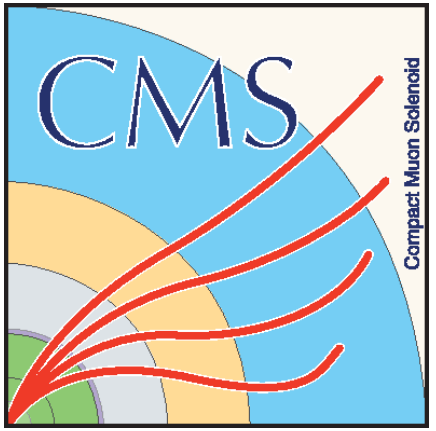
Electroweak Physics With Single and Multi Bosons

Karol Krizka

May 16, 2023



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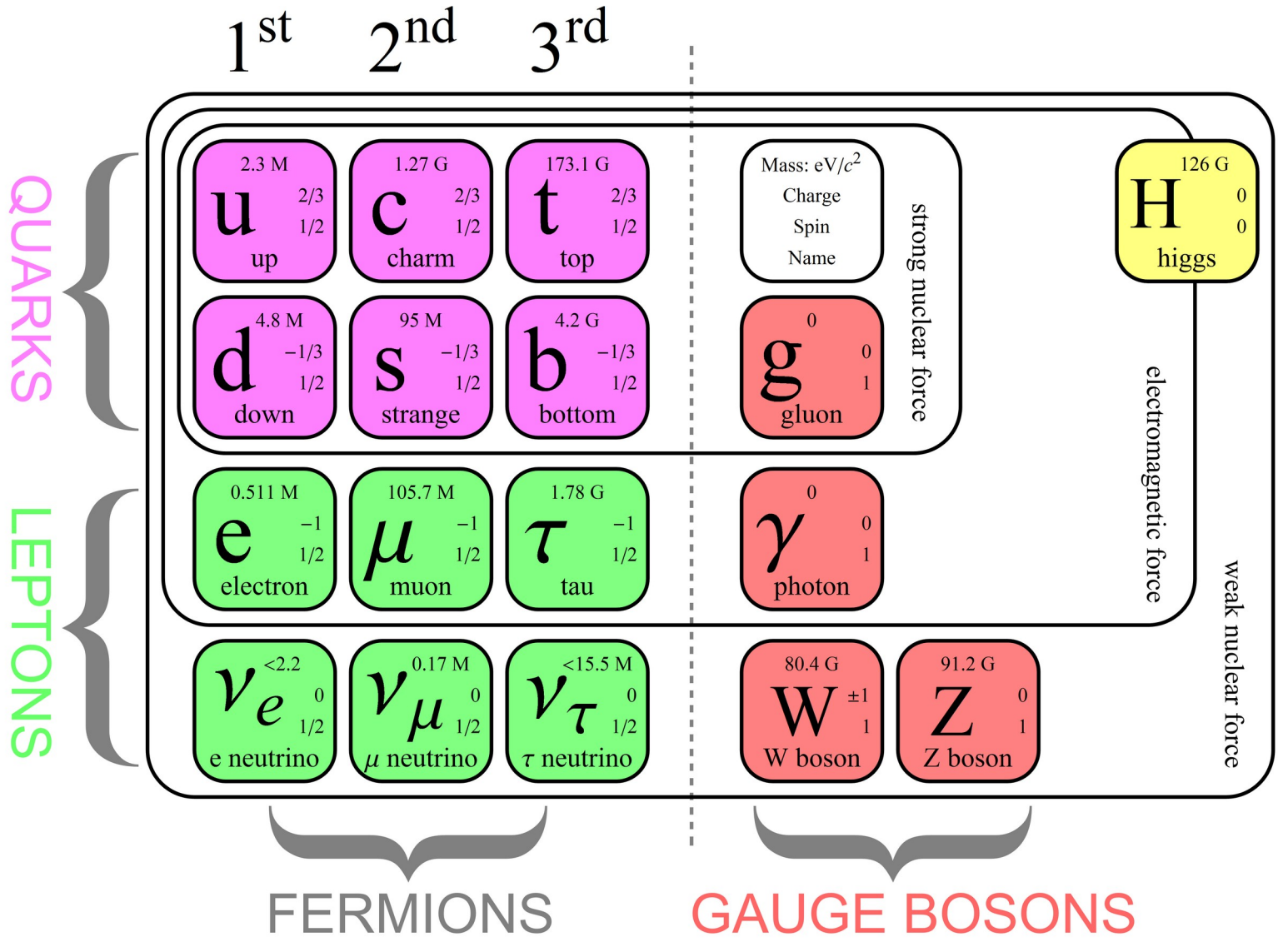
Blois 2023

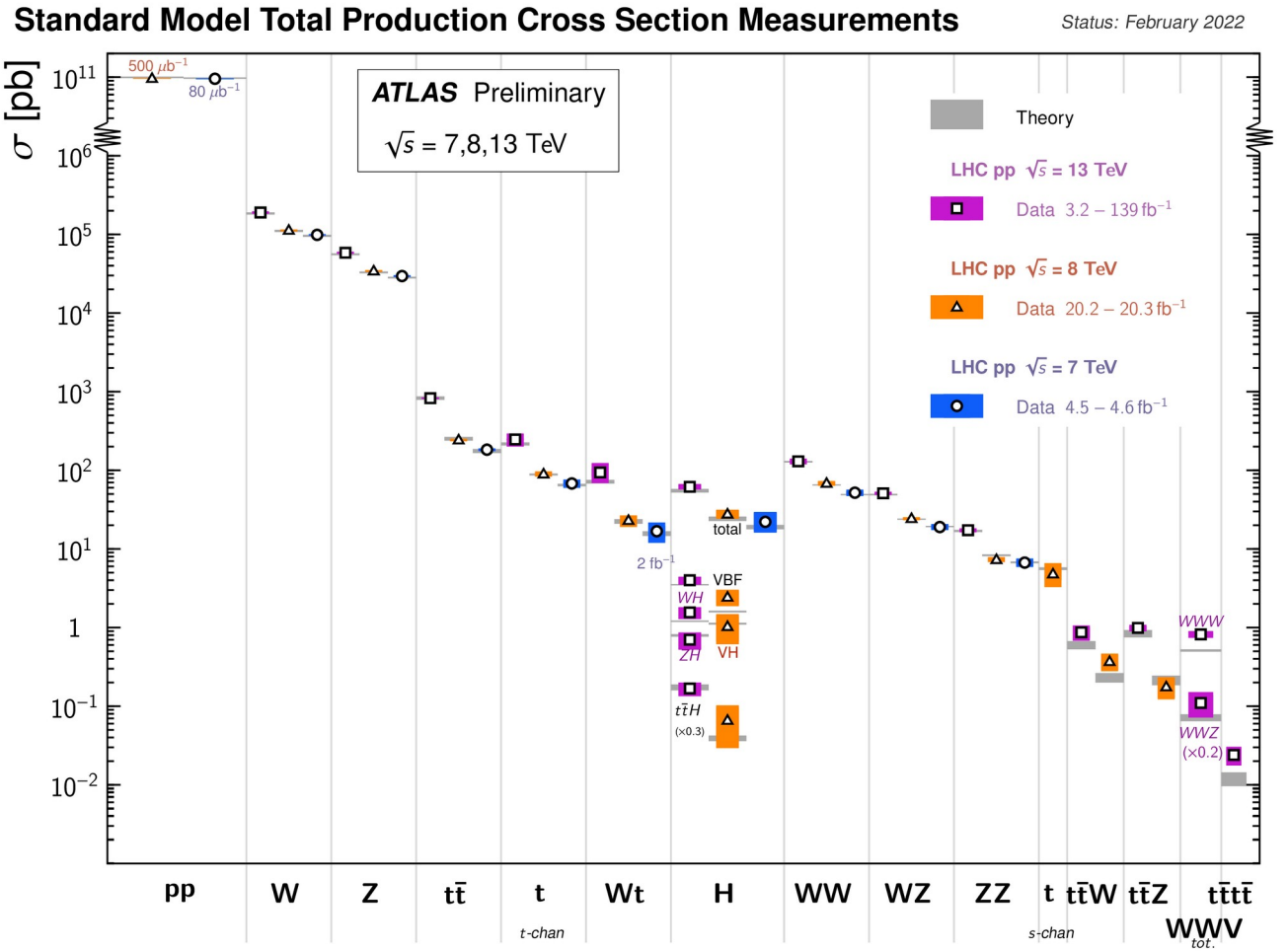
The Standard Model



Our world at the smallest level, as seen experimentally.

The Standard Model Measurements

The Standard Model is working very nicely! HEP experiments give values consistent with theorist's calculations.



But...

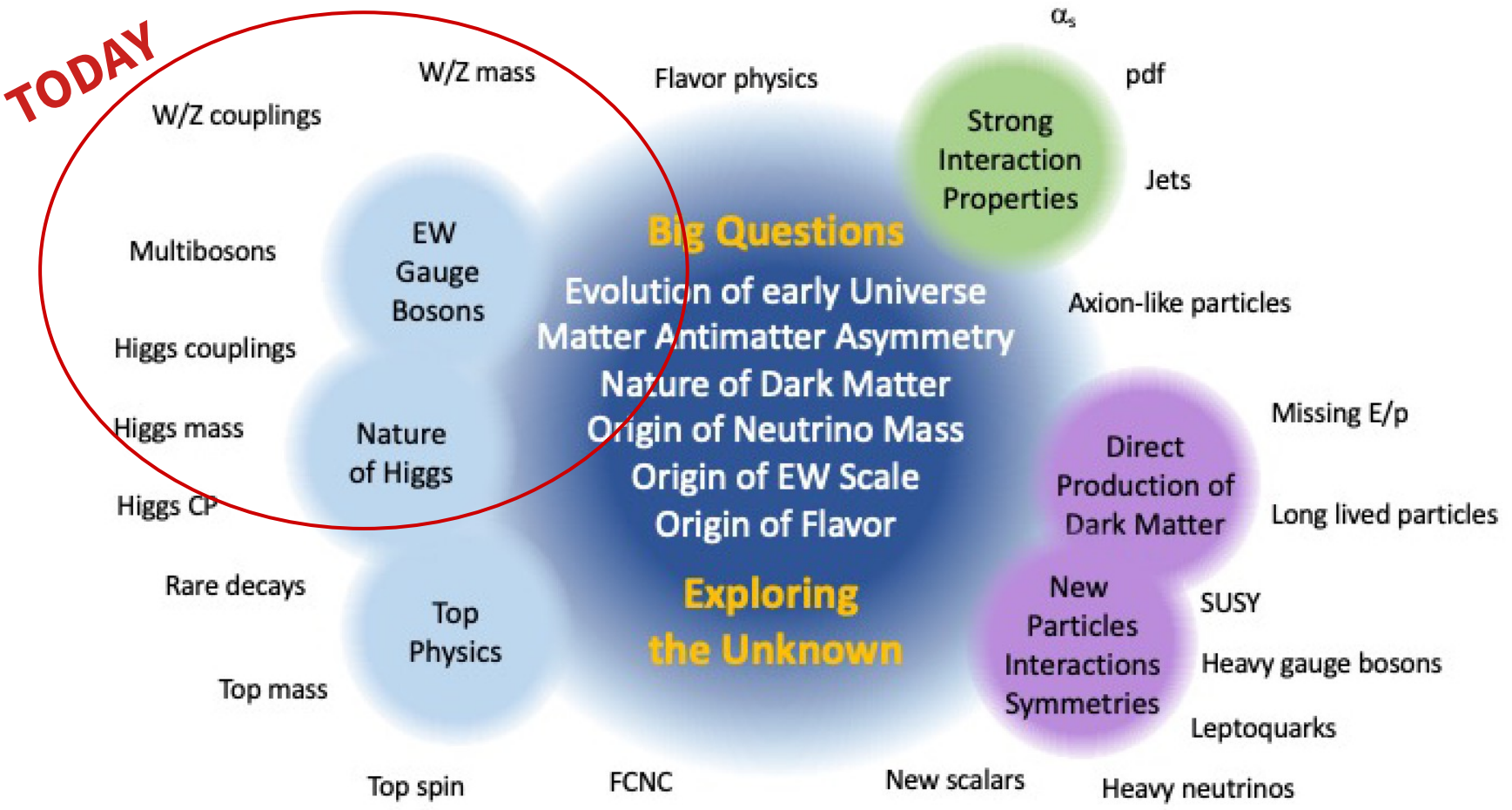
The Standard Model Problems

… not consistent with non-HEP observations

- **Hierarchy problem**
  - Higgs mass only correct if parameters are very precise for cancellations to occur
- **Matter/Antimatter asymmetry**
  - SM says matter/antimatter are almost the same, but world tells us that there is more matter
- **Dark Matter**
  - Cosmological observations show large blobs of unseen mass and SM cannot explain them
- **No gravity, Dark Energy, neutrino masses…**

Why collider experiments?

Collider experiments allow you to sample a **huge space of theories** with **one experimental setup**!

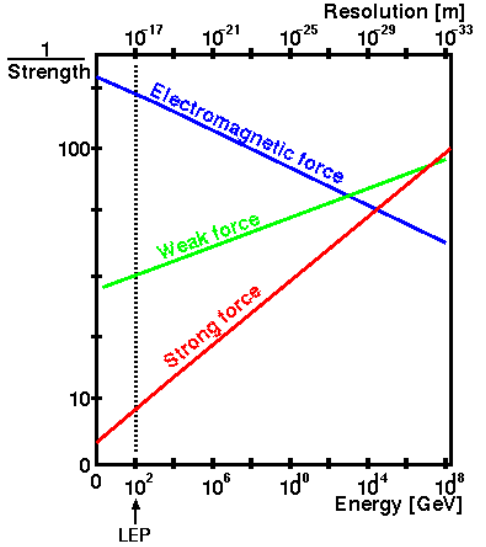


Very useful if you don't know **where to look...**

Electroweak Physics and Two Types of Bosons

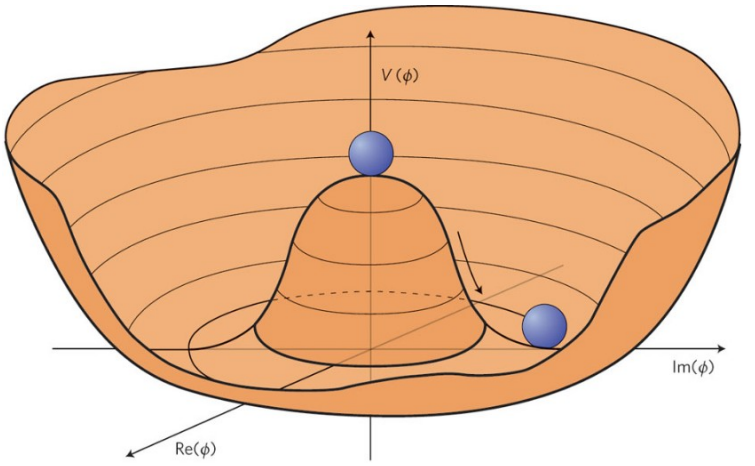
Vector Bosons

- **Indirect searches for BSM**
  - Precision measurements
  - Global SMEFT fits
- **Backgrounds/tools to Higgs**



Higgs Physics

- **Responsible for ElectroWeak Symmetry Breaking**
  - Do we have only one Higgs?
  - Shape of potential?



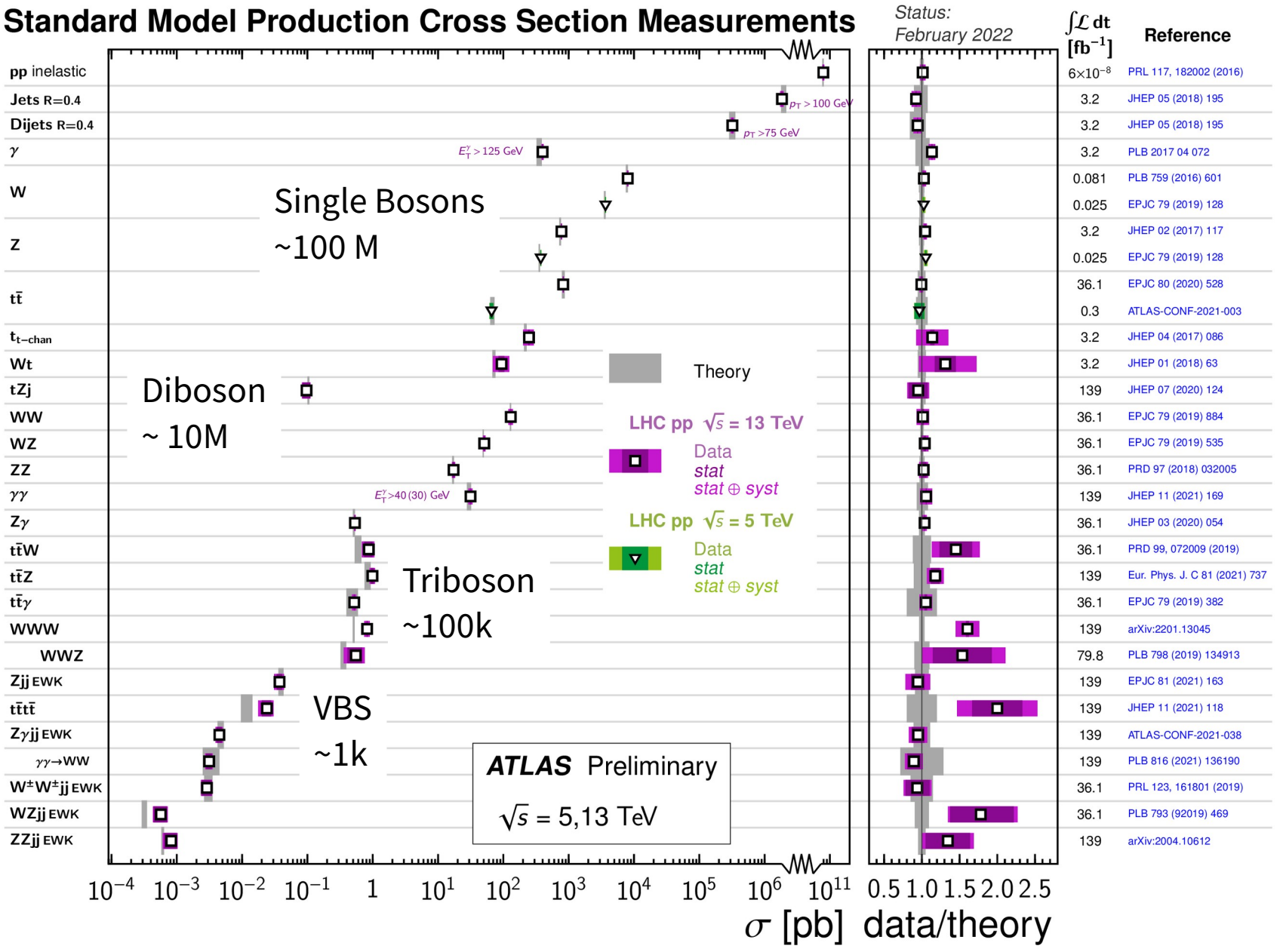
Vector Bosons

https://www.particlezoo.net

Electroweak Physics With Vector Bosons

ATLAS SM Summary Plots

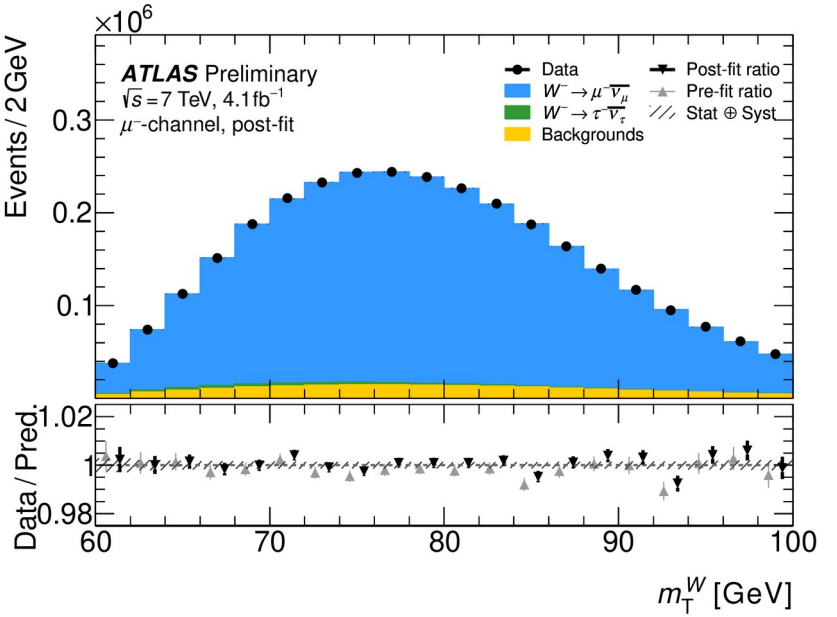
CMS Summary Plots

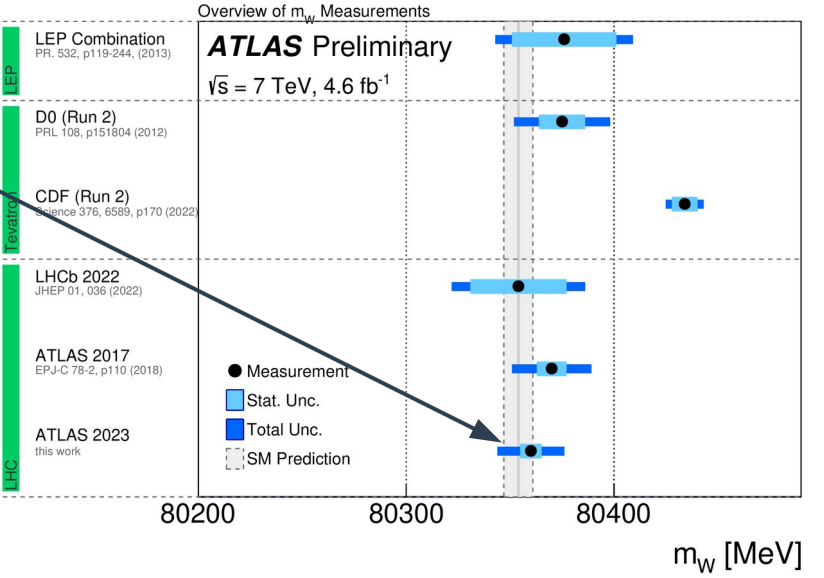


ATLAS W Mass Measurement

ATLAS-CONF-2023-004

- **SM prediction to 7 MeV**
  - Can be modified by BSM
- **New update from ATLAS**
  - Same detector description and modeling
  - Updated statistical model
  - Updated PDF's
- **LHCb measurement complementary** JHEP 01 (2022) 036
  - PDF unc. cancels in combination MWDays2023



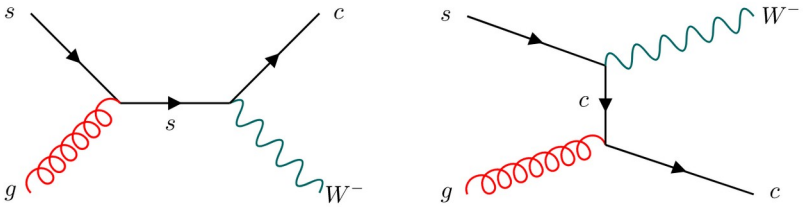


Improvements: 15%-30% 10%-40% **15%**

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_{T}^{ℓ}	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_{T}	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

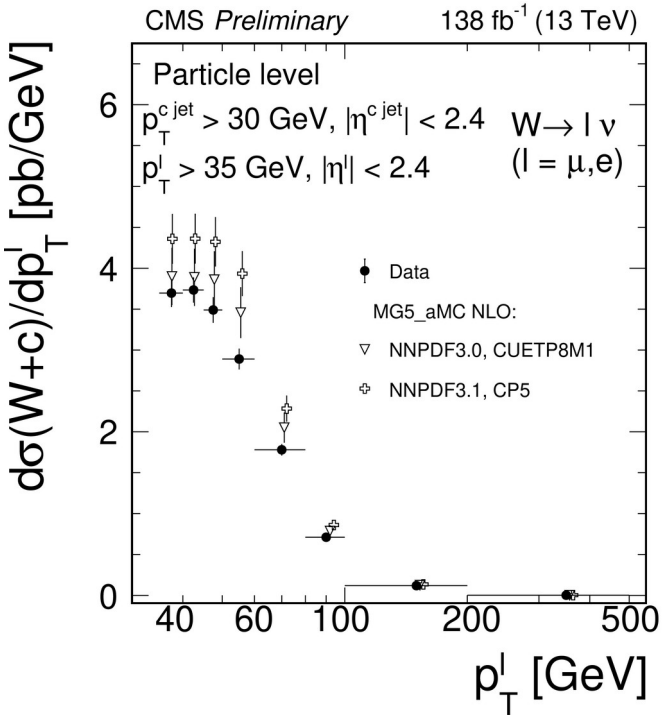
W/Z+c Measurements

ATLAS: STDM-2019-22
CMS: SMP-21-005
LHCb: Phys. Rev. Lett. 128 (2022) 082001

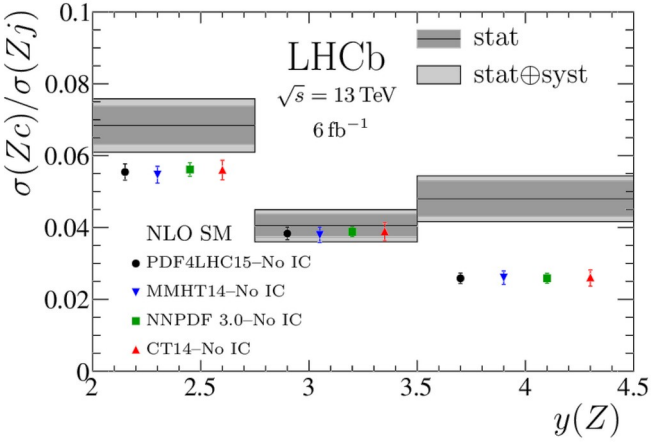


- **Constraints s-quark component of PDF.**
  - Important for VH→cc searches.
- **W+c: charge symmetric Background: charge symmetric**
  - Measurements suggest s-sbar asymmetry is small in the probed x,Q^2 region

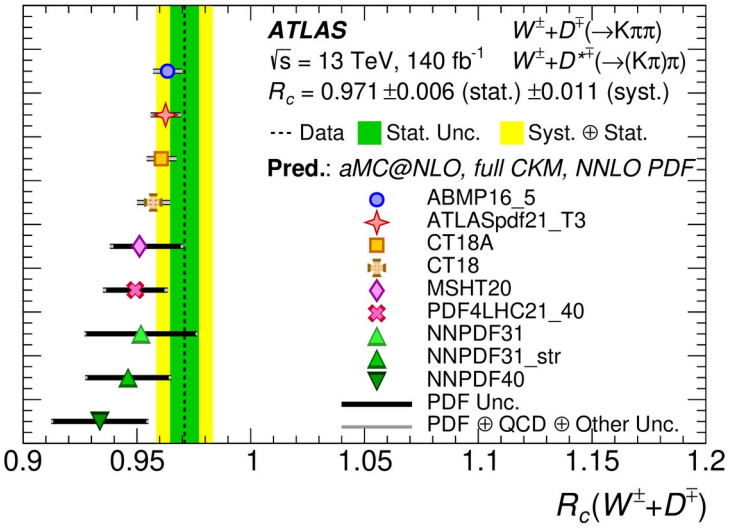
Unfolded differential results



LHCb measures Z+c in forward region.



$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)}$$

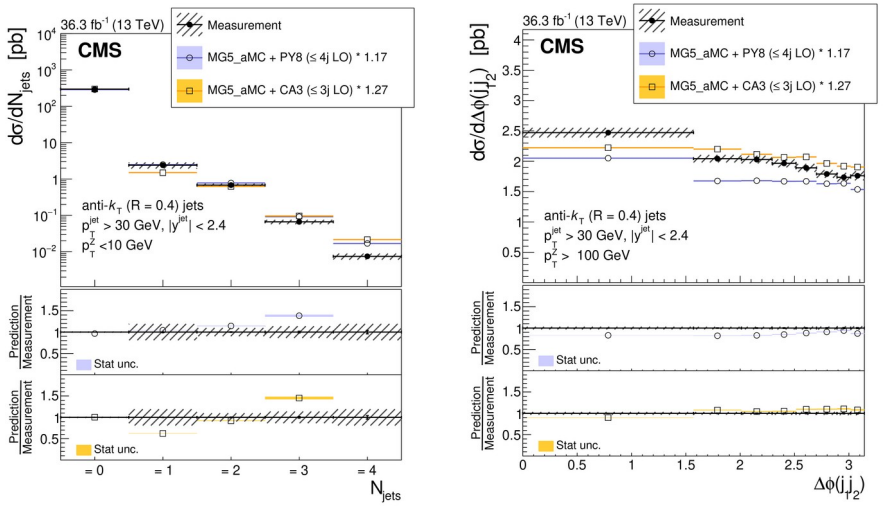


Tests of N²LO Generators and PDF's

Cristiano Tarricone
Wednesday

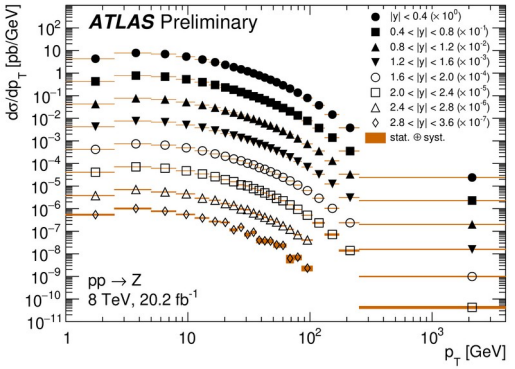
SMP-21-003

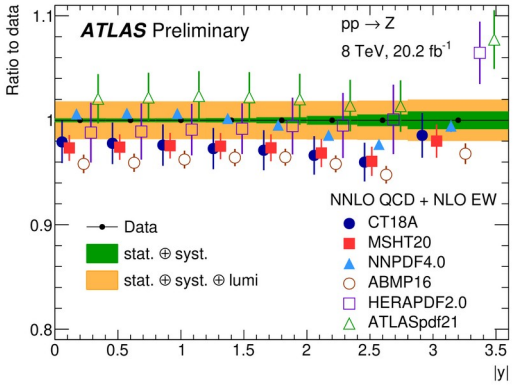
W/Z + 0,1,2 jet events allow tests of real corrections.



ATLAS-CONF-2023-015

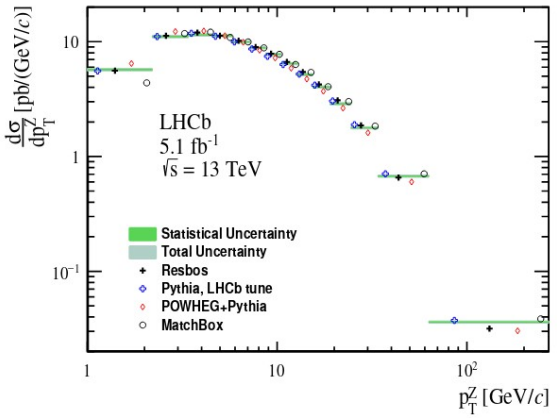
Double differential Z p_T/η measurement test PDF's.

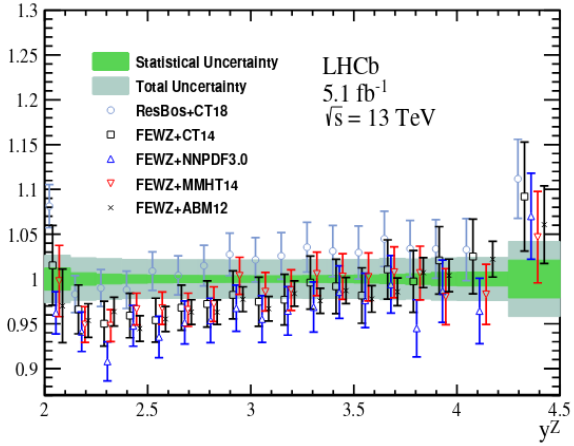




JHEP 07 (2022) 26

LHCb Z measurements of PDF's in extremes of *x*

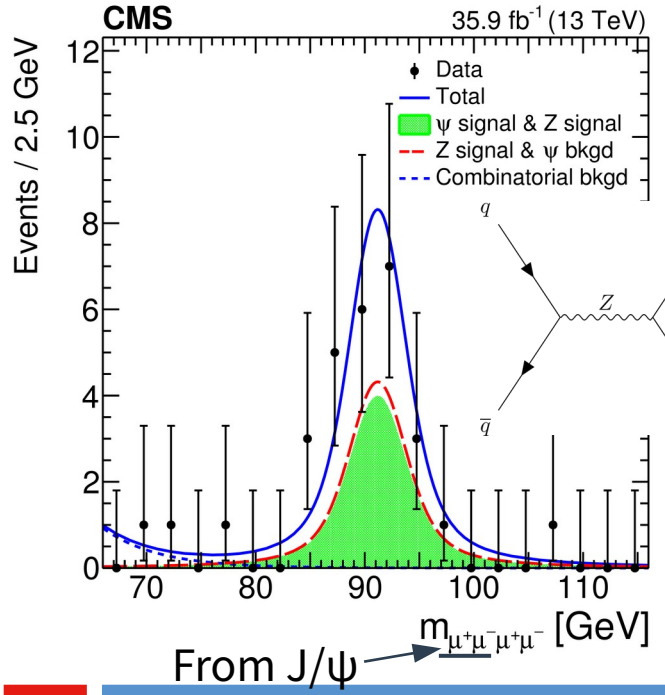




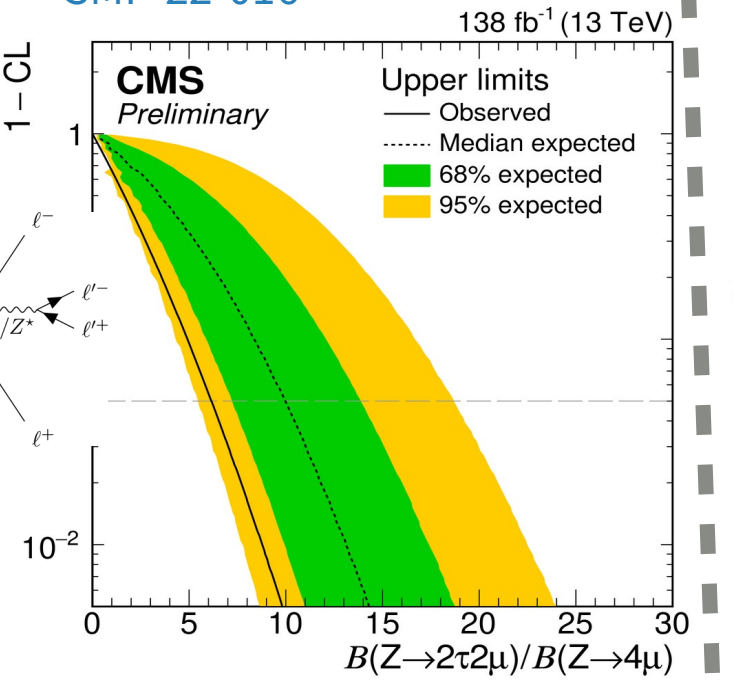
Rare Decays

- **Indirect BR's of Z's can be modified via new particles**
  - Potentially unequal couplings to τ's
- **Future background to quarkonia higgs decays.**

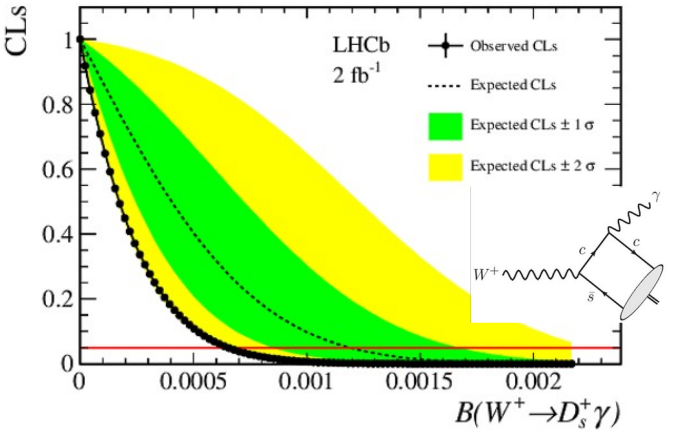
Phys. Rev. Lett. 121 (2018) 141801

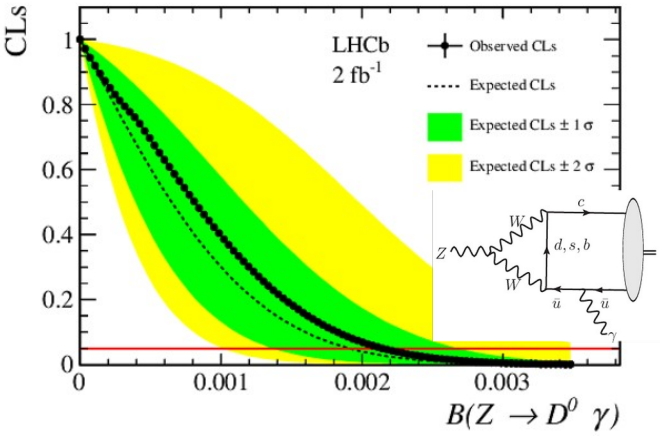


SMP-22-016



LHCb-PAPER-2022-033





Dibosons

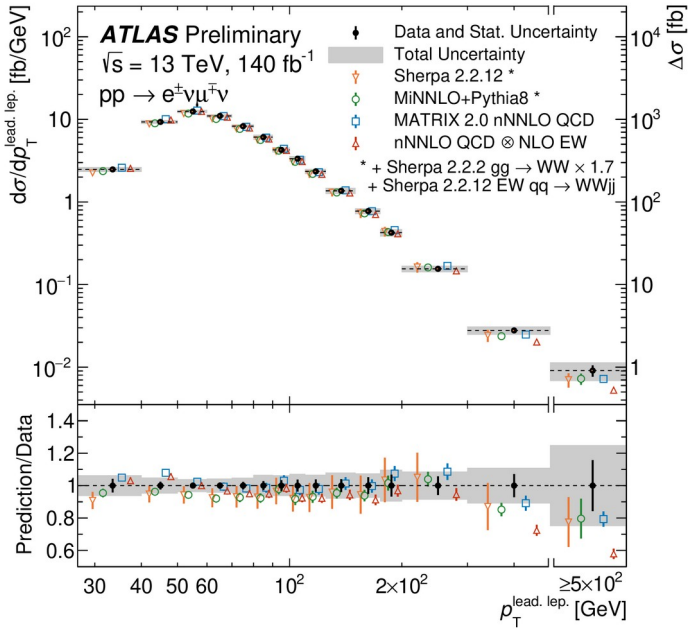
ATLAS: ATLAS-CONF-2023-012

CMS: Phys. Rev. D 102 (2020) 092001

SMP-21-013

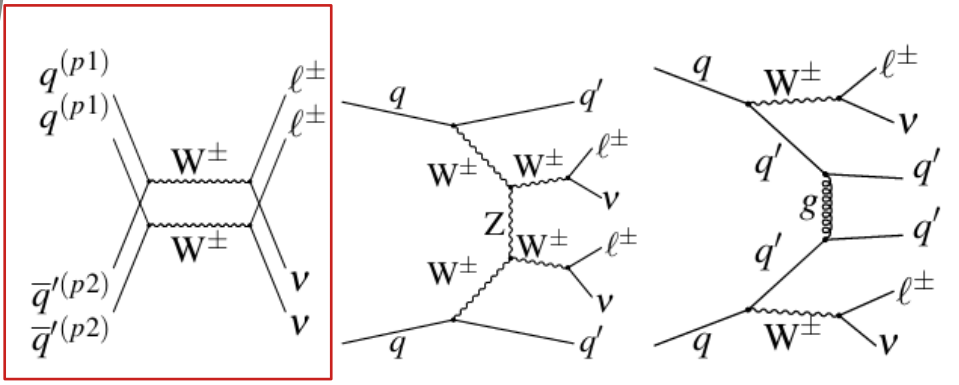
WW Measurements

- Test of pertubative QCD/EW
- Background to Higgs searches
- 12 unfolded distributions

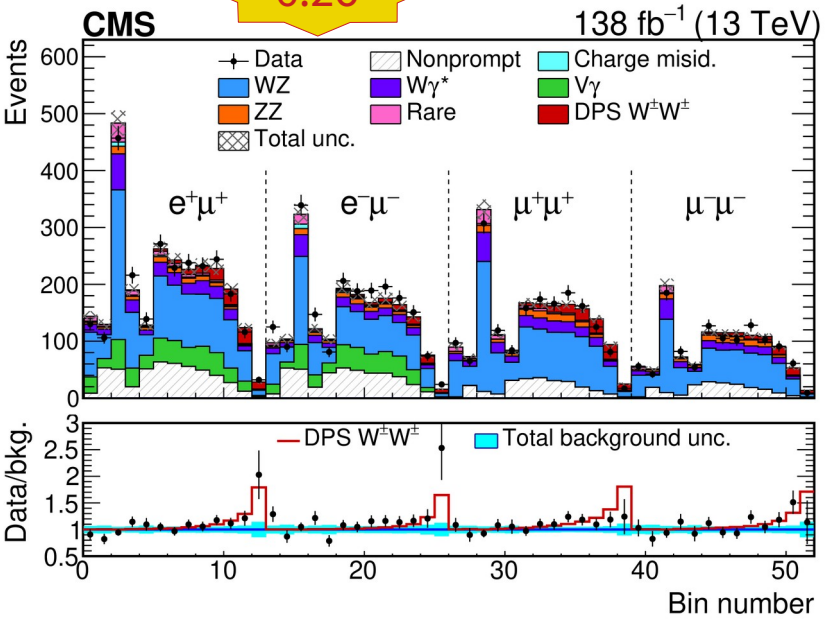


- Also measurements of ZZ/WZ

Double Parton Scattering



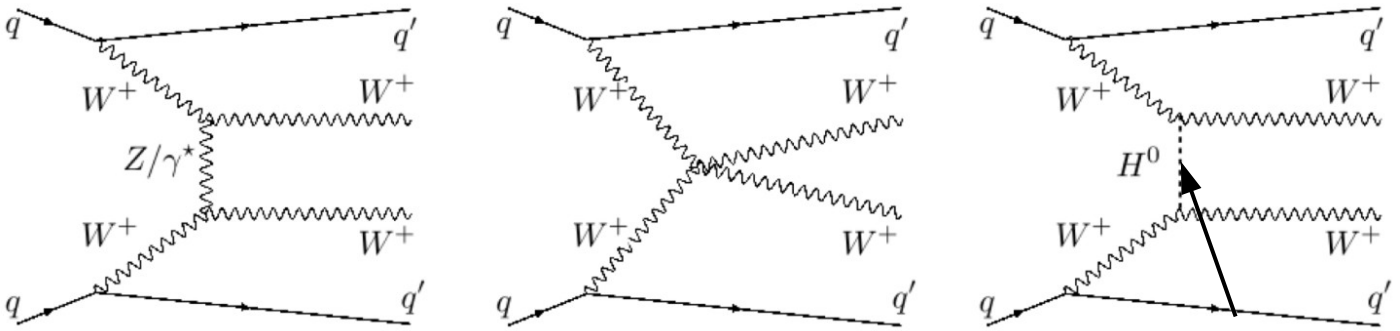
6.2σ



Vector Boson Scaterring

Danning Liu
Wednesday

Rare process sensitive to Beyond the Standard Model physics



Universality violated if SM behavior slightly off.

- Characterized with two forward jets
- Analyses target leptonic decays of V's
- Multiple VV combinations used in aQGC* fits

Process	ATLAS	CMS
ZZjj	5.7σ @ 139 ifb	4.0σ @ 137 ifb
WZjj	5.3σ @ 36.1 ifb	6.8σ @ 137 ifb
SS WWjj	6.5σ @ 36.1 ifb	5.5σ @ 35.9 ifb
OS WWjj		5.6σ @ 138 ifb
Zyjj	10σ @ 139 ifb	3.9σ @ 35.9 ifb
Wyjj		5.3σ @ 35.9 ifb

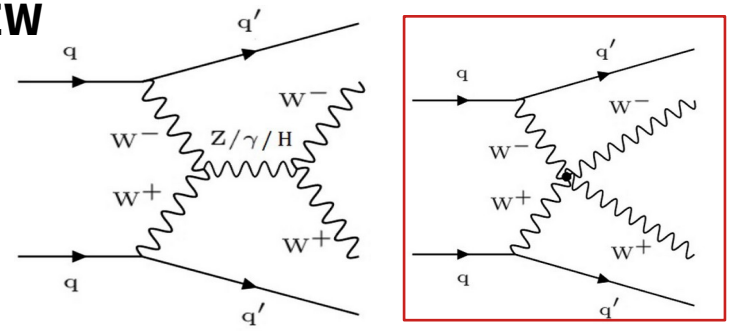
* anomalic quartic gauge coupling

Observation of Opposite Sign WW

SMP-21-001

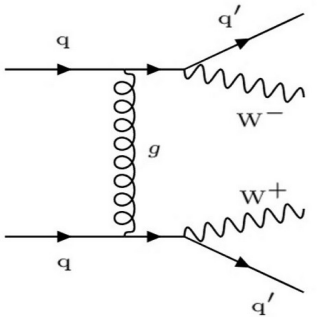
- Main backgrounds: Drell-Yall and ttbar
- Negligible interference between QCD/EW

EW

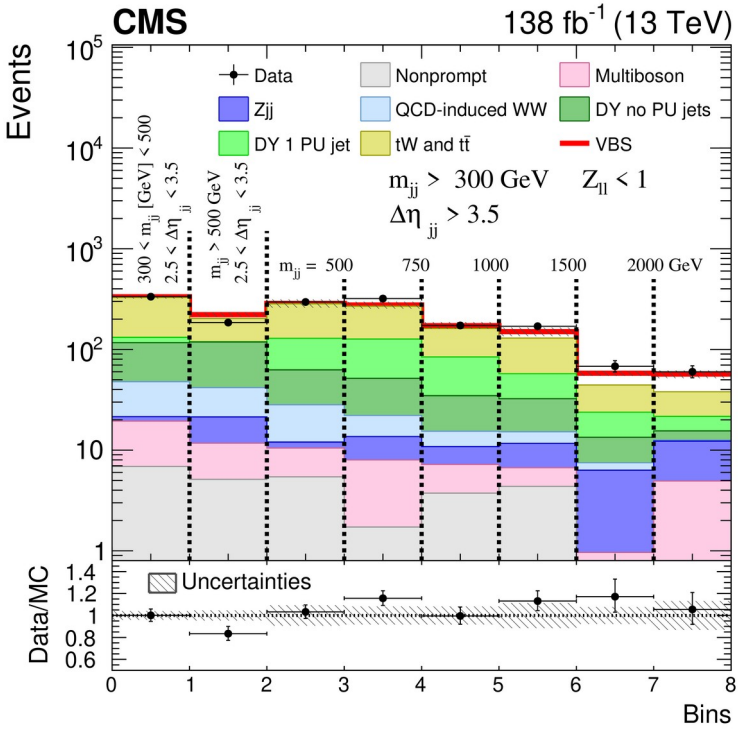


5.6σ

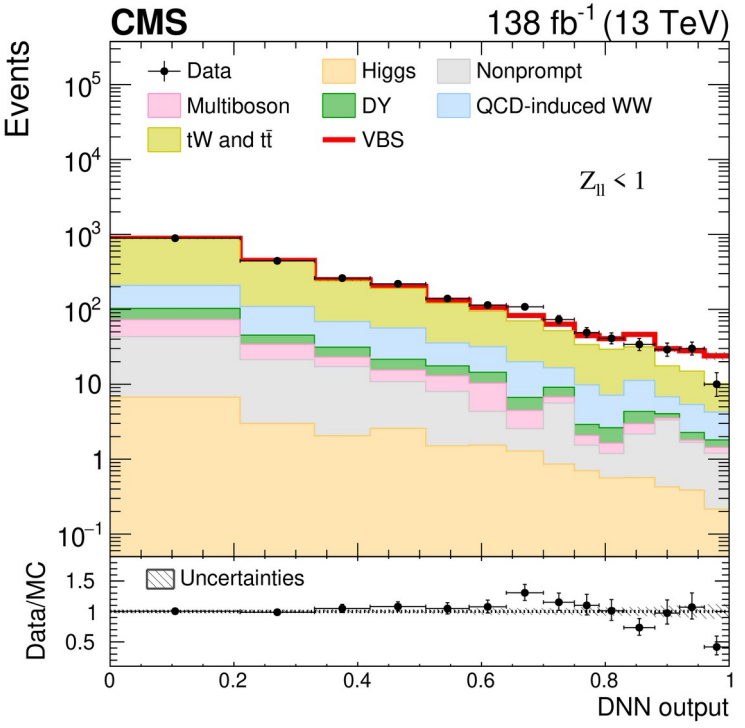
QCD



ee/μμ based on m_{jj} / Z_{ll}



eμ based on a DNN



Fiducial Cross-Section

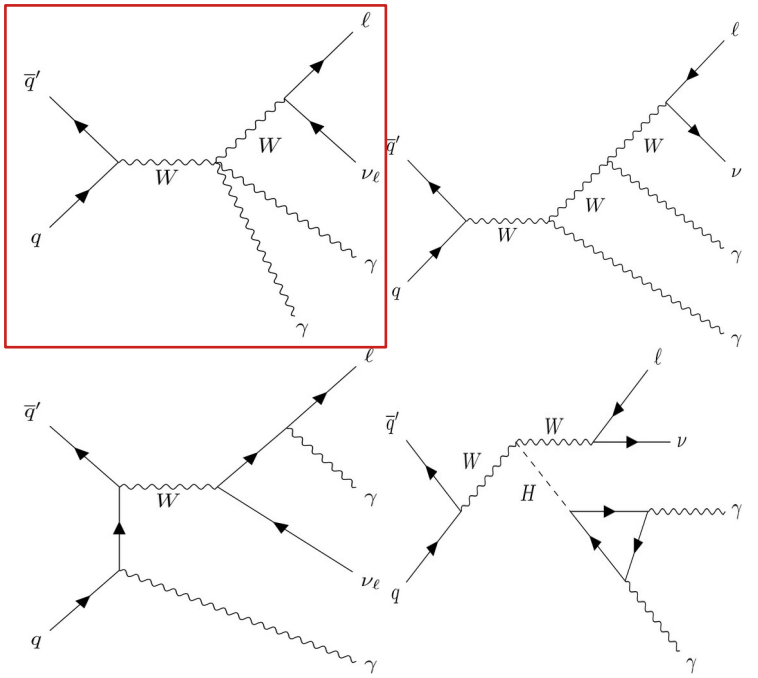
CMS: 10.2 ± 2.0 fb

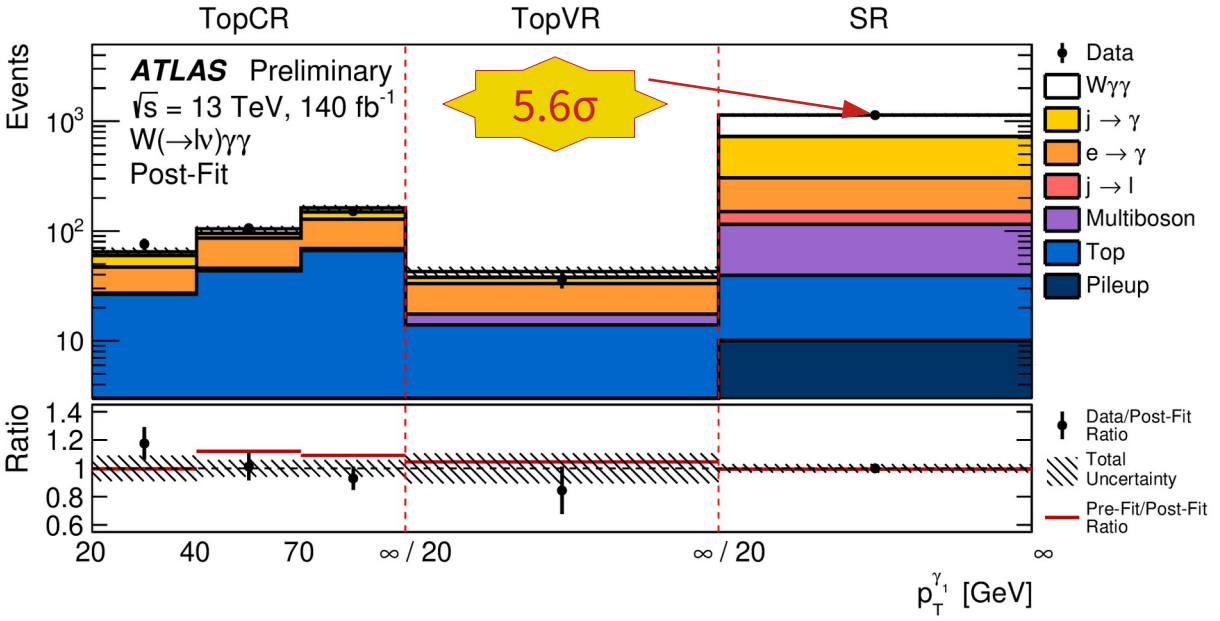
Theory (LO): 9.1 ± 0.6 fb

Observation of Wγγ

ATLAS-CONF-2023-005

- Mix of triple and quartic gauge couplings
- Soon background to to H→γγ
- Main background from fake photons
- Complimentary to CMS Wγ (SMP-21-011)



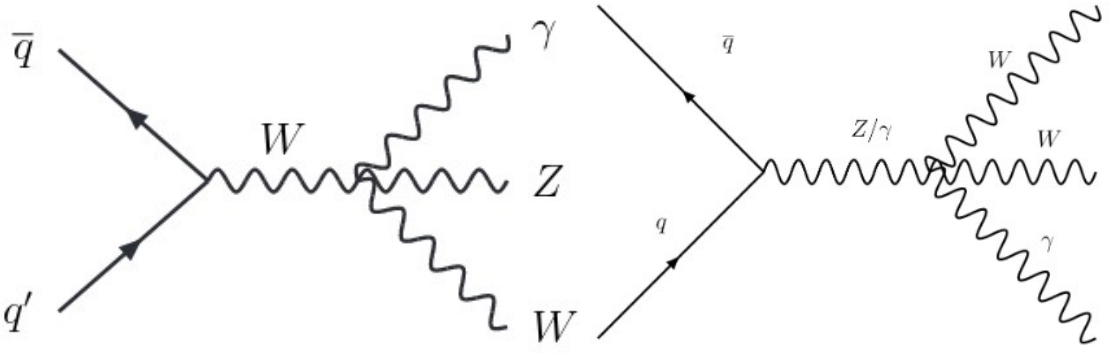


Fiducial Cross-Section

ATLAS: $12.2^{+2.1}_{-2.0}$ fb

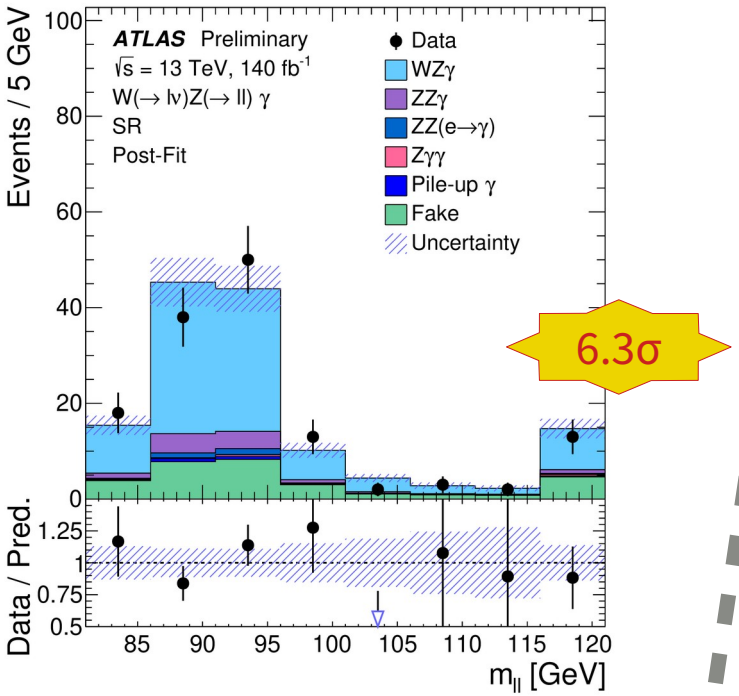
Consistent with SM predictions

Triboson



Another access to the QGC

ATLAS WZγ: ATLAS-CONF-2023-014

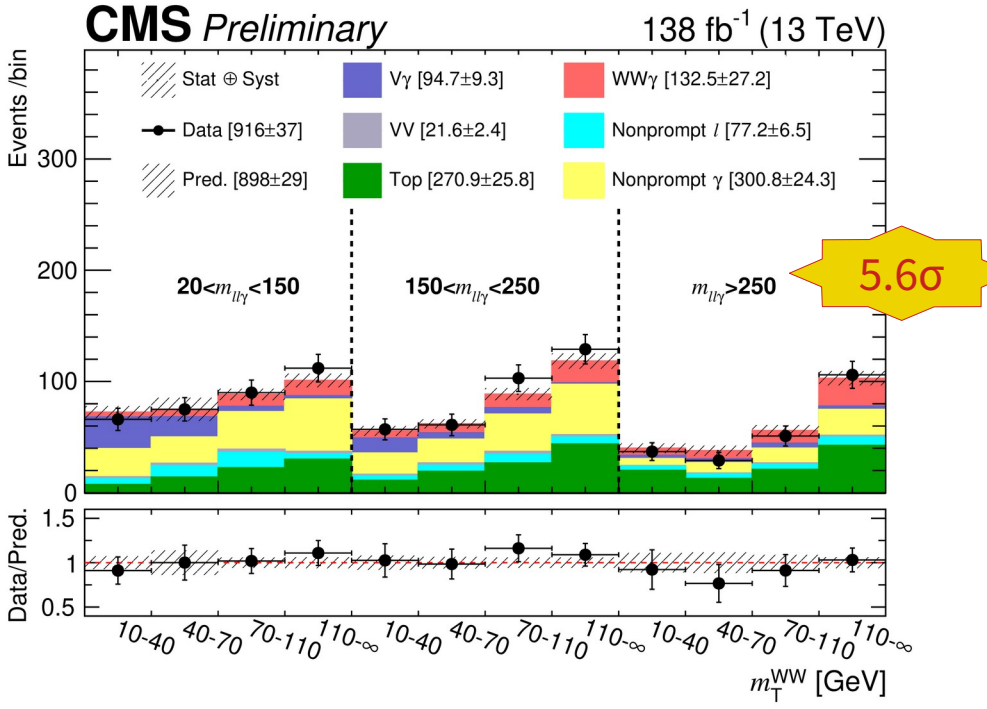


Fiducial Cross-Section

ATLAS: 2.01 ±0.33 fb

Theory: 1.05 ±0.06 fb

CMS WWγ: SMP-22-006



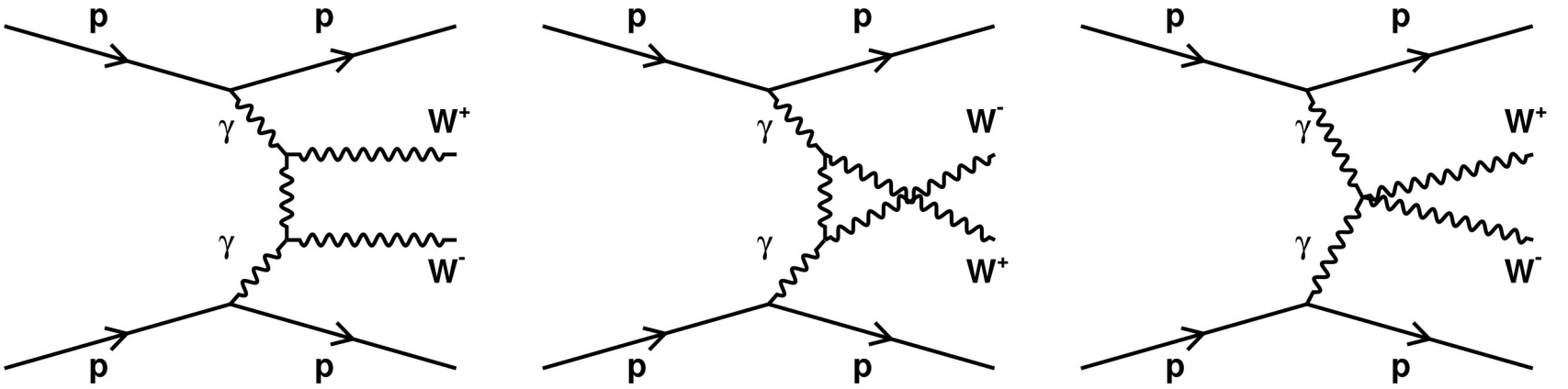
Fiducial Cross-Section

CMS: 6.0 ±1.7 fb

Theory: 4.61 ±0.34 fb

Photon Induced Processes: A Special Case of VBS

“Collision” of photons radiated off incoming protons.

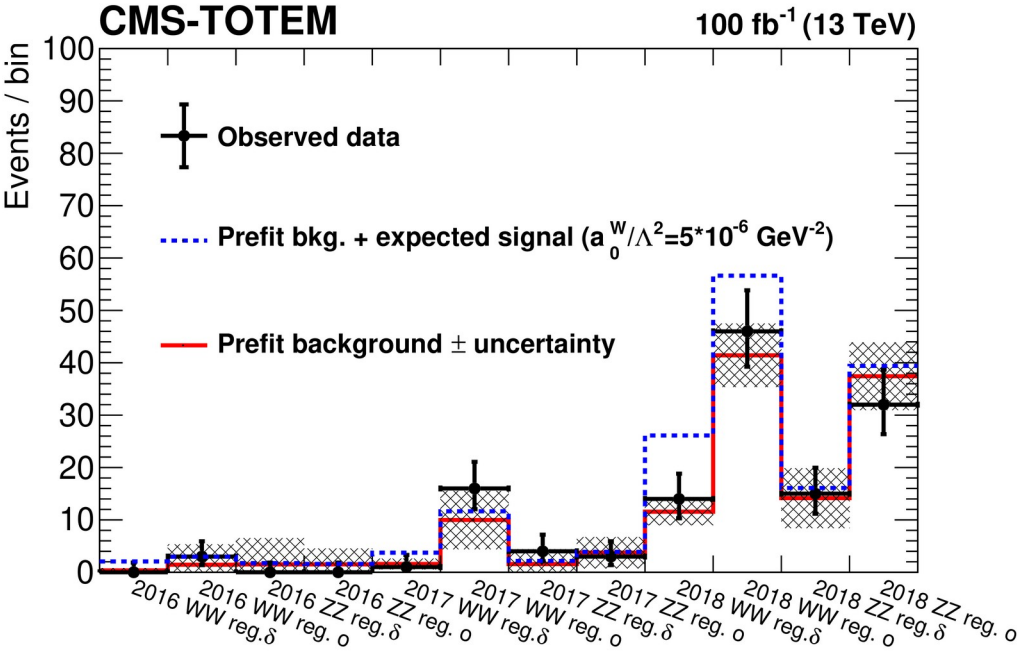


- **Clean experimental signature**
  - Protons (often) remain intact and slightly off beam.
  - Very little activity in detector (no QCD in process!)

Photon Induced VV: CMS

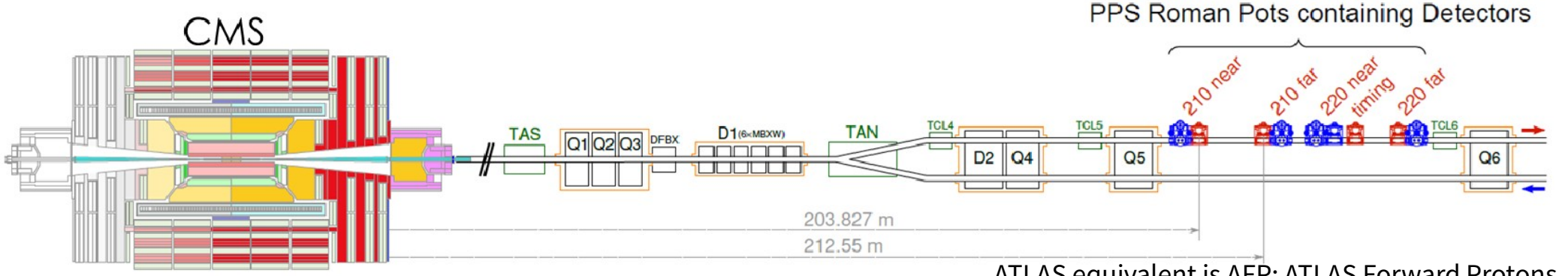
SMP-21-014

- **Reconstruct protons using PPS**
- **Hadronic decay of V's**
  - High energy regime sensitive to BSM.
- **Targets both γγWW and γγZZ**
  - γγZZ not at tree-level in SM.



No excess over background. Limits are set on aQGC.

PPS: Precision Proton Spectrometer is a forward detector to catch scattered protons.

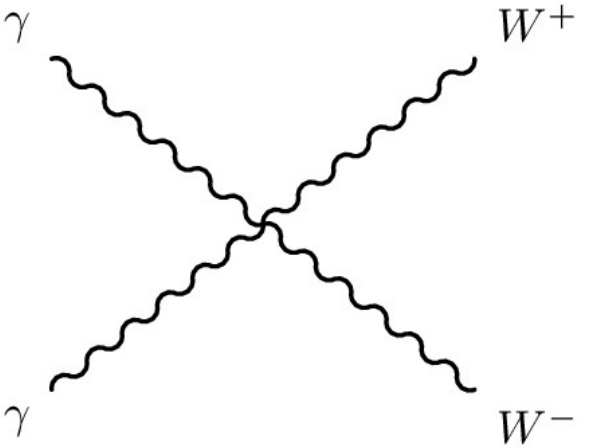


ATLAS equivalent is AFP: ATLAS Forward Protons

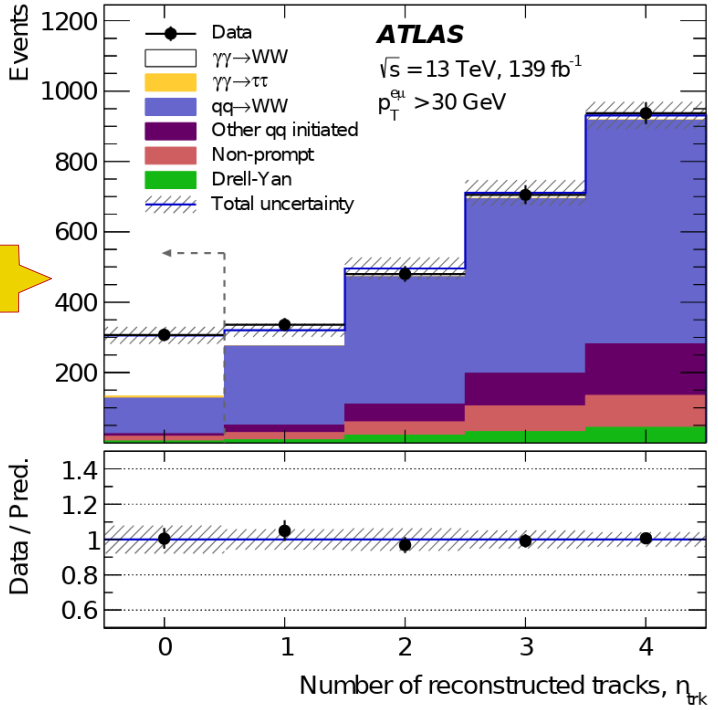
Photon Induced WW: ATLAS

Phys. Lett. B 816 (2021) 136190

- **Leptonic decay of W's**
  - Targets observation of process
- **Identify photon-induced by lack of activity**
  - No additional tracks (p_T>500 MeV) around vertex



8.4σ

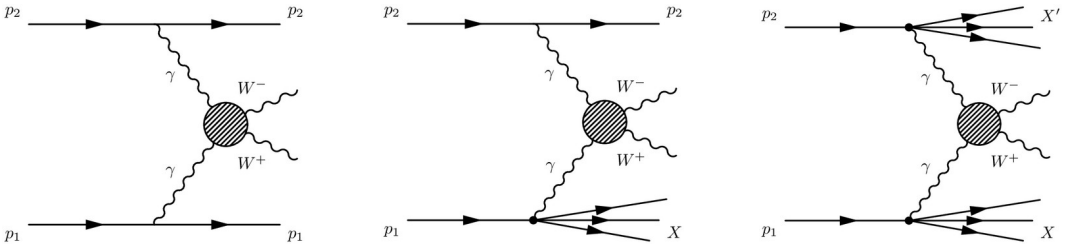


Fiducial Cross-Section

ATLAS: 3.13 ±0.31 (stat.) ±0.28 (syst) fb

Theory: 2.37 ±0.27 fb

Includes corrections for disassociated protons.



Effective Field Theory Fits to QGC

- **EFT's are used to interpret results**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j + \ldots$$

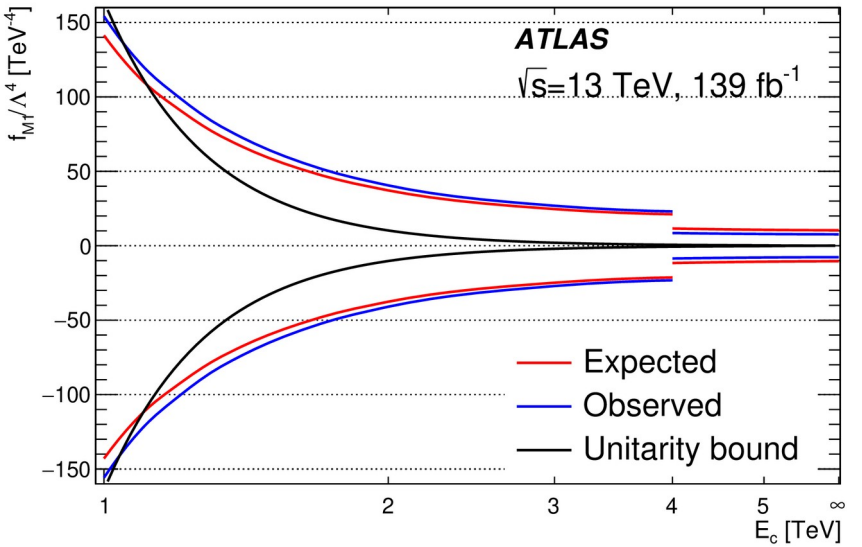
  - $O_S \rightarrow$ scalar, $O_M \rightarrow$ scalar/tensor, $O_T \rightarrow$ tensor

- **Clipping used to respect unitary**

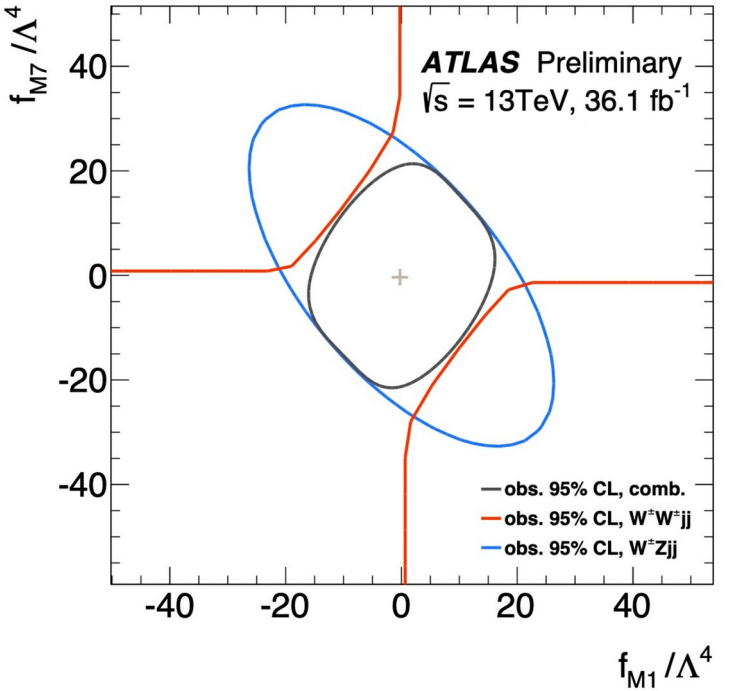
CMS Wγ (SMP-21-011)

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

Zγjj (STDM-2018-59)



WZjj + ssWWjj (ATL-PHYS-PUB-2023-002)



Higgs Boson

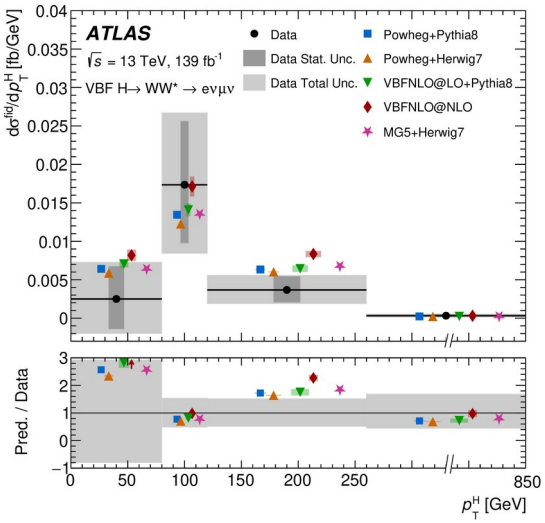
https://www.particlezoo.net

Production Cross-Sections

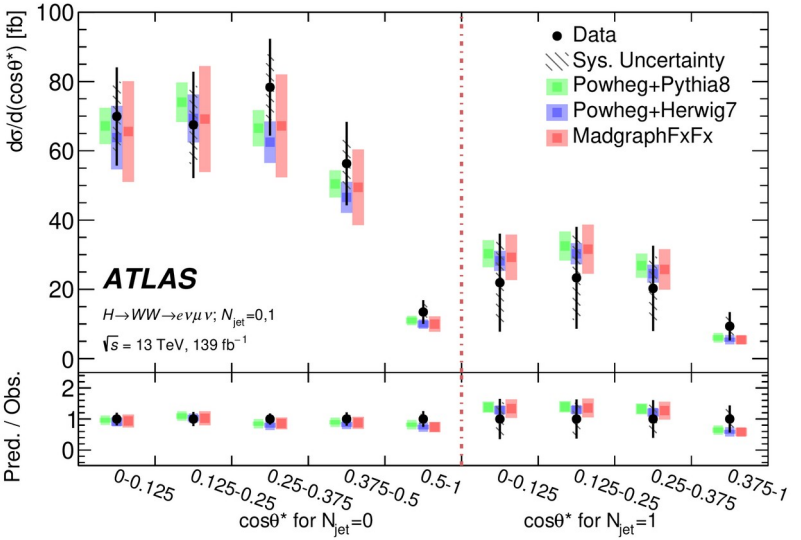
Benedetta Camaiani
Wednesday

Plenty of statistics for differential measurements.

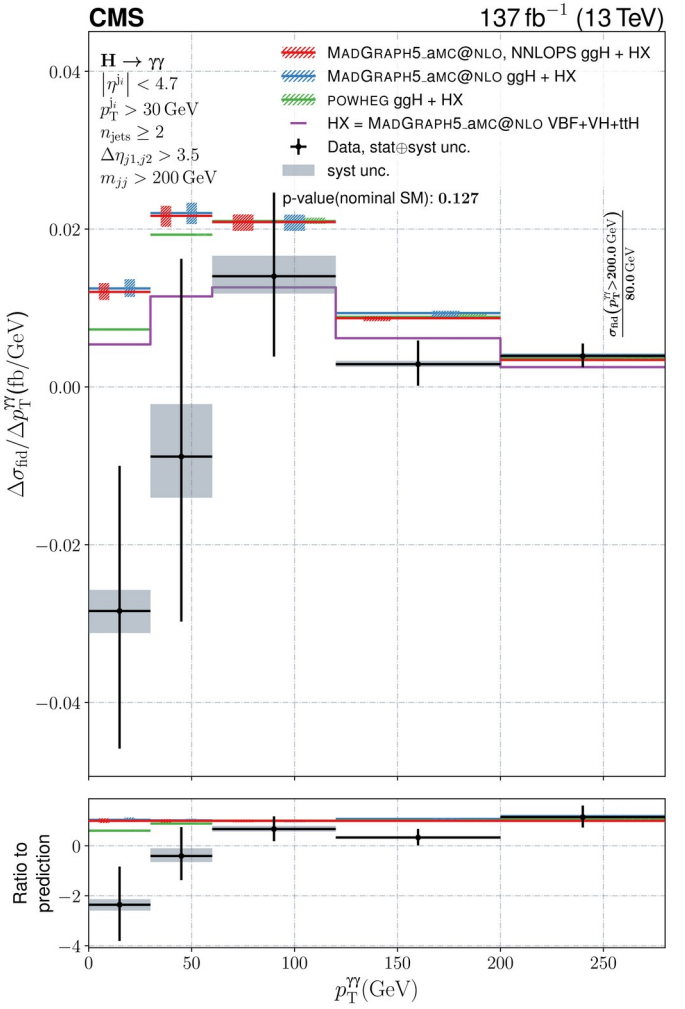
HIGG-2020-25



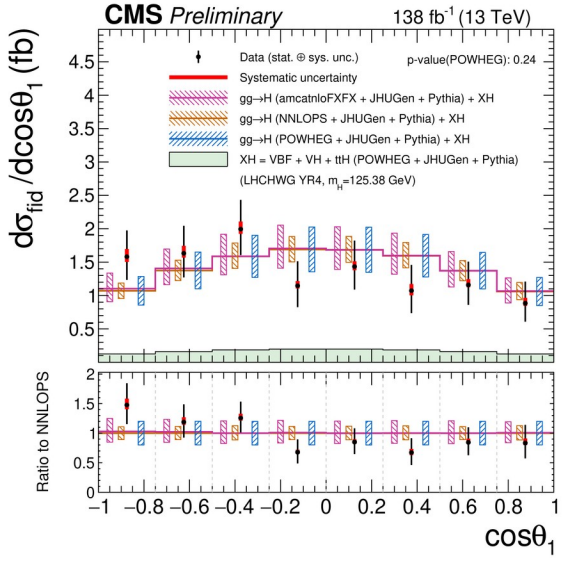
HIGG-2018-49



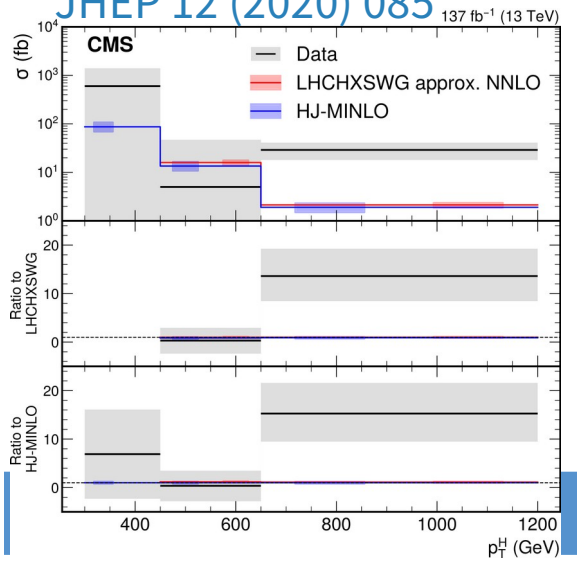
HIG-19-016



HIG-21-009



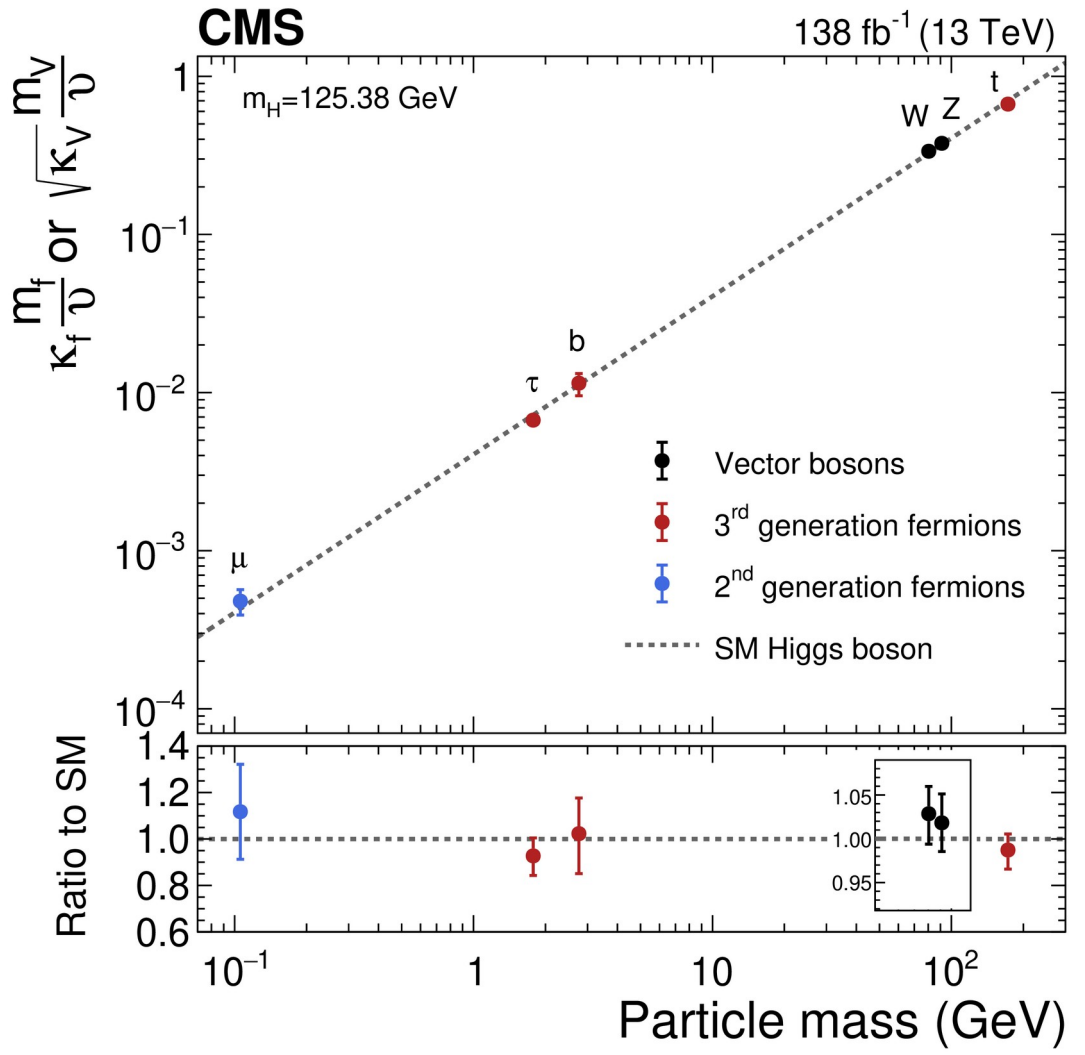
JHEP 12 (2020) 085



Couplings

Aliya Nigamova
Monday

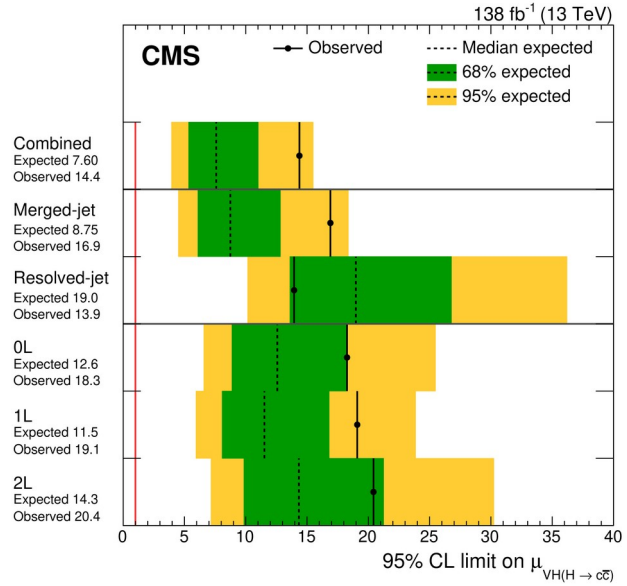
Starting to measure couplings to second generation fermions.



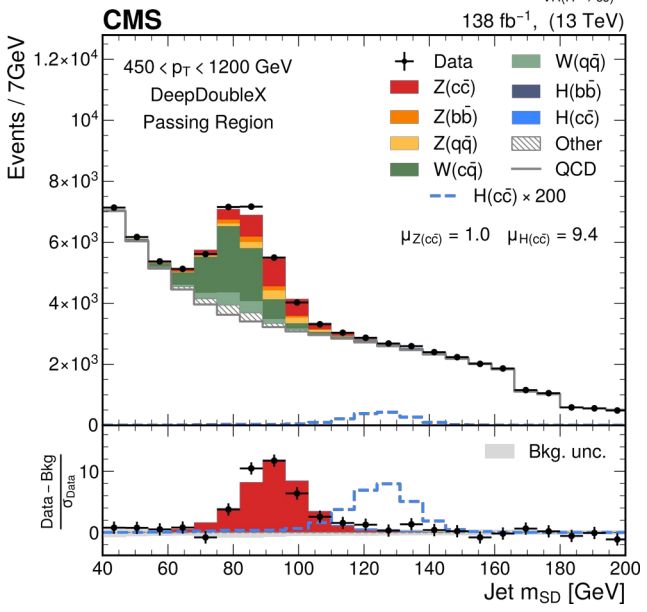
Next Milestone: H→cc

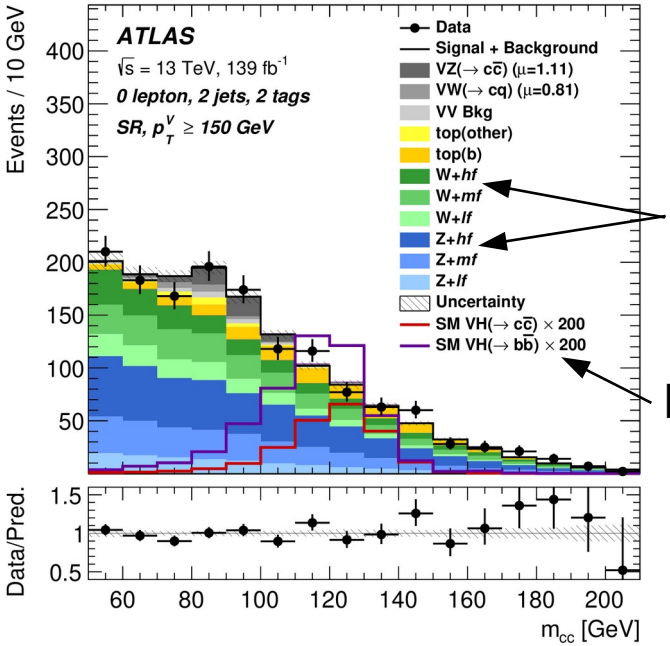
Use of boosted channels in CMS.

VH: HIG-21-008



ggF: HIG-21-012

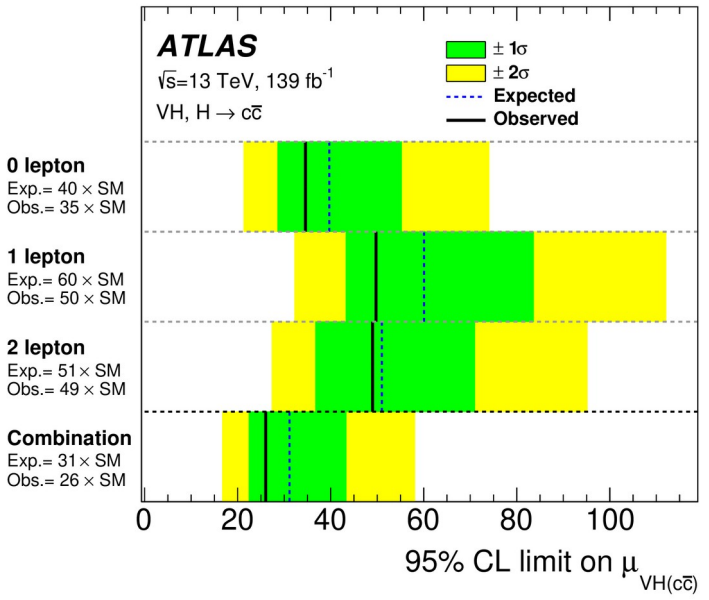




Helped by W+c measurements

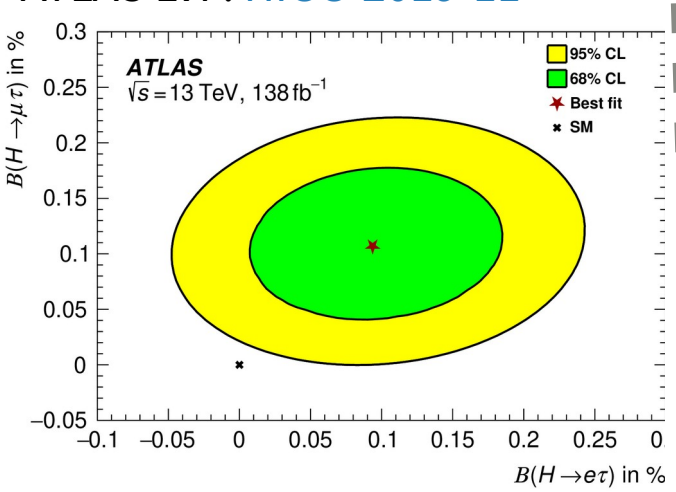
b vs c tagging

VH: Eur. Phys. J. C 82 (2022) 717

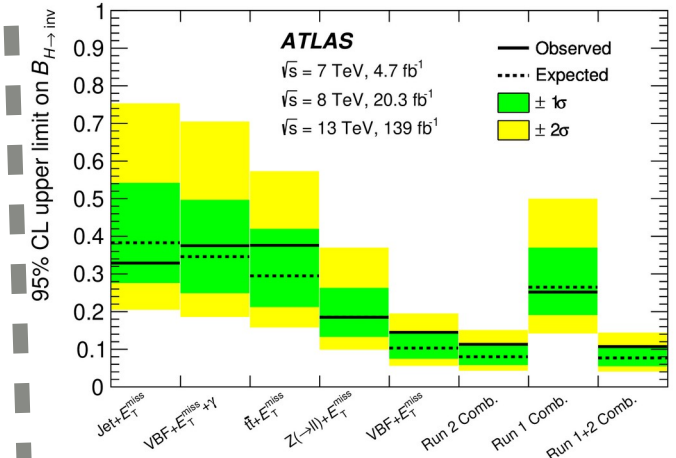


Rare Decays

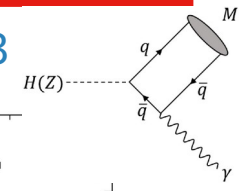
ATLAS LVF: HIGG-2019-11

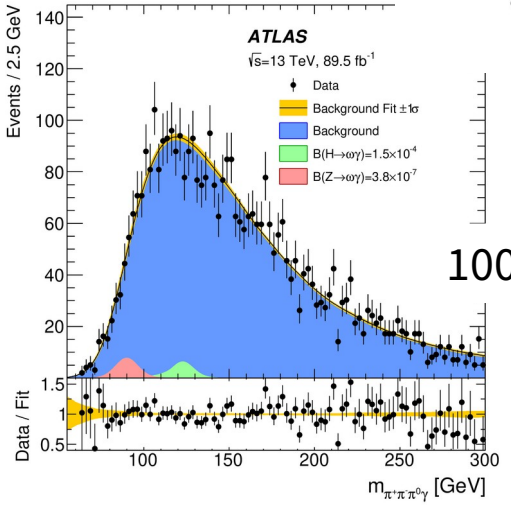


ATLAS H→inv: HIGG-2021-05



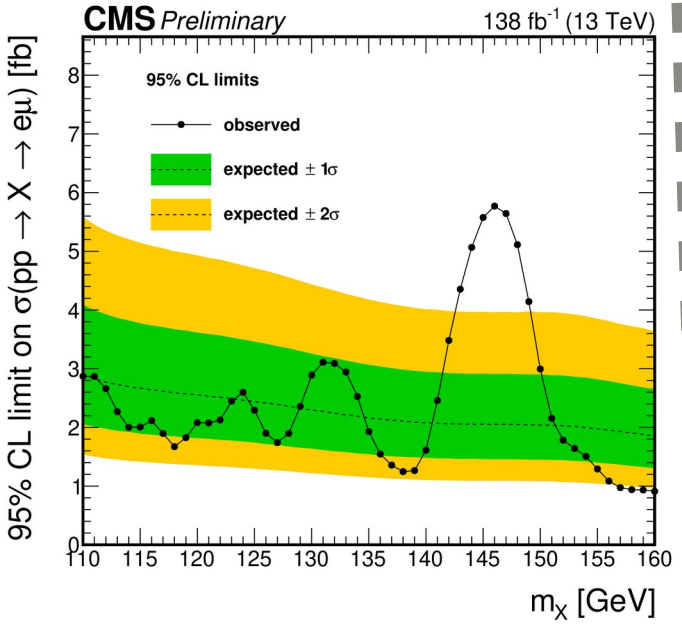
ATLAS H→ωγ: HDBS-2019-33



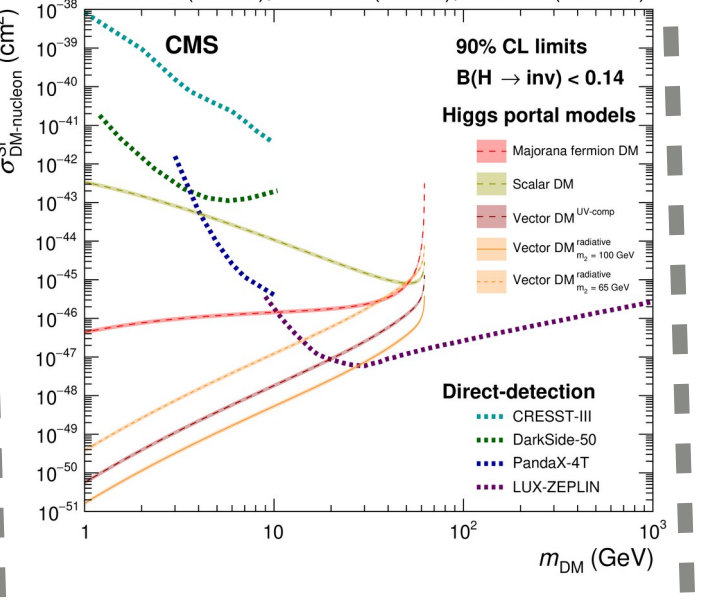


100x SM

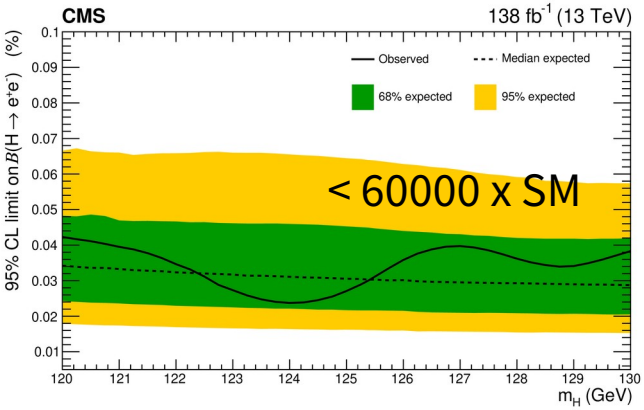
CMS LVF: HIG-22-002



CMS H→inv: HIG-21-007



CMS H→ee: HIG-21-015



< 60000 x SM

Higgs Width

Stylianos Angelidakis
Wednesday

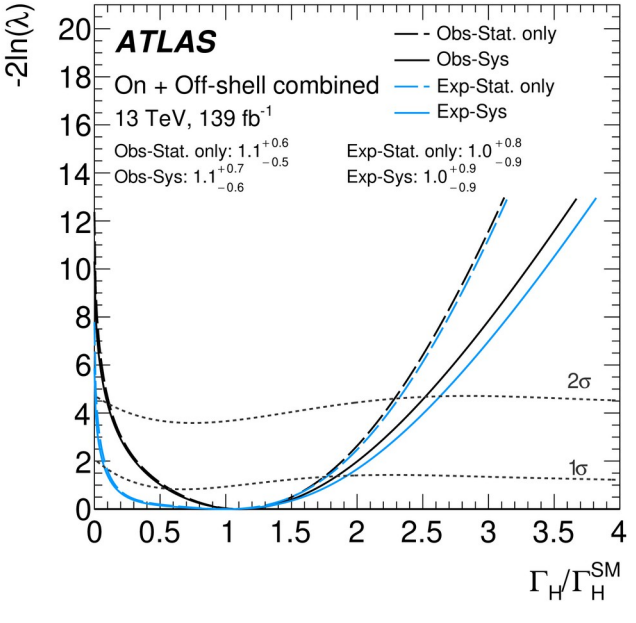
ATLAS: HIGG-2018-32
CMS: Nat. Phys. 18 (2022) 1329

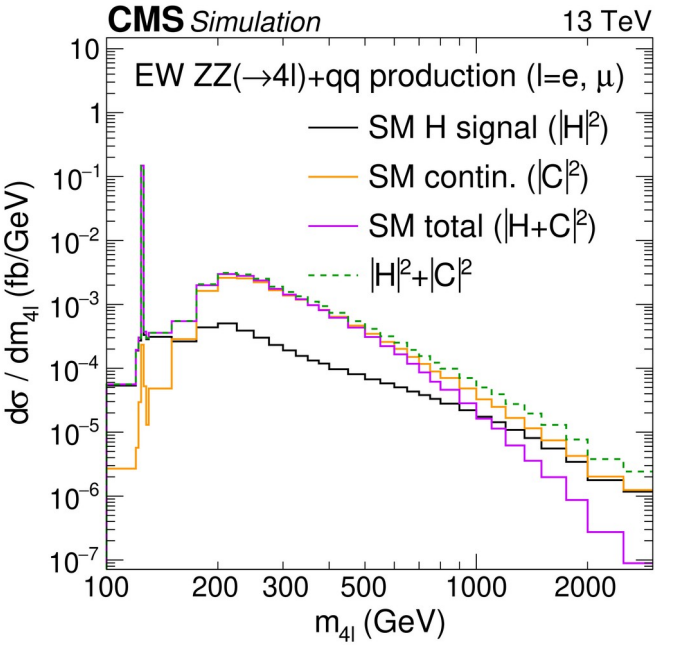
- **Predicted by SM as 4.1 MeV**
  - Don't have the detector resolution
- **Indirect measurement possible**

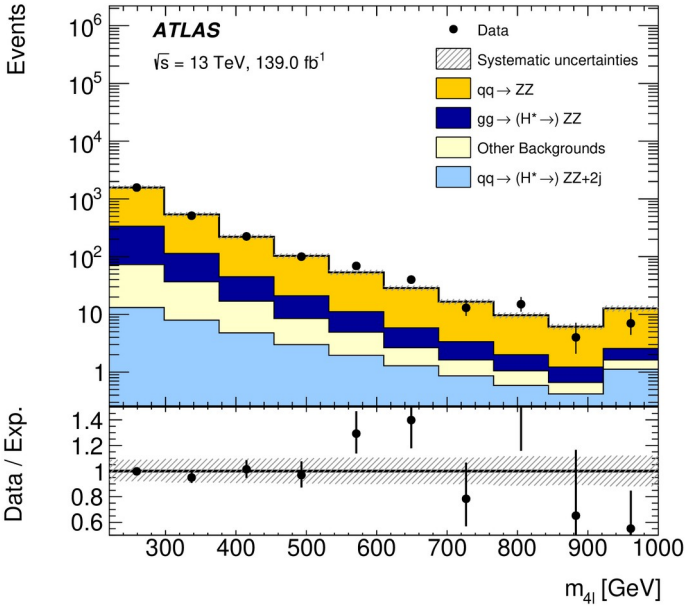
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m^2_{ZZ}}$$

- **Off-shell H→ZZ measured via deficit in ZZ**

ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV







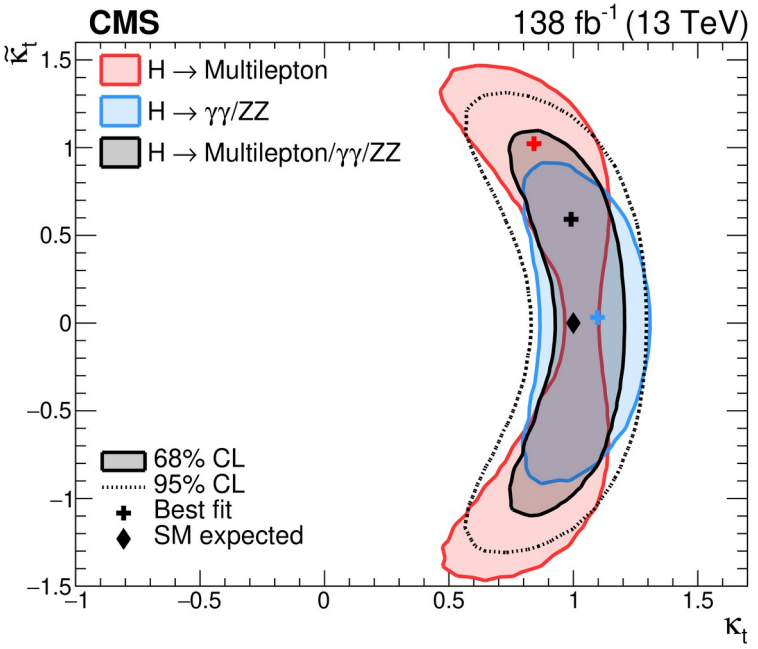
CP Violation

Stylianos Angelidakis
Wednesday

w/ fermions

- Via ttH and tHW

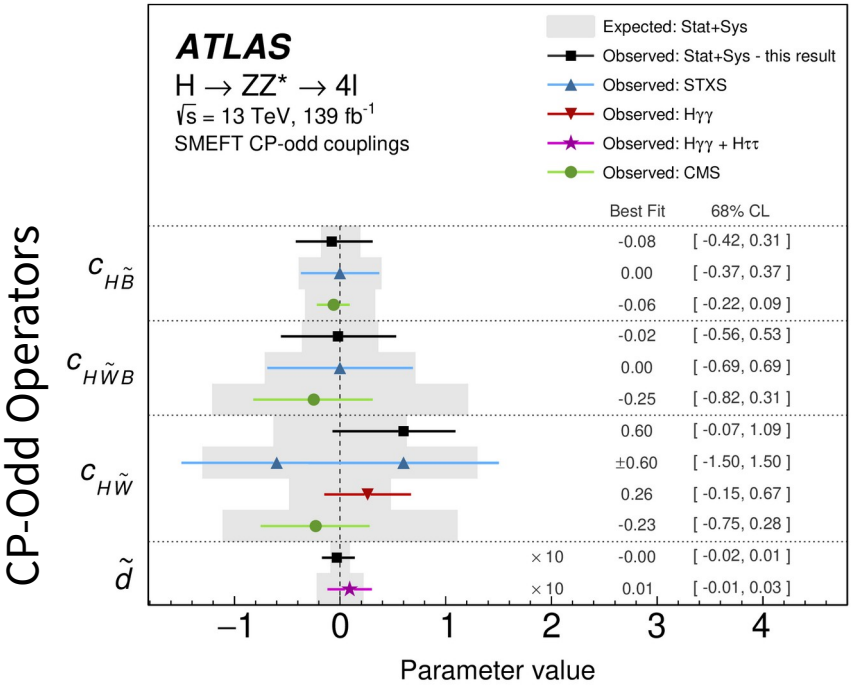
$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$



ATLAS: HIGG-2020-03
CMS: HIG-21-006

w/ bosons

- Interpreted via SMEFT operators



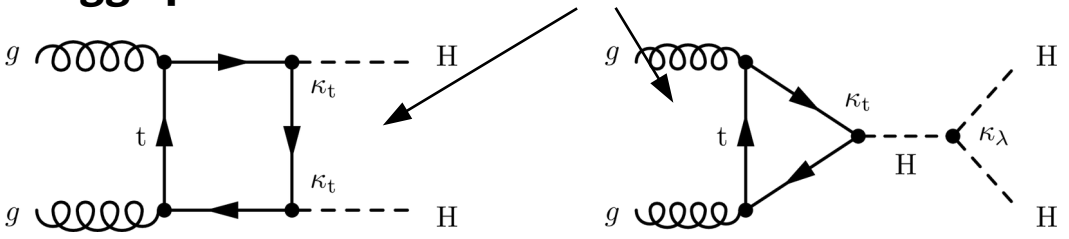
ATLAS: HIGG-2018-30
CMS: HIG-20-007

Self-Coupling

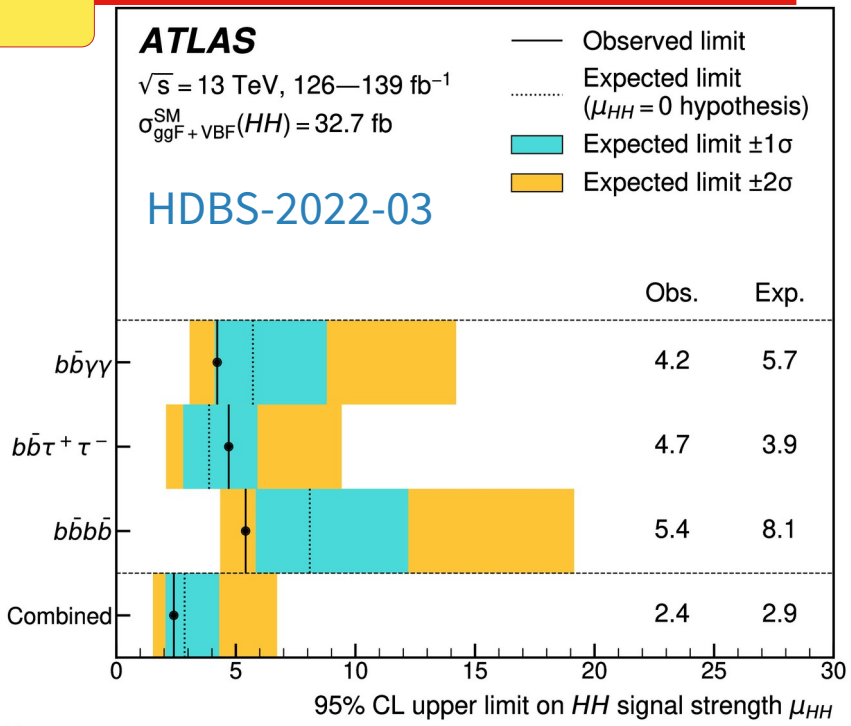
Angela Maria Burger
Wednesday

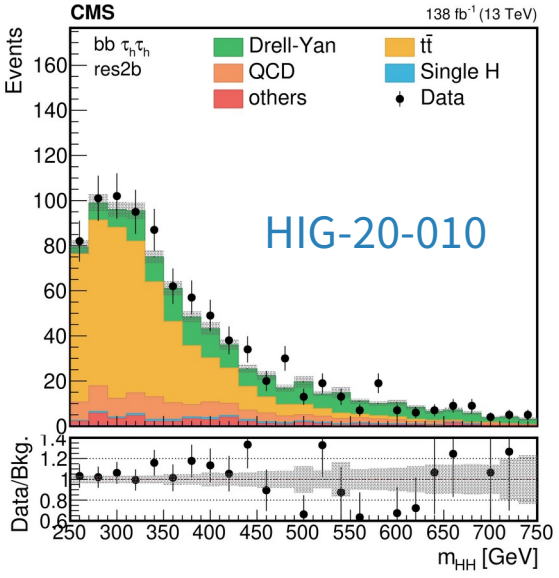
ggF production

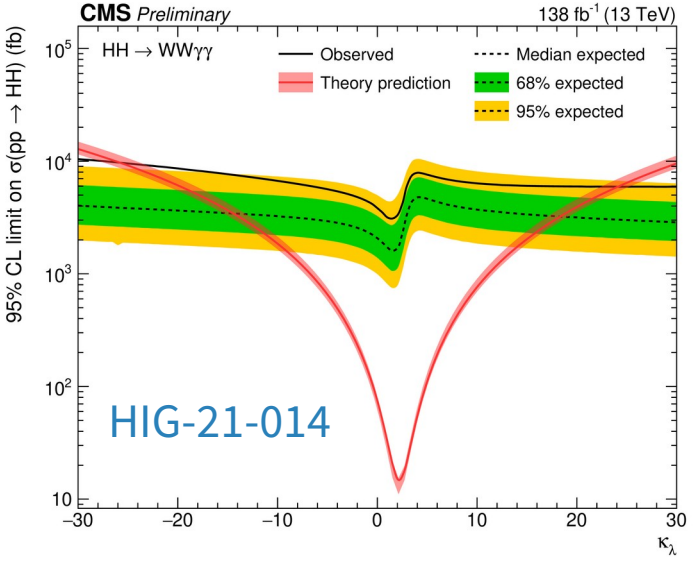
big negative interference

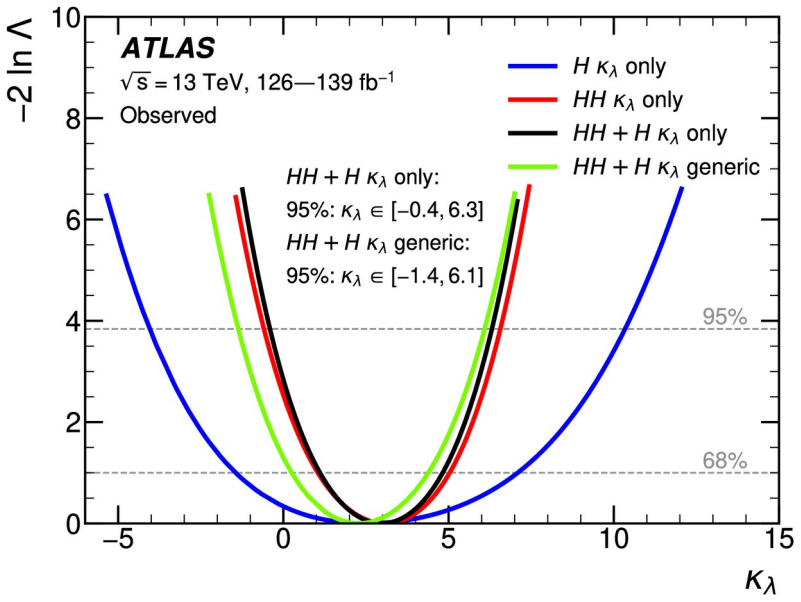


Also VBF production and single Higgs important









Conclusion

Many measurements from LHC targeting the EW sector.

- **Vector bosons**
  - Precision measurements of W/Z and VV production
  - Starting to observe rare processes: VBS, photon-induced
- **Higgs boson**
  - Forming picture of the Higgs as very SM-like
  - Self-coupling will be the next big measurement

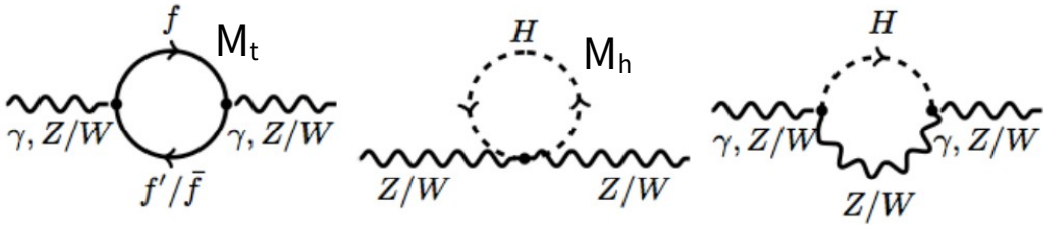
BACKUP

Mass of the W Boson

Predicted in SM to 7 MeV

Tree Level: $M_W = M_Z / \cos\theta_W$

Corrections:



Modified via BSM particles