Searching for BSM physics (with displaced signatures) at LHCb

A personal perspective

Federico Leo Redi

Workshop italiano sulla fisica ad alta intensita' - November 2023

INFN MILANO Istituto Nazionale di Fisica Nucleare Sezione di Milano

UNIVERSITÀ DEGLI STUDI DI BERGAMO

- ~~Theory introduction~~
- ~~The big players~~
- The underdog: LHCb
  - The present
    - Two cherry picked results
  - The future prospects
    - A significant upgrade example

Il segreto di Majorana. Riccioni & Rocchi

- The underdog: LHCb
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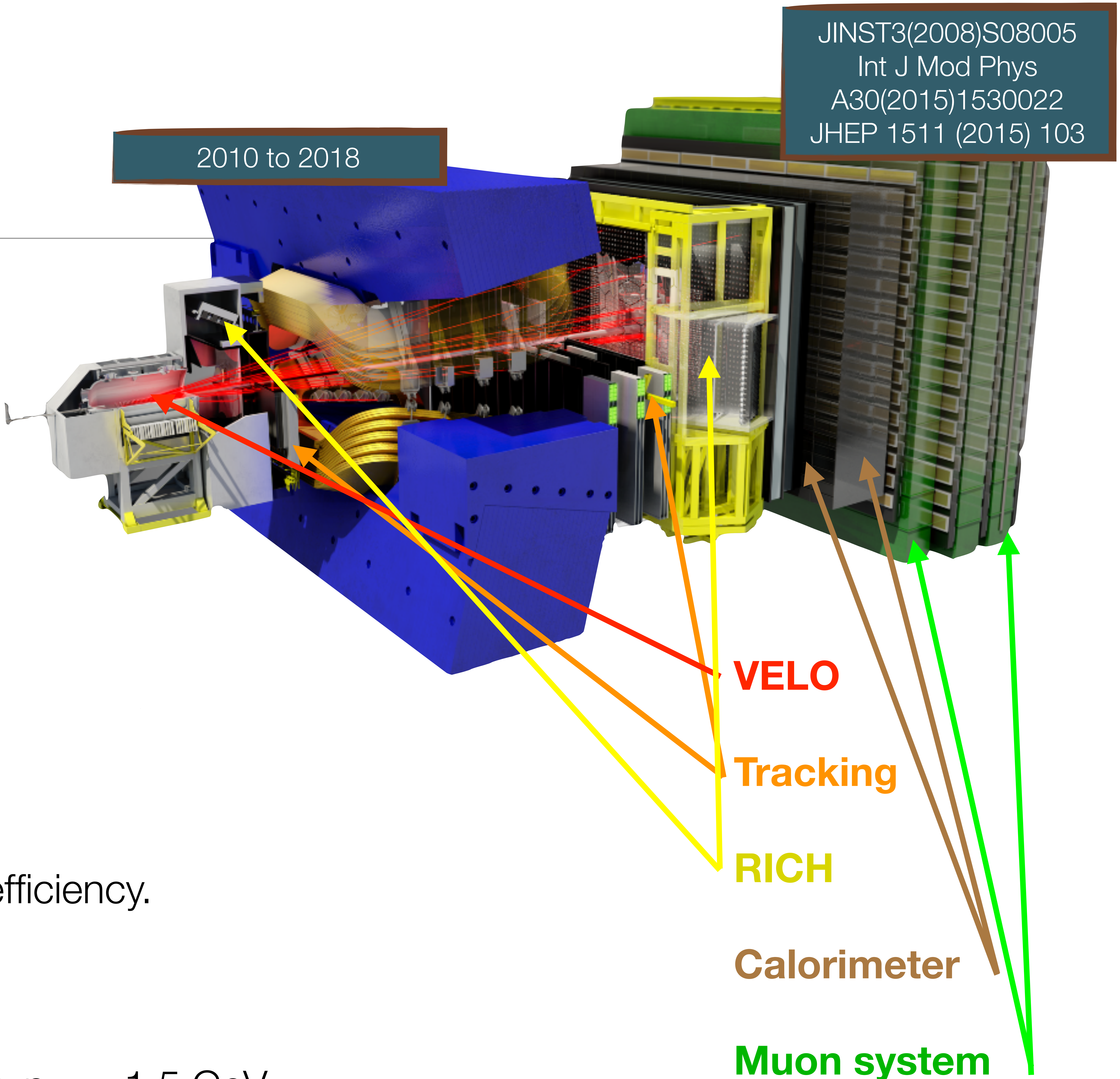
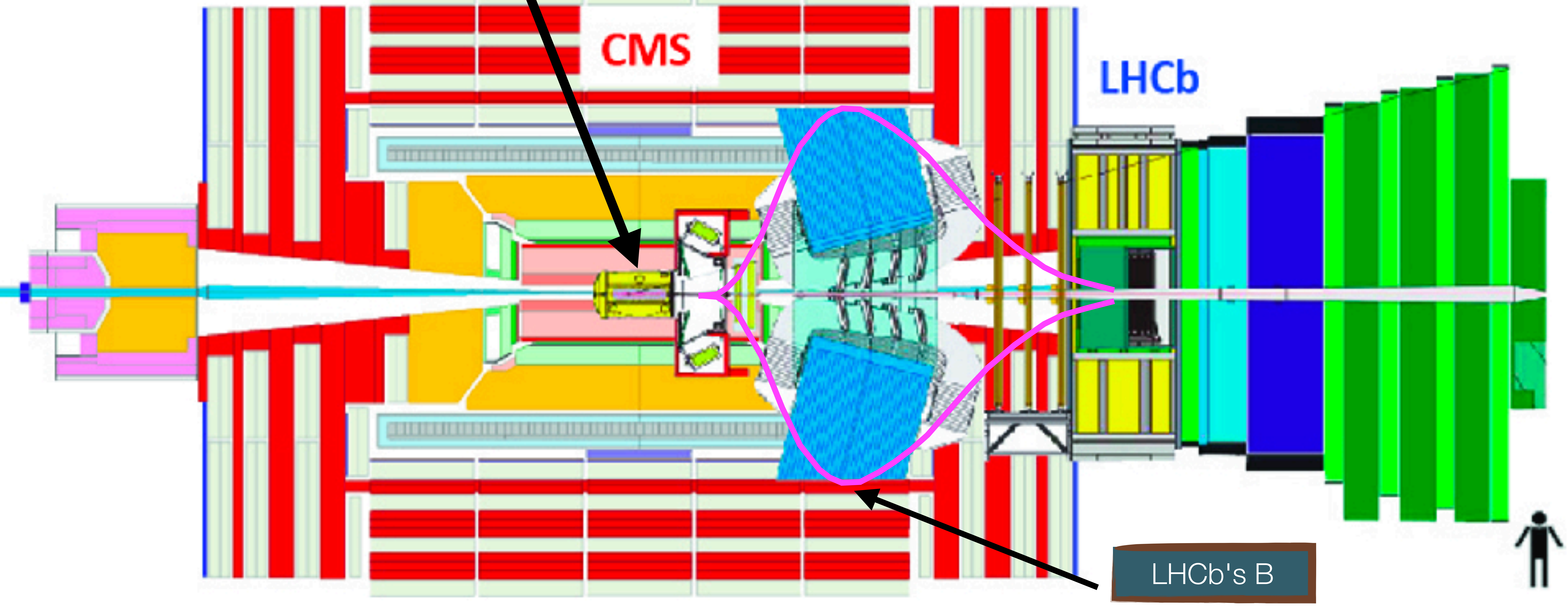
Il segreto di Majorana. Riccioni & Rocchi

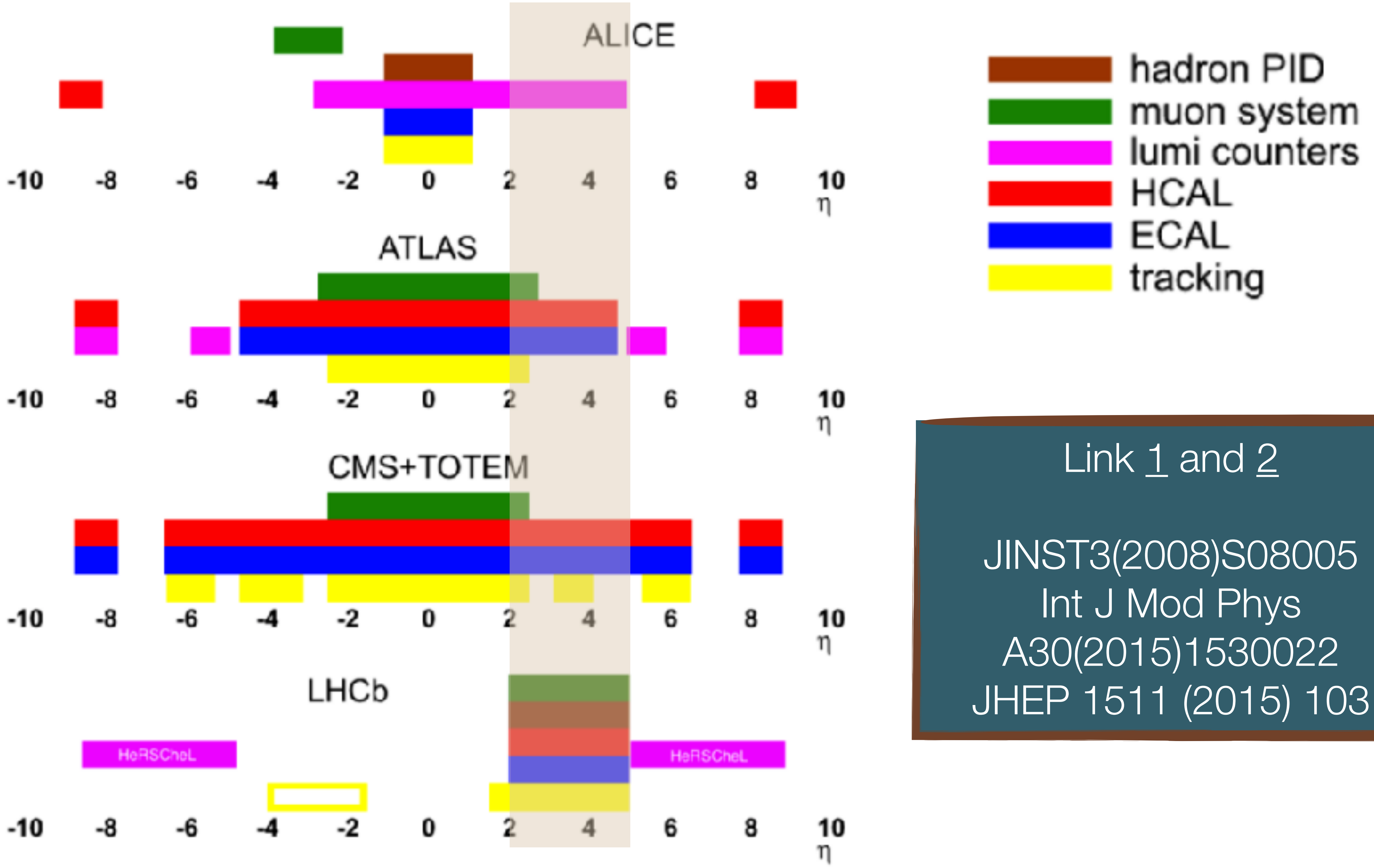
LHCb detector / 1

- **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.
  - ~ 45 fs for B0s -> J/psi phi and B0s -> Ds pi
- **Muons** clearly identified and triggered: ~ 90% $\mu^{\pm}$ efficiency.
- Great **mass resolution**: e.g. 15 MeV for J/psi.
- **Low p_T trigger** means low masses accessible. Ex: $p_{T\mu}$ > 1.5 GeV.



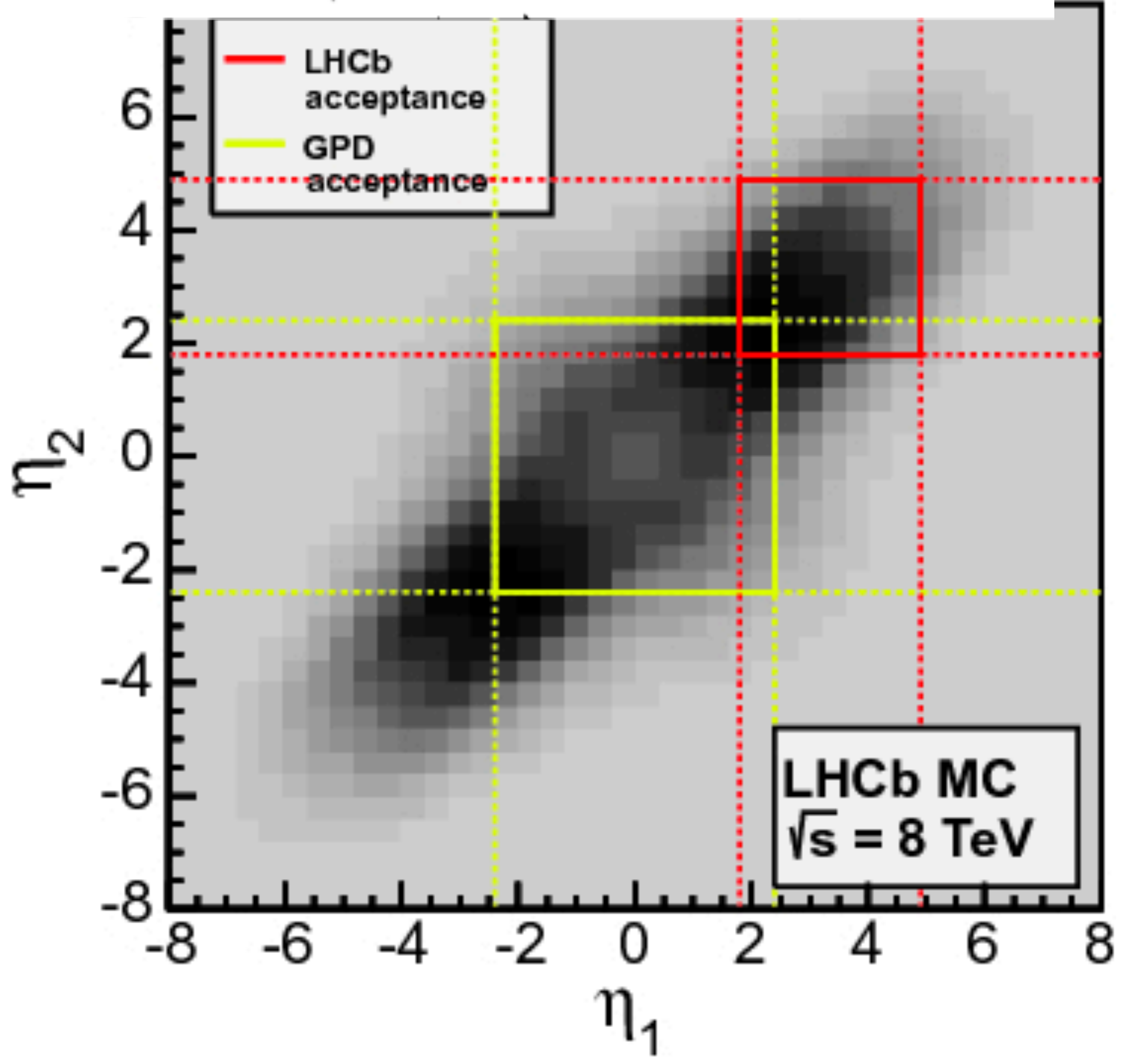
LHCb / CMS so much different?





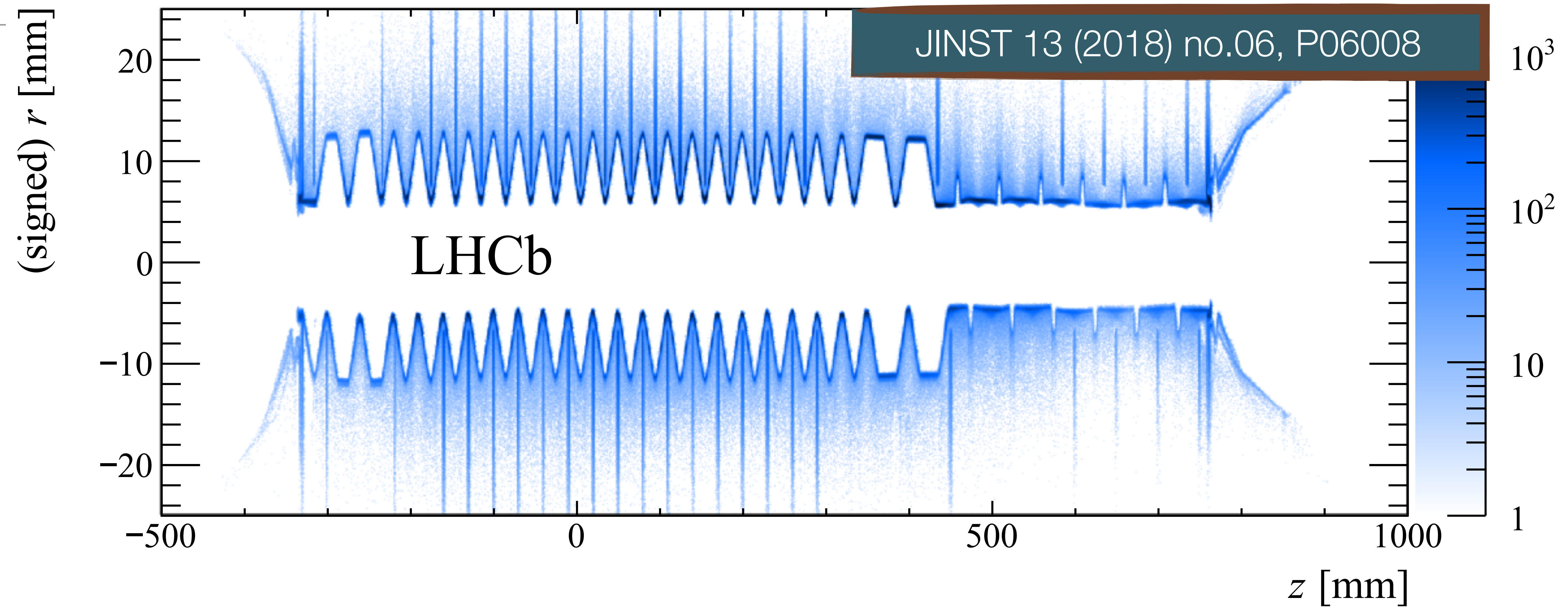
Link 1 and 2

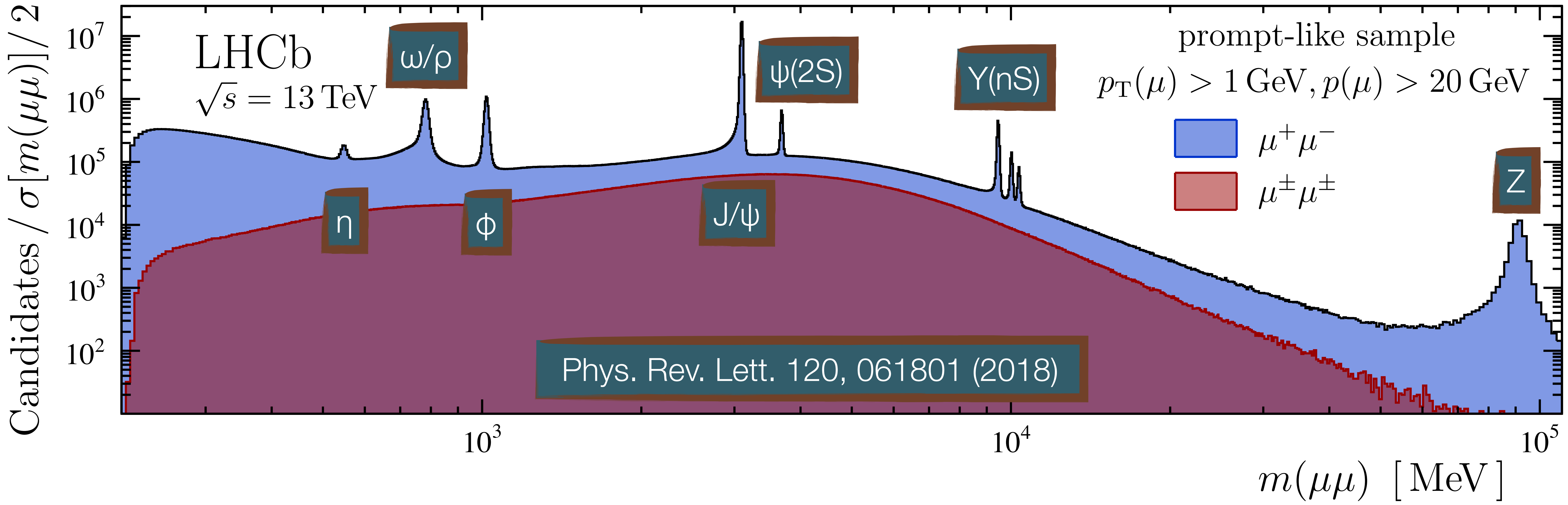
JINST3(2008)S08005
Int J Mod Phys A30(2015)1530022
JHEP 1511 (2015) 103



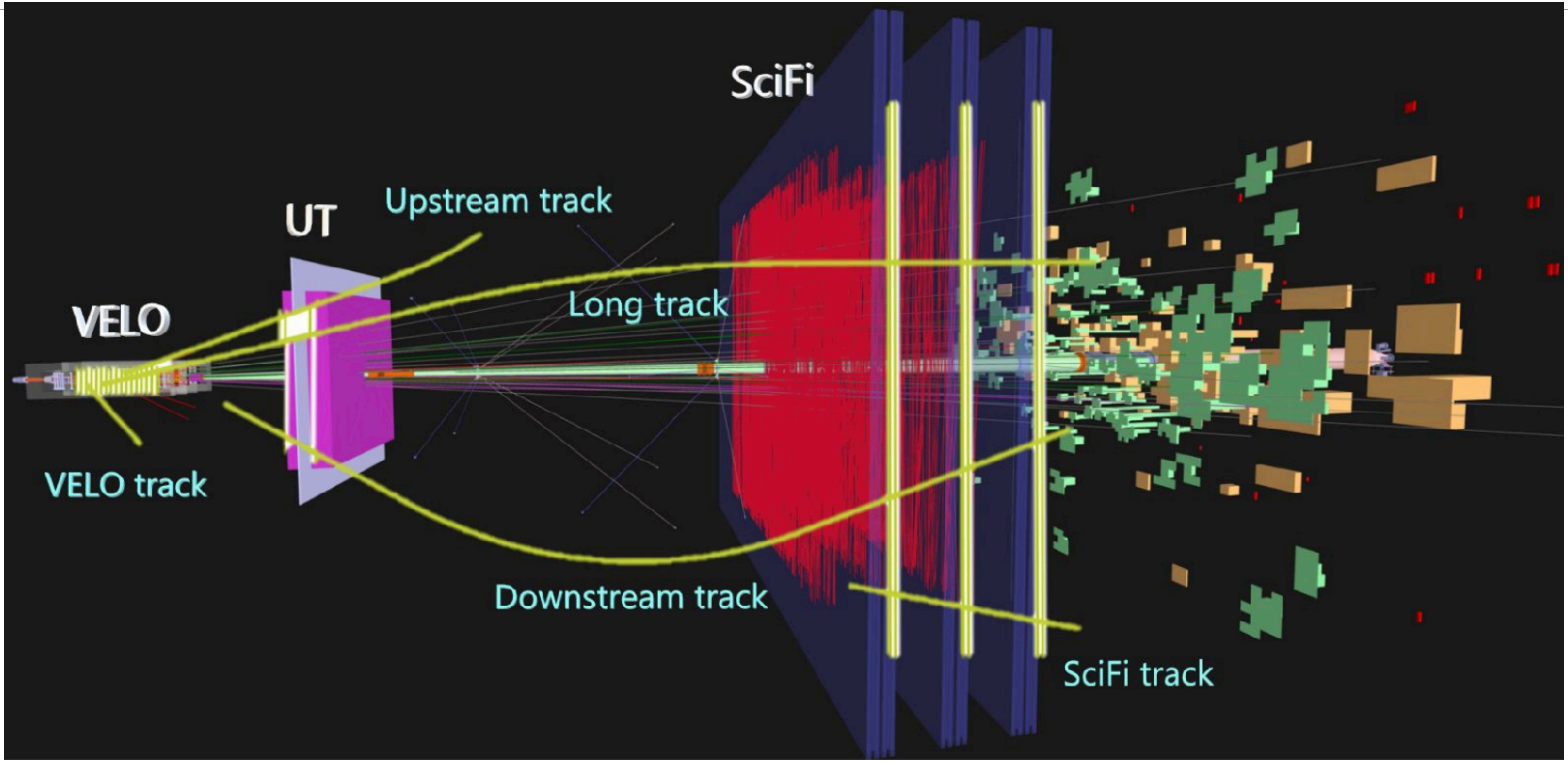
LHCb detector

- 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 and one can develop a full map the VELO material
- **Real-time calibration** in Run 2 (Turbo Stream)
- Very efficient online reconstruction e.g. in di-muon final states (50 years of SM!)

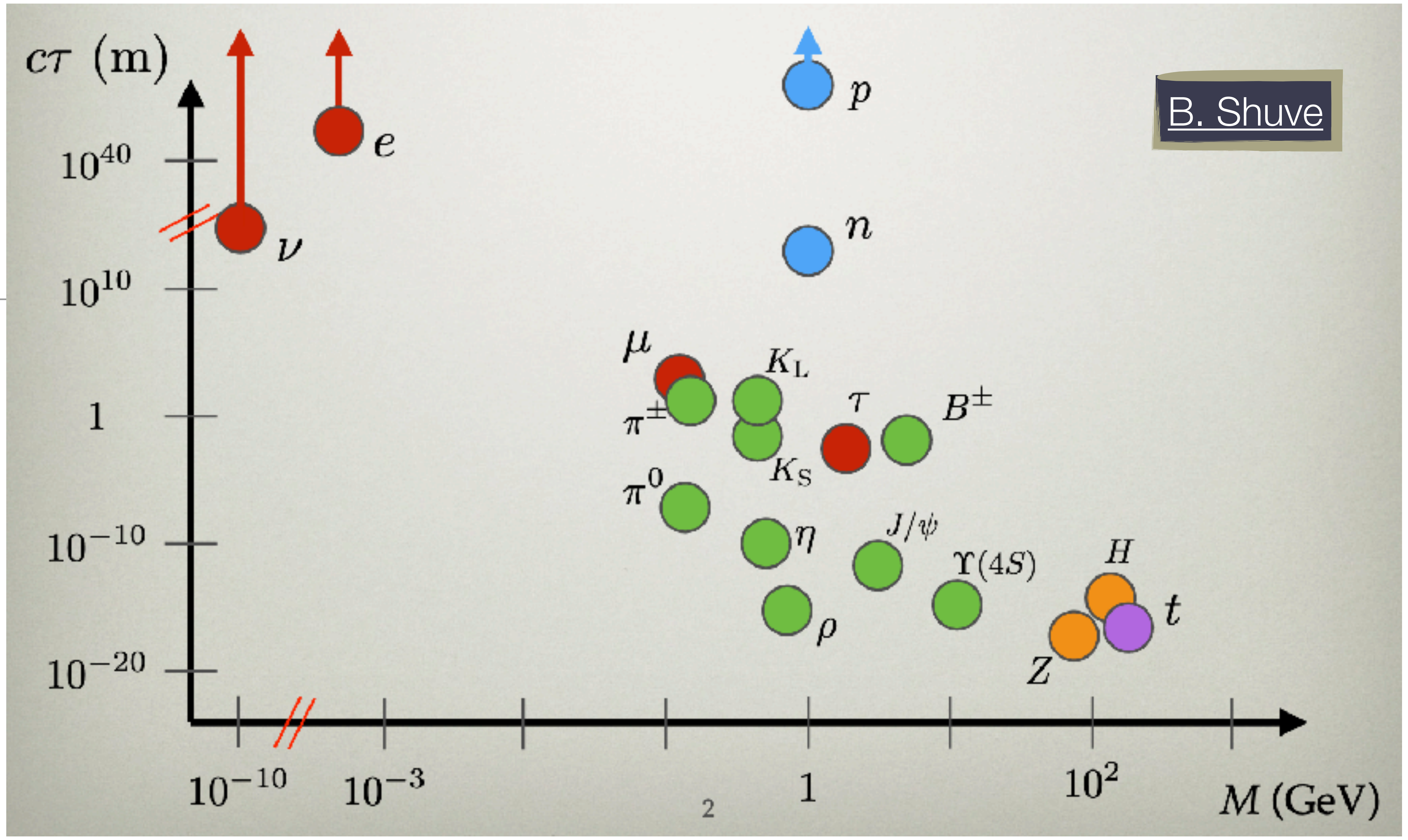




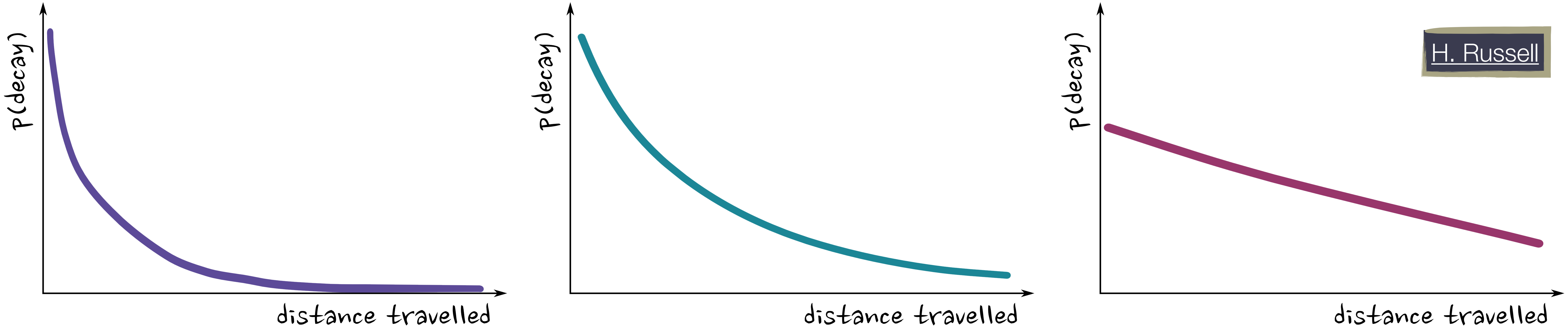
LHCb’s track types



What are long-lived particles?

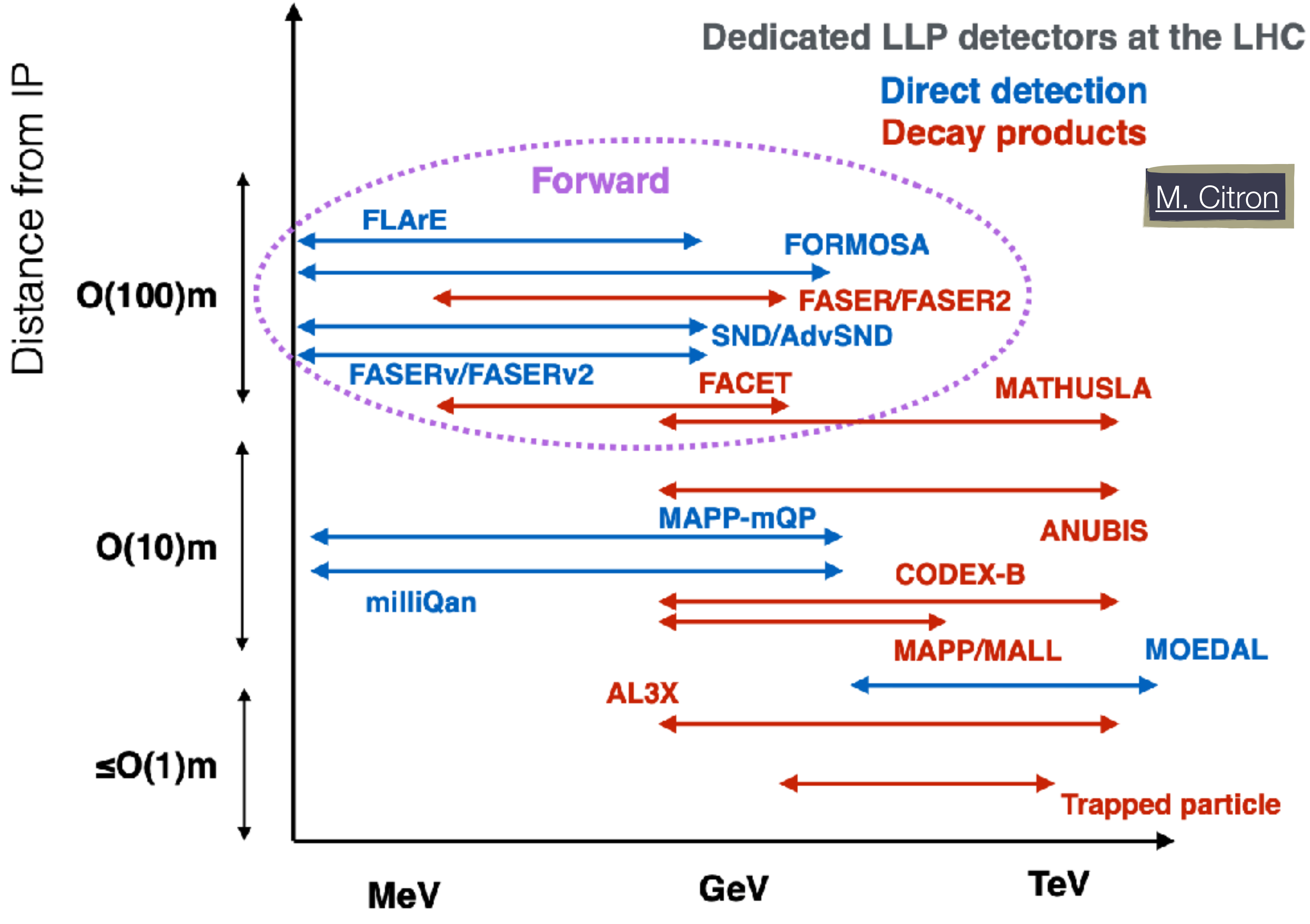


- **What is a long-lived particle?**
  - As an experimentalist: it's a particle that decays in a reconstructable distance from the production point (e.g. pp interaction point at the LHC)
  - **De-facto used for BSM particles**
  - **Lifetime is sampled from an exp, there is an additional parameter**



The community

- Started with few of us and slowly evolving in “main stream” particle physics
- Great communal effort with a bottom up approach
- Started independently and matured in the **LHC Long-lived Particles Working Group (LHC LLP WG):** Established in 2020 to serve as a formal bridge with the relevant physics groups of the approved LHC experiments



LHC LLP WG

Theory/pheno

LLP Community

Theory/pheno

AL3X

ANUBIS

BDX

FPF

ANITA

LISA

FPC

FCC

J. Beacham

- The underdog: LHCb
  - The present
    - **Two cherry picked results**
  - The future prospects
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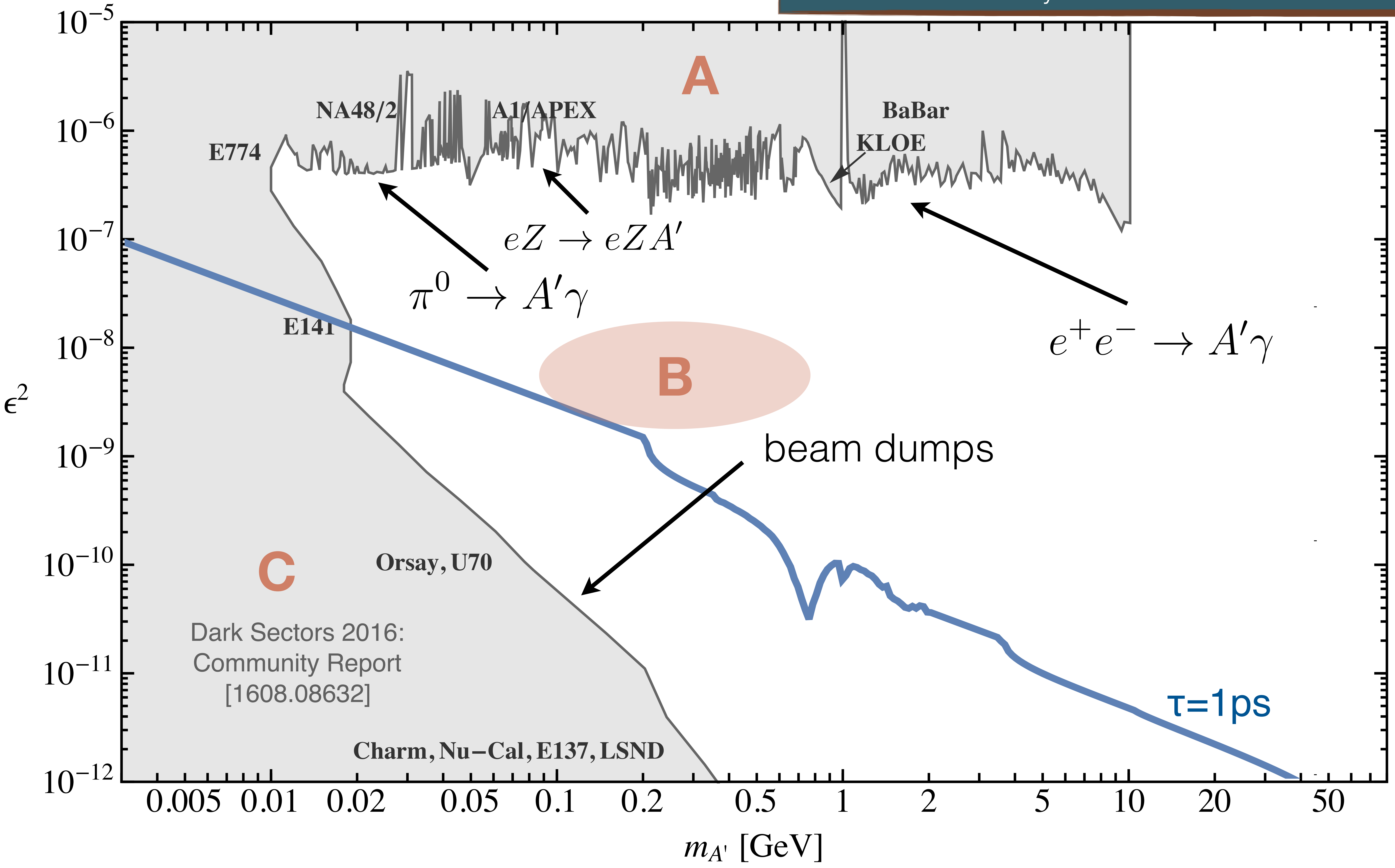
Il segreto di Majorana. Riccioni & Rocchi

Visible dark photons

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

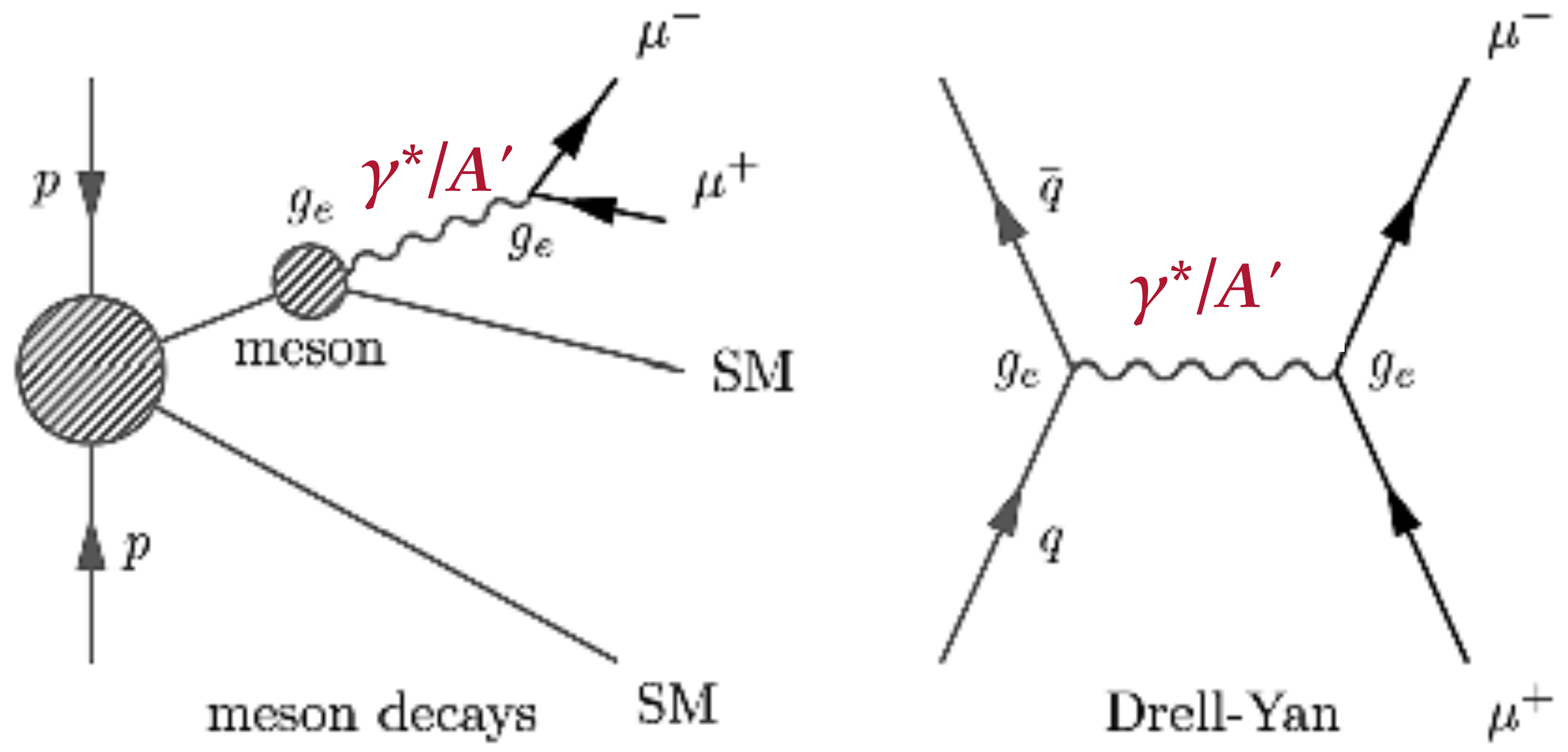
Dark Sectors 2016: Community Report [1608.08632]
Courtesy of Mike Williams



Searching for Dark Photons

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



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

off-shell photon

phase-space

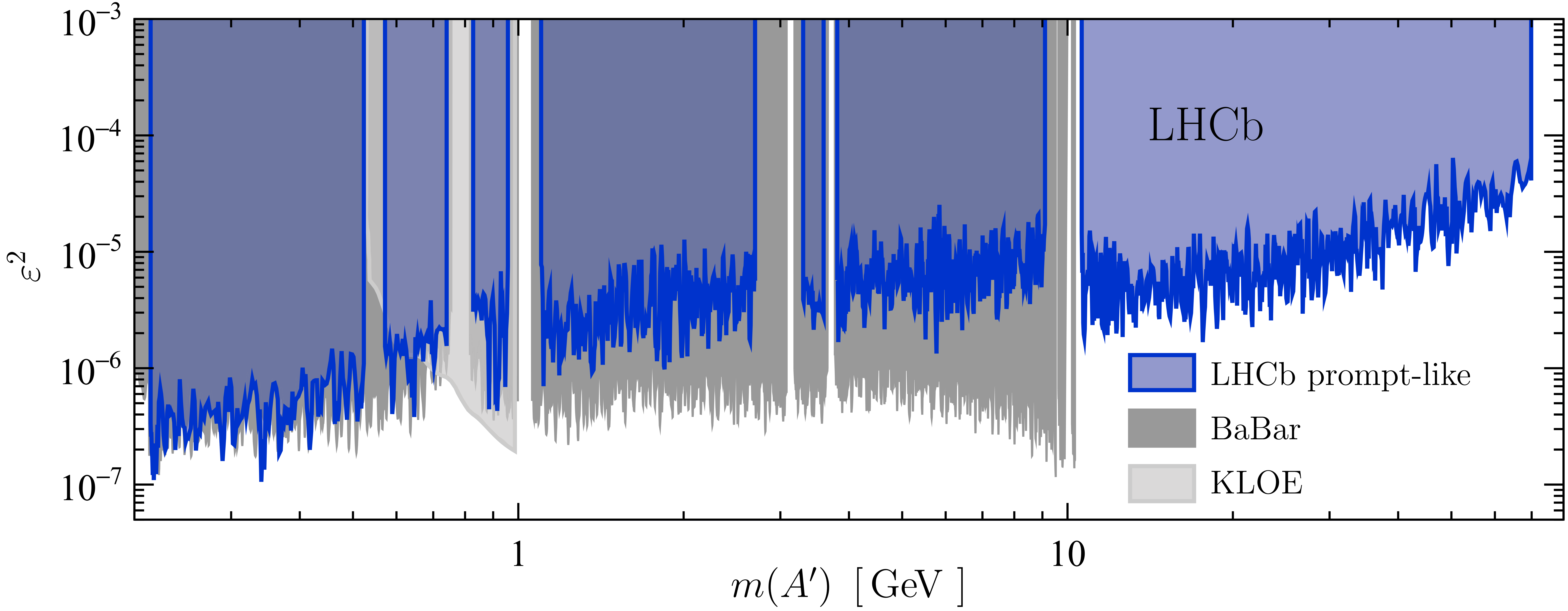
A′/γ^* eff ratio, ϵ=1 for prompt

Need to separate from background

Search for Dark Photons / Prompt

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

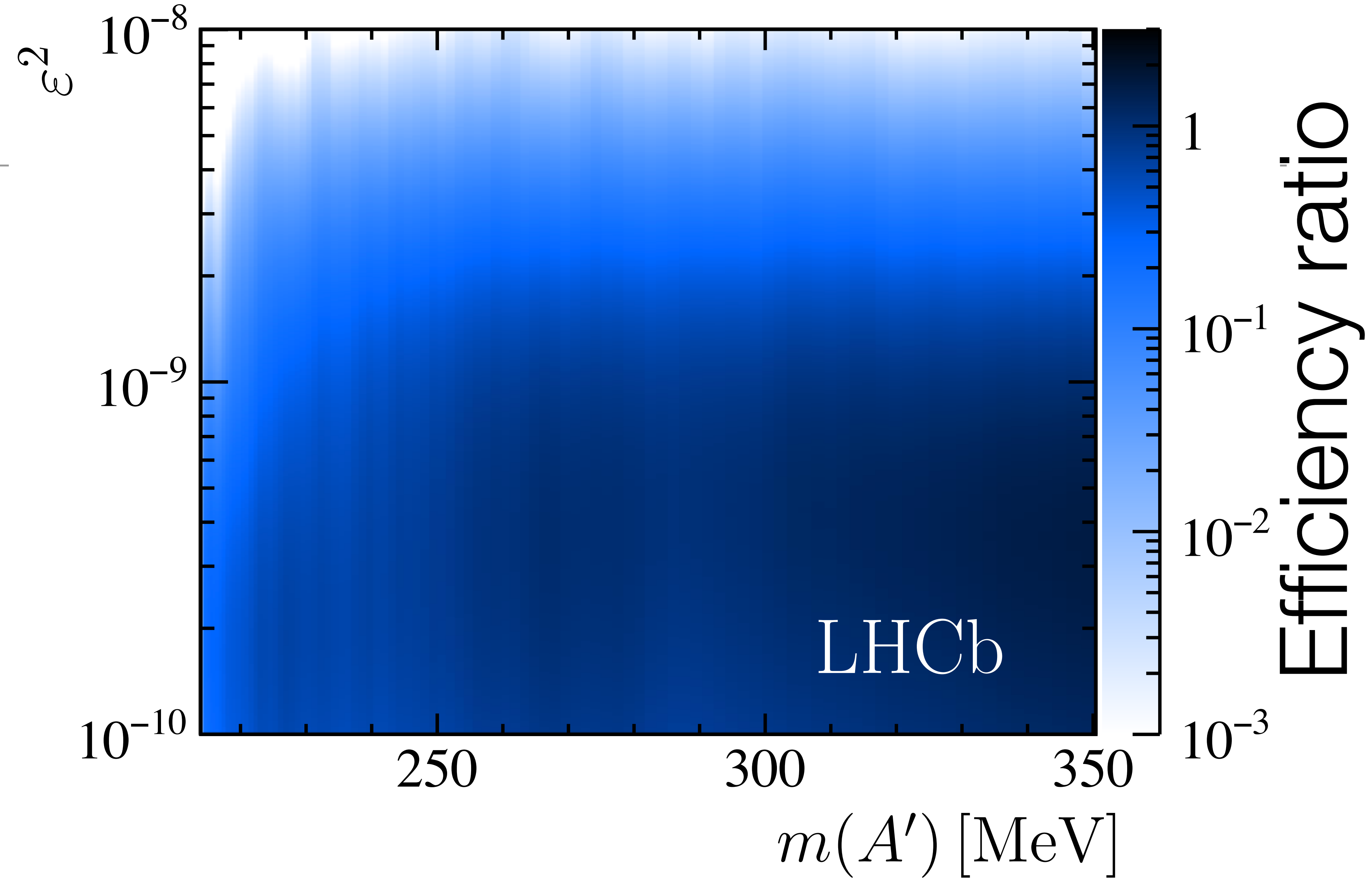
- No significant excess found - exclusion regions at 90% C.L.
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV

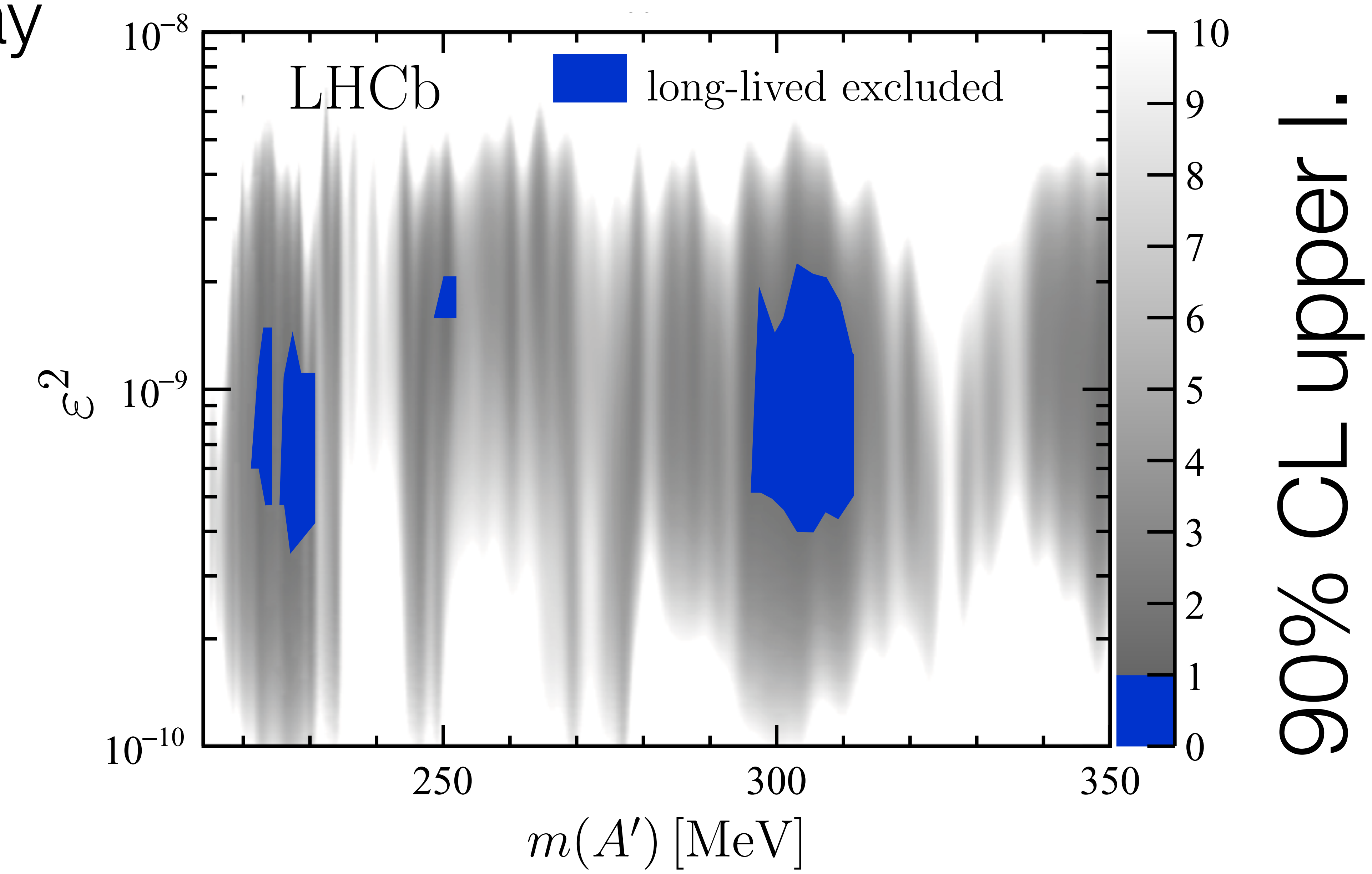


Phys. Rev. Lett. 120, 061801 (2018)

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**

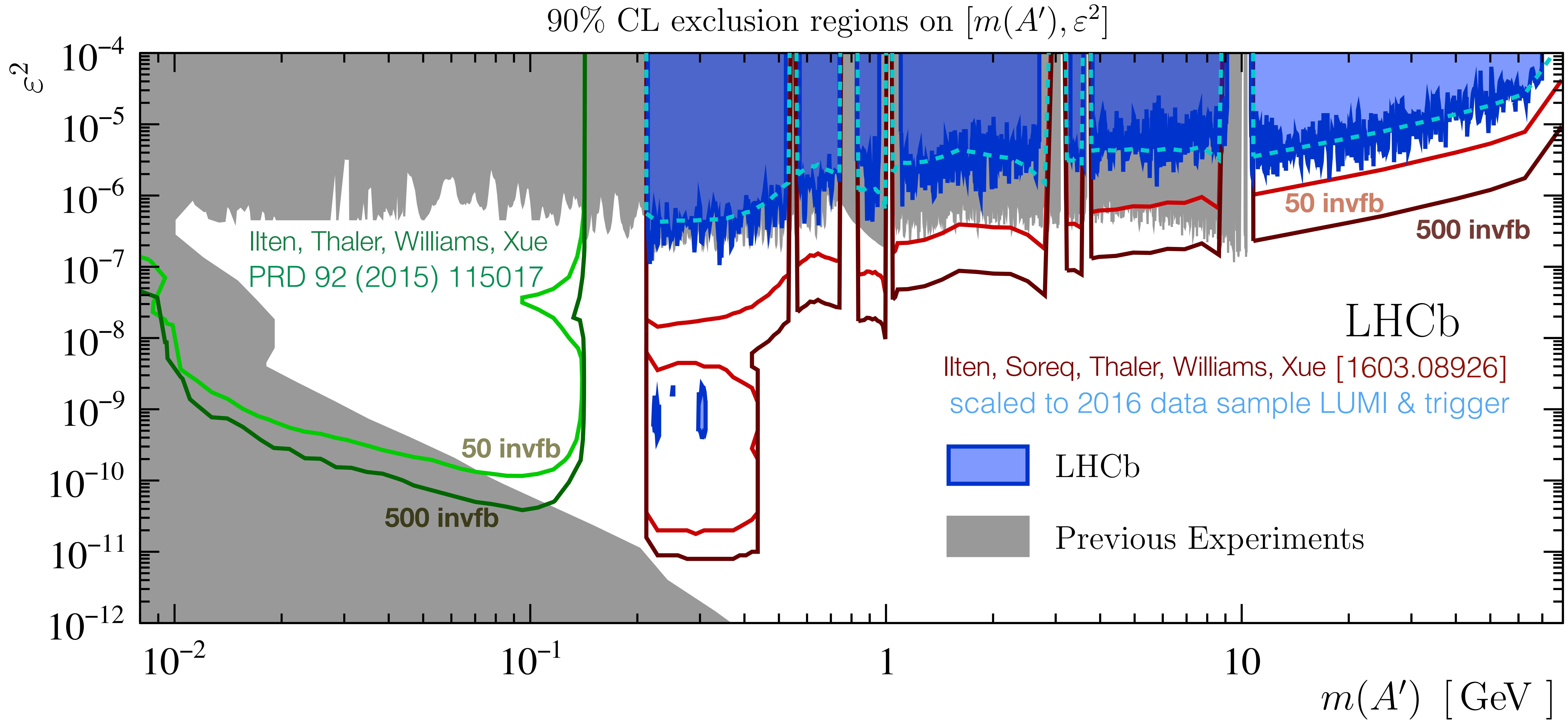




Search for Dark Photons / Results

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

- The dimuon results are consistent with (better than) predictions for prompt (long-lived) dark photons as discussed in [1603.08926]. Then onto electrons.

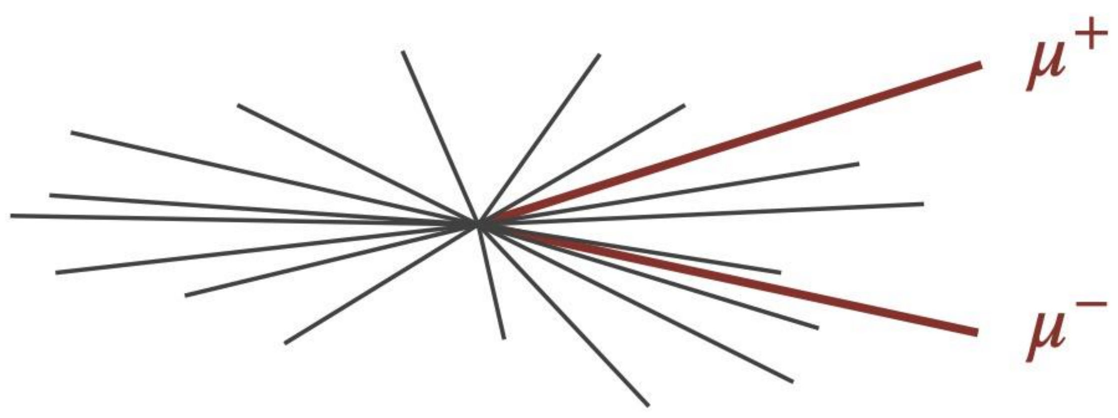


Low-mass dimuon resonances

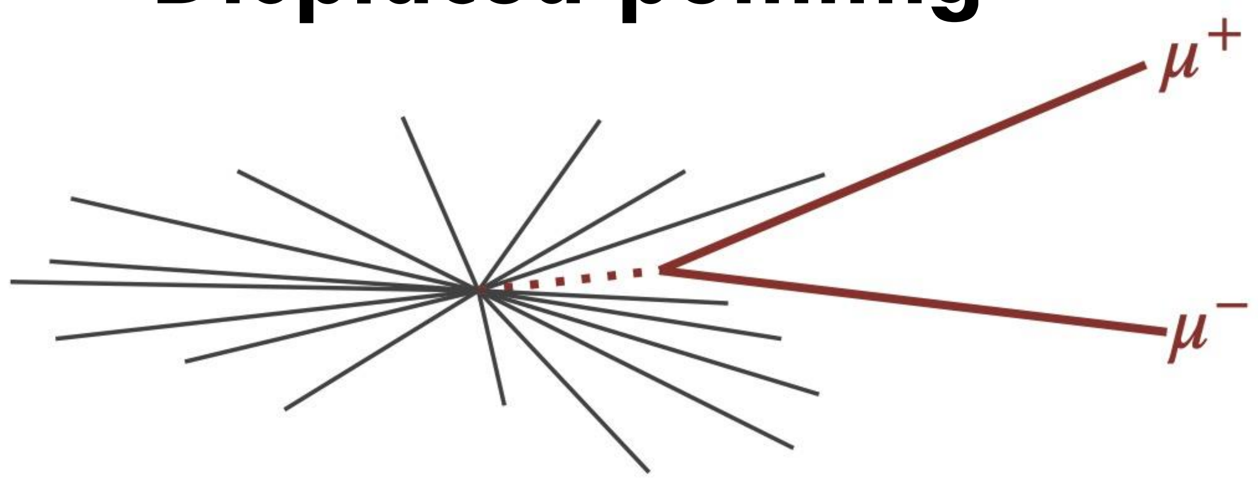
- Non-minimal searches, example signatures:

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

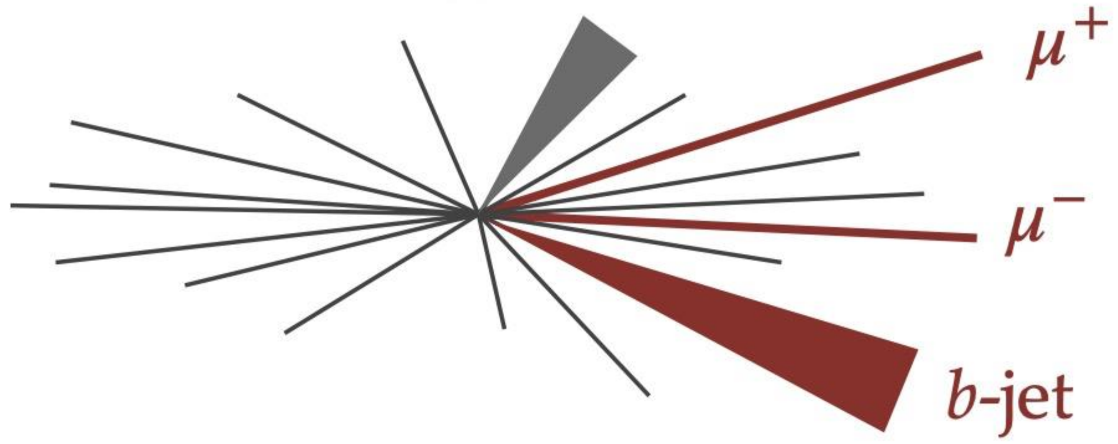


Displaced pointing

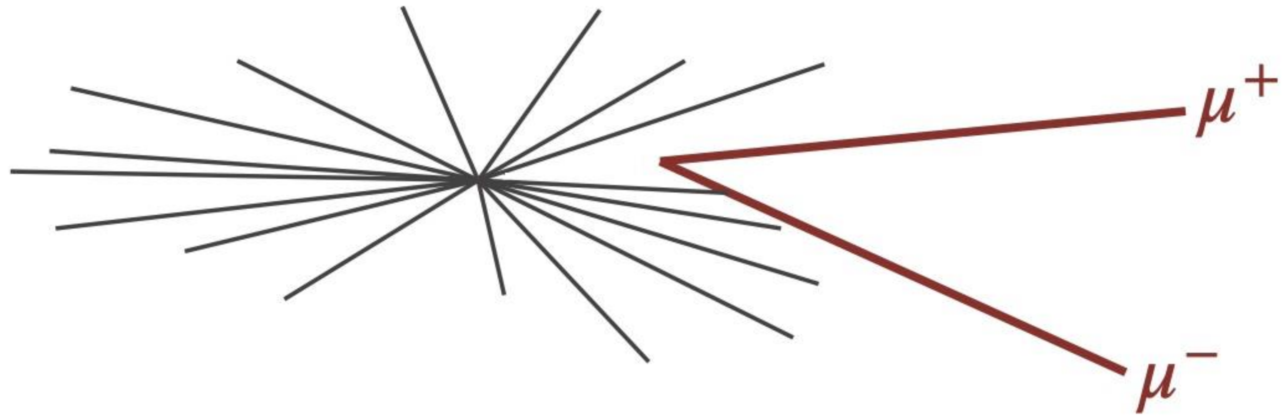


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing



Taken from I. Kostiuk's talk

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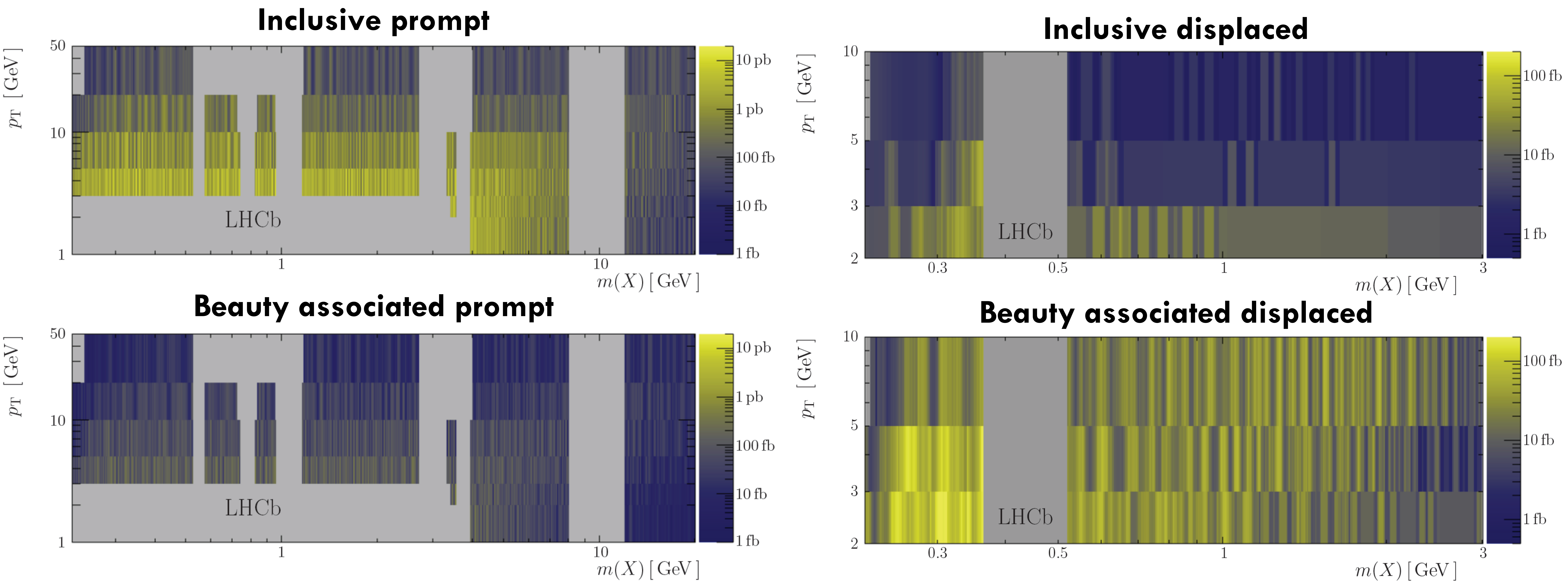
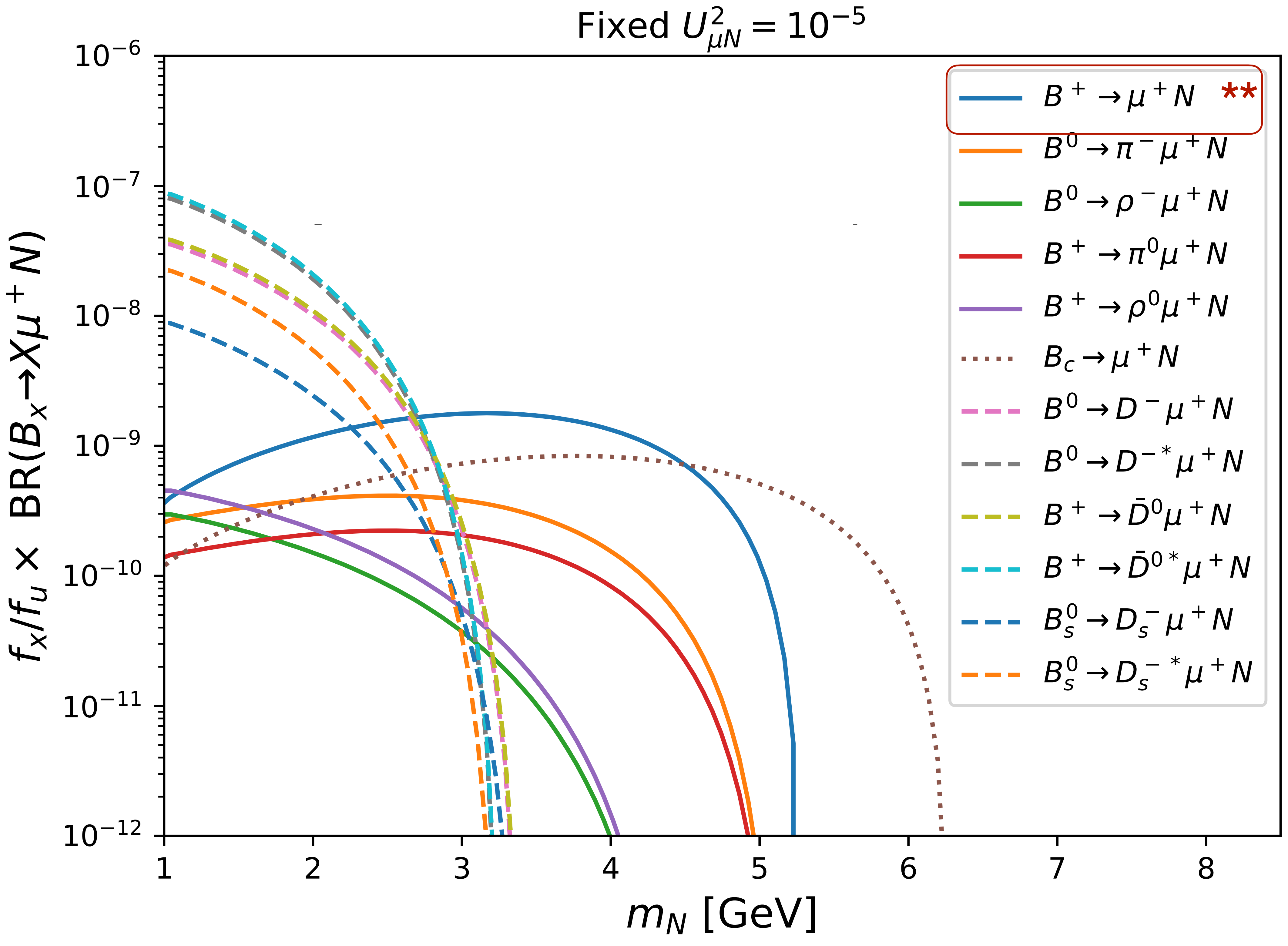
Low-mass dimuon resonances

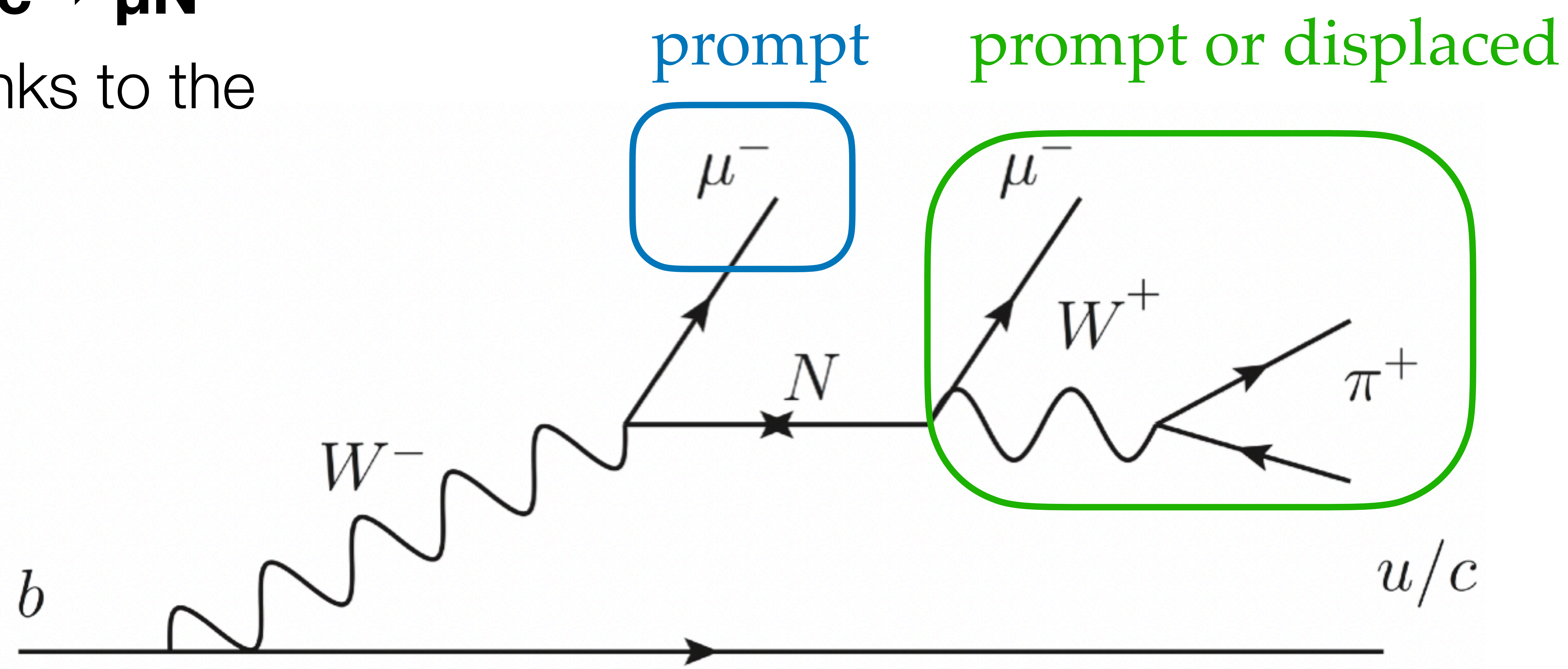
- Upper limits at 90% CL on $\sigma(X \rightarrow \mu\mu)$



What about from a *b*?

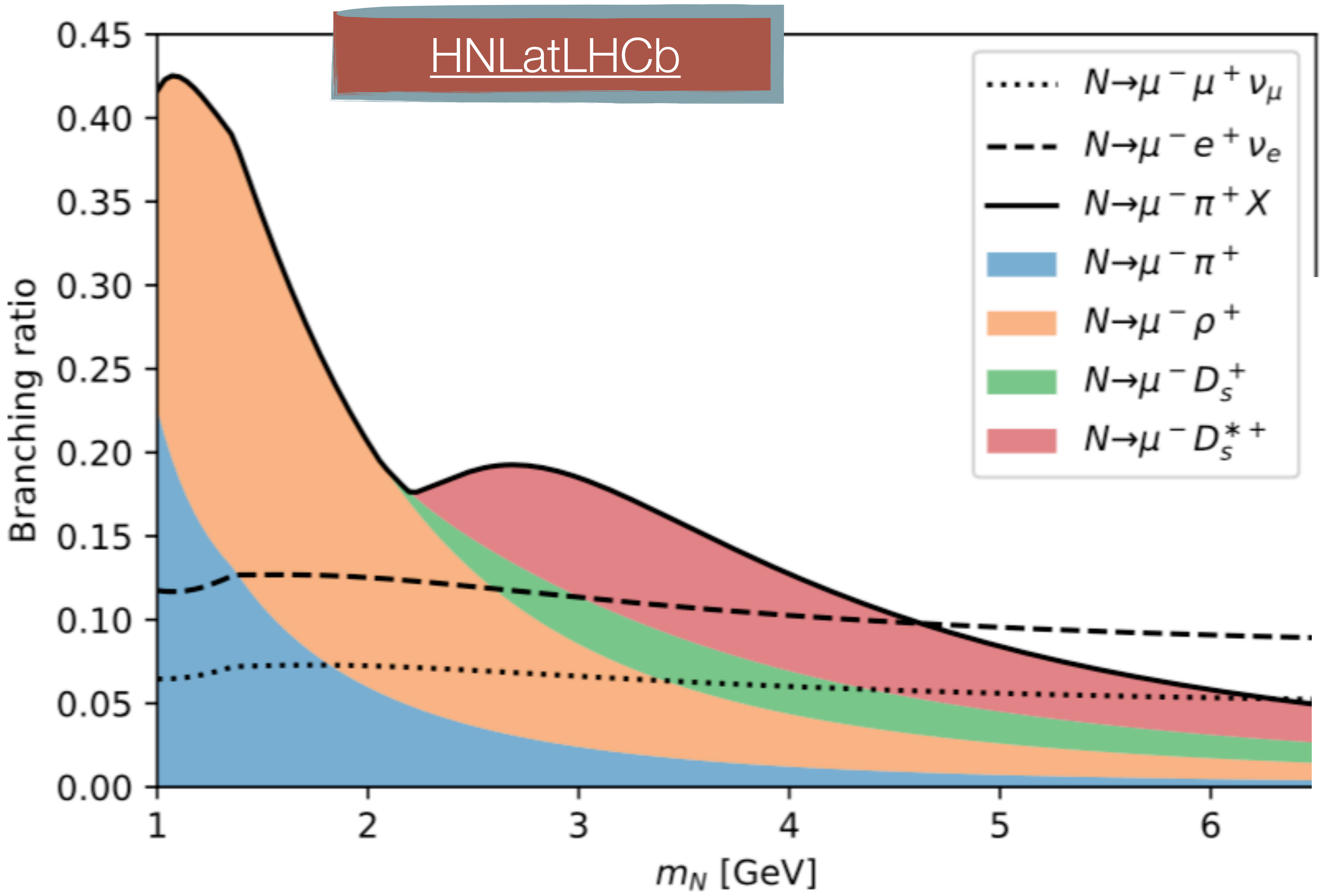
- Can one expand such narrow searches? Combine all the knowledge of b quarks and missing masses?
- Yes, e.g. in Majorana neutrino searches where it's hard to compete with LHCb in the B production region
- Previous analysis (B → μN**) only used one production mode: simple but inefficient
- **Here Xb → μN is added together with Bc→ μN**
- Multiple final states are also considered thanks to the expertise built in FLU searches containing νs:
- **Gain up to 12 times signal yield (only for displaced vertexes)**

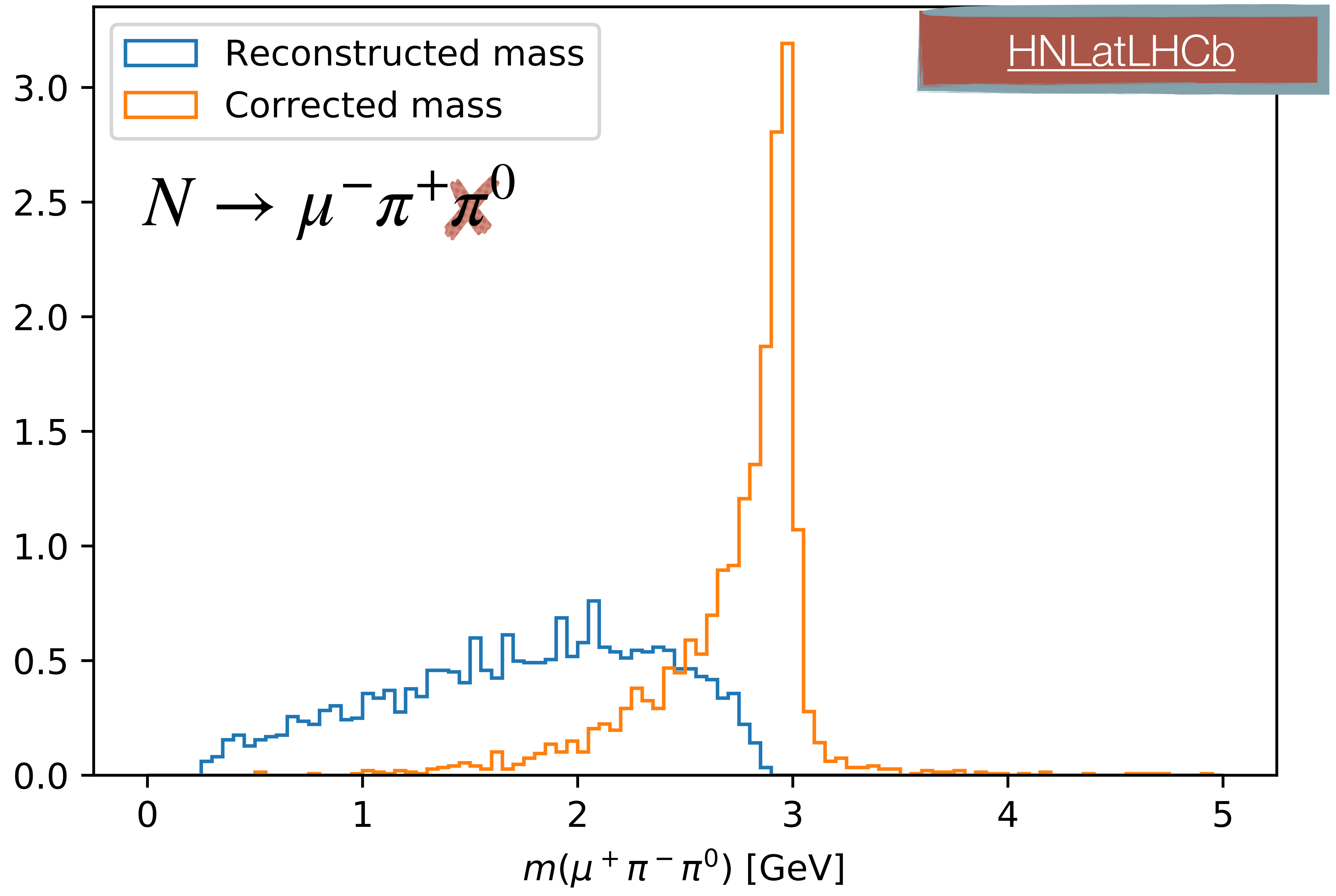


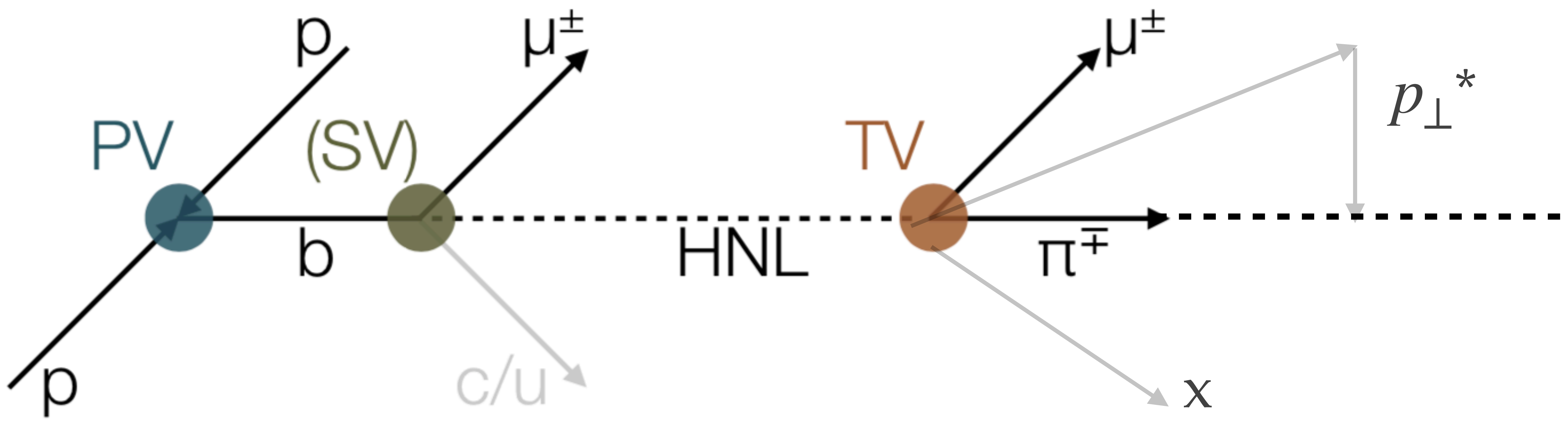


Heavy neutral leptons

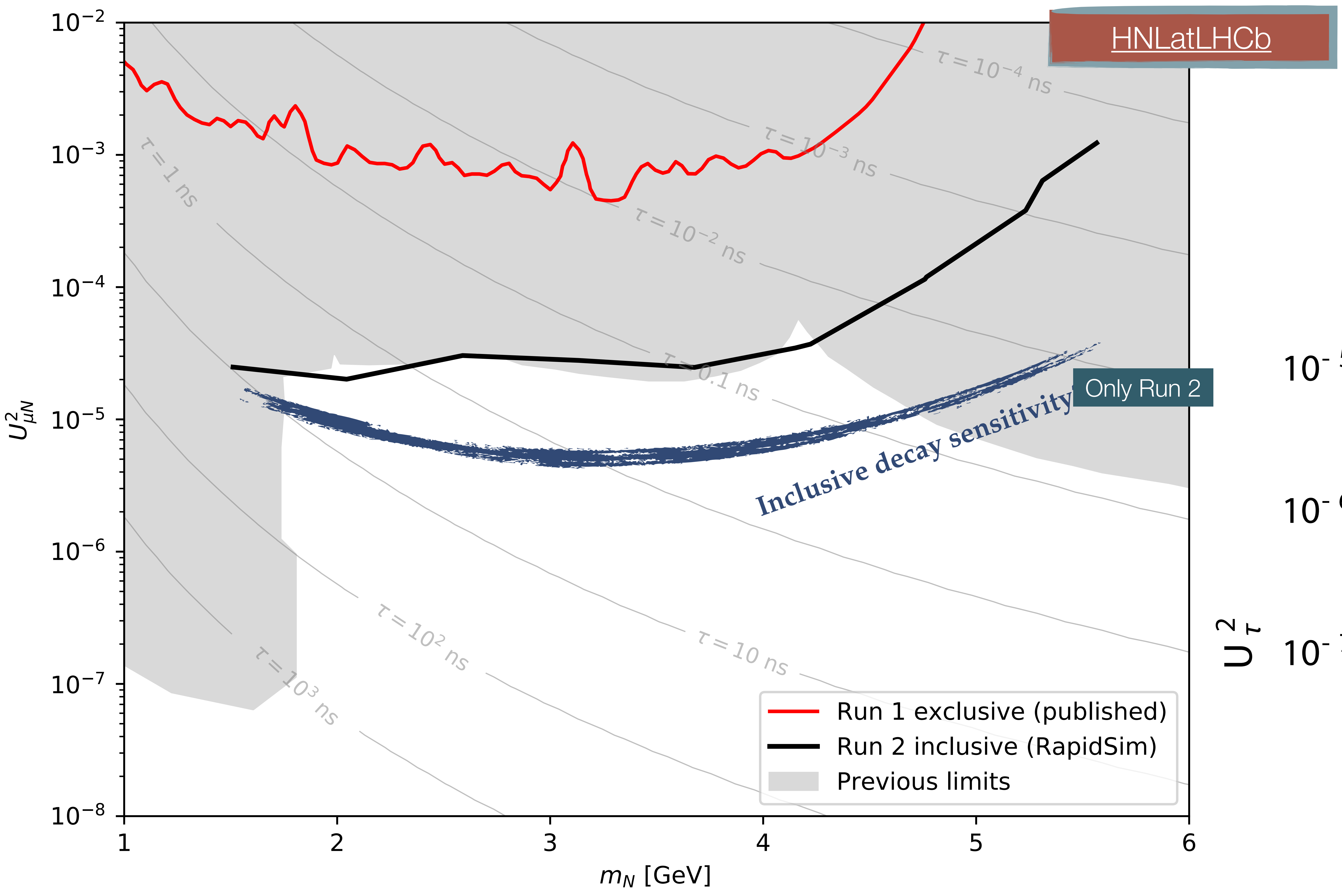
- Loose peak in invariant mass spectrum of N
- Instead use **corrected mass**: $\sqrt{p_{\perp}^2 + m_{\text{vis}}^2} + p_{\perp}$
- Derive the missing momentum from SV to TV direction create a good peak
- Coupling to other leptons is also promising

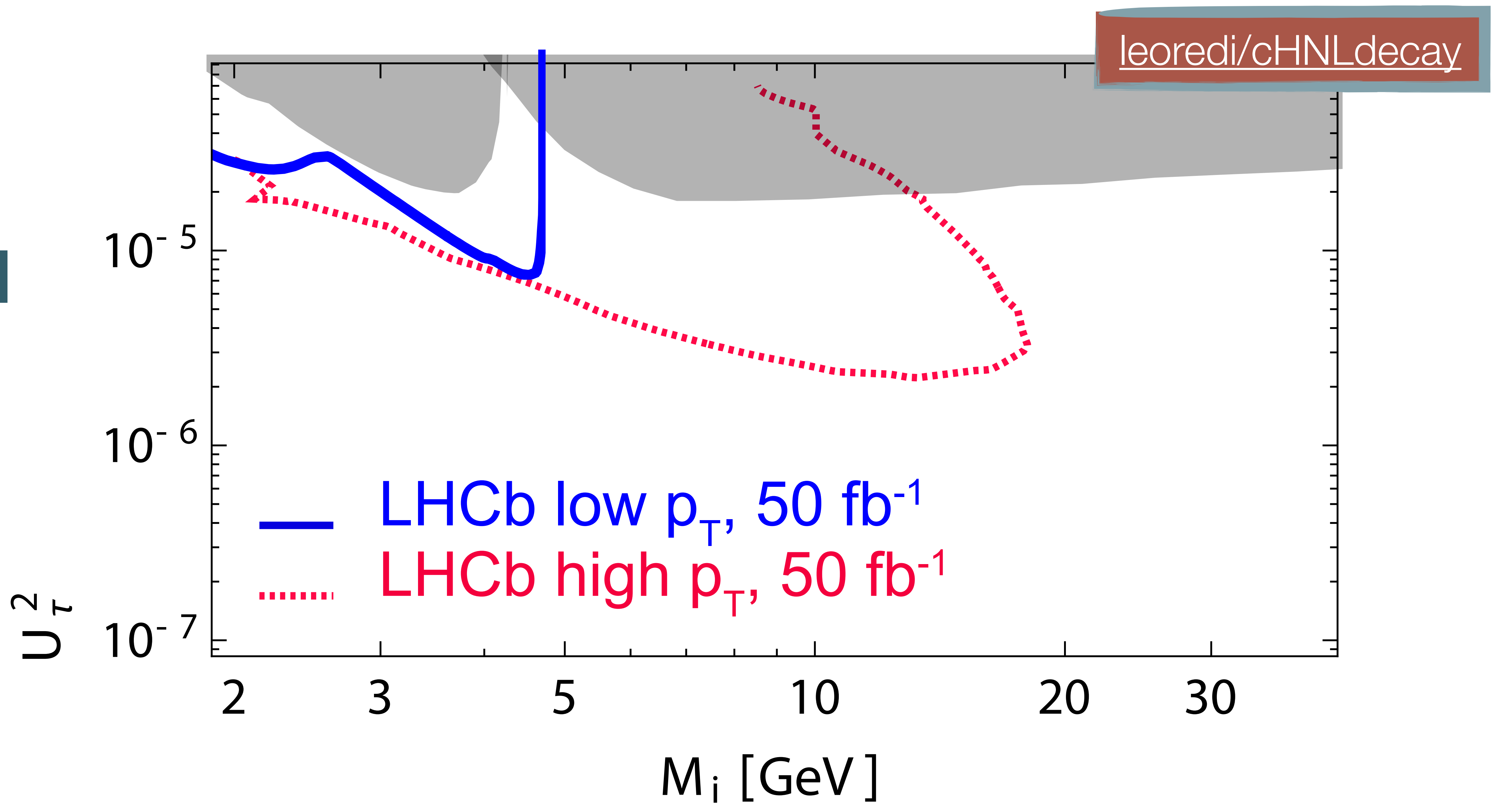






Heavy neutral leptons





- The underdog: LHCb
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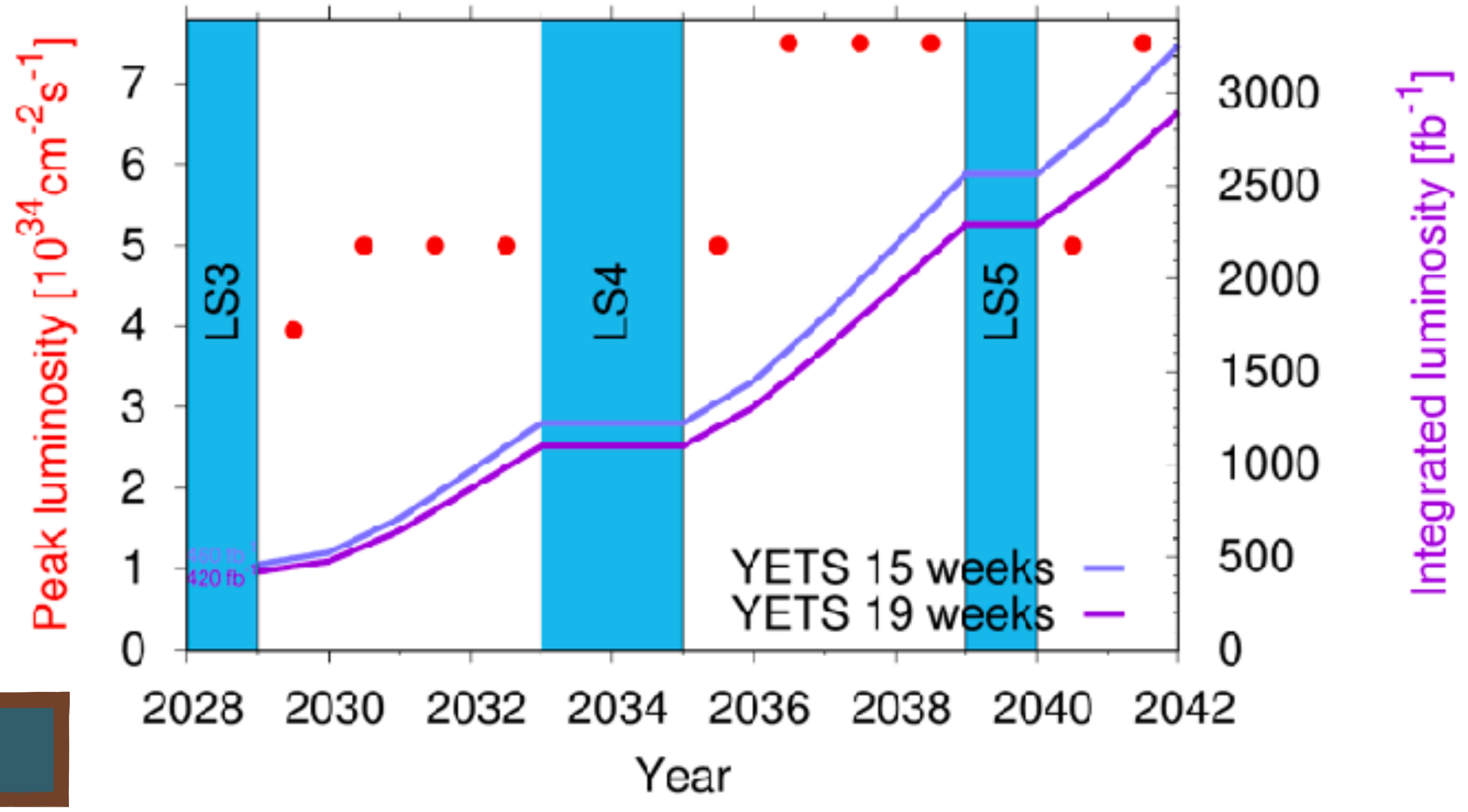
Il segreto di Majorana. Riccioni & Rocchi

Disclaimer: These figures may not be the most current but are provided for indicative purposes

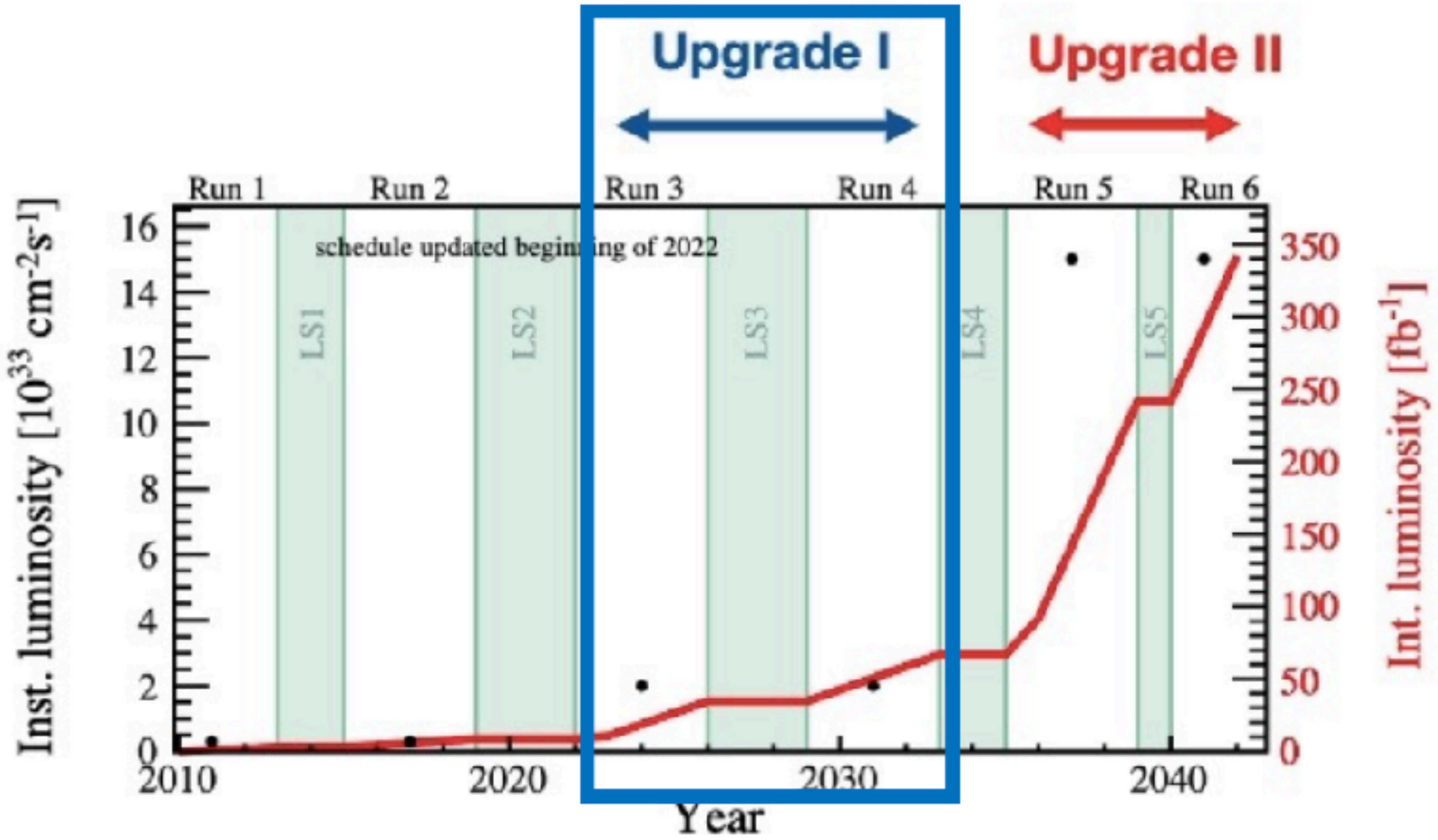
LHCb Timeline

- The amount of data and the physics yield from data recorded by the past LHCb experiment is **limited by its detector**:
- But **LHC** has **increased its performance**:
  - **Energy / beam** (3.5 to 4 to 6.5 to 7 TeV)
  - **Luminosity** (peak $8x10^{33}$ to $2x10^{34}$ $cm^{-2}s^{-1}$ to HL-LHC)
- Timeline of the Upgrades is in line with LHC timeline but **asynchronous w.r.t. CMS and ATLAS**
- New instant Lumi = $2x10^{33}$ $cm^{-2}s^{-1}$ (x5 w.r.t. Run 1)



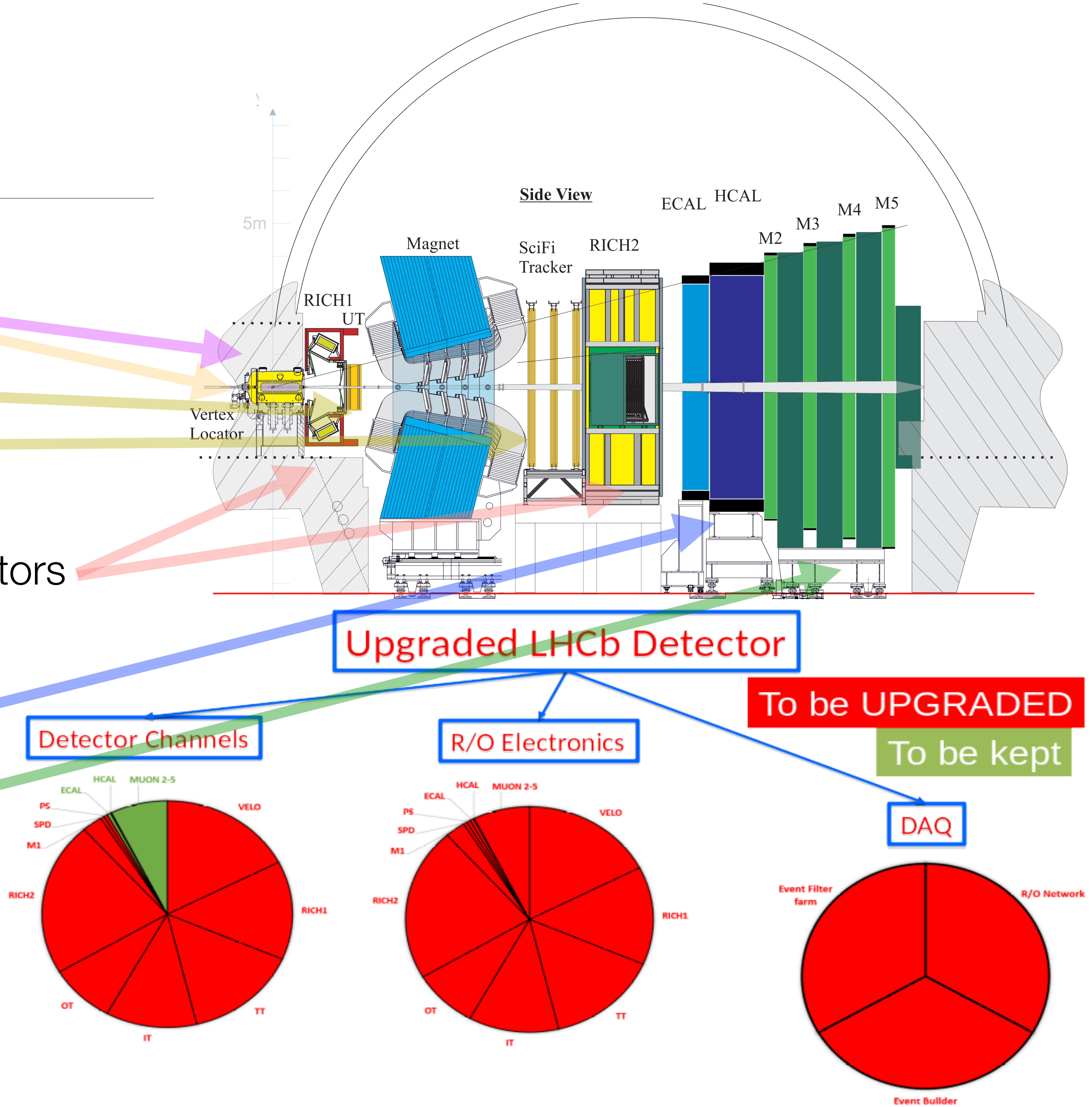
LHC

LHCb



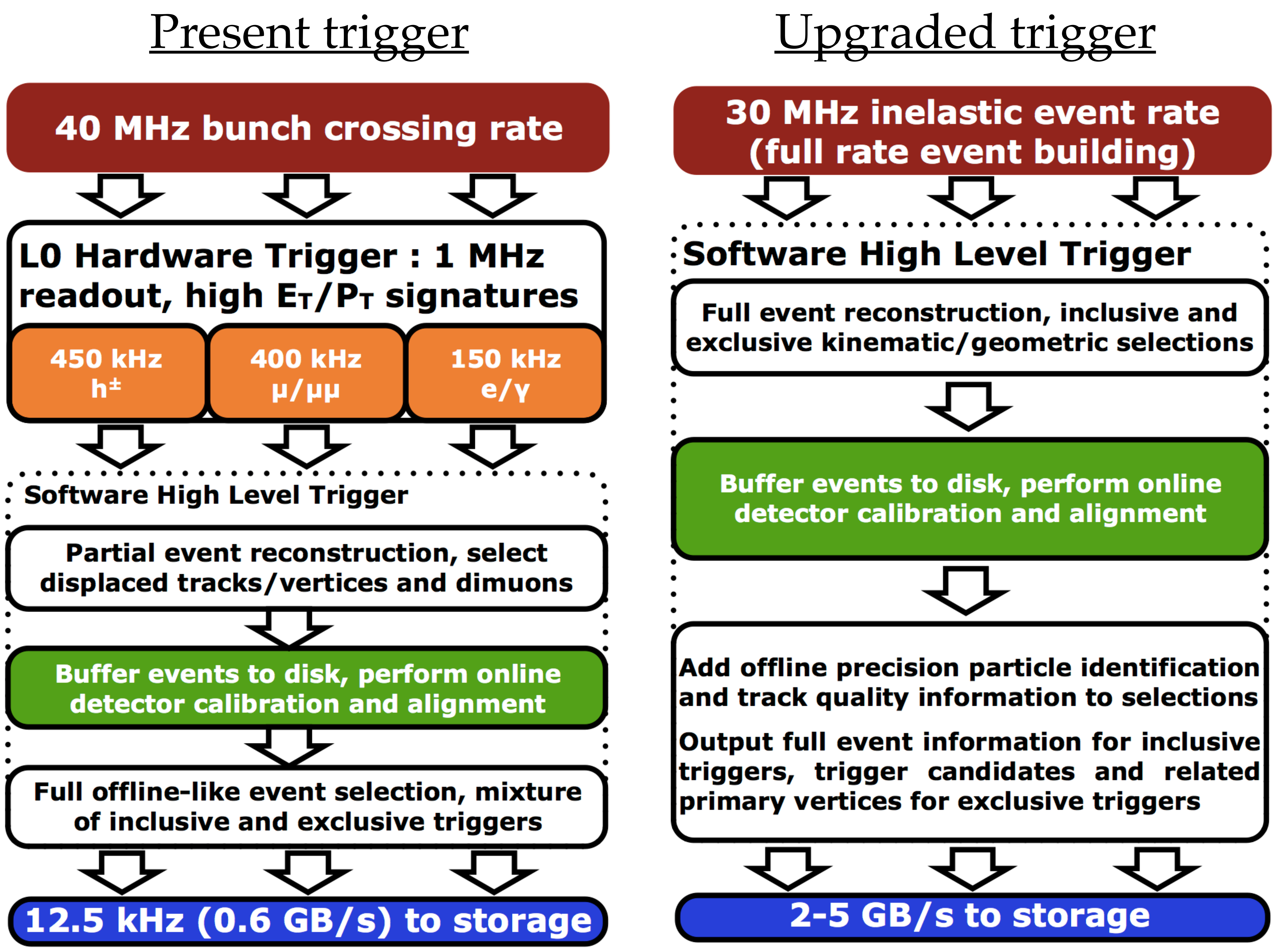
LHCb Phase-I upgrade

- **New Vertex Locator**
- **New dedicated luminometer (PLUME)**
- New silicon strip detector
- New scintillating fibre detector
- Particle ID: new optics, new photon detectors
- Calorimeters: reduce PMT gain and new electronics
- **Muon: new electronics and increased granularity**
- **No hardware trigger**

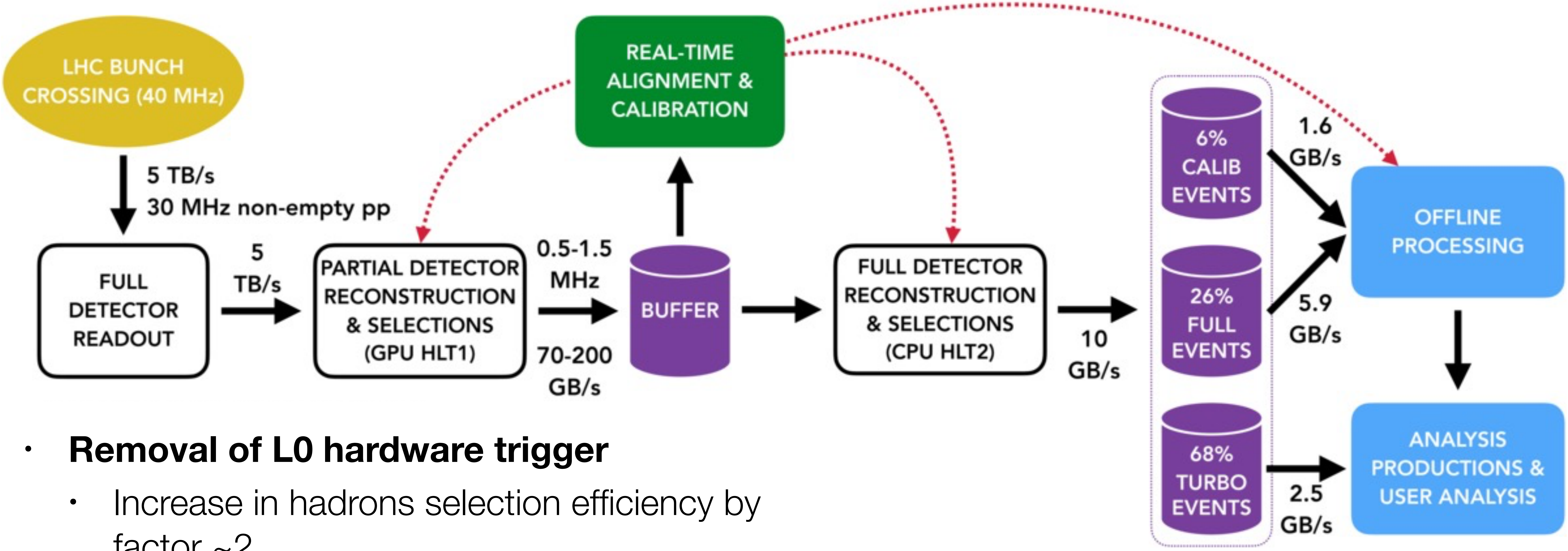


Trigger

- 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** 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 has moved to a **hardware-less readout system** for LHC Run 3, and process 5 TB/s in real time on the CPU farm.

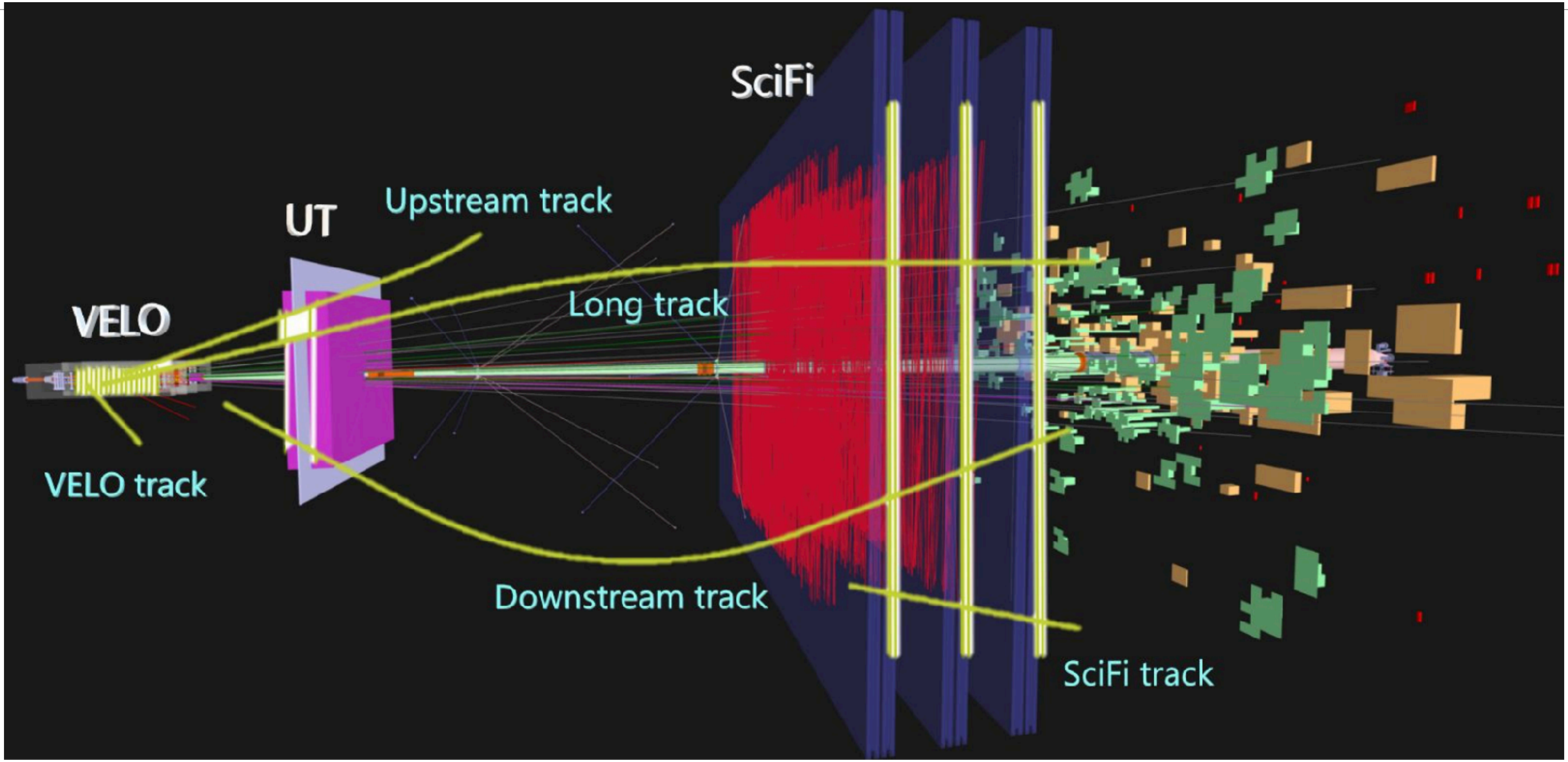


Trigger



- **Removal of L0 hardware trigger**
  - Increase in hadrons selection efficiency by factor ~2
- **HLT1 reconstruction on GPUs**
  - First GPU trigger in a HEP experiment
- **Offline reconstruction in HLT2**

LHCb's track types

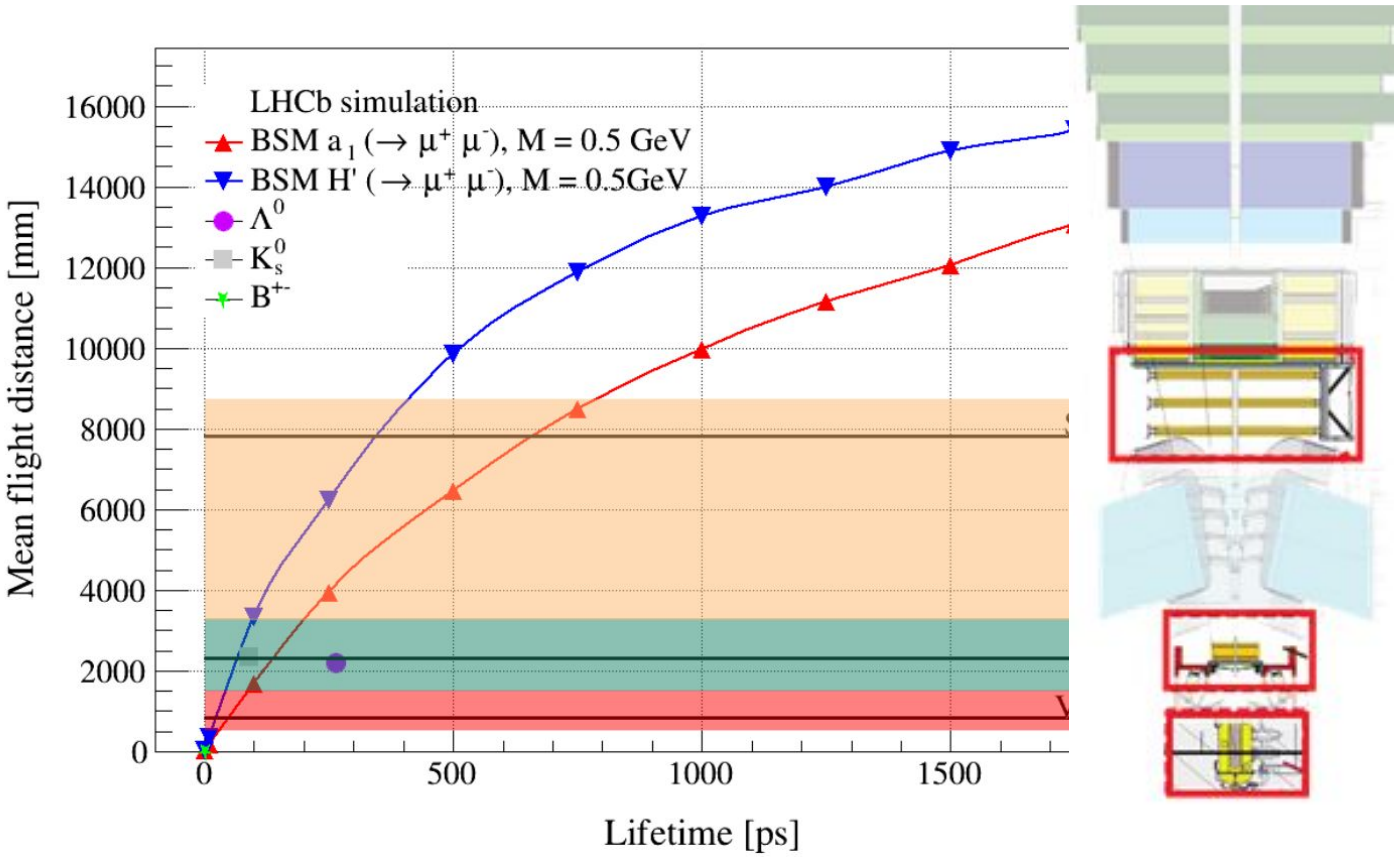


A new algorithm at LHCb to reconstruct Long-Lived particles in the first level trigger

Arantza's talk at connecting the dots

Calefice et al., Frontiers in Big Data, 2022. DOI:10.3389/fdata.2022.1008737.

- **Removal of L0 hardware trigger**
- **HLT1 reconstruction on GPUs**
- **What about lips?**
  - Great LHCb performance for *b*- and *c*-meson decays (long tracks)
  - But for particles with τ > 100ps many decays happen out of the VELO detector:
  - Produce downstream and T-tracks
  - **Now LHCb can trigger at the HLT1 level on such tracks**
    - **Sensitivity gained for SM** (baryon and mesons) **and BSM particles**



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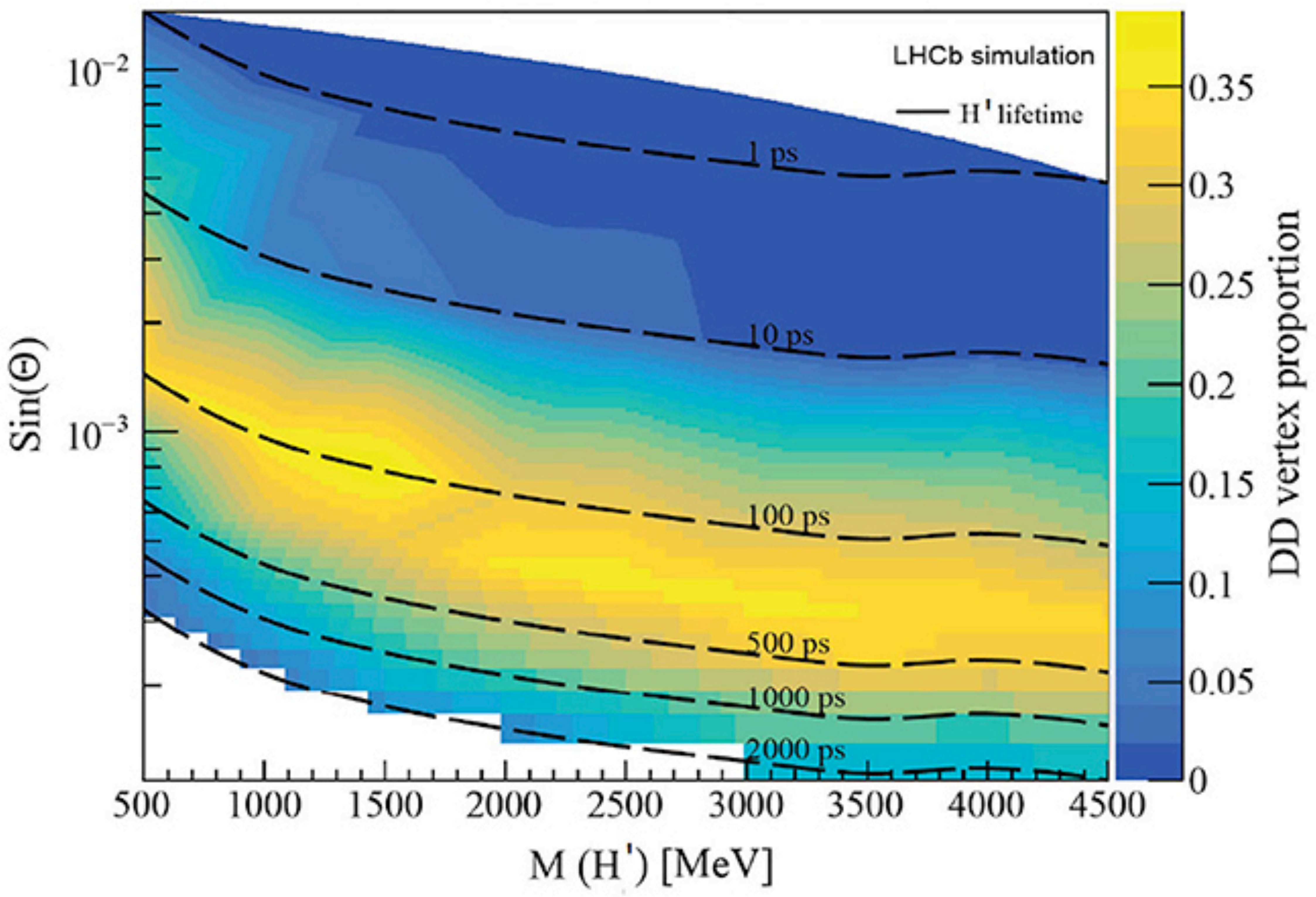
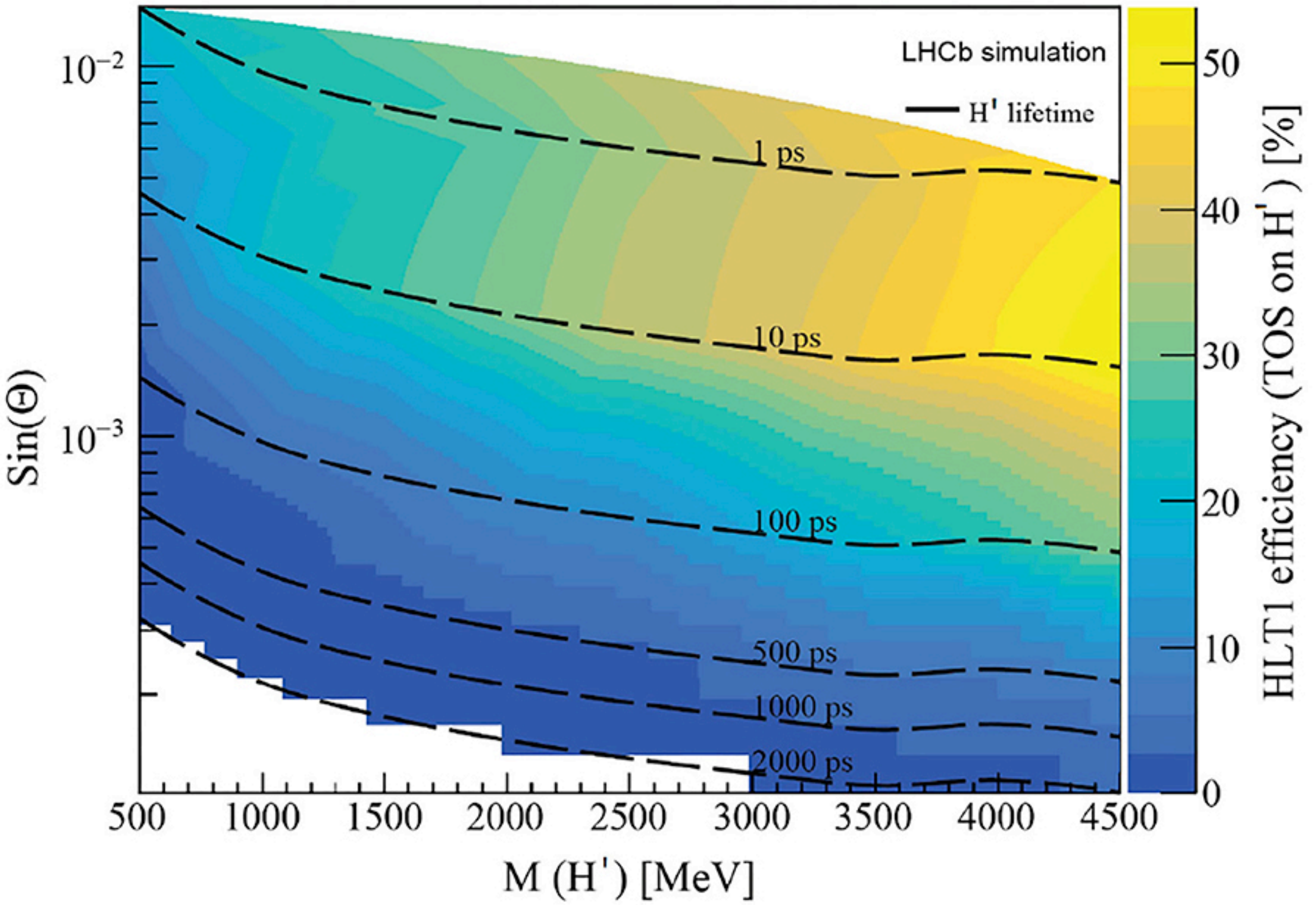


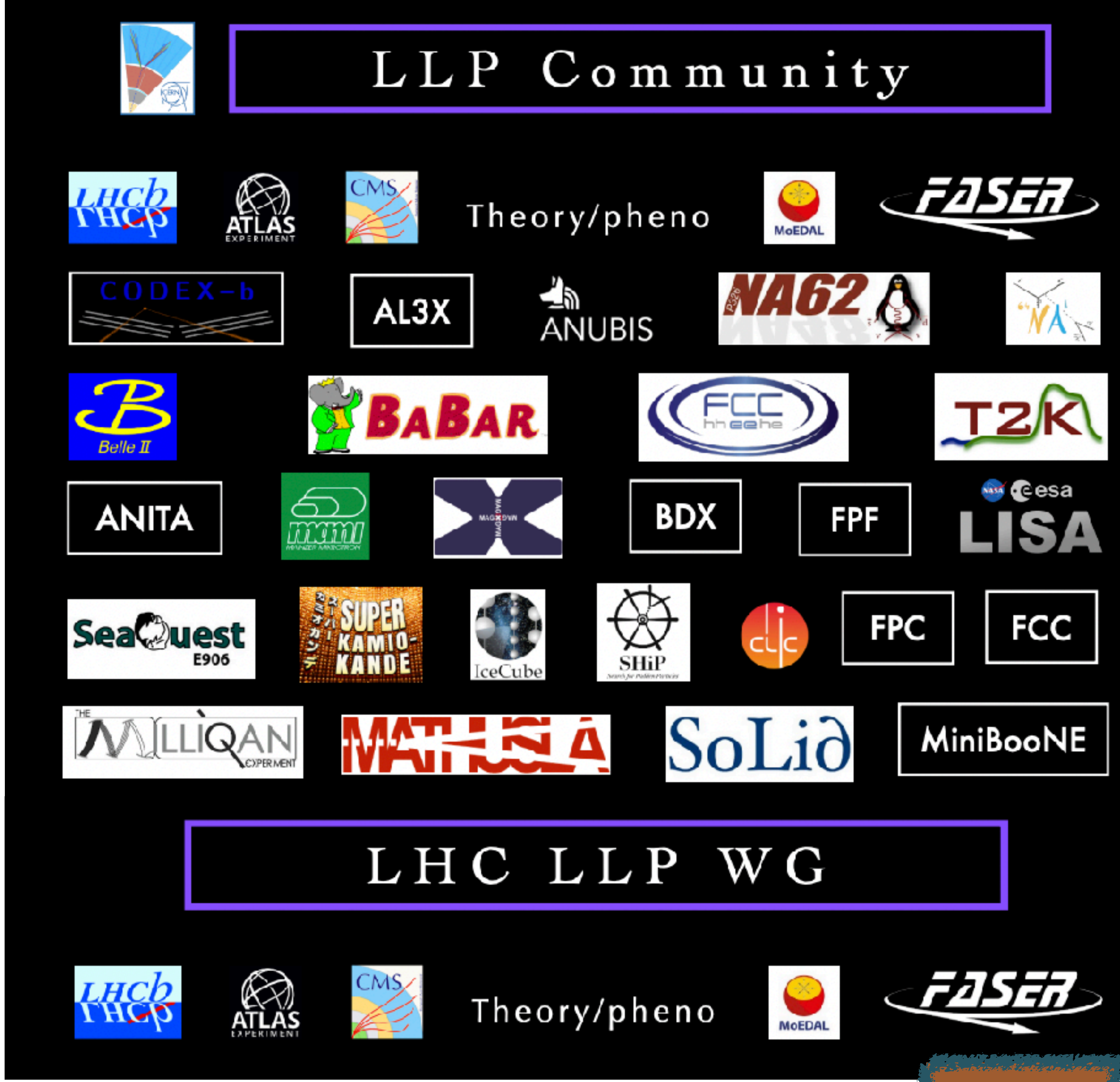


- **LHS:** . Reconstructibility of the decay vertex of the H' particle as a function of its mass and lifetime for downstream tracks
- **RHS:** proportion of events triggered by the HLT1 decision on the H' decay products (Trigger on Signal, TOS)

Conclusions

- The selection was heavily biased. A fresh look at LHCb reveals that it's not just a machine for *b*-physics; it's also an incredible tool for direct searches.
- The techniques we've developed for LFU measurements can be applied to direct searches for BSM physics. This has initiated a new field of measurements at LHCb and beyond.

- Maybe Michelangelo had it right 8 years ago after all.
- **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 [SIC] 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**



J. Beacham

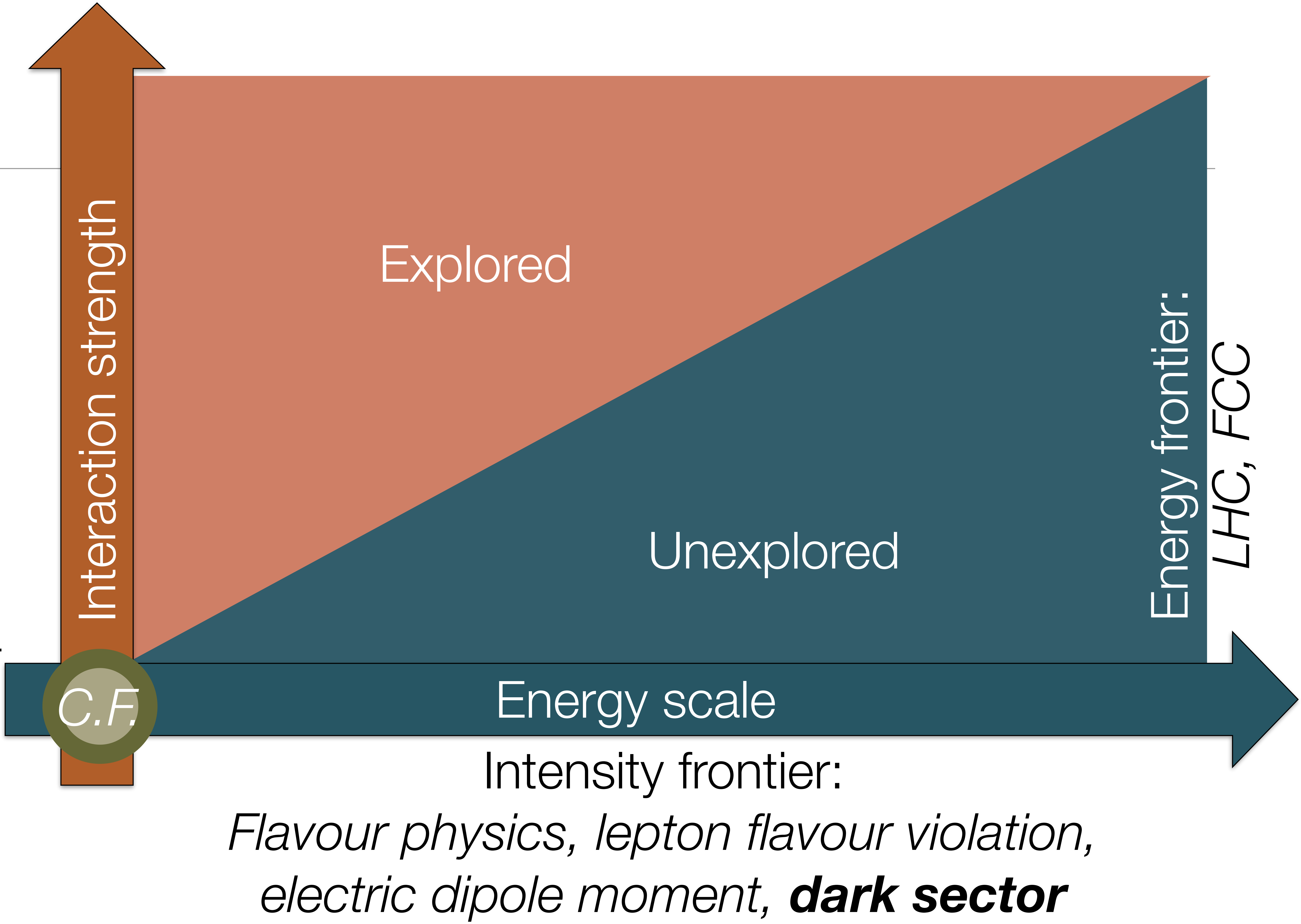
ASPEN2014 Theoretical summary - M. Mangano

Thanks for your kind attention

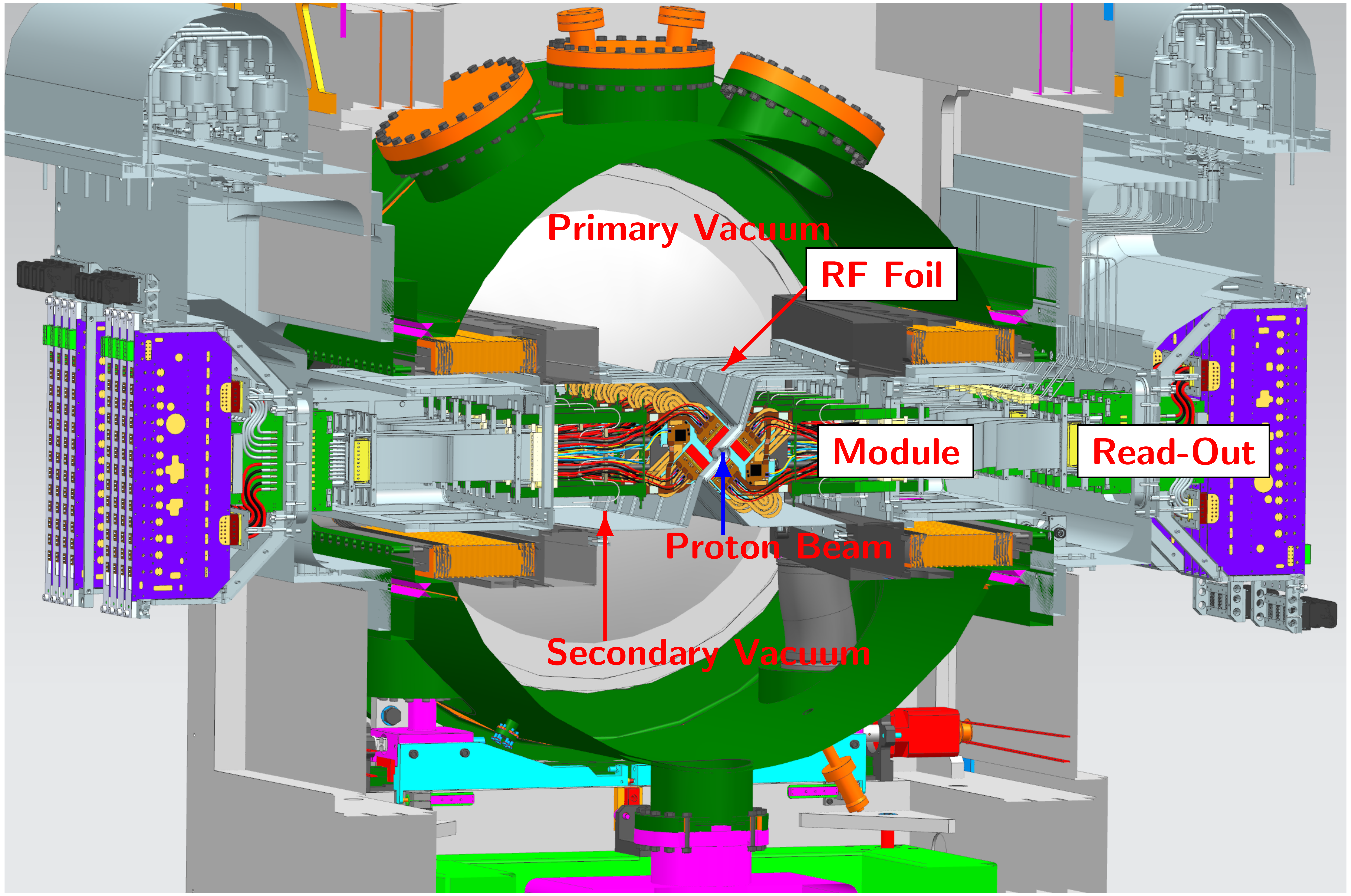
Federico Leo Redi

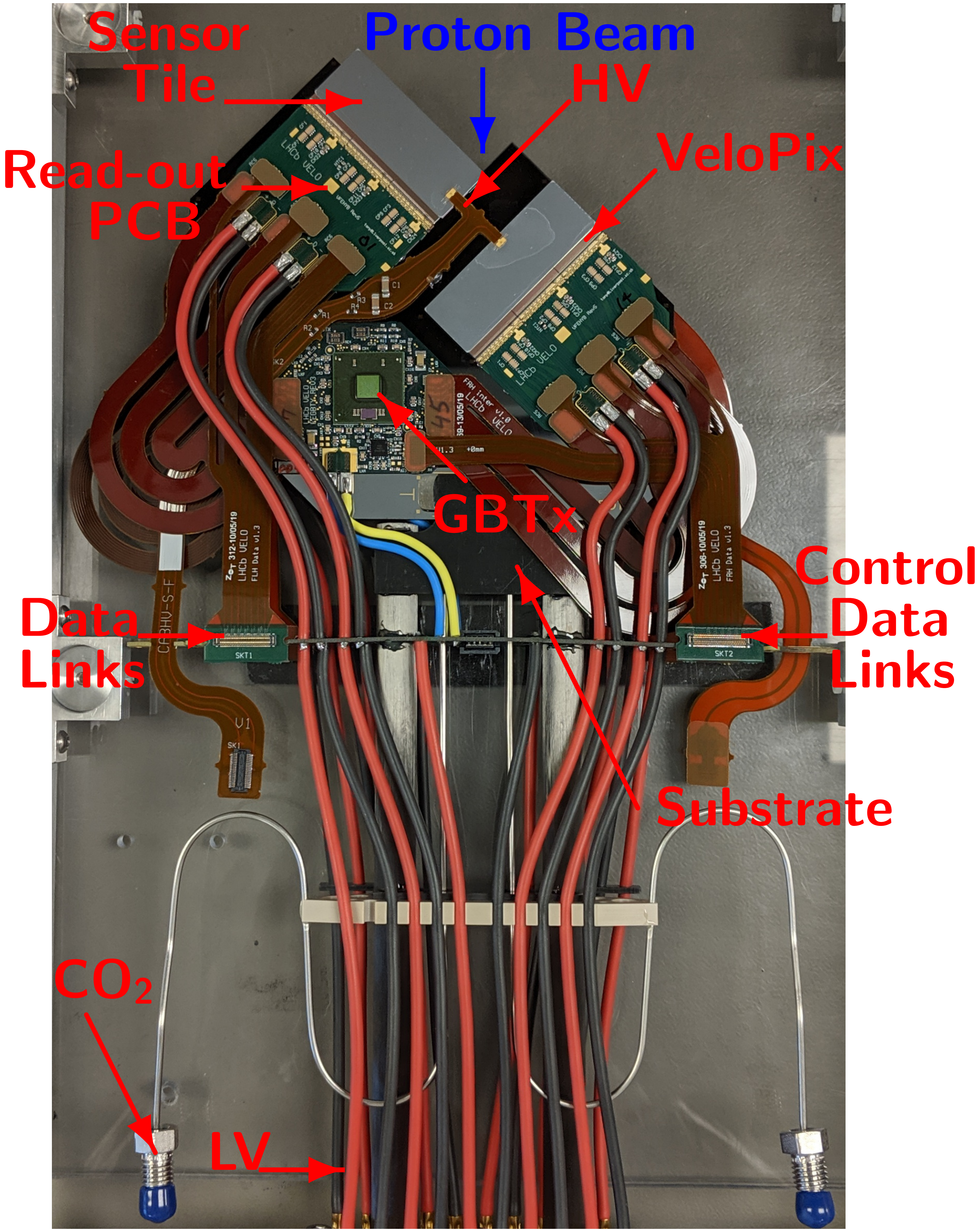
Introduction

- In this talk, I will concentrate BSM searches at LHCb
- **Landscape**: LHC results in brief:
  - No direct NP searches by ATLAS and CMS succeeded yet
  - While BSM model parameter space shrinks, **only <5% of HL-LHC data is analysed**.
    - NP discovery **still may happen**!



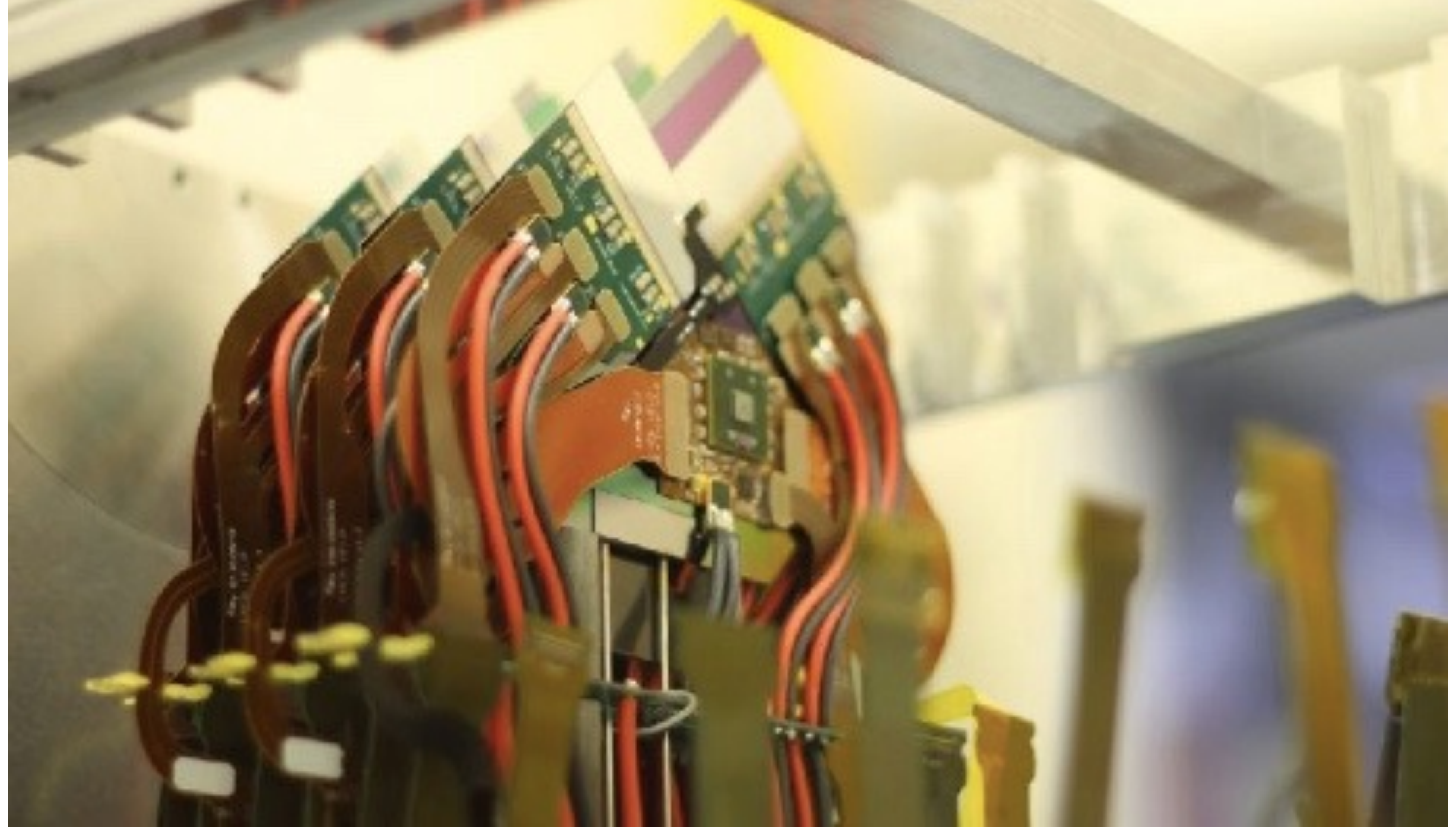
VELO

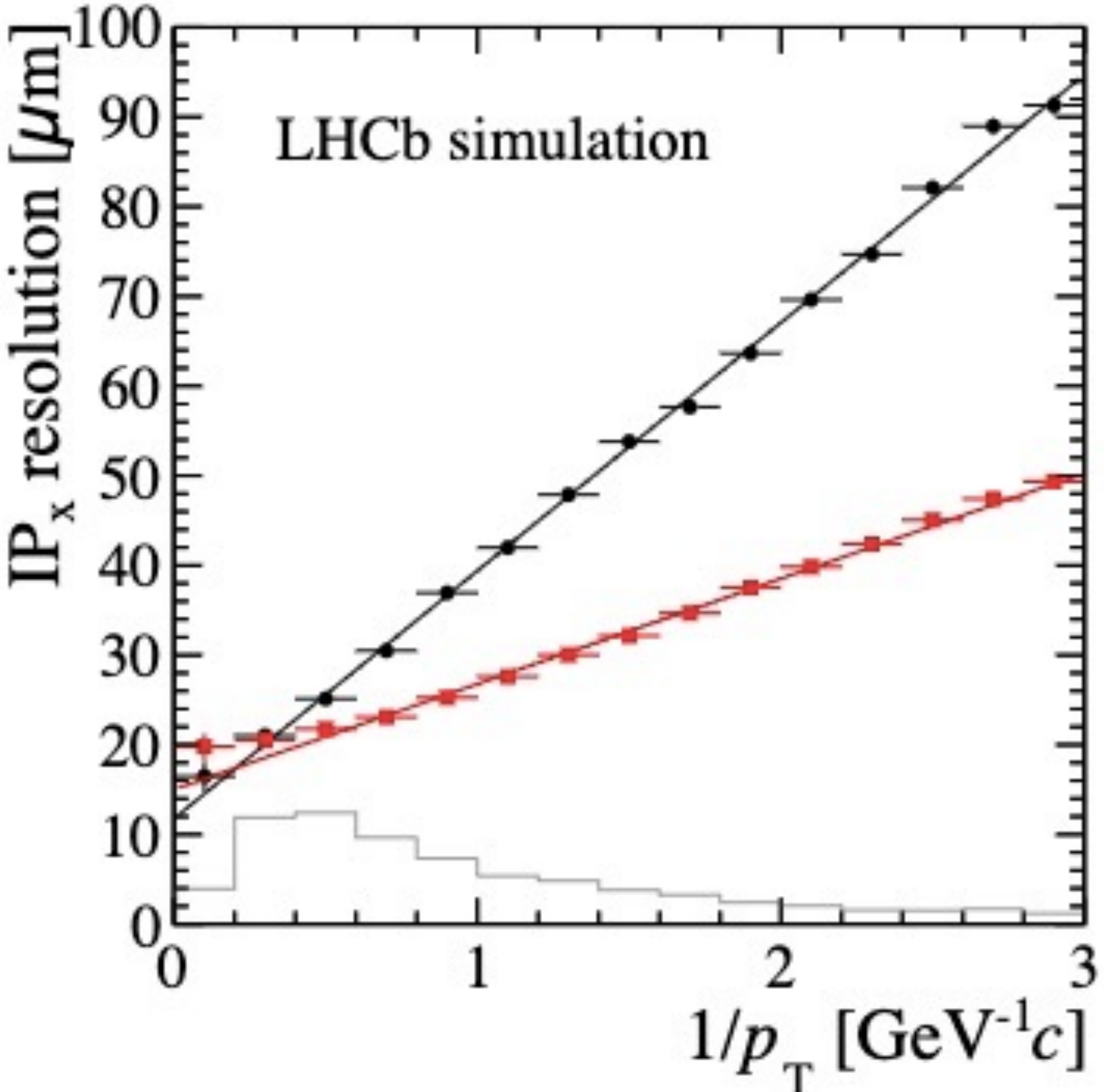

Primary Vacuum
RF Foil
Module
Read-Out
Proton Beam
Secondary Vacuum


Sensor Tile
Proton Beam
HV
VeloPix
Read-out PCB
GBTx
Control Data Links
Data Links
Substrate
CO2
LV

VELO

- 52 modules for a total of 41M pixels
  - Area ~ 1.2 m2
- **Two movable halves: get as close as 3.5 mm to the beam to improve IP resolution**
  - Separation from primary vacuum achieved with 150 μm thick RF foil
- Silicon substrate built with micro channels that will carry CO_2 for evaporative cooling
  - Designed to cool a load of up to 30W from each module
- New ASIC VeloPix, ~20 Gbps in hottest ASIC and total of ~3 Tbps

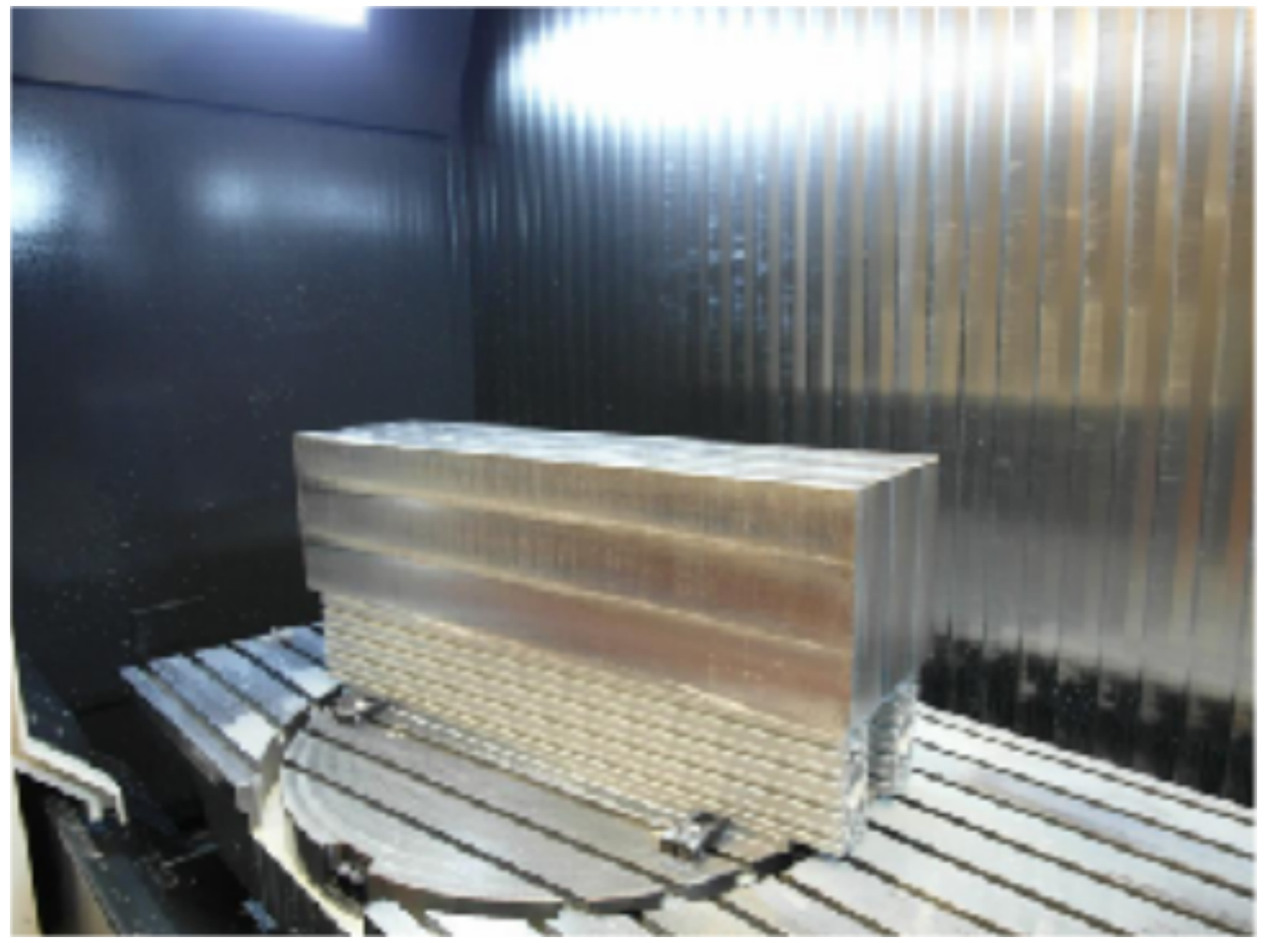




CERN-LHCC-2014-016
LHCB-TDR-016

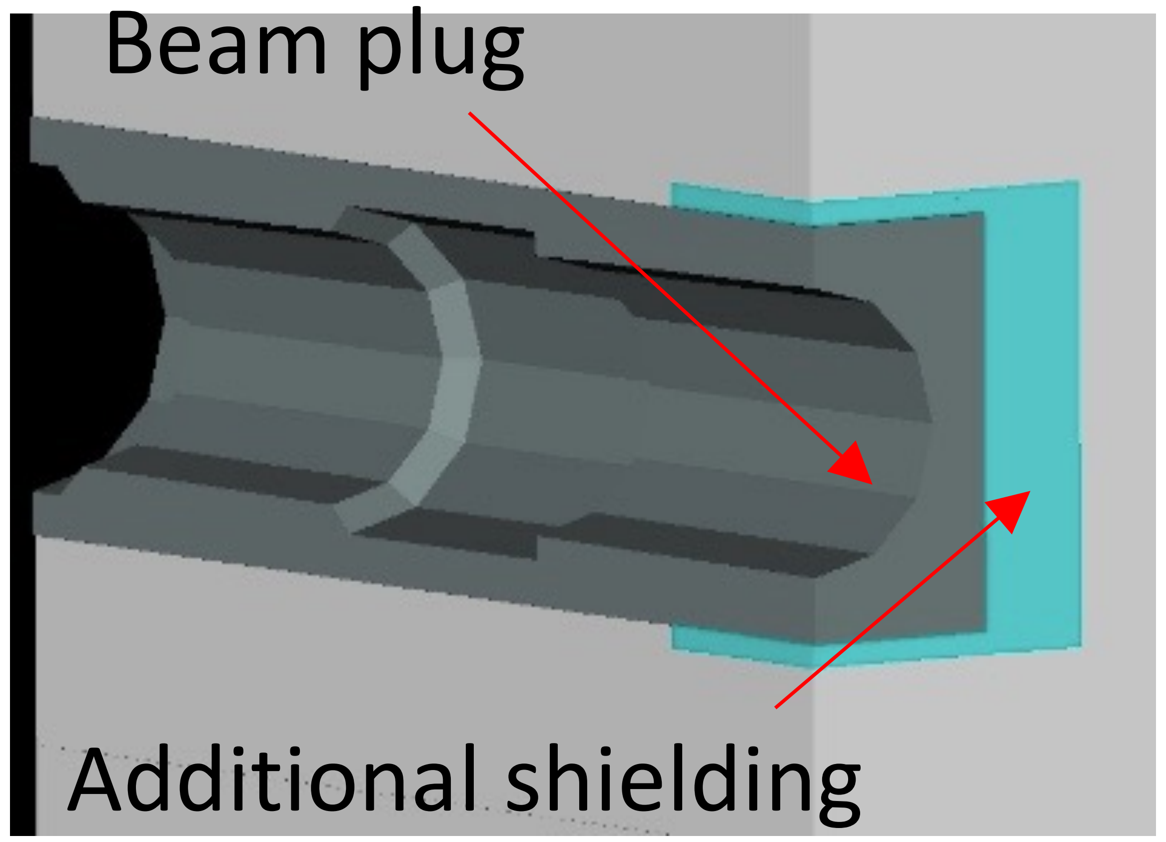
VELO

- **Example**: the RF foil separates primary to secondary vacuum
- Start from a single, forged **AlMg3** alloy block
- **98%** of material is milled away (6 months)
- Final thickness at tips of modules: on average **250 µm**
- **On the 10th of January 2023, during a VELO warm up in neon, there was a loss of control of the protection system**
- **RF foils have suffered plastic deformation up to** 14 mm and have to be replaced
    - Replace at the end of the year (run in 2023 with VELO partially open)
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned



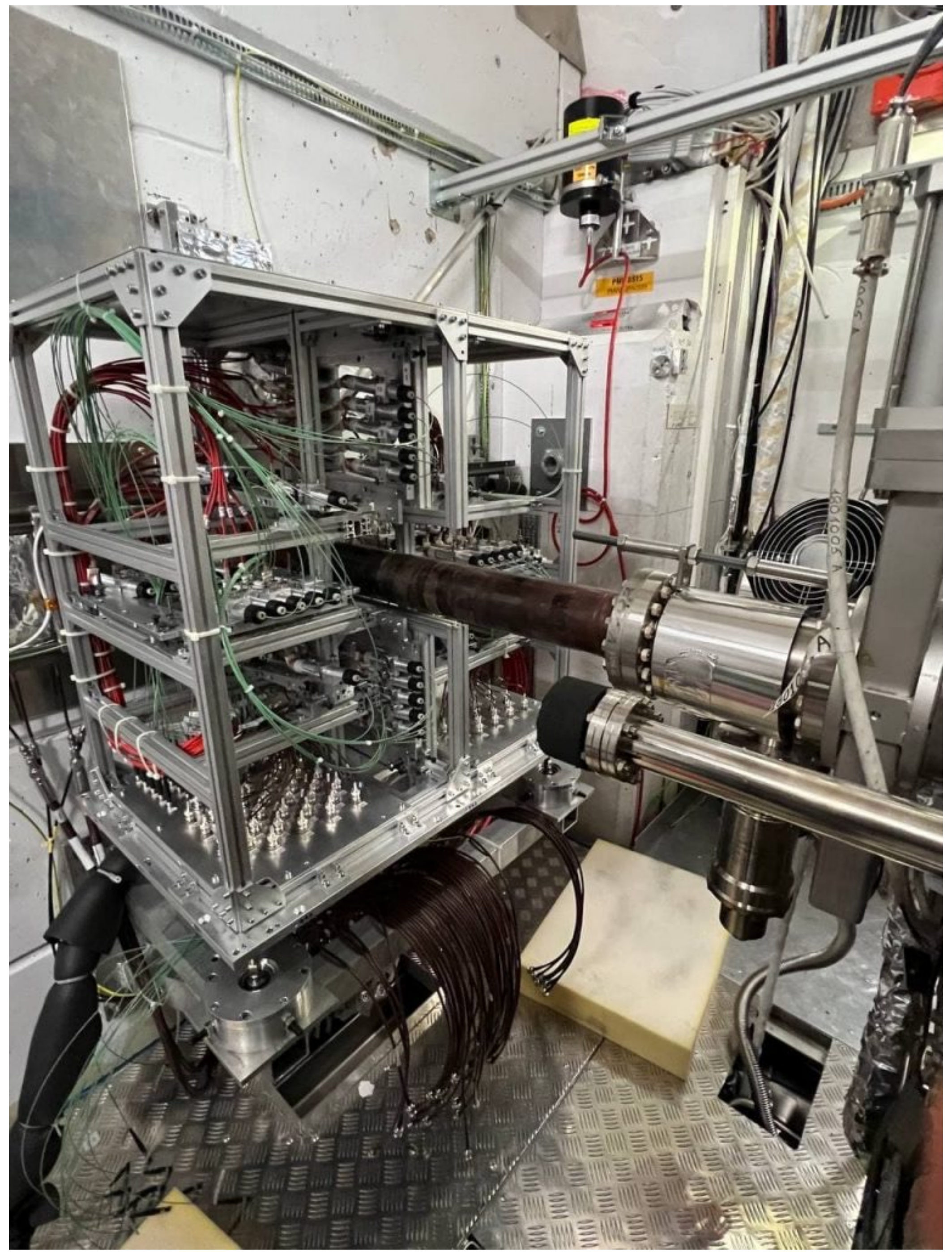
Muon stations

- **Not everything needed to be changed:**
- ECAL and HCAL and
- **Muon stations**
  - 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPCs)
- Remove first layer (M1) with GEMs, since L0 trigger level has been removed
- Therefore more space:
  - install additional shielding around beampipe to reduce particle flux in M2 inner region
- Redesign electronics to cope with 40 MHz trigger-less readout

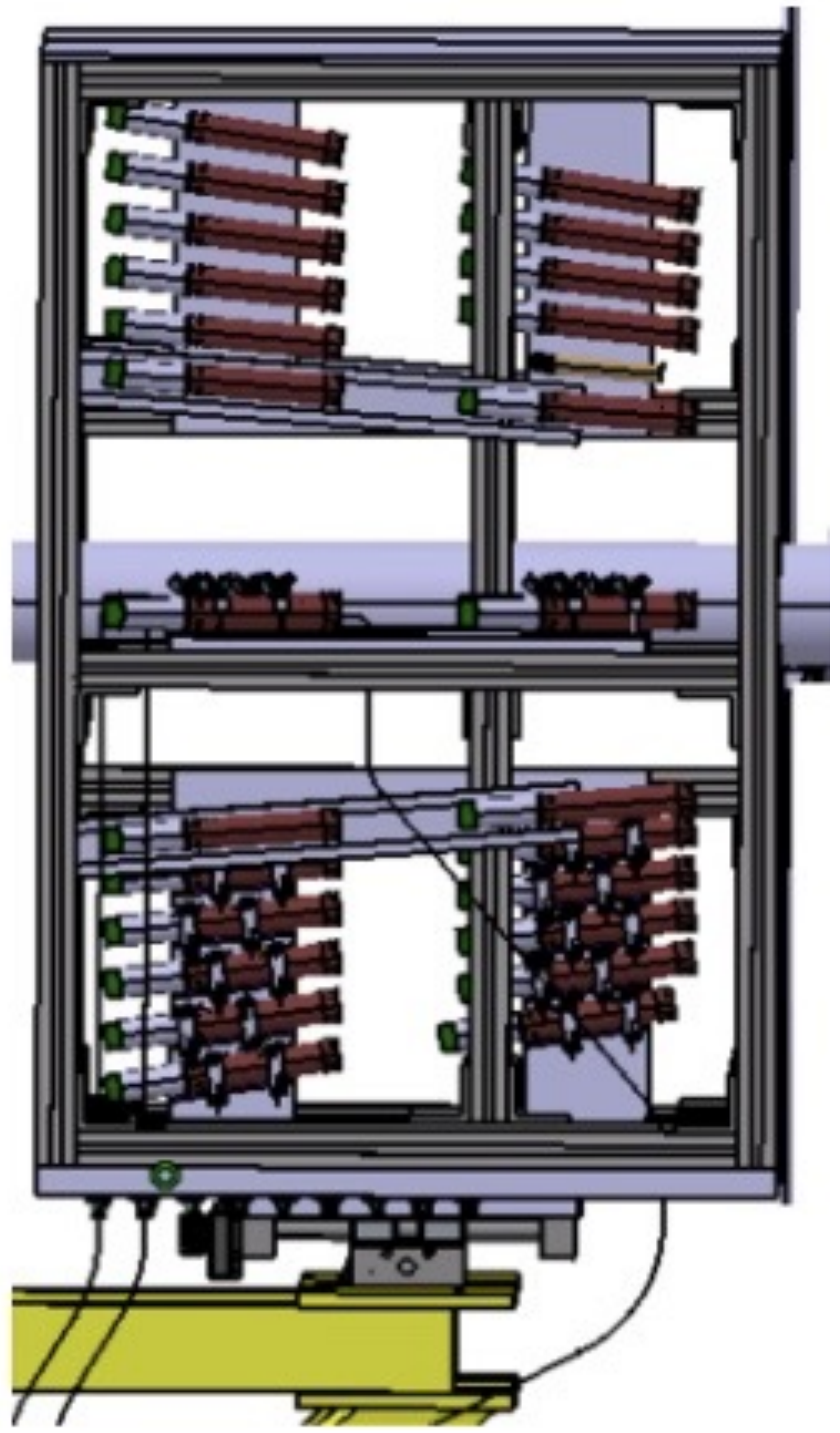


PLUME

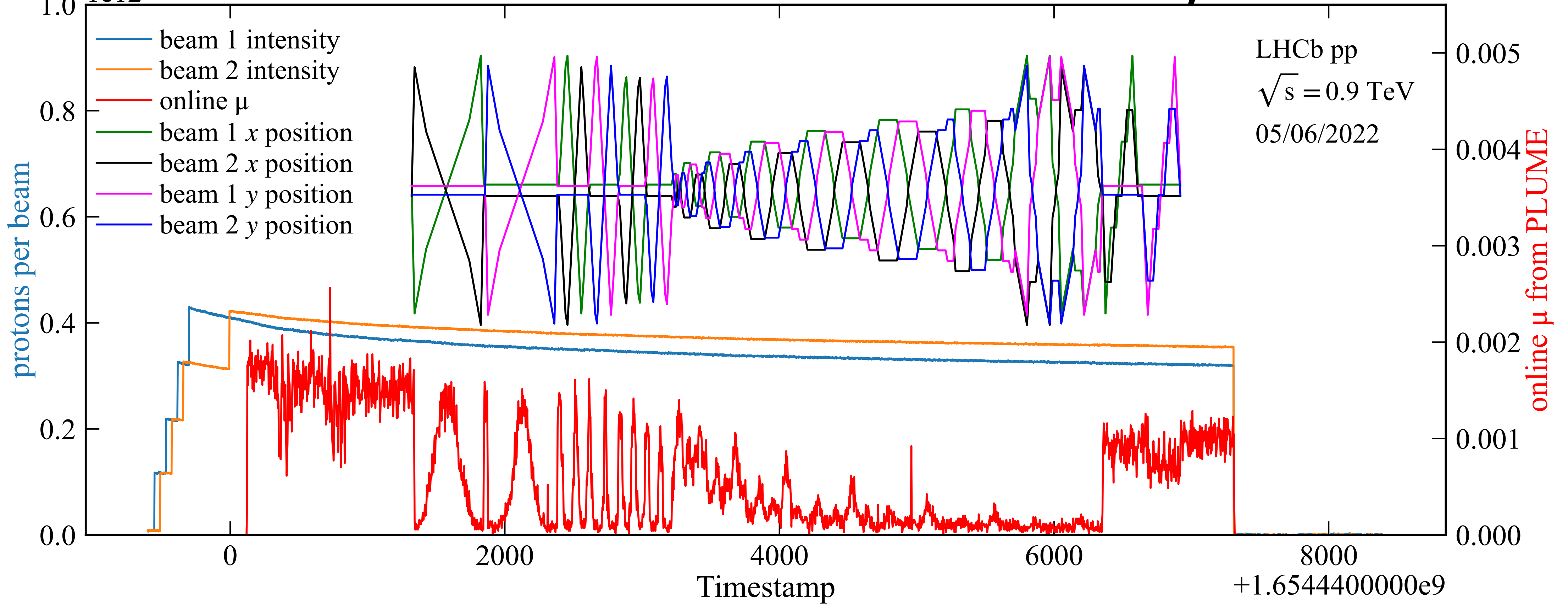
- Cross-shaped hodoscope composed by 48 PMTs, installed upstream of the VELO
  - Detect Cherenkov light from particles impinging on a quartz tablet glued to the PMTs window
- **Measure rate of coincidences every 3 seconds and compute luminosity with "logZero" method**
  - Count the number of bunch crossings without any visible interaction in the PLUME detector
  - Provide real-time feedback to the LHC to level the luminosity at IP8
- Very cheap to build but crucial for analysis without a calibration channel



Lateral view sketch

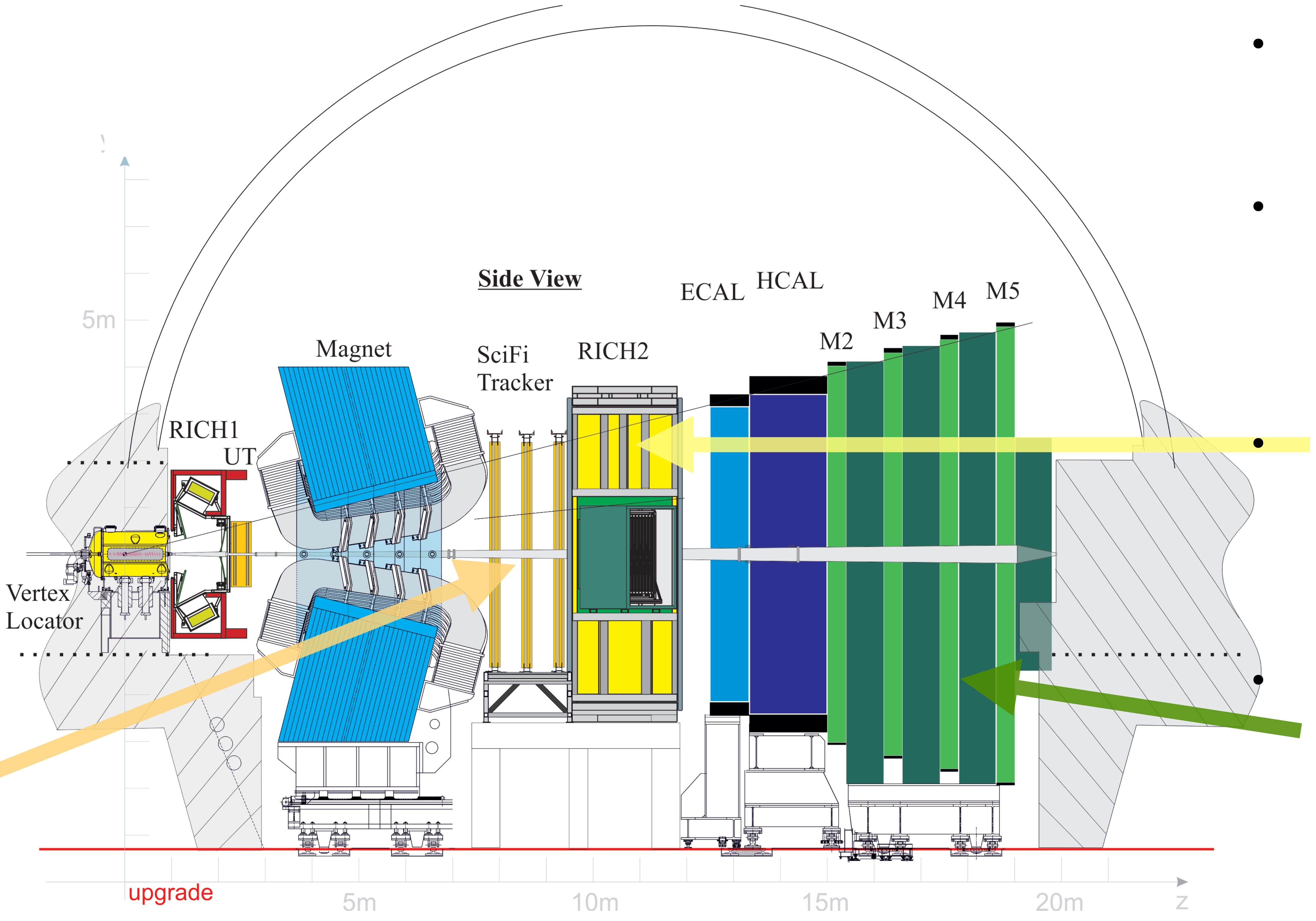


First results from PLUME vdM in July '22



LHCb Phase-II upgrade

- **VELO**
  Thinner & smaller σ_t<200 ps/hit
- **UT**
  Microstrip and **RETINA** tracking (no CPU)
- **Magnet**
  New SciFi stations inside the dipole for low p_T tracking
- **Mighty tracker**
  New silicon around beam line



- **HCAL**
  Remove
- **ECAL**
  Improve granularity and σ_t ~50ps/hit
- **TORCH**
  PID for p<10 GeV and σ_t~15 ps
- **Muon stations**
  Improve shielding and replace Multi Wire Proportional Chambers

Prospects

- **Collect 50 invfb by the end of Run 4 and 300 invfb by the end of Run 6**
- Collected 9 invfb during Run 1 and 2
- Aim at keeping same performance (or better) with Upgrades
- **Several flagship measurements still statistically** dominated and with uncertainty on predictions negligible compared to the experimental knowledge there is potential
- Even more for **displaced searches or searches with low background** where we can scale with luminosity

Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$ ($B_s^0 \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}$ ($B_s^0 \to \phi\gamma$)	0.32	[51]	0.093	0.062	0.025
α_γ ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

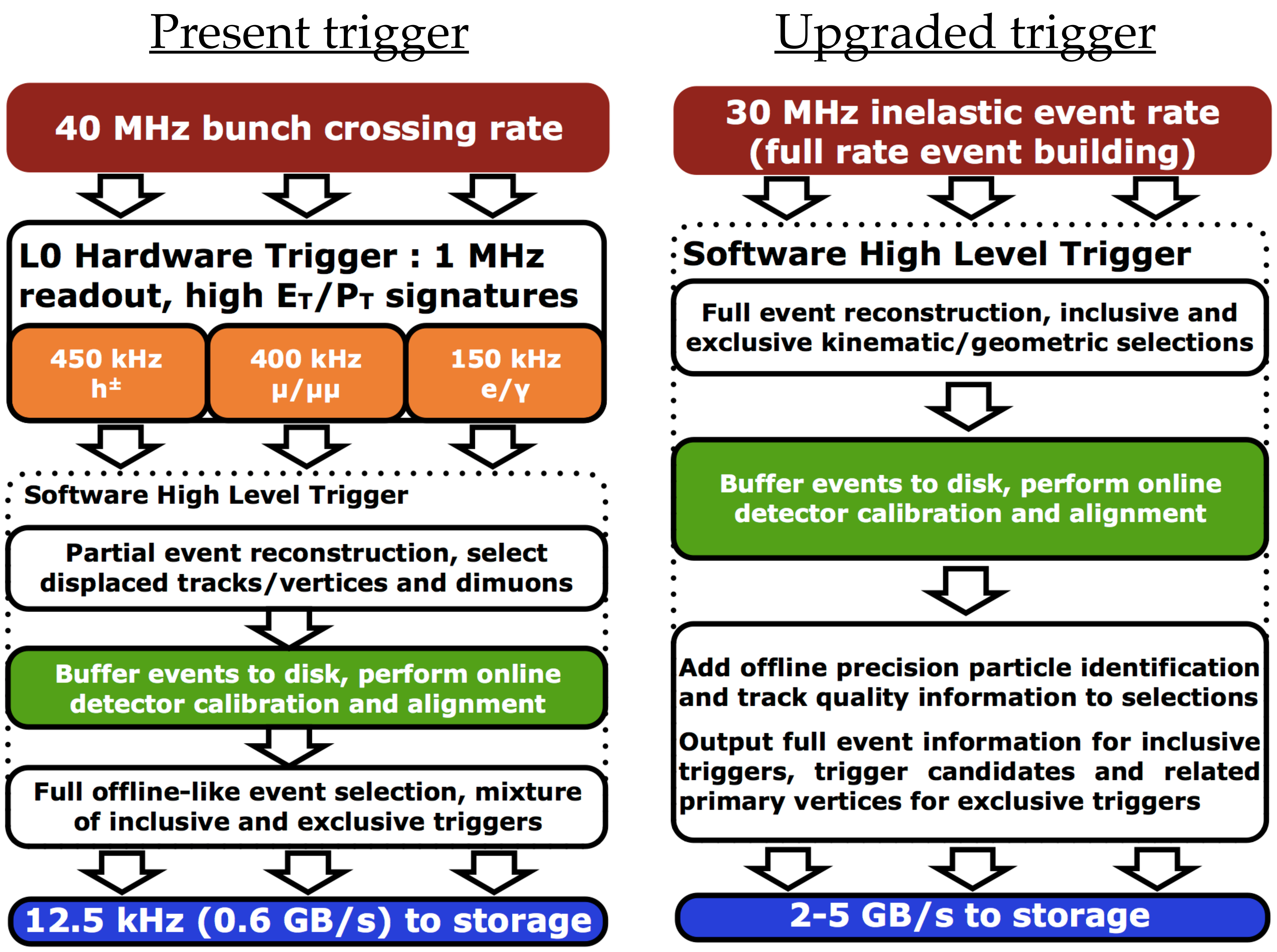
Landscape today

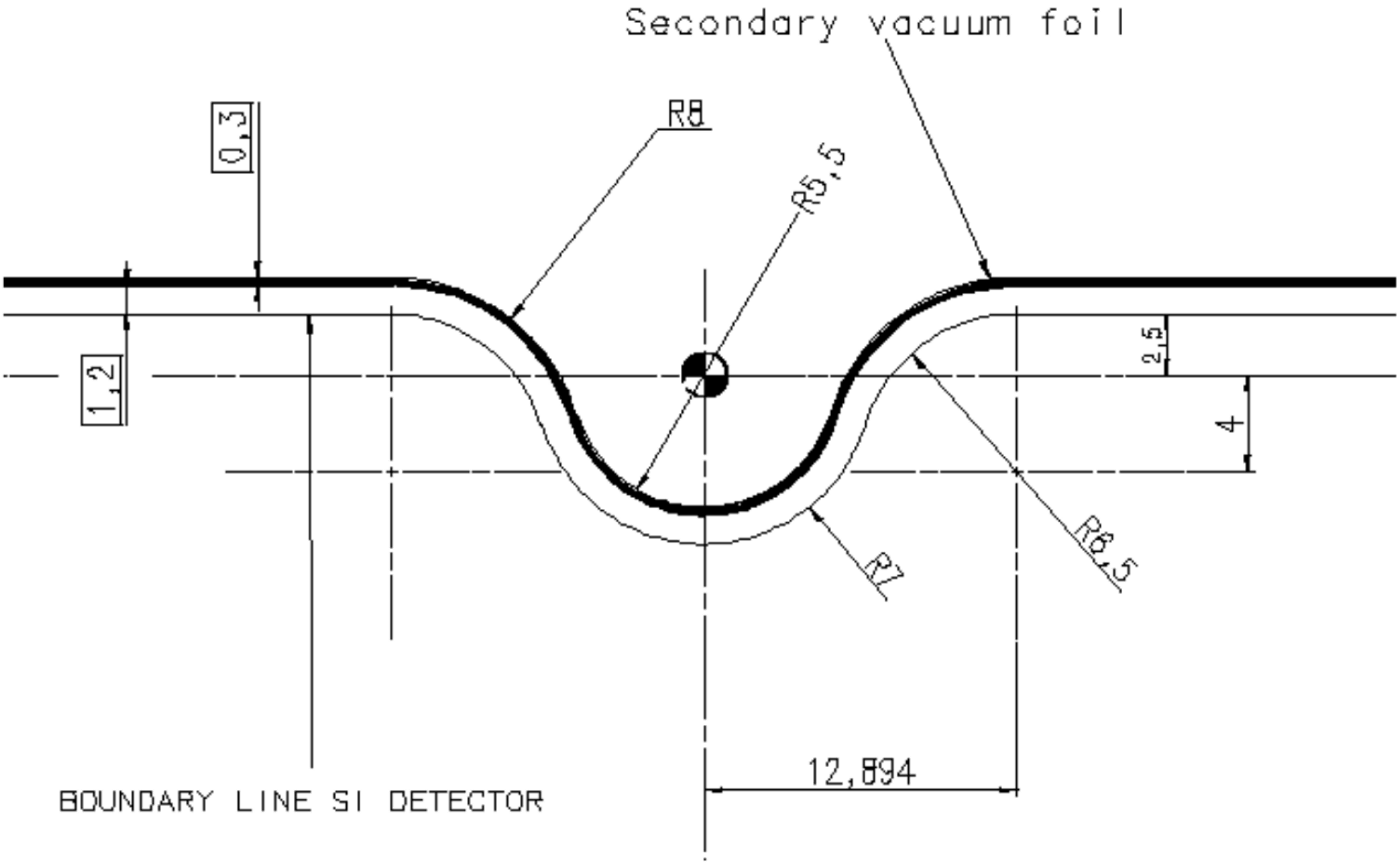
- The Intensity frontier is a **broad** and **diverse**, yet **connected**, set of science opportunities: heavy quarks, charged leptons, hidden sectors, neutrinos, nucleons and atoms, proton decay, etc...
- In this talk, I will concentrate on **displaced signature** and related physics searches.
- **Landscape**: LHC results in brief:
  - Direct searches for **NP** by **ATLAS** and **CMS** have not happened 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 (cautiously optimistic) 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 and in angular variables (P'_5)
    - Possible evidence of **BSM** physics **if substantiated** with further studies (e.g. **BELLE II**)

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

LHCb detector / 2

- 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 $p_T > 0.4$ 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 **readout system without a hardware stage** for LHC Run 3 and process 5 TB/s in real time on the CPU farm

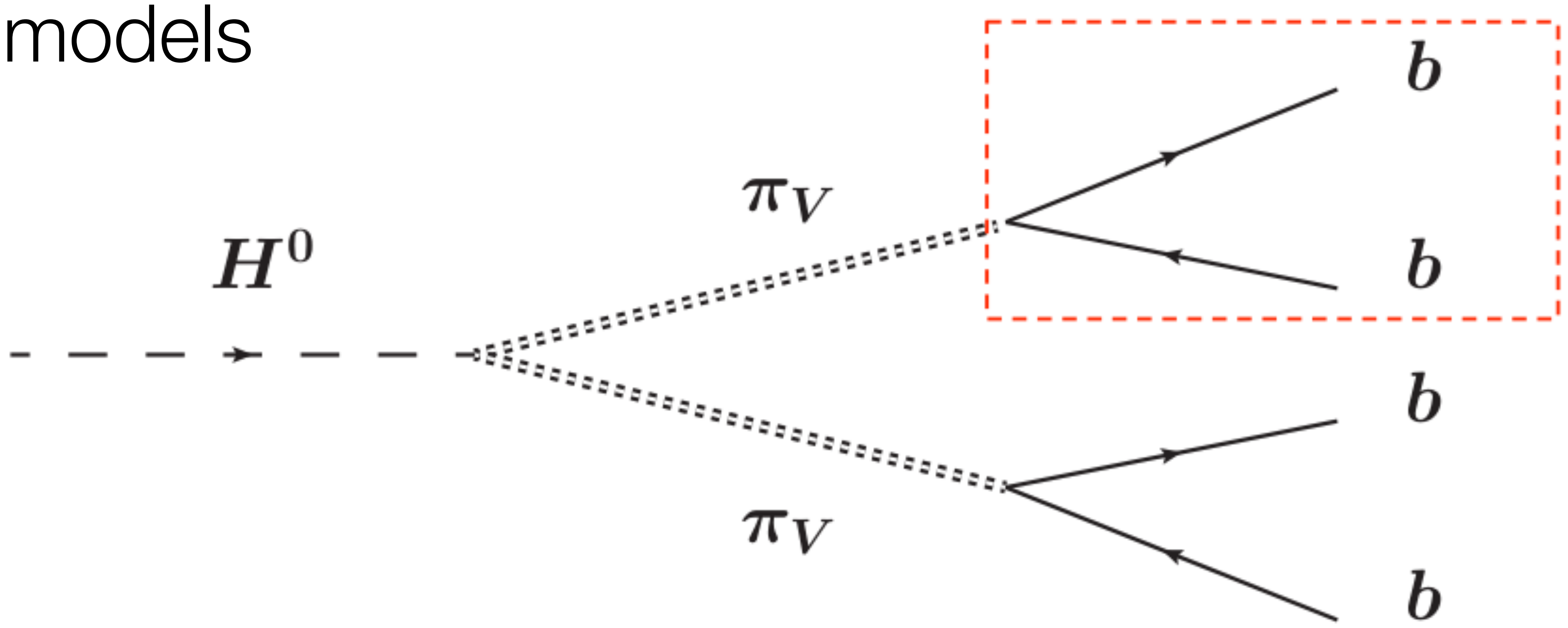


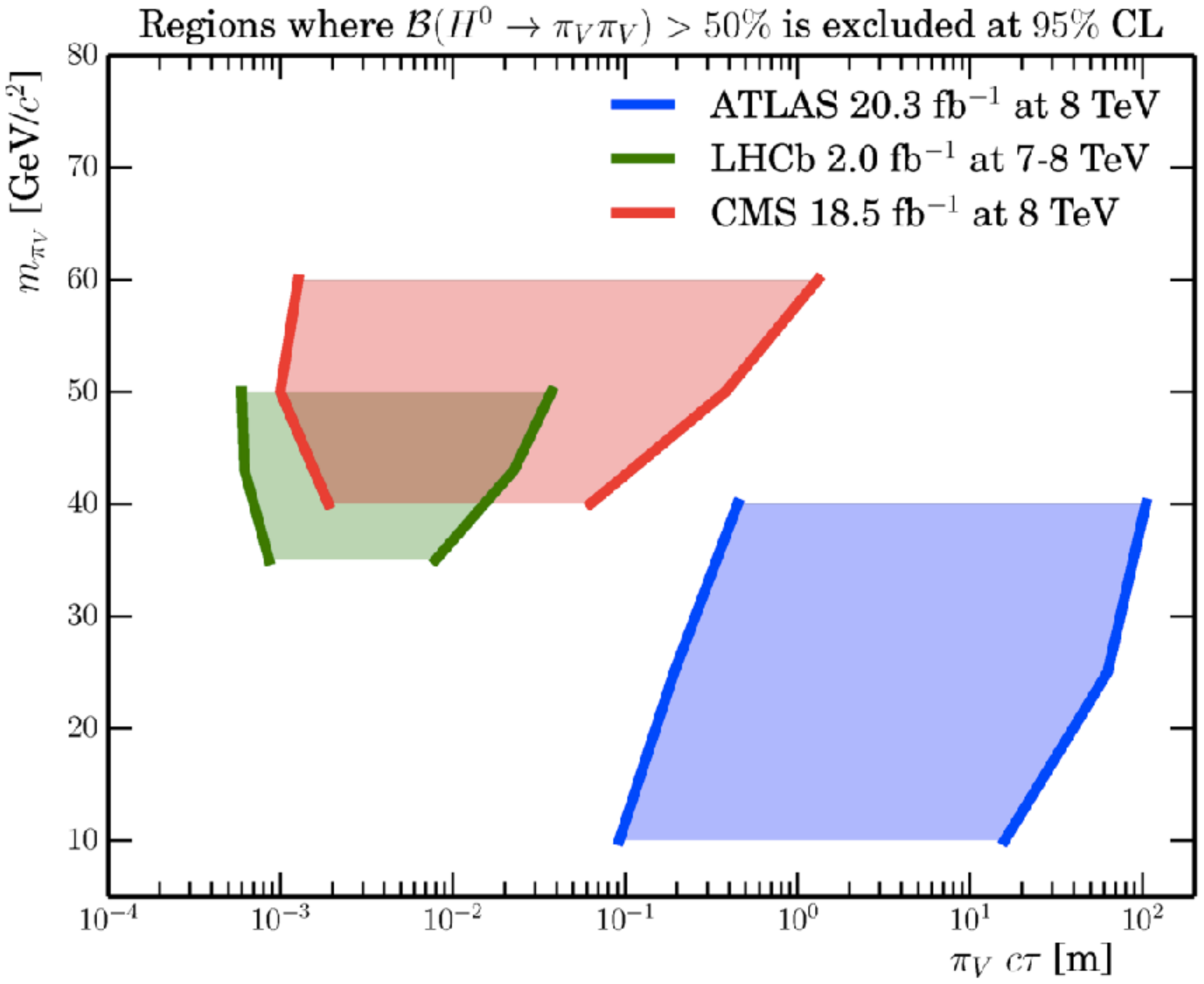


Secondary vacuum foil
R8
R5,5
0,3
1,2
2,5
4
R7
R6,5
12,894
BOUNDARY LINE SI DETECTOR

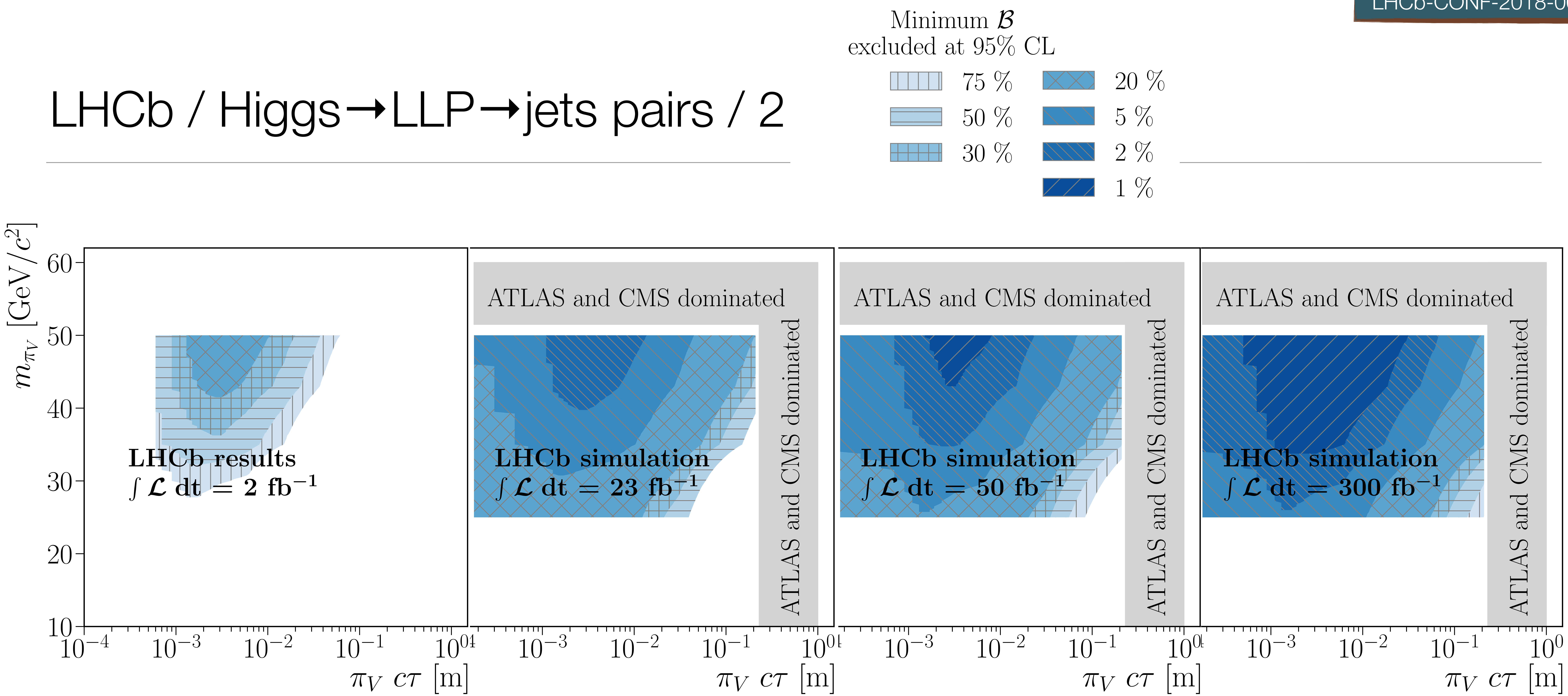
LHCb / Higgs→LLP→jet pairs

- 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)
- $\mathbf{m_{\pi V}}$**=[25; 50] GeV** and $\boldsymbol{\tau_{\pi V}}$**=[2; 500] ps**
- Background dominated by **QCD**
- No excess found: result interpreted in various models





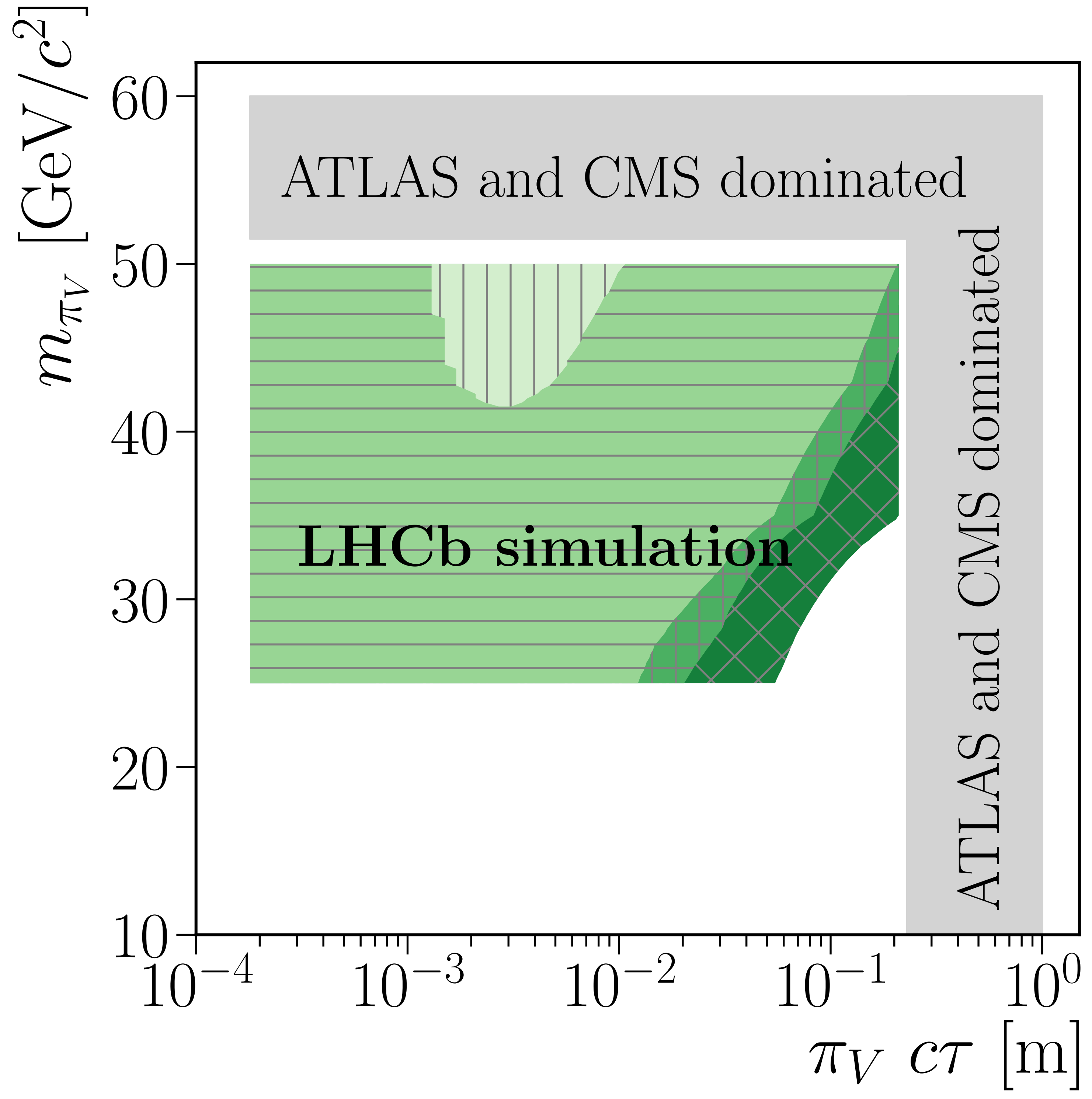
LHCb / Higgs→LLP→jets pairs / 2



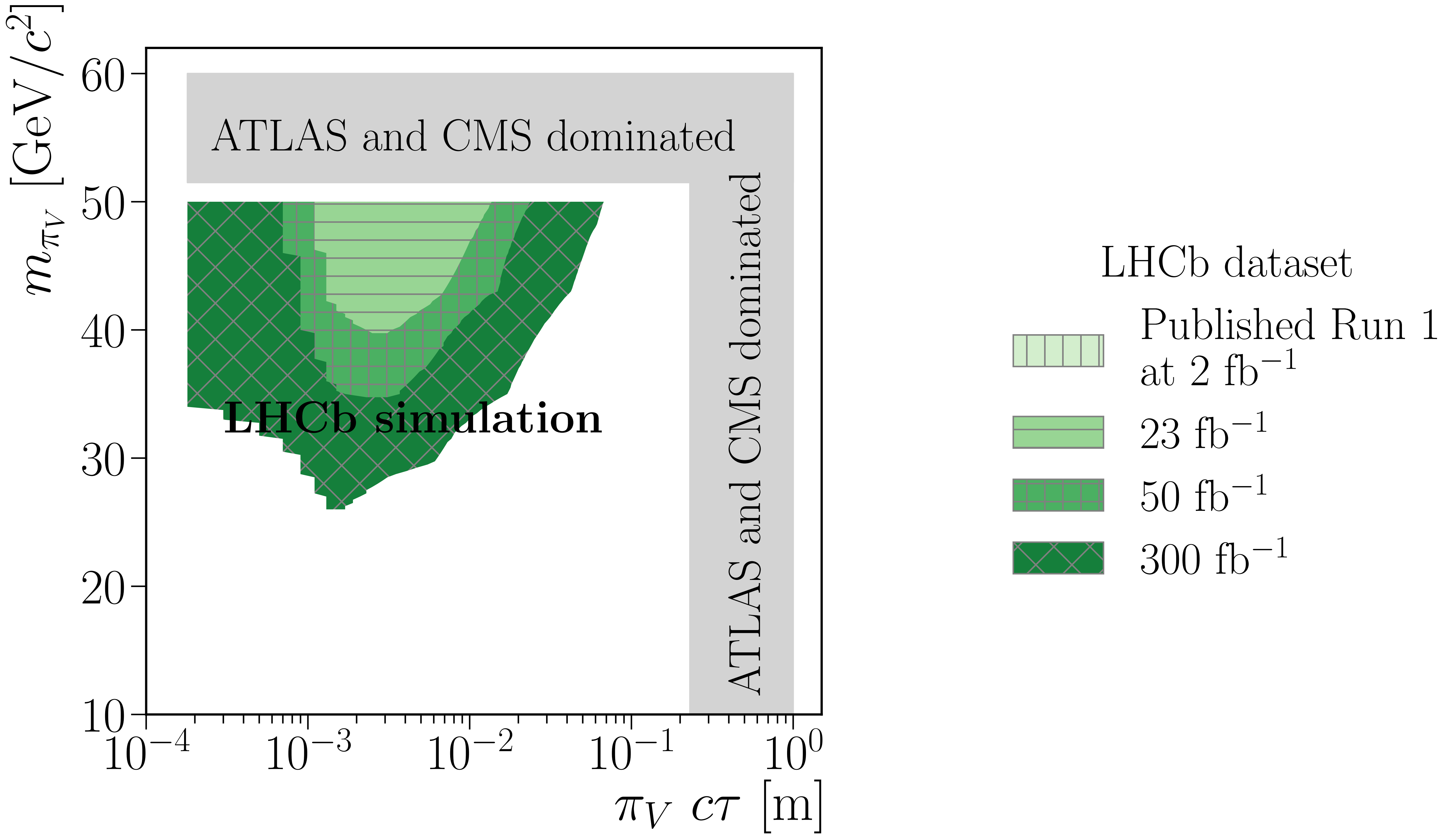
- Model independent scaling of current results to future integrated luminosity for different BFs

LHCb / Higgs→LLP→jets pairs / 3

- Model dependent scaling of current results to future integrated luminosity for two different BFs



BF(Higgs→π_V+π_V) < 20 %



BF(Higgs→π_V+π_V) < 2 %

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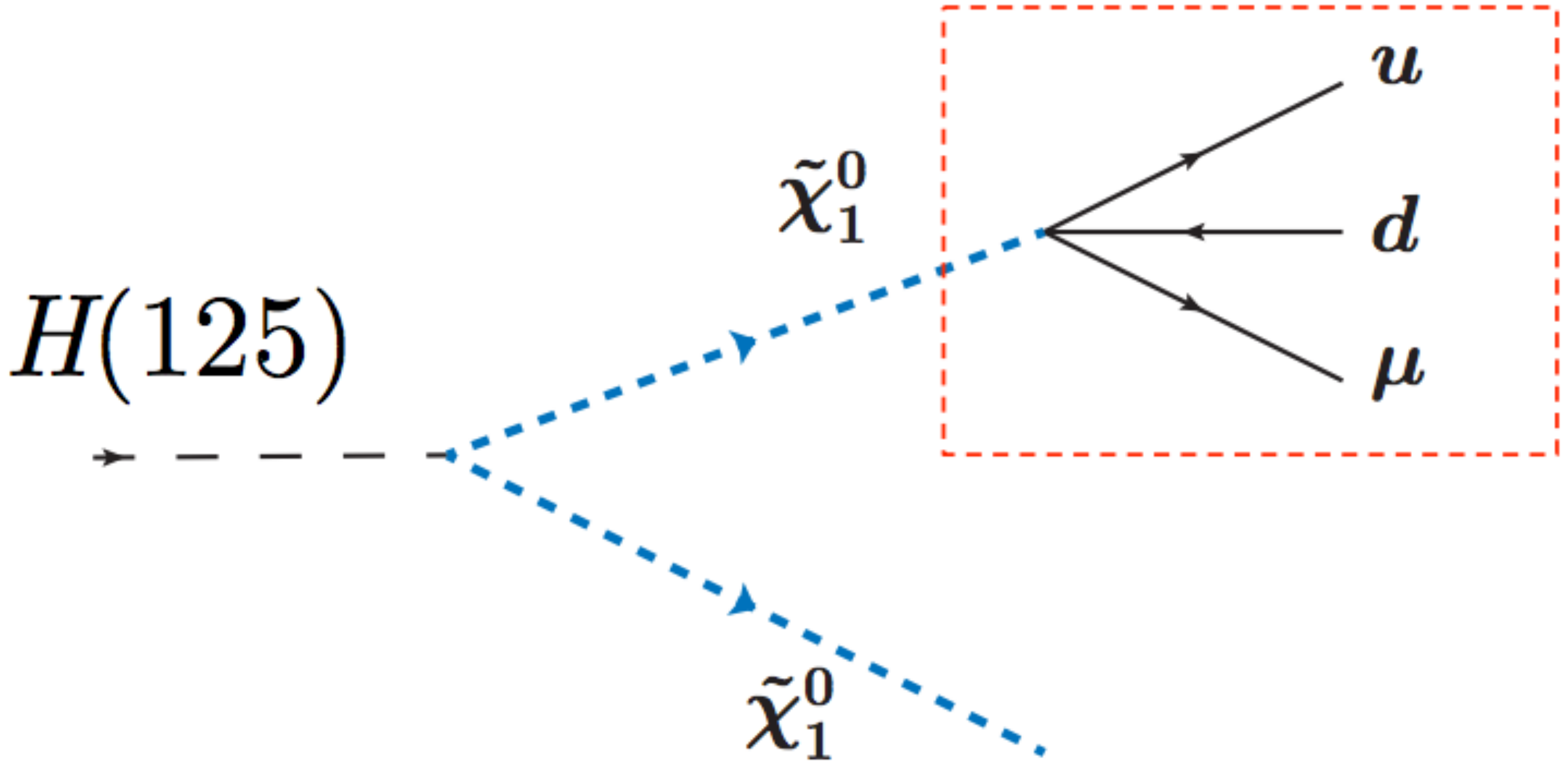
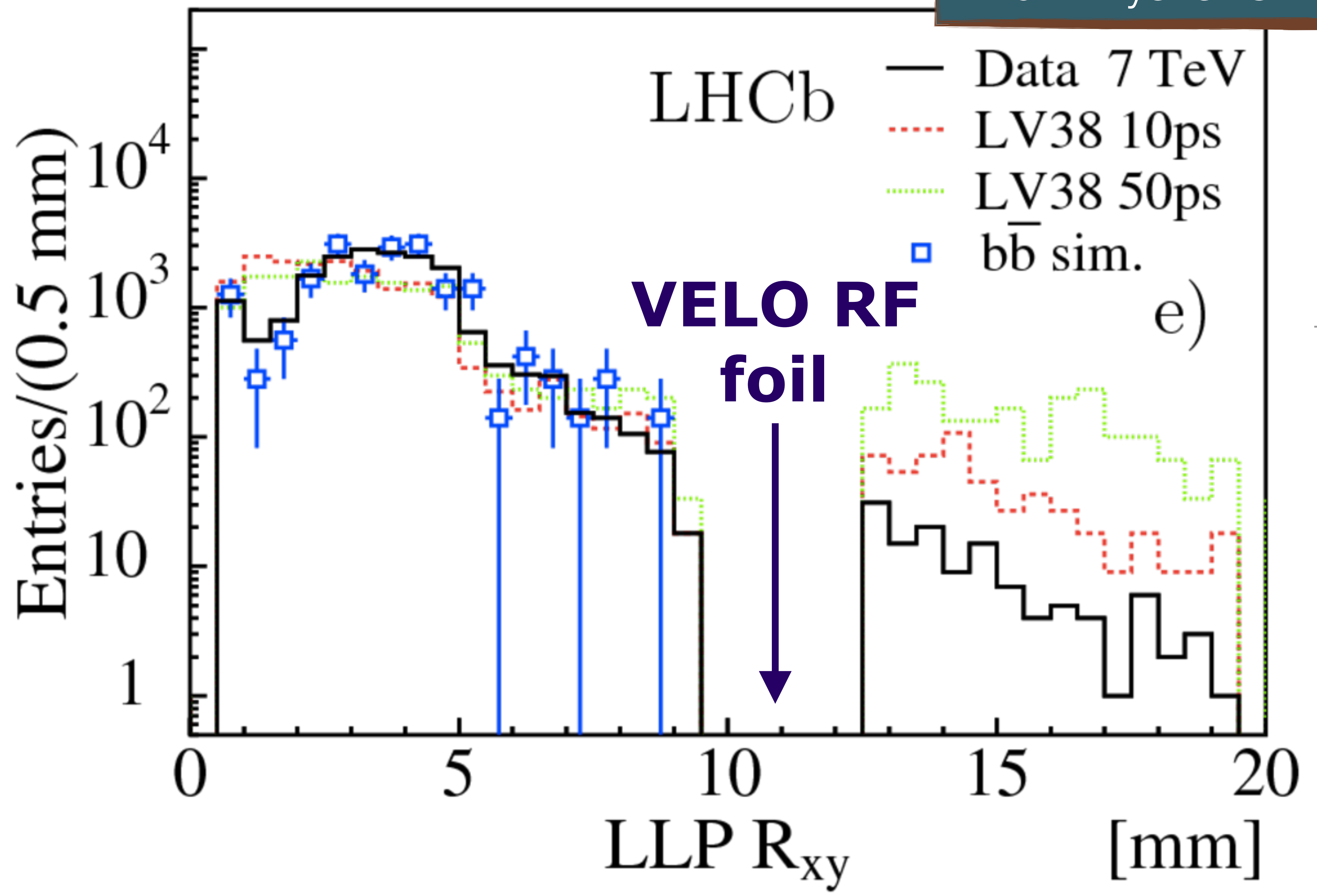
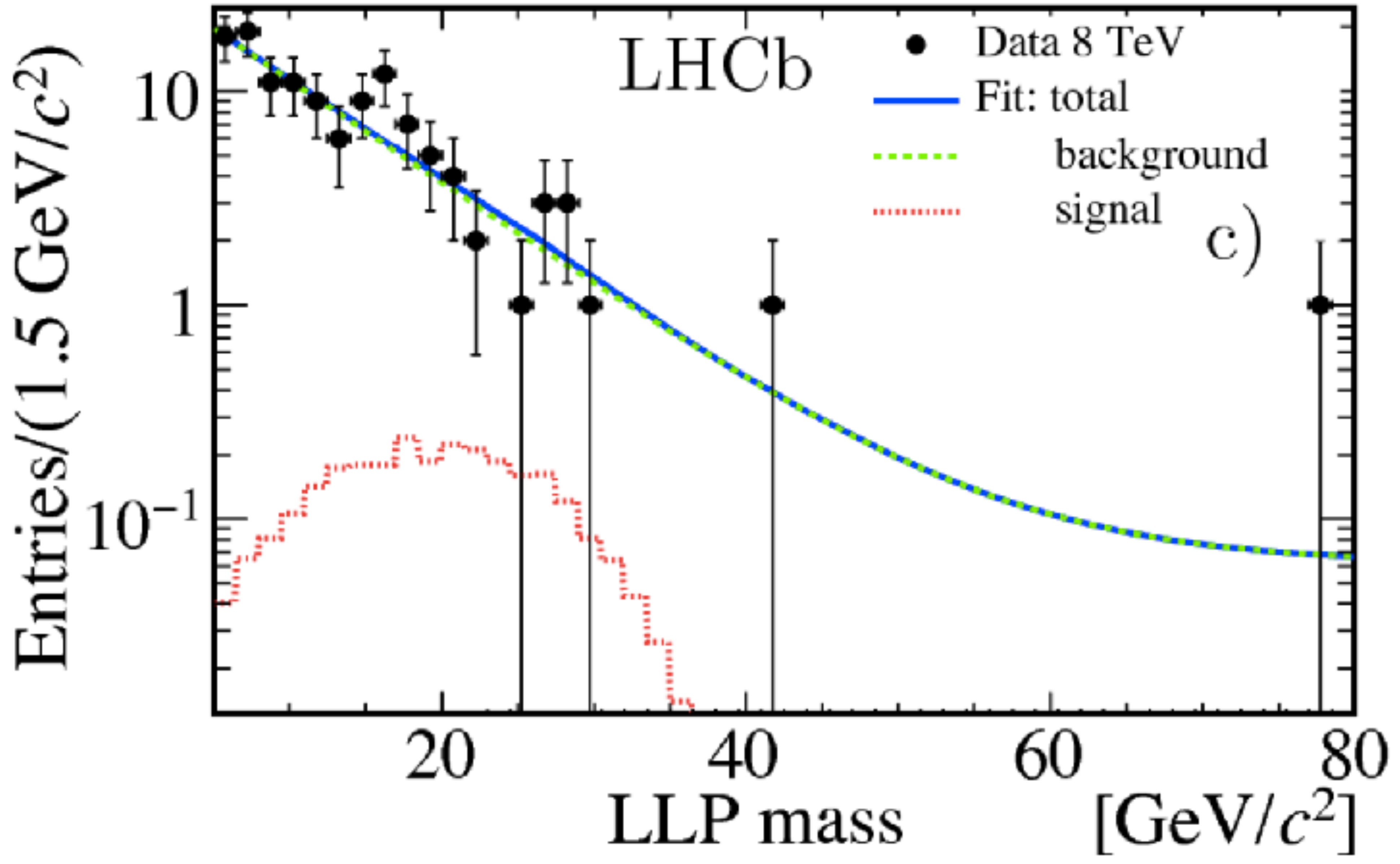
Higgs→LLP→μ+jets / 1

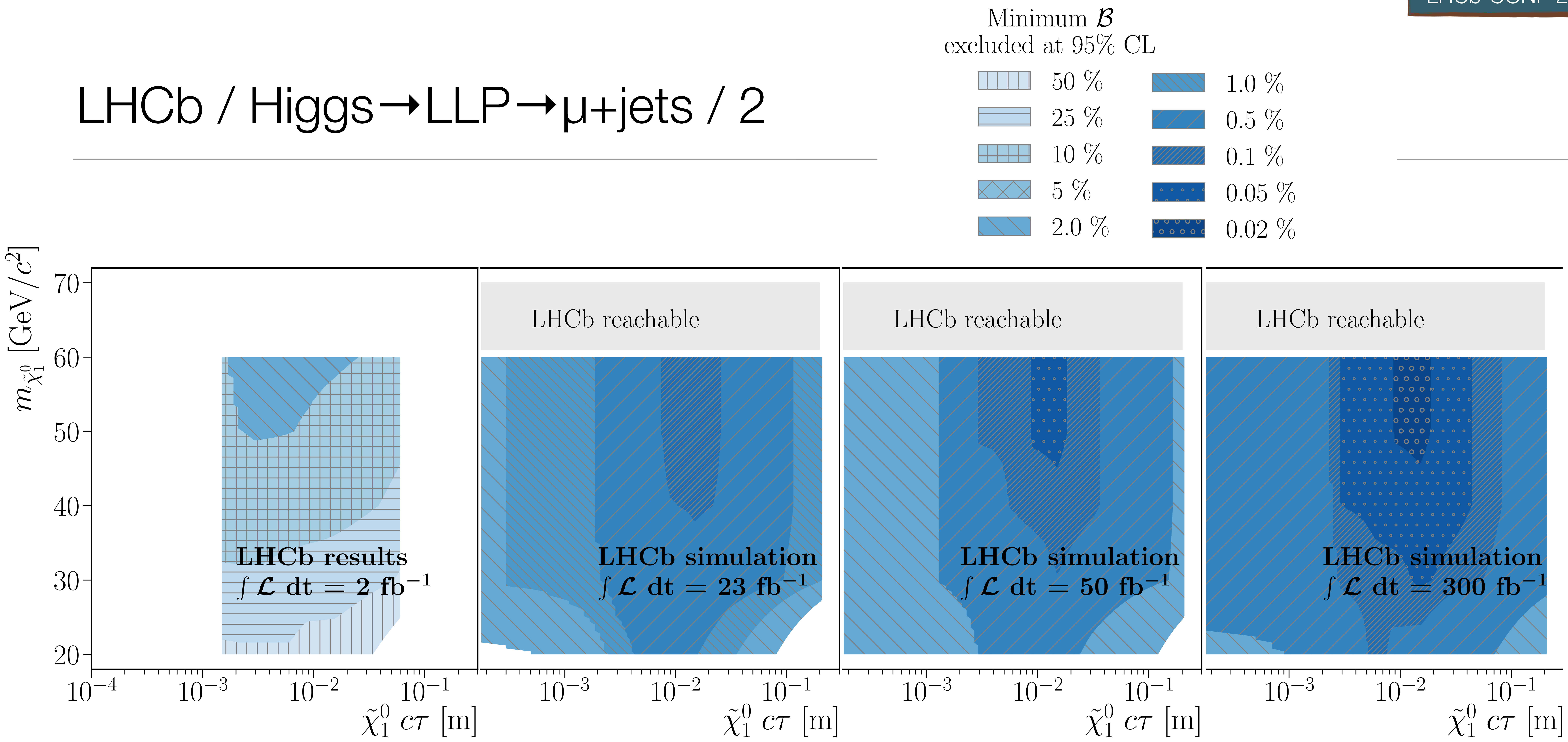
- Massive **LLP** decaying → **μ**+qq (→ **jets**)
- **Single displaced vertex** with several tracks and a high p_T muon; based on **Run-1** dataset
- Production of LLP could come e.g. from Higgs like particle decaying into pair of LLPs
- **m_{LLP}=[20; 80] GeV** and **τ_{LLP}=[5; 100] ps**
- Background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







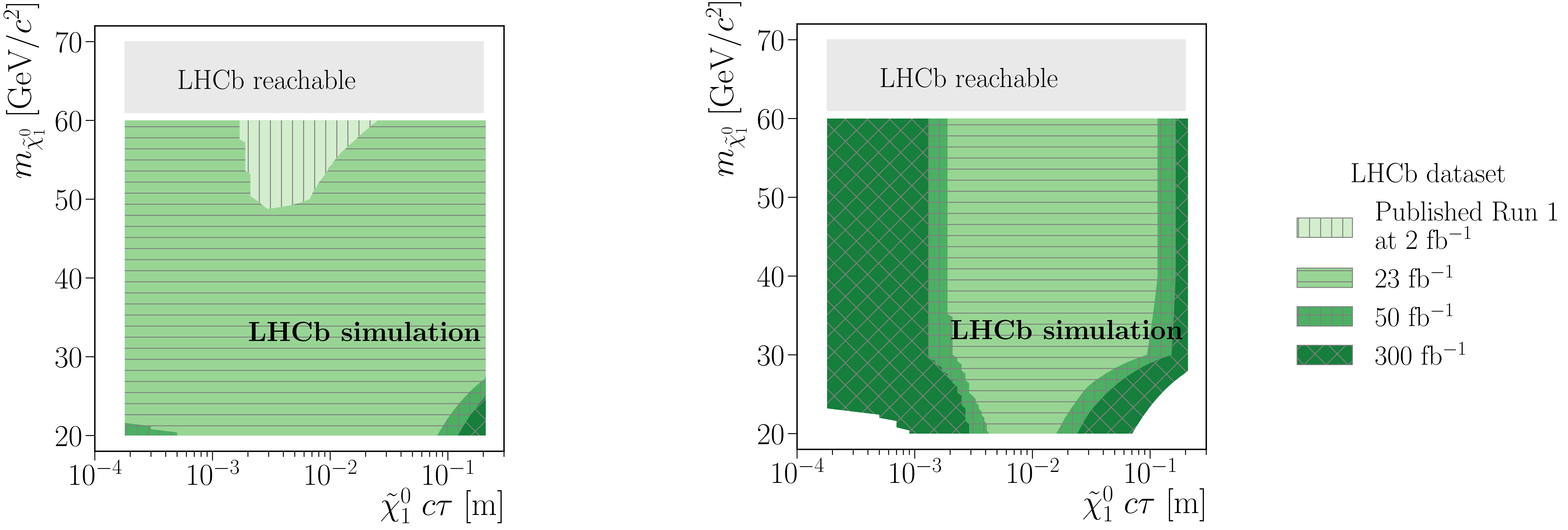
LHCb / Higgs→LLP→μ+jets / 2



- Model independent scaling of current results to future integrated luminosity for different BFs

LHCb / Higgs→LLP→μ+jets / 3

- Model dependent scaling of current results to future integrated luminosity for two different BFs



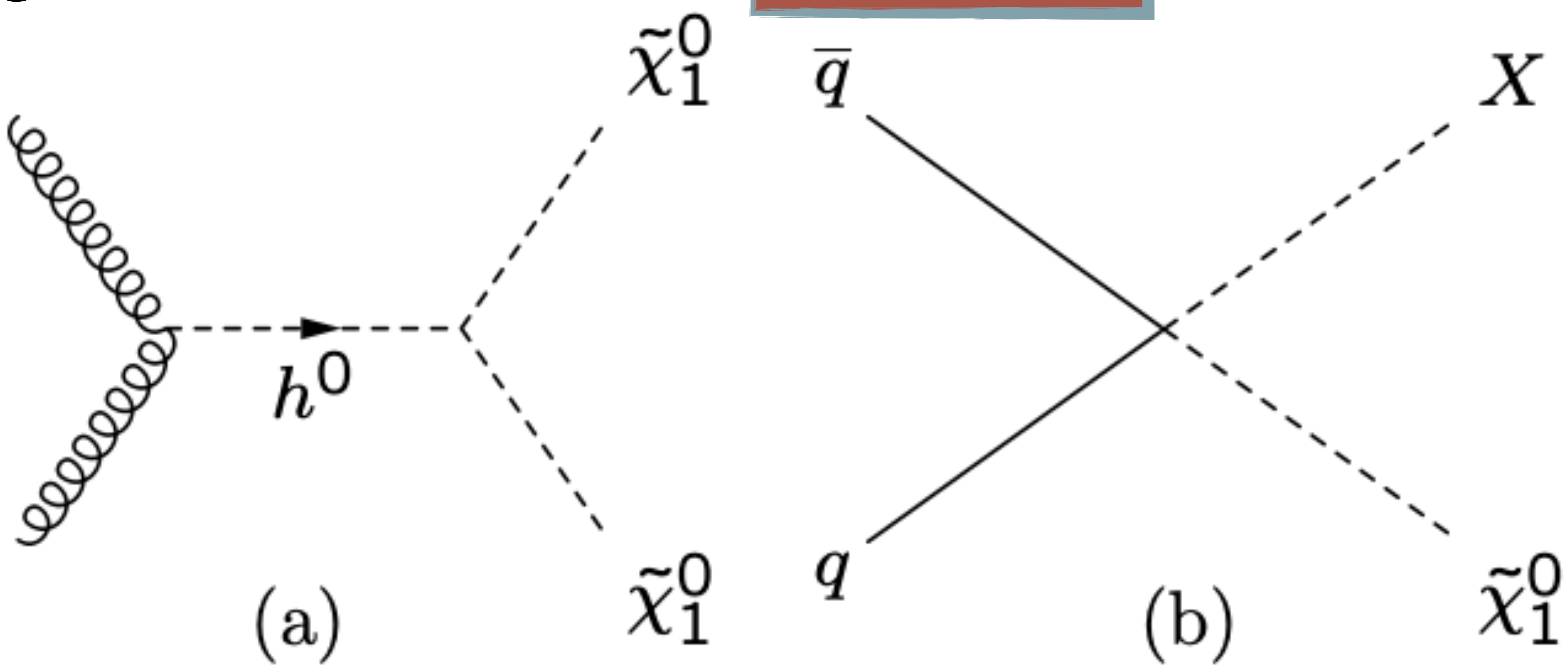
BF(Higgs→LLP+LLP) < 2 %

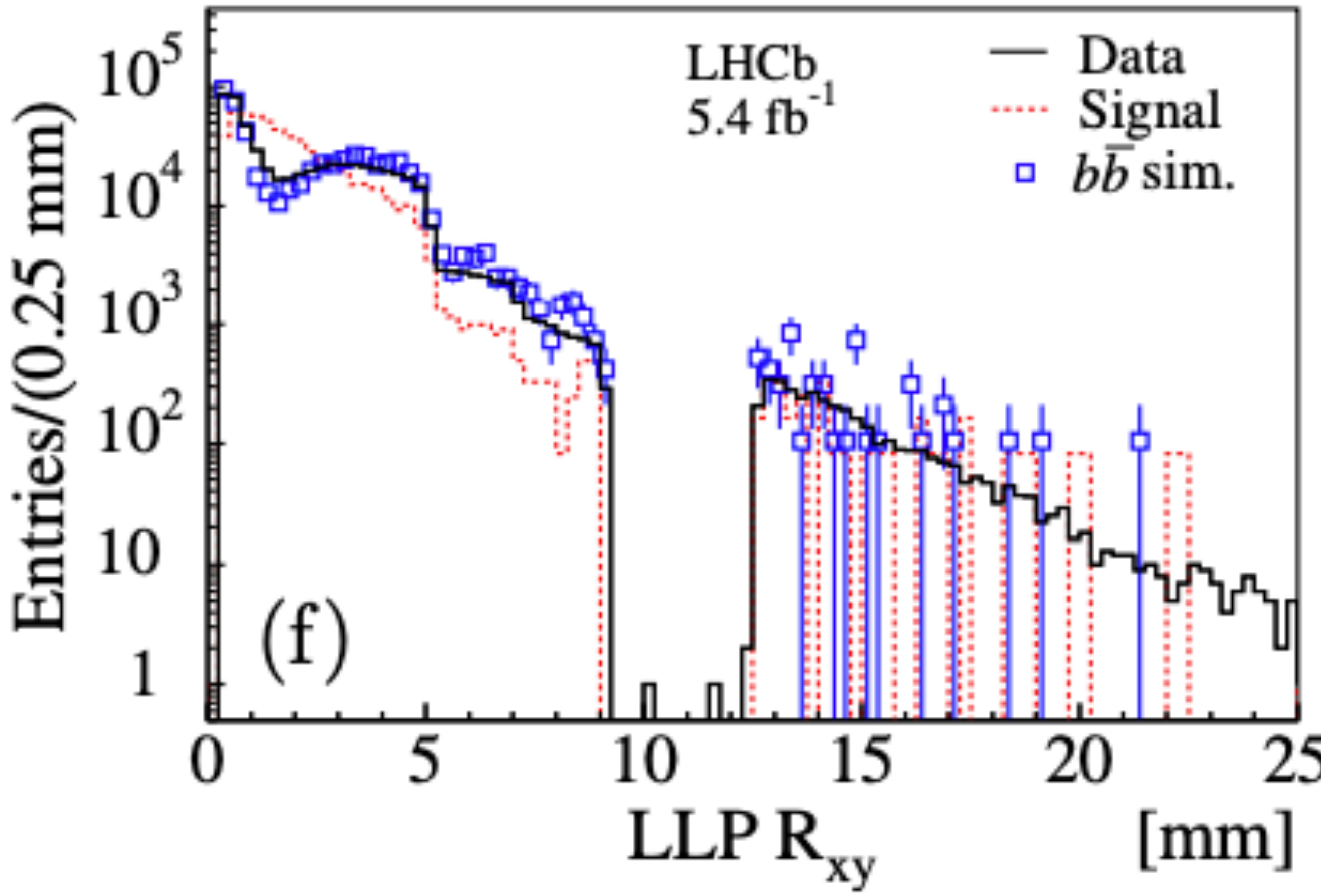
BF(Higgs→LLP+LLP) < 0.5 %

Search for massive long-lived particles decaying semileptonically

[arXiv:2110.07293]

- Production: either in gluon fusion or non-resonant
- **Lifetimes in the range [5,200] ps (compare with. B+ lifetime ~ 1 ps)**
- The LLP signature is a displaced vertex made of charged particle tracks accompanied by an isolated μ with high pT with respect to the proton beam direction
- Mass range to avoid SM b-quark states and to consider LHCb forward acceptance
- We use the fact that lifetime range is well above b-hadron lifetime but vertices still within LHCb's VELO
- Requiring a vertex displaced from any PV in the event and containing one isolated, high-pT muon
- **Particles interacting with the detector material are an important source of background: veto**

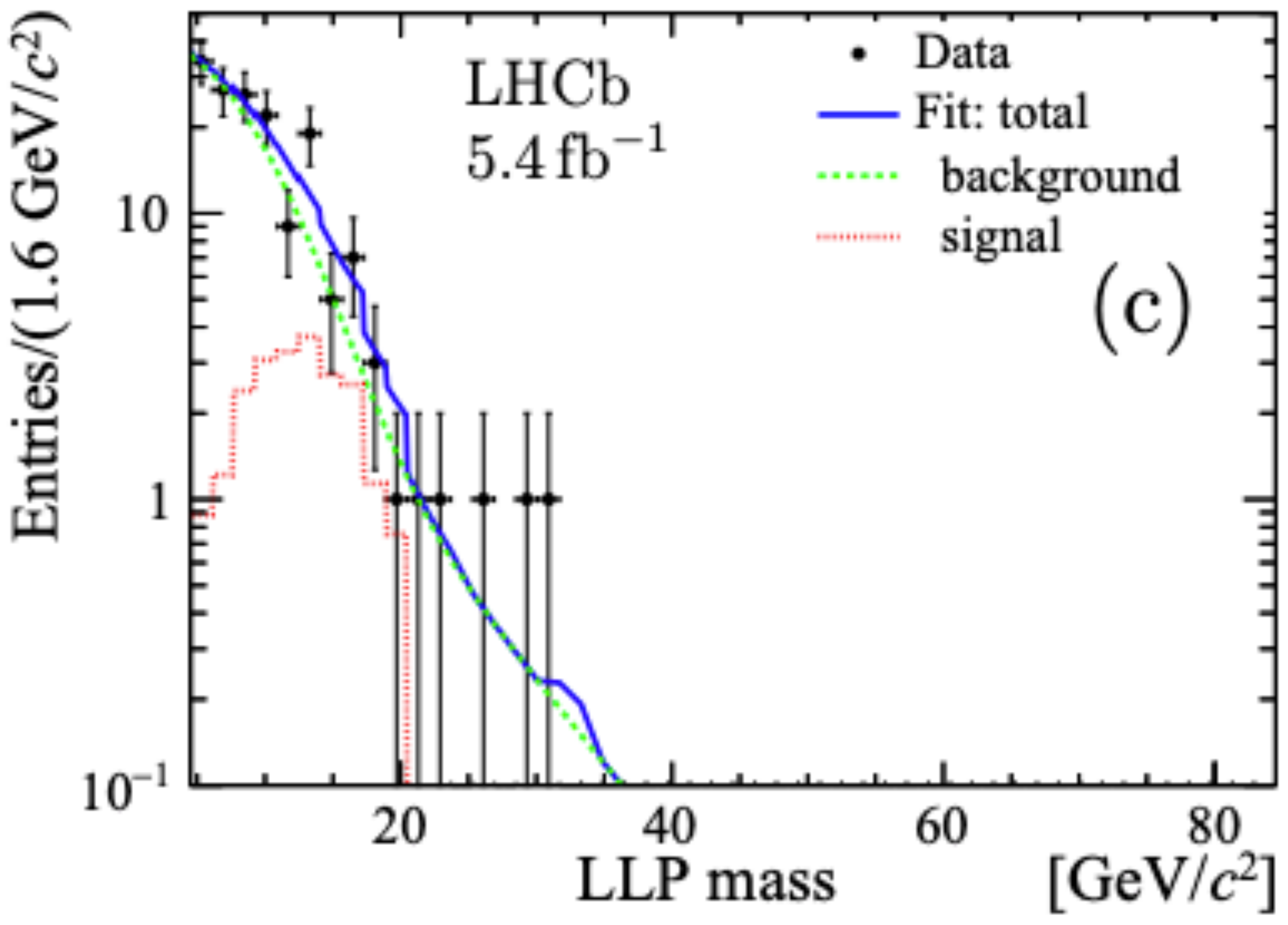


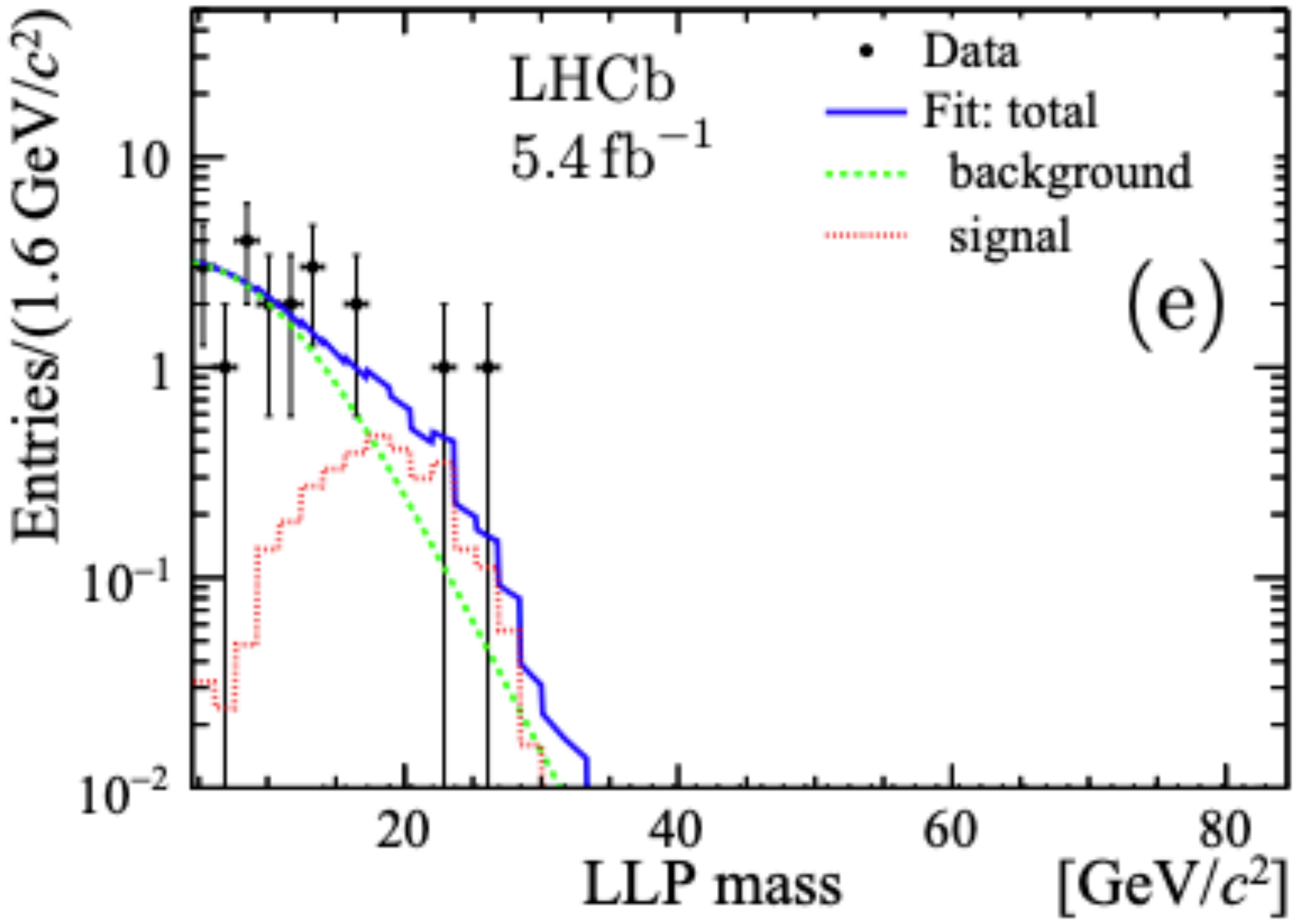


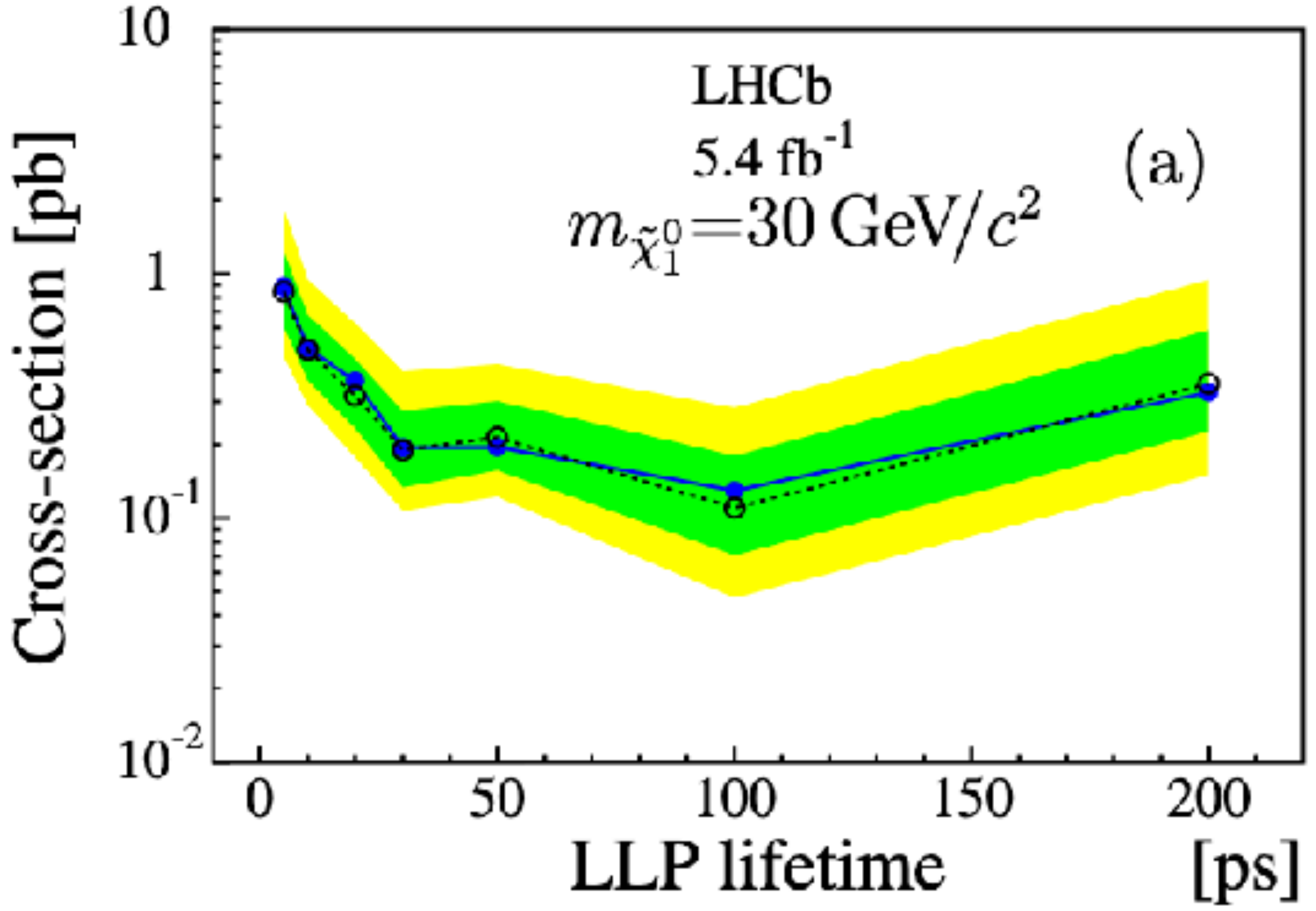
Search for massive long-lived particles decaying semileptonically

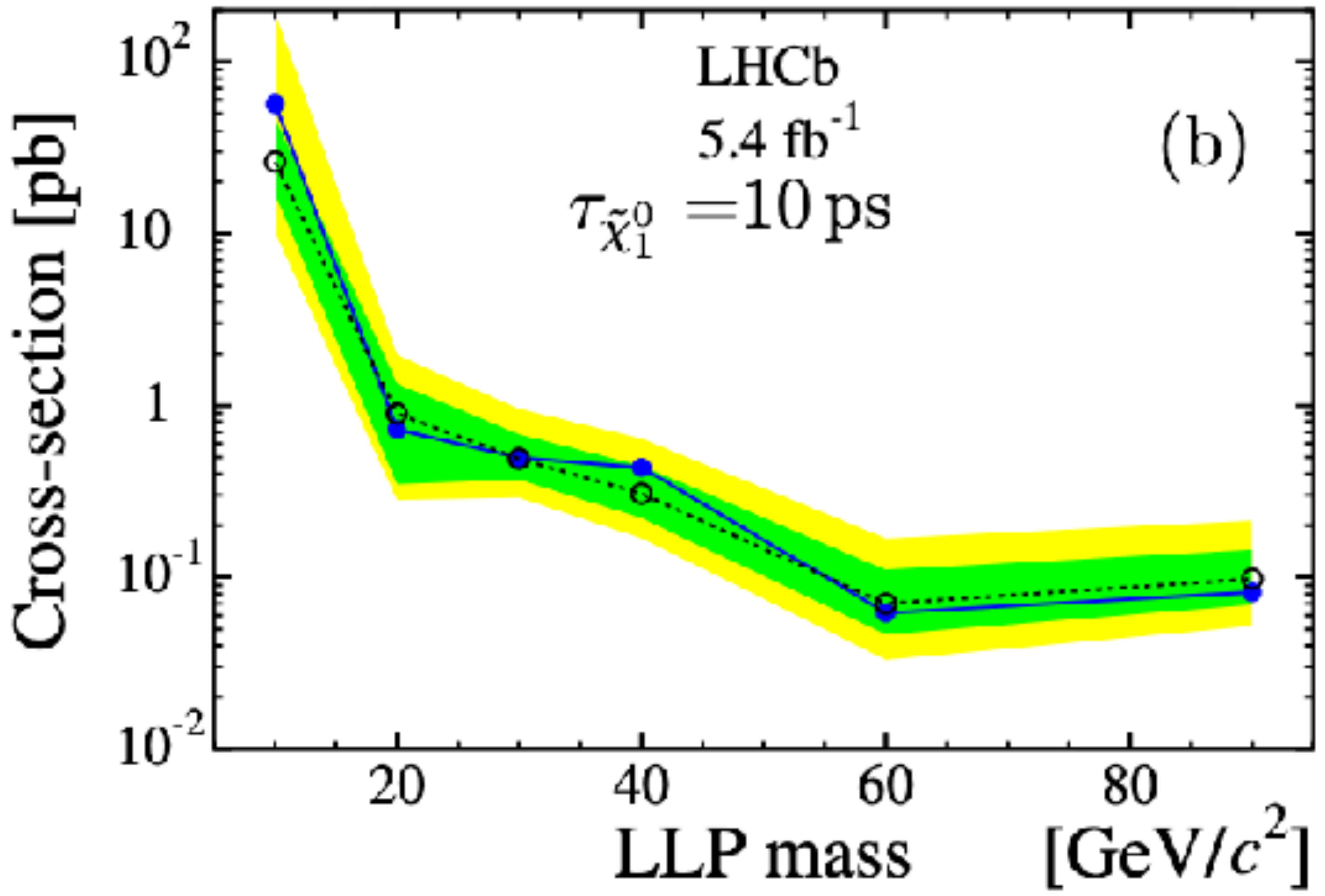
[arXiv:2110.07293]

- Un-binned extended maximum-likelihood fit to the distribution of the reconstructed LLP mass.No excess is found
- Statistical and systematic uncertainties are included as nuisance parameters
- 95% CL upper limits are computed on σ(LLPs) × B(LLPs → μqq) for both production modes
- **Very hard to compete with CMS/ATLAS in this region, what for lower masses?**





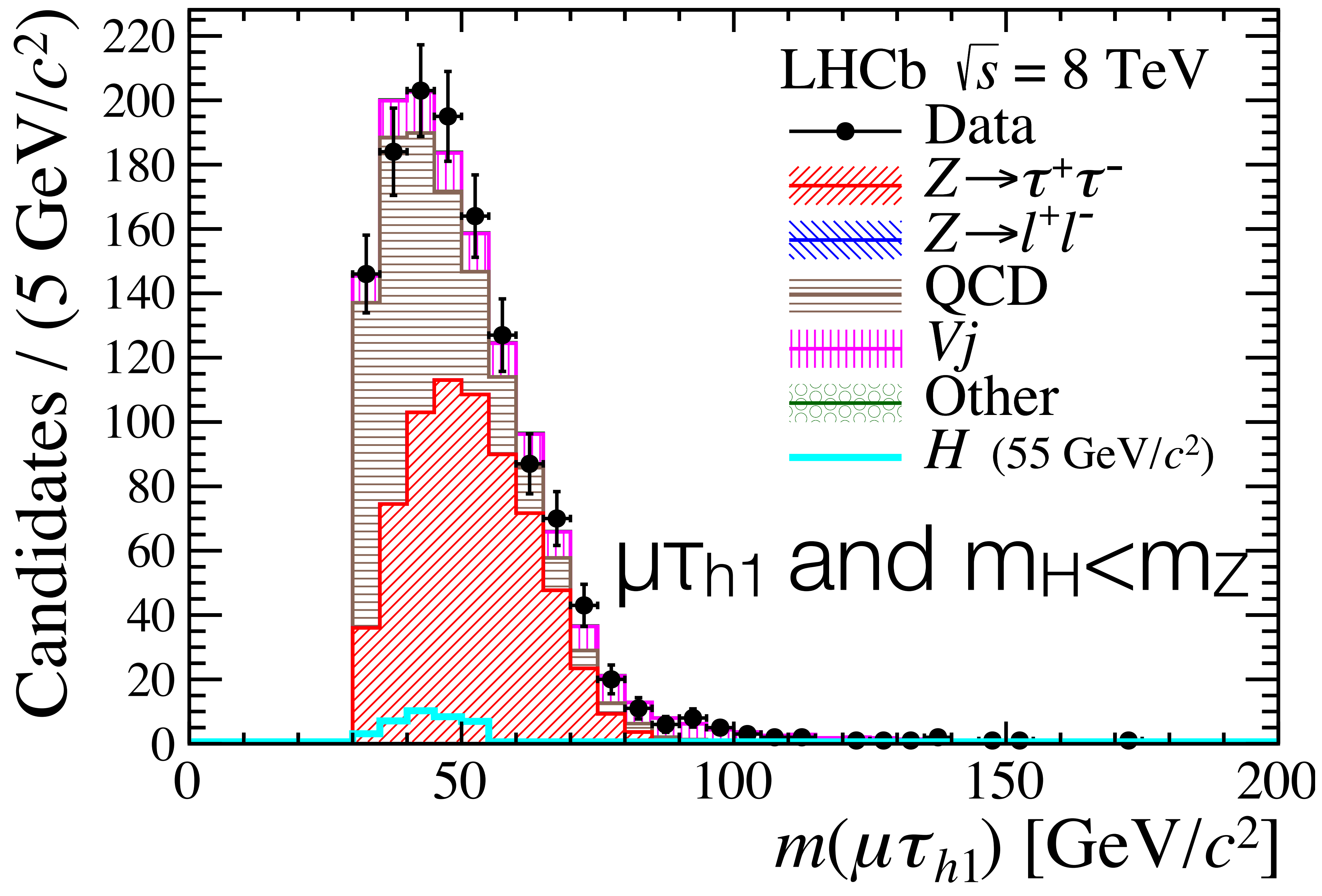


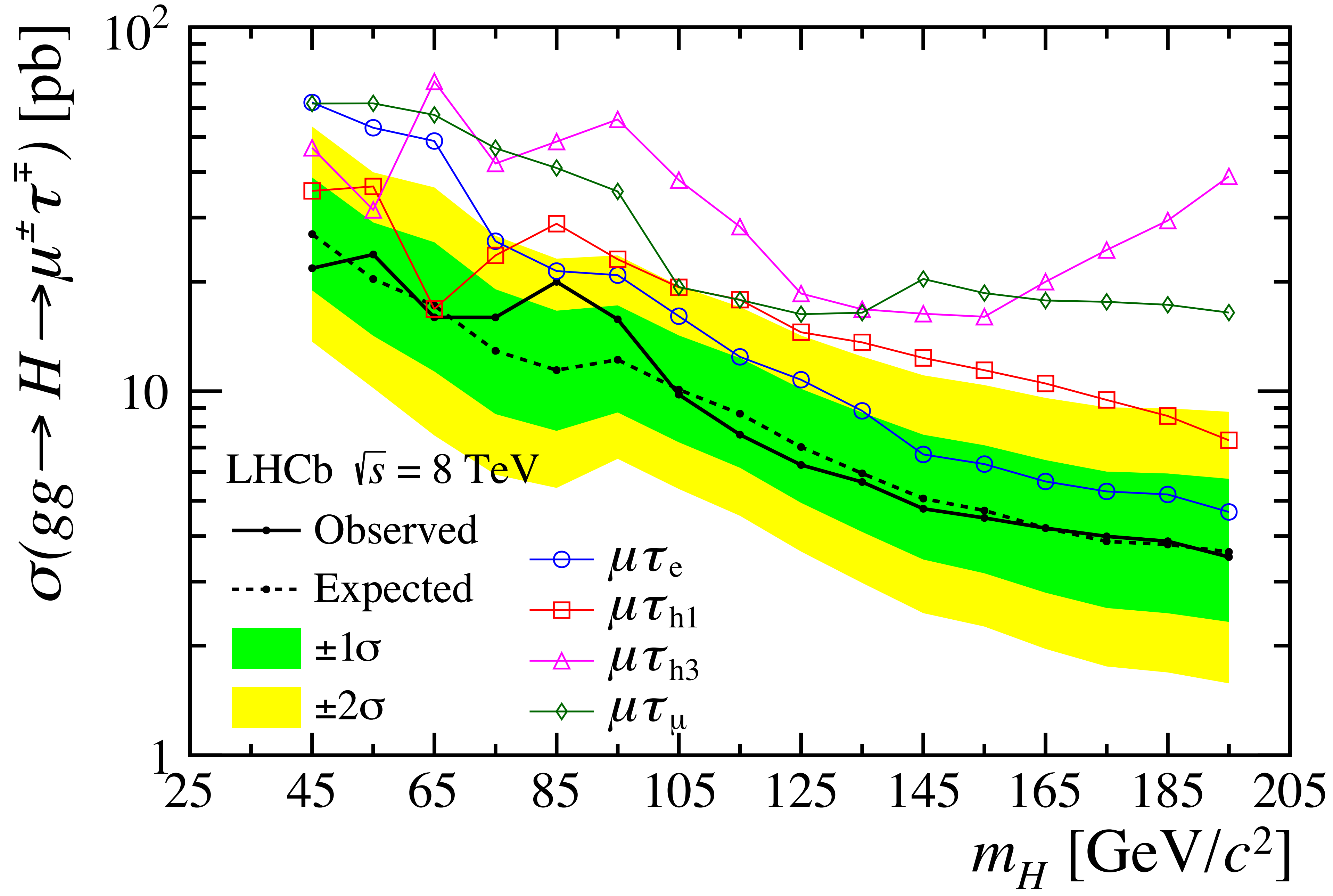


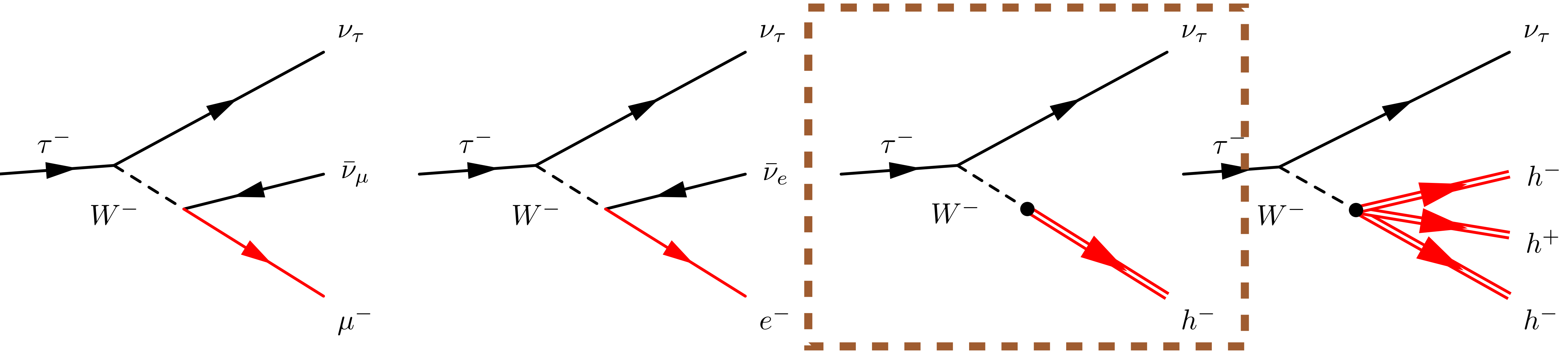
Eur.Phys.J. C78 (2018) no.12, 1008

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





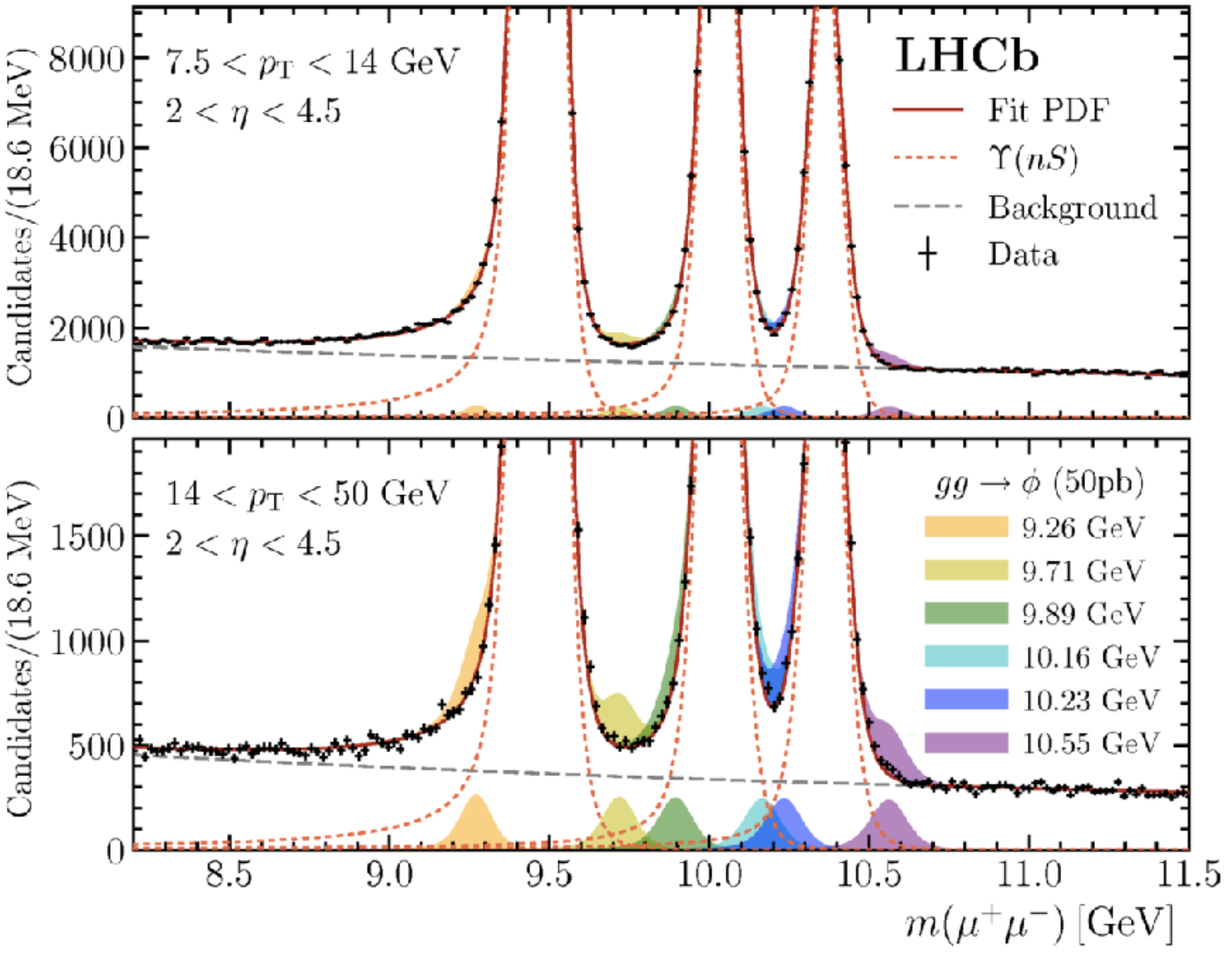


Searching in the Υ mass region / 1

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** ($[p_T, \eta]$) to maximise sensitivity
- Precise modelling of Υ(nS) tails to extend search range as much as possible
- **Mass independent** efficiency (uBDT)

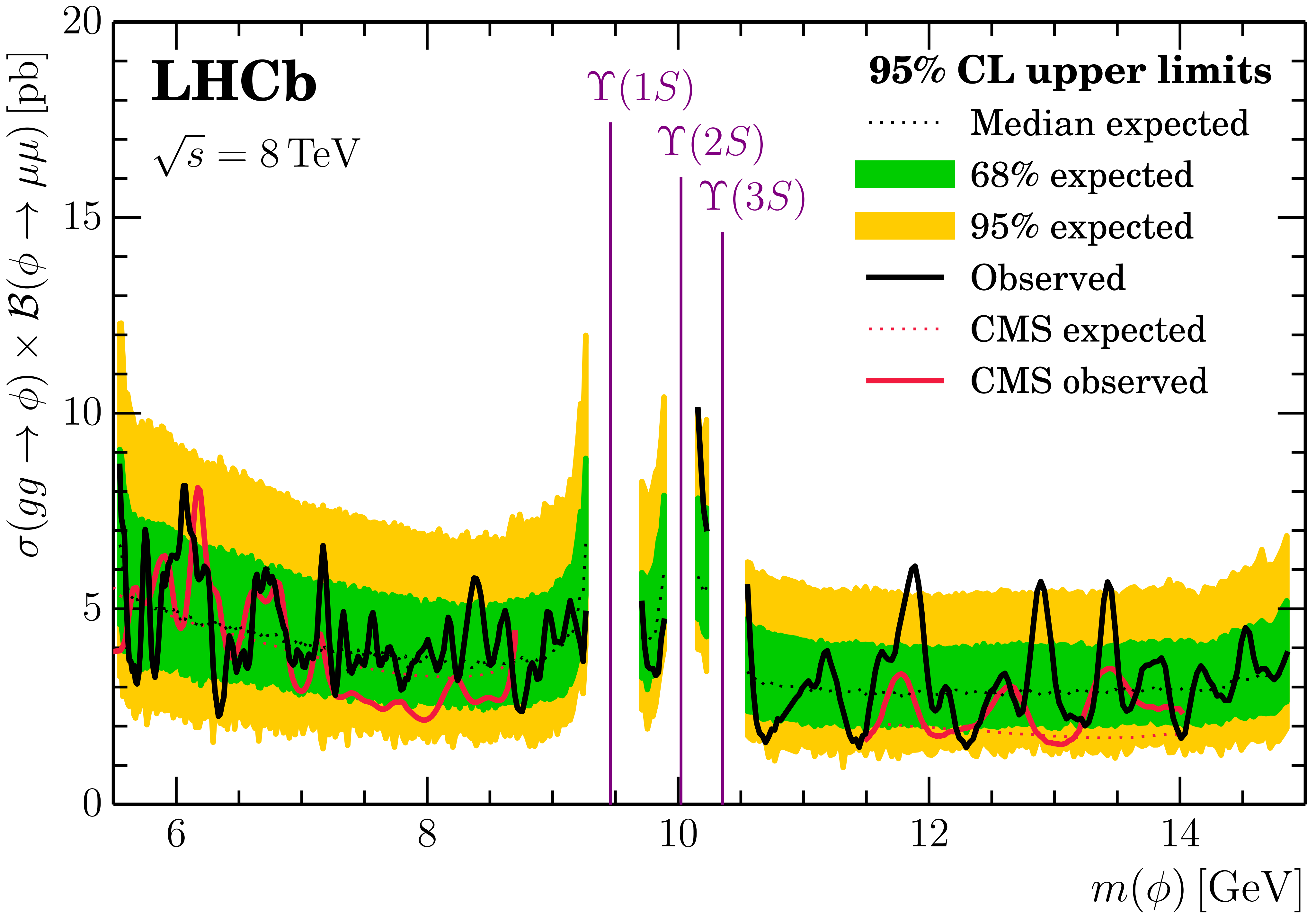
JINST 8 (2013) P12013

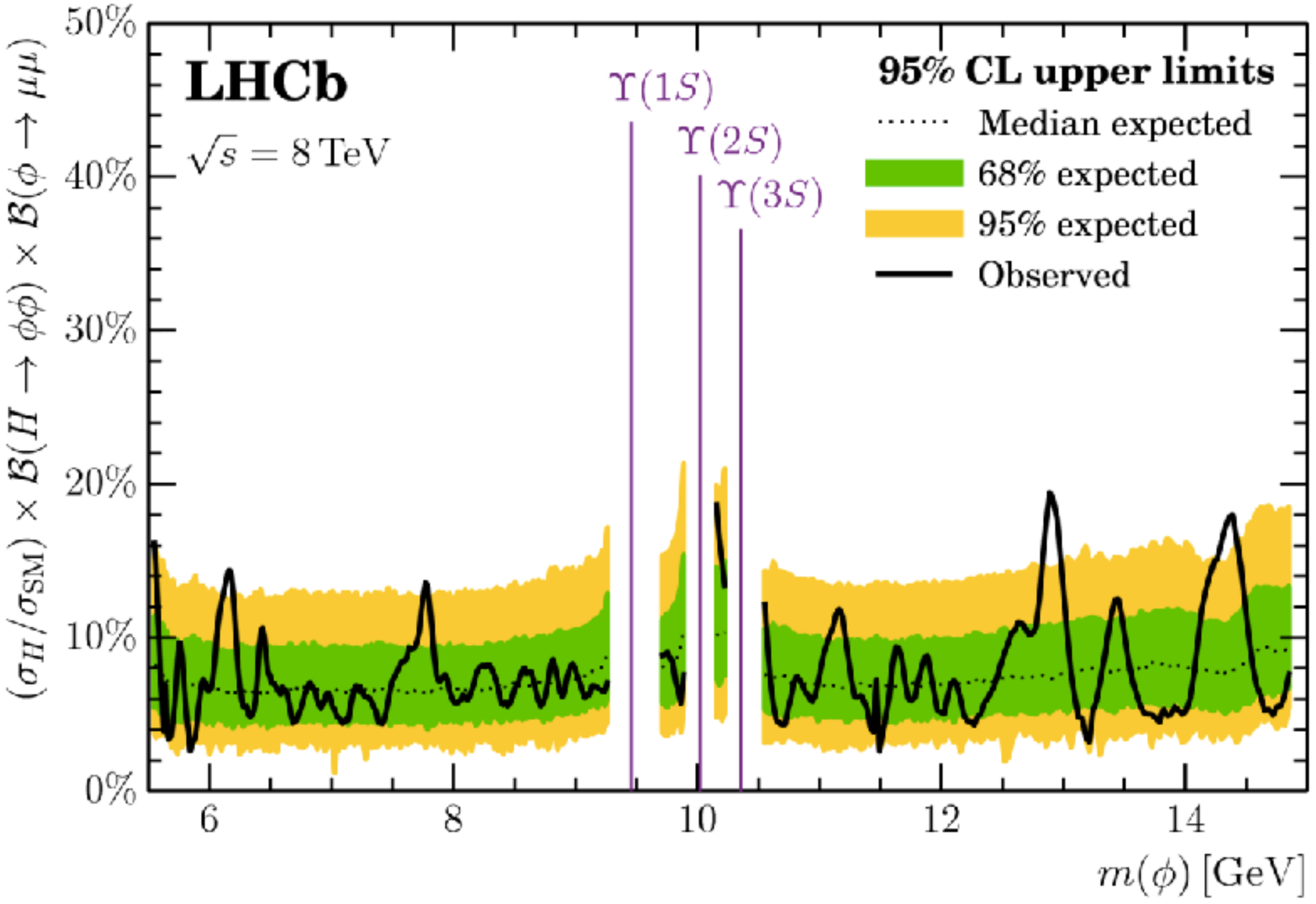


Searching in the Y mass region / 2

JHEP 1809 (2018) 147

- Search for dimuon resonance in **$m_{\mu\mu}$ from 5.5 to 15 GeV** (also between Y(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



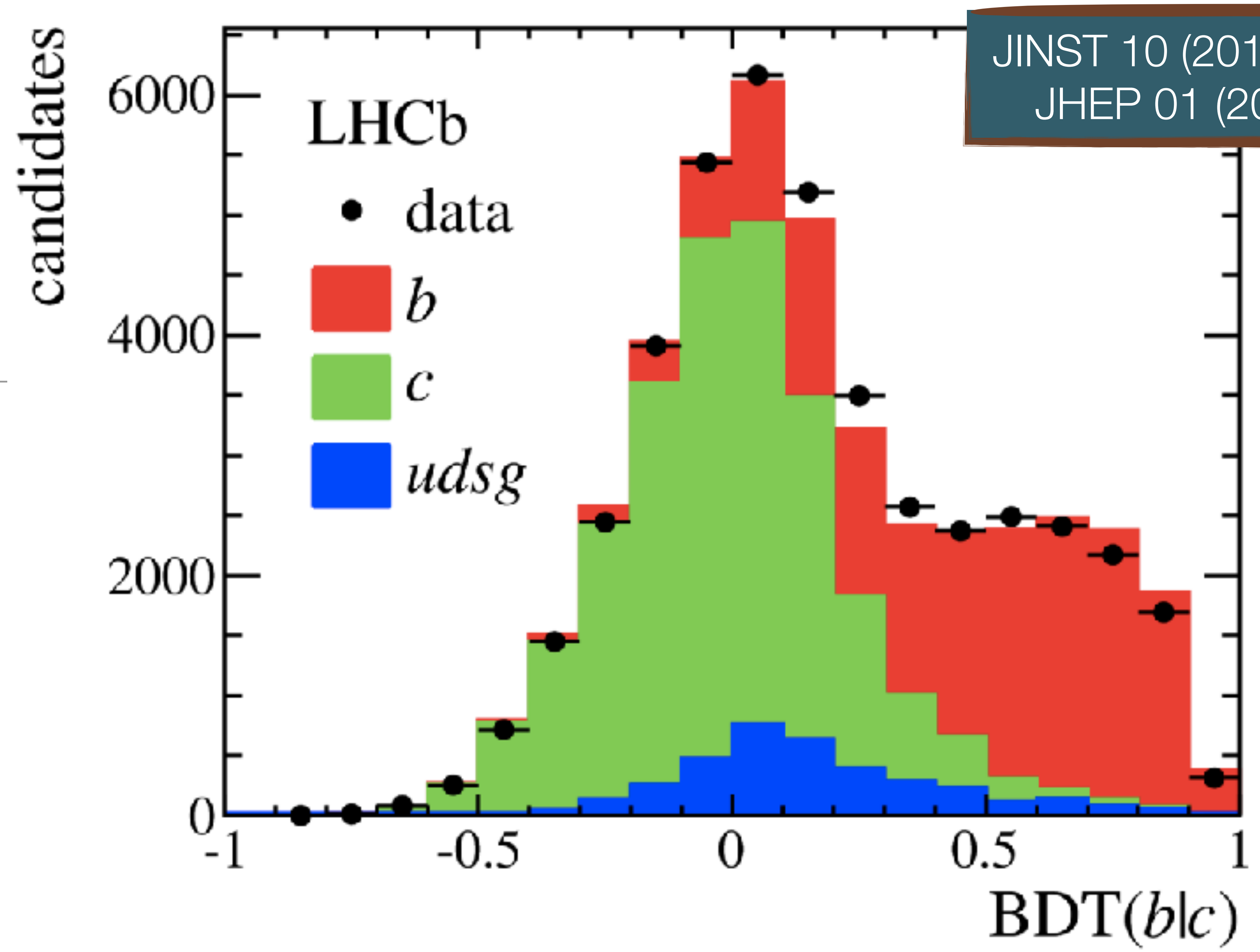


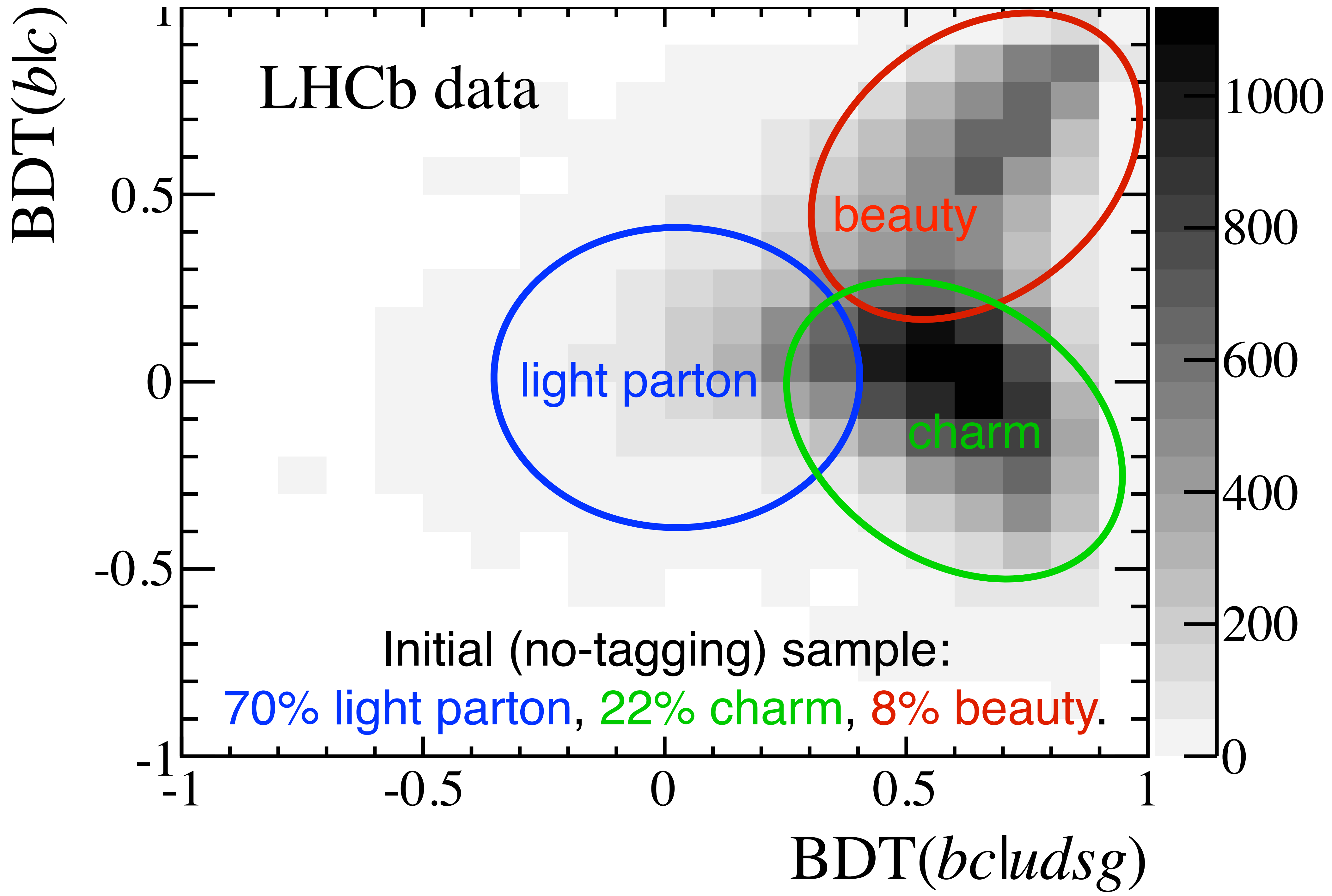
Jet physics at LHCb / 1

- 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$_{bc|udsg}$** optimised for heavy flavour versus light discrimination
  - **BDT$_{b|c}$** optimised for b versus c discrimination

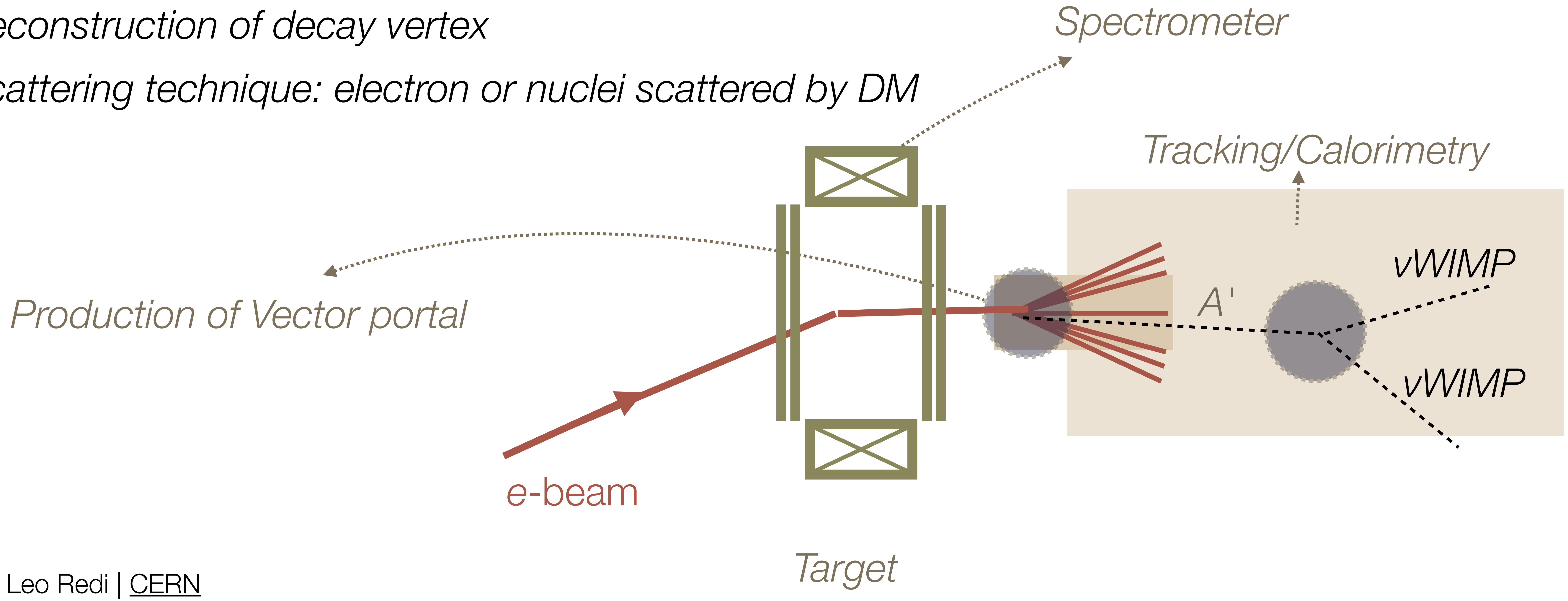
JINST 10 (2015) P06013
JHEP 01 (2014) 033





Exploring the dark sector

- ***Indirect search (signal proportional to [coupling]^2)***
    - ***Missing energy technique***
- *Direct search (signal proportional to [coupling]^4)*
    - *Reconstruction of decay vertex*
    - *Scattering technique: electron or nuclei scattered by DM*



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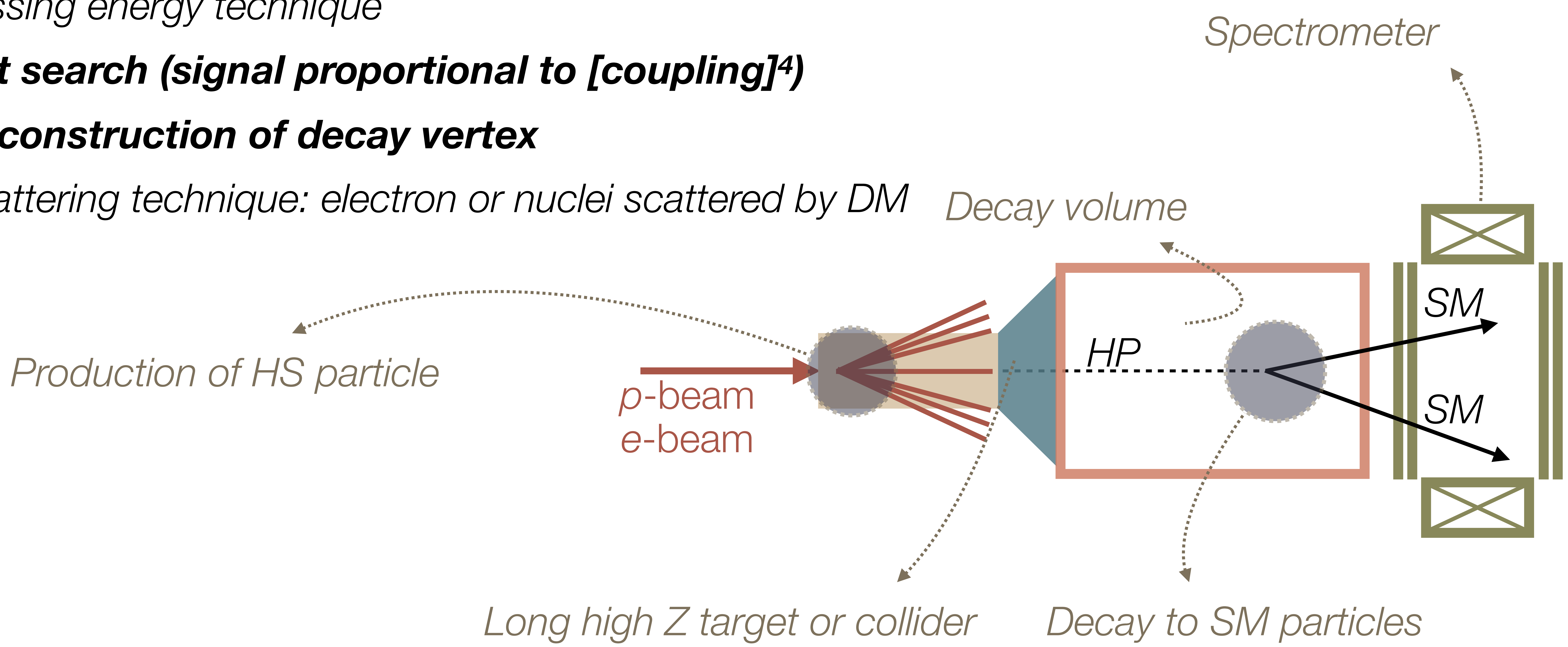

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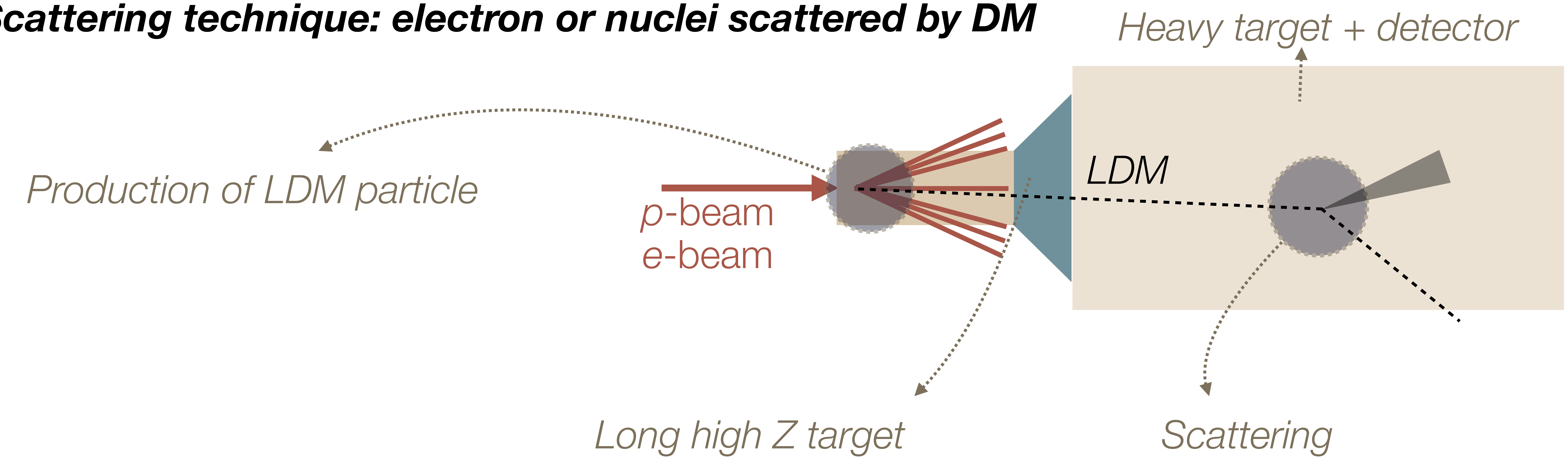

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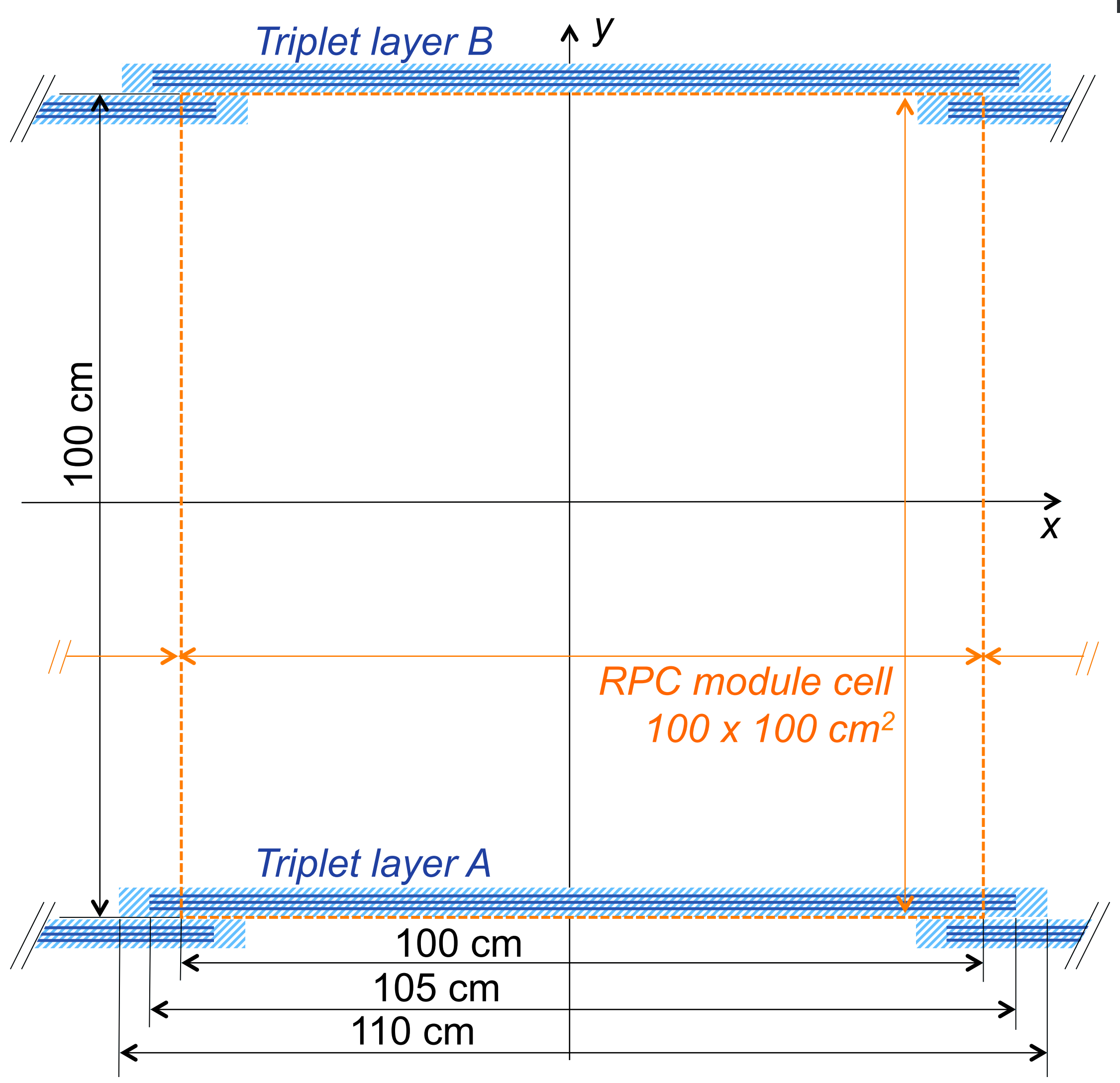
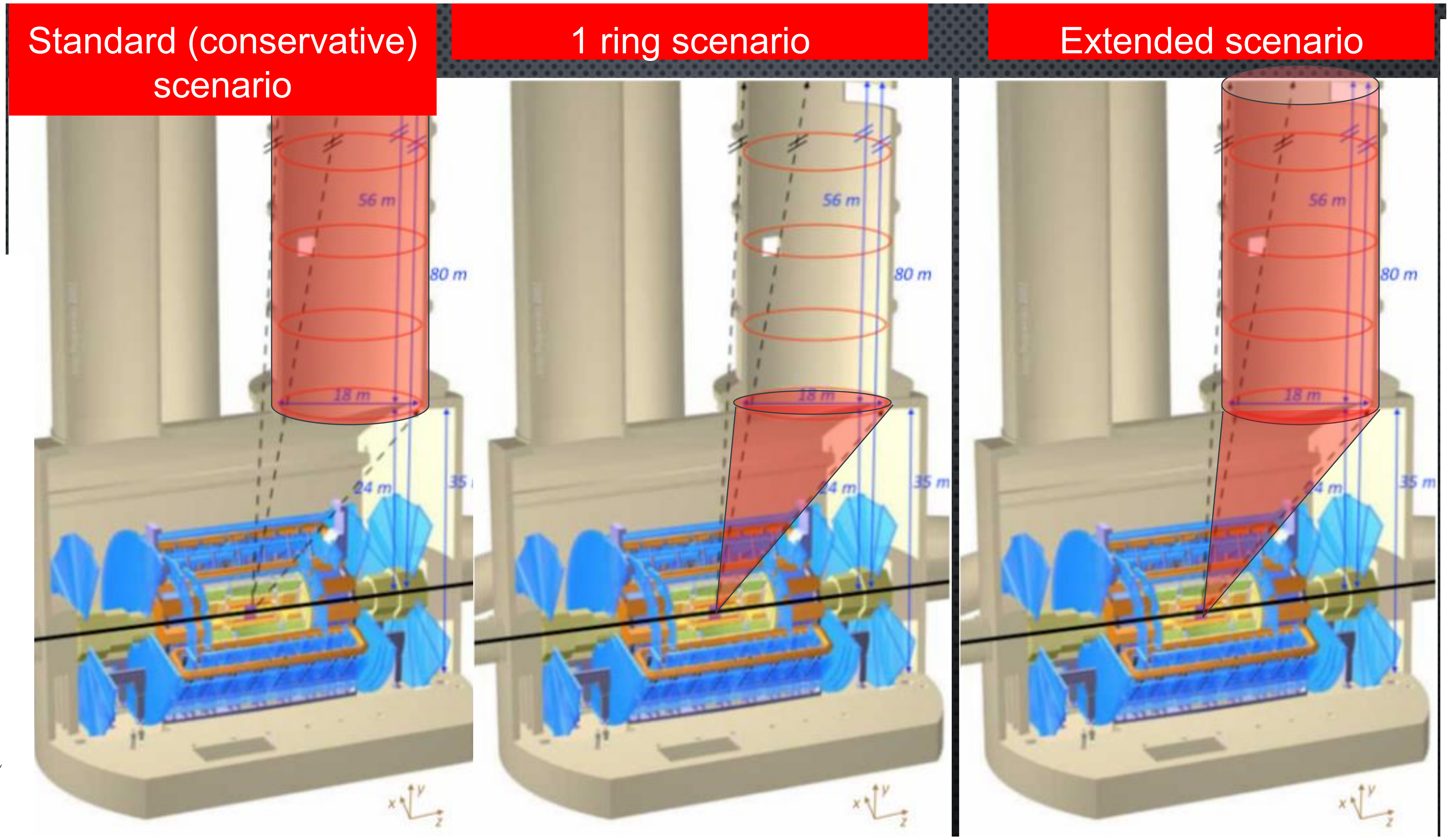
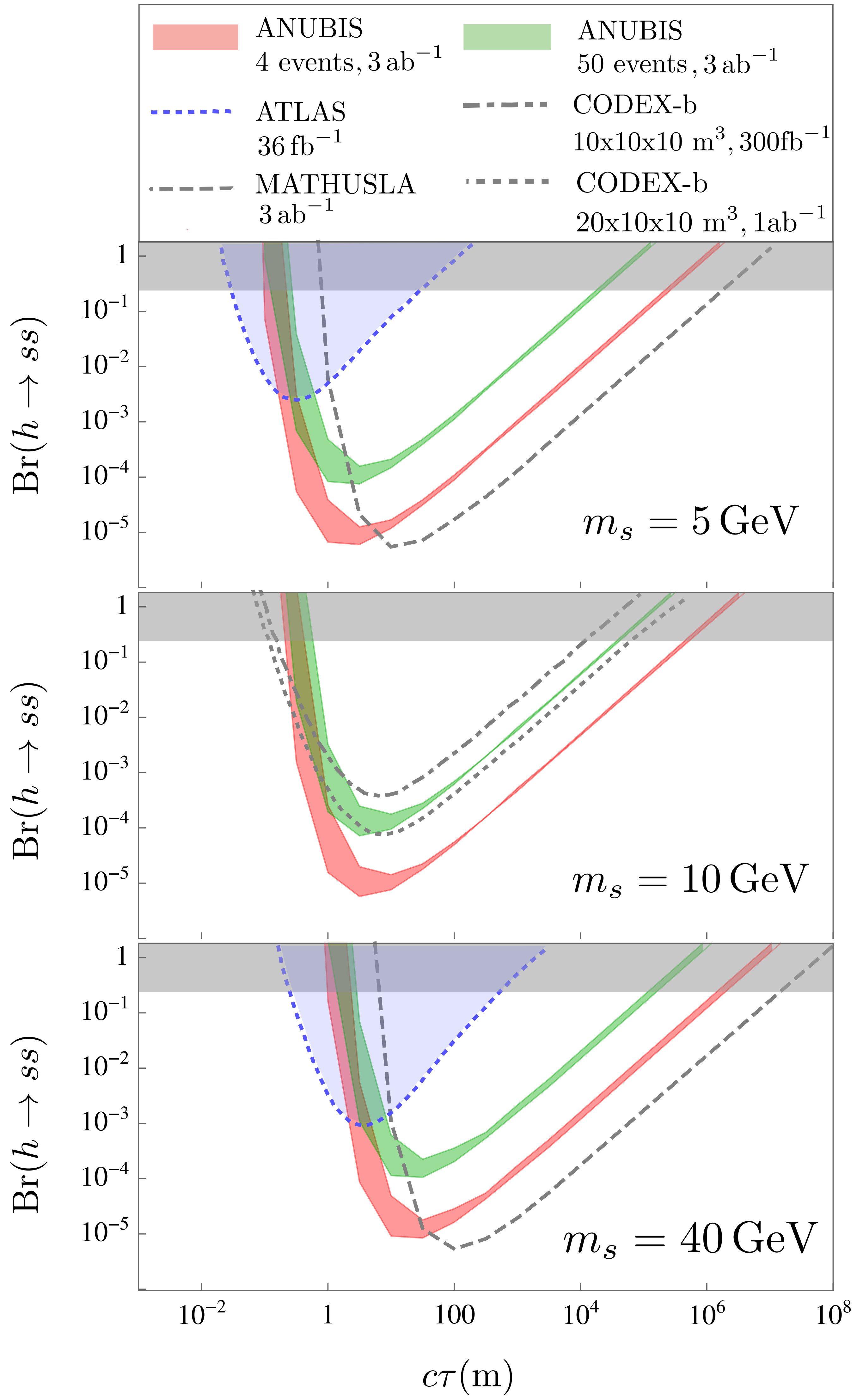




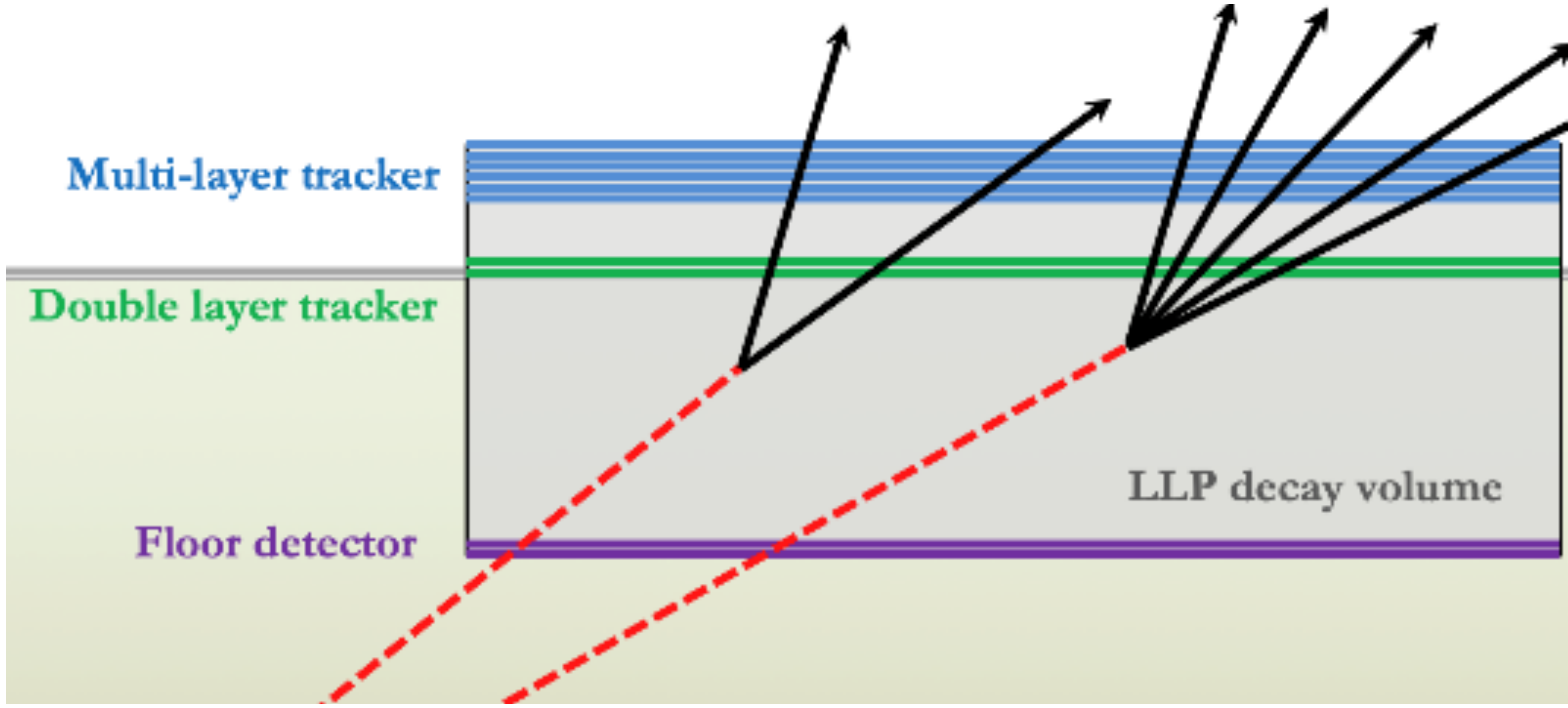


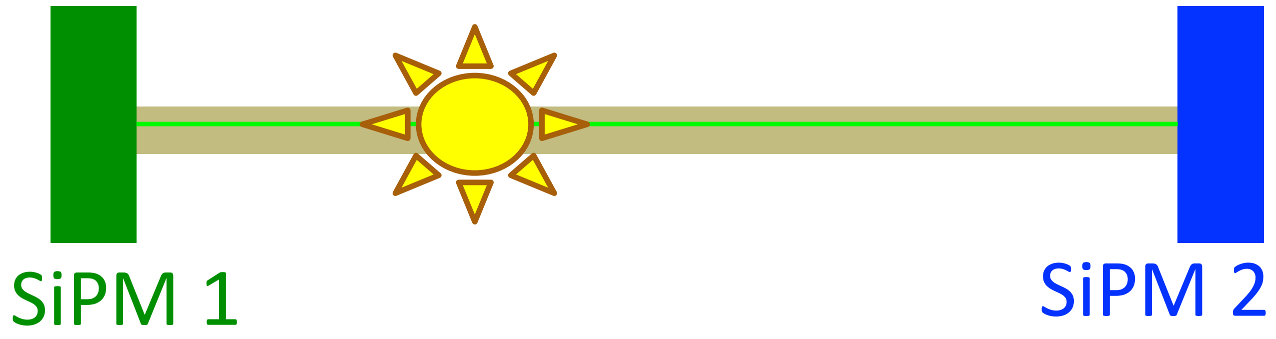
- **AN Underground Belayed In-Shaft search experiment**
- Instrument the ATLAS shaft with Resistive Plate Chamber (RPC) used for ATLAS phase-2 upgrade
- 2D readout triplet layers for a total of 2.3 km^2 instrumented area
- Benchmark: for LLPs for Higgs decays h → ss with different LLP masses
- Comparable physics reach of MATHUSLA
- **Can work together with the ATLAS detector**

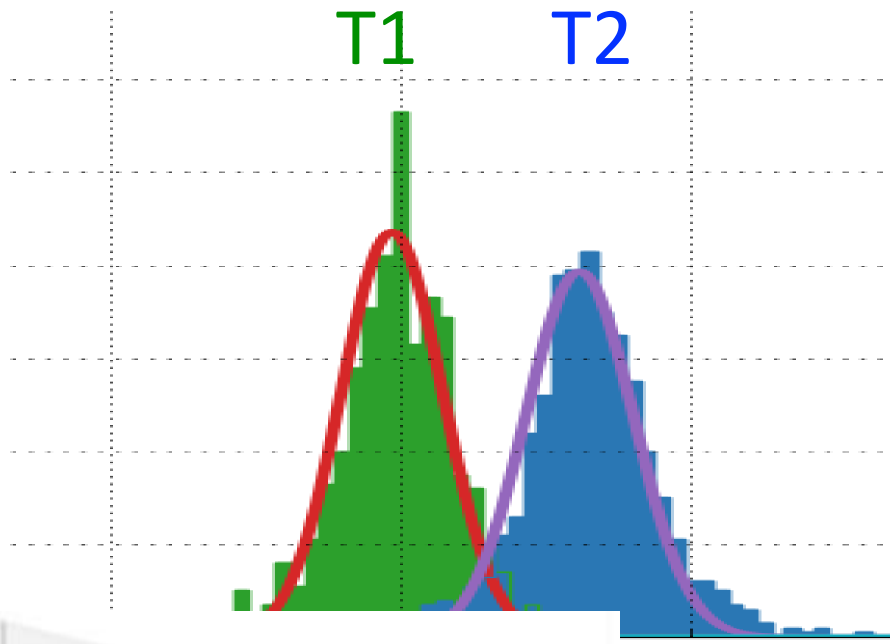
Ref

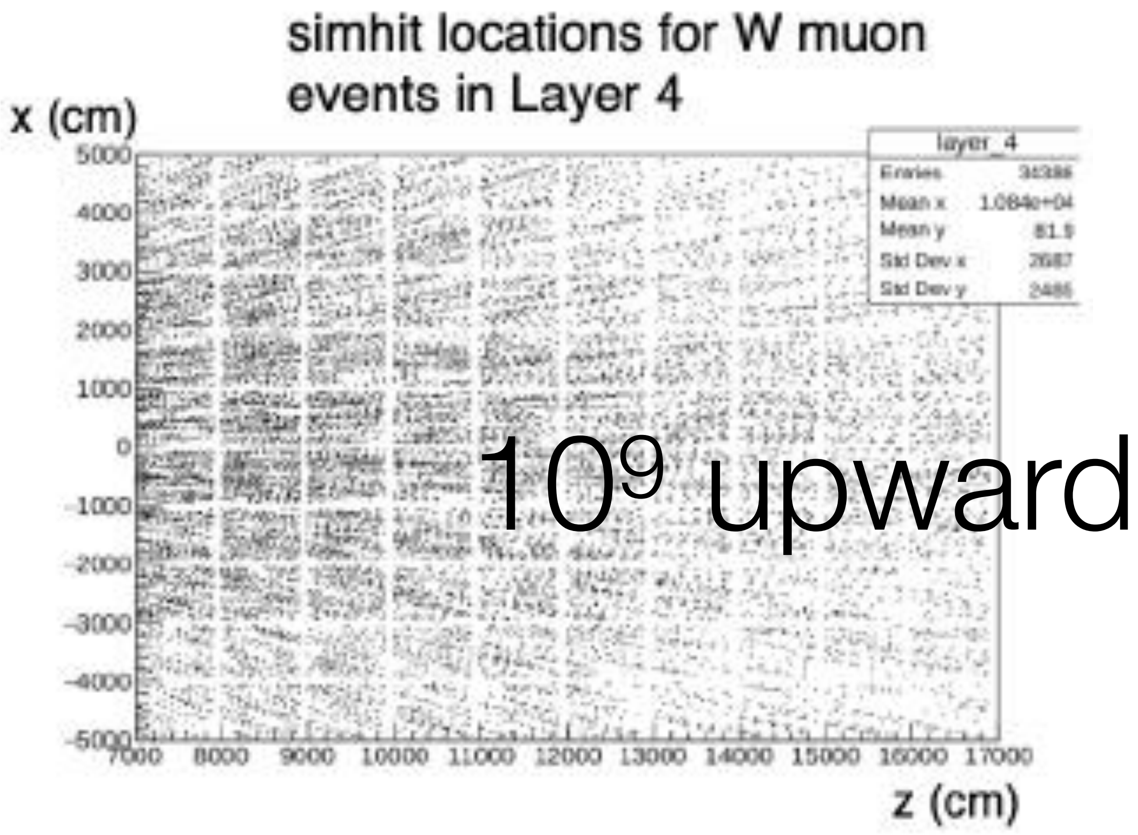
MATHUSLA

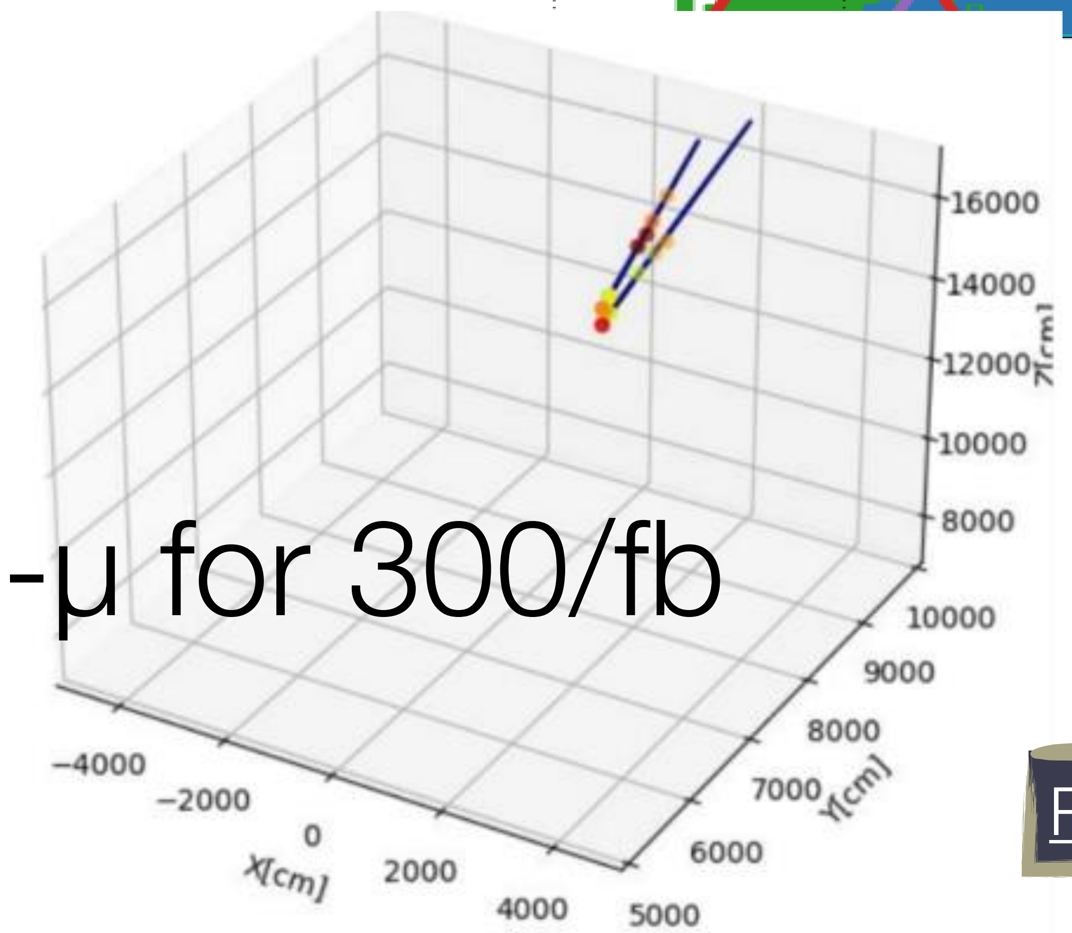
- **Massive Timing Hodoscope for Ultra Stable neutraL pArticles**
- Sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis (BBN) limit (10^7 – 10^8 m) for the HL-LHC
- ~70 m to IP on surface, with IP ~80 m below surface and ~7.5 m offset to the beam line
- 100x100x~29 m^3
- LLPs decaying inside MATHUSLA are reconstructed as displaced vertices,
- 4D tracking with ~ns timing resolution
- **Can run standalone or combined to CMS**
- **Important** Background Simulations underway with GEANT4: e.g. upward-μ











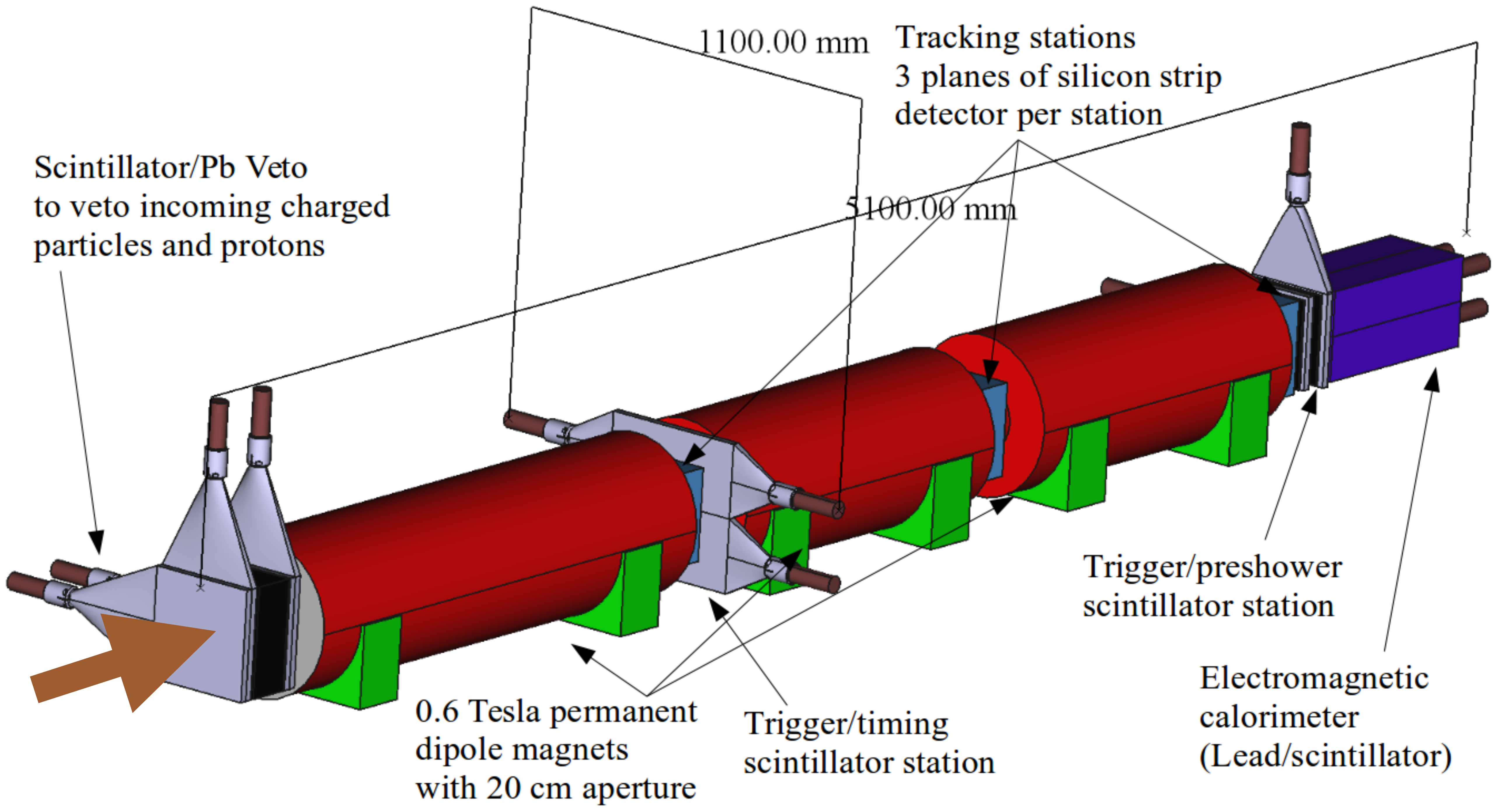
10^9 upward-μ for 300/fb

Ref

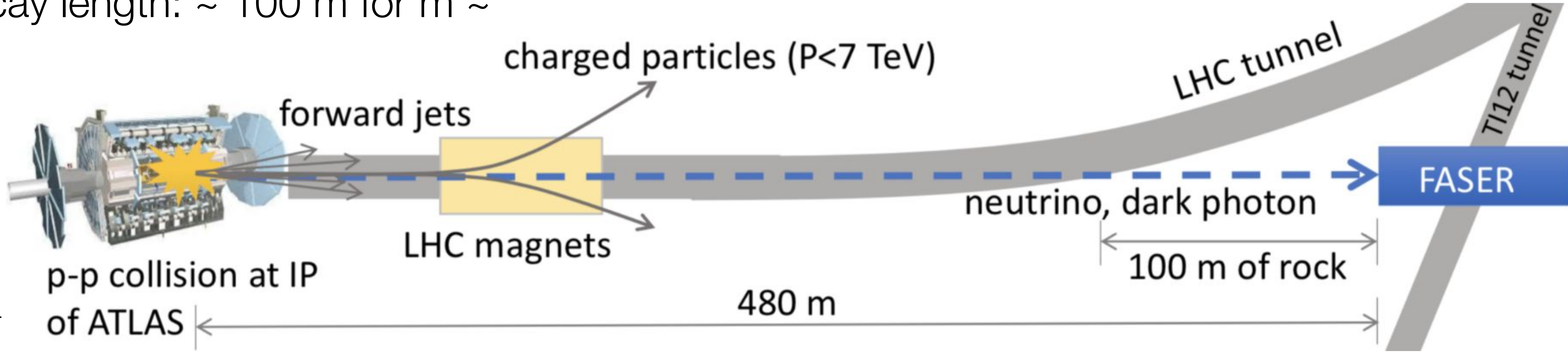
Ref

FASER

- FASER: search for new, weakly-interacting particles in the MeV - GeV range (e.g. A', HNL, ALPS)
- FASERν: first measurements of neutrinos from a collider and in unexplored energy regime (SND@LHC)
- Large inelastic pp cross-section σ_{inel}(13 TeV) ~ 7 mb → N_{inel} (Run 3, 150/fb) ~ 10^{16}
- Small production angle: θ ~ mrad
- Macroscopic decay length: ~ 100 m for m ~ 10-100 MeV



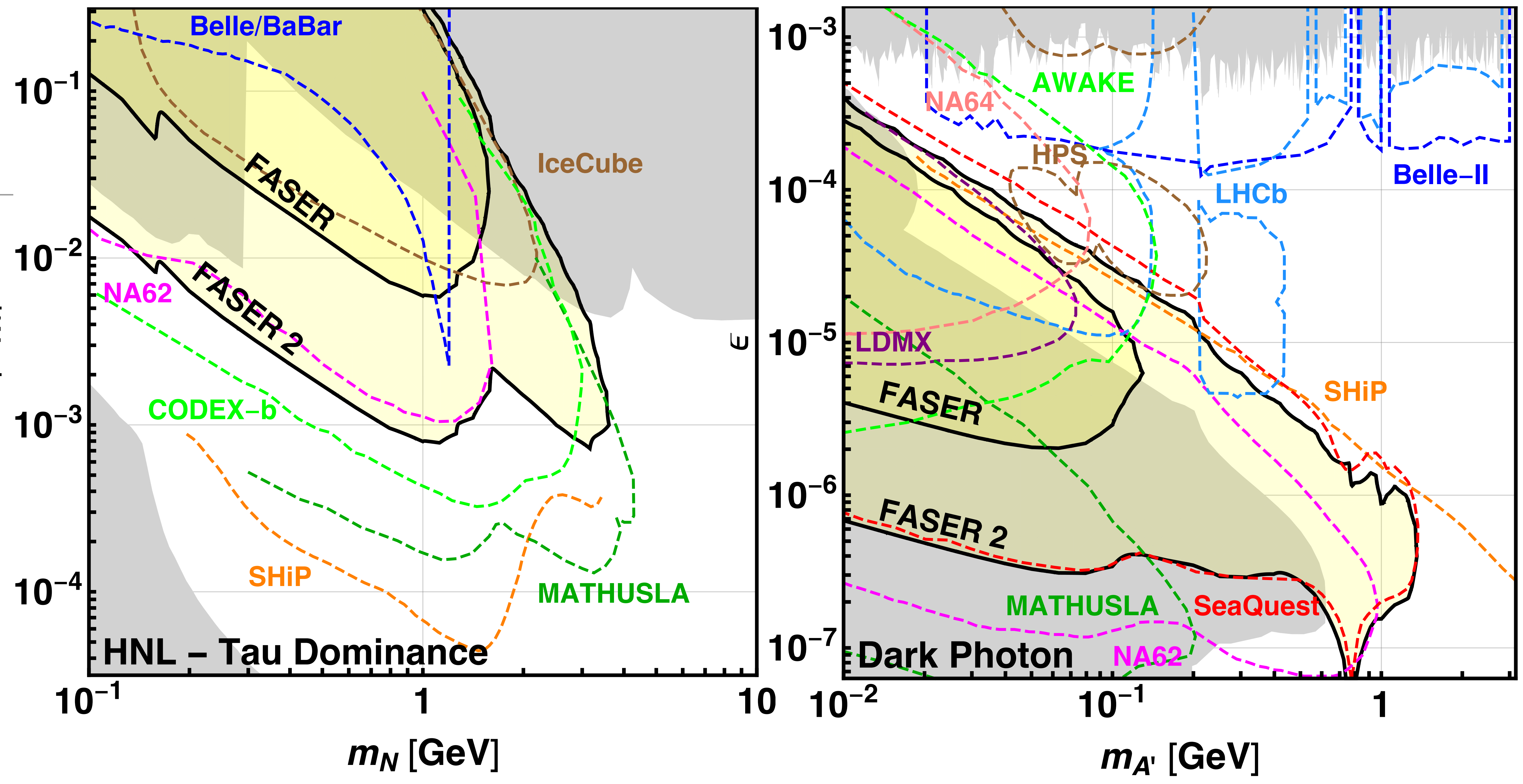
ASPEN2014 Theoretical summary - M. Mangan

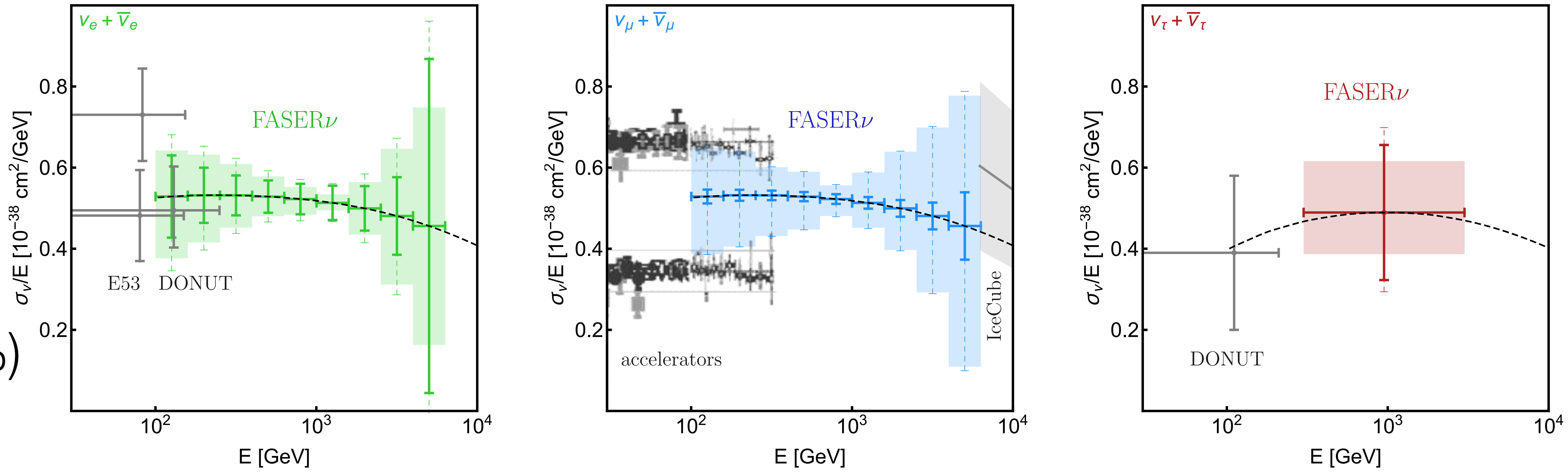


Ref

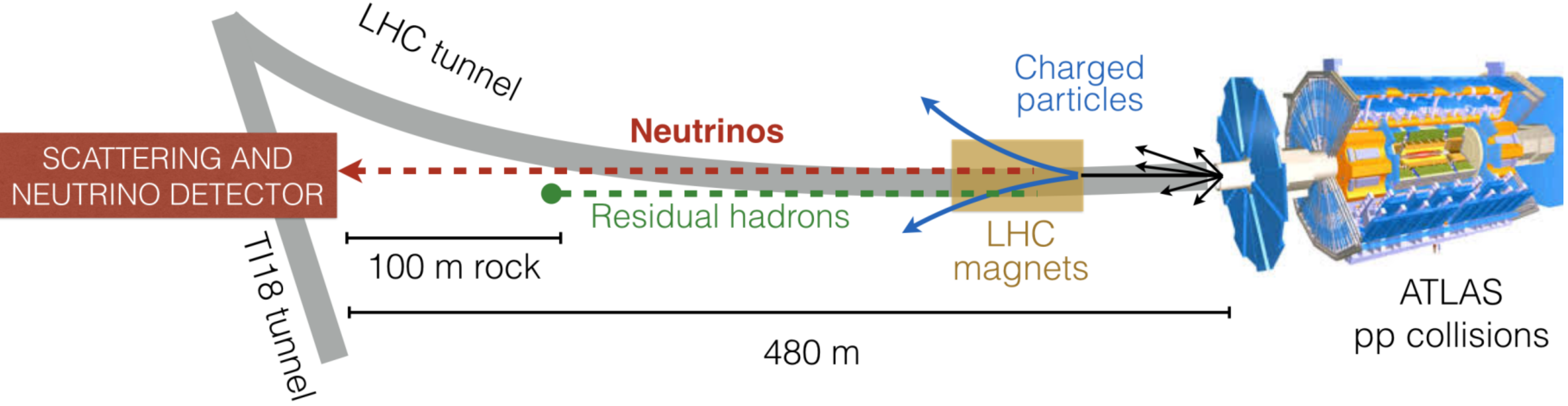
FASER

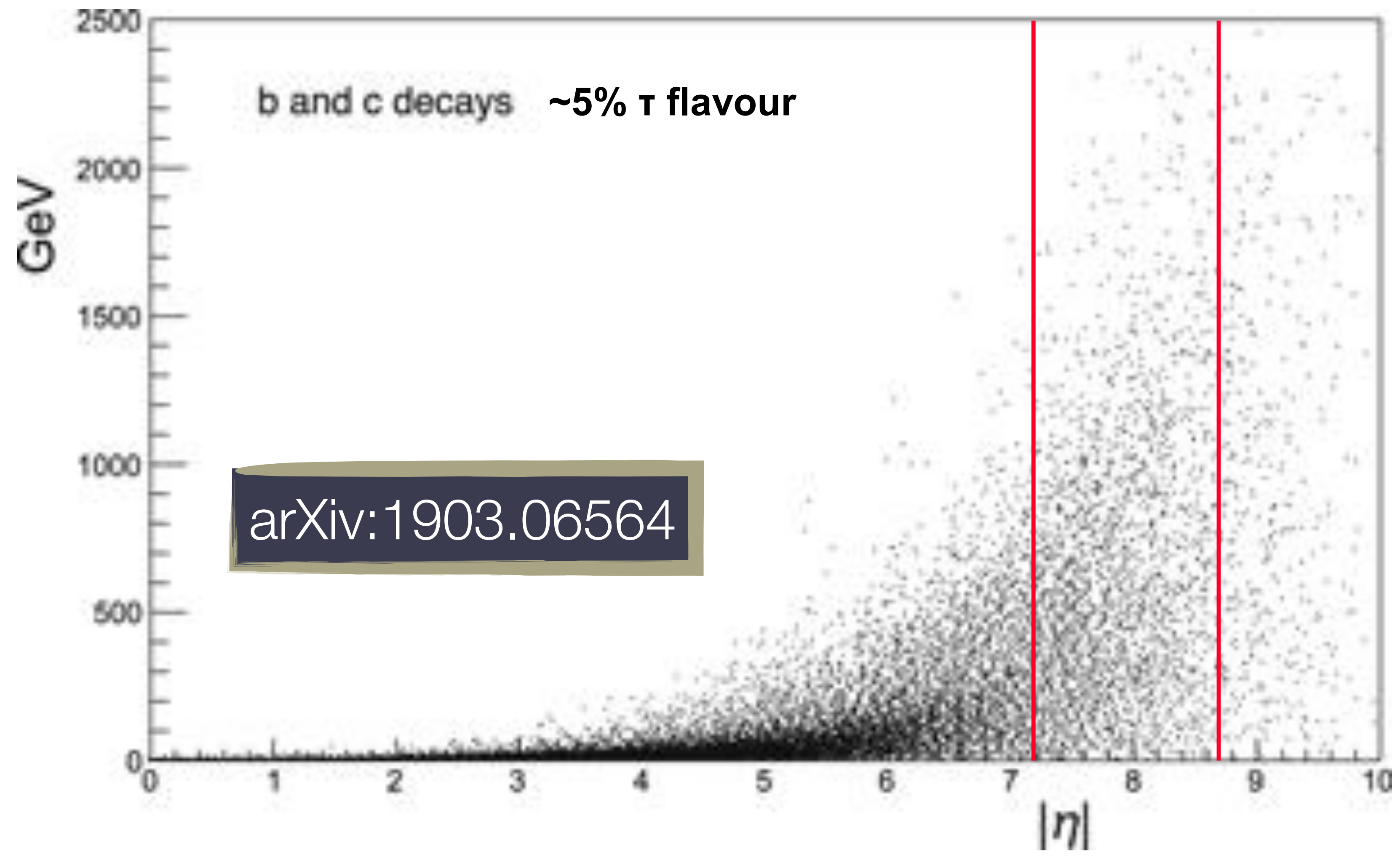
- **FASER:**
  - Benchmark physics process: Dark Photons A’
  - Produced via kinetic mixing from e.g. π^0 decays
  - Detected in decay to e^+e^- in FASER decay volume
  - Sensitive to other LLPs and decay modes as well
- **FASERν** (and InterFace Tracker):
  - Based on emulsion film therefore vertex detector with intrinsic resolution of ~ 50 nm
  - Track-finding efficiency (> 96 %)

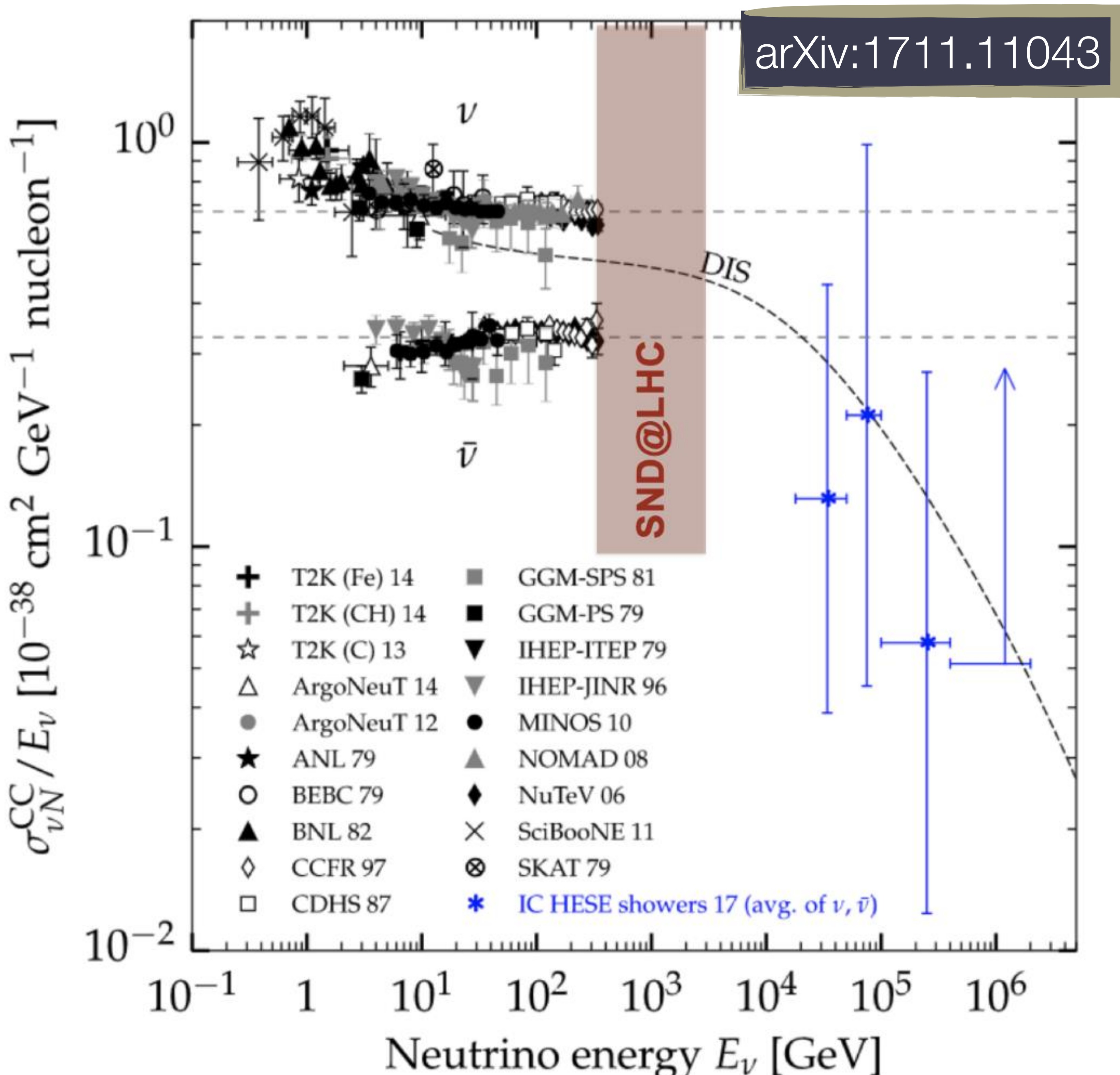




SND@LHC



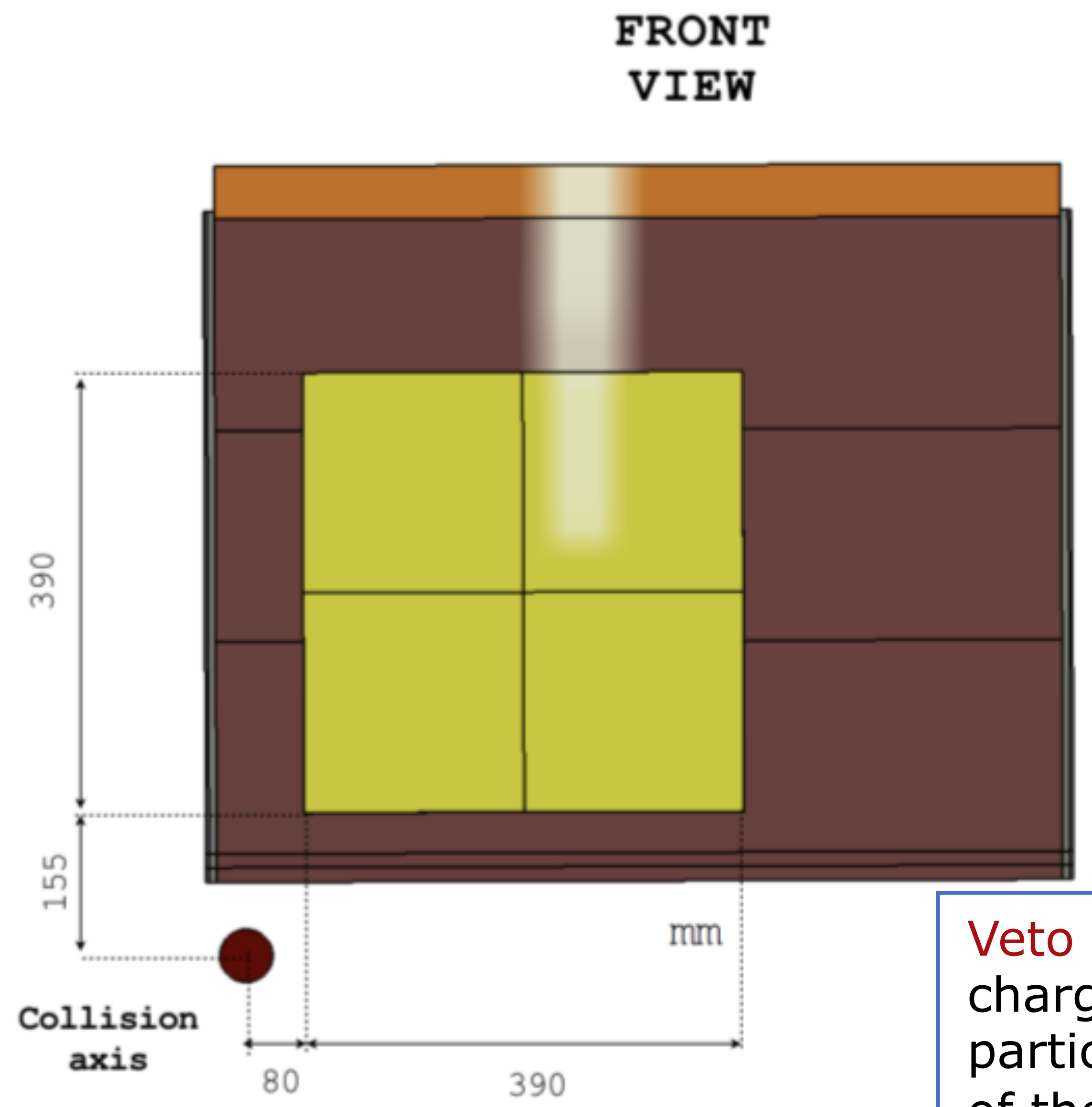




- Stand-alone experiment 480 m downstream of IP1 in TI18 to do measurements on neutrinos in the pseudorapidity region $7.2 < \eta < 8.7$
  - Large expected flux ν in forward direction
- Large brad and butter physics output; e.g.:
  - $\sigma_{pp\to\nu X}$
  - Measurement of the NC/CC ratio
  - **Direct search for feebly interacting particles through scattering**

SND@LHC

Slide taken from here



Off axis location
Angular acceptance:
7.2 < η < 8.7
Target material: Tungsten
Target mass: 830 kg
Surface: 390 x 390 mm²

Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ

Veto plane for charged particles in front of the target region

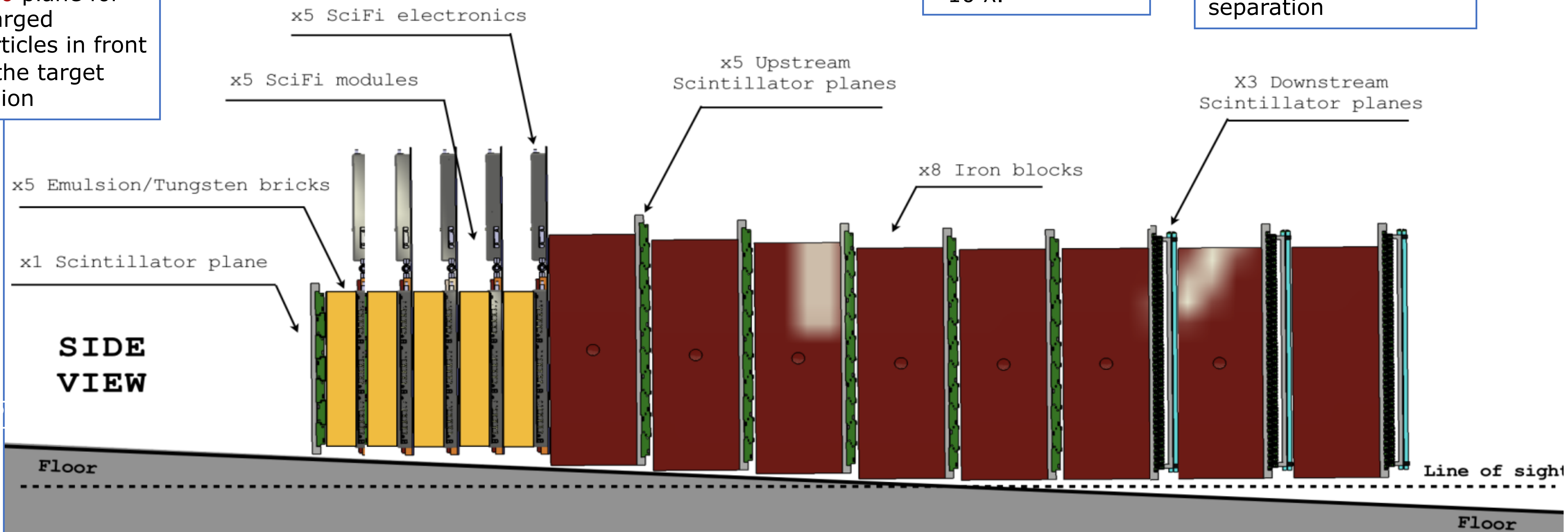
Emulsion Cloud Chamber, emulsion and W absorbers for micrometric accuracy in the detection of τ and FIPs, EM shower energy measurement.

SciFi with timing, provide time stamp to emulsion, records TOF information of events in the target region, track matching with ECCs. EM shower measurement as sampling calorimeter every ~10 X_0.

Muon system – hadronic calorimeter 8 λ, sampling every λ, with target region ~10 λ.

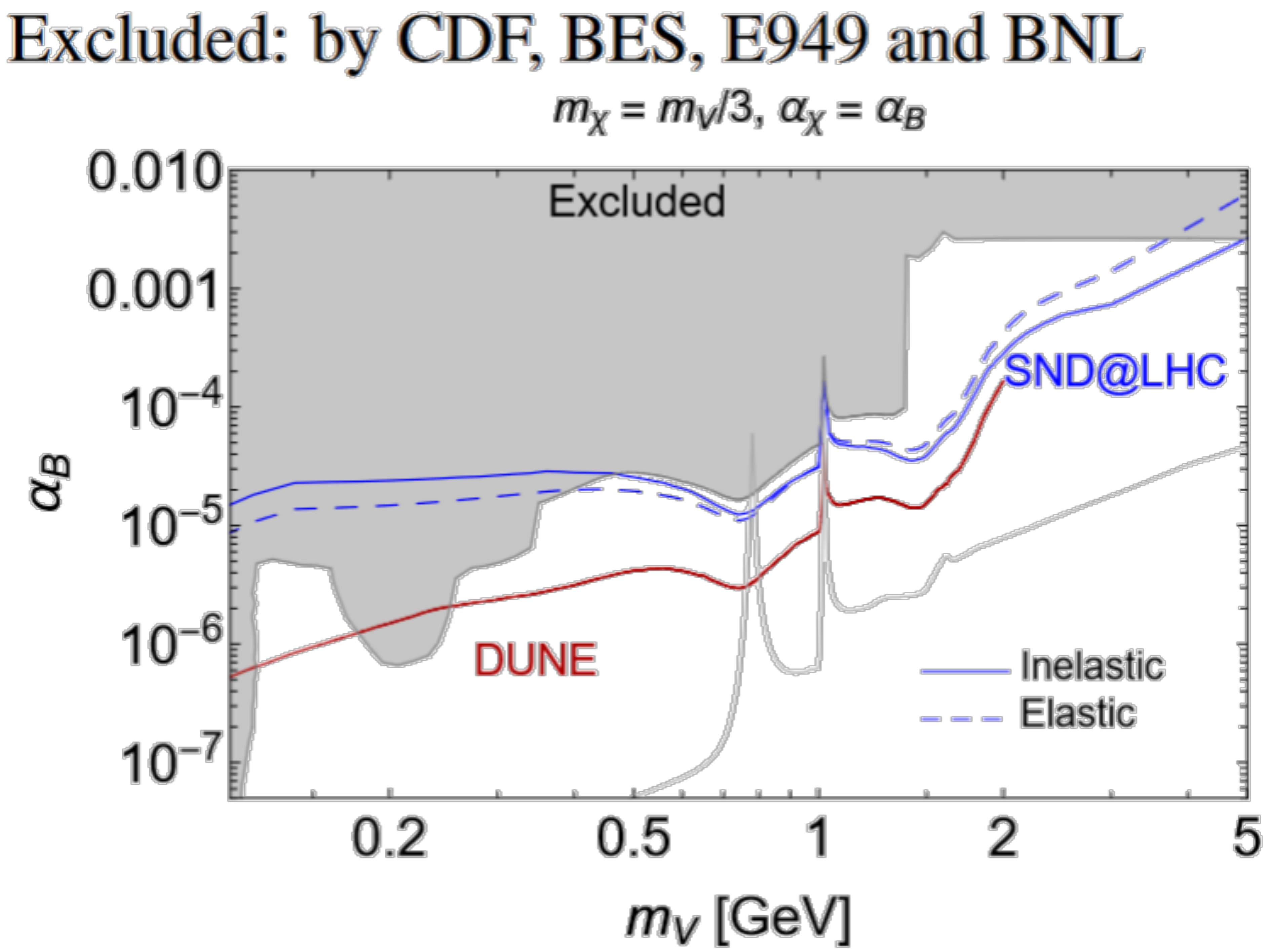
Timing upstream for the muon filtering

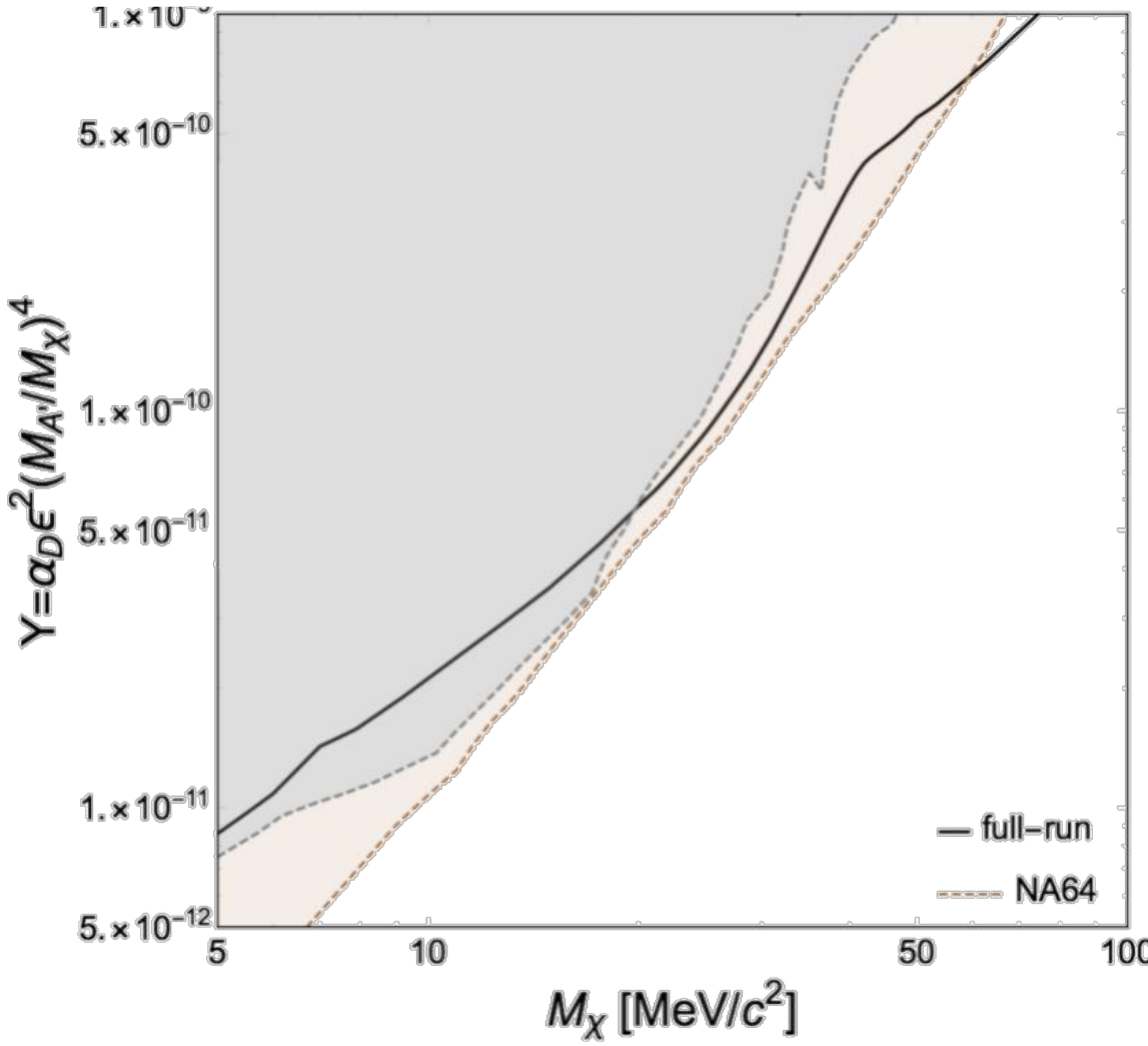
Timing downstream, double X-Y planes with higher granularity for muon-hadron separation



SND@LHC

- **Assuming 150/fb and 0 SM background**
- Some examples of LLP searches are:
- **Leptophobic portal**
  - V→χχ and elastic scattering χN→χN
  - Deep inelastic Scattering: background suppression exploiting kinematical features
- **Dark photons**
  - Search for Light **Dark Matter scattering off atomic electrons** A'→χχ with χe→χe in the target
  - DM scattering acquires and additional ε² in the yield
  - SND@LHC is an ε⁴ experiment
  - Assume a time resolution of ~200 ps, dominated by the bunch size

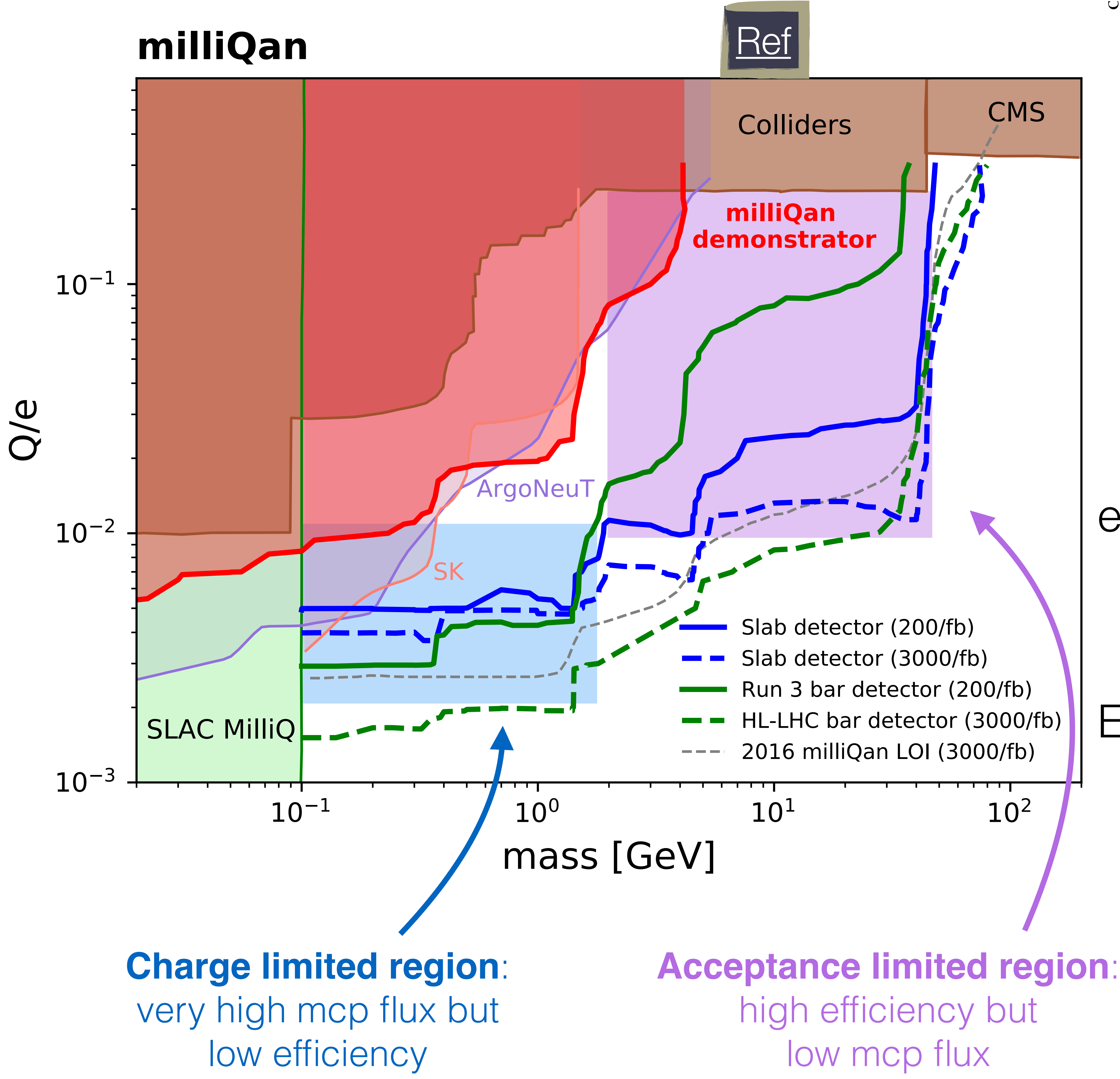


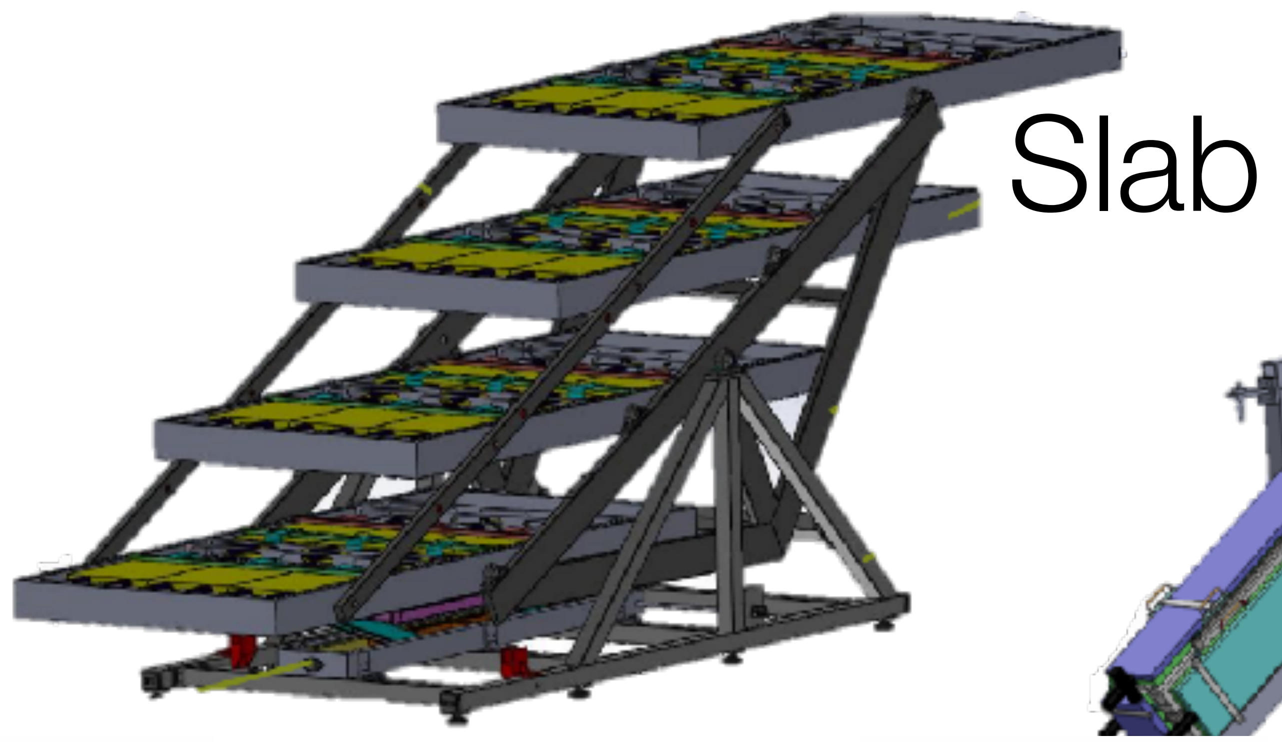


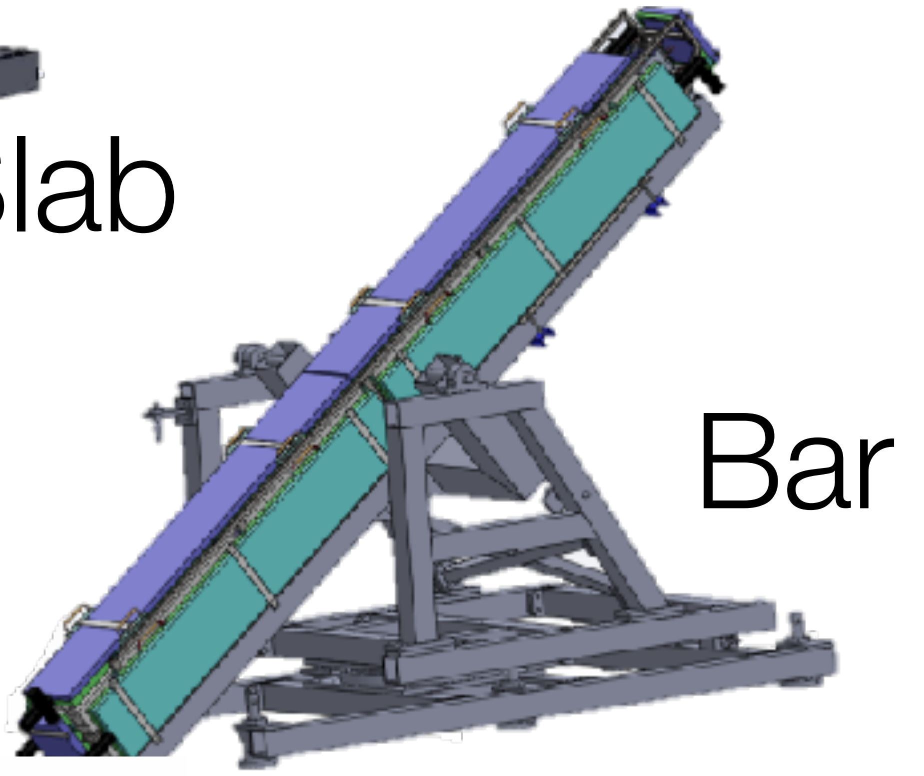
Ref

milliQan

- **milliQan** targets a gap for heavier (~ GeV) low charged particles not reachable by searches using effects on sun, stars and supernovae, cosmological bounds, etc…
- 33 m from CMS IP at an angle and 17 m of rock act as natural shielding against background coming from IP
- **Demonstrator run collecting ~35/fb, 2000h of data in 2018 (one of the few)**
- For Run 3 a bar and slab detector will be deployed
- **Bar detector** is a 4 layer, 4x4 scintillator bar
    - Essentially a larger version of demonstrator
    - Extra layer helps veto backgrounds
- **Slab detector** (new for Run 3) has 4 layers of 12 40 x 60 x 5 cm slabs
    - Dramatically improve acceptance for Q > ~0.01e



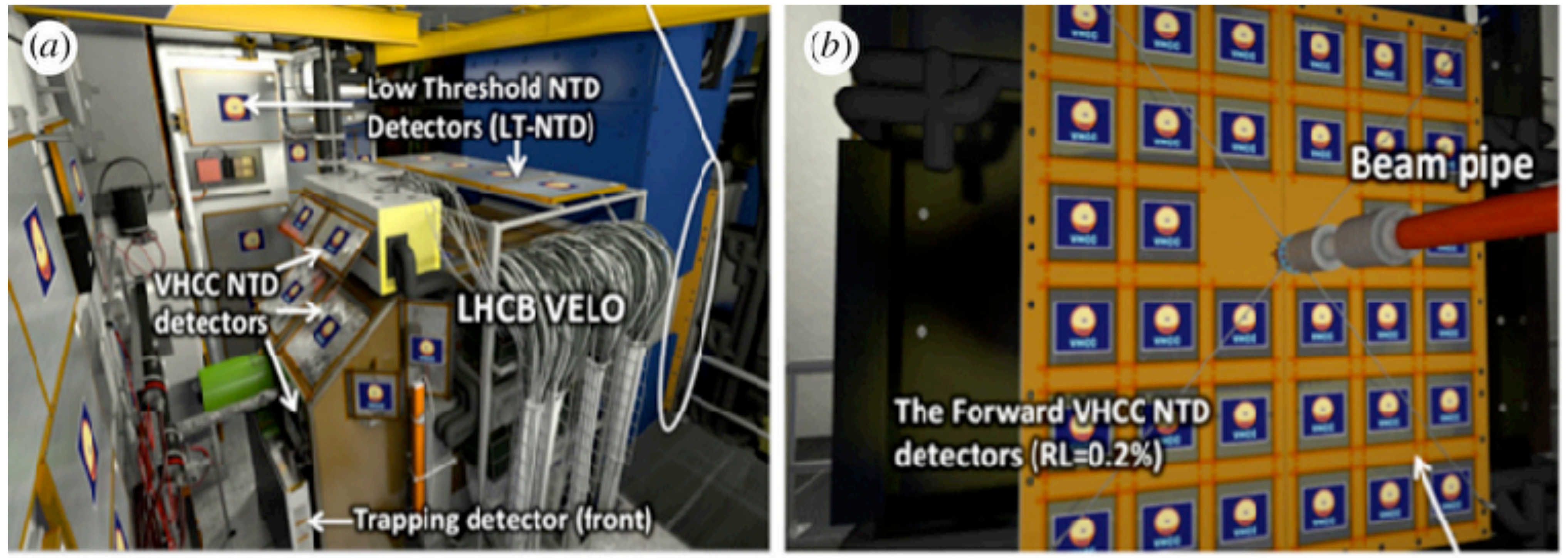


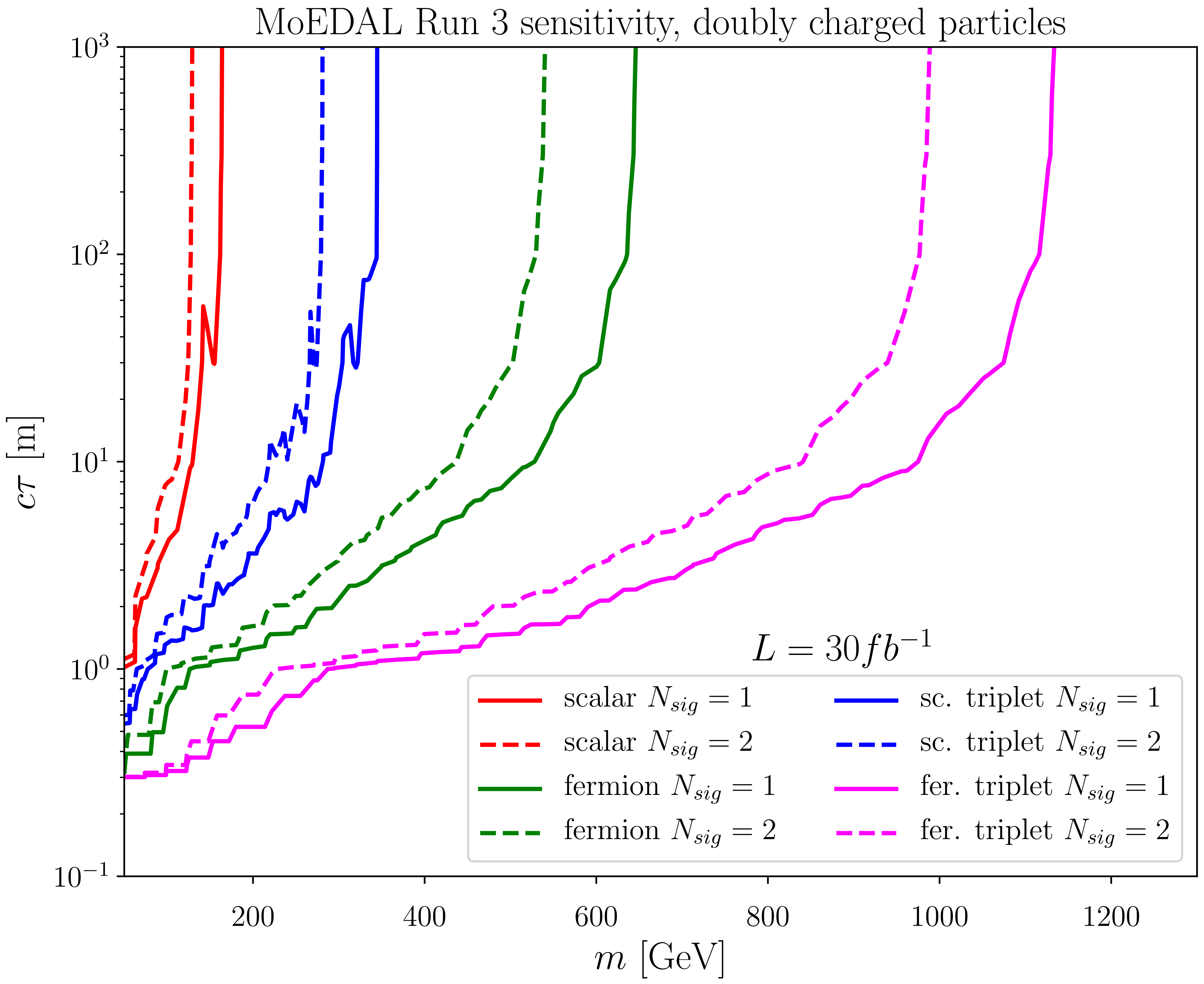


Ref

MoEDAL

- So far MoEDAL has placed the world's best direct limits on: Multiply charged magnetic monopoles, spin-1 monopoles, Schwinger's Dyon, etc…
- **Also sensitivity to Long-lived Massive Singly & Double Charged Particles**
  - **Enhanced by the installation of MAPP (MoEDAL apparatus for penetrating particles)**
  - **Planned for deployment during LHC's Run 3**
  - **Lifetimes longer than 10 years can be probed**
- MoEDAL can cover the lifetime region with ct ≥ 100 m
- Expected sensitivities for four types of doubly-charged particles, assuming a Run 3 integrated luminosity of 30/fb: a scalar singlet (red), a scalar triplet (blue), a fermion singlet (green) a fermion triplet (magenta)





The QEE PAWG

- **QEE (EW, QCD, Higgs) PAWG at LHCb:**
- Responsible for strategy, scientific oversight for all such measurements at LHCb
- **6 published papers** in the last year alone, a **further 6 papers** are in the final stages of the review process
- The initial idea of looking for LLPs with LHCb turned in a plethora of new results

- ***Displaced leptons (hard to beat us)***
  - **Dark photon**
  - Low-mass di-muon resonances
  - **Majorana neutrino**
  - LLPs decaying to eμν
- ***Displaced jets (hard to beat CMS)***
  - Majorana neutrino from Ws
  - LLPs to jet jet
  - **LLPs to μ+jets**

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Low-mass dimuon resonances

- 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