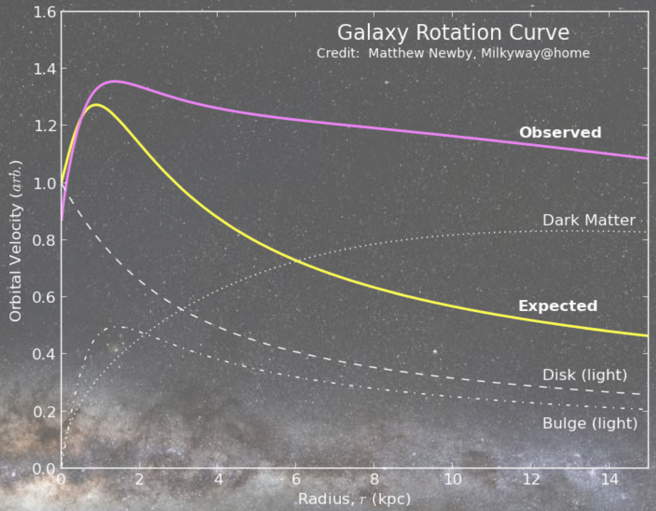


A Shot in the Dark

Searching for a Dark Sector with the CMS Experiment

Benedikt Maier, ETP

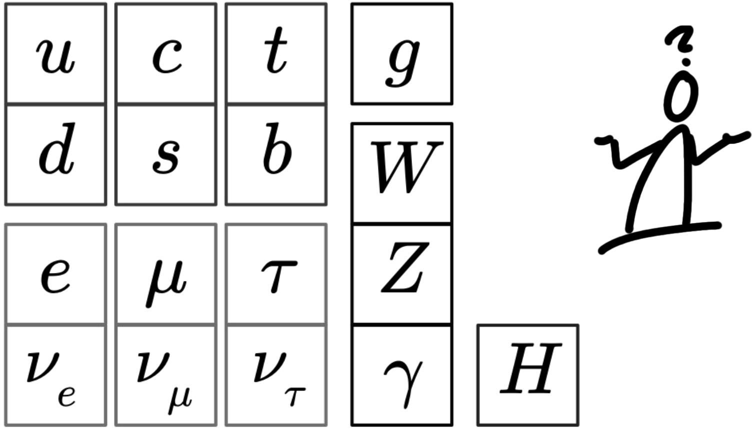
KCETA-Kolloquium, 25.05.2023

Dark matter about **5x more abundant** than visible matter

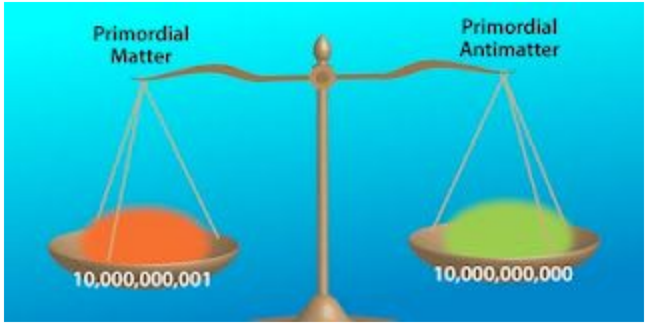
Inferred from **astrophysical observations**, like gravitational lensing or rotational curves

Dark matter about **5x more abundant** than visible matter

Inferred from **astrophysical observations**, like gravitational lensing or rotational curves



Many other open questions in cosmology and particle physics, like

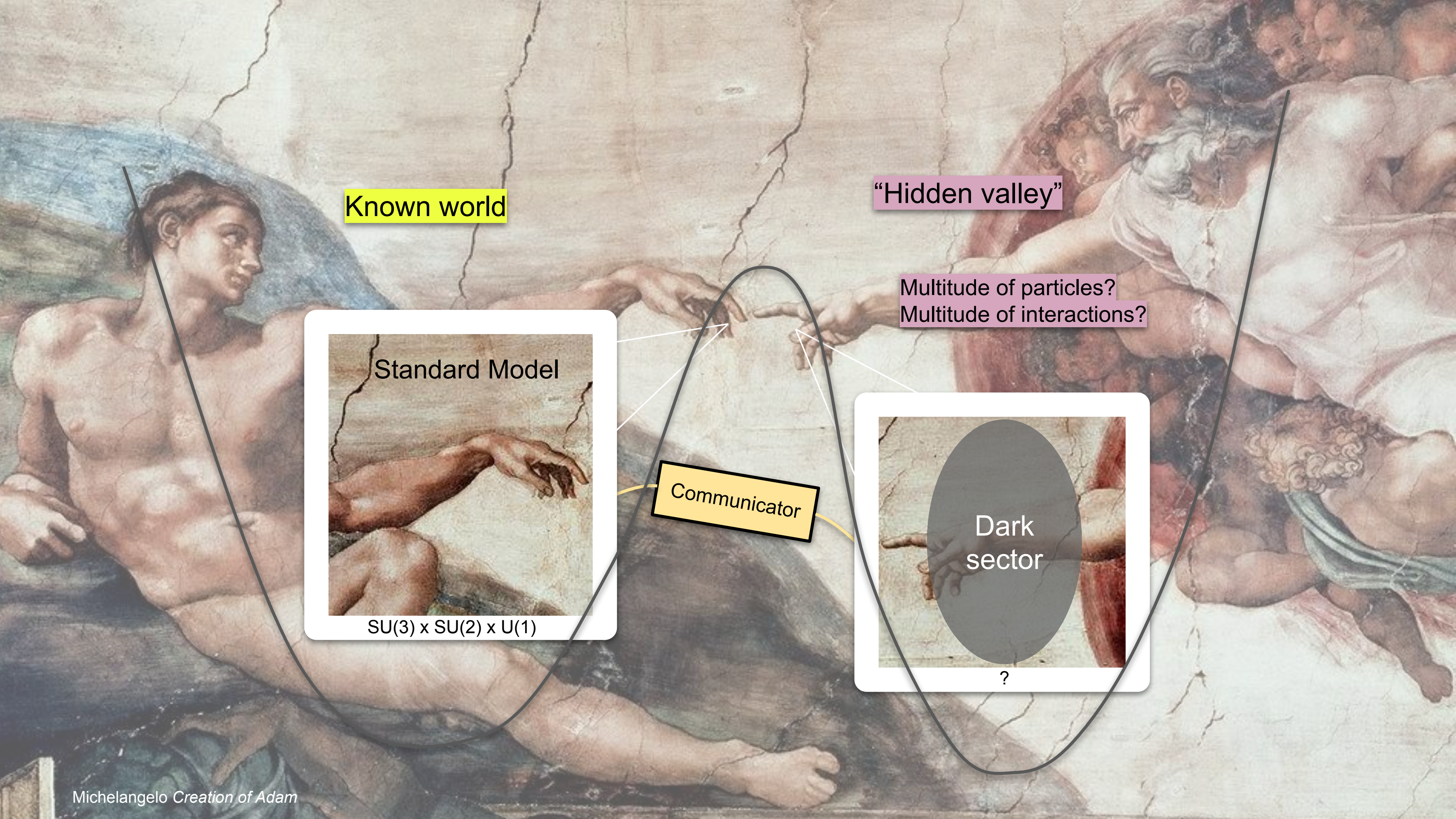


Matter-antimatter asymmetry

Hierarchy problem (weakness of gravity, fine tuning at level 10^{16})

Dark sector could hold **the answer** to some of these, depending on the theory

Probing it at colliders!


Known world
"Hidden valley"
Multitude of particles?
Multitude of interactions?
Standard Model
SU(3) x SU(2) x U(1)
Communicator
Dark
sector
?
Michelangelo *Creation of Adam*

The "simplest" case: a dark photon *A'*

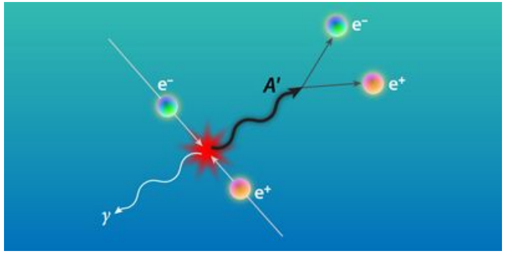
Its own field | Mixing with SM photon | Mass created by (dark?) Higgs

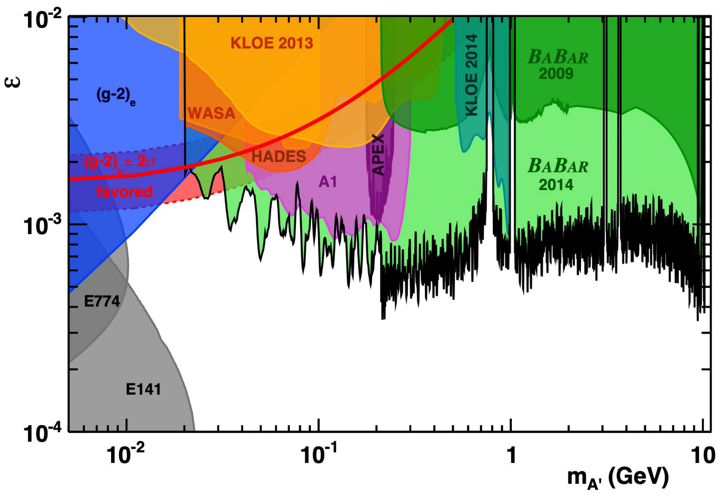
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

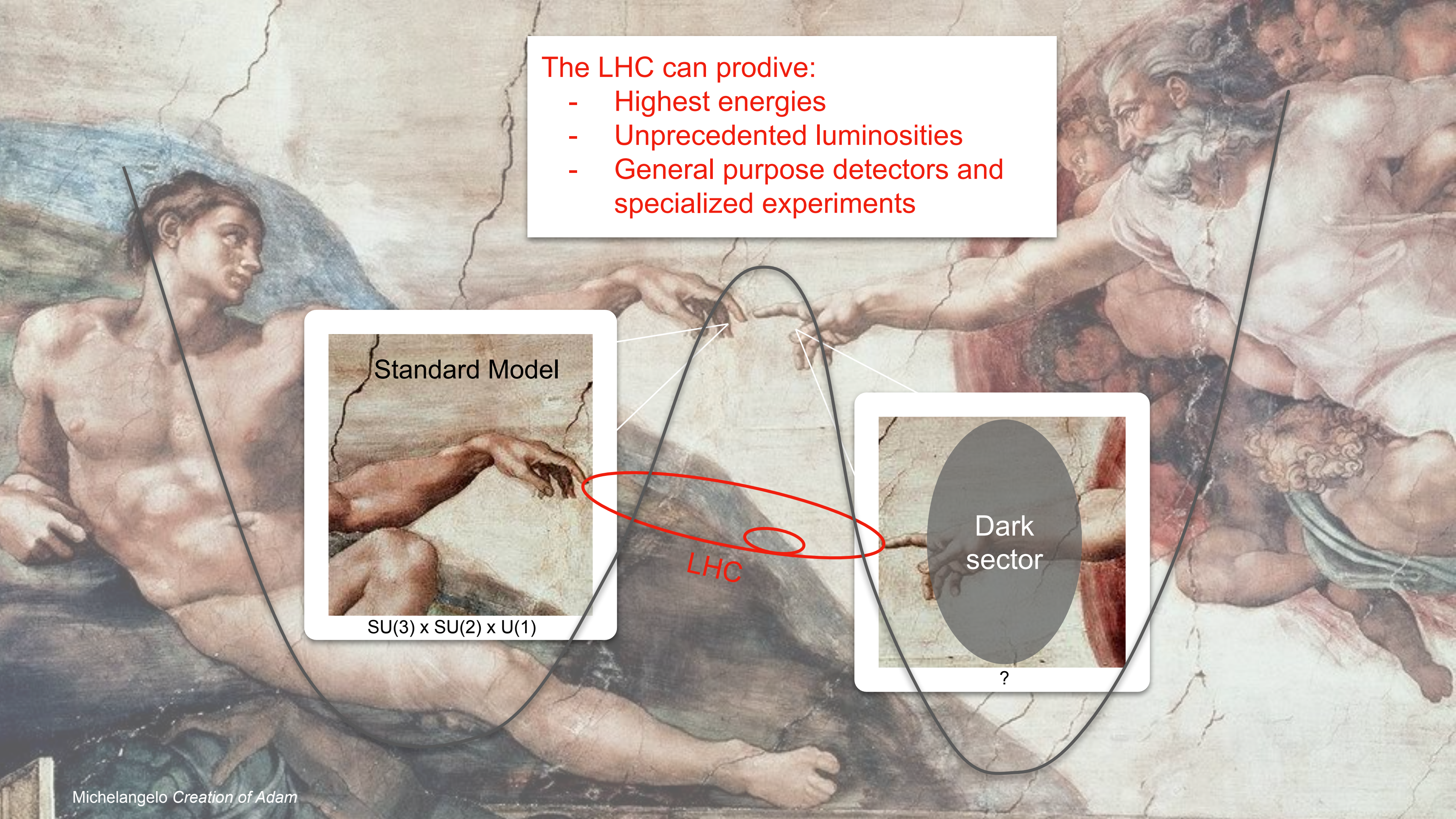
New broken $U_D(1)$ symmetry (with dark fermions charged under $U_D(1)$)

Free parameters: mixing ϵ, mass $m_{A'}$

$e^+e^- \to \gamma A'(\to e^+e^-, \mu^+\mu^-)$
Dark photons searches at **BaBar**

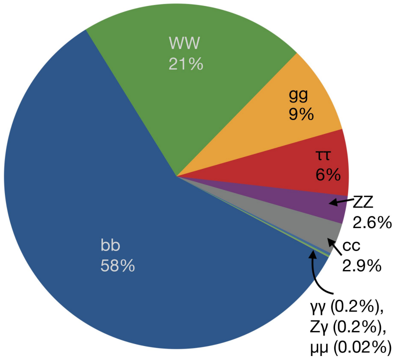


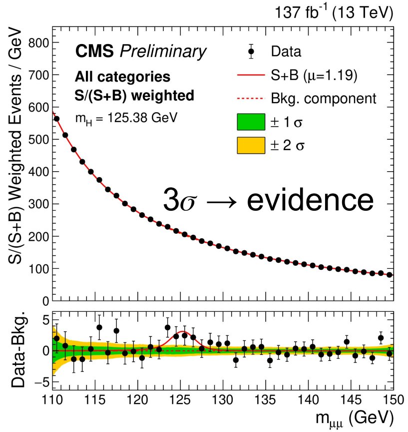


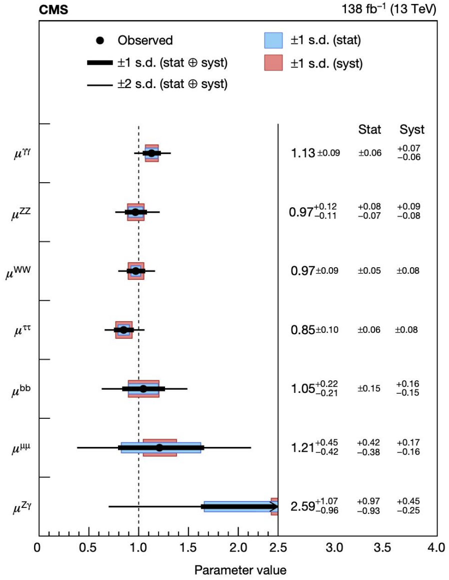

The LHC can prodive:
- Highest energies
- Unprecedented luminosities
- General purpose detectors and specialized experiments
Standard Model
SU(3) x SU(2) x U(1)
LHC
Dark sector
?
Michelangelo Creation of Adam

Higgs boson discovery, CERN, 2012

How do Higgs bosons decay according to the Standard Model?





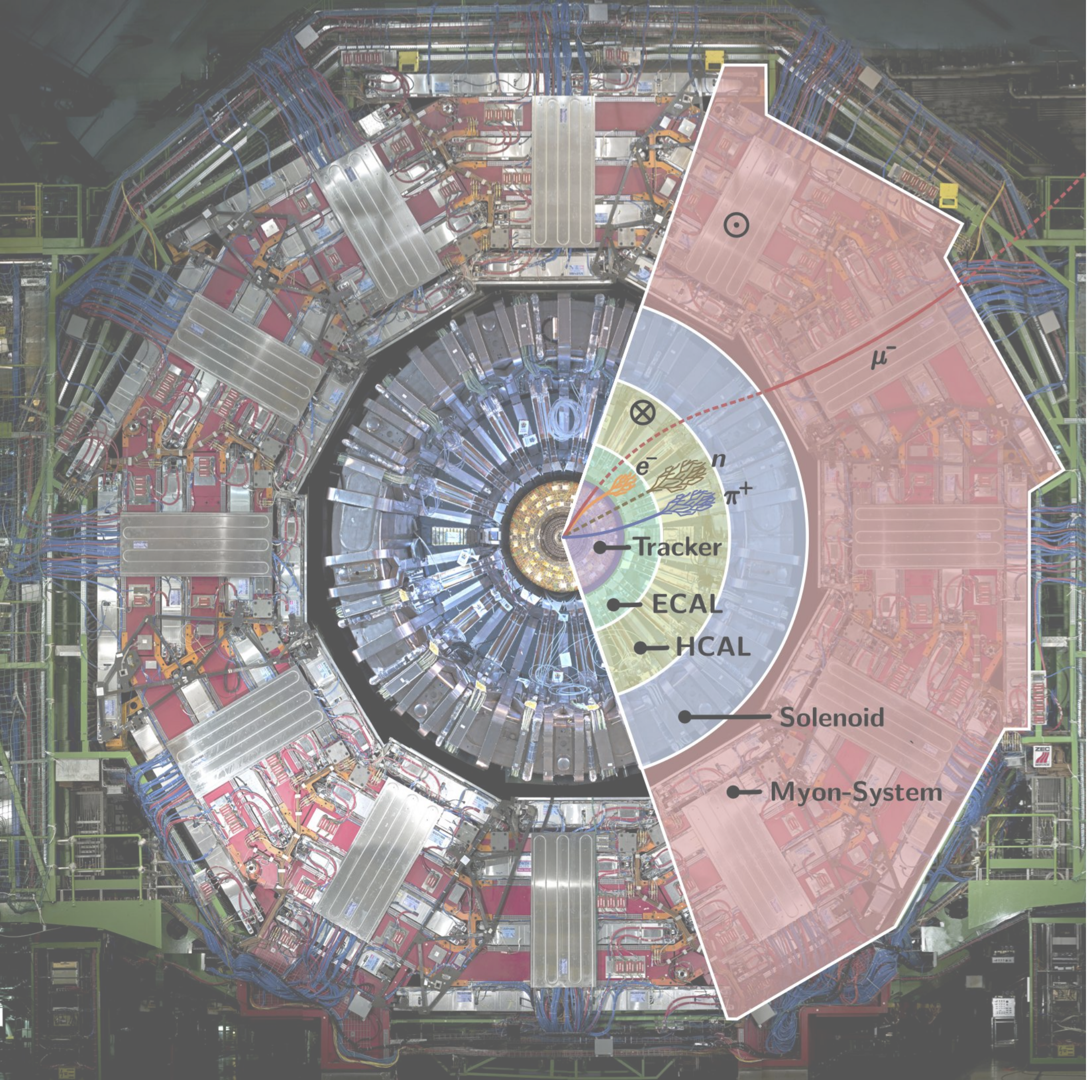


Higgs boson gives rest mass to elementary particles.
Predicted in 60s, discovered 2012

Combination of all Higgs analyses currently allows an **upper limit of 16%** for new, unknown particles as decay products

→ Motivates search for decay to dark matter particles

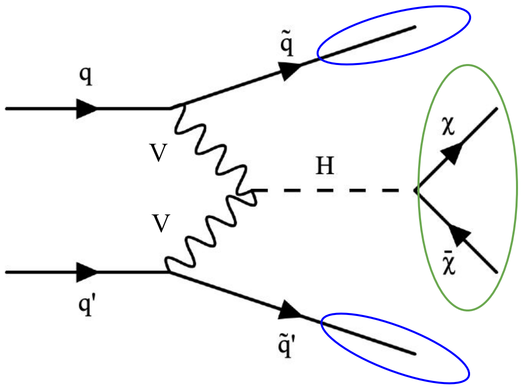
Nature 607, 60–68 (2022)



CMS uses **Particle Flow** reconstruction:

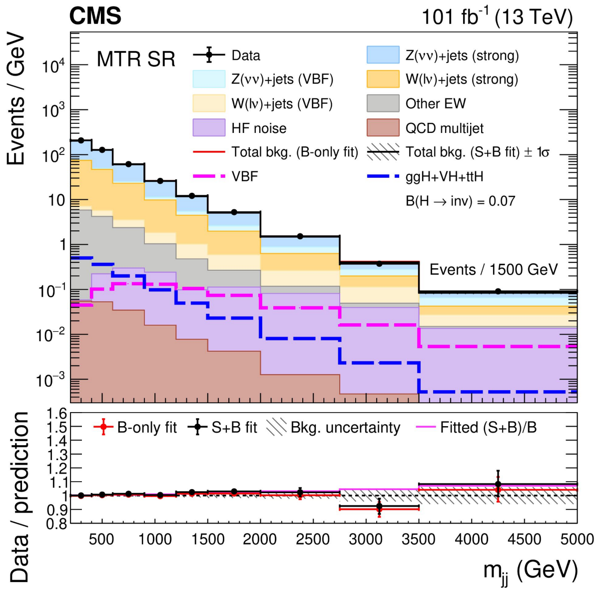
- “Follow” the path of a particle through the detector
- Match deposits between subdetector
- For each particle use subdetector with best E/momentum measurement

Disappearing Higgses ("Higgs portal")

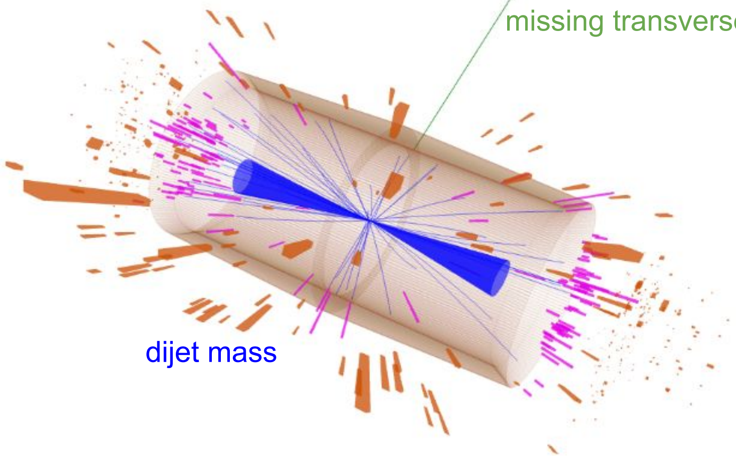


Dark matter, by definition, does not interact with the detector

- Sizable missing transverse energy (> 160 GeV)
- Requiring two jets with large pseudorapidity difference ("forward")



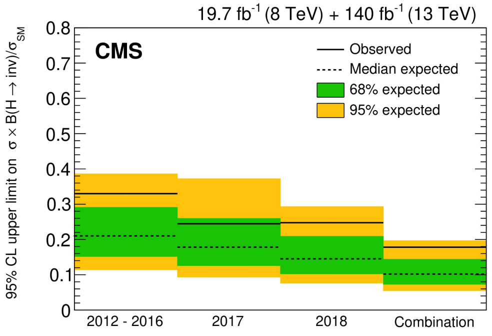
missing transverse energy



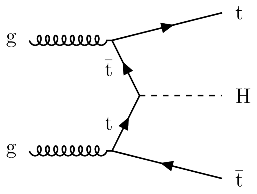
dijet mass

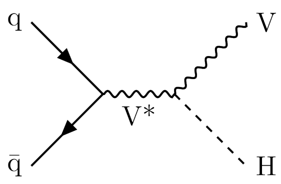
Statistical analysis of observed m_{jj} spectra gives:

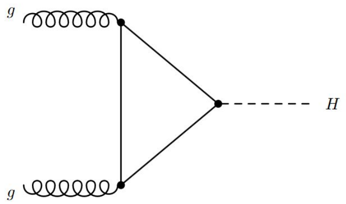
18% (10%) observed (expected) upper limit for branching ratio H → invisible

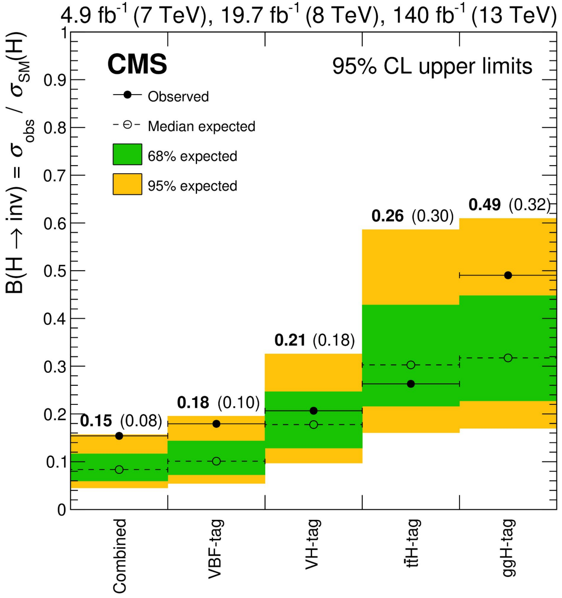


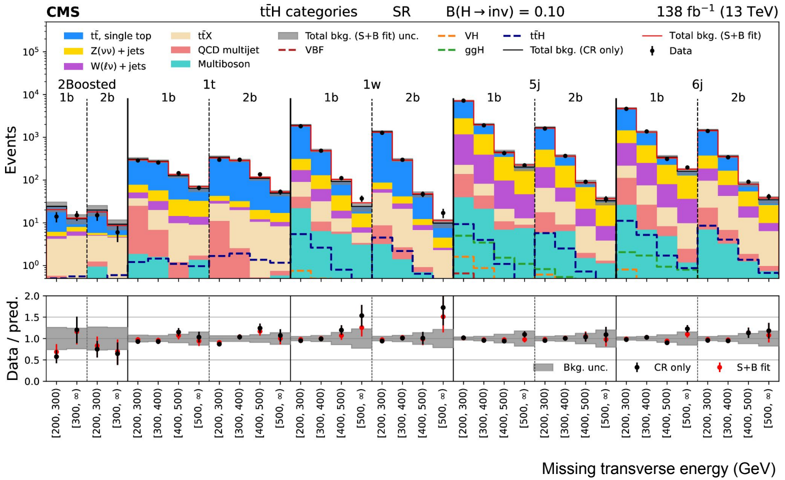
Disappearing Higgses (“Higgs portal”)





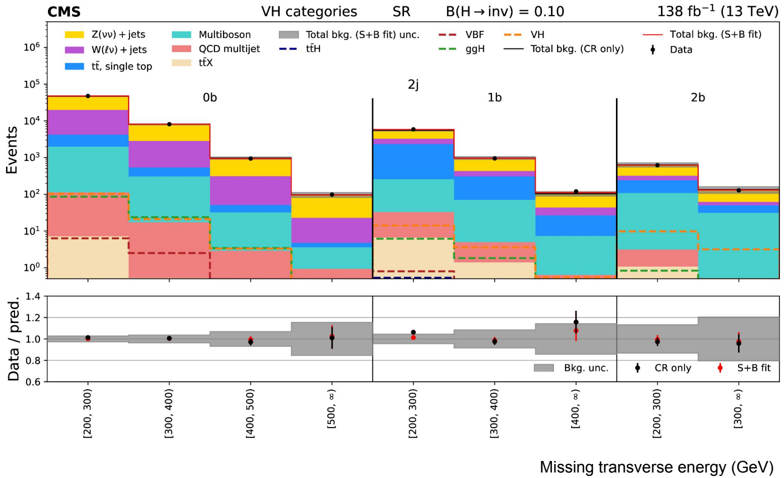




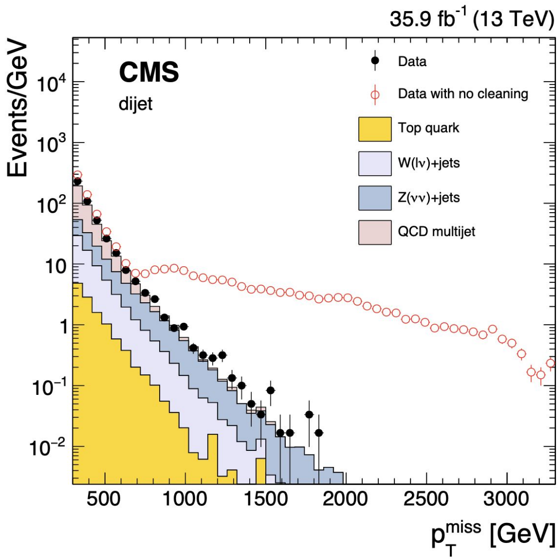


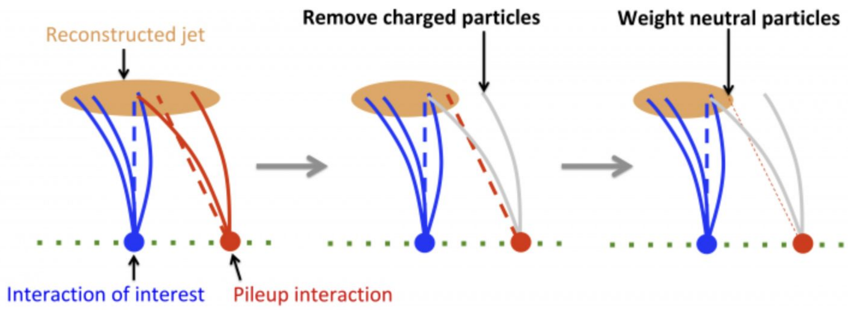
Combination of different production mechanisms gives

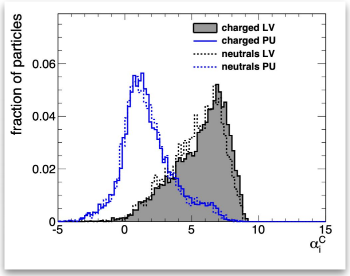
15% (8%) observed (expected) upper limit for branching ratio H → invisible



Missing transverse energy

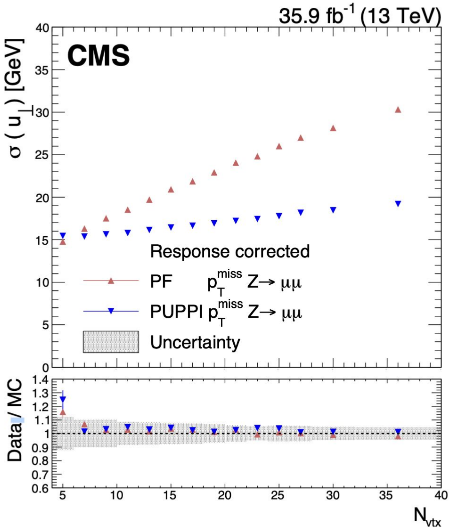






Dedicated filters reject noise events that are not modelled with MC, e.g.:

- beam halo
- dead ECAL crystals
- …



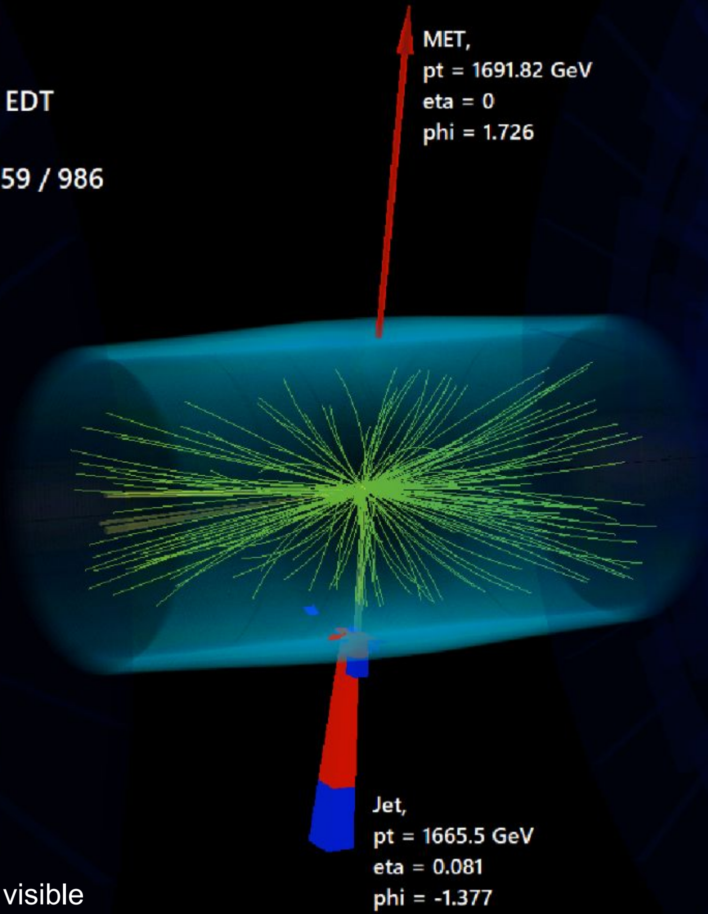
Pileup per particle identification ("PUPPI") algorithm identifies particles from subordinate proton-proton collisions

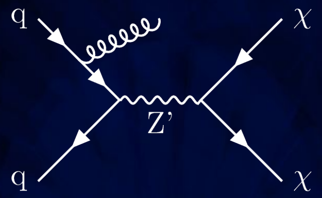
→ Dramatic improvement in resolution of missing transverse energy

CMS Experiment at the LHC, CERN

Data recorded: 2018-Jul-14 21:03:24 EDT

Run / Event / LS: 319639 / 1418428259 / 986

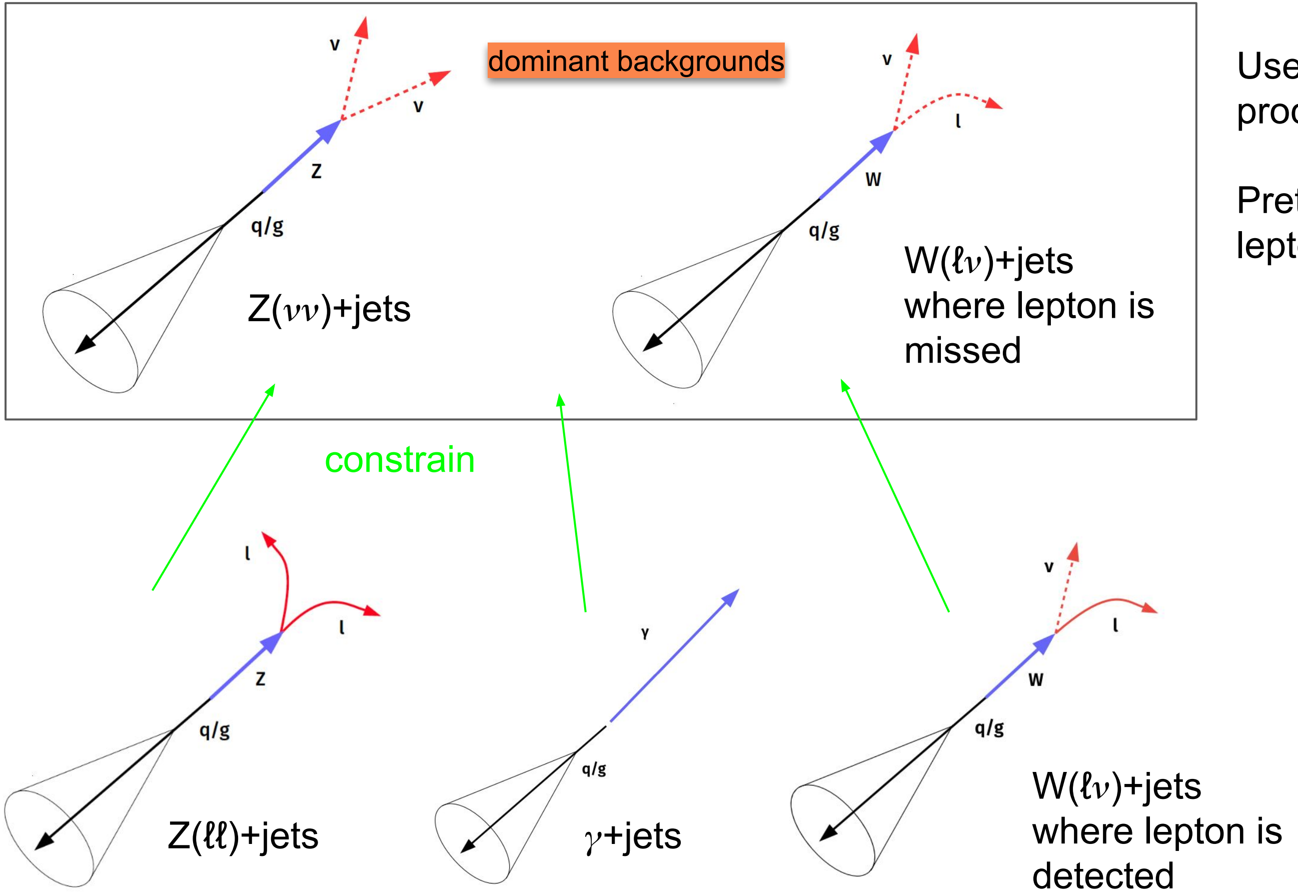




Energy frontier

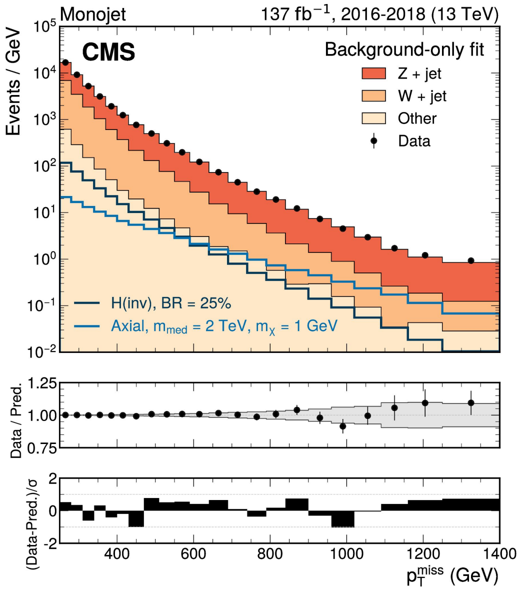
Probing the heaviest communicators between the visible and dark sector

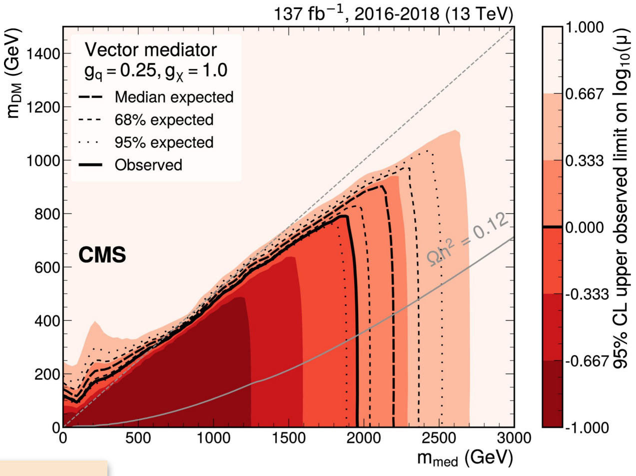
Standard Model backgrounds in dark matter searches



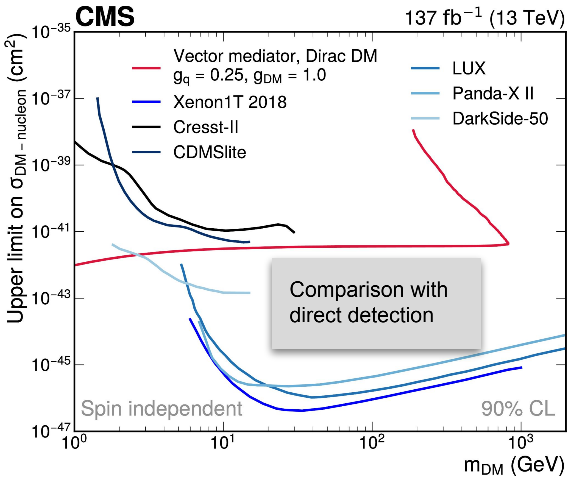
Use apparent symmetry between processes to constrain backgrounds

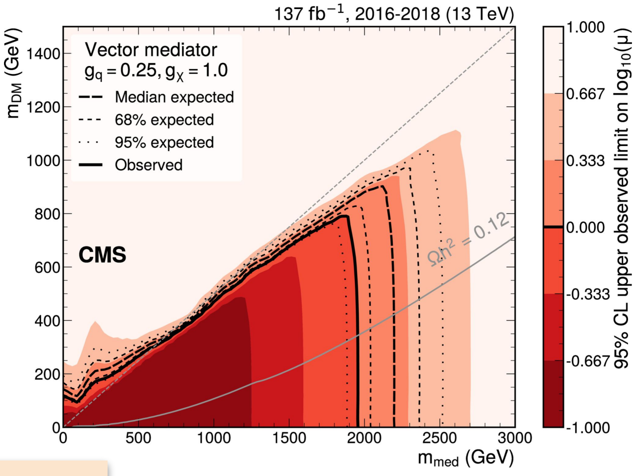
Pretending to not see photons & leptons to create a **proxy** for MET



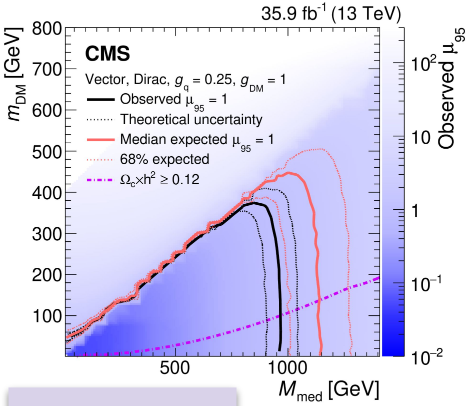

137 fb−1, 2016-2018 (13 TeV)
Vector mediator
gq = 0.25, gχ = 1.0
Median expected
68% expected
95% expected
Observed
CMS
Ωh2 = 0.12
mDM (GeV)
mmed (GeV)
95% CL upper observed limit on log10(μ)
1.000
0.667
0.333
0.000
-0.333
-0.667
-1.000

mono-jet

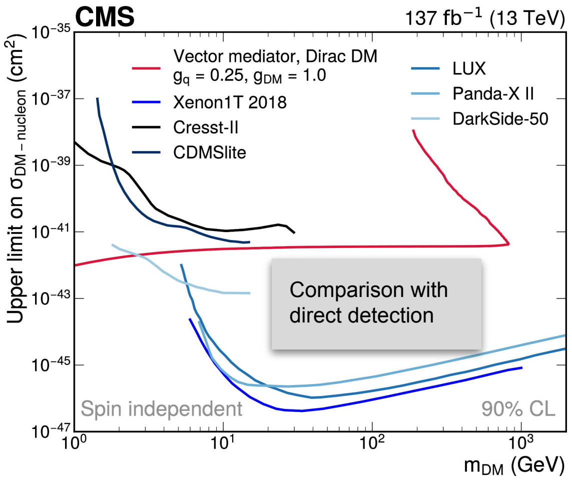

CMS
137 fb−1 (13 TeV)
Vector mediator, Dirac DM
gq = 0.25, gDM = 1.0
Xenon1T 2018
Cresst-II
CDMSlite
LUX
Panda-X II
DarkSide-50
Comparison with
direct detection
Spin independent
90% CL
Upper limit on σDM−nucleon (cm2)
mDM (GeV)



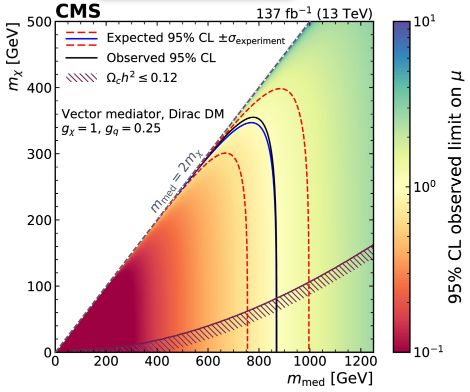
mono-jet



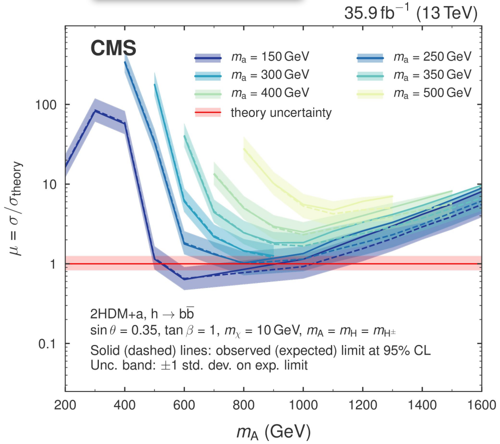
mono-photon



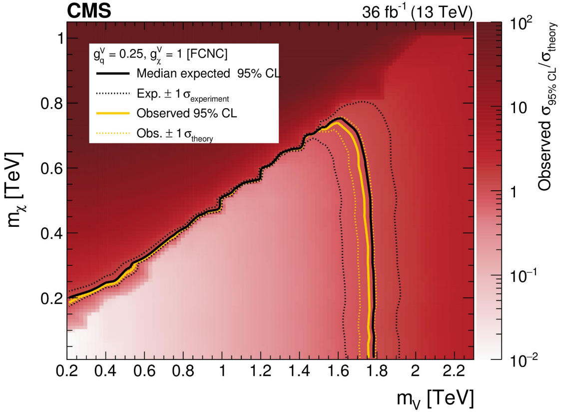
mono-Z(ll)



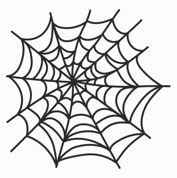
mono-H(bb)

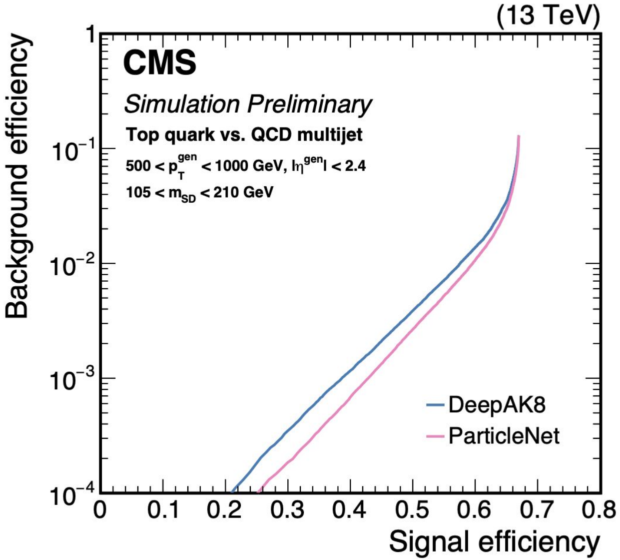


mono-top



A particle net to tag heavy resonances



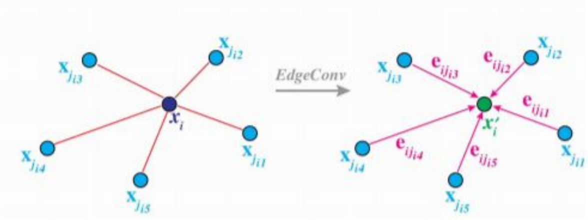


CMS at the forefront of accelerating machine learning-based solution in high energy physics

ParticleNet = current **state-of-the-art** in jet tagging

Jet constituents as graph
Edges dynamically determined in the latent space

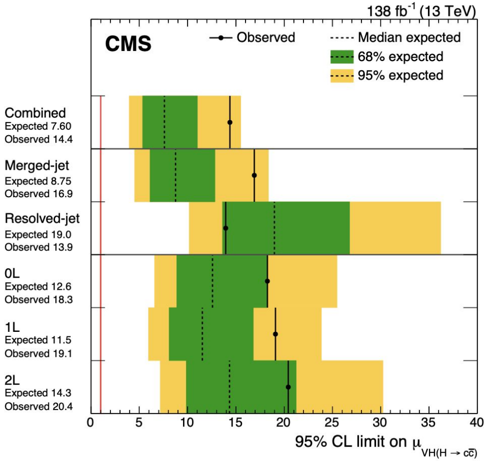
Large edge over ATLAS



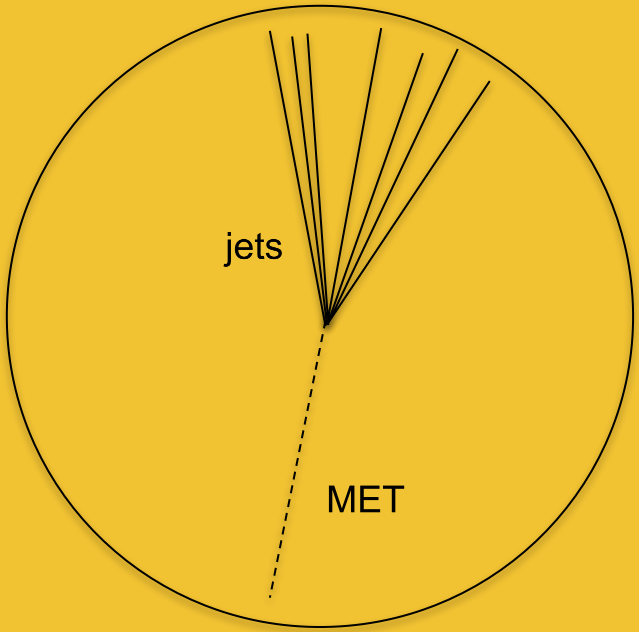
CMS expected upper limit on VH(cc): 7.8

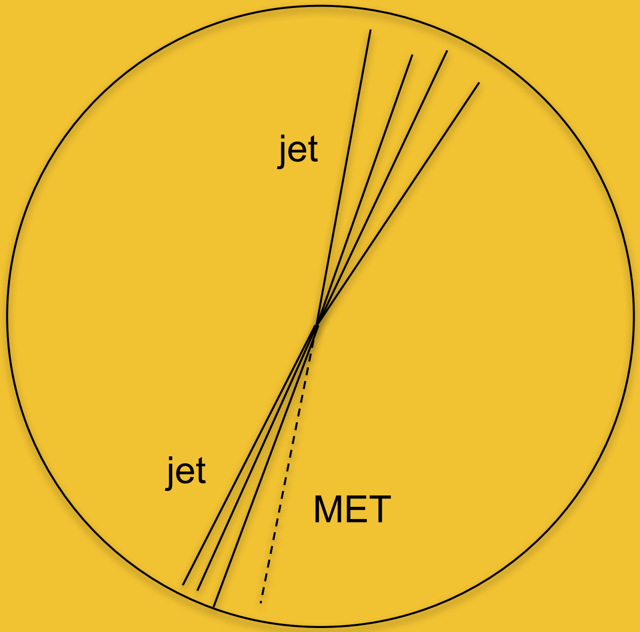
ATLAS: 31 !!!

Is as if Run-2 lasted 16 times longer for CMS



Back-to-back topology between MET and jets
Interesting, therefore kept
Easy to analyze



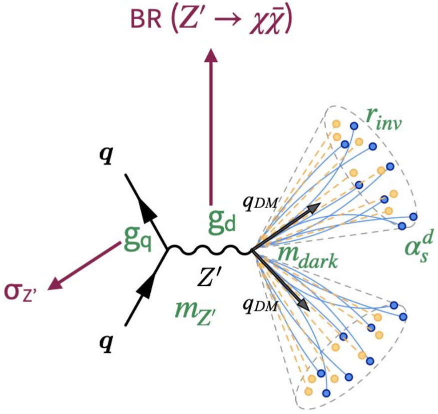


MET and jet **aligned**
Uninteresting (multijet background), thus discarded
Coming from mismeasurement of one jet … or does it?

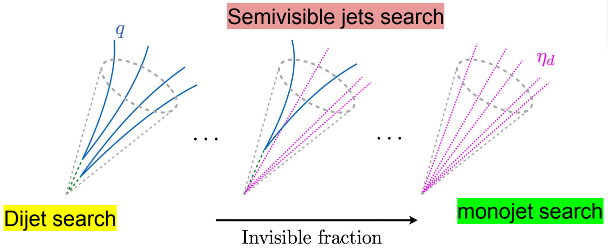
Semivisible jets – a dark version of the strong force

$SU_{dark}(N)$

$N^{c}_{dark} = 2, N^{f}_{dark} = 2$



4 parameters: $m_{Z'}, m_{dark}, r_{inv}, \alpha_{dark}$



$$r_{\rm inv} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$

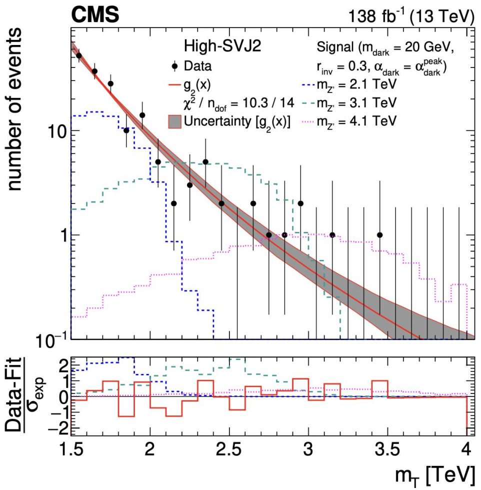
Dark showering process after leptophobic Z’ → $q_D q_D$

Some dark hadrons stable → Visible states **interspersed** with dark hadrons

E_T^{miss} aligned with jets, not back-to-back → mono-X searches not sensitive

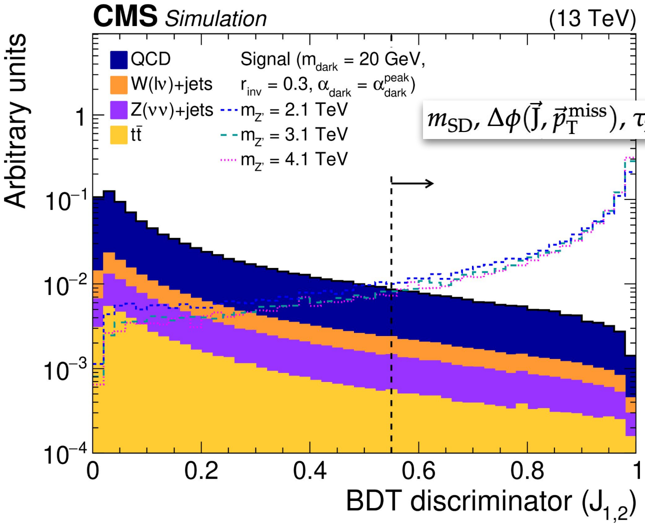
Traditional jet quality cuts not sufficient; custom filters to eliminate dead cells that create fake MET

Semivisible jets – a dark version of the strong force



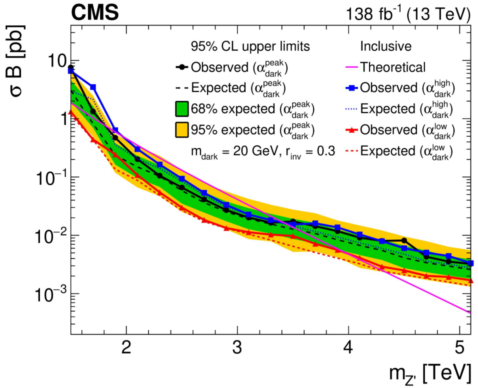
Sensitive variable: transverse mass m_T of dijet system and MET

A jet-level **boosted decision tree** is used to tag SVJs and define a high-purity category

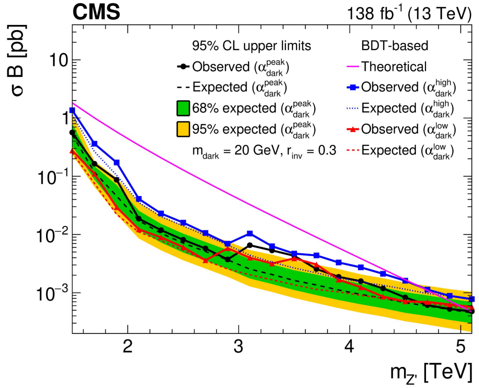


m_{SD}, $\Delta\phi(\vec{J}, \vec{p}_T^{miss})$, τ_{21}, τ_{32}, and D_{p_T}

inclusive

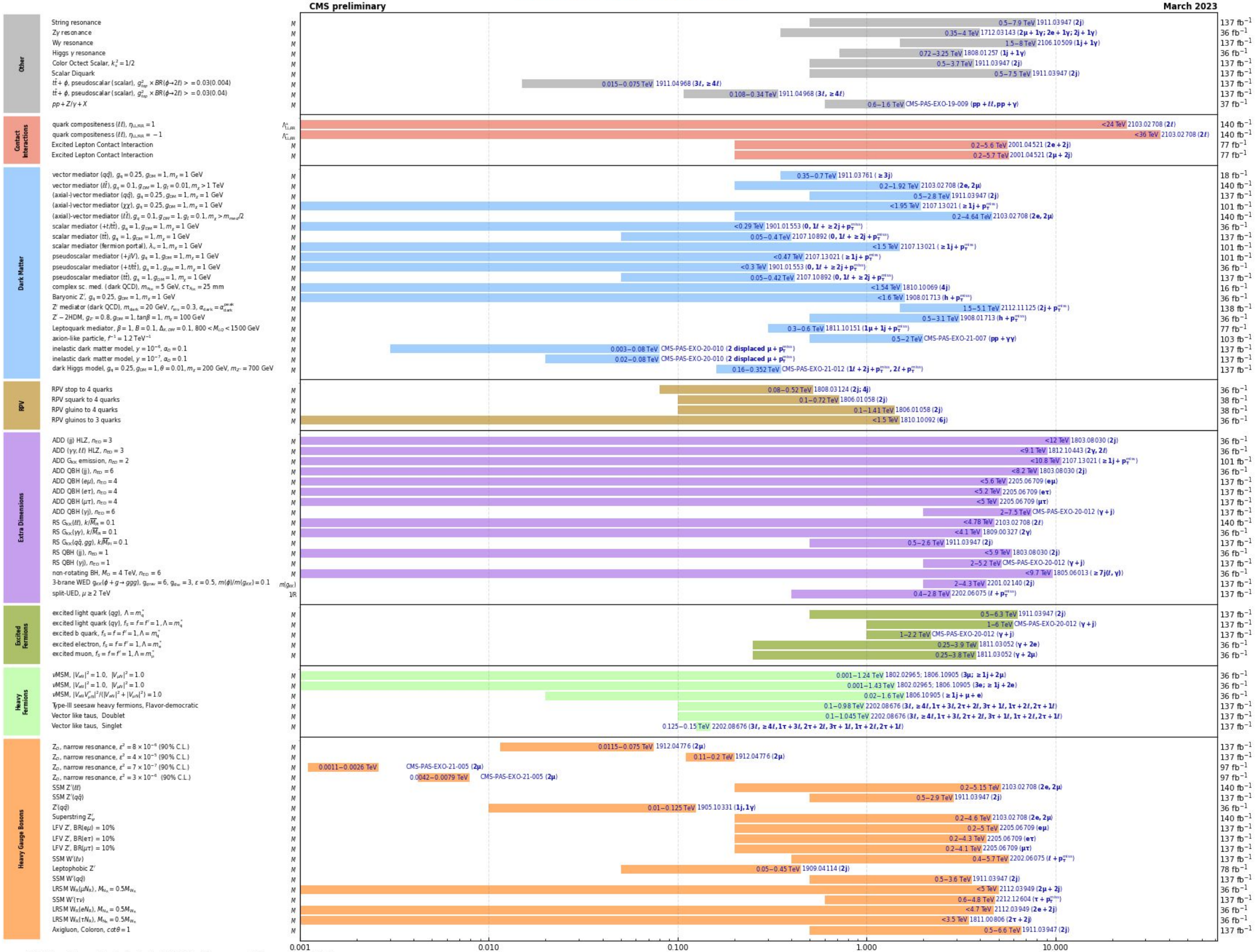


BDT



Slight excess around 3 TeV → Remains interesting for Run-3!

Overview of CMS EXO results

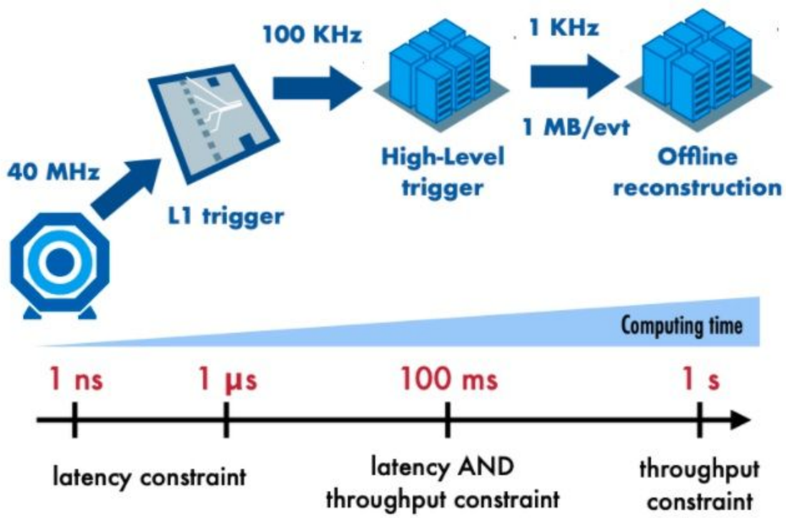


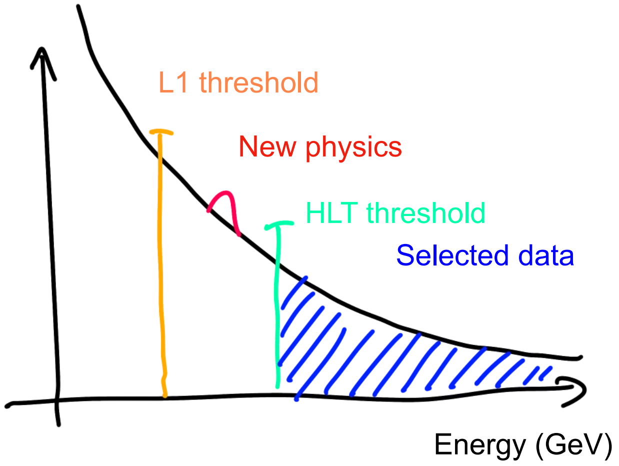
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Intensity frontier

Look at smaller masses and higher rates

Bandwidth ≙ rate ⊗ size/evt





Limited bandwidth and disk space → cannot afford to save the full detector information for every event to disk

Two-tiered **trigger system** in place to discard events in real-time (L1, on dedicated hardware) or almost-real-time (HLT, in software)

What if new physics is hiding below trigger threshold?

→ Change event content to accommodate lower thresholds
→ Save only coarse HLT information in “Scouting” datastream

Only Hardware L1 trigger constraints; HLT pass-through; 100 fb^{-1}

Scouting at CMS during Run-2

L1-Trigger

Scouting Path	L1 trigger requirements
Muon CaloScouting	$2\mu, p_T > 15/7$ GeV $3\mu, p_T > 5/3/3$ GeV 2μ, OS, $p_T > 4.5$ GeV, $\|\eta\| < 2$, $7 < m(2\mu) < 18$ GeV 2μ, OS, $p_T > 0$ GeV, $\|\eta\| < 1.5, \Delta R < 1.4$ 2μ, OS, $p_T > 4.5$ GeV, $\|\eta\| < 2.5, \Delta R < 1.2$
H_T Calo/PF-Scouting	1 jet, $p_T > 180$ GeV 2 jets, $p_T > 30$ GeV, $\|\eta\| < 2.5$, $m(2j) > 300$ GeV, $\Delta\eta < 1.5$ $H_T > 360$ GeV

Loose Cuts at HLT

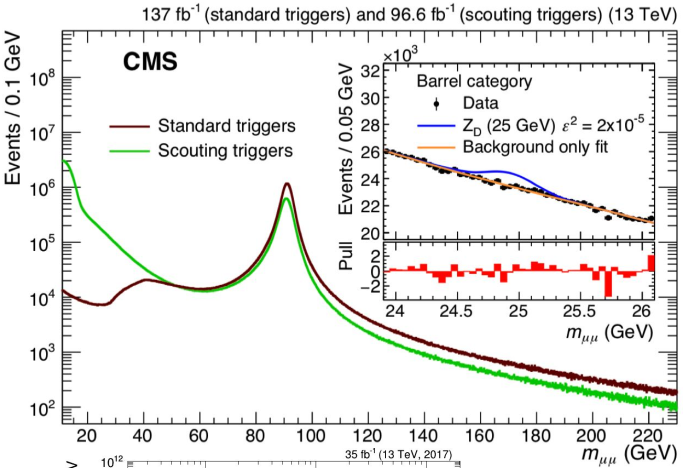
Scouting Path	Selection	Rate [kHz]	Proc. Time [ms]
Muon Calo-Scouting (2017–2018)	(2μ, $p_T > 3$ GeV)	2.7	350
H_T Calo–Scouting (2016–2018)	($H_T > 250$ GeV)	3	160
H_T PF–Scouting (2016–2018)	($H_T > 410$ GeV)	0.7	1200

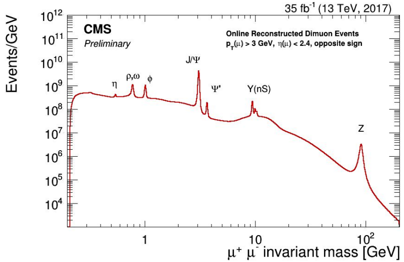
Scouting Datasets

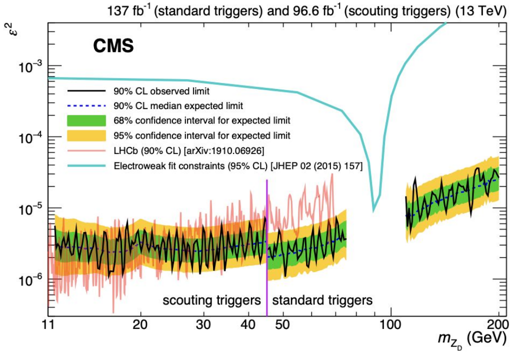
Scouting Dataset	# events	dataset size	average size per event
Muon Calo–Scouting (2017–2018)	14.4 B	56 TB	3.9 kB
H_T Calo–Scouting (2016–2018)	37.7 B	78 TB	2.1 kB
H_T PF–Scouting (2016–2018)	7.7 B	66 TB	8.6 kB

Dimuon mass resolution slightly worse than LHCb (1-1.5%), not much worse than offline

Resolution for 2 TeV resonance using calo jets -20% compared to offline







Taking it to the extreme (i.e., below the Υ)

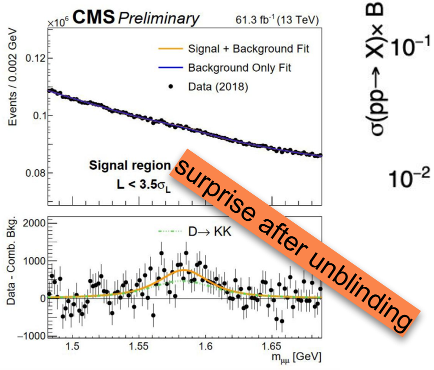
Fully exploiting Scouting data by selecting events with two muons p_T > 4 GeV (very soft!)

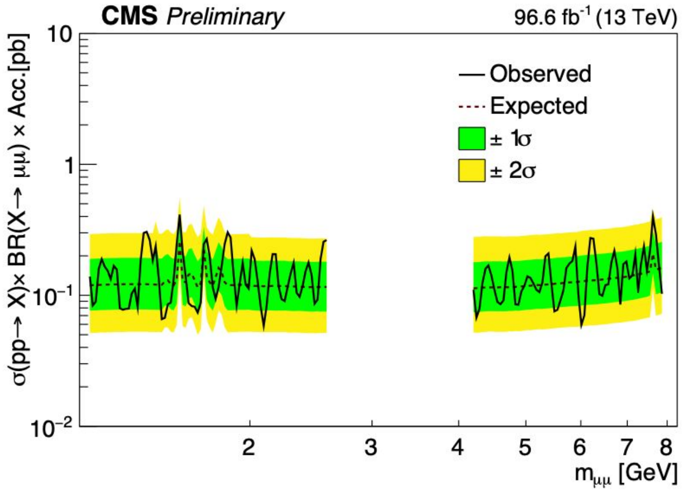
Novel MVA muon identification increases sensitivity by 30%

- Track quality
- Isolation
- Vertex information

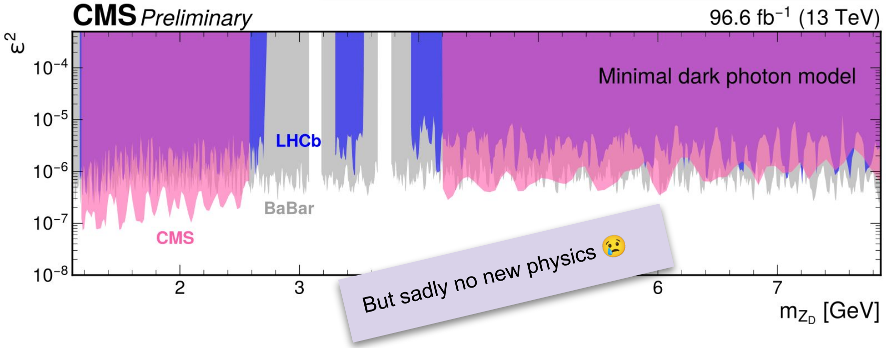
Fit to dimuon mass distribution:

- signal: double Crystal Ball + Gaussian,
- background: empirical functions (e.g. polynomial times exponential)





More sensitive than LHCb or BaBar with “2nd-grade” data 😋



Kung Fu Panda

Lifetime frontier

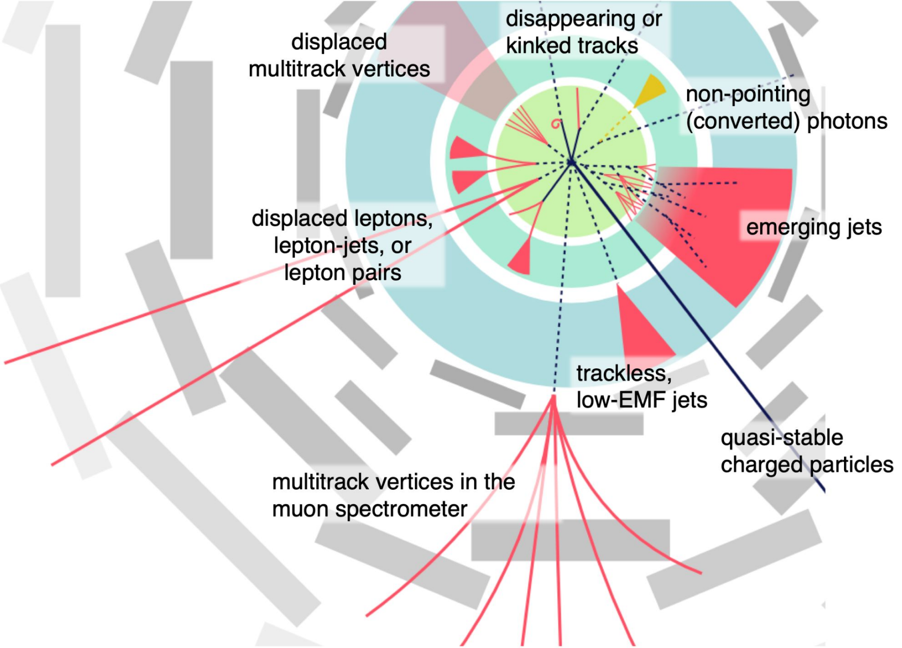
Unlocking displaced signatures

$$\Gamma \propto \varepsilon^2 \left(\frac{m}{\Lambda}\right)^{2n} \Phi$$

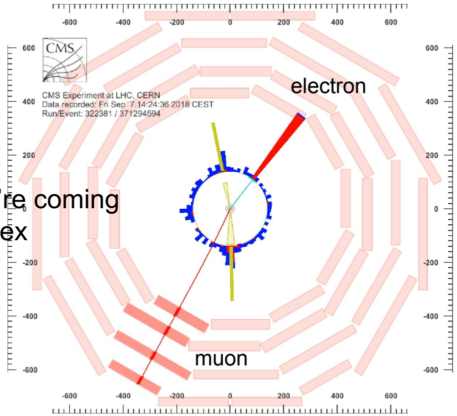
Why long-lived particles are tricky

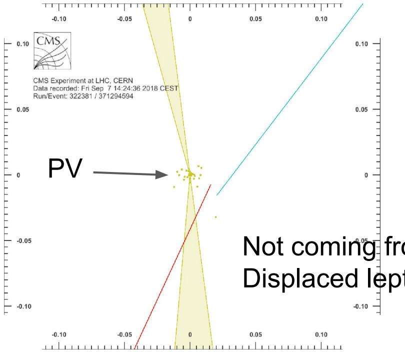
CMS was **not designed** to look for **displaced** new physics

Reconstruction algorithms, cylindrical geometry, trigger, all designed assuming particles emerge from the collision point



Looking like they're coming from primary vertex

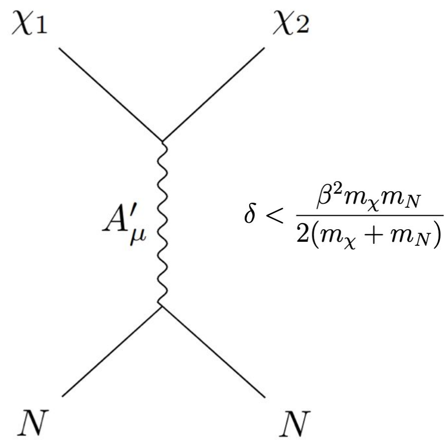




Not coming from PV!
Displaced leptons

Inelastic Dark Matter with displaced muons

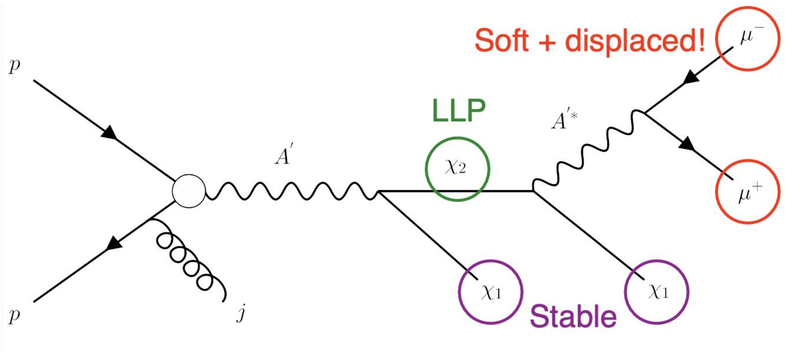
Off-diagonal matrix element dominating

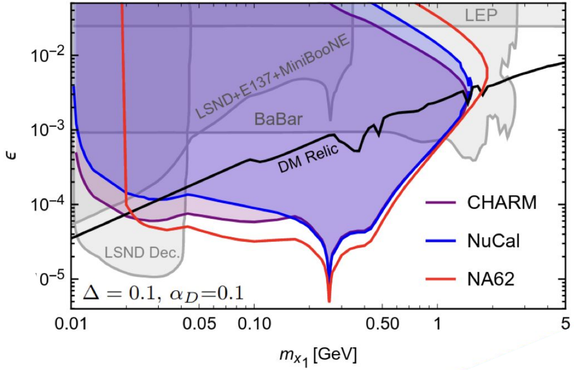


Two dark matter states with **small mass gap** coupled via dark photon. Depending on Δm_{DM}: no direct detection (“inelastic”)

Heavier DM (**χ_2**) has **long lifetime due to small mass splitting** → Pair of soft displaced muons overlapping with MET (from **χ_1**)

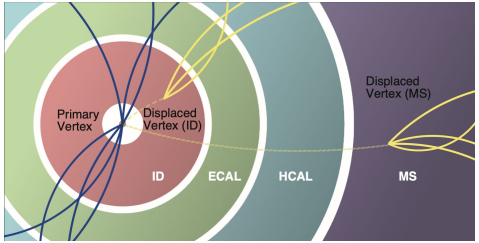
$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$; target 1mm - 1000mm range





Highly constrained by beam-dump experiments for < 1 GeV

Inelastic Dark Matter with displaced muons

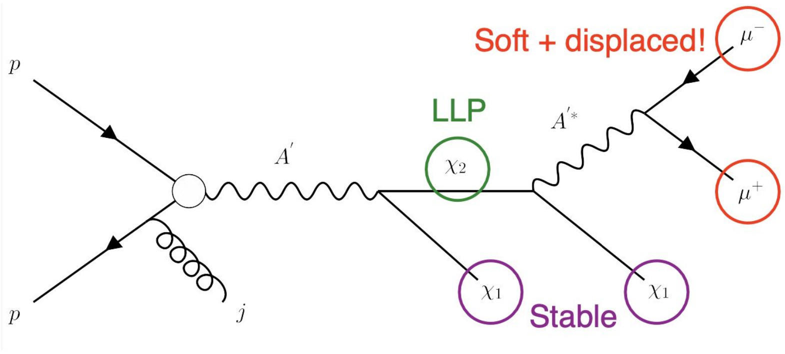


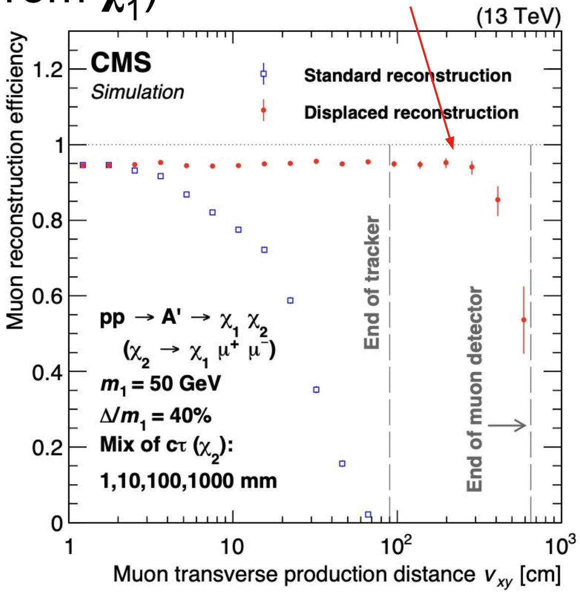
Two dark matter states with **small mass gap** coupled via dark photon. Depending on Δm_{DM}: no direct detection ("inelastic")

Heavier DM (χ_2) has **long lifetime due to small mass splitting**
→ Pair of soft displaced muons overlapping with MET (from χ_1)

$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$; target 1mm - 1000mm range

Dedicated muon reconstruction using only muon system





Inelastic Dark Matter with displaced muons

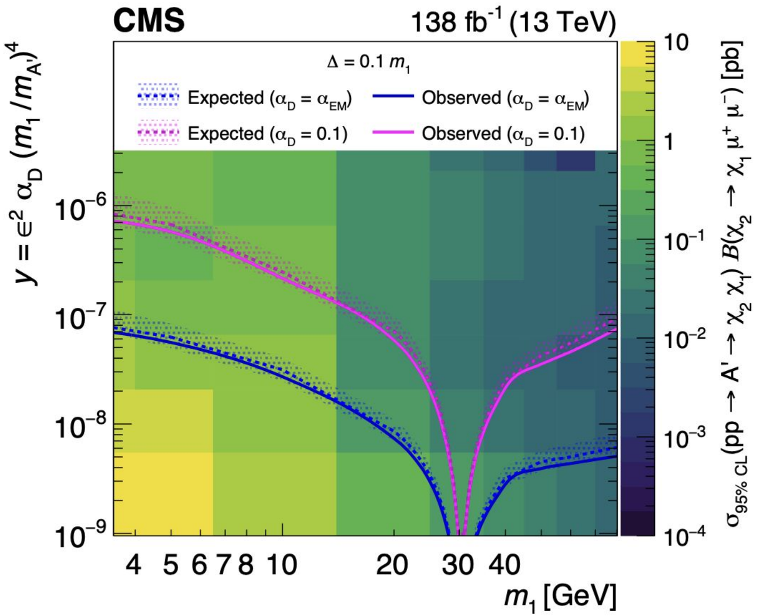
$m_{A'} = 3\, m_1$

Categorize by number of displaced muons that match in direction to a standard muon

- Fewer matches → larger displacement

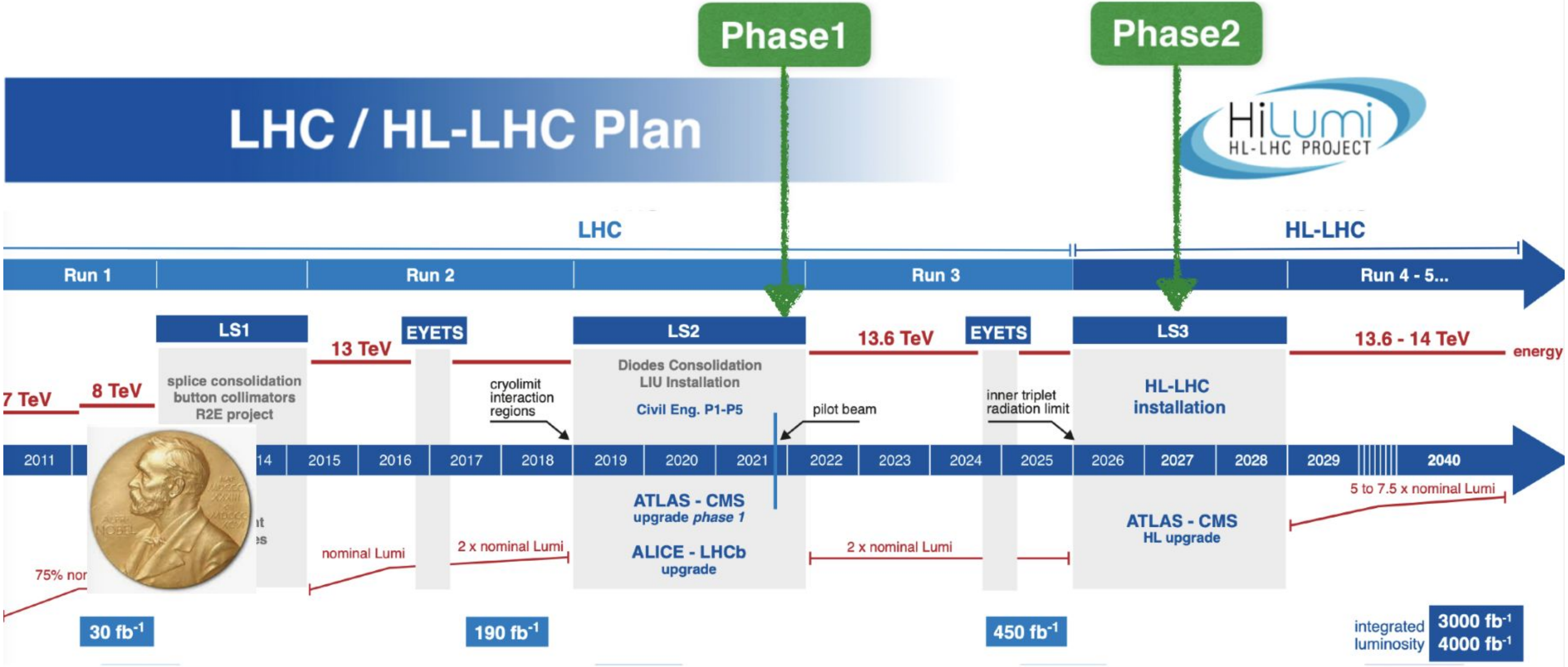
- Use kinematics, isolation, displacement parameter to both suppress and estimate background (mostly QCD)

	Events per SR category		
	0-match	1-match	2-match
Pred.	1.2 ± 0.6	0.5 ± 0.3	0.5 ± 0.3
Obs.	2	0	0

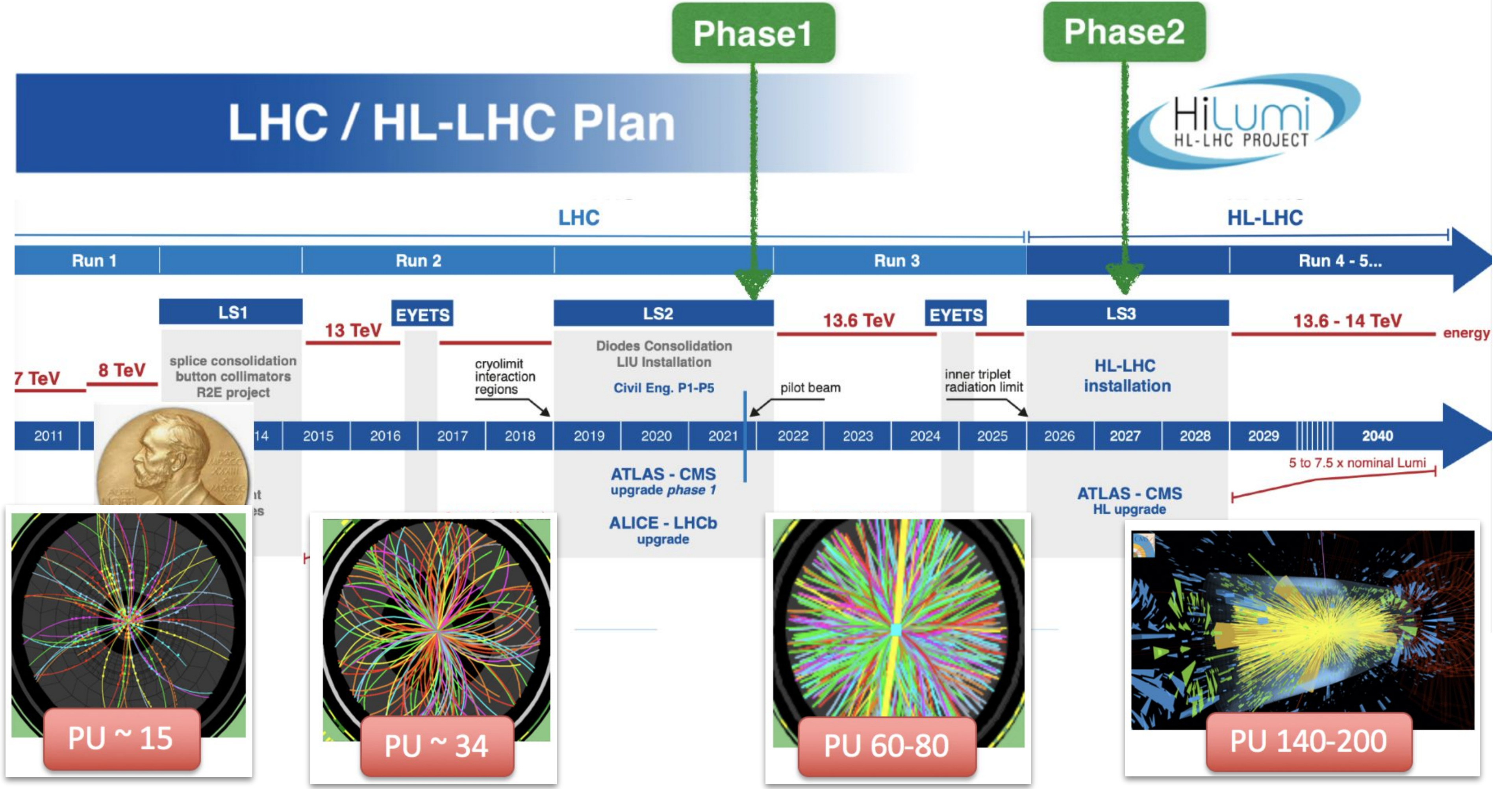


First such search at a hadron collider!

Preparing for the High-Luminosity LHC



Phase1
Phase2
LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
14
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nor
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1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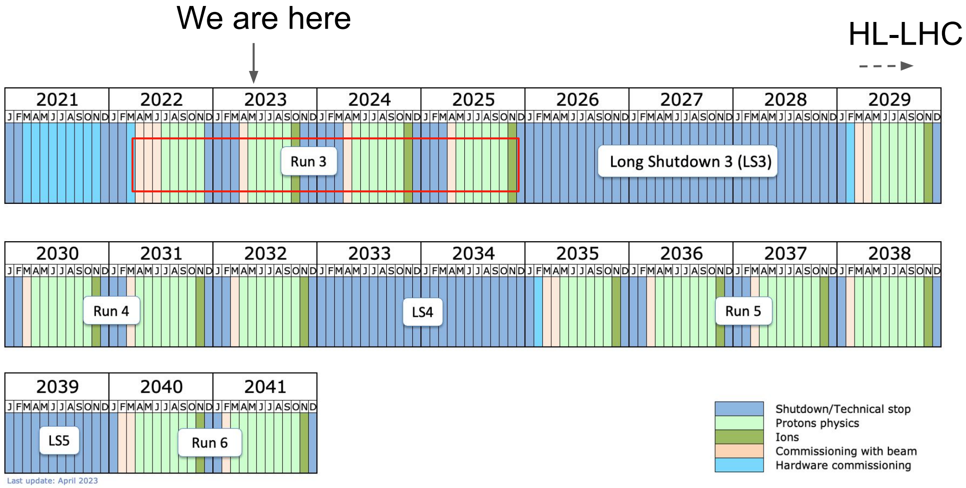
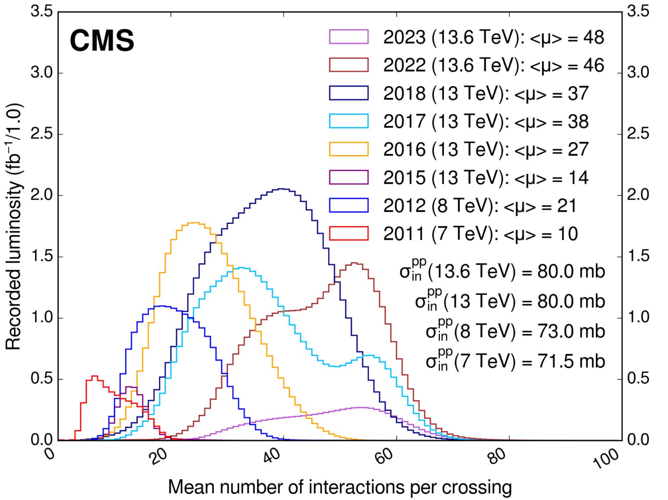
2011
14
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
5 to 7.5 x nominal Lumi
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
PU ~ 15
PU ~ 34
PU 60-80
PU 140-200

Run-3 as testbe(d/nch)





HL-LHC:
<nPU>=140

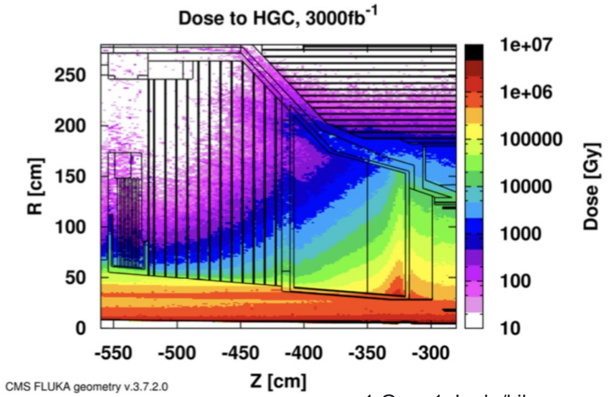
Use Run-3 to develop program for HL-LHC

- Test new analysis strategies
- Build the hardware to be installed during LS3
- Write reconstruction algorithms for new detector/environment

Preparing for the High-Luminosity LHC

Novel *Hardware*

Phase-II upgrade: **replacement of CMS endcap** instrumentation (→ very congested region) with a novel detector



1 Gy = 1 Joule/kilogram

Let's talk about **our needs**:

Withstand extreme exposure

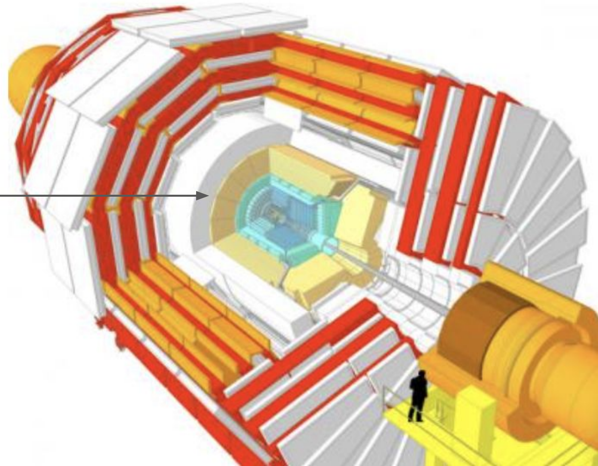
Good pileup rejection capability

Superior shower reconstruction

→ expensive endcaps

cheap endcaps

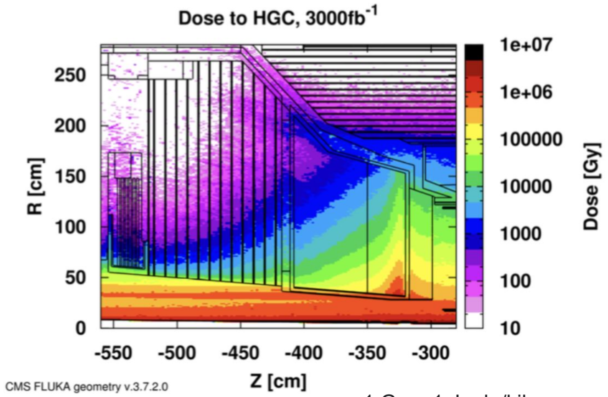
Current endcaps only designed for $< 500\ fb^{-1}$



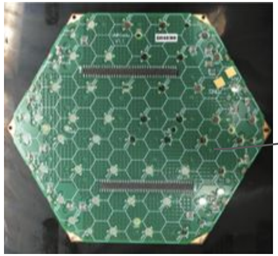
Phase-II upgrade: replacement of CMS endcap instrumentation (→ very congested region) with a Highly Granular Calorimeter (“HGCal”)

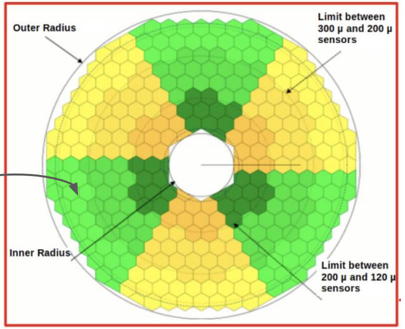
What **silicon** has to offer:

Radiation hardness	↔	Withstand extreme exposure
Fast response	↔	Good pileup rejection capability
Can be finely segmented	↔	Superior shower reconstruction



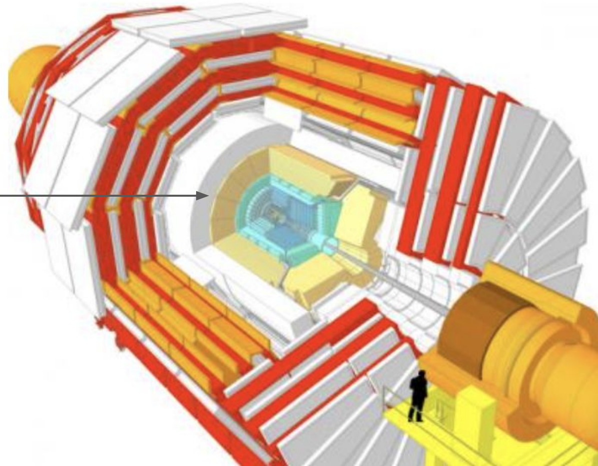
1 Gy = 1 Joule/kilogram





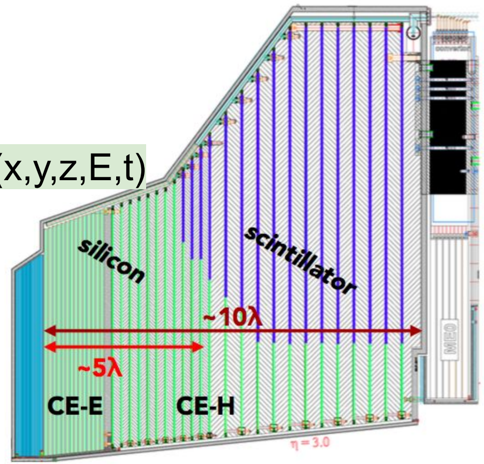
Highly Granular Calorimeter (“HGCal”) Silicon wafer

Current endcaps only designed for < 500 fb^{-1}

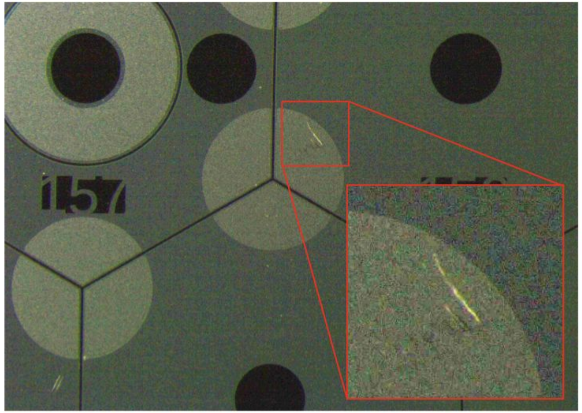


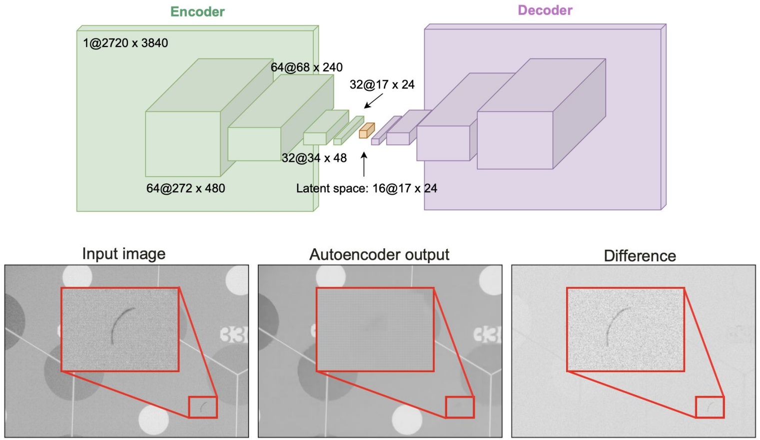
Both Endcaps	Silicon	Scintillator
Area	~620 m²	~370 m²
Channel Size	0.5 - 1.2 cm²	4 - 30 cm²
# Channels	~6 M	~240 k
# Modules	~27000	~4000
Op. Temp.	-30 C	-30 C

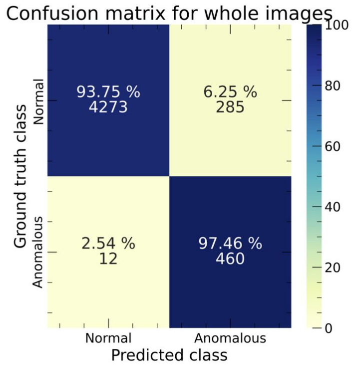
Unprecedented fine segmentation in 5D (x,y,z,E,t)



AI (autoencoder) helps at visual inspection of sensors



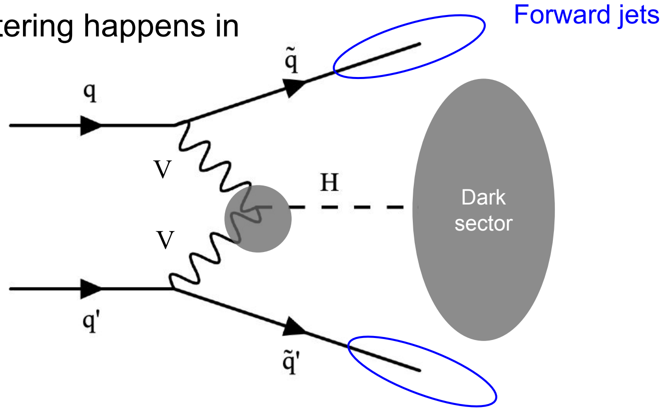


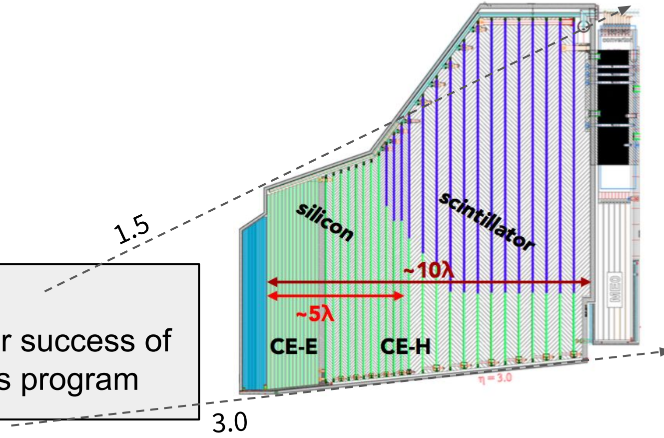


How dark sectors will gain

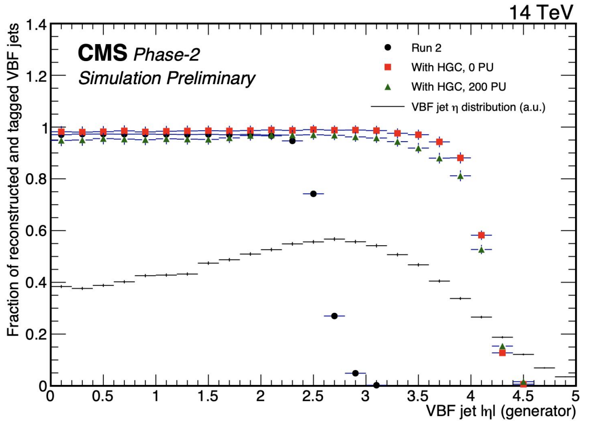
Anything vector boson fusion or vector boson scattering happens in that region!

VBF H
VBF HH
VBS …

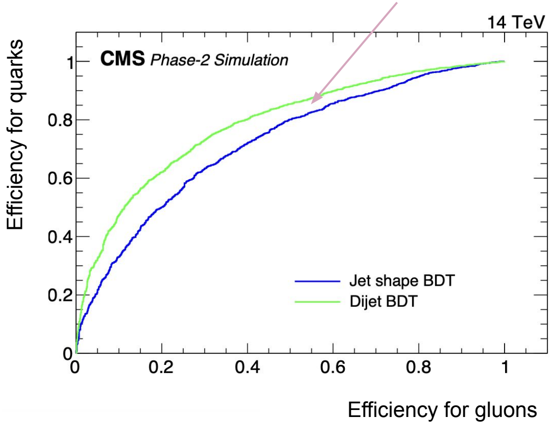




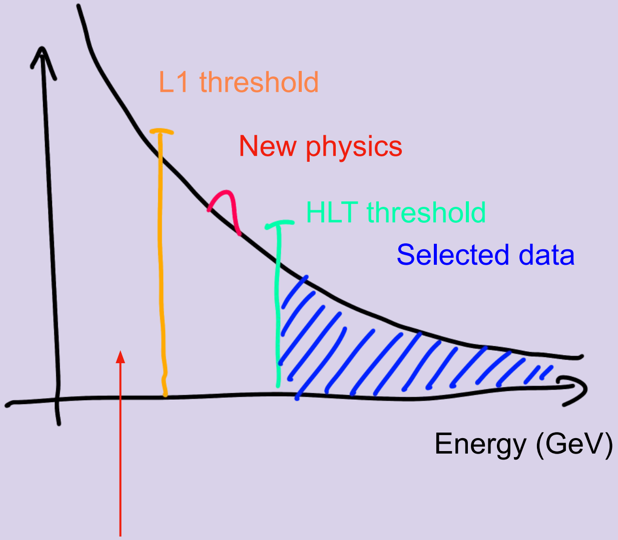
$1.5 < \eta < 3.0$
→ crucial for success of LHC physics program



Highly segmented detector allows for superb quark-gluon discrimination

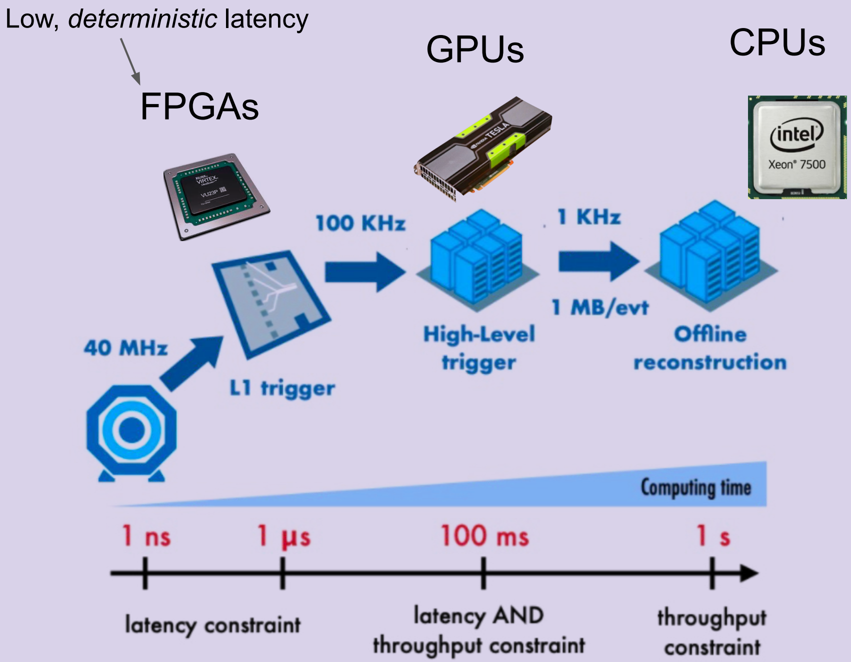


Coming back to this

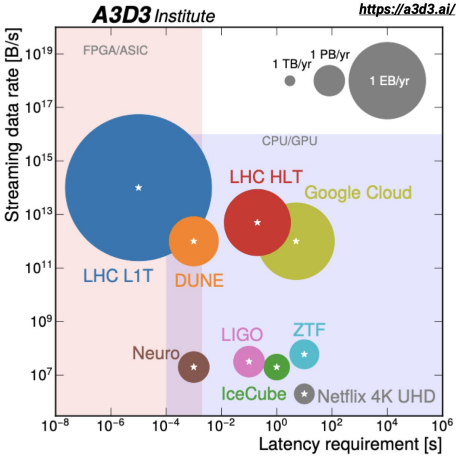


What if new physics resides below even L1 threshold?

Can we make the **hardware** detect interesting events through **AI**?



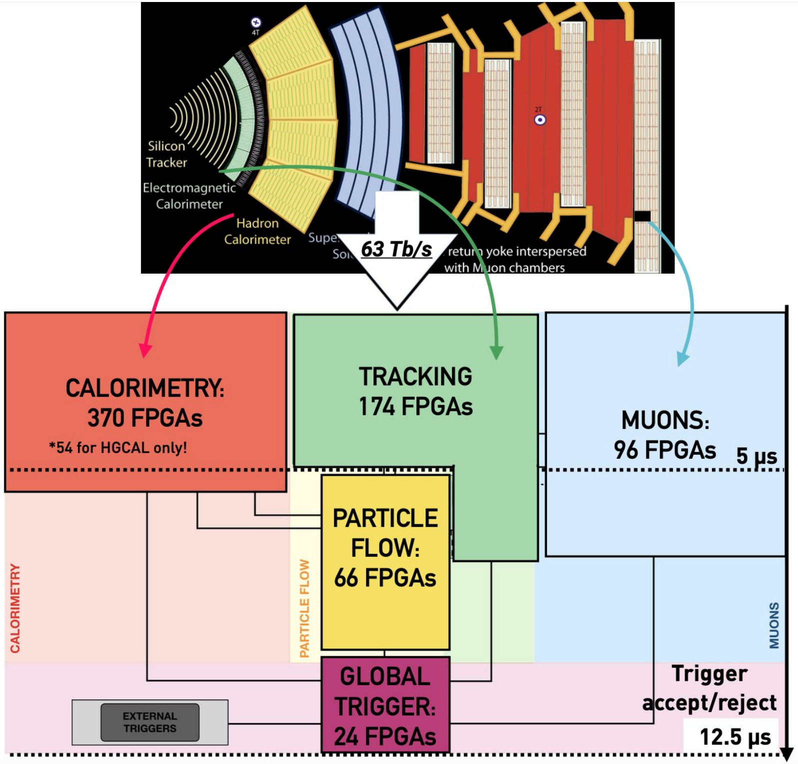
Hardware and AI melt together



The problem clearly is the low time (microseconds) available at L1 to look at the events

Yet, data intensity (>= Google) asks for AI-based solutions

FPGAs not very easy to work with …
hls4ml to the rescue

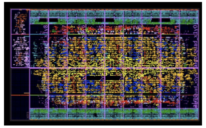


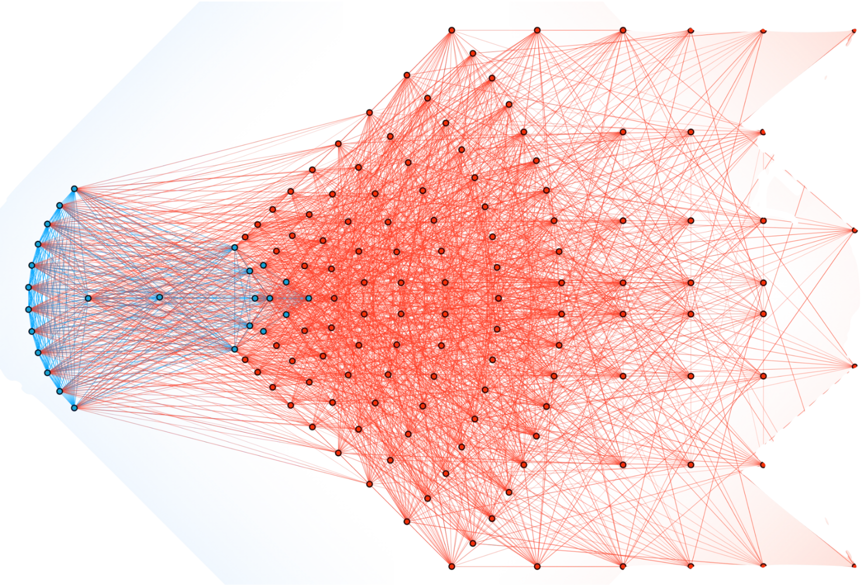

```
hls_model = hls4ml.converters.convert_from_keras_model(
    model2,
    hls_config=hls_config,
    output_dir=output_dir,
    backend=backend,
    io_type=io_type,
)

X = np.random.rand(1, 28, 28, 1)

hls_model.compile()
```

Keras
TensorFlow
PyTorch
hls4ml





How can we fit this on that?

Model quantization

Article | Published: 21 June 2021

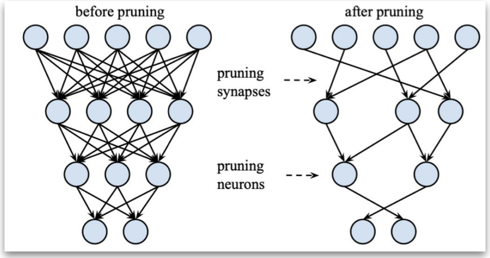
Automatic heterogeneous quantization of deep neural networks for low-latency inference on the edge for particle detectors

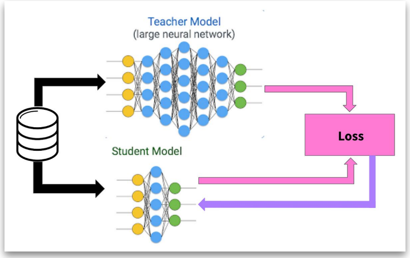
Claudionor N. Coelho Jr, Aki Kuusela, Shan Li, Hao Zhuang, Jennifer Ngadiuba, Thea Klaeboe Aarrestad, Vladimir Loncar, Maurizio Pierini, Adrian Alan Pol & Sioni Summers

Nature Machine Intelligence **3**, 675–686 (2021) | Cite this article

32bit → 8bit
1/2 memory
20x less power

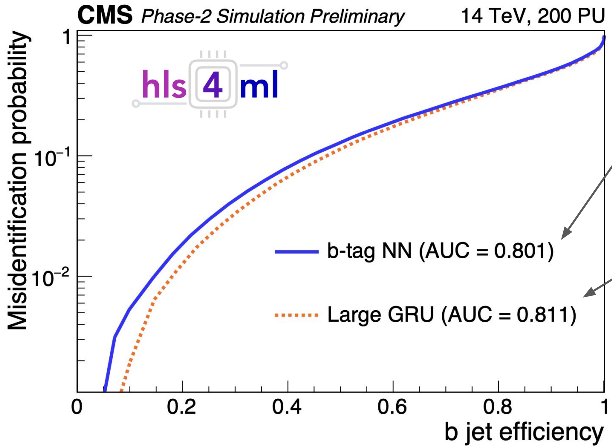
Model pruning





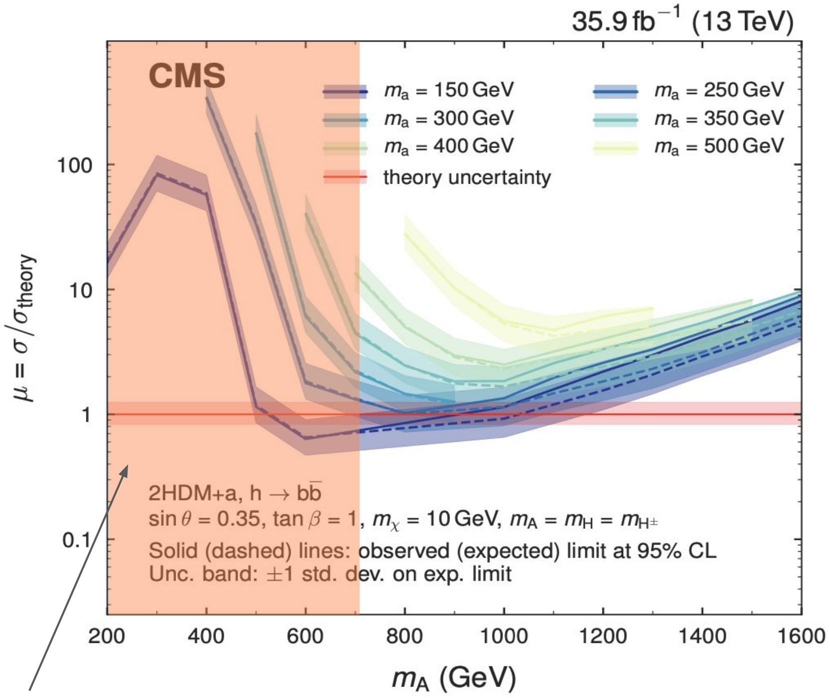
Model distillation

How dark sectors will gain



compact network

too big for FPGA



AI on FPGAs will result in (an excerpt):

- higher yield in true Higgs boson (bb) events
- Better object reconstruction
  → better MET resolution

Heavily limited by poor MET resolution at L1/HLT

Triggers fully efficient only for True MET>250 GeV

Preparing for the High-Luminosity LHC

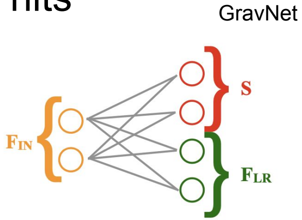
Novel *Algorithms*

Reconstruction with AI

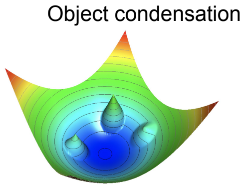
6M readout channels → traditional algorithms fail

End-to-end neural networks to perform ML-driven particle reconstruction based on hits

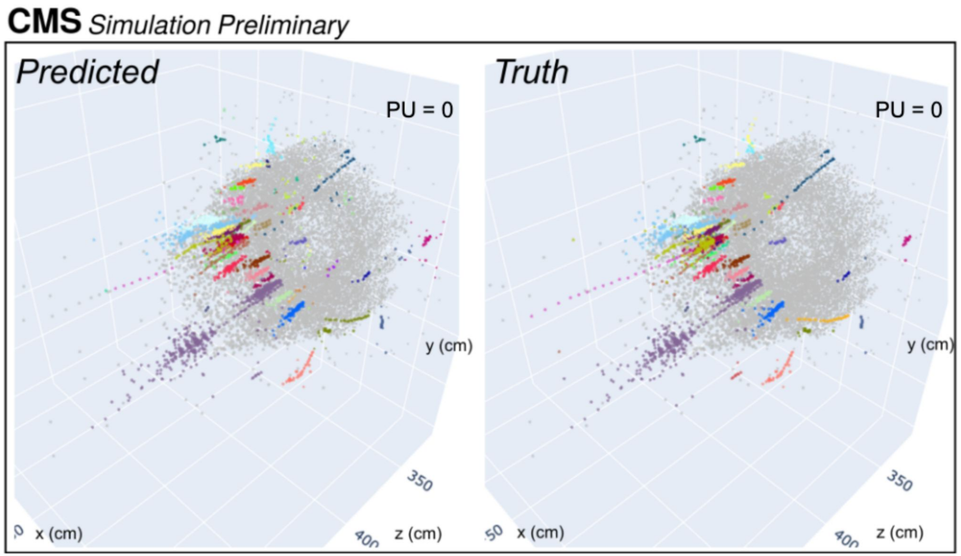
Graph neural networks with efficient kNN aggregation in latent space

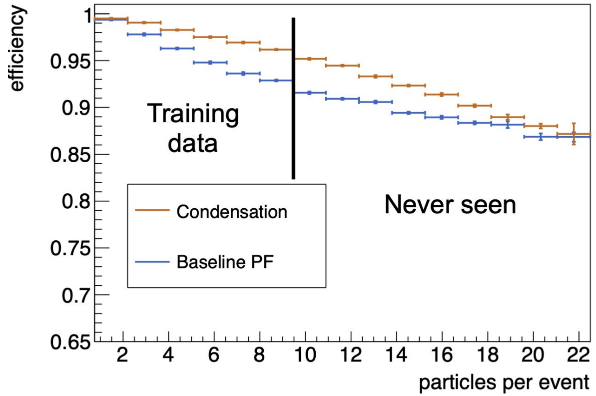


Physics-inspired loss functions to promote single hits around which other hits cluster and predict E/type of incident particles



- Outperforms classical ParticleFlow
- Excellent extrapolation (adaptation) properties



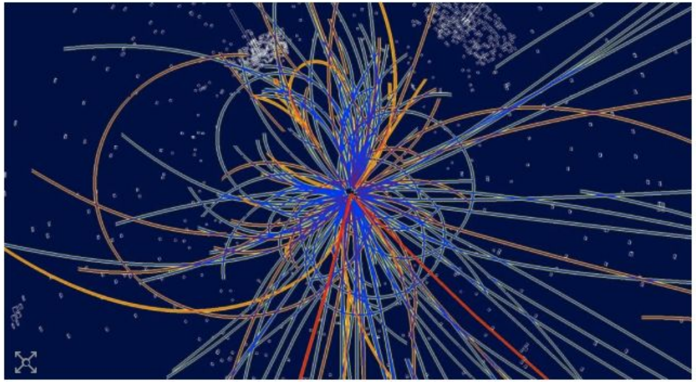


Disentangling up to 10,000 particles

PARTICLE AND NUCLEAR | RESEARCH UPDATE

Deep learning identifies head-on collisions in LHC data

23 Jun 2022



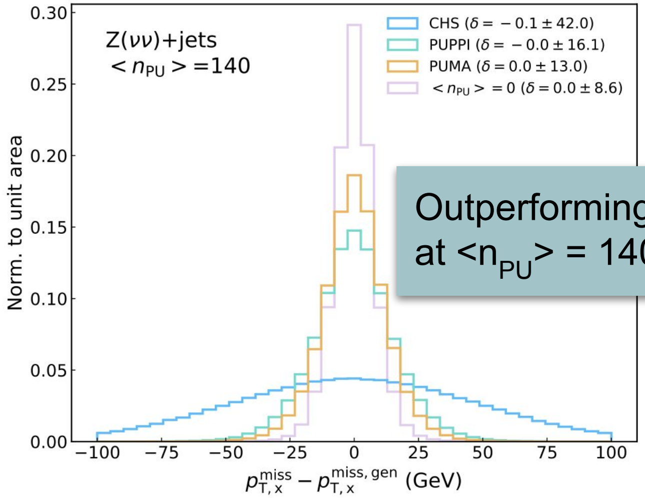
Sensory overload: simulation of a proton-proton collision at the Large Hadron Collider. (Courtesy: CERN)

Relying on **transformers** (same as ChatCPT) to "translate" a sequence with up to 10,000 particles (a sentence with up to 10,000 words)

→ Need to use **sparse attention**

Developing a **novel pileup mitigation** algorithm that predicts if a neutral particle comes from primary vertex or not

→ Replacing PUPPI as standard PU mitigation

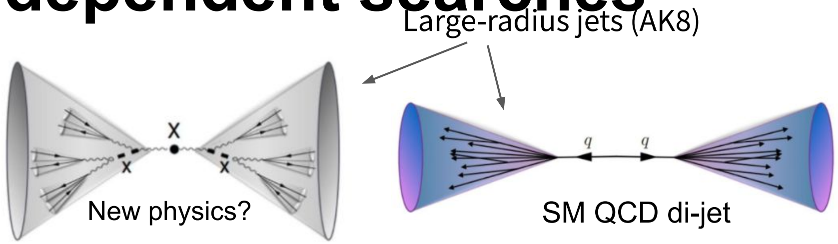


Outperforming PUPPI at $<n_{PU}> = 140$

Preparing for the High-Luminosity LHC

Novel *Strategies*

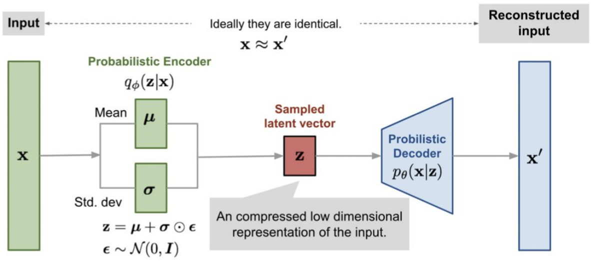
Anomaly detection for model-independent searches



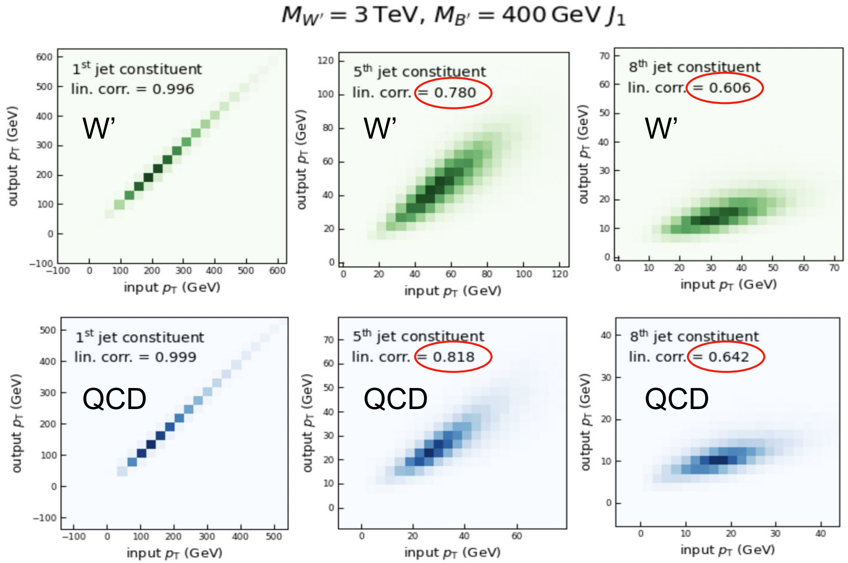
- Exotic substructure or radiation patterns are common for BSM physics

Challenge: Risk of being (mis-)guided by specific signal; need to be model-agnostic & data-driven.

Solution: Base selection on *SM jets veto* → anomaly detection based on ML to learn what SM jets look like



Train variational autoencoder (VAE) on QCD jets obtained from orthogonal control region



Worse reconstruction for BSM processes

Conclusion

CMS operates & develops at the energy, intensity, and lifetime frontiers

Pushing both software and hardware (and the merger of both) to the limits

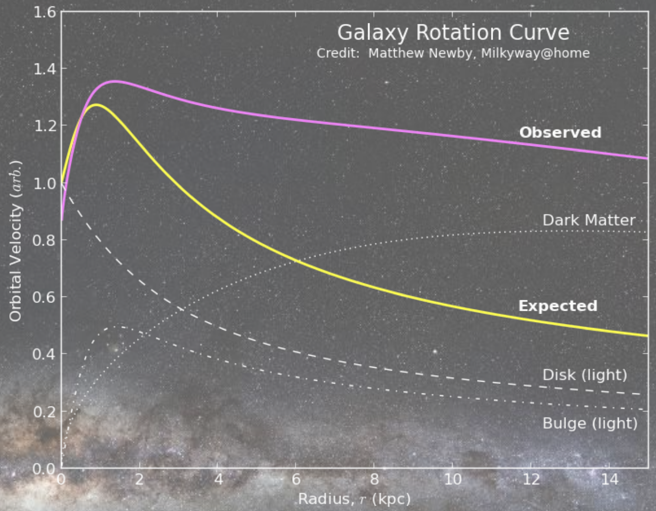
This allows for a rich search program for dark physics

The path towards the HL-LHC is pretty clear

If you're interested, come by our ETP offices at CN and CS

Karlsruhe Institute of Technology

Institute of Experimental Particle Physics



~~A Shot in the Dark~~ We have a plan
Searching for a Dark Sector with the CMS Experiment

Benedikt Maier, ETP

KCETA-Kolloquium, 25.05.2023