

KU[®]

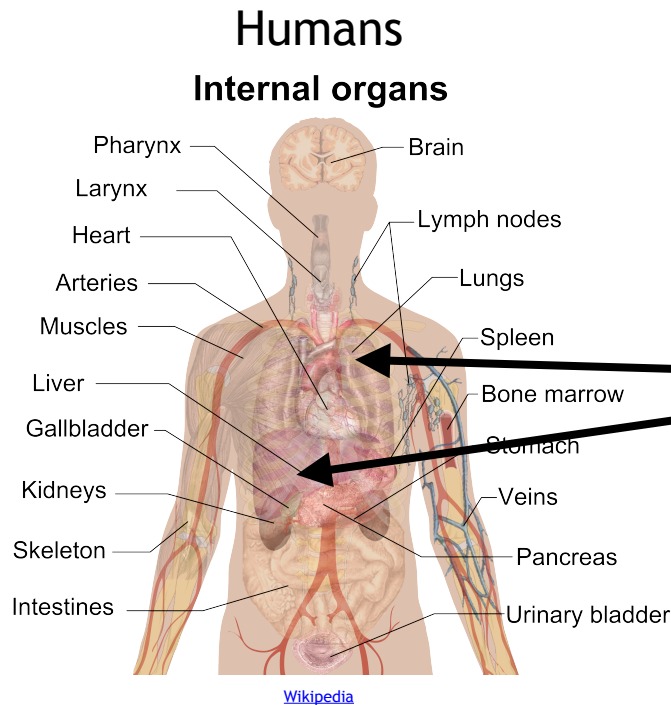
Probing the associated production of the Higgs boson and charm quarks at ATLAS

University of Warwick Seminar, 9 January 2025

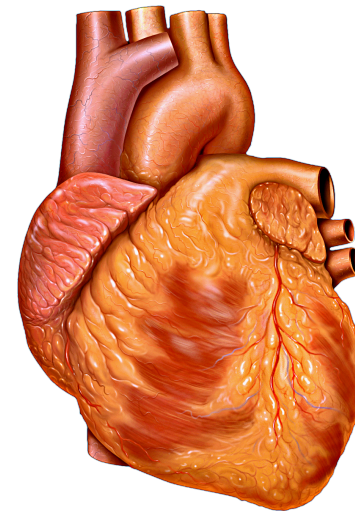
Elliot Reynolds, University of Kansas

Building Blocks of Reality

- Take this (simplified) description of human beings:



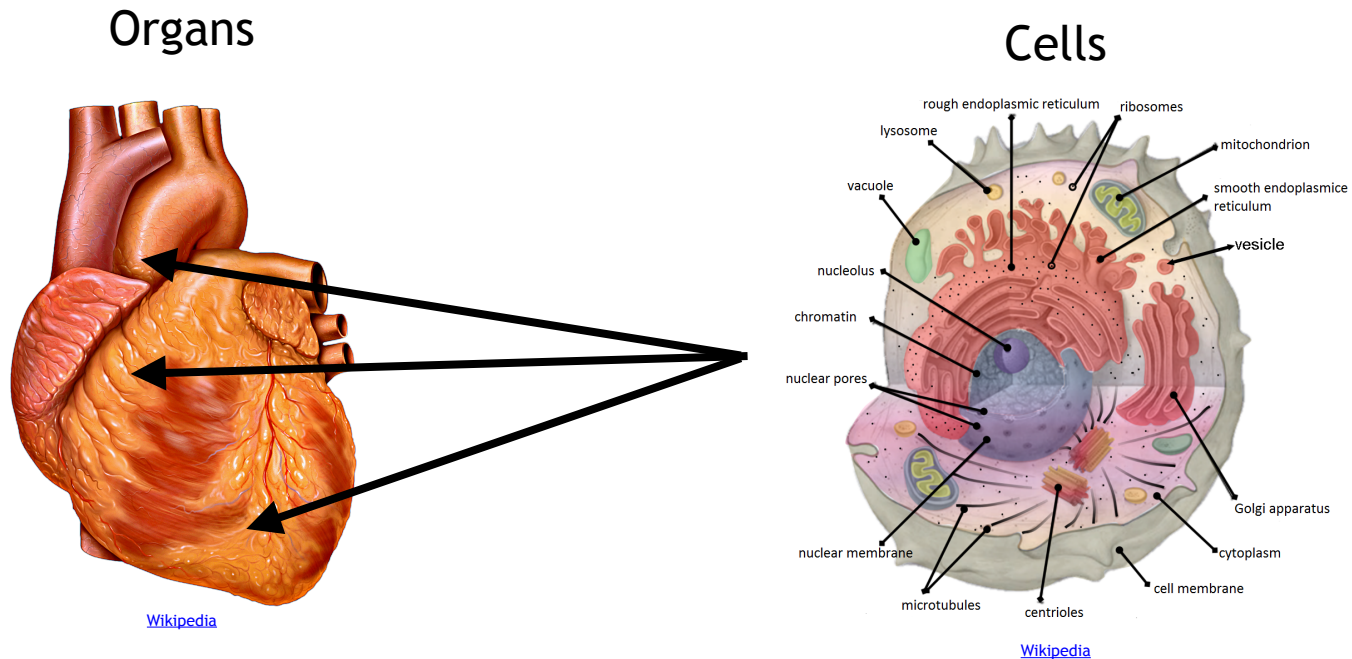
Organs (+ blood, bones etc.)



[Wikipedia](#)

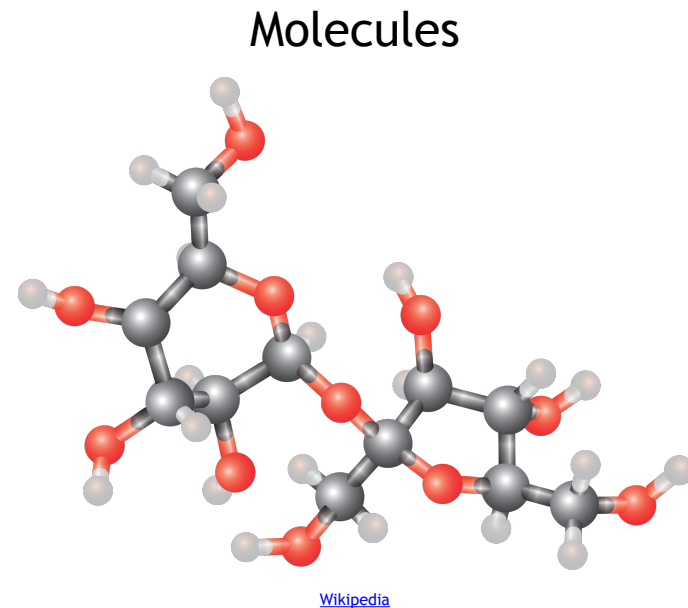
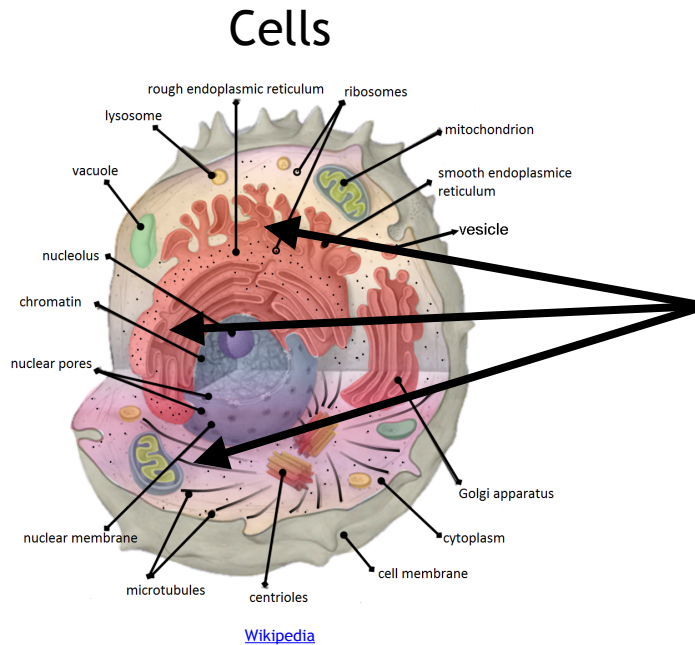
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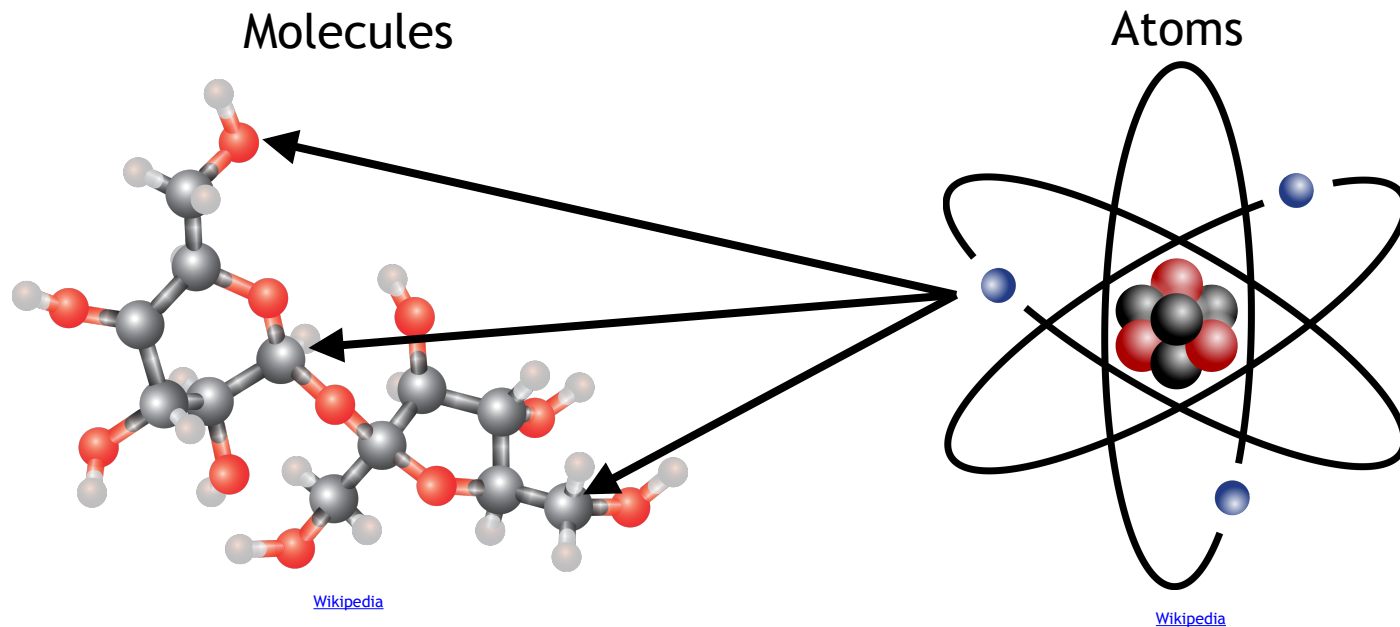
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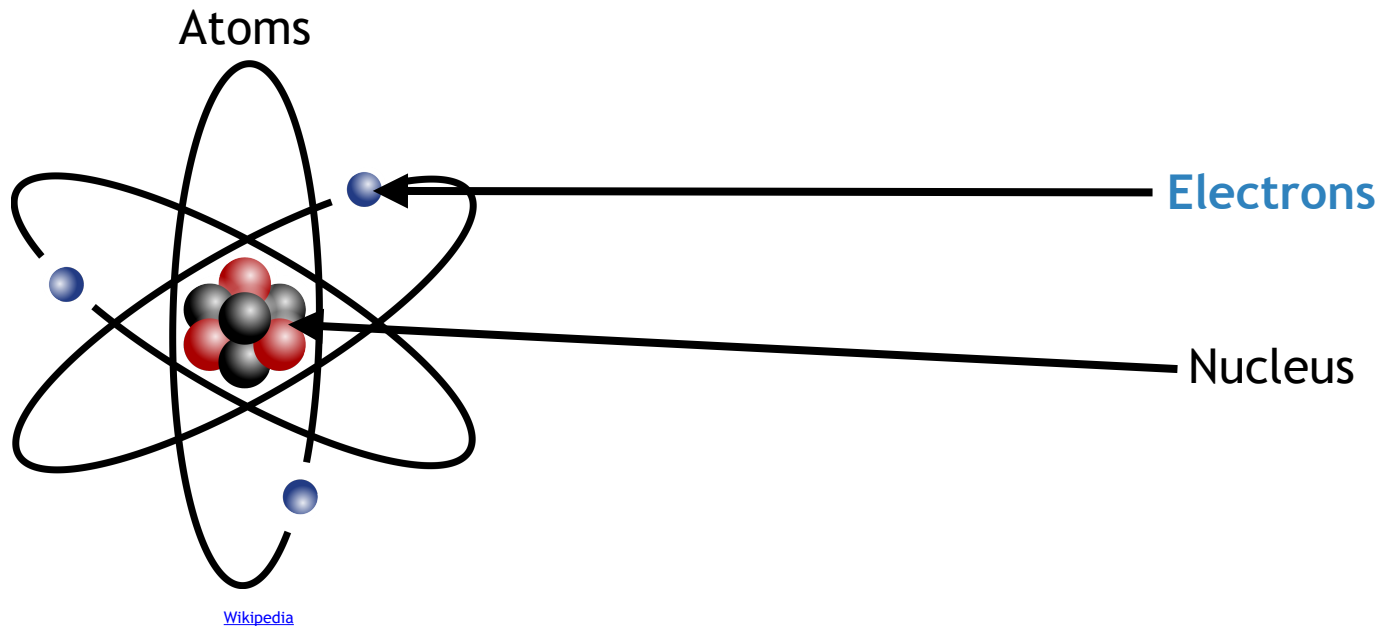
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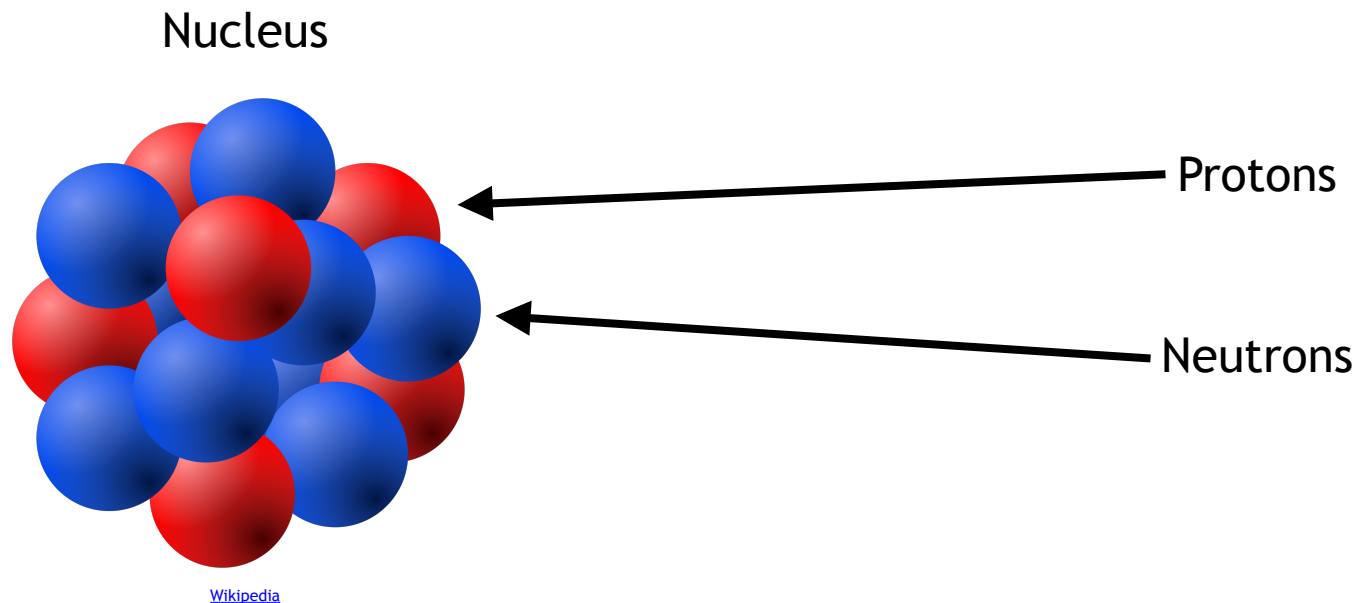
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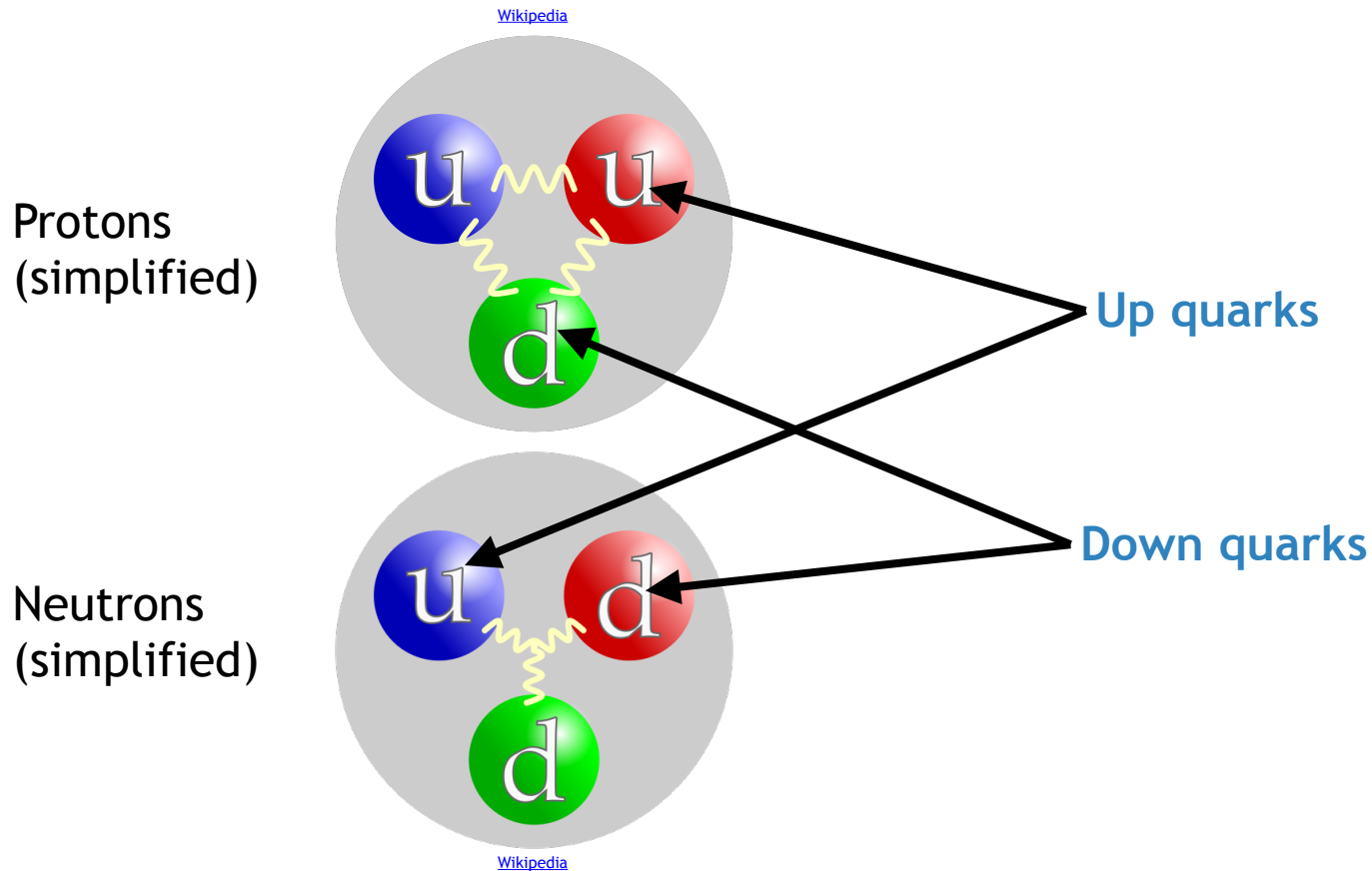
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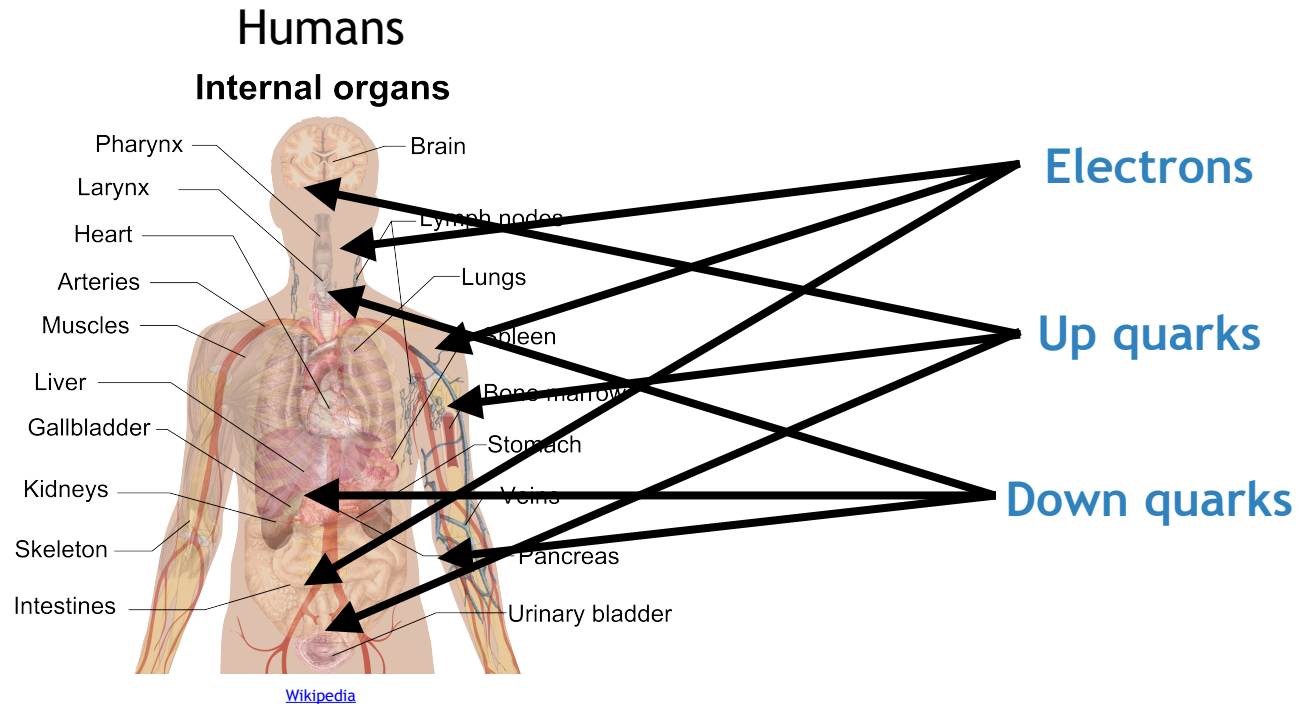
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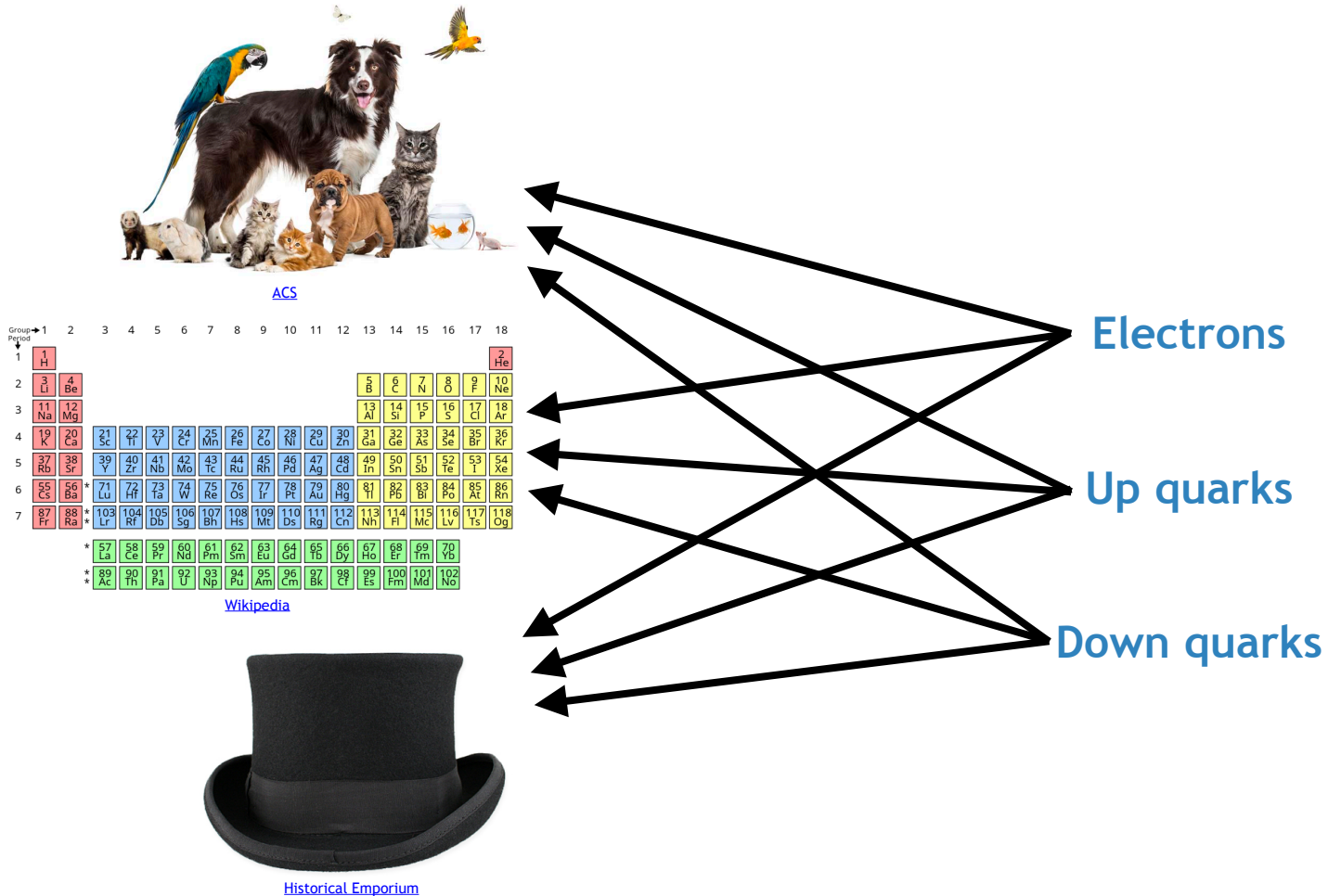
Reductionism

- Thus, humans are ~entirely made up of electrons, up quarks, and down quarks



Reductionism

- But so is almost everything else:



The fermions

three generations of matter
(fermions)

I

mass	$\approx 2.16 \text{ MeV}/c^2$
charge	$\frac{2}{3}$
spin	$\frac{1}{2}$
u up	

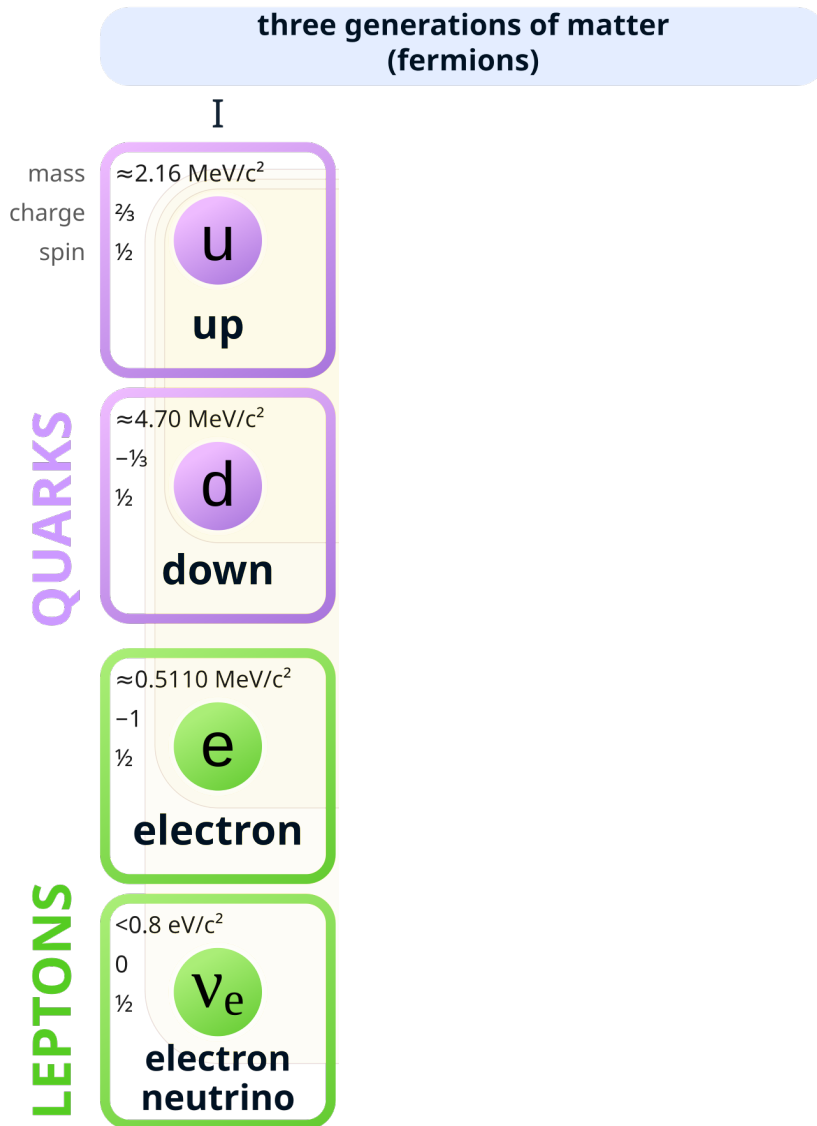
mass	$\approx 4.70 \text{ MeV}/c^2$
charge	$-\frac{1}{3}$
spin	$\frac{1}{2}$
d down	

mass	$\approx 0.5110 \text{ MeV}/c^2$
charge	-1
spin	$\frac{1}{2}$
e electron	

QUARKS

LEPTONS

The fermions



The fermions

three generations of matter (fermions)			
	I	II	III
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.2730 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$
	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
charge	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
spin	u up	c charm	t top
QUARKS	$\approx 4.70 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d down	s strange	b bottom
LEPTONS	$\approx 0.5110 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1776.93 \text{ MeV}/c^2$
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	e electron	μ muon	τ tau
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$
	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Why?

- Particle physics seeks to understand what *all* things are made of...

Why?

- Particle physics seeks to understand what *all* things are made of...
- It also seeks to understand ***why*** *all* things happen



[Independent](#)

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[Independent](#)

- 

[Wikipedia](#)



Why?

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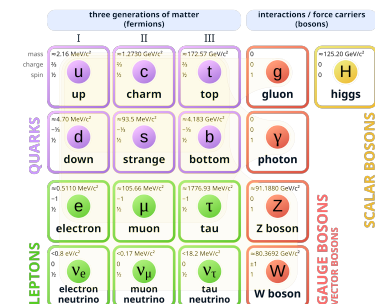
Periodic table showing elements grouped by periods and groups. The table includes elements from Hydrogen (H) to Oganesson (Og). Groups are numbered 1 to 18. Periods are numbered 1 to 7. The table is color-coded: Nonmetals (pink), Metals (blue), Transition metals (green), Lanthanides (yellow), Actinides (orange), s-block (red), f-block (purple), d-block (green), and p-block (blue).

Some elements near the dashed staircase are sometimes called metalloids.

[Wikipedia](#)



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[Wikipedia](#) (adapted)

Why?

- Particle physics seeks to understand what *all* things are made of...
- It also seeks to understand *why* *all* things happen
- **Theory of Everything!**



Periodic table showing elements grouped by periods and groups. The table includes labels for Nonmetals, Metals, Transition metals, Lanthanides, and Actinides. A dashed staircase line separates metals from nonmetals. Some elements near the staircase are labeled as metalloids.

[Wikipedia](#)



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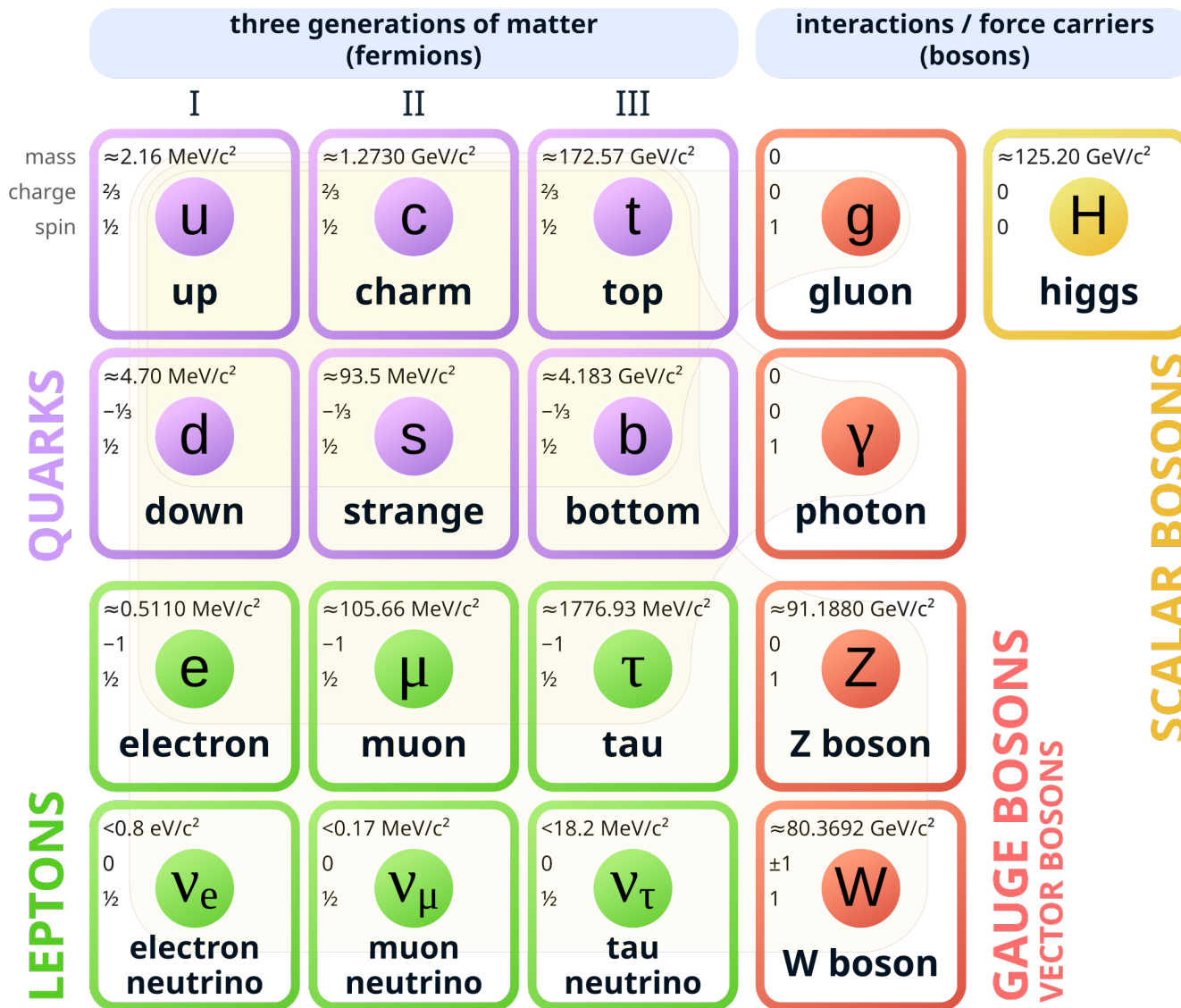
three generations of matter (fermions)				interactions / force carriers (bosons)	
QUARKS	I up u mass: ~2.16 MeV/c² charge: 2/3 spin: 1/2	II charm c mass: ~1.2730 GeV/c² charge: 2/3 spin: 1/2	III top t mass: ~172.57 GeV/c² charge: 2/3 spin: 1/2	g gluon mass: 0 charge: 0 spin: 1	H higgs mass: ~125.26 GeV/c² charge: 0 spin: 0
	down d mass: ~4.70 MeV/c² charge: -1/3 spin: 1/2	strange s mass: ~93.5 MeV/c² charge: -1/3 spin: 1/2	bottom b mass: ~4.183 GeV/c² charge: -1/3 spin: 1/2	γ photon mass: 0 charge: 0 spin: 1	
	electron e mass: ~0.5110 MeV/c² charge: -1 spin: 1/2	muon μ mass: ~105.66 MeV/c² charge: -1 spin: 1/2	tau τ mass: ~1776.93 MeV/c² charge: -1 spin: 1/2	Z boson Z mass: ~91.1880 GeV/c² charge: 0 spin: 1	
LEPTONS	electron neutrino ν _e mass: ~0.8 eV/c² charge: 0 spin: 1/2	muon neutrino ν _μ mass: ~0.17 MeV/c² charge: 0 spin: 1/2	tau neutrino ν _τ mass: ~18.2 MeV/c² charge: 0 spin: 1/2	W boson W mass: ~80.363 GeV/c² charge: ±1 spin: 1	

[Wikipedia](#) (adapted)

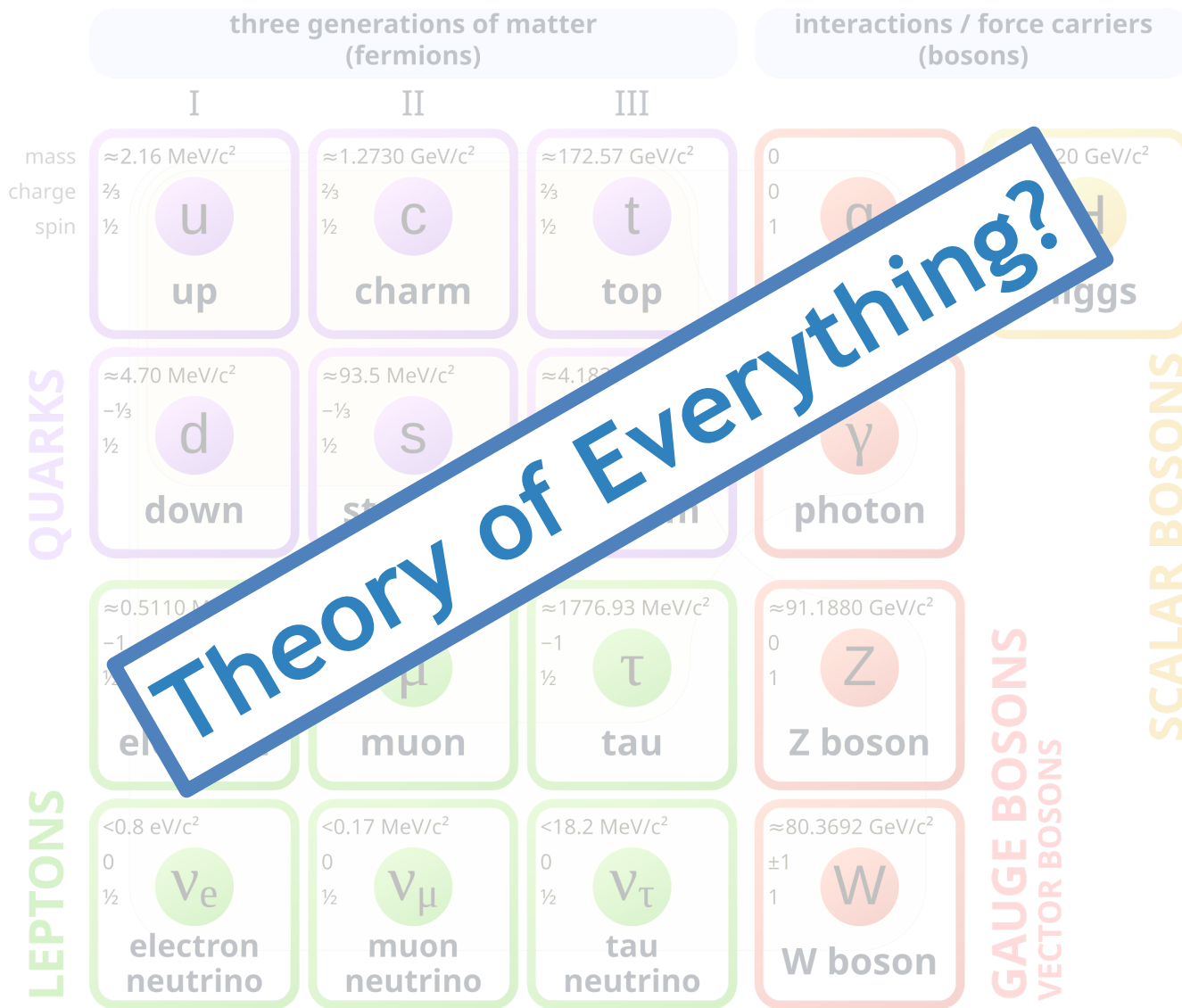
The gauge bosons

three generations of matter (fermions)				interactions / force carriers (bosons)
	I	II	III	
QUARKS	mass charge spin $\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.2730 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon
	$\approx 4.70 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon
	$\approx 0.5110 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1776.93 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 91.1880 \text{ GeV}/c^2$ 0 1 Z Z boson
LEPTONS	$< 0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.3692 \text{ GeV}/c^2$ ± 1 1 W W boson
				GAUGE BOSONS VECTOR BOSONS

The Standard Model (SM)



The Standard Model (SM)



What Next?

- The SM *does not* seem to be the Theory of Everything...
- How do we get there?

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 - 1. Theoretical consistency**
 - How to reconcile quantum mechanics & gravity?

What Next?

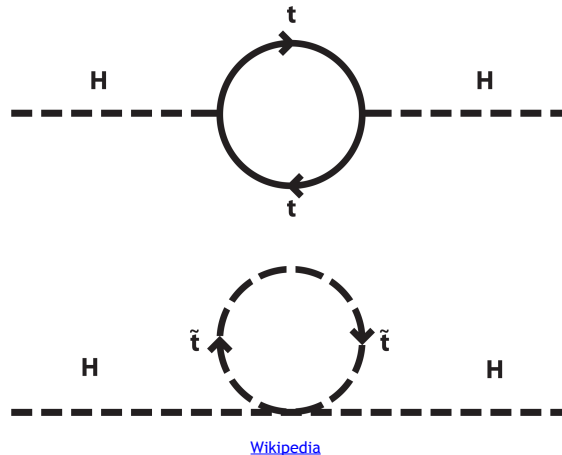
- The SM *does not* seem to be the Theory of Everything...
- How do we get there?

1. Theoretical consistency

- How to reconcile quantum mechanics & gravity?

1.1. Fine tuning and naturalness

- Why is the Higgs boson so light?



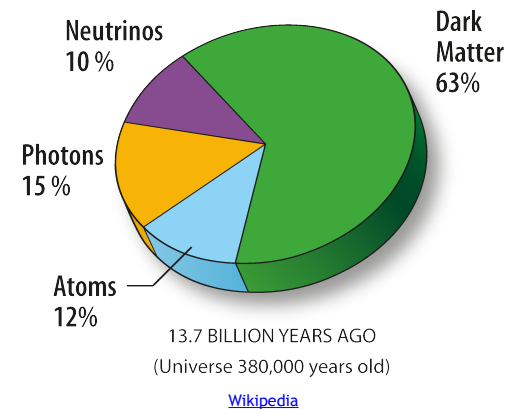
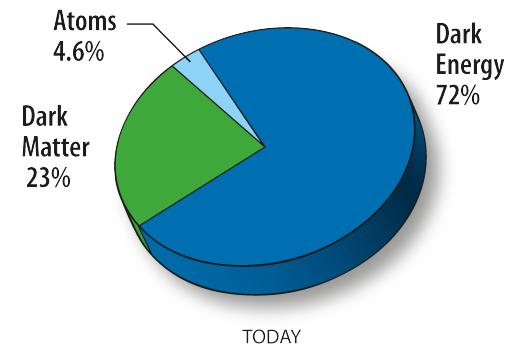
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2. Experimental consistency

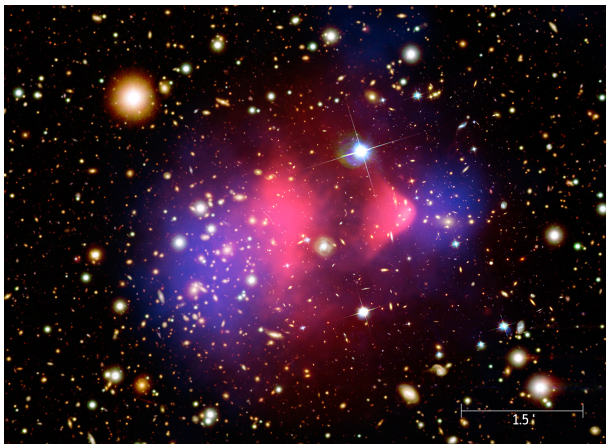
- What is dark matter?



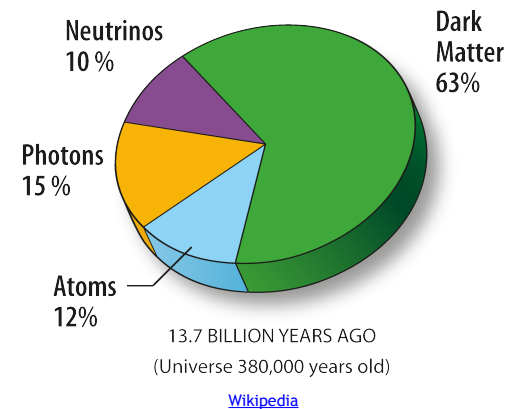
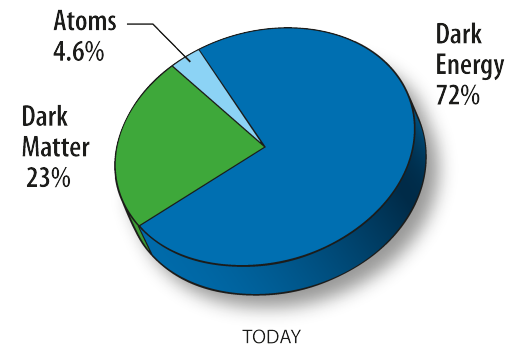
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Bullet Cluster



[Wikipedia](#)



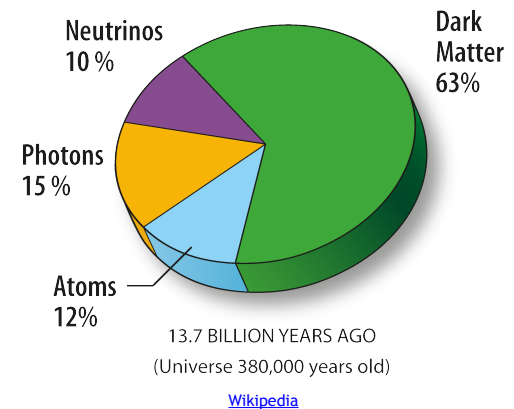
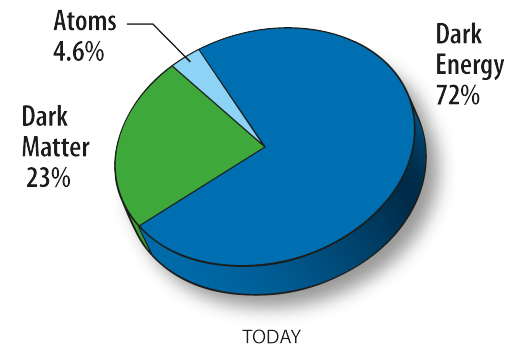
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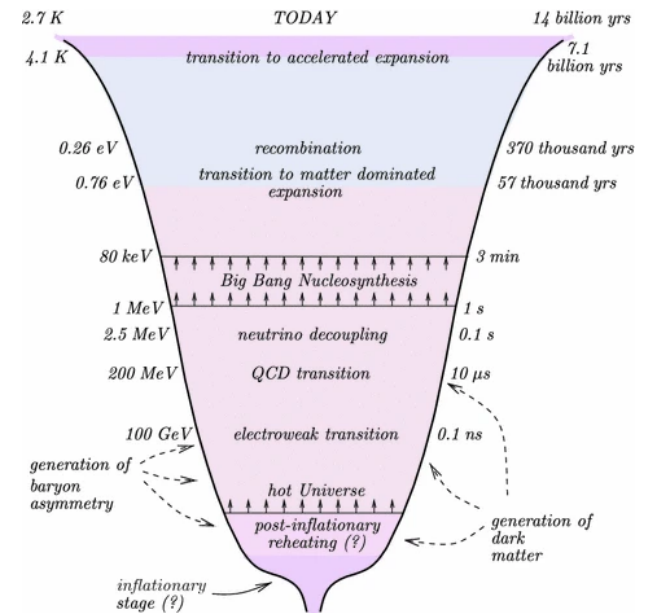
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- Why is there more matter than anti-matter?



[Springer](#)

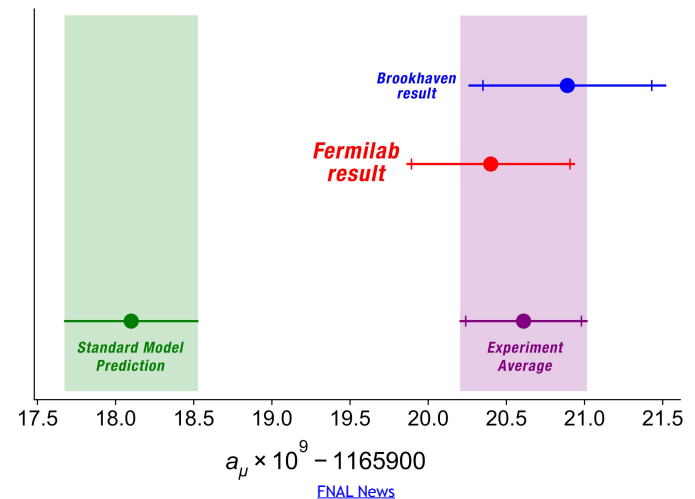
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- Any other anomalies?



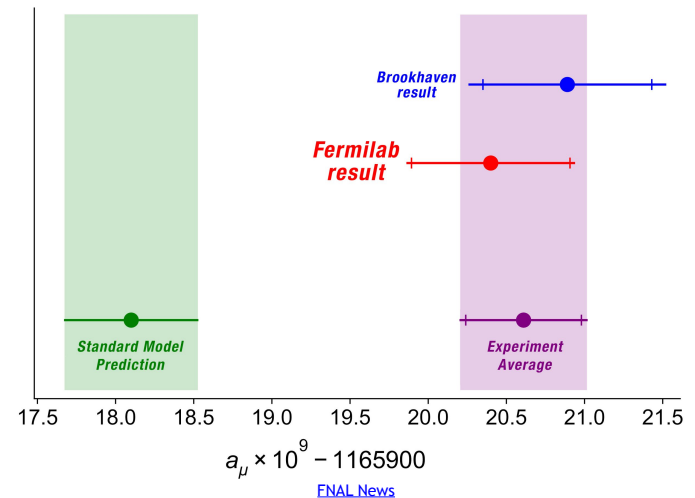
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Group ▶	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period ▼																		
	1																	Noble gases
Nonmetals	1																	2
	H																	He
Metals	2	3	4															
	Li	Be																
	11	12																
	Na	Mg																
	19	20																
	K	Ca																
	37	38																
	Rb	Sr																
	55	56																
	Cs	Ba																
	87	88																
	Fr	Ra																
	s-block (incl. He)		f-block		d-block								p-block (excl. He)					

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Periodic table showing groups (1-18) and periods (1-7). Elements are color-coded: Metals (blue), Nonmetals (green), Noble gases (yellow), and Transition metals (orange). Some elements near the dashed staircase are sometimes called metalloids.

[Wikipedia](#)



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mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.2730 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.30 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
QUARKS	d down	s strange	b bottom	γ photon	
	$\approx 4.70 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0	
	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$\approx 0.5110 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1776.93 \text{ MeV}/c^2$	$\approx 91.1880 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
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	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	

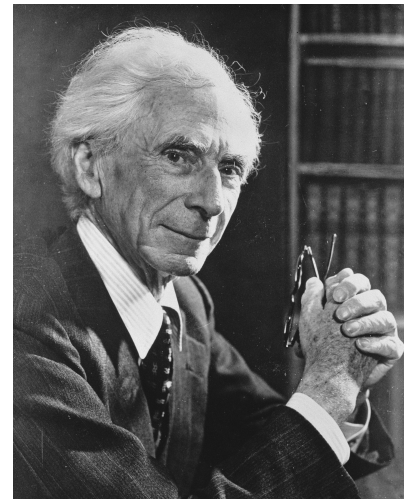
[Wikipedia](#) (adapted)

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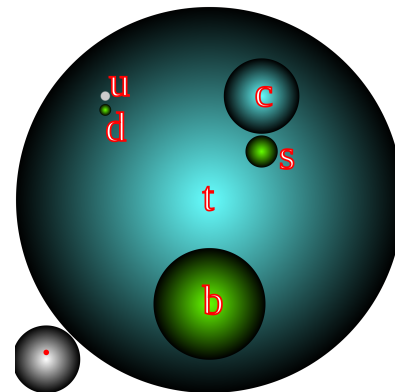
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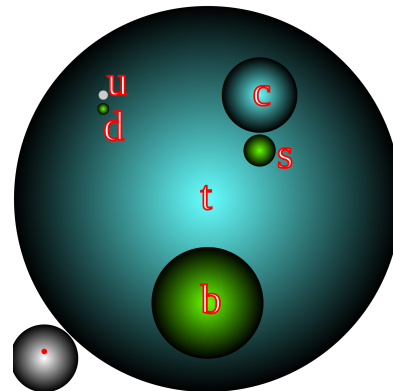
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Fermion masses in the SM

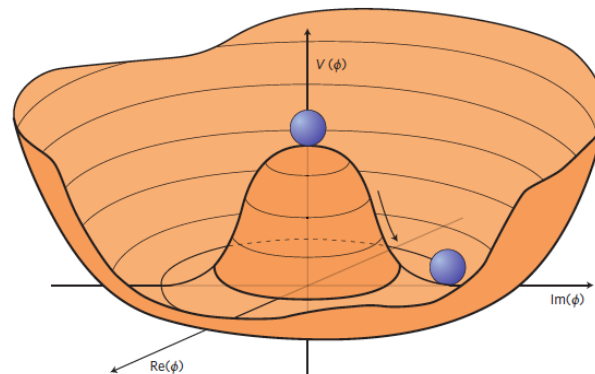
- Particles acquire their masses during spontaneous symmetry breaking (SSB) via the Higgs mechanism

Fermion masses in the SM

- Particles acquire their masses during spontaneous symmetry breaking (SSB) via the Higgs mechanism
 - Before SSB: $\mathcal{L}_f = -g_f(\bar{L}\phi R + \bar{R}\phi^\dagger L)$

Fermion masses in the SM

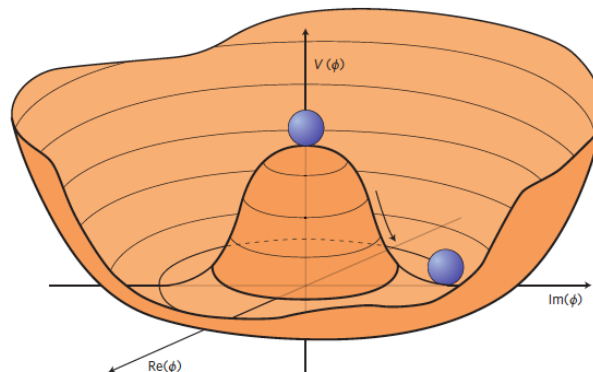
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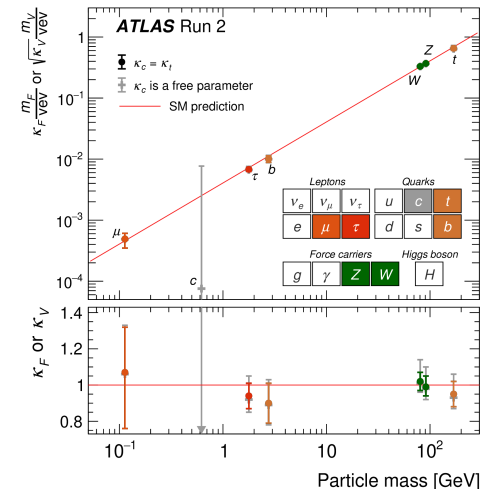
[Nat Rev Phys 3 \(2021\) 608](#)

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- The $\bar{f}fh$ coupling is $\propto m_f$



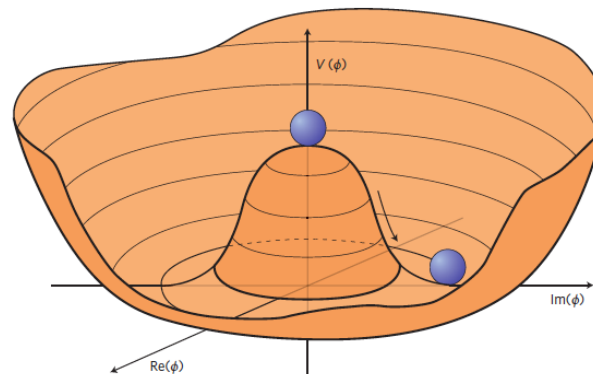
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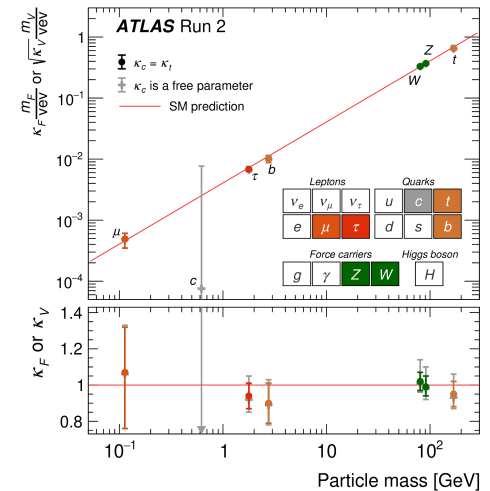
[Nature 607 \(2022\) 52](#)

Fermion masses in the SM

- Particles acquire their masses during spontaneous symmetry breaking (SSB) via the Higgs mechanism
 - Before SSB: $\mathcal{L}_f = -g_f(\bar{L}\phi R + \bar{R}\phi^\dagger L)$
 - After SSB: $\mathcal{L}_f = -m_f\bar{f}f - \frac{m_f}{v}\bar{f}fh$
- The $\bar{f}fh$ coupling is $\propto m_f$
- Fermion mass/coupling values not explained in the SM



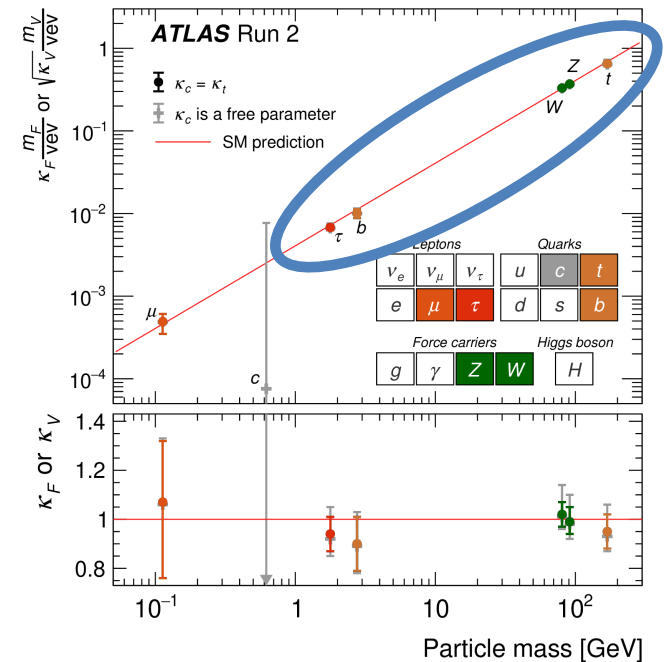
[Nat Rev Phys 3 \(2021\) 608](#)



[Nature 607 \(2022\) 52](#)

Hc Coupling: y_c

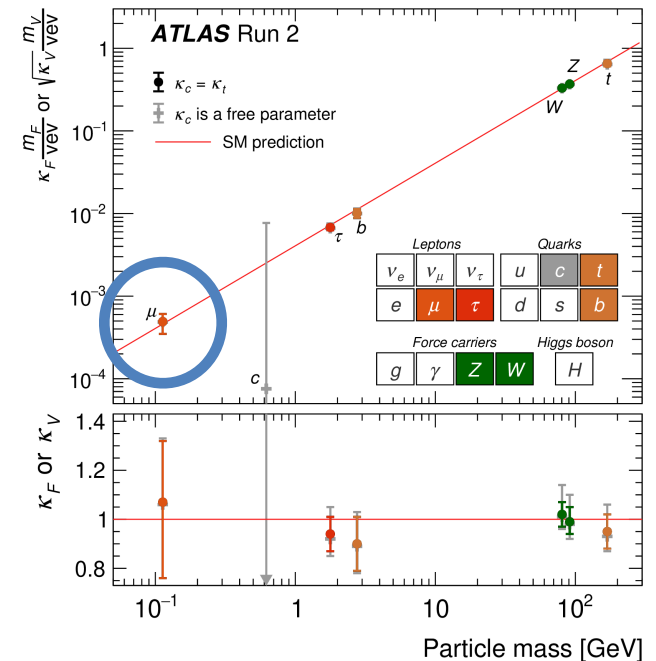
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[Nature 607 \(2022\) 52](#)

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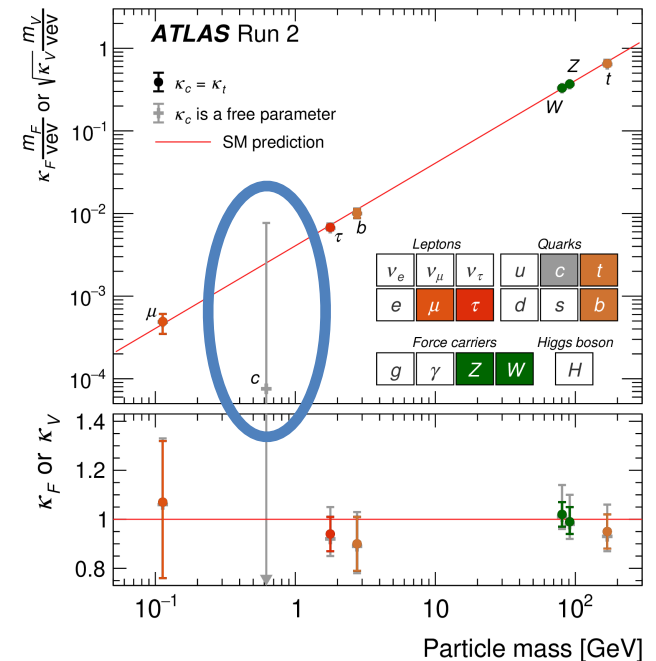
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[Nature 607 \(2022\) 52](#)

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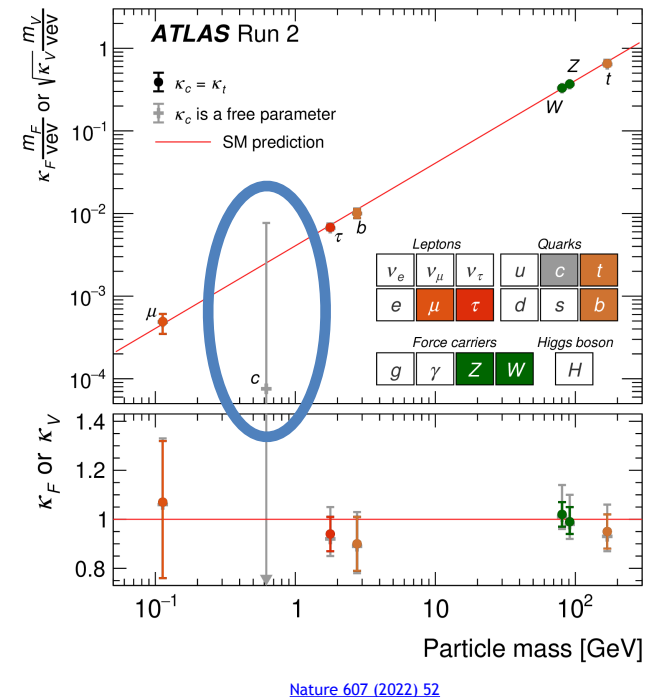
- Higgs couplings to Z and W bosons, and third generation fermions, established
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- y_c is our **best chance** to measure a first- or second-generation quark coupling
- Adequate y_c observation strategy is *not yet available*



[Nature 607 \(2022\) 52](#)

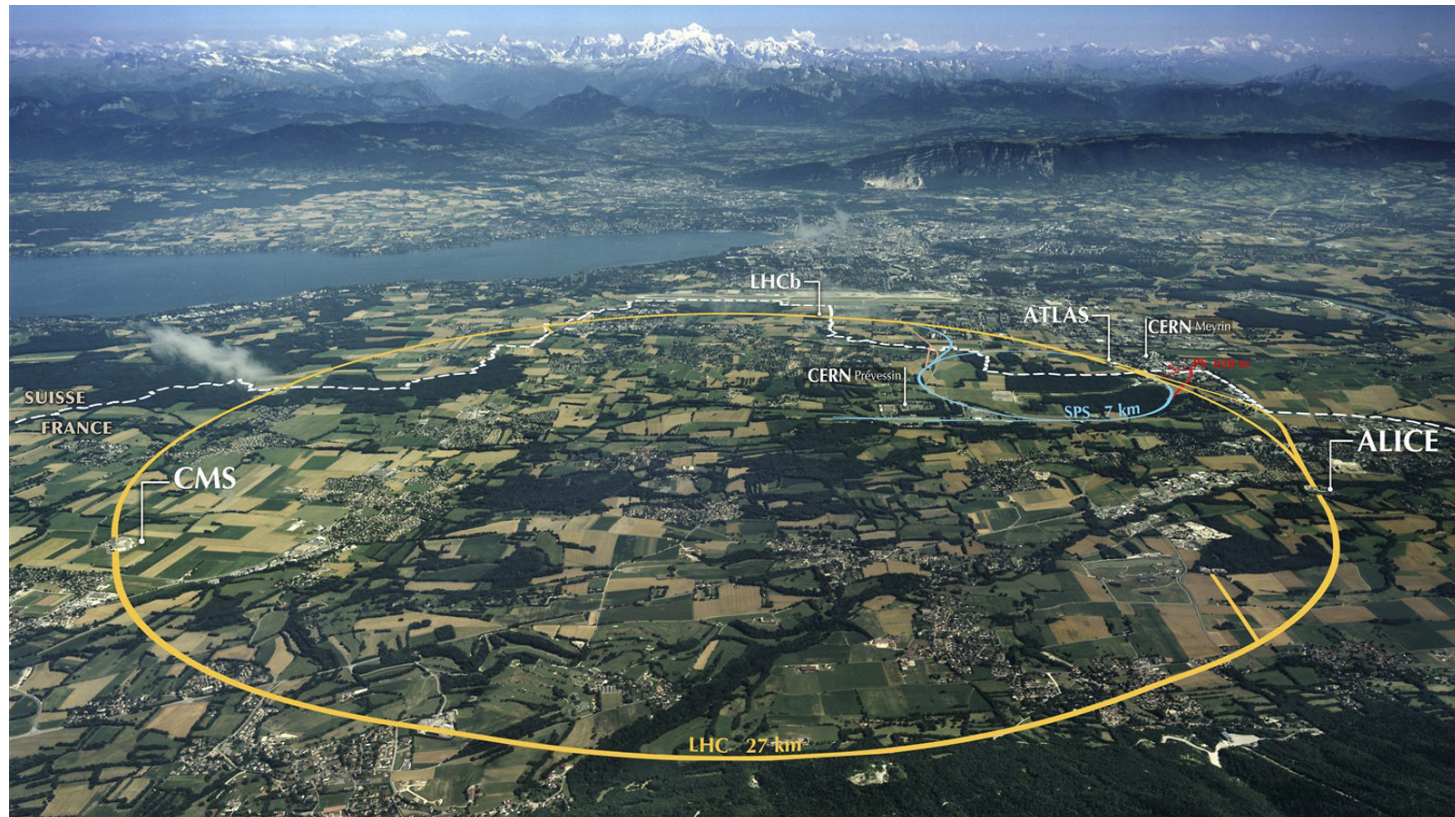
Hc Coupling: y_c

- Higgs couplings to Z and W bosons, and third generation fermions, established
- CMS has published [evidence](#) for the muon coupling
- y_c is our **best chance** to measure a first- or second-generation quark coupling
- Adequate y_c observation strategy is *not yet available*
- Sensitive to [BSM physics](#), e.g. from: [subdominant sources of EWSB](#), [Randall–Sundrum models](#), [Higgs-dependent Yukawa couplings](#), [extended Higgs sectors](#)



CERN Large Hadron Collider

LHC: 13 TeV (13.6 TeV) proton-proton collisions



[Symmetry Magazine](#)

CMS Detector

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

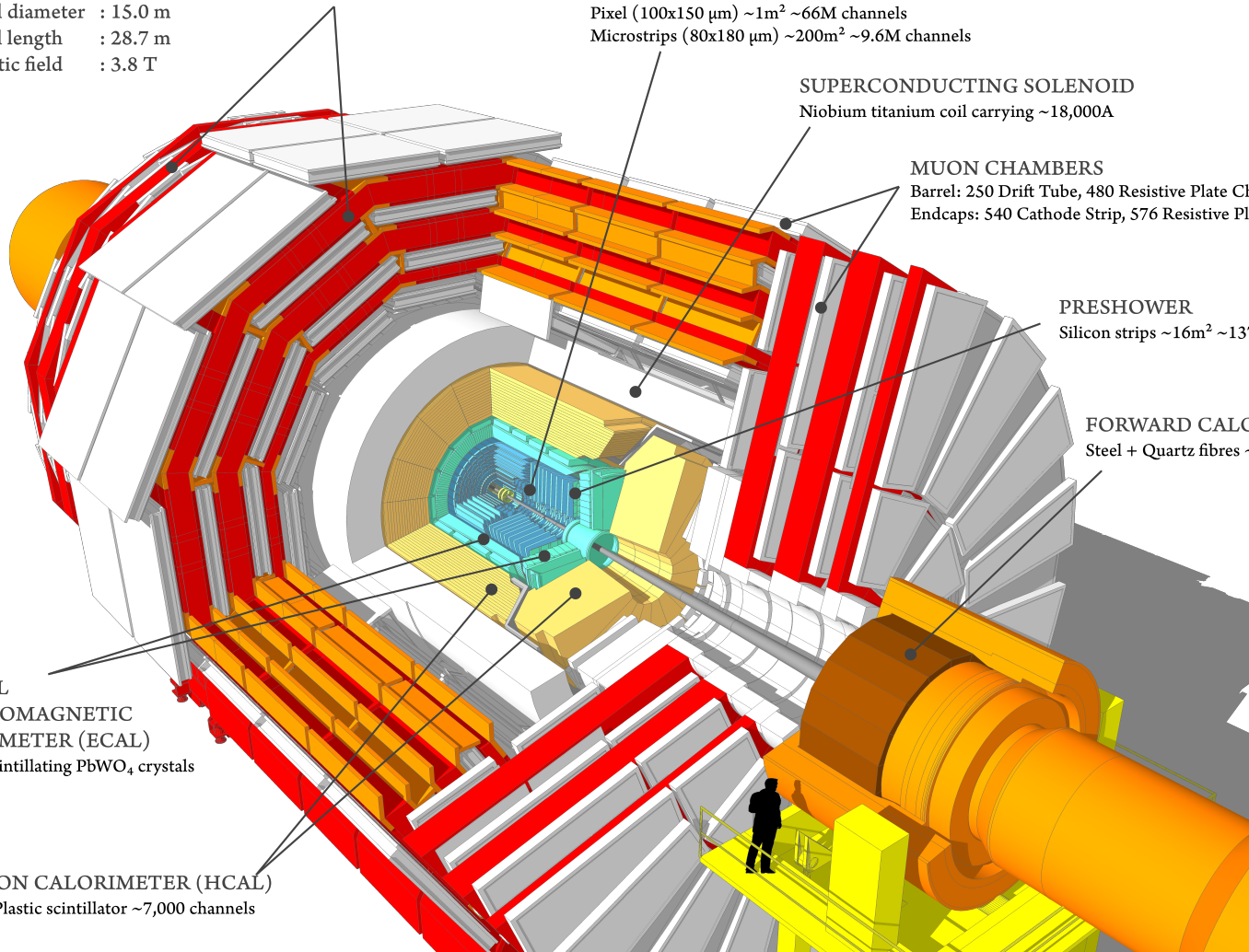
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

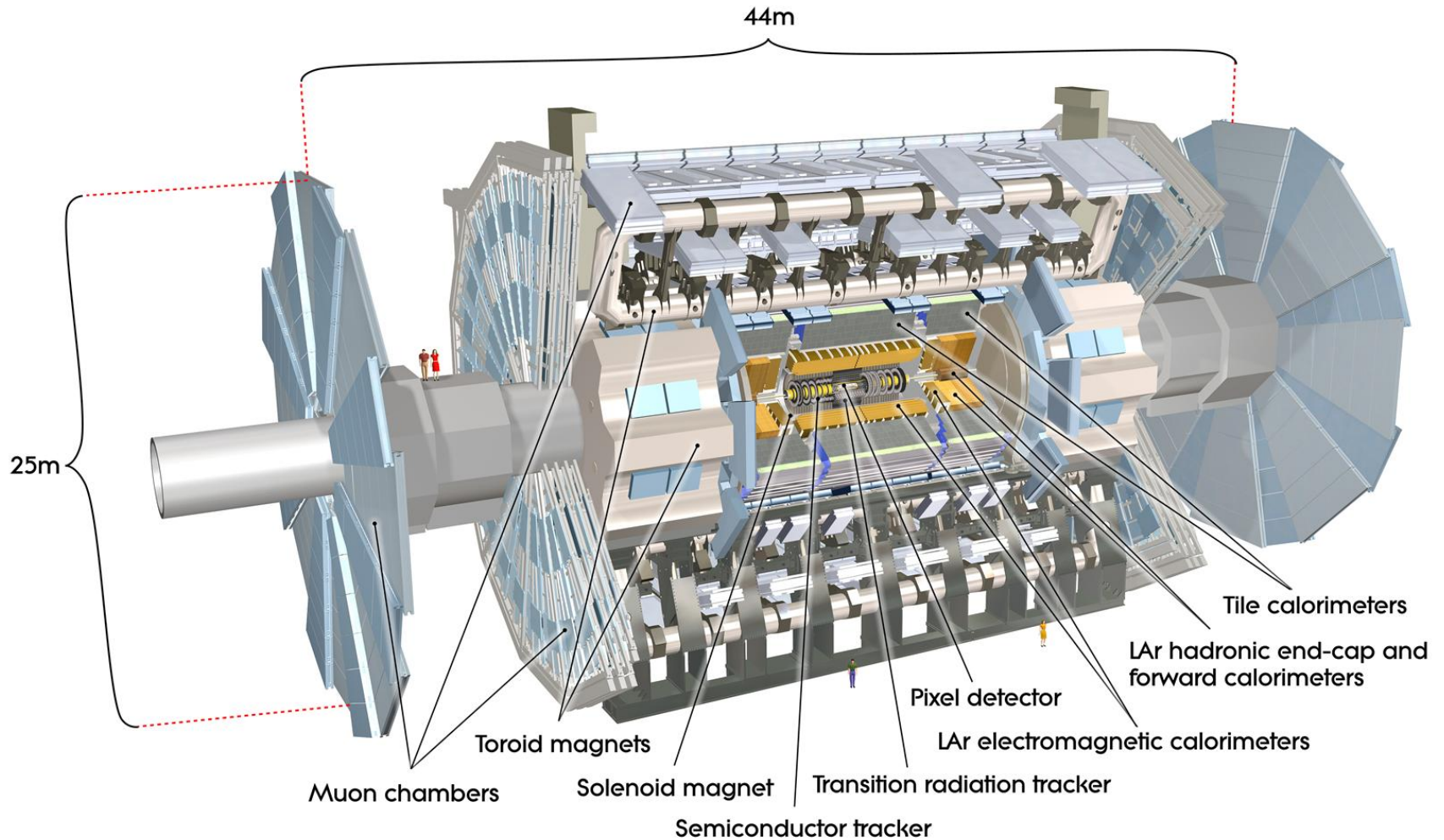
FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

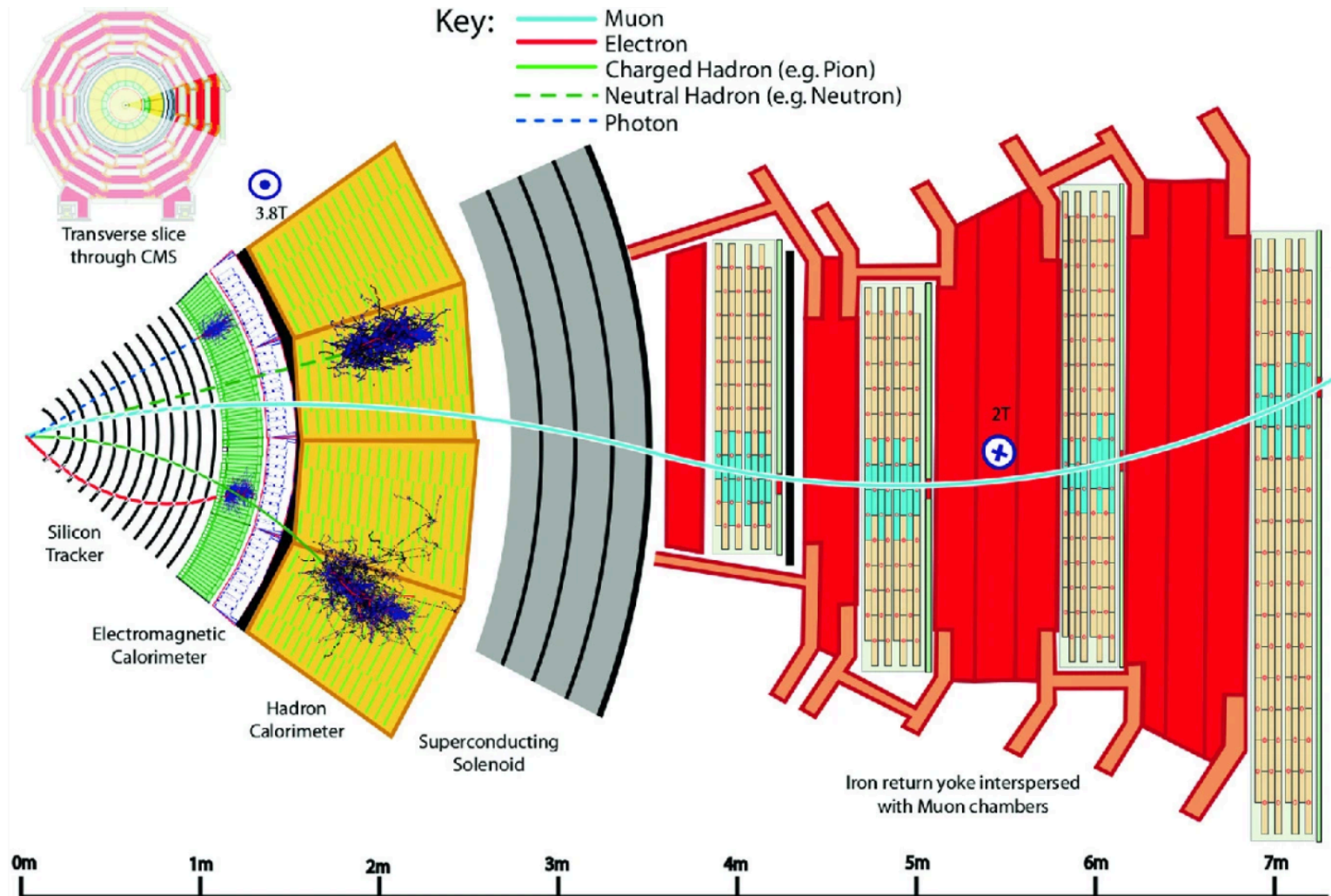


ATLAS Detector



ATLAS

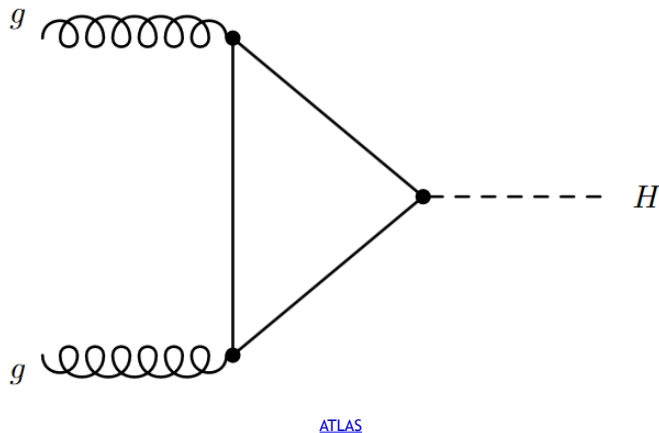
Particle reconstruction (CMS)



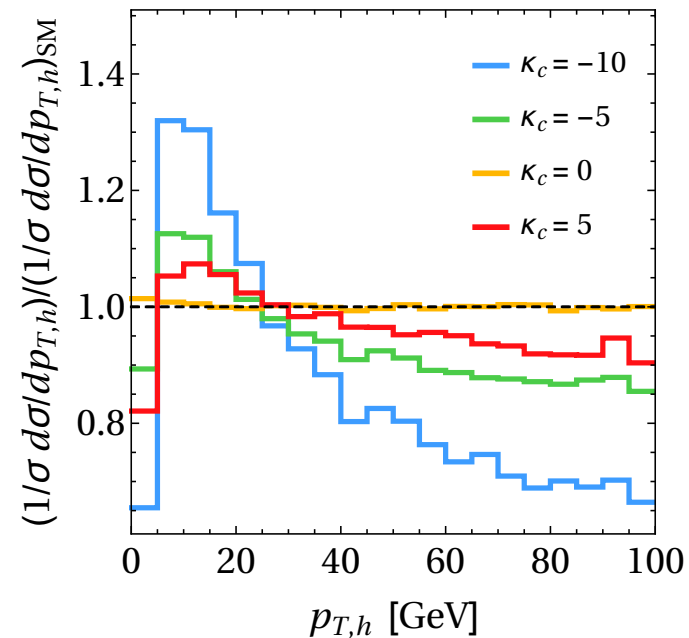
Probing y_c with the Higgs p_T

- y_c impacts shape & normalisation of Higgs transverse momentum (p_T) spectrum due to charm quarks in its gluon-gluon fusion and quark-induced production

Gluon-gluon fusion



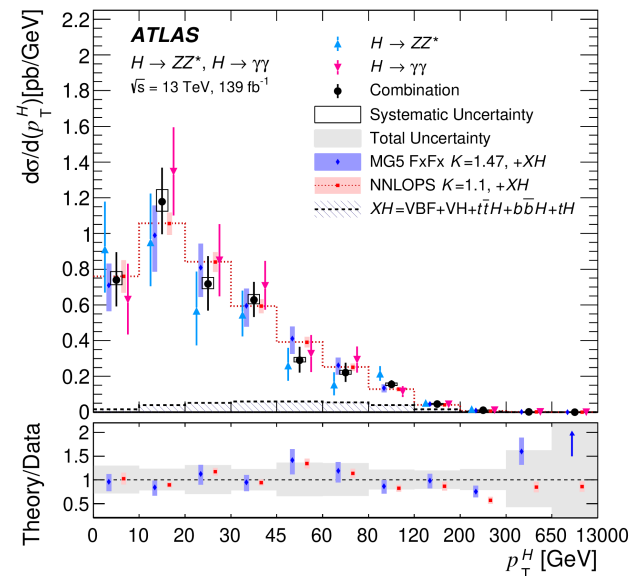
8 TeV



[PRL 118 \(2017\) 121801](#)

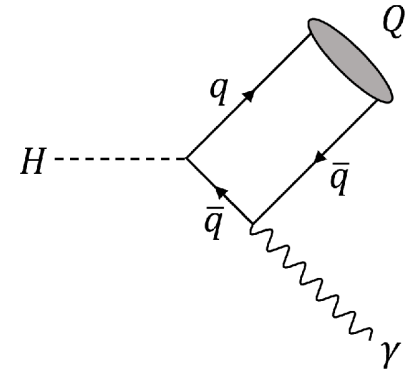
Probing y_c with the Higgs p_T

- y_c impacts shape & normalisation of Higgs transverse momentum (p_T) spectrum due to charm quarks in its gluon-gluon fusion and quark-induced production
- [ATLAS](#) used 139 fb^{-1} of pp data to constrain y_c using $H \rightarrow ZZ, H \rightarrow \gamma\gamma$ decays
- Obs (exp) 95% CL intervals on y_c/y_c^{SM} are **[-8.6, 17.3]** ([-8.5, 15.9]) with shape-only info
- Same intervals are **[-2.27, 2.27]** ✓ ([-2.77, 2.75]) with also normalisation information ✗



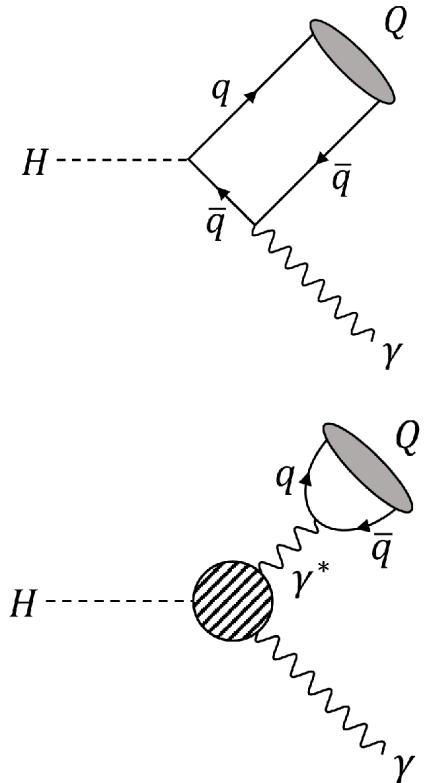
$$H \rightarrow J/\psi + \gamma$$

- $H \rightarrow J/\psi + \gamma$ decays can probe both the magnitude and sign of y_c ✓



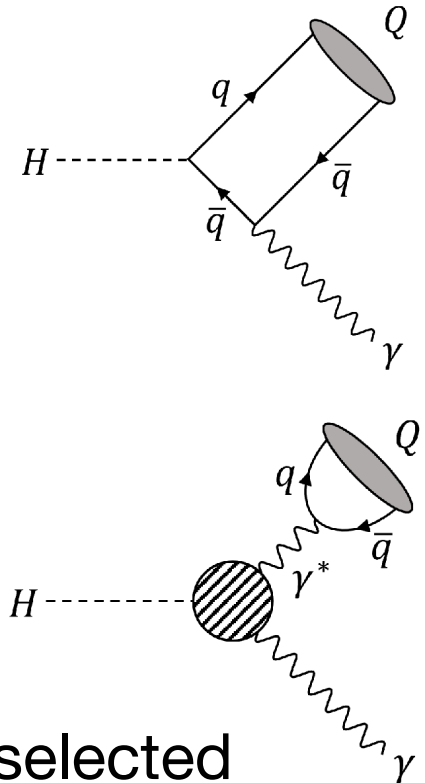
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- The diagrams interfere destructively, resulting in $\mathcal{B}(H \rightarrow J/\psi + \gamma) \sim 10^{-6}$ ✗



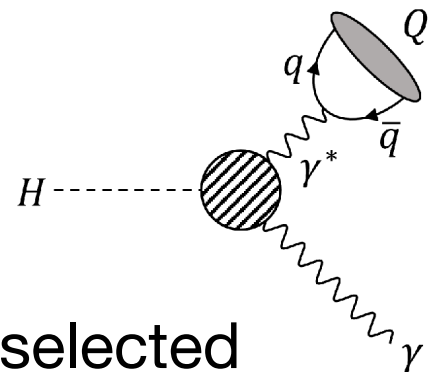
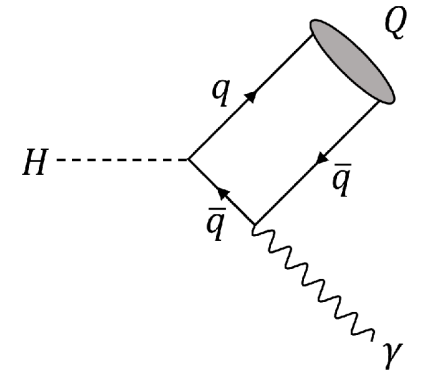
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- ATLAS has searched for this using 139 fb⁻¹ of pp data and custom triggers
- Events with two muons and a photon are selected
- The signal is modelled using simulation, and the multi-jet/ γ + jet backgrounds using a [data-driven approach](#)
- 2D likelihood fit to $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$, and combination with a $H \rightarrow \gamma\gamma$ [result](#), leads to obs (exp) constraints on $(y_c/y_c^{\text{SM}})/(y_\gamma/y_\gamma^{\text{SM}})$ of **[-133, 175]** ([-120, 161])



CMS VH , $H \rightarrow c\bar{c}$ Method

- y_c can be probed in $H \rightarrow c\bar{c}$ decays
- VH production is used for triggering and background rejection, where $V \rightarrow \ell\ell, \ell\nu, \nu\nu$
- 138 fb⁻¹ of pp data

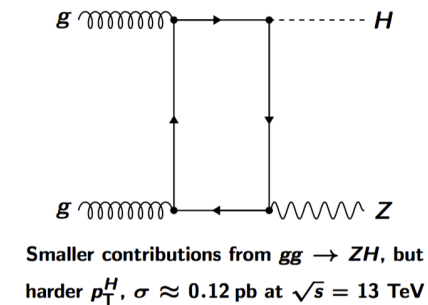
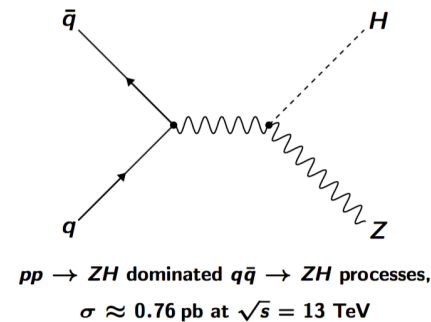
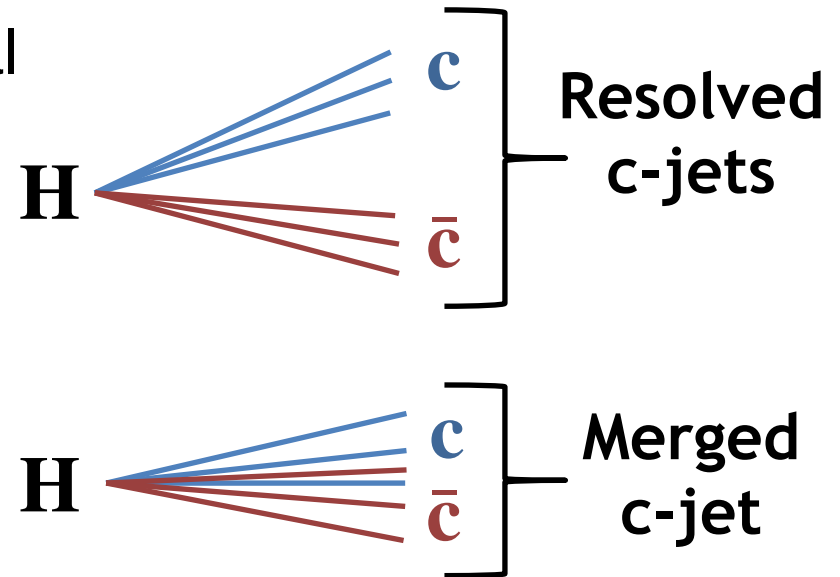


Figure (both diagrams and texts) made by Andrew Chisholm

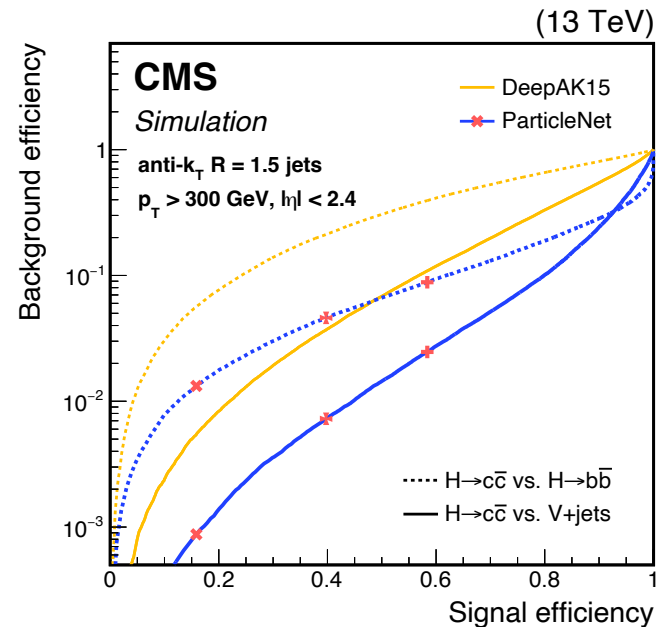
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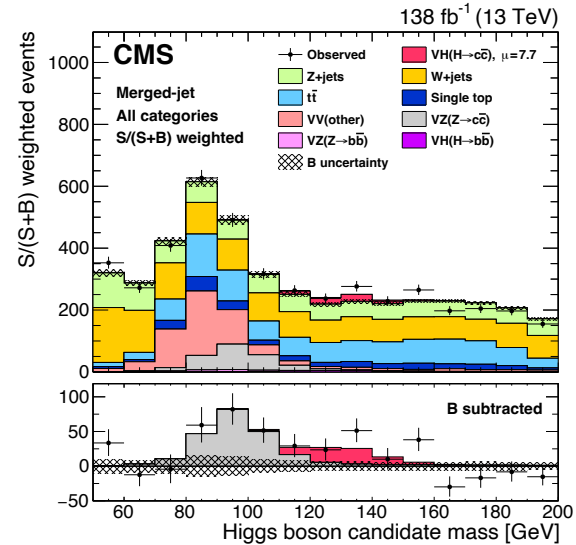
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 - Merged decays categorised using *ParticleNet*
- Boosted decision trees (BDTs) used for merged event selection



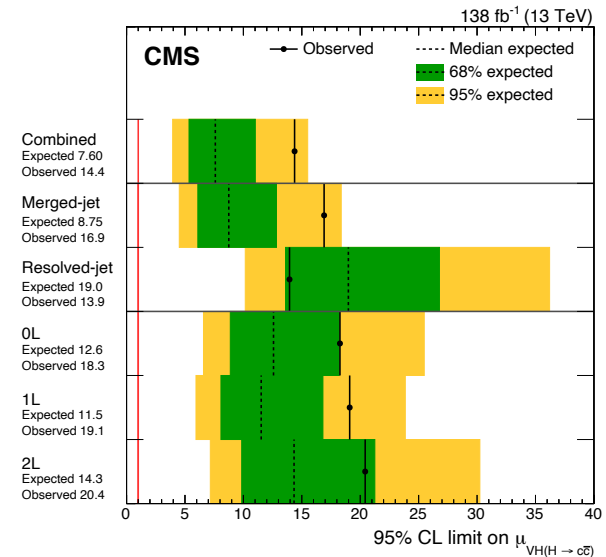
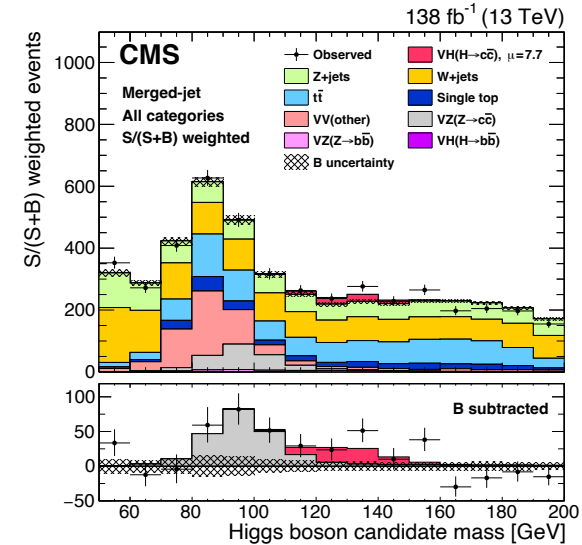
CMS $VH, H \rightarrow c\bar{c}$ Results

- Binned likelihood fit to $m(H_{\text{cand}})$ (BDT output) in the merged (resolved) categories used for interpretation
- $V + \text{jets}$ and $t\bar{t}$ yields estimated in control regions
- Analysis is statistically limited



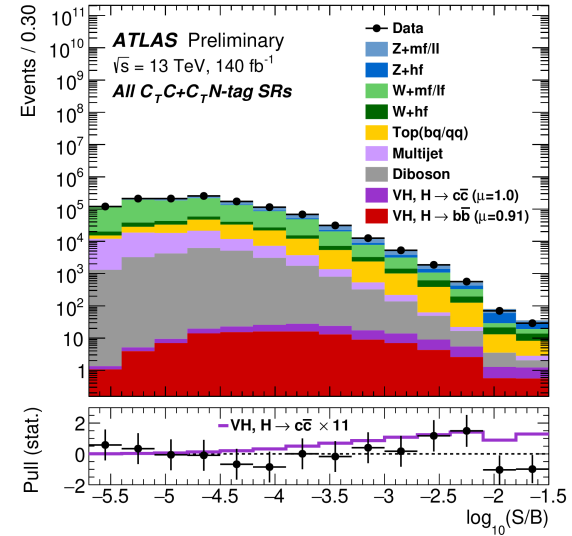
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- Obs (exp) 95% CL upper limit on $\sigma(VH)\mathcal{B}(H \rightarrow c\bar{c})$:
 $14 \times \text{SM}$ ($7.6 \times \text{SM}$)
- Obs (exp) 95% CL interval on y_c/y_c^{SM} : **$1.1\text{--}5.5$ (<3.4)**



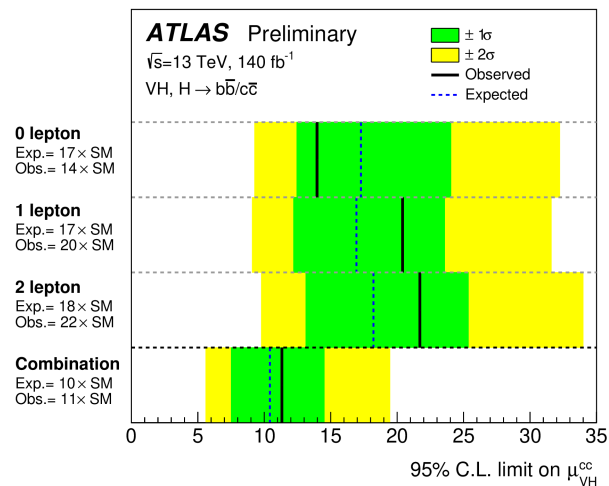
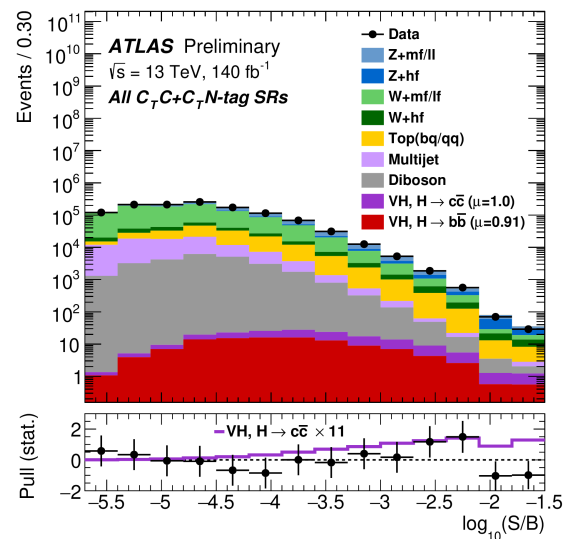
ATLAS VH, $H \rightarrow c\bar{c}$

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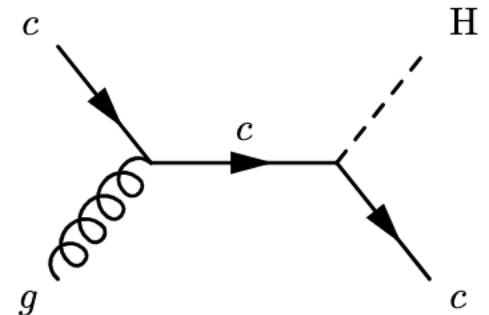
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- 139 fb⁻¹ of pp data
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- Obs (exp) $VH, H \rightarrow c\bar{c}$ 95% CL_s upper limit: **11.3 × SM** (10.4 × SM)
- Corresponding to obs (exp) upper limit on $|y_c/y_c^{\text{SM}}|$: **4.2 (4.1)**



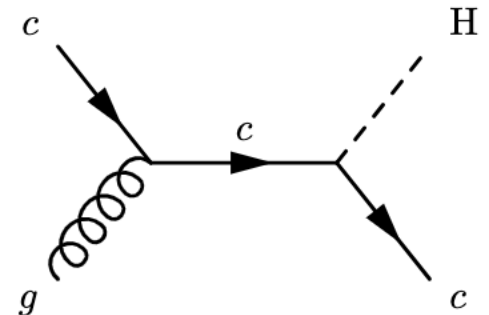
Higgs+charm production

- Probing y_c is challenging, and multiple approaches will likely be required
- Higgs+charm production was [proposed](#) to **probe y_c** , but also **tests a new Higgs boson production mode**



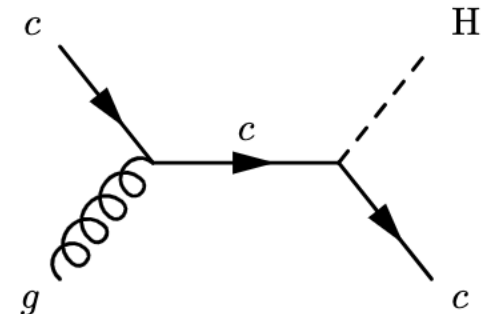
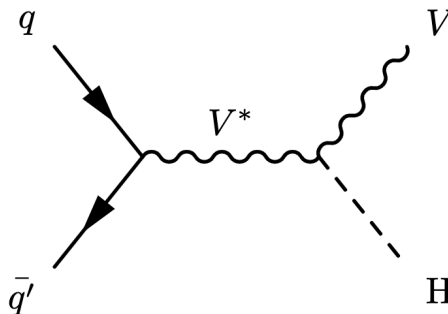
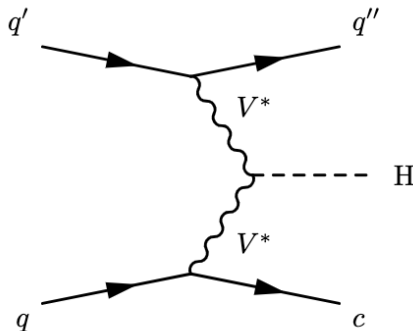
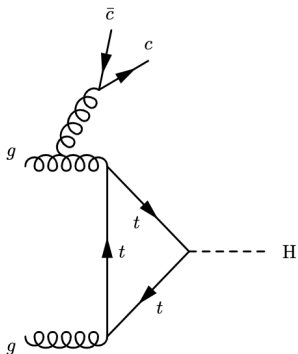
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- Only have to c-tag 1 jet ✓
- Can use most sensitive Higgs decay modes (e.g. $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$) ✓
- Only $\sim 1\%$ of signal sensitive to y_c ✗

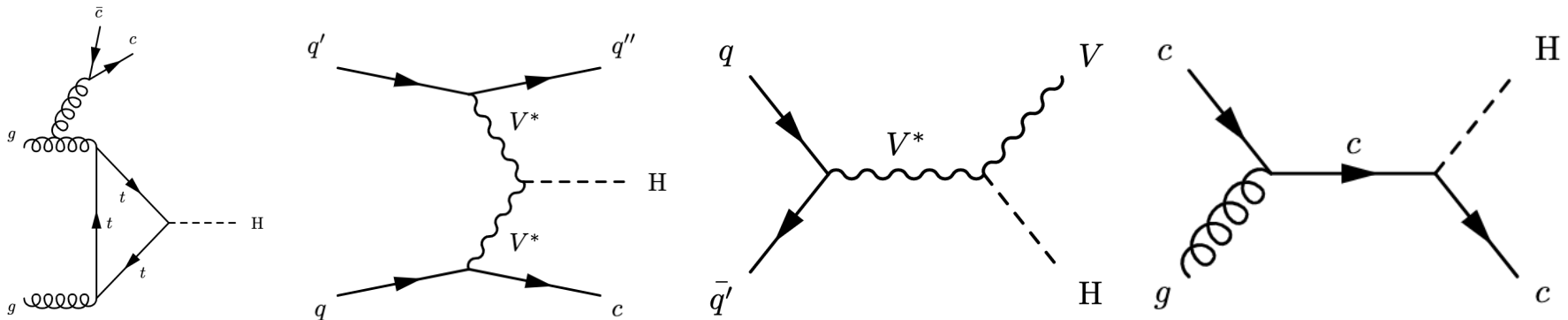


ATLAS Higgs+charm analysis

- Higgs+charm events were analysed in $H \rightarrow \gamma\gamma$ decays
- Run 2 dataset (140 fb⁻¹) used, with (di-)photon triggers

ATLAS Higgs+charm analysis

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- Run 2 dataset (140 fb⁻¹) used, with (di-)photon triggers
- **Inclusive H+c signal:** truth-level events must contain a Higgs boson and a charm-jet
 - Cross-section: **~2.9 pb**
- **Backgrounds:** non-resonant (NR) $\gamma\gamma + n_{\text{partons}}$; any resonant $H \rightarrow \gamma\gamma$ event that is not signal



Event Selection

- **Photons:** ≥ 2 isolated and *tight* identified photons with $p_T > 25$ GeV and $|\eta| < 2.37$, but not $1.37 < |\eta| < 1.52$
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- **Event-level selection:**
 - $E_T^\gamma / m_{\gamma\gamma} > 0.35$ (0.25) for (sub-)leading photon
 - $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$
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- **Categorisation:** c-tag and non-c-tag signal regions (SRs) defined based on presence of c-tagged jet
- **Discriminant variable:** $m_{\gamma\gamma}$, in region 120–130 GeV

Simulation

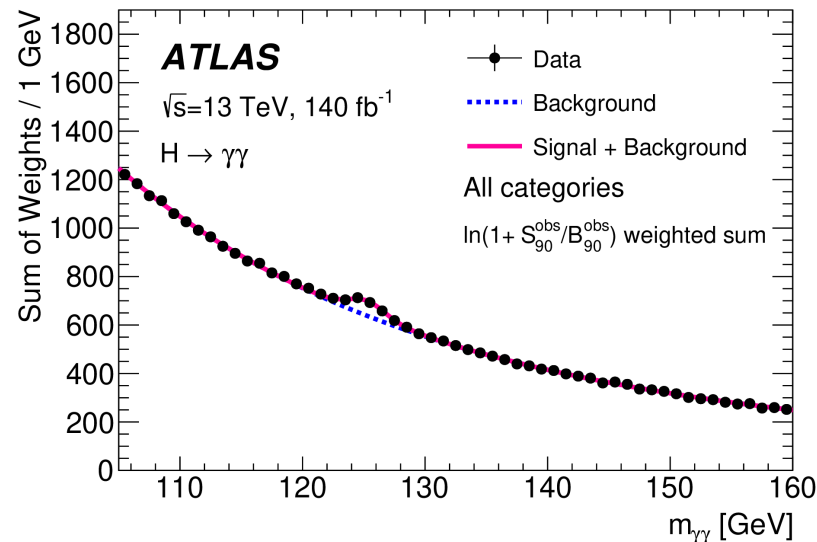
- Monte Carlo (MC) simulation is used to model the signal and resonant backgrounds
- *Geant4* ATLAS simulation used for most MC samples
- y_c -sensitive part of $H + c$ is modelled at leading order using *MadGraph5*, with *Higgs Effective Couplings* [UFO](#)

Process	Generator ME + PS	PDF set	PDF tune	σ [fb]
ggF $H, H \rightarrow \gamma\gamma$	POWHEG NNLOPS+PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	110.1
VBF $H, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	8.578
$W^- H, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.206
$W^+ H, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.902
$gg \rightarrow ZH, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	0.278
$qq \rightarrow ZH, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.725
$t\bar{t}H, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	A14NNPDF23	1.150
$b\bar{b}H, H \rightarrow \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	A14NNPDF23	1.104
y_c -sensitive $H + c, H \rightarrow \gamma\gamma$	MADGRAPH +PYTHIA 8	NNPDF3.0NNLO	A14NNPDF23	0.064
Non-resonant $\gamma\gamma + n$ parton	SHERPA (ME@NLO+PS)	NNPDF3.0NNLO	SHERPA	51823

NR background modelling

- Dominant background is from smoothly-falling NR $\gamma\gamma + n$ partons events
 - Typically modelled using analytical functions

Representative example (not used here)



[PLB 847 \(2023\) 138315](#)

NR background modelling

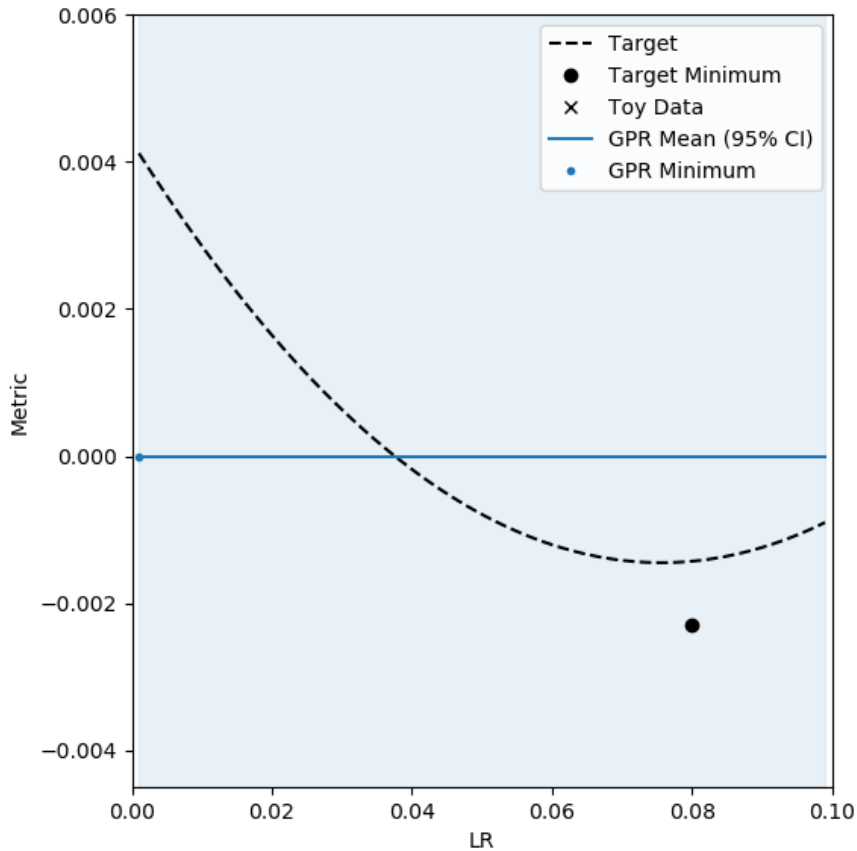
- Dominant background is from smoothly-falling NR $\gamma\gamma + n$ partons events
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- Here, we perform the first usage of [Gaussian process regression](#) (GPR) for direct background estimation in a particle physics data analysis
 - There are [pre-existing ideas](#) for using GPR in HEP
- GPR is a machine learning algorithm that provides a **Bayesian posterior distribution** over functions
 - **Explores complete space of functions**, so is always able to model true function

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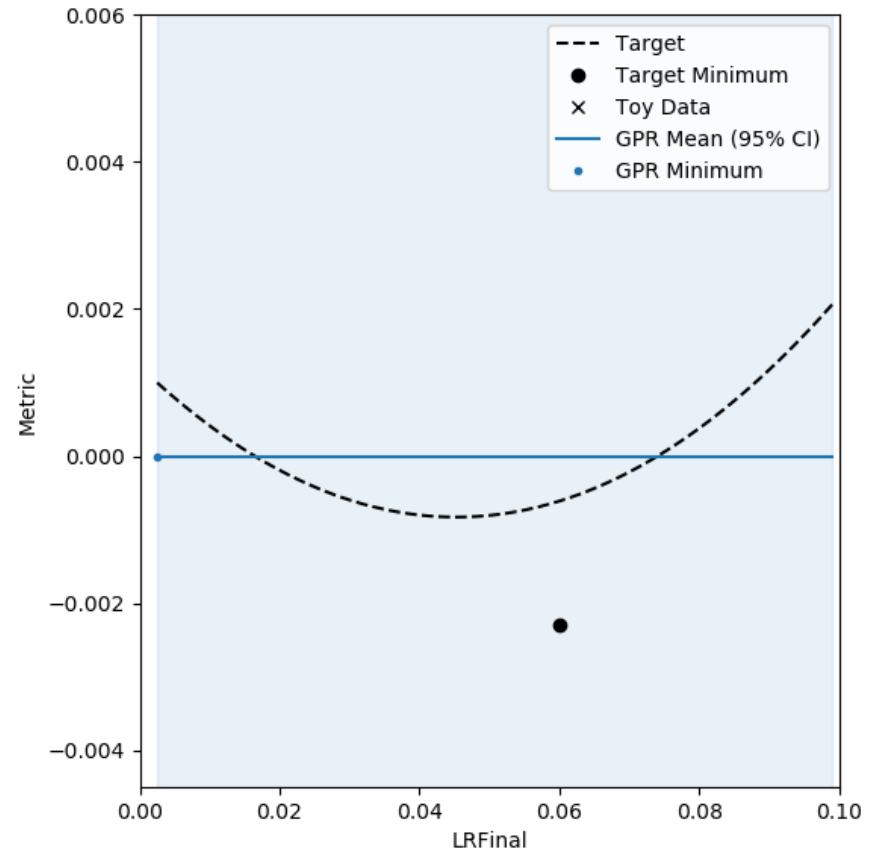
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 - **Explores complete space of functions**, so is always able to model true function
- Here, GPR (with [RBF kernel](#)) is used to **interpolate from data in sidebands into SRs**, providing distribution over possible background PDFs

Toy GPR Demonstration

0 training events



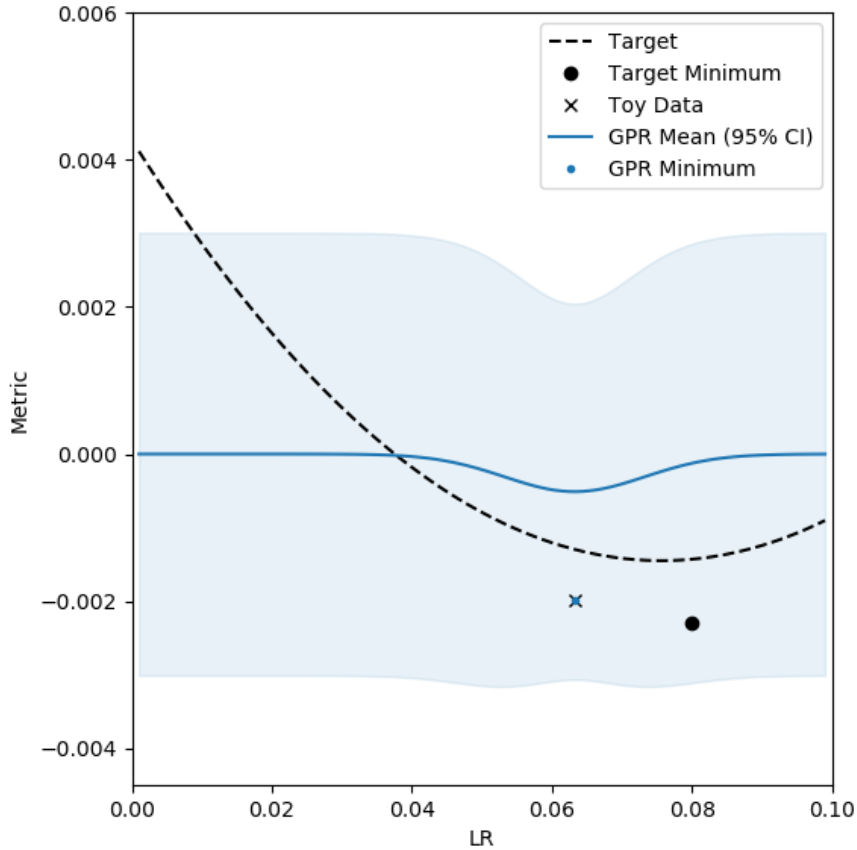
N/A error



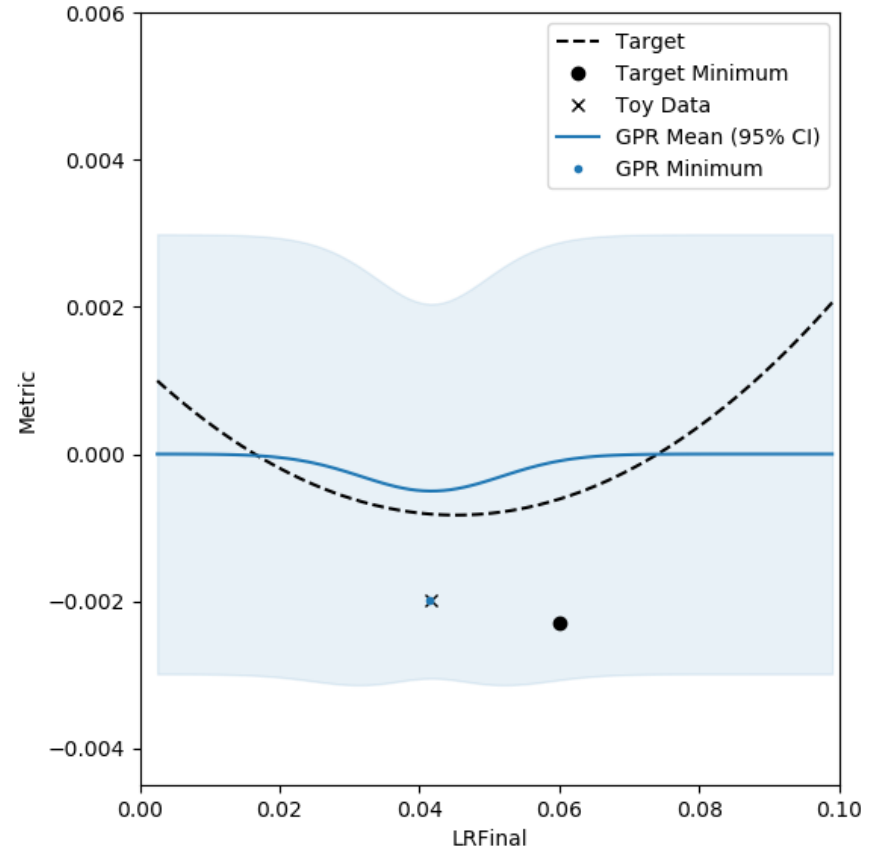
N/A error

Toy GPR Demonstration

1 training event



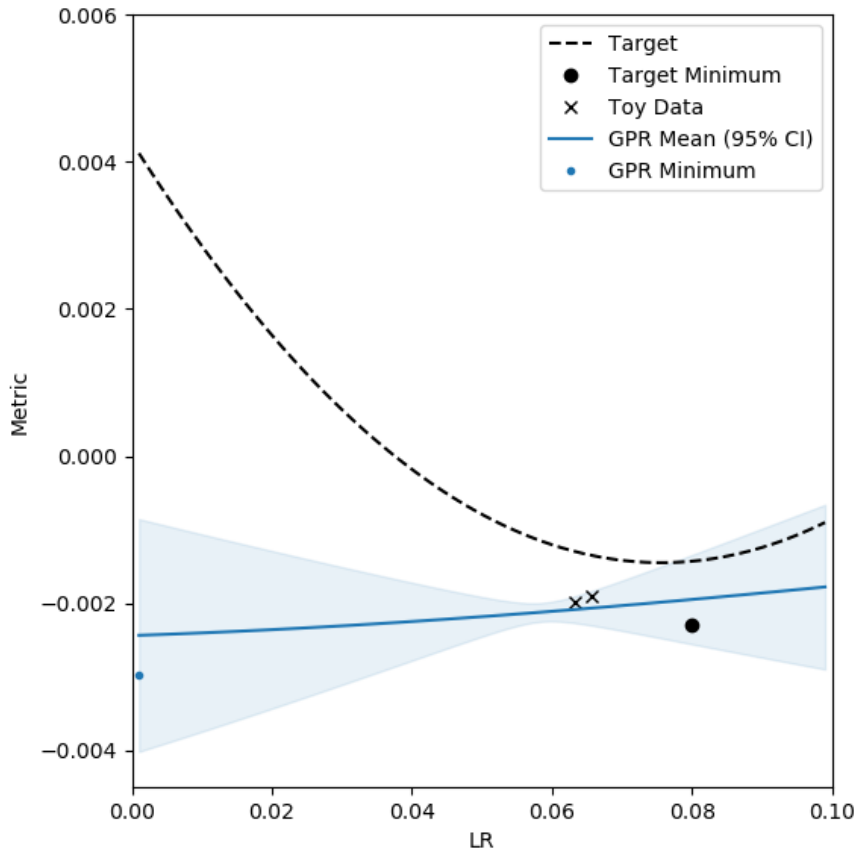
21% error



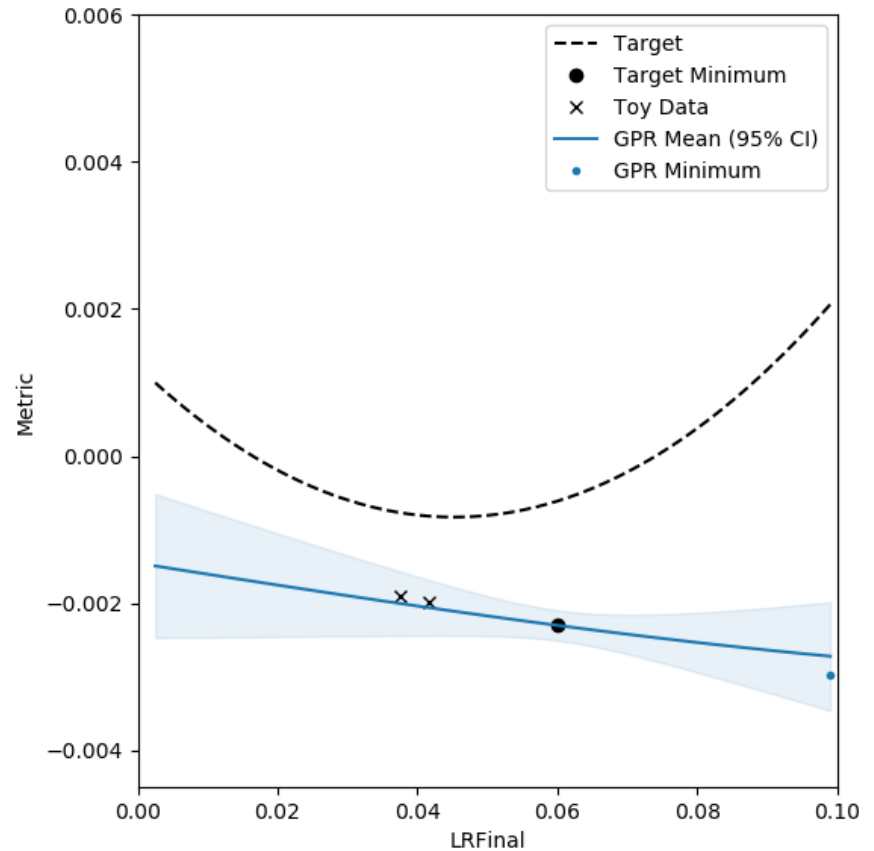
31% error

Toy GPR Demonstration

2 training events



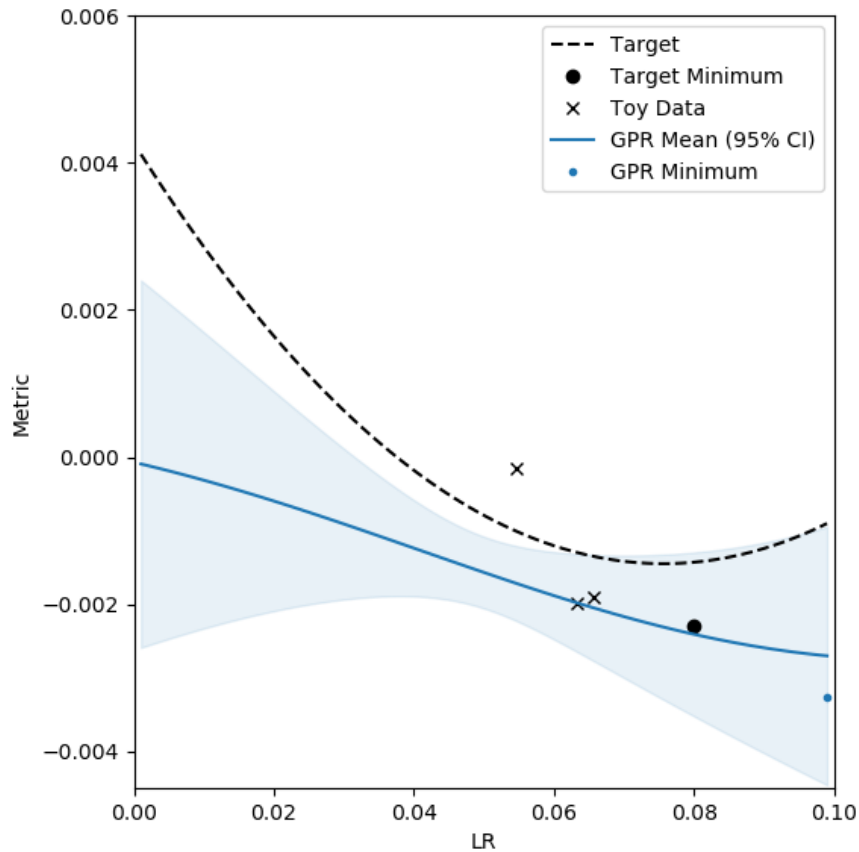
99% error



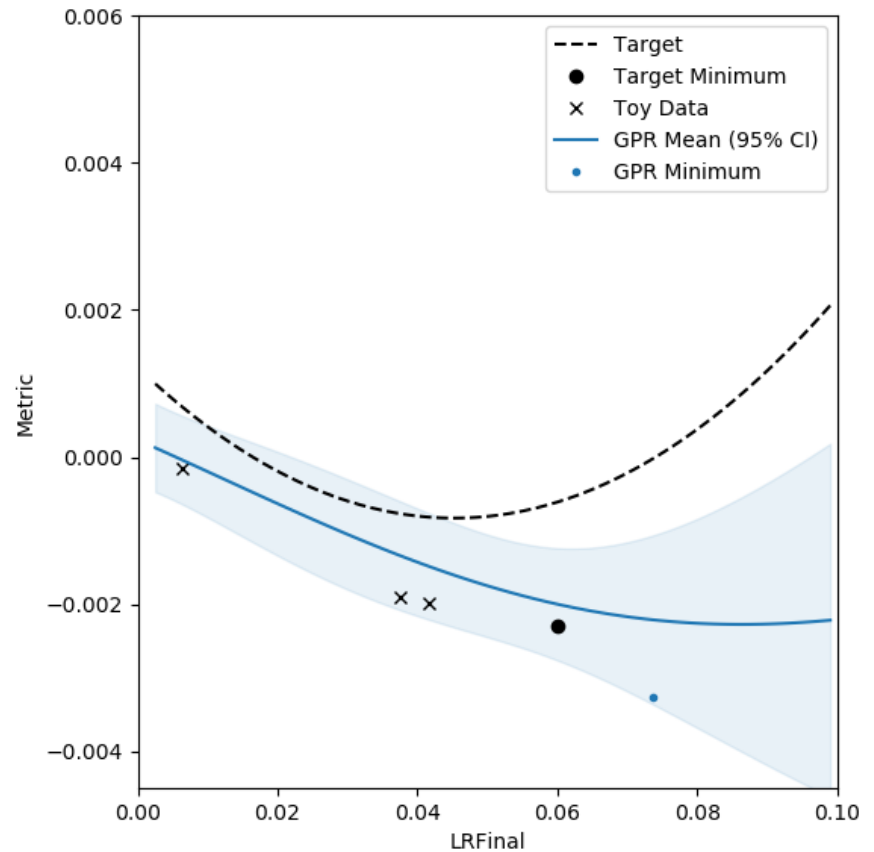
65% error

Toy GPR Demonstration

3 training events



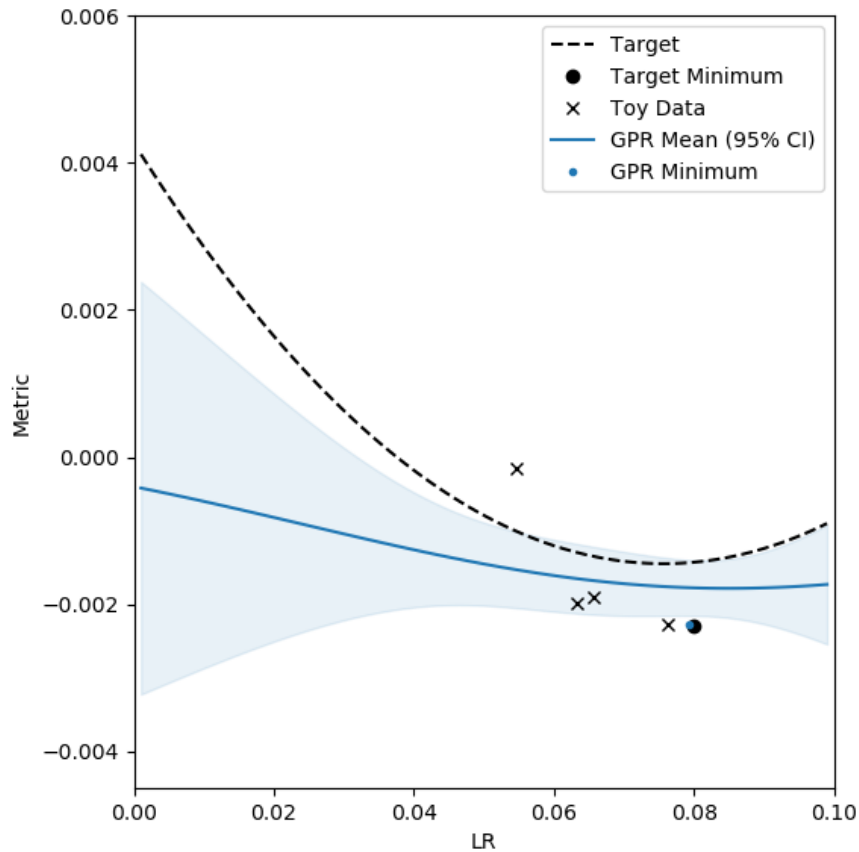
24% error



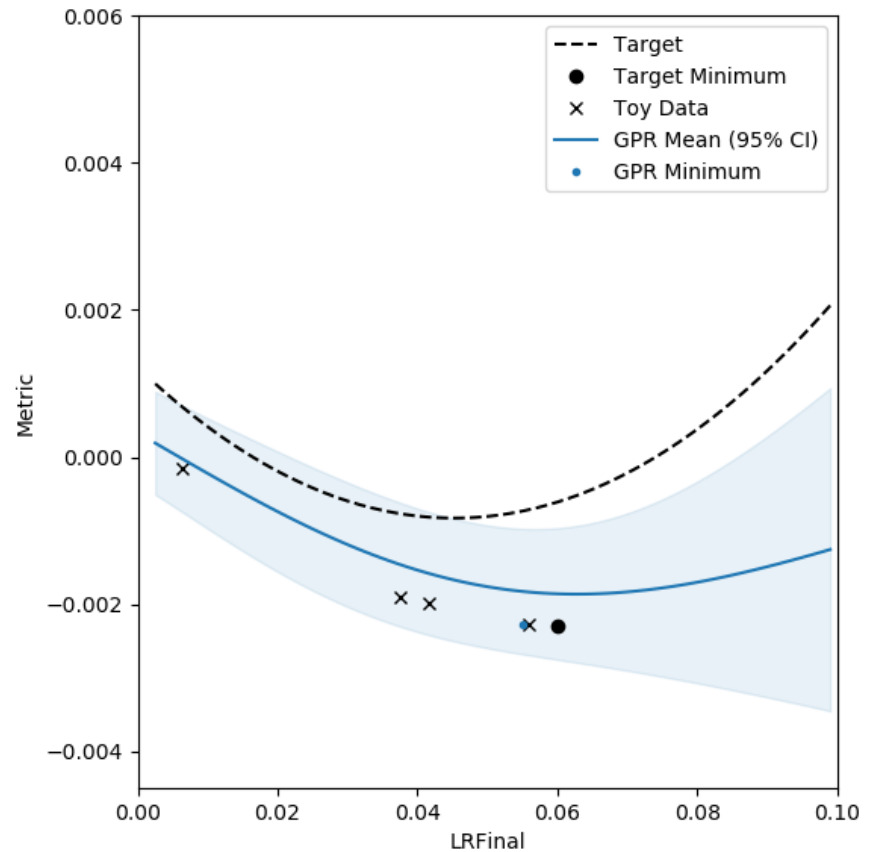
23% error

Toy GPR Demonstration

4 training events



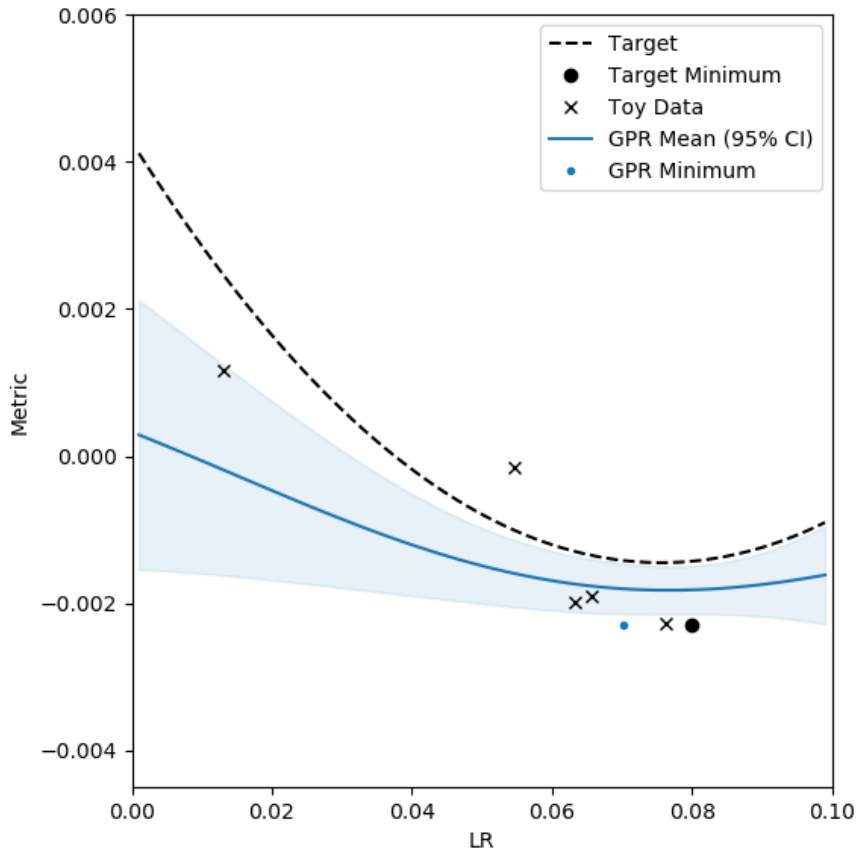
0.99% error



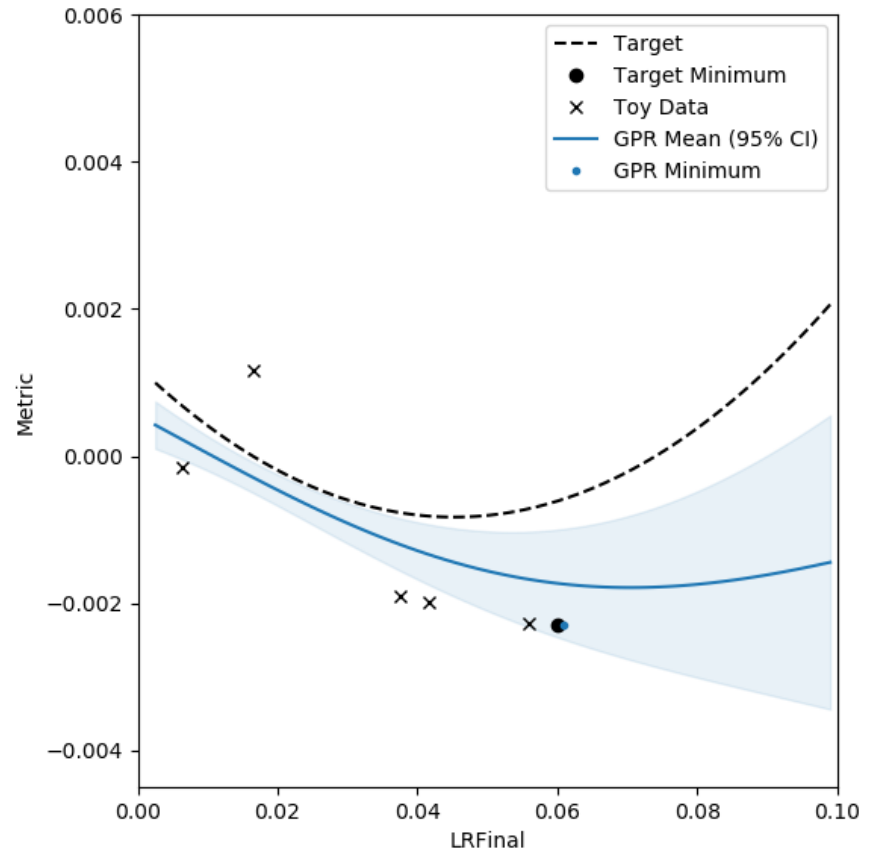
8.1% error

Toy GPR Demonstration

5 training events



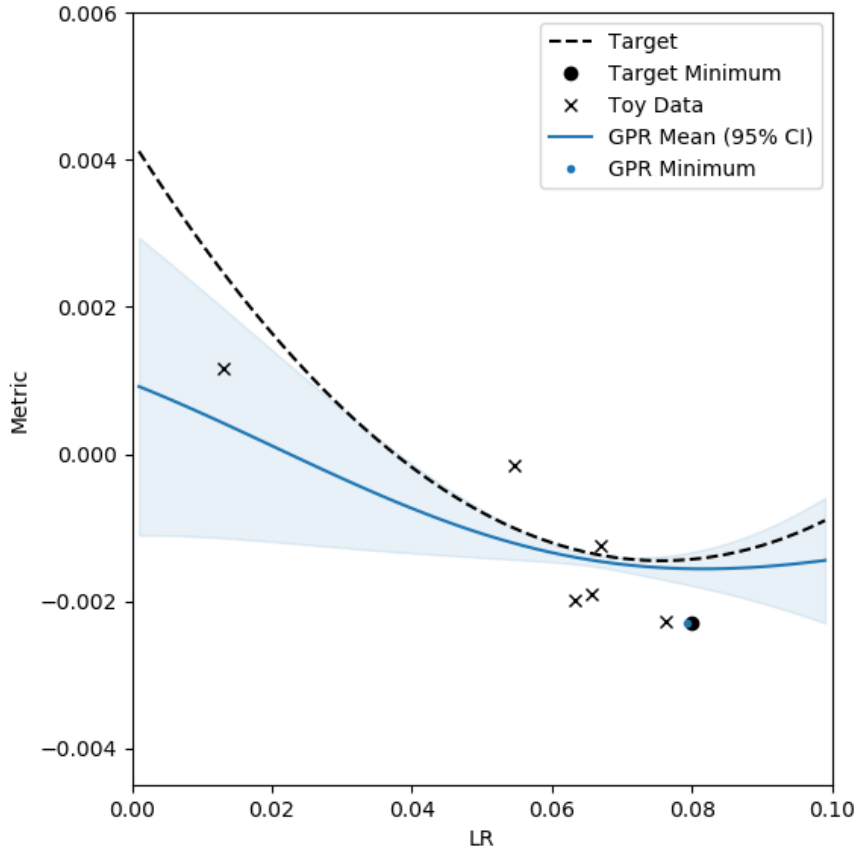
12% error



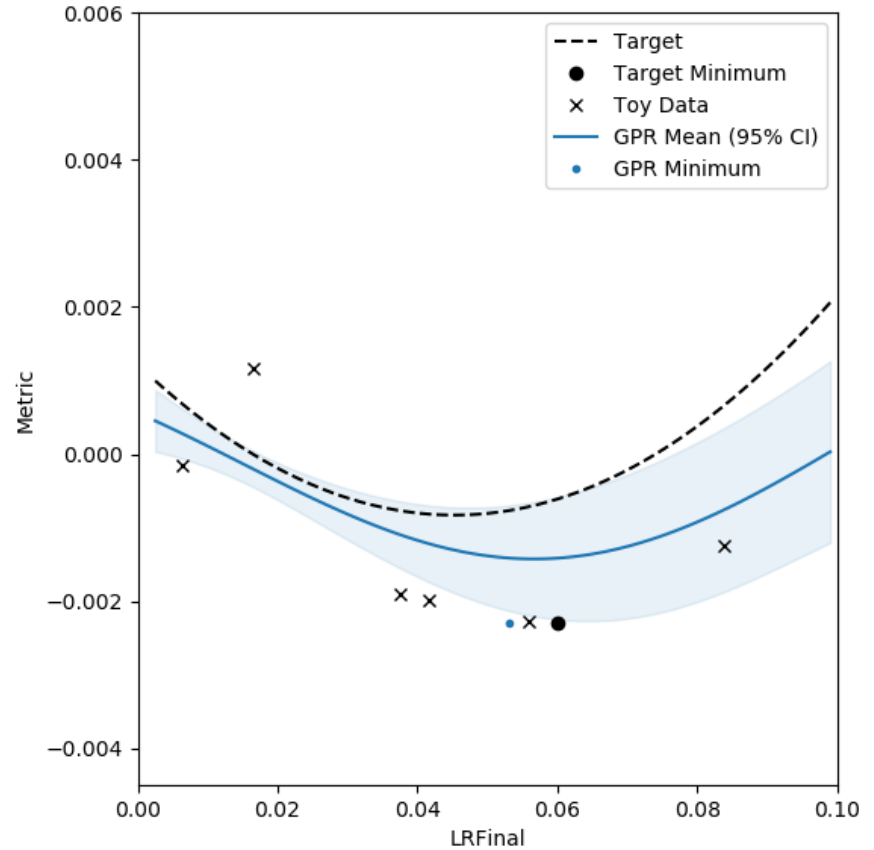
1.7% error

Toy GPR Demonstration

6 training events



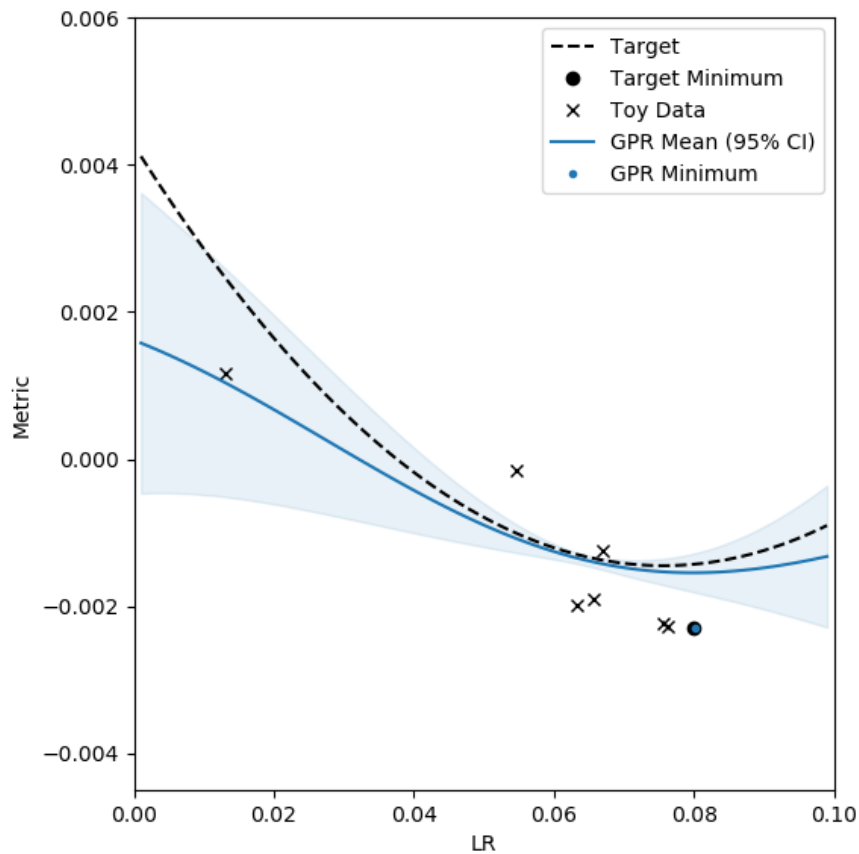
0.99% error



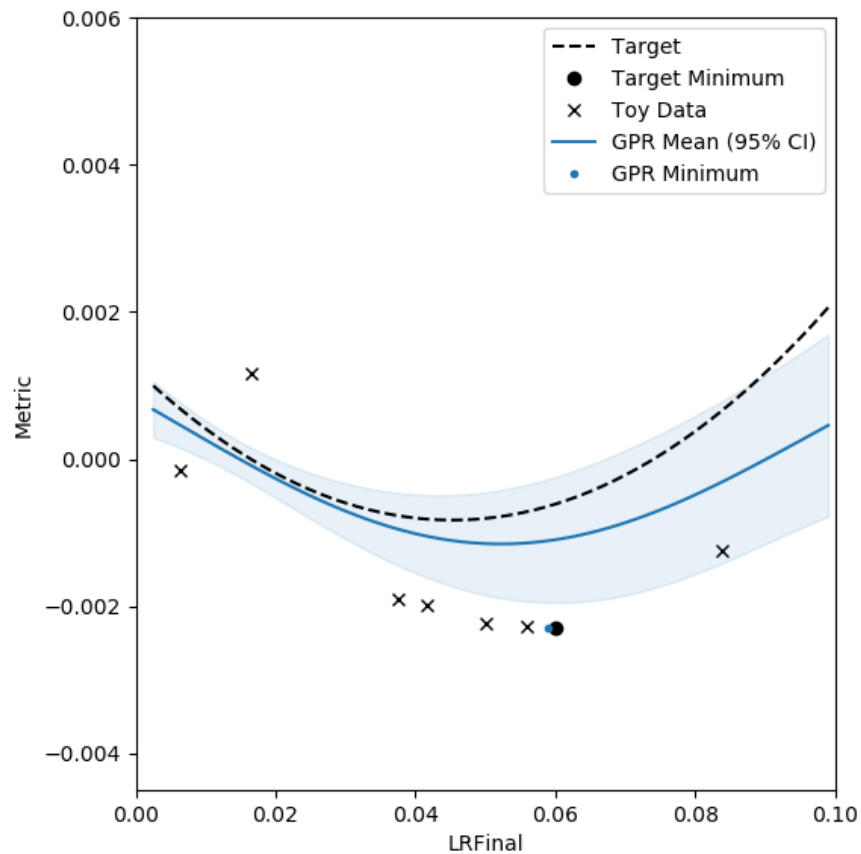
11% error

Toy GPR Demonstration

7 training events



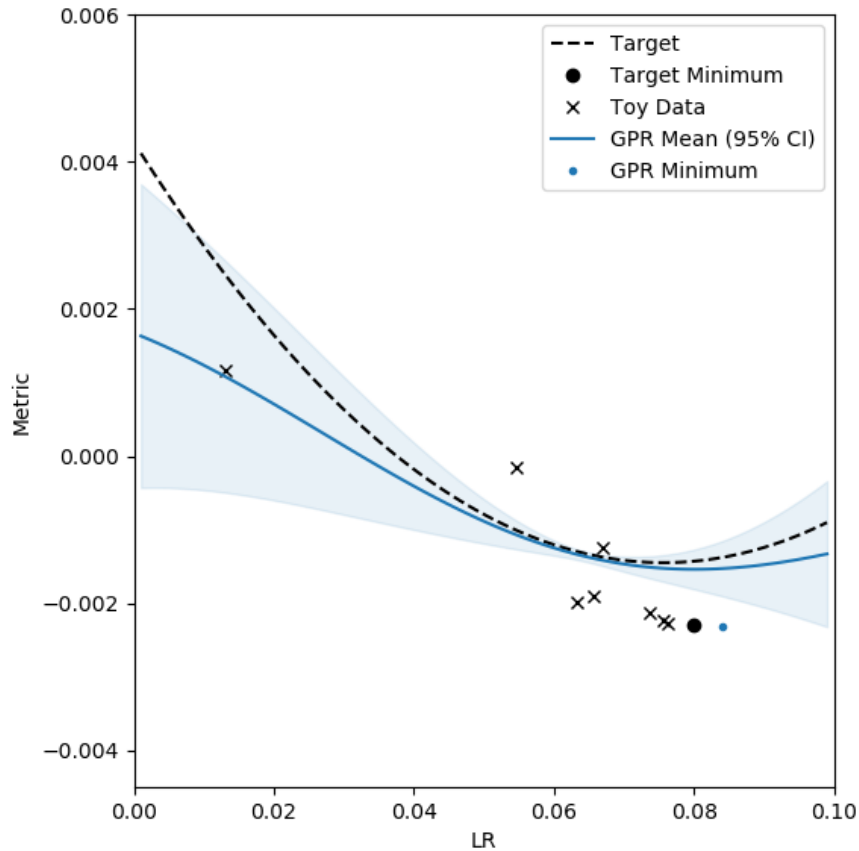
<0.25% error



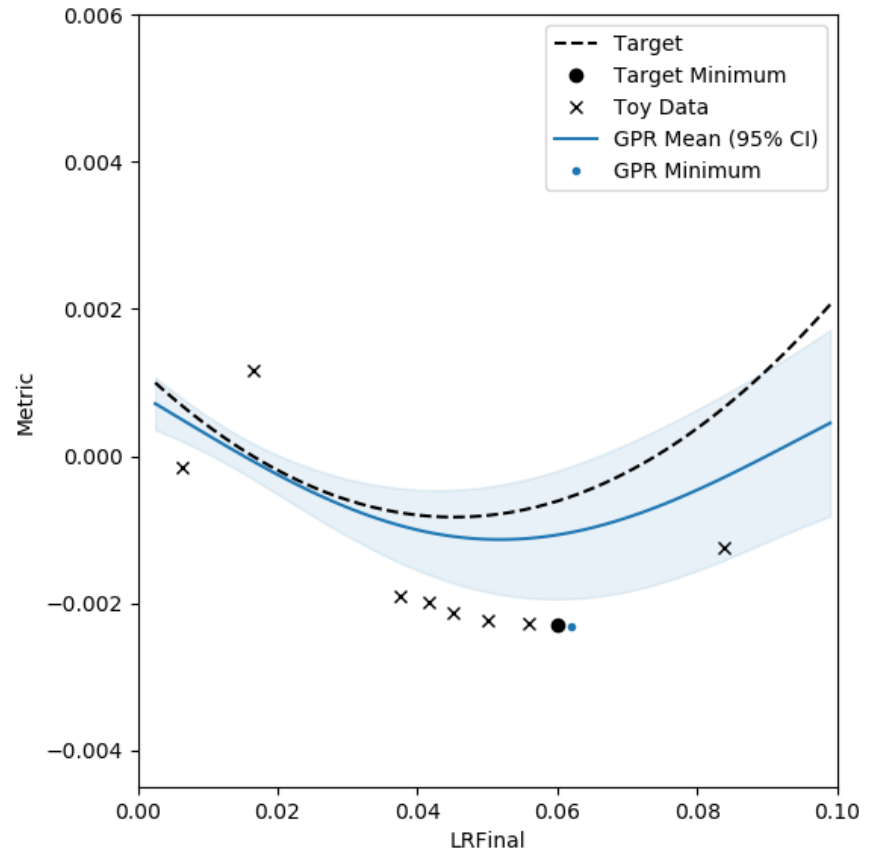
1.6% error

Toy GPR Demonstration

8 training events



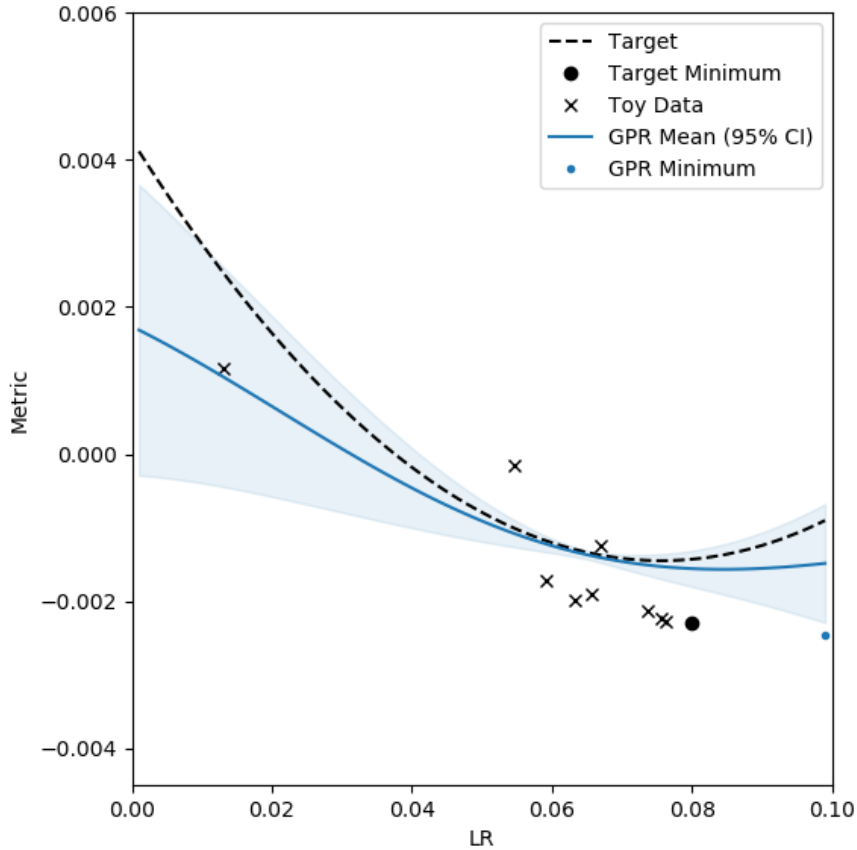
5.2% error



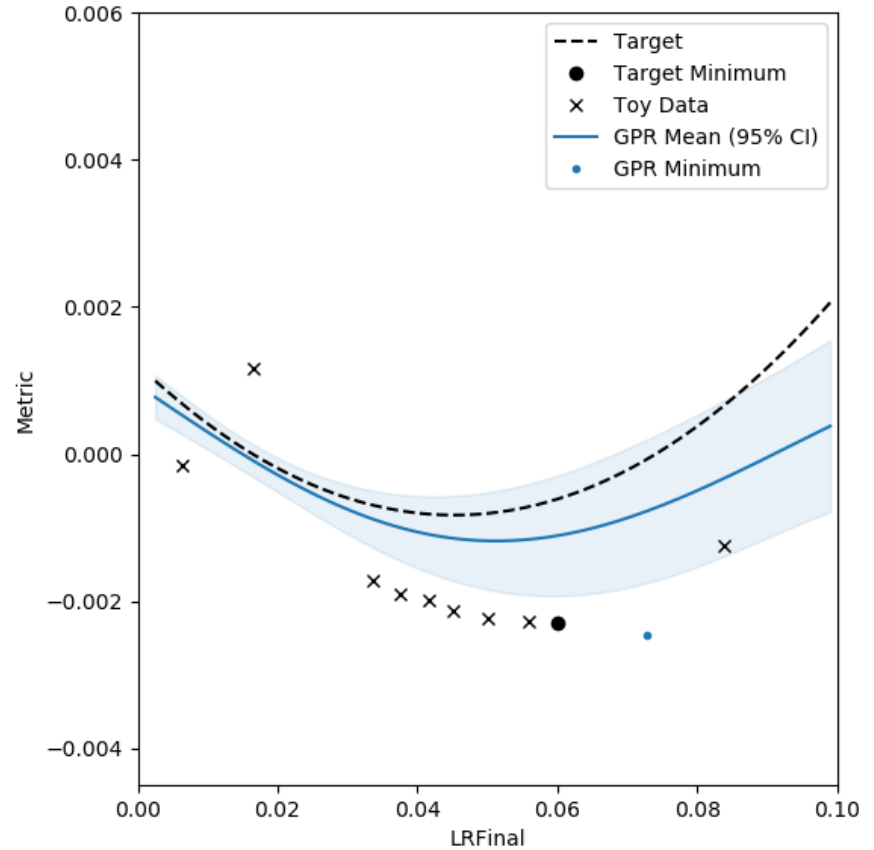
3.3% error

Toy GPR Demonstration

9 training events



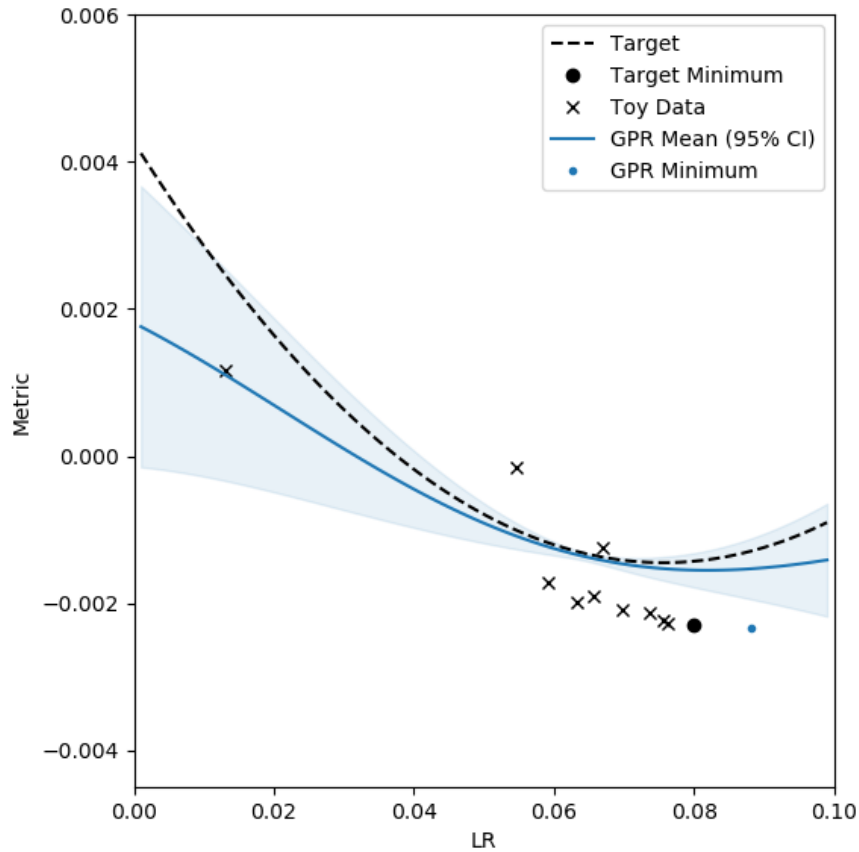
24% error



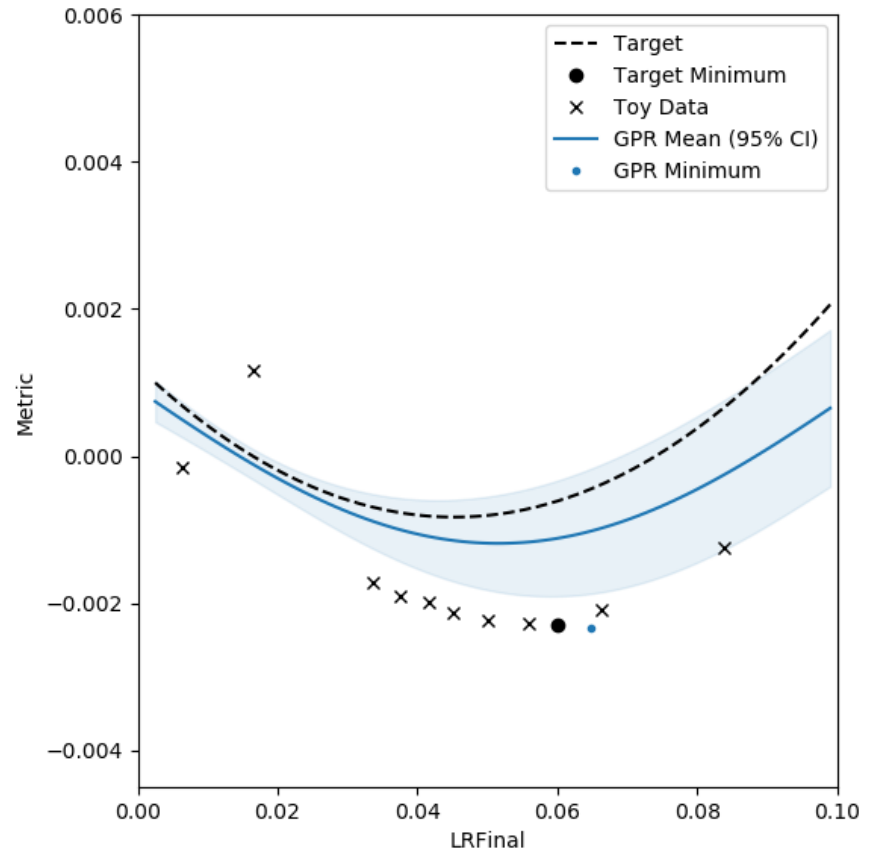
21% error

Toy GPR Demonstration

10 training events



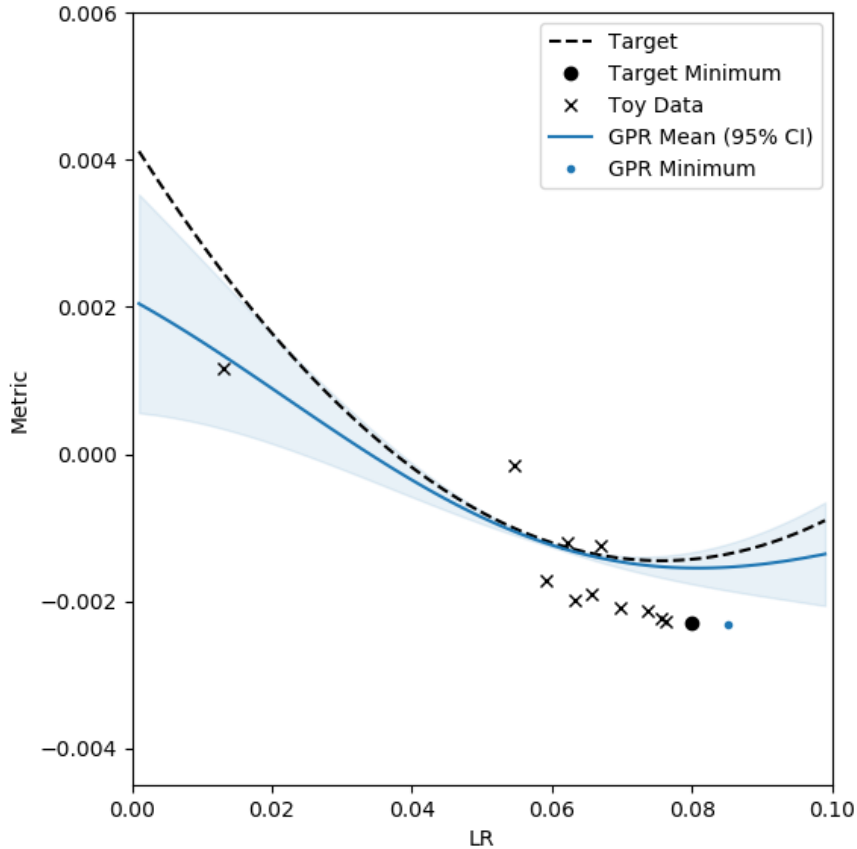
10% error



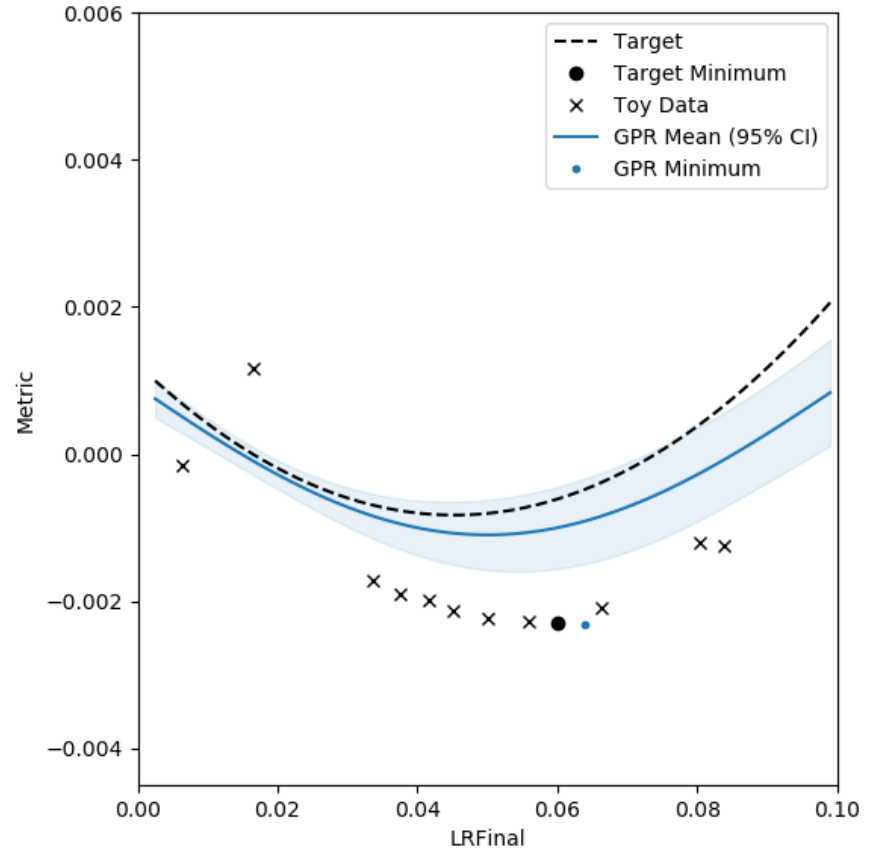
8.2% error

Toy GPR Demonstration

11 training events



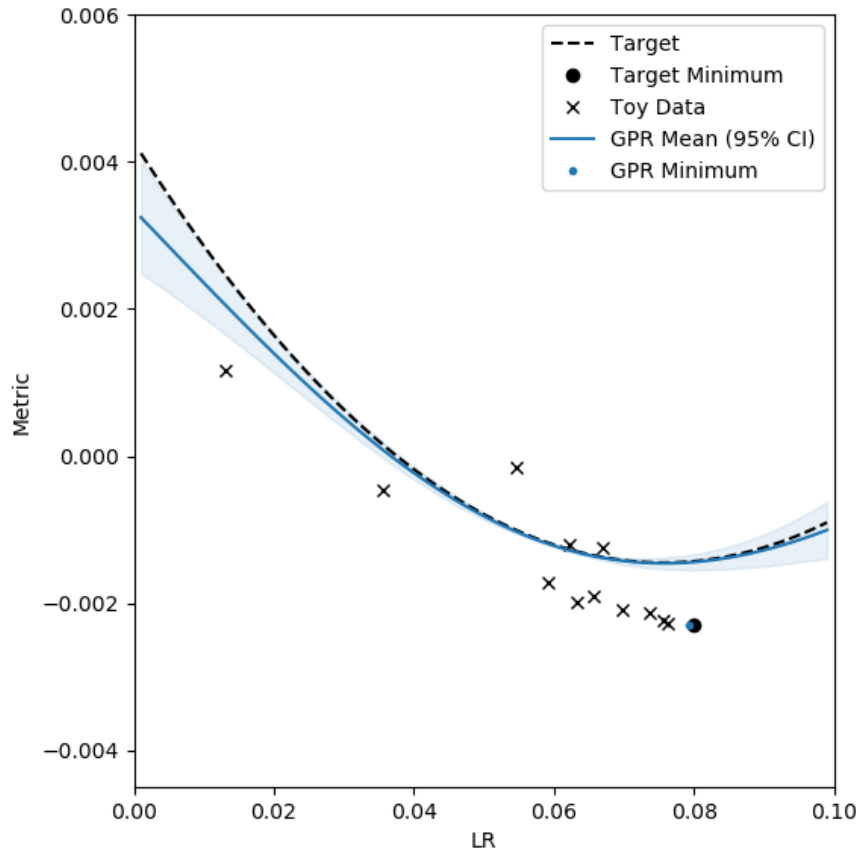
6.4% error



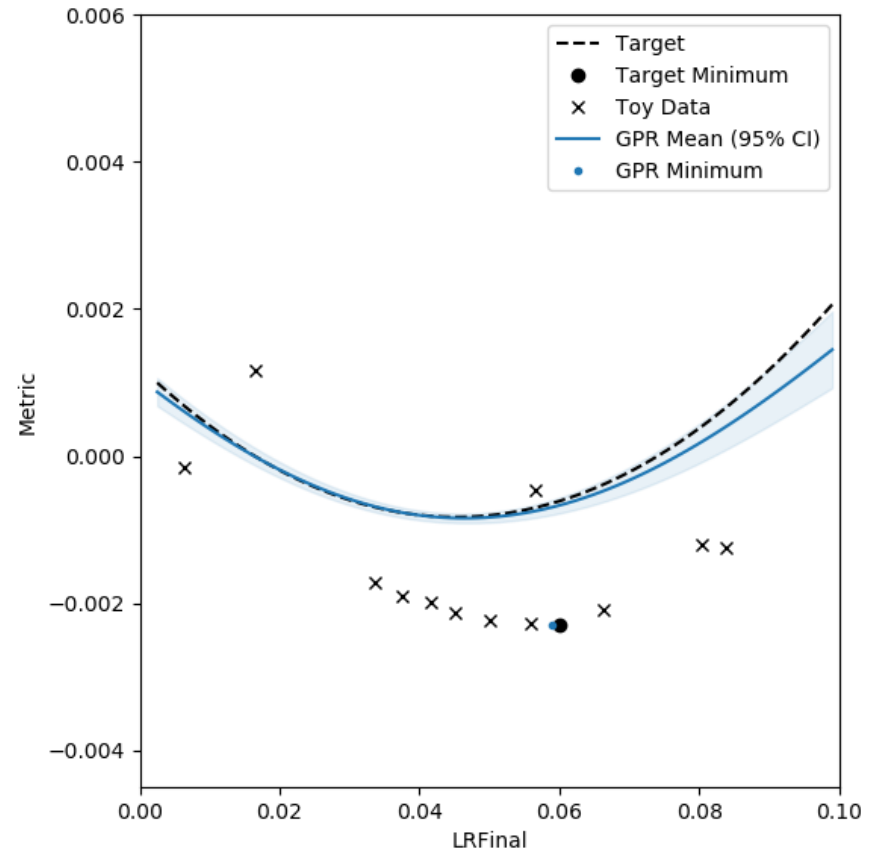
6.5% error

Toy GPR Demonstration

12 training events



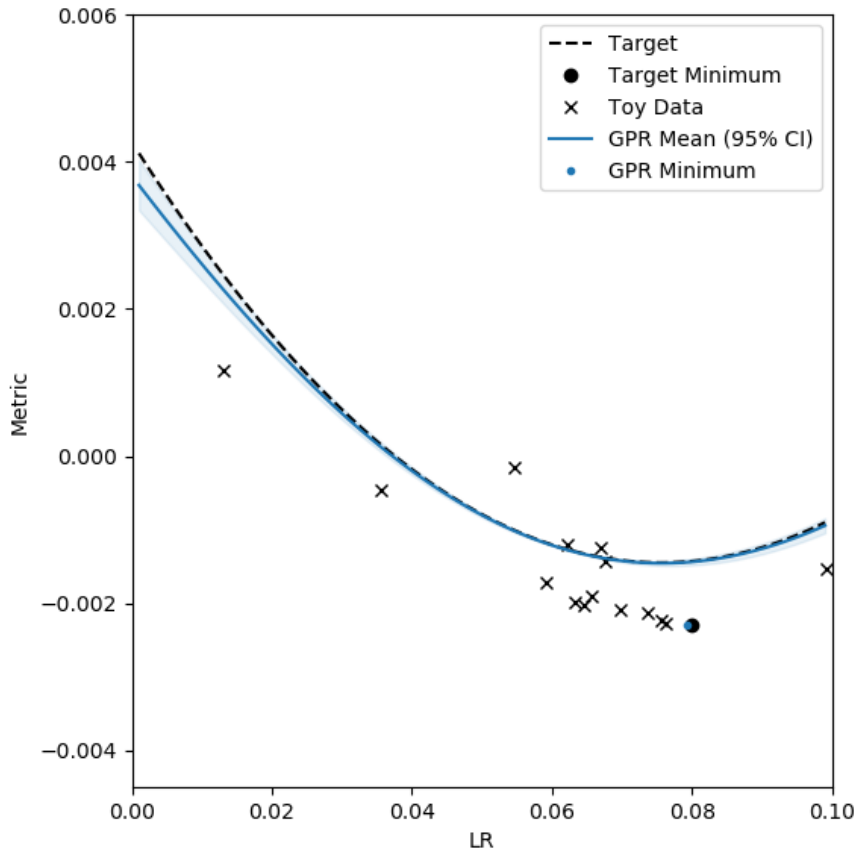
0.99% error



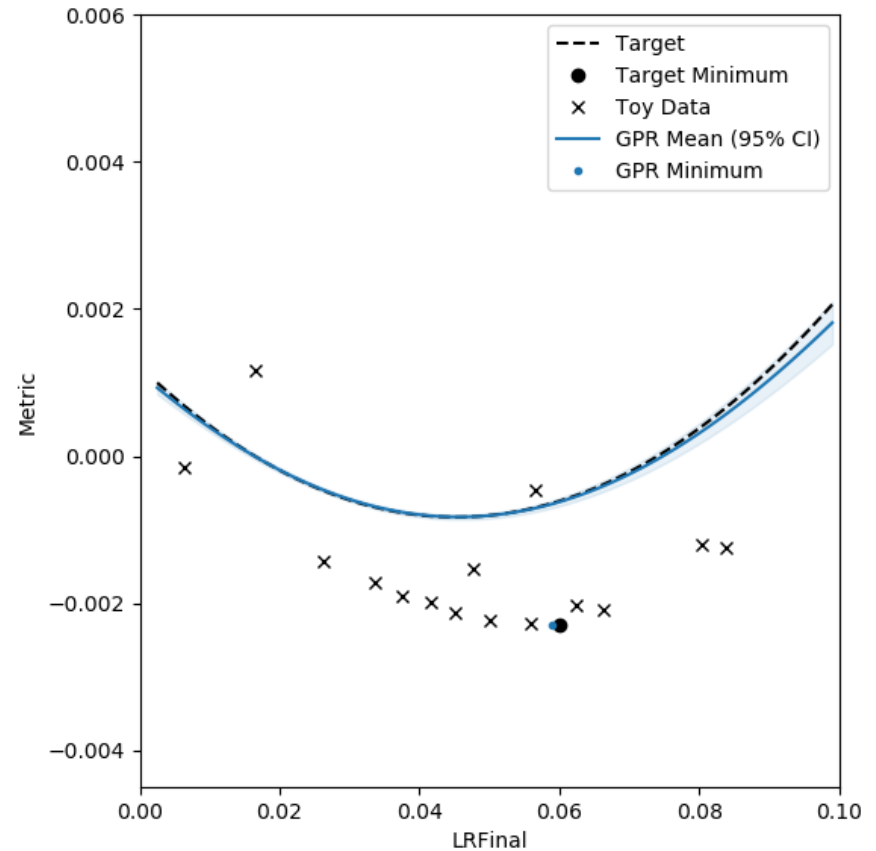
1.6% error

Toy GPR Demonstration

15 training events



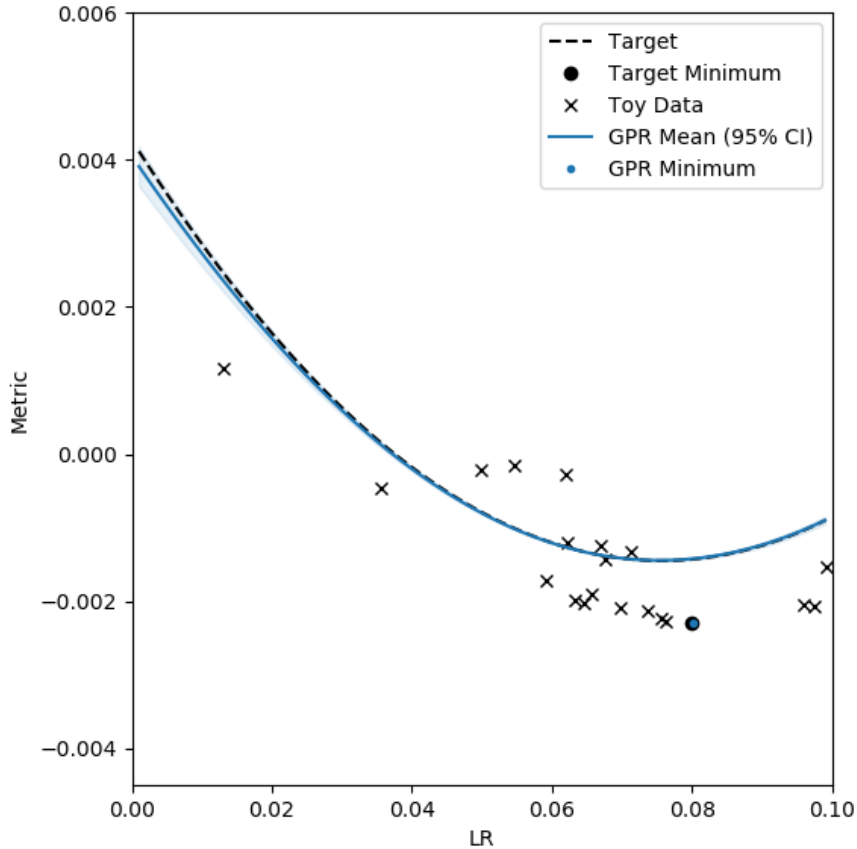
0.99% error



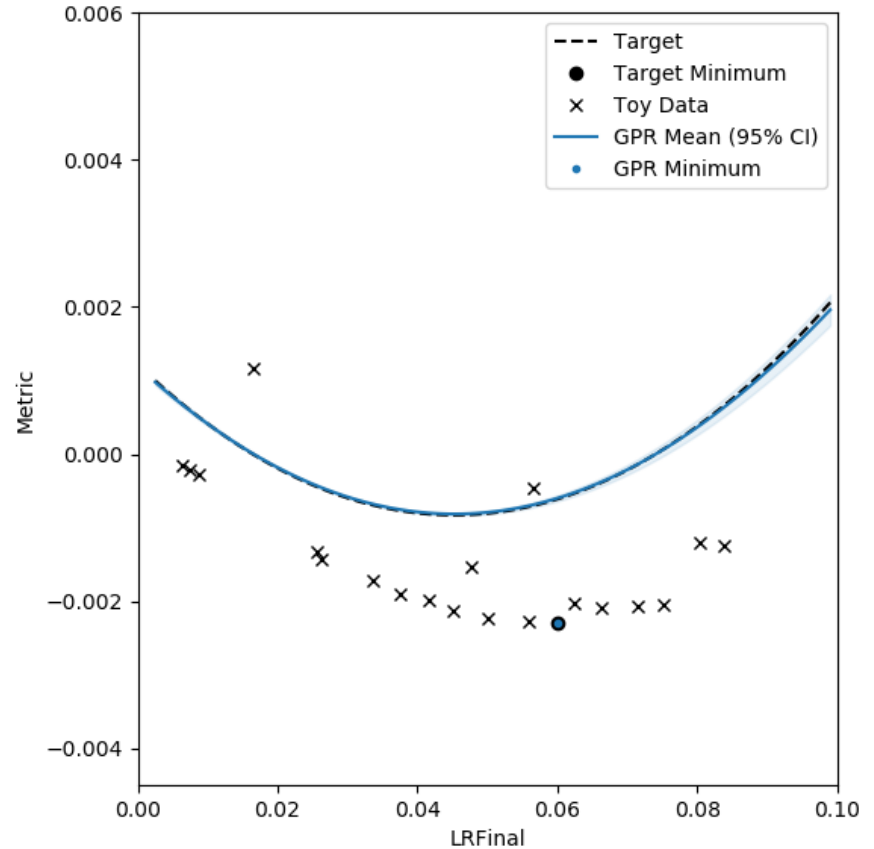
1.6% error

Toy GPR Demonstration

20 training events



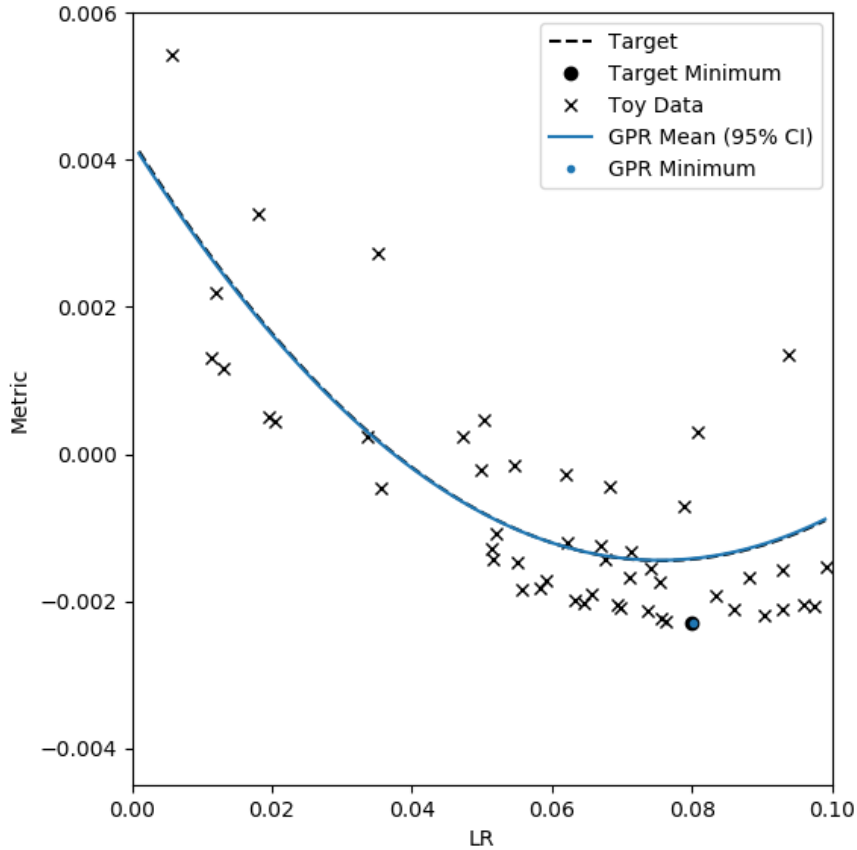
<0.25% error



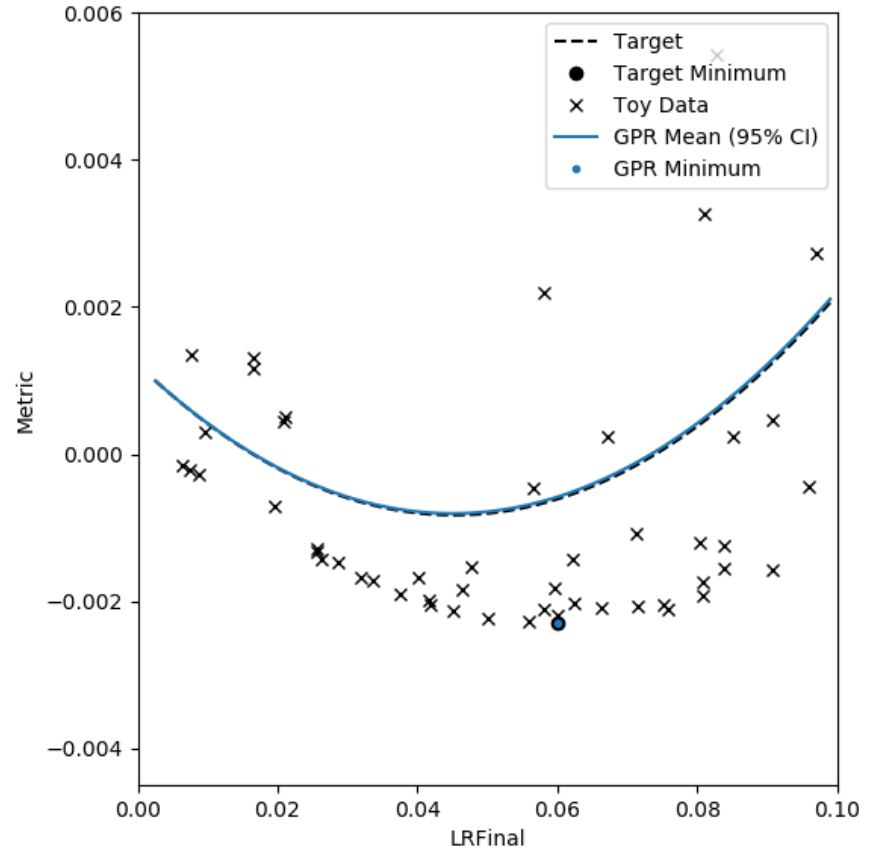
<0.042% error

Toy GPR Demonstration

50 training events



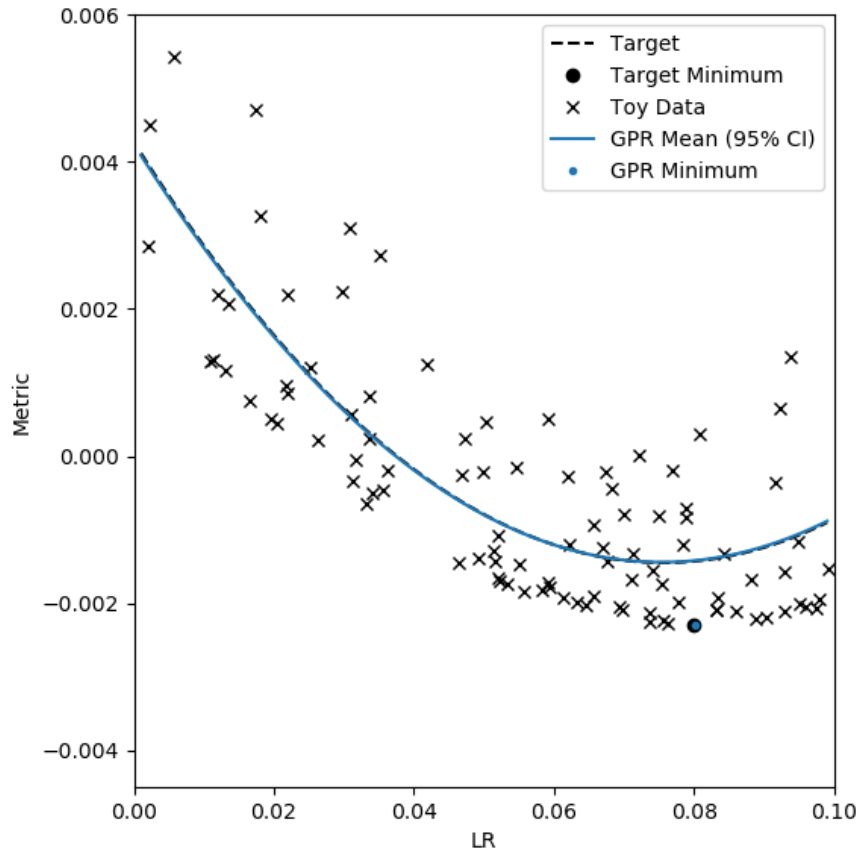
<0.25% error



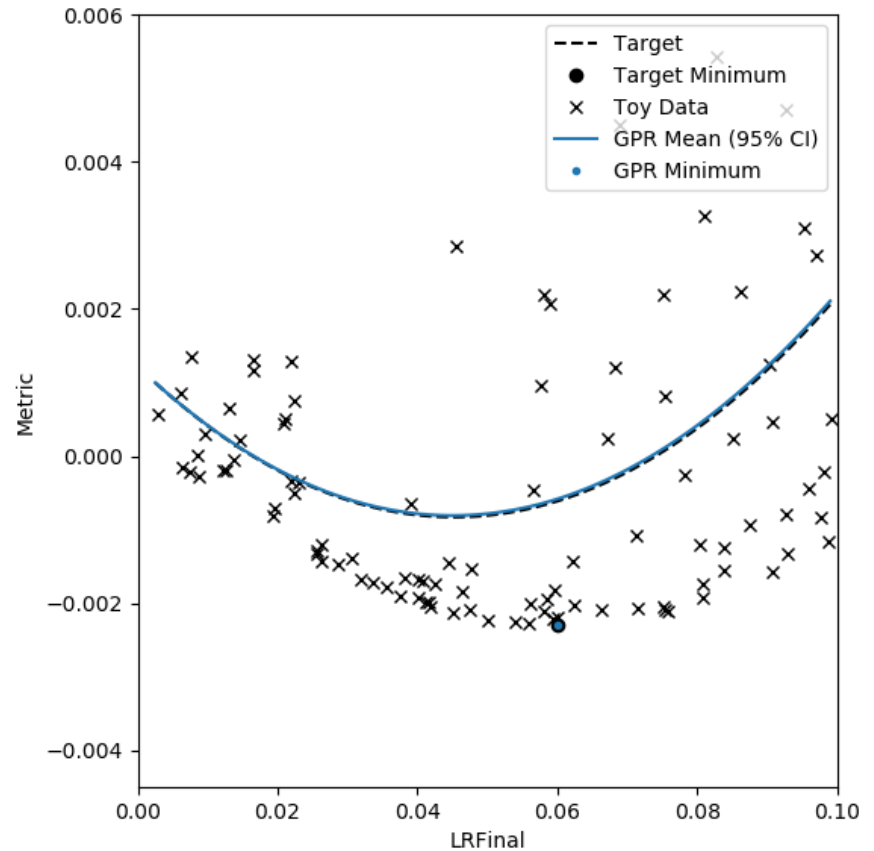
<0.042% error

Toy GPR Demonstration

100 training events



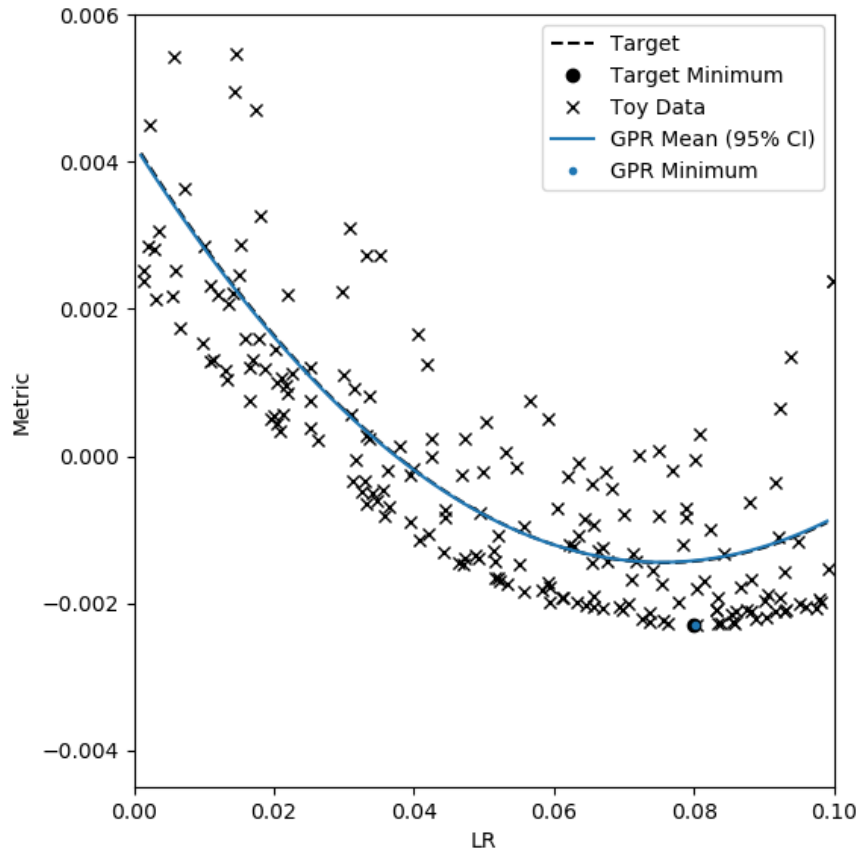
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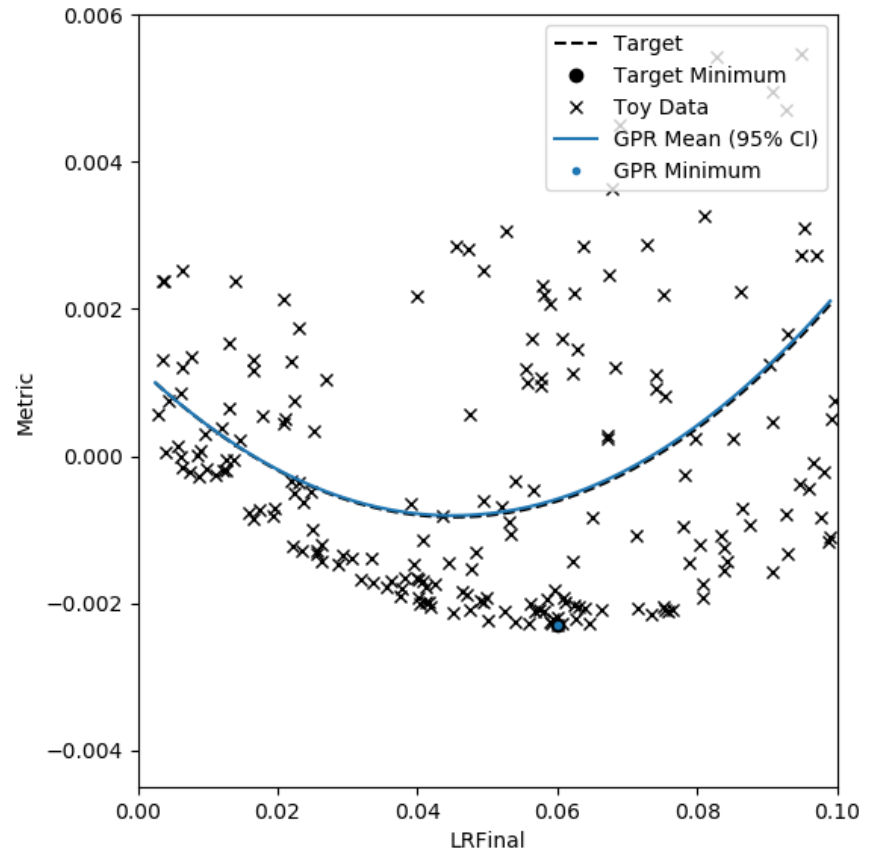
<0.042% error

Toy GPR Demonstration

200 training events

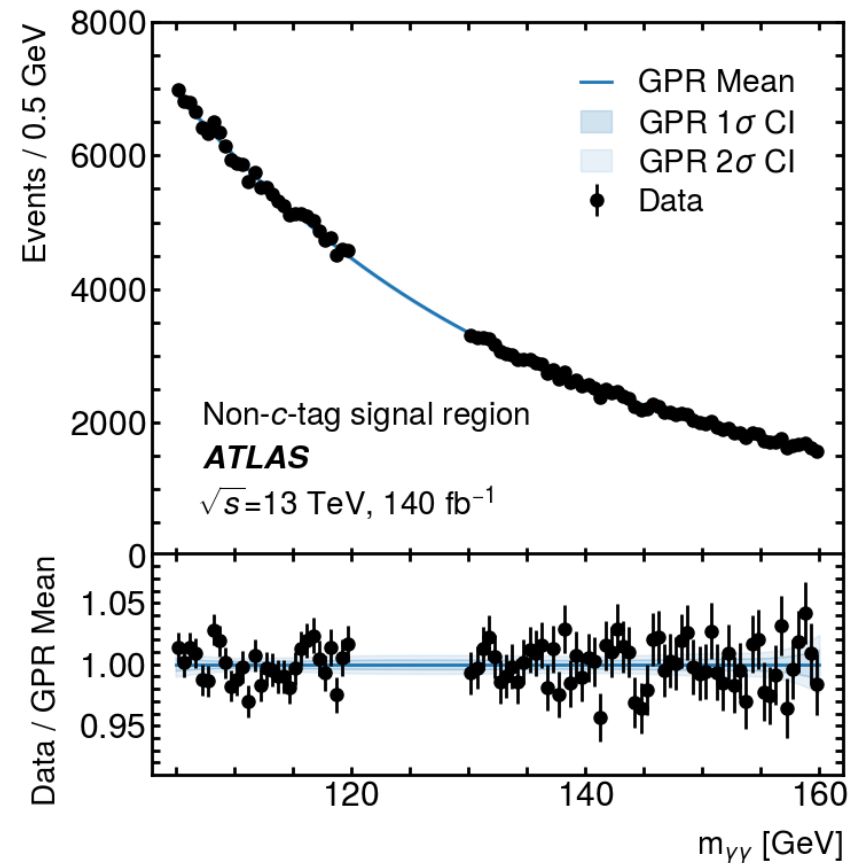
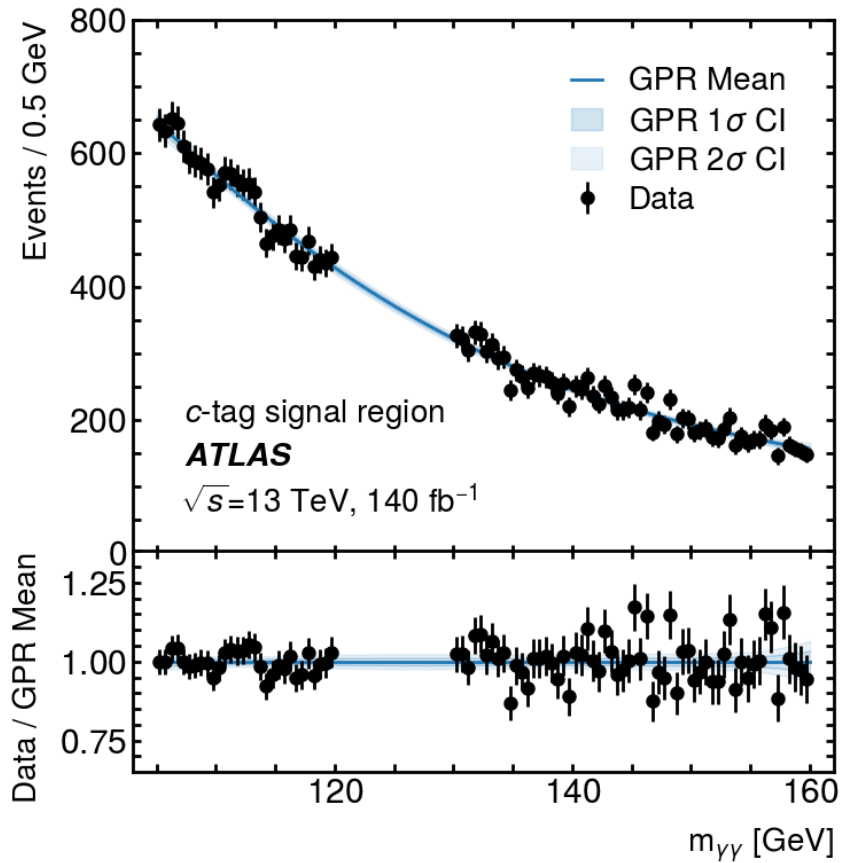


7.7×10^{-9} error



3.0×10^{-9} error

NR background GPR means

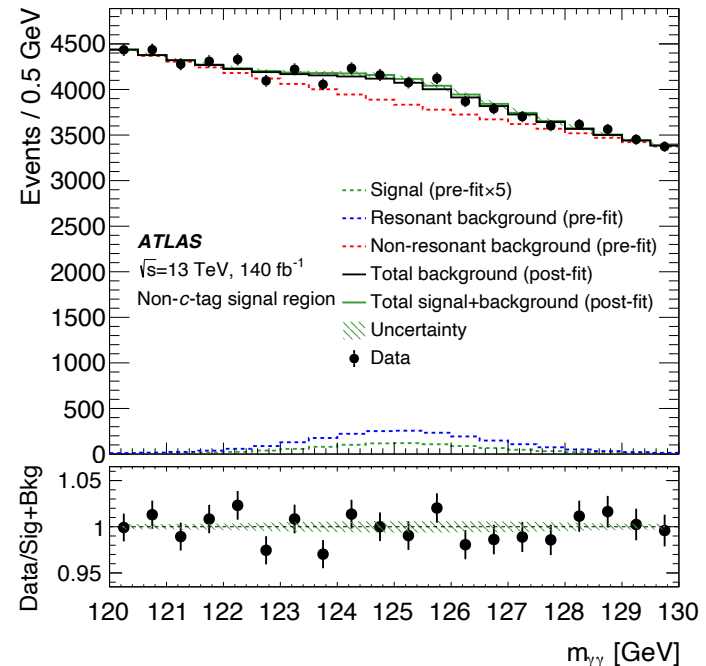
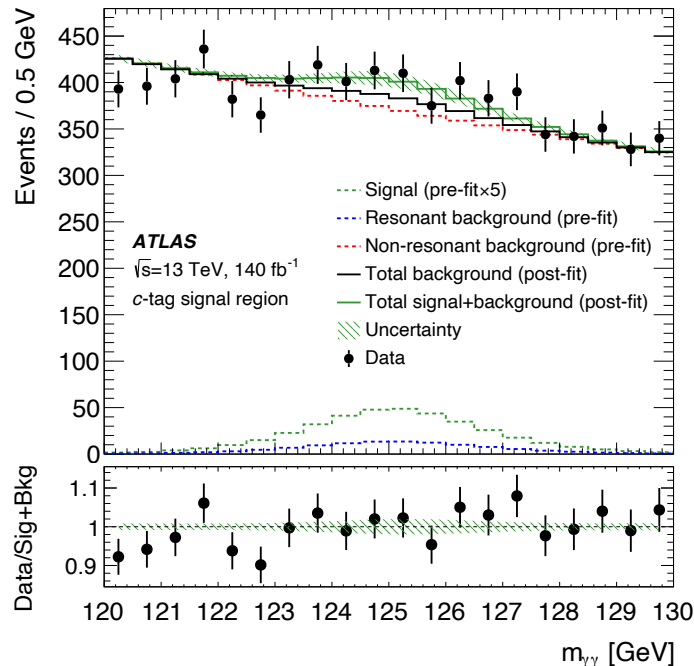


Analysis Uncertainties

Uncertainty	$H + c$ uncertainty impact
Statistical (incl. GPR)	78%
GPR posterior	46%
Systematic (excl. GPR)	63%
Theory	43%
c -tagging	29%
Photons	27%
Jets	20%
Spurious signal	11%
Pile-up	2%

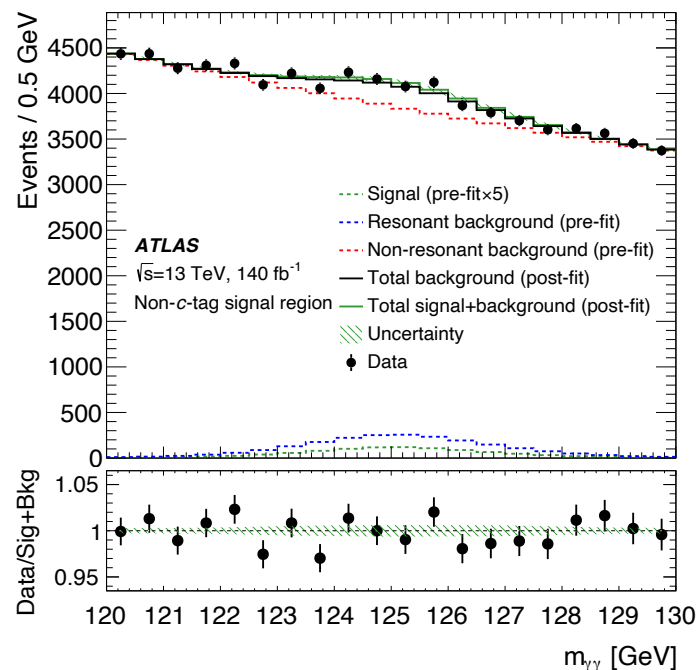
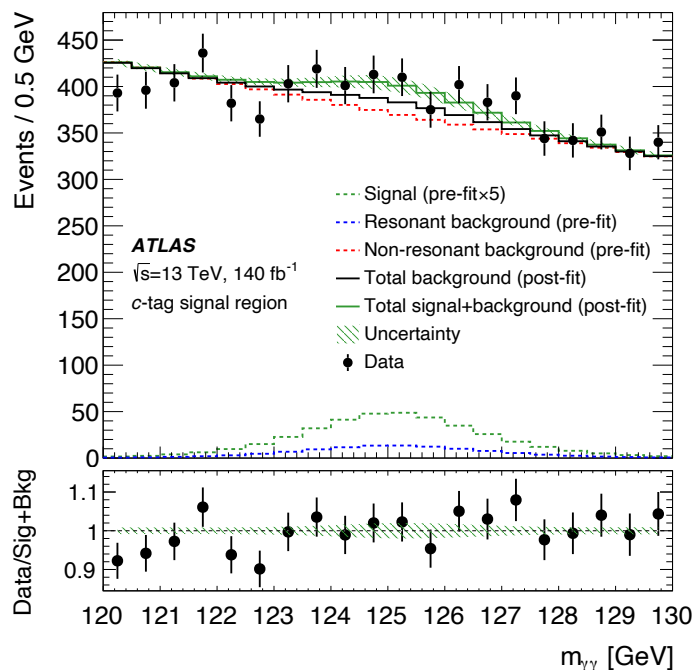
Putting everything together

- Binned likelihood fit to $m_{\gamma\gamma}$ distributions in both SRs
- $H + c$ signal shape, and resonant background shape and normalisation, from simulation
- NR background shape and normalisation from GPR



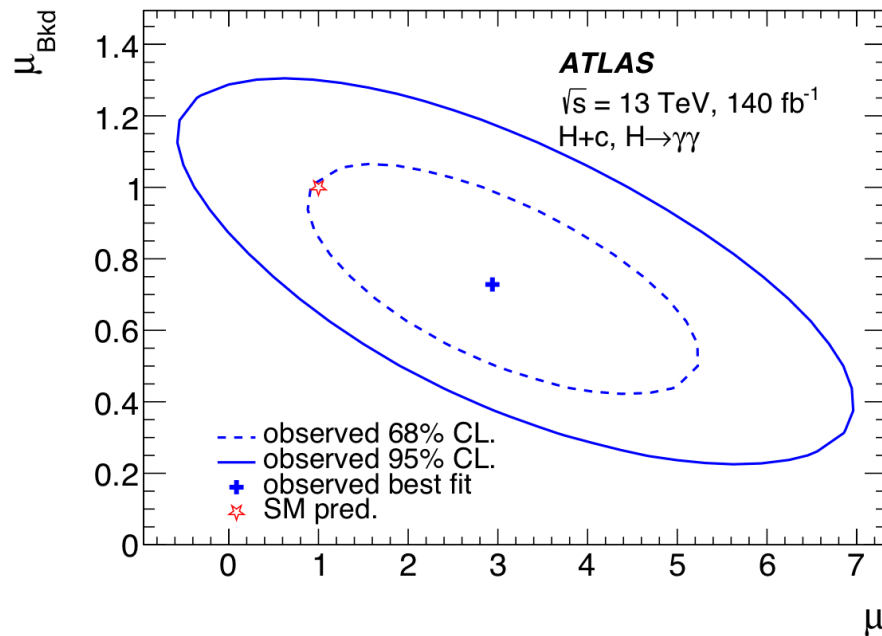
Results

- Obs (exp) $H + c$ cross-section: **5.3 ± 3.2 pb** (2.9 ± 3.1 pb)
- Obs significance: **1.7σ**
- Obs (exp) 95% CL_s upper limit: **10.6 pb** (8.8 pb)



2D results

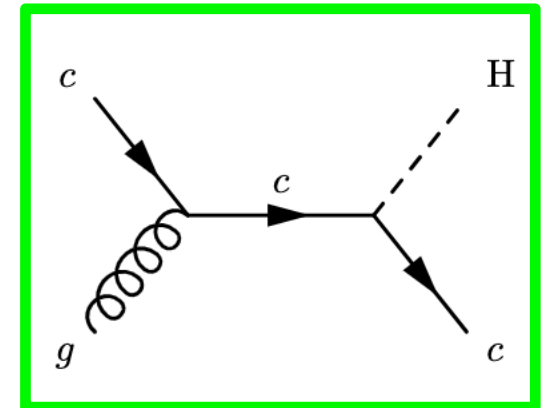
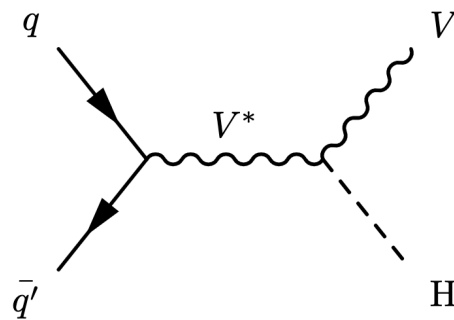
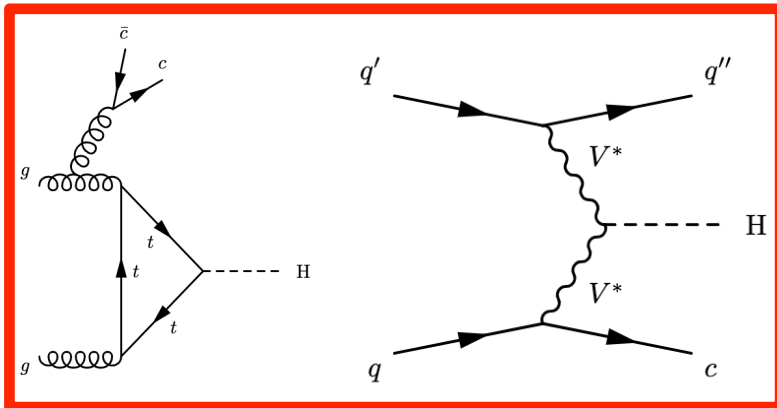
- 2D likelihood scan over μ and μ_{Bkd} also performed
 - μ_{Bkd} is a free resonant background normalisation
- Expected limit deteriorates by 18% with free μ_{Bkd}
- Correlation between μ and μ_{Bkd} in Asimov is -64%



Approximate y_c interpretation

“Back-of-the-envelope” non-ATLAS interpretation

- No y_c result from ATLAS for this analysis due to **lack of accepted modelling** of parts of inclusive $H + c$ signal



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 - Result derived largely from cross-section limit
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 - $m_{\gamma\gamma}$ distributions not adjusted
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- See backup for more details

H + c outlook

- Major progress has been made in probing y_c , but no plan in place for observation, [even for at the HL-LHC](#)

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H + c outlook

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- $H + c$ production might provide a useful input to constraining y_c
- **Significant gains possible** here:
 - Largest uncertainty is statistical, so larger/HL-LHC datasets significant
 - Introduction of additional decay modes (e.g. $H \rightarrow ZZ$)
 - Possible analysis improvements (e.g. from ML), beyond this first iteration

CMS $H + c$ Result

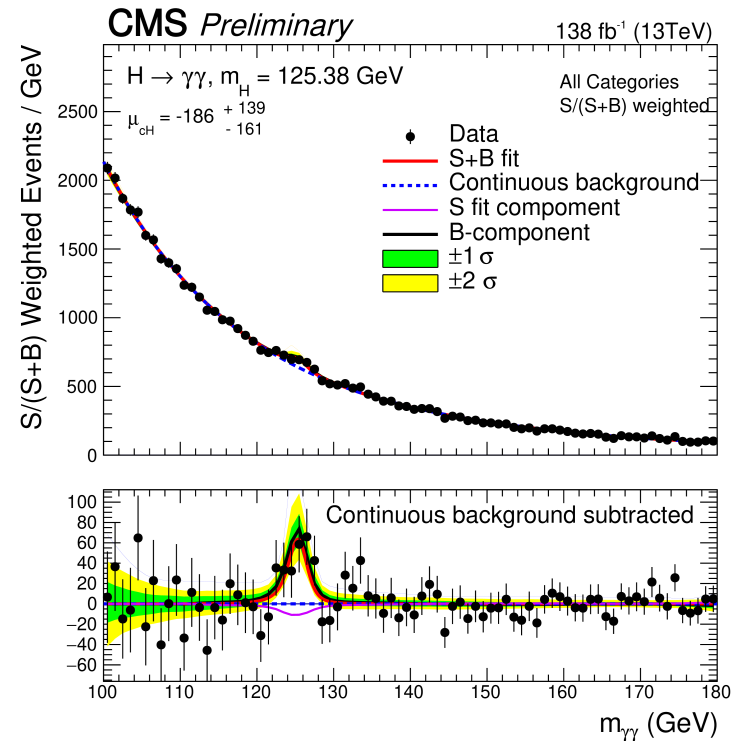
- CMS also interested in $H + c$, and have a [PAS](#)
- 138 fb⁻¹ of pp collision data
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- Only a subset of the inclusive $H + c$ signal was targeted
- Obs (exp) 95% CL upper limits on $|y_c/y_c^{\text{SM}}|$:
38.1 (72.5)



Conclusions

- Asking *why* the SM is as it is leads naturally to an inspection of the fermion masses
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Conclusions

- Asking *why* the SM is as it is leads naturally to an inspection of the fermion masses
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- **First inclusive $H + c$ measurement!**
- Measured $H + c$ cross-section: **5.3 ± 3.2 pb**
 - Compatible with SM expectation: **~ 2.9 pb**
- Substantial improvements possible in future analyses
- $H + c$ may play a key role in constraining y_c down the road, but theory inputs will be needed

Thanks for listening!

Any questions?

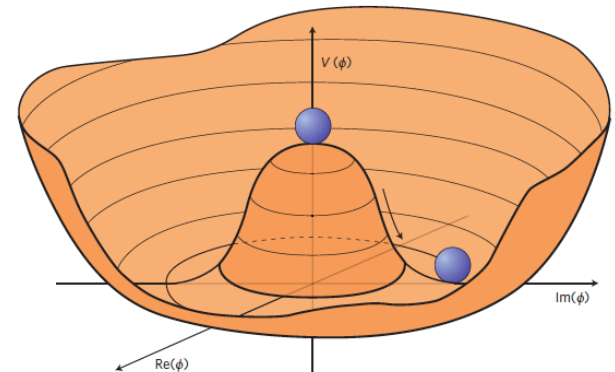
Backup slides

The Higgs boson

- A **newly discovered and unique** fundamental particle and interaction

The Higgs boson

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- Causes electroweak symmetry breaking
 - Fundamental to the electromagnetic and weak nuclear forces
- The source of mass of all fundamental particles



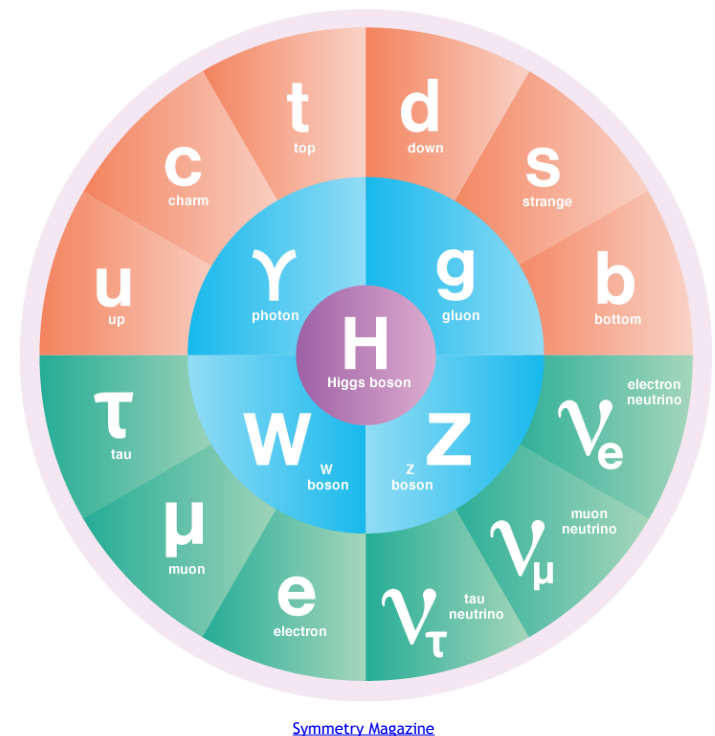
[Nat. Rev. Phys. 3 \(2021\) 608](#)

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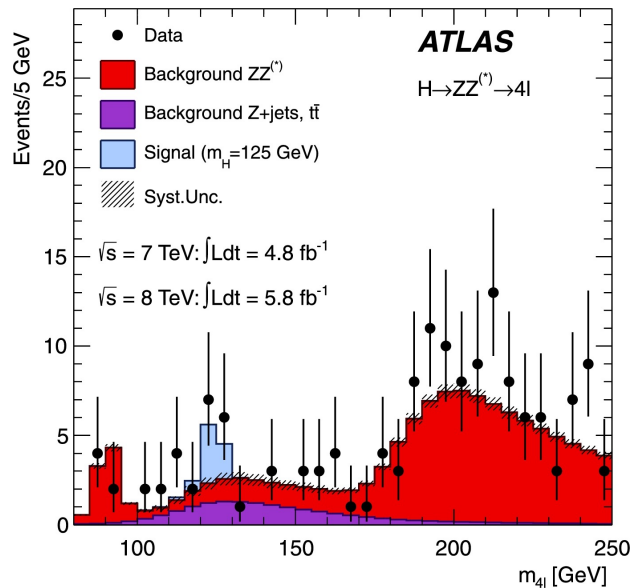
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- Completes the Standard Model



Higgs boson discovery

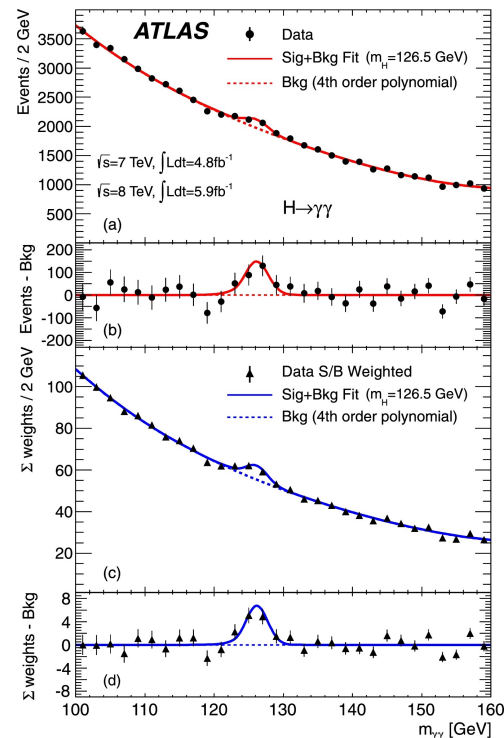
Single neutral Higgs boson (**H**) with a mass of 125 GeV discovered in 2012 by ATLAS and CMS

$$H \rightarrow ZZ^* \rightarrow 4\ell, \ell = e^\pm \text{ or } \mu^\pm$$



[PLB 716 \(2012\) 1](#)

$$H \rightarrow \gamma\gamma$$



[PLB 716 \(2012\) 1](#)

CMS $VH, H \rightarrow c\bar{c}$ Simulation

- Signal modelled at NLO in QCD using Powheg v2
 - Exception: gluon-induced ZH production is LO
- V + jets modelled at NLO using MG5
- $t\bar{t}$ and single top modelled at NLO using Powheg v2
 - NNLO+NNLL corrections applied to cross-section
- WW modelled at NLO with Powheg v2, and WZ and ZZ modelled at NLO with Powheg v2
- p_T -dependent NNLO QCD + NLO EW corrections applied to signal, $t\bar{t}$ and diboson simulation samples
- NNPDF3.0(3.1) PDF sets used for 2016 (2017 & 2018)
- Pythia 8 used for modelling $H \rightarrow c\bar{c}$ decays, parton showers, hadronisations and pileup
- Detector response modelled using Geant4

CMS VH, $H \rightarrow c\bar{c}$ Reconstruction

- Jets are formed from particle-flow candidates, and must be within tracker acceptance
 - Anti- k_T ($R=0.4$) jets are used to reconstruct individual c-jets, which must have $p_T > 25$ GeV
 - Anti- k_T ($R=1.5$) jets are used to reconstruct boosted $H \rightarrow c\bar{c}$ systems, which must have $p_T > 200$ GeV
- Small- R jets c-tagged using *DeepJet*, and have neutrino-based p_T corrections
- Data corrections applied for tagging in both categories

CMS VH, H $\rightarrow$ c $\bar{c}$ Resolved Selection

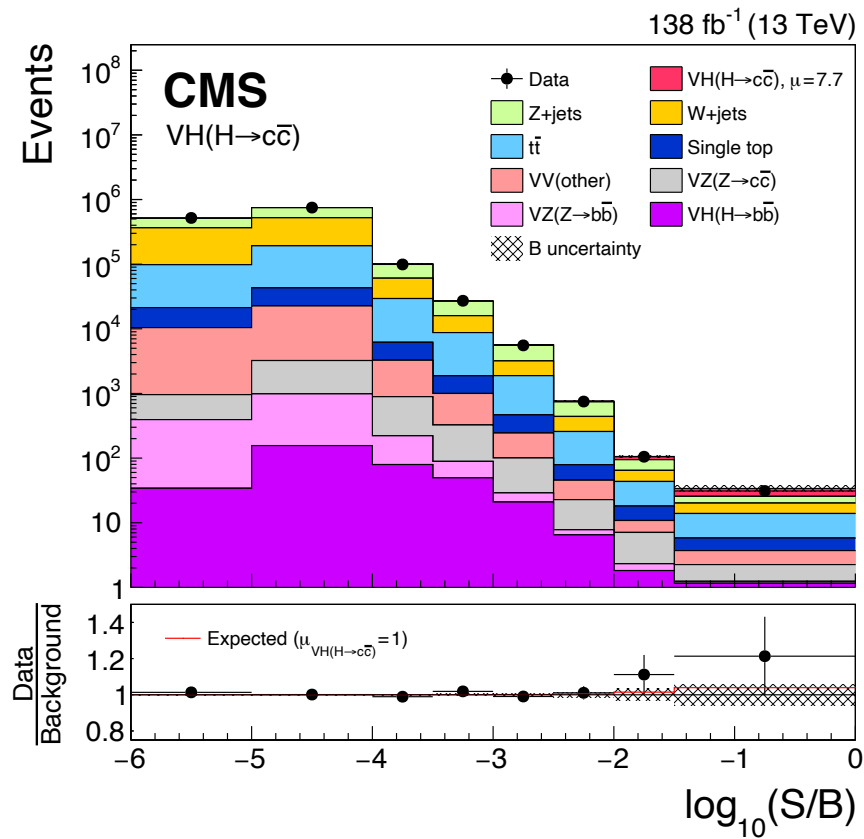
- Merged/resolved events defined as events with $p_T(H)$ above/below 300 GeV
 - Resolved channel contains about 95% of events, but merged channel drives analysis sensitivity
- FSR jets included in Higgs boson reconstruction
- Kinematic fit improves Higgs boson mass resolution
- BDTs used for selection in resolved category

CMS $VH, H \rightarrow c\bar{c}$ Systematics

TABLE I. The relative contributions to the total uncertainty in the signal strength modifier μ for the $VH(H \rightarrow c\bar{c})$ process, where the best fit is $\mu_{VH(H \rightarrow c\bar{c})} = 7.7^{+3.8}_{-3.5}$.

Uncertainty source	$\Delta\mu/(\Delta\mu)_{\text{tot}}$ (%)
Statistical	85
Background normalizations	37
Experimental	48
Sizes of the simulated samples	37
c jet identification efficiencies	23
Jet energy scale and resolution	15
Simulation modeling	11
Integrated luminosity	6
Lepton identification efficiencies	4
Theory	22
Backgrounds	17
Signal	15

CMS VH, $H \rightarrow c\bar{c}$ S/B



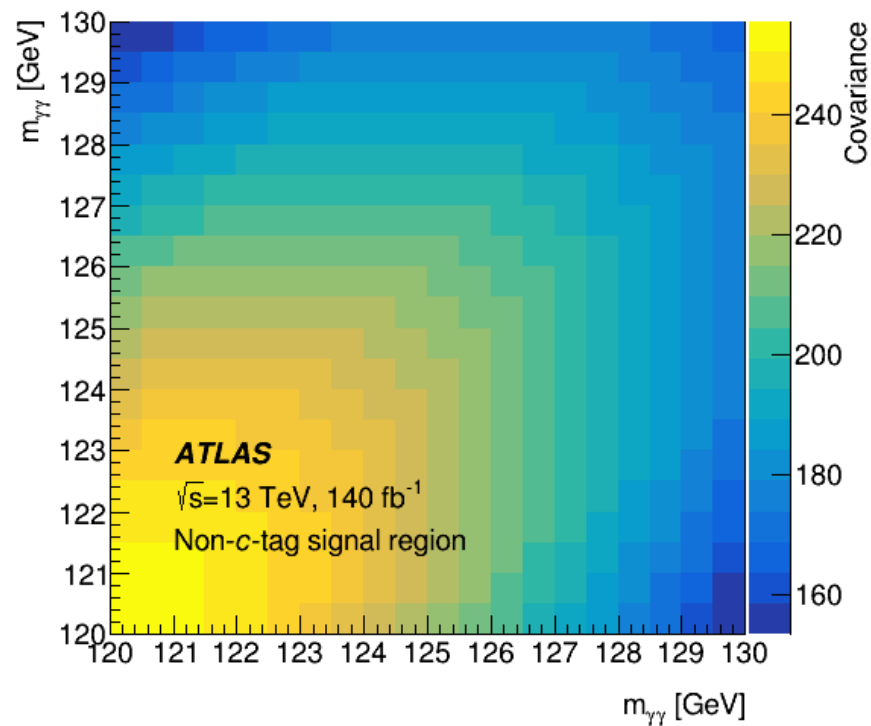
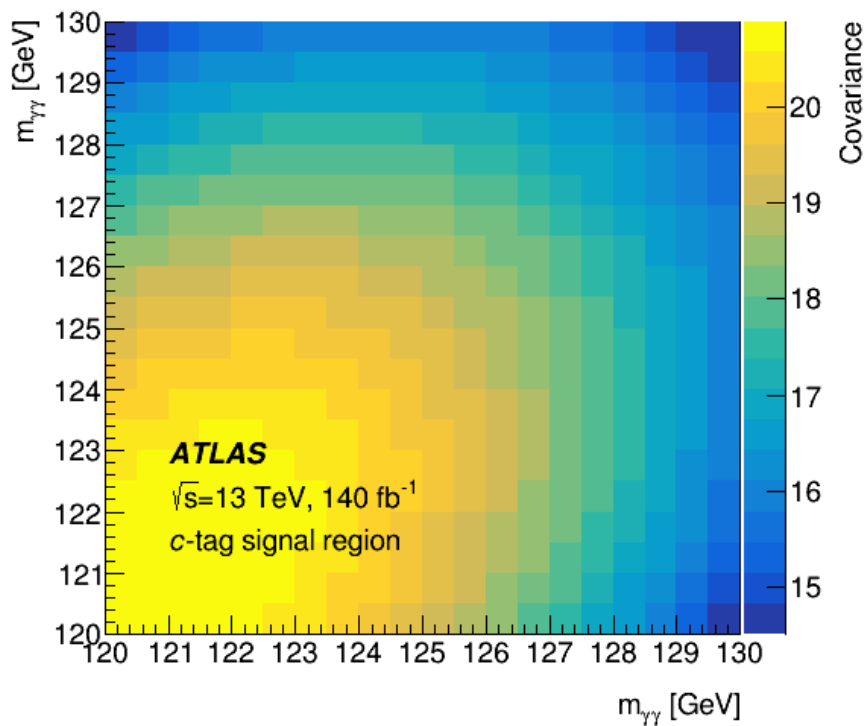
ATLAS H+c signal definition

- An inclusive H+c signal definition was used, where truth-level events must contain:
 - A Higgs boson
 - At least one anti- k_t ($R=0.4$) c-jet with $p_T > 25$ GeV and $|\eta| < 2.5$
 - Must be within $\Delta R < 0.3$ of a charm hadron with $p_T > 5$ GeV
 - The charm hadron must not originate from the cascade decay of a b-hadron

Signal and resonant background compositions

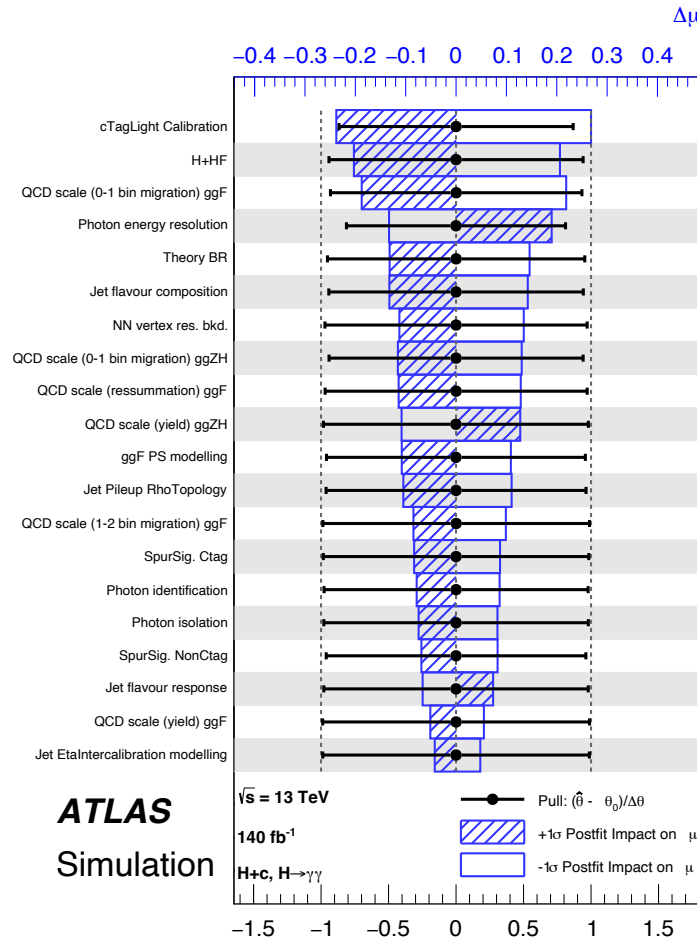
Process	<i>c</i> -tag signal region		Non- <i>c</i> -tag signal region	
	Signal	Resonant background	Signal	Resonant background
ggF H	39	82	110	1800
VBF H	17	13	34	220
WH	9.5	4.7	23	59
ZH	4.5	5.1	7.8	50
$t\bar{t}H$	7.0	4.6	20	24
$b\bar{b}H$	0.11	1.9	0.35	16
y_c -sensitive $H + c$	0.37	0.046	0.78	0.48
Total	77	110	190	2100

GPR covariances

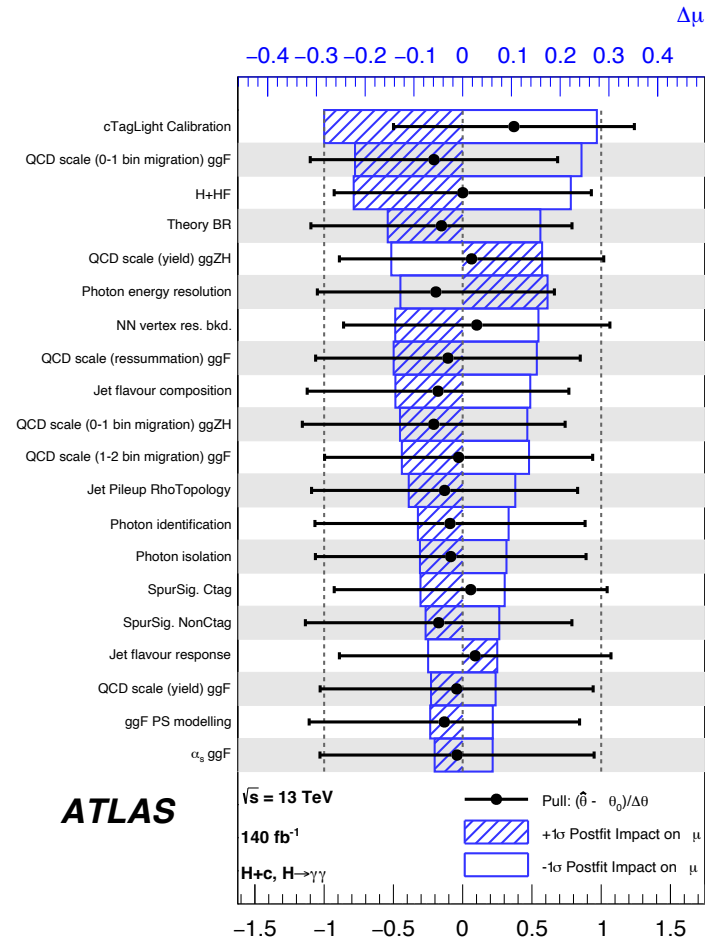


Main Nuisance Parameters

Expected/Asimov



Observed/Data



Approximate κ_c interpretation

“Back-of-the-envelope” non-ATLAS interpretation

- A. Our obs (exp) limit is ~ 3.7 (~ 3.0) times the SM expected cross-section (ignoring cross-section uncertainties)
- B. In the (dominant) c-tag category, the κ_c -sensitive events are $\sim 0.5\%$ the size of the signal
- C. From A & B: the obs (exp) upper limit is ~ 770 (~ 640) times the number of κ_c -sensitive events (assuming current $m_{\gamma\gamma}$ shapes and modelling uncertainties)
- D. Assuming $\mathcal{B}(H \rightarrow \gamma\gamma) = \mathcal{B}_{\text{SM}}(H \rightarrow \gamma\gamma)$
 - Could approximately result from simultaneous fit
- E. From C & D: the obs (exp) upper limit on κ_c is **~ 28 (~ 25)**