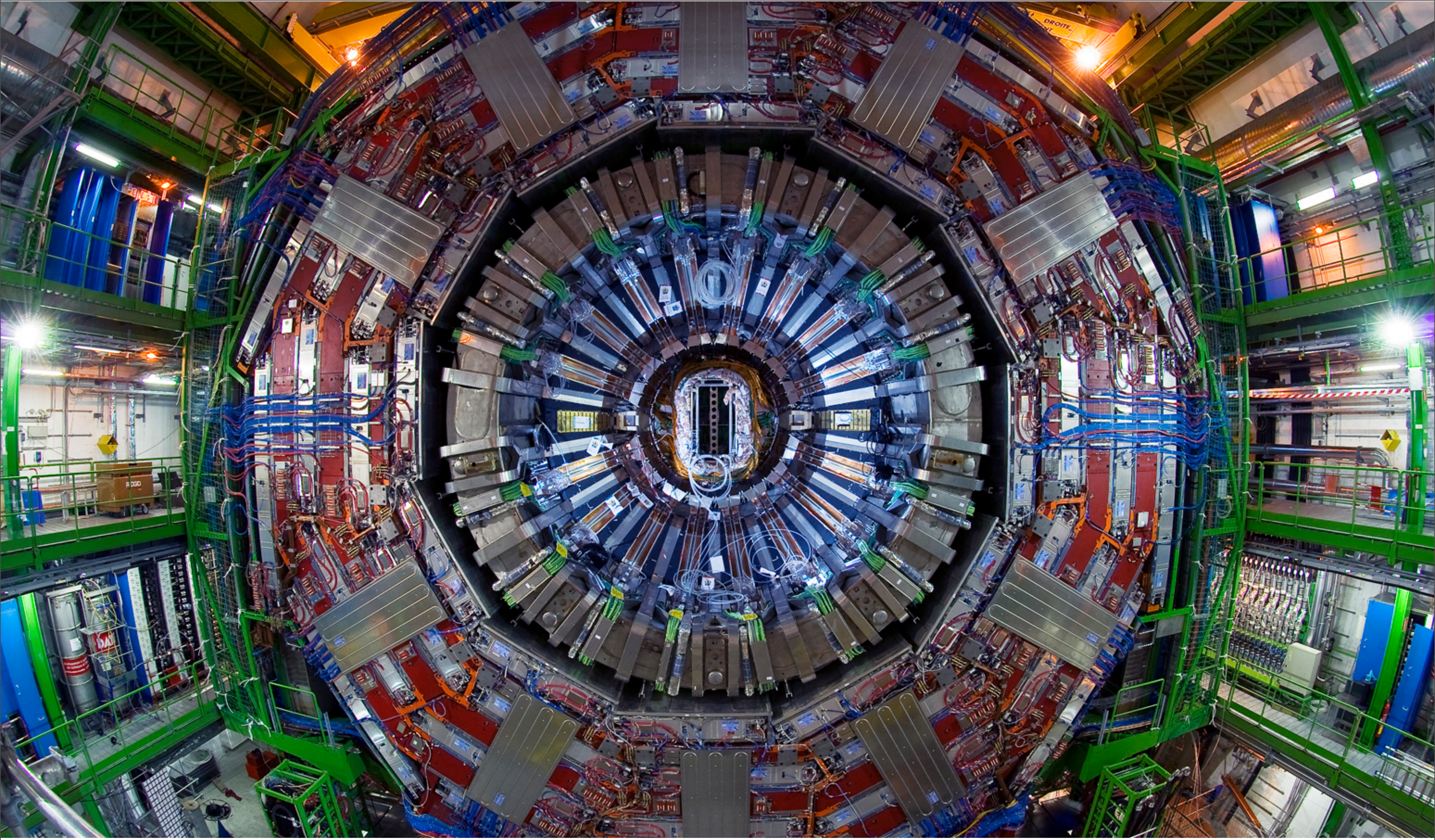
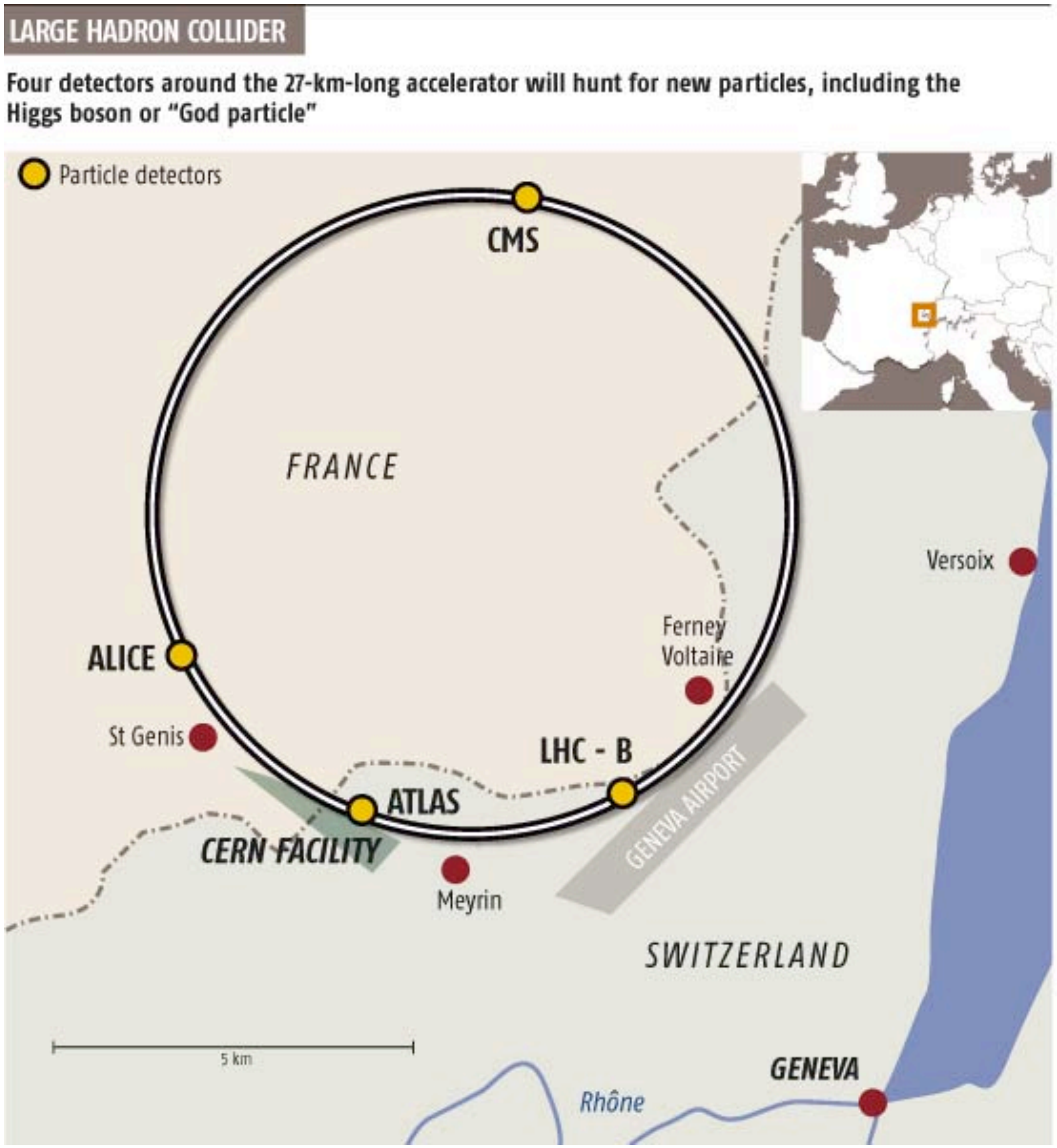


Metastable Particles at the LHC

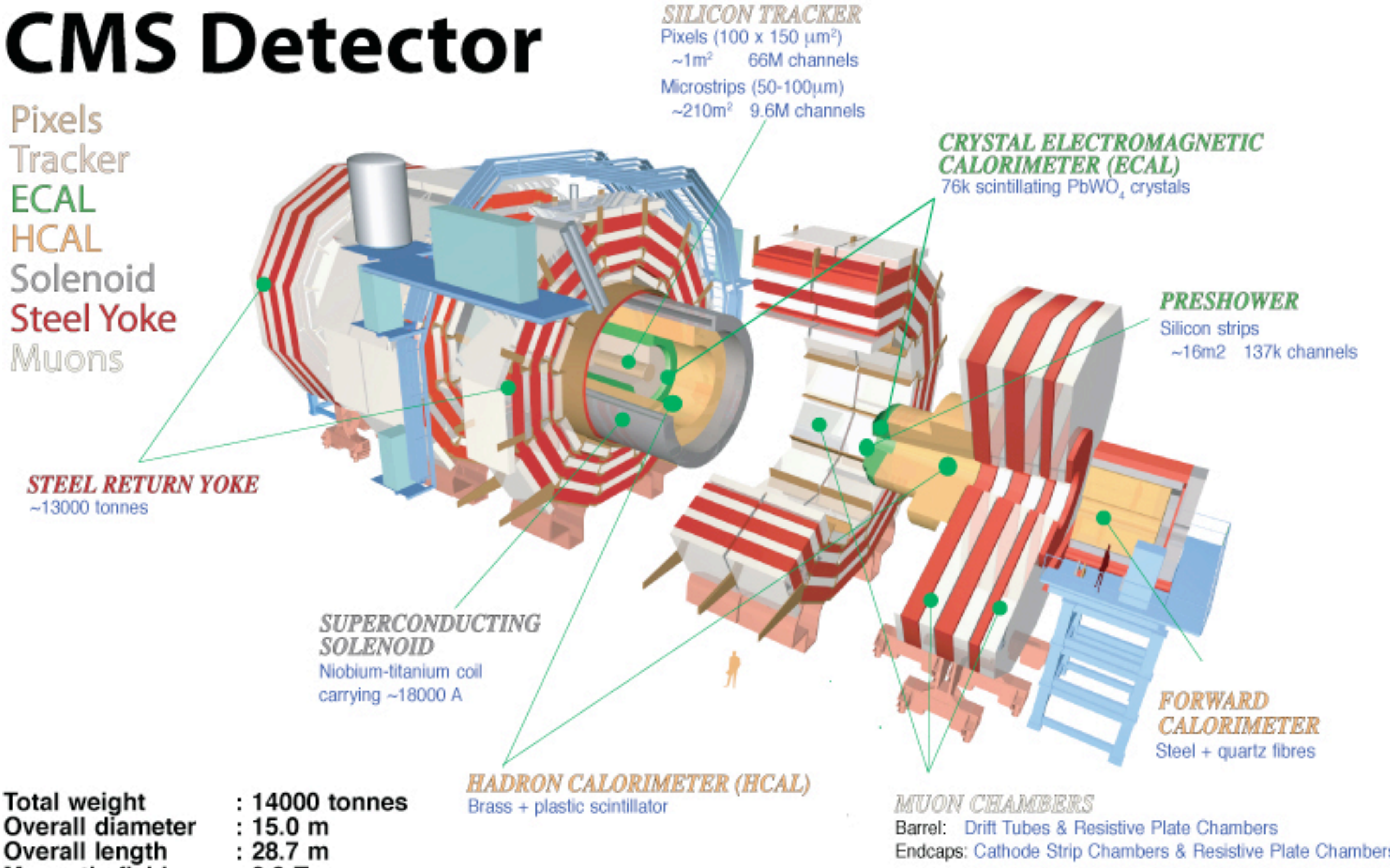
Christopher S. Hill
University of Bristol/Ohio State

When I said LHC, I really meant CMS



- There are two general purpose experiments at the LHC (ATLAS & CMS) in addition to several other more specialised experiments
- Everything I talk about **applies to ATLAS as well as to CMS**
- I will speak only about CMS since I am on CMS
    - ATLAS results not yet available

CMS Detector



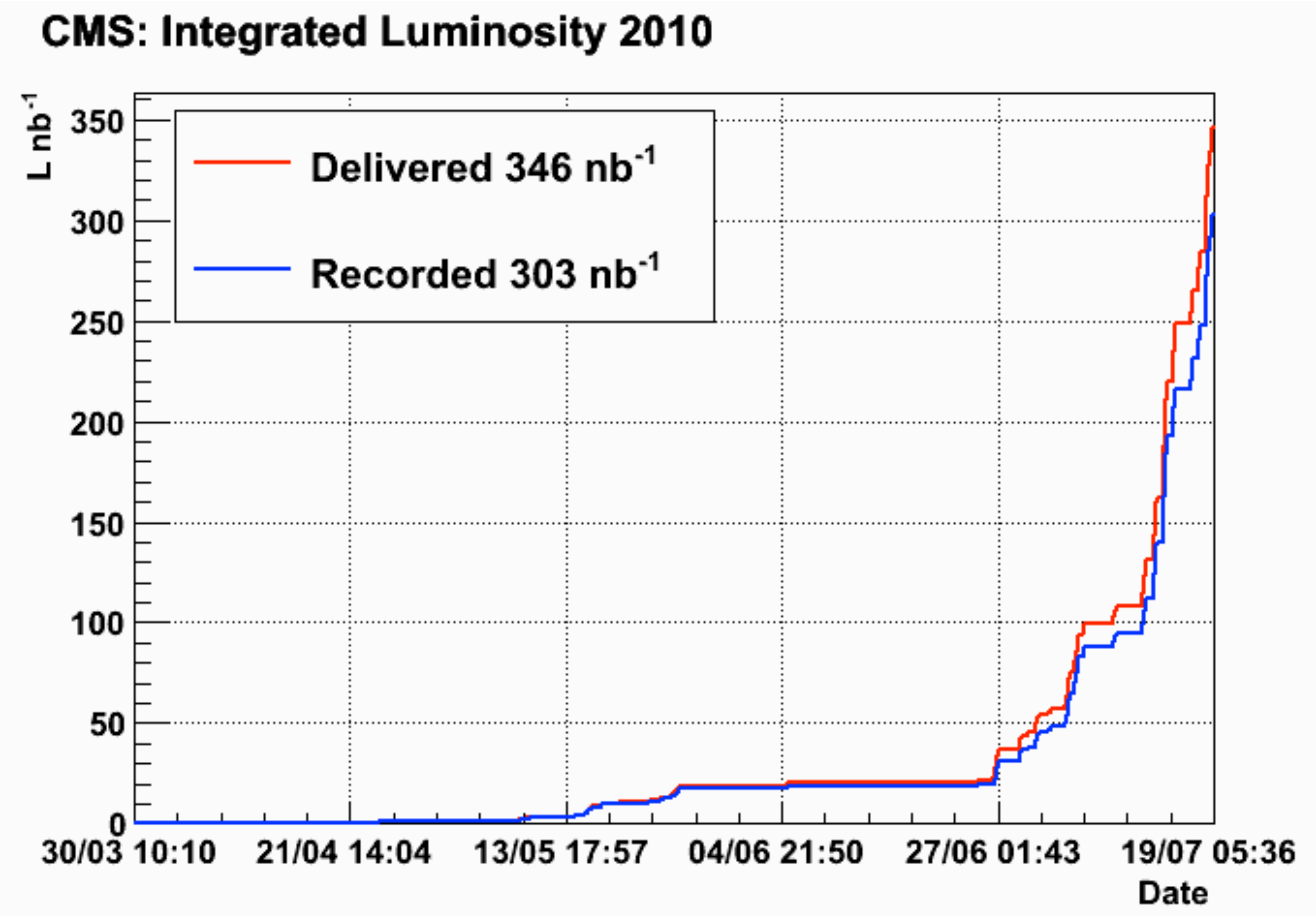
Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

CMS completed and functioning beautifully since ~2008

Long time with no beam from LHC - **important** (come back to this later)

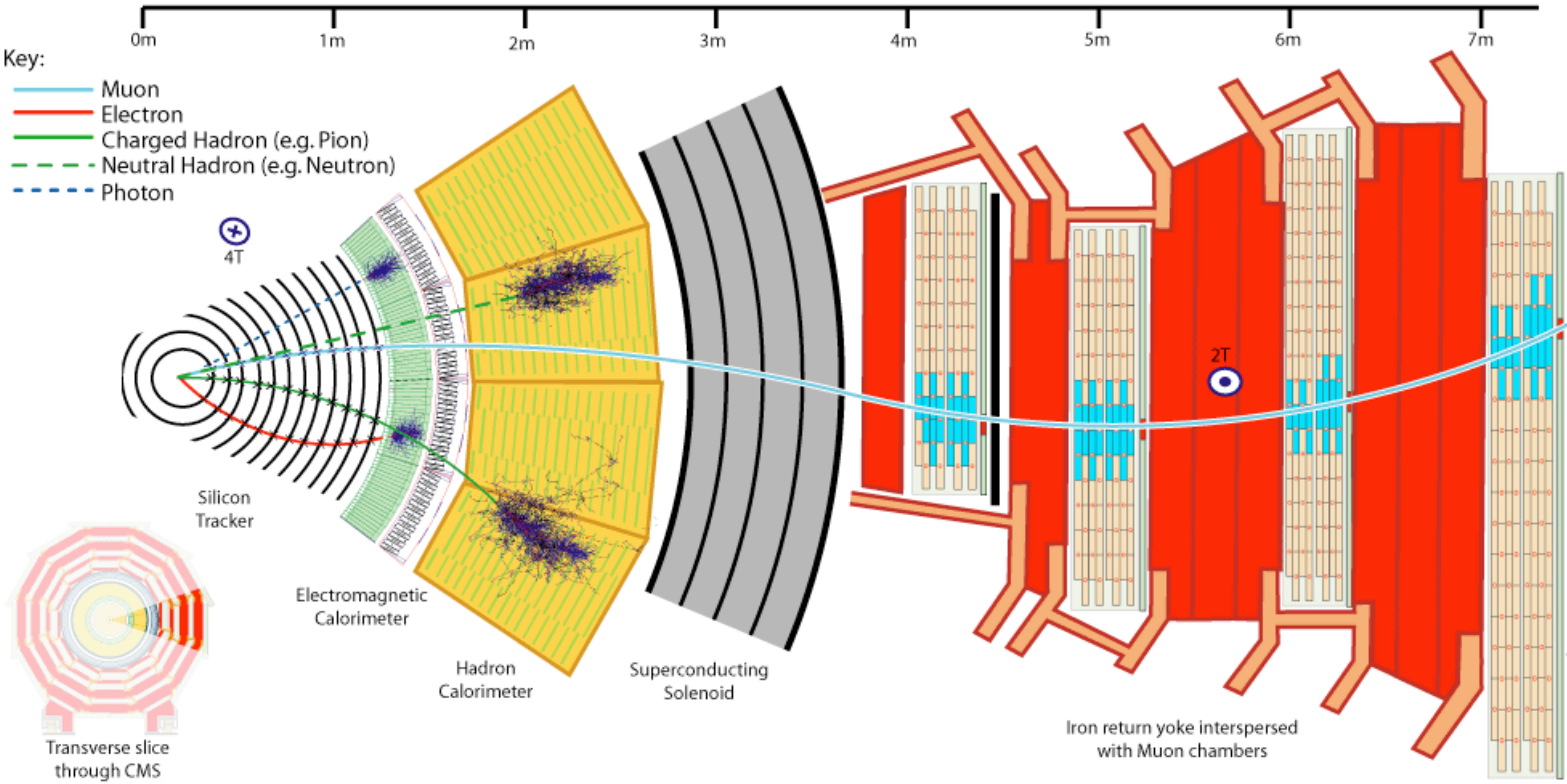
Since late 2009, LHC has also been functioning beautifully

- Short $\sqrt{s}$ = 900 GeV run in Decemeber
- $\sqrt{s}$ = 7 TeV run started on March 30th 2010.
- Very rapid rise in amount of pp collision data recently
  - **Already sensitive to new strongly produced particles** (with lowish masses)



What will we find in these data?

- Well known problems (e.g. hierarchy) with the standard model
- Many extensions to SM have been proposed
- Finding out which, if any, of these exciting ideas are correct is **what the LHC (and CMS) was built to do**
- We will find SUSY, extra-dimensions, black-holes, unparticles, etc if they exist
    - As you know, some of these things provide good dark matter candidates



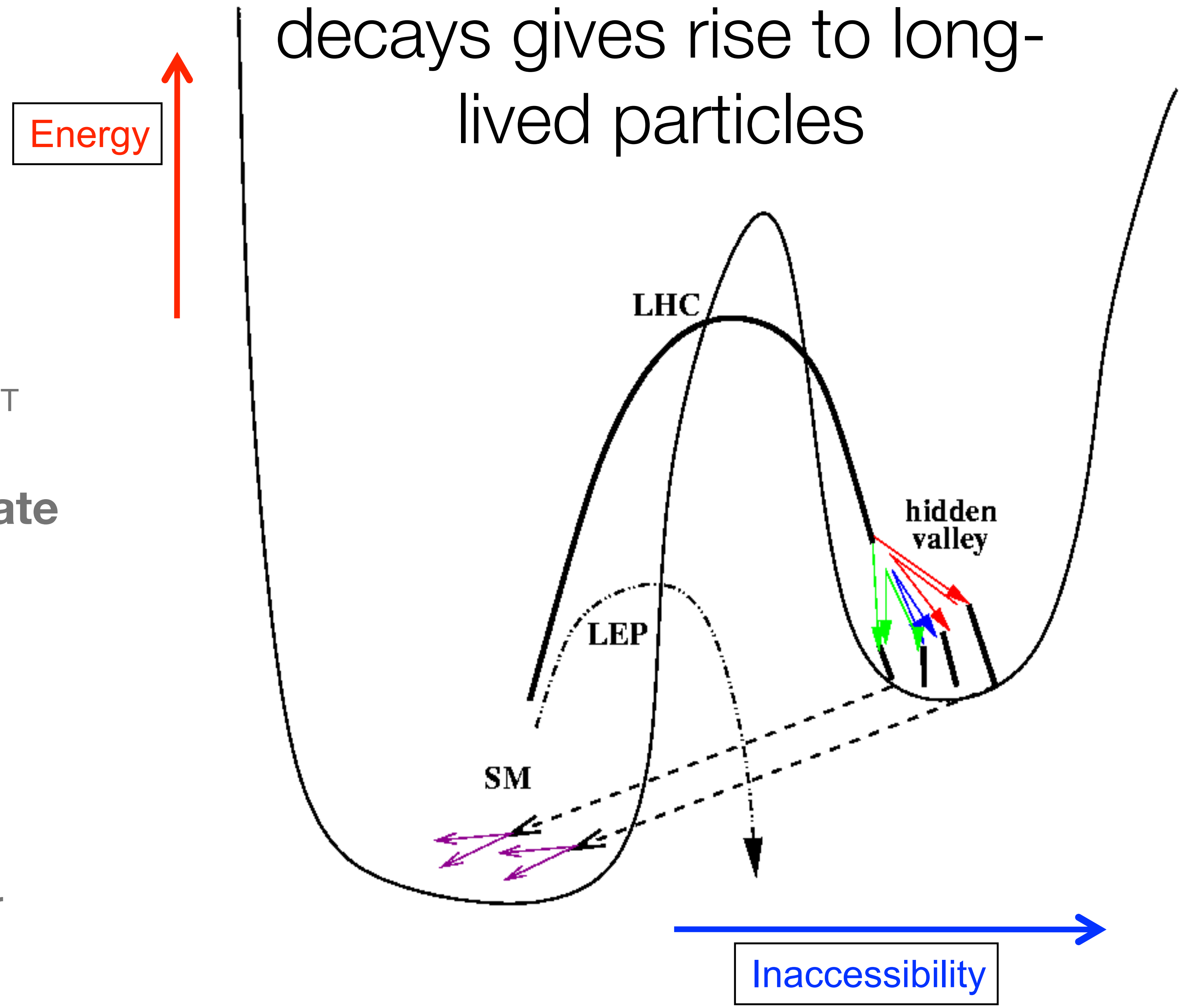
But wait. What I just said is only guaranteed true if the new particles decay ≤ 10 ns

Because normal event reconstruction won't "work" for long-lived particles

But there is a lot of physics we could miss then!

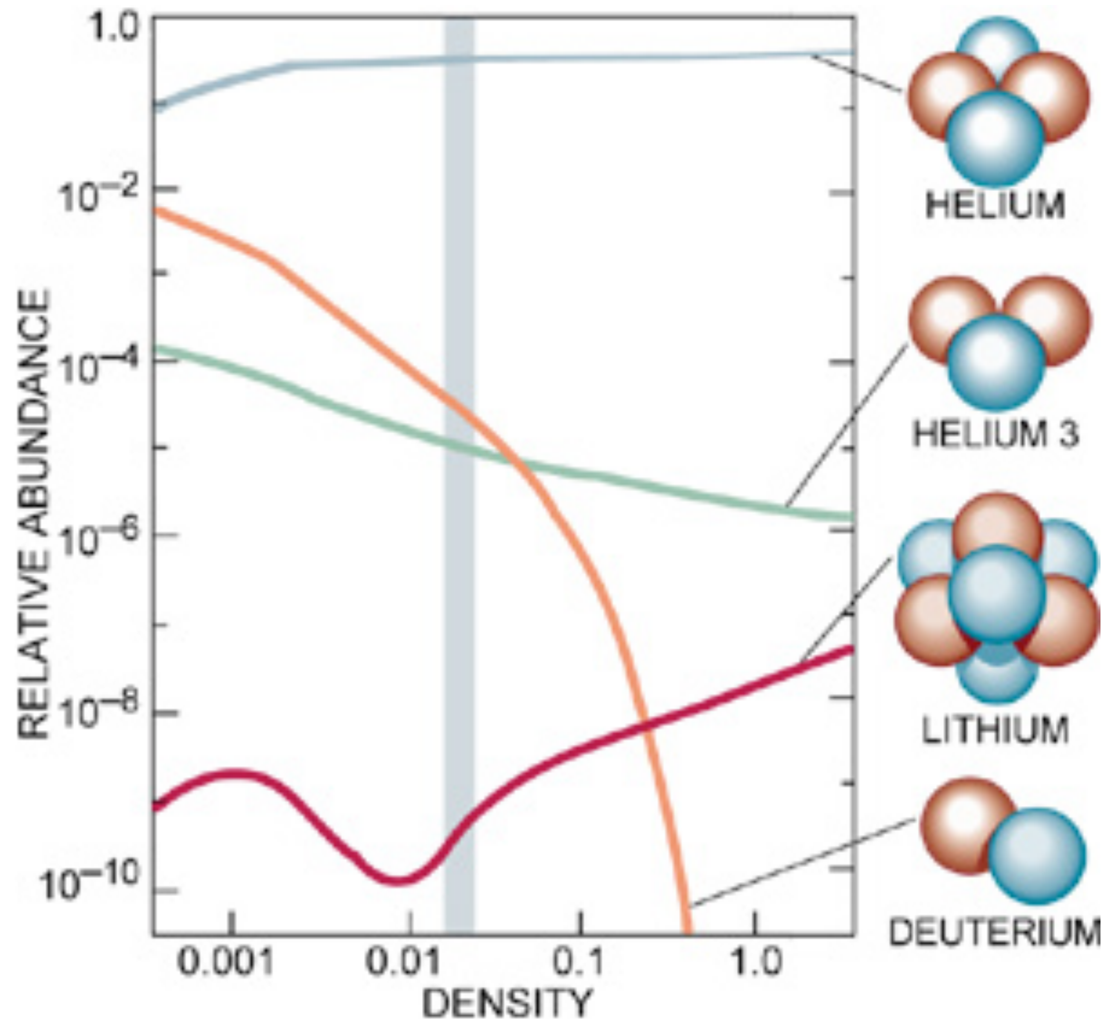
- There are many theoretical scenarios in which a particle could have a long lifetime
  - **Hidden Valleys** - a barrier separates HV from SM
  - **GUTs** - suppressed by M_{GUT}
  - SUSY with nearly **degenerate masses** - suppressed by phase space factor
  - **“Split” SUSY**
  - Some of these might have implications for dark matter

Any physics with suppressed decays gives rise to long-lived particles



There are cosmological reasons for long-lived particles too

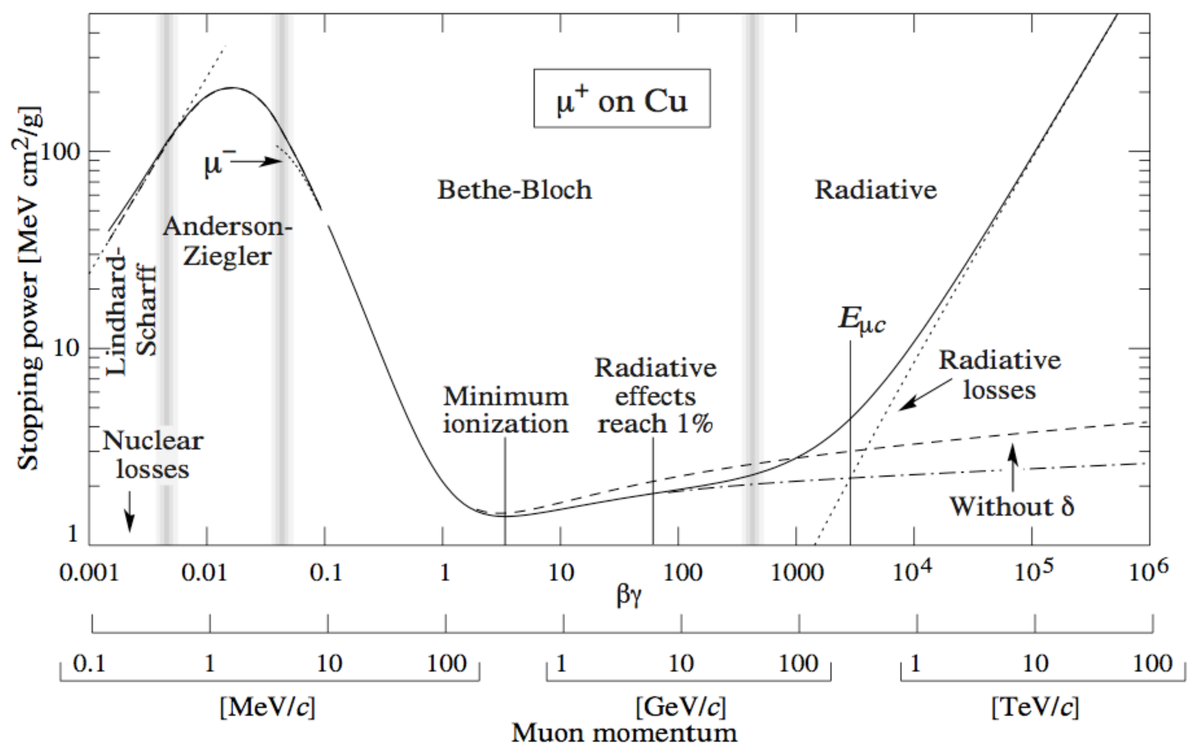
- New heavy particles will leave an imprint on abundances of light elements during BBN
  - Energetic neutrons from their decay impinge on nuclei affecting reactions
  - **Observed ^{7}Li is below that predicted** by conventional BBN
  - **Observed ^{6}Li abundance** significantly **above**
- Long lived **particle with τ~1000 s** can naturally destroy the correct amount of ^{7}Li and produce the correct amount of ^{6}Li



If **τ**~1000 s, could resolve Li anomaly

How do you look for these long-lived particles?

- Firstly, you **hope they are charged** (at least some of the time)
  - Complete neutrals can only be inferred from missing energy which I won't cover today
- Because, if charged, these **particles will lose energy as they traverse the detector**
- *Traditional approach* - exploit fact that being new heavy-ish particles, they will be slow moving
  - Consequently will have **longer than normal time-of-flight**
  - Will lose energy more quickly than "normal" minimum ionizing particles, i.e. **higher dE/dx**



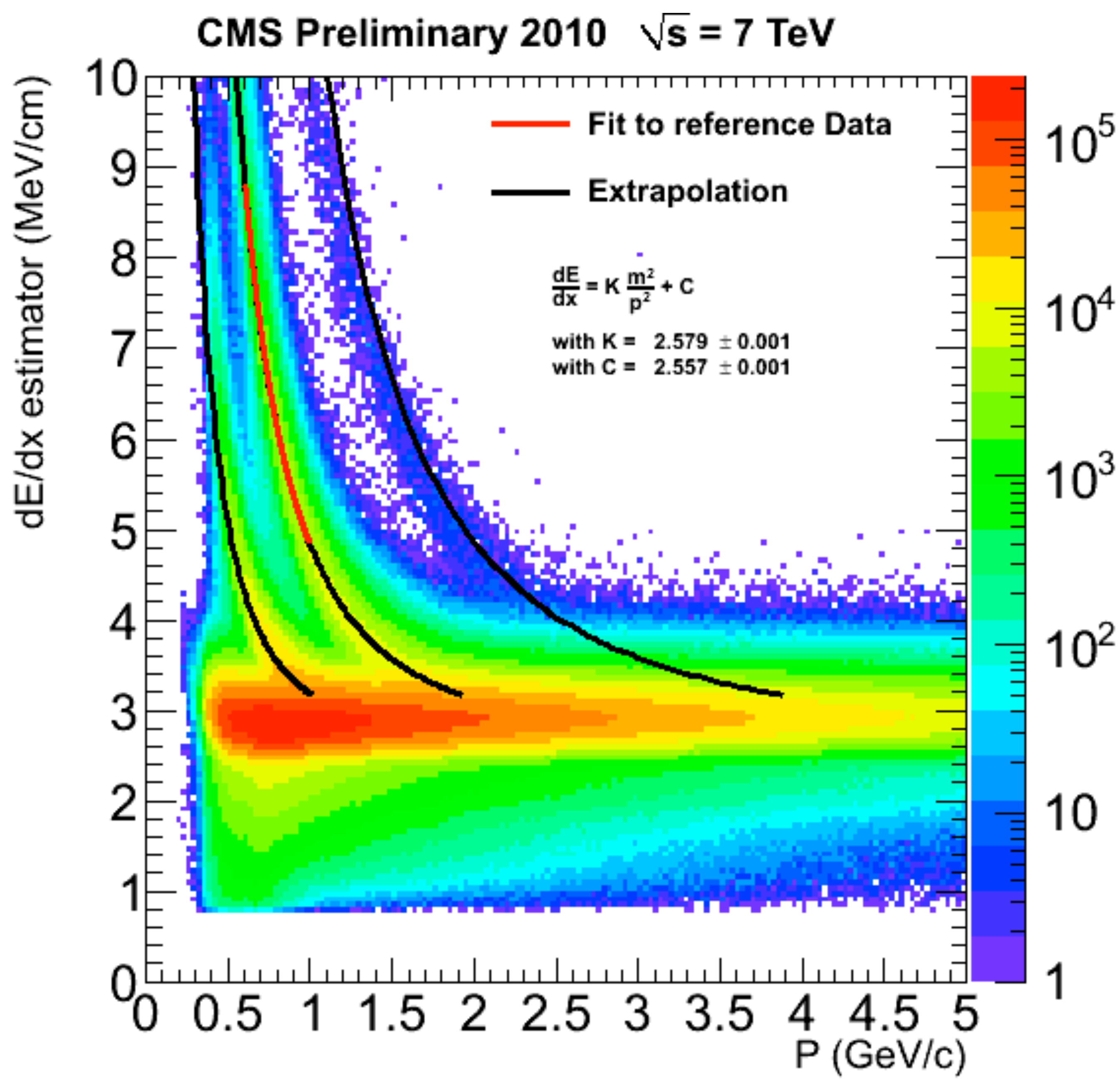
But these techniques only get you access to slightly longer lifetimes … at some point the particles exit CMS

CMS has carried out such a search for Heavy Stable Charged Particles (HSCP)

- Select tracks with high p_T and dE/dx
- Mass reconstruction
  - Approximate Bethe-Bloch formula before minimum

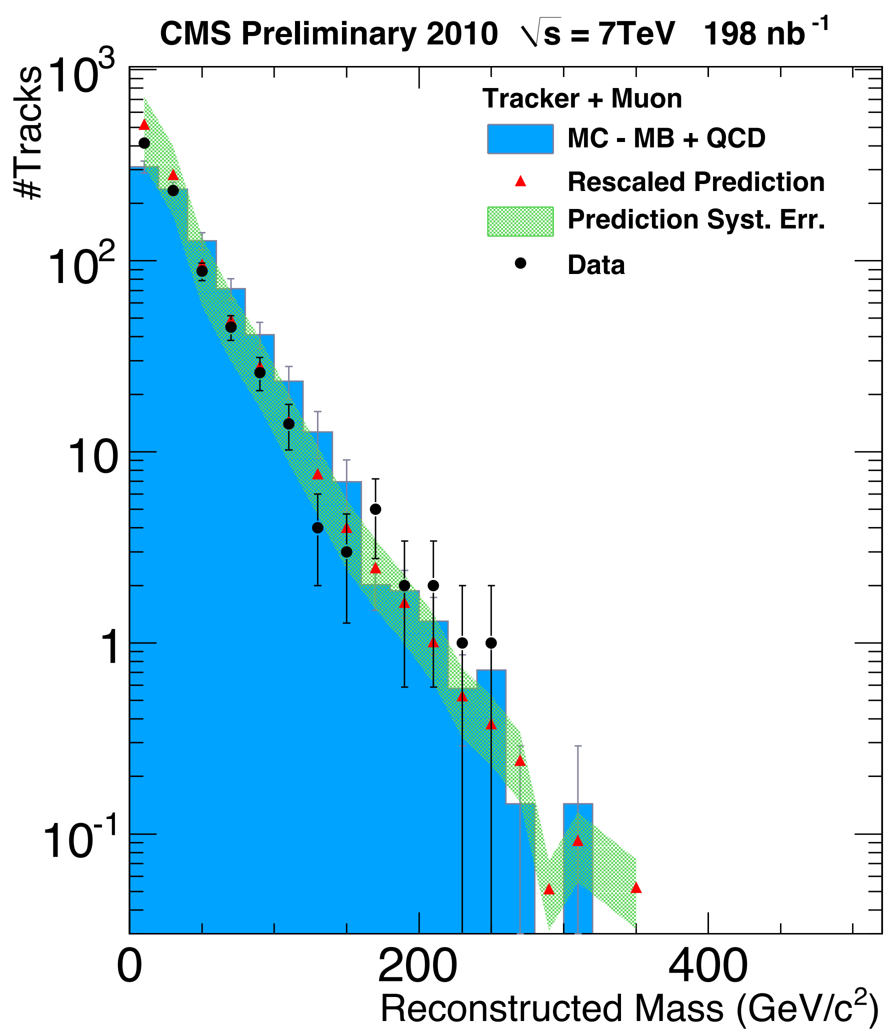
$$I_h = K\frac{m^2}{p^2} + C$$

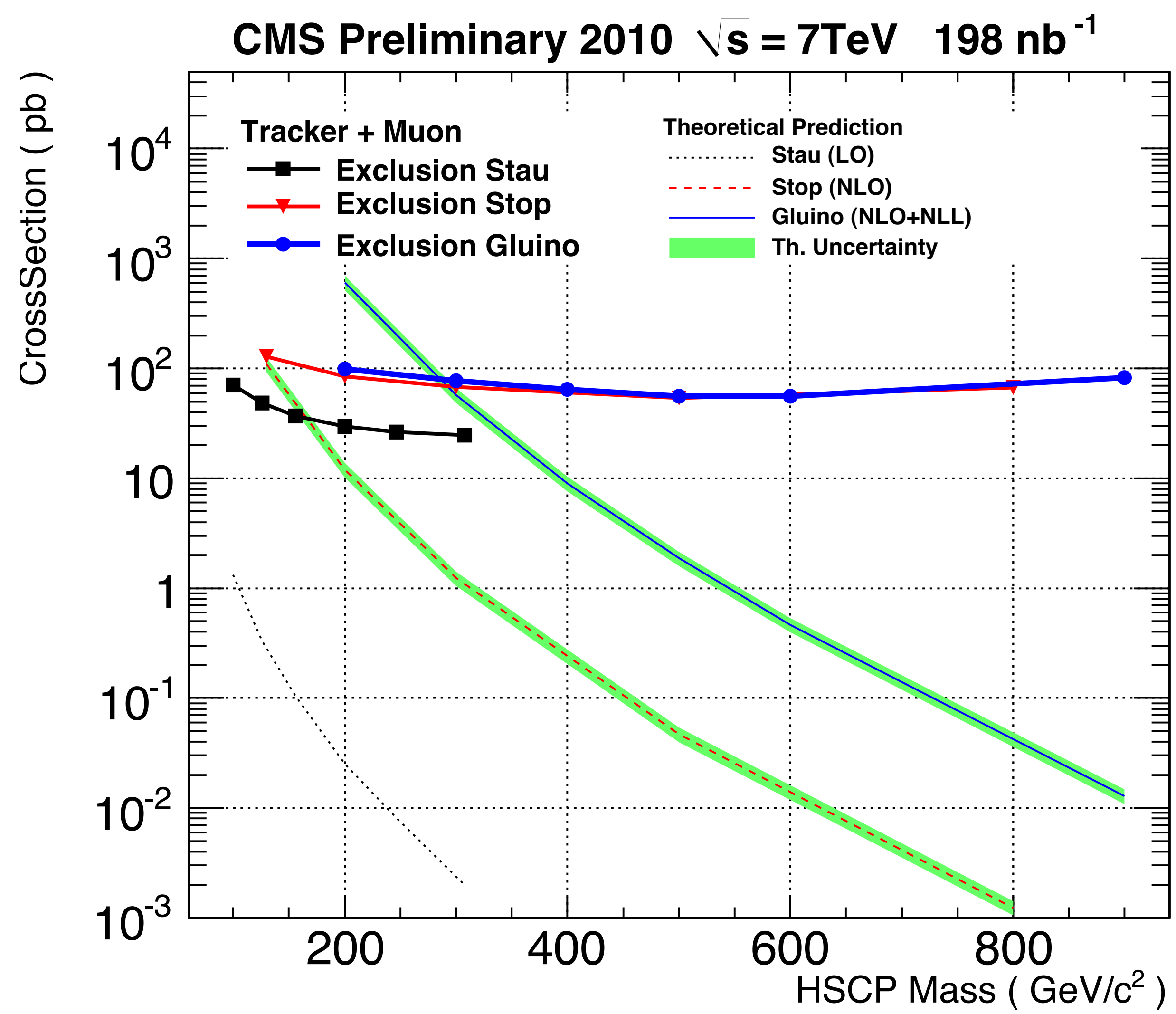
- Extract parameters K, C by fitting to the proton line
- Reverse to compute higher masses



Results of HSCP Search in 198 nb^{-1}

- Mass distribution as expected, no events observed in signal region
- Set 95 % C.L. limits on gluinos (bound into R-hadrons), stop, stau, production





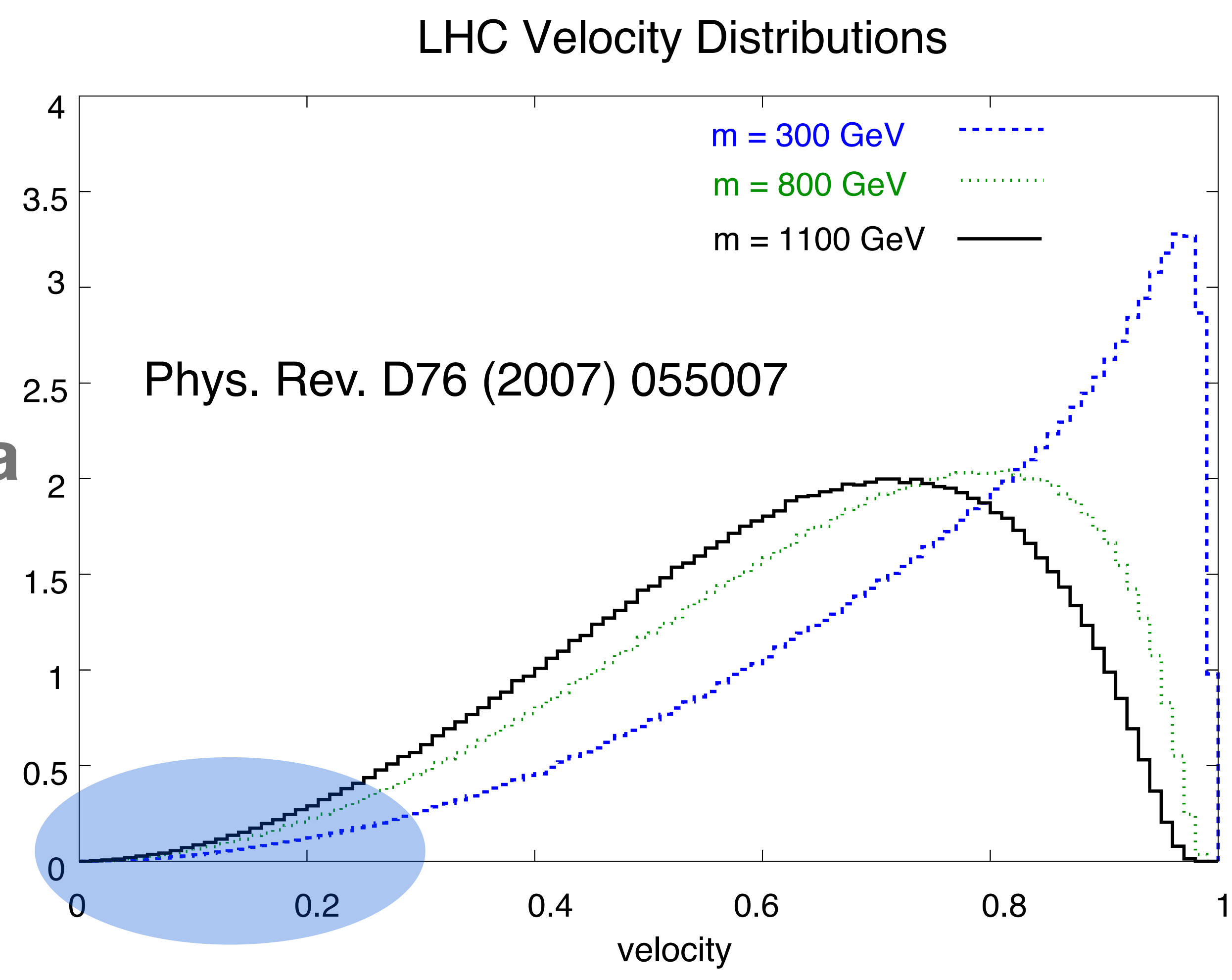
TIGHT	Exp.	Obs.	Exp. in full spectrum	Obs. in full spectrum
Muon-like	0.153 ± 0.061	0	0.249 ± 0.050	0
Tk-only	0.060 ± 0.021	0	0.060 ± 0.011	0

Exclude m_{g} < 284 GeV/c^2

(not yet competitive with Tevatron)

Another Approach - Stopped Gluinos

- As said, gluinos bound into R-hadrons will **lose energy**
  - via ionization (if charged)
  - and/or nuclear interactions
- **Some fraction, those with less than a critical velocity will come to rest** somewhere inside the detector volume
  - most likely in the densest regions

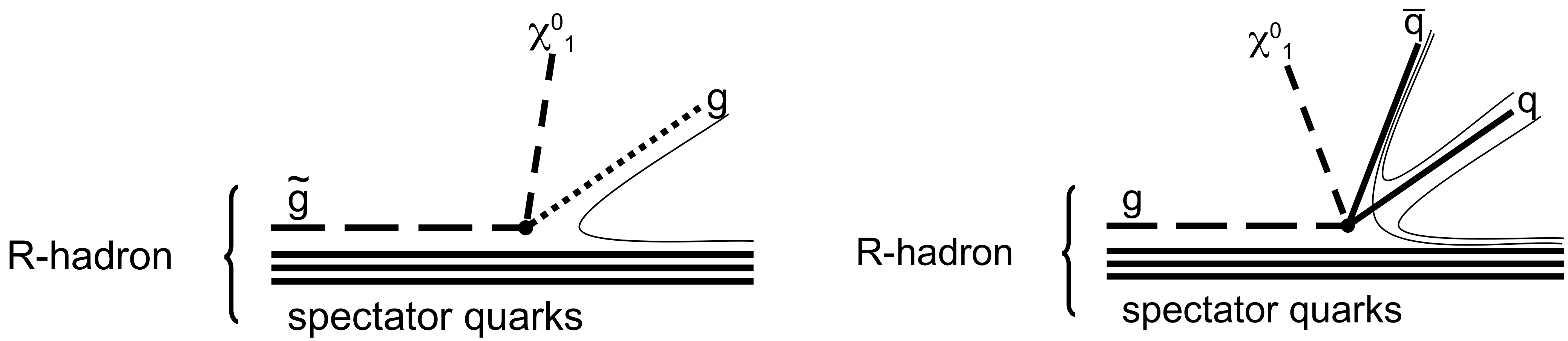


$$v \leq \left(\frac{4x}{x_0}\right)^{\frac{1}{4}} \left(\frac{500\text{GeV}}{m_{\tilde{g}}}\right)^{\frac{1}{4}}$$

Can only stop the slowest gluinos, but this fraction is not negligible even for relatively light masses

x is thickness of material, x_0 is material dependent parameter

They're long-lived, not immortal



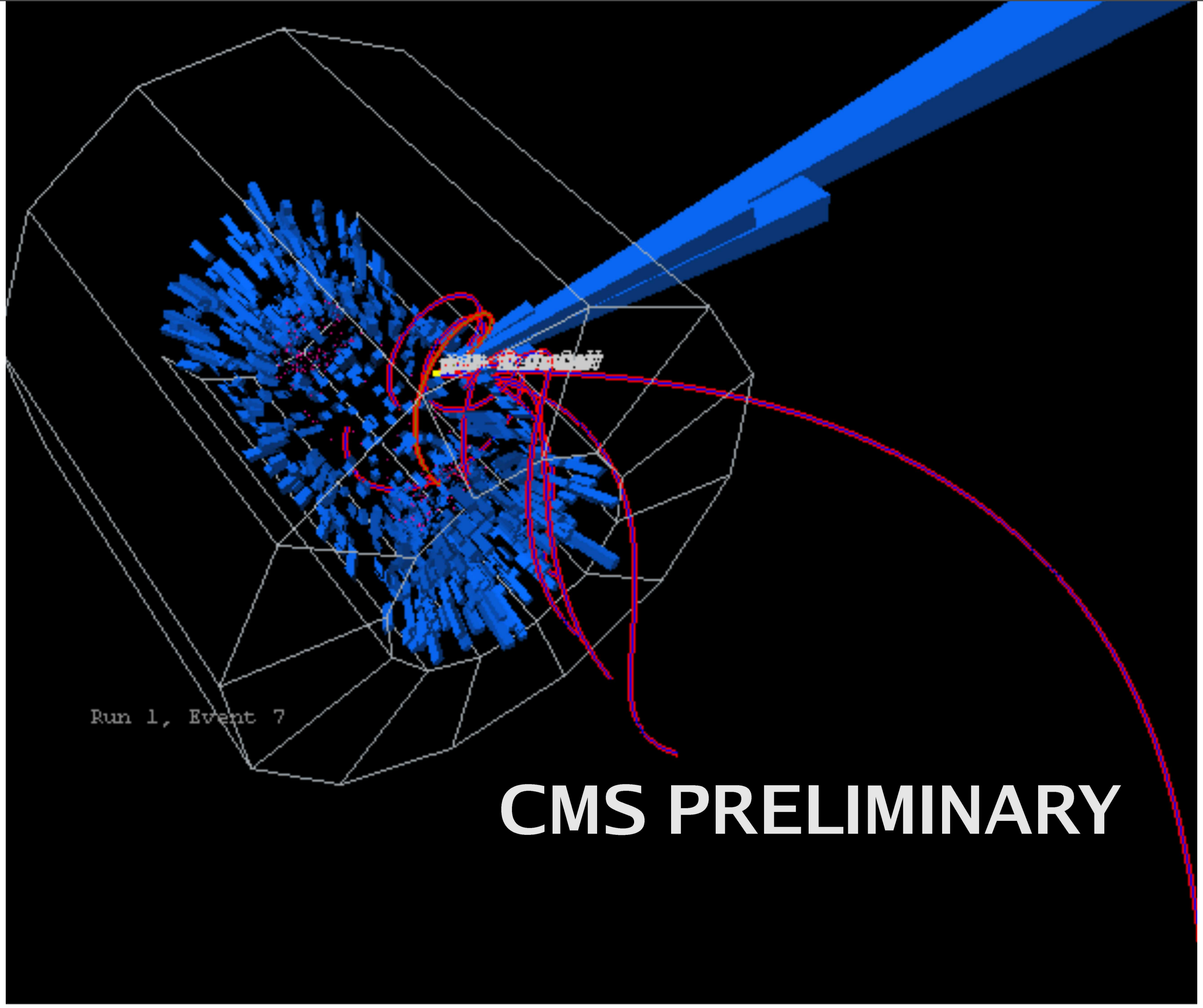
- **R-hadron decay is essentially a gluino decay**, quarks are spectators (though they play an important role in subsequent hadronization)
  - $m_R = m_{\tilde{g}} + (0.65\text{-}1.8)$ GeV depending on R-hadron flavor
- Gluino can decay via either monojet or dijet modes:
  - For analysis presented in this talk, BR (monojet) = 100% is assumed

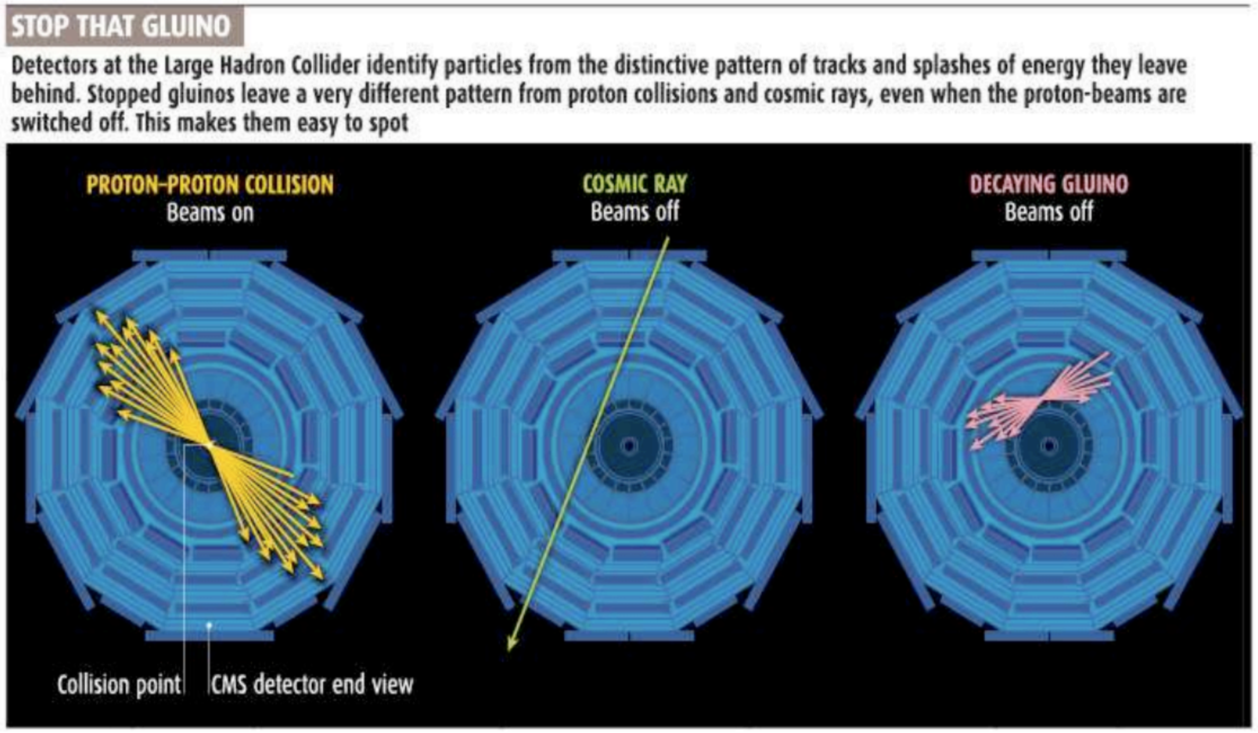
$$\Delta^{++}_{\tilde{g}}[\tilde{g}\,u(uu)] \rightarrow g\chi^0_1 u(uu)$$

χ^0 a Dark Matter Candidate, of course

These decays will be very distinctive

- They will deposit **a lot of energy**
- Will not **originate from nominal beam interaction region**
  - But will look quite different than cosmic rays
- Will not be in time with beam crossing
- **Should be easy to find, especially if ...**





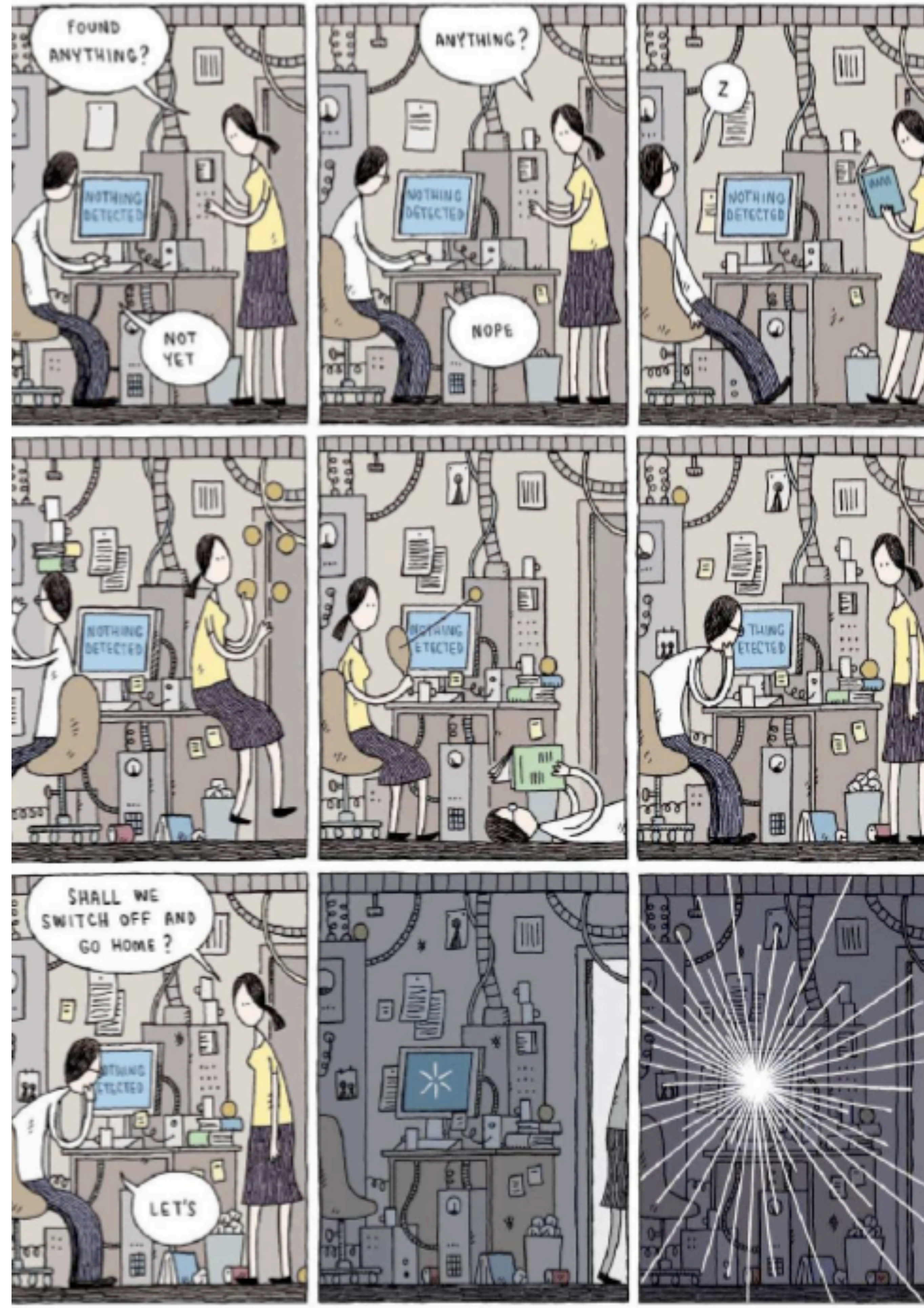
Look when there is **no** beam **background**

Chris Hill at the University of Bristol in the UK works on one of the LHC's particle detectors, called the Compact Muon Solenoid

"The best time to see a gluino go bang is when the LHC is switched off"

(CMS). His interest was piqued when he read a paper about stopped gluinos, and decided to work out how to spot them. "It occurred to me that the absolute best time to look for these things was when nothing else was going on," he says.

New Scientist, July 21, 2008 issue

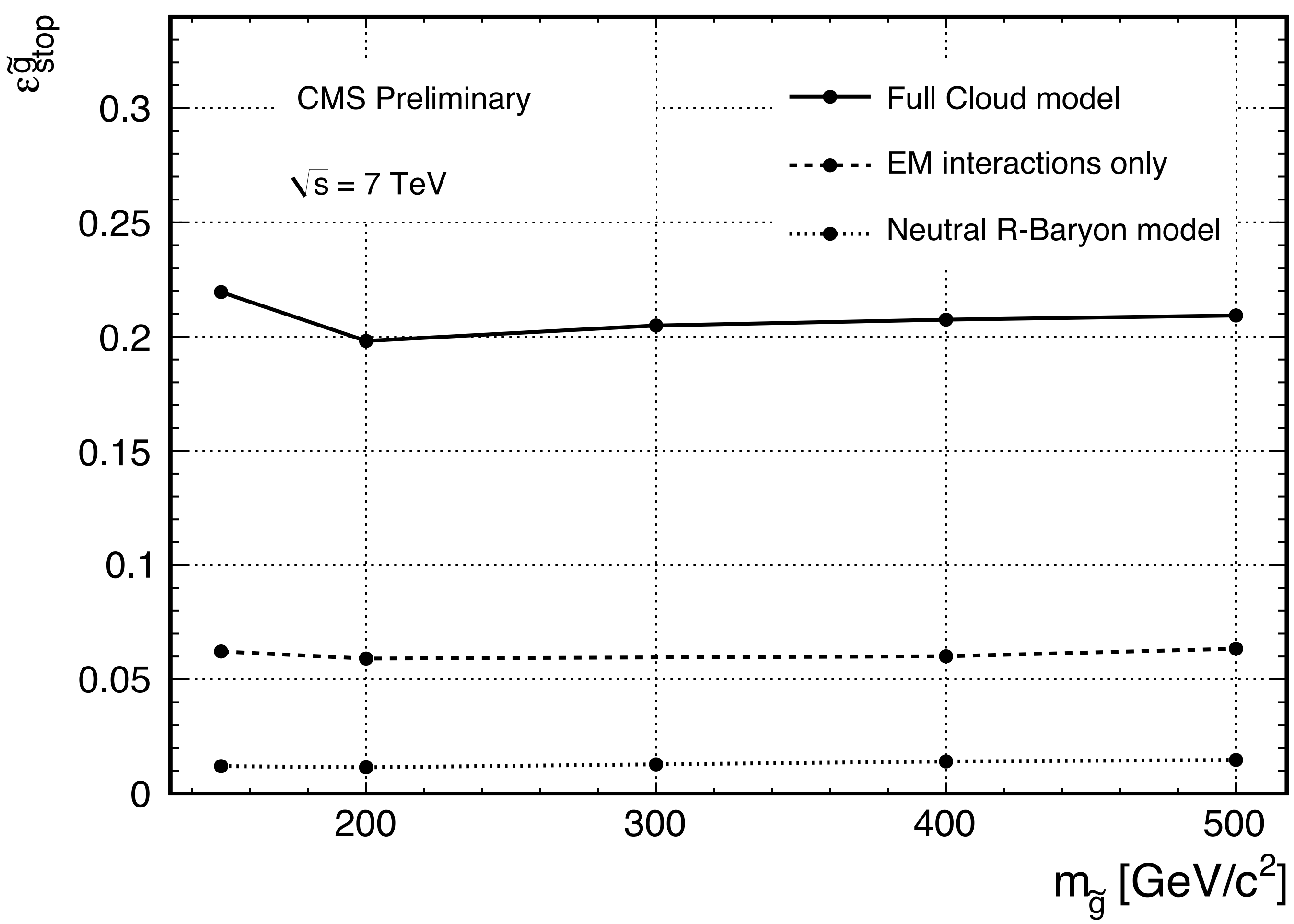


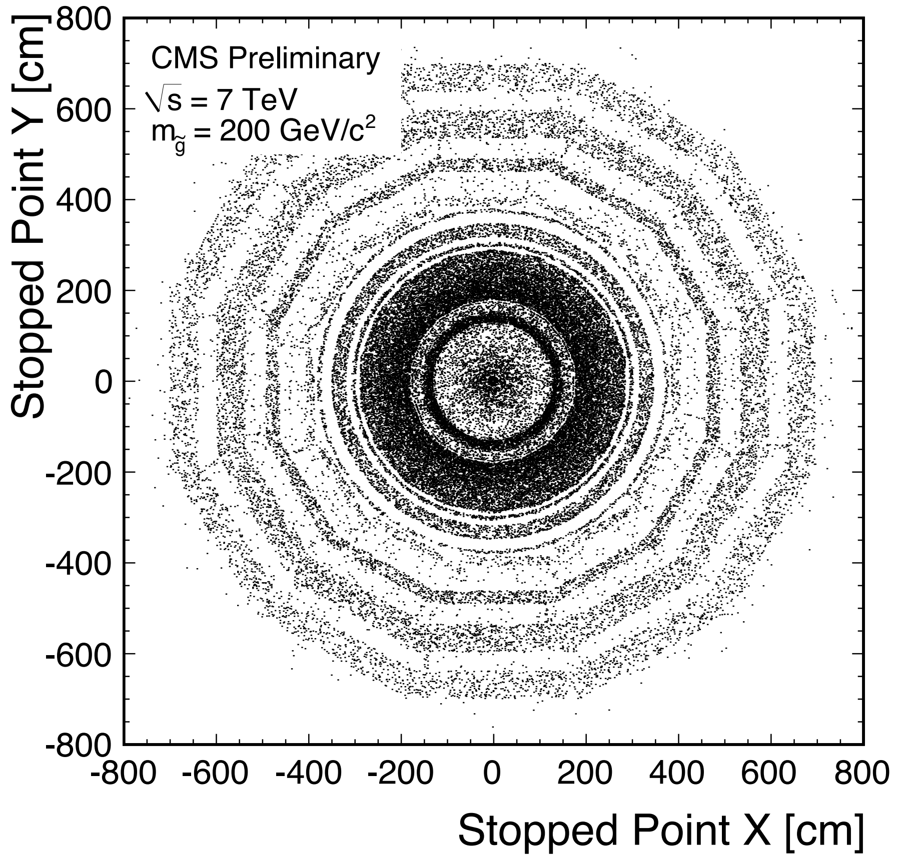
Need to capture & record these delayed decays

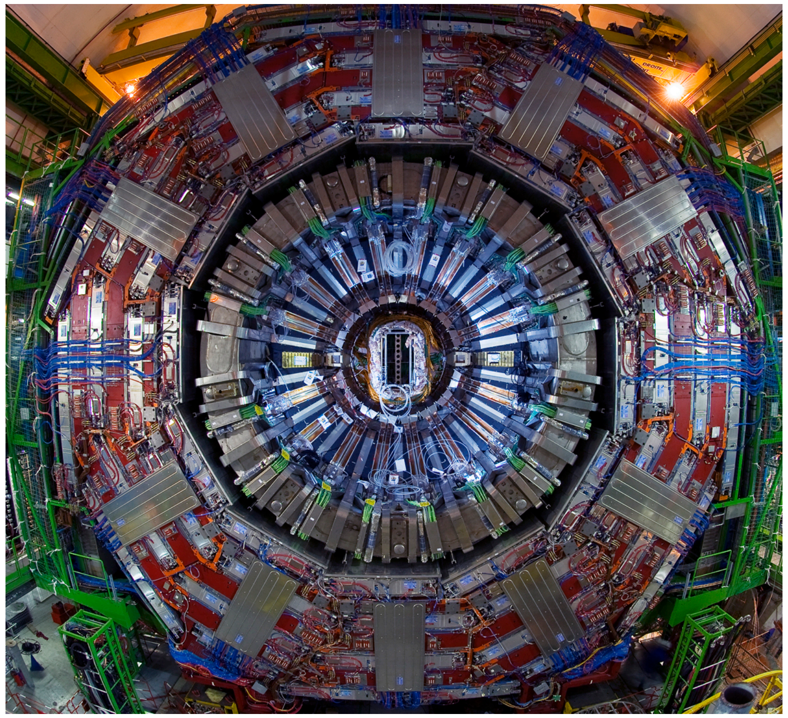
- Fortunately these decays will be occurring in a **particle physics detector**
  - If they have become stopped in an **instrumented region**, then at least some of the **decay particles should pass through active areas**
    - The detector will see a **signal**
  - But **have to get the timing right**

First figure out where they will stop

~20% gluinos can be stopped somewhere in CMS



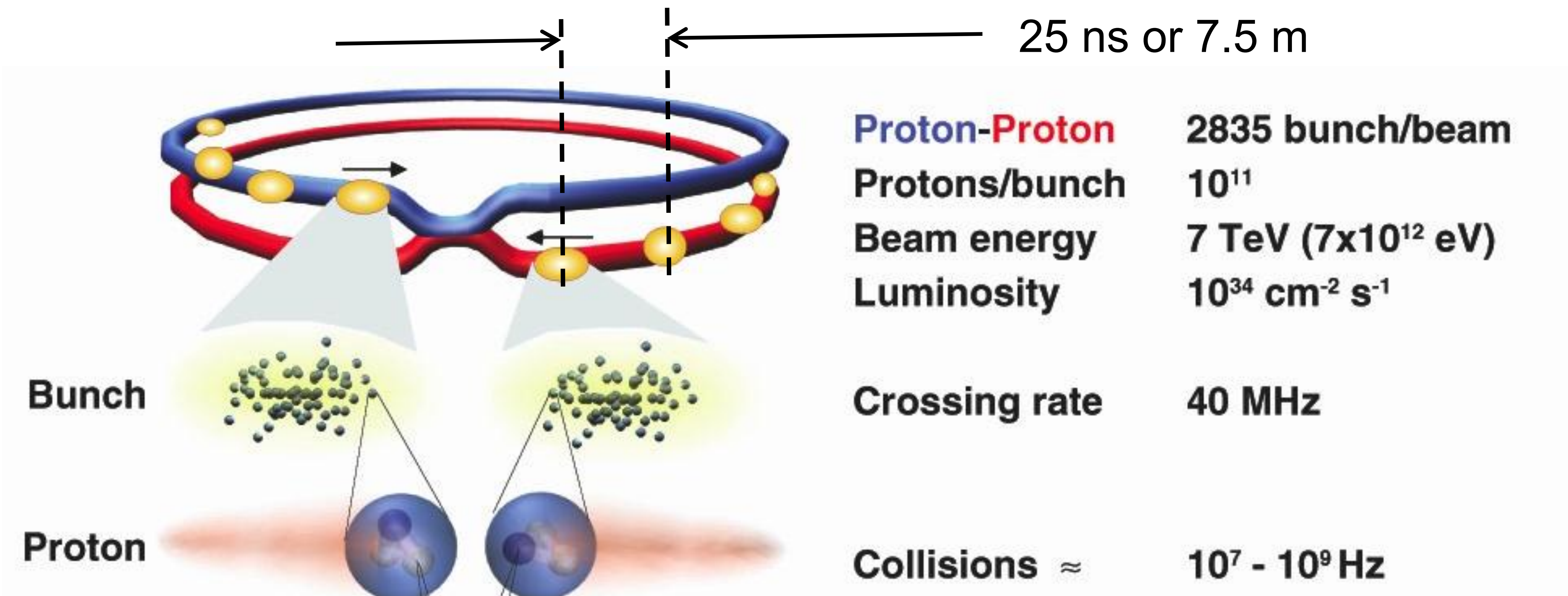


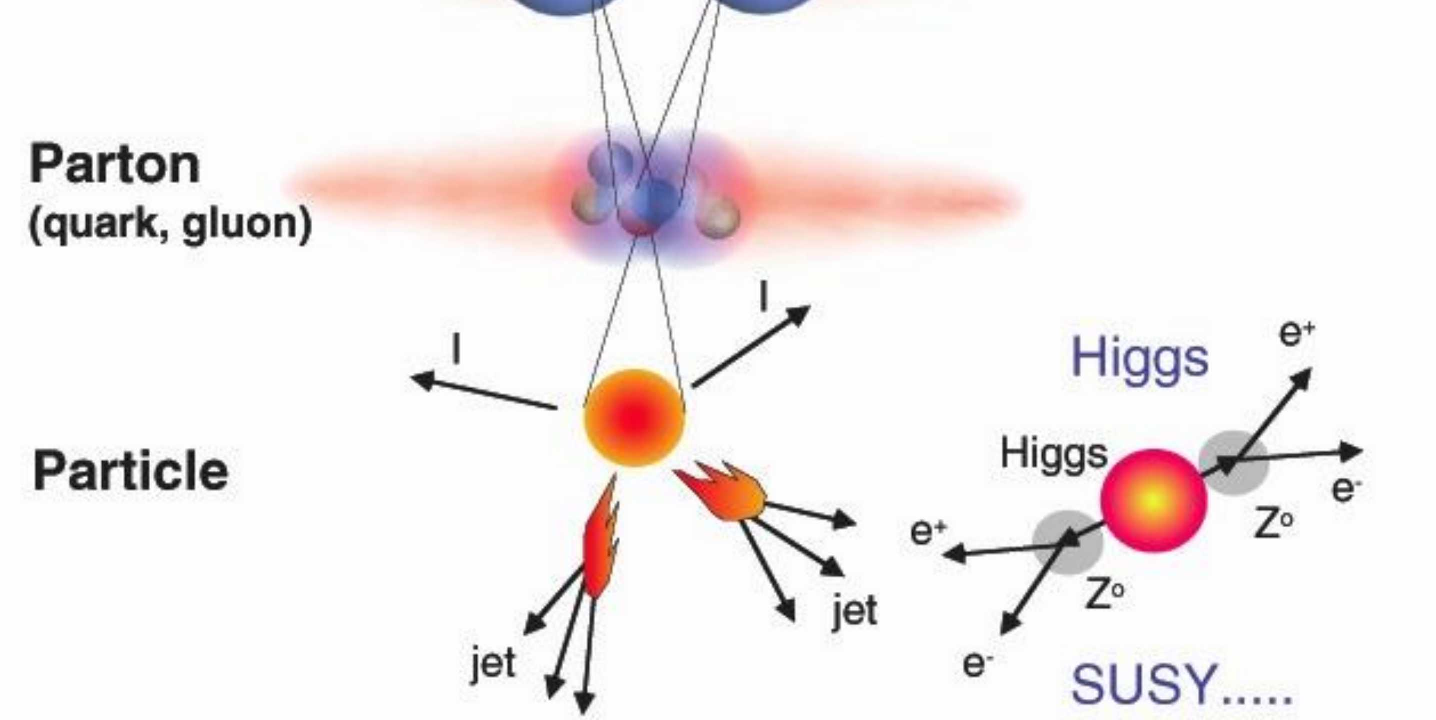


Of those **60% stop in instrumented regions** which allow detection of the subsequent decay

That’s the where, what about the when?

In between proton bunches of LHC “beam”

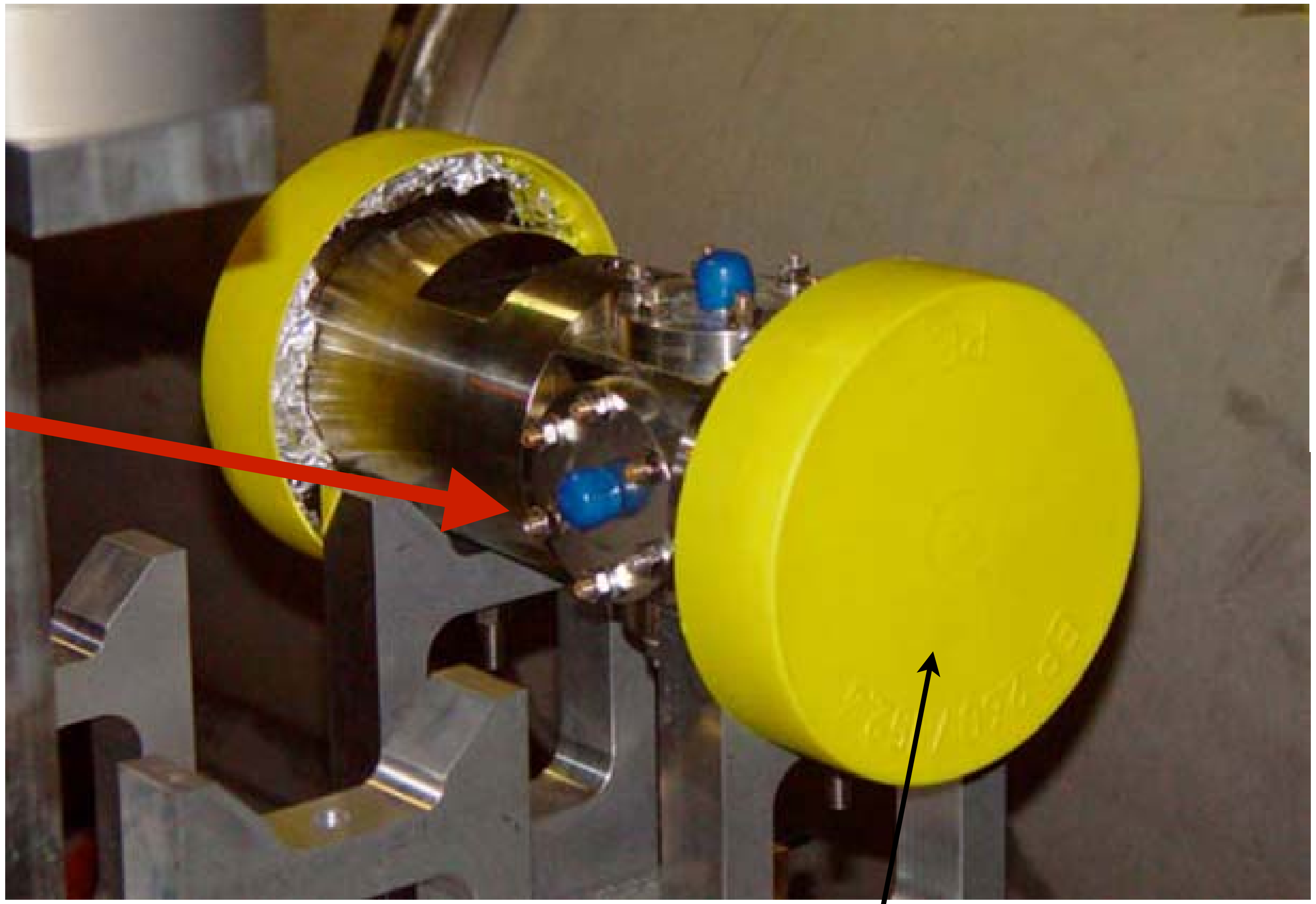




There is a lot of **off** time (especially now in the early days of LHC) when “beam” is **on** if we can make use of it

Beam Position and Timing Monitors (BPTX)

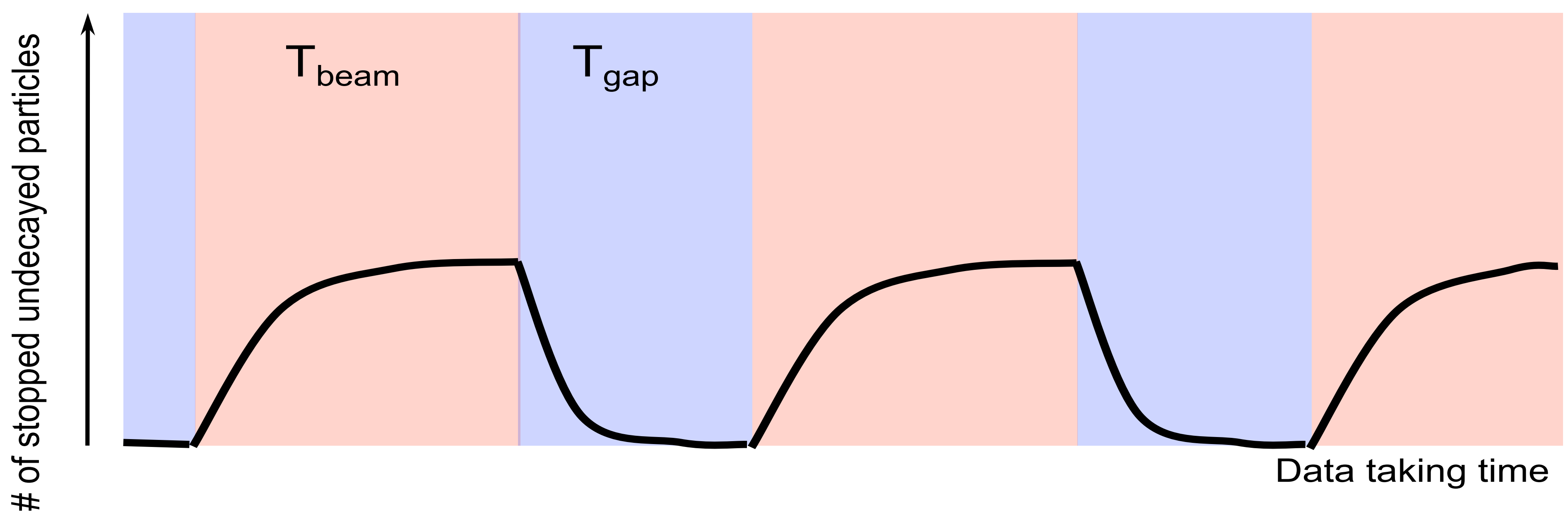
- BPTX
    - Electrostatic pickups in x,y directions on either side of the IP in CMS
    - Designed to measure the beam-position in these coordinates (and the time between ± z)
- **A coincidence in both BPTX means colliding beams**
    - Used as a zero-bias trigger
- We require there **not to be such a coincidence**
    - **Guarantees in a beam gap**



Beampipe (absent) through here

How much of a stopped gluino signal can we expect at CMS?

$$\text{For } \tau \ll T_{beam},\ \sigma_{effective} = (\sigma_{prod} \times \varepsilon_{stop}^{\tilde{g}\tilde{g}}) \times \varepsilon_{reco} \times \frac{\tau}{T_{beam} + T_{gap}} \times (1 - e^{-T_{gap}/\tau})$$



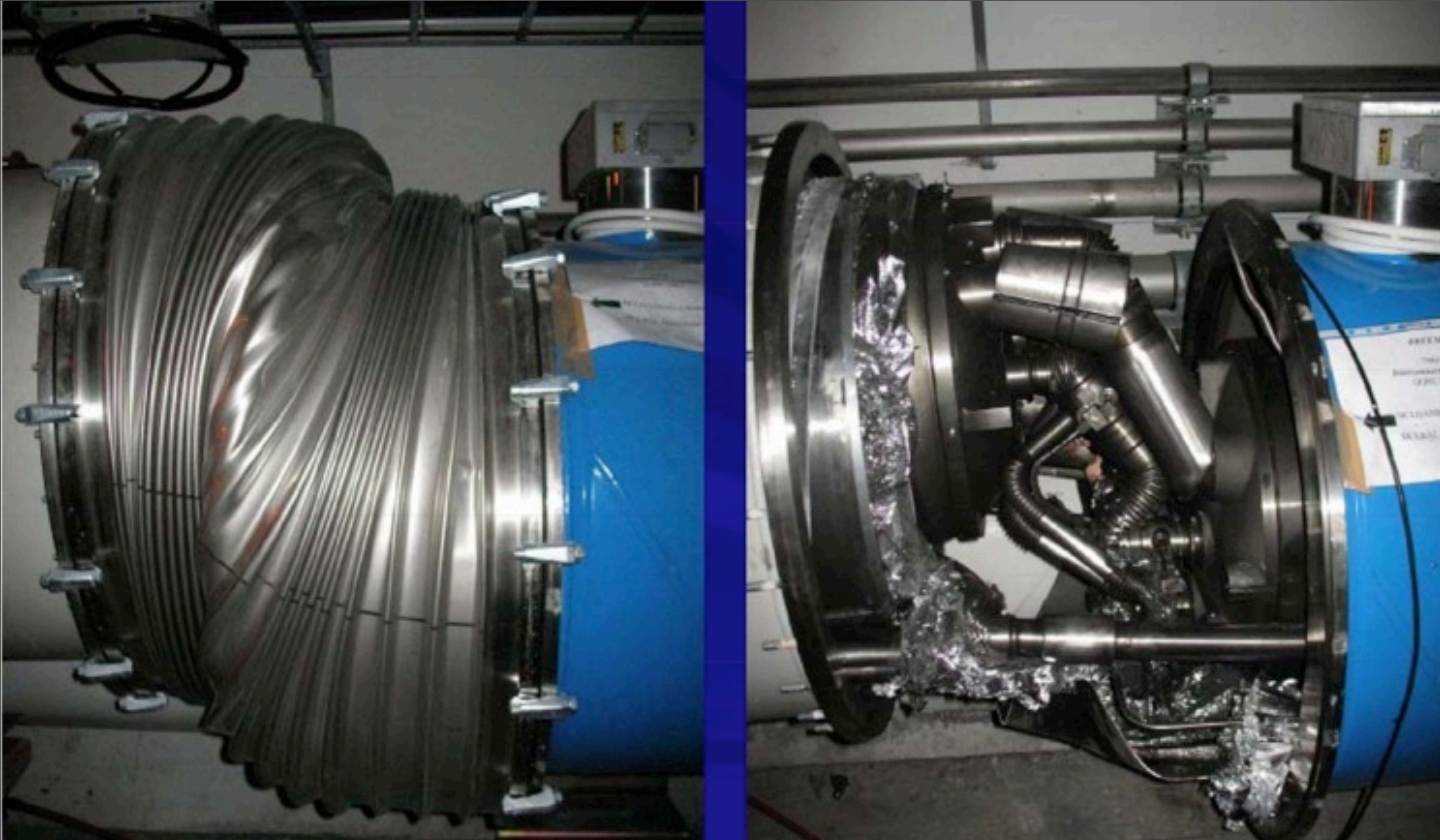
BACKGROUNDS?

- Since these data will be collected when there are no pp collisions

- Only significant physics background source will be **cosmic rays**

    - The rate of these is low since CMS is 100 m underground

- **Instrumental noise** (HPD's in the HCAL) is the dominant background source

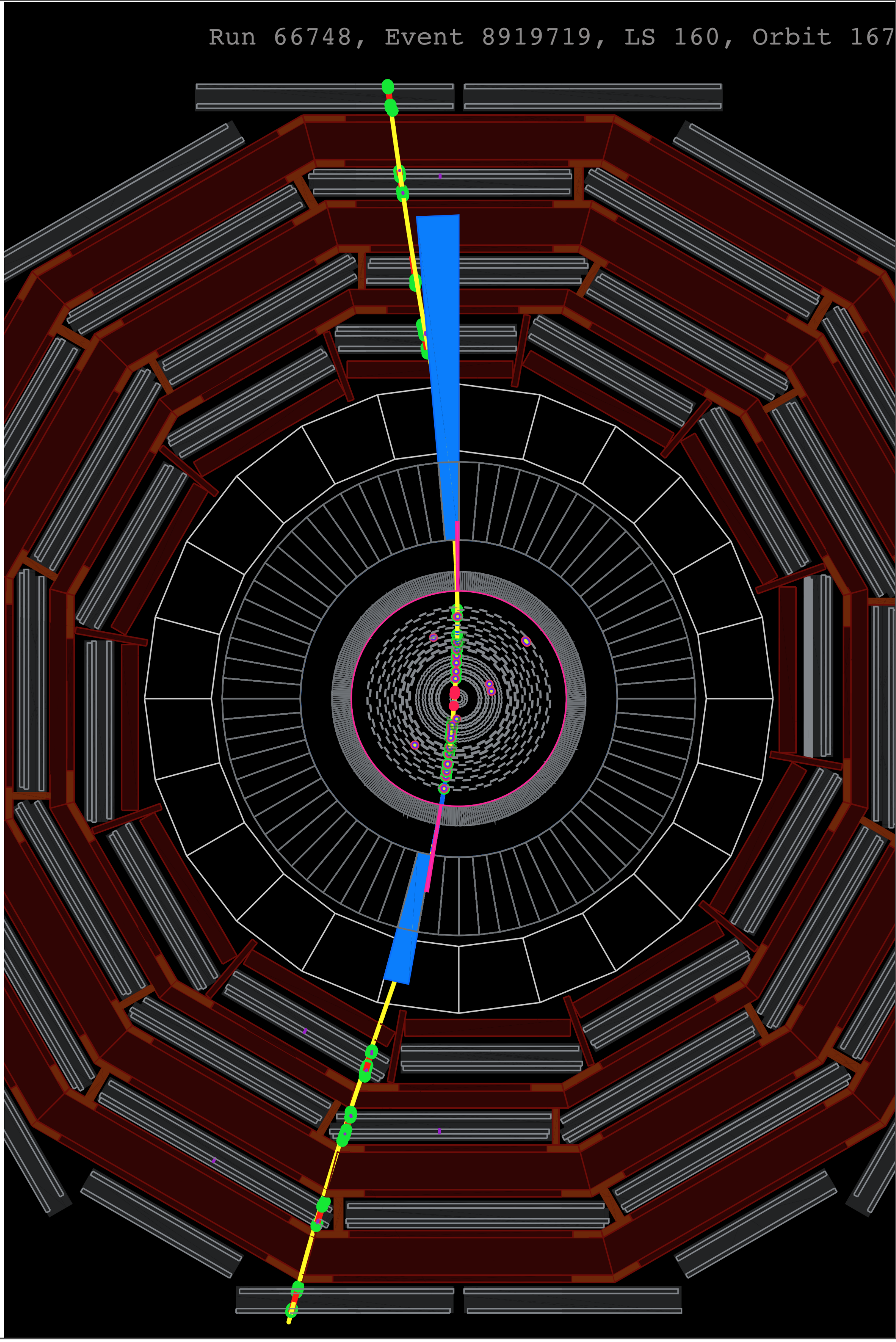


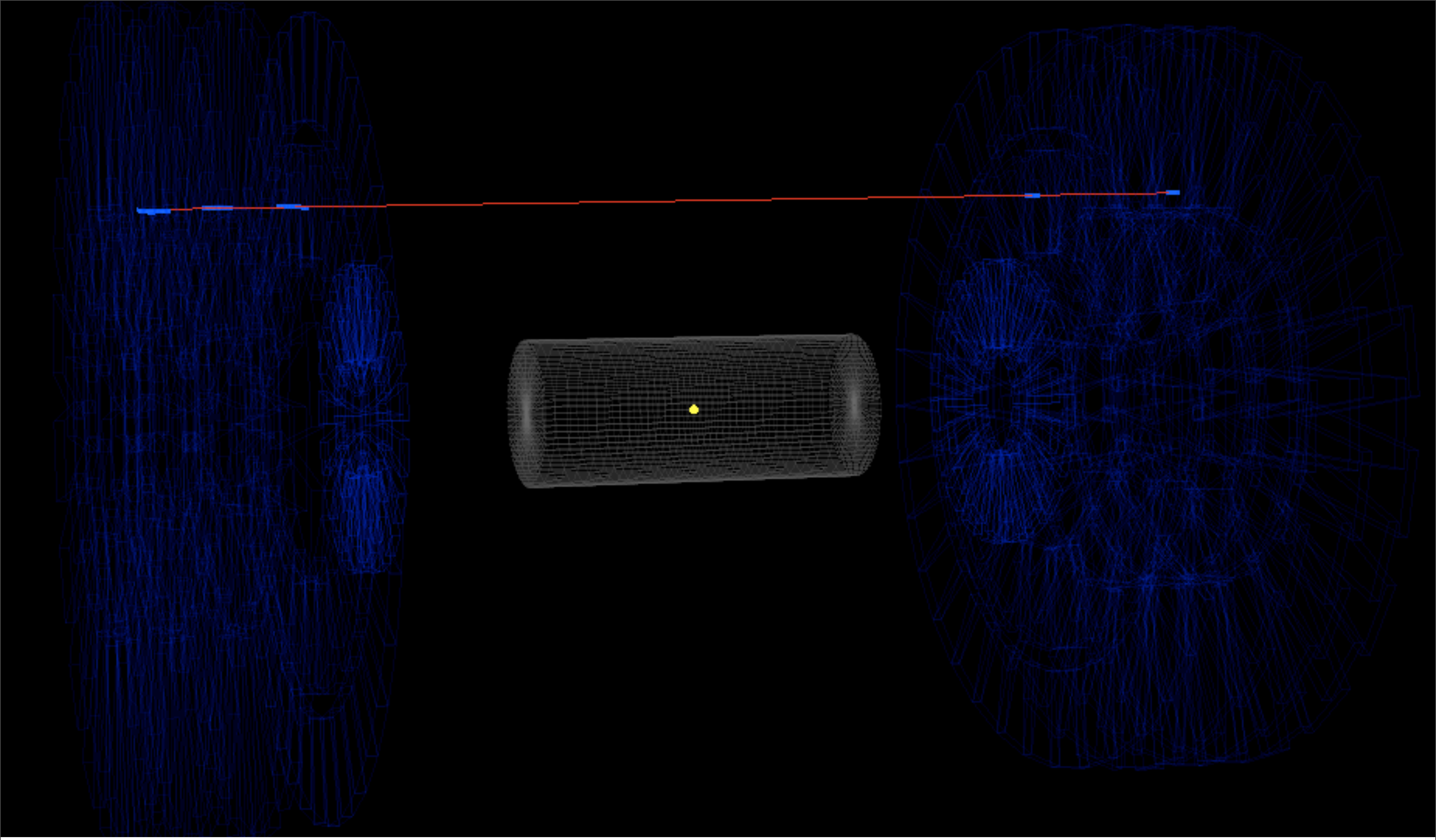
Every cloud has a silver lining ...

LHC accident Sep 19, 2008

Background Estimate

- CMS was ready for collisions, but had to wait while LHC was repaired
- Took advantage of this time to **measure** the background rate over the last year with **100's M triggers**
  - "CRAFT09"
  - **Perfect control sample**
  - **Obviously, no signal** in these data since before any LHC collisions





Are there other backgrounds when beam is circulating? e.g. Beam Halo Muons?

Checked with 900 GeV collision data, **not a significant background and easily rejected**

Event Selection & Final Background Estimate

- We divide the 7 TeV collision data into two sets :
  - The first, **low luminosity dataset is used to measure the background rate** again (cross-check with CRAFT09 and 900 GeV data)
- Then **perform the search in the second dataset obtained in higher intensity** running period

Beam background rejection

Cosmic rejection

Jet topology cuts

Calorimeter pulse shape cuts

Selection Criteria	Background Rate (Hz)
L1+HLT (HB+HE)	3.27
Calorimeter noise filters	1.12
BPTX/BX veto	1.11
muon veto	6.6×10^{-1}
$E_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 1.3$	7.6×10^{-2}
$n_{60} < 6$	7.6×10^{-2}
$n_{90} > 3$	3.1×10^{-3}
$n_{phi} < 5$	1.3×10^{-4}
$R_1 > 0.15$	1.1×10^{-4}
$0.1 < R_2 < 0.5$	8.5×10^{-5}
$0.4 < R_{peak} < 0.7$	7.9×10^{-5}
$R_{outer} < 0.1$	6.9×10^{-5}

Rates measured in low lumi 7 TeV collision runs (2-7 × 10^{27} $cm^{-2}s^{-1}$)

Signal efficiency ~17% (of all R-hadrons that stop anywhere in CMS)

Counting Experiment Results

- Perform a counting experiment in bins of lifetime, τ
  - For small τ, select events in a window 1.256 x τ after each collision
  - Lint = 203 (232) nb^{-1} recorded (delivered)

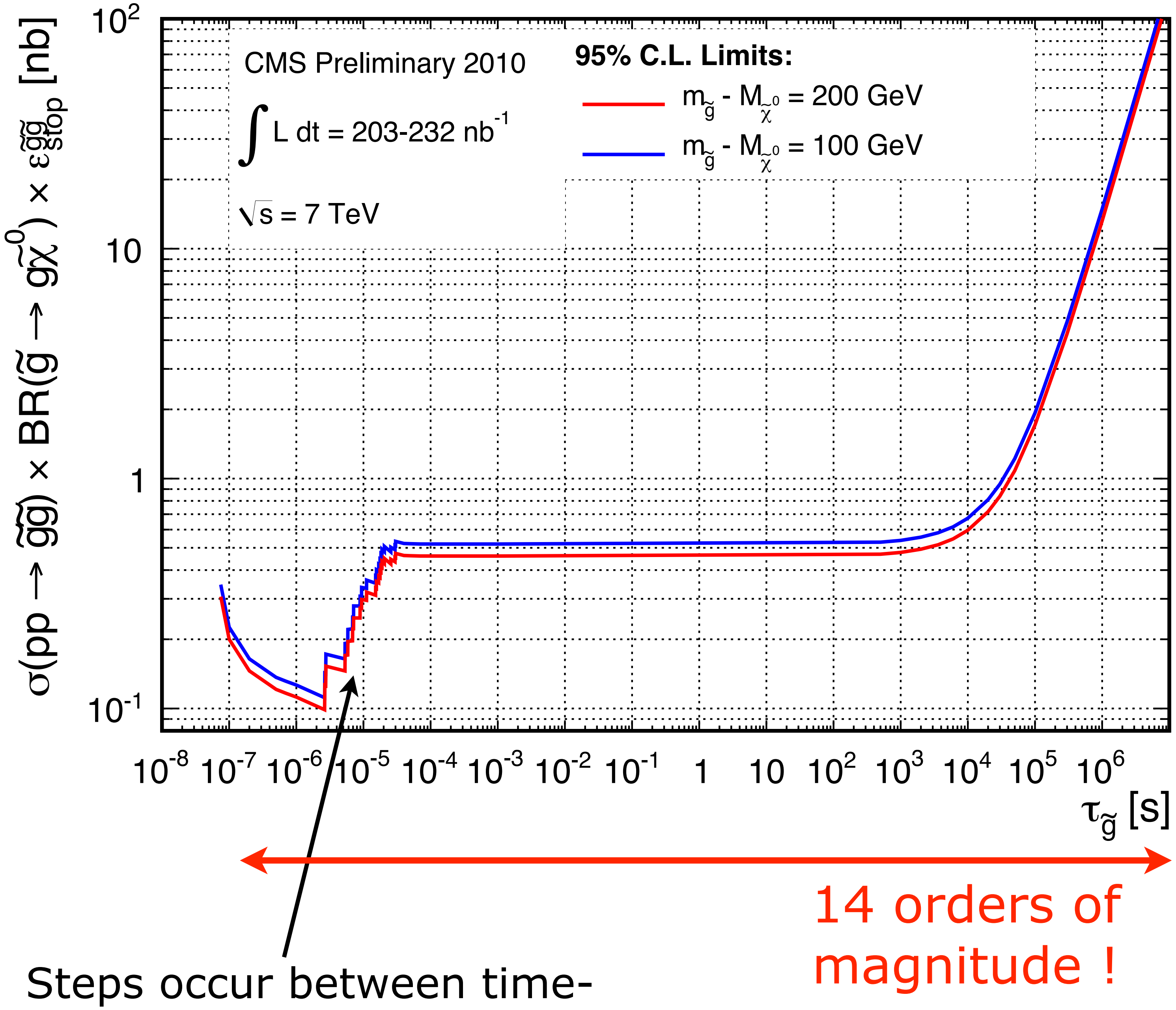
Lifetime [s]	Expected Background ($\pm$ stat $\pm$ syst)	Observed
1e-07	$0.15 \pm 0.04 \pm 0.05$	0
1e-06	$1.8 \pm 0.5 \pm 0.5$	0
1e-05	$11.7 \pm 3.2 \pm 3.5$	8
1e-04	$28.3 \pm 7.8 \pm 8.5$	19
1e-03	$28.3 \pm 7.8 \pm 8.5$	19
1e+03	$28.3 \pm 7.8 \pm 8.5$	19
1e+04	$28.3 \pm 7.8 \pm 8.5$	19
1e+05	$28.3 \pm 7.8 \pm 8.5$	19
1e+06	$28.3 \pm 7.8 \pm 8.5$	19

No excess above expected background observed, proceed to set 95% C.L. limits

Stopping Model Independent Results

- **τ < few 100 ns**
  - Decays occur during vetoed BXs
- **$\tau < T_{orbit}$ (~10^{-4} s)**
  - Decays occur within the orbit, but we optimise the time window
- **$T_{orbit} < \tau < T_{fill}$ (~10^{4} s)**
  - Accept events over the full orbit - sensitivity plateau
- **$\tau > T_{fill}$**
  - Lose sensitivity as increasing fraction of decays occur post-fill

Cross-section x stopping probability



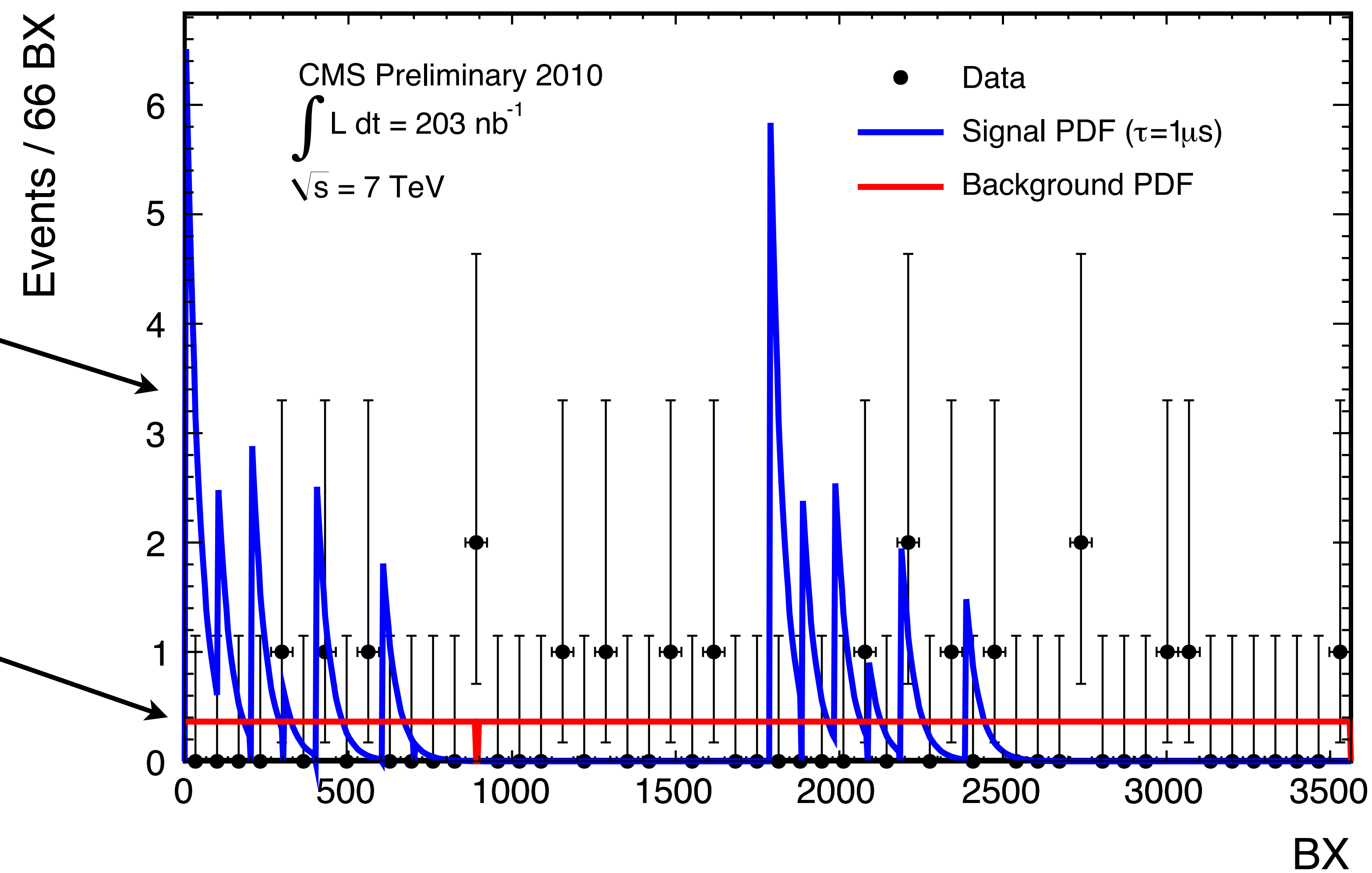
Steps occur between time-windows as N_{obs} increments for each observed event

Time Profile Results - Exploit Location of Events *in Time*

- As well as counting expt, we analyse the distribution of observed event times
  - For a given lifetime hypothesis, **calculate a PDF for signal event time**, using the delivered luminosity profile
  - **Background PDF is flat in time**
- Fit data and calculate a 95% CL on the signal
  - We do this for lifetimes less than ~100 μs, using event time within the orbit, ie. BX

Signal PDF peaks at collision BXs

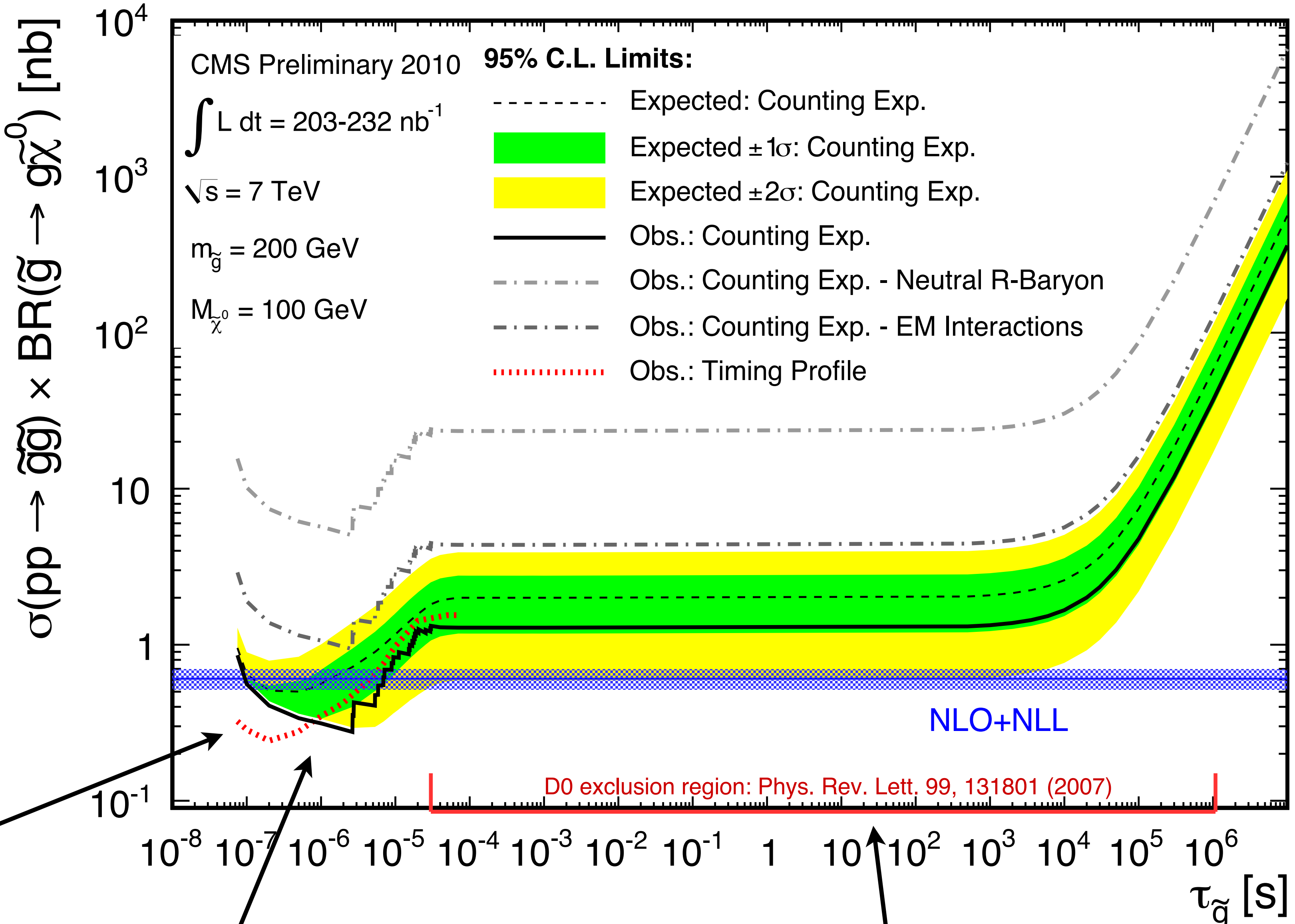
Background PDF is flat



Gluino Cross-Section Limits

- Use the stopping probability to obtain a limit on the cross-section
  - For $m_{\tilde{g}}$=200, M_{χ^0}=100 GeV
- Stopping probability depends on models of R-hadron interactions
  - Default “Cloud model”
  - “EM only”
  - “Neutral R-Baryon” model

Cross-section limit



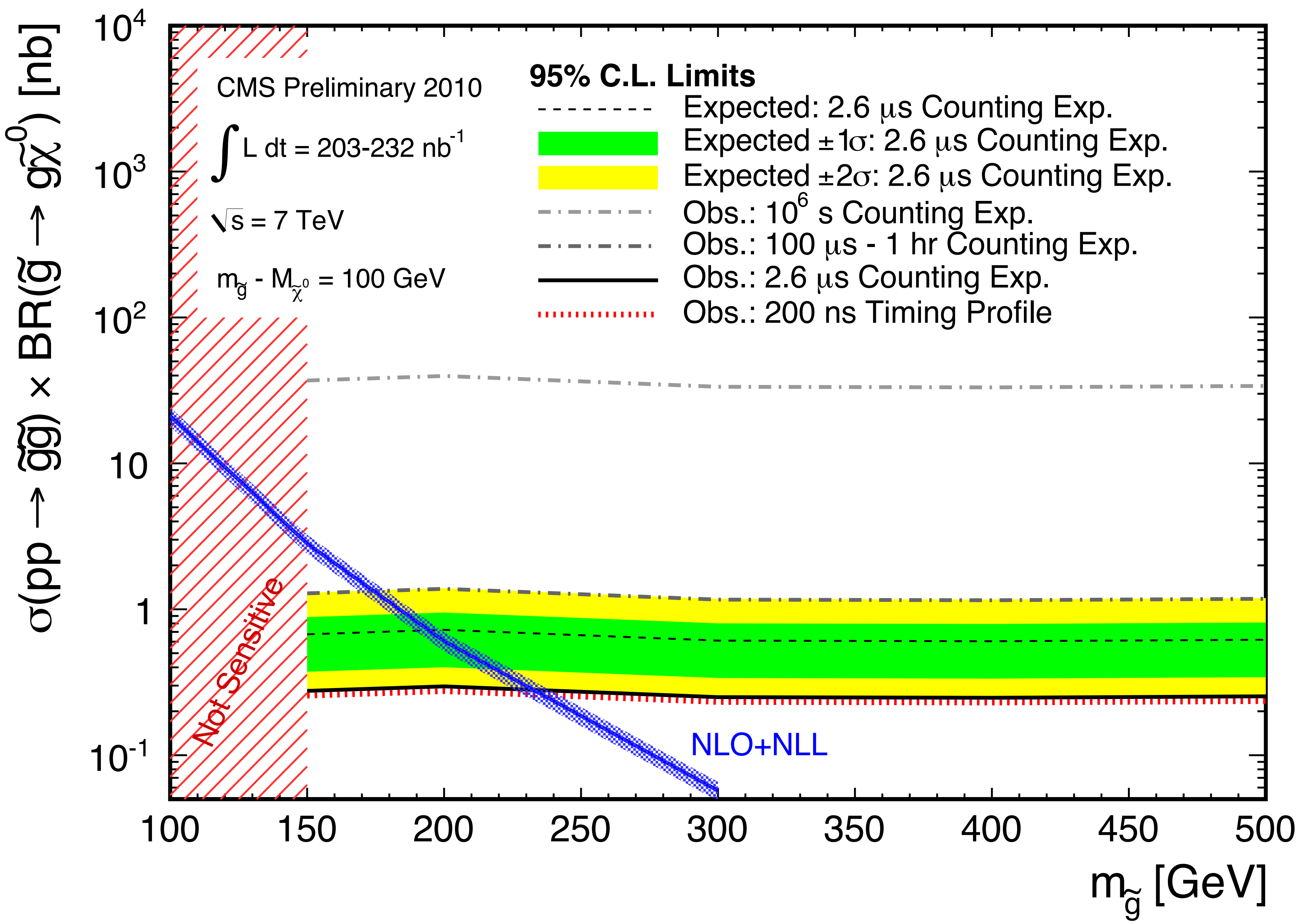
Time profile analysis improves sensitivity to small lifetimes

For $m_{\tilde{g}}$<200 GeV, ***exclude lifetimes 75 ns < τ < 6 μs***

Extends D0 limit (valid for τ > 30 μs)

Gluino Mass Limits

- Present limit for (selected) fixed lifetimes, as a function of m_g,$M_{\chi 0}$
- Fixed m_g-$M_{\chi 0}$=100 GeV
  - Trigger x reco x stopping efficiency is roughly flat
  - And valid for mass differences > 100 GeV
- Results not presented for region below m_g=150 GeV
  - LEP neutralino limit
  - Trigger/reco efficiency declines



Time profile analysis:
for τ=200 ns,
exclude m_g < 229 GeV

Counting experiment:
for τ=2.6 μs,
exclude m_g < 225 GeV

Summary & Outlook

- CMS has conducted two searches for long-lived particles in about 200 nb^{-1} *pp* collision data with $\sqrt{s}$=7 TeV

- "Traditional" search for HSCPs with for high-pt, high dE/dx tracks (*CMS EXO-10-004*)
    - **Exclude gluino masses below 284 GeV/c^2** (but no statement on lifetime)

- Additionally, CMS has searched for decays of particles stopped in CMS using a novel trigger to record decays during gaps between LHC collisions (*CMS EXO-10-003)*
    - For gluinos of mass up to 200 GeV/c^2, **exclude lifetimes from 75 ns < τ < 6 μs**
    - For lifetimes of 2.6 μs, **exclude gluinos of mass up to 225 GeV/c^2**
    - For lifetimes of 200 ns, **exclude gluinos of mass up to 229 GeV/c^2**
    - *Extends previous Tevatron limits on lifetimes of gluinos*

- LHC has begun to weigh in on the existence of long-lived particles (which can decay to dark matter candidates) **over 14 orders of magnitude in lifetime.** Currently only sensitive to lightest strongly produced particles, but plenty more data is already on the way … **stay tuned!**

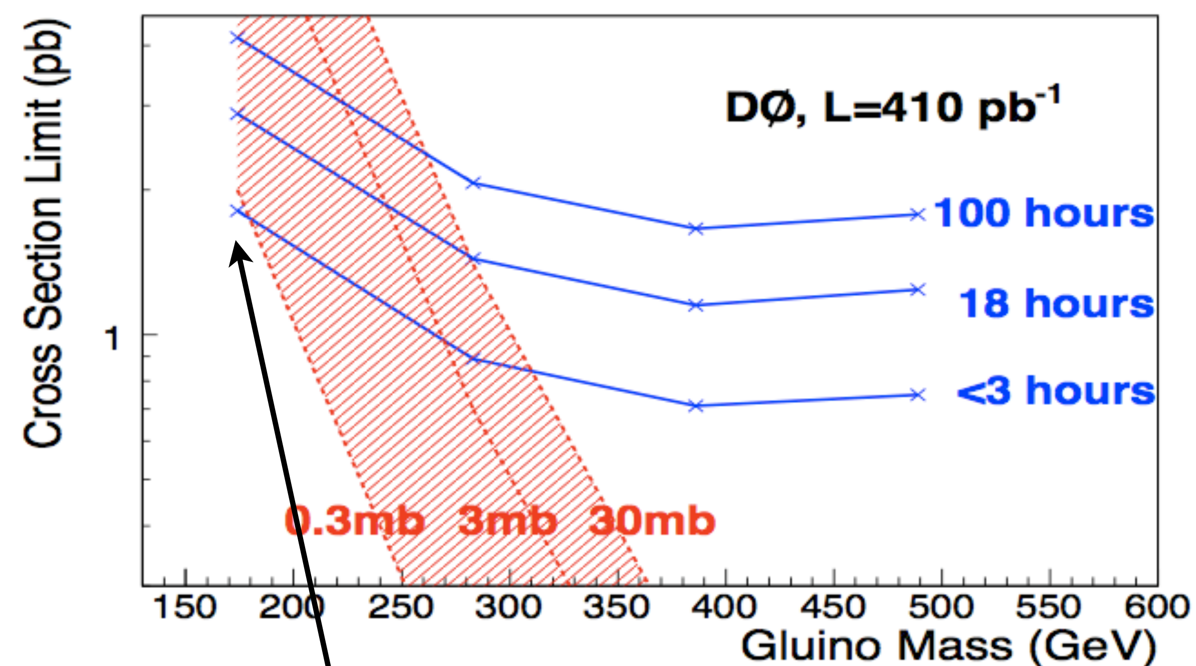
Additional Material

Tevatron Search for Stopped Gluinos at $\sqrt{s}$ =1.96 TeV (D0 collaboration)

- Excludes gluino masses < 270 GeV for lifetimes, 30 μs - 100 hr
- Less sensitive search than what we will achieve at LHC
  - They did not have a zero-bias trigger like that implemented at CMS
  - Cross-section much lower
  - Longer, and regular, bunch spacing at Tevatron not as well suited for search as LHC
  - Larger cosmic-ray background (they are located on the surface)

Phys. Rev. Lett. 99, 131801 (2007)

$m_{\tilde{\chi}^0} = 50, 90, 200 \text{ GeV}$



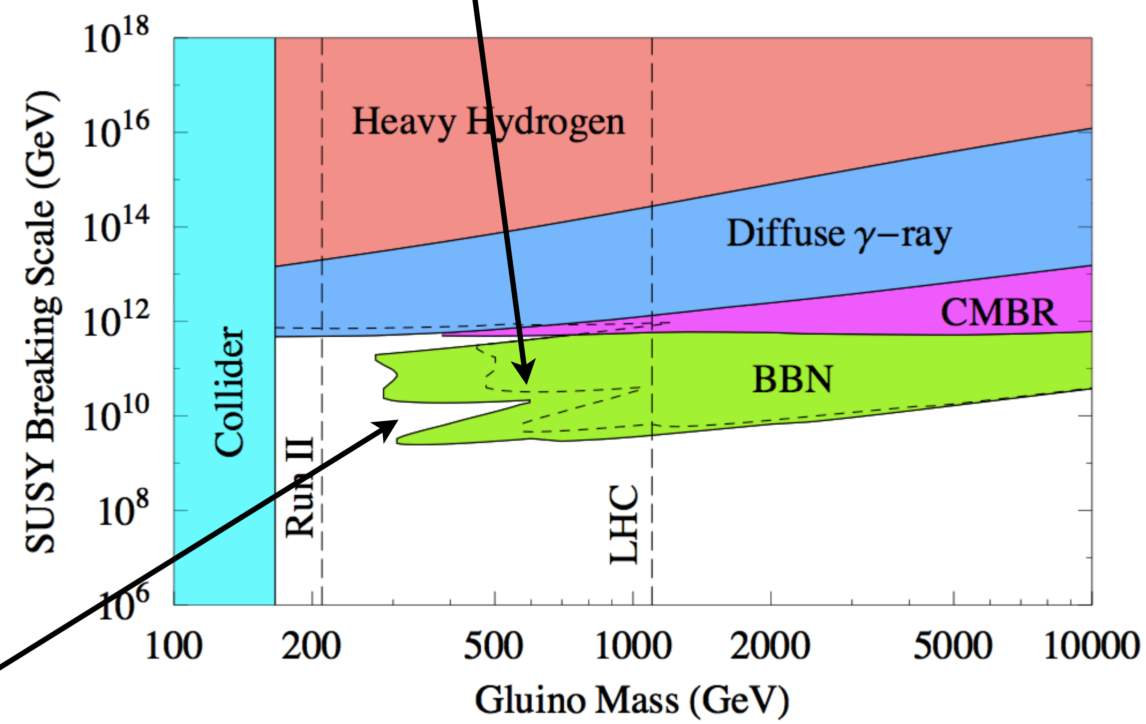
N.B assumes 100% Br($\tilde{g} \rightarrow g\tilde{\chi}_1^0$)

Compare to this point. It took D0 a year and a half to be sensitive to the theory prediction of ~1 pb at the Tevatron

Indirect constraints on gluino's lifetime

- A. Arvanitaki et al (Phys.Rev.D72:075011,2005) set limits from various sources on possible gluino masses & susy breaking scales (and thus lifetimes)
- if gluino mass > 300 GeV (500 with different assumptions) strongest constraints come from Big Bang Nucleosynthesis (BBN)
  - Authors' claim lifetime < 100 seconds
    - Unless in these holes in the exclusion curve
  - N.B. these results rely on highly speculative R-hadron cross-sections

Alternative assumptions about unknown R-hadron interactions



If mass < 300 (500) GeV, lifetime limit is weak, 10^6 years