Interactions within Interactions within Interactions

Perspectives of Multi-Boson Physics

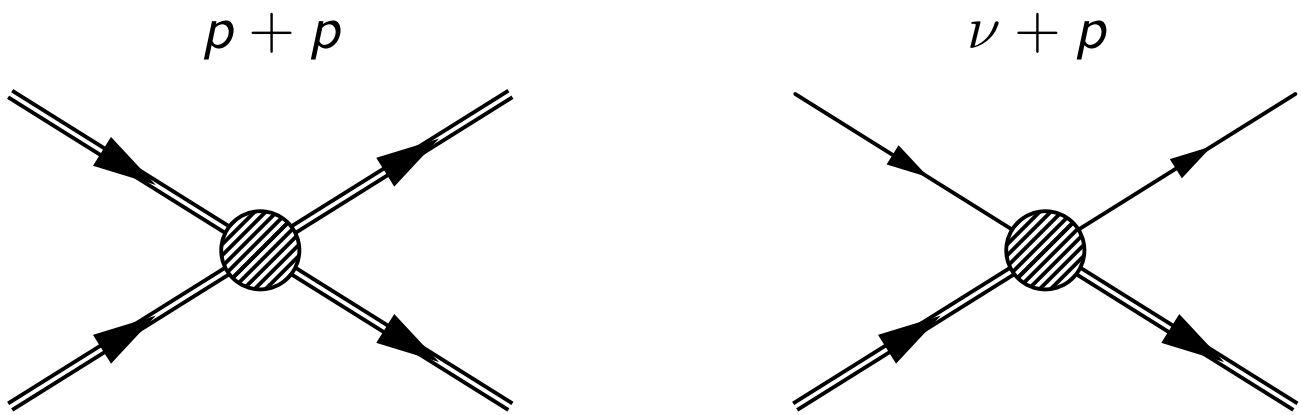
Wolfgang Kilian

CPPS, University of Siegen

MBI 2024 – Toulouse, Sep 27, 2024

(1) Resolving interactions

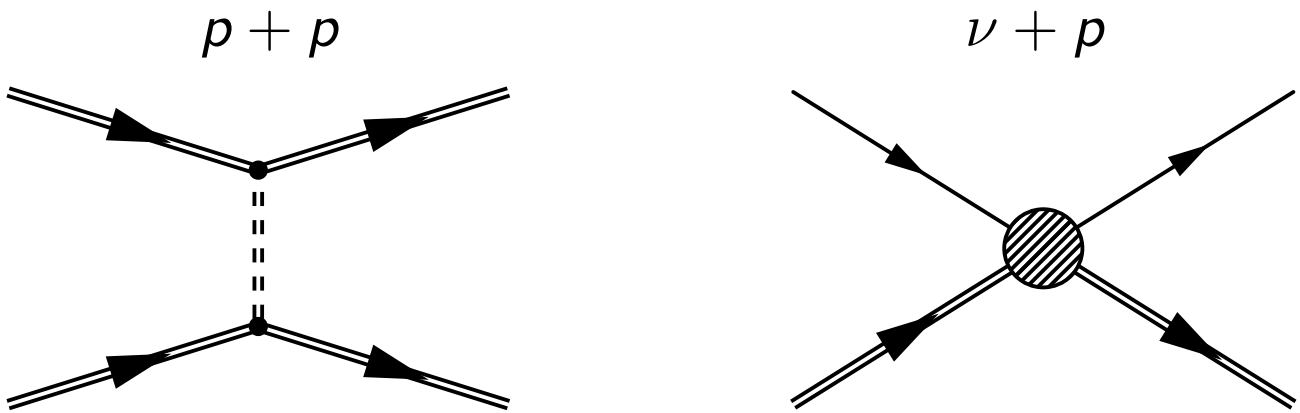
Nuclear + weak interactions = local on atomic scales



1 MeV

(1) Resolving interactions

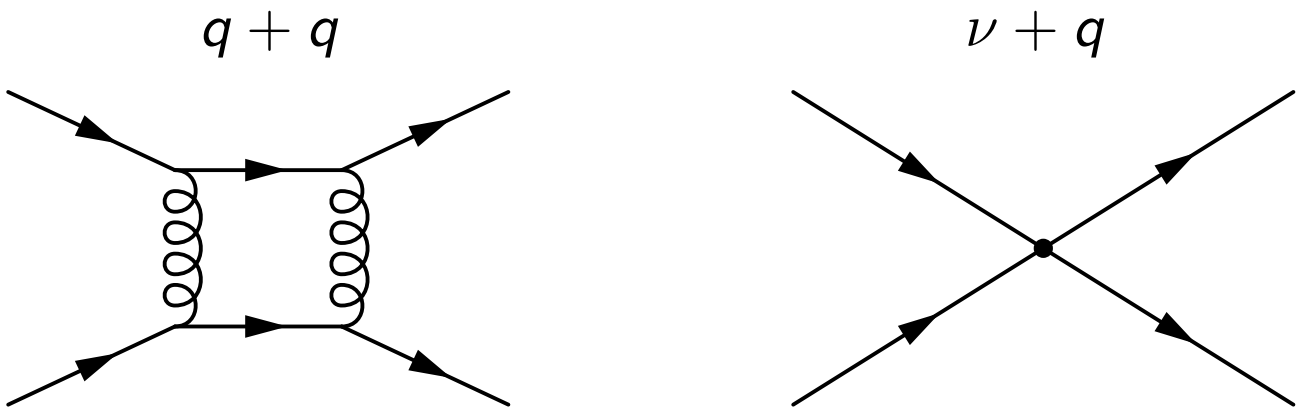
Nuclear + weak interactions $\Rightarrow$ non-local via bosonic fields



100 MeV

(1) Resolving interactions

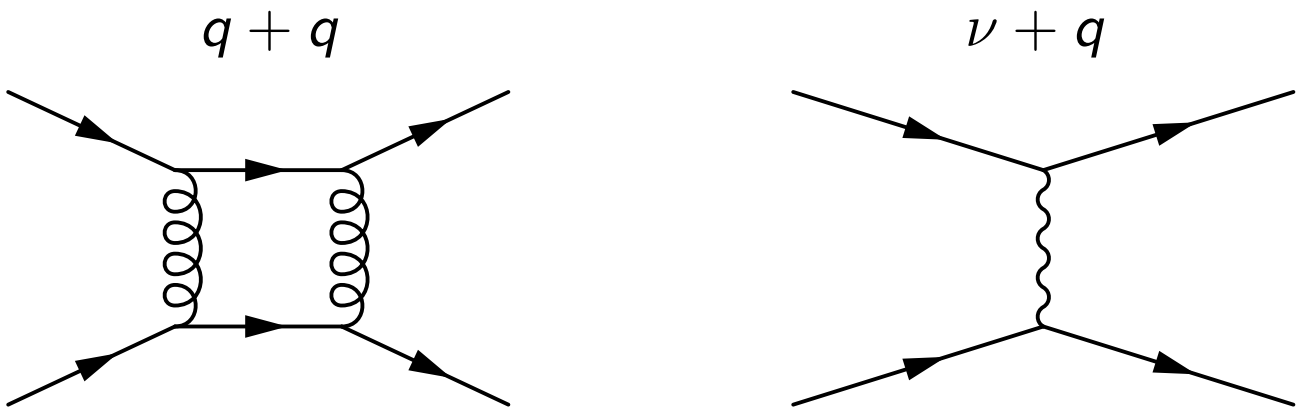
Nuclear + weak interactions $\Rightarrow$ non-local via bosonic fields



10 GeV

(1) Resolving interactions

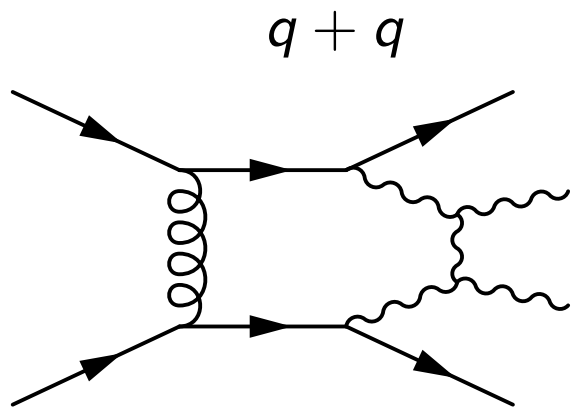
Nuclear + weak interactions $\Rightarrow$ non-local via bosonic fields



1 TeV

(1) Resolving interactions

Nuclear + weak interactions $\Rightarrow$ non-local via bosonic fields

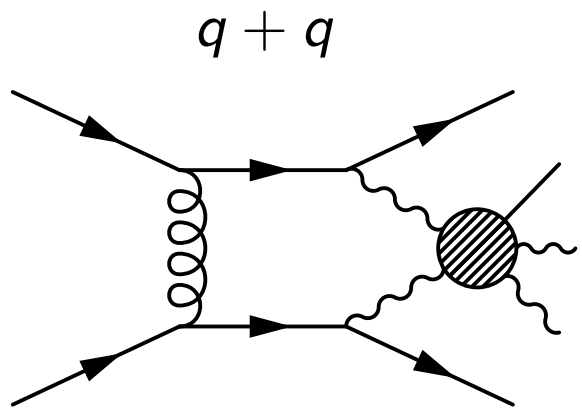


1 TeV

LHC: probe EW interactions in detail (pCM up to $O(1\ \text{TeV})$)

(1) Resolving interactions

Nuclear + weak interactions $\Rightarrow$ non-local via bosonic fields



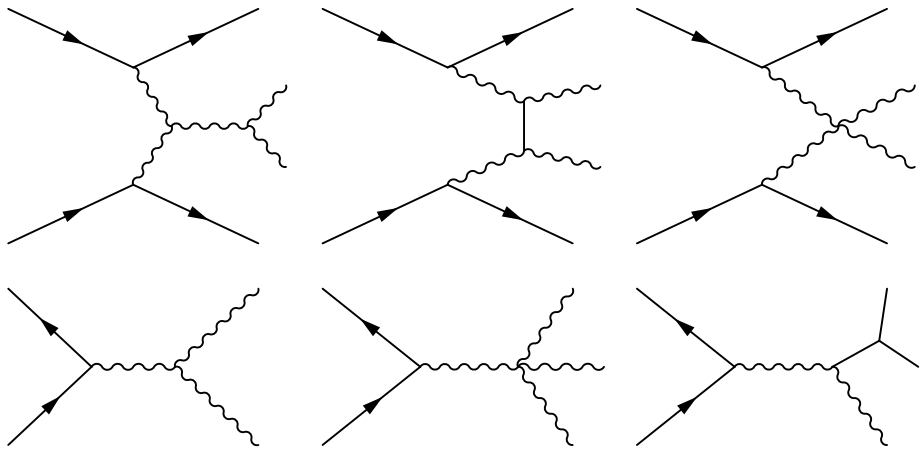
1 TeV

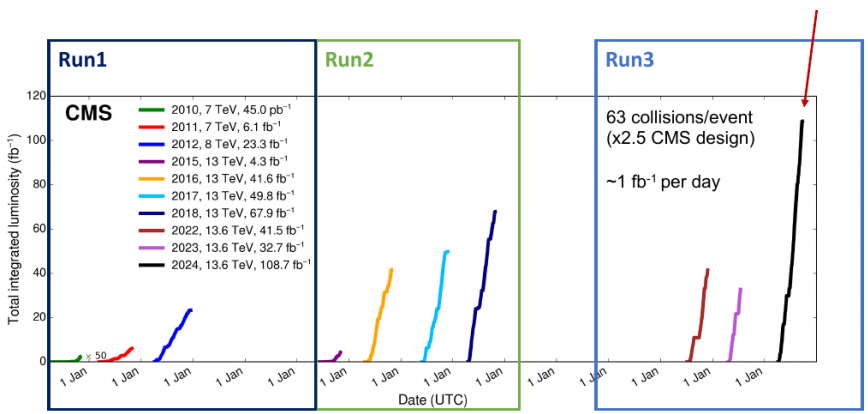
LHC: probe EW interactions in detail (pCM up to $O(1\ \text{TeV})$)

Interactions within interactions? Local? New fields?

(2) Interactions within interactions @LHC

LHC data and analyses: VBS and di-(multi-) boson production

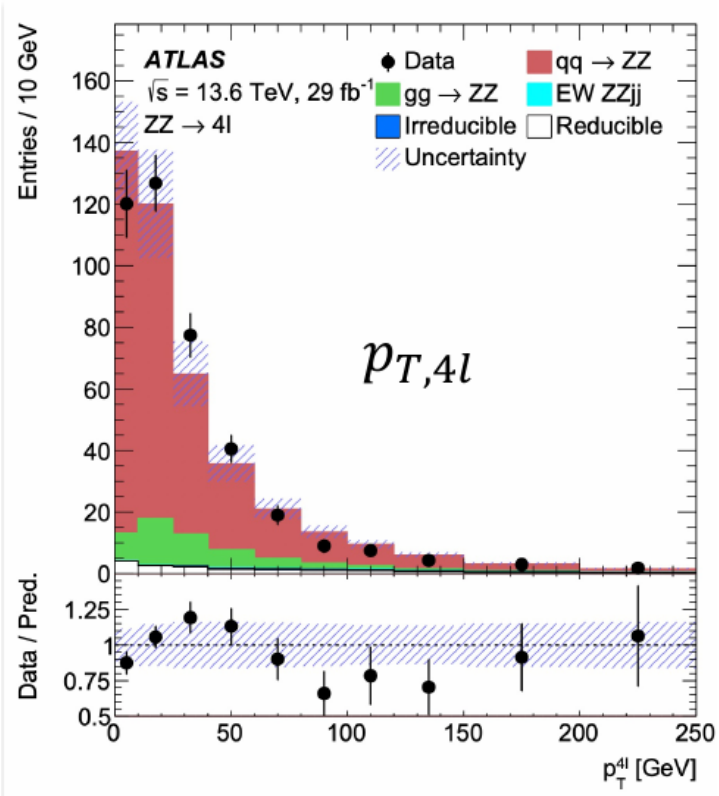


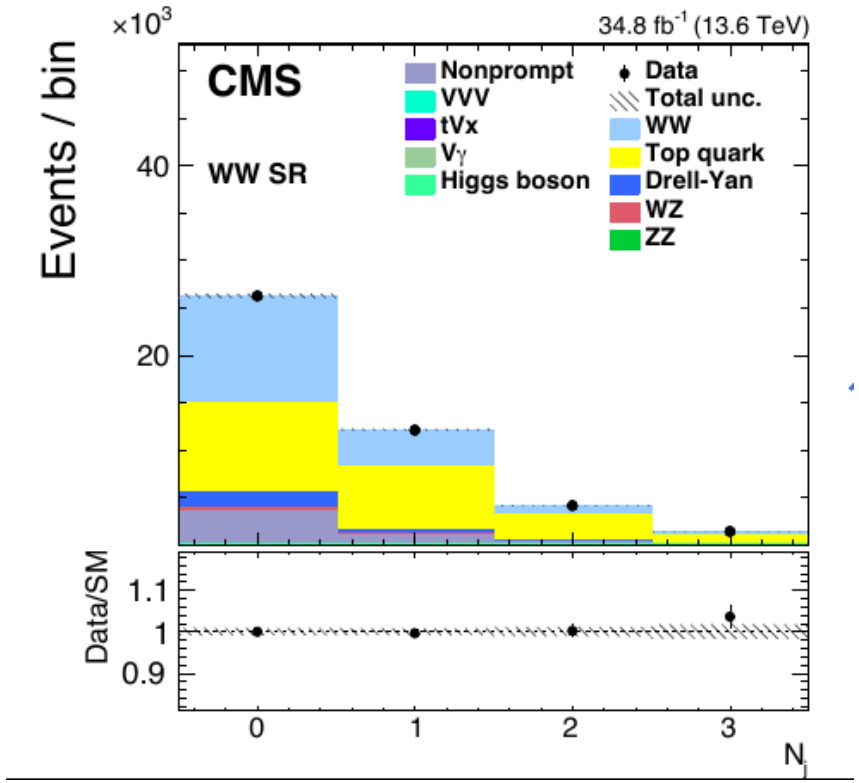


$\Rightarrow$ HL-LHC $\Rightarrow$???

(2) Interactions within interactions @LHC

Looking at: EW gauge and Higgs interaction + (N)NLO QCD (NLO EW):
diboson production



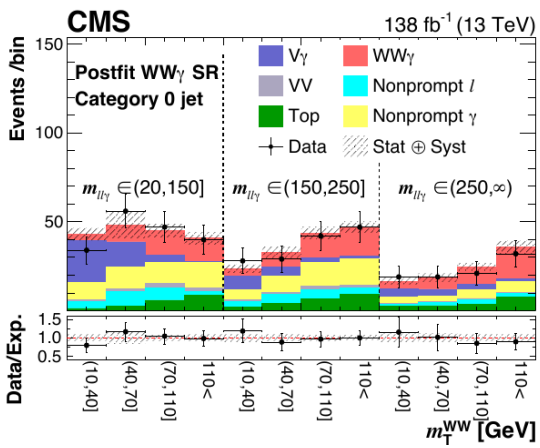


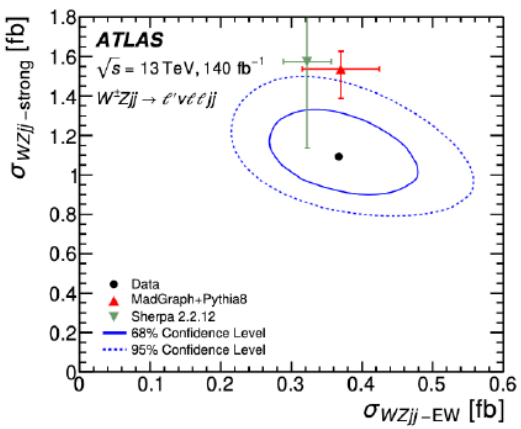
CMS (**Talk:** Sergio Blanco Fernandez): *WW*, *WZ*, $\gamma\gamma$, *ZZ**
ATLAS (**Talk:** Xingyu Wu): *ZZ*

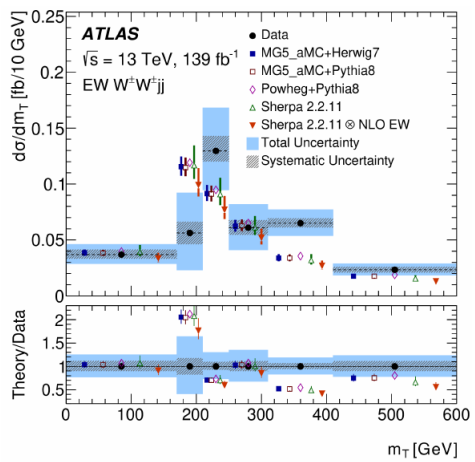
(2) Interactions within interactions @LHC

Looking at: EW trilinear / quartic / Higgs interplay: triboson and VBS
Saptaparna Bhattacharya (CMS); Eirini Kasimi, Iro Koletsou (ATLAS):

- $WWjj$, $Z\gamma jj$, $WZjj$, $ZZjj$
- $WZ\gamma$, $WW\gamma$, $W\gamma\gamma$

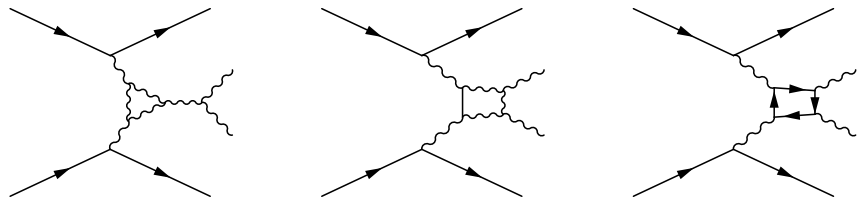






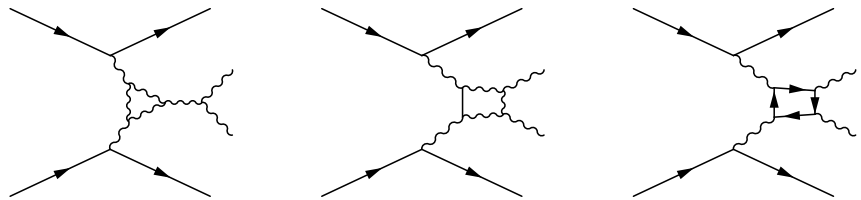
(3) Interactions within interactions: calculation

LHC theory: Loop corrections to scattering

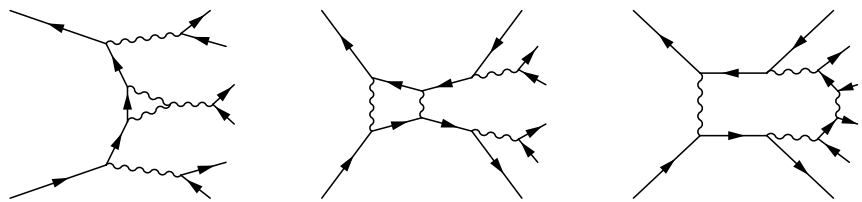


(3) Interactions within interactions: calculation

LHC theory: Loop corrections to scattering

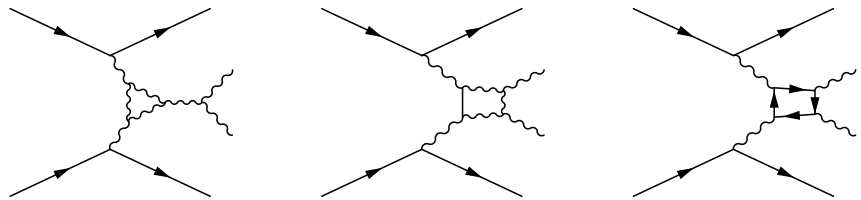


+ multi-boson production/decay and non-resonant terms

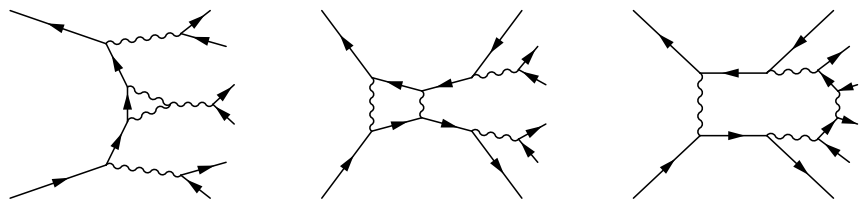


(3) Interactions within interactions: calculation

LHC theory: Loop corrections to scattering



+ multi-boson production/decay and non-resonant terms



+ QCD (NNLO) + parton shower + ...

(3) Interactions within interactions: calculation

- SM perturbation theory as basis
- Unified NLO-SM 6-fermion final state (triboson / VBS at NLO-SM)
  [cf. Denner, Lombardi, Chavez, Pelliccioli 2024]
- Calculations/tool accessibility towards fully automated NLO accuracy + QCD (N)NLO + QCD environment

  Sherpa, MG5, Powheg, Whizard, VBFNLO, MATRIX, ...
- QCD (+QED) Shower at NNLO+ $\Rightarrow$ **Talk:** Melissa van Beekveld
- Separation of QCD vs EW in hard processes to disappear

(4) Interactions within interactions: polarization modes

- Asymptotically: transition $W/Z + h \to (W_T/Z_T) + (h/W_L/Z_L)$
- Approximate separation via pole expansion of amplitudes
- Implemented in matrix-element/MC generators
  $\Rightarrow$ Polarization workshop Monday

(4) Interactions within interactions: polarization modes

- Asymptotically: transition $W/Z + h \to (W_T/Z_T) + (h/W_L/Z_L)$
- Approximate separation via pole expansion of amplitudes
- Implemented in matrix-element/MC generators
  $\Rightarrow$ Polarization workshop Monday

- LHC: polarized diboson analysis **Talk:** Miaoran Lu (ATLAS)

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Non-prompt background	68 ± 29	2.8 ± 1.1
Total Expected	1640 ± 60	222 ± 8
Data	1740	236

(4) Interactions within interactions: polarization modes

- Asymptotically: transition $W/Z + h \to (W_T/Z_T) + (h/W_L/Z_L)$
- Approximate separation via pole expansion of amplitudes
- Implemented in matrix-element/MC generators
  $\Rightarrow$ Polarization workshop Monday

- LHC: polarized diboson analysis **Talk:** Miaoran Lu (ATLAS)

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Non-prompt background	68 ± 29	2.8 ± 1.1
Total Expected	1640 ± 60	222 ± 8
Data	1740	236

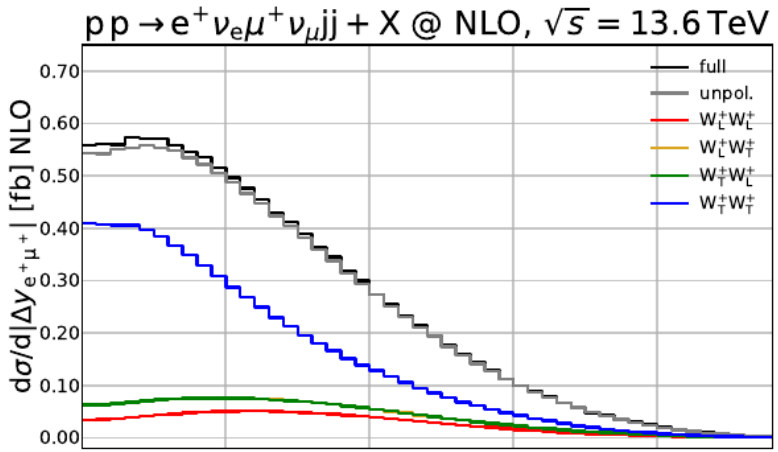
- Caveat (LHC): production near threshold dominates $\Rightarrow$ HL-LHC

(4) Interactions within interactions: polarization modes

- **Talk:** Giovanni Pellicioli; Christoph Haitz

code	OS approx.	LO	loop-ind.	NLOQCD	NNLOQCD	NLOEW	LOPS	NLOPS
MoCaNLO	DPA	✓	✓	✓	✗	✓	✗	✗
STRIPPER	DPA	✓	✓	✓	✓	✗	✗	✗
MulBos	DPA	✓	✓	✓	✗	✓	✗	✗
BBMC	DPA	✓	✗	✓	✗	✓	✗	✗
Sherpa	NWA	✓	✗	(✓)	✗	✗	✓	(✓)
MadGraph	NWA	✓	✓	✗	✗	✗	✓	✗
PowHeg-Box	DPA	✓	✗	✓	✗	✗	✓	✓

- Calculations for diboson production — and VBS ($\Delta y(e\mu)$):

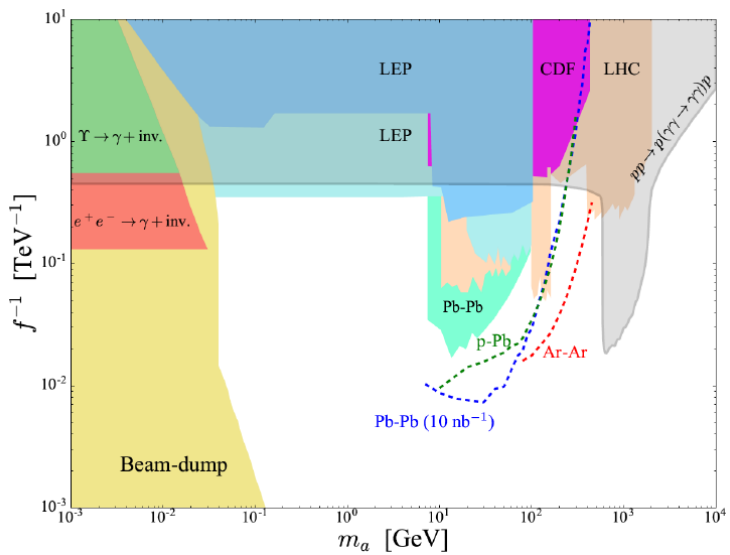


(5) Interactions within interactions within interactions

Many unsolved particle/cosmology problems: no known connection to physical (including undetected) particles

. . . dark energy, dark matter, neutrino mixing, strong CP, EW transition, . . .

- Look for interactions hidden within EM/EW/Higgs interactions — possibly, not necessarily short-range



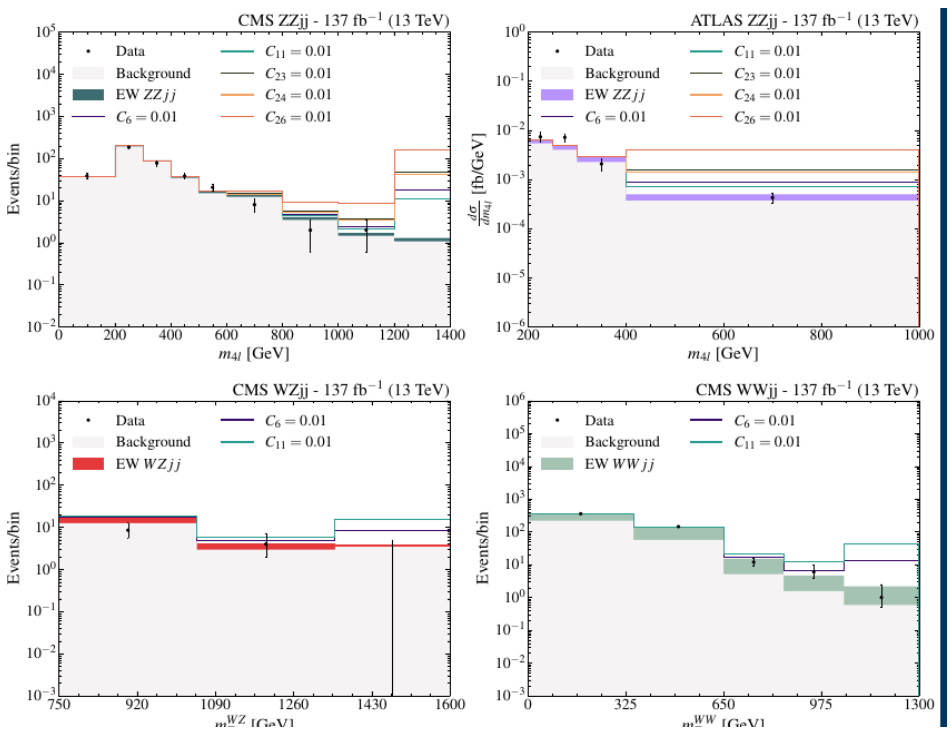
- **Talk:** Christophe Royon: new interactions/particles in elastic *pp*

(5) Interactions within interactions within interactions

Potential significant deviations in bosonic (heavy-particle) self-interactions
⇒ gauge symmetry as a technical device at TeV-scale

1980s (Weinberg; Appelquist; Longhitano,. . .): HEFT/SMEFT

- **Talk:** Oscar Eboli: HEFT parameterization of quartic gauge couplings



(5) Interactions within interactions within interactions

New interactions more local than EW scale (decoupling property)

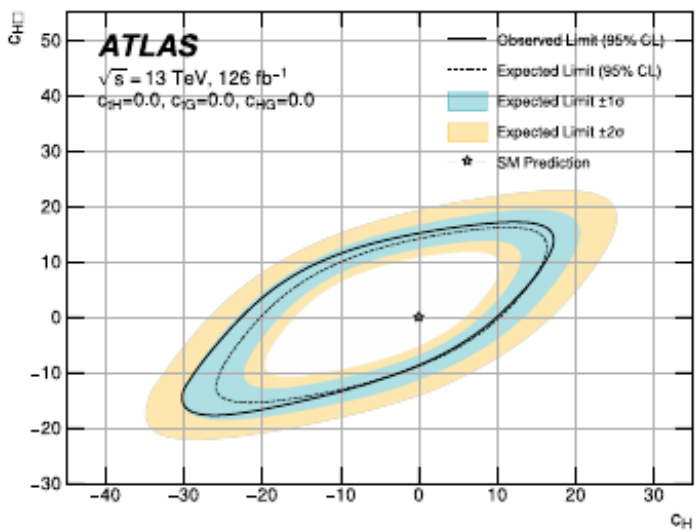
$\Rightarrow$ Power-counting $v/\Lambda \Rightarrow$ SMEFT

(do not expect power counting to be reliable; cf. SM Yukawa sector)

Higgs-pair production

Talk: Anna Tegetmeier (ATLAS)

$\boxed{hhh,\ h(\partial h)(\partial h)}$, hWW, hZZ, hgg couplings



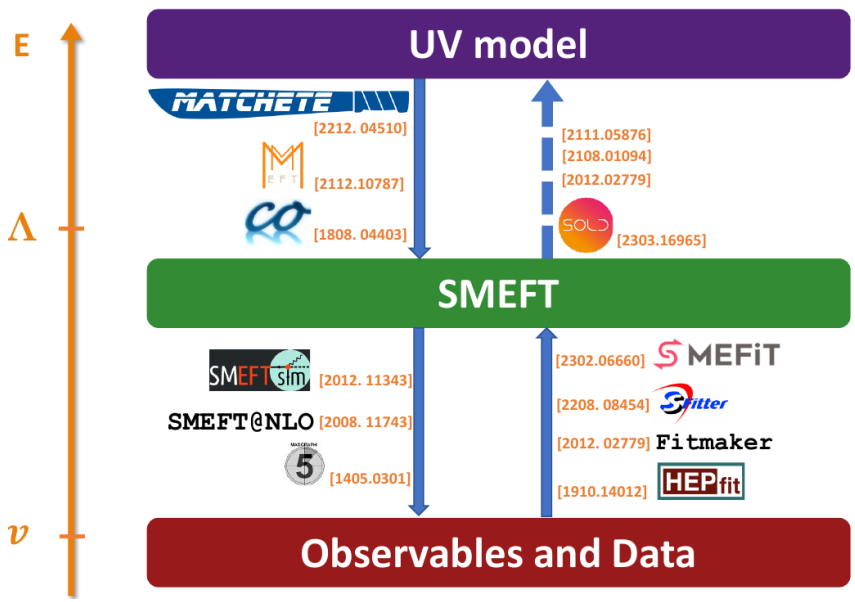
c_H : $(\varphi^\dagger\varphi)^3$

$c_{\Box H}$: $(\varphi^\dagger\varphi)\partial^2(\varphi^\dagger\varphi)$

(5) Interactions within interactions within interactions

The relation between new local interactions (with decoupling property) and SMEFT Lagrangian parameters can be computed by automated tools.

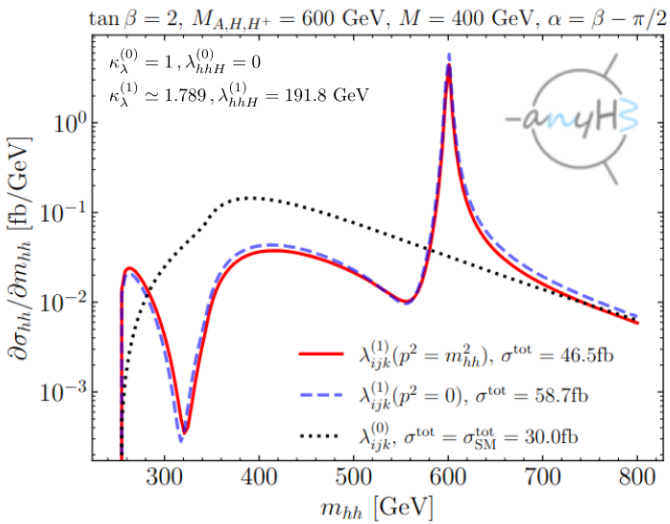
Talk: Alejo Rossia



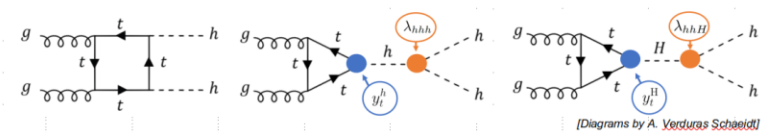
(5) Interactions within interactions within interactions

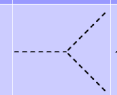
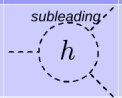
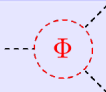
Large modifications to the Higgs self-coupling(s) are completely reasonable

Talk: Johannes Braathen

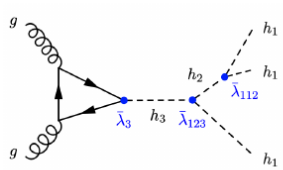


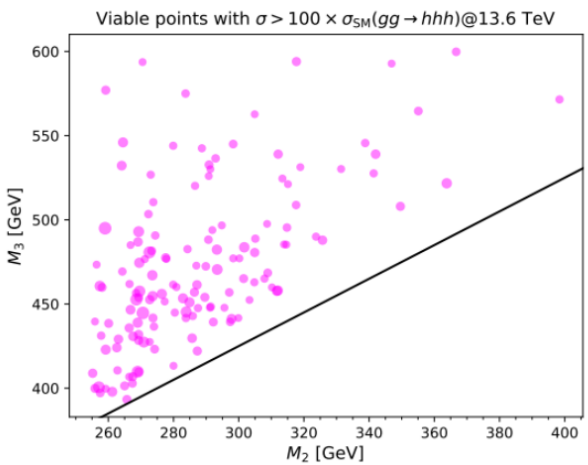
[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]



Coupling/Order	0L	1L
g_{hhhh}		subleading 
$g_{(h)h\Phi\Phi}$ $\left[g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}\right]$	-	

Talk: Osama Karkout

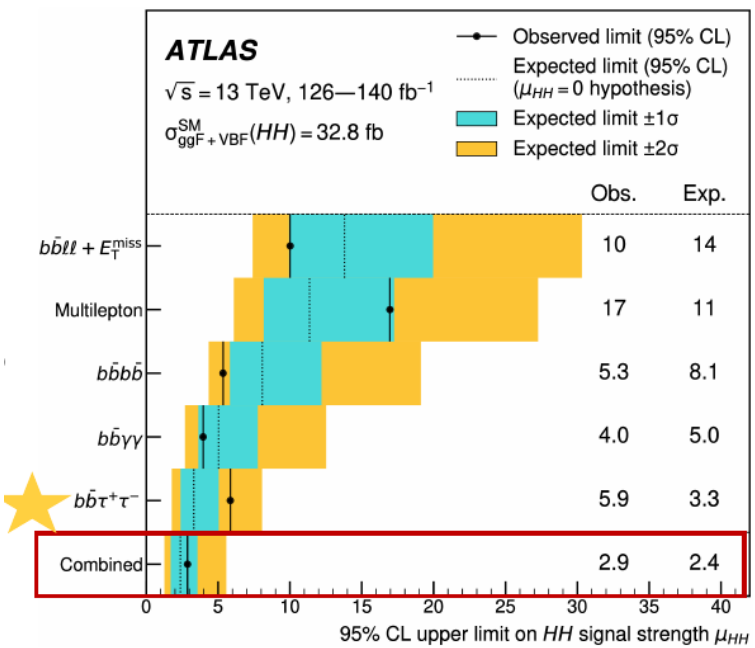




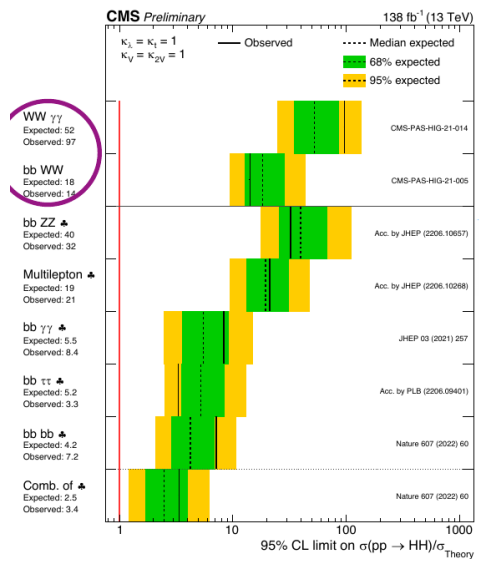
(5) Interactions within interactions within interactions

Large modifications to the Higgs self-coupling(s) are completely reasonable

Talk: Giulia Di Gregorio (ATLAS)

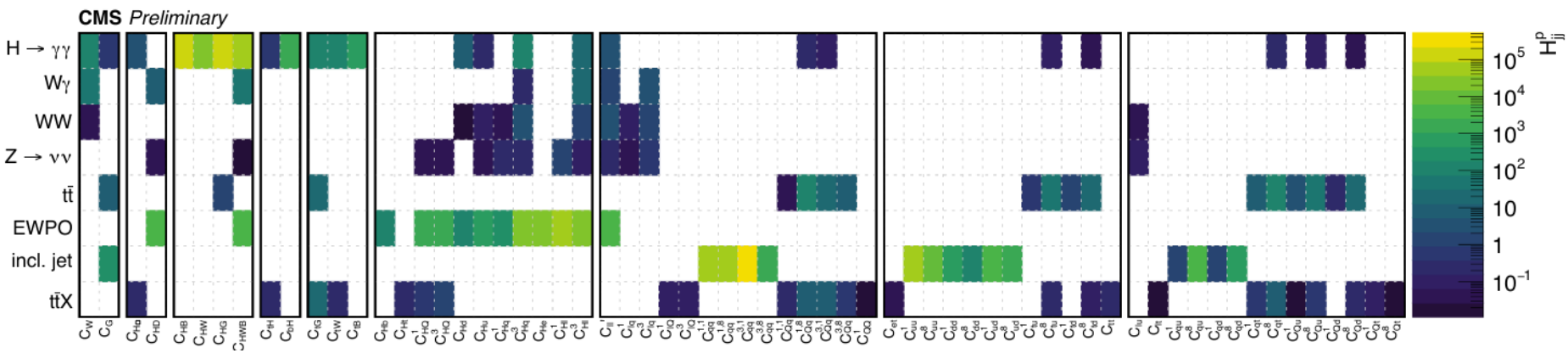


Talk: Lisa Paspalaki (CMS)

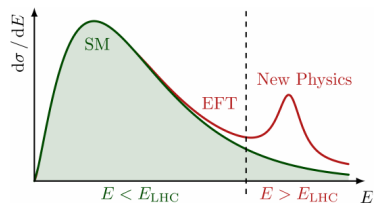


(5) Interactions within interactions within interactions

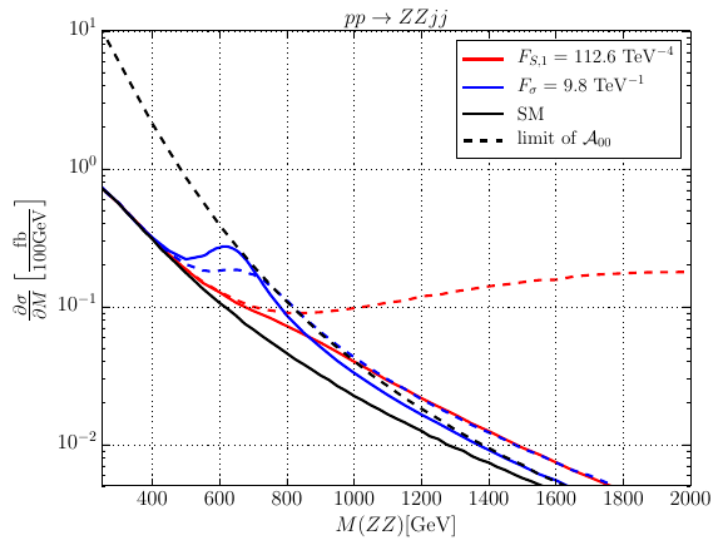
- Complete account of (accessible) form factors / SMEFT coefficients
- Angular observables give access to C/P violating effects
- **Talk:**
  - Hesham El Faham: TGC in diboson: a SMEFT view from every angle
  - Leo Boudet (ATLAS): study of CP violating bosonic operators
  - Fabian Stäger: combined EFT fits in ATLAS and CMS



Interlude: how not to apply (SM)EFT



Example: heavy scalar-isoscalar resonance at LHC vs EFT

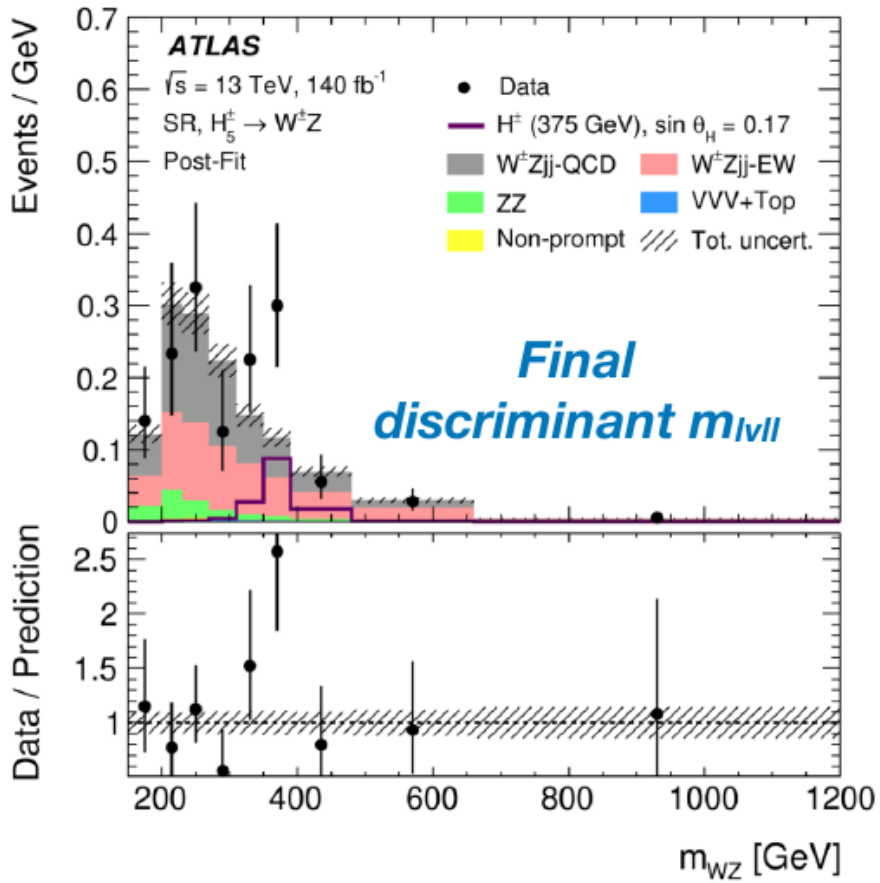


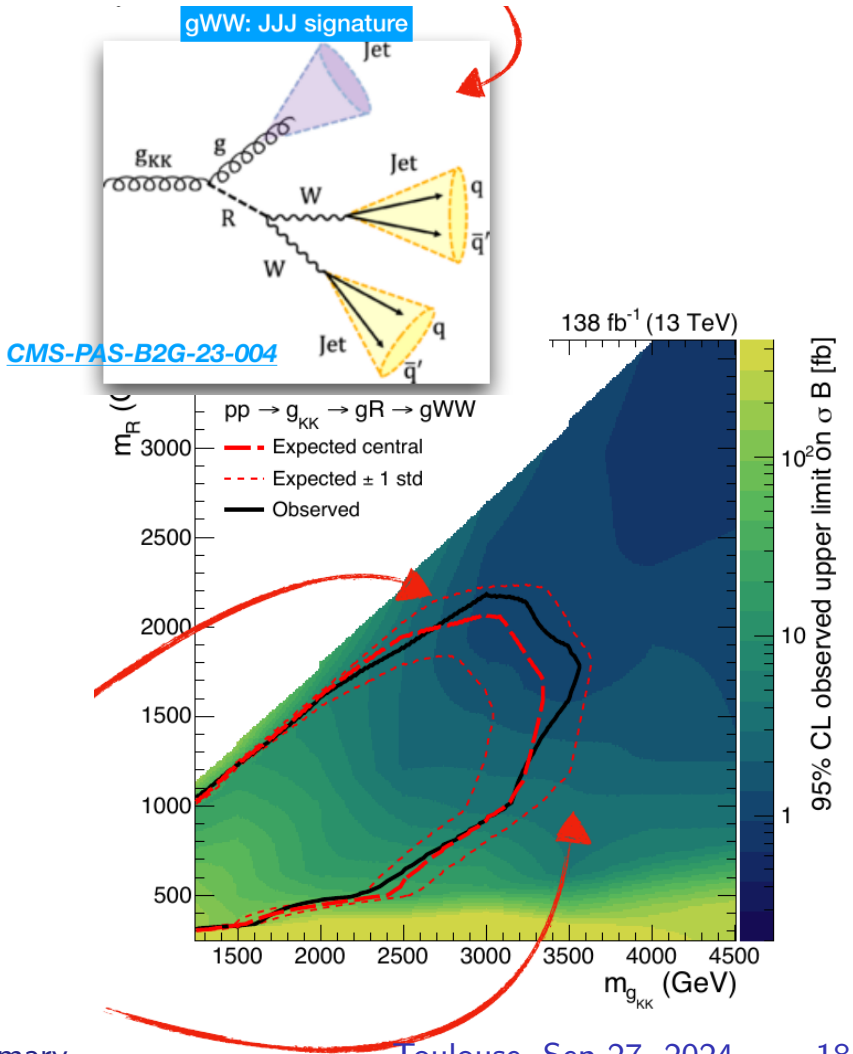
[WK, Ohl, Reuter, Sekulla 2015; see also: Lang, Schäfer-Siebert, Zeppenfeld 2021]

(6) Interactions within interactions within interactions

Talk: Antonio Giannini

⇒ direct searches for interactions embedded in EW interactions @ ATLAS



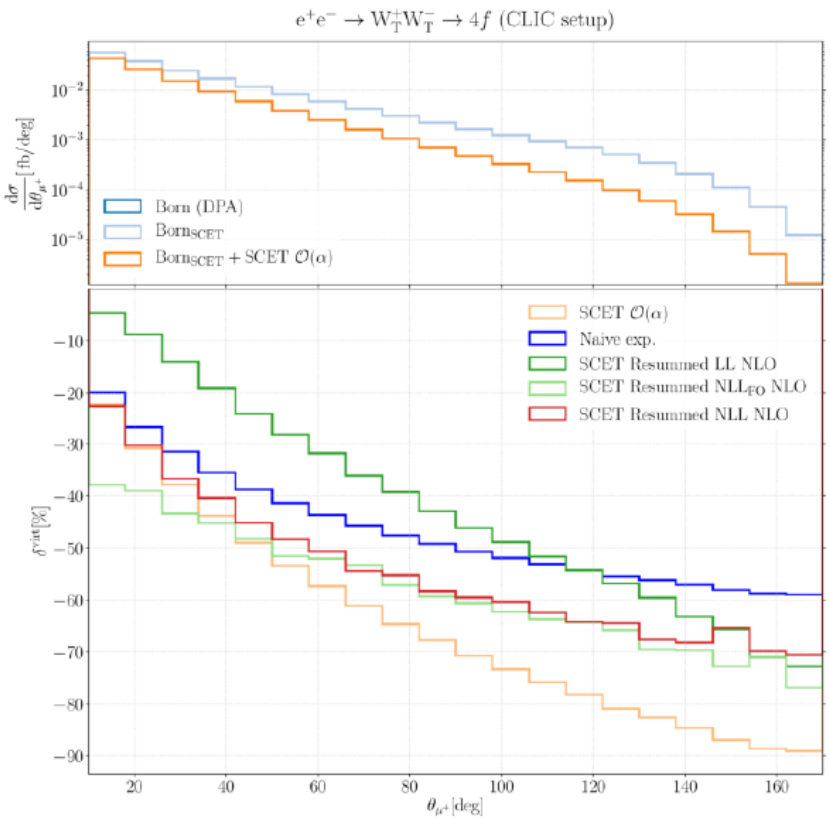


(6) Interactions . . . *ad infinitum* (CLIC, FCC-hh, μCol)

- Multi-boson production and radiation transform into a QCD-like conglomerate of PDF, hard interactions, shower, . . .

Talk: Ansgar Denner

- EW-symmetric inclusive cross sections (in SM) rise only moderately
  $\Rightarrow$ asymptotic suppression of any exclusive final state: Sudakov
- Sudakov logs dominates all fixed-order EW corrections



(7) Interim report – 10(11) years after MBI #1 (#0)

Multi-boson physics is about identifying interactions within interactions, directly.

Theory calculations and tools make these effects accessible to data analysis with high accuracy.

EFT parameterizations provide a universal language for dealing with new and unknown effects.

LHC analyses extract all possible information out of actual data. (Accessibility is limited by LHC environment and parameters. HL-LHC on the horizon.)

(7) Interim report – 10(11) years after MBI #1 (#0)

Multi-boson physics is about identifying interactions within interactions, directly.

Theory calculations and tools make these effects accessible to data analysis with high accuracy.

EFT parameterizations provide a universal language for dealing with new and unknown effects.

LHC analyses extract all possible information out of actual data. (Accessibility is limited by LHC environment and parameters. HL-LHC on the horizon.)

Genuine multi-boson physics to be seen with pCM $\gtrsim$ 10 TeV ...