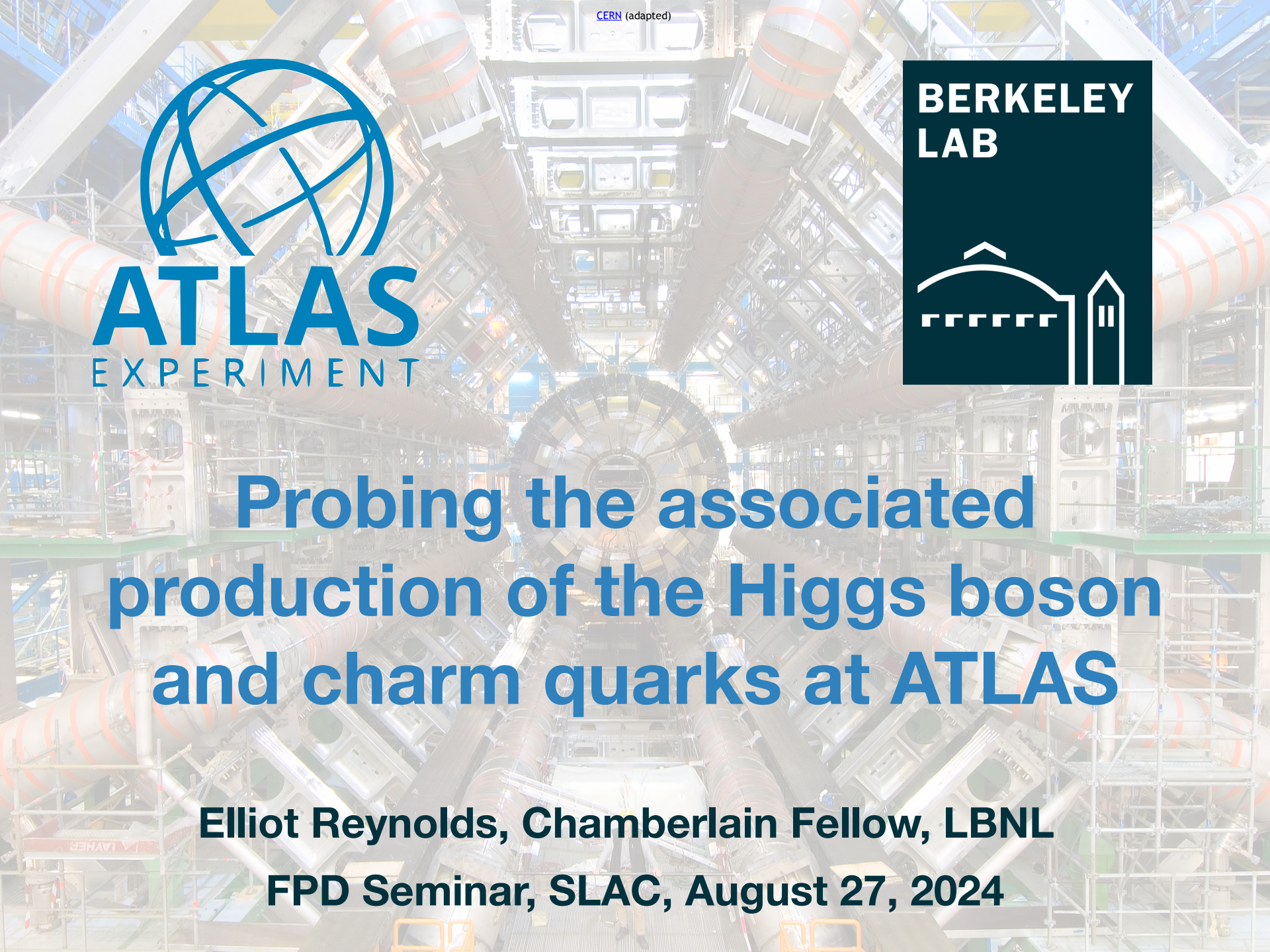


Probing the associated production of the Higgs boson and charm quarks at ATLAS

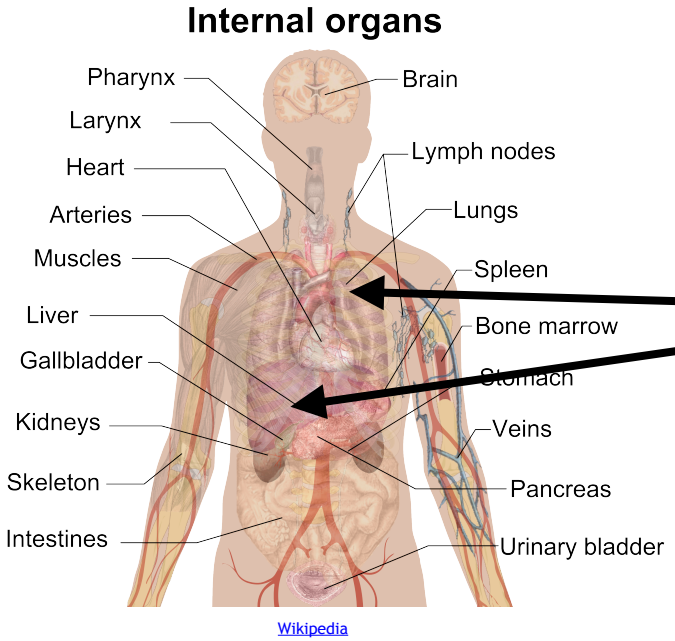
Elliot Reynolds, Chamberlain Fellow, LBNL

FPD Seminar, SLAC, August 27, 2024

Building Blocks of Reality

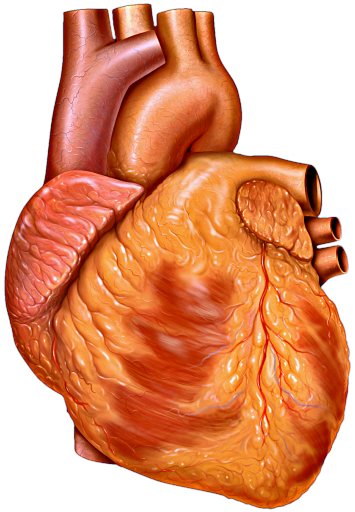
- Take this (simplified) description of human beings:

Humans



Wikipedia

Organs (+ blood, bones etc.)



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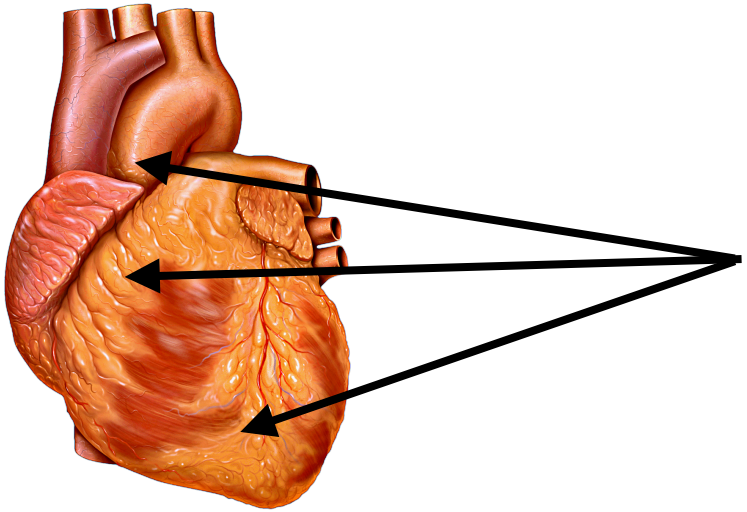
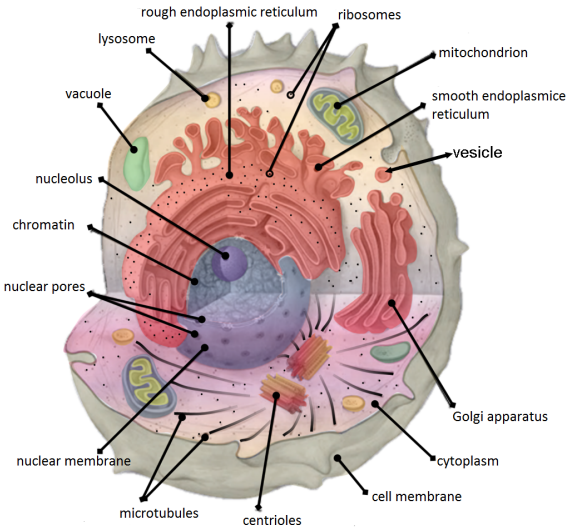


Wikipedia

Cells



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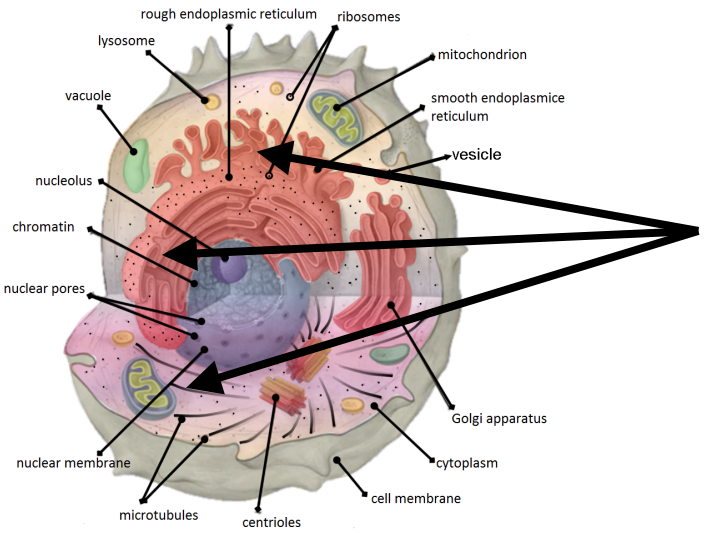

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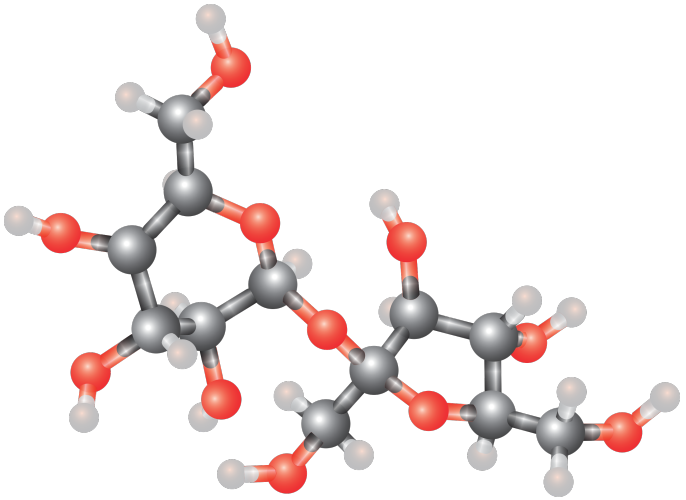

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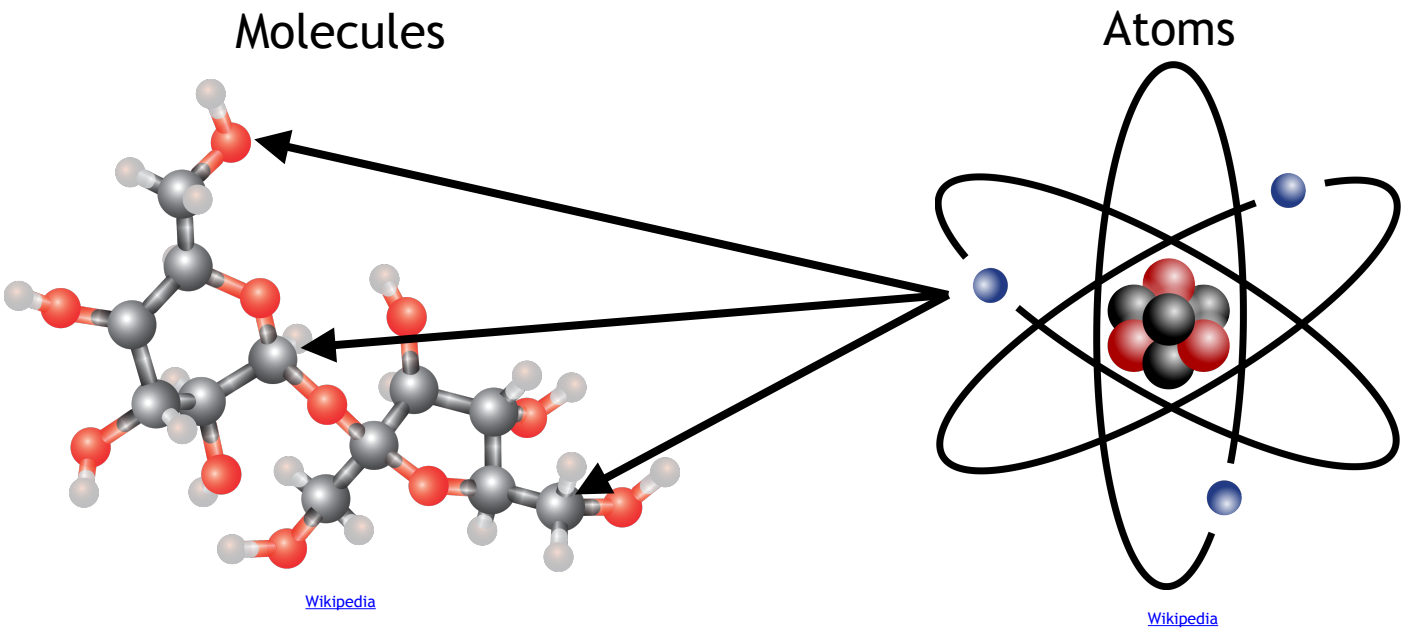

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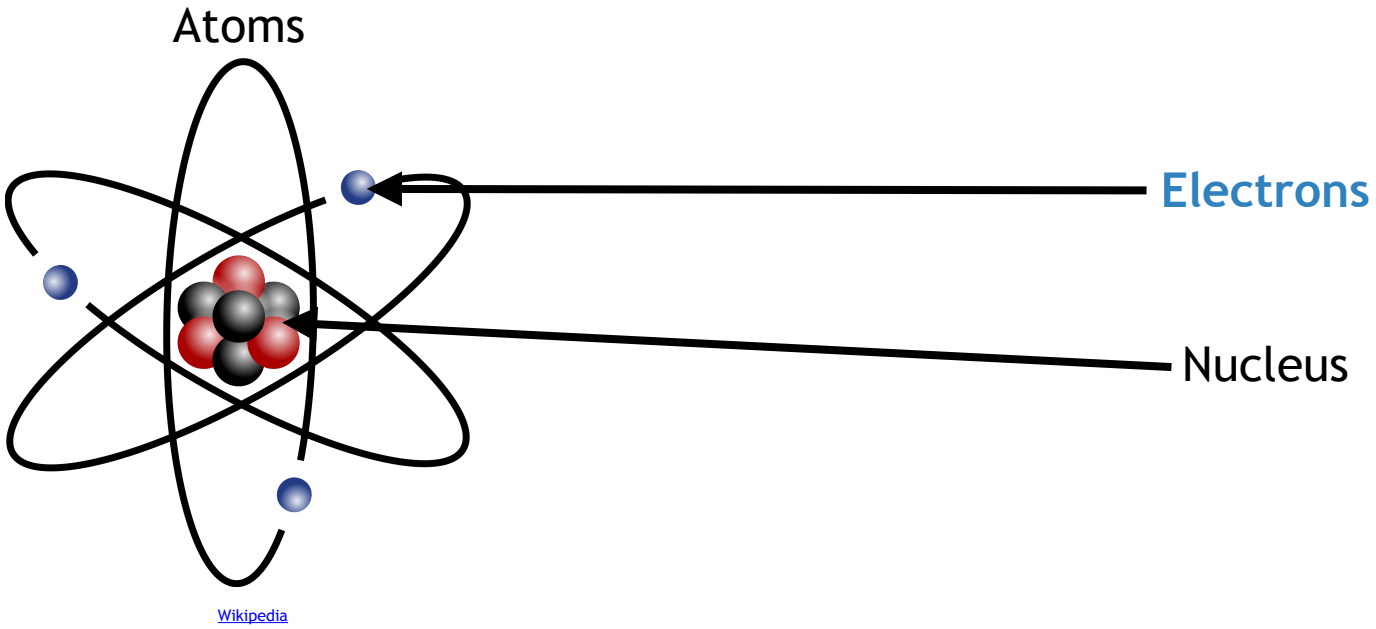

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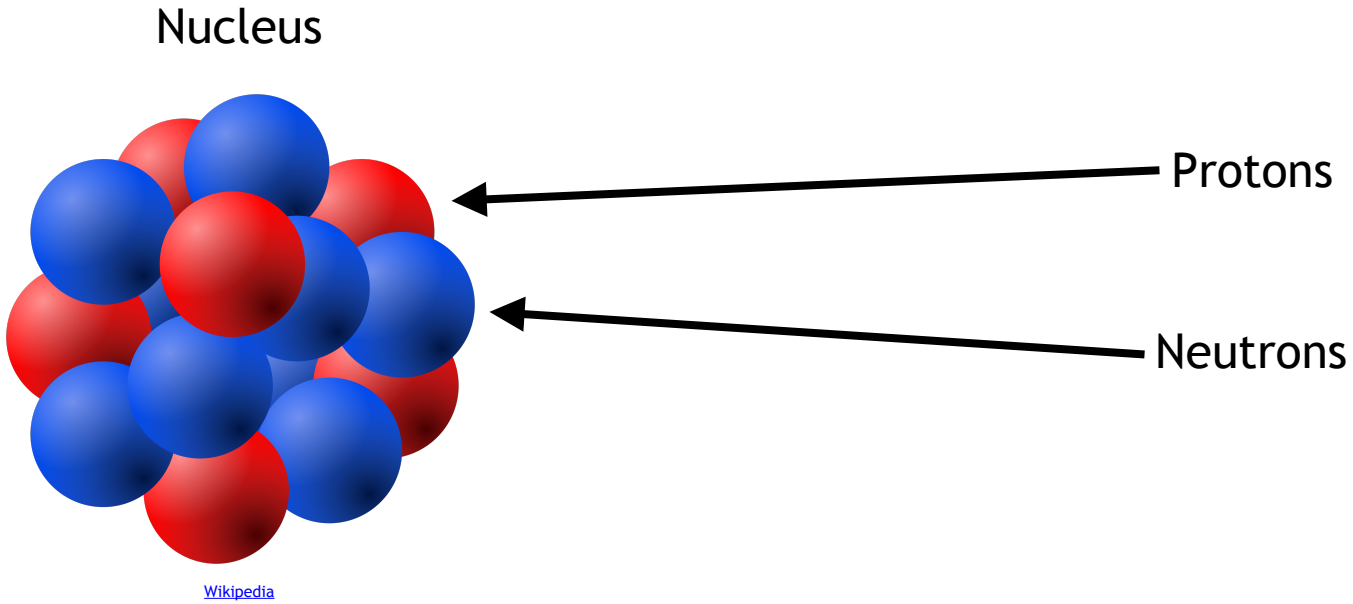

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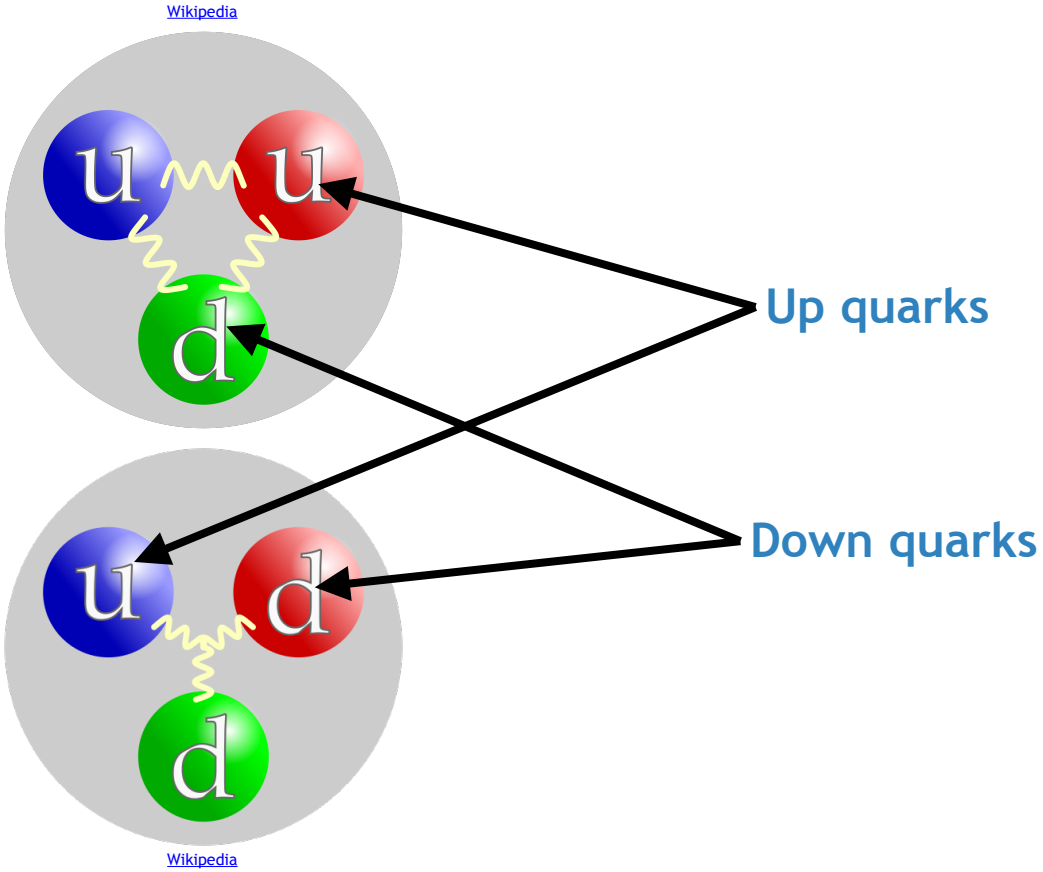
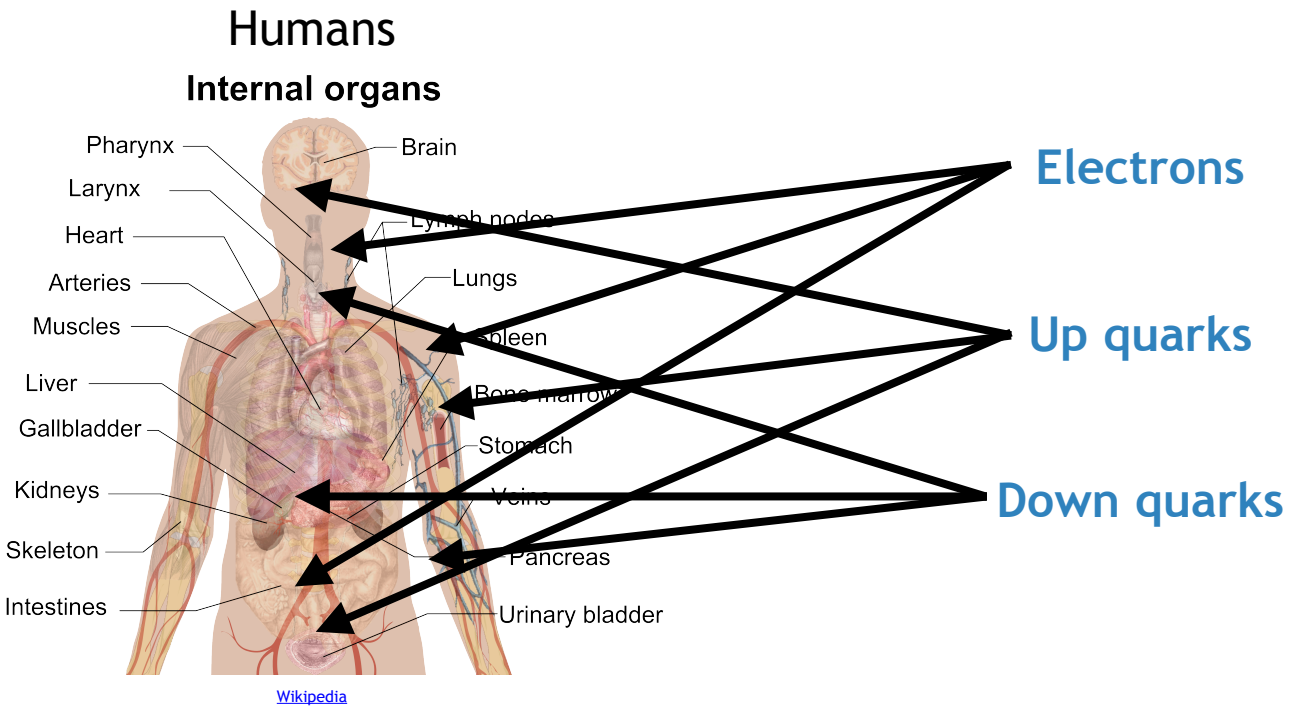


Reductionism

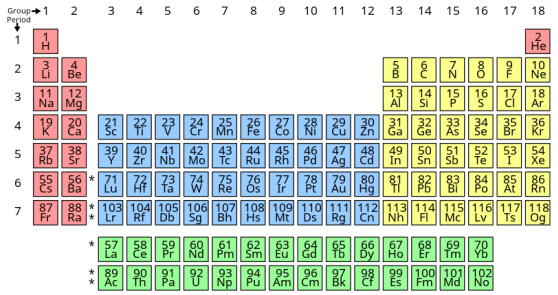
- Thus, humans are ~entirely made up of electrons, up quarks, and down quarks



Reductionism

- But so is almost everything else:

ACS



Wikipedia

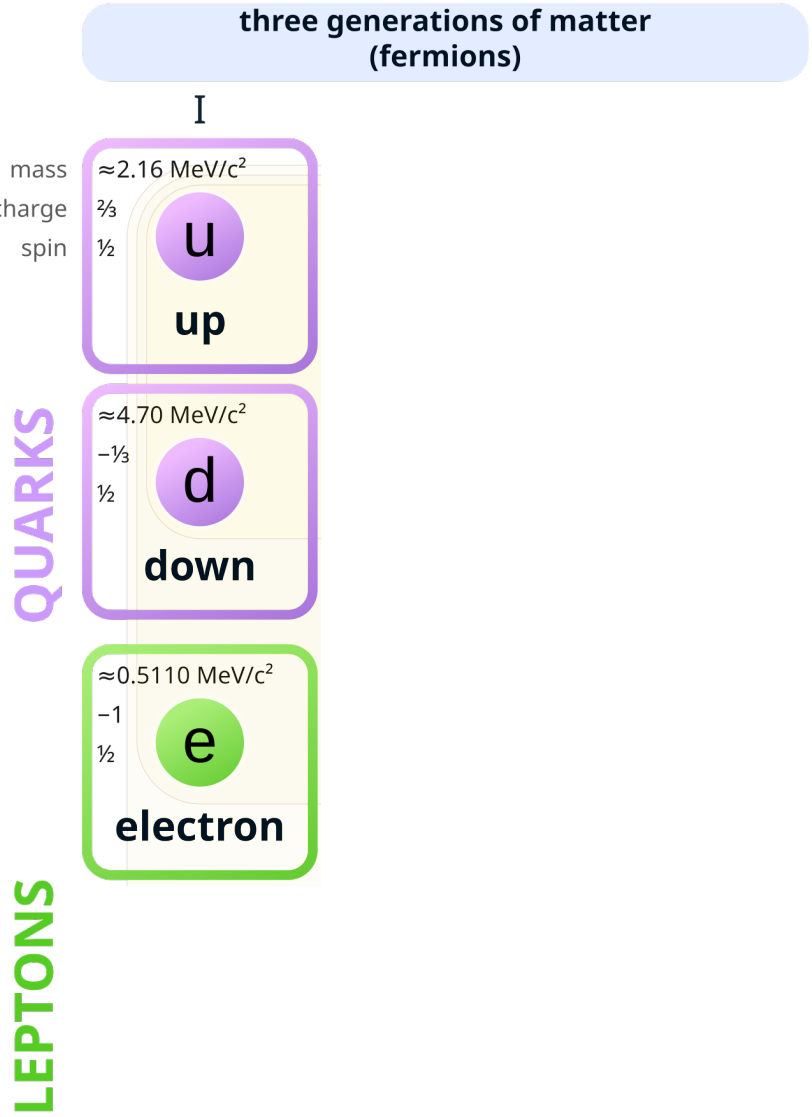
Historical Emporium

Electrons

Up quarks

Down quarks

The fermions



Wikipedia (adapted)

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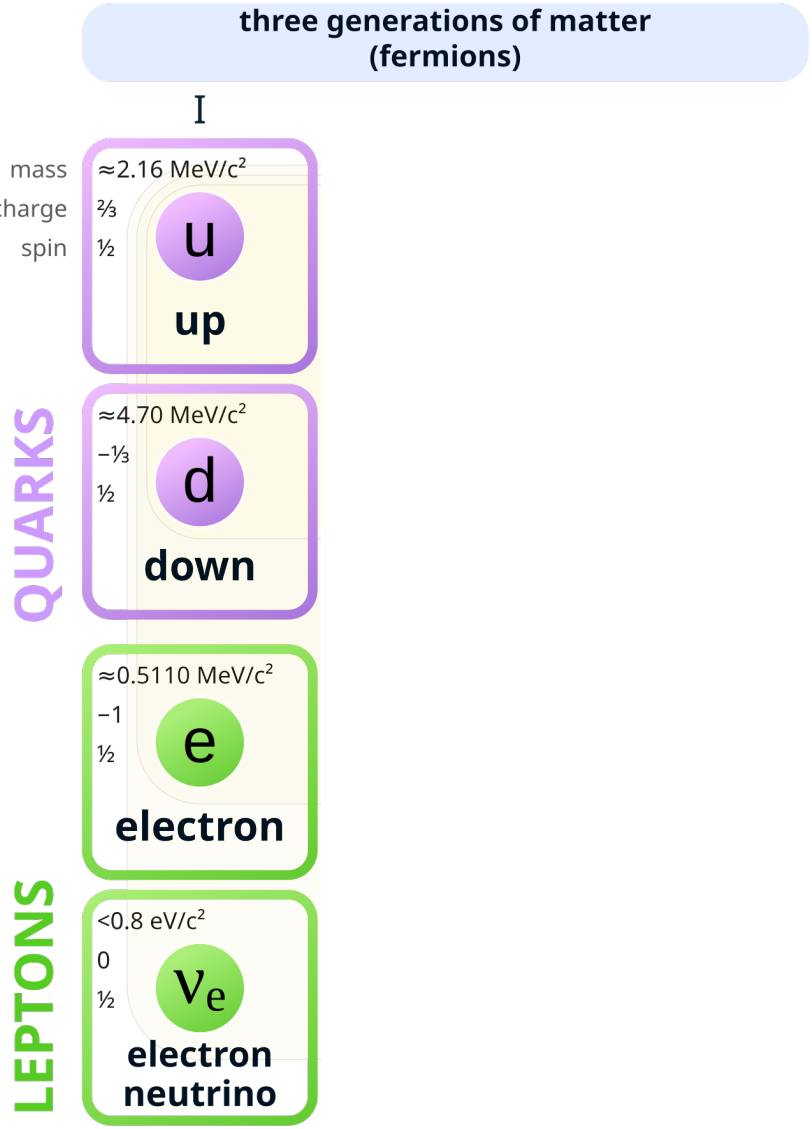

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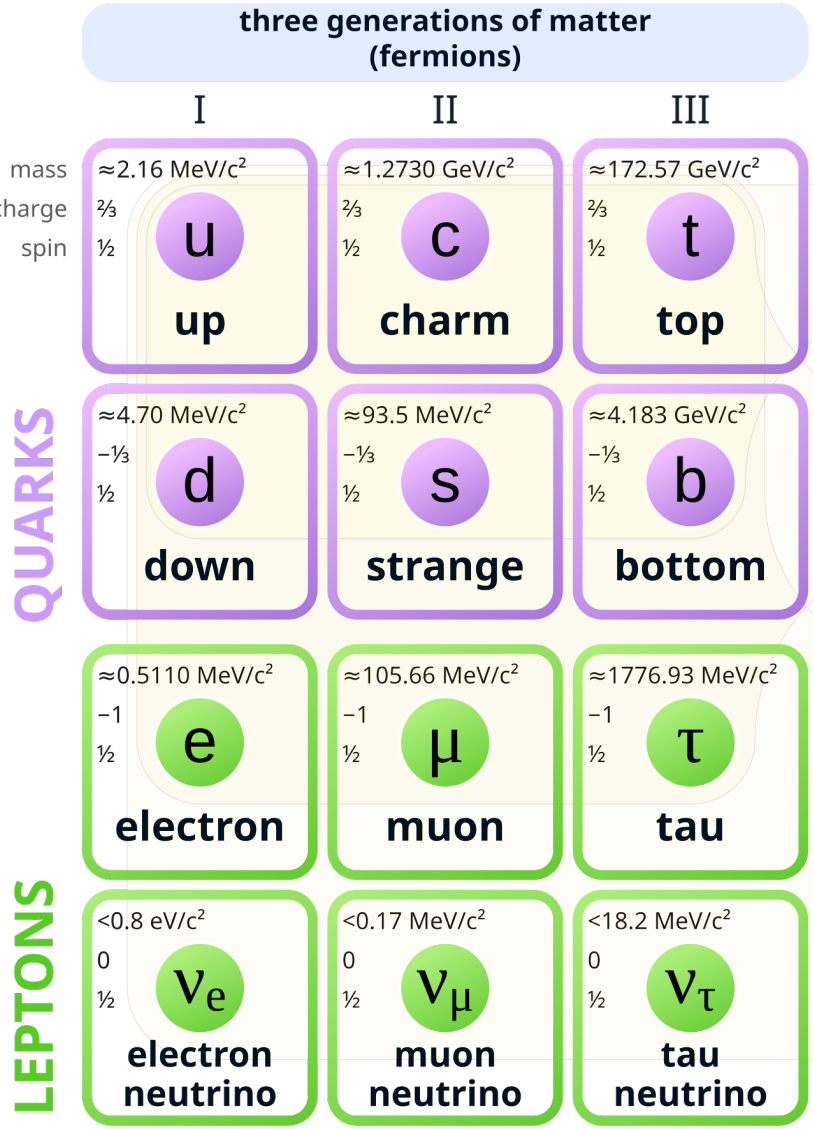

Wikipedia (adapted)

Why?

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- Particle physics seeks to explain what *all* things are made of…
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Independent

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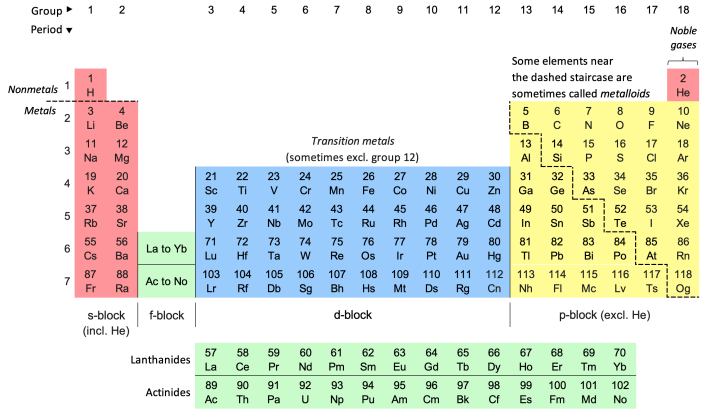

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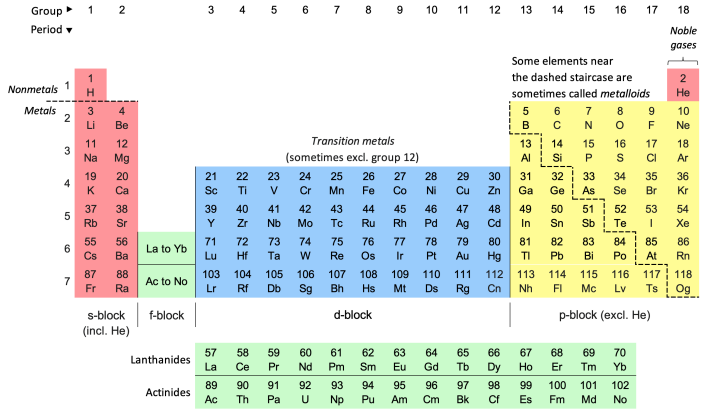

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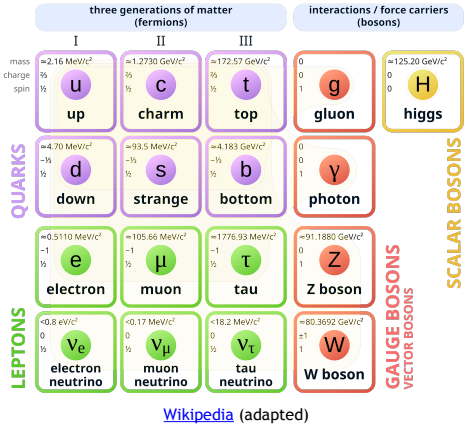

Wikipedia (adapted)

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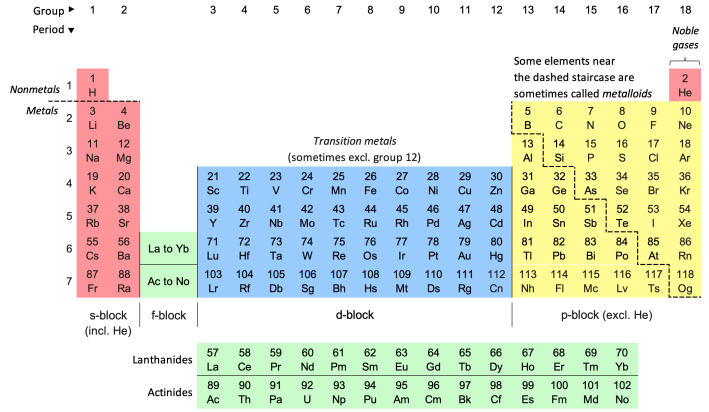
- Particle physics seeks to explain what *all* things are made of…
- It also seeks to explain ***why*** *all* things happen
- **Theory of Everything**!



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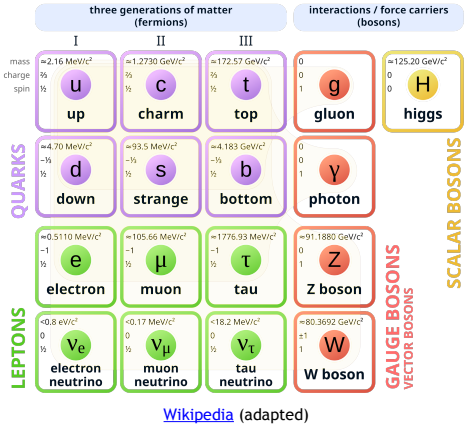
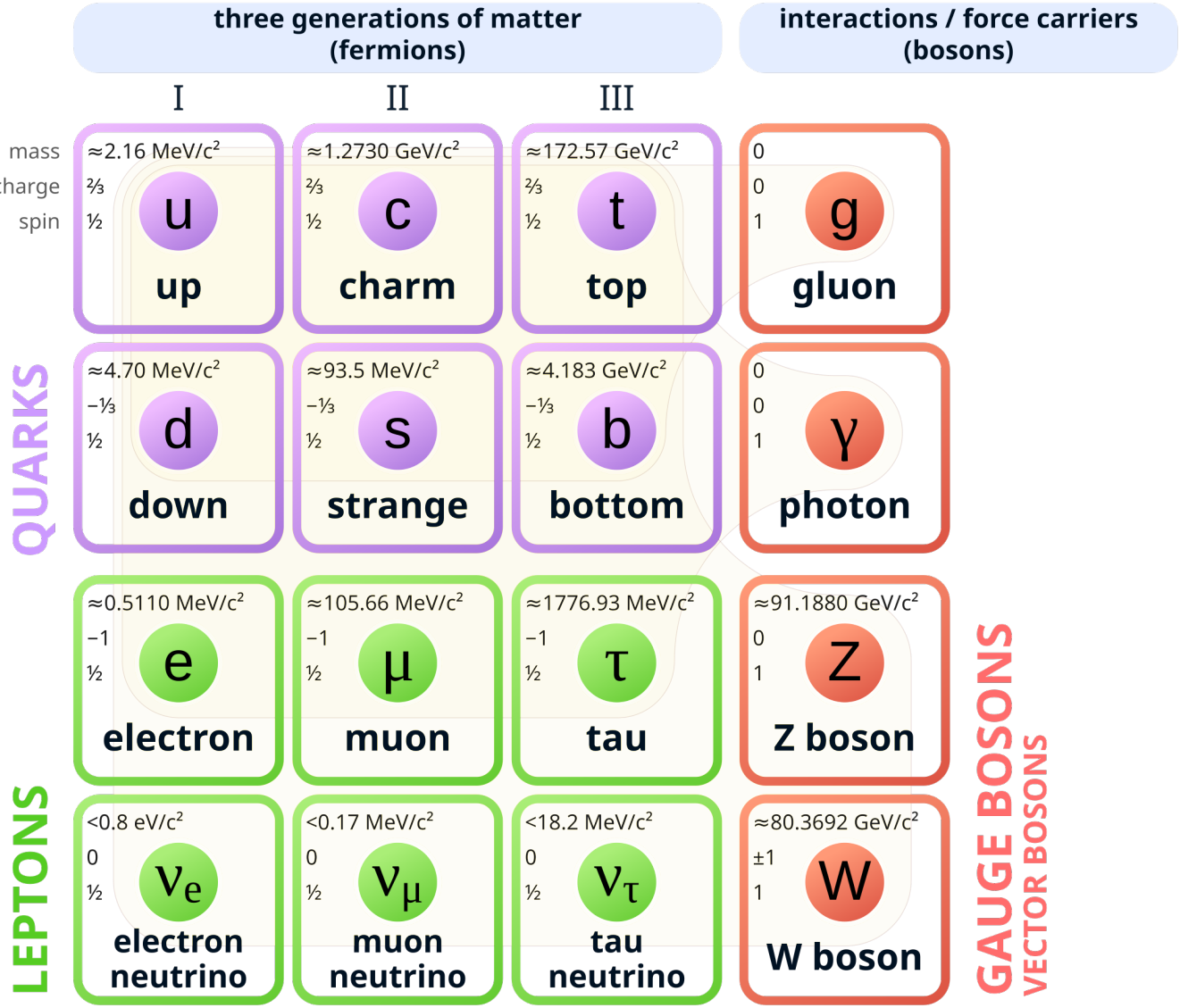


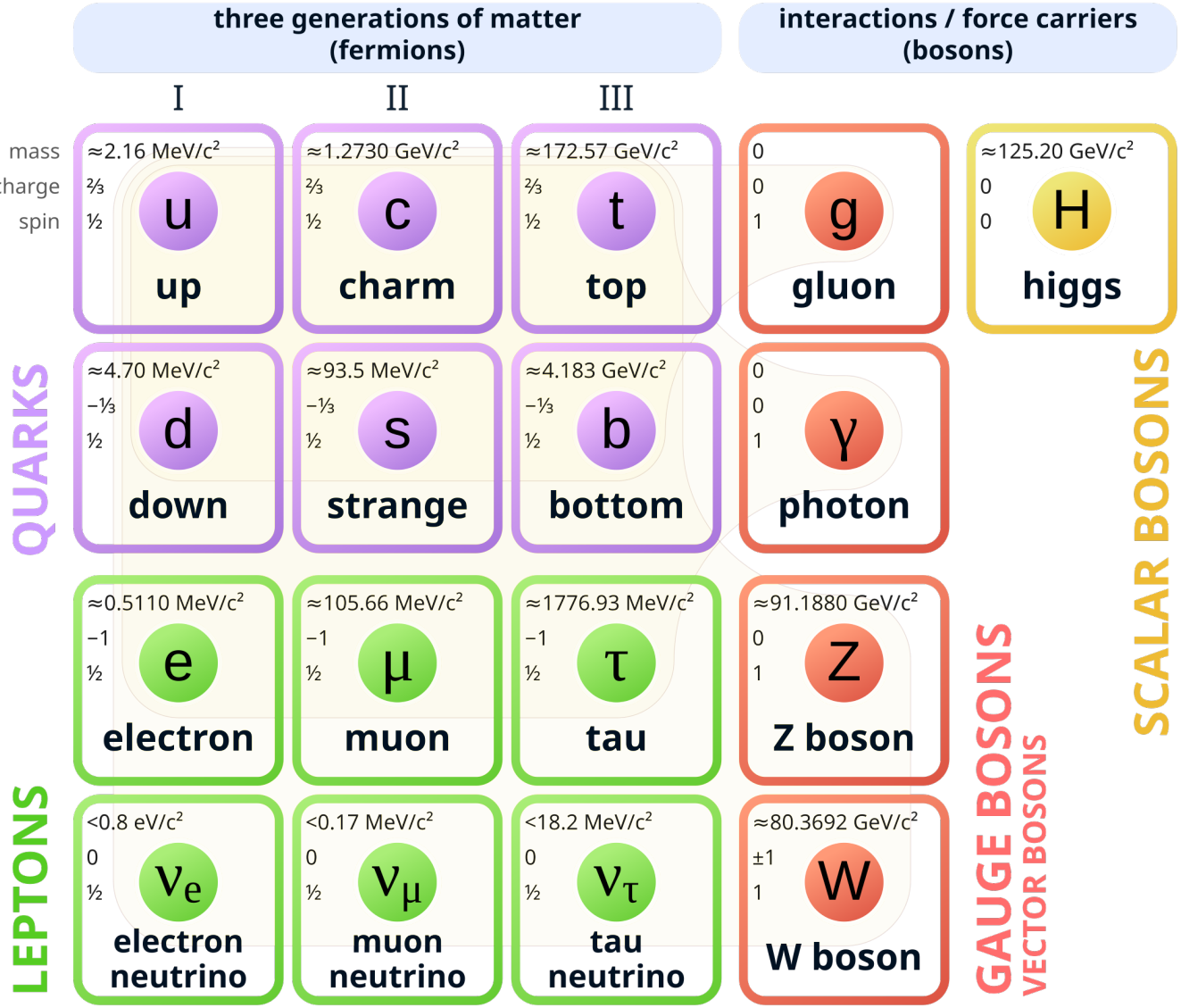
Wikipedia (adapted)

The gauge bosons



Wikipedia (adapted)

The Standard Model (SM)



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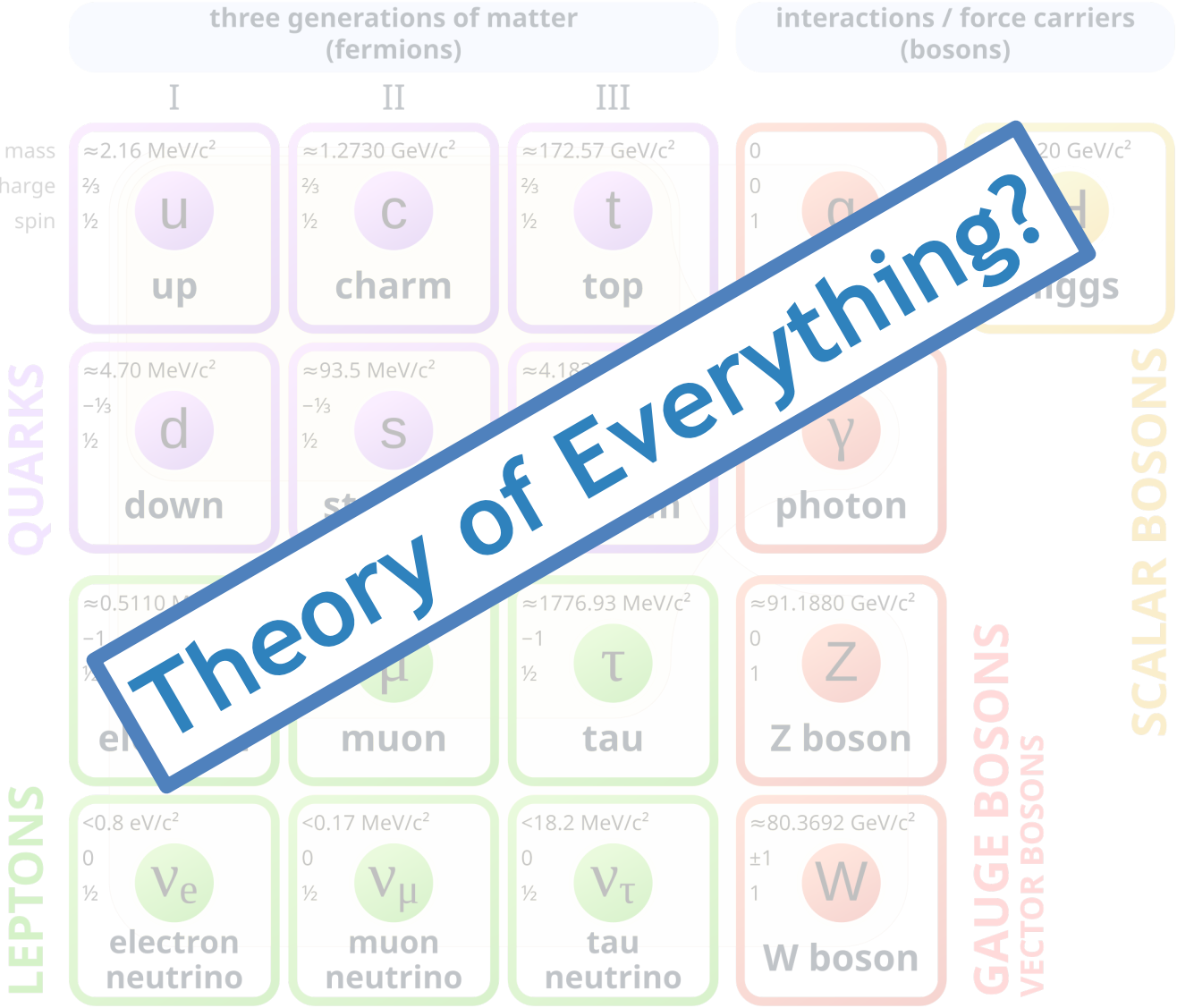

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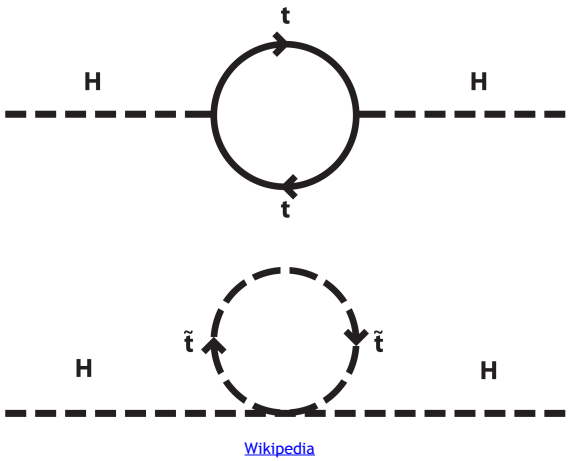
1.1. Fine tuning and naturalness

- Why is the Higgs boson so light?



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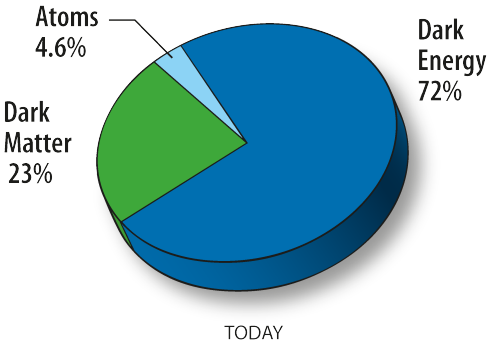
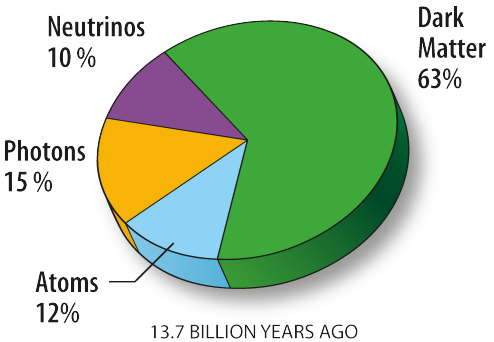


TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

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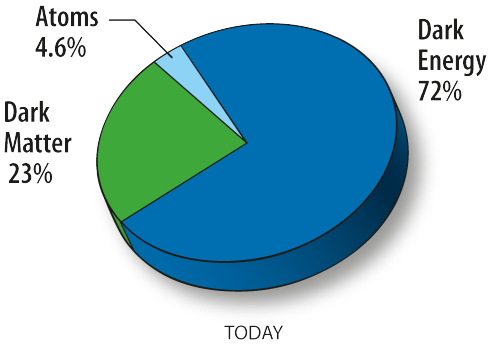
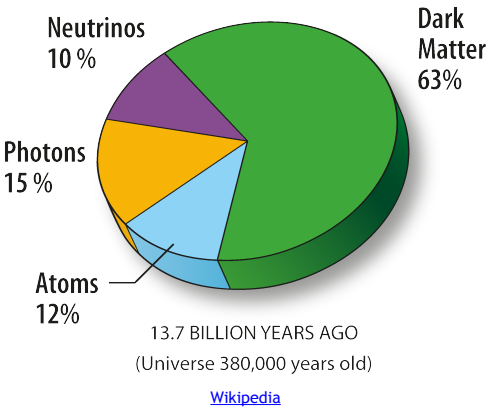
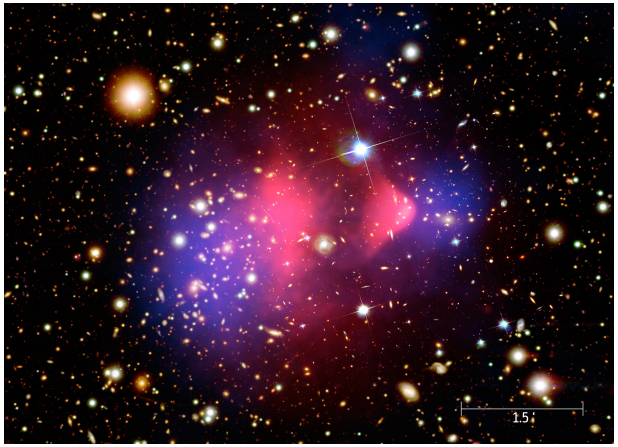




Wikipedia

Bullet Cluster



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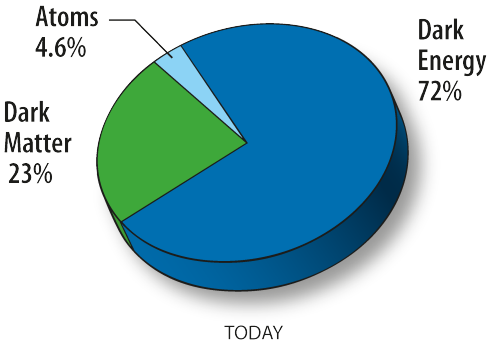

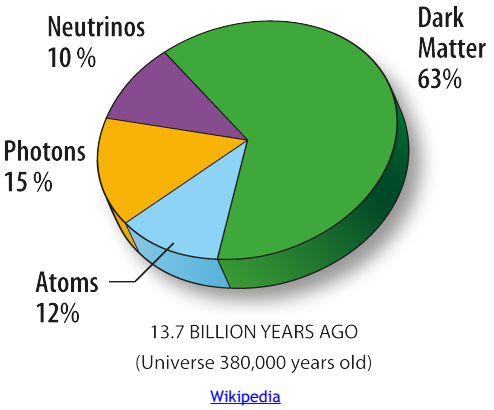

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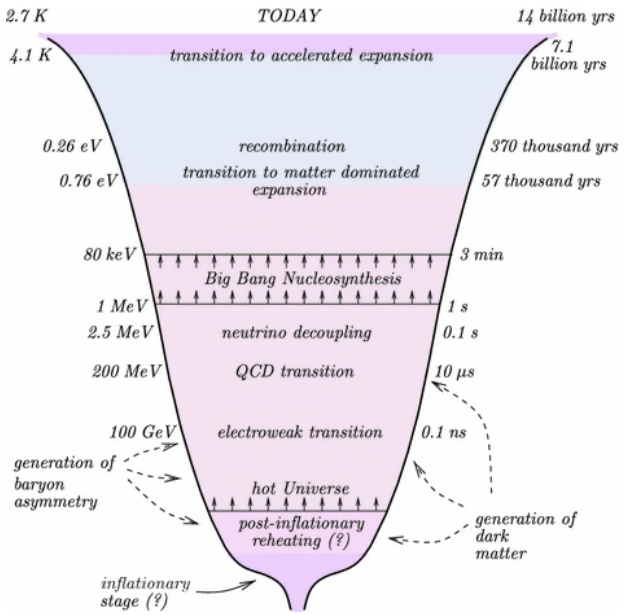

Springer

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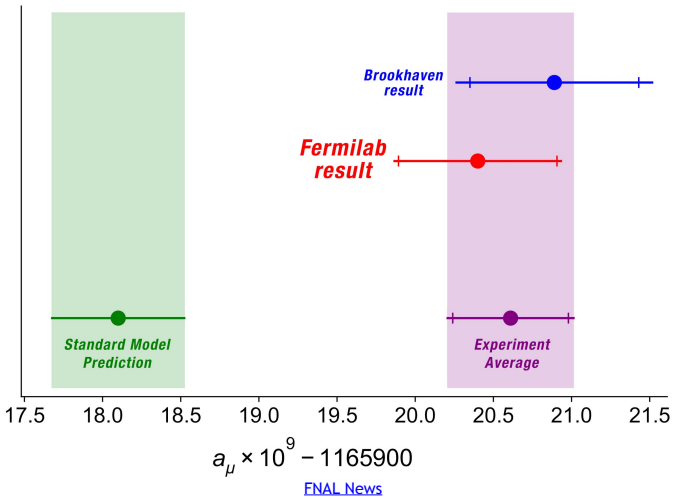

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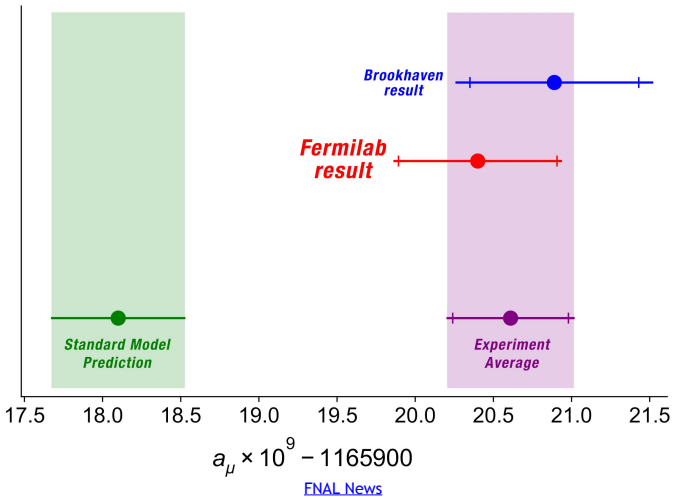

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Independent

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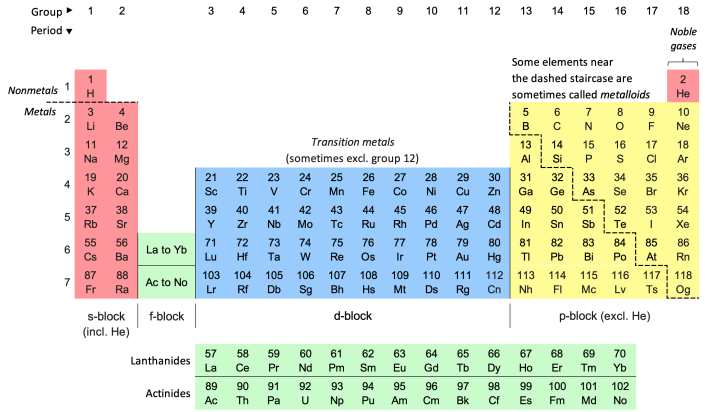

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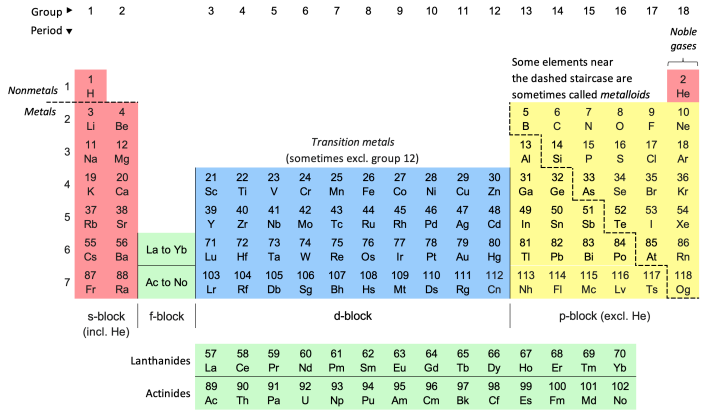

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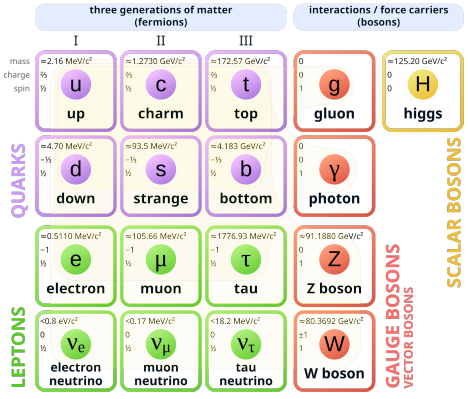

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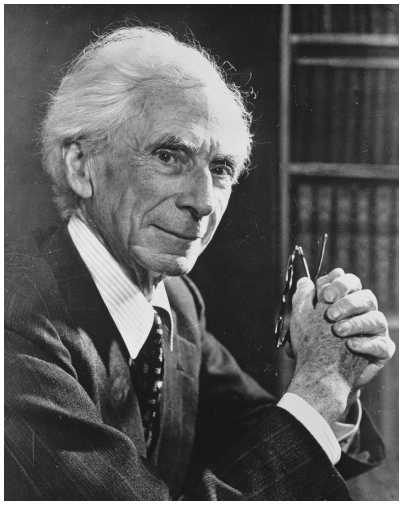

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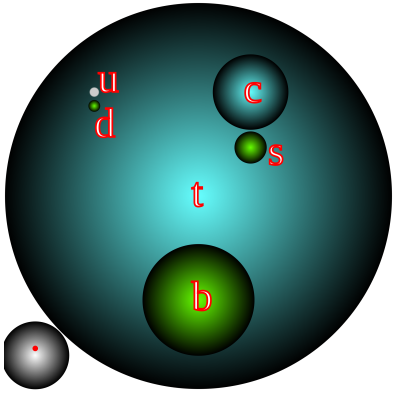

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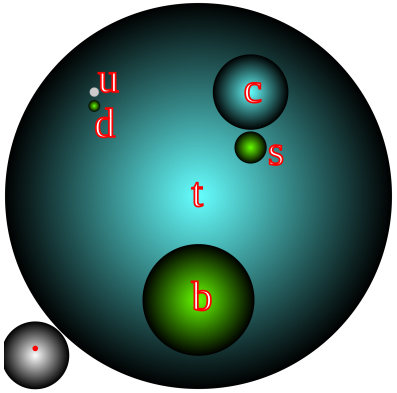

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Fermion masses in the SM

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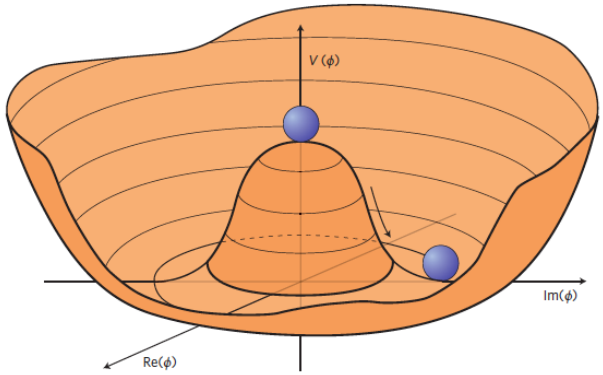

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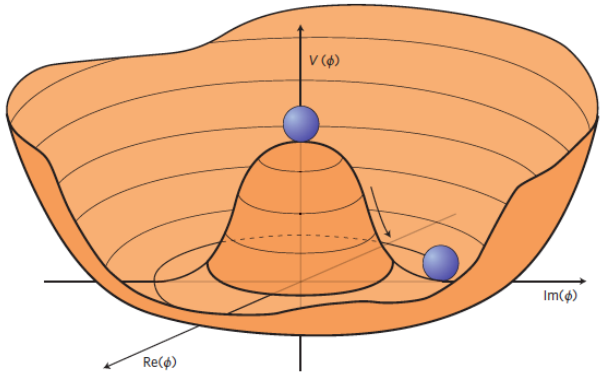

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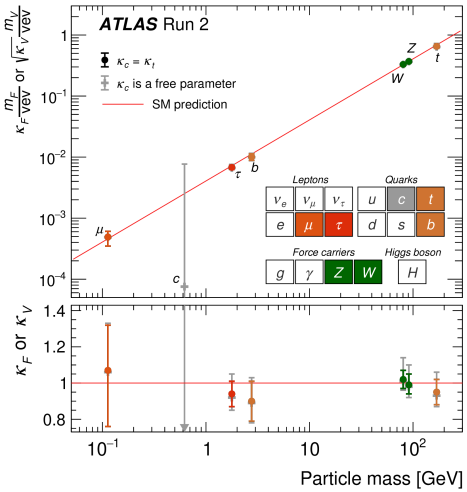

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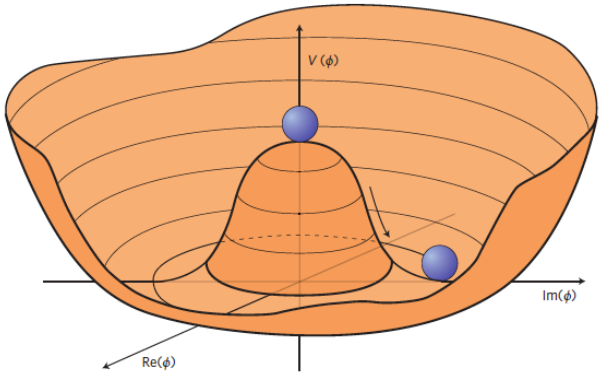
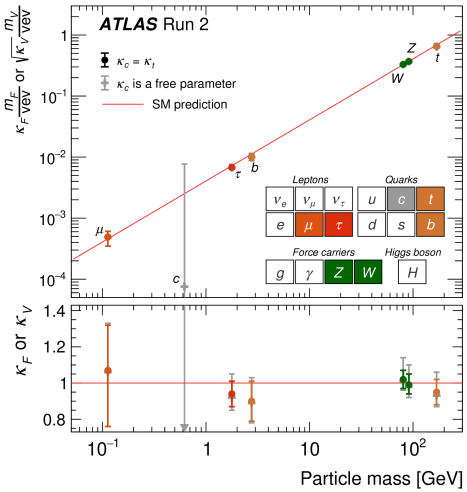
- Fermion mass/coupling values not explained in the SM



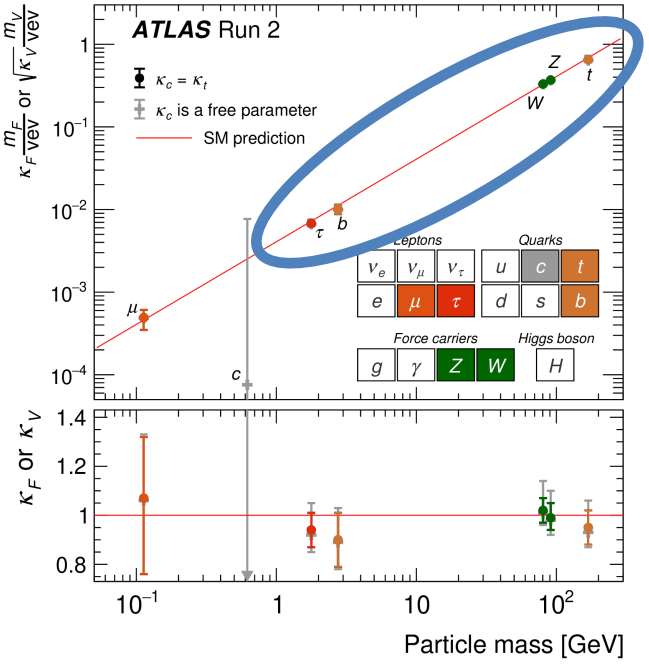
Nat Rev Phys 3 (2021) 608



Nature 607 (2022) 52

Hc Coupling: y_c

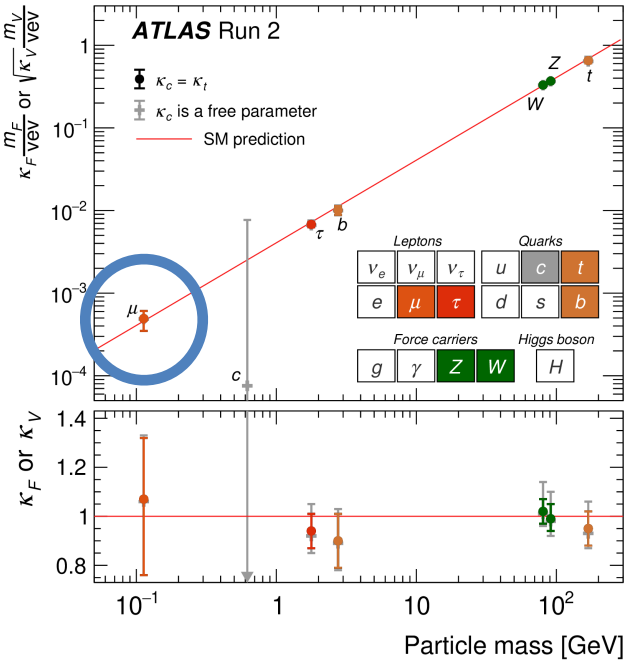
- Higgs couplings to Z and W bosons, and third generation fermions, established



Nature 607 (2022) 52

Hc Coupling: y_c

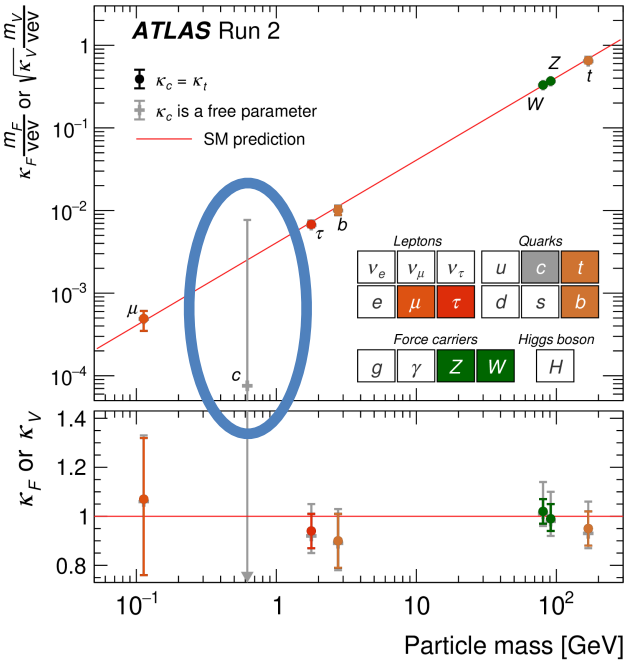
- Higgs couplings to Z and W bosons, and third generation fermions, established
- CMS has published evidence for the muon coupling



Nature 607 (2022) 52

Hc Coupling: y_c

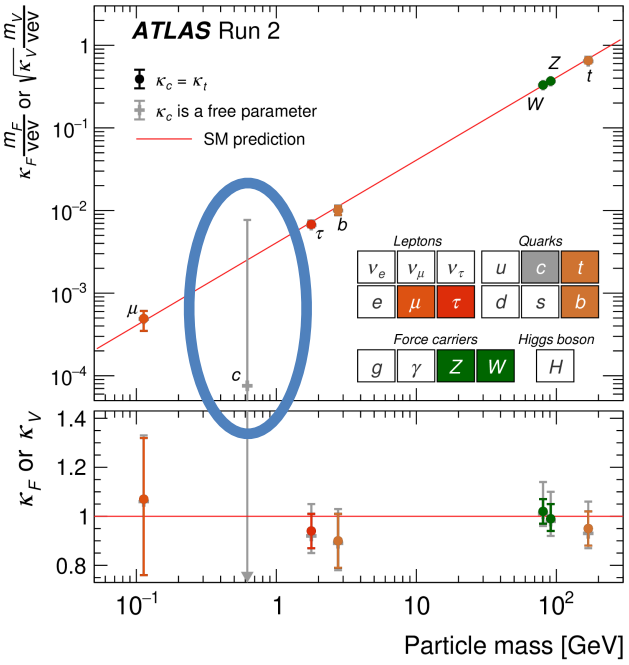
- Higgs couplings to Z and W bosons, and third generation fermions, established
- CMS has published evidence for the muon coupling
- y_c is our **best chance** to measure a first- or second-generation quark coupling
- Adequate y_c observation strategy is *not yet available*



Nature 607 (2022) 52

Hc Coupling: y_c

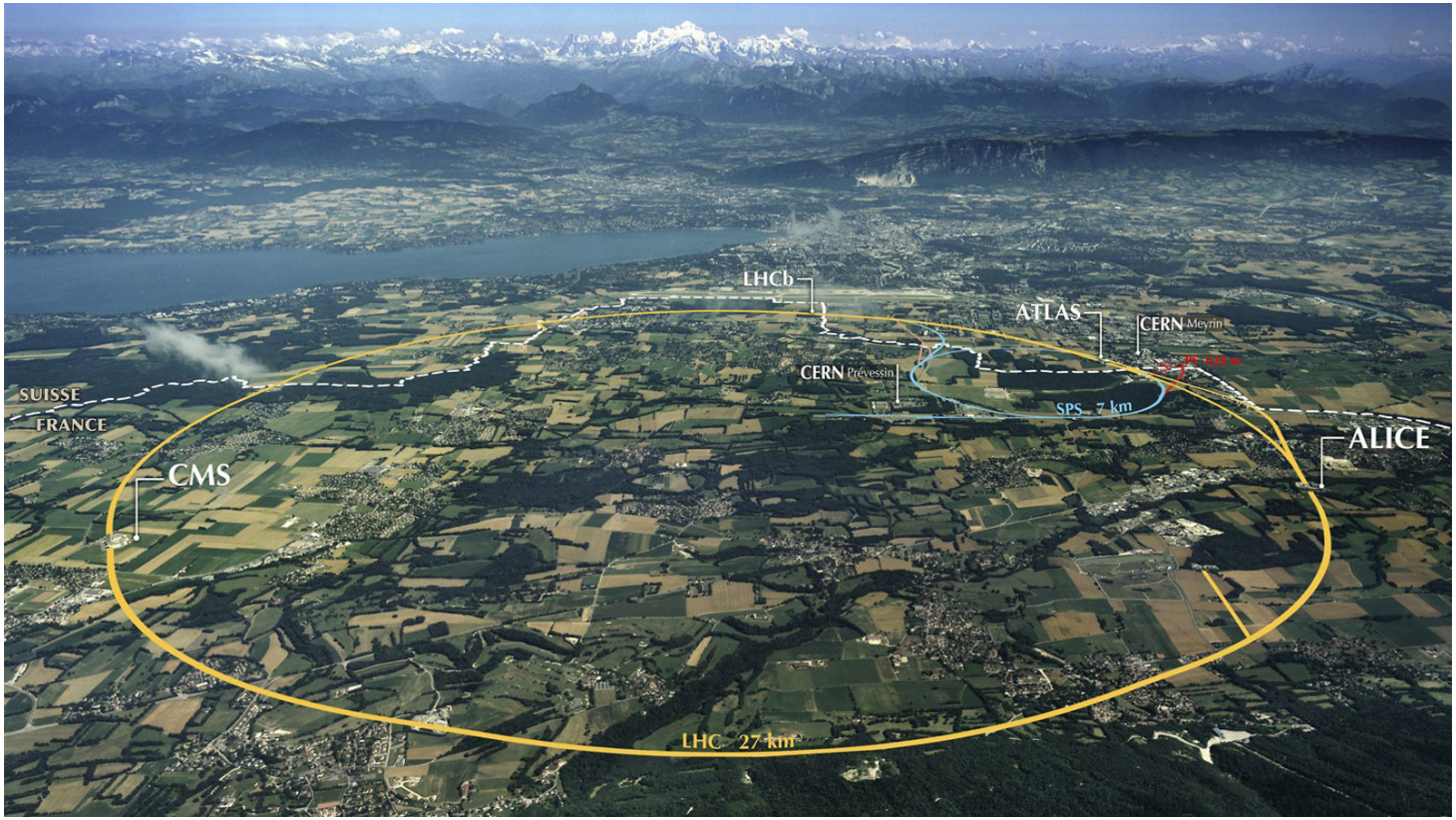
- Higgs couplings to Z and W bosons, and third generation fermions, established
- CMS has published evidence for the muon coupling
- y_c is our **best chance** to measure a first- or second-generation quark coupling
- Adequate y_c observation strategy is *not yet available*
- Sensitive to BSM physics,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



Nature 607 (2022) 52

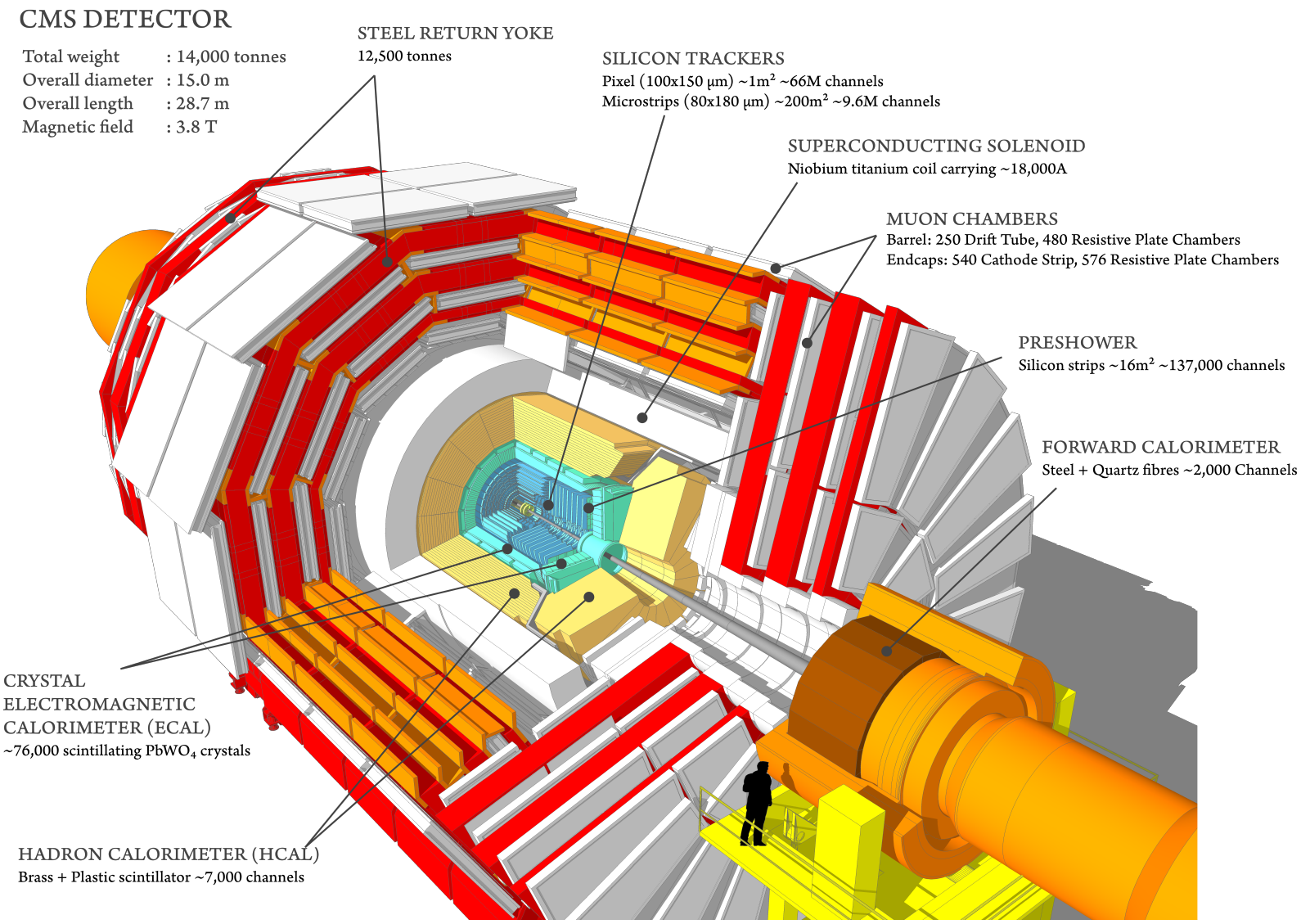
CERN Large Hadron Collider

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



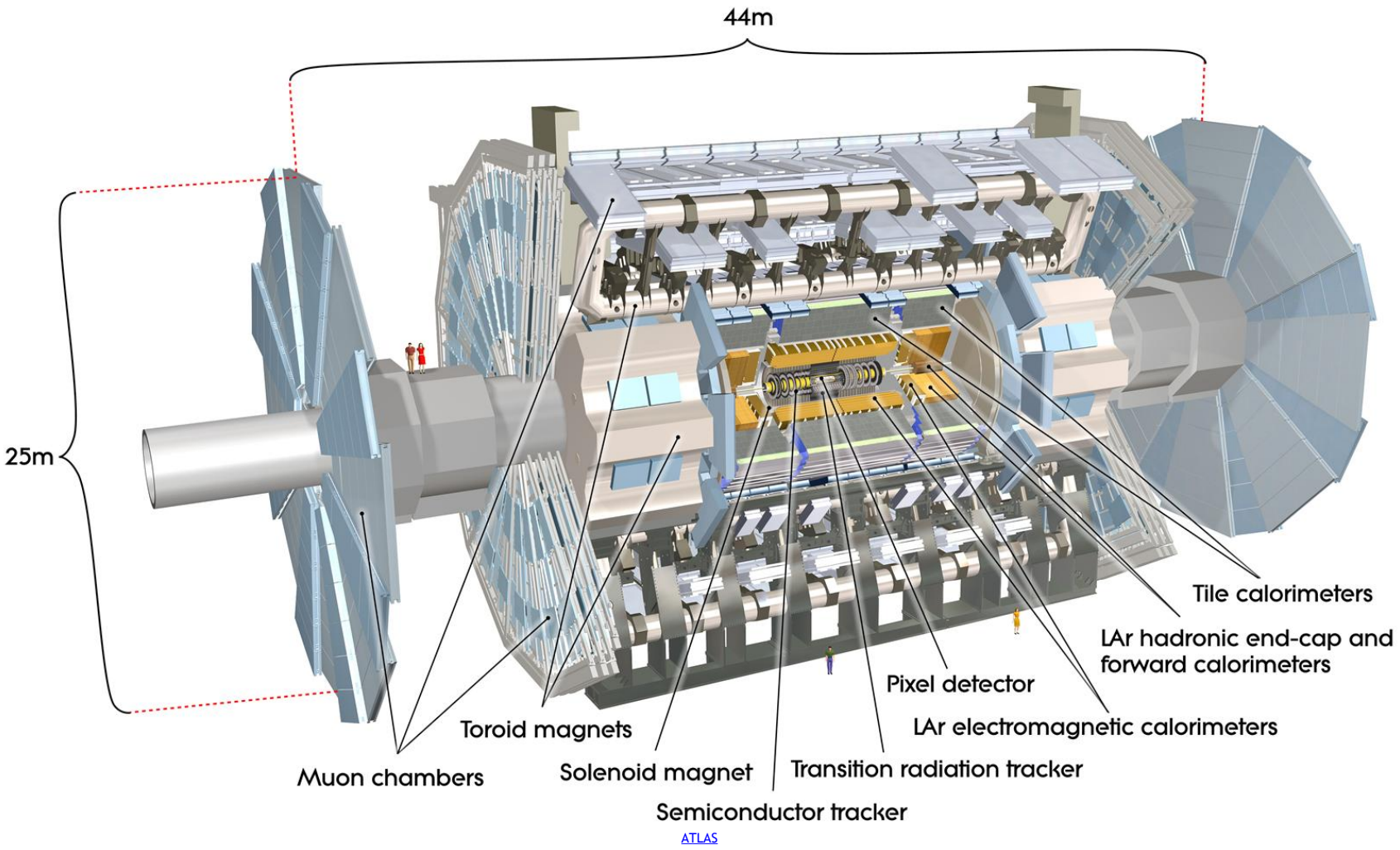
Symmetry Magazine

CMS Detector

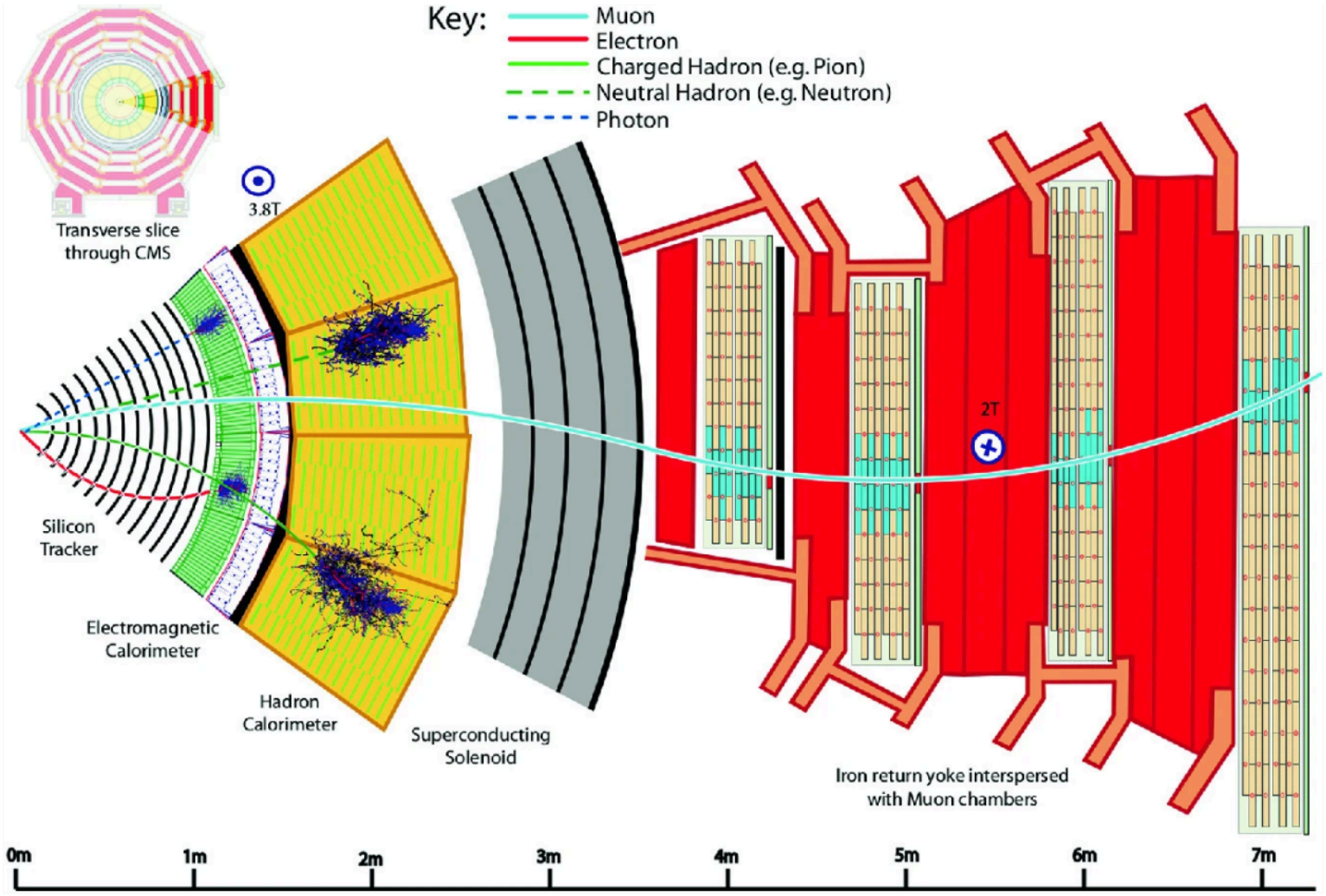


CMS

ATLAS Detector



Particle reconstruction (CMS)

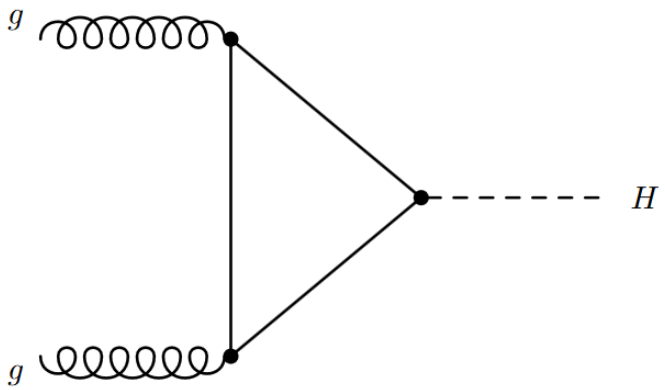


Event Reconstruction in CMS

Probing y_c with the Higgs p_T

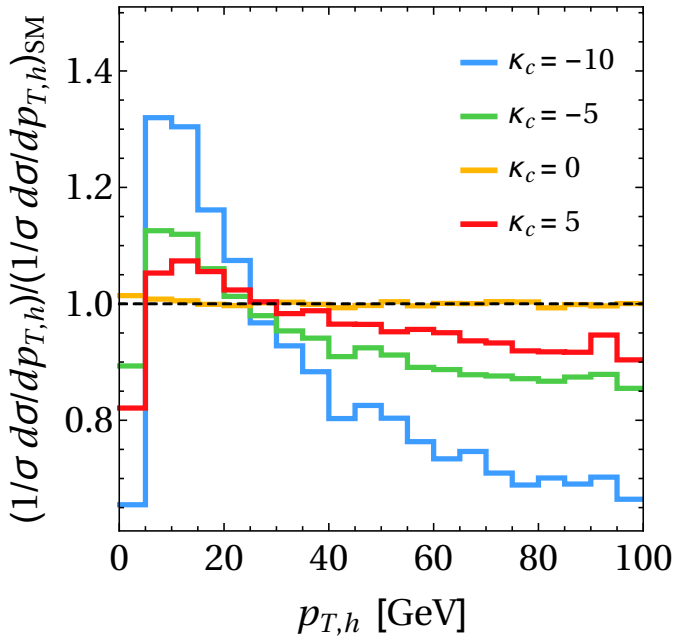
- y_c impacts shape & normalisation of Higgs transverse momentum (p_T) spectrum due to charm quarks in its gluon–gluon fusion and quark-induced production

Gluon–gluon fusion



ATLAS

8 TeV

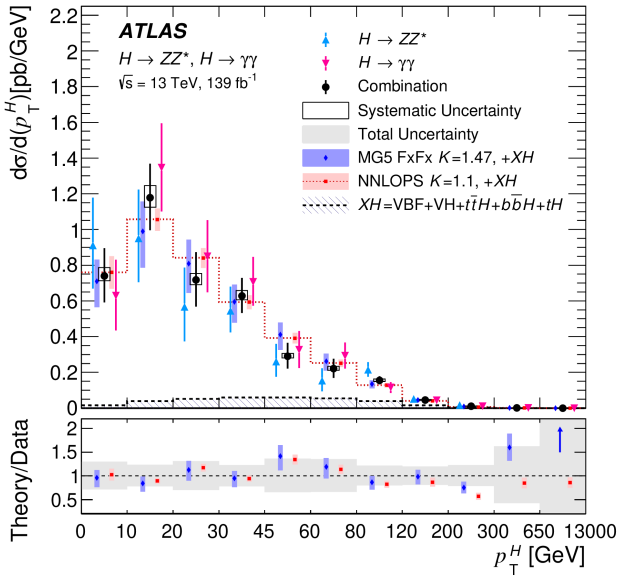


PRL 118 (2017) 121801

JHEP 05 (2023) 28

Probing y_c with the Higgs p_T

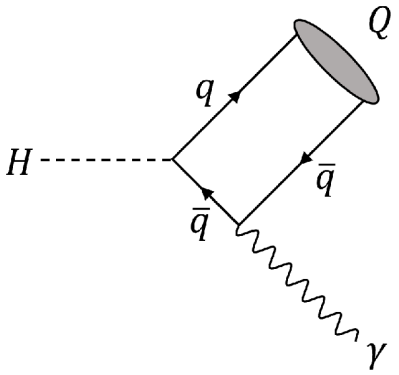
- y_c impacts shape & normalisation of Higgs transverse momentum (p_T) spectrum due to charm quarks in its gluon–gluon fusion and quark-induced production
- ATLAS used 139 fb^{-1} of pp data to constrain y_c using $H \to ZZ, H \to \gamma\gamma$ decays
- Obs (exp) 95% CL intervals on y_c/y_c^{SM} are **[-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 ✗



JHEP 05 (2023) 28

$\mathbf{H \to J/\psi + \gamma}$

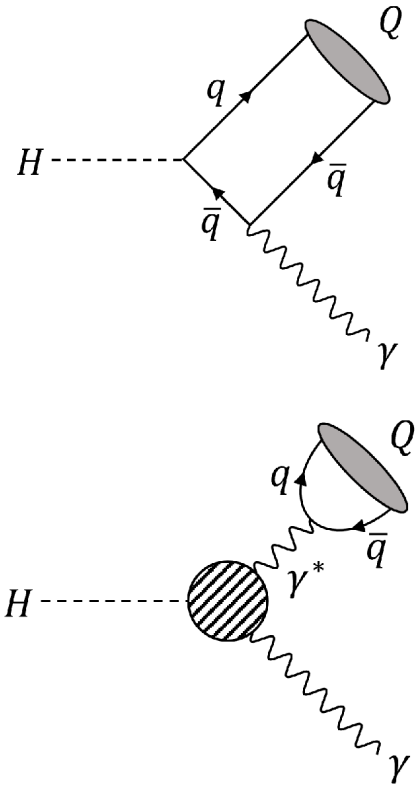
- $H \to J/\psi + \gamma$ decays can probe both the magnitude and sign of y_c ✔



EPJ C 83 (2023) 781

$\mathbf{H \to J/\psi + \gamma}$

- $H \to J/\psi + \gamma$ decays can probe both the magnitude and sign of y_c ✓
- There is a dominant Feynman diagram not sensitive to y_c ✗
- The diagrams interfere destructively, resulting in $\mathcal{B}(H \to J/\psi + \gamma) \sim 10^{-6}$ ✗



EPJ C 83 (2023) 781

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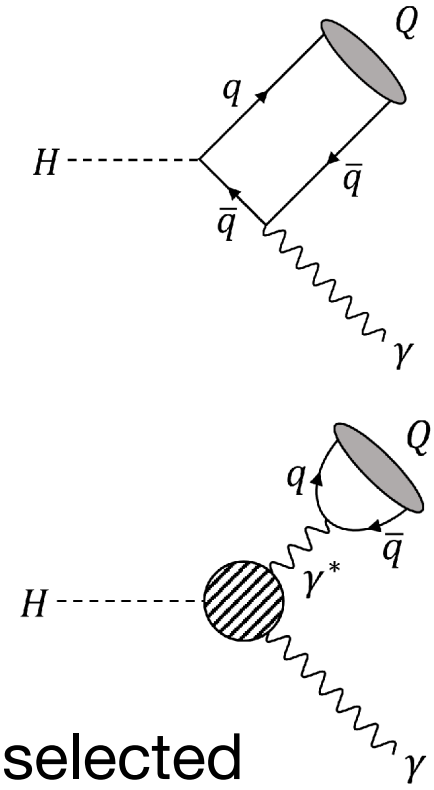
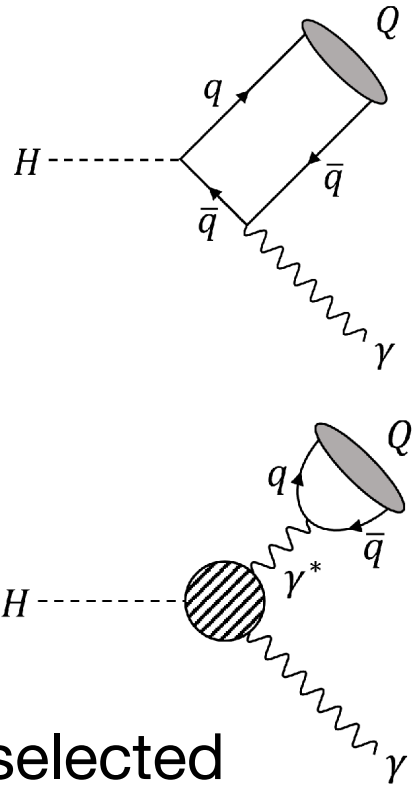
- Events with two muons and a photon are selected



EPJ C 83 (2023) 781

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

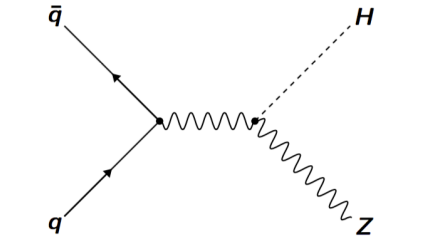


- $H \to J/\psi + \gamma$ decays can probe both the magnitude and sign of y_c ✔
- There is a dominant Feynman diagram not sensitive to y_c ✘
- The diagrams interfere destructively, resulting in $\mathcal{B}(H \to J/\psi + \gamma) \sim 10^{-6}$ ✘
- ATLAS has searched for this using 139 fb^{-1} of pp data 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 $H \to \gamma\gamma$ result, leads to obs (exp) constraints on $(y_c/y_c^{SM})/(y_\gamma/y_\gamma^{SM})$ of **[-133, 175]** ([-120, 161])

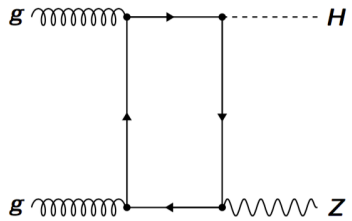
EPJ C 83 (2023) 781

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

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



$pp \to ZH$ dominated $q\bar{q} \to ZH$ processes,
$\sigma \approx 0.76$ pb at $\sqrt{s} = 13$ TeV



Smaller contributions from $gg \to ZH$, but
harder p_T^H, $\sigma \approx 0.12$ pb at $\sqrt{s} = 13$ TeV

Figure (both diagrams and texts) made by Andrew Chisholm

PRL 131 (2023) 061801

CMS VH, H → c$\bar{c}$ Method

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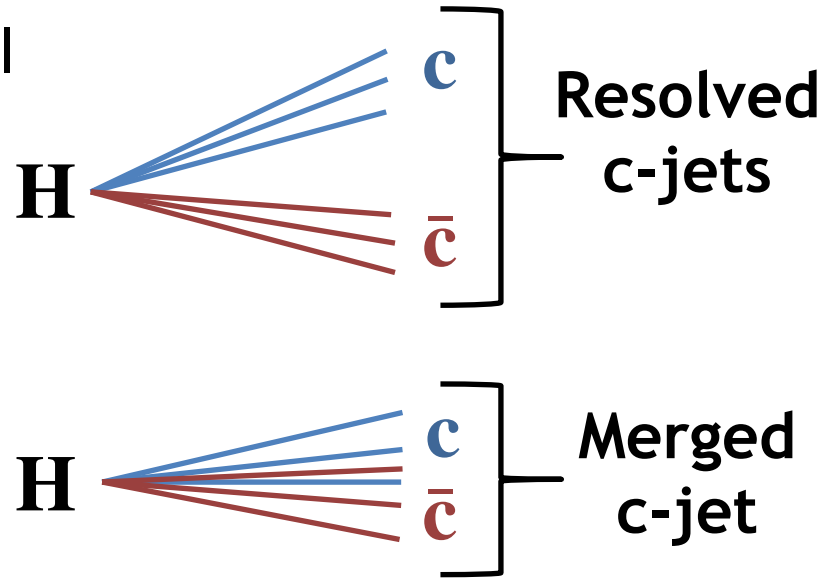
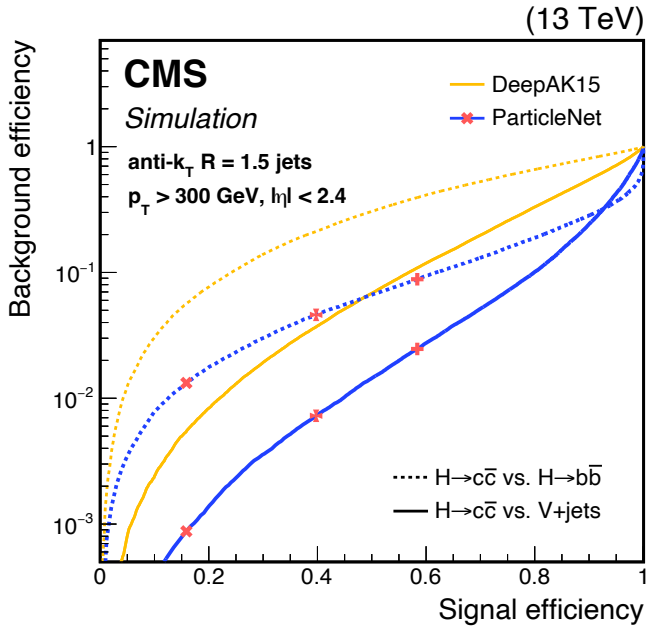
- VH production is used for triggering and background rejection, where $V \to \ell\ell, \ell\nu, \nu\nu$
- 138 fb^{-1} of pp data
- Physics objects are reconstructed using a global particle-flow algorithm
- Resolved and merged $H \to c\bar{c}$ decays targeted



PRL 131 (2023) 061801

CMS VH, H → cc̄ Method

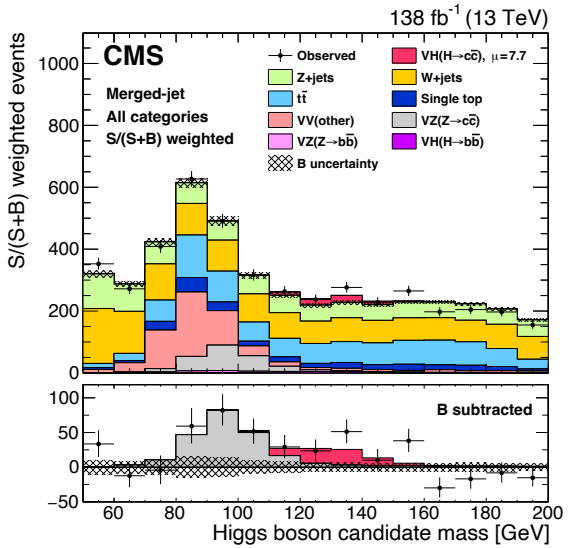
- y_c can be probed in $H \to c\bar{c}$ decays
- VH production is used for triggering and background rejection, where $V \to \ell\ell, \ell\nu, \nu\nu$
- 138 fb^{-1} of pp data
- Physics objects are reconstructed using a global particle-flow algorithm
- Resolved and merged $H \to c\bar{c}$ decays targeted
  - Merged decays categorised using *ParticleNet*
- Boosted decision trees (BDTs) used for merged event selection



PRL 131 (2023) 061801

CMS VH, H → $c\bar{c}$ Results

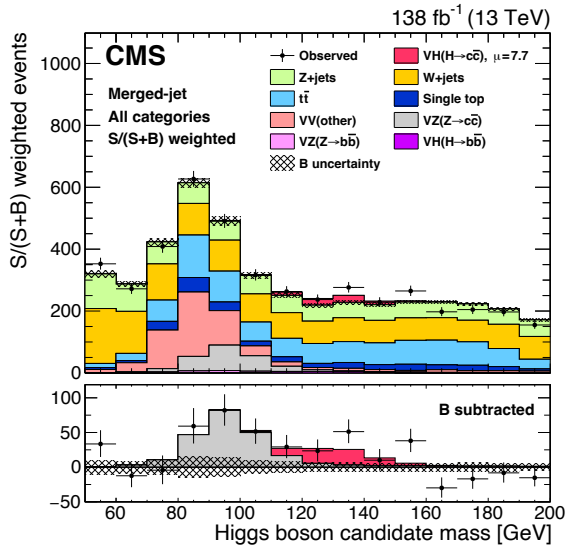
- Binned likelihood fit to $m(H_{\text{cand}})$ (BDT output) in the merged (resolved) categories used for interpretation
- V + jets and $t\bar{t}$ yields estimated in control regions
- Analysis is statistically limited

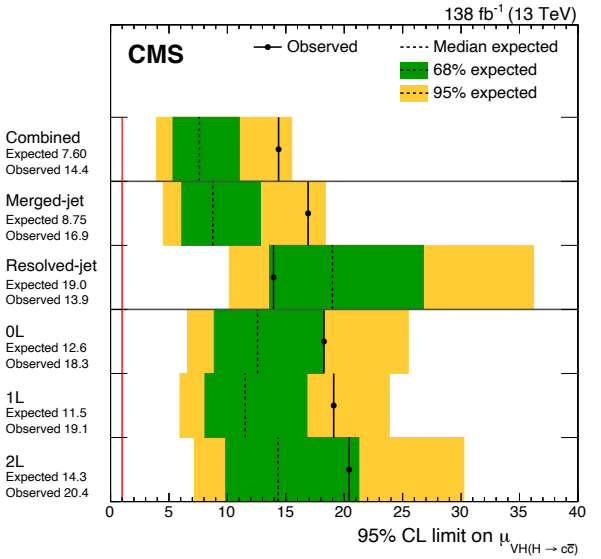


PRL 131 (2023) 061801

CMS VH, H → $c\bar{c}$ Results

- Binned likelihood fit to $m(H_{\text{cand}})$ (BDT output) in the merged (resolved) categories used for interpretation
- V + jets and $t\bar{t}$ yields estimated in control regions
- Analysis is statistically limited
- Obs (exp) 95% CL upper limit on $\sigma(VH)\mathcal{B}(H \to c\bar{c})$: **14 × SM** (7.6 × SM)
- Obs (exp) 95% CL interval on y_c/y_c^{SM}: **1.1–5.5** (<3.4)

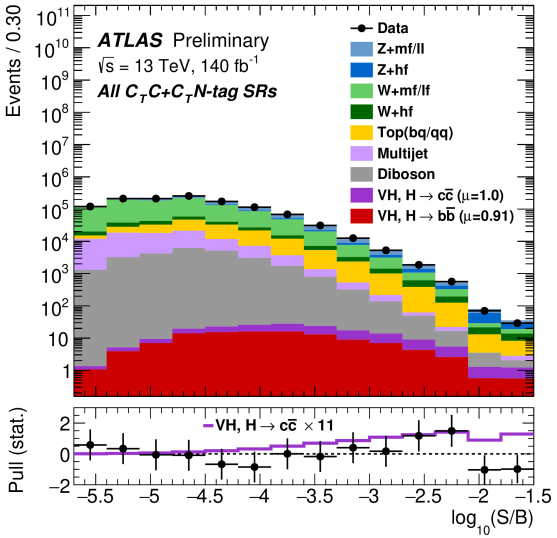




PRL 131 (2023) 061801

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

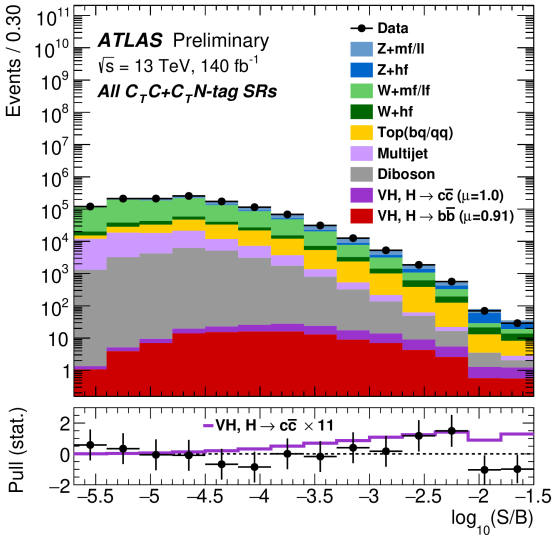
- ATLAS has analysed $H \to c\bar{c}$ and $H \to b\bar{b}$ decays, using VH production
- 139 fb^{-1} of pp data
- Only resolved events are used for $H \to c\bar{c}$ here

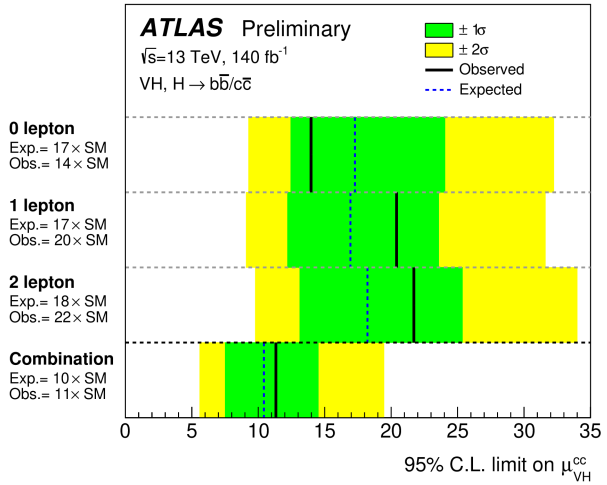


ATLAS-CONF-2024-010

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

- ATLAS has analysed $H \to c\bar{c}$ and $H \to b\bar{b}$ decays, using VH production
- 139 fb^{-1} of pp data
- Only resolved events are used for $H \to c\bar{c}$ here
- Obs (exp) $VH, H \to c\bar{c}$ 95% CL_s upper limit: **11.3 × SM** (10.4 × SM)
- Corresponding to obs (exp) upper limit on $|y_c/y_c^{SM}|$: **4.2** (4.1)

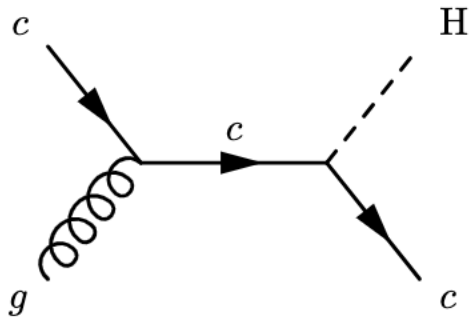




ATLAS-CONF-2024-010

Higgs+charm production

- Probing y_c is challenging, and multiple approaches will likely be required
- Higgs+charm production was proposed to **probe $\mathbf{y_c}$,** but also **tests a new Higgs boson production mode**



arXiv:2407.15550 [hep-ex]

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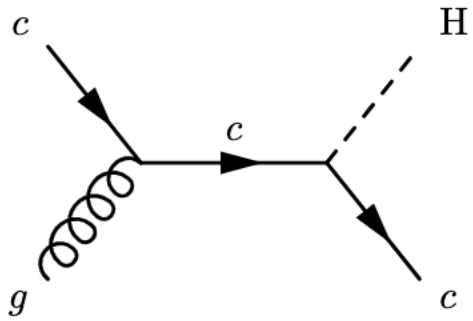
- Only have to c-tag 1 jet ✓
- Can use most sensitive Higgs decay modes (e.g. $H \to \gamma\gamma$ and $H \to ZZ$) ✓



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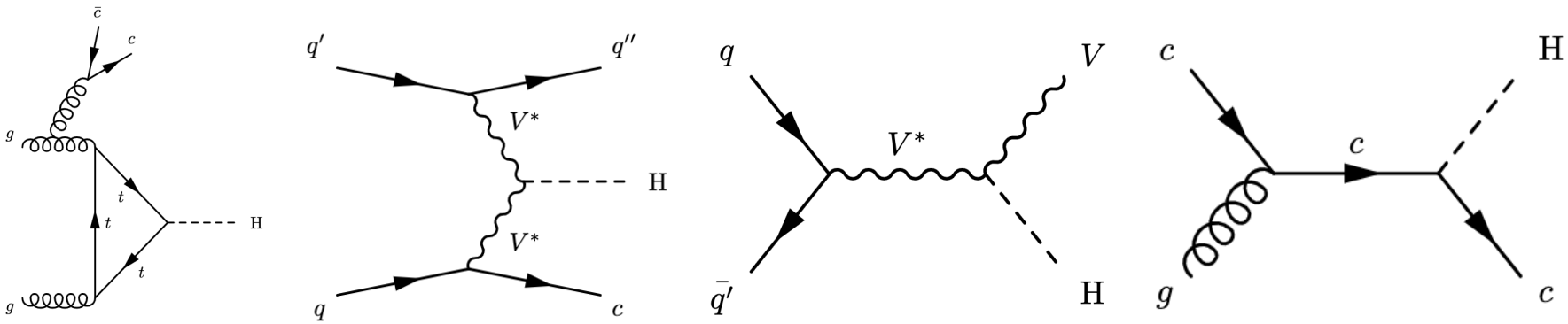
- Higgs+charm production was proposed to **probe $\mathbf{y_c}$**, but also **tests a new Higgs boson production mode**
- Only have to c-tag 1 jet ✓
- Can use most sensitive Higgs decay modes (e.g. $H \to \gamma\gamma$ and $H \to ZZ$) ✓
- Only ~1% of signal sensitive to y_c ✗



arXiv:2407.15550 [hep-ex]

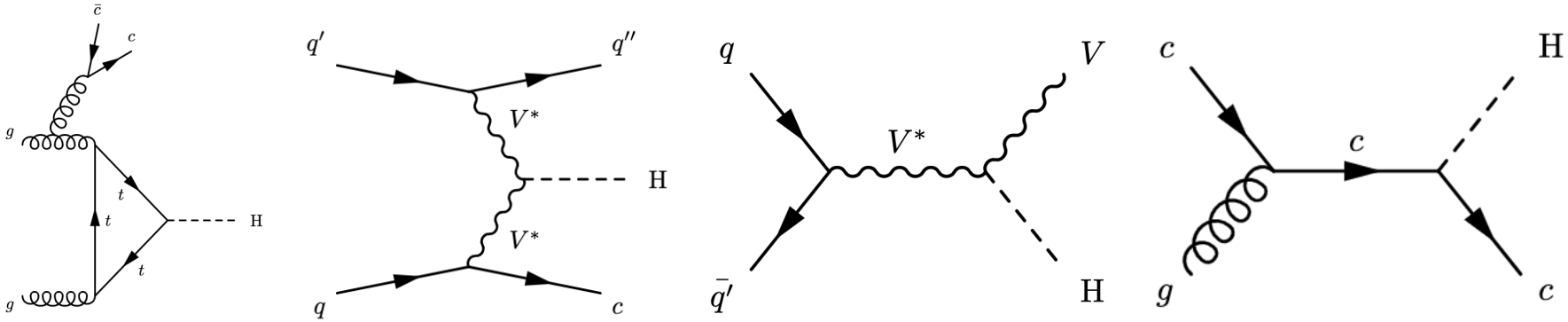
ATLAS Higgs+charm analysis

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

arXiv:2407.15550 [hep-ex]

ATLAS Higgs+charm analysis

- Higgs+charm events were analysed in $H \to \gamma\gamma$ decays
- 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 $H \to \gamma\gamma$ event that is not signal



arXiv:2407.15550 [hep-ex]

Event Selection

- **Photons**: ≥ 2 isolated and *tight* identified photons with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.37$, but not $1.37 < |\eta| < 1.52$
- **Jets**: 1–2 jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$

arXiv:2407.15550 [hep-ex]

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- **Jets**: 1–2 jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$
- **Event-level selection**:
  - $E_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma} > 0.35\ (0.25)$ for (sub-)leading photon
  - $105\ \mathrm{GeV} < m_{\gamma\gamma} < 160\ \mathrm{GeV}$
  - $\Delta R(j, \gamma_{1,2}) > 1$

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  - $E_{\mathrm{T}}^{\gamma}/m_{\gamma\gamma} > 0.35\ (0.25)$ for (sub-)leading photon
  - $105\ \text{GeV} < m_{\gamma\gamma} < 160\ \text{GeV}$
  - $\Delta R(j, \gamma_{1,2}) > 1$
- **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

arXiv:2407.15550 [hep-ex]

Simulation

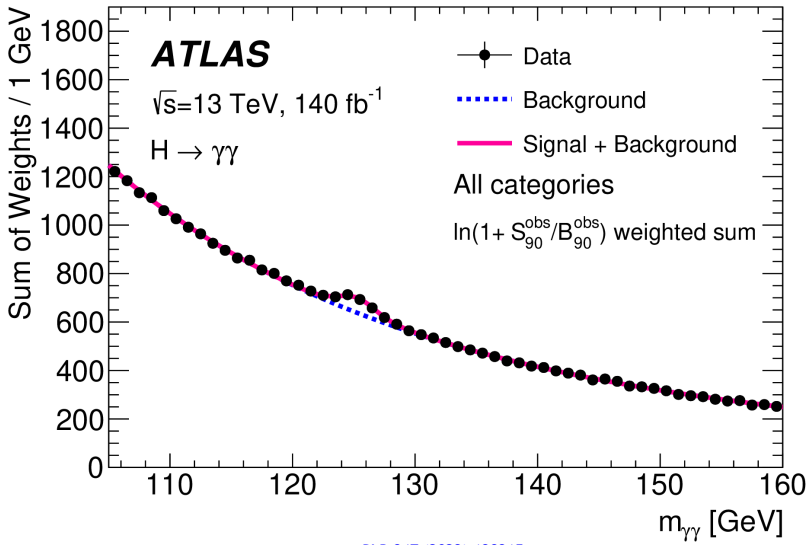
- Monte Carlo (MC) simulation is used to model the signal and resonant backgrounds
- *Geant4* ATLAS simulation used for most MC samples
- y_c-sensitive part of $H + c$ is modelled at leading order using *MadGraph5*, with *Higgs Effective Couplings* UFO

Process	Generator ME + PS	PDF set	PDF tune	σ [fb]
ggF $H, H \to \gamma\gamma$	POWHEG NNLOPS+PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	110.1
VBF $H, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	8.578
$W^- H, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.206
$W^+ H, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.902
$gg \to ZH, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	0.278
$qq \to ZH, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	AZNLOCTEQ6	1.725
$t\bar{t}H, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	A14NNPDF23	1.150
$b\bar{b}H, H \to \gamma\gamma$	POWHEG BOX +PYTHIA 8	PDF4LHC15	A14NNPDF23	1.104
y_c-sensitive $H + c, H \to \gamma\gamma$	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

arXiv:2407.15550 [hep-ex]

NR background modelling

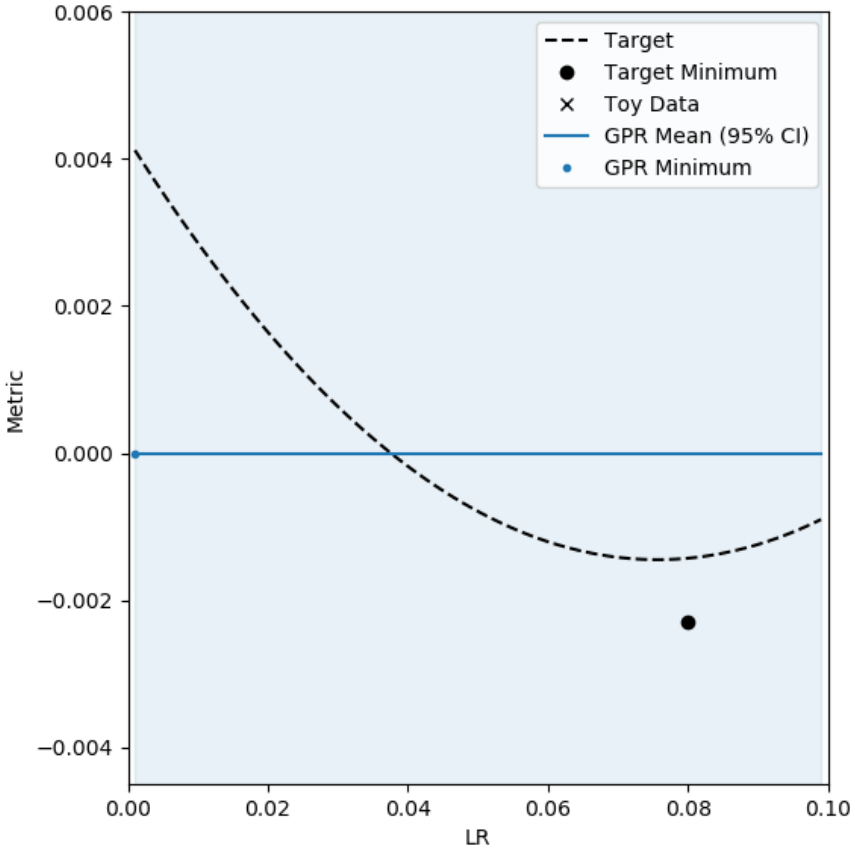
- Dominant background is from smoothly-falling NR $\gamma\gamma + n$ partons events
  - Typically modelled using analytical functions
- Here, we perform the first usage of Gaussian process regression (GPR) for direct background estimation in a particle physics data analysis
  - There are pre-existing 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

NR background modelling

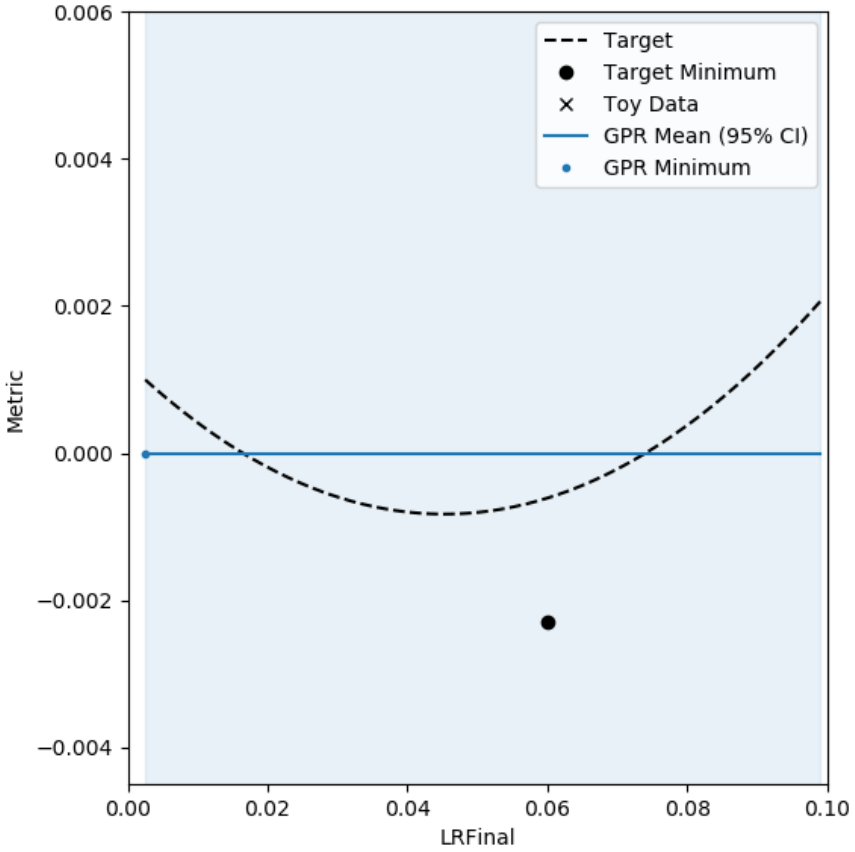
- Dominant background is from smoothly-falling NR $\gamma\gamma + n$ partons events
  - Typically modelled using analytical functions
- Here, we perform the first usage of Gaussian process regression (GPR) for direct background estimation in a particle physics data analysis
  - There are pre-existing 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
- 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



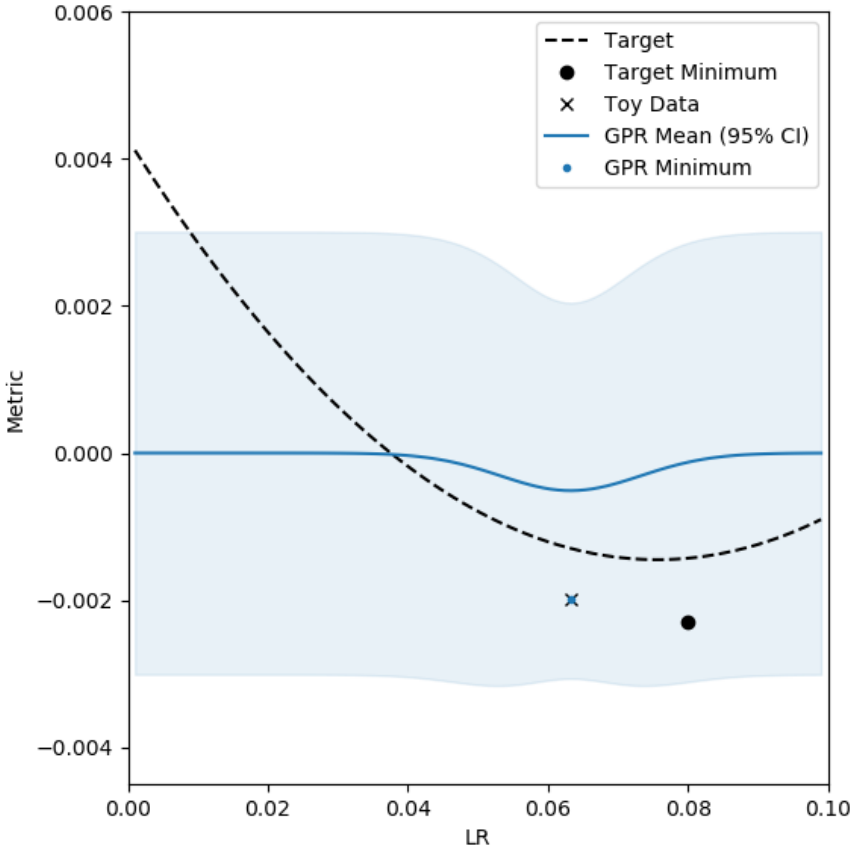
N/A error



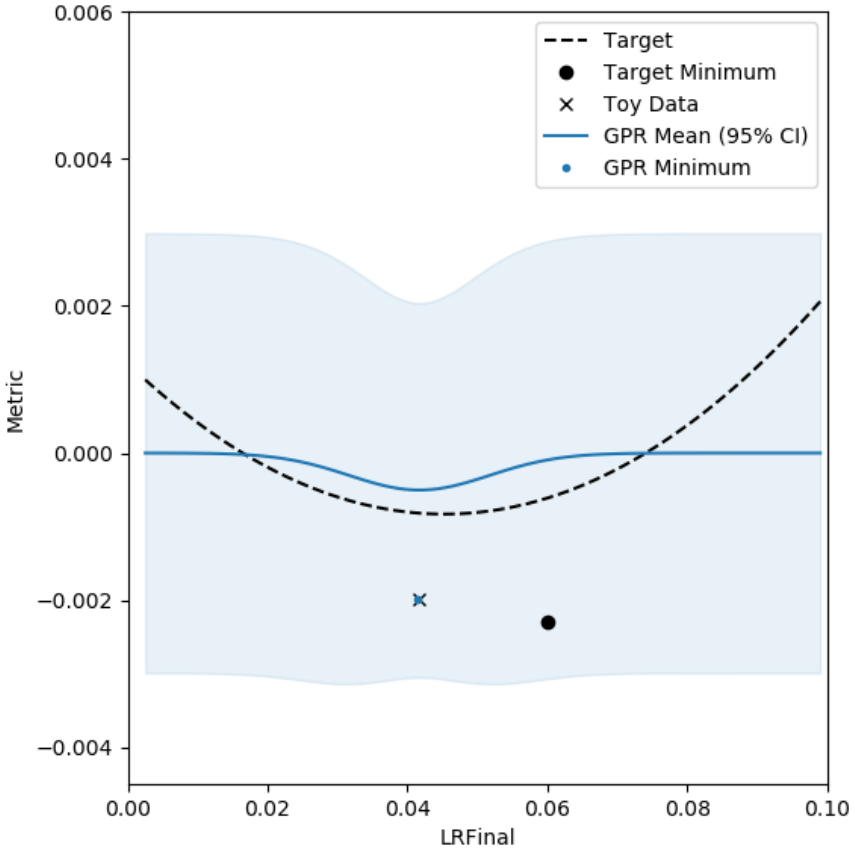
N/A error

Toy GPR Demonstration

1 training event



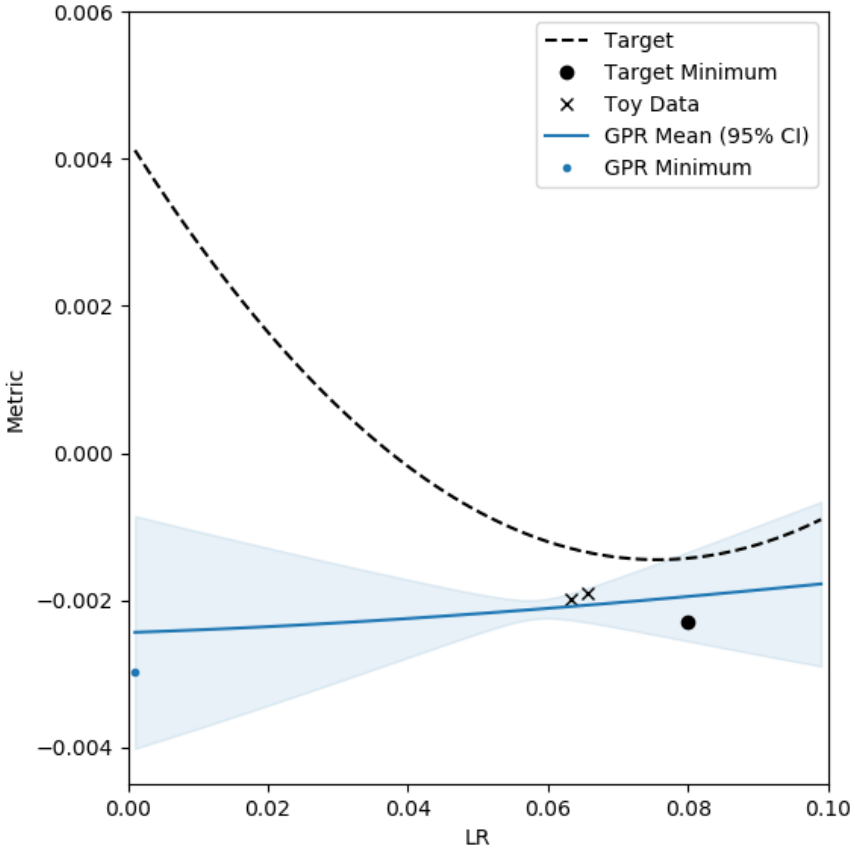
21% error



31% error

Toy GPR Demonstration

2 training events



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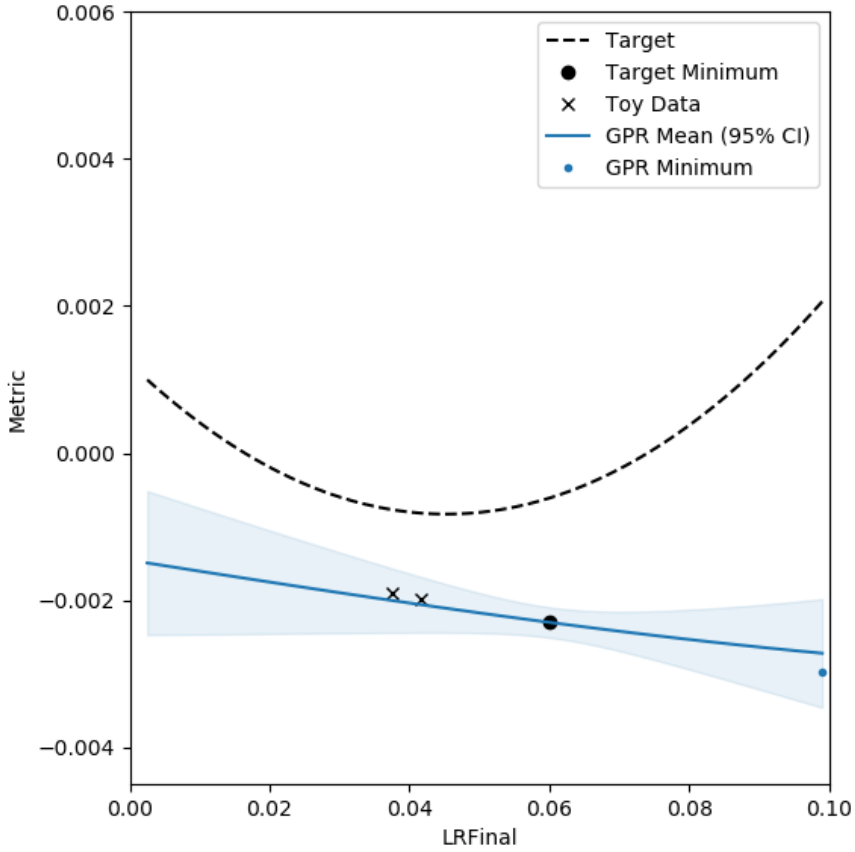

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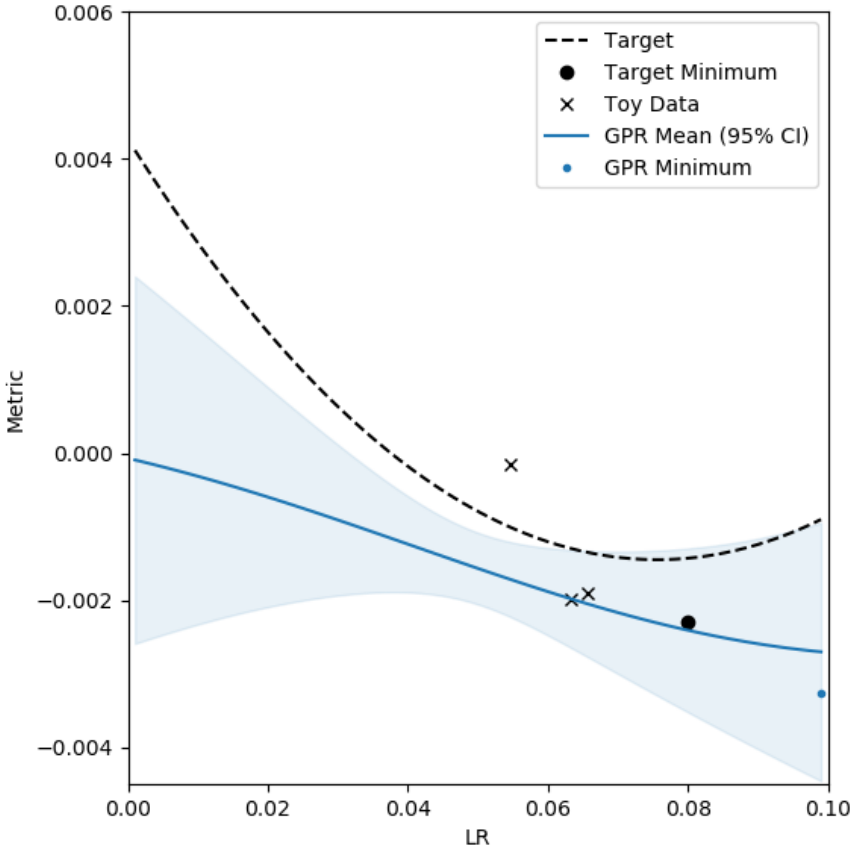
Toy GPR Demonstration

3 training events



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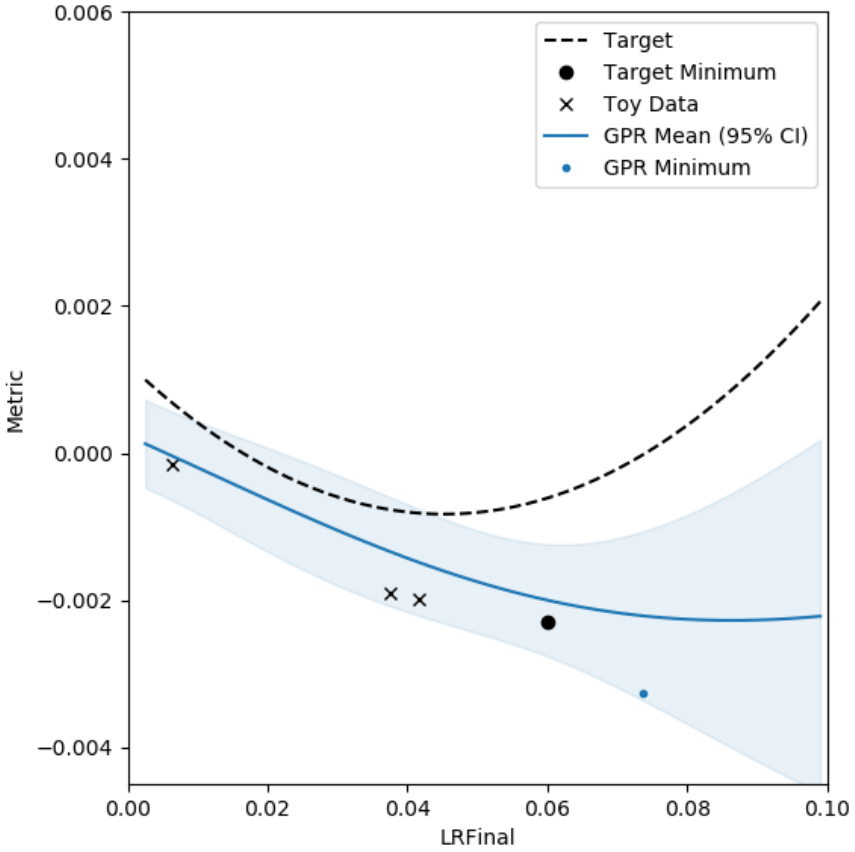
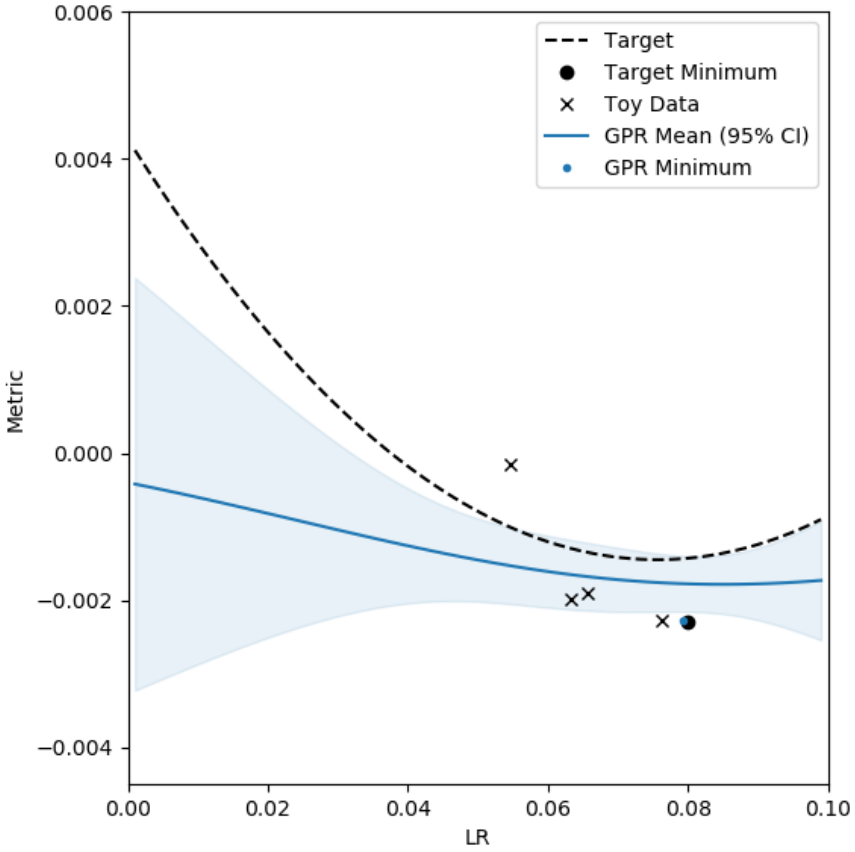
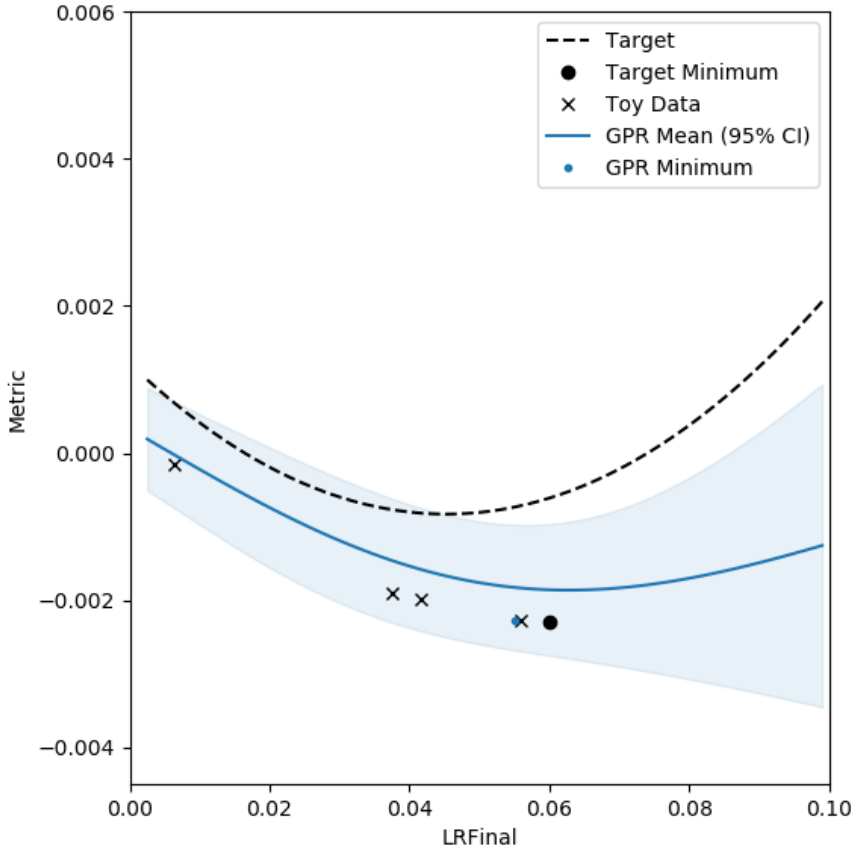


23% error

Toy GPR Demonstration

4 training events



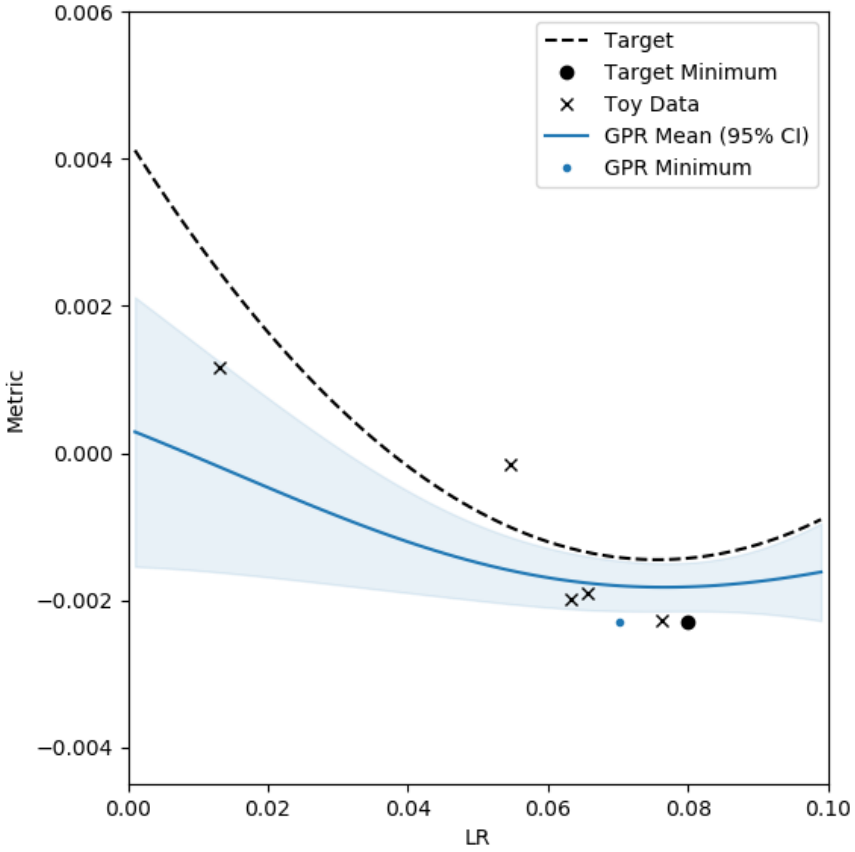


0.99% error

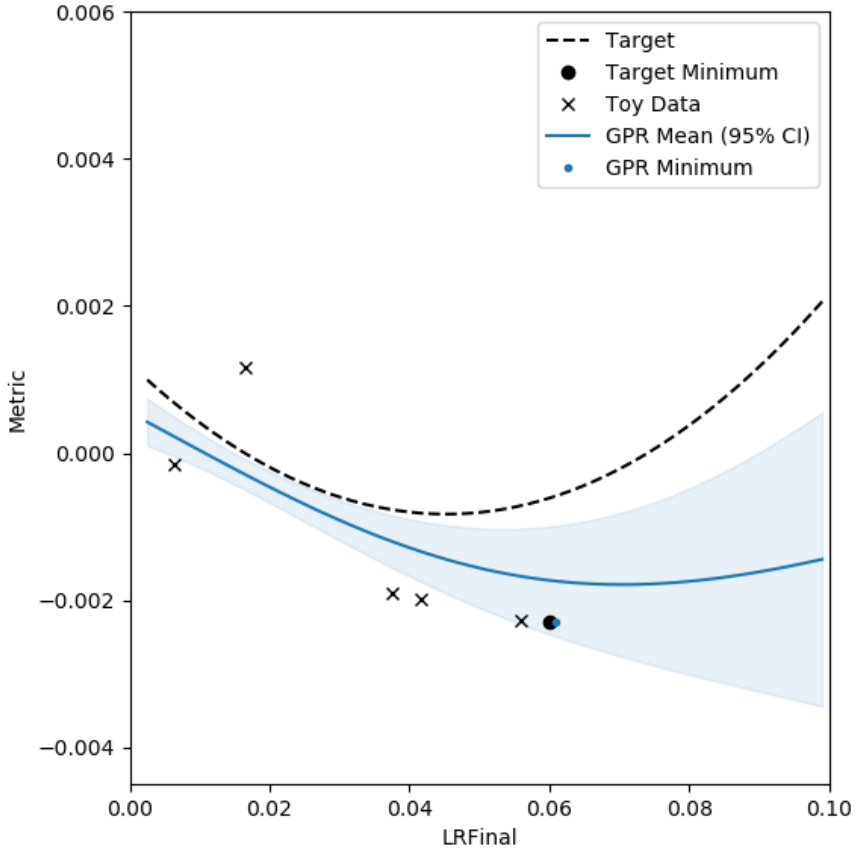
8.1% error

Toy GPR Demonstration

5 training events



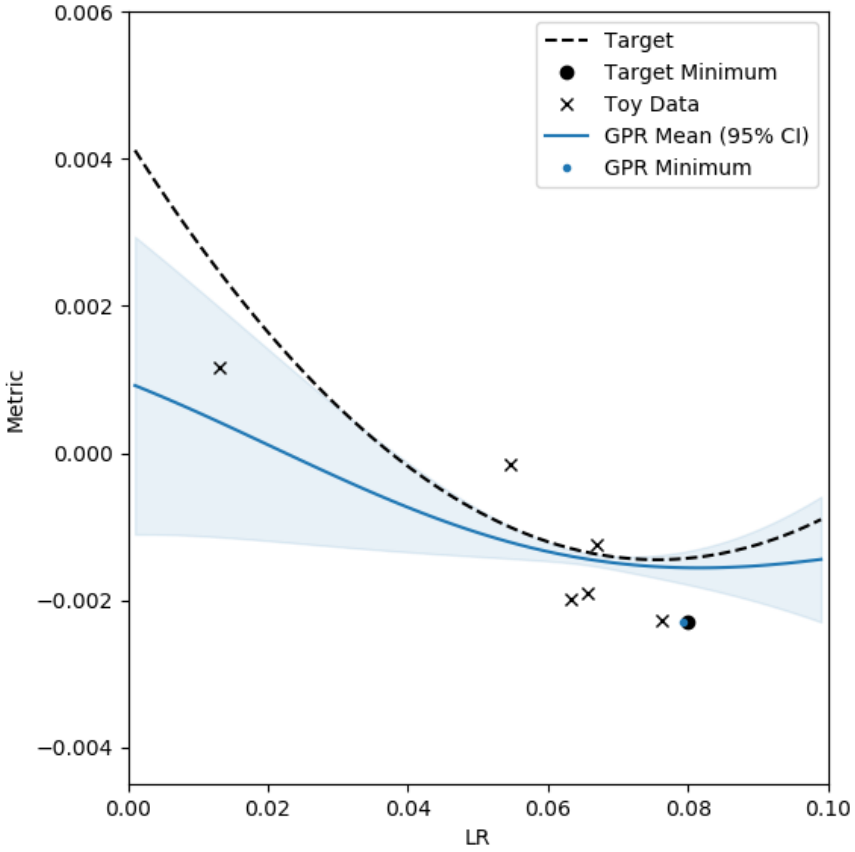
12% error

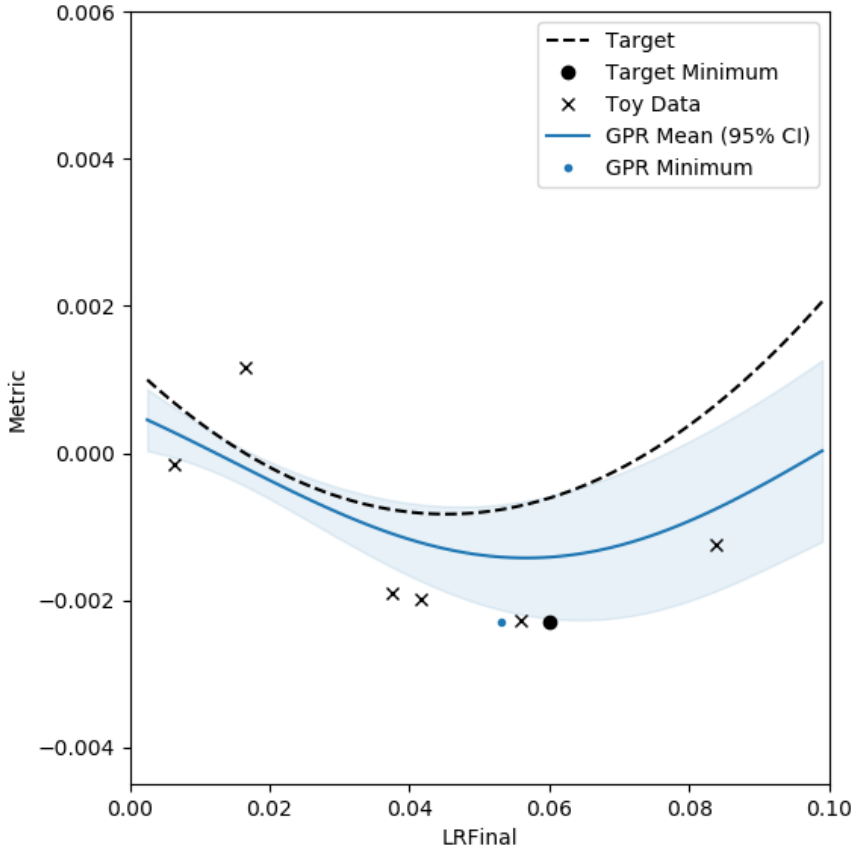


1.7% error

Toy GPR Demonstration

6 training events



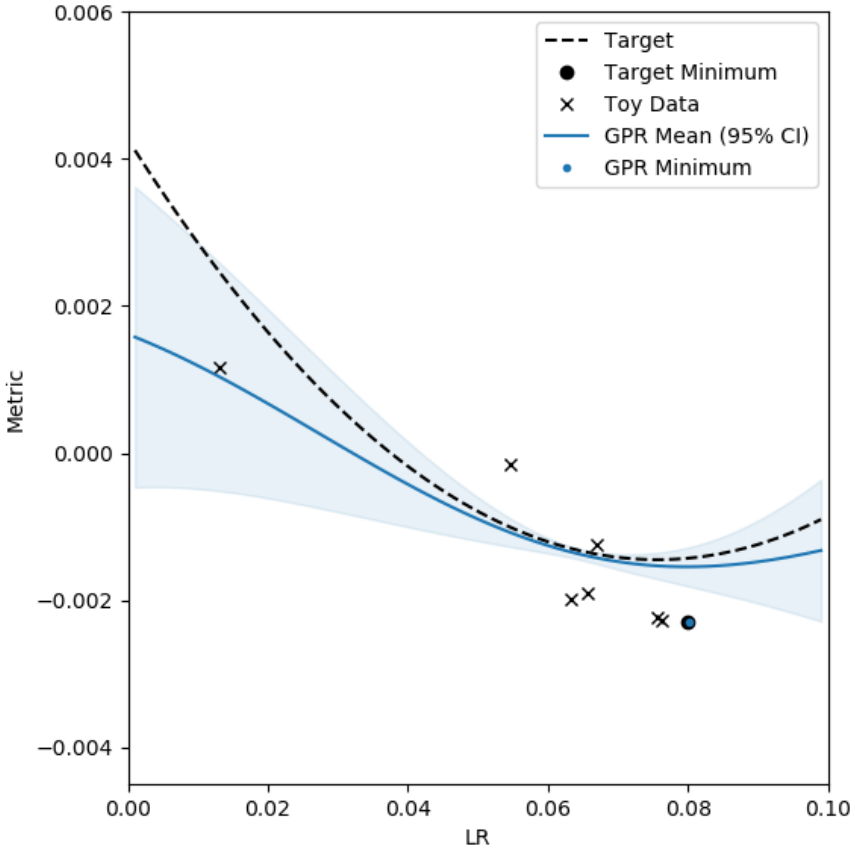


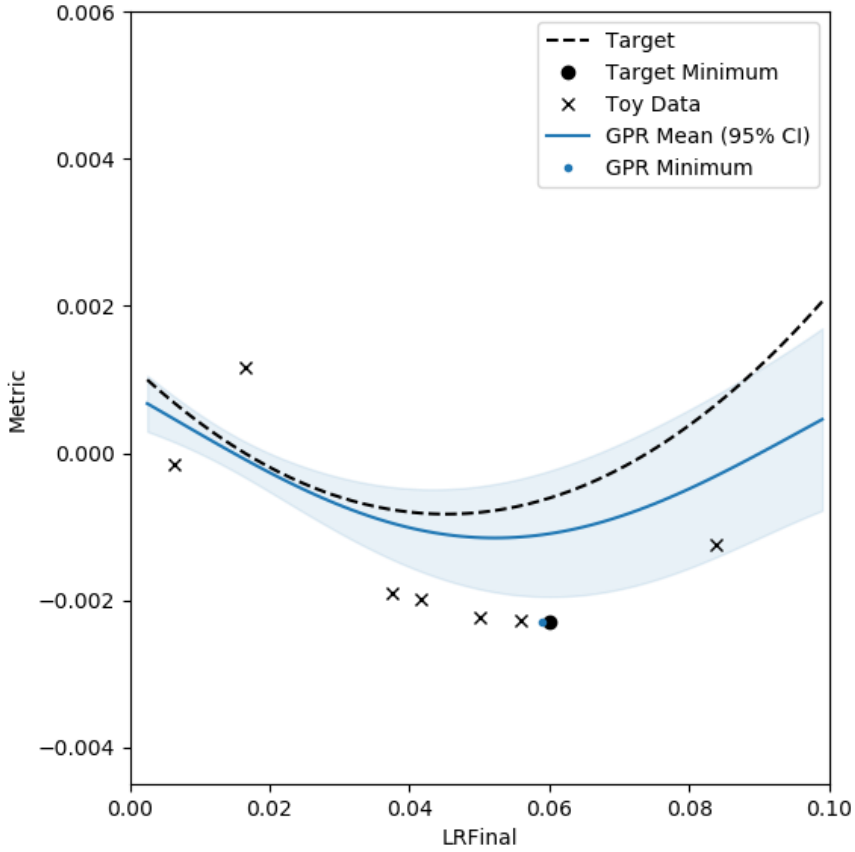
0.99% error

11% error

Toy GPR Demonstration

7 training events



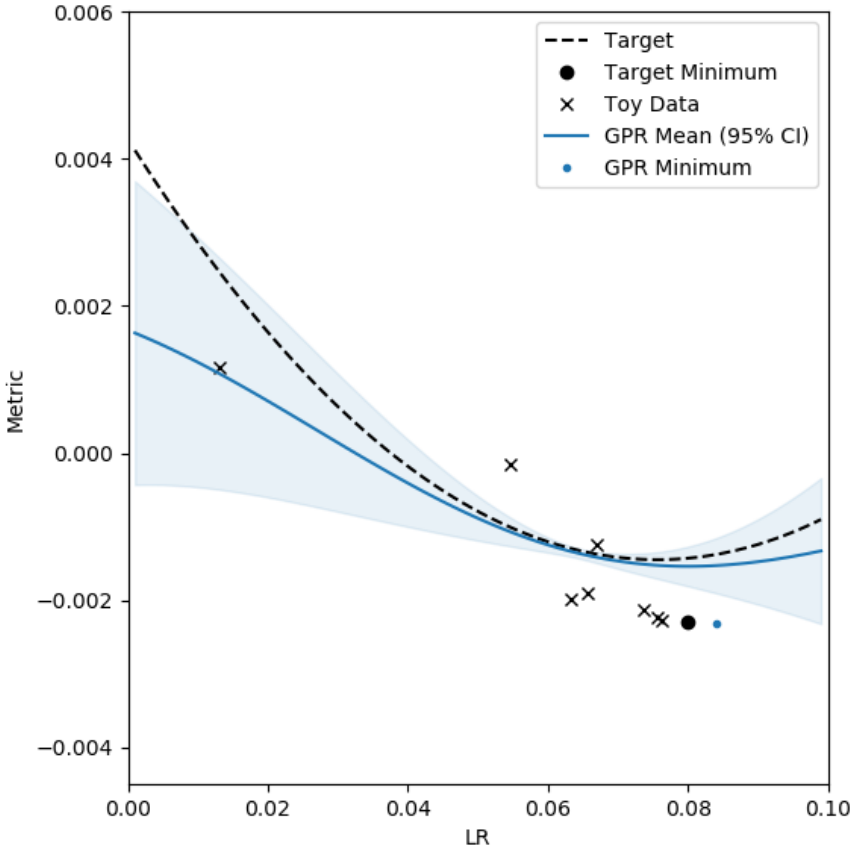


<0.25% error

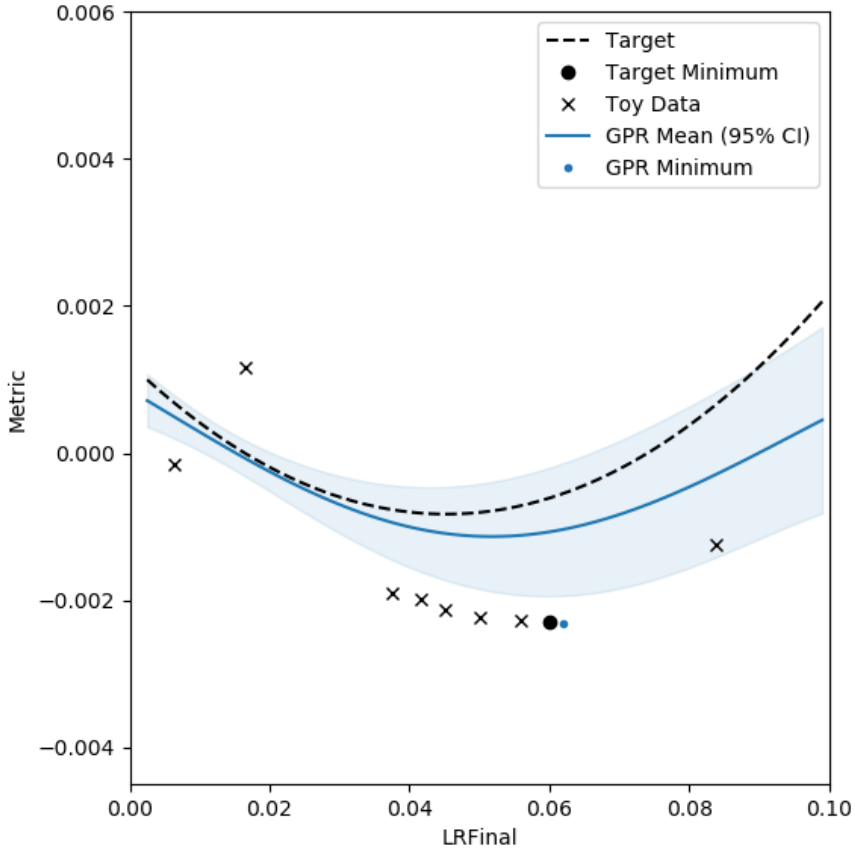
1.6% error

Toy GPR Demonstration

8 training events



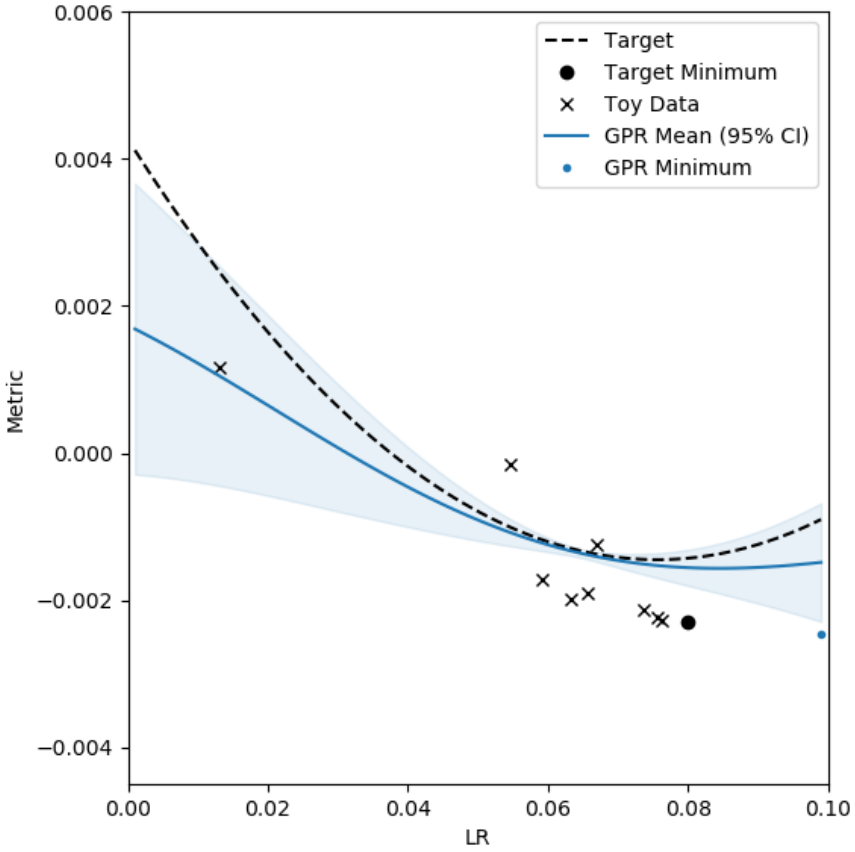
5.2% error



3.3% error

Toy GPR Demonstration

9 training events



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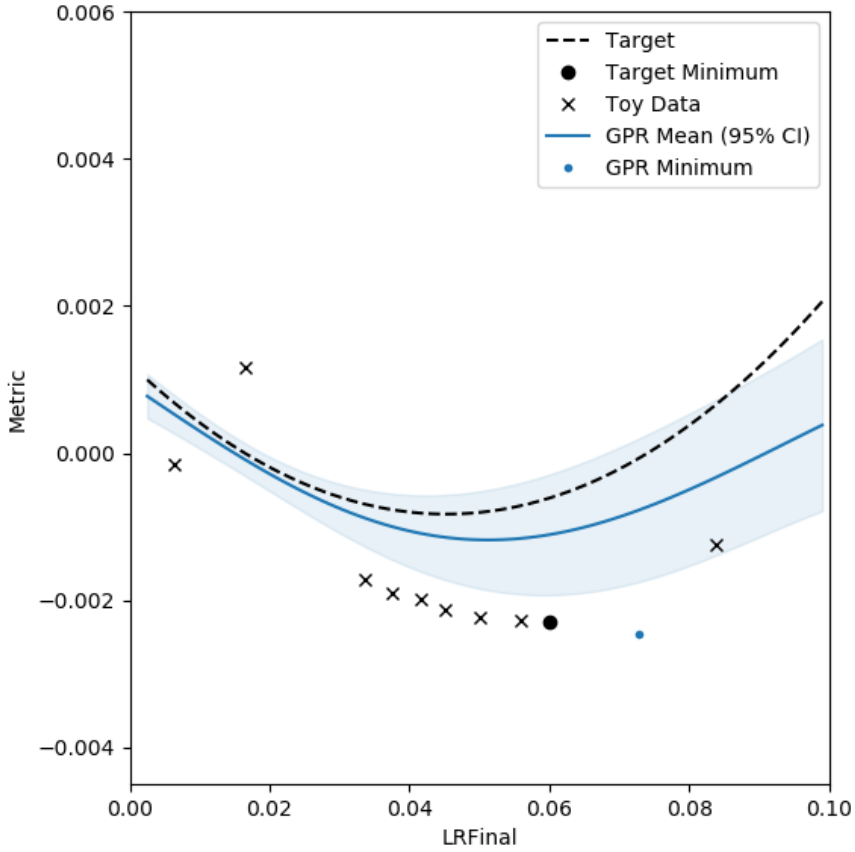
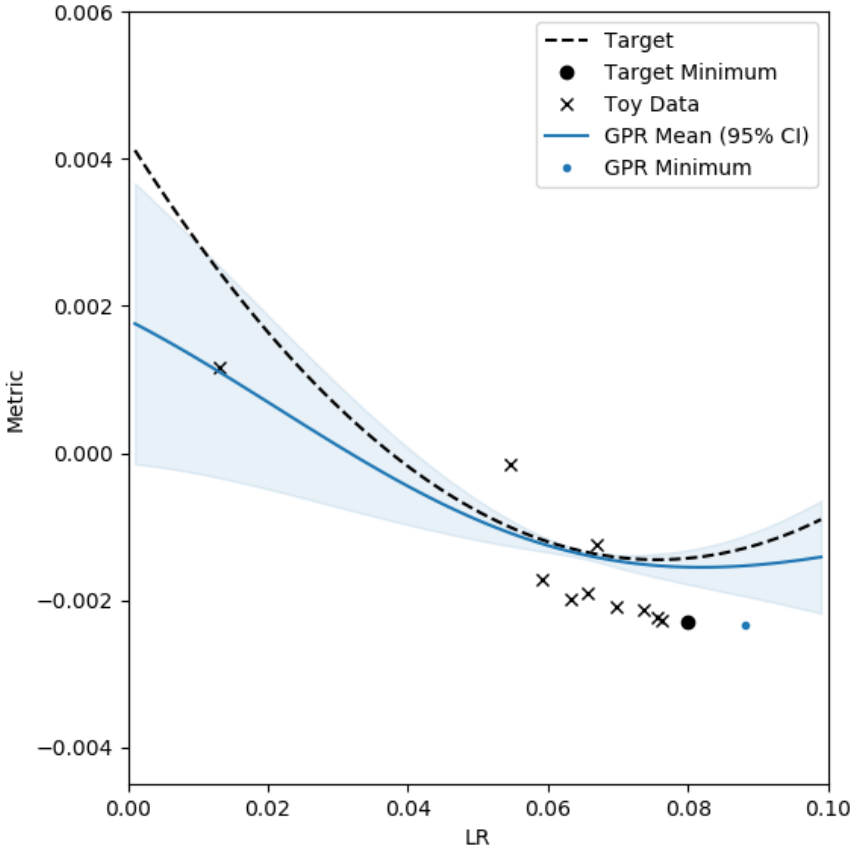


21% error

Toy GPR Demonstration

10 training events



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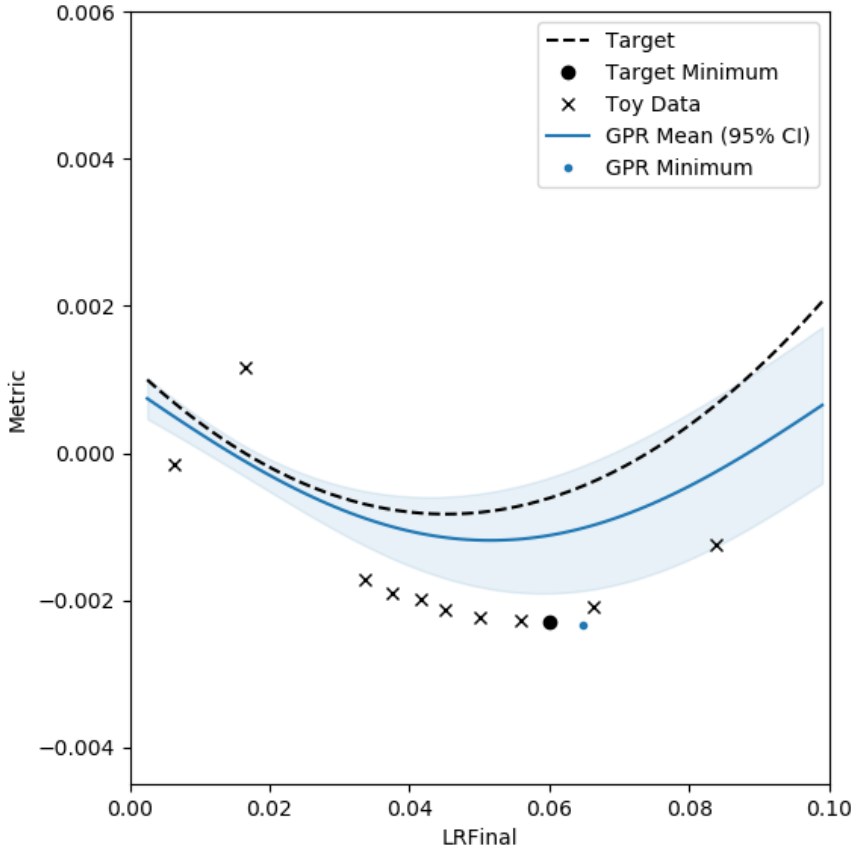
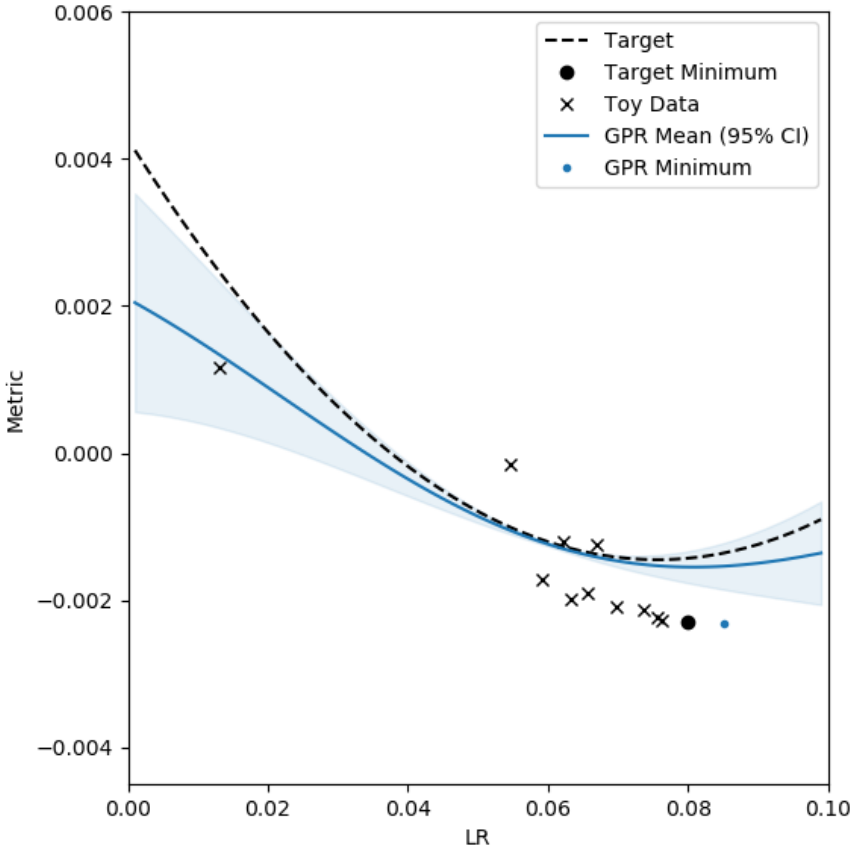


8.2% error

Toy GPR Demonstration

11 training events



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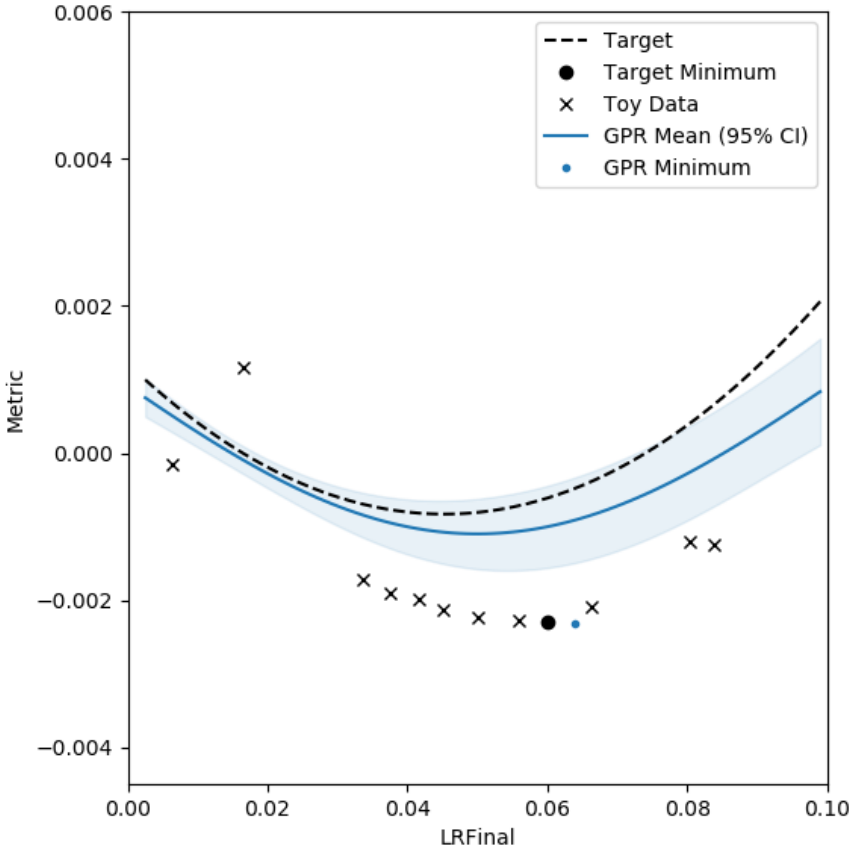
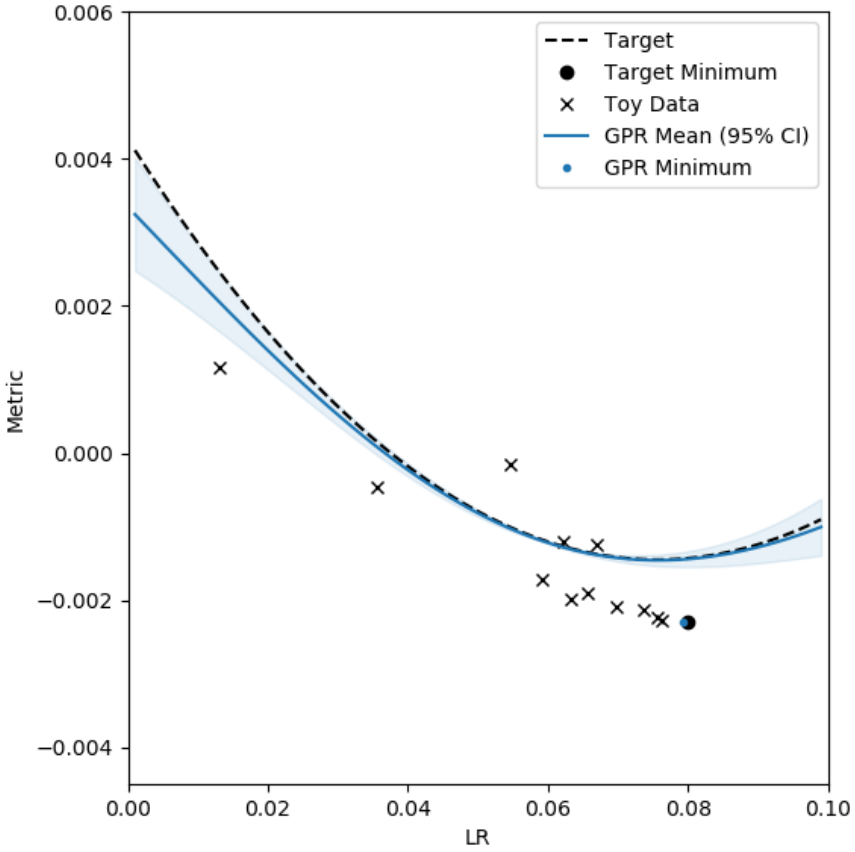
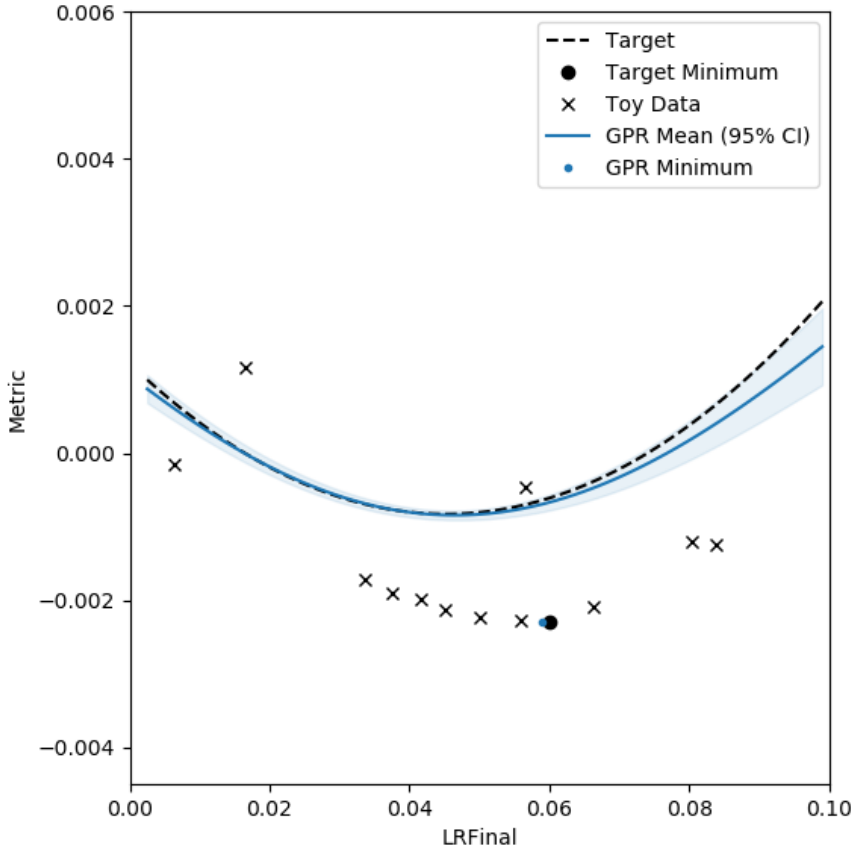


6.5% error

Toy GPR Demonstration

12 training events



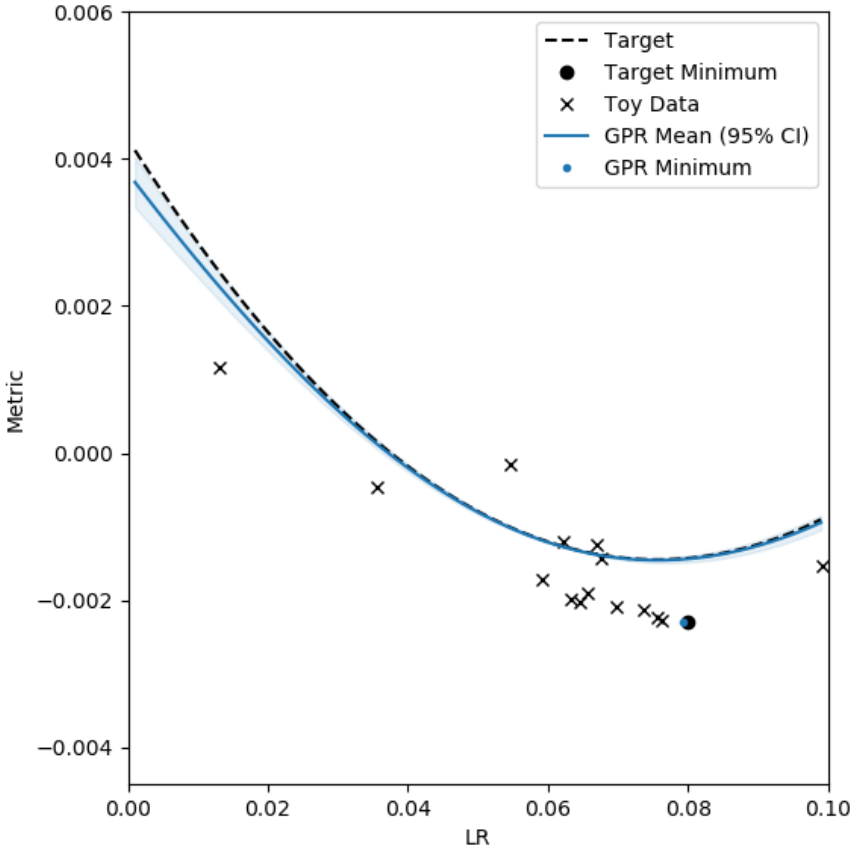


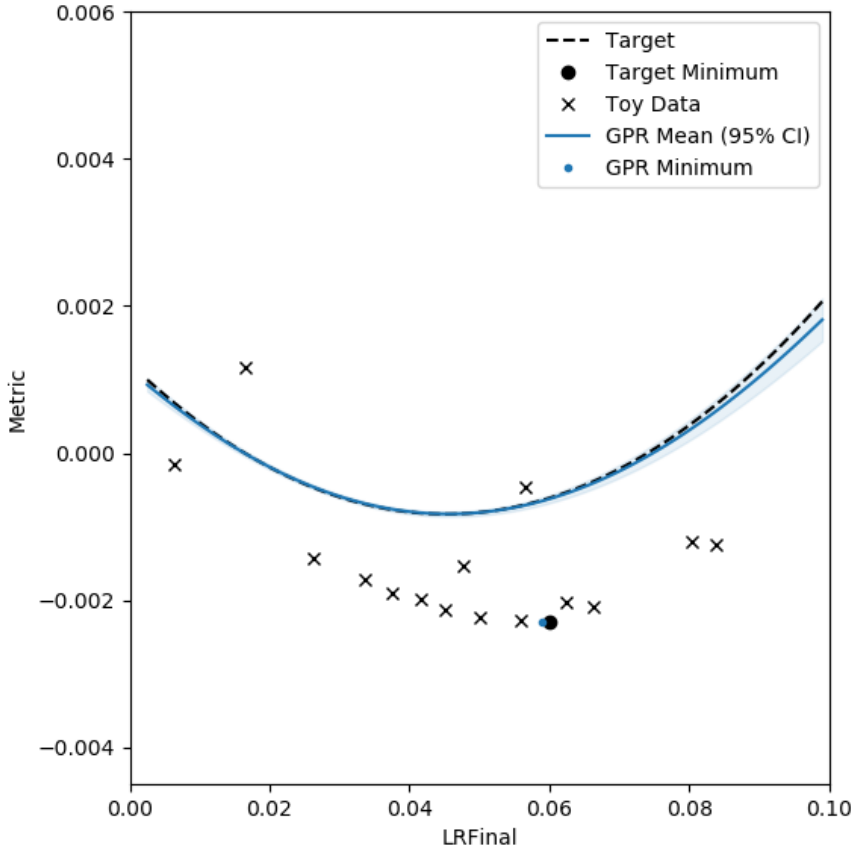
0.99% error

1.6% error

Toy GPR Demonstration

15 training events





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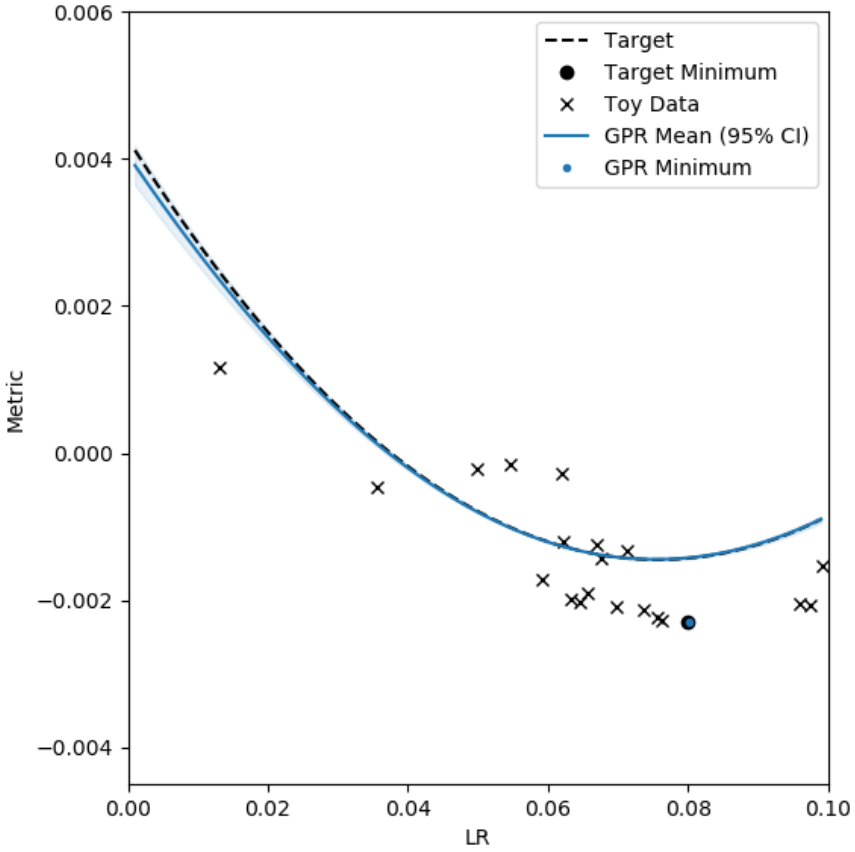
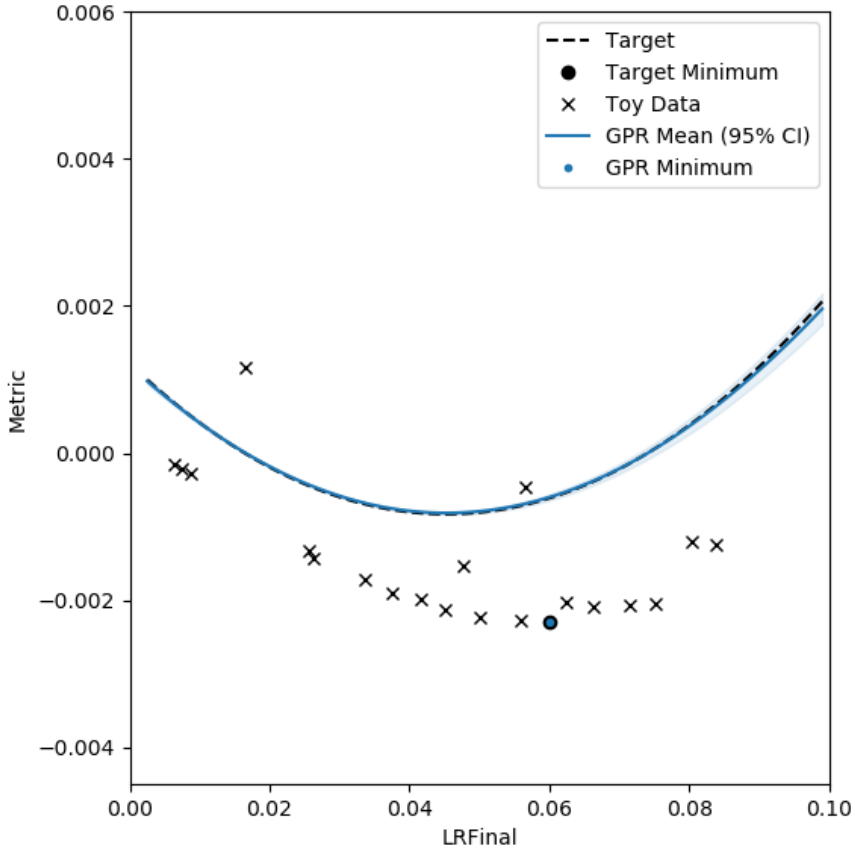
Toy GPR Demonstration

20 training events



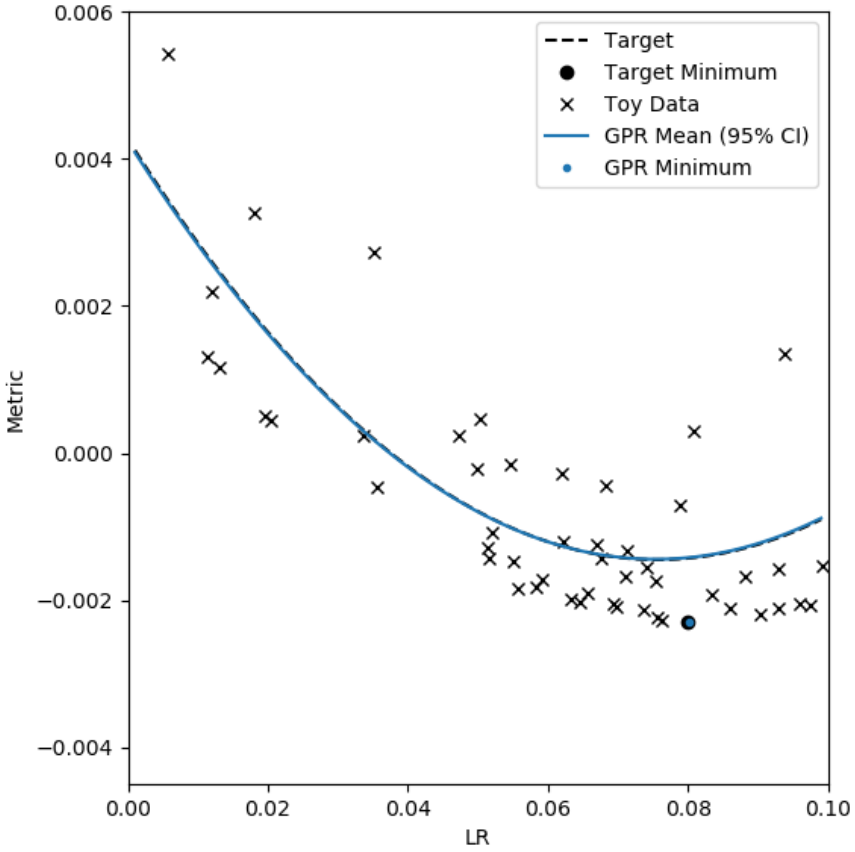


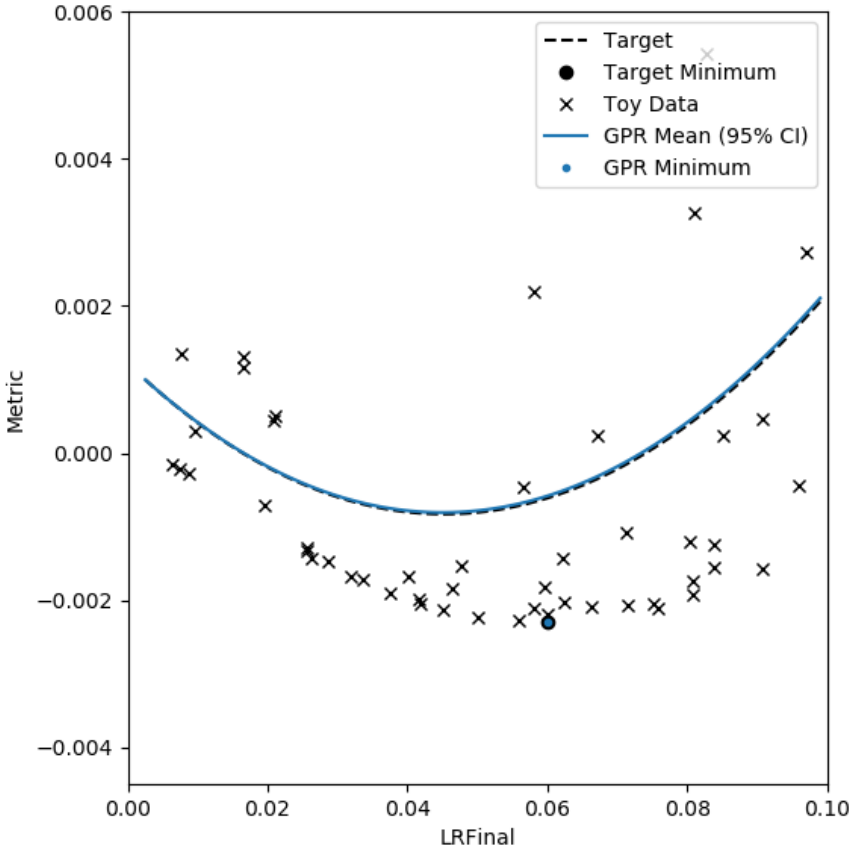
<0.25% error

<0.042% error

Toy GPR Demonstration

50 training events





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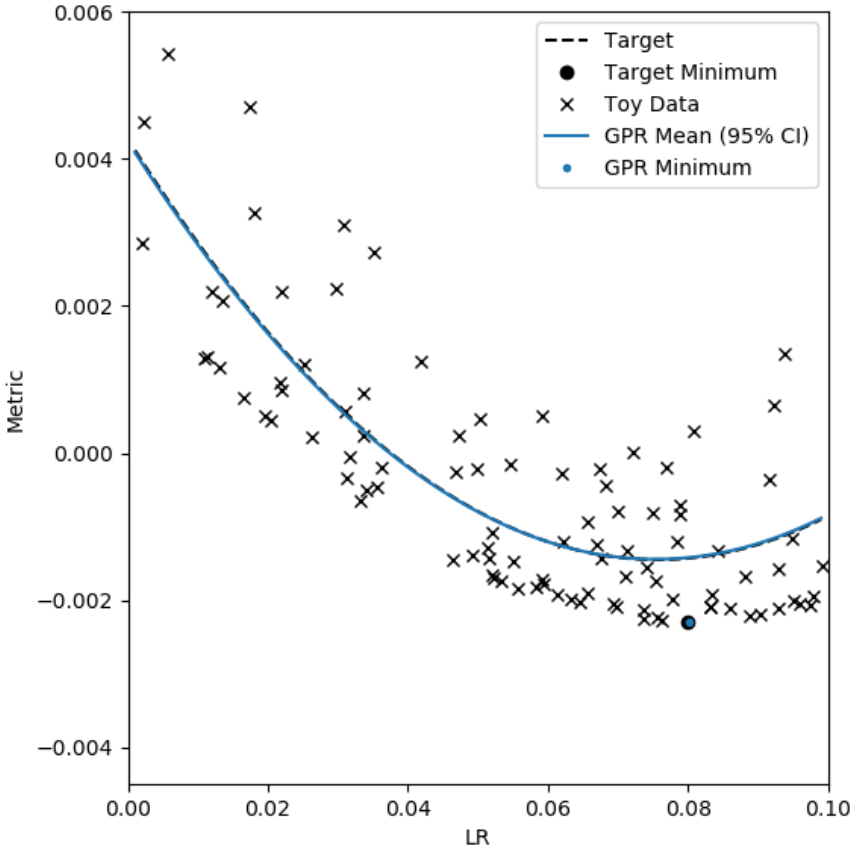
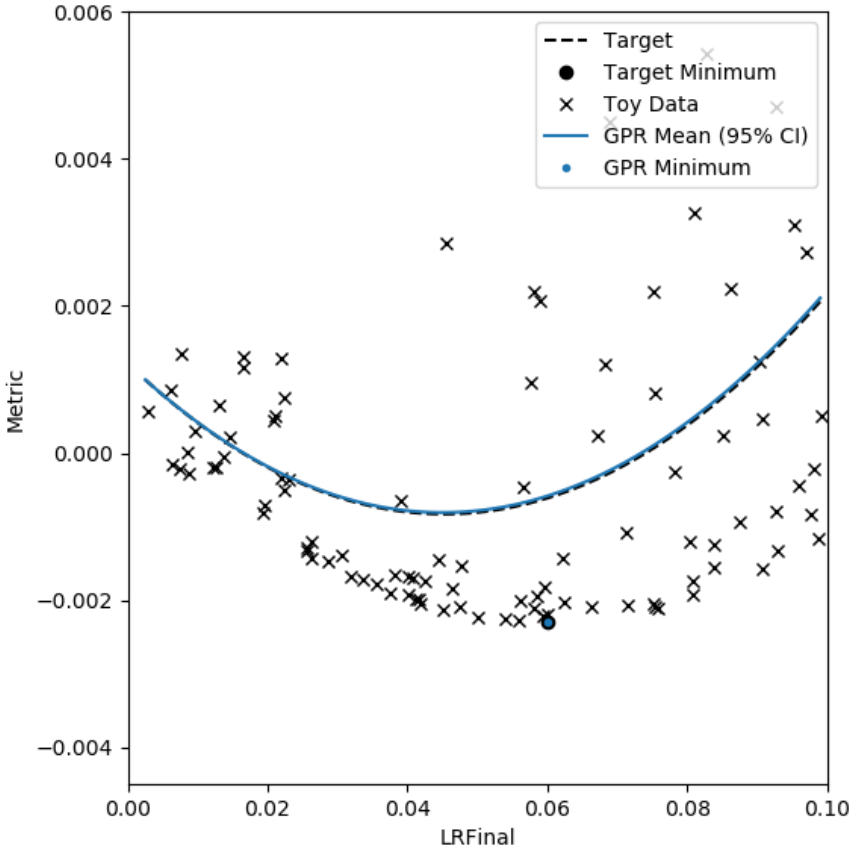
Toy GPR Demonstration

100 training events





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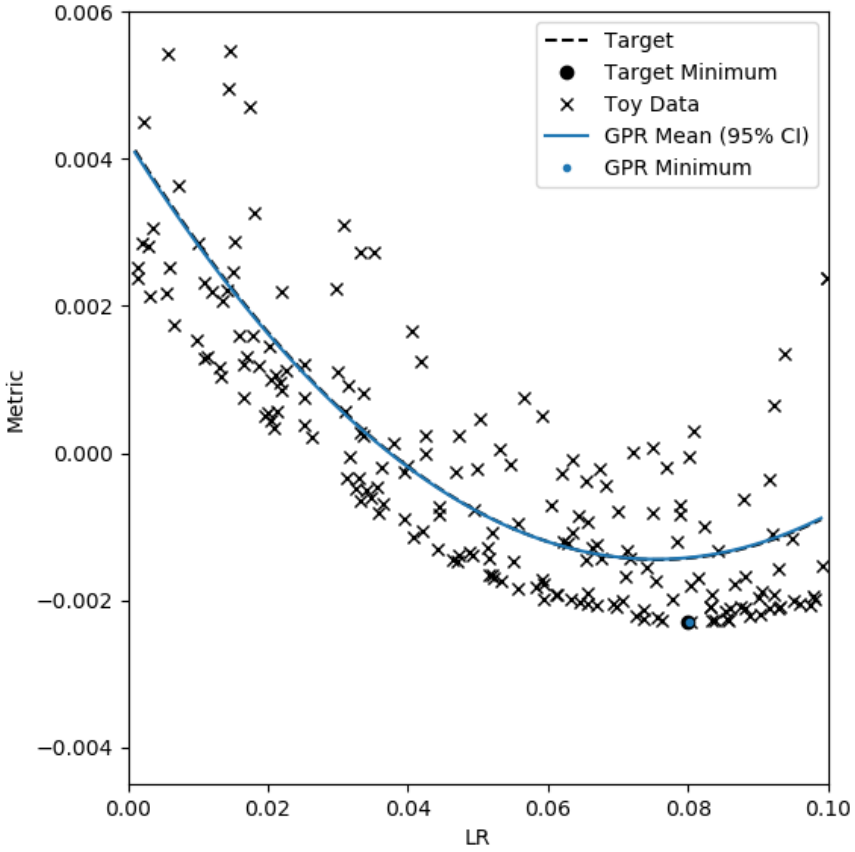
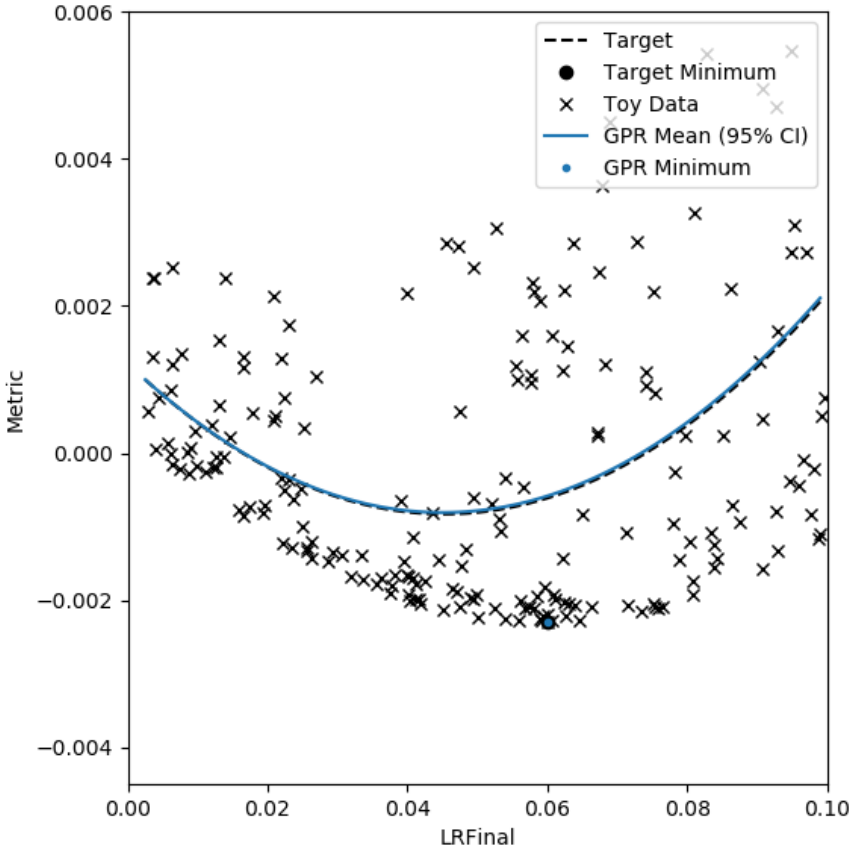
Toy GPR Demonstration

200 training events

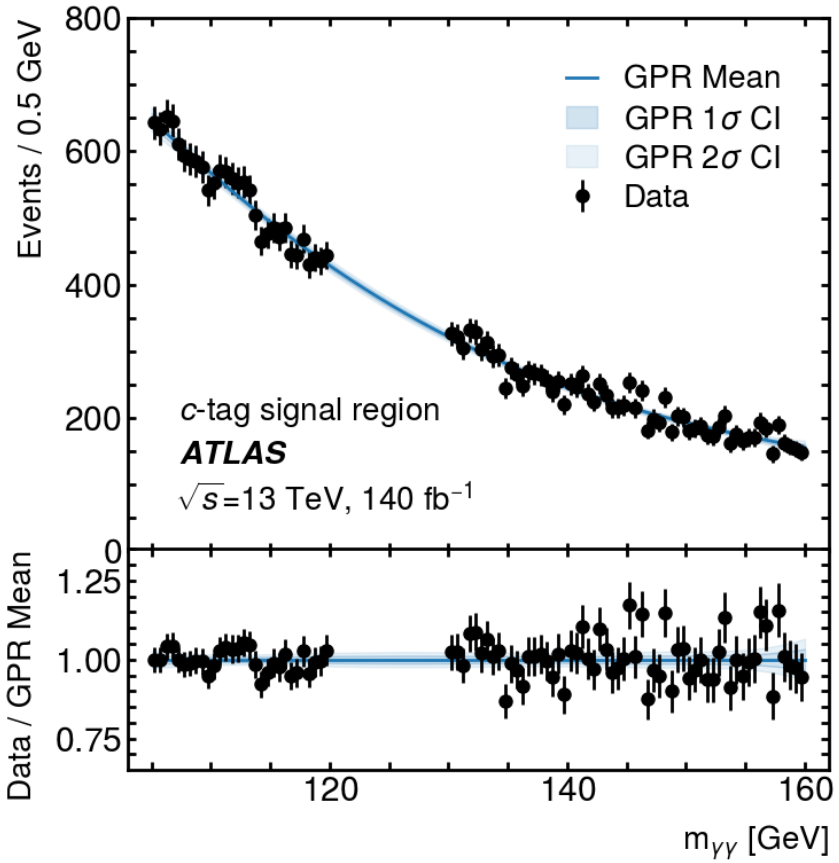


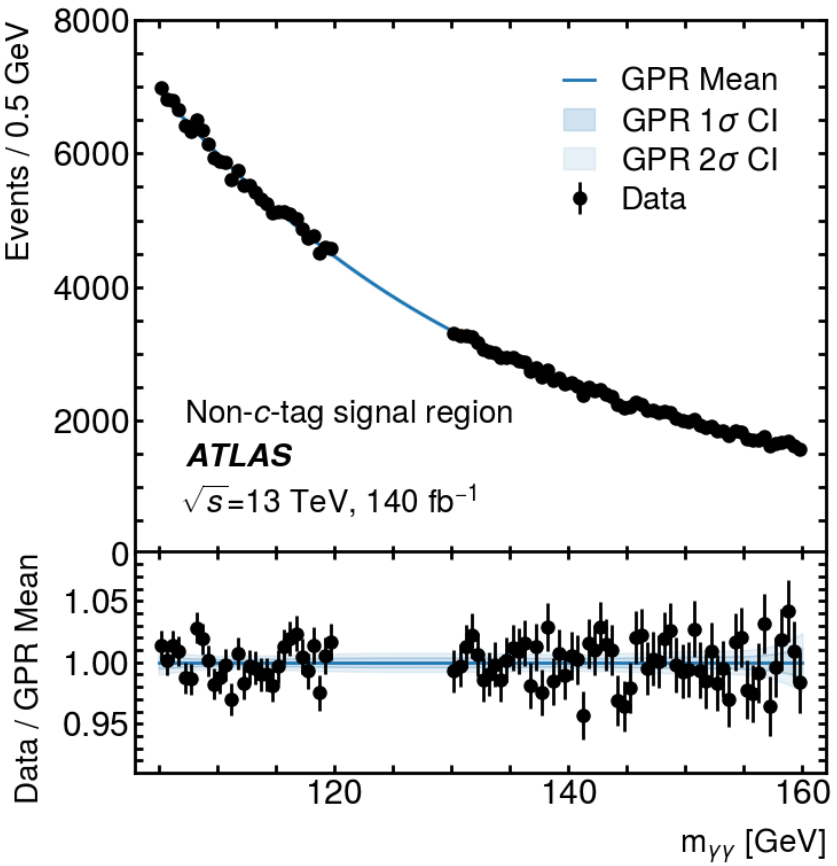
7.7×10^{-9} error



3.0×10^{-9} error

NR background GPR means





arXiv:2407.15550 [hep-ex]

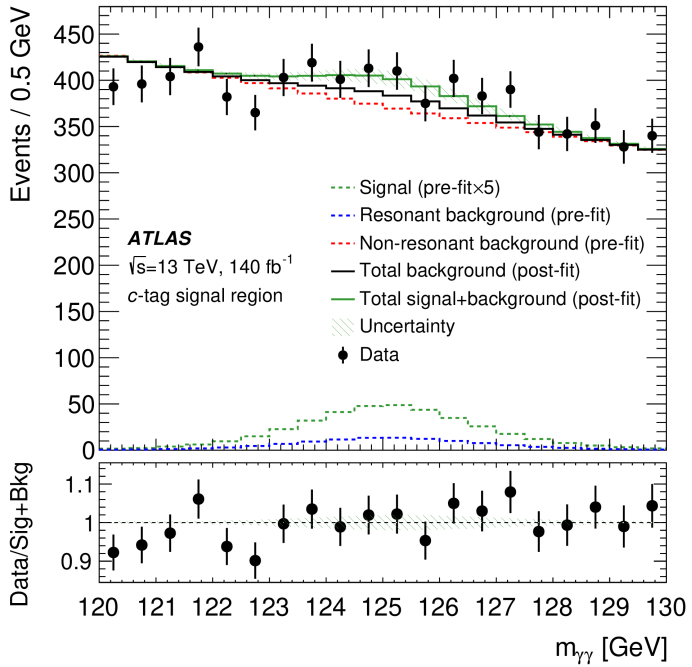
Systematic Uncertainties

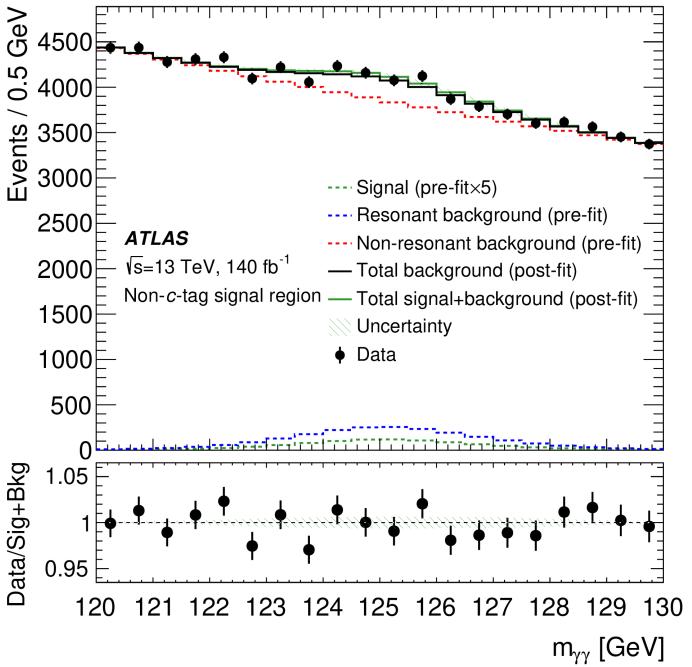
Uncertainty	$H + c$ uncertainty impact
Statistical (incl. GPR)	79%
GPR posterior	47%
Systematic (excl. GPR)	61%
Theory	40%
Photons	29%
c-tagging	29%
Jets	22%
Spurious signal	12%
Pile-up	5%

arXiv:2407.15550 [hep-ex]

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

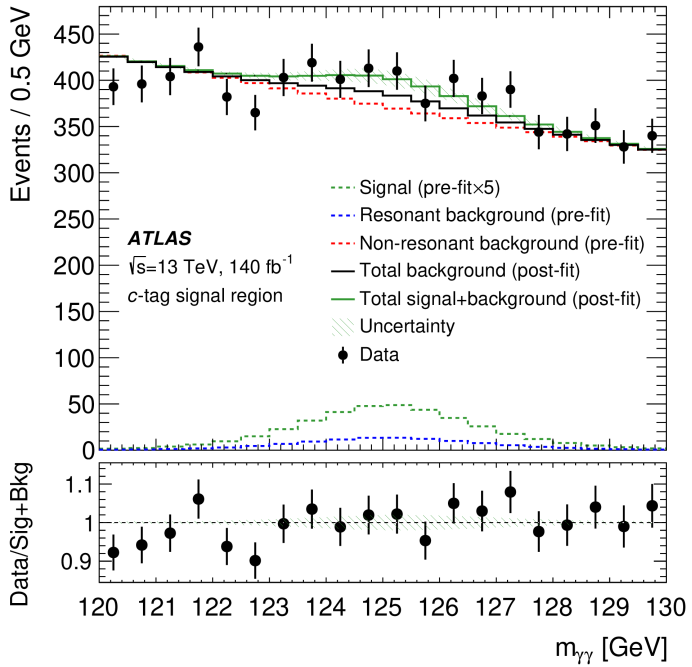


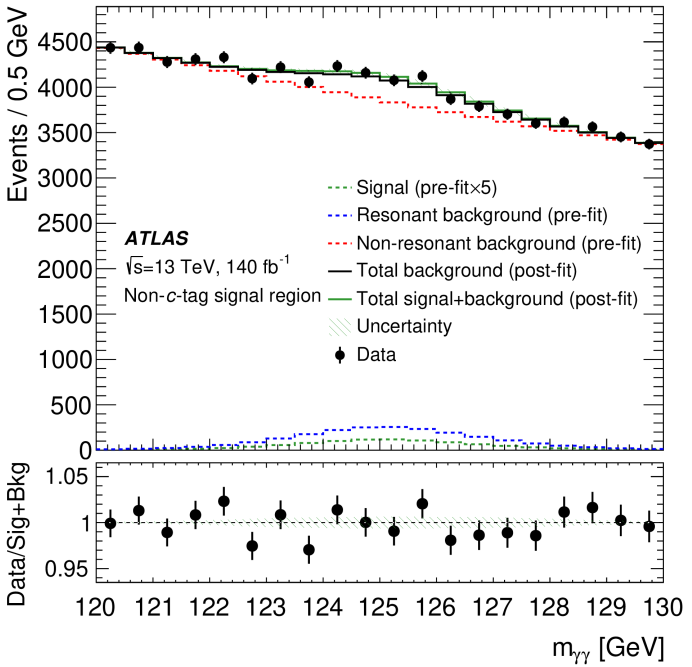


arXiv:2407.15550 [hep-ex]

Results

- Obs (exp) $H + c$ cross-section: **5.2±3.0 pb** (2.9±2.8 pb)
- Obs significance: **1.7σ**
- Obs (exp) 95% CL_s upper limit: **10.4 pb** (8.6 pb)

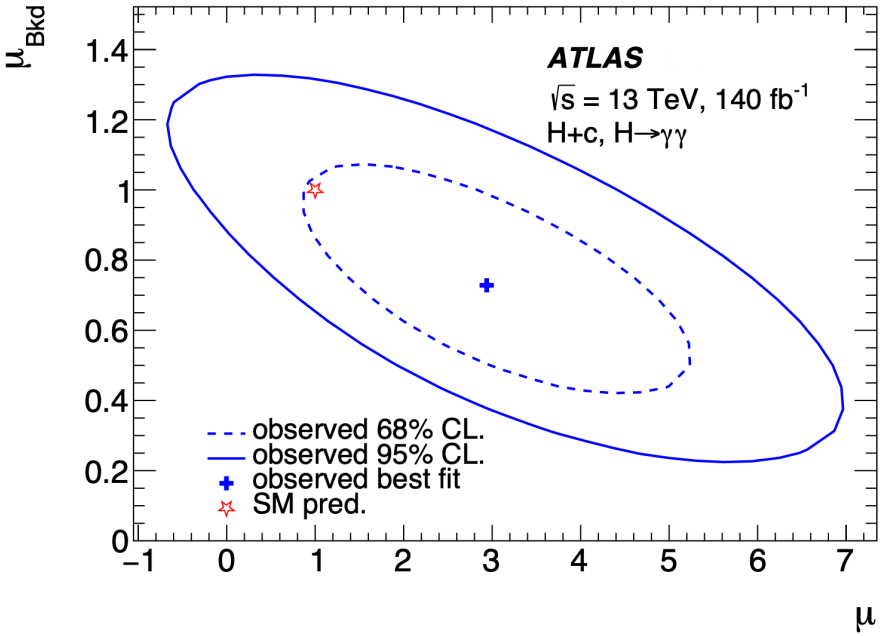




arXiv:2407.15550 [hep-ex]

2D results

- 2D likelihood scan over μ and μ_{Bkd} also performed
  - μ_{Bkd} is a free resonant background normalisation
- Limit deteriorates by 22% with free μ_{Bkd}
- Correlation between μ and μ_{Bkd} is -66%

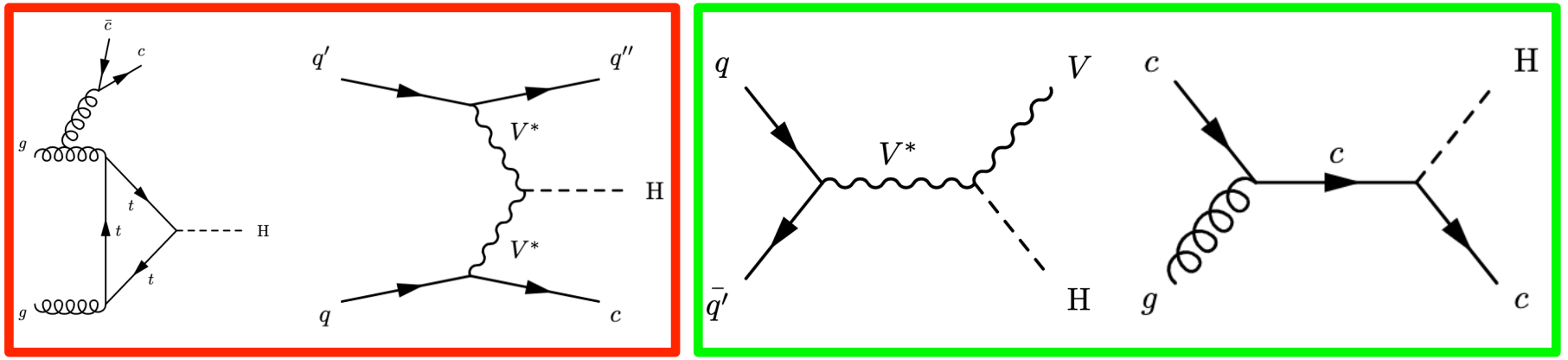


arXiv:2407.15550 [hep-ex]

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 result
  - Current signal and resonant background theory and **modelling uncertainties not modified**
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- Obs (exp) upper limit on y_c/y_c^{SM}: **~26 (~24)**
- 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

- Major progress has been made in probing y_c, but no plan in place for observation, even for at the HL-LHC
- $H + c$ 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. $H \to ZZ$)
  - Possible analysis improvements (e.g. from ML), beyond this first iteration

arXiv:2407.15550 [hep-ex]

CMS $H + c$ Result

- CMS also interested in $H + c$, and have a PAS
- 138 fb^{-1} of pp collision data
- $H \rightarrow \gamma\gamma$ decays were used

CMS-PAS-HIG-23-010

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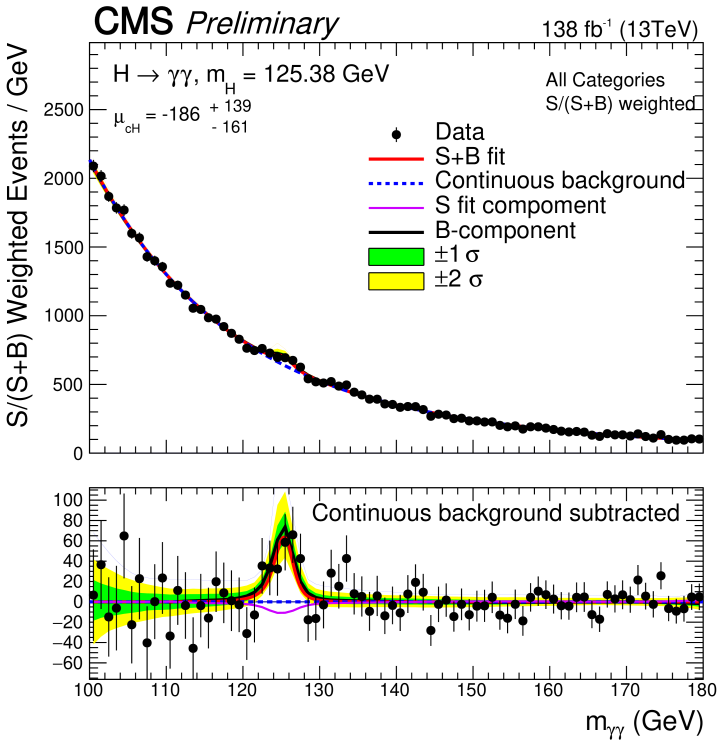
- Obs (exp) 95% CL upper limits on $|y_c/y_c^{SM}|$: **38.1** (72.5)



CMS-PAS-HIG-23-010

Conclusions

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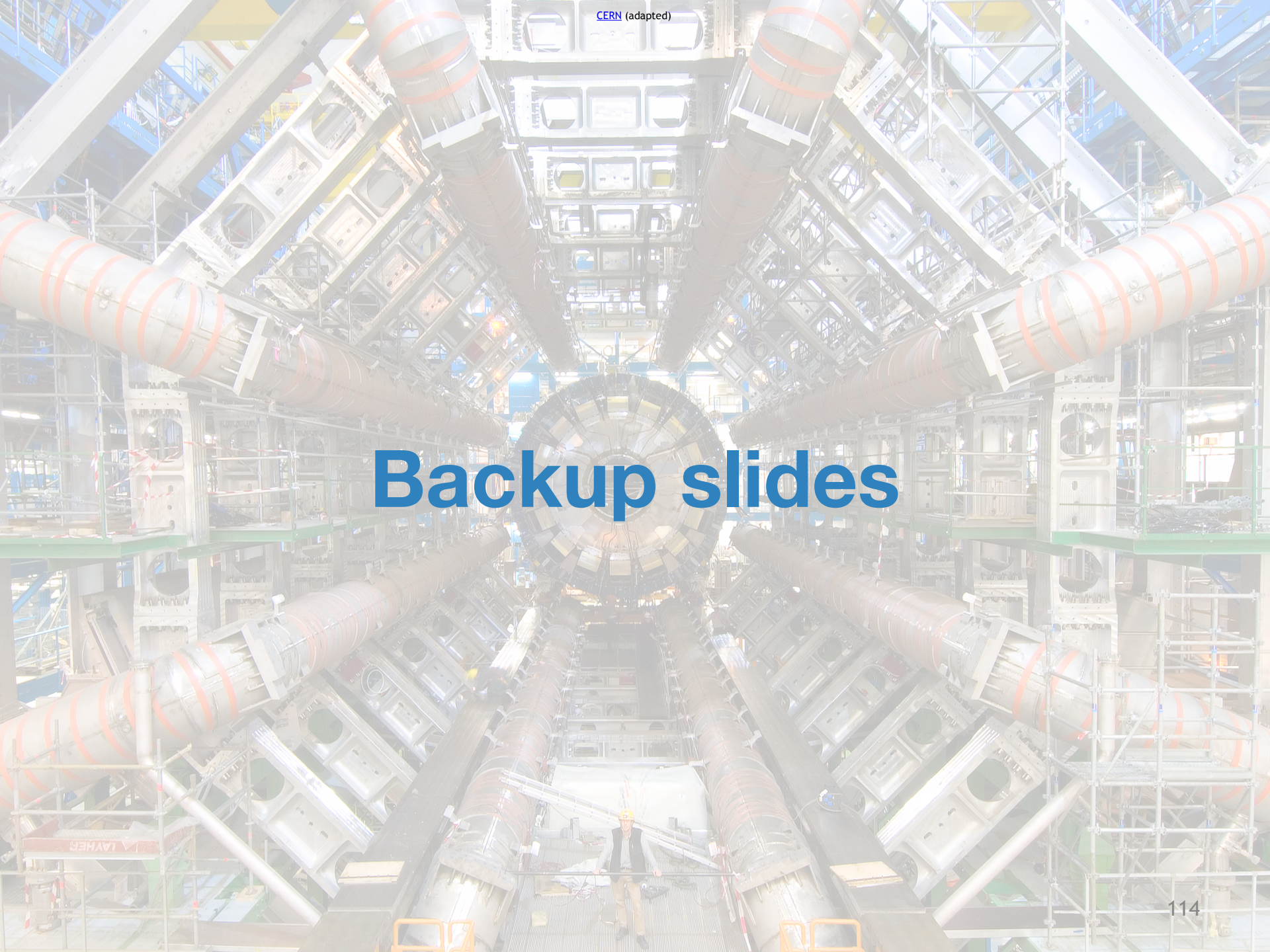
- **First inclusive $H + c$ measurement!**
- Measured $H + c$ cross-section: **5.2 ± 3.0 pb**
  - Compatible with SM expectation: **2.9 pb**
- Substantial improvements possible in future analyses
- $H + c$ may play a key role in constraining y_c down the road, but theory inputs will be needed

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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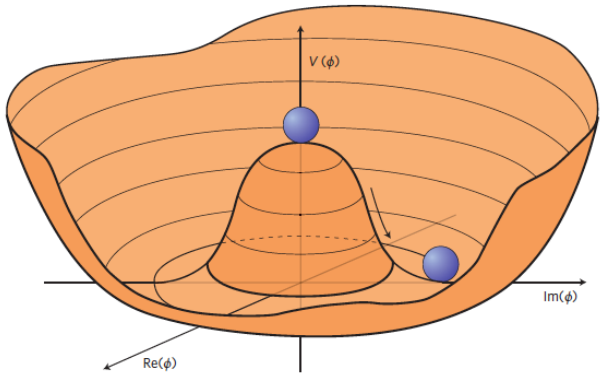
- Only particle with a non-zero vacuum expectation value
- Causes electroweak symmetry breaking
  - Fundamental to the electromagnetic and weak nuclear forces
- The source of mass of all fundamental particles



Nat Rev Phys 3 (2021) 608

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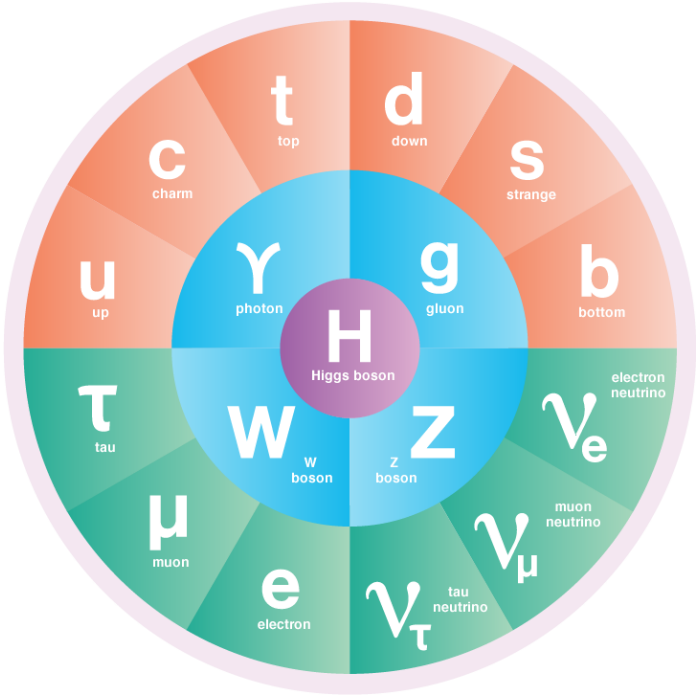
- Completes the Standard Model

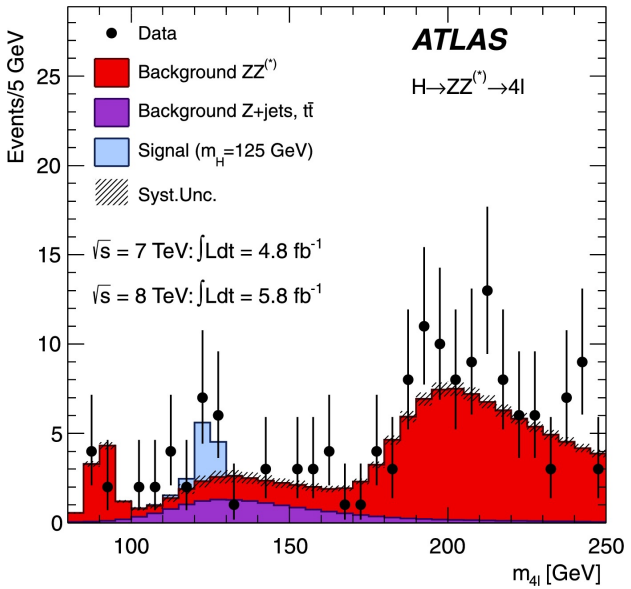


Symmetry Magazine

Higgs boson discovery

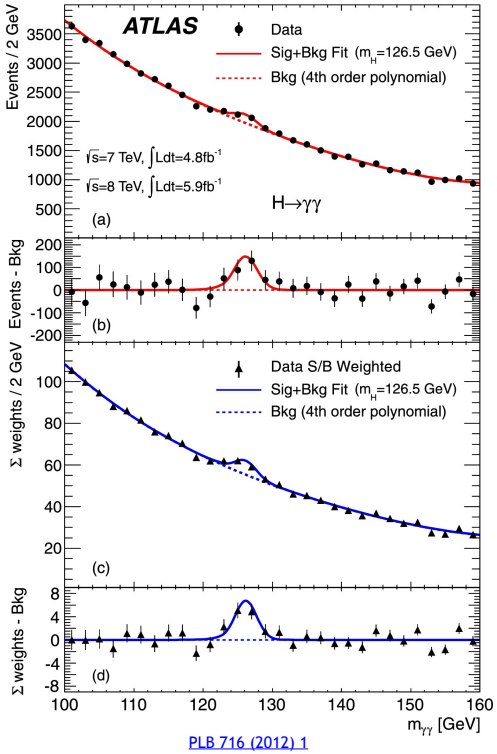
Single neutral Higgs boson (H) with a mass of 125 GeV discovered in 2012 by ATLAS and CMS

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



PLB 716 (2012) 1

$H \to \gamma\gamma$



PLB 716 (2012) 1

CMS VH, $H \to c\bar{c}$ 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 $H \to c\bar{c}$ decays, parton showers, hadronisations and pileup
- Detector response modelled using Geant4

PRL 131 (2023) 061801

CMS VH, H → cc̄ 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 $H \to c\bar{c}$ 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

PRL 131 (2023) 061801

CMS VH, $H \to c\bar{c}$ 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

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CMS VH, H → cc̄ Systematics

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

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

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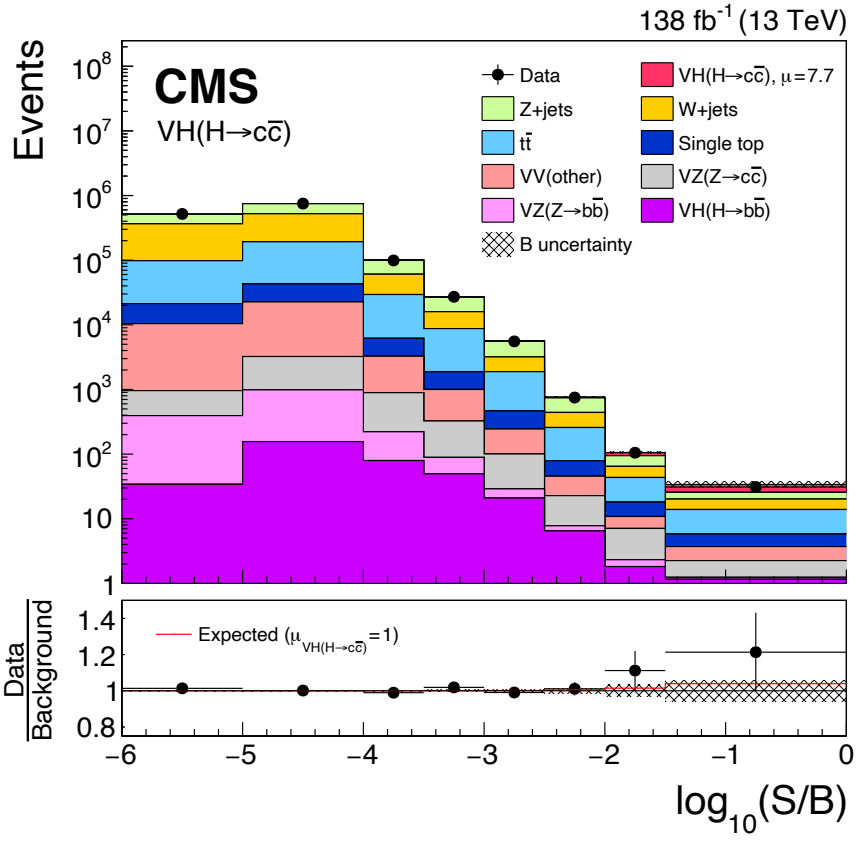
CMS VH, H → $c\bar{c}$ S/B



PRL 131 (2023) 061801

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

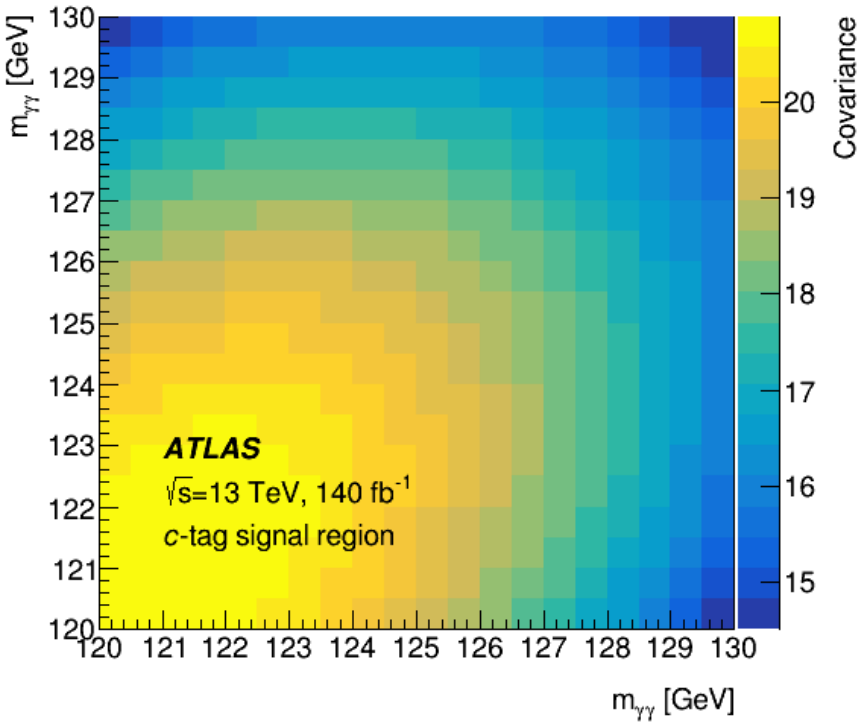
arXiv:2407.15550 [hep-ex]

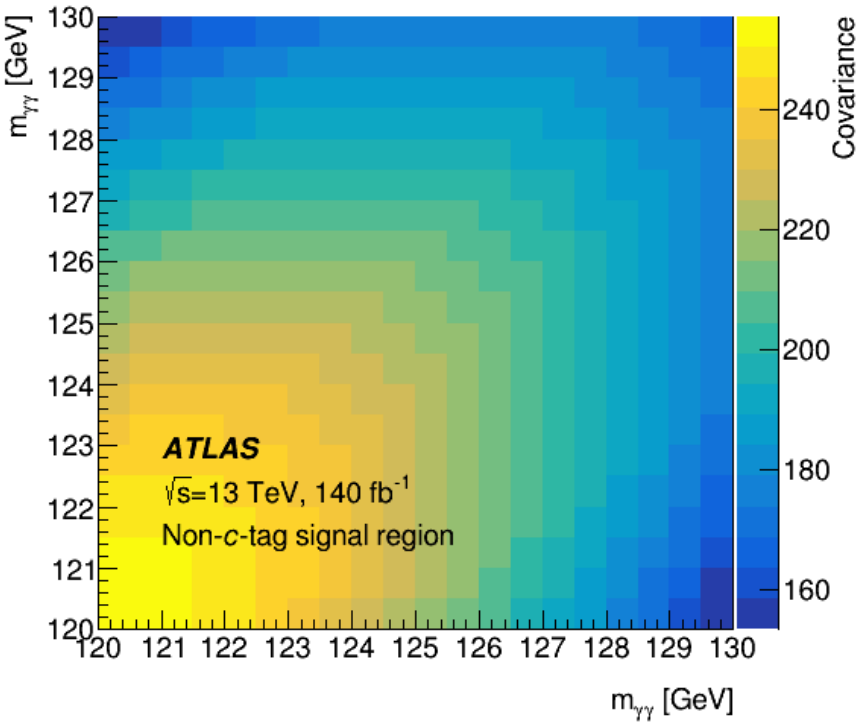
Signal and resonant background compositions

Process	c-tag signal region		Non-c-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

arXiv:2407.15550 [hep-ex]

GPR covariances

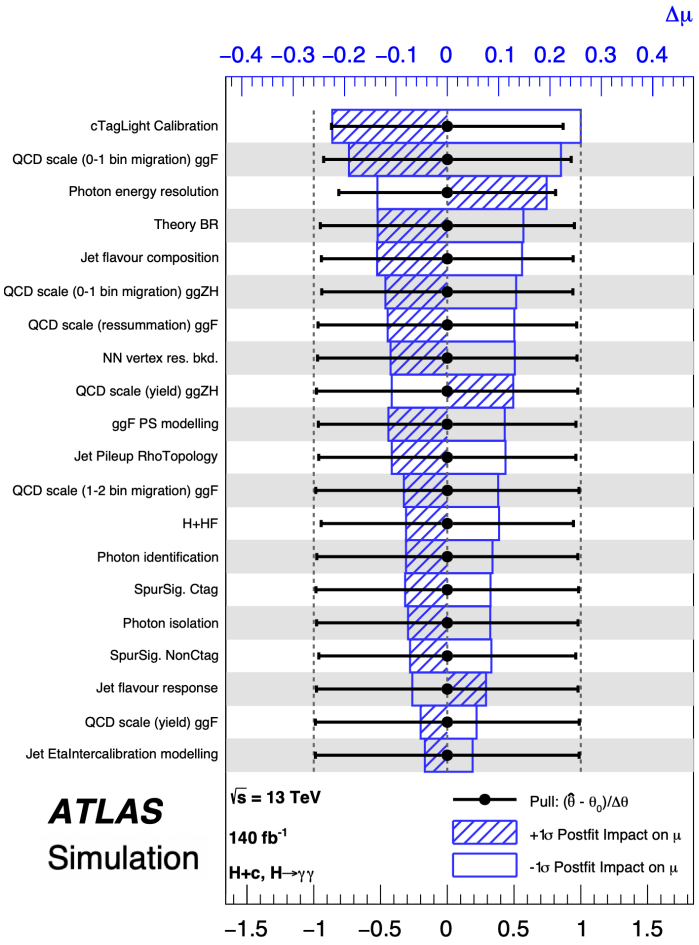




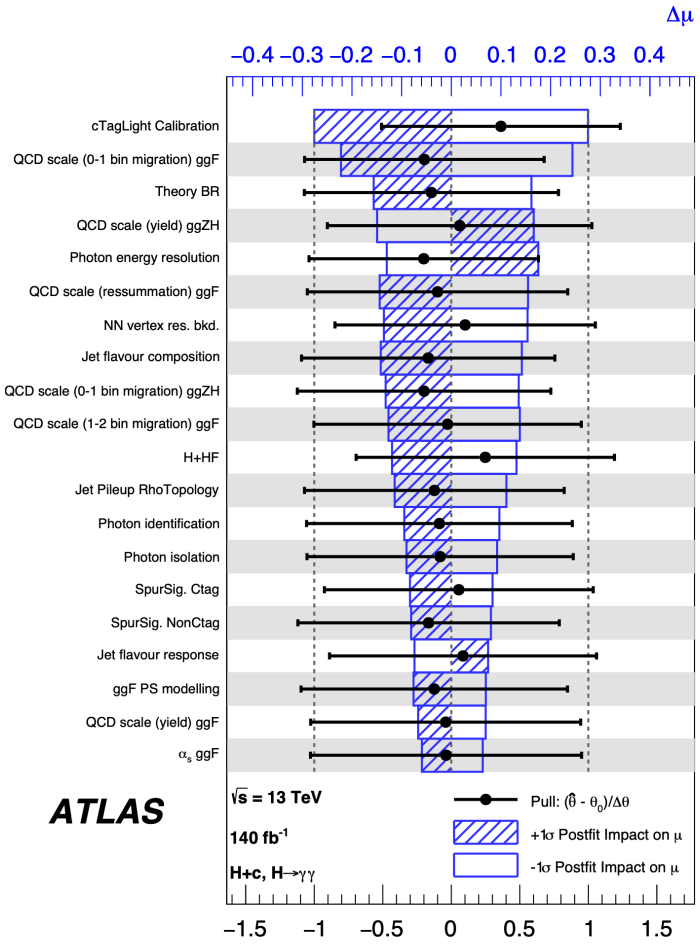
arXiv:2407.15550 [hep-ex]

Main Nuisance Parameters

Expected/Asimov



Observed/Data



arXiv:2407.15550 [hep-ex]

Approximate κ_c interpretation

"Back-of-the-envelope" non-ATLAS interpretation

A. Our obs (exp) limit is ~3.6 (~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 0.5% the size of the signal

C. From A & B: the obs (exp) upper limit is ~670 (~550) times the number of κ_c-sensitive events (assuming current $m_{\gamma\gamma}$ shapes and modelling uncertainties)

D. Assuming $\mathcal{B}(H \to \gamma\gamma) = \mathcal{B}_{\mathrm{SM}}(H \to \gamma\gamma)$
   A. Could approximately result from simultaneous fit

E. From C & E: the obs (exp) upper limit on κ_c is **~26 (~24)**