EW Physics and LLPs with LHCb

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Les Rencontres de Physique de la Vallée d'Aoste

March 2024

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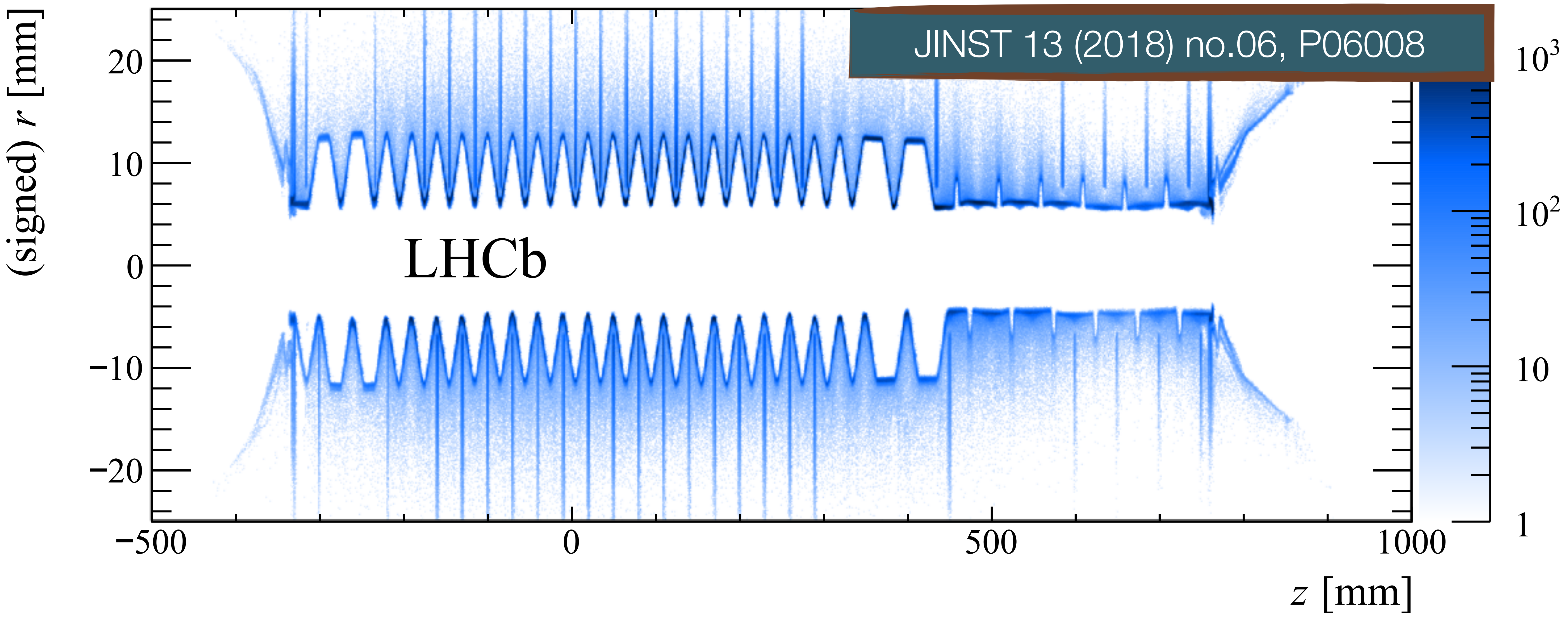
ADIACENZE APS

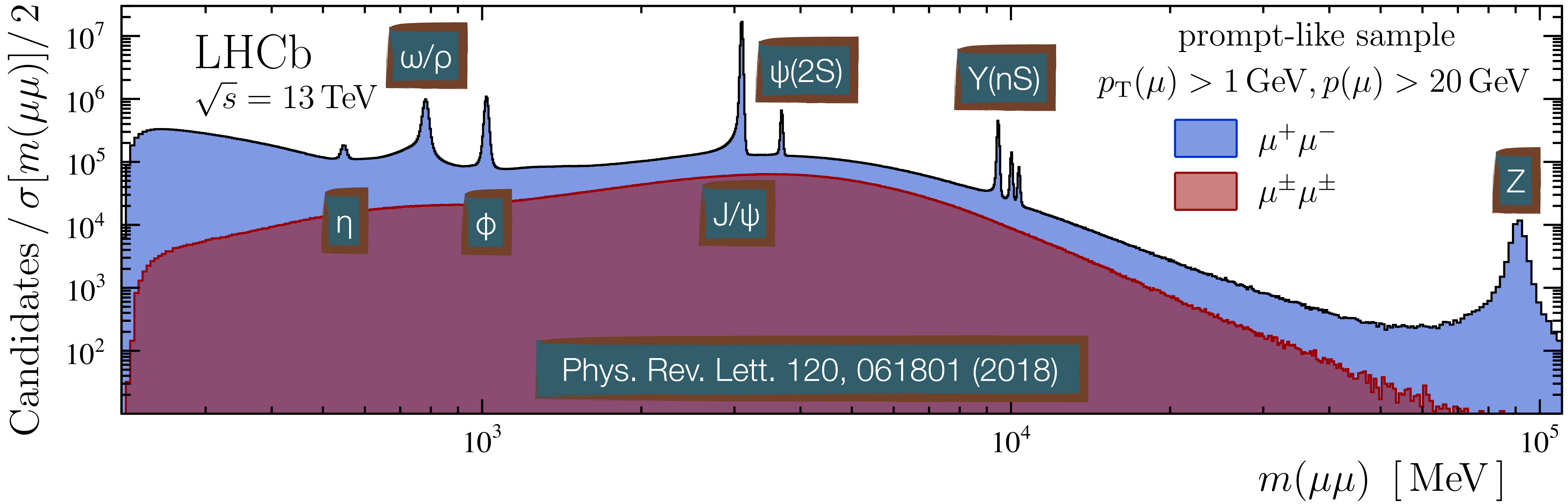
- **Intro**
- LLPs
- EW

Il segreto di Majorana. Riccioni & Rocchi

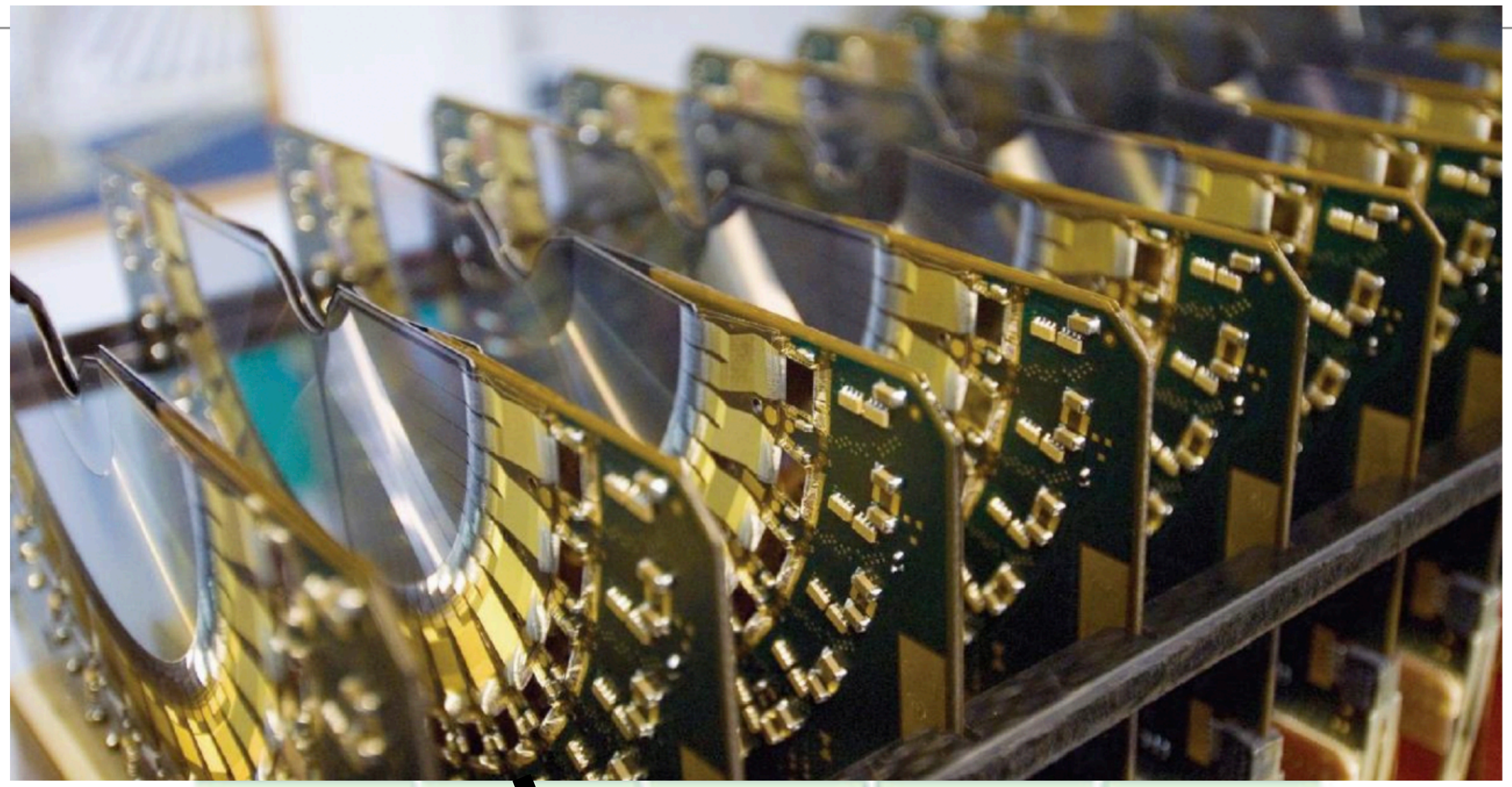
LHCb detector in Run 1&2

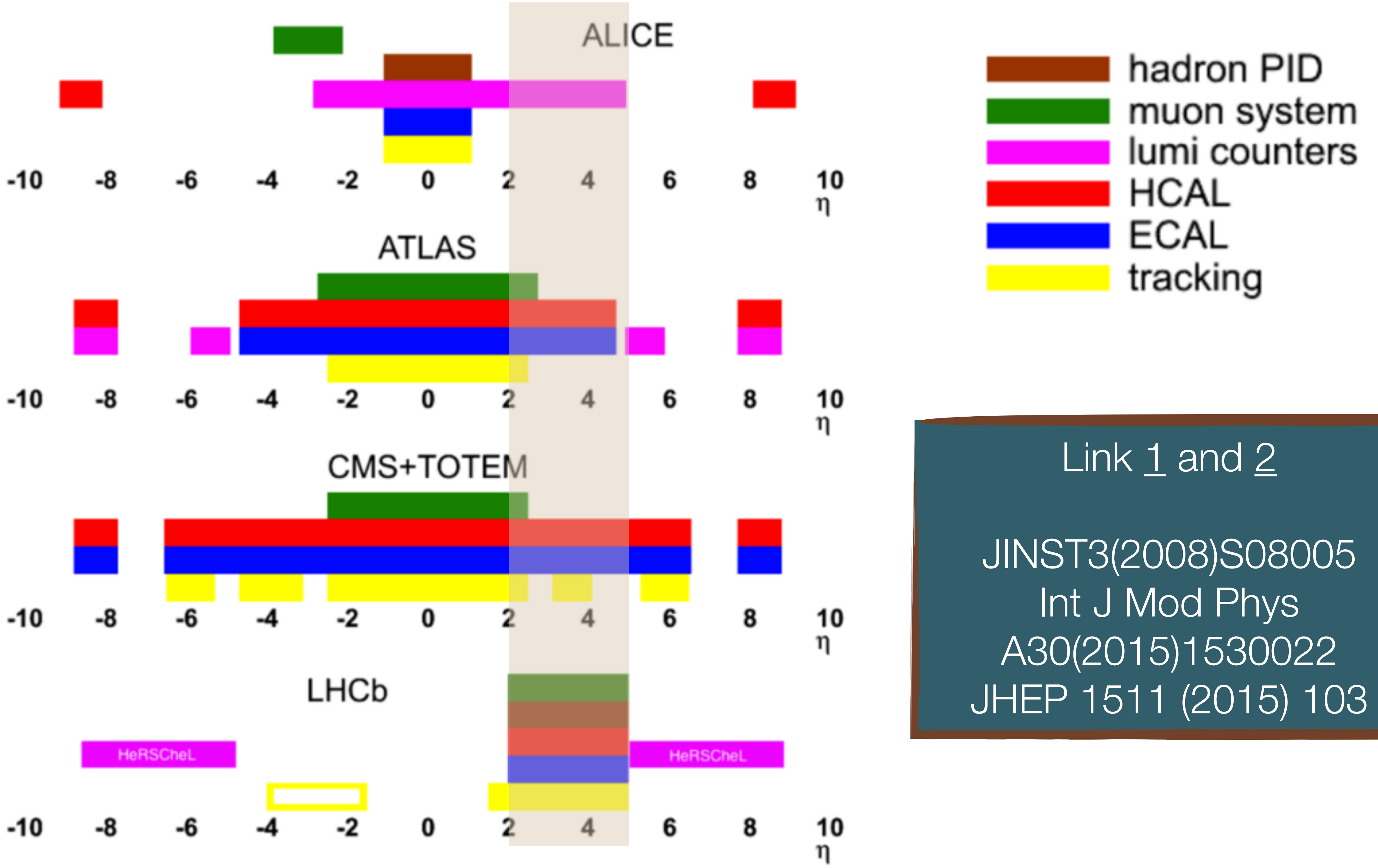
- Precise knowledge of the location of the material in the LHCb VELO is essential to reduce the background in searches for long-lived exotic particles
- LHCb data calibration process can align active sensor elements and one can develop a full map the VELO material
- **Real-time calibration** in Run 2 (Turbo Stream)
- Very efficient online reconstruction e.g. in di-muon final states (50 years of SM!)





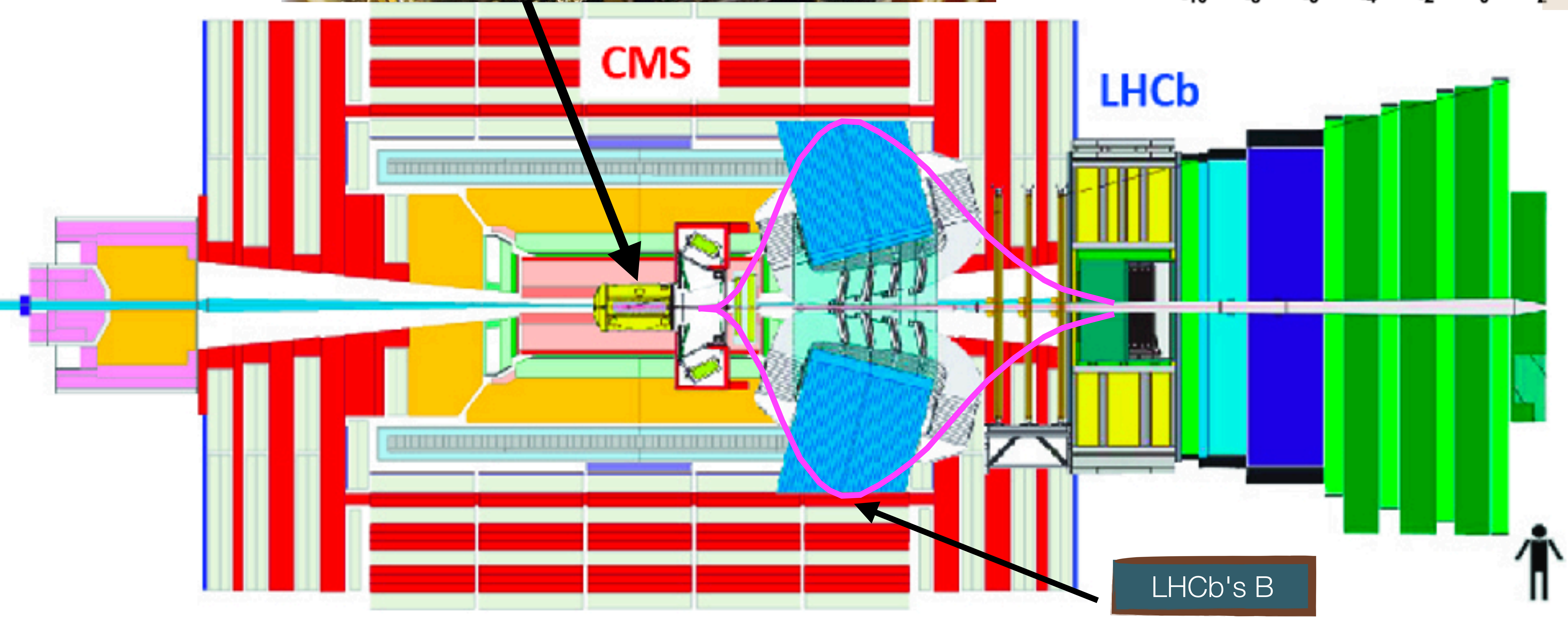
LHCb / CMS so much different?



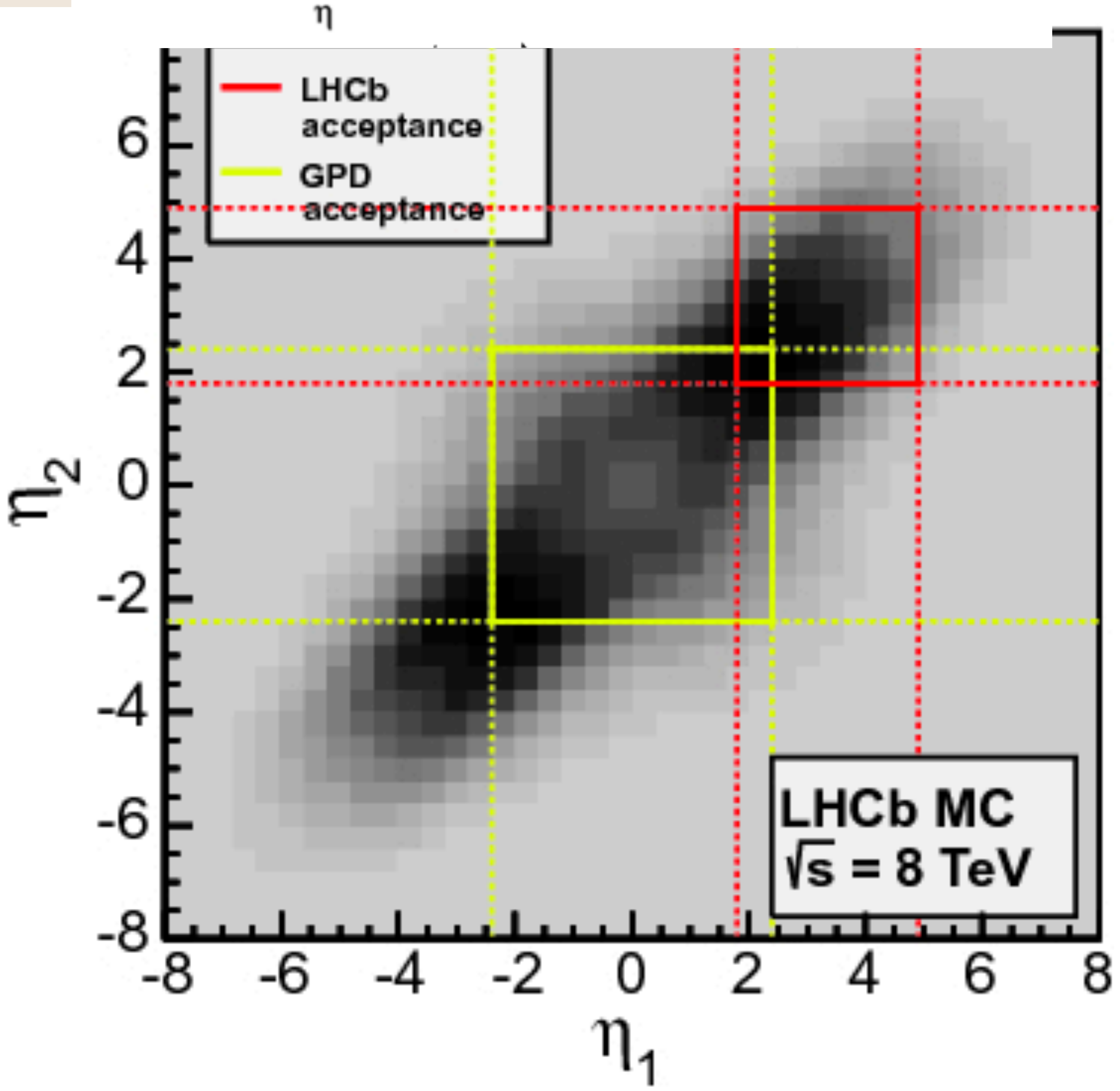


Link 1 and 2

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

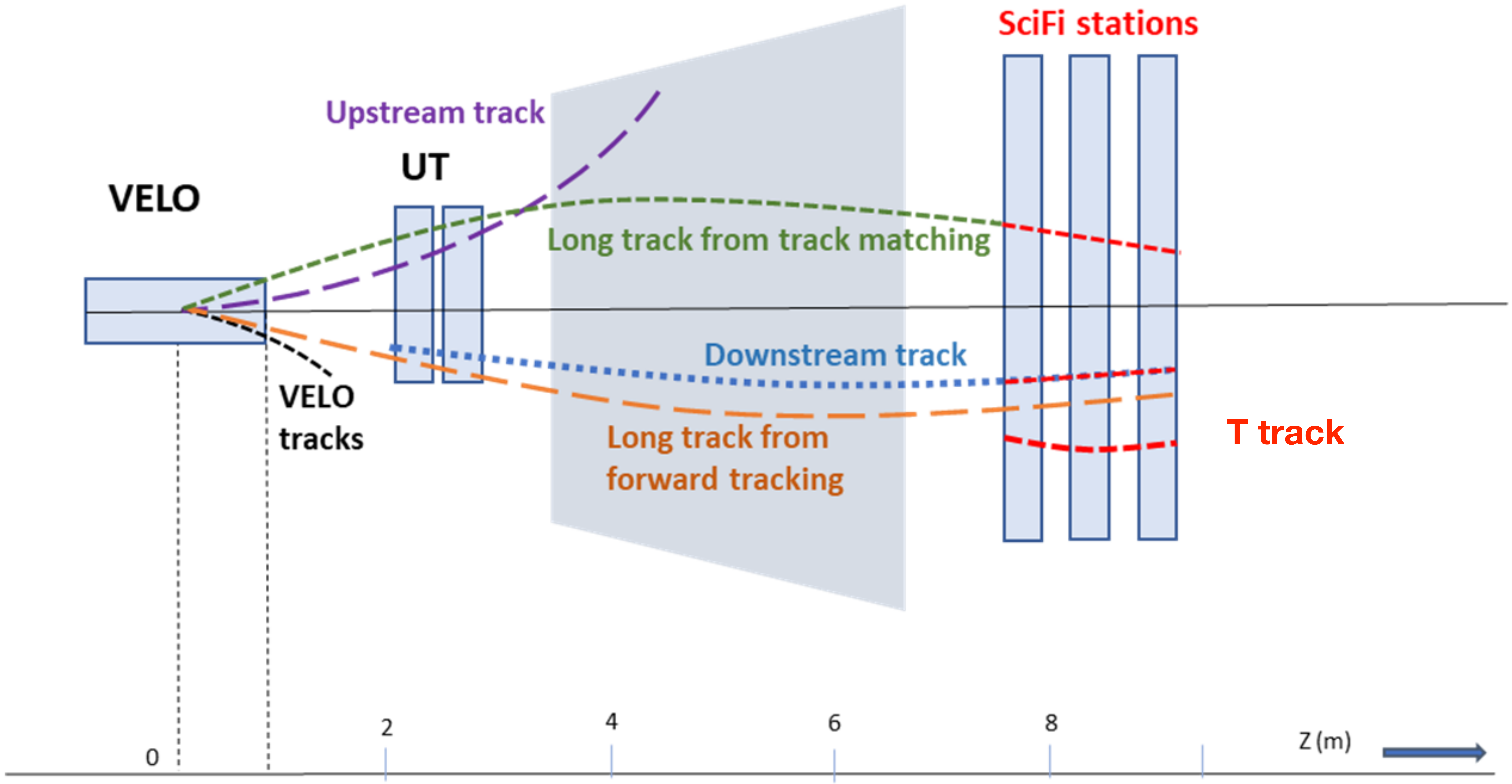


LHCb's B



LHCb’s track types

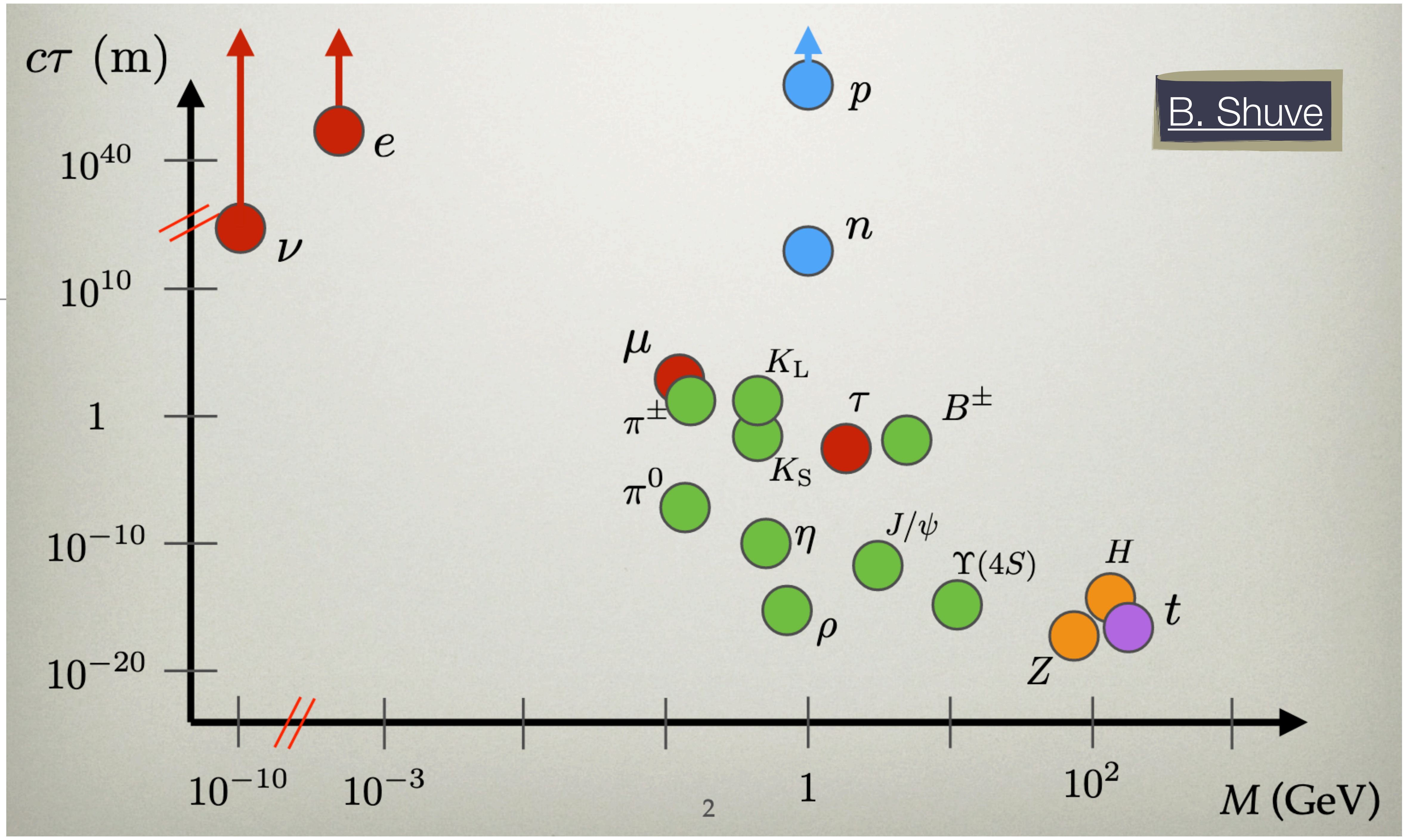
J. Brij - Standalone track reconstruction and matching algorithms for GPU-based High level trigger at LHCb



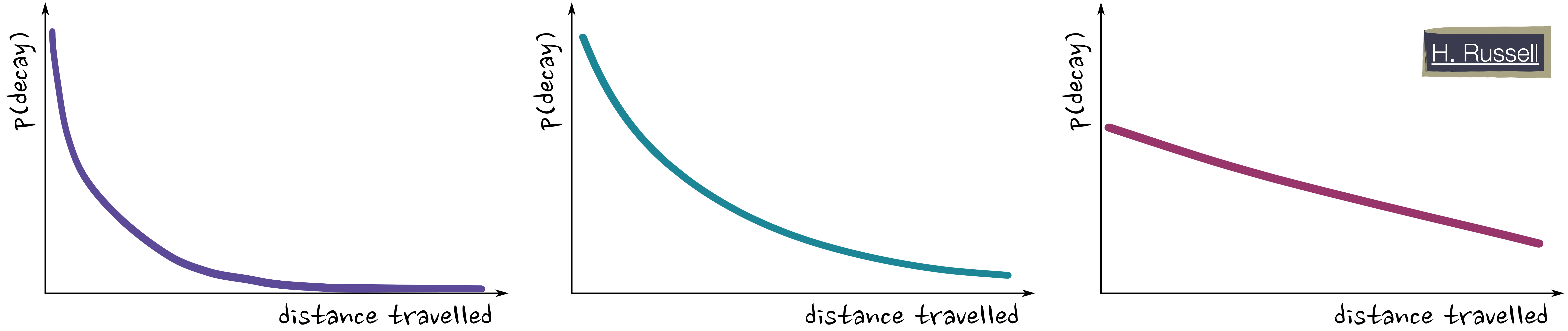
- Intro
- **LLPs**
- EW

Il segreto di Majorana. Riccioni & Rocchi

Who is long lived?



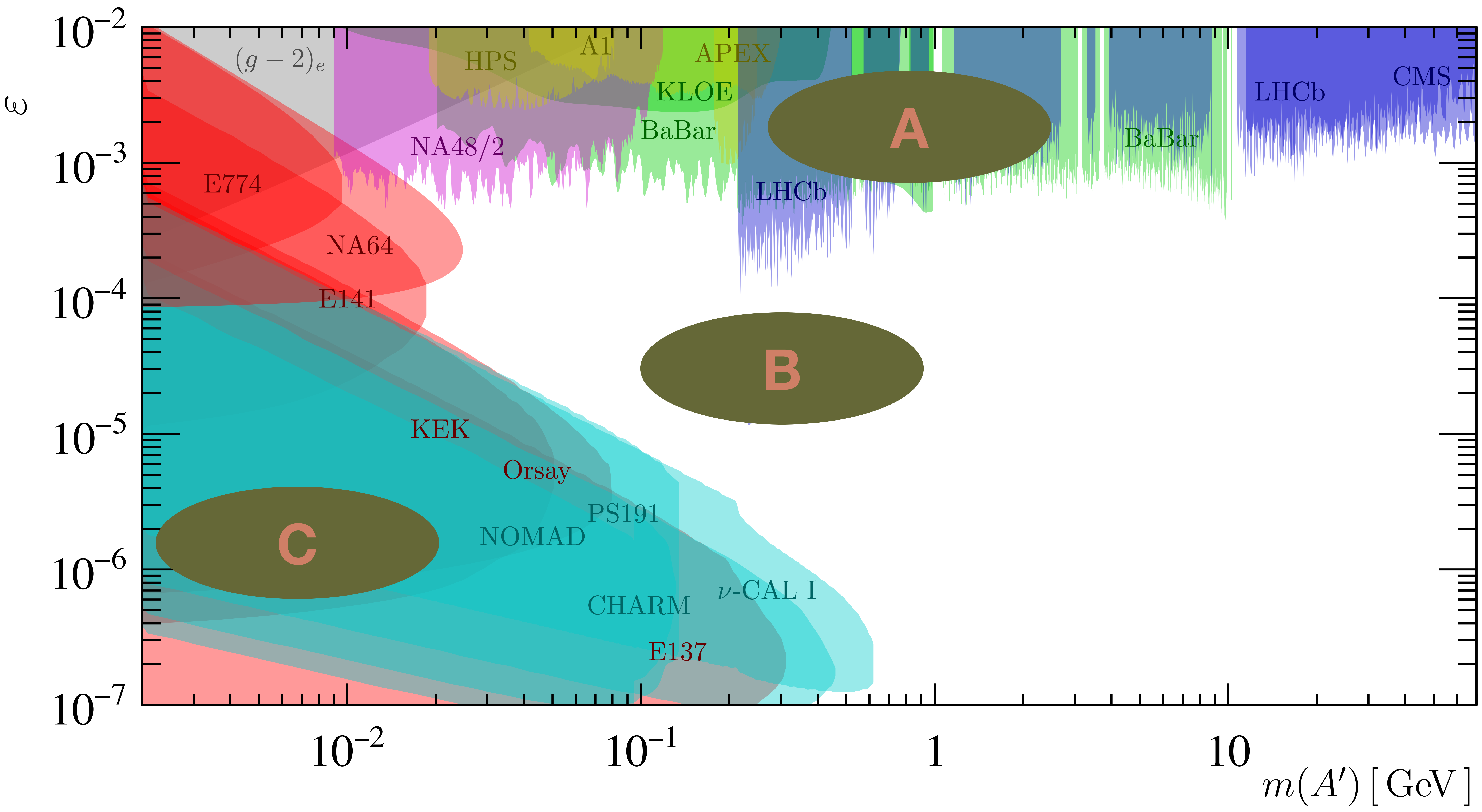
- **What is a long-lived particle?**
  - As an experimentalist: it's a particle that decays in a reconstructable distance from the production point (e.g. pp interaction point at the LHC)
  - **De-facto used for BSM particles**
  - **Lifetime is sampled from an exp, there is an additional parameter**



Visible dark photons

2104.10280

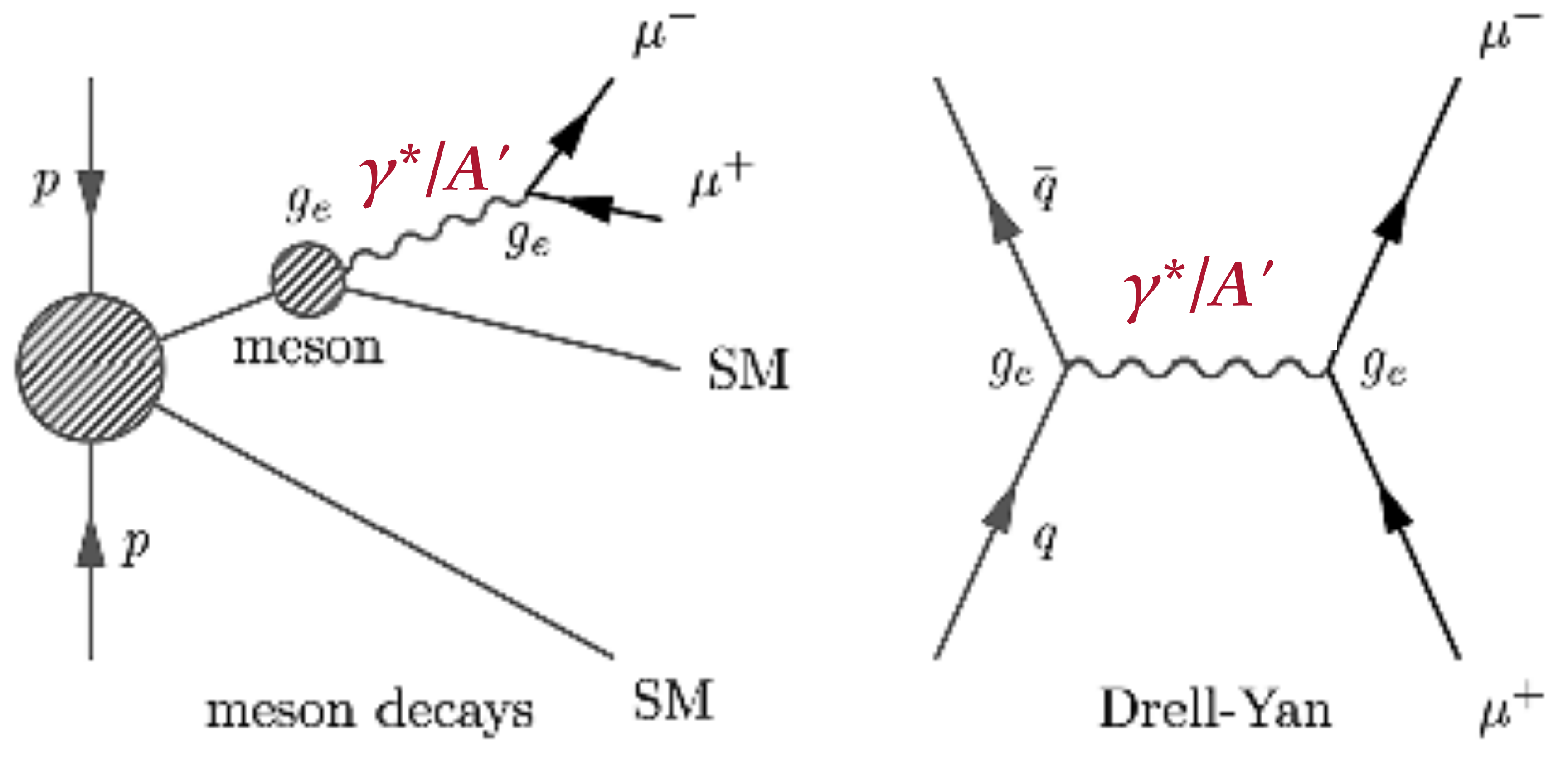
- **A**: Bump hunts, visible or invisible
- **B**: Displaced vertex searches, short decay lengths
- **C**: Displaced vertex searches, long decay lengths



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
- Prompt-like search (up to 70 GeV/c²)
- Displaced search (214-350 MeV/c²)



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

off-shell photon

phase-space

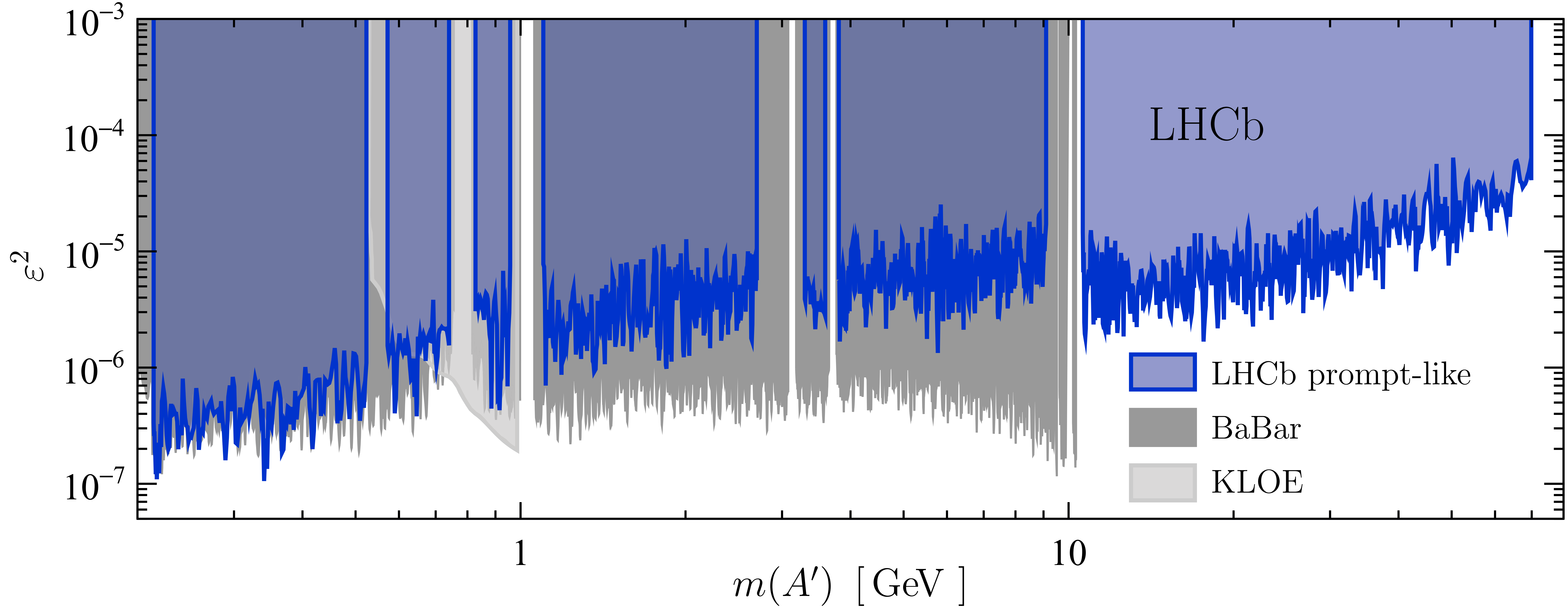
A′/γ^* eff ratio, ϵ=1 for prompt

Need to separate from background

Search for Dark Photons / Prompt

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

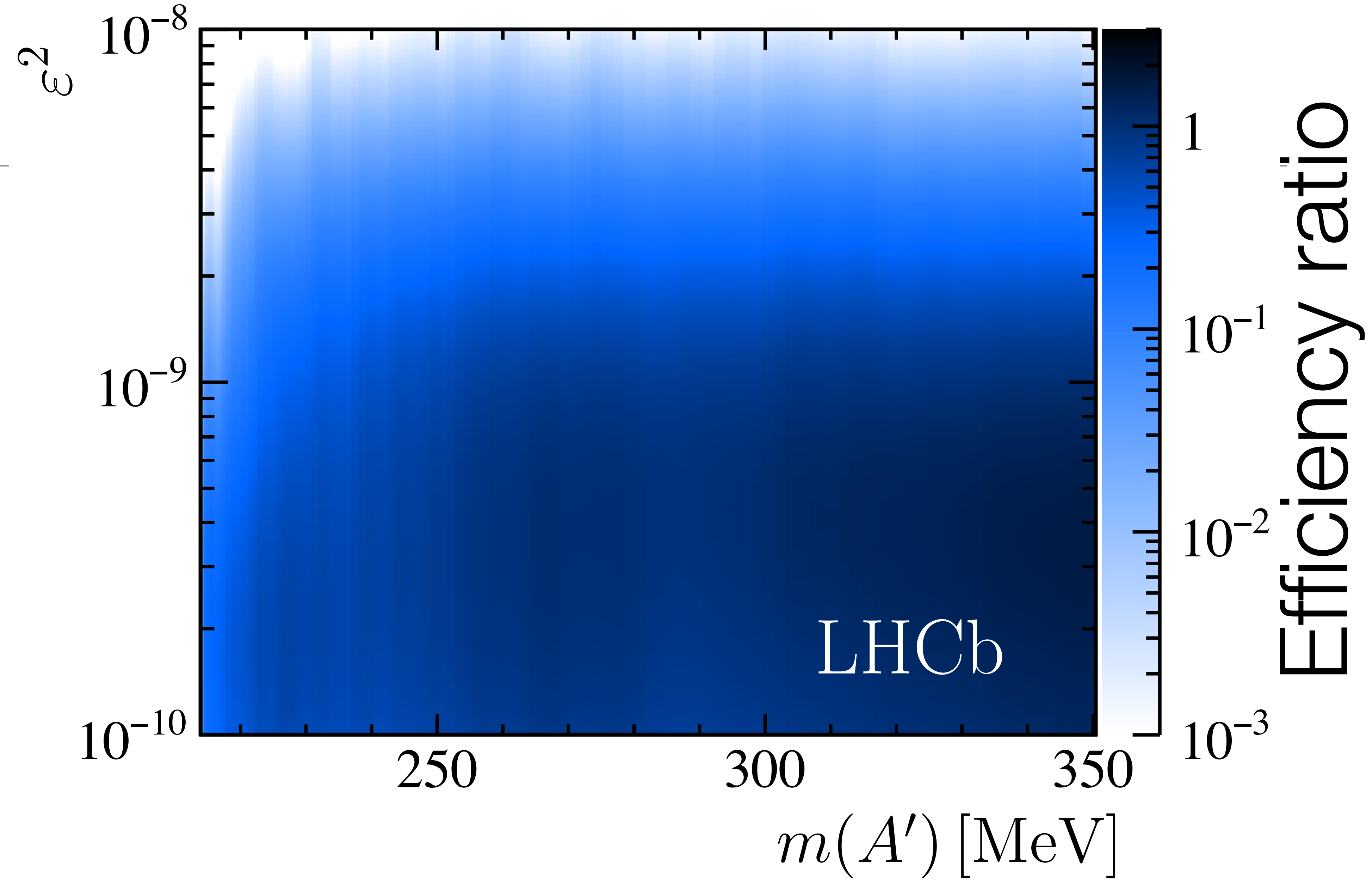
- No significant excess found - exclusion regions at 90% C.L.
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV

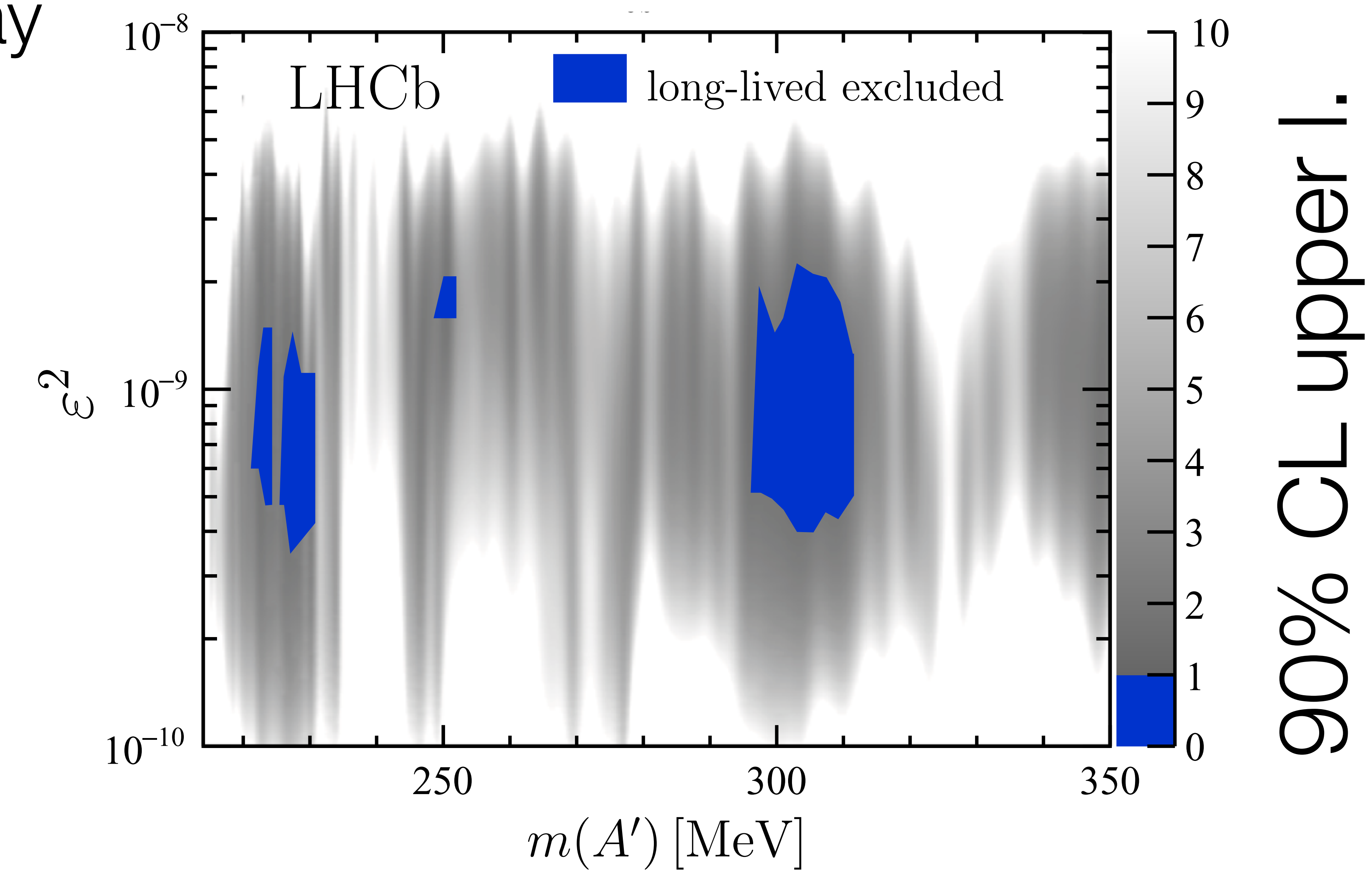


Phys. Rev. Lett. 120, 061801 (2018)

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 in a displaced region**





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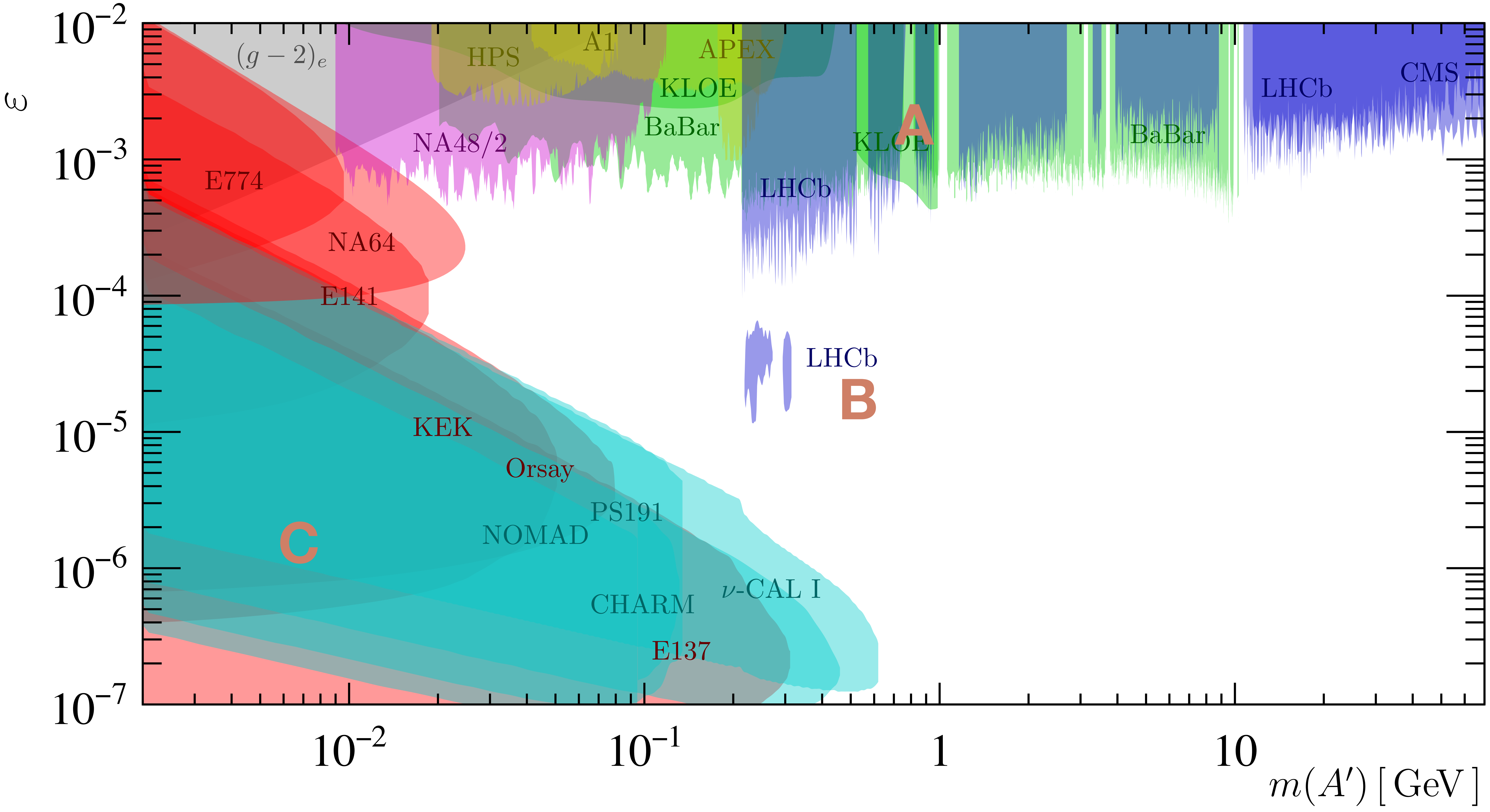


Taken from one of Martino's talks

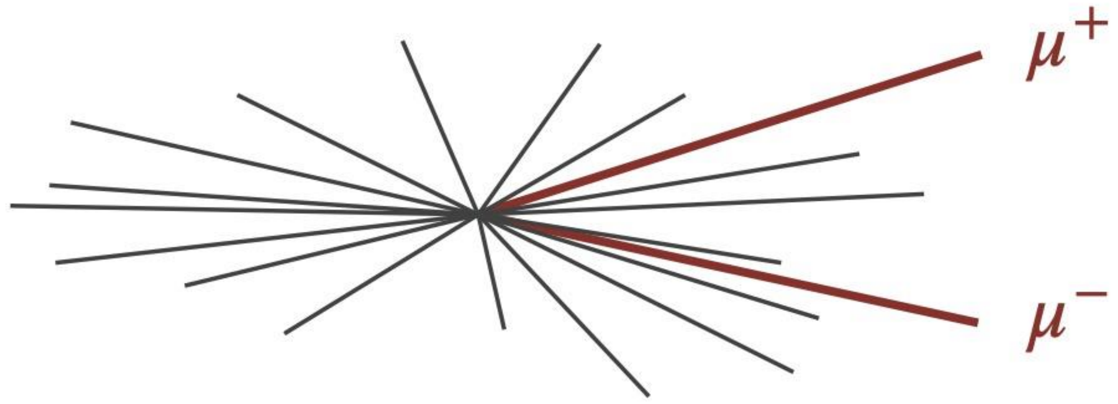
JHEP 10 (2020) 156

Low-mass dimuon resonances

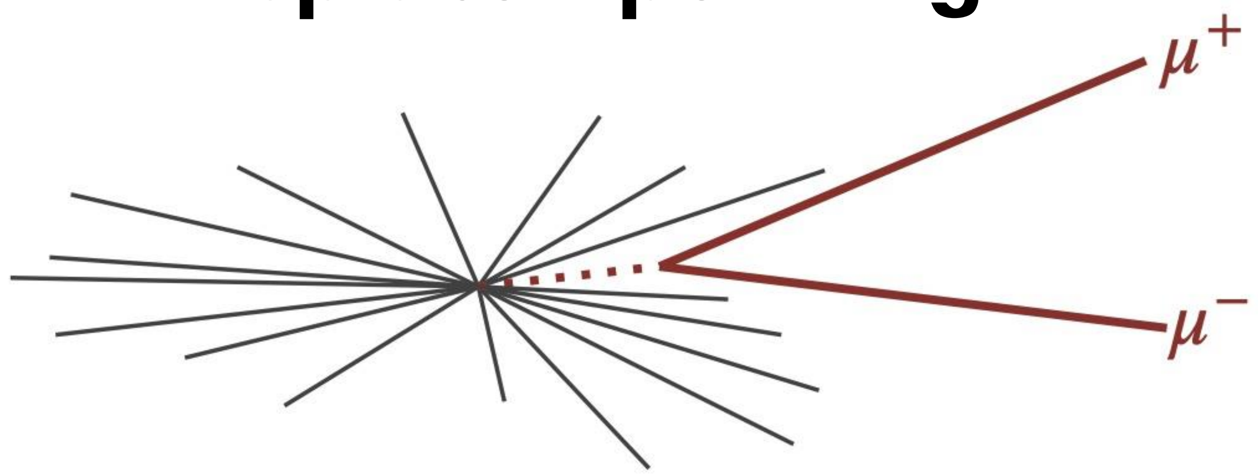
- ❑ Non-minimal searches, example signatures:

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

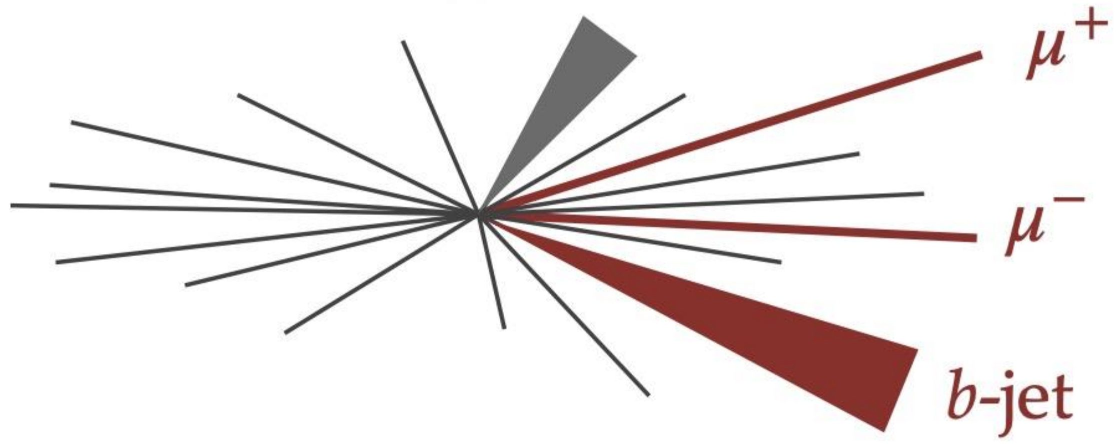


Displaced pointing

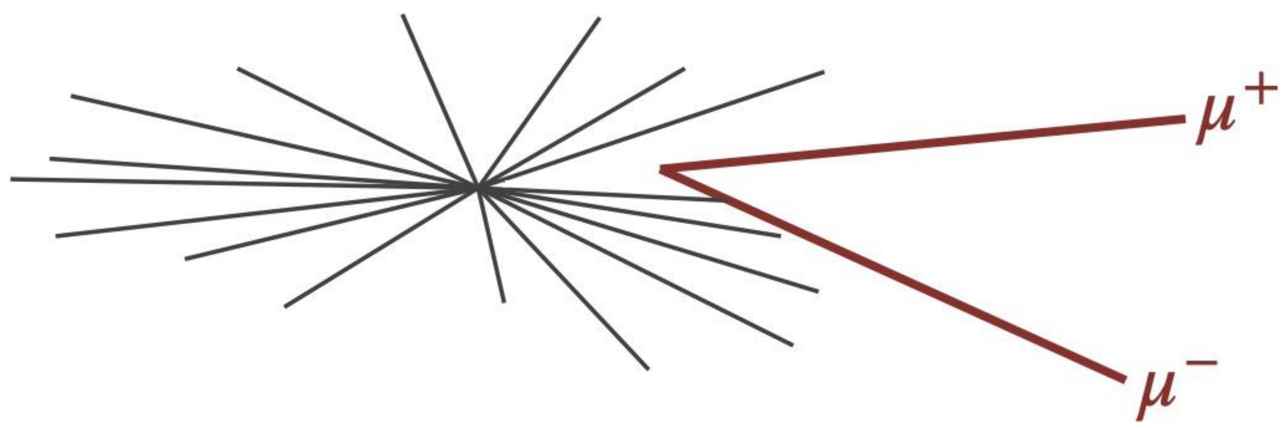


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing

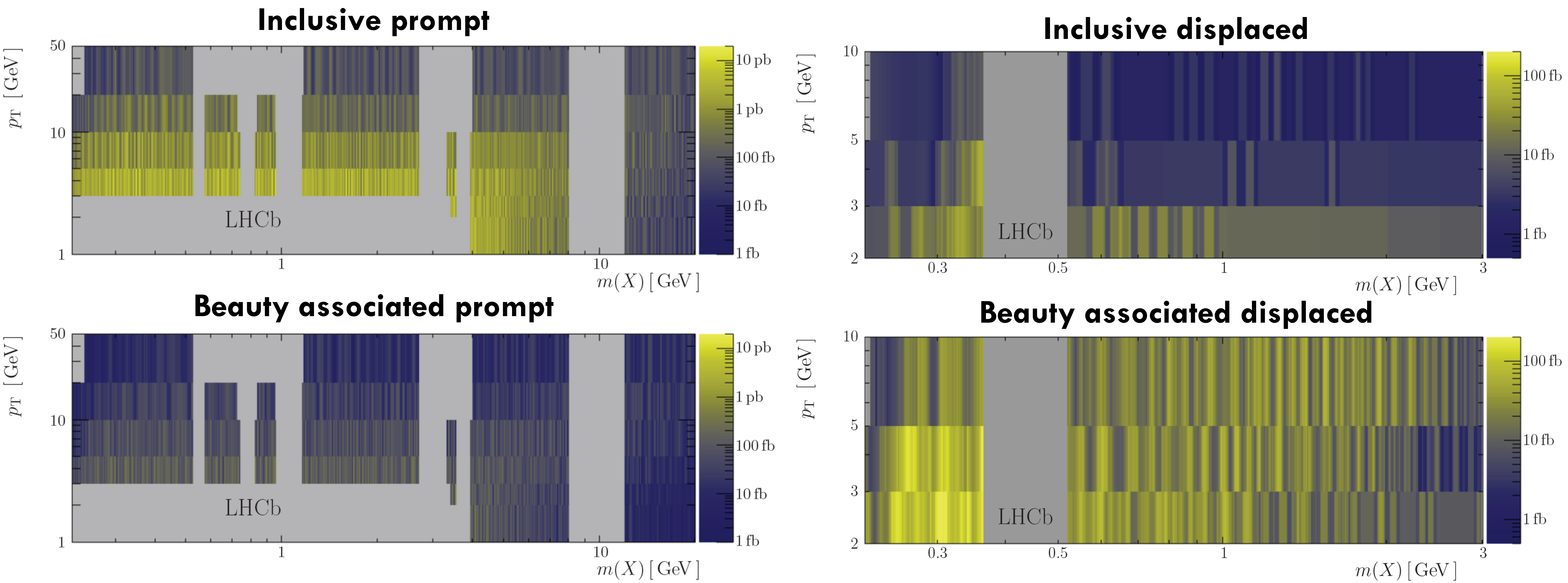


[Taken from I. Kostiuk's talk](#)

[JHEP 10 (2020) 156](#)

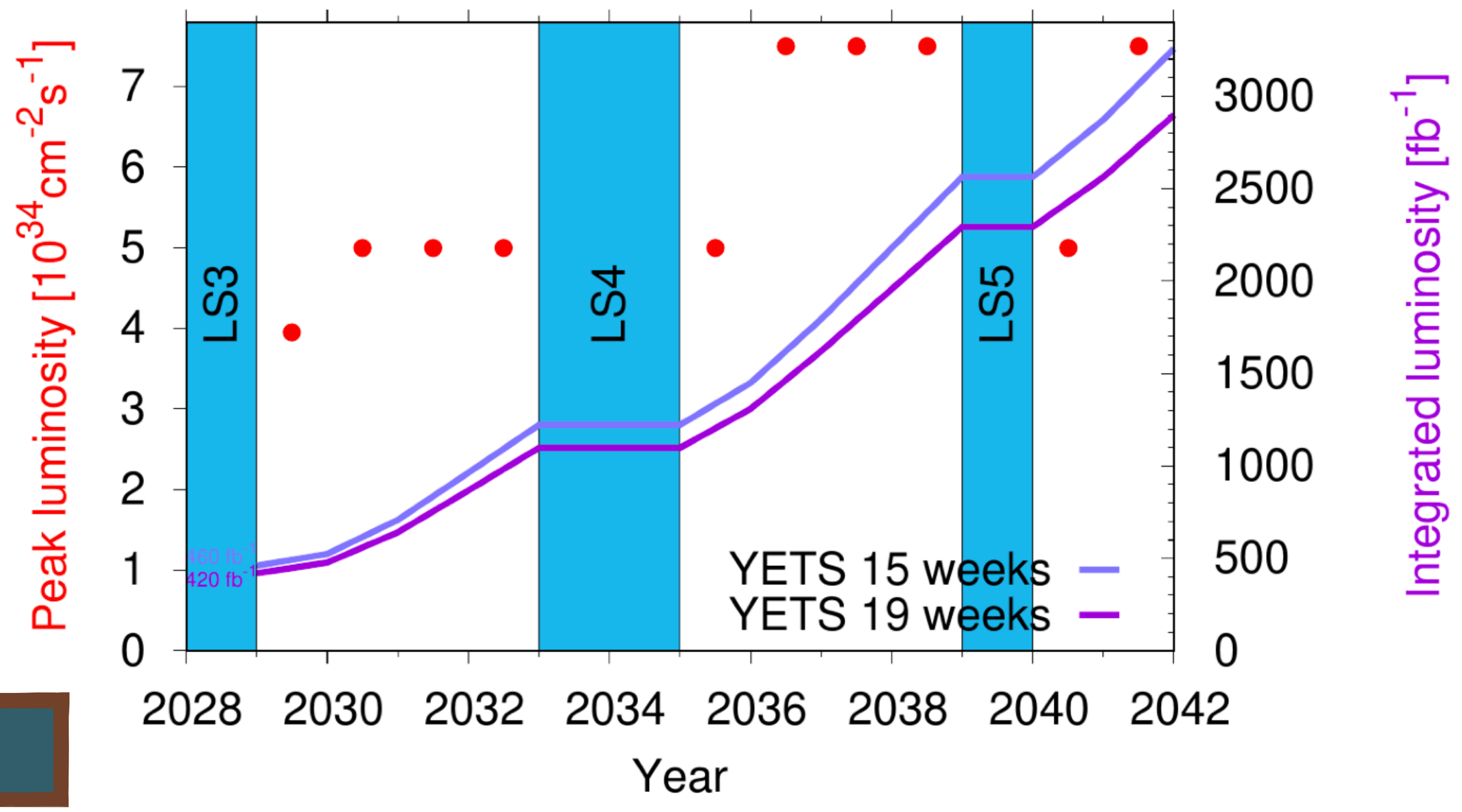
Low-mass dimuon resonances

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

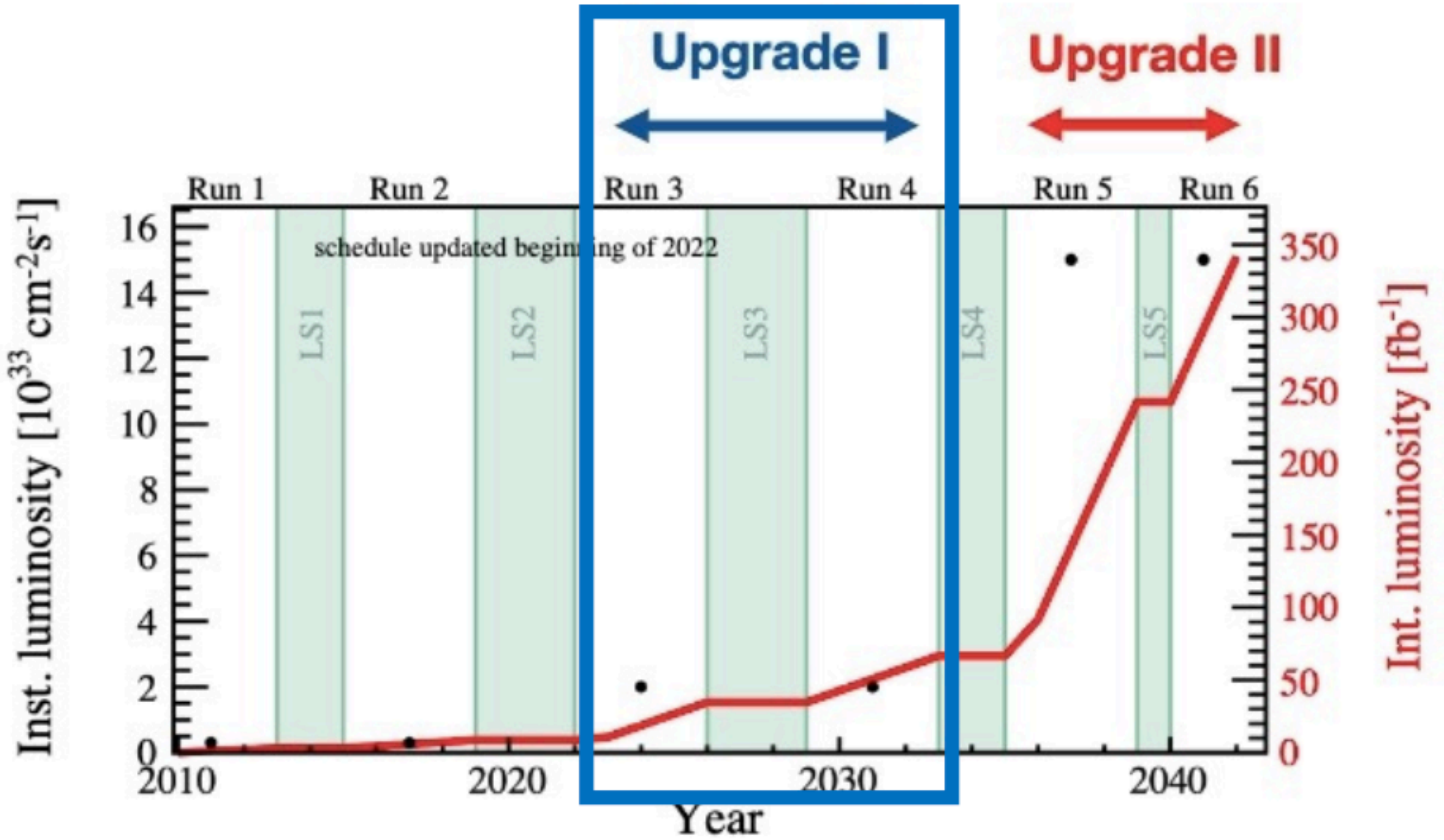


LHCb Timeline

- 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



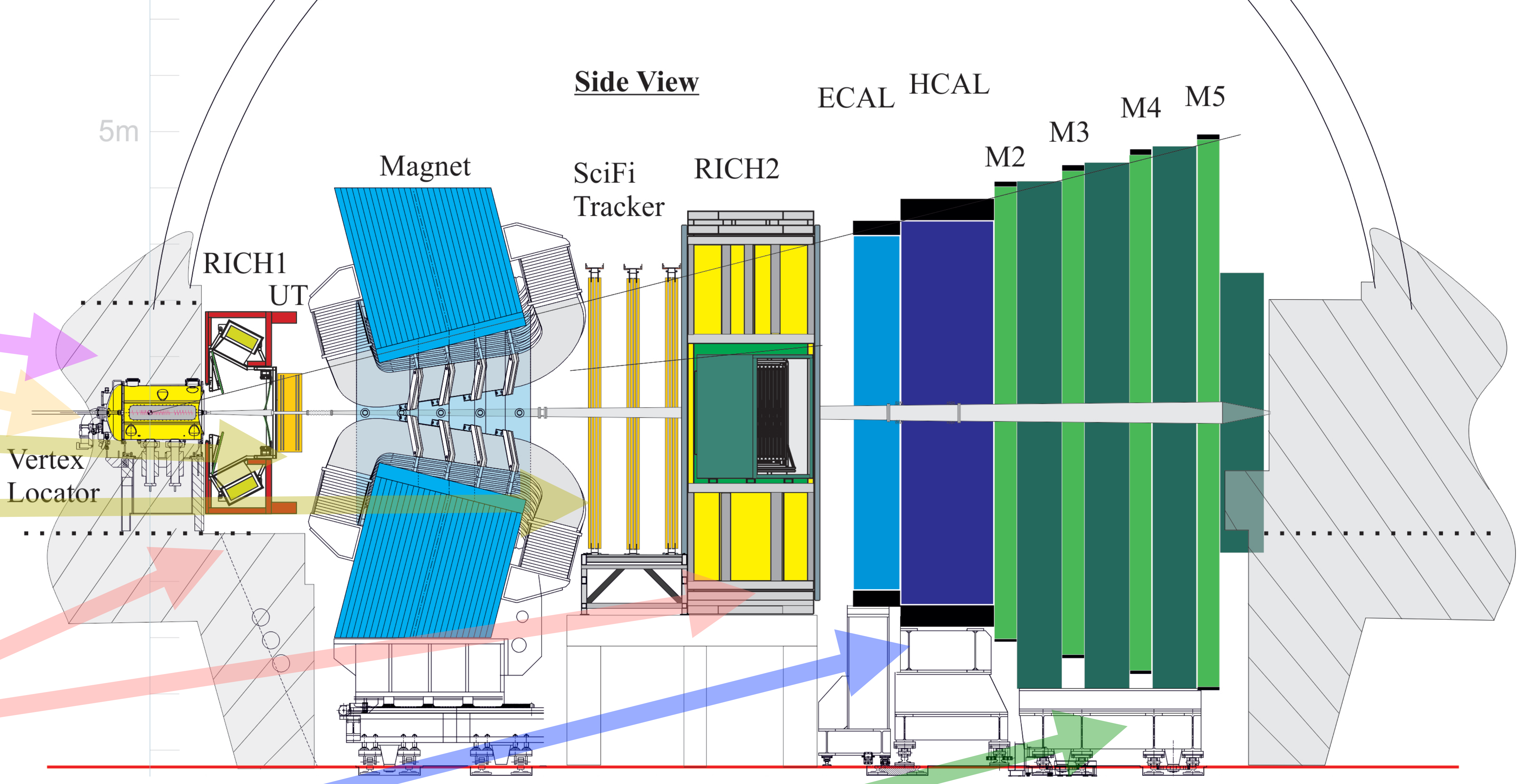
LHCb

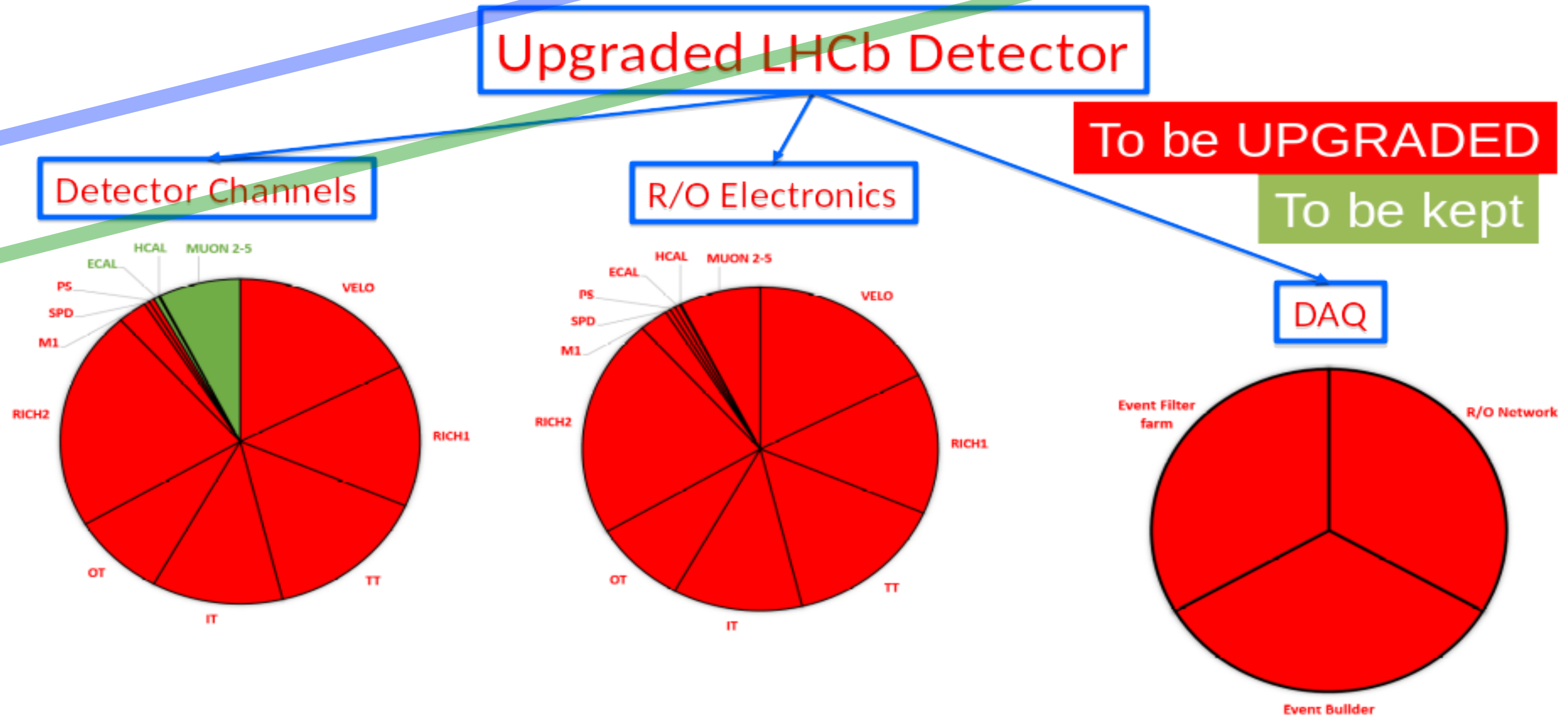
[Framework TDR for the LHCb Upgrade]

[The LHCb upgrade I]

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**





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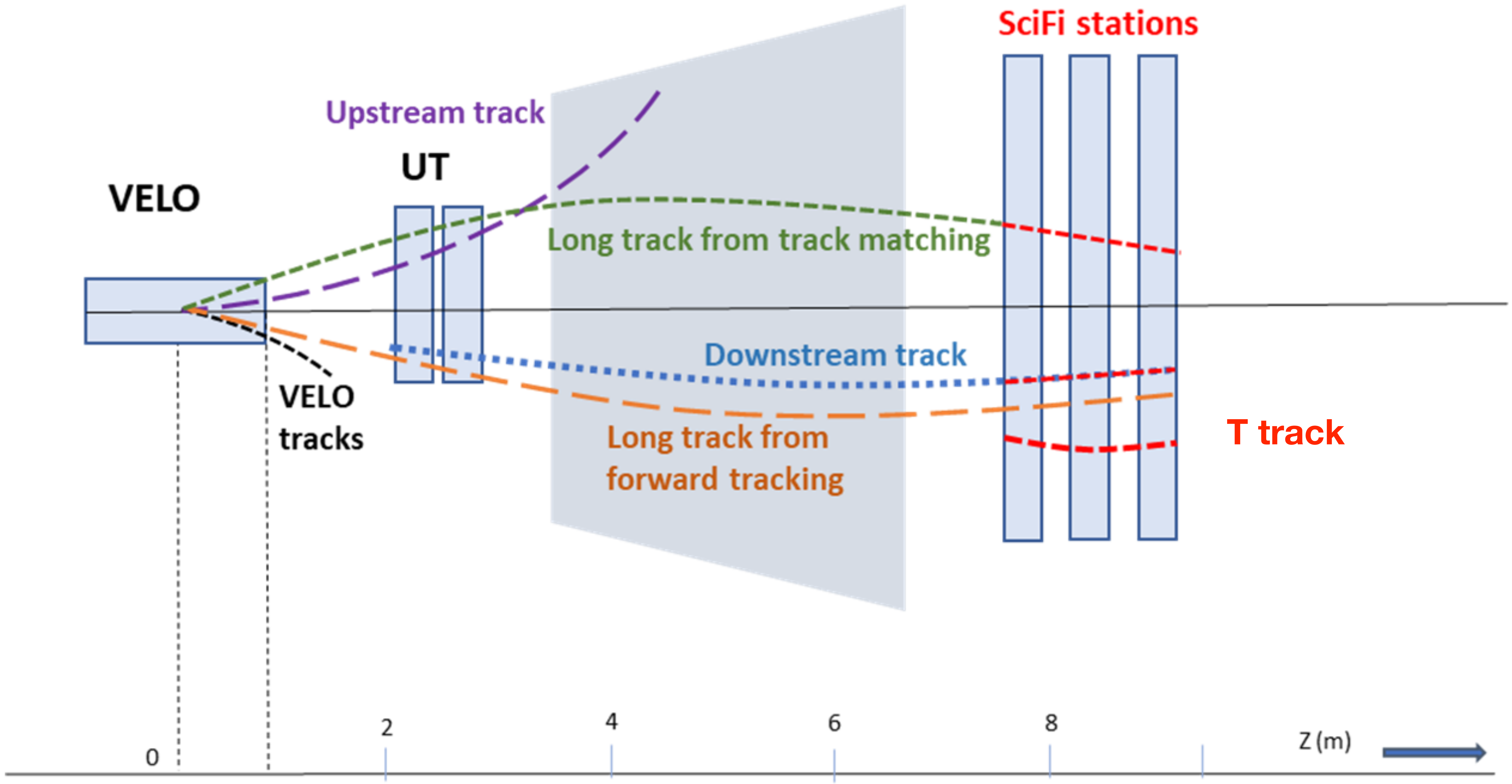
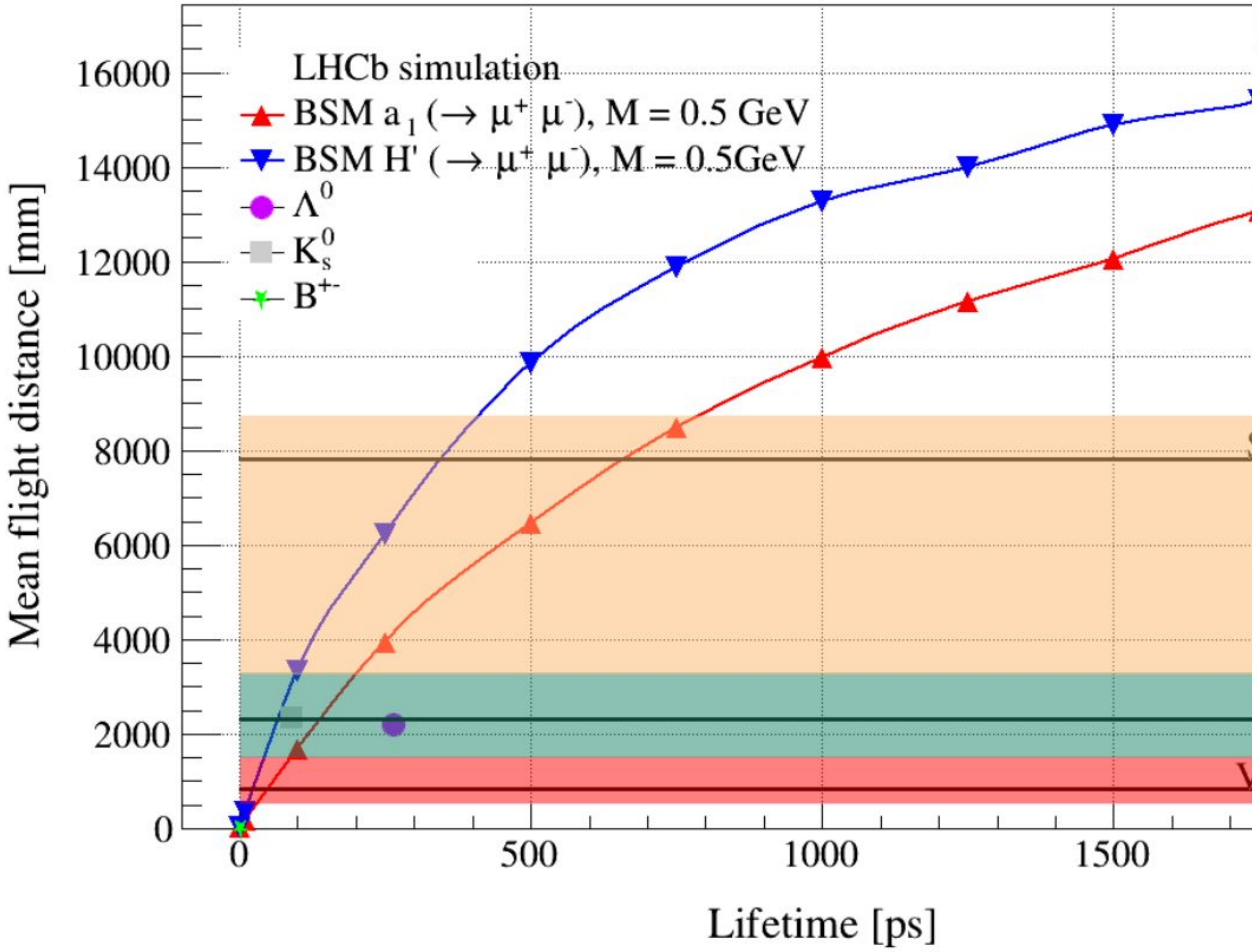


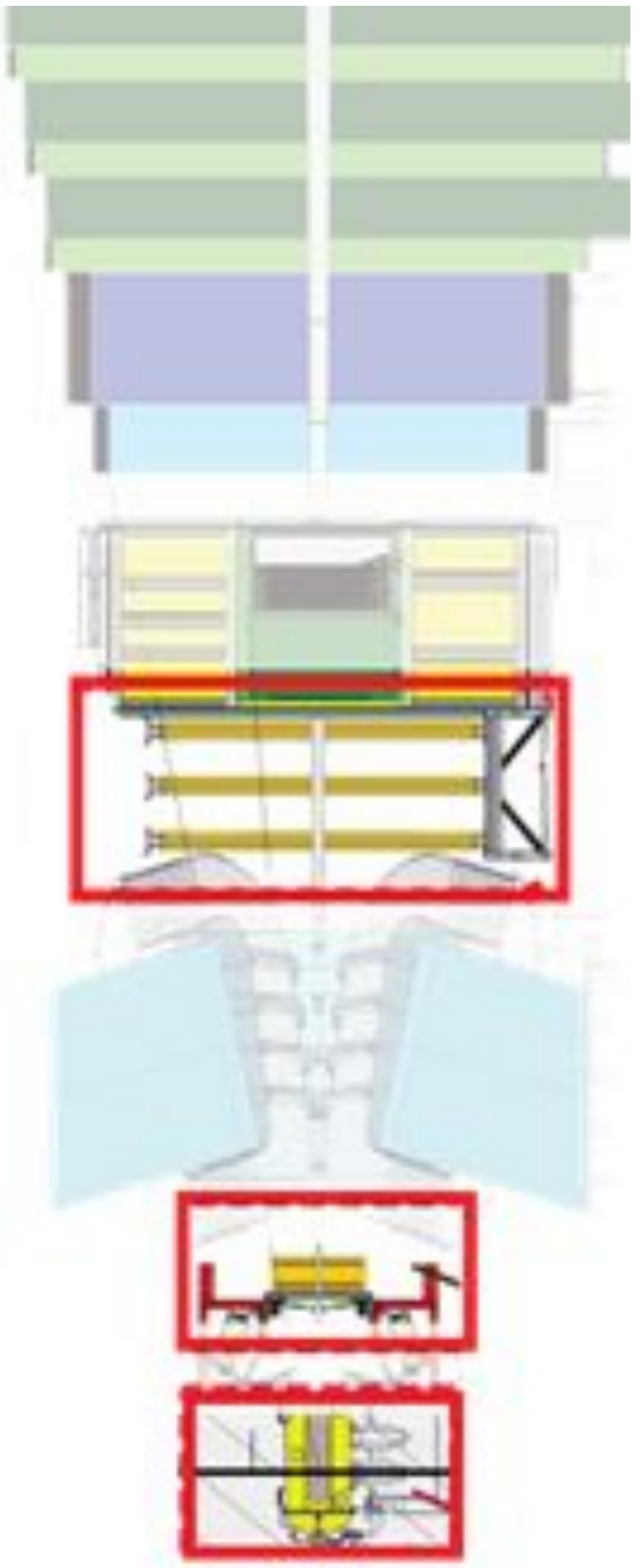
A new algorithm at LHCb to reconstruct Long-Lived particles in the first level trigger

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 hadrons and BSM particles**

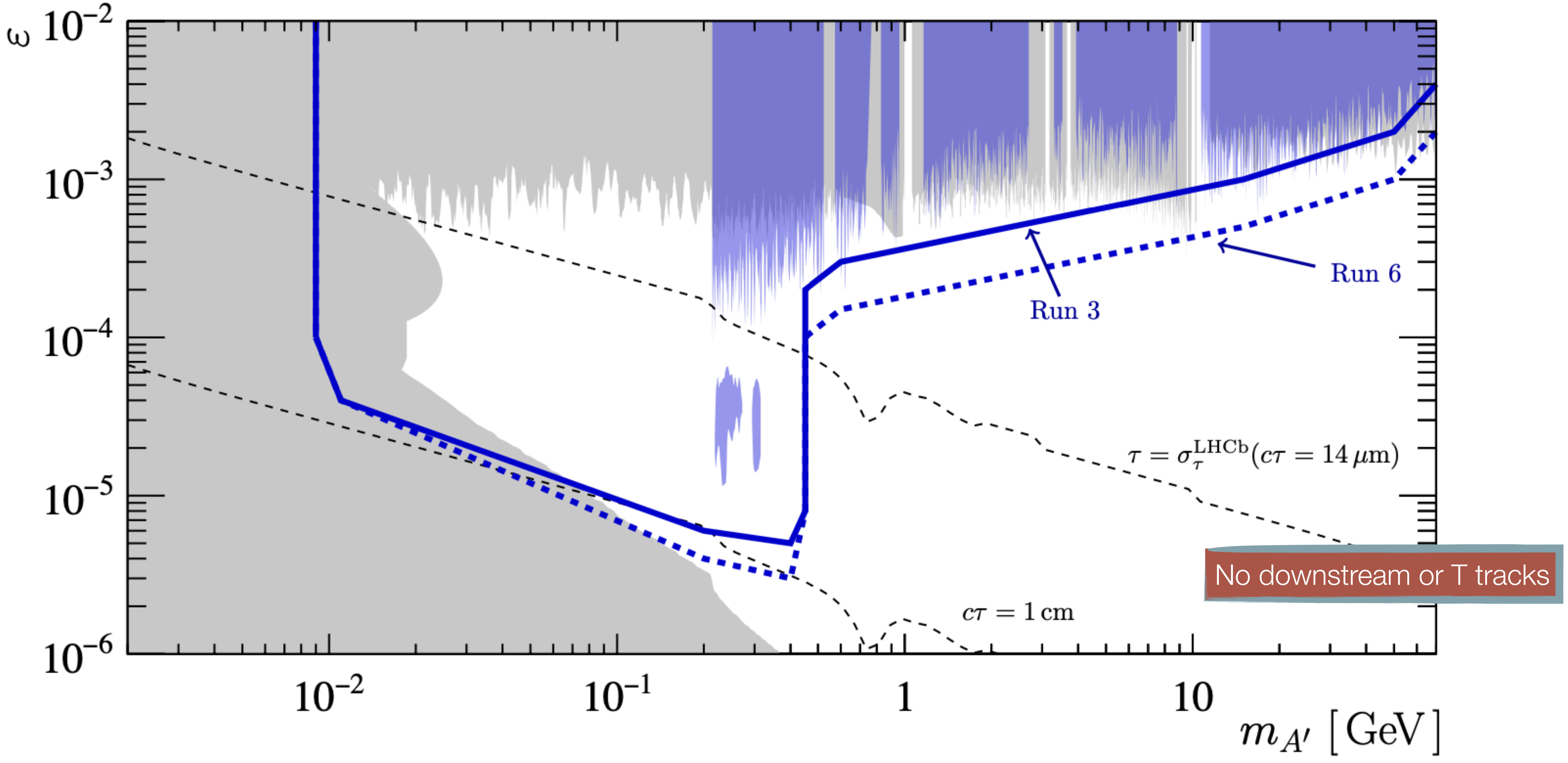




Search for Dark Photons / Results

Phys. Rev. Lett. 120, 061801 (2018) and 2203.07048

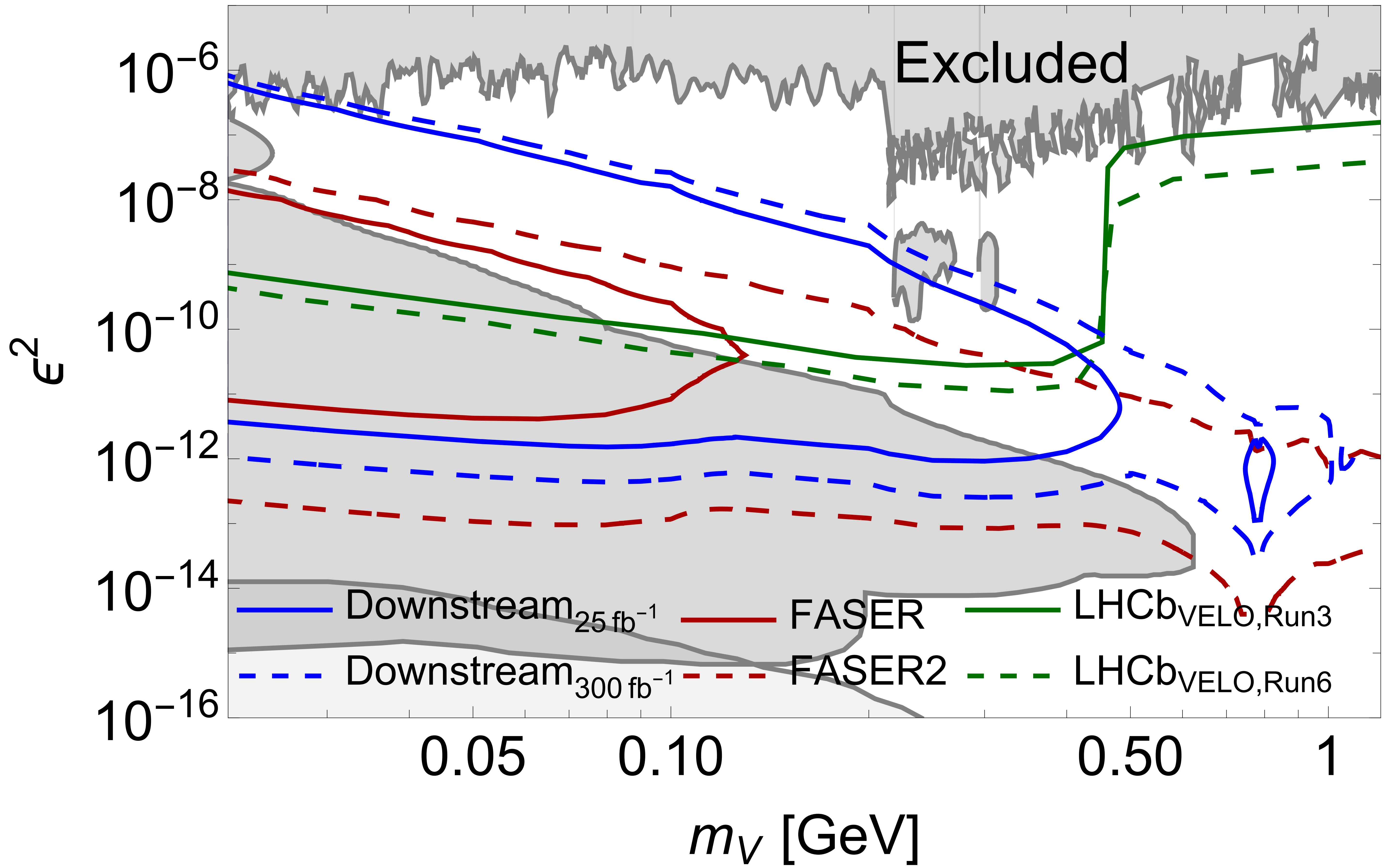
- Dimuon is used for higher masses, for lower masses estimations use dielectrics final states (thanks to GPU triggering and no L0). **Minimal increase with increased luminosity** [300 invfb]



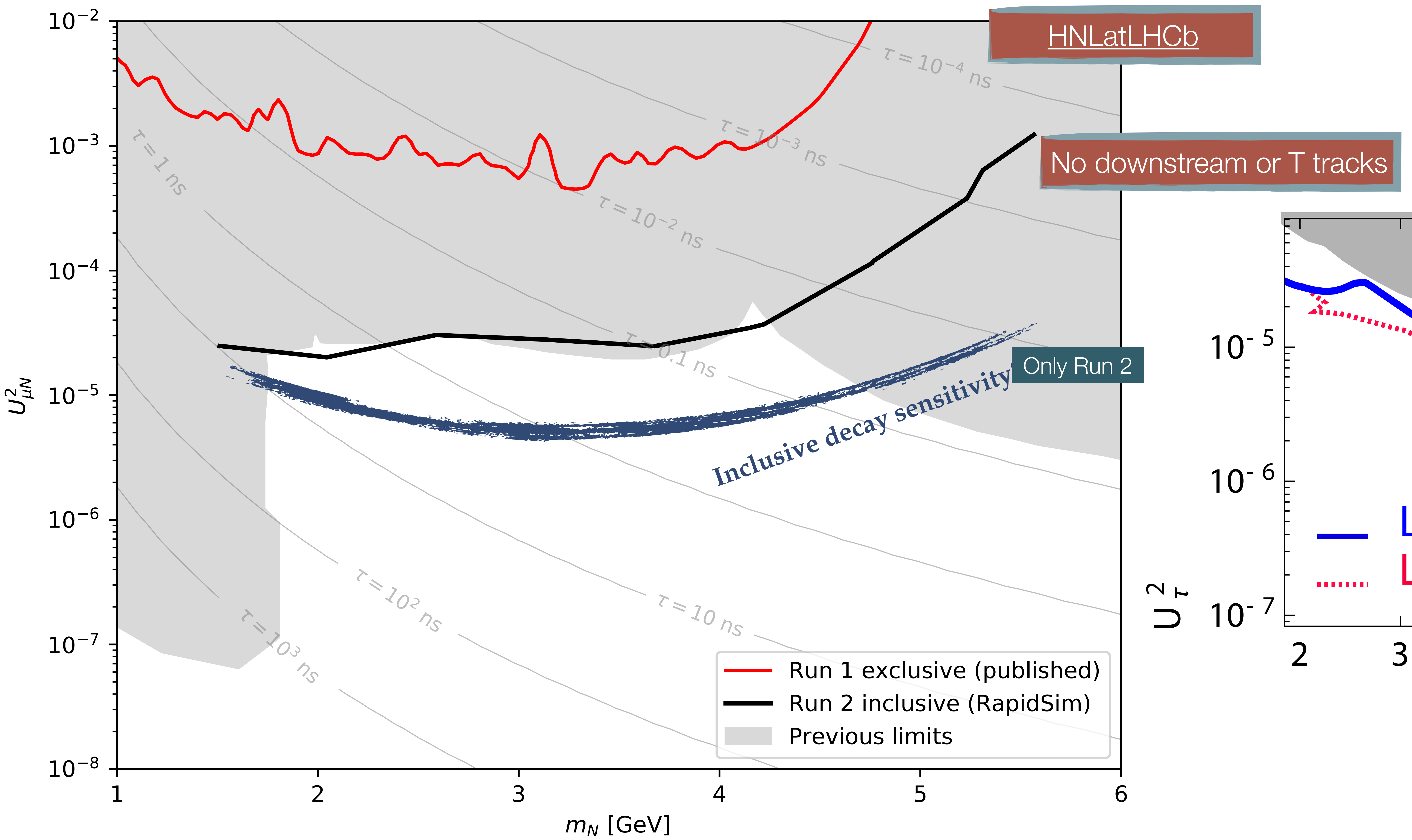
Search for Dark Photons / Results

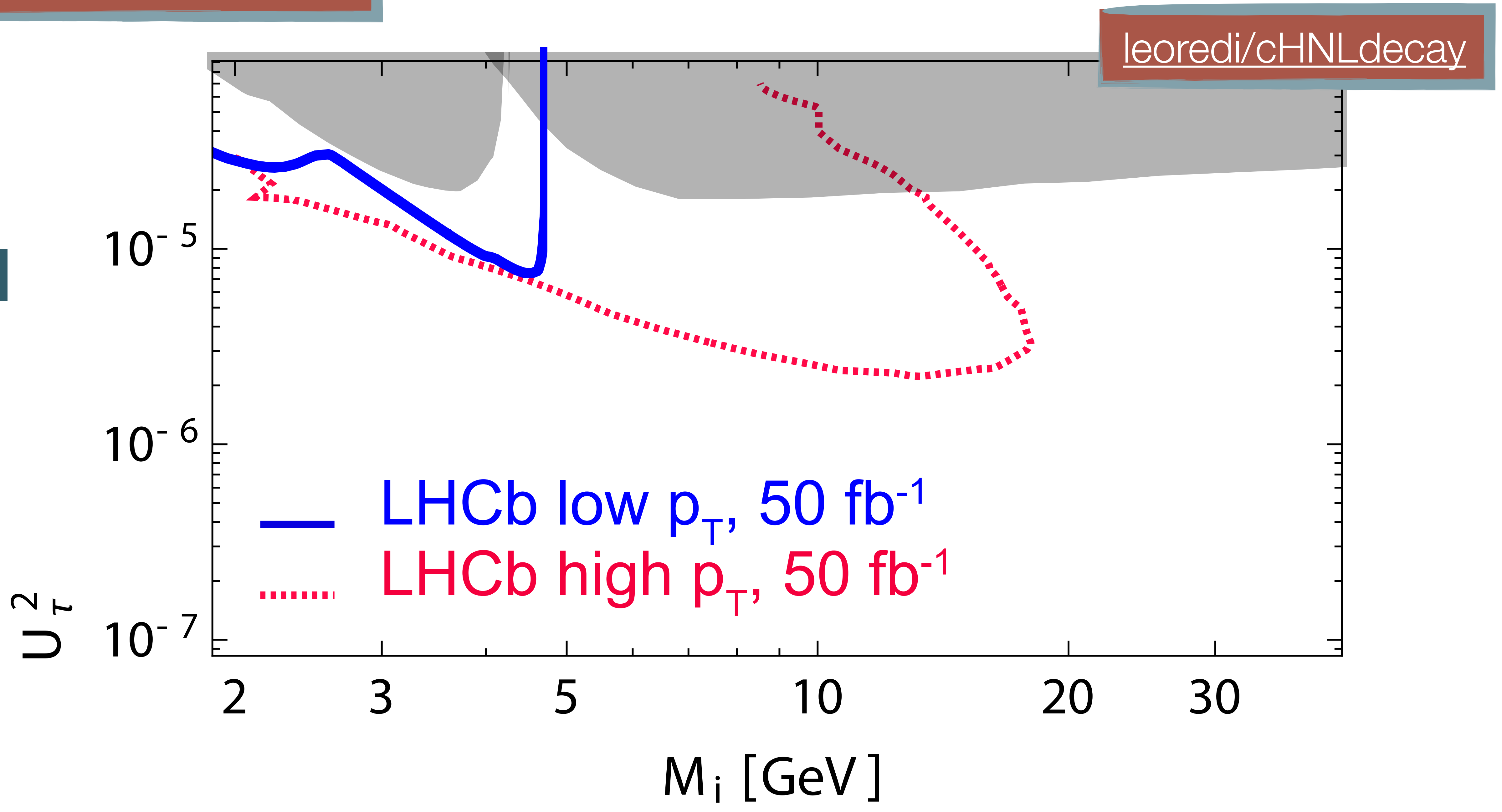
2312.14016

- The use of a downstream setup not only allowed to probe longer lifetime **but also shorter one** in the same search. In this model this is beneficial.



Heavy neutral leptons

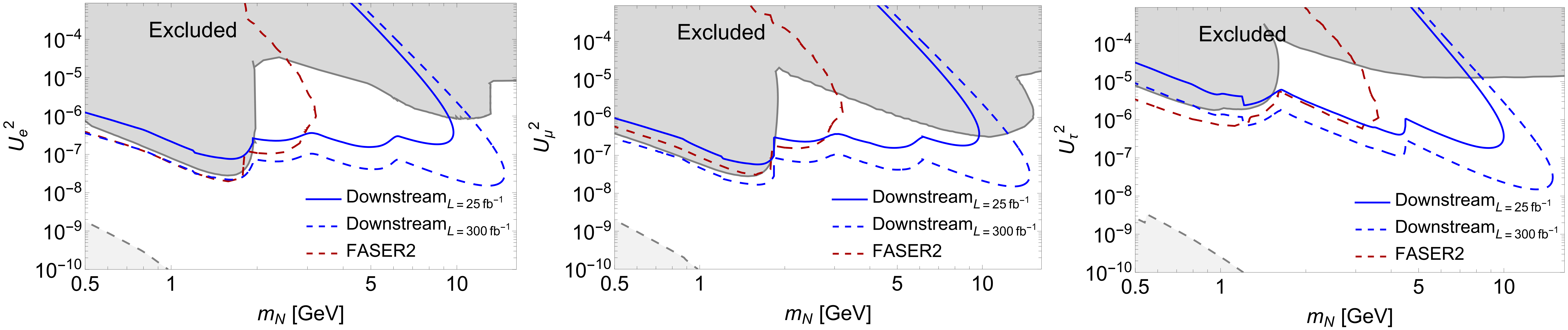




Heavy neutral leptons

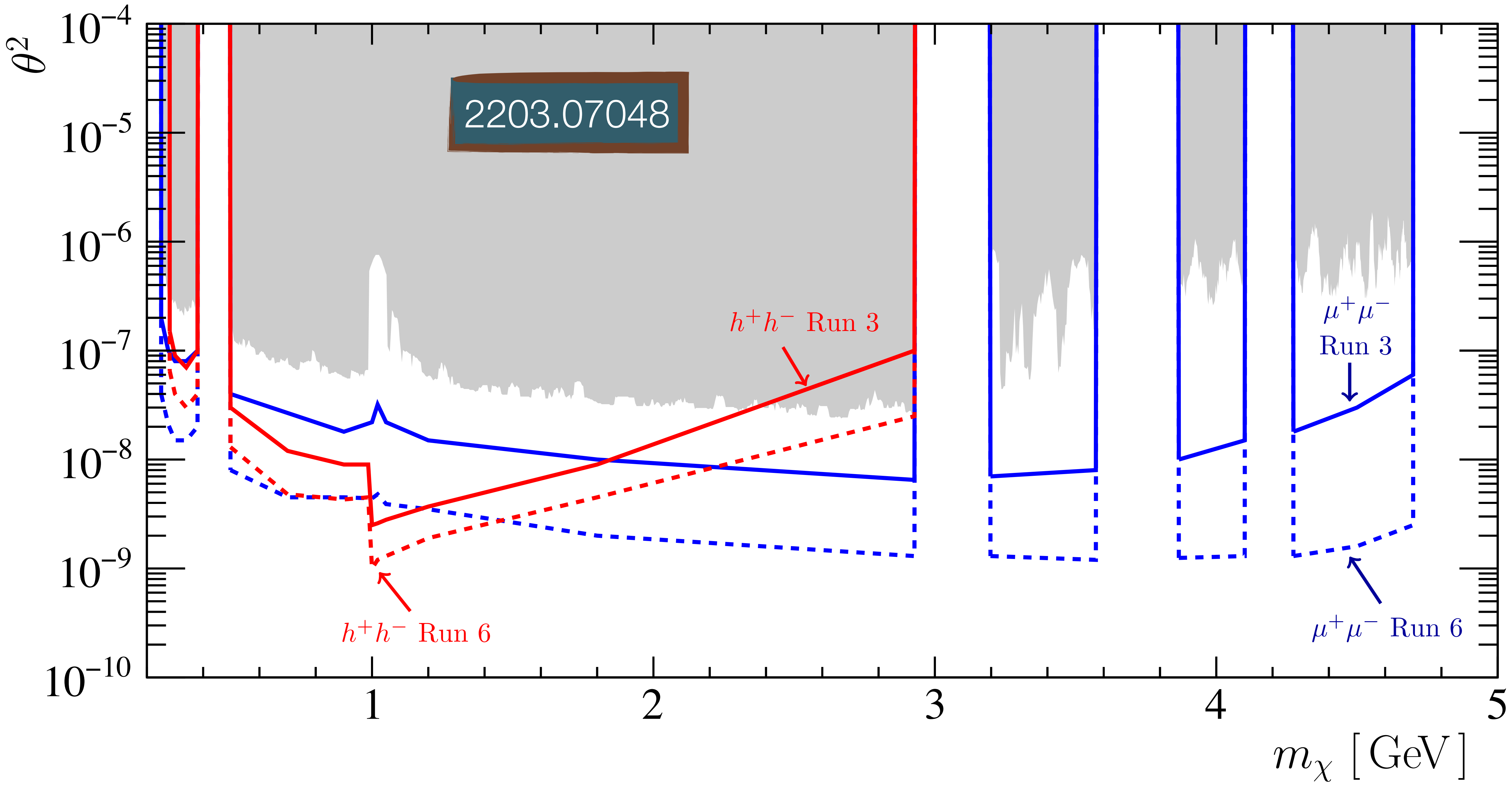
2312.14016

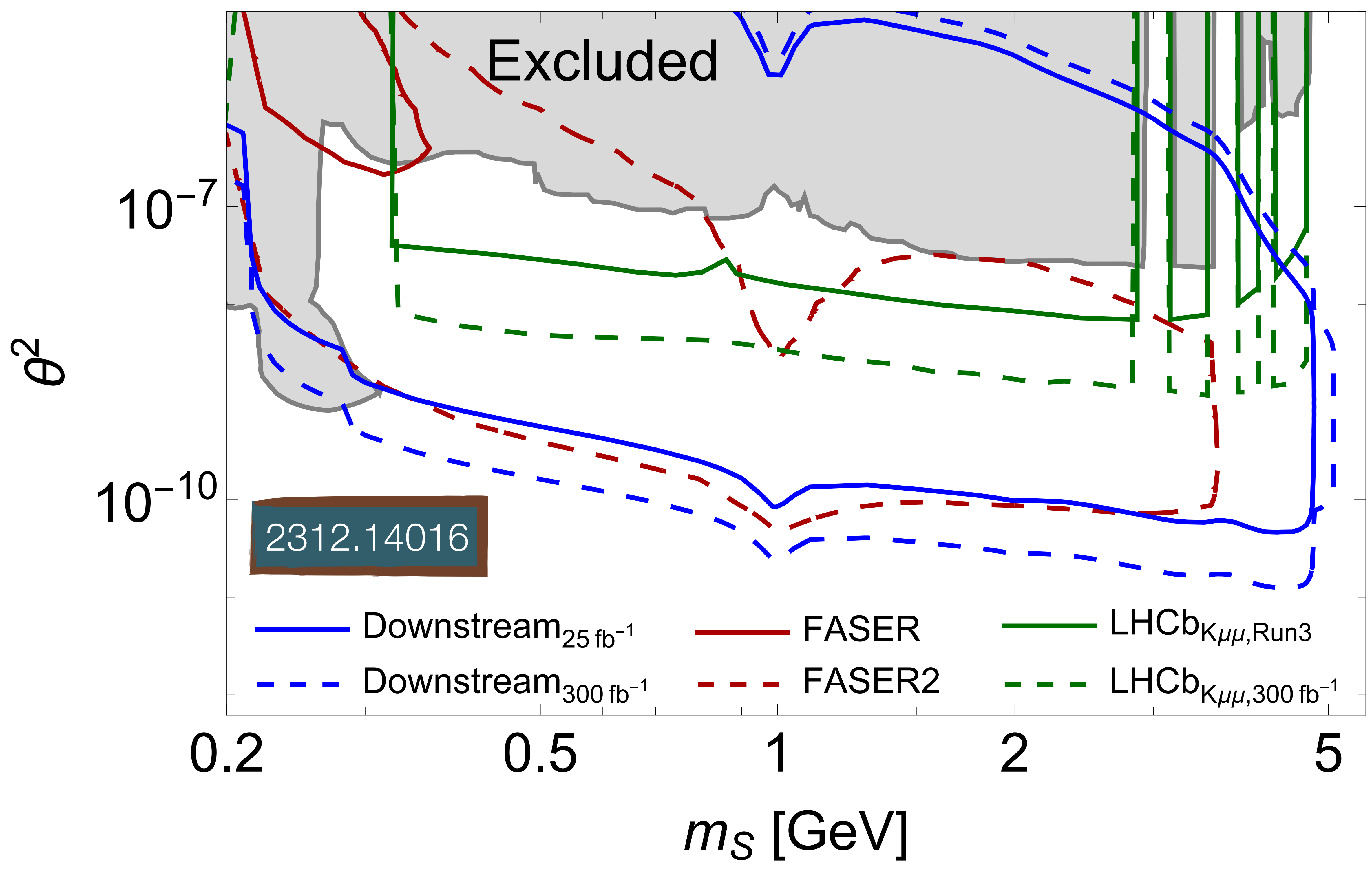
- In this case lower lifetime have already been explored. **D/τ production is not used** (mN<2 GeV), instead B (2GeV<mN<(mBc–ml)) and (partially) W (mN>mBc) are used



What about other popular models?

- For **a higgs mediated dark scalar** very similar effect on the exclusion plots. In this scenario the decay B → K(*)χ(μμ) is used





- Intro
- LLPs
- **EW**

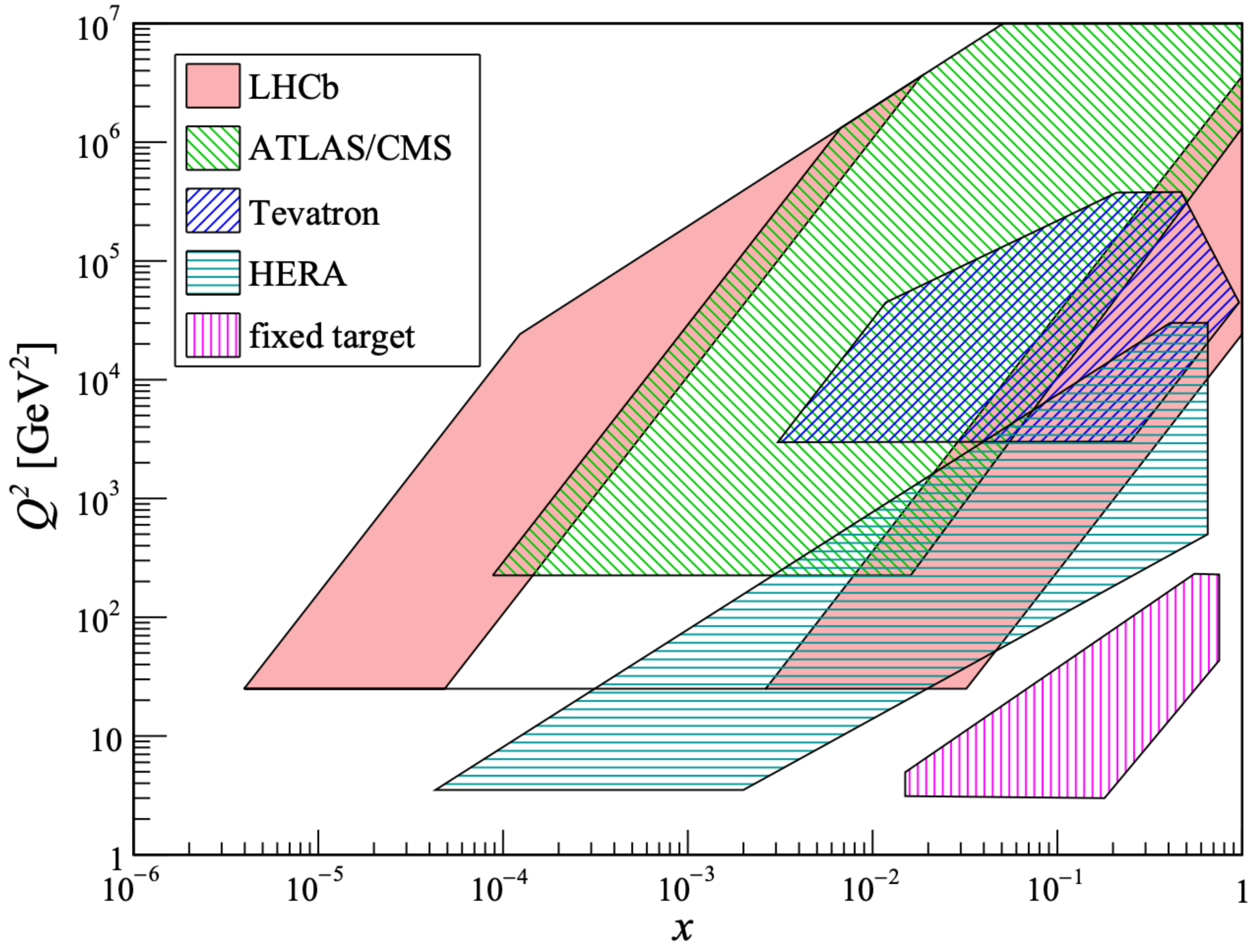
Il segreto di Majorana. Riccioni & Rocchi

The menu

- **Not enough time therefore: selection bias**

- Measurement of the W boson mass (mW) with 2016 data
- First measurement of the $Z \rightarrow \mu\mu$ angular coefficients at forward pseudorapidities of *pp* collisions
- Measurement of Z boson production cross-section in pp collisions at $\sqrt{5.02}$ TeV

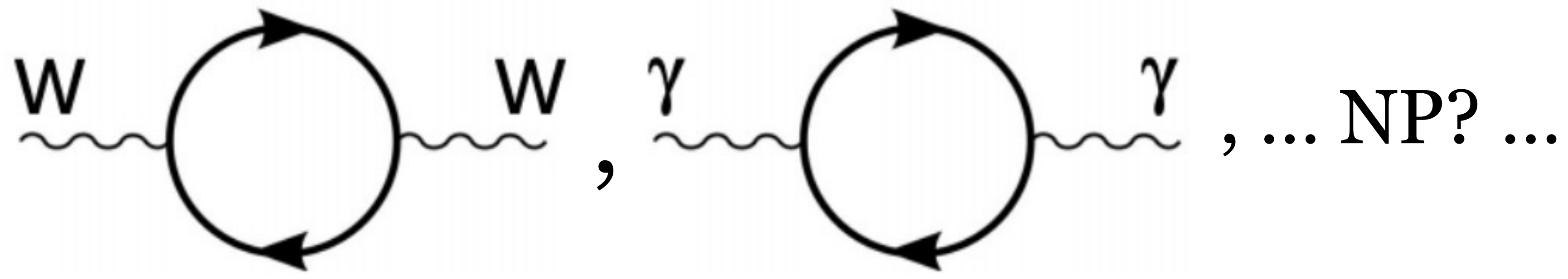
Phys. Rev. D 93, 074008 (2016)

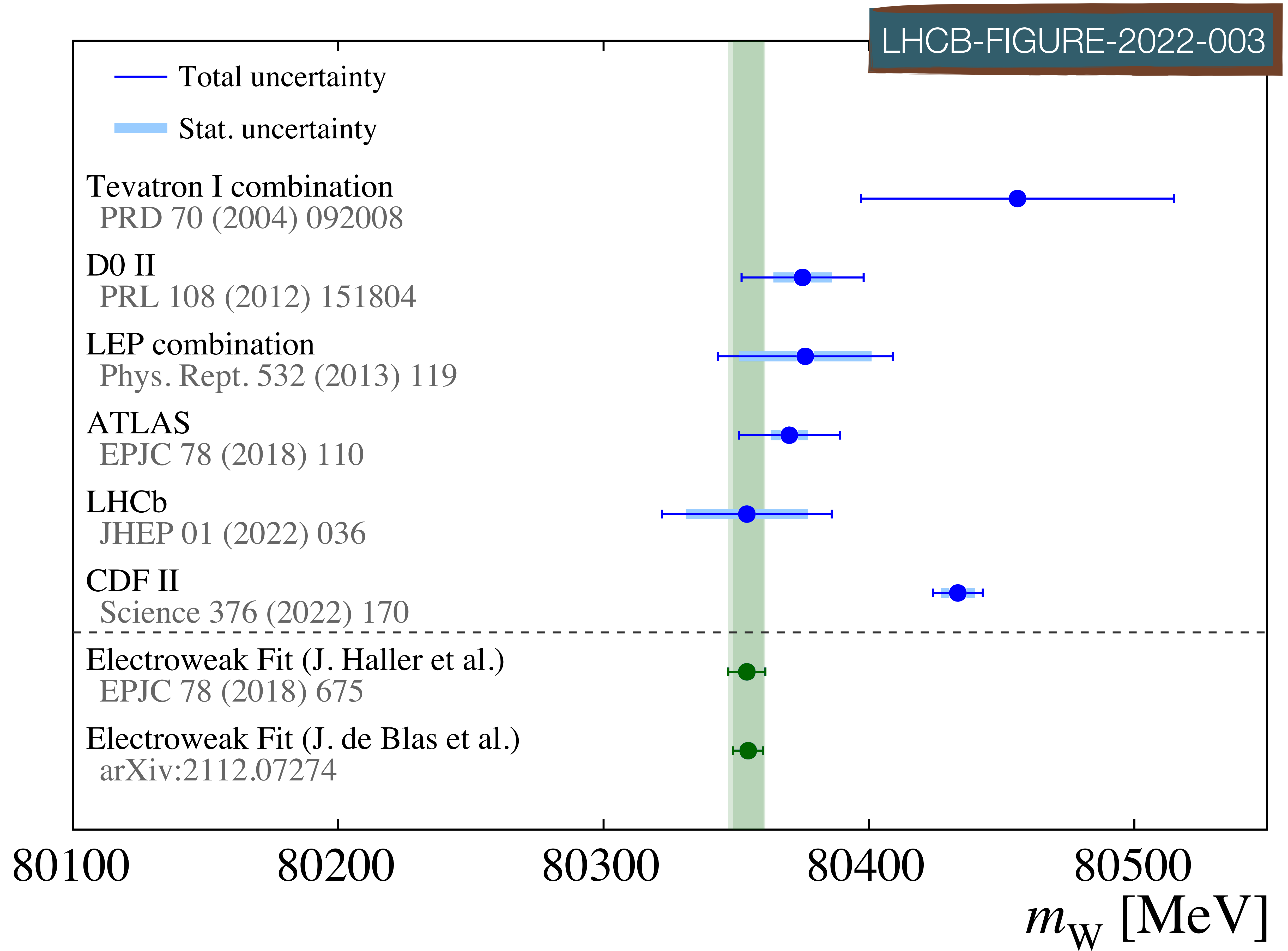


mW

- As always comparing **indirect SM predictions** with **direct mW measurements** can constrain BSM physics
- 2021 EW fit prediction and ATLAS measurement have uncertainties oscillating between 6 and 19 MeV
- Radiative corrections include quantum loop corrections due to the interactions of particles not accounted for in the tree-level SM… or NP
- **LHC experiments can achieve a sensitivity closer to the global EW fit (~7 MeV)**

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

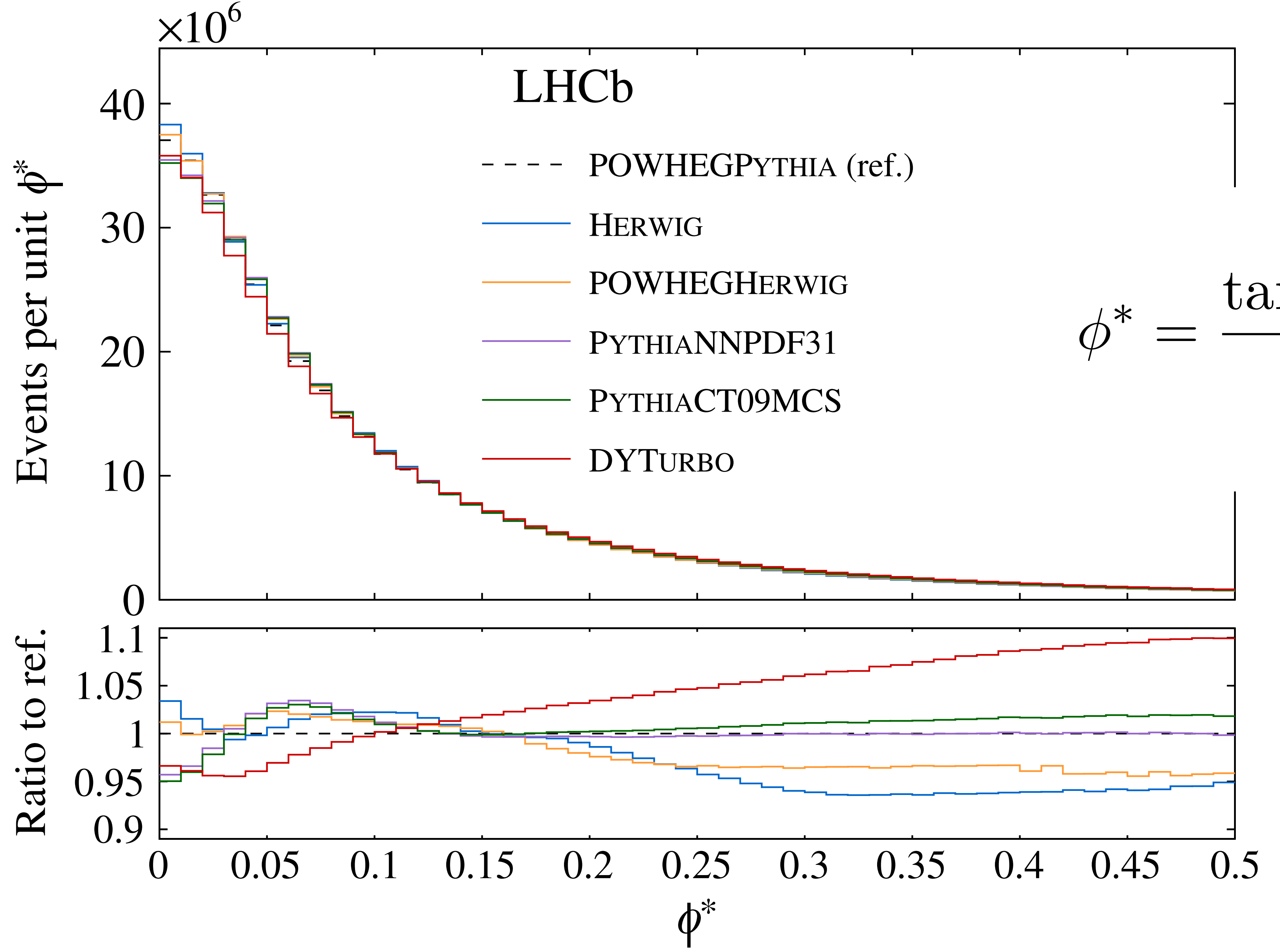




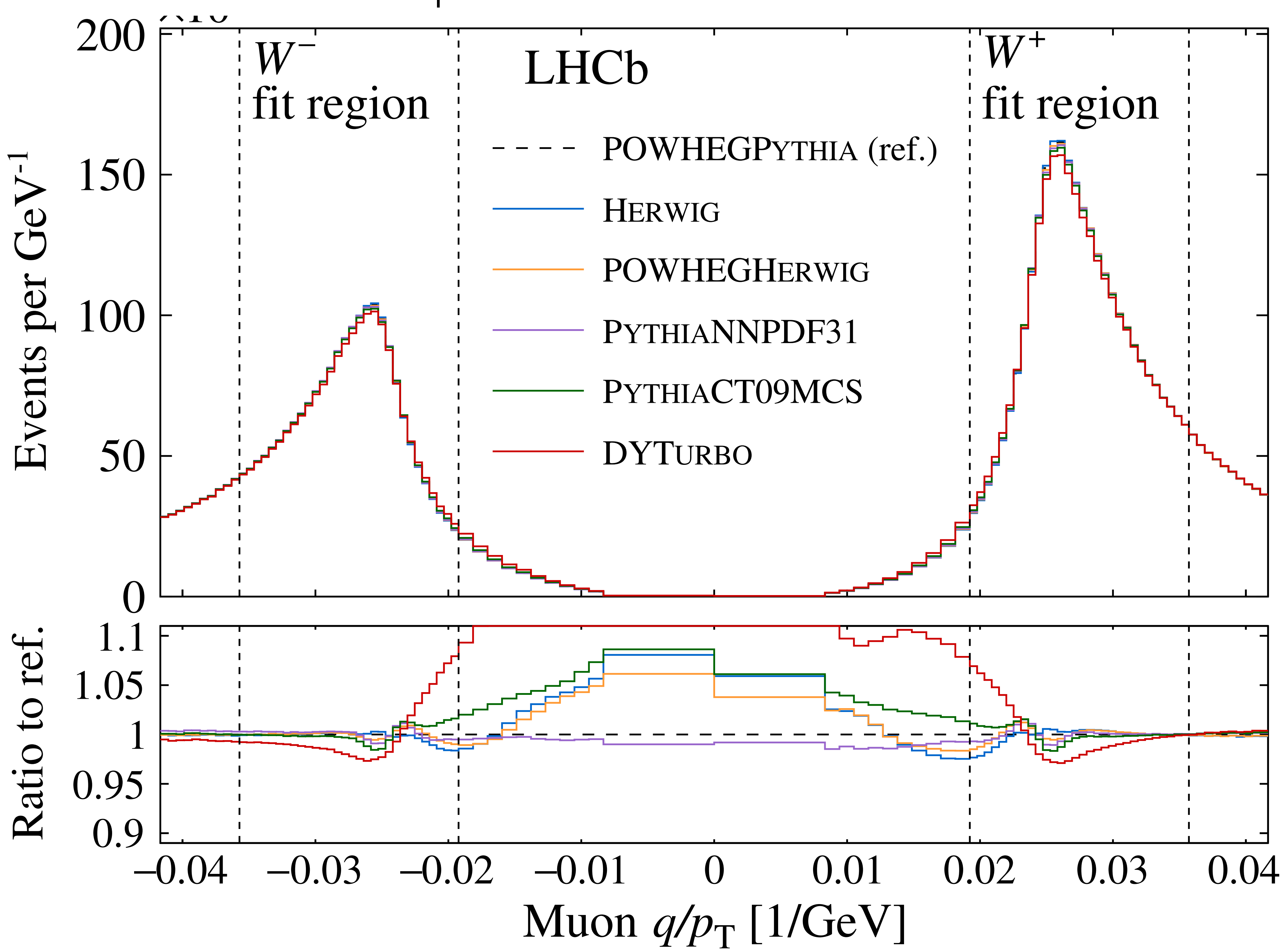
mW

JHEP01(2022)036 (1)

- Accurately track muon transverse momentum
- Because $W \to \mu\nu$ gives in LHCb a single, high-pT, isolated muon
- **Adjust for efficiency variances in selection processes** (reconstruction, trigger, topology, offline criteria)
- Assess and ascertain backgrounds via simulations, excluding hadron decay-in-flight contributions and **use isolation**
- Obtain the W mass by fitting reweighed simulation plots to data, modifying several nuisance factors and the W mass



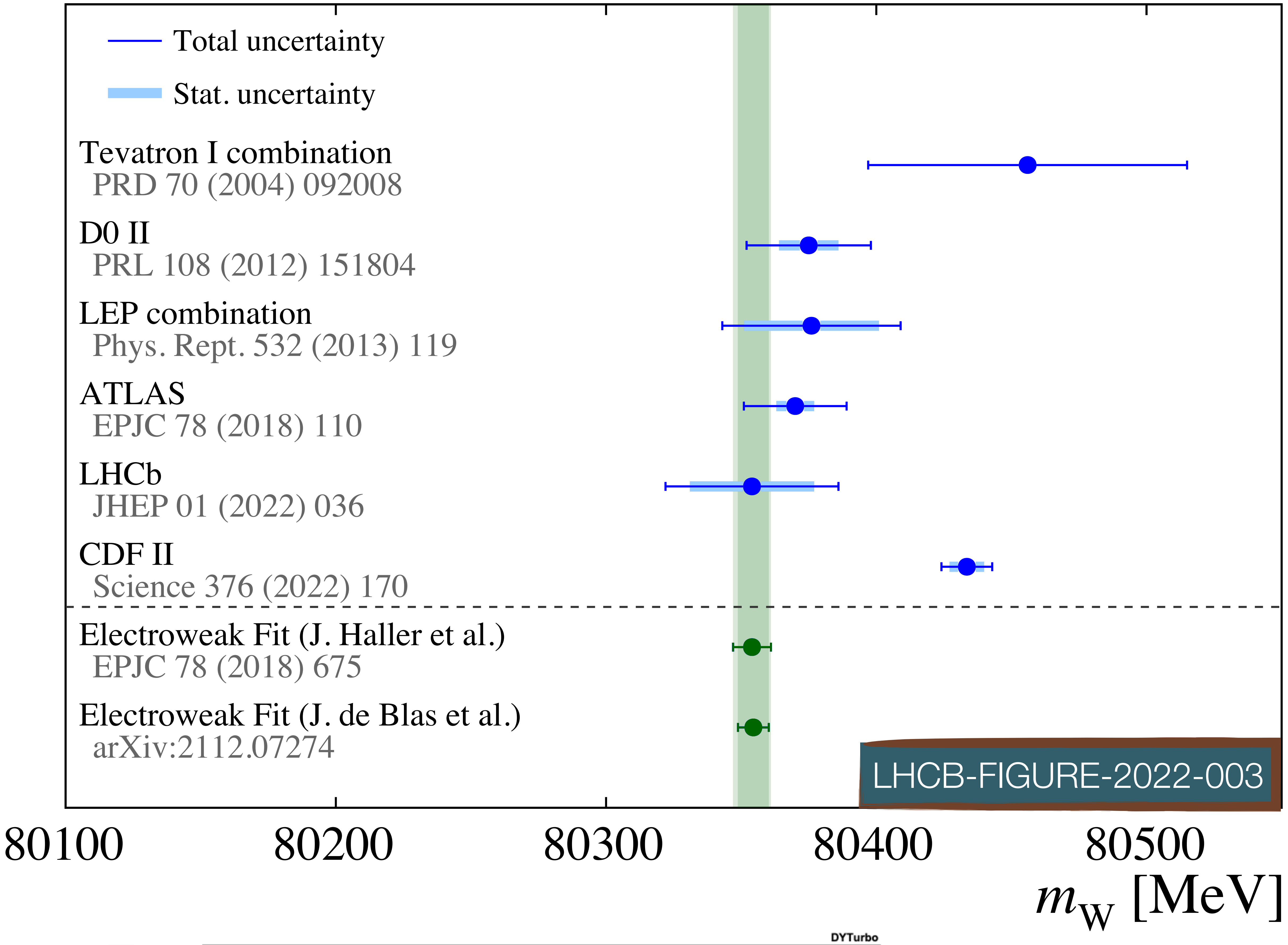
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_T^Z}{M},$$

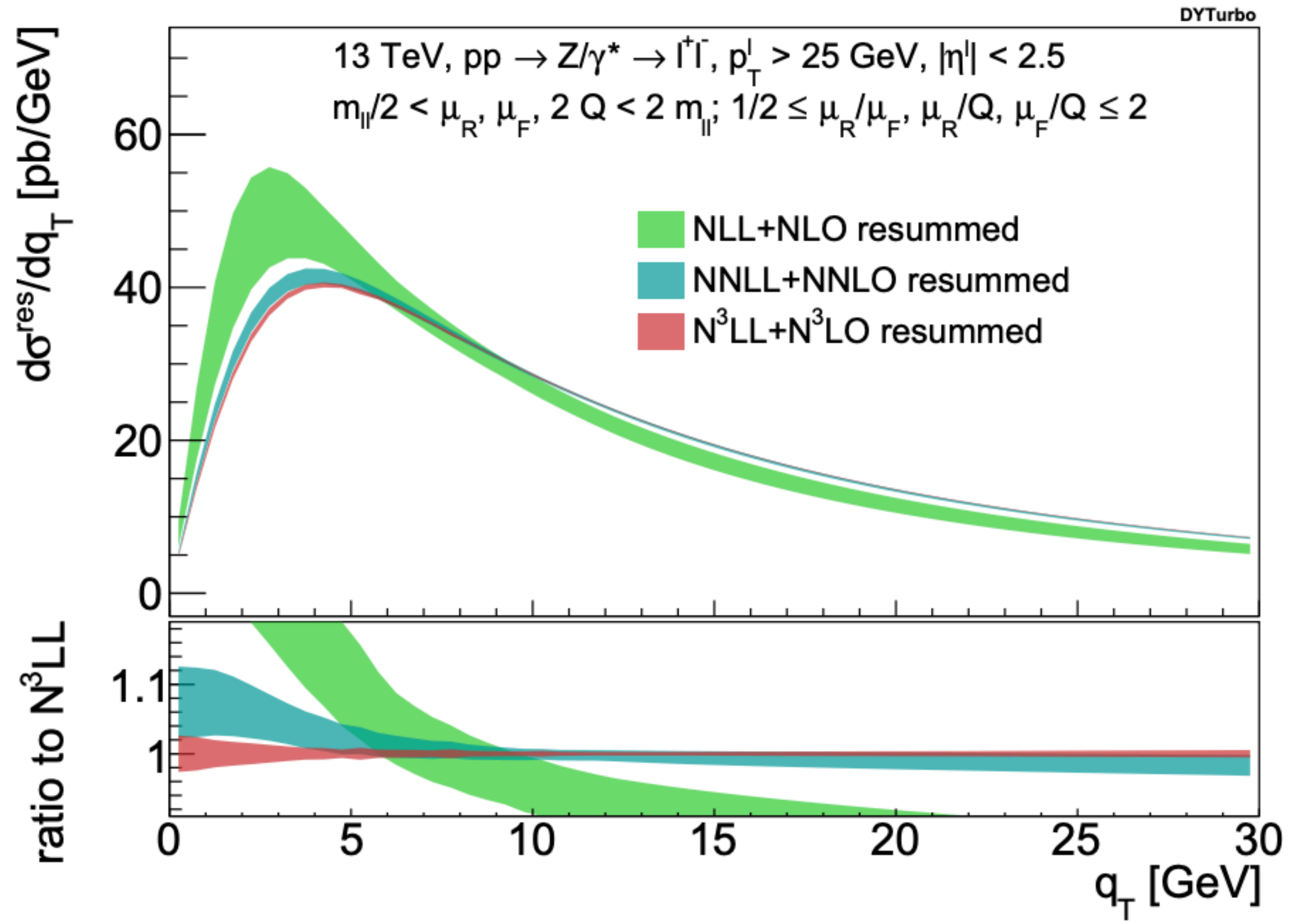


mW

JHEP01(2022)036 (1)

- LHCb achieves a precision of ~ 32 MeV using roughly 1/3 of the Run-II dataset
- 2016 analysis had 1.7 invfb. Further ~ 4 invfb of Run-2 data to add ➞ precision of ~ 14 MeV
- Experimental systematics will reduce with more study and data
- **QCD predictions with higher perturbative accuracy are available e.g. from DYTurbo**
- Effort now on improving the modeling and reducing the systematic uncertainties





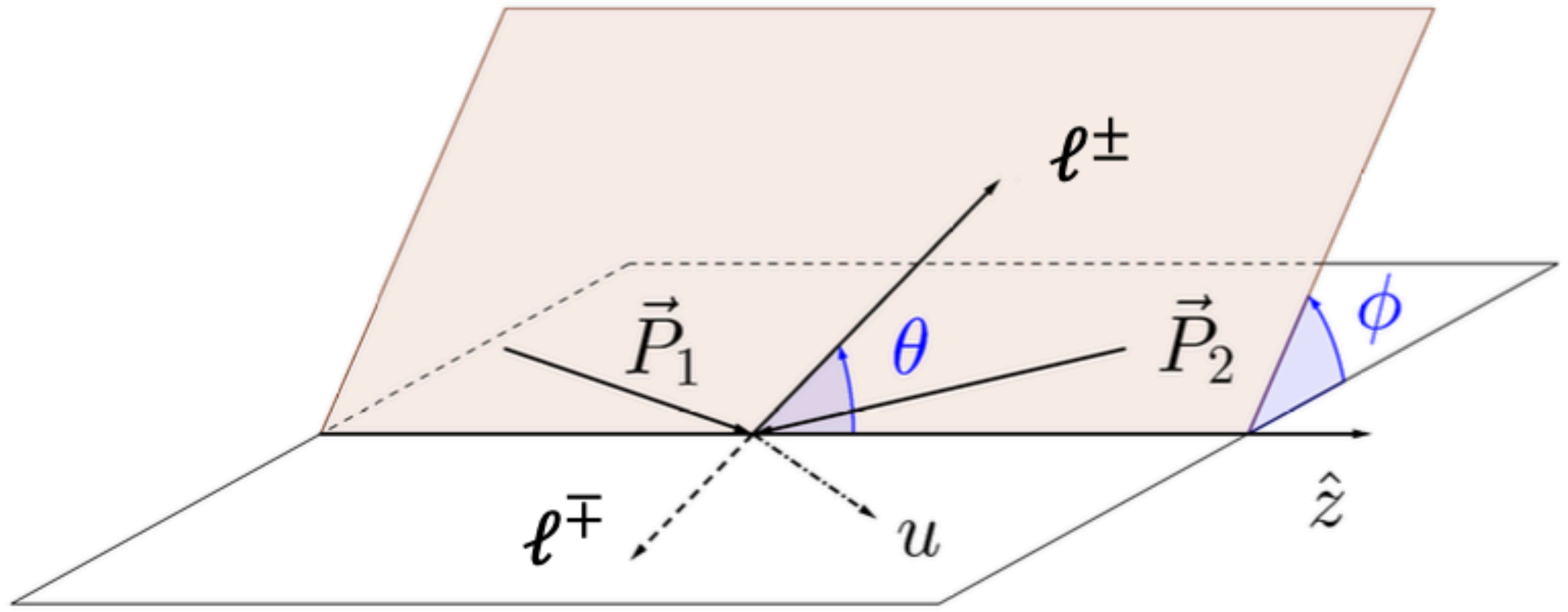
First measurement of the Z → μμ angular coefficients at forward pseudorapidities of pp collisions

Phys. Rev. Lett. 129 (2022) 091801

- The kinematic distribution of the final-state leptons provides a **direct probe of the polarization of the intermediate gauge boson**
- Using full Run 2 dataset (5.1 invfb)
- Dimuon angular distribution in $Z \to \mu\mu$ expressed (at Born level) in 8 coefficients *Ai*
- *Ai* extracted with unbinned maximum likelihood fit to muon cosθ and ϕ
- It is the first measurement of Ai (i = 0 — 4) in the forward region of *pp* collisions at 13 TeV

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi,$$

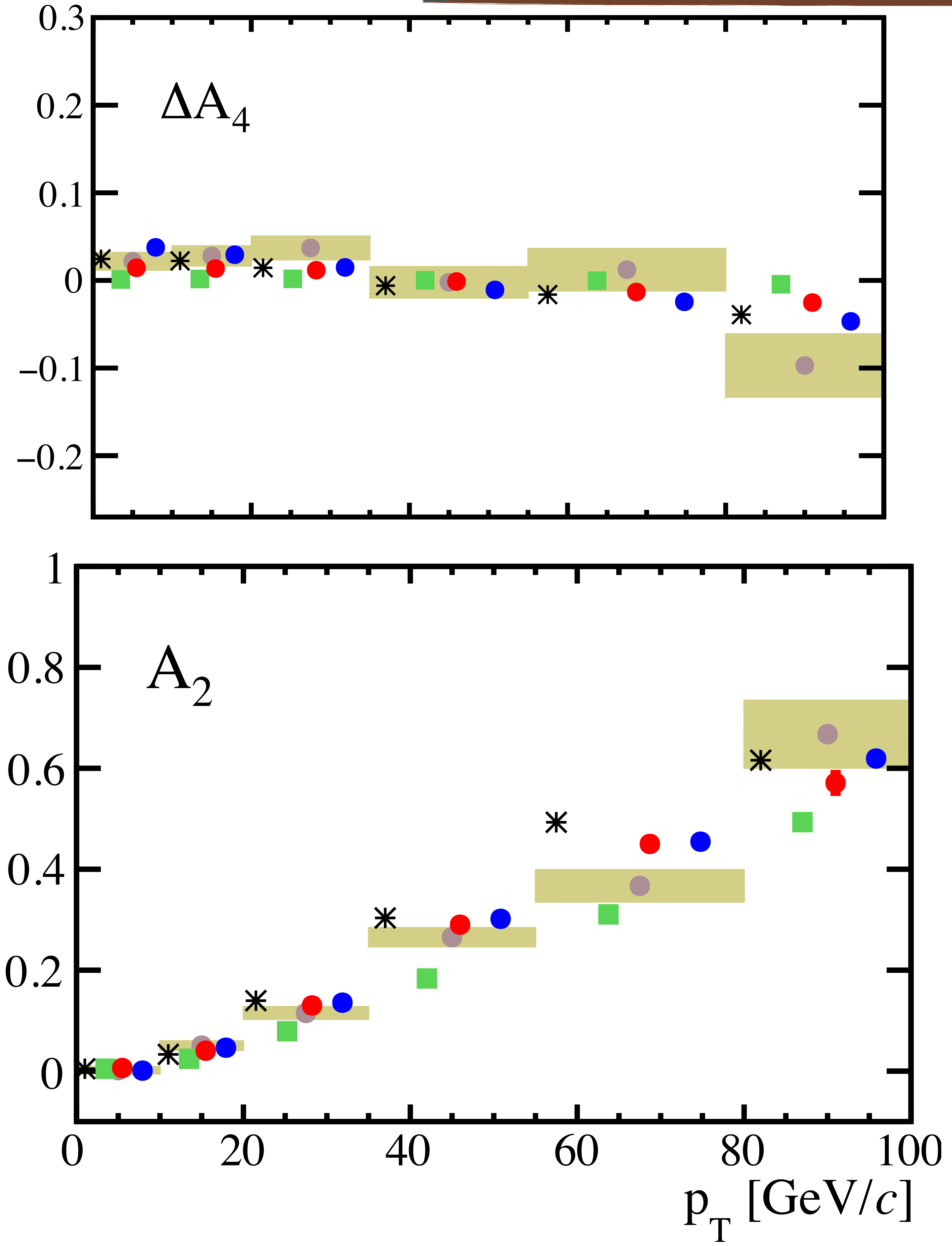
Collins-Soper frame



First measurement of the Z → μμ angular coefficients at forward pseudorapidities of pp collisions

Phys. Rev. Lett. 129 (2022) 091801

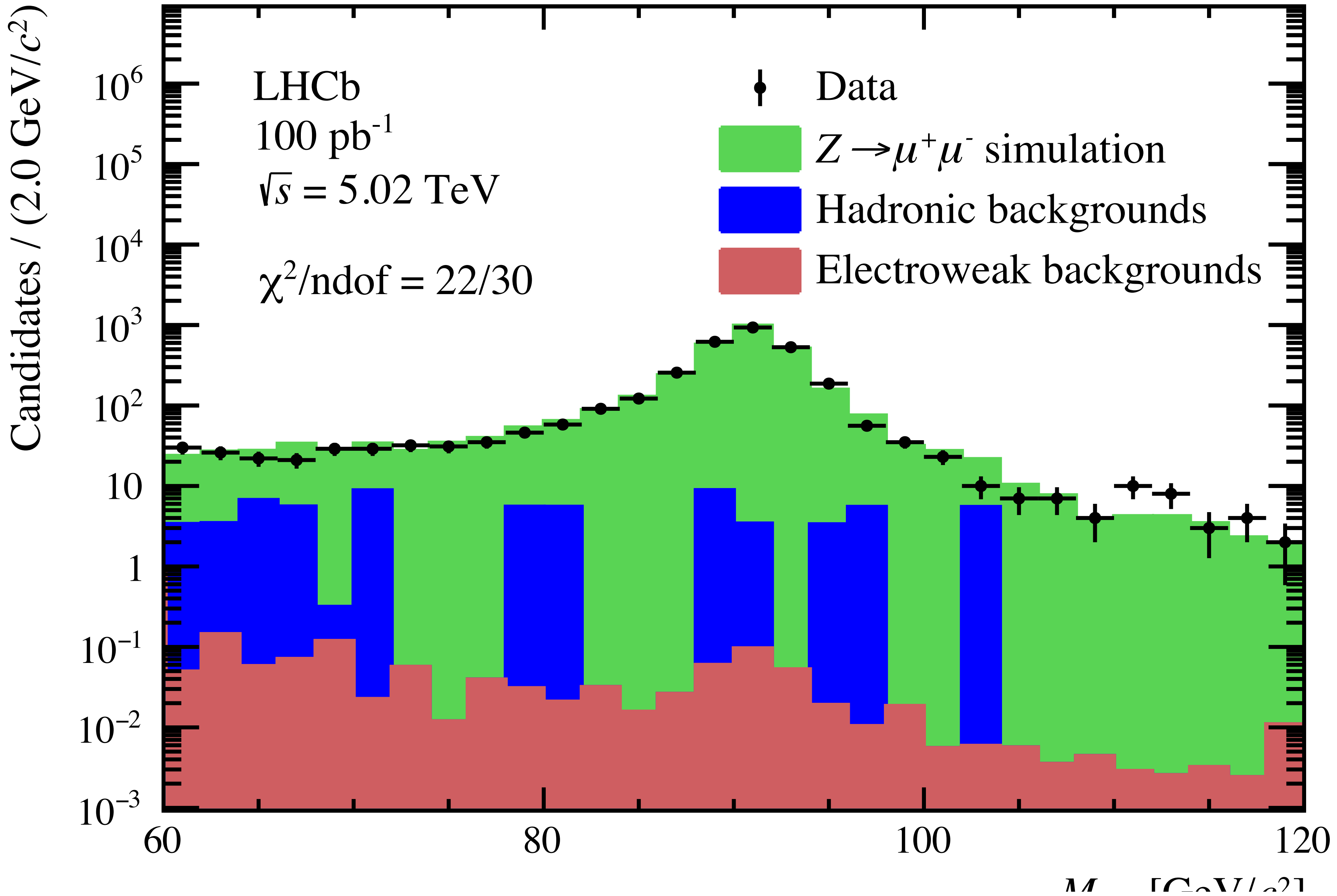
- Unfolded results at the Born level as a function of transverse momentum
- **ΔA4** := A4 - mean(A4) decouples measurement from the value of the weak mixing angle
  - Compared with 4 sets of theoretical predictions
  - Good agreements modulo Pythia8 in LHCb configuration
- **A2** proportional to convolution of TMD PDFs:
  - **This measurement can improve constraints on this non-perturbative QCD phenomenon**

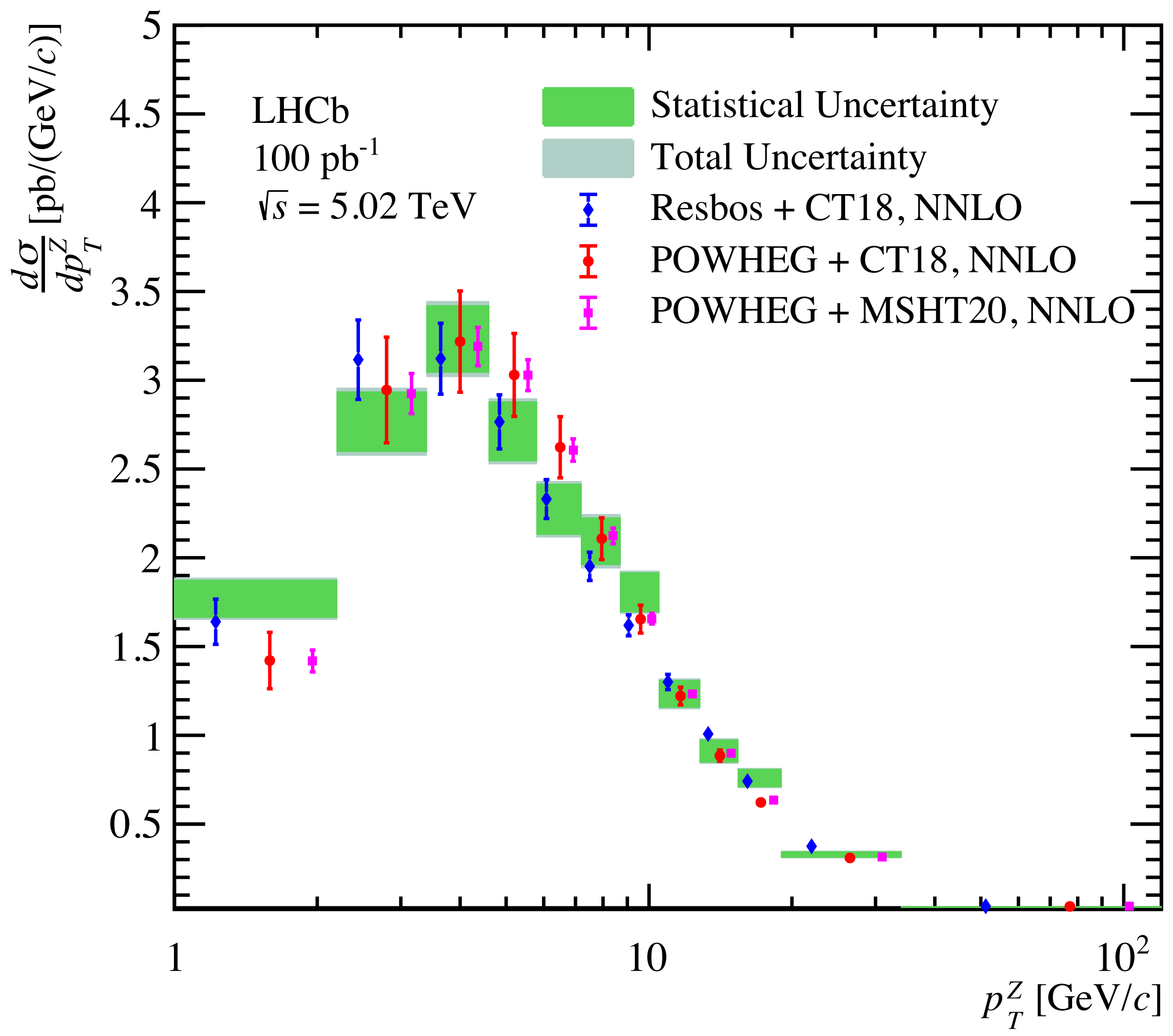


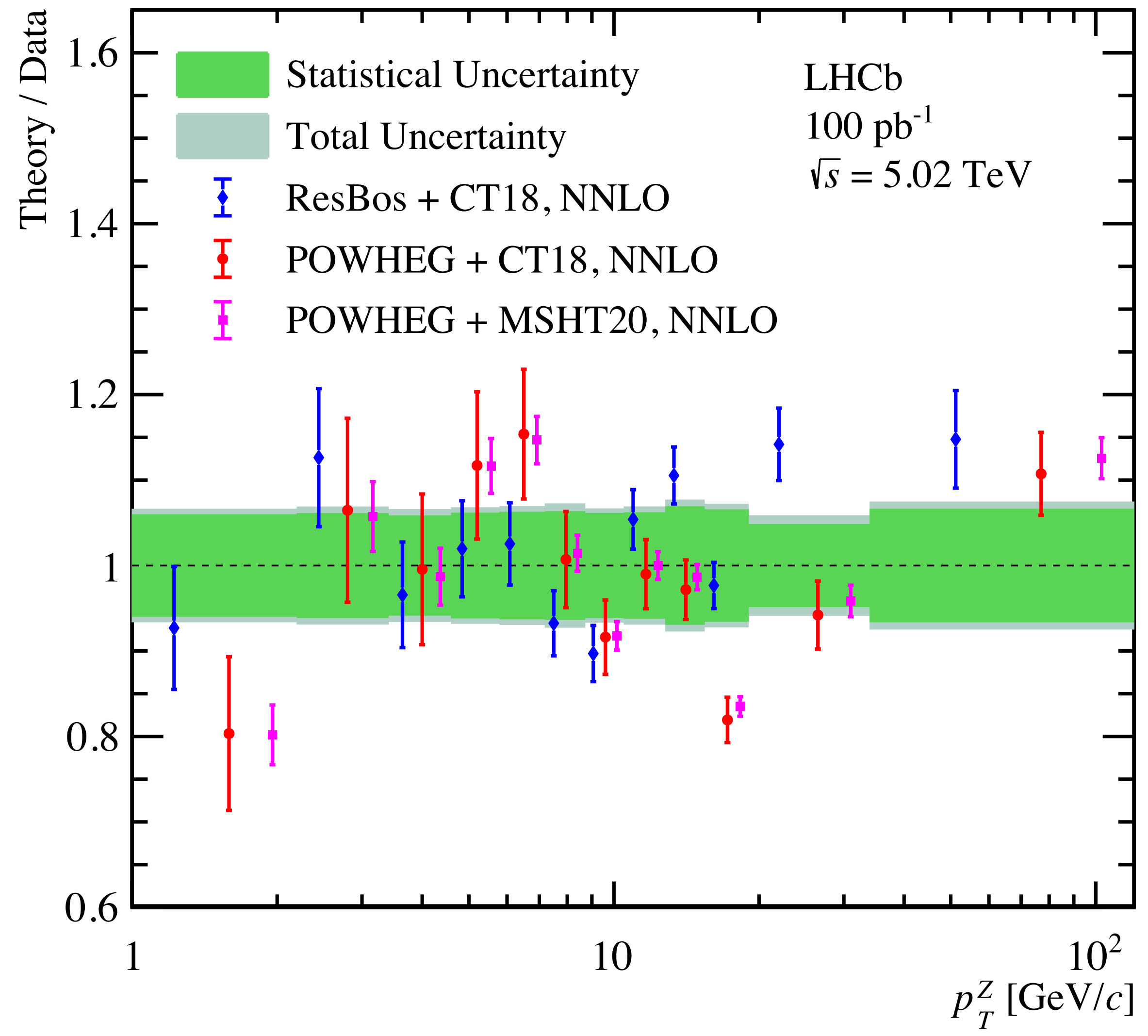
JHEP02(2024)070

Measurement of Z boson production cross-section in pp collisions at √5.02 TeV

- pp ➞ Z ➞ μ+μ– an important channel to study the QCD and EW sectors of the SM at LHC energies
- Constraining the uncertainties of PDF at 5 TeV
- **Performed with 2017 pp dataset of around 100 invpb**
- 2.0 < η < 4.5 with transverse momentum pT > 20 GeV
- Dimuon mass studies is 60 < Mμμ < 120
- **General good agreement between simulation and data in observables**



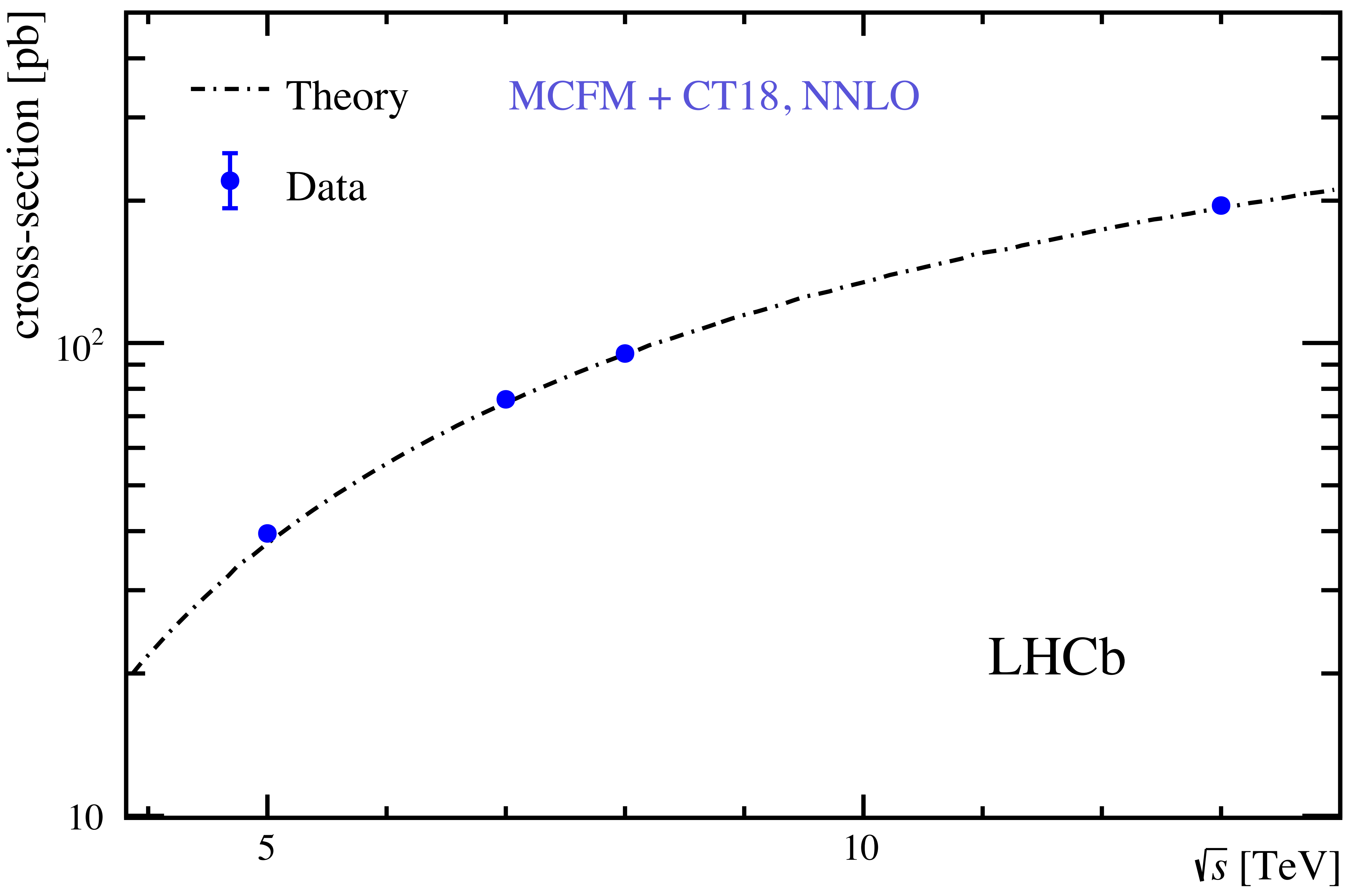


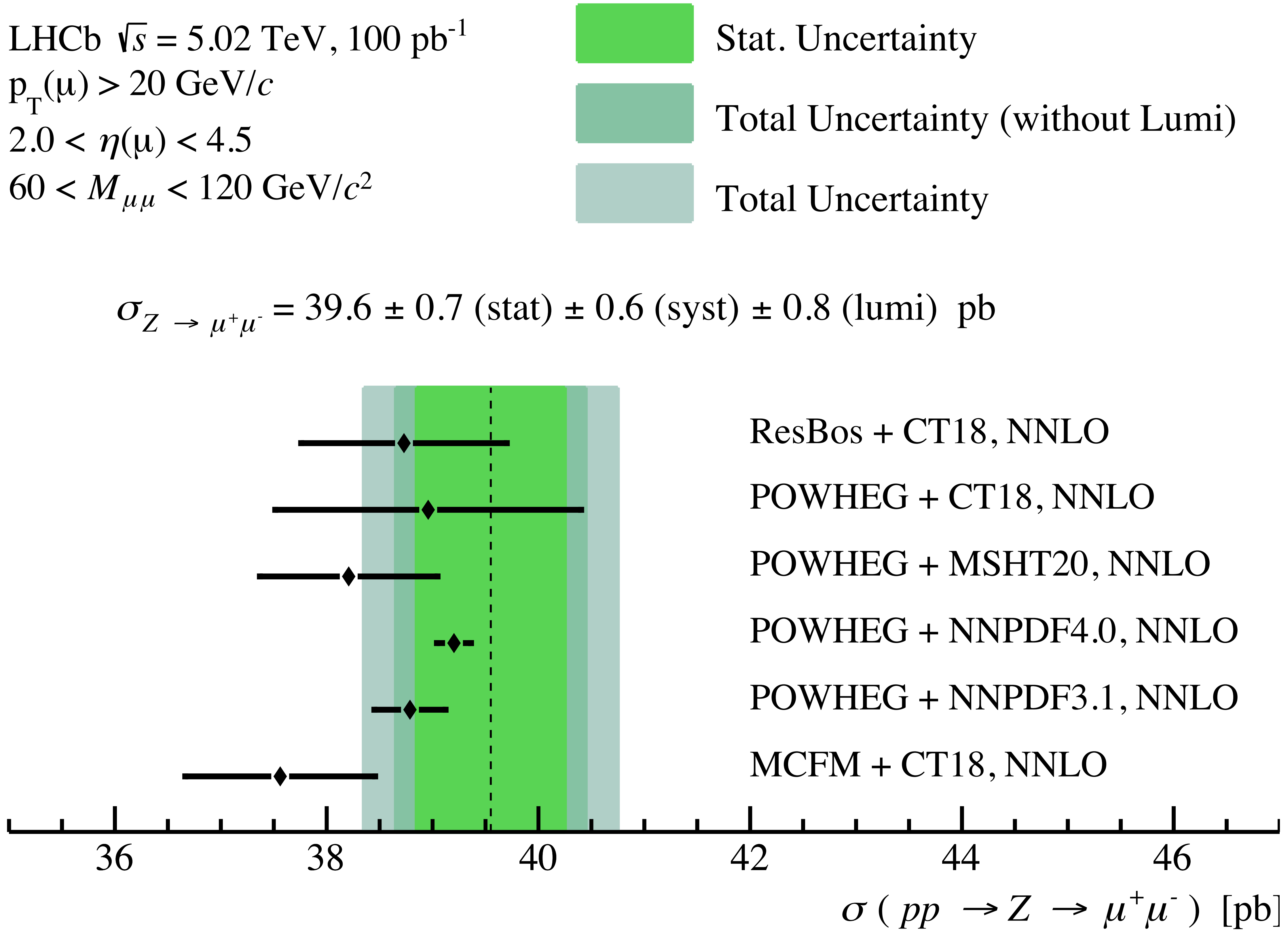


JHEP02(2024)070

Measurement of Z boson production cross-section in pp collisions at √5.02 TeV

- **Good agreement confirmed in total cross section measurement**





Conclusions

- LHCb was designed to do b-physics. But I hope I have convinced you that **LHCb will be able to tackle physics beyond its original design purpose even further than what it is already doing**
  - **Bright future for LLP direct searches**
  - **Exciting landscape already here for EW measurements**

- 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**

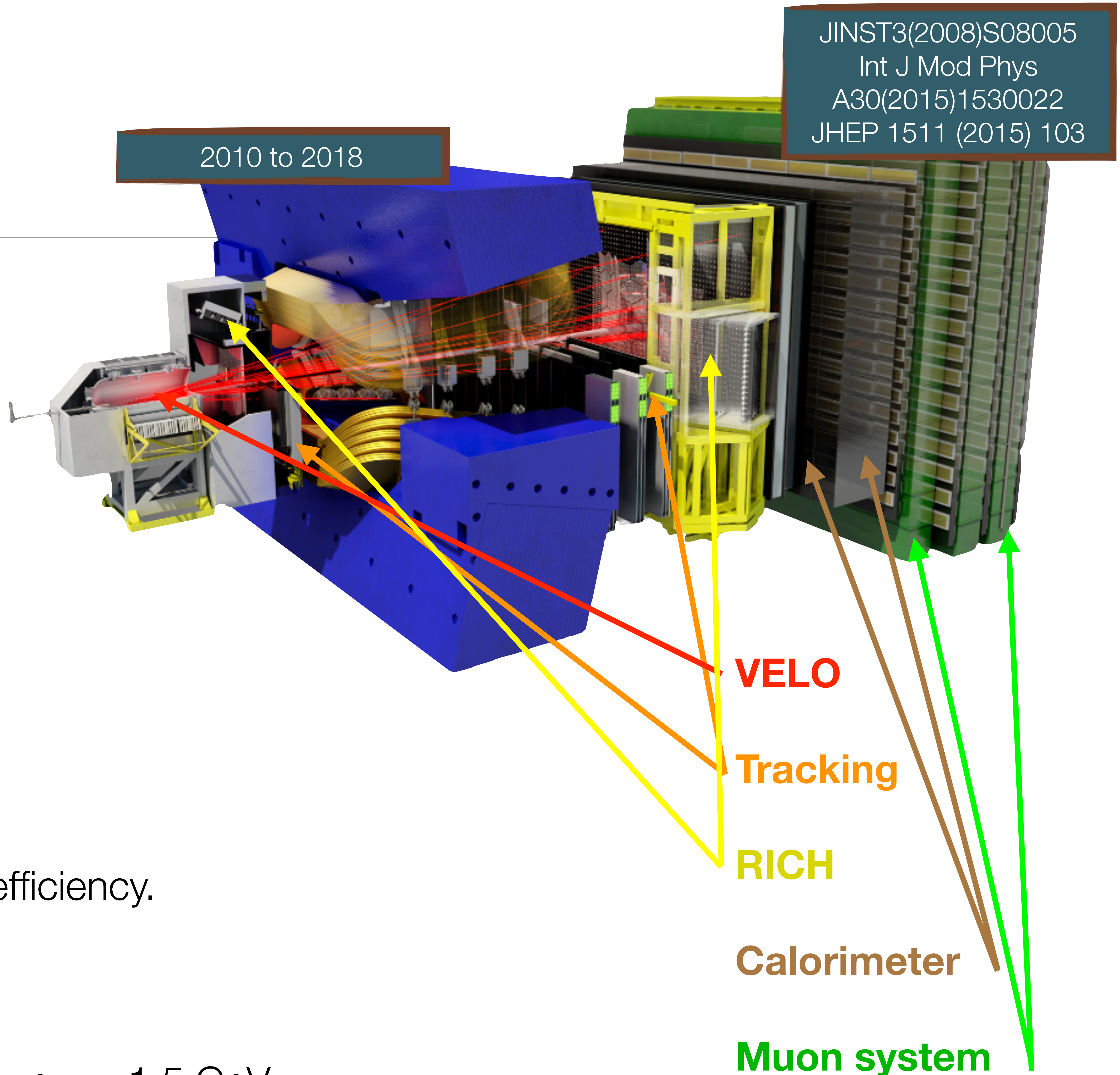
ASPEN2014 Theoretical summary - M. Mangano

Backup

Federico Leo Redi

LHCb detector in Run 1&2

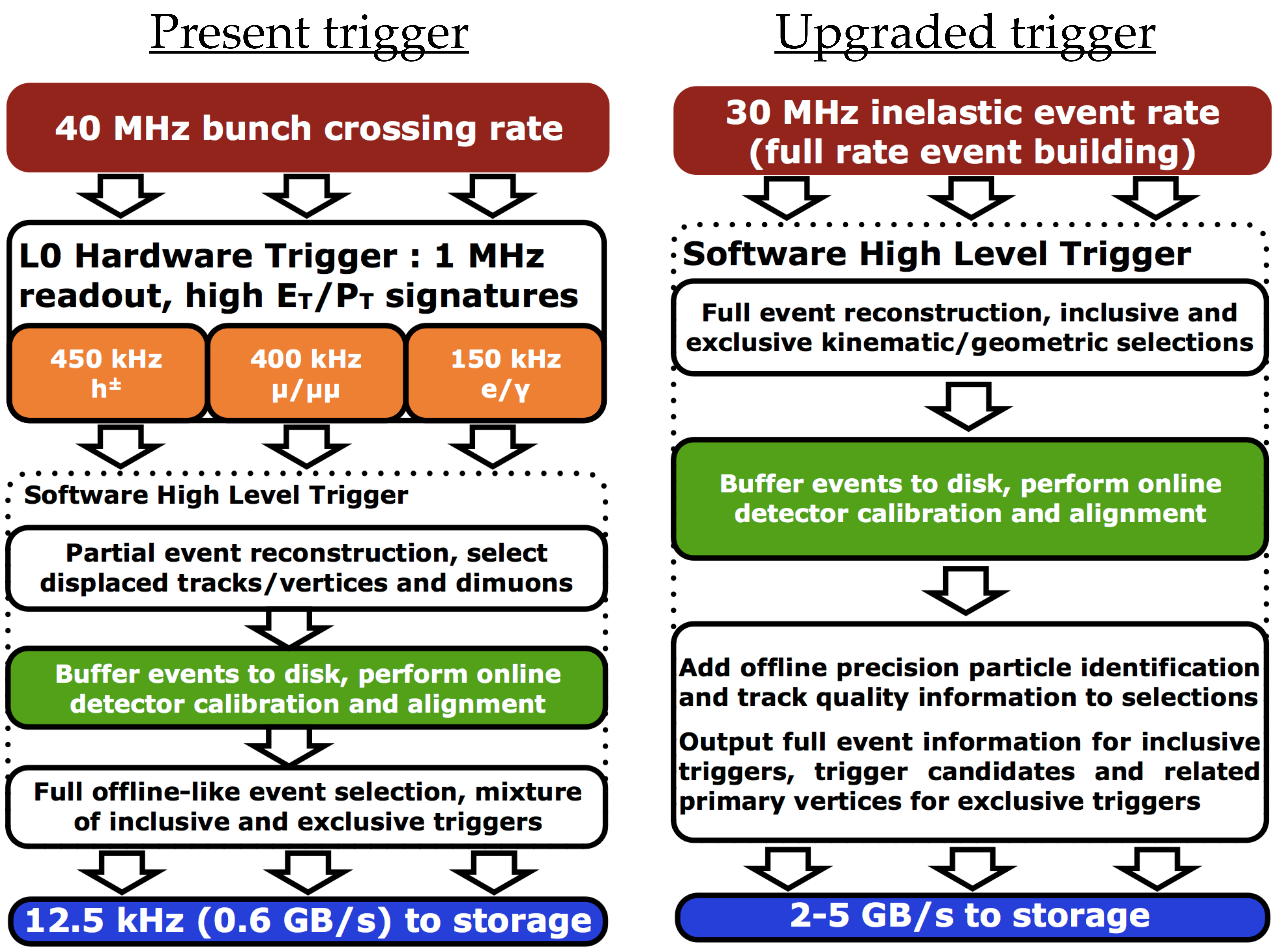
- **LHCb** is a dedicated flavour experiment in the **forward region** at the LHC ($1.9 < \eta < 4.9$) (~1°-15°)
- **Precise vertex reconstruction** < 10 μm vertex resolution in transverse plane.
- Lifetime resolution of ~ 0.2 ps for $\tau = 100$ ps.
  - ~ 45 fs for B0s -> J/psi phi and B0s -> Ds pi
- **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.



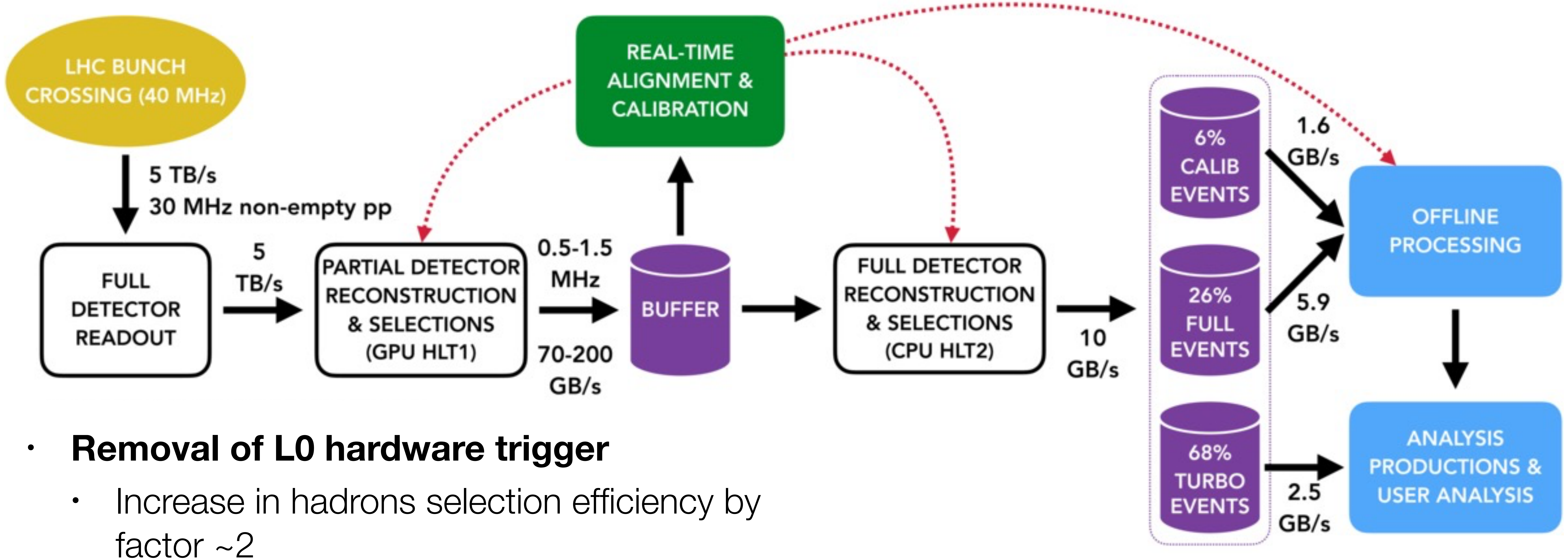
CERN-LHCC-2014-016
LHCB-TDR-016

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

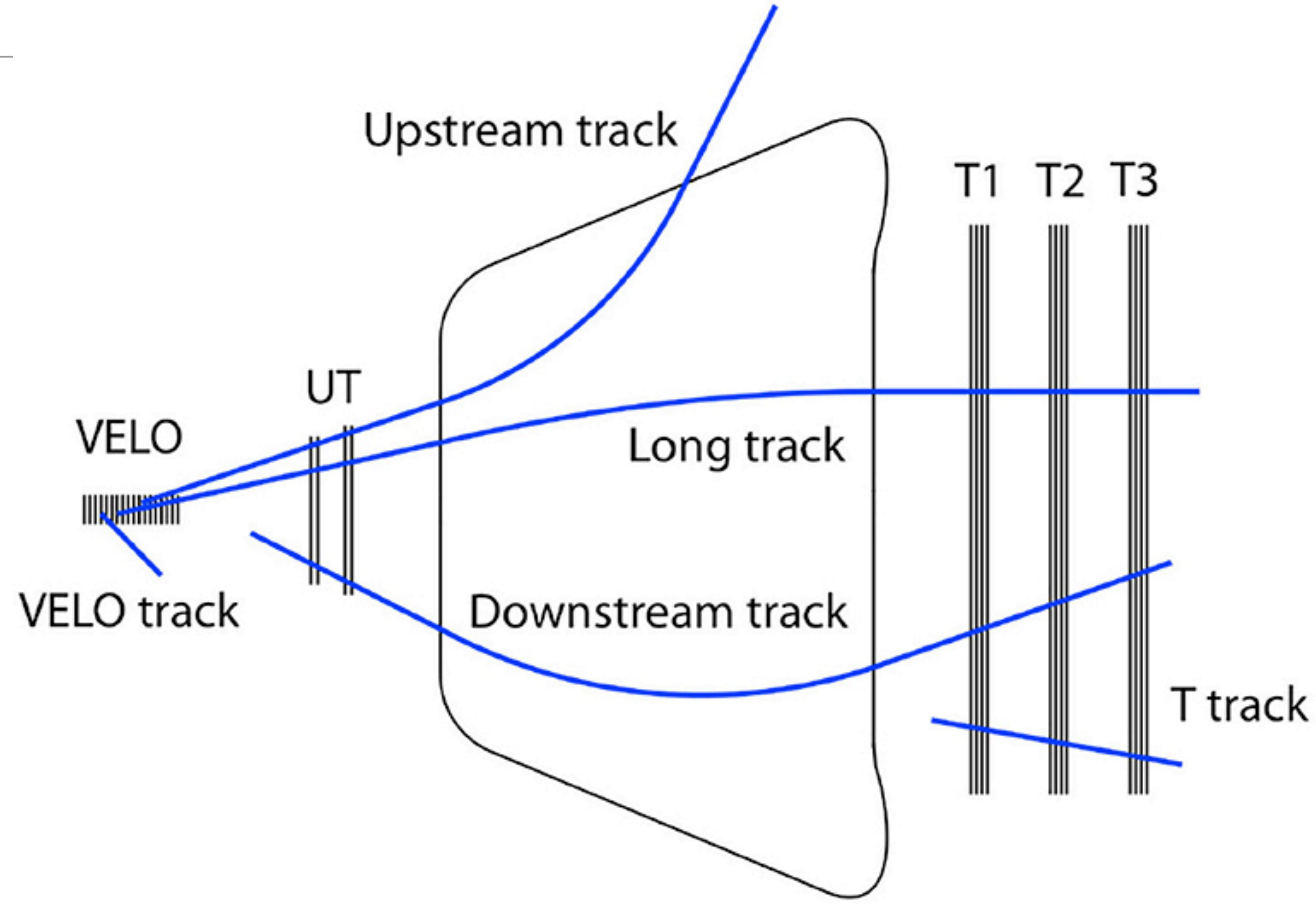


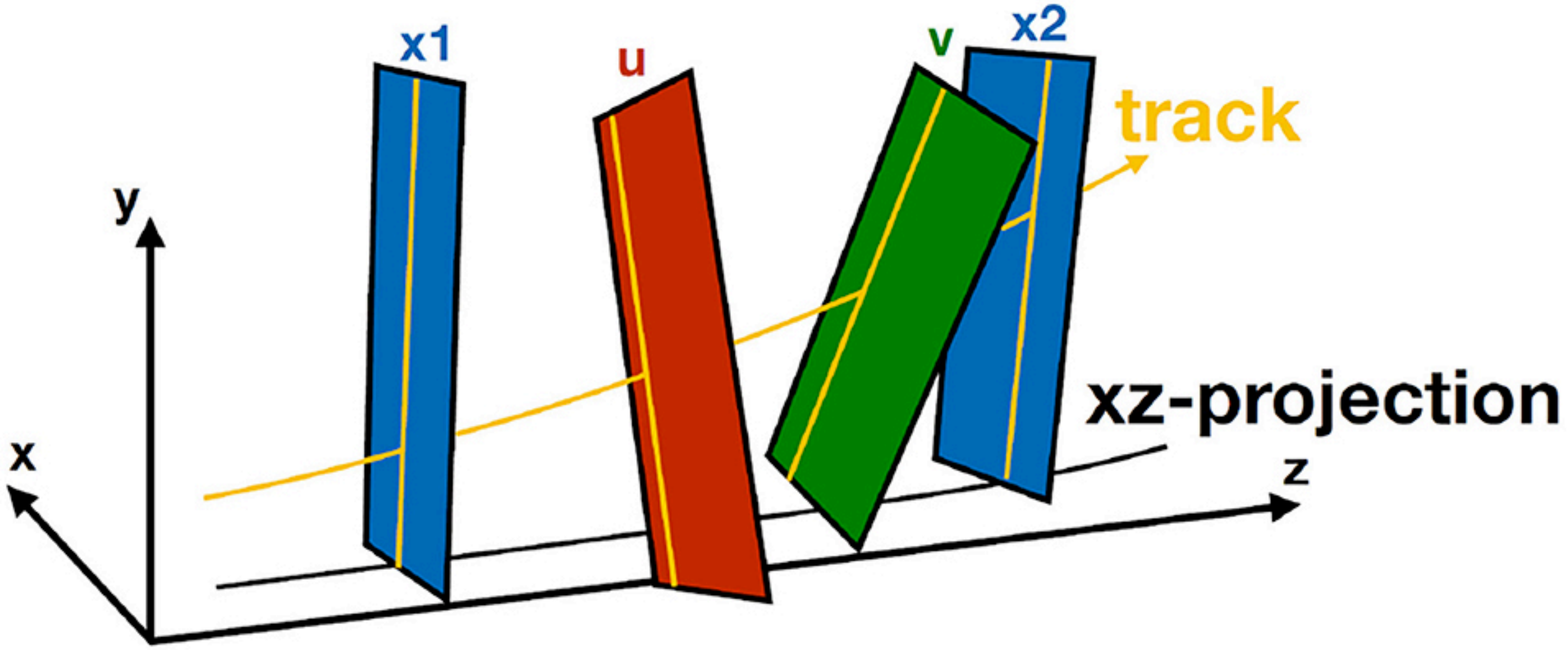
- **Removal of L0 hardware trigger**
  - Increase in hadrons selection efficiency by factor ~2
- **HLT1 reconstruction on GPUs**
  - First GPU trigger in a HEP experiment
- **Offline reconstruction in HLT2**

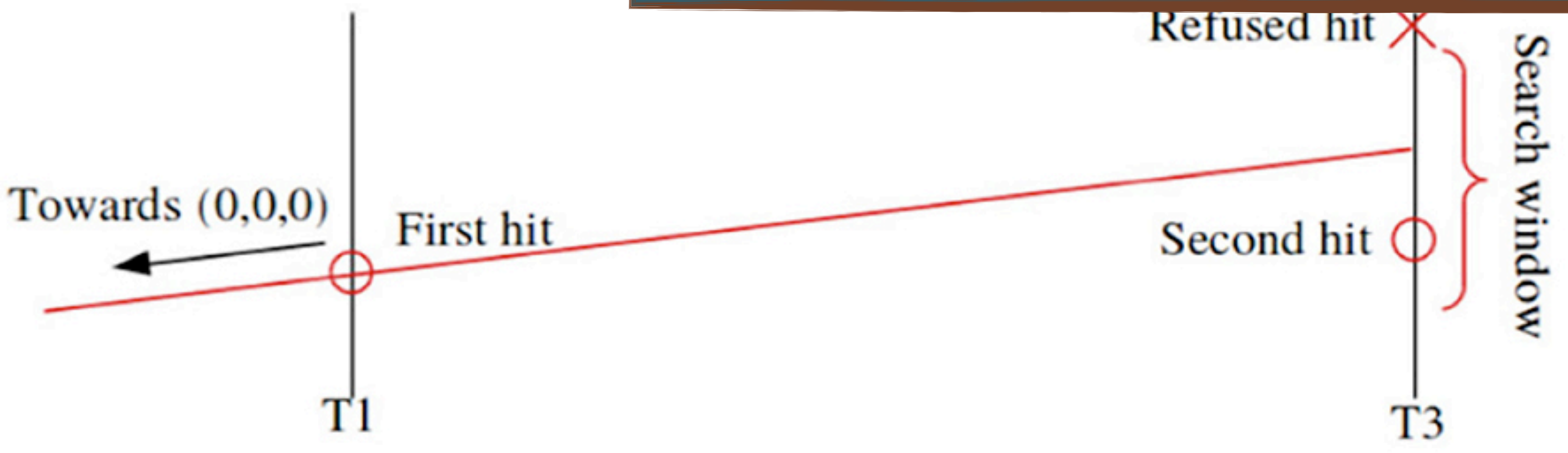
A new algorithm at LHCb to reconstruct Long-Lived particles in the first level trigger

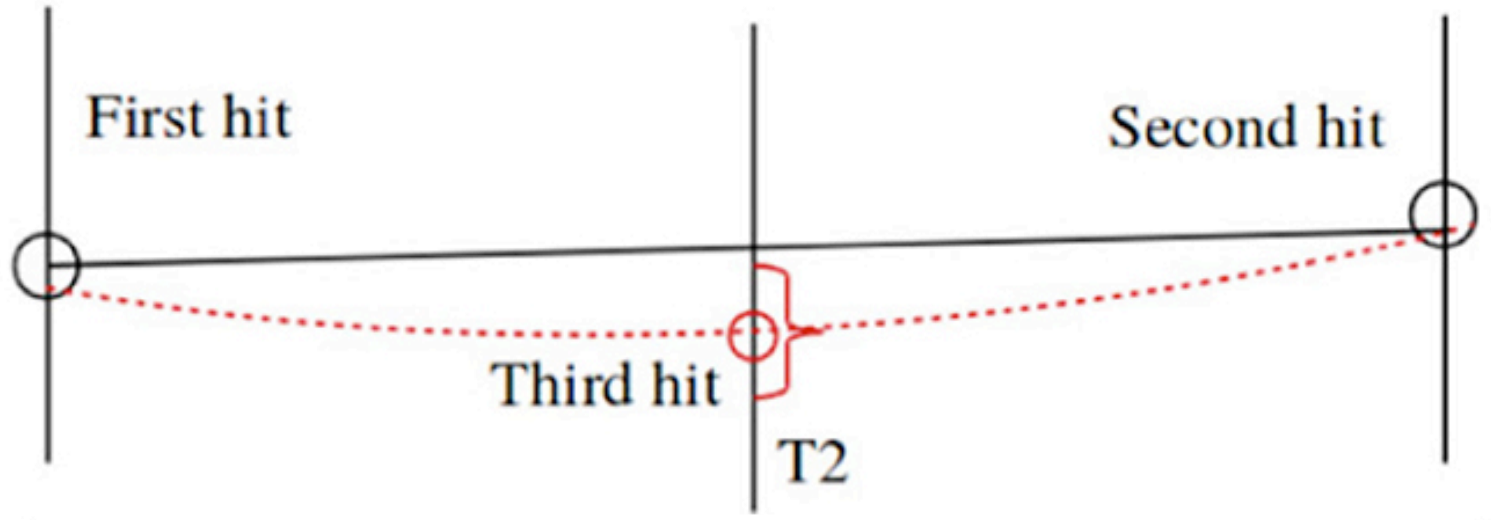
Arantza’s talk at connecting the dots

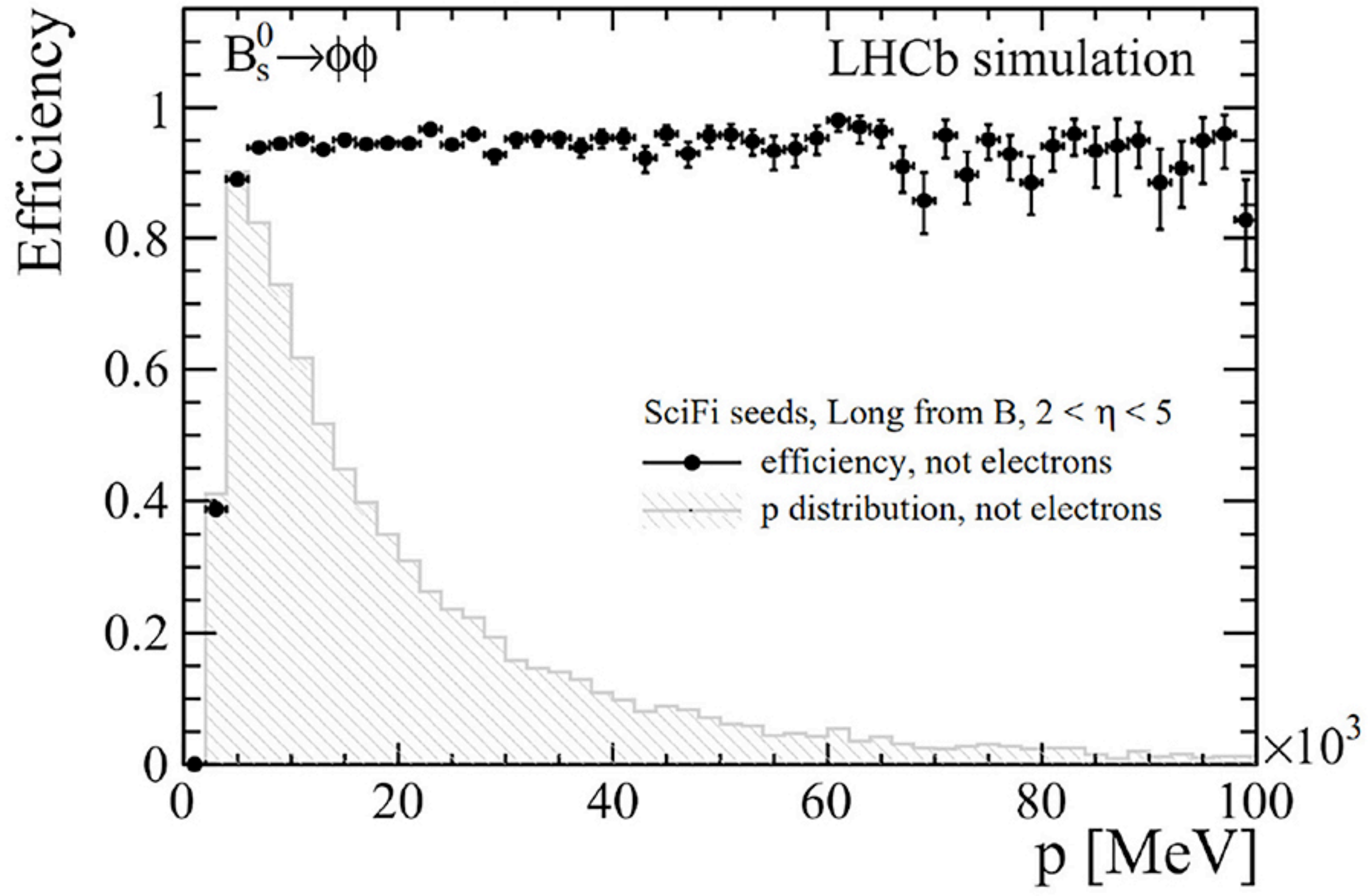
Calefice et al., Frontiers in Big Data, 2022. DOI:10.3389/fdata.2022.1008737.



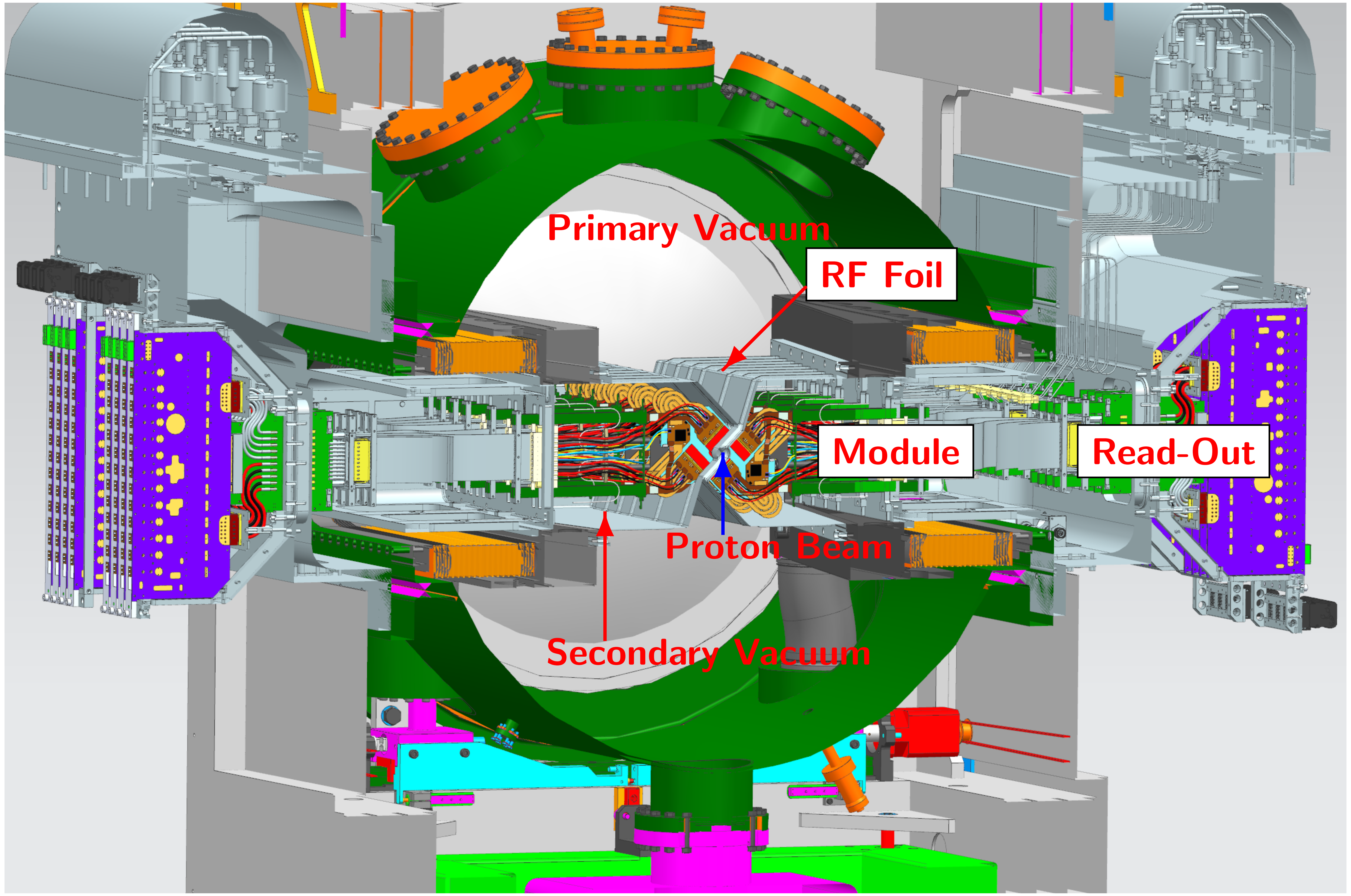


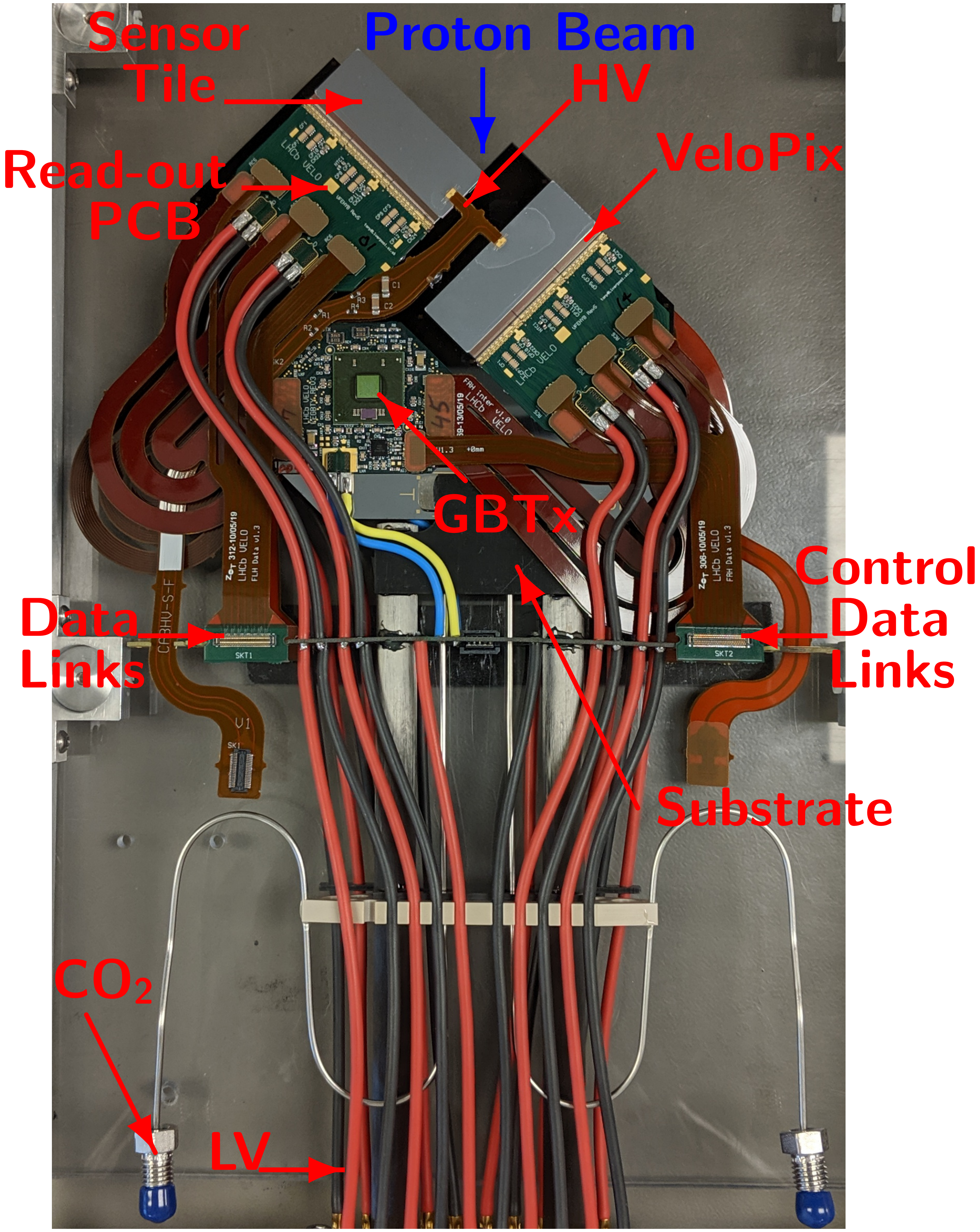






VELO

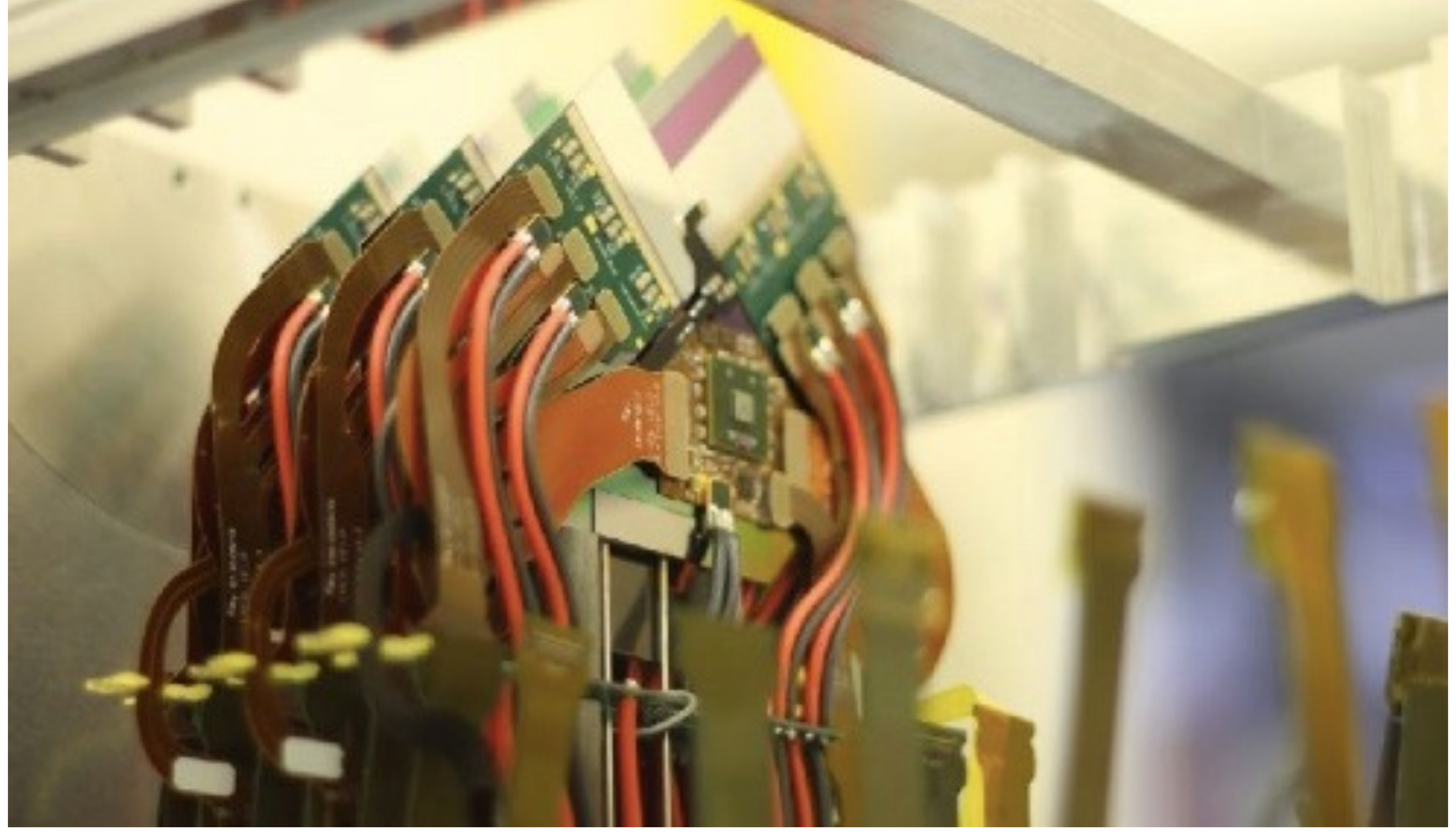

Primary Vacuum
RF Foil
Module
Read-Out
Proton Beam
Secondary Vacuum

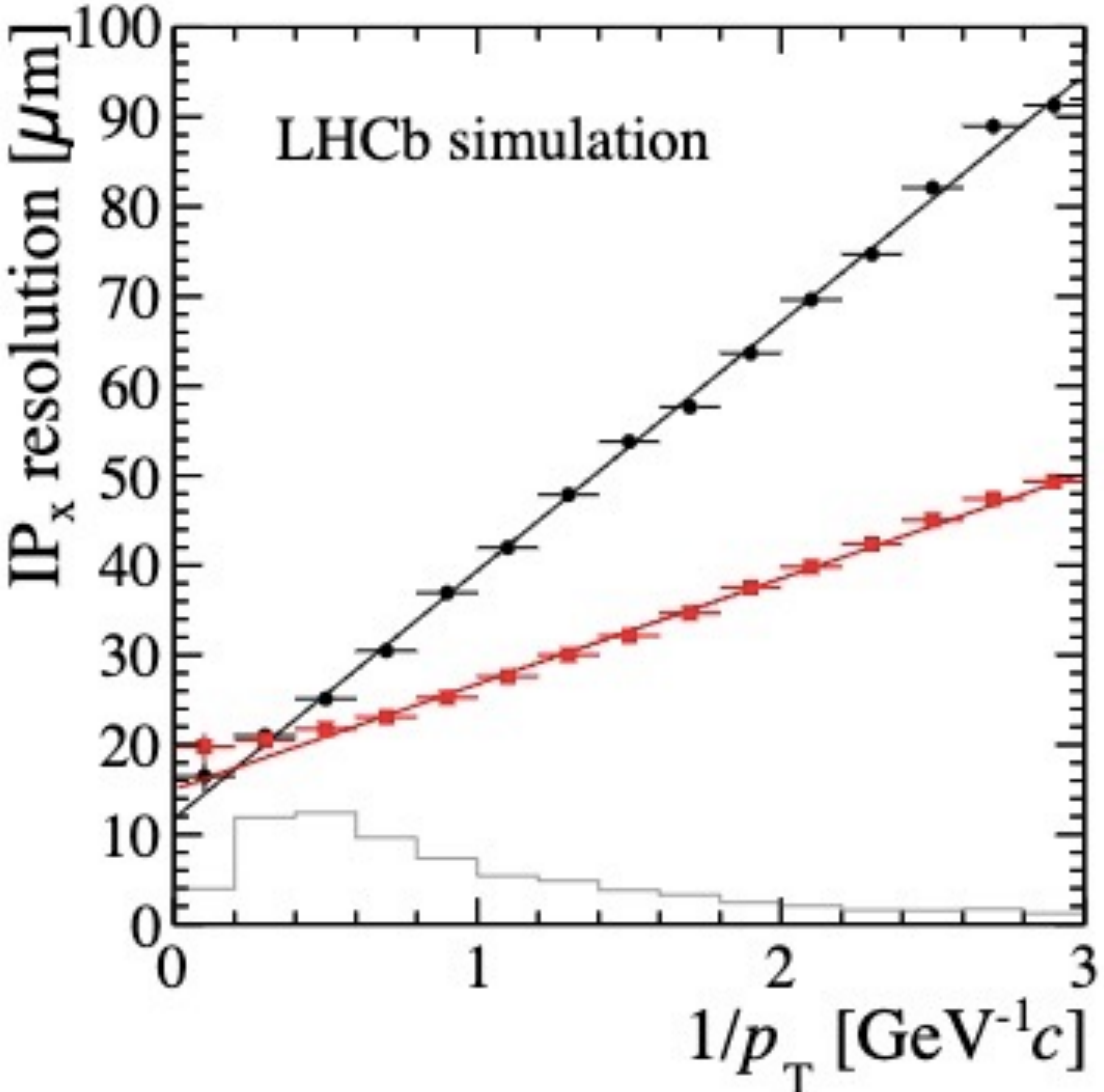

Sensor Tile
Proton Beam
HV
VeloPix
Read-out PCB
GBTx
Control Data Links
Data Links
Substrate
CO2
LV

CERN-LHCC-2013-021 and LHCB-TDR-013

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 CO2 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

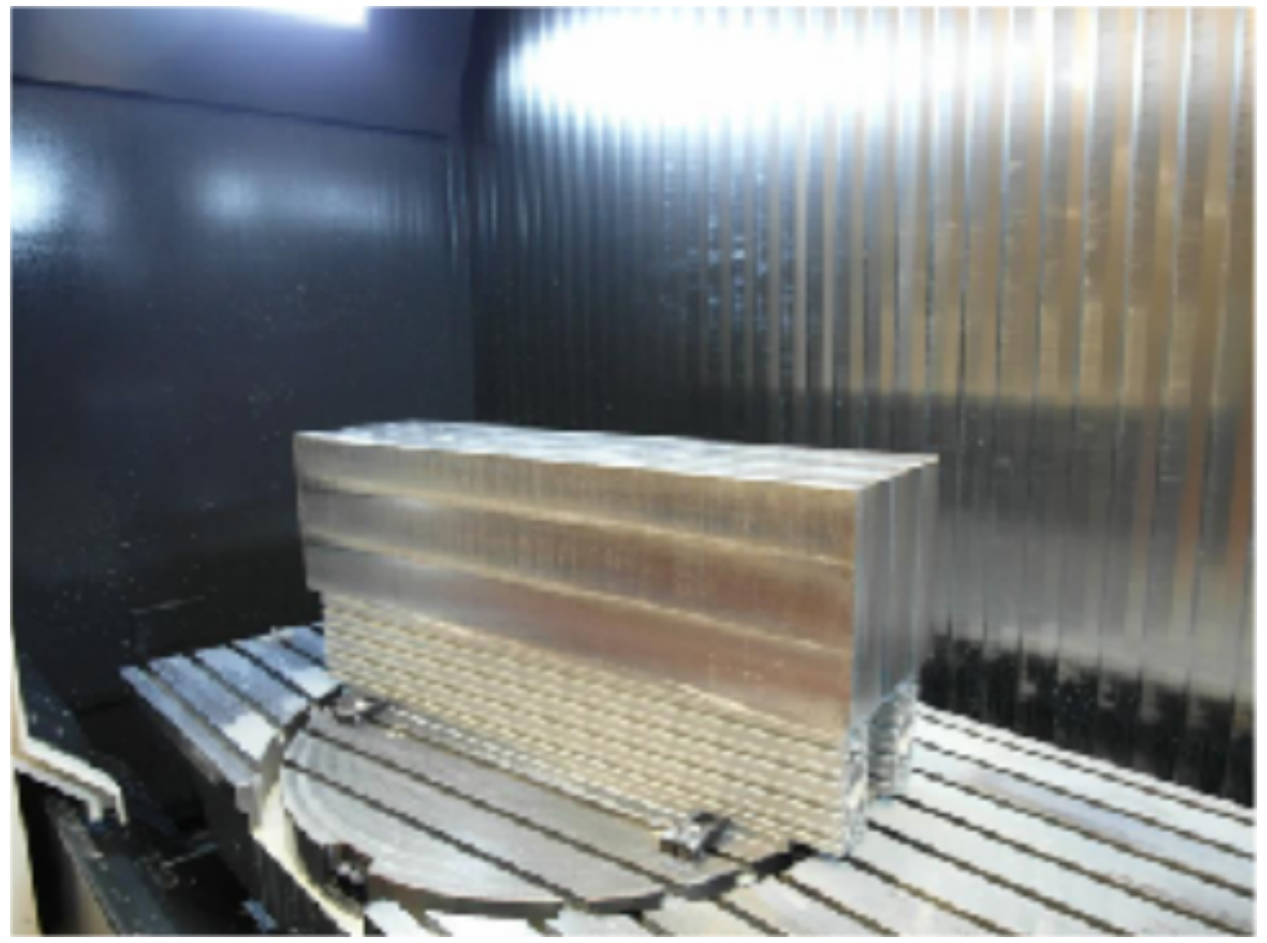


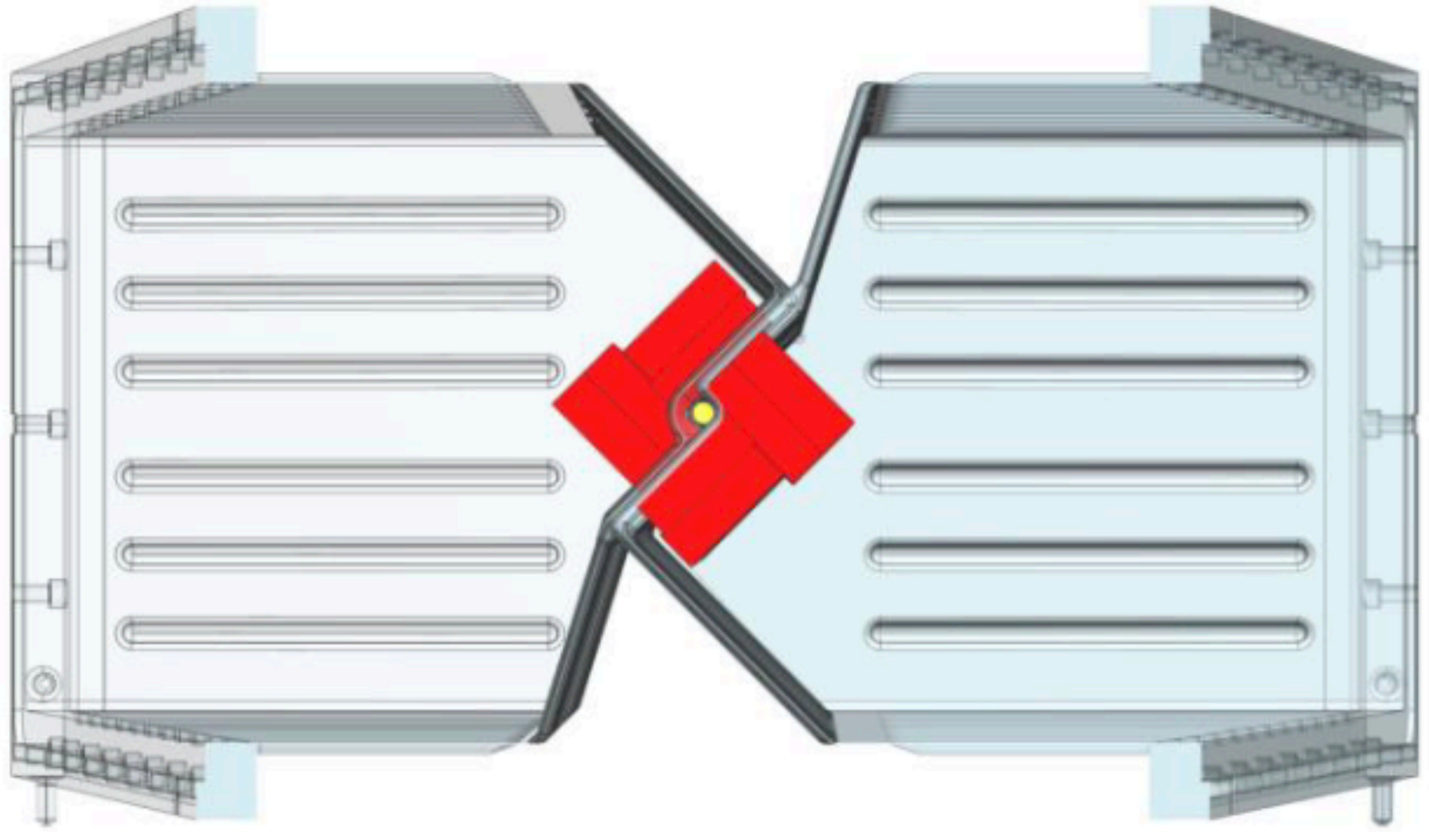


CERN-LHCC-2014-016
LHCB-TDR-016
F. Sanders' slides

VELO

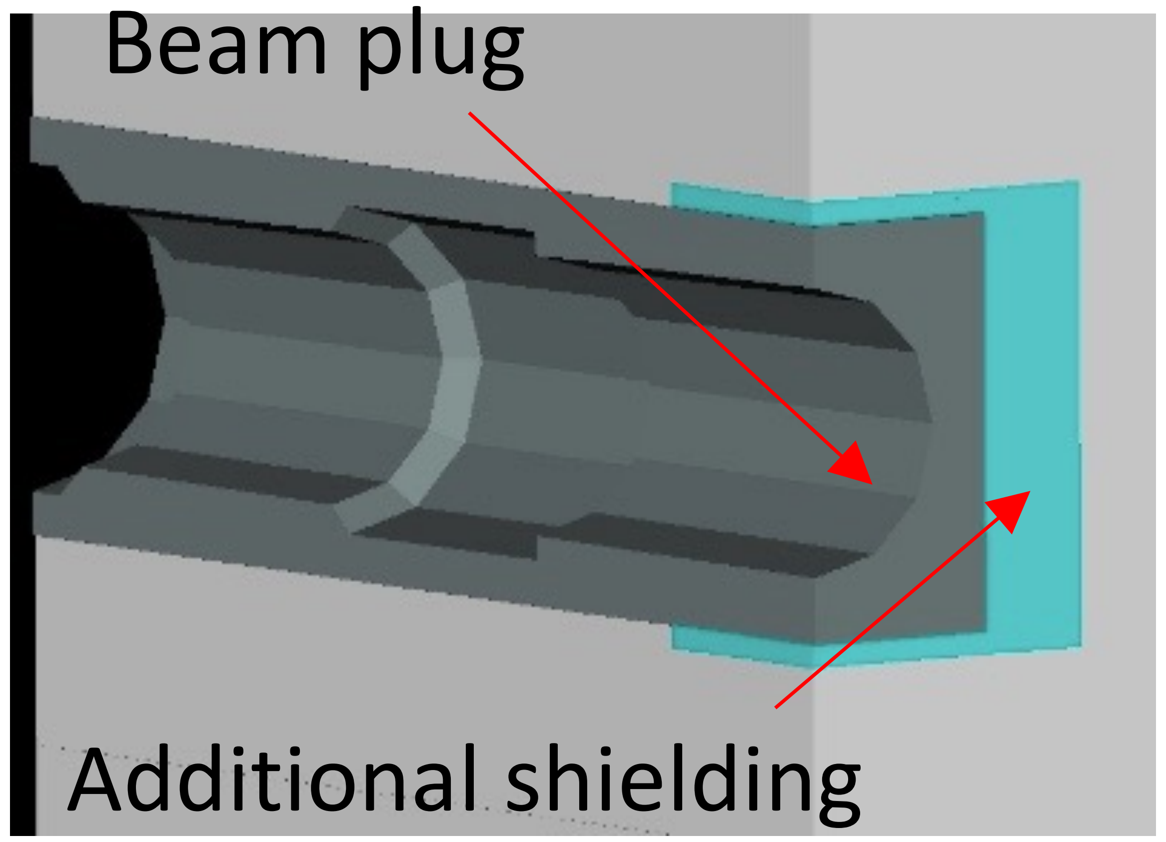
- **Example**: the RF foil separates primary to secondary vacuum
- Start from a single, forged **AlMg3** alloy block
- **98%** of material is milled away (6 months)
- Final thickness at tips of modules: on average **250 µm**





Muon stations

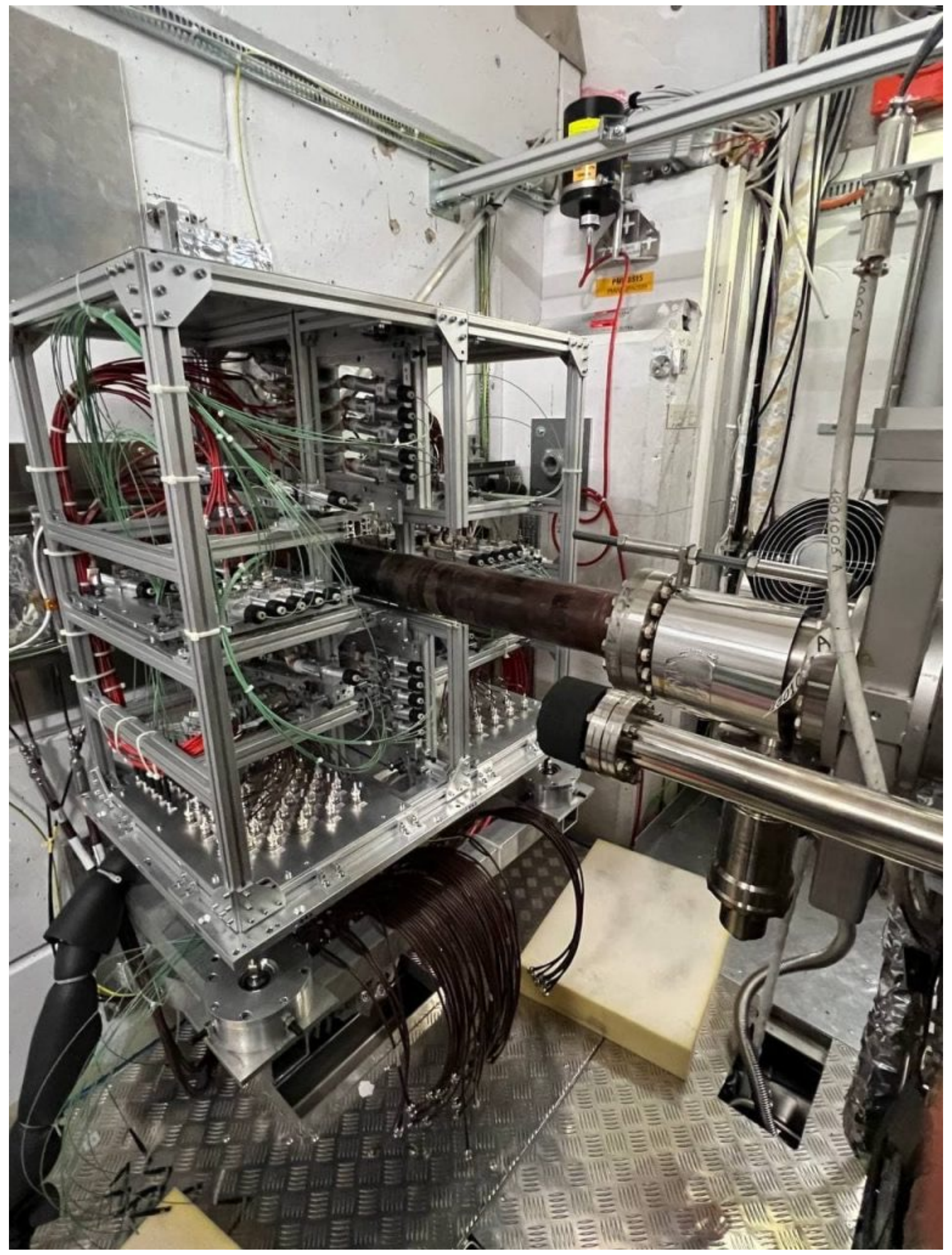
- **Not everything needed to be changed:**
- ECAL and HCAL and
- **Muon stations**
    - 4 layers (M2-M5) of Multi-Wire Proportional Chambers (MWPCs)
- Remove first layer (M1) with GEMs, since L0 trigger level has been removed
- Therefore more space:
    - install additional shielding around beampipe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



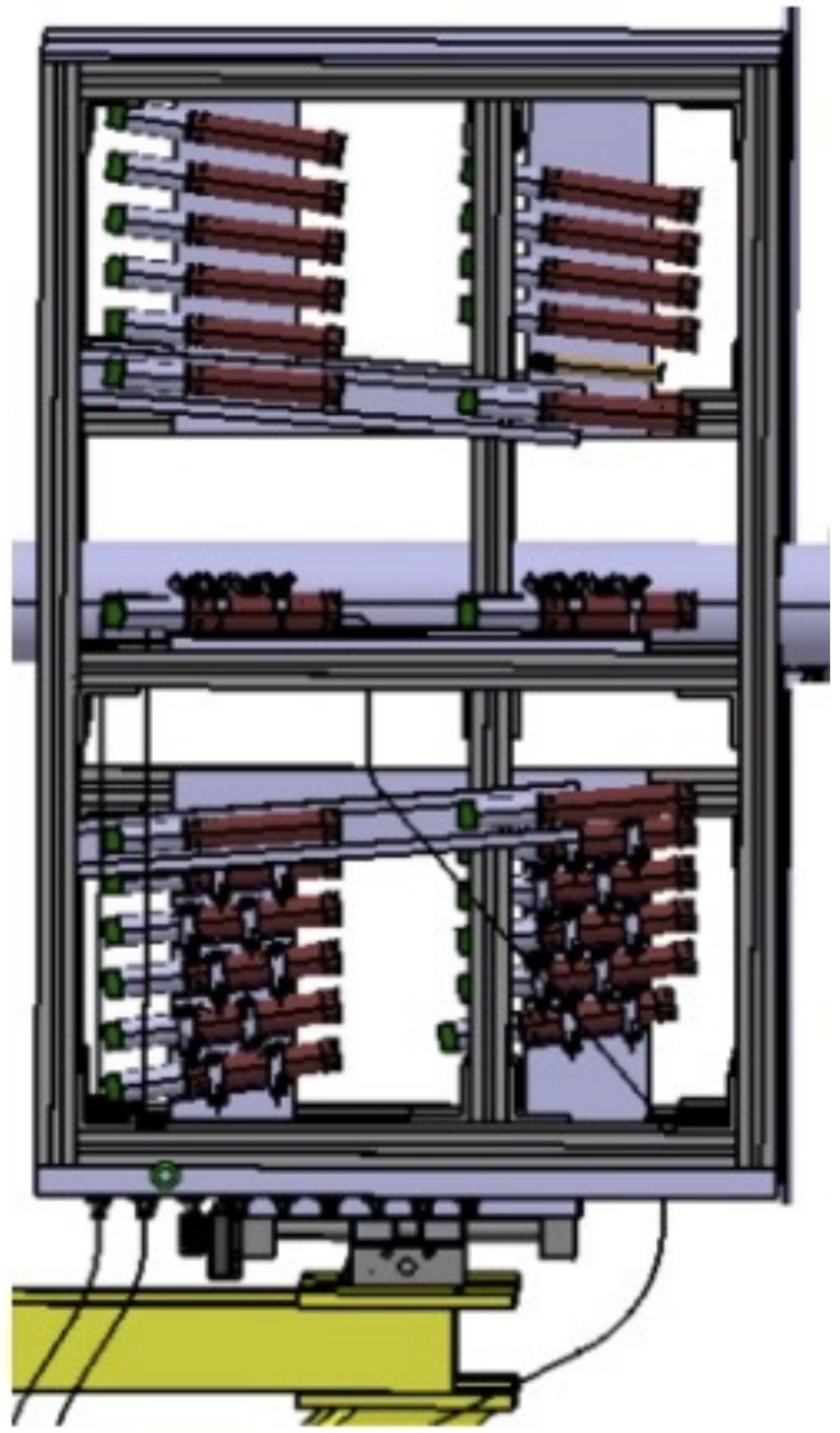
CERN-LHCC-2021-022

PLUME

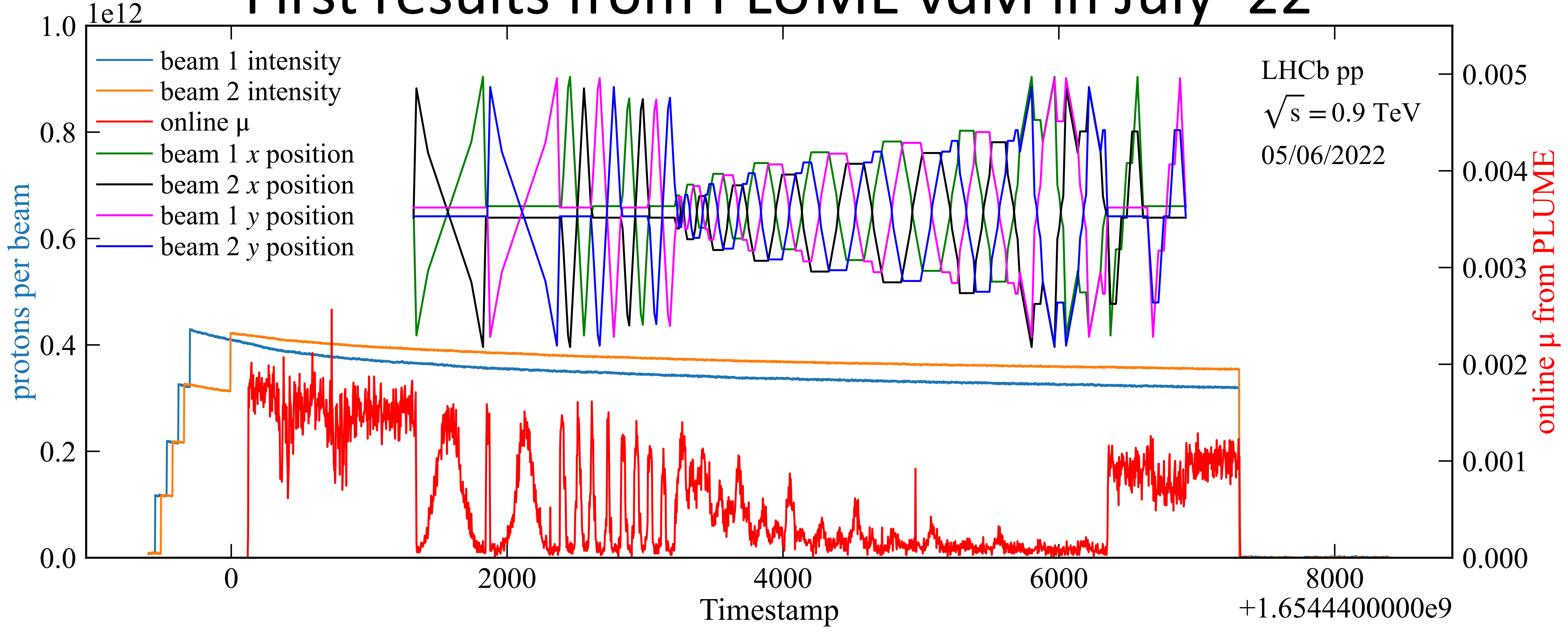
- Cross-shaped hodoscope composed by 48 PMTs, installed upstream of the VELO
  - Detect Cherenkov light from particles impinging on a quartz tablet glued to the PMTs window
- **Measure rate of coincidences every 3 seconds and compute luminosity with "logZero" method**
  - Count the number of bunch crossings 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

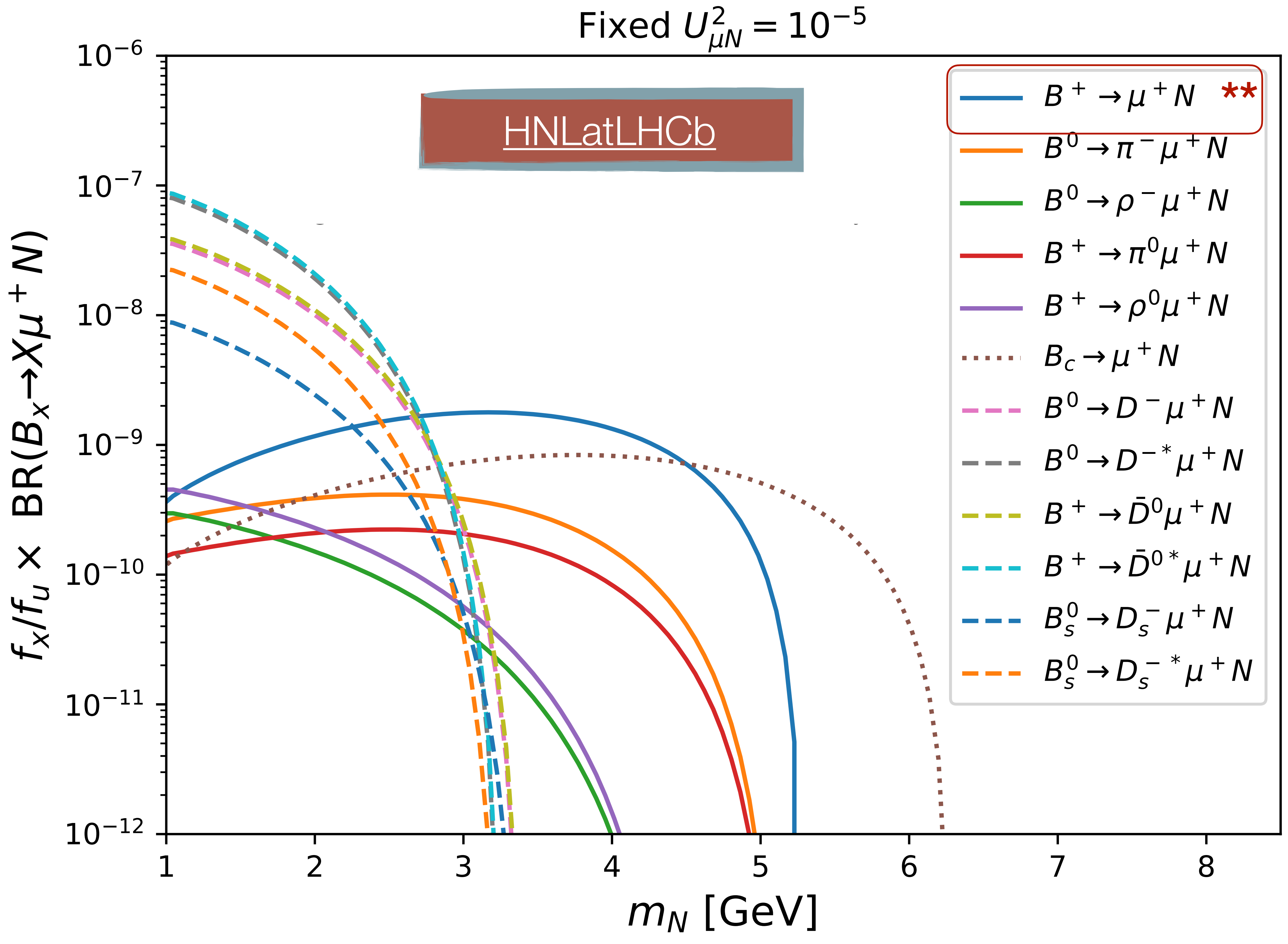


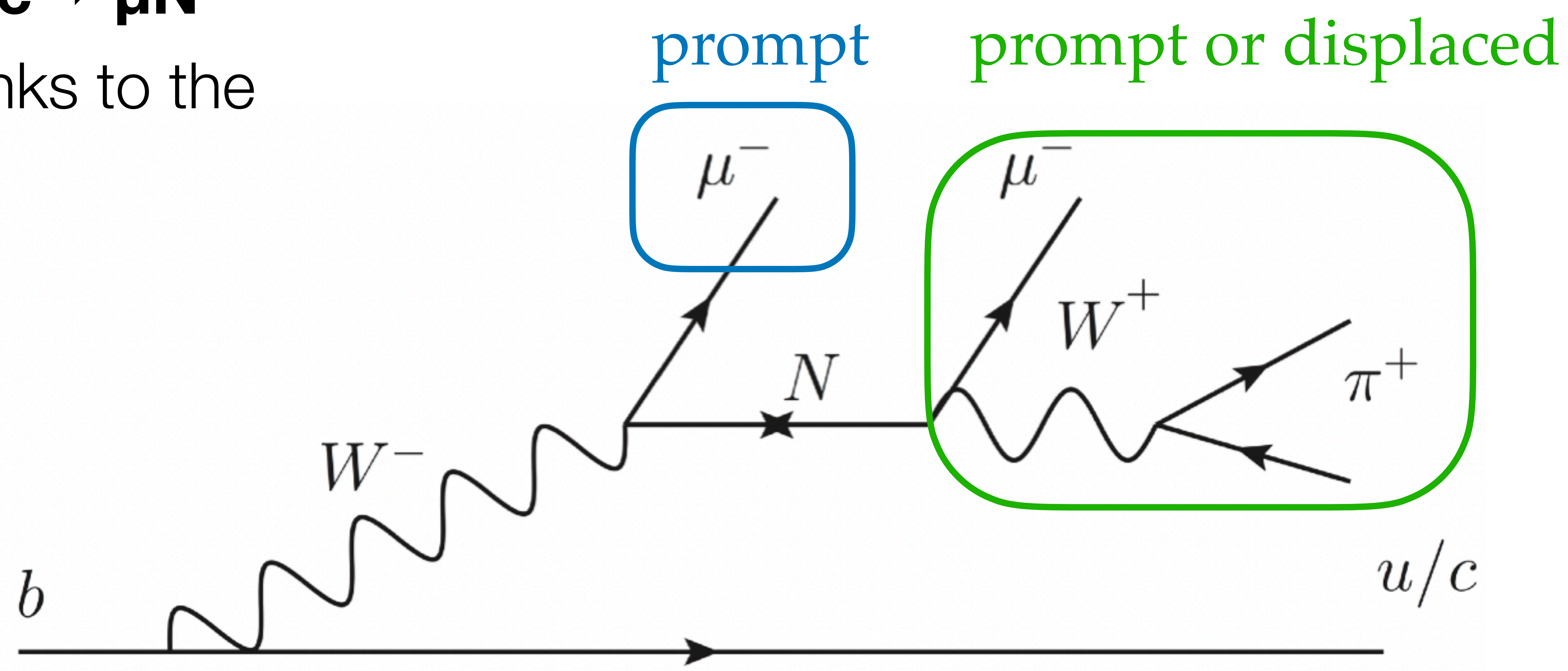
First results from PLUME vdM in July '22



What about from a *b*?

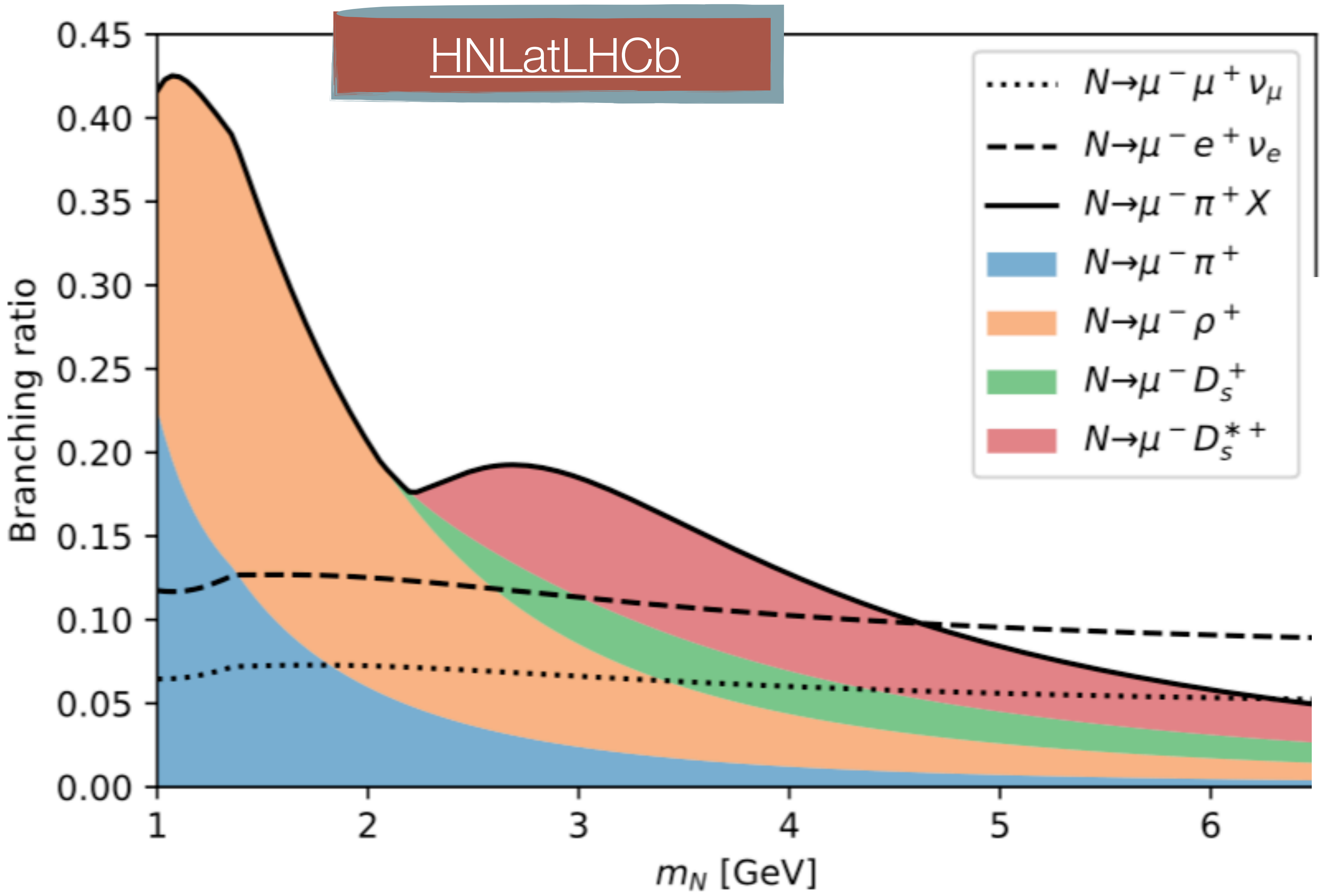
- Can one expand such narrow searches? Combine all the knowledge of b quarks and missing masses?
- Yes, e.g. in Majorana neutrino searches where it's hard to compete with LHCb in the B production region
- Previous analysis (B → μN**) only used one production mode: simple but inefficient
- **Here Xb →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

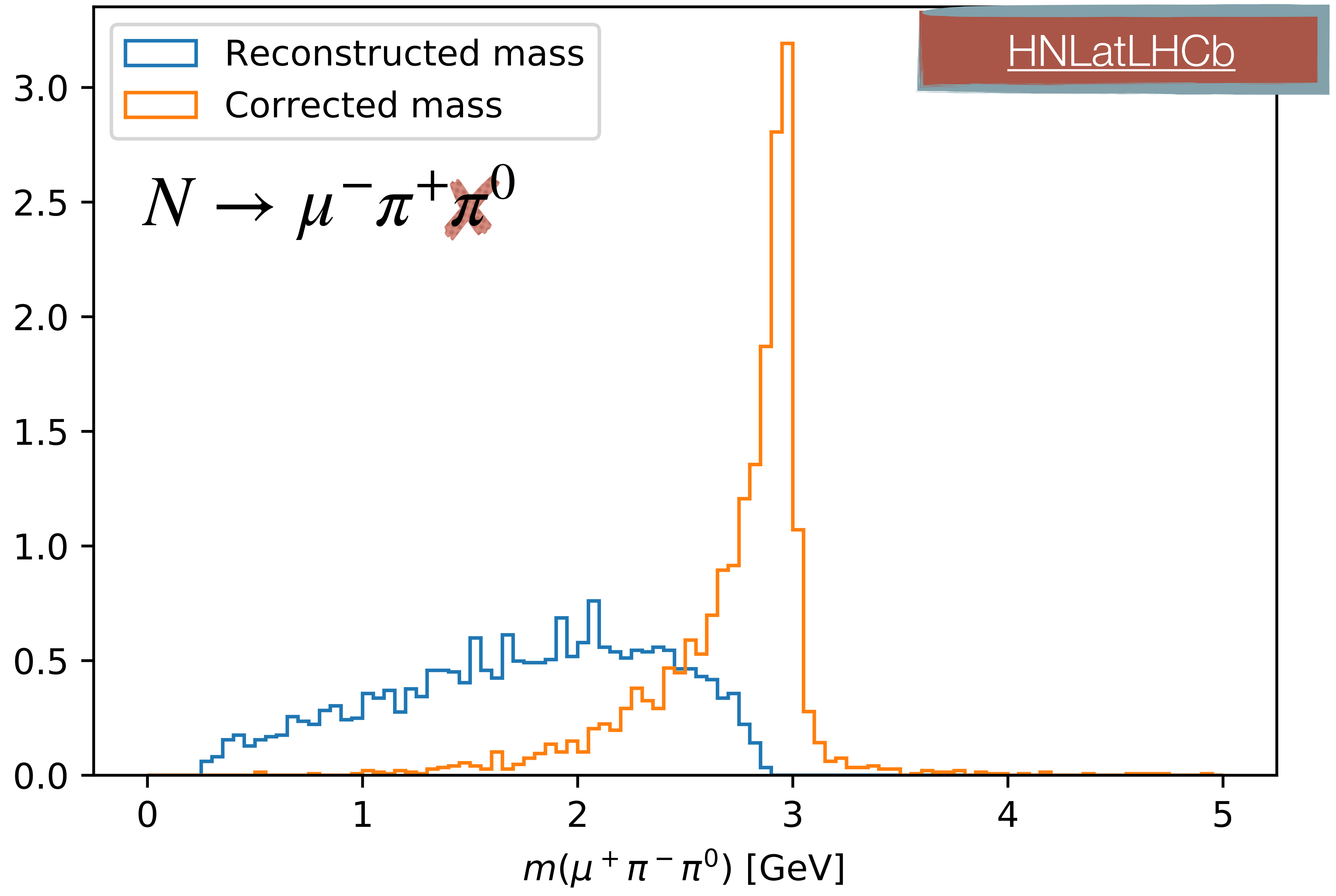


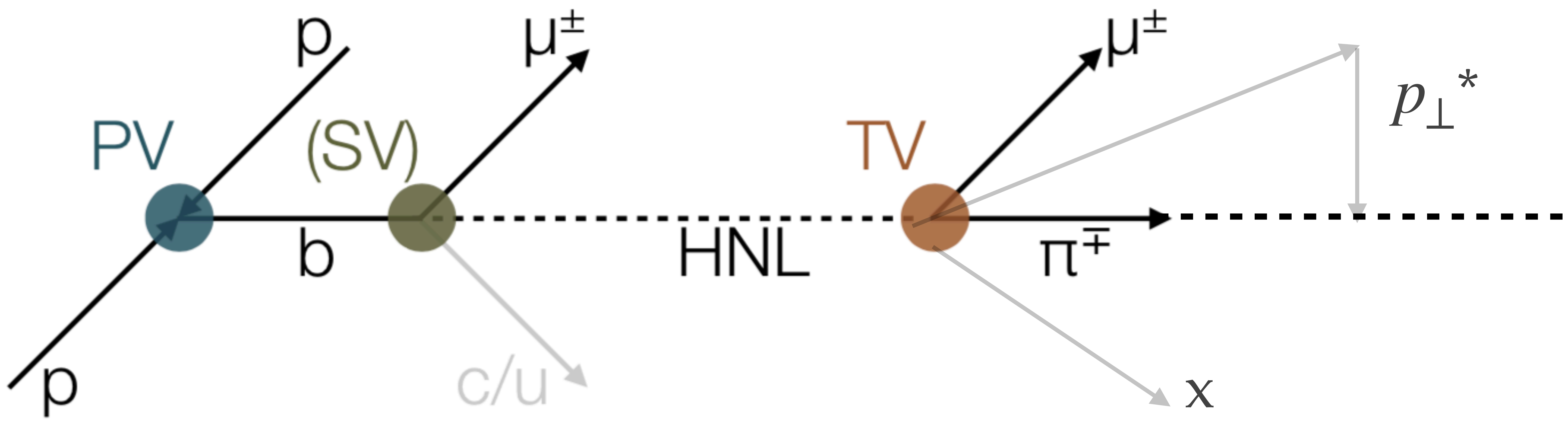


Heavy neutral leptons

- 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

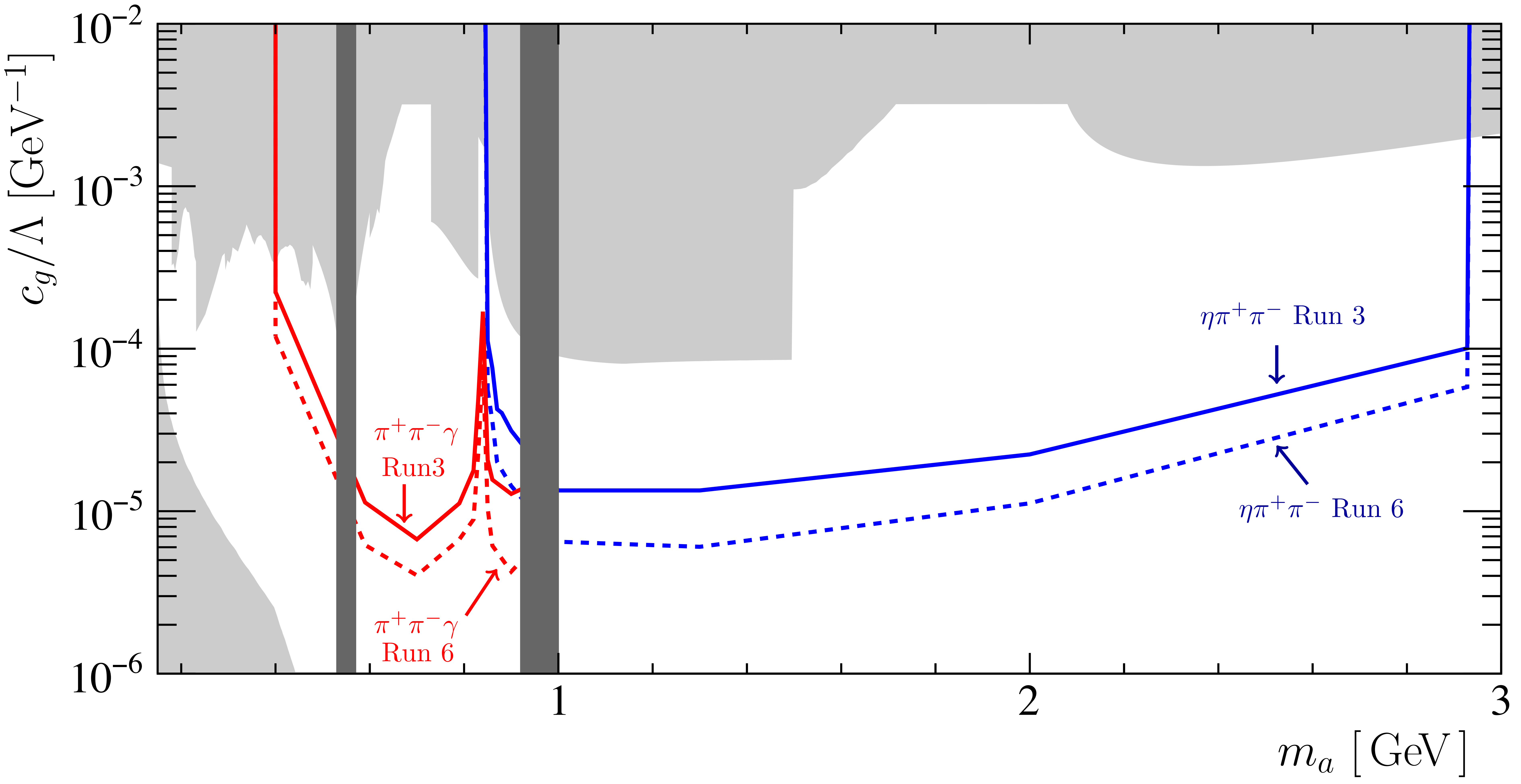






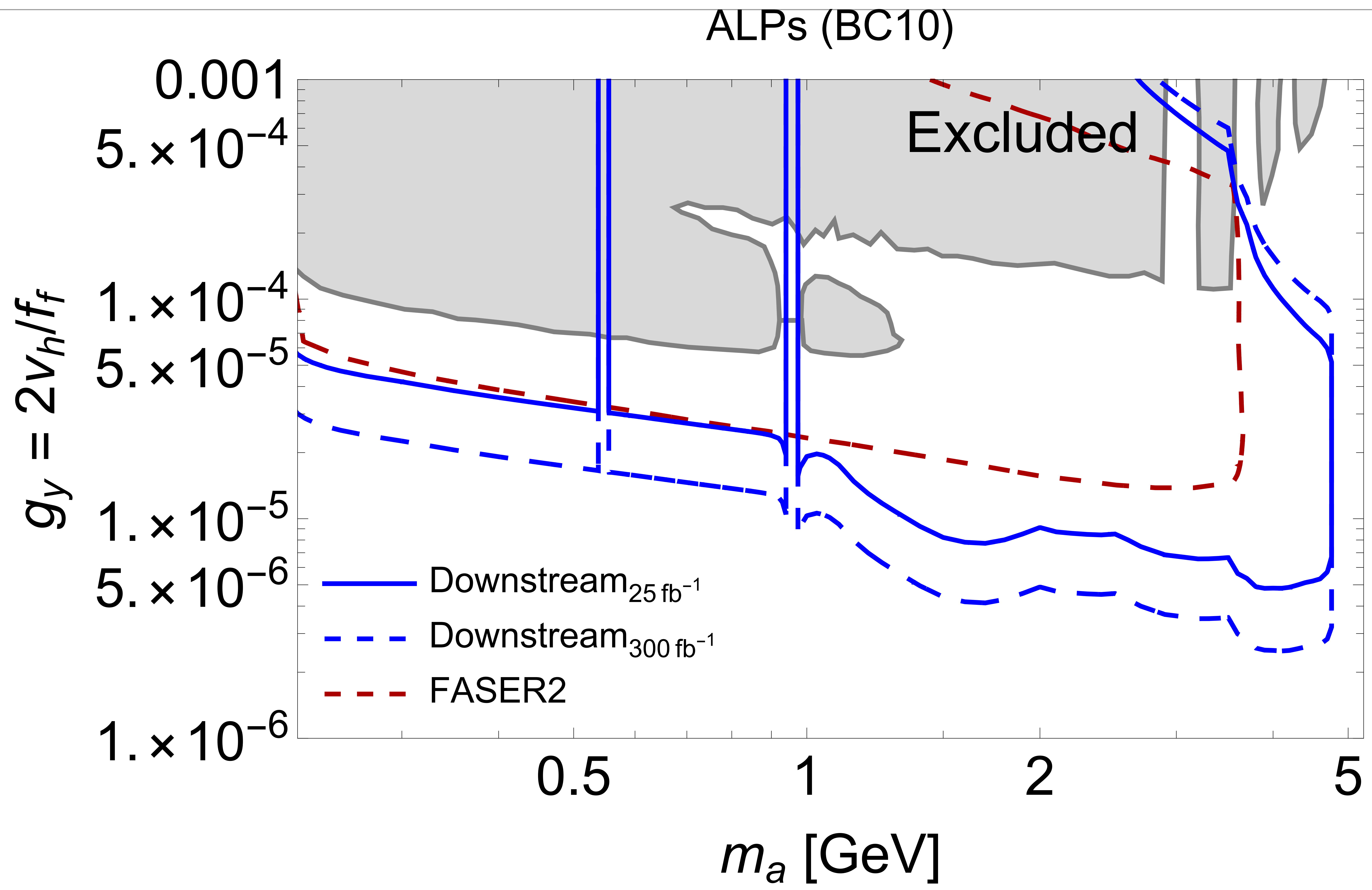
ALPs

2203.07048



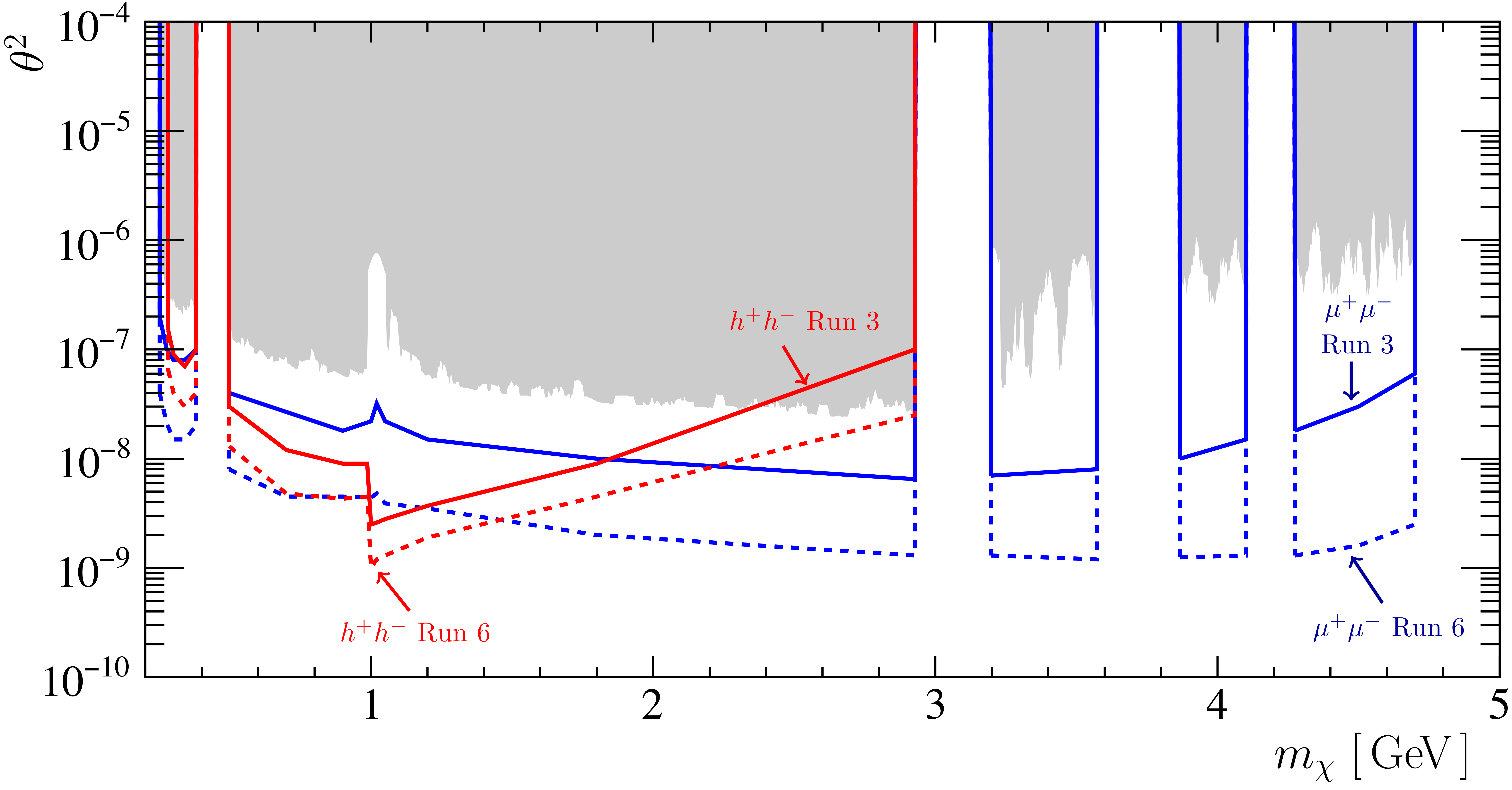
ALPs with downstream

2312.14016



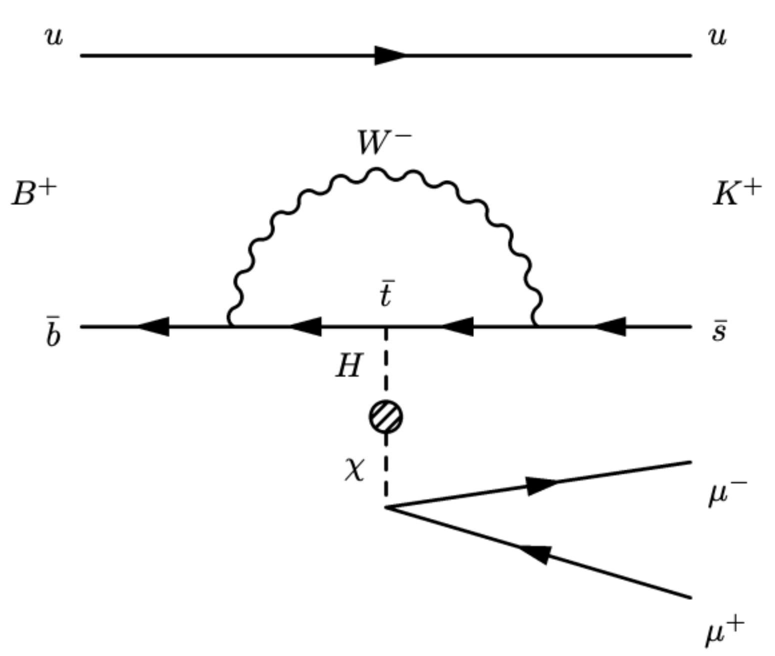
Higgs portal

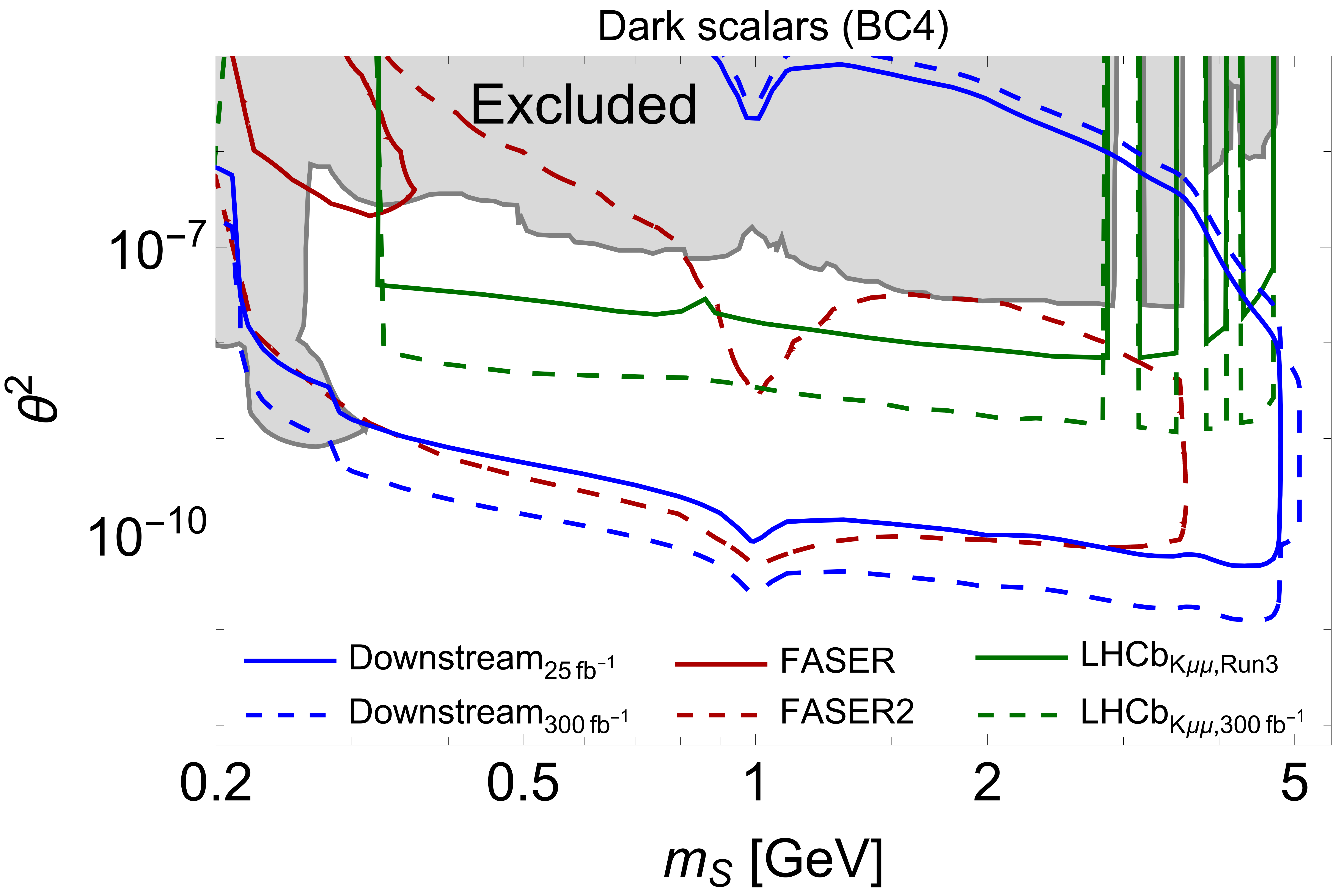
2203.07048



Higgs portal with downstream

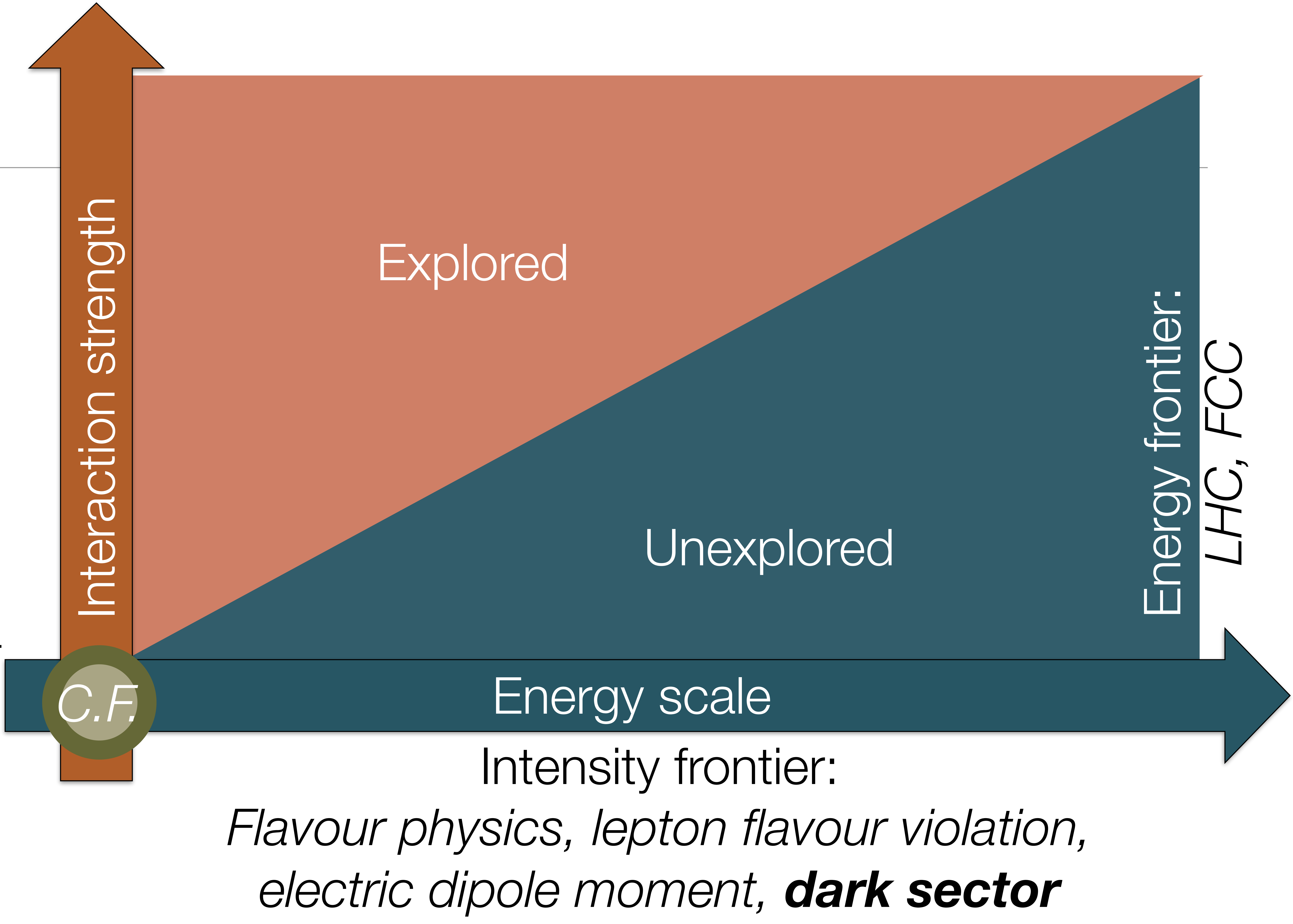
2312.14016





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**!



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**)

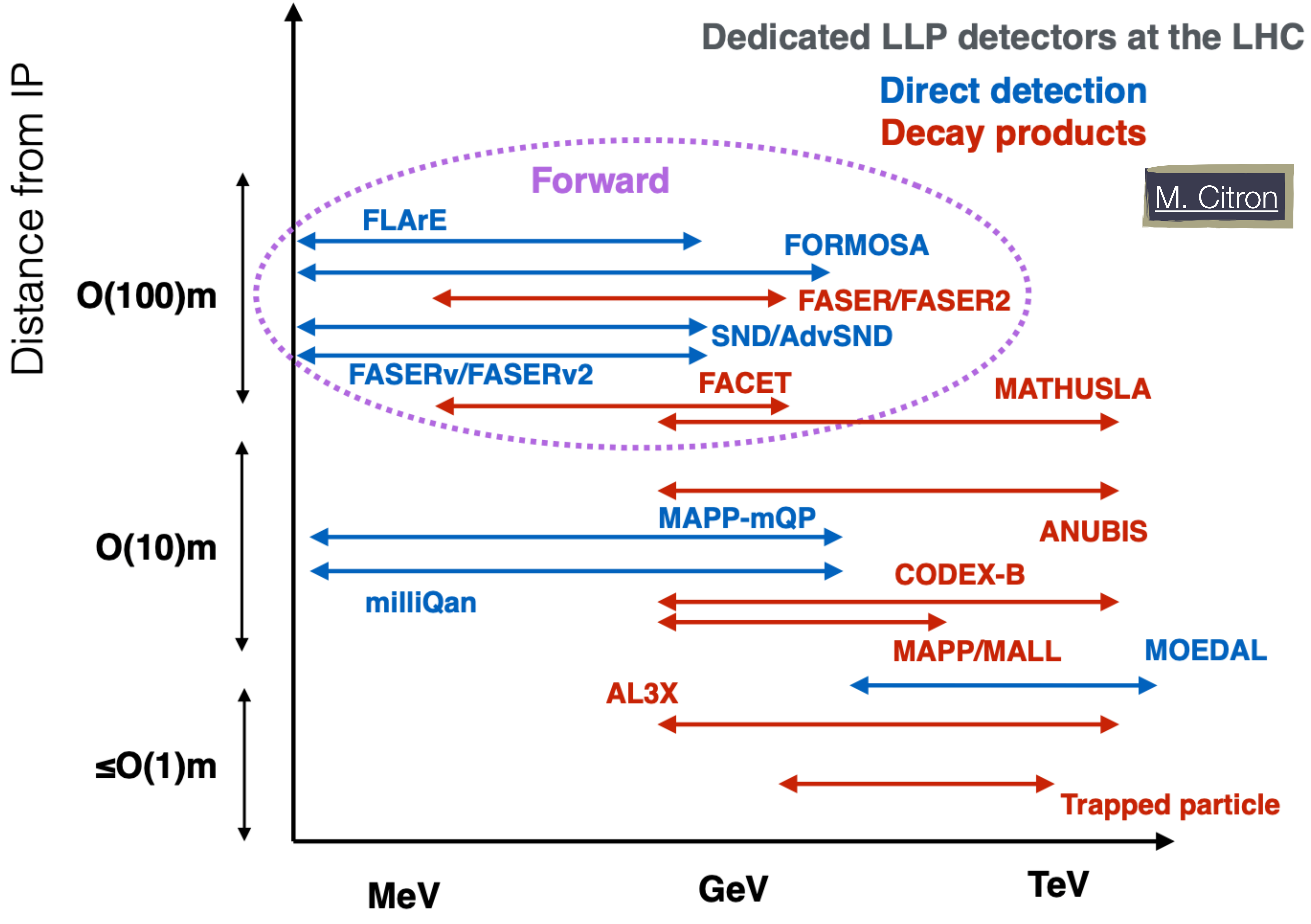
The QEE PAWG

- **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**

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

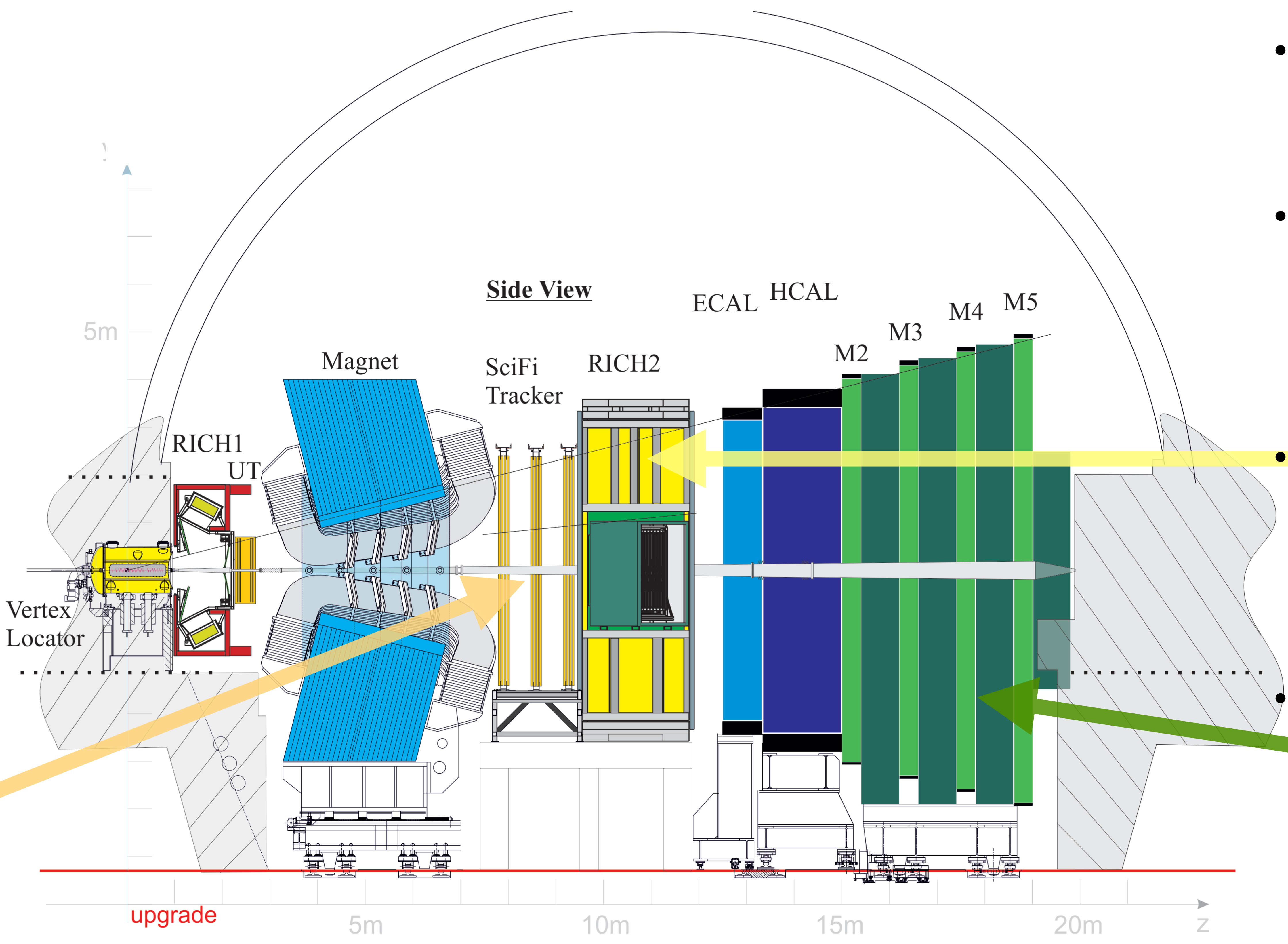
CODEX-b AL3X ANUBIS NA62 BaBar FCC T2K ANITA BDX FPF LISA SeaQuest FPC FCC

J. Beacham

CERN-LHCC-2018-027

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



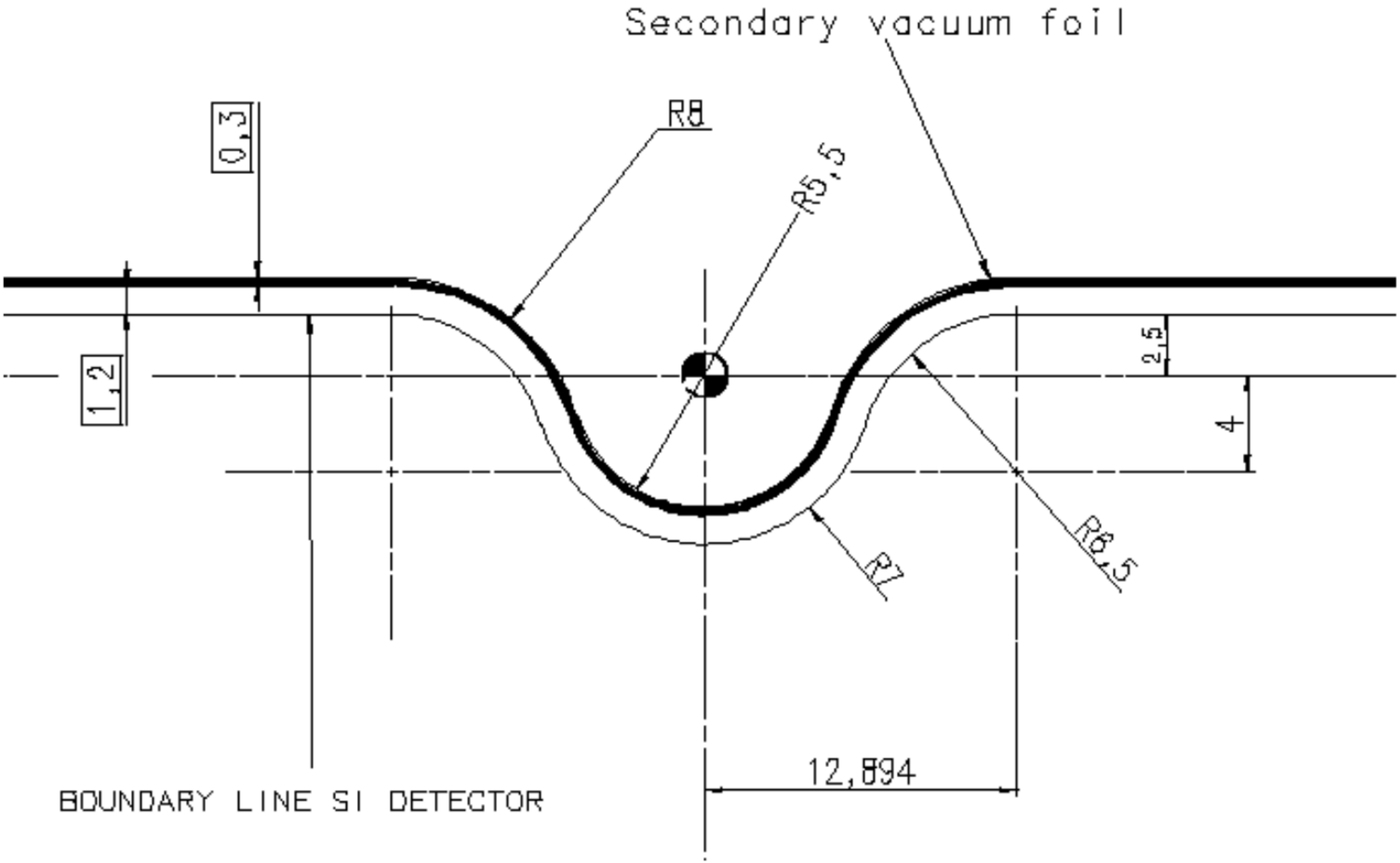
- **HCAL**
  Remove
- **ECAL**
  Improve granularity and σ_t ~50ps/hit
- **TORCH**
  PID for p<10 GeV and σ_t~15 ps
- **Muon stations**
  Improve shielding and replace Multi Wire Proportional Chambers

CERN-LHCC 2021-012

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 $9\,\text{fb}^{-1}$)		Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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 ($D^0 \to K^0_S\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—		—	—	0.2
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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

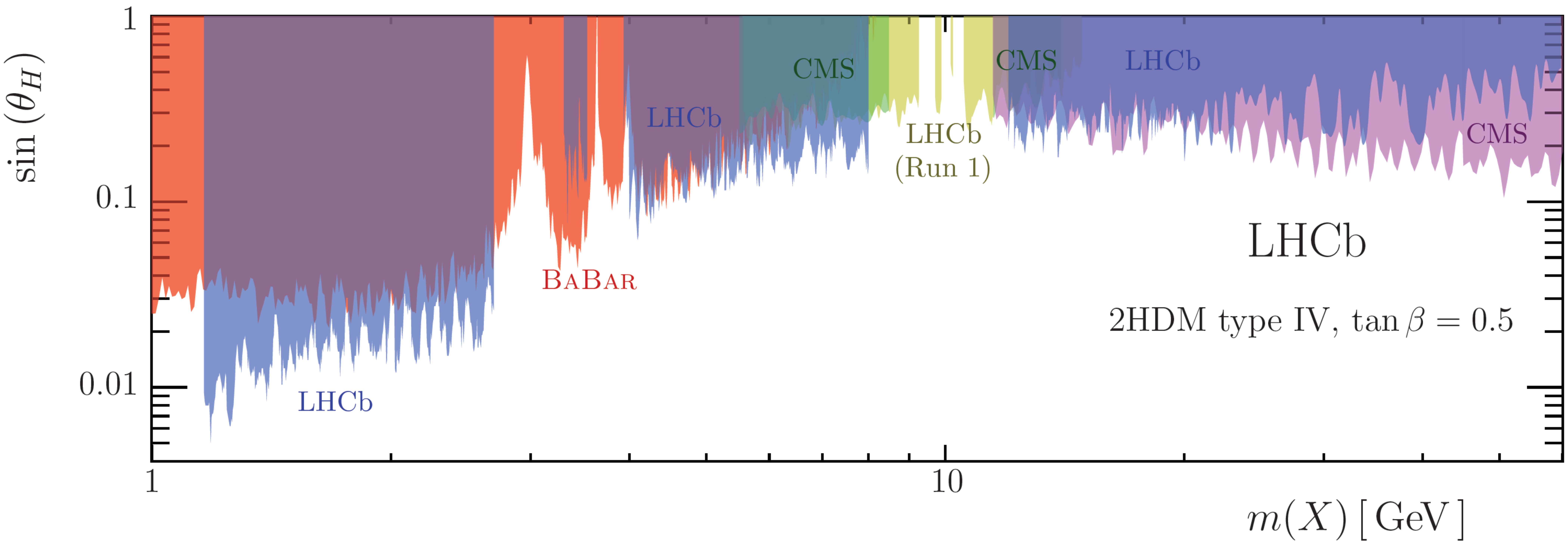


Secondary vacuum foil
R8
R5,5
0,3
1,2
2,5
4
R7
R6,5
12,894
BOUNDARY LINE SI DETECTOR

JHEP 10 (2020) 156

Low-mass dimuon resonances

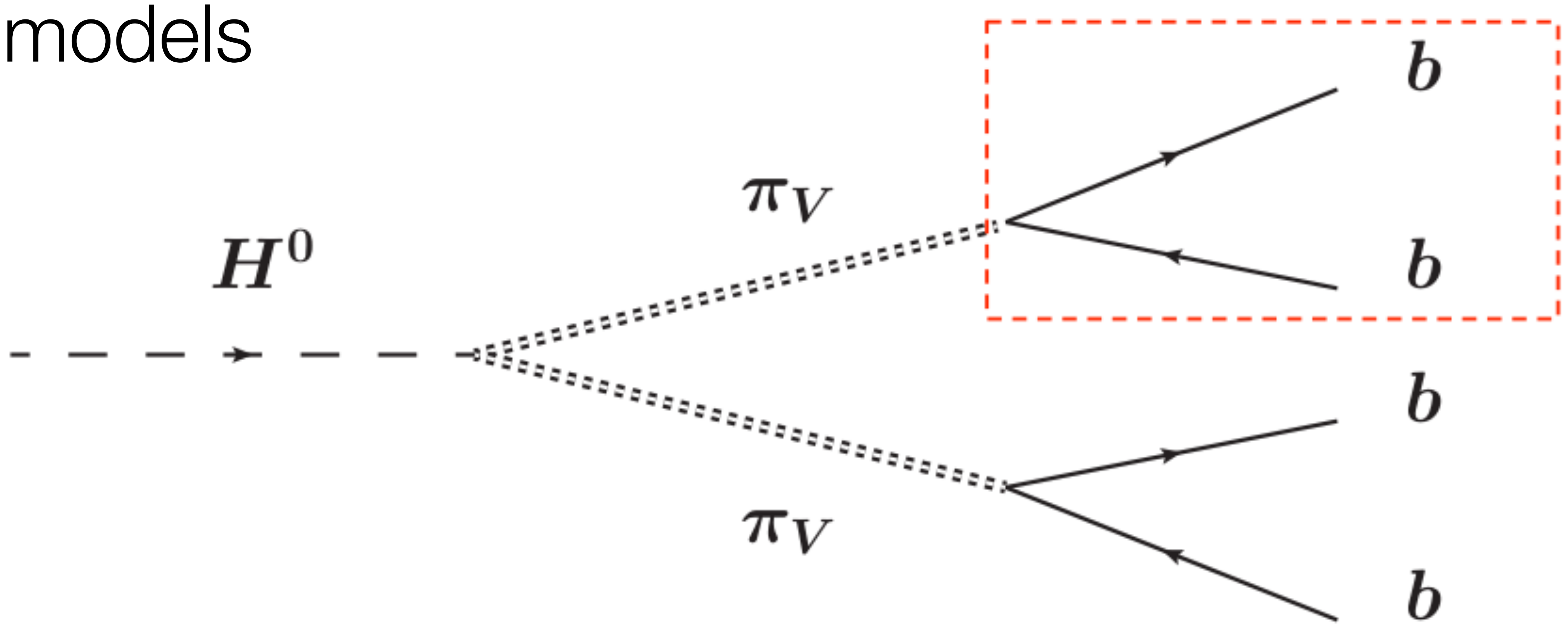
- A complex scalar singlet is added to the two-Higgs doublet (2HDM) potential
- E.g. a scenario where the pseudoscalar boson acquires all of its couplings to SM fermions through its mixing with the Higgs doublets; the corresponding X–H mixing angle is denoted as θ_H

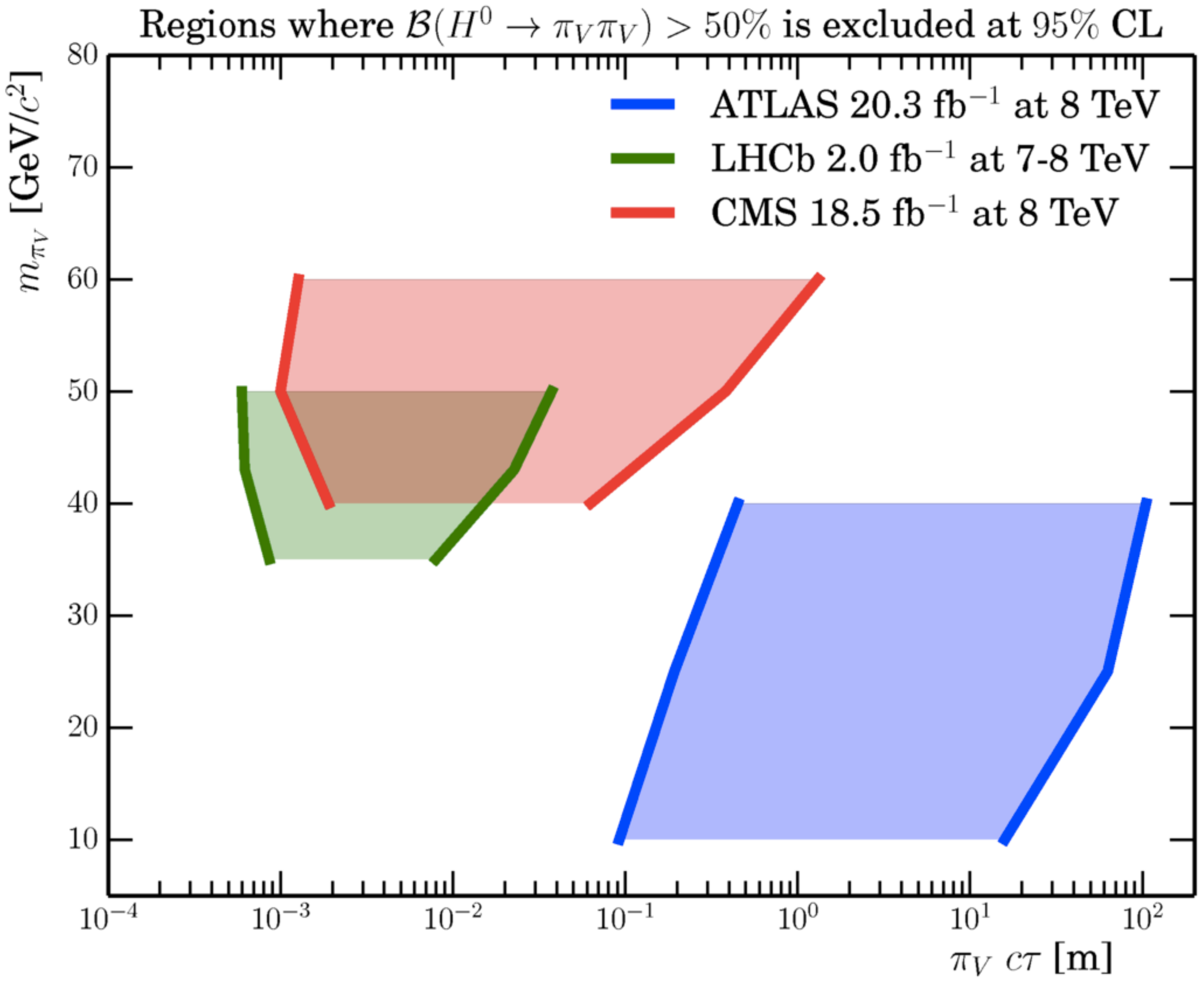


Eur. Phys. J. C77 812

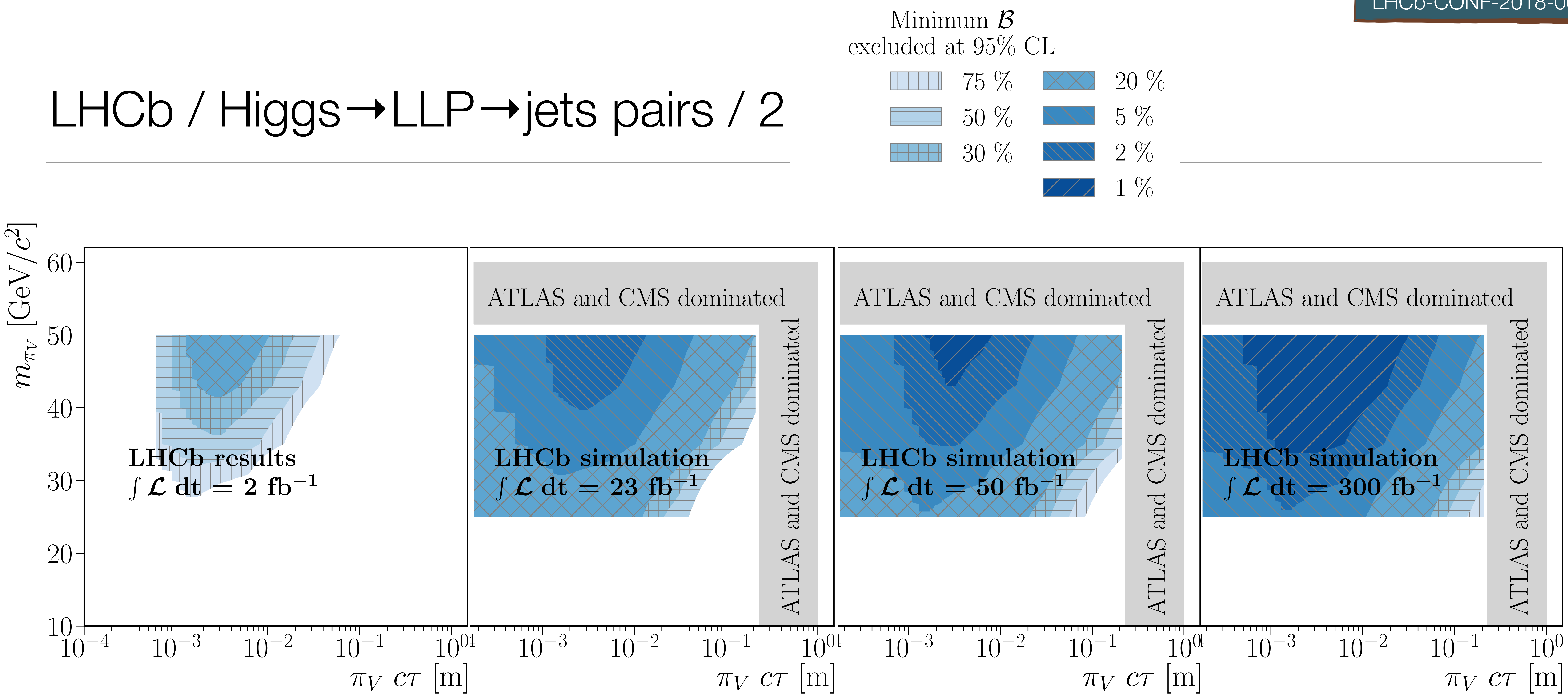
LHCb / Higgs→LLP→jet pairs

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





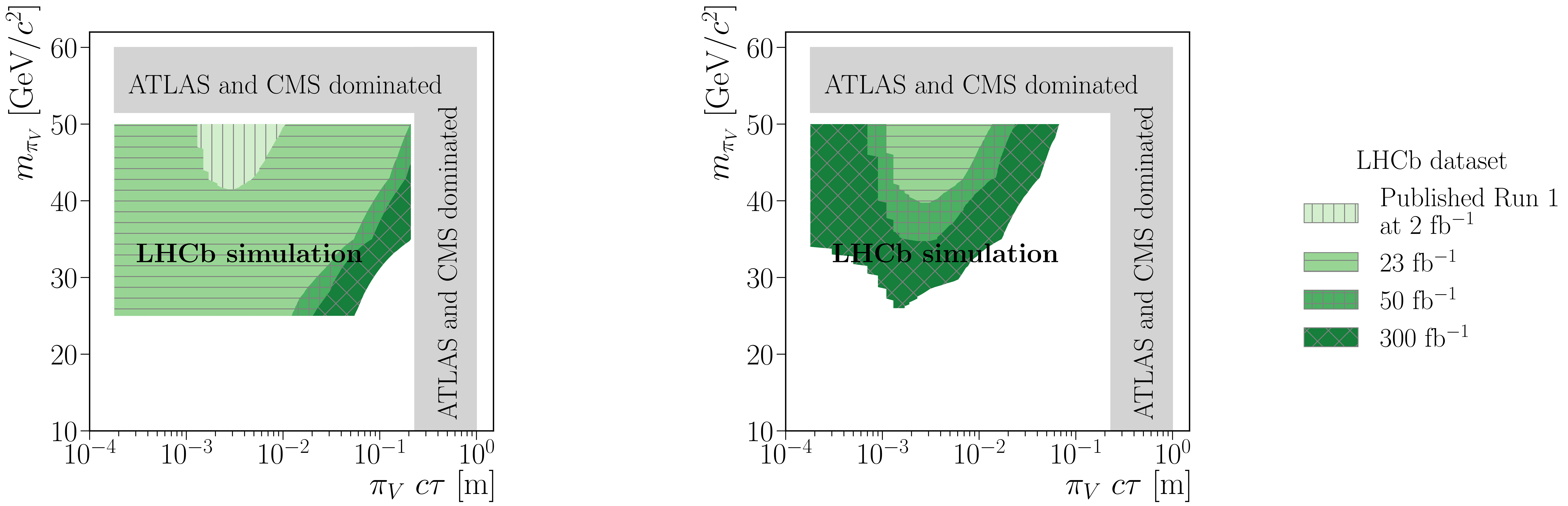
LHCb / Higgs→LLP→jets pairs / 2



- 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

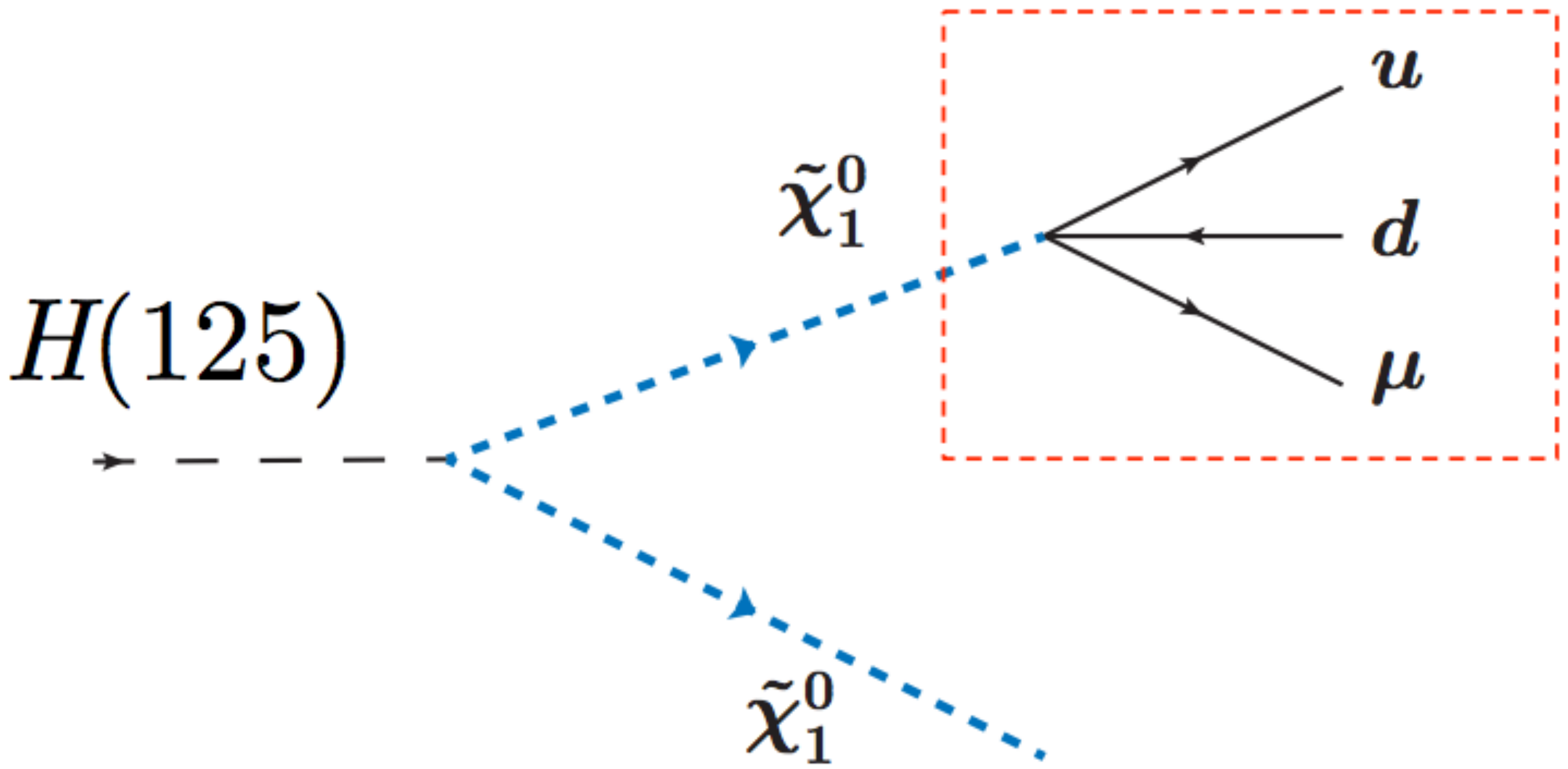


BF(Higgs→πV+πV) < 20 %

BF(Higgs→πV+πV) < 2 %

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



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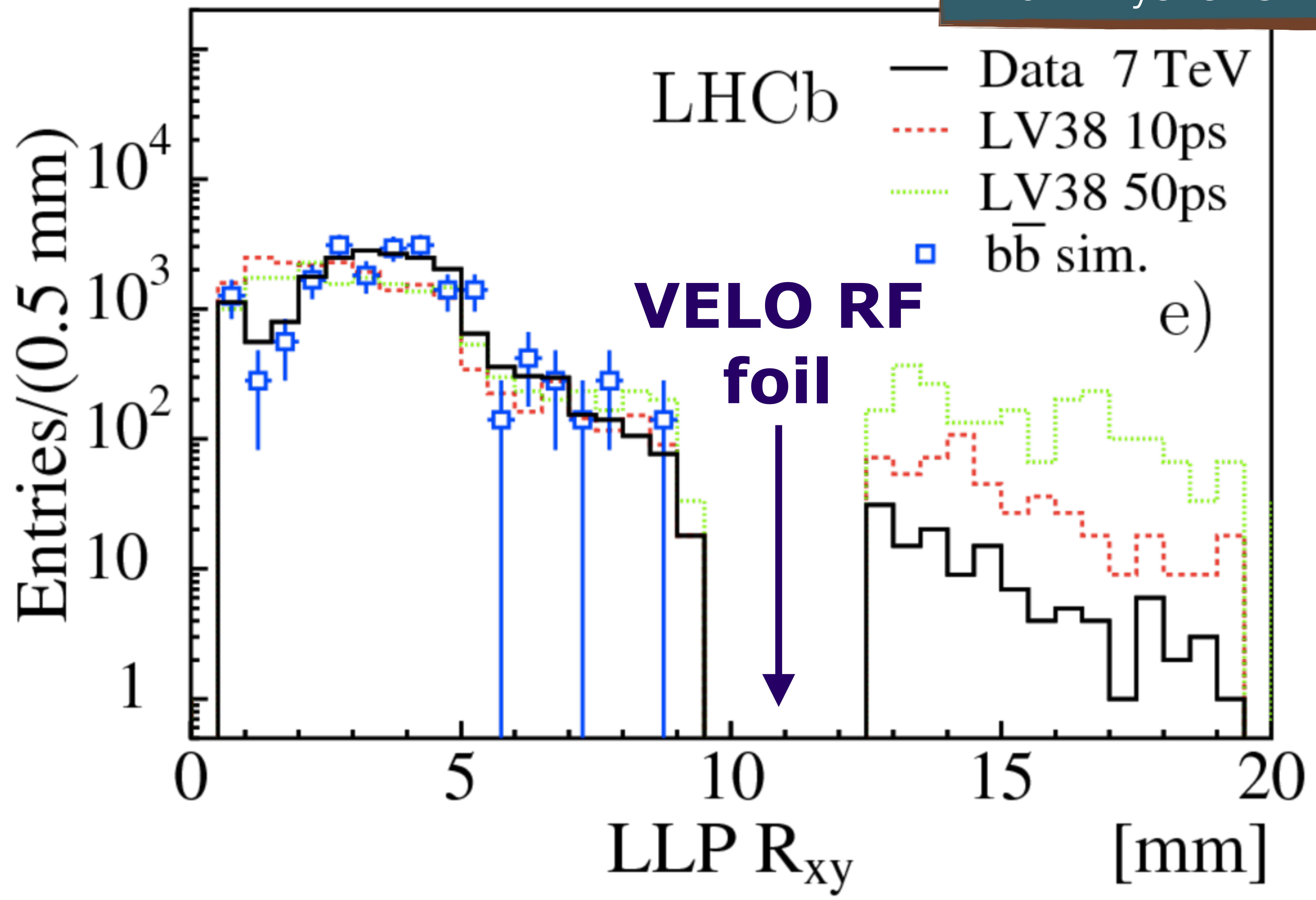
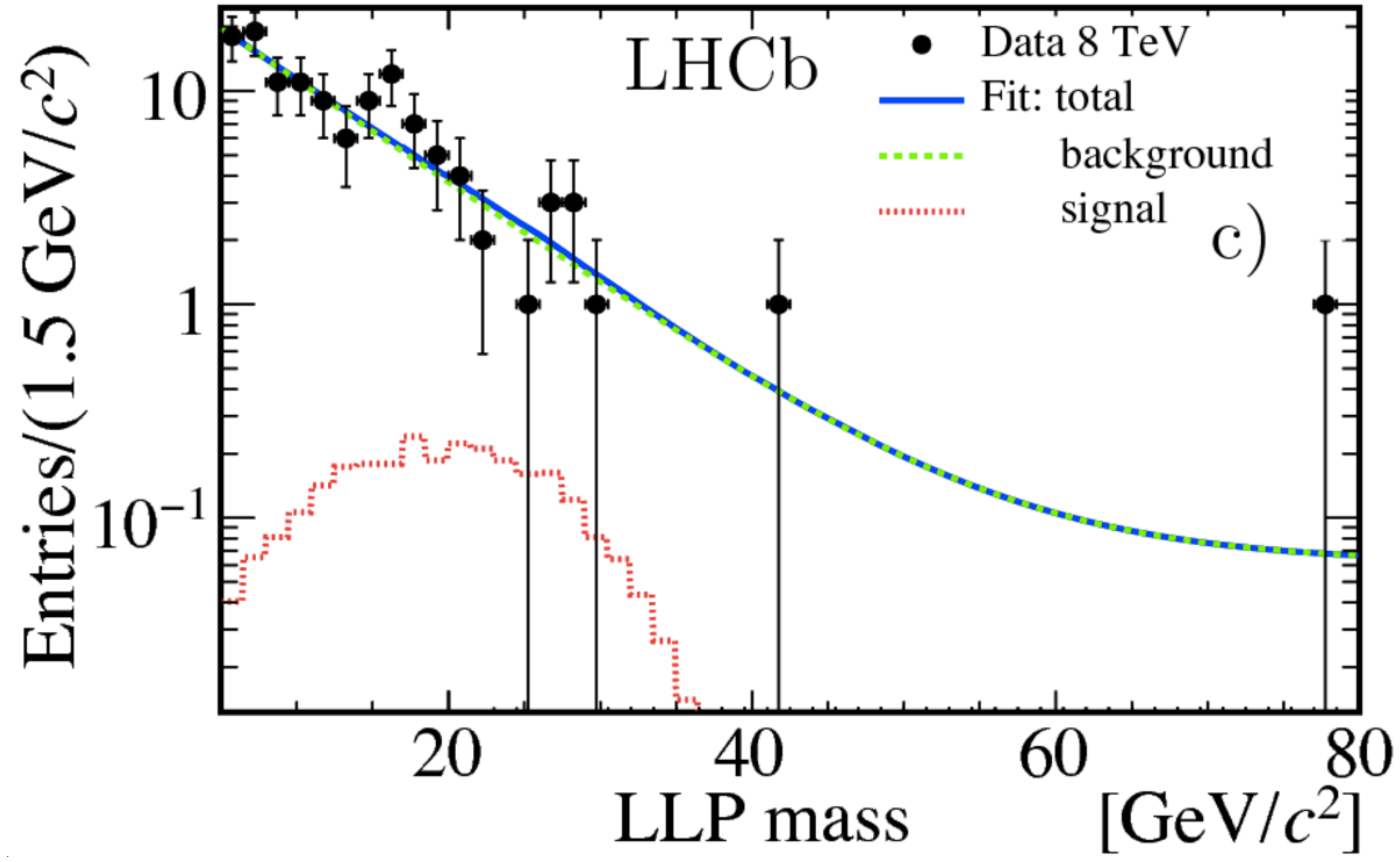
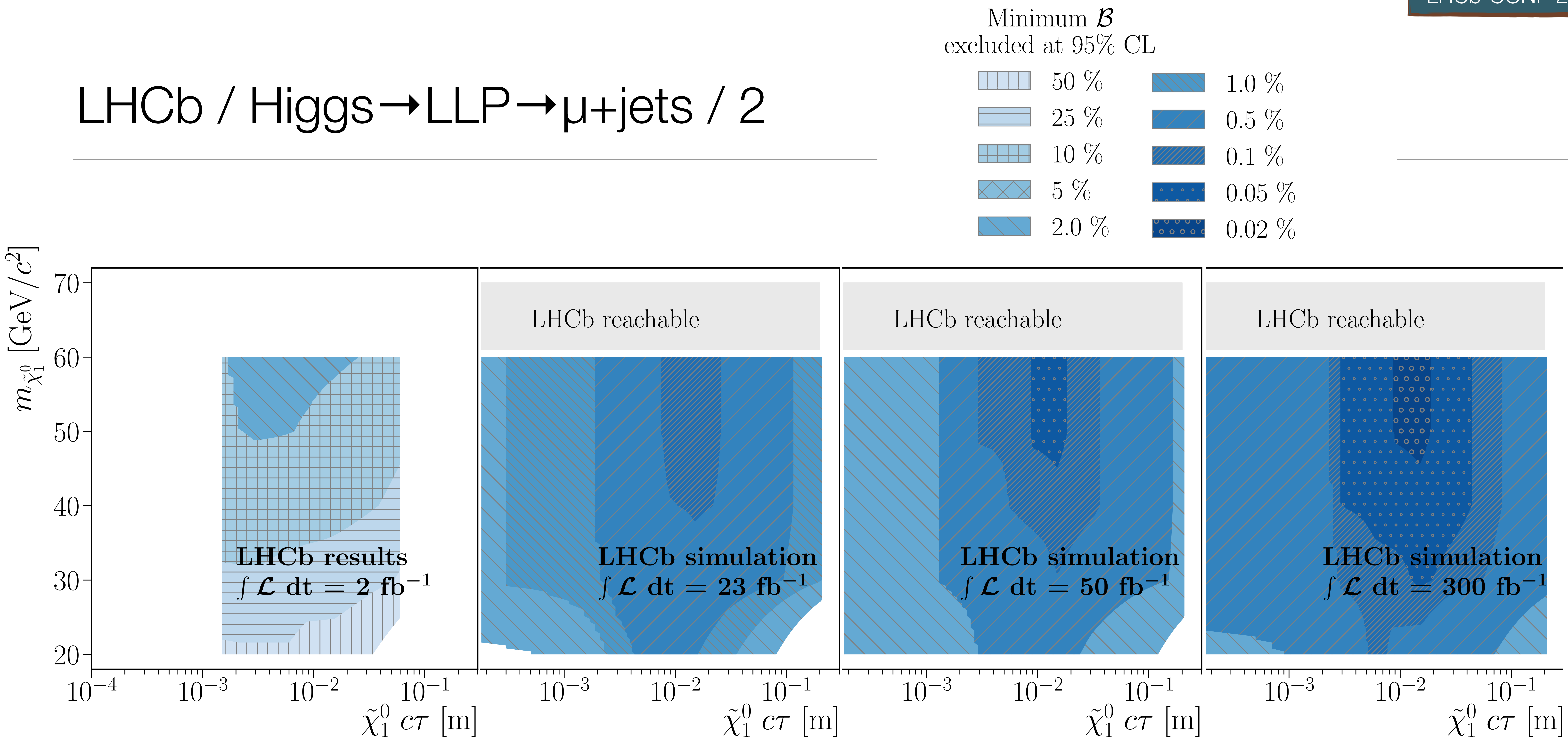




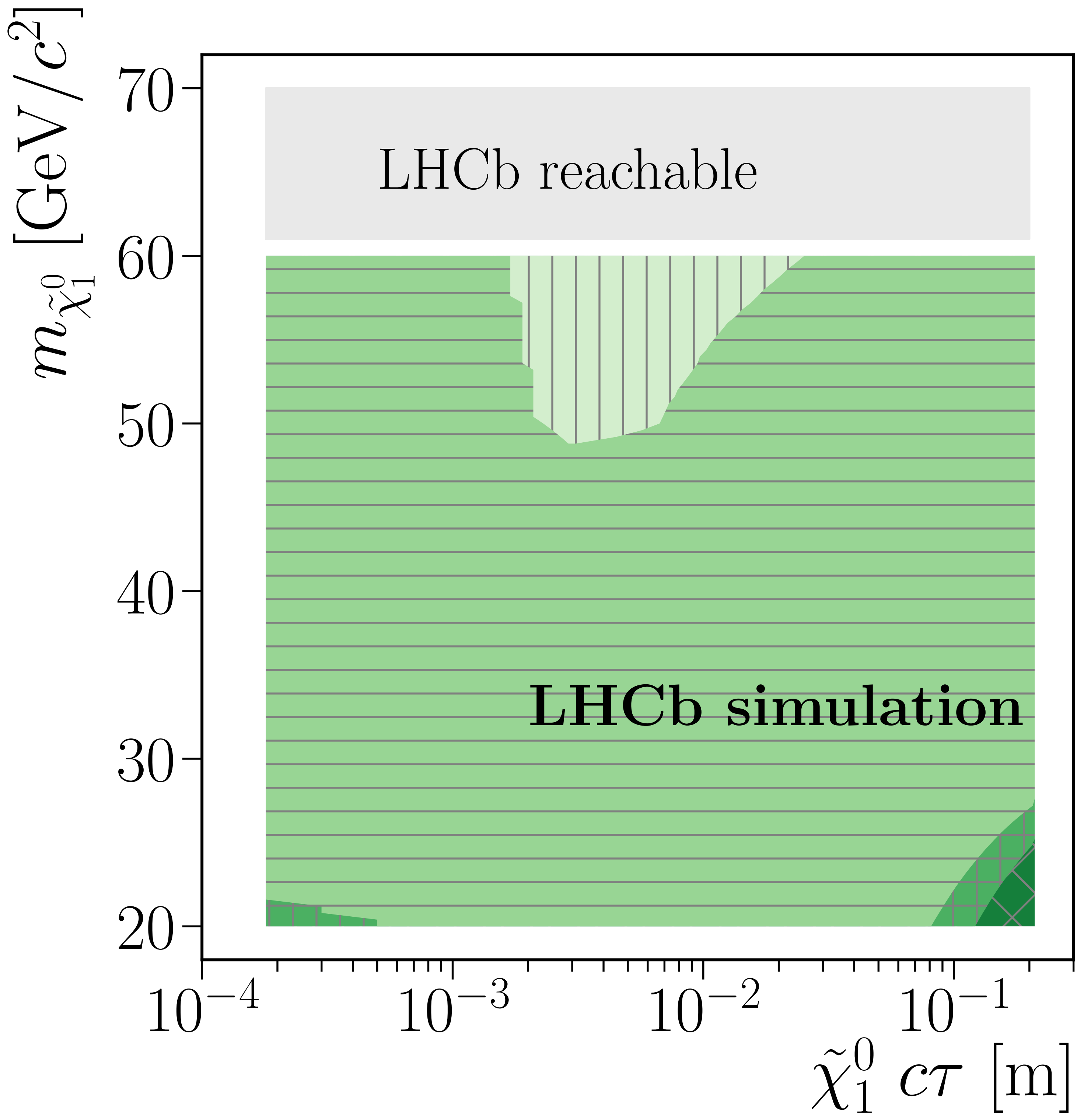
LHCb / Higgs→LLP→μ+jets / 2



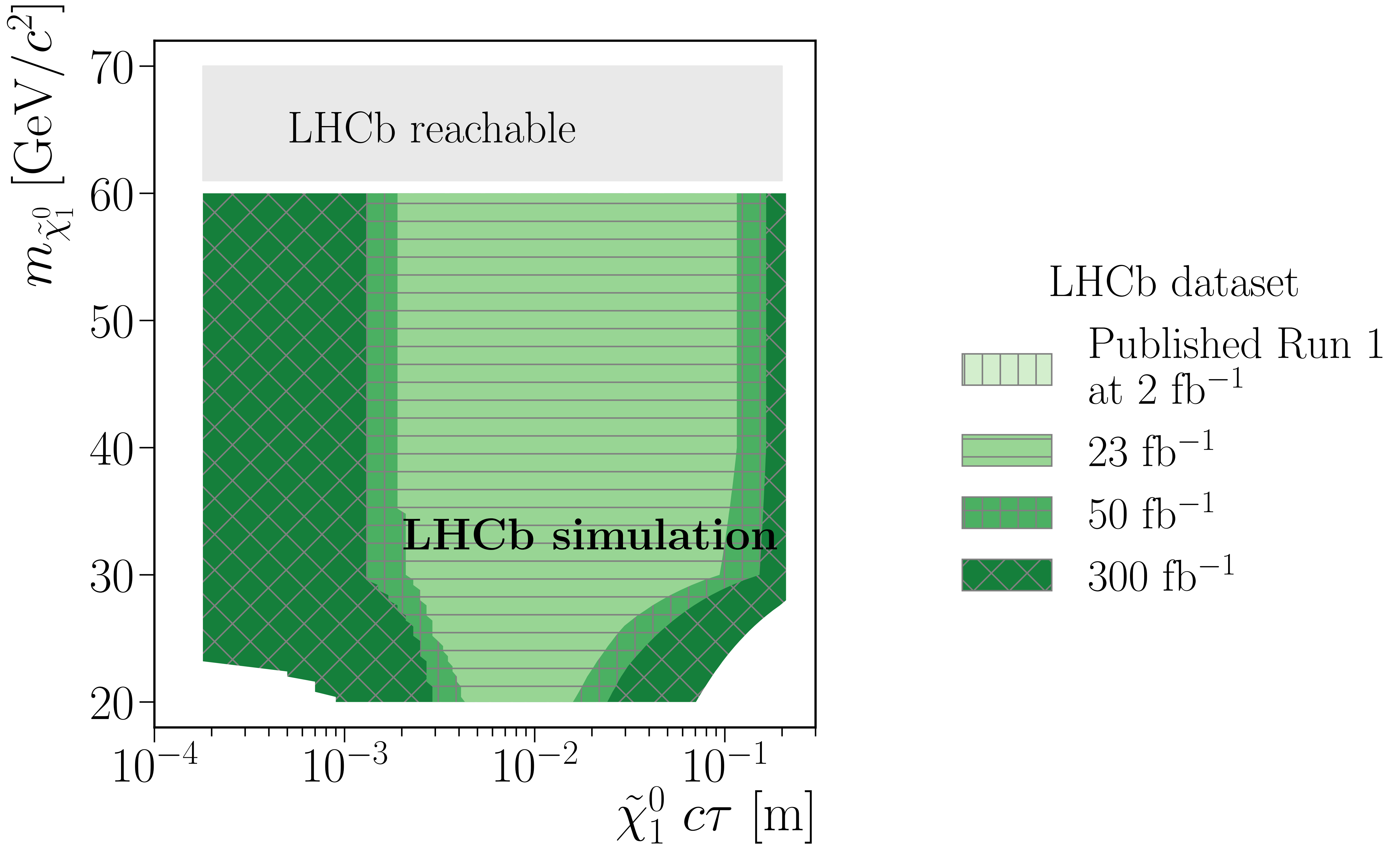
- Model independent scaling of current results to future integrated luminosity for different BFs

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 %

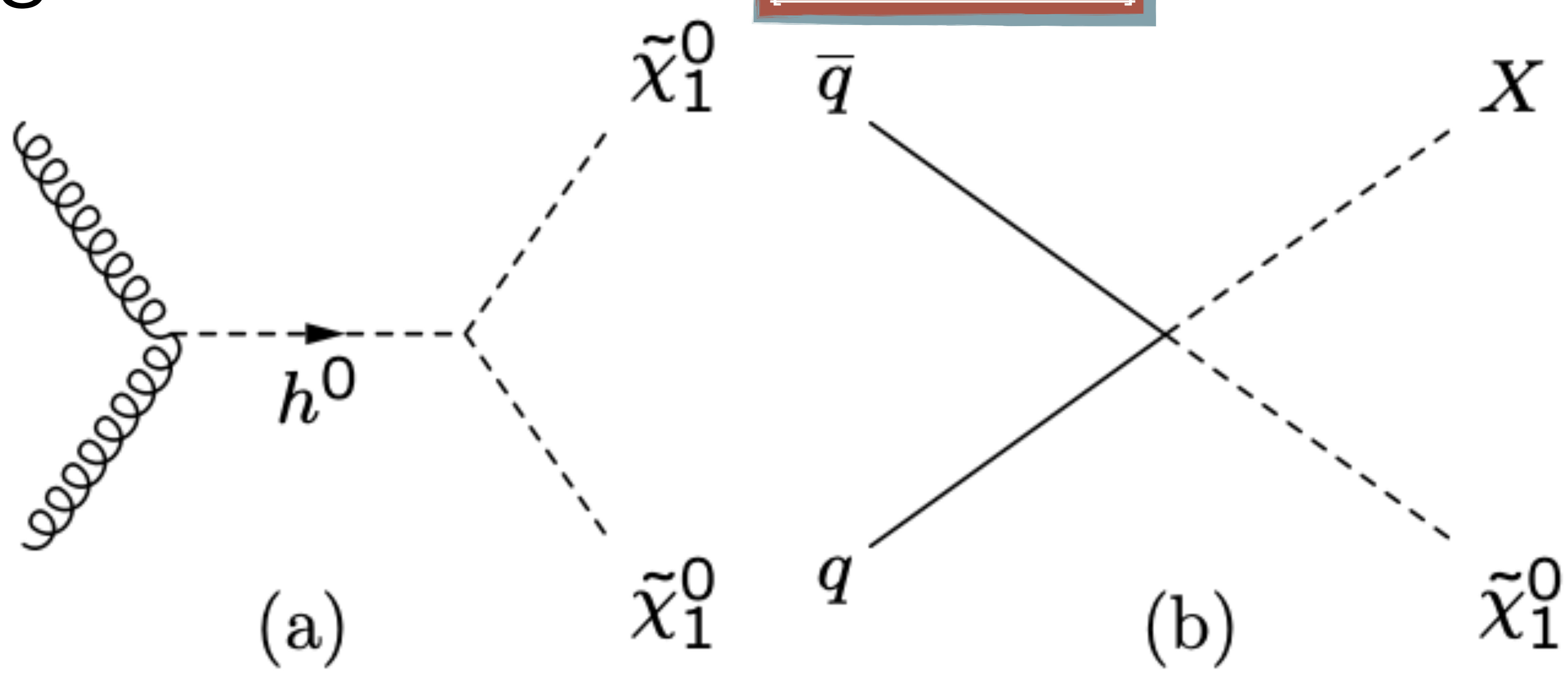


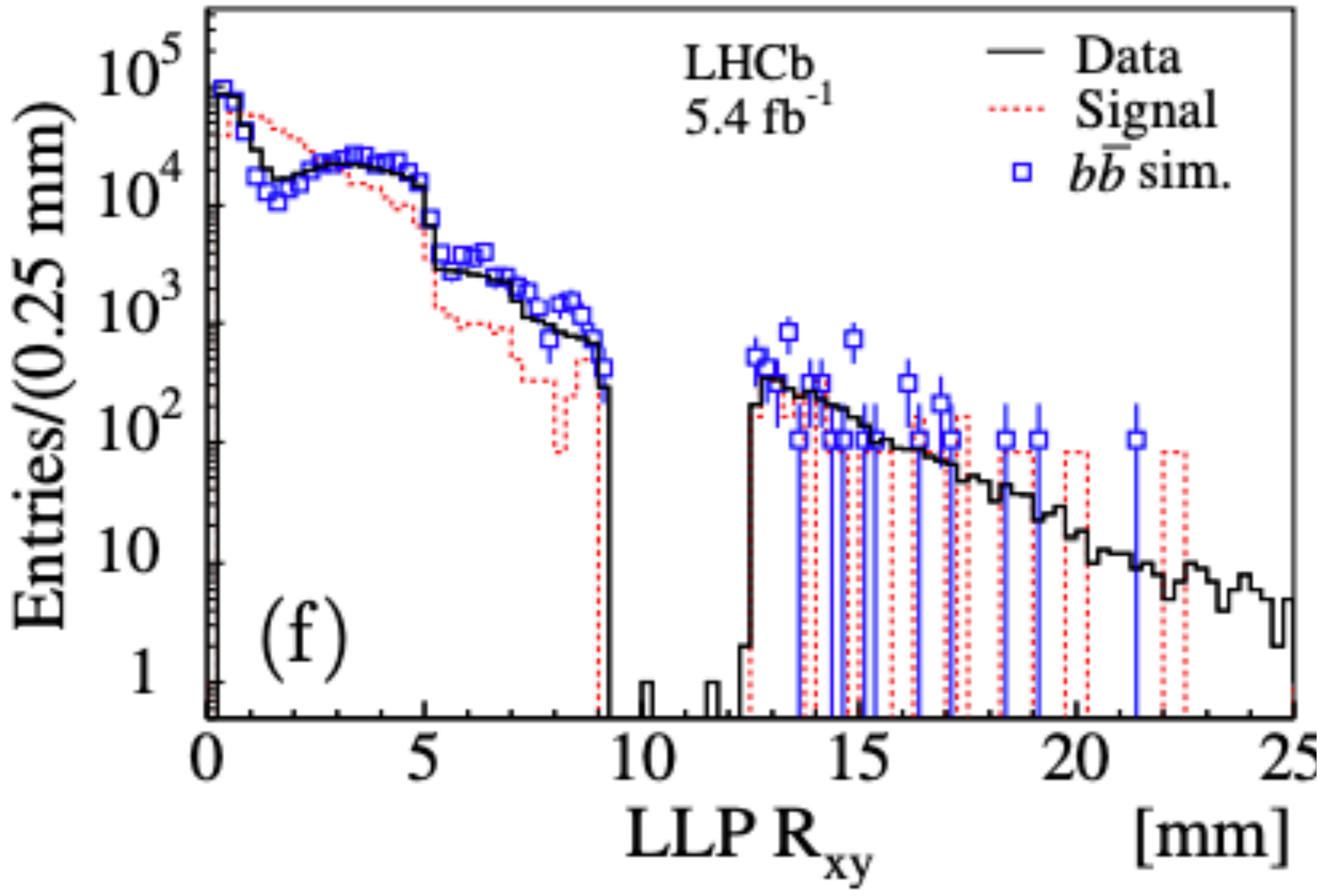
BF(Higgs→LLP+LLP) < 0.5 %

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**

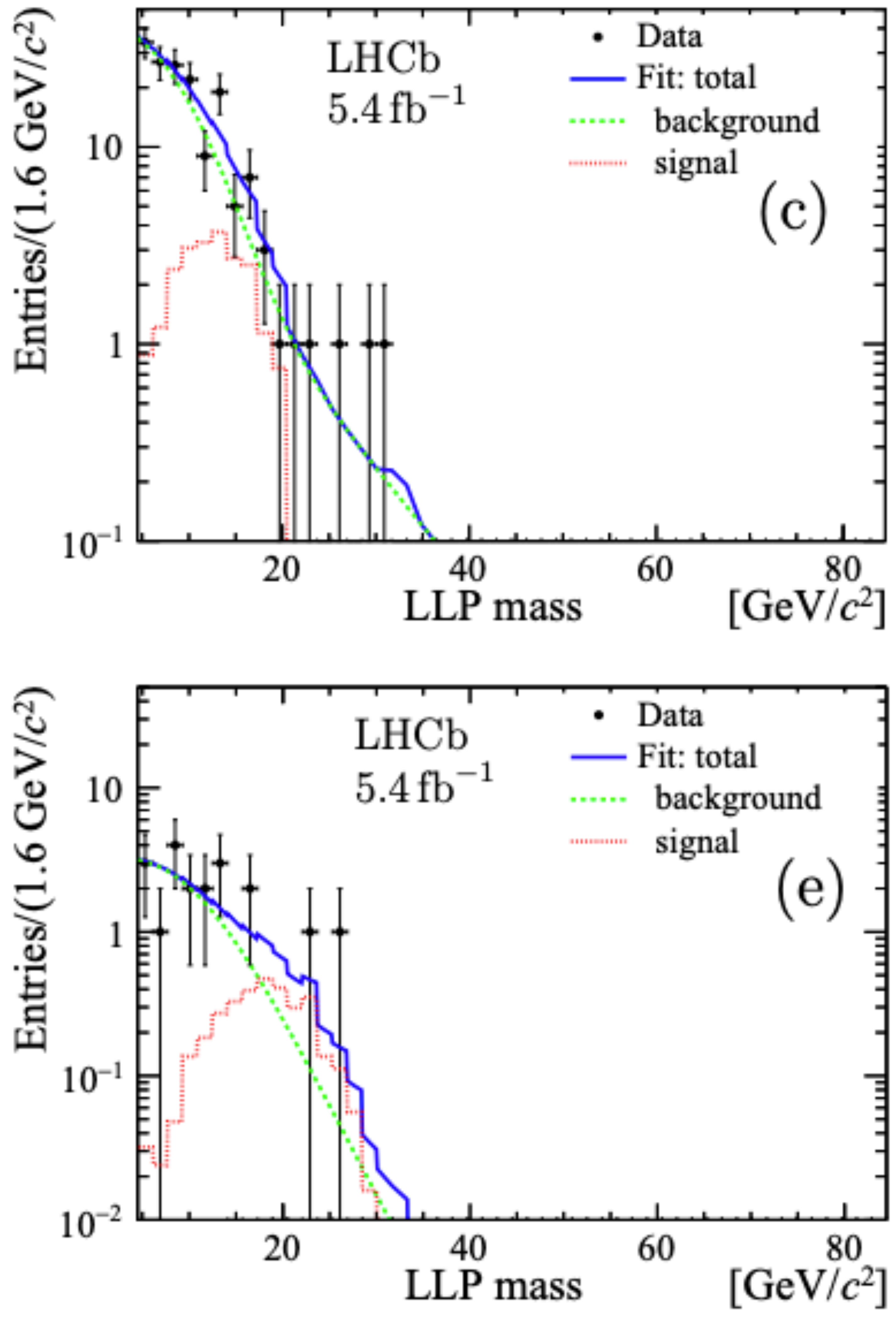


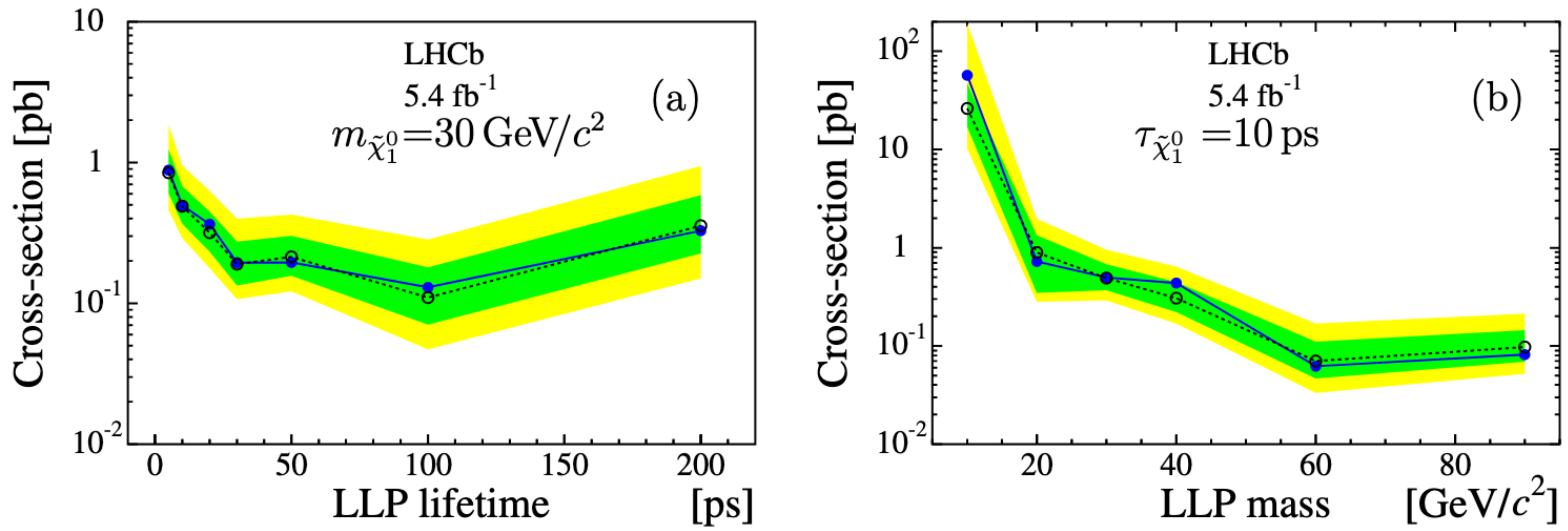


Search for massive long-lived particles decaying semileptonically

[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?**





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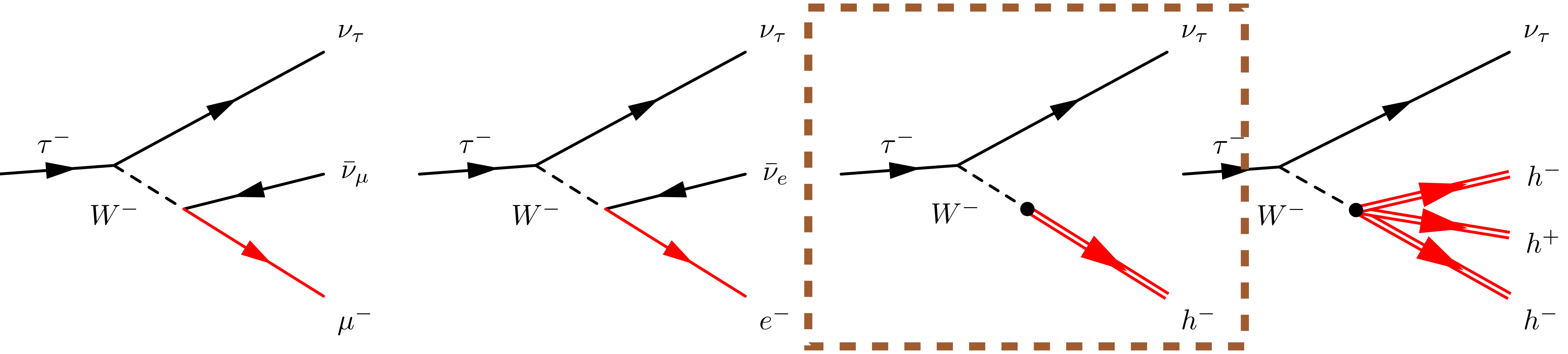
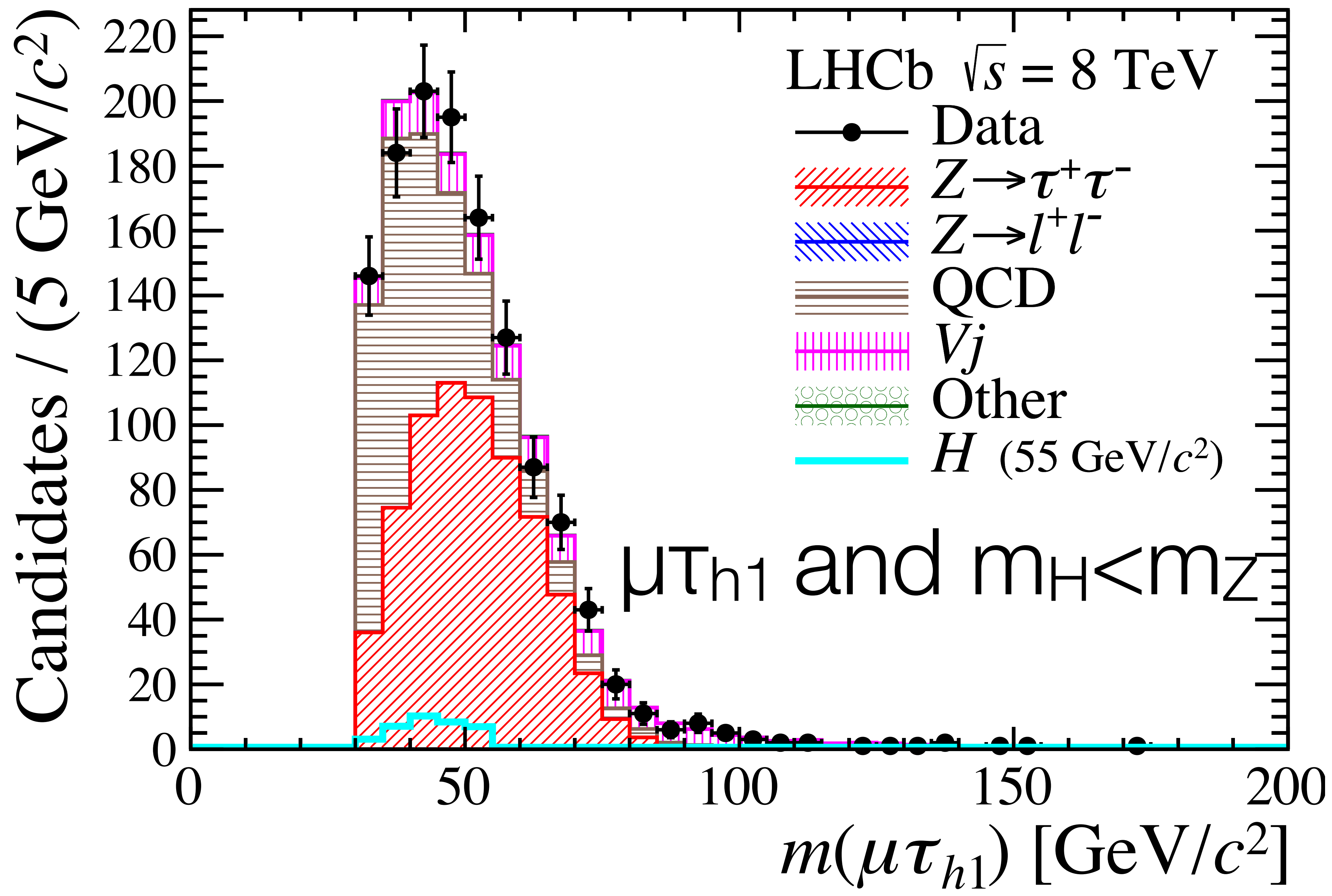
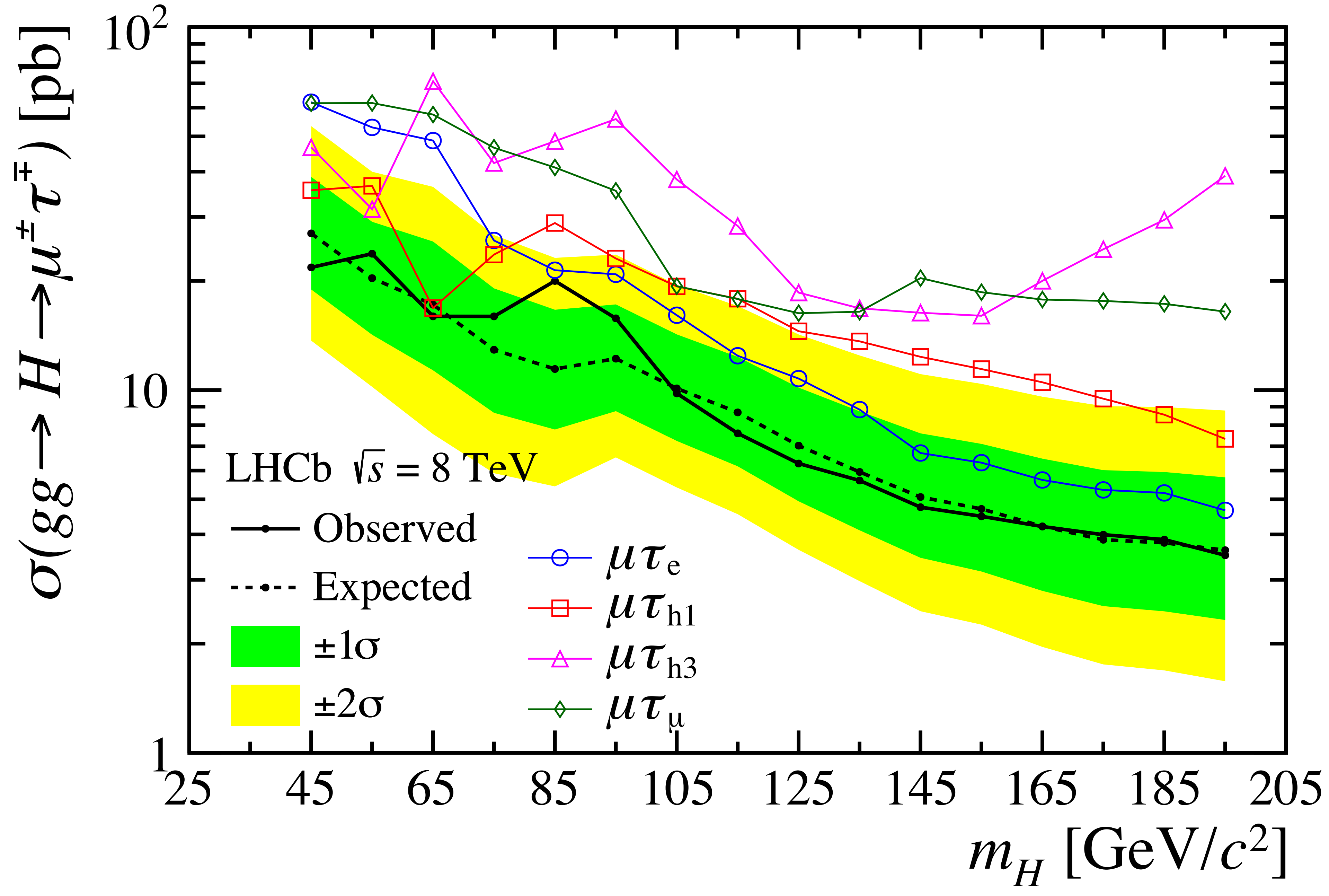
H→μτ decays / 1

- 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



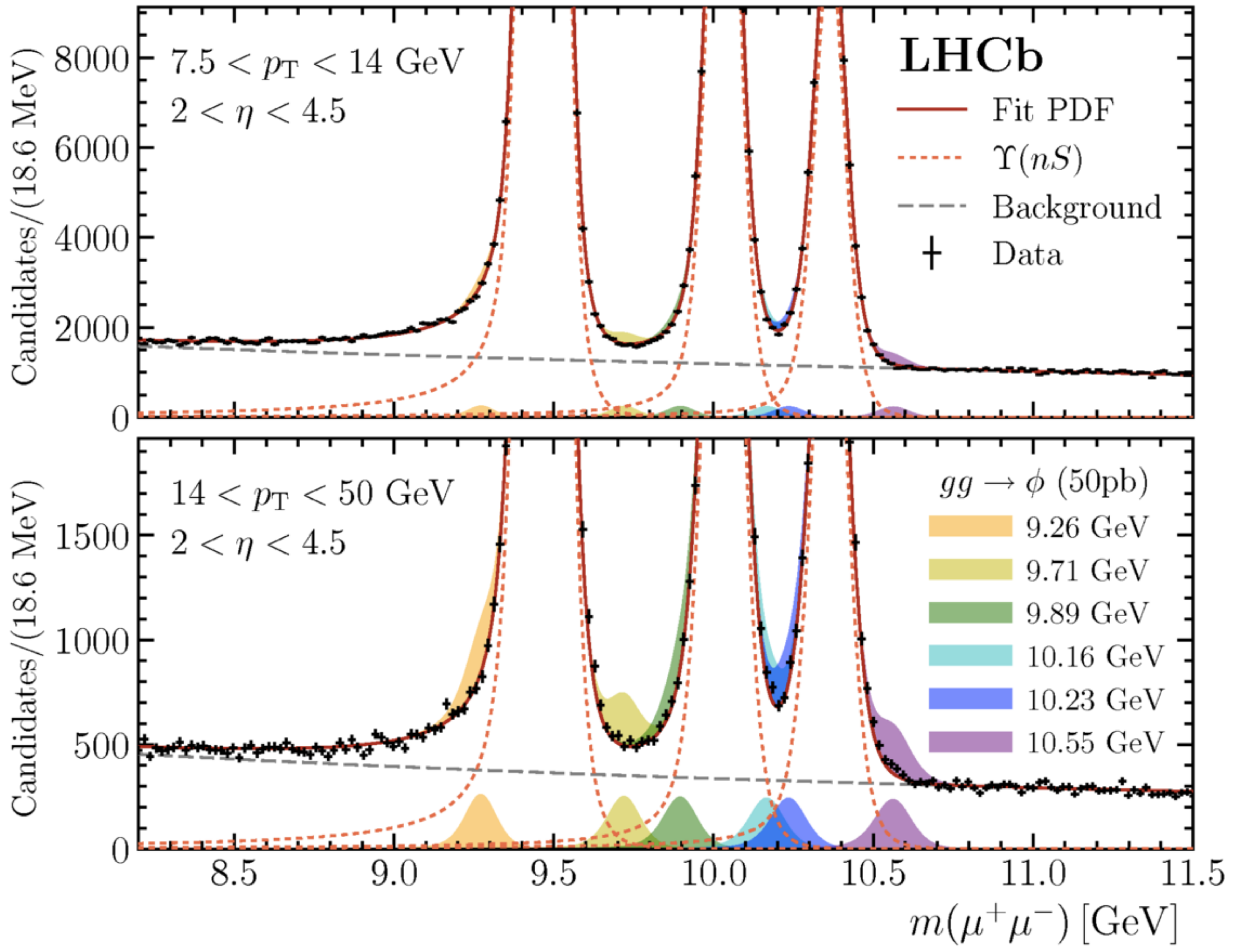




Searching in the Y mass region / 1

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

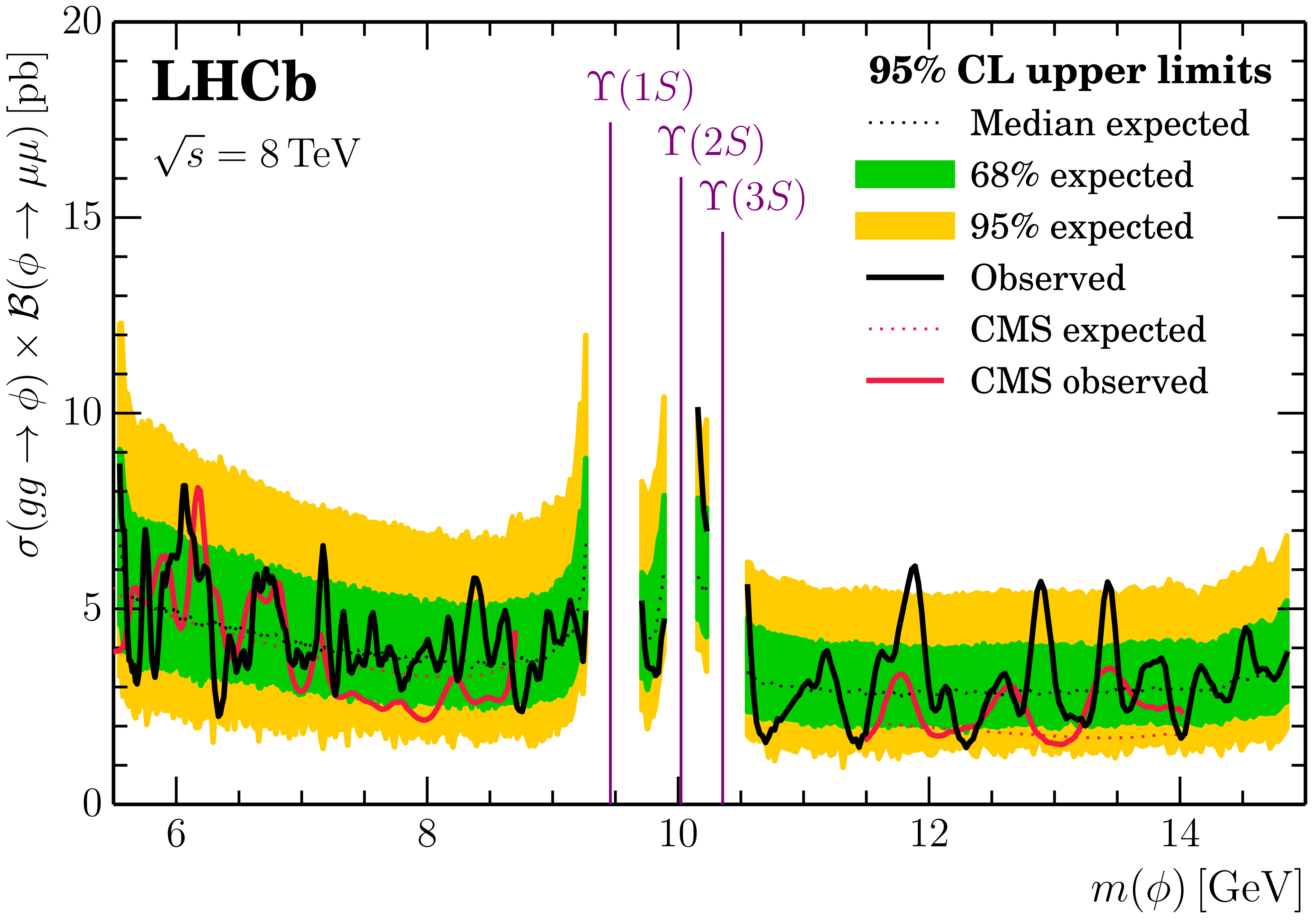


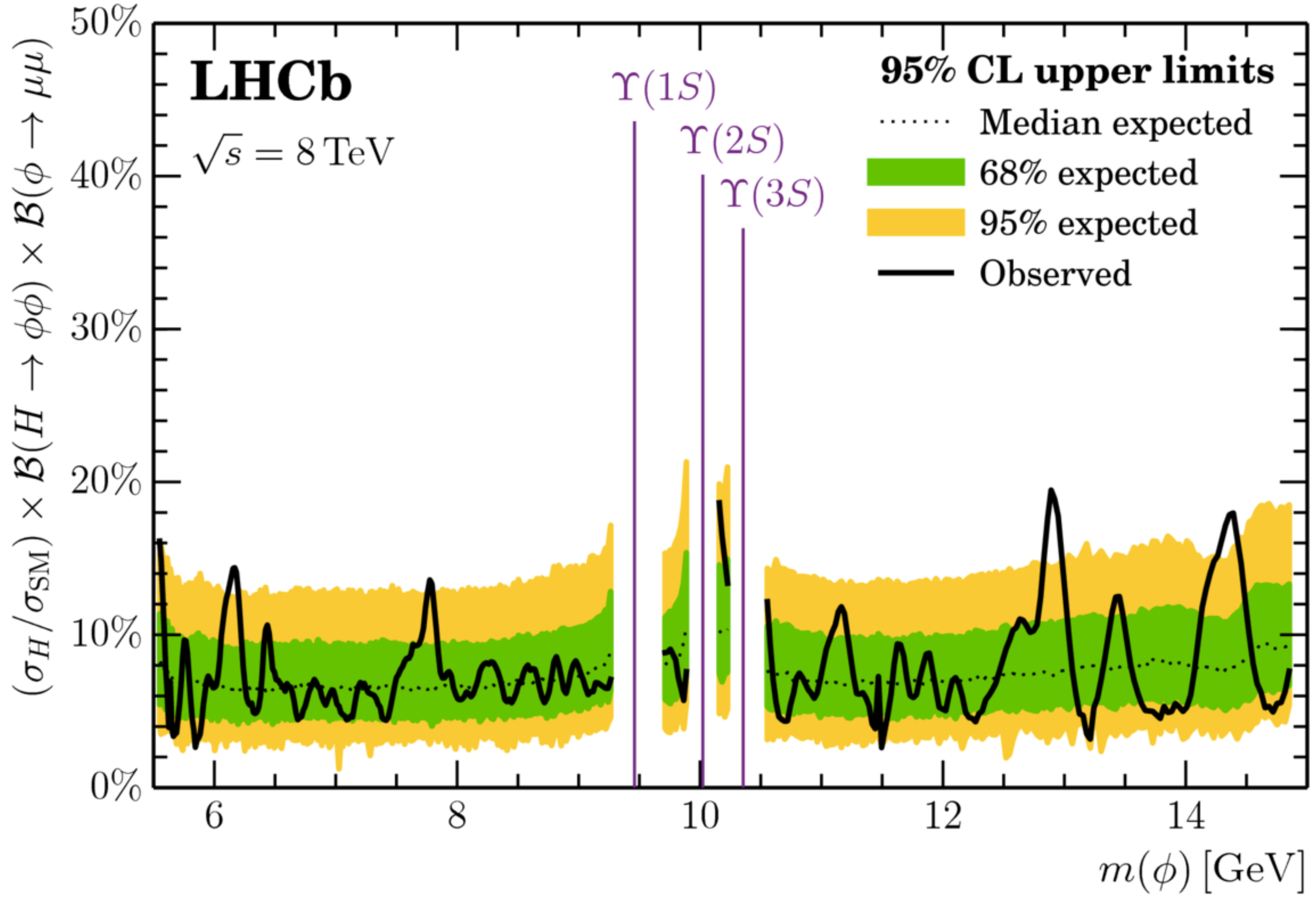
JINST 8 (2013) P12013

Searching in the Y mass region / 2

JHEP 1809 (2018) 147

- Search for dimuon resonance in $\mathbf{m_{\mu\mu}}$ **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



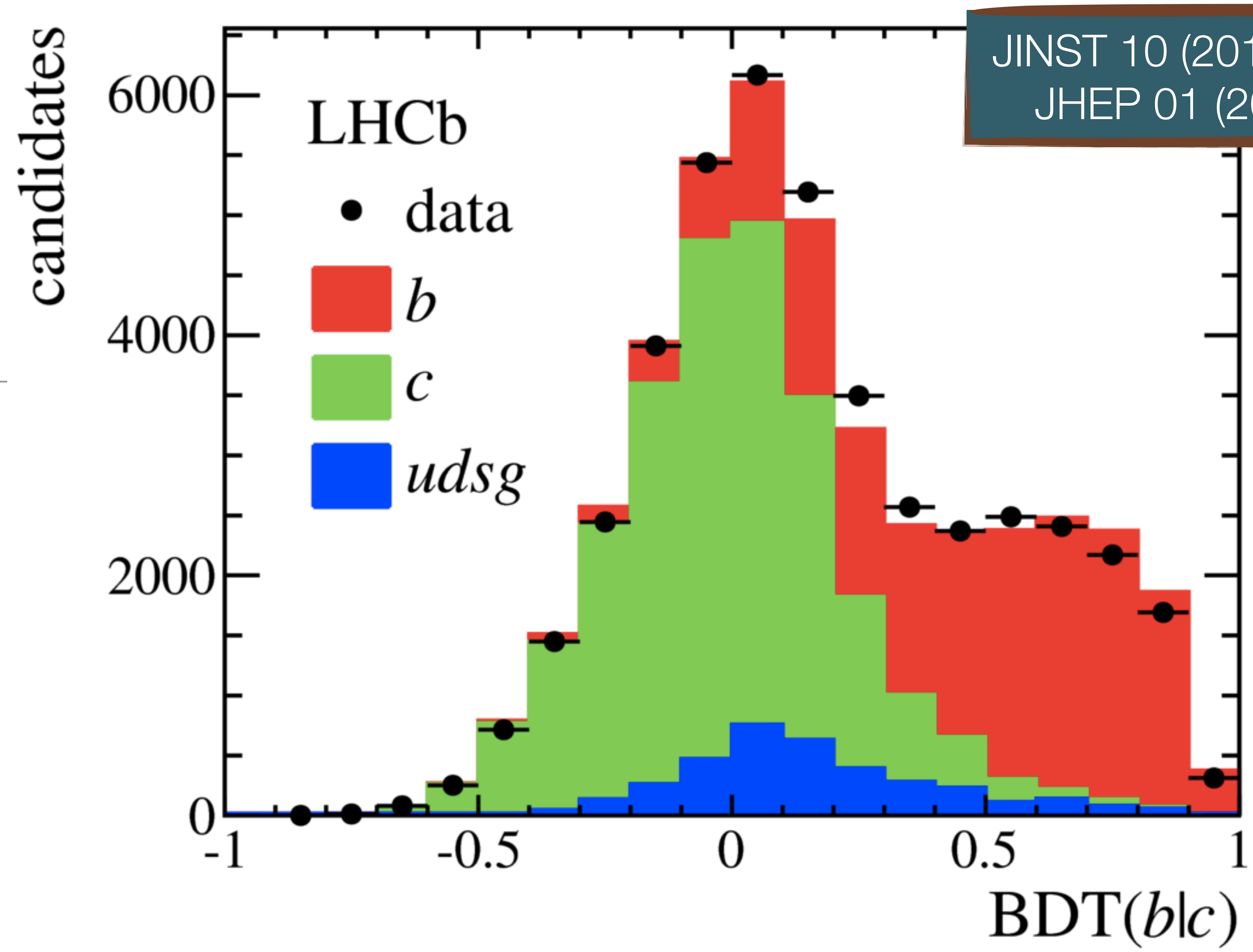


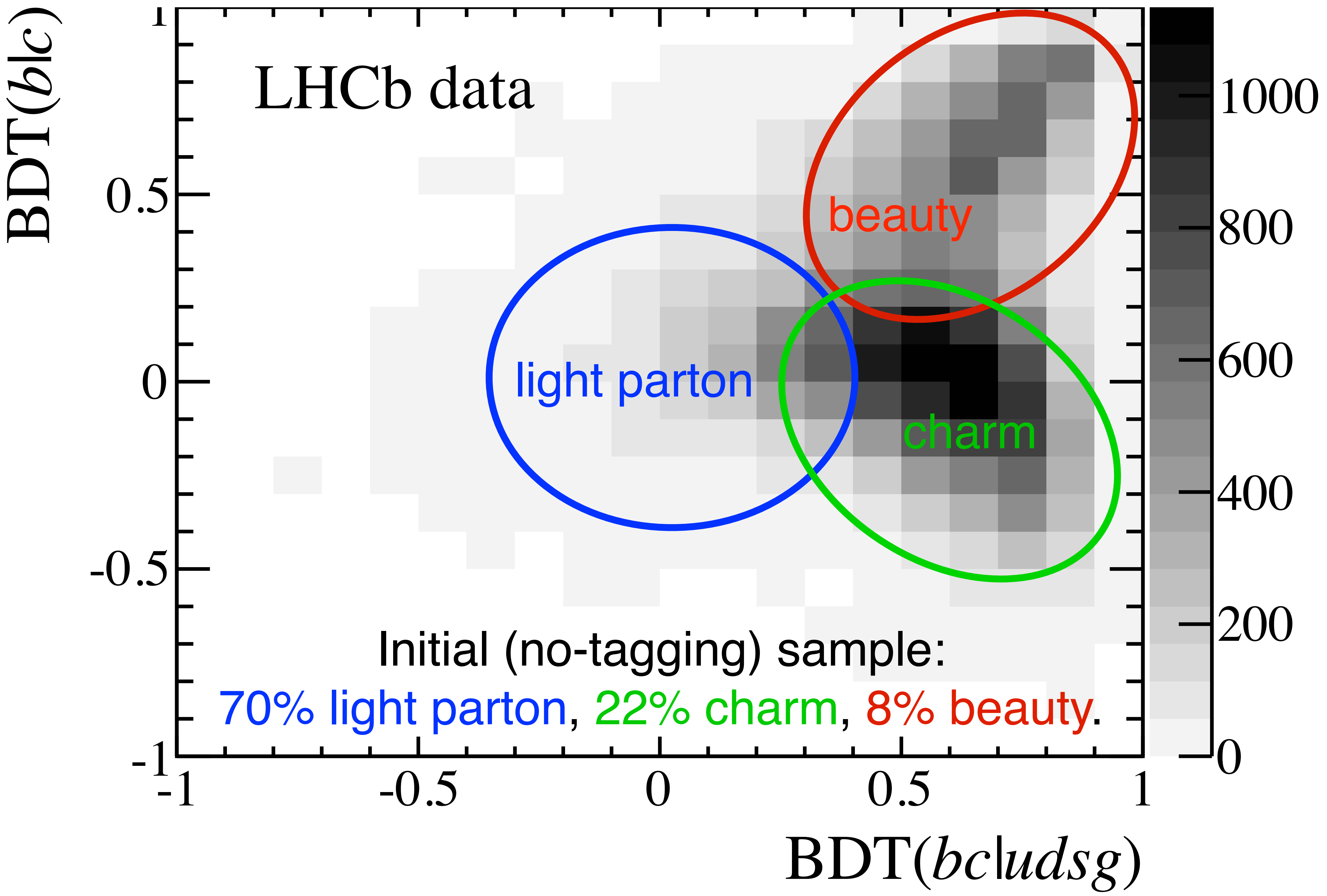
JINST 10 (2015) P06013
JHEP 01 (2014) 033

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%, ε_b ~ 65%, ε_c ~ 25%

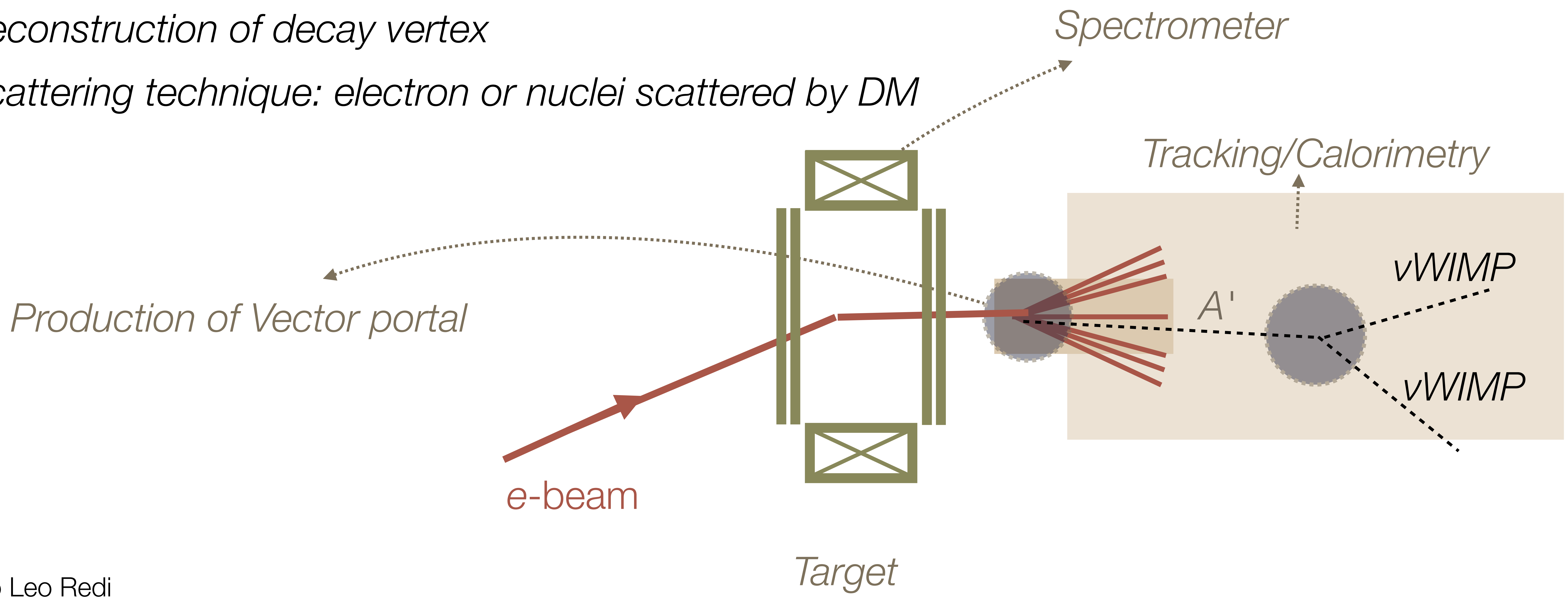
- SV properties (**displacement**, **kinematics**, **multiplicity**, etc) and jet properties combined in **two** BDTs
  - **BDT$_{bc|udsg}$** optimised for heavy flavour versus light discrimination
  - **BDT$_{b|c}$** optimised for b versus c discrimination





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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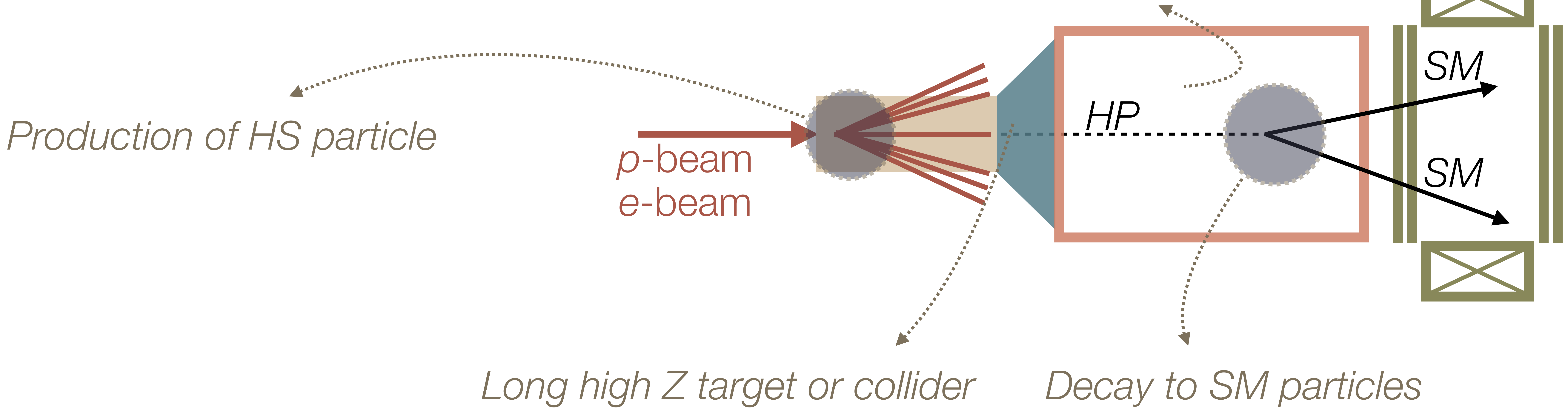

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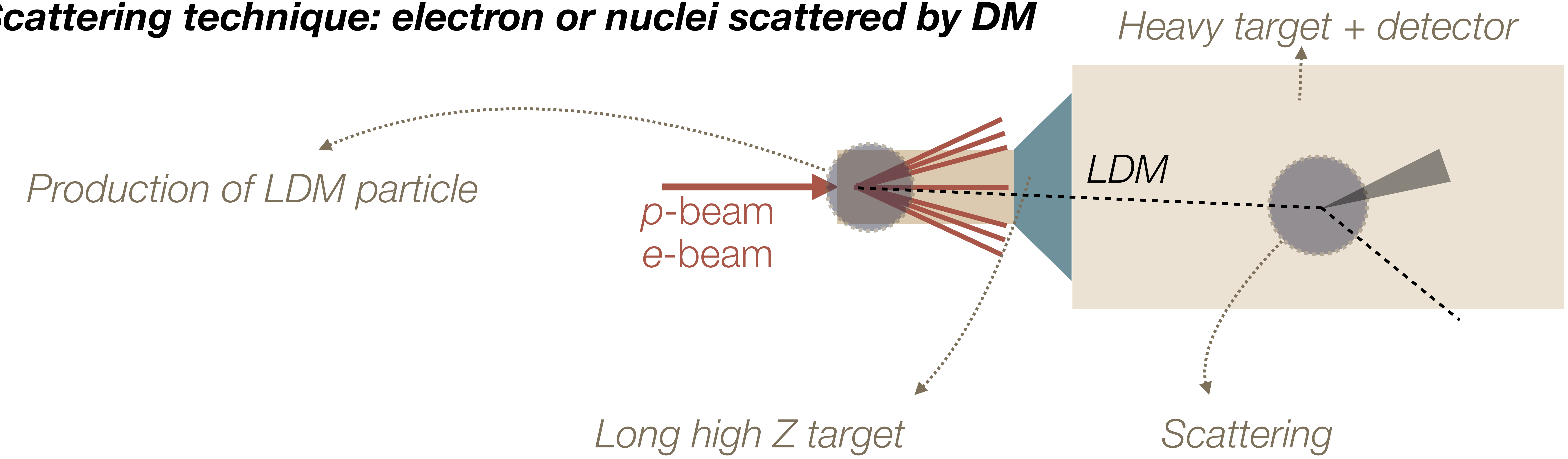
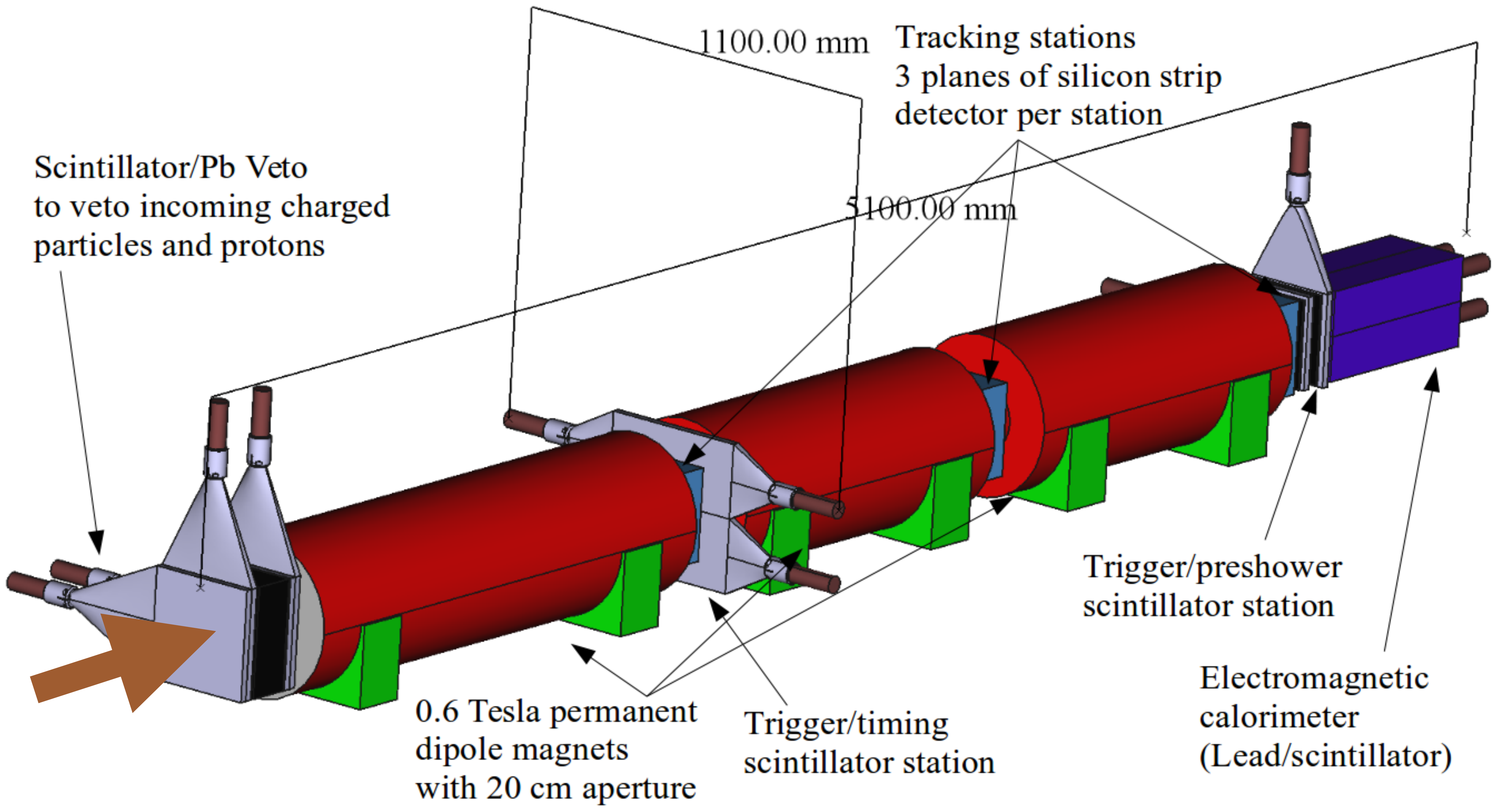


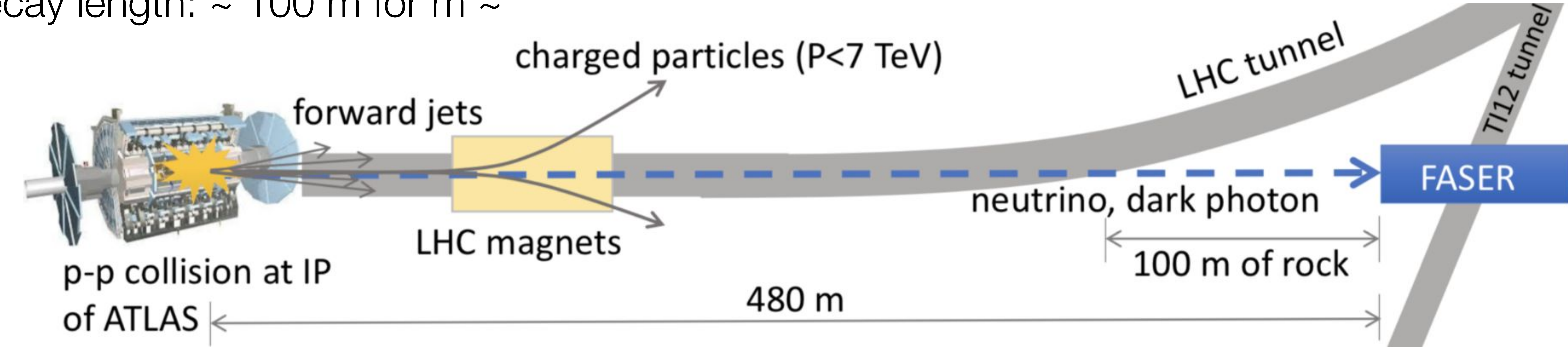
Ref

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



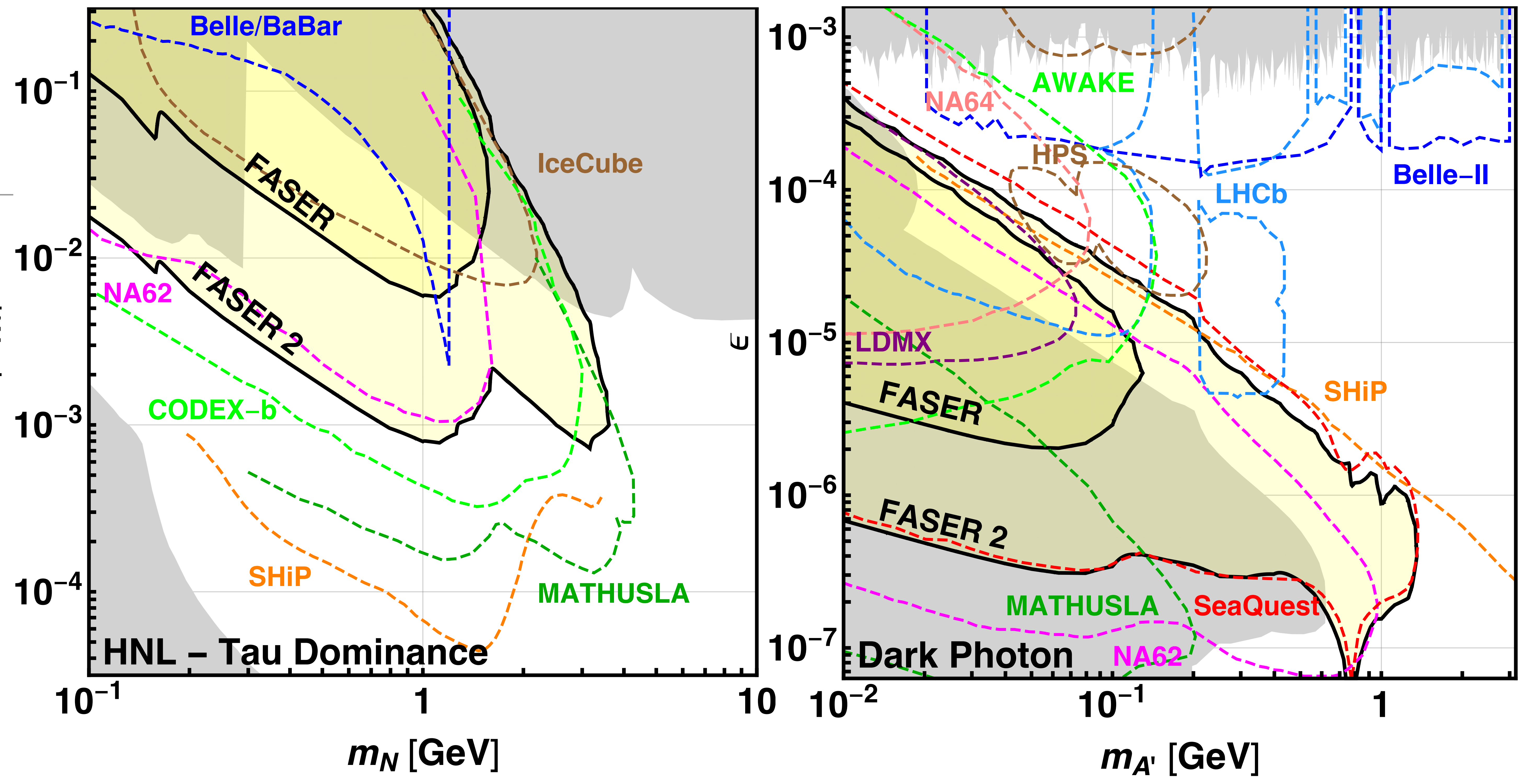
ASPEN2014 Theoretical summary - M. Mangar

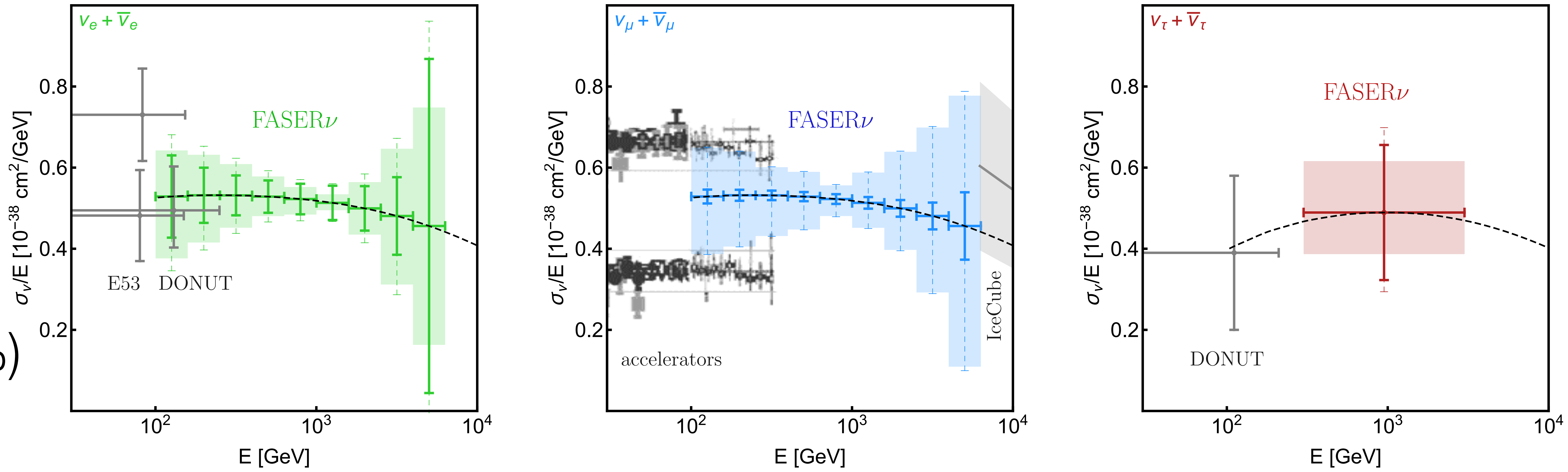


Ref

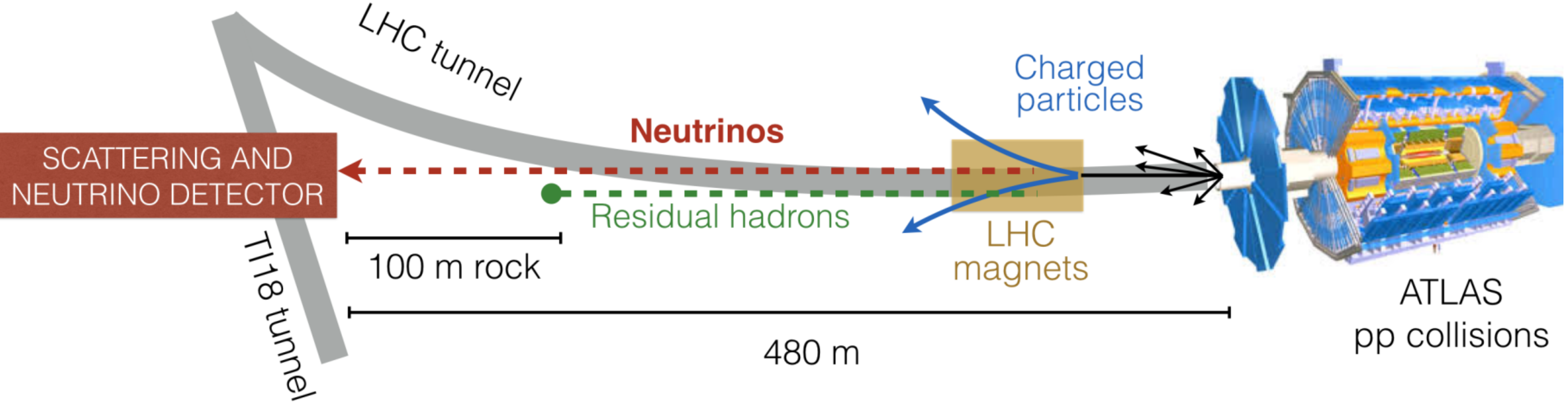
FASER

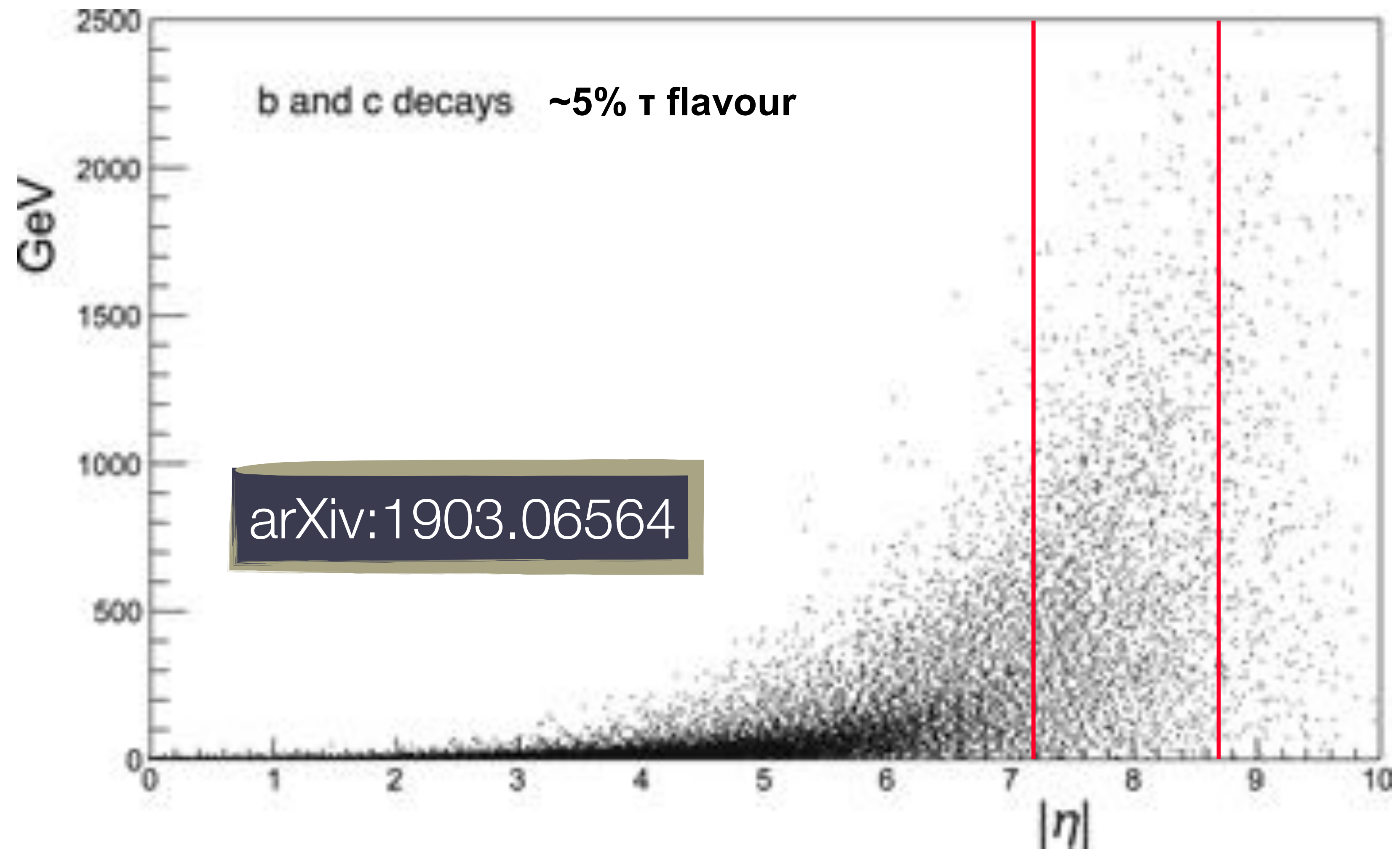
- **FASER:**
  - Benchmark physics process: Dark Photons A’
  - Produced via kinetic mixing from e.g. π^0 decays
  - Detected in decay to e^+e^- in FASER decay volume
  - Sensitive to other LLPs and decay modes as well
- **FASERν** (and InterFace Tracker):
  - Based on emulsion film therefore vertex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

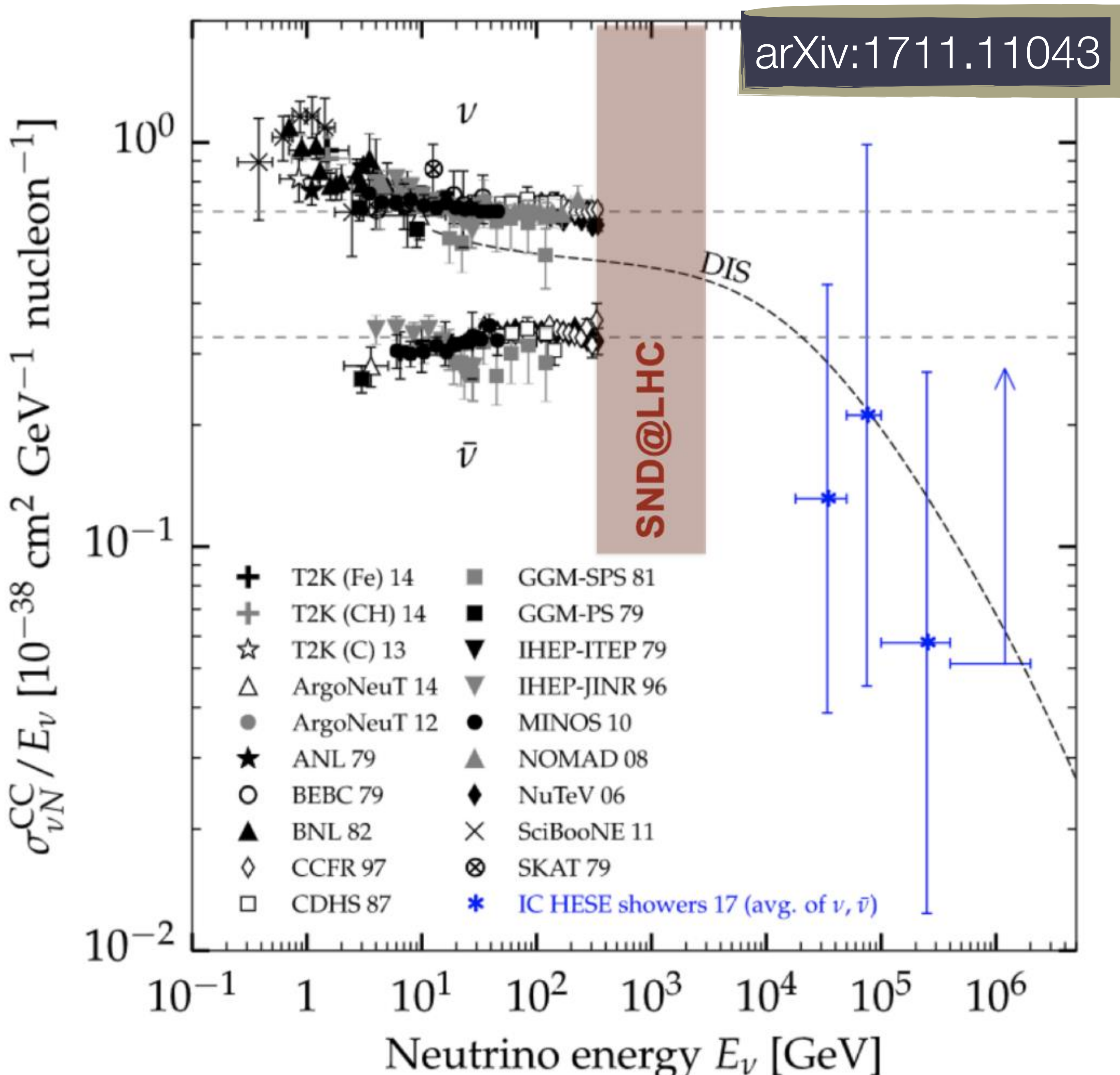




SND@LHC



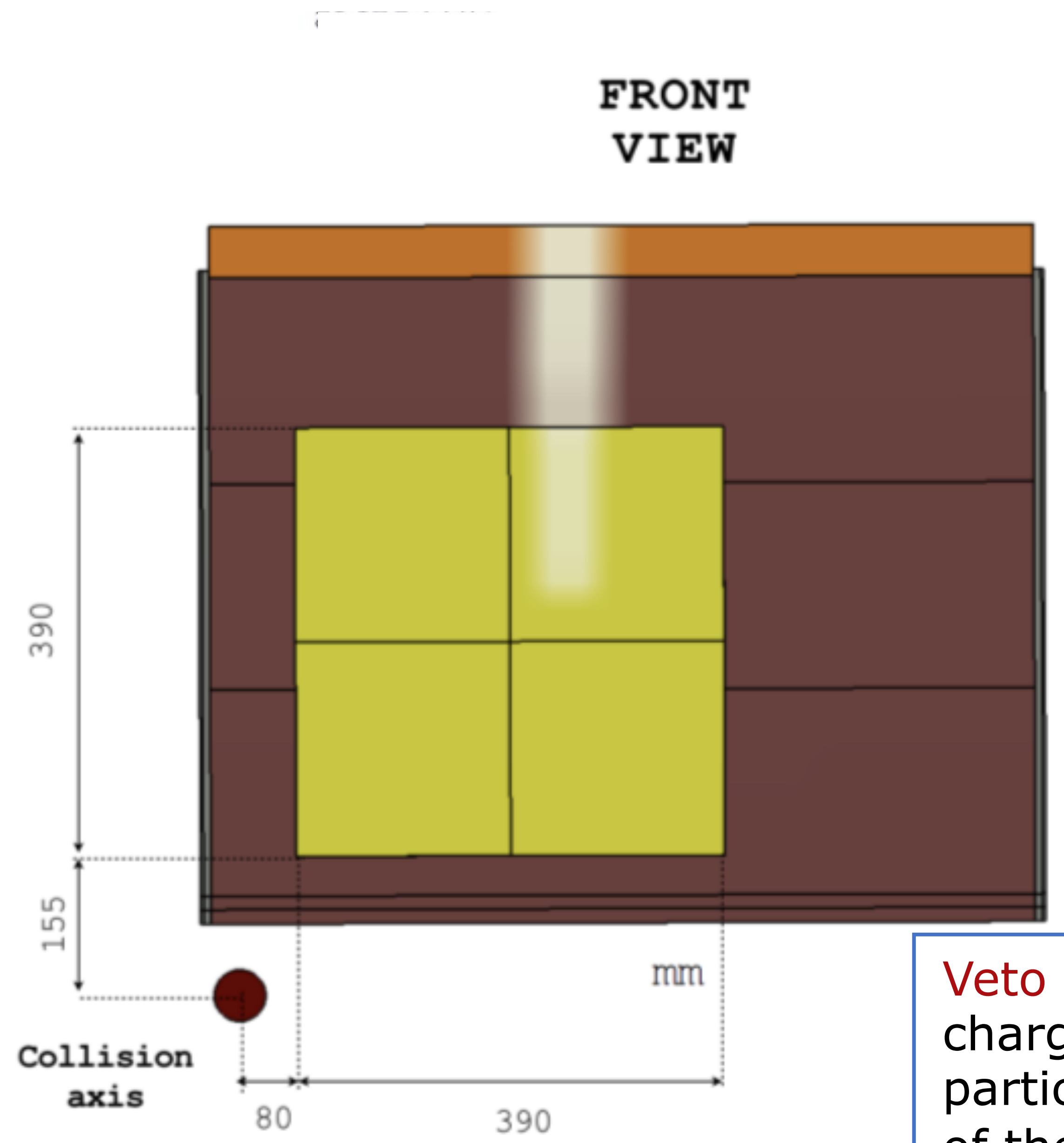




- Stand-alone experiment 480 m downstream of IP1 in TI18 to do measurements on neutrinos in the pseudorapidity region $7.2 < \eta < 8.7$
  - Large expected flux ν in forward direction
- Large brad and butter physics output; e.g.:
  - $\sigma_{pp \to \nu X}$
  - Measurement of the NC/CC ratio
  - **Direct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

SND@LHC

Slide taken from here



Off axis location
Angular acceptance:
$7.2 < \eta < 8.7$
Target material: Tungsten
Target mass: 830 kg
Surface: 390 x 390 mm^2

Electromagnetic calorimeter
~40 X_0

Hadronic calorimeter
~10 λ

Veto plane for charged particles in front of the target region

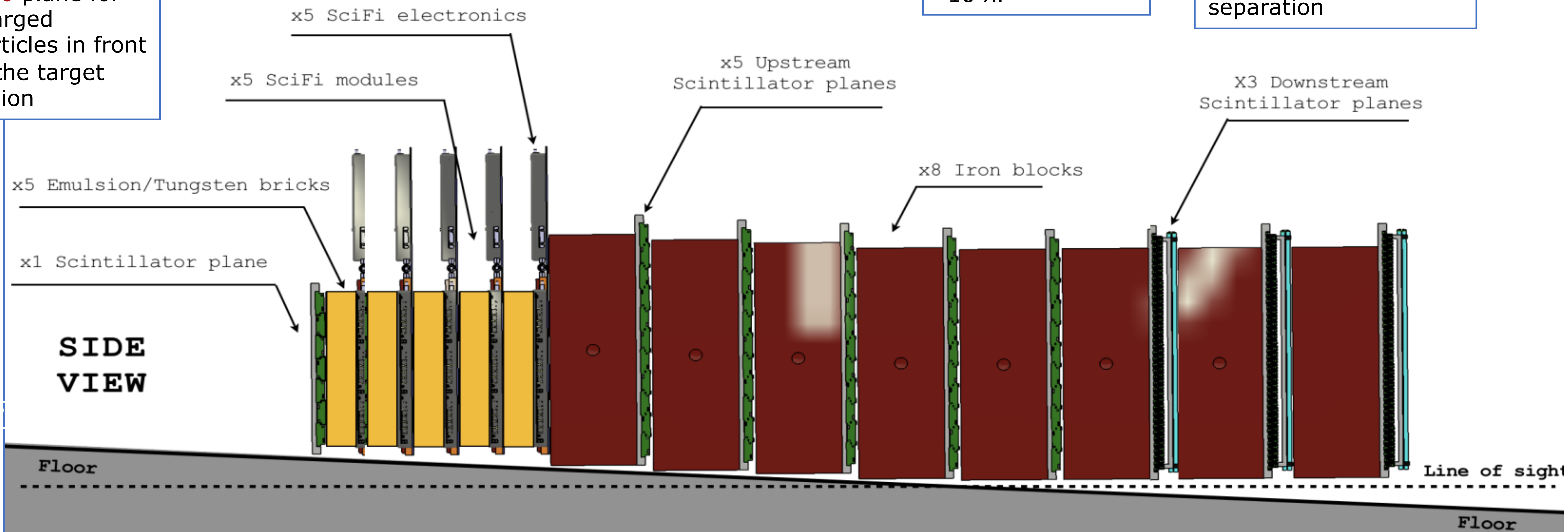
Emulsion Cloud Chamber, emulsion and W absorbers for micrometric accuracy in the detection of τ and FIPs, EM shower energy measurement.

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

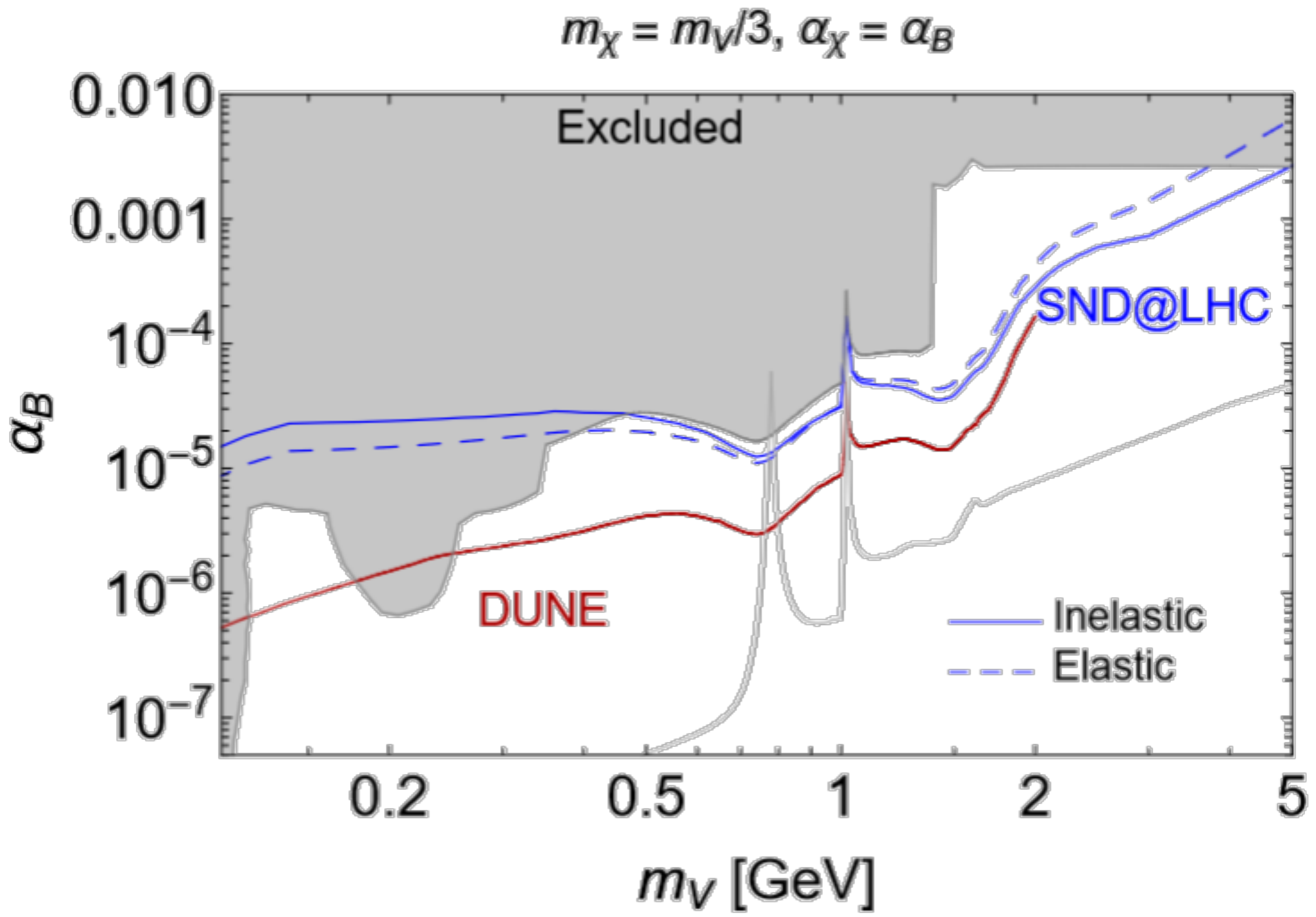
Timing downstream, double X-Y planes with higher granularity for muon-hadron separation

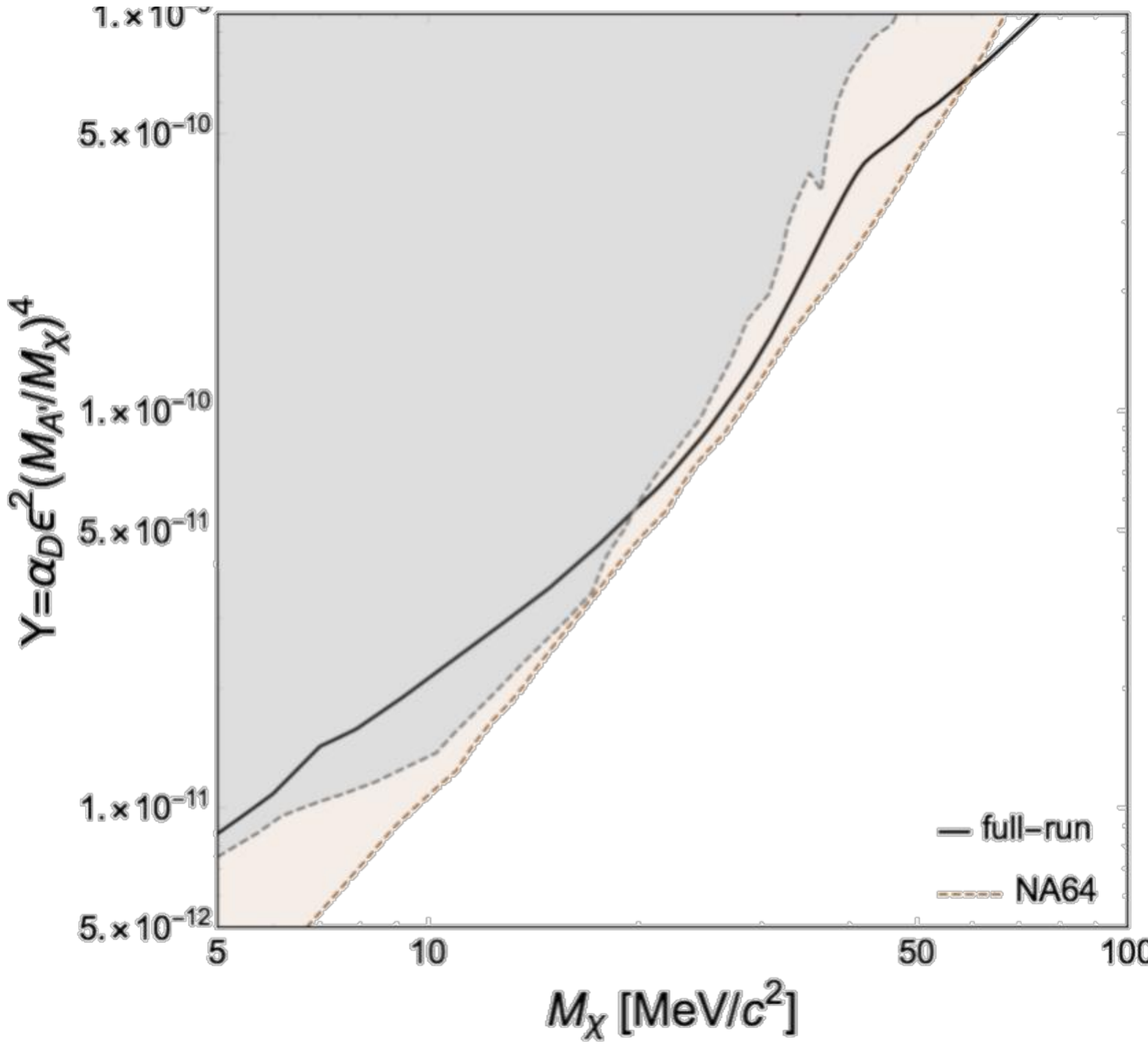


SND@LHC

- **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 ε^2 in the yield
    - SND@LHC is an ε^4 experiment
    - Assume a time resolution of ~200 ps, dominated by the bunch size

Excluded: by CDF, BES, E949 and BNL





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