Searches for long-lived particles and other non-conventional signatures

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On behalf of the

CMS Collaboration

SUSY17

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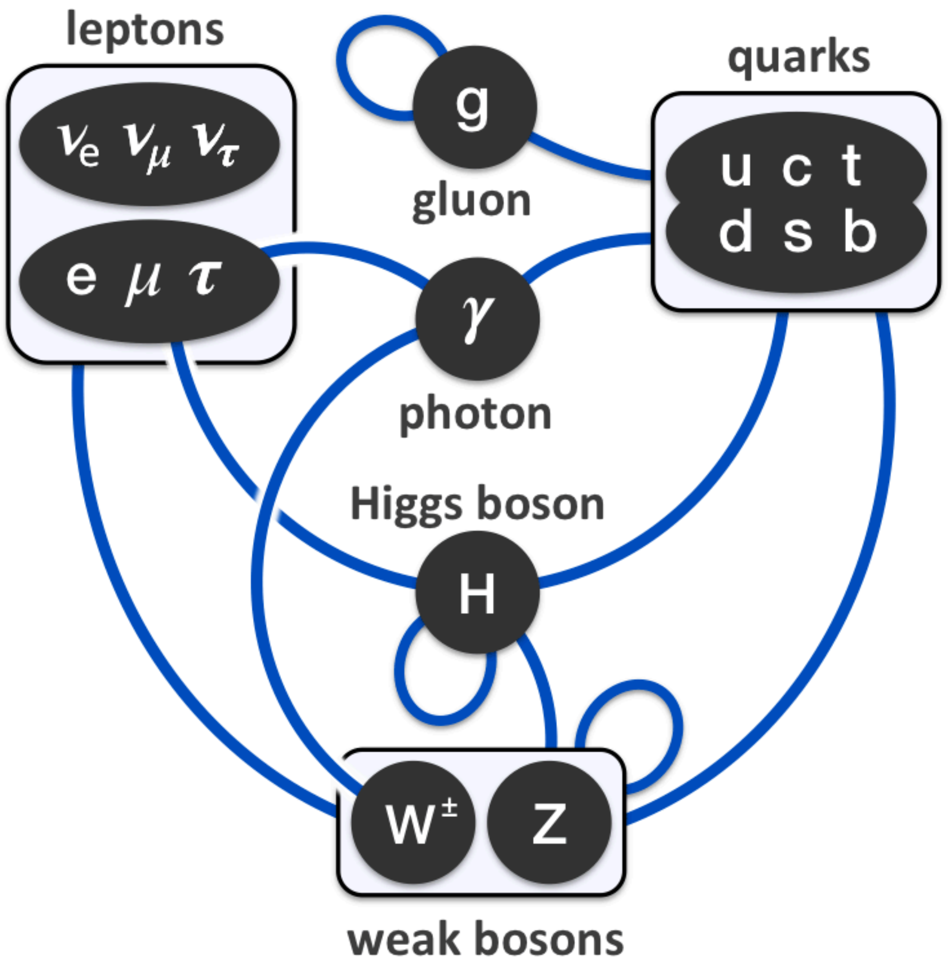
Gazing beyond the Standard Model

- Standard Model (SM): our current theory of matter and interaction

- Unfortunately, it cannot provide a complete description of the Universe:
  - → Higgs Mass is unprotected against quantum corrections in the SM: $m_h^2 \sim m_{h0}^2 - \alpha\lambda_f^2\Lambda^2$
  - → Baryogenesis:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

  - → Neutrino physics
  - → Dark Matter
  - → …



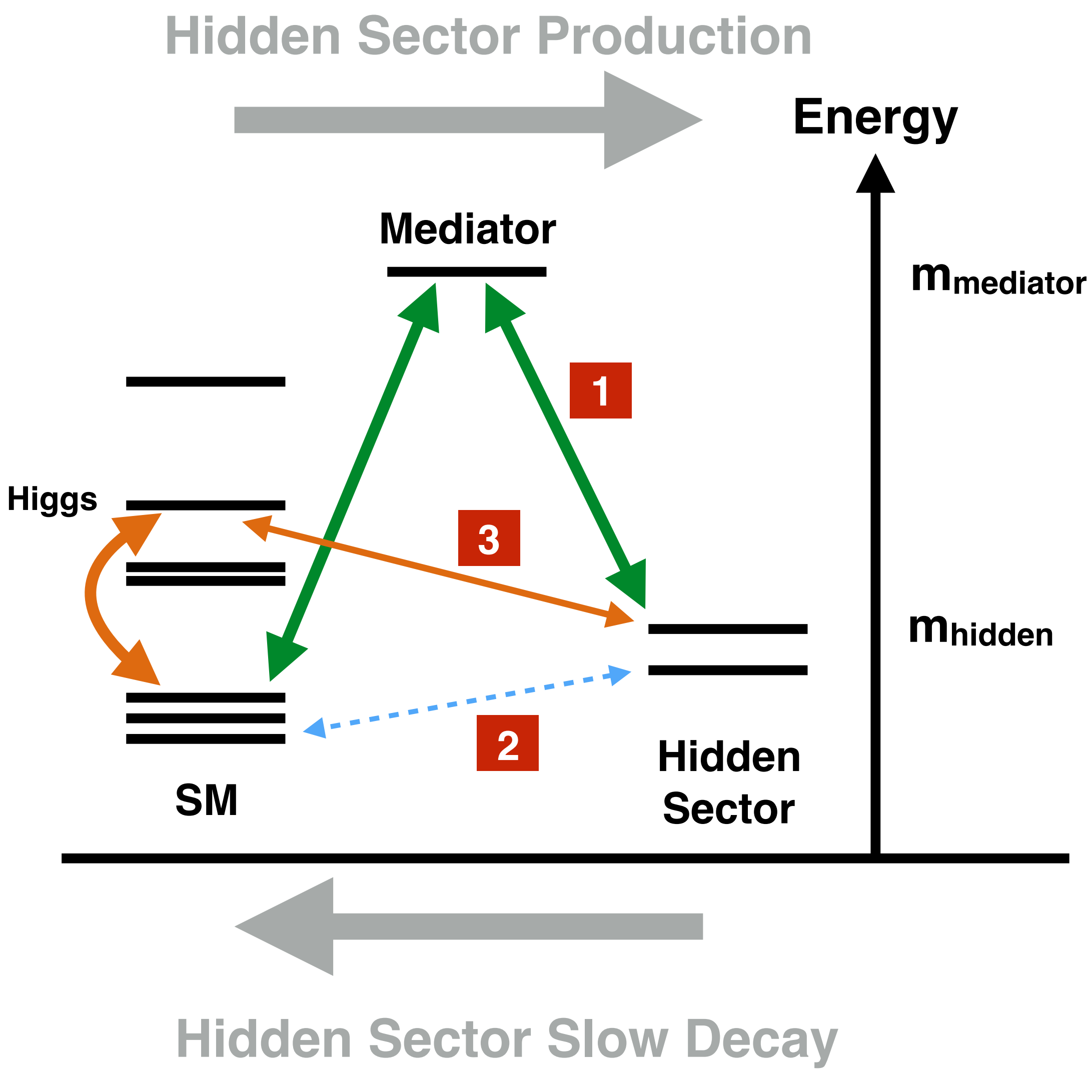
- No hints of physics beyond the Standard Model:
  - → Still room for BSM decay of Higgs boson or additional Higgs (2HDM, 2HDM+S models)
  - → But… are we looking in the right place?
    - → Null results may point us towards the true nature of the Universe (E.g.: hidden sectors with tiny interactions with the SM, unconventional signatures!)

Where hidden sectors could hide?

- Possible for a hidden sector to contain just 1 species of particles with no non-gravitational interactions but…
  - → BSM is motivated if the hidden sectors play a part in solving SM shortcoming
  - → Hidden sectors can be connected to the SM via small effective couplings (portals)

- Quest for new physics is not one-dimensional!
  - → New physics not necessarily at higher energies
  - → New physics could lie at m_{hidden} < TeV (hidden by small coupling to SM)

- Rich phenomenology depending on Mediator nature (Heavy mediator, photon-dark photon oscillation, etc…)

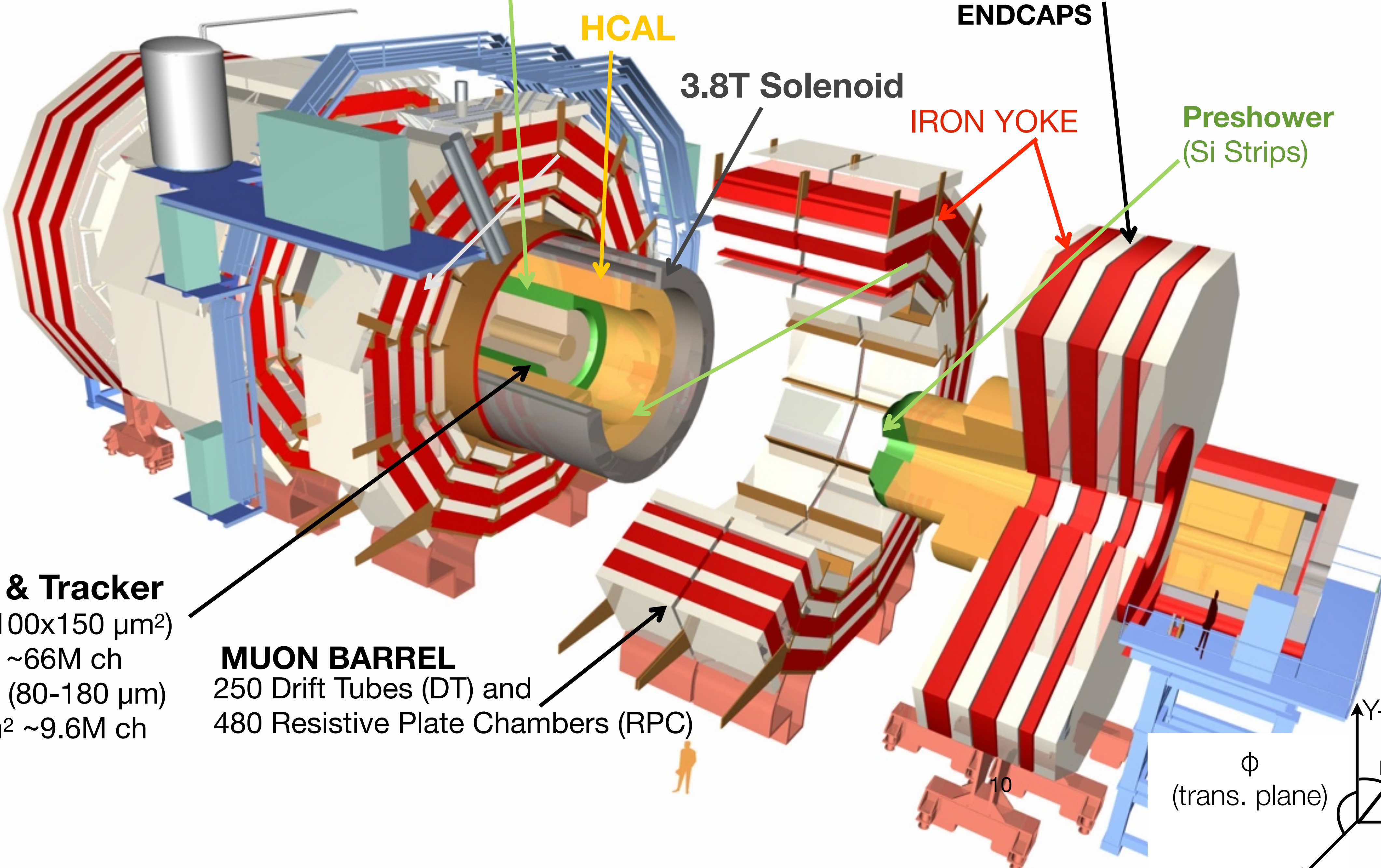


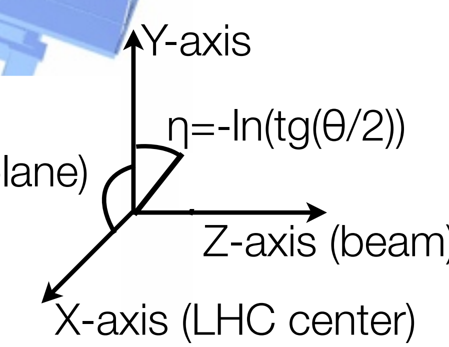
- Portal is a tiny keyhole: decay can take a long time (Long-Lived Particles, LLP)

Flashes of Hidden Worlds at Colliders, D. Curtin and R. Sundrum, Submitted to Physics Today, arXiv:1702.02524

Taking pictures of particle collisions

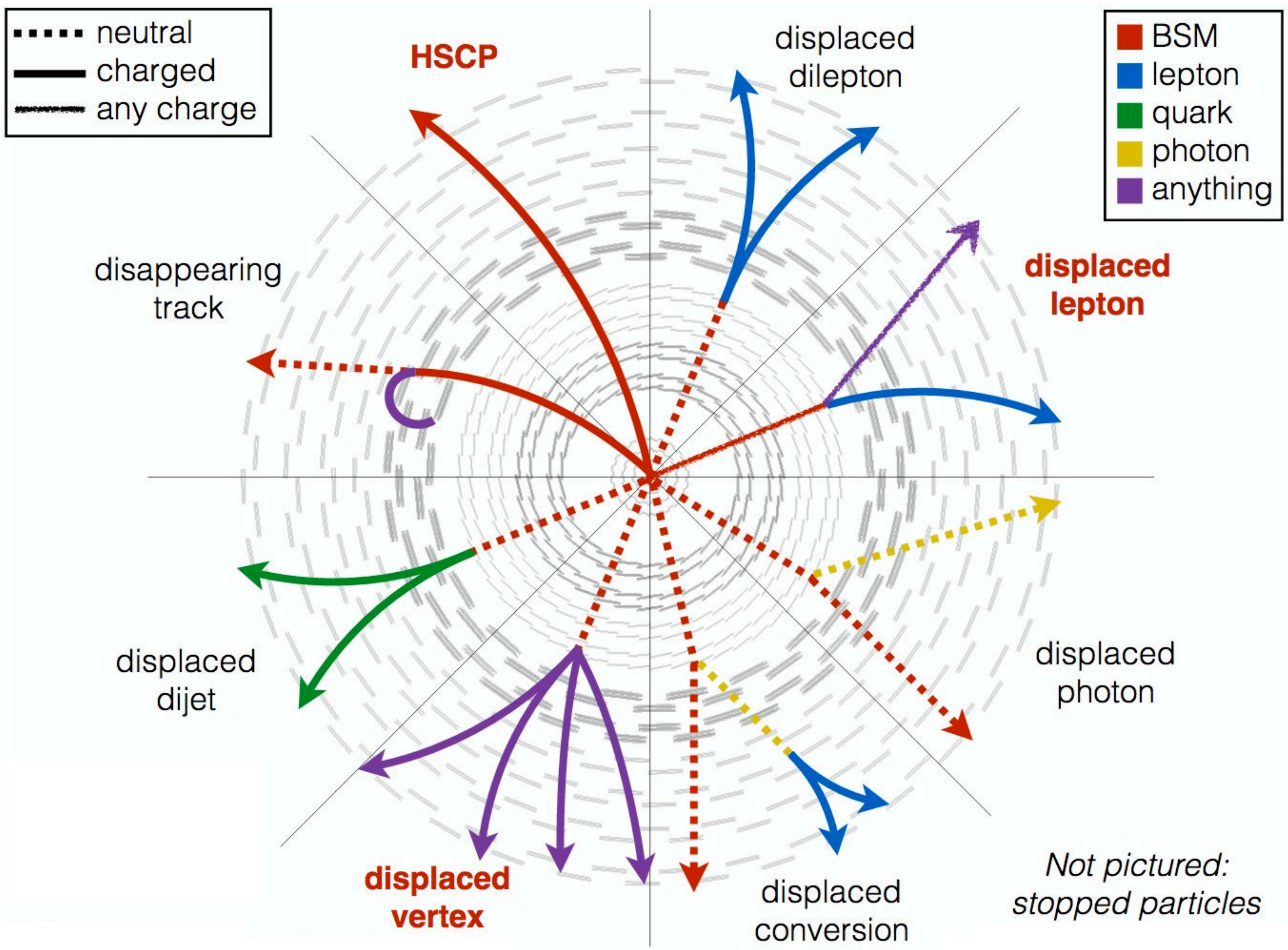
Total weight **14000 t**
Diameter **15 m**
Length **28.7 m**





Long Lived Particle at Colliders

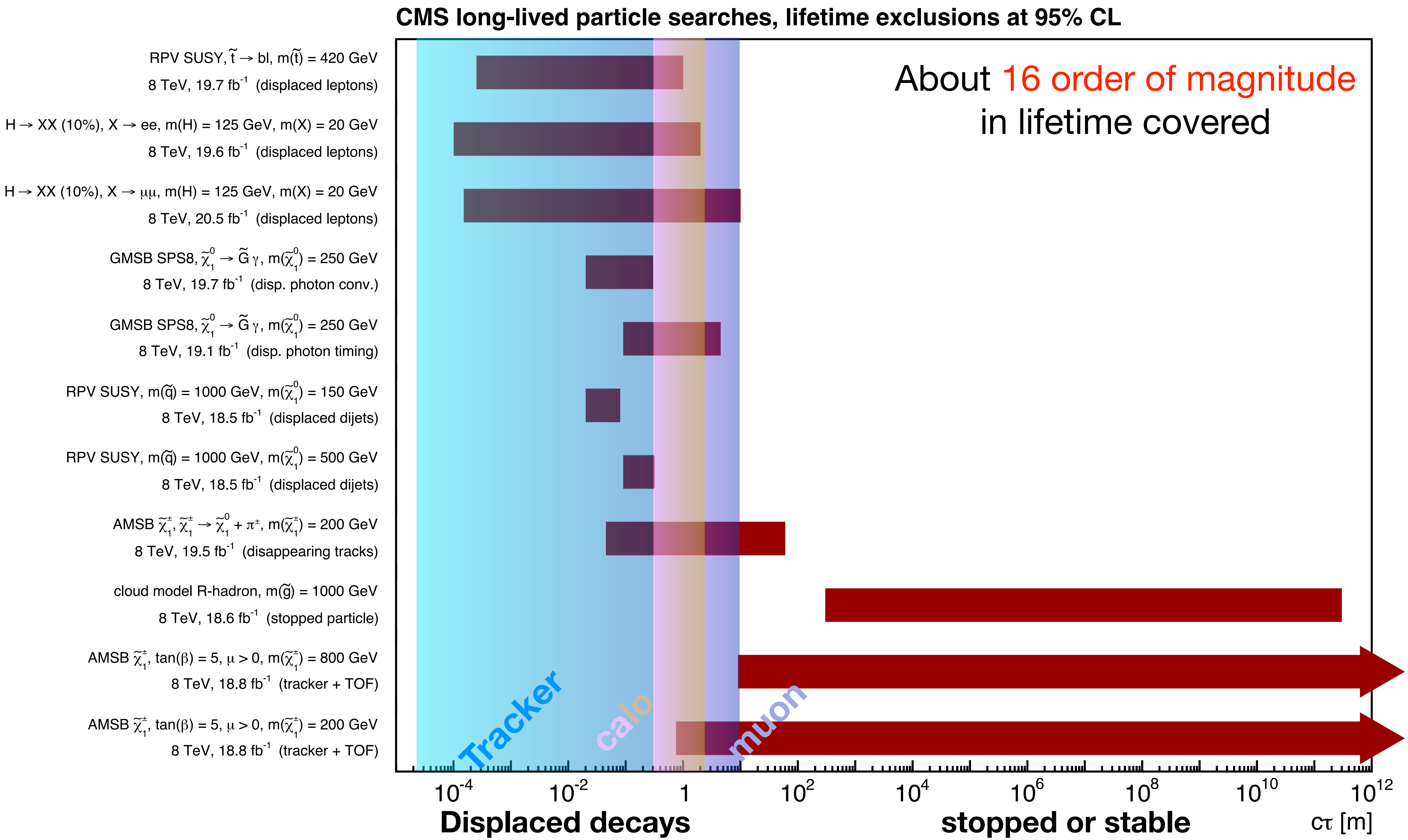
- LHC allows to probe Hidden Sectors with $m_{mediator}$ or m_{hidden} at/above the EWK scale
- High-Luminosity (HL) LHC upgrade will increase number of collisions by factor 10



- LLP production: low rates, but so spectacular that SM are orders of magnitude lower
- From Big Bang Nucleosynthesis constrain we know LLP parameter space is finite*!
- Not pictured: Stopped Heavy Stable Charged Particle

*Karsten Jedamzik. Big bang nucleosynthesis constraints on hadronically and electromagnetically decaying relic neutral particles. Phys. Rev., D74:103509, 2006.

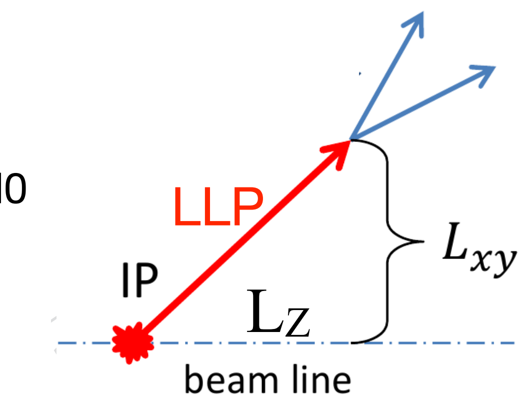
What about CMS?



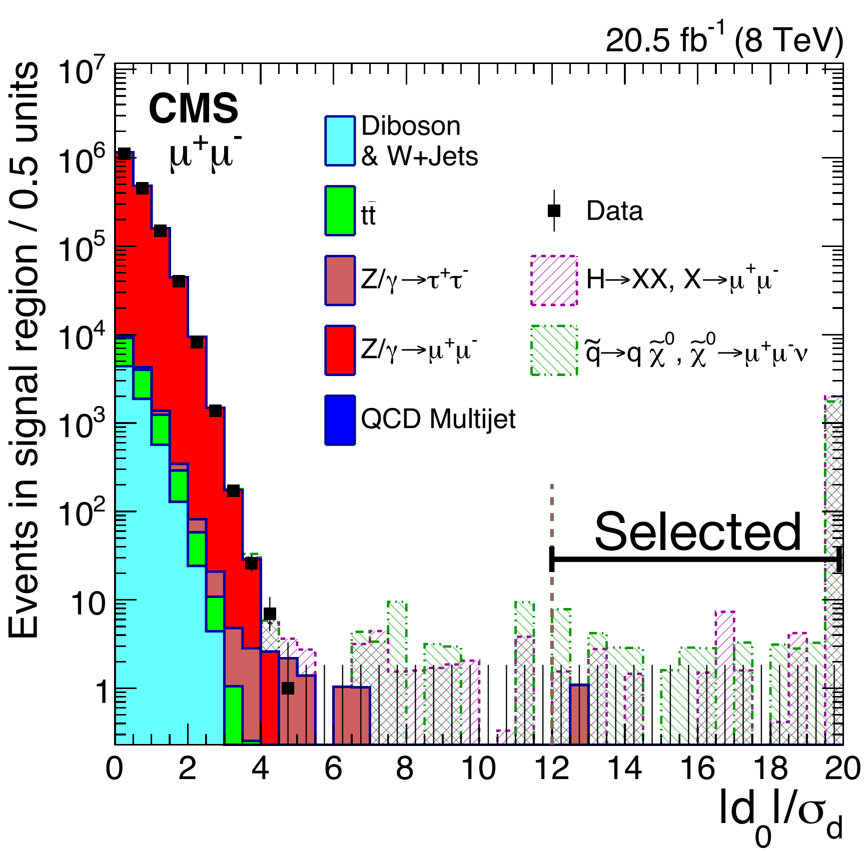
Decays to dark sector particles at CMS: long-lived signatures Ted Kolberg (Florida State University) Dark Interactions 2016, BNL

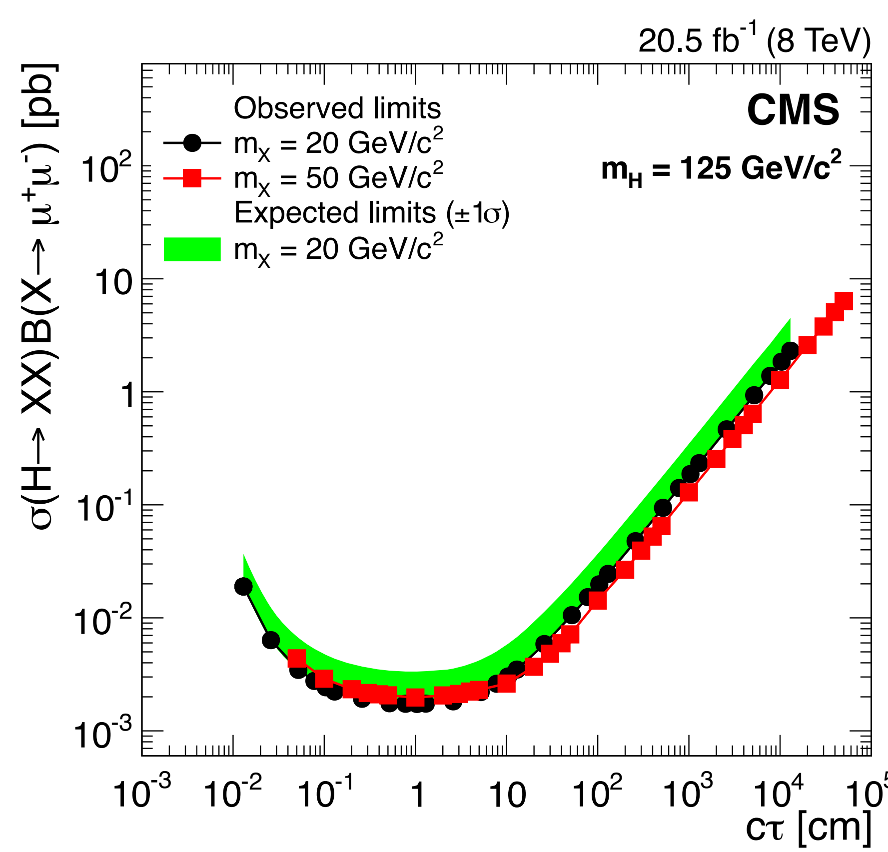
Displaced di-leptons

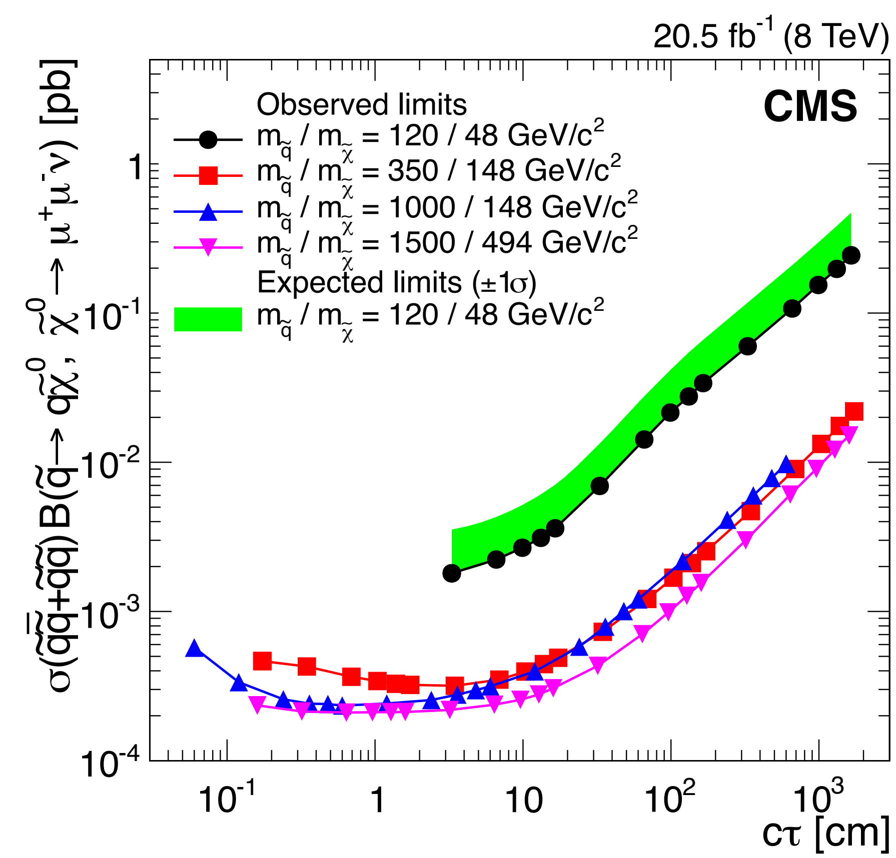
- Long-lived particles decaying into muons or electrons pairs
  - → Based on CMS tracker system (L_{xy} ~ 50 cm)
  - → Selection based on transverse impact parameter significance: $|d_0|/\sigma_{d0}$
  - → Muon pairs with $p_T > 26$ GeV (oppositely charged)
  - → Electrons pairs with $p_T > 25$-40 GeV



- Benchmark scenario: non-SM Higgs, SUSY squark production
  - → Limits presented in a model independent way





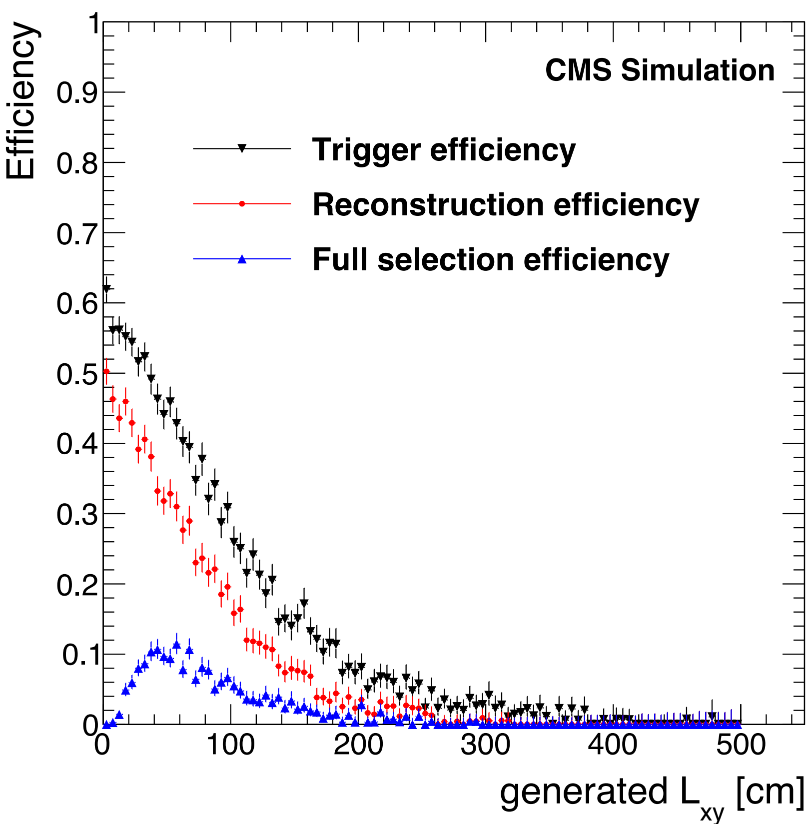


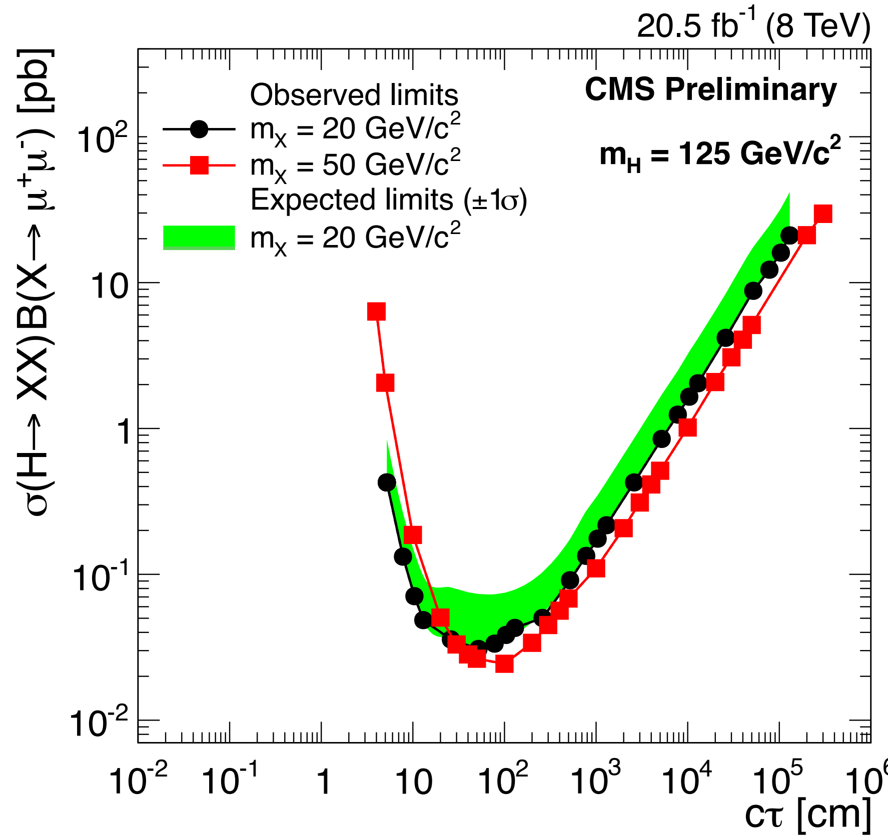
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.052012

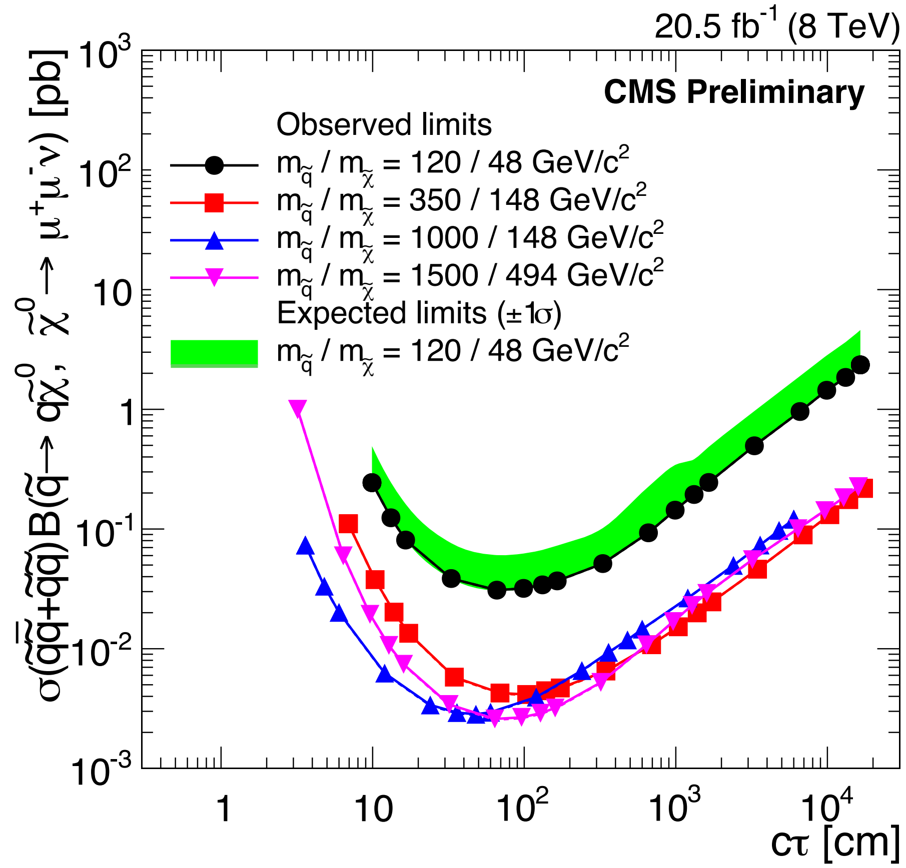
Displaced di-muons

- Long-lived particles decaying into muons pairs using ONLY the CMS muon system
  - → Muons rejected if can be matched to a track in the silicon tracker with p_T>10 GeV
  - → Muon p_T > 26 GeV and $|\eta|$ < 2
  - → Non-negligible cosmic muon contamination: at least 17 hits (DT, CSC, RPC)
  - → Transverse impact parameter significance > 4
  - → Tracker veto allow to drop Iso. requirement: sensitivity to displaced b-quarks

- Additional extension in cτ wrt the tracker only analysis (complementary)





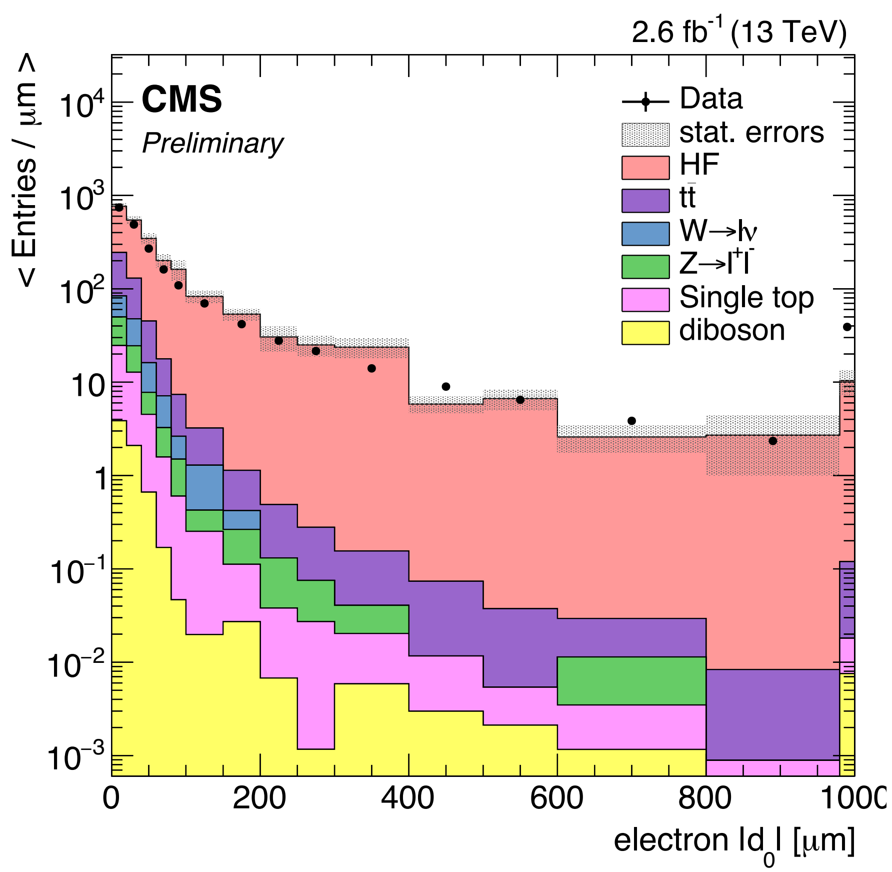


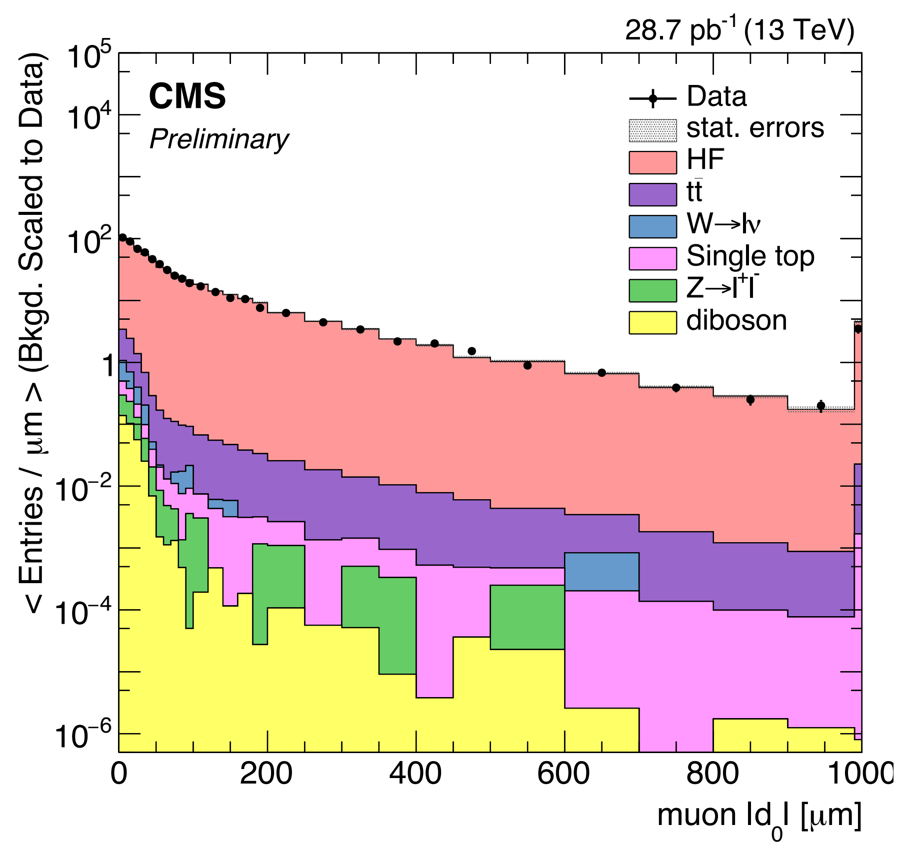
https://cds.cern.ch/record/2005761?ln=en (CMS-PAS-EXO-14-012)

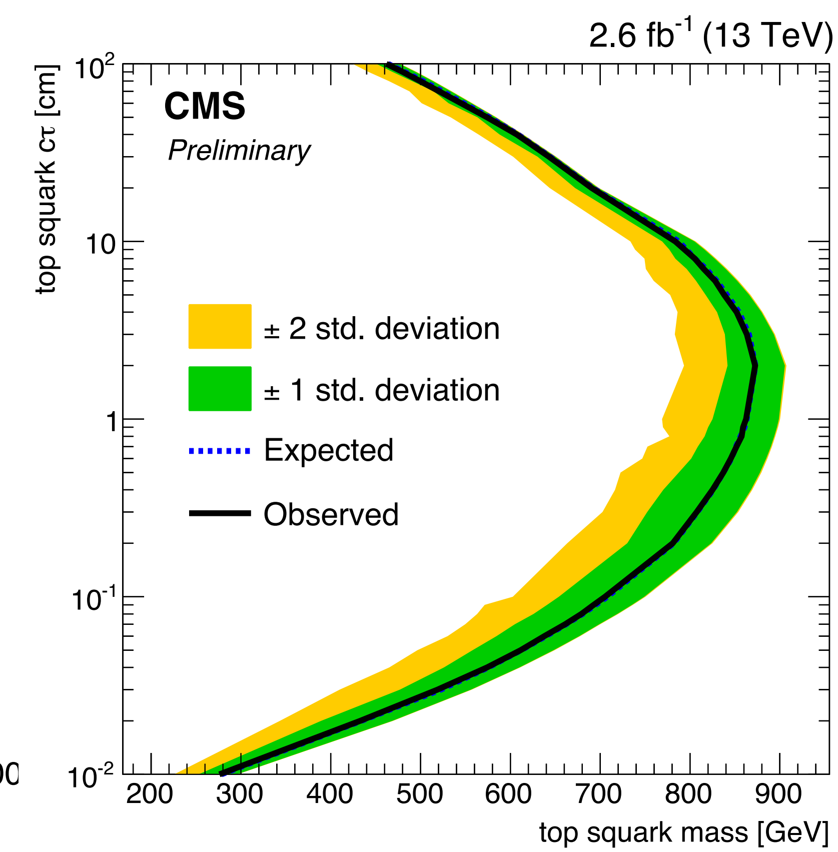
Displaced electron-muons

- Events with an electron and muon, both with transv. impact parameter d_0: 200 μm-10 cm
  - → Sensitivity to any model with displaced leptons, regardless the presence of jets, $\not{E}^{miss}_T$, etc…

- Preselection: two well identified and isolated leptons (e and μ) of opposite charge
  - → Prompt control region: also require $|d_0| < 100\ \mu m$
  - → Displaced control region: also require $100\ \mu m < |d_0| < 200\ \mu m$
  - → Several Signal regions depending on $|d_0|$



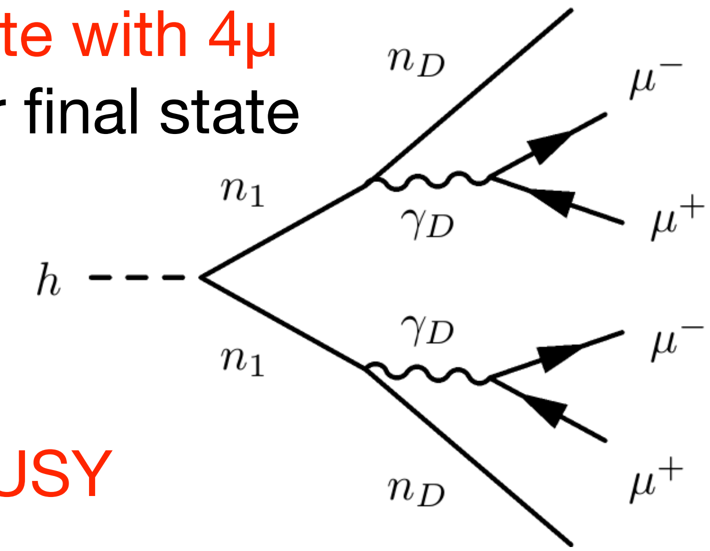




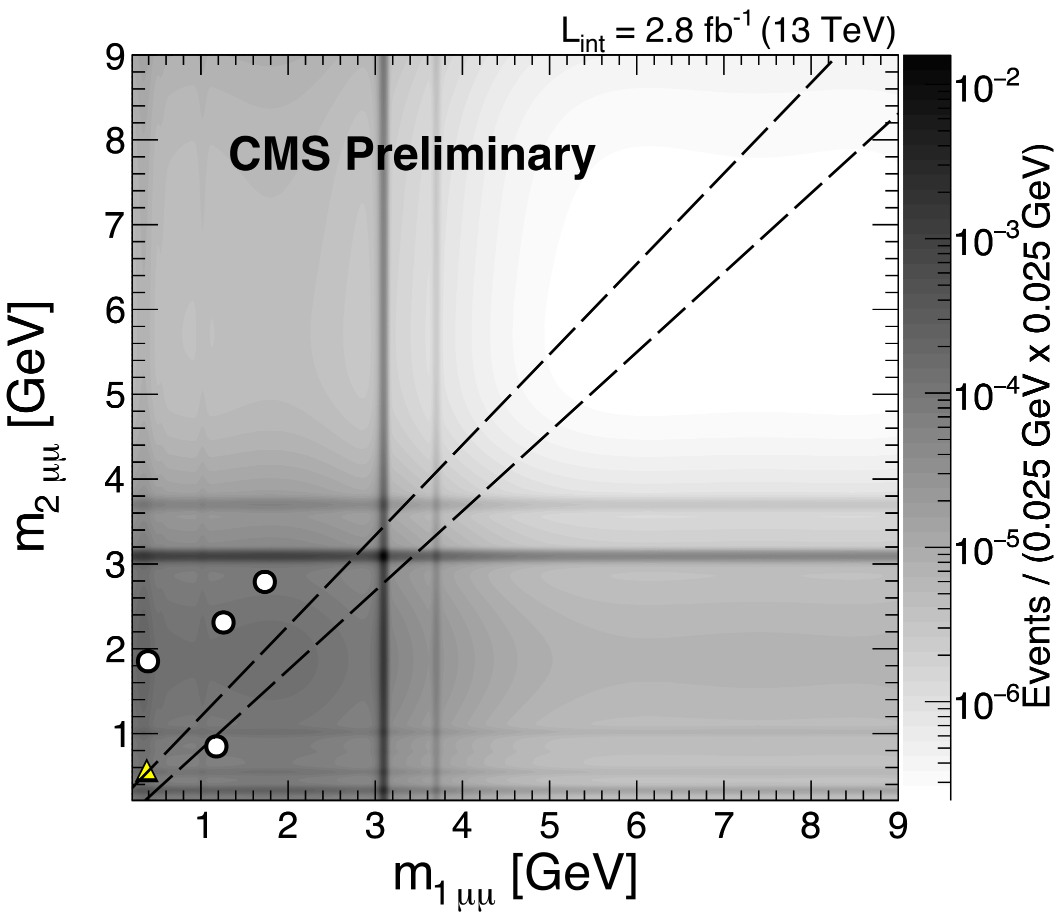
https://cds.cern.ch/record/2205146?ln=en (CMS-PAS-EXO-16-022)

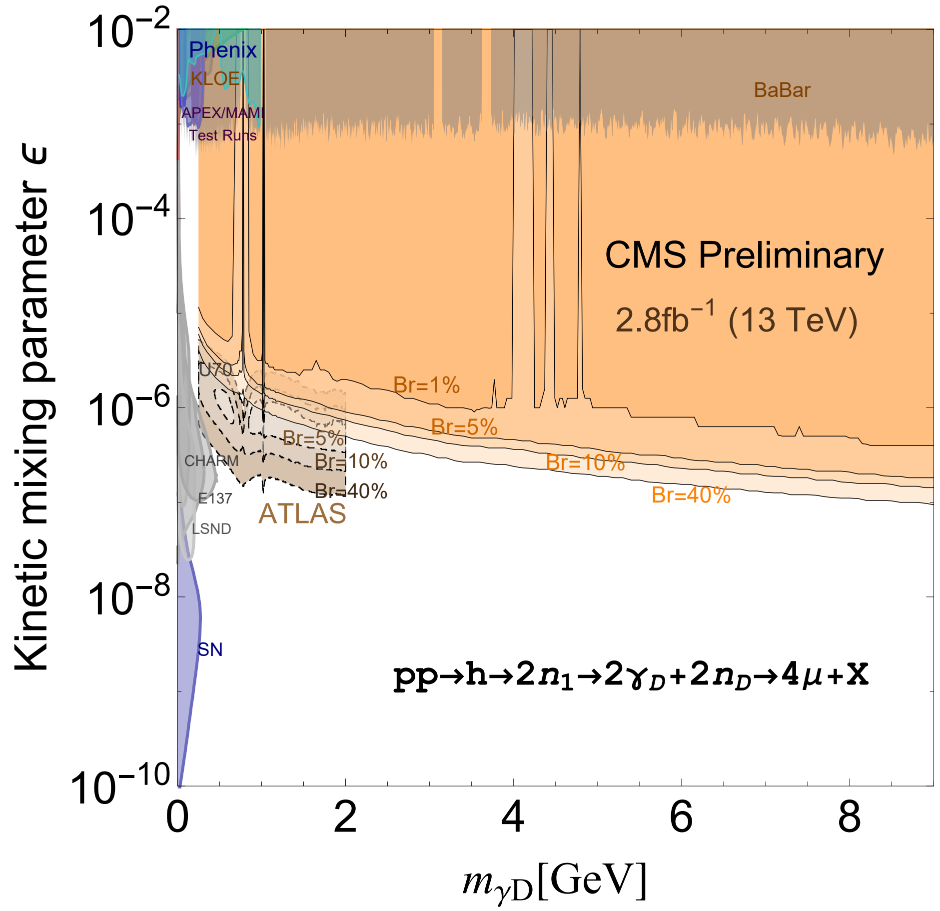
Light bosons to di-muons

- Exploration of Beyond the Standard Model scenarios using final state with 4μ
  - → Easy reinterpretation for new physics models that predict similar final state
  - → Ad-hoc trigger for displaced muon signatures
  - → Data-drive estimation for $b\bar{b}$ and prompt double J/Ψ back.



- Model independent limits translated in term of NMSSM and Dark SUSY



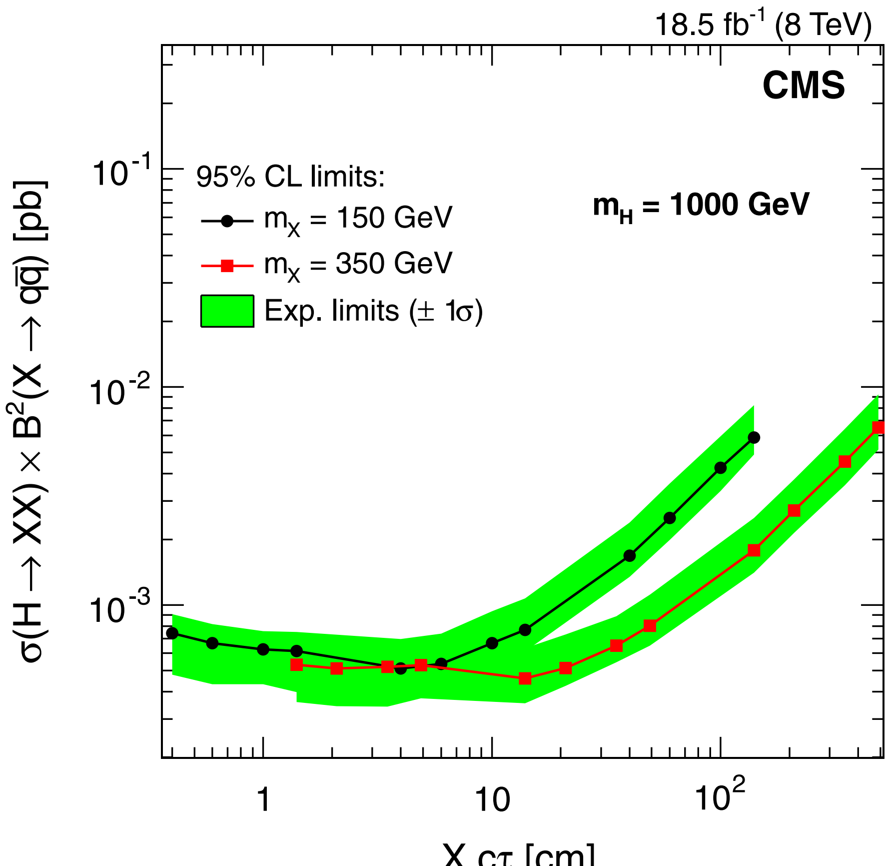


https://cds.cern.ch/record/2232052?ln=en (CMS-PAS-HIG-16-035)

Displaced jets

- Long-lived massive neutral particles decaying to quark-antiquark pairs:
  - → Up to two displaced dijet vertices. Decay length studied: 0.4-200 cm
  - → Jets considered if $p_T > 60$ GeV and $|\eta| < 2$ + tracker information
  - → Jet has no more than two associated tracks with impact parameters < 300 μm

- Displaced jets:
  - → Trigger based on H_T (scalar p_T sum of all jets), no more than 2 prompt track
  - → Displaced jets multiplicity used to search for lifetime between 1 mm and 1000 mm



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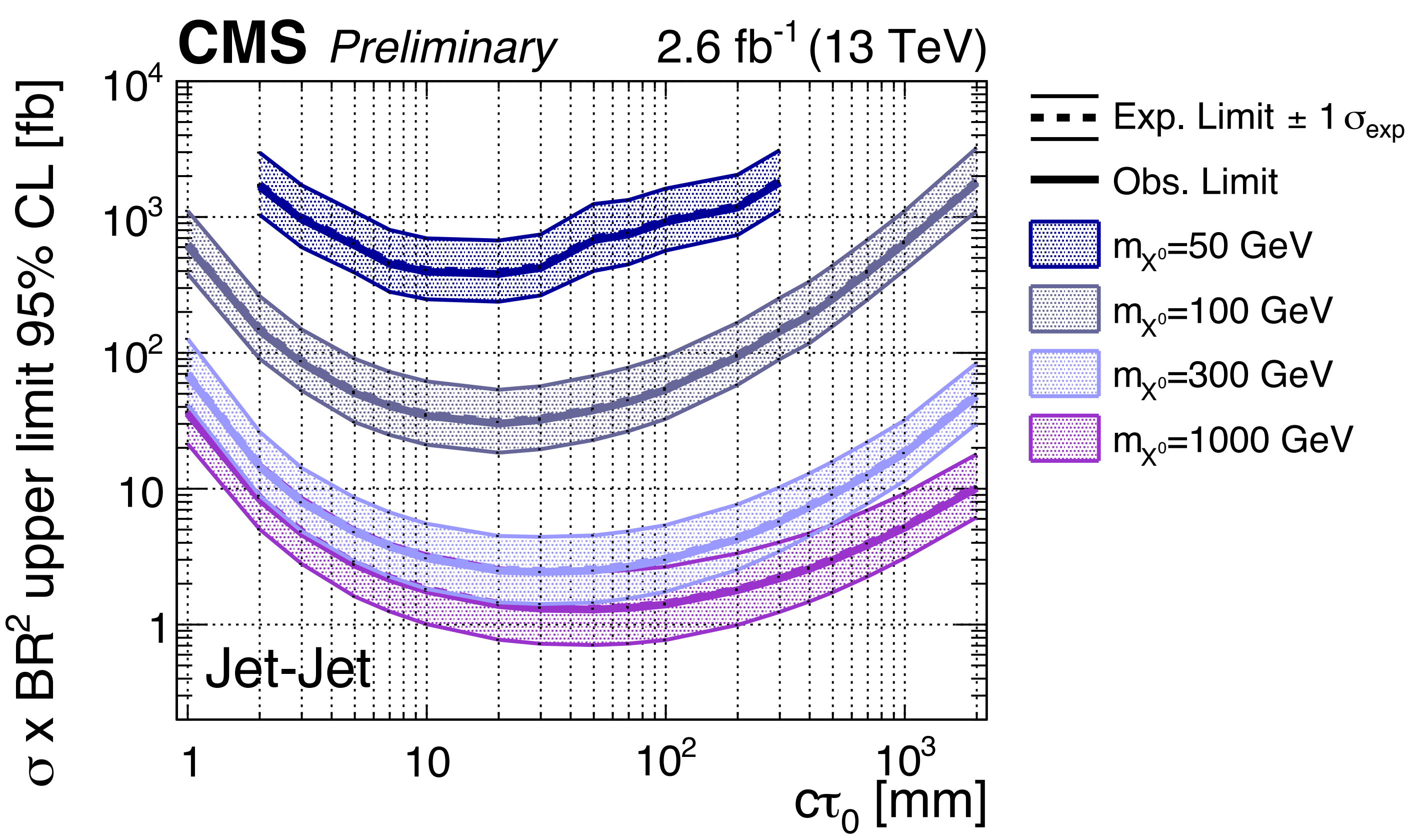

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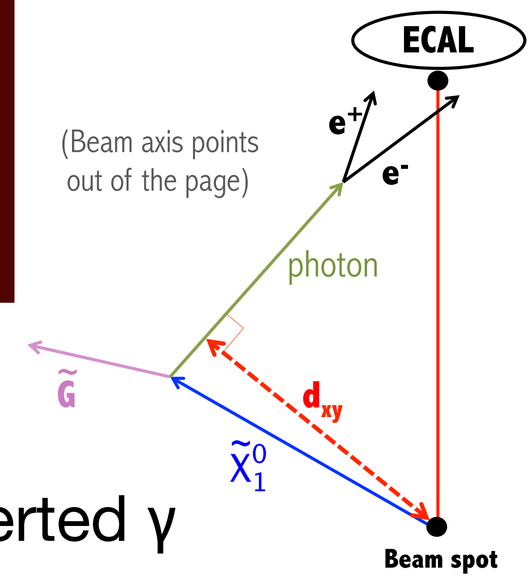
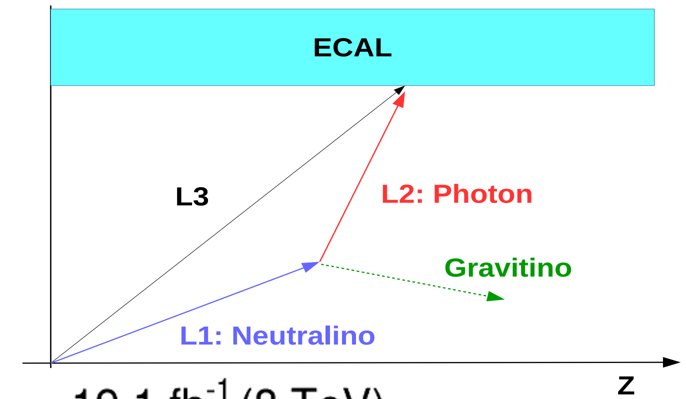
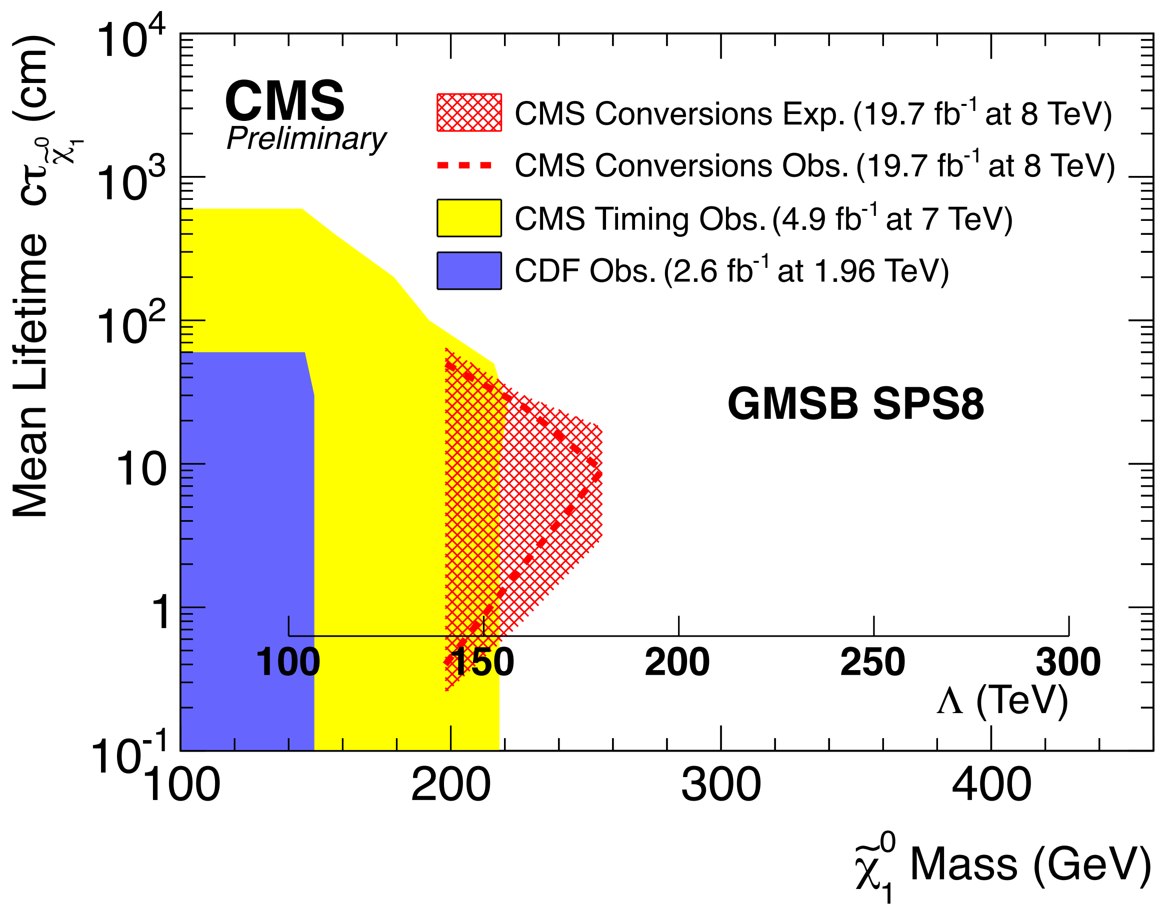
Displaced Photons

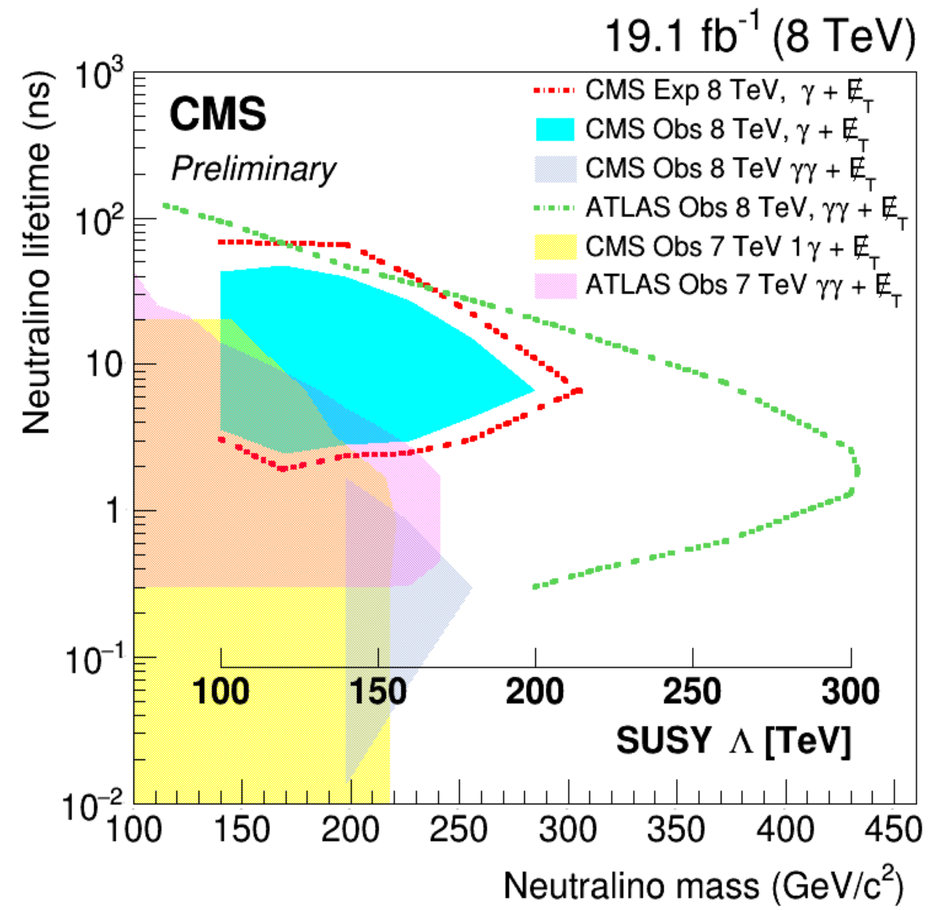
❖ LLP decaying to γ and invisible particles:
- → ≥ 2 γ (at least one has converted to *ee*), ≥ 2 jets, E^{miss}_T
- → Transverse impact parameter reconstructed using converted γ
- → CR to estimate γ+jet (based on ISO and E^{miss}_T)



❖ Search for long LLP in delayed γ and E^{miss}_T
- → Exploit ECAL barrel precise timing (cτ from 1.6 to 34 ns)
- → Analyzed the γ cluster shape to reject background







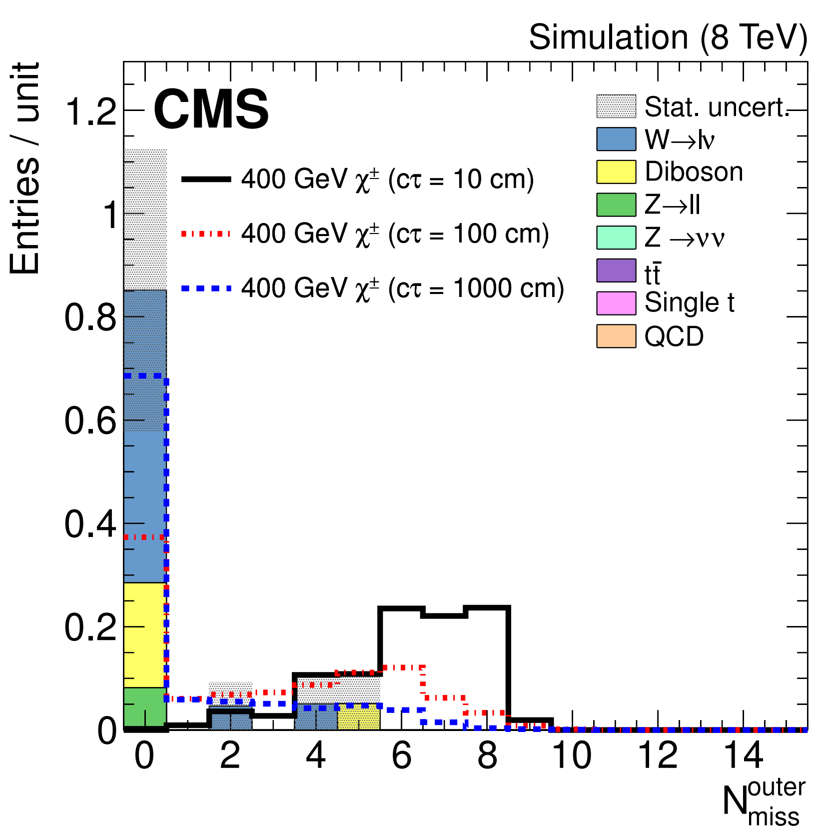
$$\tau \propto \frac{M_P^2 m_{\tilde{G}}^2}{m_{\tilde{\chi}^0}^5}$$

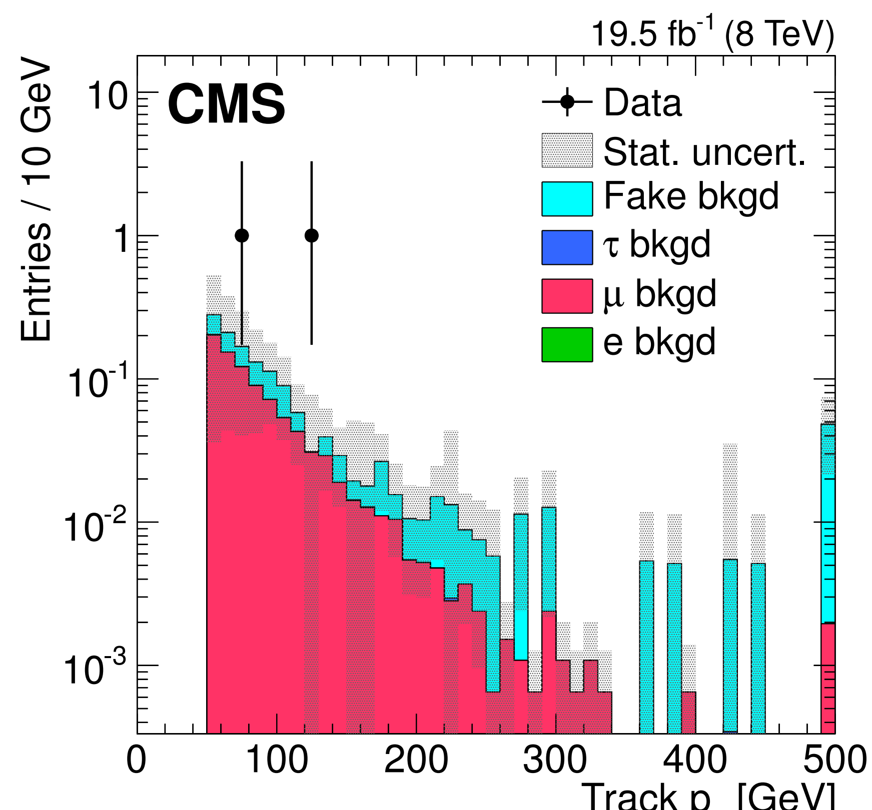
https://cds.cern.ch/record/2019862?ln=en https://cds.cern.ch/record/2063495?ln=en

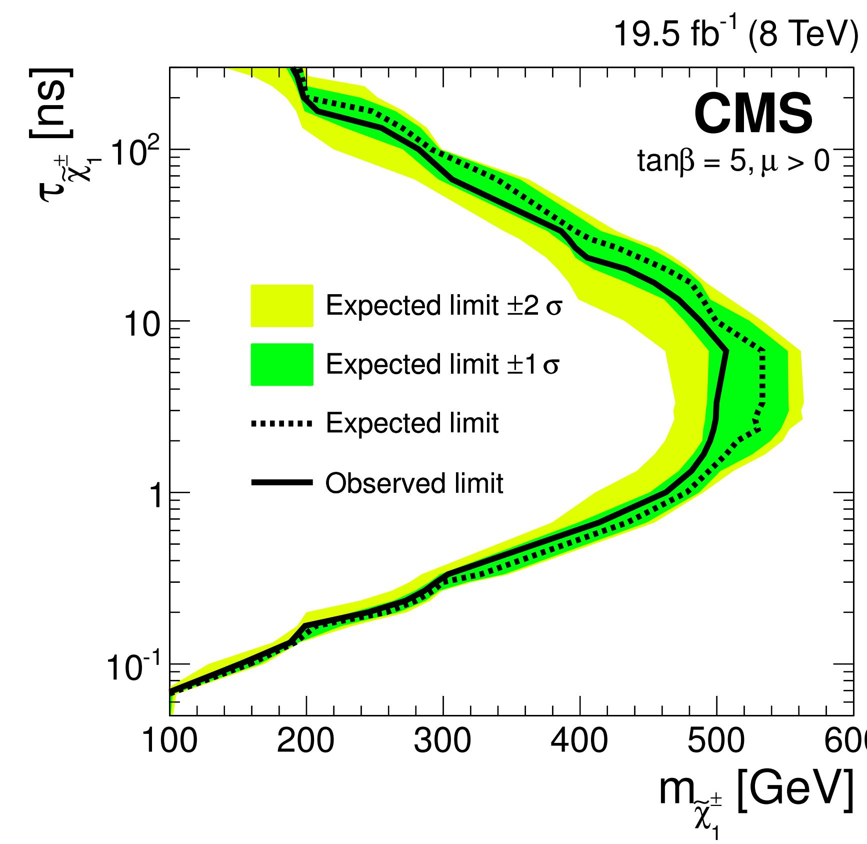
Disappearing tracks

❖ Long-lived charged particles that decay within the CMS detector: disappearing track
→ Little associated calorimeter energy and with missing hits in outer tracker layers
→ Disappearing track recorded if it radiate a jet or more ($\not{E}^{miss}_T$ ~ BSM signal)
→ $\not{E}^{miss}_T > 100$ GeV, p_T(jet) > 110 GeV, p_T(track) > 50 GeV
→ Missing outer hits in the tracker N_{outer} used to discard SM background
(SM particles mimic signal as the result of interactions with the tracker material)

❖ Benchmark scenario: Anomaly-mediated supersymmetry breaking



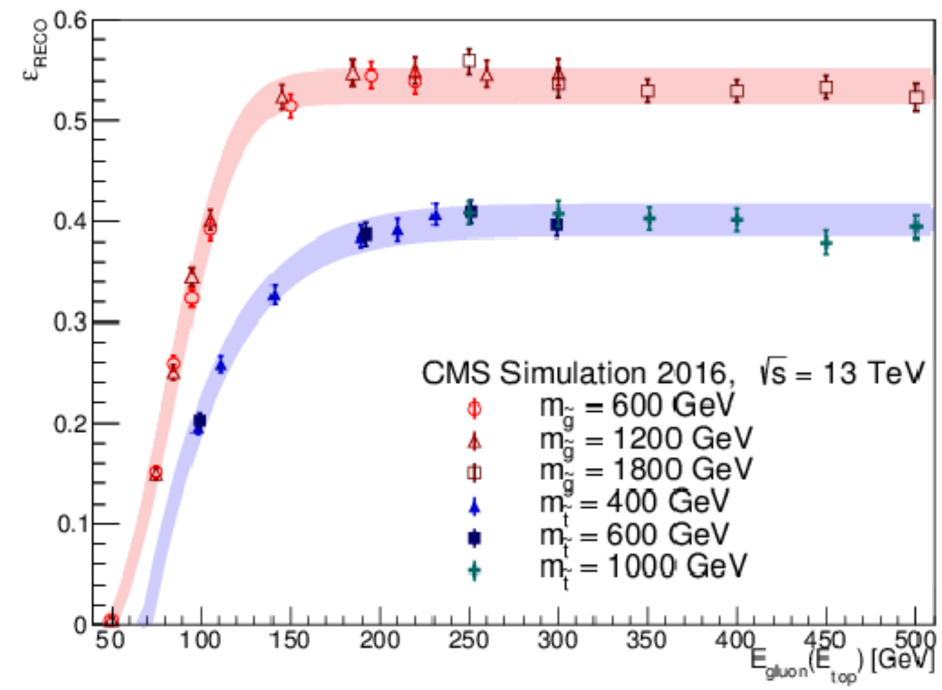




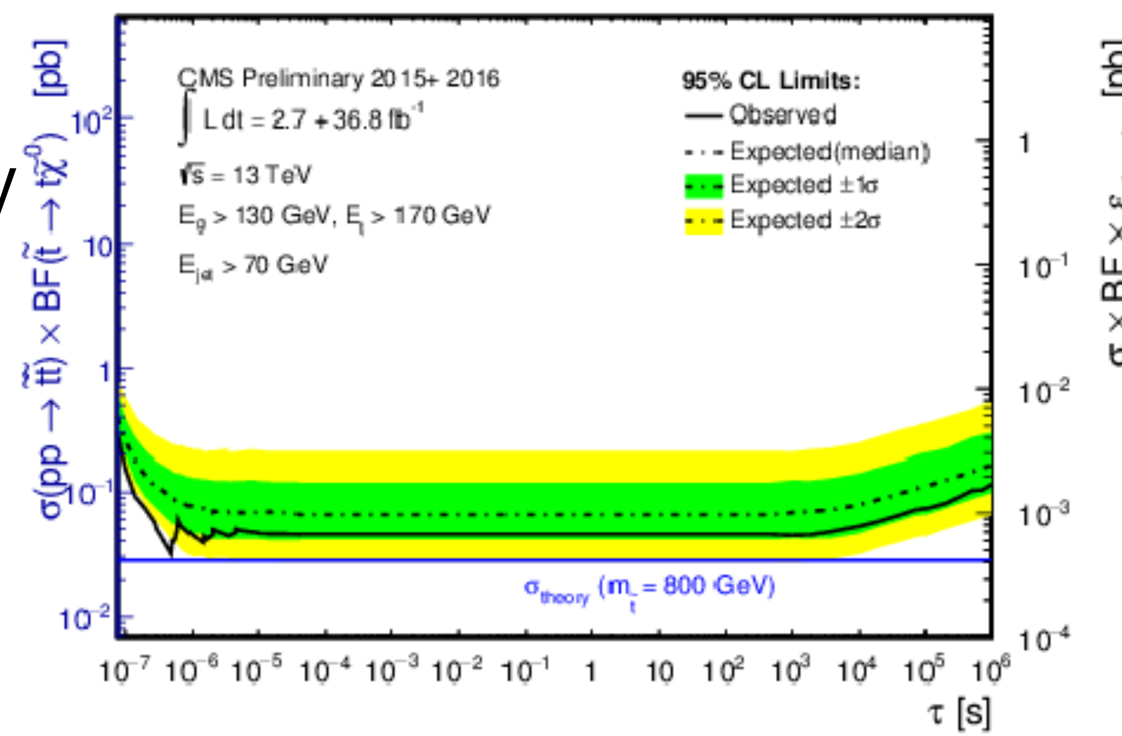
https://link.springer.com/article/10.1007%2FJHEP01%282015%29096

Stopped Long Lived Particles (hadr.)

- LLP (gluinos, stops..) could be pair produced and hadronize into R-hadrons that interact with detector material (nuclear interactions & ioniz.)
  - → Below a critical velocity, kinetic energy go to zero and (some later time) decays
- If LLP decays to at least one SM particle:
  - → High-energy jet not coincident with collisions
  - → Only rare background processes



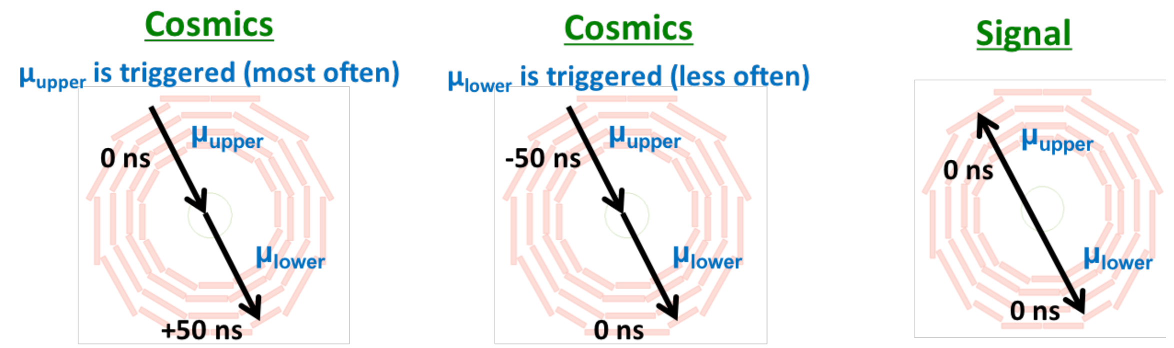
- Dedicated trigger used to select out-of-time events
  - → At least two BXs away from bunches passing the detector
  - → Trigger requires at least one jet with E > 50 GeV
  - → Calorimeter-based jet with E > 70 GeV
- Main background: halo muons, cosmics
  - → Can emit photons striking calorimeters
  - → Rejecting events with hits in CSC, segments in opposite DT regions or far from the jet direction

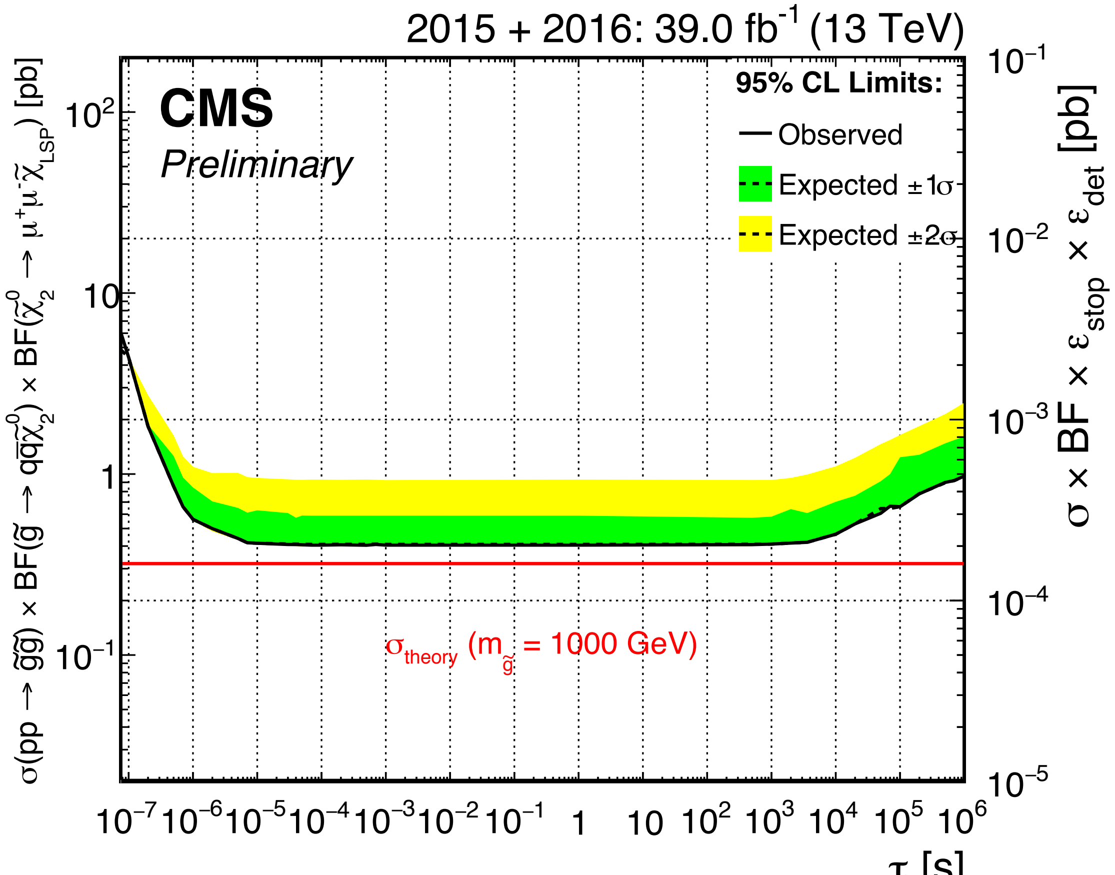


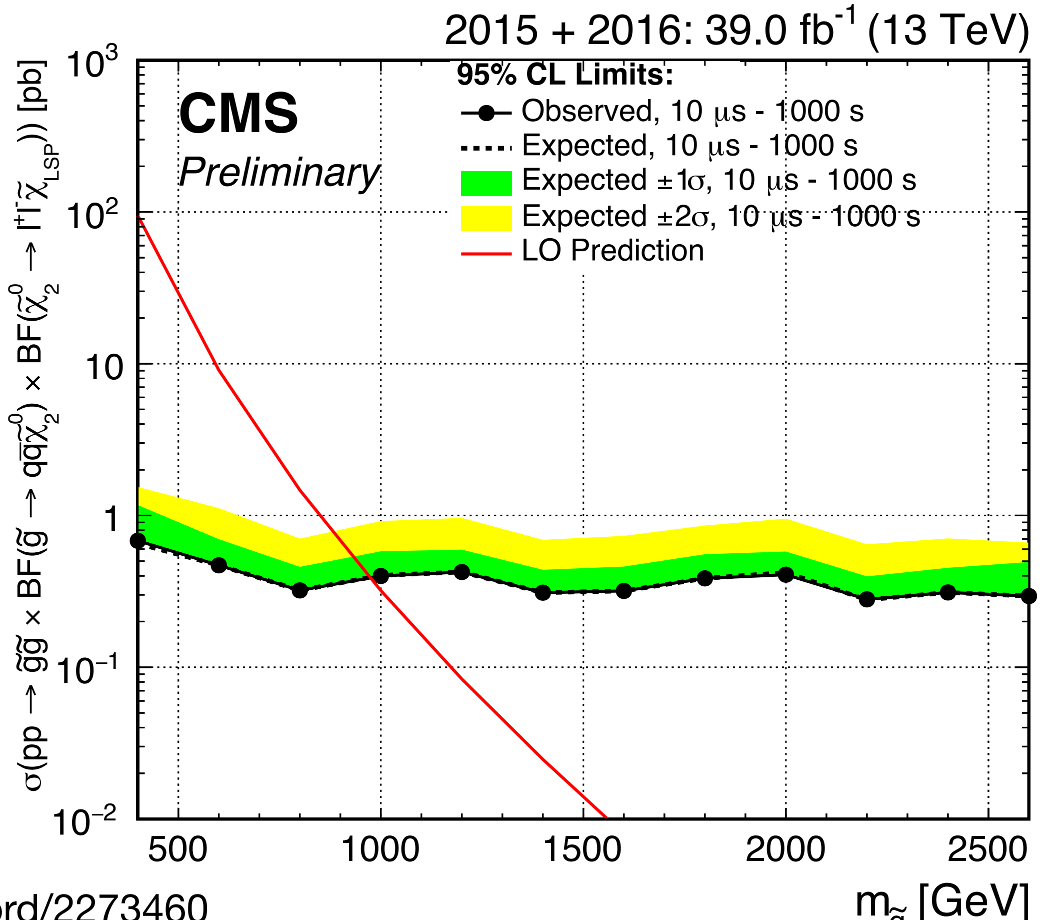
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-004/index.html

Stopped particle: muons

- Long-lived particles come to rest in CMS and decay to muons
  - → Decays could be observed during the intervals between LHC beam crossings
    - → Custom trigger designed to record events that are out-of-time with collisions
    - → Trigger used also when no pp collision where present (cosmic data)
  - → Offline criteria to reject cosmic μ
    - → Muon TOF information from DTs and RPCs
    - → DSA tracks: only hits in the muon chambers, no constraints on beam spot



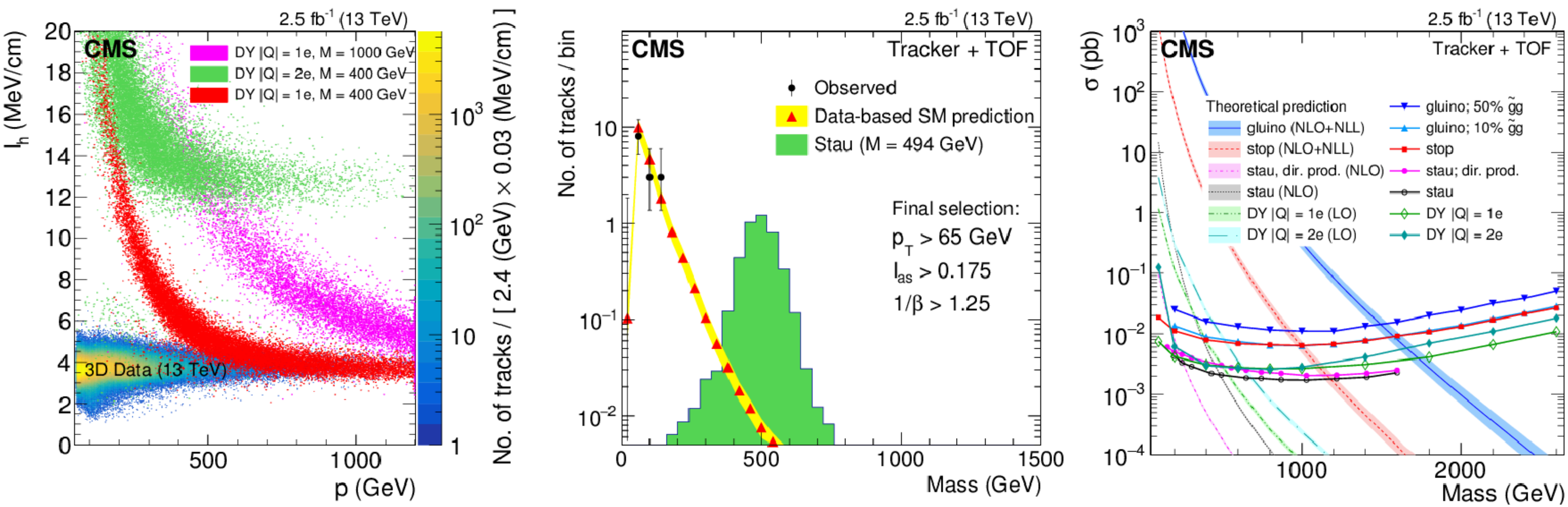




https://cds.cern.ch/record/2273460

Charged Long Lived Particles

- HSCP might have high momentum, speed smaller than *c*, and/or Q not equal to the elementary charge ±e
- Possible to distinguish |Q|≥1e particles with $\beta < 0.9$ from light SM particles using E loss
- Two ways to reconstruct HSCP:
  - → Requiring tracks only in the silicon detectors (tracker-only)
  - → Requiring tracks in both the silicon detectors and muon system (tracker+TOF)
- Muon trigger more efficient than E_t^{miss} trigger
- Very well reconstructed track (muon) on the tracker-only (tracker-TOF) analysis



http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-15-010/index.html

Conclusions

- CMS has a broad physics program for Long Lived particles
  - → Signatures motivated by broad range of phenomenology
  - → Tendencies to move to more model independent analysis when possible
  - → Strong interest to present results via simplified models

- Exotic long-lived particles searches will benefit from the upgraded detectors
  - → New pixel detector in 2017 (heavy stable charged particles)
  - → High-Luminosity LHC will be a time of exciting physics potential and many experimental challenges, i.e. precise timing!
    - → High Granularity Calorimeter (which also offer 50 ps time resolution)
    - → Timing detector for MIP

- Long Lived Particles searches start from trigger design
  - → Trends from Run1 to Run2 have mostly been to either raise thresholds in order to cope with pileup or design a more signal-specific trigger
  - → Planned to include tracker information into trigger decision
  - → Planned to trigger on muons produced outside tracker acceptance

STAY TUNED!

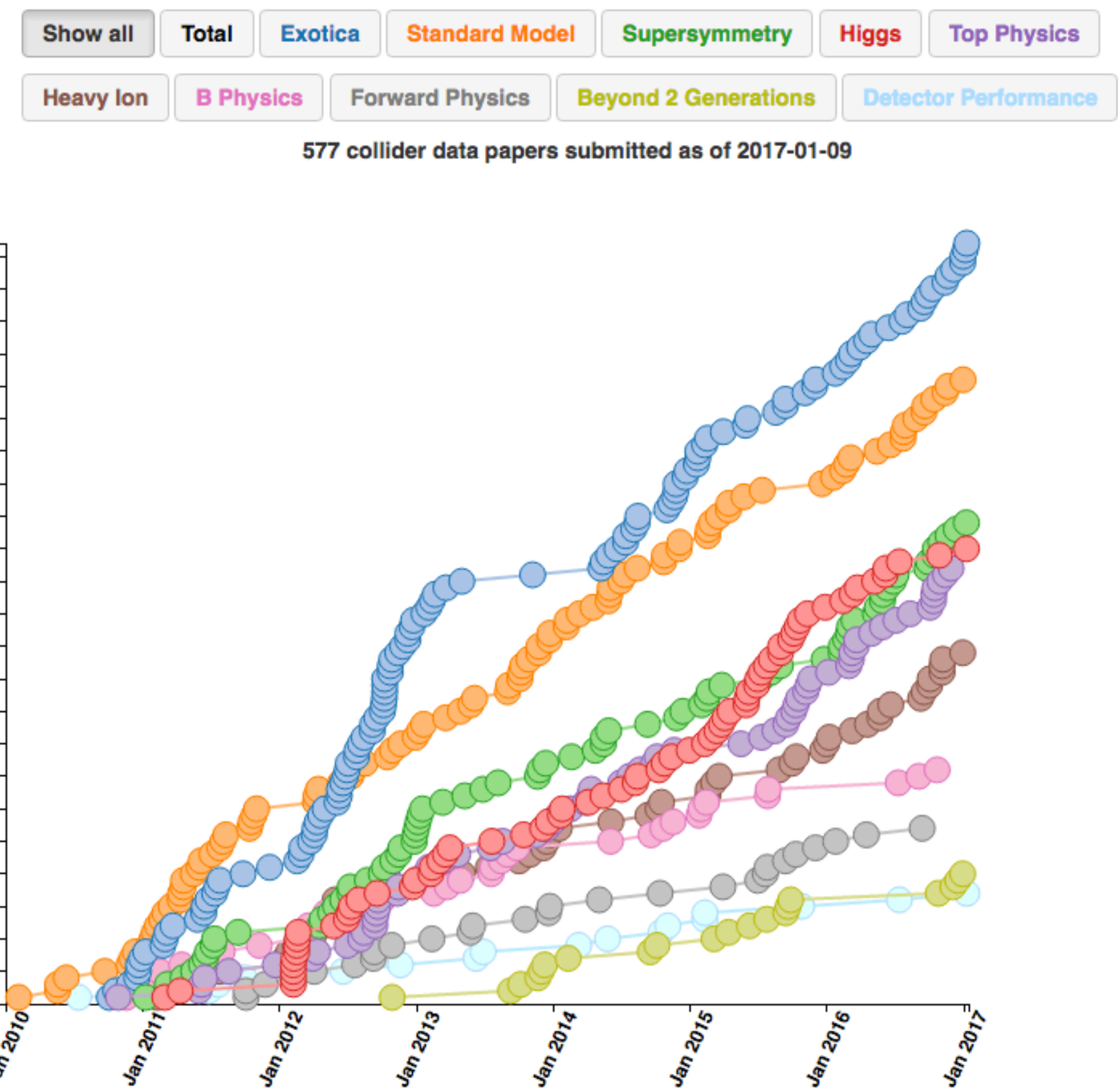
Backup

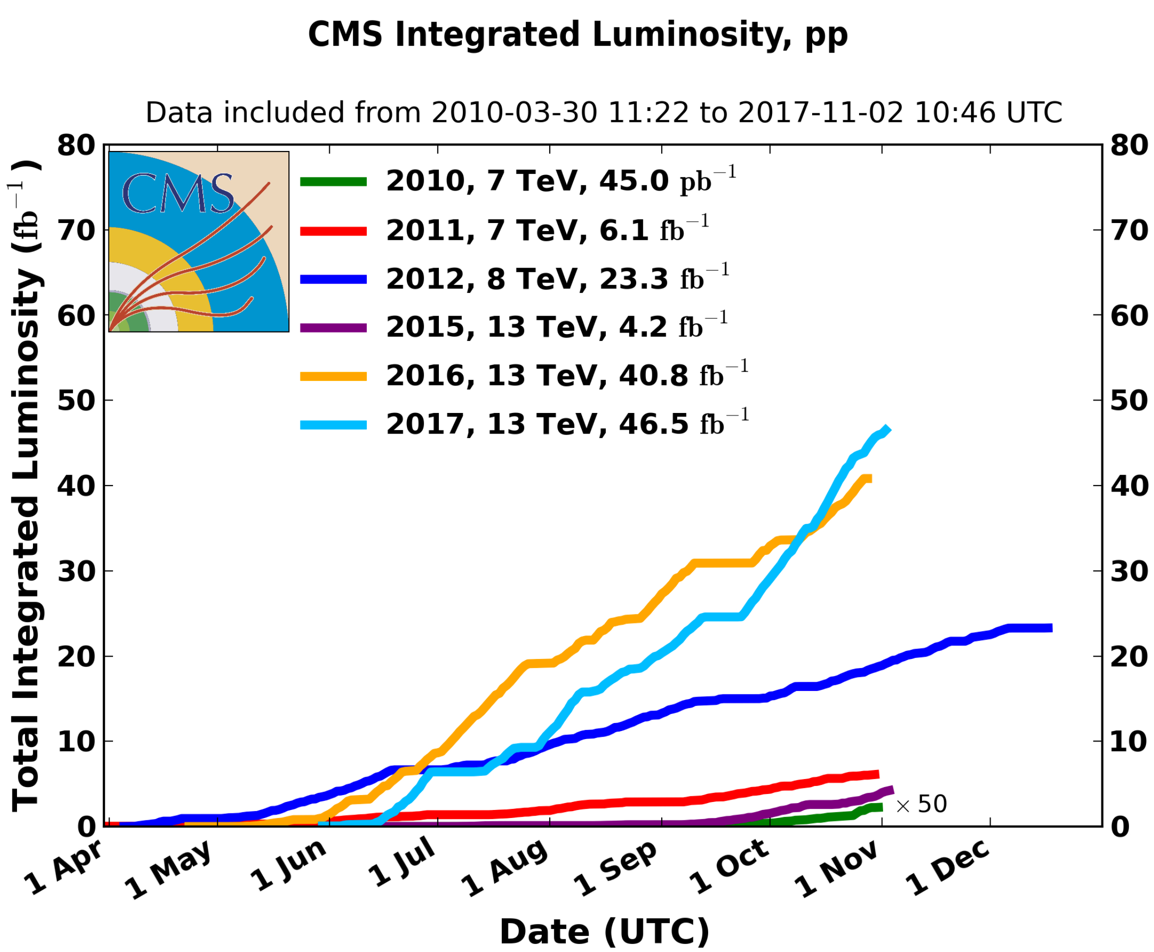
Run II Performance

- Thanks to LHC: approaching 100 fb^{-1} → Average pileup ~27

  Advantageous ratios of LHC parton luminosities (between 13 and 8 TeV)!!

- Exotic searches include a vast amount models (everything is non Higgs-non and susy related)



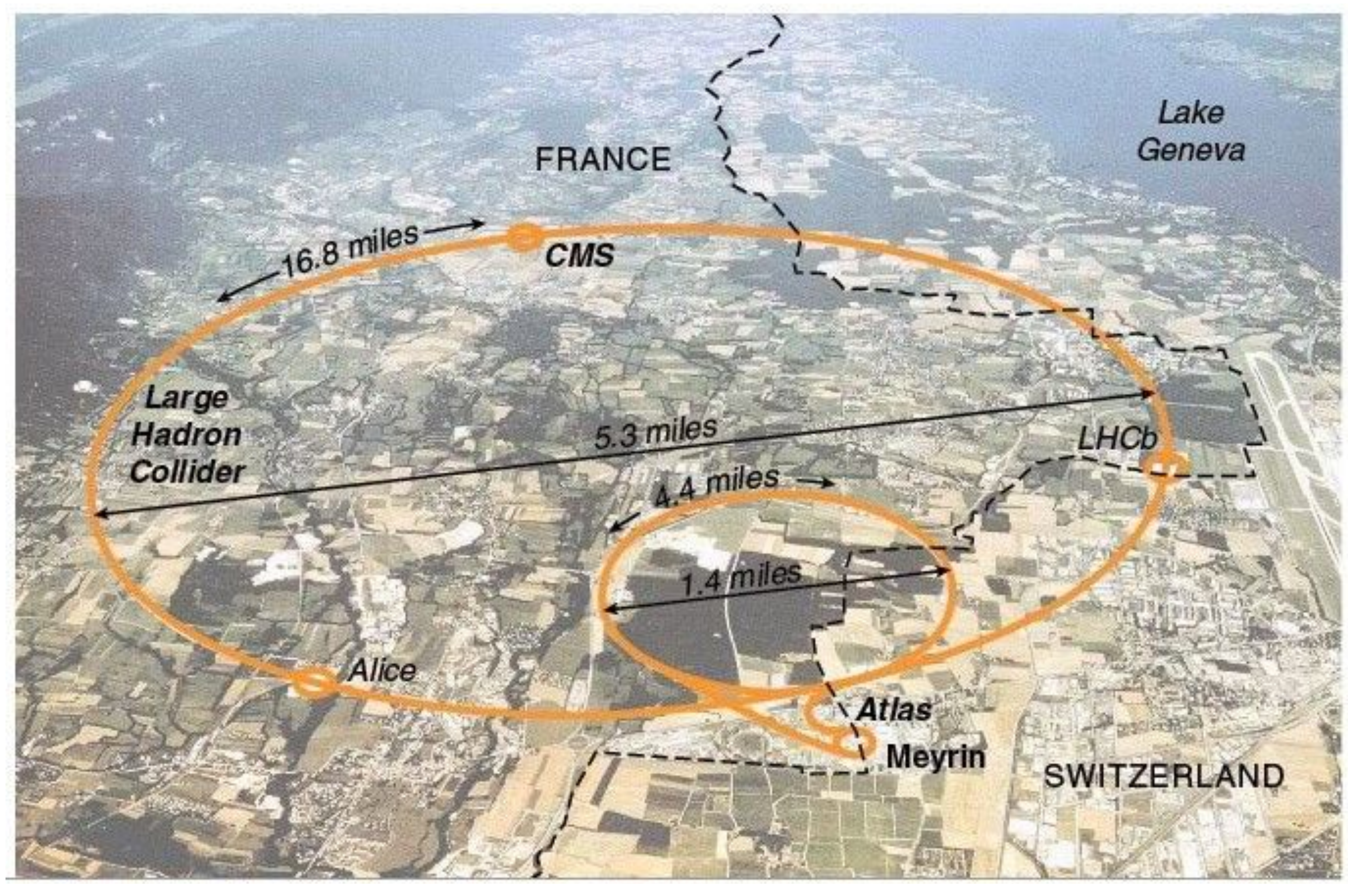


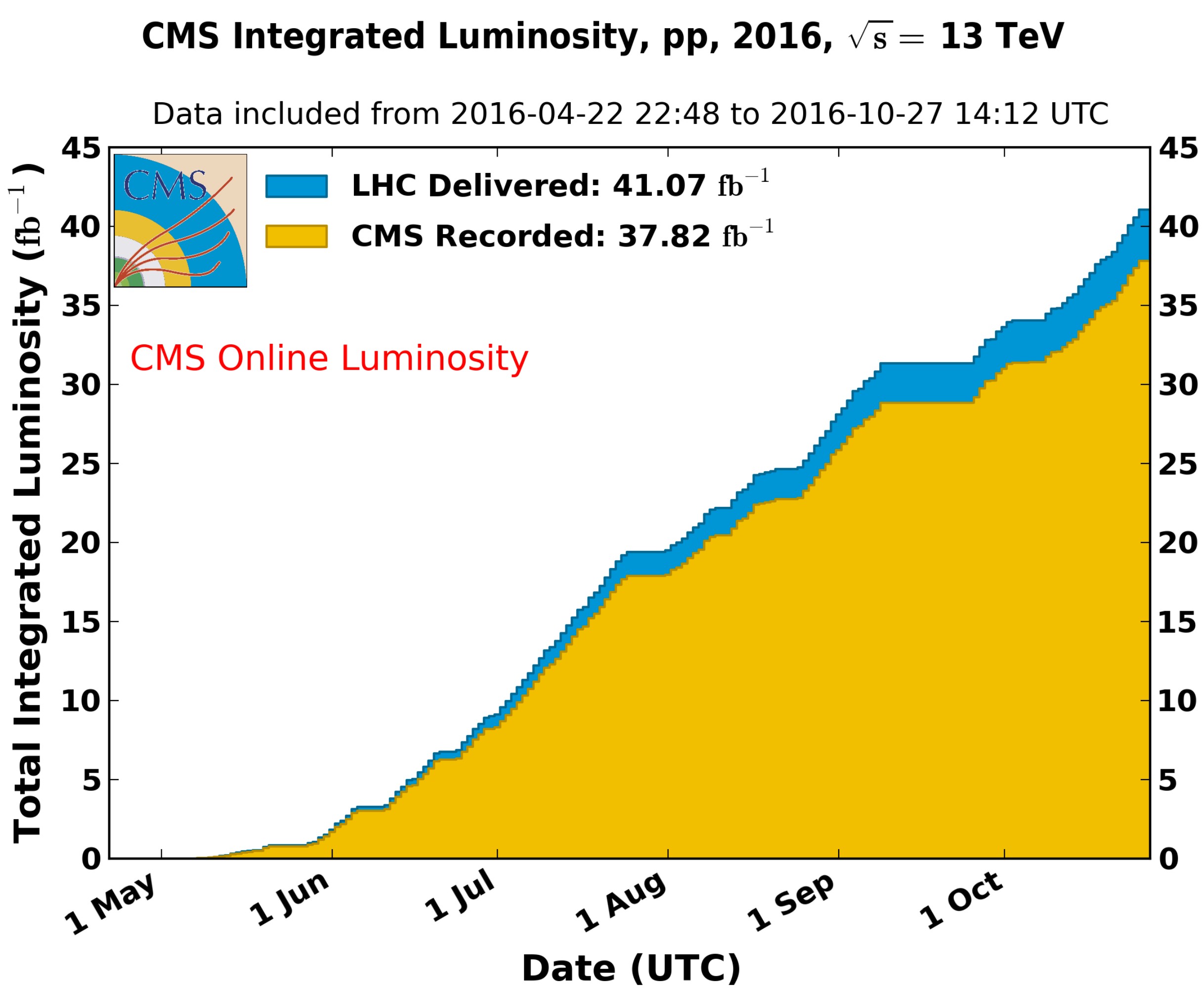
The Large Hadron Collider

- Run 2 is officially started!
  → About 3 fb^{-1} collected in 2015
  → 37.8 fb^{-1} by the end of 2016

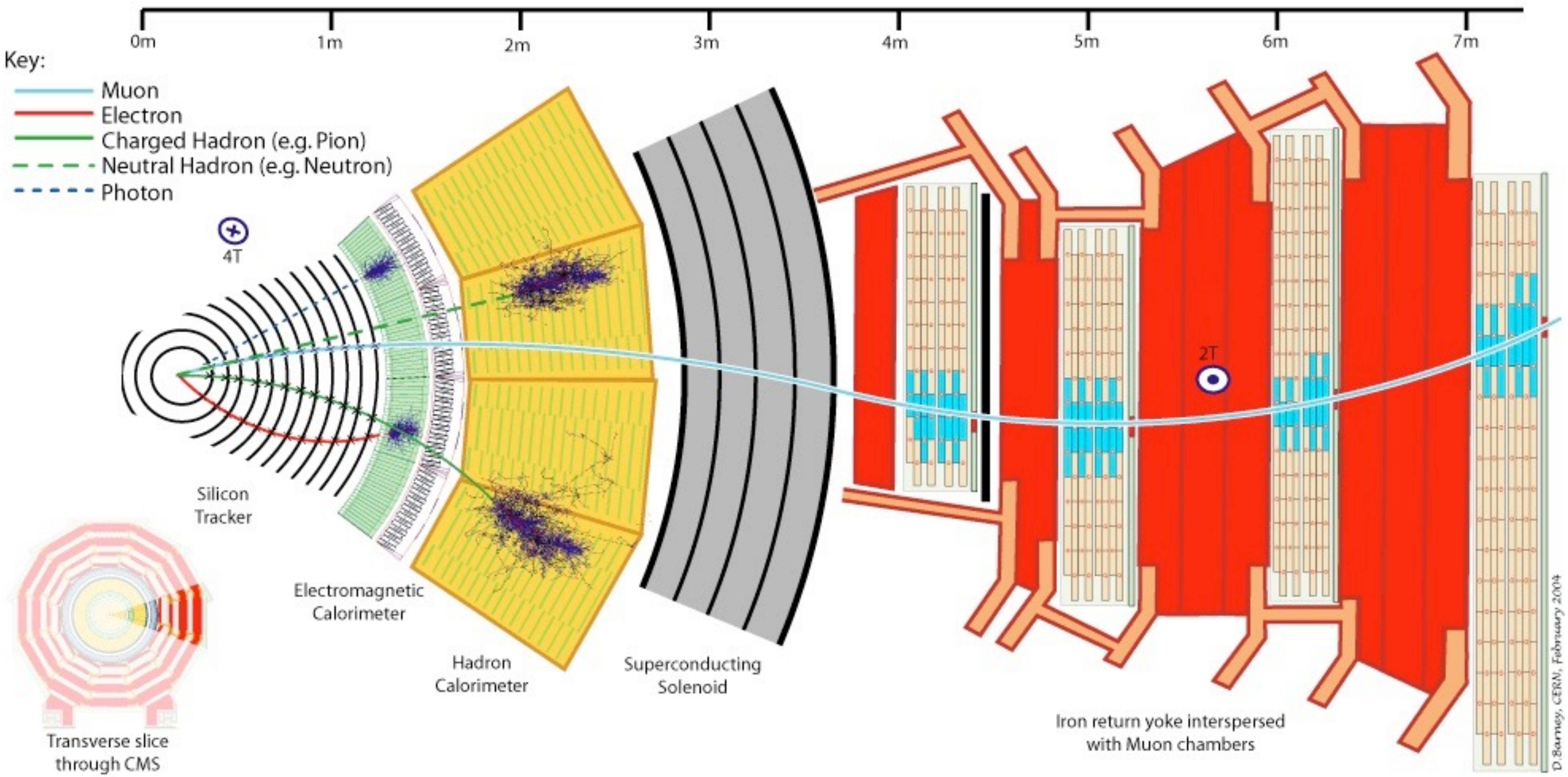
- Comparison with 8 TeV:

- 160% larger collision energy → $\sqrt{s}$=13 TeV
- 200% larger number of bunches → 2800 bunches
- 200% larger pileup → 40 interactions/crossing
- 33% smaller β* → 40 cm
- 170-220% larger peak Lumi. → (13-17)x10^{33} $cm^{-2}s^{-1}$

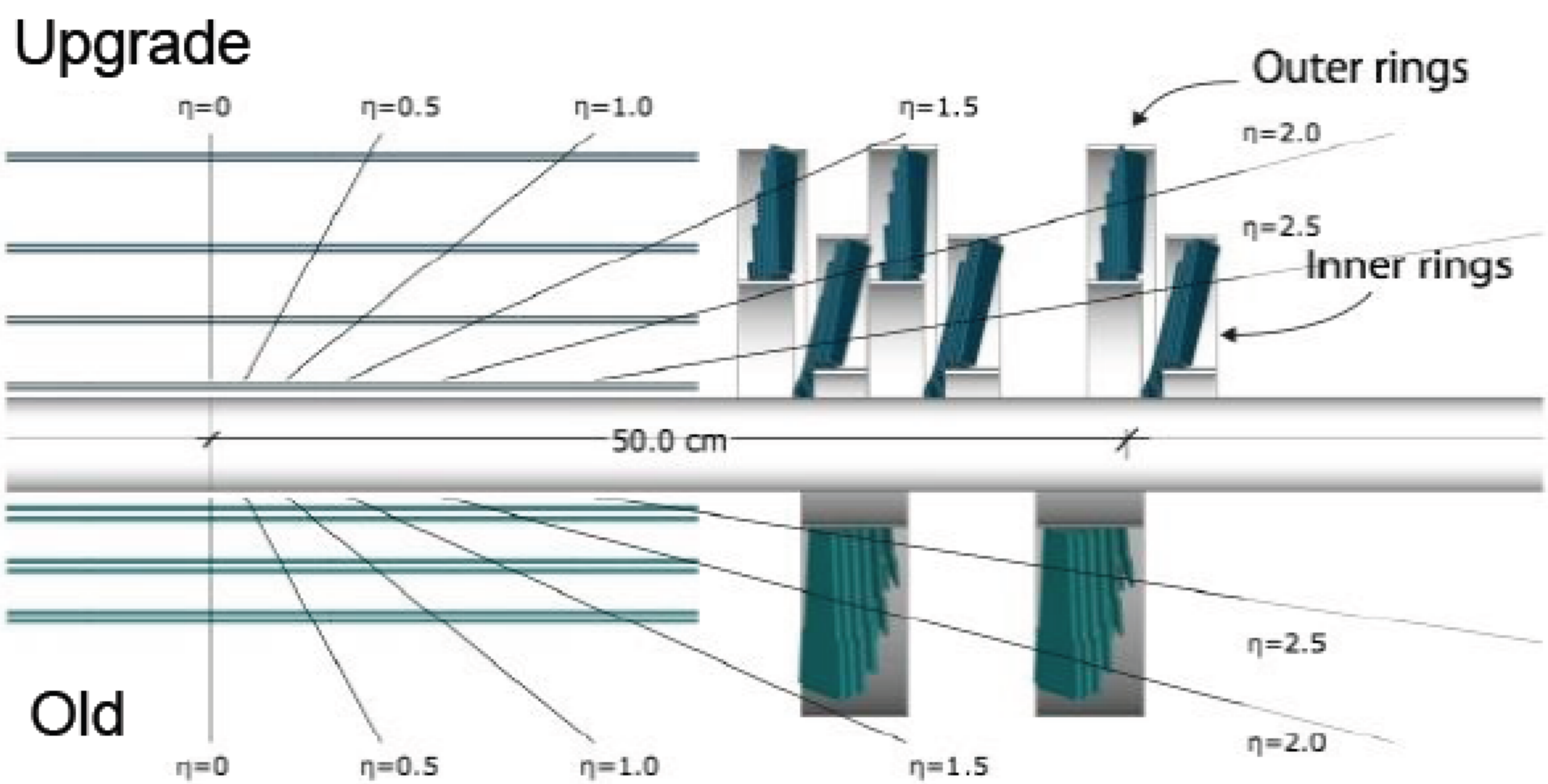


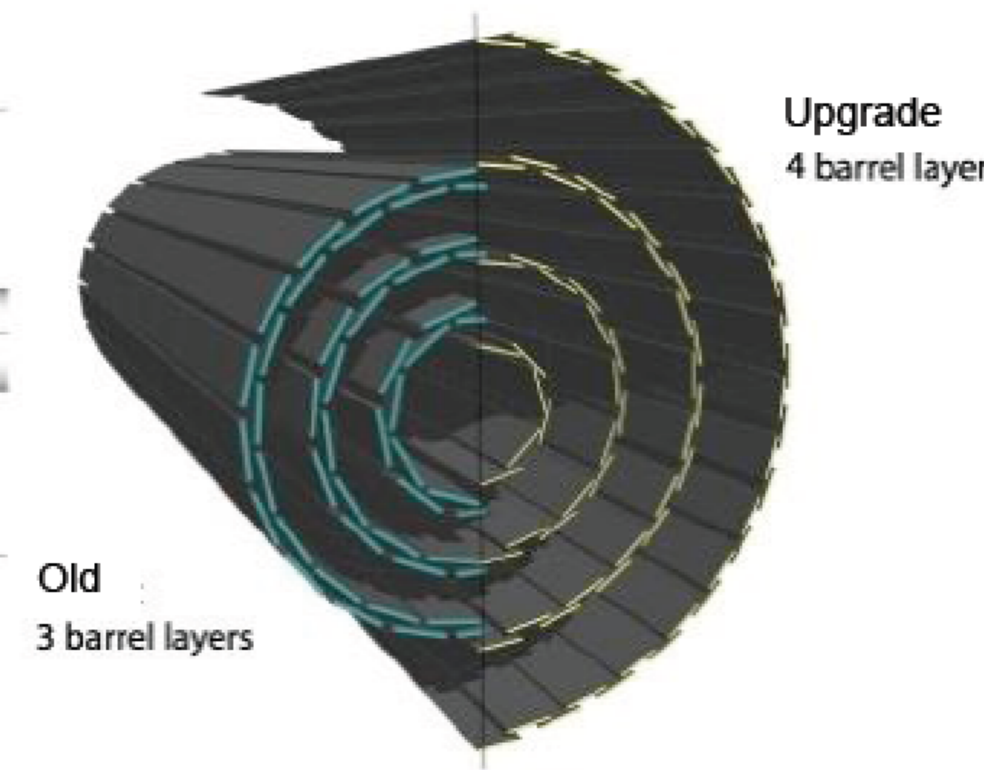


The Compact Muon Solenoid



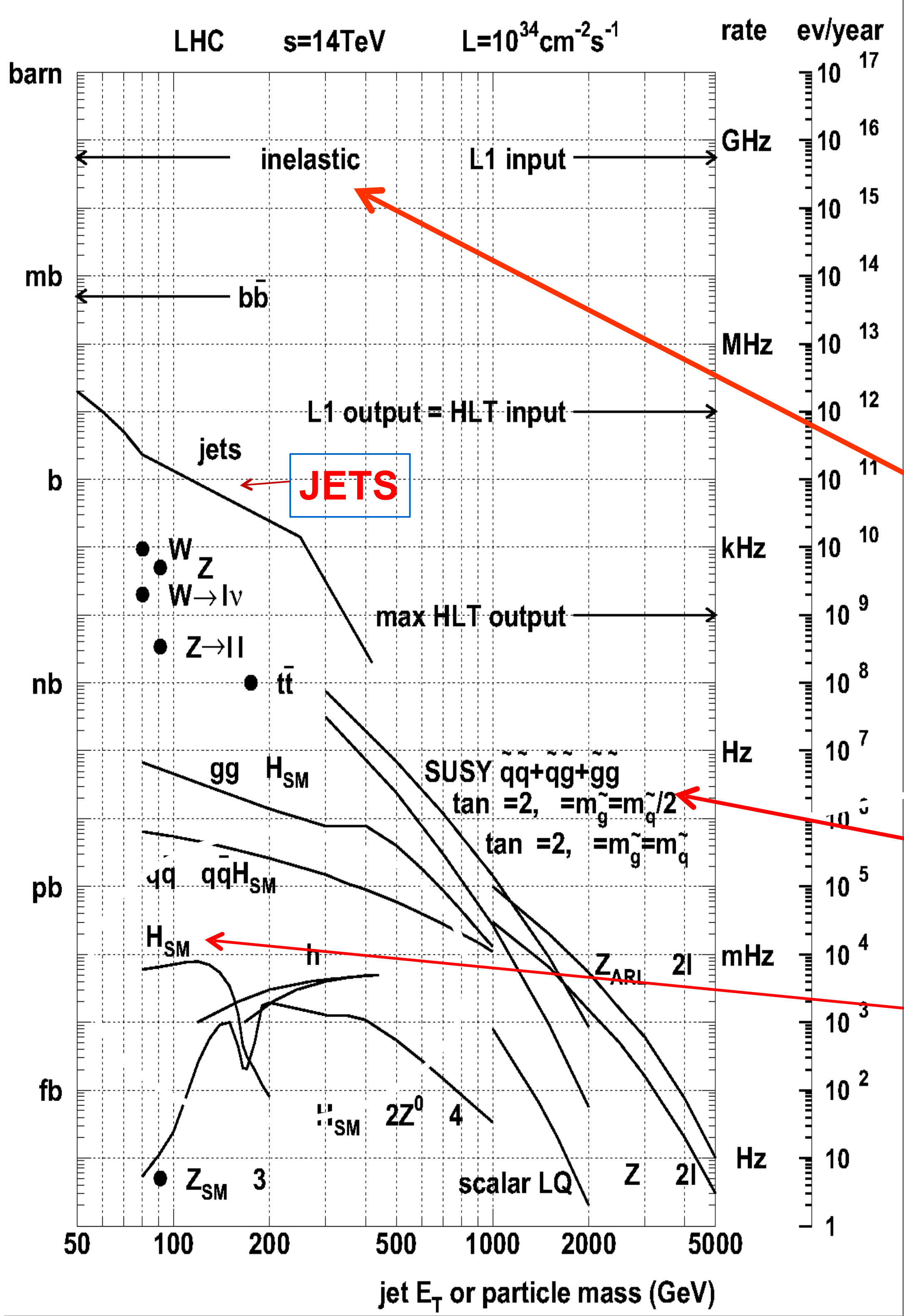
2017: new pixel detector





- 4 layers and 3 disks
  → Smaller radius of the inner layer: 3cm
- New readout chip
  → Better efficiency at high rate, and high pileup
- Less material

Cross section



- Cross sections and background estimates (measured, calculated/ predicted) tell us what minimum energy and luminosity we need from the colliding beams and therefore what rates the detector must be able to handle
- Production dynamics determine the range of energies and angles we need to measure

Inelastic "background" events produced at a rate of 1 GHz.

Supersymmetry ~ 1Hz

Detectable Higgs production ~ 1 milliHz

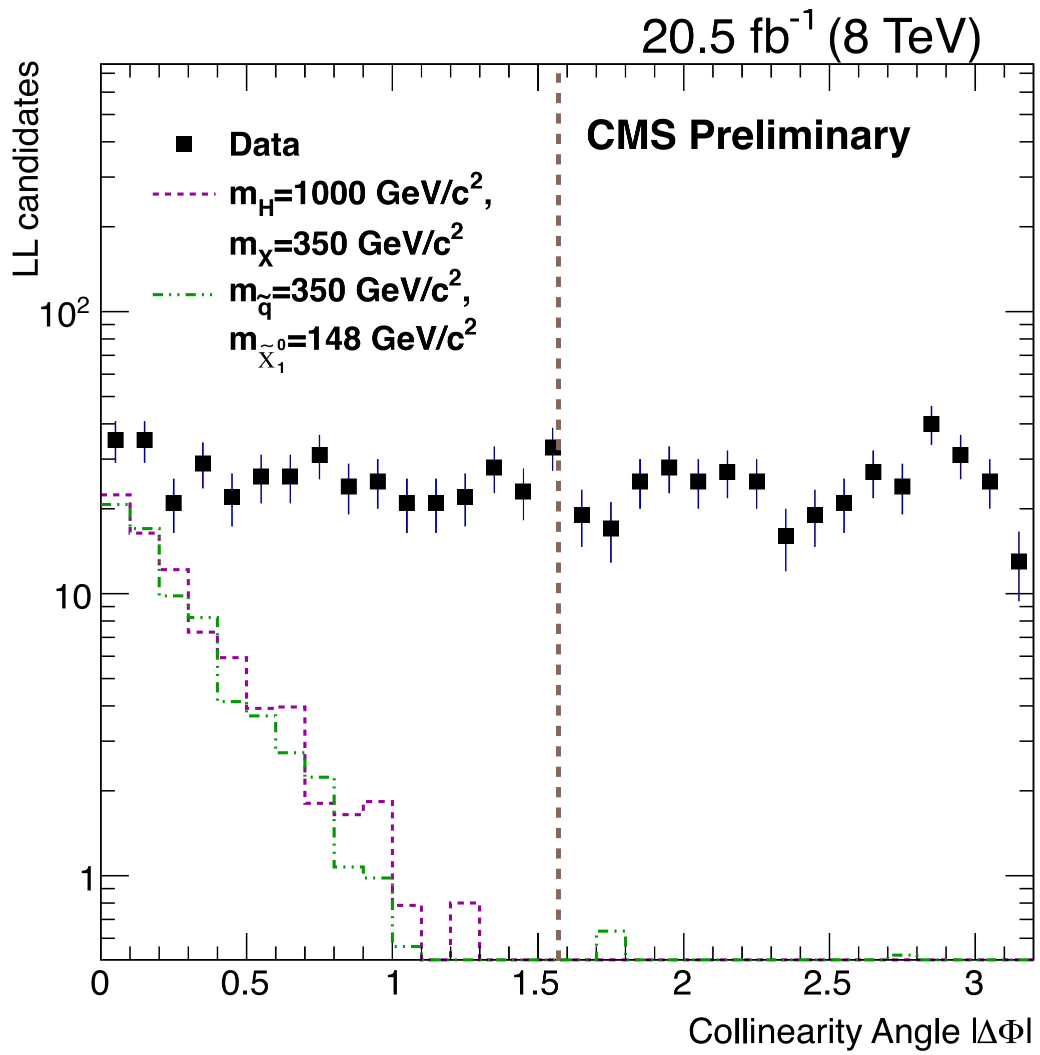
Displaced di-leptons

- Both lepton candidates are required to be isolated, to reject background from jets
- The two tracks are fitted to a common vertex, which is required to have χ^2/dof < 10(5) in the electron (muon) channel.
- The number of hits, between the centre of CMS and the vertex position, that are assigned to the tracks is no more than 1
- To eliminate background from J/ψ and Y decays, and from γ conversions, LL particle candidates are required to have a dilepton invariant mass larger than 15 GeV/c
- To reject cosmics the 3D opening angle between 2 muons must be ≤ 2.48 radians
- Owing to the difficulty of modeling the low trigger efficiency for closely spaced muon pairs, the two muons are required to be separated by $\Delta R > 0.2$
- $\Delta\Phi$ between p_{ll} and the vector from the primary vertex to the dilepton vertex (v_{ll}) is required to satisfy $|\Delta\Phi| < \pi/2$. Dilepton candidates satisfying all other selection requirements, but with $|\Delta\Phi| > \pi/2$, are used to define a control region

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.052012

Displaced di-muons

- All muons paired together combinatorially (poor charge measurement for displaced muons)
- To eliminate background from J/ψ and Y decays, and from γ conversions, LL particle candidates are required to have a dilepton invariant mass larger than 15 GeV/c
- Owing to the difficulty of modeling the low trigger efficiency for closely spaced muon pairs the two muons are required to be separated by $\Delta R > 0.2$
- Background distribution expected to be symmetric in $|\Delta\Phi|$ around $\pi/2$ due to the absence of a displaced secondary vertex
- No data observed after the full selection is applied in control region. This determines the expected background in signal region to be zero



https://cds.cern.ch/record/2005761?ln=en (CMS-PAS-EXO-14-012)

Displaced Jets

- In the first model, a long-lived, scalar, neutral exotic particle, X, decays to qq. It is pair-produced in the decay of a non-SM Higgs boson (i.e. $H \to 2X$, $X \to qq$)

- In the second model, the long-lived particle is a neutralino $\tilde{\chi}^0_1$, which decays into two quarks and a muon through an R-parity violating coupling. The neutralinos are produced in events containing a pair of squarks, where an squark can decay via the process $\tilde{q} \to q \tilde{\chi}^0_1 \to q q' \bar{q}'' \mu$: up to two displaced dijet vertices

- For each reconstructed track, an impact parameter is computed by measuring the shortest distance between the extrapolated trajectory and the primary vertex. Accept an event at the trigger level: at least two of the selected jets pass:
  → The jet has no more than two associated tracks with three-dimensional impact parameters smaller than 300 μm
  → No more than 15% of the jets total energy is carried by associated tracks with transverse impact parameters smaller than 500 μm

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.012007

Displaced Jets

- Tracks are classified as prompt if their transverse impact parameter relative to the beam line, IP^{2D}, is less than 1mm

- **Jet-Jet** model predicts pair-produced long-lived scalar neutral particles X^0, each decaying to a light quark-antiquark pair, where light refers to u, d, s, c, and b. The two scalars are produced through a 2→2 scattering process, mediated by a Z^* propagator. The m_{X^0} and $c\tau_0$ are varied between 50 and 1500 GeV and between 1 and 2000 mm

- **B-Lepton** model contains pair-produced long-lived top squarks. Each top squark decays to one b quark and a lepton. The m_{t} and e $c\tau_0$ are varied between 300 and 1000 GeV and between 1 and 1000 mm, respectively
  - → **B-Mu**, **B-Ele**, and **B-Tau** models are derived from the B-Lepton model with 100% branching fraction to muons, electrons, and taus, respectively

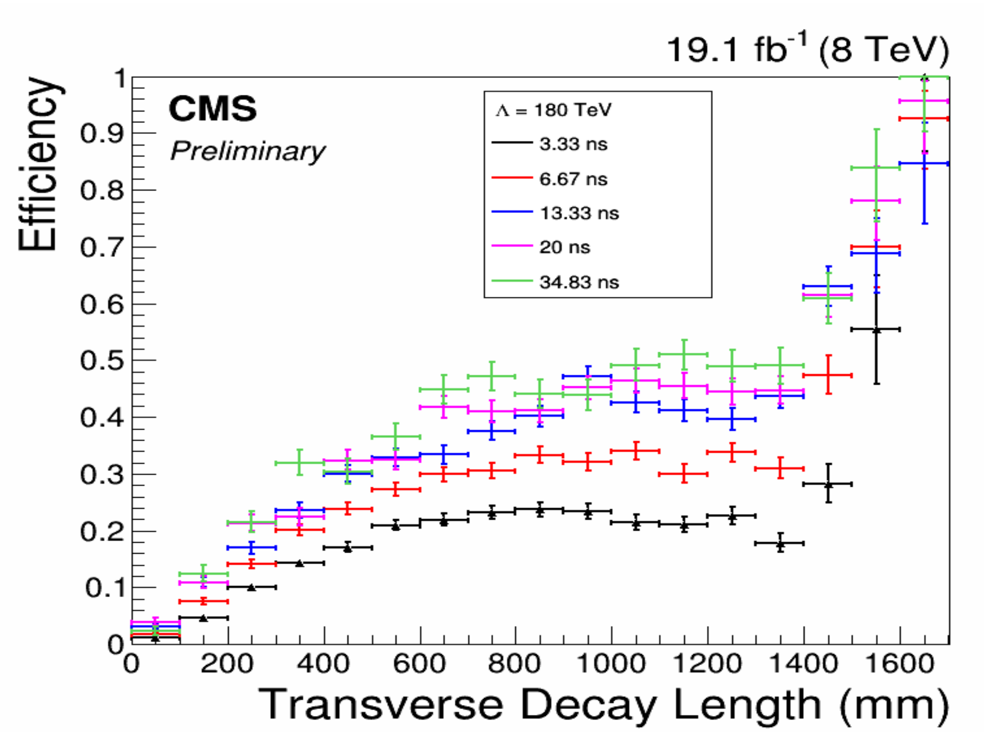
- Misidentification rate is measured in a control sample defined as events with $N_{tags} \leq 1$, while the signal region requires $N_{tags} \geq 2$. Signal categories: $N_{tags} = 2$ and $N_{tags} \geq 3$

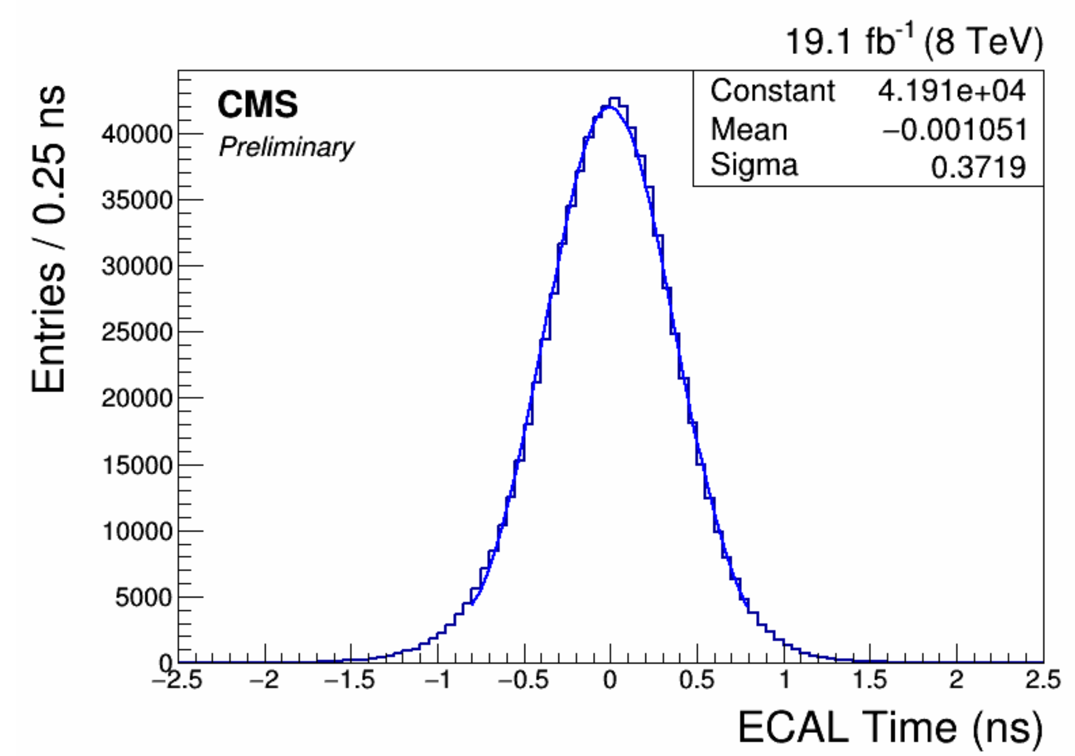
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.012007

Displaced Photons

- ECAL time resolution ~372 ps (measured in with single photon events)
  → Delay due to Neutralino (slower), and extra path to be done

- Left: efficiency as a function of the neutralino transverse decay length. The efficiency is higher for longer lifetime. In these cases, lower p_T neutralinos are more likely to decay inside ECAL and they are more likely to produce late photons as their speeds are markedly slower than the speed of light. The efficiency peaks around 1 m and levels off above 1.4 m or even starts increasing again. This happens because when the decays happens half way through the tracking volume, the mechanism to delay the photon via Δt_2 works best, while the decays near ECAL is favorable to produce delays via Δt_1





https://cds.cern.ch/record/2019862?ln=en https://cds.cern.ch/record/2063495?ln=en

Disappearing tracks

- Anomaly-mediated supersymmetry breaking (AMSB) which predicts a particle mass spectrum that has a small mass splitting between the lightest chargino and the lightest neutralino. The chargino can then decay to a neutralino and a pion.
  The phase space for this decay is limited by the small chargino-neutralino mass splitting. As a consequence, the chargino has a signifi- cant lifetime, and the daughter pion has momentum of ≈100 MeV, typically too low for its track to be reconstructed.
  → Benchmark in terms of its sensitivity to the chargino mass and chargino-neutralino mass splitting

https://link.springer.com/article/10.1007%2FJHEP01%282015%29096

Stopped particle: muons

- If LLP is colored, it will hadronize prior to traversing the detector, creating a R-hadron, which will eventually stop in the detector. These stopped particles or R-hadrons could then decay seconds, days, or weeks after the proton-proton collision.

- Split SUSY is a model in which SUSY is broken near the unification scale. This results in the supersymmetric squarks and sleptons being very heavy (> 1 TeV), while the gauginos remain relatively light and account for the unification of the gauge couplings. The gluino is the only colored particle at this low mass scale, so it can only decay through t-channel exchanges of a virtual squark. Since the squarks are very massive, this decay will be suppressed and thus, the gluino can have a long lifetime, possibly up to 100 s. Gluinos are pair produced, and they would form R-hadrons in the detector, interacting via the strong force and hadronizing with quarks. The gluino could have a three-body decay. The gluino decays to a quark-antiquark pair and a NLSP neutralino ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_2$). Then the NLSP neutralino decays to a pair of oppositely-signed muons, and the LSP neutralino ($\tilde{\chi}^0_2 \rightarrow \mu^+\mu^-\tilde{\chi}^0_{LSP}$). The mass of the LSP neutralino was chosen to be 1/4 of the gluino mass, and the mass of the NLSP neutralino was chosen to be 2.5 times the LSP neutralino mass

https://cds.cern.ch/record/2273460