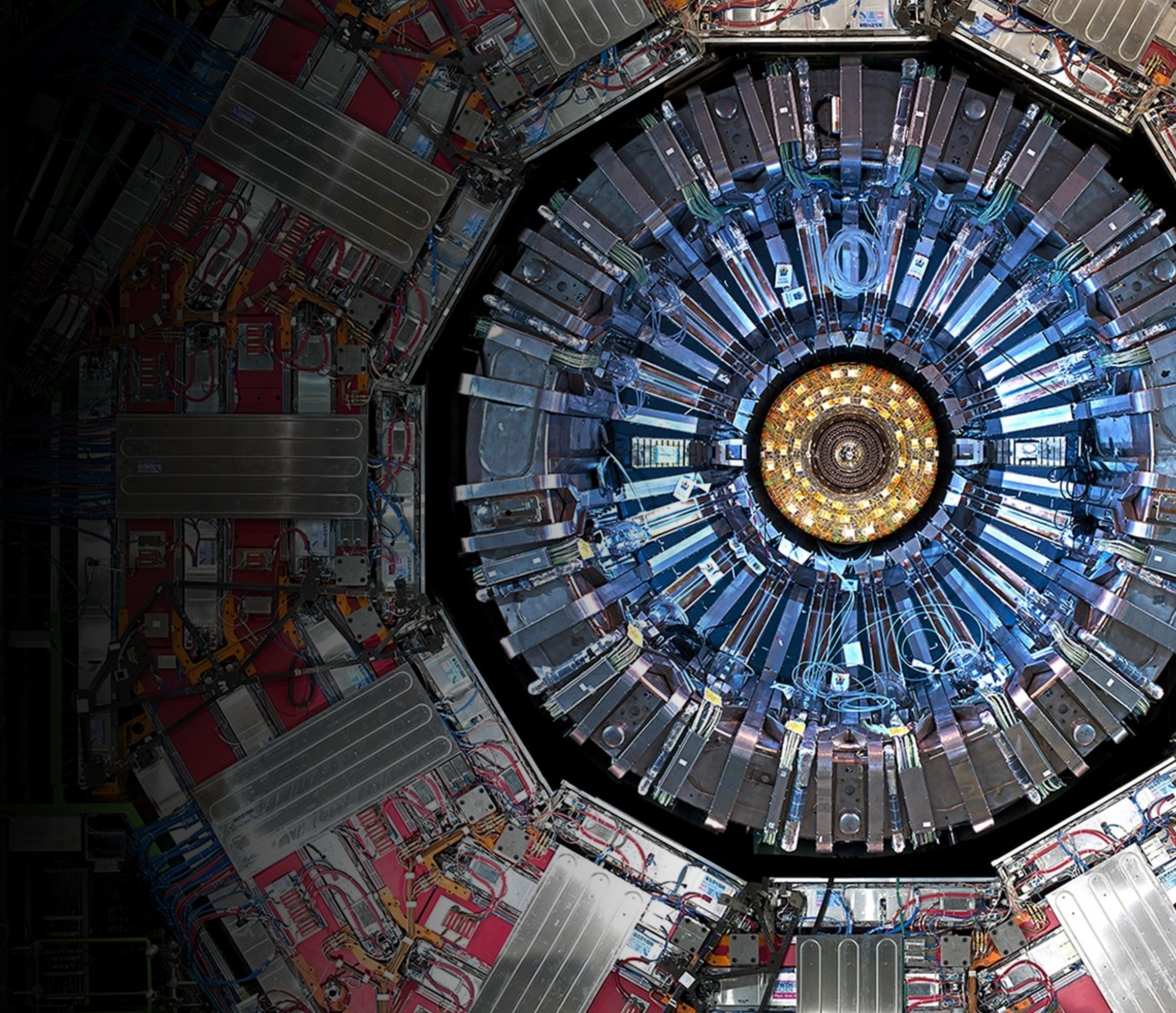
Dark Matter in the Time of Colliders



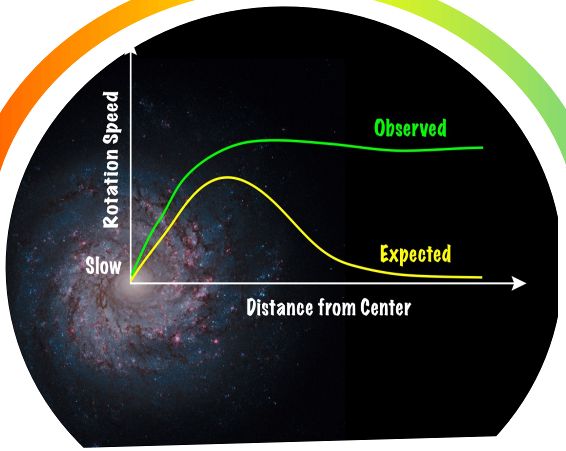
Indara Suarez

October 23, 2025

35 years of Hubble

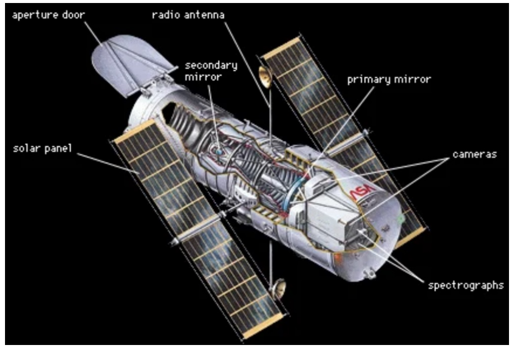
A 92 year journey, going strong

1933 Zwicky's "dunkle Materie"

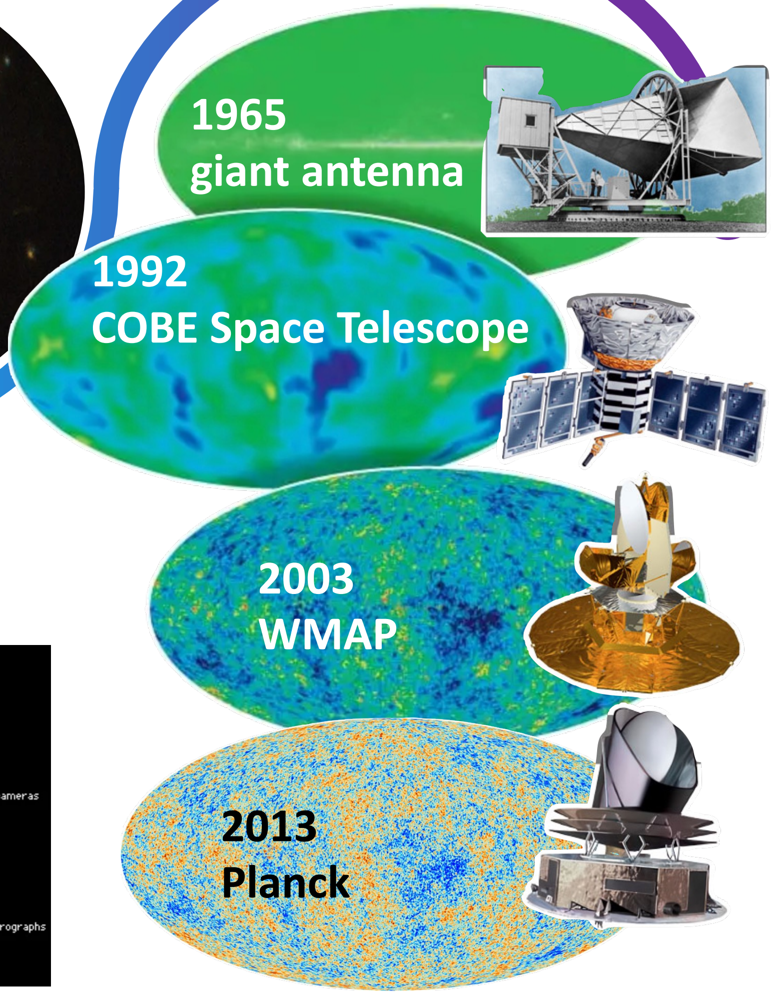


Vera Rubin's Rotational Velocities

Gravitational lensing



Cosmic Microwave Background



1965 giant antenna

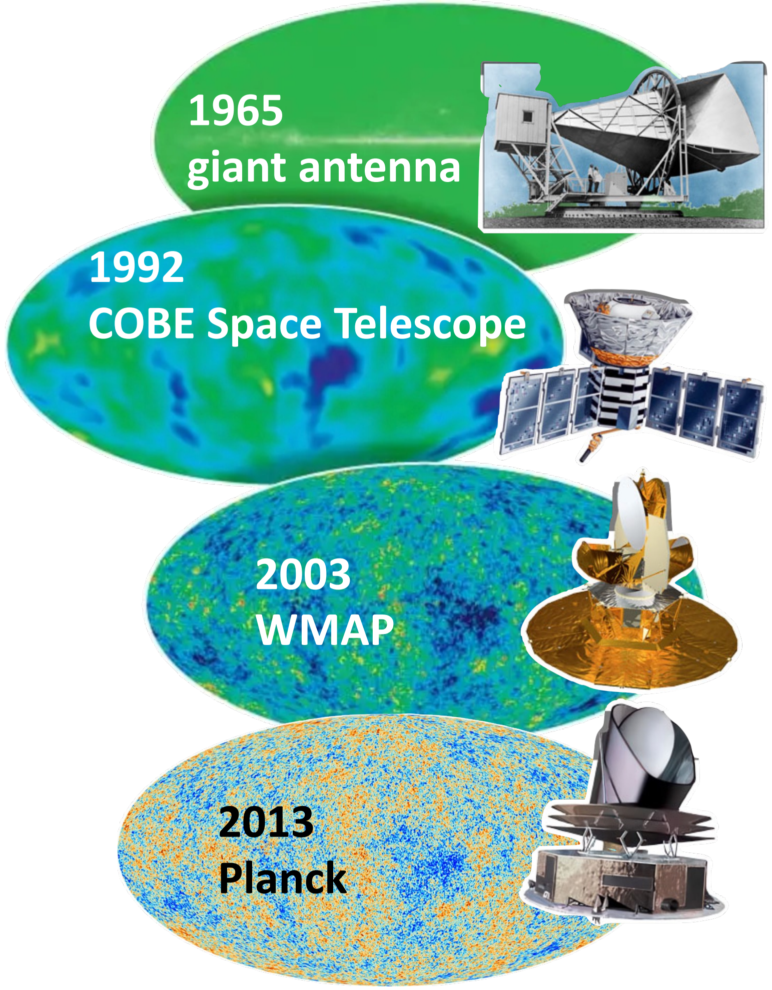
1992 COBE Space Telescope

2003 WMAP

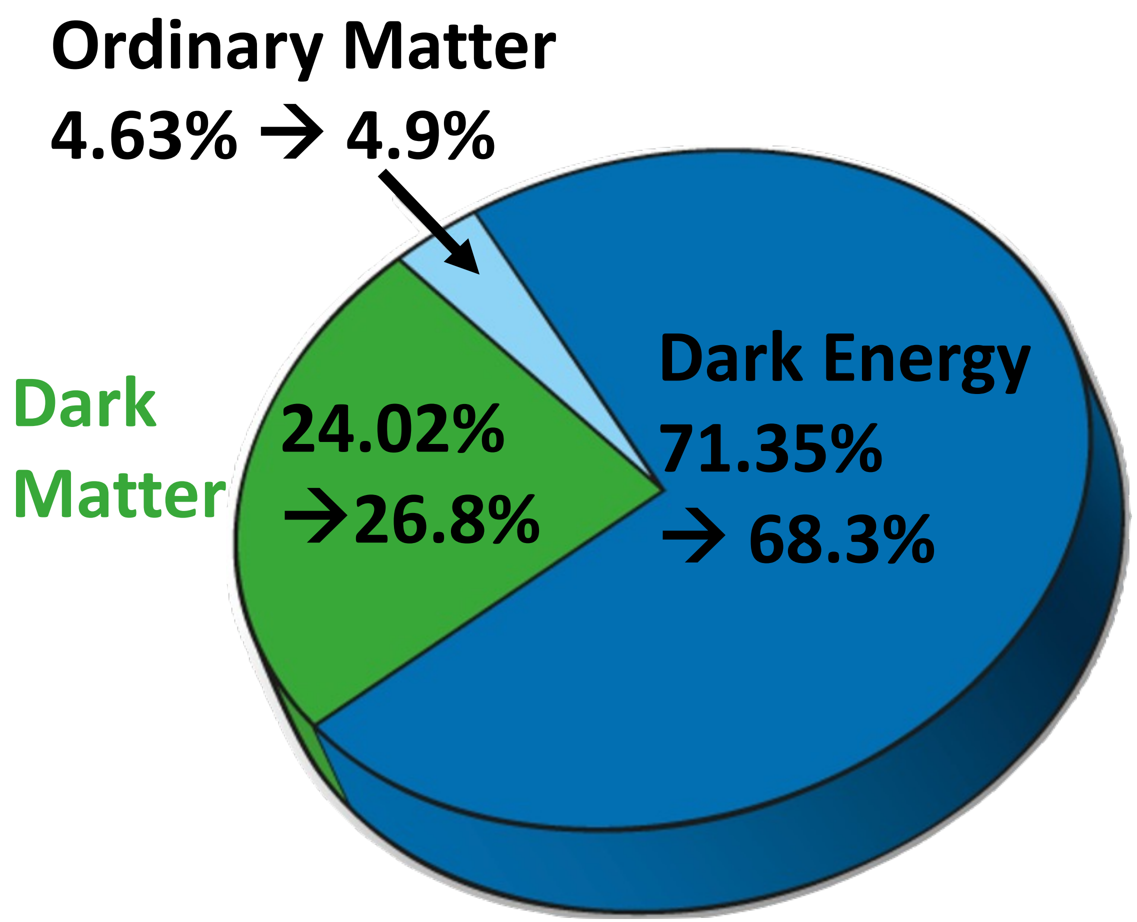
2013 Planck

The Composition of the Universe

Penzias & Wilson accidental discovery

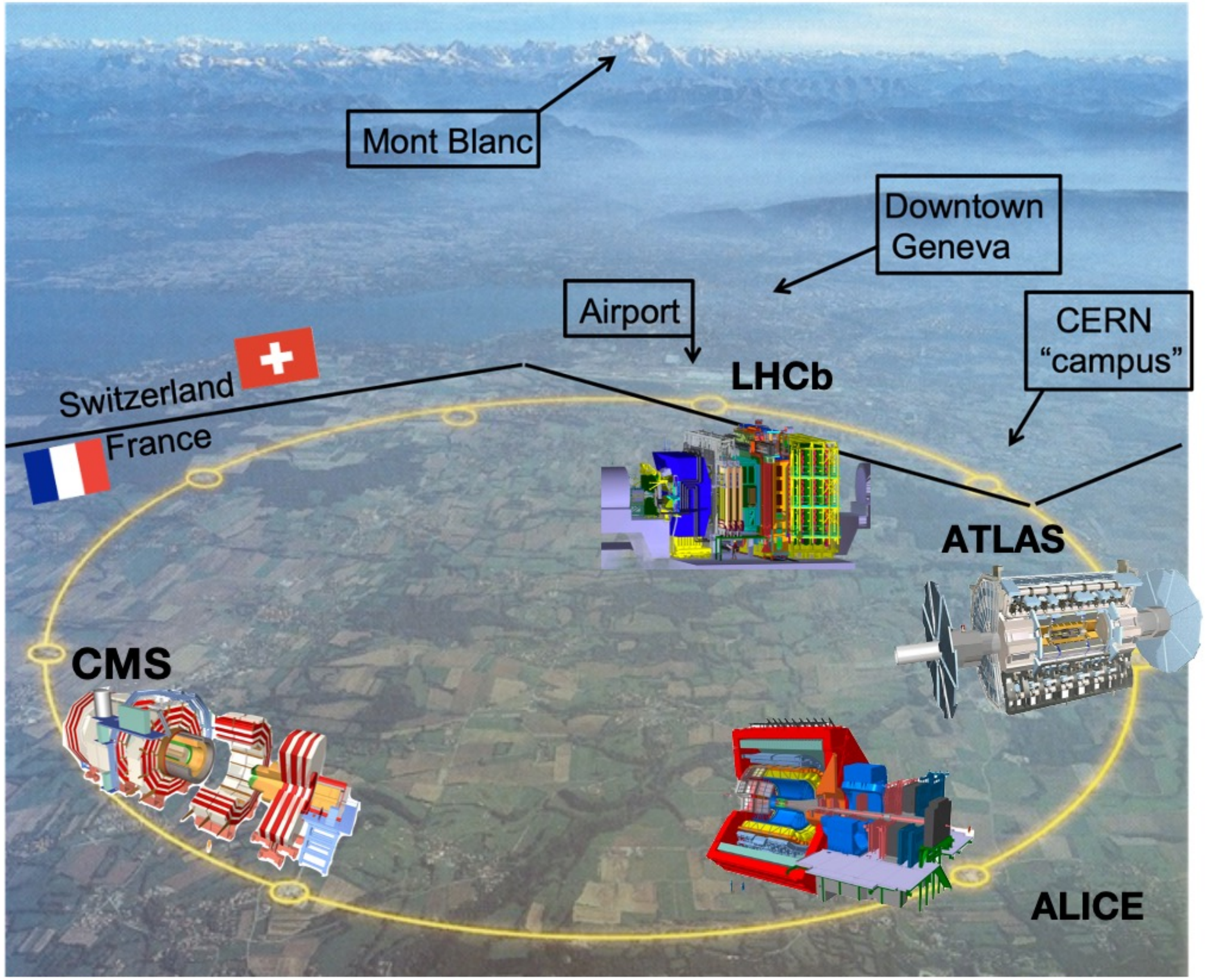


Precision Measurements of the Universe



DM makes up 84.5% of all matter in the universe

The Large Hadron Collider, at the right time

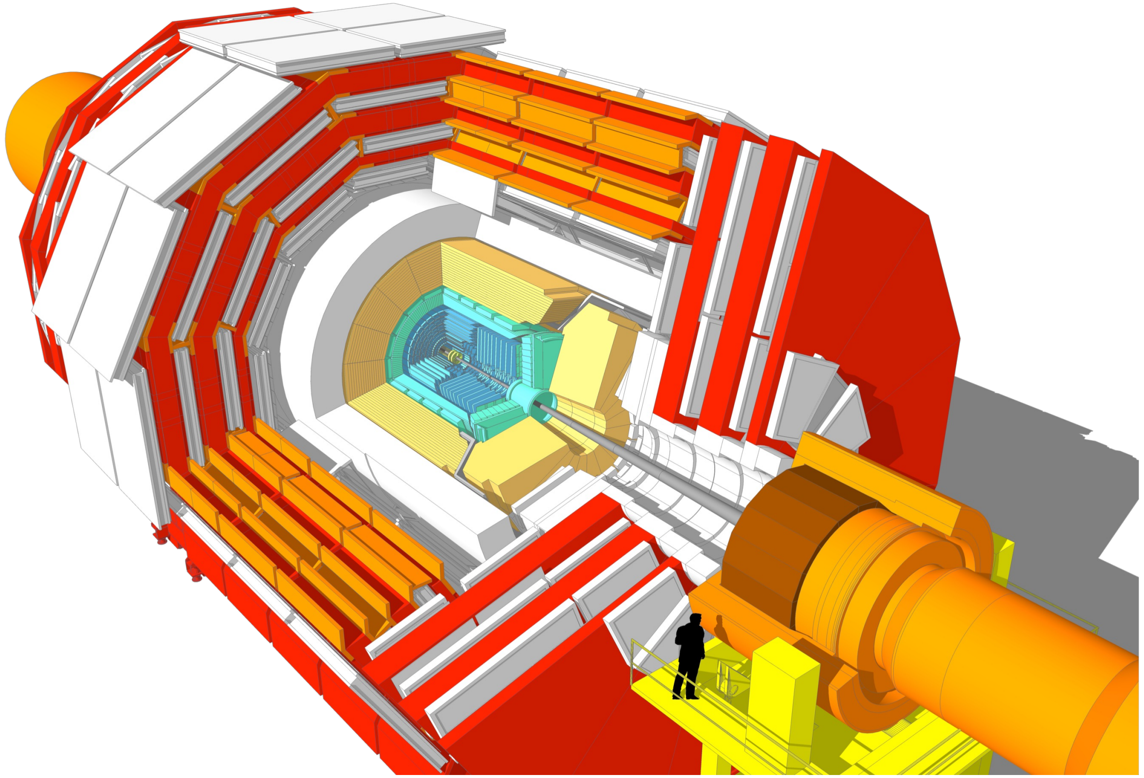


The LHC was built to investigate physics at the TeV scale

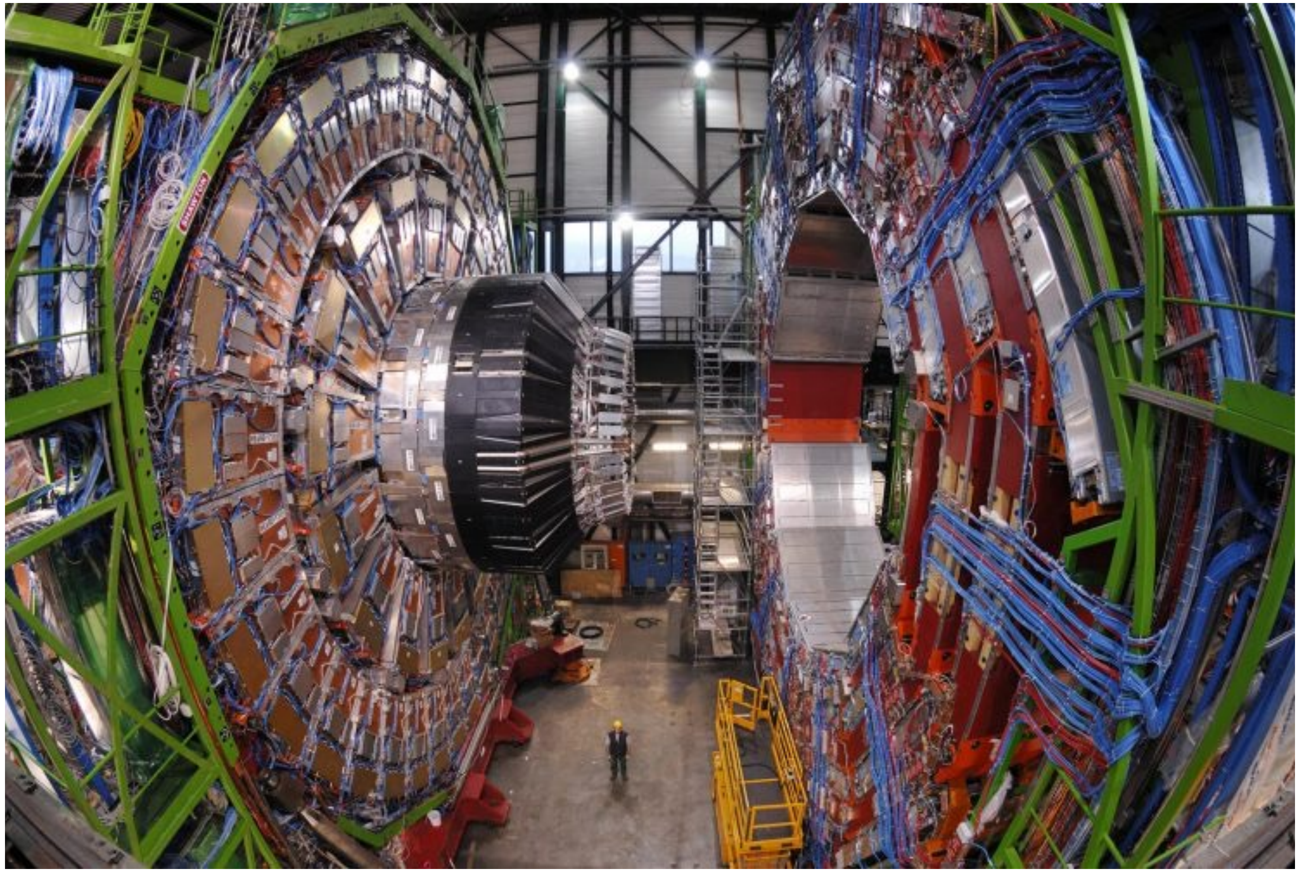
CMS Technical Design Report 2006

The prime goals of CMS are to explore physics at the TeV scale and to study the mechanism of **electroweak symmetry breaking**—through the **discovery of the Higgs particle** or otherwise. To carry out this task, CMS must be prepared to search for **new particles**, such as the Higgs boson or **supersymmetric partners** of the Standard Model particles, from the start-up of the LHC since **new physics at the TeV scale may manifest itself with modest data samples of the order of 1 fb^{-1} or less.**

The Compact Muon Solenoid Detector

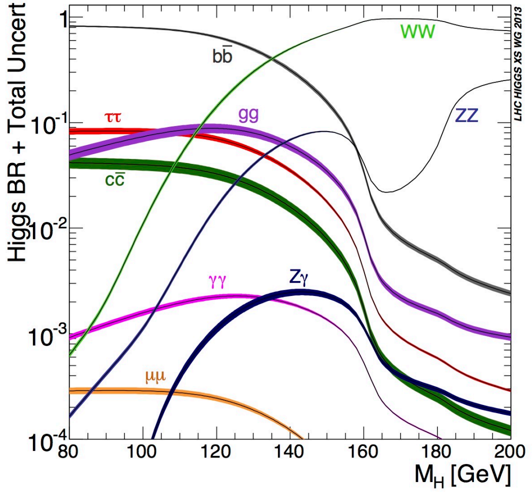


2942	1065	281	229	51
PHYSICISTS (1036 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

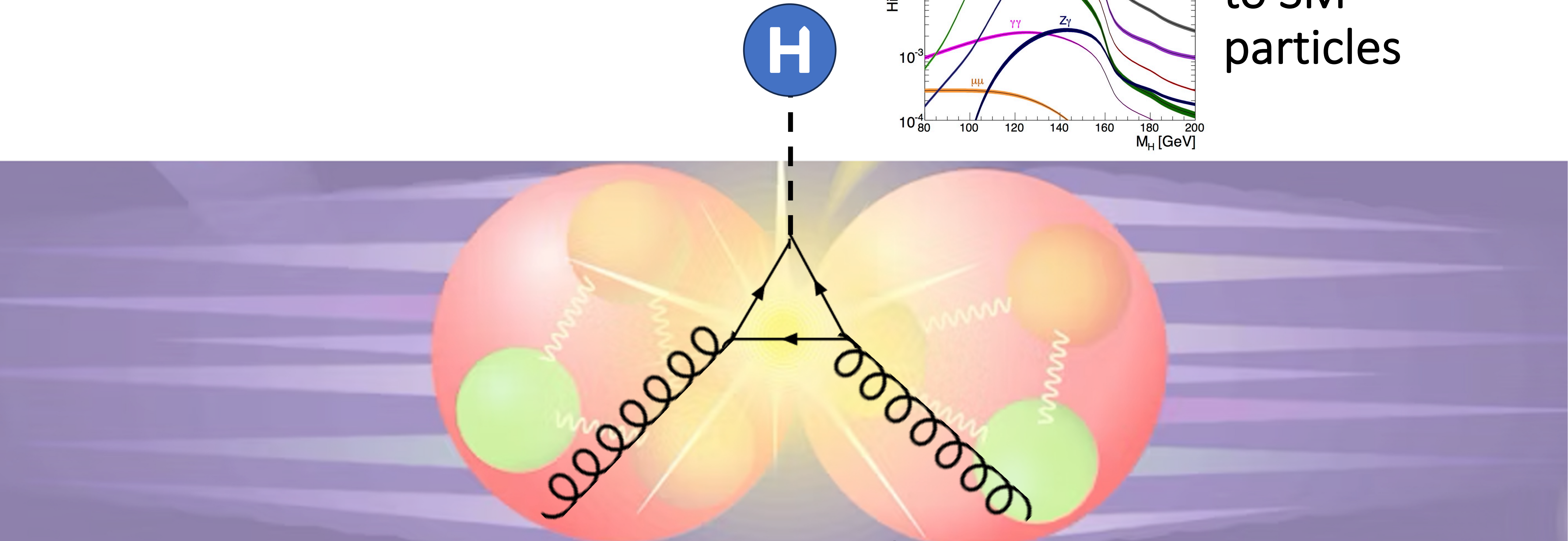


How do we detect these particles?

Higgs boson quickly decays

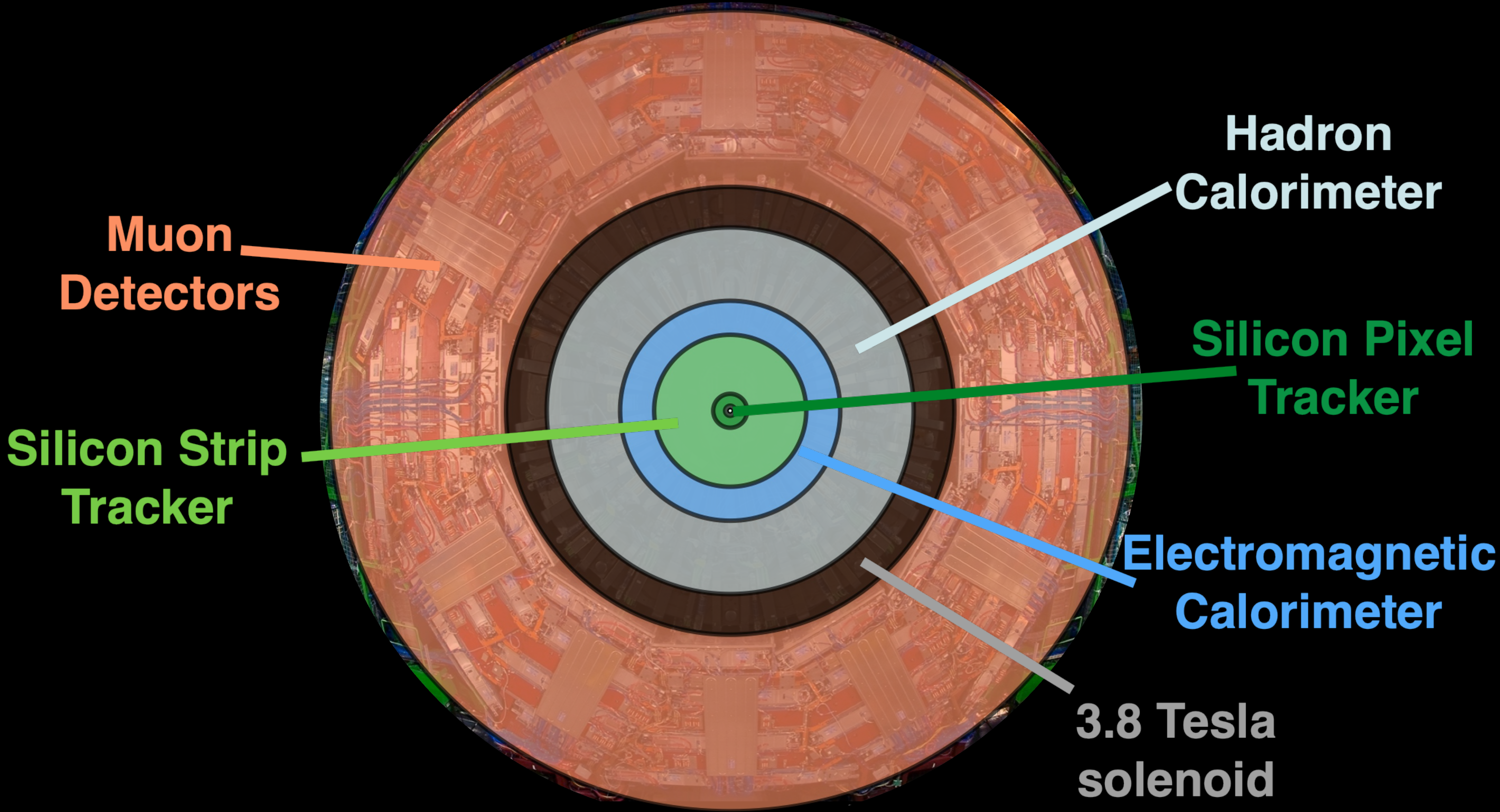


Higgs couples to SM particles



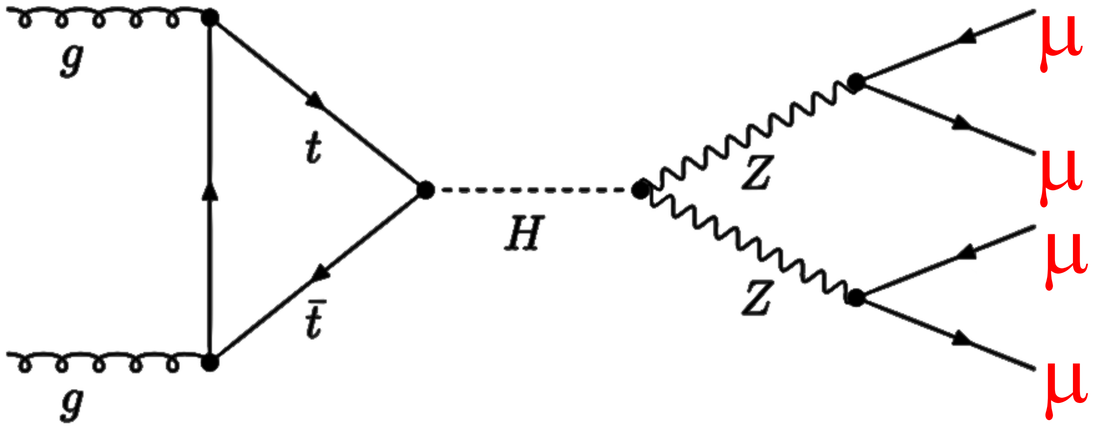
Protons, near the speed of light, collide

Compact Muon Solenoid

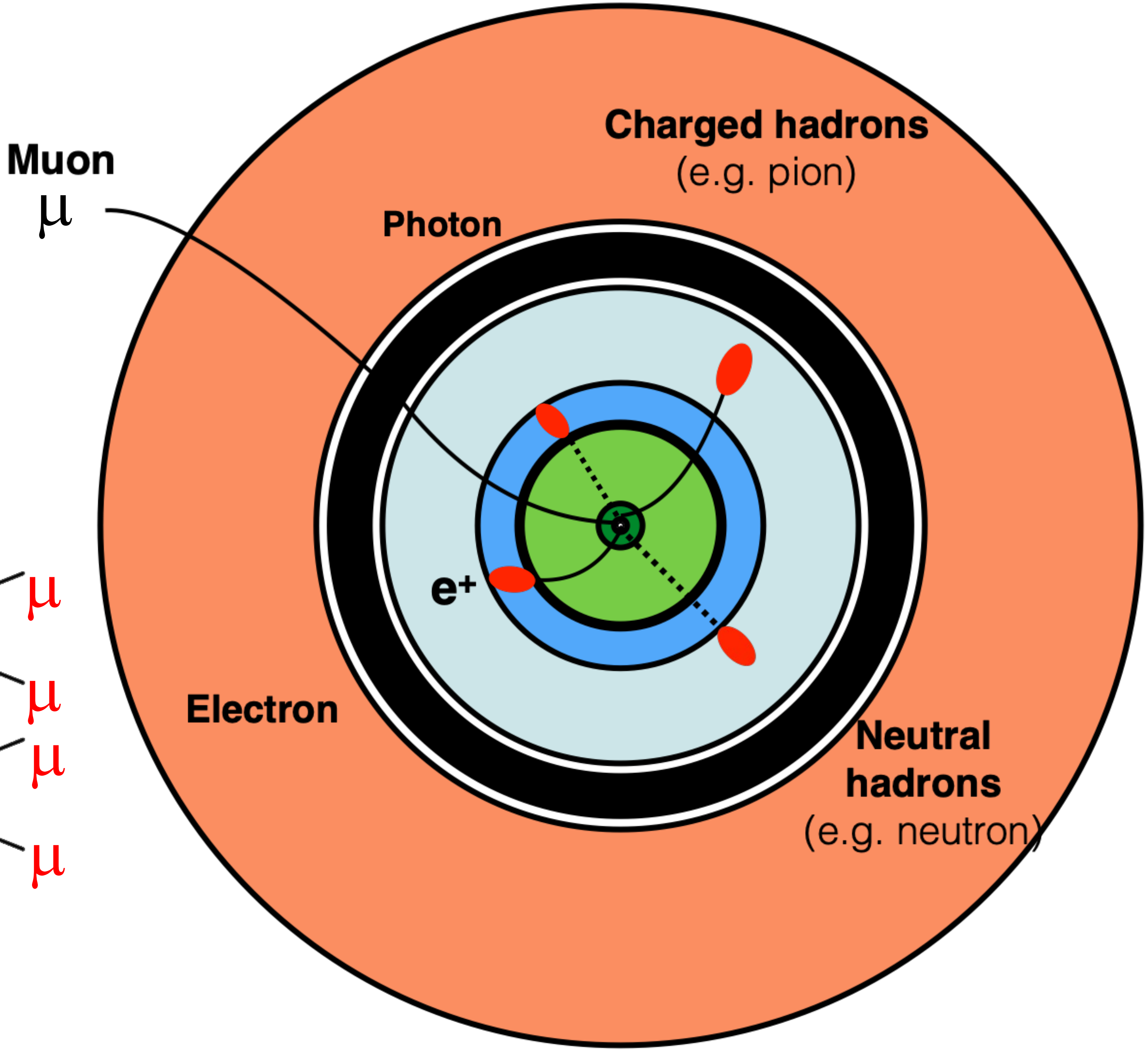


Compact Muon Solenoid

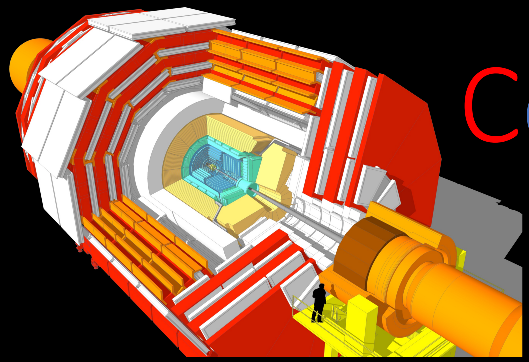
Typical analyses: build picture from ~5 types of promptly produced SM particles

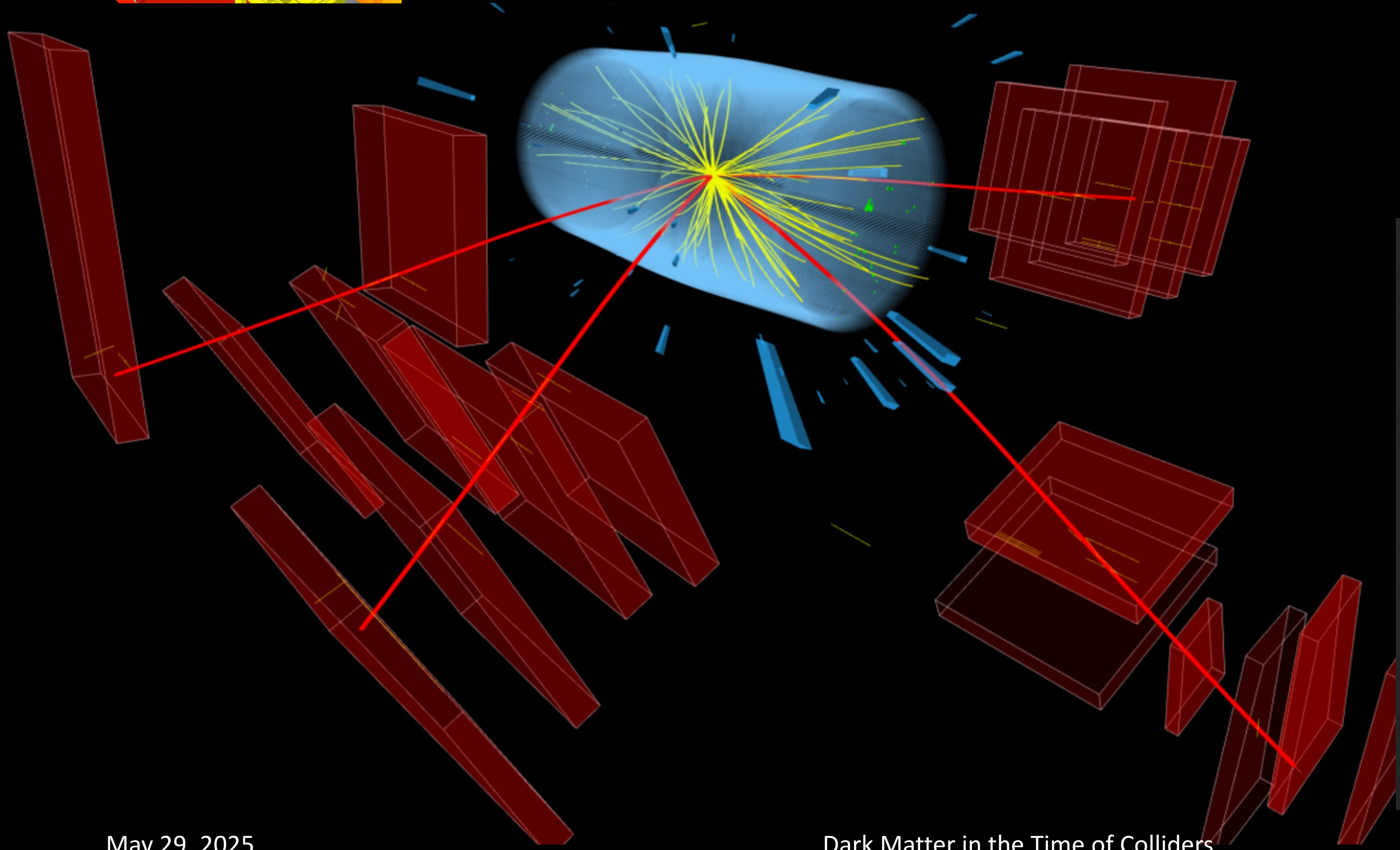


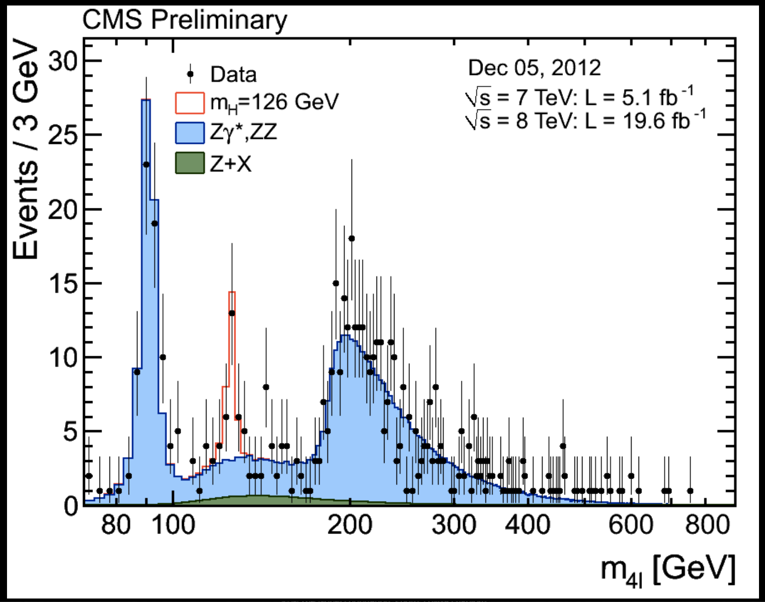
Compact μ Solenoid

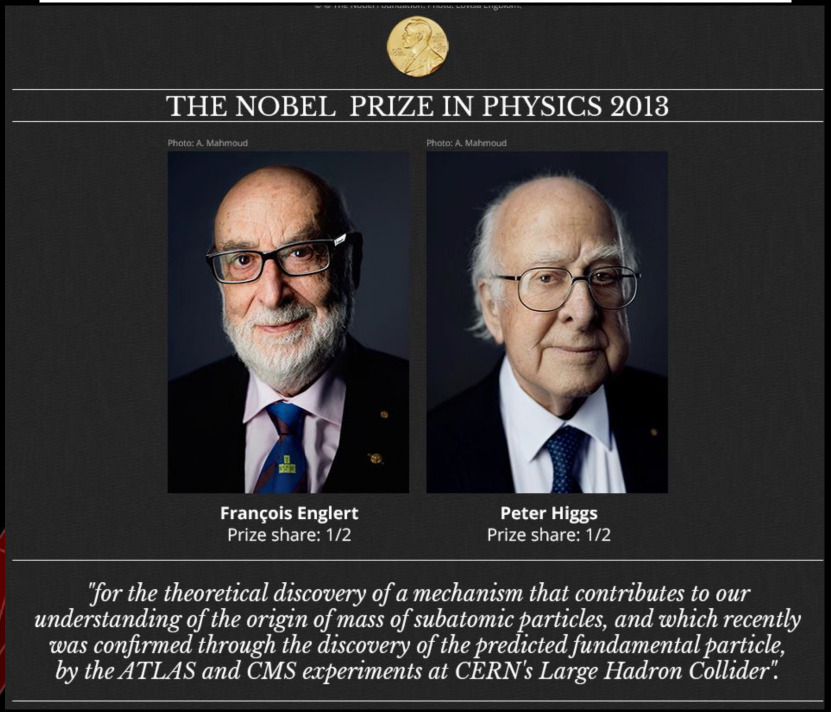


Compact Muon Solenoid









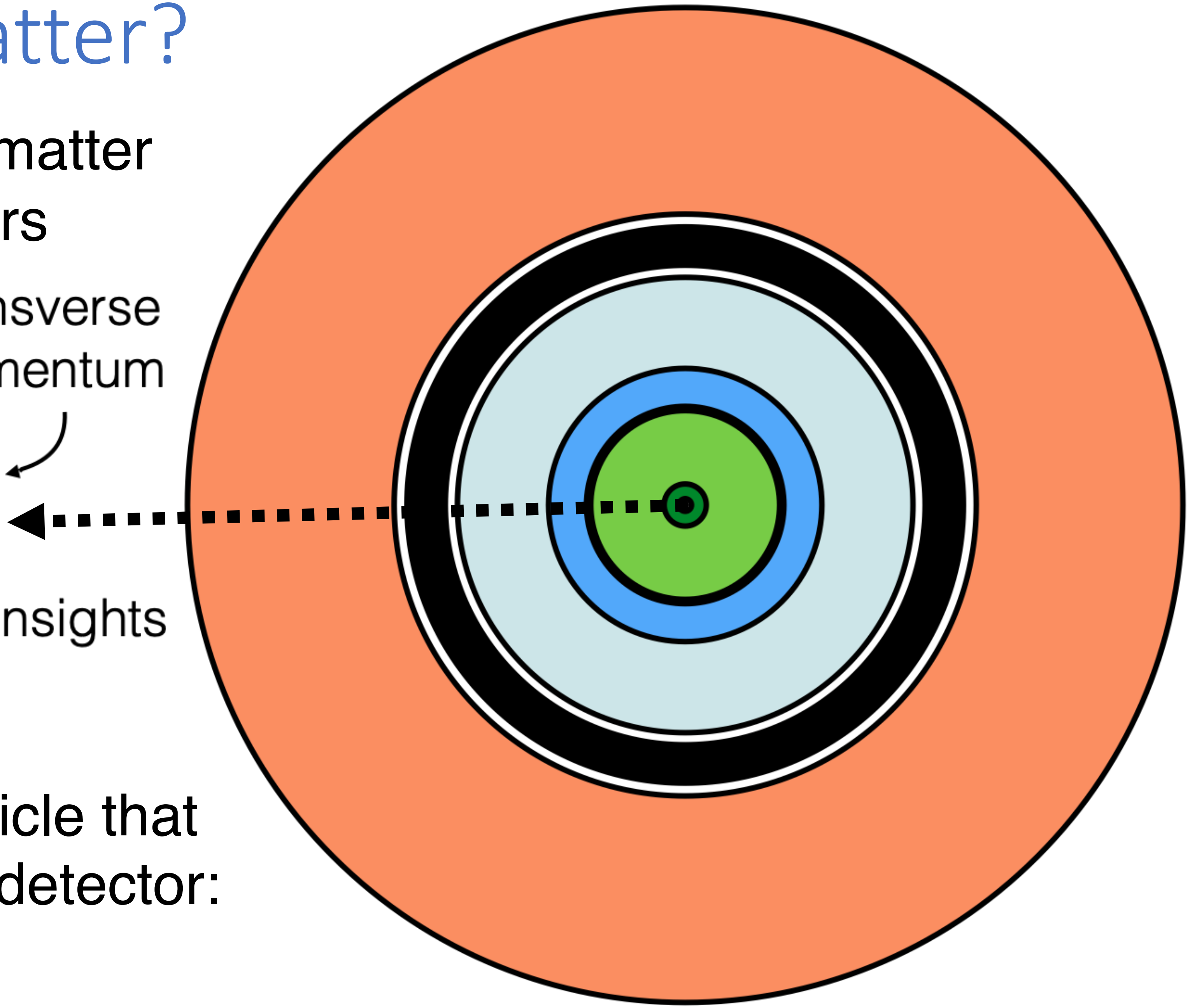
What about Dark Matter?

Interacts very weekly with matter
→ goes unseen by detectors

Transverse momentum

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

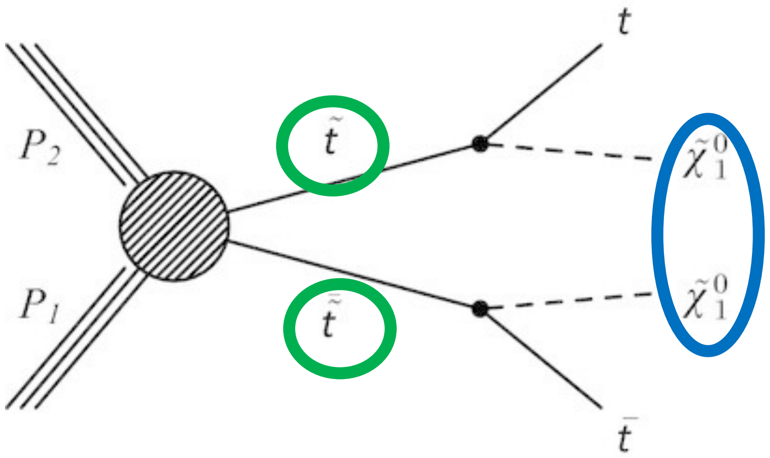
Momentum imbalance provides insights into invisible particles



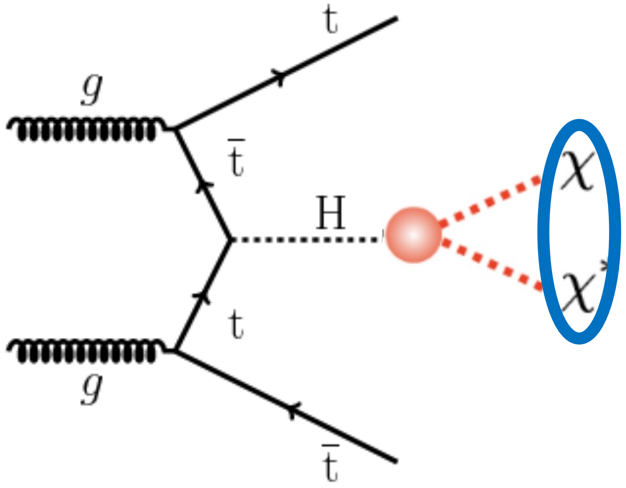
$\vec{p}_T^{miss}$ Could be any particle that is not seen in the detector: neutrinos, DM, …

Looked for Dark Matter using large $\vec{p}_T^{miss}$

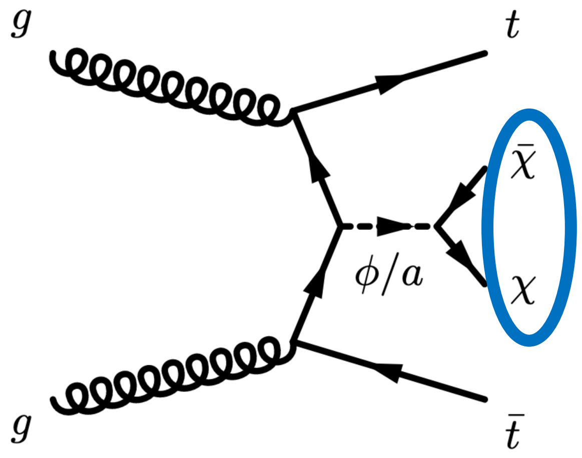
Produced via SUSY



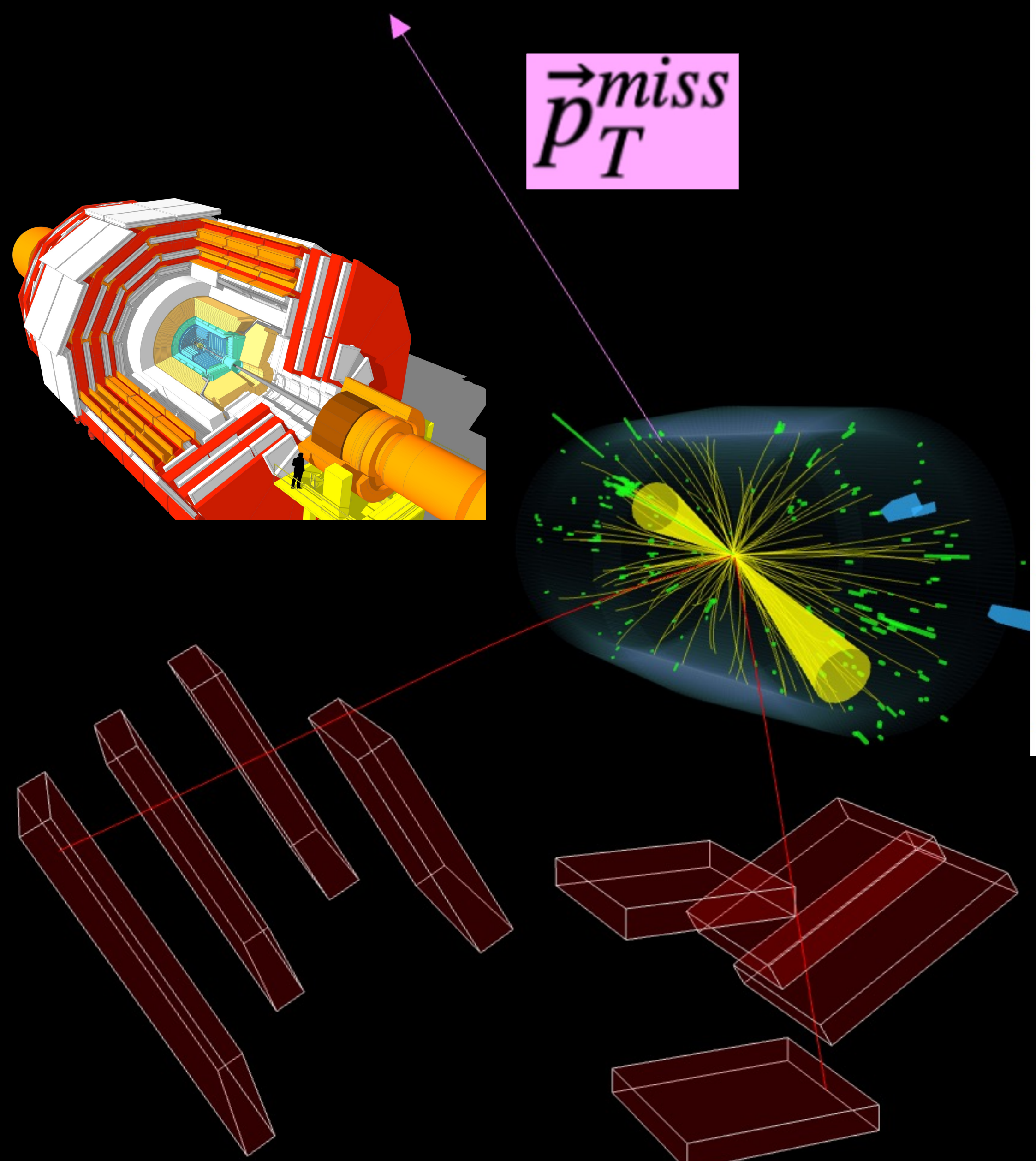
Coupling to the Higgs



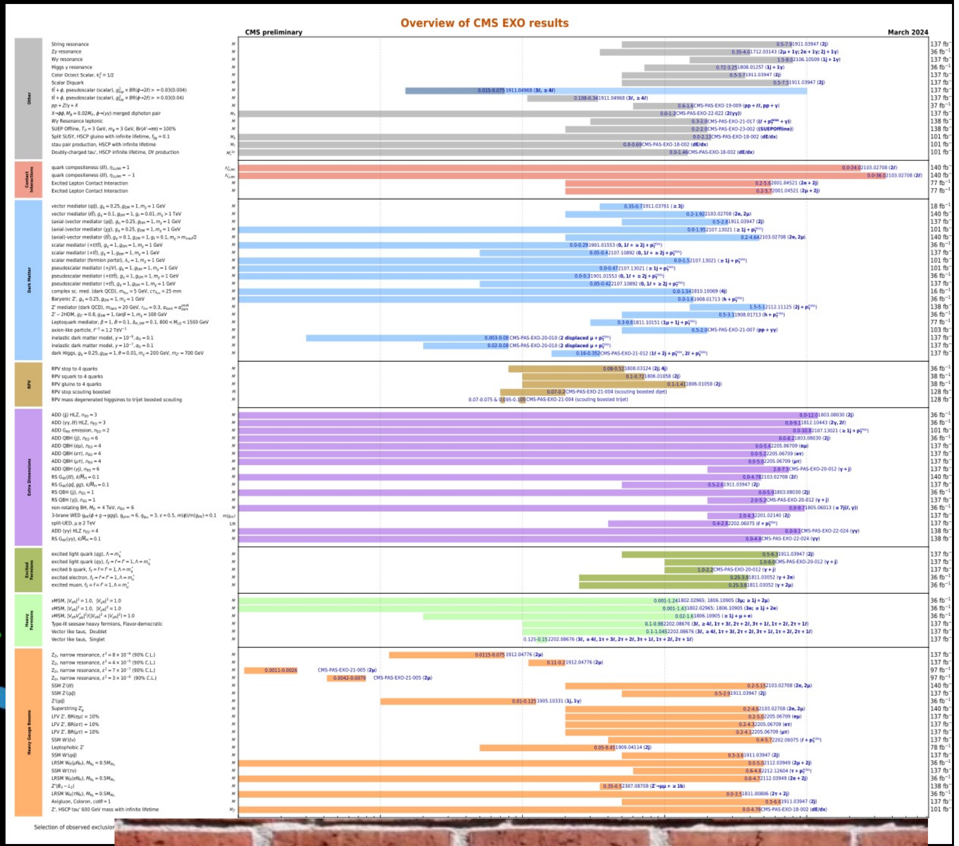
Simplified DM models



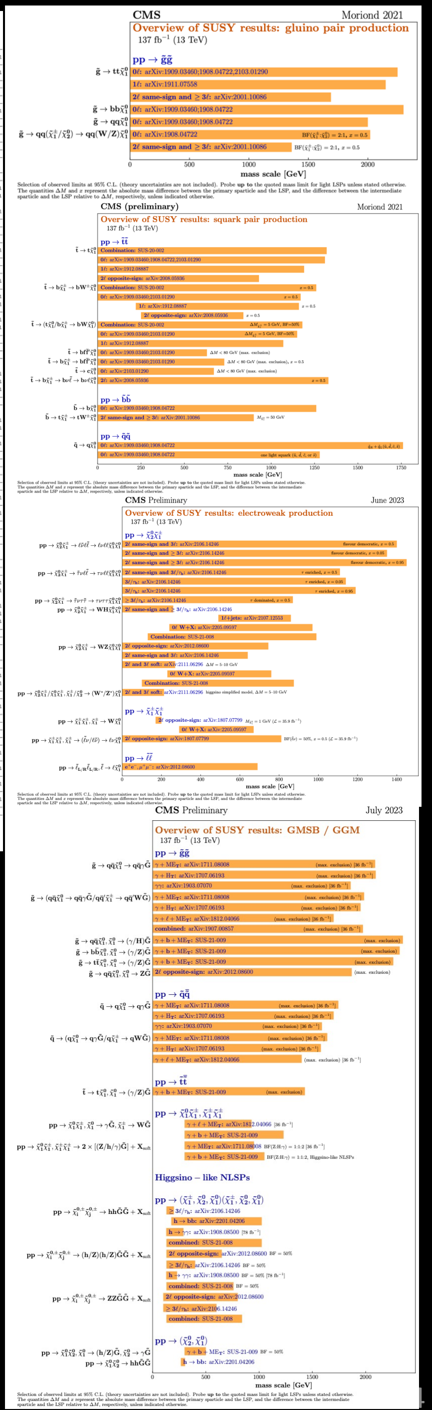
Only some examples



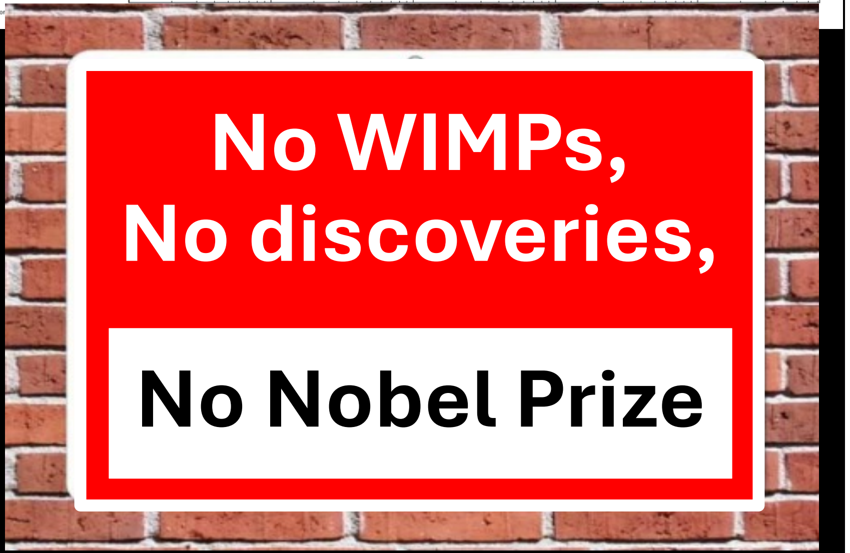
$\vec{p}_T^{miss}$



Overview of CMS EXO results
CMS preliminary
March 2024



CMS
Moriond 2021
Overview of SUSY results: gluino pair production
CMS (preliminary)
Moriond 2021
Overview of SUSY results: squark pair production
CMS Preliminary
June 2023
Overview of SUSY results: electroweak production
CMS Preliminary
July 2023
Overview of SUSY results: GMSB / GGM



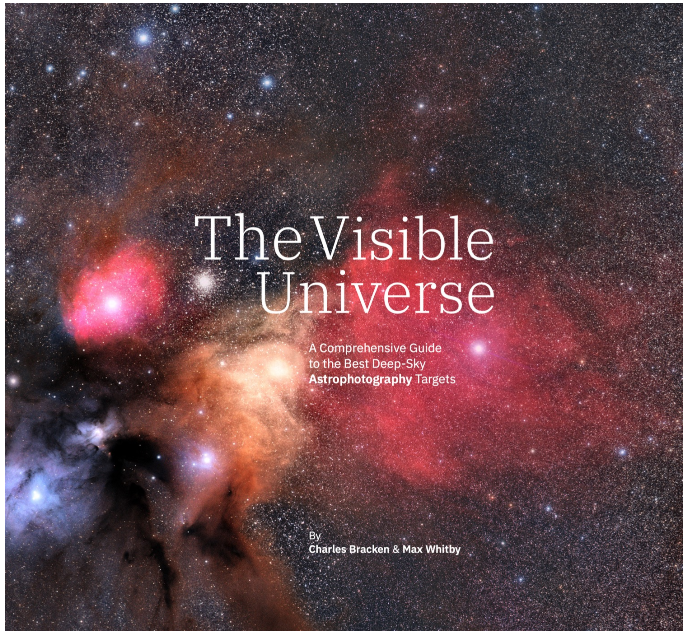
No WIMPs,
No discoveries,
No Nobel Prize

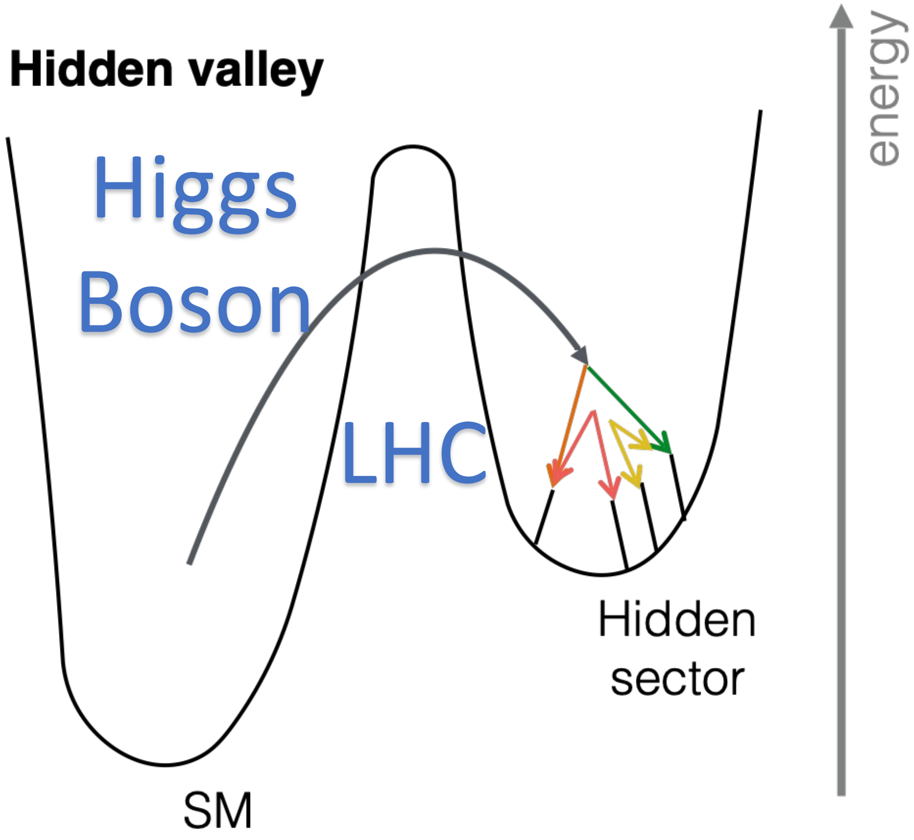
What did we miss?

- Looking for heavy particles
  - Higgs, WIMPS, Supersymmetry, …
- What about light new particles?
- Quickly Decay to SM particles
  - Energy deposits in each sub-detector help us reconstruct the collision
- What about particles that travel through the detector before decaying?
- We have looked everywhere
  - But we can only look in the data that we store
- But can we store more?

Back to the basics

- What composition of DM is more complex?
  - dark matter could be part of a **“hidden” universe** with **no SM gauge interactions**





M. Strassler

Why Haven't we seen them yet?

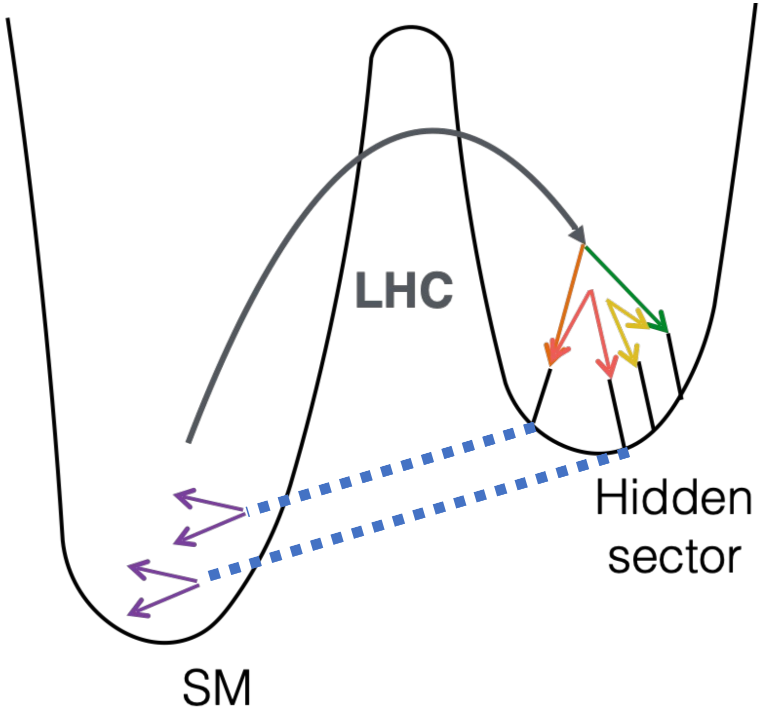
- Dark sector particles decay back to standard model "suppressed" by heavy mediator →light long-lived particles

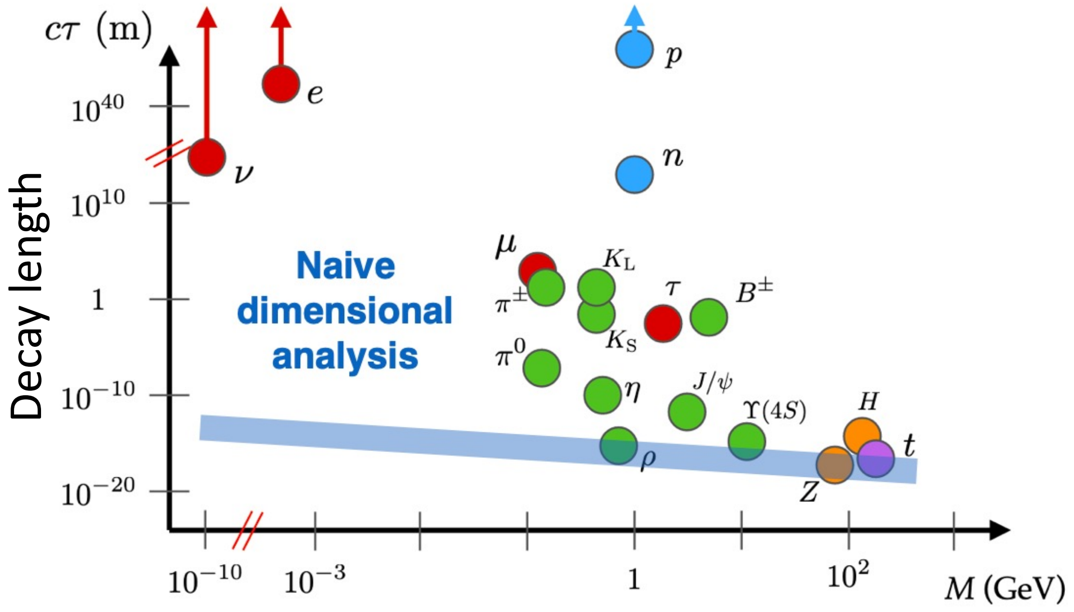
$$\Gamma \propto \frac{g^2}{8\pi}\left(\frac{m_{\mathrm{LLP}}}{m_{\mathrm{mediator}}}\right)^n m_{\mathrm{LLP}}$$

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

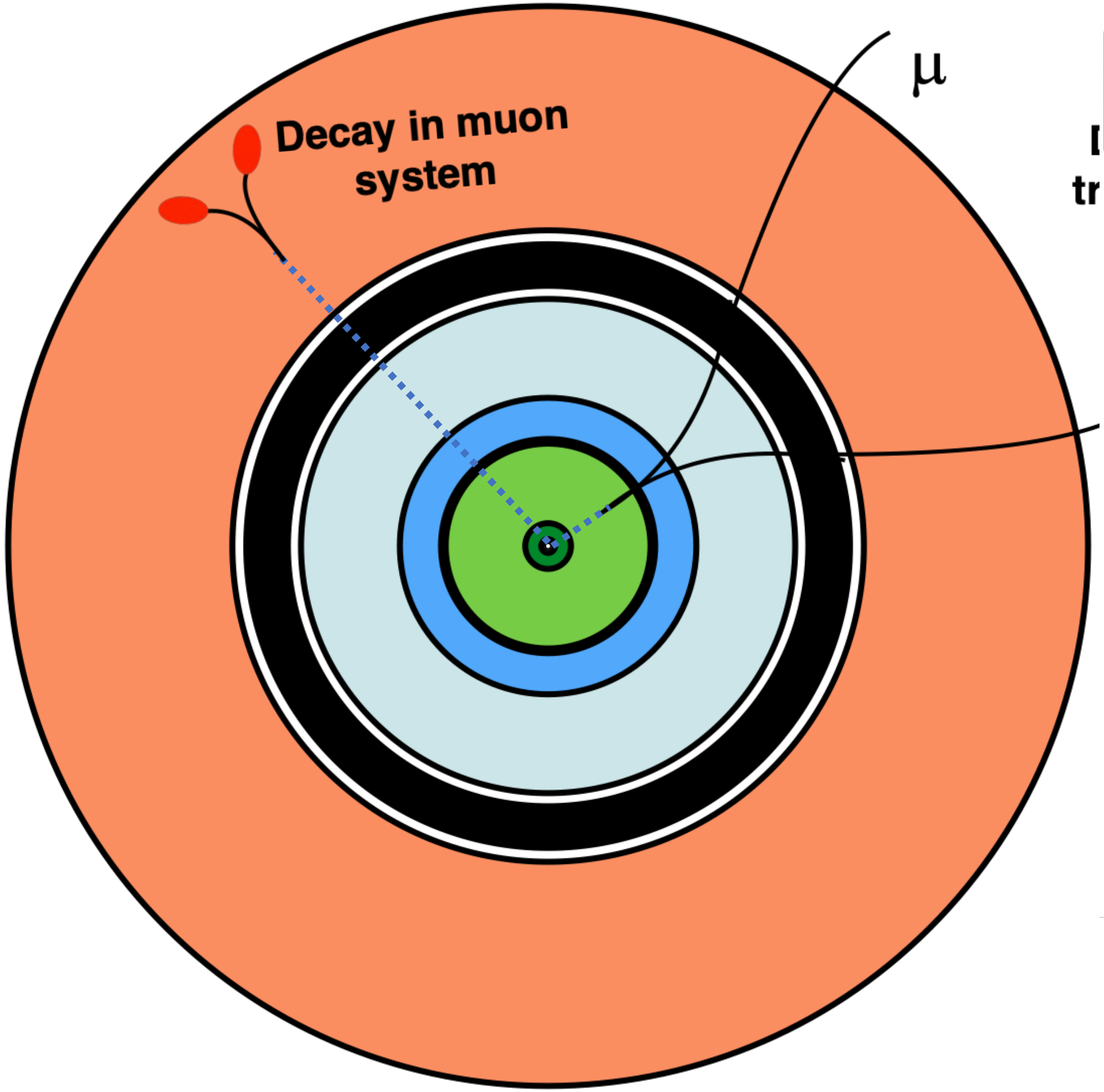
~0.1 GeV

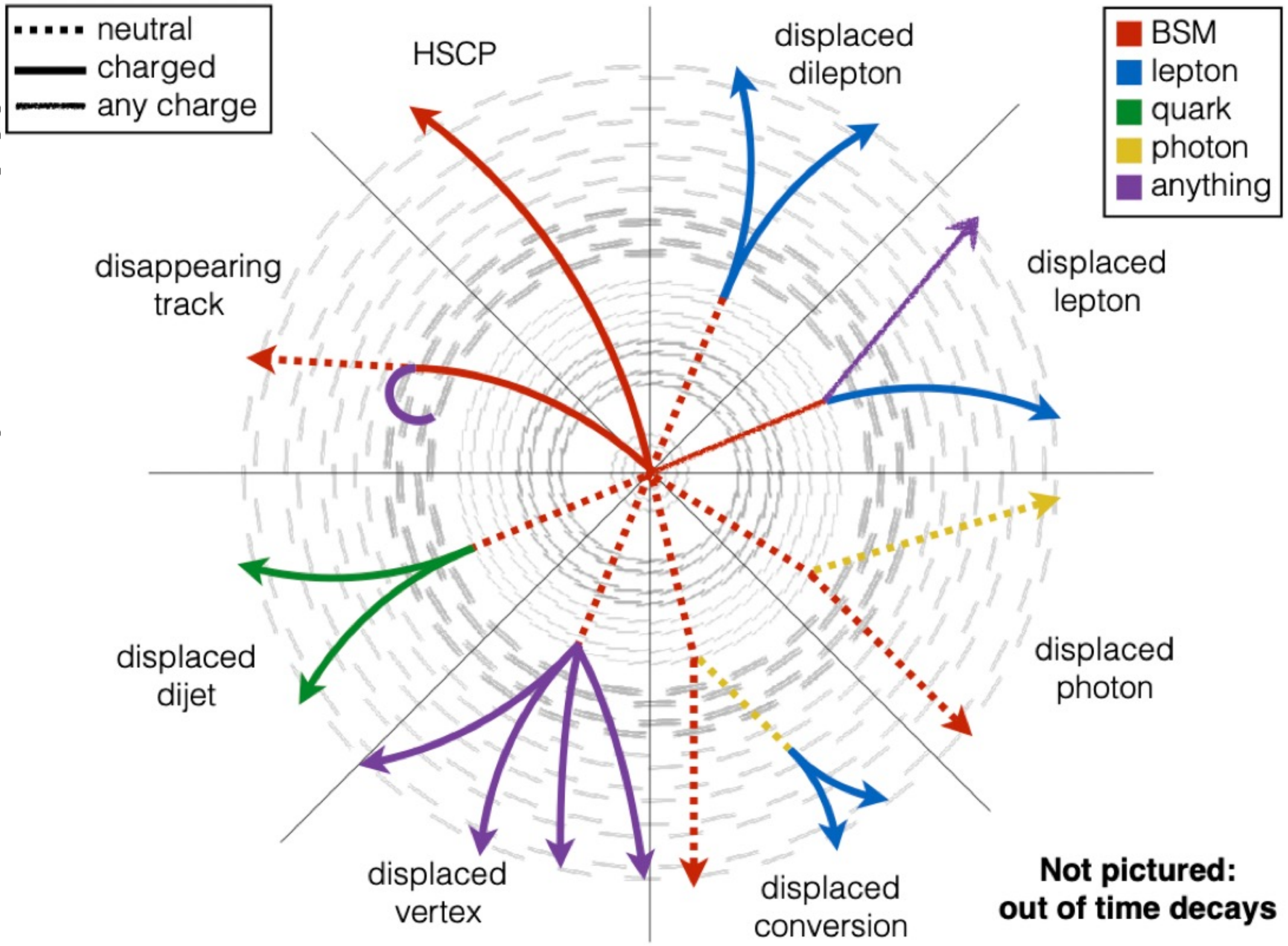
~80 GeV





Signatures that may escape detection





Many more like these:
“long-lived” particles

Signatures that may escape detection

A guide to hunting long-lived particles at the LHC arXiv:2212.03883

Simon Knapen[1,2], Steven Lowette[3]

Lore 4.2

You cannot trigger on LLPs, so you always need to use MET or an associated hard lepton etc.

False

Lore 3.1

The LHC detectors were not equipped for LLP detection.

False

Lore 5.1

LLP searches are background free.

False

Rethink

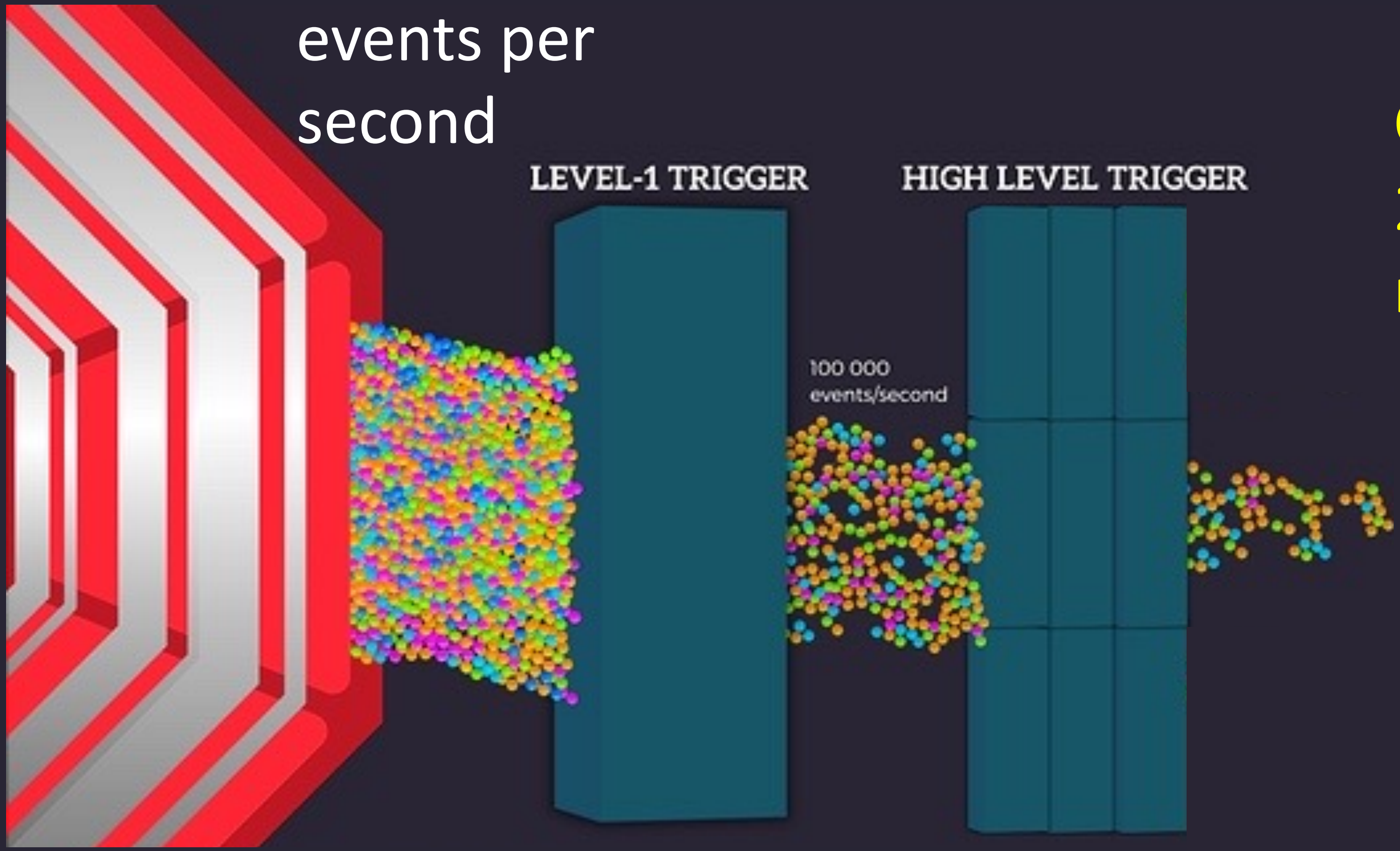
Triggering

Reconstruction

Analysis tools & methods

Smart data filters

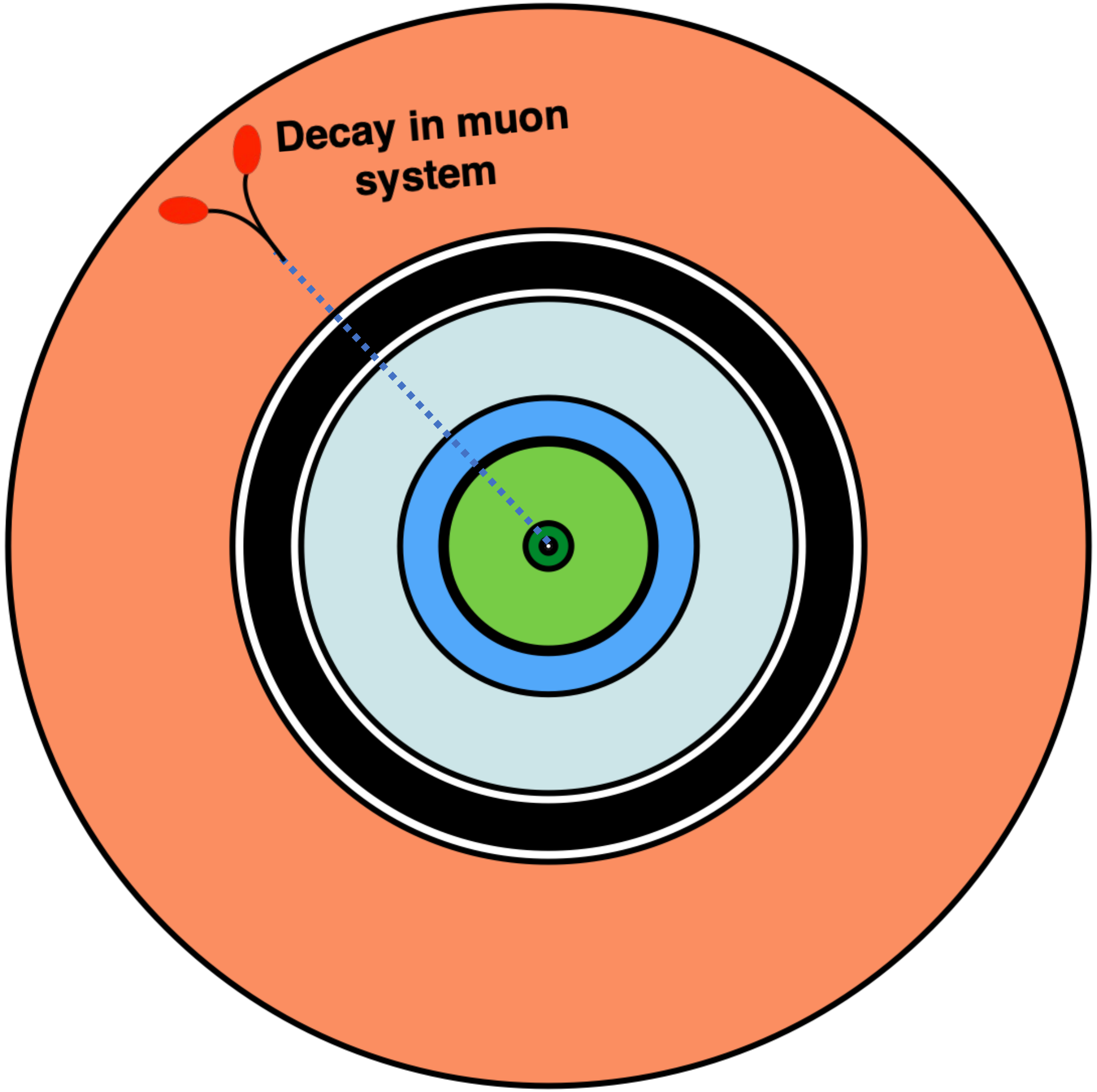
40,000,000 events per second

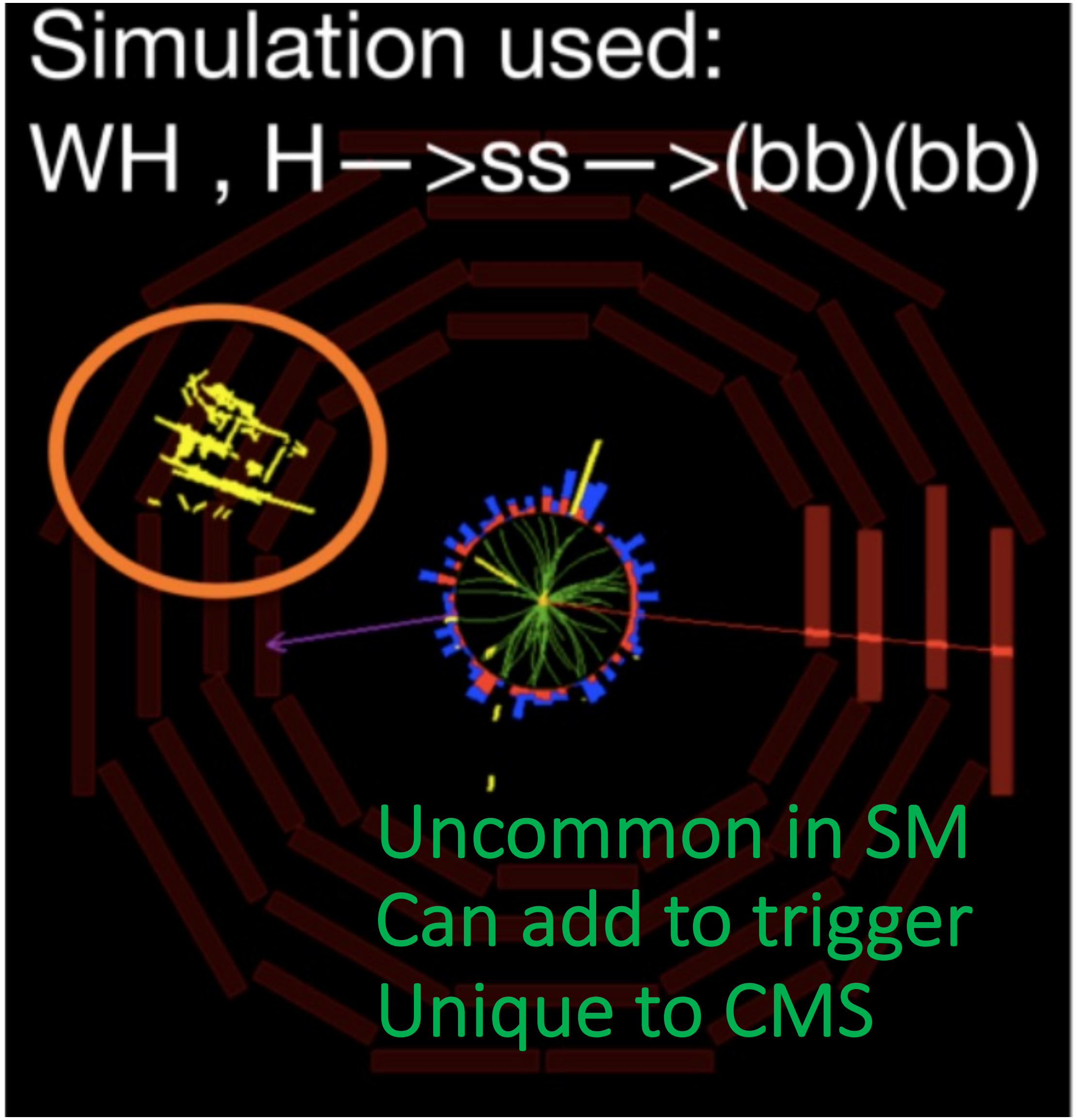


Collisions happening every 25 ns, so these decisions must happen fast

Can only store and reconstruct 1/40,000 event

Rethinking triggers

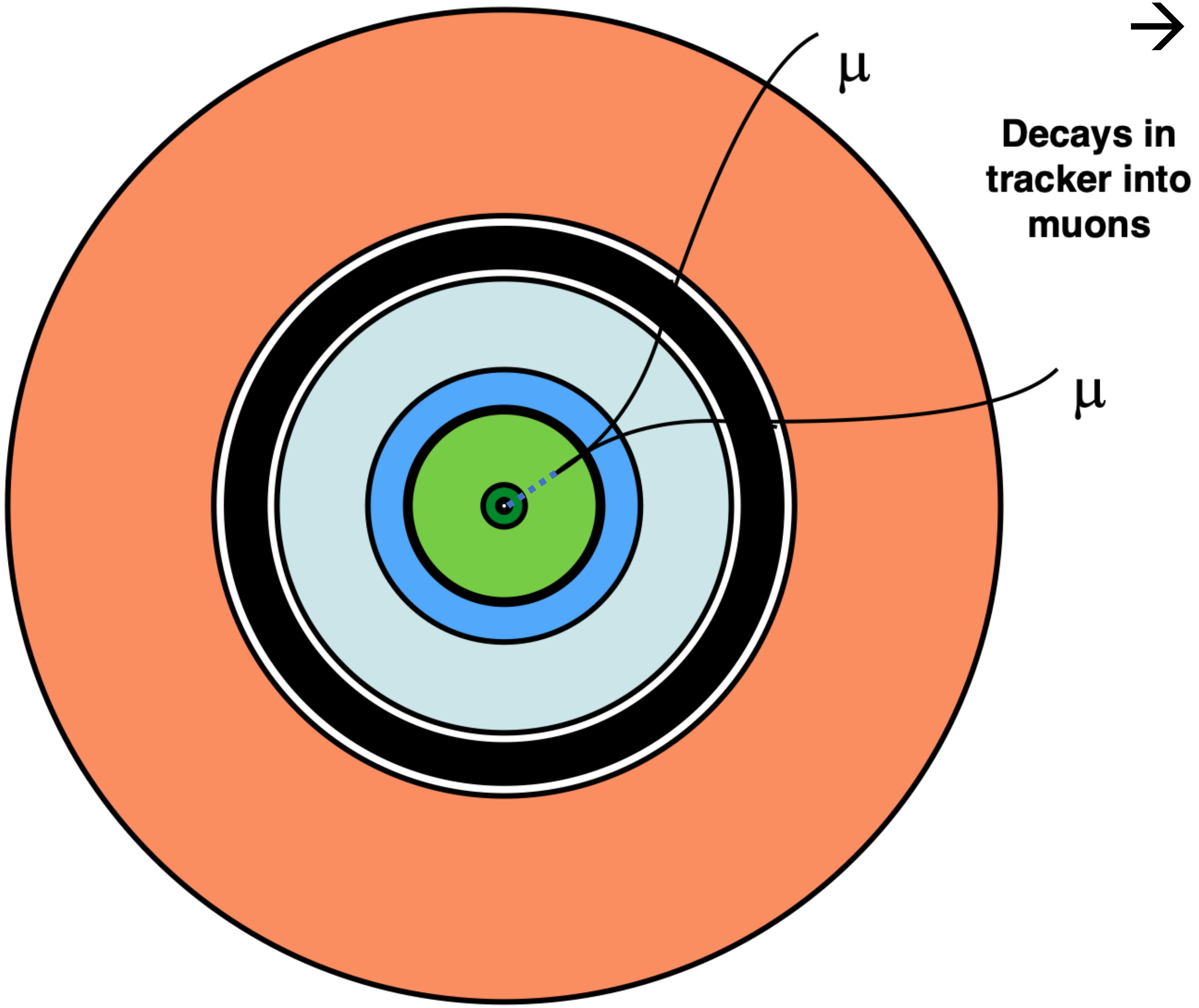


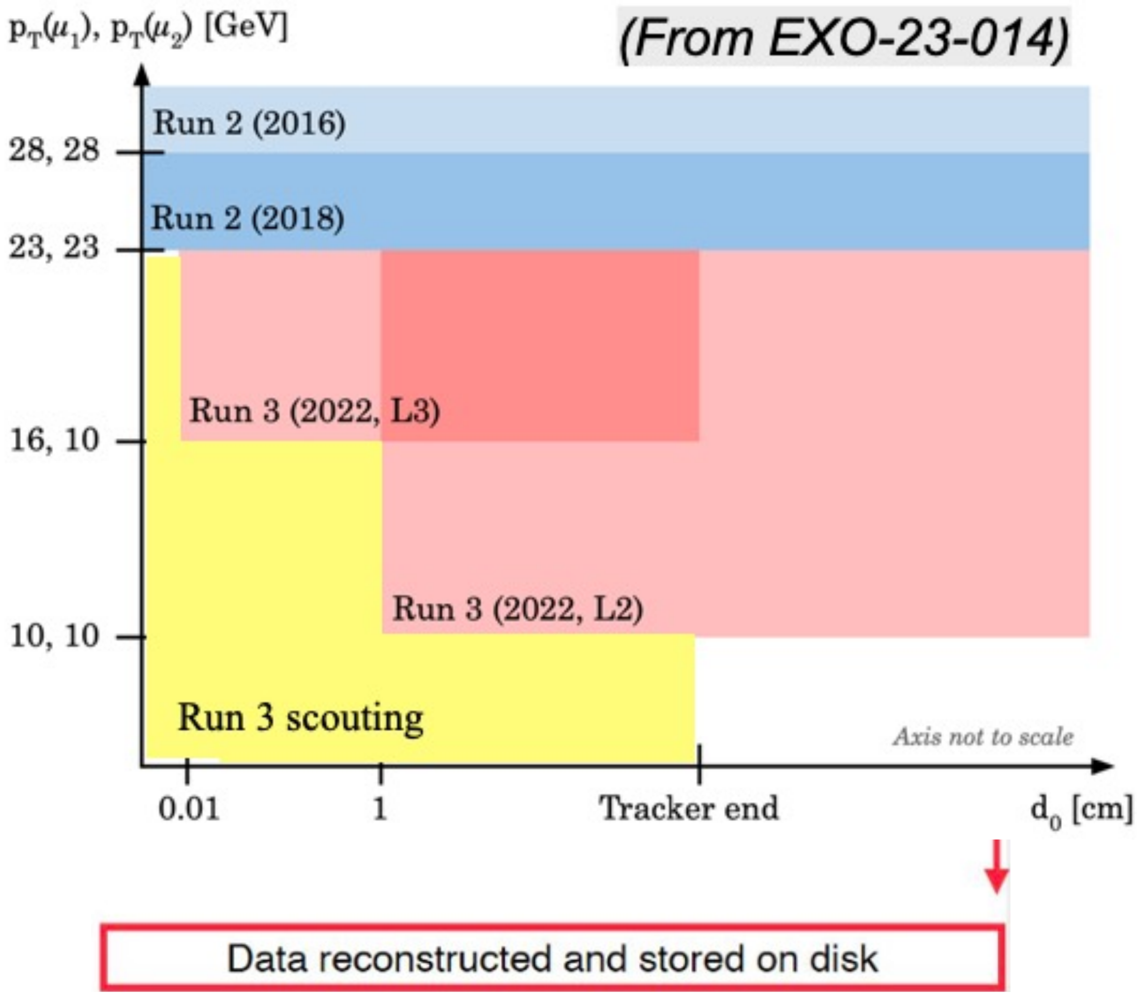


Uncommon in SM
Can add to trigger
Unique to CMS

Rethinking triggers

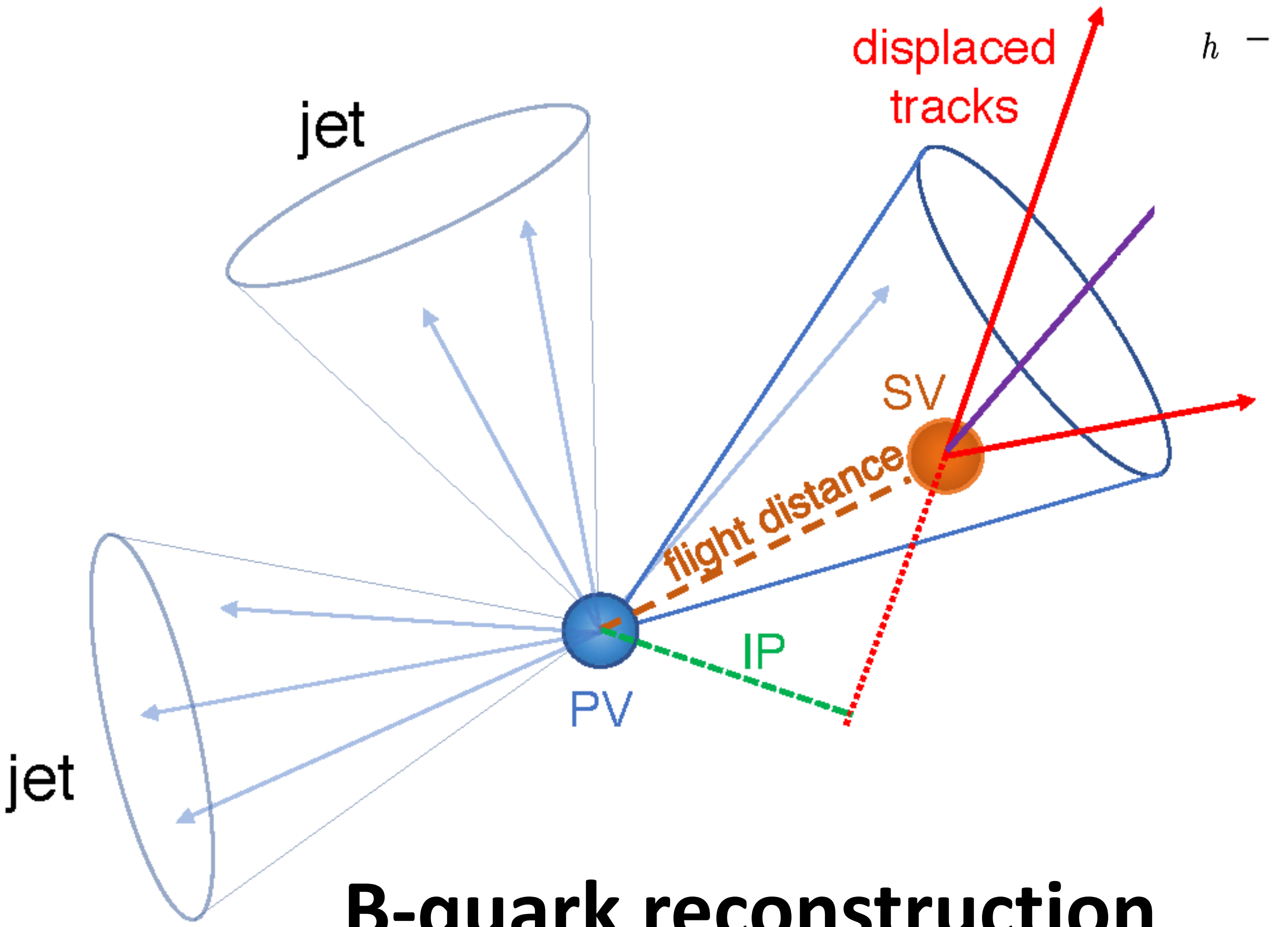
- Challenging when muons are low-pT
  → new methods of triggering needed



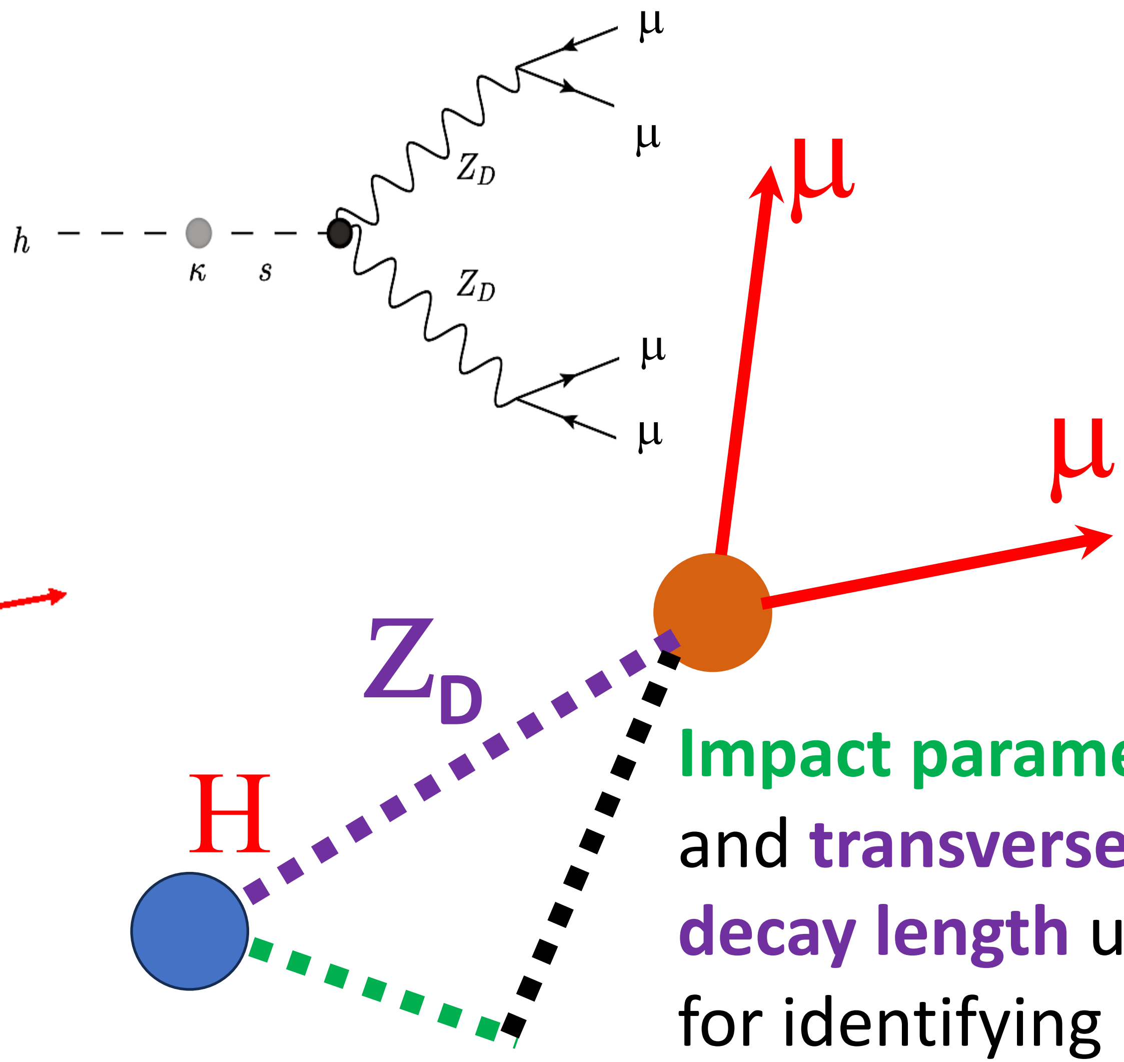


How do we reconstruct these particles?

- Reconstructing long-lived particles



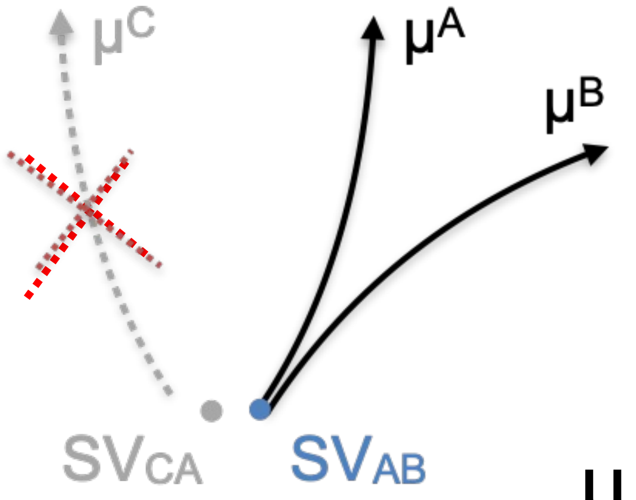
B-quark reconstruction

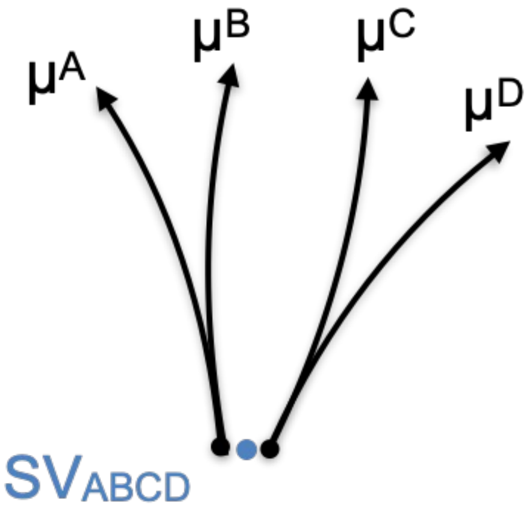


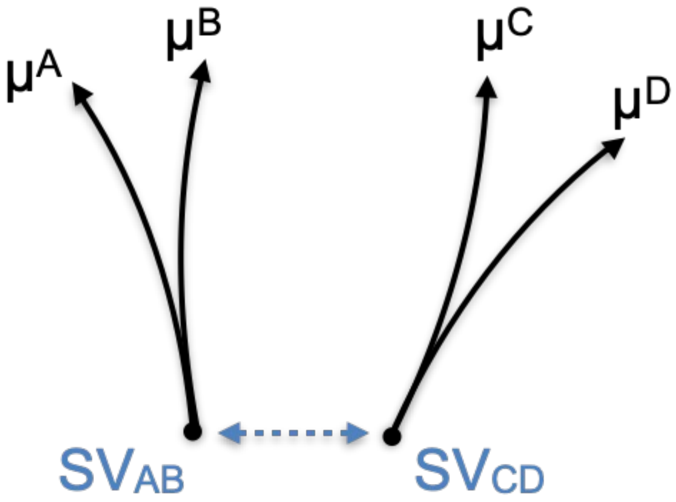
Impact parameter and **transverse decay length** useful for identifying displaced particles

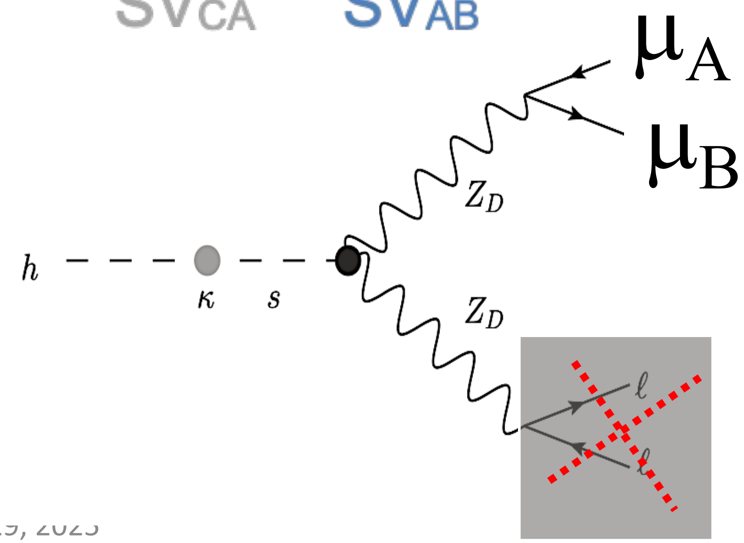
Uncovered parameter space → Generic Search

- **Signature-based analysis:** soft displaced dimuons from a displaced secondary vertex (SV)

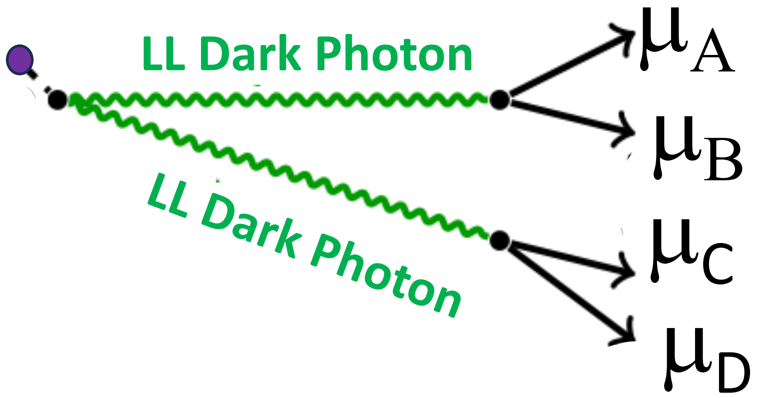






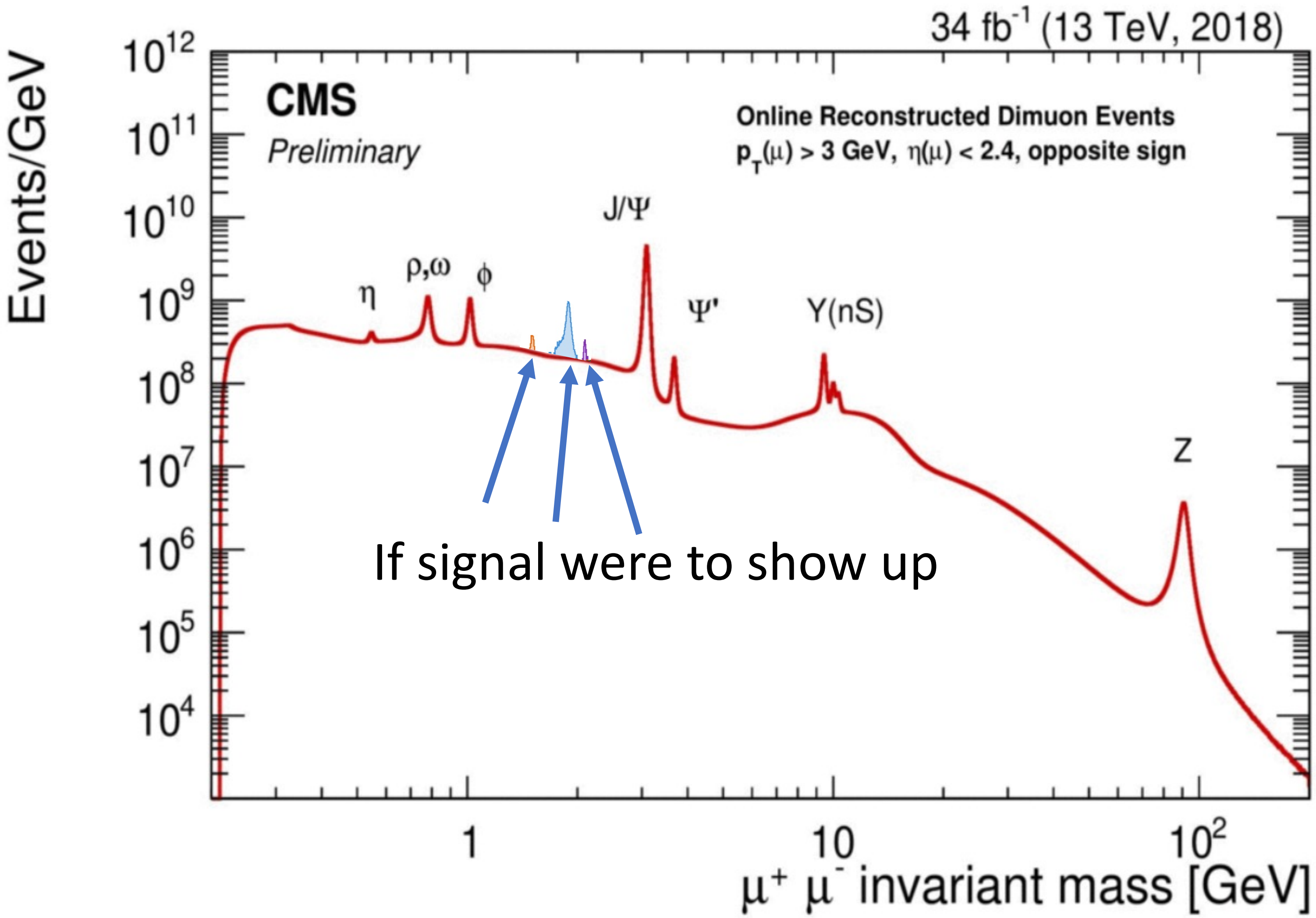


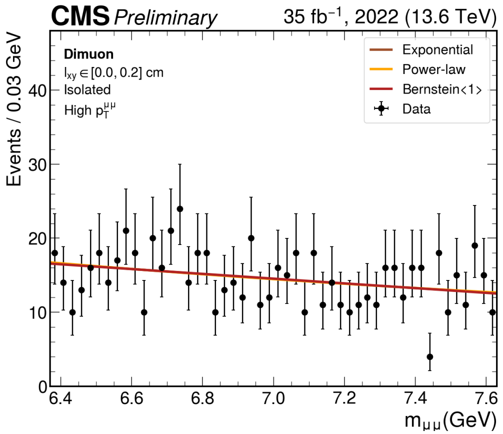
Dark pion produced in Higgs decay

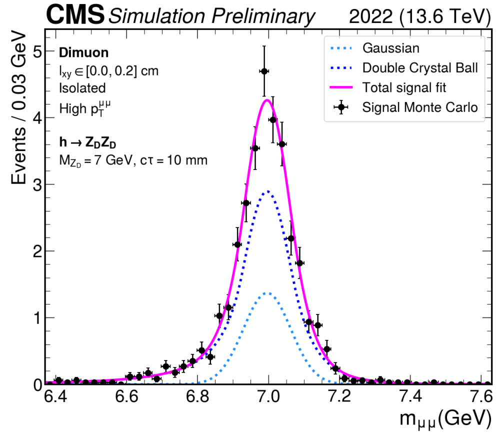


Analysis strategy: look for a bump

Look for a resonant peak in di-/four-muon invariant mass distribution



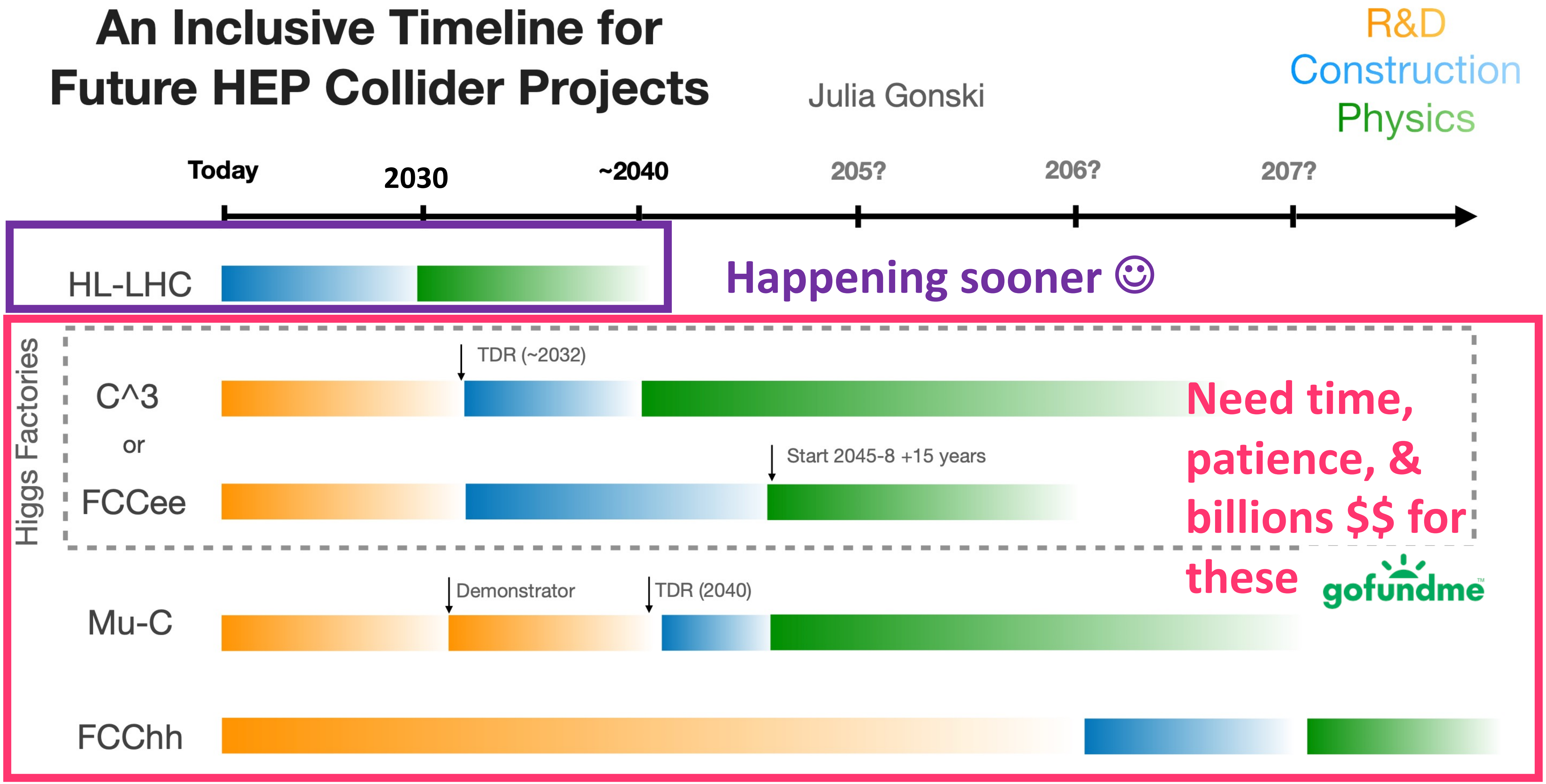




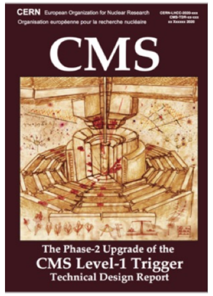
Where we are now

- We have only analyzed 2022 + 2023 data & preparing for one of the first publications using Run 3 data
  - We have extended our sensitives to low mass and high displacement
  - Even improved sensitivity to dimuon masses above 10 GeV where typically one uses standard triggers & full reconstruction
  - Continuing this search with Full Run 3 data (2024 – 2026)
- These developments have helped us expand the scientific output of CMS
- Non-traditional triggers now developed and used for several efforts, including the search for higgs pair production
- There are many more years of data planned…..

Future Colliders



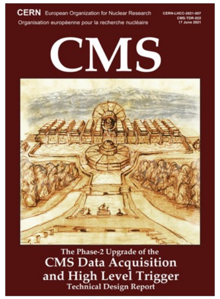
The High Luminosity LHC Upgrade



L1-Trigger

https://cds.cern.ch/record/2714892

- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger

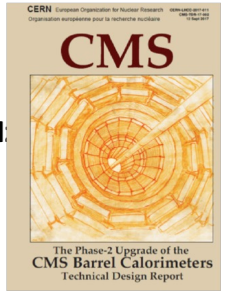
https://cds.cern.ch/record/2759072

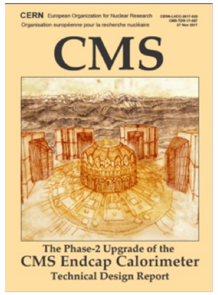
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MH
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

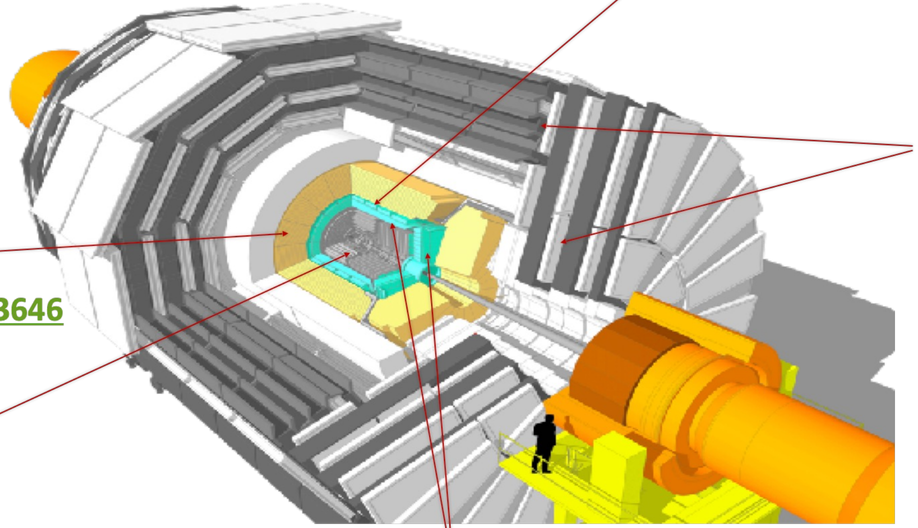




Calorimeter Endcap

https://cds.cern.ch/record/2293646

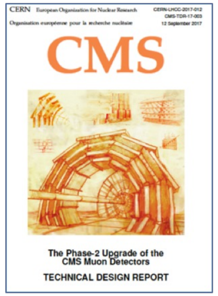
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

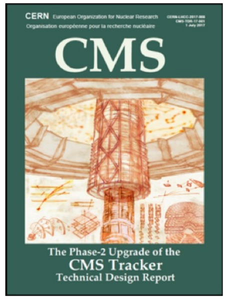


Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

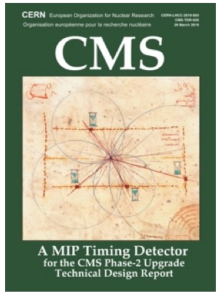




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8



MIP Timing Detector

https://cds.cern.ch/record/2667167

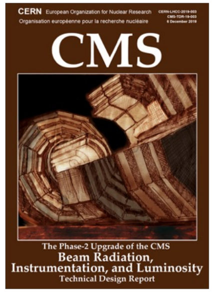
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

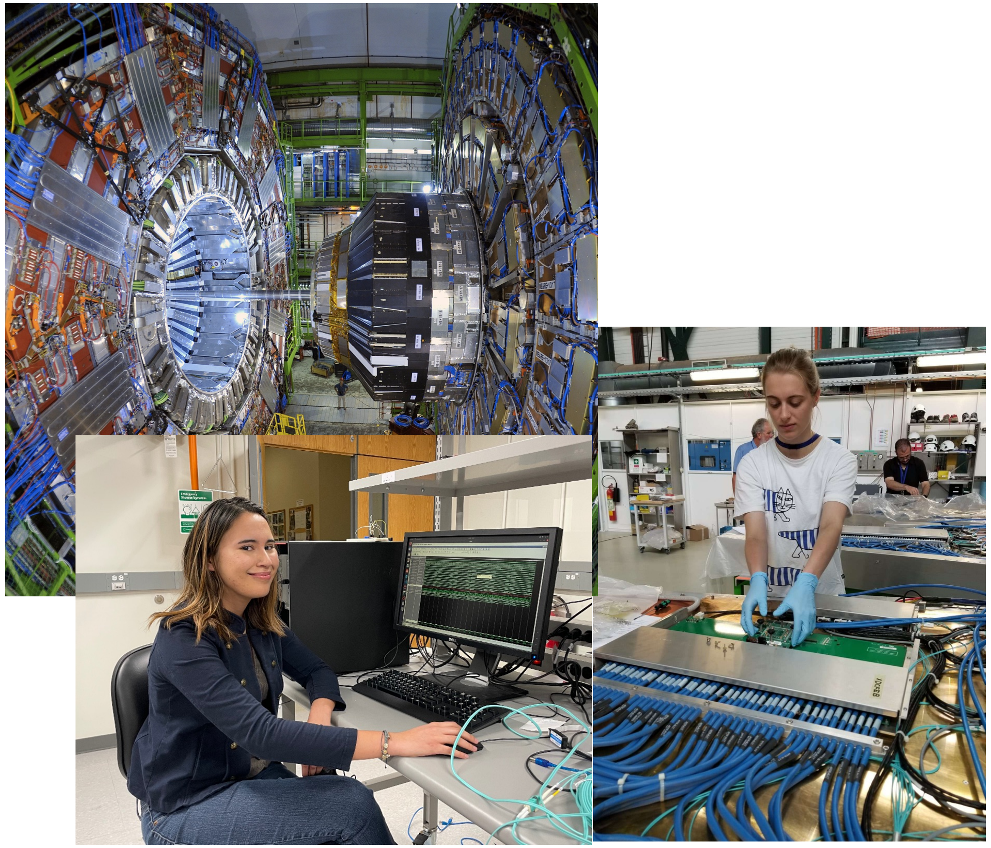
Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

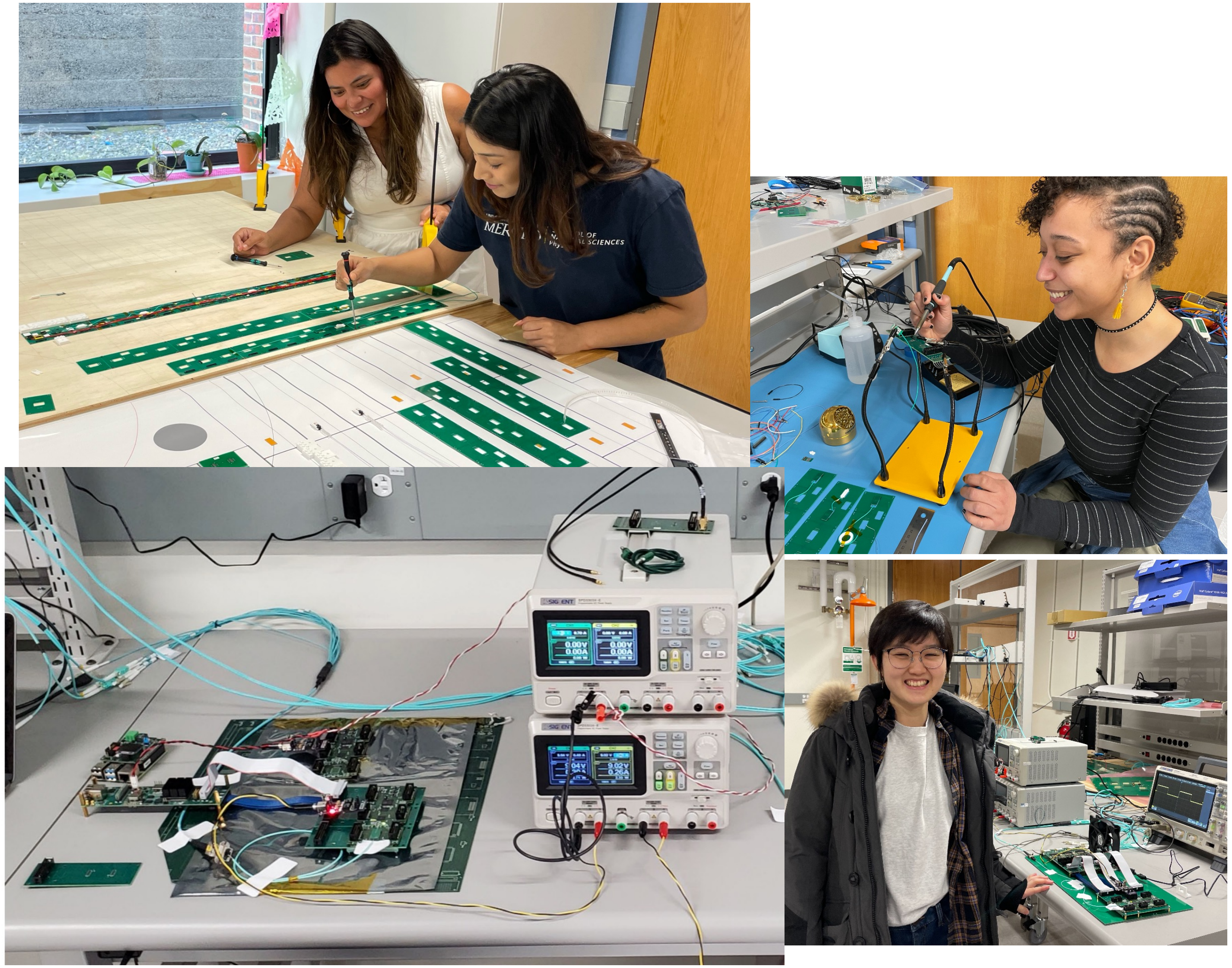
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors



Building detector electronics

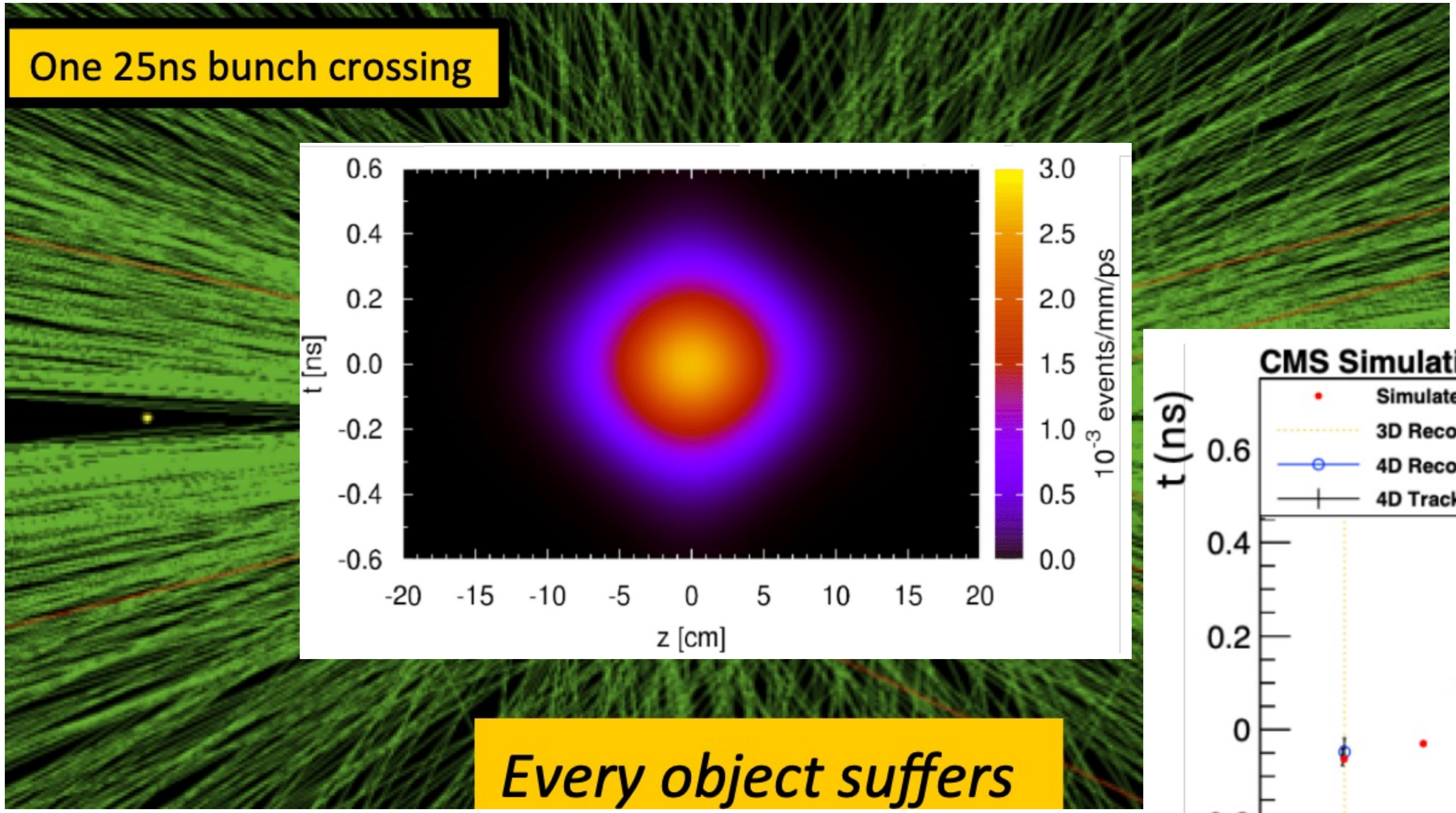


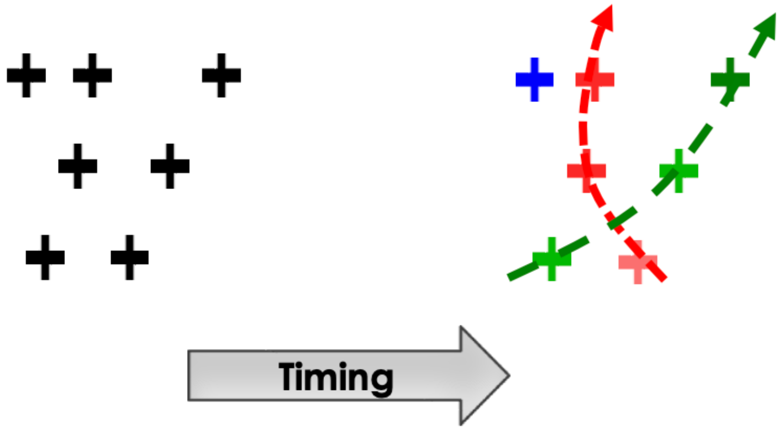
Muon Detectors

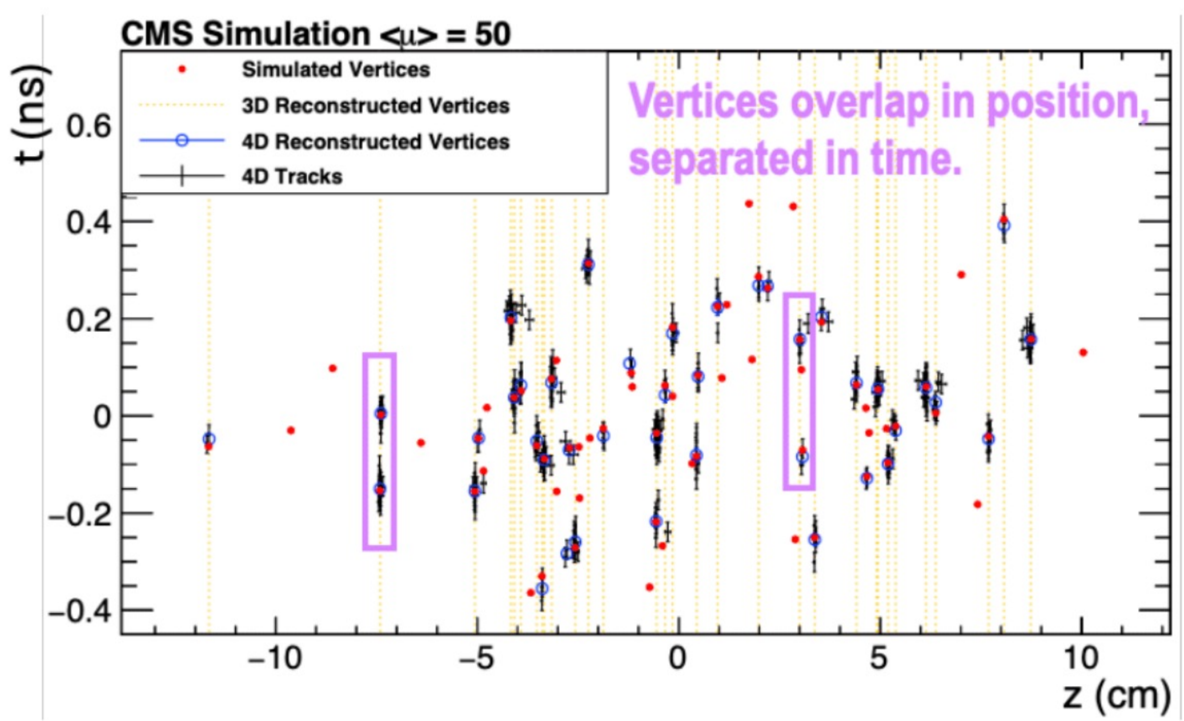


New Precision Timing Detectors

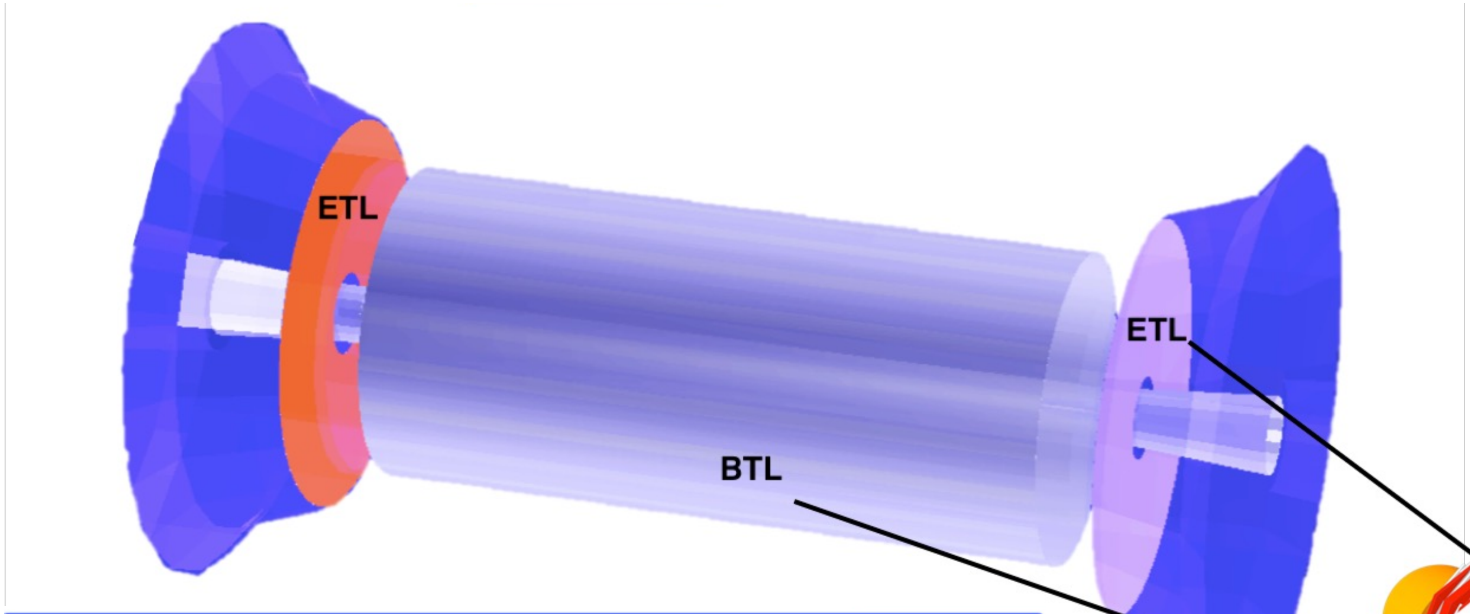
The Challenge of the High Luminosity LHC



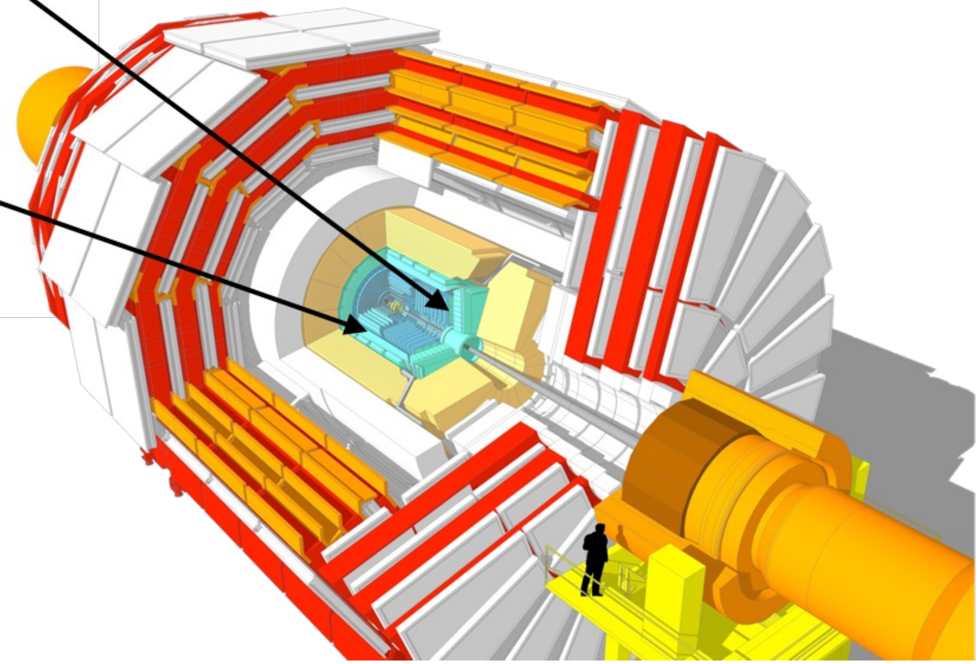




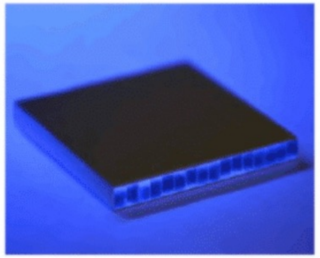
Precision Timing Technology



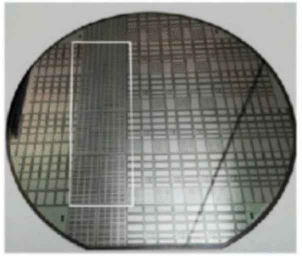
(Almost) hermetic coverage up to $|\eta|<3.0$



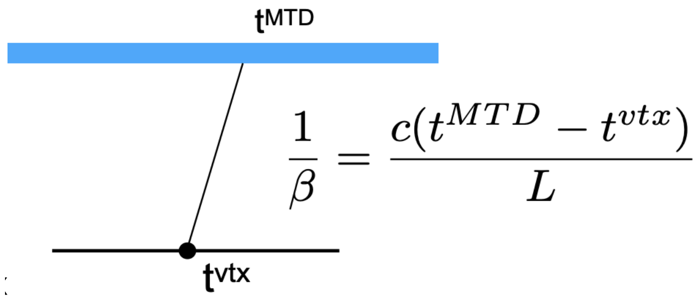
BTL: LYSO bars + SiPM read-out
- TK/ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2

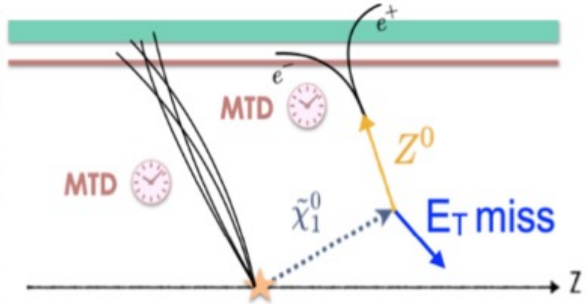


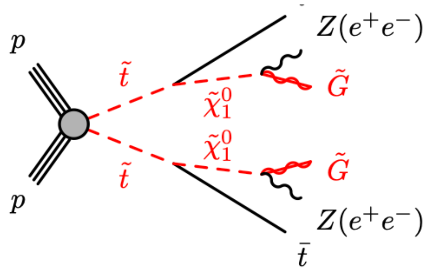
ETL: Si with internal gain (LGAD)
- On the HGC nose ~ 99 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



New Capability: Time-of-flight

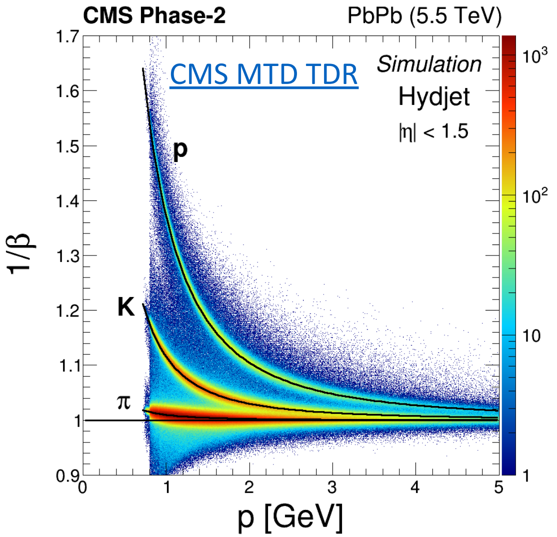


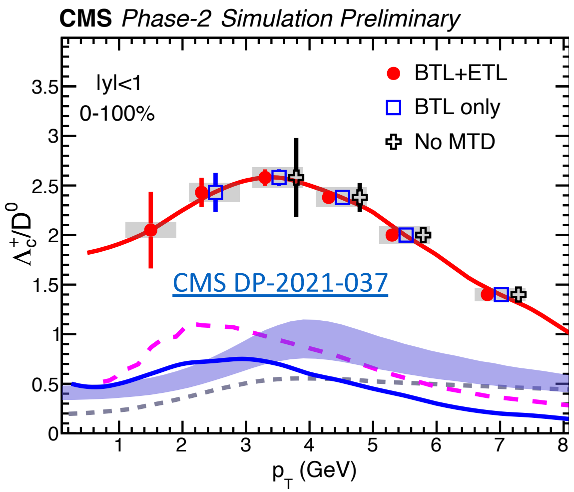


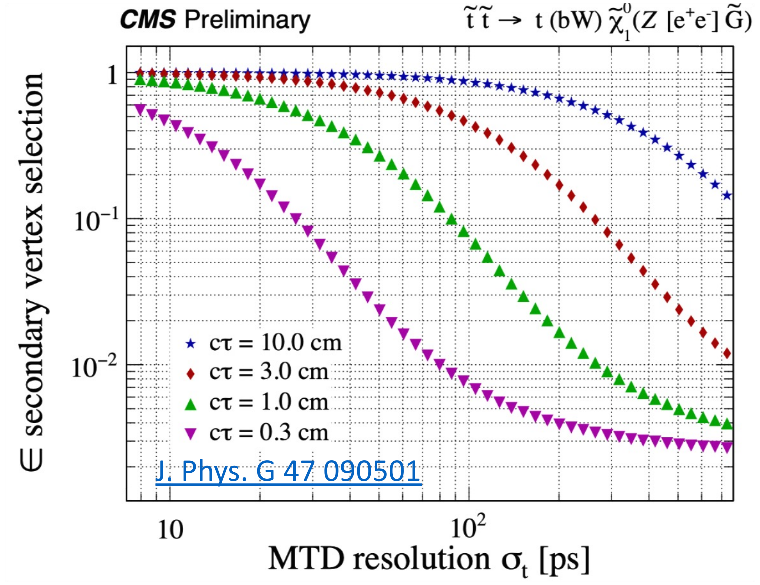


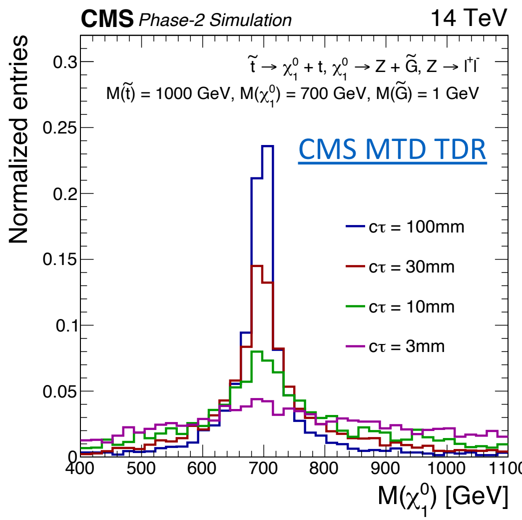
Flavor physics with heavy ions
π/K separation up to 2-3 GeV
and K/p separation up to 5 GeV

BSM: LLP, heavy stable charged particles, …
Vast acceptance extension from vertex-object timing fundamentally changes how we execute these searches

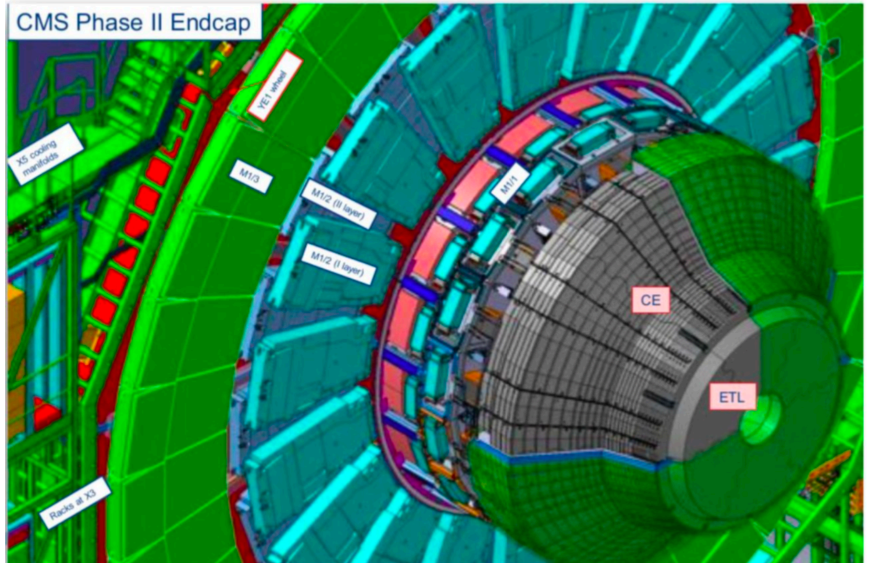


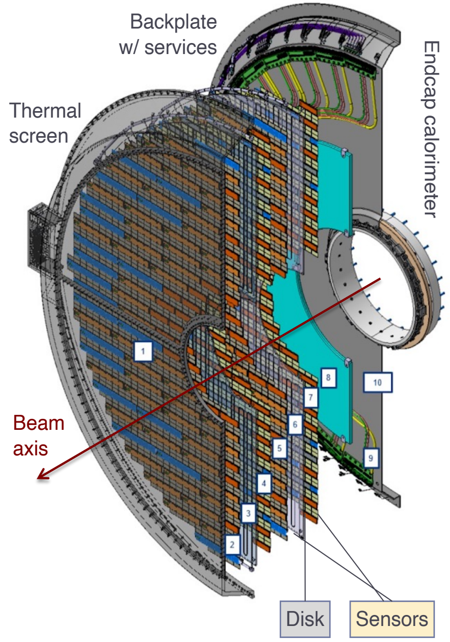






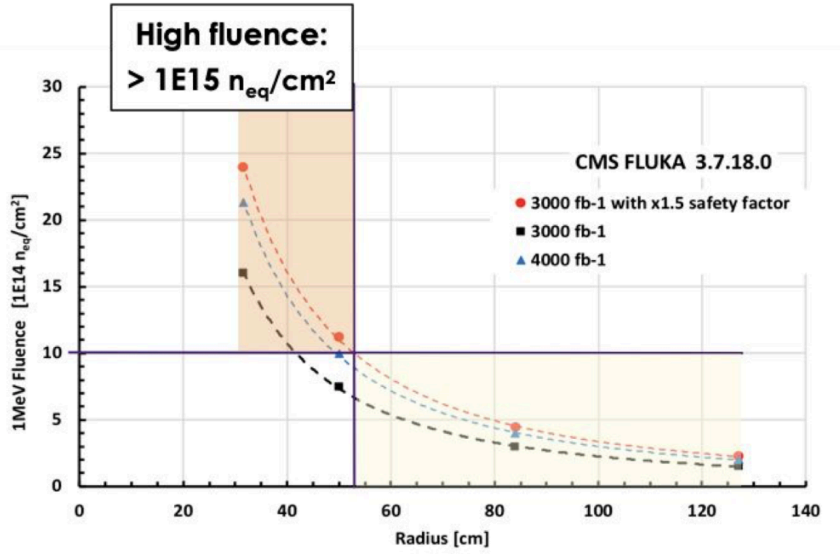
Design of the Endcap Timing Layer (ETL)

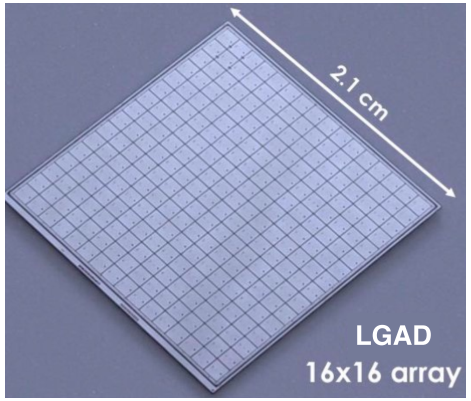


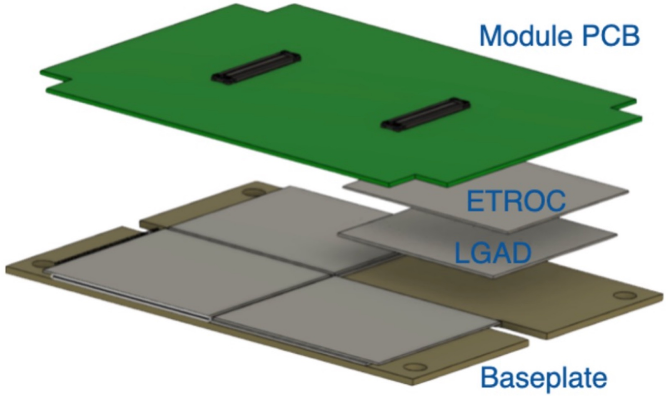


Each endcap is comprised of 2 cooling disks.

Detector modules, comprised of Low Gain Avalanche Diode (LGAD) sensors bump-bonded to a custom readout ASIC (ETROC) are mounted on both sides of each disk, providing up to two measurements (50ps/hit) per track (35 ps).







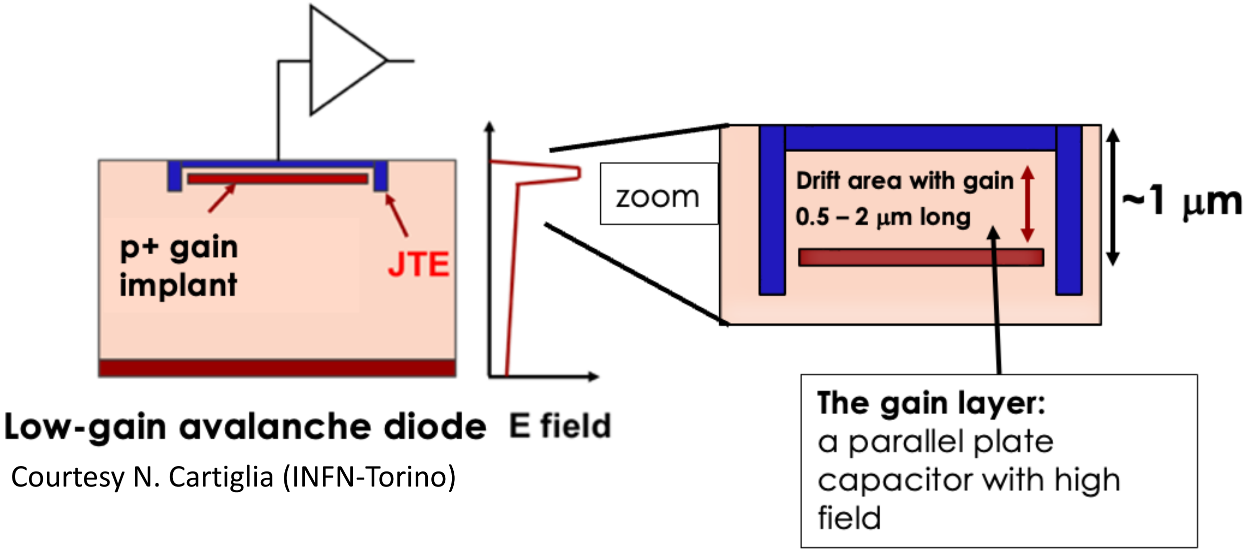
Design and operation targets and challenge:

- ETROC targets handling small signals, down to ~5 fC.
- Sensor targets >8 fC at end-of-life; fluence >1 x 10^{15} n_{eq}/cm^2 in the 15% innermost region

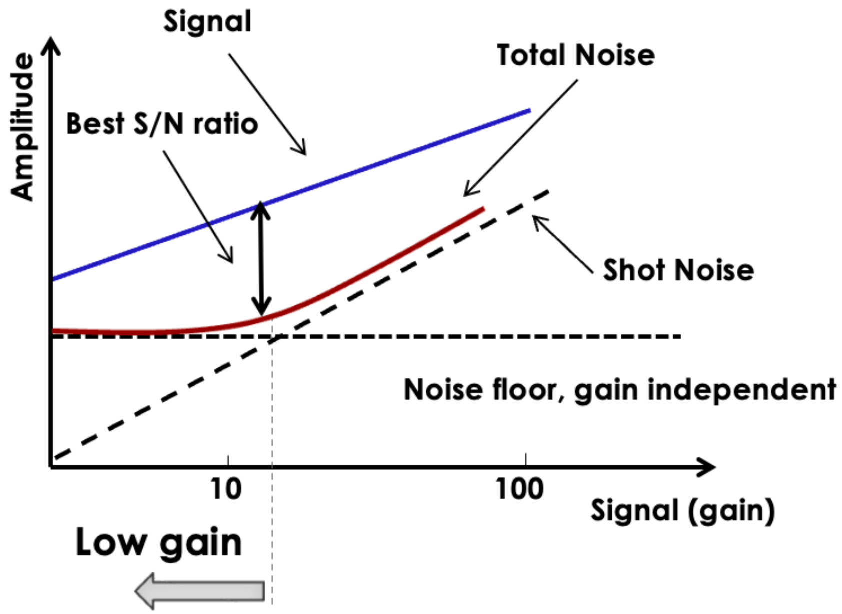
Precision timing in high radiation environment: LGAD sensors

Silicon structure optimized for time measurements (~30 ps from sensor).

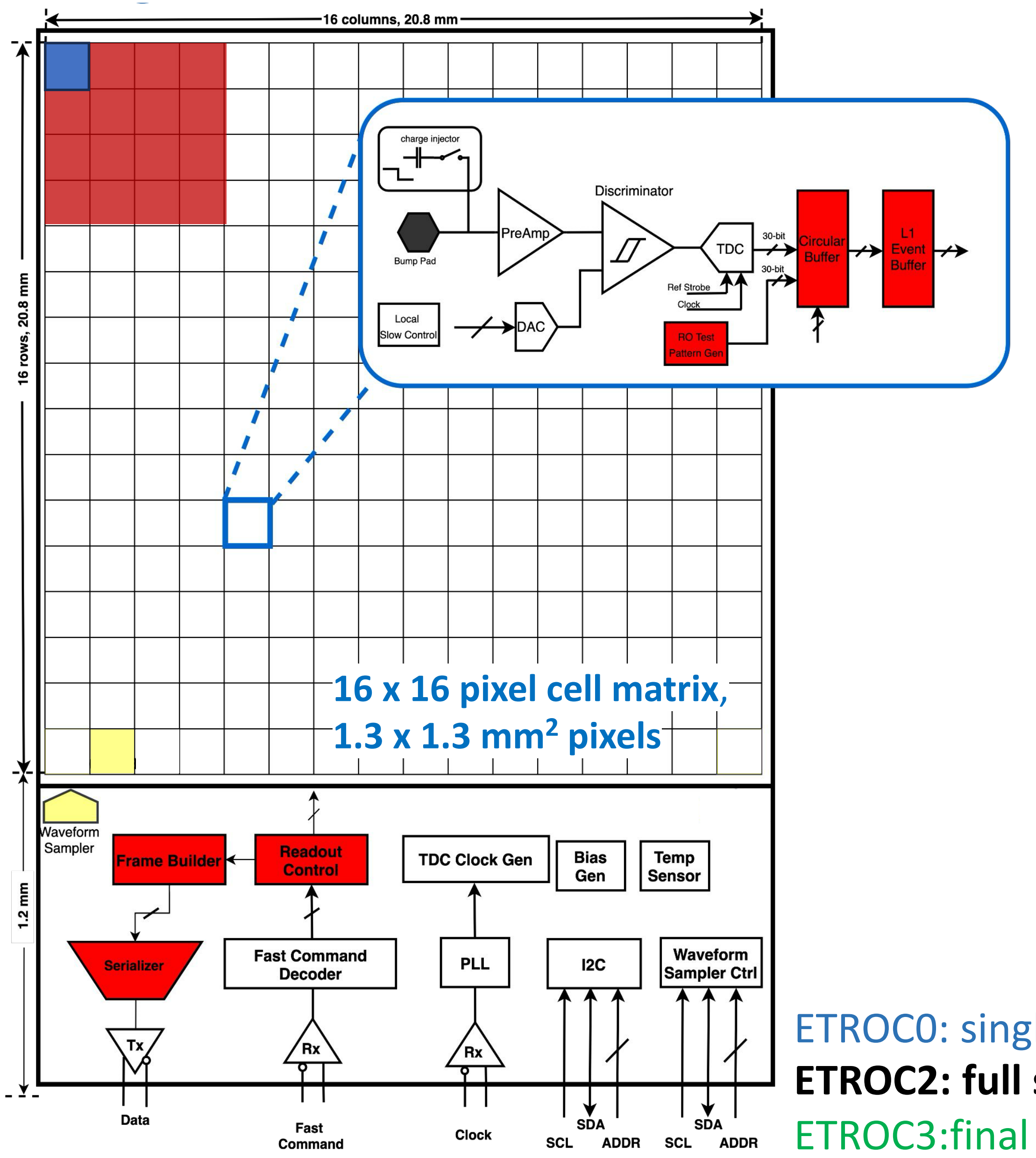
- A p-doped implant creates a volume of high field, where charge multiplication happens.
- Thin gain layer increases the electric field and helps meet threshold for charge multiplication
- When charge particle goes through, signal avalanches quickly (30 - 40 ps timing resolution)
- The success of LGADs is due to the sensor noise is hidden by the electronic noise.



Courtesy N. Cartiglia (INFN-Torino)



Precision timing at low power: ETROC ASIC



Design features:

- Preamplifier + discriminator, auto threshold calibration
- Single TDC measures Time-Of-Arrival (TOA) and Time-Over-Threshold (TOT), and delay cell time (CAL)
- 16x16 clock tree distribution
- Radiation hard waveform sampler
- Charge injection for testing & calibration

Performance specifications:

- TSMC 65nm technology, 100 MRad (TID spec)
- Low noise and fast rise time
- Low power: $\lesssim$ 4 mW / channel at end-of-life
- ASIC contribution to time resolution $\lesssim$ 40 ps at end-of-life

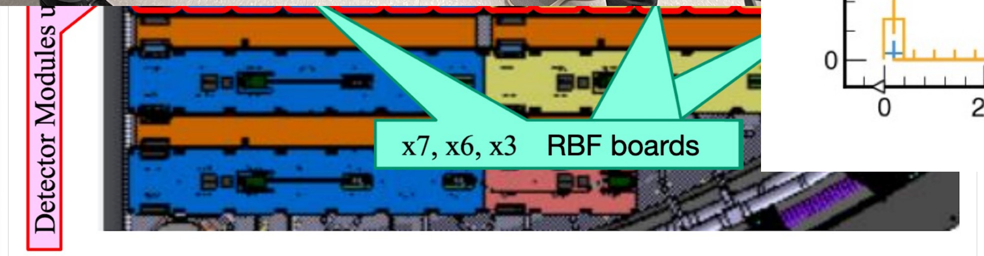
ETROC0: single analog channel

ETROC1: with TDC, 4x4 channel-clock tree

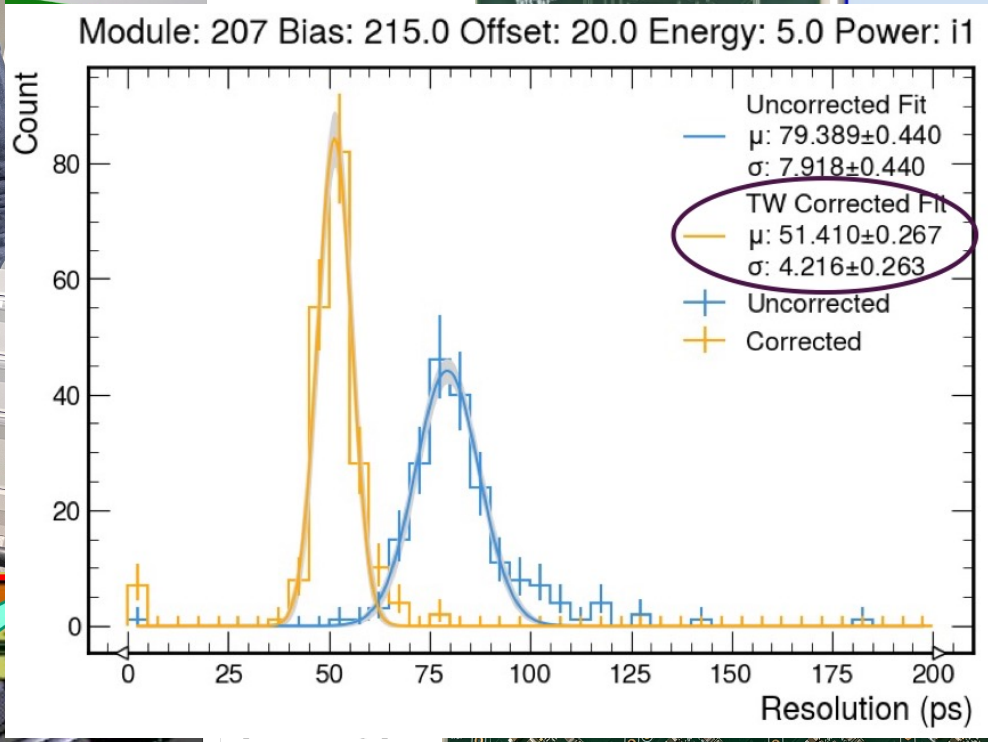
ETROC2: full size, full functionality, testing now!

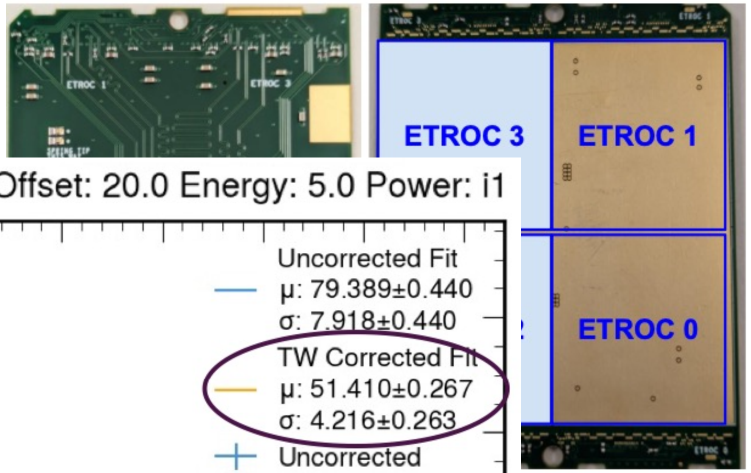
ETROC3:final chip, submit next year

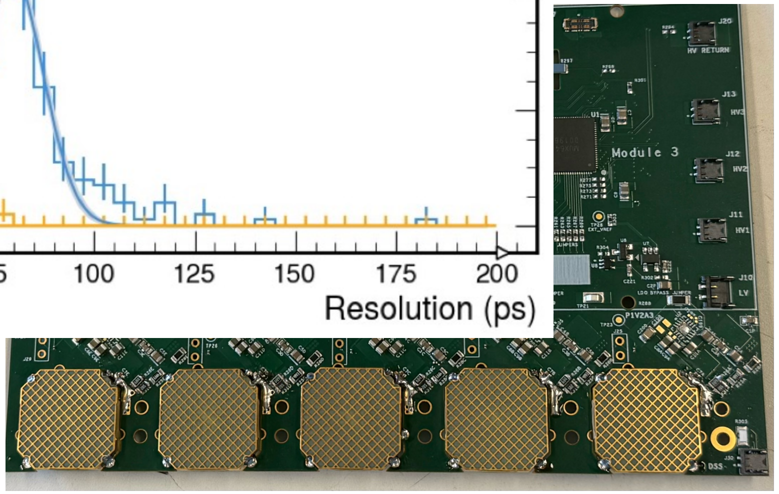
Putting it all together



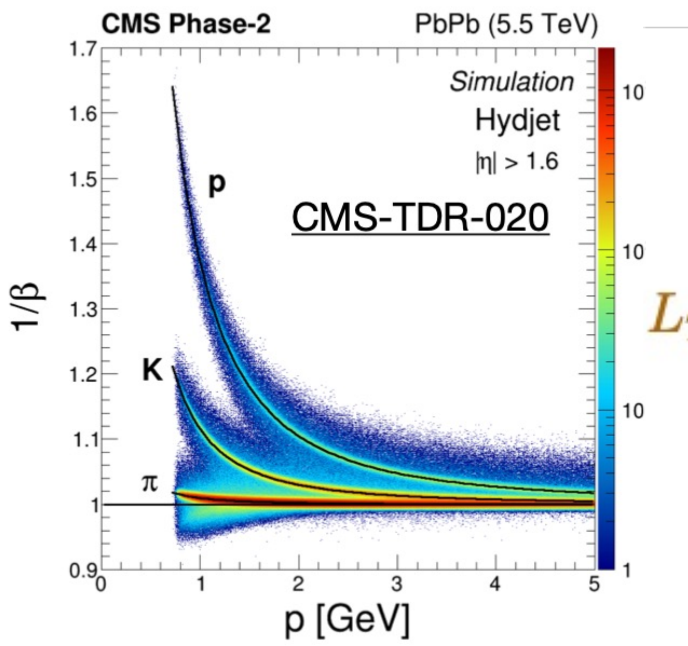
Fraction of the disk

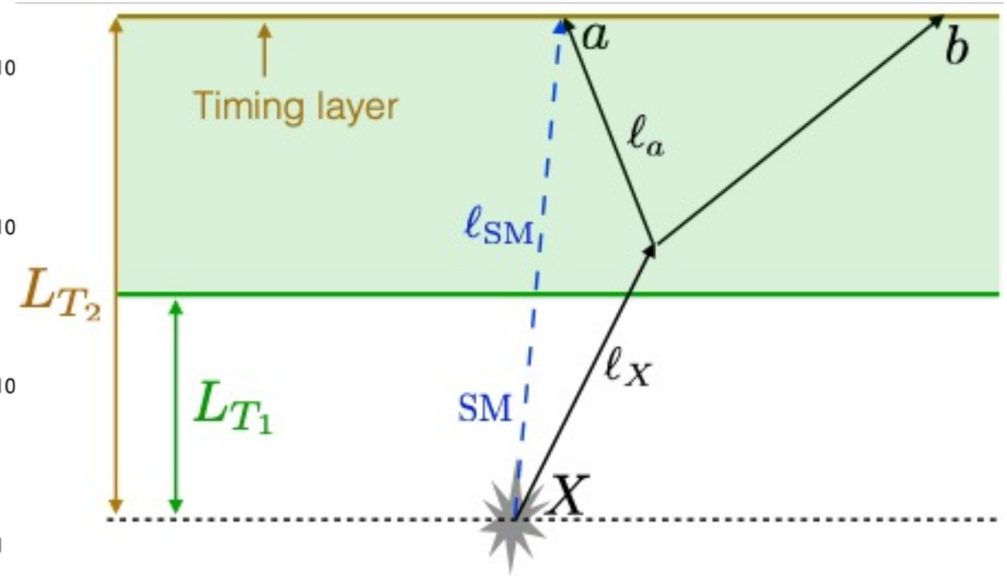


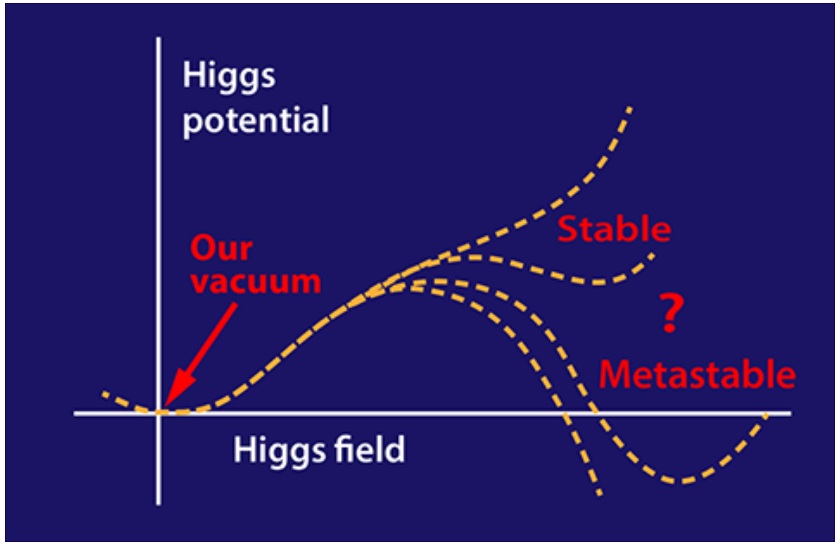




The Physics This Enables





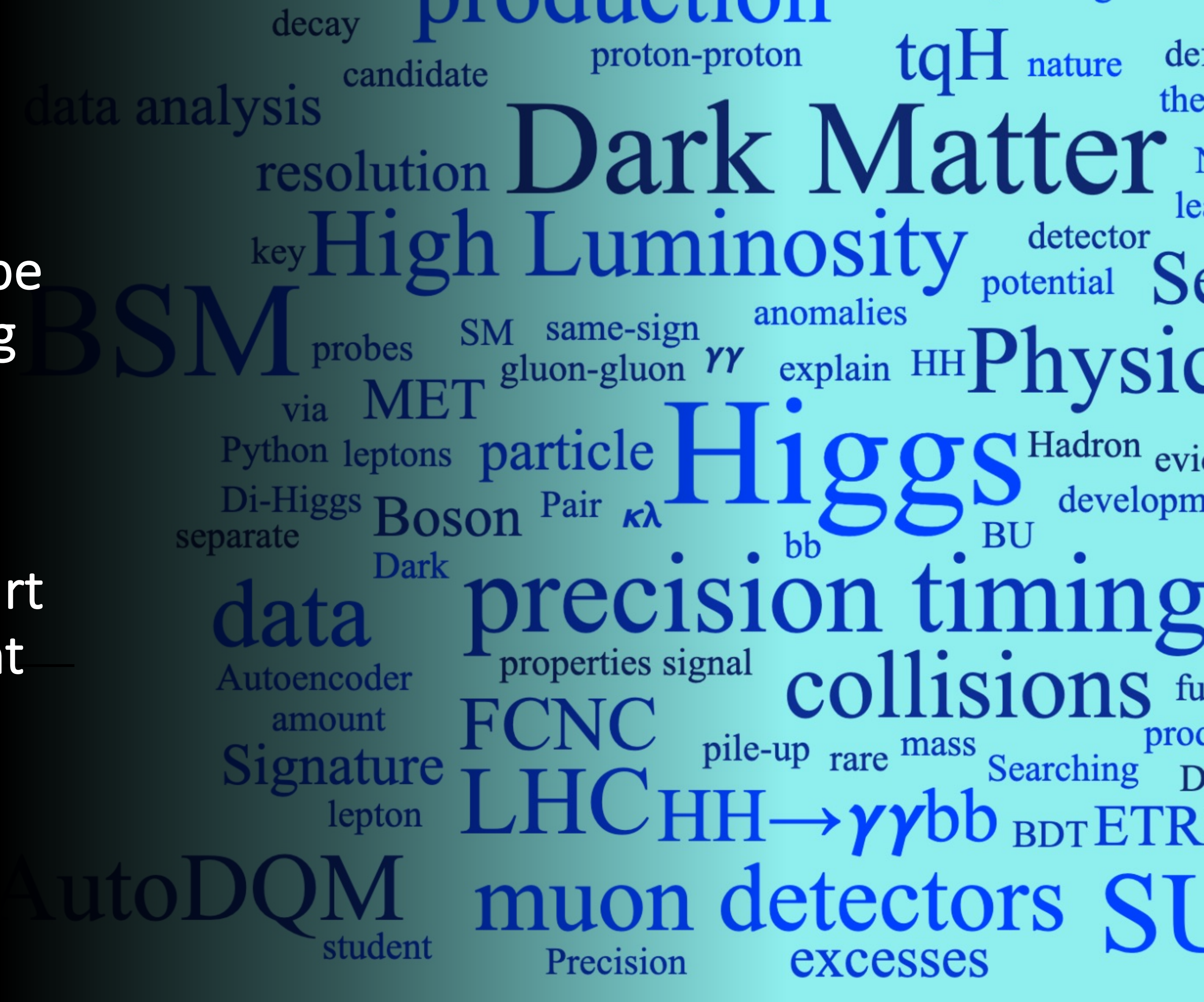


	MTD improvement	analysis impact	physics impact
$H \to \gamma\gamma$ $H \to 4\ell$	lepton isolation vertex identification	+25% statistical precision on cross sections	Higgs boson couplings
VBF $H \to \tau\tau$	isolation VBF jet tagging p_T^{miss} resolution	+30% statistical precision on cross sections	Higgs boson couplings
HH	isolation b tagging	+20% in signal yield	consolidate searches
EWK SUSY	p_T^{miss}	+40% reducible background reduction	+150 GeV mass reach
LLP	β_{LLP} from timing of displaced vertices	peaking mass reconstruction	unique discovery potential

My team

Precision instrumentation will be key to understanding Dark Matter

Exciting time to be part of an LHC experiment



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