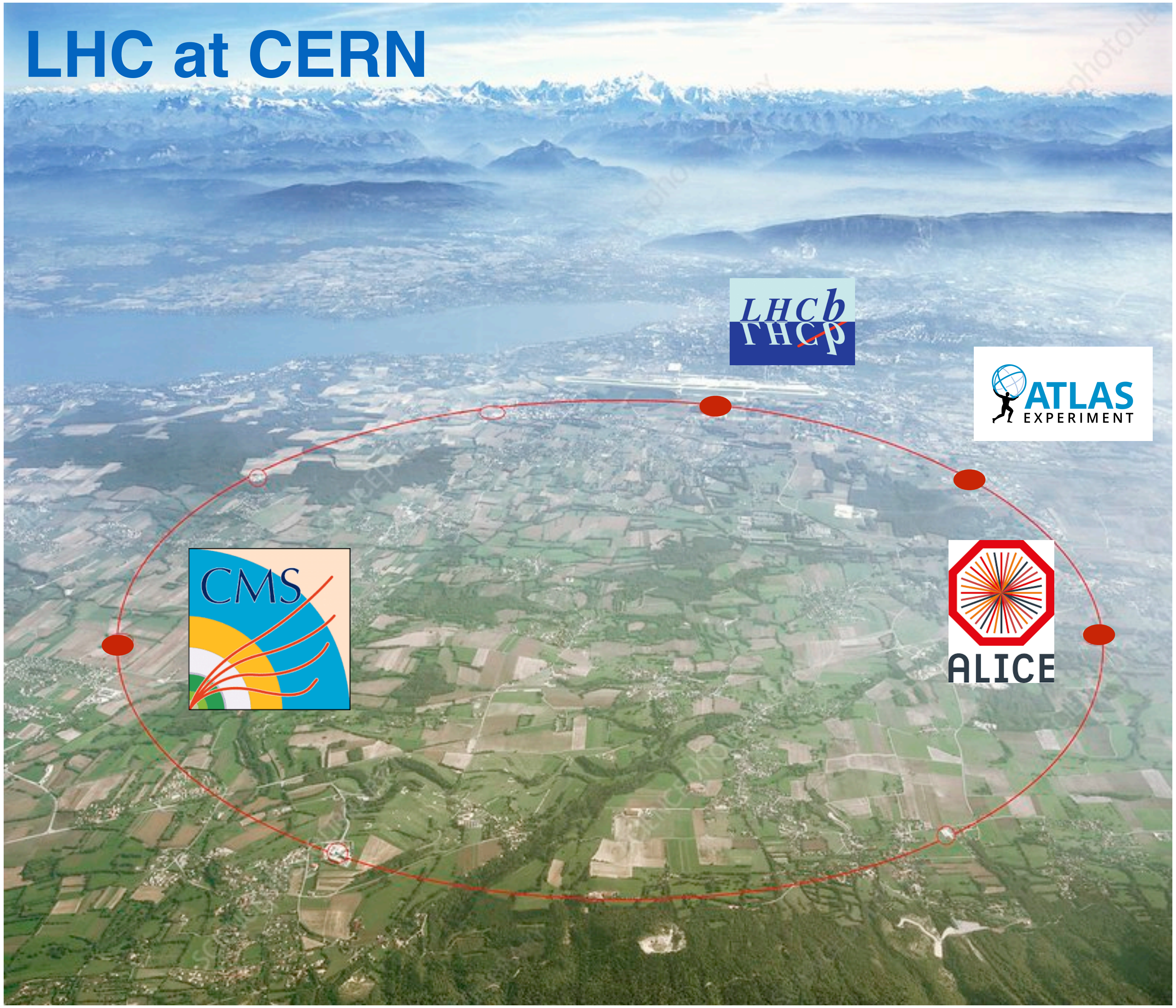
Physics at CMS

Matthew Citron for the CMS collaboration

The LHC ***is** the Energy Frontier

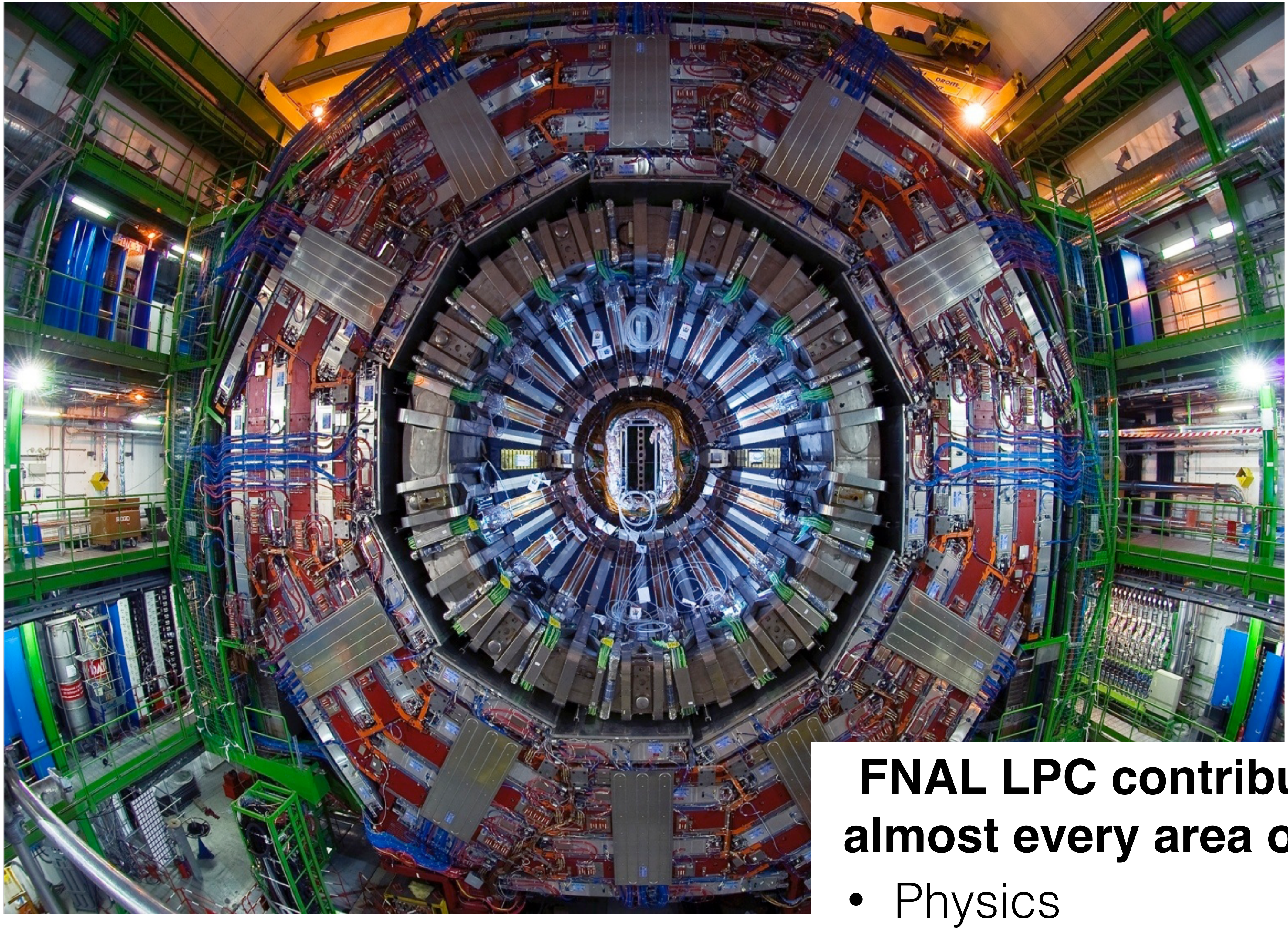


Now providing proton collisions at **13.6 TeV** and **record luminosity**!

M. Citron mcitron@ucdavis.edu

*currently - see Larry's talk

The **C**ompact **M**uon **S**olenoid detector



FNAL LPC contributes to almost every area of CMS!

- Physics
- Operations (ROC)
- Detector Construction/R&D

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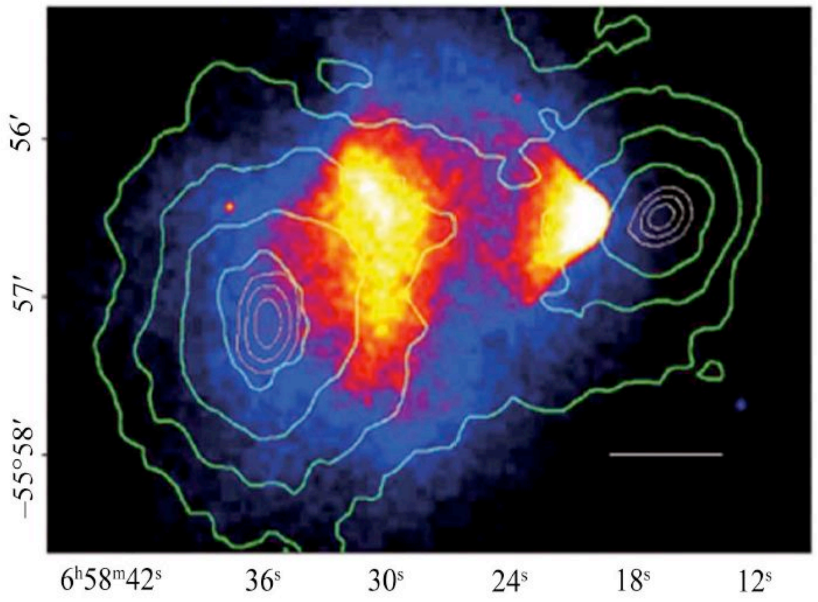
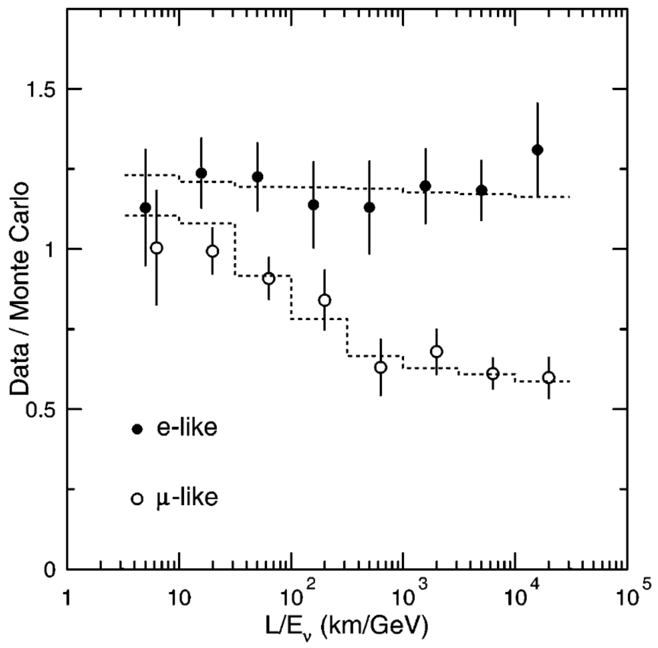
CMS explores mysteries in our understanding of the universe

Many fundamental questions

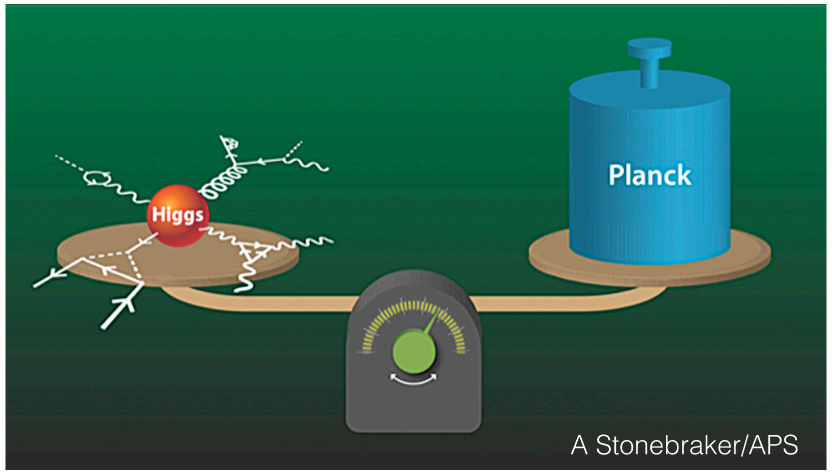
What is DM?



How do neutrinos get their mass?

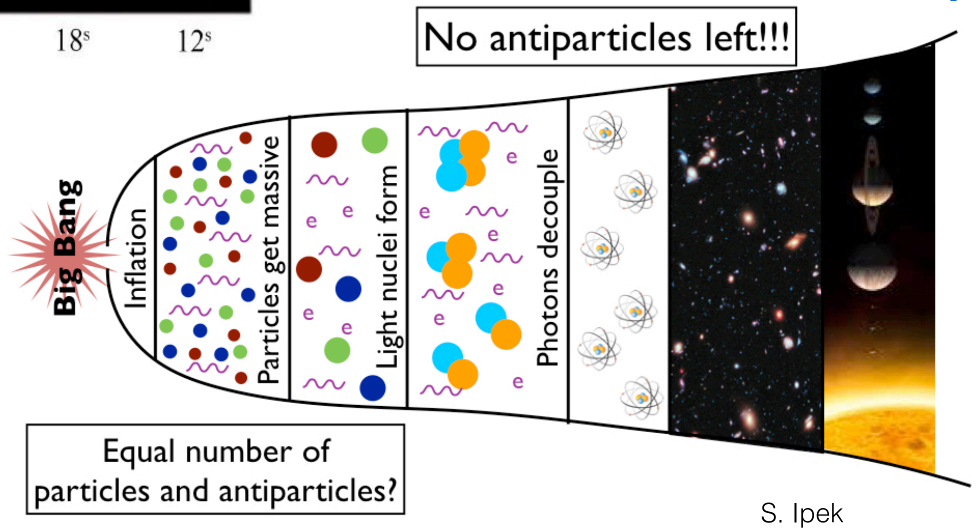


Why is the Higgs so light?



A Stonebraker/APS

What causes matter/anti-matter asymmetry?



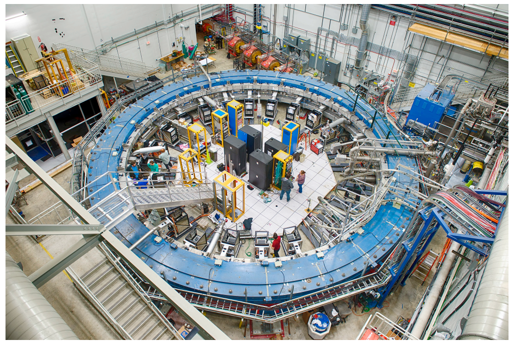
S. Ipek

+ more

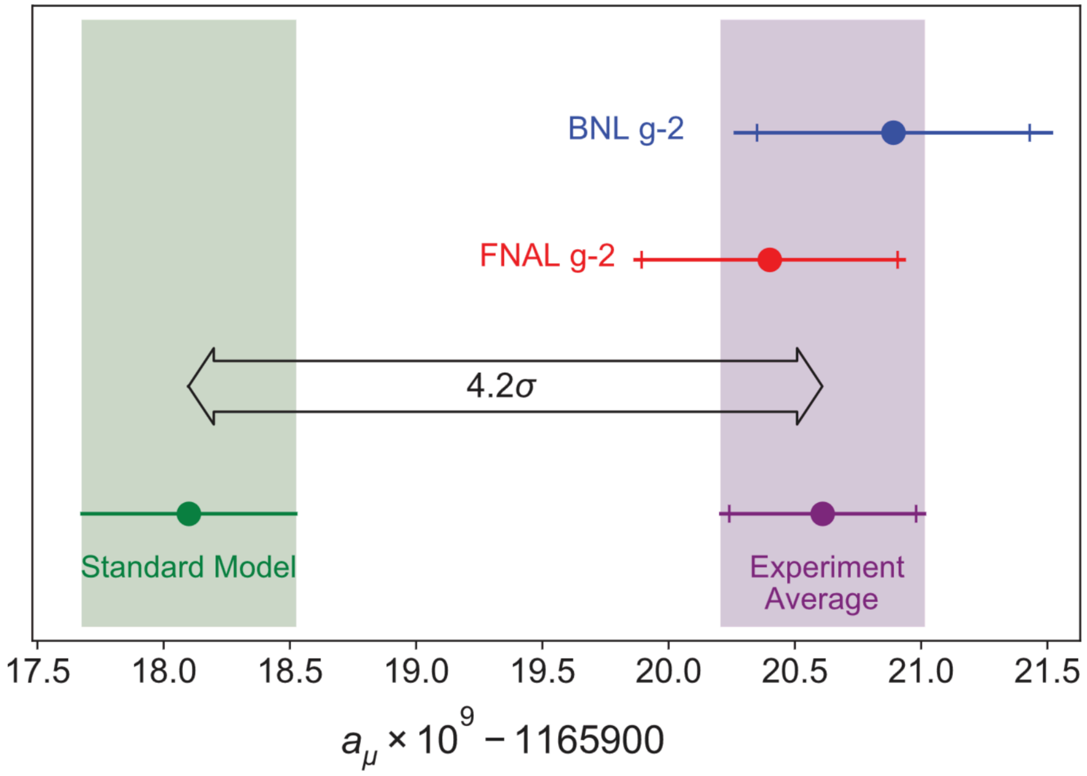
CMS explores mysteries in our understanding of the universe

Potential cracks observed in the SM

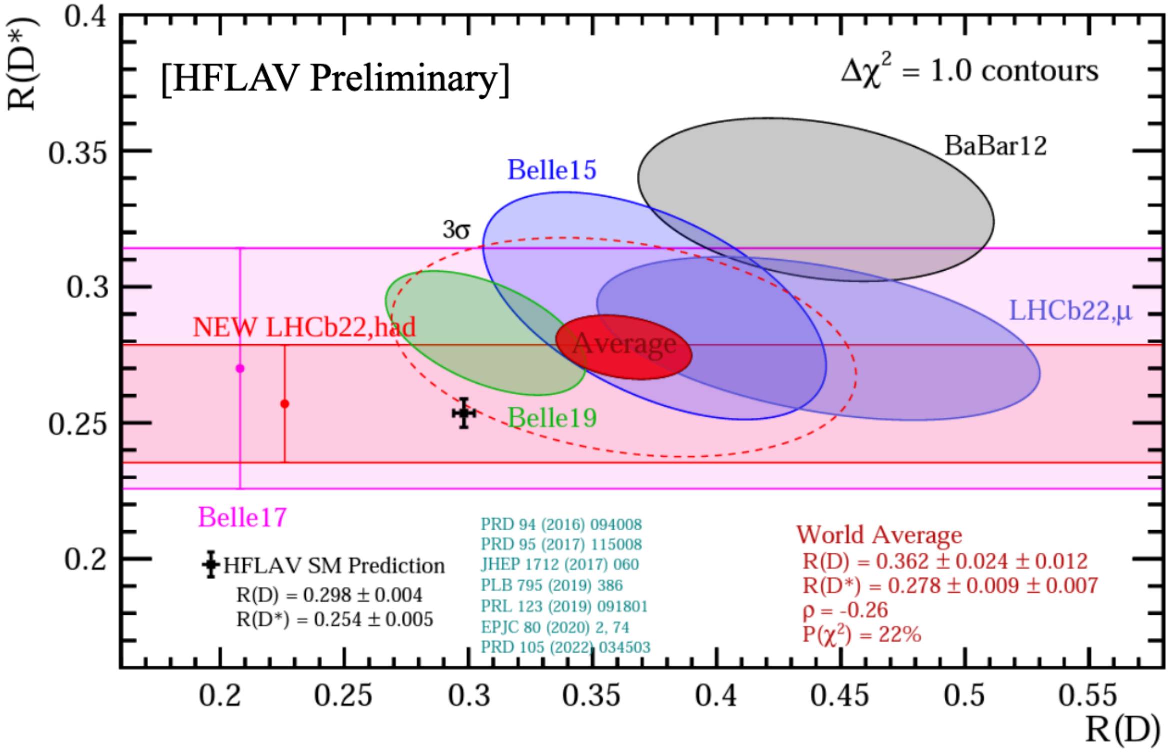
(g-2)$_\mu$



Ring at FNAL



B physics anomalies



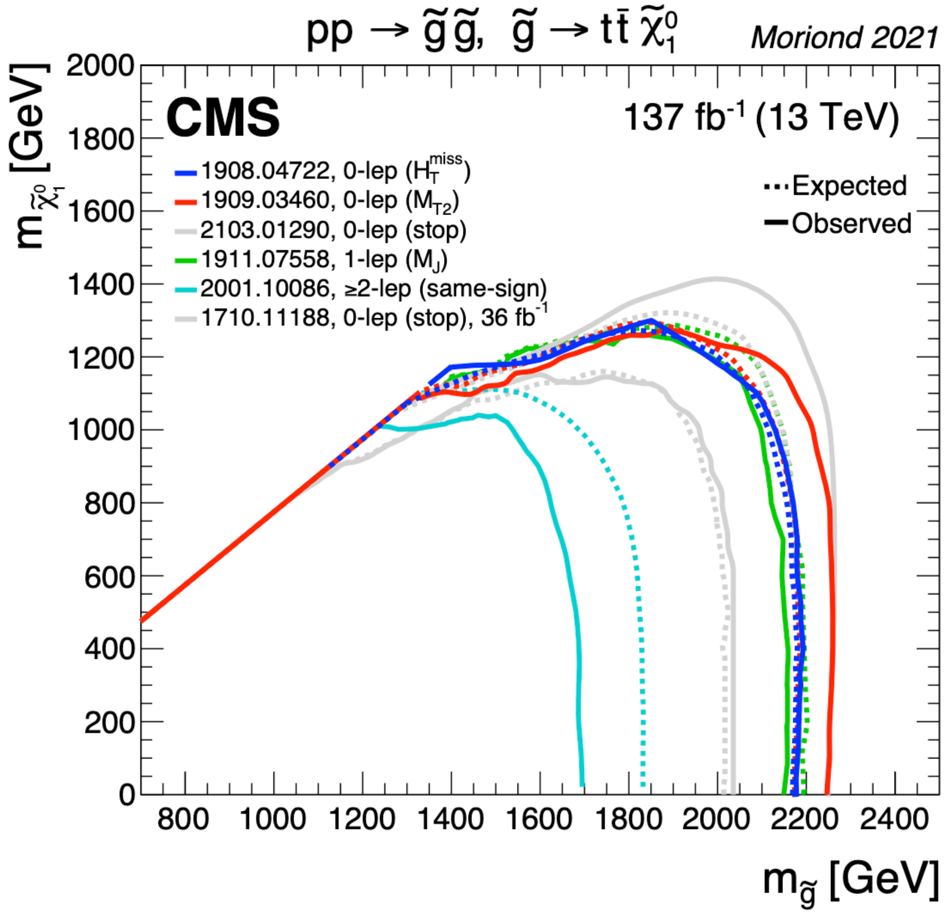
~3 sigma from the SM

Aim to study and discover the BSM particles and forces that may be responsible!

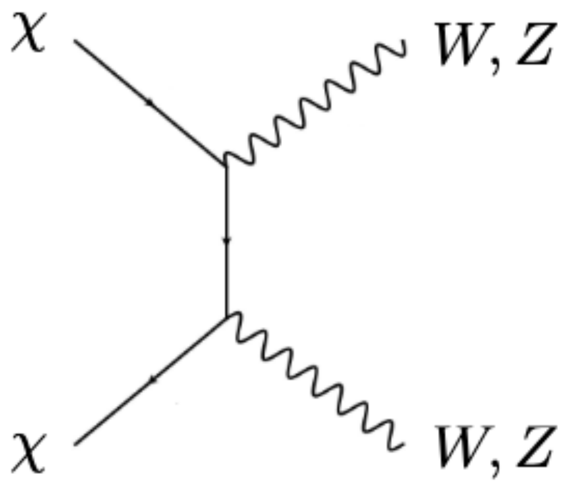
PhysRevLett.126.141801

LHCb-PAPER-2022-052

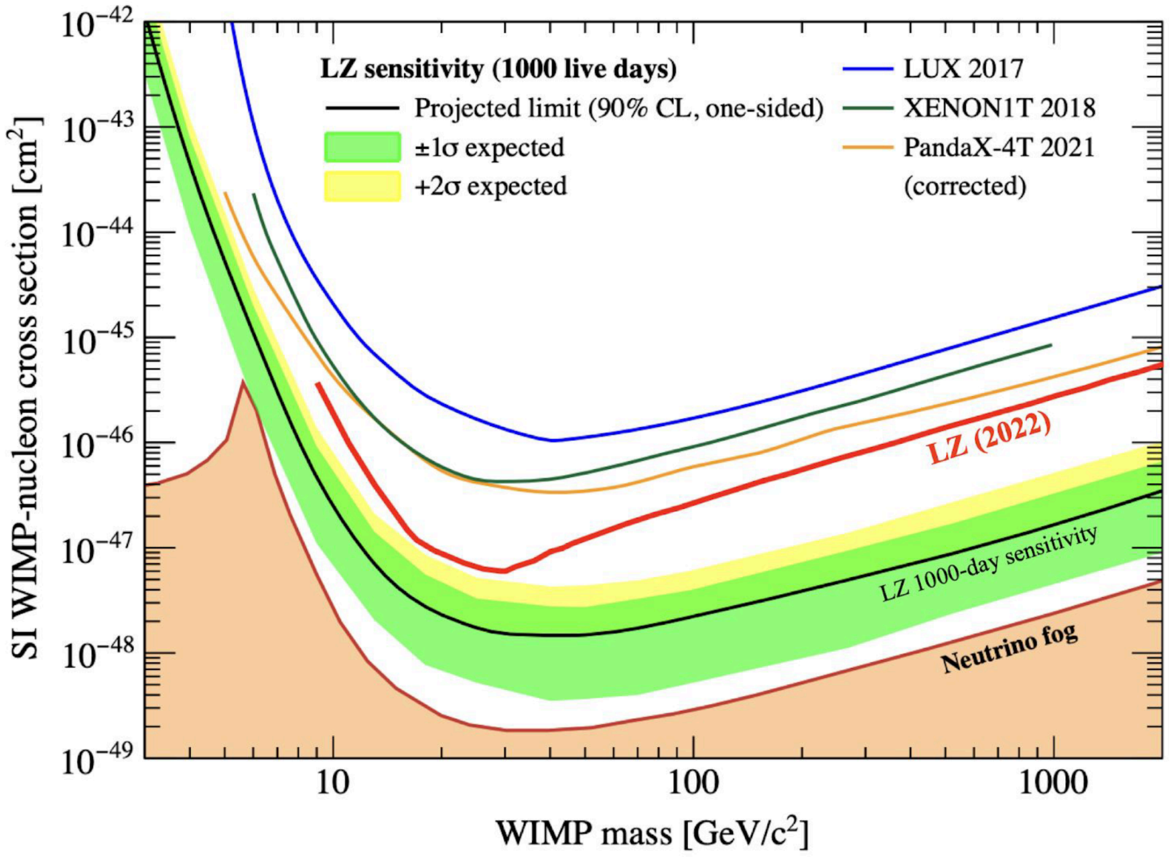
How to answer these mysteries?



Pre-LHC: SUSY and WIMP miracle was the answer!



WIMP DM (e.g. supersymmetric neutralino)



Lack of observation of SUSY at the LHC and no discovery at direct detection experiments → **WIMP-like DM under pressure!**

What if DM has no SM interaction?

Standard model

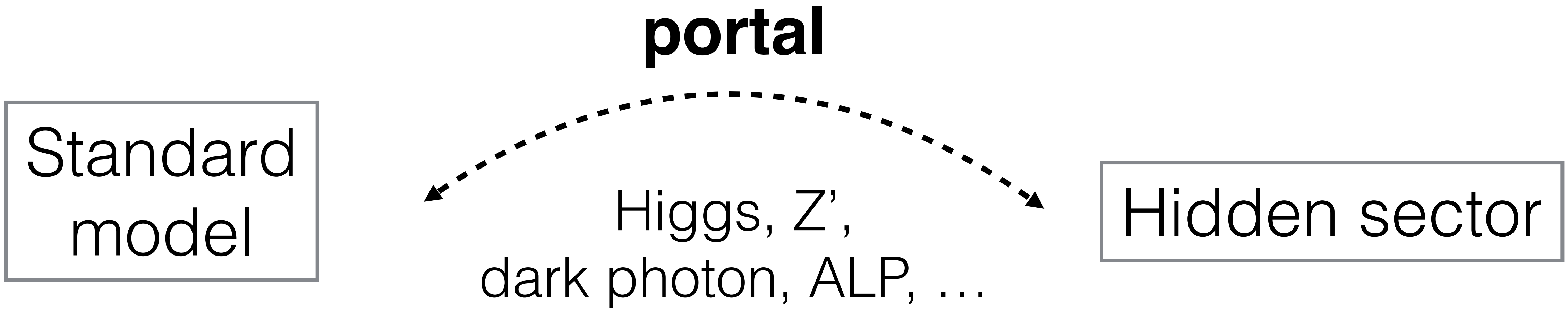
We are here

Hidden sector

DM is here

- Intriguing possibility: dark matter could be part of a **“hidden” universe** with **no SM gauge interactions**
- Hidden universe can have **complex structure** and provide solutions to mysteries beyond DM: naturalness, neutrino masses, baryogenesis, …

Connecting two worlds



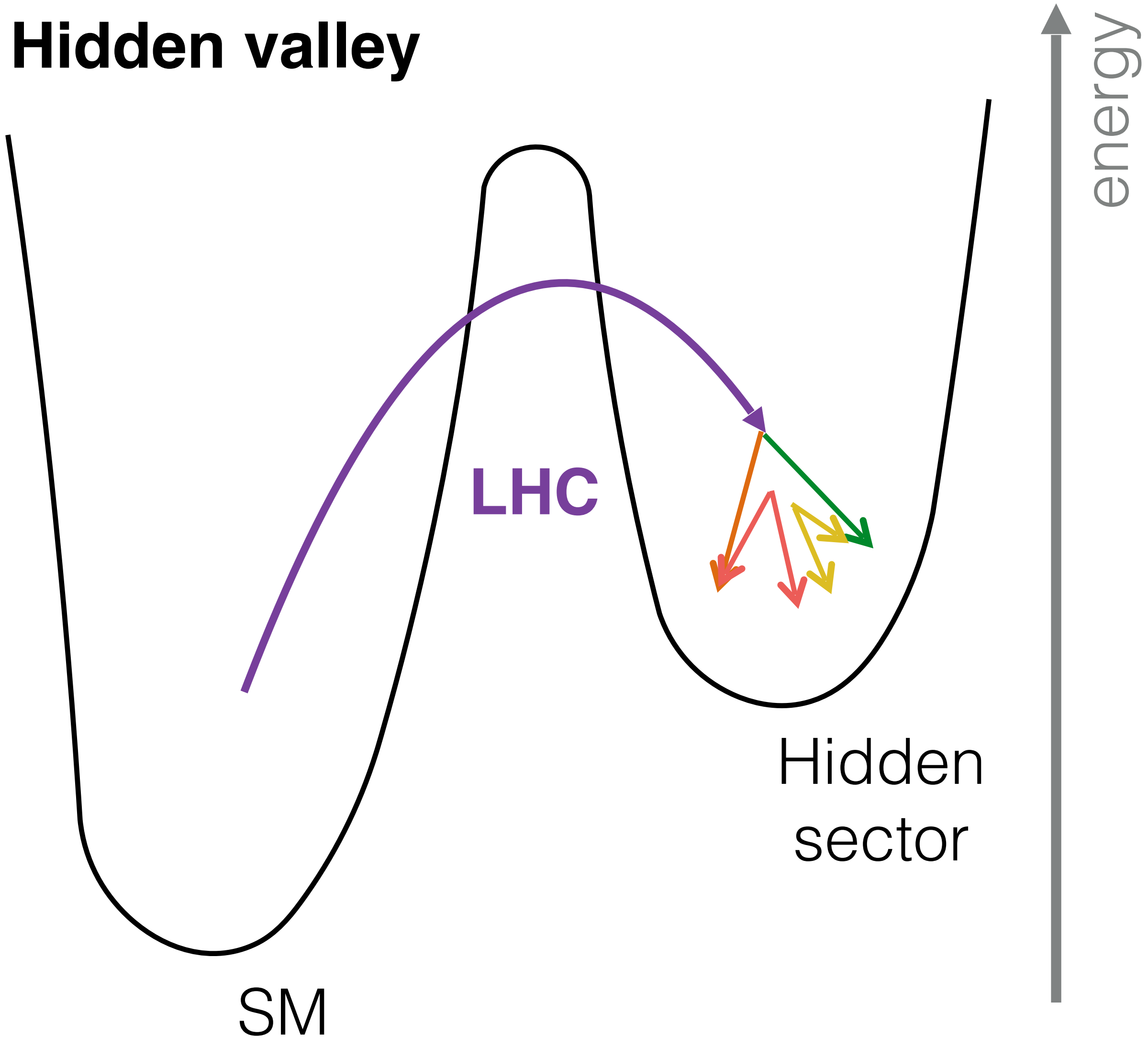
portal

Standard model

Higgs, Z',
dark photon, ALP, …

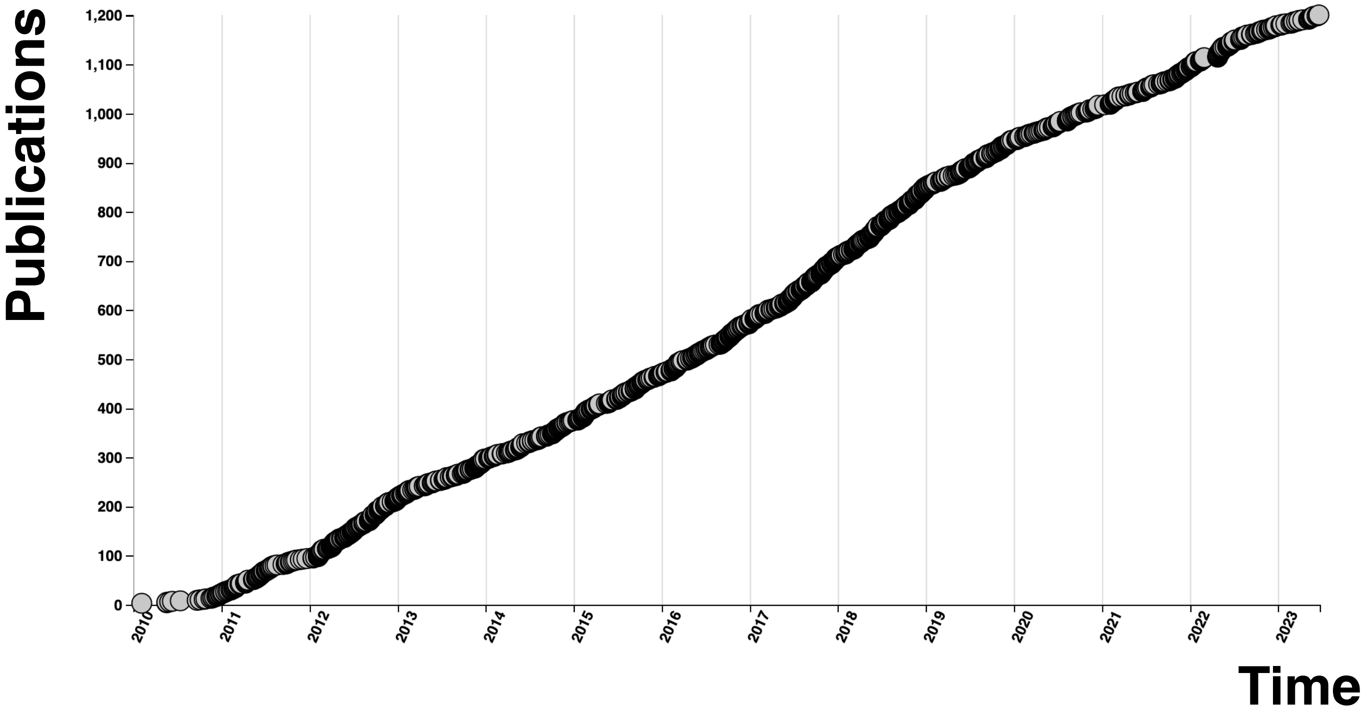
Hidden sector

- Consider a heavy particle connecting our sectors
- High energy collisions at the LHC could **overcome the barrier** and produce hidden sector particles!
- Many CMS searches and measurements **now motivated directly by hidden sector**!



Review recent results to show how CMS is exploring fundamental mysteries

total ~ 1200!



Won't try to give standard overview but instead focus on highlighting CMS **innovations** and **bold new directions**

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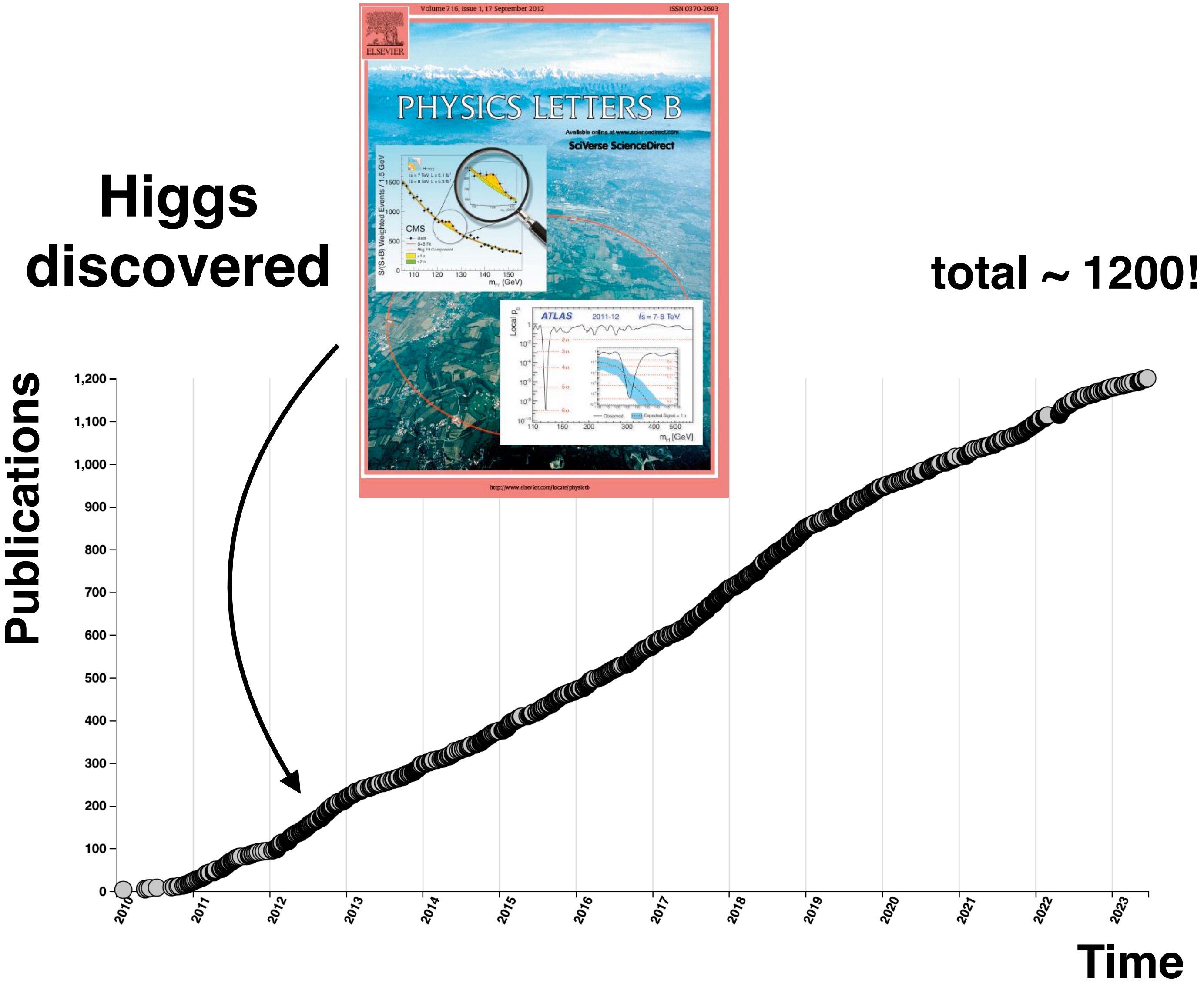
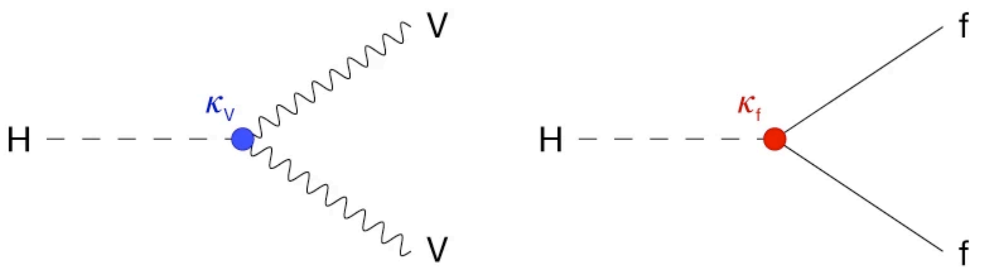
Review recent results to show how CMS is exploring fundamental mysteries

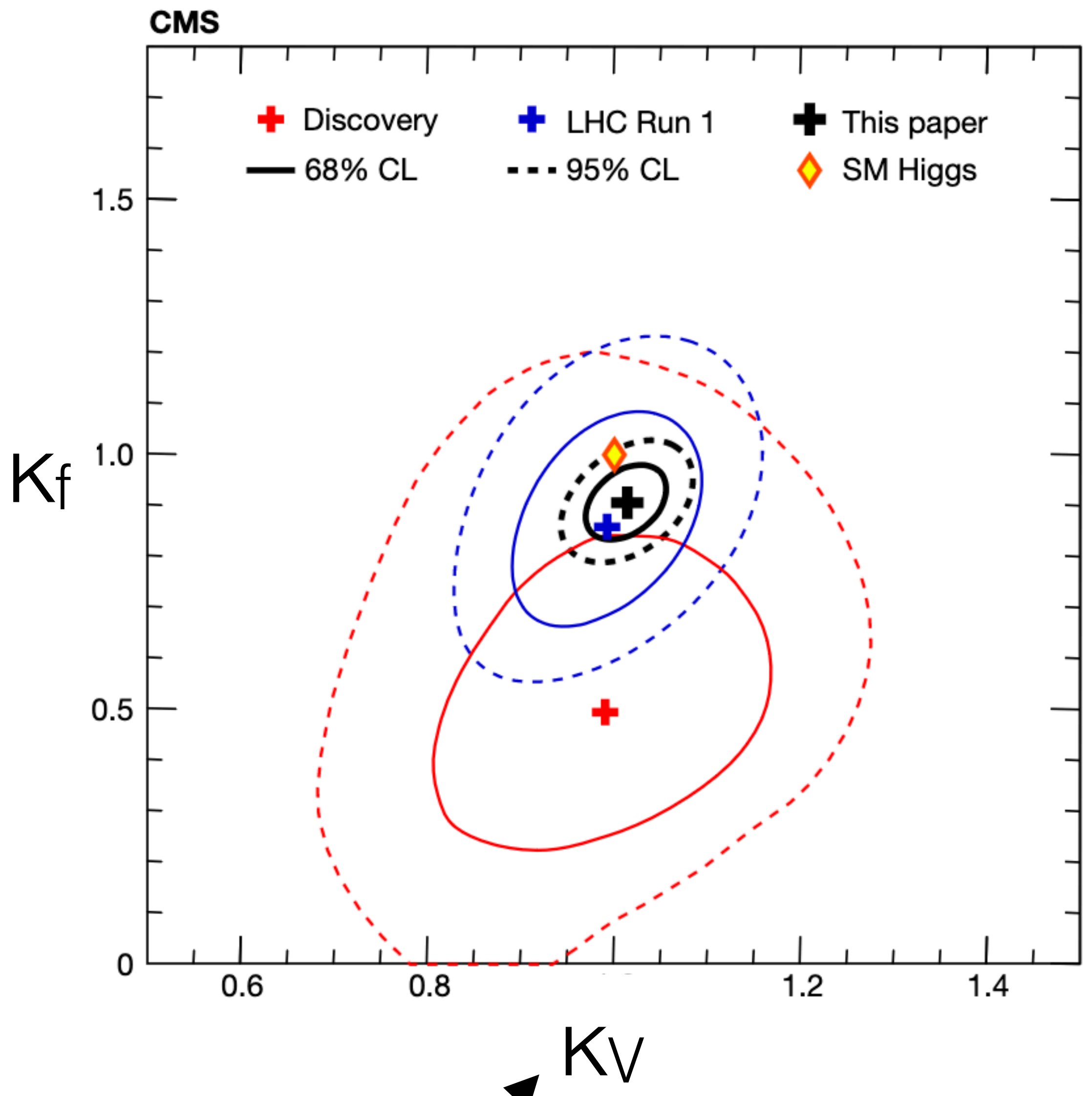


Start with Higgs then highlight variety of results with connections to **hidden sectors**, **anomalies** and **fundamental questions**

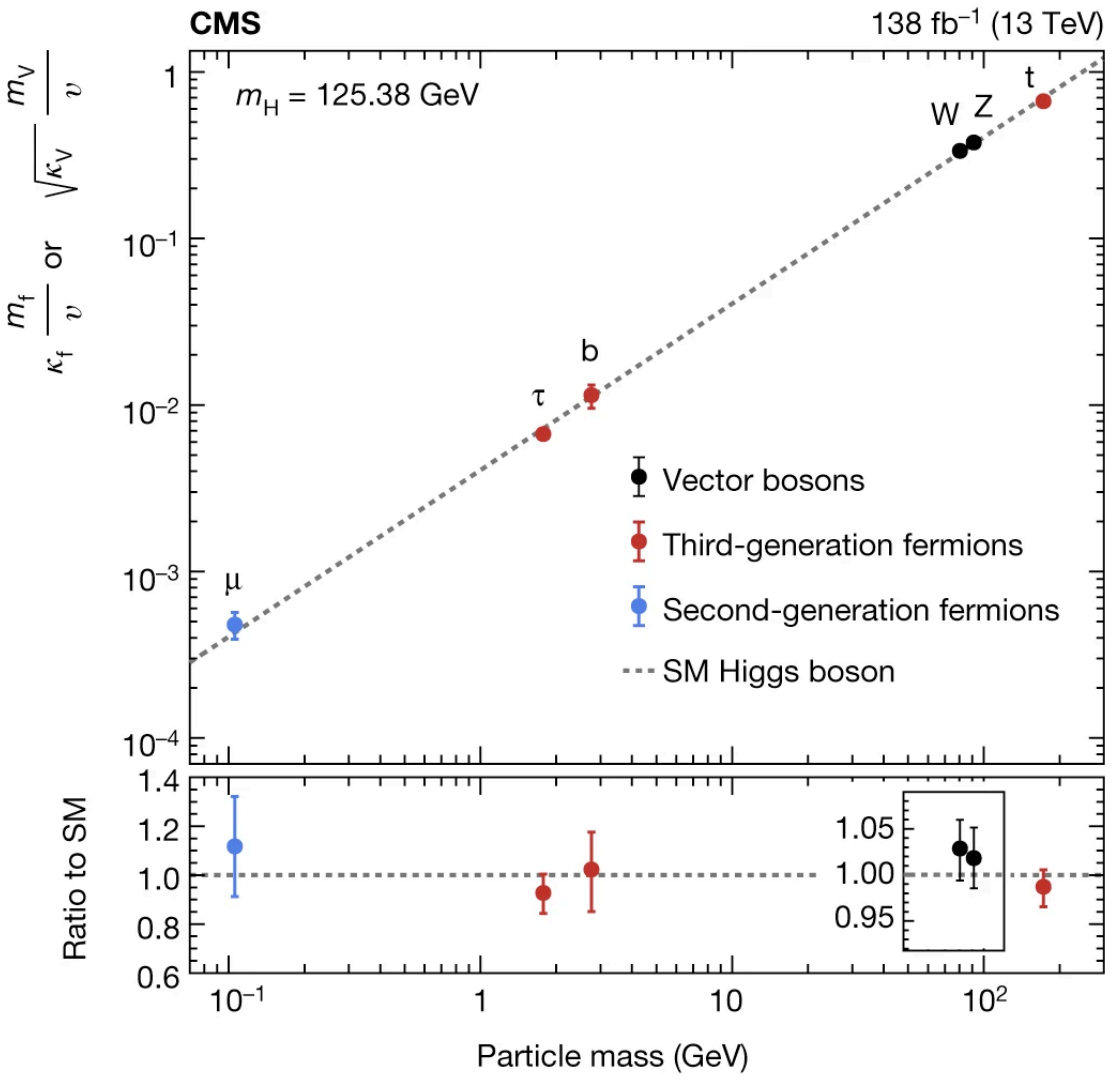
Higgs: from **discovery** to **precision** measurement

Couplings





Coupling relative to SM expectation



Nature 607 60–68 (2022)

Consistency with SM predictions **hugely impactful** on new physics

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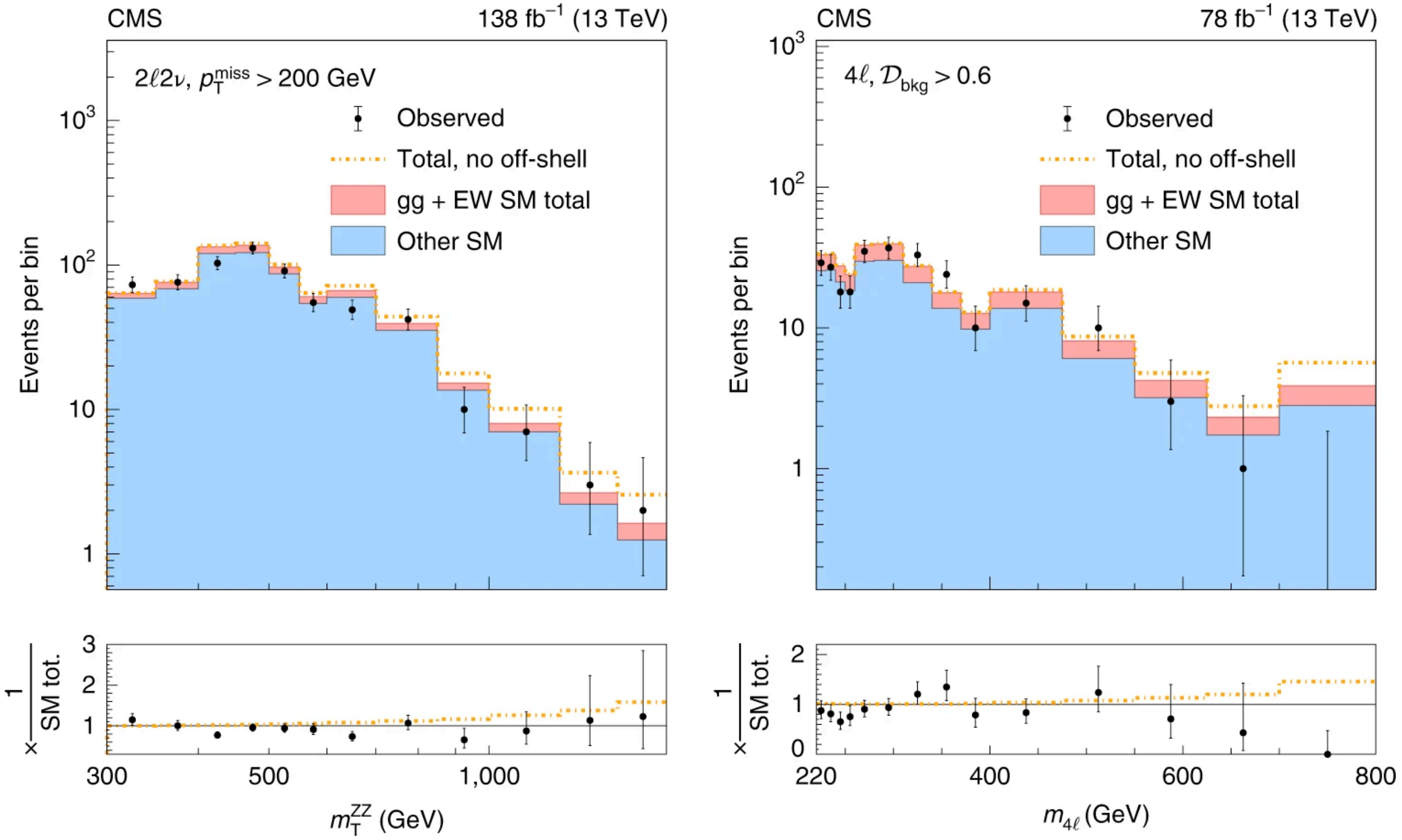
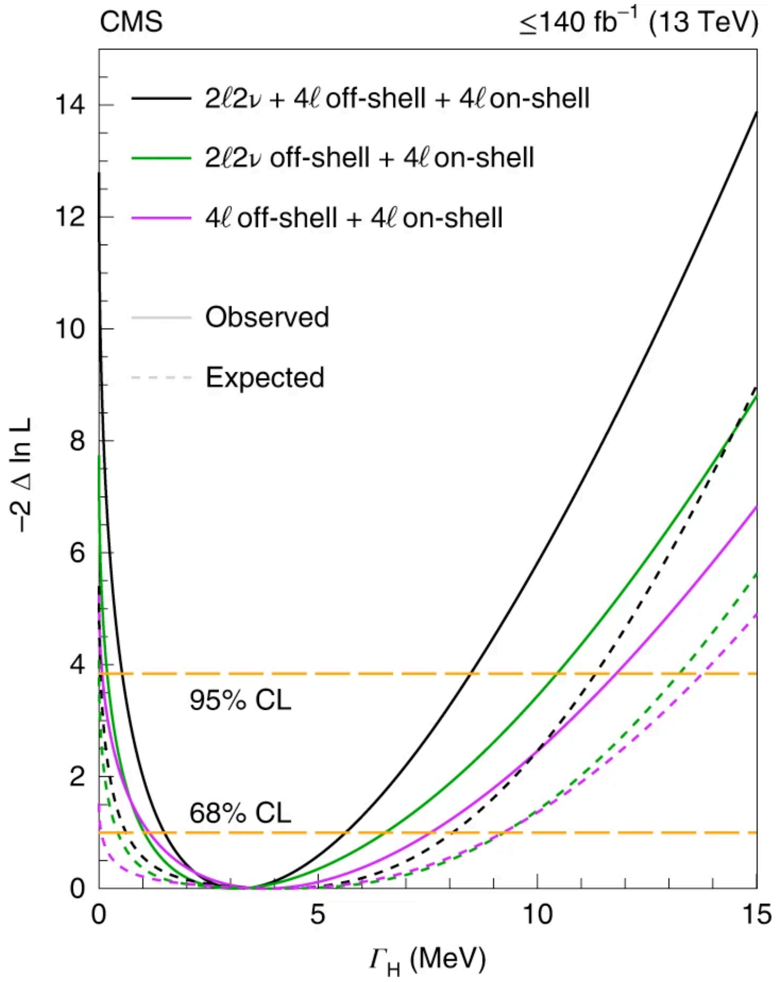
Width measurement from H → ZZ

$m_H < 2\,m_Z$ → either H or Z off shell



No off-shell production scenario excluded at 3.6 σ



Measure off-shell Higgs component through fits of **kinematic distributions** → Higgs width can be extracted from **off-shell/on-shell ratio**

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

Nature Physics 18 1329–1334 (2022)

Consistency with SM predictions **hugely impactful** on new physics

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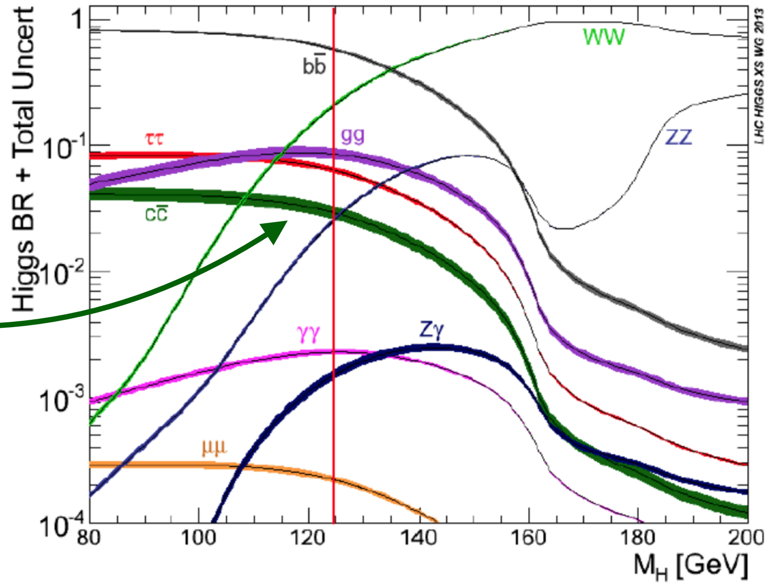
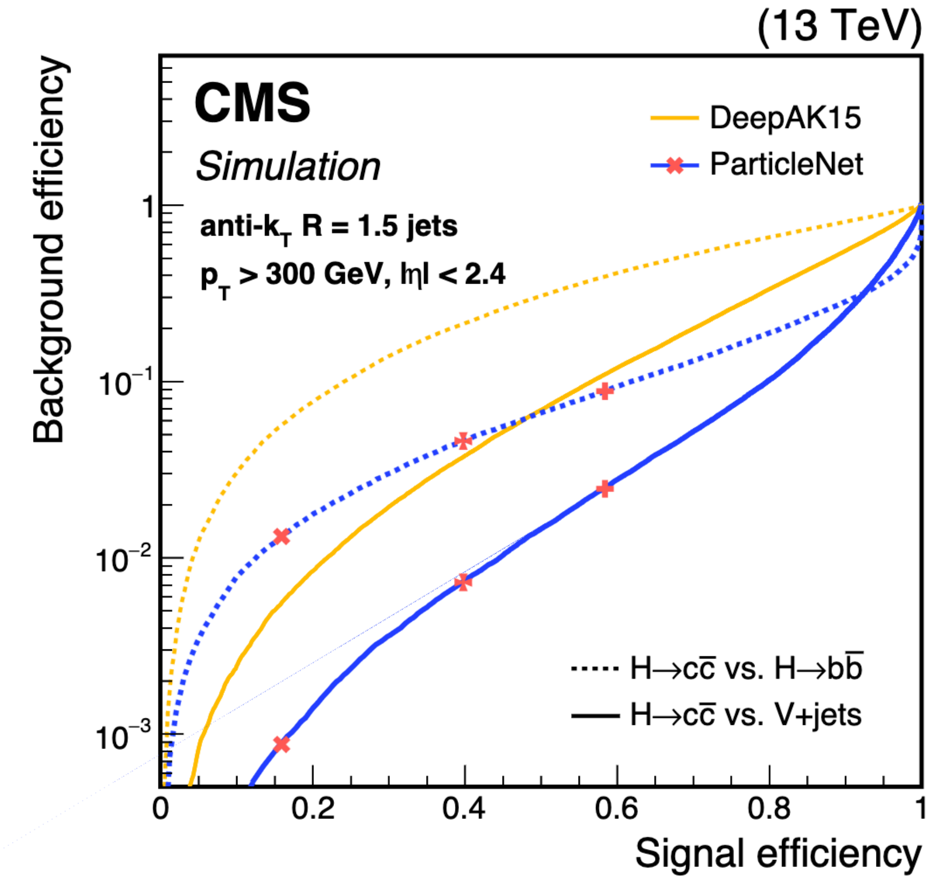
Continuing to track down more final states: **H → cc**

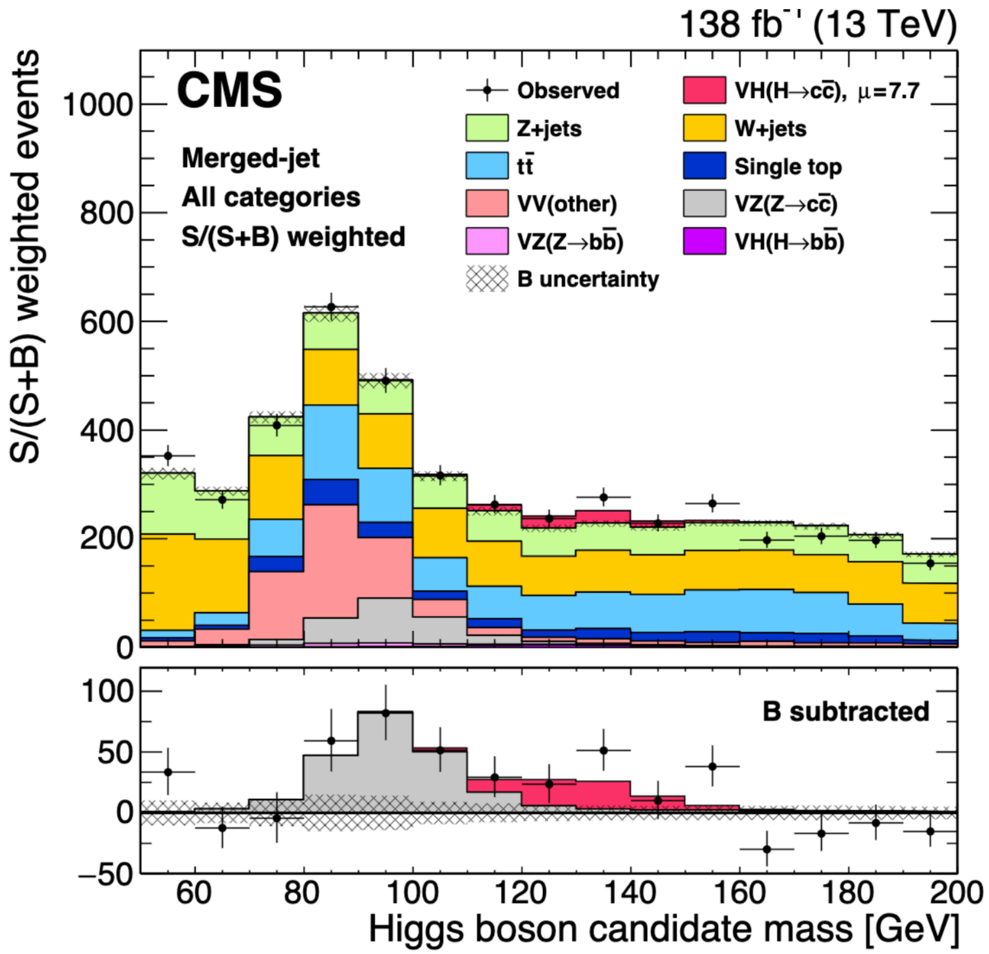
2205.05550

Initially even H → bb thought to be impossible, **but now we are narrowing in on a process with ~1/20th of its BF!**





Requires **advanced ML strategies (GNN)**

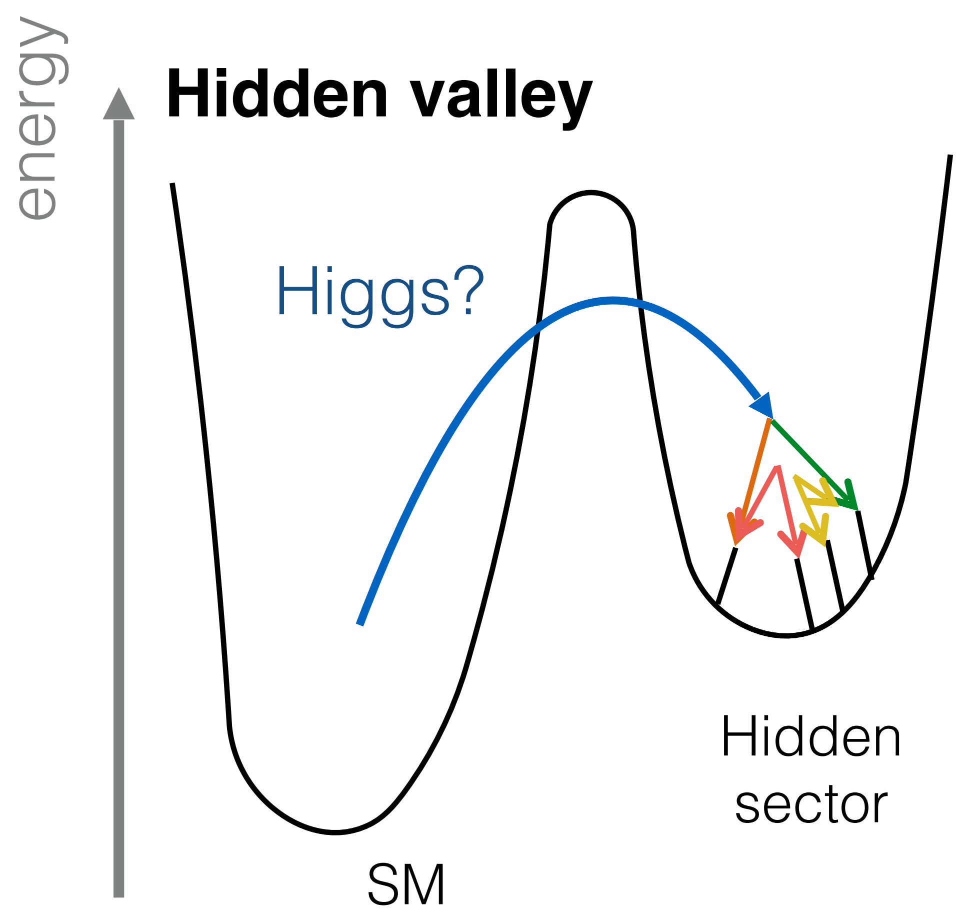


95% CL interval: $1.1 < |\kappa_c| < 5.5$

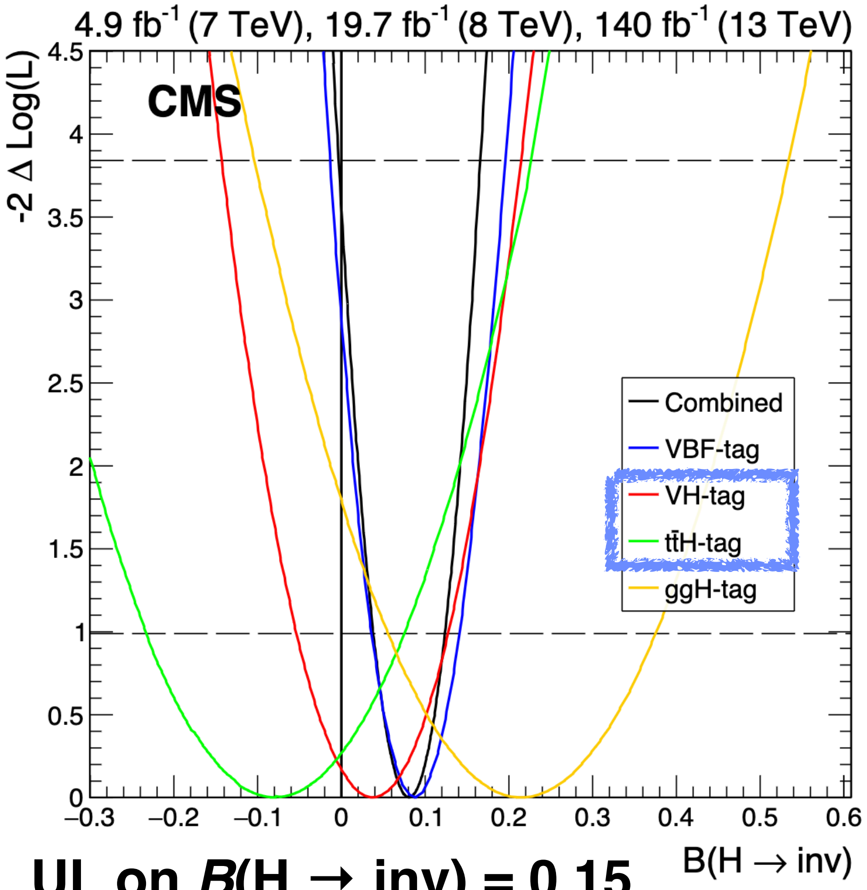
Higgs → BSM

The Higgs could provide the link to a hidden sector → invisible final states, visible decays

Mysteries studied: naturalness, DM

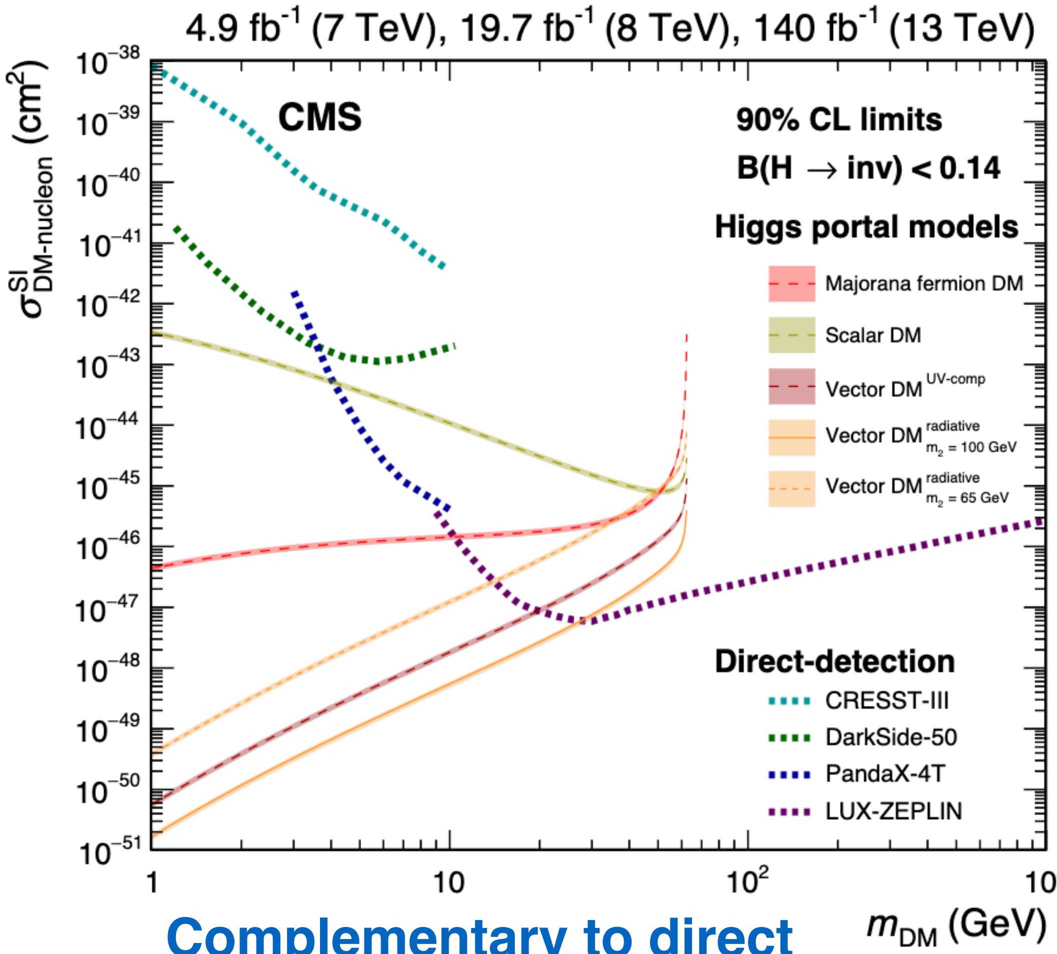


H → invisible



New!

95% CL UL on $B(H \rightarrow \text{inv}) = 0.15$



Complementary to direct detection efforts!

arXiv:2303.01214

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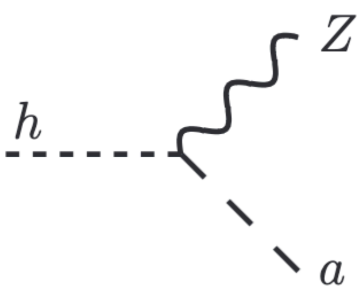
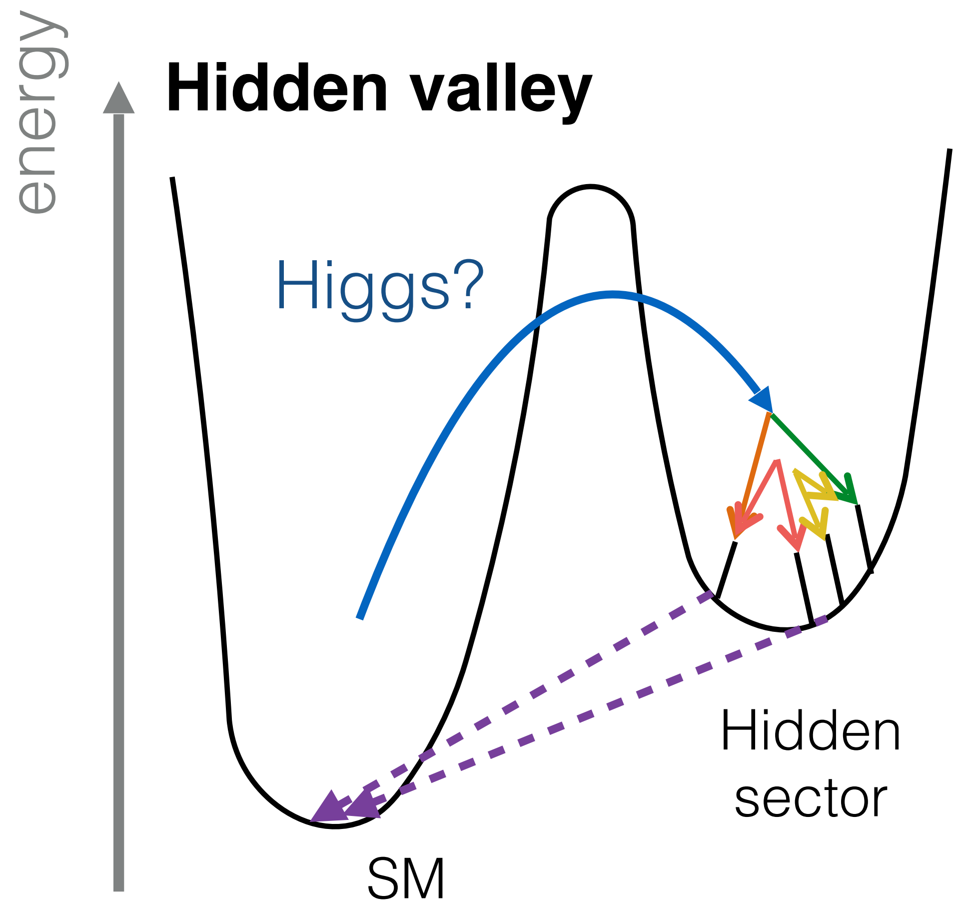
Higgs → BSM

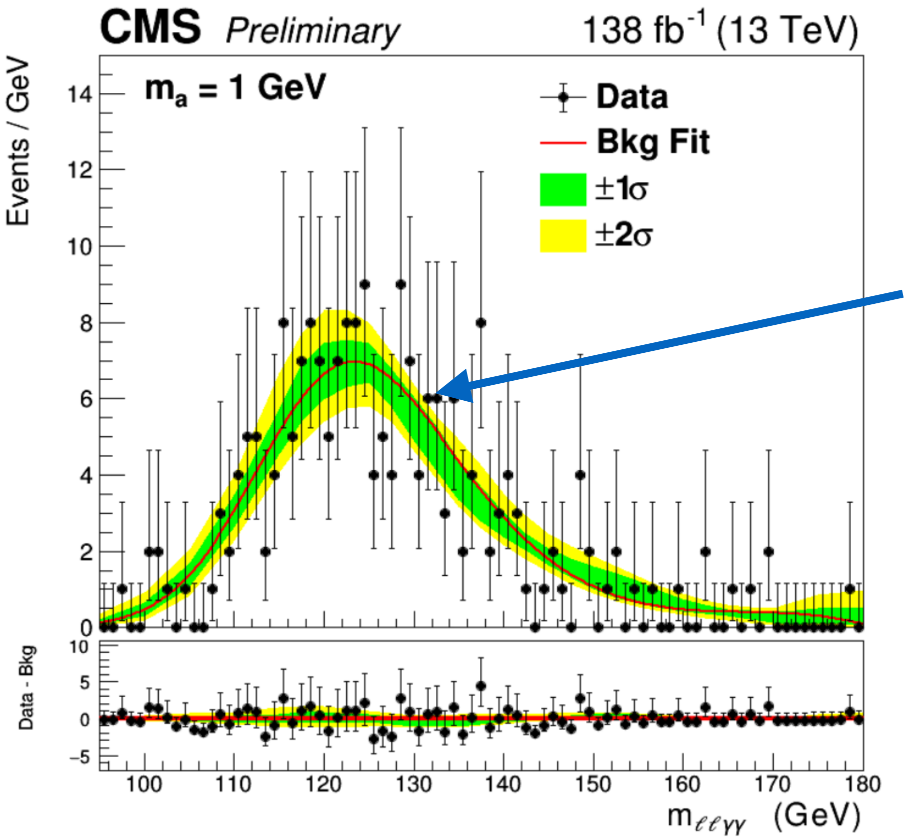


The Higgs could provide the link to a hidden sector → invisible final states, visible decays

Mysteries studied: DM, g-2



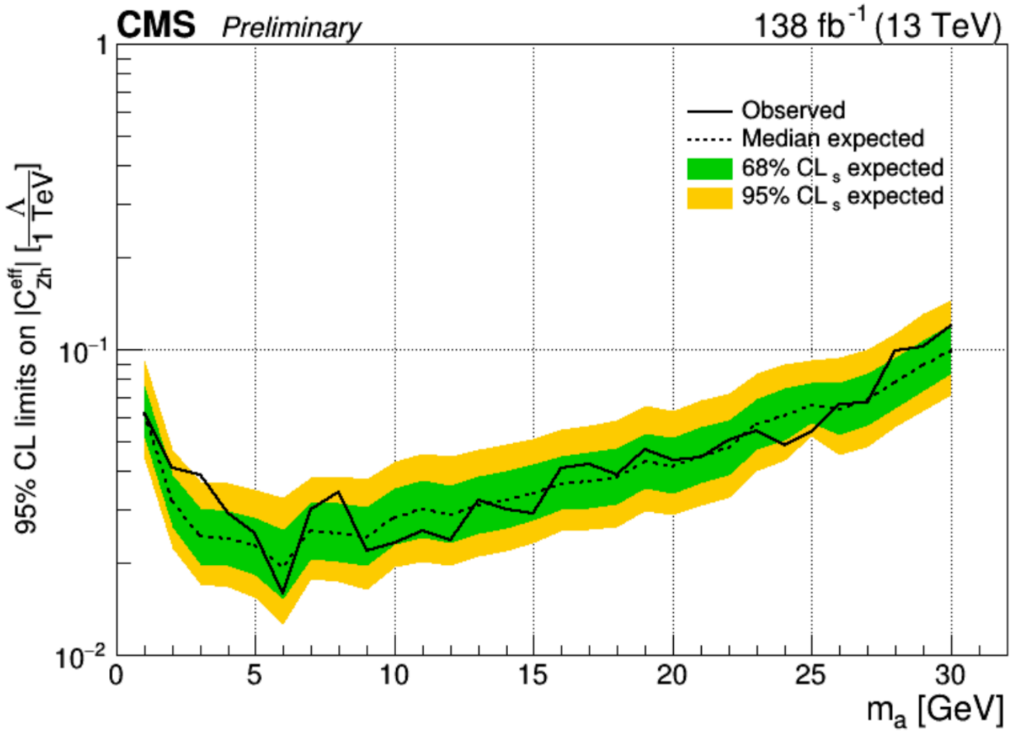
H → Za → llγγ



BDT for background rejection
then search for mass peak

Looking for narrow peak here

Complementary probe to ALP searches using beam dumps, supernovae, etc… (see backup)



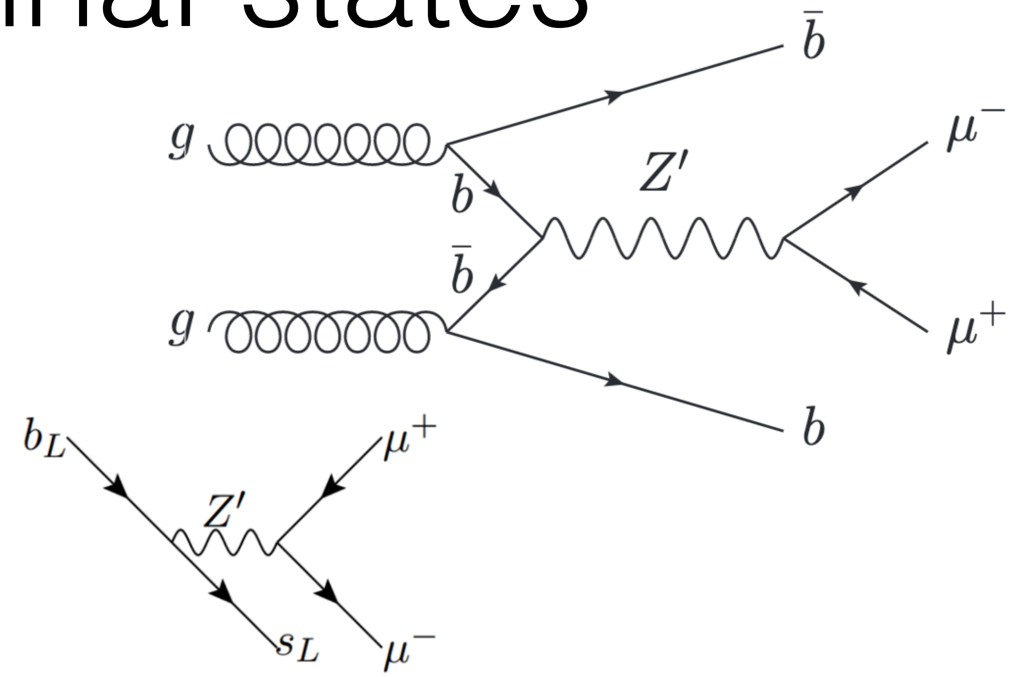
C^{eff}_{ZH} describes the coupling between the Higgs boson, Z boson, and ALP

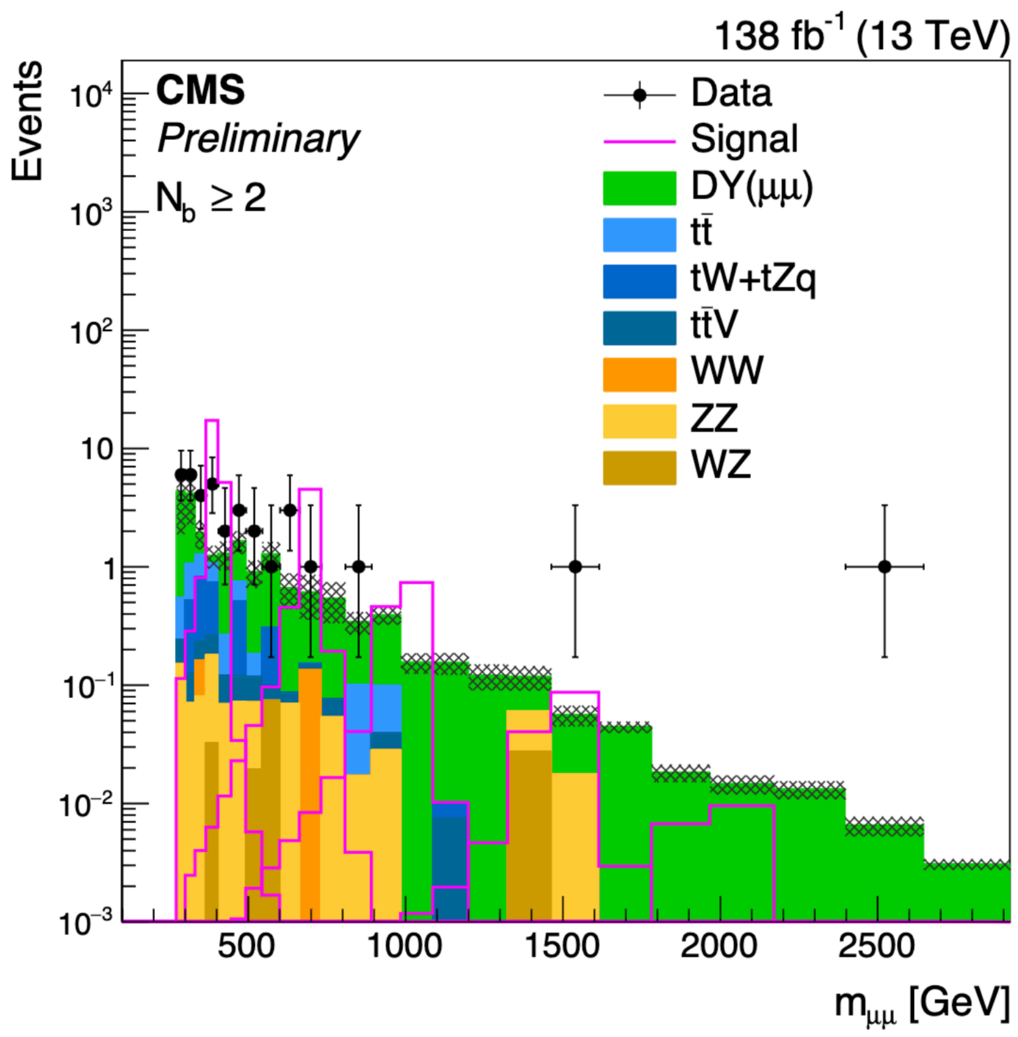
HIG-22-003

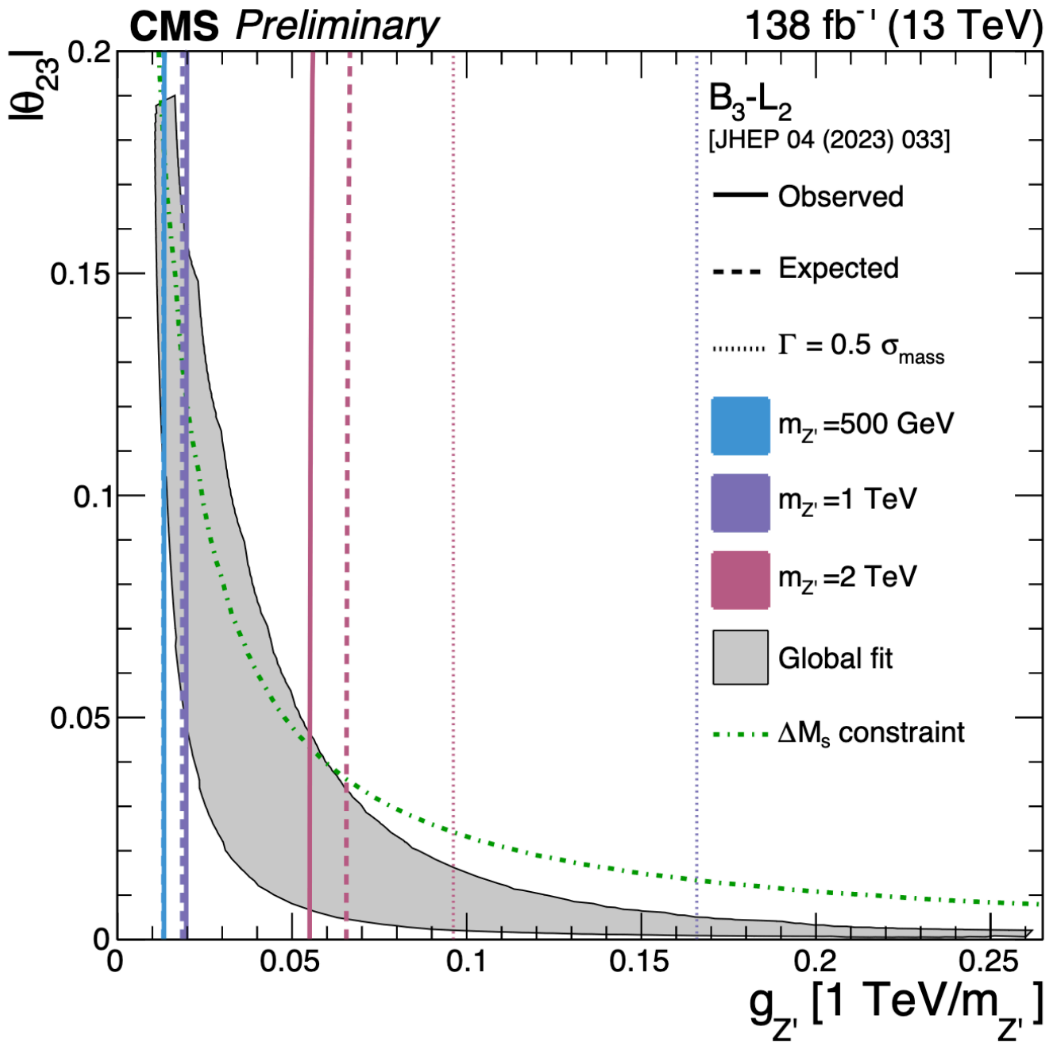
EXO-22-016

Probing new heavy BSM final states

- CMS moving **beyond simple heavy resonances**
- New search sensitive to models that may cause anomalies observed in B meson decays







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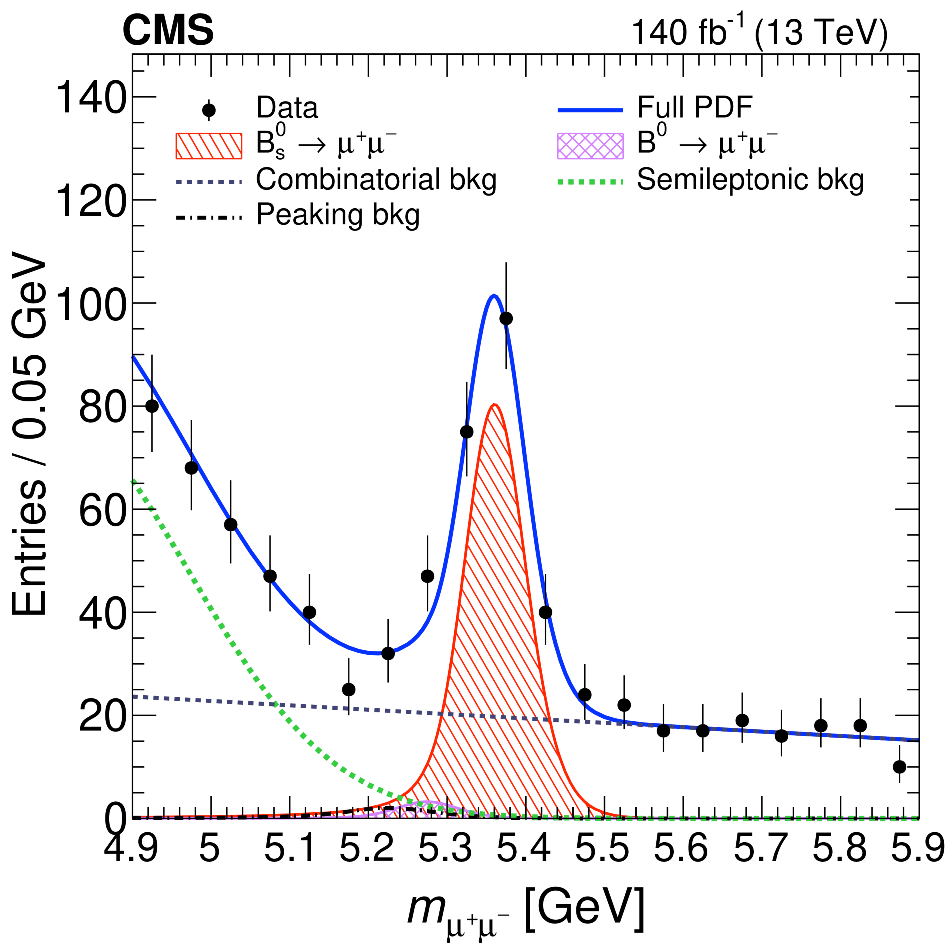
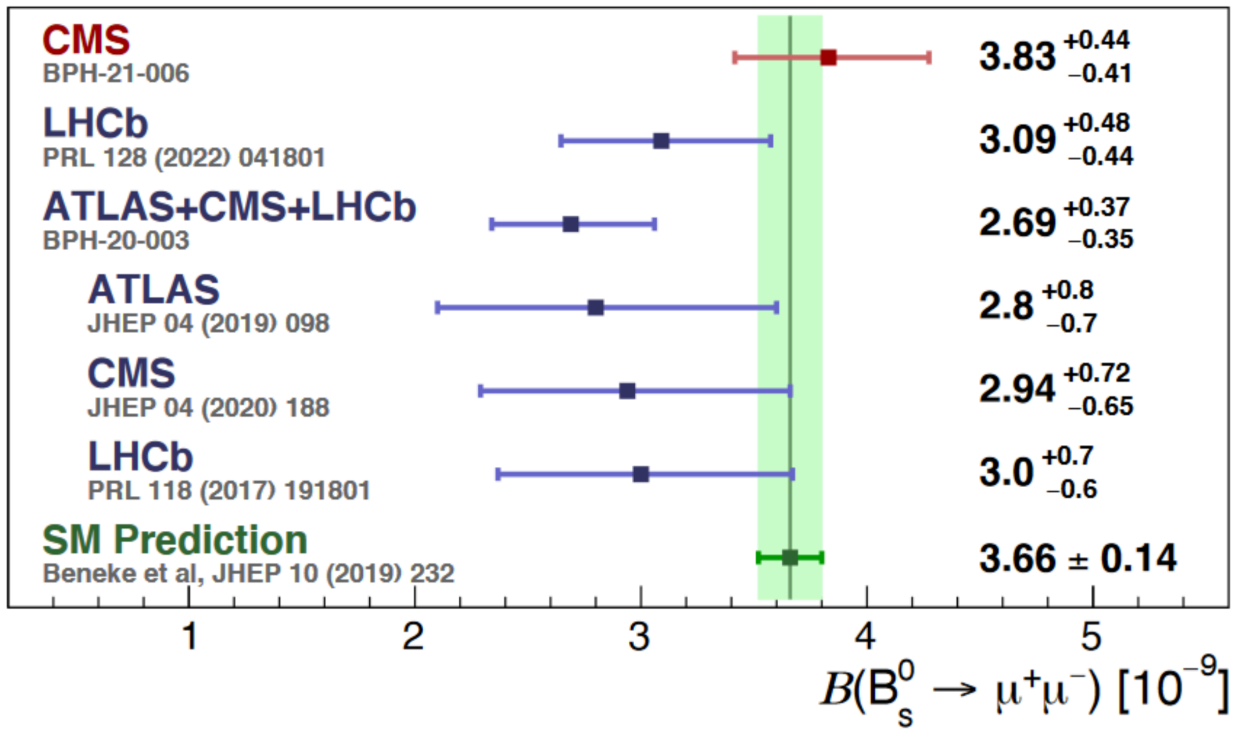
Mysteries studied: B anomalies

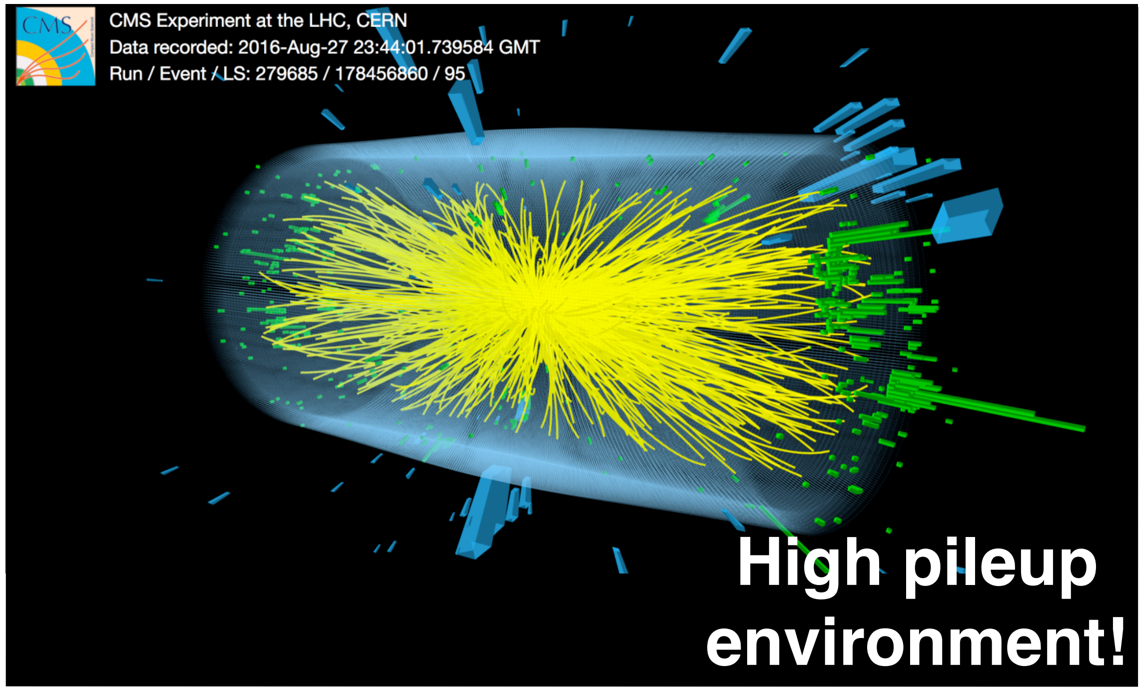
CMS is doing B-physics: $B_S^0 \to \mu\mu$



ML used for background rejection



$$+\ B(B^0 \to \mu\mu) < 1.9 \times 10^{-10} \text{ at } 95\,\% \text{ CL}$$



High pileup environment!

Comparable sensitivity to LHCb despite significantly more demanding environment!

Much more to come: crucial probe of anomalies!

Mysteries studied: B anomalies

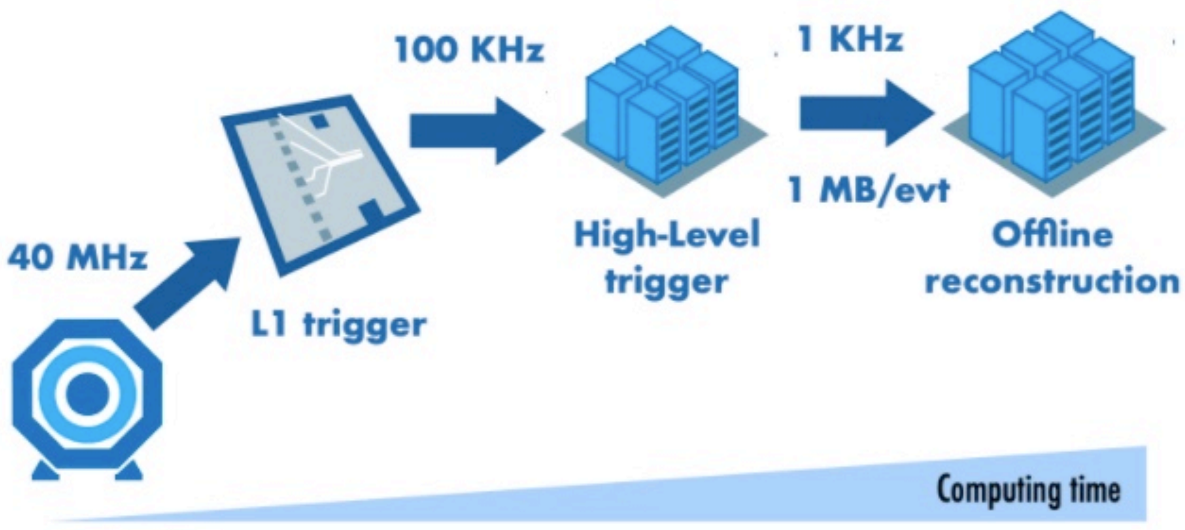
2212.10311

Pushing energy thresholds down

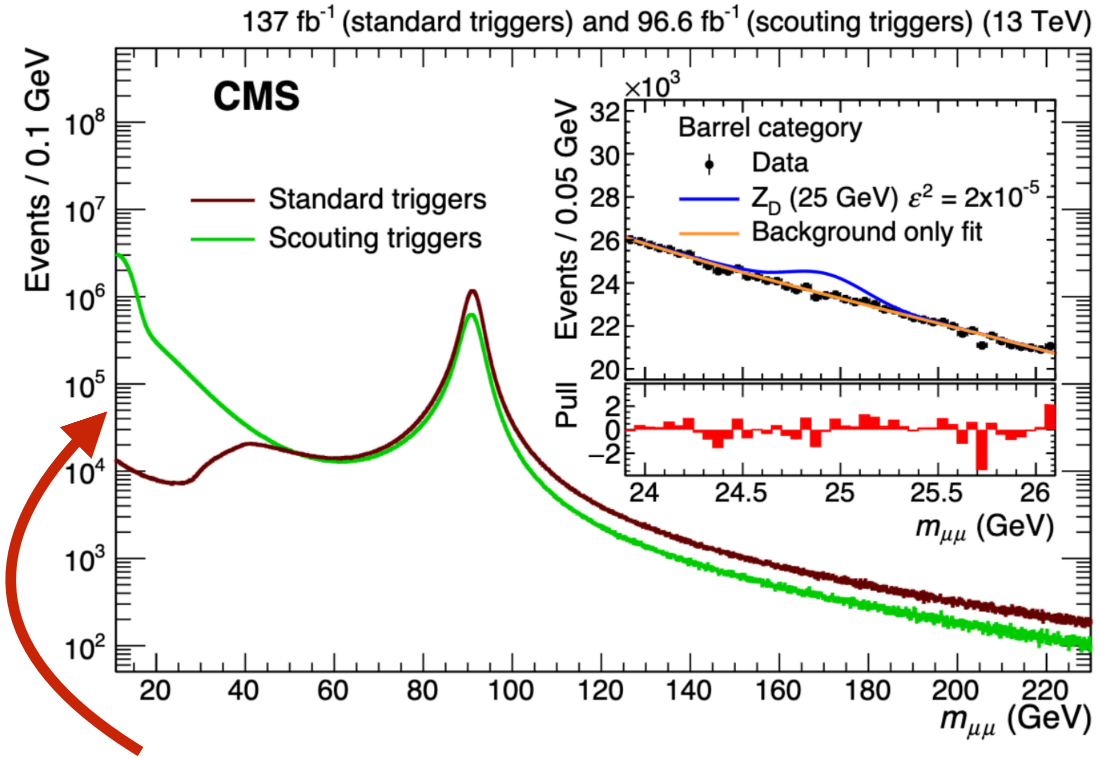
- Two methods to allow substantially increased acceptance at the **trigger**
- **Parking**: keep data on disk (unreconstructed) until extended LHC stops
- **Scouting**: save partial event reconstruction to reduce event size

More details to come in Mia's talk

Rejected events are lost forever!



https://a3d3.ai/hep.html



Huge efficiency gains at low mass

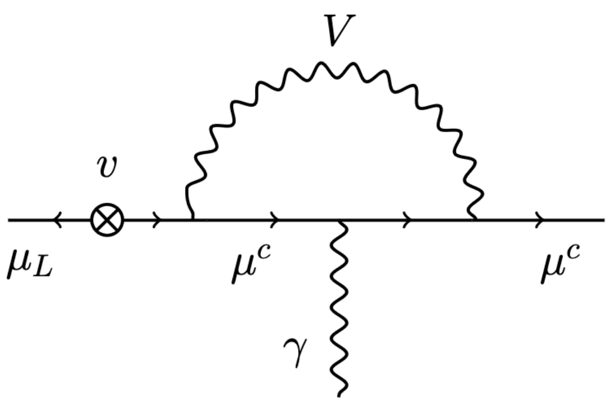
1912.04776

EXO-21-005

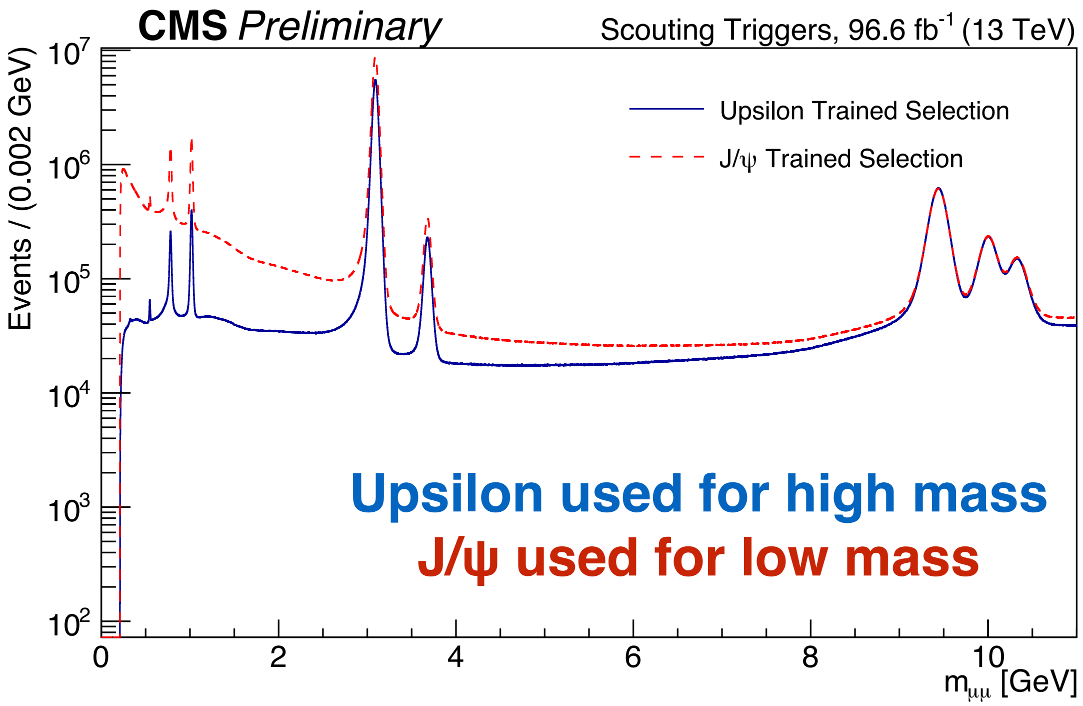
Search for BSM GeV-scale resonance

- **Scouting** triggers allows very low (down to 3 GeV) threshold muon p_T requirements
- Probe masses down to 1 GeV for hidden sector theories which could explain $(g-2)_\mu$ and other mysteries!

Mysteries studied: g-2, DM

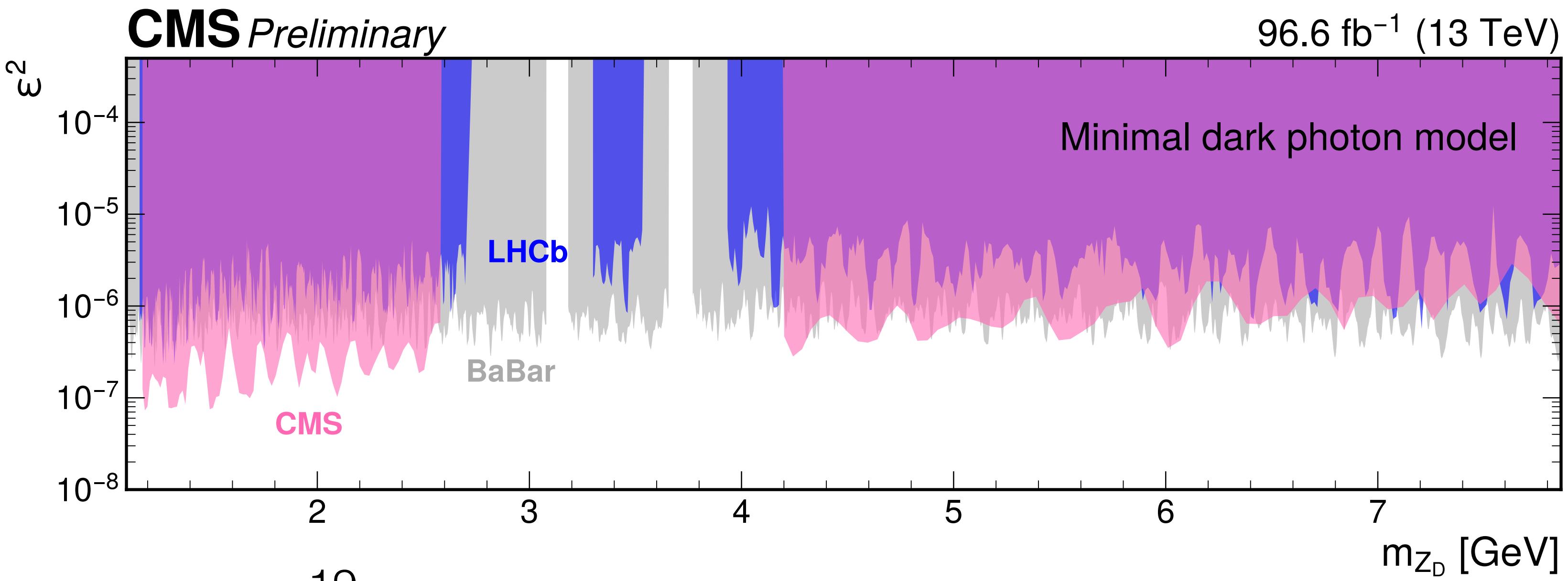


2101.10334



Upsilon used for high mass
J/ψ used for low mass

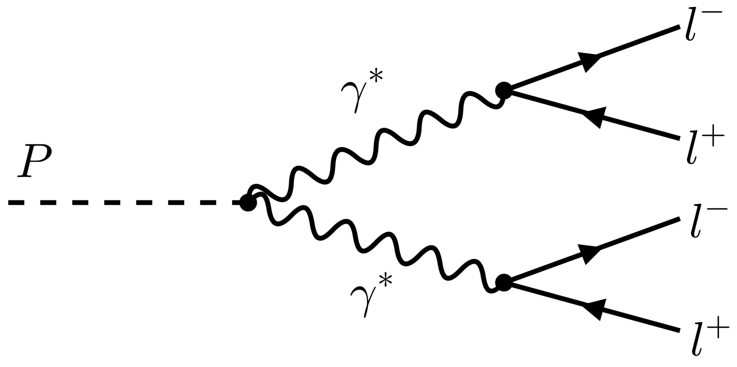
Muon ID using MVAs trained with data provides ~30% sensitivity improvement

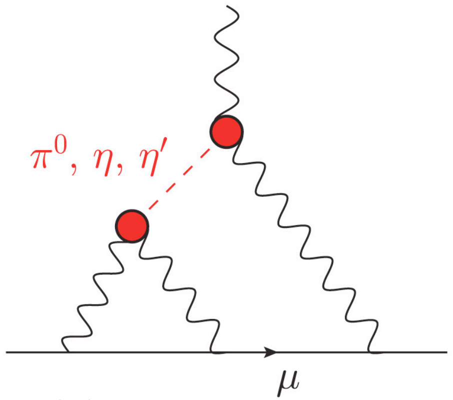


2305.04904

Observation of v → μμμμ

Mysteries studied: g-2





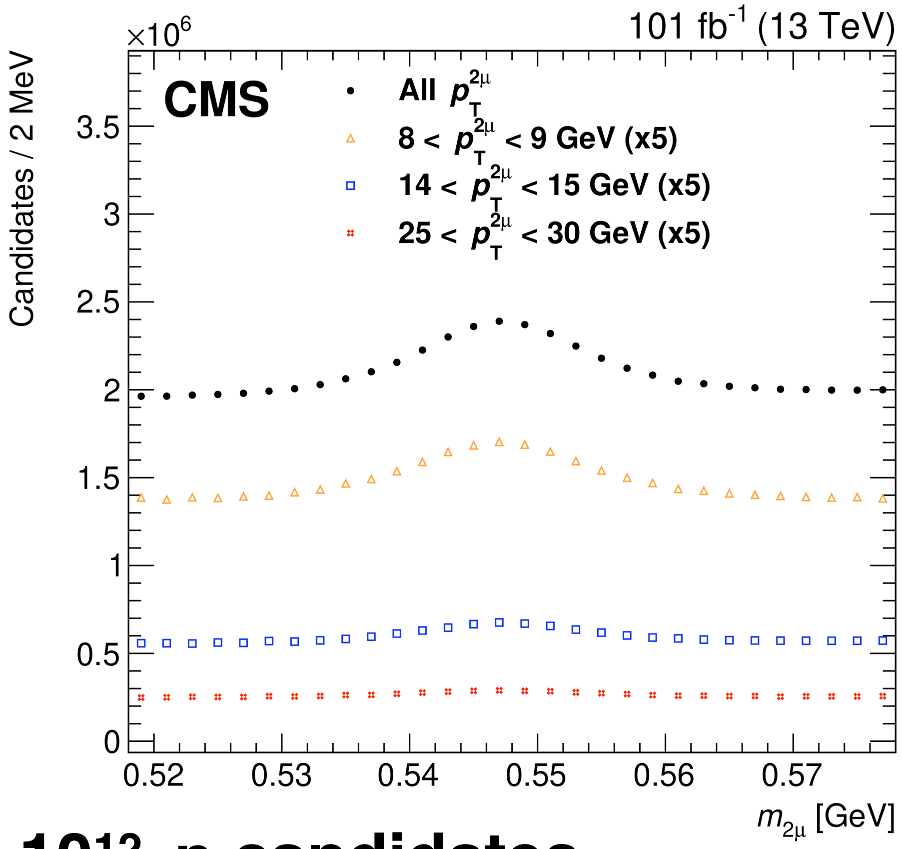
j.physrep.2021.11.001

hadronic light-by-light component of $(g\text{-}2)_\mu$

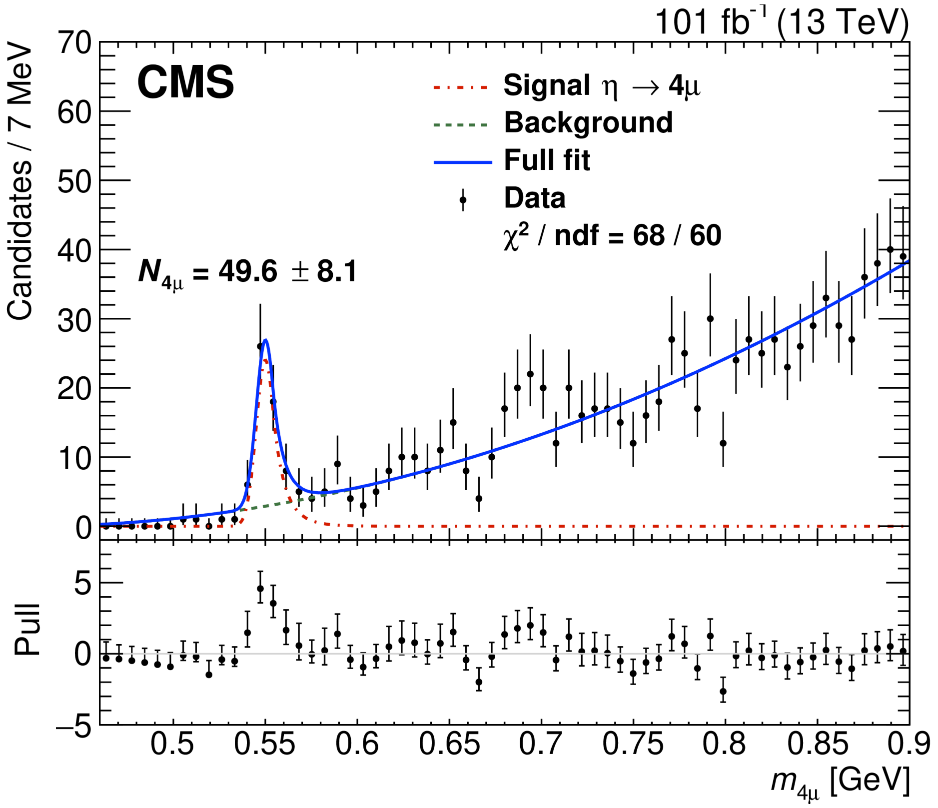
- **Scouting** allows low muon pT thresholds needed for **first observation** of this rare process
- Provides **precision test** of the SM as well as an important input to calculating $(g\text{-}2)_\mu$

Measure:

$$B(\nu \to \mu\mu\mu\mu) = (5.0 \pm 0.8(stat) \pm 0.7(syst) \pm 0.7(B2\mu)) \times 10^{-9}$$



~10^{12} η candidates



~50 4μ candidates!

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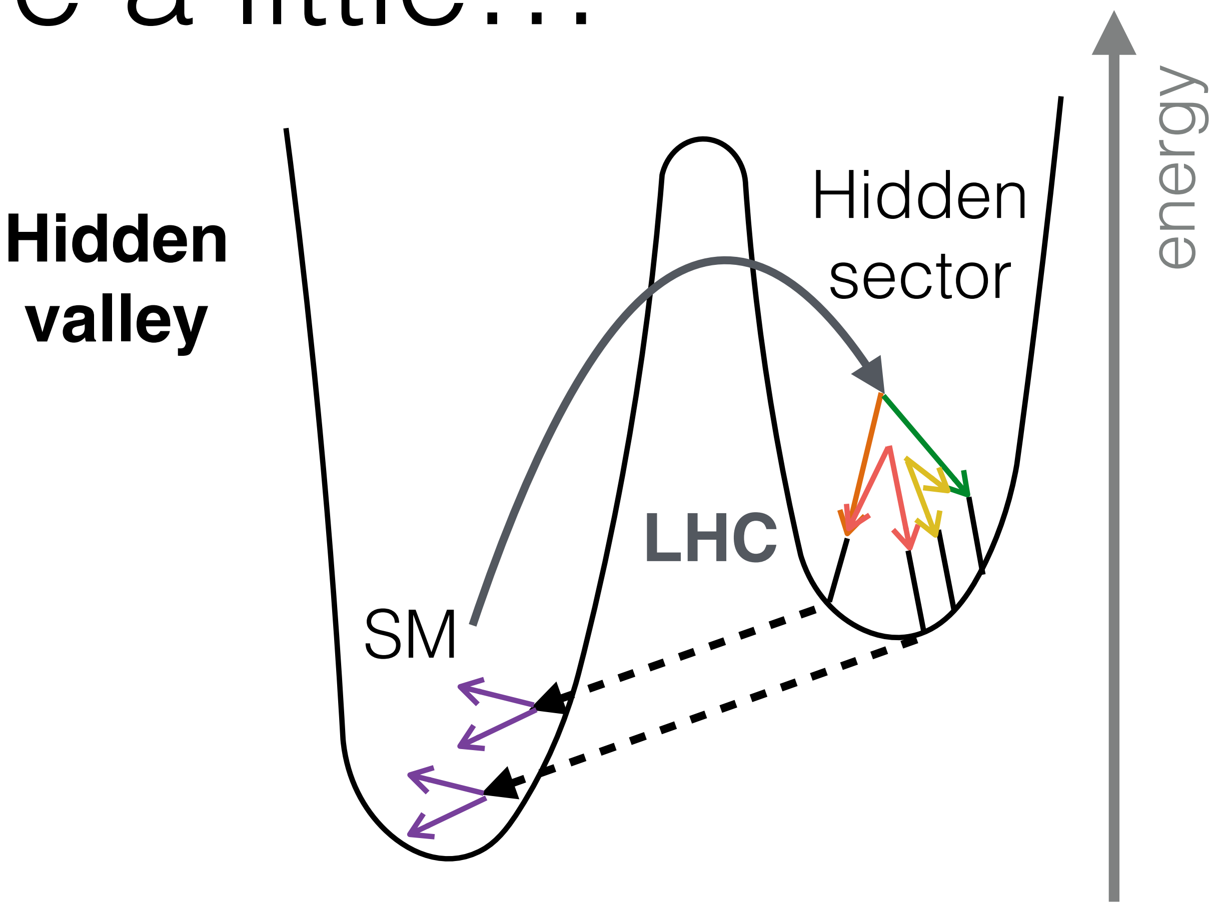
Let’s let new physics live a little…

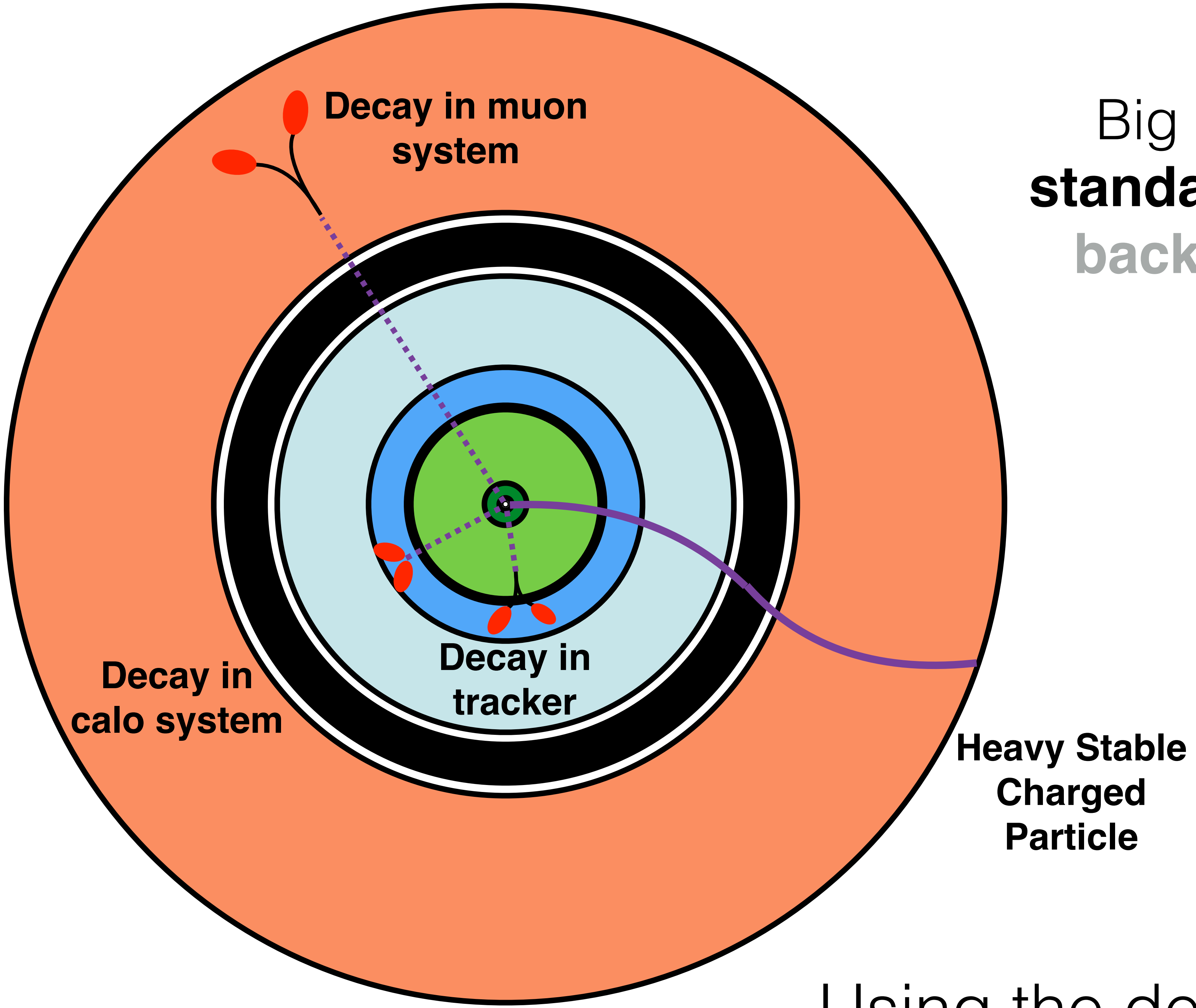
- **Long-lived particles** very well motivated within hidden sector models
- Discovery of a new LLP would provide **deep insights** into BSM physics
- Lifetime connected to the **mass hierarchies** and **symmetries** within the underlying model
- How to search for them?



$$\Gamma \propto \frac{g^2}{8\pi}\left(\frac{m_{\mathrm{LLP}}}{m_{\mathrm{mediator}}}\right)^n m_{\mathrm{LLP}}$$

Long-lived = metastable on detector length scales

Long-lived searches: non-standard signatures require innovative approaches!



Big challenges: **non-standard reconstruction, background rejection**

NB: non-exhaustive examples!

Using the detector in ways it was not originally intended!

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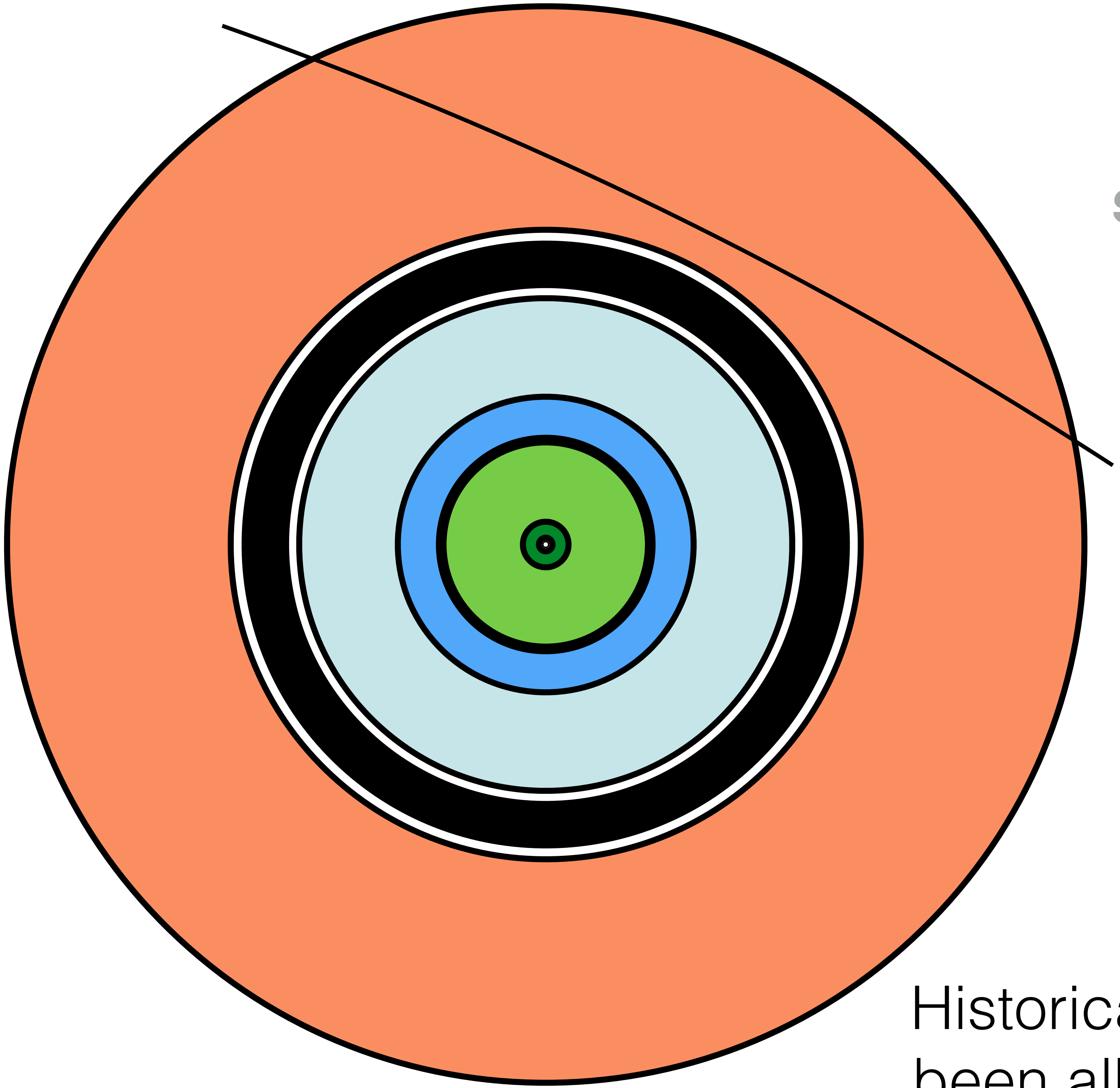
Long-lived searches: non-standard signatures require innovative approaches!



Big challenges: **non-standard reconstruction, background rejection**

e.g. cosmic muon

Historically these challenges have been alleviated by focus on ~ TeV scale BSM but now CMS is again **pushing down thresholds**!

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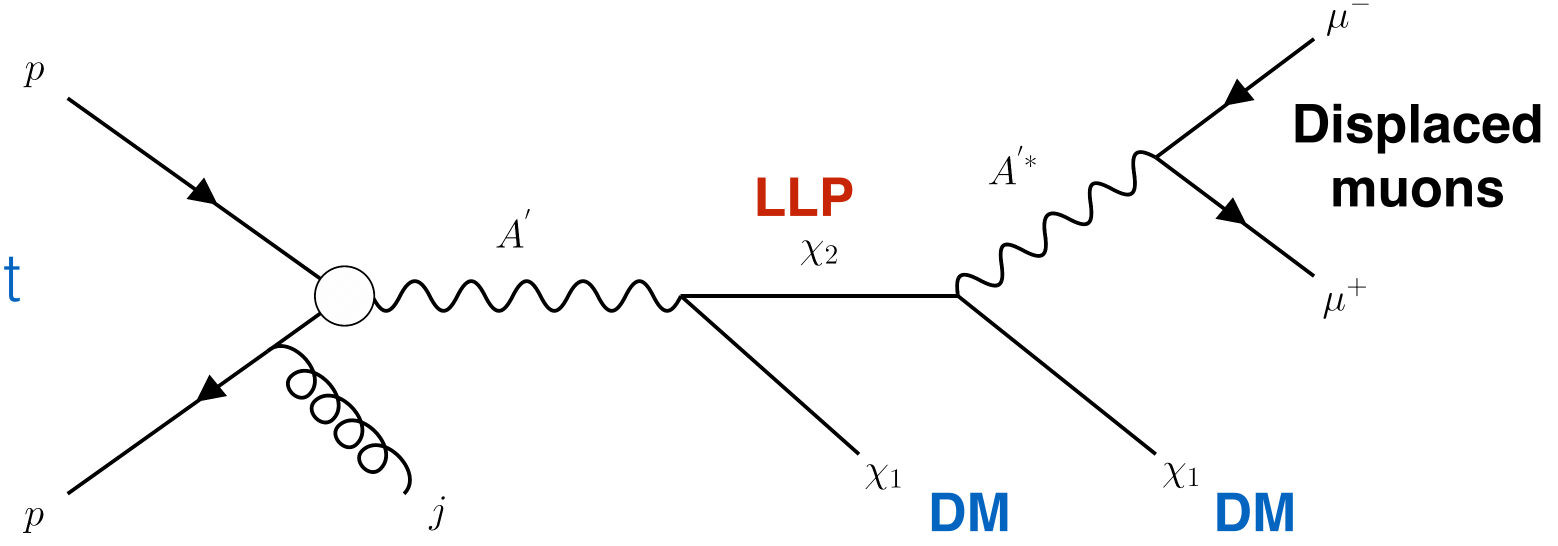
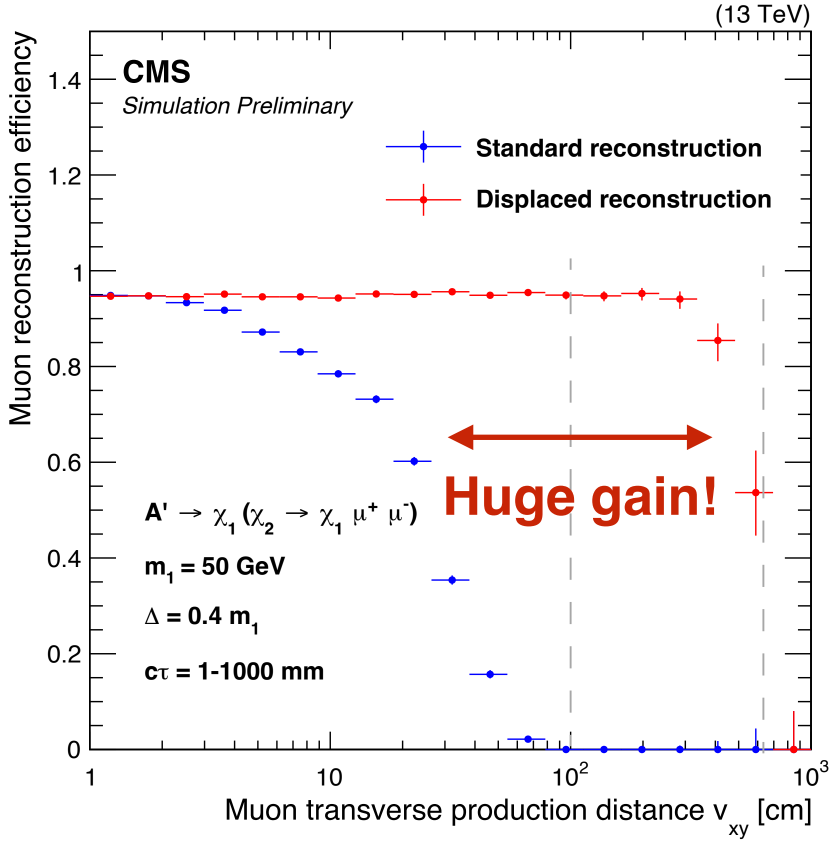
Search for Inelastic Dark Matter

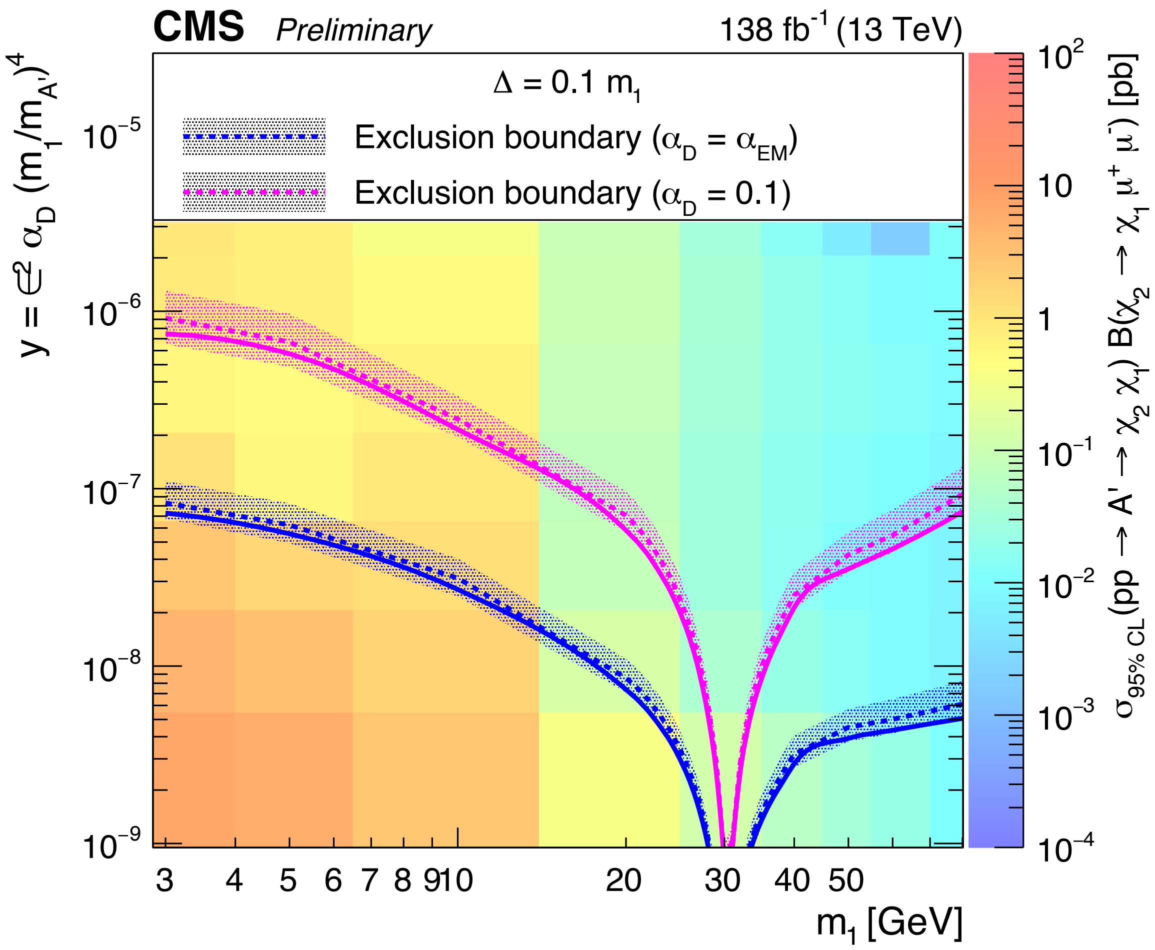
Signature: Highly collimated displaced muons + momentum imbalance boosted against “ISR” jet

Dark photon portal hidden sector
Mysteries studied: DM





First ever collider sensitivity to inelastic DM!



Dedicated displaced reconstruction provides high efficiency for O(m) displacements

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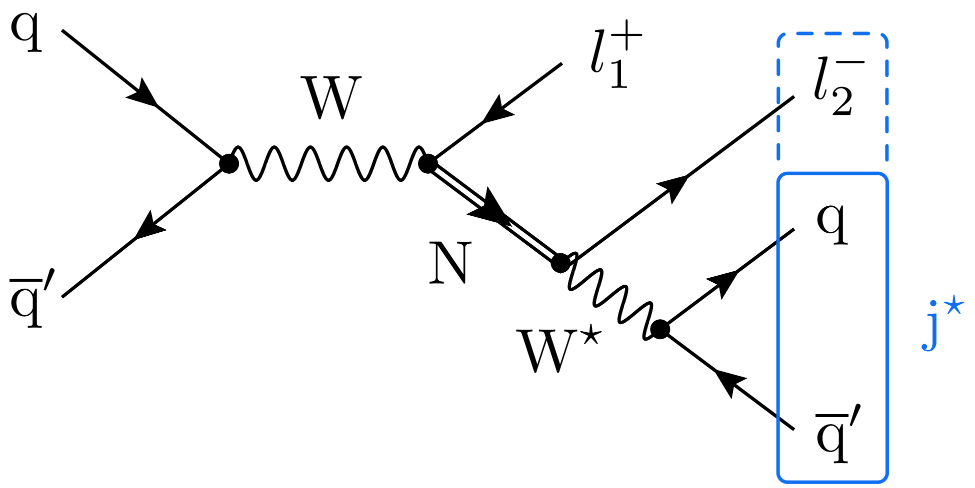
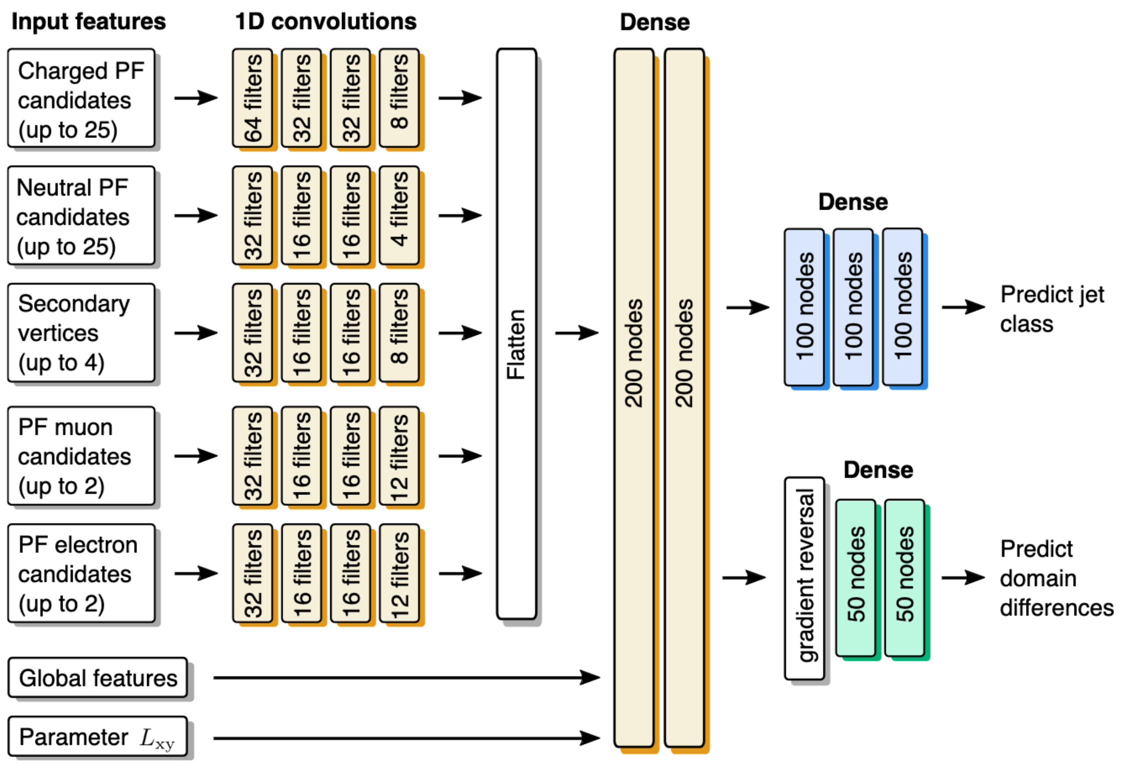
EXO-21-010

Search for HNLs with a DNN tagger

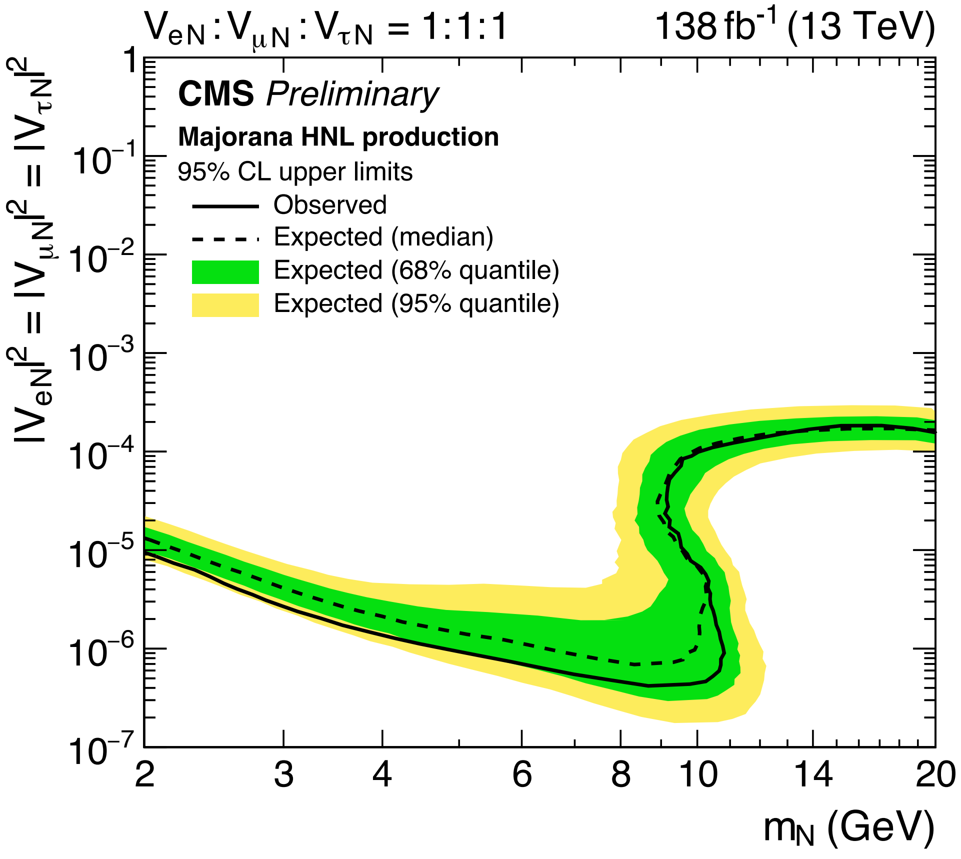
Neutrino portal hidden sector
Mysteries studied: ν masses, DM



Signature: displaced jet and lepton (merged or resolved) + prompt lepton



Use DNN for **displaced jet tagging** with up to 1500 features/jet!



Sensitivity to couplings to **all three lepton generations** for both **Dirac and Majorana HNLs**

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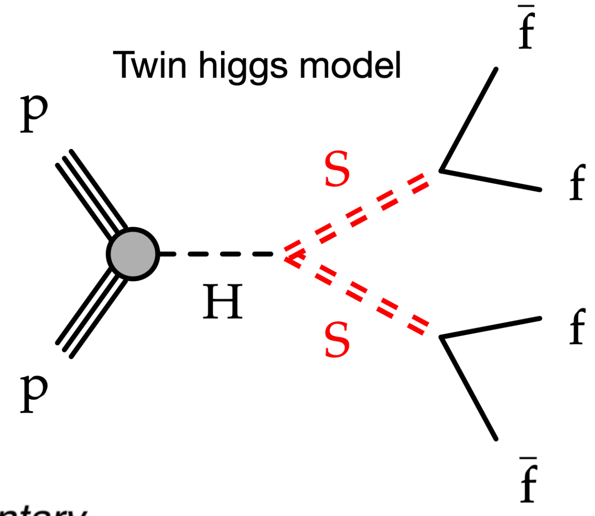
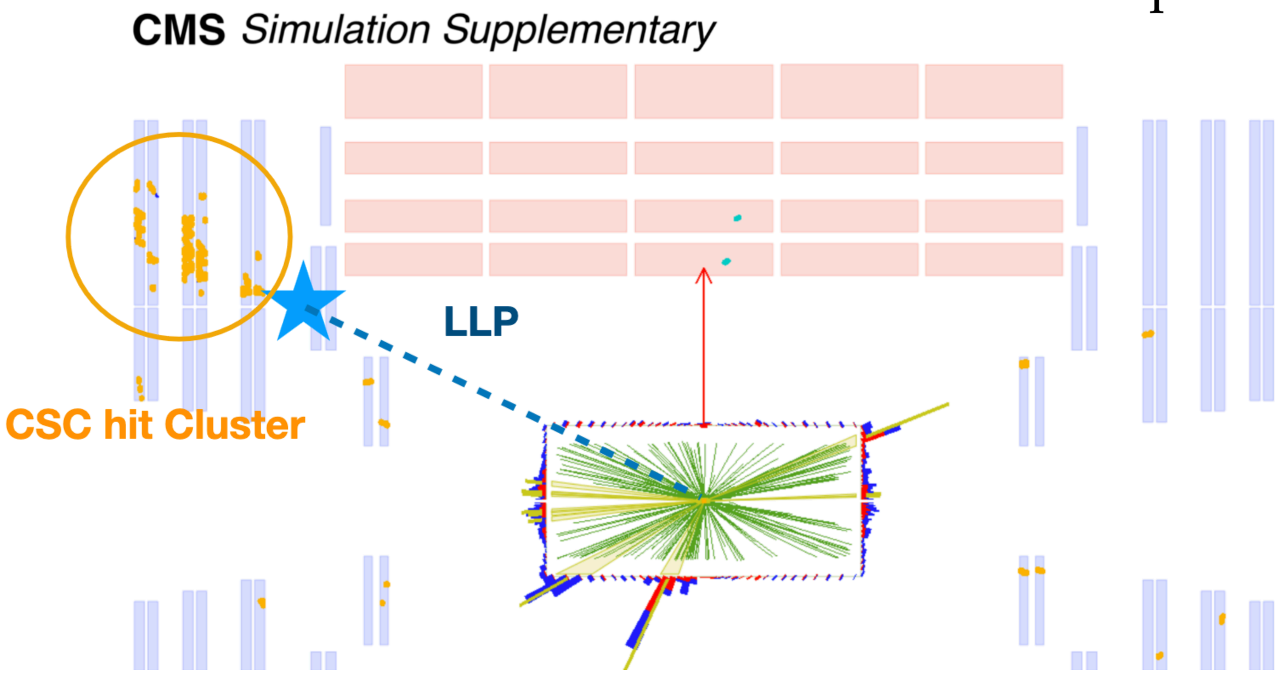
EXO-21-013

Search for H → LLPs with muon system clusters

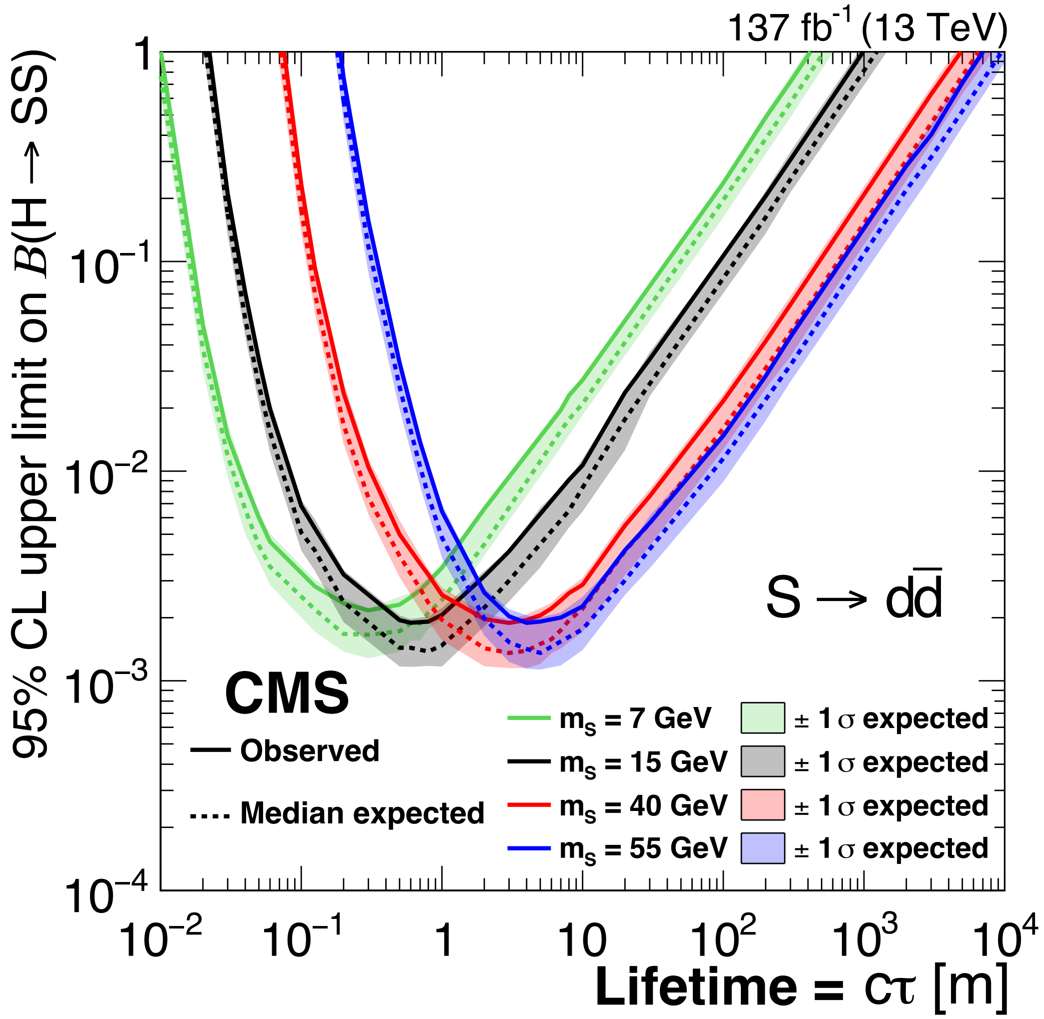




New reconstruction technique: look for clusters of hits from “showers” in muon system

EXO-20-015

Higgs portal hidden sector
Mysteries studied: naturalness, DM



“Calorimetric” signature (showers initiating in iron return yoke) rather than tracker allows sensitivity to **(very) low mass LLPs!**

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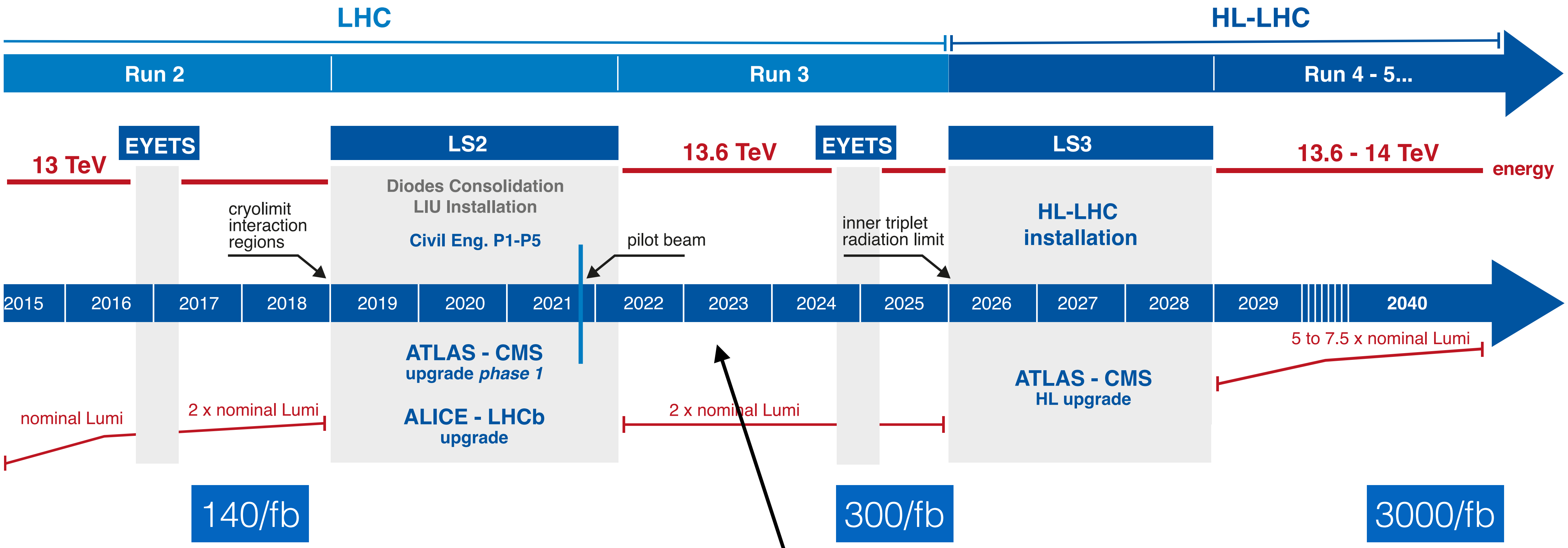
What's coming?



We are here (~200/fb)

Another ~20 years and ~2800/fb to go!

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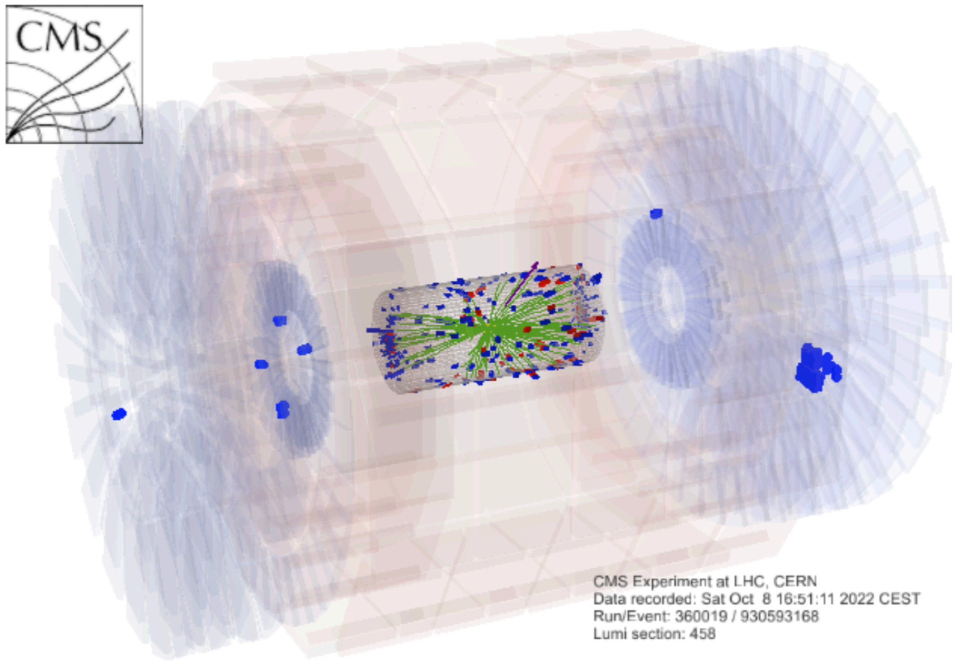
Run 3 underway

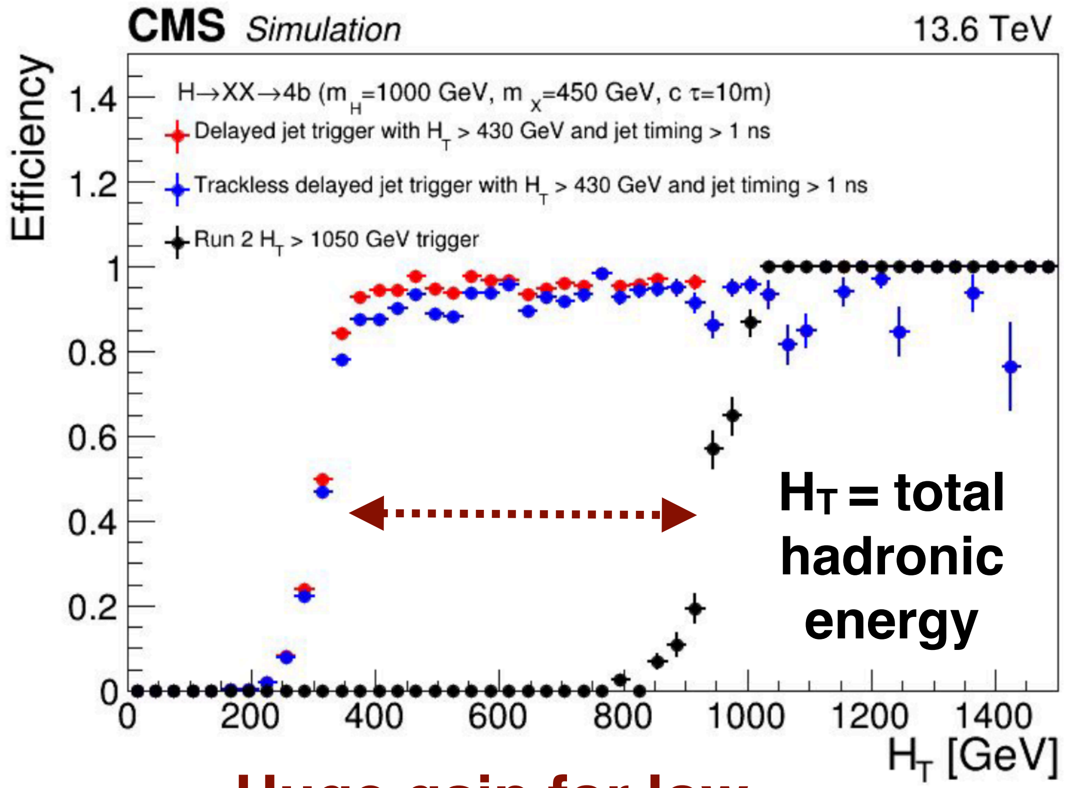
- LHC Run 3 **doubling** our previous dataset!
- CMS will extend sensitivity with **more data** at **higher energy** and **new trigger** selections and strategies
- ***AI autoencoding strategies*** being added to probe "unknown unknowns"

New muon system cluster trigger

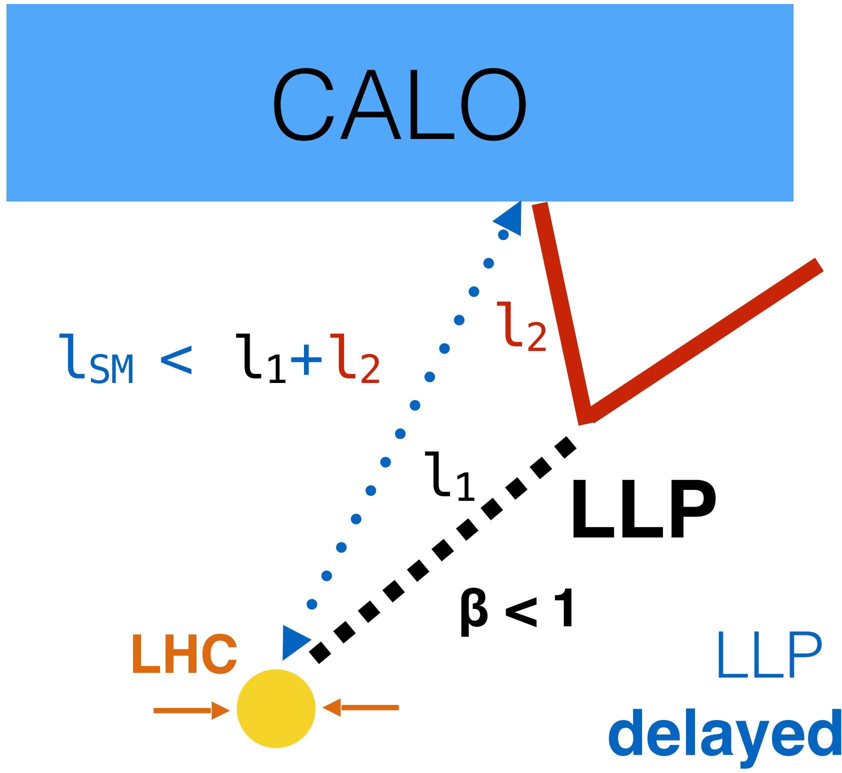


DP2022_062

New ECAL and HCAL timing triggers

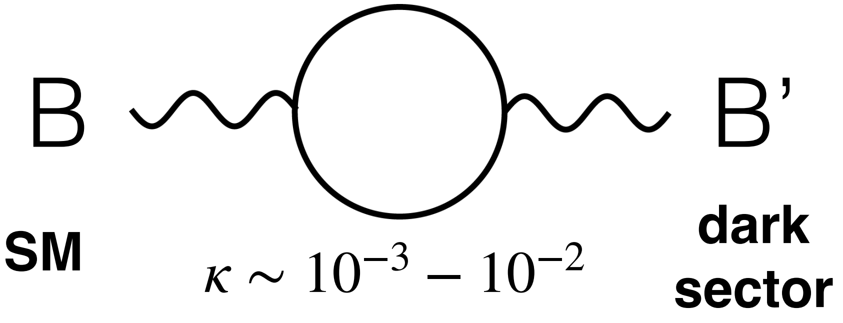


Huge gain for low energy displaced signatures!



LLP jets are **delayed** compared to jets from light SM

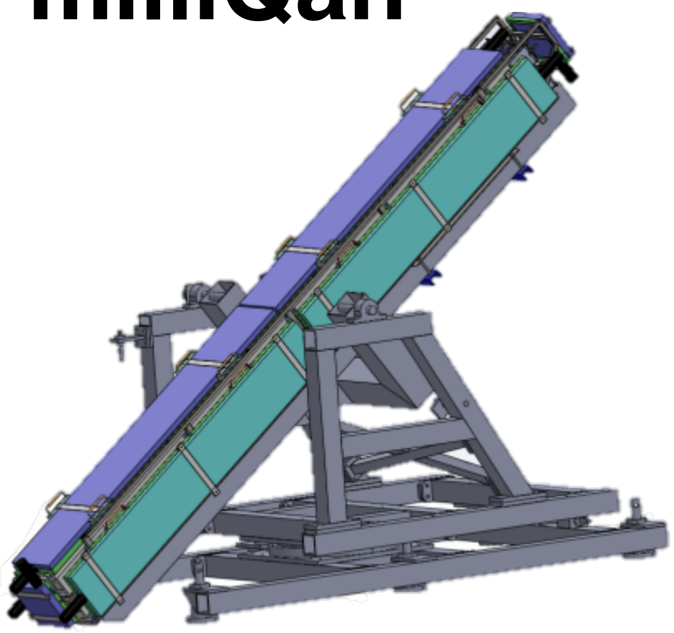
A new CMS “subdetector”!

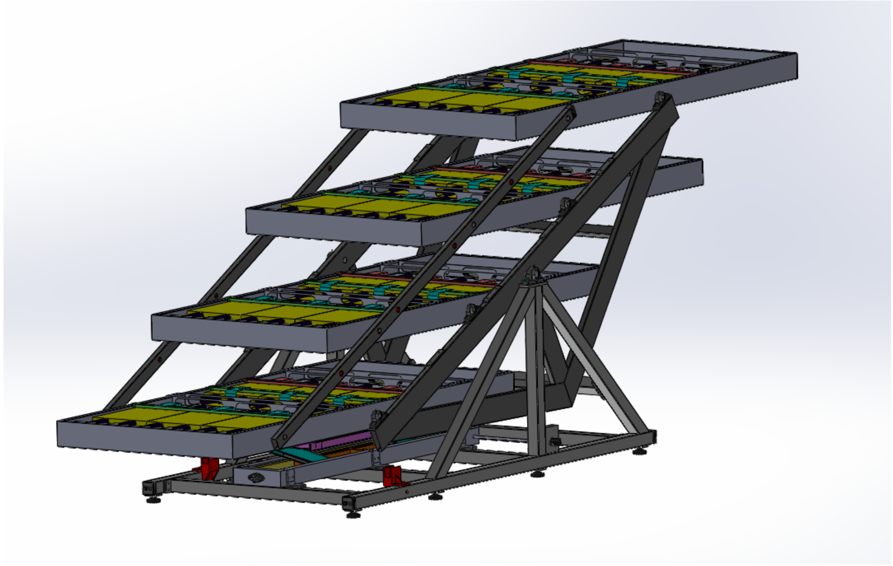


$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim 1/16\pi^2$)

milliQan

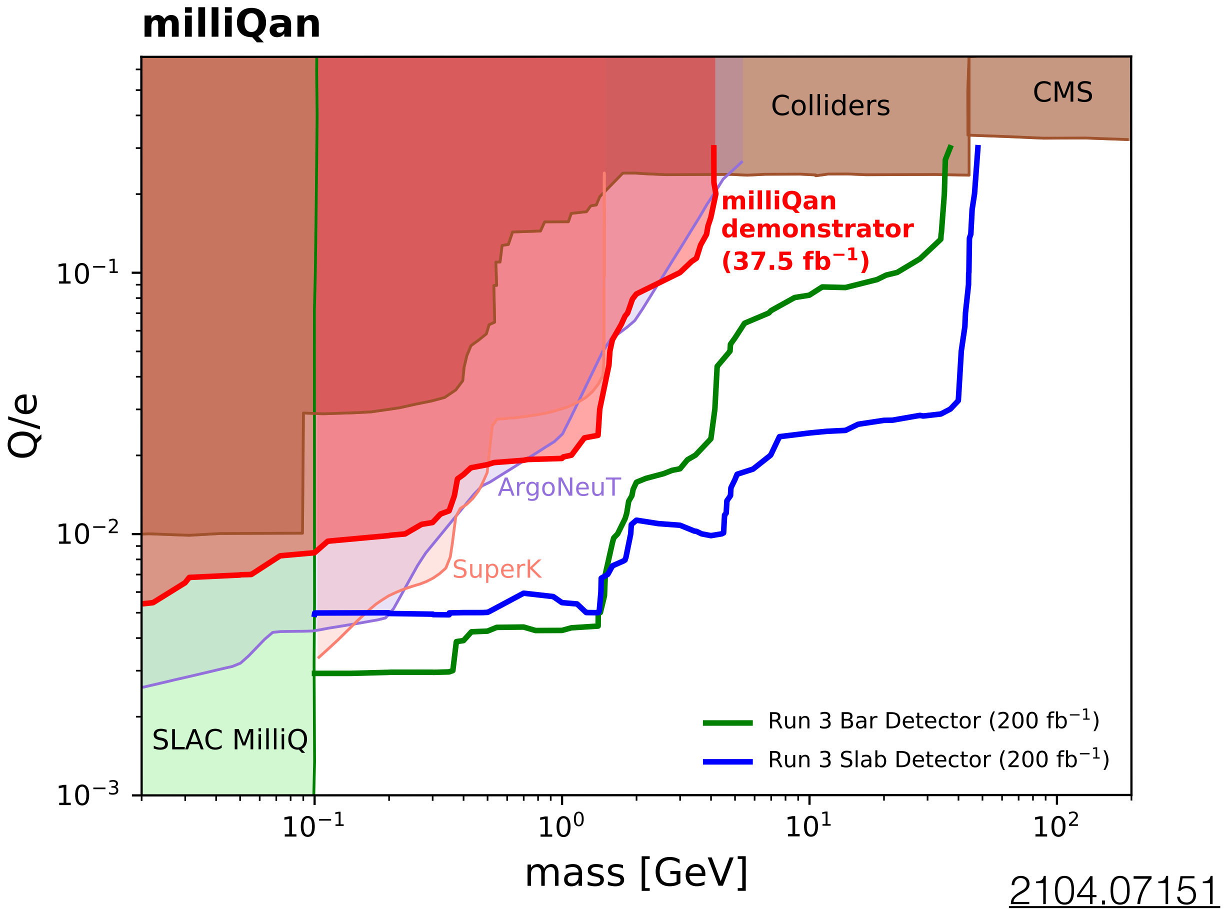




Photon portal hidden sector
Mysteries studied: DM

- Combination of two **scintillator-based** detectors will provide excellent sensitivity to **millicharged particles**

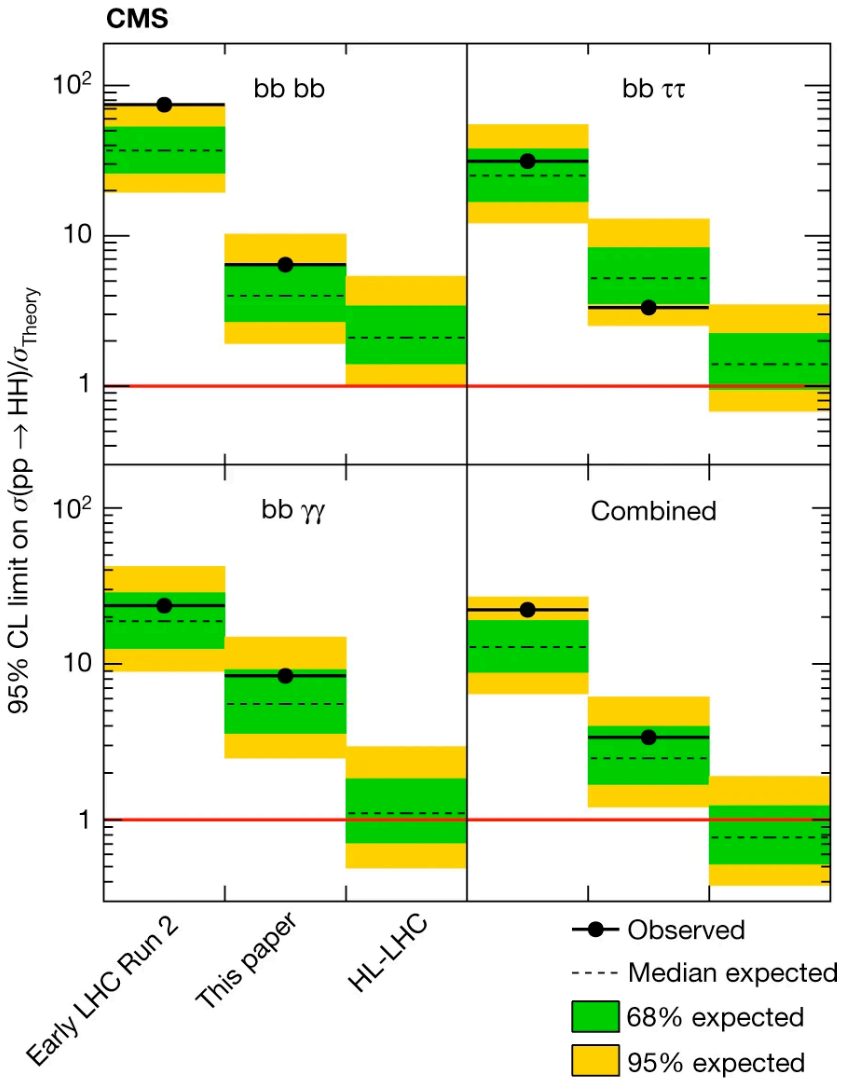
- Installed and taking data now!

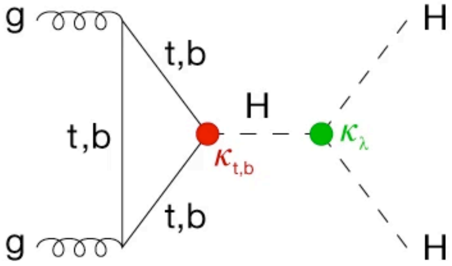


2104.07151

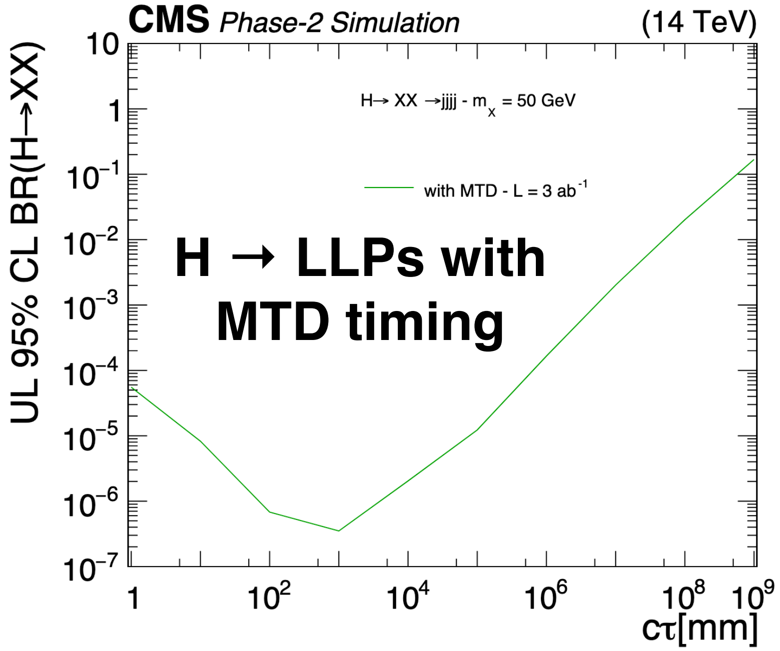
Looking to the future: HL-LHC

H → HH



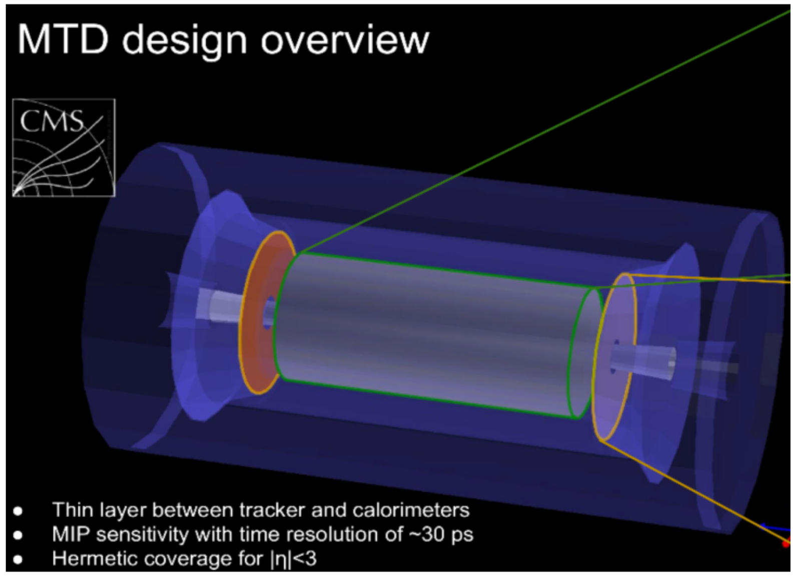


Nature 607 60–68 (2022)



H → LLPs with MTD timing

DP2022_025



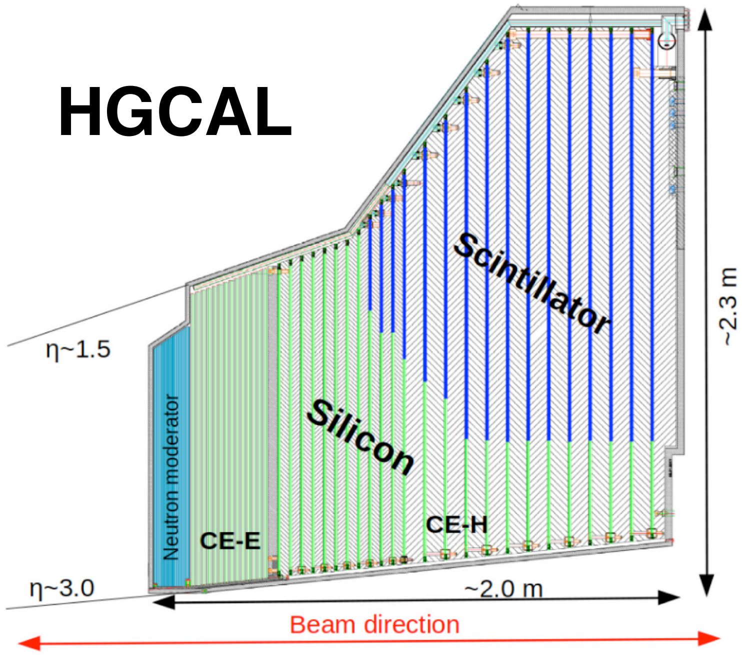
MTD design overview

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for |η|<3

30ps resolution

Huge dataset and new/ upgraded sub-detectors will provide excellent SM measurements and BSM discovery potential

HGCAL



5D reconstruction!

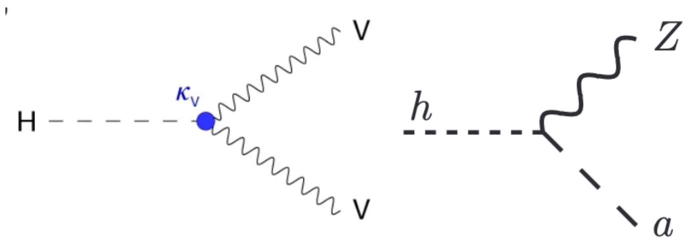
CMS-TDR-019

More details to come in Christian's talk

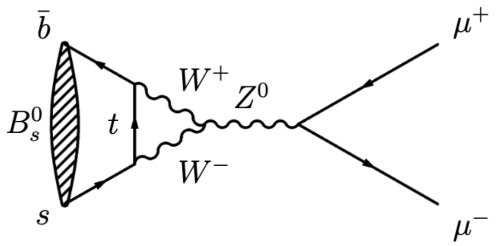
Summary

CMS is pushing the limits of the SM with measurements and searches for BSM signatures

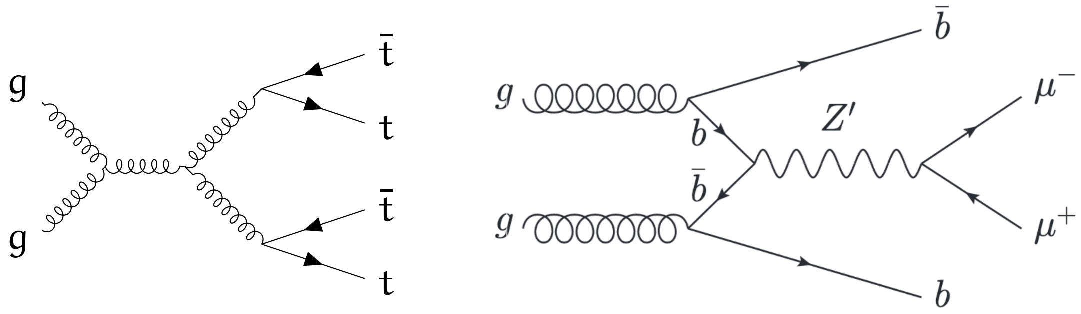
Higgs



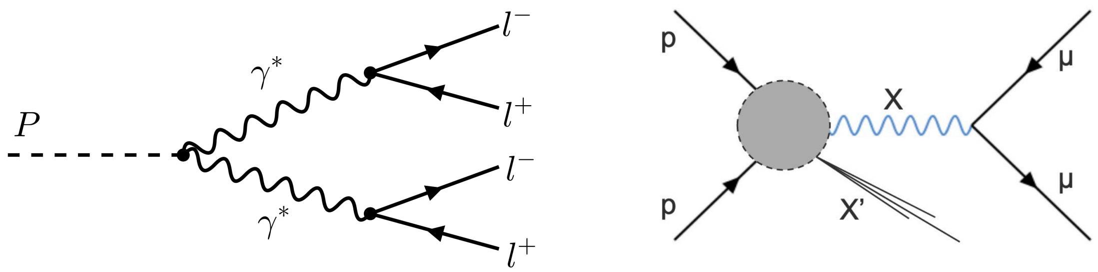
B physics measurements



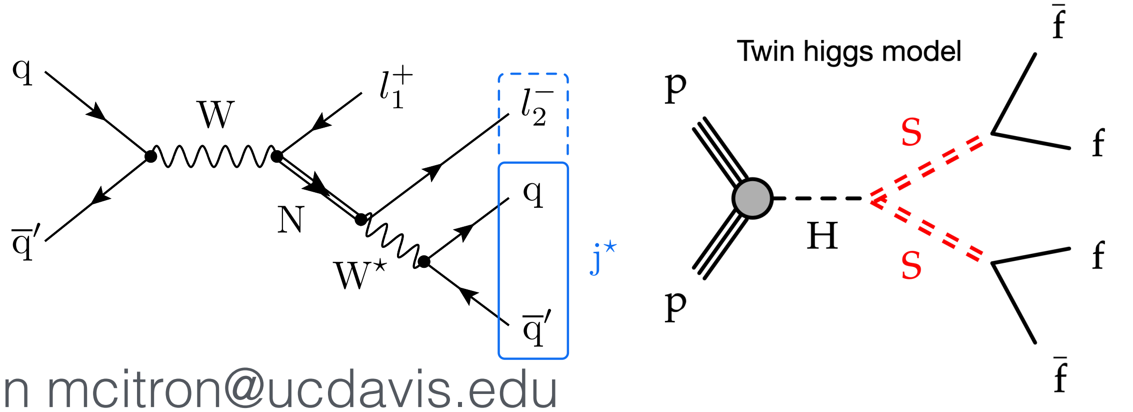
High mass (SM and BSM)



Low mass (SM and BSM)



Long-lived signatures



+ much more!

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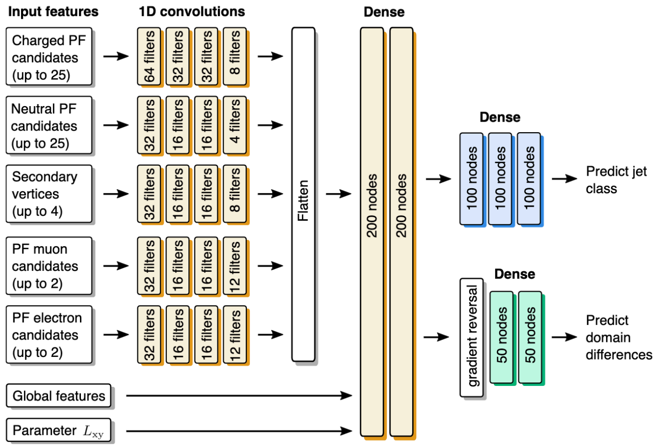
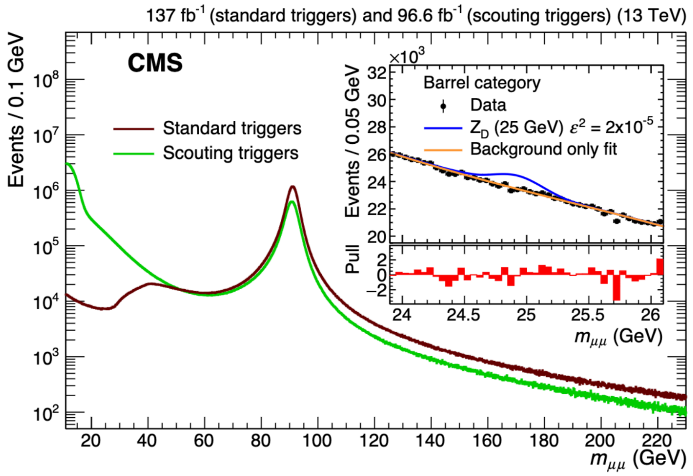
Summary

How? A wide array of innovative methods!

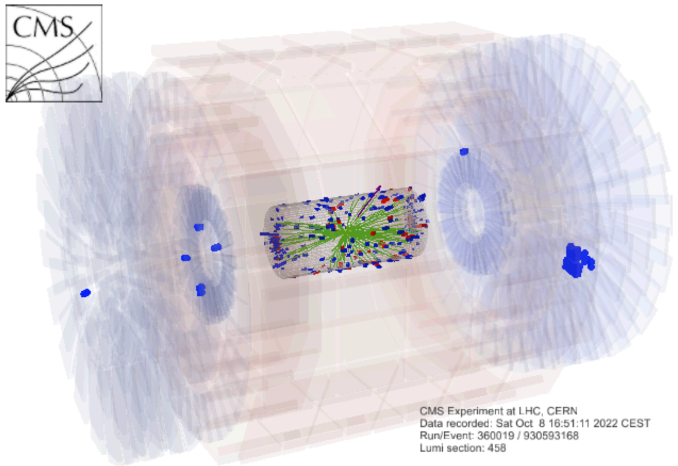
Machine learning



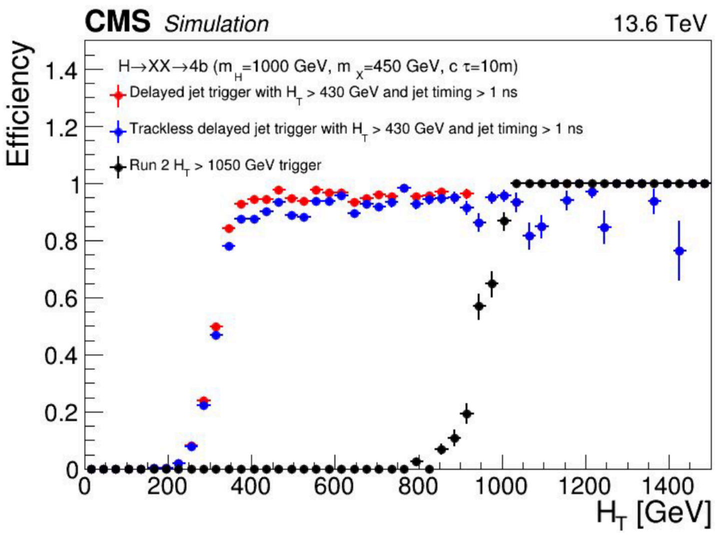
Low threshold trigger streams



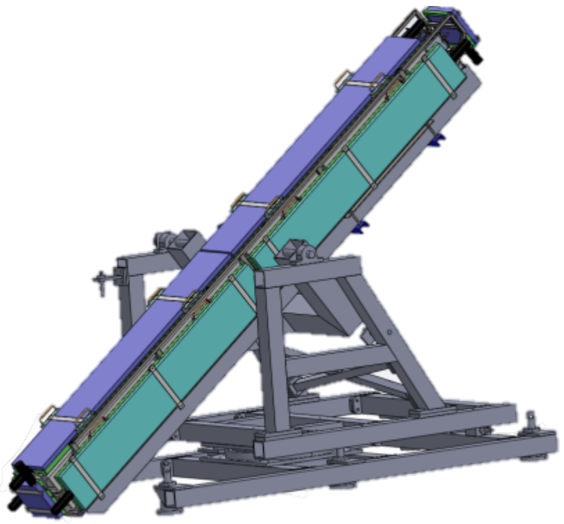
Exotic reconstruction



New exotic triggers



Even new detectors!



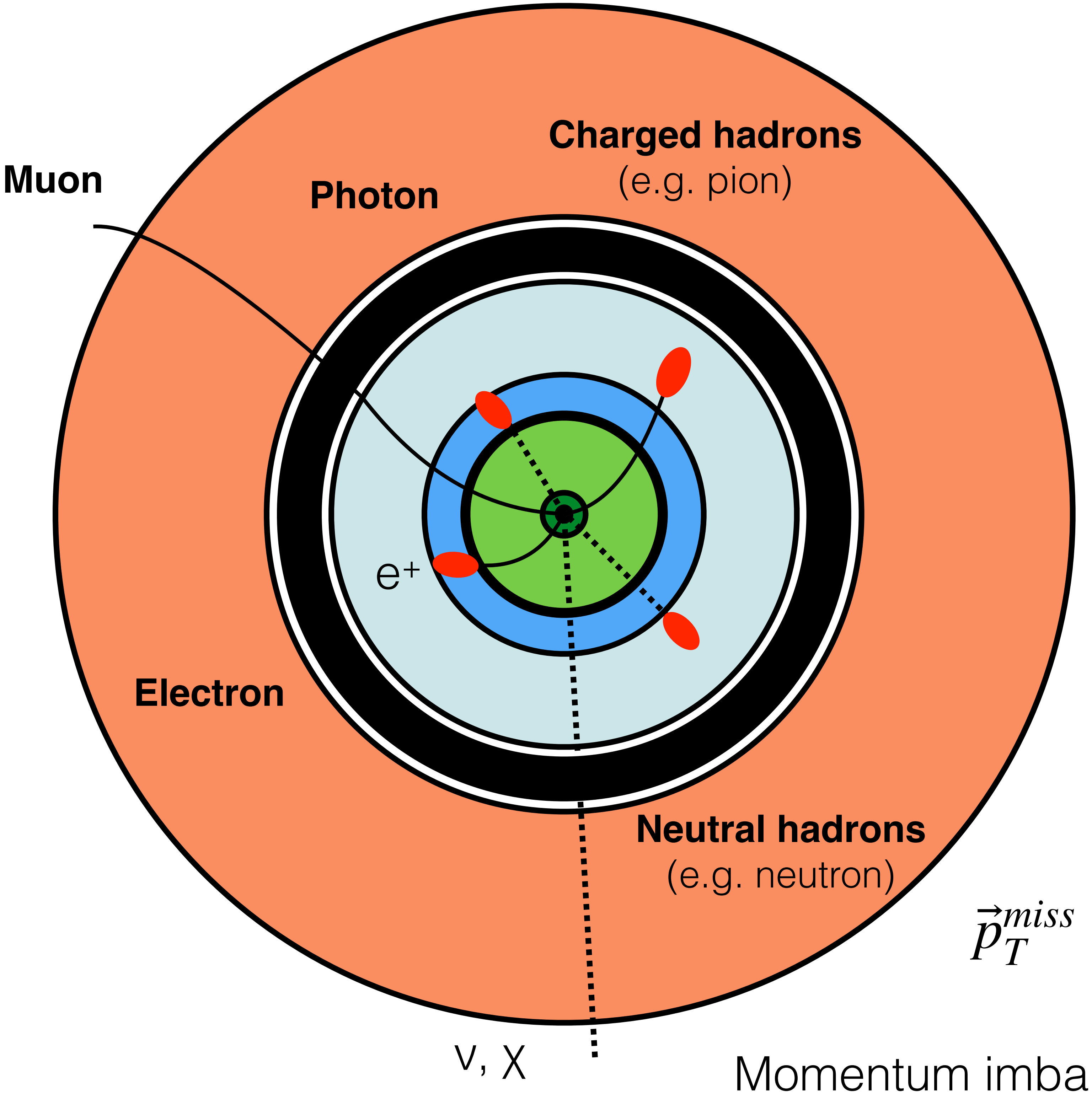
CMS is in an excellent position to discover whatever new physics might be waiting at the LHC!

Thanks for your attention!

This speaker supported by
funding from DOE Office of Science

Backup

Most analyses: build picture from ~5 types of promptly produced SM particles



Transverse momentum

$$\vec{p}_T^{miss} = - \sum_{\text{particles}} \vec{p}_T$$

Momentum imbalance provides insights into invisible particles

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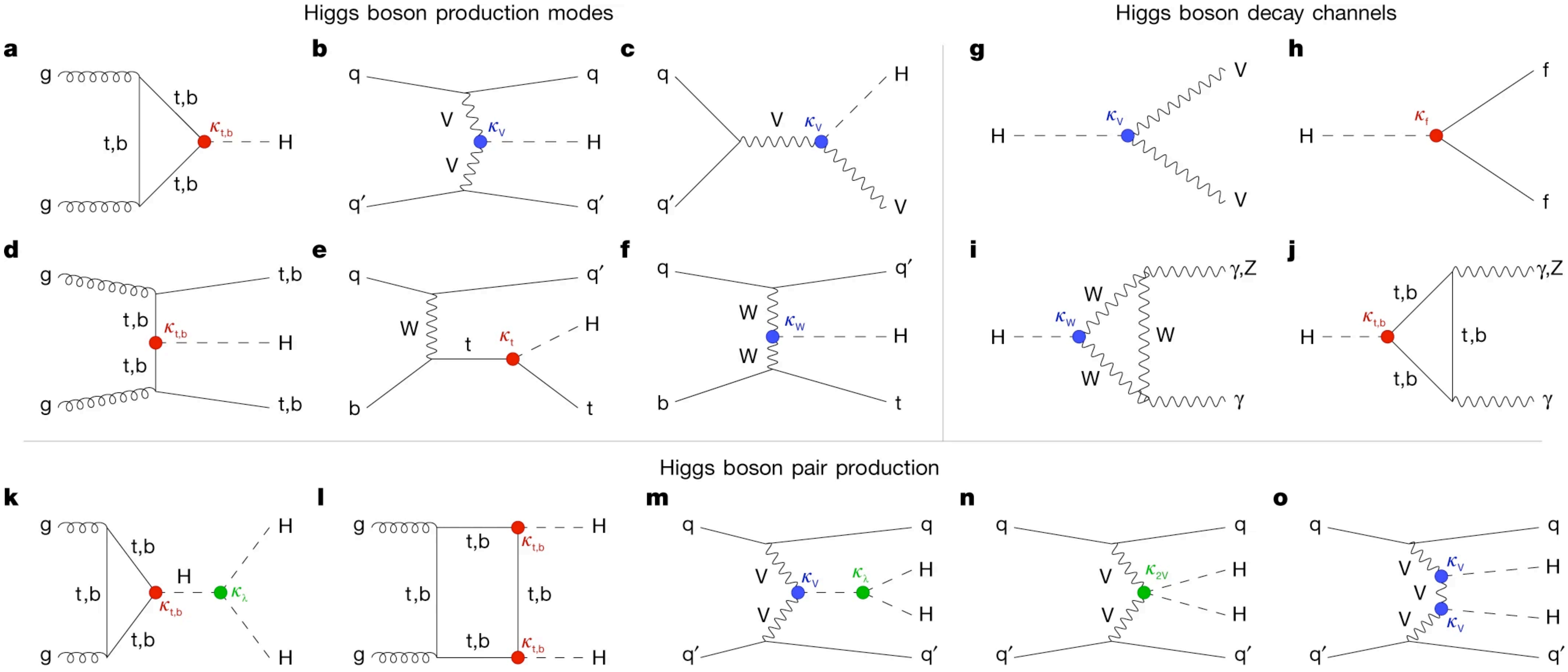
Kappa framework



https://www.nature.com/articles/s41586-022-04892-x/figures/1

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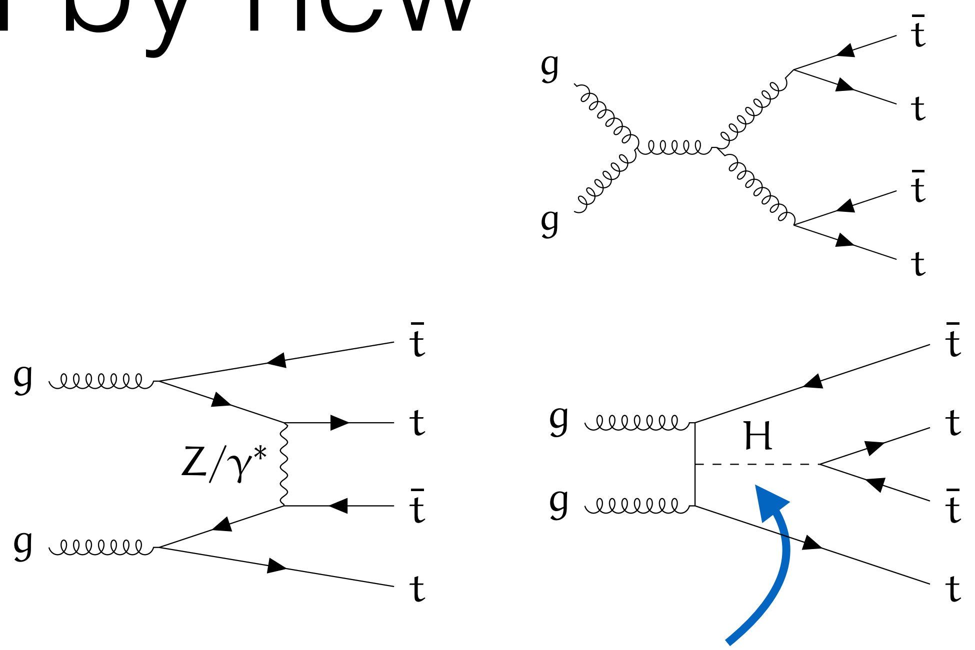
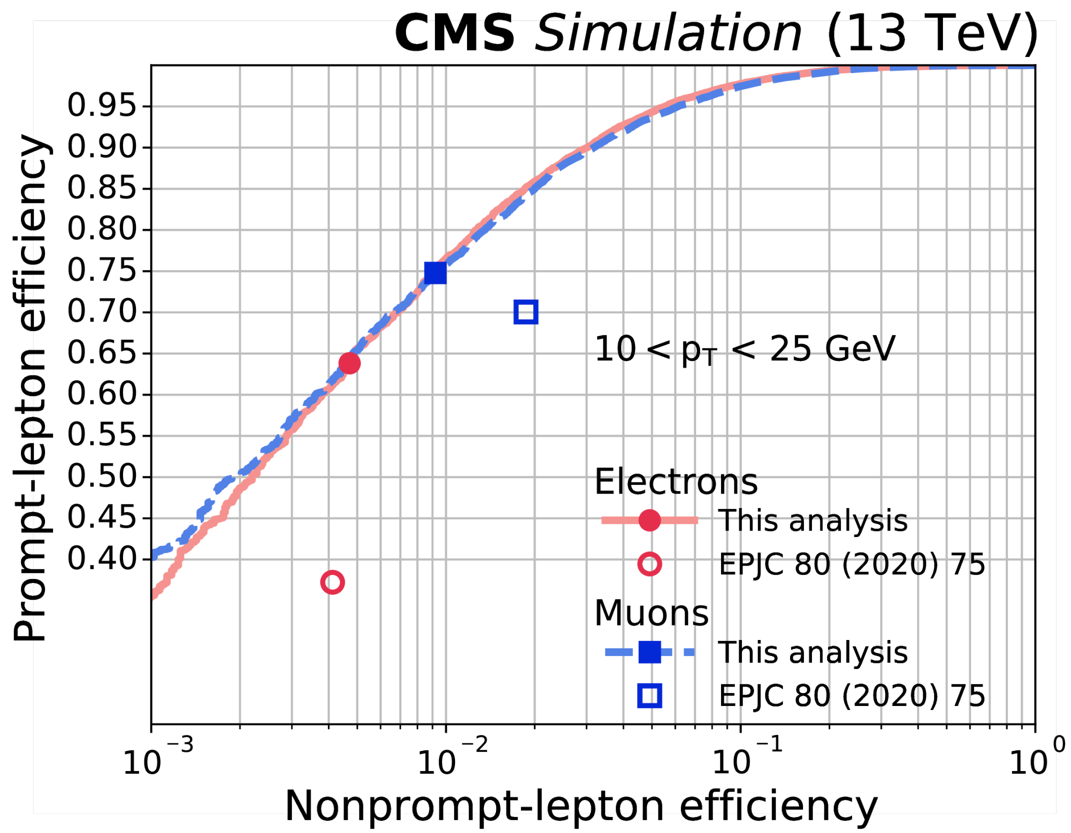
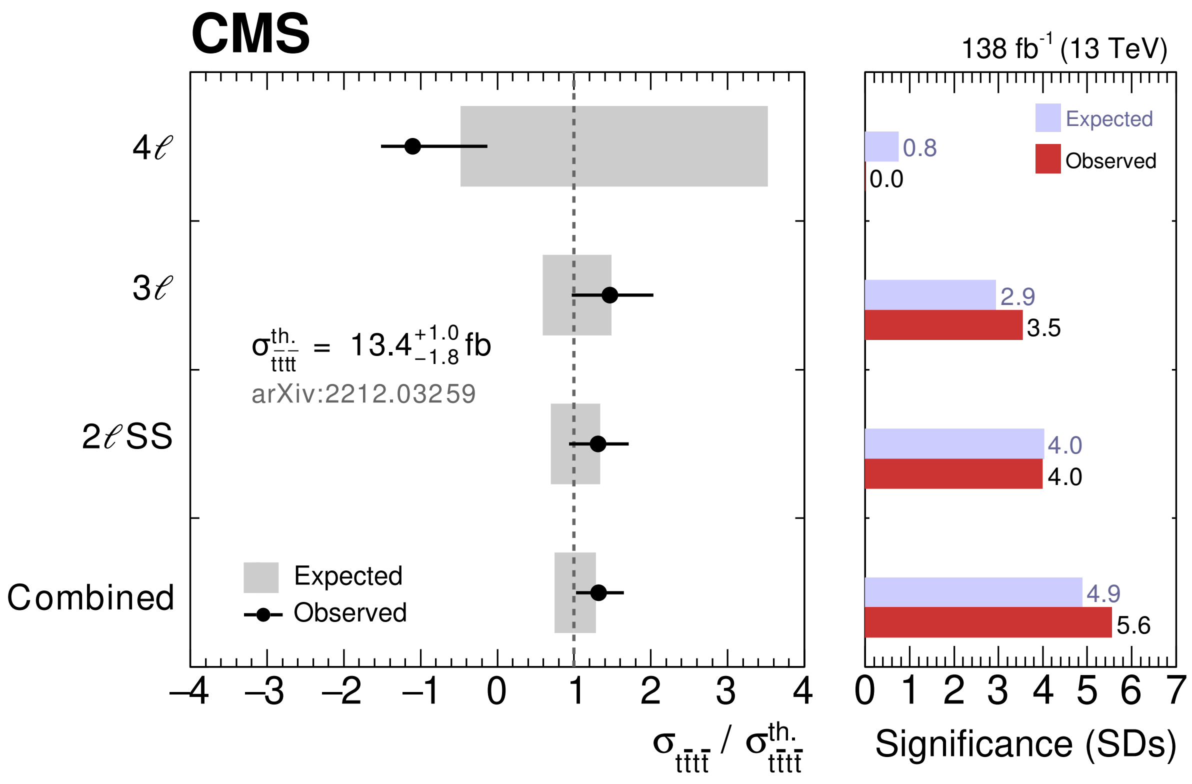
Hidden sectors also probed by new measurements

- Four tops: **heaviest** final state ever observed
- Multiple **ML** uses: BDT for lepton ID, DNN for b-tagging, BDT for final discrimination
- Measure $\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.9}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})\ \text{fb}$ from only ~2000 four-top events



Crucial probe of hidden sectors - new physics here?





Mysteries studied: naturalness, DM

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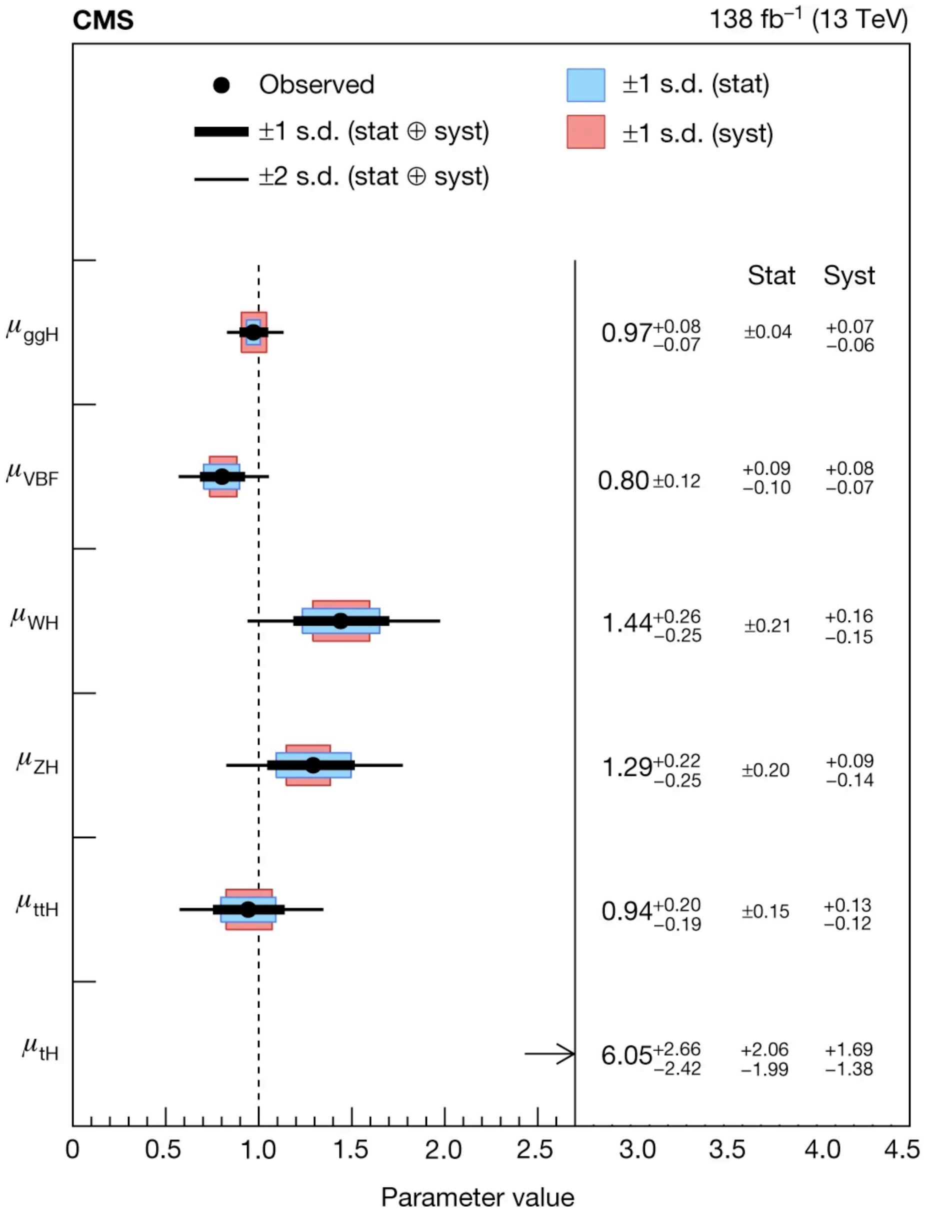
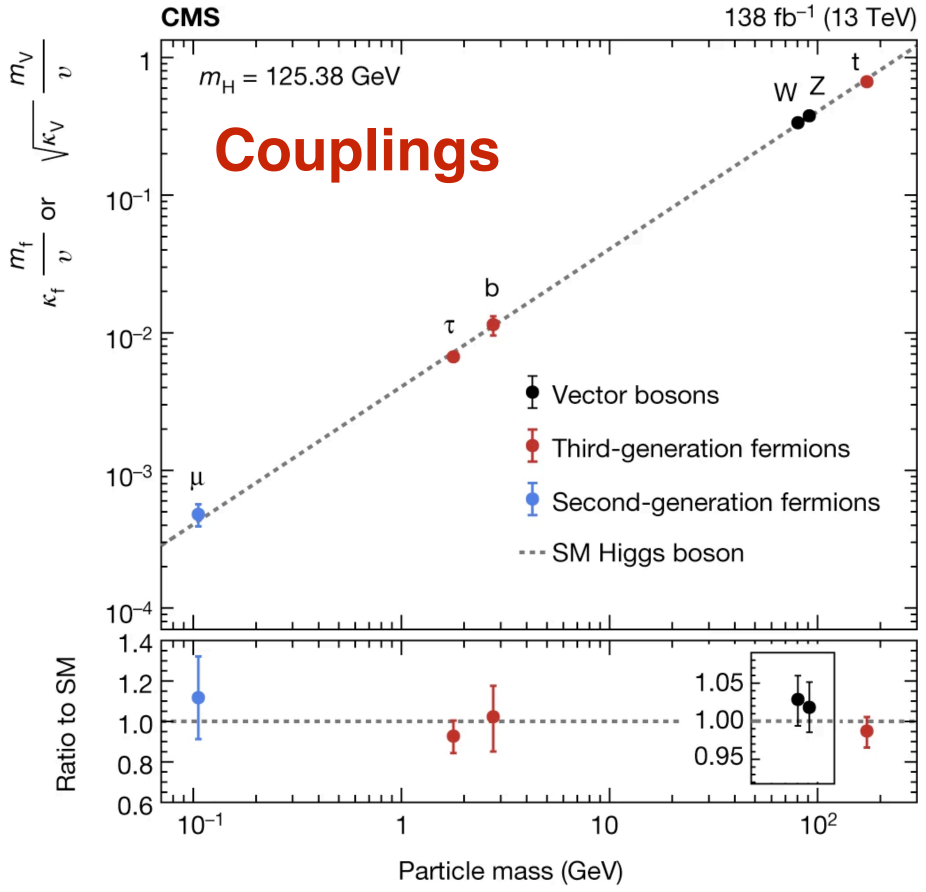
2305.13439

Higgs: precision measurement

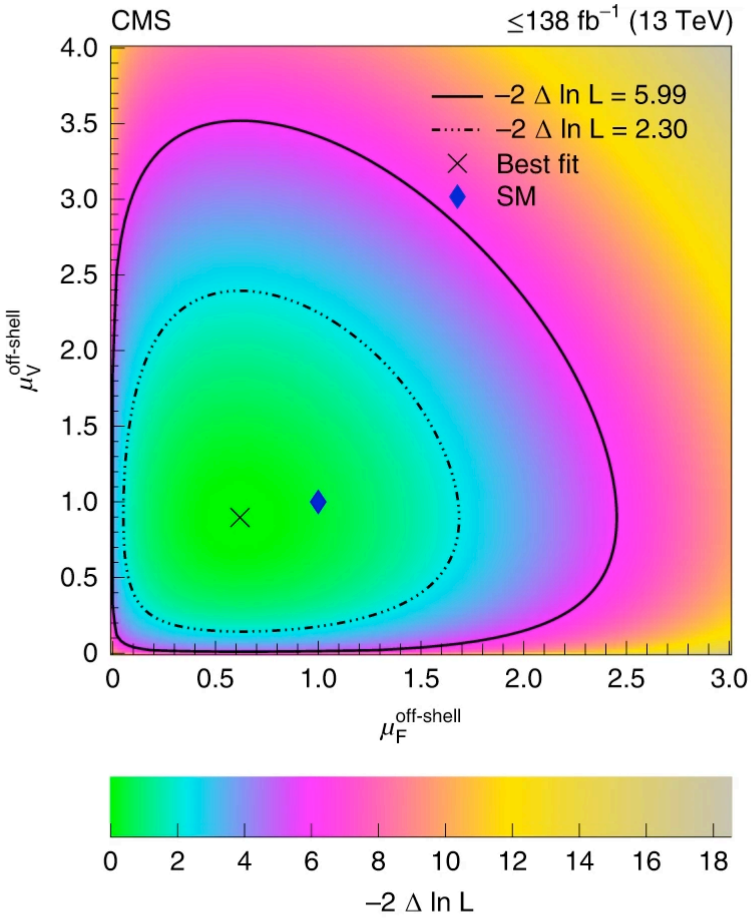
Production mechanisms



Couplings



Width + evidence of off-shell contribution to ZZ



$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

Many properties of the **first fundamental scalar** now measured with **precision**

Nature 607 60–68 (2022)

Nature Physics 18 1329–1334 (2022)

Consistency with SM predictions **hugely impactful** on new physics

The off-shell method for the width

Combine with on-shell signal strength measurement to extract Γ_{H} [1]:

$$\sigma = \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2 + m_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^2} \ldots dm^2$$

On-shell

Off-shell

$$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_{\mathrm{H}}} \propto \mu_{prod}$$

$$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2} \ldots dm^2 \propto \underbrace{\mu_{prod} \cdot \Gamma_{\mathrm{H}}}_{\mu_{prod}^{off-shell}}$$

Take on-shell signal strength from final states ZZ or WW

Ratio of off-shell to on-shell signal strengths for each production mode gives Γ_{H}

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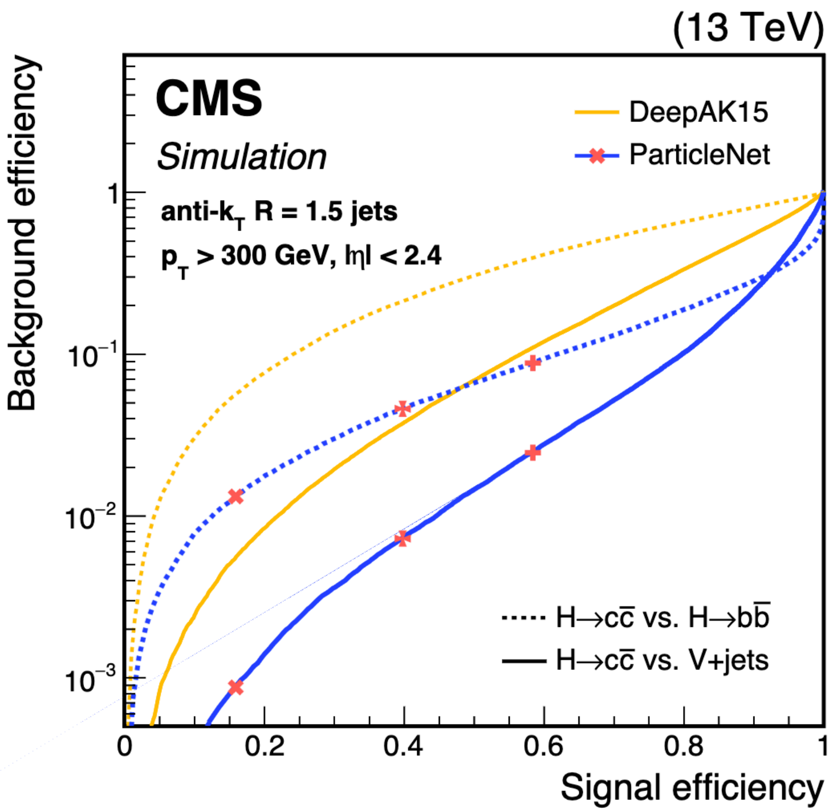
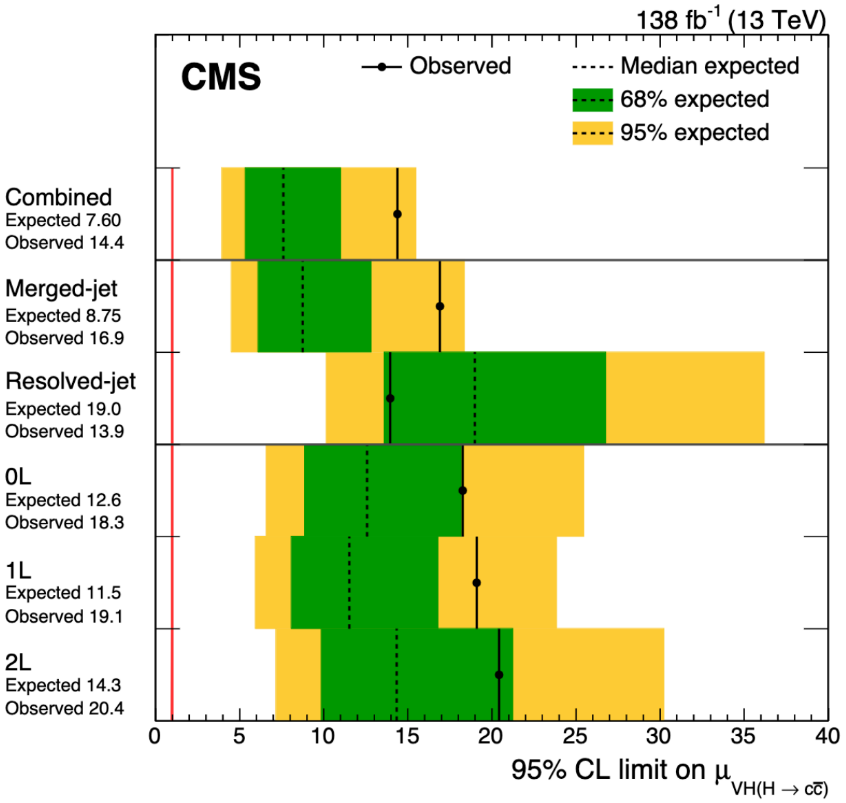
Recent Higgs measurements

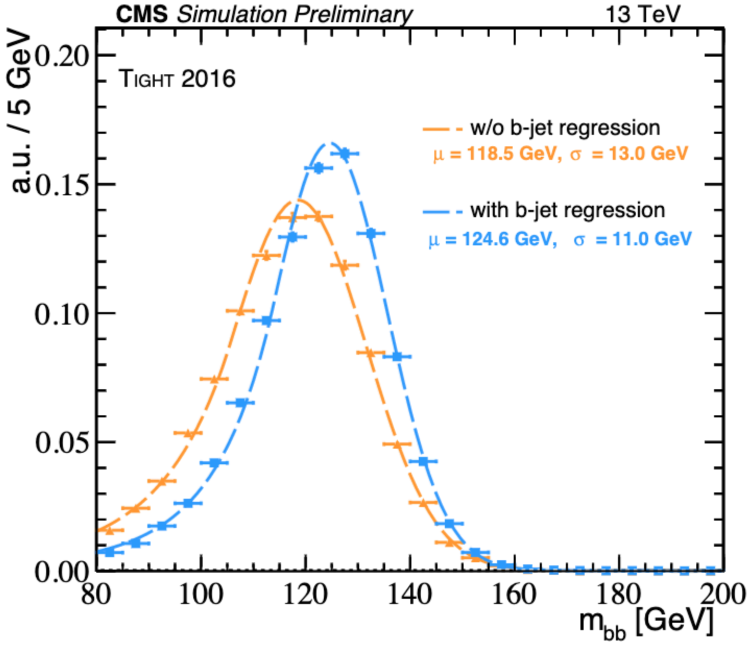


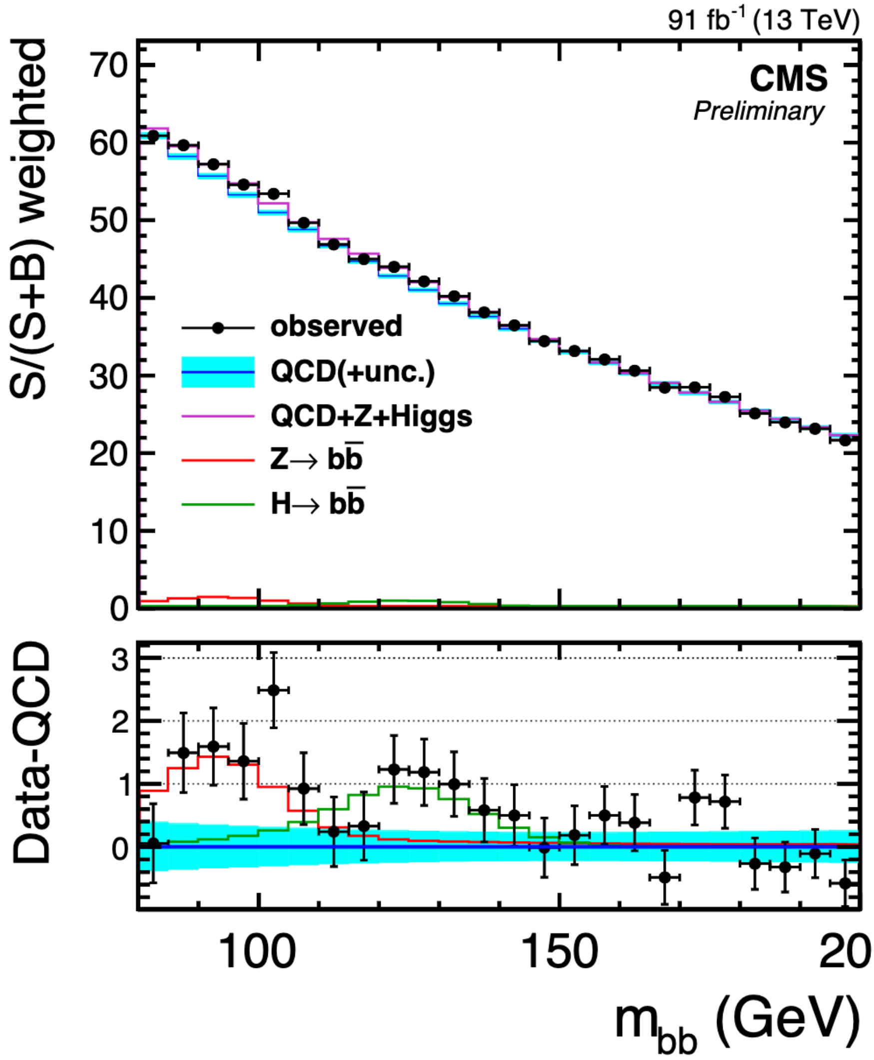


H->cc (arXiv 2205.05550)
VBF H->bb (HIG-22-009)

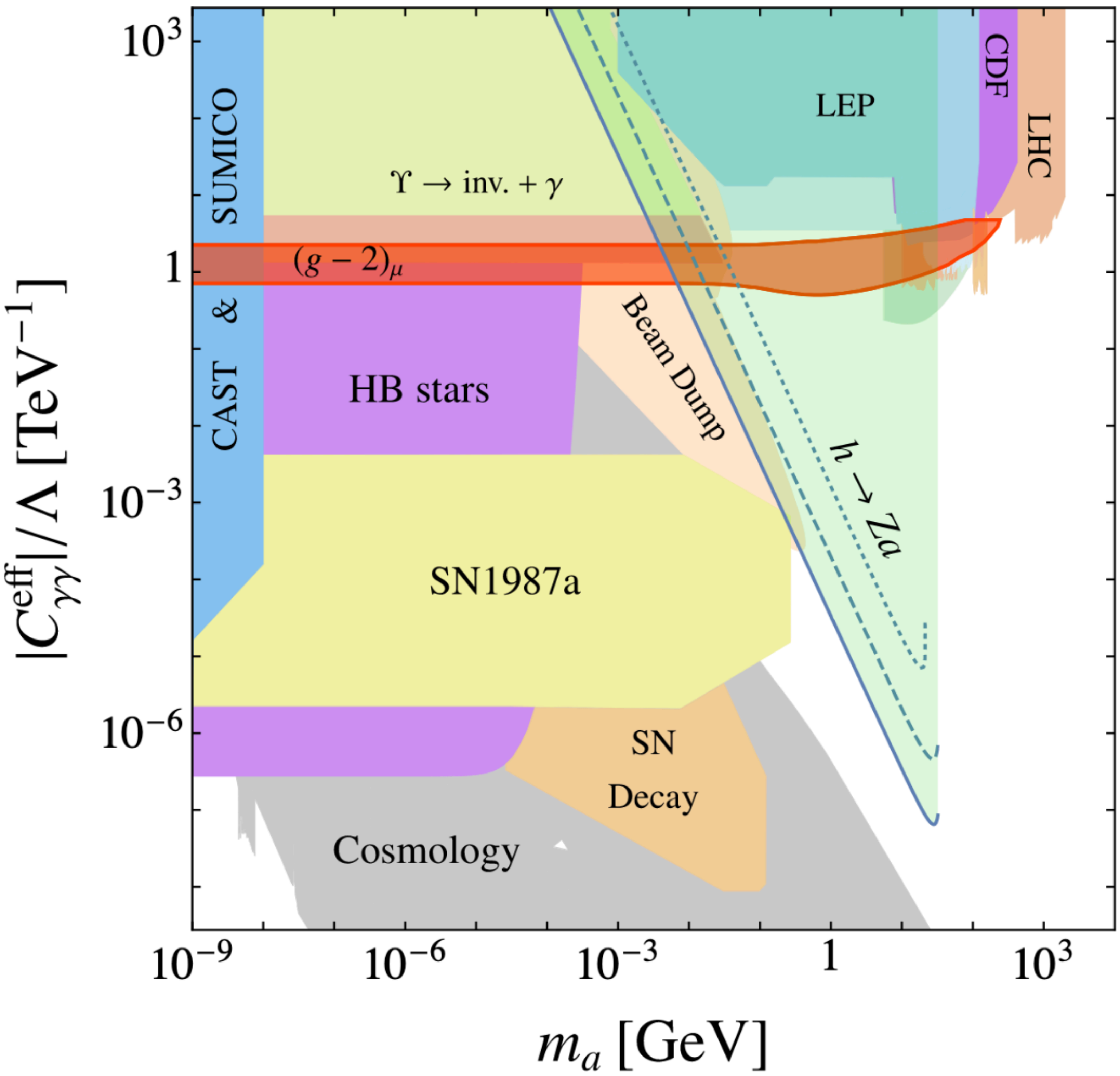
95% CL interval: 1.1 < |κc| < 5.5

Narrowing in on H → cc and VBF H → bb with advanced ML techniques



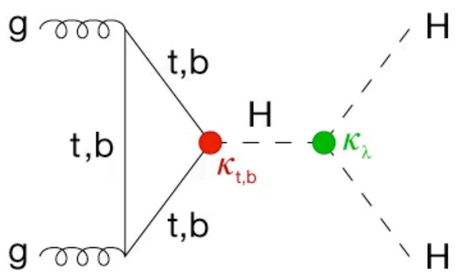


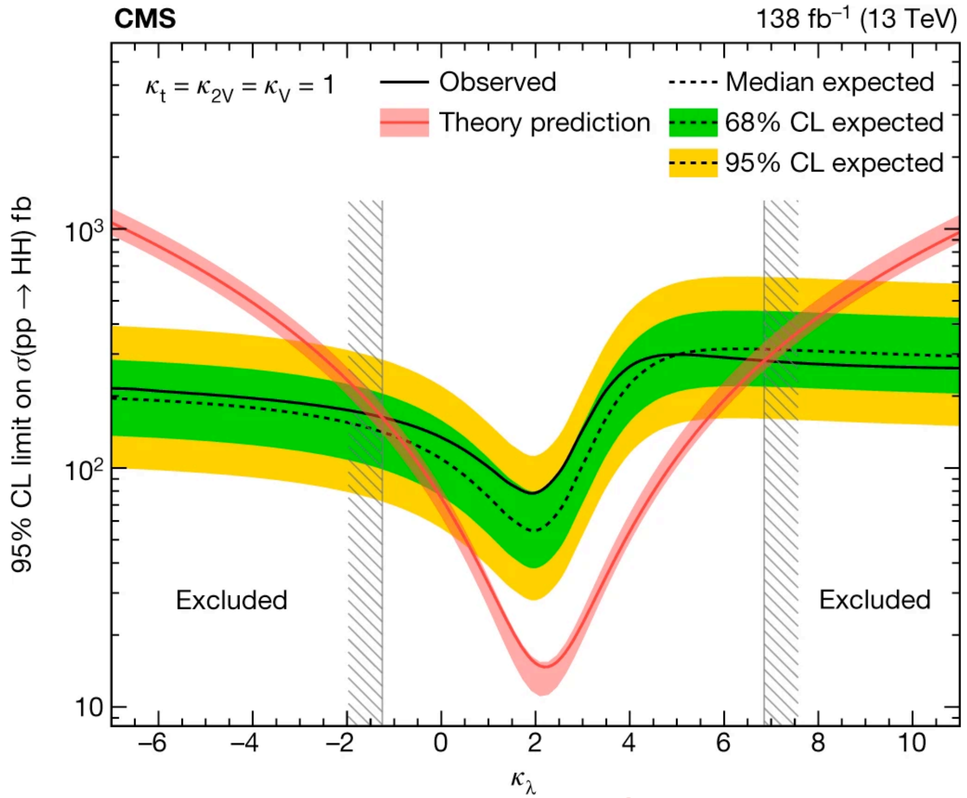
H -> Za complementarity



https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.031802

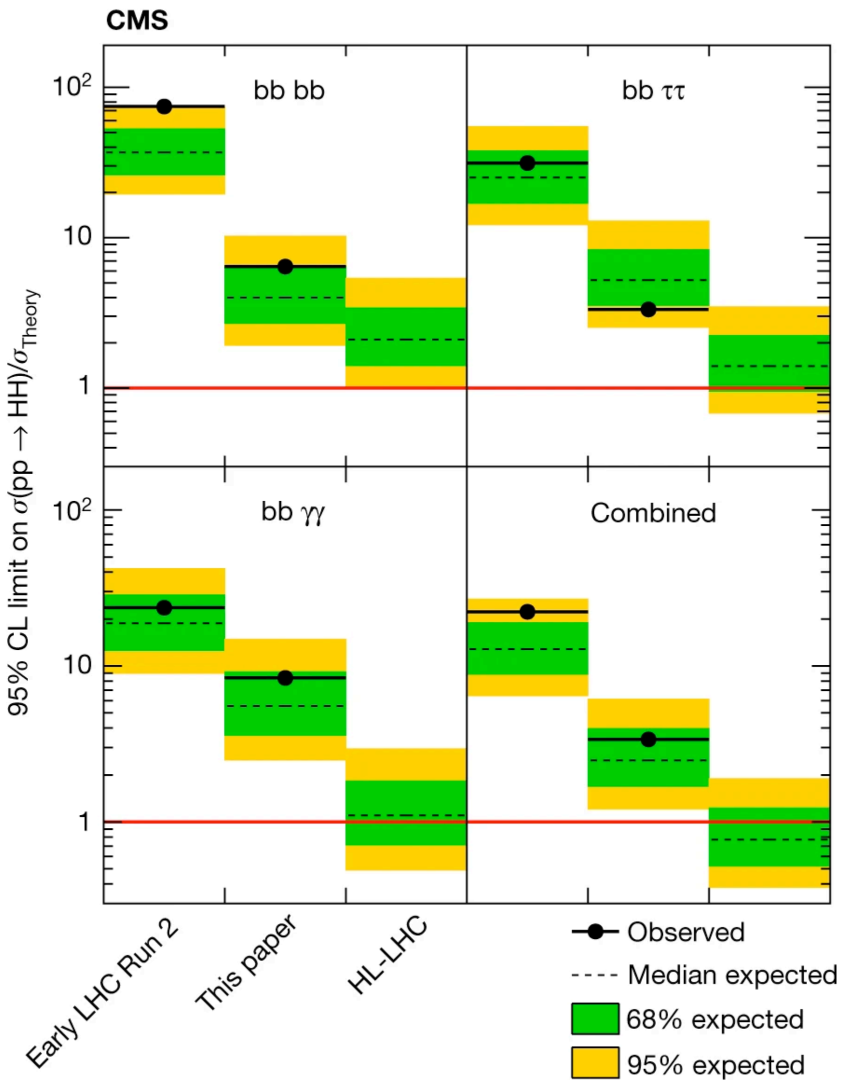
diHiggs





Self coupling

HH



CMS-PAS-HIG-20-001

Nature 607 60–68 (2022)

Nature Physics 18 1329–1334 (2022)

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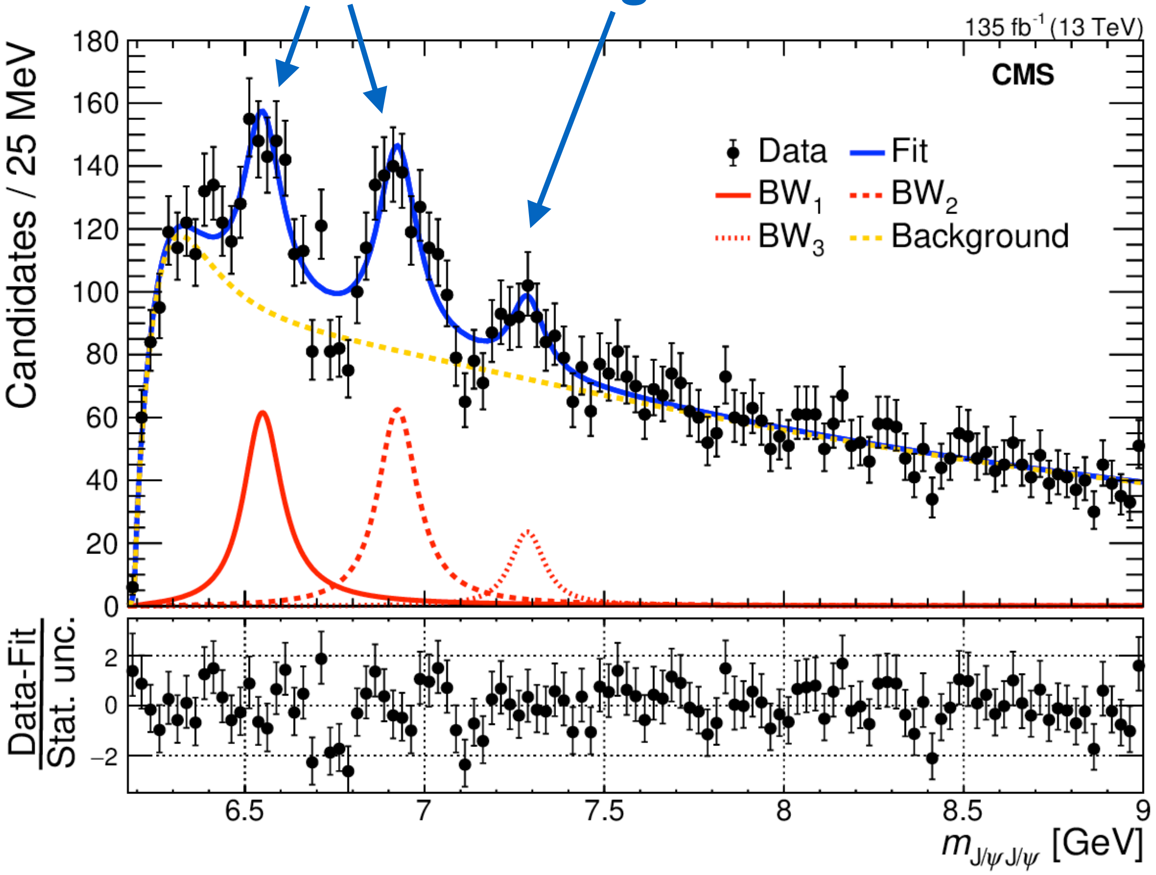
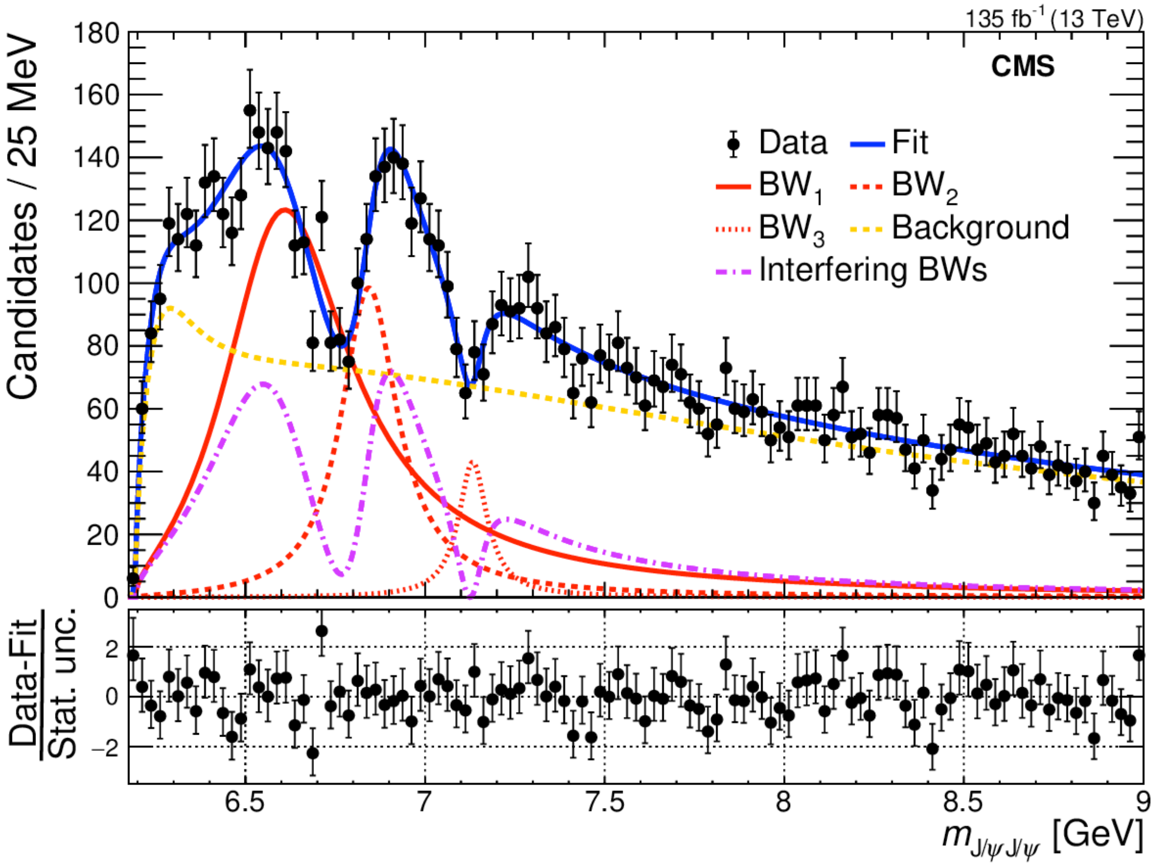
CMS is doing soft physics!

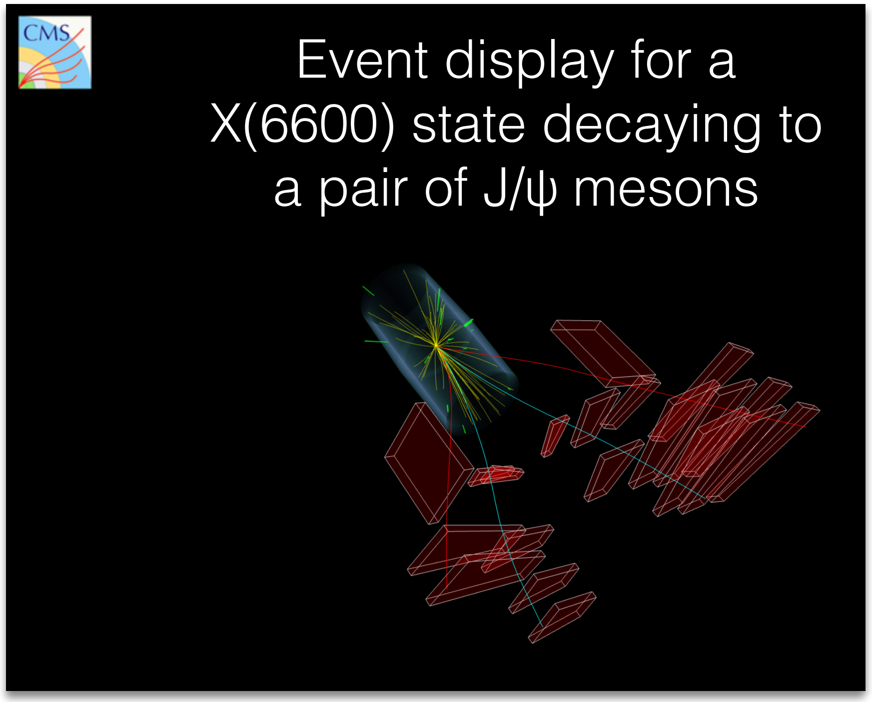
>5 sigma **4.1 sigma**



Observation of new structure in the J/ψJ/ψ mass spectrum



- Discovering new states: resonances could be all-charm **tetraquark states!**
- Interference is favored → supports states with **same quantum numbers**



Event display for a X(6600) state decaying to a pair of J/ψ mesons

Four top

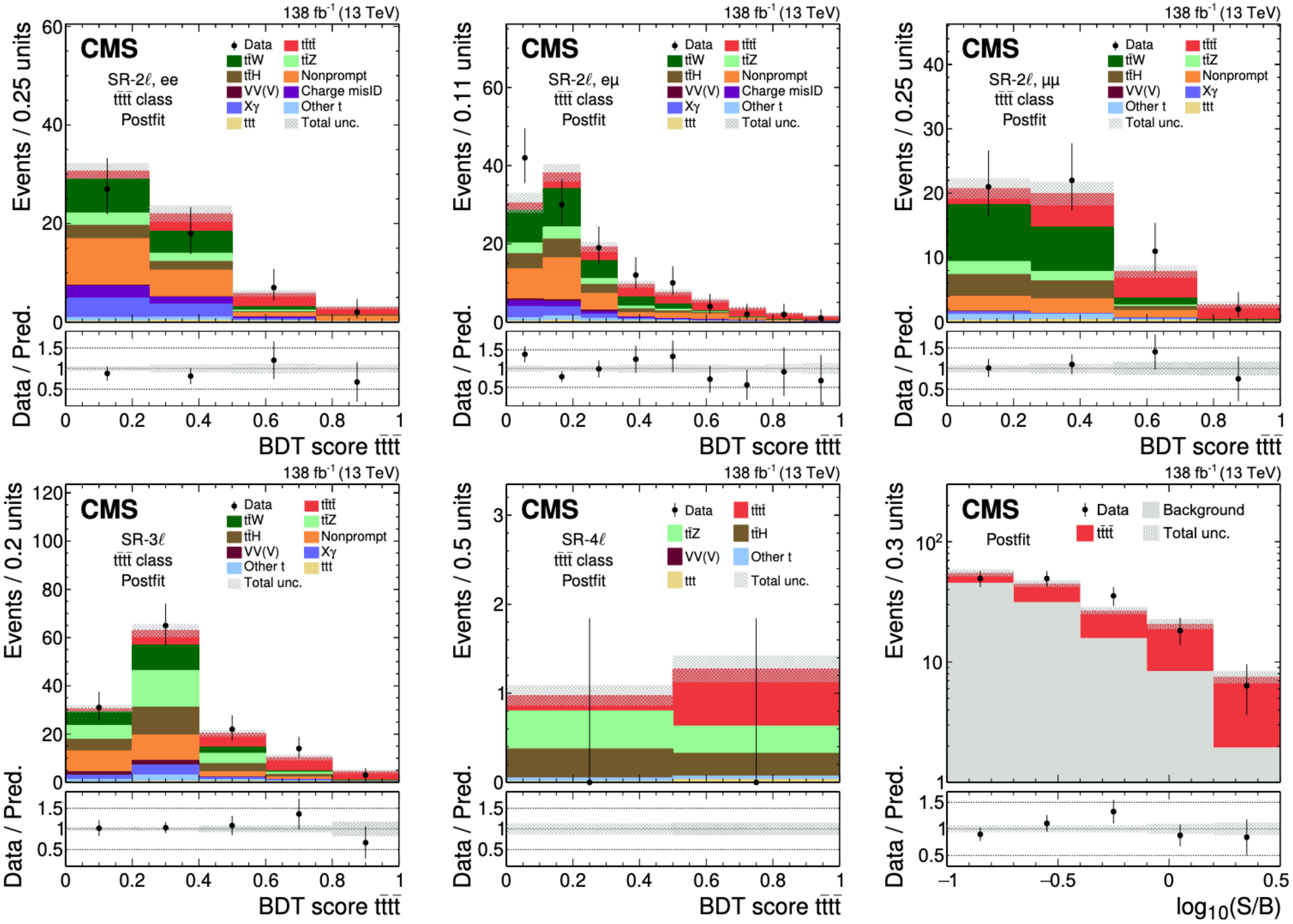


Figure 7: Comparison of the number of observed (points) and predicted (colored histograms) events in the BDT score $t\bar{t}t\bar{t}$ in the $t\bar{t}t\bar{t}$ classes of SR-2ℓ, shown for the ee (upper left), eμ (upper middle), and $\mu\mu$ (upper right) categories, of SR-3ℓ (lower left) and of SR-4ℓ (lower middle). Additionally, the comparison is shown for all SRs combined as a function of $\log_{10}(S/B)$ (lower right), where S and B are evaluated for each bin of the fitted distributions as the predicted signal and background yields before the fit to data. Bins with $\log_{10}(S/B) < -1$ are not included, and bins with $\log_{10}(S/B) > 0.5$ are included in the last bin. The vertical bars on the points represent the statistical uncertainties in the data, and the hatched bands the total uncertainty in the predictions. The signal and background yields are shown with their best fit normalizations from the simultaneous fit to the data ("postfit").

2305.13439

Parking

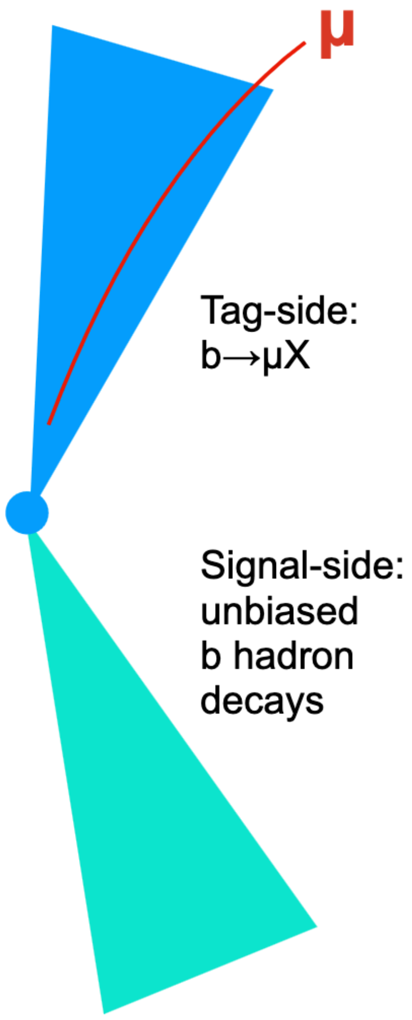
Trigger strategy

During June−Nov 2018, approximately 12 billion events were recorded with a trigger logic that requires the presence of a single, displaced muon. The sample comprises $b\bar{b}$ events with high purity. The muon candidate responsible for the positive trigger decision originates from the "tag-side" b hadron that undergoes a $b \to \mu X$ decay. The "signal-side" b hadron decays naturally as it is not biased by the trigger requirements.

The L1 μ trigger logic requires $|\eta| < 1.5$ and is subject to the p_T thresholds summarised in the table below. The HLT trigger logic also requires thresholds to be met on the p_T and IP_{sig} (track impact parameter significance), which improves the trigger purity.

The thresholds evolve during a fill, as the instantaneous luminosity ($\mathcal{L}_{inst}$) falls, to maximise number of signal-side b hadron decays within acceptance. The trigger purity is determined from simulation to be in the range 60−90% depending on the thresholds.

Settings	**Peak $\mathcal{L}_{inst}$ [10^{34} cm^{-2} s^{-1}]**	**L1 μ p_T threshold [GeV]**	**HLT μ p_T threshold [GeV]**	**HLT μ IP_{sig} threshold**	**Trigger purity [%]**	**Peak rate [kHz]**
1	1.7	12	12	6	92	1.5
2	1.5	10	9	6	87	2.8
3	1.3	9	9	5	86	3.0
4	1.1	8	8	5	83	3.7
5	0.9	7	7	4	59	5.4

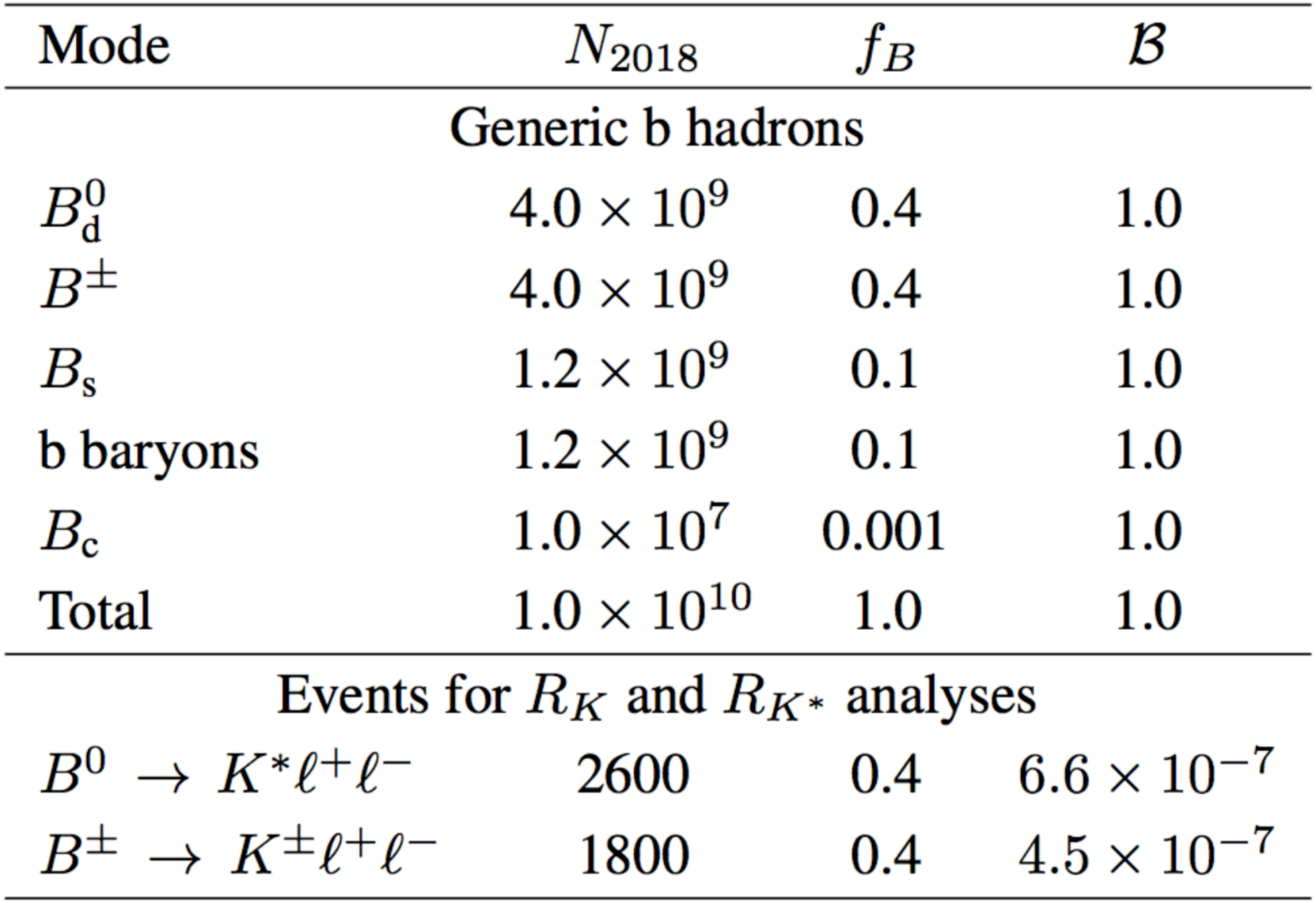


DP2019_043

Parking

Modes of unbiased B hadron decays on tape

The table indicates the number of unbiased decays of different types of B hadrons recorded to tape in 2018 (N_{2018}). The fractions of B hadron type that are produced (f_B) and their branching fraction ($\mathcal{B}$) are also indicated.



Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B_d^0	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
Events for R_K and R_{K^*} analyses			
$B^0 \to K^* \ell^+ \ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm \ell^+ \ell^-$	1800	0.4	4.5×10^{-7}

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DP2019_043

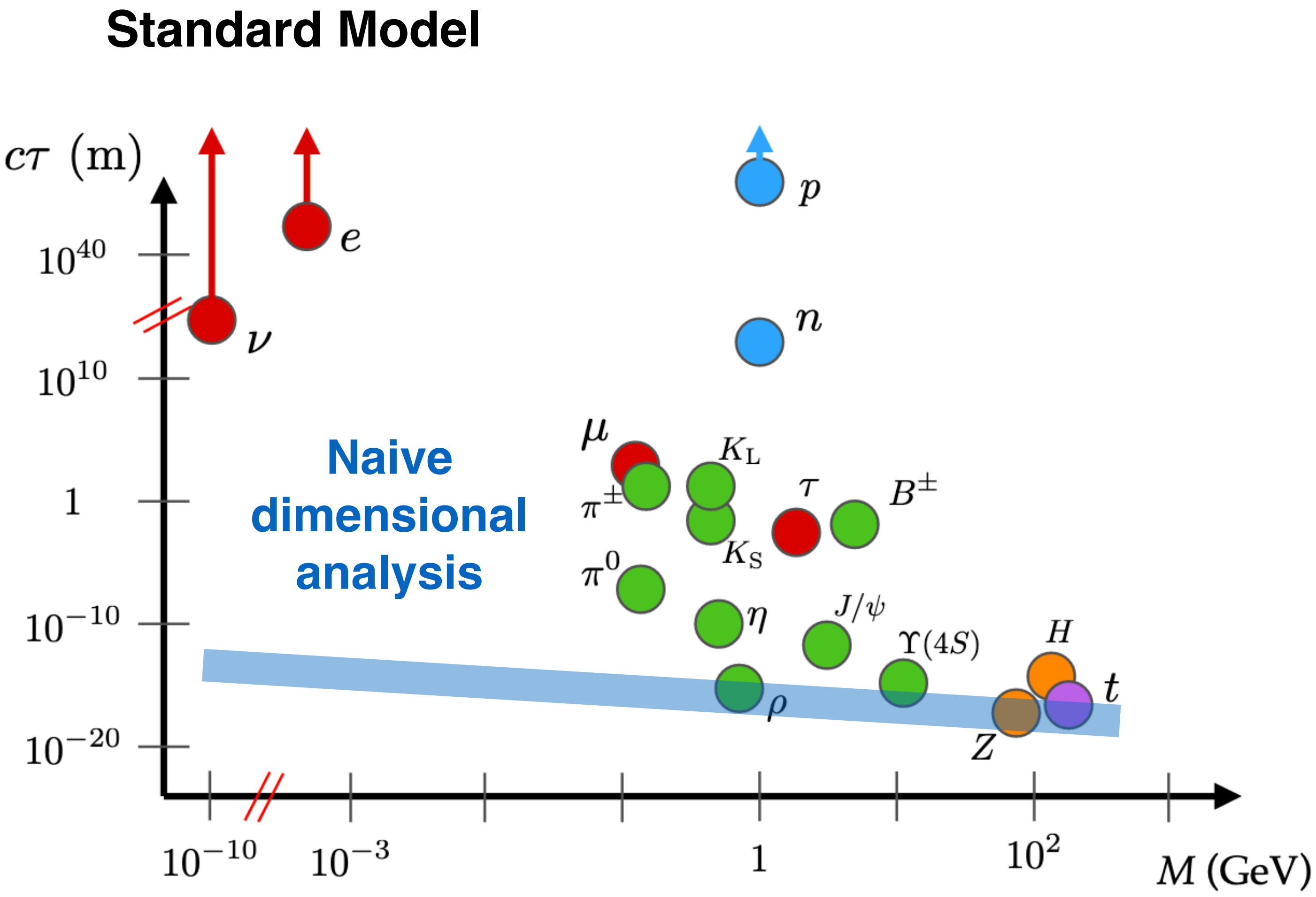
Long-lived particles in the Standard Model

e.g. π⁻ decay rate
suppressed by **heavy W**

$$\Gamma \propto g^2 \left(\frac{m_{\pi^-}}{m_W}\right)^4 m_{\pi^-}$$

~0.1 GeV

~80 GeV



1903.04497

HNLs

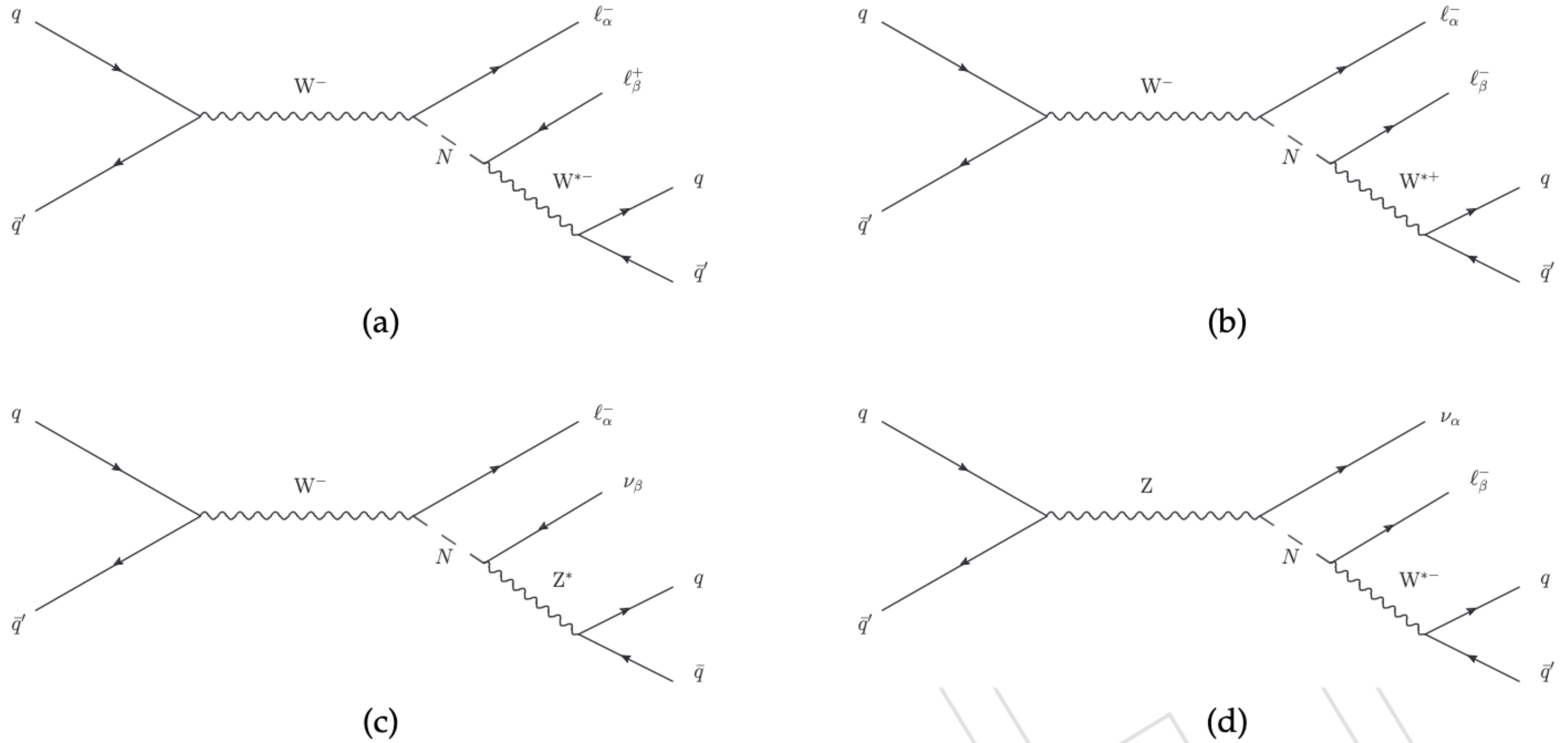


Figure 3: Feynman diagrams for HNL production and decay. In a) and b), charged current production and decay with OS and SS dilepton final states is illustrated. For Dirac HNLs, only the LNC diagram a) is possible, while for Majorana HNLs LNV is present (sum of a) and b)). Diagrams c) and d) corresponds to either the decay or production occuring via the neutral current interaction. In this case, the observable final state is the same for Dirac and Majorana HNLs.

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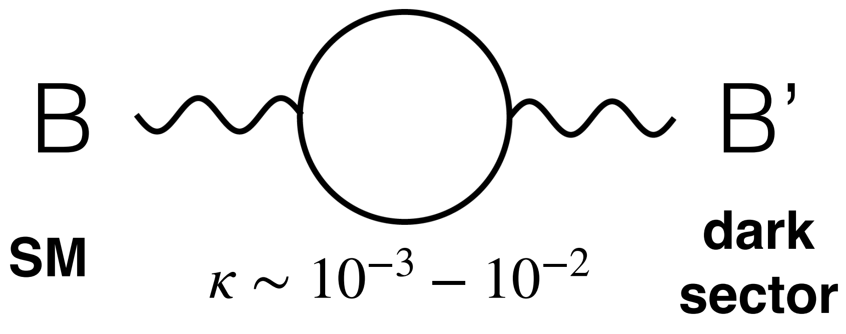
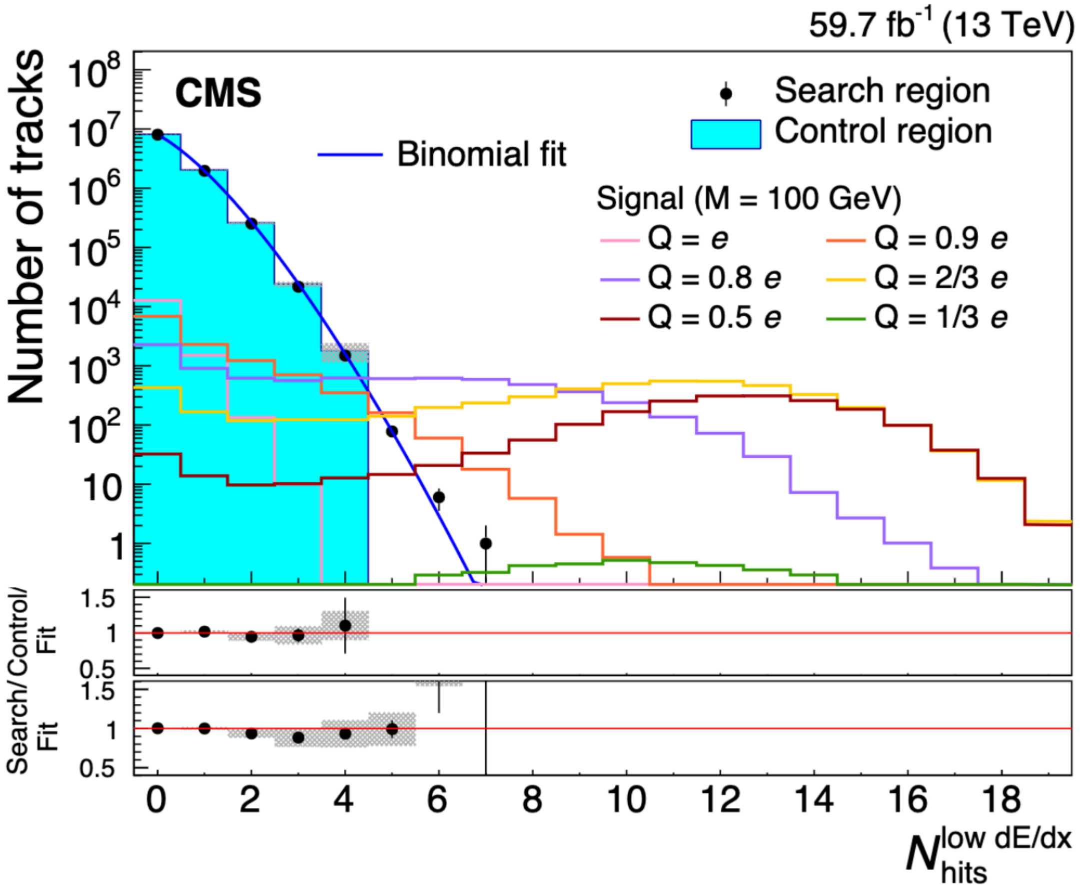
Fractionally charged particles

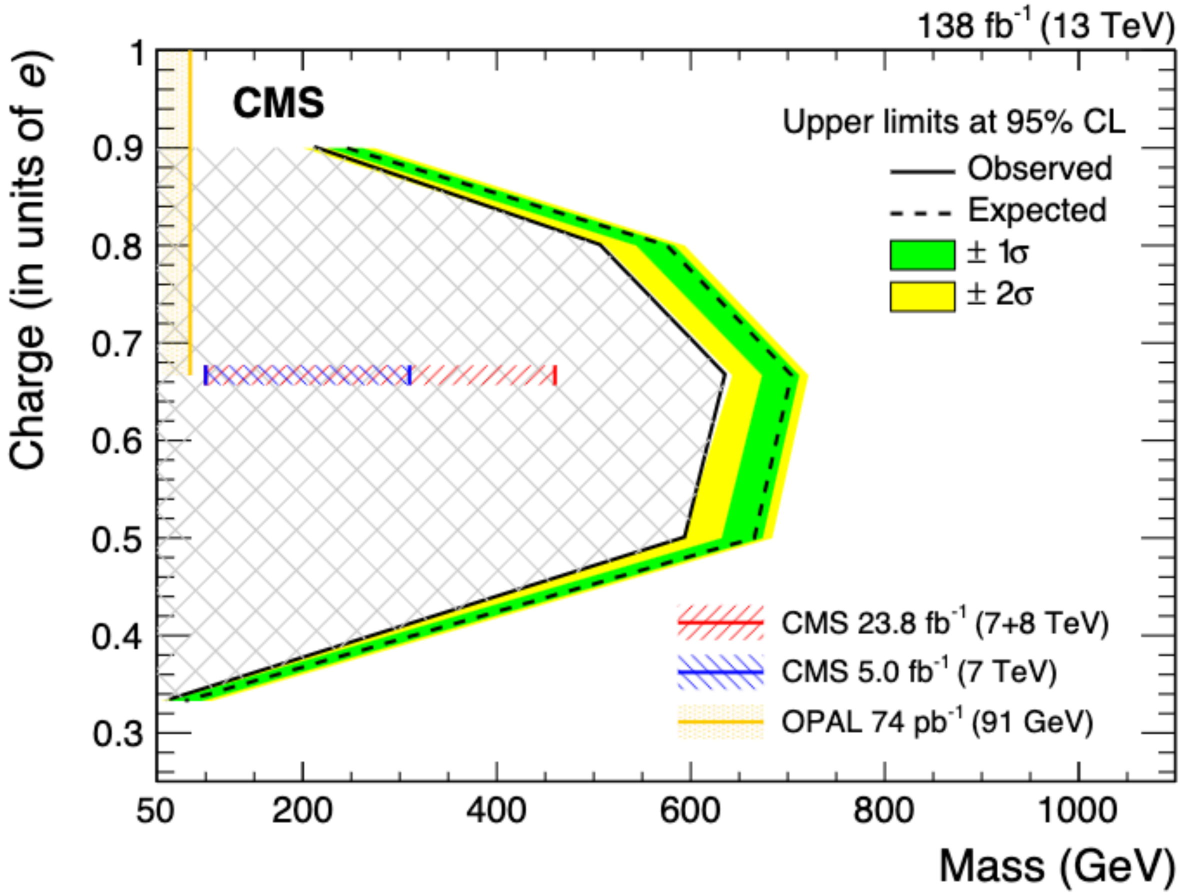


$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim 1/16\pi^2$)

- Low dE/dx hits in the tracker provides **sensitivity down to Q ~0.3e**
- Below this not enough energy deposited in detector to reconstruct

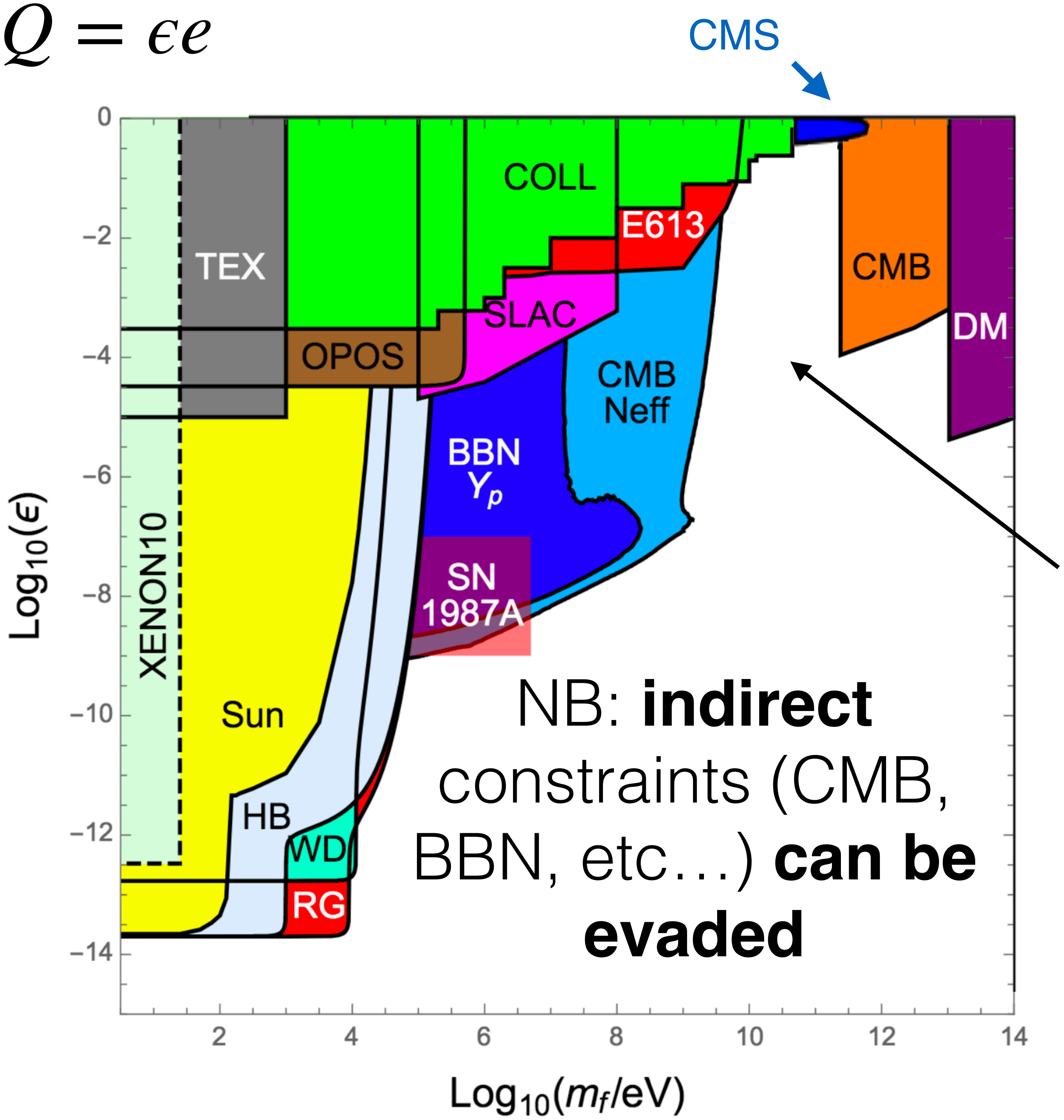




EXO-19-006

Searching for millicharged particles

$$Q = \epsilon e$$



NB: **indirect** constraints (CMB, BBN, etc…) **can be evaded**

arXiv:1511.01122

Searches using colliders, effects on sun, stars and supernovae, cosmological bounds,… cover wide range in masses/charges

but

big gap for heavier (~ GeV) low charged particles

general purpose LHC detectors insensitive (**dE/dx ~ Q^2**)

→ target with **milliQan**!

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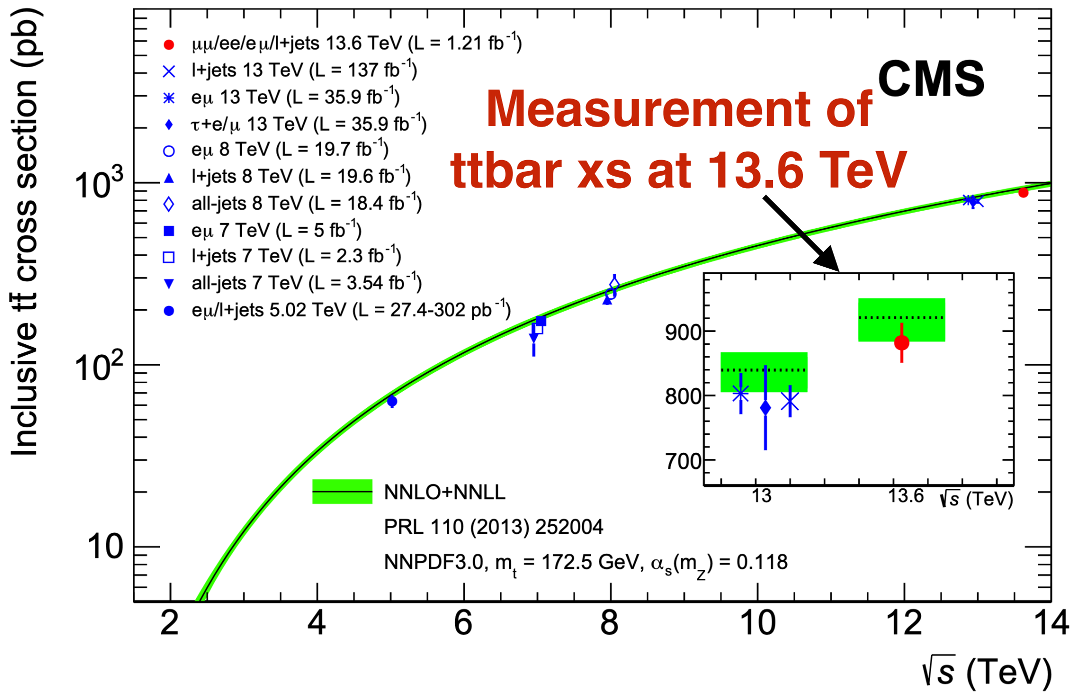
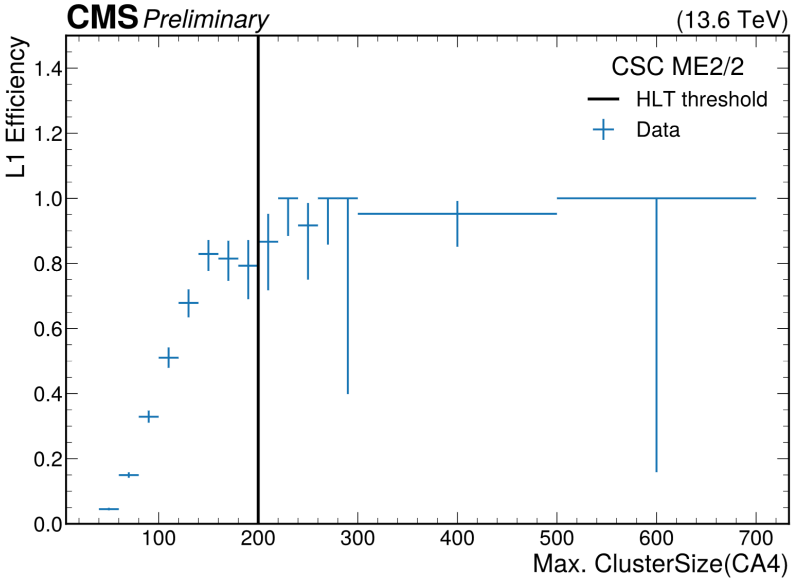
Run 3 ongoing!



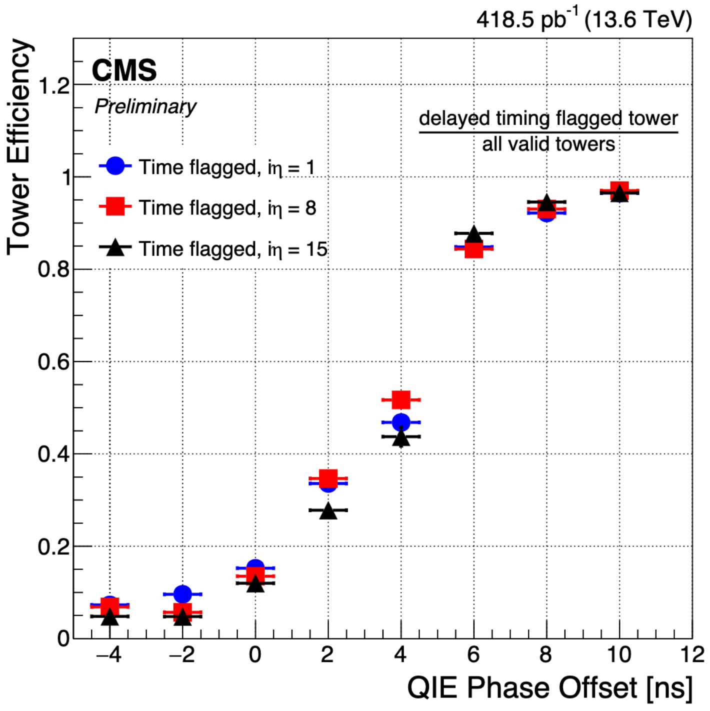
Measurement of ttbar xs at 13.6 TeV

- Will more than **double** our dataset with a higher energy than ever before!
- Excellent opportunity to extend sensitivity with more data and **new trigger** selections

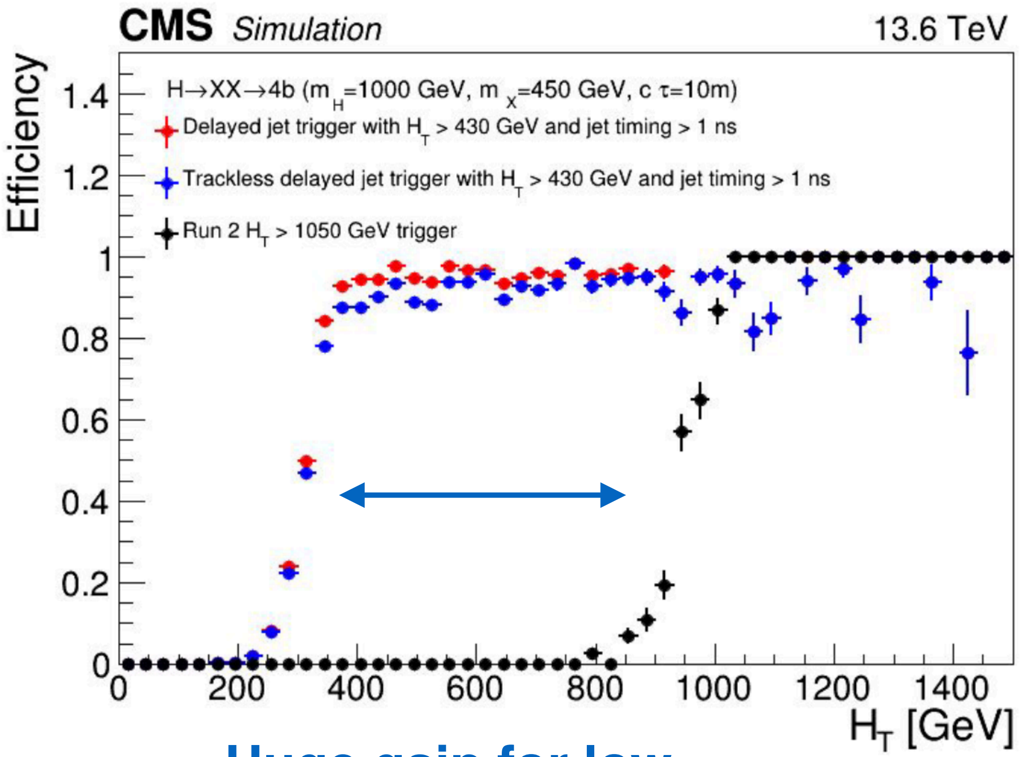
Muon system cluster trigger



HCAL timing trigger



ECAL timing trigger



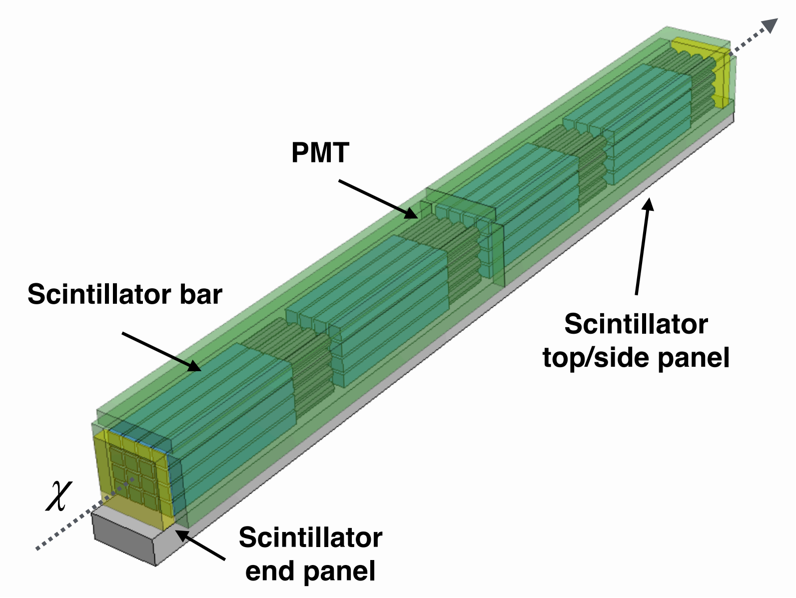
Huge gain for low energy signatures!

Run 3 milliQan experiment

Fully funded and under construction!

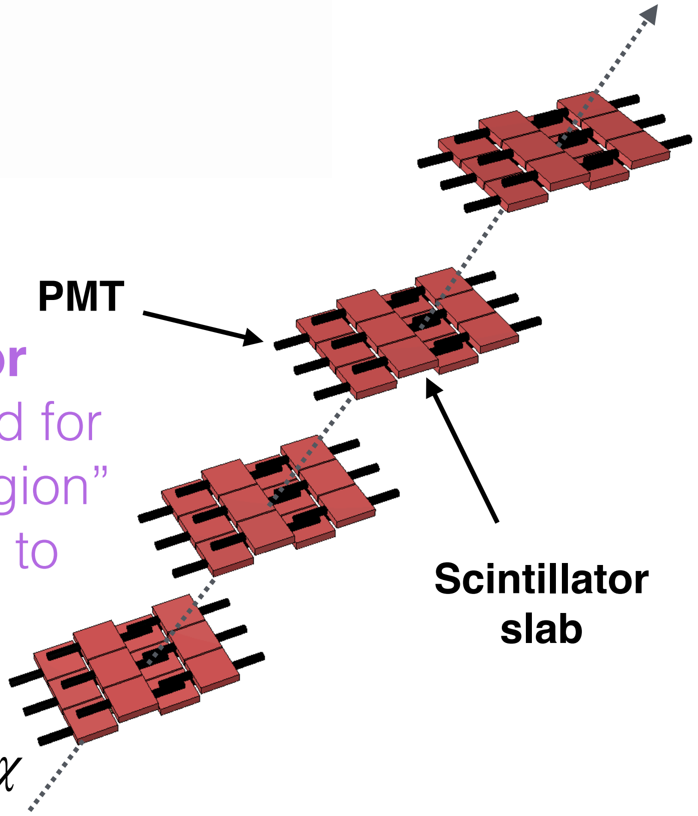
Run 3 bar detector

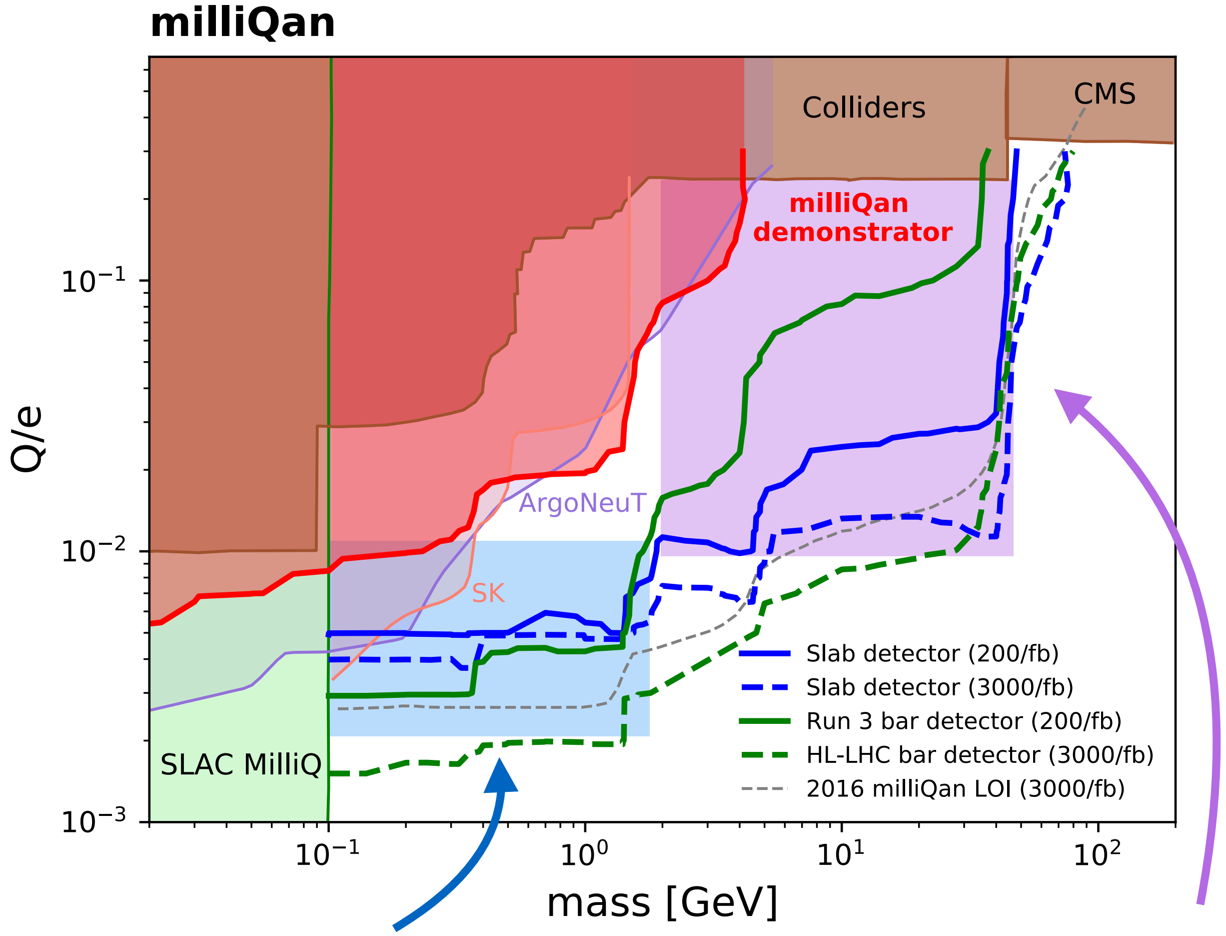
design based on lessons from demonstrator: expanded size (4x4 bars), four layers, thicker veto panels, signal amplification



Run 3 slab detector

thinner slabs optimised for "acceptance limited region" (total area equivalent to >1000 bars!)





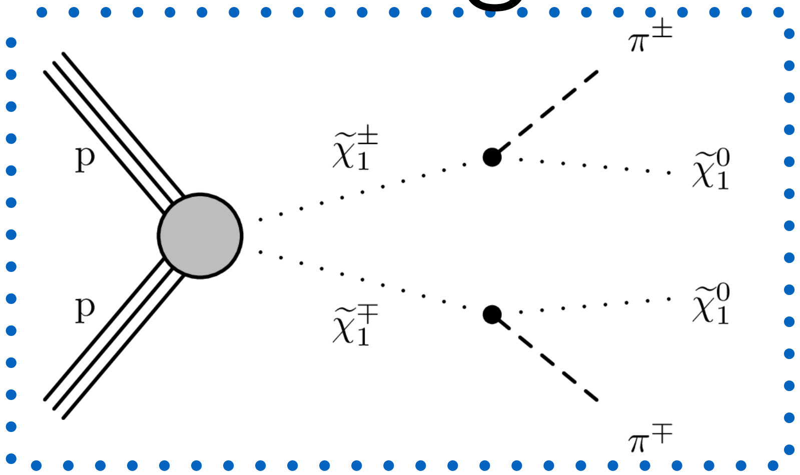
Charge limited region: very high mcp flux but low efficiency

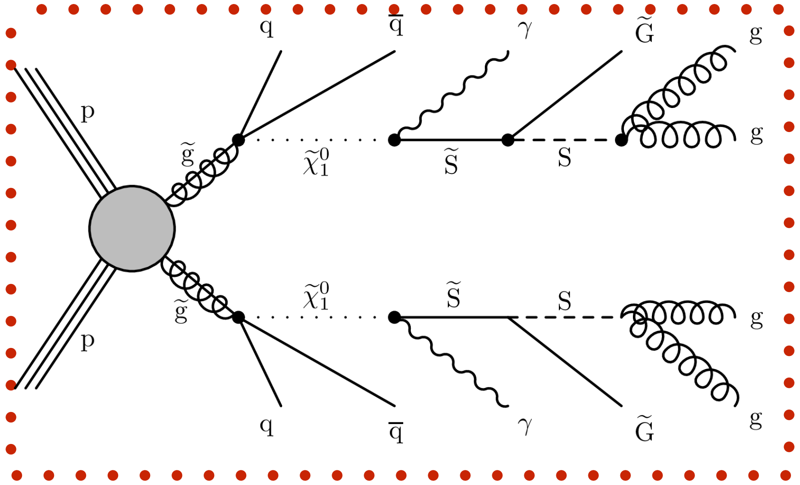
Acceptance limited region: high efficiency but low mcp flux

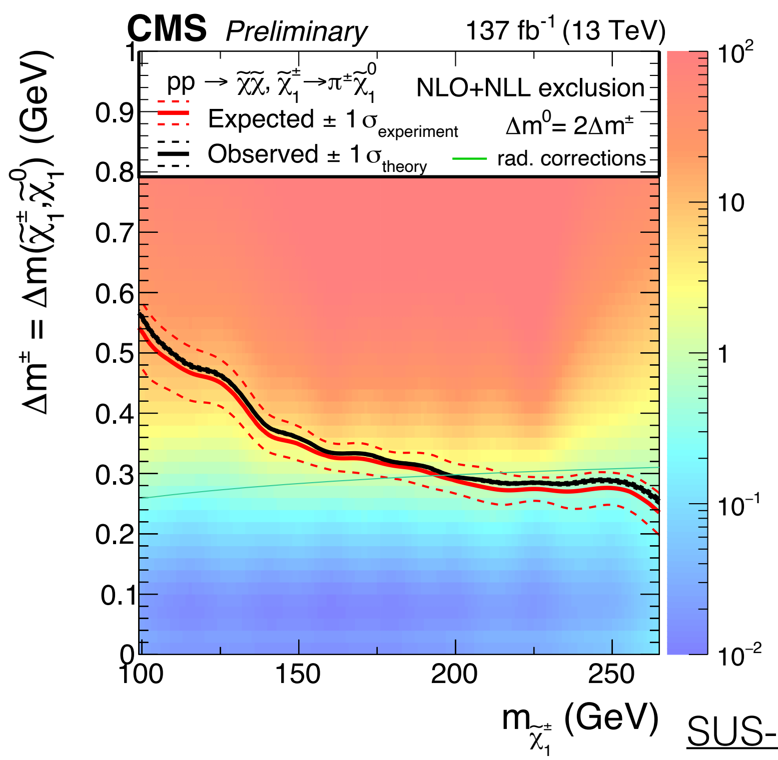
Backgrounds/signal efficiencies estimated using **data collected by demonstrator**

Expect world leading sensitivity for **0.1 < m < 45 GeV** using **combination** of **slab and bar** detector

SUSY signatures

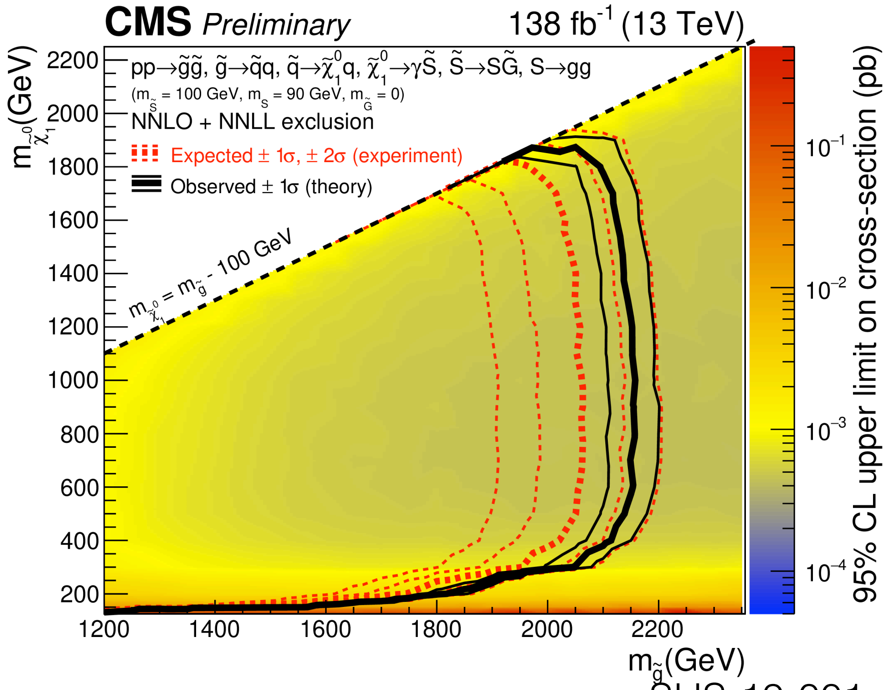






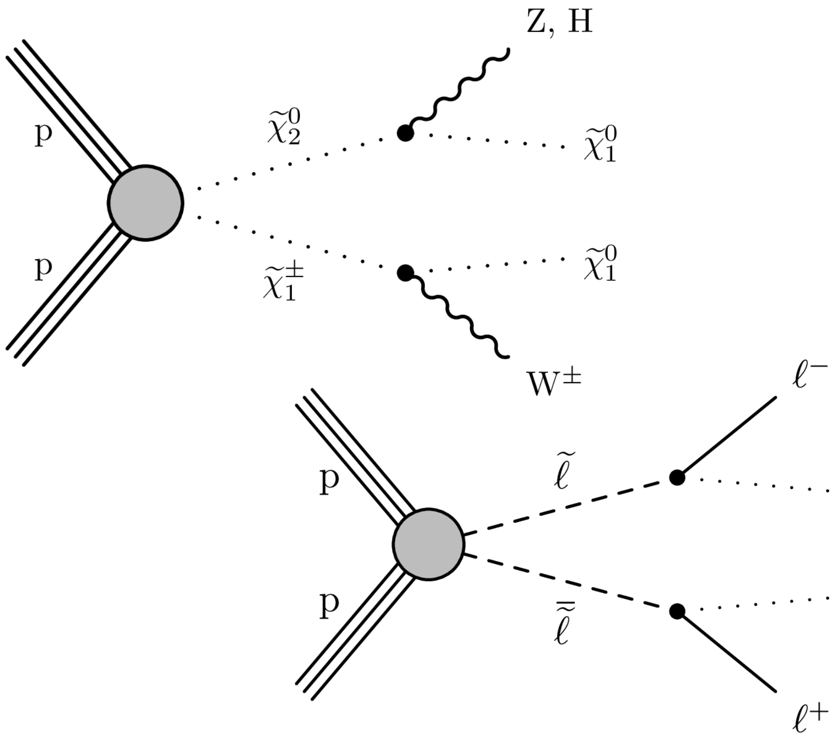
SUS-19-006

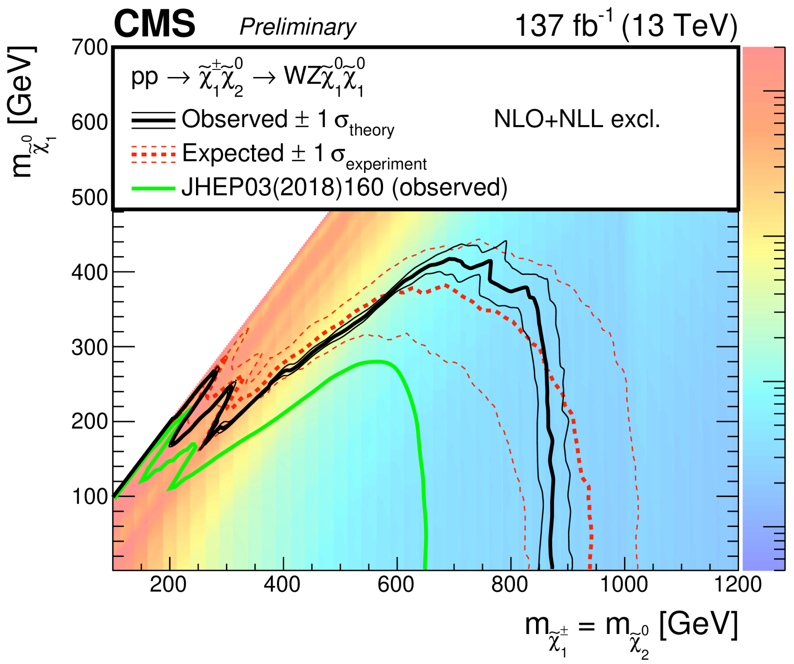
Disappearing tracks: first use of BDT for disappearing track purity

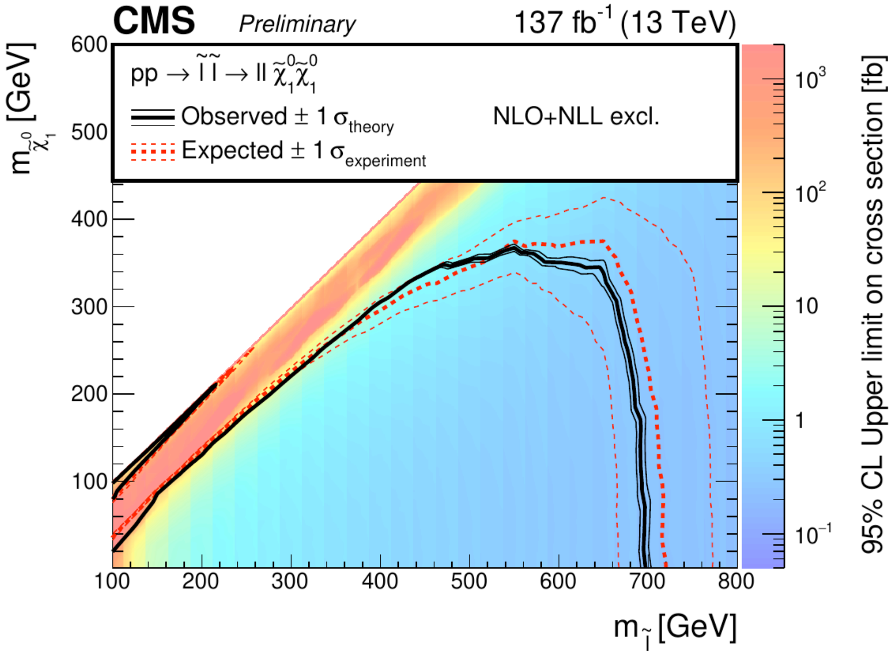


SUS-19-001

Stealth SUSY + photons (low MET final states)







Ewk combination for C1N2 and sleptons (+ many other final states!)

SUS-19-009

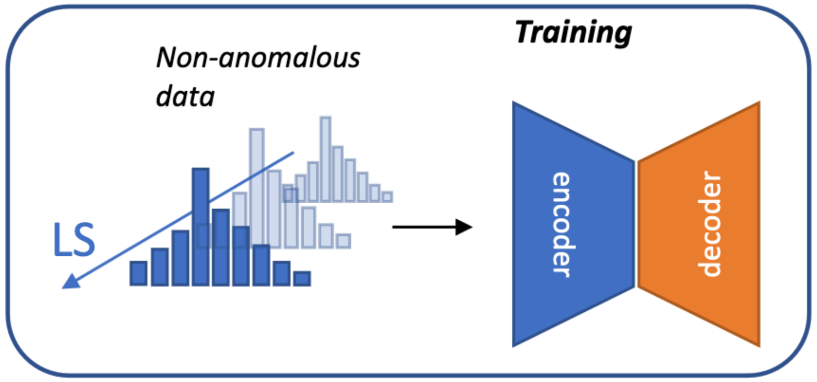
AutoEncoder-based Anomaly Detection Tool

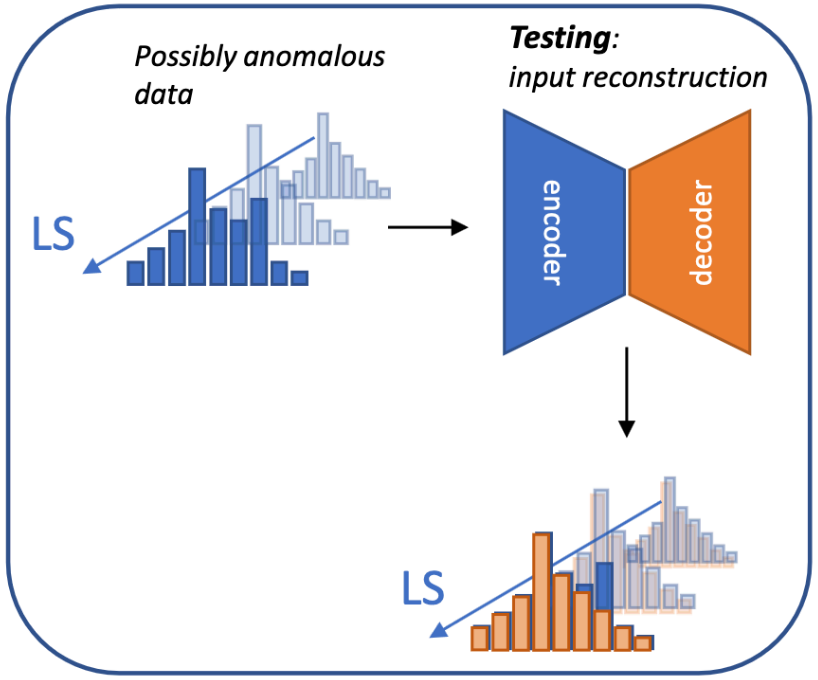
- The model is trained on non-anomalous data from *GOOD* runs: histograms of specific MEs are fed to the model with an LS granularity to allow the AE to learn a «normal» non-anomalous behavior of that specific ME. The training is performed via the minimization of the reconstruction loss, a measure of the distance between the input and output of the AE. In this case the reconstruction loss is the mean squared error:

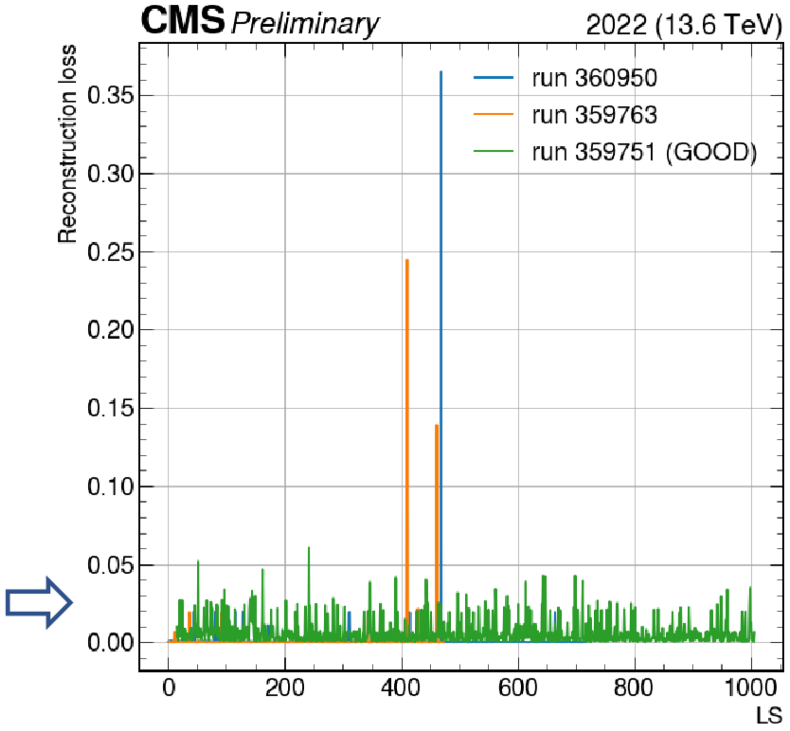
$$\mathrm{MSE} = \frac{1}{\mathrm{n}} \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - \hat{y}_i)^2$$

where y and $\hat{y}$ are respectively the input and the output of the AE and n is the bin number.

- Possibly anomalous runs under investigation are tested by looking again at the reconstruction loss: peaks in this function indicate LSs containing histograms that deviate from the learned behavior.
- The comparison between the reconstruction losses of the three runs under study is on the right.







DP2023_010