Search for Long Lived Particles at CMS

FSP Workshop: **Long-lived particles at Belle II**

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Emmy Noether-Programm
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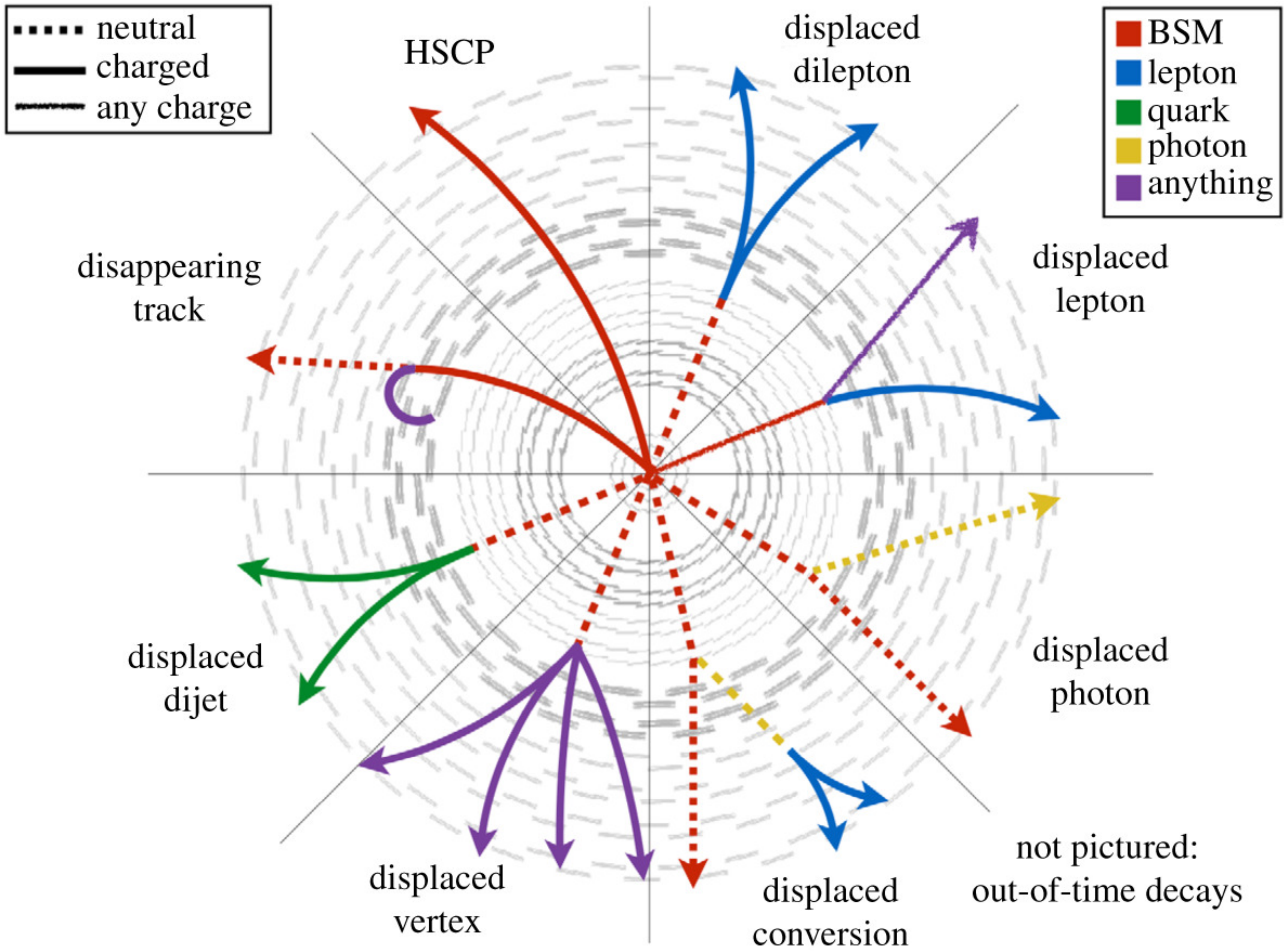
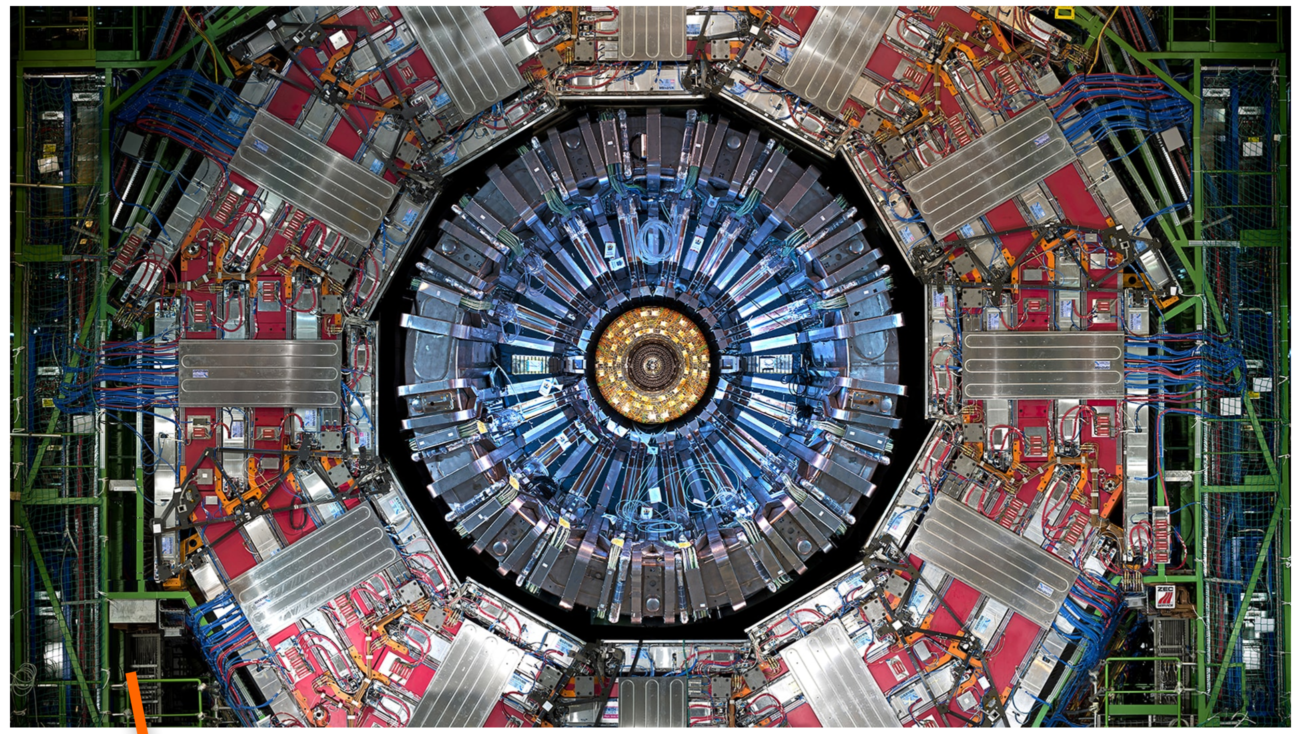
CMS

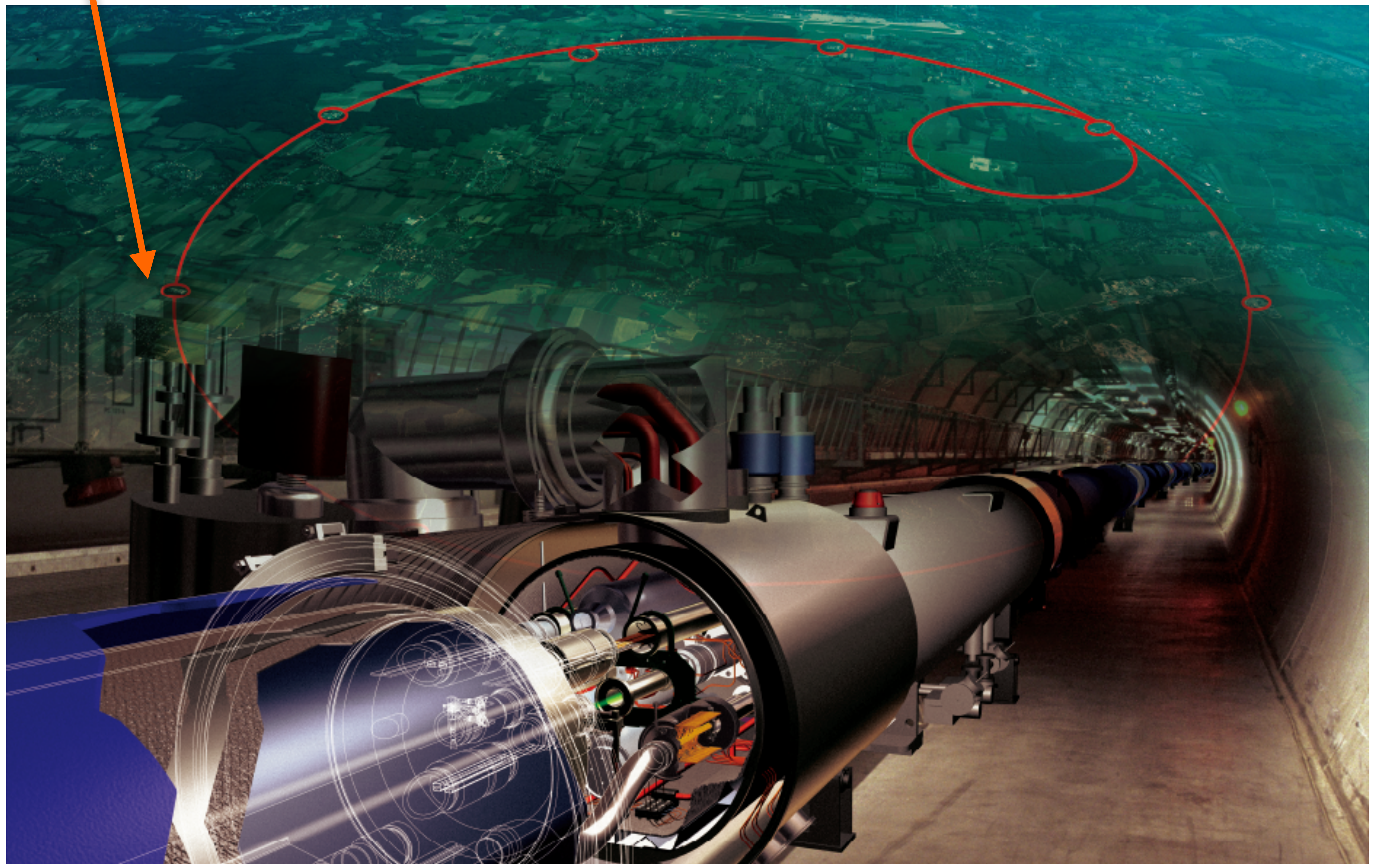
Introduction: LLP searches @ CMS

- Very broad LLP program at CMS!
- In this talk:
  - what can be done with current CMS detector
  - new ideas for the future (trigger and reconstruction)
- Few examples, span through different lifetimes: LLP searches with
  - tracker (jets with displaced vertices)
  - calorimeters (delayed jets)
  - muon systems (showers in the muon chambers)

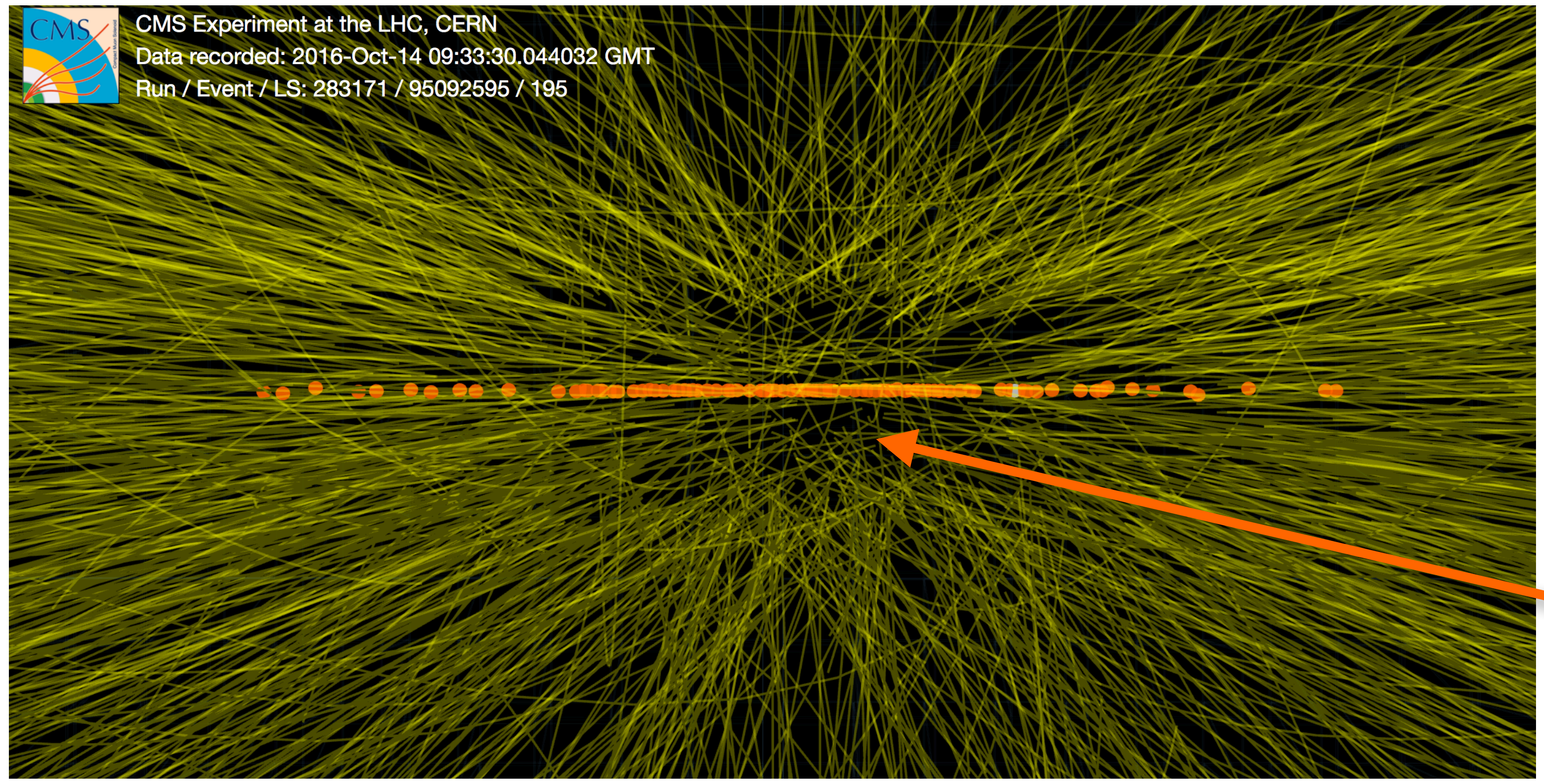


Introduction: LHC and CMS



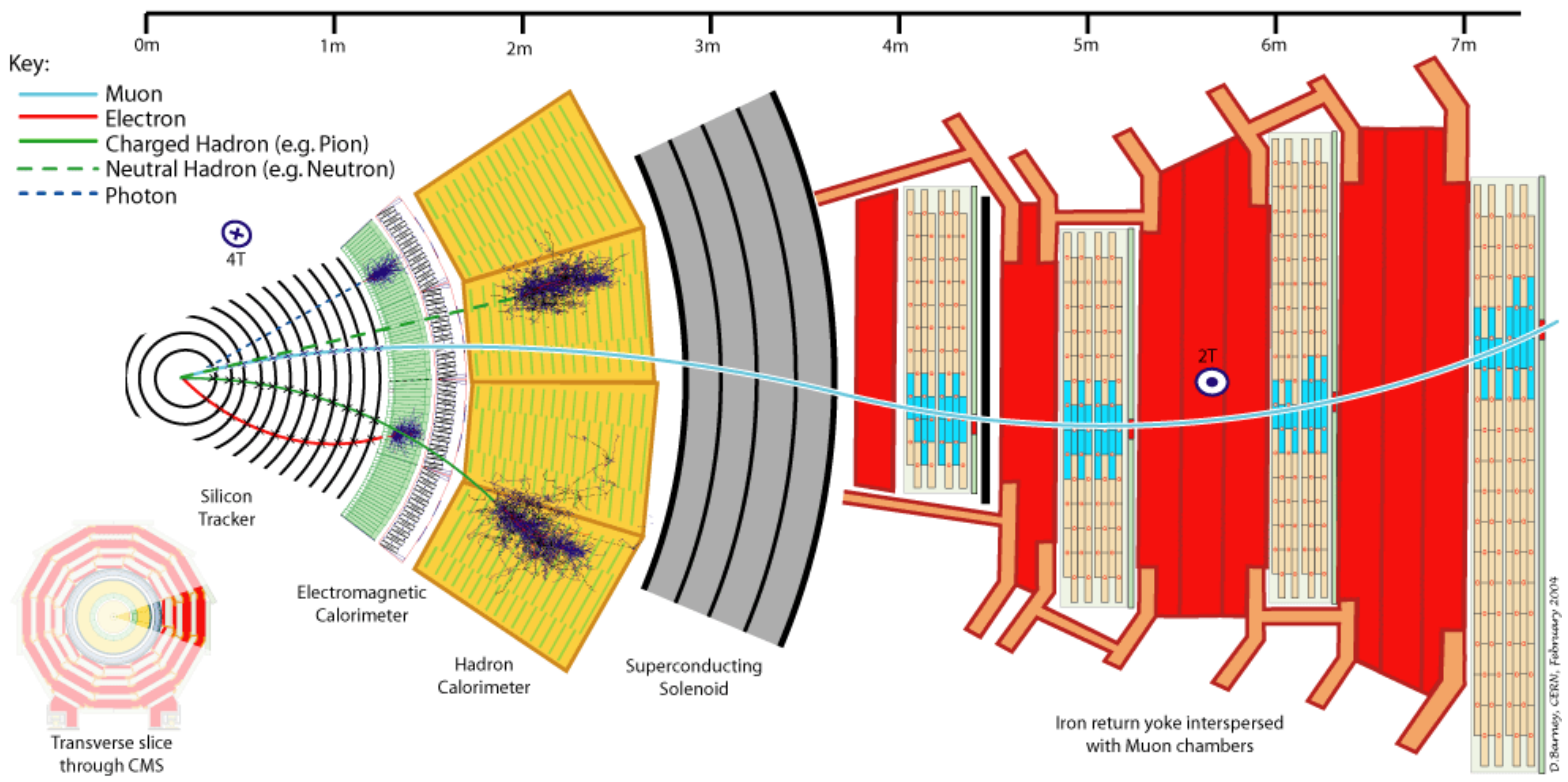


- LHC: proton-proton collisions at 13 TeV (Run2, 2015-2018); preparing Run3 (in 2022)
- Challenges:
  - momentum of quarks/gluons unknown → hard to precisely model what happens
  - bunch crossing at 40 MHz (25 ns): fast decision → sophisticated trigger systems @ experiments
  - beam organised in bunches of 10^{11} protons: multiple collisions at each crossing (pile-up), up to ~80



High pile-up environment

Introduction: CMS trigger and reconstruction



- CMS organised in layers to detect different particles
- Particle Flow algorithm connects info from sub detectors → precise momentum measurements and particle identification
- But… standard algorithms not designed for LL signatures!

L1 trigger

- Hardware based, information from calorimeters and muon systems only
- First pattern recognition and raw measurements
- Skims rate to 100 kHz (in total)

High level trigger (HLT)

- Fully software, includes info from tracker
- Similar algorithms as those applied offline
- Skims rate to 1 kHz max (in total)

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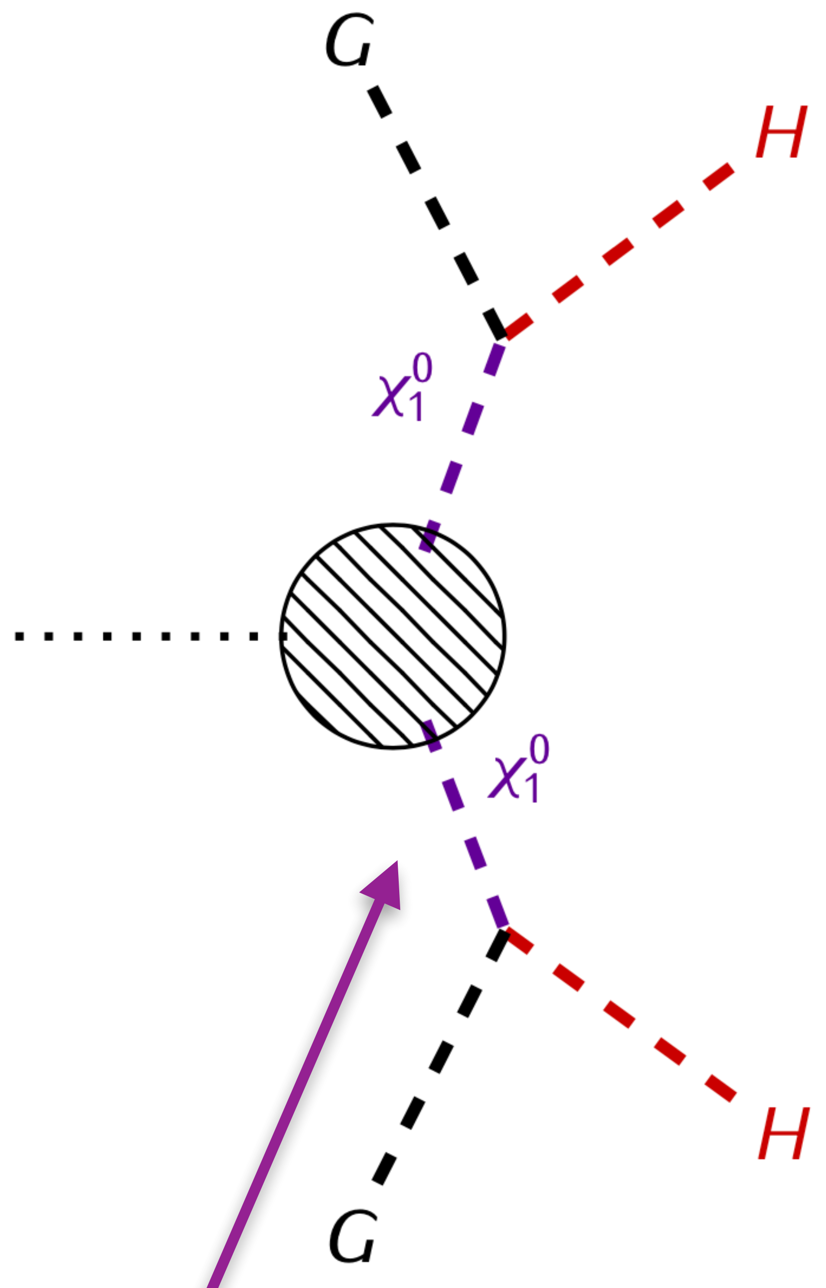
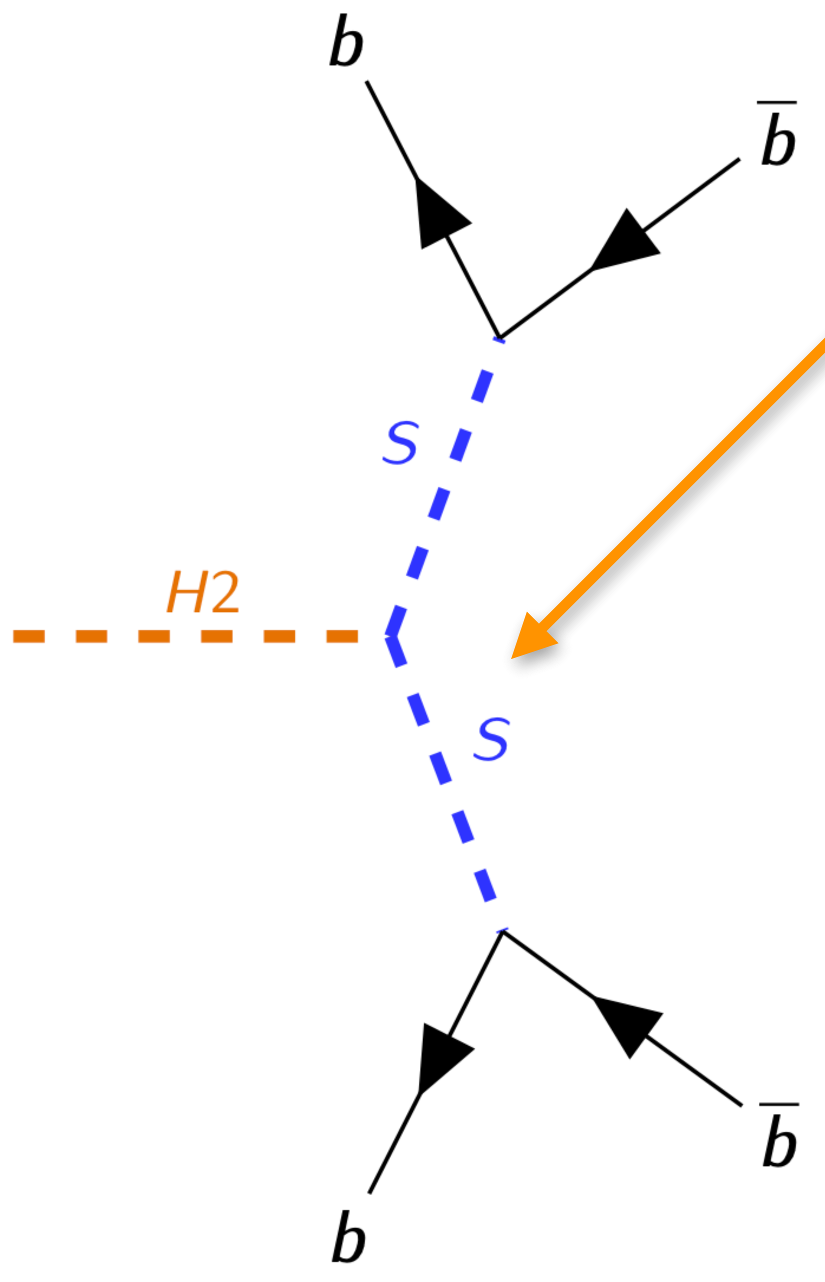
Long lived particles: benchmark models

- Standard Model doesn't answer all the questions about matter and interaction (dark matter, gravity, Higgs mass hierarchy problem)
- Extensions of SM predict partners of SM particles (**SUSY**), or **dark sectors** communicating with SM only via Higgs boson
- New particles are **long lived**: peculiar signatures
- New particles can have different masses: different kinematical features
- This presentation:
  - focus on **neutral LLPs** → invisible
  - focus on **decays involving quarks** and **gluons**

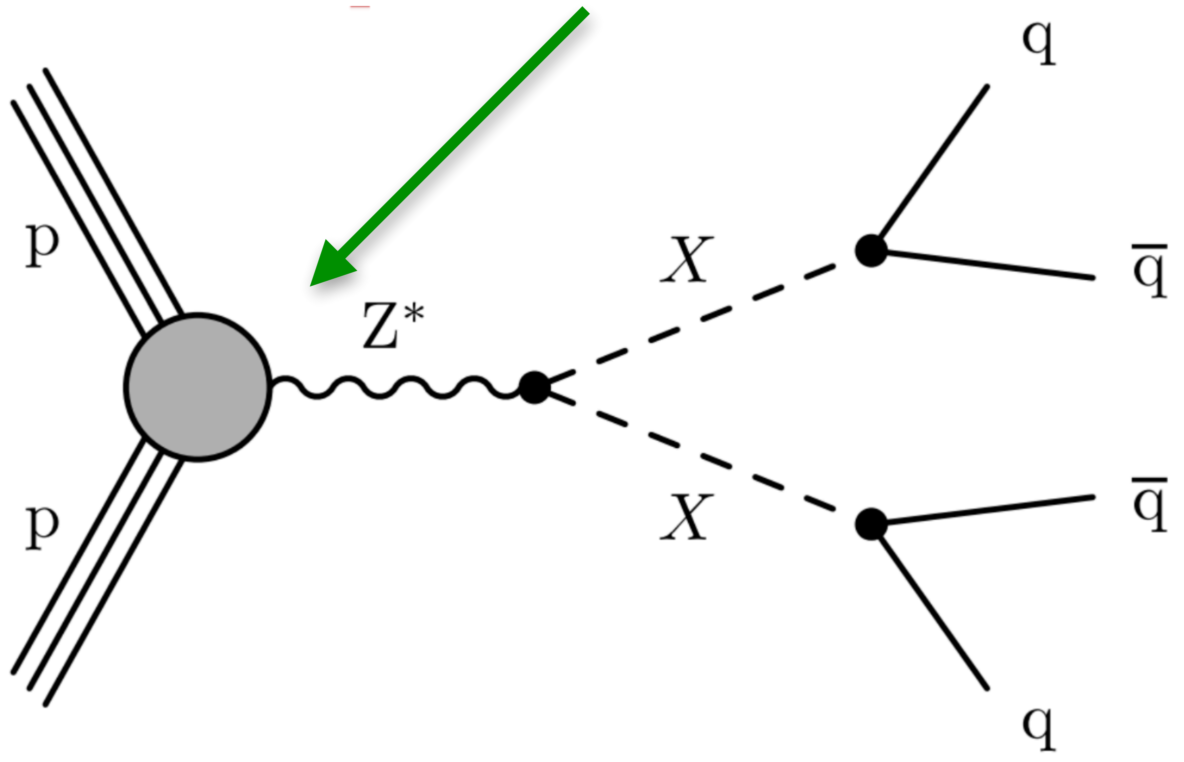


SUSY (I): $XX \to HH\tilde{G}\tilde{G} \to b\bar{b}b\bar{b}\tilde{G}\tilde{G}$
X is long lived (neutralino)
H is SM Higgs
G is light and undetected
SUSY (II): $XX \to gg\tilde{G}\tilde{G}$
X is long lived (gluino)
g is SM gluon



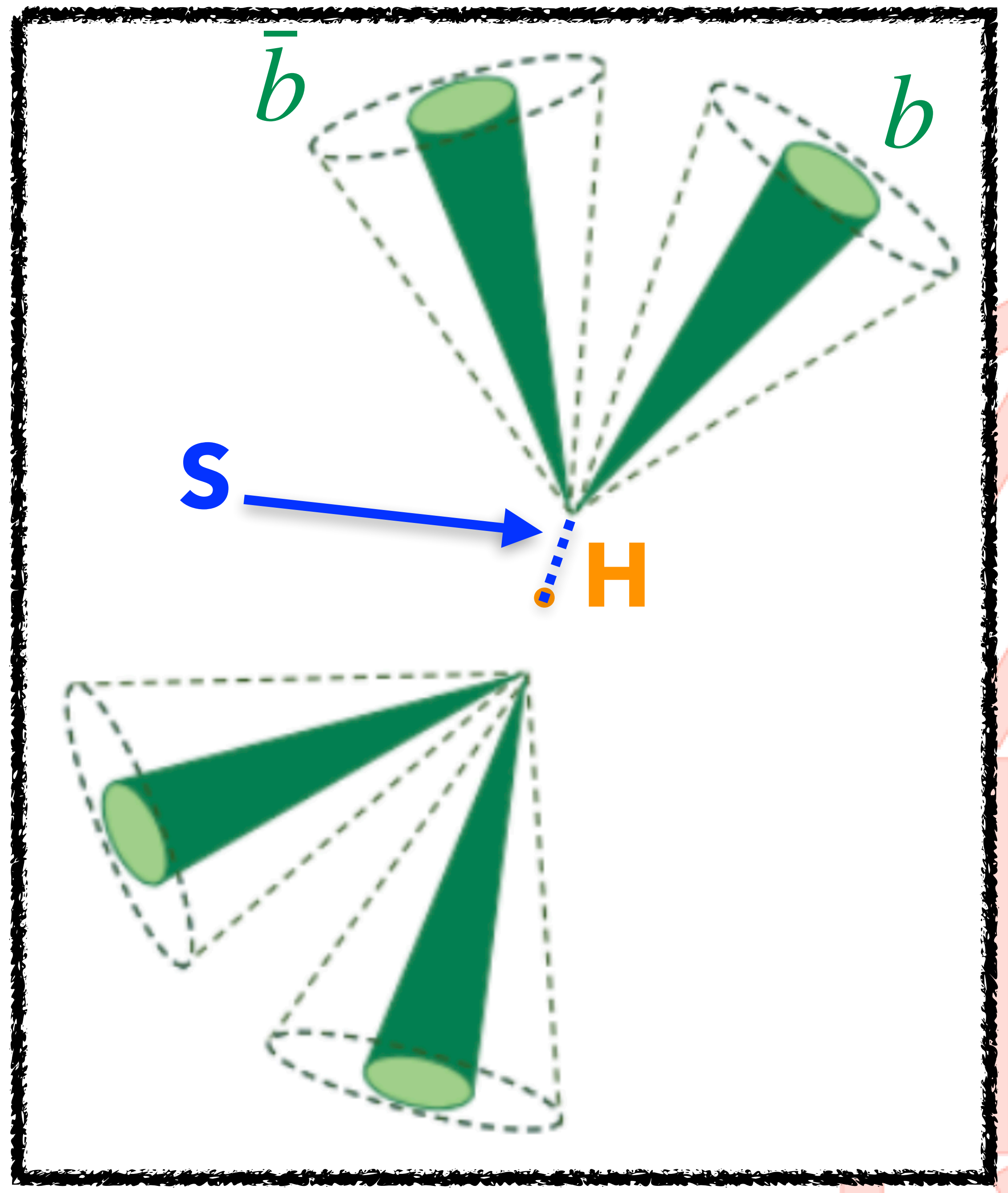
BSM Higgs: $H2 \to SS \to b\bar{b}b\bar{b}$
S is long lived
H2 can also be the SM Higgs

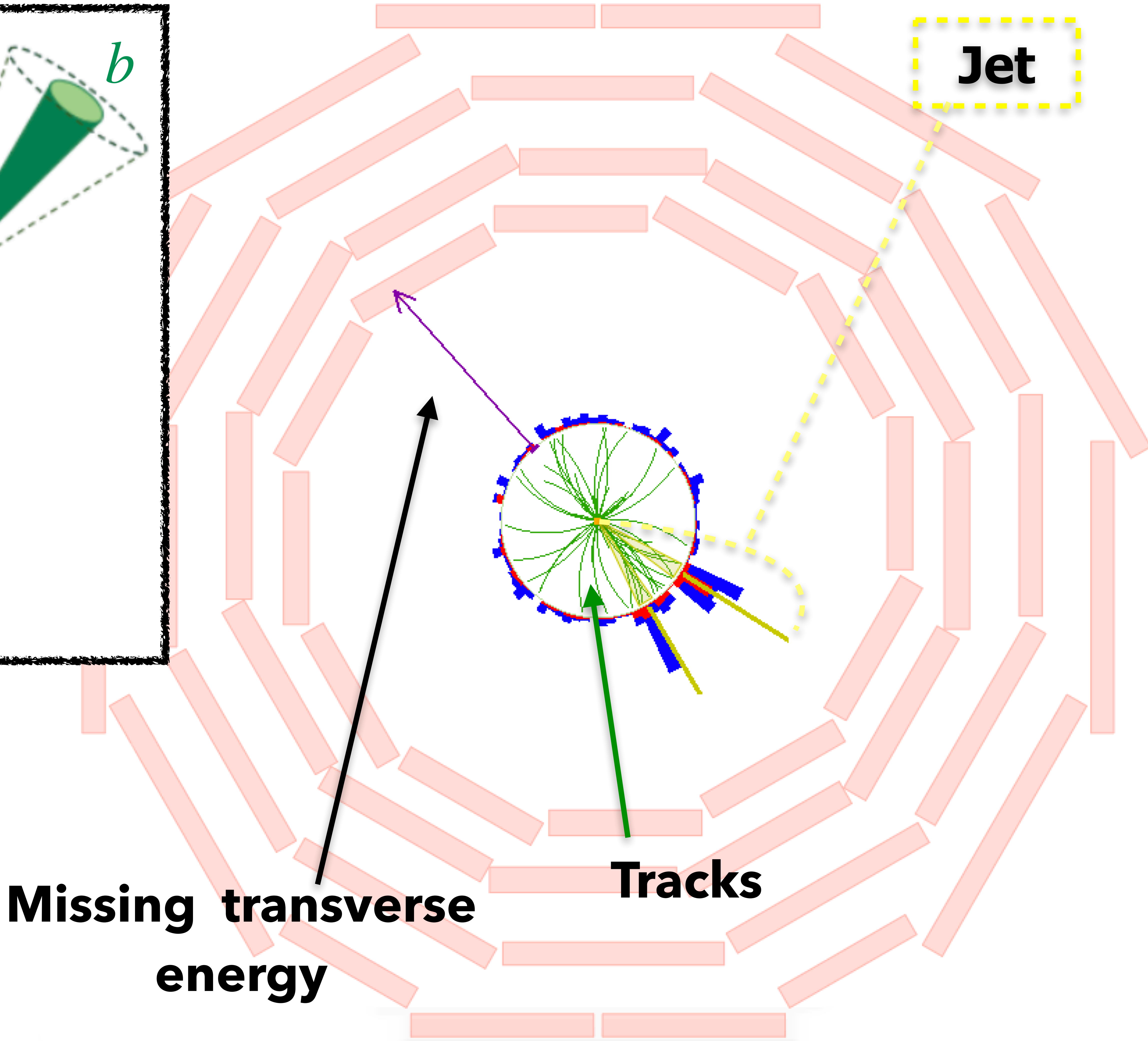
Simplified jet-jet model:
$Z* \to XX \to q\bar{q}q\bar{q}$
X is long lived
Z* off shell SM Z



LLPs signatures at CMS covered today

- quarks/gluons: due to strong interaction, they hadronize in **jets** of particles
- They are produced with a certain delay (decay length cτ) affecting the topology
- Decays in tracker system:
  - **Tracks** are displaced w.r.t. p-p collision point
- Decays in calorimeters:
  - Few tracks associated to a jet
  - Large **energy deposits** in **calorimeters**: crystals measure a certain delay w.r.t. p-p collision
- Decays in muon systems:
  - Peculiar showers in the muon chambers





LLPs signatures in CMS tracker

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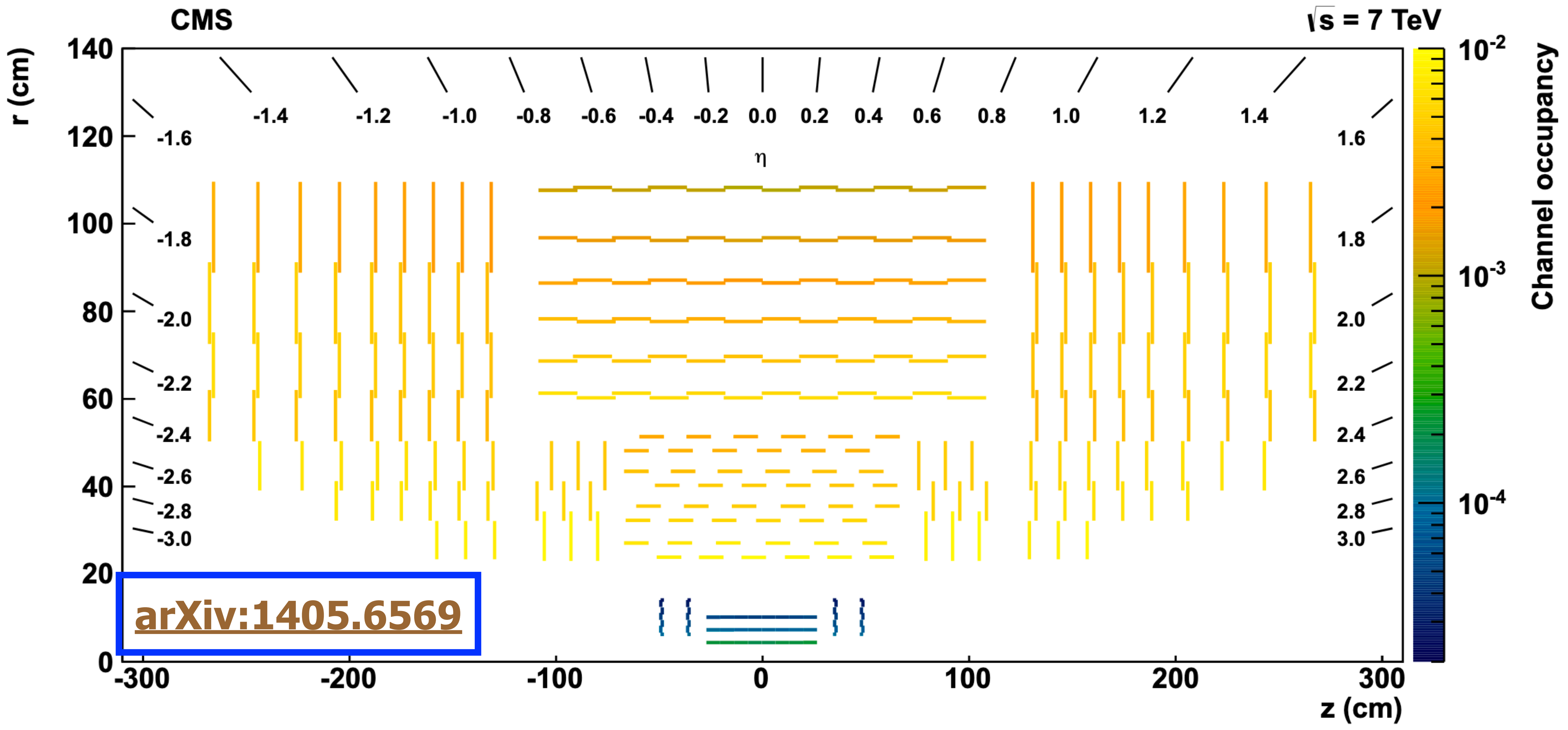
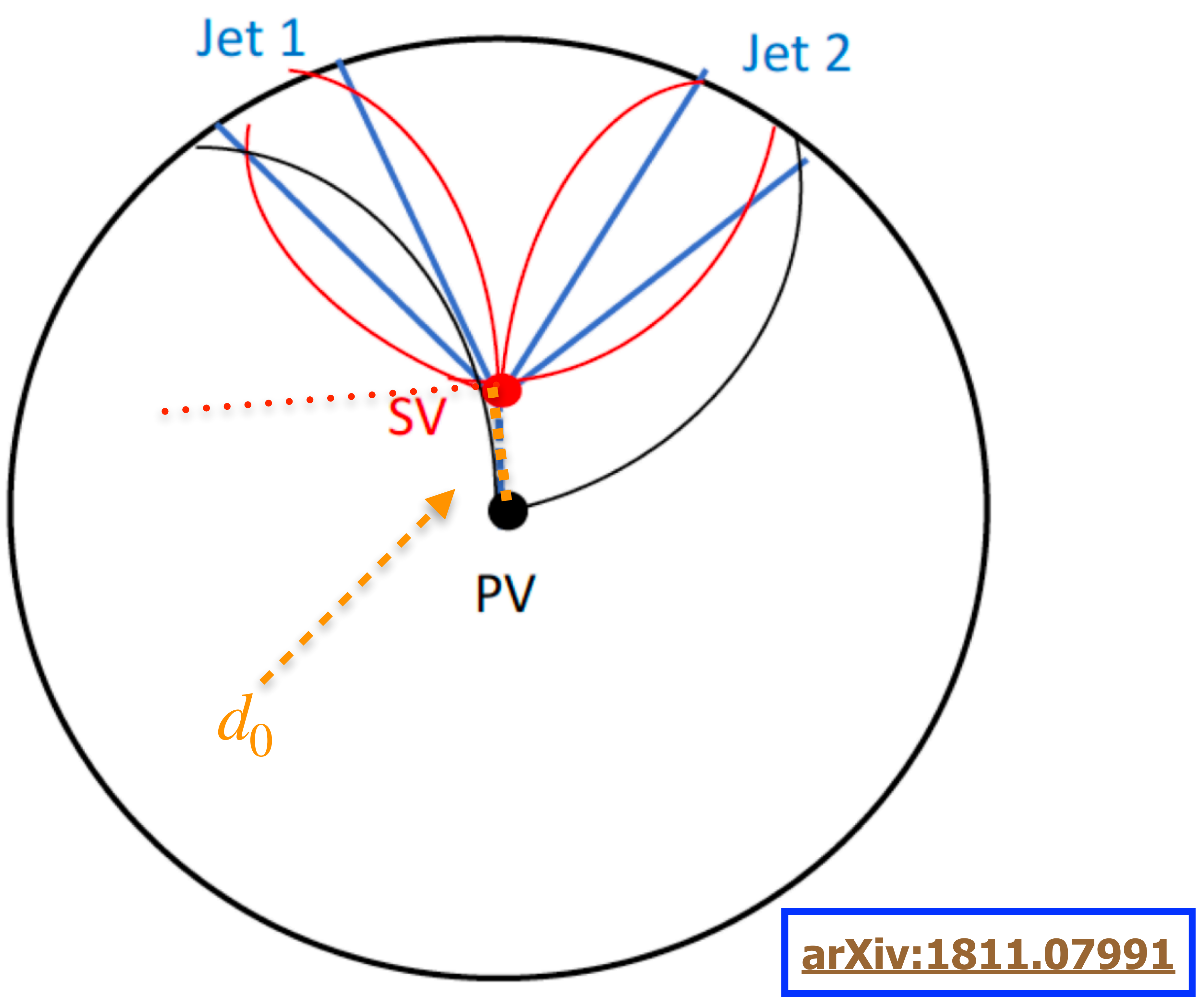
LLPs signatures in CMS tracker



- Long lived hadronic decay in tracker: jet with associated displaced tracks
- Displaced tracks have large impact parameters d_0



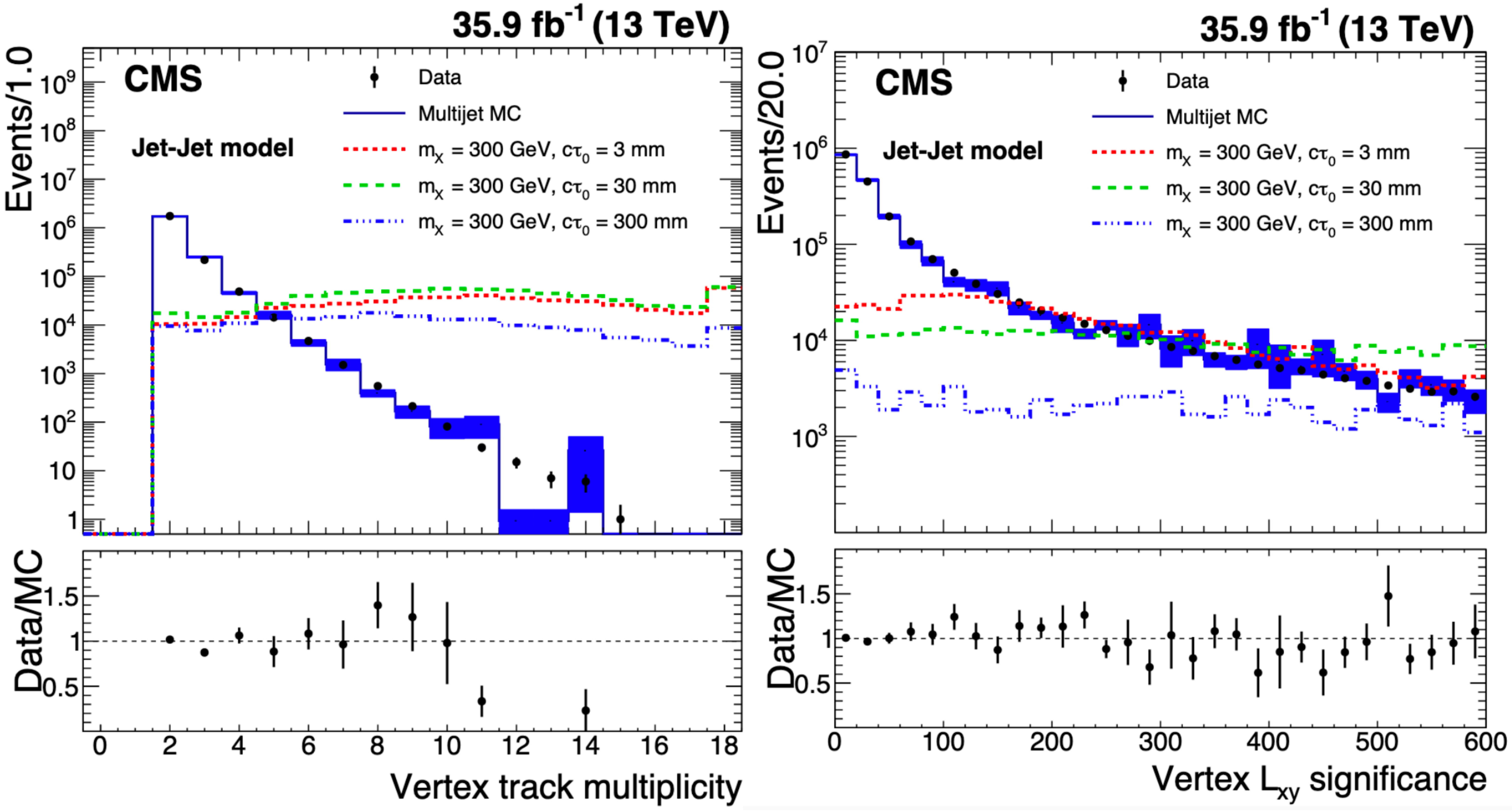
Tracking and vertexing @ CMS

- Hits combined as tracks (Kalman filter based algorithms)
- Tracks combined into primary and secondary vertices (PV and SV)
  - PV: distinguish leading vertex from pile-up vertices (track p_T)
  - SV: identify SM “long lived” particles (b-quarks), relies on impact parameters

LLPs in tracker: jets + displaced vertices

- LLPs hadronic decay in tracker: jet with associated displaced tracks
- Displaced tracks have large impact parameters d_0
  - Select tracks with high d_0 inside the jet cone
  - Re-run vertexing algo → displaced SV
- Tracker material enhances nuclear interactions → geometrical veto

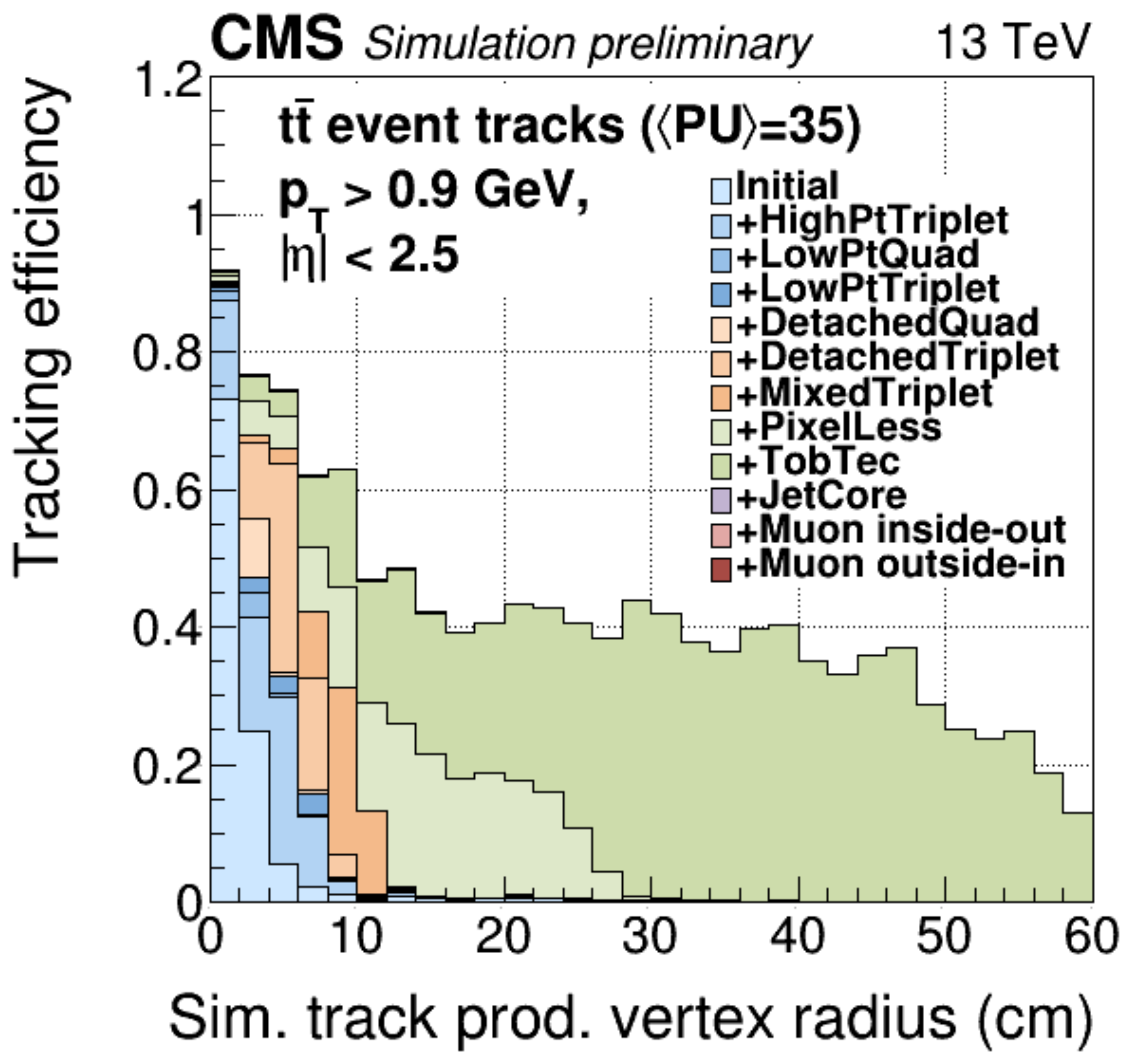
- Signal: high track multiplicity in displaced SVs
- Signal: longer transverse decay length of SVs



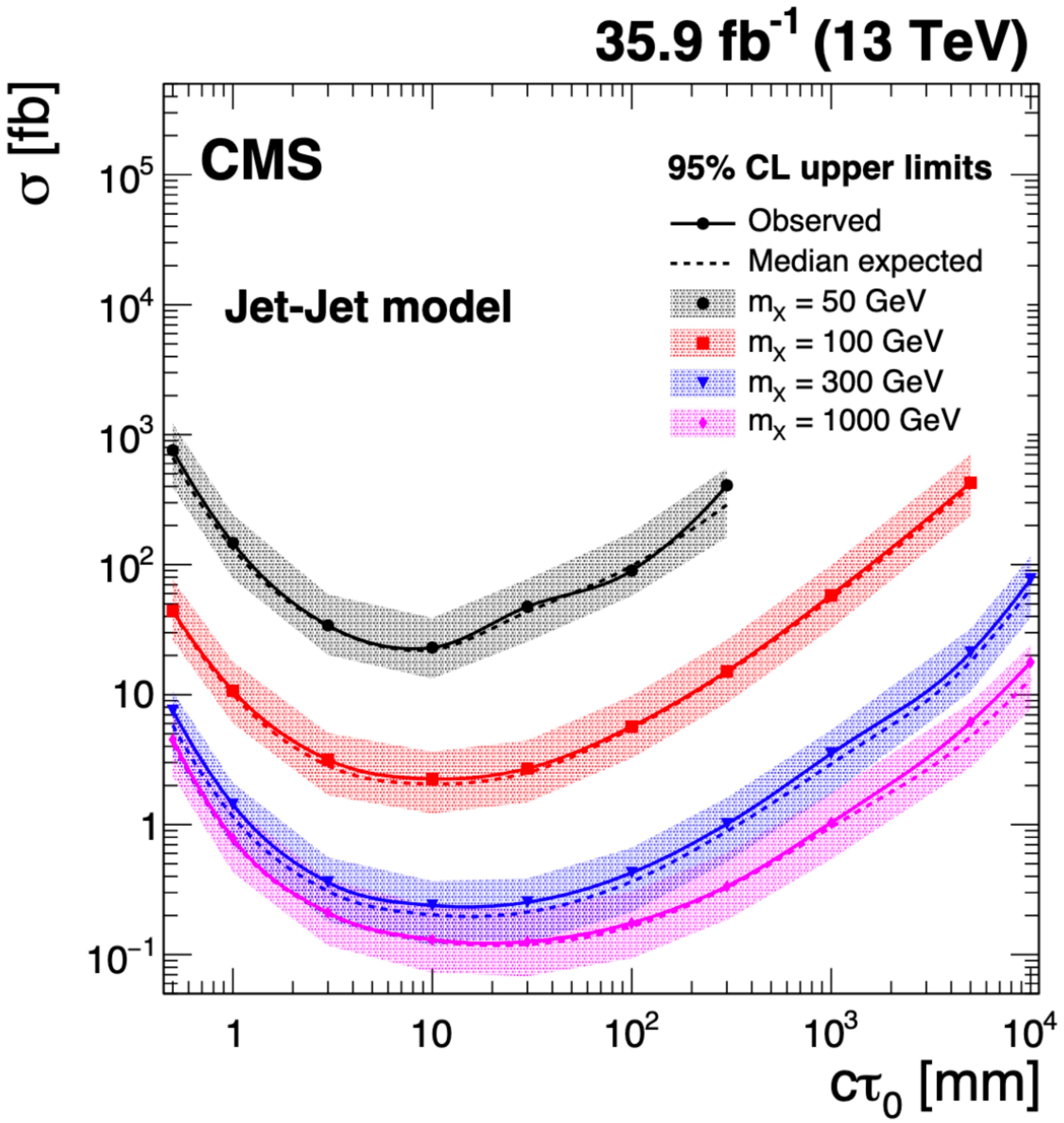
arXiv:1811.07991

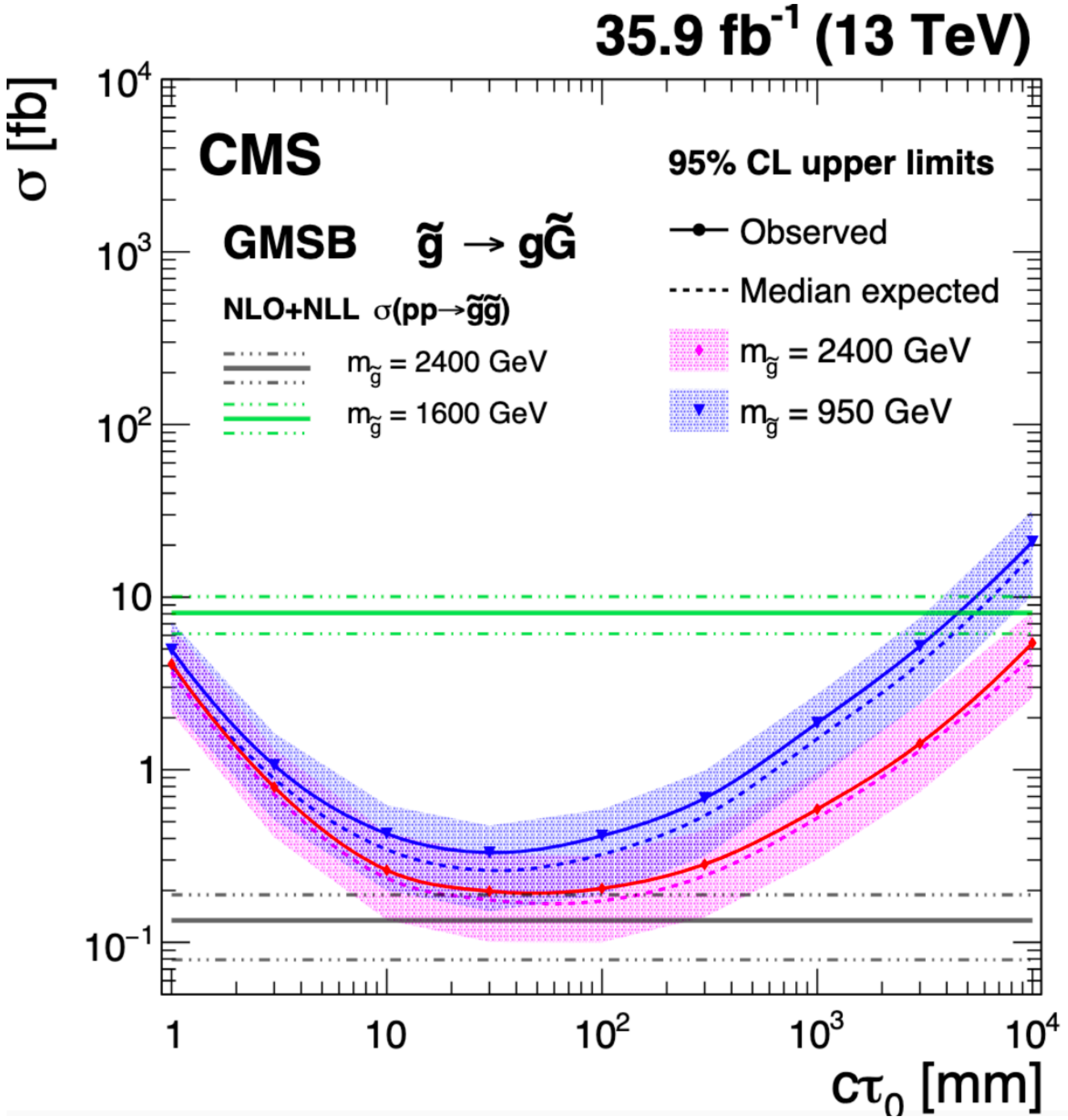
LLPs in tracker: jets + displaced vertices

- Sensitivity: 10 mm - 1 cm
- Reason: tracking efficiency drops with displacement



arXiv:1405.6569





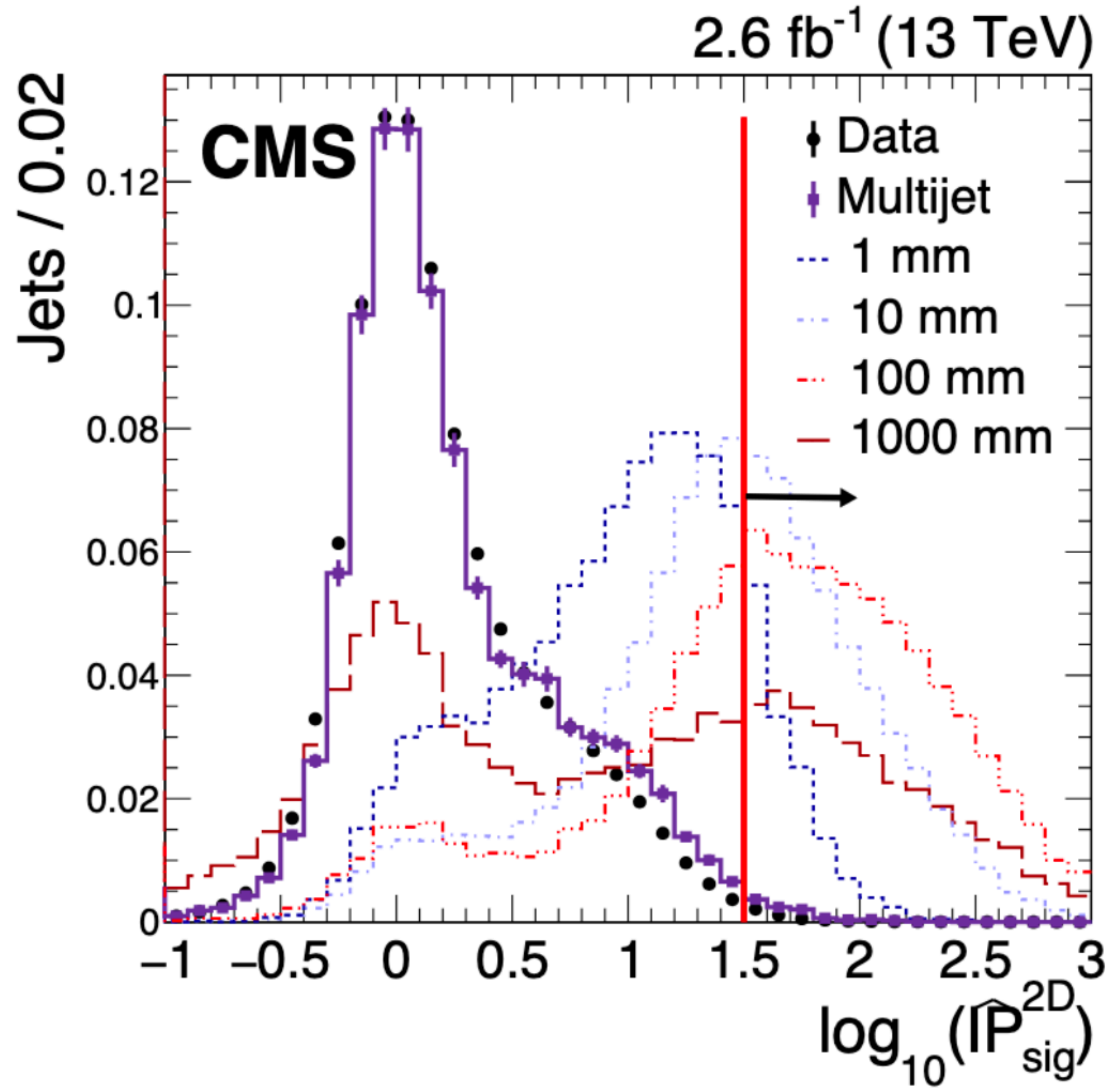
arXiv:1811.07991

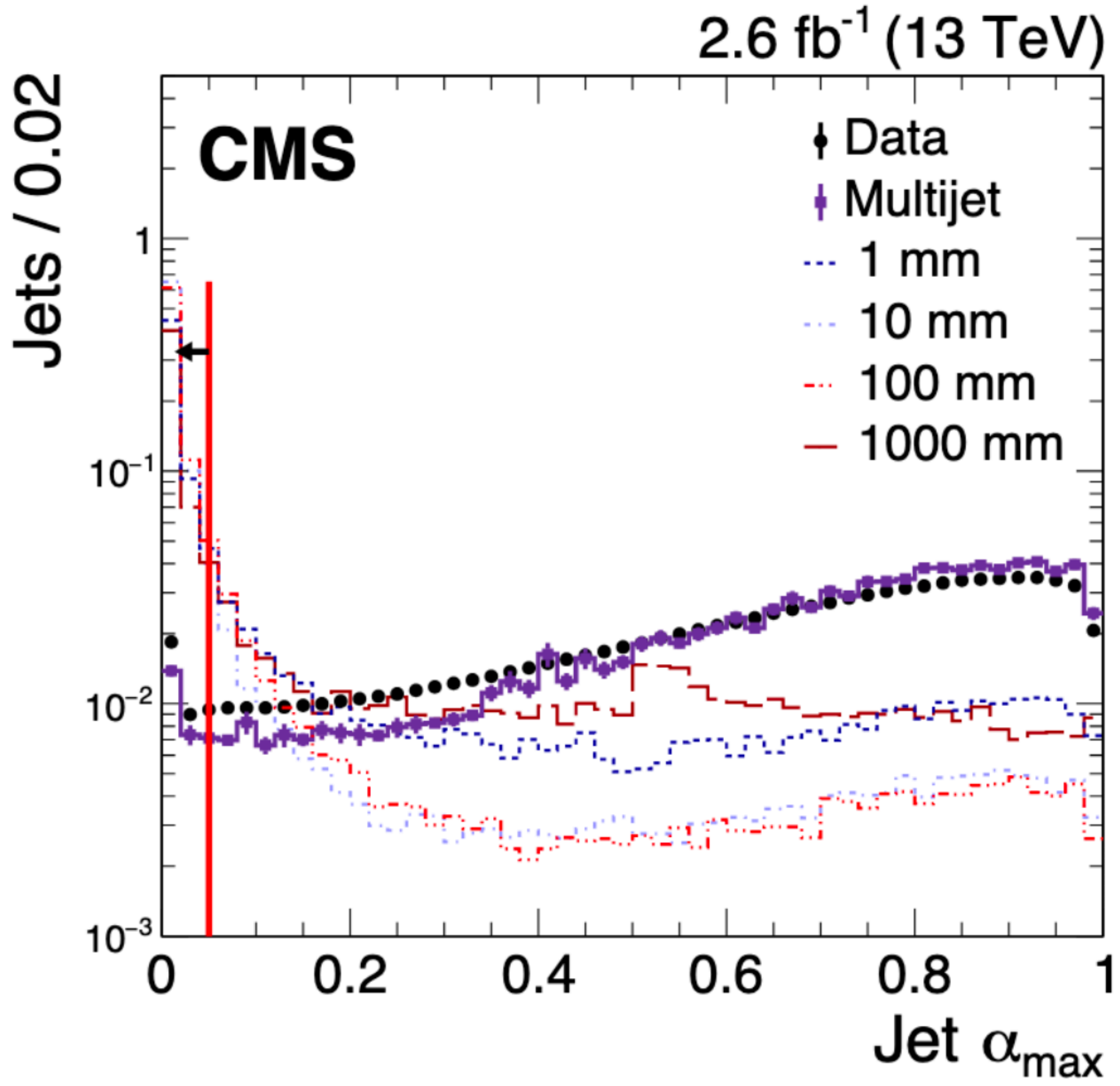
LLPs in tracker: jets + displaced tracks

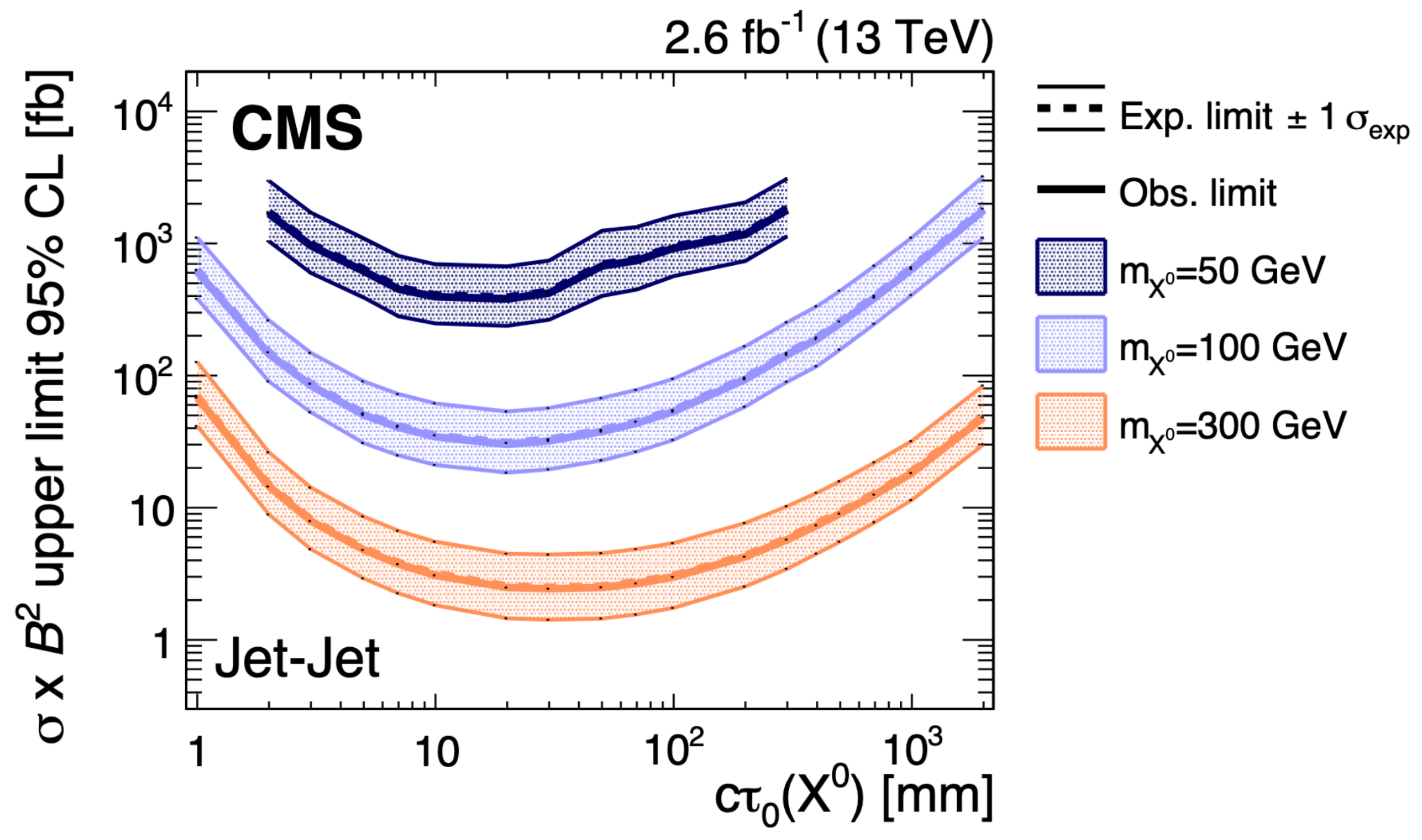
- LLPs decay in tracker: jet with associated displaced tracks
- Displaced tracks have large impact parameters
- Displaced tracks most likely do not originate from a PV

$$\alpha_{jet}(PV) = \frac{\sum_{tracks \in PV} p_T}{\sum_{tracks} p_T}$$

- Tracks median/maximum values computed per-jet
- Similar sensitivity (10 mm - 1 cm) but slightly longer cτ ➞ single tracks vs. SVs!







arXiv:1711.09120

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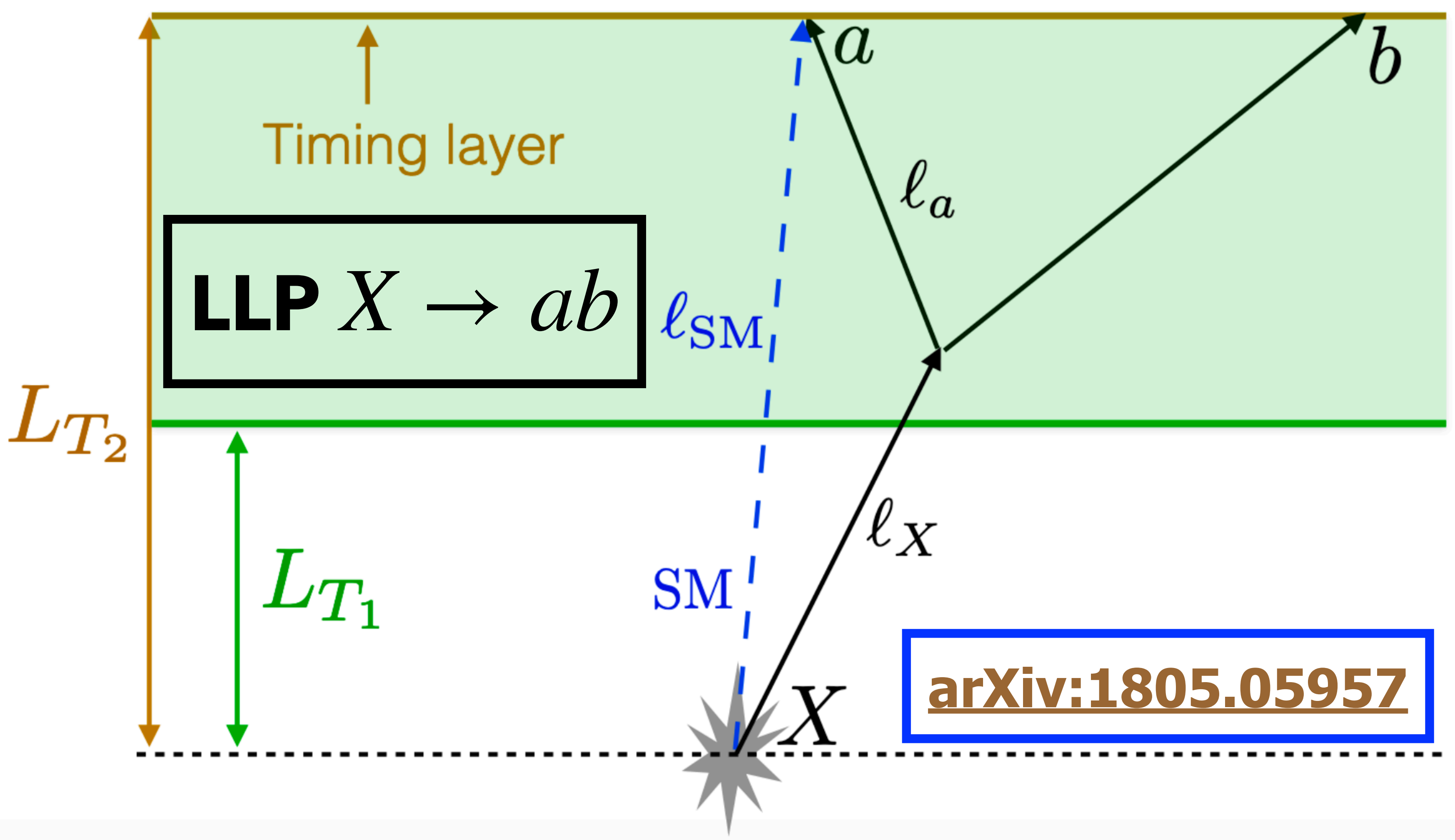
LLPs signatures in CMS calorimeters

LLPs signatures in CMS calorimeters

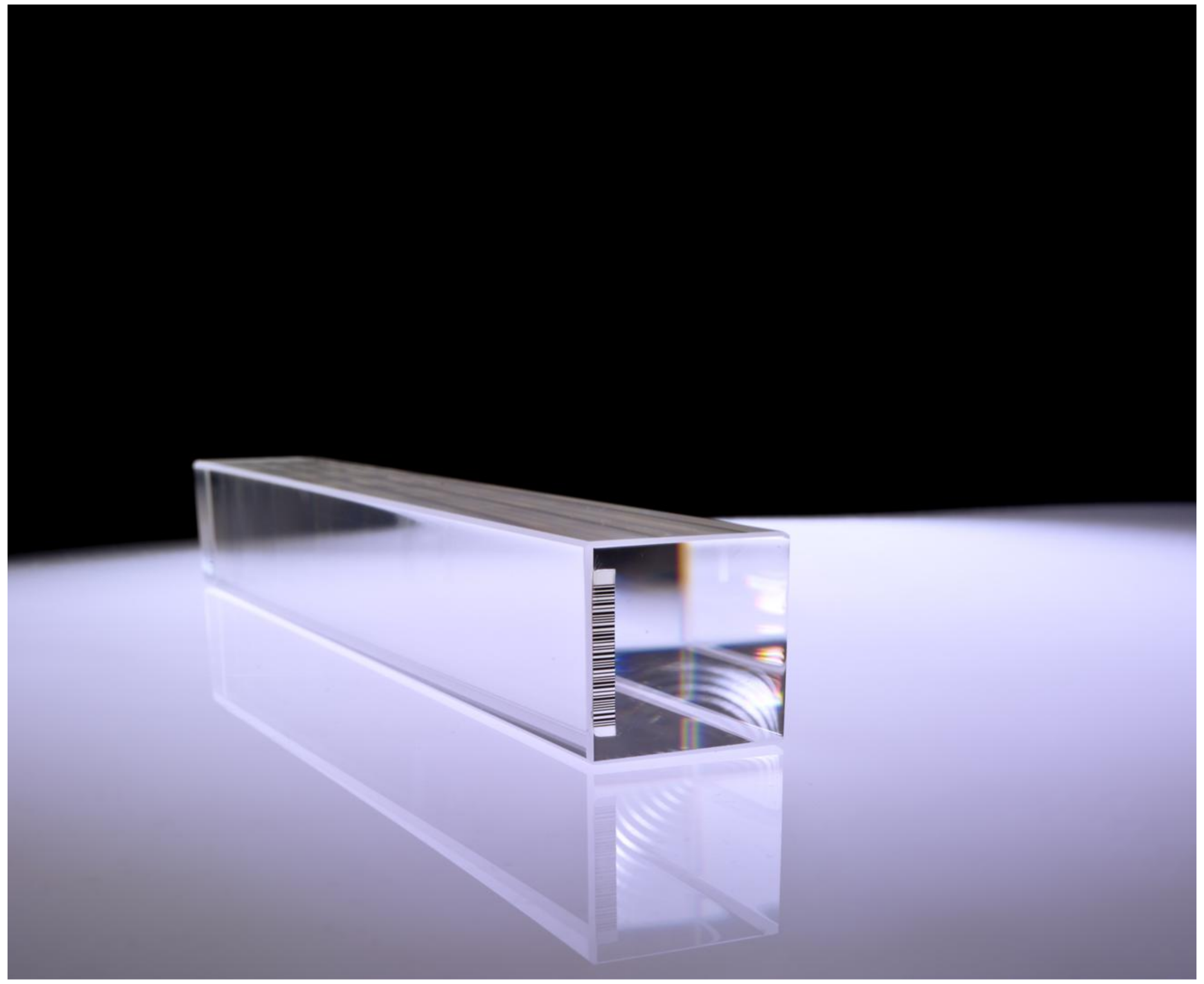


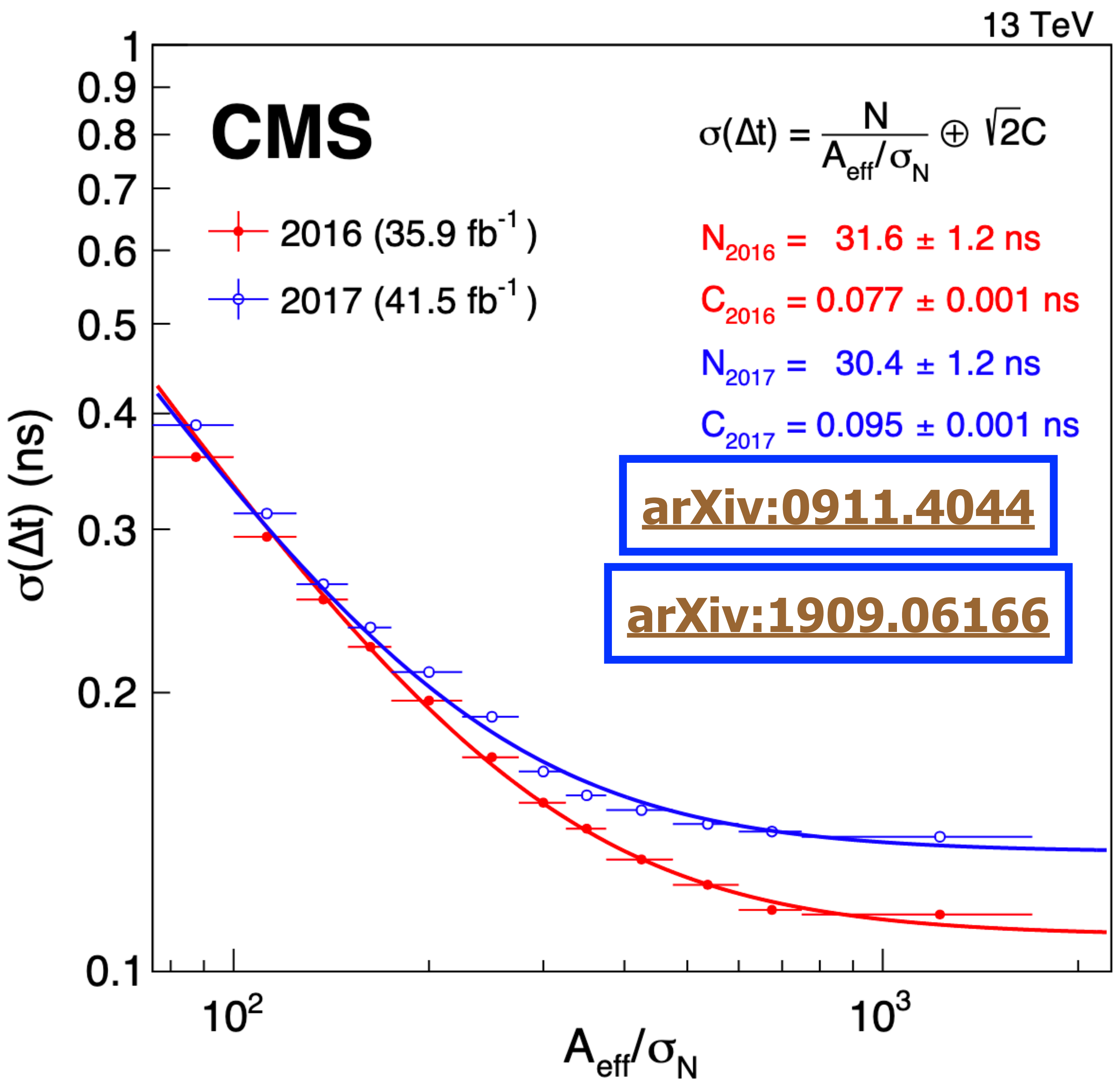
- a @ timing layer with delay

$$\Delta t = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$

- Sources of delay:
  - Small β_X due to heavy X
  - Kink in trajectories
- Timing layer @ CMS: ECAL!

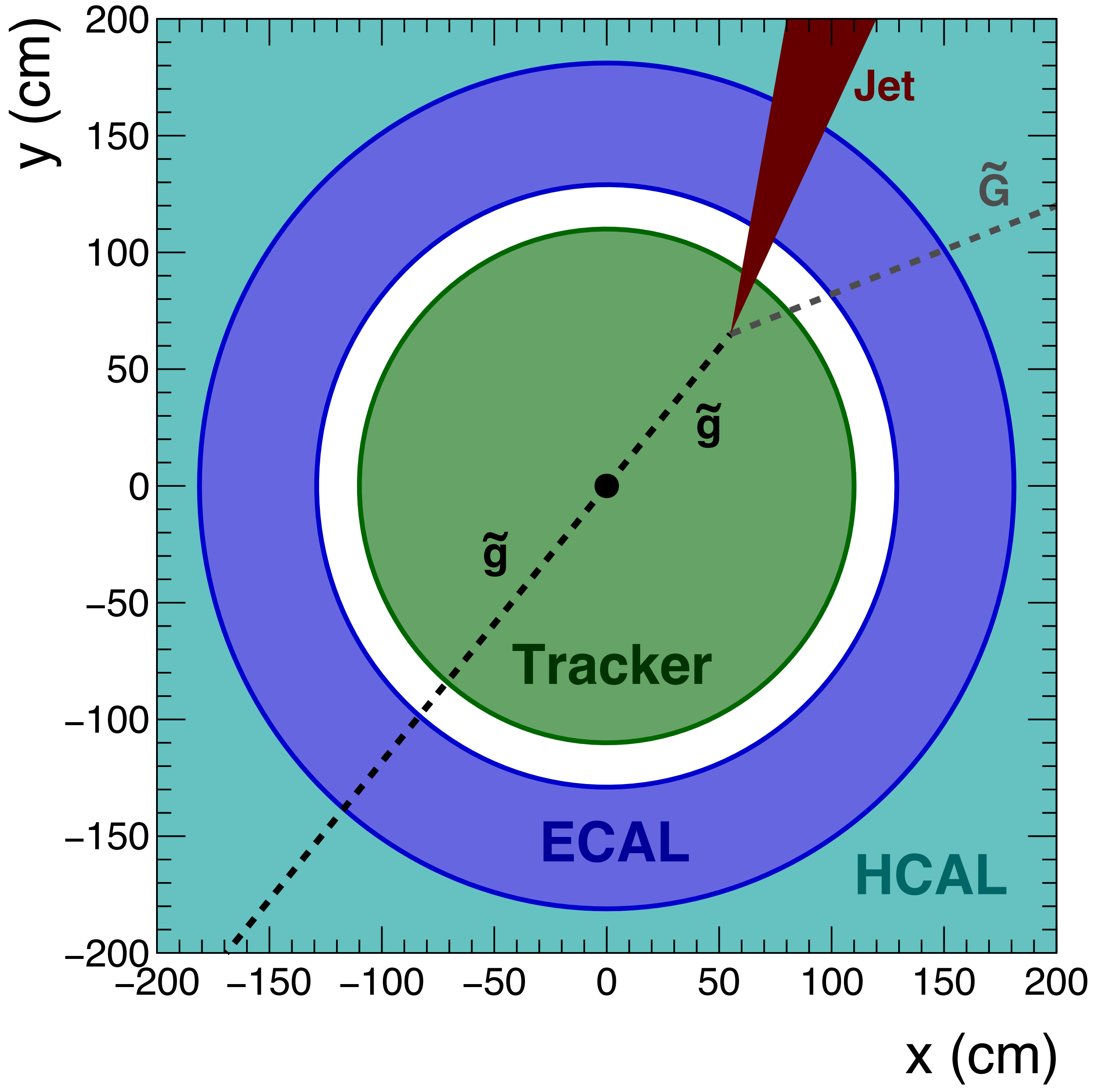
- ECAL made of $PbWO_4$ scintillating crystals, sending signal pulses
- Time calibration: particle produced @ PV travelling at c arrives at $t = 0$ ns
- Good time resolution (~1 ns): ability to detect delays due to LLPs

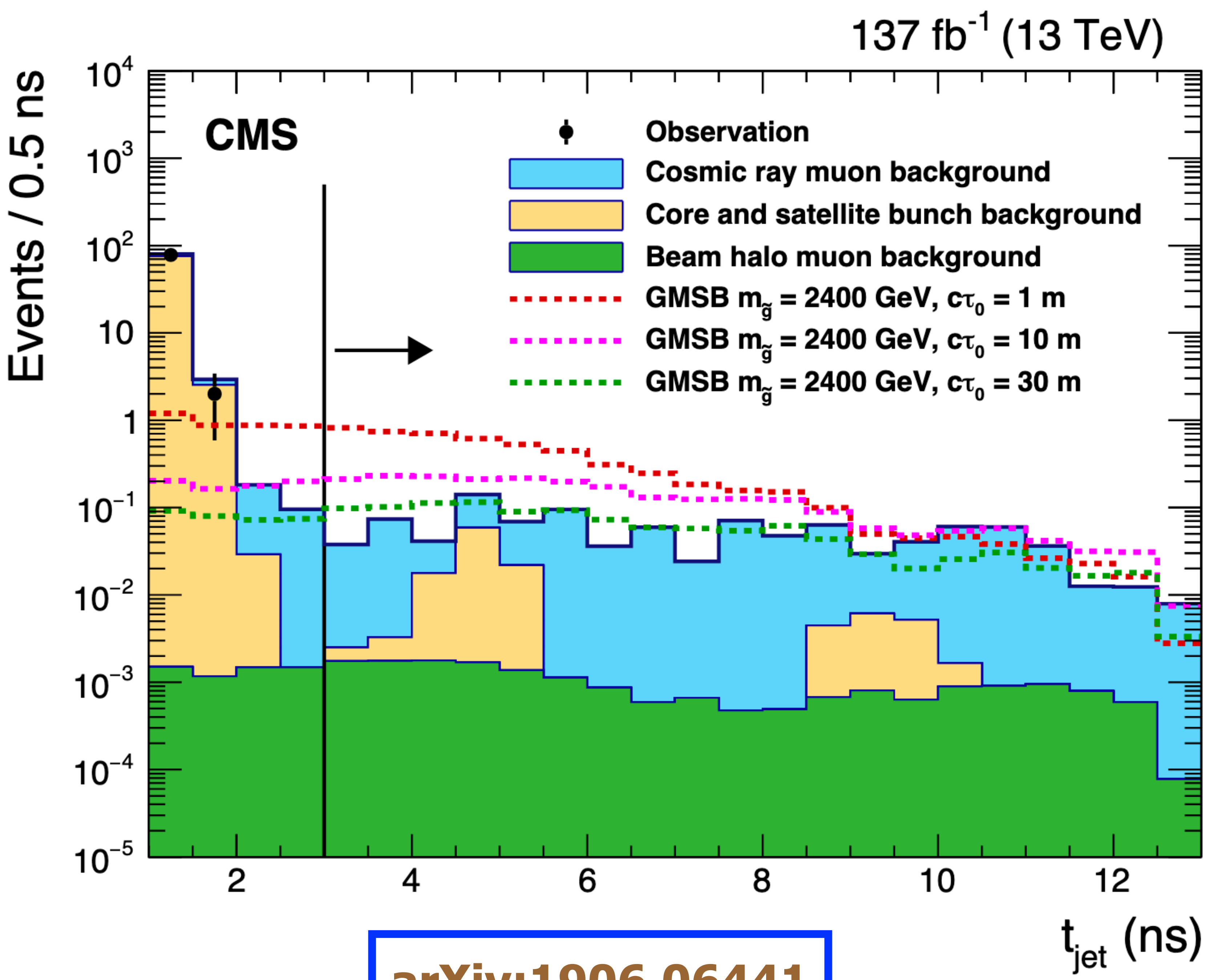




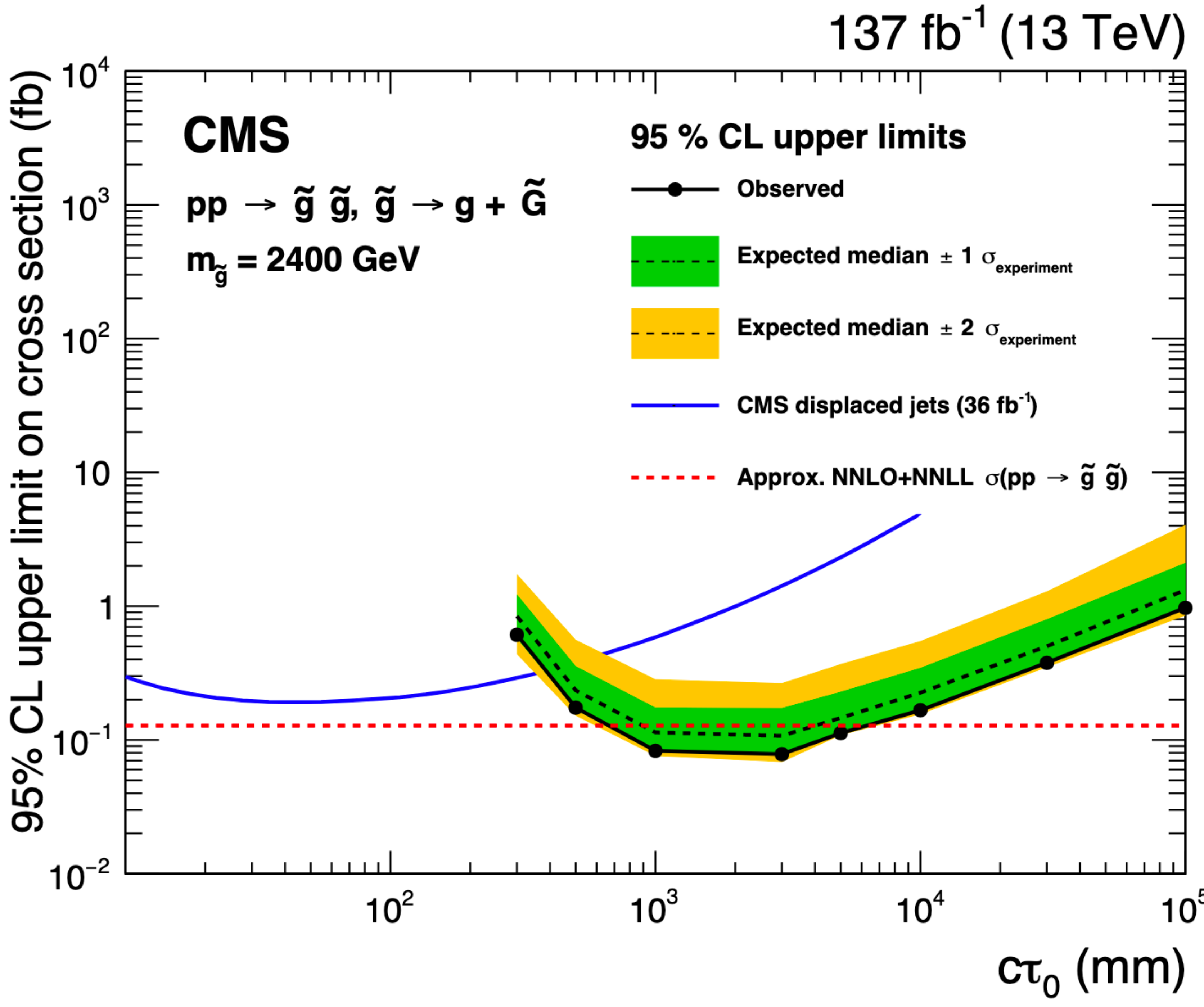
LLPs in calorimeters: delayed jets

- Jet time: median time of ECAL crystals in jet cone → more delay in signal
- Crystal energy threshold and quality criteria applied to reject background (pile-up, satellite bunches, beam halo effects, electronic noise)
- Best sensitivity at 1-2 m





[arXiv:1906.06441](https://arxiv.org/abs/1906.06441)



LLPs signatures in CMS muon systems

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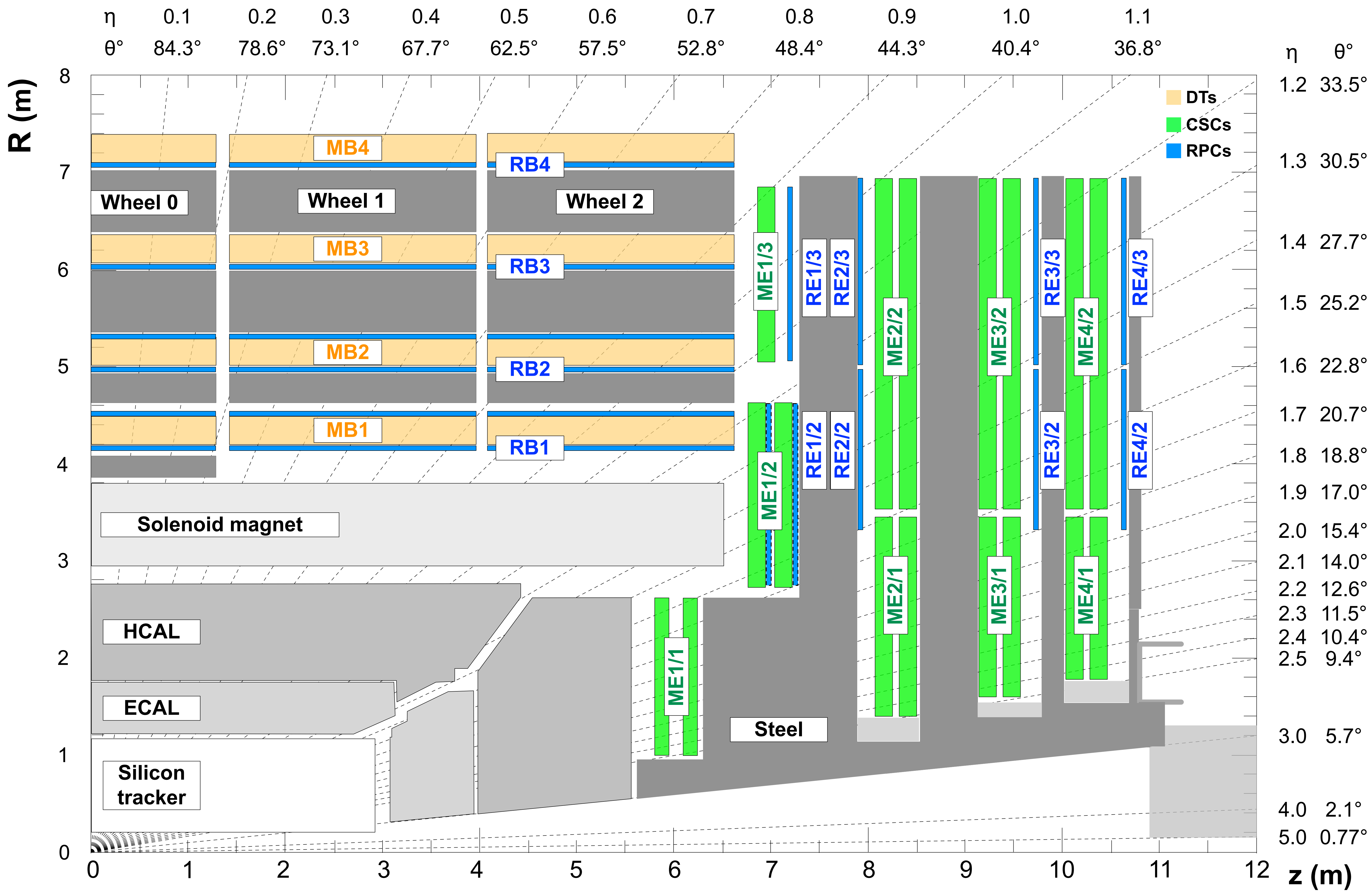
LLPs signatures in CMS muon systems

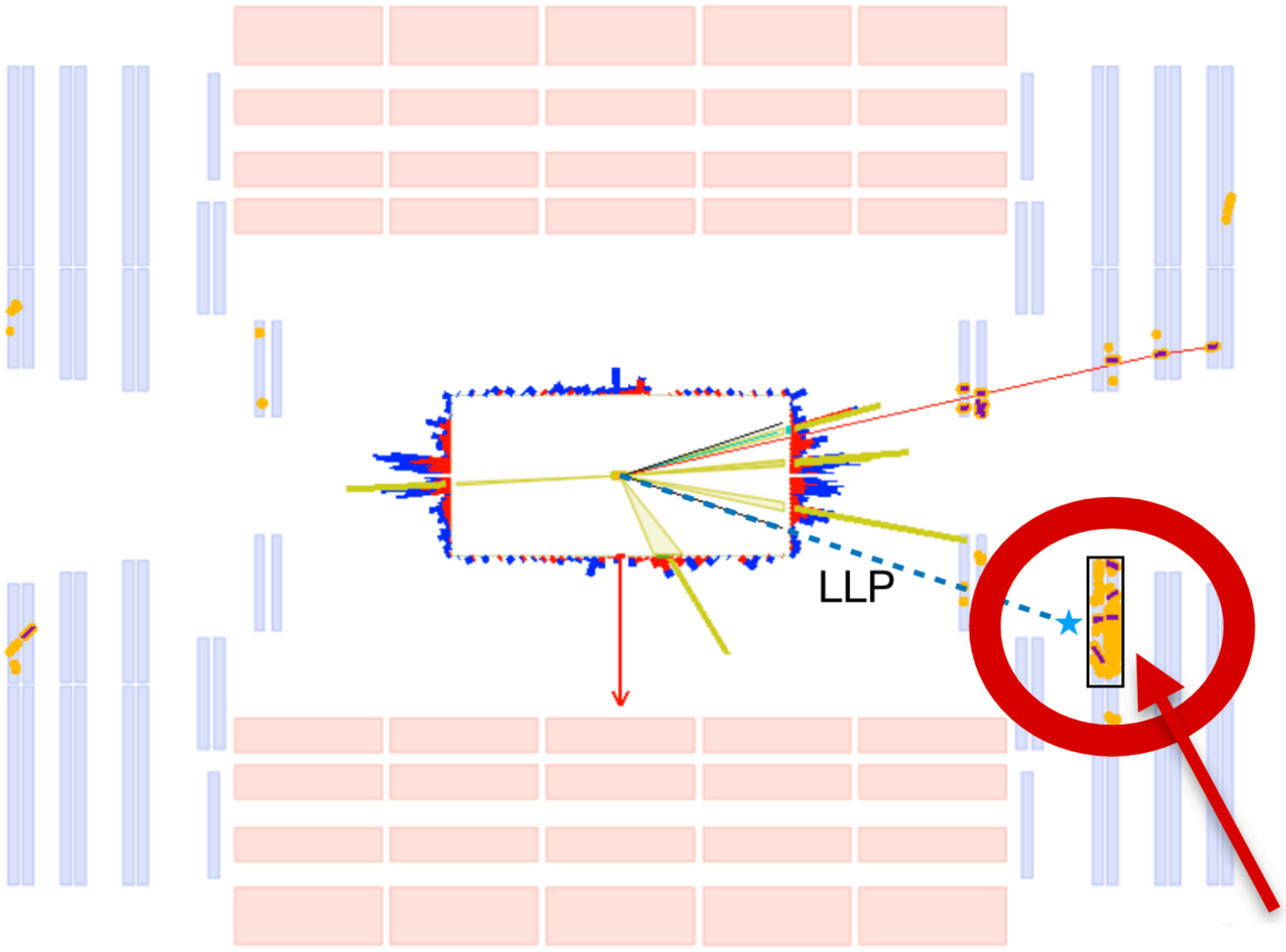


arXiv:1306.6905

- Muon system: gas detectors and iron (passive material + return yoke)
- **Drift tubes** (DTs) in barrel:
  - Uniform magnetic field, low rate
  - Very good spatial resolution (~100 μm) and time resolution (5 ns)
- **Cathode strip chambers** (CSCs) in endcaps:
  - Non uniform magnetic field, high rate
  - Fast time response (short drift path) and very good resolution (3 ns)
- Time information
  - Ability to trigger
  - Potentially useful to detect LLPs

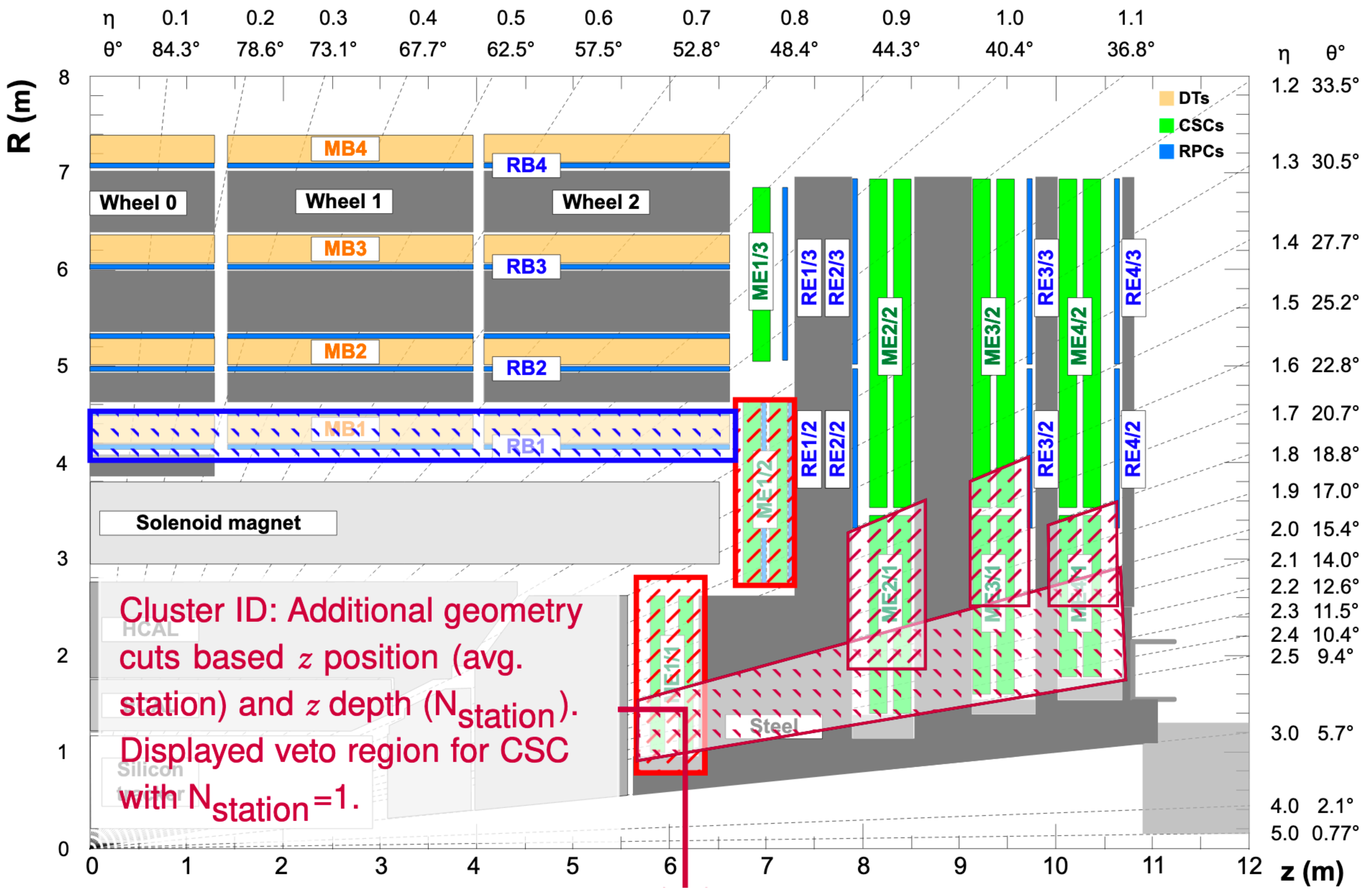
LLPs in CSC muon systems: hit clusters

- Neutral LLPs ($c\tau > 1$ m) decaying after calorimeters into quarks/gluons: produce no tracks, no jets, but showers in muon system → clusters of hits in CSCs
- Pro: CSCs act as a sampling calorimeter
  - Iron: suppresses punch through jet → less background
  - Sensitivity to a broad range of decays (also light particles → hard to reconstruct in tracker/calorimeter)
- Con: lack of dedicated trigger
  - Using missing energy → pair of LLPs, one decays outside of CMS
  - Technically challenging: need to look at raw data (detector hits)
- First CMS effort to cover this signature



LLPs in CSC/DT muon systems: hit clusters

- Hits are geometrically clustered → dedicated cluster definition to improve S/B
  - Hit multiplicity: main discriminating variable
  - Veto geometrical regions with noise/background (punch through jets, cosmic rays, pile-up, noise, bremsstrahlung)
  - Define control regions asynchronous w.r.t. bunch-crossing to validate the background estimation
- DTs analysis: same strategy, but DTs don't store the bunch-crossing time
  - Workaround: match hits of the **RPCs** to the DTs
- Analyses in progress, but very good results are coming soon!



LLPs signatures @ CMS: future developments

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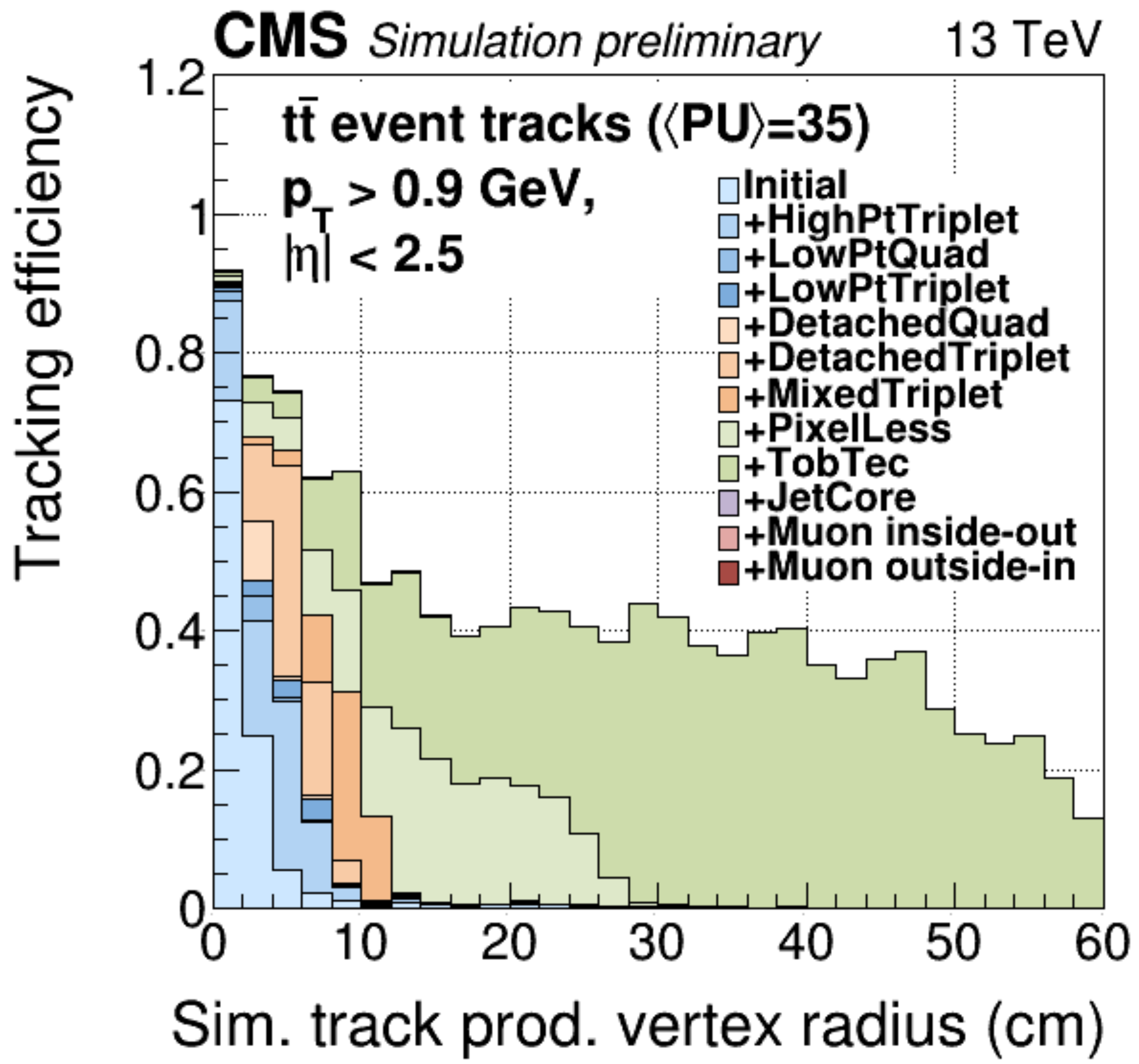
CMS Compact Muon Solenoid

Displaced tracking for Run3

- Track displacement → loss of efficiency → reconstruction challenging!
  - Displaced tracks are lost
  - Displaced vertices are lost



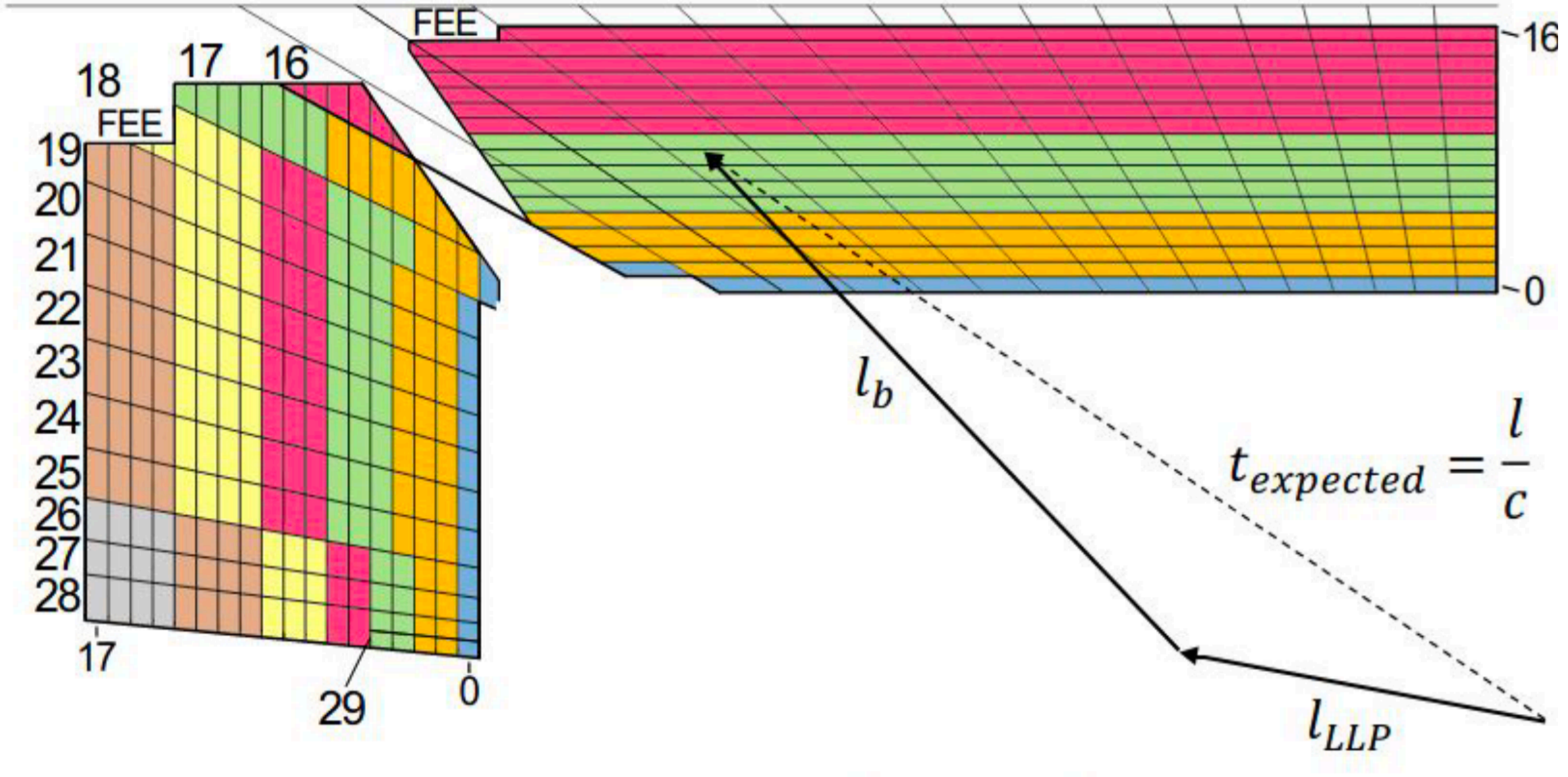
Tracking @ HLT

- Current baseline:
  - single iteration seeded by pixel tracks
  - efficiency loss @ 1 cm
- Developments:
  - use strip-seeded iteration to recover efficiency for larger displacement
  - used in Run2 for dedicated HLT triggers (not standard tracking)

Tracking offline

- New iteration using Regions of interest (ROI)
  - pairwise tracks combined together into vertices
  - vertices clustered in spherical ROIs, radius 1 cm, tagged with an MVA (DeepSets)
  - tagged ROIs used in tracking algorithm

Trigger for LLPs in calorimeters: HCAL time and depth

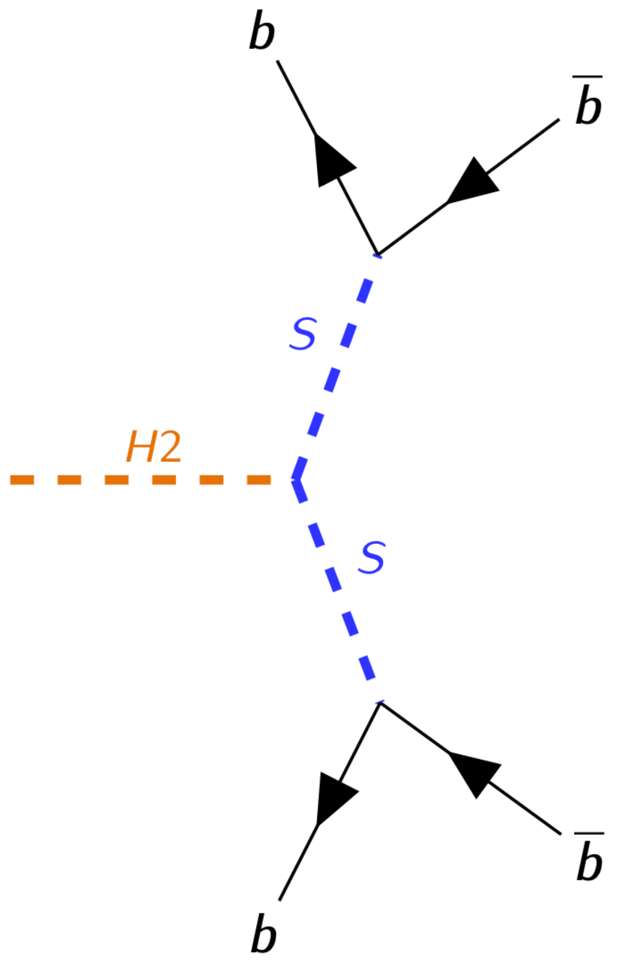


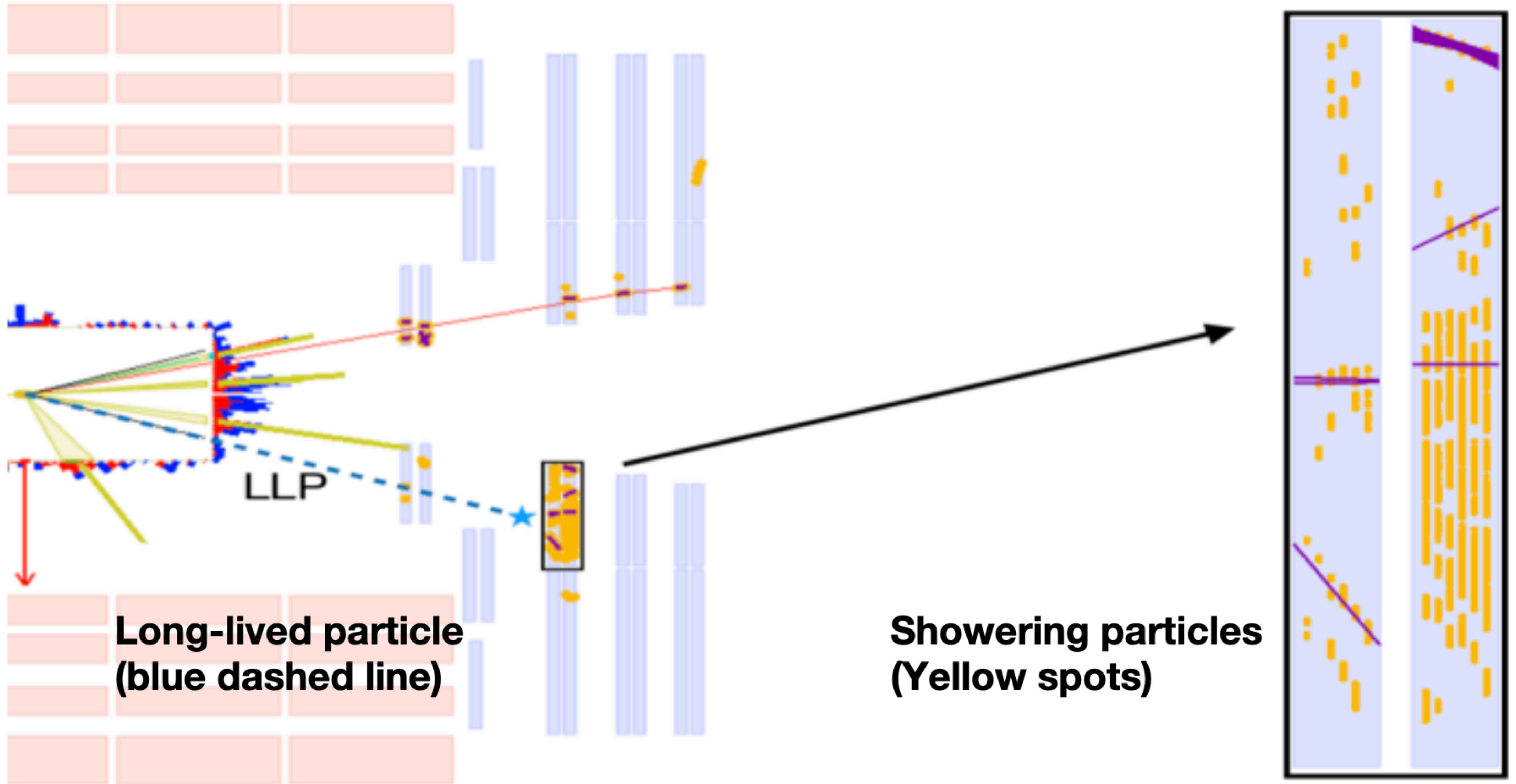
$$\Delta t = \frac{l_{LLP}}{v_{LLP}} + \frac{l_b}{c} - \frac{l}{c}$$

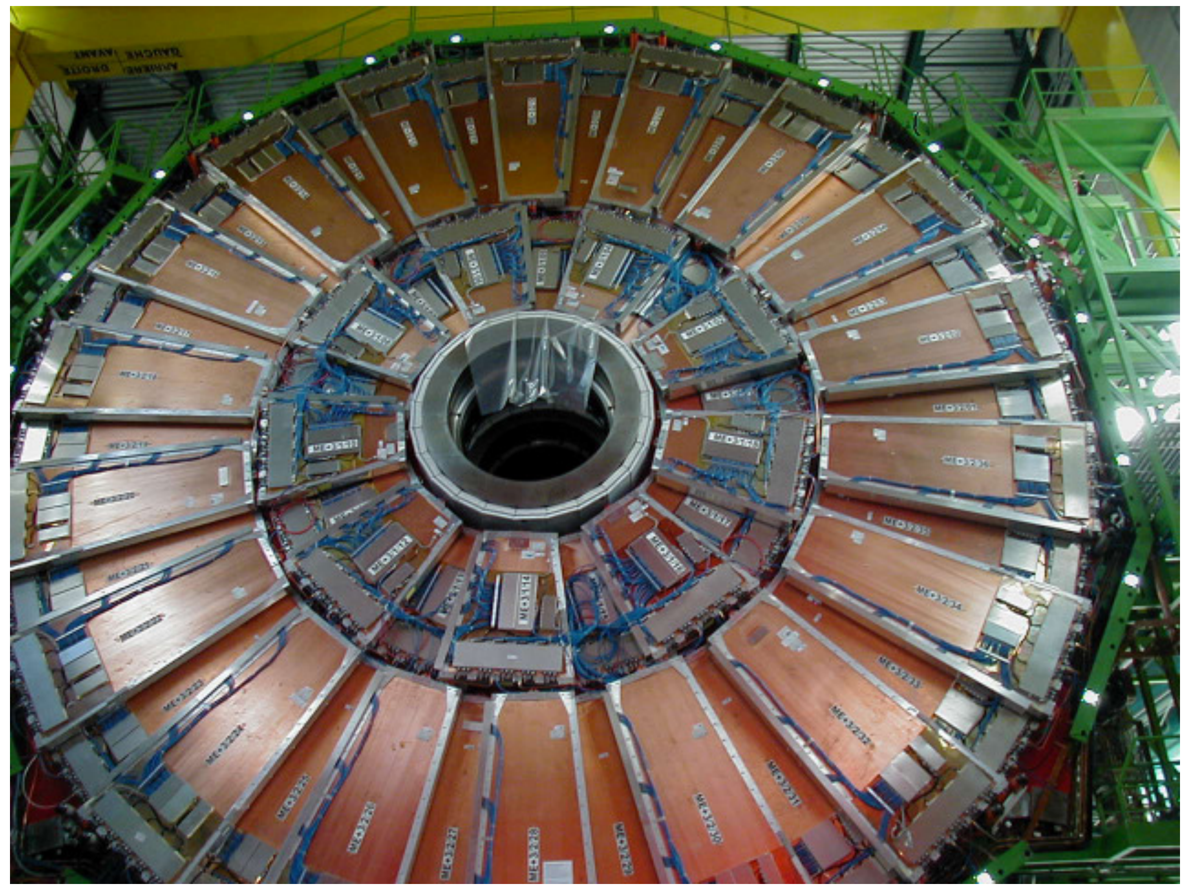
- Hadronic sampling calorimeter (HCAL): plastic scintillator and brass
- Some L1 trigger possibilities not fully exploited so far:
  - Timing information (resolution 0.5 ns) → delay due to kinks/heavy LLP mass
  - Longitudinal depth (4 layers in barrel in Run3, 7 layers in endcaps in Run2) → S/B discrimination (S: deeper showers)
  - Energy ratio E_{HCAL}/E_{ECAL} → successful at killing multi jet background, lower rate

Trigger for LLPs in muon system: CSC showers

- Trigger strategy based on the CSC analysis
  - benchmark signal: H →XX →bbbb
    LLPs decay products shower in CSC
  - count cathode/anode hits → threshold optimised for S/B and for reasonable L1 trigger rates
  - provides very low rates at HLT ~ 1 Hz
  - improves the missing energy approach of Run2 by a factor >10x
- Work in progress, very promising for Run3







LLPs @ CMS: conclusions

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Conclusions

- Very broad LLP program @ CMS
  - Small selection of searches: many other searches completed and in progress, with very different signatures
  - Emphasis on hadronic decays in tracker, calorimeters and muon systems
  - Many strategies to workaround the lack of dedicated trigger/reconstruction algorithms
- Many developments currently in progress
  - New **trigger** ideas
  - New **reconstruction** strategies
  - **Unexplored signatures**
  - Not mentioned: **machine learning**, getting more and more important and exploited (graph networks)
- Ideas exchange among different experiments and theorists is fundamental
  - Hope this will trigger discussion!

Backup

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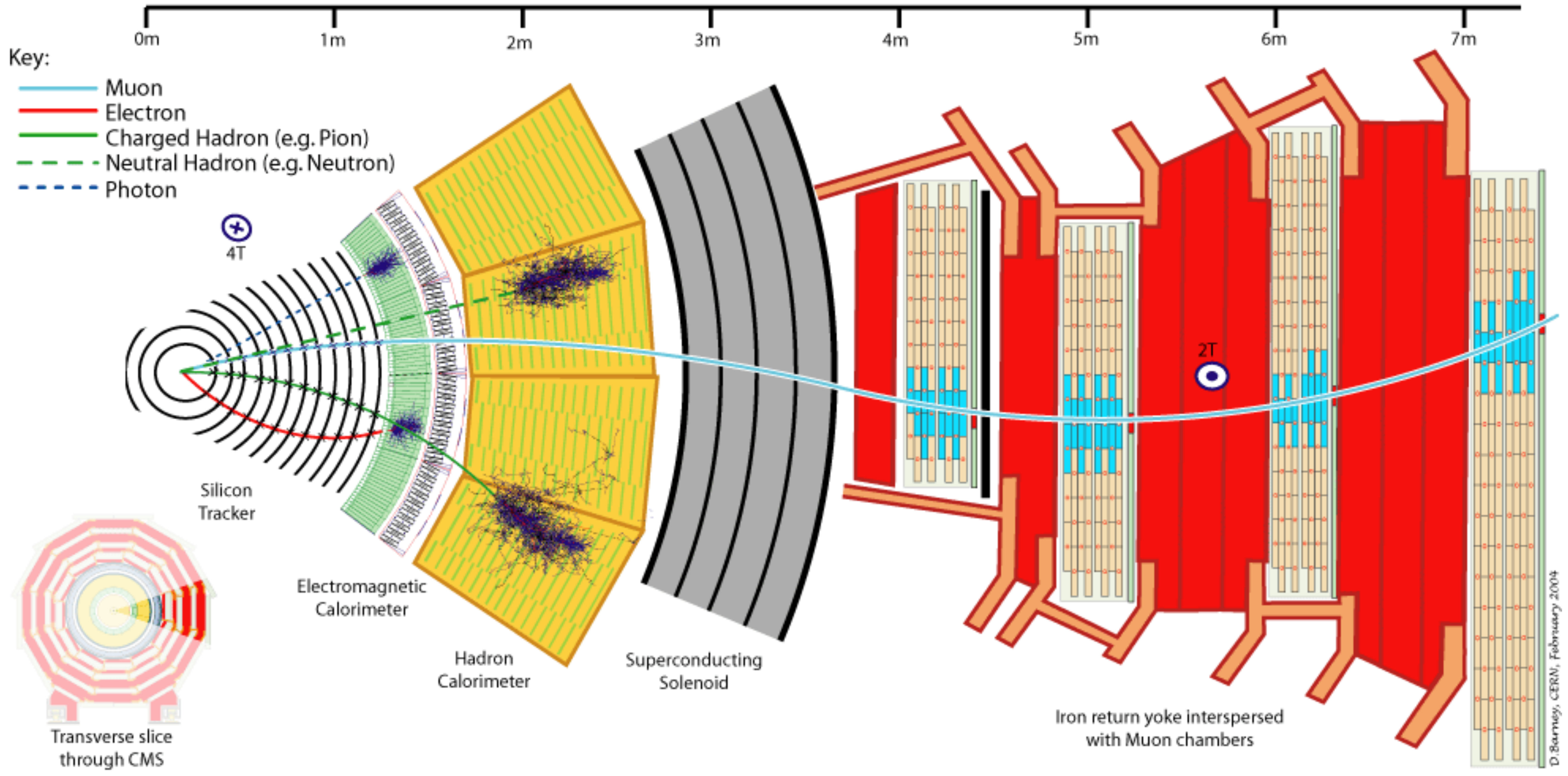
CMS trigger and reconstruction



- CMS organised in layers to detect different particles
- Particle Flow algorithm connects info from sub detectors → precise momentum measurements and particle identification
- But… standard algorithms not designed for LL signatures!

L1 trigger

- Hardware based, information from calorimeters and muon systems only (regional triggers combined to global)
- First pattern recognition and raw measurements
- Fixed latency: 4 μs to accept/reject
- Skims rate to 100 kHz (in total)

High level trigger (HLT)

- Fully software, includes info from tracker
- Similar algorithms as those applied offline
- Latency: 300 ms/event
- Skims rate to 1 kHz max (in total)

Tracker

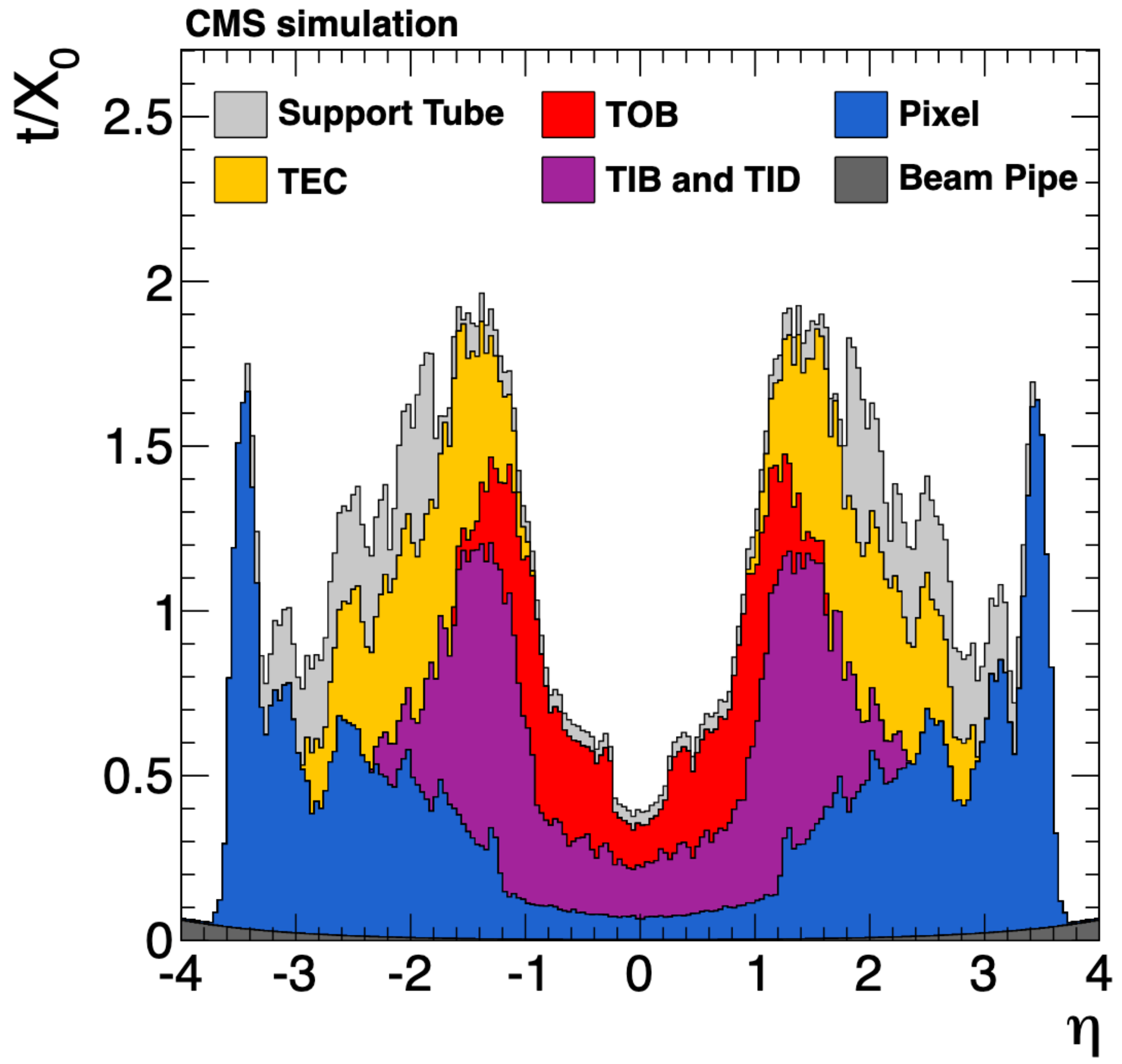
Pixel detector

- 66 M cells, 100×150 μm², 285 μm thickness
- resolution: 10 μm transverse plane, ~20 μm along longitudinal coordinate

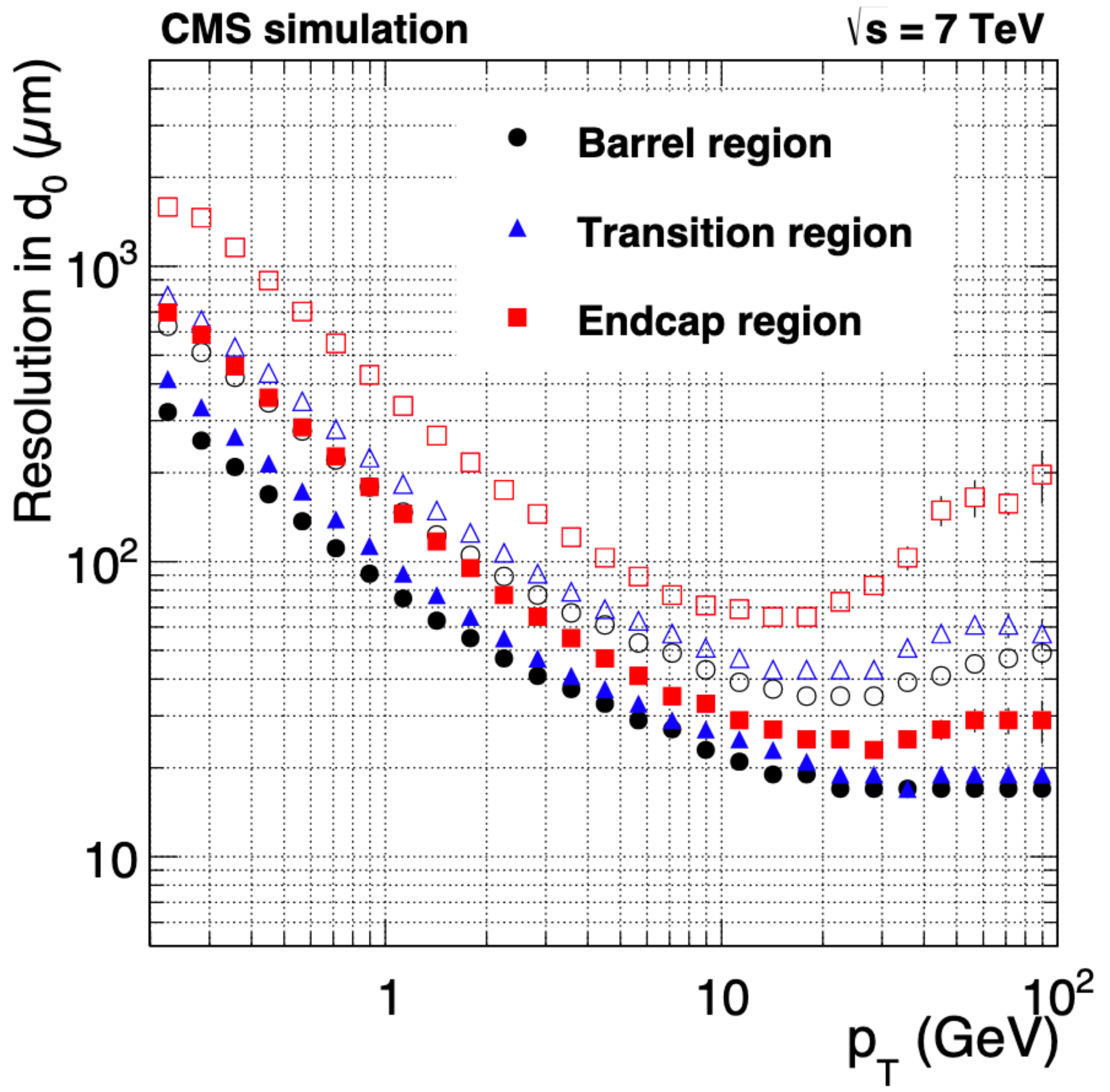
Strip detector

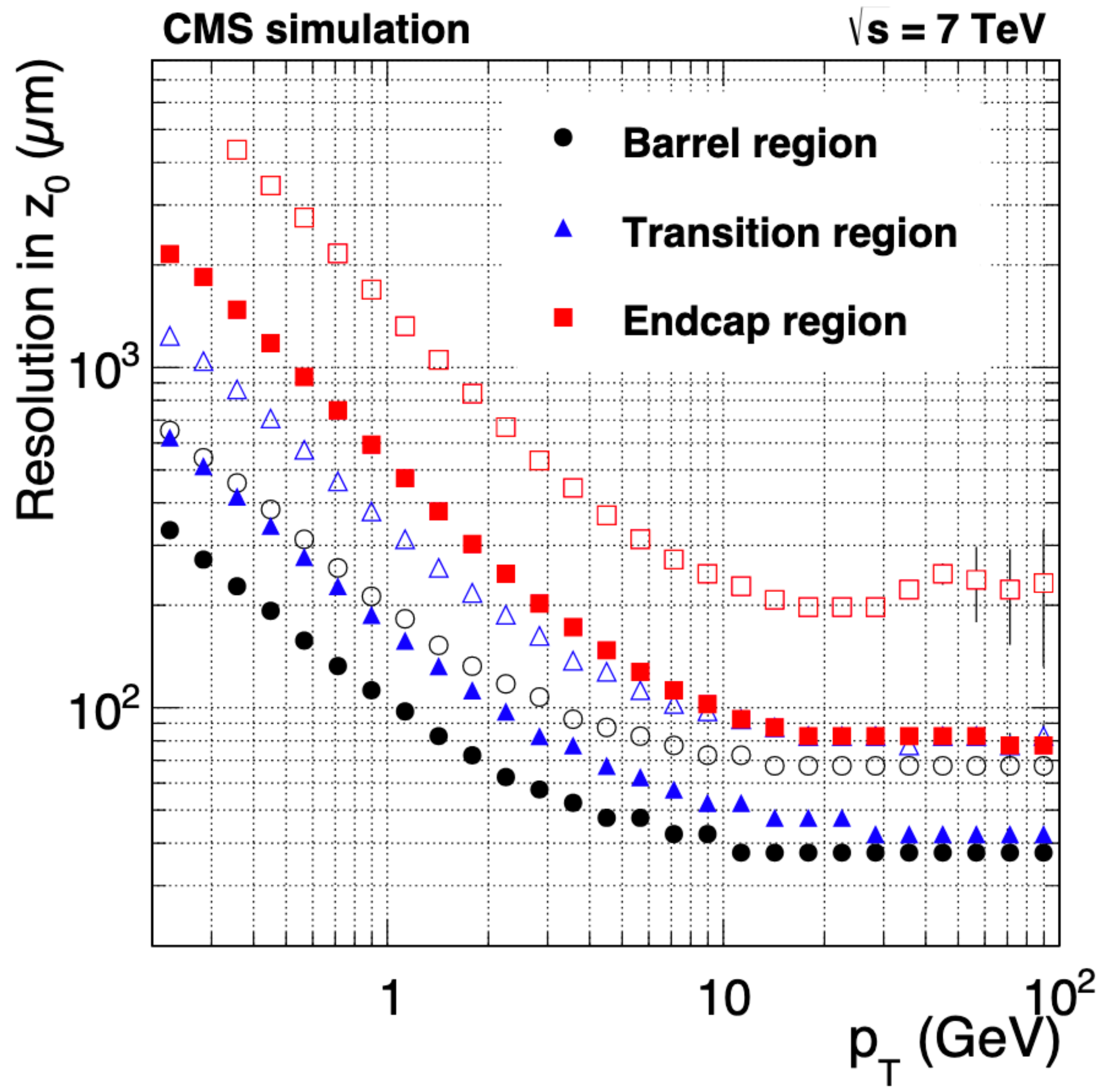
- 15k modules, coverage: 20 < r < 110 cm
- 320 μm thick, 10 cm long, pitch 80 -120 μm
- resolution: 20 – 50 μm transverse plane, 200 – 500 μm along longitudinal coordinate

- Resolution on vertex position: 10-40 μm in (r,φ), 15-50 μm in z



arXiv:1405.6569

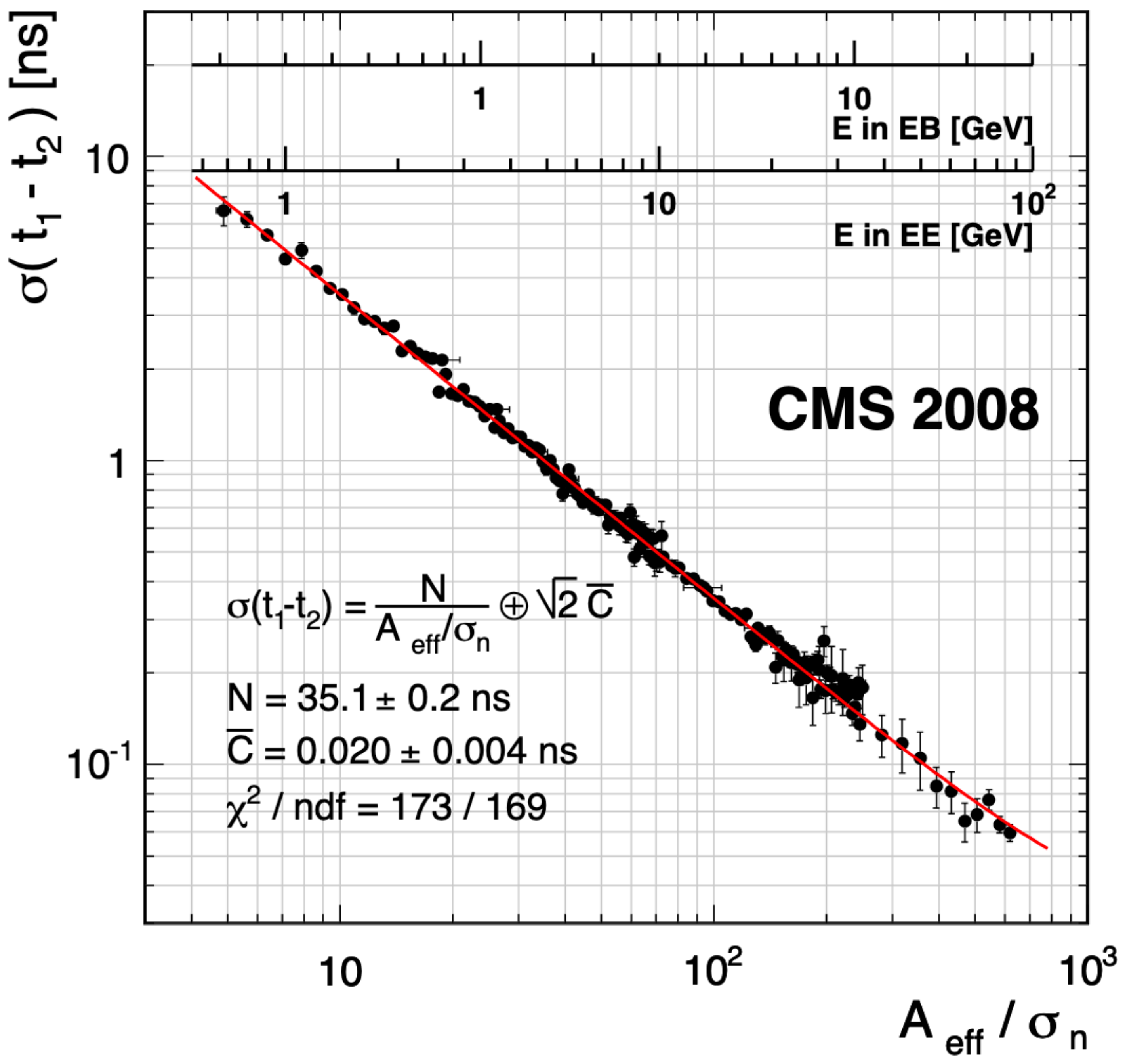


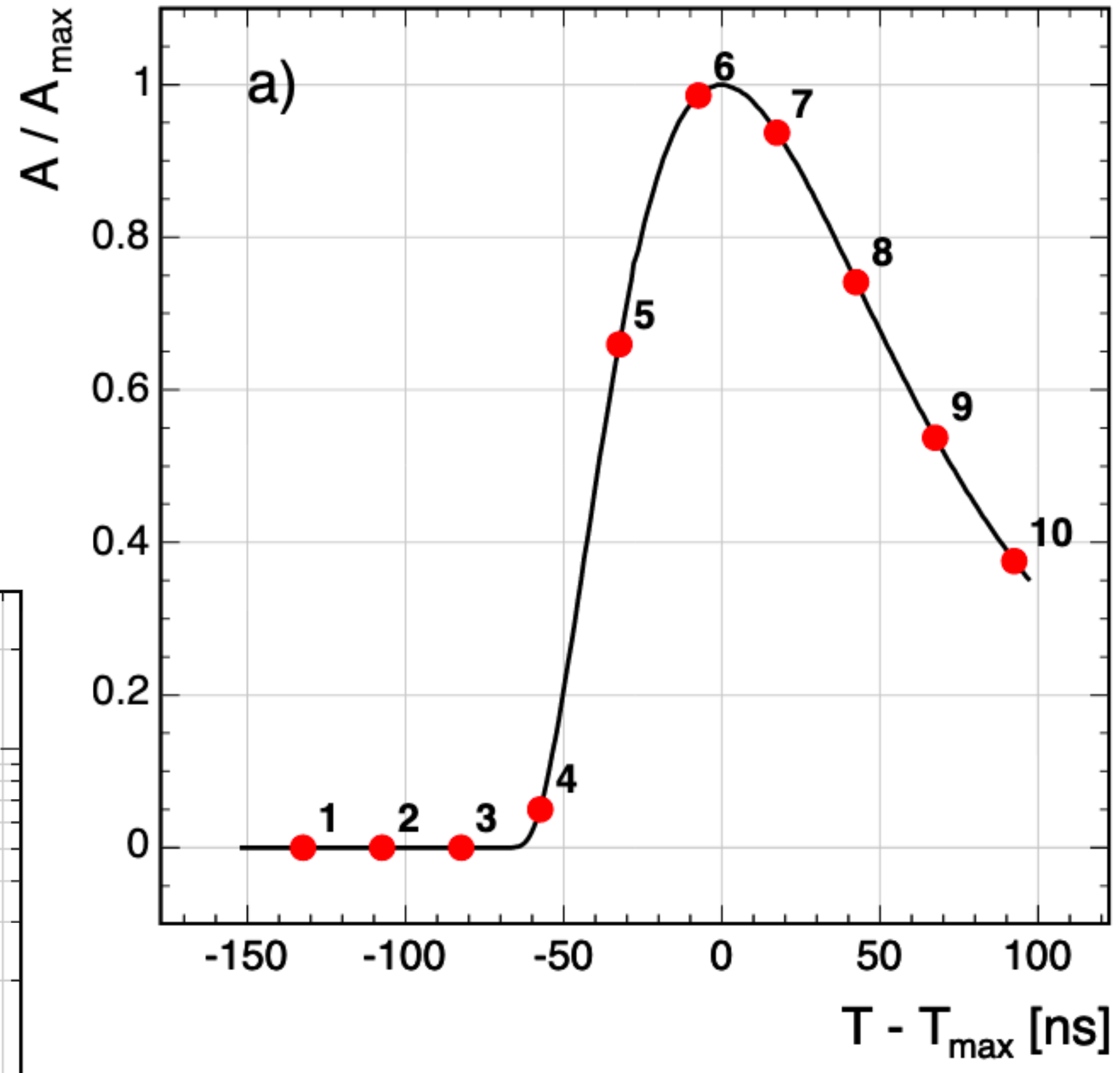


ECAL

- 61200 crystals in barrel, (22×22) mm^2×23 cm
- 7324 crystals in endcaps, (28.6×28.6) mm^2×22 cm
- 1.3 < r < 1.8 m
- Radiation length X_0=0.89 cm, Molière radius 2.19 cm
- Fast time response (85% scintillating light emitted at BX)
- Amplification of scintillating light with avalanche photodiodes (barrel)

$$\sigma^2(t) = \left(\frac{N\sigma_n}{A}\right)^2 + \left(\frac{S}{\sqrt{A}}\right)^2 + C^2$$

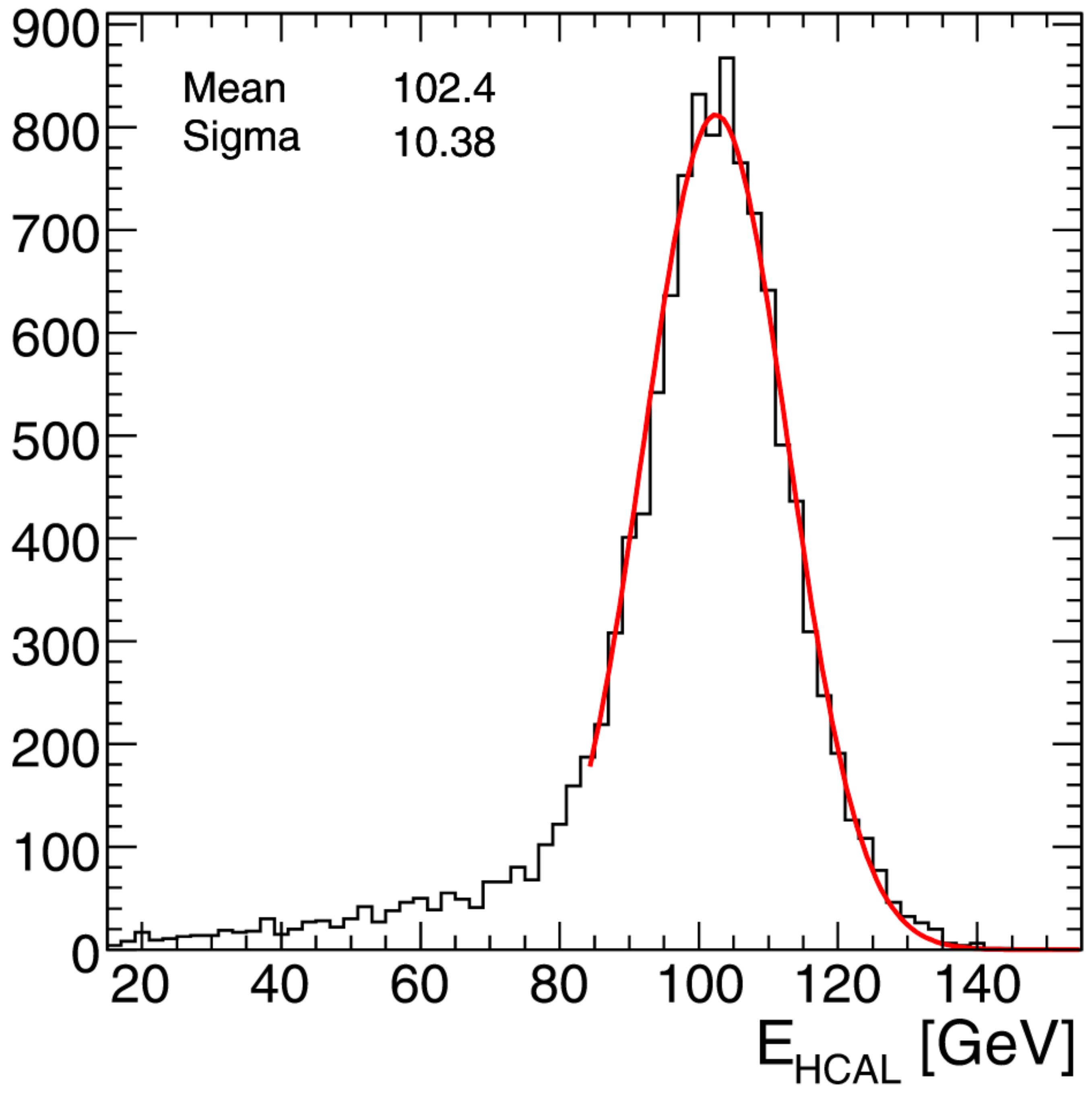




arXiv:0911.4044

HCAL

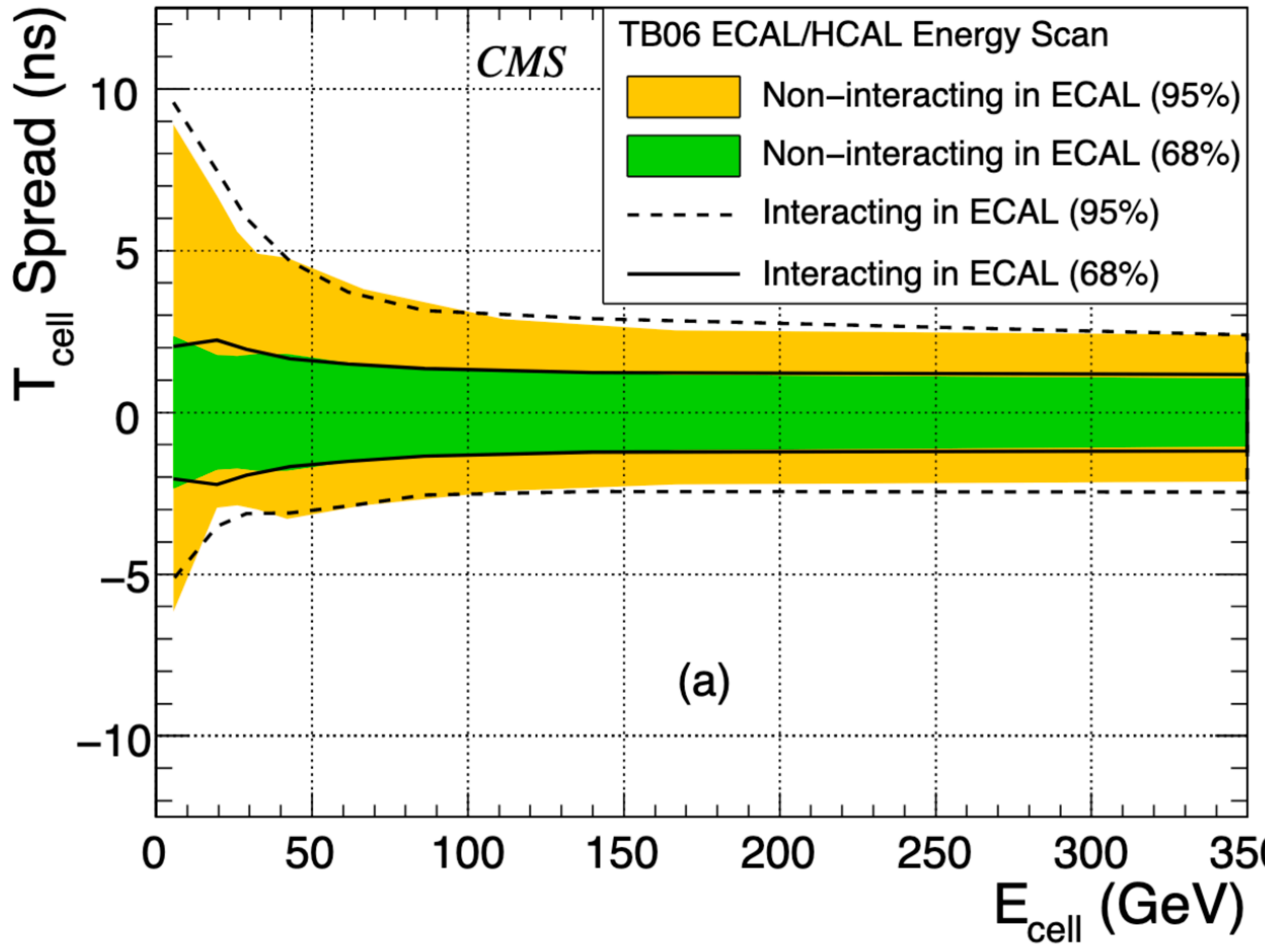
- Sampling calorimeter, brass (5-11 interaction lenghts) + plastic scintillator layers
- 1.8 < r < 3 m
- Longitudinal segmentation, good hermeticity



Pion test beam

100 GeV

10.1140/epjc/s10052-008-0573-y

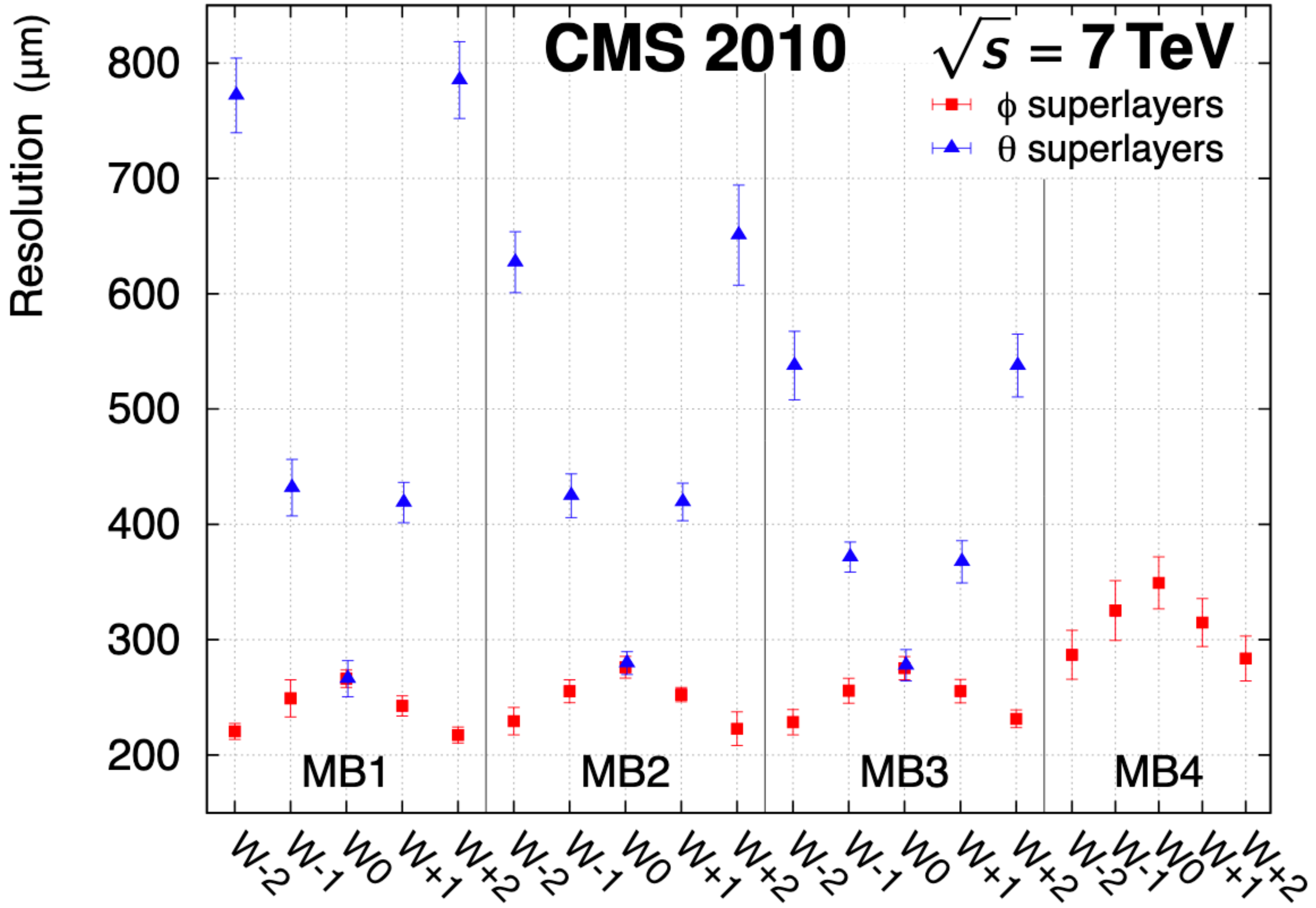


arXiv:0911.4877

DTs

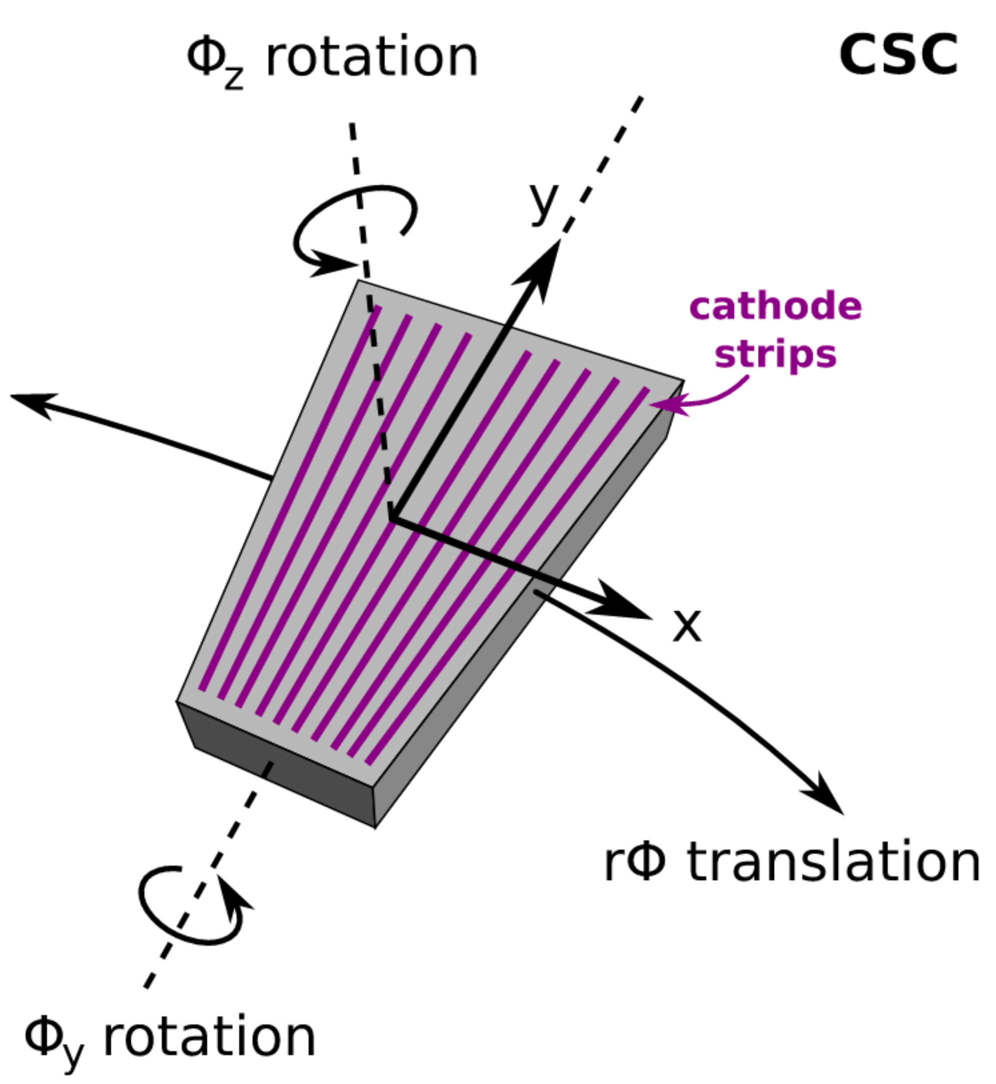
arXiv:1306.6905

- DT cell: 42×13 mm^2, gas mixture (85% argon, 15% CO_2)
- Ionisation electrons drift from the 50 μm thick steel anodic wire, in the center, towards the aluminium cathodic strips
- Electric field: electron drift speed uniform, muon position from drift time
- Cells oriented with wire along z → measure φ; wire along r → measure z
- Resolution: 100 μm in (r,φ) plane, 1 mrad in φ, 150 μm in longitudinal z coordinate
- Arranged in 4 stations, 5 wheels

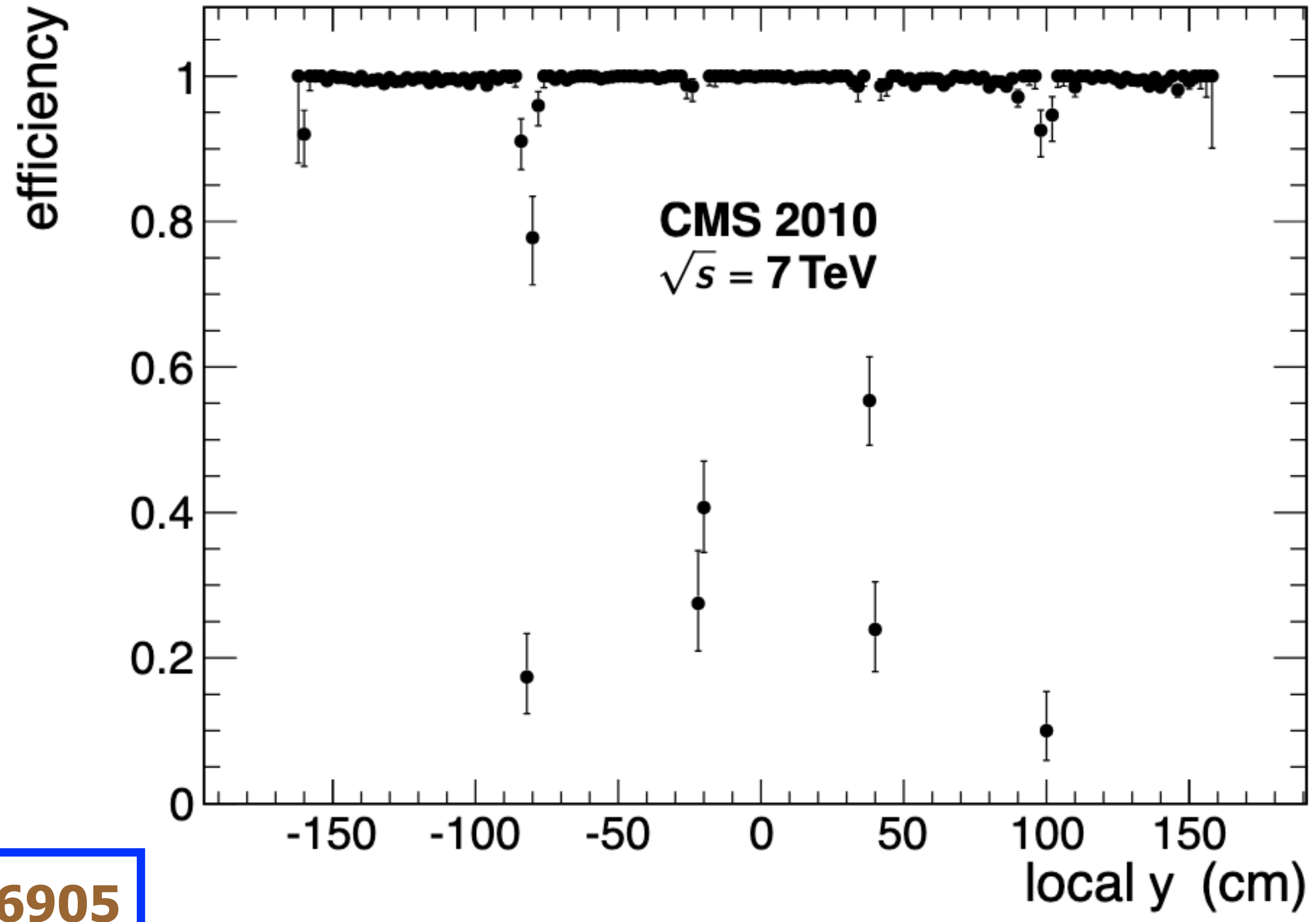


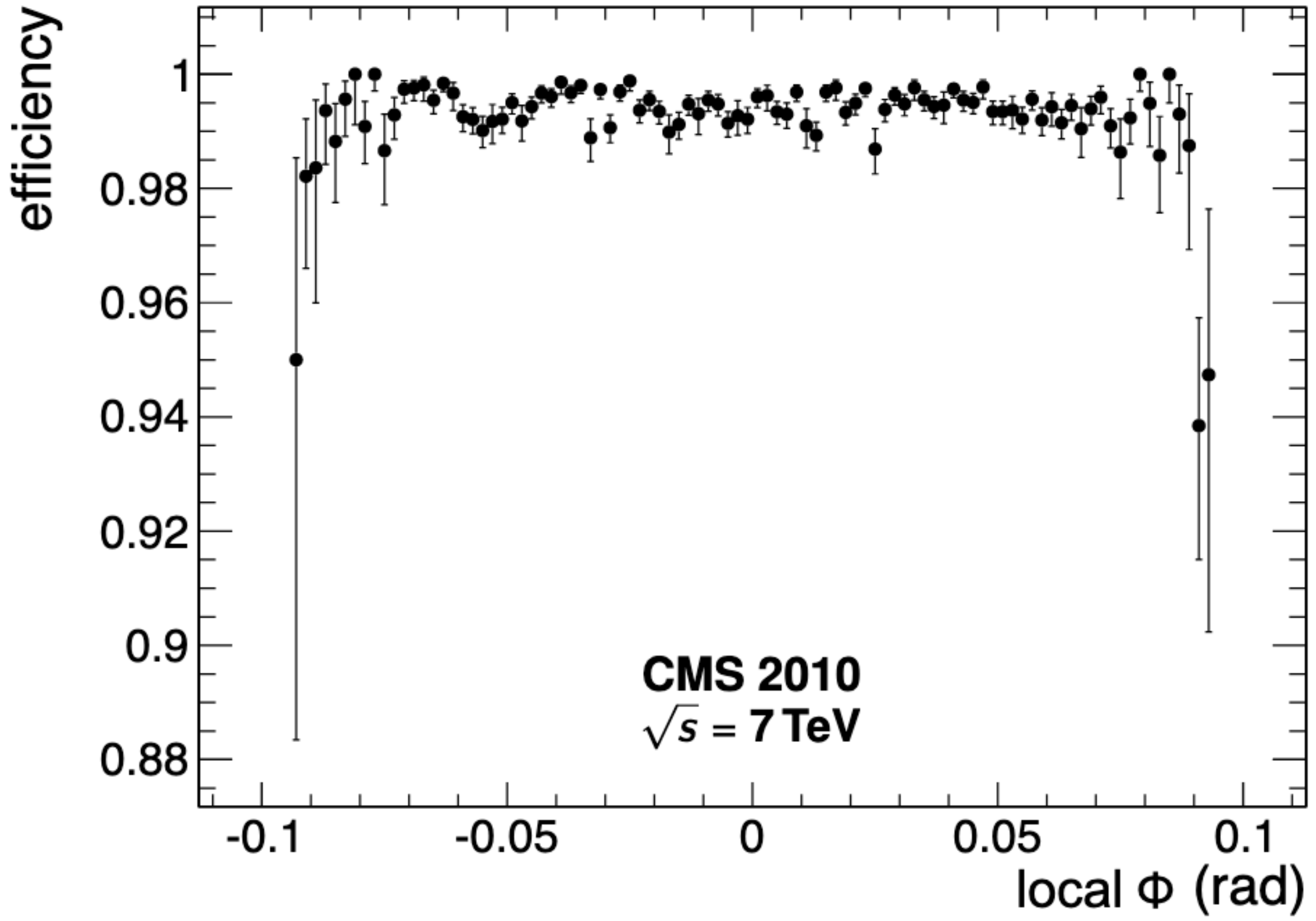
CSCs

- Anodic wires in 6 planes, measure r
- Perpendicular cathodic strips (along r) measure φ
- Ionisation electrons migrate from anodes, inducing a charge distribution on cathodes → azimuthal coordinate
- Resolution: 75 – 150 μm in (r,φ) plane



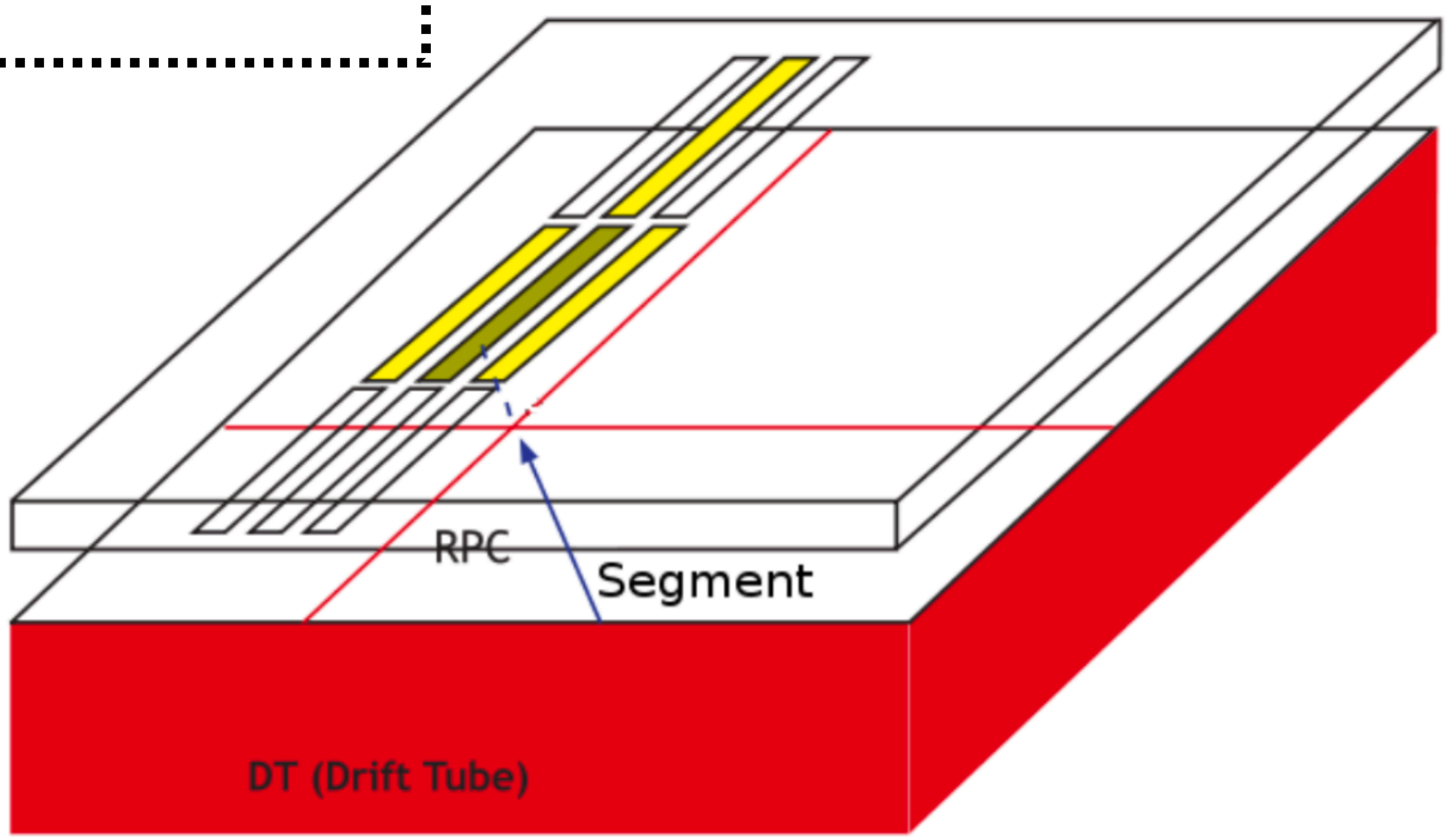
arXiv:1306.6905

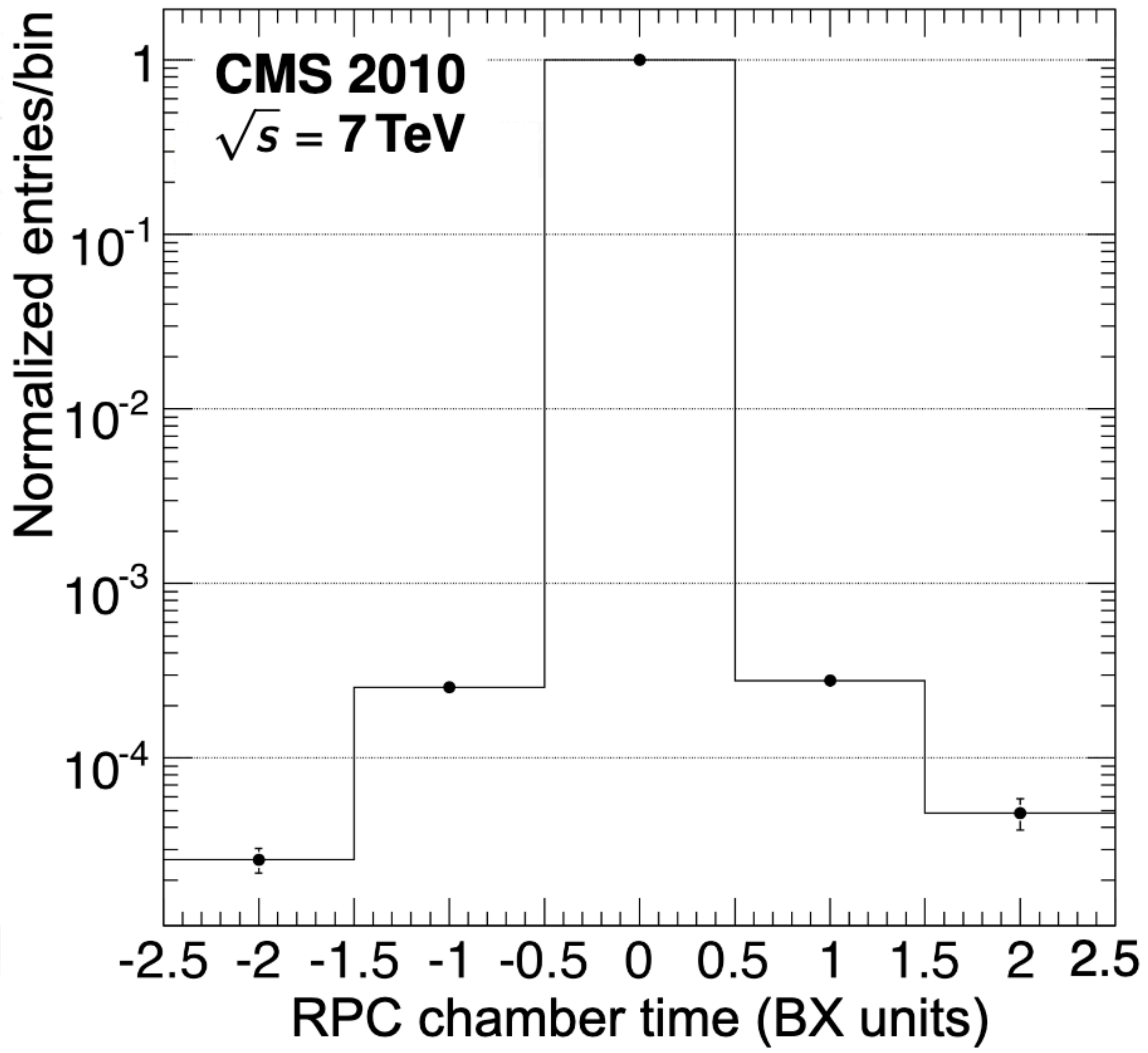




RPCs

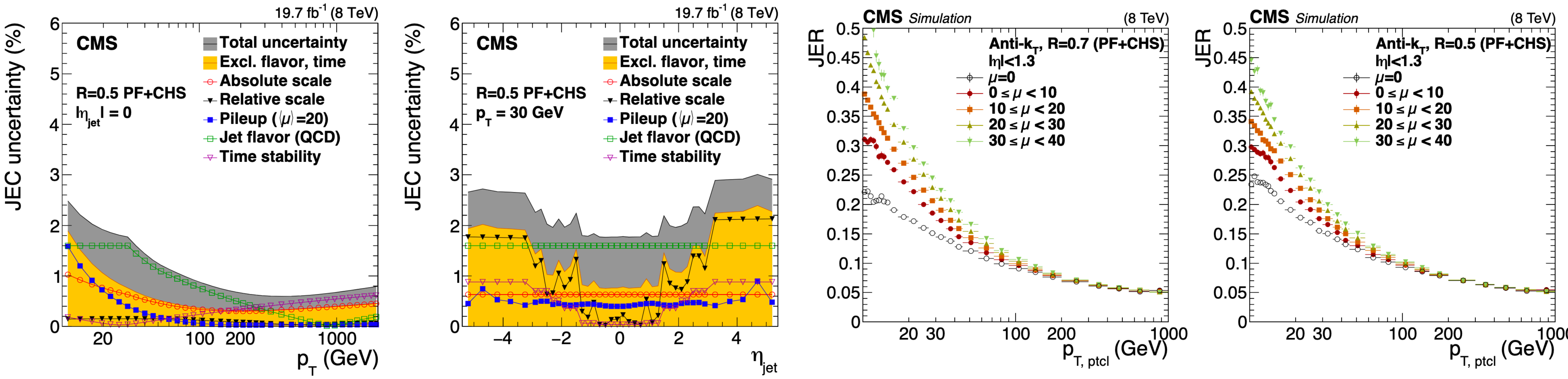
- Resistive Plate Chambers both in barrel and endcaps
- Charged at high voltages, work in avalanche ionisation mode
- Plastic resistive plates equipped with readout strips
- Spatial resolution low (1-2 cm), but fast timing response (2-3 ns) and good time resolution (1 ns) → additional triggering system + precise measurement of bunch-crossing time





arXiv:1306.6905

Jet energy corrections and momentum resolution



arXiv:1607.03663