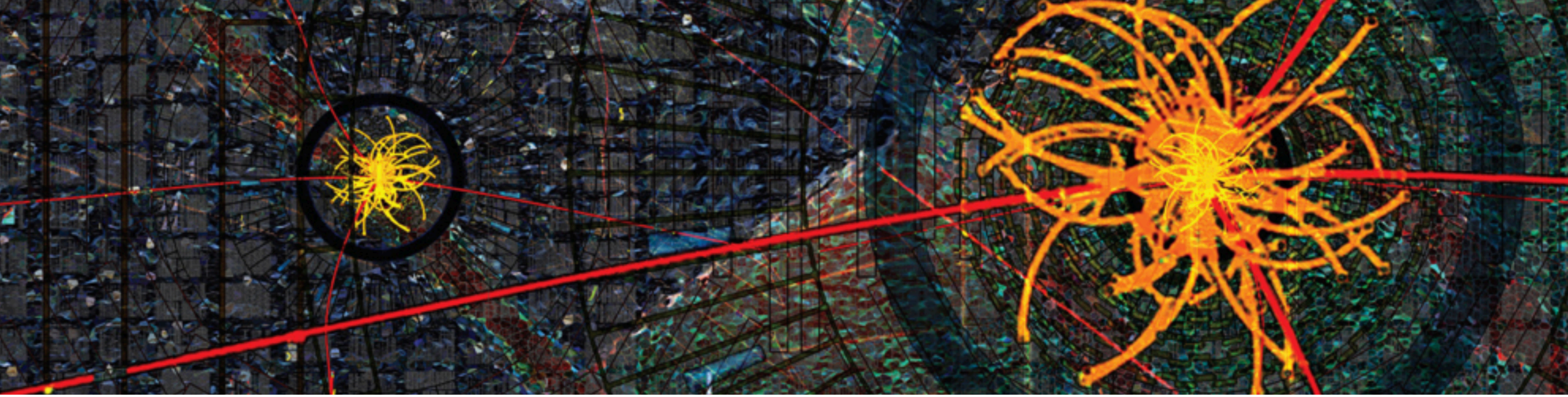


BSM searches in experimentally challenging regions of phase space

Swagata Mukherjee, IIT Kanpur

In-house HEP symposium, IIT Kanpur, February 2-3, 2024

Hadron collider vs e^+e^- colliders

Discovery machine.

Can go to very high energy.

More events, more messy events.

One example: TRIGGER SYSTEM

↓

Must needed for hadron colliders.

Introduces an addition layer of complexity.

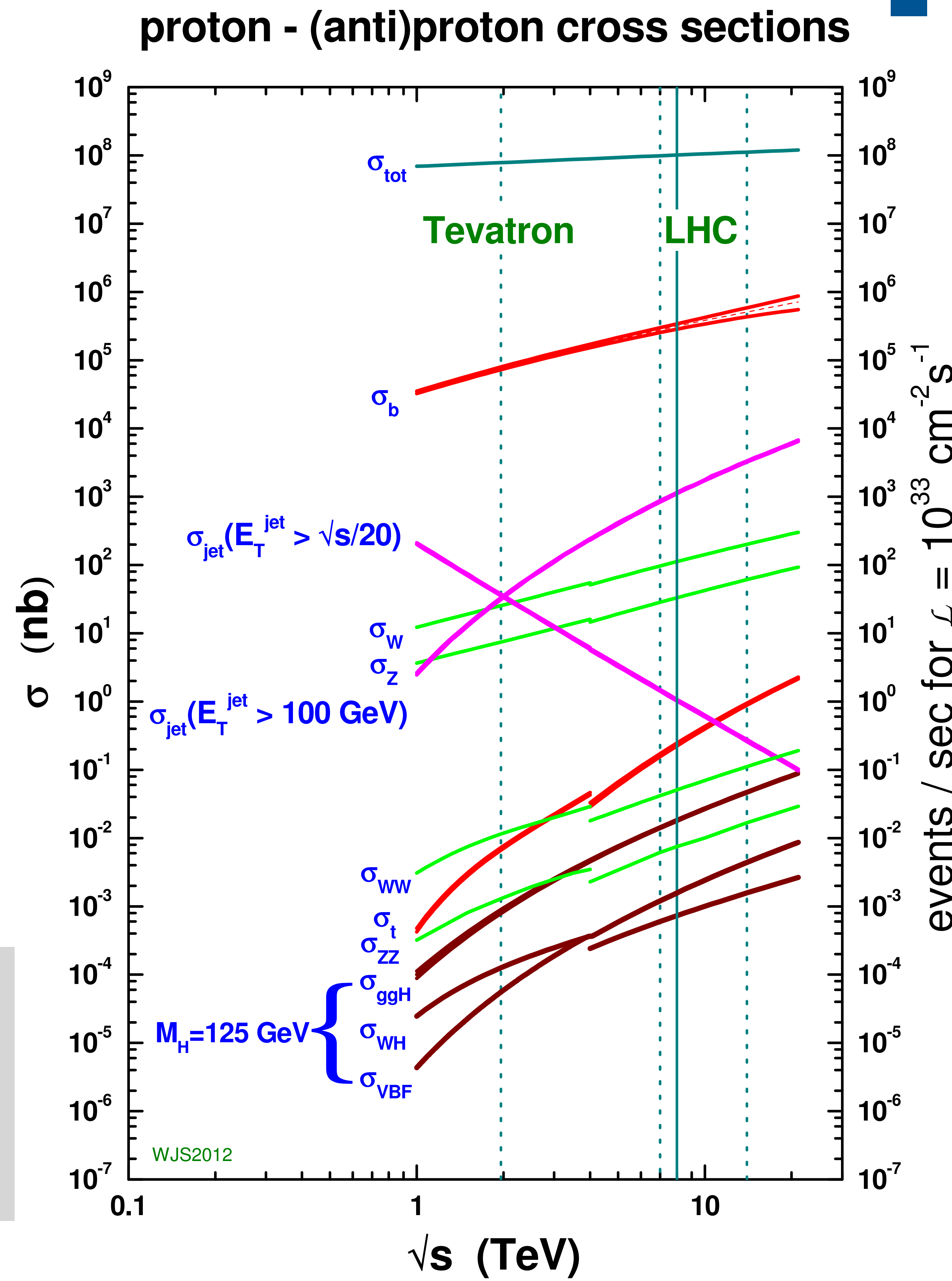
Excellent machine for precision physics !!

Clean events.

Energy loss due to synchrotron radiation in circular e^+e^- machines, so can't go too high in energy

- LHC produces ~1 billion p-p collisions per second
- Saving all these collision events are not possible.
- Do we even need such large amount of data ?
- Interesting processes are much rarer than the p-p scattering !
- Filter out uninteresting events
  - TRIGGER !

Events that are not selected by trigger system are lost, **forever!**



DESPITE ALL HARDSHIP, LHC IS A SUCCESS SO FAR

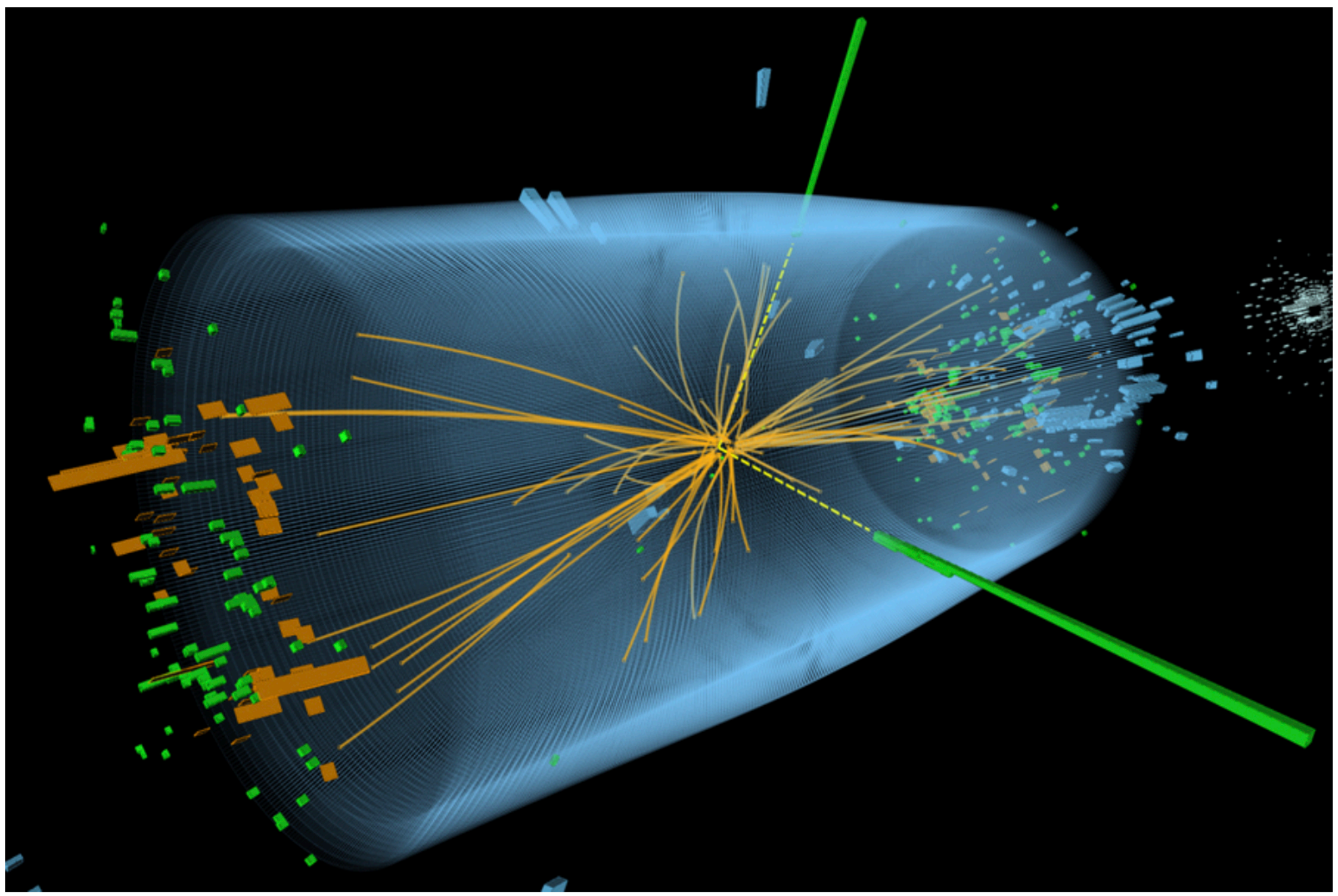
The LHC experiments are very successful in these areas

- Higgs physics
- Direct searches for BSM
- Top quark physics,
- Precision EW measurements
- Precision B-physics
- Heavy-ion physics

Would not be possible without theoretical and phenomenological breakthroughs of the past decade: Higher-order calculations, modern Monte Carlo generators, reduced PDF uncertainties..

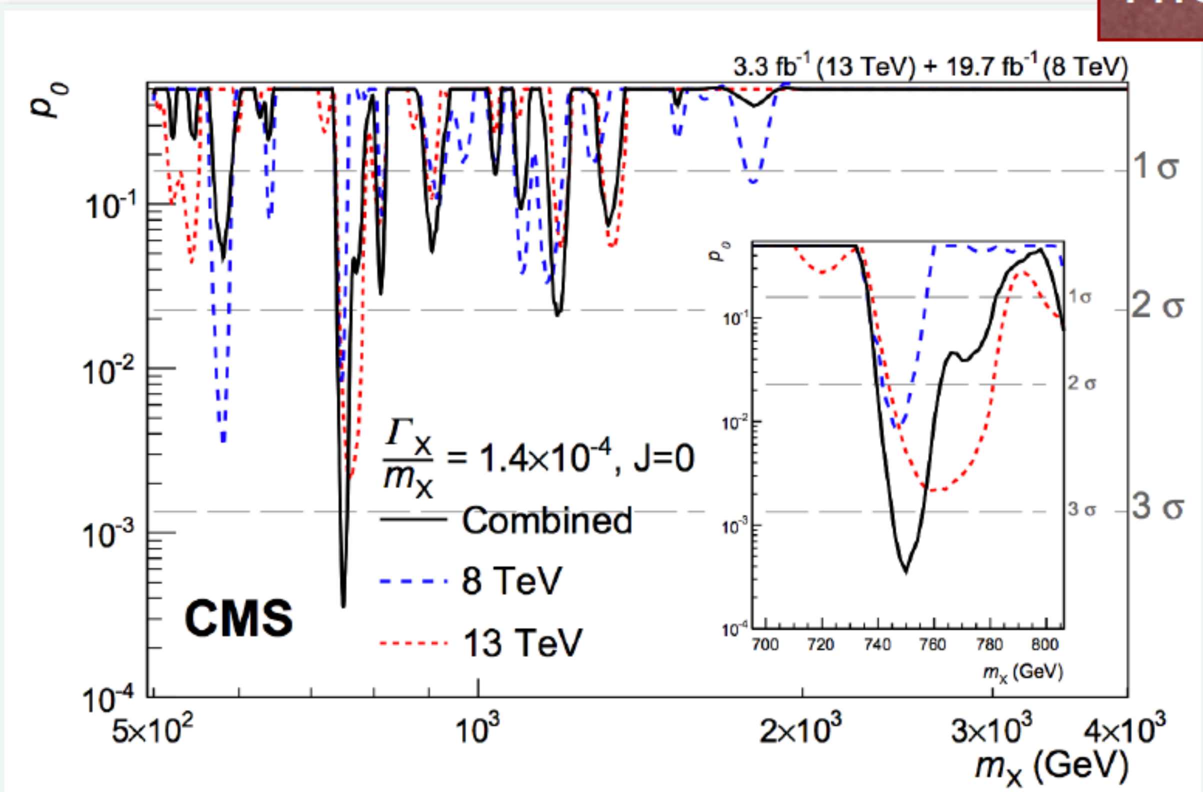
DISCOVERY OF HIGGS 😀

July 2012



"MISCOVERY" OF 750 GEV DIPHOTON RESONANCE 😟

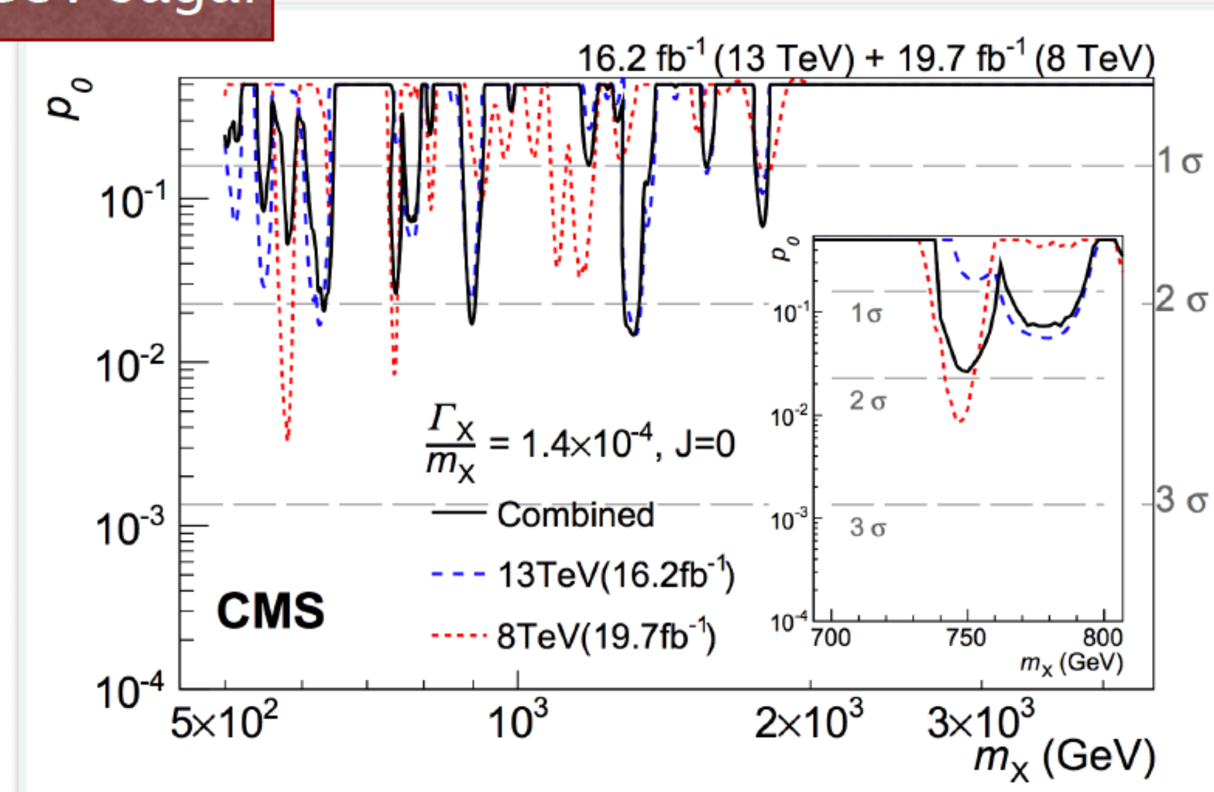
The 750 GeV saga!



High mass γγ search June 2016

Phys. Rev. Lett. 117, 051802 (2016

>3σ



High mass γγ search September 2016

Phys. Lett. B 767 (2017) 147

2σ

Next time, I won't believe it until it is 5 sigma

WHERE IS BSM HIDING?

You lost your key somewhere.

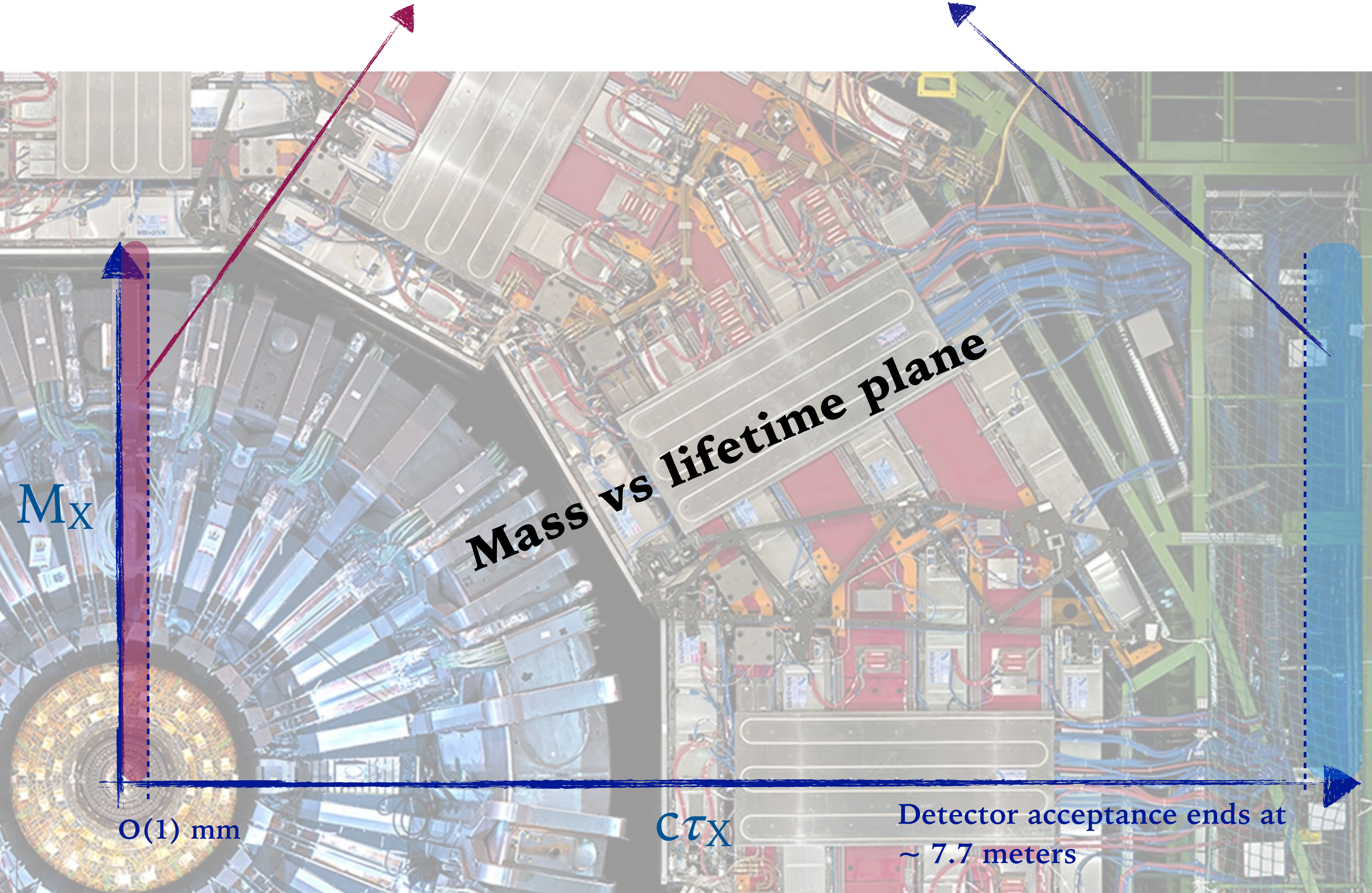
Obviously you'd search under the lamppost first, before searching in the darker areas!

Similarly, CMS/ATLAS invested initial efforts on bread-and-butter BSM searches.

High-mass dijet / dielectron / dimuon / diphoton.. etc..

The low-hanging fruits are mostly gone now..

Majority of BSM searches focus here



Prompt particle.

Decays as soon as it is produced.

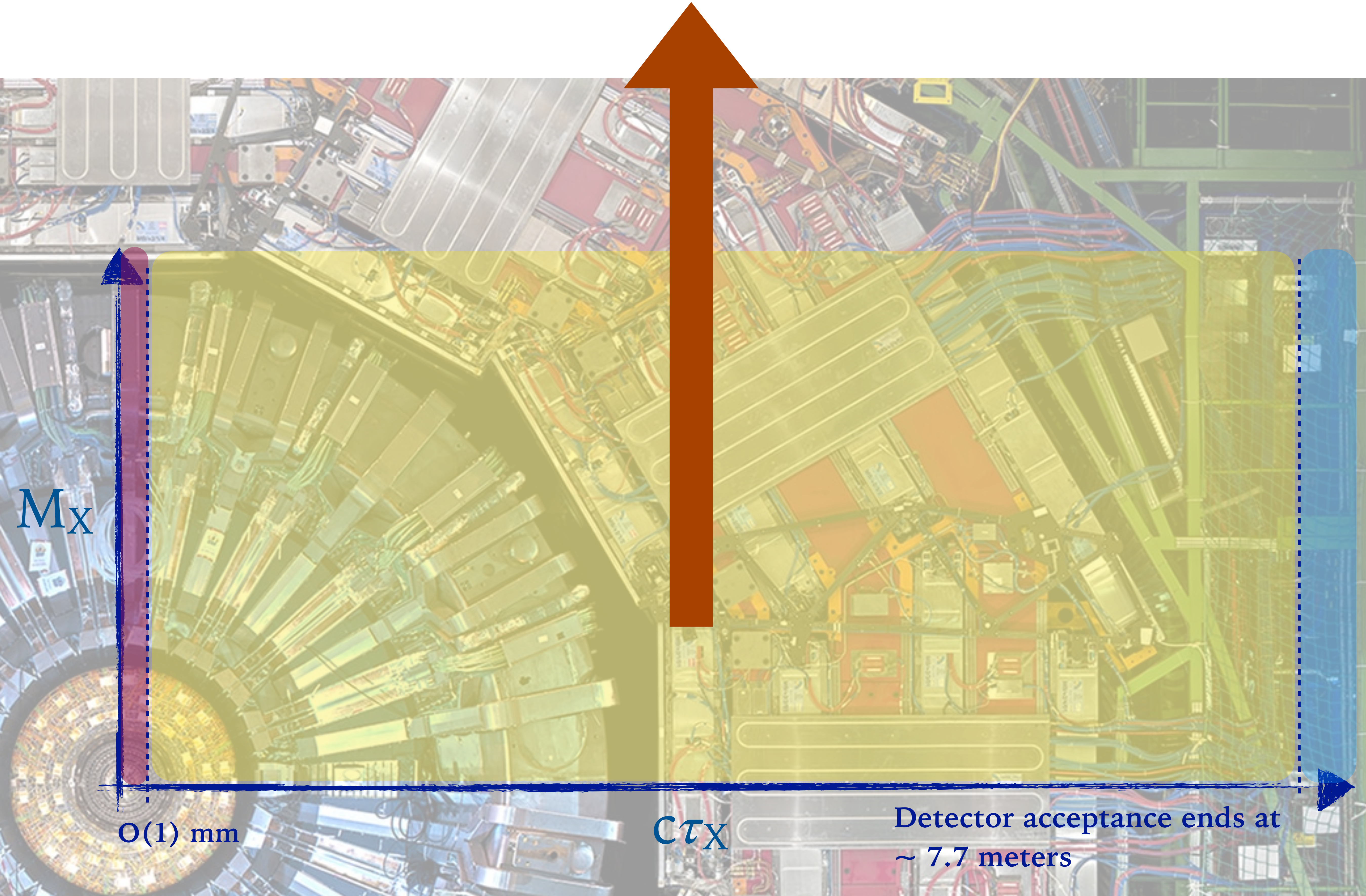
Example: Z boson, Higgs etc

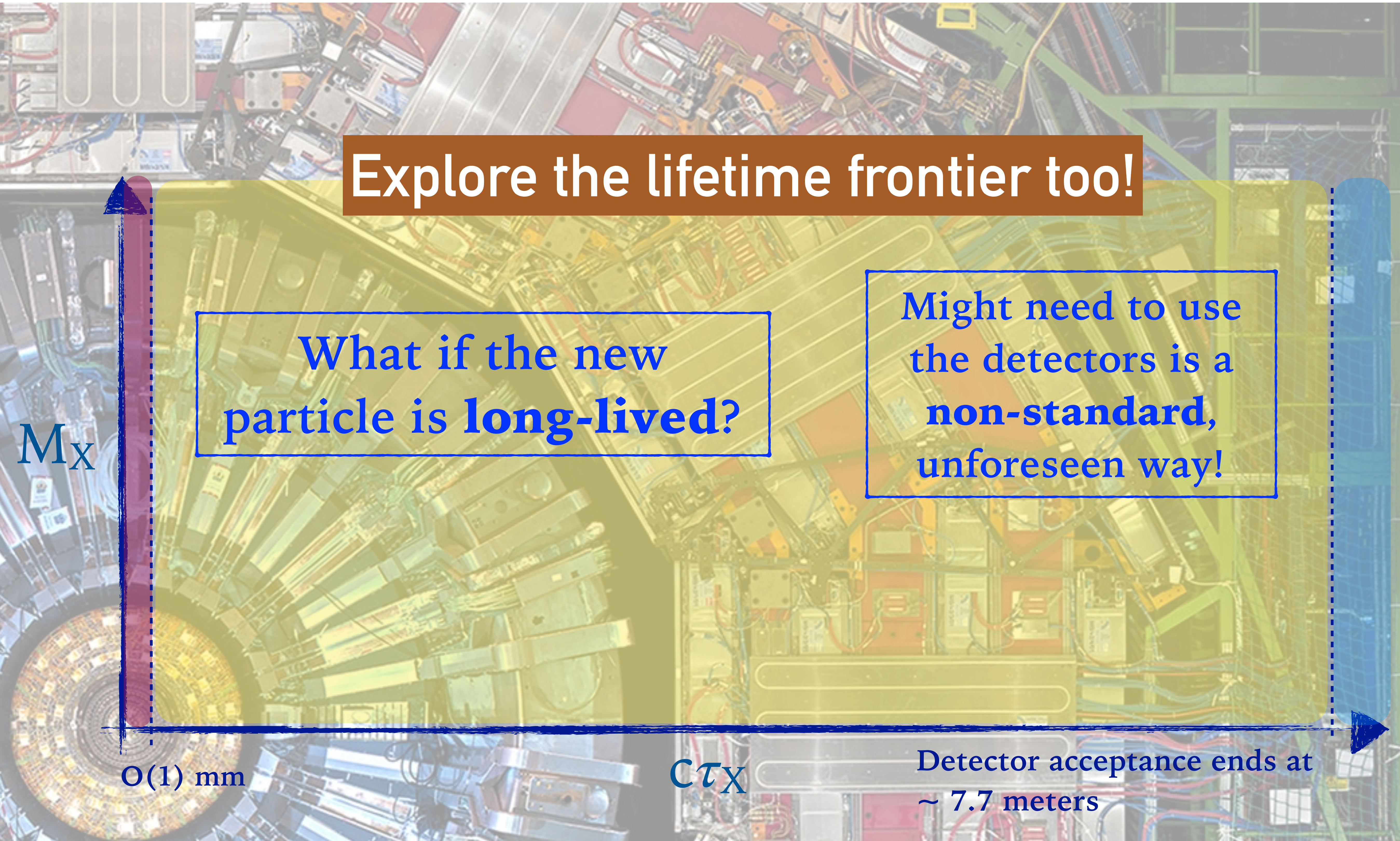
Detector-stable particle.

Does not decay inside detector.

Example: Dark-matter

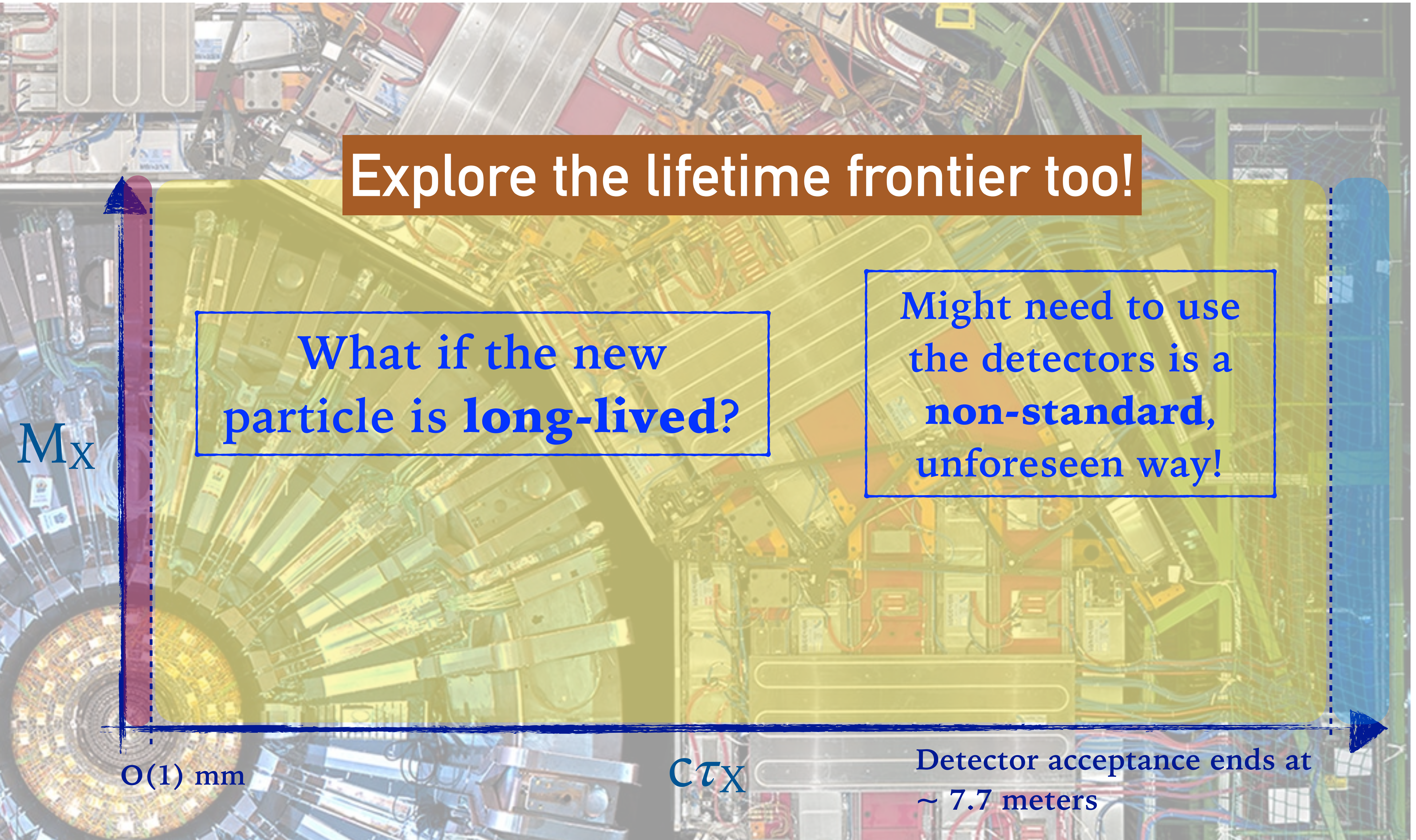
What if BSM is hiding here?




Explore the lifetime frontier too!
What if the new particle is **long-lived**?
Might need to use the detectors is a **non-standard**, unforeseen way!
M_X
O(1) mm
$c\tau_X$
Detector acceptance ends at ~ 7.7 meters

Challenge:

Our detector design, object reconstruction algorithms, trigger strategy are geared towards identifying **prompt** particles



Our detector design, object reconstruction algorithms, trigger strategy are geared towards identifying prompt particles

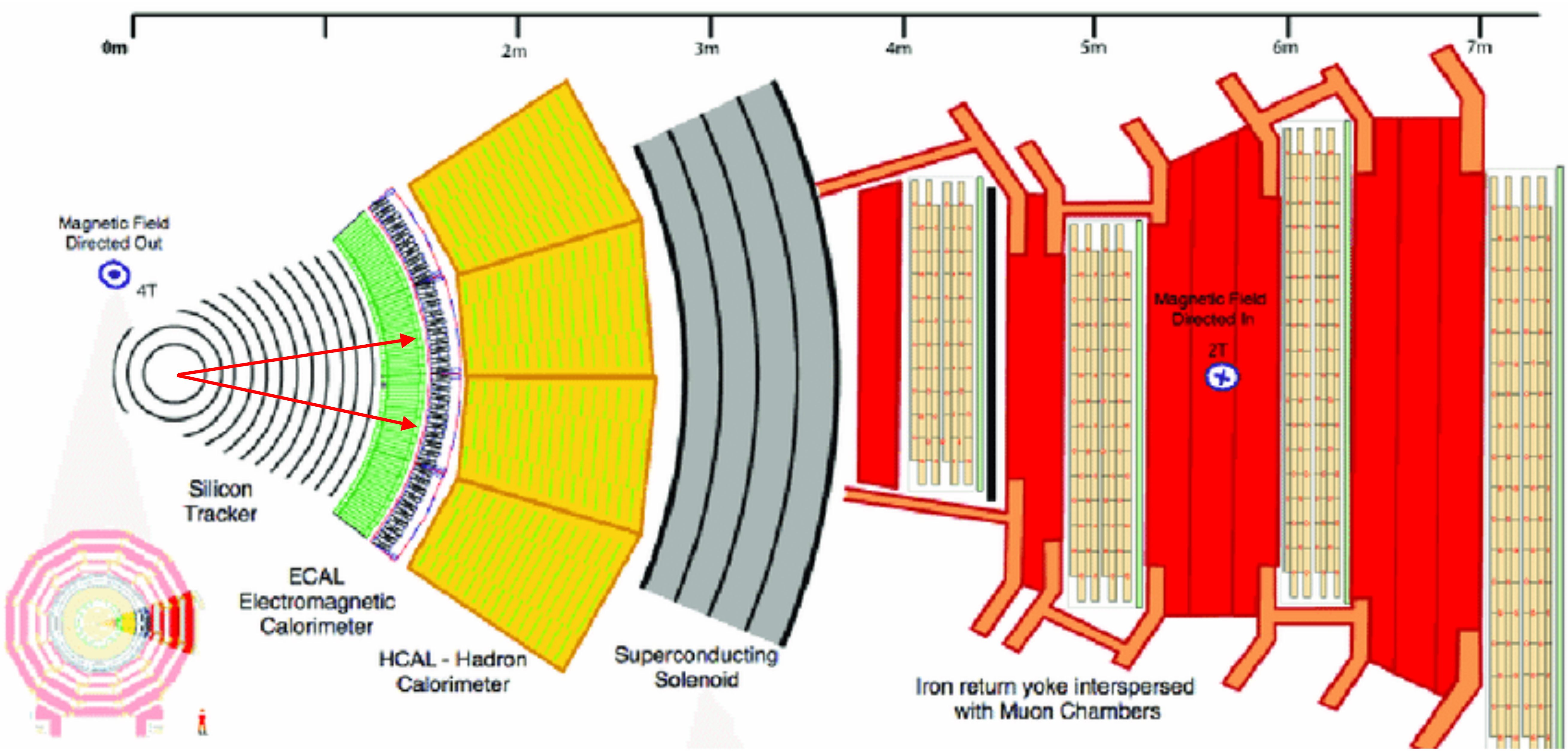
This is simply because it has worked great so far!

Higgs discovery in CMS and ATLAS

Top quark discovery in CDF and D0

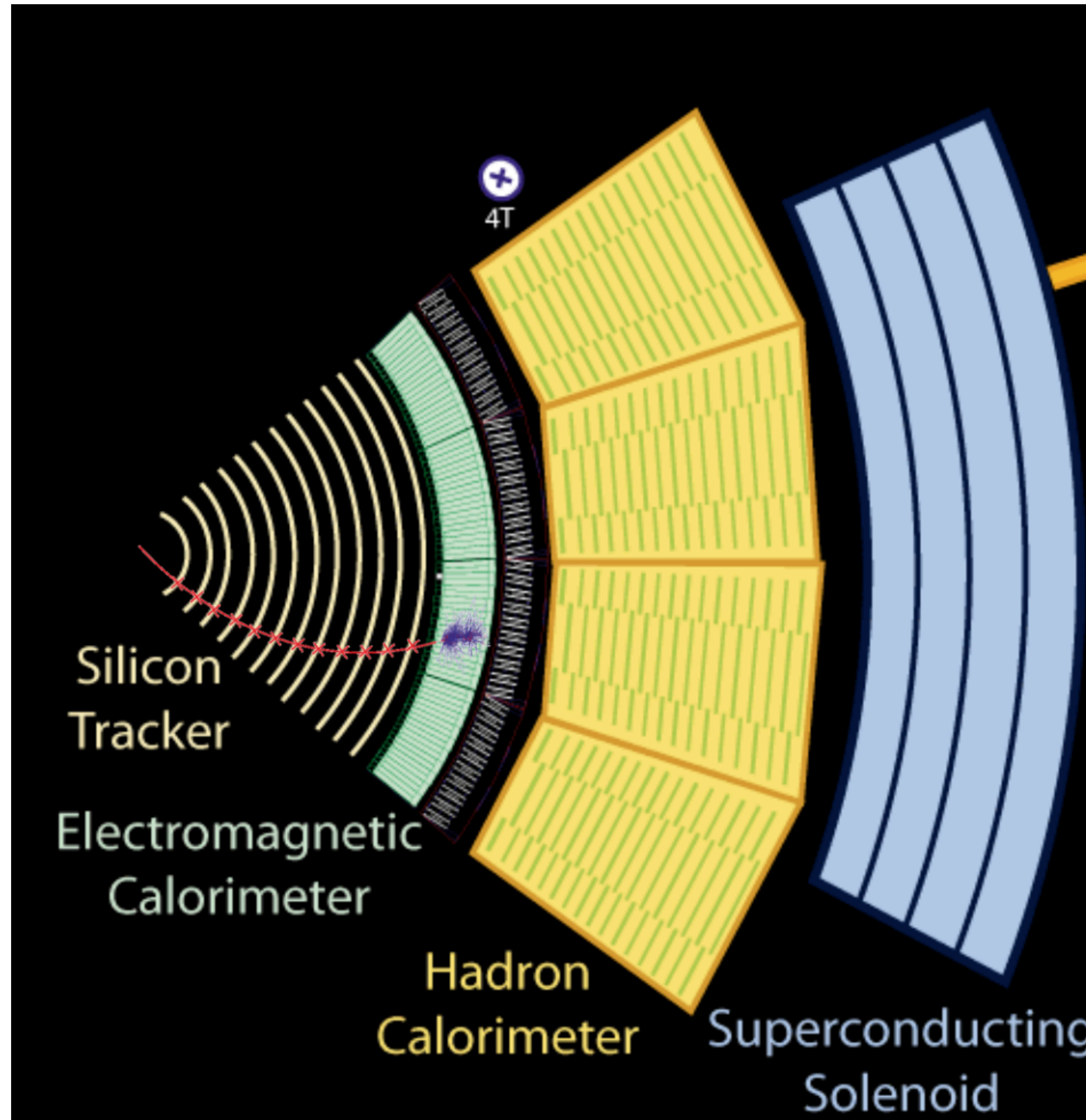
W & Z discovery by UA1/UA2

$X \to ee$ (prompt)



How do we know when an electron is produced?

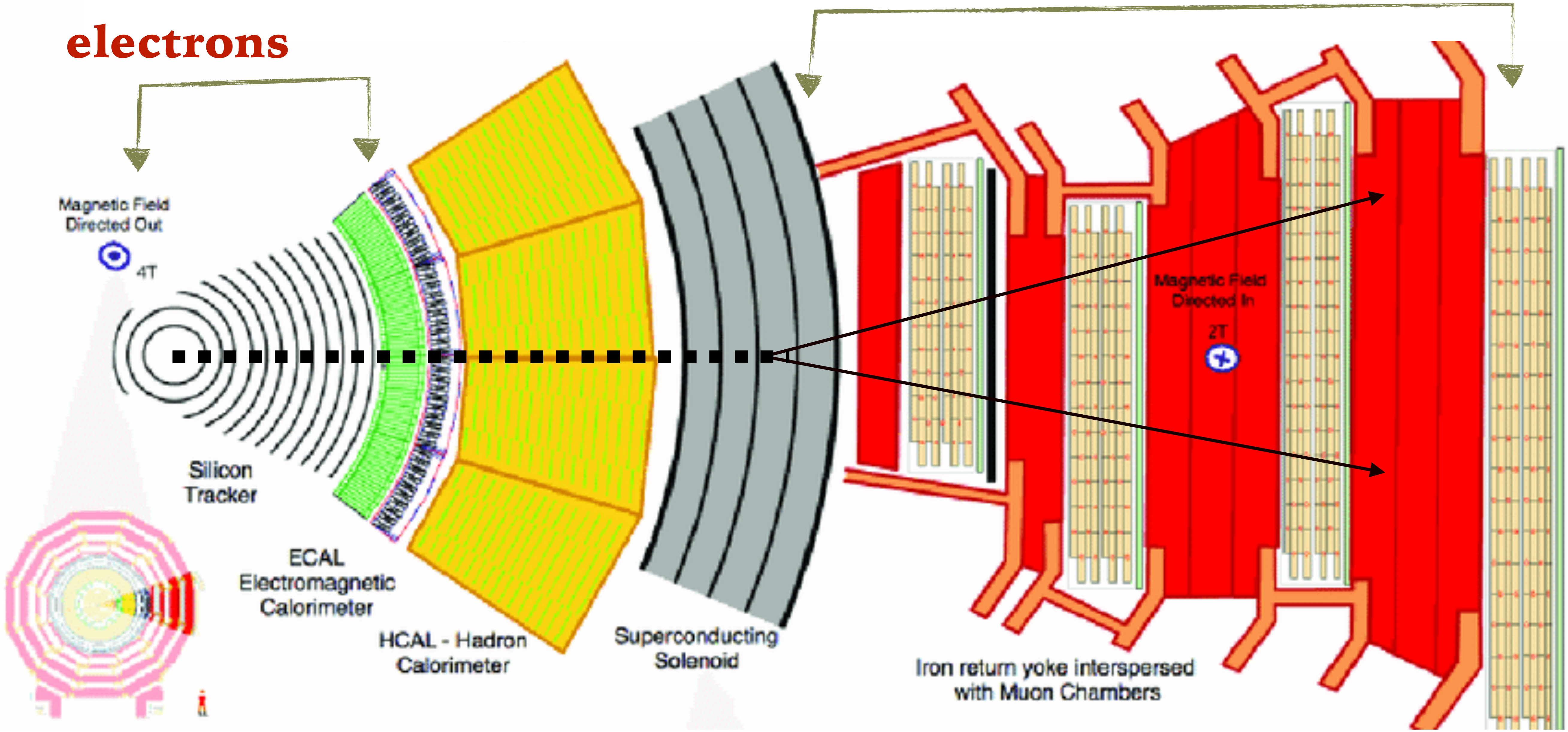
- We rely on a software cmssw Public
- The software contains elaborate reconstruction algorithm
- It efficiently reconstructs electron from the interaction of electron with CMS detector.
- It also tells us the electrons energy and position in the detector.
- BUT, ONLY IF THE ELECTRON IS PRODUCED AT THE COLLISION POINT



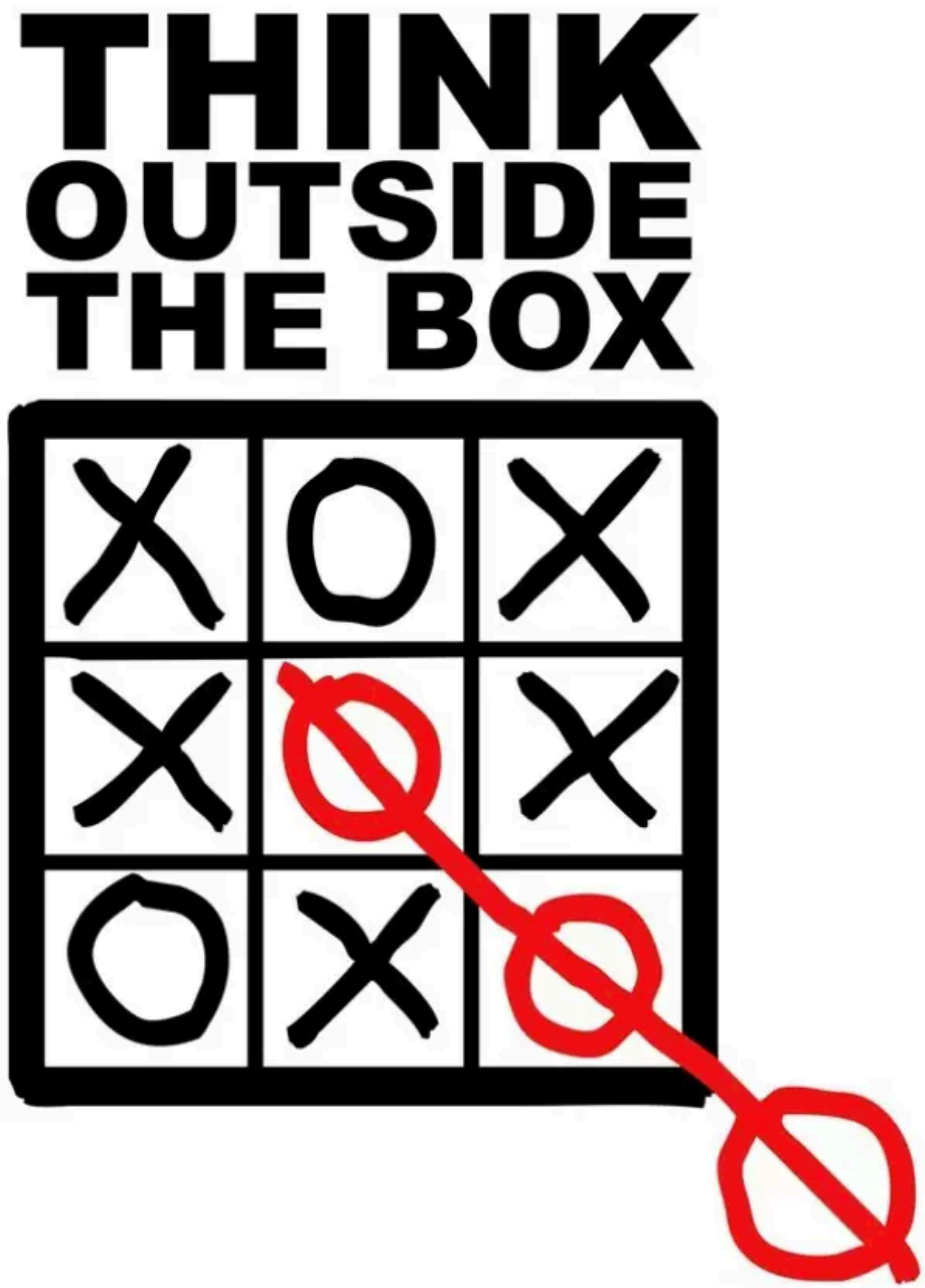
$X \rightarrow ee$ (displaced)

This part of CMS is built to detect electrons

But the electron is here! Do we know how to deal with this?



How does an electron look in muon spectrometer? People are starting to ask these weird questions, pushing boundaries, breaking norms and coming up with novel, innovative ideas.

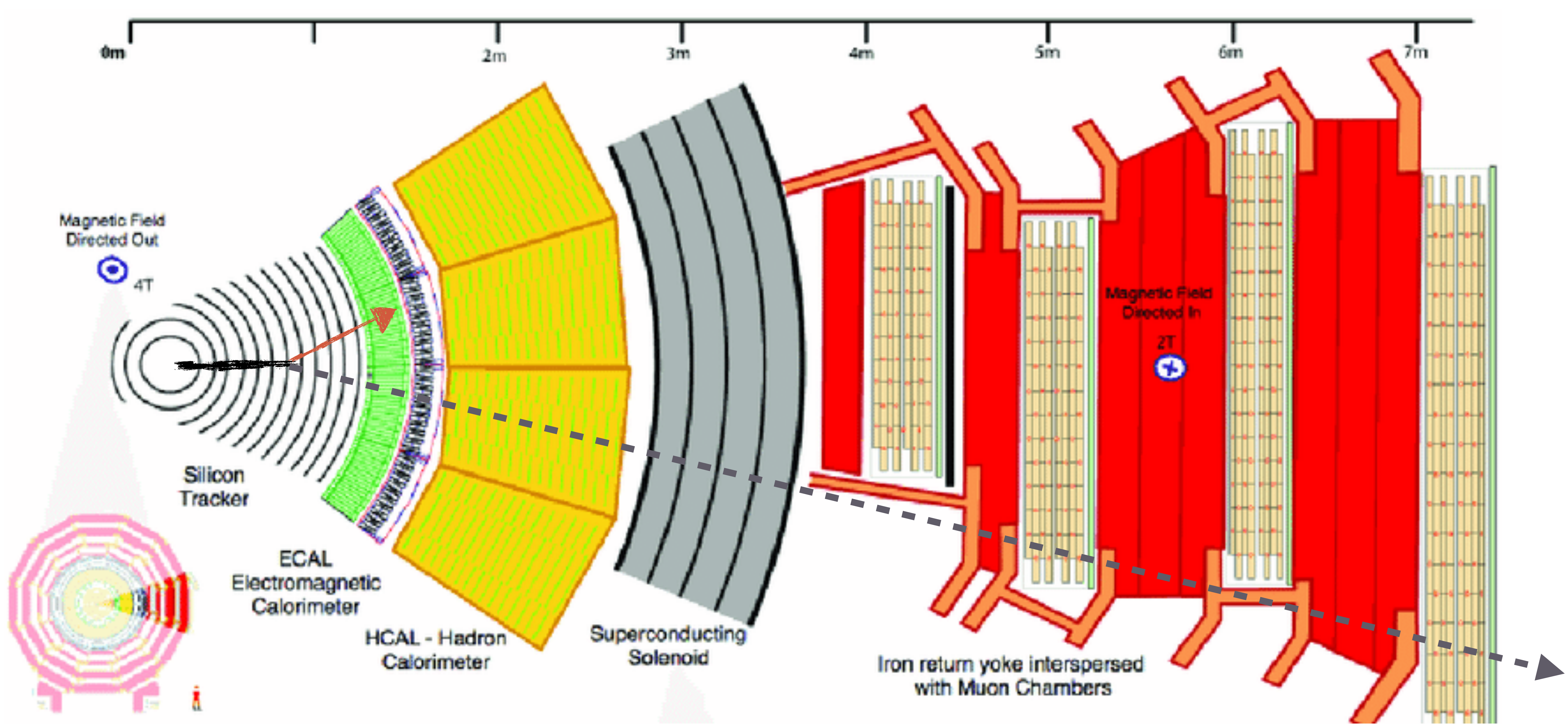


How does an electron look in muon spectrometer? People are starting to ask these weird questions, pushing boundaries, breaking norms and coming up with novel, innovative ideas.

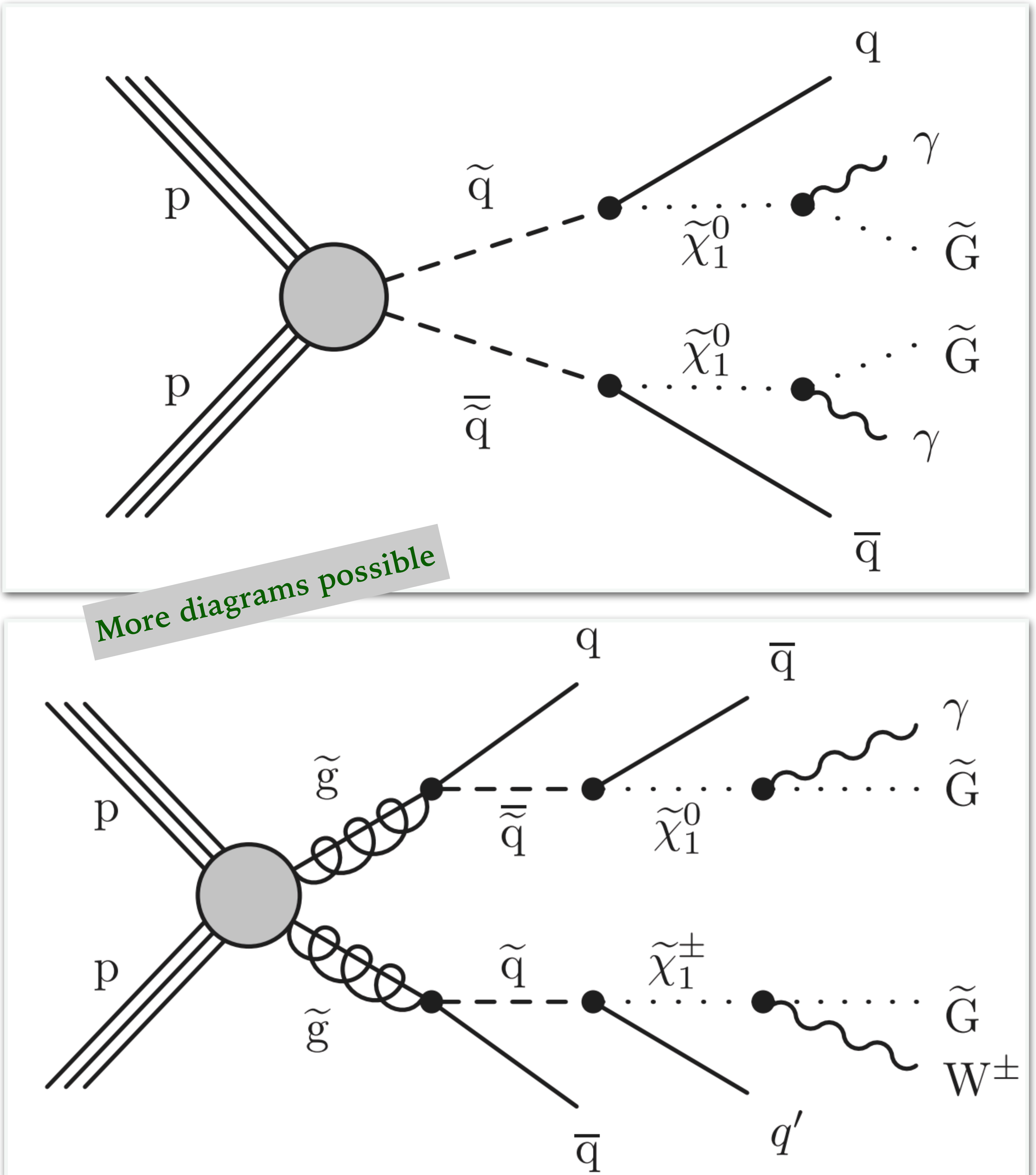
Several such EXOTIC signatures studied and searched for in last few years.

Today, I have time to speak about only ONE of them.

Signature: displaced photon arriving in ECAL late in time.

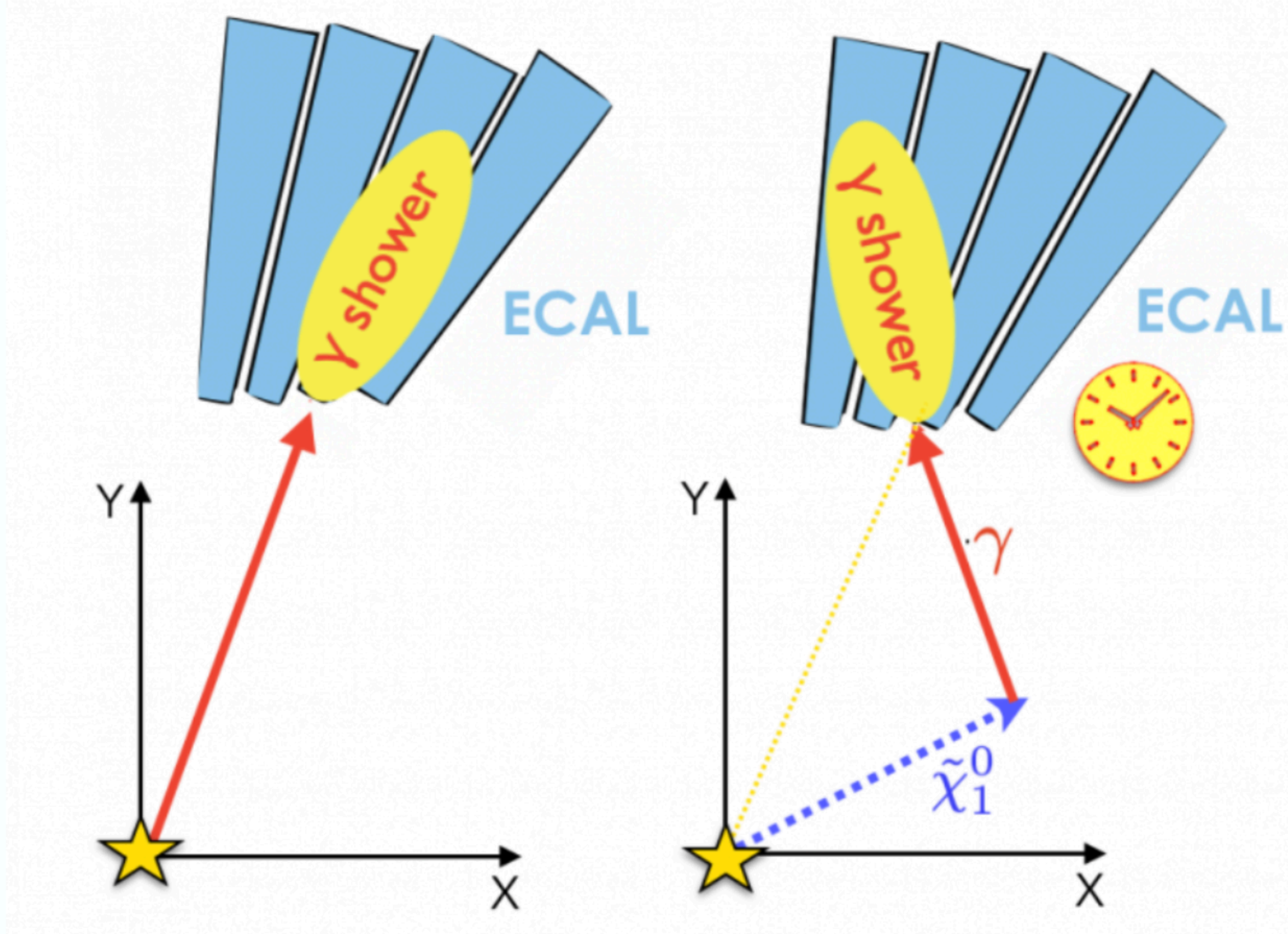


MODEL



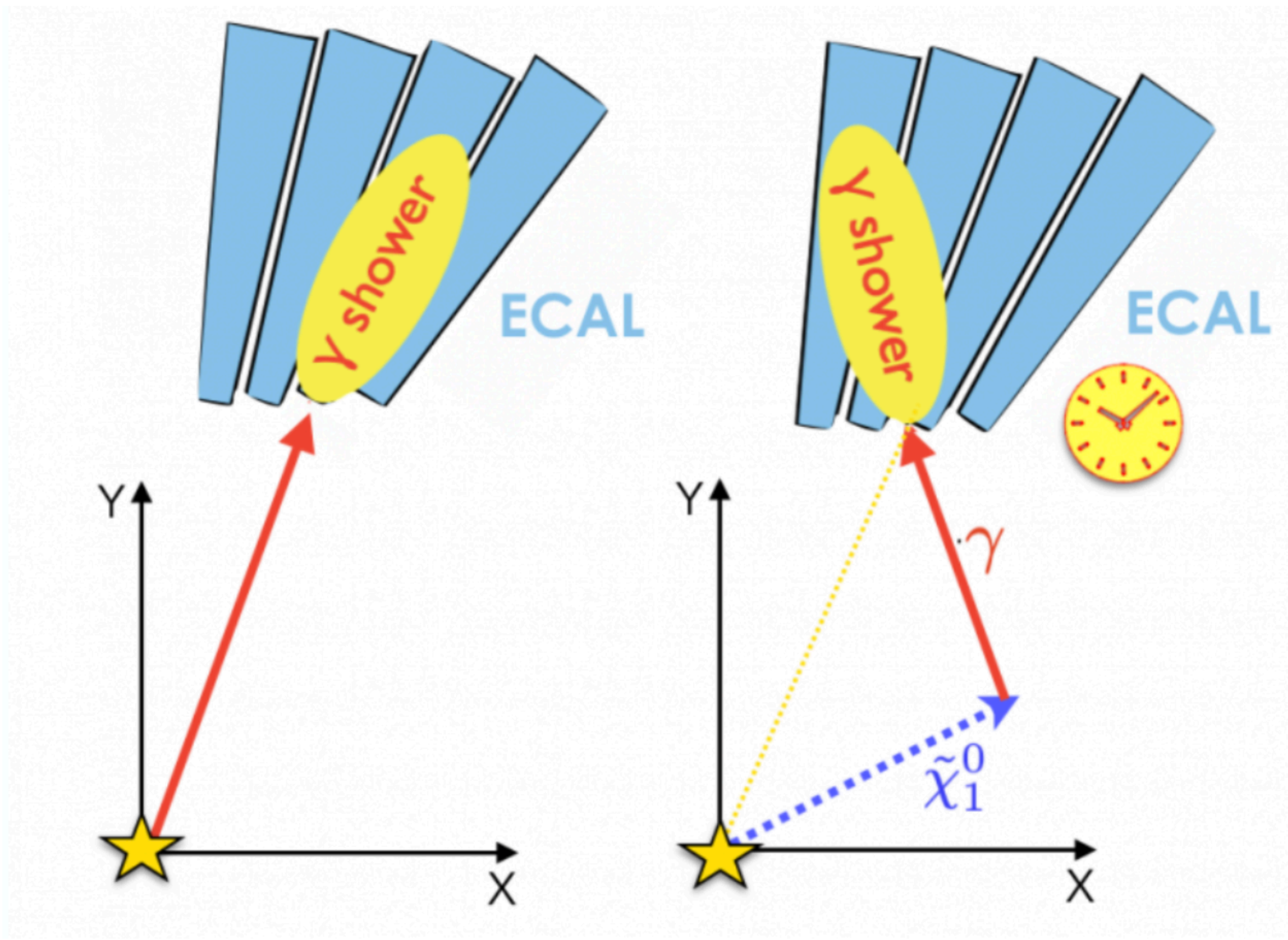
- Gauge-mediated SUSY breaking (GMSB) Dine, Nelson et. al.
- Benchmark scenario commonly known as “Snowmass points and slopes 8” (SPS8) https://www.arxiv.org/abs/hep-ph/0202233
- Gravitino is lightest SUSY particle (LSP)
- Lightest neutralino is next-to-lightest SUSY particle (NLSP)
- Mass of NLSP is is linearly related to the effective scale of SUSY breaking (Λ)
- NLSP-Gravitino coupling can be very weak, leading to long NSLP lifetime
- NLSP to photon+Gravitino is the dominant decay mode

SIGNATURE



Signature: Photon delayed (by order of ns) and slanted at ECAL

SIGNATURE



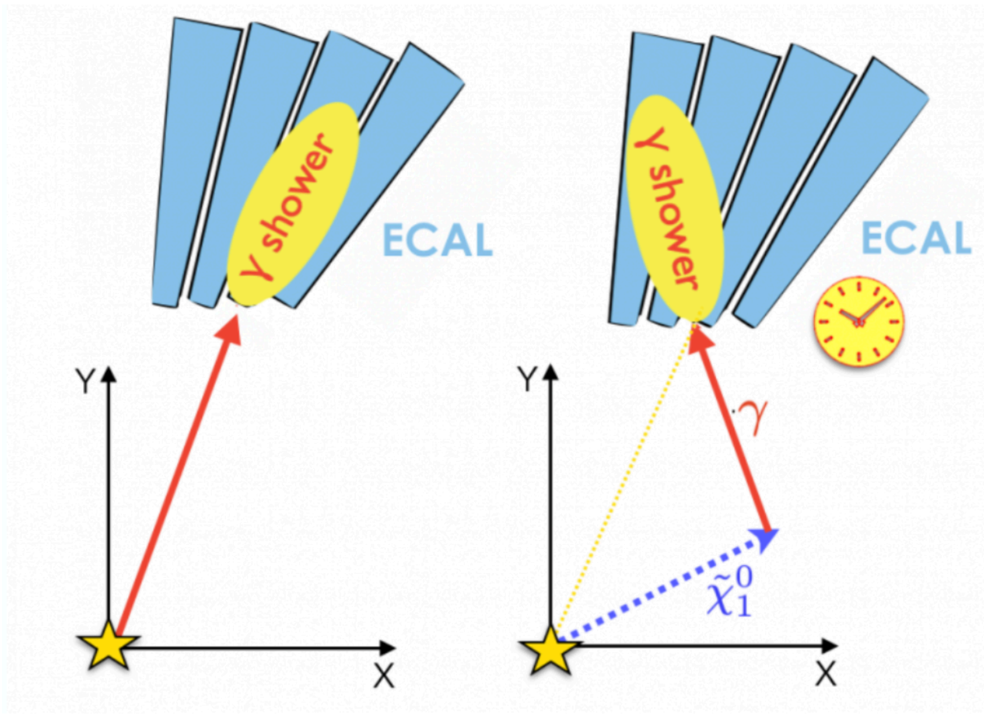
Delayed photons are **missed by usual photon reconstruction algorithm**, due to a cut on ECAL timing, meant to remove out-of-time pile-up.

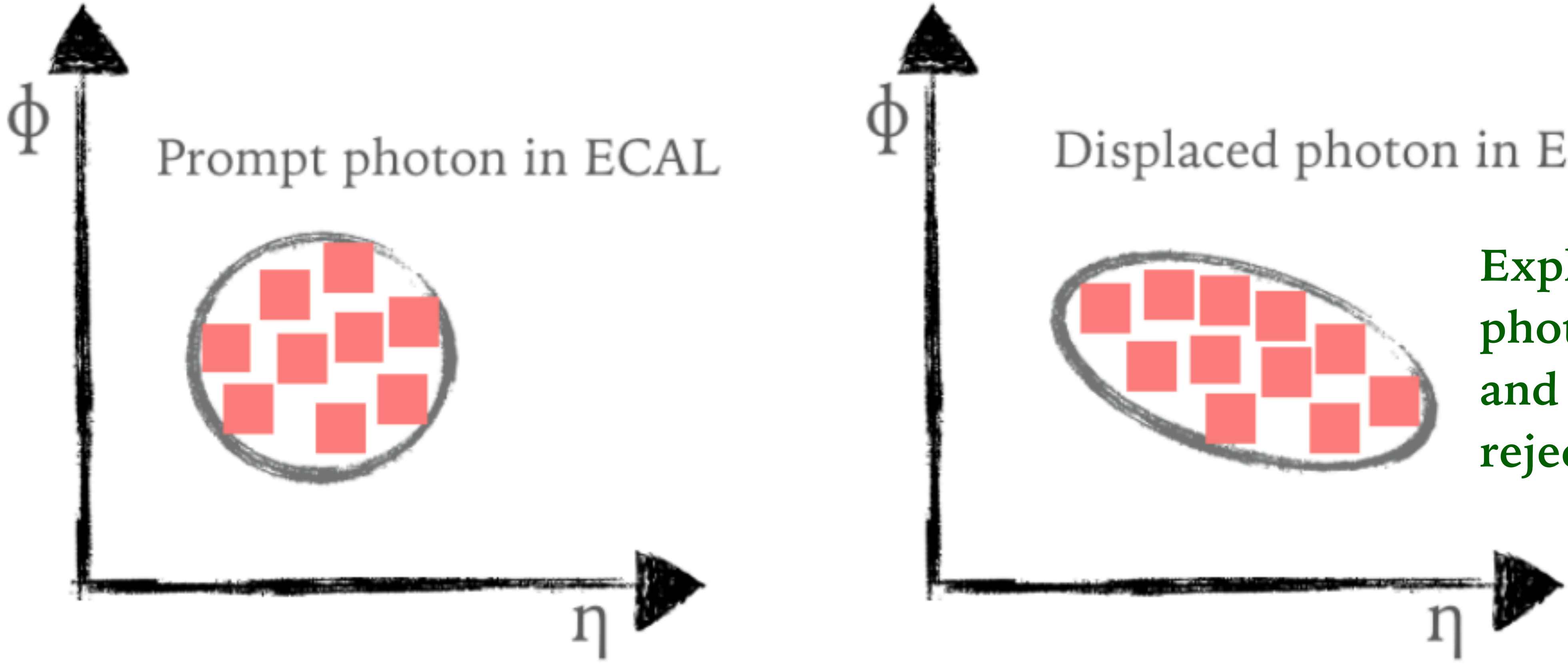
We **removed the timing cut** to be able to perform this search.

We also **introduced a new trigger** to efficiently accept events with displaced photons.

Signature: Photon delayed (by order of ns) and slanted at ECAL

SIGNATURE





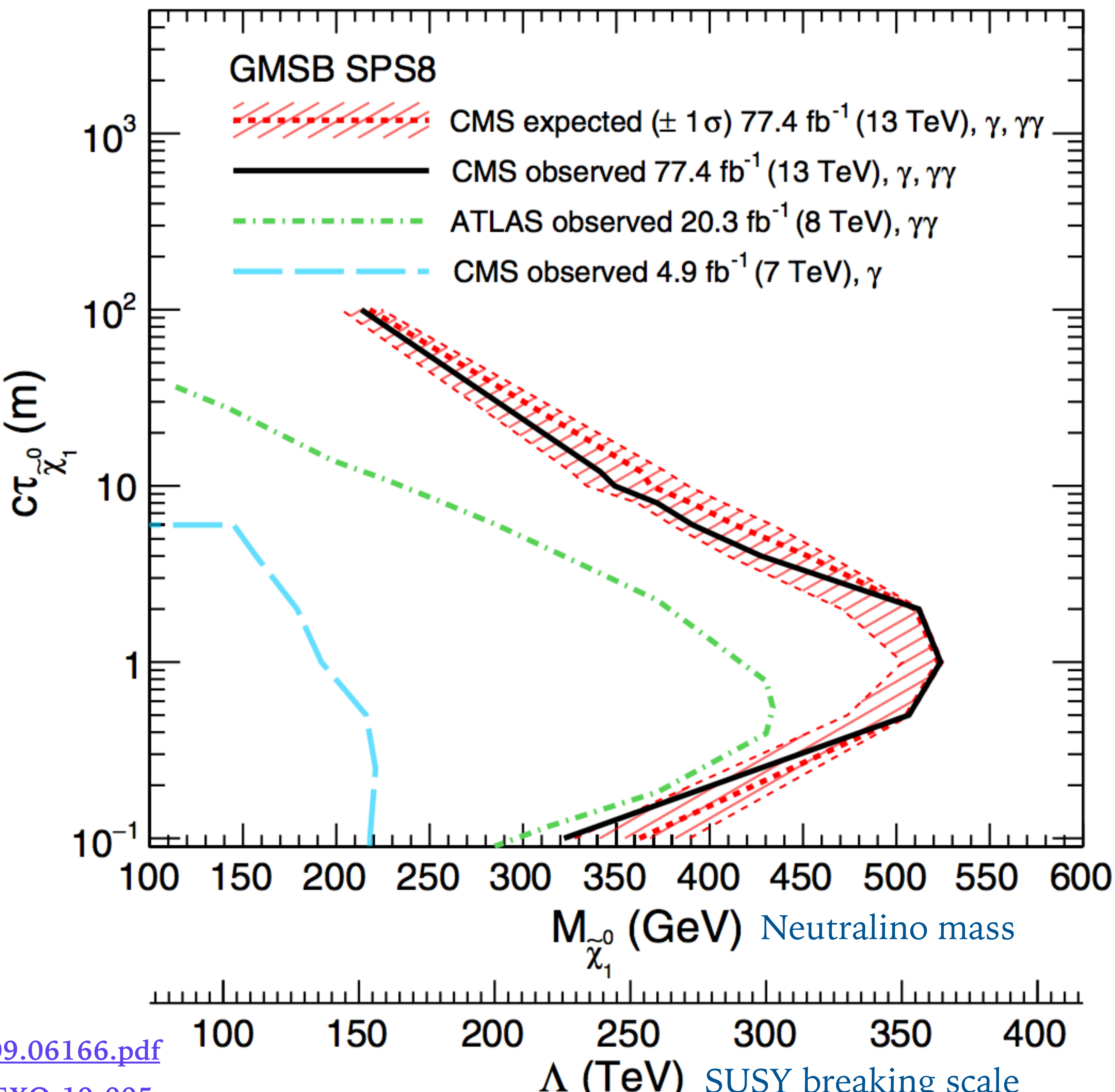
Exploited this in photon identification and background rejection.

Signature: Photon delayed (by order of ns) and slanted at ECAL

- ✓ Armed with a **dedicated trigger**, **tweaked reconstruction algorithm**, and **dedicated photon identification**, the search was performed using 2016+2017 data.

- ✓ No hint of BSM was observed.

Neutralino proper decay length

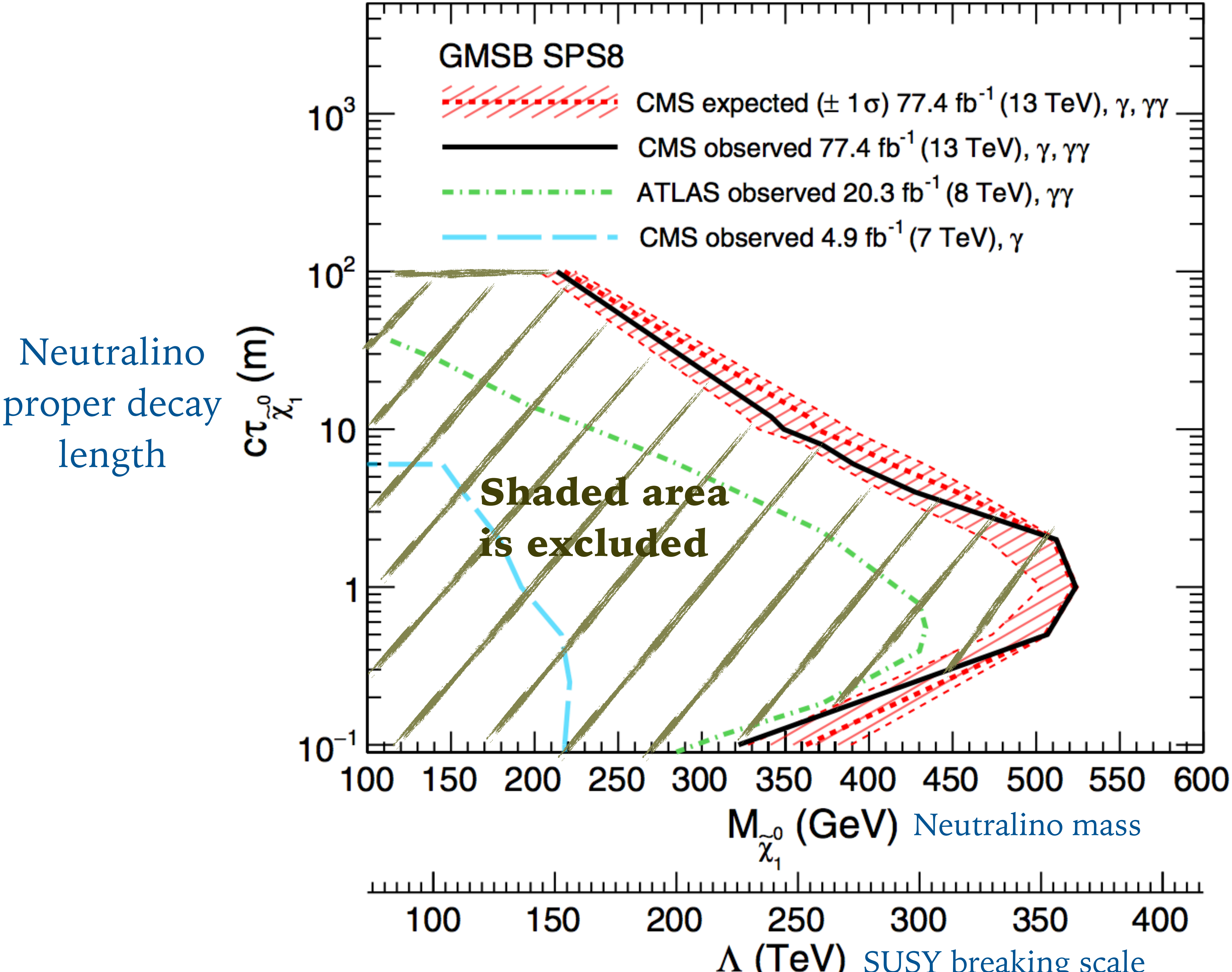


Neutralino mass

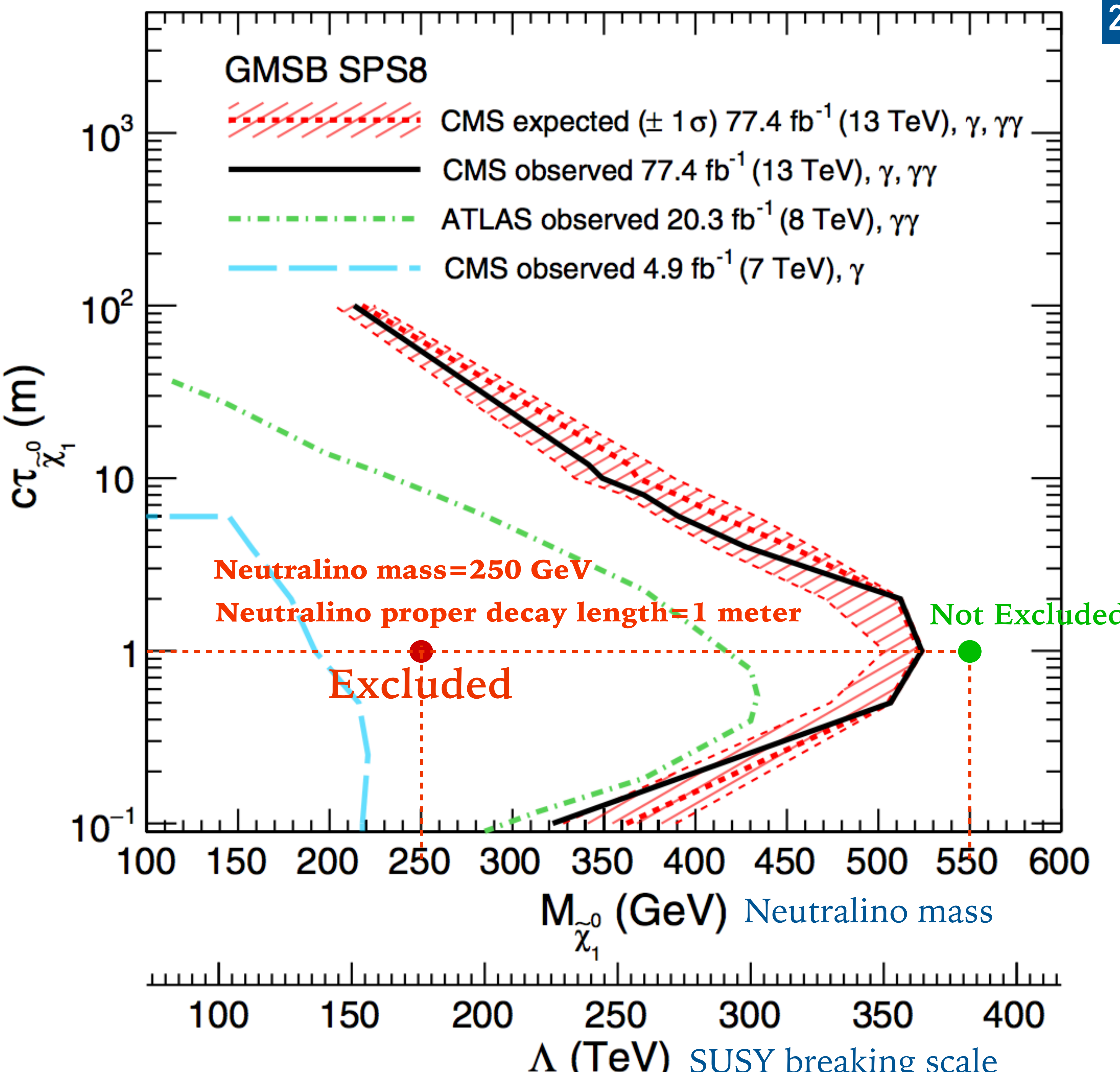
SUSY breaking scale

https://arxiv.org/pdf/1909.06166.pdf

Published in PRD, CMS-EXO-19-005


GMSB SPS8
CMS expected (± 1σ) 77.4 fb-1 (13 TeV), γ, γγ
CMS observed 77.4 fb-1 (13 TeV), γ, γγ
ATLAS observed 20.3 fb-1 (8 TeV), γγ
CMS observed 4.9 fb-1 (7 TeV), γ
Shaded area is excluded
Neutralino proper decay length
cτ (m)
10^3
10^2
10
1
10^-1
100 150 200 250 300 350 400 450 500 550 600
M (GeV) Neutralino mass
100 150 200 250 300 350 400
Λ (TeV) SUSY breaking scale

Neutralino proper decay length



Neutralino mass

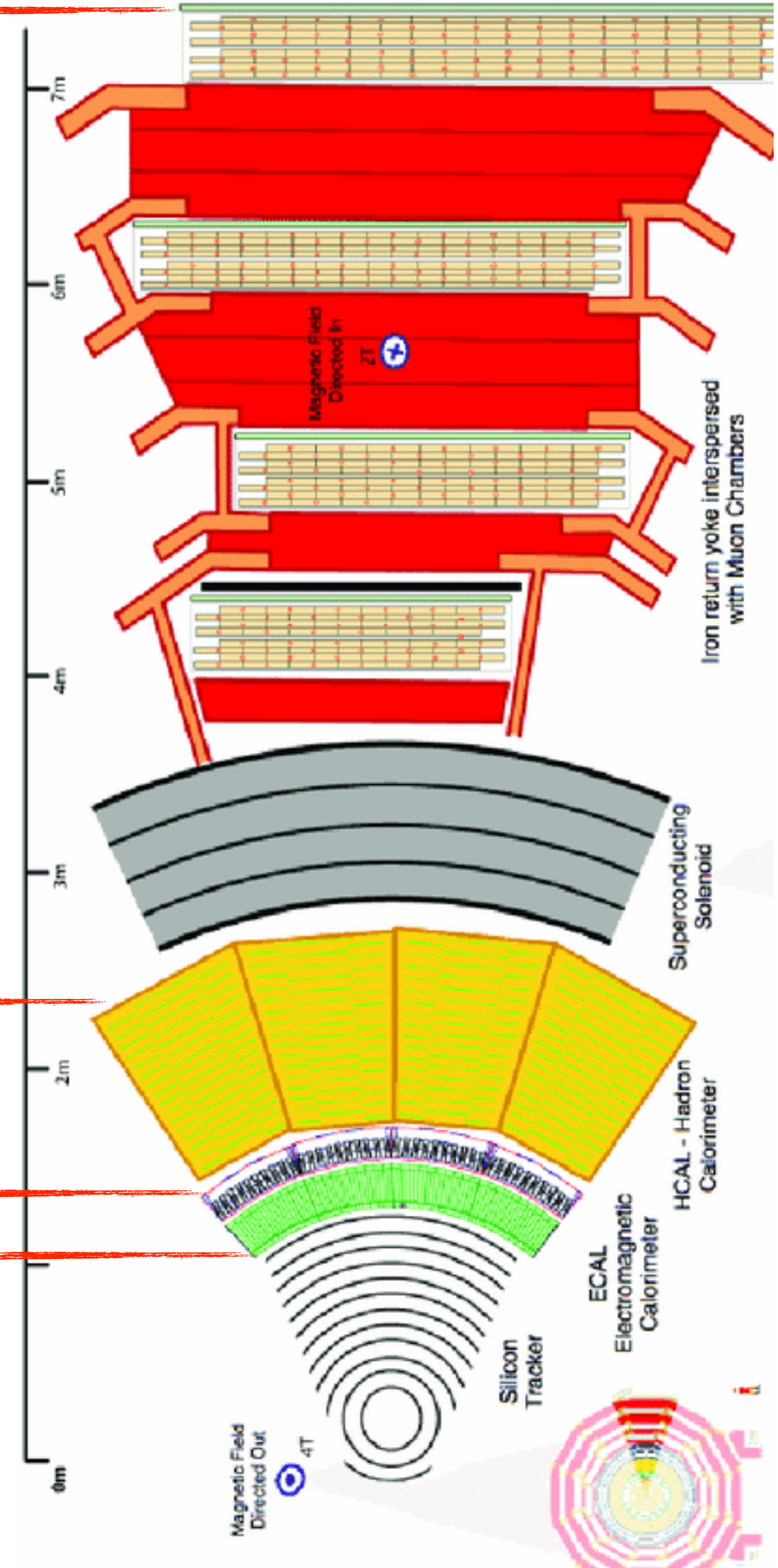
SUSY breaking scale

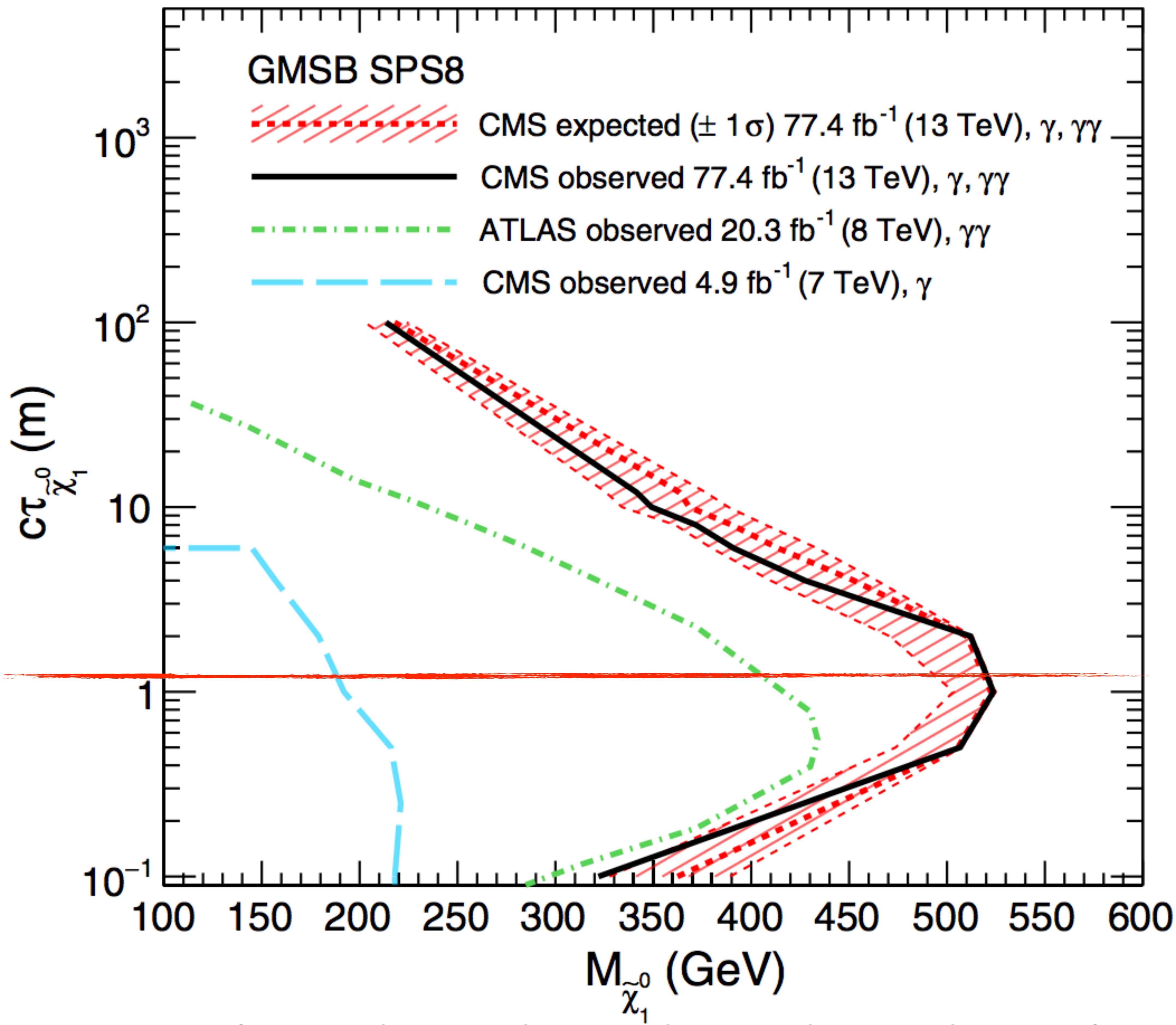
~7.5 meters, end of CMS muon system

~2.9 meters, end of HCAL, beginning of magnet

~1.8 meters, end of ECAL, beginning of HCAL

~1.2 meters, end of tracker, beginning of ECAL



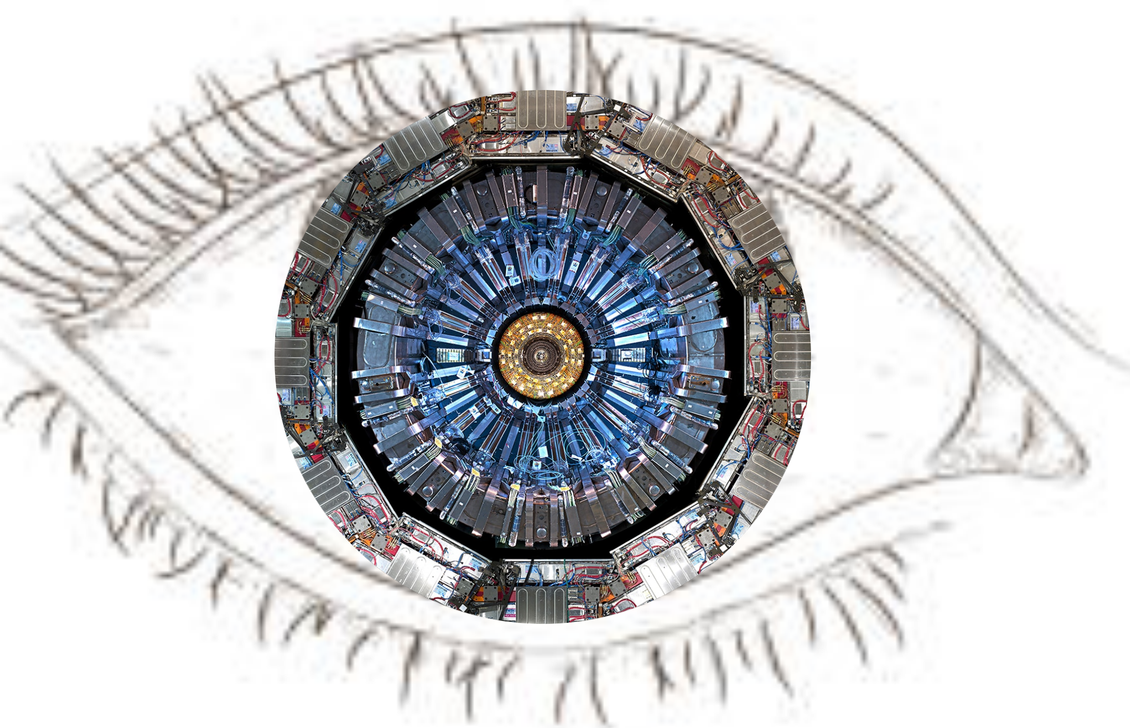


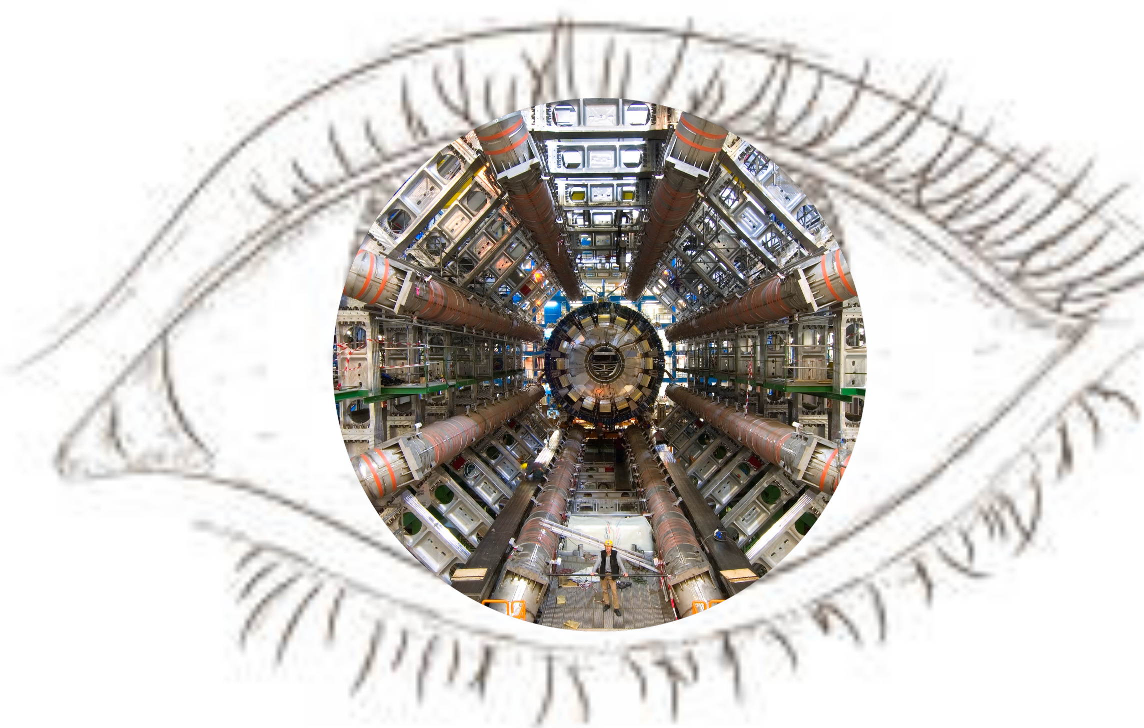
~1.2 meters, end of tracker, beginning of ECAL

Strongest limit

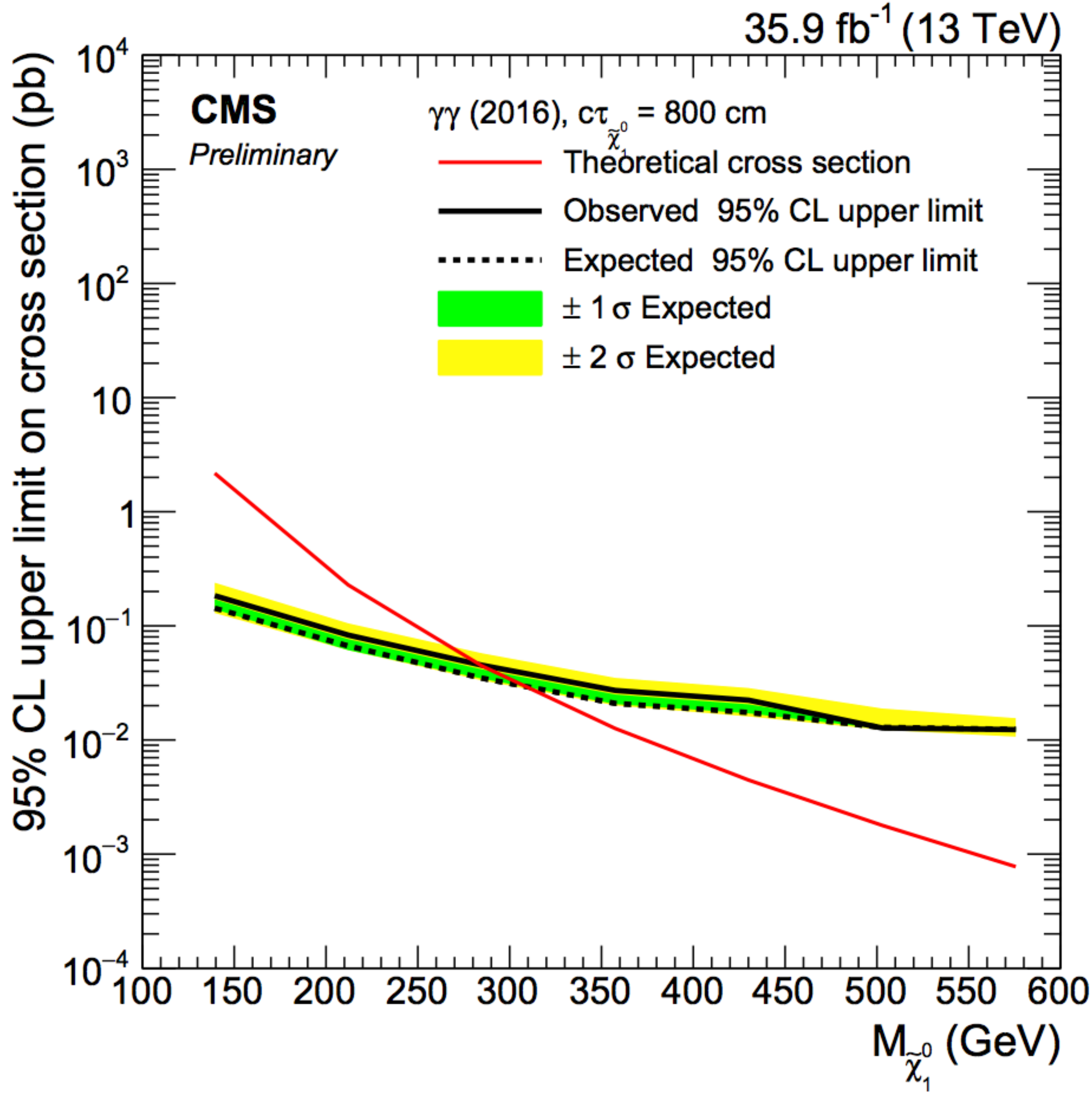
SUMMARY

Both CMS and ATLAS experiments are looking into **complex**, **experimentally challenging** and **innovative** final states in the context of BSM search.

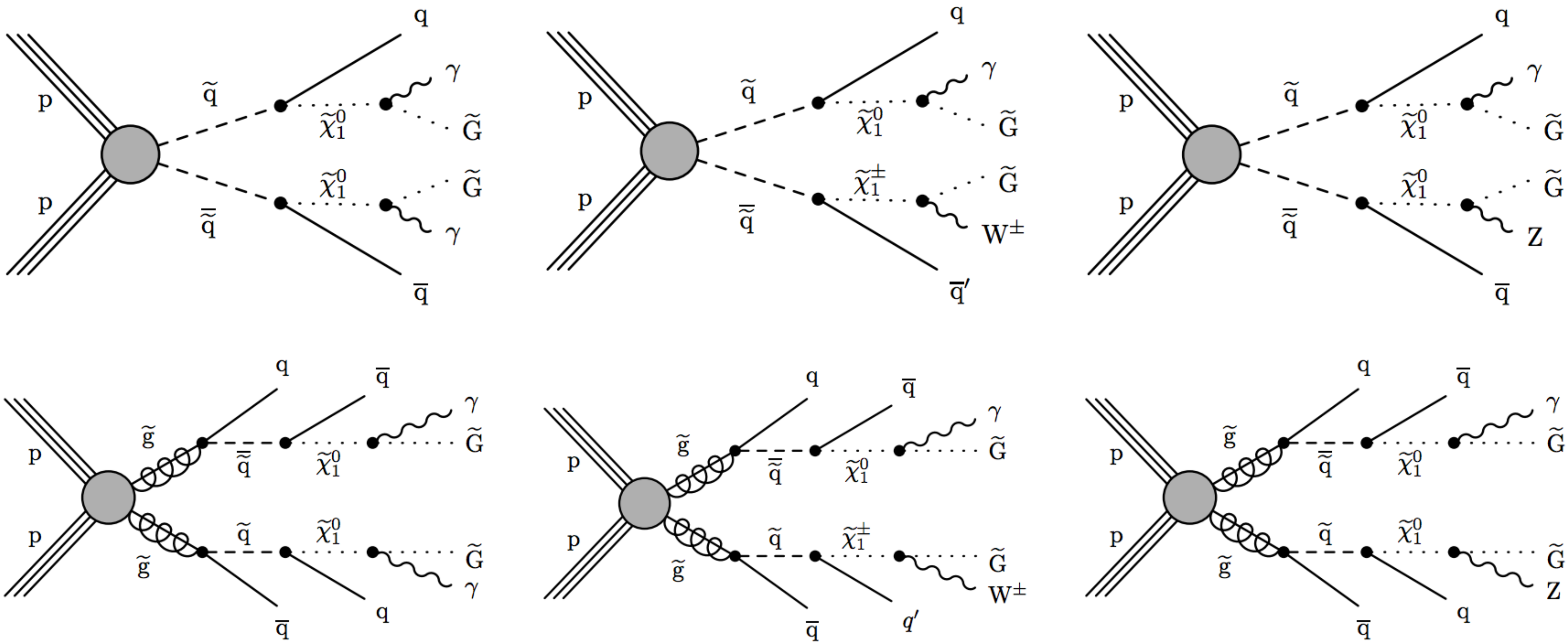




EXTRA SLIDES



35.9 fb^{-1} (13 TeV)
CMS
Preliminary
γγ (2016), $c\tau_{\tilde{\chi}_1^0}$ = 800 cm
Theoretical cross section
Observed 95% CL upper limit
Expected 95% CL upper limit
± 1 σ Expected
± 2 σ Expected
95% CL upper limit on cross section (pb)
$M_{\tilde{\chi}_1^0}$ (GeV)


p
p
$\tilde{q}$
$\bar{\tilde{q}}$
q
$\bar{q}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
γ
$\tilde{G}$
$\tilde{G}$
γ
p
p
$\tilde{q}$
$\bar{\tilde{q}}$
q
$\bar{q}'$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
γ
$\tilde{G}$
$\tilde{G}$
$W^\pm$
p
p
$\tilde{q}$
$\bar{\tilde{q}}$
q
$\bar{q}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
γ
$\tilde{G}$
$\tilde{G}$
Z
p
p
$\tilde{g}$
$\tilde{g}$
q
$\bar{q}$
$\bar{\tilde{q}}$
$\tilde{q}$
$\bar{q}$
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
γ
$\tilde{G}$
$\tilde{G}$
γ
p
p
$\tilde{g}$
$\tilde{g}$
q
$\bar{q}$
$\bar{\tilde{q}}$
$\tilde{q}$
$\bar{q}$
q'
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm$
γ
$\tilde{G}$
$\tilde{G}$
$W^\pm$
p
p
$\tilde{g}$
$\tilde{g}$
q
$\bar{q}$
$\bar{\tilde{q}}$
$\tilde{q}$
$\bar{q}$
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
γ
$\tilde{G}$
$\tilde{G}$
Z

SUSY breaking is communicated through gauge interactions with messenger fields

scale Mm (small compared to the Planck scale), proportional to gauge couplings times Λm.

no flavor changing neutral currents.

messenger fields form complete SU(5) representations to preserve the unification of the coupling constants.

- $\Lambda_m = F_m / M_m$: the scale of SUSY breaking, typically 10–100 TeV;
- $M_m > \Lambda_m$: the messenger mass scale; ***2 times Λm***
- N_5: the equivalent number of $5 + \bar{5}$ messenger fields. ***1***
- $\tan\beta$: the ratio of Higgs vacuum expectation values at the electroweak scale; ***15***
- $\mathrm{sgn}\,\mu = \pm 1$: the sign of the Higgsino mass term; ***+1***
- $C_{\mathrm{grav}} \geq 1$: the ratio of the gravitino mass to the value it would have had if the only SUSY breaking scale were F_m.

```
#  ISAJET SUSY parameters in SUSY Les Houches Accord 2 format
#  Created by ISALHA 2.0 Last revision: C. Balazs 21 Apr 2009
Block SPINFO   # Program information
     1   ISASUGRA from ISAJET          # Spectrum Calculator
     2   7.80   29-OCT-2009 12:50:36   # Version number
Block MODSEL   # Model selection
     1     2   # Minimal gauge mediated (GMSB) model
Block SMINPUTS   # Standard Model inputs
     1     1.27836258E+02   # alpha_em^(-1)
     2     1.16570000E-05   # G_Fermi
     3     1.17200002E-01   # alpha_s(M_Z)
     4     9.11699982E+01   # m_{Z}(pole)
     5     4.19999981E+00   # m_{b}(m_{b})
     6     1.75000000E+02   # m_{top}(pole)
     7     1.77699995E+00   # m_{tau}(pole)
Block MINPAR   # SUSY breaking input parameters
     1     1.00000000E+05   # Lambda scale of soft SSB
     2     2.00000000E+05   # M_mess overall messenger scale
     3     1.50000000E+01   # tan(beta)
     4     1.00000000E+00   # sign(mu)
     5     1.00000000E+00   # N_5 messenger index
     6     9.35083008E+00   # c_grav gravitino mass factor
    51     1.00000000E+00   # N5_1  U(1)_Y messenger index
    52     1.00000000E+00   # N5_2 SU(2)_L messenger index
    53     1.00000000E+00   # N5_3 SU(3)_C messenger index
   101     1.00000000E+00   # Rsl
   102     0.00000000E+00   # dmH_d^2
   103     0.00000000E+00   # dmH_u^2
   104     0.00000000E+00   # d_Y
```

non-minimal GMSB.
NOT USED FOR ANALYSIS

- $\not{R}$, an extra factor multiplying the gaugino masses at the messenger scale. (Models with multiple spurions generally have $\not{R} < 1$.)
- $\delta M^2_{H_d}$, $\delta M^2_{H_u}$, Higgs mass-squared shifts relative to the minimal model at the messenger scale. (These might be expected in models which generate μ realistically.)
- $D_Y(M)$, a $U(1)_Y$ messenger scale mass-squared term (D-term) proportional to the hypercharge Y.
- N_{5_1}, N_{5_2}, and N_{5_3}, independent numbers of gauge group messengers. They can be non-integer in general.

SPS	Point						Slope
mSUGRA:	m_0	$m_{1/2}$	A_0	$\tan\beta$			
1a	100	250	-100	10			$m_0 = -A_0 = 0.4\,m_{1/2},\;\; m_{1/2}$ varies
1b	200	400	0	30			
2	1450	300	0	10			$m_0 = 2\,m_{1/2} + 850\,\mathrm{GeV},\;\; m_{1/2}$ varies
3	90	400	0	10			$m_0 = 0.25\,m_{1/2} - 10\,\mathrm{GeV},\;\; m_{1/2}$ varies
4	400	300	0	50			
5	150	300	-1000	5			
mSUGRA-like:	m_0	$m_{1/2}$	A_0	$\tan\beta$	M_1	$M_2 = M_3$	
6	150	300	0	10	480	300	$M_1 = 1.6\,M_2,\; m_0 = 0.5\,M_2,\;\; M_2$ varies
GMSB:	$\Lambda/10^3$	$M_{\mathrm{mes}}/10^3$	N_{mes}	$\tan\beta$			
7	40	80	3	15			$M_{\mathrm{mes}}/\Lambda = 2,\;\; \Lambda$ varies
8	100	200	1	15			$M_{\mathrm{mes}}/\Lambda = 2,\;\; \Lambda$ varies
AMSB:	m_0	$m_{\mathrm{aux}}/10^3$		$\tan\beta$			
9	450	60		10			$m_0 = 0.0075\,m_{\mathrm{aux}},\;\; m_{\mathrm{aux}}$ varies

SPS 8: GMSB scenario with neutralino NLSP

The NLSP in this scenario is the lightest neutralino. The second lightest neutralino has a significant branching ratio into h when kinematically allowed. The decay of the NLSP into the Gravitino (and a photon or a Z boson) in this scenario can be chosen to be prompt, delayed or quasi-stable.

Point:

$$\Lambda = 100\,\mathrm{TeV}, \quad M_{\mathrm{mes}} = 200\,\mathrm{TeV}, \quad N_{\mathrm{mes}} = 1, \quad \tan\beta = 15, \quad \mu > 0.$$

Slope:

$$M_{\mathrm{mes}}/\Lambda = 2, \quad \Lambda \text{ varies}.$$

The point equals GMSB point 2 of the "Points d'Aix". The slope equals model line E.