Review of recent searches for long-lived particles at the LHC

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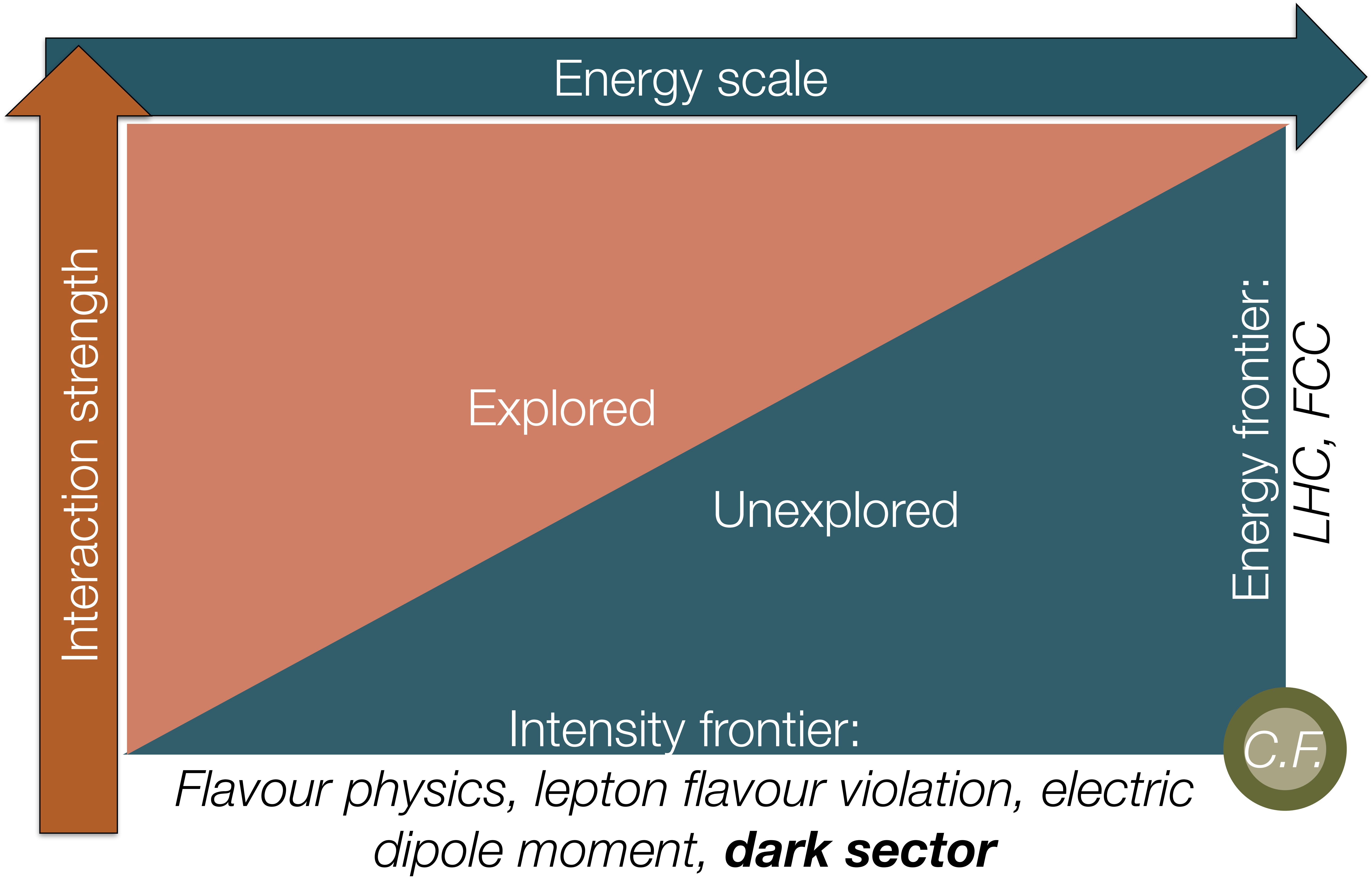
on behalf of the ATLAS, CMS, and LHCb collaborations

(Re)interpreting the results of new physics searches at the LHC
15-19 February 2021

Introduction

The talk will focus on the recent LLP searches at the LHC, with an emphasis on the ones that are not already well known by the reinterpretation community (ie **not focusing on the disappearing tracks or displaced Inner Detector vertex analyses**).
Besides discussing the analyses and signatures covered, the talk will cover which auxiliary material is available for reinterpretation if any, comparing the different approaches used by the collaborations for this material when relevant.



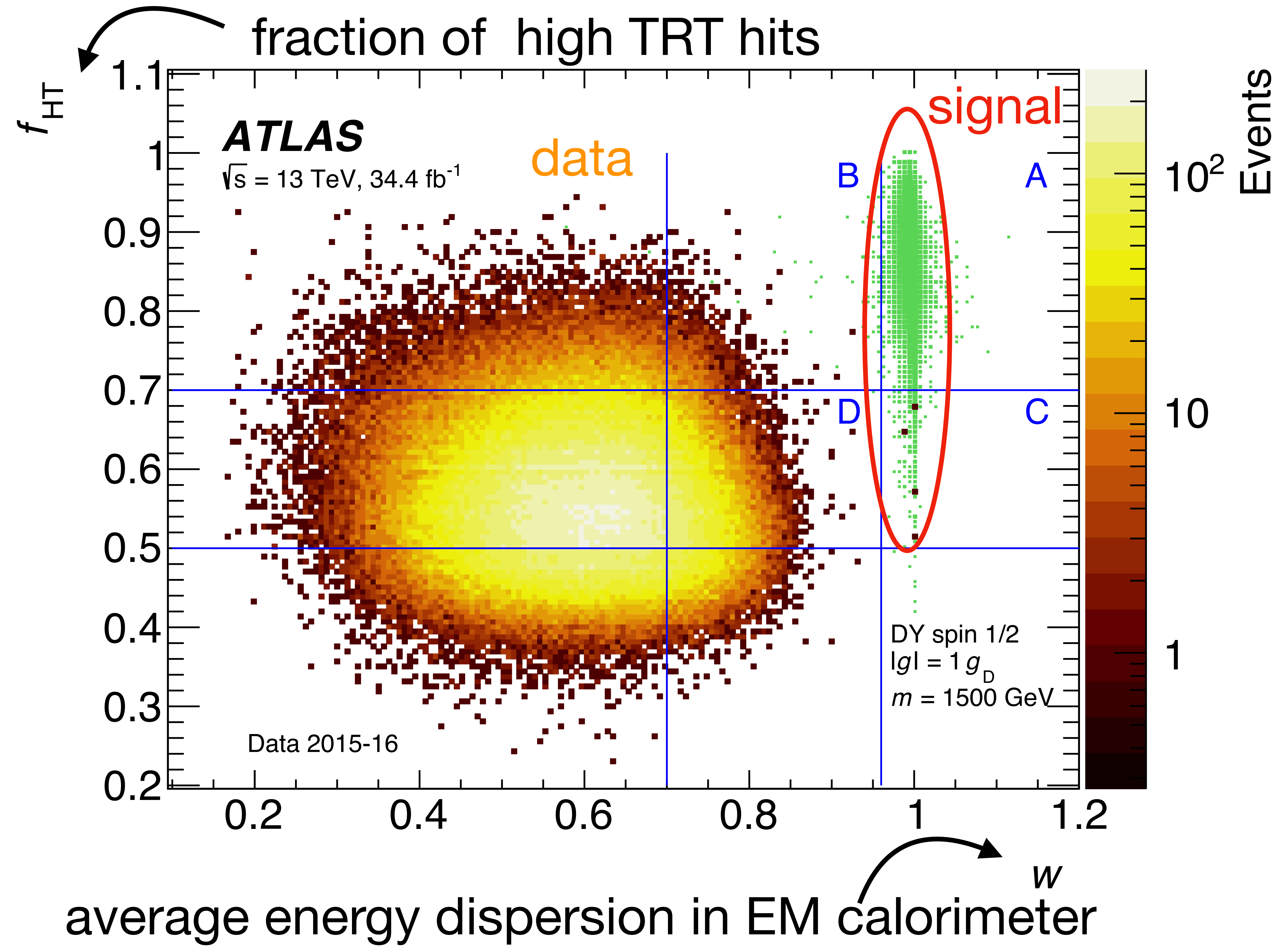
Summary of results

- **Searching for long lived particles at the LHC 4π detectors:**
  - **At CMS**
    - **Nonprompt jets**
      Phys. Lett. B 797 (2019) 134876
    - **Delayed photons**
      Phys. Rev. D 100, 112003 (2019)
    - **Displaced jets**
      CERN-EP-2020-202
    - ***LLPs to trackless jets***
      CMS-PAS-EXO-17-010
    - ***LLPs to jets***
      CMS-PAS-EXO-19-013
    - *Disappearing tracks [other talks]*
      Phys. Lett. B 806 (2020) 135502

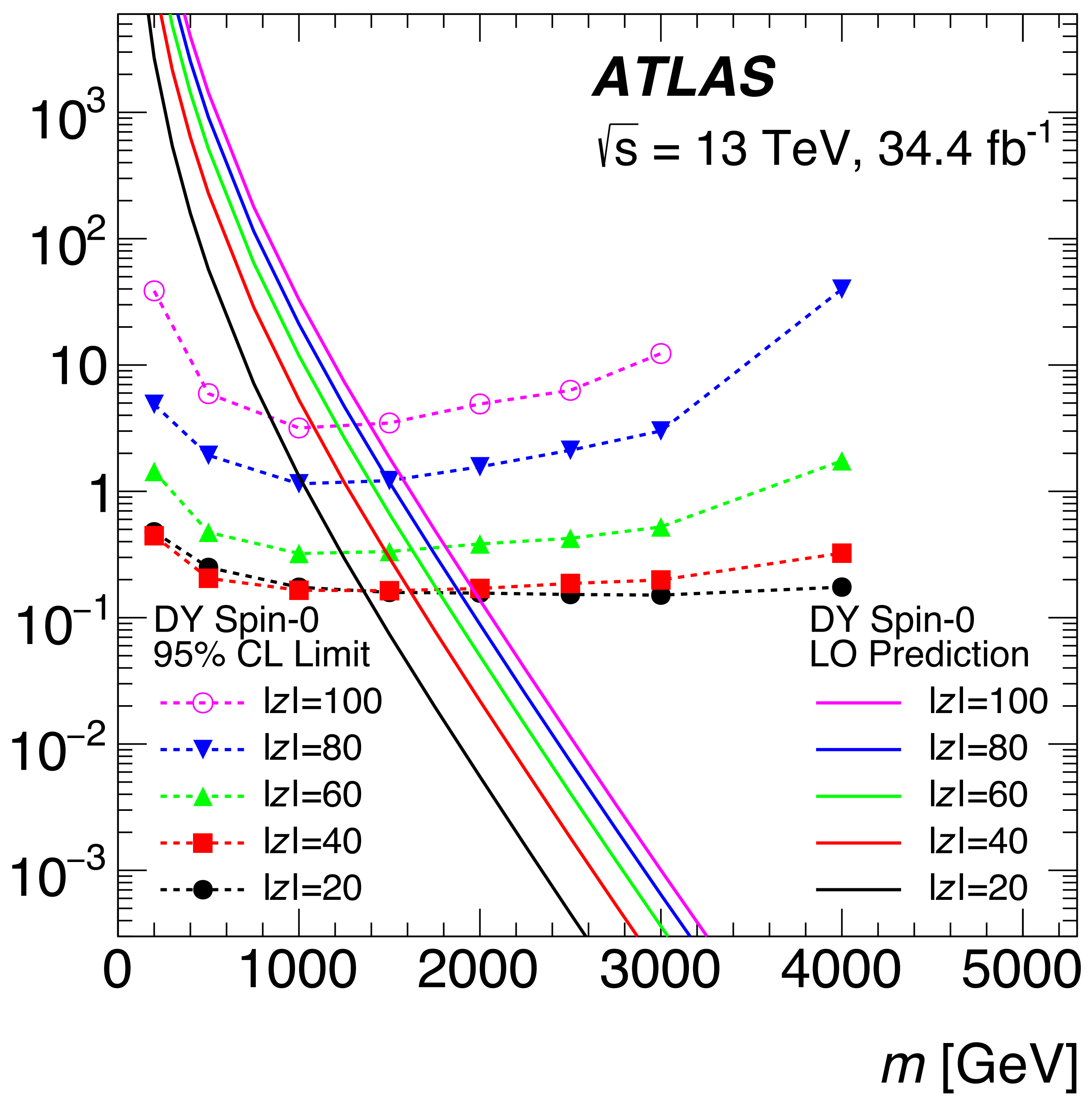
- **Searching for long lived particles at the LHC 4π detectors:**
  - **At ATLAS**
    - *LLP + Z*
      Phys. Rev. Lett. 122, 151801 (2019)
    - ***Multi-charged LLPs***
      Phys. Rev. D 99, 052003 (2019)
    - **LLPs to light hadrons or collimated leptons**
      Eur. Phys. J. C 80 (2020) 450
    - **Magnetic monopoles**
      Phys. Rev. Lett. 124, 031802 (2020)
    - *LLPs to hadronic jets*
      Phys. Rev. D 101, 052013 (2020)
    - *LLPs to μ jet(s)*
      Phys. Rev. D 102, 032006 (2020)
    - *LLPs to leptons*
      CERN-EP-2020-205

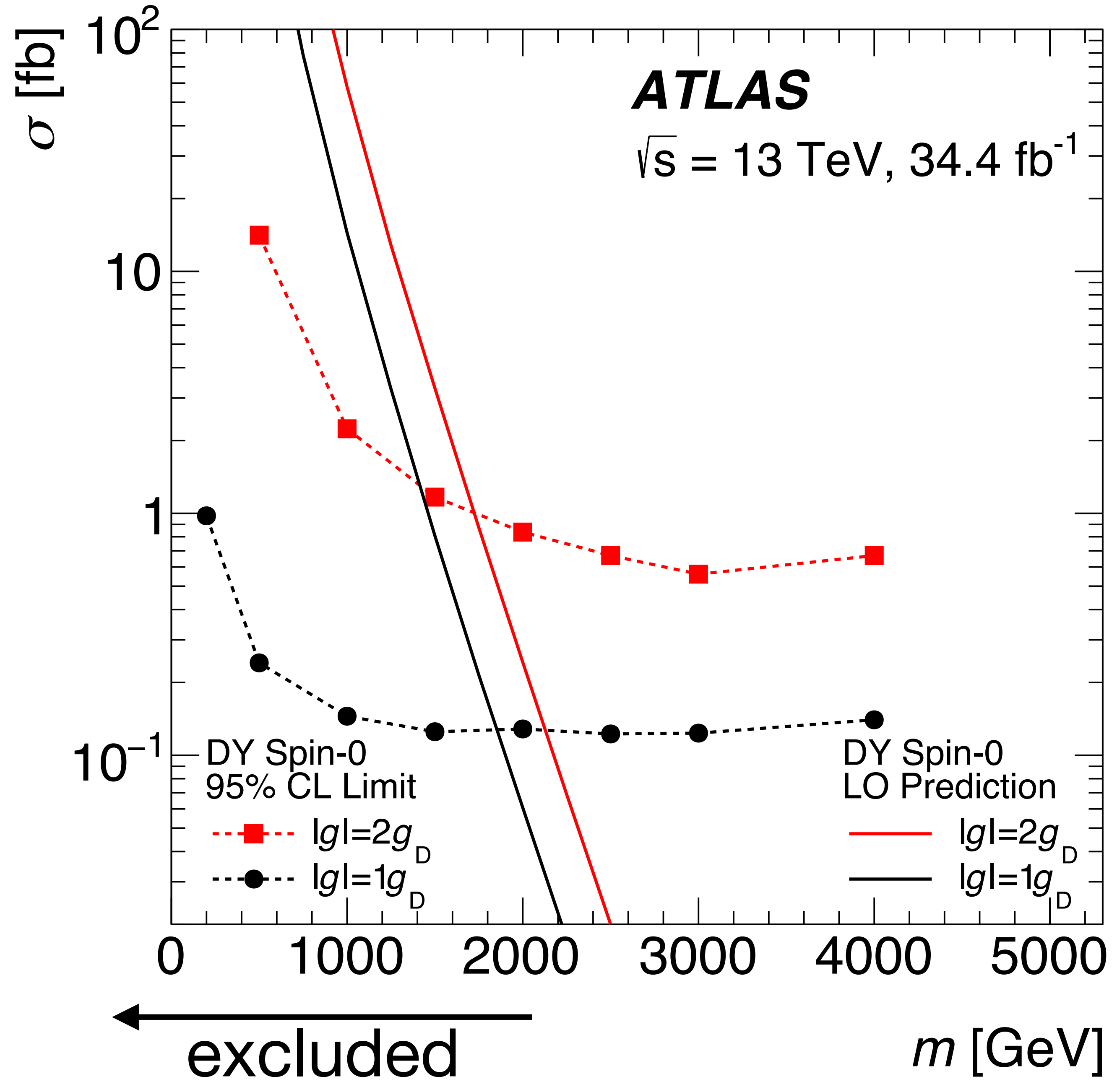
- **Searching for long lived particles at the LHC in the forward region:**
  - **At LHCb**
    - **Displaced leptons**
      - **Dark Photons:**
        Phys. Rev. Lett. 120, 061801 (2018)
        Phys. Rev. Lett. 124, 041801 (2020)
      - **Low-mass dimuon resonances**
        JHEP 10 (2020) 156
      - LLPs in eμν
        CERN-EP-2020-212
      - HNLs
        Phys. Rev. Lett. 112, 131802 (2014)
      - Light bosons in b to s
        Phys. Rev. Lett. 115, 161802 (2015)
        Phys. Rev. D 95, 071101 (2017)
    - **Displaced jets**
      - HNLs
        CERN-EP-2020-194
      - LLPs to jet jet
        Eur. Phys. J. C (2017) 77:224
      - **LLPs to μ jets**
        Eur. Phys. J. C77 (2017) 812

ATLAS: Search for magnetic monopoles



- Search for stable monopoles: 5000x more ionisation loss than proton
- Signature: high ionisation in TransitionRadiationTracker but narrow signature in EM calorimeter
- Background estimated using ABCD with TRT hits and EM energy deposition
  - Expected: 0.20 ± 0.11 (stat) ± 0.40 (syst), observed: 0
- Exclude monopole up to 1.85 TeV

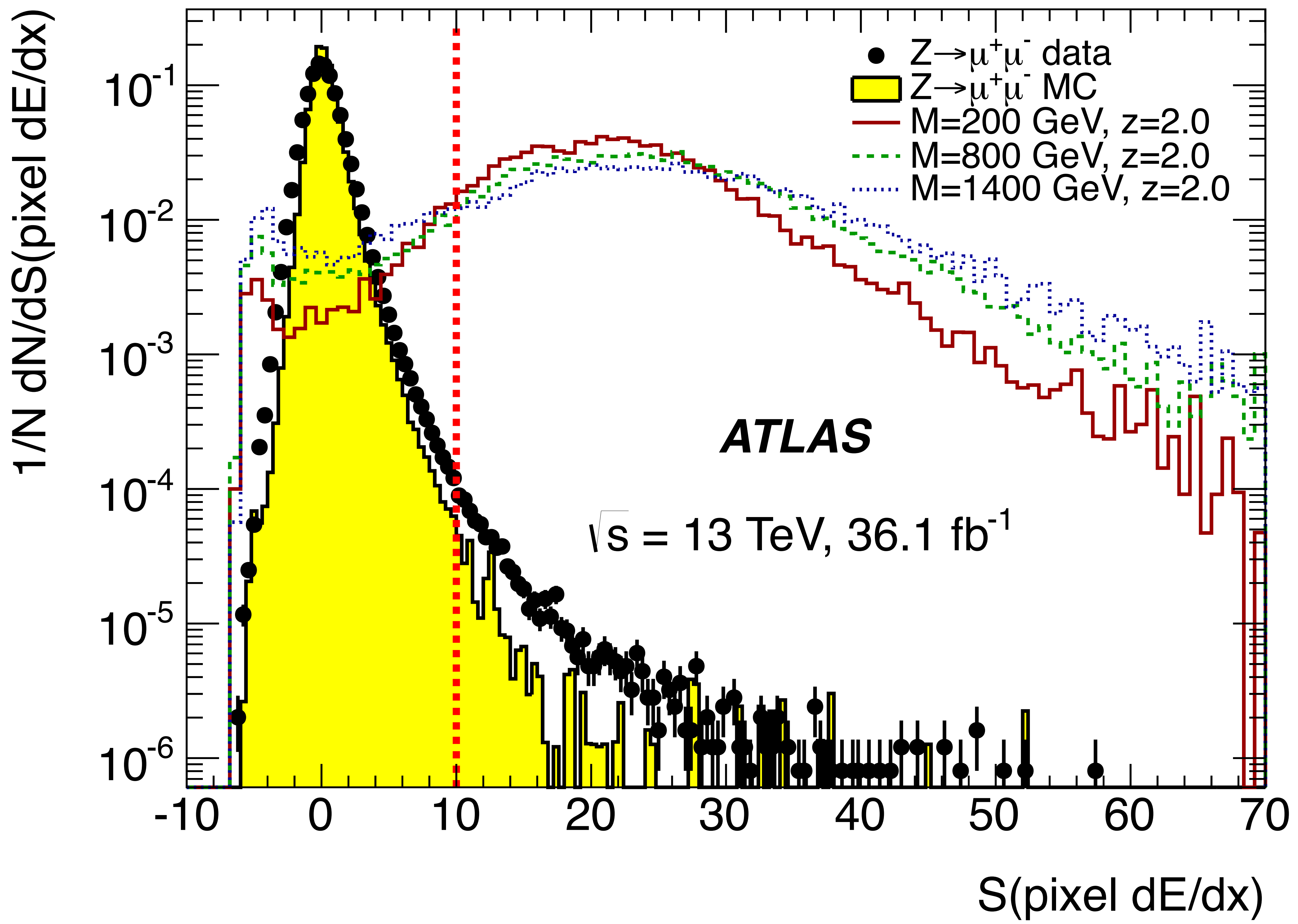


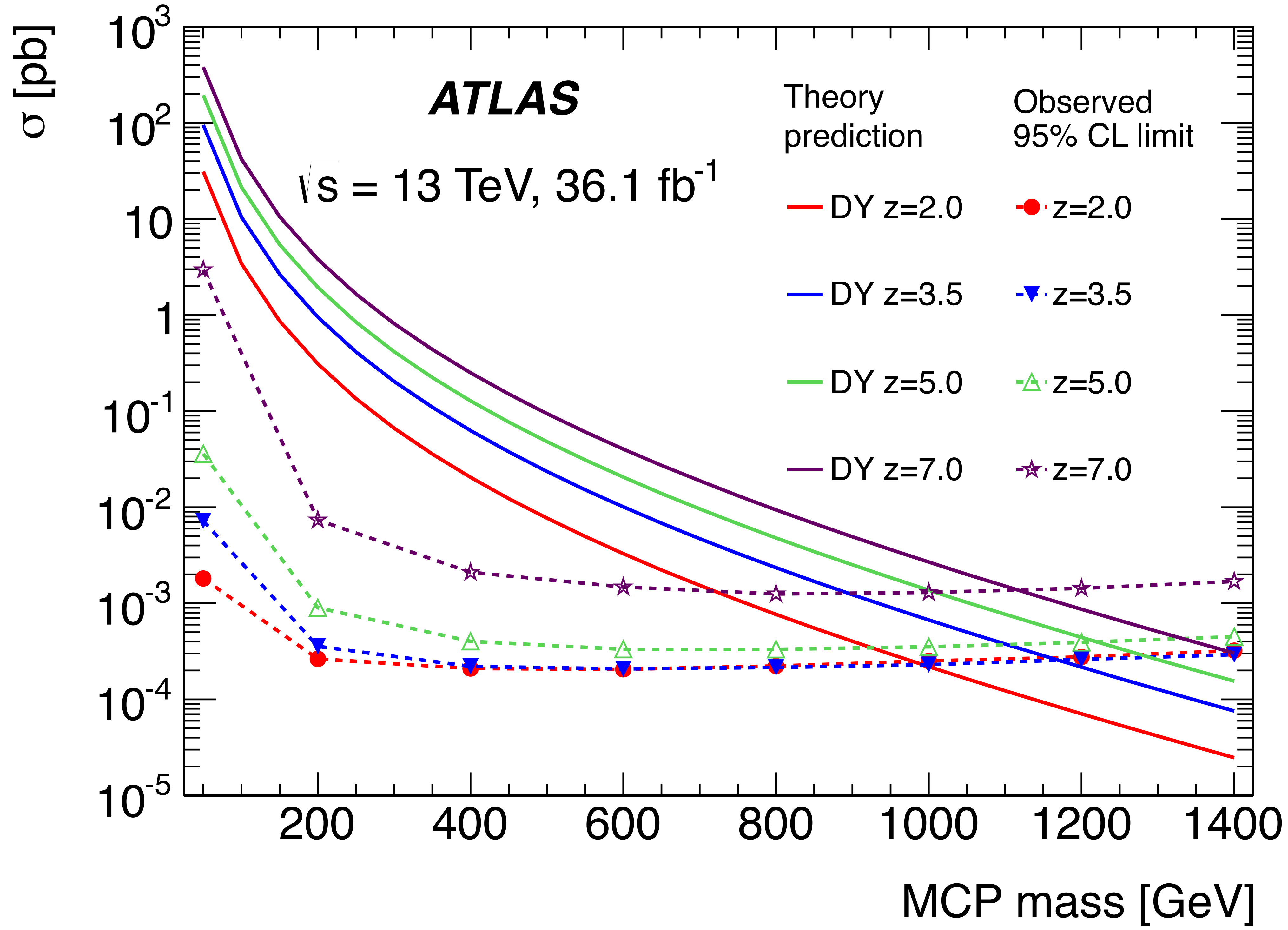


Phys. Rev. D 99, 052003 (2019)

ATLAS: Multi-charged LLPs

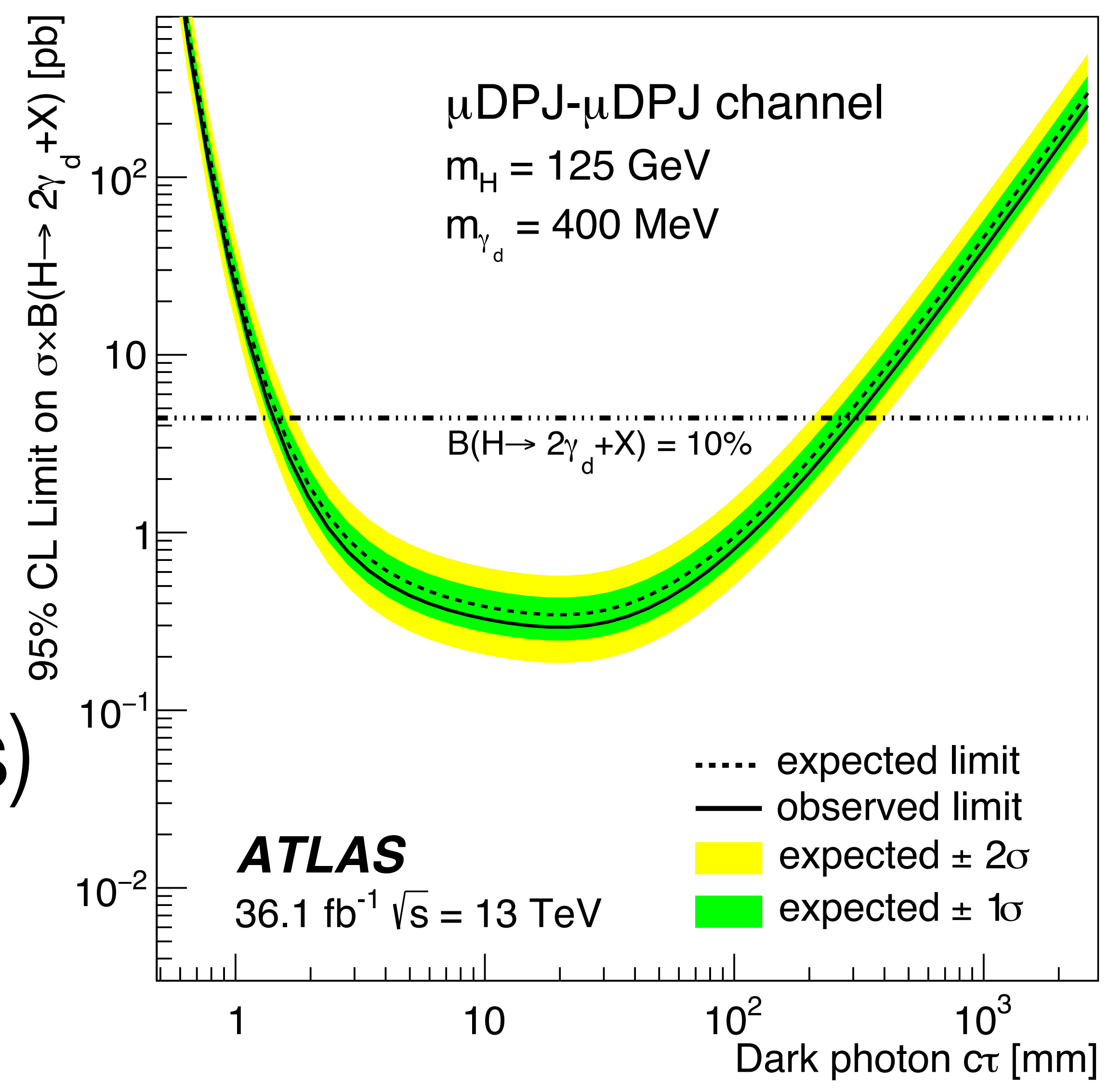
- MCPs are highly ionising, and thus generate an abnormally large ionisation signal, dE/dx
- Use control sample of Z→μμ
- Charges are *ze*
- Upper limits and theoretical cross-sections as functions of the lepton-like MCP's mass for several values of z between 2 and 7

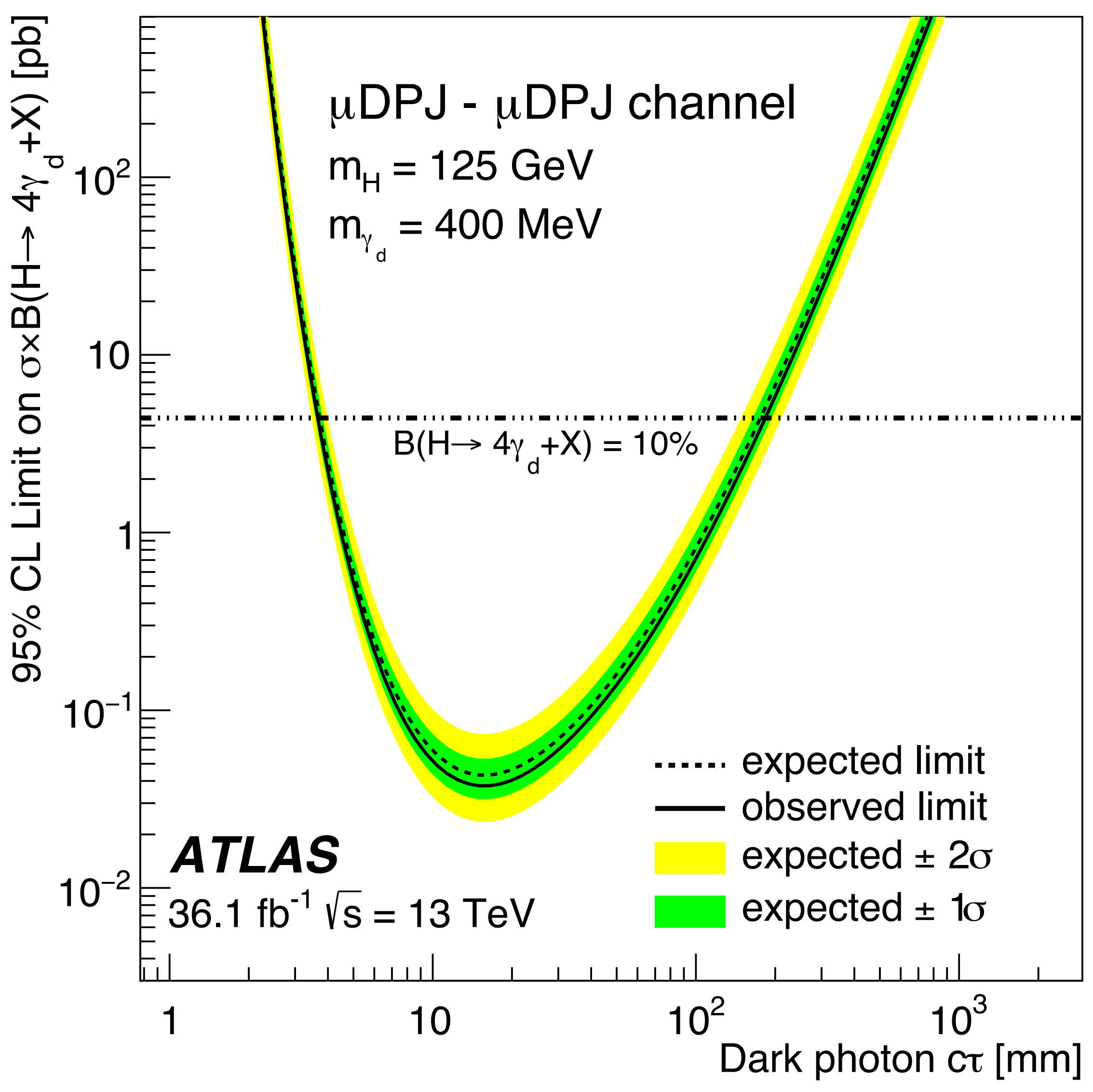


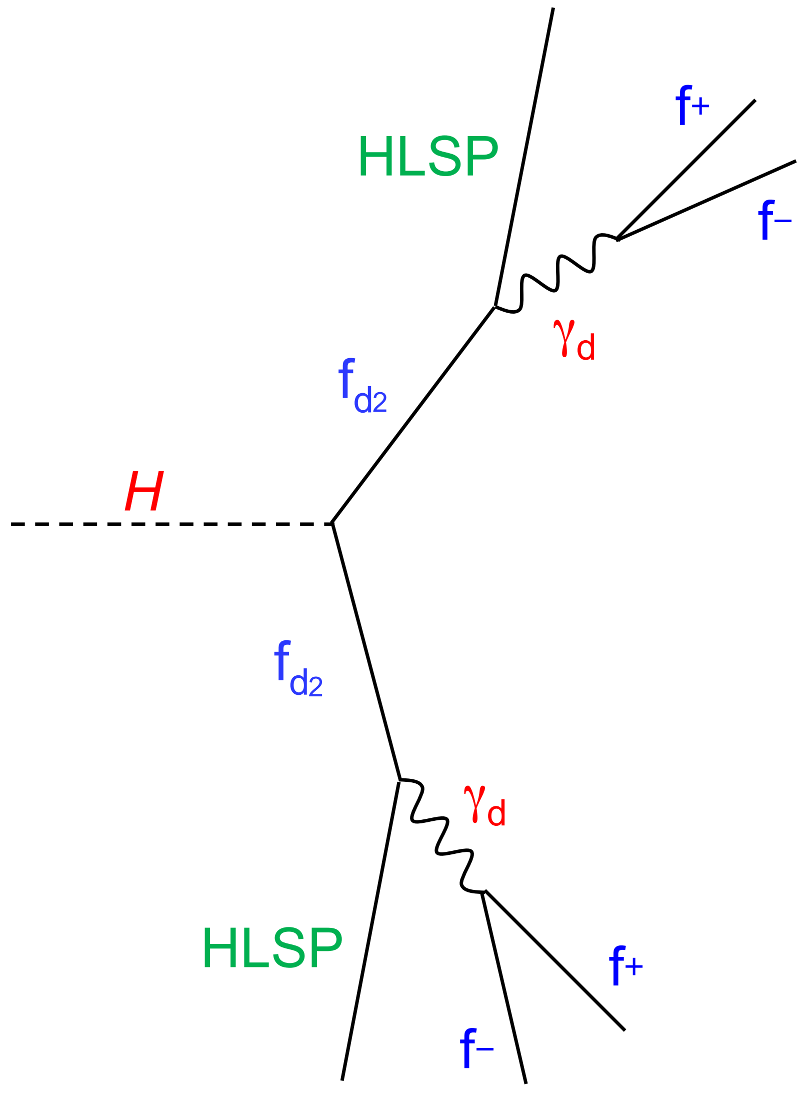


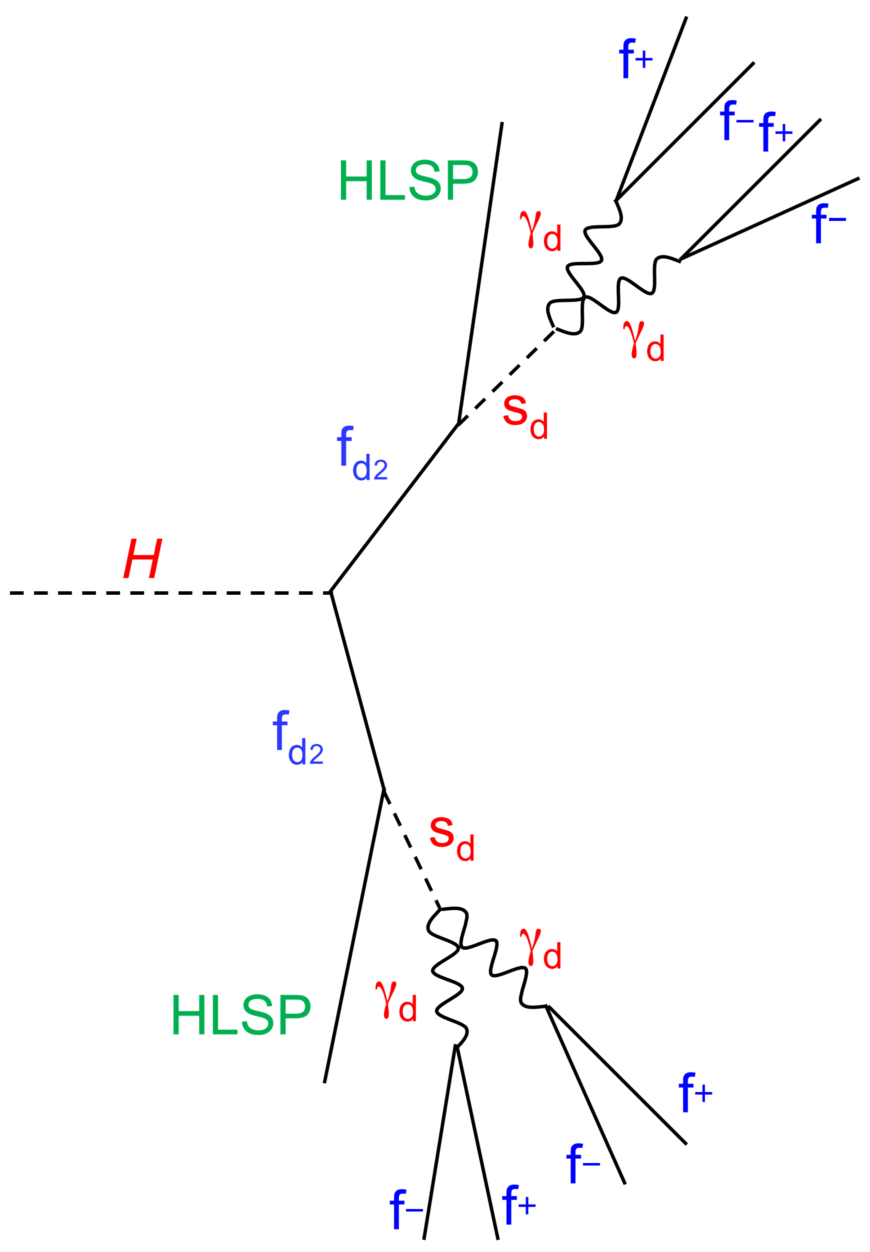
ATLAS: LLPs to light hadrons or collimated leptons

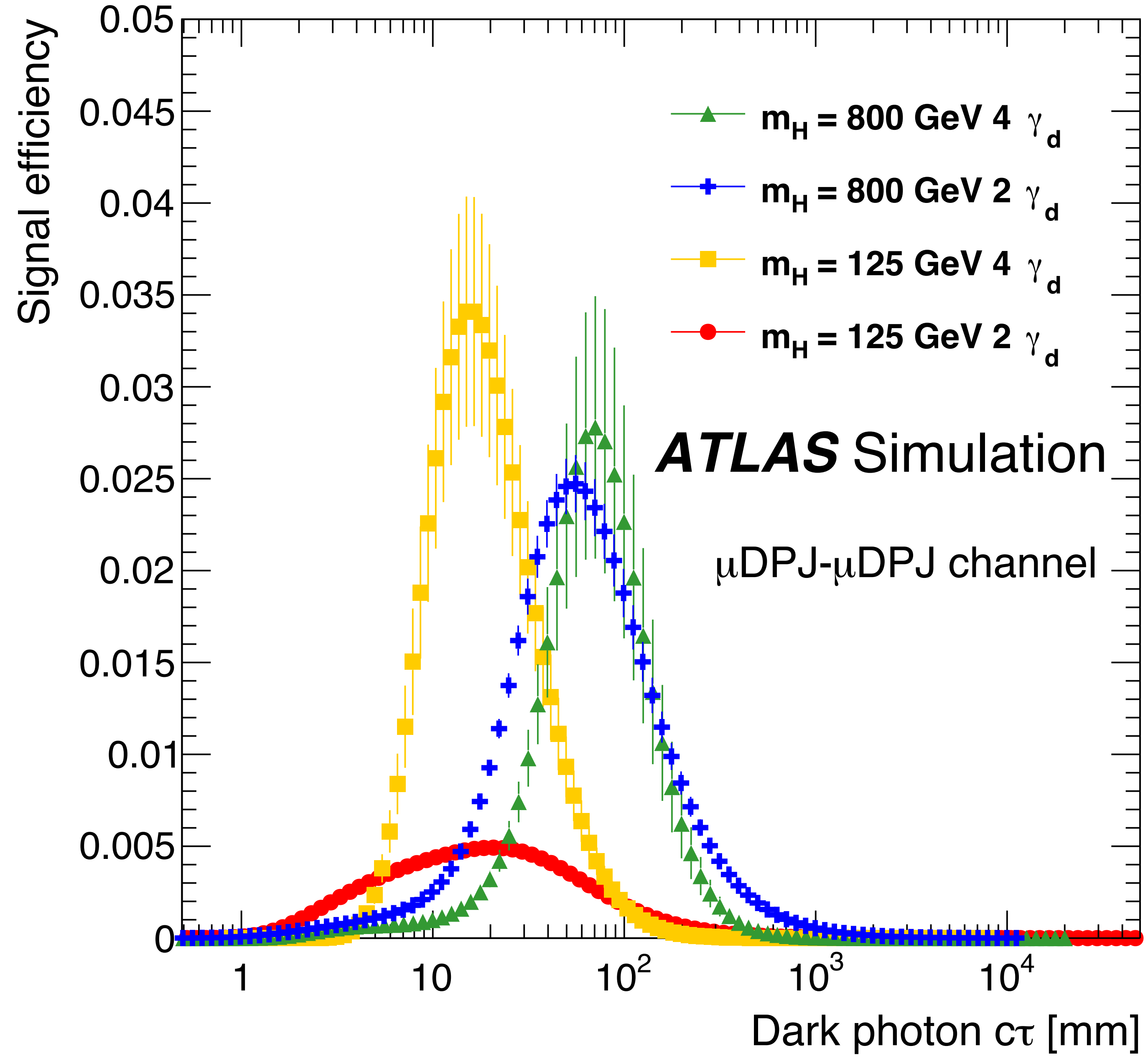
- Collimated groups of leptons and light hadrons in a jet-like structure == Dark photon jets (DPJs)
- μDPJ or hDPJ (*e* and pions)
- ABCD used and not excess measured
- Extrapolated signal efficiency for the
  - $H \rightarrow 2\gamma_d + X$
  - $H \rightarrow 4\gamma_d + X$ processes
- as a function of $c\tau$ of the dark photon in the
  - μDPJ–μDPJ
  - μDPJ–hDPJ
  - hDPJ–hDPJ channels





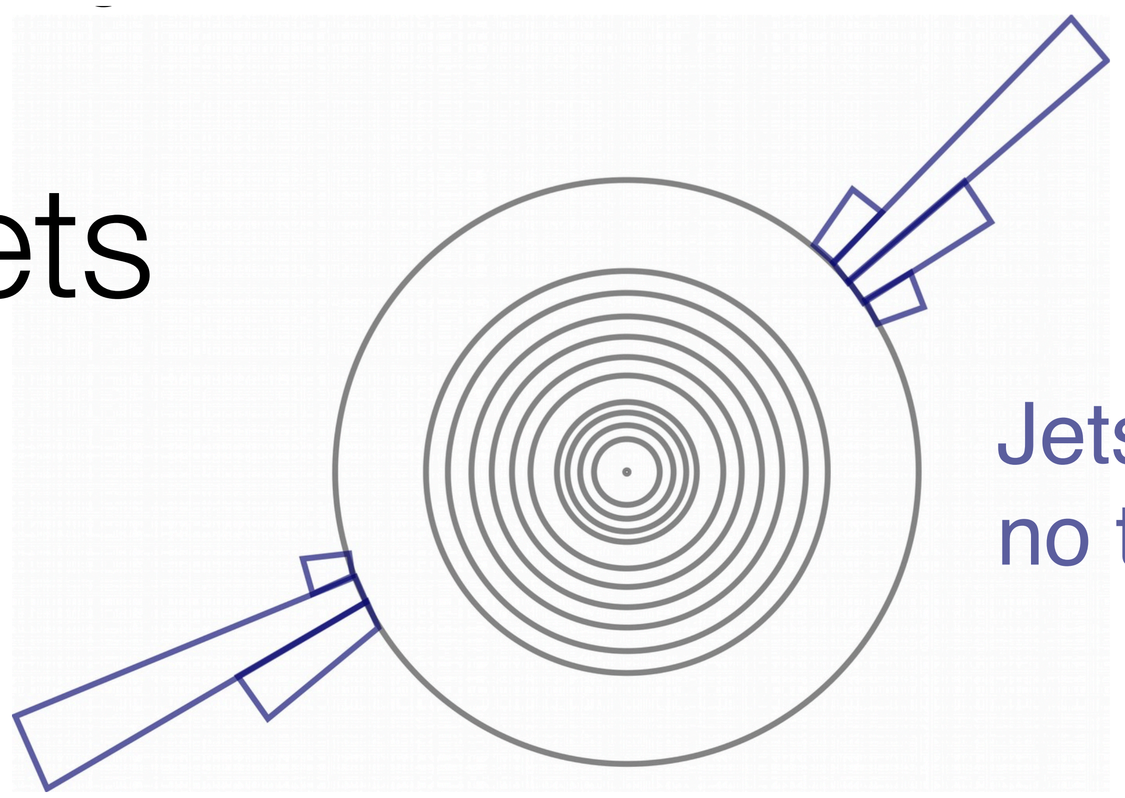


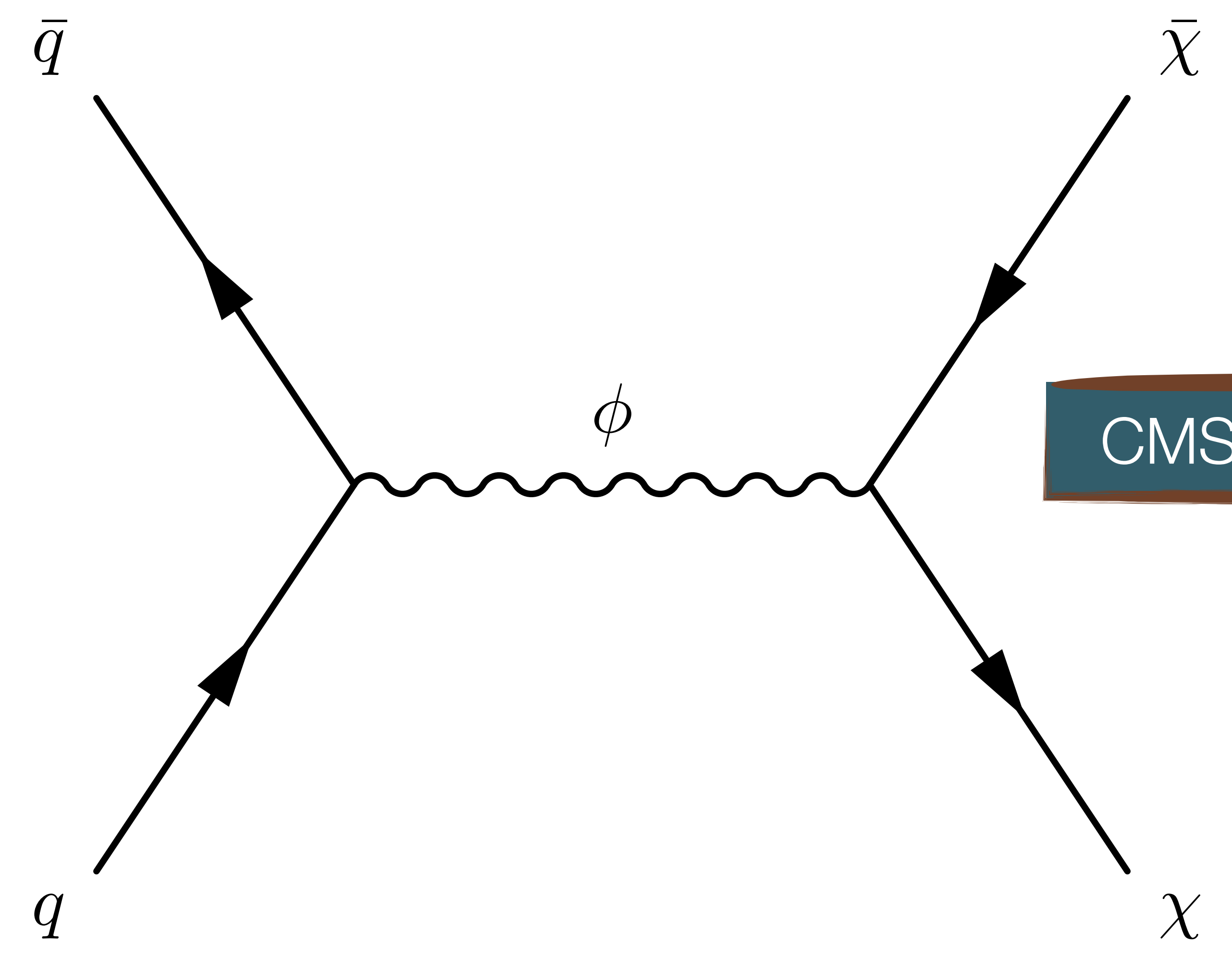




Eur. Phys. J. C 80 (2020) 450

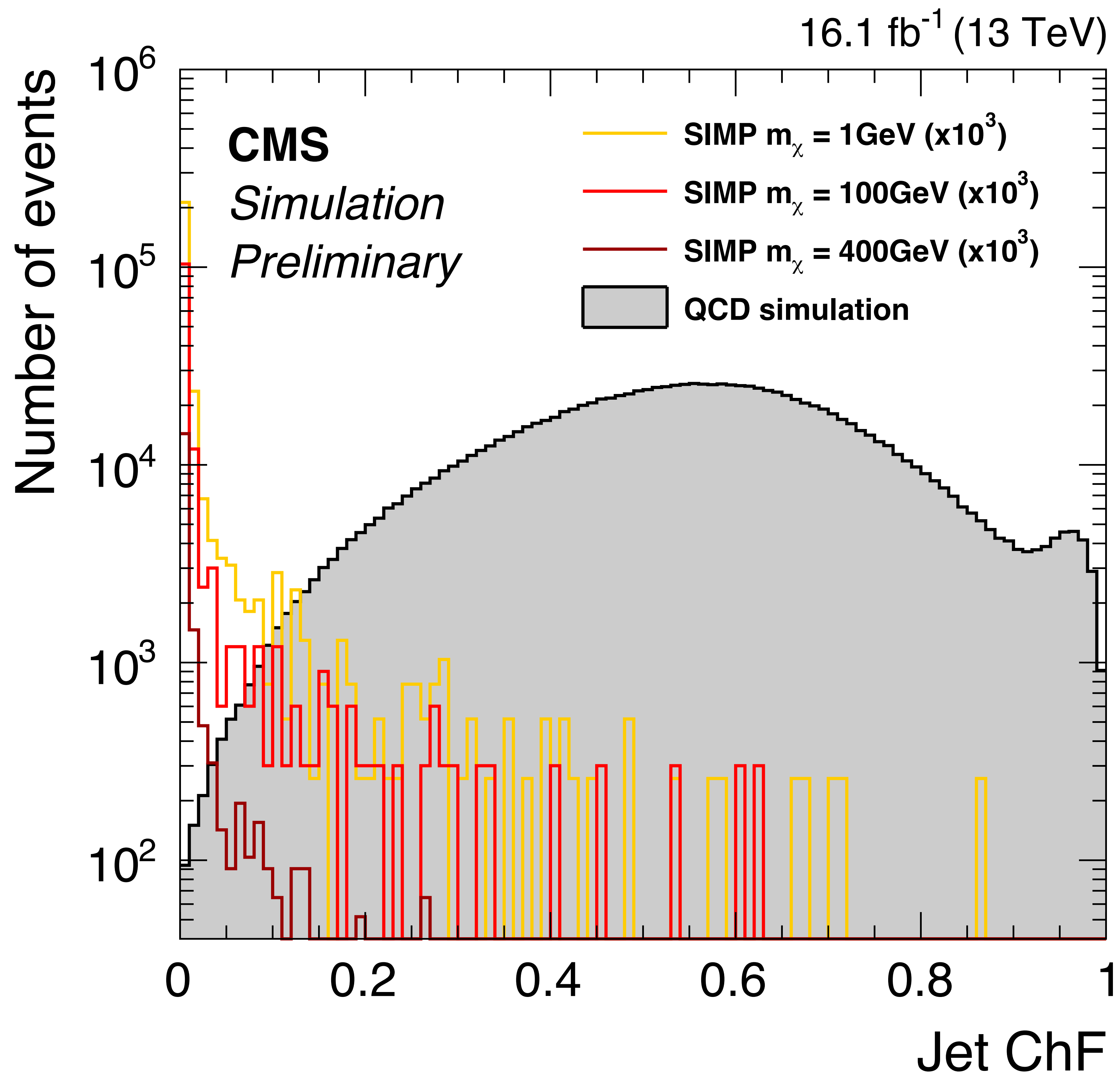
CMS: Search for SIMPs with trackless jets





CMS-PAS-EXO-17-010

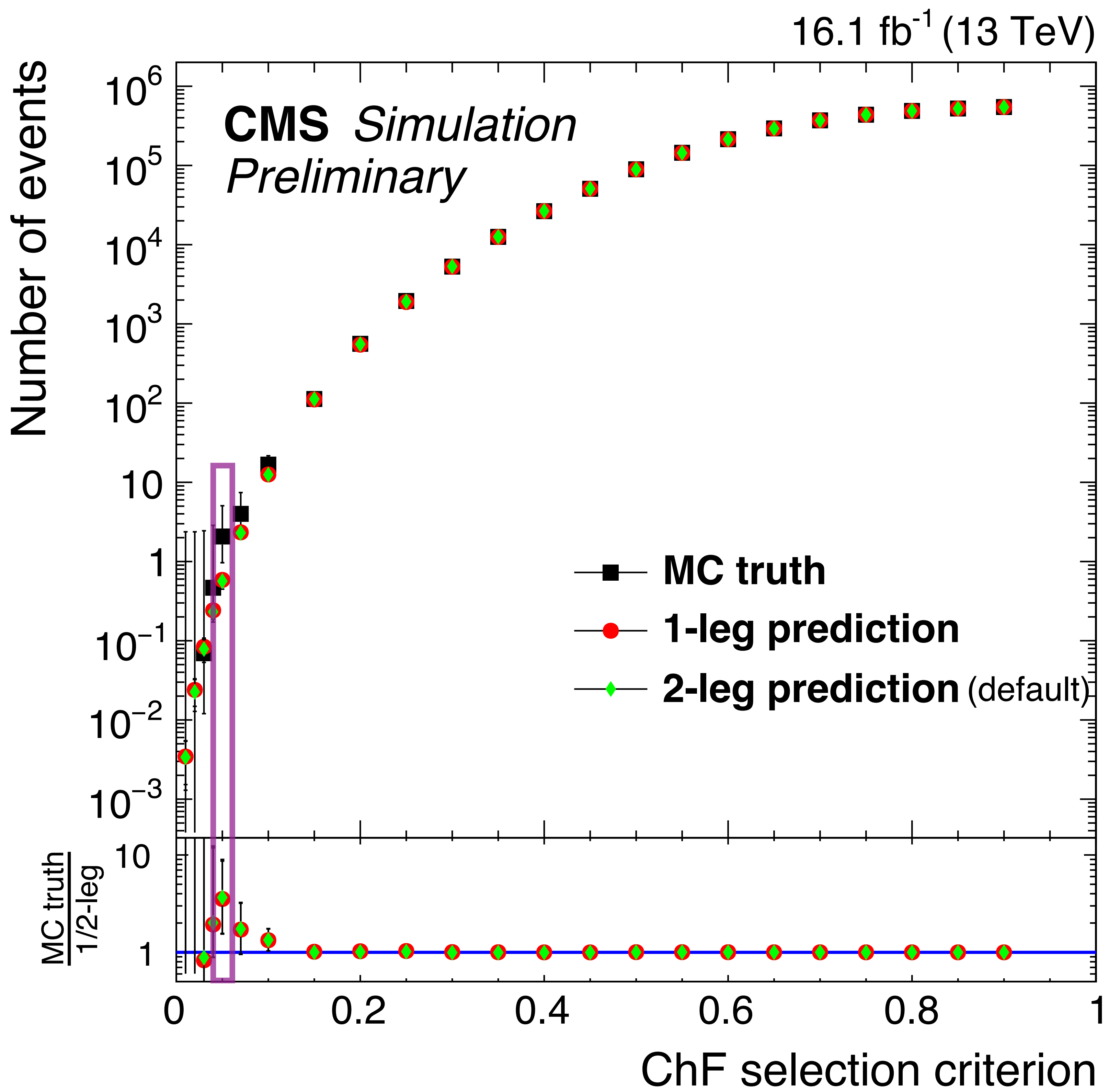
- Not only WIMP but also SIMP can be displaced DM
- Repulsive SIMP-nucleon couplings to avoid bound states
- SIMPs (χ) produced via mediator (ϕ) and interact strongly with SM
- Simplified model (1503.05505) has couplings which result in hadronic showers that start and are contained in the HCAL
- SIMPs have small fraction of their energy from charged particles.
- Use charged energy fraction (ChF) as the primary discriminator against background!

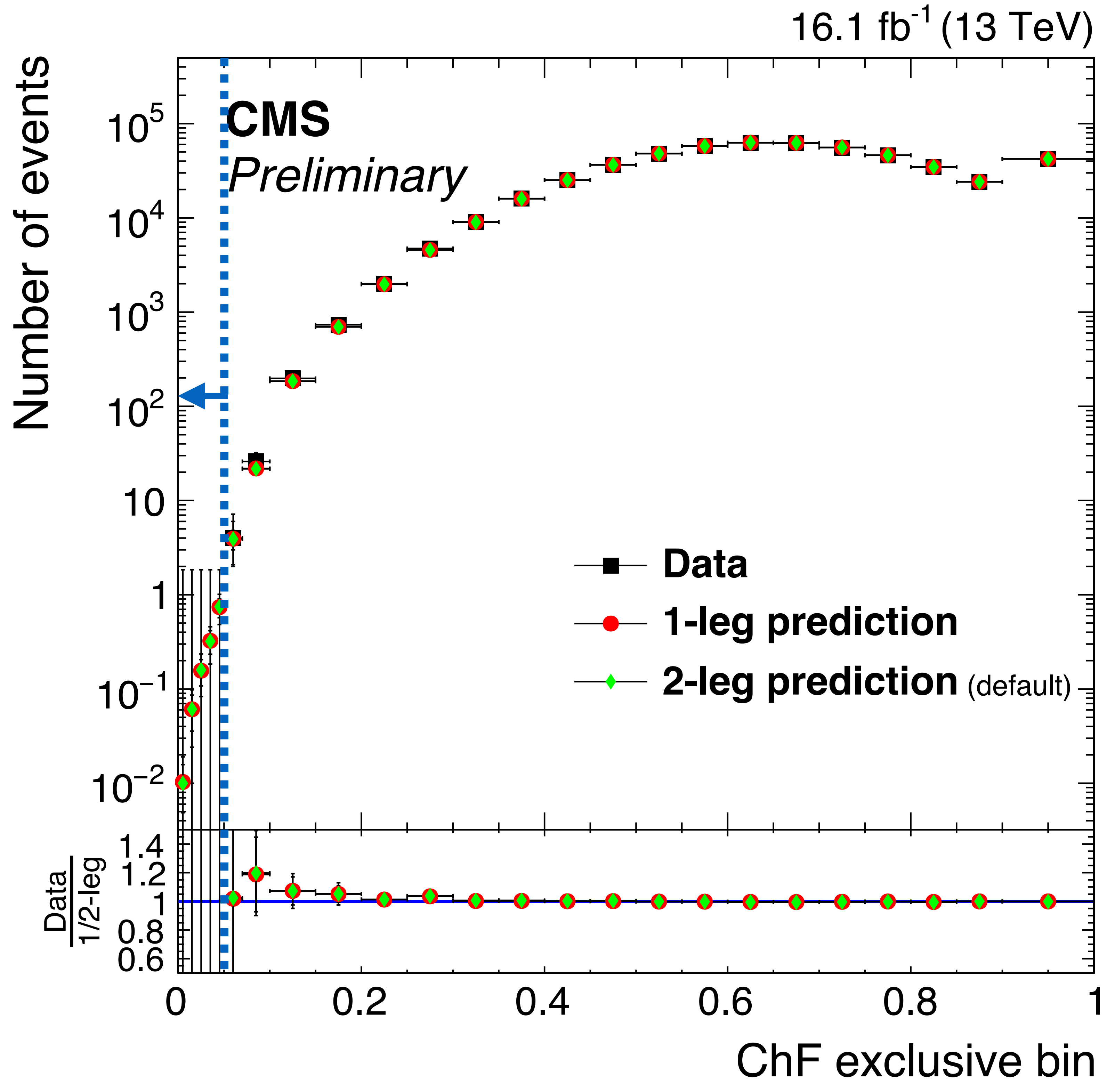


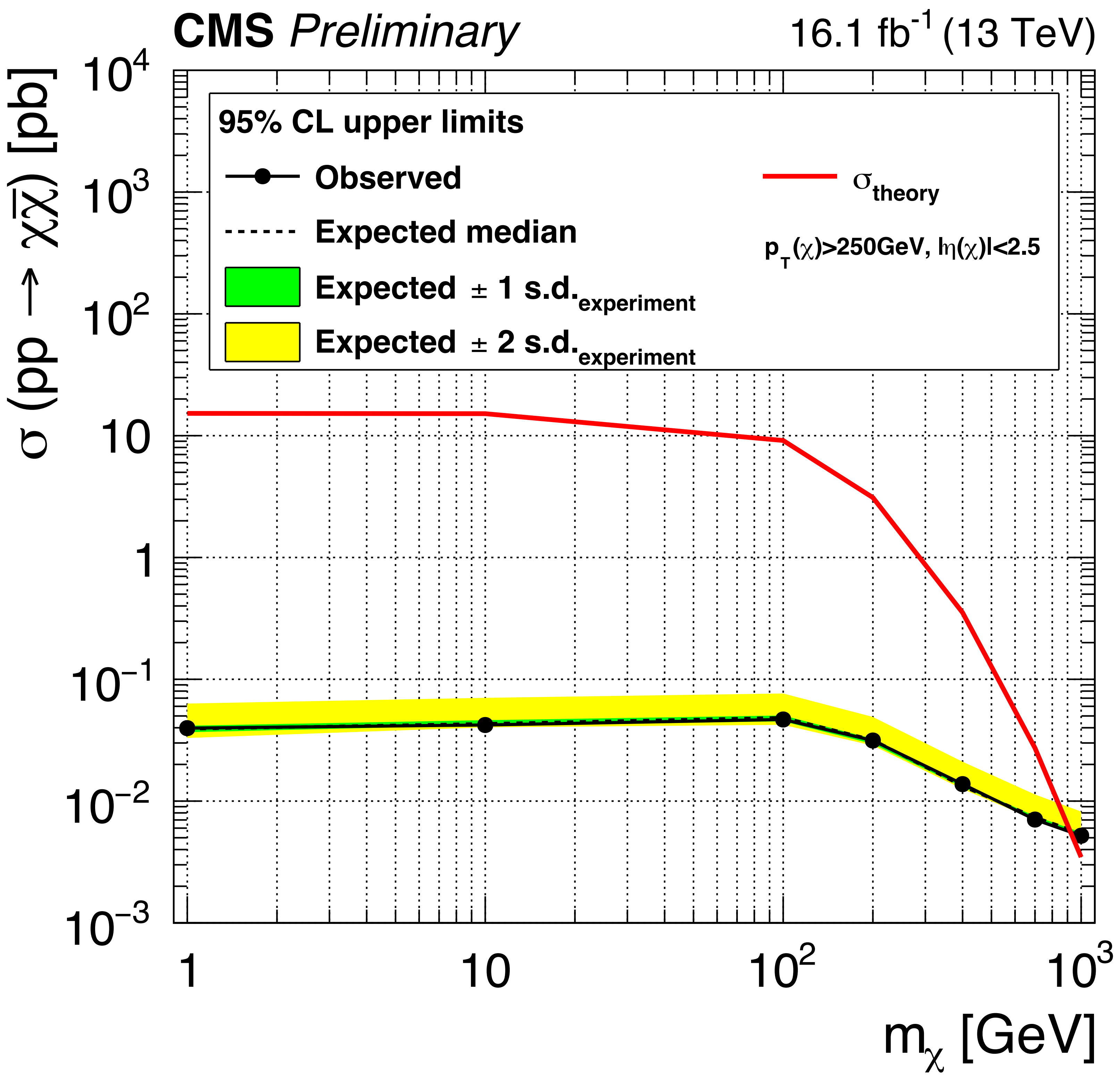
CMS: Search for SIMPs with trackless jets

CMS-PAS-EXO-17-010

- MC closure test validates the procedure (differences used as input for syst uncertainty)
- In the search region with ChF < 0.05, zero data events observed
- SIMPs excluded for masses up to 900 GeV!



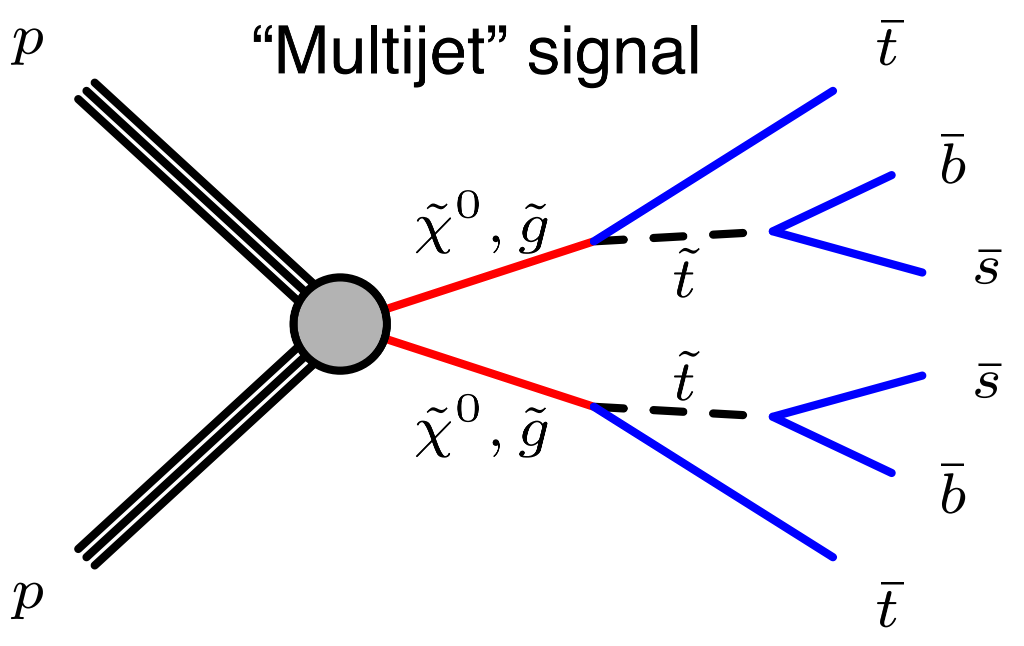


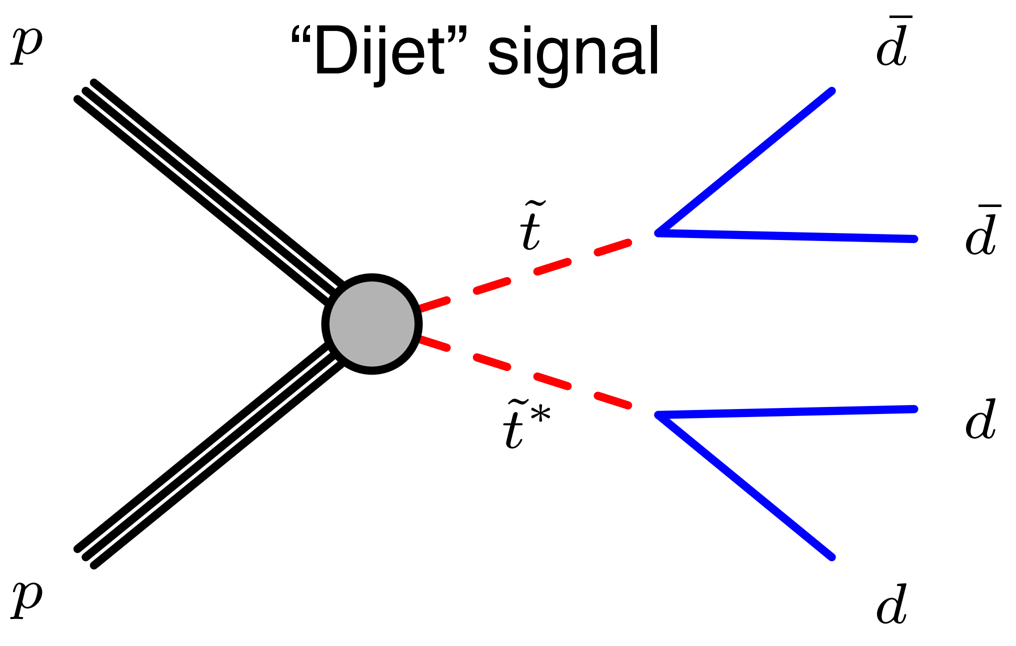


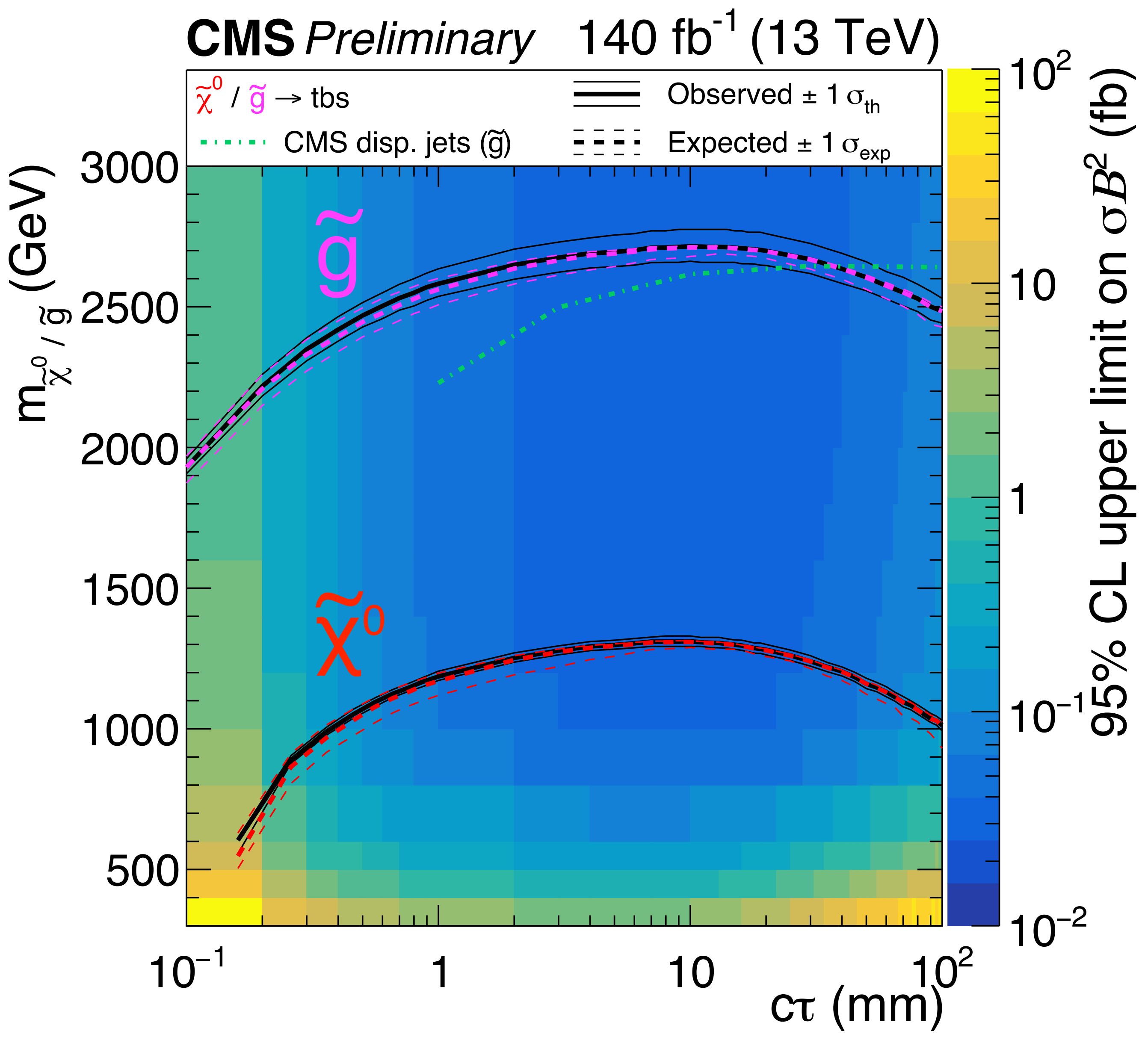
CMS: Search for long-lived particles decaying to jets with displaced vertices

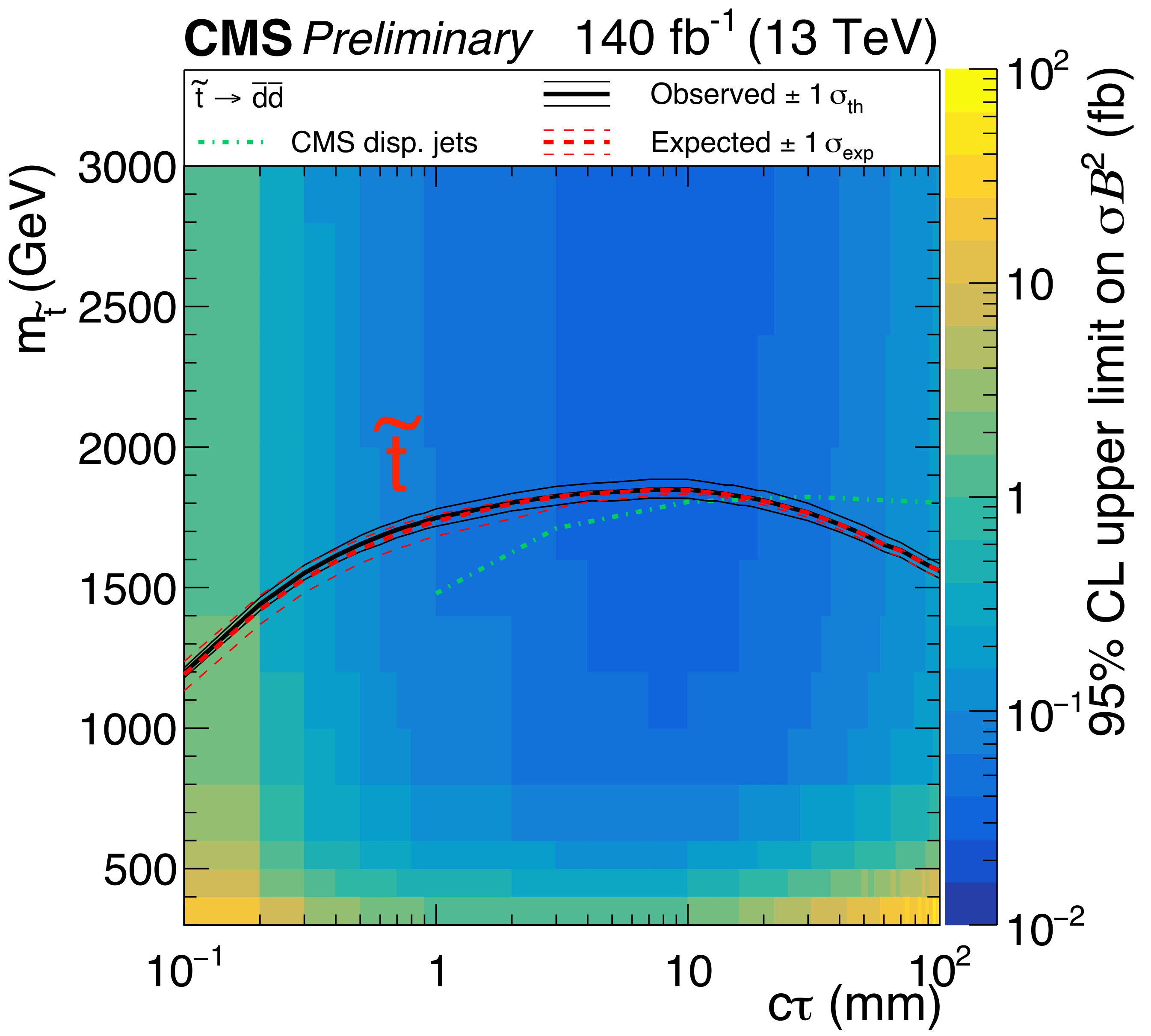
CMS-PAS-EXO-19-013

- Extension of Phys. Rev. D 98, 092011 (2018) now with the full Run 2 dataset (+ the upgraded CMS Pixel Tracker)
- Model independent search: LLP decay points as two displaced vertices (HT trigger; require HT > 1200 GeV and ≥4 jets)
- Interesting appendix available to facilitate
- Extending results to different signal models (beyond RPV SUSY)
- E.g. generator-level selection requirements





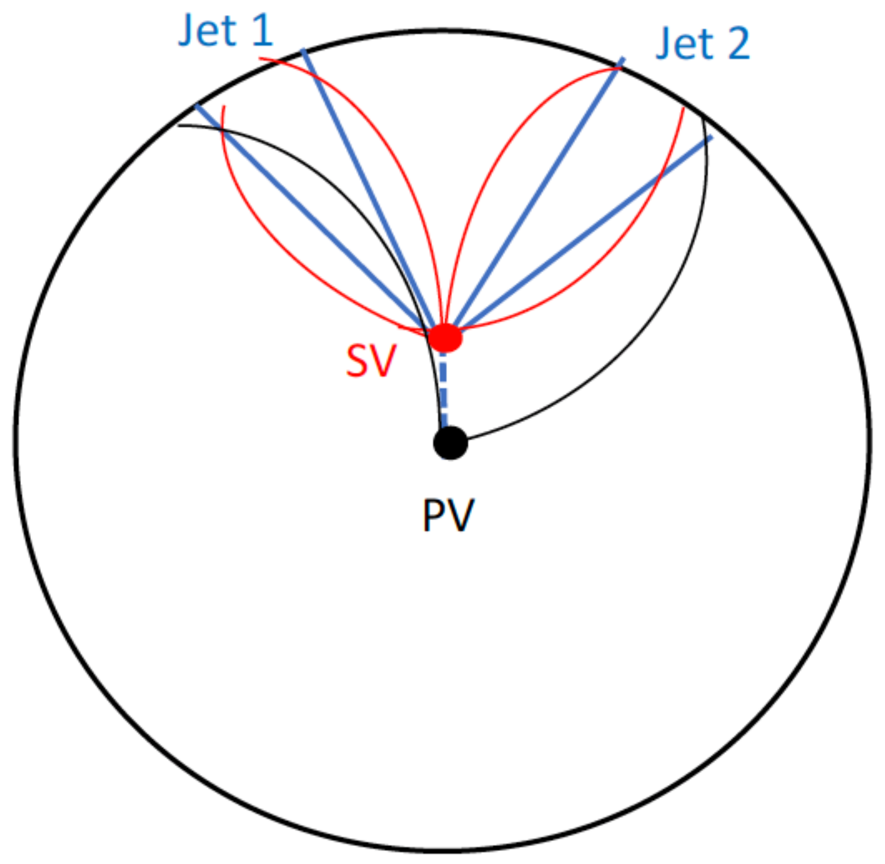


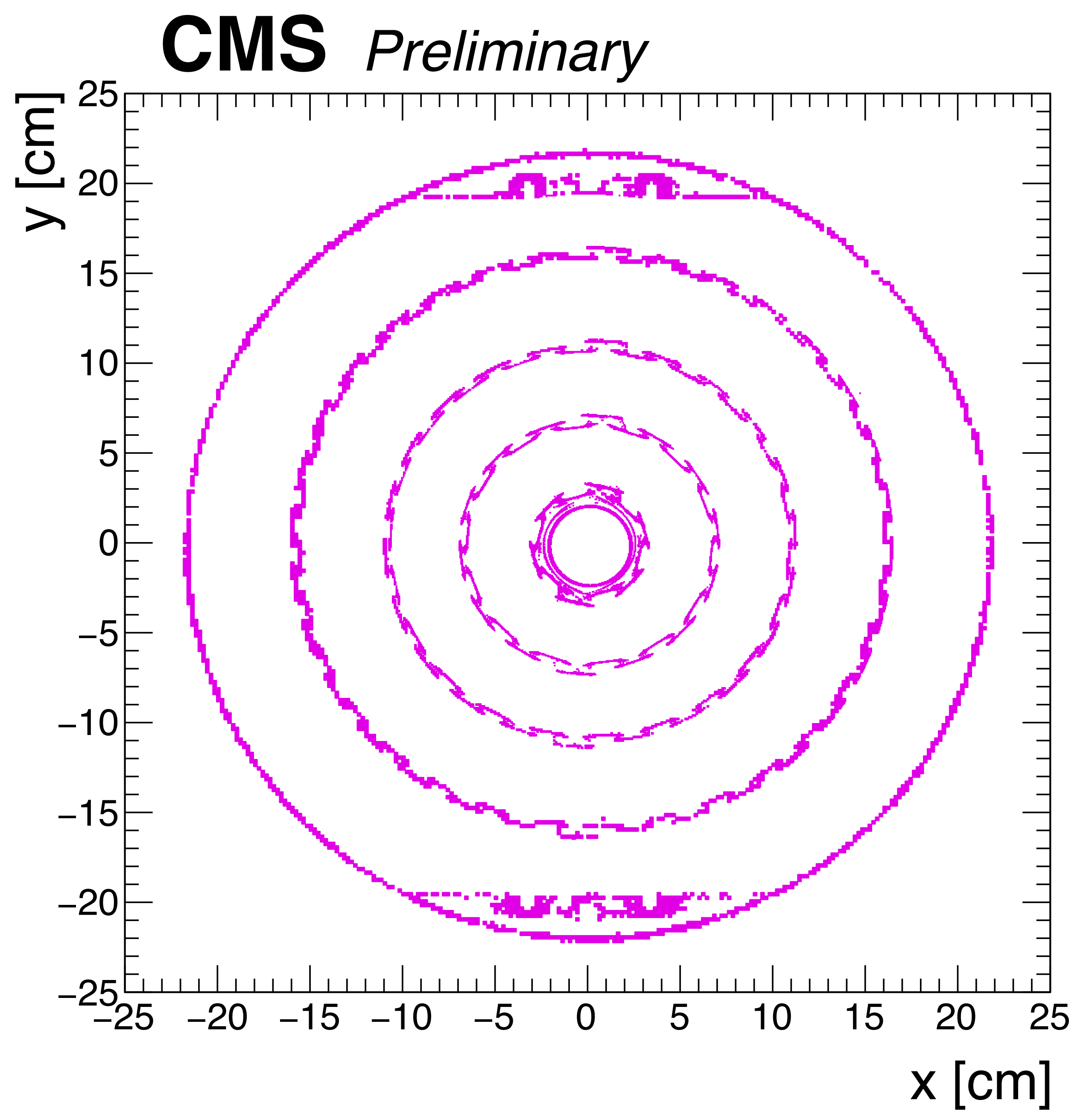


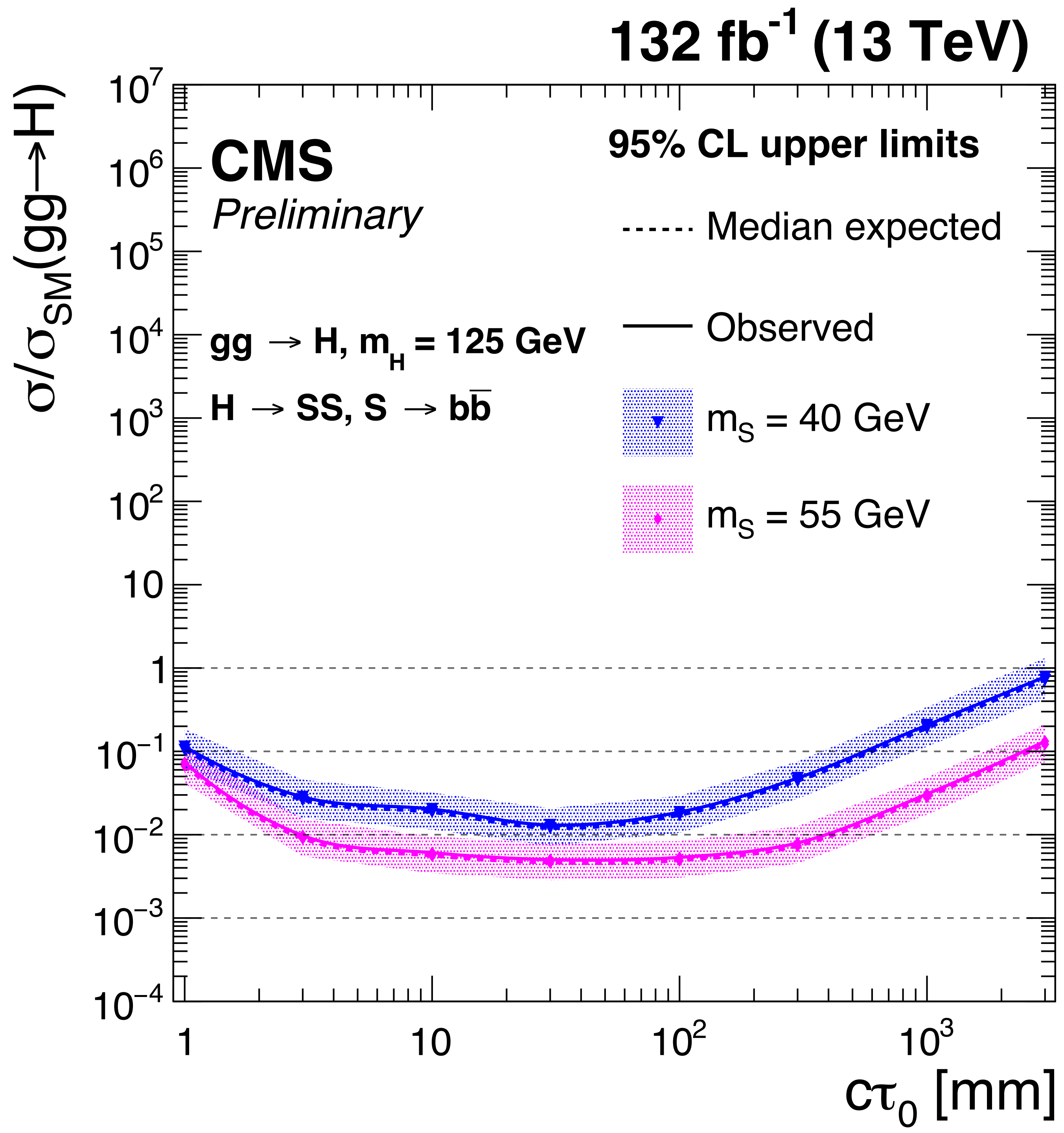
CMS-EXO-19-021

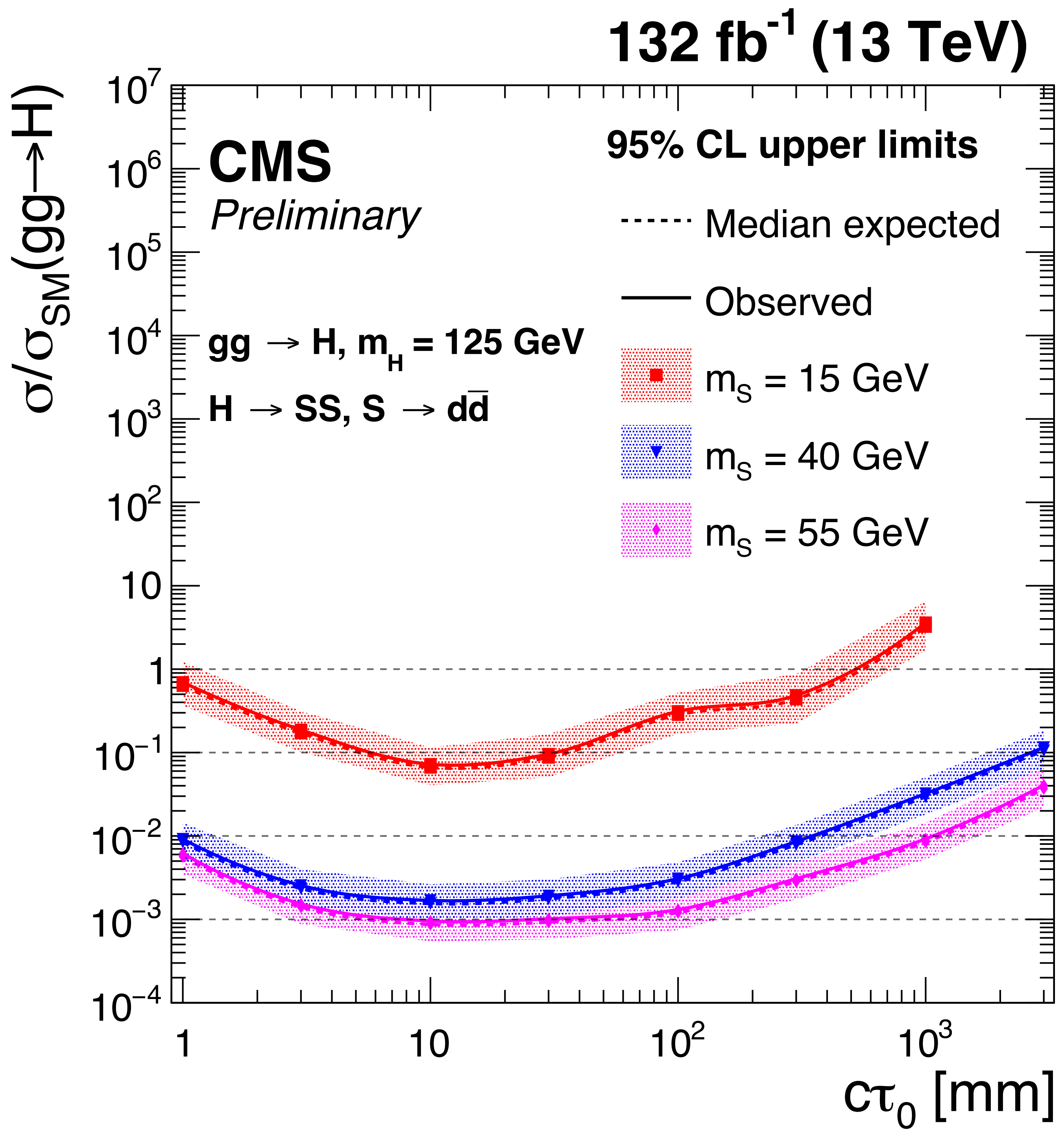
CMS: LLPs to displaced jets

- Distinctive topology of displaced tracks and displaced vertices associated with a dijet system (so SV a la LHCb)
- Specialised triggers, MVA, variables…
- Using NuclearInteraction-veto-map (again a la LHCb material veto)
- Exotic decay of 125GeV Higgs : SM Higgs decays to two long-lived scalars in the hidden sector, each of them then decays to a quark-antiquark pair
- Higgs as a portal to the hidden/dark sector



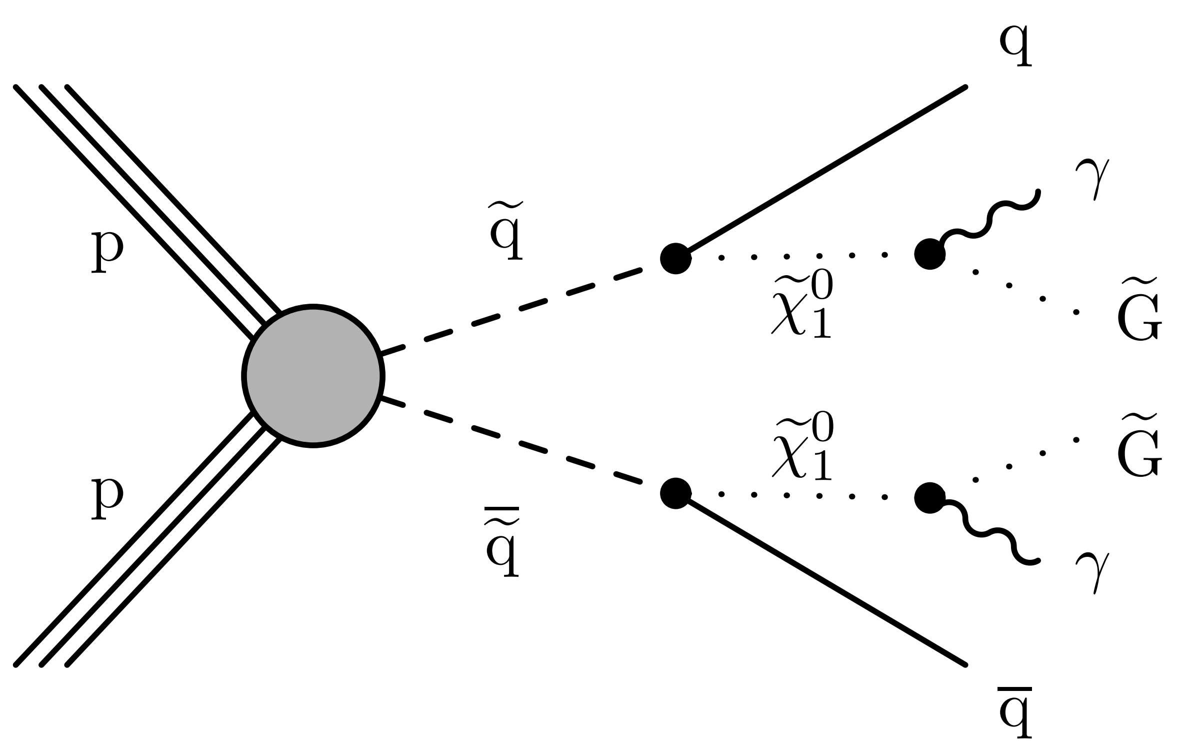




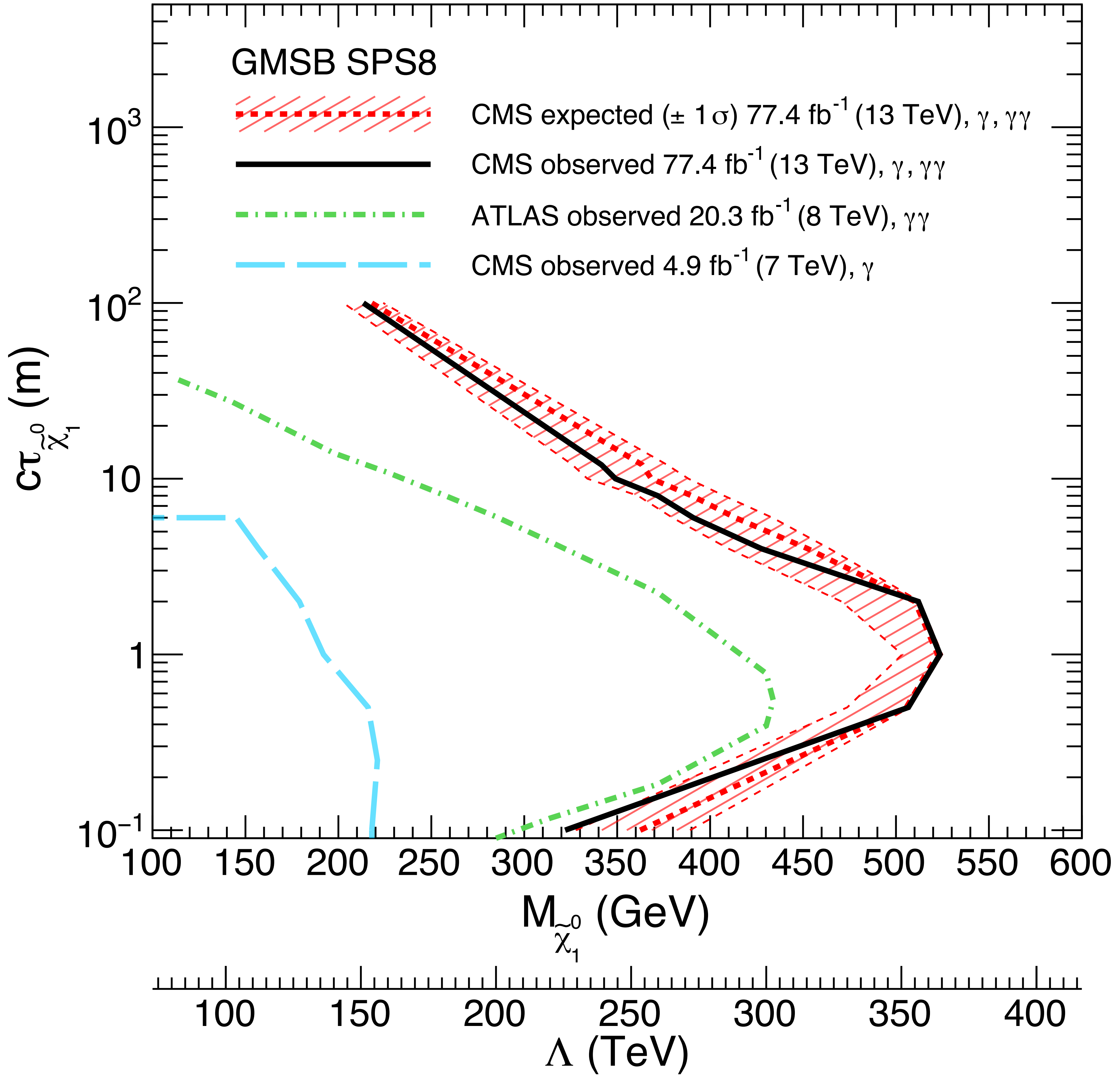


CMS: LLPs to delayed photons

Phys. Rev. D 100, 112003 (2019)



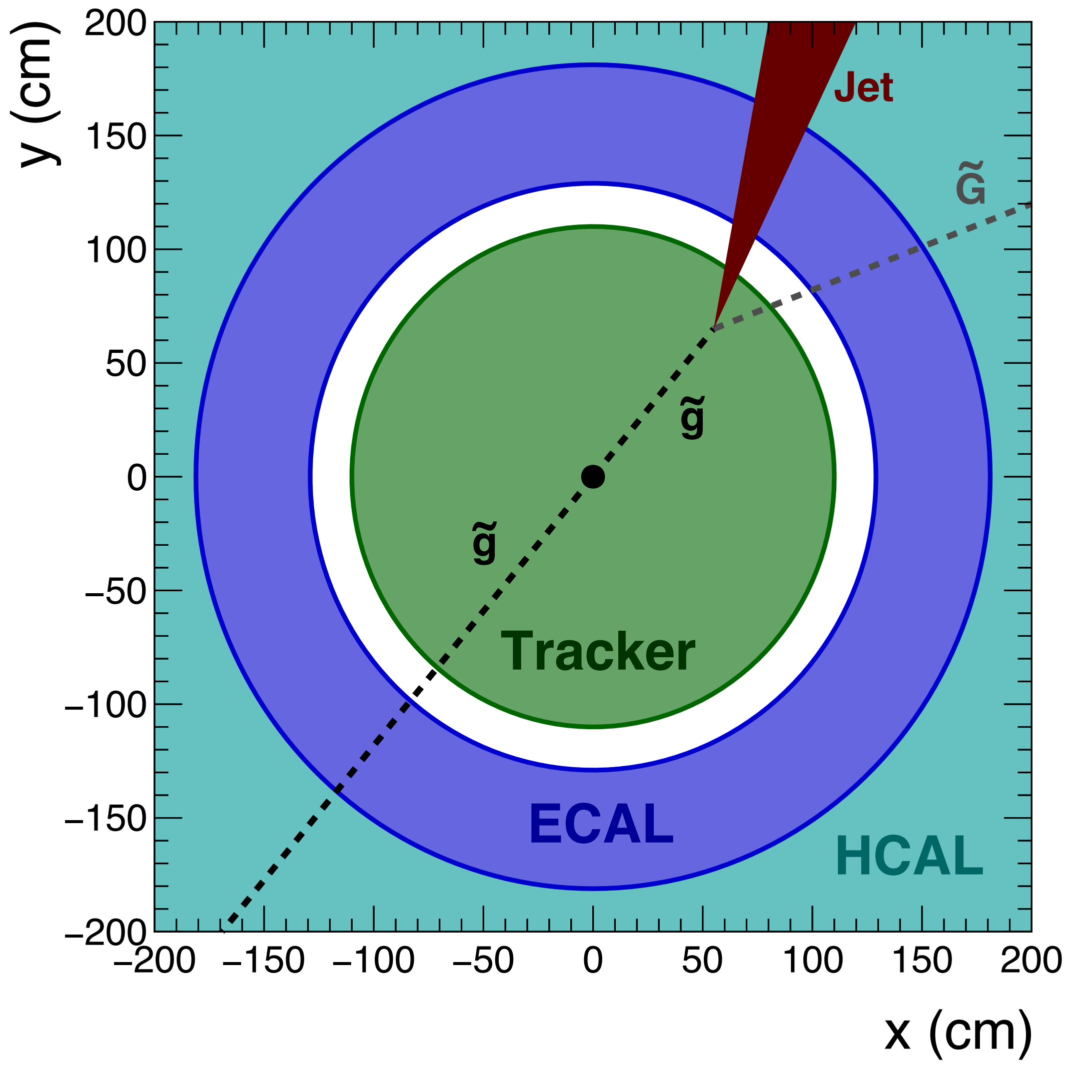
- Search for long-lived particles (LLP) decaying to a photon and a weakly-interacting particle
- A benchmark scenario of supersymmetry (SUSY) with gauge-mediated SUSY breaking (GMSB) is employed
- Specialized triggers and dedicated photon reconstruction and identification criteria are used
- Difference between the search selections for the 2016 and 2017 data sets, because of the introduction of a targeted HLT algorithm implemented for the 2017 data set
- Results interpreted as GMSB neutralino production cross section, shown as functions of the neutralino mass, or equivalently the SUSY breaking scale, Λ, in the GMSB SPS8 model, and the neutralino proper decay length

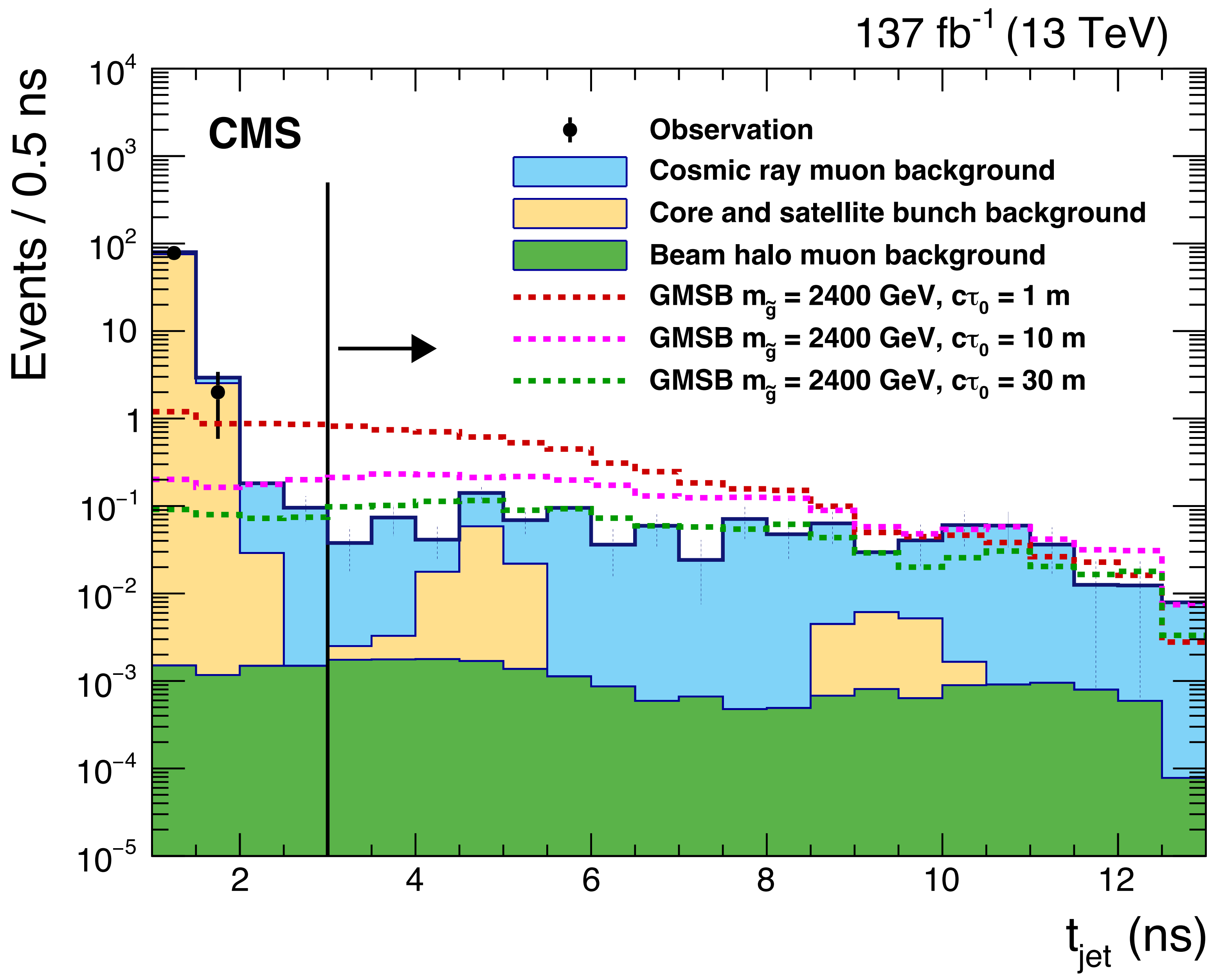


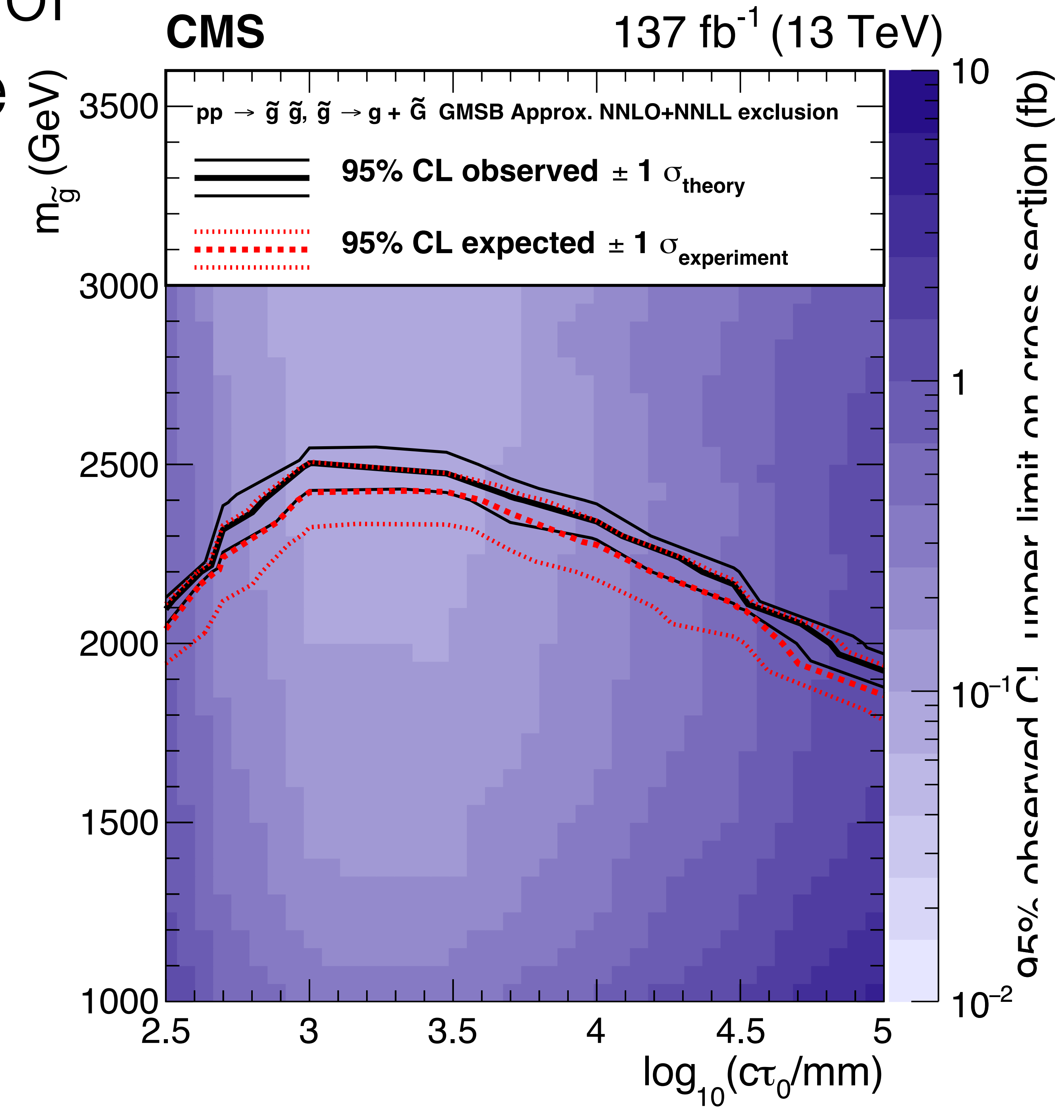
Phys. Lett. B 797 (2019) 134876

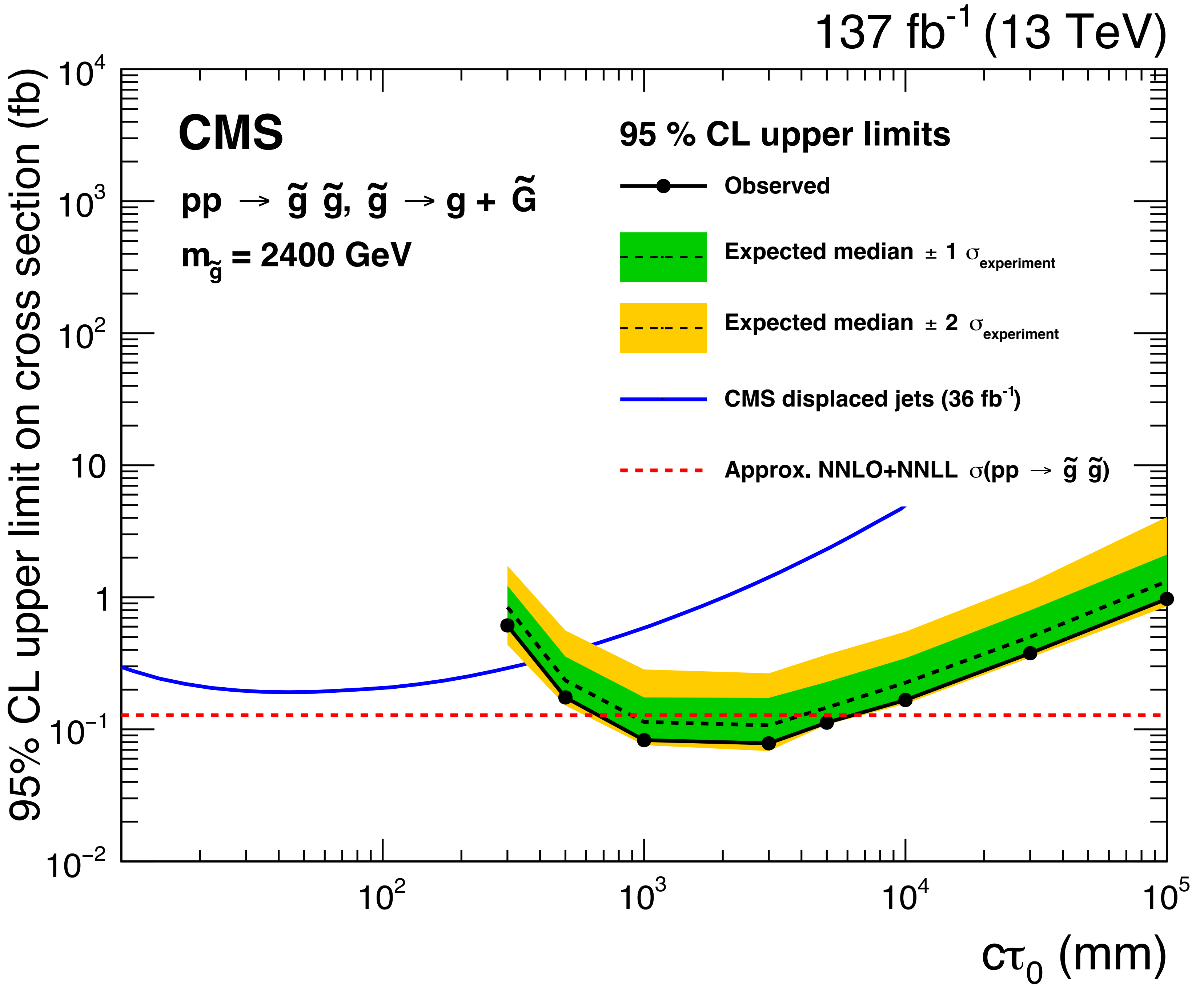
CMS: LLPs to nonprompt jets

- The timing capabilities of the CMS electromagnetic calorimeter (ECAL) are used to identify nonprompt jets produced by the displaced decays of heavy long-lived particles within the ECAL volume or within the tracking volume bounded by the ECAL.
- Gauge-mediated SUSY breaking (GMSB) interpretation used as a benchmark

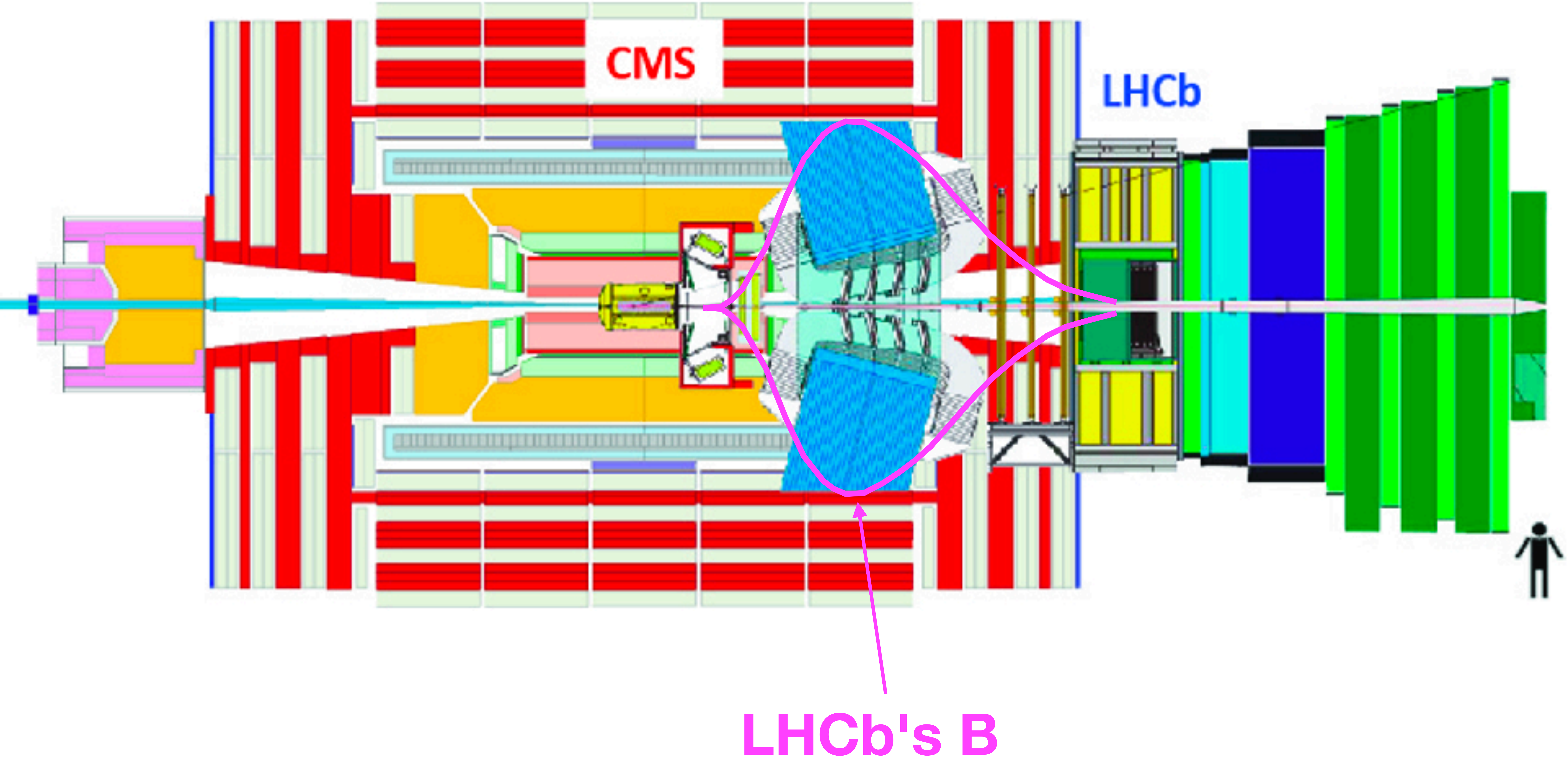


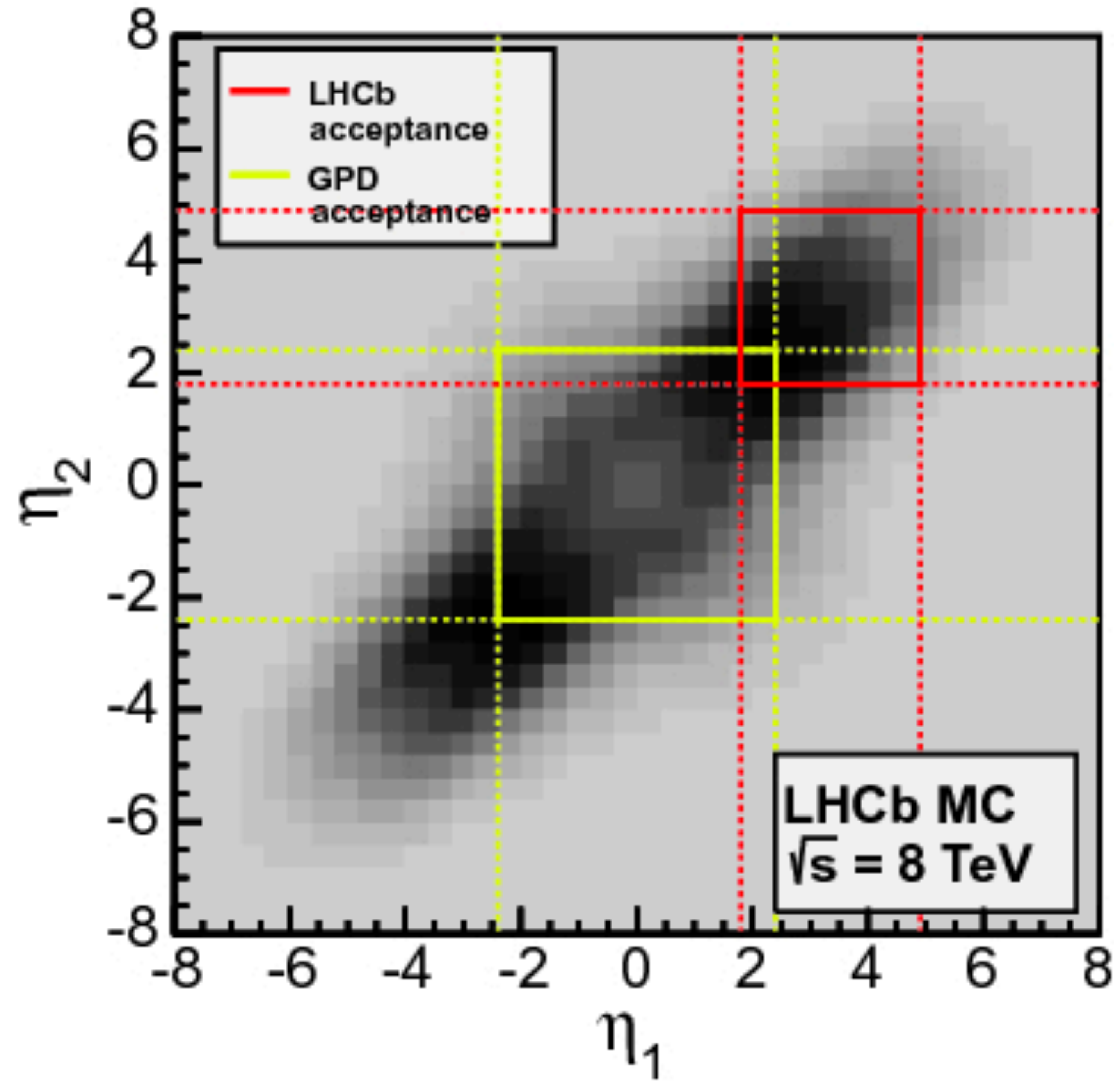






LHCb and CMS complementarities



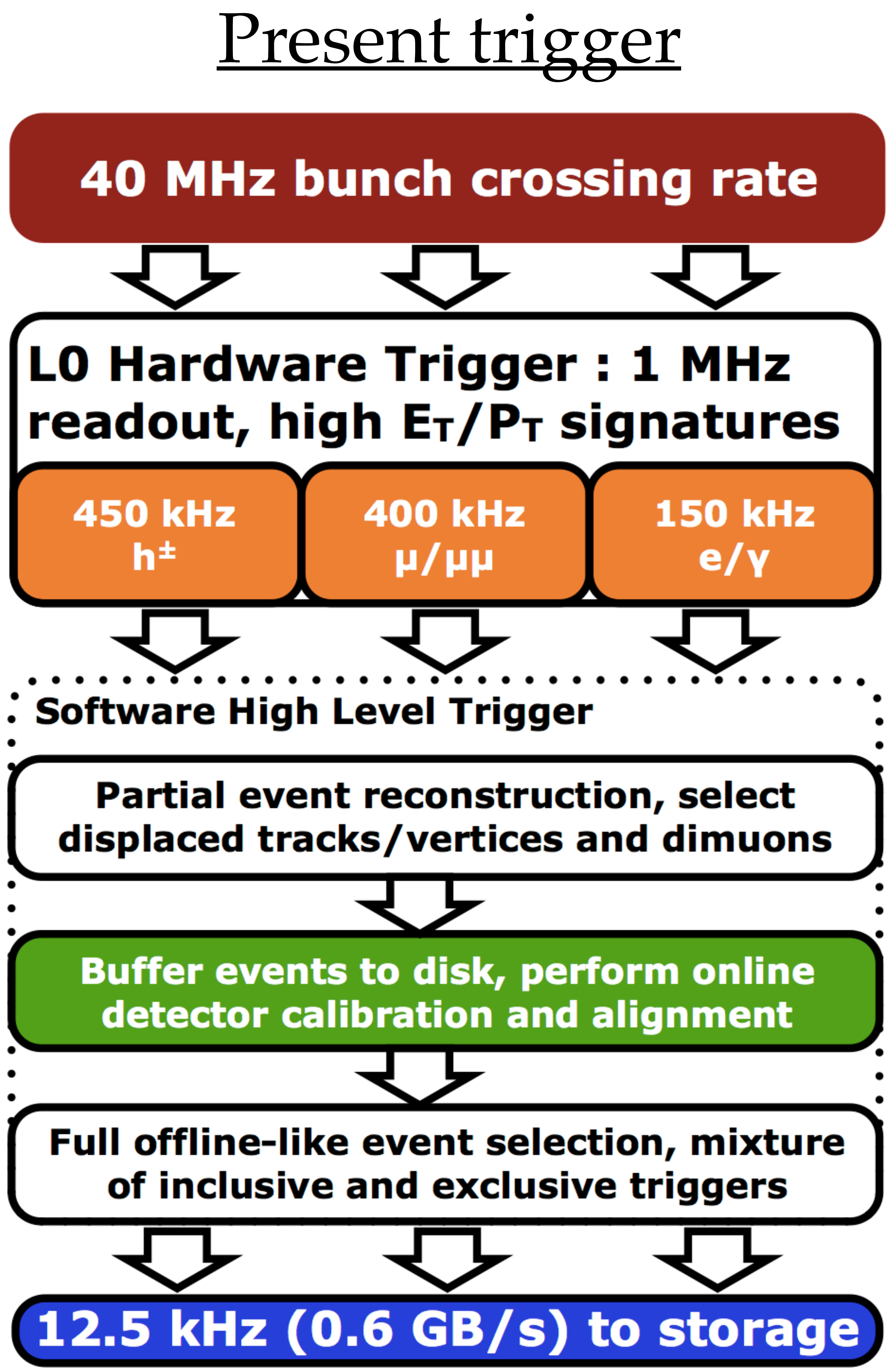


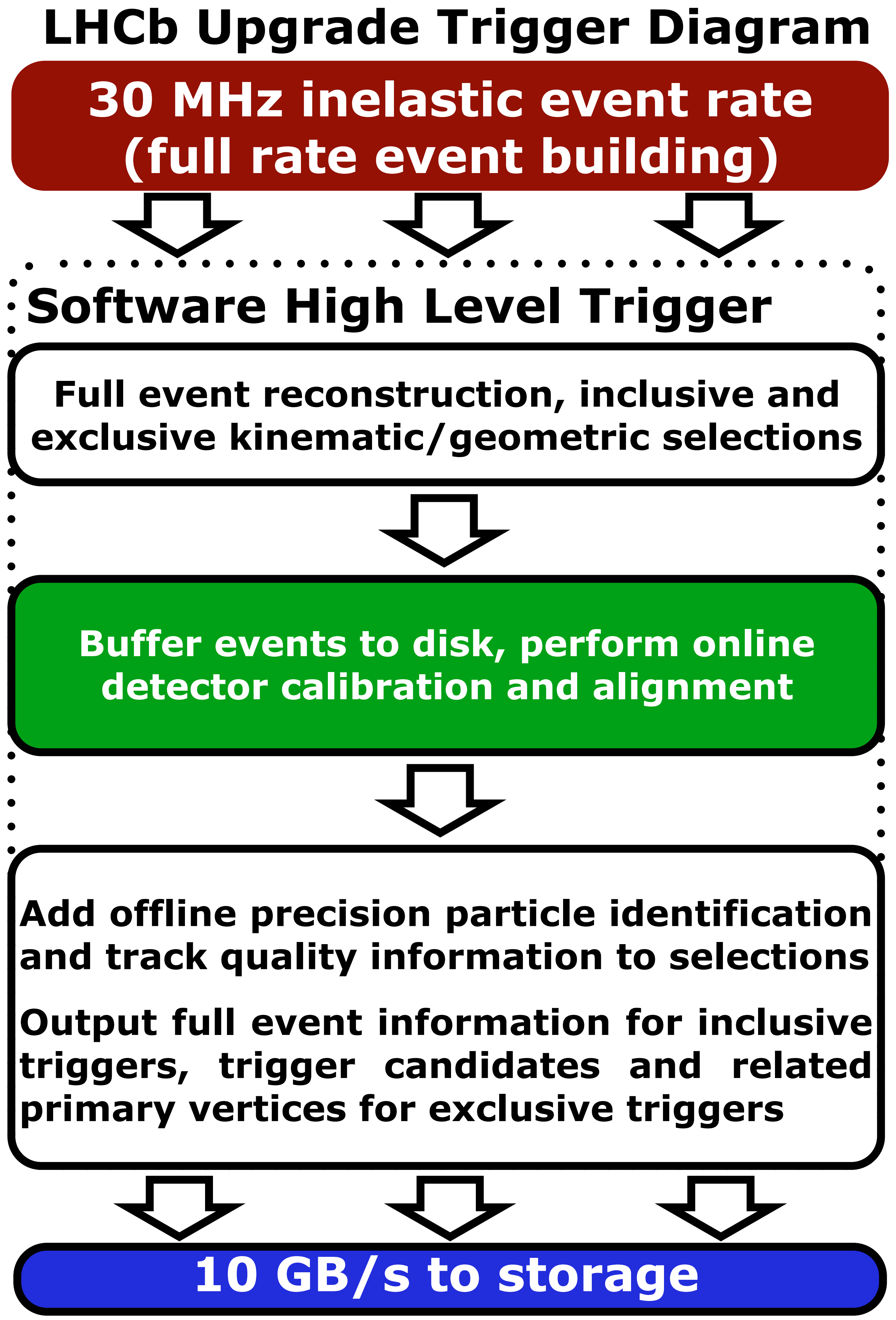
Link 1 and 2

CERN-LHCC-2014-016
LHCB-TDR-016

LHCb Trigger

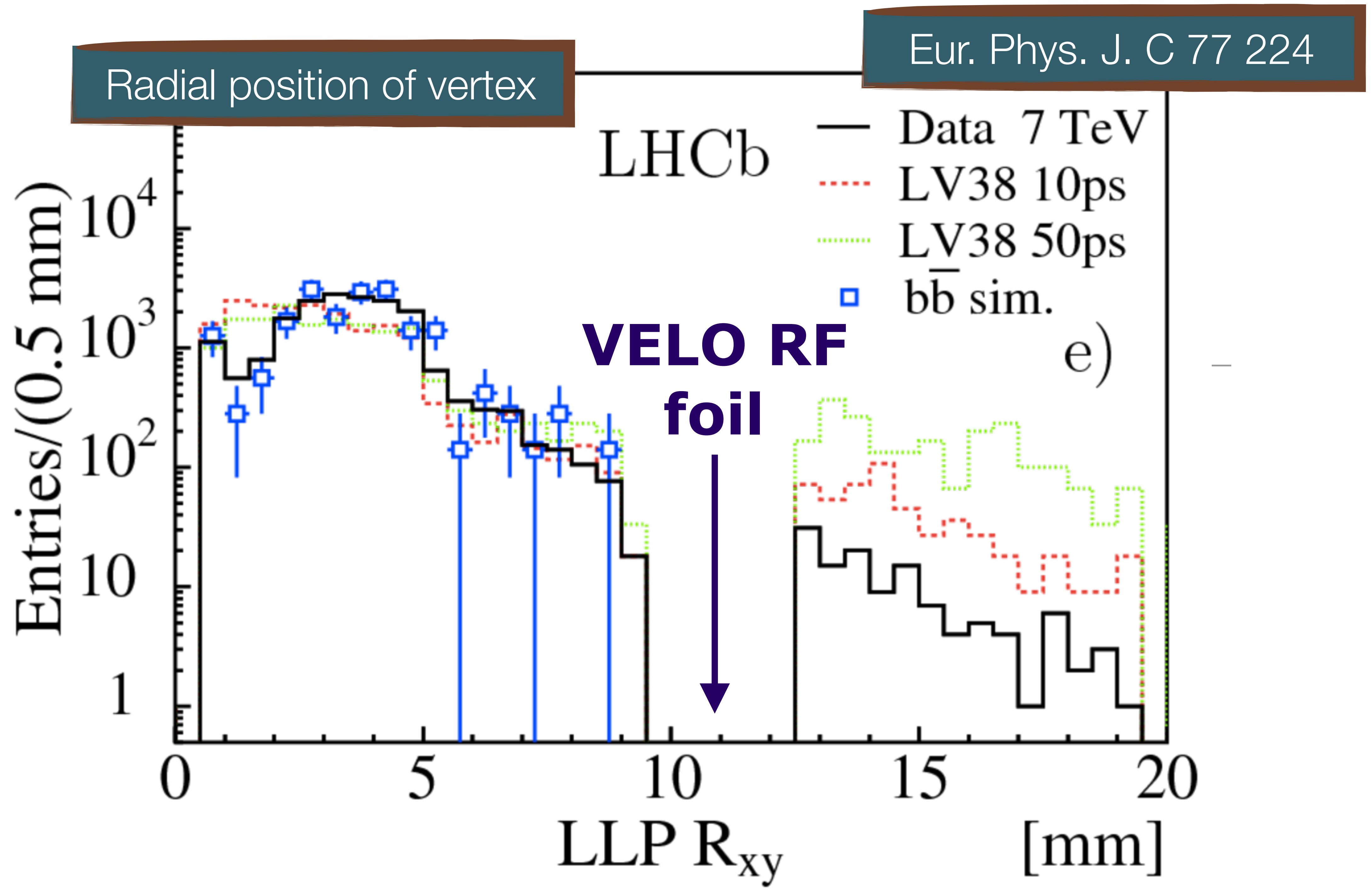
- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- **Run 2:**
  - **Full real-time reconstruction** (since 2015) for all charged particles with $p_T >$ 0.5 GeV
  - We go from 1 TB/s (post zero suppression) to 0.6 GB/s (mix of full + partial events)
- **Run 3**:
  - LHCb will move to a **hardware-less readout system** for LHC Run 3 (2022-2024), and process 5 TB/s in real time to get 10 GB/s to storage

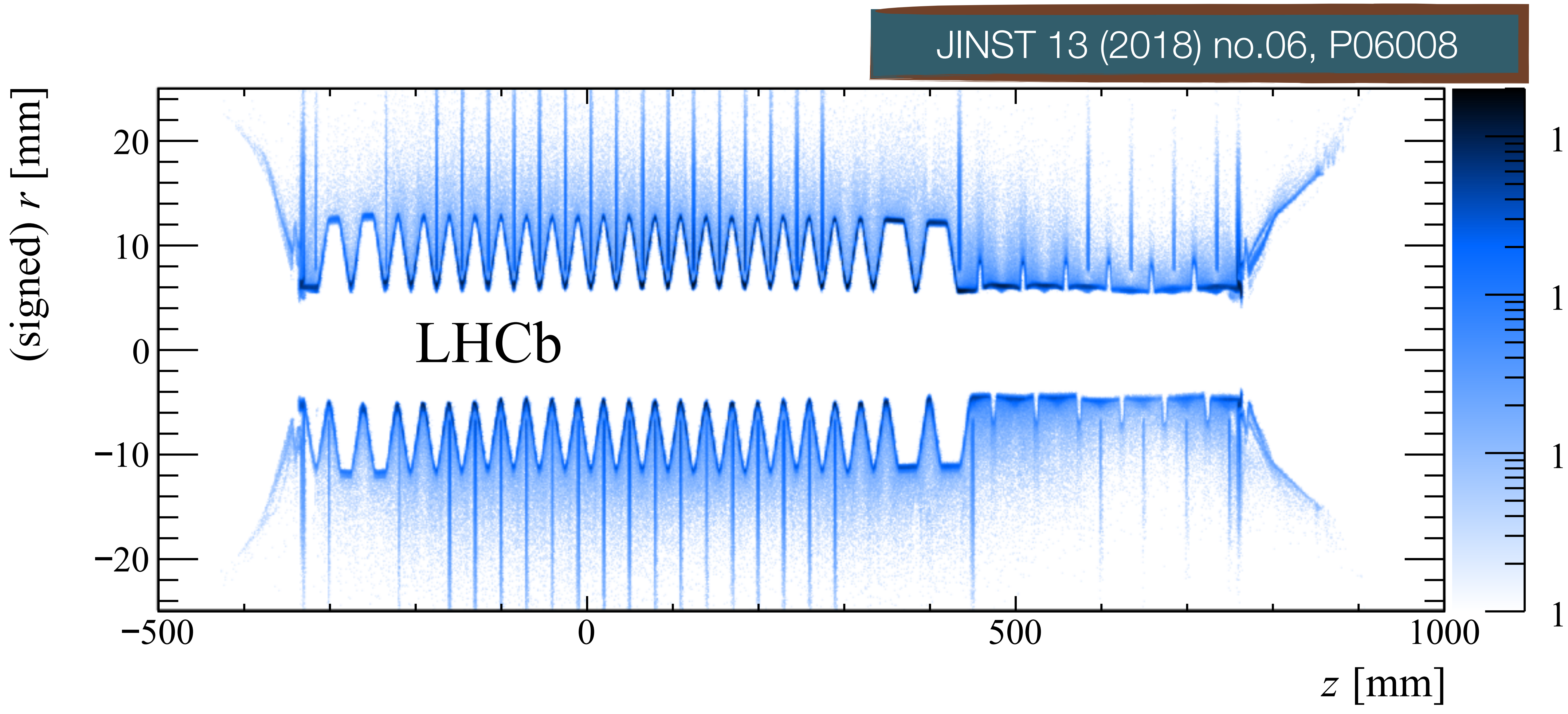


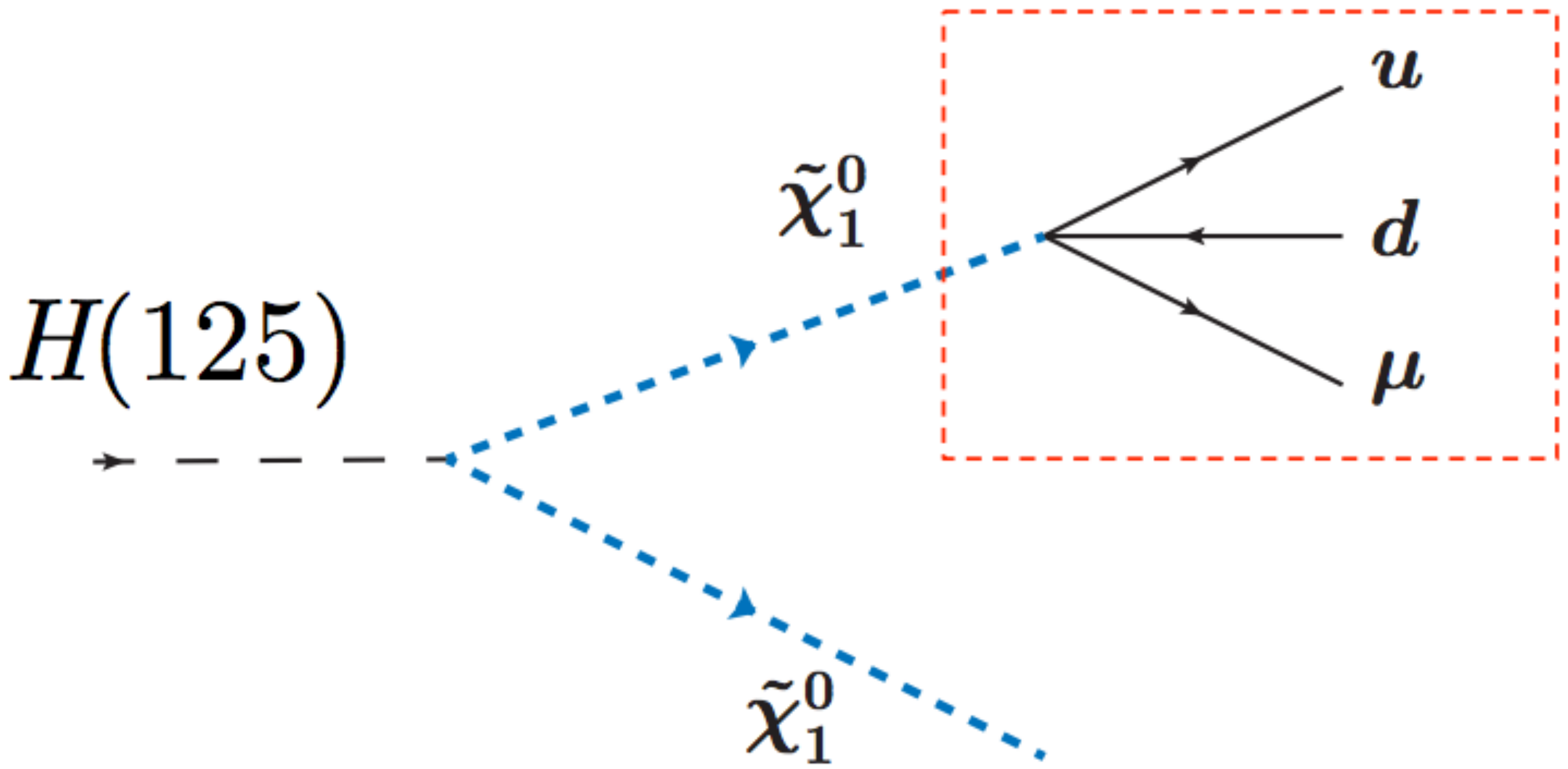


Higgs→LLP→μ+jets / 1

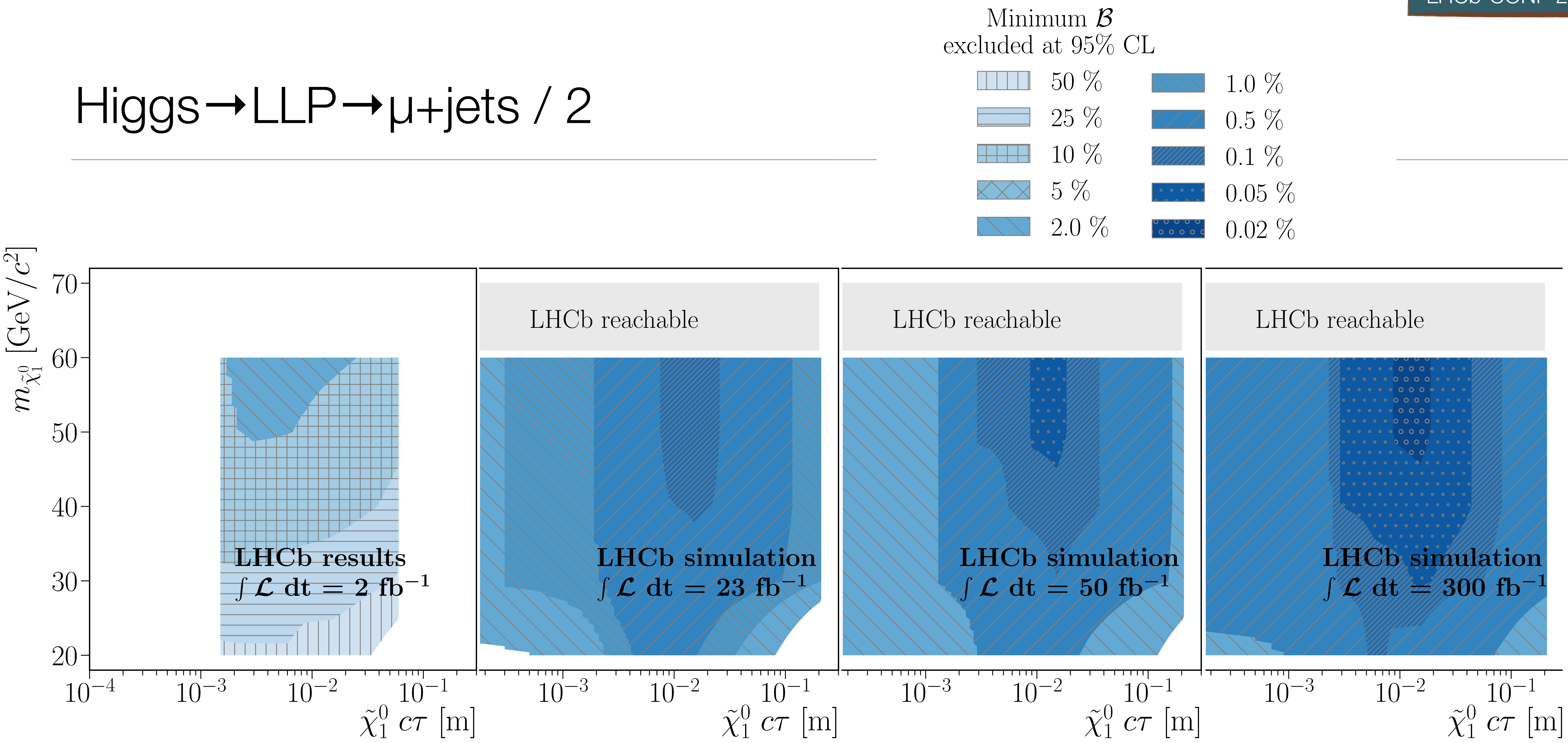
- Massive **LLP** decaying → **μ+jets**
- **Single displaced vertex** with several tracks and a high p_T muon; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- **m_{LLP}=[20; 80] GeV** and **τ_{LLP}=[5; 100] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models



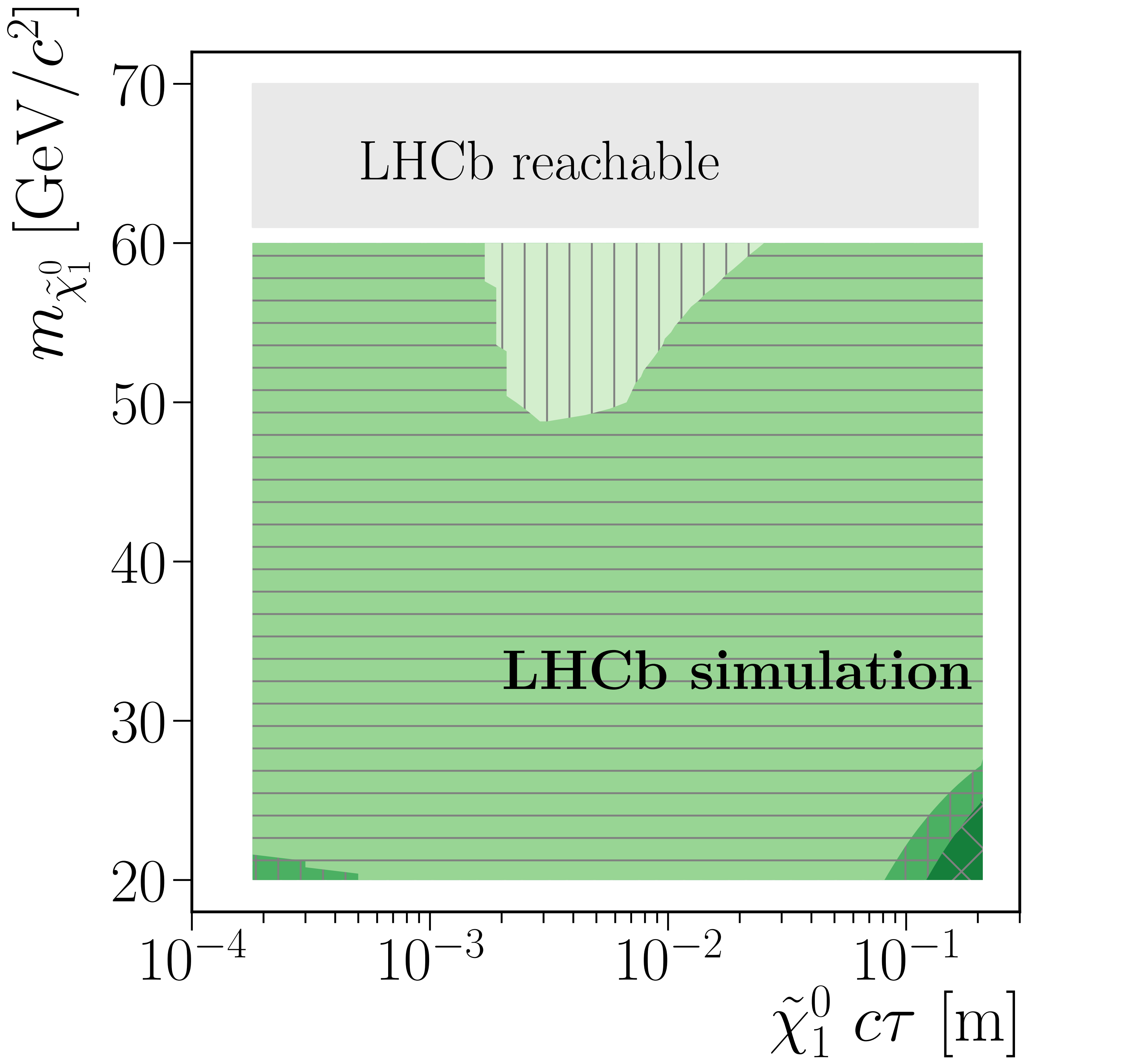




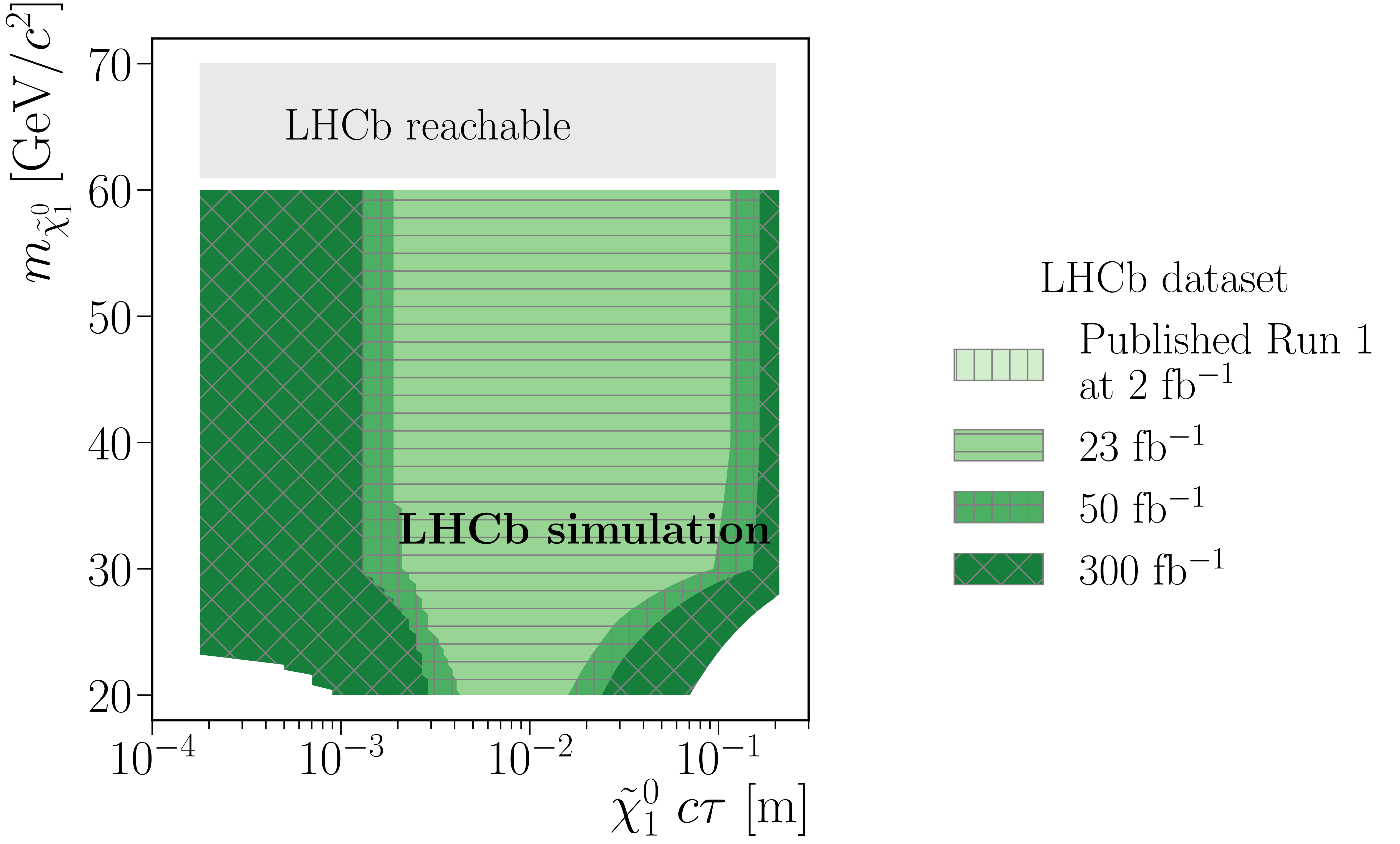
Higgs→LLP→μ+jets / 2



Higgs→LLP→μ+jets / 3



BR(Higgs→LLP+LLP) < 2 %



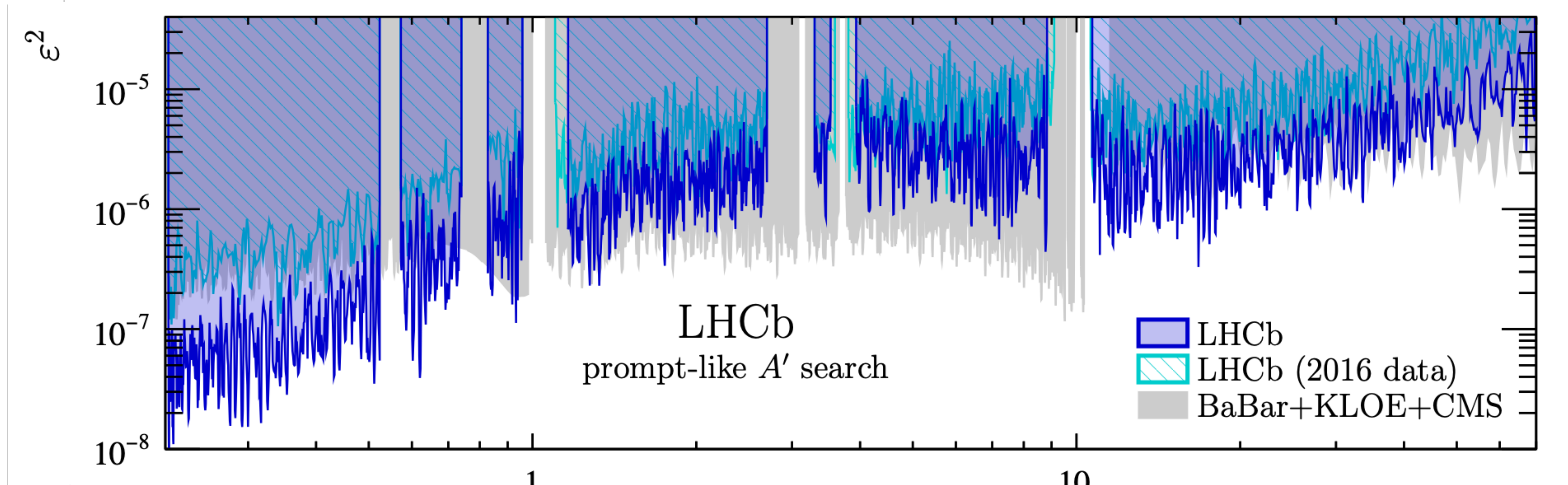
BR(Higgs→LLP+LLP) < 0.5 %

PRL 120 (2018) 061801
PRL 124 (2020) 041801

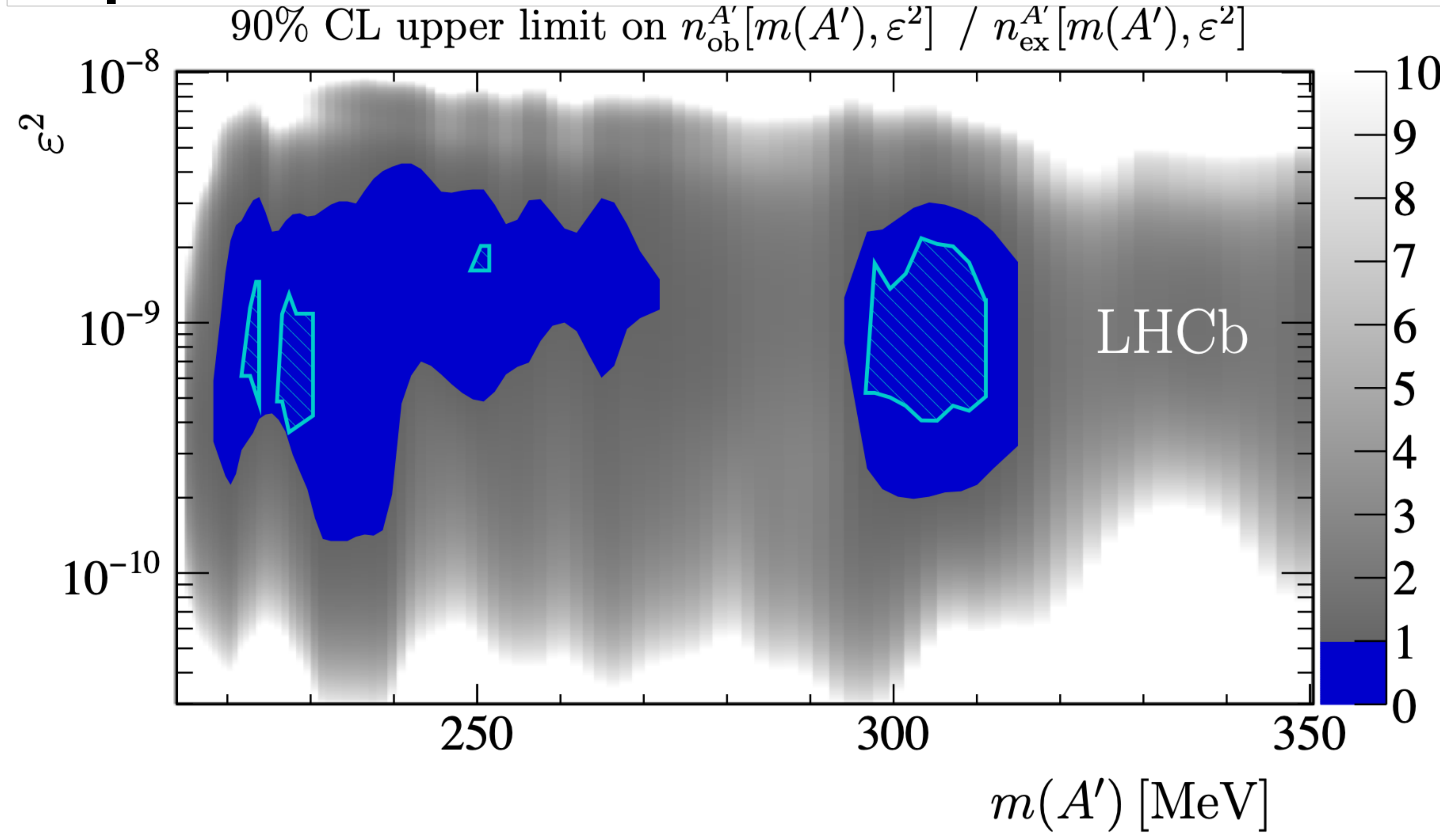
Searching for Dark Photons / 1

- Search for dark photons decaying into **a pair of muons**
- Used **5.5 fb^{-1}** of Run 2 LHCb data (13 TeV)
- Kinetic mixing of the dark photon (A′) with **off-shell photon** (γ^*) by a factor ε:
    - A′ inherits the production mode mechanisms from γ^*
    - A′ → $\mu^+\mu^-$ can be **normalised** to γ^* → $\mu^+\mu^-$
    - No use of MC → no systematics from MC → fully **data-driven** analysis
- Separate γ^* signal from background and measure its fraction
- Prompt-like search (up to 70 GeV/c^2) → displaced search (214-350 MeV/c^2)
    - A′ is long-lived only if the mixing factor is really small
- No significant excess found - exclusion regions at 90% C.L.

Prompt results



Displaced results



Taken from I. Kostiuk's talk

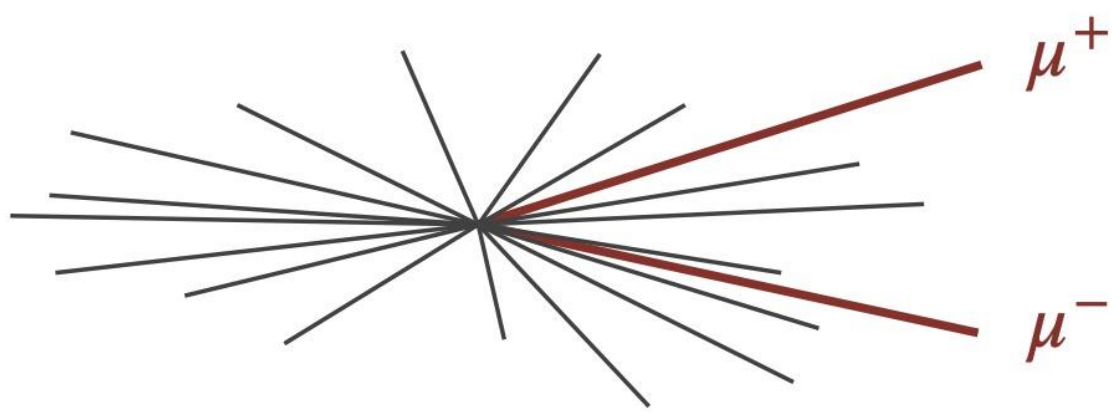
JHEP 10 (2020) 156

Low-mass dimuon resonances / 1

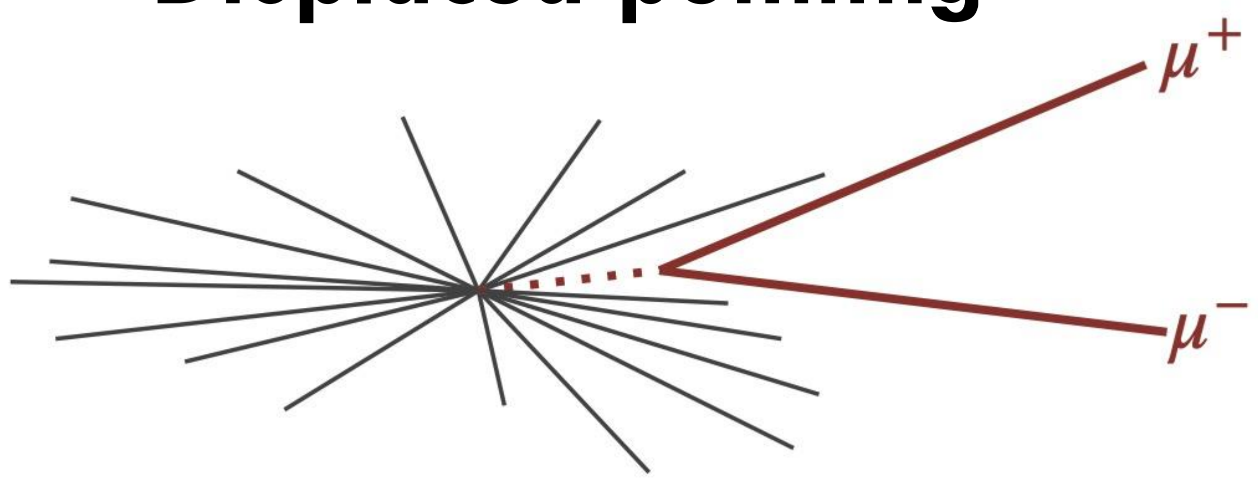
- Non-minimal searches, example signatures:

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

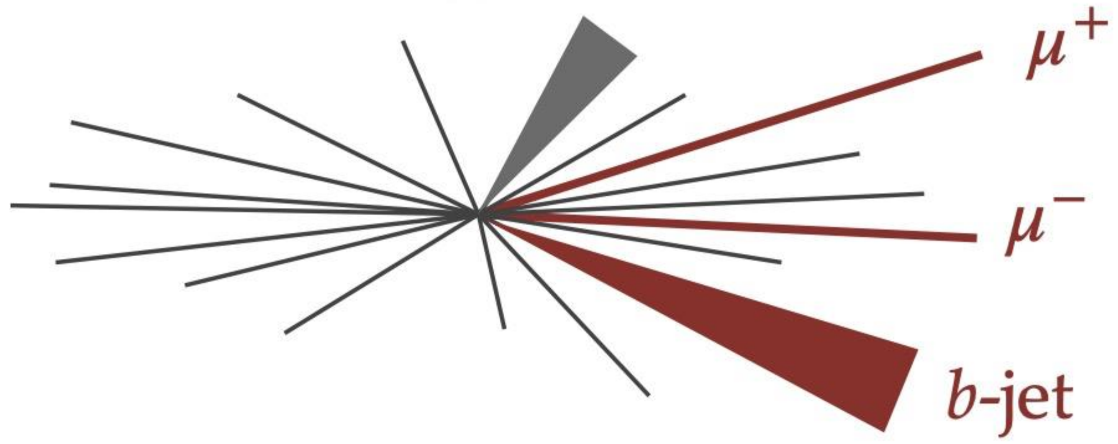


Displaced pointing

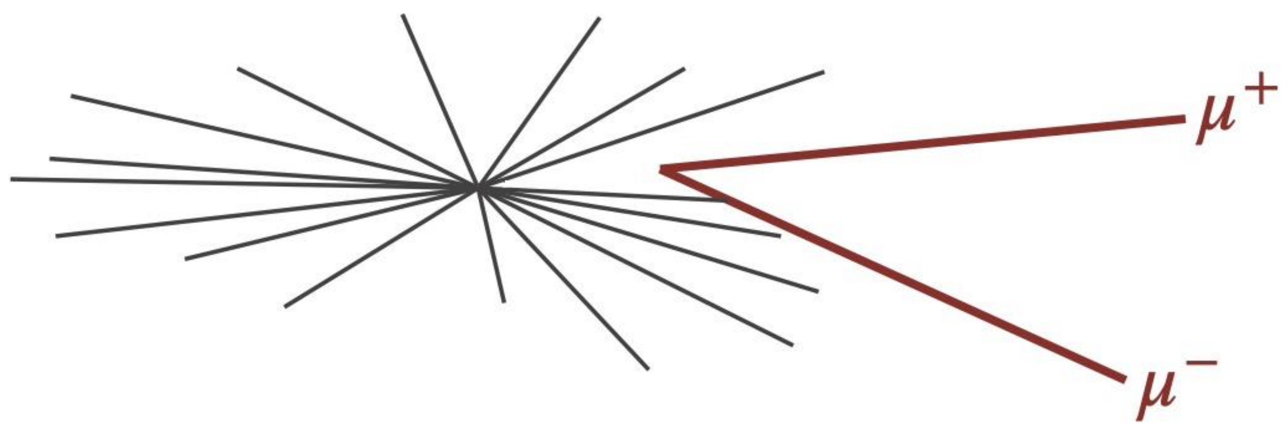


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing



Taken from I. Kostiuk's talk

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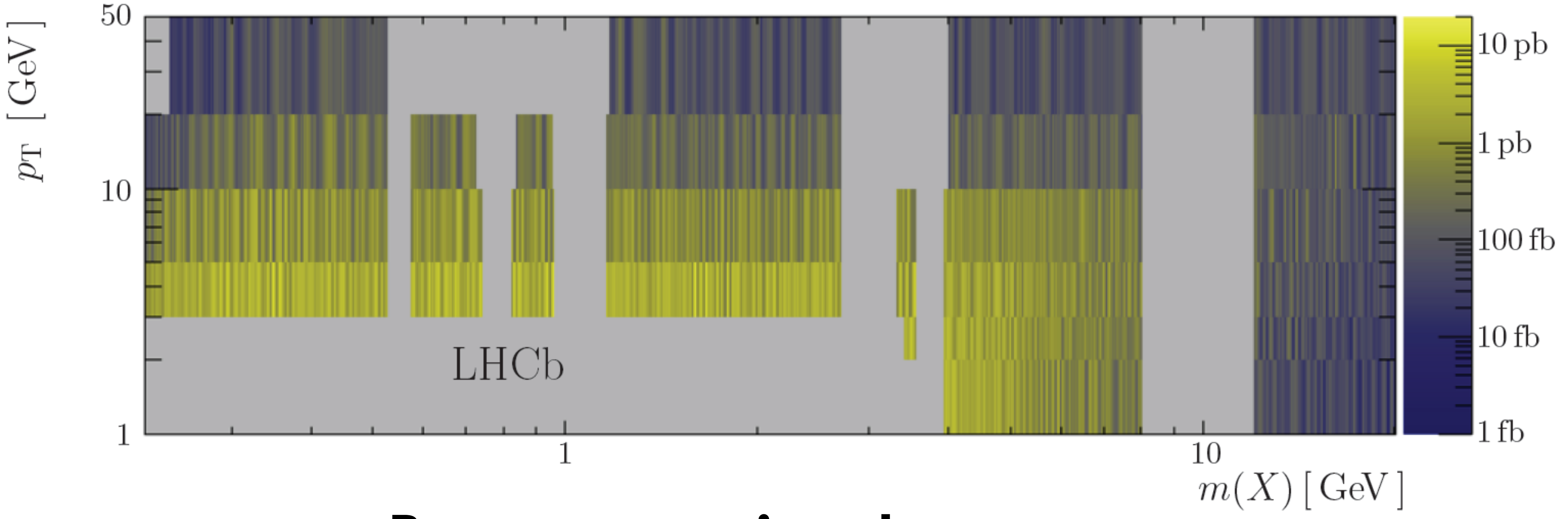
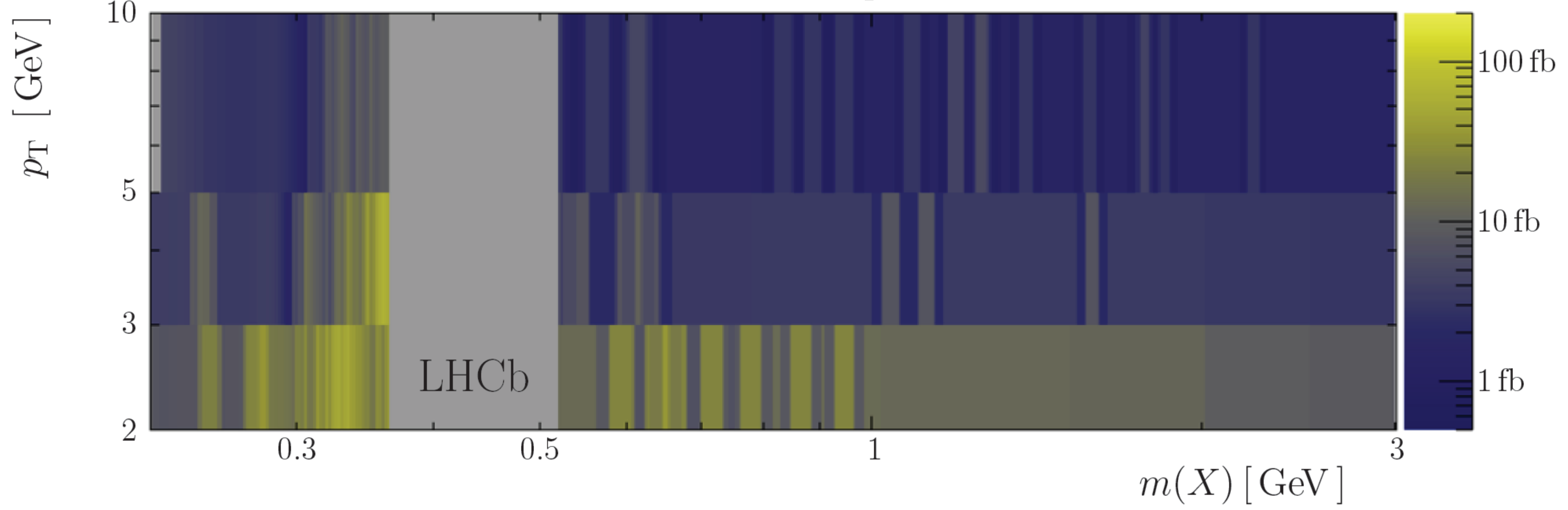
Low-mass dimuon resonances / 2

- Upper limits at 90% CL on $\sigma(X \to \mu\mu)$

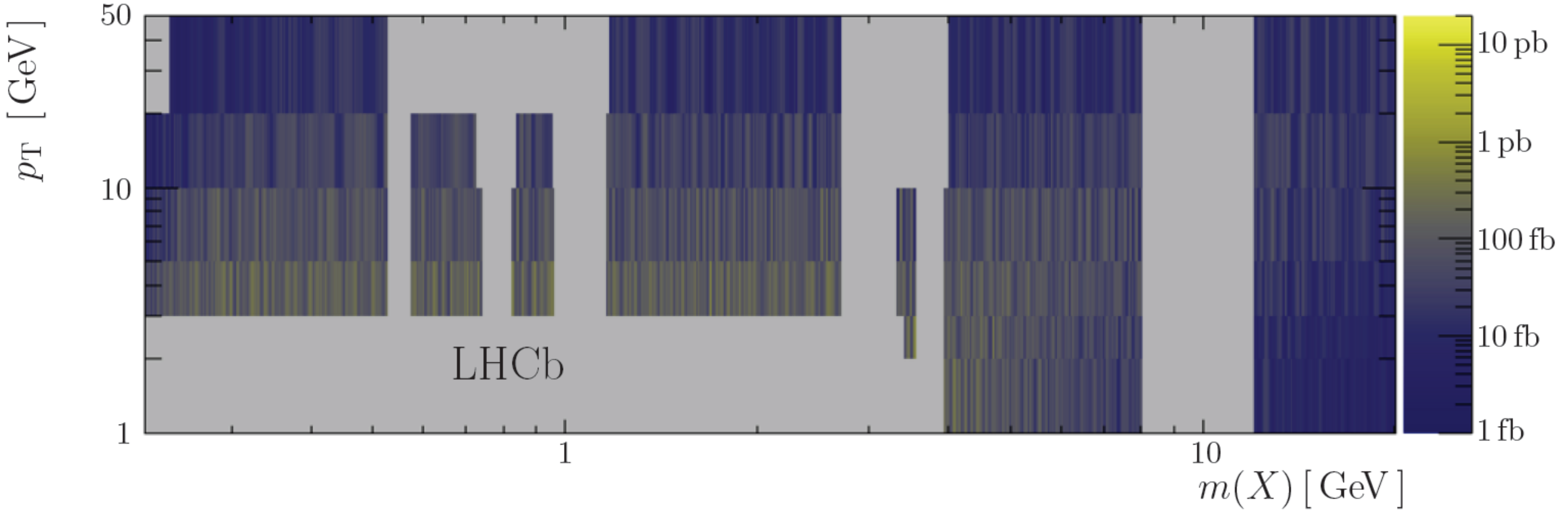
Inclusive prompt



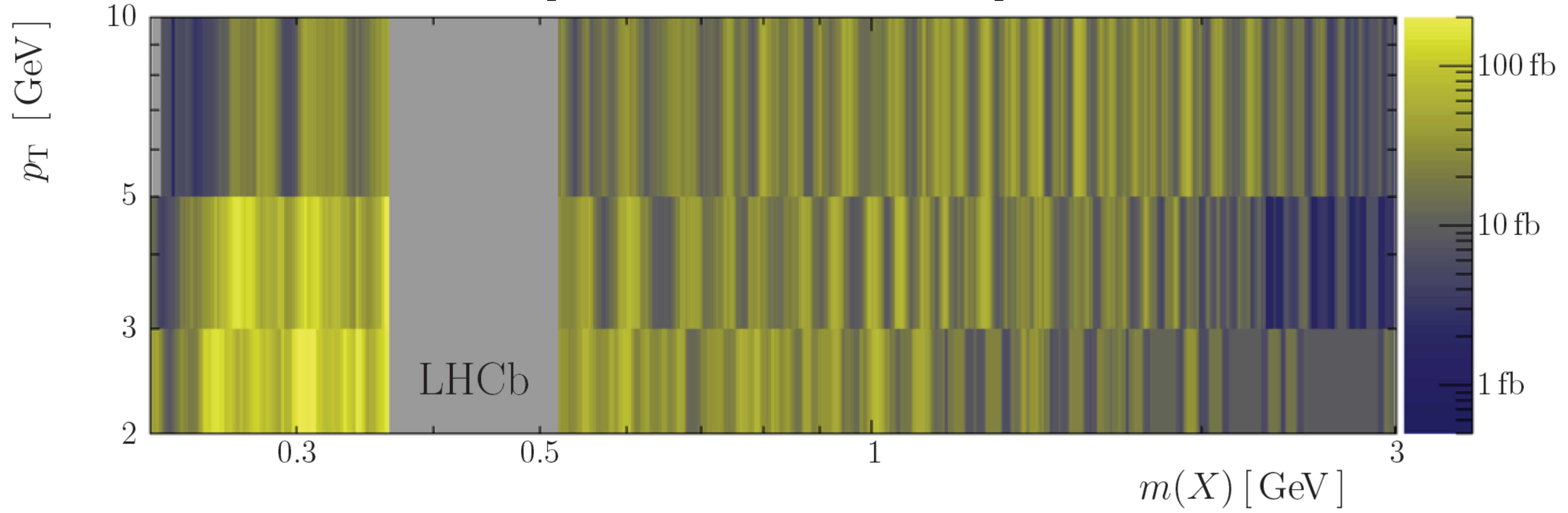
Inclusive displaced



Beauty associated prompt



Beauty associated displaced



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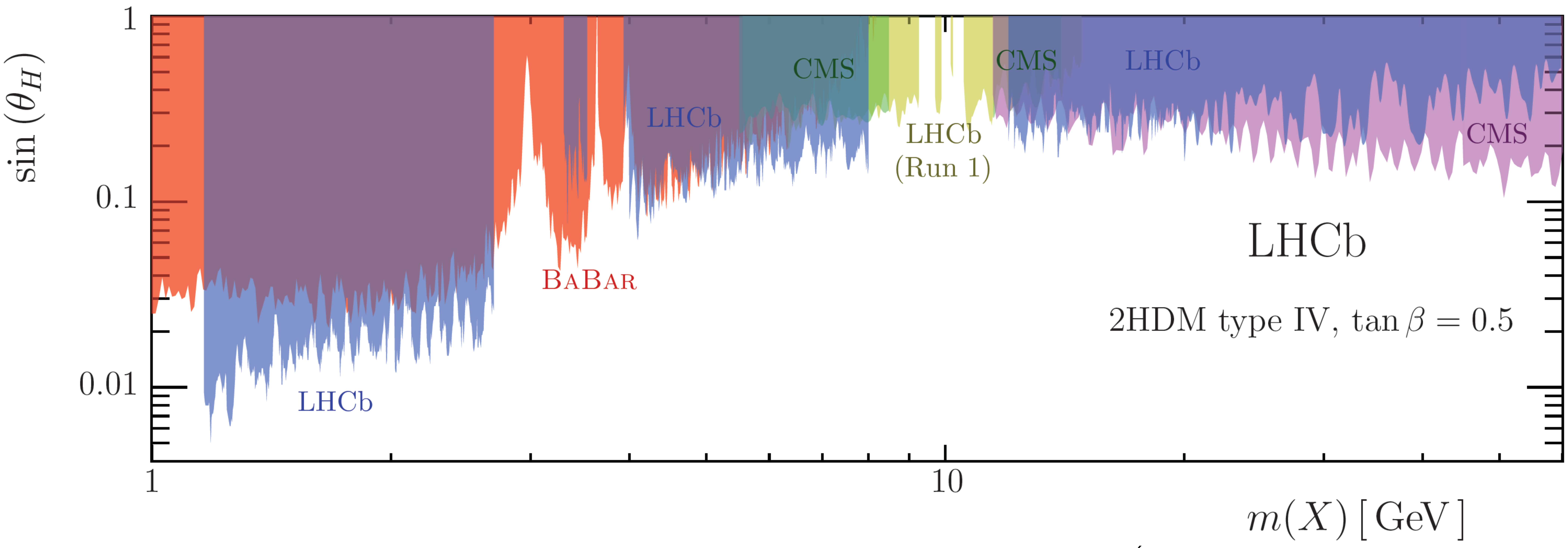
Low-mass dimuon resonances / 3

- A complex scalar singlet is added to the two-Higgs doublet (2HDM) potential
- E.g. a scenario where the pseudoscalar boson acquires all of its couplings to SM fermions through its mixing with the Higgs doublets; the corresponding X–H mixing angle is denoted as θ_H



Conclusions

- Plenty of results, really hard to cover everything in 20 minutes, so sorry to the people whose analyses I have missed!

- The days of `guaranteed' discoveries or of no-lose theorems in particle physics are over, at least for the time being...
- ... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU,...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

ASPEN2014 Theoretical summary - M. Mangano

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	203?

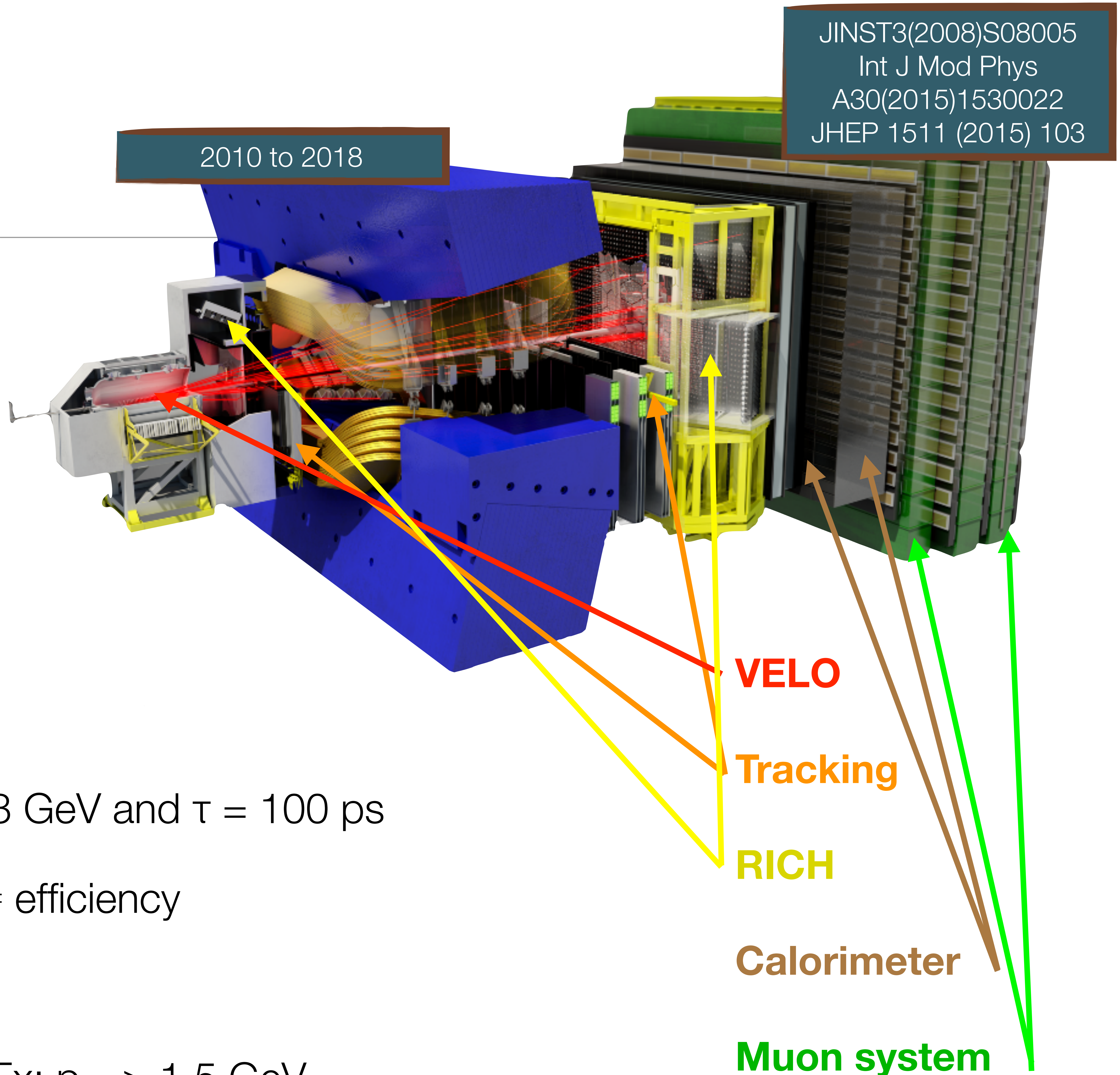
LS2	**RUN 3**	LS3	**RUN 4**	LS4	**RUN 5**
LHCb 40 MHz Upgrade Ia	$L = 2 \times 10^{33}$	LHCb Upgrade Ib	$L = 2 \times 10^{33}$; **50 fb^{-1}**	LHCb Upgrade II (proposed)	$L = 2 \times 10^{34}$; **300 fb^{-1}** (proposed)

Thanks

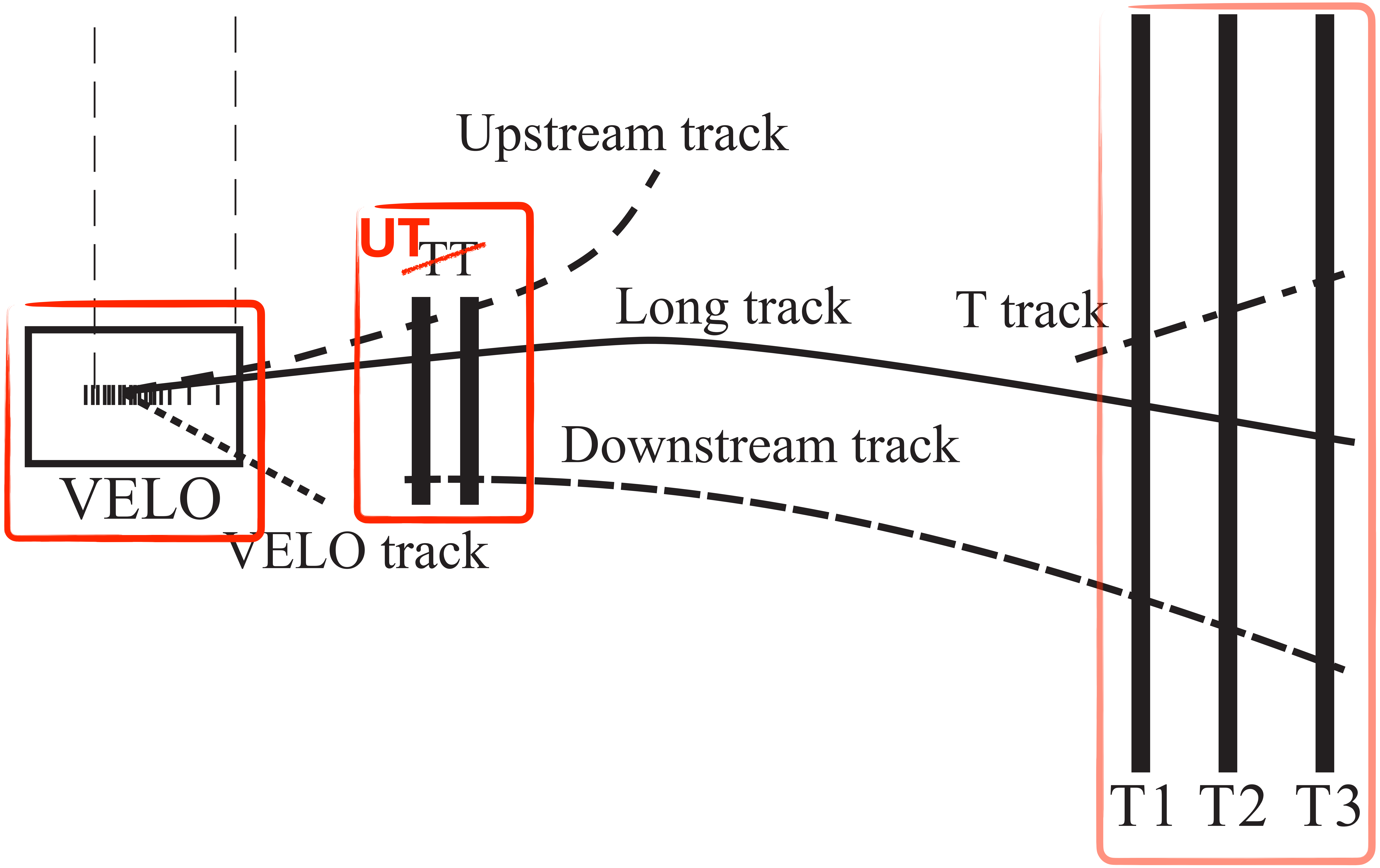
Federico Leo Redi

The LHCb detector

- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC ($1.9 < \eta < 4.9$) (~1°-15°)
- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane.
- Lifetime resolution of
  - ~ 50 fs for a J/ψ
  - ~ 0.2 ps for long lived neutral particle of m = 3 GeV and τ = 100 ps
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency
- Great **mass resolution**: e.g. 15 MeV for J/ψ
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV



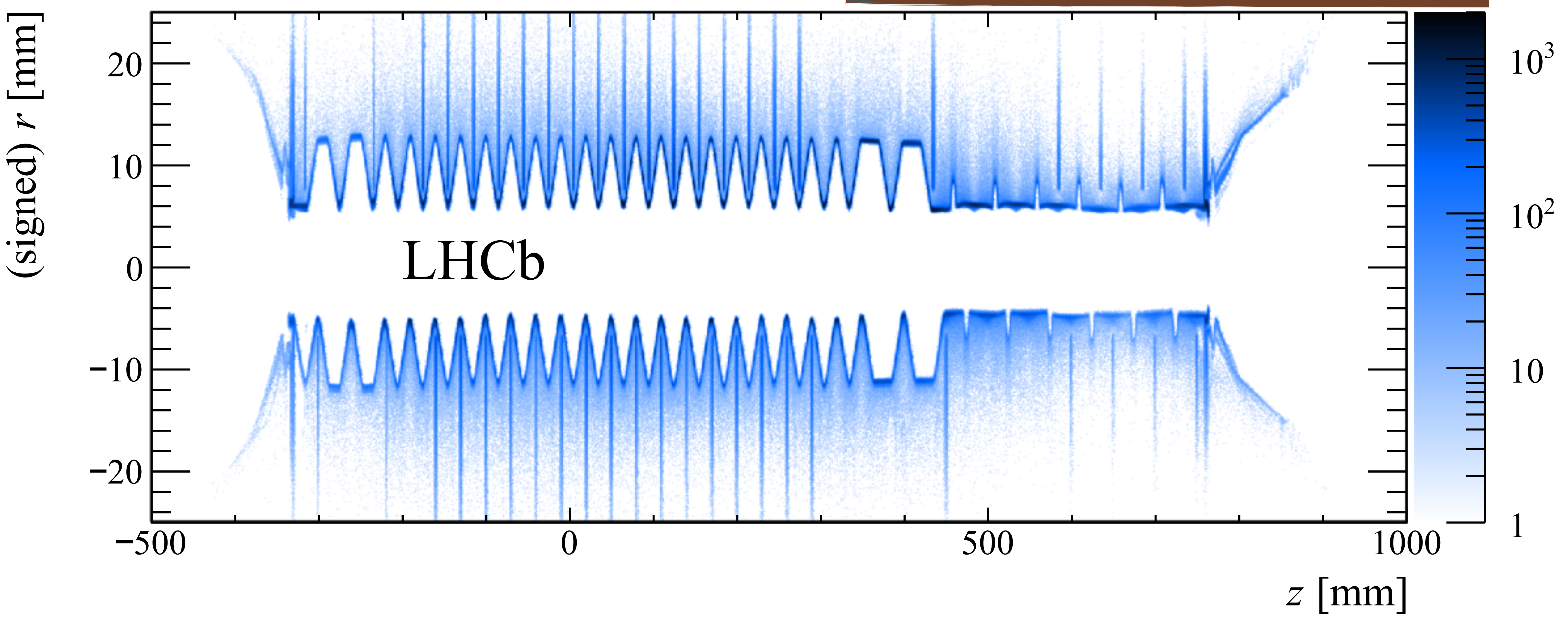
LHCb track types

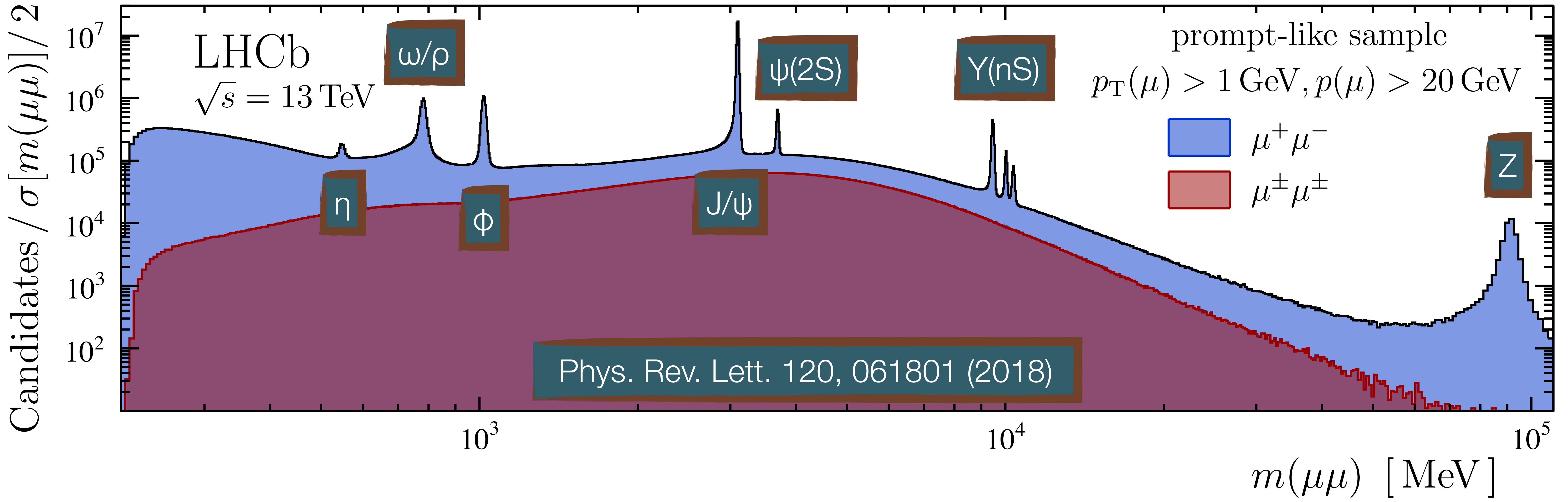


LHCb data

- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements, an **alternative approach** is required to fully map the VELO material
- **Real-time calibration** in Run 2 (Turbo Stream)
- Hardware trigger is still there, and only ~10% efficient at low pT

JINST 13 (2018) no.06, P06008

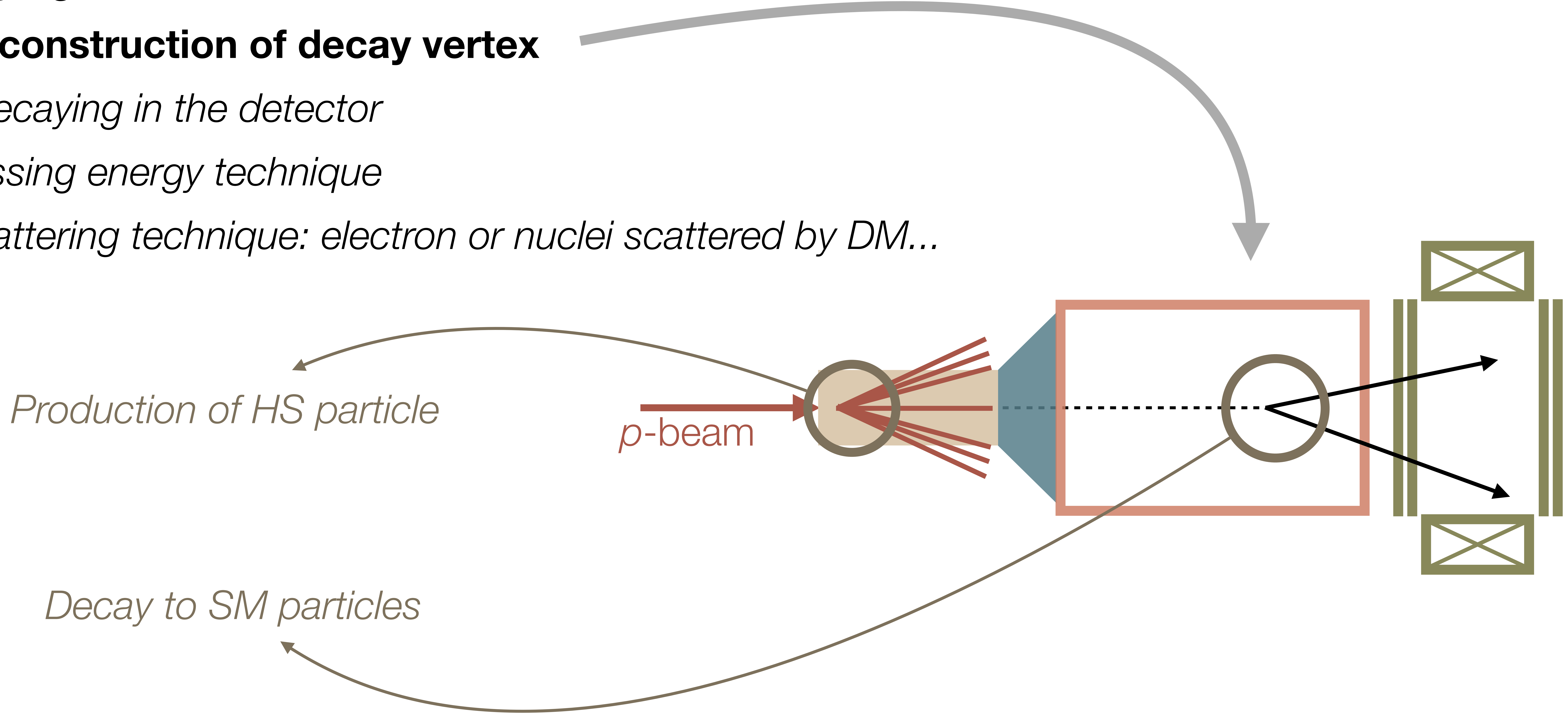




Phys. Rev. Lett. 120, 061801 (2018)

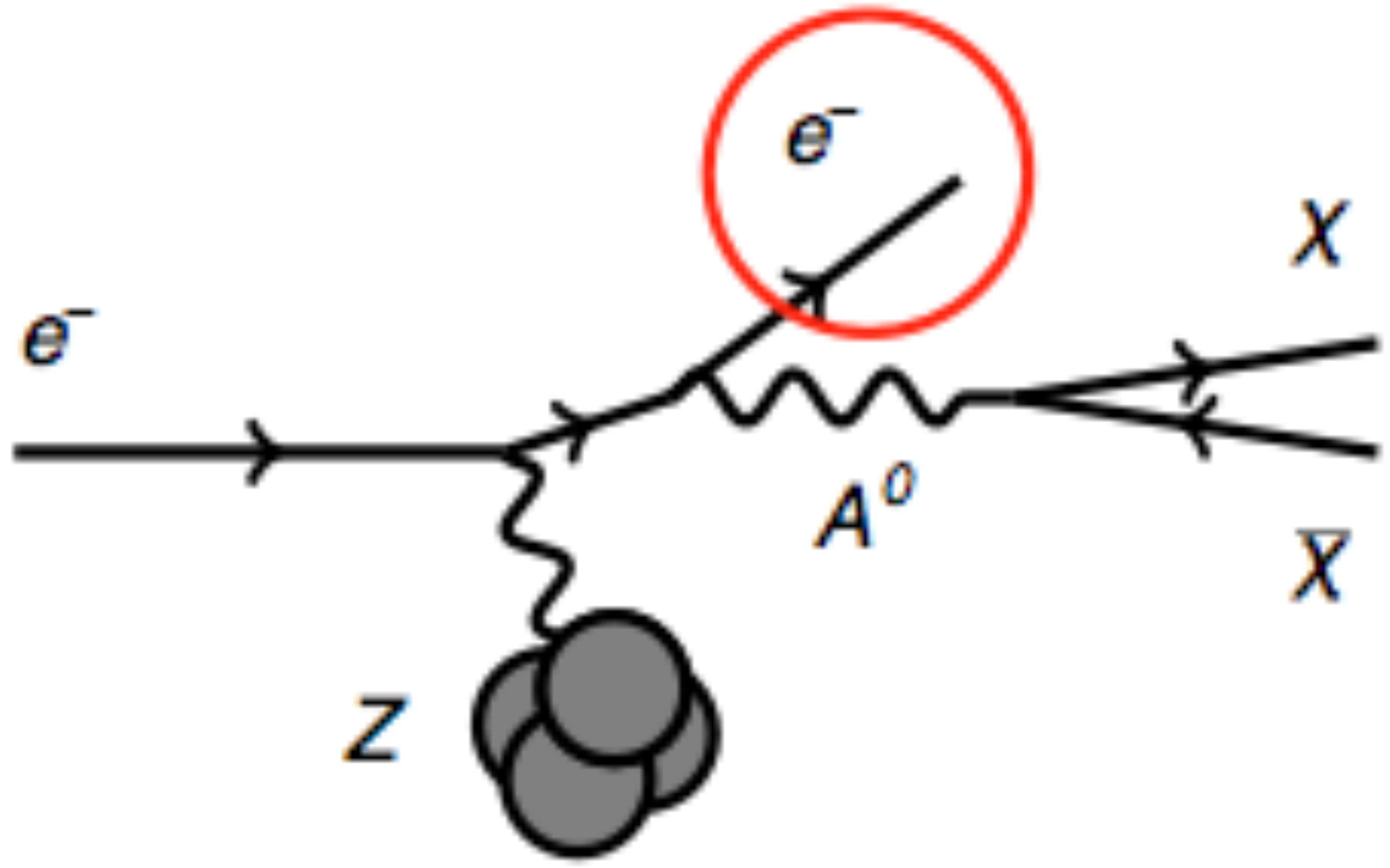
Exploring the dark sector / 2

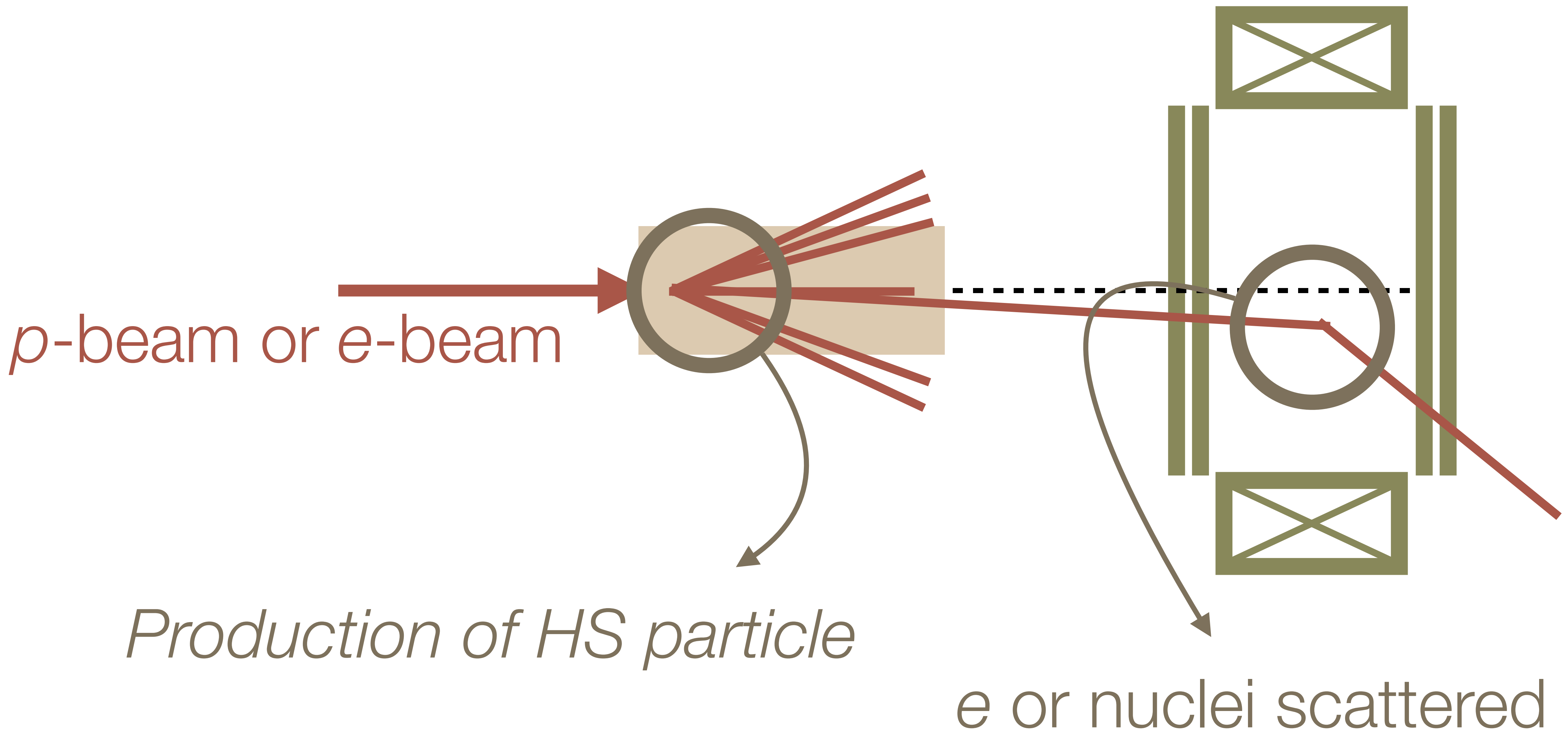
- **Decaying in the detector**
  - **Reconstruction of decay vertex**
- *Not decaying in the detector*
  - *Missing energy technique*
  - *Scattering technique: electron or nuclei scattered by DM...*



Exploring the dark sector / 3

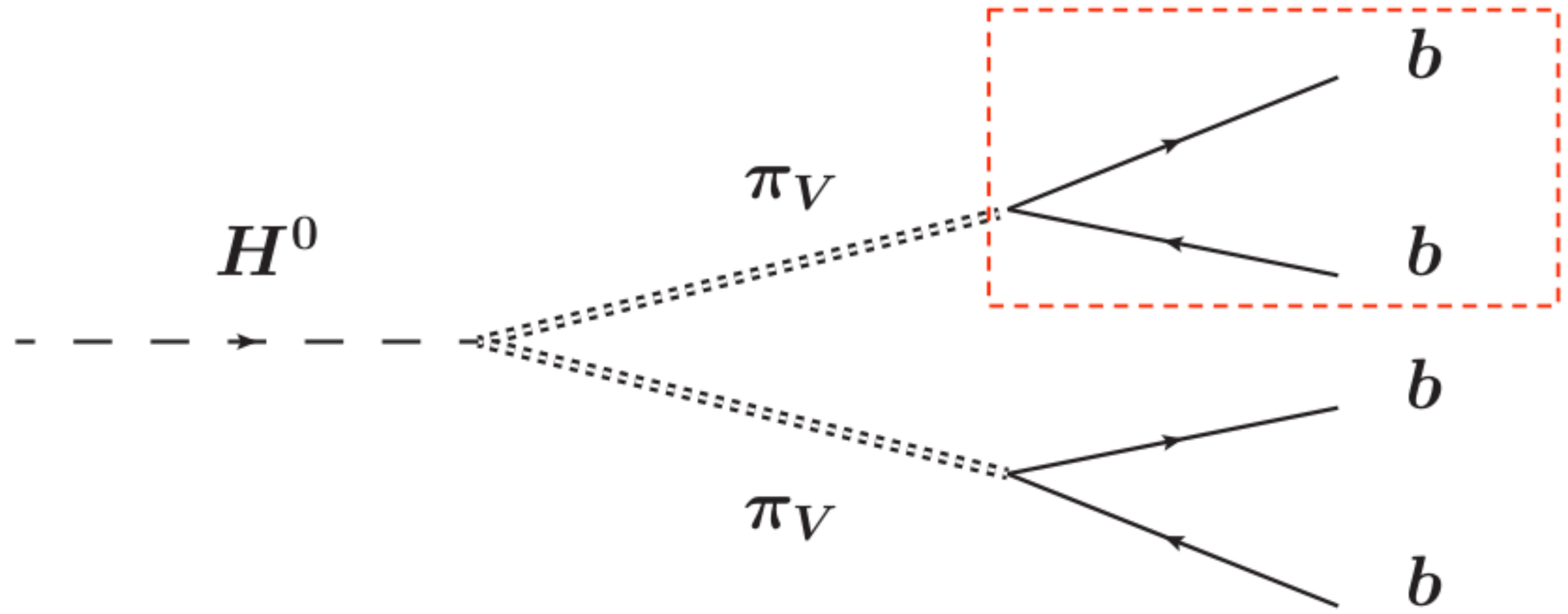
- *Decaying in the detector*
  - *Reconstruction of decay vertex*
- **Not decaying in the detector**
  - **Missing energy technique**
  - **Scattering technique: electron or nuclei scattered by DM**

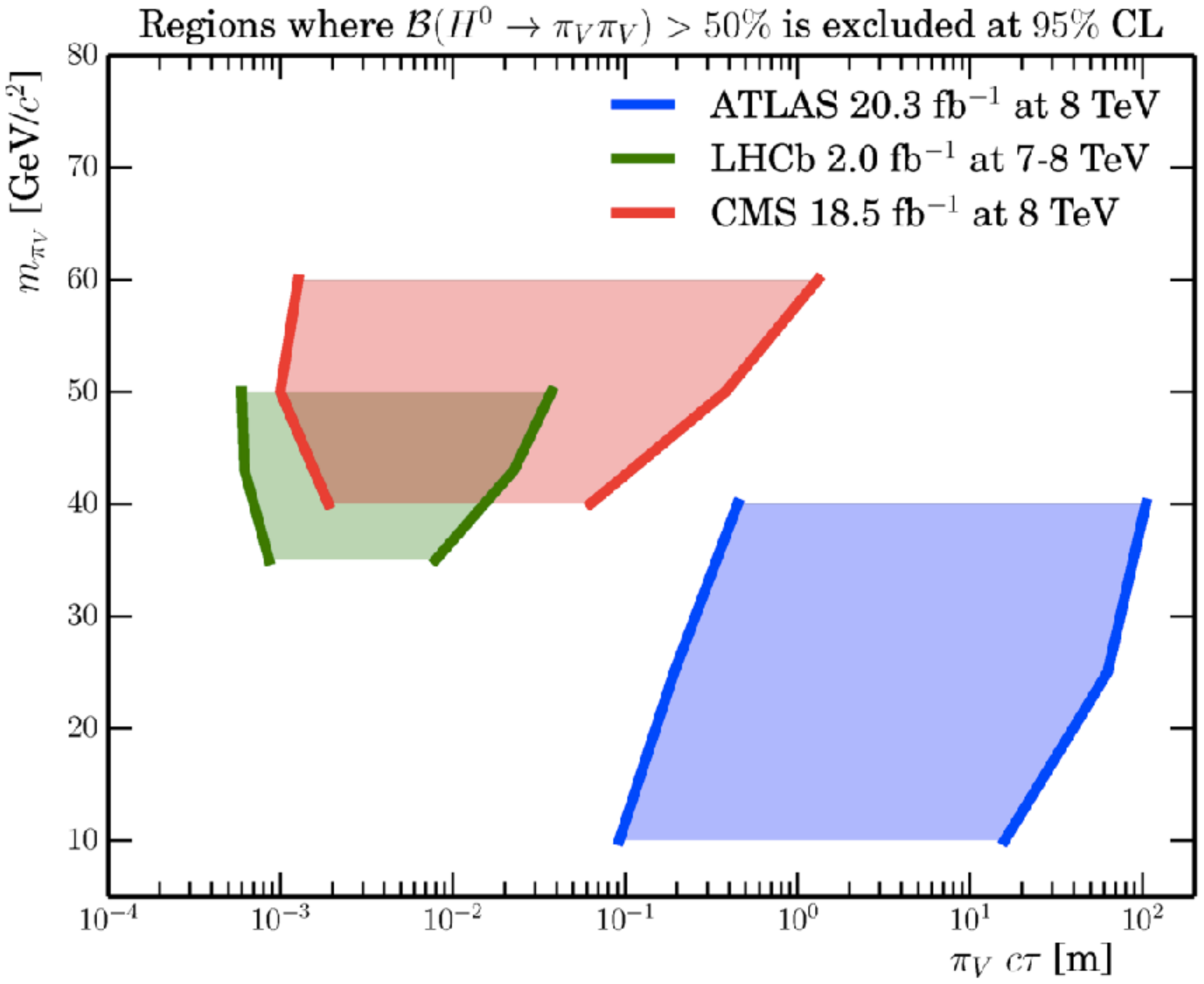




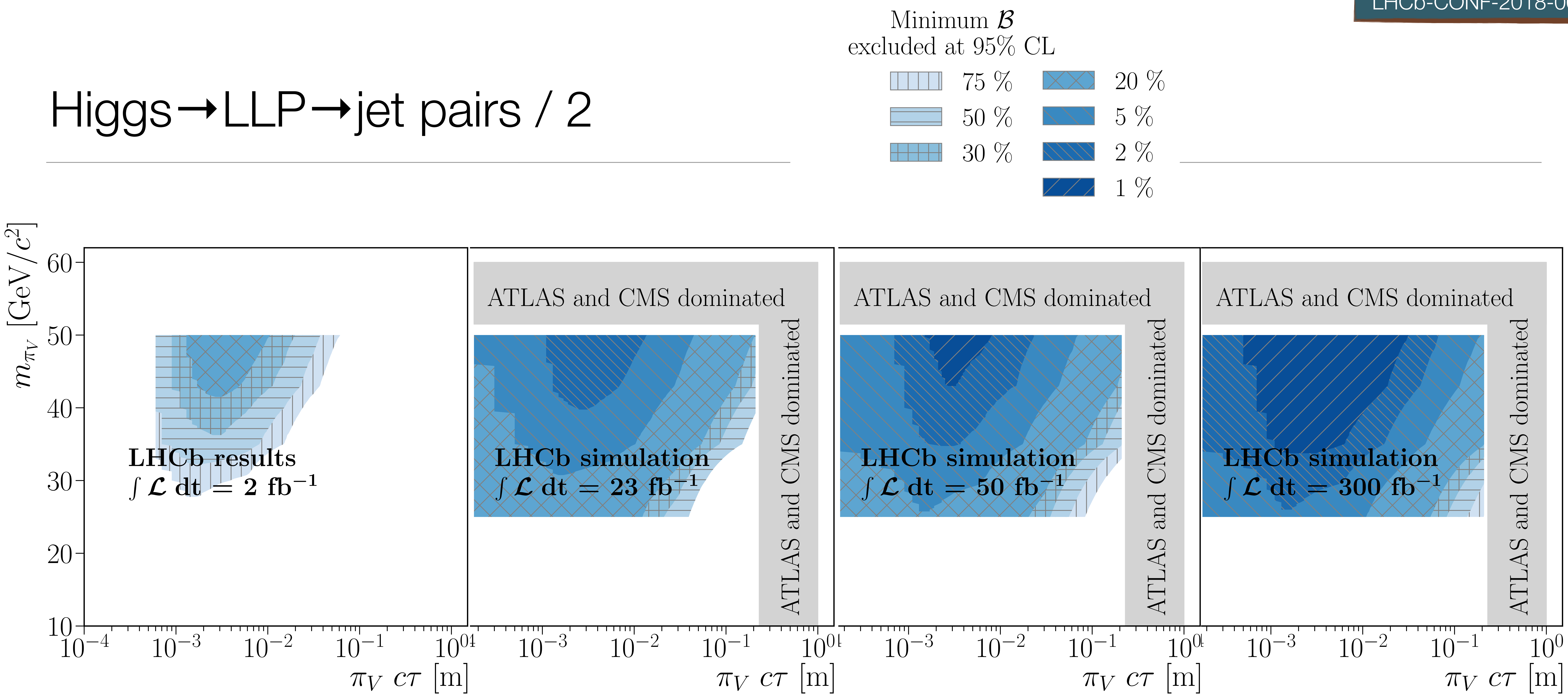
Higgs→LLP→jet pairs / 1

- Massive **LLP** decaying → **jets**
- **Single displaced vertex** with two associated tracks; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs (e.g. π_V)
- **$m_{\pi V}$=[25; 50] GeV** and **$\tau_{\pi V}$=[2; 500] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models

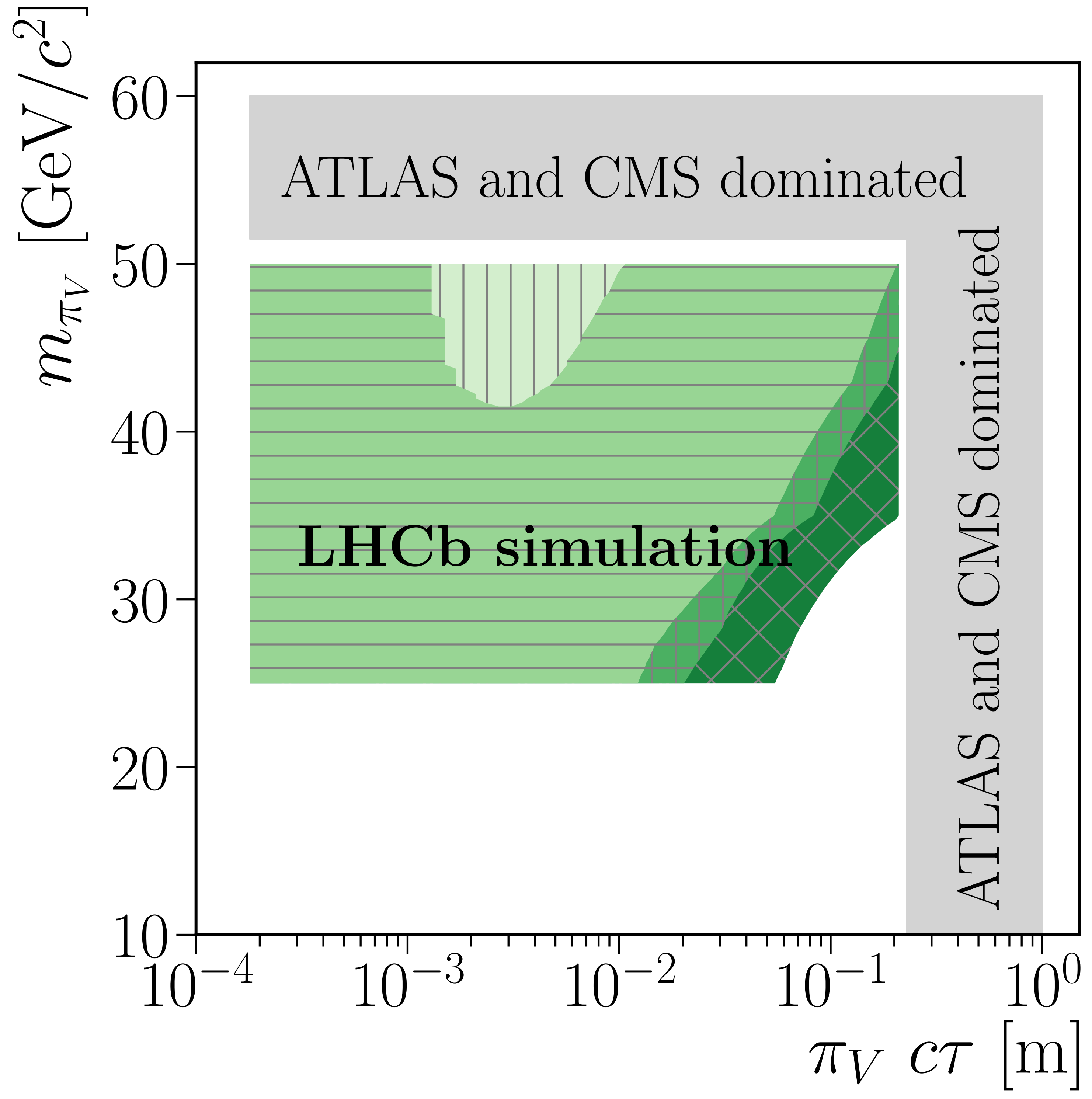




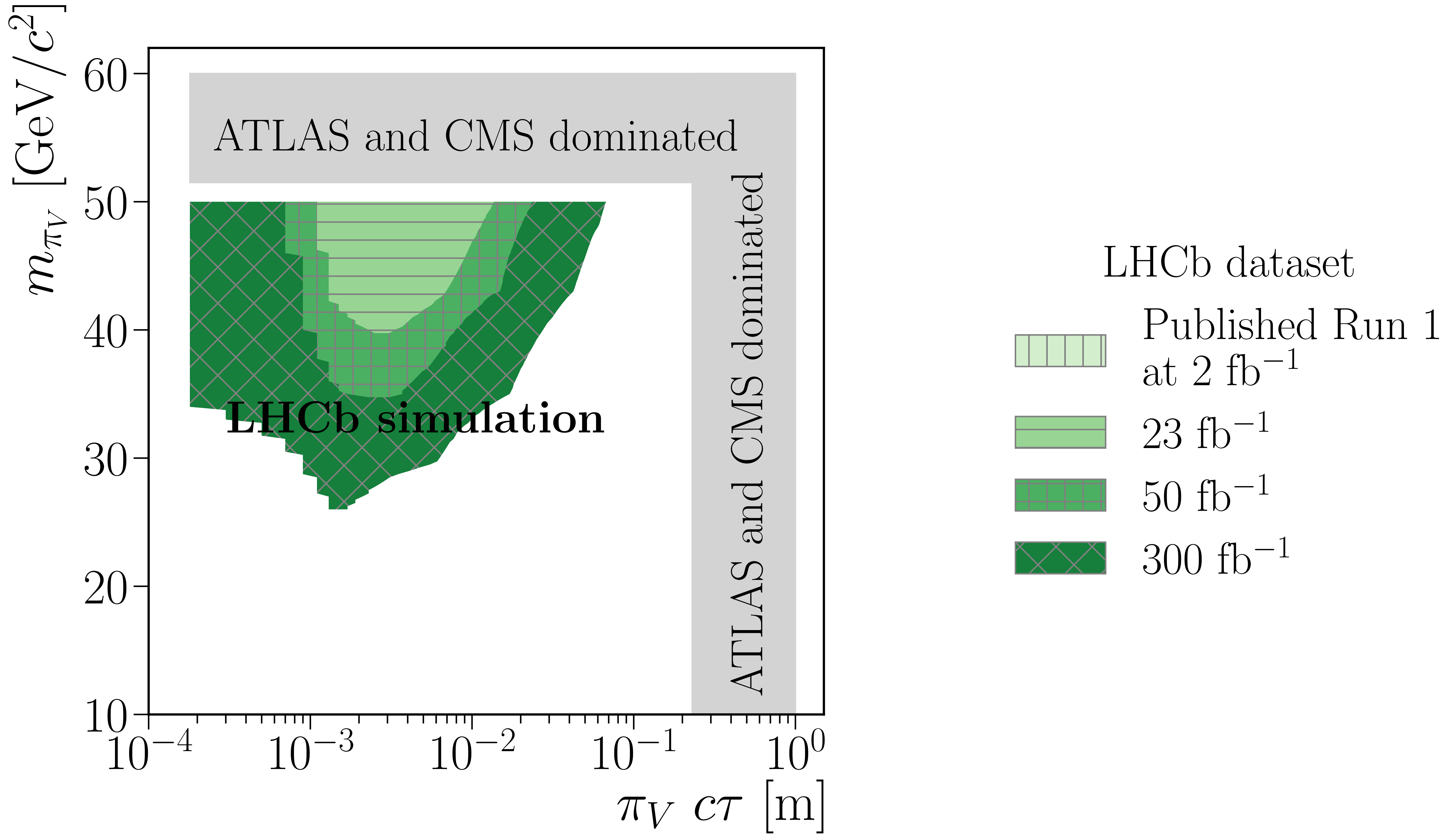
Higgs→LLP→jet pairs / 2



Higgs→LLP→jet pairs / 3



BR(Higgs→πV+πV) < 20 %



BR(Higgs→πV+πV) < 2 %

CMS: disappearing tracks

- One long-lived charged particle decaying within the CMS tracker
- Assuming it decays outside of the detector so track "disappears"
  - Neutral, weakly interacting
  - Too low momentum to be reconstructed
- Observation would be a clear sign of BSM physics
  - Arises in many models
  - Multiple handles to study — decay length, mass, dE/dx, potential recovery of decay products

- Event selection is:
- No tracking information at L1 trigger
  - Trigger on MET from ISR jets at L1
  - At HLT, OR of several MET requirements
    - MET > 105-300 GeV
    - Lowest threshold: MET > 105 GeV and pt > 50 GeV isolated track
- At the offline reconstruction level, require event is consistent with ISR jet
  - MET > 120 GeV
  - ≥1 jet with pt > 110 GeV

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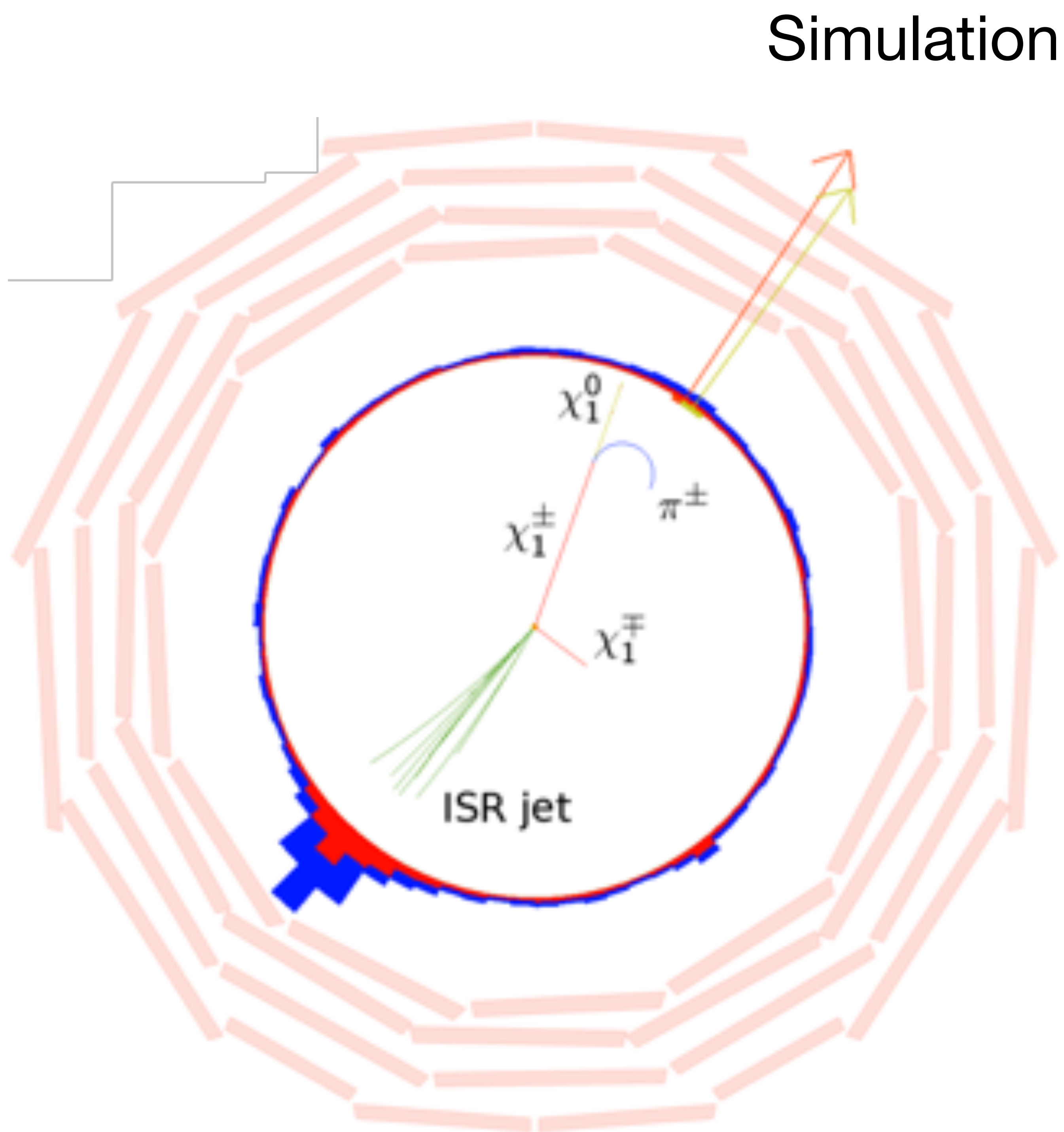
CMS: disappearing tracks



- pt > 55 GeV, isolated from other tracks/jets
- Require high track quality:
  - ≥4 pixel hits
  - No missing inner/middle hits
- Veto all tracks identified as leptons ($e/\mu/\tau_h$)
- Reject tracks in regions of lower lepton reconstruction efficiency
- "Disappearing" is defined as:
  - ≥3 missing outer hits — rejects most SM tracks
  - <10 GeV energy deposited within $\Delta R < 0.5$
    - Rejects most electrons and charged hadrons efficiency
    - E.g. electrons with significant brem. energy causing a track reconstruction failure

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CMS: disappearing tracks

- Results consistent with backgrounds estimations
- In the context of AMSB, these results exclude charginos
  - Wino-like neutralino case — 884 (474) GeV for a lifetime of 3 (0.2) ns
  - Higgsino-like neutralino case — 750 (175) GeV for a lifetime of 3 (0.05) ns
  - New interpretation for 2017-8 data