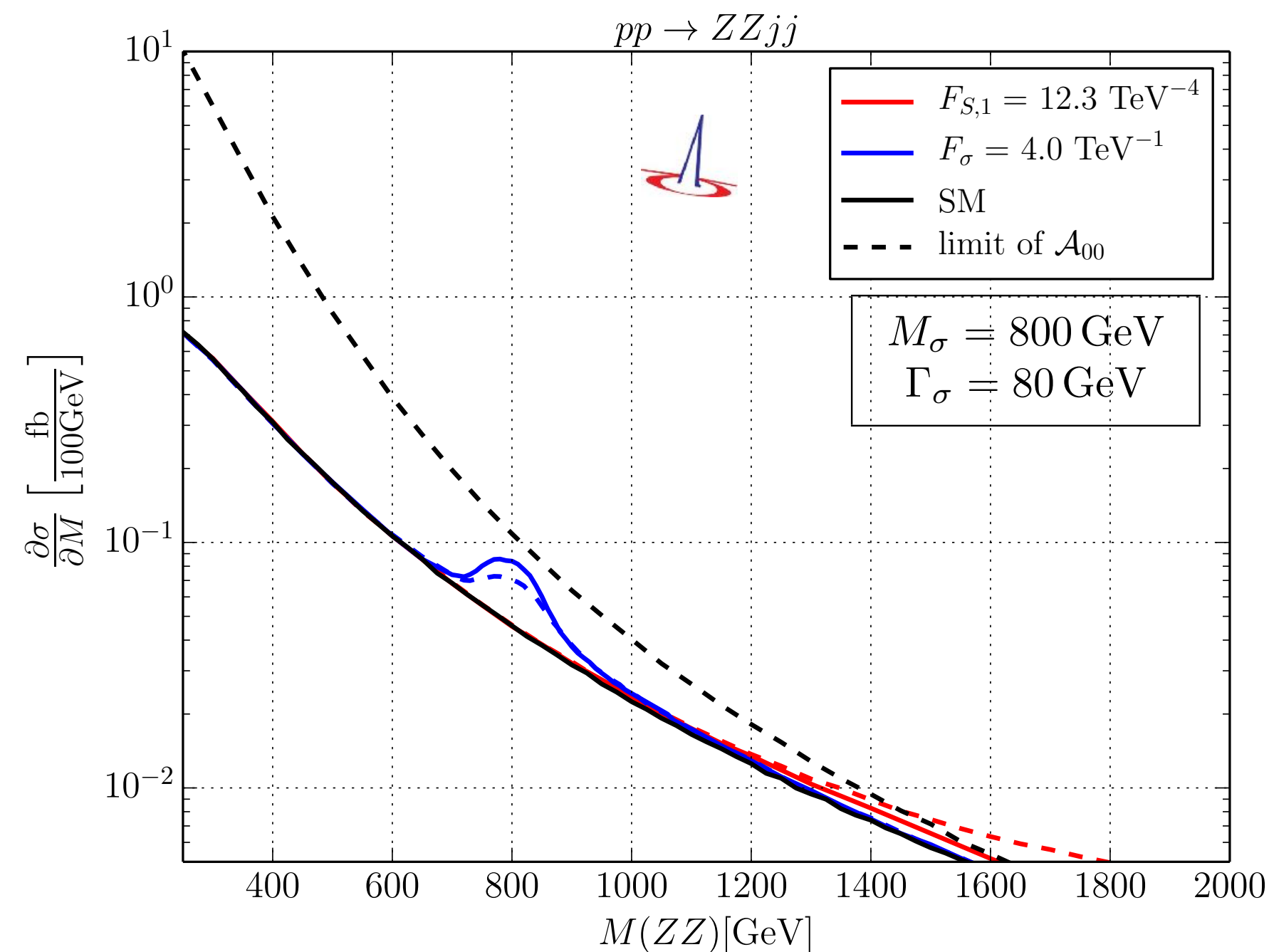
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$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$

	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	$\left(X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++} \right)$ X_v^-, X_v^0, X_v^+ X_s^0
...	...	...

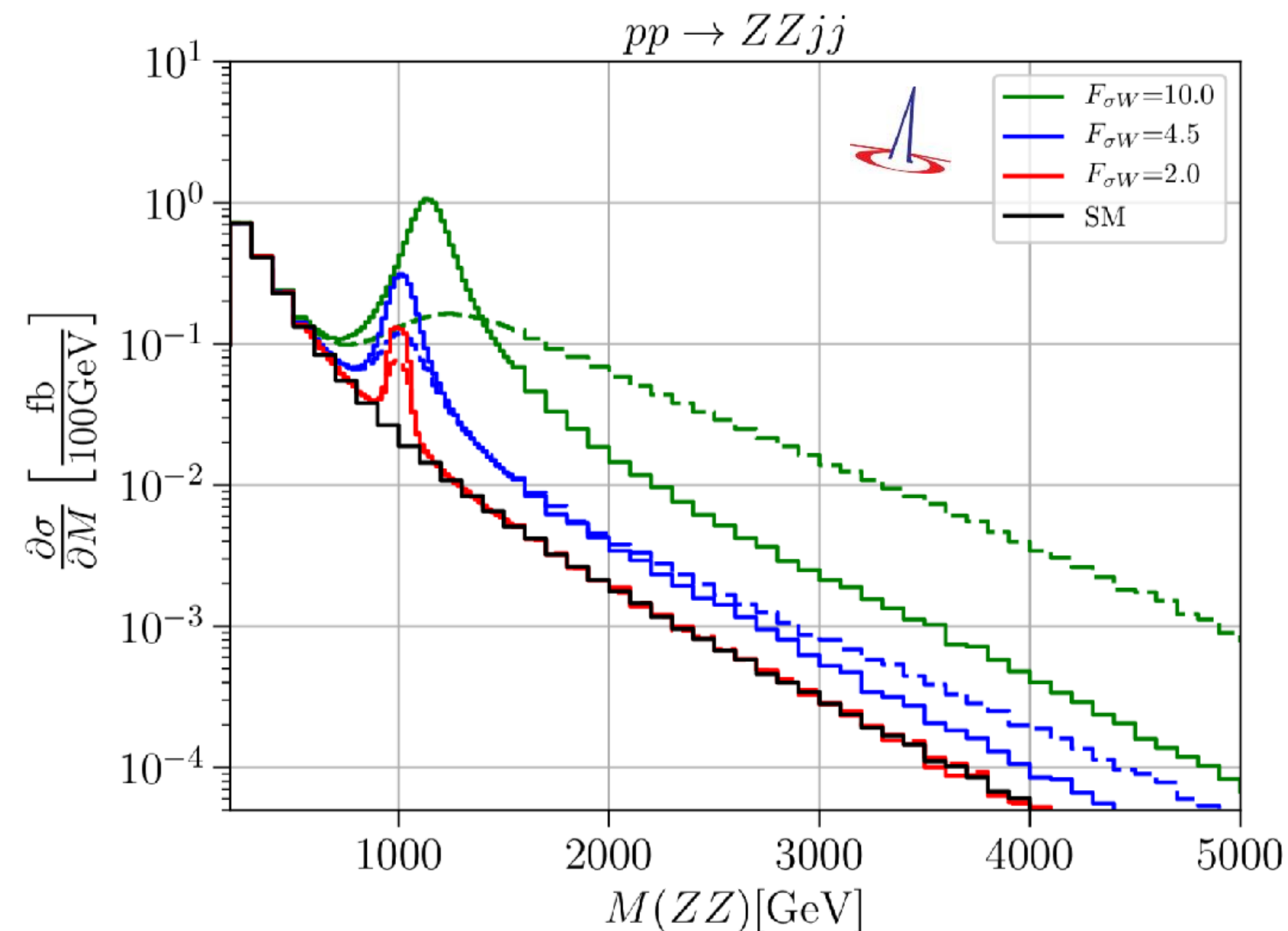
Translation into Wilson coefficient below resonance

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

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

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs singlet?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

Alboreanu/Kilian/JRR, 0806.4145; Kilian et al., 1511.00022; Braß et al., 1807.02512
Delgado et al., 1907.11957



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

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



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?

🕒 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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- ϕ : $\partial_{\mu} \partial_{\nu} f^{\mu\nu}$
- A^{μ} : $\partial_{\nu} f^{\mu\nu}$
- σ : f^{μ}_{μ}

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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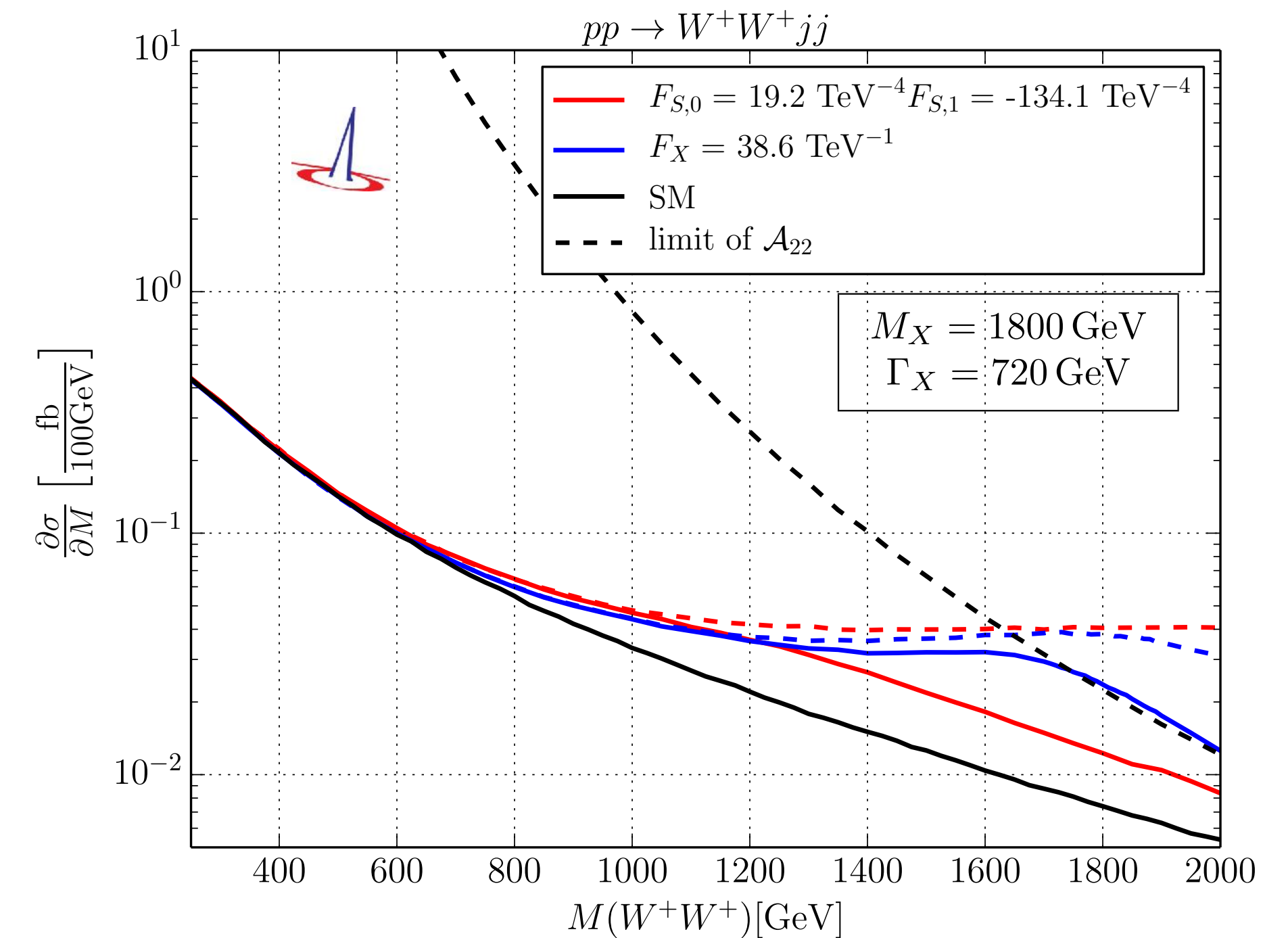
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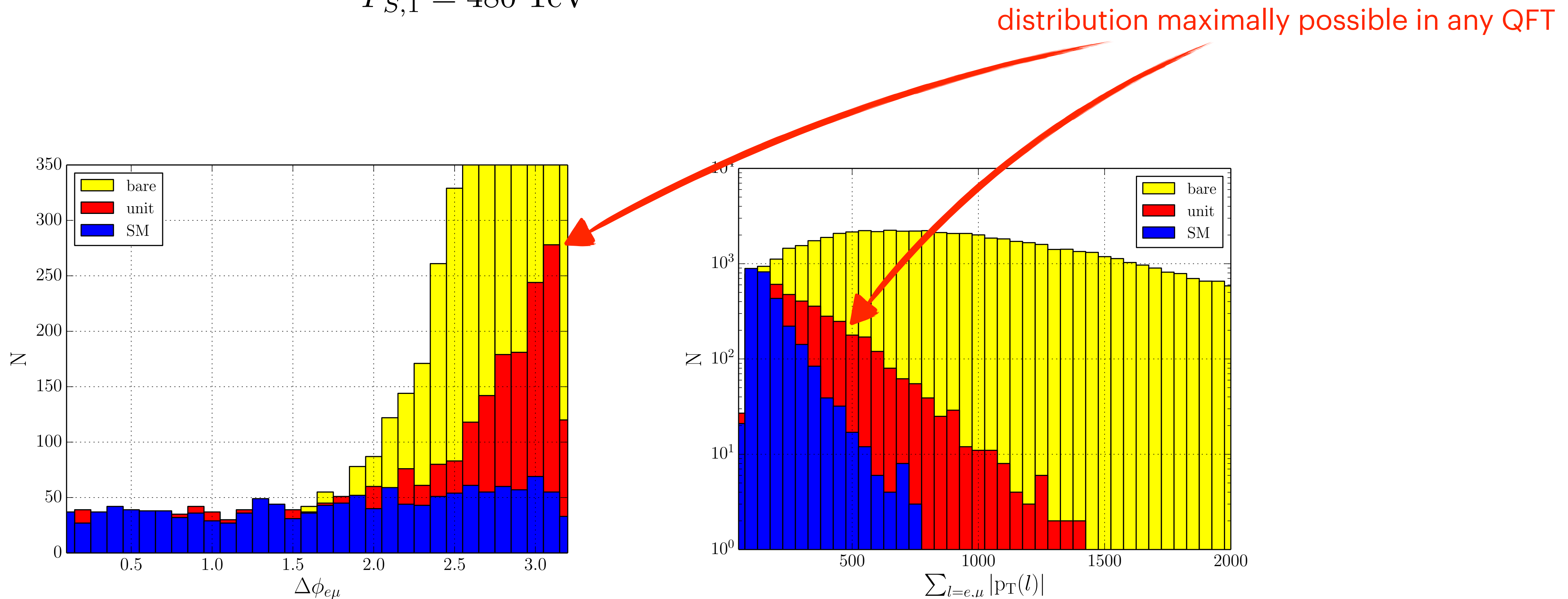


Differential Spectra in VBS

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

Kilian/Ohl/JRR/Sekulla, 1408.6207

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



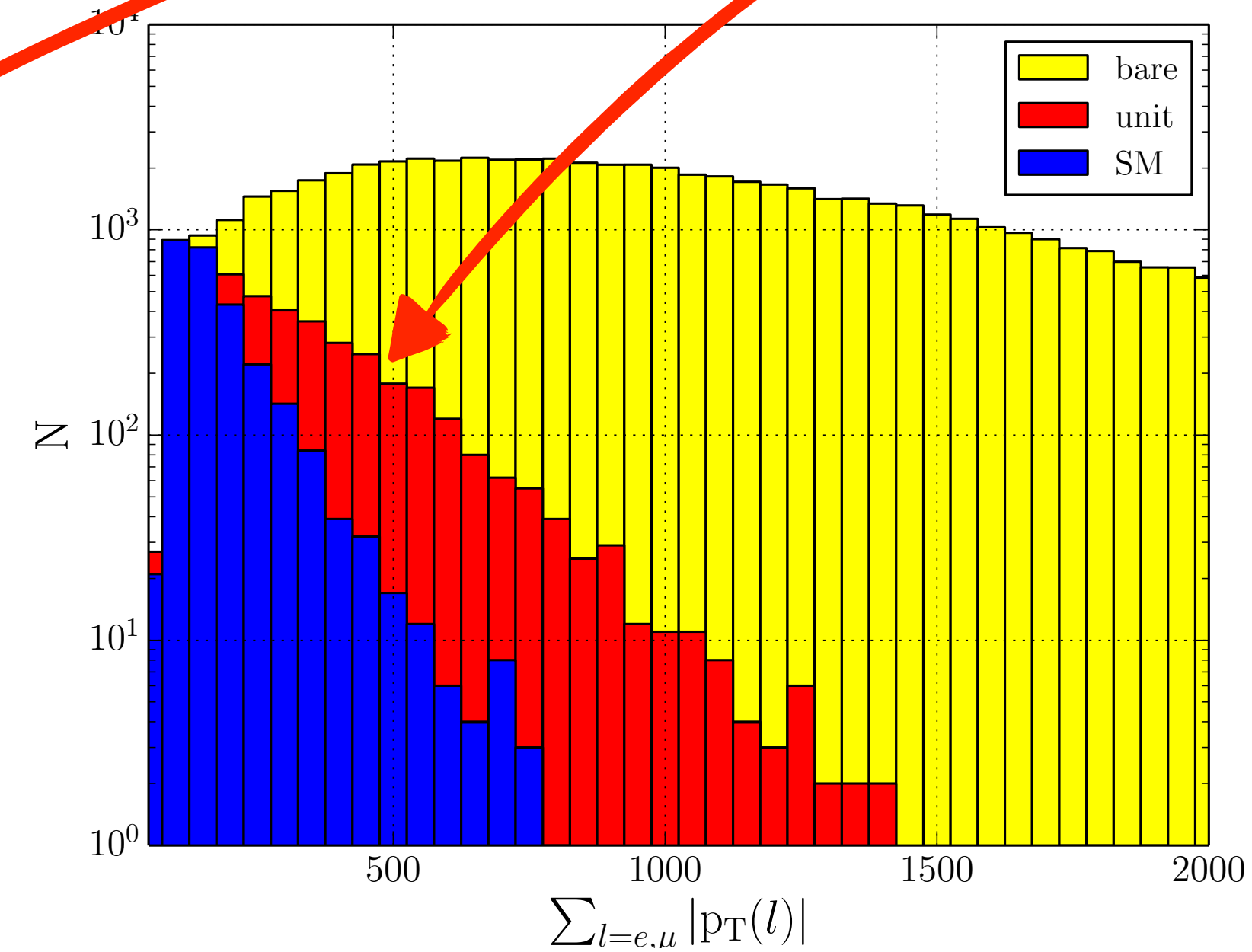
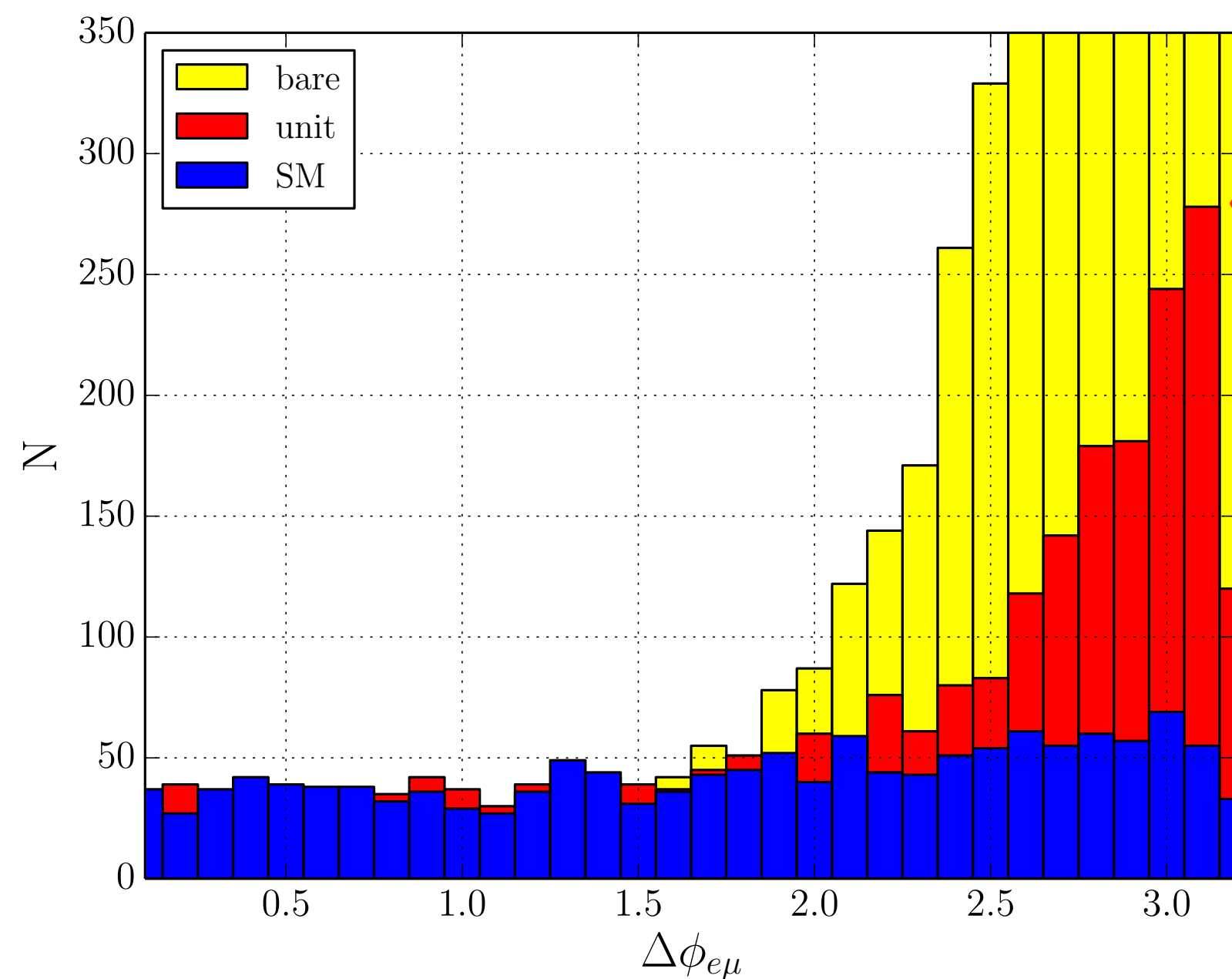
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distribution maximally possible in any QFT

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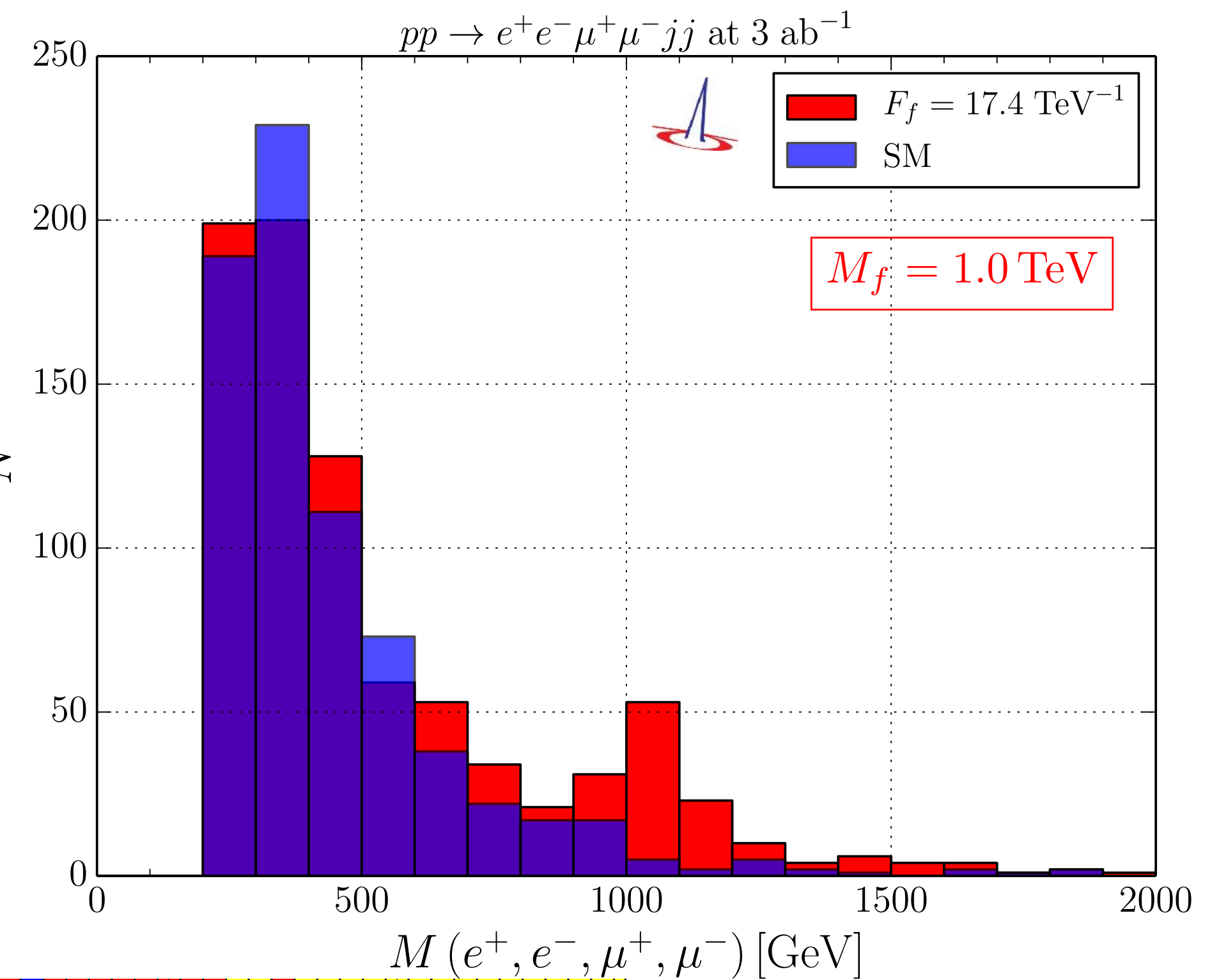
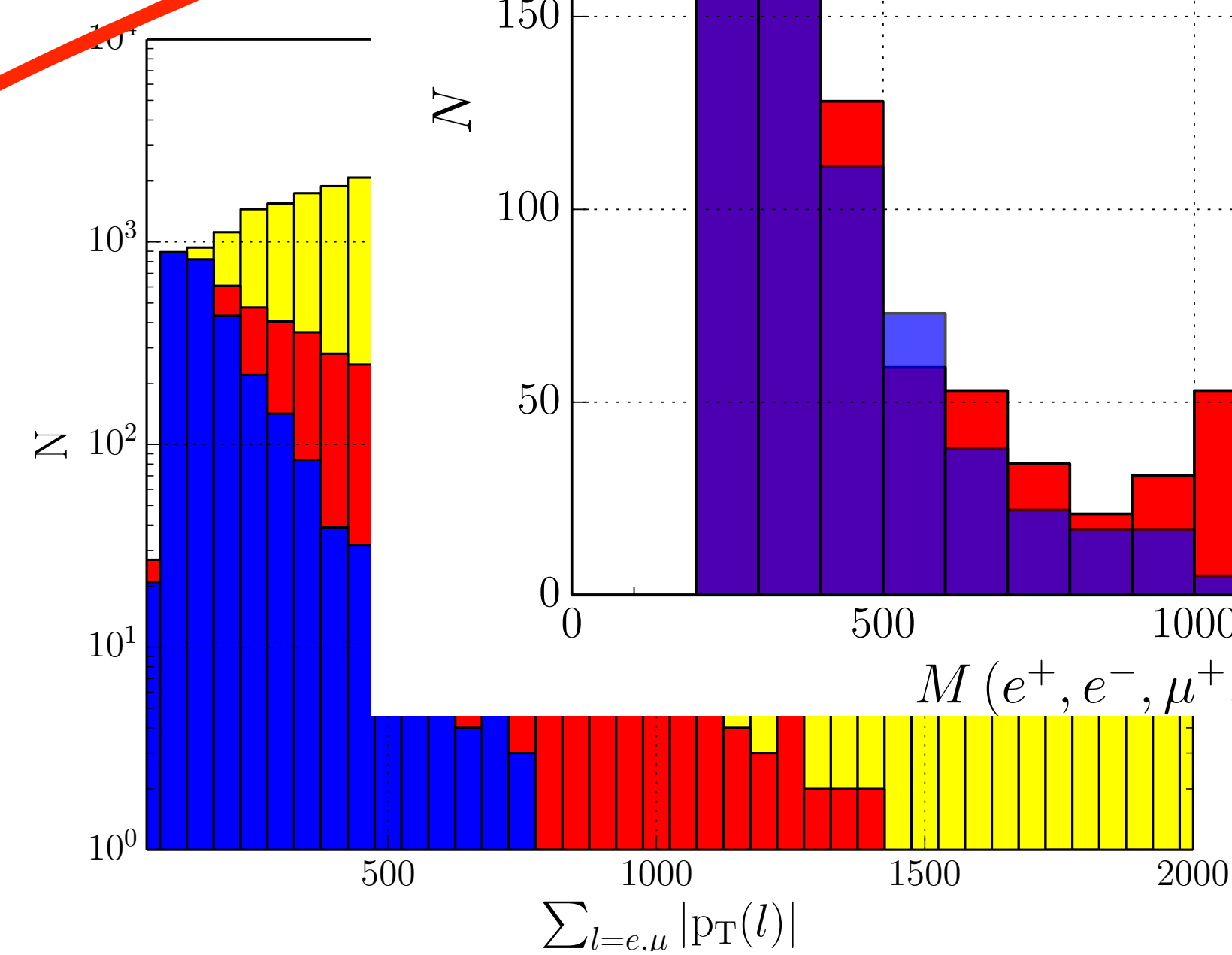
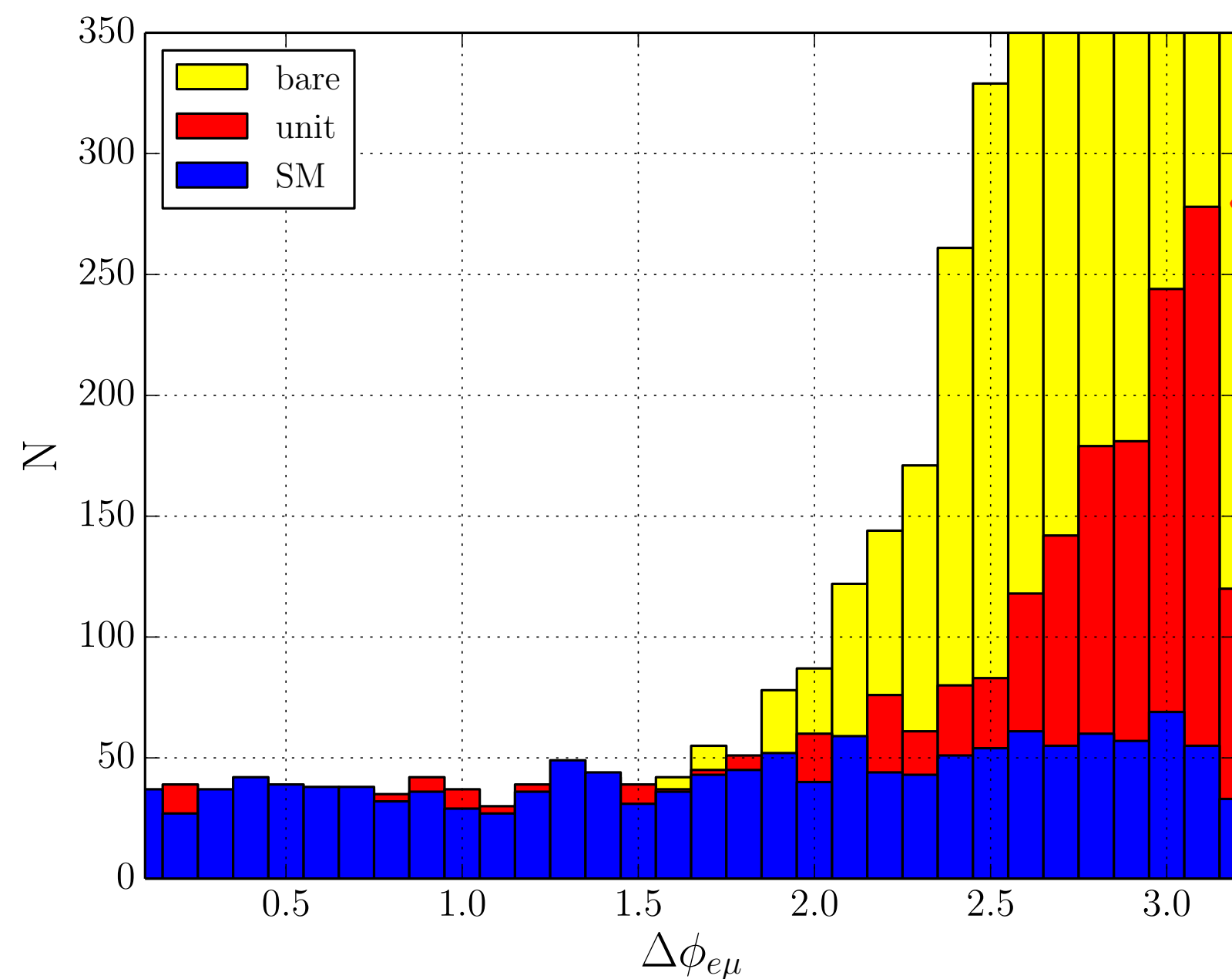
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Dedicated New Physics Models in VBS

25 / 31

- 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.
- Important: dedicated comparison of UV-(quasi-)complete model with EFT descriptions
- Example: HVT [Bruggisser/Geoffrey/Kilian/Krämer/Luchmann/Plehn/Summ, 2108.01094; Summ, 2103.02487](#)

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$$\mathcal{L}_{HVT} = \mathcal{L}_{SM} - \frac{1}{4} \tilde{V}_{\mu\nu}^A \tilde{V}_{\mu\nu}^A + \frac{\tilde{m}_V^2}{2} \tilde{V}_{\mu}^A \tilde{V}_{\mu}^A - \frac{\tilde{g}_M}{2} \tilde{V}_{\mu\nu}^A \tilde{W}_{\mu\nu}^A$$

$$+ \tilde{g}_H \tilde{V}_{\mu}^A J_{H\mu}^A + \tilde{g}_l \tilde{V}_{\mu}^A J_{l\mu}^A + \tilde{g}_q \tilde{V}_{\mu}^A J_{q\mu}^A + \frac{\tilde{g}_{VH}}{2} |H|^2 \tilde{V}_{\mu}^A \tilde{V}_{\mu}^A$$

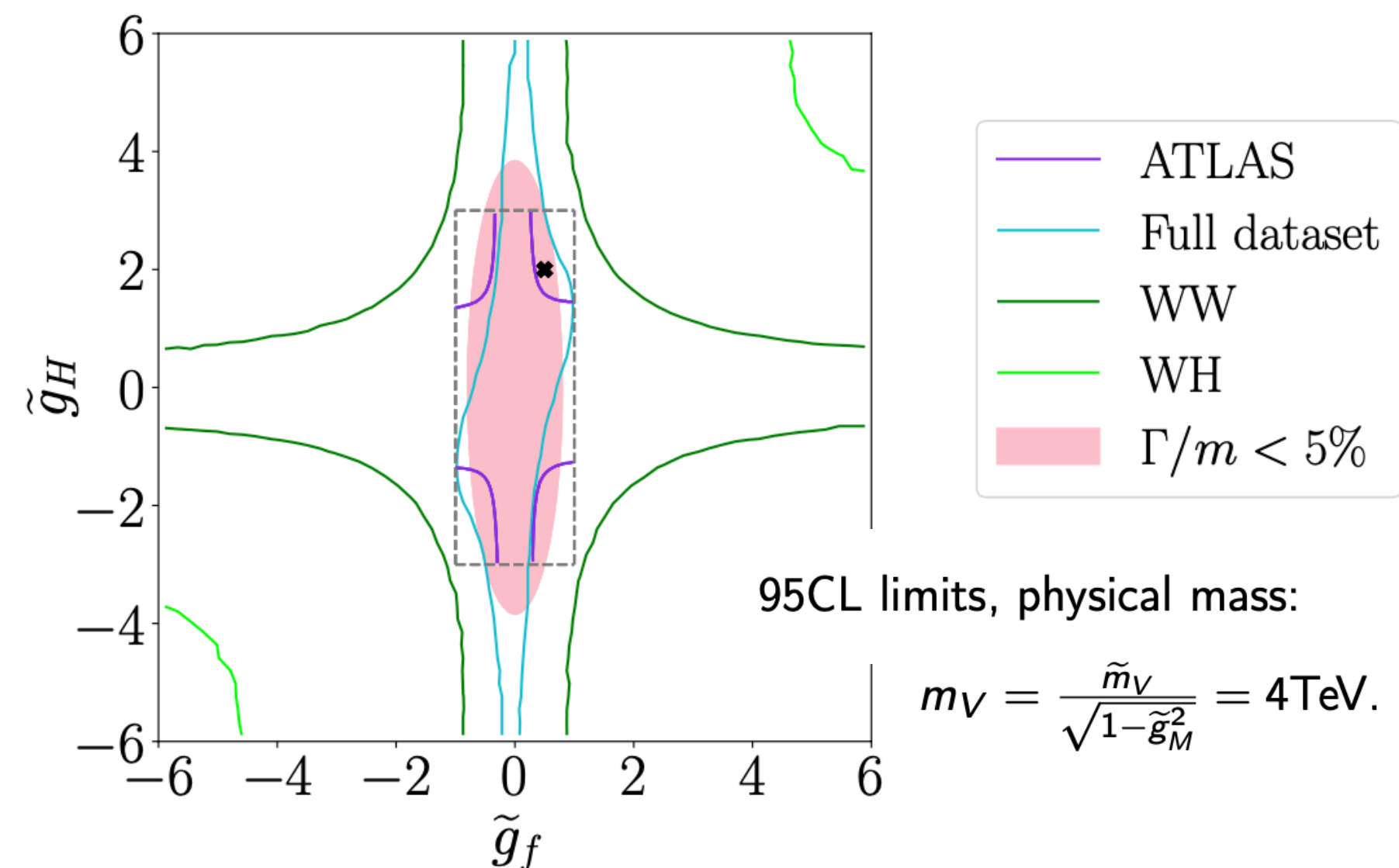
- 5 UV parameters, 1 matching scale Q
- 1-loop matching to 17 dim-6 operators: $\frac{c_i}{\Lambda^2} (\tilde{g}_M, \tilde{g}_H, \tilde{g}_l, \tilde{g}_q, \tilde{g}_{VH}, \tilde{m}_V, Q)$
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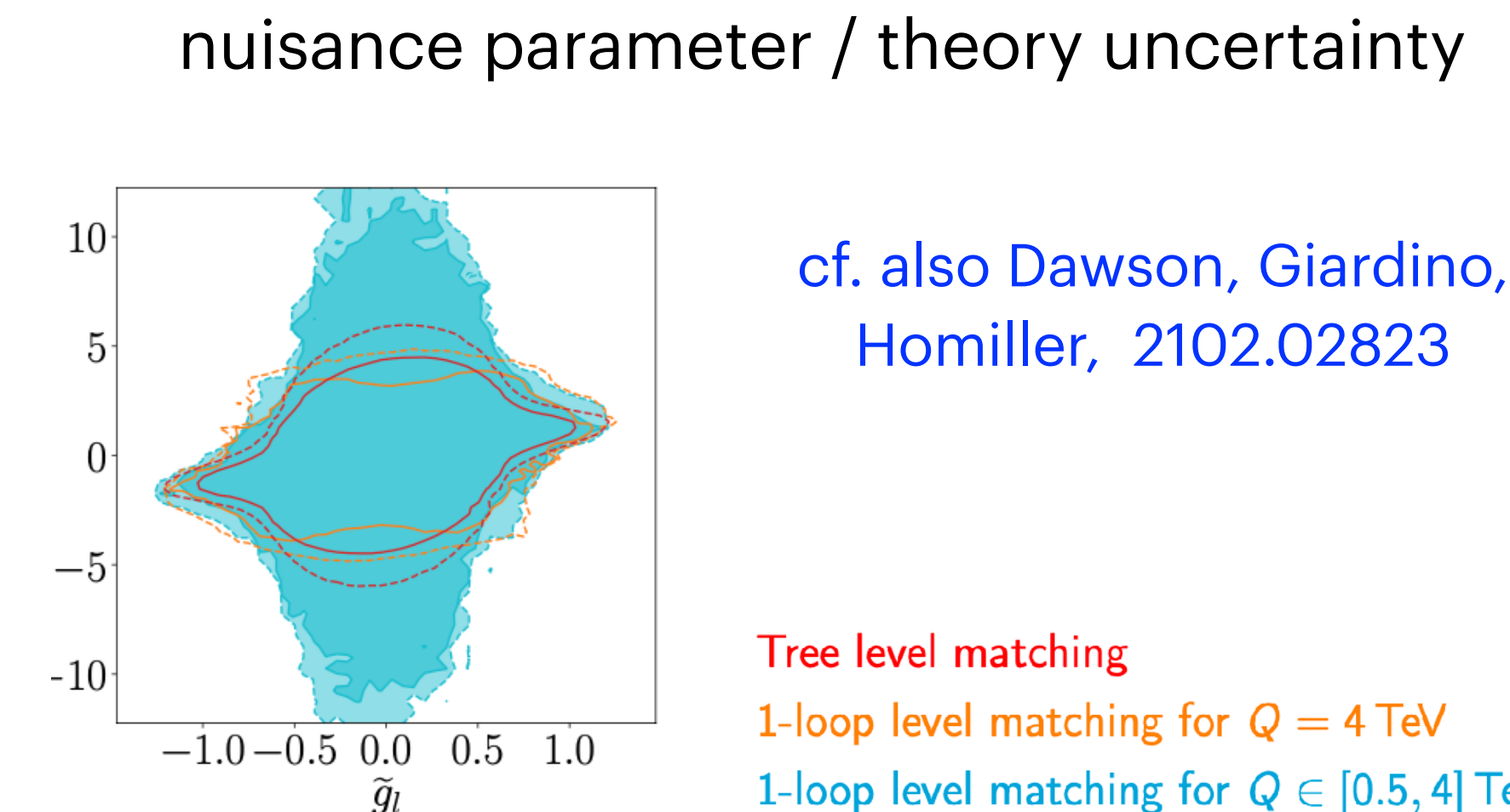
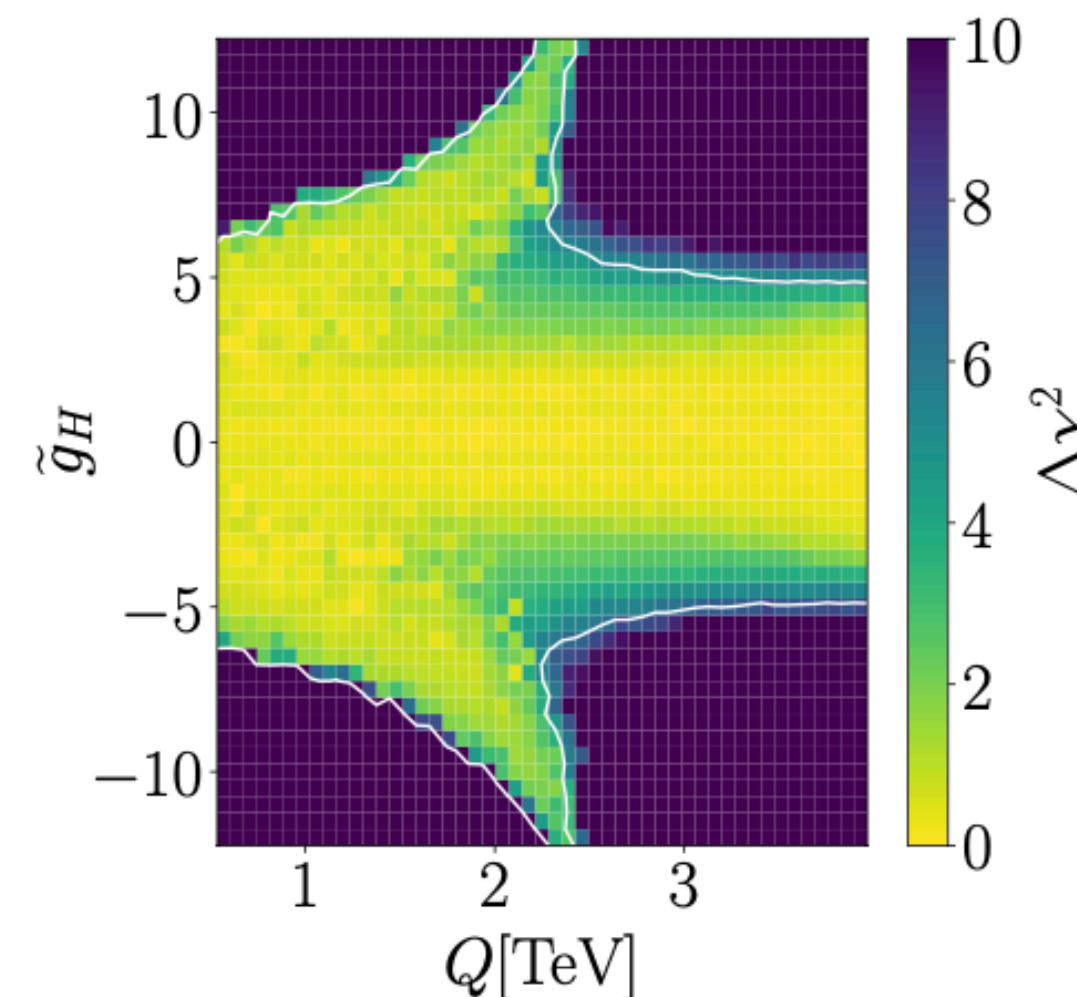
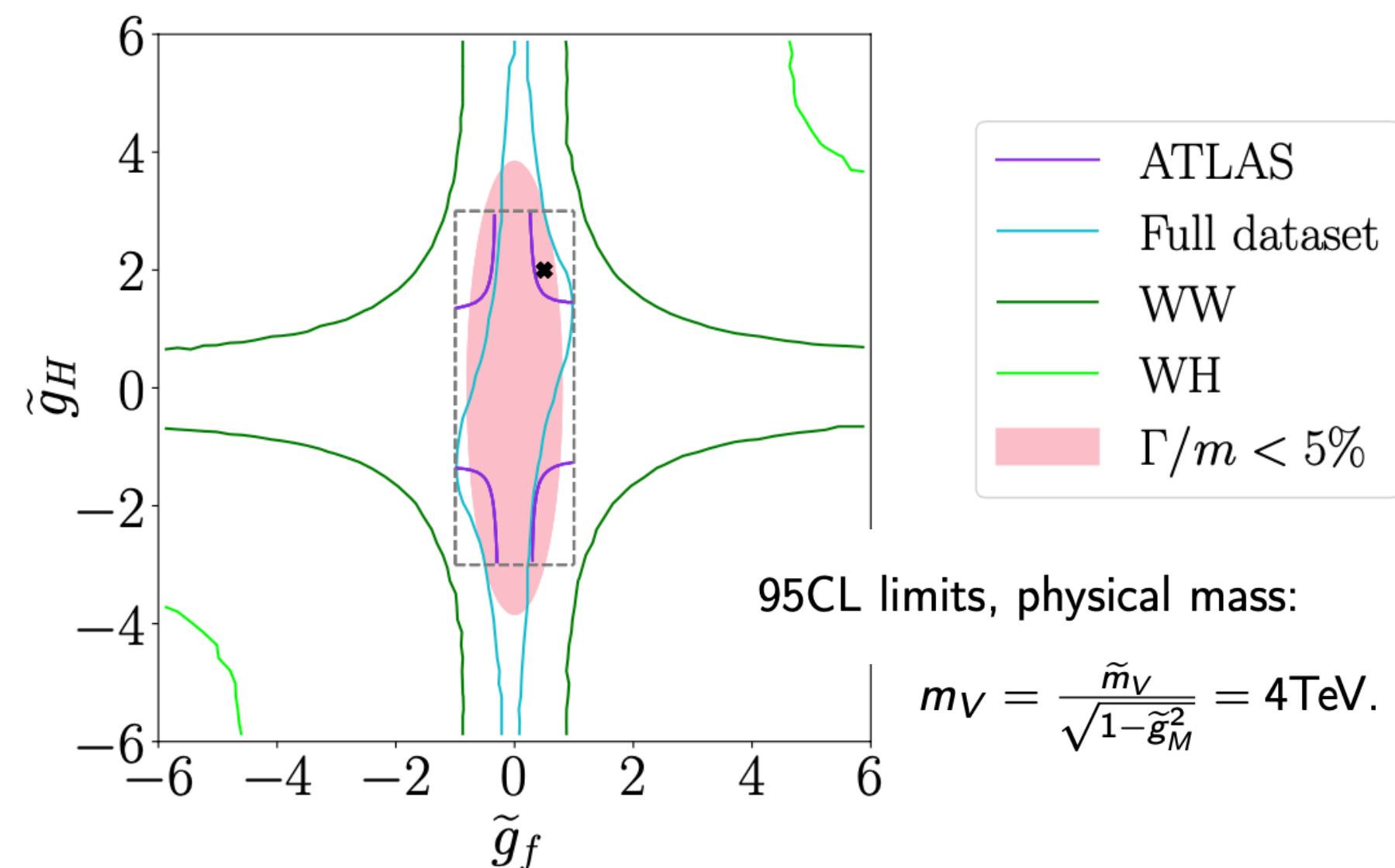


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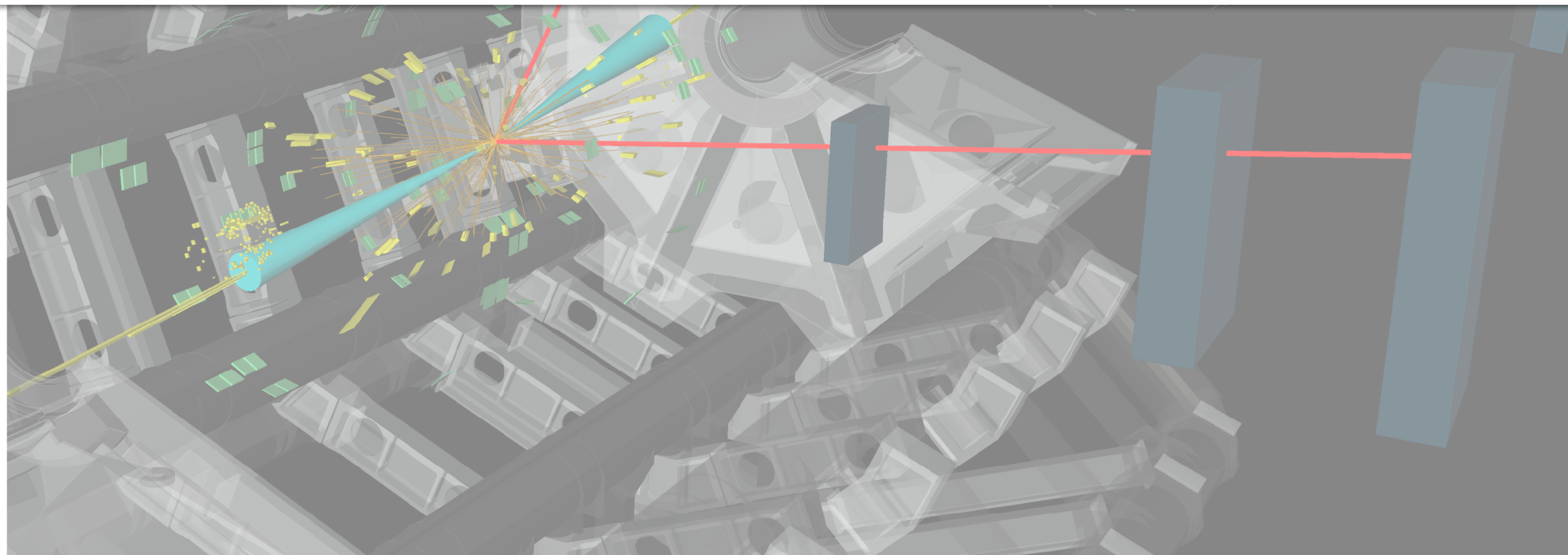
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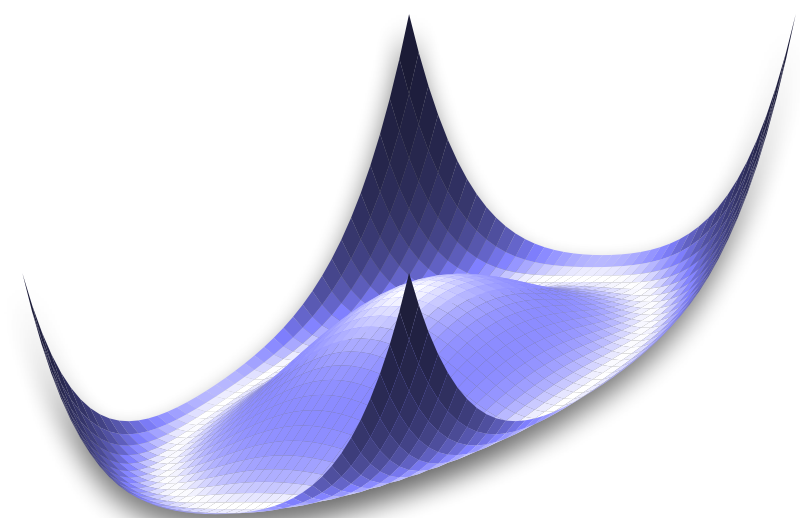
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POLARIZATION in VBS





Polarization in VBS

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Courtesy to René Poncelet for many polarization figures/plots

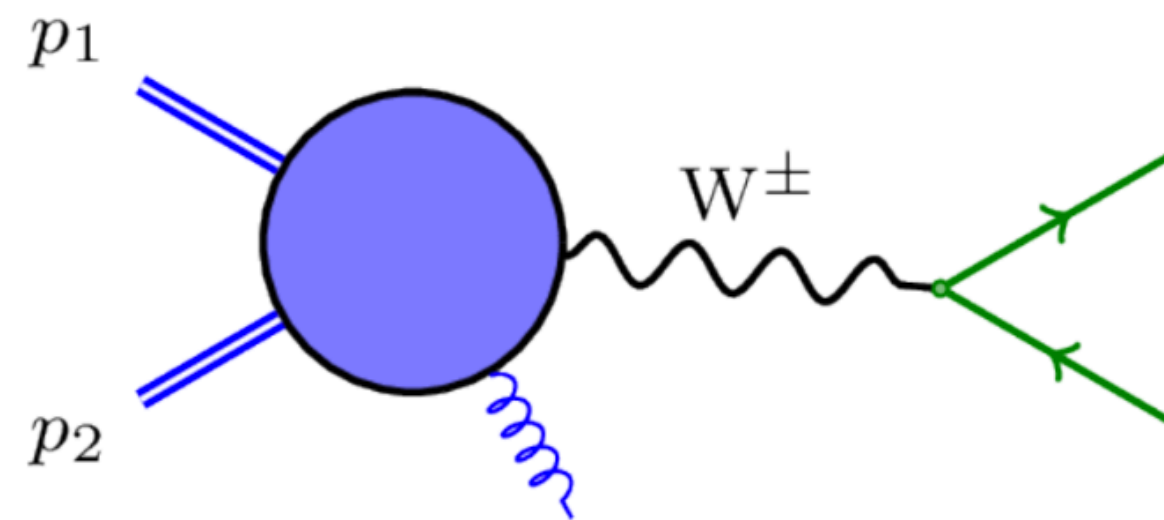
Polarized bosons discriminate between “gauge” and “Goldstone” modes: “Yang-Mills vs. EWSB”

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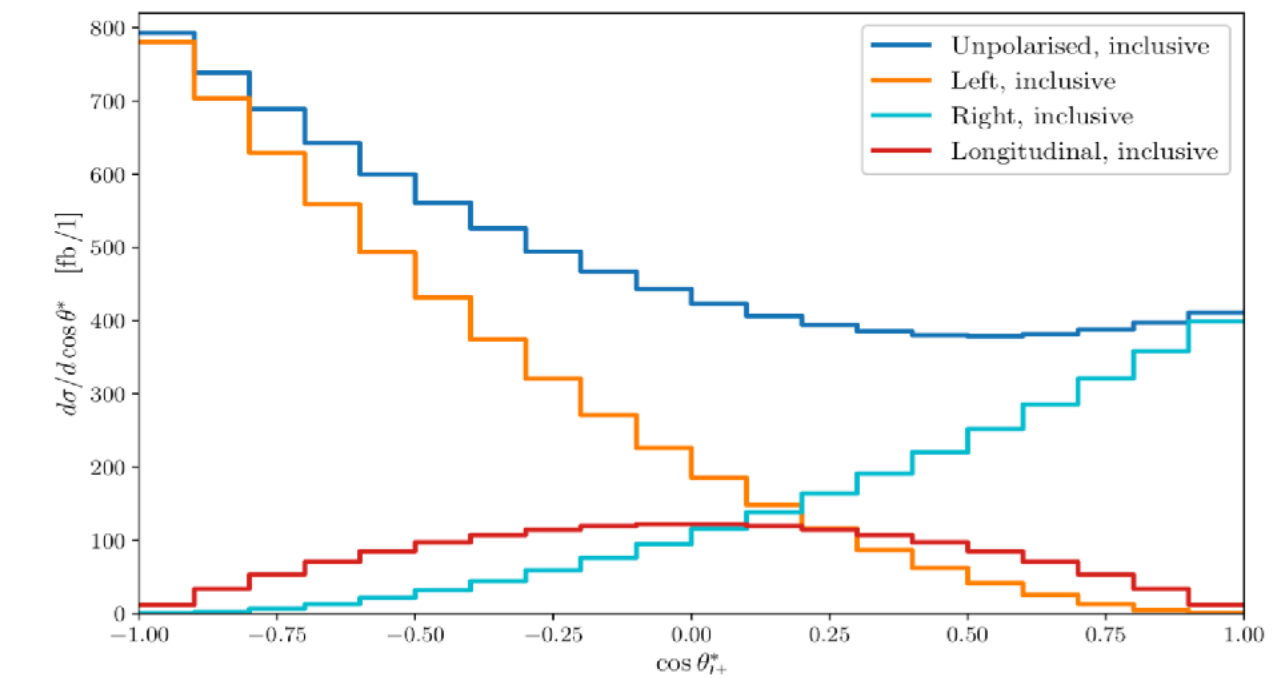
Polarization only accessible via decay products; definition of polarizations “as on-shell as possible”



$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

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

On-shell vector bosons (NWA or DPA)

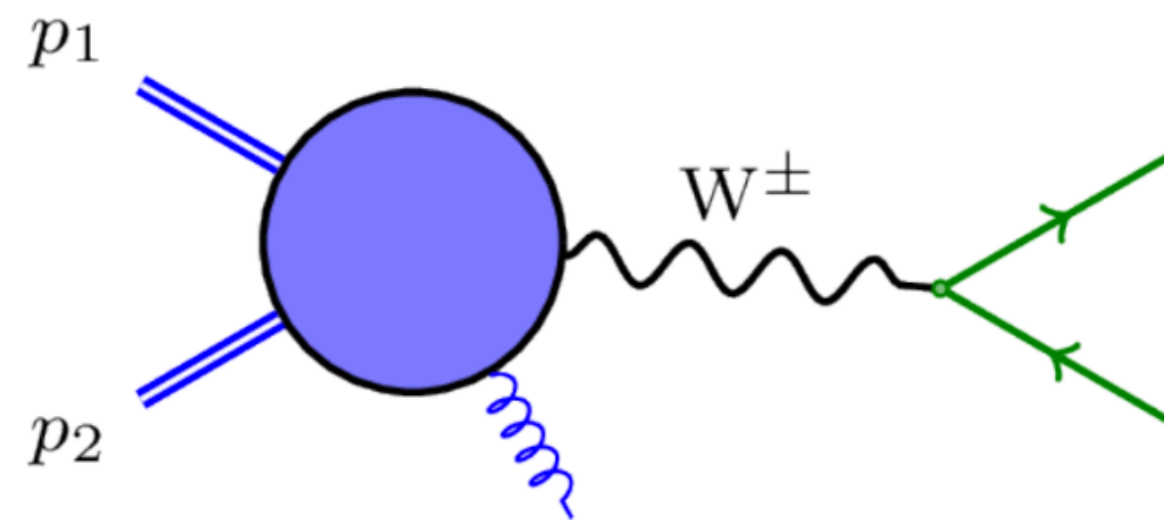


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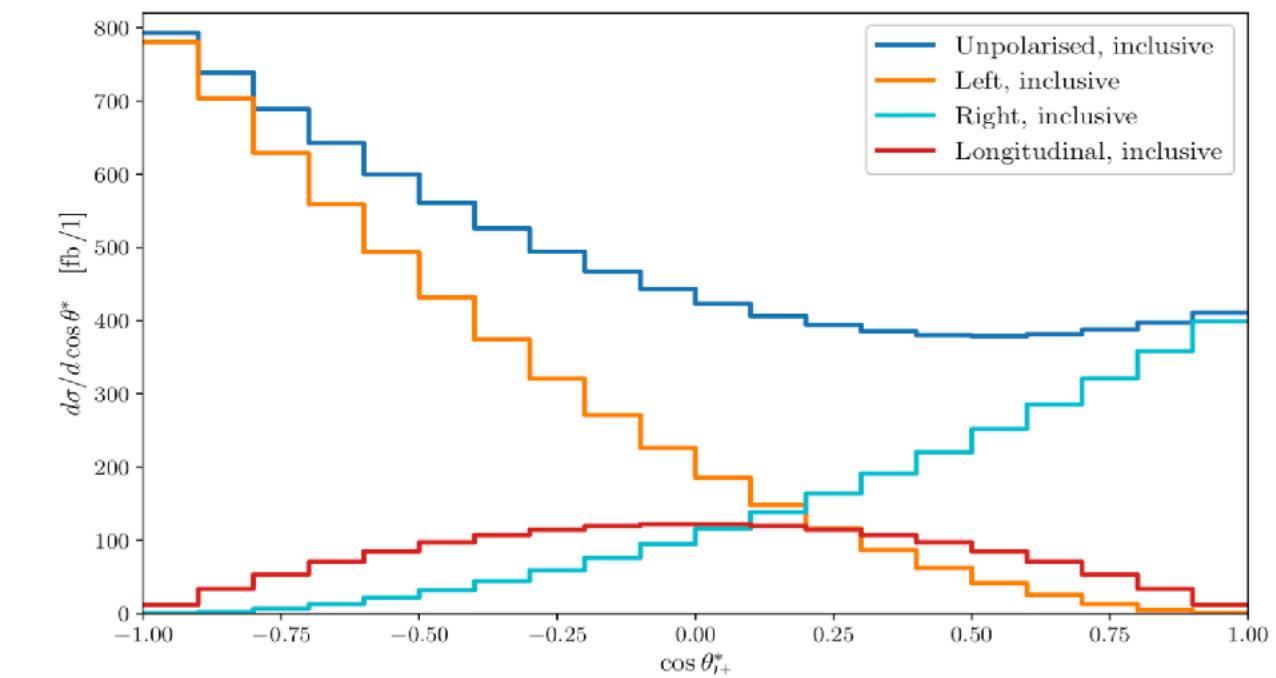
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Extract polarization fractions via projections and/or fits

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

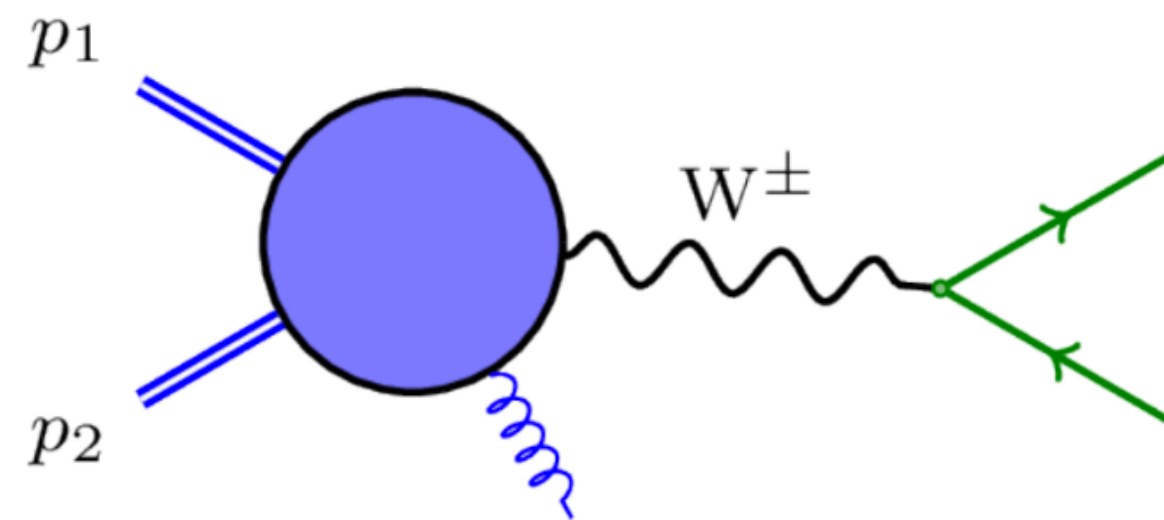


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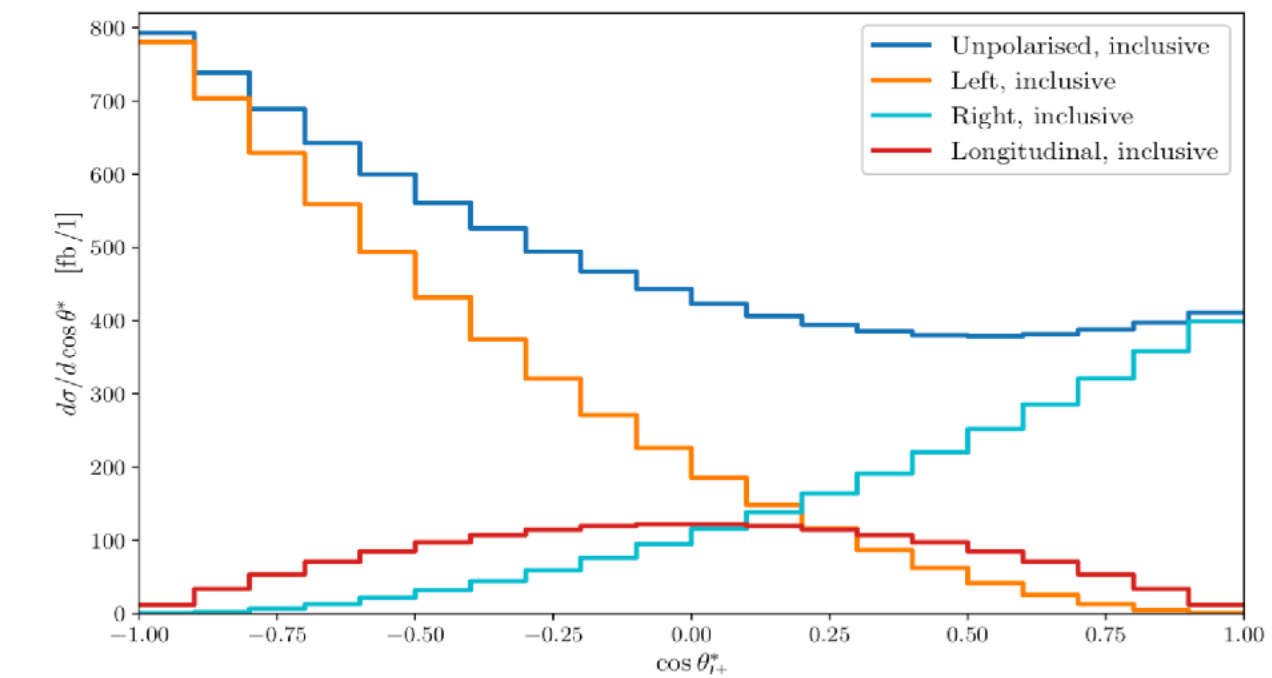
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Problems

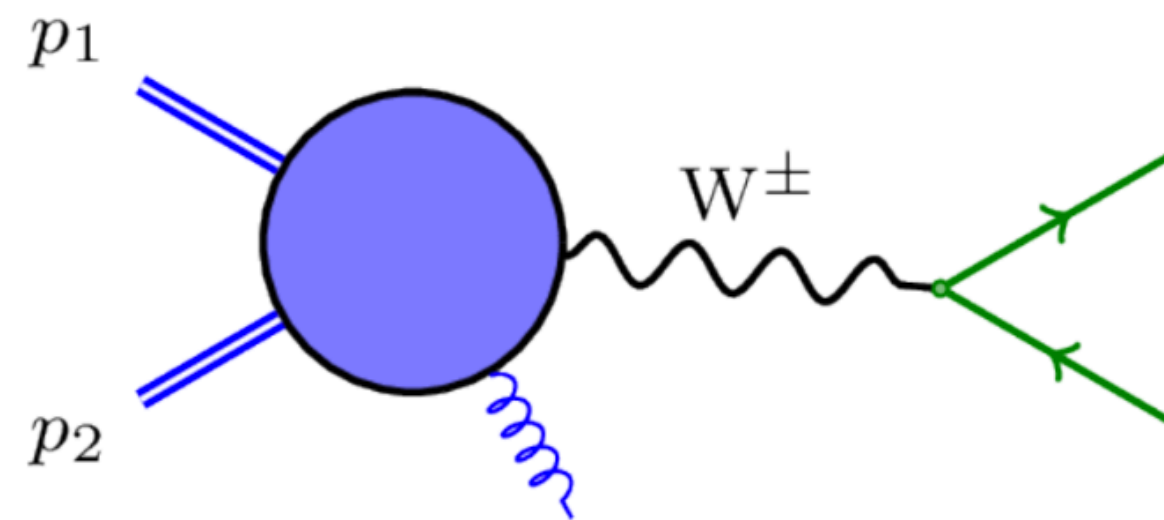
- Fiducial cuts on leptons: disturb relations between angular correlations and polarization fractions
- Decay: Higher order corrections affect ang. decomposition
- Vector boson rest frame ok for Z, difficult for W

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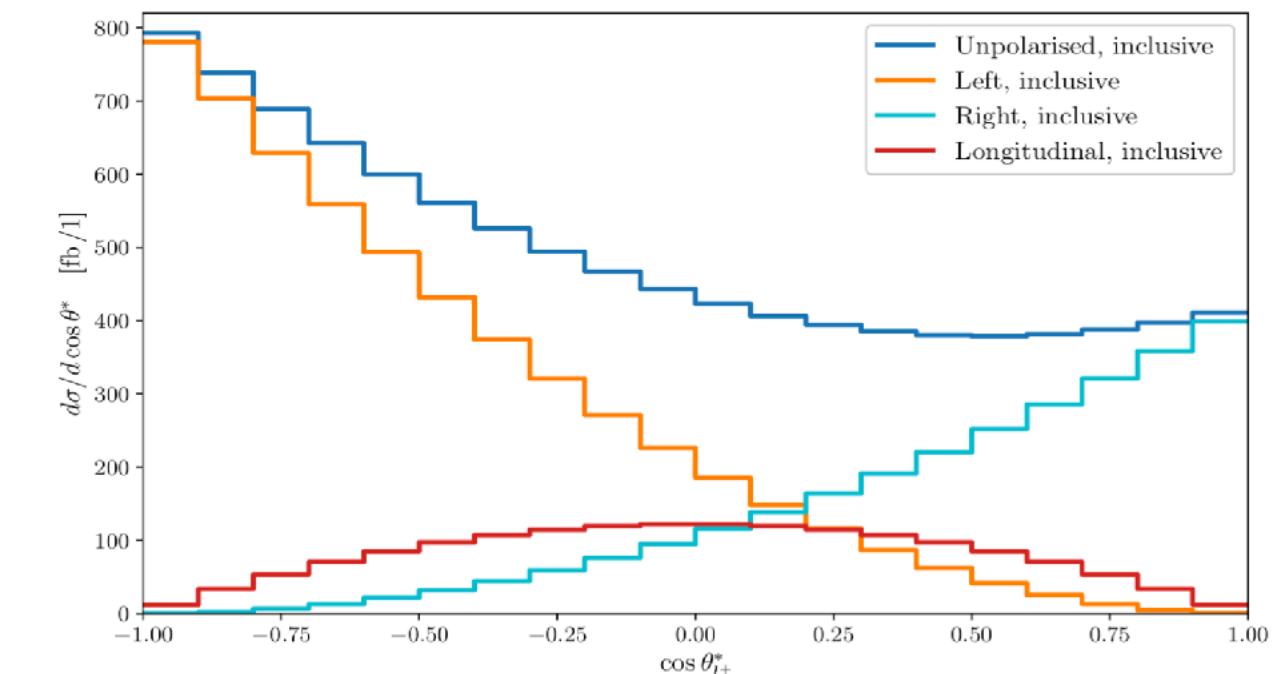
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Decay angle in vector boson rest frame $\cos\theta^*$

Better: use signal model with polarized events

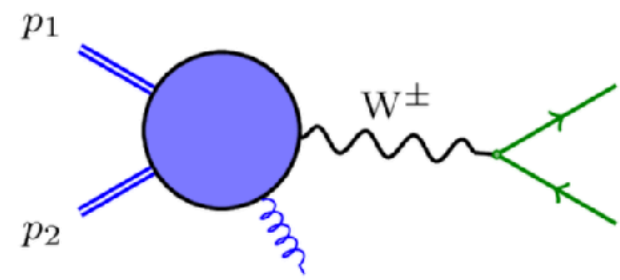


Problems

- Fiducial cuts on leptons: disturb relations between angular correlations and polarization fractions
- Decay: Higher order corrections affect ang. decomposition
- Vector boson rest frame ok for Z, difficult for W

Definition of polarized vector bosons

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$$M_\lambda = \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

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

Polarized cross section/
squared matrix element

Spin correlations/
interferences

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

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

Impact of higher order/spin correlations ?

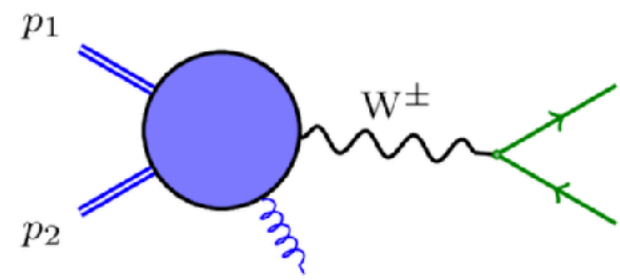
$$\frac{d\sigma}{d\mathcal{O}} = f_\perp \frac{d\sigma_\perp}{d\mathcal{O}} + f_\parallel \frac{d\sigma_\parallel}{d\mathcal{O}} \quad \left[+ f_{corr.} \frac{d\sigma_{corr.}}{d\mathcal{O}} \right]$$

select regions with small/tiny interferences

- ☑ 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.)

Definition of polarized vector bosons

28 / 31



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$$pp \rightarrow ZZ \rightarrow \ell\ell\ell\ell + X$$

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](#)

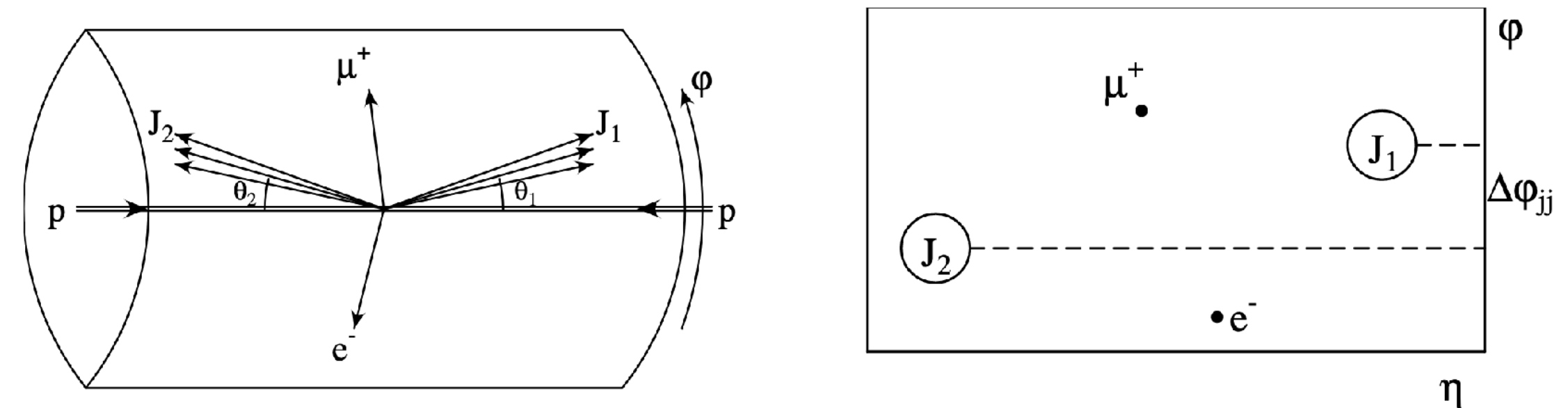
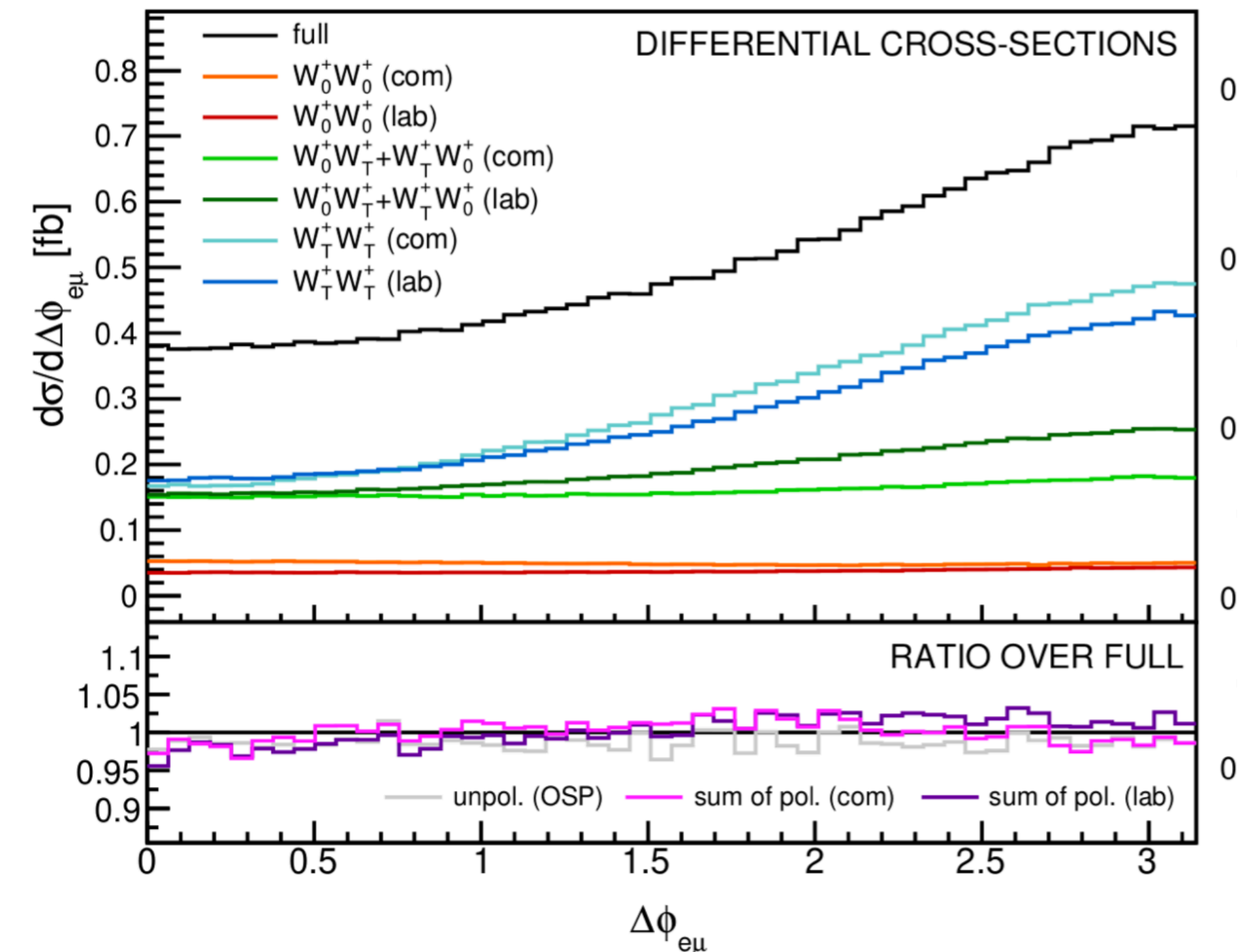
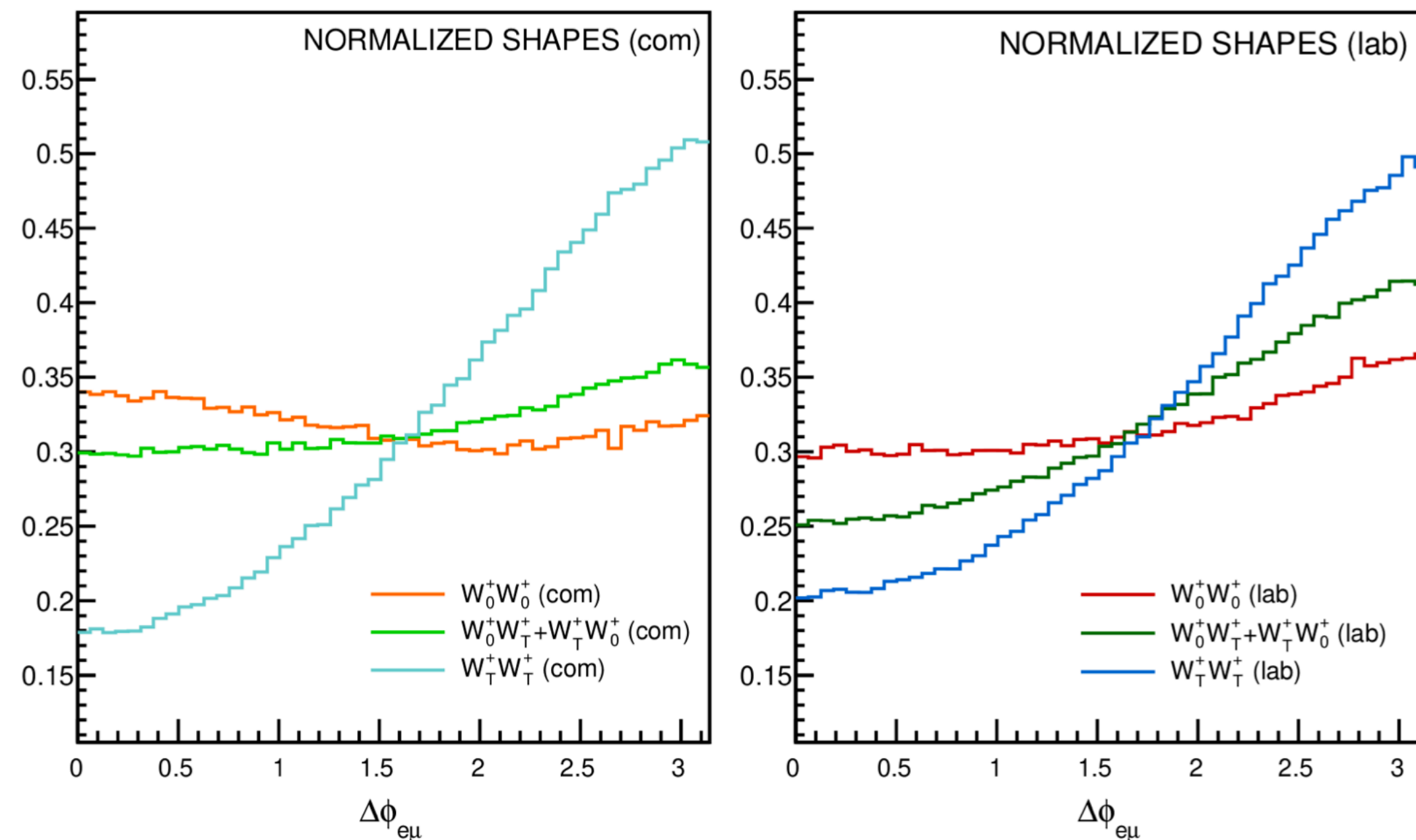


Polarized Vector boson scattering

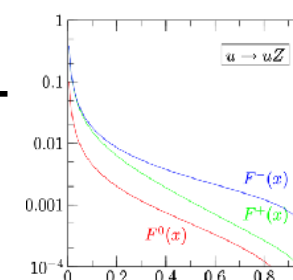
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- ✓ Many LO tools available: MG5_aMC@NLO, PHANTOM, WHIZARD
- ✓ Singly-/doubly-polarized VBS studied at LO
- ✓ Frame of polarization definition
- ✓ Impact of fiducial selection criteria
- ✓ Study of off-shell effects / spin correlations (“interferences”)

Ballestrero, Maina, Pelliccioli, 2007.07133



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



J. R. Reuter, DESY

Seminar, University of Pittsburgh, 22.9.2022



Polarized Vector boson scattering

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Ballestrero, Maina, Pelliccioli, 2007.07133

W+W+

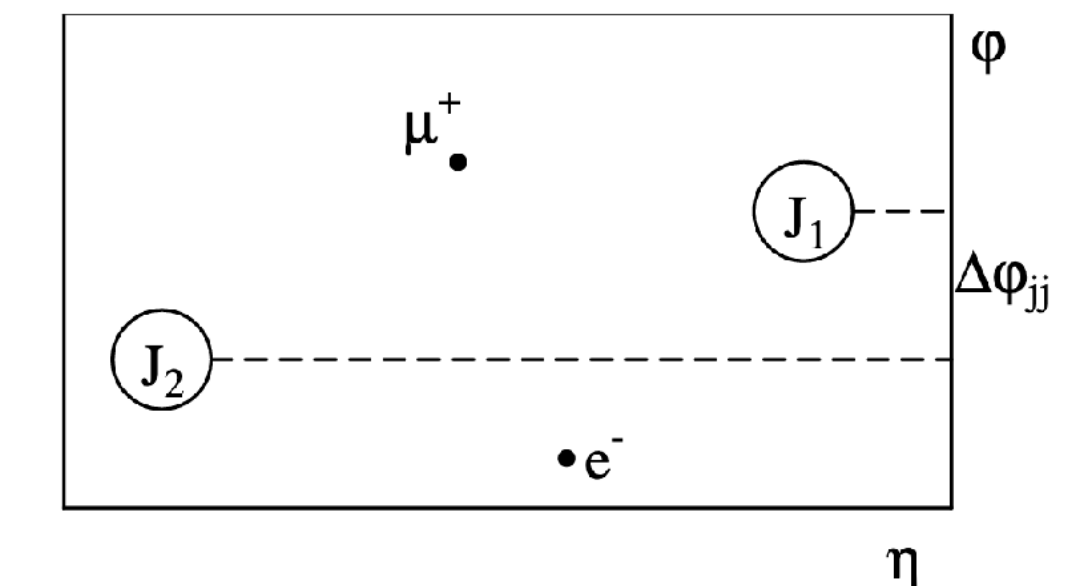
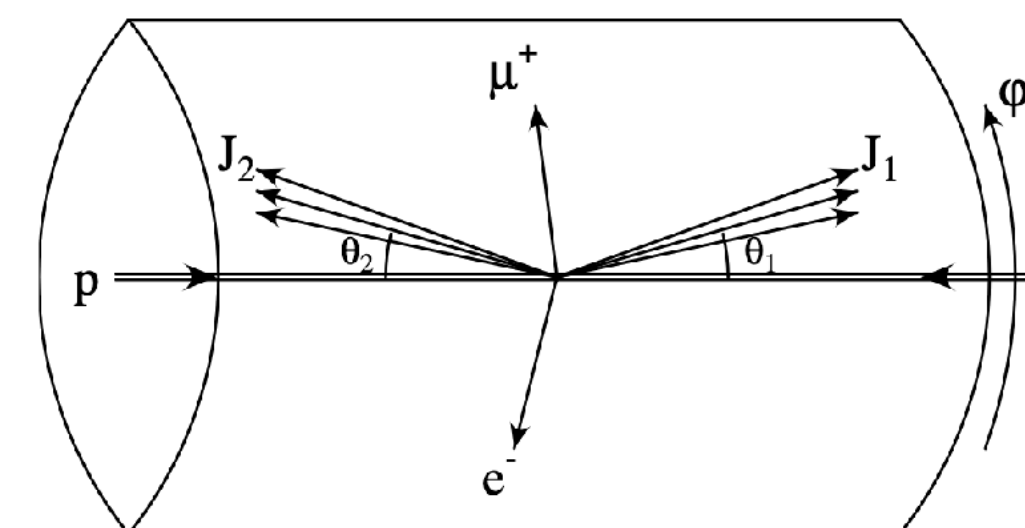
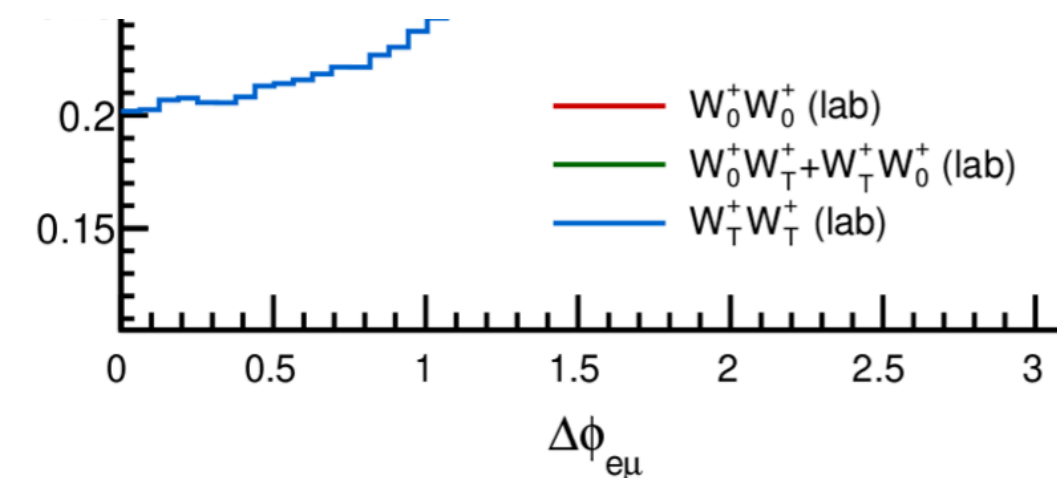
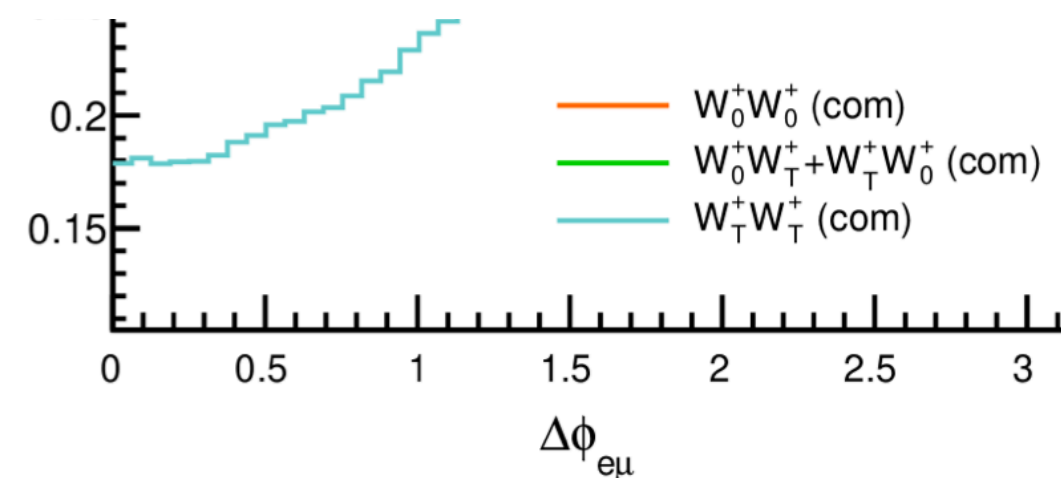
W+W-

WZ

	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

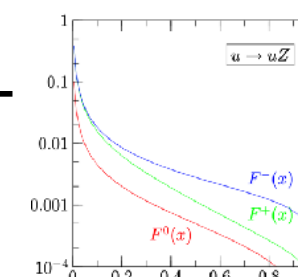
	Lab	WW CoM	ratio
full	4.651(2)	-	-
unpol	4.641(2)	-	-
0-unpol	1.186(1)	1.146(1)	0.97
T-unpol	3.456(2)	3.494(2)	1.01
unpol-0	1.2226(4)	1.1905(5)	0.97
unpol-T	3.418(1)	3.450(1)	1.01
0-0	0.3314(2)	0.3786(3)	1.14
0-T	0.8545(4)	0.7669(3)	0.90
T-0	0.8912(4)	0.8119(4)	0.91
T-T	2.563(1)	2.683(1)	1.05

	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



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○ Drastically different angular correlations ($\Delta\phi_{e\mu}$) for LL

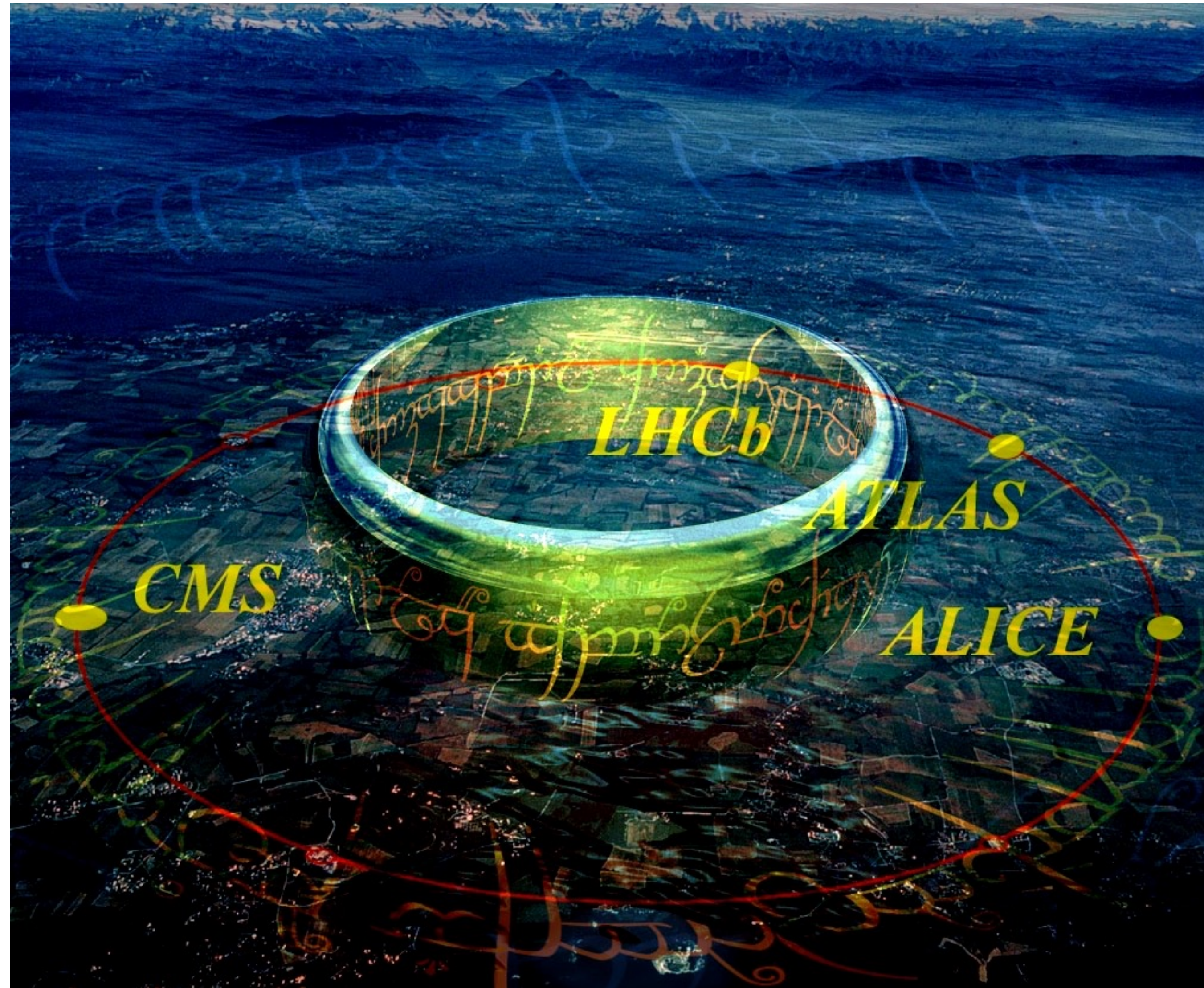


- Multi-boson + Higgs final states: multi-messenger detectors for electroweak sector **will shine in Run 3**
- **Vector Boson Scattering: rare processes, potential to direct access to EWSB**
- **EFT interpretation difficult; model-dependence through truncation and assumptions**
- Comparison with explicit 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

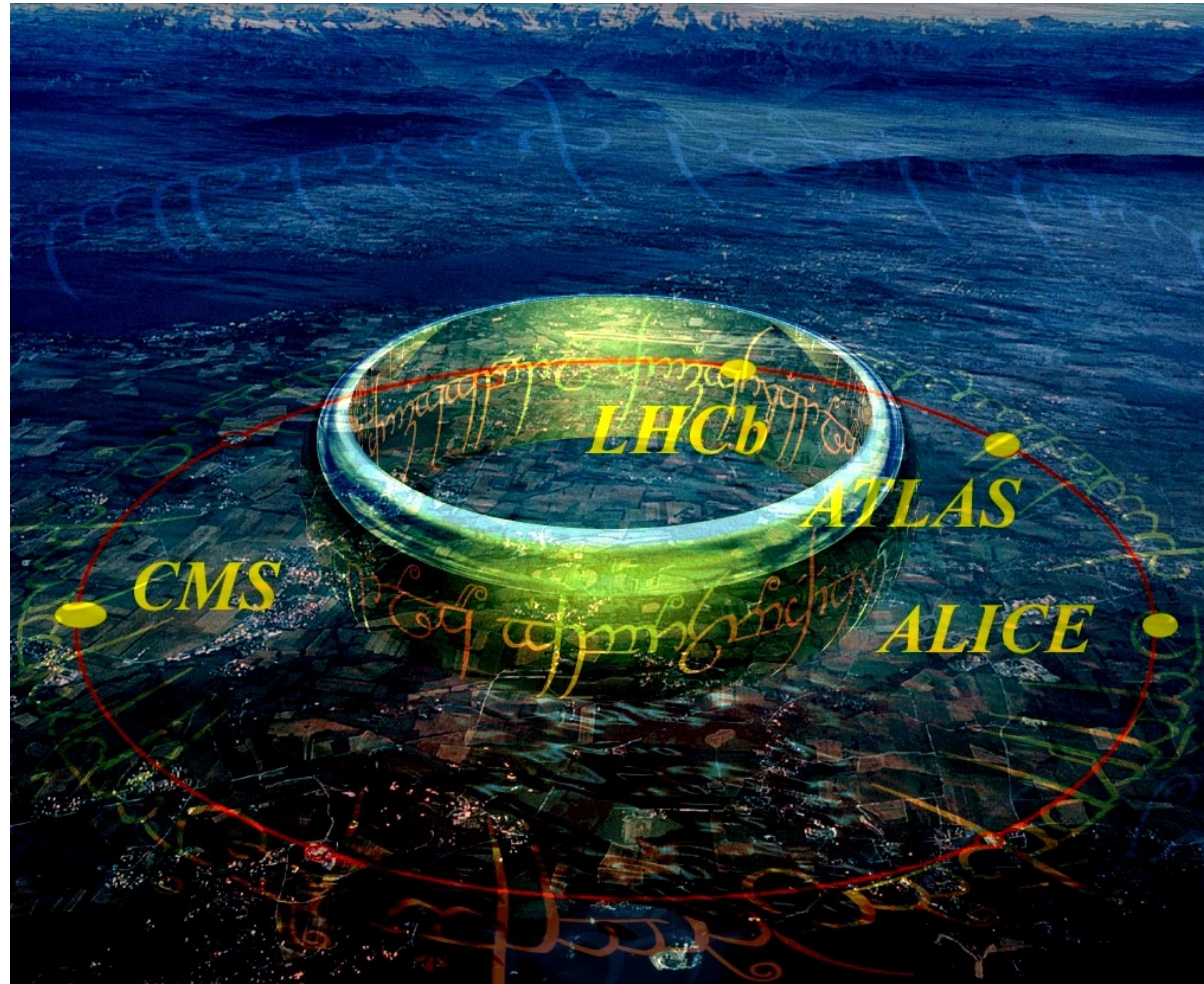
One Ring To Find Them,

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One Ring To Rule Them Out

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One Ring To Rule Them Out

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B A C K U P

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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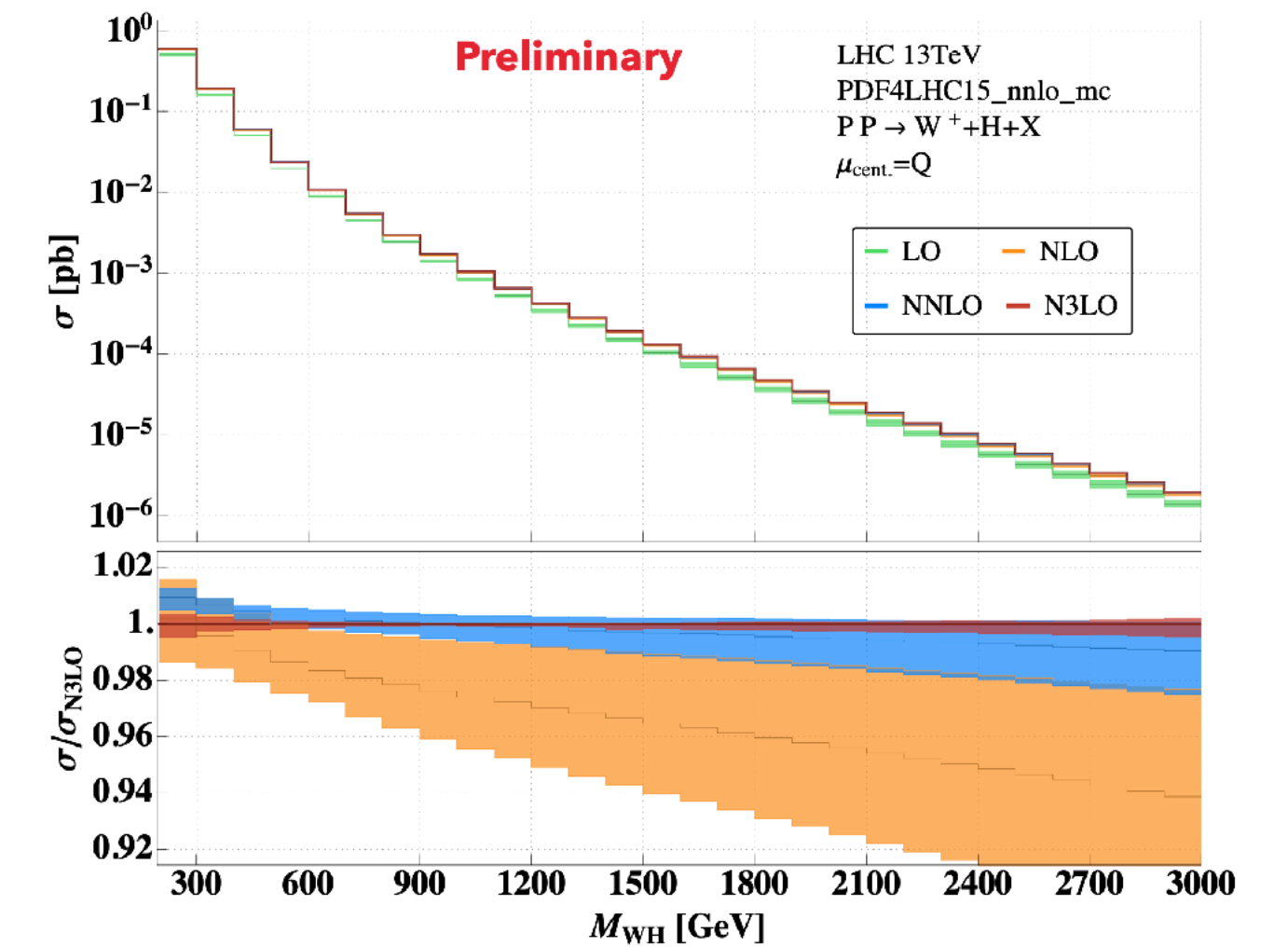
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- NNNLO soon available [Bernhard Mistlberger, MBI 2022](#)
- Behaves very similar to charged-current Drell-Yan
- Lowest bin has no overlap of scale variations

Preliminary

Process	σ^{LO} [pb]	σ^{NLO} [pb]	K^{NLO}	σ^{NNLO} [pb]	K^{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
ZH	$0.678^{+2.40\%}_{-3.11\%}$	$0.780^{+1.26\%}_{-1.05\%}$	1.16	$0.793^{+0.26\%}_{-0.30\%}$	1.16	$0.786^{+0.29\%}_{-0.31\%}$	1.16



Quick excursion to Higgsstrahlung

33 / 31

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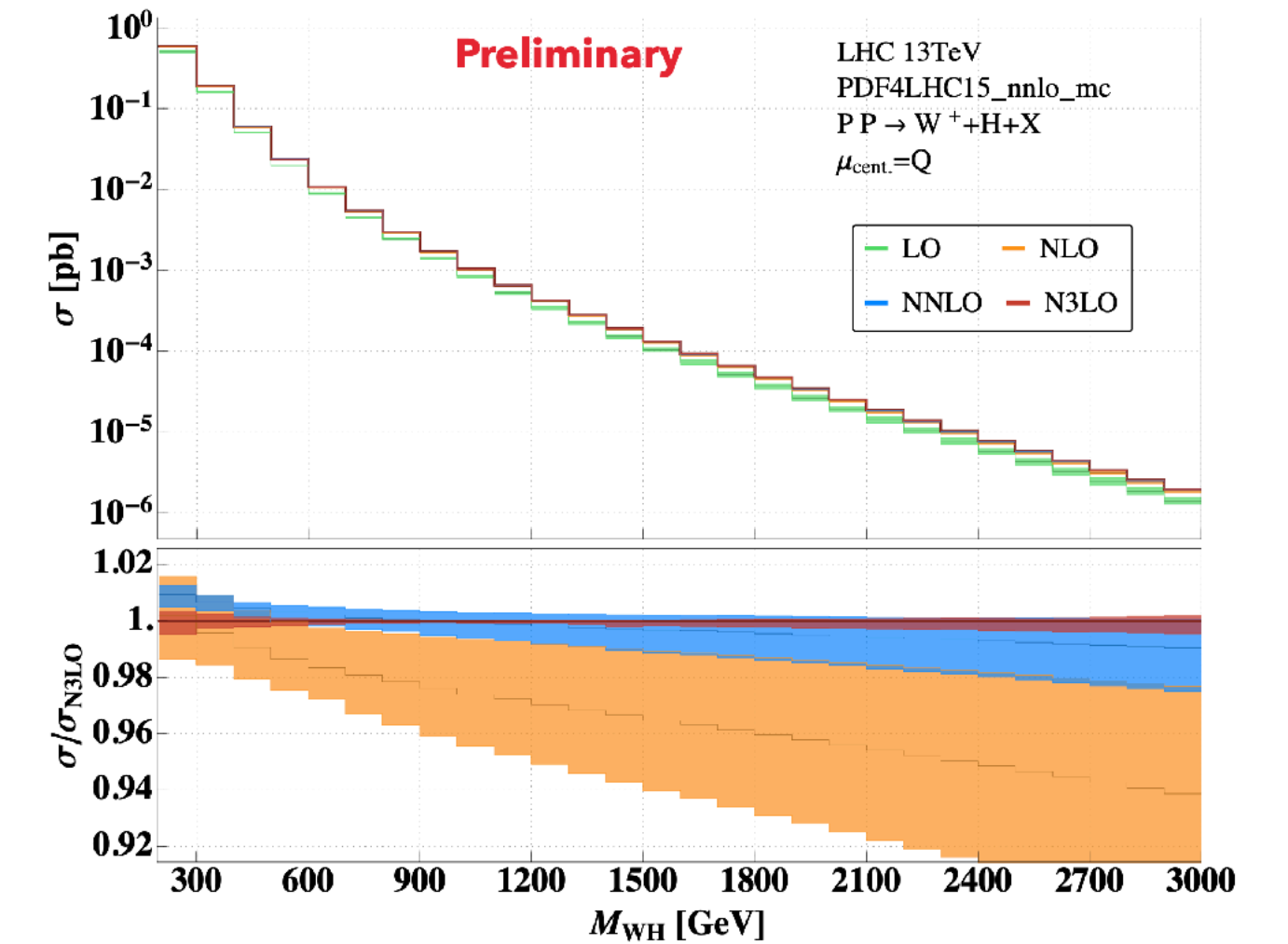
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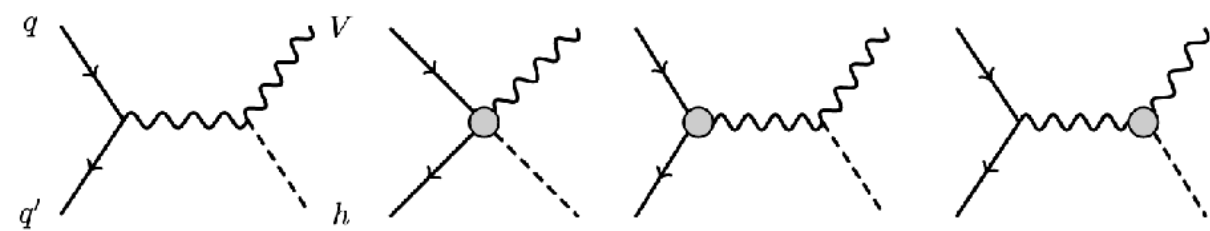
Bernhard Mistlberger, MBI 2022

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Preliminary



Bishara, P. Englert, Grojean,
Panico, Rossia, [2208.11134](#)

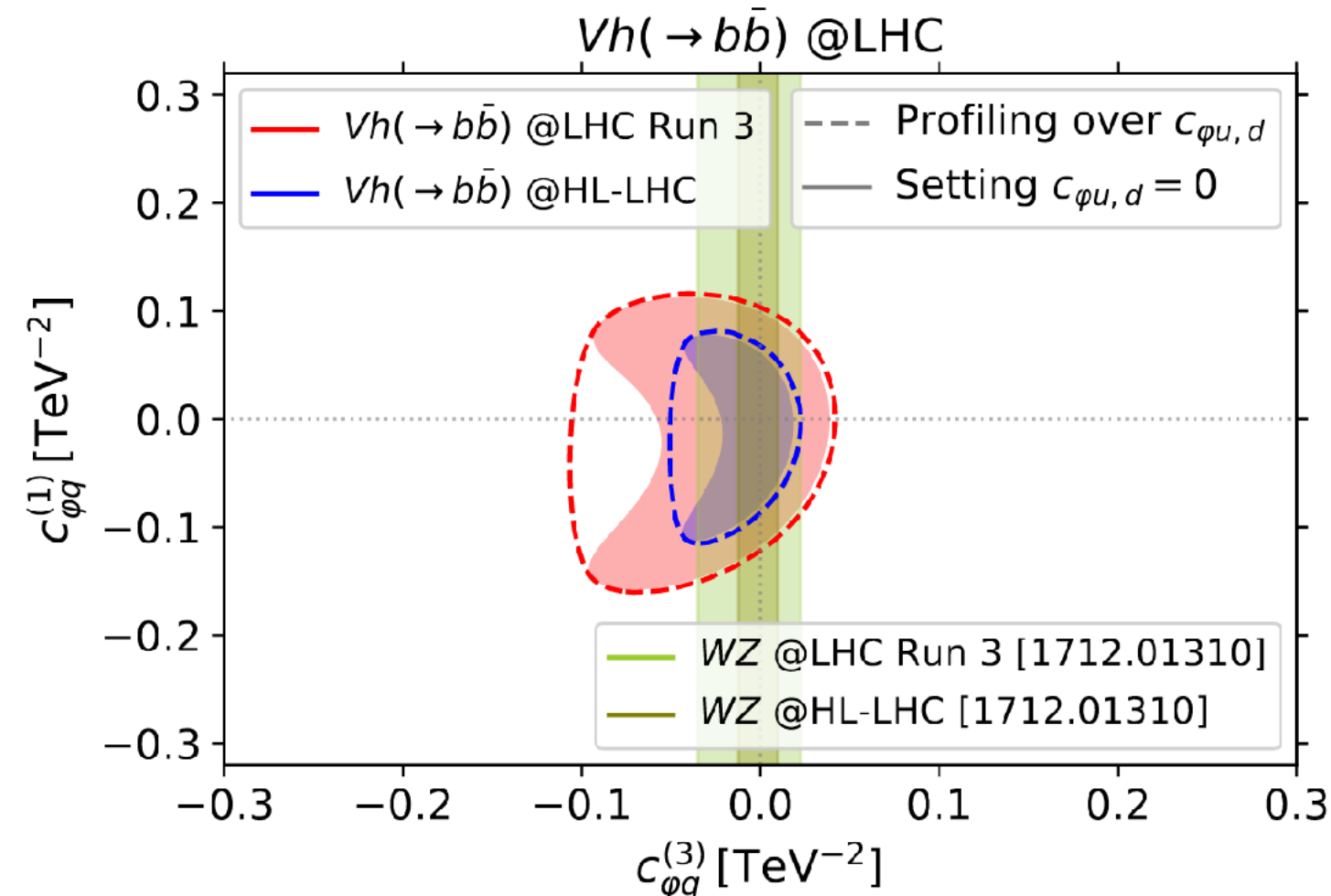


$$\mathcal{O}_{\varphi q}^{(1)} = (\bar{Q}_L \gamma^\mu Q_L) \left(i H^\dagger \overleftrightarrow{D}_\mu H \right),$$

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

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

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



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



$pp \rightarrow WW \rightarrow l\nu l\nu + X$ NNLO QCD

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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%}

$pp \rightarrow WW \rightarrow l\nu l\nu + X$ NNLO QCD

34 / 31

Poncelet, Popescu, 2102.13583

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- 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

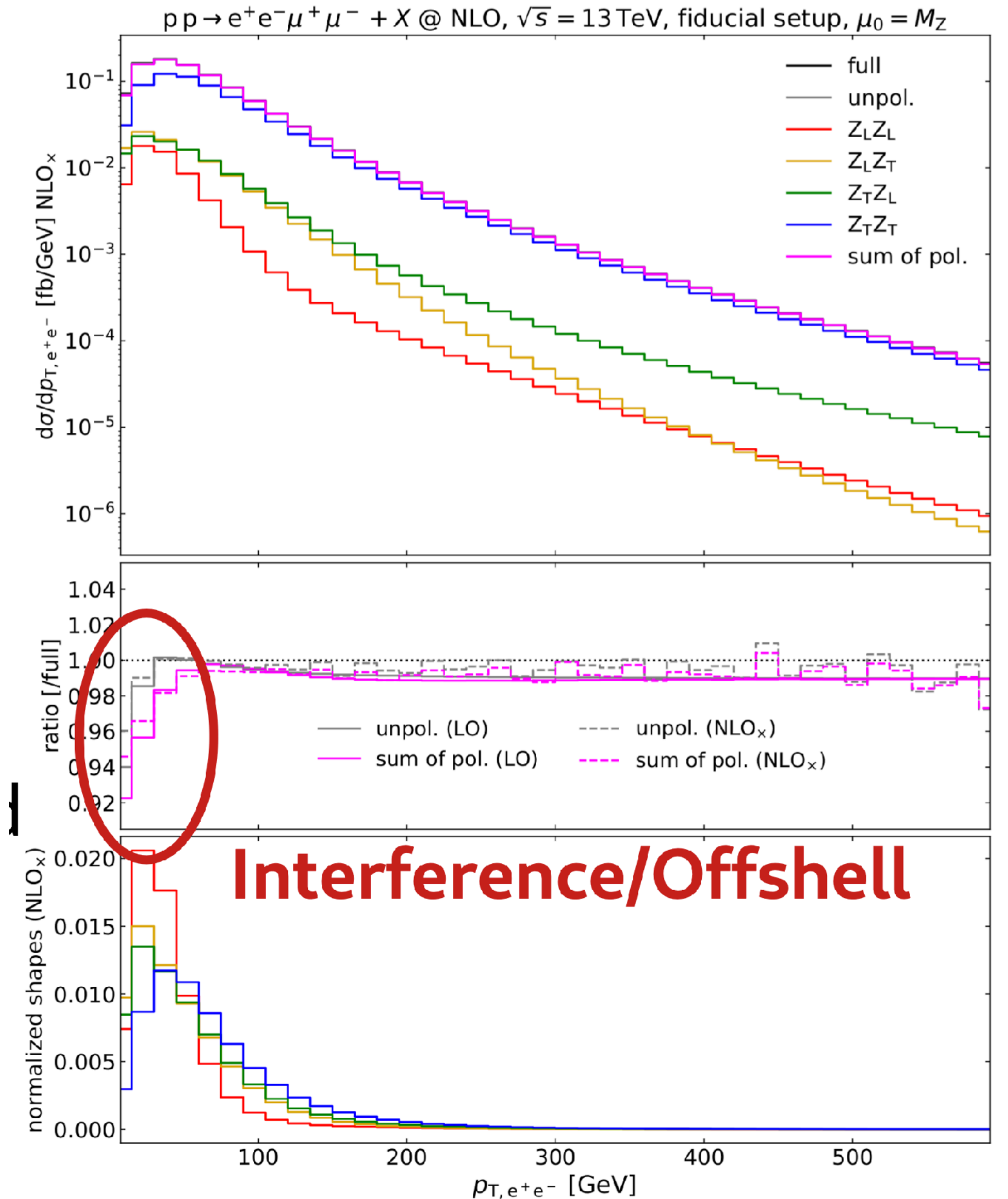
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Denner, Pelliccioli, 2107.06579

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

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



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

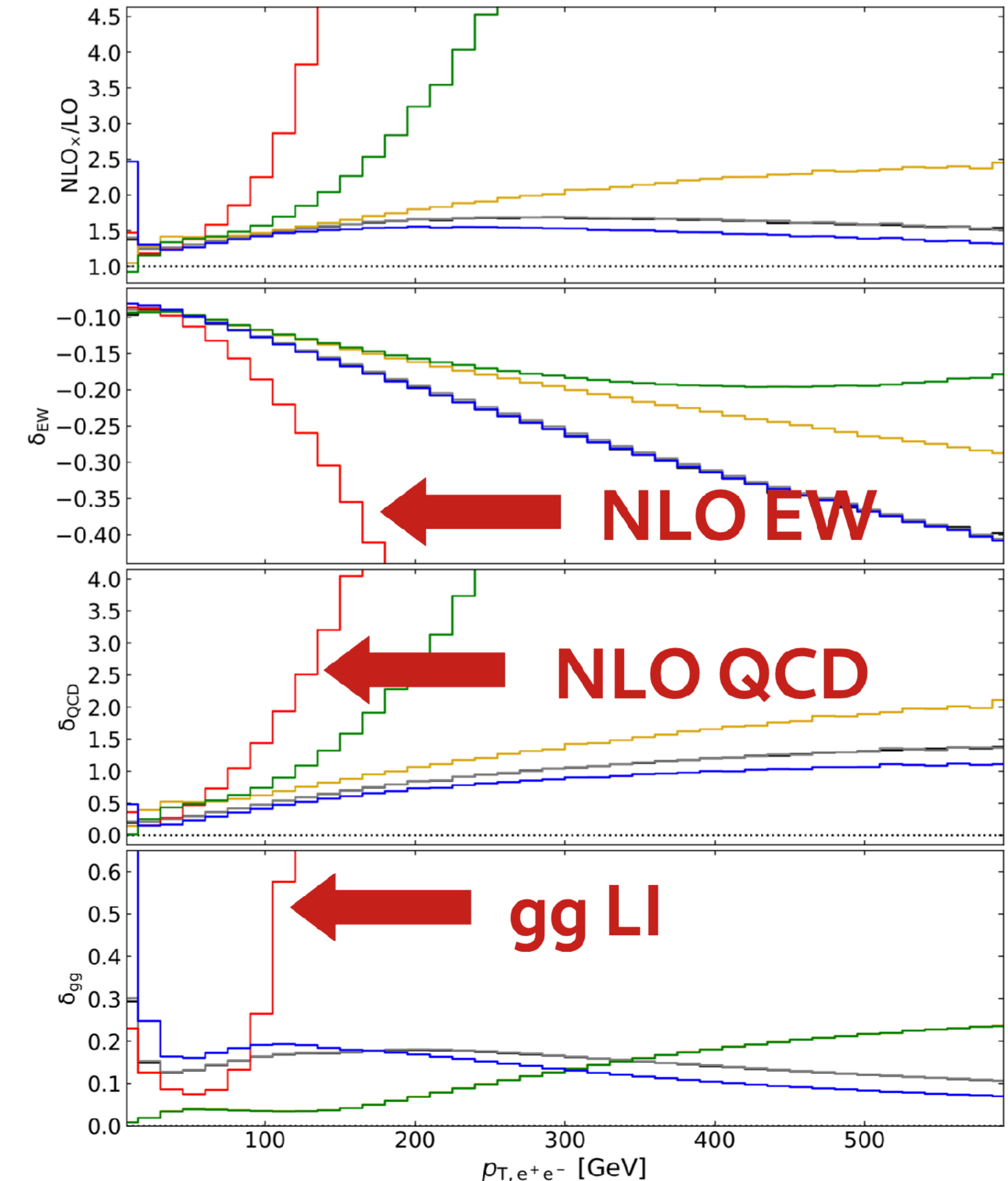
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Denner, Pelliccioli, 2107.06579

mode	σ_{LO} [fb]	δ_{QCD}	δ_{EW}	δ_{gg}	$\sigma_{\text{NLO}+}$ [fb]	$\sigma_{\text{NLO} \times}$ [fb]
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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!



$pp \rightarrow WZ \rightarrow \ell\bar{\ell}\nu + X$ @ ATLAS

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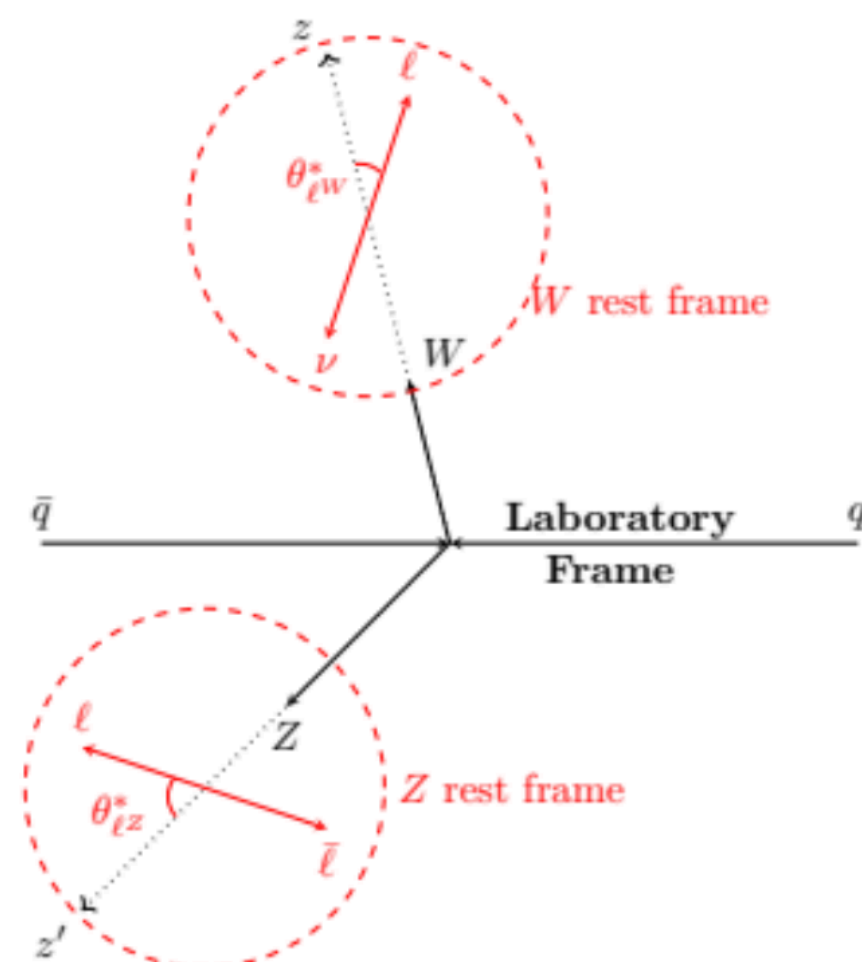
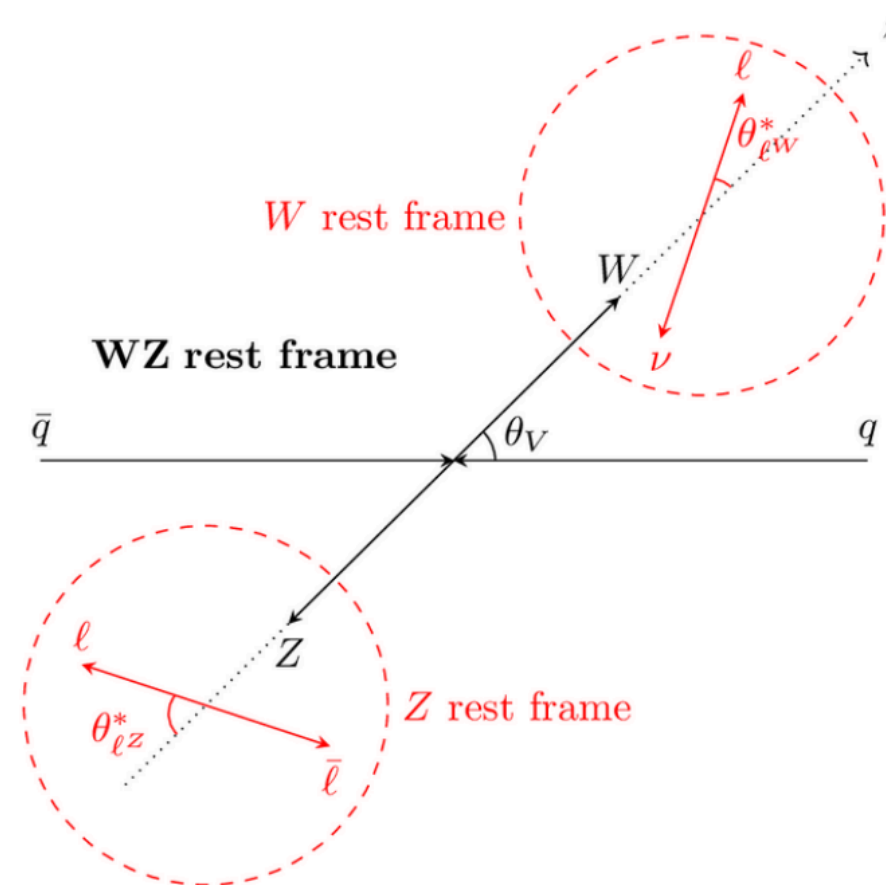
ATLAS-CONF-2022-053 ;
L. Selem, Talk MBI 2022

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

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

Polarisation fraction $f_{h_0}(\mathbf{v}_1)$ in
bin around $\mathbf{v}_1$ for variable V_1
= **applied weight** !

Distribution of
variable V_1 for an
unpolarised boson



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

$$f_{00} = \rho_{0000} ,$$

$$f_{TT} = \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++} ,$$

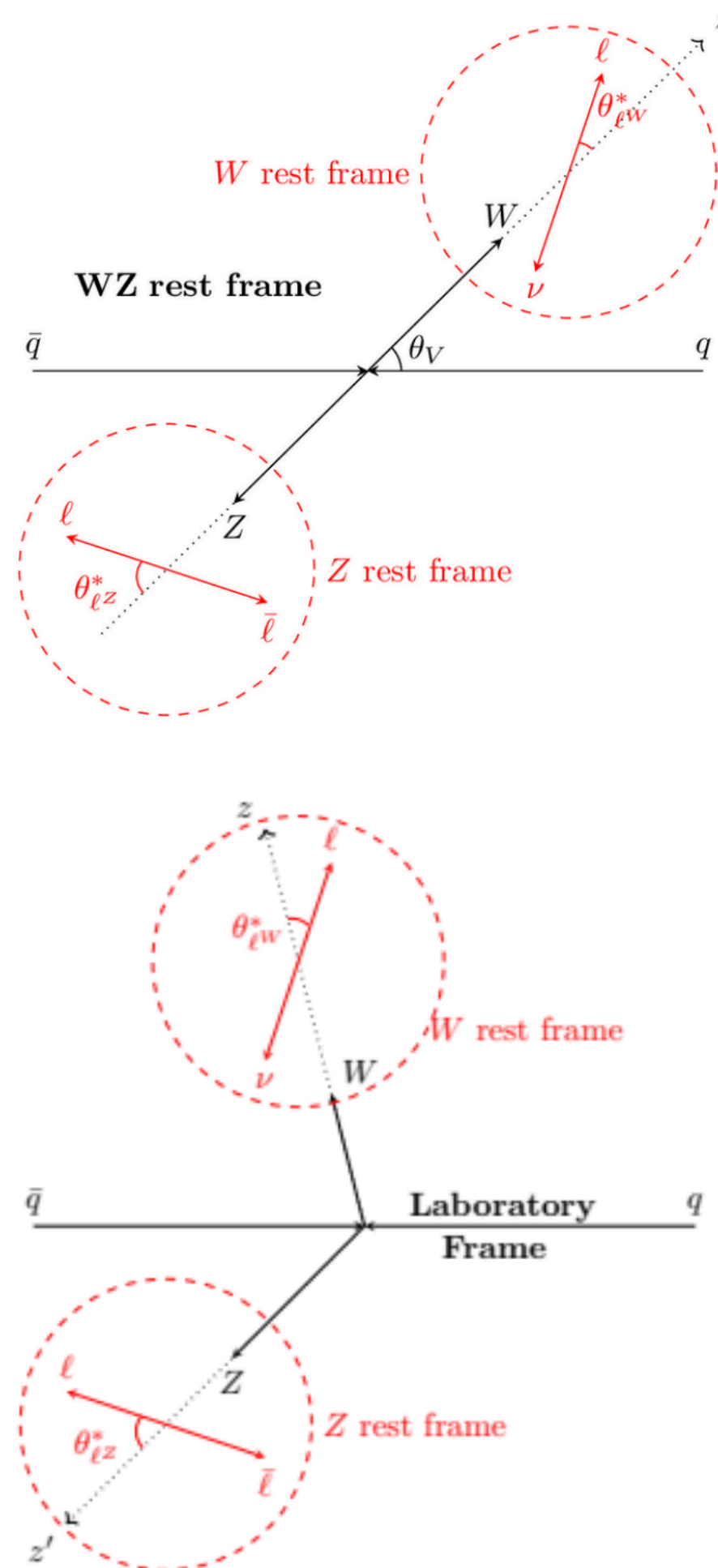
$$f_{0T} = \rho_{00--} + \rho_{00++} ,$$

$$f_{T0} = \rho_{--00} + \rho_{++00} .$$

$pp \rightarrow WZ \rightarrow \ell\bar{\ell}\nu + X$ @ 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 $H=h_0$

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

- 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:

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

$$f_{00} = \rho_{0000} ,$$

$$f_{TT} = \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++} ,$$

$$f_{0T} = \rho_{00--} + \rho_{00++} ,$$

$$f_{T0} = \rho_{--00} + \rho_{++00} .$$

$pp \rightarrow WZ \rightarrow \ell\ell\nu + X$ @ ATLAS

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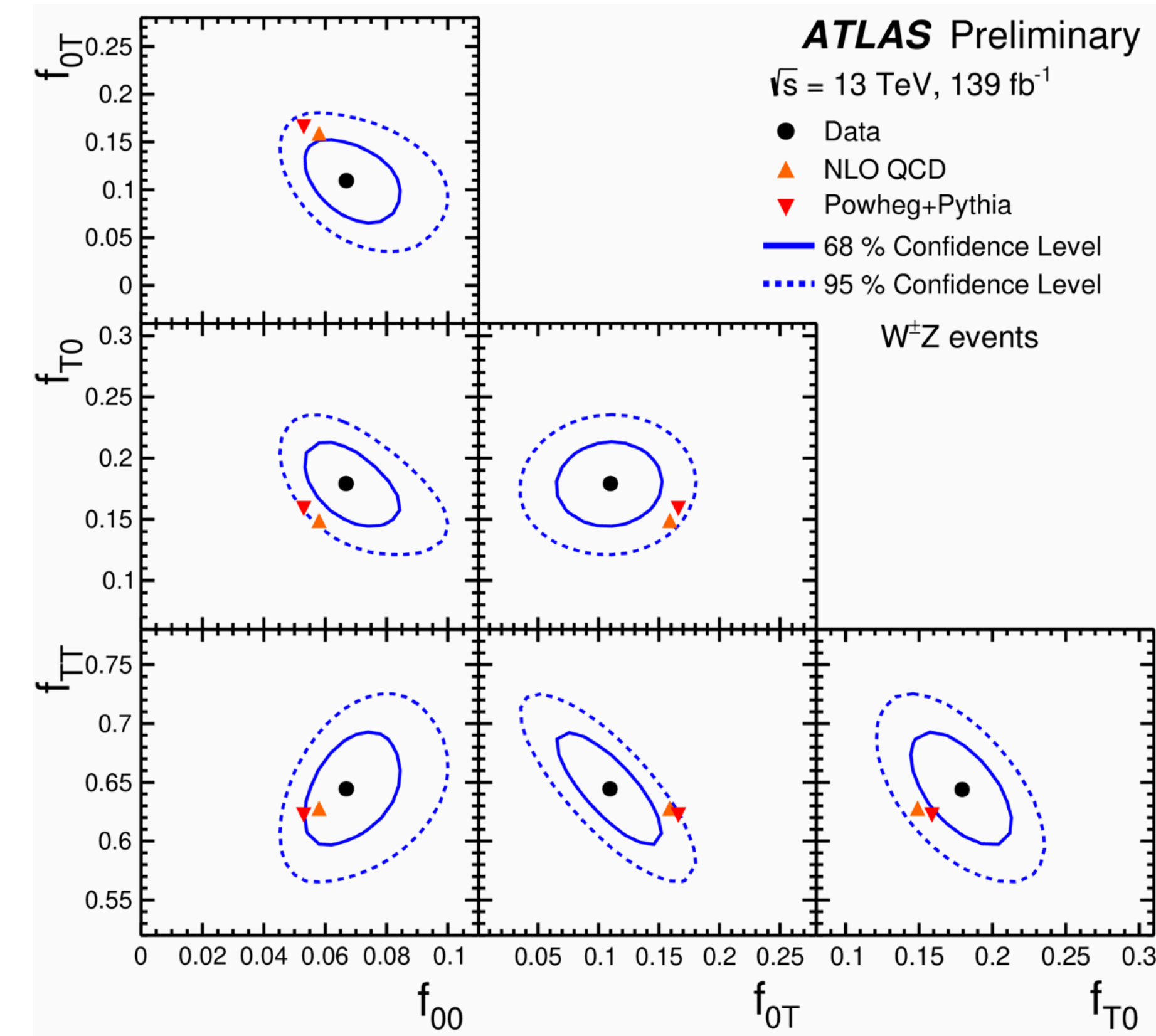
$$\mathbb{P}(V_1(v_1) \cap H = h_0) = \mathbb{P}(H = h_0 | V_1(v_1)) \mathbb{P}(V_1(v_1))$$

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Distribution of
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- Independent fit of f_{TT} , f_{OT} , f_{OO} , N_{tot}
- Decouple polarization fraction shapes from overall normalization
- Iterative Bayesian unfolding of polarization-sensitive variables:



$$p_{NLO}^{hh'}(x) \propto p_{LO}(x) \times f_{hh'}(x) \times g_{LO \rightarrow NLO}(x)$$

