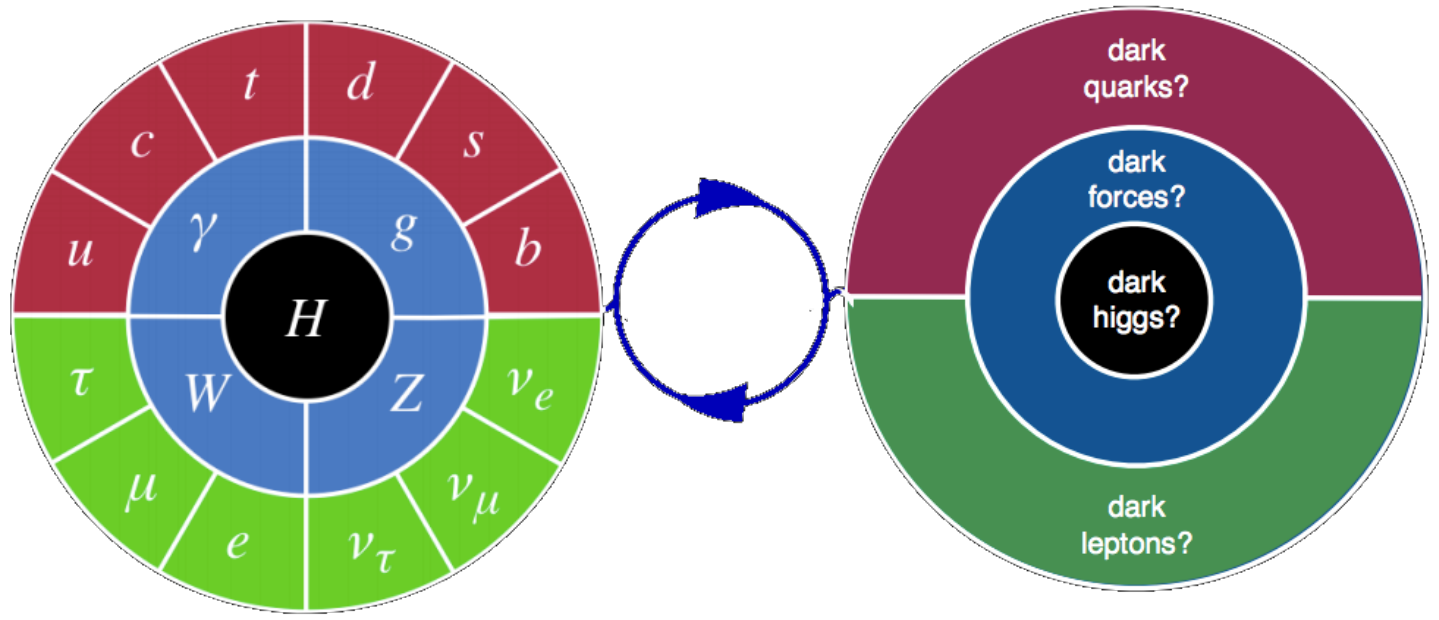
Dark sectors searches at high-intensity colliders

Federico Leo Redi

Joint Annual Meeting of SPS and ÖPG, 26 - 30 August 2019, Zürich

EPFL

Landscape today / 1

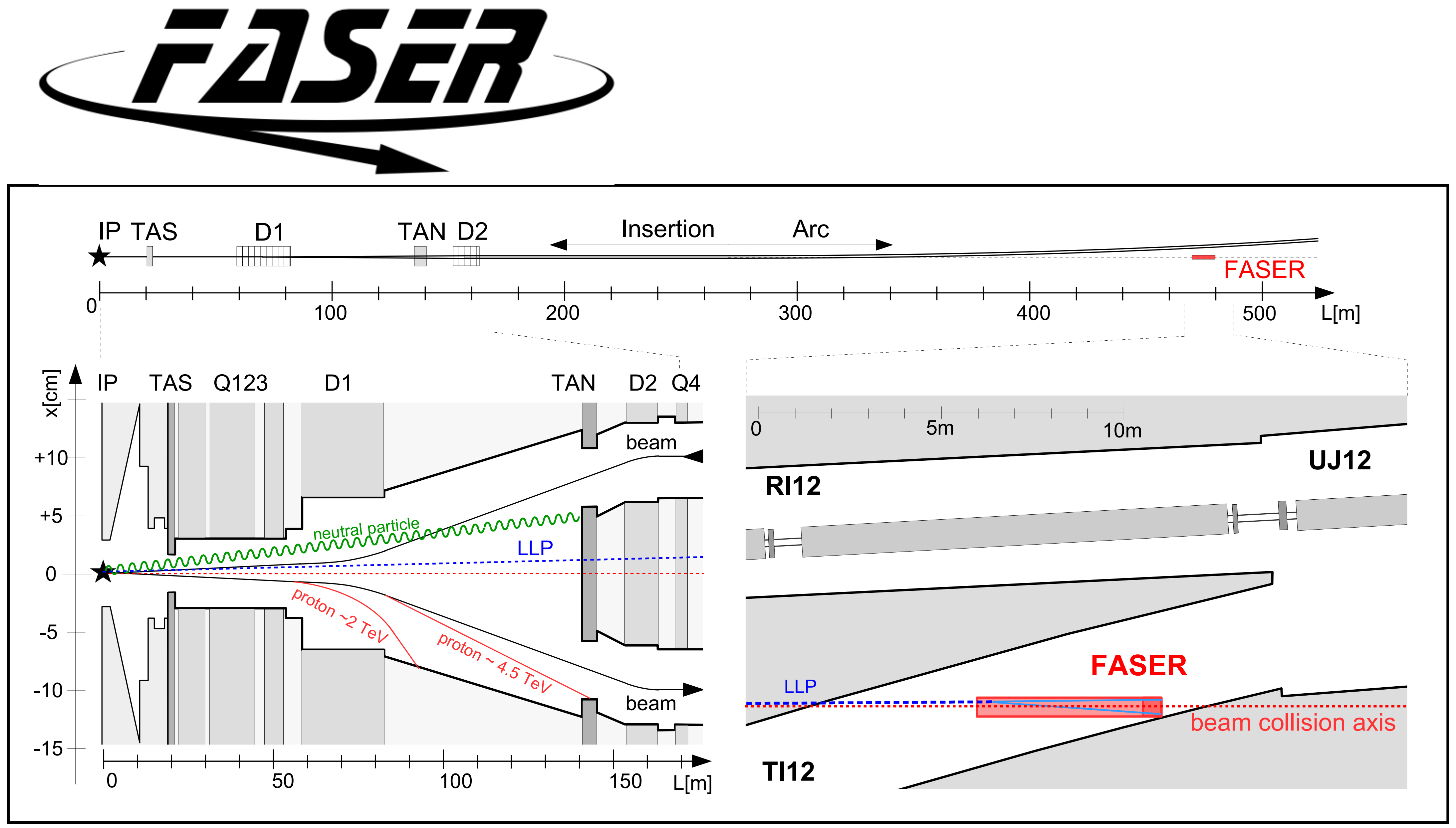


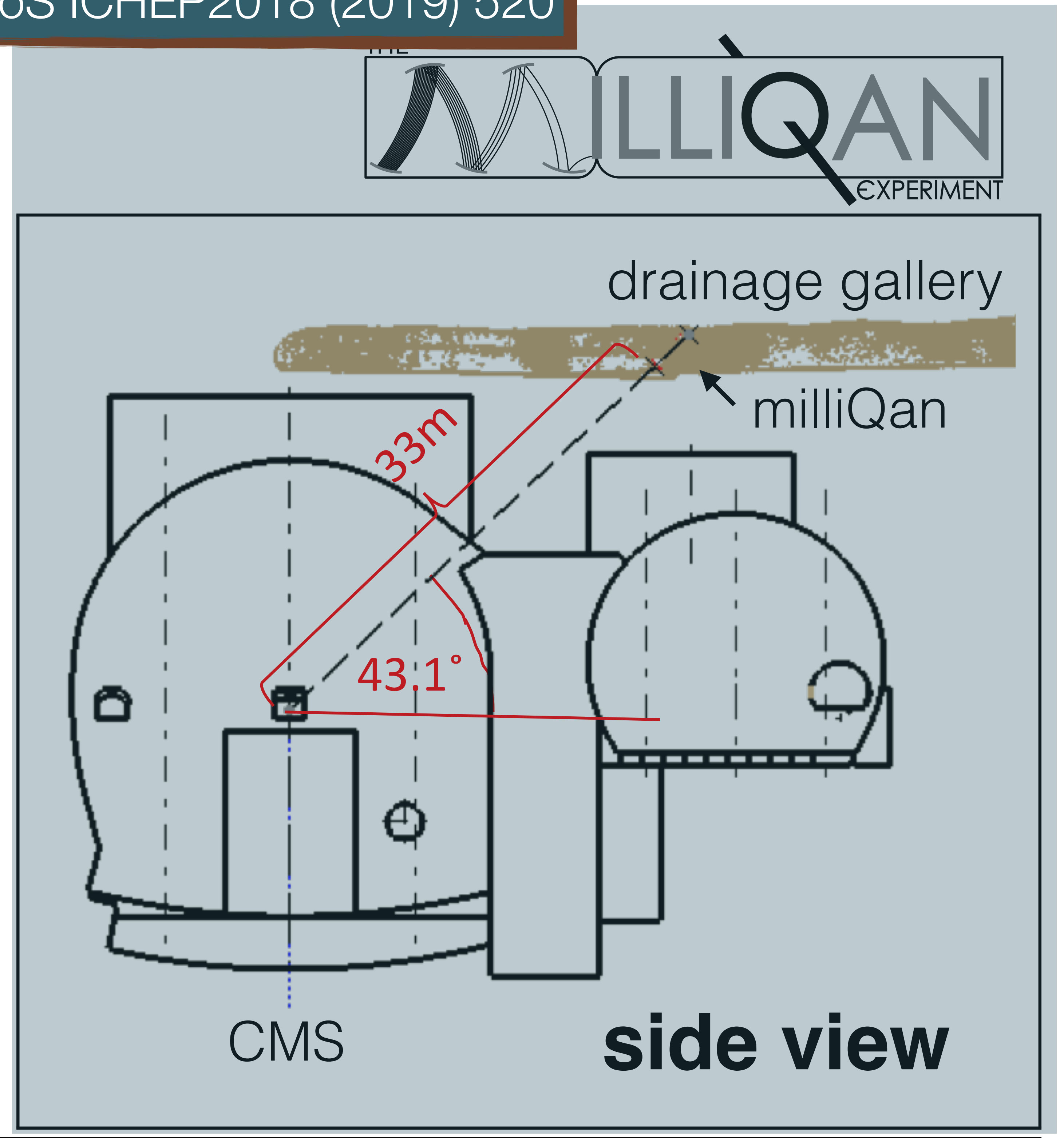
- There exist only **three (four?) portals**:
  1. The **dark photon** portal, thanks to which a new (generically) massiv photon and the Z-boson of the SM
  2. The **Higgs portal**, thanks to which a new dark scalar will interact with the Higgs of the SM. This portal can also induce the mixing of the dark scalar with the SM Higgs
  3. The **neutrino portal**, thanks to which a new dark fermion (a sterile neutrino) will mix with the SM neutrinos (See **Elena's talk**)
  4. Gravity...
- Two strategies of searching for mediators at accelerators:
  Not decaying in the detector (signal proportional to **<coupling>4**)
  Decaying in the detector (signal proportional to **<coupling>2**)

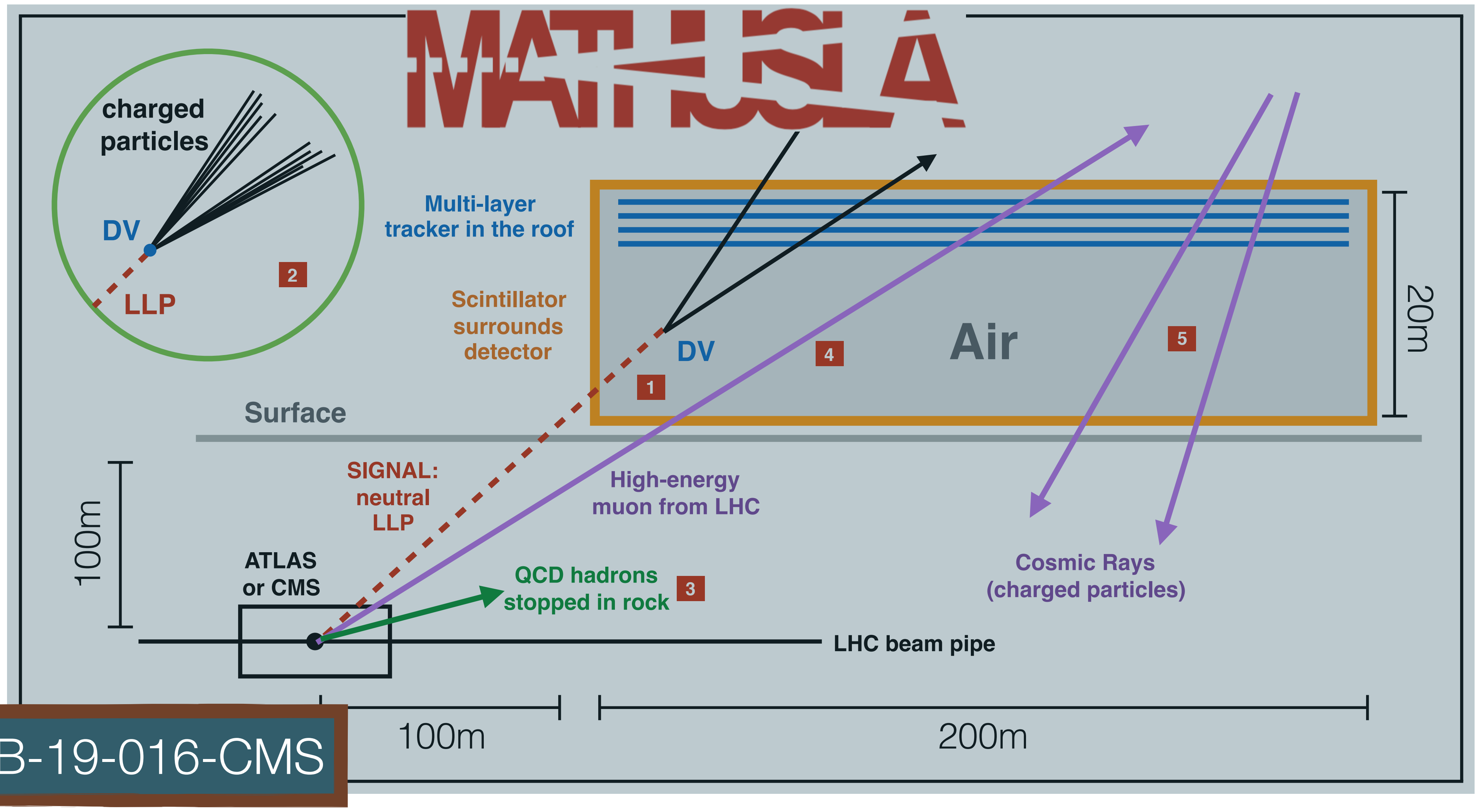
Dark sector far detectors at LHC / 1

- Long-lived particles (LLP) that decay in detector volume
- Fractionally charged particles directly interact in detector

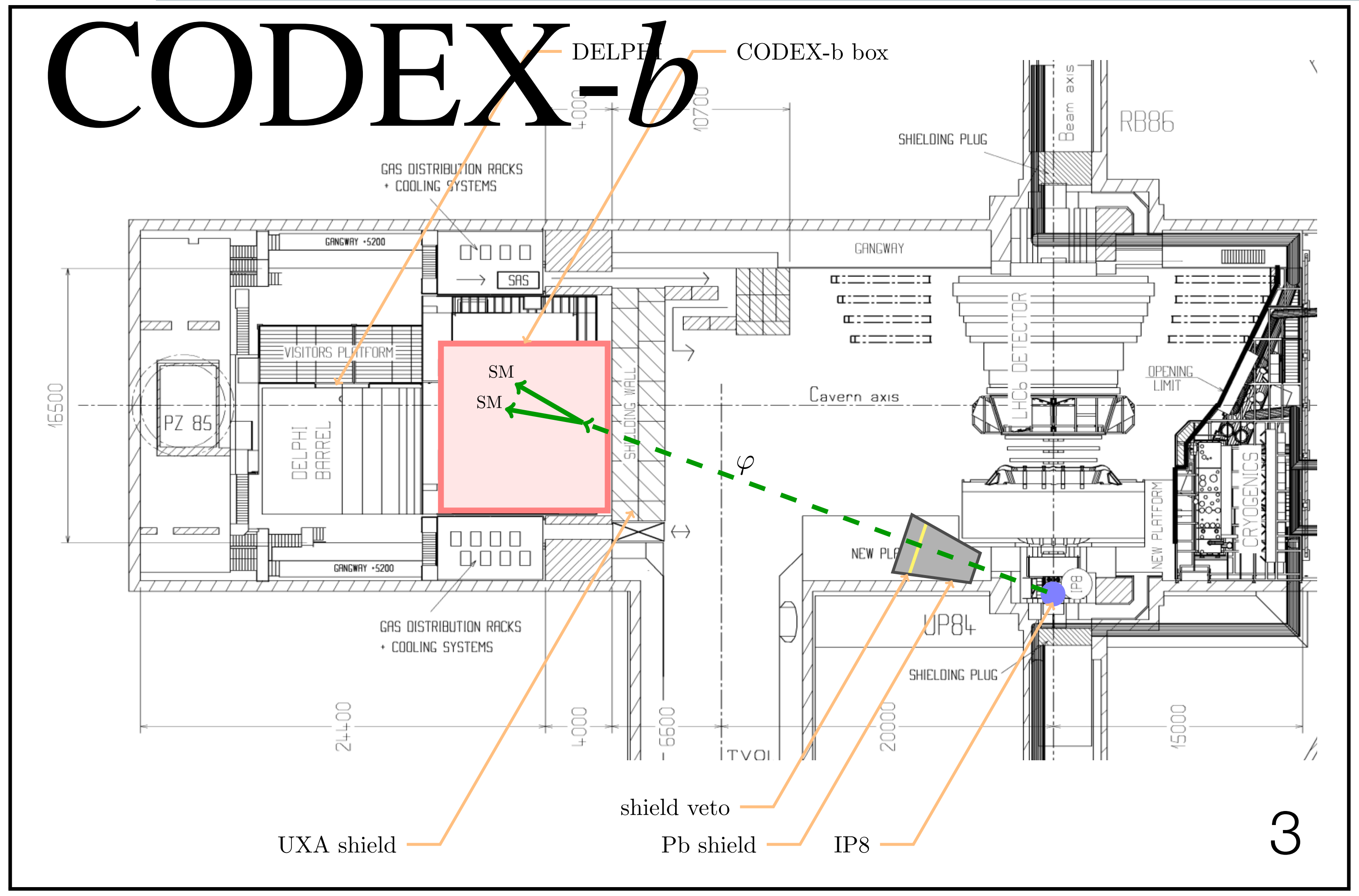
PoS ICHEP2018 (2019) 520







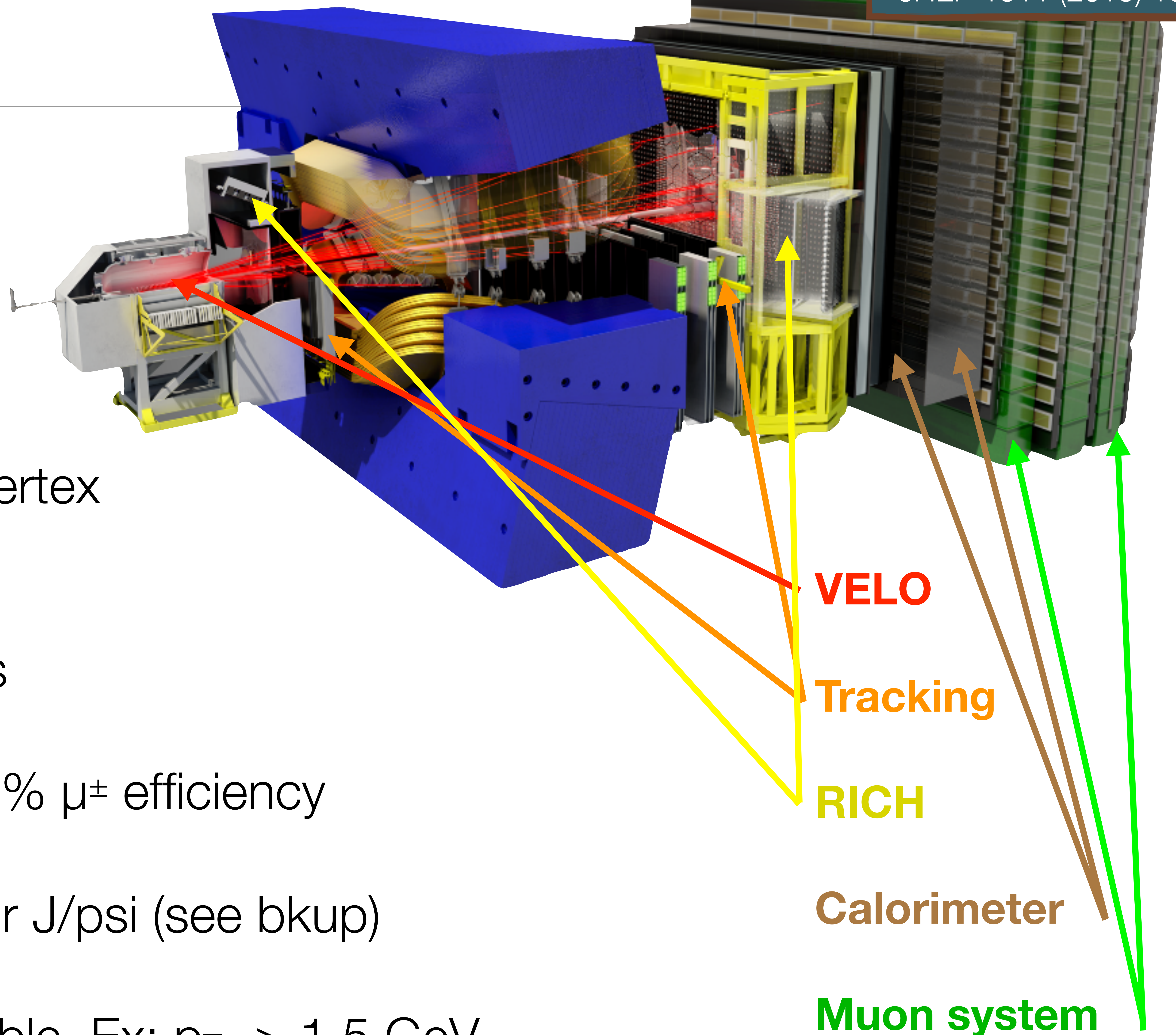
FERMILAB-PUB-19-016-CMS



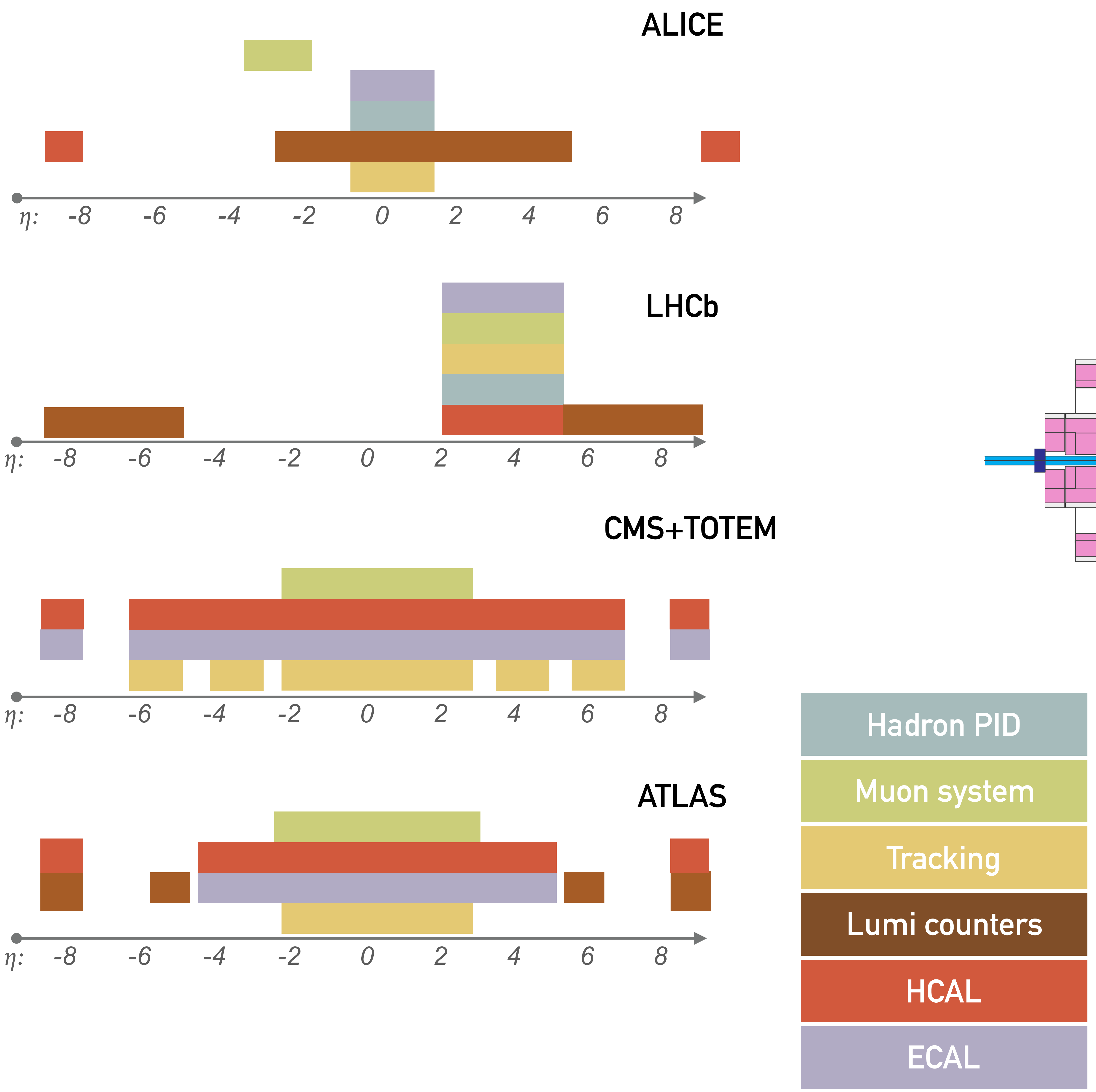
LHCb detector / 1

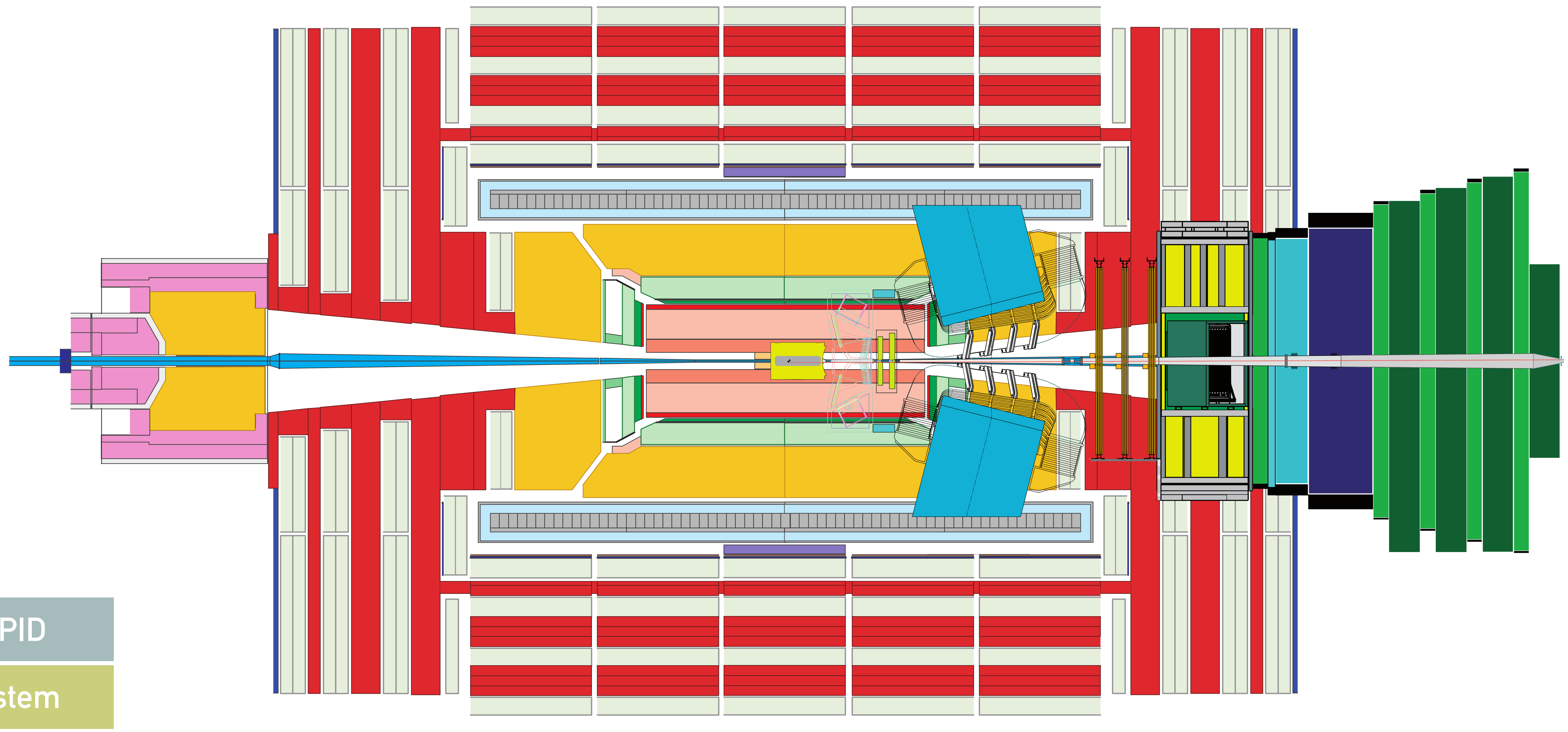
JINST3(2008)S08005
Int J Mod Phys A30(2015)1530022
JHEP 1511 (2015) 103

- **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 ~ 0.2 ps for τ = 100 ps
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency
- Great **mass resolution**: e.g. couple MeV for J/psi (see bkup)
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu} > 1.5$ GeV



LHCb detector / 2

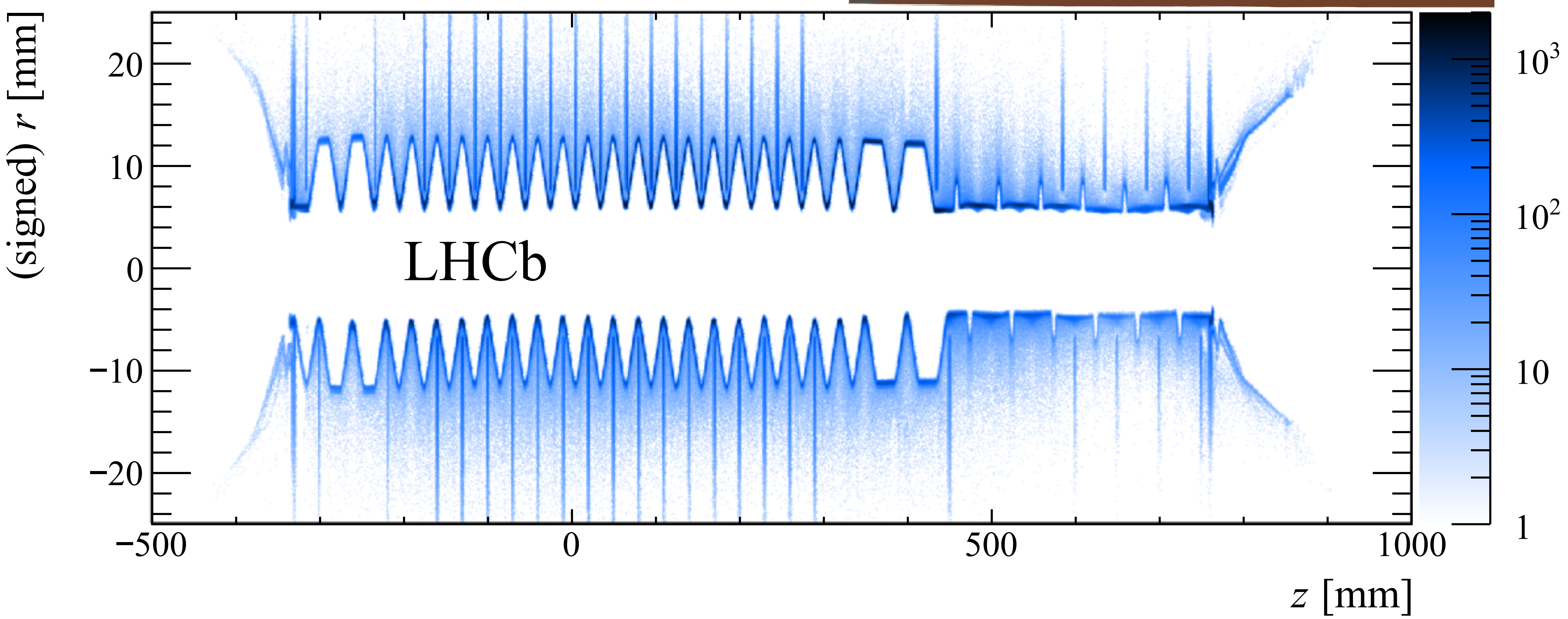


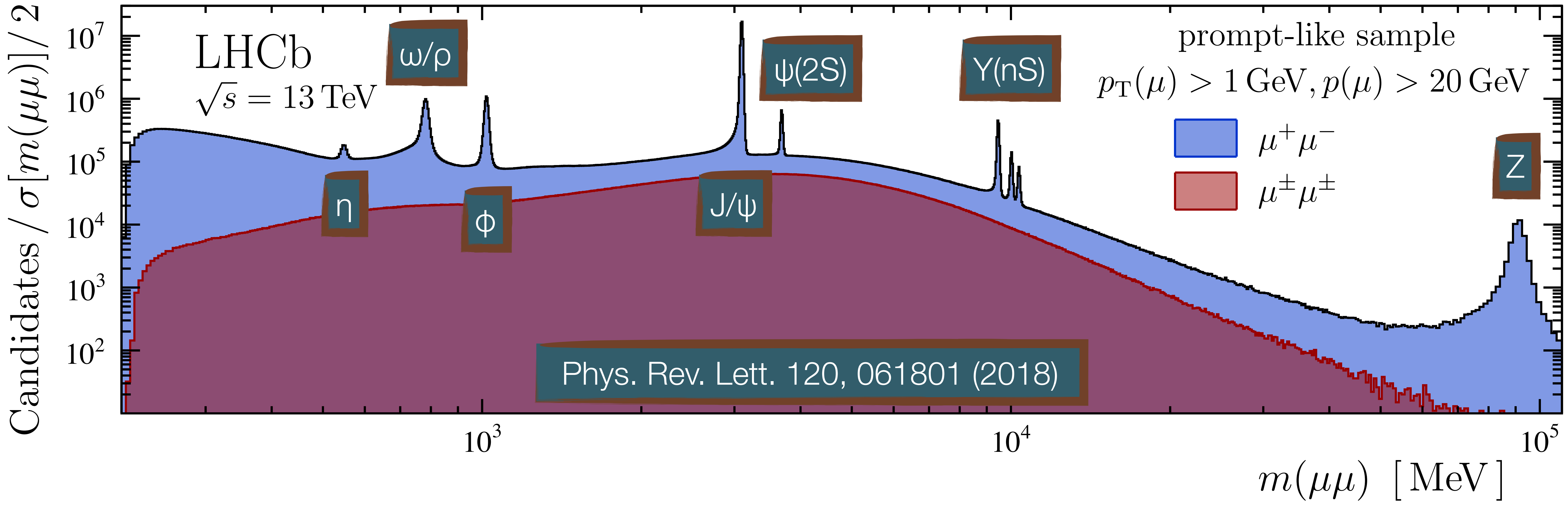


LHCb detector / 3

- 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
- Hardware trigger is still there, and only ~10% efficient at low pT

JINST 13 (2018) no.06, P06008



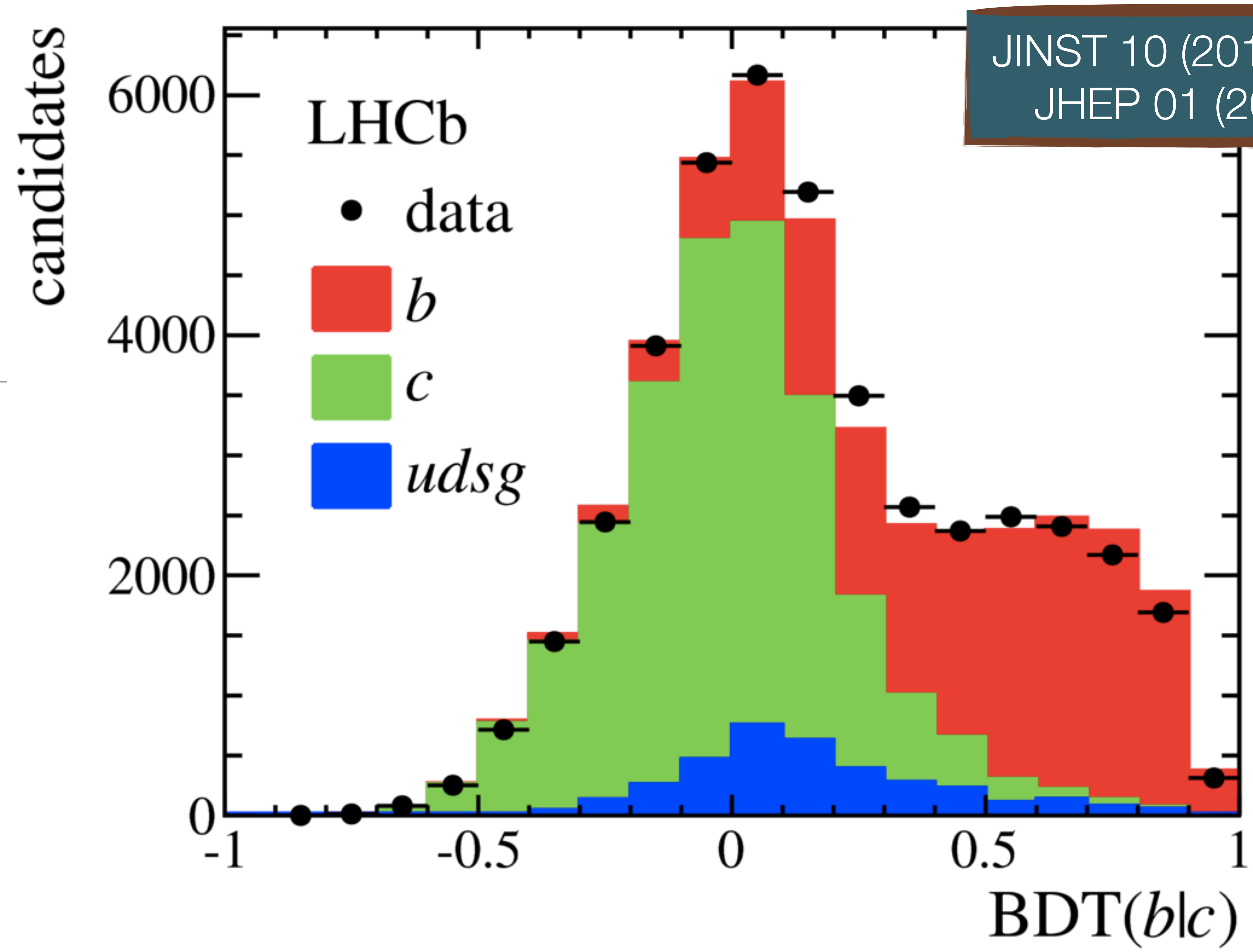


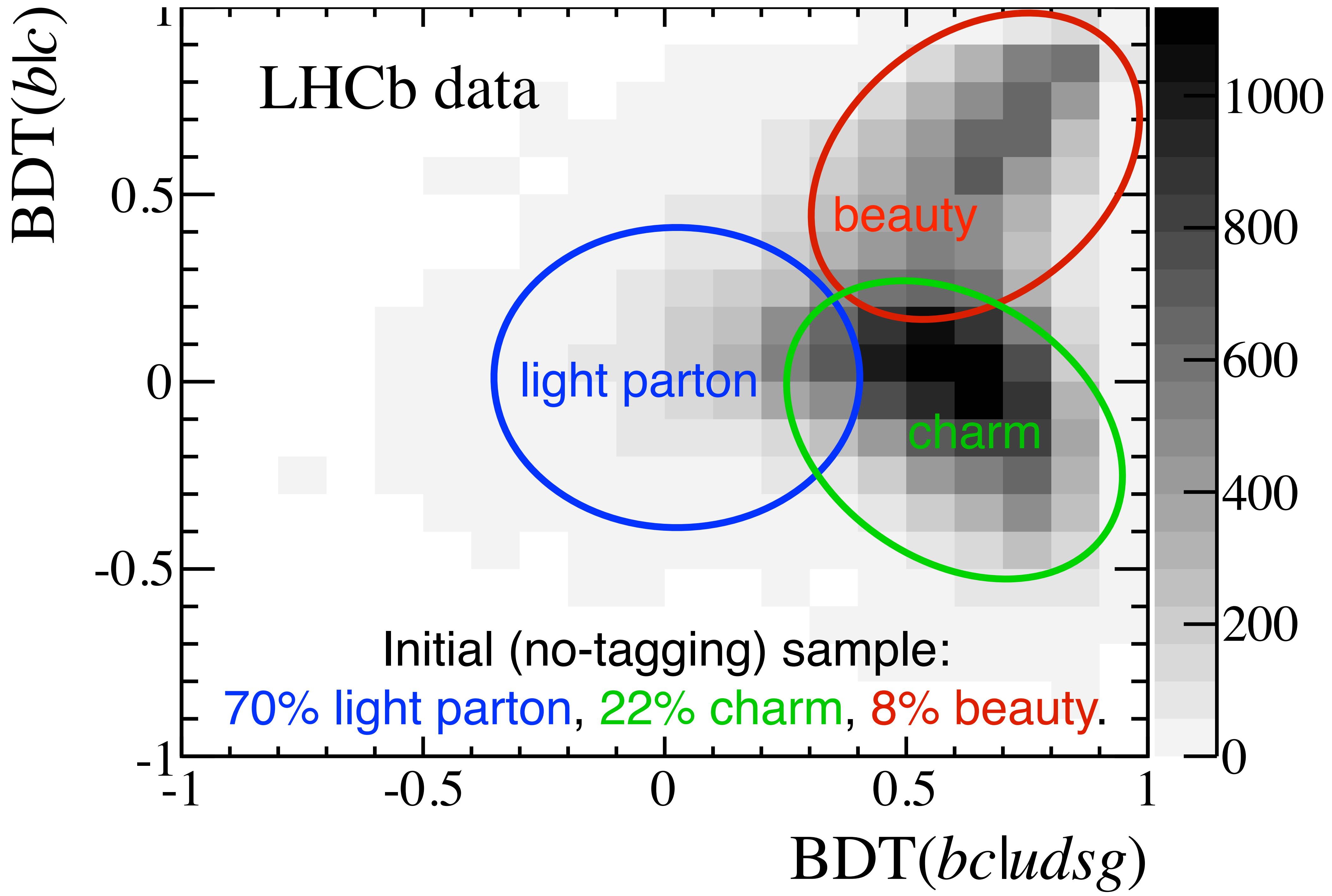
Phys. Rev. Lett. 120, 061801 (2018)

Jet physics at LHCb / 1

- Efficiency above 90% for jets with p_T above 20 GeV
- Jets reconstructed both online and offline!
- **b and c jet tagging**
- Require jets with a secondary vertex reconstructed close enough
- **Light jet** mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$
- SV properties (**displacement**, **kinematics**, **multiplicity**, etc) and jet properties combined in **two** BDTs
  - **BDT$_{b|c}$** optimised for b versus c discrimination
  - **BDT$_{bc|udsg}$** optimised for heavy flavour versus light discrimination

JINST 10 (2015) P06013
JHEP 01 (2014) 033

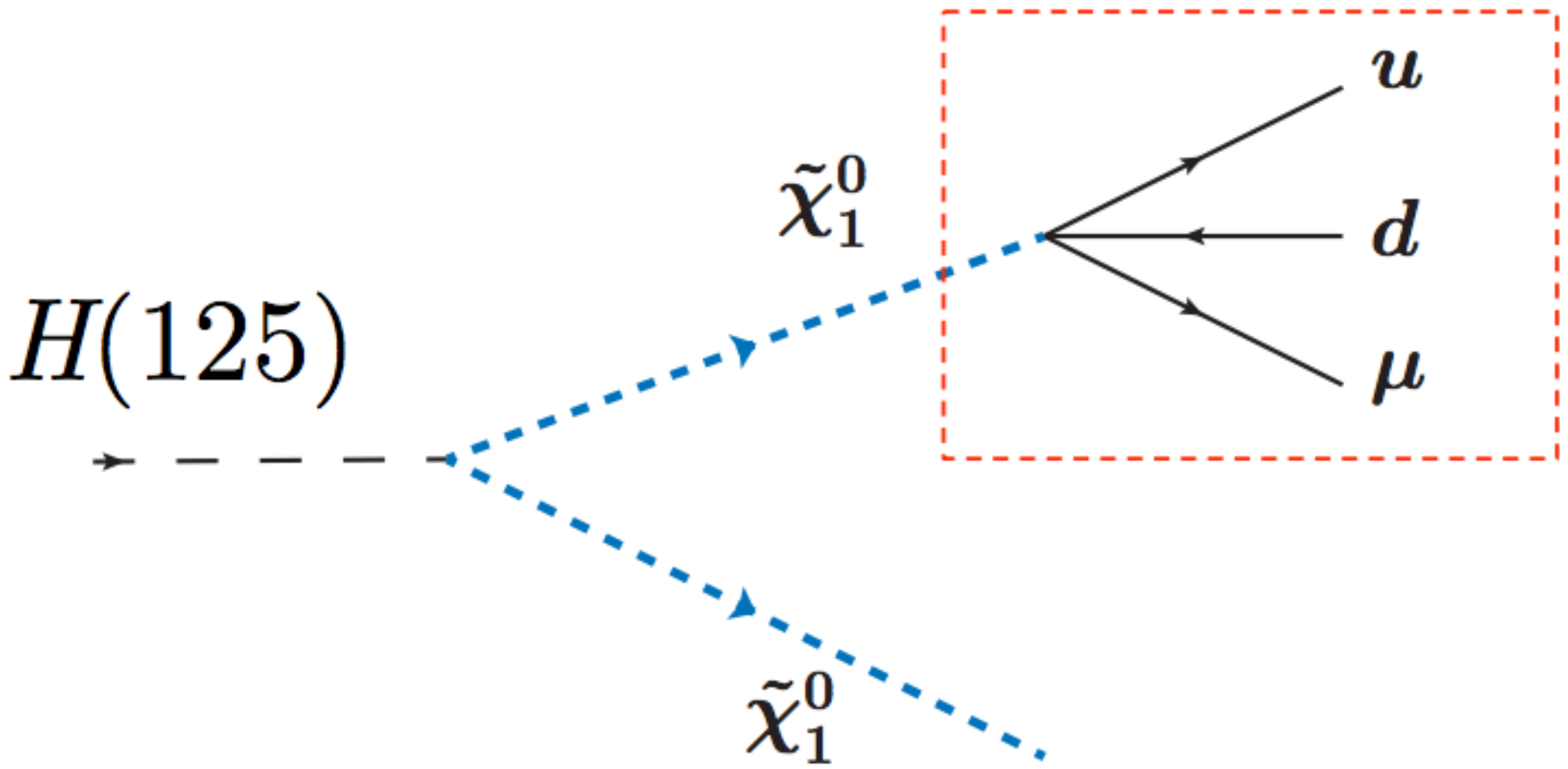


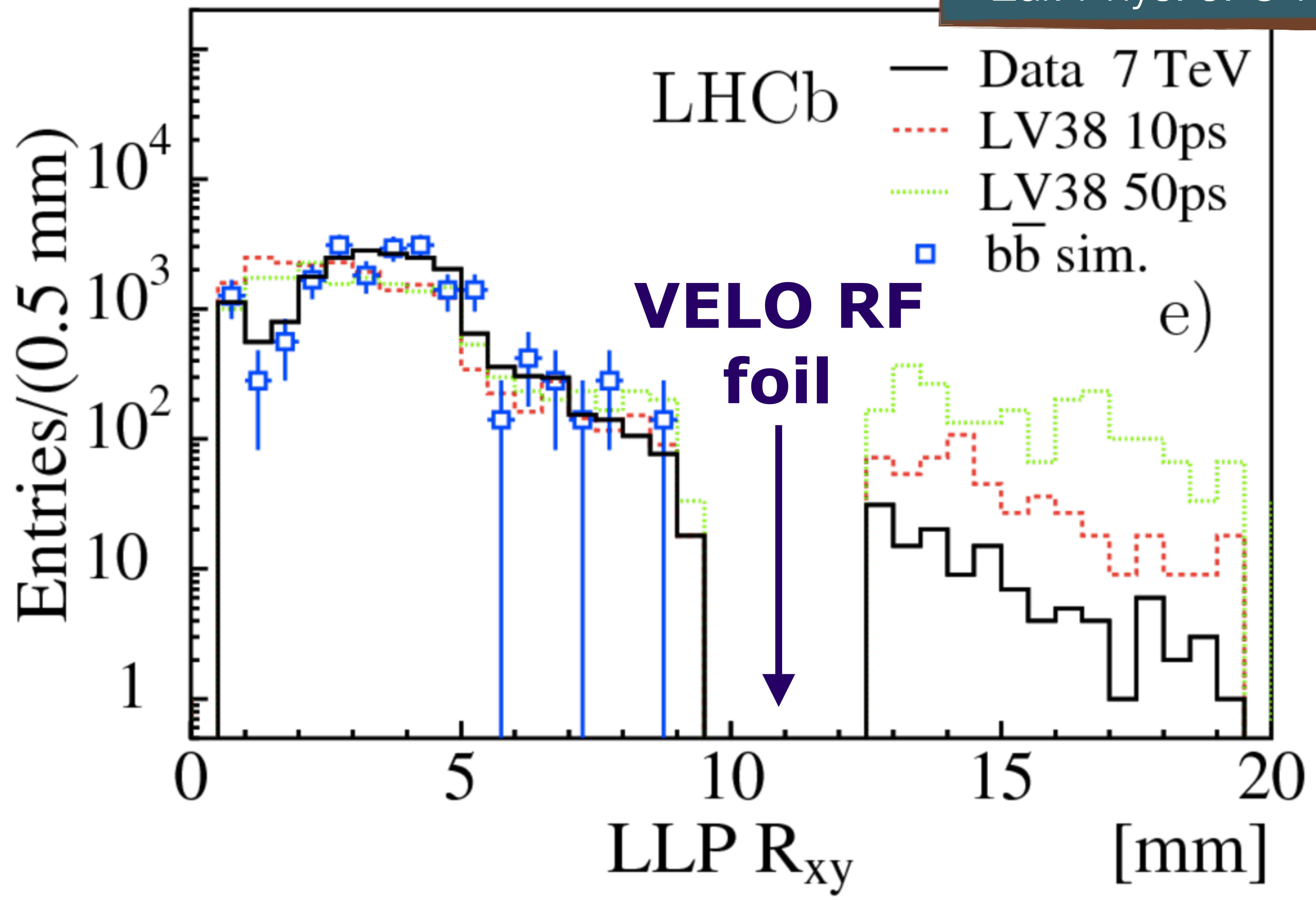


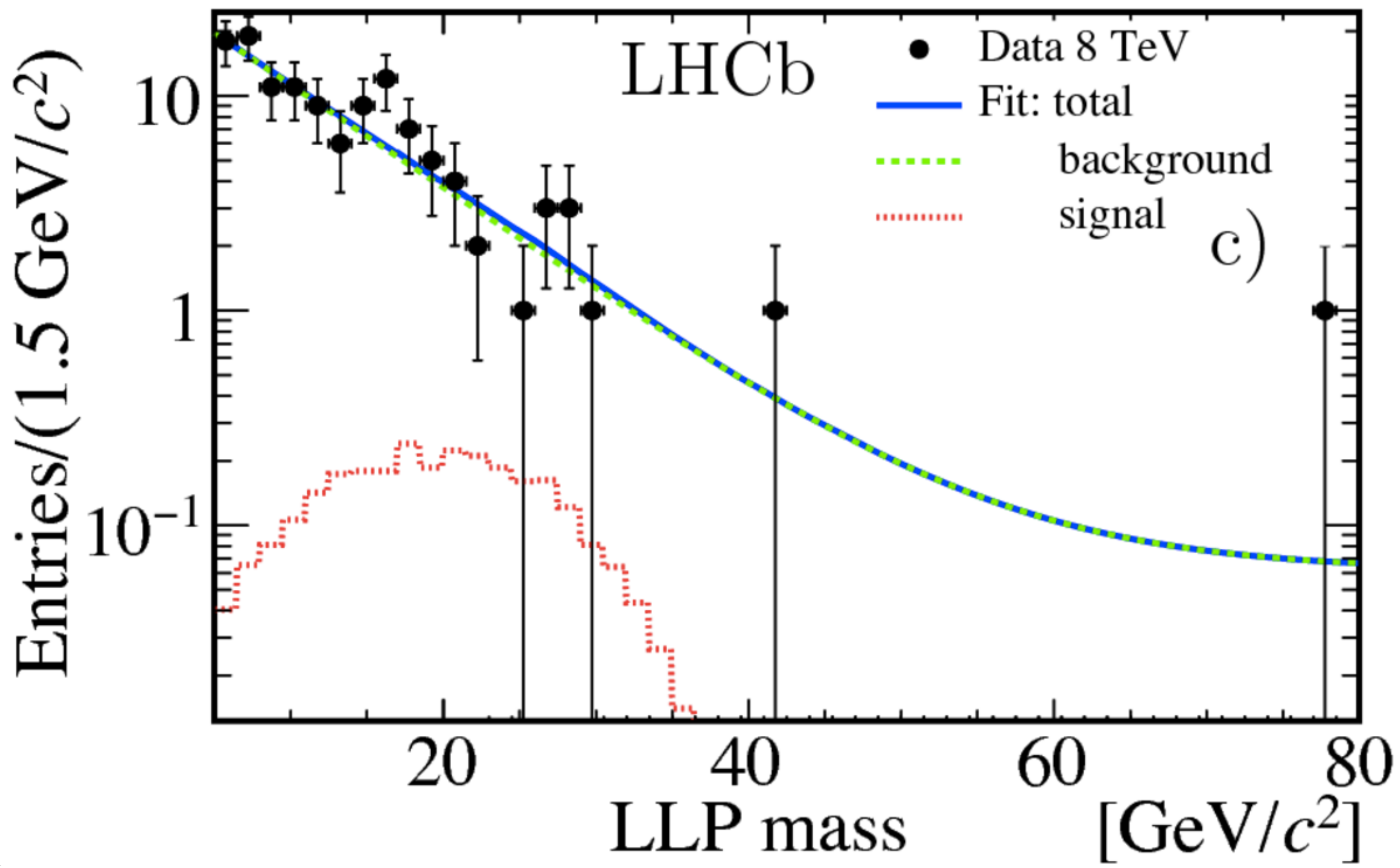
Eur. Phys. J. C 77 224

Higgs→LLP→μ+jets / 1

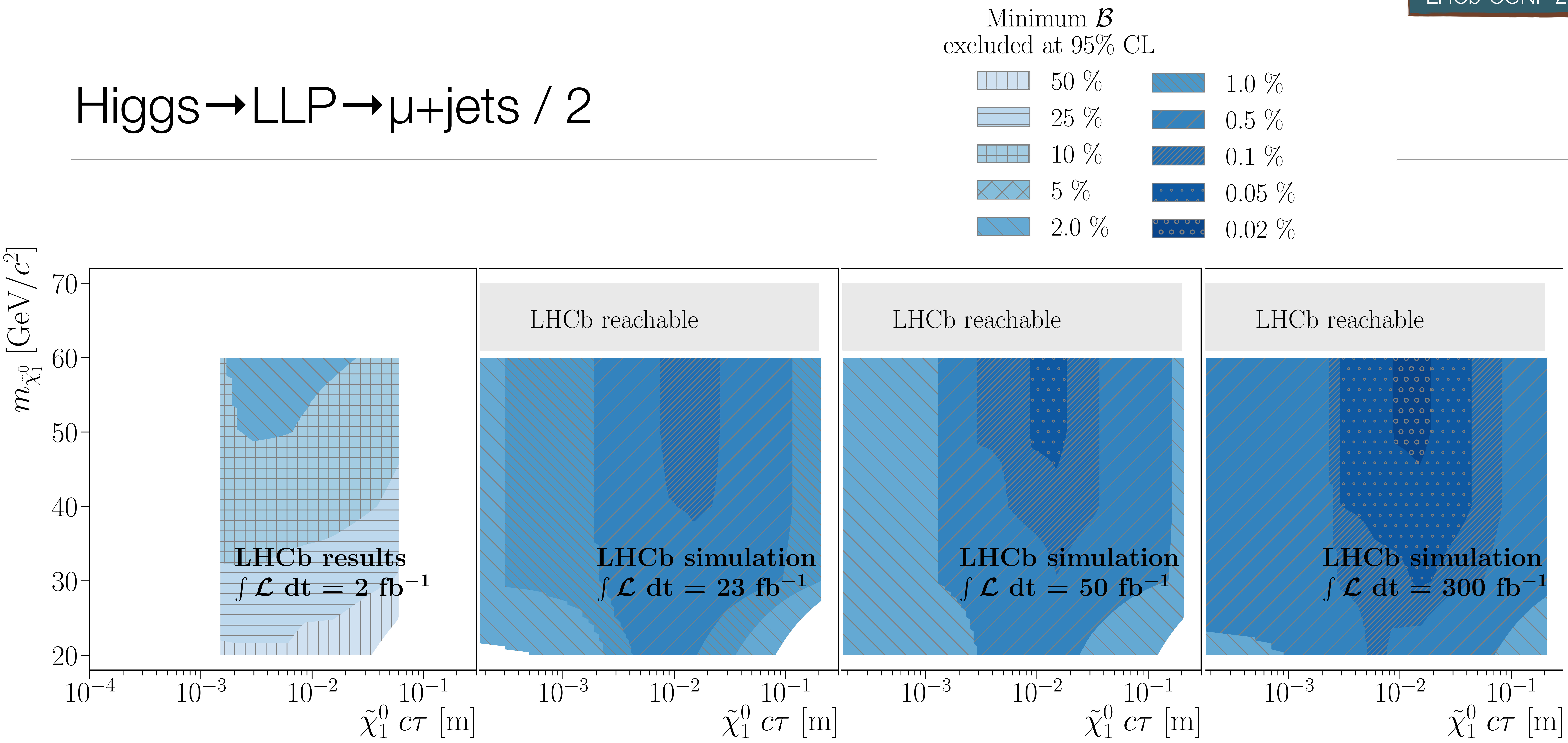
- Massive **LLP** decaying → **μ**+qq (→ **jets**)
- **Single displaced vertex** with several tracks and a high p_T muon; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- **m_{LLP}=[20; 80] GeV** and **τ_{LLP}=[5; 100] ps**
- Background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



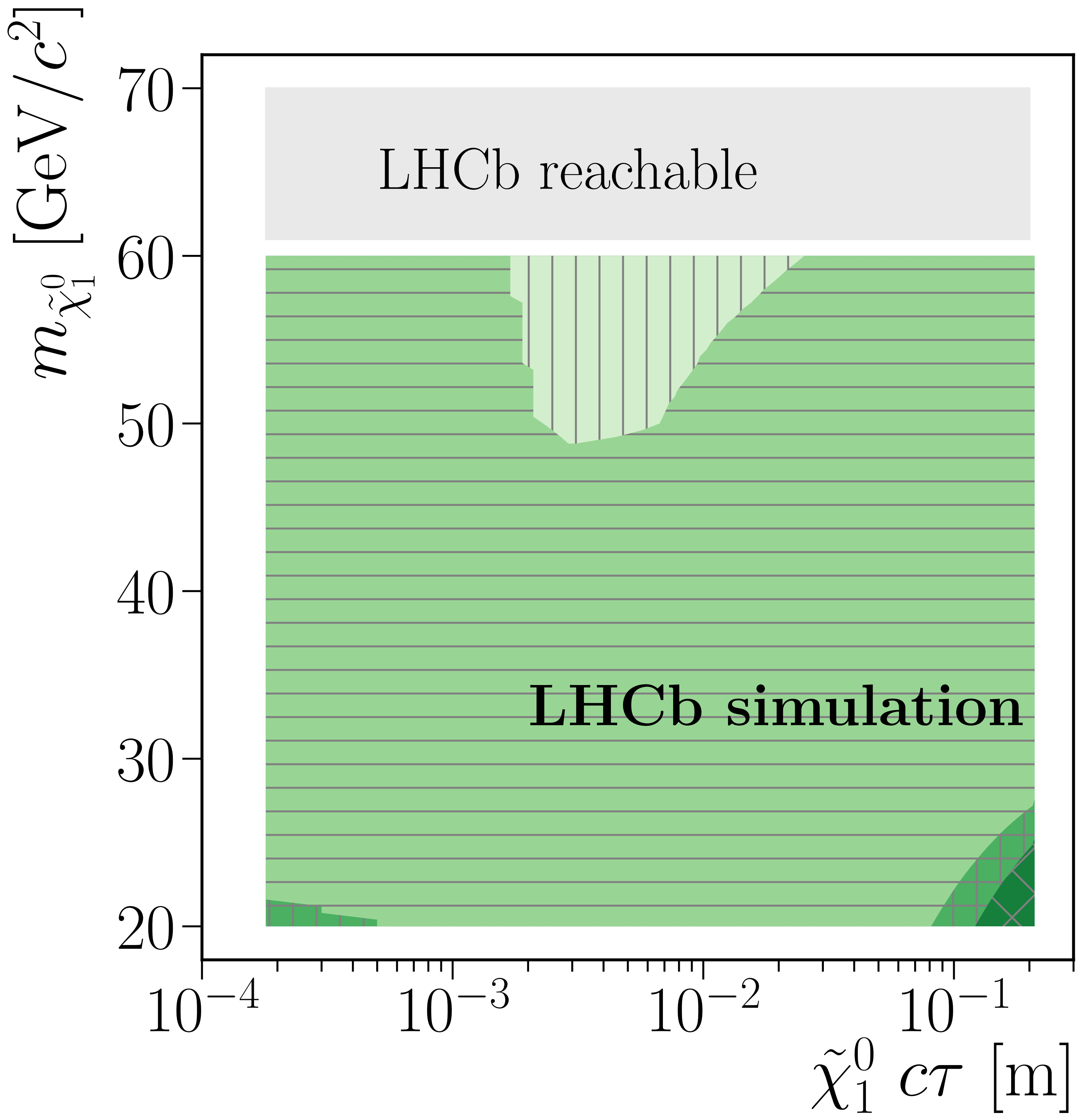




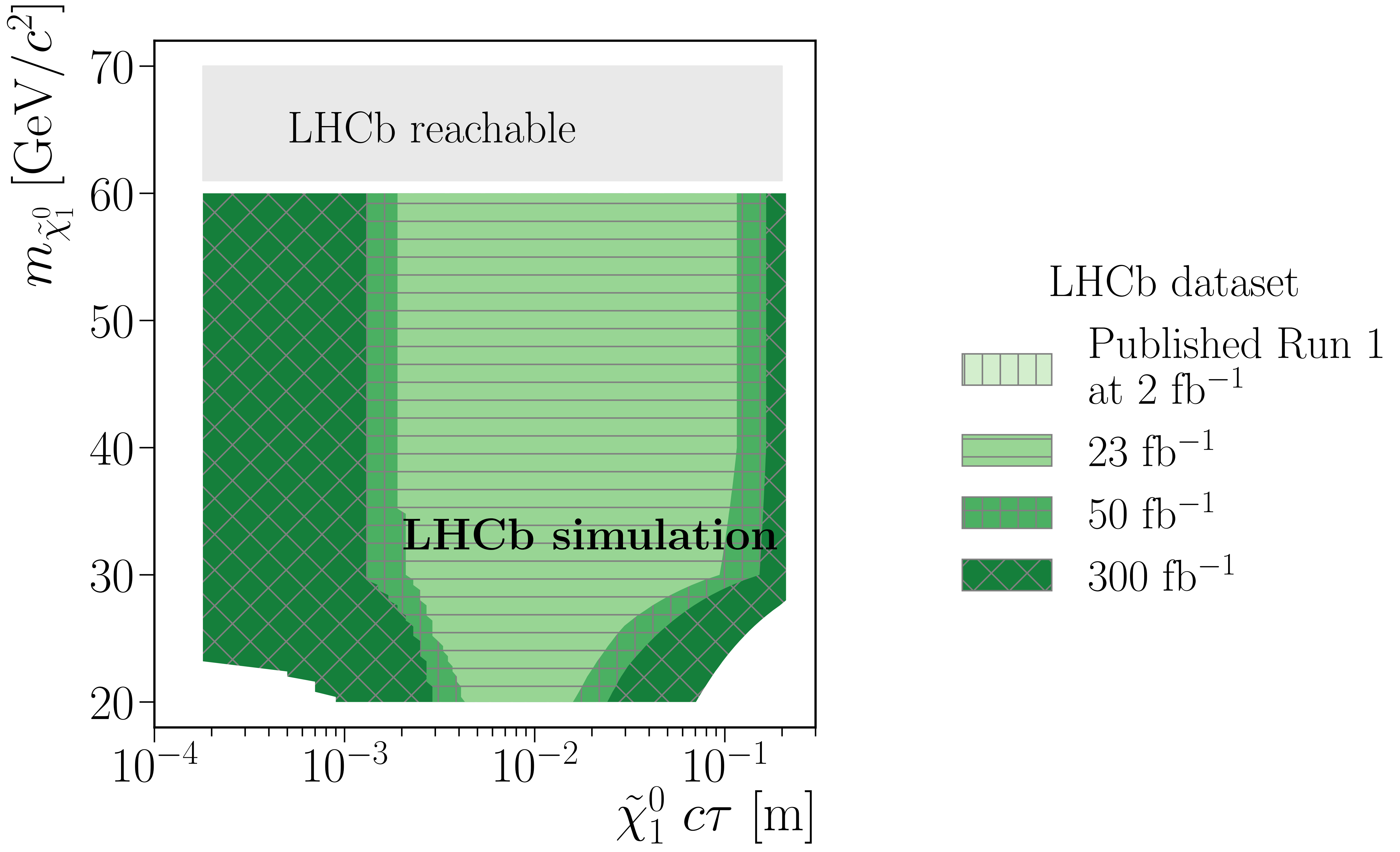
Higgs→LLP→μ+jets / 2



Higgs→LLP→μ+jets / 3



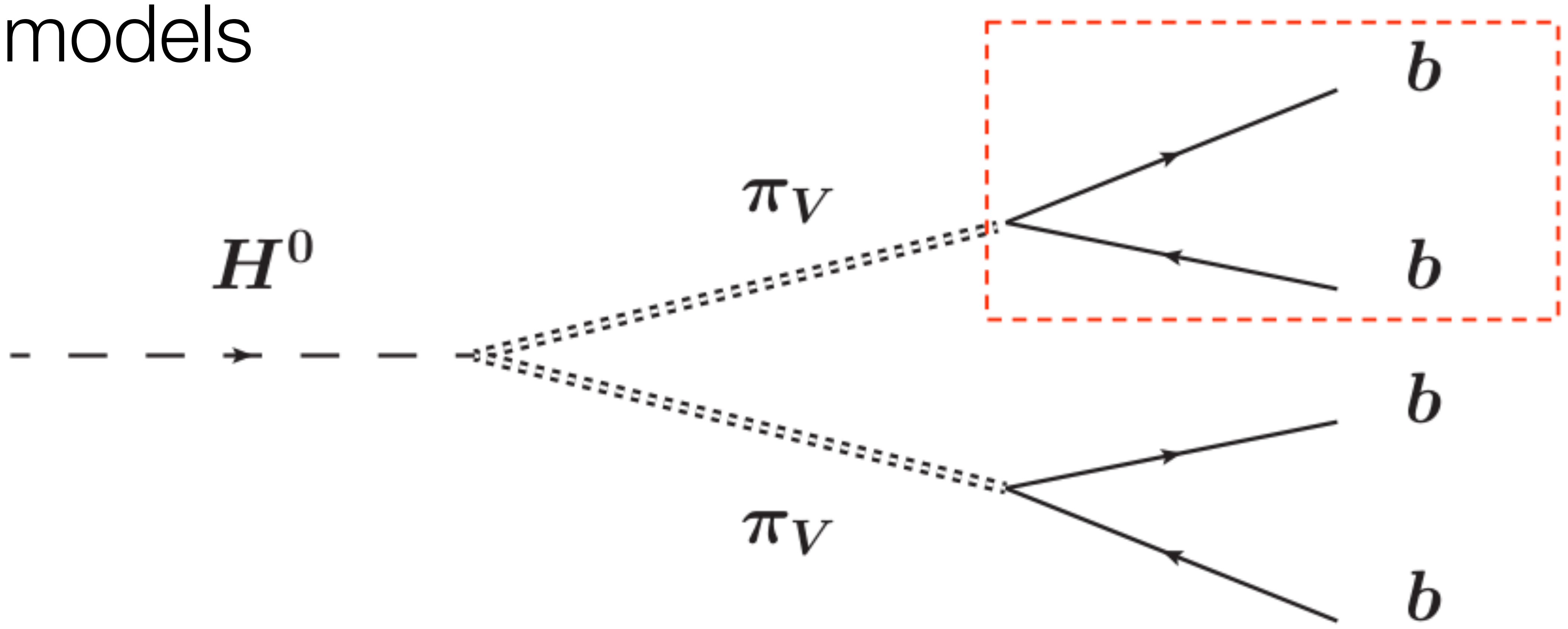
Bf(Higgs→LLP+LLP) < 2 %

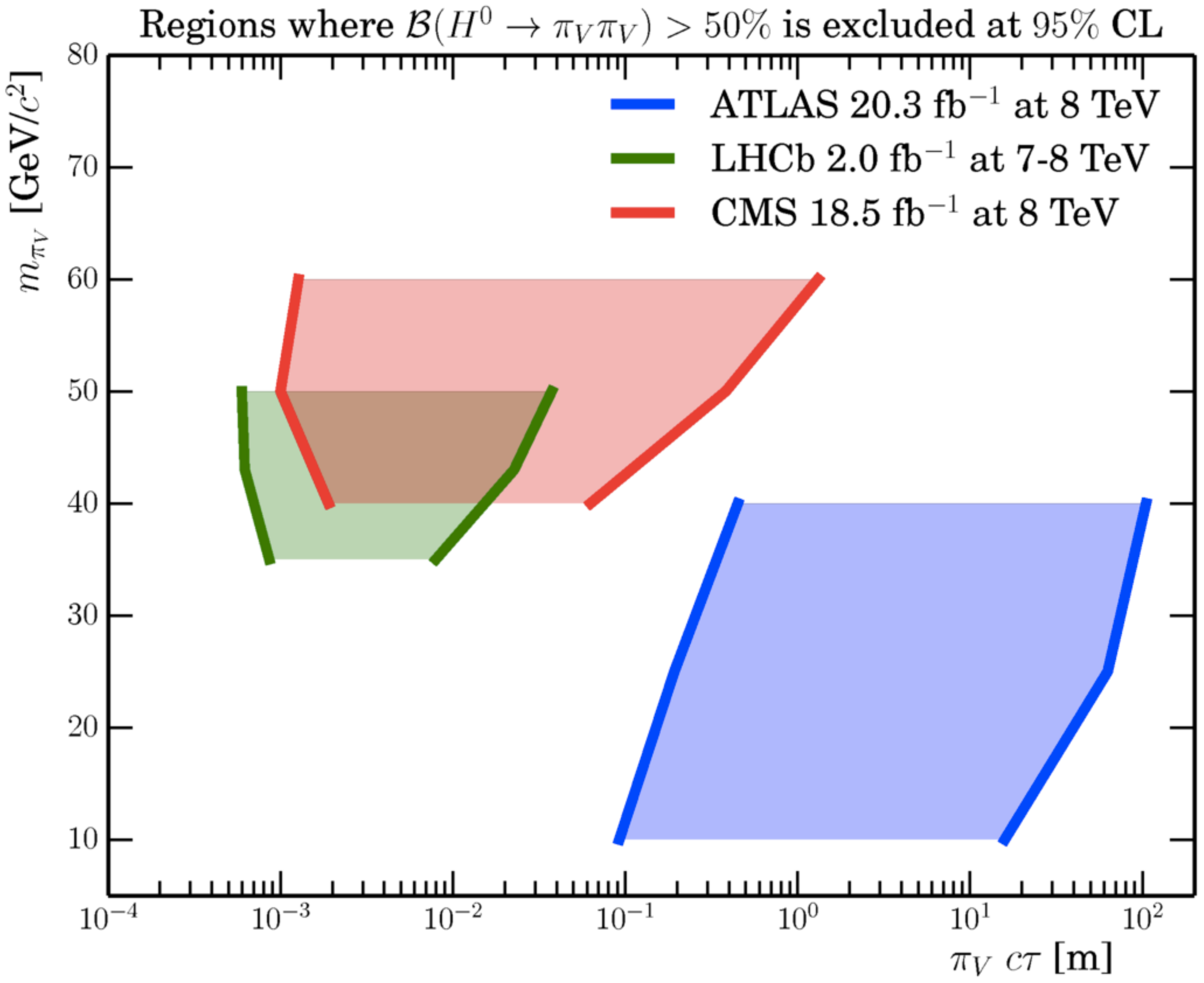


Bf(Higgs→LLP+LLP) < 0.5 %

Higgs→LLP→jet pairs / 1

- Massive **LLP** decaying →bb+bb with bb → **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

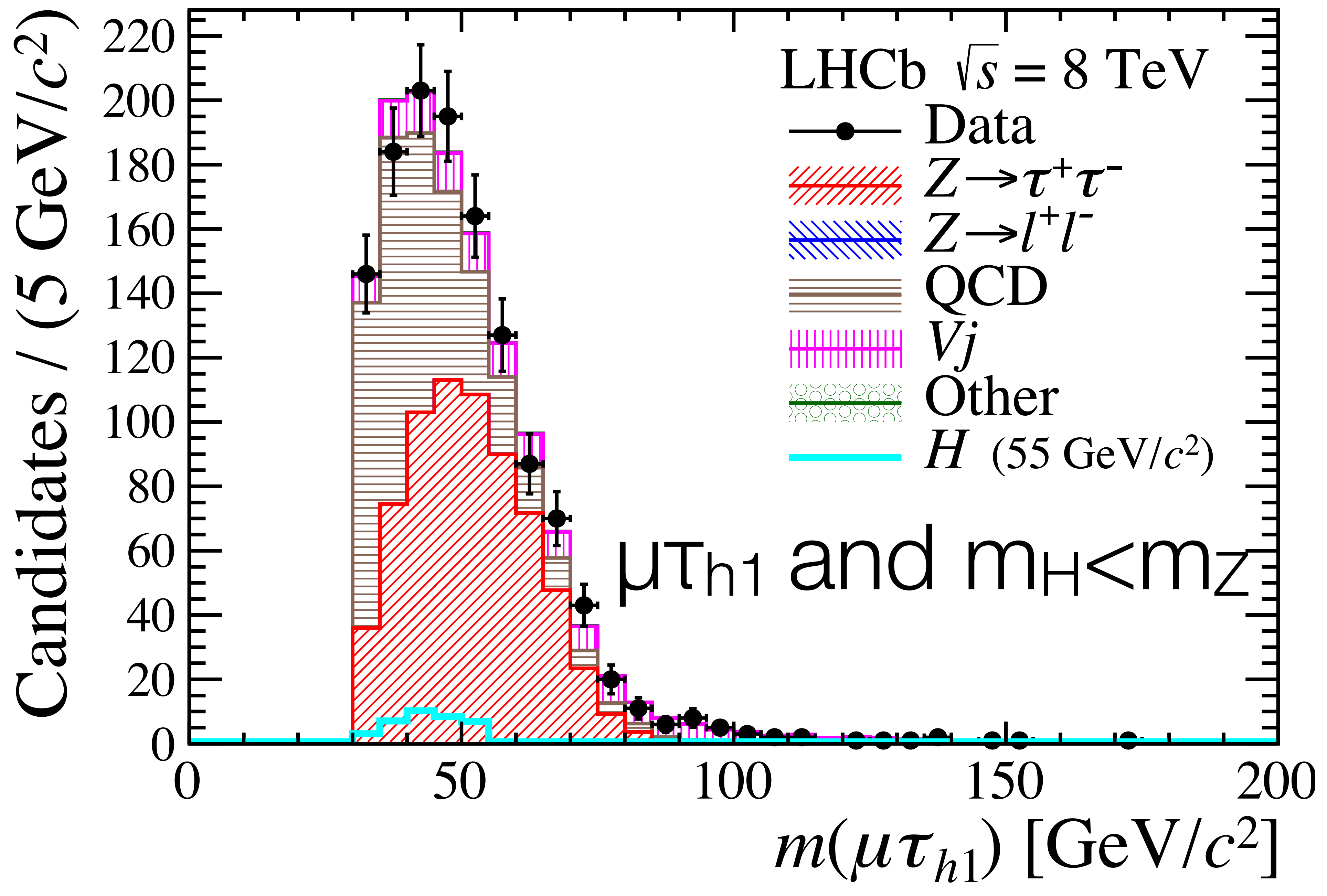


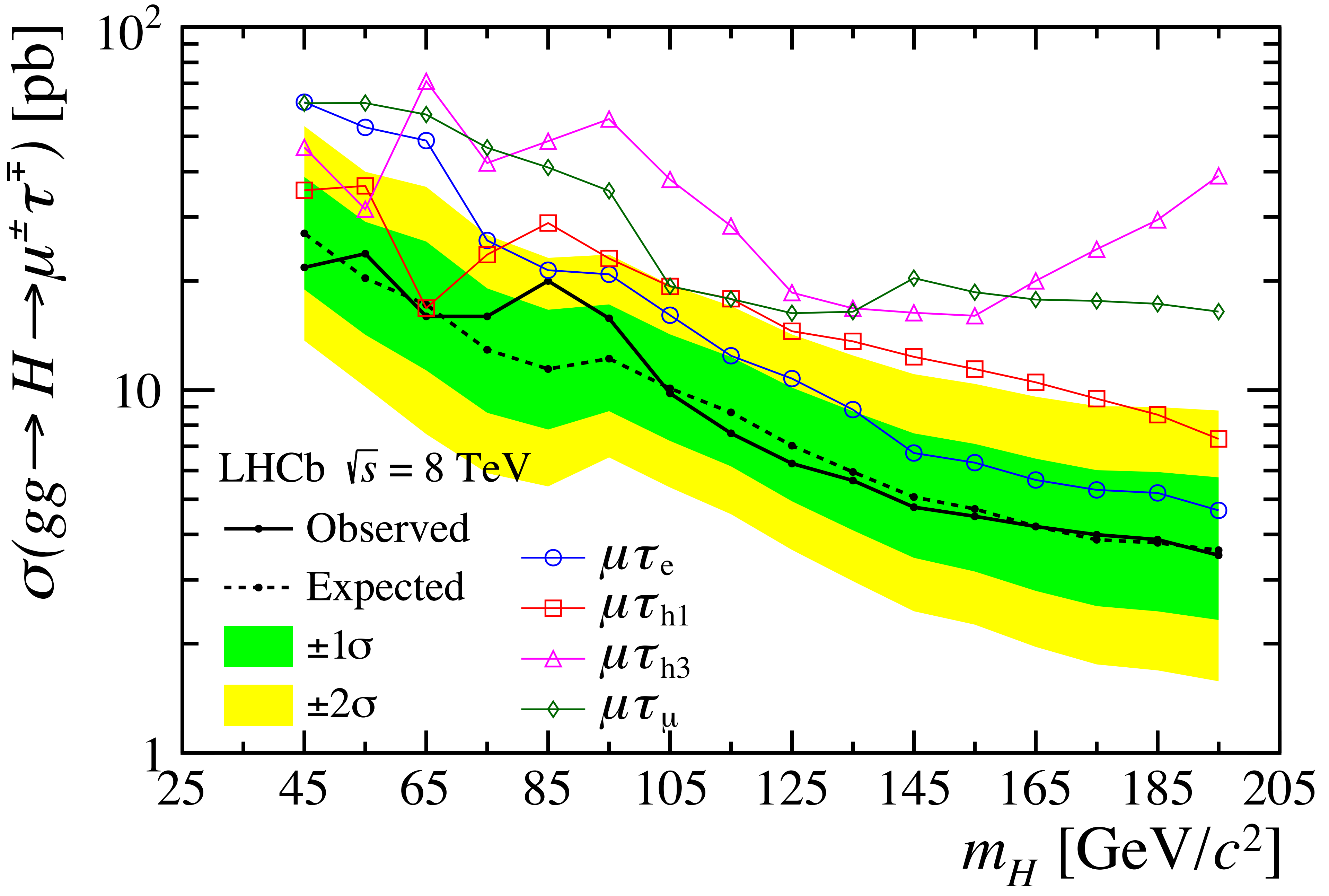


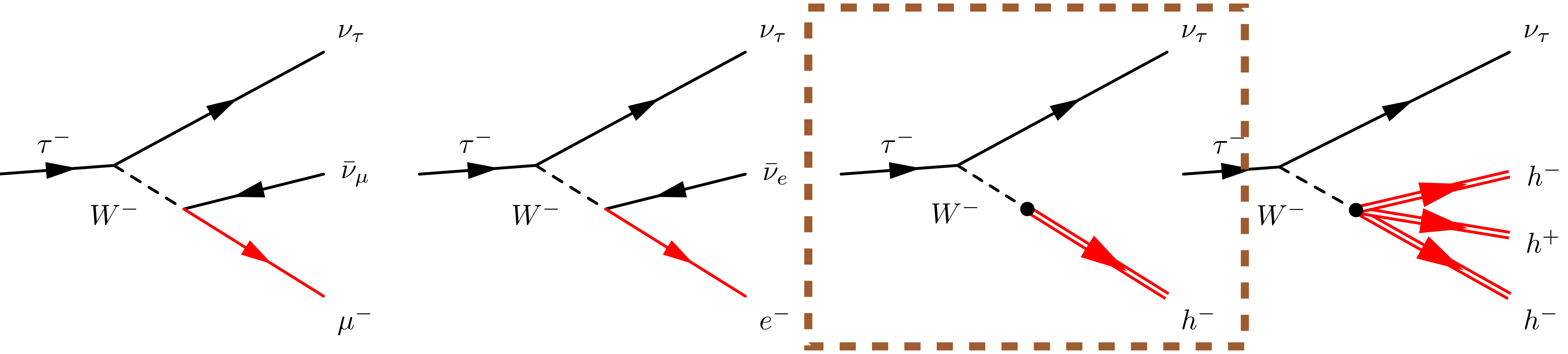
Eur.Phys.J. C78 (2018) no.12, 1008

H→μτ decays / 1

- Higgs-like boson decaying → μτ charged-lepton flavour-violating (CLFV)
- Analysis is separated into **four channels**
- **m_H=[45; 195] GeV** and **minimal flight distance** (impact parameter) of the reconstructed candidate is imposed
- Three different selections based on **m_H** w.r.t. **m_Z**
- Background dominated by **QCD**, **Z→ττ**, **Vj**
- No excess found



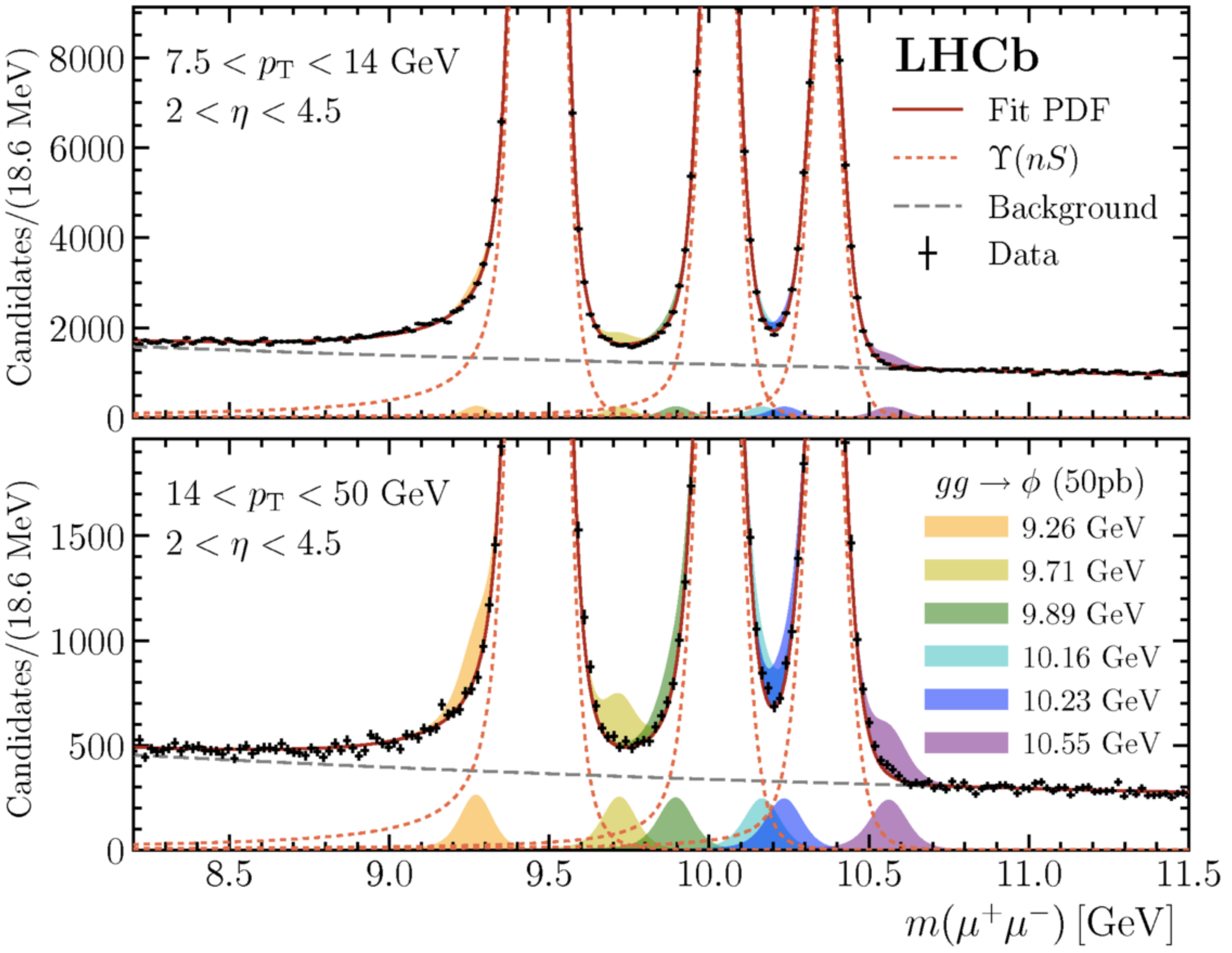




Searching in the Y mass region / 1

JHEP 1809 (2018) 147

- Other light spin-0 particles in which LHCb can do well are light bosons from pp; **only Run 1**
- Spin-0 boson, ϕ, using Run 1 **prompt** $\phi \to \mu^+\mu^-$ decays, have been searched for
- Use **dimuon** final states:
  - Access to different mass window w.r.t γγ or ττ searches in 4π experiments
- Done in **bins of kinematics** ([p_T,η]) to maximise sensitivity
- Precise modelling of Y(nS) tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)

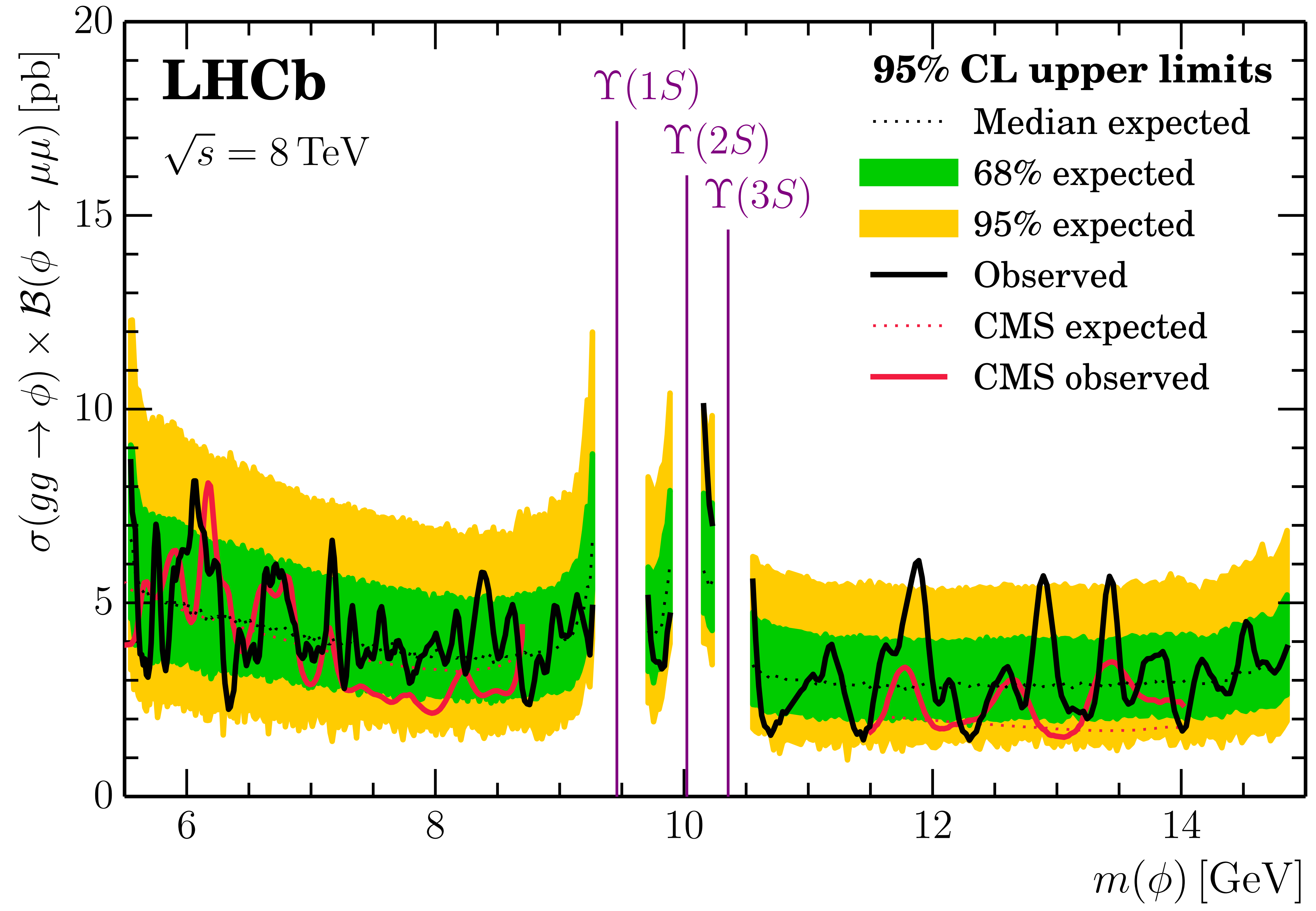


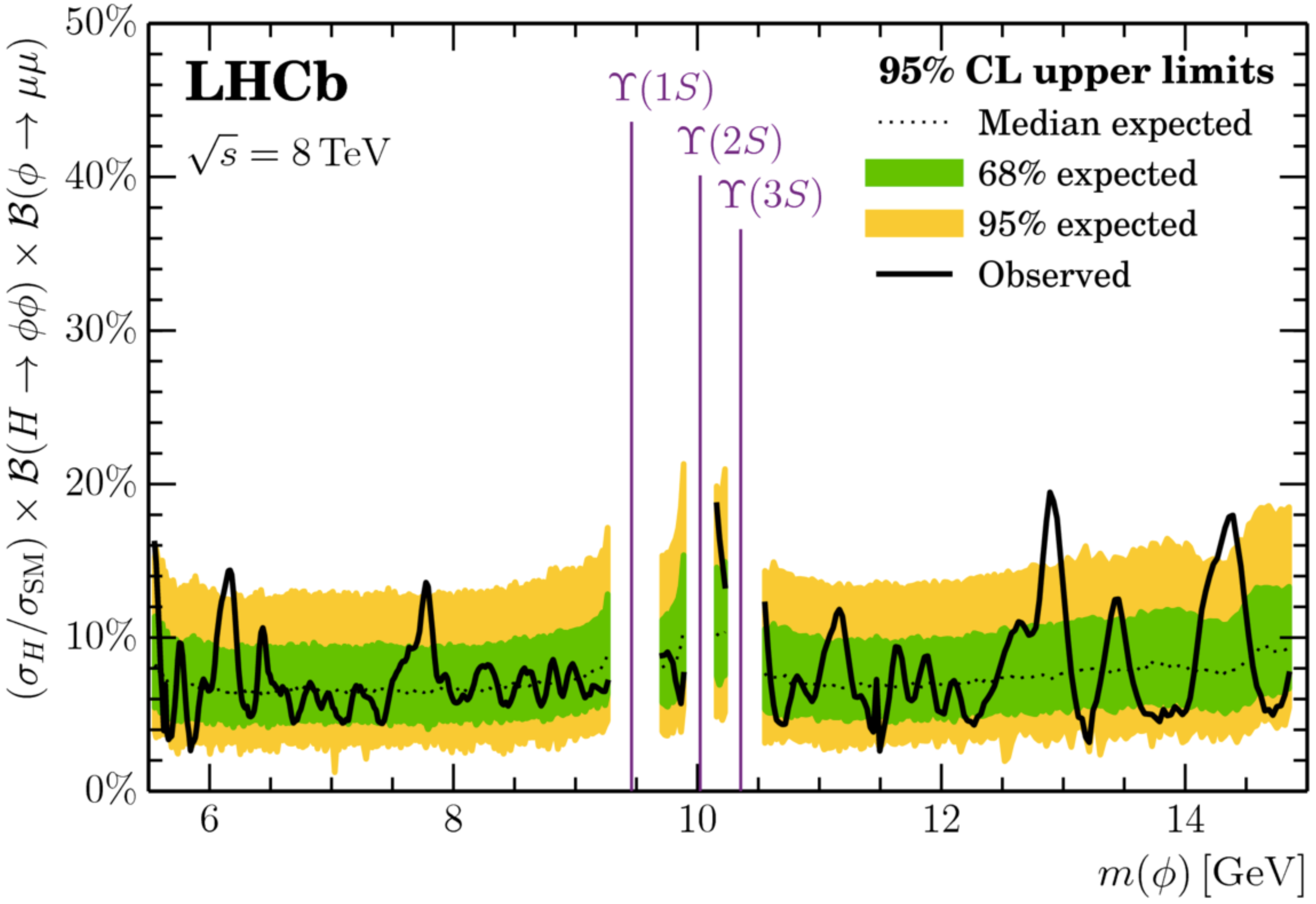
JINST 8 (2013) P12013

Searching in the Υ mass region / 2

JHEP 1809 (2018) 147

- Search for dimuon resonance in **$m_{\mu\mu}$ from 5.5 to 15 GeV** (also between Υ(nS) peaks)
- No signal: limits on σ•BR set on (pseudo)scalars as proposed by **Haisch** & **Kamenik** [1601.05110]
- First limits in 8.7-11.5 GeV region - elsewhere competitive with CMS
- Interpreted as a search for a scalar produced through the SM Higgs decay

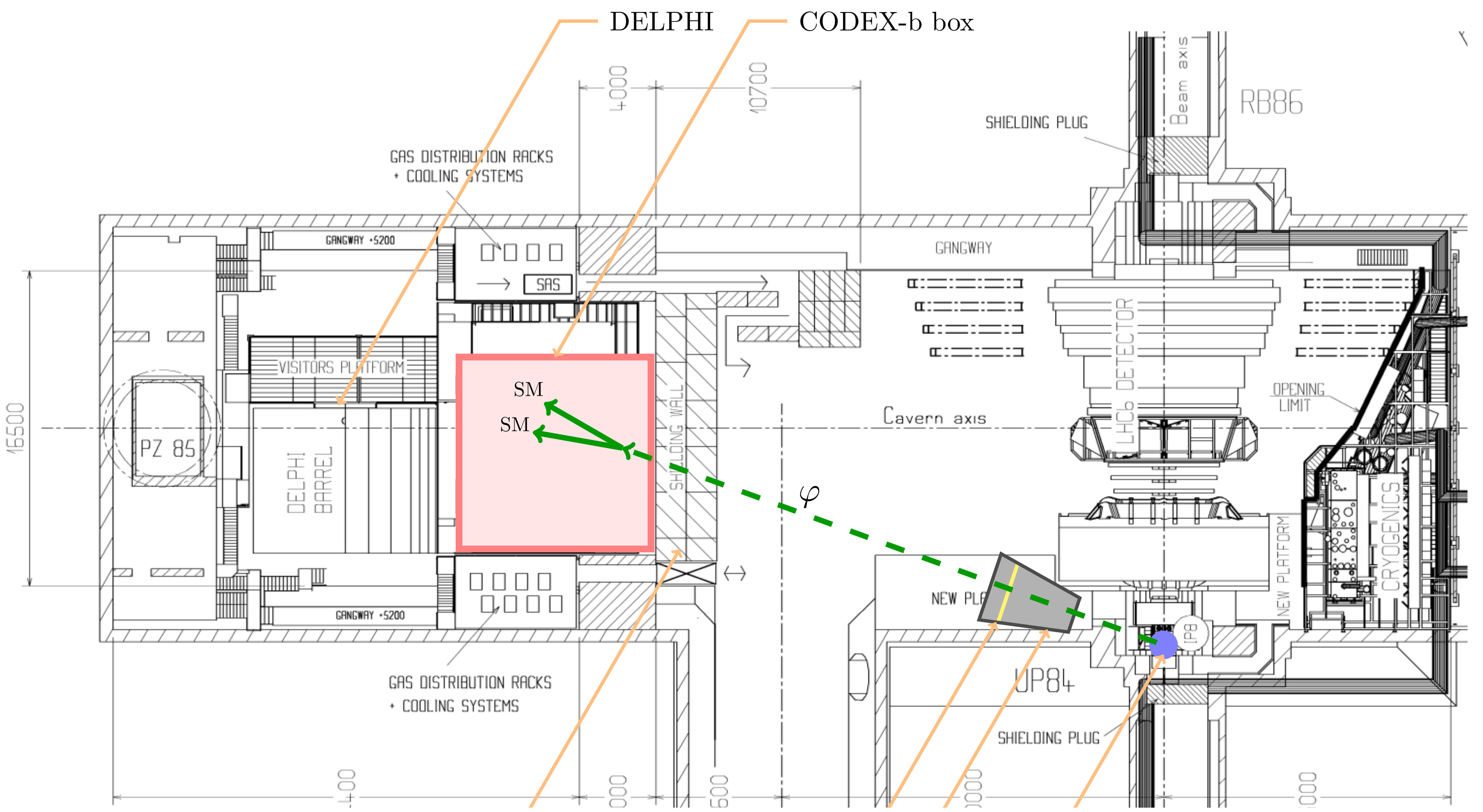


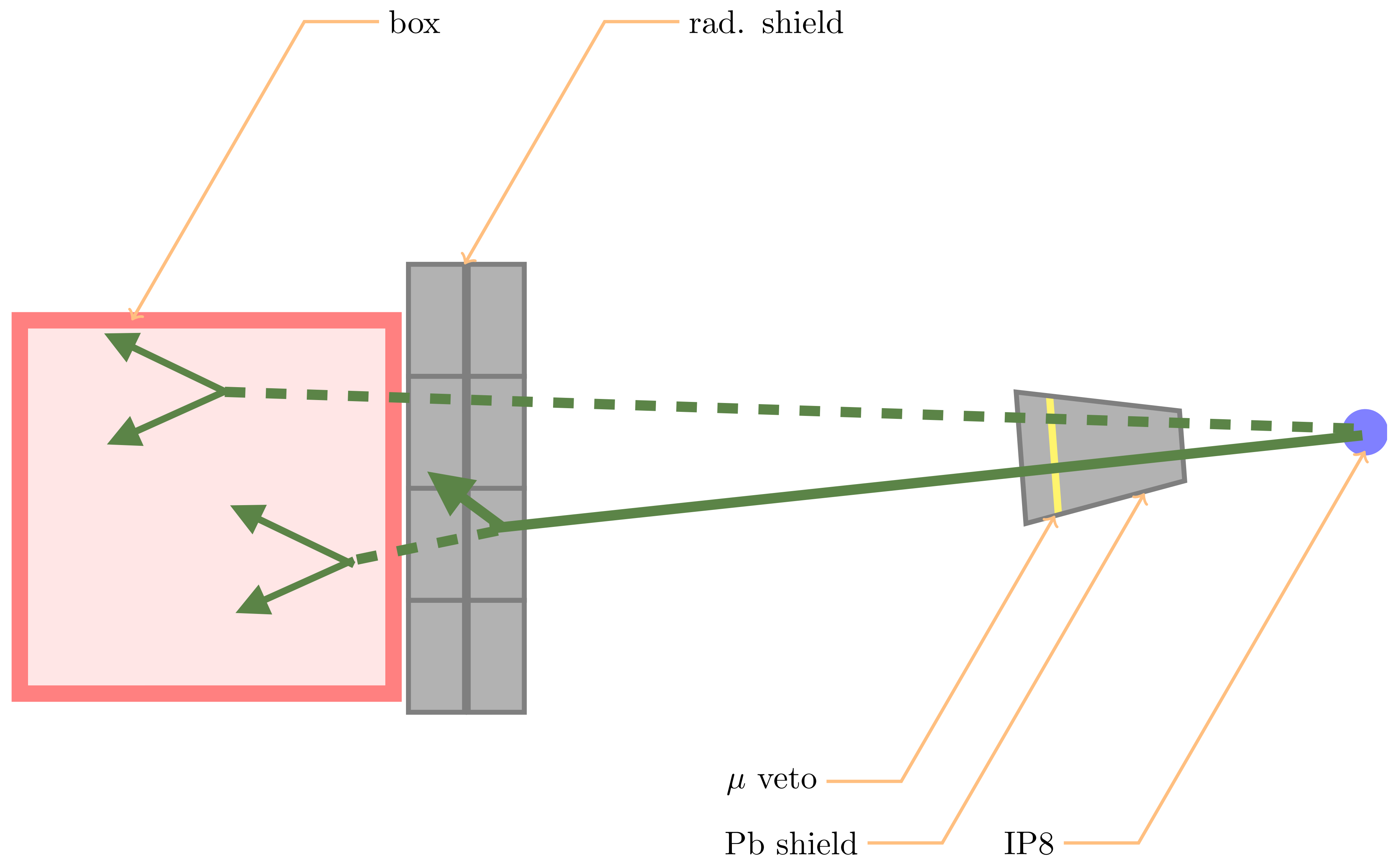


Phys.Rev. D97 (2018) no.1, 015023

Codex-b / 1

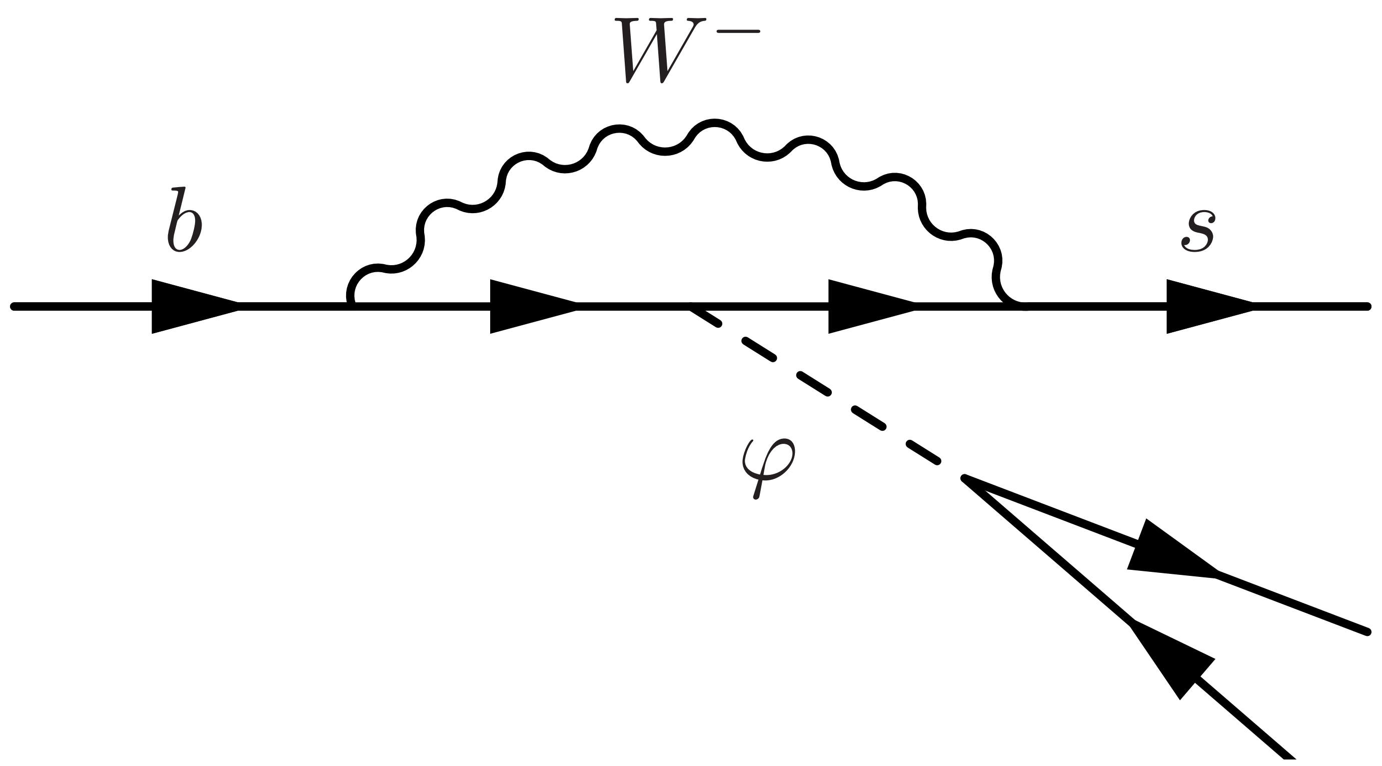
- Distance is only ~ 4 bunch crossing times for relativistic objects: Integrate CODEX-b into the DAQ & readout, and treat as LHCb sub-detector
- **Identification and at least partial reconstruction of the LLP event**
- Fiducial volume ('the box') is 10 × 10 × 10 m; angular acceptance 1%
- Absorb neutral hadrons in shield **(irreducible background)**
- Veto muon-induced backgrounds with muon veto + front face of the detector **(reducible background)**
- Precision timing and spatial resolution, 100 ps or futuristic 50 ps resolution possible required for LLP mass reconstruction

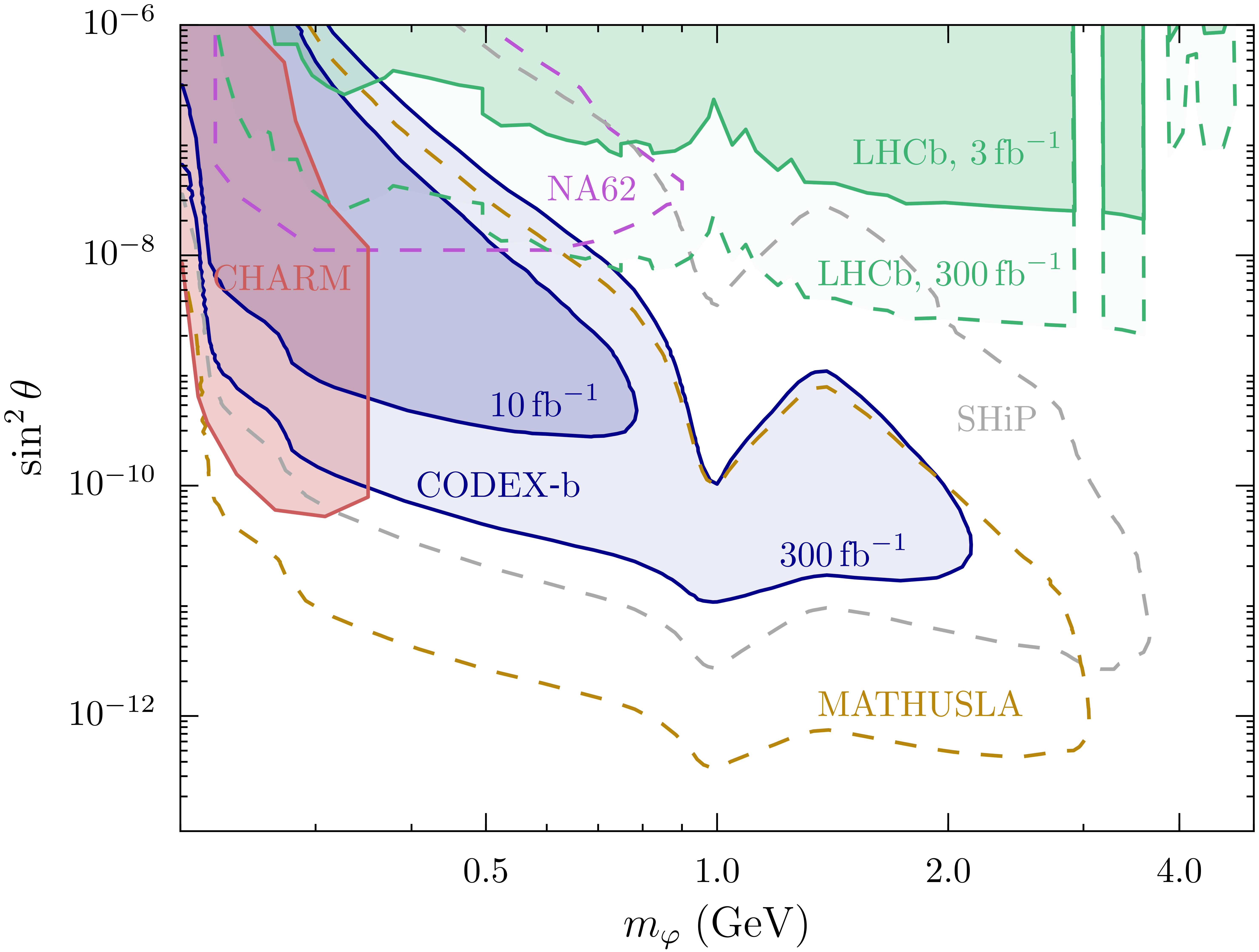




Codex-b / 2

- Large theory uncertainties for m_ϕ>1 GeV
- Single parameter portal: Higgs-scalar mixing angle, θ, controls production rate and lifetime
- LHCb information must be used to reach prospected limits

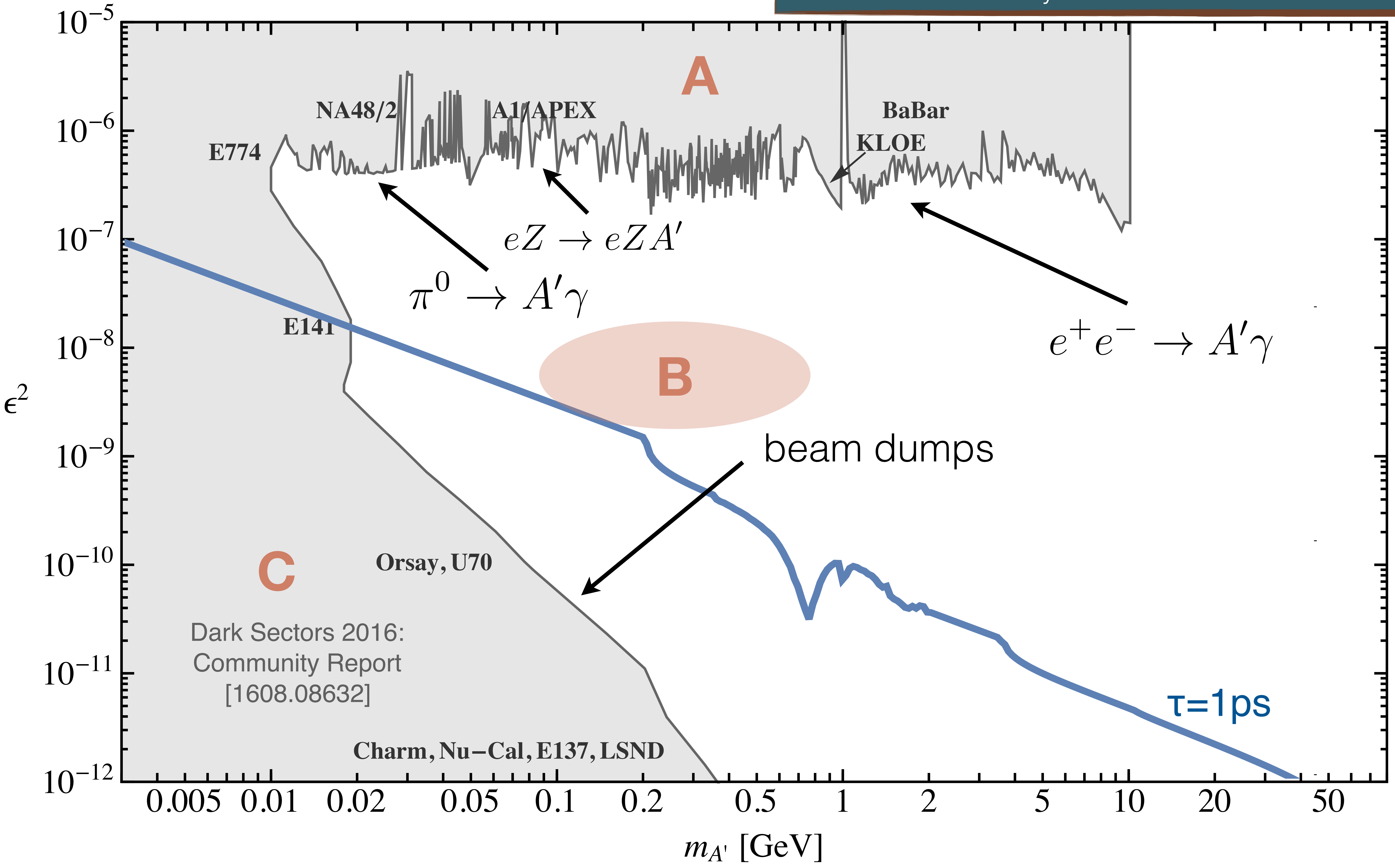




Visible (SM) dark photons / 1

- **A**: Bump hunts, visible or invisible
- **B**: Displaced vertex searches, short decay lengths
- **C**: Displaced vertex searches, long decay lengths

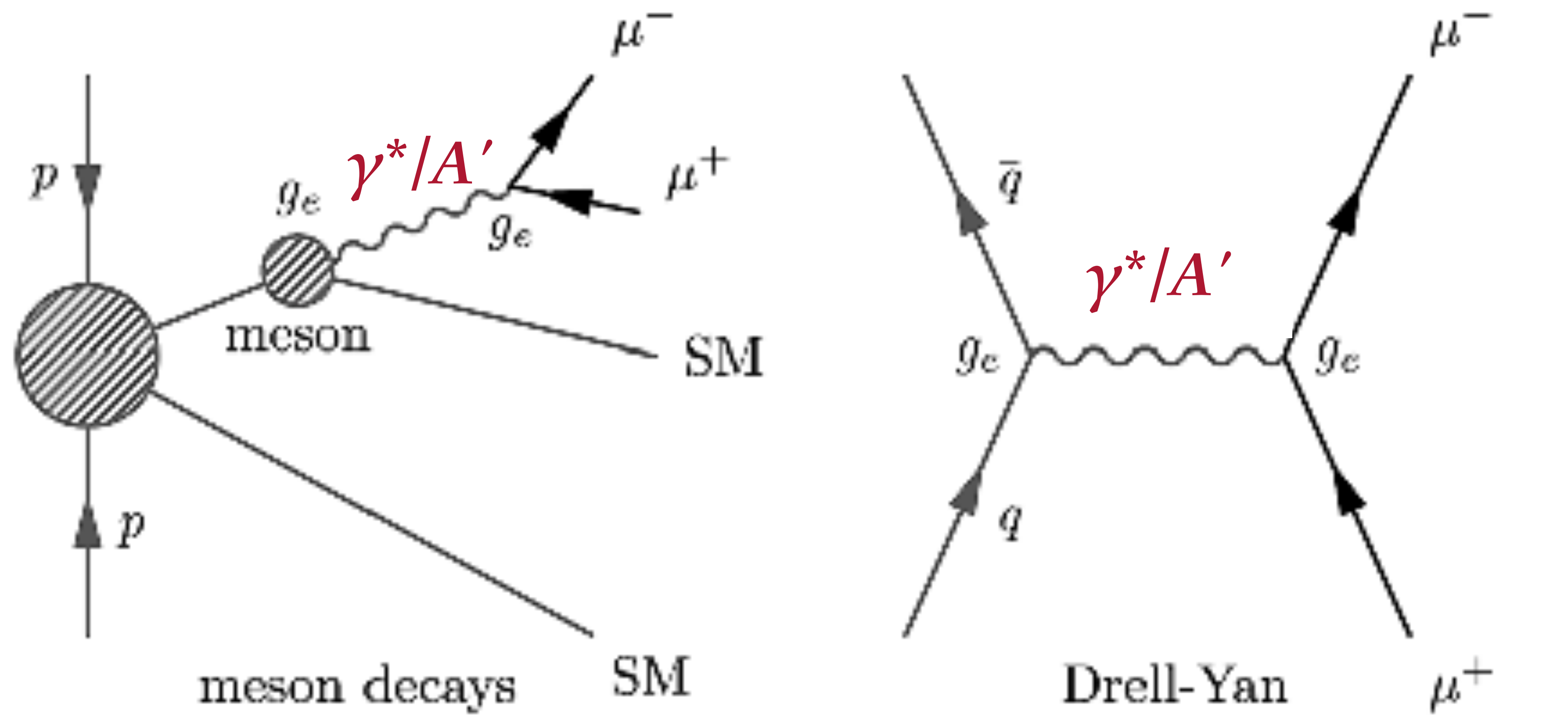
Dark Sectors 2016: Community Report [1608.08632]
Courtesy of Mike Williams



Searching for Dark Photons / 1

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

- Search for dark photons decaying into **a pair of muons**
- Used **1.6 fb^{-1}** of 2016 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



$$n_{\mathrm{ex}}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\mathrm{ob}}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\,\epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

off-shell photon

phase-space

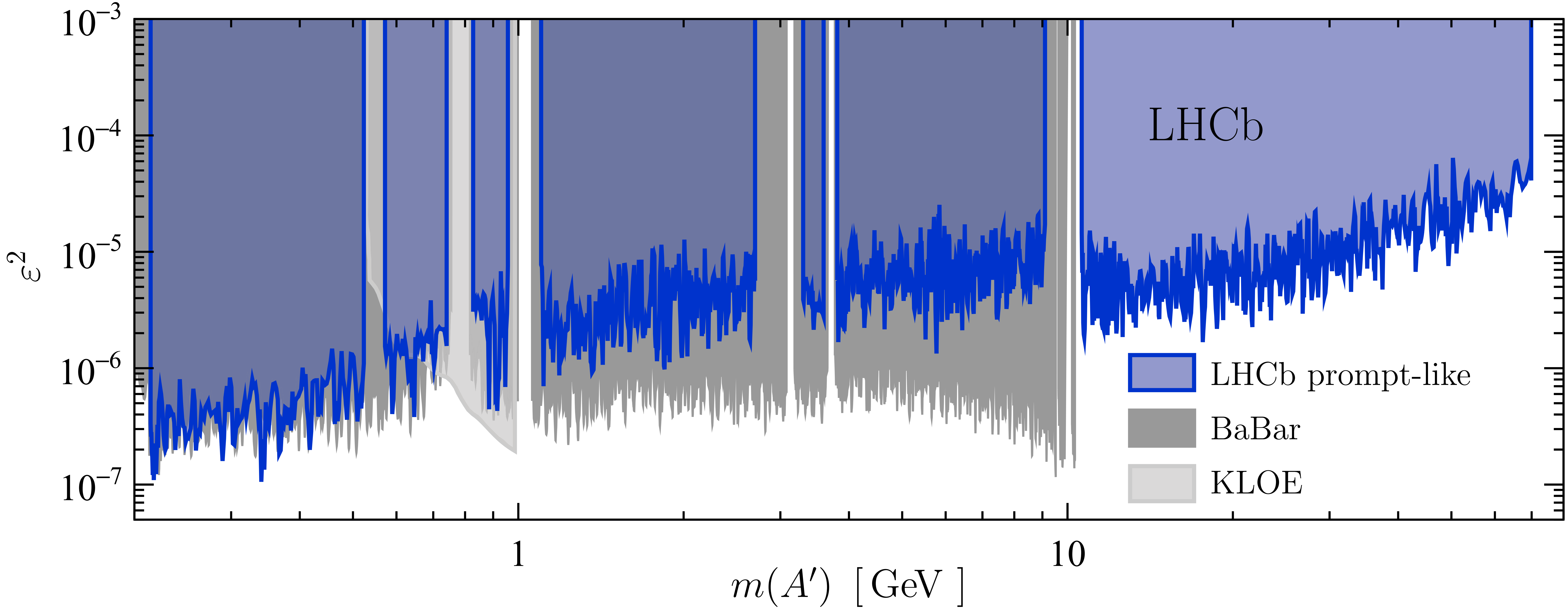
A′/γ^* eff ratio, ϵ=1 for prompt

Need to separate from background

Search for Dark Photons / Prompt

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

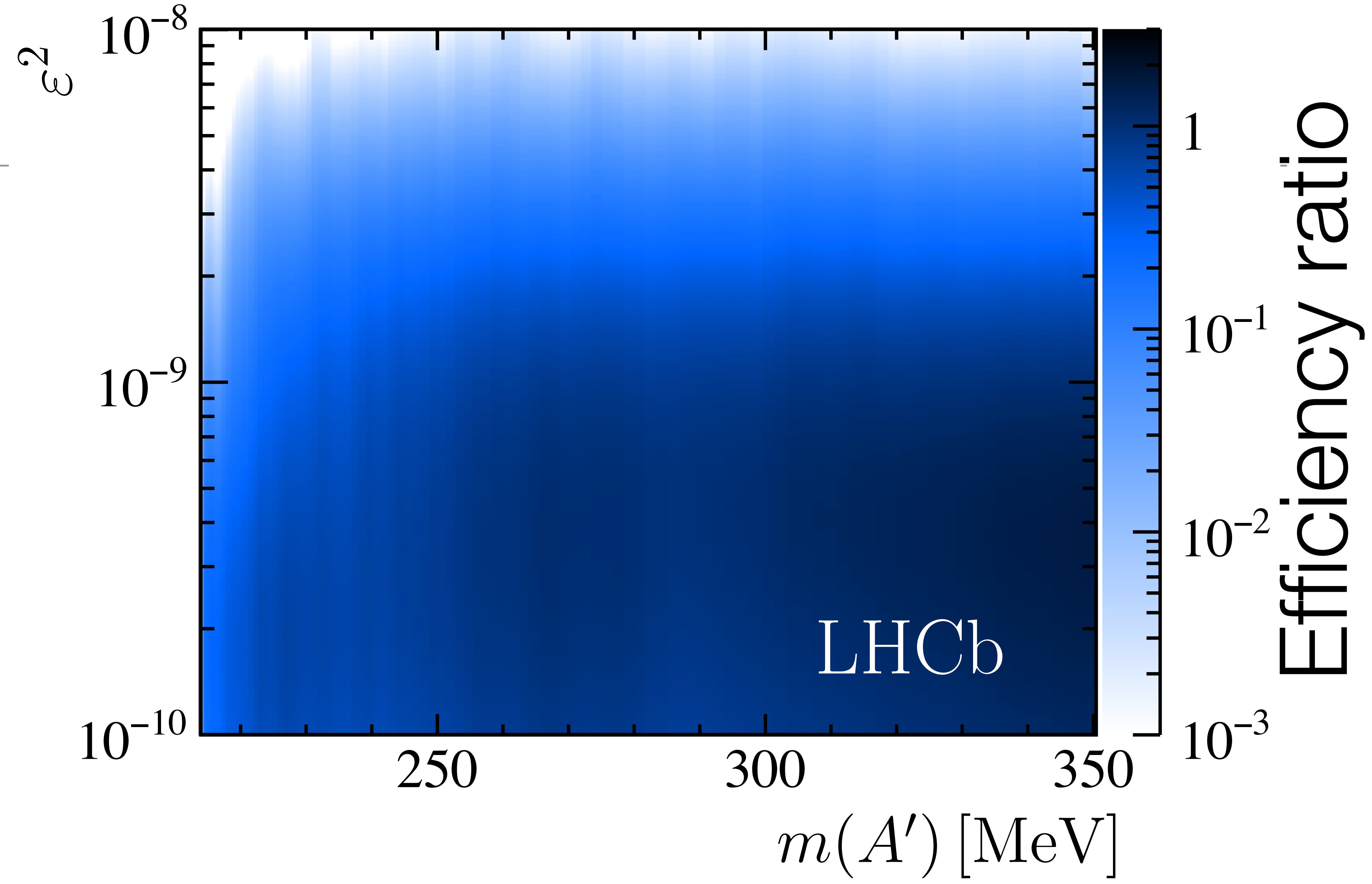
- No significant excess found - exclusion regions at 90% C.L.
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV

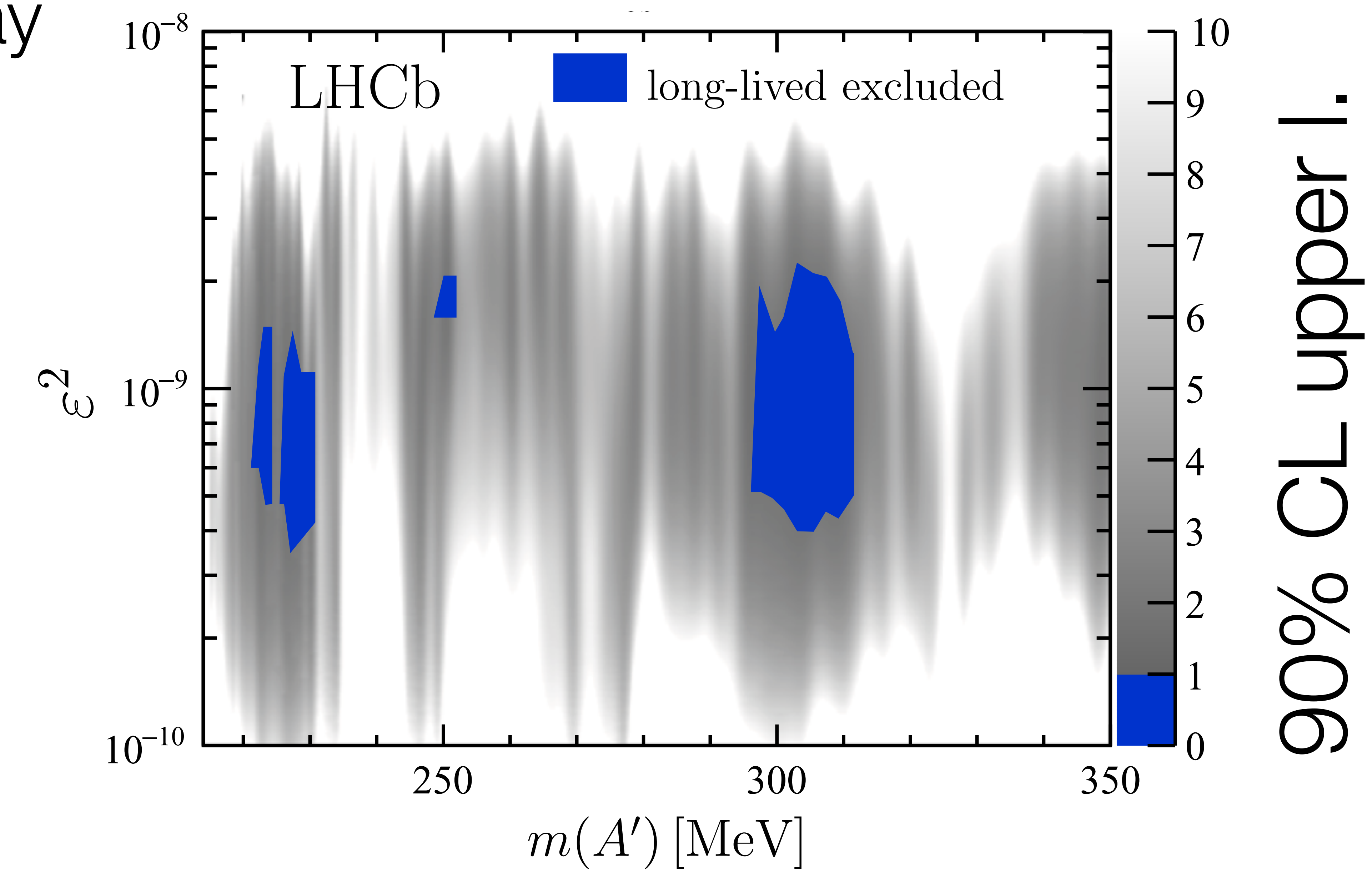


Phys. Rev. Lett. 120, 061801 (2018)

Search for Dark Photons / Displaced

- **Looser requirements** on muon transverse momentum
- **Material background** mainly from photon conversions
- Isolation decision tree from $B^0_s \to \mu^+\mu^-$ search
  - Suppress events with additional number of tracks, i.e. μ from b-hadron decays
- Fit in **bins of mass and lifetime** – use consistency of decay topology χ^2
- Extract p-values and confidence intervals from the fit
- No significant excess found small parameter space region excluded
- **First limit ever not from beam dump**

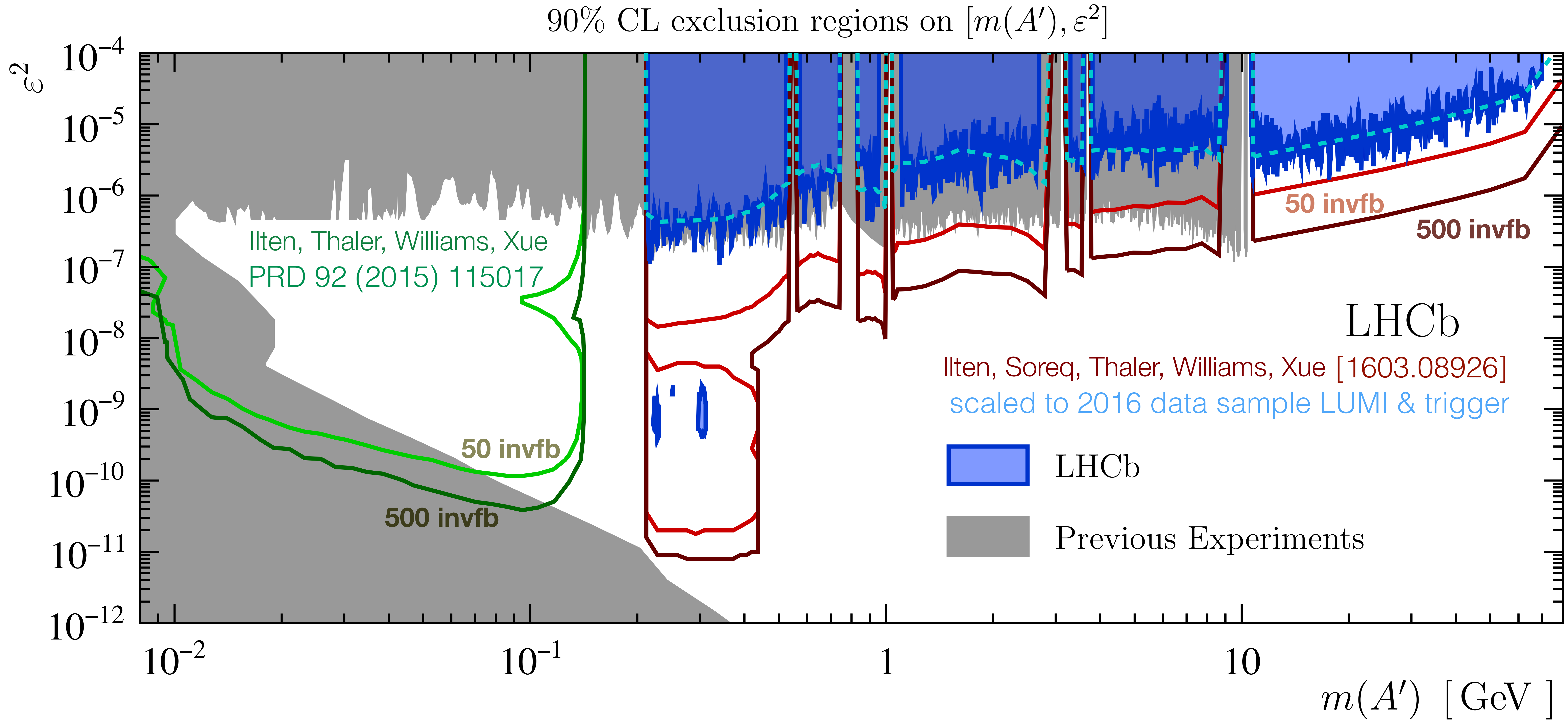




Search for Dark Photons / Results

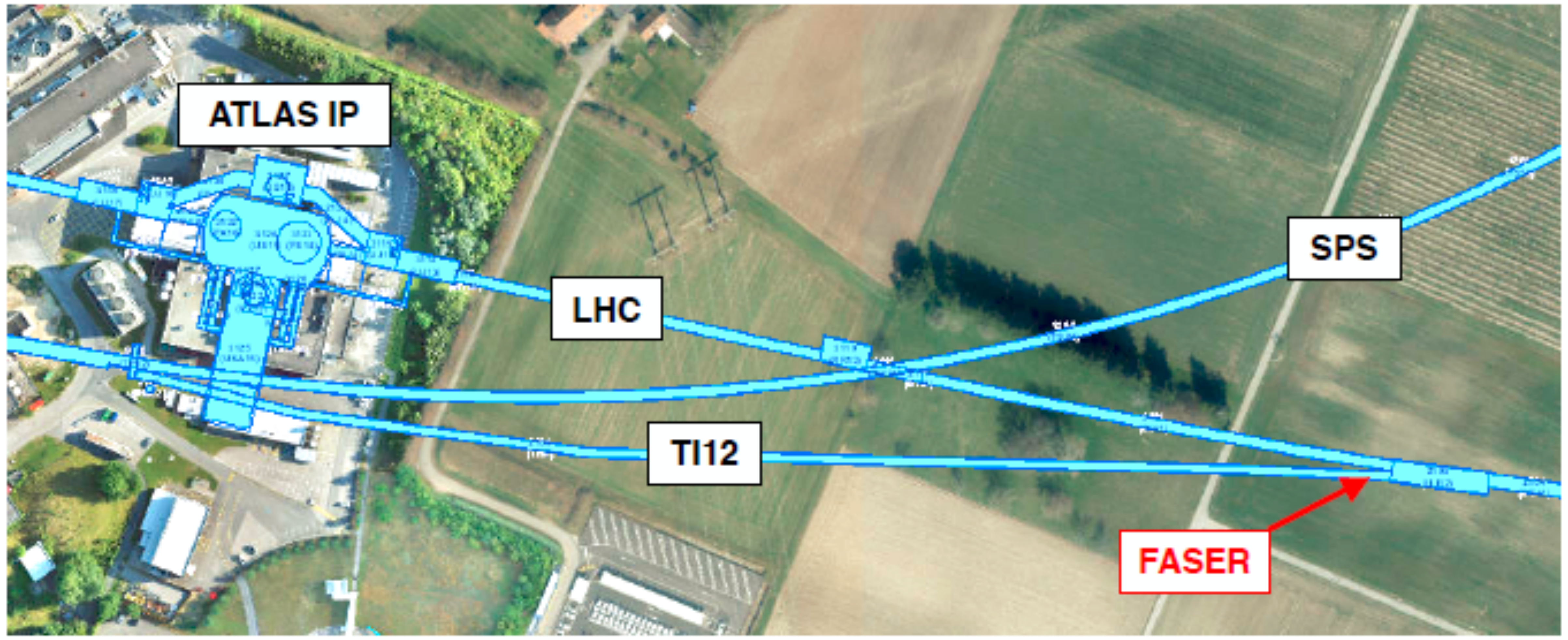
Phys. Rev. Lett. 120, 061801 (2018)

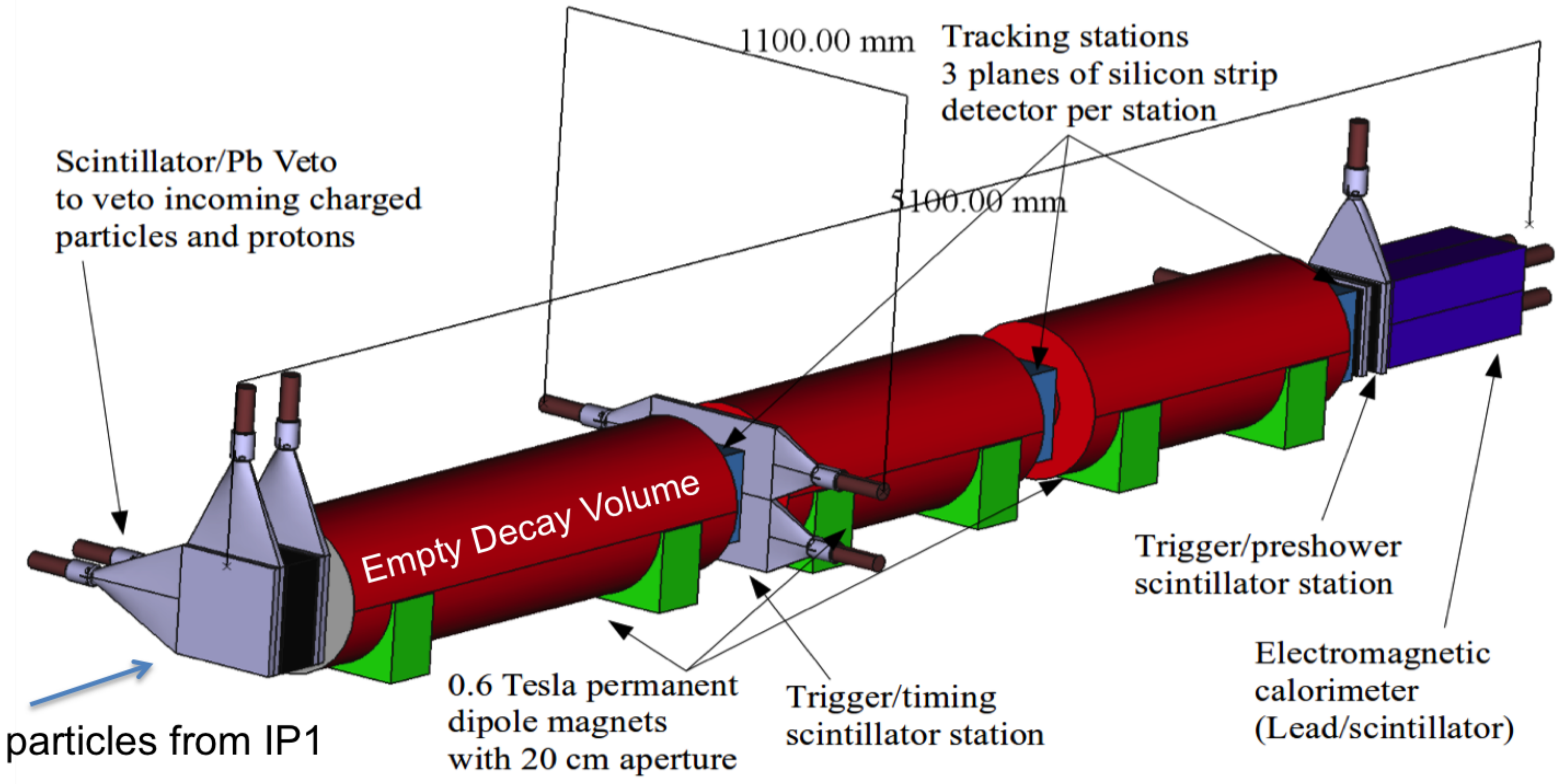
- The 2016 dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. We implemented huge improvements in the 2017 triggers for low masses, so plan quick turn around on 2017 dimuon search - then onto electrons.



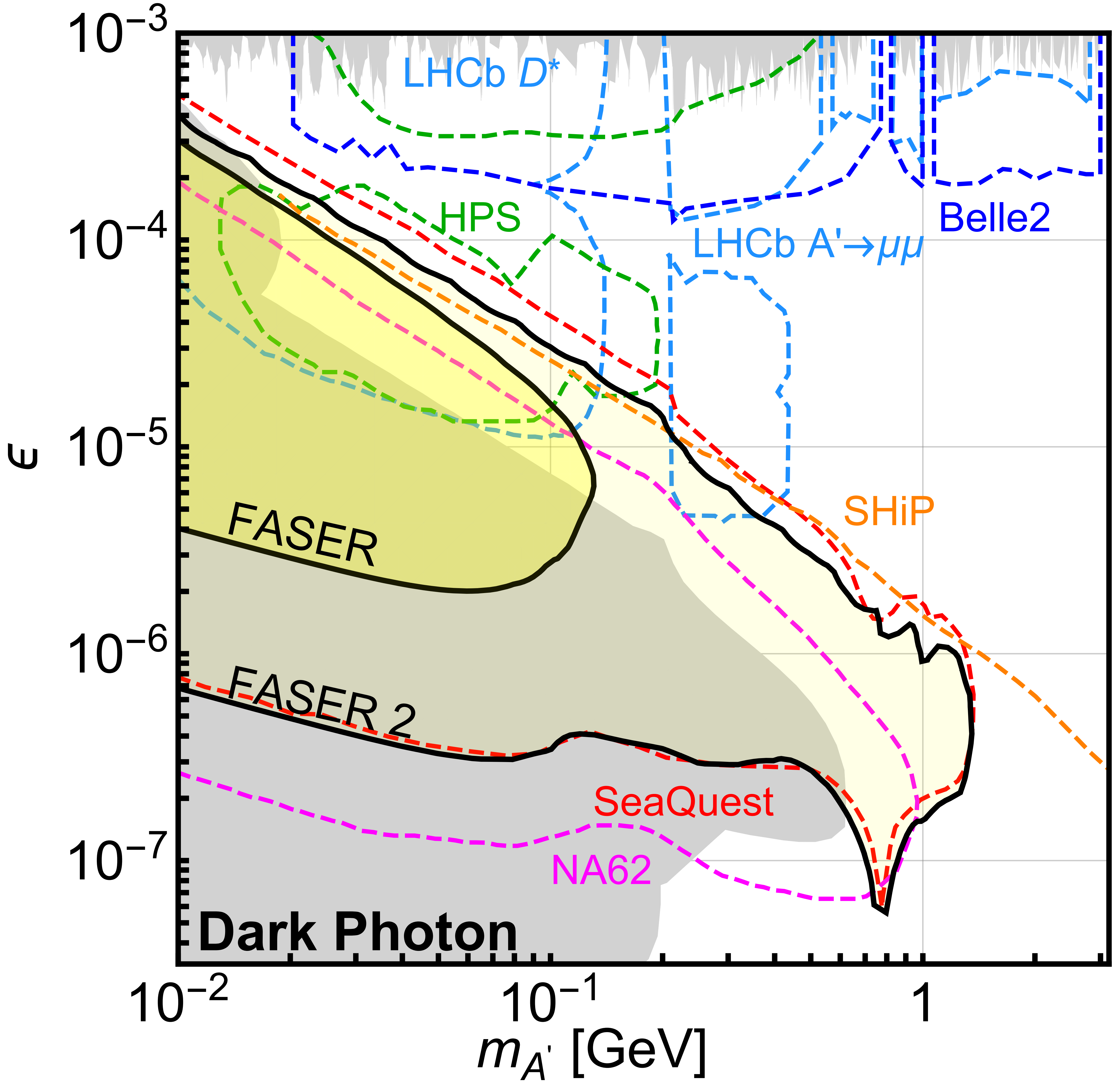
Faser / 1

- Huge forward π rate (~ 10^{15}) in FASER acceptance
- Large suppression (ε^2) in π → A' X but substantial rates of A' in acceptance
- Multi-TeV LLP produced at ATLAS IP; 480 m to FASER, including 100 m of concrete
- Decay within 1.5 m decay volume to charged particle pair, e.g. e^+e^-
- Oppositely charged tracks separated by spectrometer B field
- Silicon strip tracker (from ATLAS) to measure charged track trajectory
- EM calorimeter (from LHCb) to measure energy, e vs. μ ID





Faser / 2



- FASER probes new parameter space with just 1 fb–1 starting in 2021
  - FASER 2 larger volume (R = 1 m, L = 5 m) and HL-LHC Lumi

Conclusions

- The search for **dark matter** and **dark sectors** at collider experiments is a broad and growing field both at existing and at feature facilities and experiments
- Important effort should also be spent in **exploiting existing experiments** further
- These searches can lead to major milestones in our understanding of the shortcomings of the Standard Model
- Specific mass **scale of NP unknown**, DM points to a dark sector of particles not interacting through the known SM forces and therefore only feebly-coupled to the SM
- [...] *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(es)*** [M. Mangano, emphasis added]

2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	203+
LS2		**RUN III**			LS3			**RUN IV**			LS4		**RUN V**	
		L = 2e33						L = 2e33; 50 fb^{-1}					300 fb^{-1}	

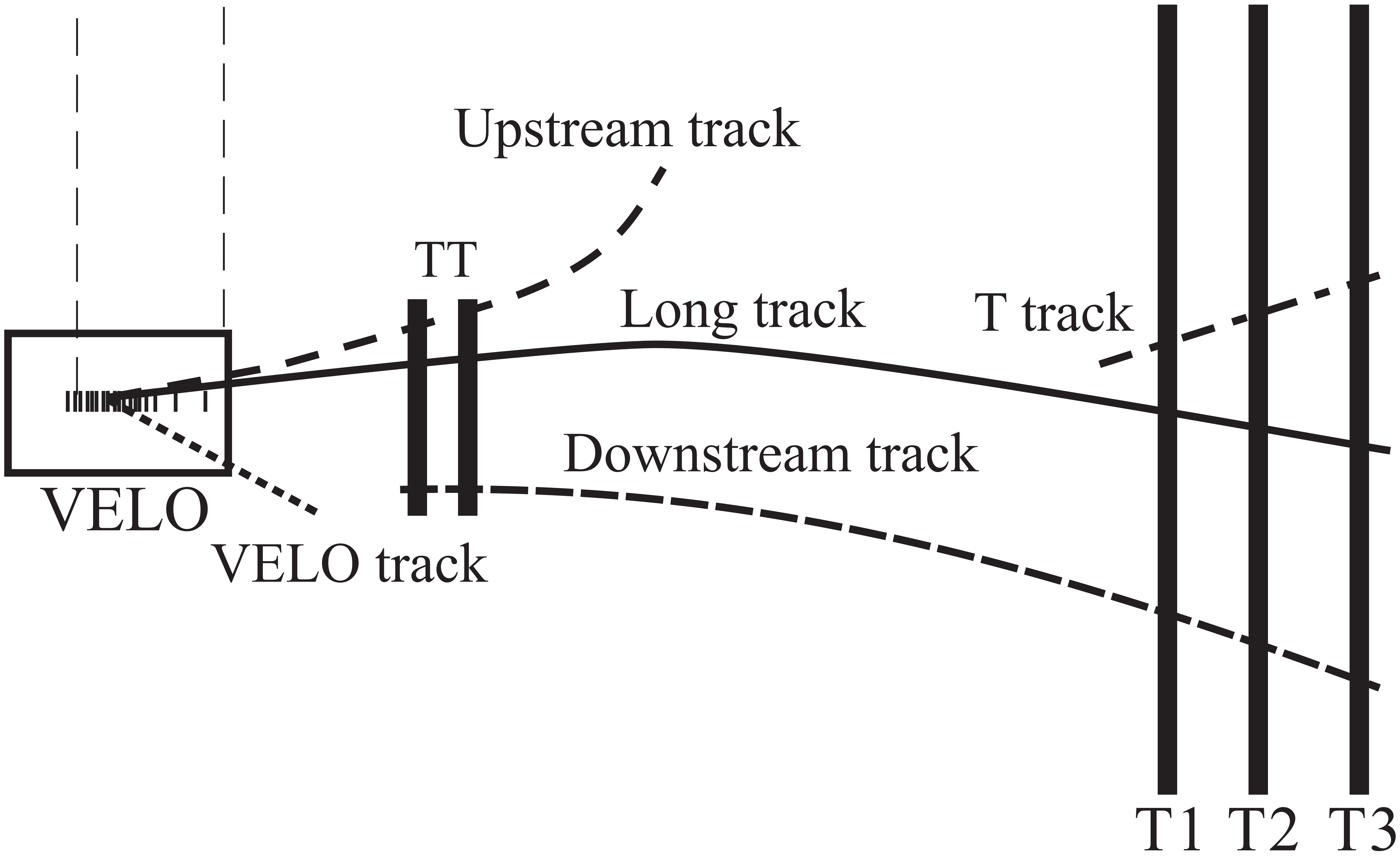
Il segreto di Majorana. Riccioni & Rocchi

- 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 wide open** (hierarchy problem, flavour, neutrinos, DM, BAU, etc.)
- 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(es)** [M. Mangano, emphasis added]

Thanks

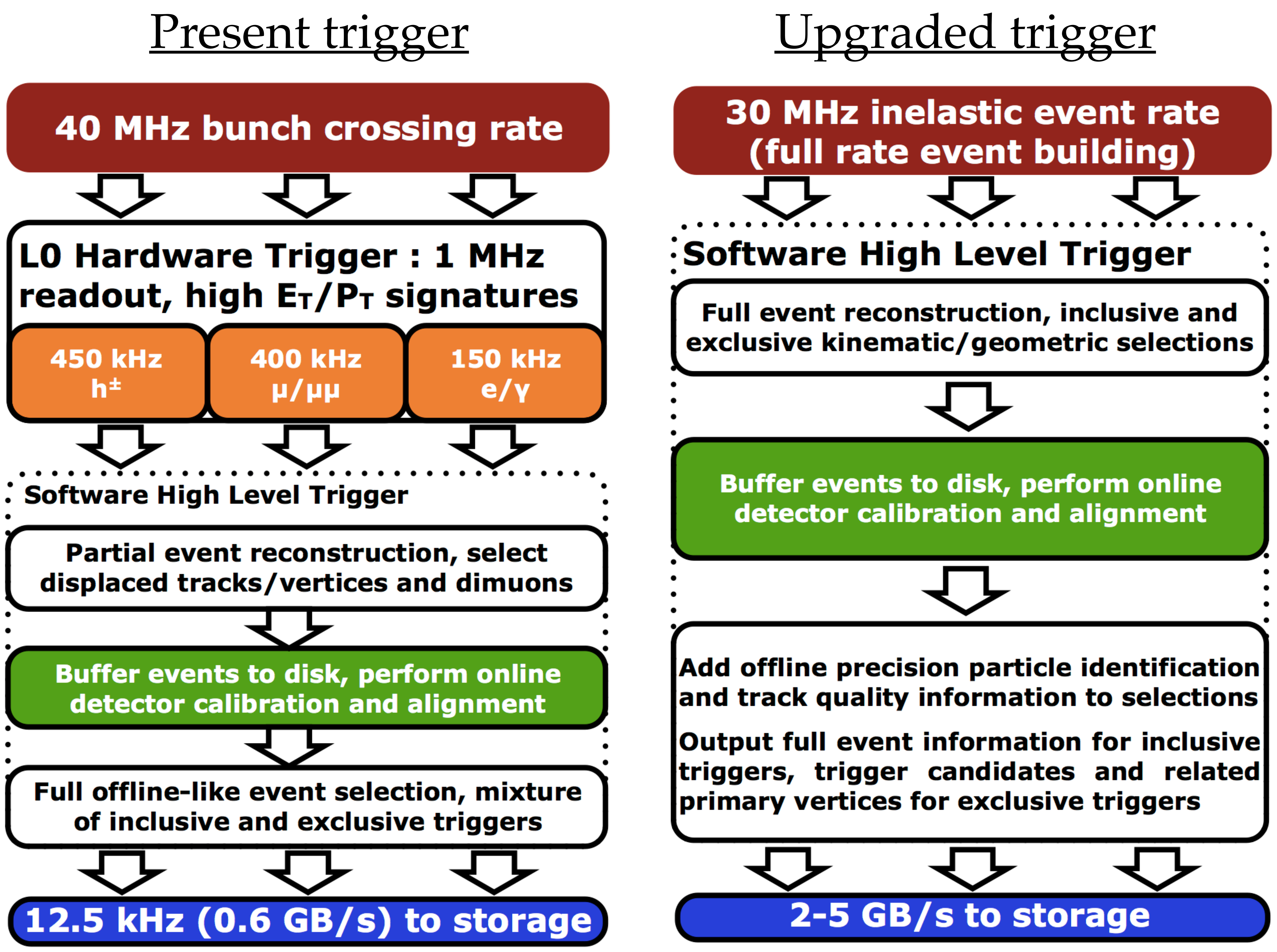
Federico Leo Redi

LHCb detector / 1bk



LHCb detector / 2bk

- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- Hardware **L0 trigger** to be removed
- **Full real-time** reconstruction for all particles available to select events (since 2015)
  - **Real-time reconstruction** for all charged particles with $p_T > 0.5$ GeV
  - We go from 1 TB/s (post zero suppression to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **trigger-less readout system** for LHC Run 3 (2021-2023), and process
  5 TB/s in real time on the CPU farm



LHCb detector / 3bk

JHEP 1511 (2015) 103

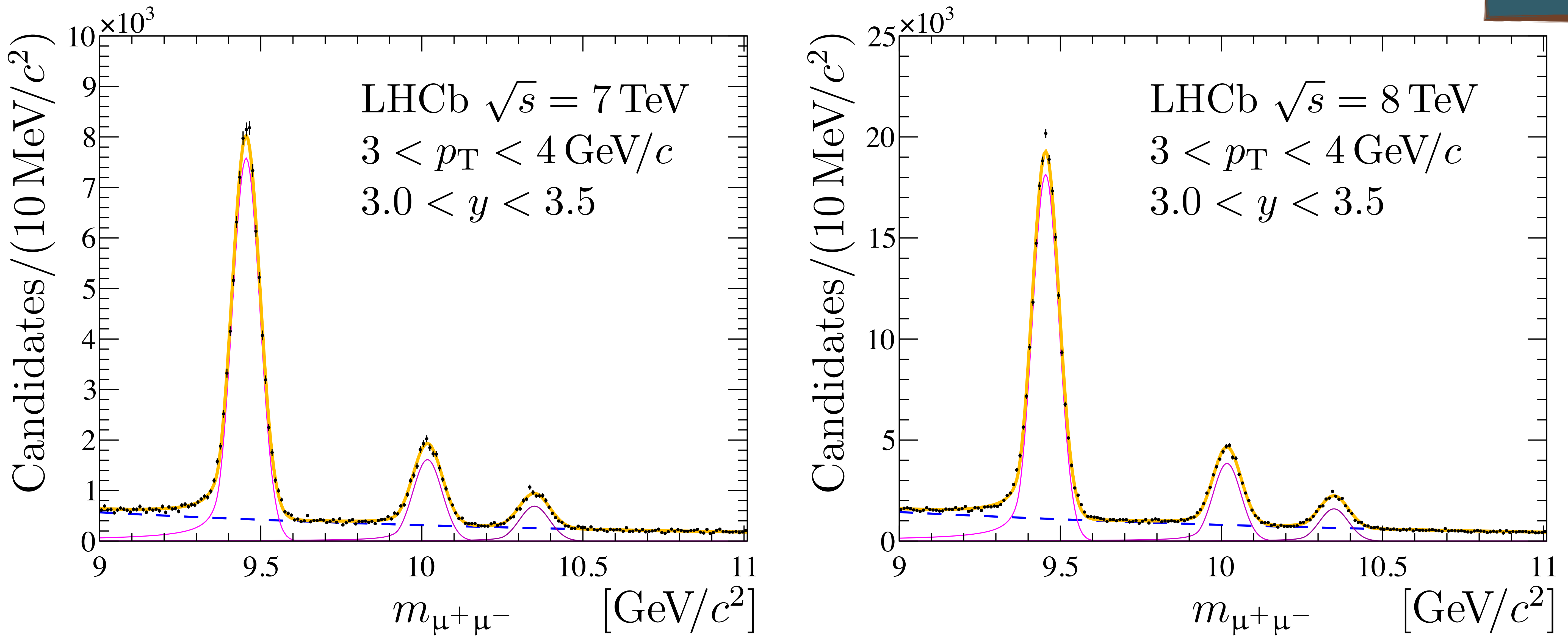
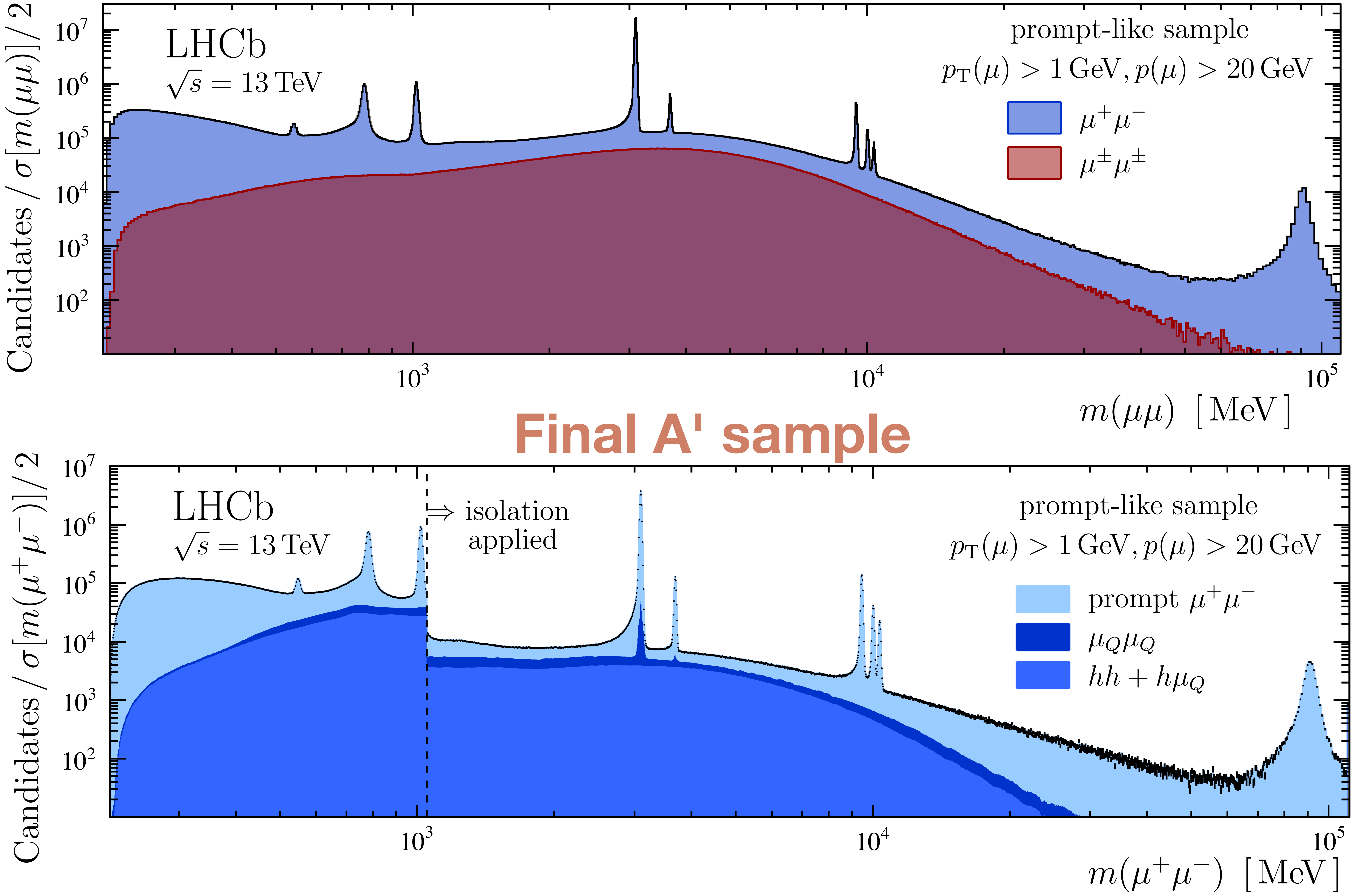


Figure 1: Efficiency-corrected dimuon mass distributions for (left) $\sqrt{s} = 7\,\text{TeV}$ and (right) $\sqrt{s} = 8\,\text{TeV}$ samples in the region $3 < p_T < 4\,\text{GeV}/c$, $3.0 < y < 3.5$. The thick dark yellow solid curves show the result of the fits, as described in the text. The three peaks, shown with thin magenta solid lines, correspond to the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ signals (left to right). The background component is indicated with a blue dashed line. To show the signal peaks clearly, the range of the dimuon mass shown is narrower than that used in the fit.

Searching for Dark Photons / 1bk

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

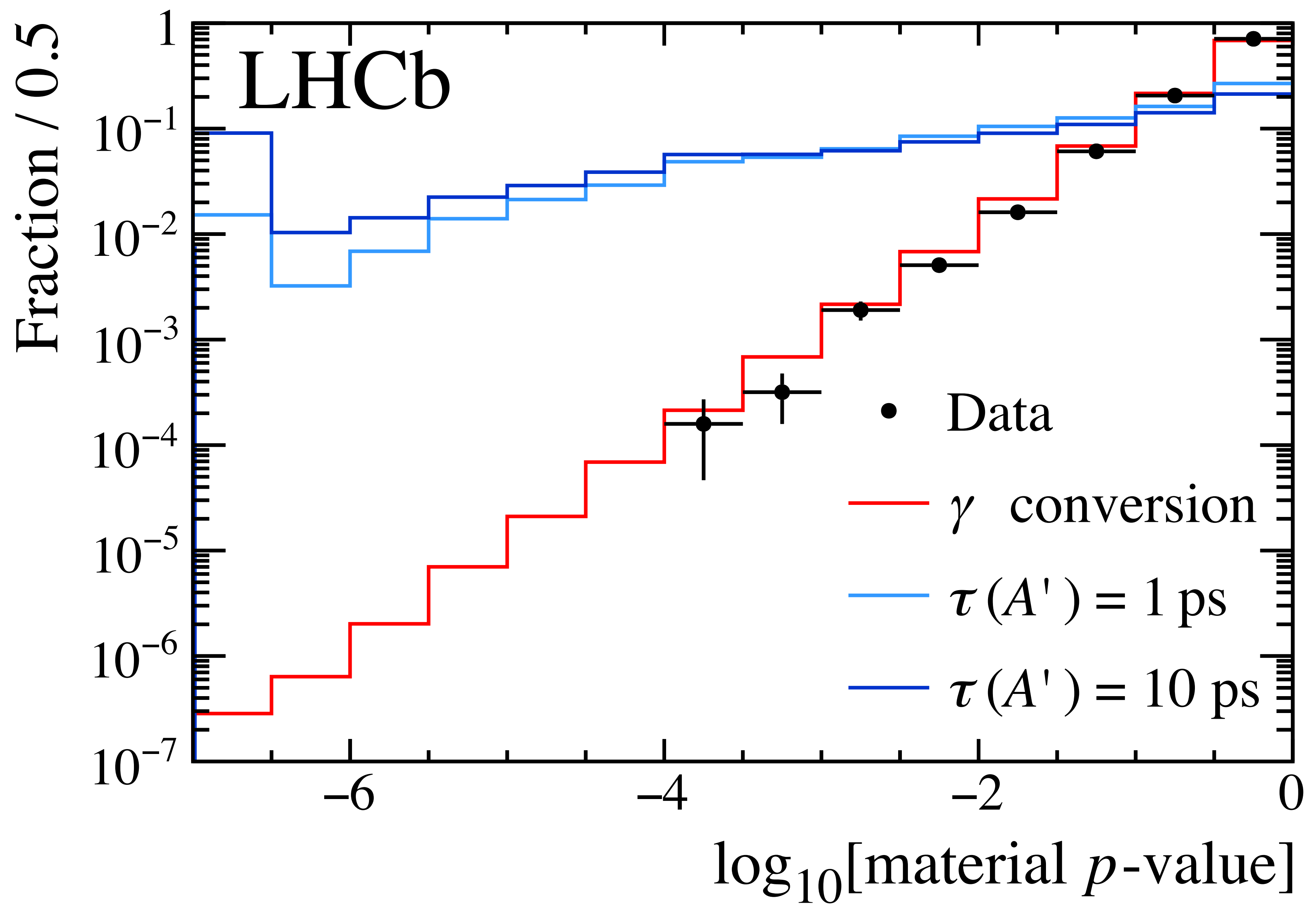
- Suppressing misidentified (non-muon) backgrounds and reducing the event size enough to record the **prompt-dimuon sample**
- Accomplished these by moving to **real-time calibration** in Run 2
- Hardware trigger is still there, and only ~10% efficient at low pT

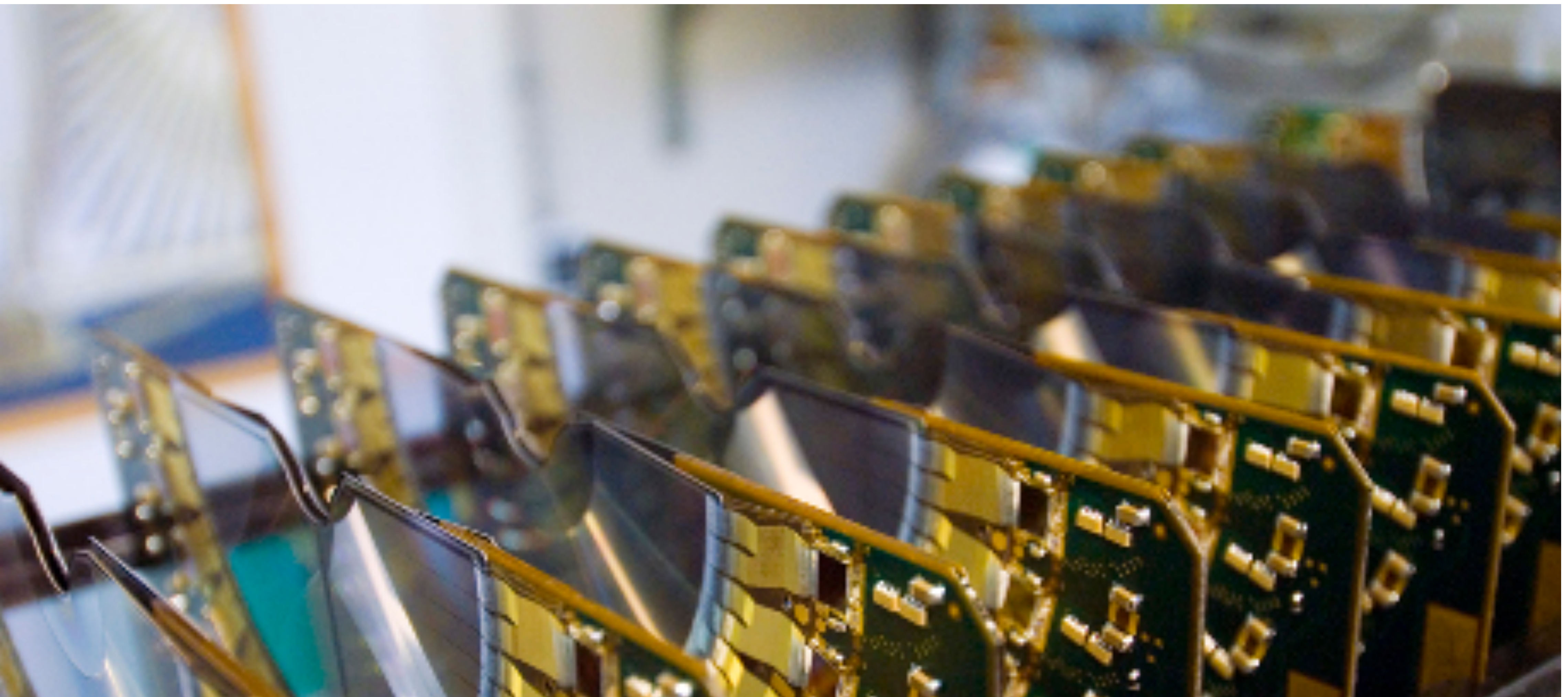


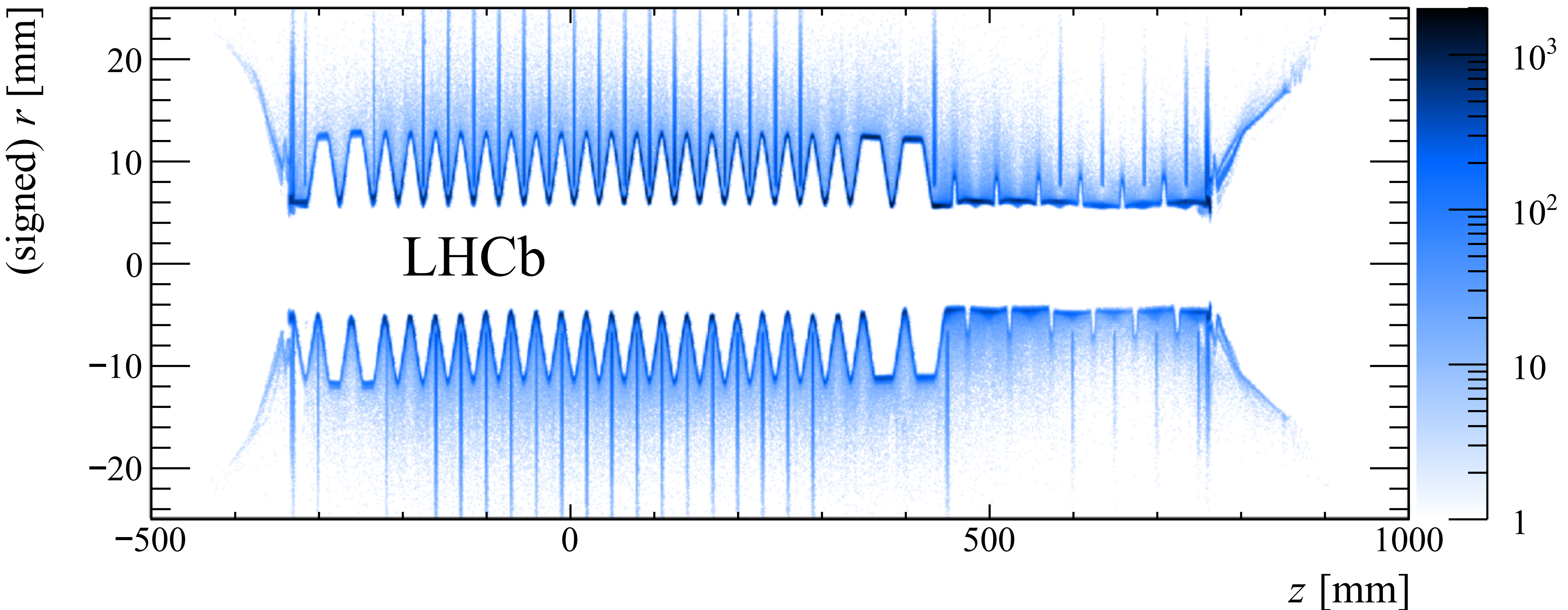
Searching for Dark Photons / 2bk

arXiv:[1803.07466]

- Background dominated by **material interactions** for displaced searches at LHCb
- 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







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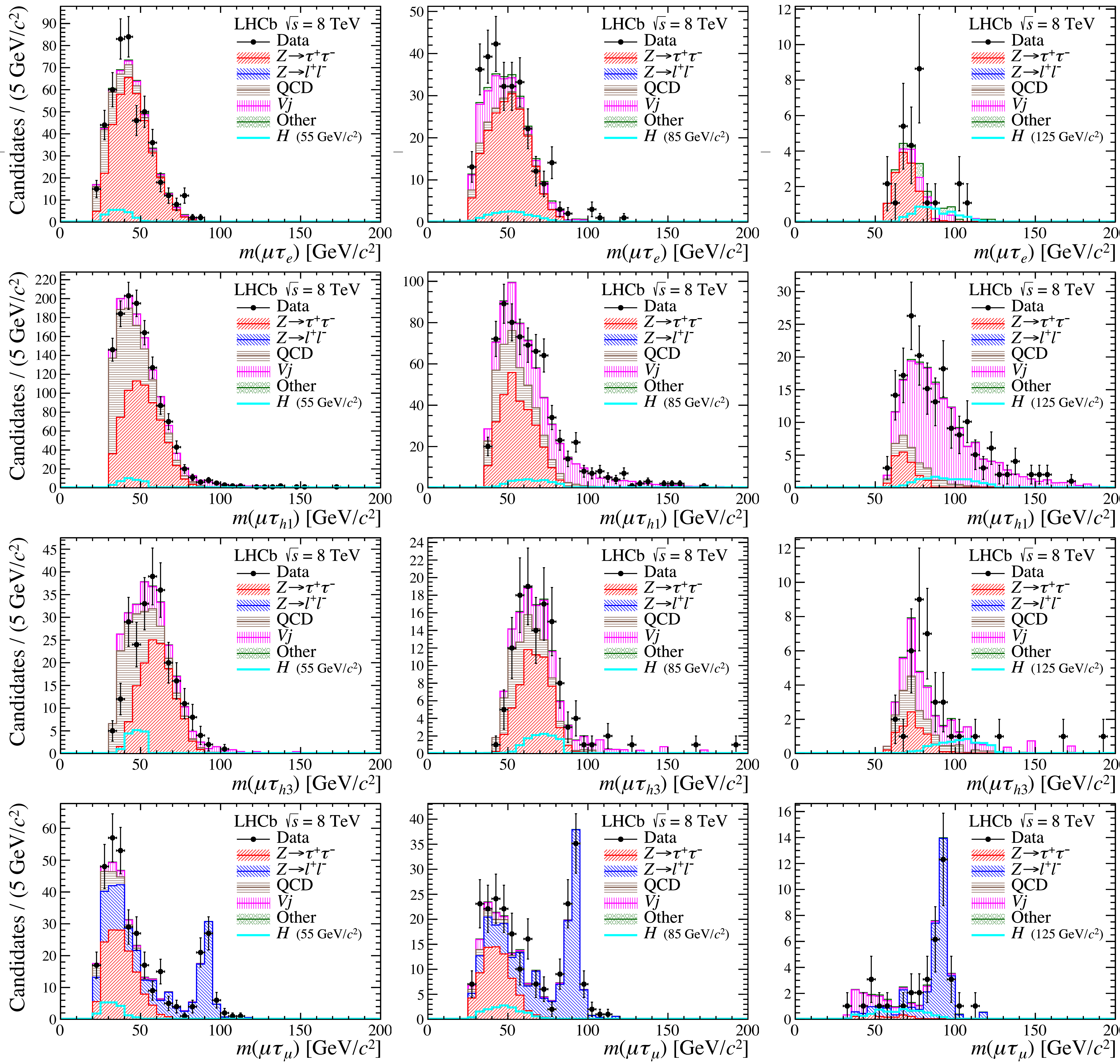
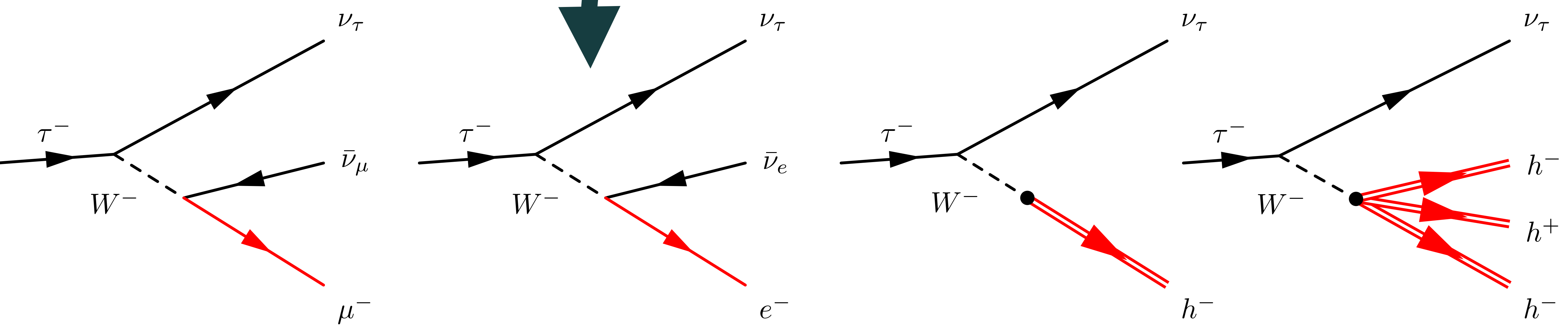
H→μτ decays / 1bk

from top to bottom: $\mu\tau_e$, $\mu\tau_{h1}$, $\mu\tau_{h3}$, $\mu\tau_\mu$

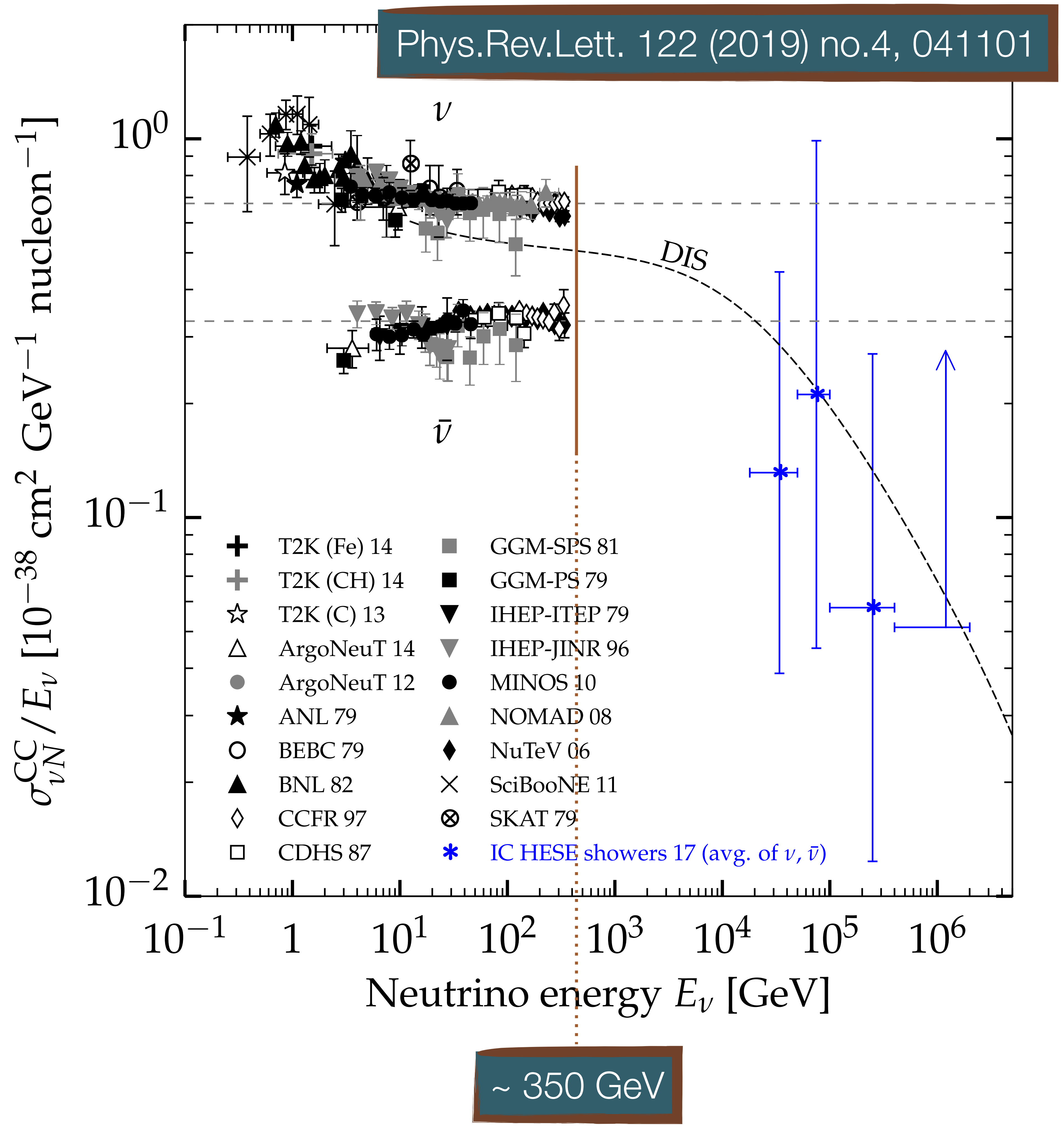
from L to R: $\mu\tau_\mu$, $\mu\tau_e$, $\mu\tau_{h1}$, $\mu\tau_{h3}$,



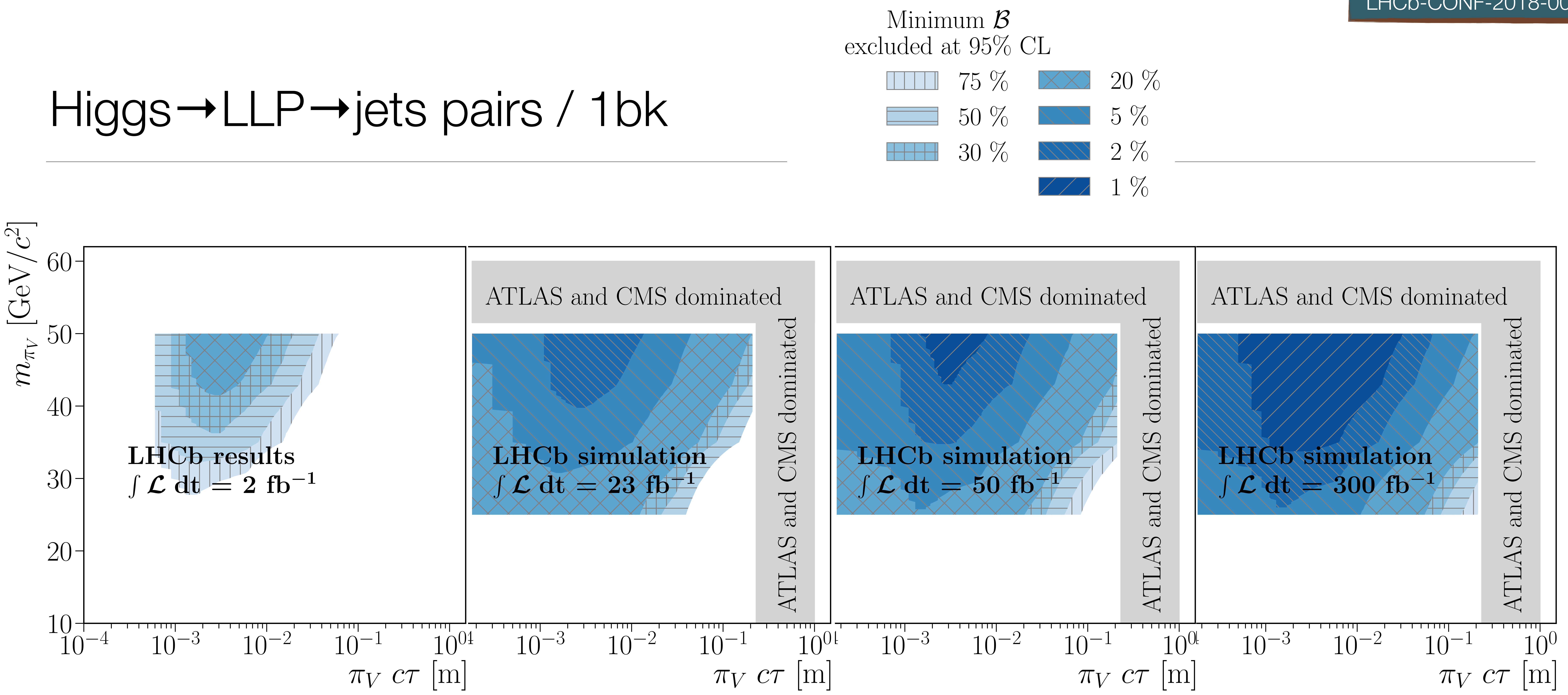


Neutrino detector at TI18 and/or TI12 / 1bk

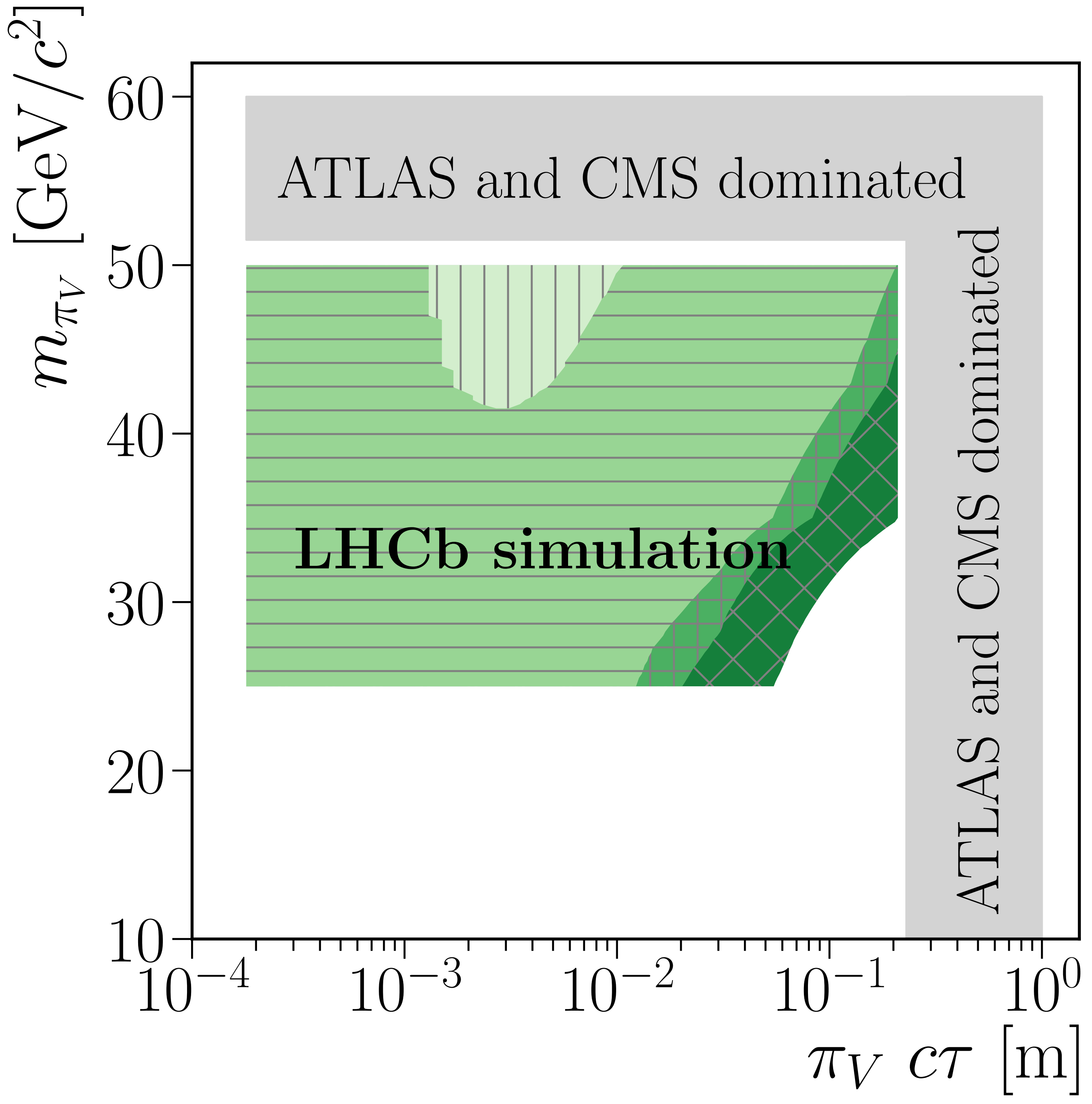
- Charged current neutrino-nucleon cross section measurements show a gap in measurements
- First detection of collider neutrinos in far forward location, where high-energy neutrino flux is concentrated
- Cross-section measurements of all flavours in unexplored energy region
- Search for new physics effects in high-energy neutrino interactions



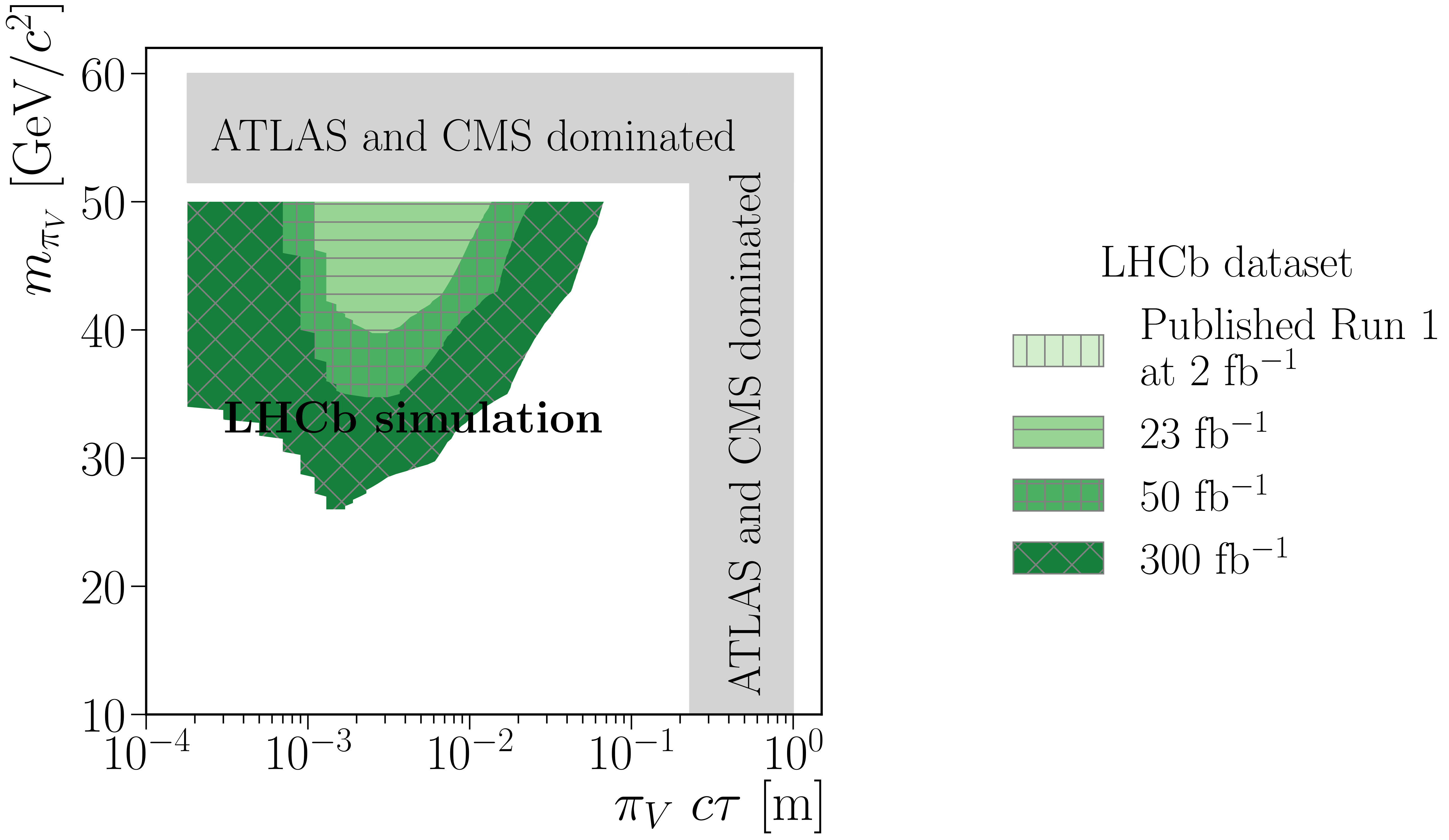
Higgs→LLP→jets pairs / 1bk



Higgs→LLP→jets pairs / 2bk



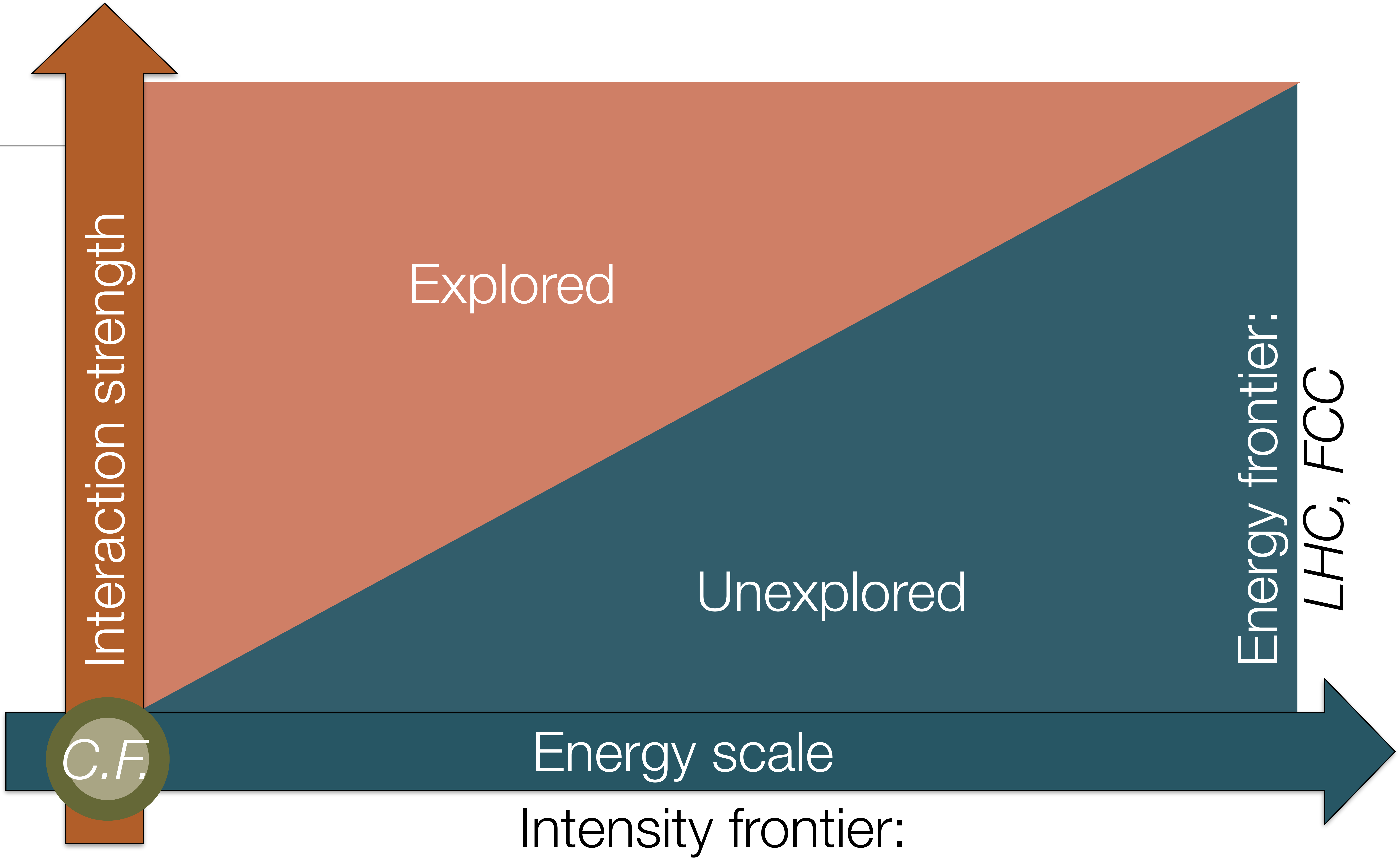
Bf(Higgs→πV+πV) < 20 %



Bf(Higgs→πV+πV) < 2 %

Introduction / 1bk

- Naturalness does not seem to be a **guiding principle** of Nature
- There are some **anomalies in flavour physics** which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that **we have a 2D problem** (Mass VS Coupling)
- Low coupling → Long Lived



Intensity frontier:
Flavour physics, lepton flavour violation, electric dipole moment, ***dark sector***

Landscape today / 1bk

- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **dark sector** and related physics searches.
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not been successful so far
    - Parameter space for popular **BSM** models is **decreasing rapidly**, but only < 5% of the complete HL-LHC data set has been delivered so far
    - NP discovery **still may happen**!
  - **LHCb** reported intriguing hints for the violation of lepton flavour universality
    - In $b \to c\mu\nu$ / $b \to c\tau\nu$, and in $b \to se^+e^-$ / $b \to s\mu^+\mu^-$ decays
    - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)