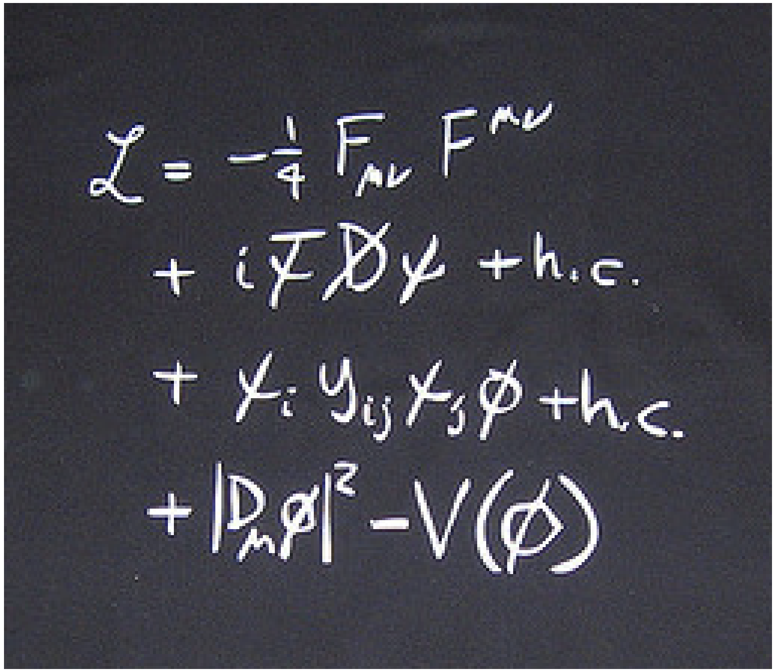
A window to new physics: Diboson production at the LHC



Kristin Lohwasser
University of Sheffield

Seminar, University of Liverpool, May 30th 2018

The Standard Model: A success story

Fermions:
Matter particles

Quarks

u c t

d s b

Leptons

ν_e ν_μ ν_τ

e μ τ

Bosons:
Force carriers

g — Strong force

γ — Electro-magentic force

Z, W — Weak force

Higgs Boson:
Found at last

H

describes fundamental forces and particles

complete and self-consistent theory

The Standard Model: Free parameters

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)

Parameters of the Standard Model [hide]

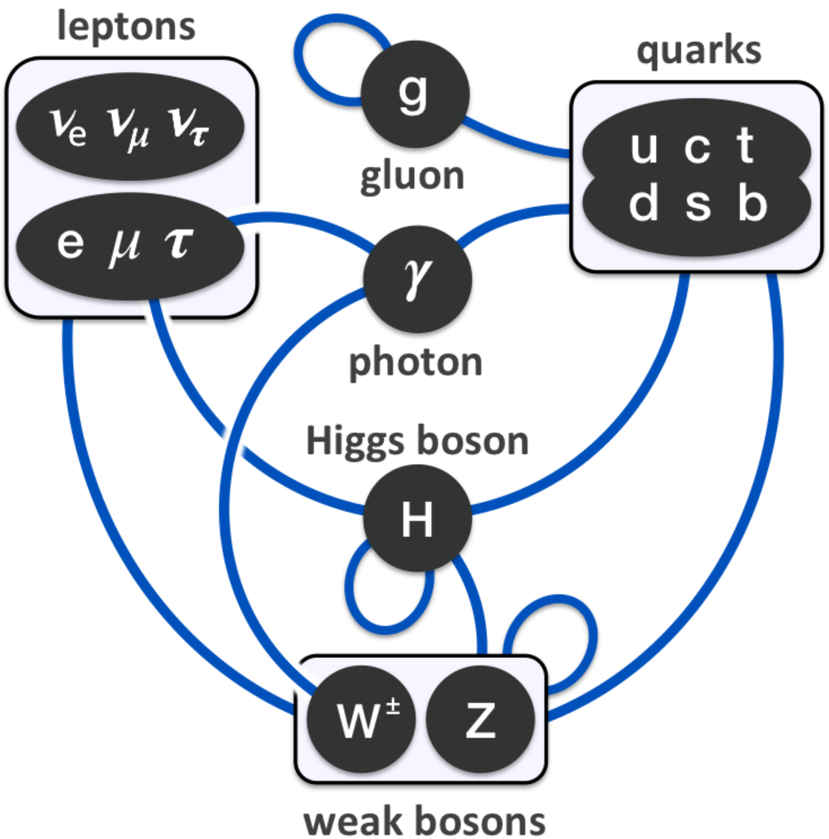
19 free parameters

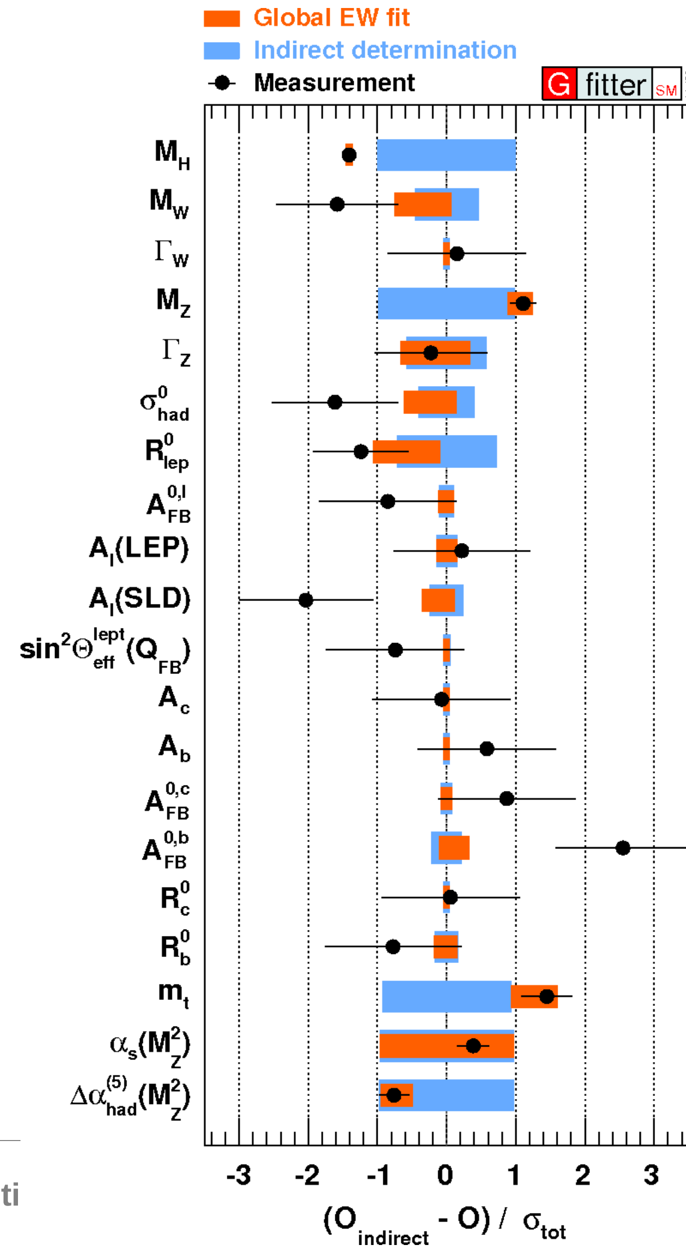
- particle masses
- CKM mixing angle (mass and electroweak eigenstates of quarks)
- Gauge couplings (strength of forces)
- Symmetry properties of QCD
- Parameters of electroweak symmetry breaking (Higgs mass and vaccum expection value)

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

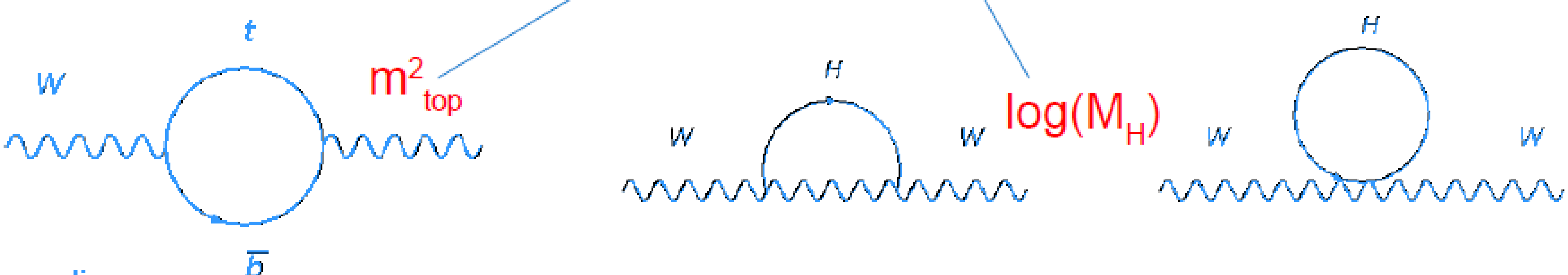
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

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

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

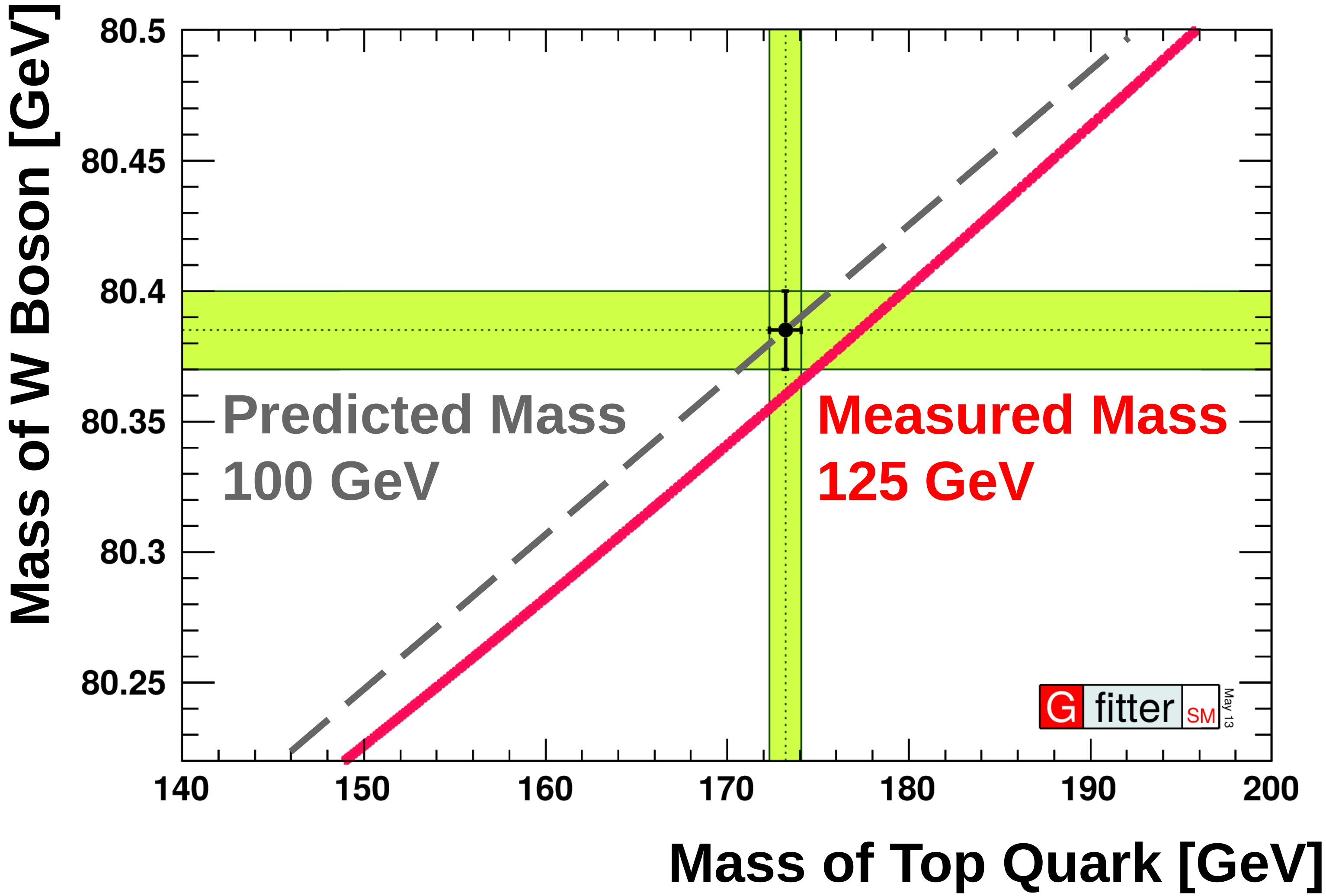
radiative corrections

$\Delta r \sim 3\ \%$

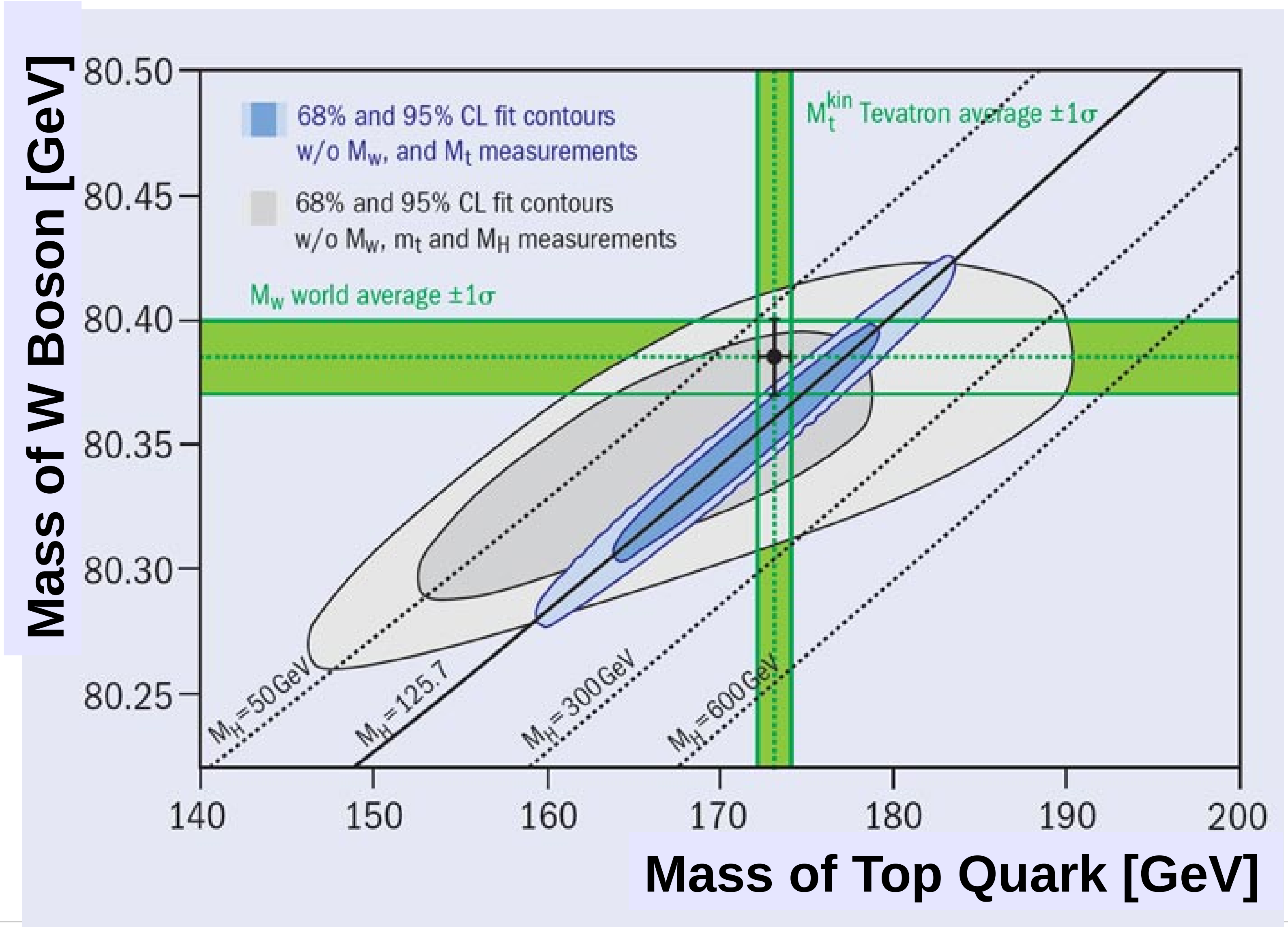


Feynman diagrams:
graphical representations of integrals
→ result: numerical prediction of probability of process

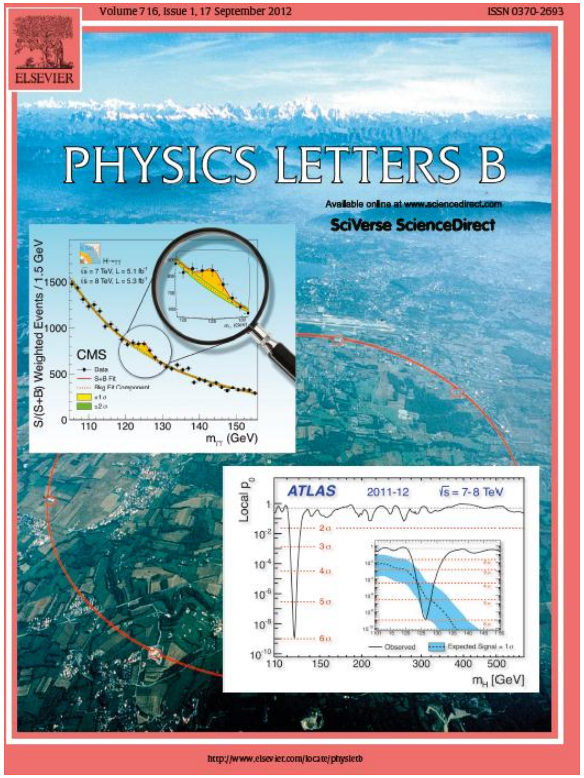
Indirect determination of Higgs boson mass

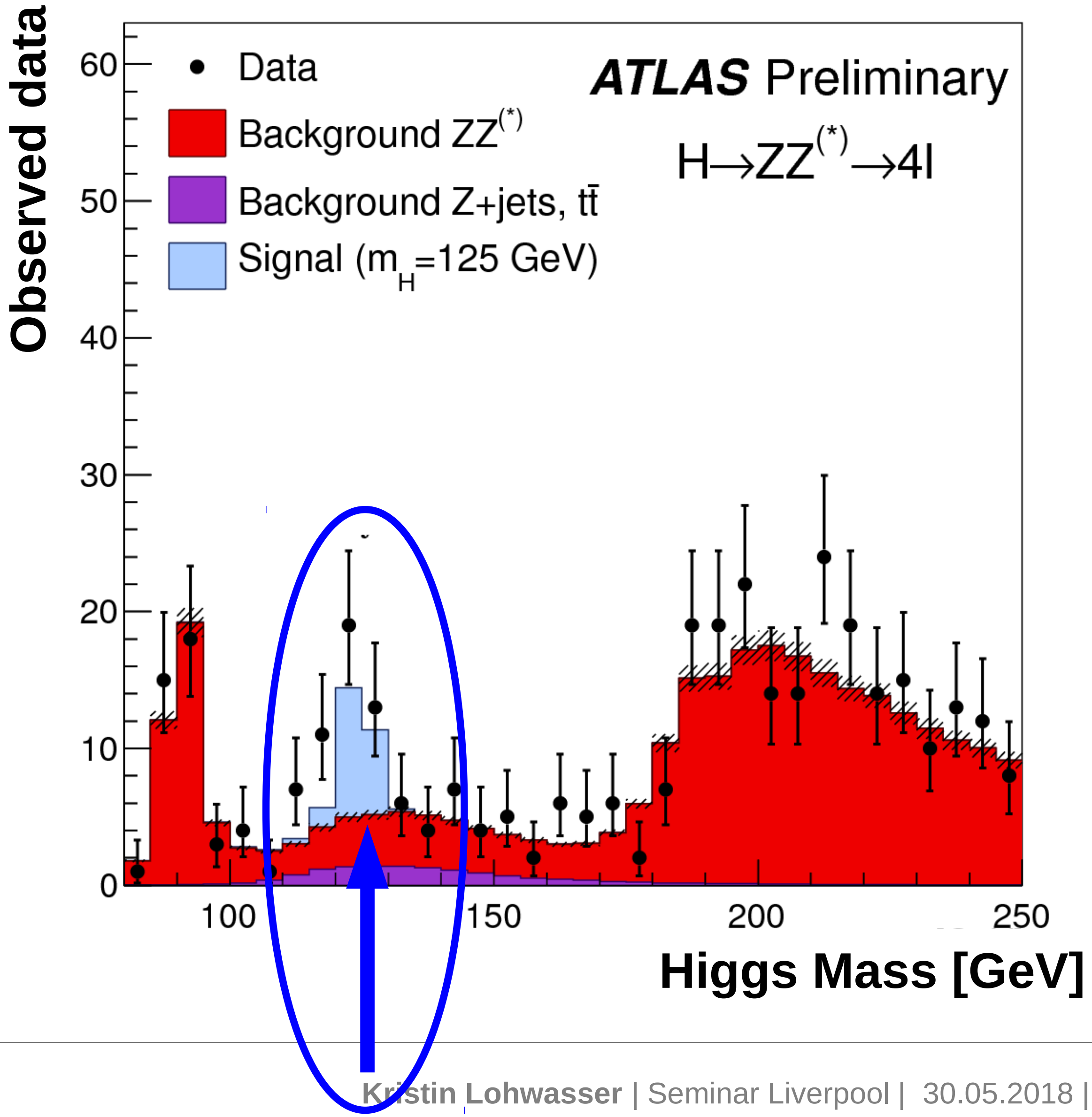


Indirect determination of Higgs boson mass



A long-awaited discovery





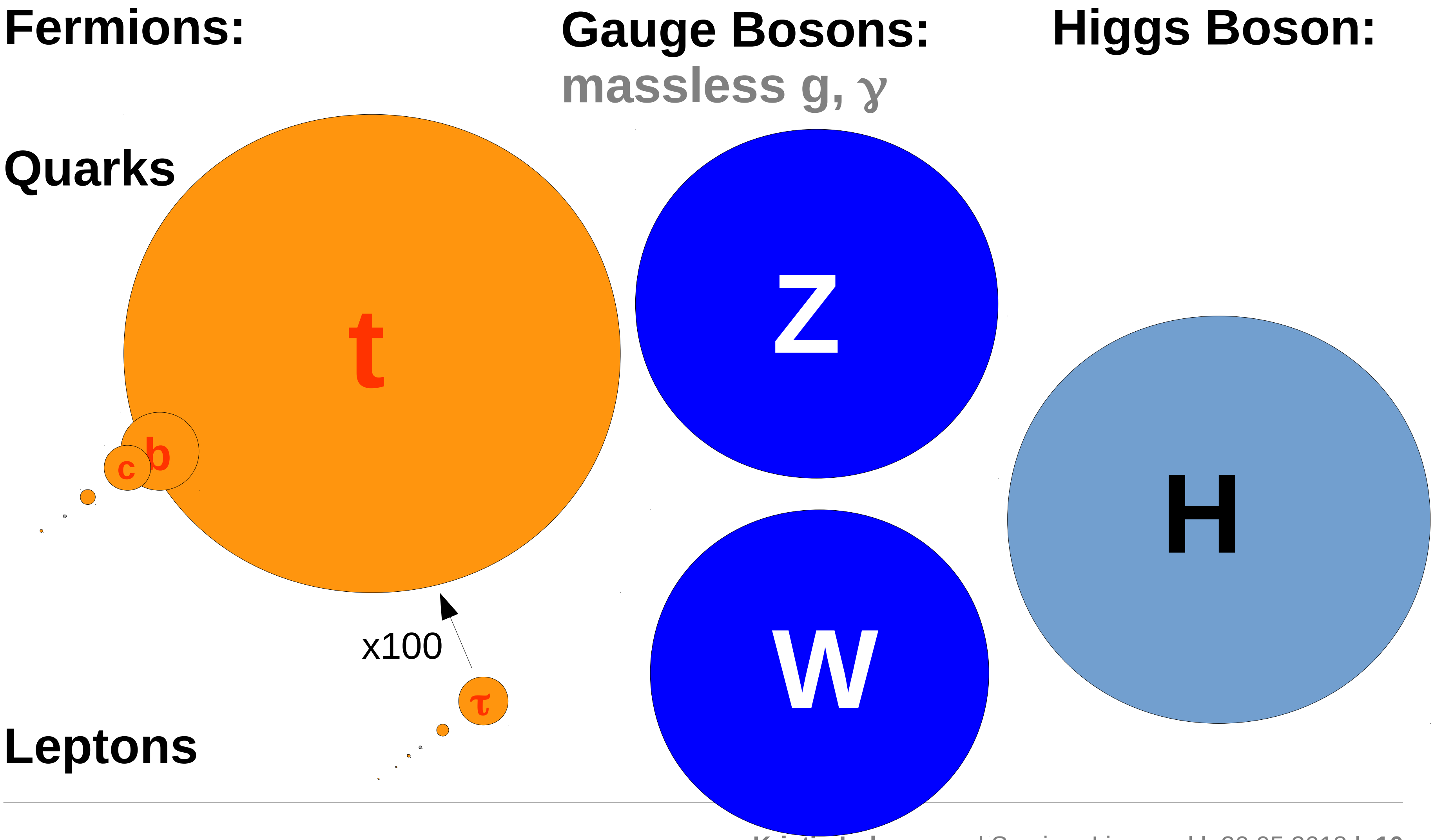
The last missing piece in the Standard Model

H

July 2012

But there are a few puzzling facts...

- **Why are the particle masses so different?**



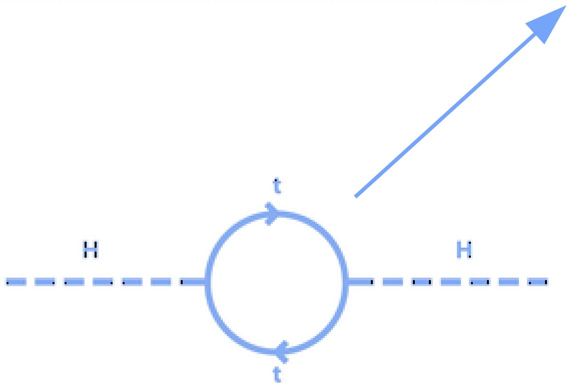
But there are a few puzzling facts...

- **Why are weak force and gravity so different?**

100 000 000 000 000 000 000 000 000 000 000 (10^{32}) stronger

- **Hierarchy problem:**

$$m_H = m_{H,0} + \Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2} M^2$$



Radiative correction to Higgs mass very large, if no other new physics of mass M

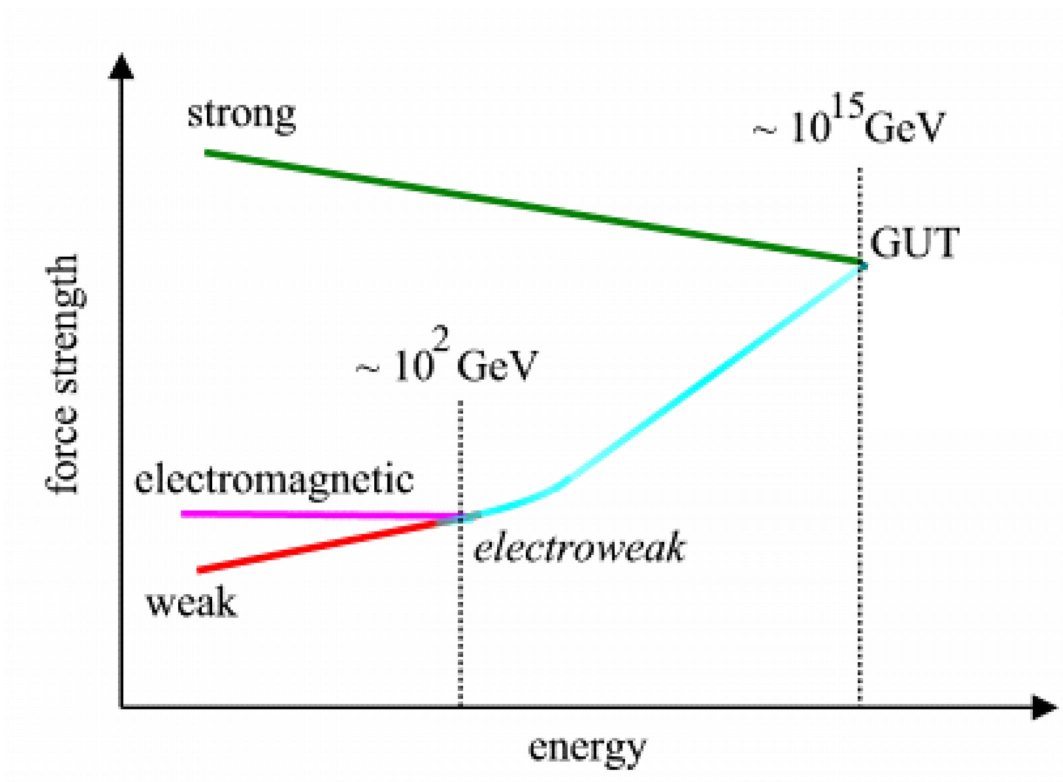
$$M < \left(\frac{10\%}{\text{tuning}} \right) 1 \text{ TeV}$$

Relation by John March-Russell

But there are a few puzzling facts...

- **Why are weak force and gravity so different?**

100 000 000 000 000 000 000 000 000 000 000 (10^{32}) stronger



$$M < \left(\frac{10\%}{\text{tuning}}\right) 1\ \text{TeV}$$

Allow for massive fine tuning ~ 10^{-15} GeV

(nothing up to GUT scale)

0.05 – 2 TeV

0.005 – 20 TeV

Relation by John March-Russell

Take-away message

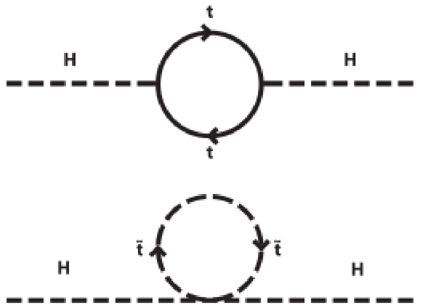
- Apart from 19 free parameters: All interactions and other parameters within the Standard Model of particle physics are fixed
- Allows the indirect determination of parameters
- Questions: Why this large number of parameters? Why the large difference between energy scales?

The “New Physics” landscape....

H. Murayama

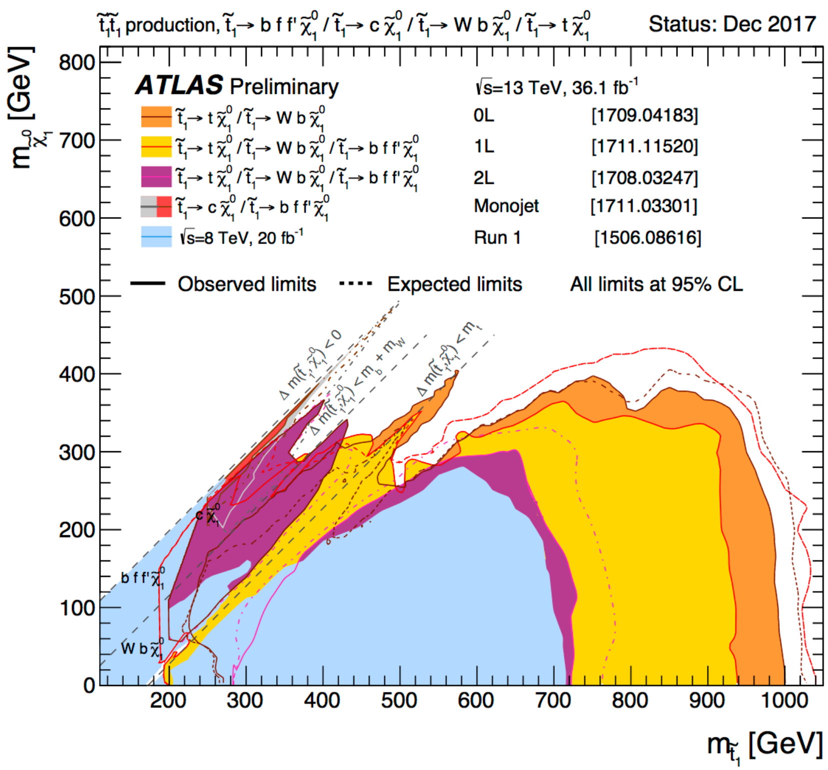
Pick your most favourite model: SUSY

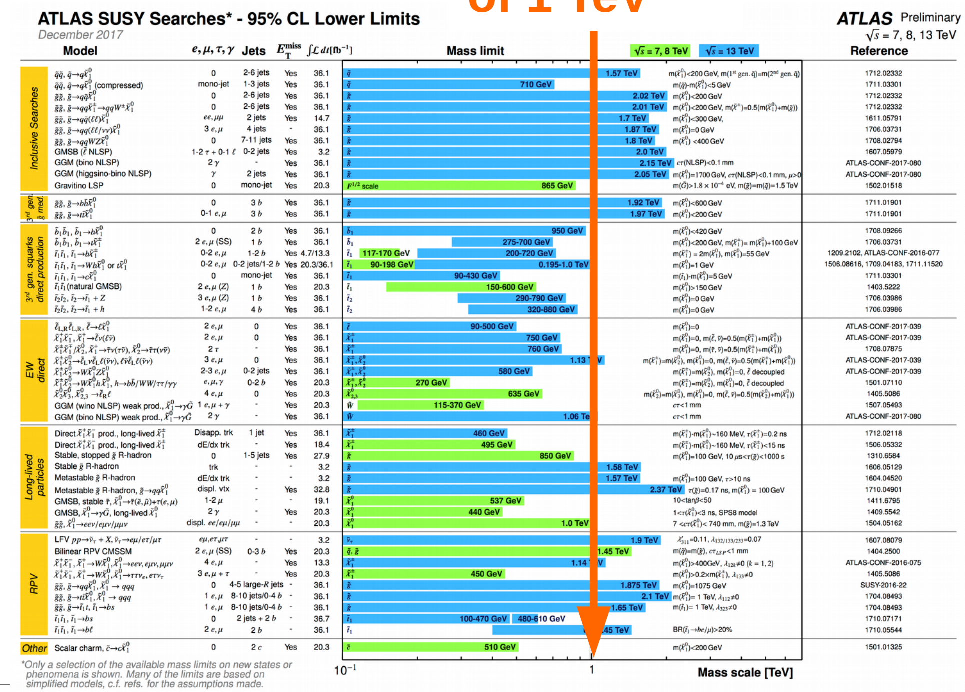
- Supersymmetry: broken symmetry between particles (known) and sparticles (not yet found)
- Precise predictions for sparticles with only a few free parameters



Solves hierarchy problem

Mass scale of 1 TeV

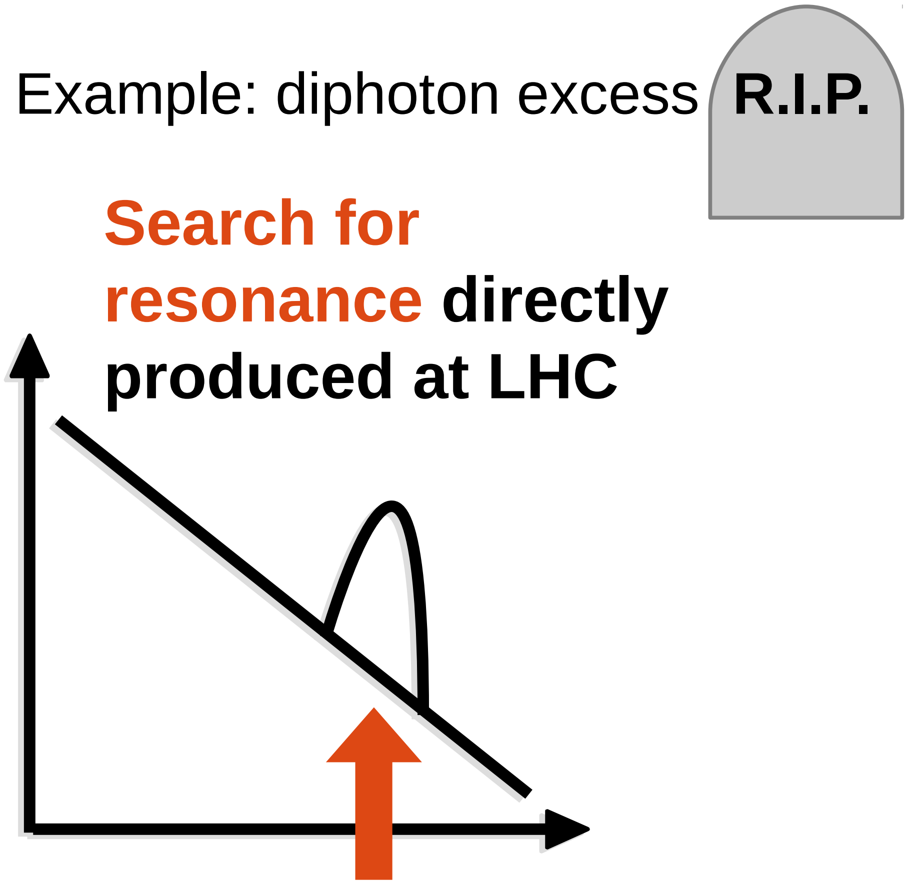




Generic searches for resonances

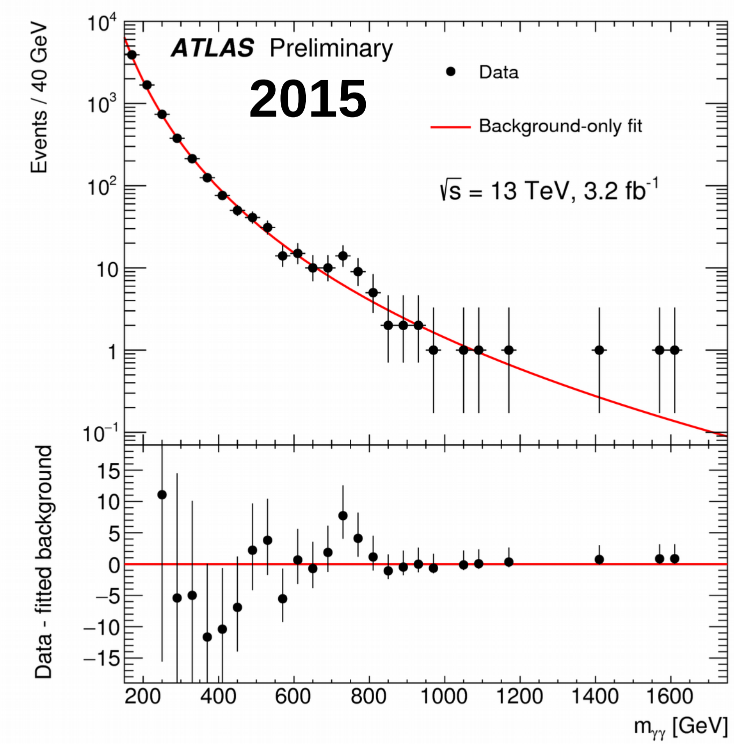
- Generic search for resonance in a (falling) distribution
- Not necessarily connected a priori with a striking theoretical motivation

Example: diphoton excess



Search for resonance directly produced at LHC

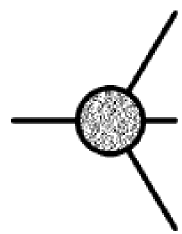
- (Feb 2016) **~ 170 papers**
  ~165 spin-0 resonance
  ~5 spin-2 resonance
  ~1 spin-1 resonance
  ~5 parent resonance/kinematic edge



Generic searches for resonances

- Narrow width approximation (NWA)
  - width << mass (here width < 0.5% of m_H)
  - Decay products lighter, m<<M

× $\frac{1}{2m\Gamma}$ ×



or $\Gamma \rightarrow 0$

for $\Gamma \neq 0$

ion to obtain

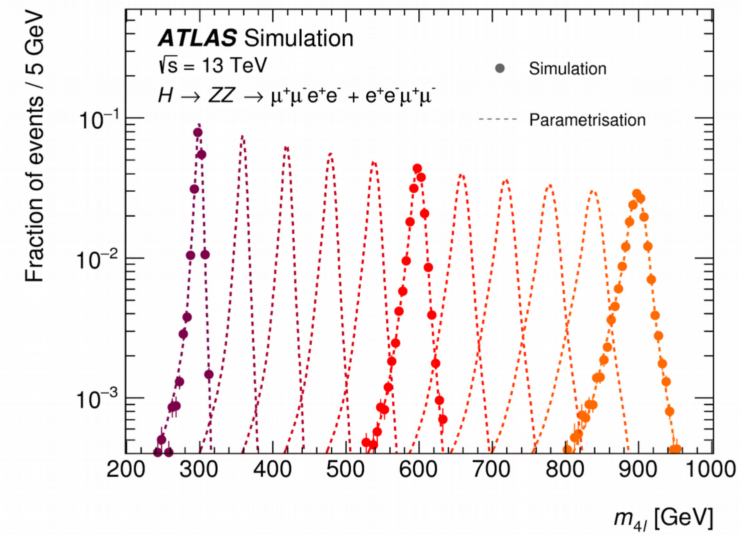
$_{part}/\Gamma_{total}$

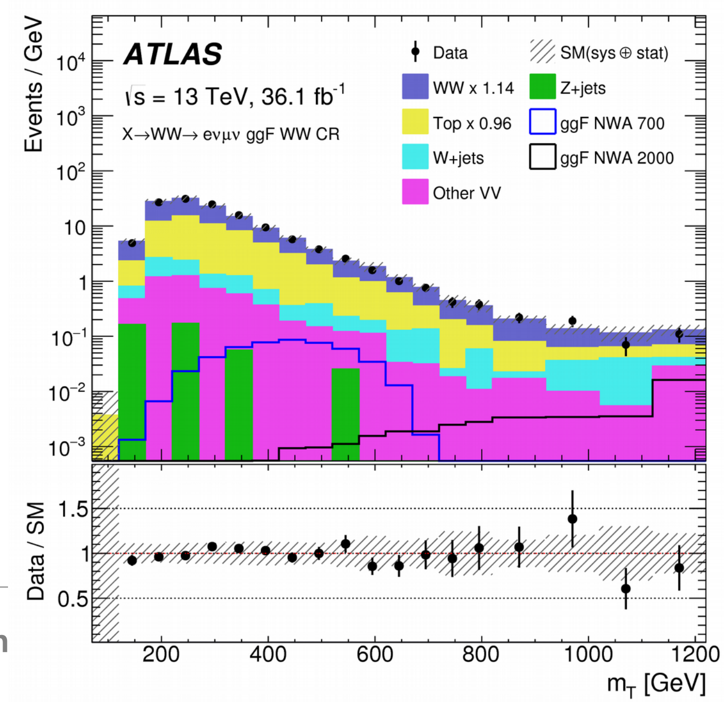
lculation of separate production and

lations feasible

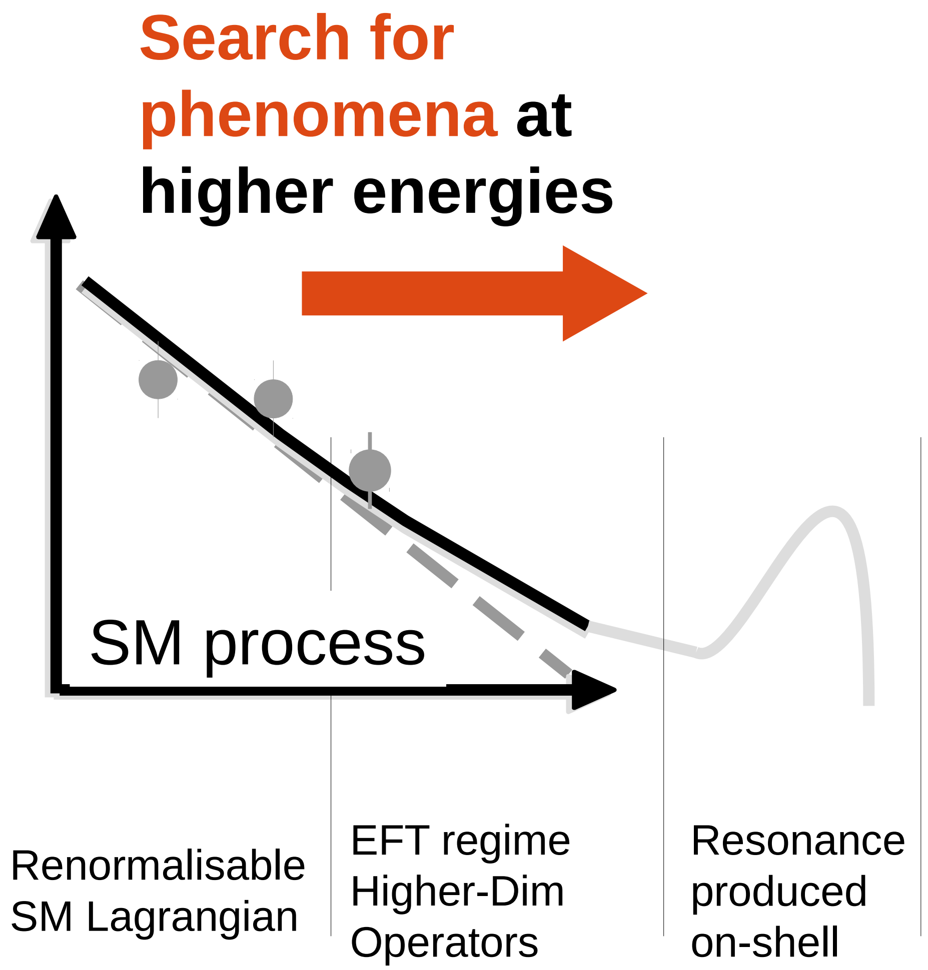
.k

Kristin



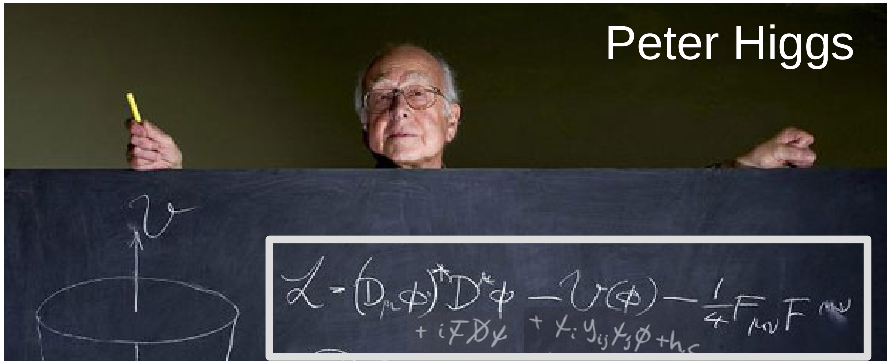


What if we don’t reach the resonance? Effective field theory



- Generic search for **deviations in distributions** sensitive to new physics effects
- Could be sensitive to much **higher energies scales** compared to resonance searches
- Detects also new physics **without resonances or very broad resonances**

A framework to characterise the new phenomena



Operators:
Which particles interact?

Coupling strength:
How strong is the interaction?

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

Standard model

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

$d \leq 4$ → Standard model

$d = 5$ → *Neutrino masses*

$d \geq 6$ → Unknown phenomena

Dimension-6 parameter

- 59 non-redundant parameters (CP-even, ignoring flavours)

SILH-Basis (hep-ph/0703164,1308.2803)

EWPTs	Higgs Physics	TGCs
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$		
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$		$\mathcal{O}_{3W} = g\frac{\epsilon_{abc}}{3!} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}_\gamma = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	
$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_f = y_f \lvert H\rvert^2 \bar{F}_L H^{(c)} f_R + \text{h.c.}$	
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	

EWK precision data:
DY, charge current
→ usually LEP

https://arxiv.org/abs/1609.08157

Higgs physics:
first measured and
determined at LHC

Dibosons:
first measured at LEP
high precision at LHC

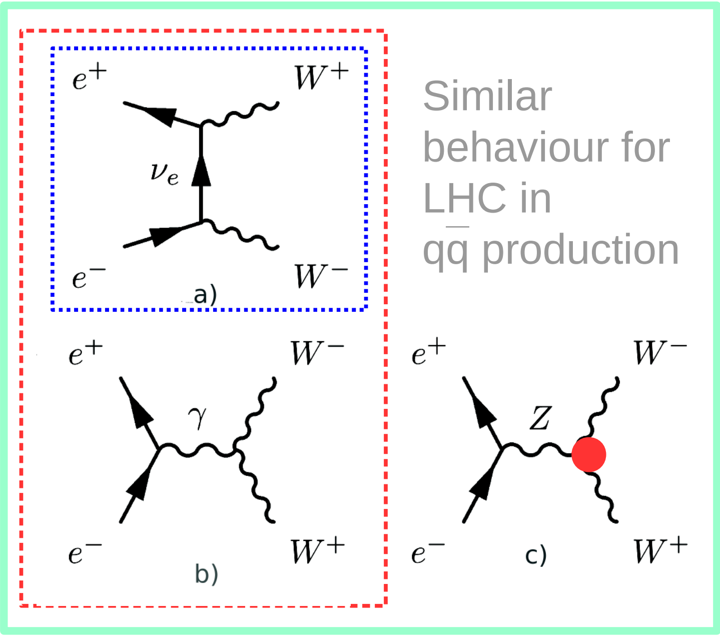
Translating into interactions

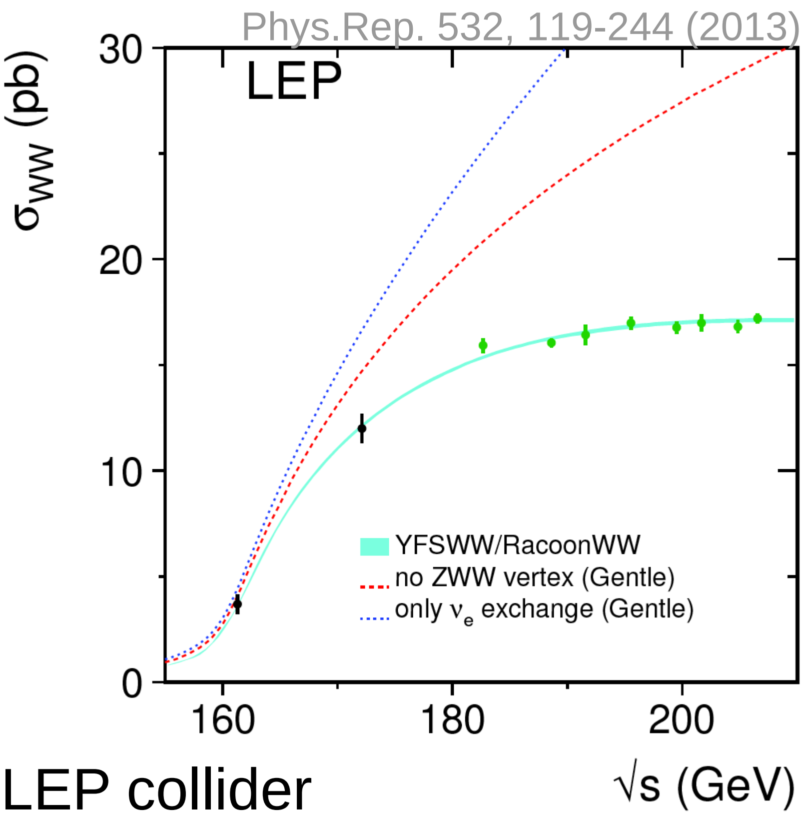
	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	X	X					X	X	X	X
$\mathcal{O}_{W}$	X	X	X	X	X		X	X	X	
$\mathcal{O}_{B}$	X	X		X	X					
$\mathcal{O}_{\Phi d}$			X	X						
$\mathcal{O}_{\Phi W}$			X	X	X	X				
$\mathcal{O}_{\Phi B}$				X	X	X				
$\mathcal{O}_{\tilde{W}WW}$	X	X					X	X	X	X
$\mathcal{O}_{\tilde{W}}$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

- A = Photon
- H = Higgs
- W, Z

Diboson production: WW process as example

Confirmation of Abelian self-coupling of the electroweak gauge bosons





- Negative interference confirmed at LEP collider
- What still holds: A tiny deviation in the self coupling – the dampening of the cross section at high energies is lost

Using proton collisions at the LHC

- Typical production cross sections:
  O(fb) - O(10^2pb)

- For 10 fb^{-1} expect:
  10 – 1 million Events
  (before detector)

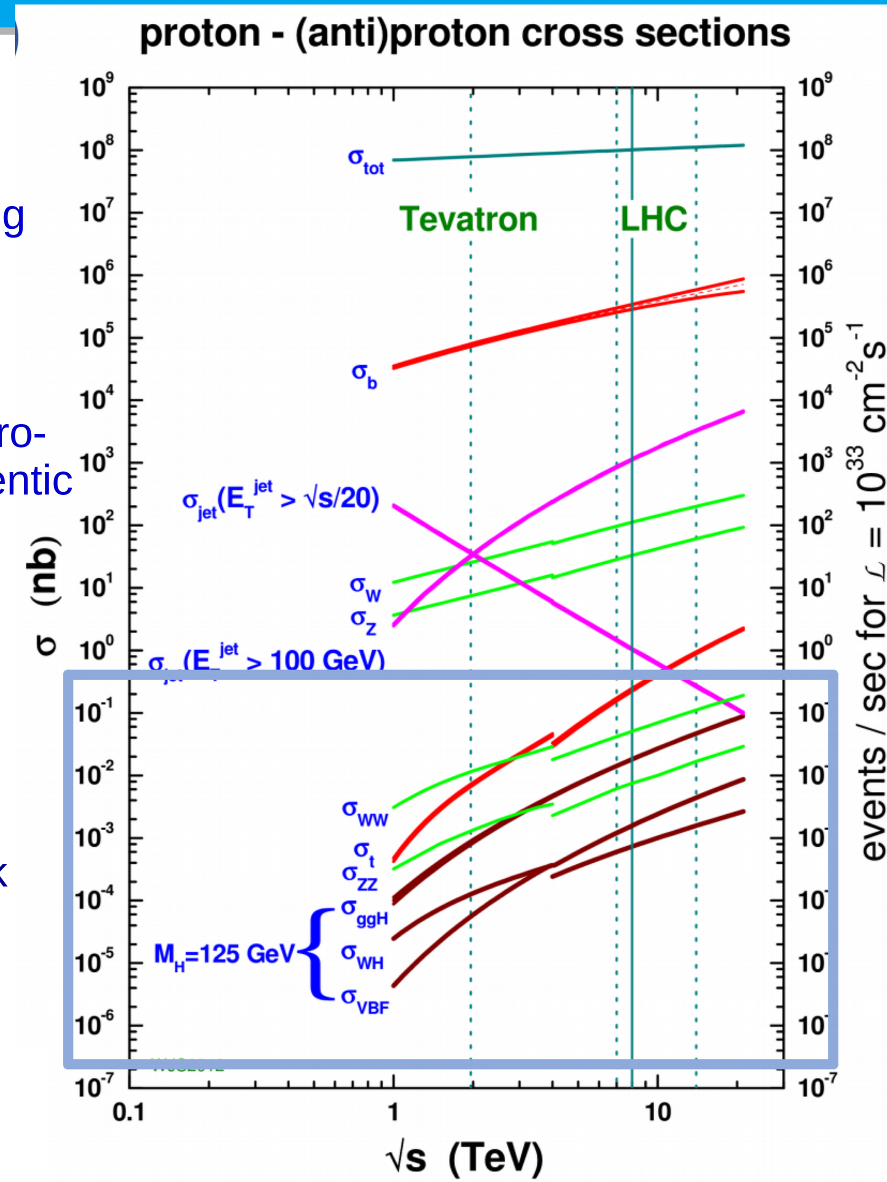
- Some channels can be measured for the first time

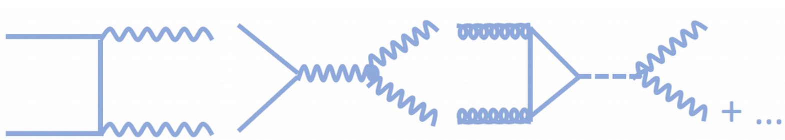
- some can be studied **with precision** for the first time

Strong force

Electro-magentic force

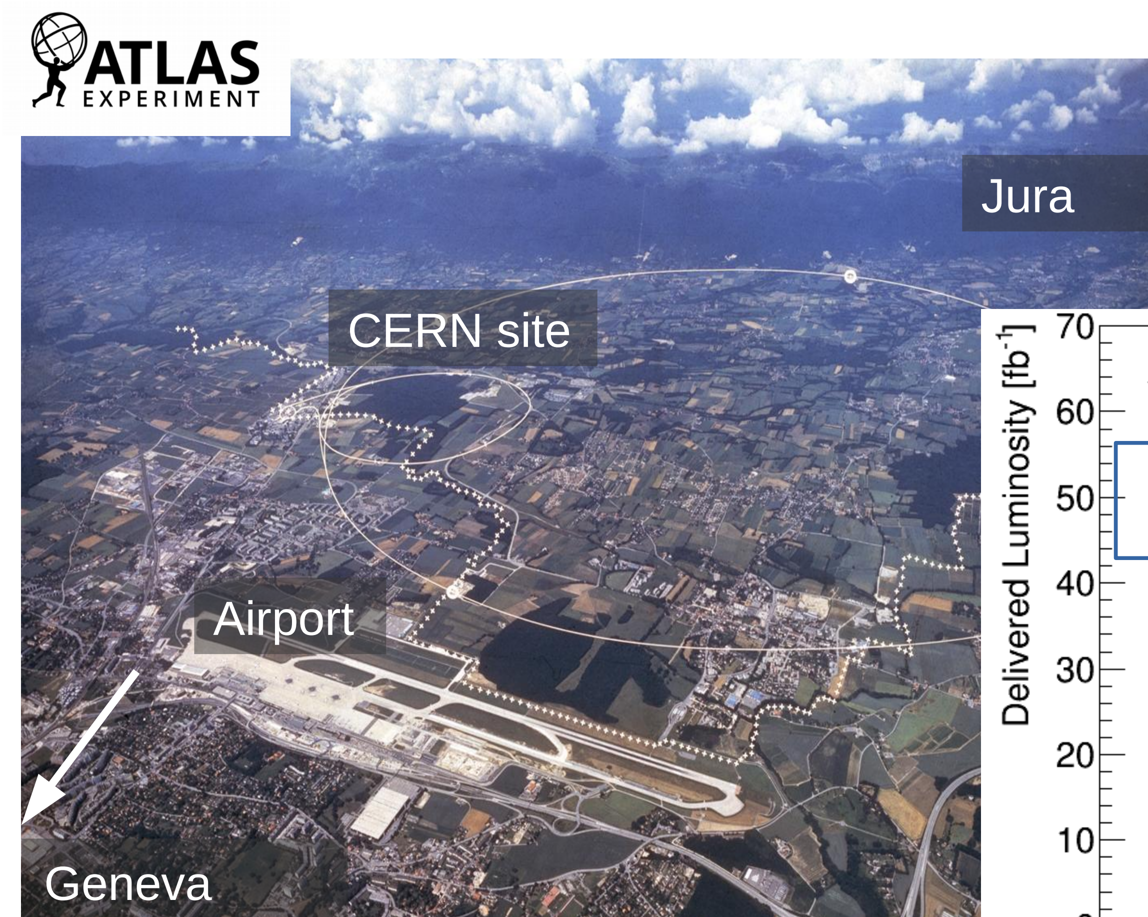
Weak force





Tree-level qq->VV Higgs contributes at O(α_s^2)

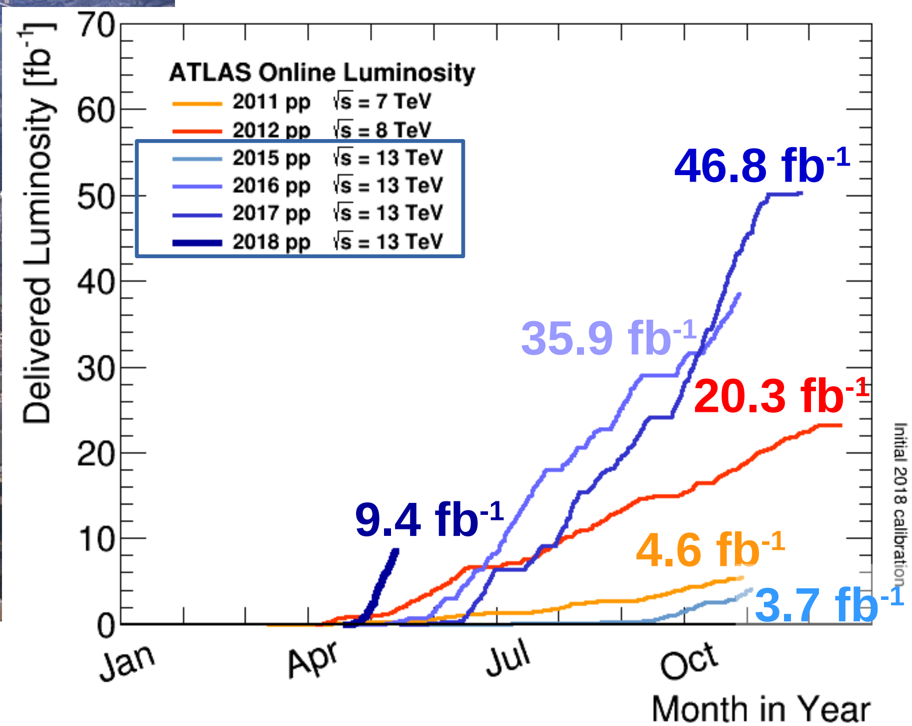
Using proton collisions at the LHC



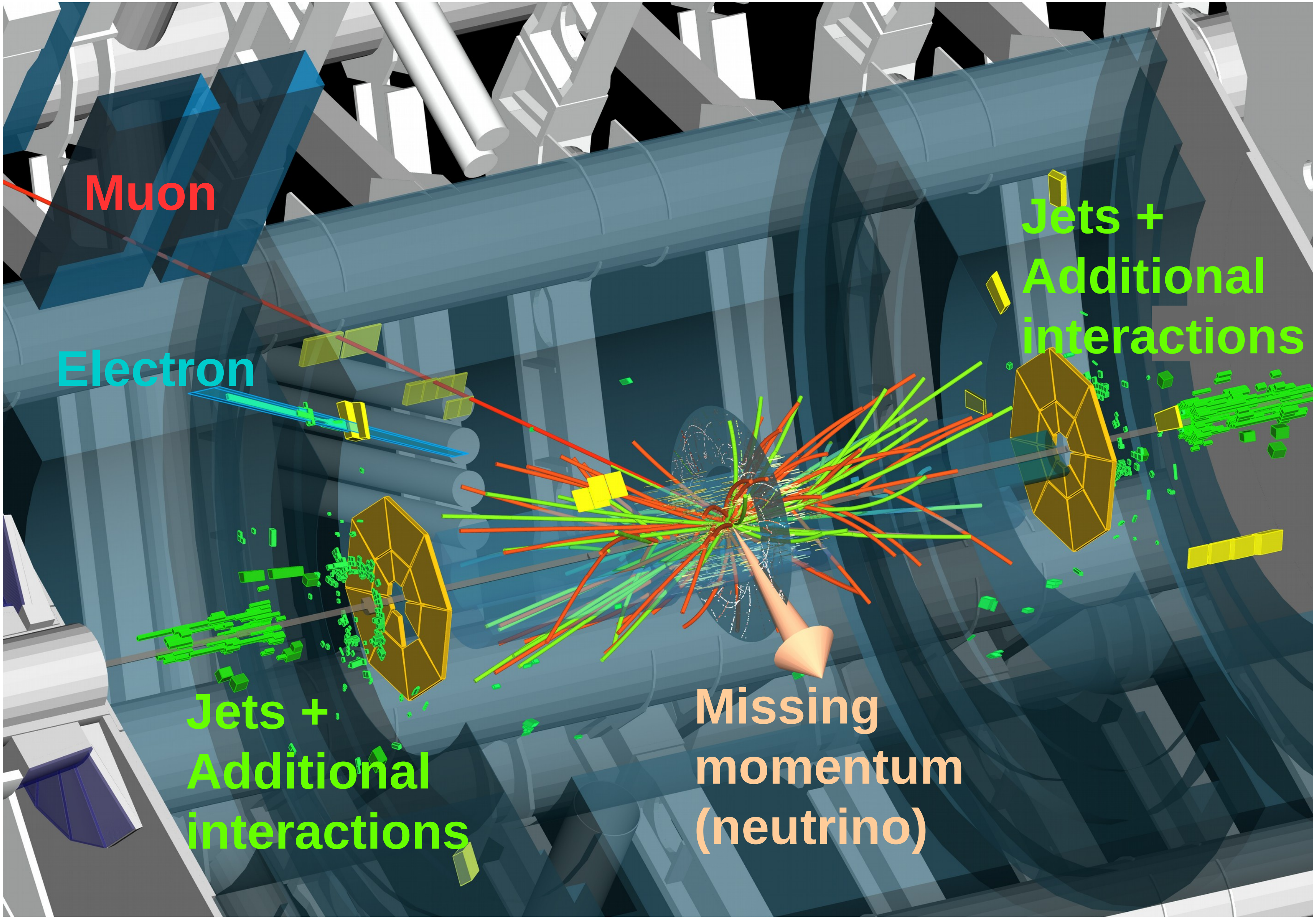
Data collected:

More than 100 fb^{-1} at 13 TeV

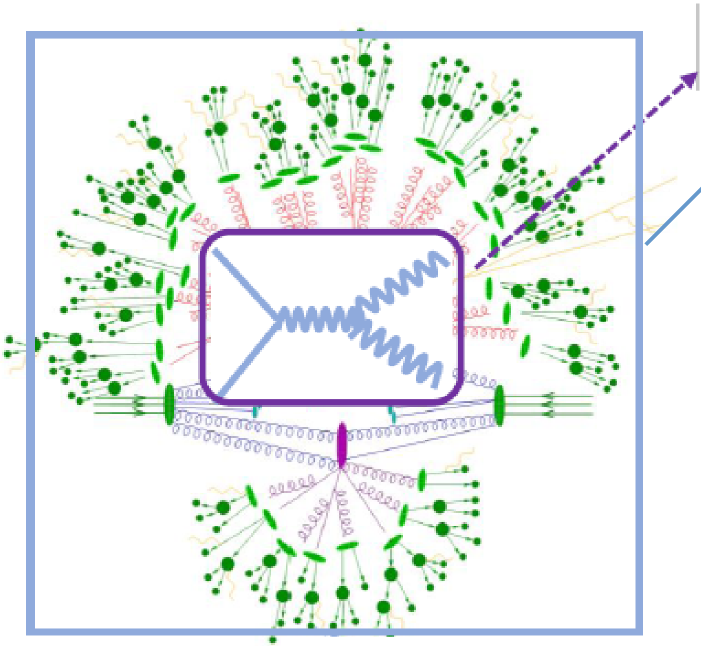
– a wealth of results to come



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


Muon
Electron
Jets +
Additional
interactions
Jets +
Additional
interactions
Missing
momentum
(neutrino)

Translation into (re-interpretable) cross section



Fix-order calculation (for hard process)

Description of the collision: hadronization, underlying event, multiple interactions

- Need to understand our predictions before we can quantify deviations

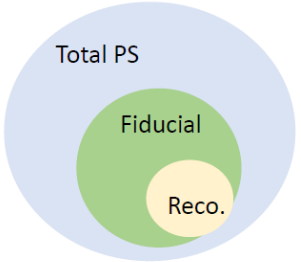
signal events

$$\sigma_{\text{fid}}^{\ell\ell'}(WW) = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{WW} \times \mathcal{L}}$$

Correction factor

Luminosity

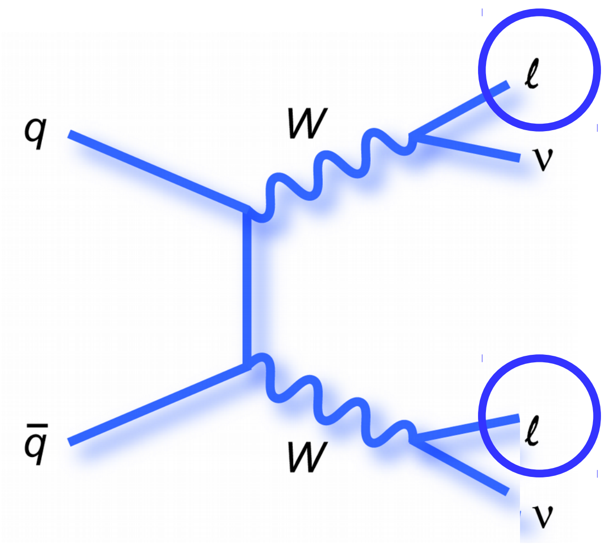
Reconstruction level:
What we see in the detector



Fiducial cross section:
correct for resolution and efficiencies

Total phase space:
correct for acceptance to compare to theory

WW as an example measurement



Measure WW process by selecting the decay processes and rejecting similar "background" processes by kinematic selections

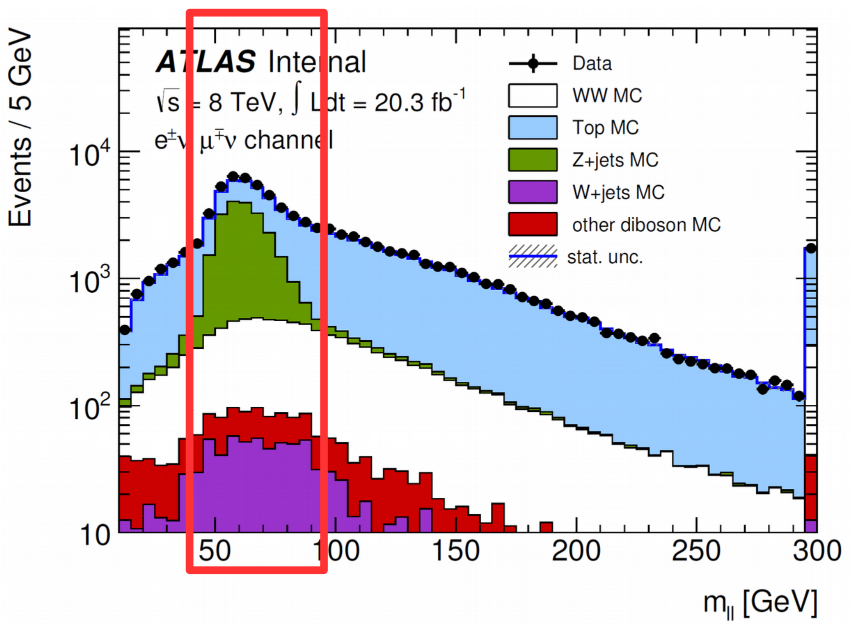
Two energetic leptons

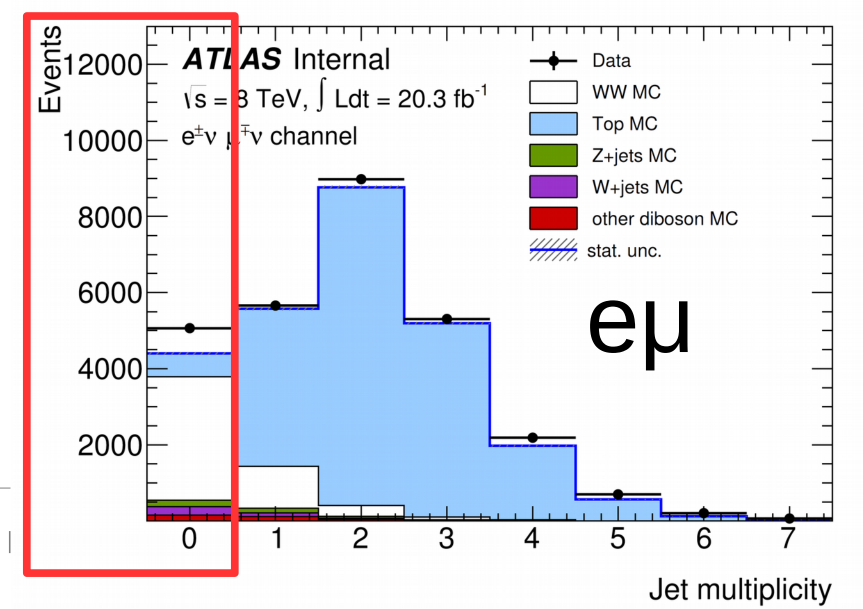
- Large missing transverse energy,

outside Z mass window

- reject any event with jets in the final state,

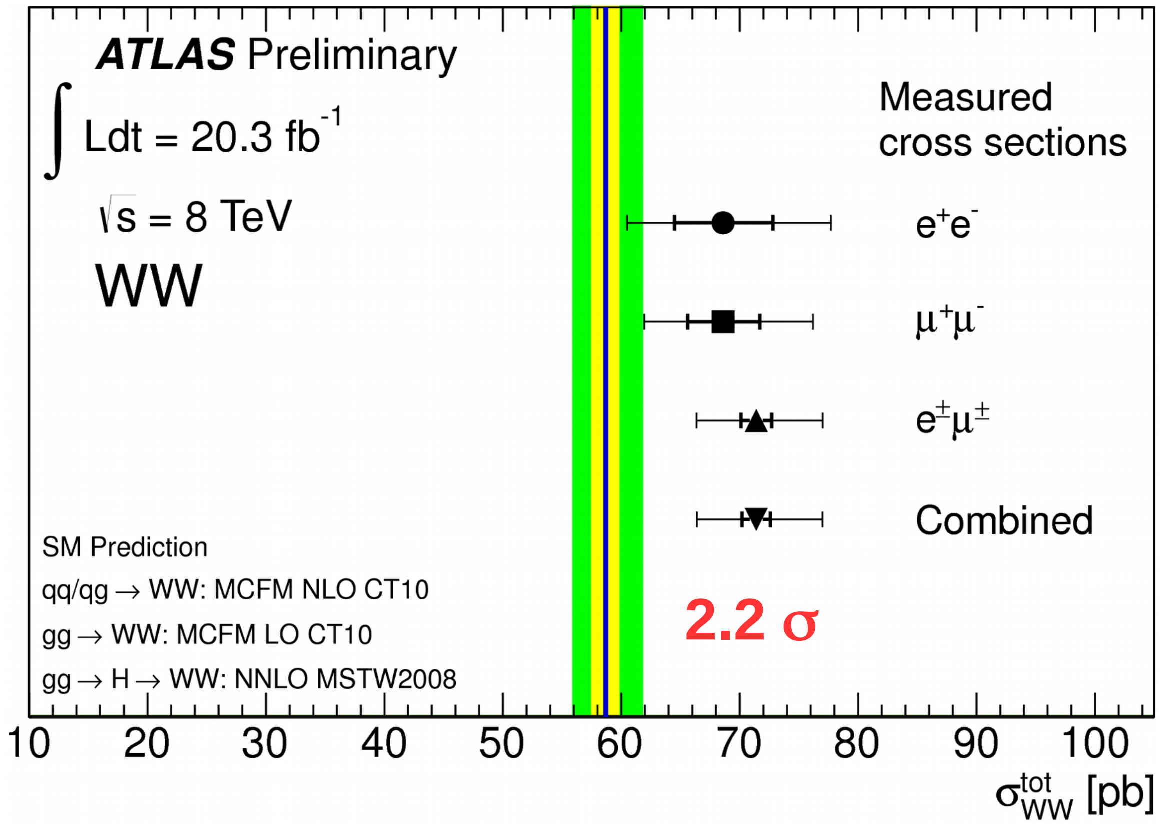
remove large top background





WW excess in 2014

- Good agreement between the channels
- eμ dominates due to smaller uncertainty and larger statistics



$$\sigma_{WW}^{tot} = 71.4\ ^{+1.2}_{-1.2}(\text{stat})\ ^{+5.0}_{-4.4}(\text{syst})\ ^{+2.2}_{-2.1}(\text{lumi})\ \text{pb}$$

Standard Model prediction: $58.7^{+1.0}_{-1.1}$ (PDF) $^{+3.1}_{-2.7}$ (total) pb

Theoretical Predictions

'Stop' that ambulance! New physics at the LHC?

Jong Soo Kim,[a] **Krzysztof Rolbiecki,**[a] **Kazuki Sakurai,**[b] **and Jamie Tattersall**[c]

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ABSTRACT: A number of LHC searches now display intriguing excesses. Most prominently, the measurement of the W^+W^- cross-section has been consistently $\sim 20\%$ higher than the theoretical prediction across both ATLAS and CMS for both 7 and 8 TeV runs. More

Theoretical Predictions

'Stop' that ambulance! New physics at the LHC?

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ABSTRACT: A nu
the measurement c
theoretical predict

Transverse momentum resummation effects in W^+W^- measurements

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Abstract

The W^+W^- cross section has remained one of the most consistently discrepant channels compared to SM predictions at the LHC, measured by both ATLAS and CMS at 7 and 8 TeV. Developing a better modeling of this channel is crucial to understanding properties of the Higgs and potential new physics. In this paper we investigate the effects of NNLL transverse momentum resummation in measuring the W^+W^- cross

Theoretical Predictions

(will be inserted by the editor)

‘Stop’ that ambulance! New physics at the

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On the excess in the inclusive $W^+W^- \to l^+l^-\nu\bar{\nu}$ cross section

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Abstract In this note we analyse the excess in the W^+W^- *inclusive* cross section recently me
We point out that in fact for the ATLAS *fiducial* cross sections there is no excess in the meas
to the NLO QCD predictions. We also argue that higher order effects to the fiducial cross se
tend to cancel each other, hence the inclusion of NNLO and NNLL corrections will not mo
significantly. We find that at 8 TeV a substantial part of the disagreement with the NLO pre
cross section observed by ATLAS is due to the extrapolation carried out with POWHEG.

Theoretical Predictions

(will be inserted by the editor)

‘Stop’ that ambulance! New physics at the

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Abstract: A nu
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Transverse momen effects in W^+W^-

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channels compared to SM
at 7 and 8 TeV. Developi
properties of the Higgs
effects of NNLL transve

ph] 17 Jul 2014

On the excess in the inclusive $W^+W^- \to l^+l^-\nu\bar{\nu}$ cross section

Pier Francesco Monni[a,1], Giulia Zanderighi[b,1,2]

[1] Rudolf Peierls Centre for Theoretical Physics,University of Oxford,1 Keble Road, Oxford OX1 3RH, U
[2] CERN, Theory Division, CH-1211 Geneva 23, Switzerland

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An Explanation of the WW Excess at the LHC by Jet-Veto Resummation

Prerit Jaiswal[1] and **Takemichi Okui**[2]

[a] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*

Abstract

The W^+W^- production cross section measured at the LHC has been consistently exhibiting a mild excess beyond the SM prediction, in both ATLAS and CMS at both 7-TeV and 8-TeV runs. We provide an explanation of the excess in terms of resummation of large logarithms

Theoretical Predictions

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ZU-TH 29/14
MITP/14-053

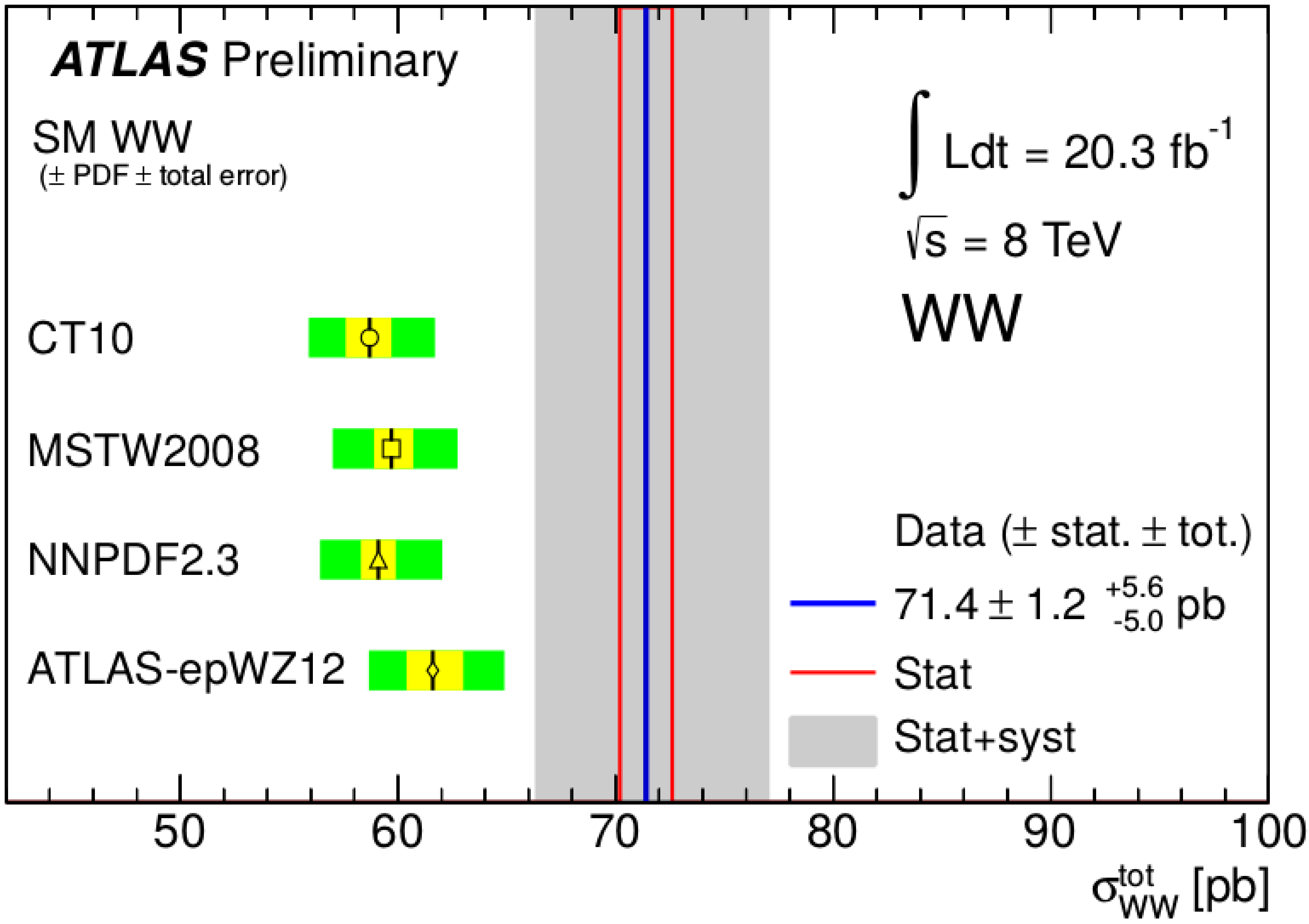
W^+W^- production at hadron colliders in NNLO QCD

T. Gehrmann,[1] M. Grazzini,[1] S. Kallweit,[1] P. Maierhöfer,[1]
A. von Manteuffel,[2] S. Pozzorini,[1] D. Rathlev,[1] and L. Tancredi[1]

[1] Physik-Institut, Universität Zürich, CH-8057 Zürich, Switzerland
[2] PRISMA Cluster of Excellence, Institute of Physics,
Johannes Gutenberg University, D-55099 Mainz, Germany

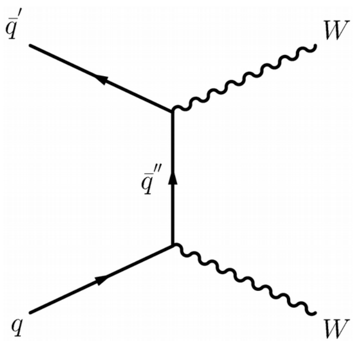
Charged gauge boson pair production at the Large Hadron Collider allows detailed probes of the fundamental structure of electroweak interactions. We present precise theoretical predictions for on-shell W^+W^- production that include, for the first time, QCD effects up to next-to-next-to-leading

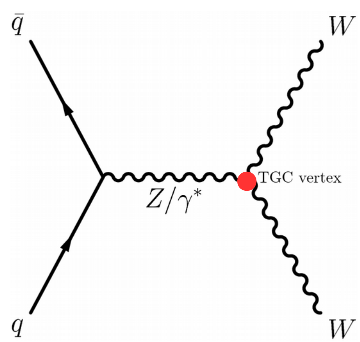
PDF uncertainties?



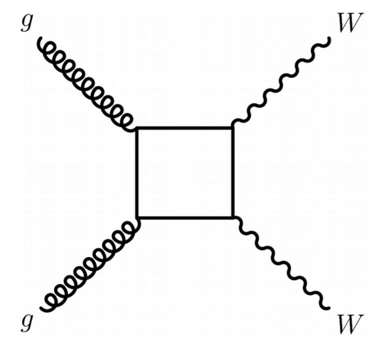
Theoretical Predictions

Predictions obtained using perturbation theory in orders of coupling constant α

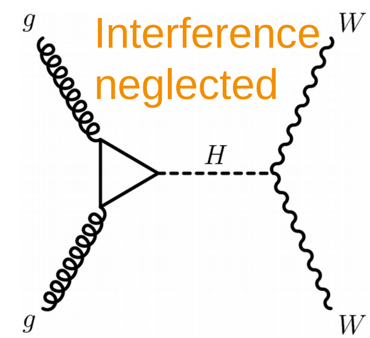




~91%



~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)

Is anything missing from the calculation?

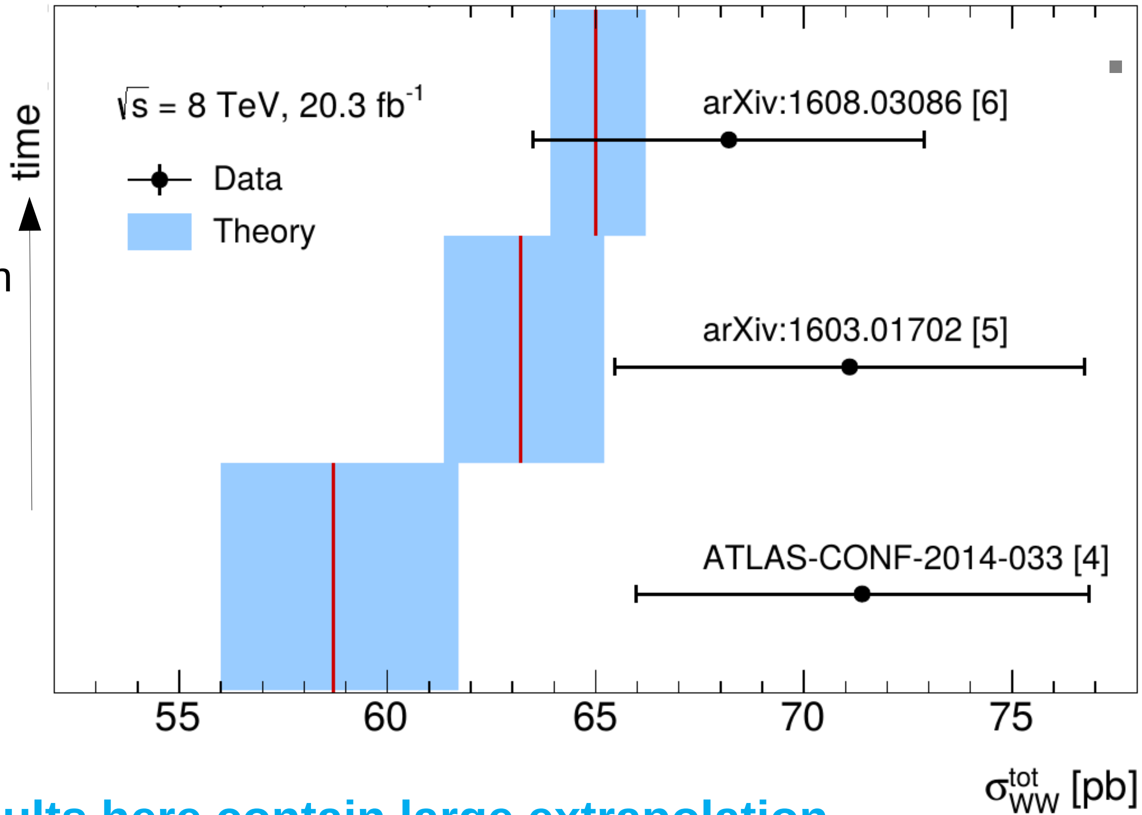
Updated theoretical predictions

> **Theory Progress**

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

> **Experimental Progress**

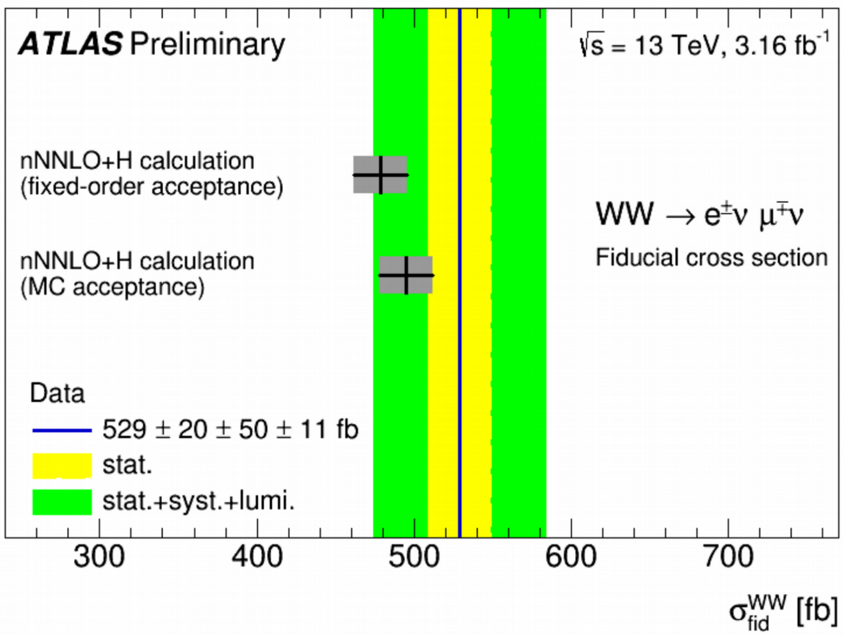
- Extension of fiducial phase space

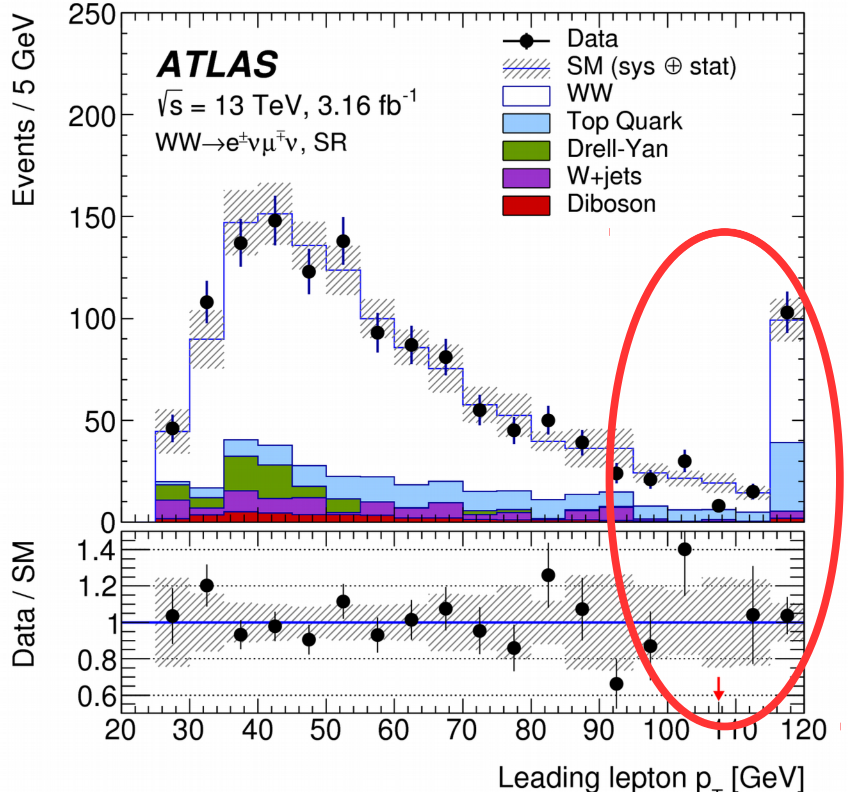


> **Experimental results here contain large extrapolation**

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

And new results at 13 TeV





- ~good agreement of theory and data
- Kinematic acceptance modeled with either fixed-order or Parton-showers

Detector level → Particle level correction of ~50% (object reconstruction)

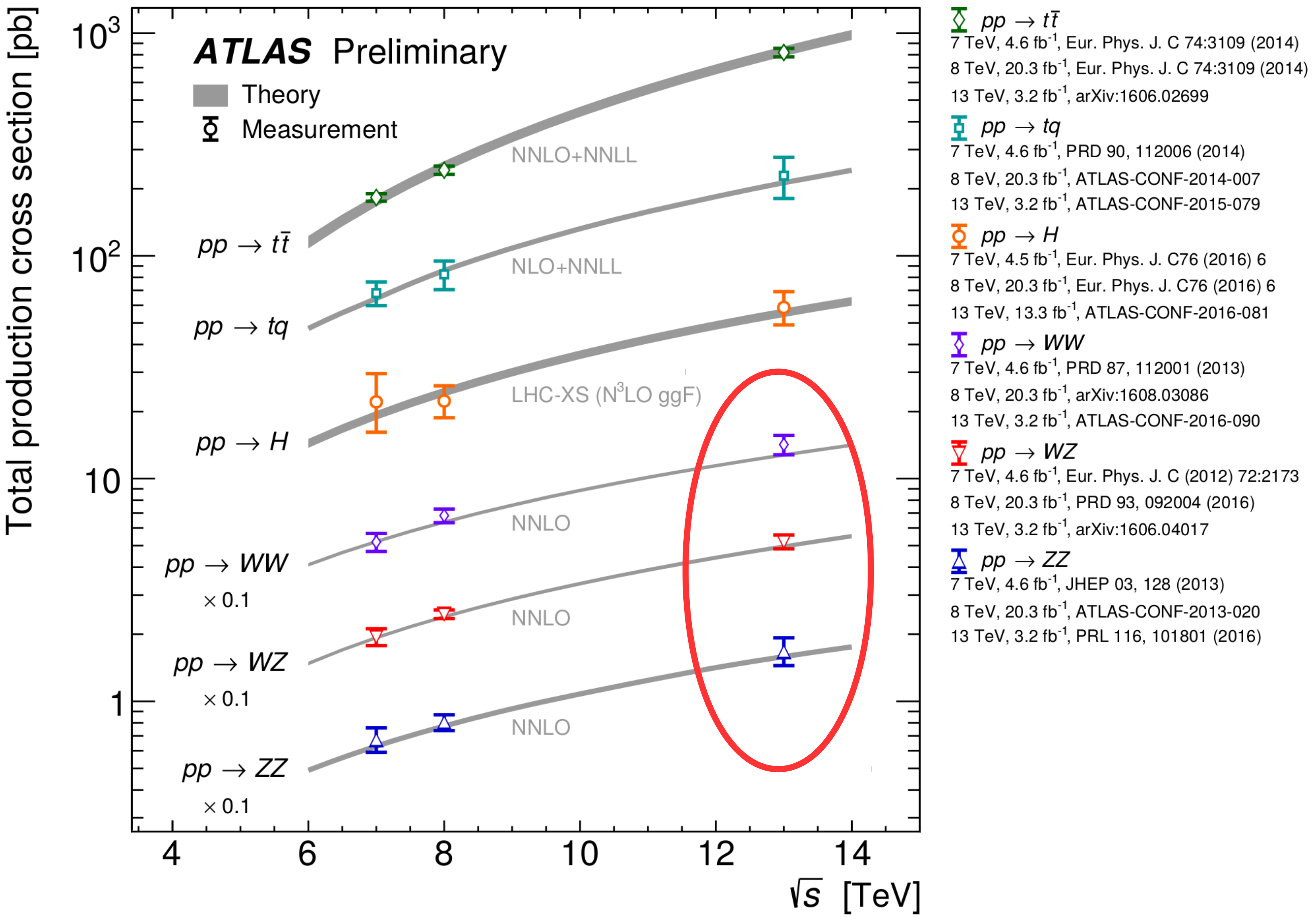
- No differential cross-section measured (EFT sensitivity from 2015 13 TeV should be ~same as 2012 8 TeV)

WW uncertainties at 13 TeV

Sources of uncertainty	Relative uncertainty for $\sigma^{\mathrm{fid}}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
$E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\mathrm{miss}}$	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multi-jet background	3.8%
Other diboson backgrounds	1.1%
Parton shower	3.1%
PDF	0.2%
QCD scale	0.2%
MC statistics	1.2%
Data statistics	3.7%
Total uncertainty	11%

- Require careful balancing

Diboson results at ATLAS

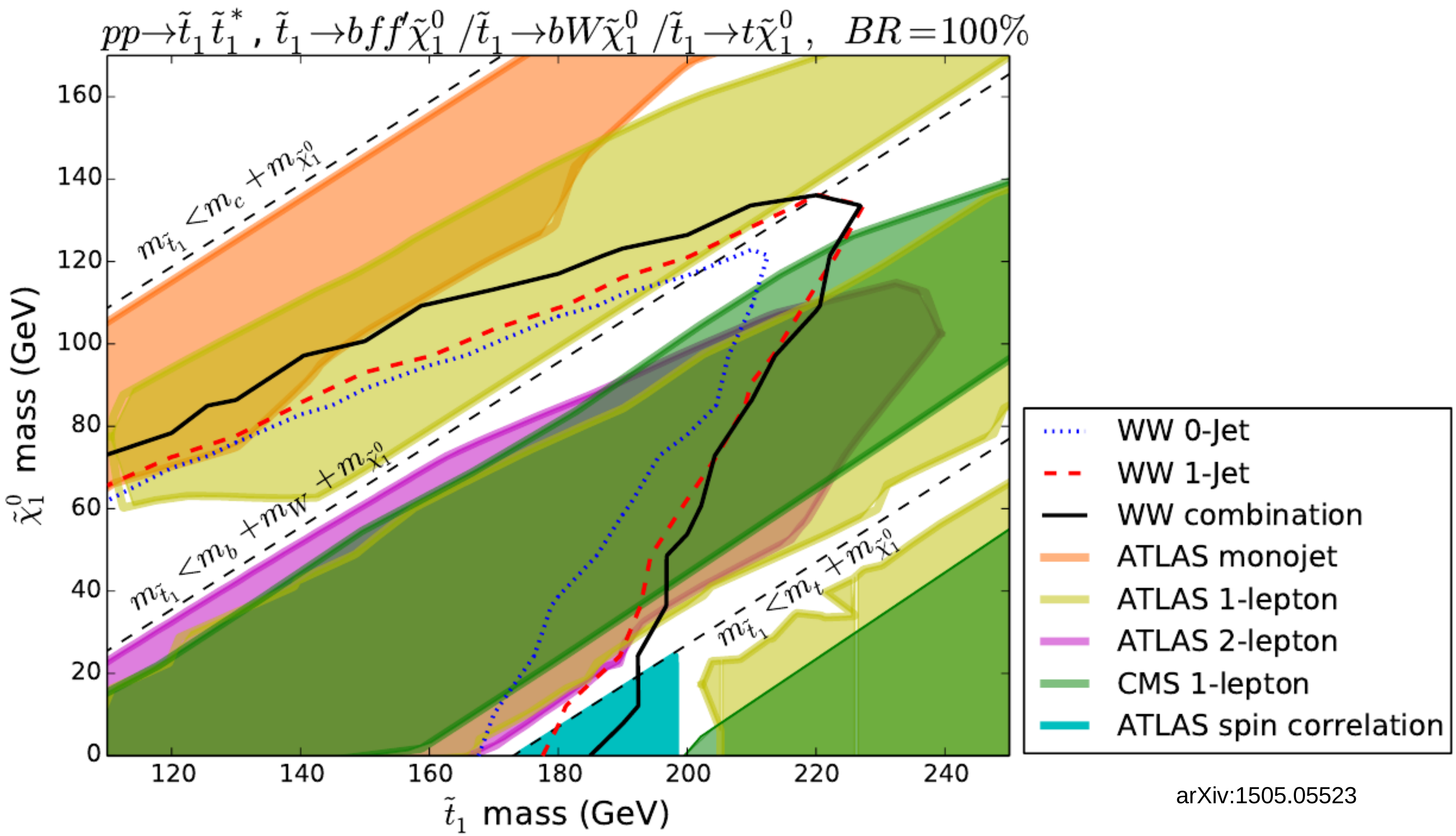


Take-away message

- Diboson measurements at LHC can yield high level of precision
- Need corresponding accurate theoretical predictions for comparisons
- Crucial for the constraints on new physics as deviations ***from the Standard Model predictions***

But what do we gain?

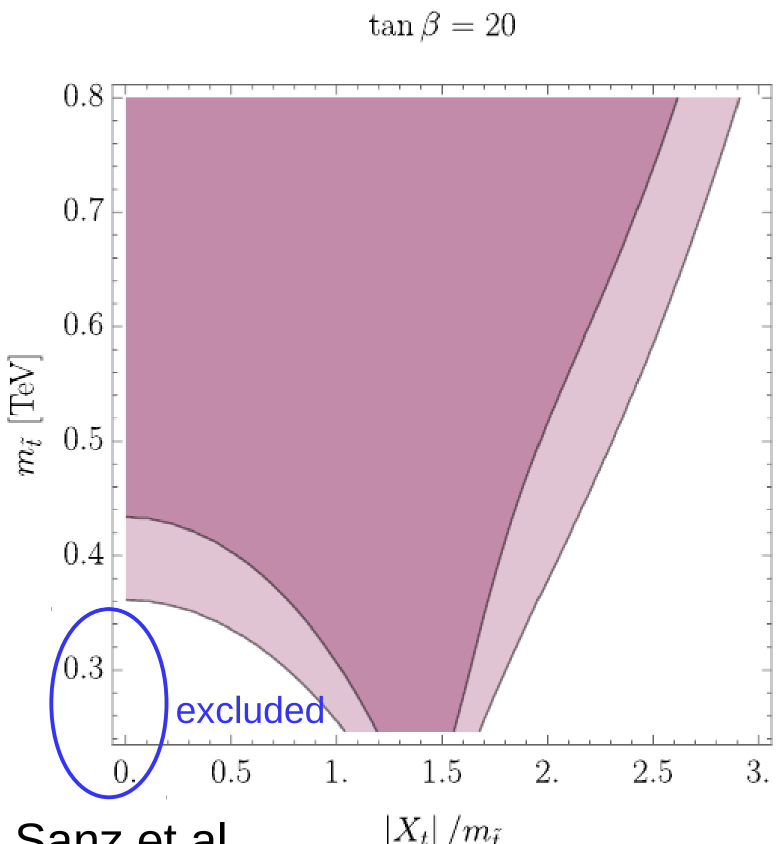
- Surely a measurement can't be better than a dedicated search
- Well apparently yes (though things might have changed in Run-2)



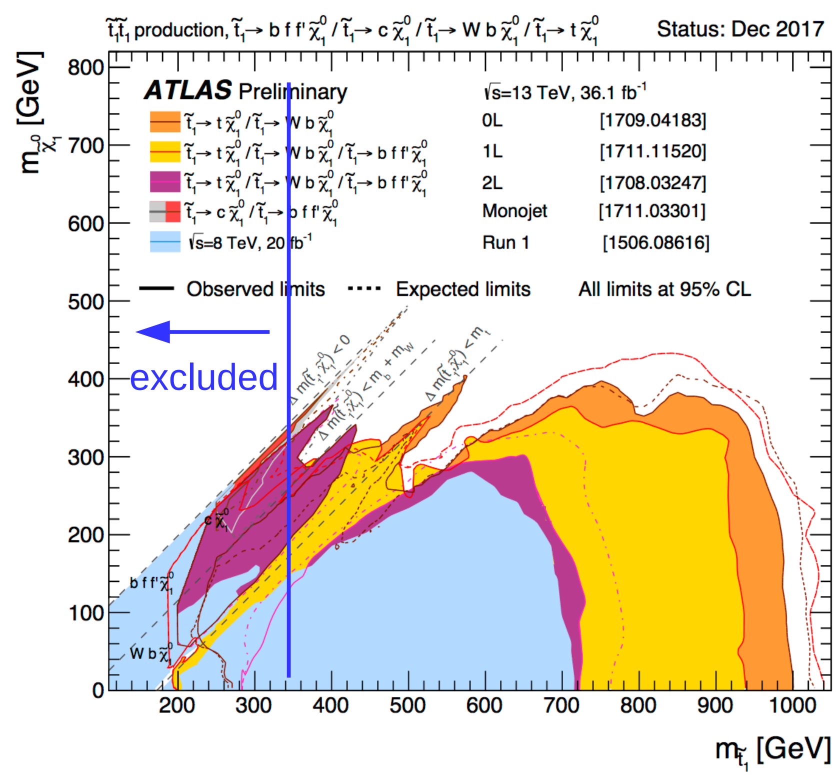
arXiv:1505.05523

But what do we gain?

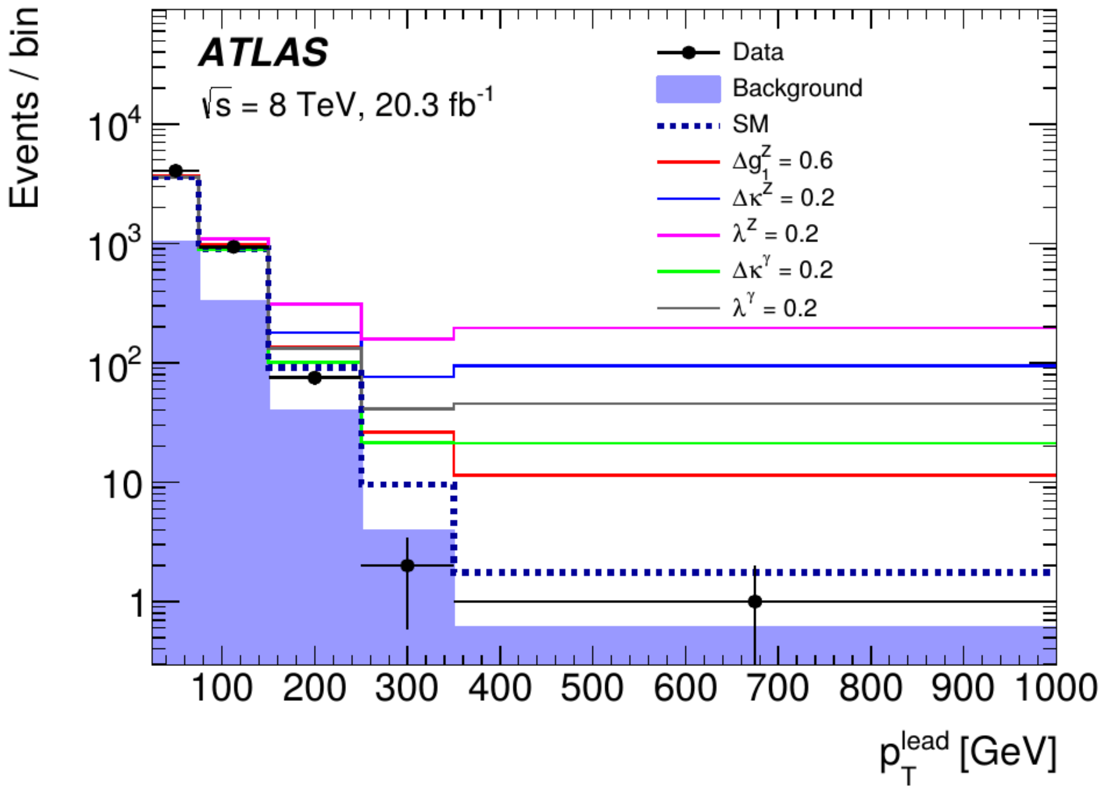
- This was from a direct measurement, surely constraints on EFT parameters cannot be as useful…
- Translation not as straightforward, but limits seem competitive

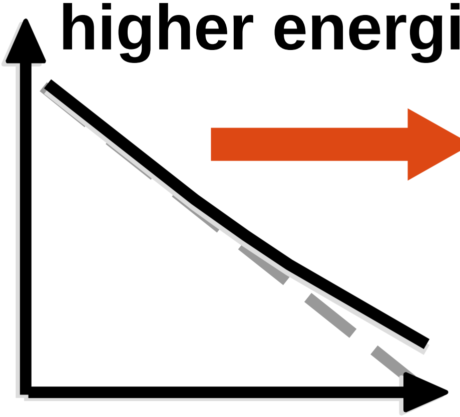


Sanz et al
arXiv:1803.03252v1



Effects of these new phenomena on WW production





Search for phenomena at higher energies

Δg_1^Z $\Delta\kappa_1^Z$ $\Delta\lambda^Z$ $\Delta\kappa^\gamma$ $\Delta\lambda^\gamma$

(should be all zero in the SM)

Comparing WW and WZ constraints

WZ

EFT coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[−3.7 ; 7.6]	[−4.3 ; 6.8]
c_B/Λ^2	[−270 ; 180]	[−320 ; 210]
c_{WWW}/Λ^2	[−3.9 ; 3.8]	[−3.9 ; 4.0]

arXiv:1603.01702

WW

Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
	C_{WWW}/Λ^2	[−7.62, 7.38]	[−4.61, 4.60]
EFT	C_B/Λ^2	[−35.8, 38.4]	[−20.9, 26.3]
	C_W/Λ^2	[−12.58, 14.32]	[−5.87, 10.54]

Phys. Rev. D 93, 092004 (2016)

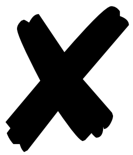
- Best constraints marked
- Obtained setting others to zero
- More true to the situation and an improvement to remove statistical constraints:

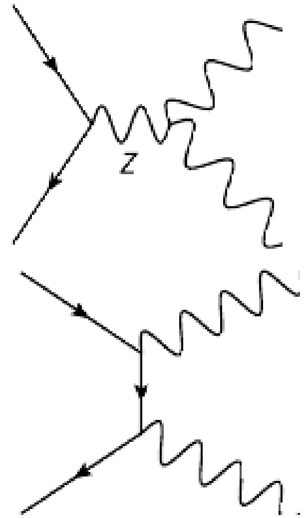
Conducting combined fit to all measurements sensitive to these parameters

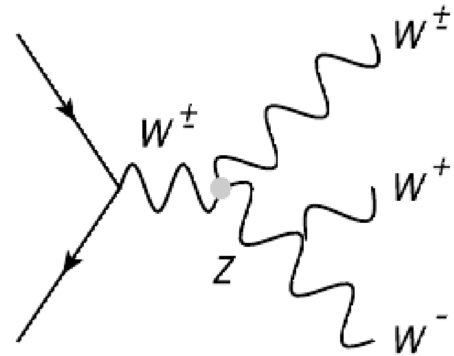
Triple and quartic Gauge Couplings

	Single boson	Multiboson	Triboson

Inclusive production

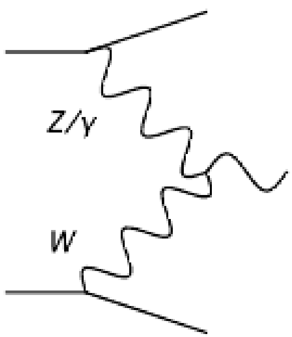


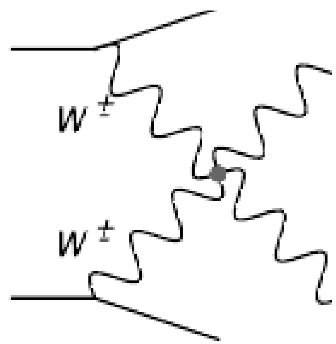




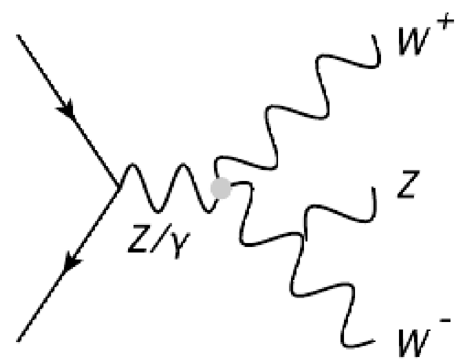
multilepton final state

Vector Boson Fusion or Scattering (VBF/VBS)





two jets with large rapidity gap



Triple and quartic Gauge Couplings

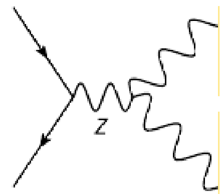
Inclusive production

Single boson

- 7 TeV
- 8 TeV
- 13 TeV
- not measured

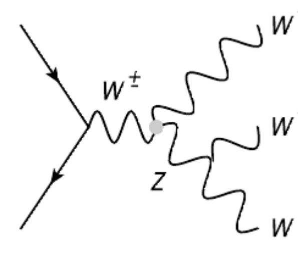
Multiboson

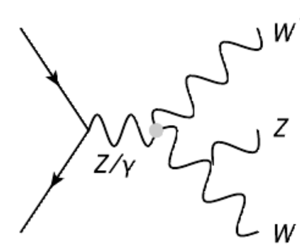
- WW
- WZ
- ZZ
- Zγ
- Wγ



Triboson

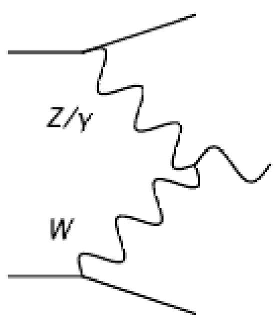
- WWW
- WWZ
- WZZ
- WWγ
- WZγ
- Wγγ
- ZZZ
- ZZγ
- Zγγ
- γγγ



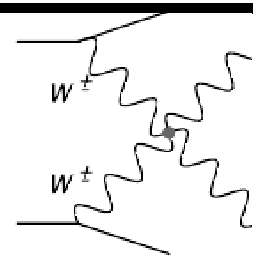


Vector Boson Fusion or Scattering (VBF/VBS)

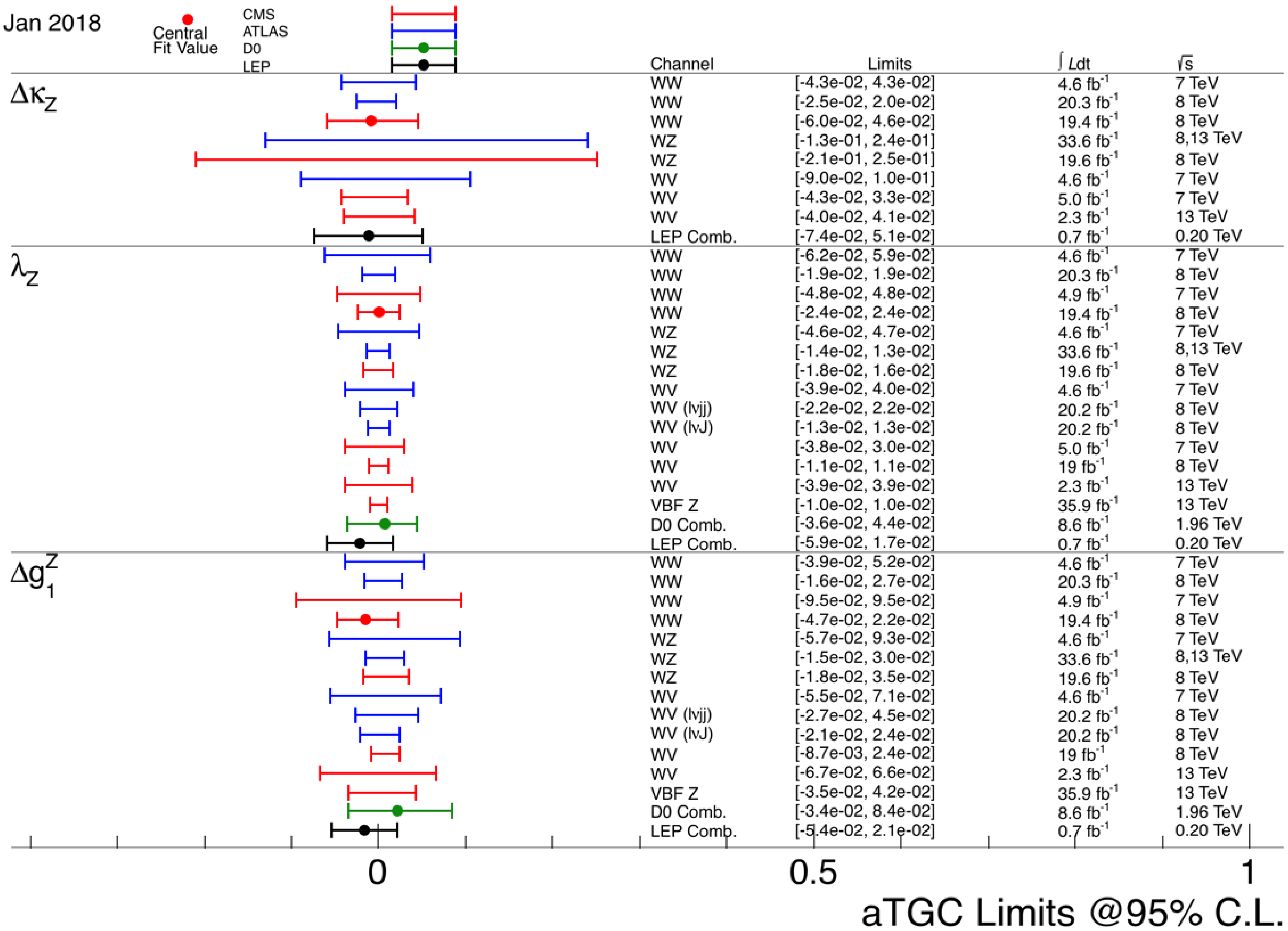
- W
- Z
- γ not measured



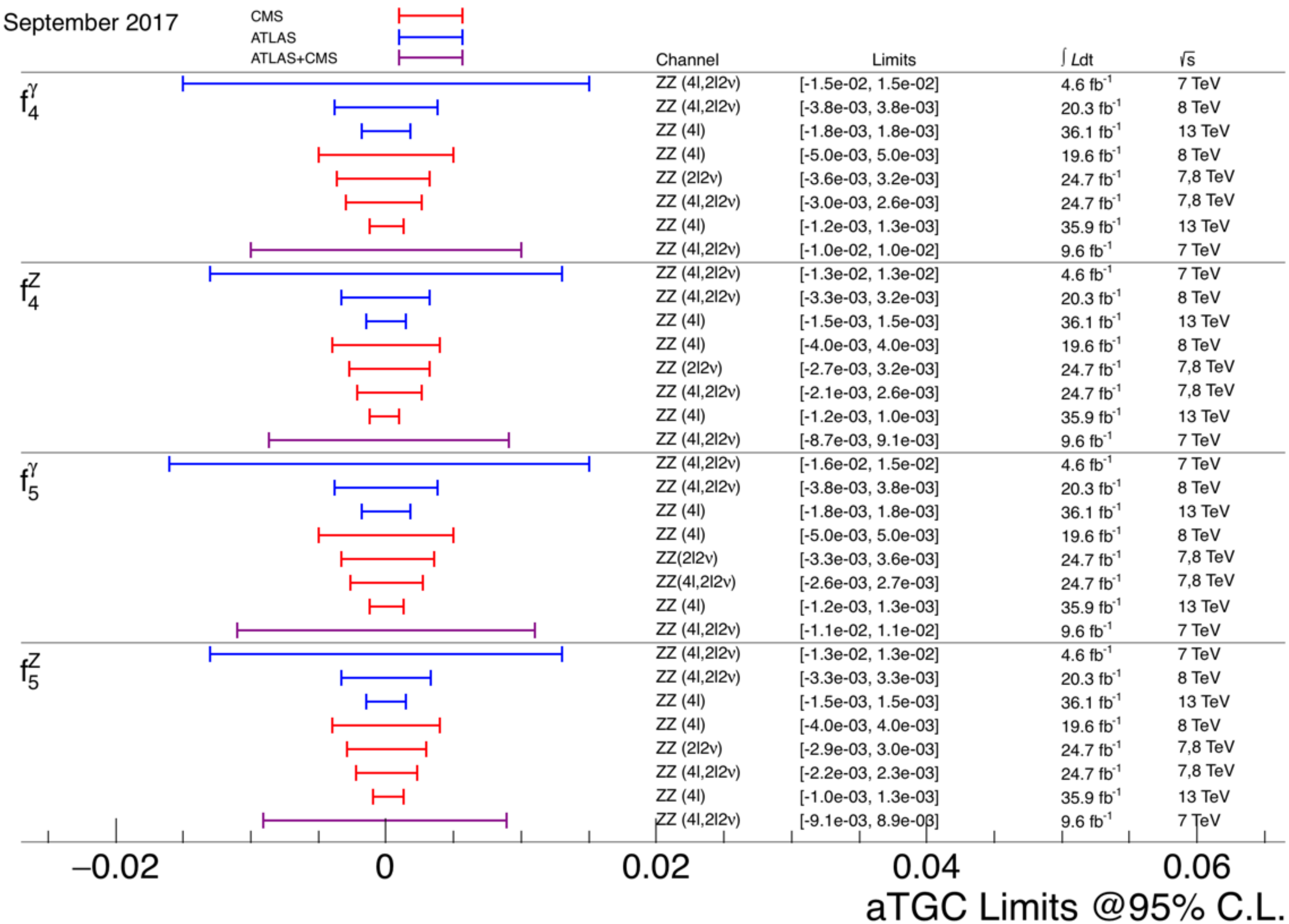
- WW
- WZ
- ZZ VBS
- Zγ VBS
- Wγ VBS



Summary of constraints: Processes with W's



ZZ processes



	Channel	Limits	$\int Ldt$	$\sqrt{s}$
f_4^γ	ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
f_4^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
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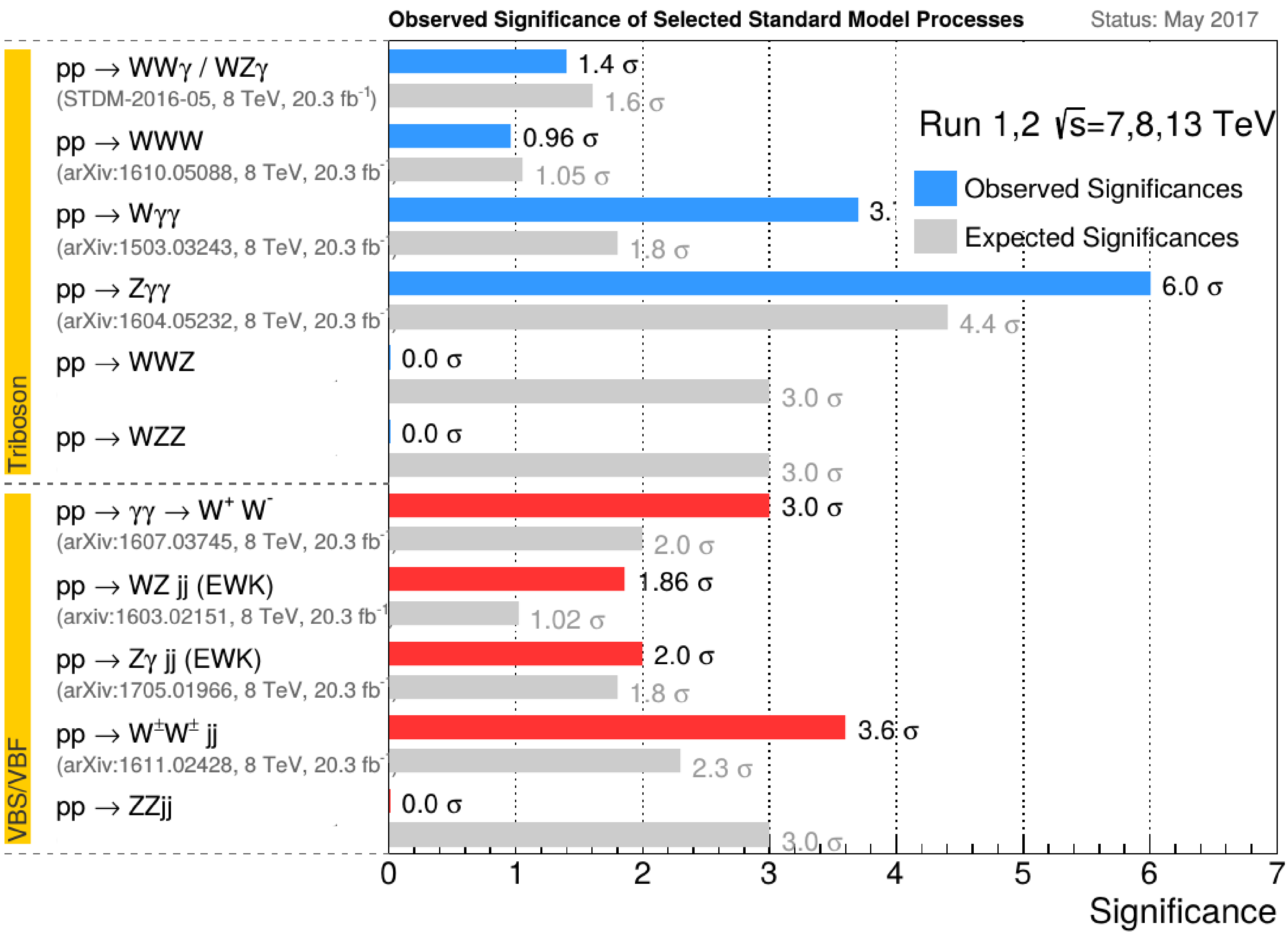
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.0e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
f_5^γ	ZZ (4l,2l2ν)	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ(4l,2l2ν)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.1e-02, 1.1e-02]	9.6 fb^{-1}	7 TeV
f_5^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.3e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.0e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-9.1e-03, 8.9e-03]	9.6 fb^{-1}	7 TeV

What's in store?

- With no significant deviations from the SM → new physics (if any) must be moderately "decoupled" (i.e. at higher energies)
- A programme of EFT measurements allows to evaluate the SM as a whole and to characterize it globally, possibly shedding light on whatever comes next (as LEP did for the Higgs)
- Experiments moving slowly from non-Higgs LEP-style EFTs and Higgs characterization models to a more comprehensive programme
- Above all: in the process of exploiting currently incoming data – measuring some processes for the first time!

Still to come



Conclusions

- Diboson cross sections measured with great precision O(5%)
- Only NNLO predictions can describe these processes up to this level of precision
- Diboson production sensitive to new phenomena
  Stringent constraints set – so far no hints for new physics
- Looking forward to new measurements and improved physics interpretation

Backup slides.

The Standard Model's biggest triumph

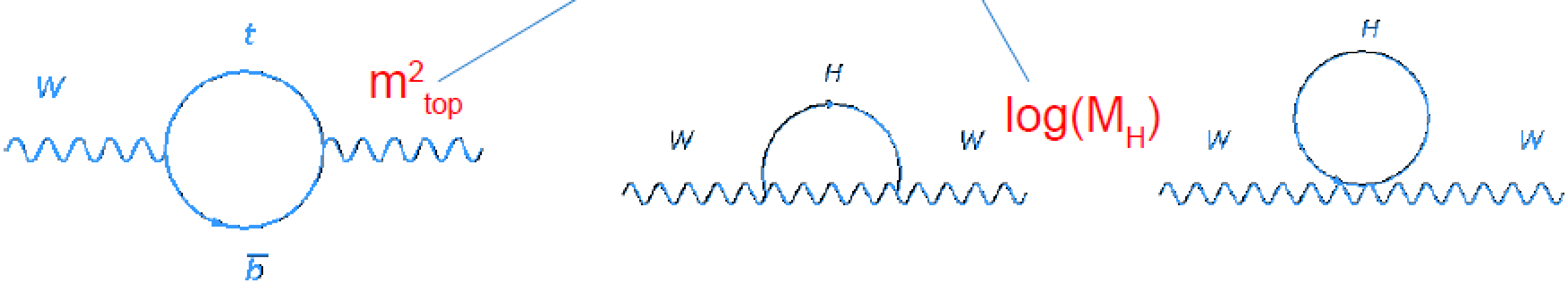
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

$$v = \left(\sqrt{2}\, G_F\right)^{-1/2} \simeq 246.22\ \mathrm{GeV} \qquad \alpha = \frac{e^2}{\hbar c}. \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

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

radiative corrections

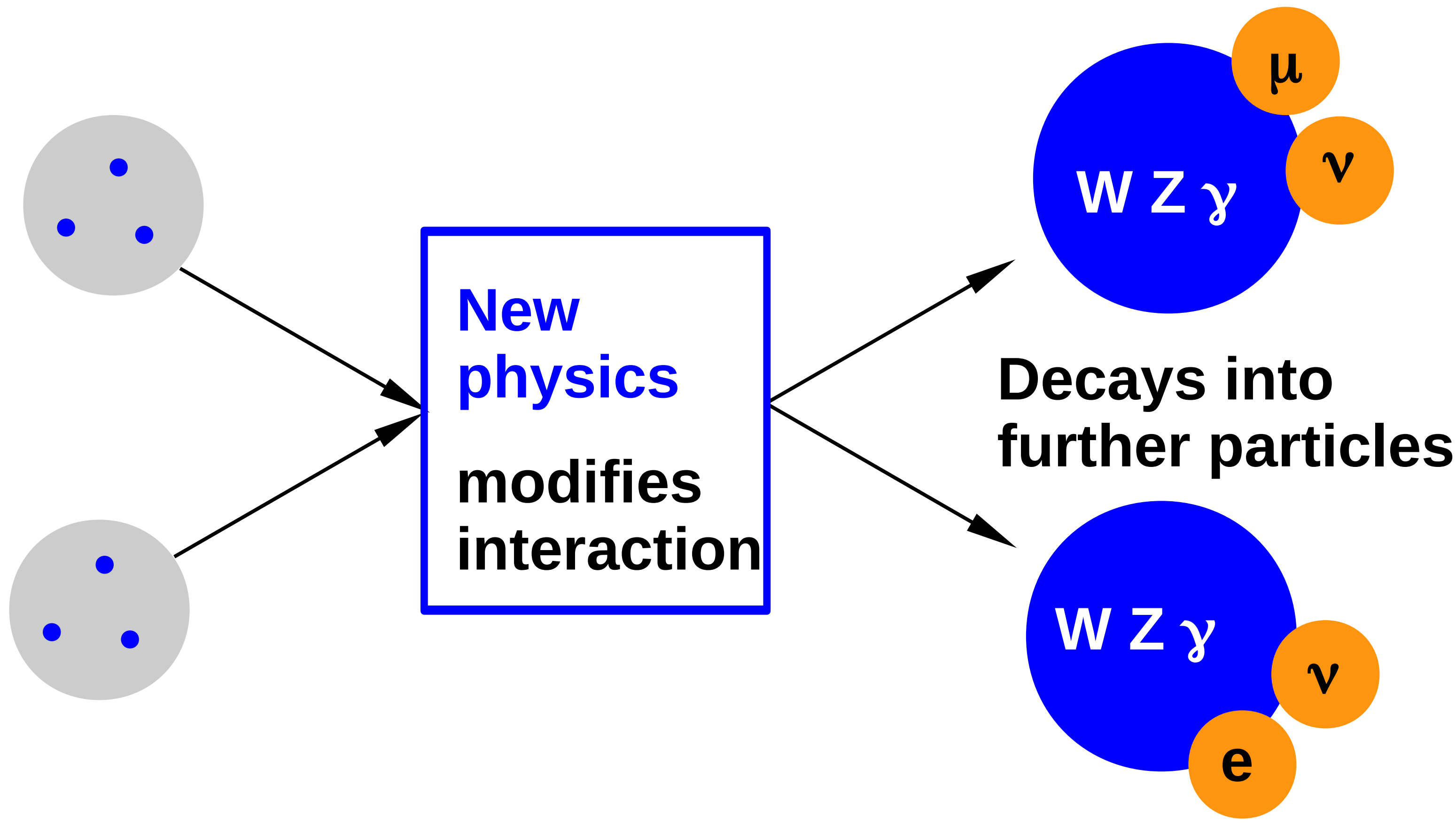
$\Delta r \sim 3\ \%$



How do we investigate the Standard Model?

Proton Collisions

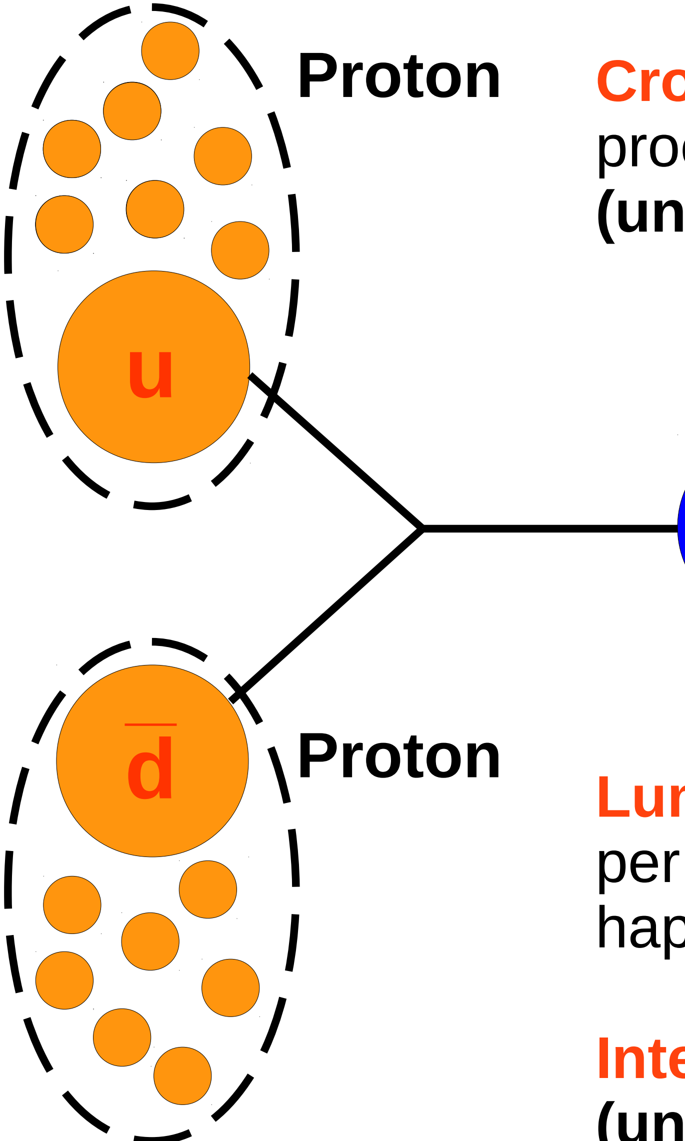
Diboson Production



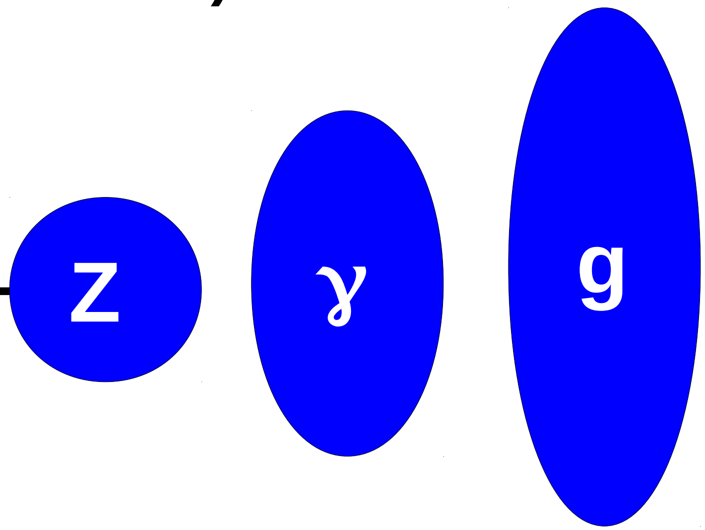
Quarks, gluons,
photons, W/Z bosons

Dibosons
WW final states most sensitive

How do we investigate the Standard Model?



Cross section: measure of probability of process to happen (strength of interaction) **(unit: area)**



Luminosity: How many colliding particles cross per unit area and second (how much could happen?) **(unit: 1/(area×time))**

Integrated Luminosity: size of data set **(unit: 1/area)**

Detector and Performance