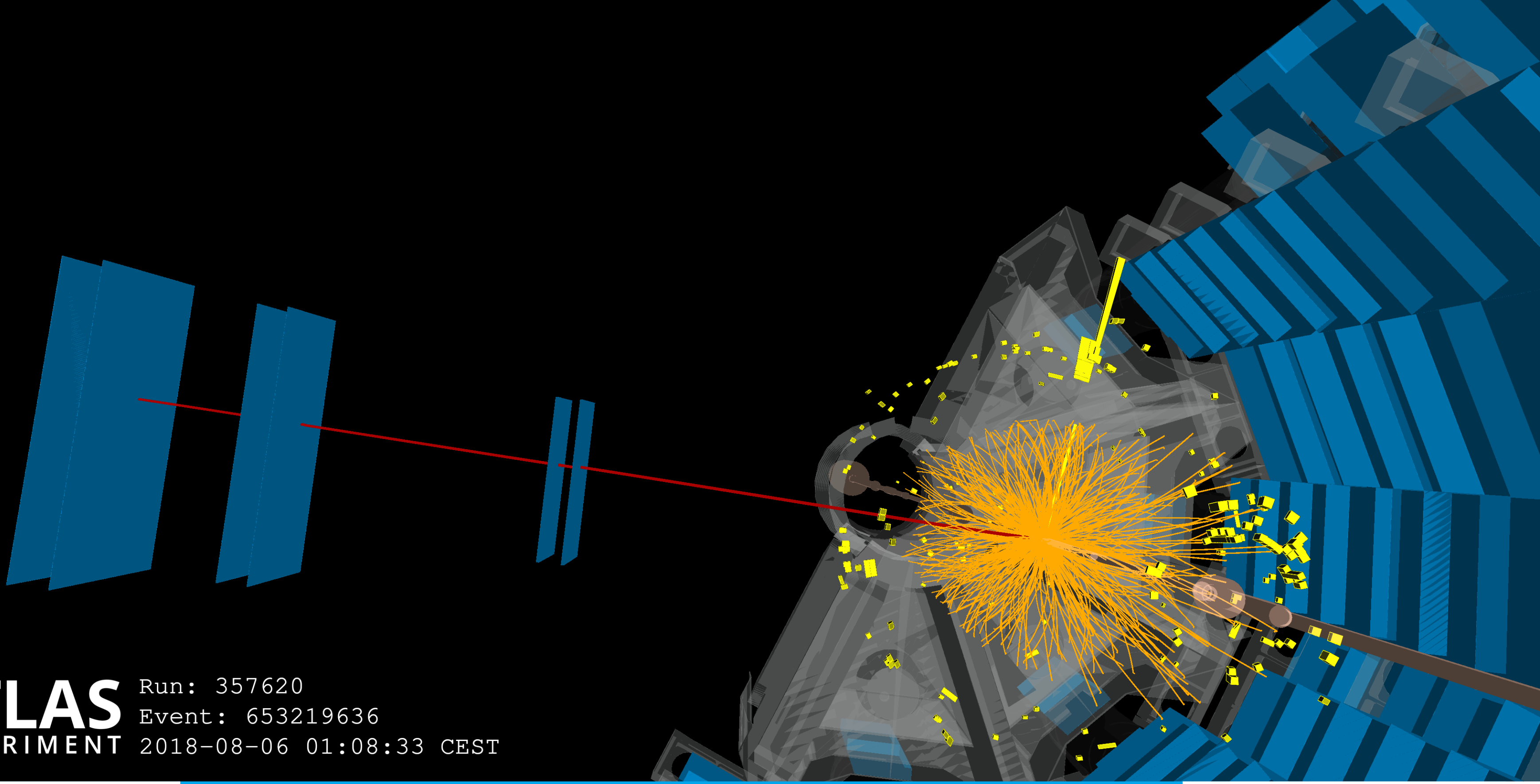
Probing the electroweak sector at the LHC



Kristin Lohwasser
University of Sheffield

Seminar, Zürich, April 4th 2022

The
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Of
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The Standard Model of Particle Physics

- Mathematical formulation finalized in the mid-1970s – and since then confirmed though observations
  – last in line: Higgs Boson (2012)

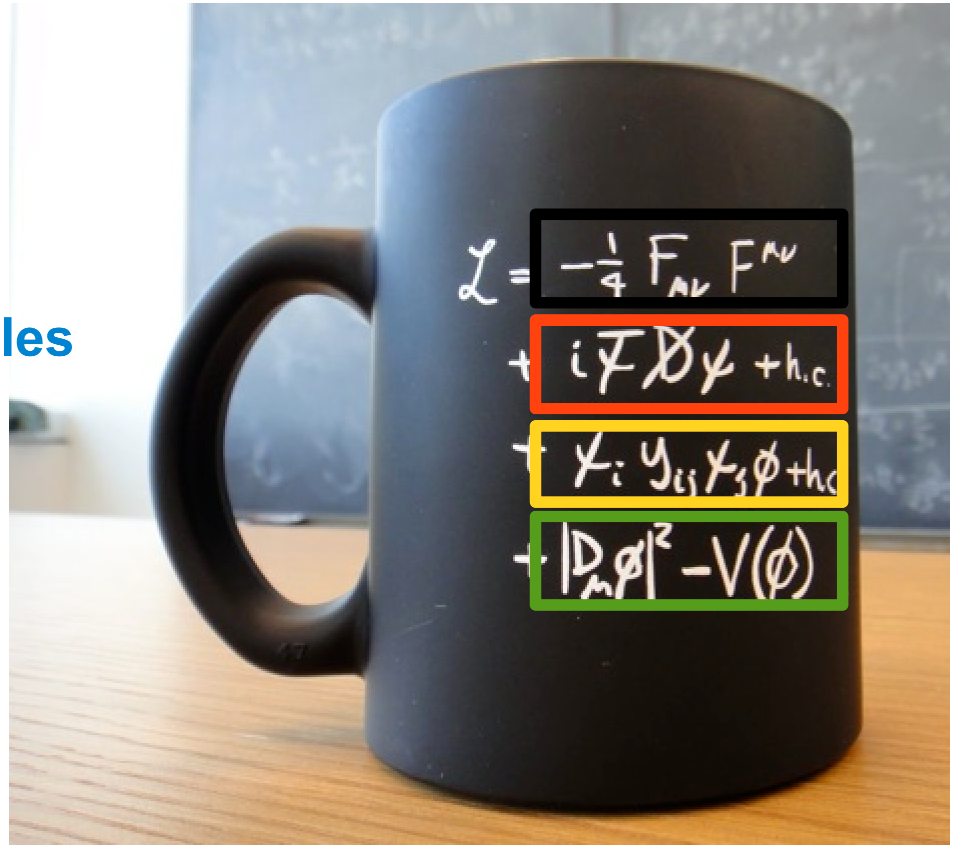
- Correctly describes

  propagation of interaction particles (spin-1 bosons)

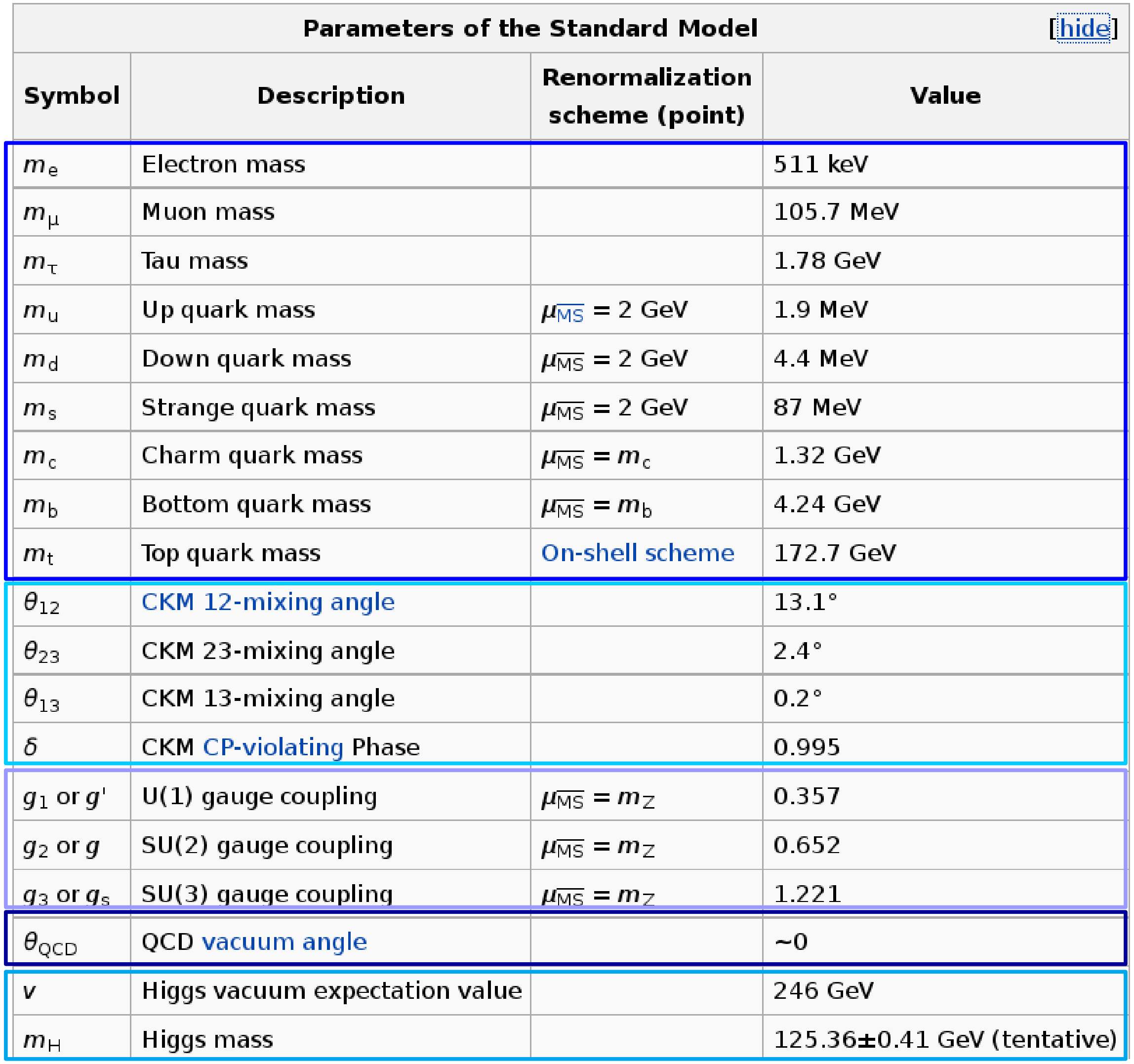
  interactions of matter particles (spin-1/2 fermions)

  masses of matter particles

  masses of interaction particles
  + Higgs self-interactions



The Standard Model: Free parameters



Parameters of the Standard Model [hide]

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		125.36±0.41 GeV (tentative)

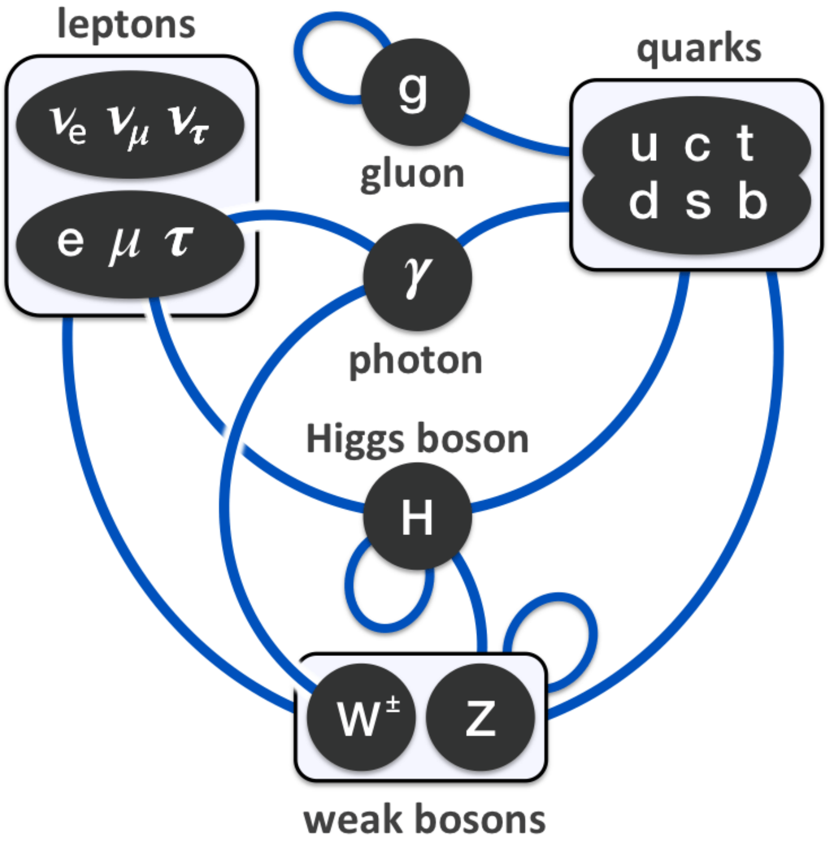
19 free parameters

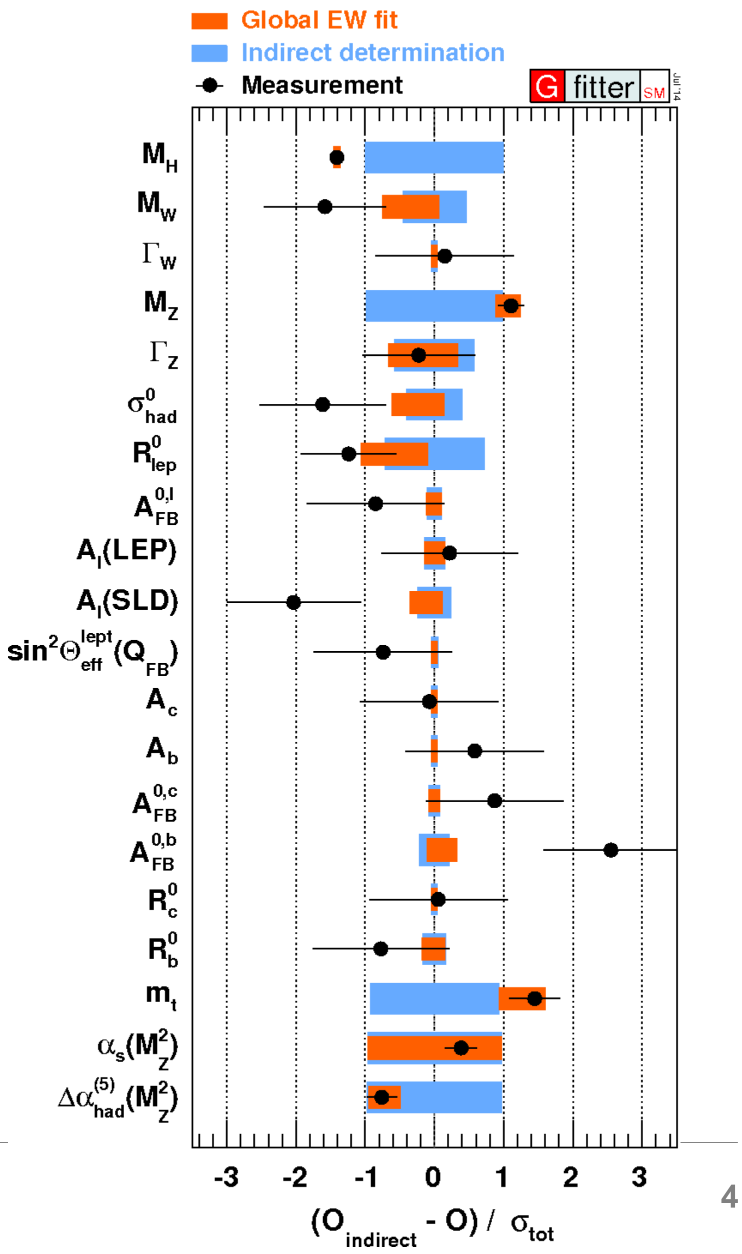
- particle masses
- CKM mixing angle (mass and electroweak eigenstates of quarks)
- Gauge couplings (strength of forces)
- Symmetry properties of QCD
- Parameters of electroweak symmetry breaking (Higgs mass and vaccum expection value)

The Standard Model: Extremely predictive

Once parameters are known, everything else is “fixed”

Extremely precise predictions allow for consistency tests of the SM





The Standard Model's biggest triumph

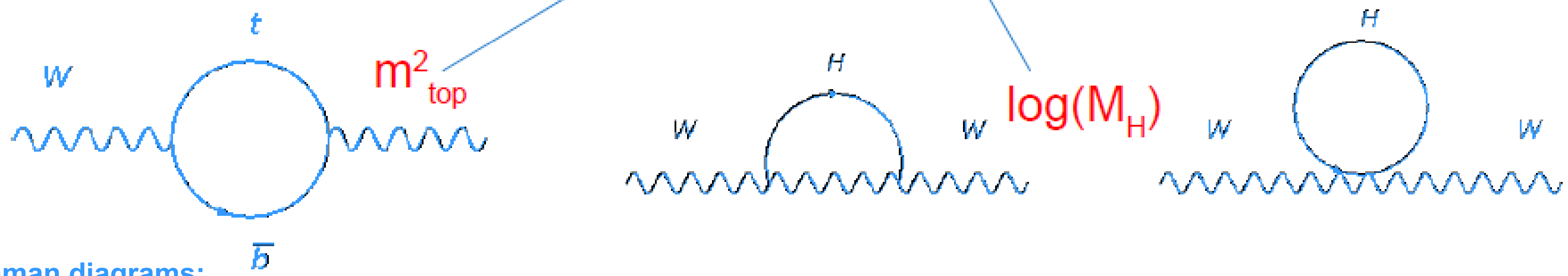
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

- Even before the direct discovery, indirect constraints on Higgs mass through connections with W and top

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \boxed{\Delta r}}}$$

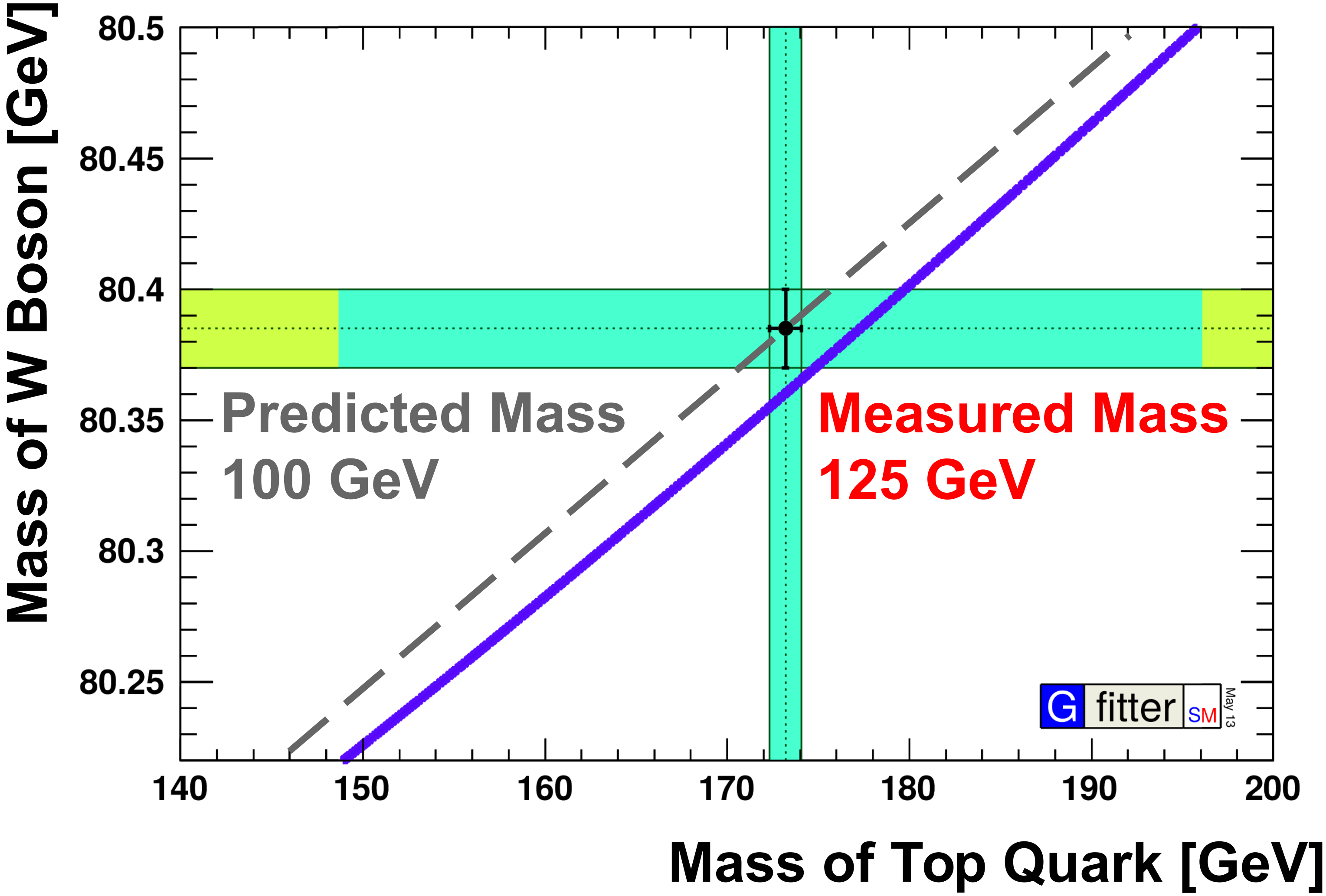
radiative corrections

$\Delta r \sim 3\ \%$



Feynman diagrams:
graphical representations of integrals
→ result: numerical prediction of probability of process

Indirect determination of Higgs boson mass



Tests of the Standard Model

- Standard Model measurements can be grouped into

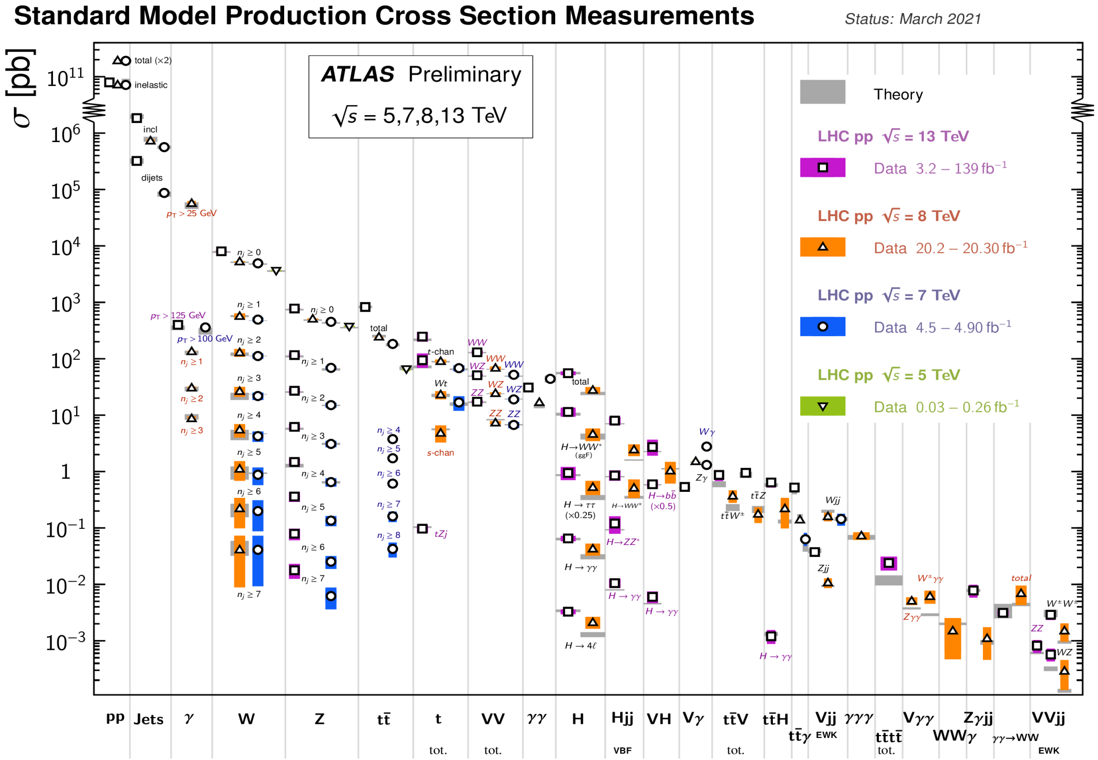
  – **High precision tests** (high statistics available)

  vs.

  – **High energy behaviour** as ultimate tests of the Standard Model

Consistent, complete but does not cover all we can observe in the universe

Effective field theory (EFT) provides framework for general SM tests



Large statistics
→ **High precision**

Rare processes
→ **High energy behaviour**

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-05/

- Apart from 19 free parameters: All interactions and other parameters within the Standard Model of particle physics are fixed
- Measuring SM processes is a stringent test of our understanding of nature → at high energies and statistics
- Will present a number of processes probing the the SM and finally towards a global fit to test the SM

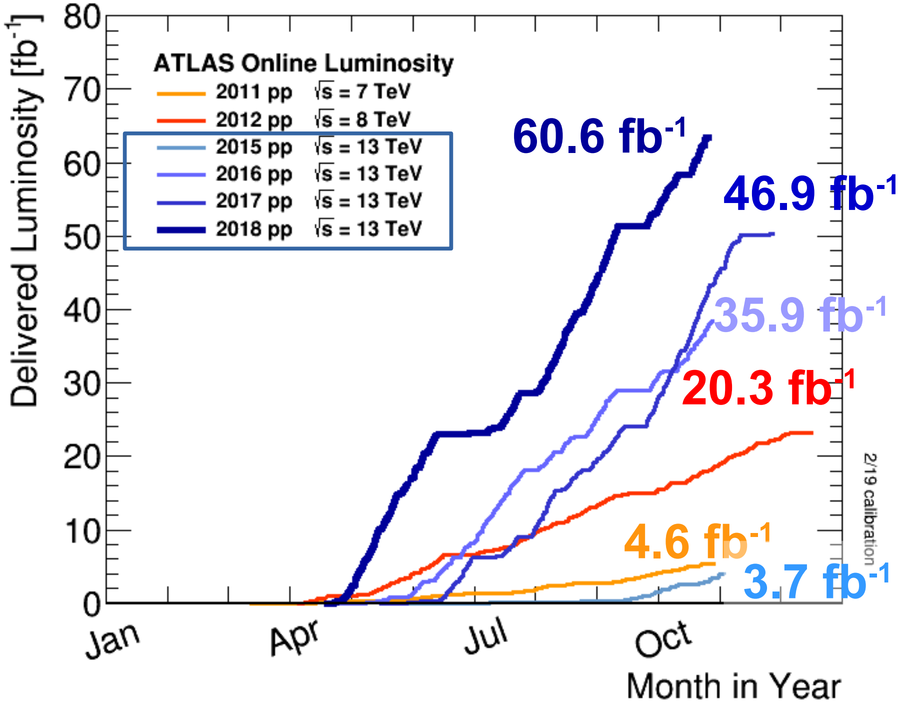
> Measurements with (two) W bosons via different production mechanisms

  - Vector boson scattering (quartic coupling)
  - Diboson production (triple coupling)
  - Photon-induced production

Using protons….

Data collected:

More than 140 fb^{-1} at 13 TeV



High energy proton-proton collisions

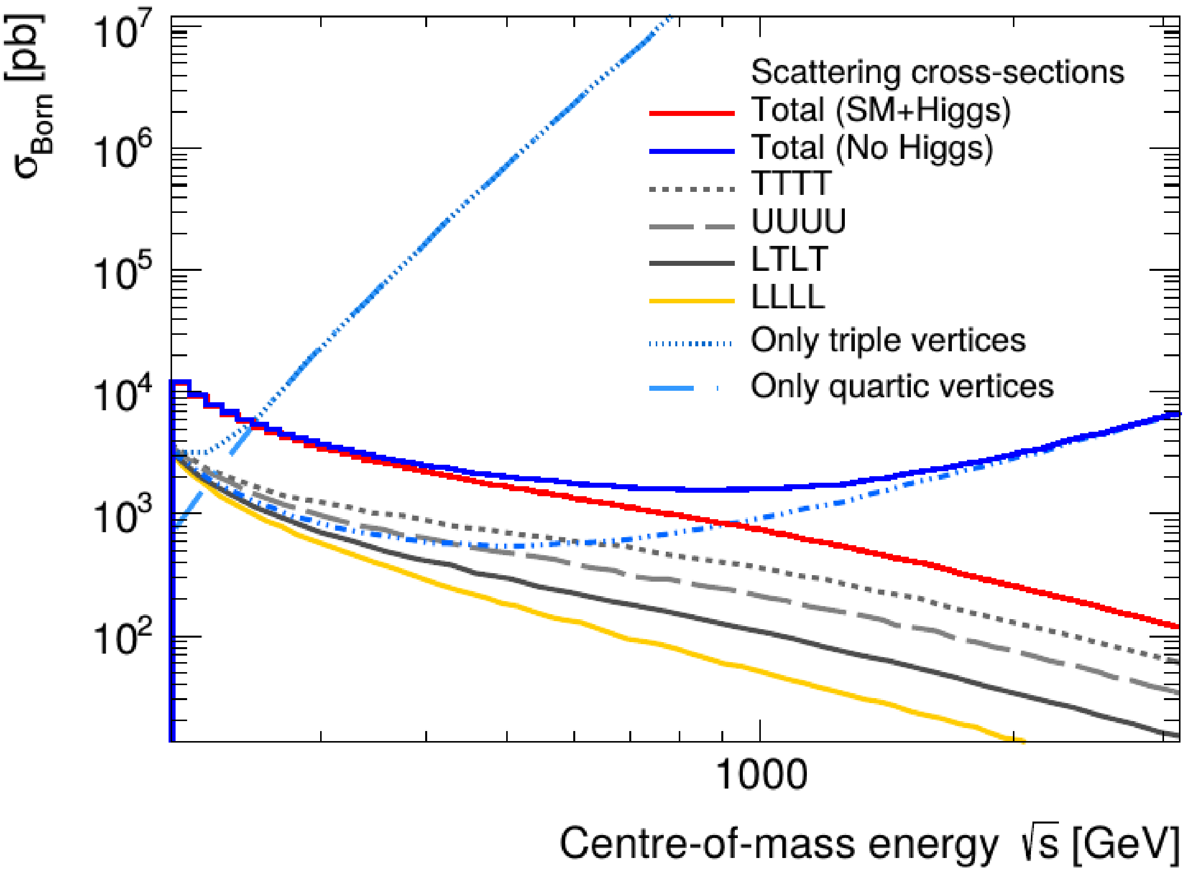
center-of-mass energy of $\sqrt{s}$ = 7, 8 and 13 TeV

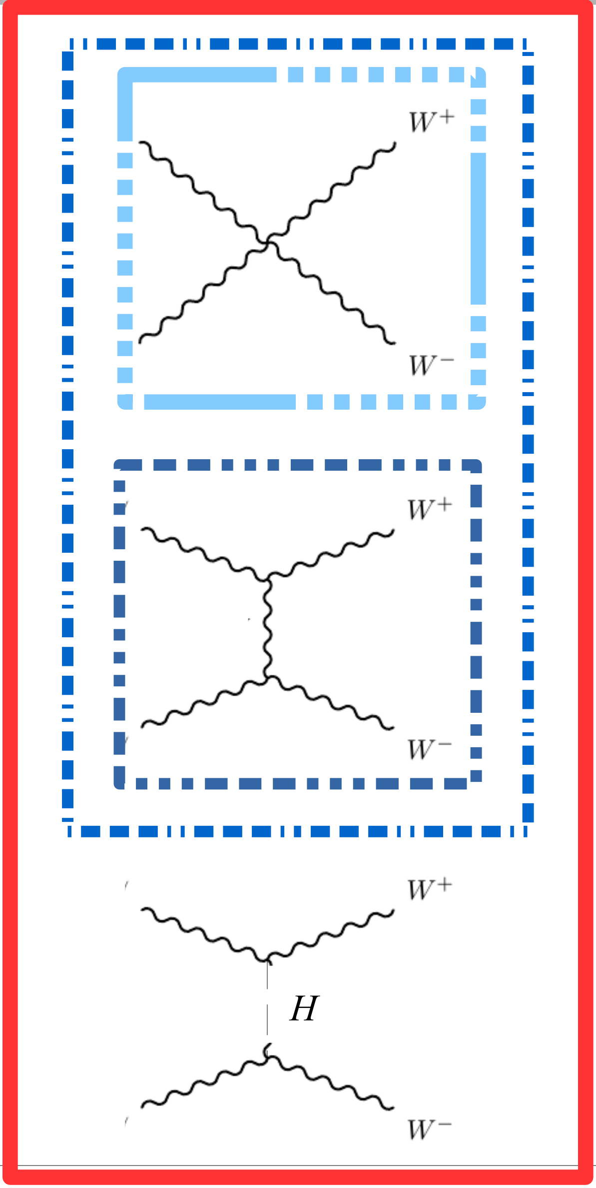
…. and other collisions (photons!)

Processes with W Bosons

- Scattering of (longitudinal) W Bosons: Motivation for Higgs mechanism and building the LHC

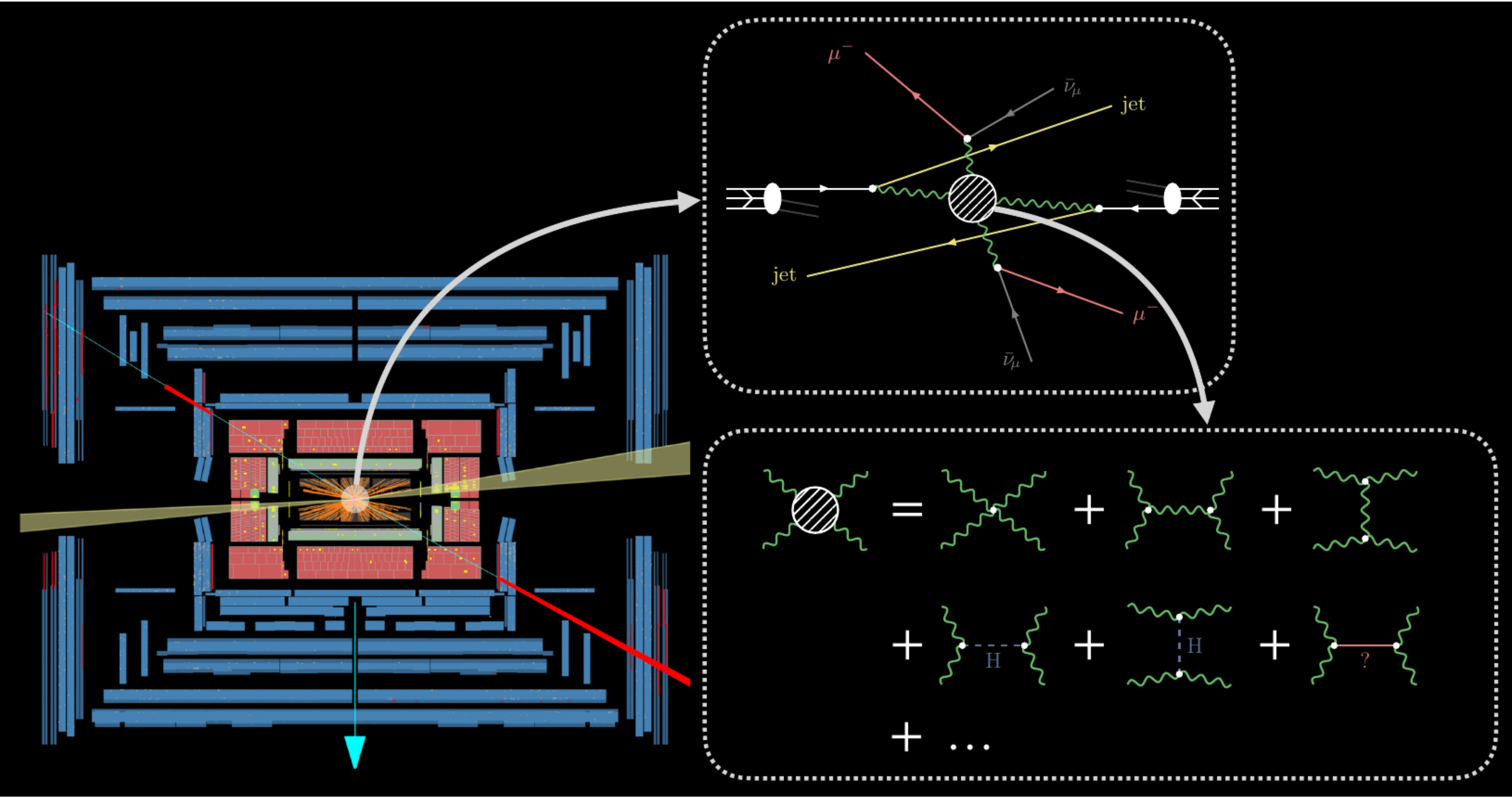
- Diverging beyond 1 TeV





Same-sign WW scattering

- Two forward jets, two same-charge leptons inbetween: Typical VBS signature



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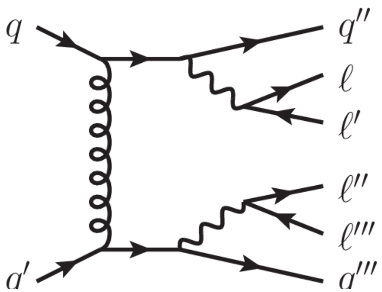
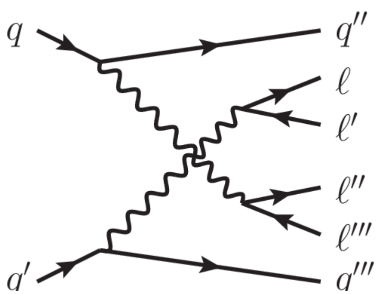
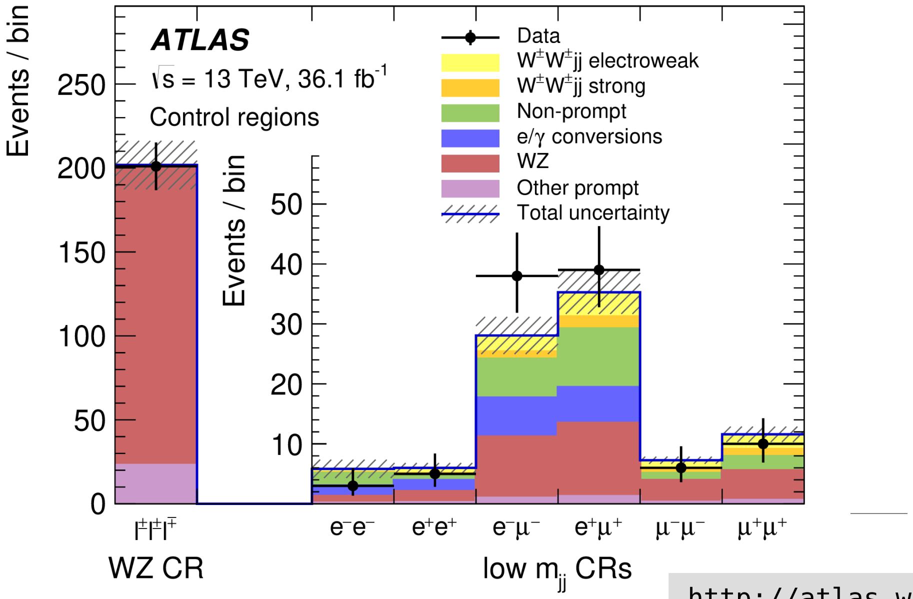
QCD vs. electroweak production

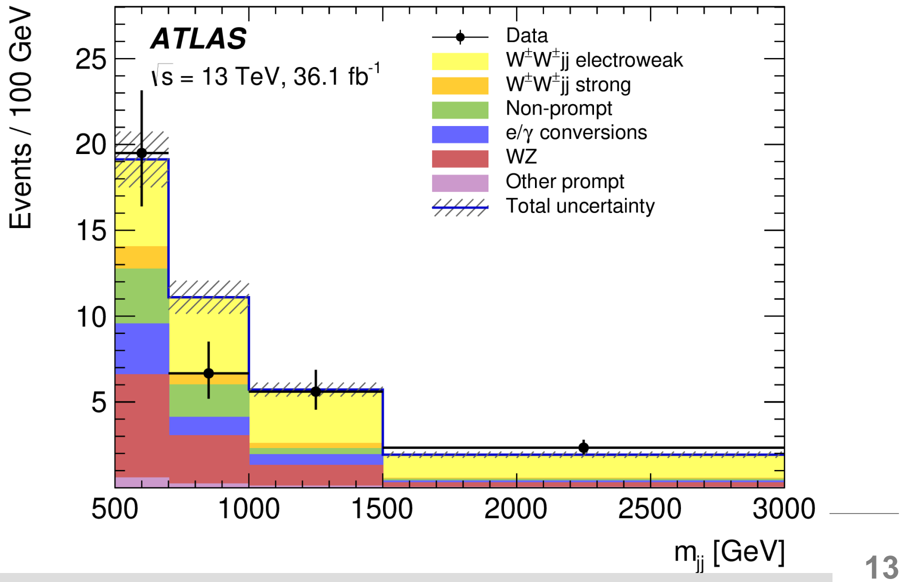
- At lowest order: QCD ($\alpha_s^2 \alpha_{ewk}^4$) and pure EWK signal ($\alpha_{ewk}^6$) interference (<10%)
- Observed with 6.5 σ

theory: 3.08 +0.45 -0.46 fb
exp: 2.98 +0.51 -0.48 (stat) +0.29 -0.28 (syst) fb









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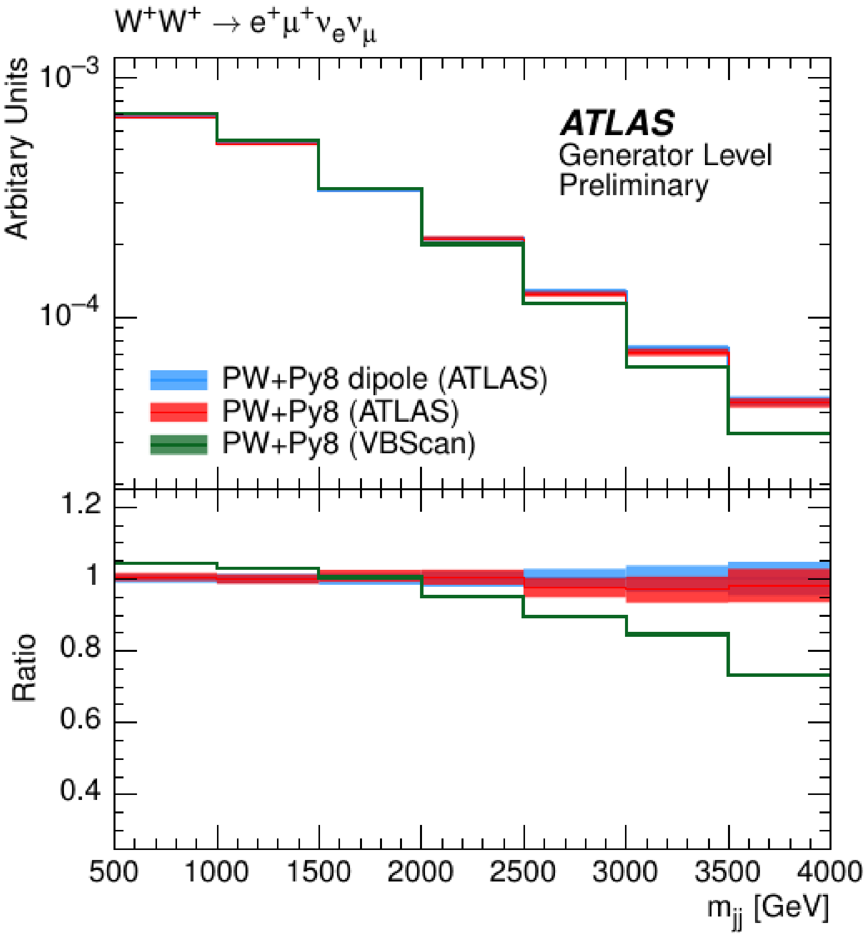
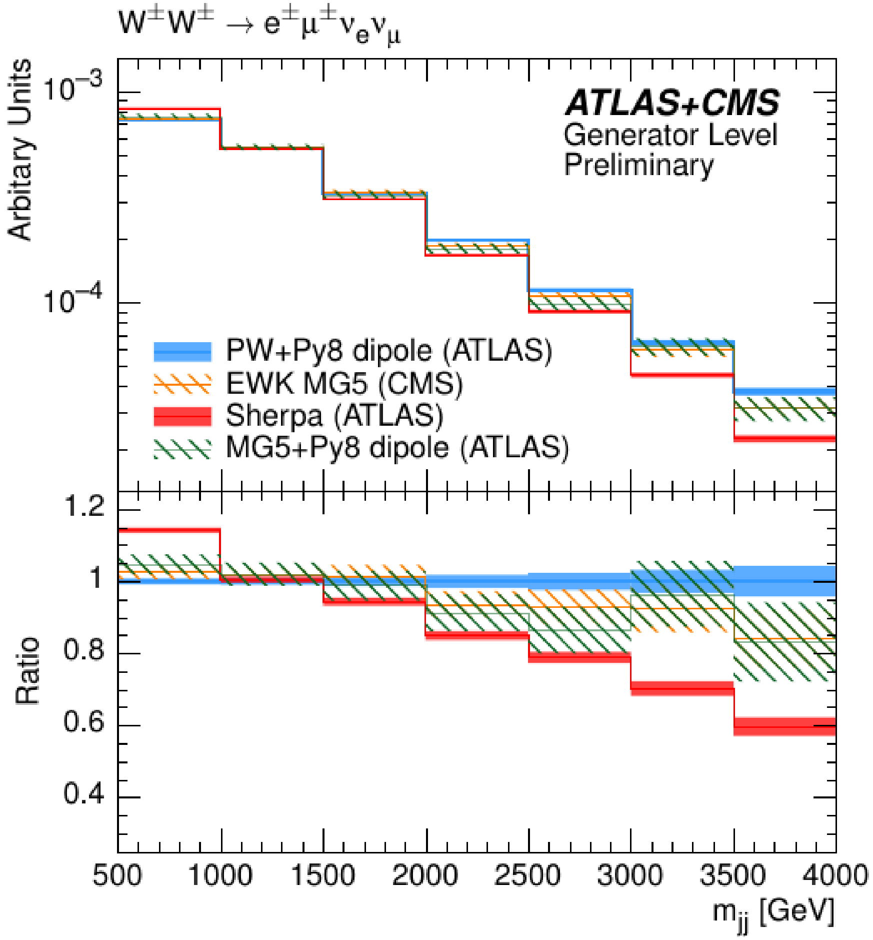
Theoretical description is important

- Same-sign measurement relies on description of m_{jj} (and other characteristic) distributions
- Very dependent on Parton Shower modelling (and a problem in the early days)





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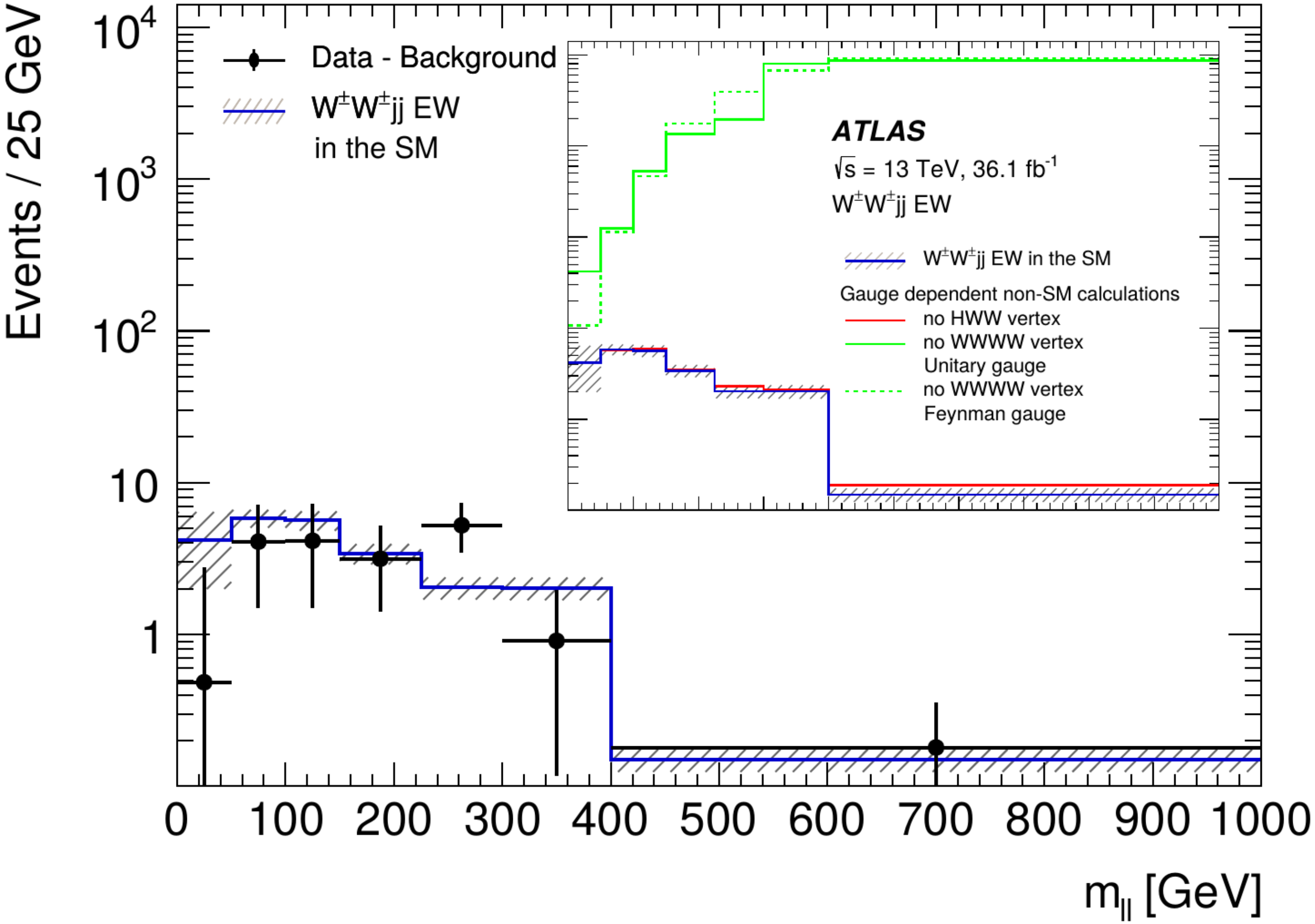
Outlook: What is still in store?

- *Longitudinal* scattering would diverge without Higgs, but we are still far from a clear signal



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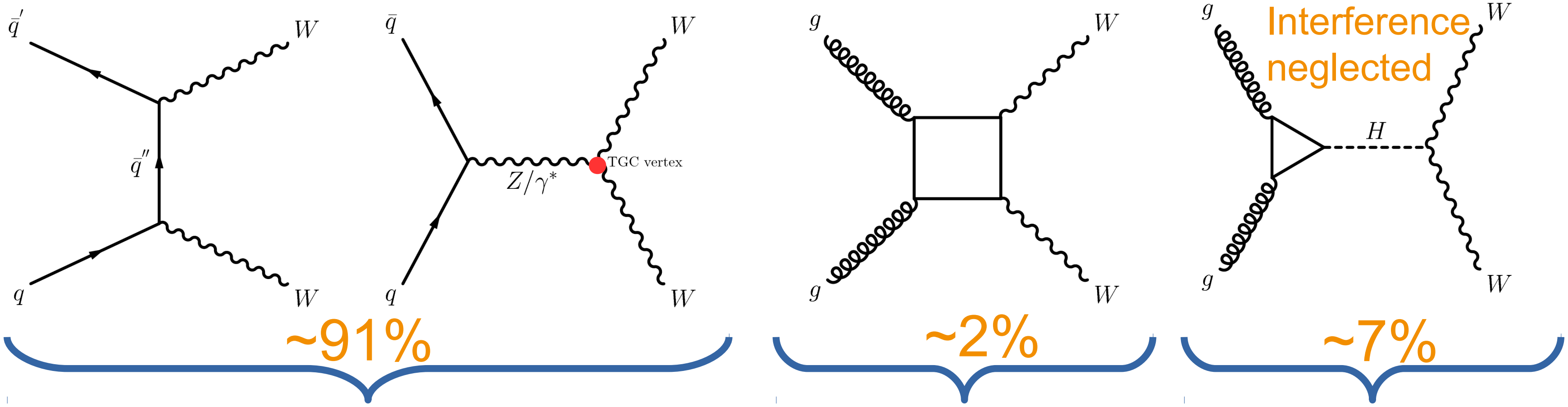
The University Of Sheffield.

Similar issues with WW diboson production

Predictions obtained using perturbation theory in orders of coupling constant α



Interference neglected

~91%

~2%

~7%

NLO (α^1)
contains *triple gauge coupling*
(enhanced cross section for high energy and new physics)

LO (α^2)
large NLO
correction?

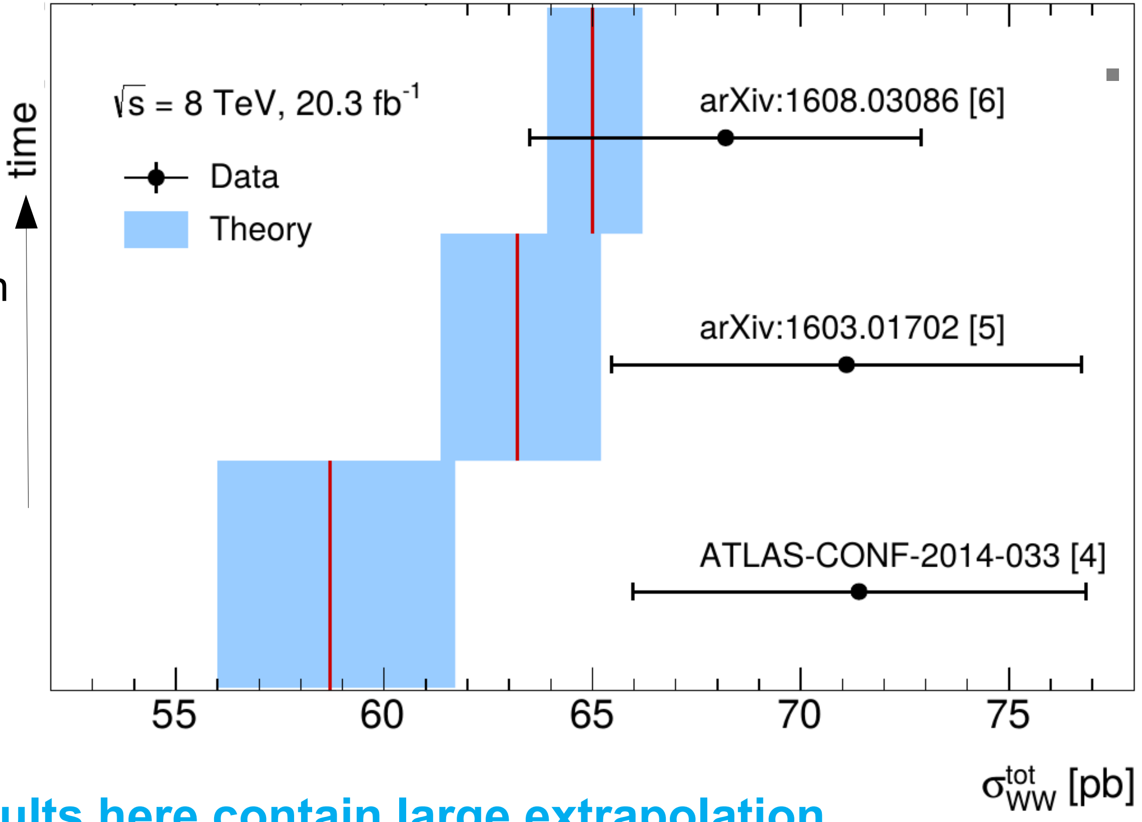
NNLO (α^4)

Large discrepancies (~20% / 2 σ) in first measurements

Experimental progress in Run-1

> **Theory Progress (Matrix made in Zürich!)**

- Non-resonant gg NLO
- Higgs N3LO prediction
- (qq → WW) NNLO predictions
- Resummation effects due to jet veto



> **Experimental Progress**

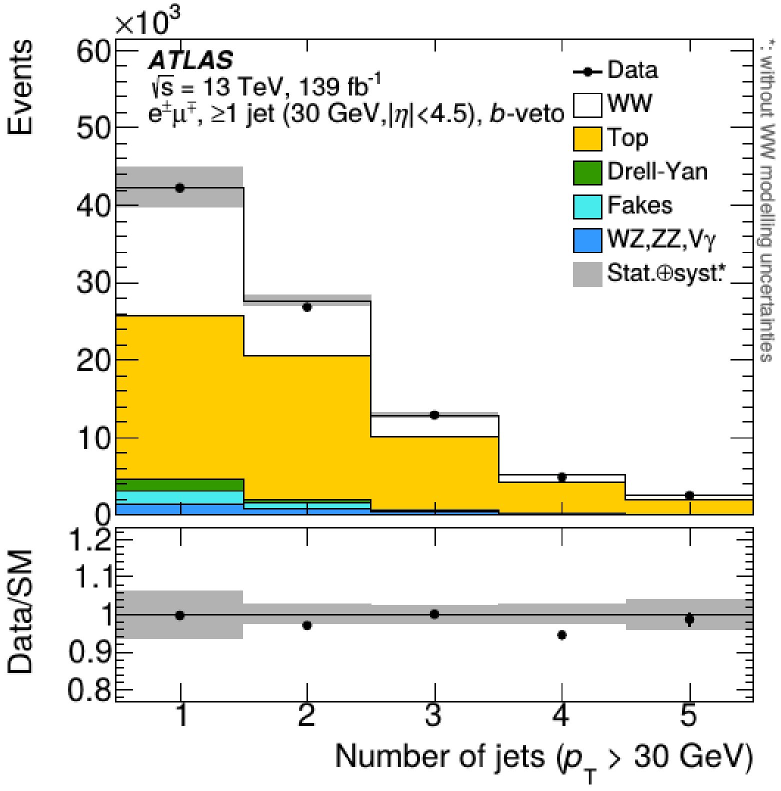
- Extension of fiducial phase space

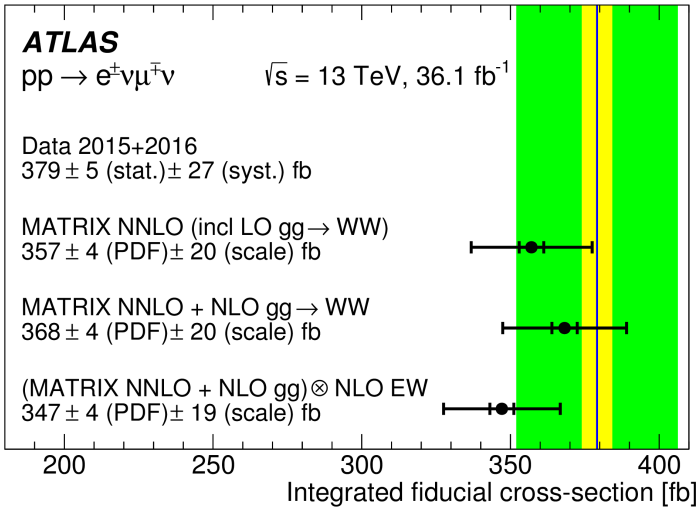
> **Experimental results here contain large extrapolation**

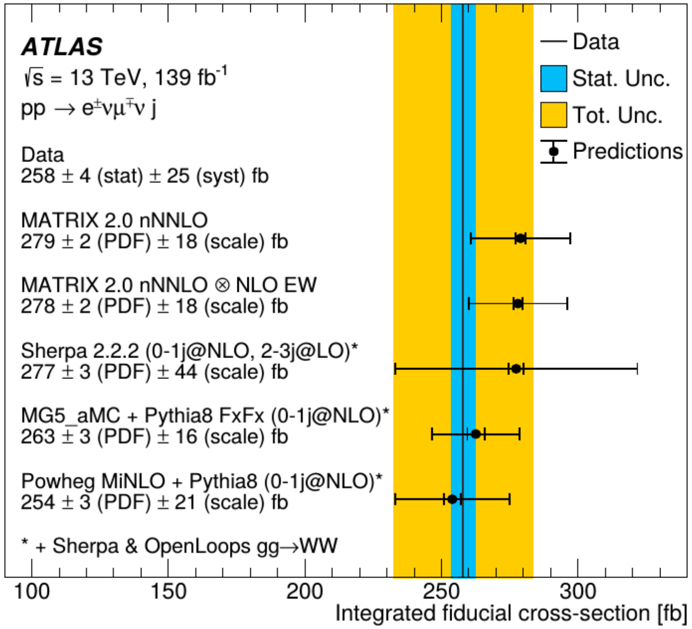
> **Desirable: Compare theory to best fiducial measurement**

Newer measurements with 0 and 1 jets

- Measurement usually constrained to 0-jet final state due to large top contribution
- Generally, this introducted problems to to presences of two scales in calculation: jet energy vs. centre-of-mass of process







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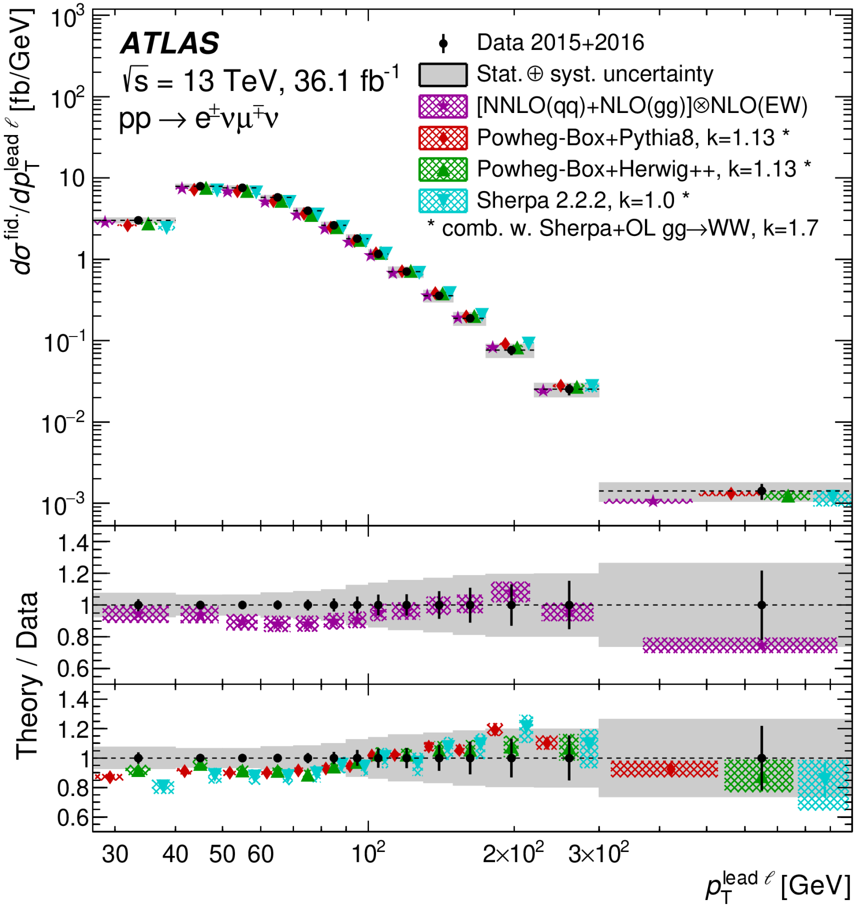
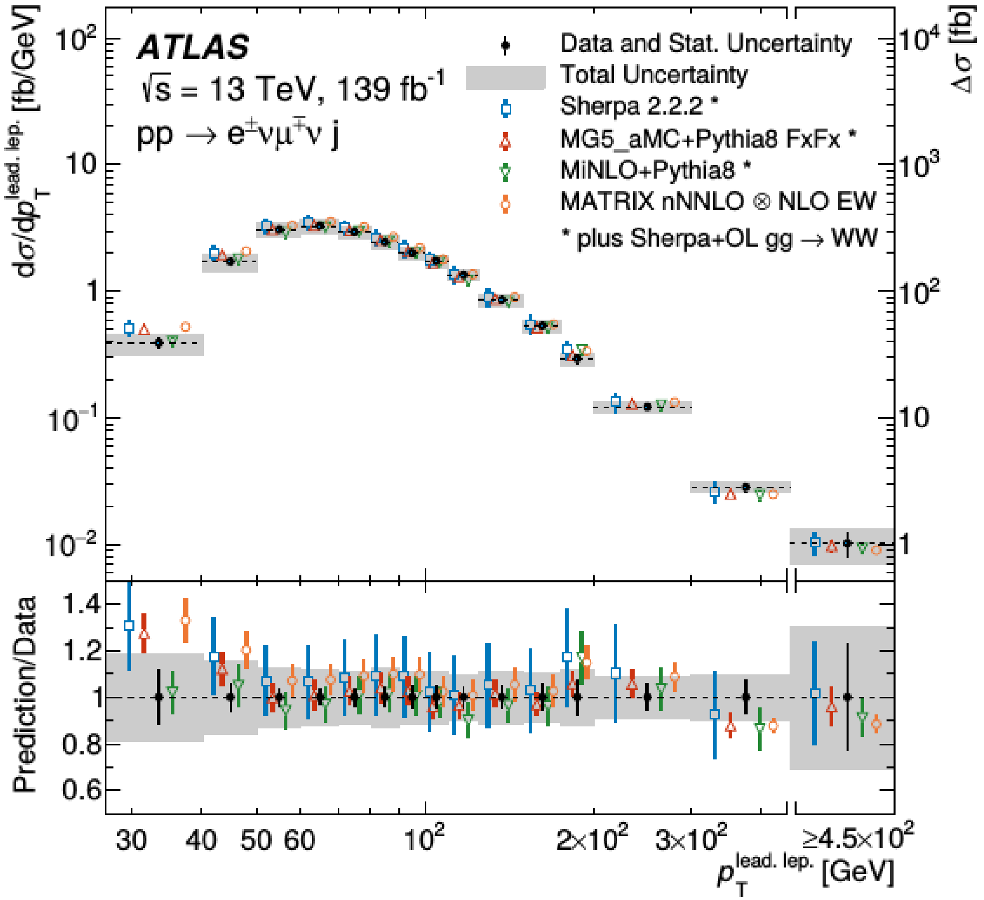
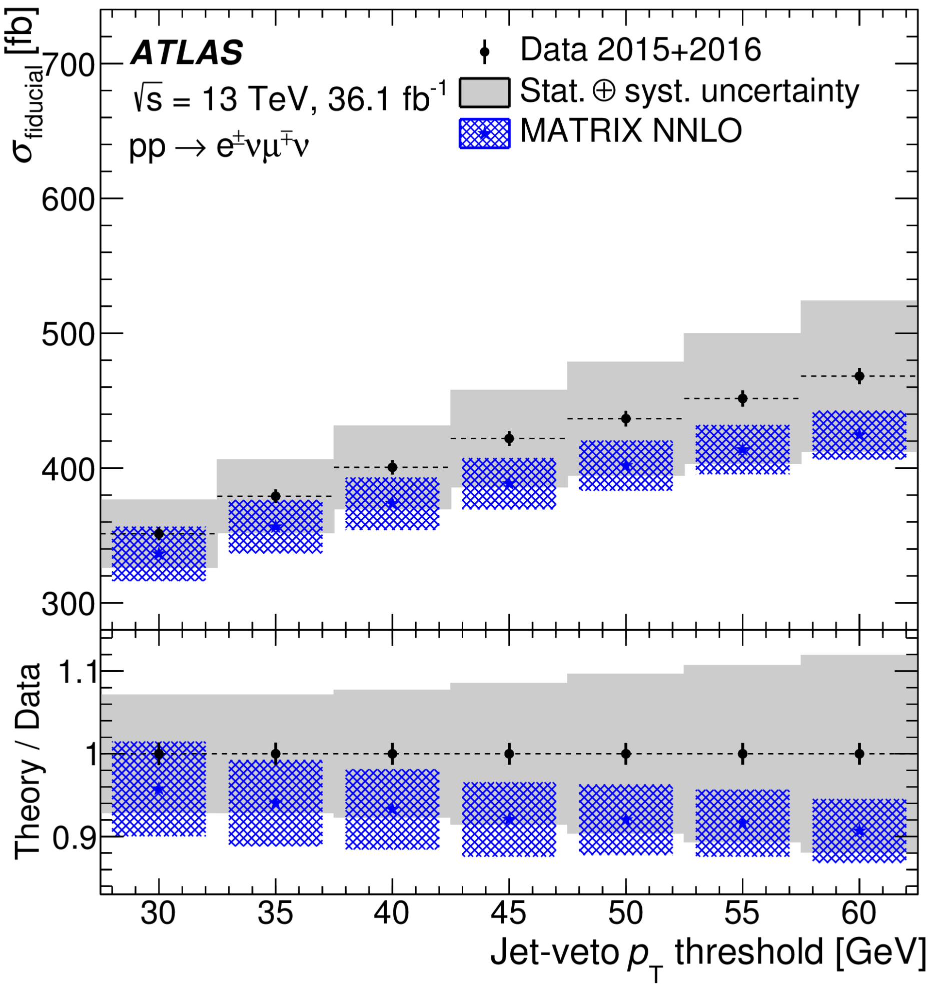
Large statistics allows for differential measurements

- Generally well-described within uncertainties though some trends are visible
- Useful as inputs to general SM constraints





Outlook: What is still in store?



- Ambition to further investigate more general phase space

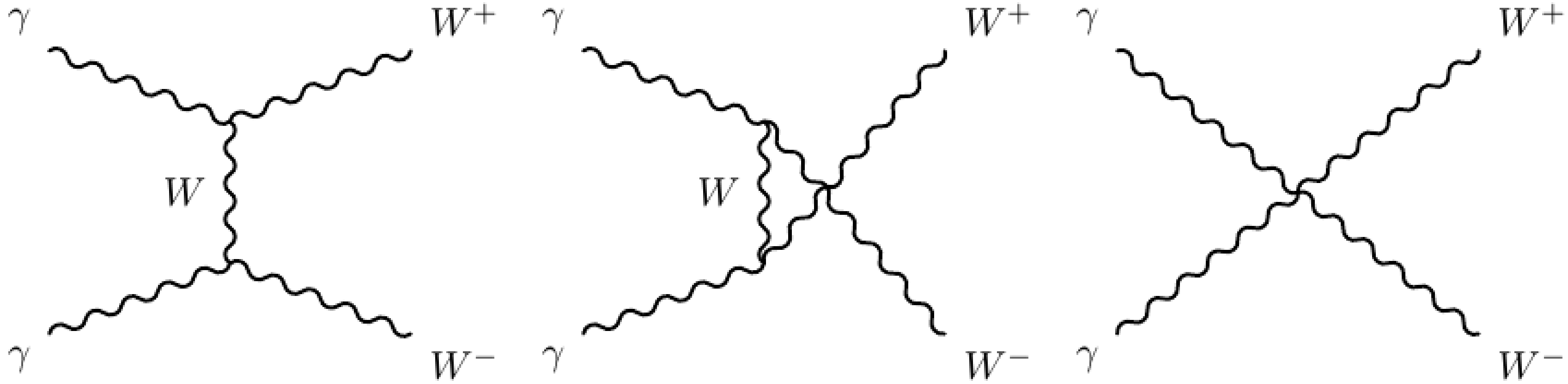
  → pT-dependent jet-vetoes

  → fully inclusive measurements

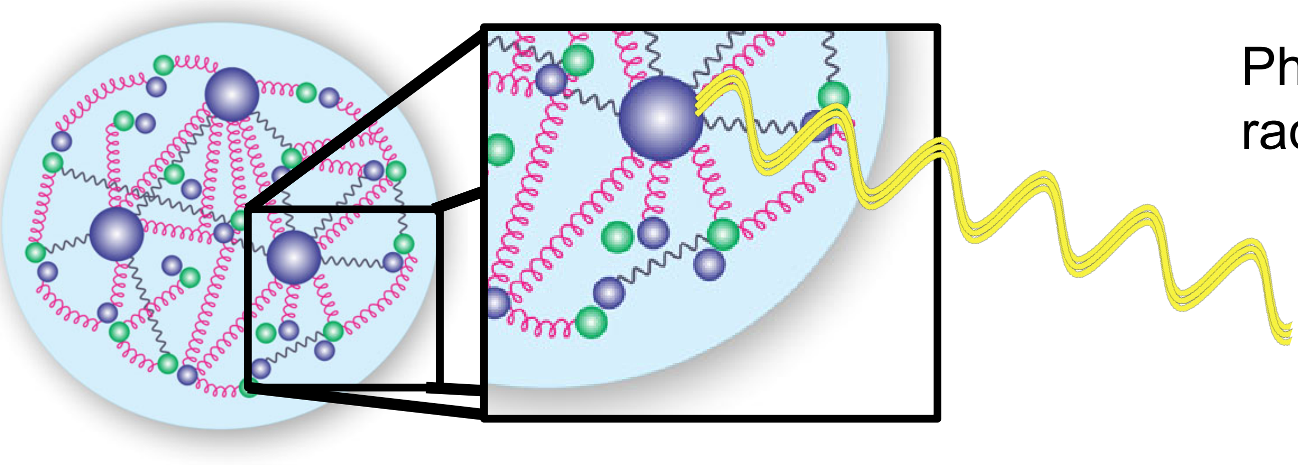
$\gamma\gamma \rightarrow$ WW is incredibly sensitive

- At leading order, ***only*** diagrams with triple and quartic couplings contribute

- Incredibly sensitive to electroweak interactions → but need to improve theory prediction and measurement



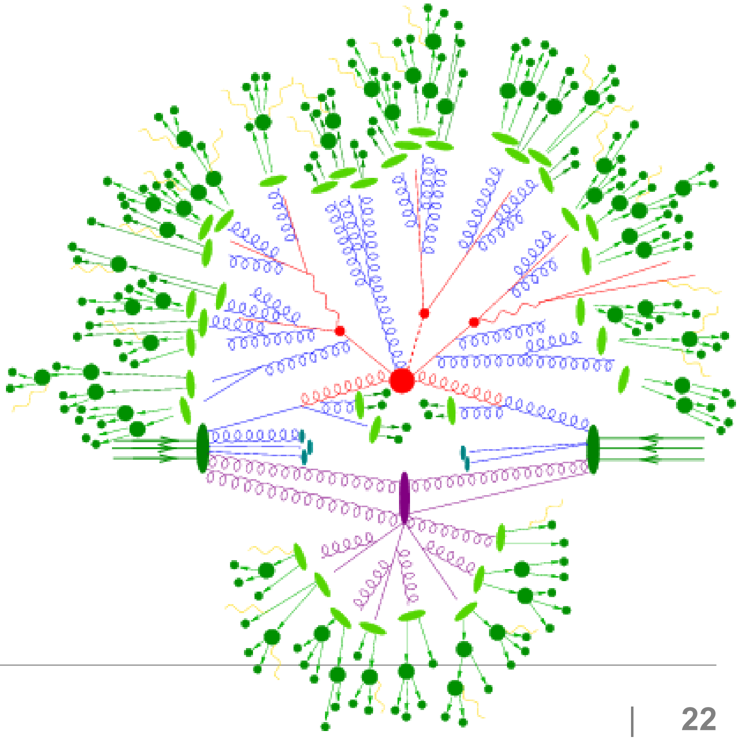
Mechanisms for photon collisions: resolved/dissociative



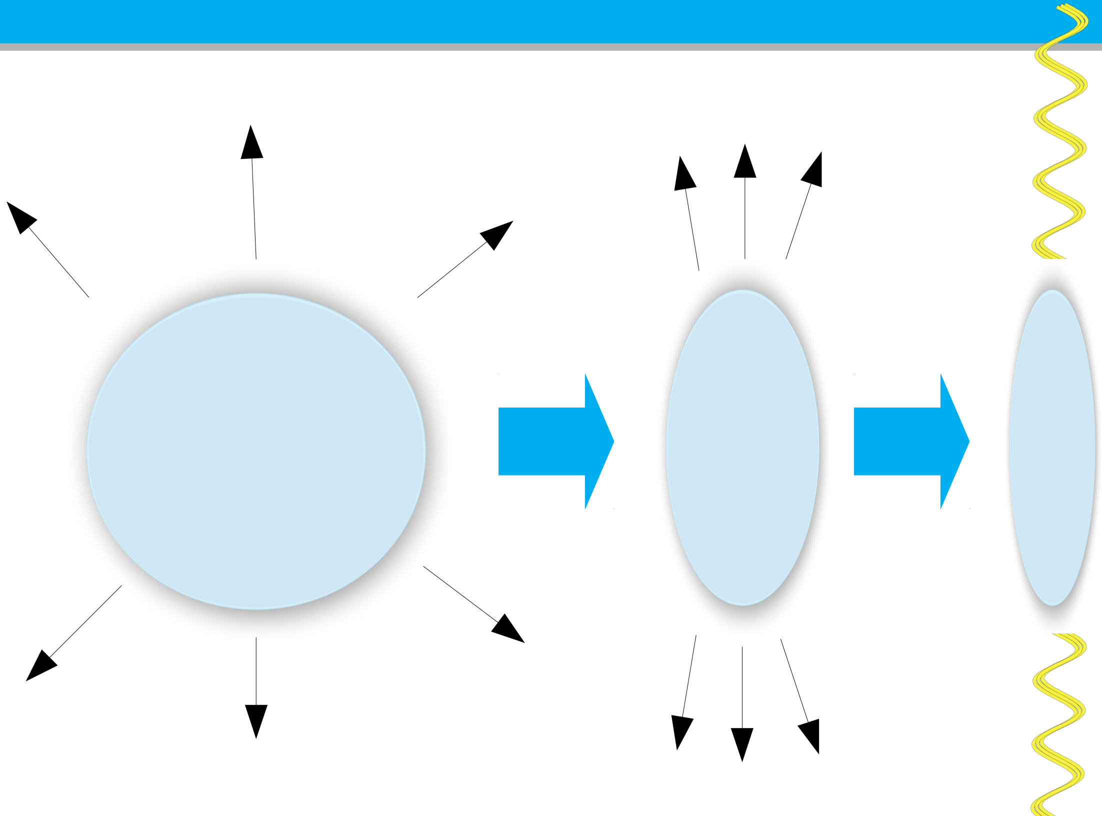
Photon is
radiated off parton

It breaks up, event looks similar to normal *pp* collision

→ dissociative production

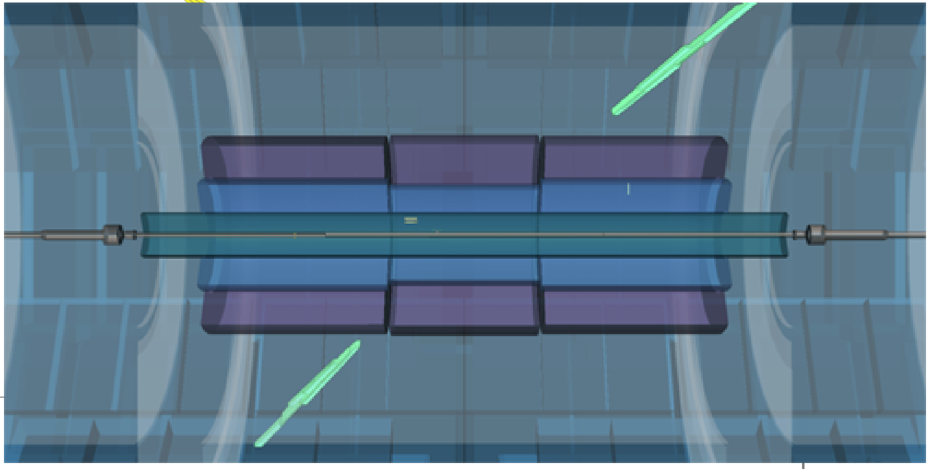


Mechanisms for photon collisions at the LHC

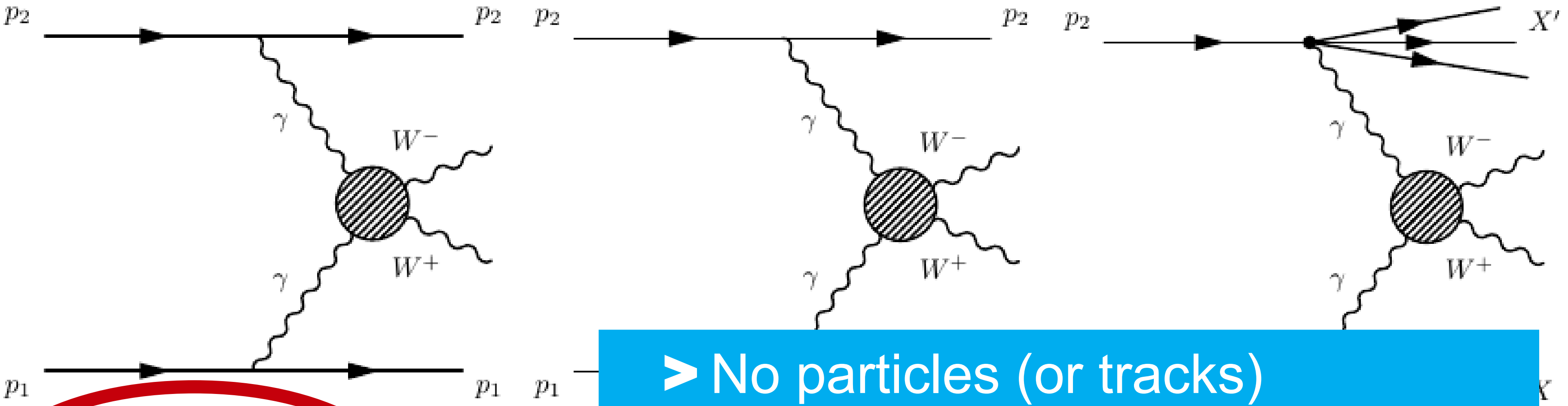


Photon is radiated off proton as a whole

“intact” proton: It continues to travel in the direction of the beam – **empty event** (here: Pb Pb → γγ, even more empty, no pileup)



$\gamma\gamma \rightarrow$ WW production at the LHC



elastic (EE)

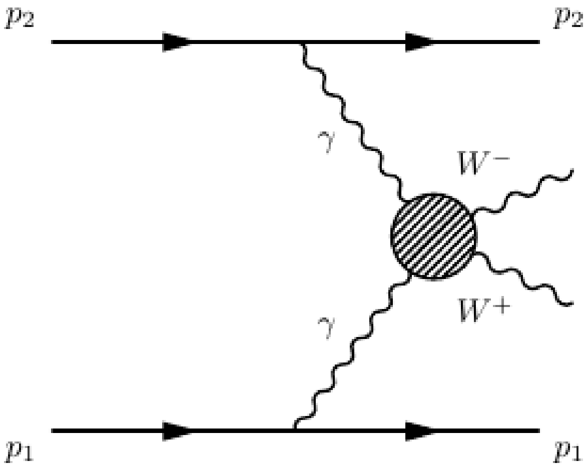
no particles other than W decay products

semi-dis

D)

- No particles (or tracks) associated with the primary interaction vertex
  → **Track reconstruction**
  → **Vertex definition**

$\gamma\gamma \rightarrow$ WW production at the LHC



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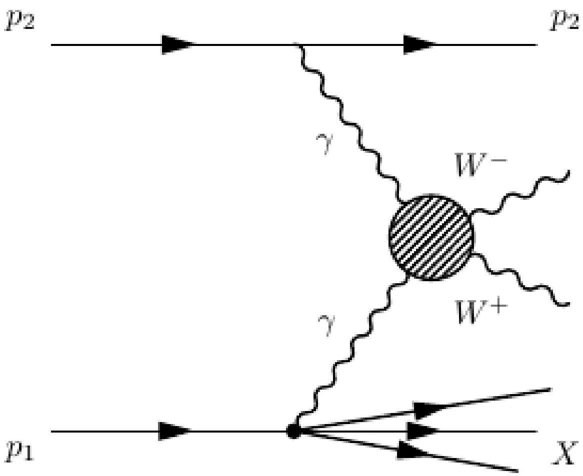
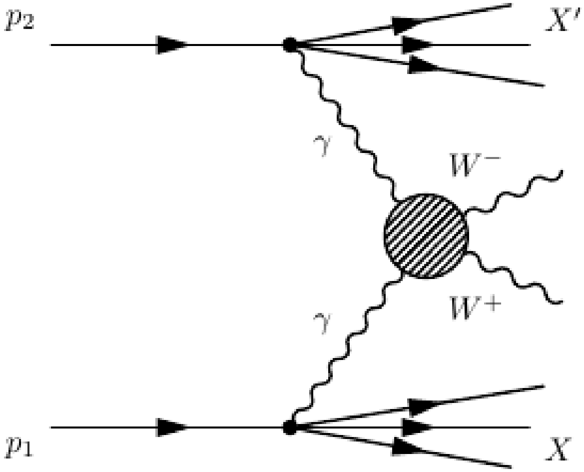
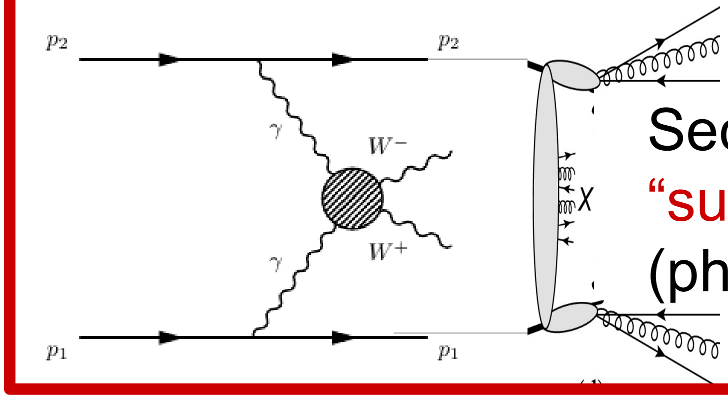


semi-dissociative (SD)



double-dissociative (DD)



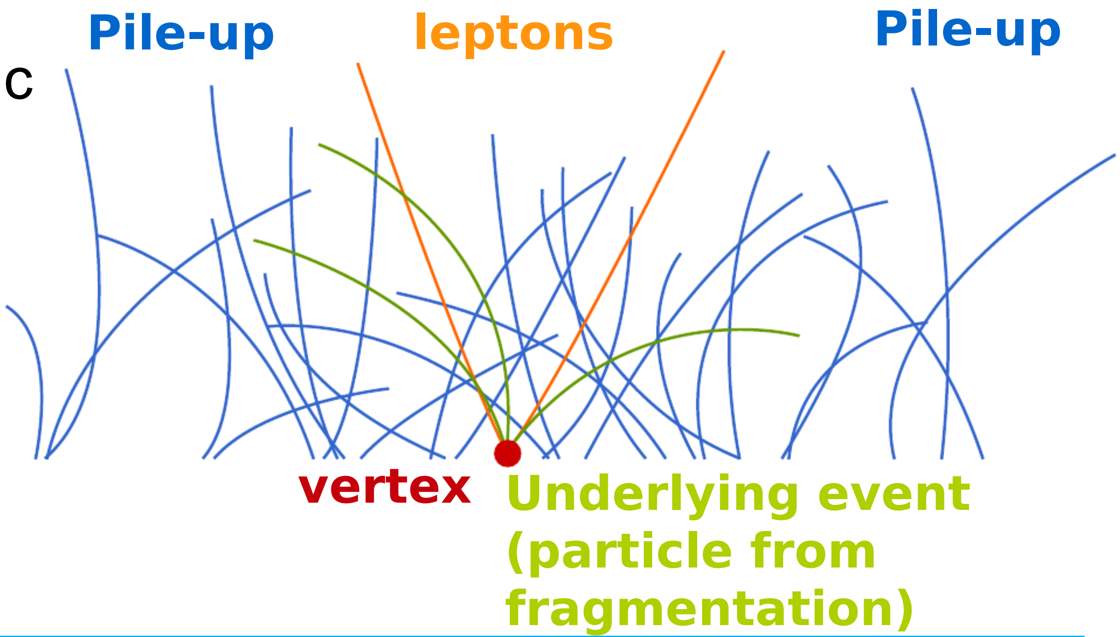
Second scattering:
“survival factor”
(phenomenological)

Reduces “visible” cross-section of elastic production (additional particles)

→ **Signal correction**

Event selection

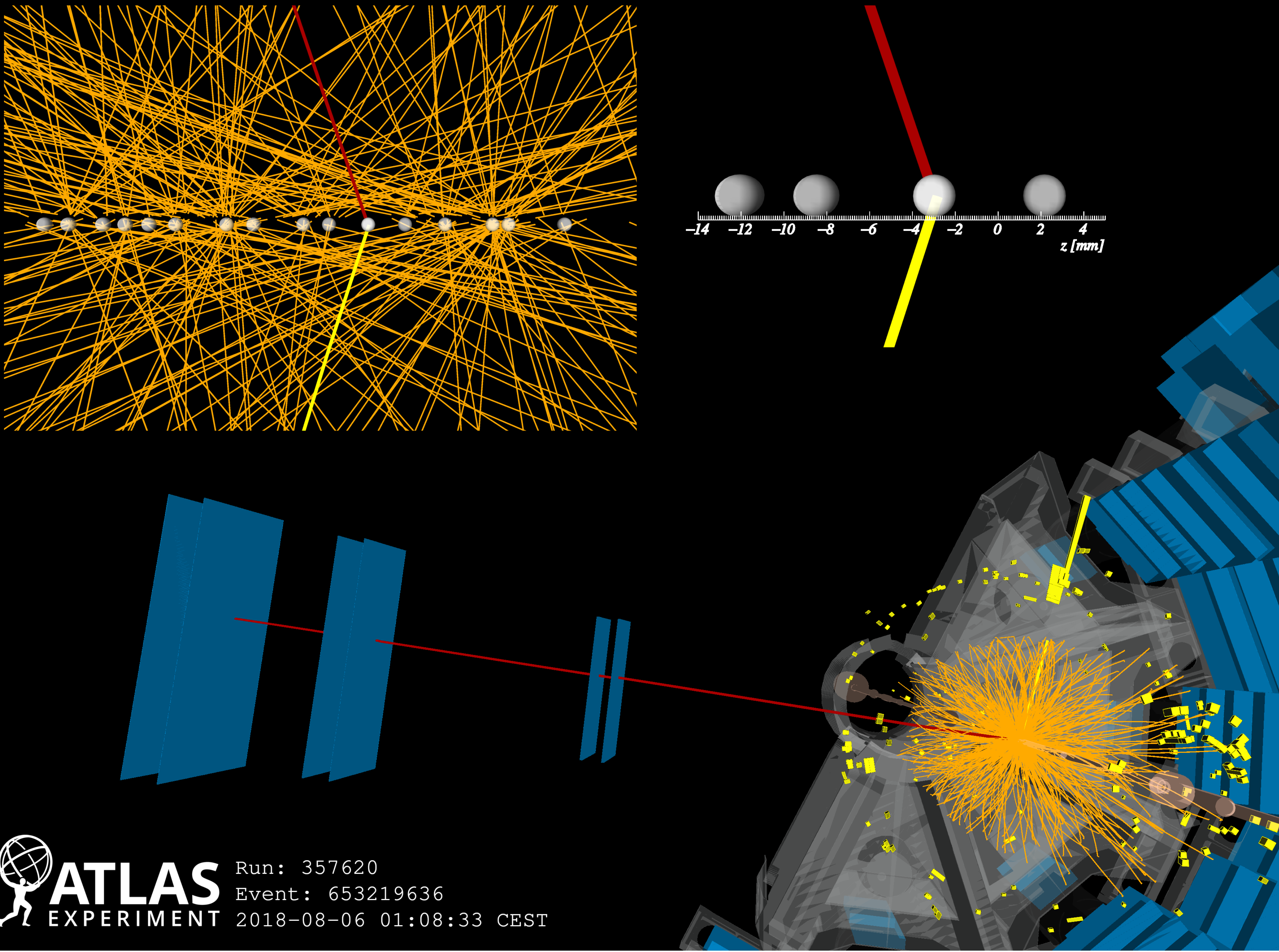
- exactly one electron and muon with opposite electric charge
- p_T (ll) > 30 GeV, m(ll) > 20 GeV
- no tracks associated with primary interaction vertex



> Modeling of **pileup** (random interactions close to vertex)

> Modeling of **underlying event** of backgrounds

> **Modeling of the signal** (“survival factor”)



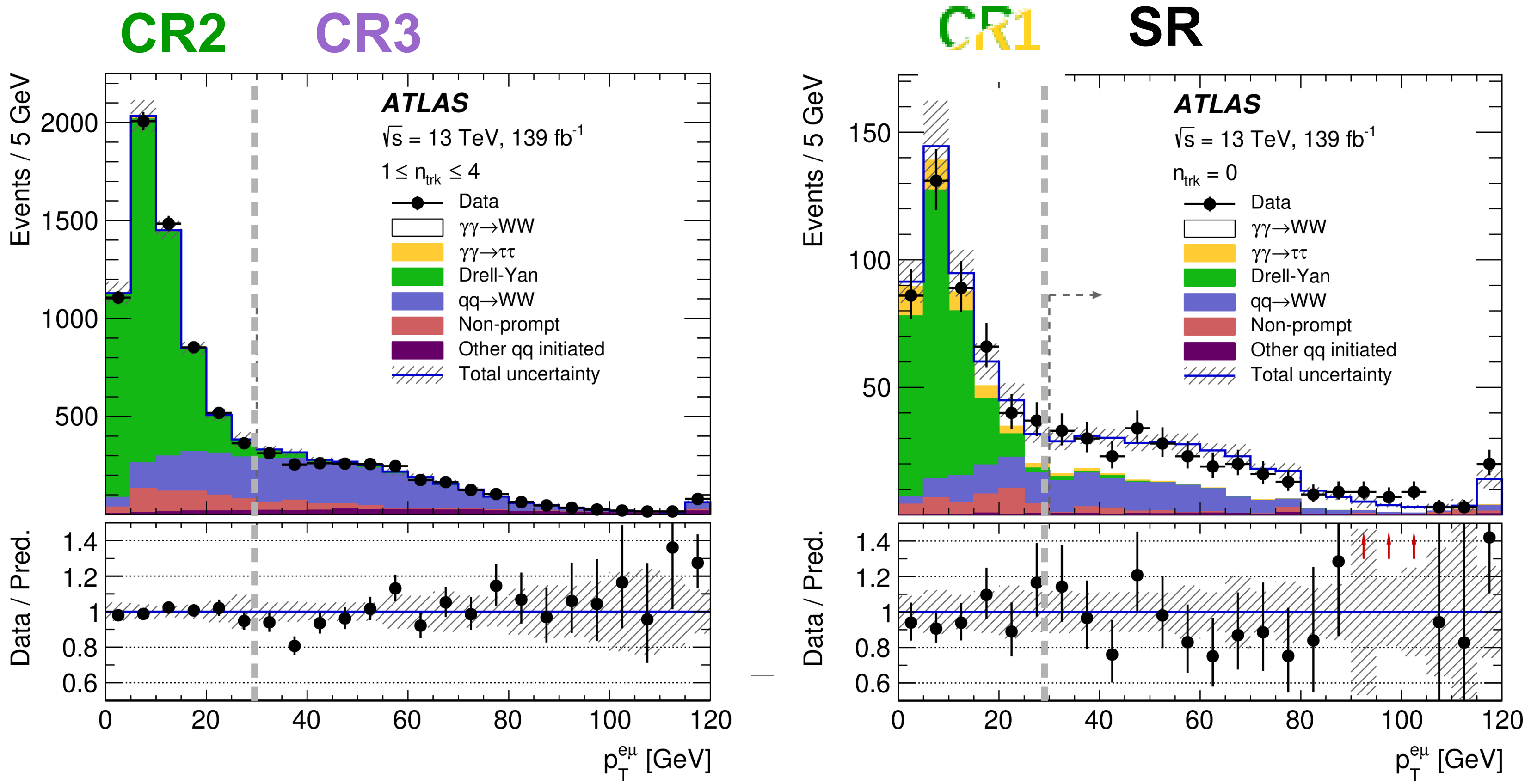
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Signal extraction: Putting it all together

- Using profile LH fit over 3+1+1 regions (1 SR + 3 CR + signal modelling CR) → 4 free normalization parameters ($\gamma\gamma \rightarrow$WW, $\gamma\gamma \rightarrow$ll, DY, qq→WW)

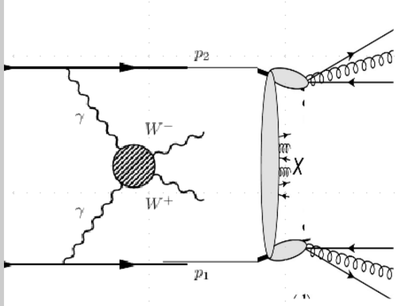
	$n_{trk}=0$	$1 \leq n_{trk} \leq 4$
p_T (ll) < 30 GeV	**CR1**	**CR2**
p_T (ll) > 30 GeV	**SR**	**CR3**

- Signal region: $\gamma\gamma \rightarrow$WW (57%), qq→WW (33%)



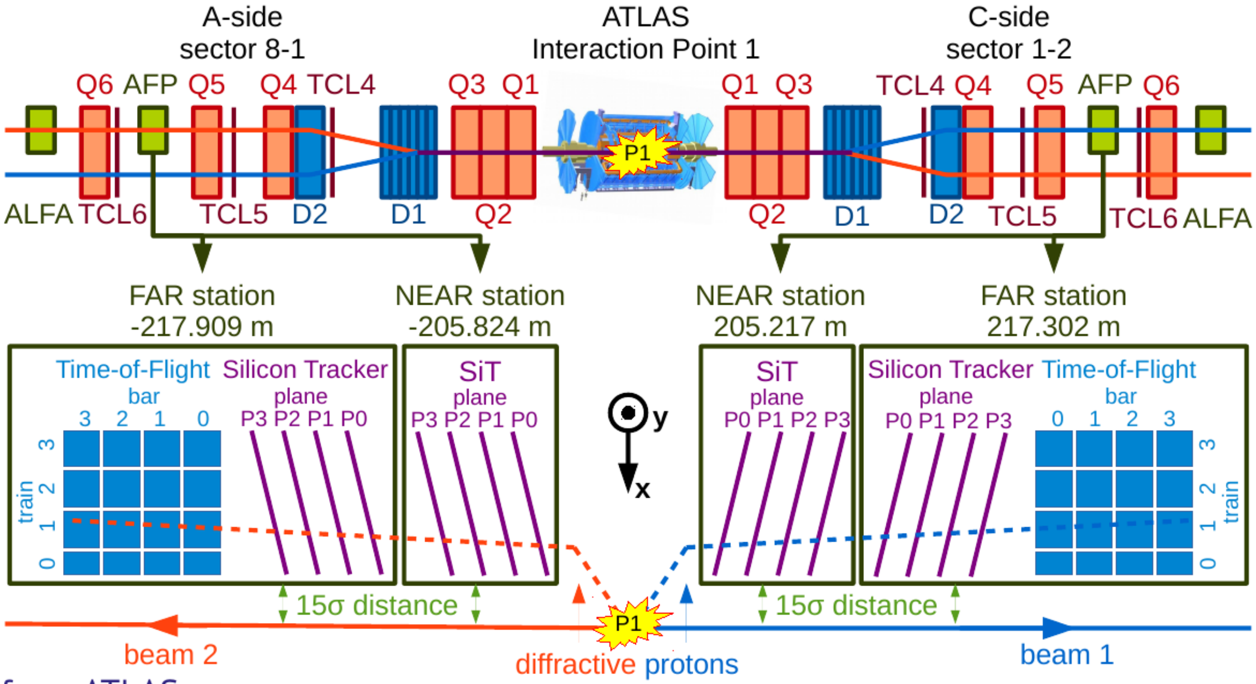
Results

- Background-only hypothesis rejected with **significance of 8.4 σ** (6.7σ exp.)
- **First observation of photon-induced WW production (γγ →WW) in exclusive phase space (without any associated tracks)**
- Uncertainties dominated by WW modelling and background statistics
- Large range of theoretical models: Uncertainty dominated by data-driven scaling or scale uncertainties (SD) and second scattering probability

	cross section	**uncertainty**
σ(meas)	**3.13 fb**	±0.31 (stat) ±0.28 (syst) fb
σ(EExSF– our expectation)	0.65 fb × 3.59 **2.34 fb**	±0.15 (exp) ±0.39 (transfer, ll→WW) fb ±0.27 (total) fb
σ(pure theory prediction)	4.3 fb ±1.0 (scale) ±0.12 (syst) (without second scattering)	× 0.65 = **2.8** **±0.8** (total) fb × 0.82 = **3.5** **±1.0** (total) fb 

Outlook: What is still in store?

- Differential measurements with current data are possible
- The AFP spectrometer installed between 2016 and 2017 at z=200m
- Direct detection of scattered protons that leave the interaction intact



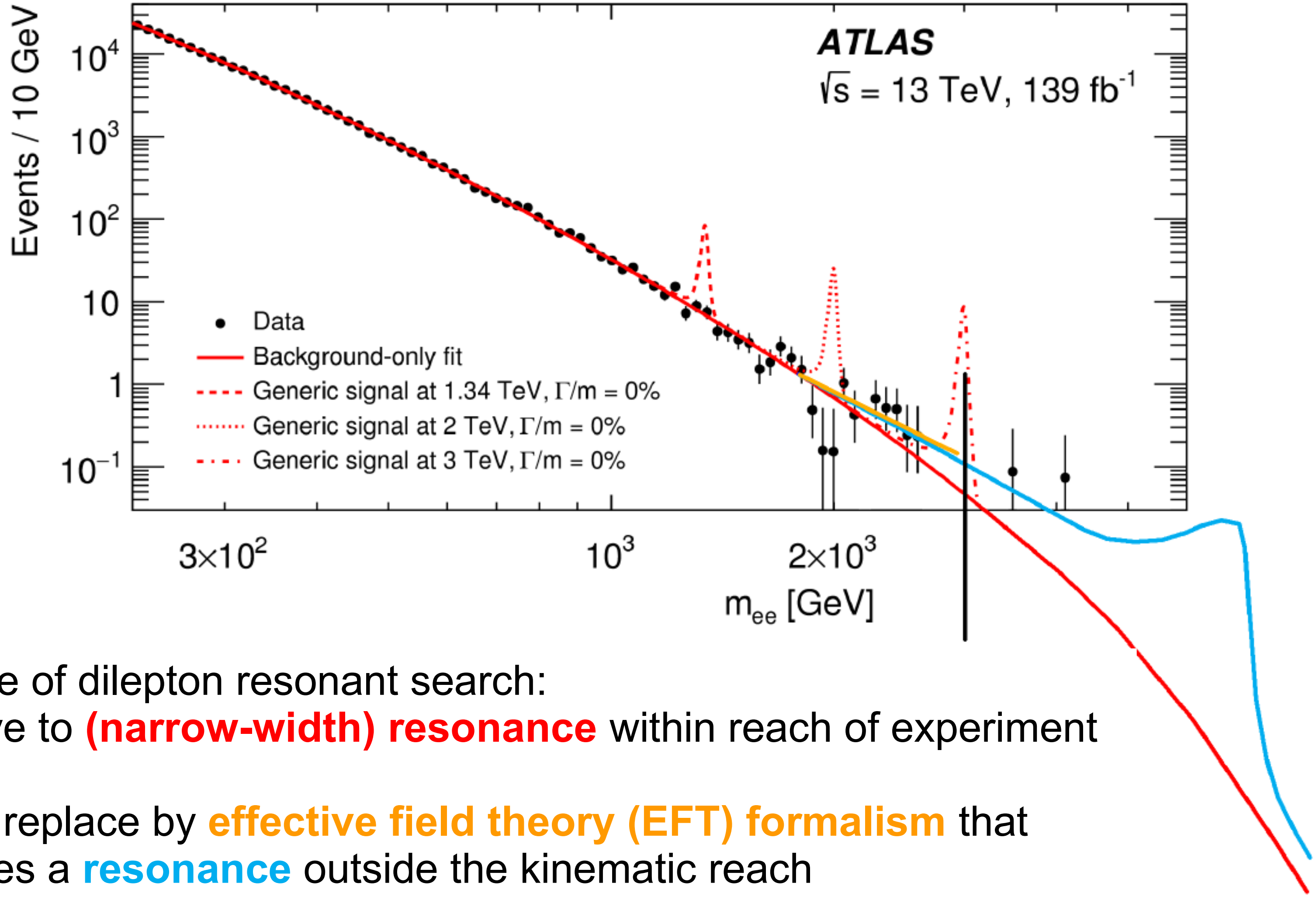
from ATLAS

- Allows to reconstruct invariant mass of events

$$W = \sqrt{s\xi_1\xi_2} = m_{WW}$$

- Presented measurements with (two) W bosons via different production mechanisms
  - Vector boson scattering (quartic coupling)
  - Diboson production (triple coupling)
  - Photon-induced production
- How can these be used in general tests of the Standard Model?

Tests of the Standard Model



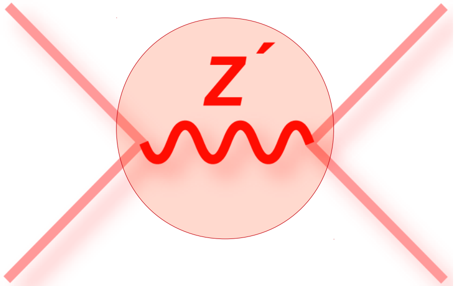
- Example of dilepton resonant search:
  Sensitive to **(narrow-width) resonance** within reach of experiment

- Can be replace by **effective field theory (EFT) formalism** that describes a **resonance** outside the kinematic reach (i.e. below some cut-off scale) → more general applicable limits

Sketch by Hannes Mildner using Phys. Lett. B 796 (2019) 68)

Effective Field theory: In a nutshell

$$\frac{1}{p^2 - M_{Z'}^2} = \frac{1}{-M_{Z'}^2}\left[1 + \frac{p^2}{M_{Z'}^2} + \left(\frac{p^2}{M_{Z'}^2}\right)^2 + \ldots\right]$$



$$c' = -\frac{c}{M_{Z'}^2}$$

Effective Lagrangian as extension of SM Lagrangian

→ Taylor expansion of local operators of “light” degrees of freedom

→ removes explicit description of “heavy” / high energy physics
(suppressed by orders of energy scale Λ >> E_{CM})

$$\mathcal{L}^{(\mathrm{dim})} = \frac{1}{\Lambda}\sum_{\boxed{k}} \boxed{C_k^{(\mathrm{dim})}}\boxed{Q_k^{(\mathrm{dim})}}$$

Number of Operator

Wilson Coefficient

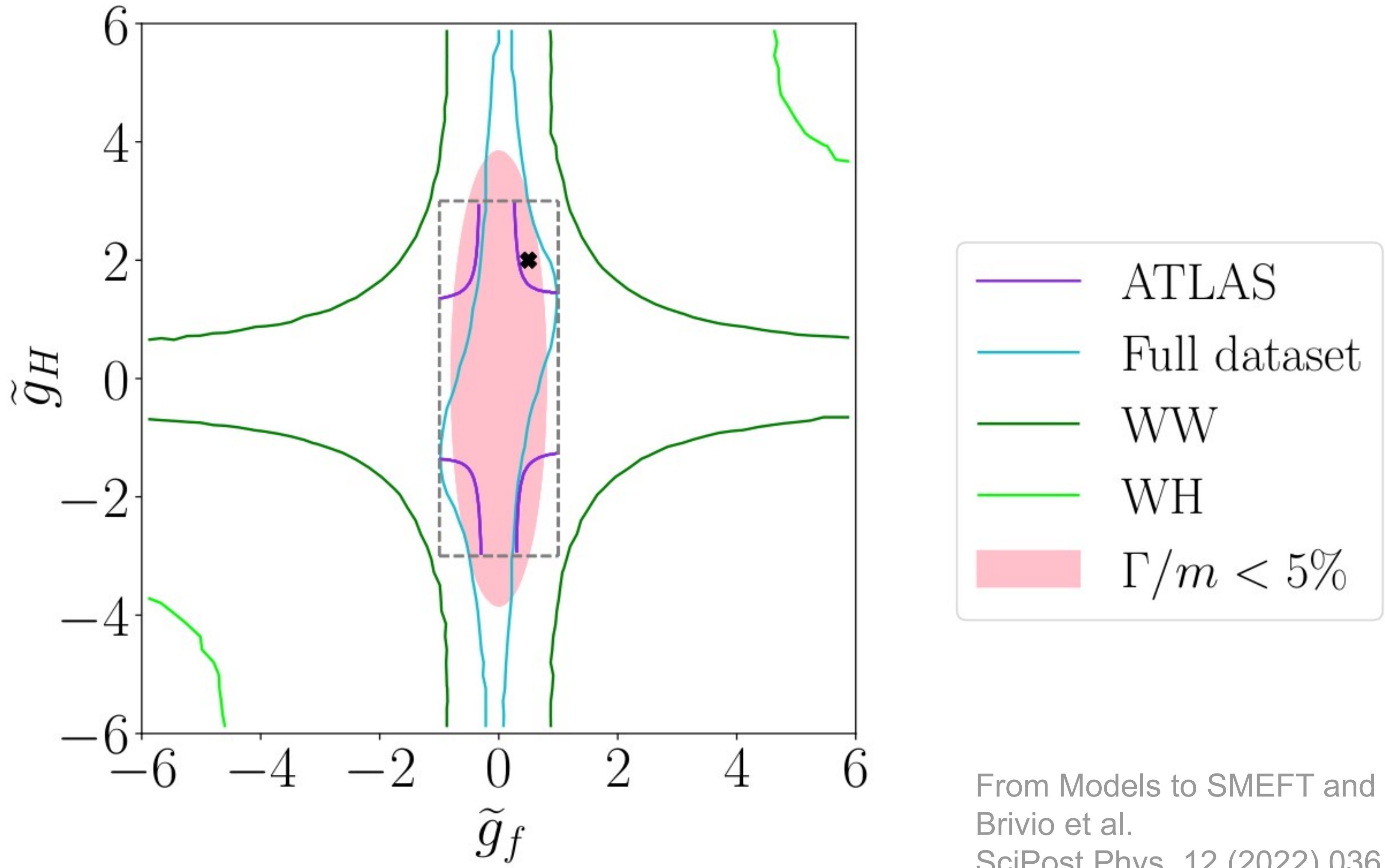
Operator

Systematic measure of SM deviations that can be linked to new physics phenomena

$$\boxed{\mathscr{L}_{EFT} = \mathscr{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)}$$

- SM up to dim-4
- dim-5:
  neutrino masses but
  lepton-flavour violating
- dim-6:
  most studied at LHC
- dim-8:
  studied for VBS
  processes

Complementarity with direct searches

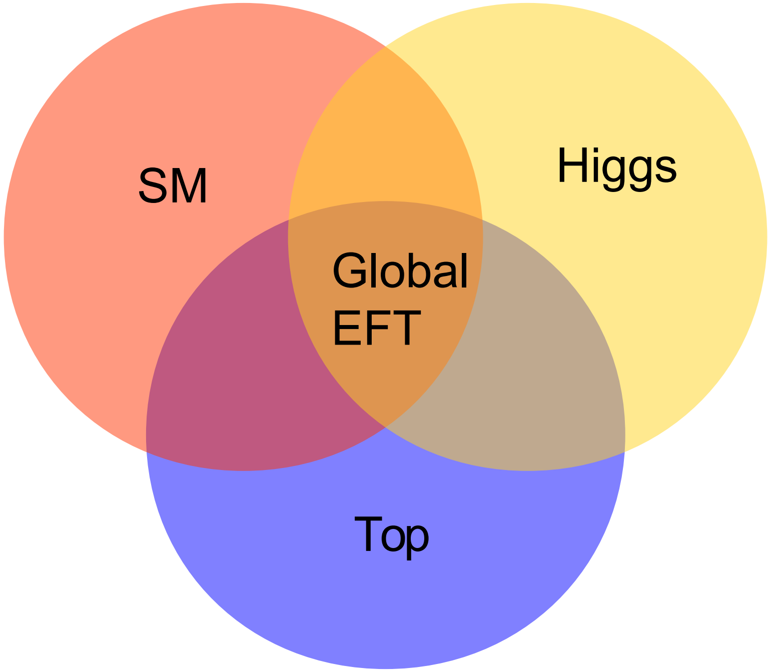


From Models to SMEFT and Back?
Brivio et al.
SciPost Phys. 12 (2022) 036
2108.01094 [hep-ph]

Global EFT fits

> Any final state is usually impacted by a number of Wilson coefficients

- Combination of different final states allows to disentangle effects



What is out there?

Theory Fitting groups
Overview of available codes: https://indico.cern.ch/event/971727/

- Provide bases, theoretical tools (feynrules)
- Use publicly available results

LHC EFT WG
https://lpcc.web.cern.ch/lhc-eft-wg

- Enhance comparability
- Common conventions and (conversion) tools
- Common standards for systematics

LHC top WG
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

LHC Higgs XS WG
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

LHC EW (MB) WG
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEW

- “Topical” EFT interpretations and combinations

CMS

ATLAS

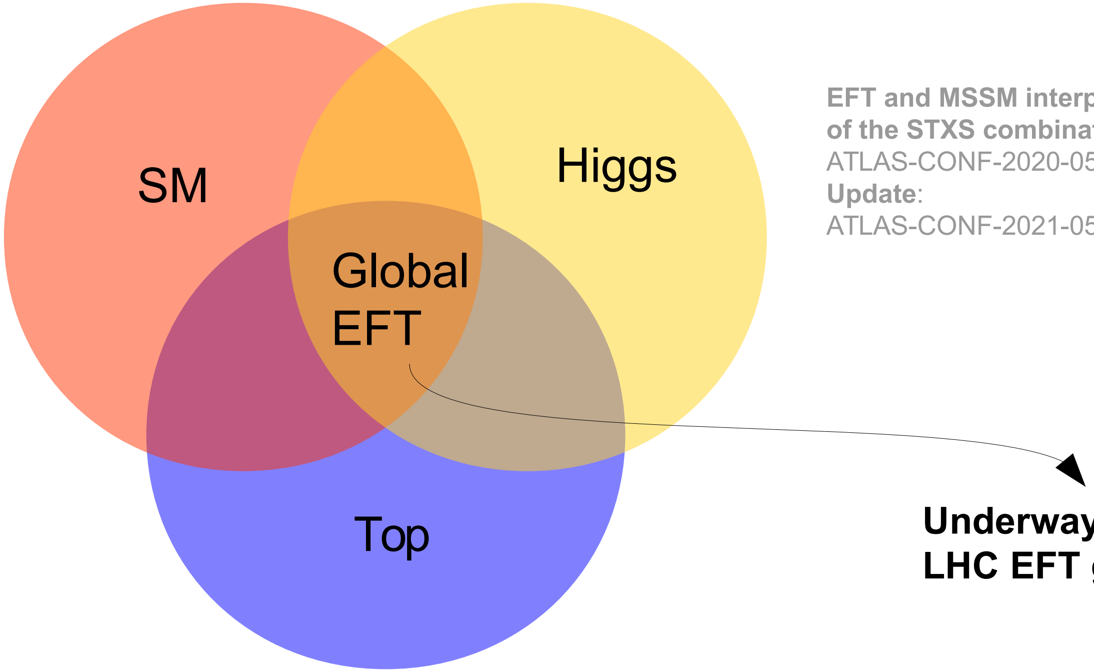
- Long-term goal: accurate likelihood-level global EFT combination of ATLAS and CMS
- In parallel: more complex combinations planned within experiments

Global EFT fits

> Case for Fit by Experimental Collaborations:

- Most accurate interpretations
- Make optimal use of data
- Fit can guide measurements strategy
- Makes sure all relevant information is published

Combined EFT interpretation of H to WW and WW processes
ATL-PHYS-PUB-2021-010



Combined EFT analysis of WW, WZ, ZZ, VBF Z processes
ATL-PHYS-PUB-2021-022

EFT and MSSM interpretations of the STXS combination
ATLAS-CONF-2020-053
Update:
ATLAS-CONF-2021-053

Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at s√= 13 TeV (dimension-8)
CMS-SMP-19-012

Underway within LHC EFT group

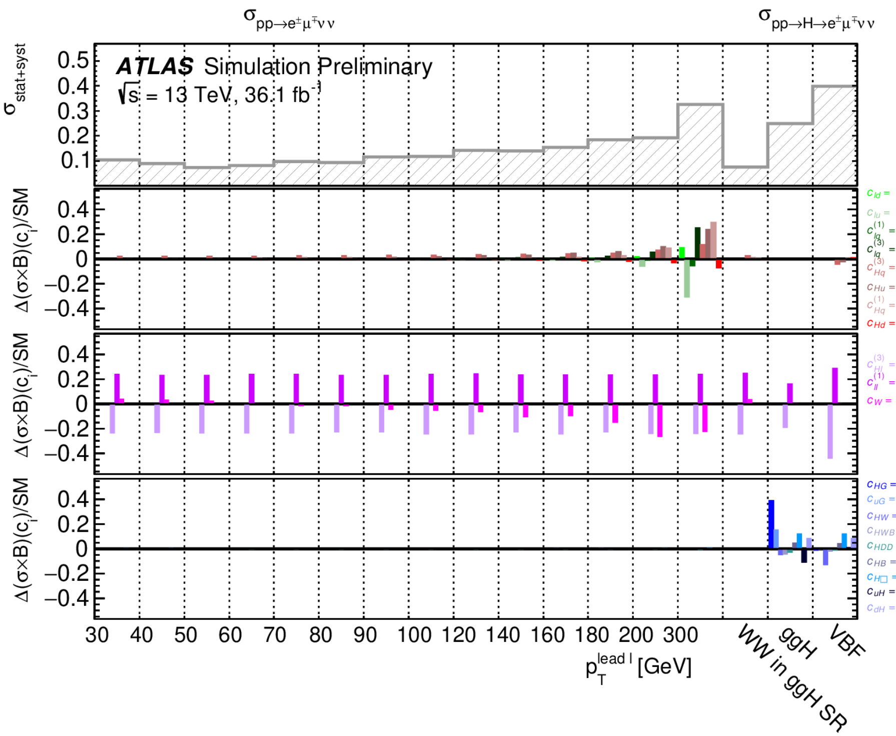
Search for new physics in top quark production with additional leptons in proton-proton collisions at s√= 13 TeV using effective field theory
CMS-TOP-19-001

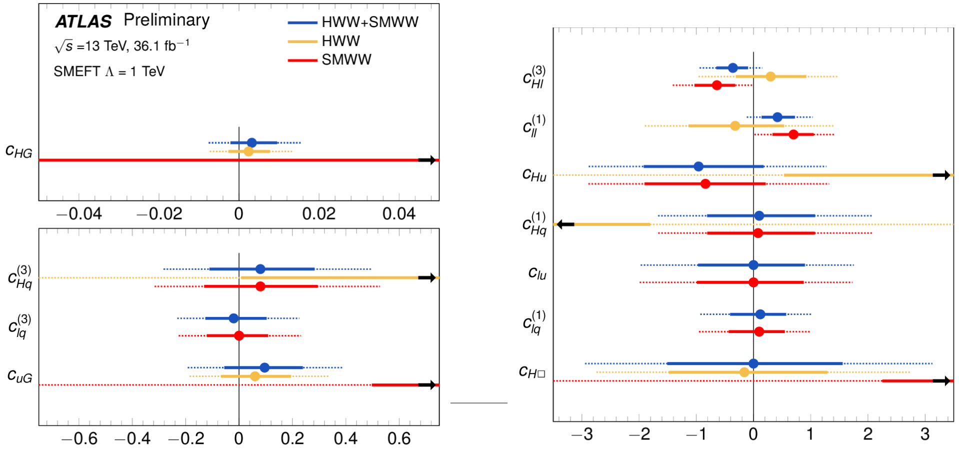
Top EFT summary plots December 2021
ATL-PHYS-PUB-2021-043

ATLAS: HWW and WW cross-section combination

- Combination uses the **likelihood function obtained in the signal strength fit** of the Higgs measurement together with the **unfolded differential cross-sections** for the WW process
- Technically ambitious combination and proof of principle of feasibility due to combination of different “flavours” of measurements and overlaps (signal definition however orthogonal)
- There is partially overlapp with the control regions used in the Higgs analysis

  → Degradation of 10% of ggH measurement





Parameter value (single operator fit)

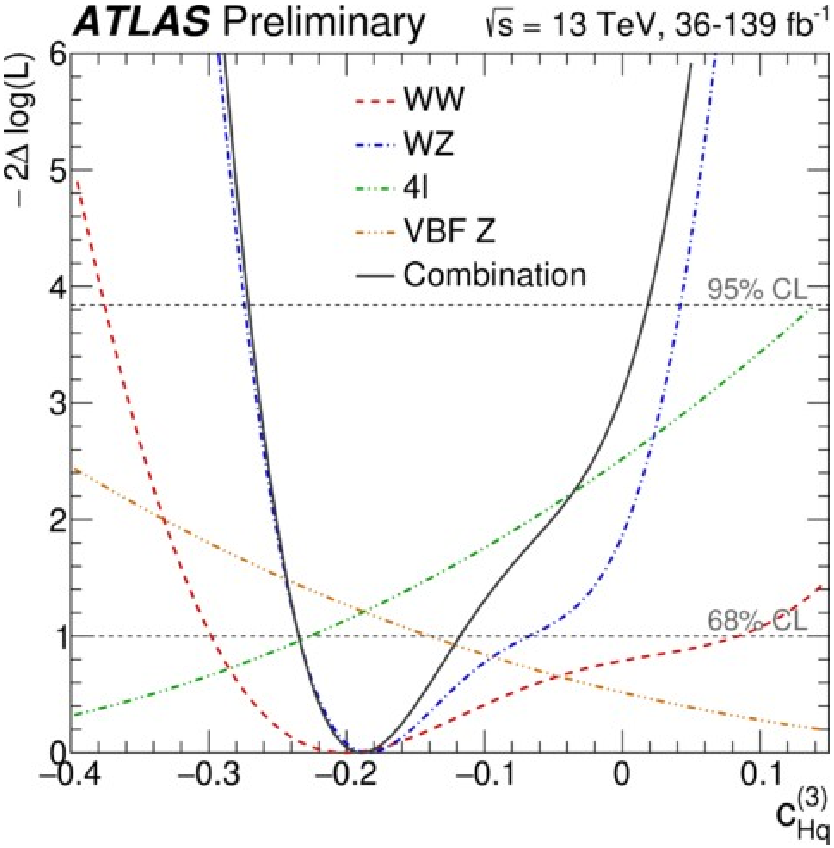
Combined EFT interpretation of H to WW and WW processes
ATL-PHYS-PUB-2021-010

ATLAS: SM cross-section combination

- Post-mortem combination of unfolded differential cross-sections of WW, WZ, 4-lepton and Z+2jets
- Combined likelihood function accounts for experimental uncertainties and correlation as well as theory uncertainties
- Correlations lead to degradation of profiled limits
→ will improve once more measurements are included
- Constrain of single operators whilst others are set to zero can be misleading:

  → UV-BSM models rarely translate to one operator only

  → one-operator fits can yield non-zero values



Combined EFT analysis of WW, WZ, ZZ, VBF Z processes
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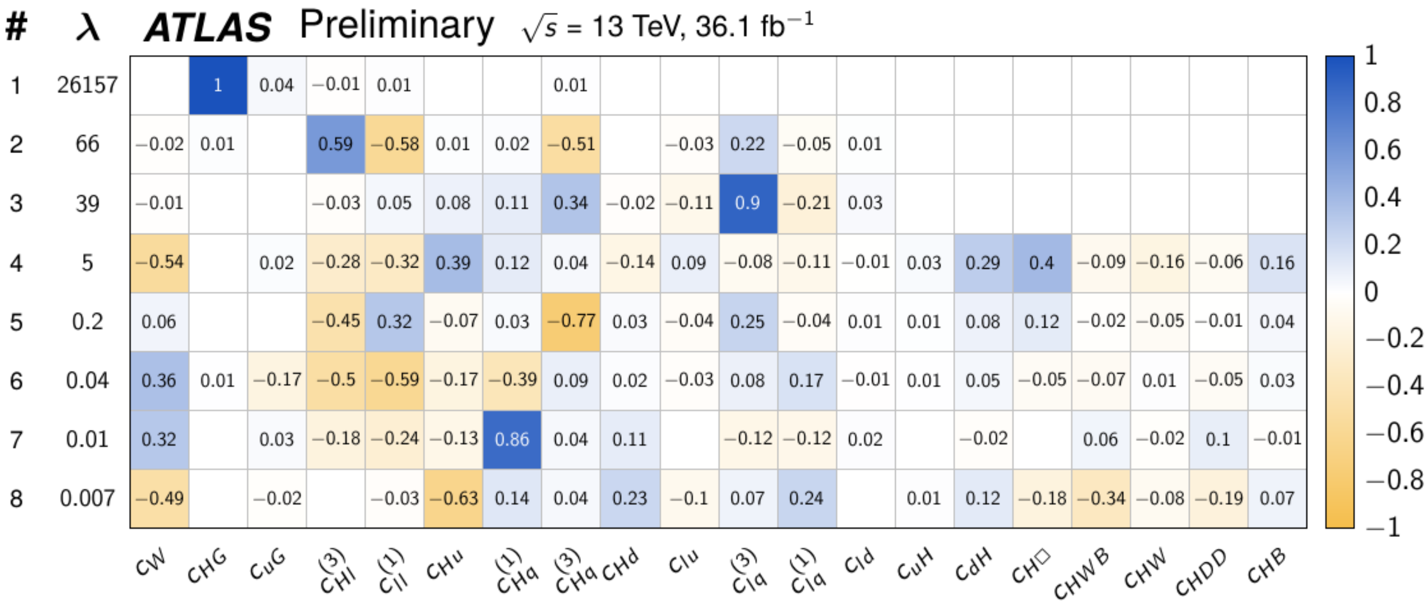
Principle component analysis (PCA)

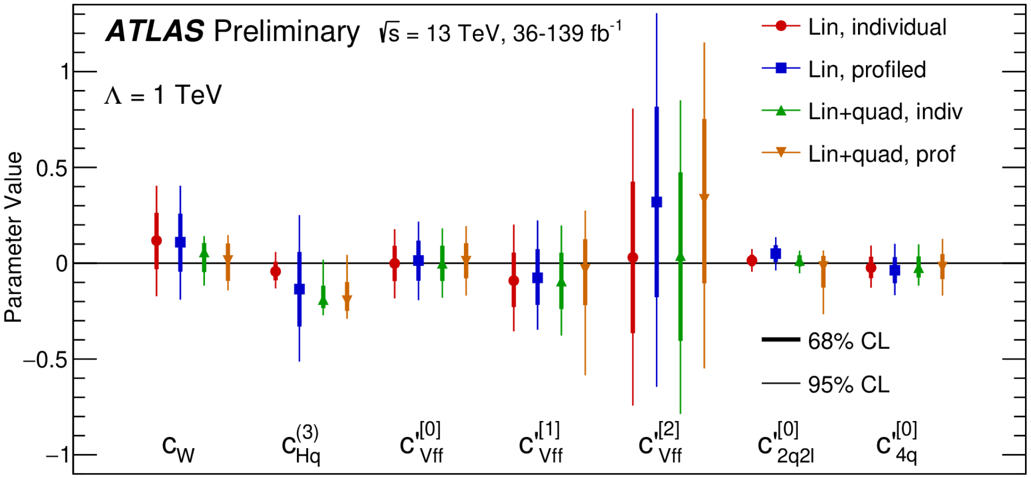


#	λ	c_W	c_{HG}	c_{uG}	$c_{Hl}^{(3)}$	$c_{ll}^{(1)}$	c_{Hu}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$	c_{Hd}	c_{lu}	$c_{lq}^{(3)}$	$c_{lq}^{(1)}$	c_{ld}	c_{uH}	c_{dH}	$c_{H\Box}$	c_{HWB}	c_{HW}	c_{HDD}	c_{HB}
1	26157		1	0.04	−0.01	0.01			0.01												
2	66	−0.02	0.01		0.59	−0.58	0.01	0.02	−0.51		−0.03	0.22	−0.05	0.01							
3	39	−0.01			−0.03	0.05	0.08	0.11	0.34	−0.02	−0.11	0.9	−0.21	0.03							
4	5	−0.54		0.02	−0.28	−0.32	0.39	0.12	0.04	−0.14	0.09	−0.08	−0.11	−0.01	0.03	0.29	0.4	−0.09	−0.16	−0.06	0.16
5	0.2	0.06			−0.45	0.32	−0.07	0.03	−0.77	0.03	−0.04	0.25	−0.04	0.01	0.01	0.08	0.12	−0.02	−0.05	−0.01	0.04
6	0.04	0.36	0.01	−0.17	−0.5	−0.59	−0.17	−0.39	0.09	0.02	−0.03	0.08	0.17	−0.01	0.01	0.05	−0.05	−0.07	0.01	−0.05	0.03
7	0.01	0.32		0.03	−0.18	−0.24	−0.13	0.86	0.04	0.11		−0.12	−0.12	0.02		−0.02		0.06	−0.02	0.1	−0.01
8	0.007	−0.49		−0.02		−0.03	−0.63	0.14	0.04	0.23	−0.1	0.07	0.24		0.01	0.12	−0.18	−0.34	−0.08	−0.19	0.07

- Constraints often strongly correlated (especially in linear fit)
- Using PCA to find sensitive and blind directions
- Directions correspond to eigenvectors of Hessian matrix at minimum of Likelihood

ATLAS: SM cross-section combination

- Sensitive to 33 operators – constrained are 2 operators (cW, $cHq^{(3)}$) and 13 linear combinations
- Comparison of linear and quadratic limits can give estimate of convergence of SMEFT extension and uncertainties



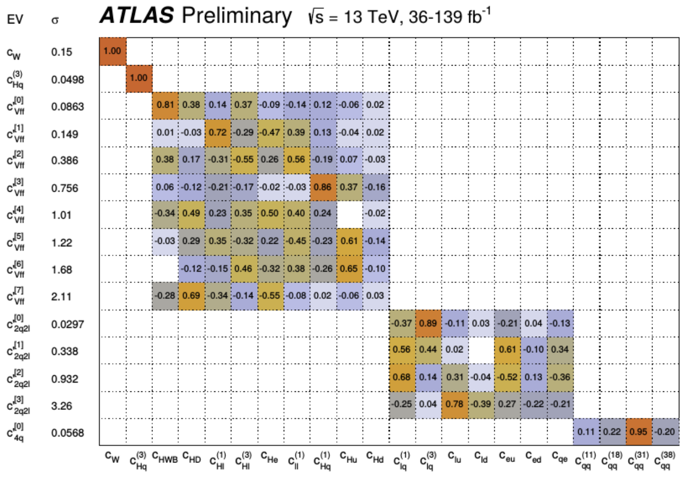
$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c_{Hl}^{(1)} + 0.37c_{Hl}^{(3)} - 0.14c_{ll}^{(1)} + 0.12c_{Hq}^{(1)}$

$c'^{[1]}_{Vff} \approx 0.73c_{Hl}^{(1)} - 0.28c_{Hl}^{(3)} - 0.48c_{He} + 0.38c_{ll}^{(1)} + 0.13c_{Hq}^{(1)}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c_{Hl}^{(1)} - 0.53c_{Hl}^{(3)} + 0.25c_{He} + 0.59c_{ll}^{(1)} - 0.21c_{Hq}^{(1)}$

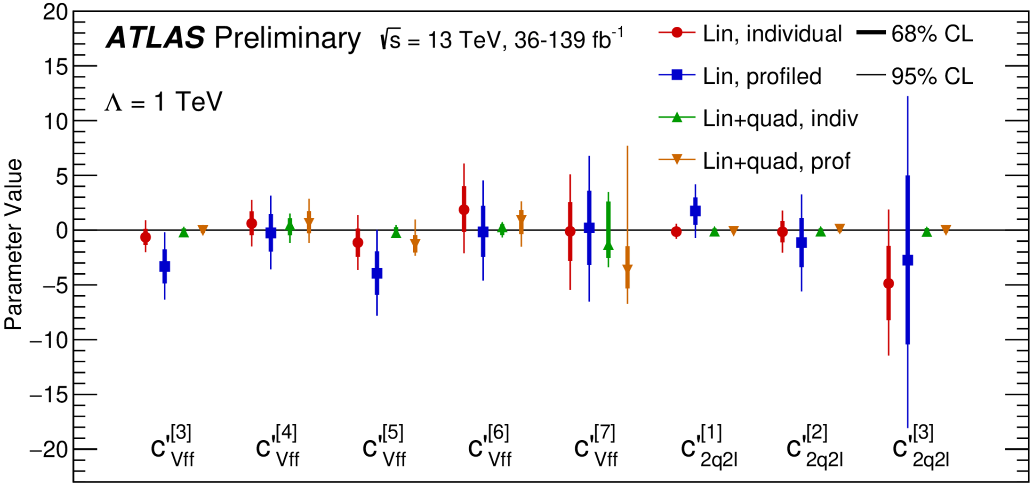
$c'^{[0]}_{2q2l} \approx -0.37c_{lq}^{(1)} + 0.89c_{lq}^{(3)} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c_{qq}^{(11)} + 0.22c_{qq}^{(18)} + 0.95c_{qq}^{(31)} - 0.2c_{qq}^{(38)}$



ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 36-139 fb^{-1}

EV	σ	c_W	$c_{Hq}^{(3)}$	c_{HWB}	c_{HD}	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	c_{He}	$c_{ll}^{(1)}$	$c_{Hq}^{(1)}$	c_{Hu}	c_{Hd}	$c_{lq}^{(1)}$	$c_{lq}^{(3)}$	c_{lu}	c_{ld}	c_{eu}	c_{ed}	c_{qe}	$c_{qq}^{(11)}$	$c_{qq}^{(18)}$	$c_{qq}^{(31)}$	$c_{qq}^{(38)}$
c_W	0.15	1.00																					
$c_{Hq}^{(3)}$	0.0498		1.00																				
$c'^{[0]}_{Vff}$	0.0863			0.81	0.38	0.14	0.37	-0.09	-0.14	0.12	-0.06	0.02											
$c'^{[1]}_{Vff}$	0.149			0.01	-0.03	0.72	-0.29	-0.47	0.39	0.13	-0.04	0.02											
$c'^{[2]}_{Vff}$	0.386			0.38	0.17	-0.31	-0.55	0.26	0.56	-0.19	0.07	-0.03											
$c'^{[3]}_{Vff}$	0.756			0.06	-0.12	-0.21	-0.17	-0.02	-0.03	0.86	0.37	-0.16											
$c'^{[4]}_{Vff}$	1.01			-0.34	0.49	0.23	0.35	0.50	0.40	0.24		-0.02											
$c'^{[5]}_{Vff}$	1.22			-0.03	0.29	0.35	-0.32	0.22	-0.45	-0.23	0.61	-0.14											
$c'^{[6]}_{Vff}$	1.68				-0.12	-0.15	0.46	-0.32	0.38	-0.26	0.65	-0.10											
$c'^{[7]}_{Vff}$	2.11			-0.28	0.69	-0.34	-0.14	-0.55	-0.08	0.02	-0.06	0.03											
$c'^{[0]}_{2q2l}$	0.0297												-0.37	0.89	-0.11	0.03	-0.21	0.04	-0.13				
$c'^{[1]}_{2q2l}$	0.338												0.56	0.44	0.02		0.61	-0.10	0.34				
$c'^{[2]}_{2q2l}$	0.932												0.68	0.14	0.31	-0.04	-0.52	0.13	-0.36				
$c'^{[3]}_{2q2l}$	3.26												-0.25	0.04	0.78	-0.39	0.27	-0.22	-0.21				
$c'^{[0]}_{4q}$	0.0568																			0.11	0.22	0.95	-0.20



$c'^{[3]}_{Vff} \approx -0.19c_{Hl}^{(1)} - 0.14c_{Hl}^{(3)} + 0.86c_{Hq}^{(1)} + 0.41c_{Hu} - 0.17c_{Hd}$

$c'^{[4]}_{Vff} \approx -0.35c_{HWB} + 0.49c_{HD} + 0.26c_{Hl}^{(1)} + 0.35c_{Hl}^{(3)} + 0.51c_{He} + 0.38c_{ll}^{(1)} + 0.18c_{Hq}^{(1)}$

$c'^{[5]}_{Vff} \approx 0.25c_{HD} + 0.33c_{Hl}^{(1)} - 0.22c_{Hl}^{(3)} + 0.18c_{He} - 0.35c_{ll}^{(1)} - 0.3c_{Hq}^{(1)} + 0.71c_{Hu} - 0.16c_{Hd}$

$c'^{[6]}_{Vff} \approx -0.22c_{Hl}^{(1)} + 0.52c_{Hl}^{(3)} - 0.39c_{He} + 0.44c_{ll}^{(1)} - 0.22c_{Hq}^{(1)} + 0.52c_{Hu}$

$c'^{[7]}_{Vff} \approx -0.28c_{HWB} + 0.71c_{HD} - 0.31c_{Hl}^{(1)} - 0.21c_{Hl}^{(3)} - 0.5c_{He} - 0.14c_{ll}^{(1)}$

$c'^{[1]}_{2q2l} \approx 0.56c_{lq}^{(1)} + 0.44c_{lq}^{(3)} + 0.61c_{eu} - 0.1c_{ed} + 0.34c_{qe}$

$c'^{[2]}_{2q2l} \approx 0.68c_{lq}^{(1)} + 0.15c_{lq}^{(3)} + 0.33c_{lu} - 0.51c_{eu} + 0.13c_{ed} - 0.37c_{qe}$

$c'^{[3]}_{2q2l} \approx -0.27c_{lq}^{(1)} + 0.79c_{lu} - 0.39c_{ld} + 0.26c_{eu} - 0.22c_{ed} - 0.16c_{qe}$

Combined EFT analysis of WW, WZ, ZZ, VBF Z processes
ATL-PHYS-PUB-2021-022

Towards a global fit: LHC EFT WG

- Goal of the LHC EFT WG: provide guidance for the interpretation of LHC data in the context of effective field theories (EFTs).
  https://lpcc.web.cern.ch/lhc-eft-wg

- **Areas of interest:**
  → Basics / EFT formalism
  → Predictions and tools
  → Experimental measurements and observables
  → **Fits and related systematics**
  → Benchmark scenarios from UV models
  → Interplay/connection with flavour

- **Experimental combination between ATLAS and CMS**
  → Kick-off: https://indico.cern.ch/event/1007581/ **(Feb 22, 2021)**
  - Use combination project to get feedback and advice from the LHC WG but also to help focus the WG discussions on something concrete and help those discussions converge, in some cases break the symmetry

Scope of combination:
- Cross-experimental (ATLAS+CMS)
- Cross-topical (i.e. including top, Higgs and EWK measurements)

- Effective field theory is a general extension of the SM
- Constraints on EFT operators provide constraints on BSM physics that are more general than direct searches
- However: Need to combine a larger number of measurements
- Global EFT fits within experiments have started
  - Complementary to fits of theory collaborations

Conclusion

- Global effective field theories are a way to test the SM
- Complementary approach to direct BSM searches
- Requires strong interplay between theory and experiment

  → Demonstrated for measurements with two W-boson

  → Precision predictions and measurements are important
- Steps towards global EFT fits within the experiments

  → Working towards combined fit between ATLAS and CMS

Backup slides.

Characterise the Standard Model

- Effective field theory is a general SM extension
- Allows to identify deviations in a systematic (and renormalizable) way

Operators:
Which particles interact?

Coupling strength:
How strong is the interaction?

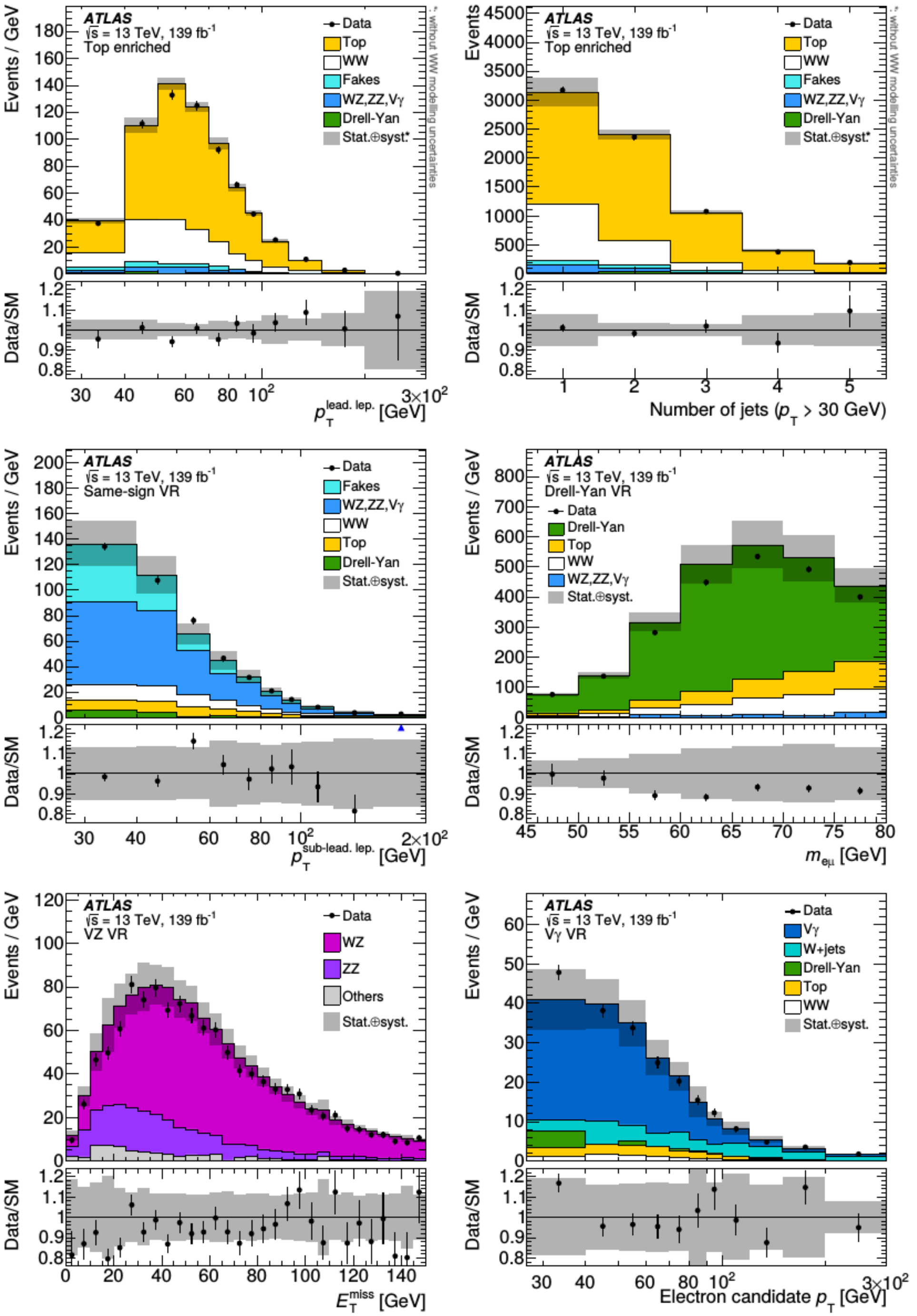
$$\mathcal{L} = \underset{\text{Standard model}}{\boxed{\mathcal{L}_{\mathrm{SM}}}} + \sum_{d>4}\sum_{\mathrm{i}} \frac{\boxed{c_{\mathrm{i}}^{d}}}{\boxed{\Lambda^{d-4}}} \boxed{\mathcal{O}_{\mathrm{i}}^{d}}$$

General extension: describes **any new phenomena** suppressed by $\boxed{\textbf{energy scale } \Lambda^{(\text{dimension d - 4})}}$

d ≤ 4 → Standard model
d = 5 → *Neutrino masses*

d ≥ 6 → Unknown phenomena

WW production at the LHC



Dimension-6 EFT Bases

There are 2499 CP-even dimension-6 operators

- Need to reduce redundancy → also using some assumptions
- Usually: minimal flavour violation, no CP-violation, lepton/baryon numbers

Further requirements

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ should be included
- EFT should reduce to SM (if there are no undiscovered light particles)
- Higgs field is included (not te case for anomalous triple gauge couplings) and linearly realised (otherwise: Higgs-EFT)
- Wilson coefficients are arbitrary (and can differ between bases!)

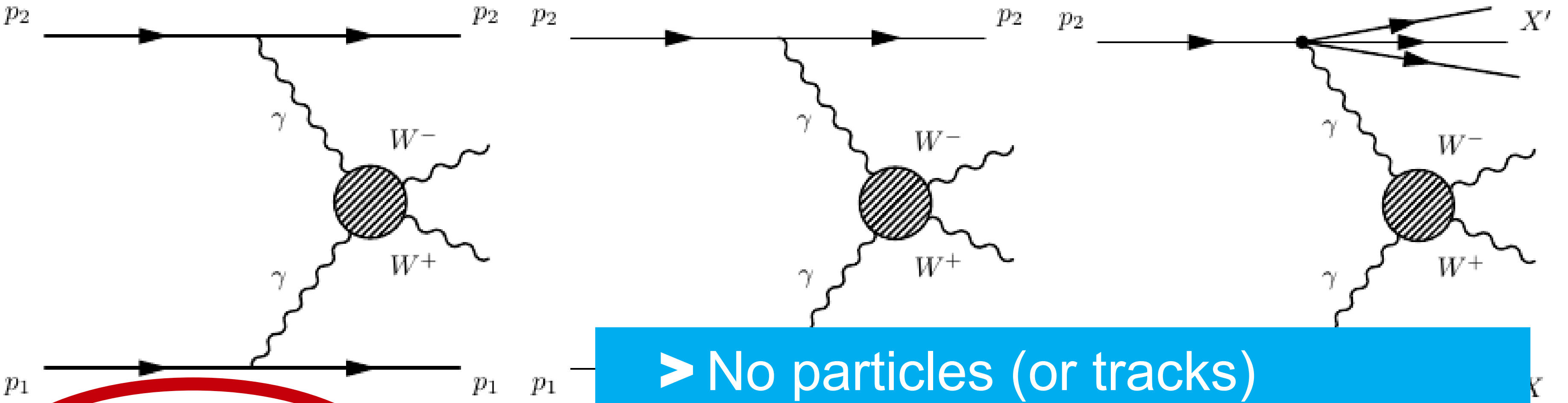
Most popular: Warsaw basis

- 59 operators (when considering only 1 generation)
- Renormalization Group and 1-loop finite renormalization (SMEFT@NLO)

Still not trivial: what is the order of the EFT expansion to be considered?

$$\sigma = \sigma_{\text{SM}} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\sigma_i^{\text{dim-6-interf}}}_{\text{Linear}} + \underbrace{\sum_{ij} \frac{c_i c_j}{\Lambda^4}\sigma_{ij}^{(\text{dim-6})^2}}_{\text{quadratic}} + \underbrace{\sum_k \frac{c_k}{\Lambda^4}\sigma_k^{\text{dim-8-interf}}}_{\text{dim-8}} + \ldots$$

$\gamma\gamma \rightarrow$ WW production at the LHC



elastic (EE)

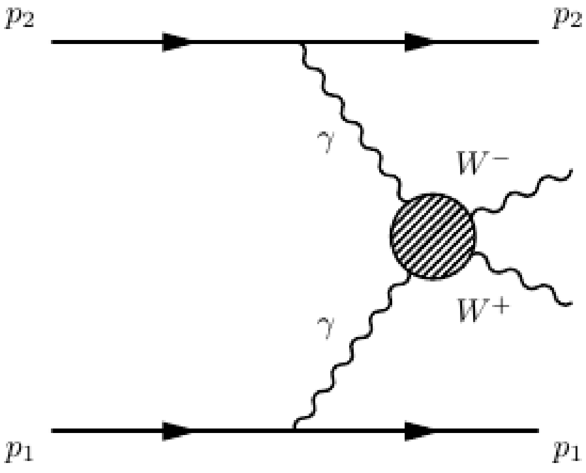
no particles other than W decay products

semi-dis

D)

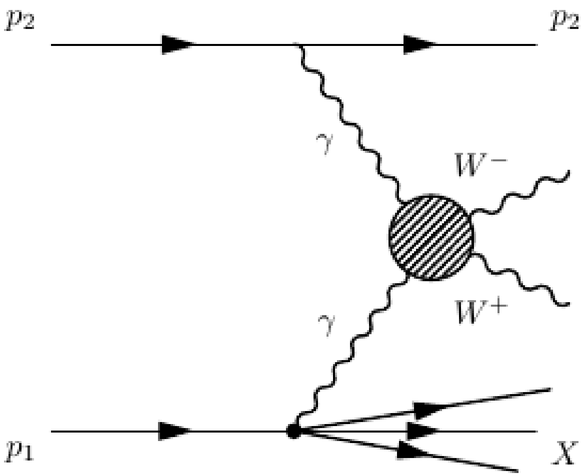
- No particles (or tracks) associated with the primary interaction vertex
  → **Track reconstruction**
  → **Vertex definition**

$\gamma\gamma \rightarrow$ WW production at the LHC

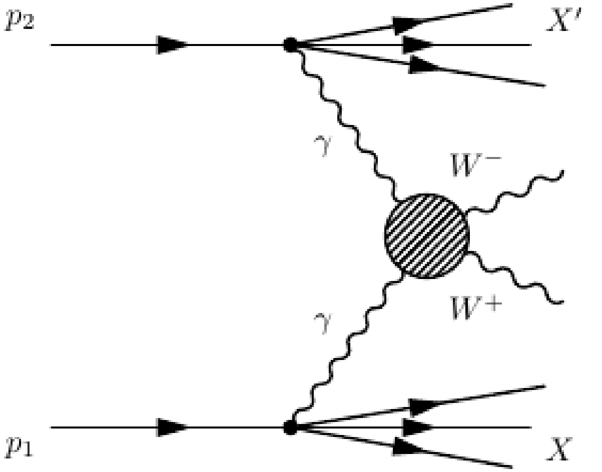


elastic (EE)

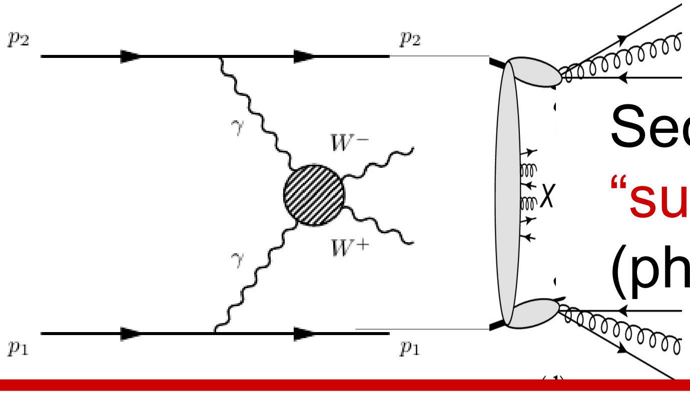
no particles other than W decay products



semi-dissociative (SD)



double-dissociative (DD)

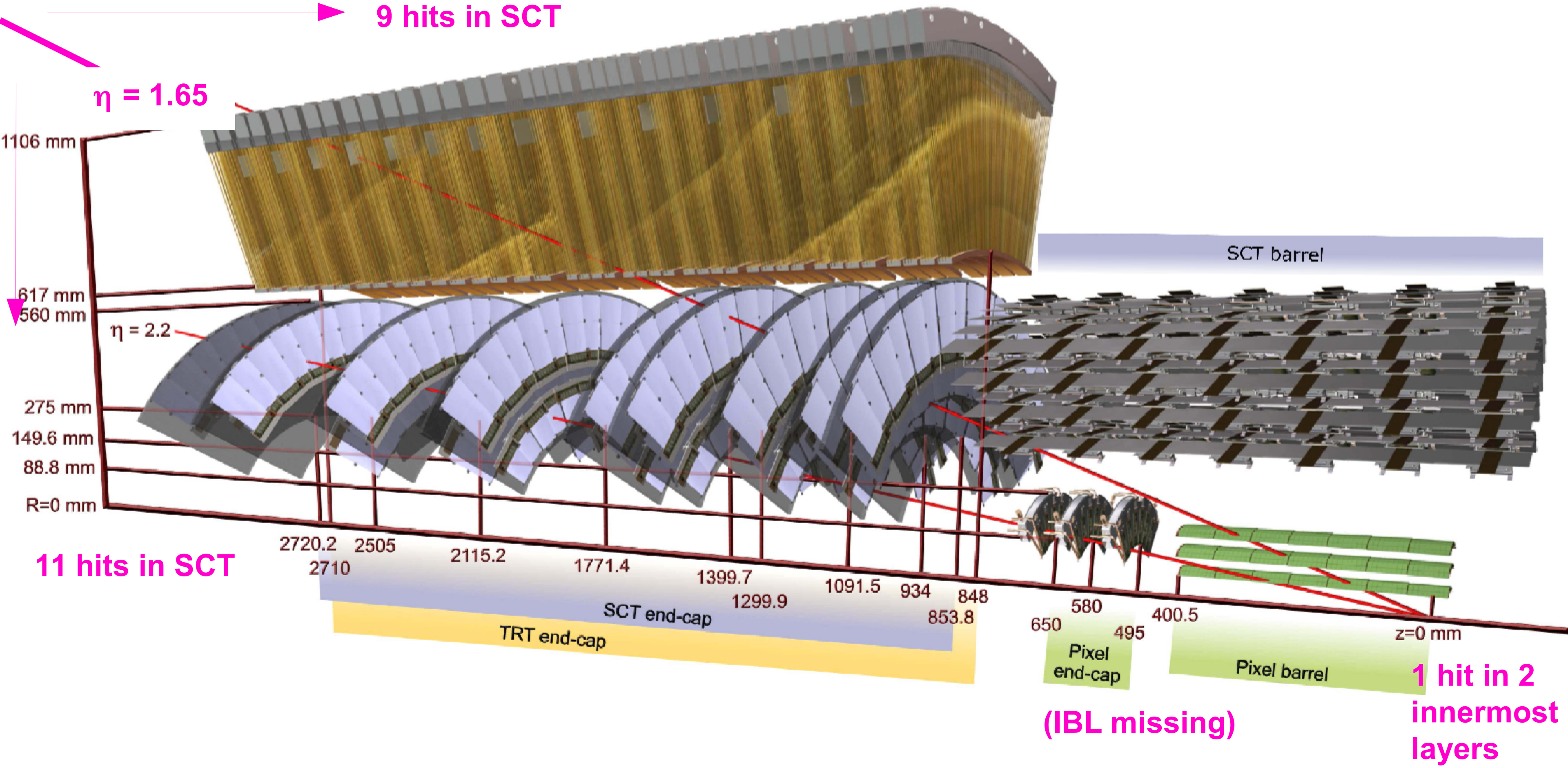


Second scattering:
"survival factor"
(phenomenological)

Reduces "visible" cross-section of elastic production (additional particles)

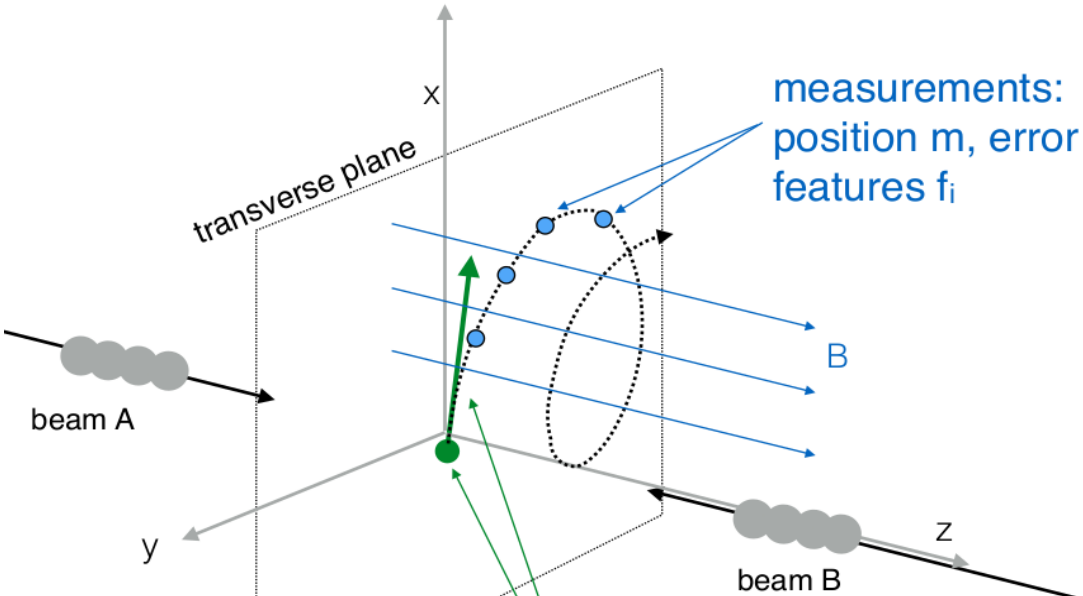
→ **Signal correction**

The ATLAS inner detector



- Accurately reconstructing as many charged-particle tracks as possible is key!
- Innermost tracking layer at r = 33.5 mm (pixel size: 50 × 250 μm^2)
  Intrinsic spacial resolution: 10 × 75 μm^2

Track reconstruction

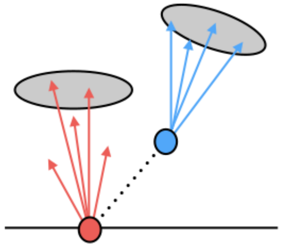


measurements:
position m, error σ(m),
features f_i

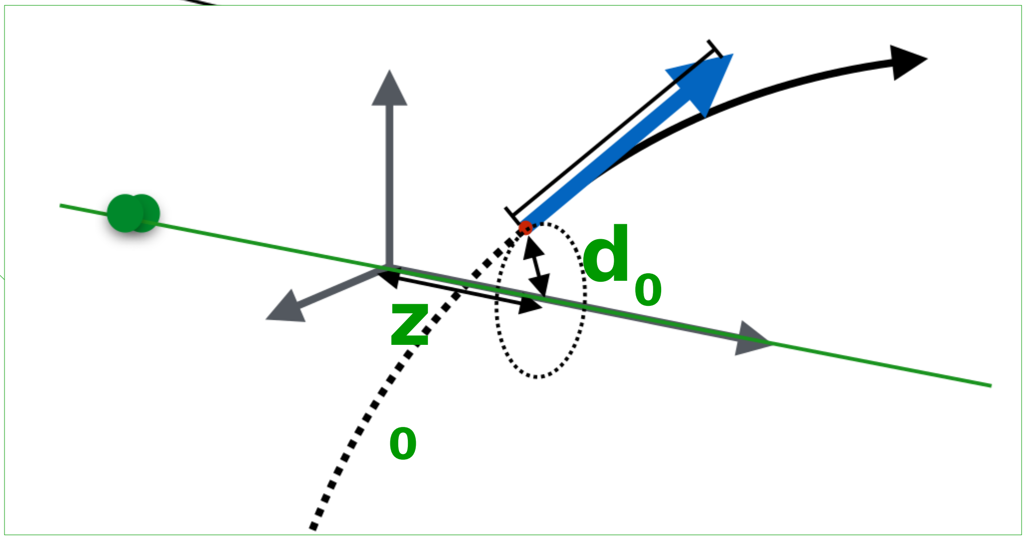
Track parameters:
ϕ, θ, q/p, $\boxed{d_0,\ z_0}$

pseudo-rapidity η
charge
transverse momentum

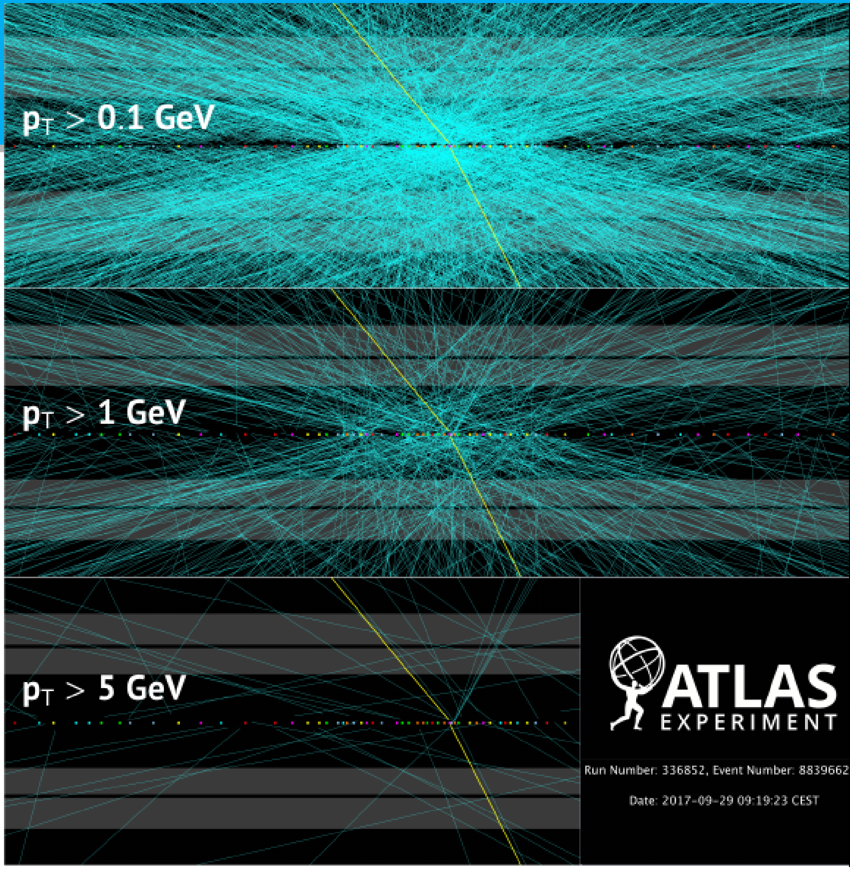
- PT > 500 MeV
- |η| < 2.5
- $|d_0|$<1mm
- **$|z_0|$<1mm**



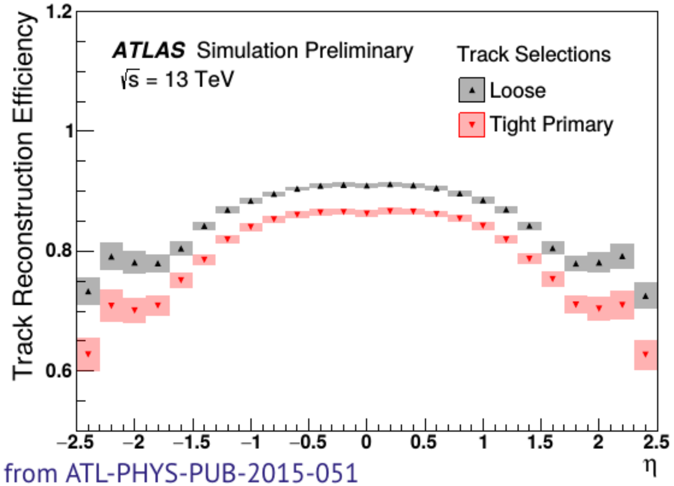
Secondary particles



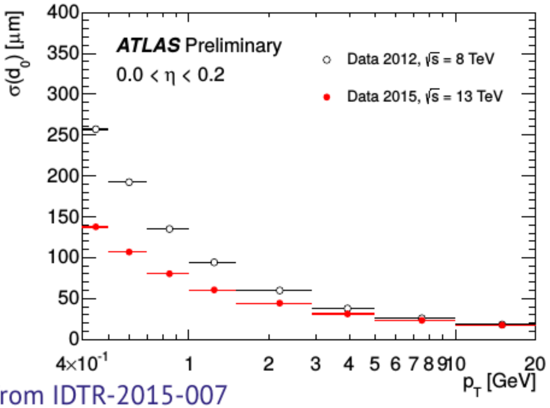
Tracking performance



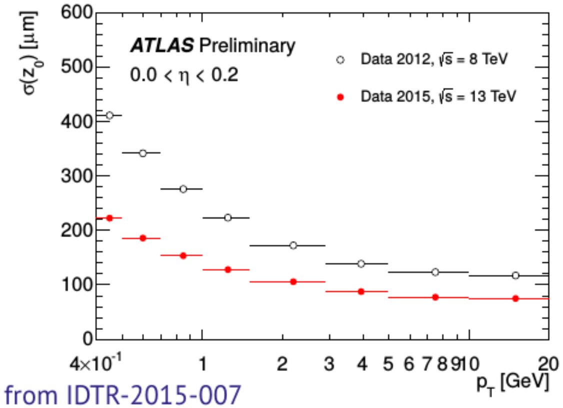
- Track efficiency ~75-80%
- Tracks are the largest consumer of CPU and disk space in ATLAS → only tracks with pT > 500 MeV are available for analysis
- Lower pT → worse resolution (multiple scattering)



from ATL-PHYS-PUB-2015-051



from IDTR-2015-007



from IDTR-2015-007

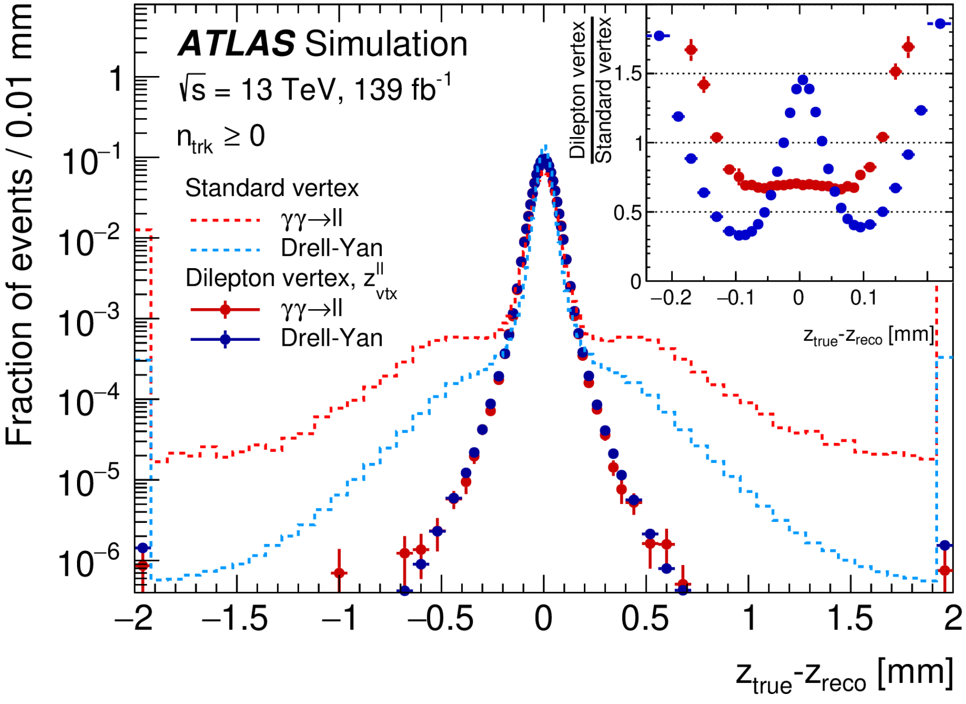
Vertex reconstruction

- ATLAS standard is to choose vertex with the largest $\sum p_T^2$ as *primary*
- Not optimal for photon-induced processes, here leptons are used to reconstruct the interaction vertex:

$$z_{\mathrm{vtx}}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

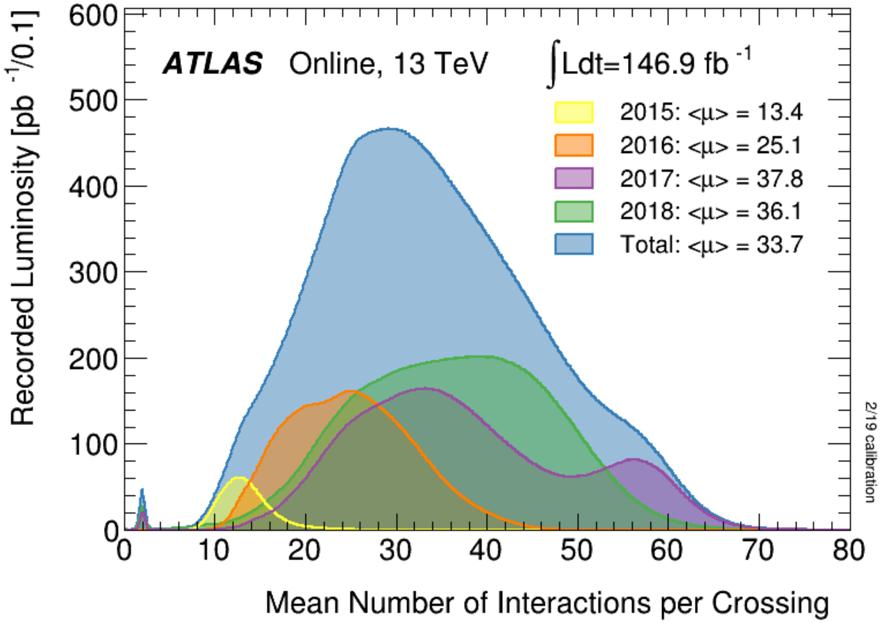
($\sin^2\theta$ parametrizes uncertainty on measured z position)

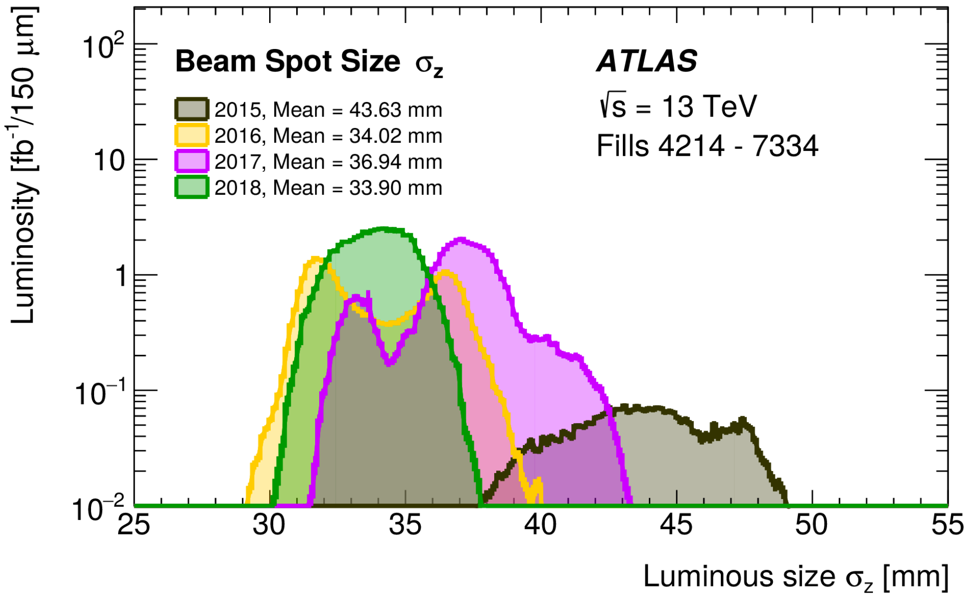
- This definition is **more efficient** and **unbiased*** by close-by pileup tracks



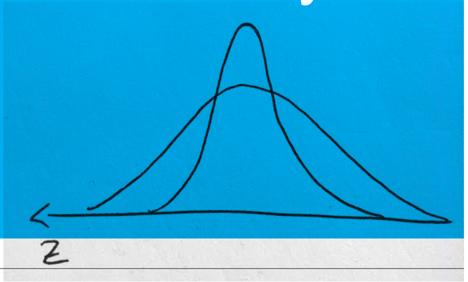
*backup

Pile-up in the context of the measurement



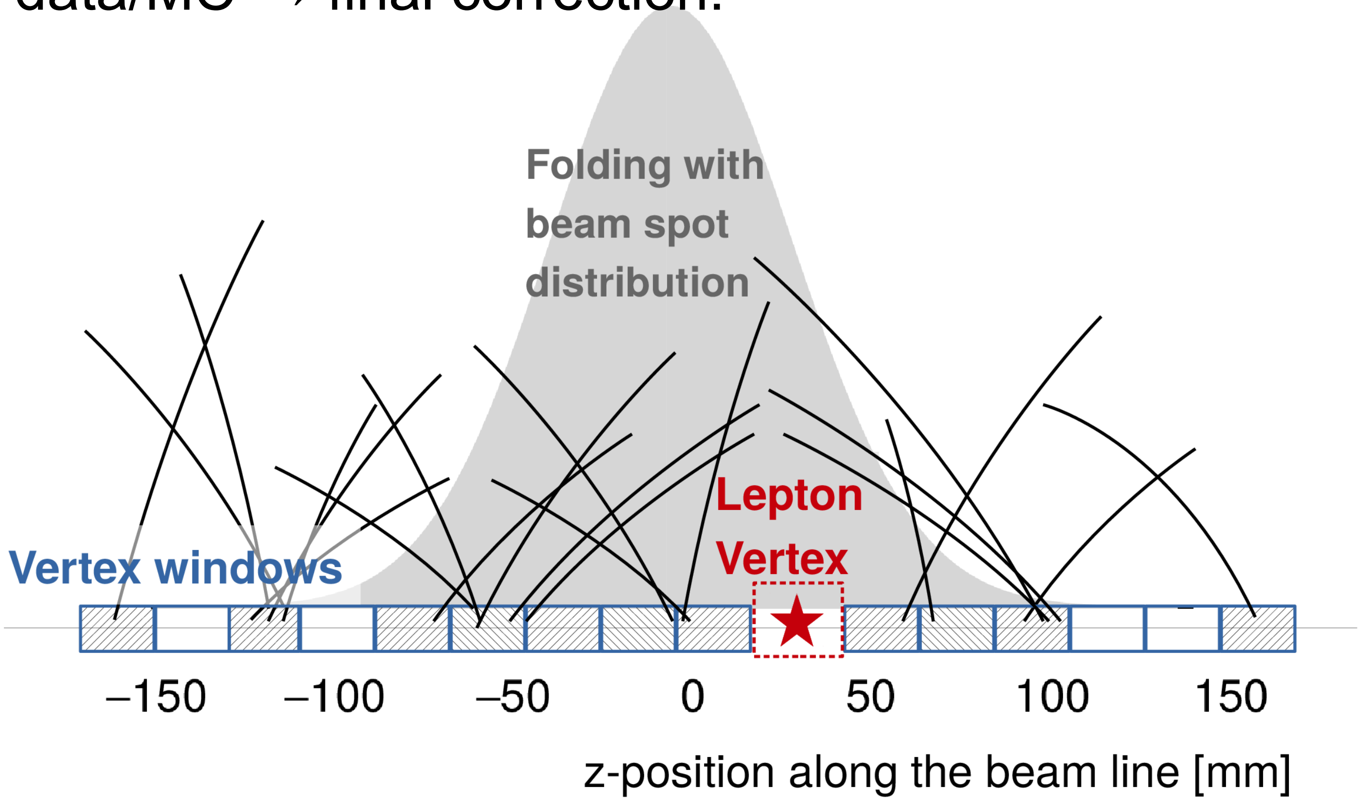


- Pile-up is the number of *pp* interactions per bunch crossing
- Longitudinal width of the beam spot determines density of additional *pp* interaction along z
- Corrected for using reweighting approach



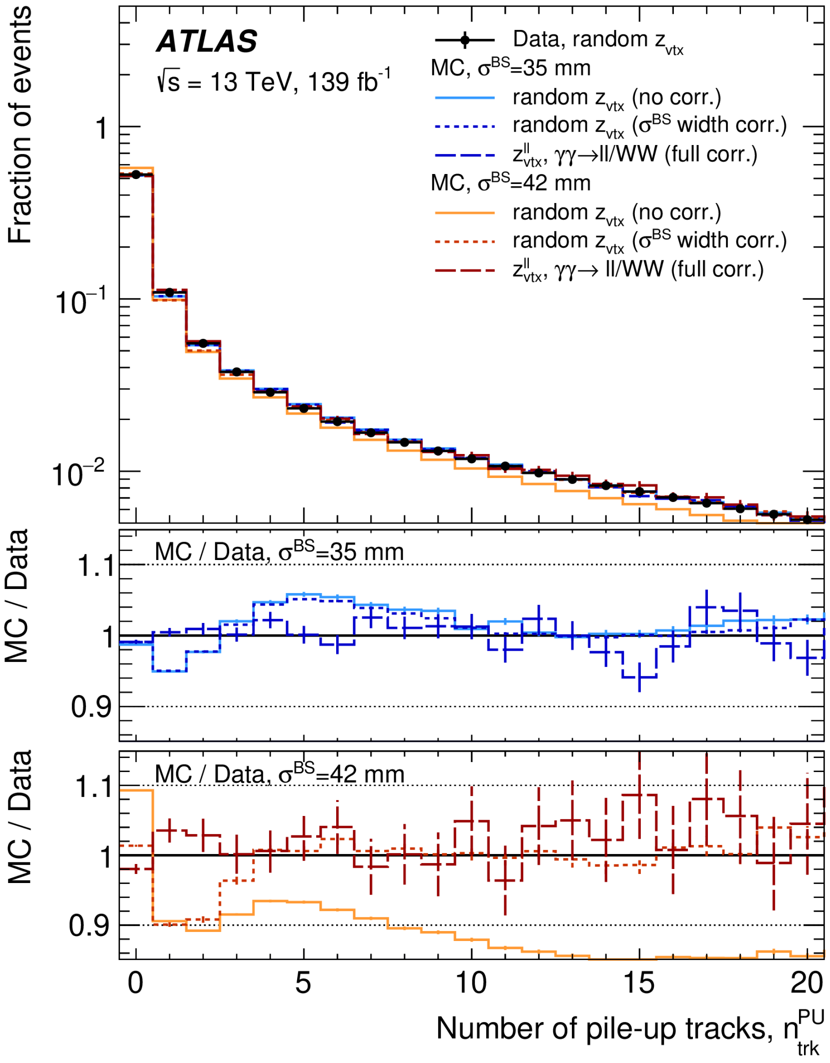
Correcting number of tracks per pile-up vertex

- Same procedure in data and MC: Sample number of tracks in random windows along z (away from lepton vertex)
- Weight with beam spot distribution
- Divide data/MC → final correction!



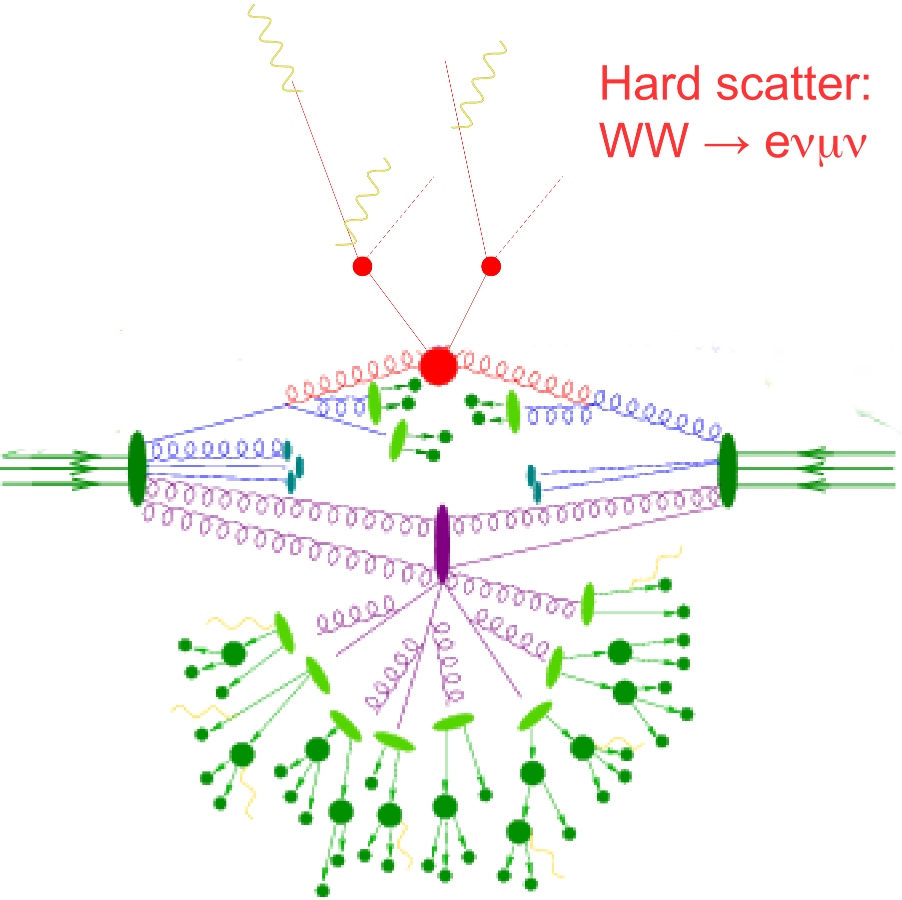
Pile-up correction at work

- Full set of correction gives good agreement between data and MC
- Efficiency to select 0-tracks in presence of pile-up is on average 52.6% for Run 2 *(exclusive efficiency)*
- Large source of efficiency loss → worsens with number of interactions*



*backup

Modelling of underlying event



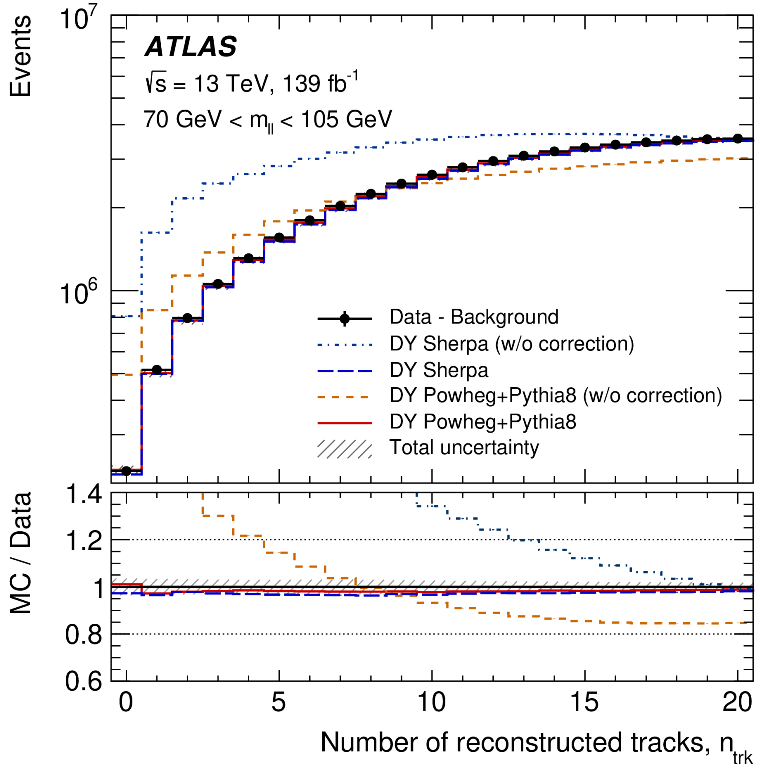
Hard scatter:
WW → eνμν

Underlying event: Interactions of proton remnants, fragmentations

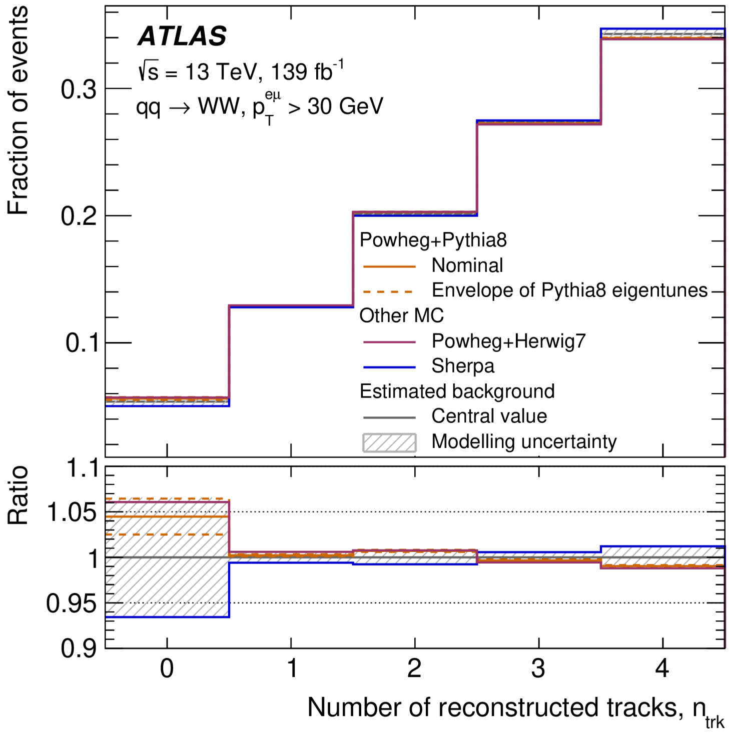
- qq/gg → WW has the same final state as γγ →WW apart from underlying event
- Problems with modelling of charge particle (track) multiplicity at low momentum are well known*
→ **need to apply in-situ correction to model WW background correctly**
- Use Z boson and unfold charged particle distribution as function of:
– particle multiplicity
– p_T(ll) (measure for p_T([di]boson))

*backup

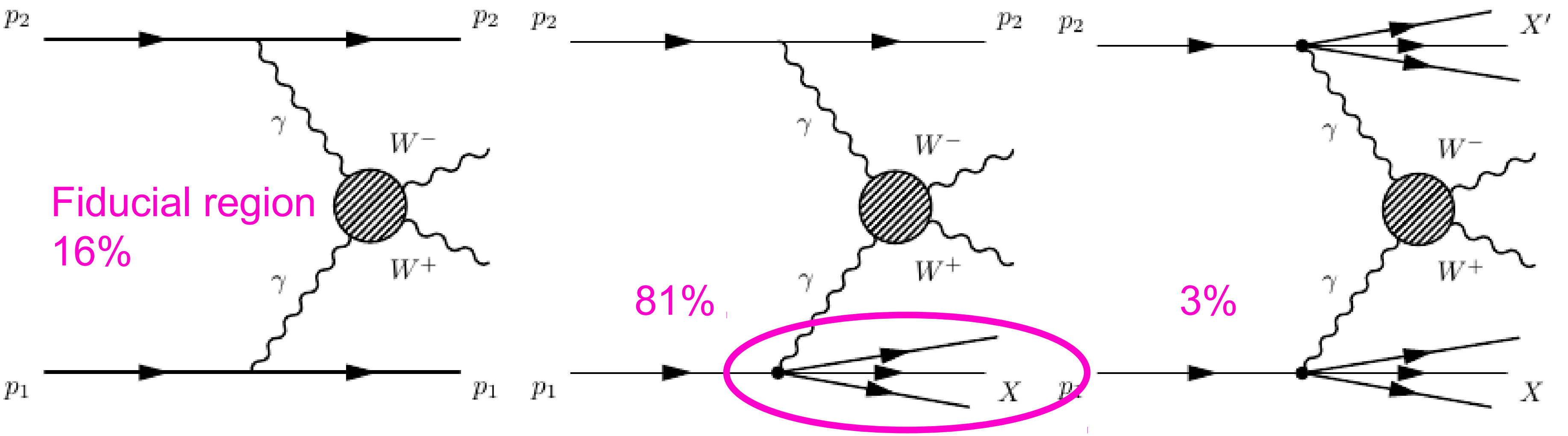
Modelling of underlying event



- For qq→WW: Good agreement for $1 \leq n_{trk} \leq 4$ but $n_{trk}=0$ has large differences between hadronic models
- Use midpoint and envelope for WW prediction (7% syst.)
- Correction can be up to a factor of 5! → good agreement with data afterwards
- Apply unfolded charged particle distribution as function of $p_T(V)$ to DY (as function of $p_T(VV)$ to diboson events)



Signal Modelling: Why?



Fiducial region 16%

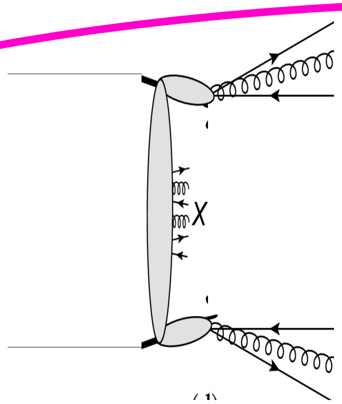
81%

3%

elastic (EE) semi-dissociative (SD) double-dissociative (DD)

most reliable theory

Difficult to model!!

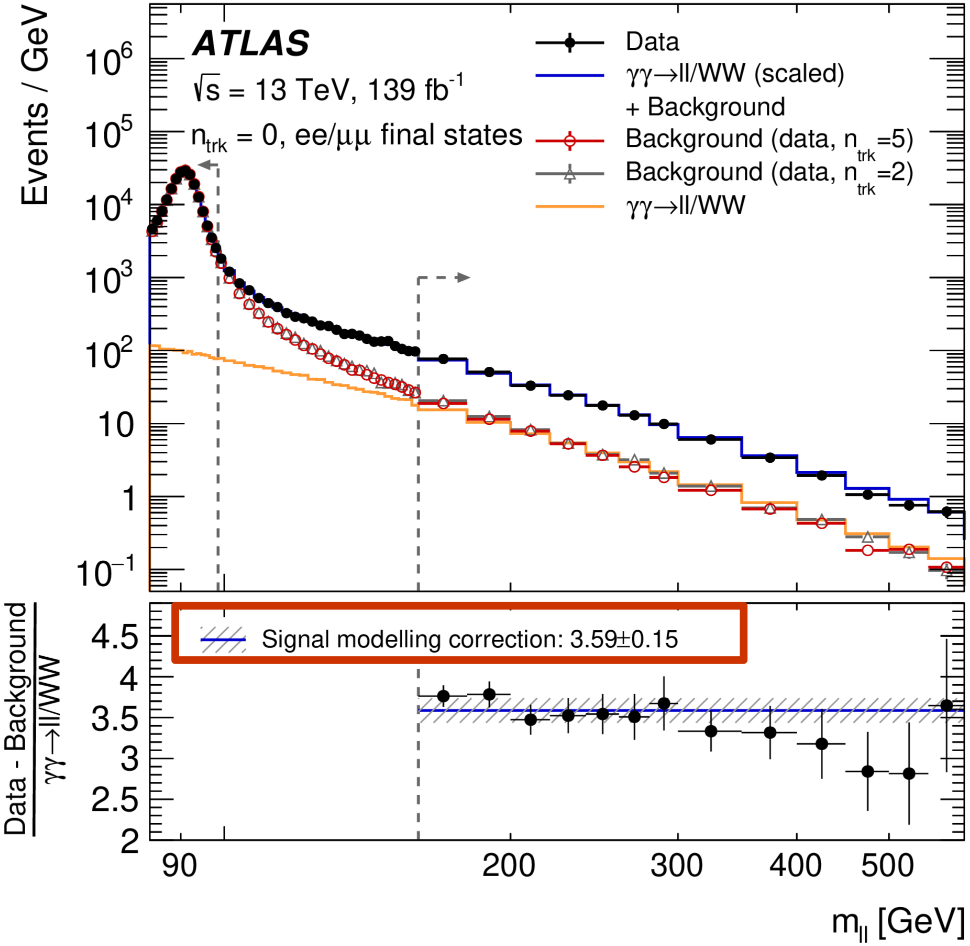


Second scattering: "survival factor" (phenological)

Reduces "visible" cross-section of elastic production → additional particles

Signal Modelling: How?

- Data-driven scaling of $\gamma\gamma \rightarrow WW$ using $\gamma\gamma \rightarrow \ell\ell$ same flavour events for a signal-like selection (n_{trk}=0, $m_{\ell\ell}$ > 160 MeV)



- **Shape** of pp-induced backgrounds extracted for **n_{trk}= 5** (less than 1% γγ)
- **Normalization** from *Z*-peak region (**m_Z+/- 7.5 GeV**) (~0.5% of γγ)
- Both varied for systematics ~4%
- Scaling of **$\gamma\gamma \rightarrow WW/\ell\ell$** by **3.59 ± 0.15** yields good data/MC agreement