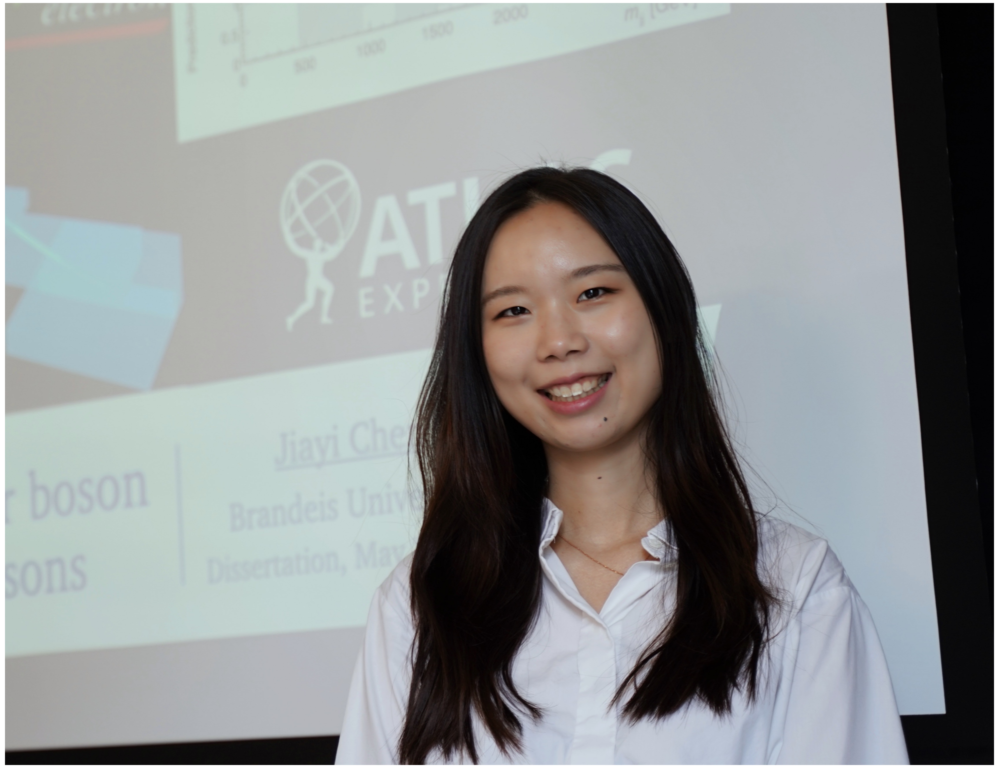
Gertrude Scharff-Goldhaber Prize 2022 presented to Jiayi Chen



- "My dream to become a scientist was planted at an early age by my family and reinforced when I conducted my first particle physics project at CERN."
- Chen's study of the Higgs boson began in the summer of 2018 under the supervision of Alessandro Tricoli and Gaetano Barone from Brookhaven Lab
- Chen has been working on the development of a new silicon-based inner tracker for the ATLAS experiment in collaboration with Brookhaven's David Lynn, Gerrit van Nieuwenhuizen, Stefania Stucci, and Alessandro Tricoli

ATLAS EXPERIMENT

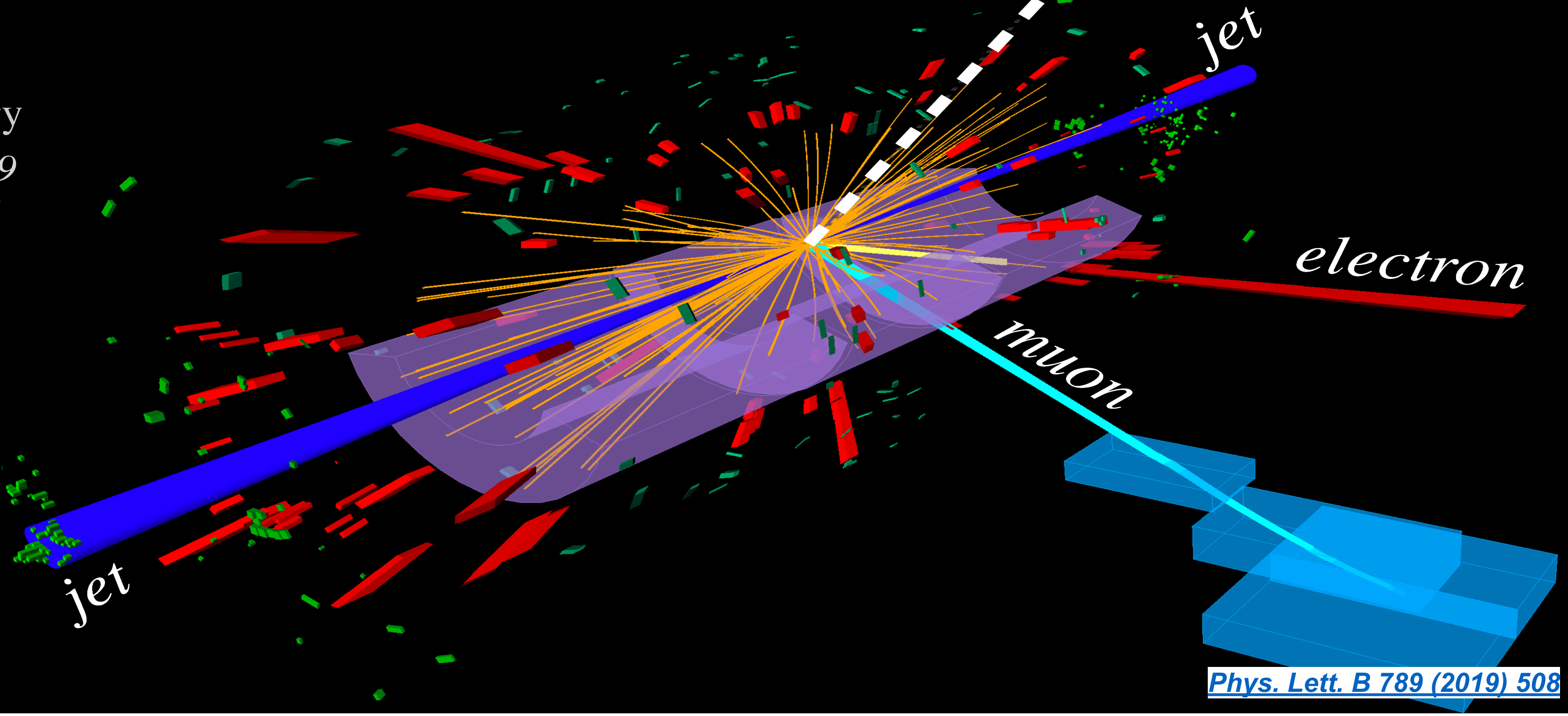
Brandeis UNIVERSITY

Brookhaven National Laboratory

Unveiling new physics signature with the Higgs bosons and the ATLAS detector

H→*WW**→*eνμν* candidate
and two jets with VBF topology
Run 305618, Ev. no. 2461194919
Aug. 05, 2016, 08:37:53 CEST

ATLAS EXPERIMENT



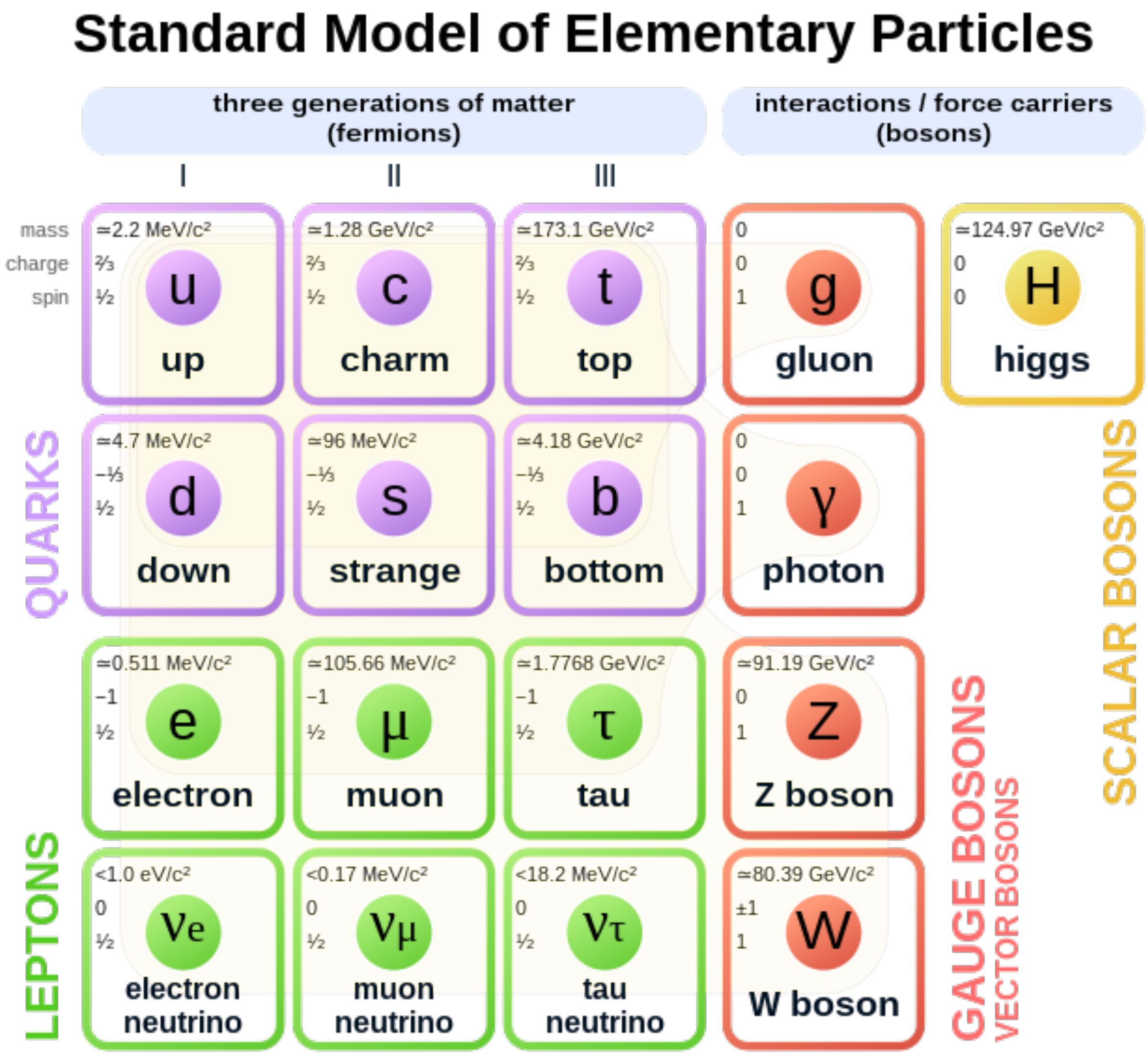
Phys. Lett. B 789 (2019) 508

Jiayi Chen
Scharff-Goldhaber Prize Ceremony
June 24 2022

Brandeis University
Brookhaven National Laboratory

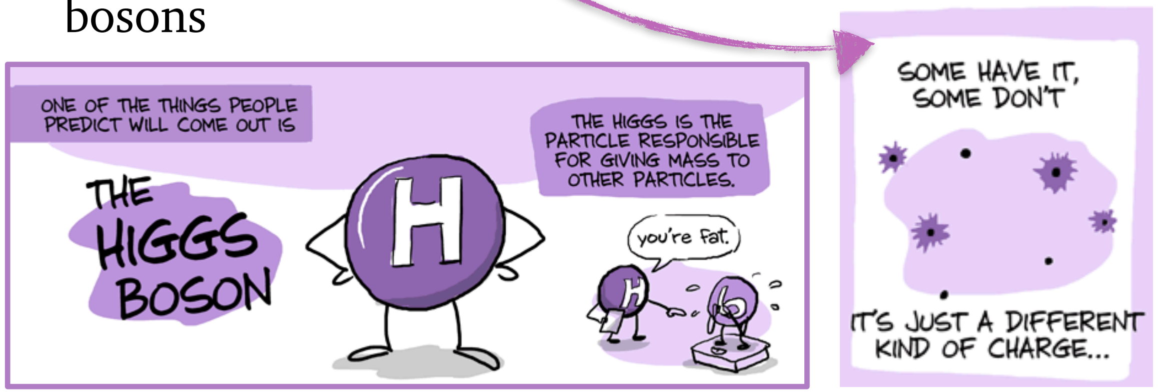
The Standard Model and beyond

What we already know about particle physics



Wikipedia contributors.

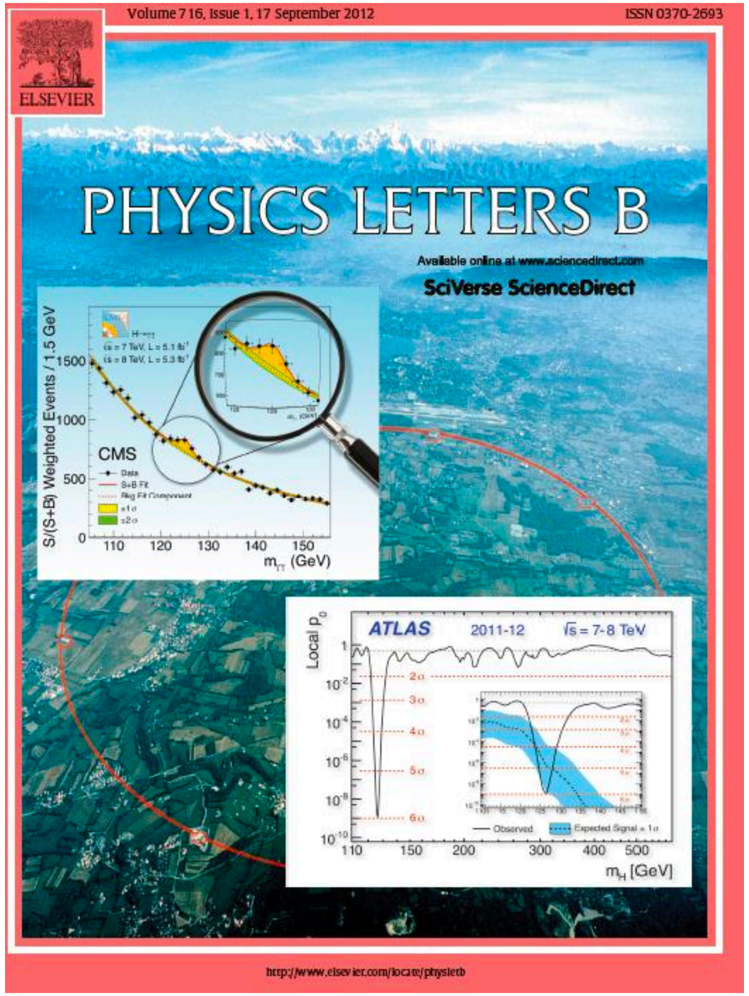
- The Standard Model (SM) - most successful model describing the past 50 years of experimental data
- Fermions make up matter in the Universe
  - proton = 2 up + 1 down quarks
  - Hydrogen atom = proton + electron lepton
- Force carrier bosons:
  - Gluon: strong force
  - Photon, Z boson and W boson: electroweak force
- Higgs boson gives mass to fermions and gauge bosons

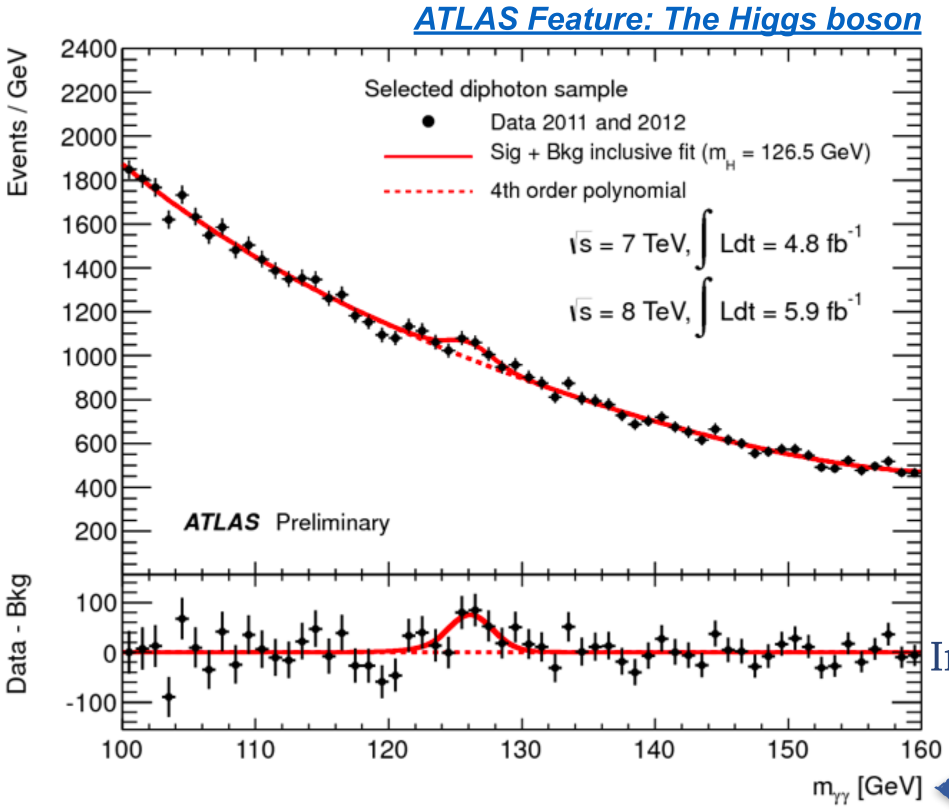


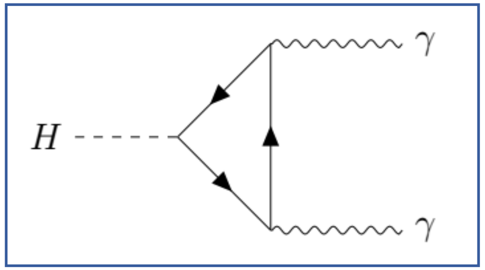
PhD Comics, "We have no idea"

10-year anniversary of the Higgs boson discovery

The Higgs boson co-discovered by ATLAS and CMS collaborations in 2012





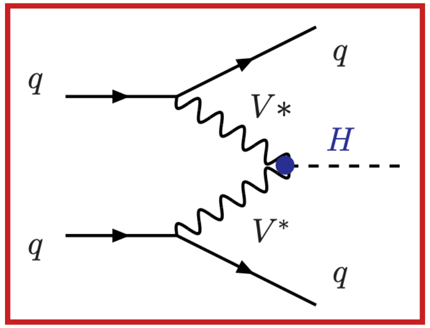


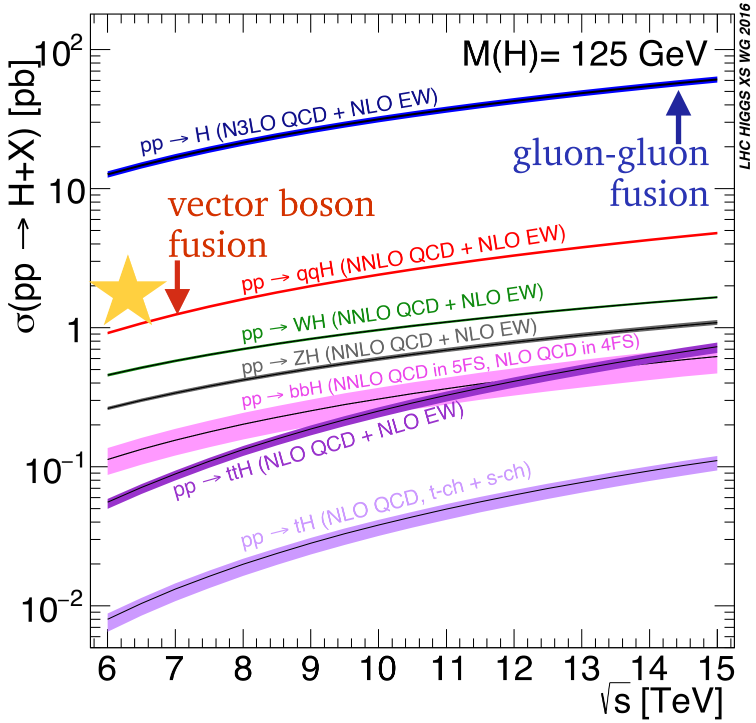
Invariant mass of the photons from the Higgs decay

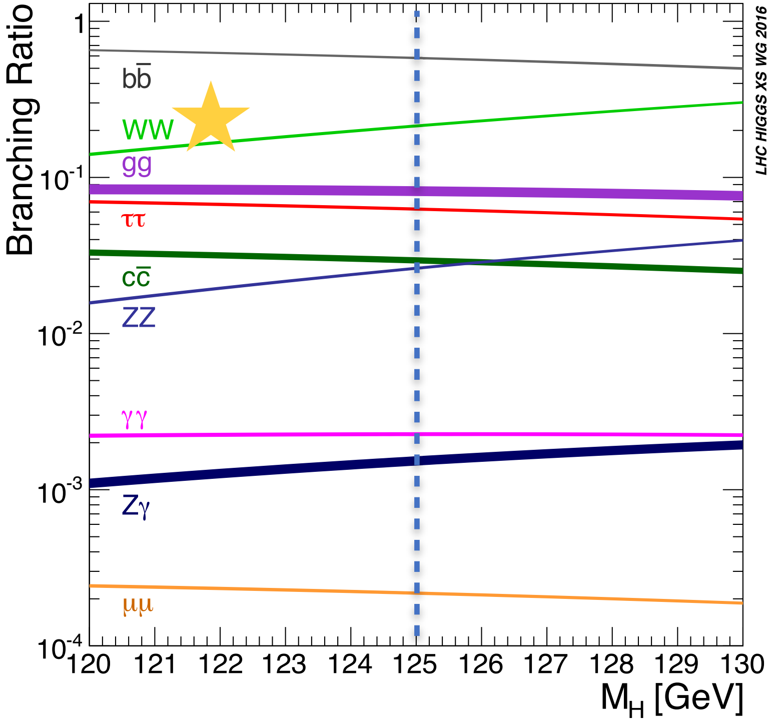
- Total energy of the decay products is the mass energy in the rest frame of the original particle (invariant mass)

Higgs production and decay simulation

Dominant production and decay modes measured by ATLAS and CMS in agreement with SM hypothesis





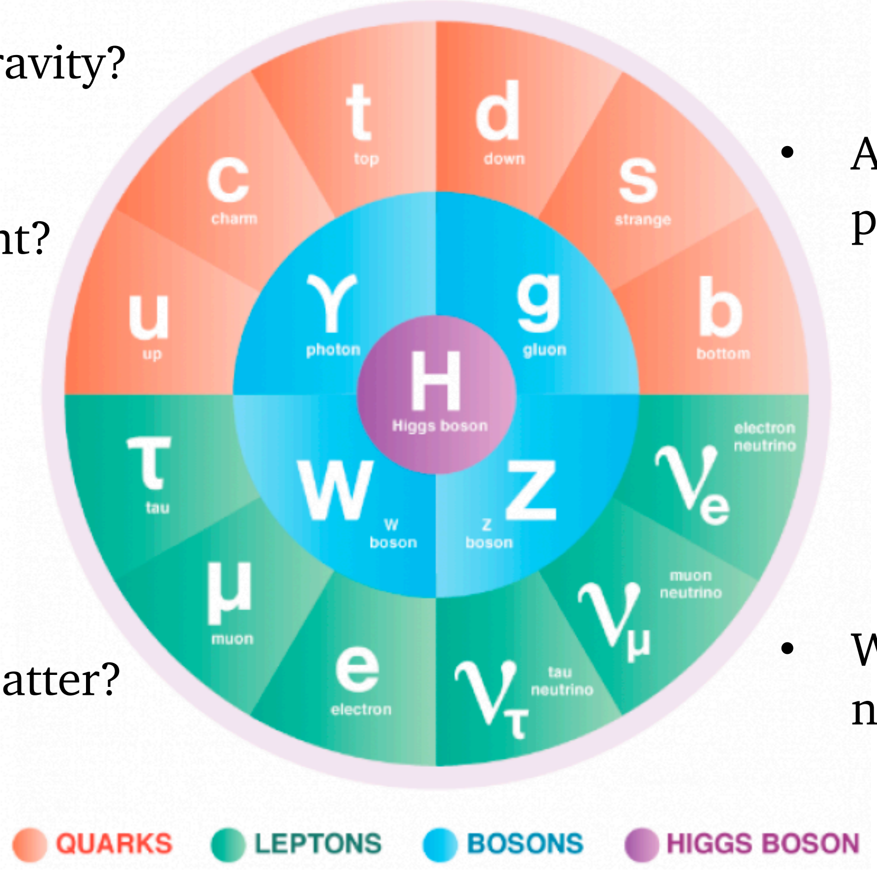


- Production modes ordered by *cross section* - a measure of probability of a particular interaction
- Decay modes ordered by *branching ratio (BR)* - probability for a particle to decay in a channel

Handbook of LHC Higgs Cross Sections

We got Higgs, what else?

- Matter-antimatter asymmetry in the Universe
- What about gravity?
- A large mass range of SM particles (order of 10^5)
- Why is the Higgs so light?



Symmetry magazine

- Where is Dark Matter?
- What is the nature of neutrino mass?

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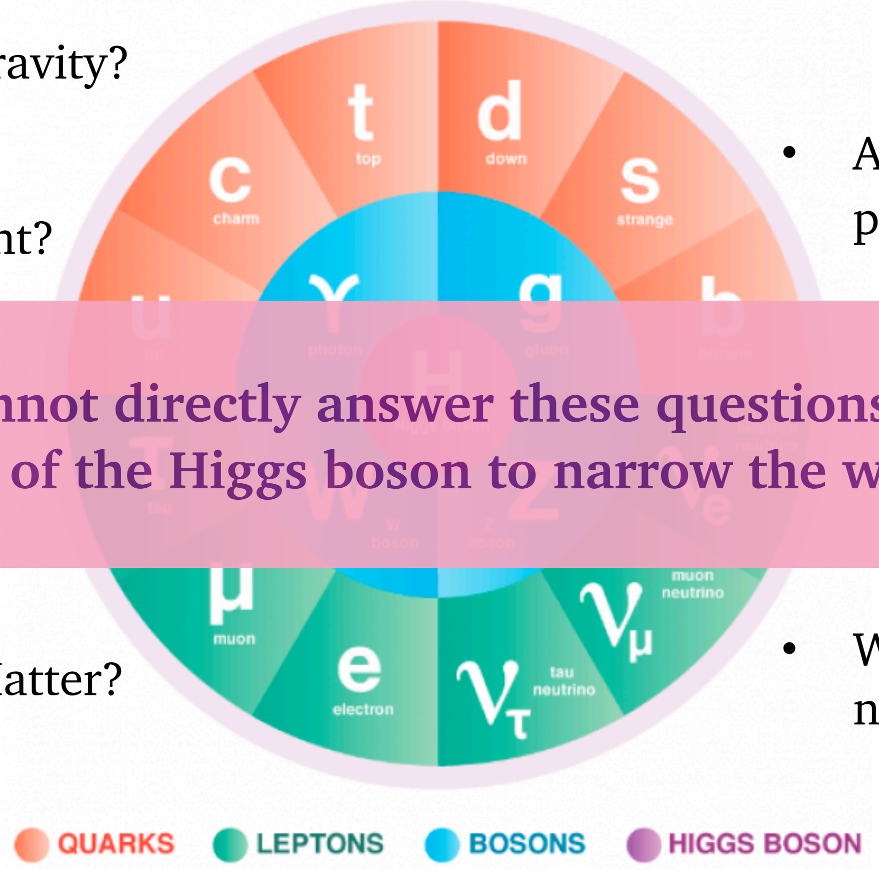


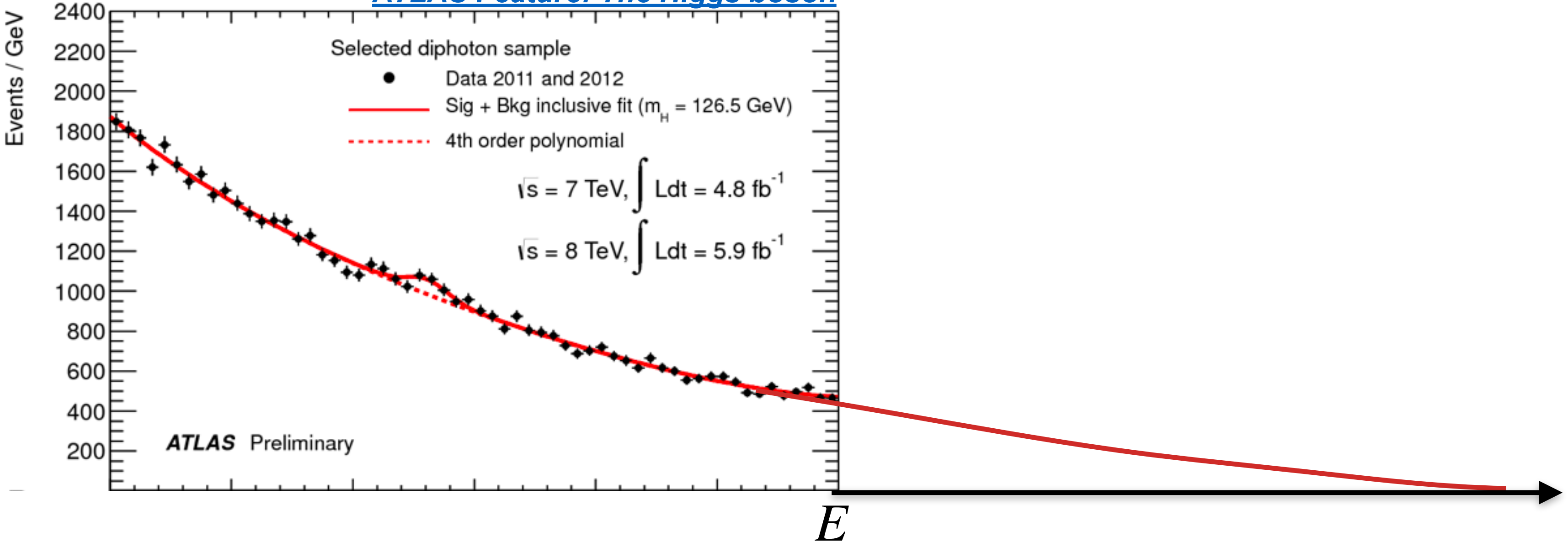
While my study cannot directly answer these questions, I aim to use cross-section measurement of the Higgs boson to narrow the window for new physics

- Where is Dark Matter?
- What is the nature of neutrino mass?

Symmetry magazine

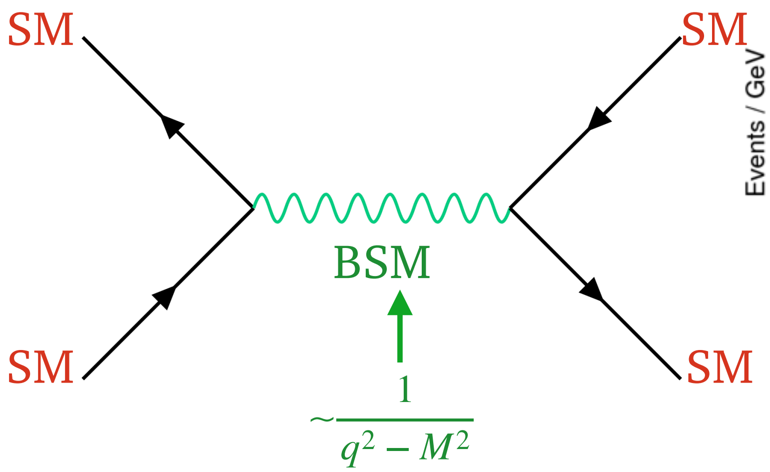
Effective Field Theory - a model-independent approach

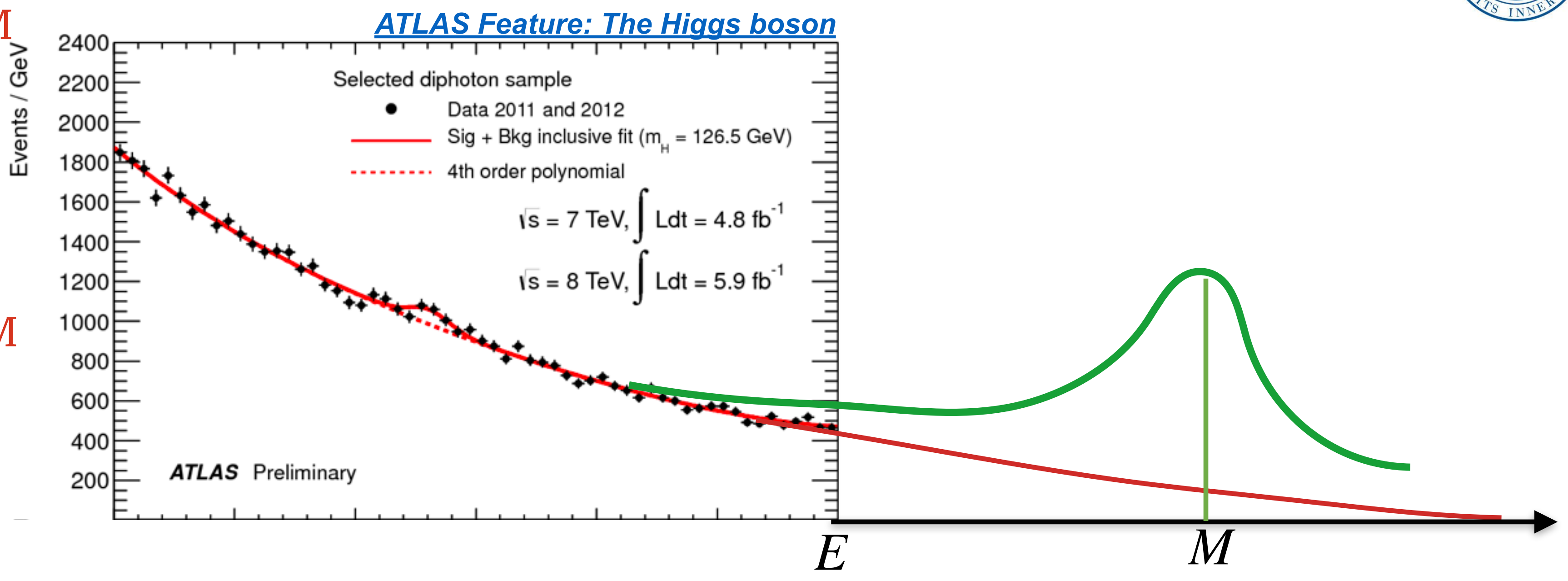
ATLAS Feature: The Higgs boson



- The SM with no new resonance

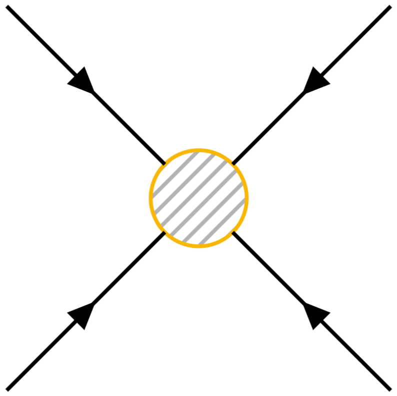
Effective Field Theory - a model-independent approach





- The SM with no new resonance
- Complete beyond the Standard Model (BSM) theory with new resonance with mass M

Effective Field Theory - a model-independent approach

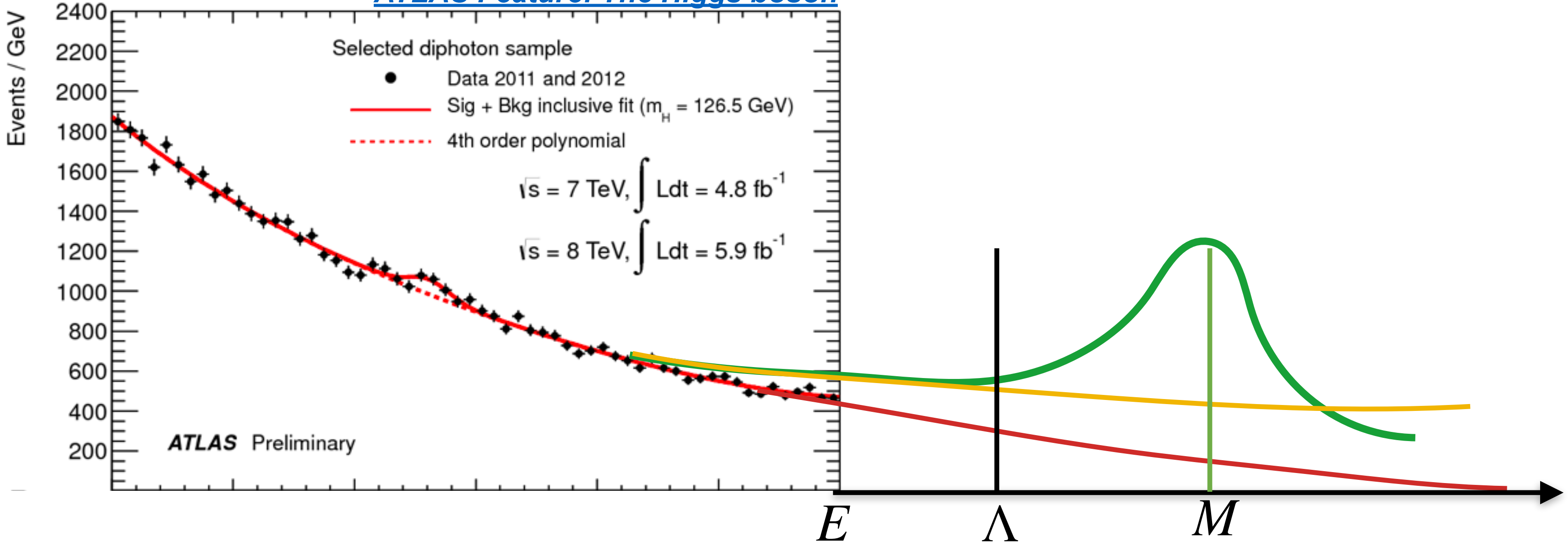


$$\sim \frac{1}{M^2}(1 + \mathcal{O}(M^{-2}))$$

$$\downarrow$$

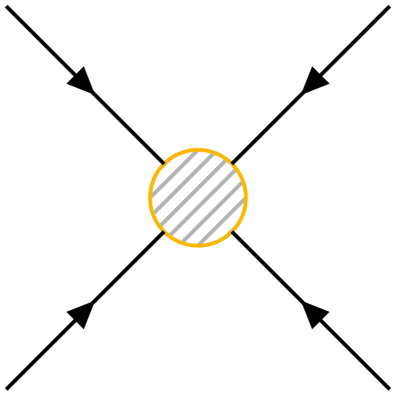
$$\sim \frac{c}{\Lambda^2}$$

ATLAS Feature: The Higgs boson



- The SM with no new resonance
- Complete BSM theory with new resonance with mass M
- The effective theory
  - "integrates out" the heavy new particle field **—> model-independent!**
  - equivalently describes the phenomena at energy below cut-off scale Λ
  - has no knowledge of the the resonance

Effective Field Theory - a model-independent approach

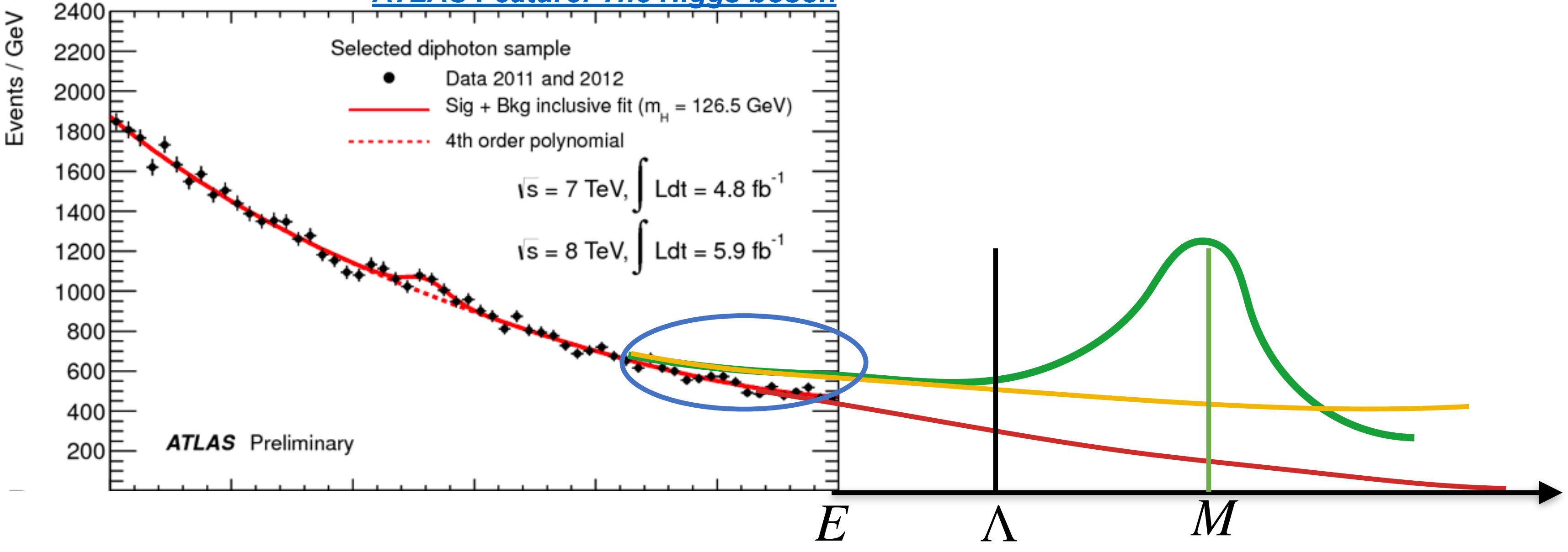


$$\sim \frac{1}{M^2}\left(1 + \mathcal{O}(M^{-2})\right)$$

↓

$$\sim \frac{c}{\Lambda^2}$$

ATLAS Feature: The Higgs boson

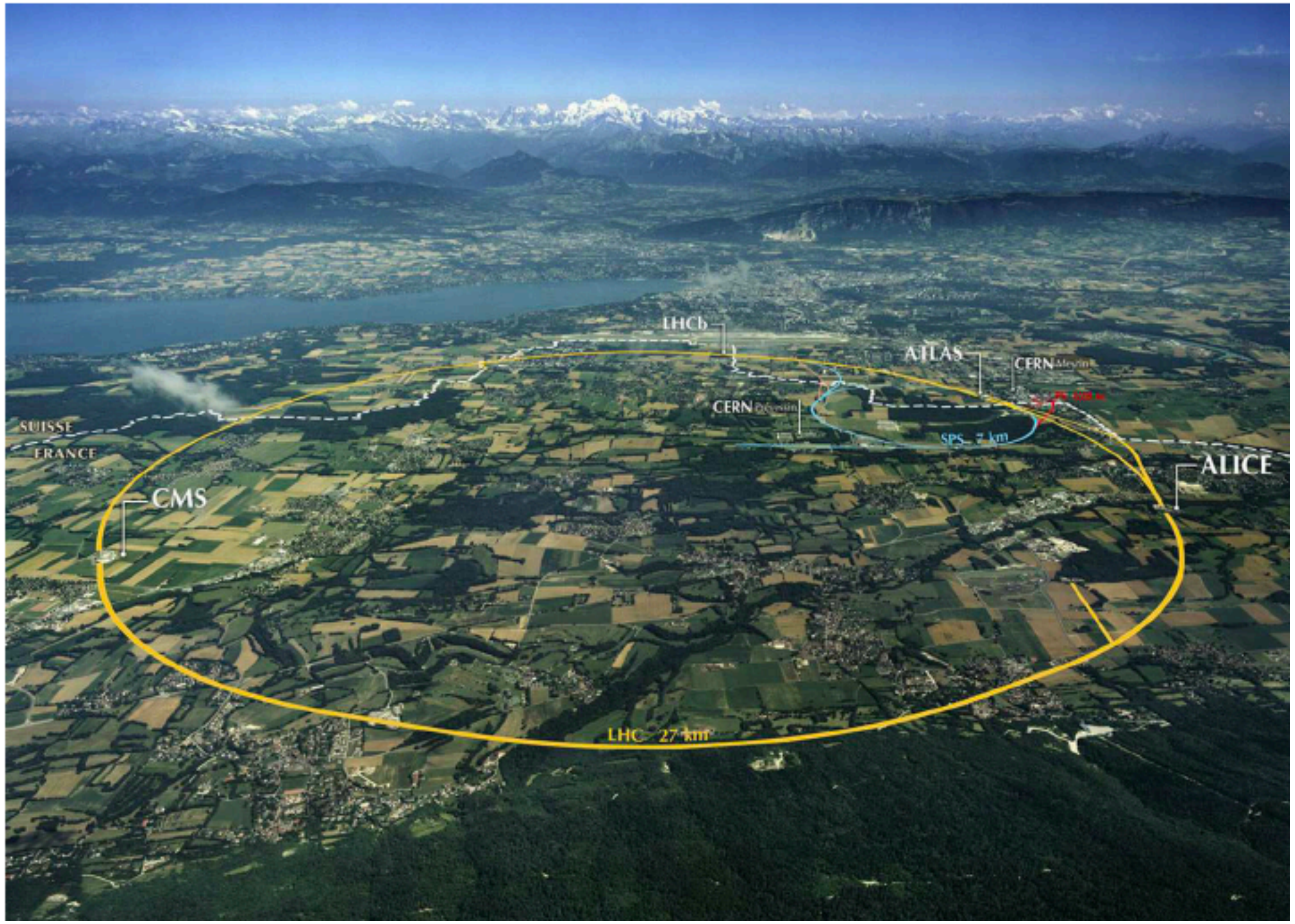


- The SM with no new resonance
- Complete BSM theory with new resonance with mass M
- The effective theory
  - "integrates out" the heavy new particle field **—> model-independent!**
  - equivalently describes the phenomena at energy below cut-off scale Λ
  - has no knowledge of the the resonance
- The focus of my study uses the deviations between the measured cross-sections and the SM hypothesis and interpret it with the EFT formalism

Apparatus

The Large Hadron Collider

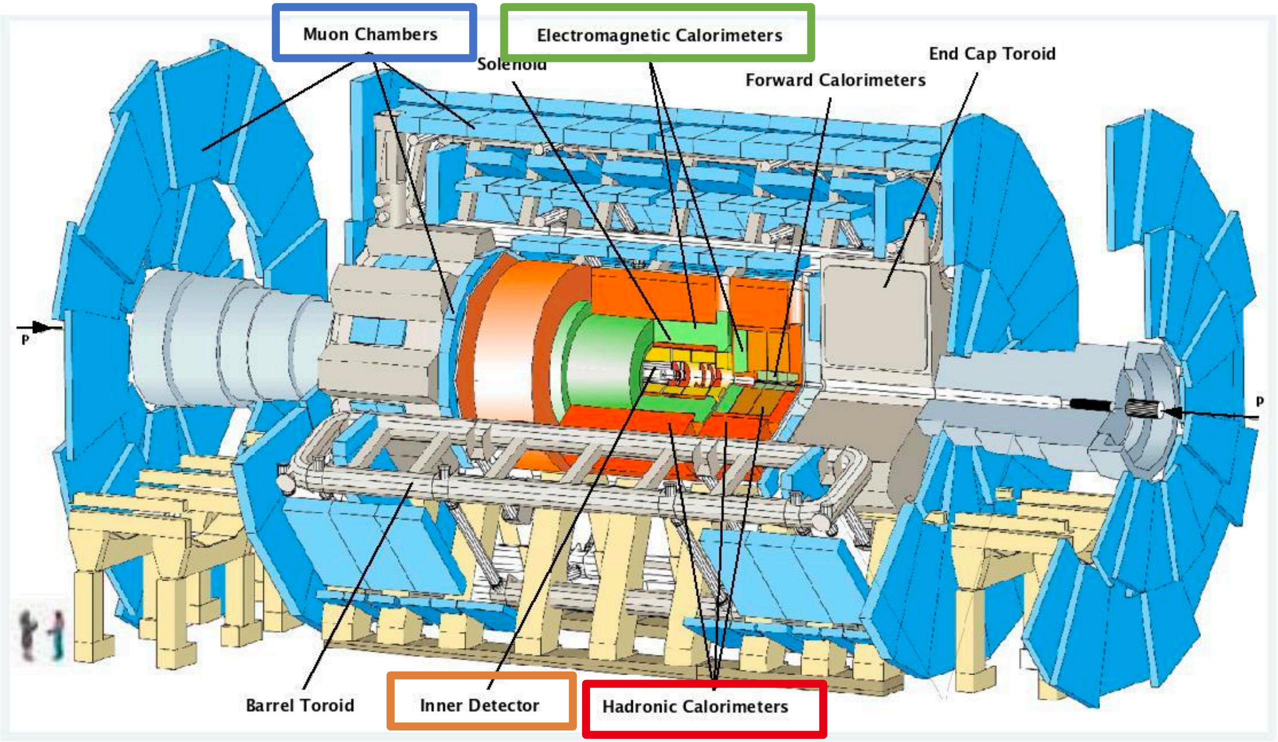
- World's largest (27-km long) and most powerful collider
- Proton-proton (*pp*) collision energy up to 14 TeV (proton speed nearly at speed of light)
- Dataset collected during the second operational run (Run-2) from 2015-2018 with an *integrated luminosity* (L) of $139\ \text{fb}^{-1}$
  - $1\ \text{fb}^{-1} \sim 100$ trillion *pp* interactions



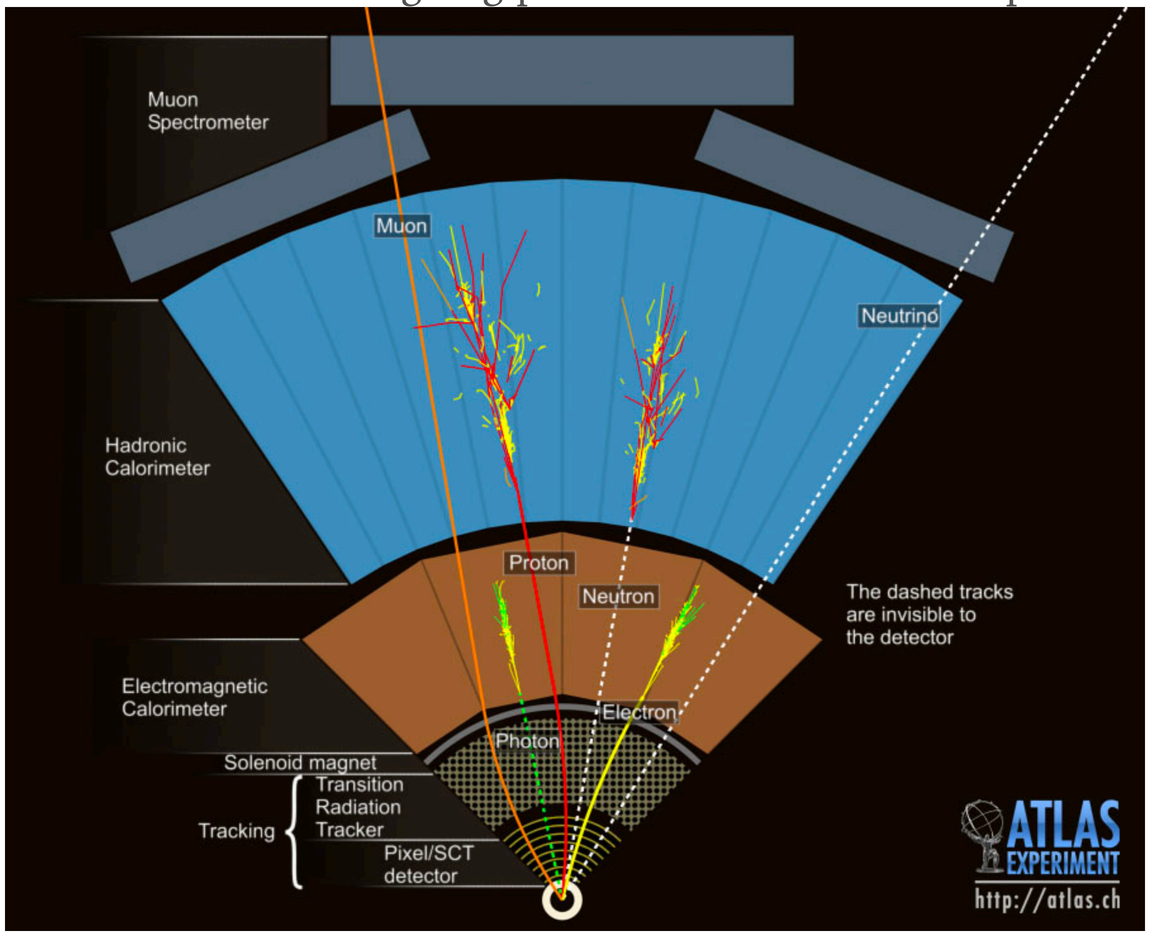
Photograph by Maximilien Brice (CERN)

The ATLAS detector

- **A T**oroidal **L**HC **A**pparatu**S**: a general-purposed cylindrical-shaped multi-layer detector
- Collision at the center and outgoing particles leave signatures (tracks or energy) in each sub-detector



Visualization of outgoing particles in the transverse plane

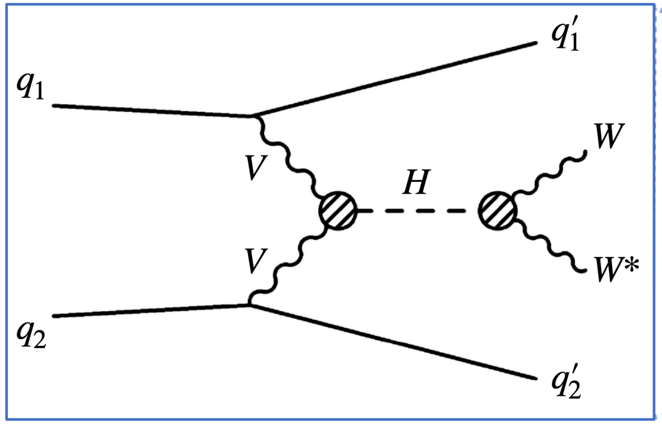


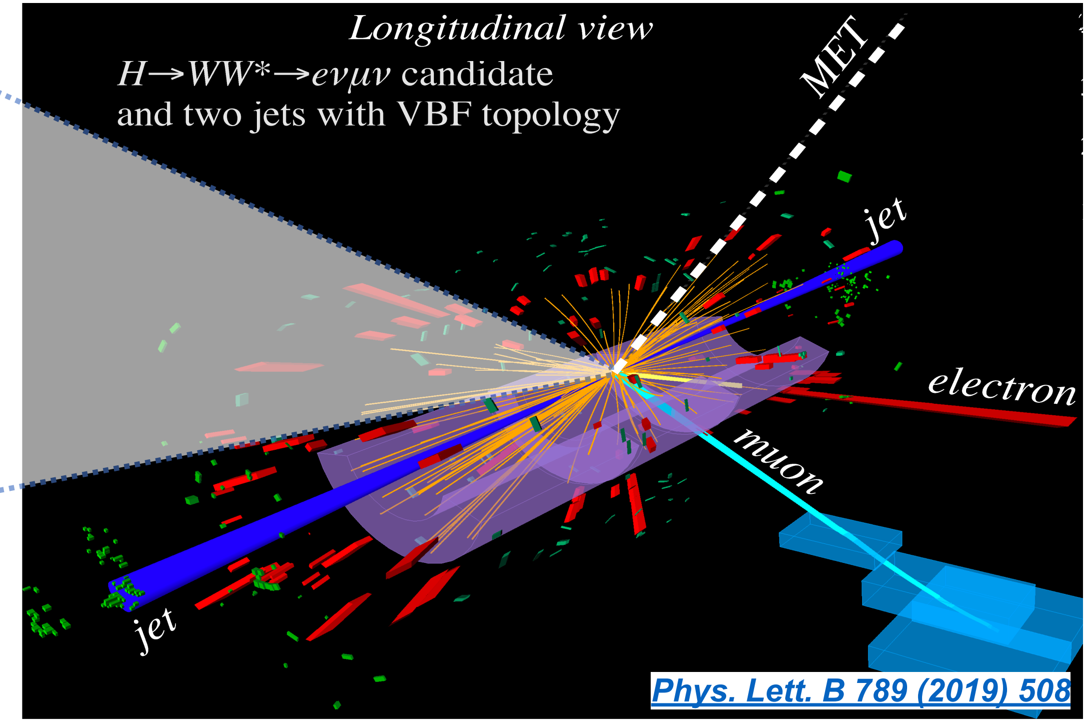
- From beamline going outward
  - Inner detector (ID) in a 2T magnetic field in z-direction
  - Electromagnetic calorimeter (ECAL)
  - Hadronic calorimeter (HCAL)
  - Muon Spectrometer (MS) with toroidal magnet at 3.5T

VBF and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

- cross-section measurements
- EFT interpretation

Analysis overview





Observable
M_{ll}
M_{jj}
$Cos(\theta^*)$
Δy_{ll}
Δy_{jj}
$\Delta\phi_{ll}$
$\Delta\phi_{jj}$
Higgs p_{T}
$p_{\mathrm{T}}^{\ell\ell}$
Leading Lepton p_{T}
Subleading Lepton p_{T}
Leading Jet p_{T}
Subleading Jet p_{T}

Signal optimization

Use techniques, including machine learning, to extract small signal from large background

Unfolding

- Correct for detector inefficiency and resolution

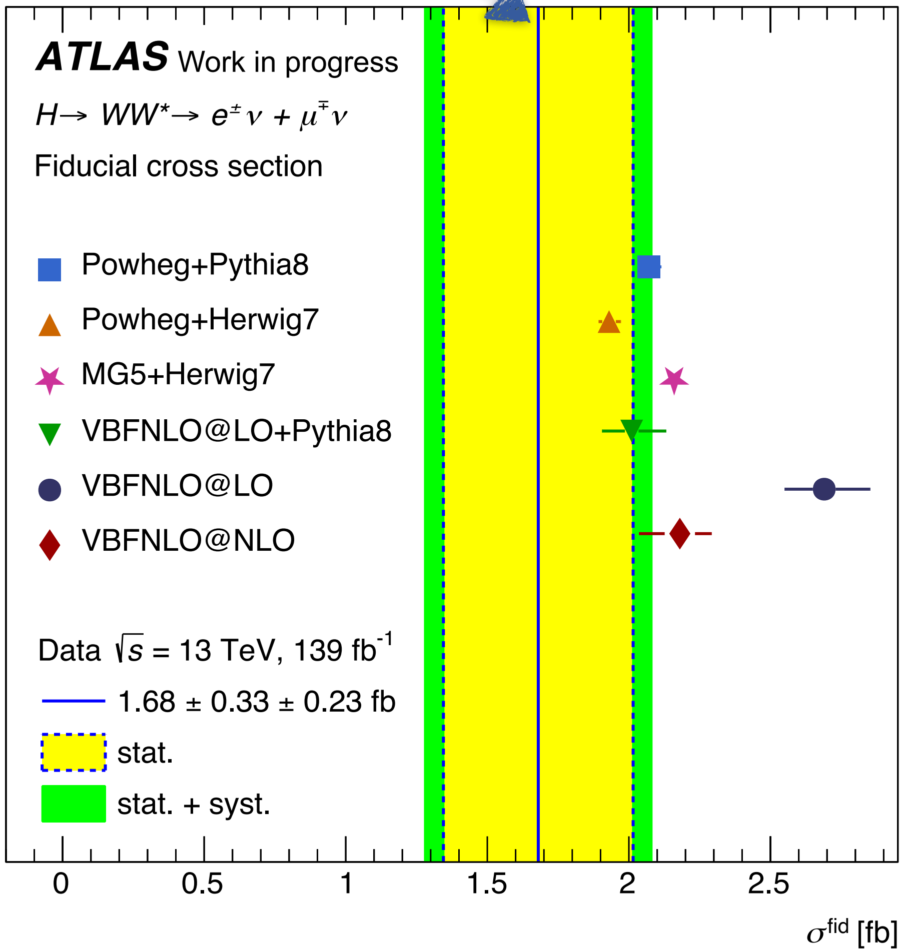
Measurements

- Cross sections in a *fiducial phase space* inclusively and *differentially*
- Re-interpretation to constrain anomalous interactions of the SM particles

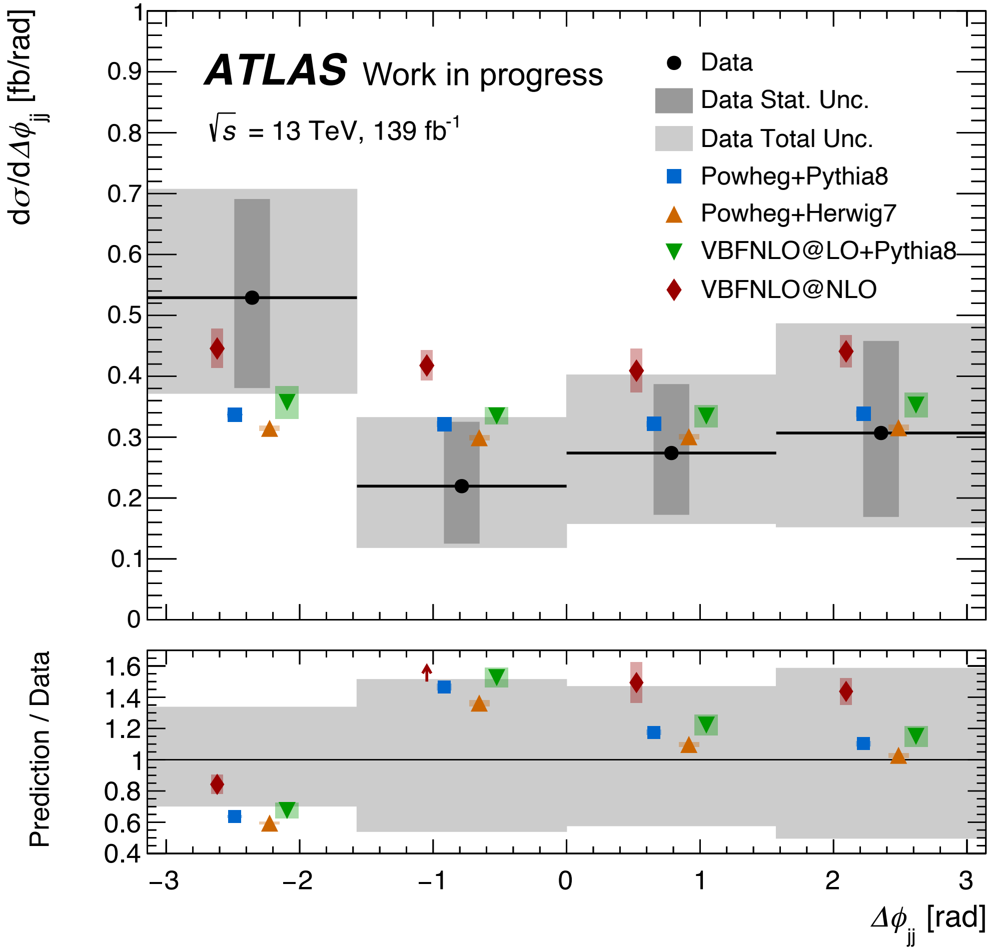
Strategy optimized with Monte Carlo simulation and applied to Run-2 dataset

Fiducial and differential cross-section results

$$\sigma^{\text{fid}}_{\text{obs}} = 1.68^{+0.40}_{-0.38}\,\text{fb} = 1.68^{+0.33}_{-0.32}\,(\text{stat})\,^{+0.23}_{-0.21}\,(\text{sys})\,\text{fb}$$

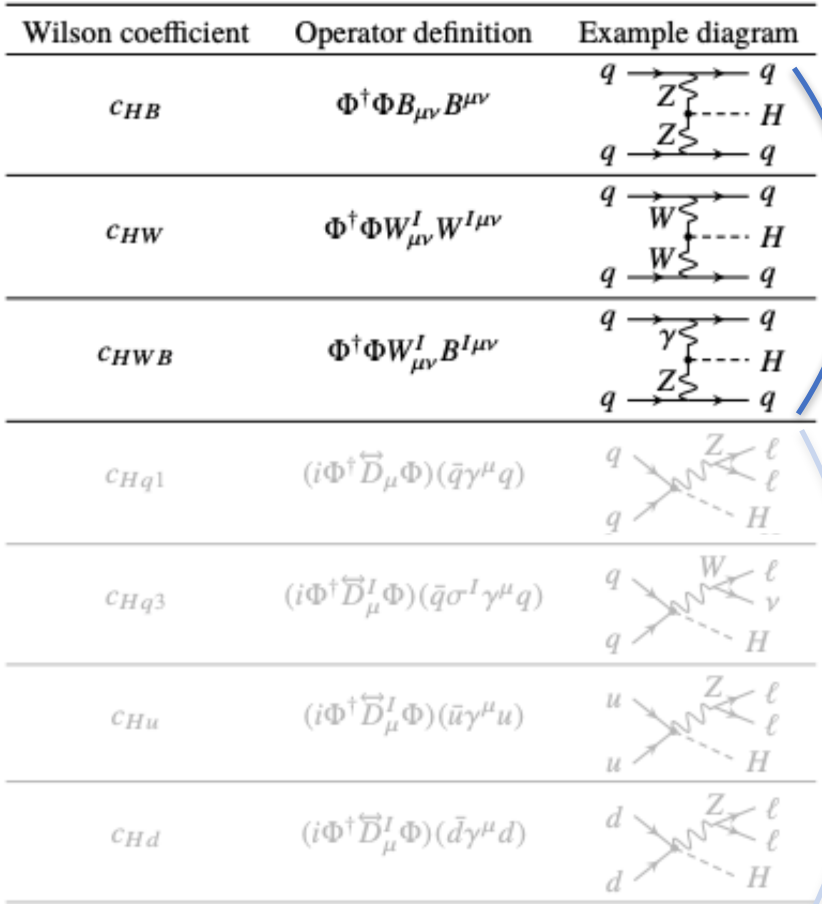


- All measured cross sections found compatible with the SM predictions



Standard Model as an effective theory

- SMEFT operators constructed by SM fields
- Has unit of energy to the power six



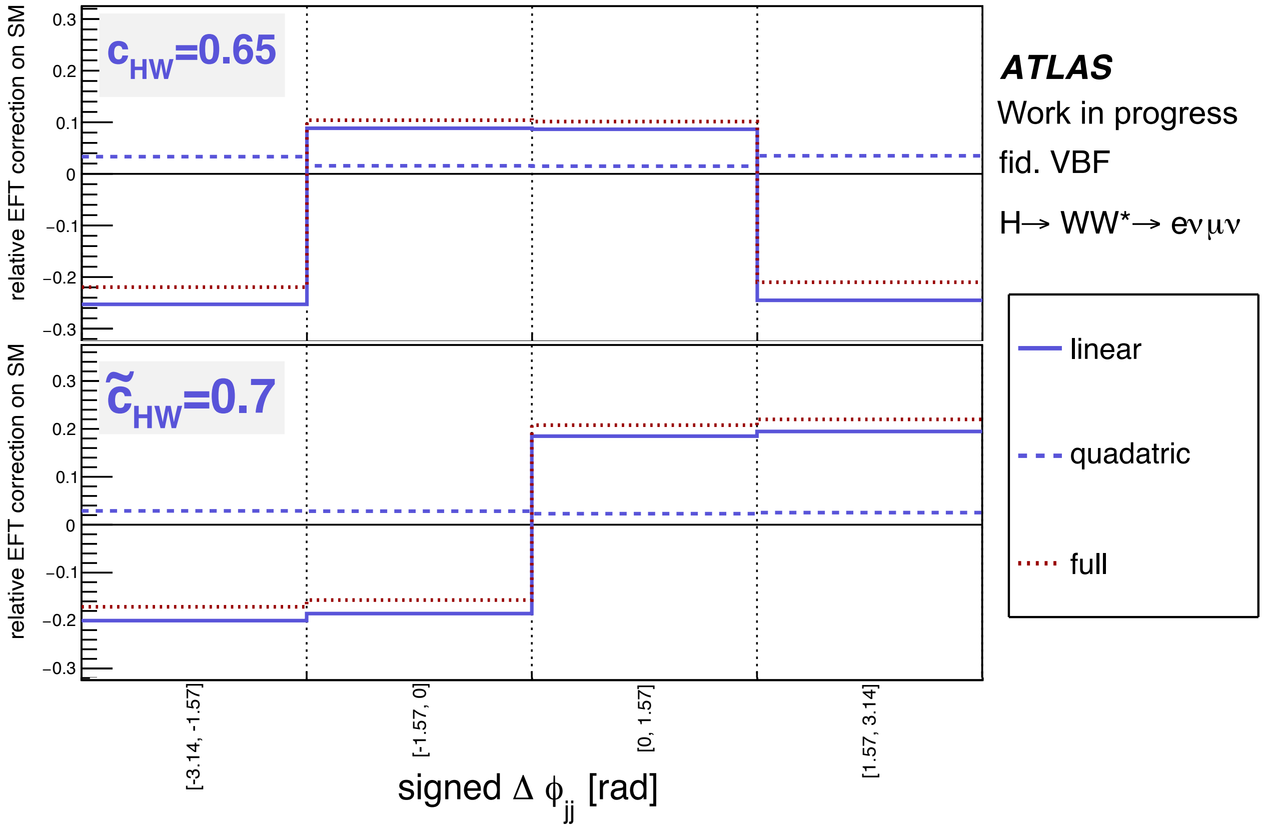
Wilson coefficient	Operator definition	Example diagram
c_{HB}	$\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$	
c_{HW}	$\Phi^\dagger\Phi W^I_{\mu\nu}W^{I\mu\nu}$	
c_{HWB}	$\Phi^\dagger\Phi W^I_{\mu\nu}B^{I\mu\nu}$	
c_{Hq1}	$(i\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$	
c_{Hq3}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{q}\sigma^I\gamma^\mu q)$	
c_{Hu}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{u}\gamma^\mu u)$	
c_{Hd}	$(i\Phi^\dagger\overleftrightarrow{D}^I_\mu\Phi)(\bar{d}\gamma^\mu d)$	

c_{HW} group (with the CP odd partners)

c_{Hq3} group

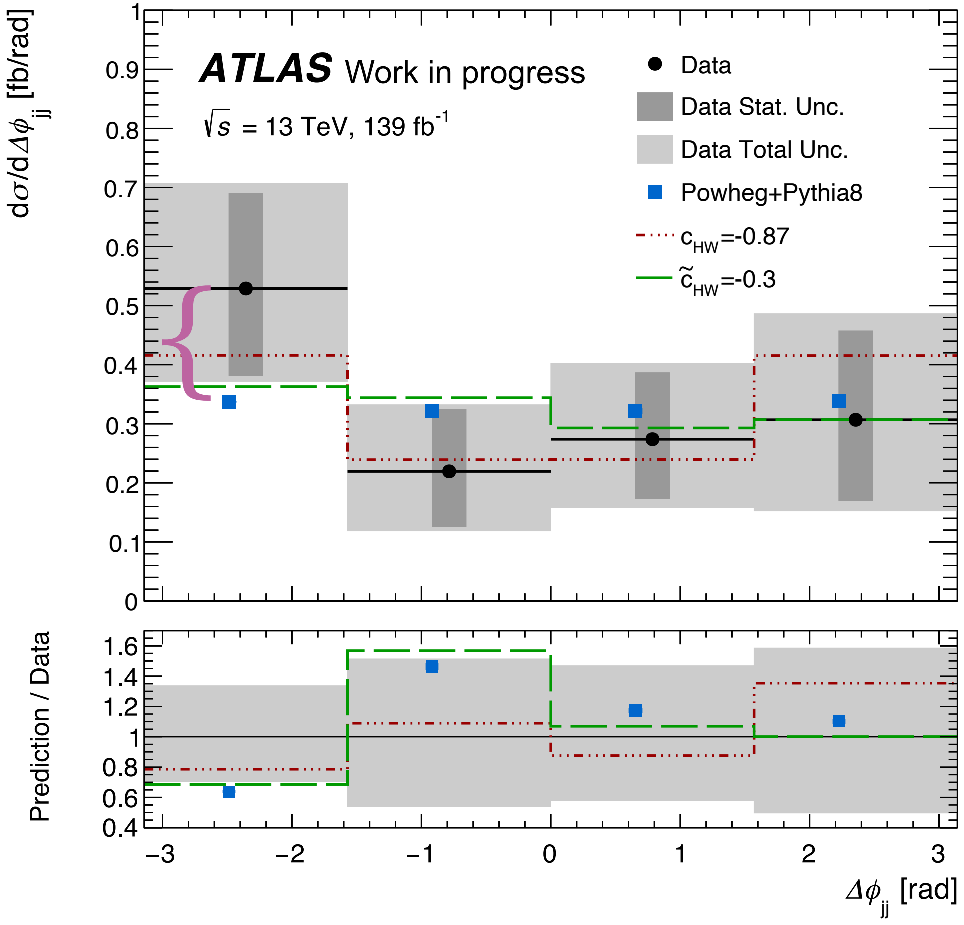
ATLAS-CONF-2020-053

- Relative EFT corrections on azimuthal angle between the forward and central jets symmetric (asymmetric) from CP even (odd) operators



Constrain anomalous couplings

- First bin in $\Delta\phi_{jj}$ drives the EFT constraint of the c_{HW} group
  - Observed cross section greater than SM expectation by $\sim$1 standard deviation
  - Setting limits on Wilson coefficients —> narrowed window for new physics

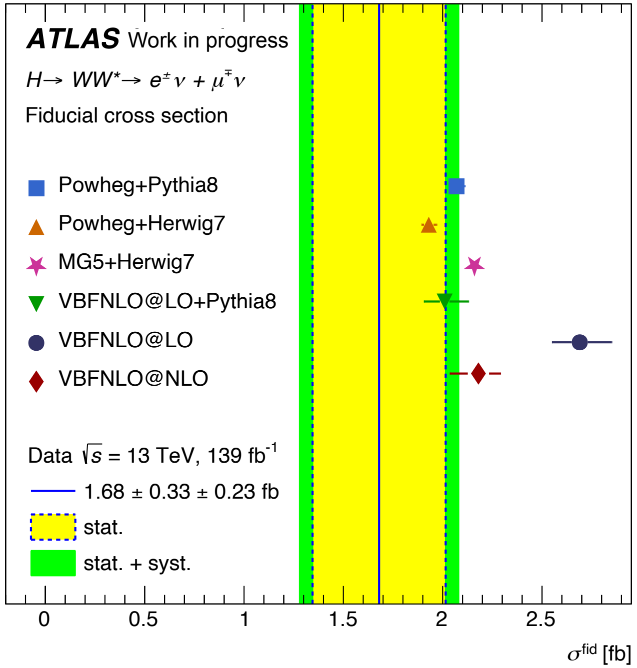


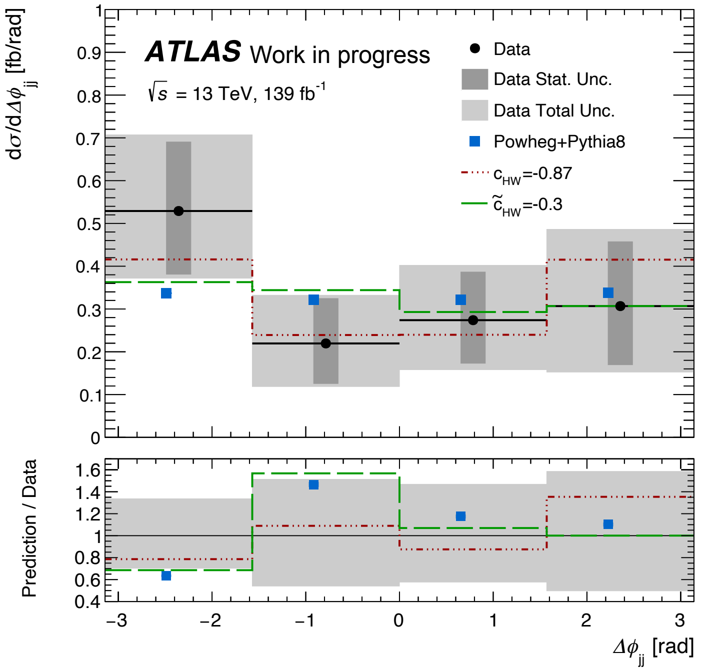
Parameter	Optimal observable	Linear + Quadratic Best-fit value [TeV^{-2}]	Linear + Quadratic 2σ limits [TeV^{-2}]
c_{HW}/Λ^2	$\Delta\phi_{jj}$	-0.87	$[-1.80, 0.61]$
$\tilde{c}_{HW}/\Lambda^2$	$\Delta\phi_{jj}$	-0.30	$[-1.09, 1.37]$
c_{HWB}/Λ^2	$\Delta\phi_{jj}$	-0.50	$[-1.24, 1.08]$
$\tilde{c}_{HWB}/\Lambda^2$	$\Delta\phi_{jj}$	-0.39	$[-1.17, 1.14]$
c_{HB}/Λ^2	$\Delta\phi_{jj}$	-0.18	$[-0.60, 0.66]$
$\tilde{c}_{HB}/\Lambda^2$	$\Delta\phi_{jj}$	-0.21	$[-0.63, 0.63]$

- Constrained Wilson coefficients compatible with SM ($c = 0$)
- Stringent limits (approximately ± 1) set on the c_{HW} group of parameters
- Recall, this group affects the *HVV* vertices and the VBF HWW channel has two of such vertices

Summary and outlook

- Precision measurement on kinematic distributions of the Higgs boson help to distinguish new physics signature from statistical noise
- For the first time, an ATLAS differential measurements in the VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ channel is reported and found compatibility with SM predictions

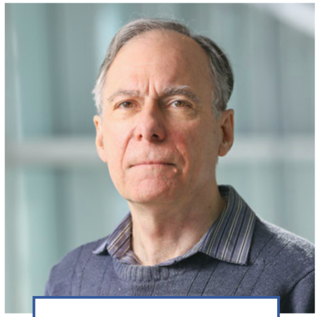




- EFT is a general tool to interpret data-prediction differences as heavy new resonance's effect at low energy
- The VBF HWW sensitivity can be further improved using upcoming dataset collected during Run-3 and the High-Luminosity phase of the LHC
  - ❖ I will continue working as part of the ATLAS collaboration as a postdoctoral fellow at Simon Fraser University with a focus on the EFT and ATLAS upgrade projects

Acknowledgement

Brandeis ATLAS group



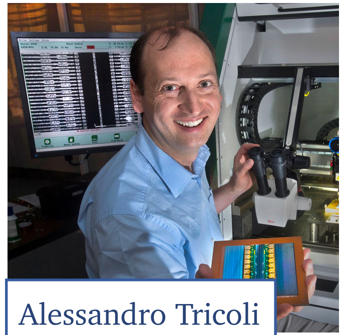
Craig Blocker

Gabriella Sciolla

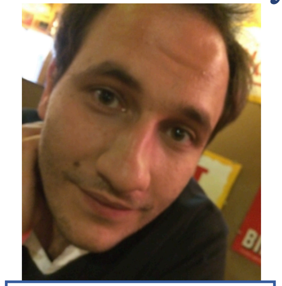
Brandeis-BNL ATLAS ITk team

David Lynn

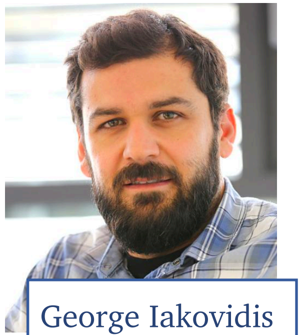
HWW differential analysis team



Alessandro Tricoli



Gaetano Barone



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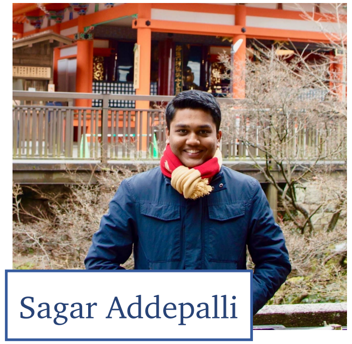
Stefania Stucci

Chara Kitsaki

Laura Bergsten

Guy Rosin



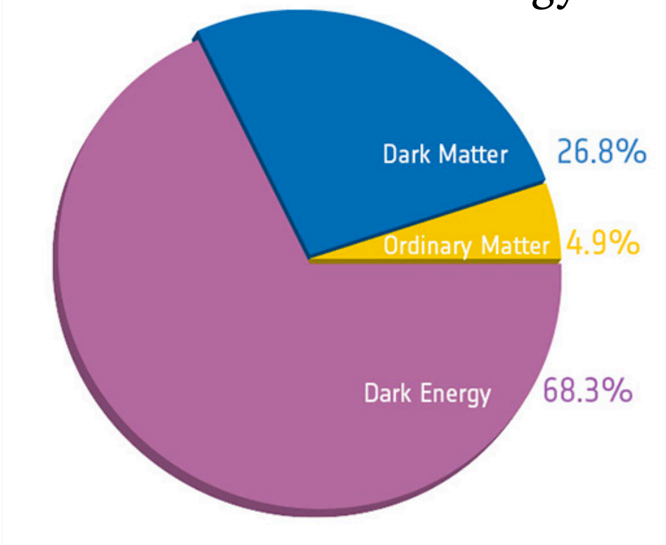
Sagar Addepalli

Thank you for patiently listening!

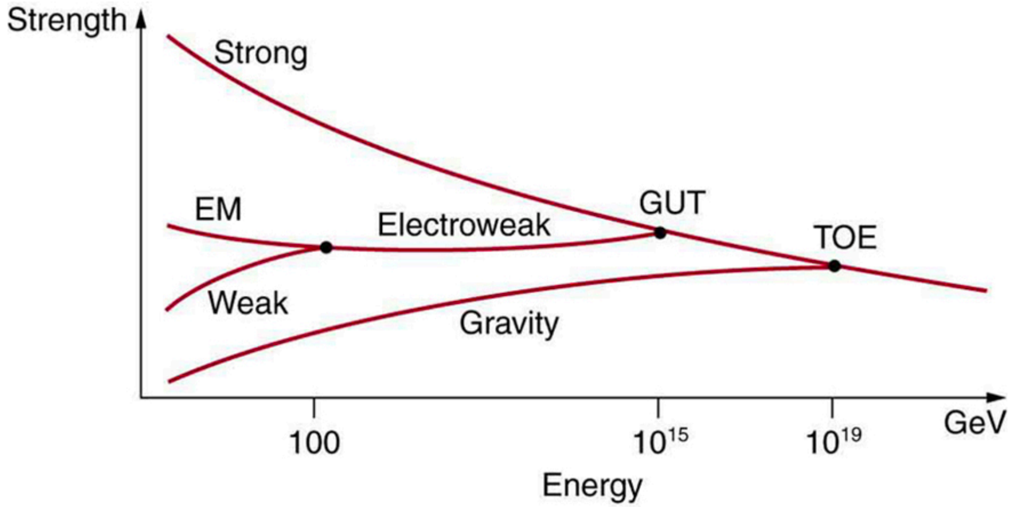
Backup

New physics

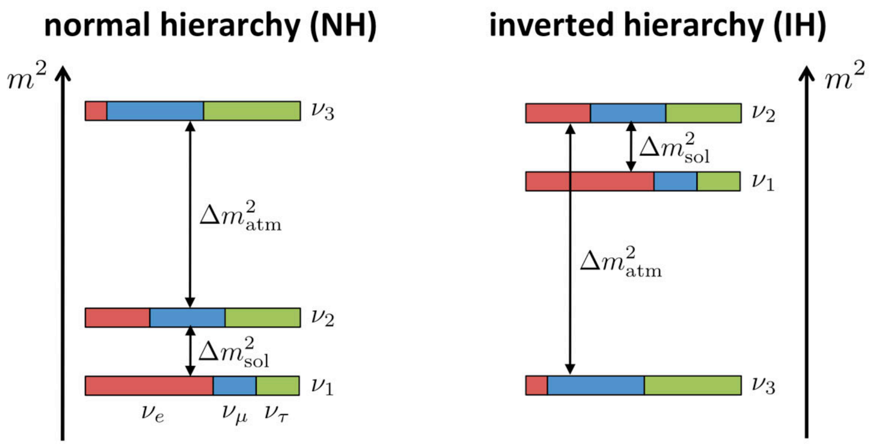
- Dark Matter and Dark Energy



- Unification of strong, electroweak and gravity force?



- Neutrino mass hierarchy



- Light Higgs mass - supersymmetry?