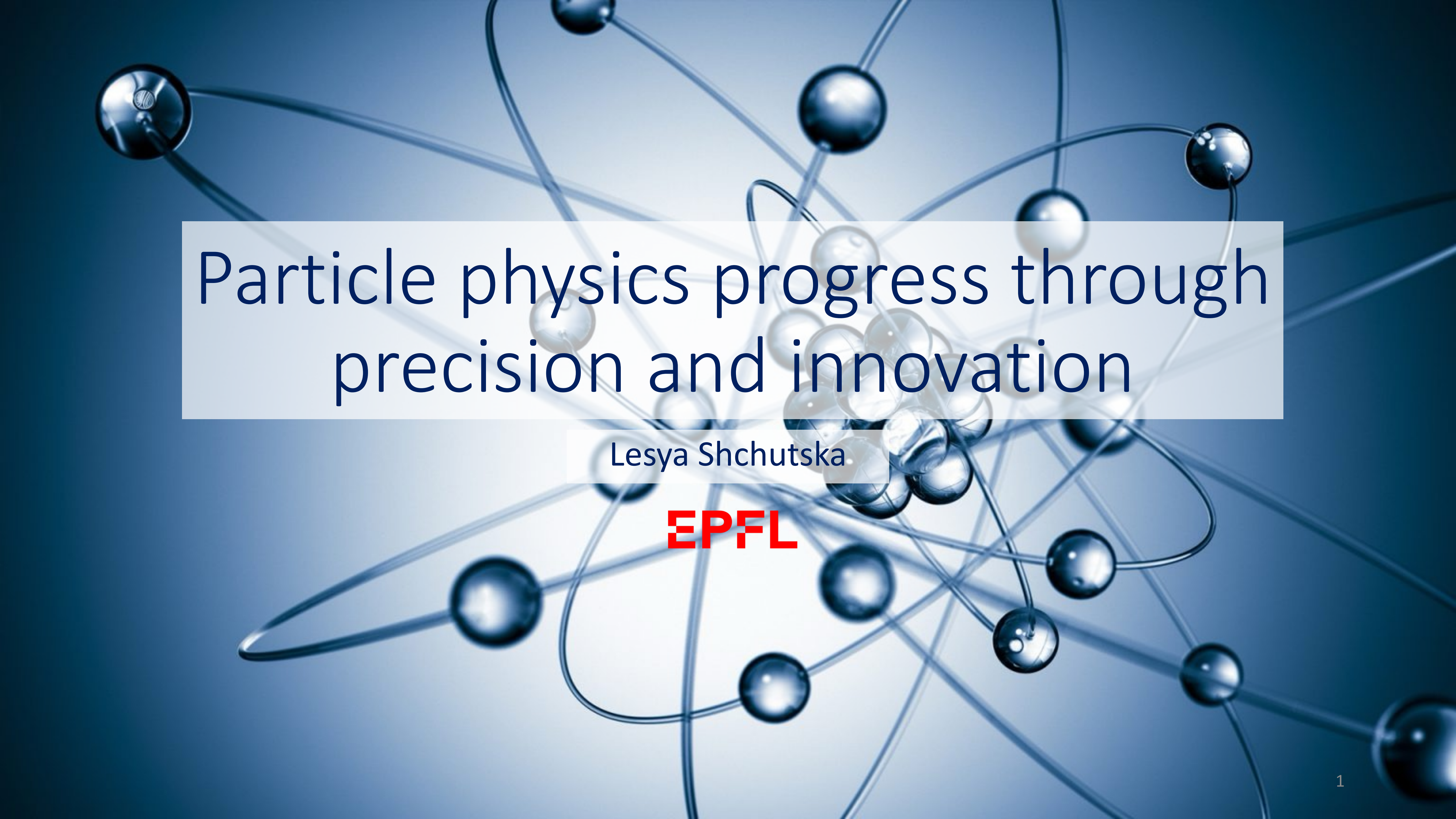


Particle physics progress through precision and innovation

Lesya Shchutska

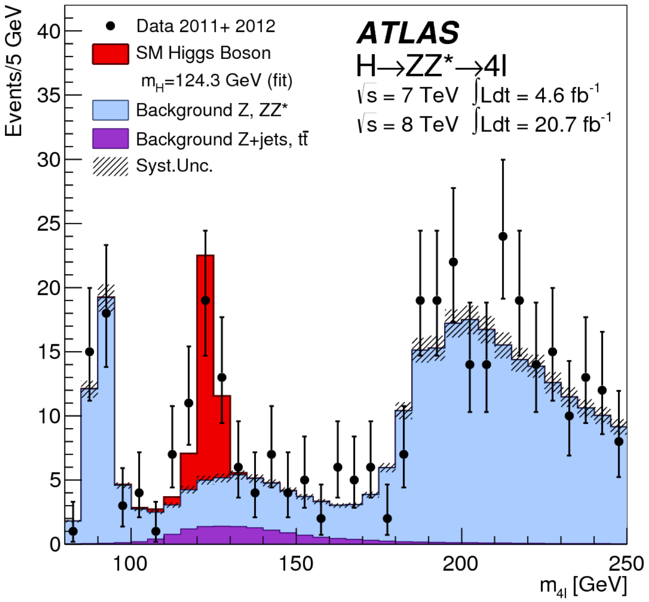
EPFL

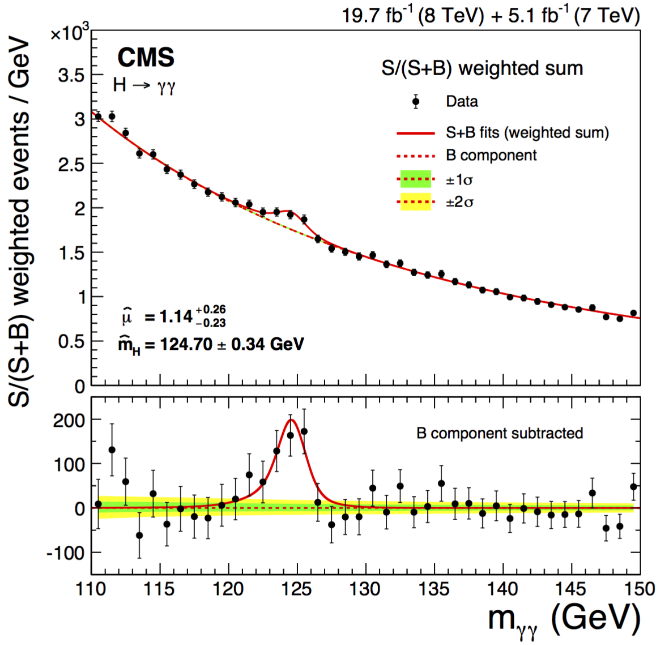
Particle physics

- Particle physics seeks to answer two basic questions:
  - What are the fundamental constituents of matter?
  - What are the fundamental interactions between them?
- And particle physicists are inventing new instruments and approaches to address these questions

Last piece of the puzzle: Higgs boson

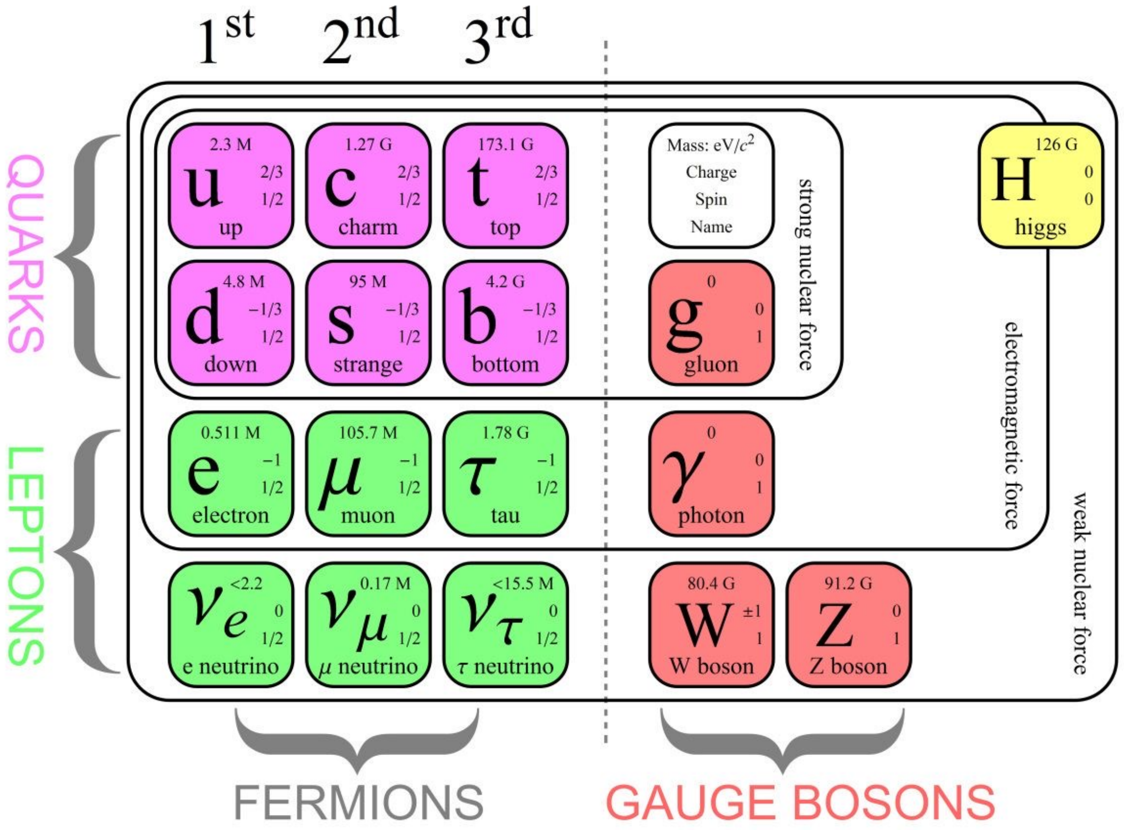
- underlying theory developed and a new particle predicted in 1962-1964
- expected range for Higgs boson mass **motivated and defined** the LHC parameters





- Higgs boson discovered in 2012!

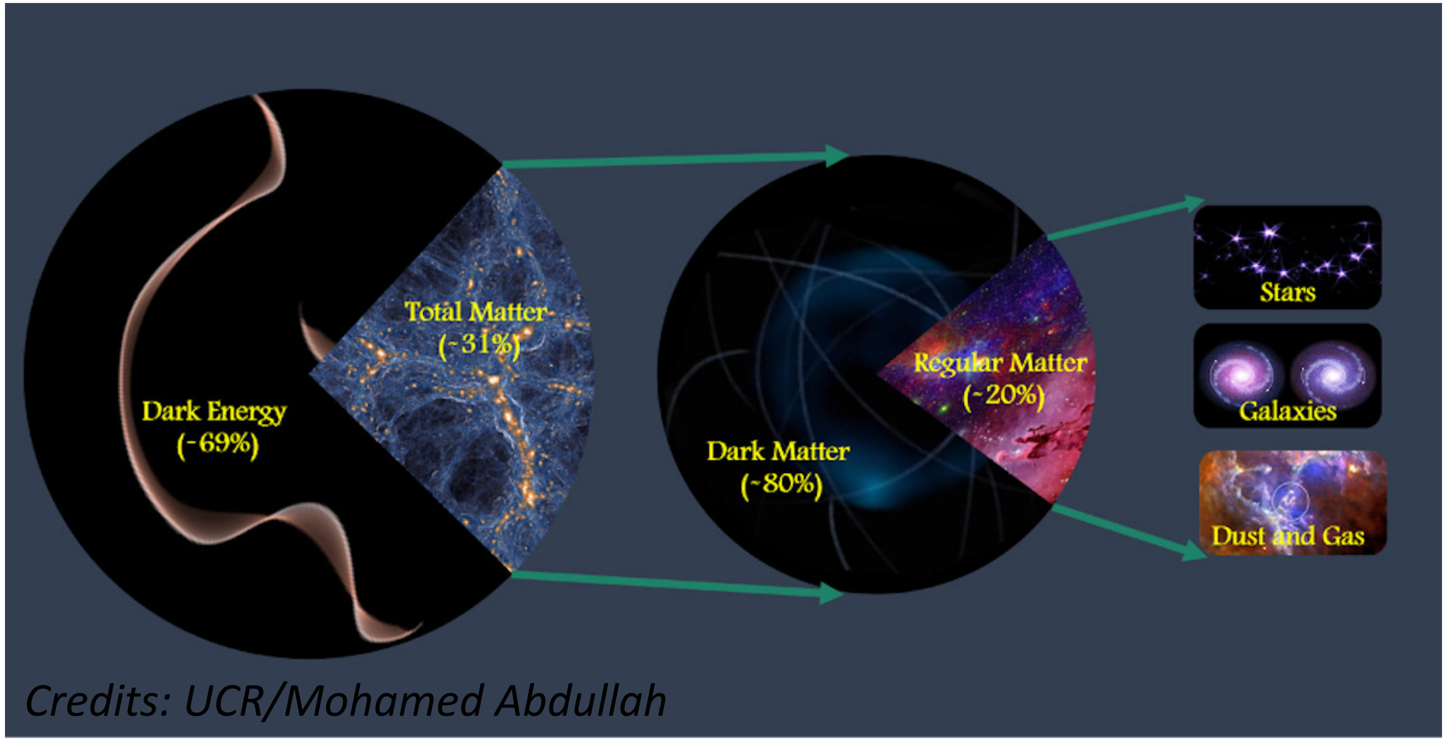
Standard model of particle physics



- is complete now:
  - 3 generations of matter particles, identical apart from their mass
  - carriers for 3 forces
  - Higgs mechanism for particle mass

- works very well for all observed in the lab phenomena:
  - several tensions here and there exist

Why particle physicists do not stop?



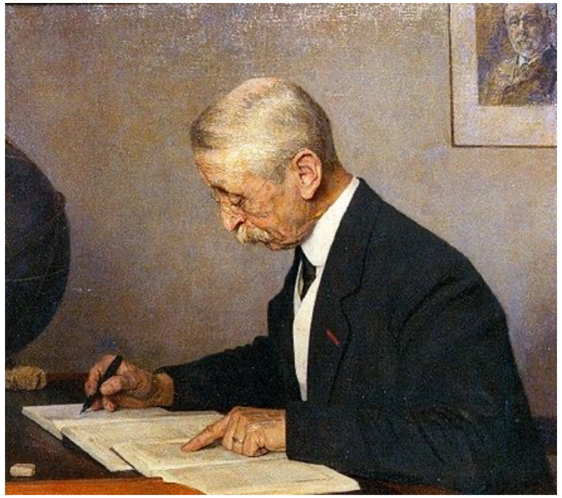
Credits: UCR/Mohamed Abdullah

- standard model accounts for about 5% of the content of the universe
- dark matter is "discovered" more than 100 years ago – and still no explanation for its nature

- + there are many more arguments of why standard model of particle physics is not an ultimate theory

All those motivate numerous "new physics" searches

> 100 years of DM?

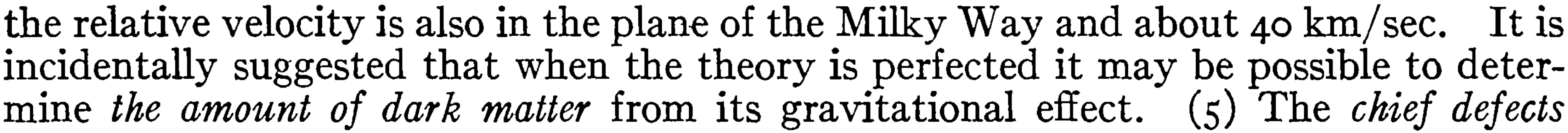


J.C. Kapteyn

“First Attempt at a Theory of the Arrangement and Motion of the Sidereal System”

Astrophysical Journal ***55*** *302, doi:10.1086/142670*

May 1922



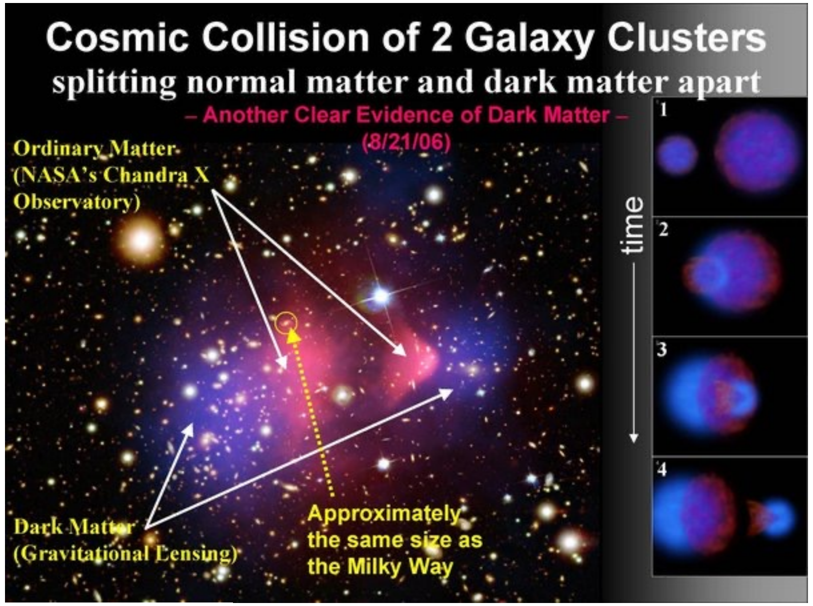
the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects*

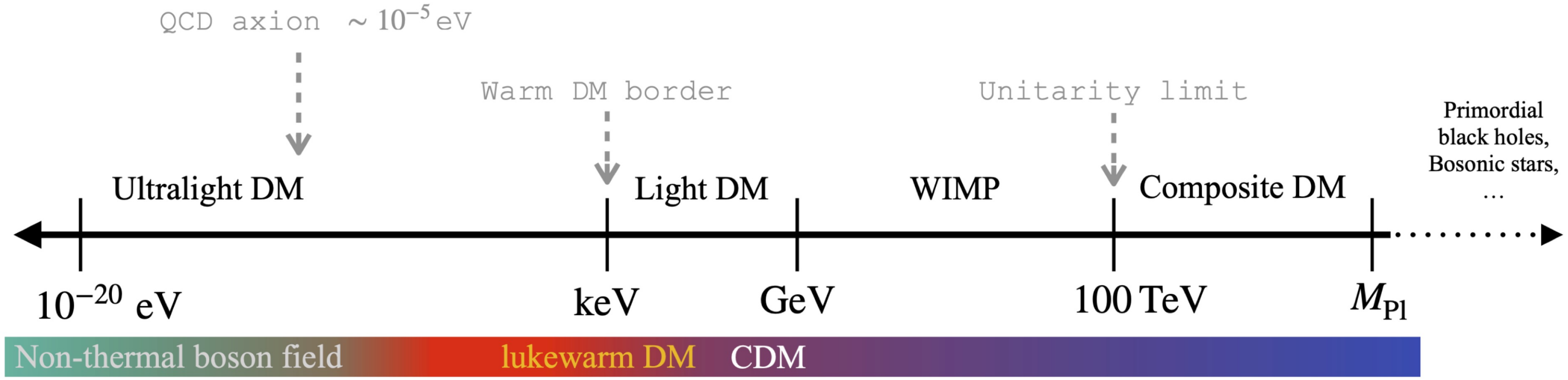
45 years before the formulation of the SM in its modern form

… and DM still is a mystery!

Unknown matter is around us

- Ordinary Matter:
  - successfully explained by the Standard Model of particle physics
- Dark Matter:
  - has properties incompatible with known particles
  - requires new fundamental particles to exist
  - **allowed mass range spans orders of magnitude**





QCD axion $\sim 10^{-5}$ eV

Warm DM border

Unitarity limit

Ultralight DM

Light DM

WIMP

Composite DM

Primordial black holes, Bosonic stars, …

10^{-20} eV

keV

GeV

100 TeV

M_{Pl}

Non-thermal boson field

lukewarm DM

CDM

Symmetry 13 (2021) 10, 1945

Where is “new physics”?

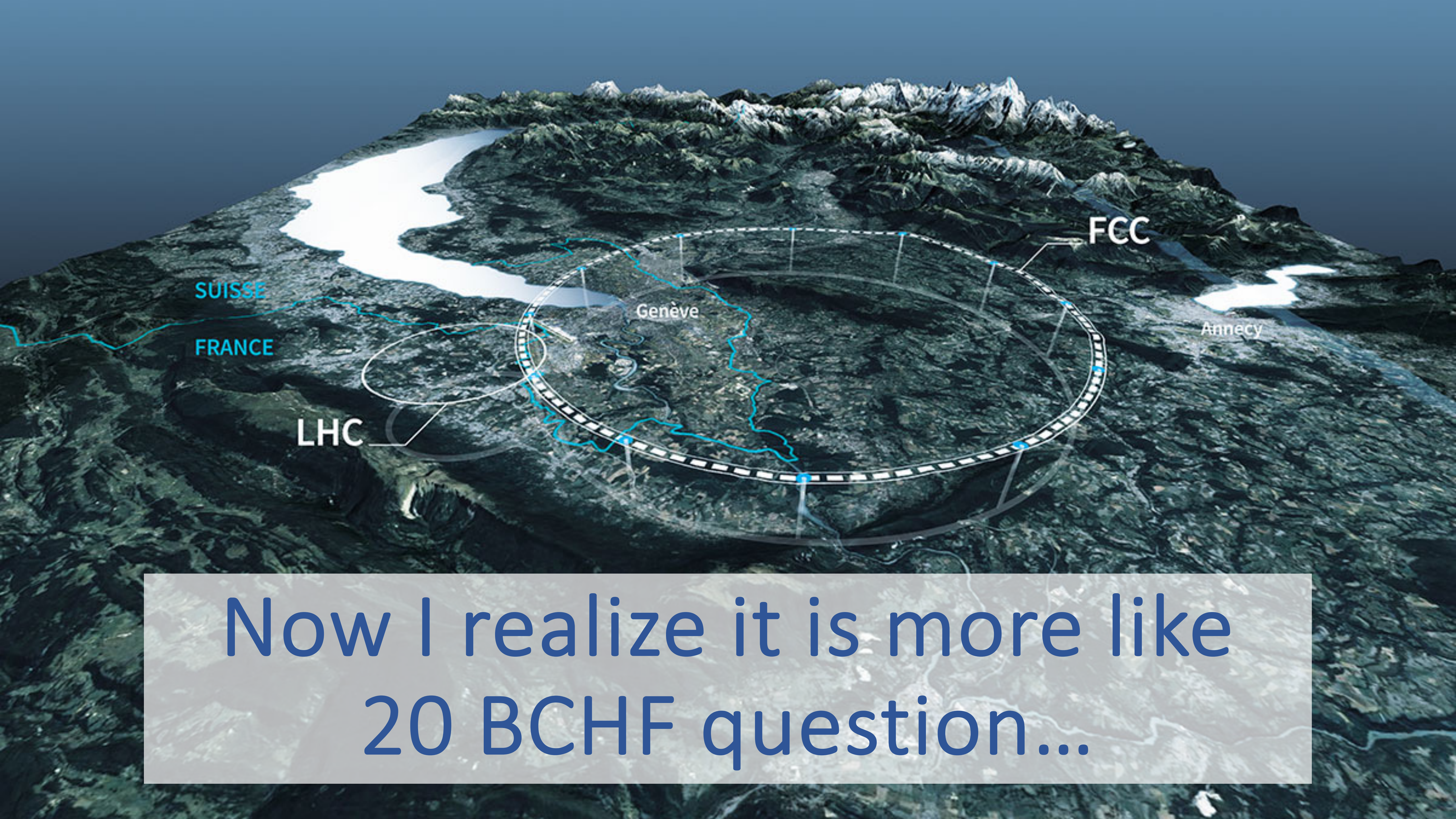
Is the million-dollar question…

Where is “new physics”?

Is the million-dollar question…

or 11.0 million Swedish kronor to be more precise

according to https://www.nobelprize.org/prizes/about/the-nobel-prize-amounts/



Now I realize it is more like
20 BCHF question…

LHC and detectors: our main tool now

First idea in 1976

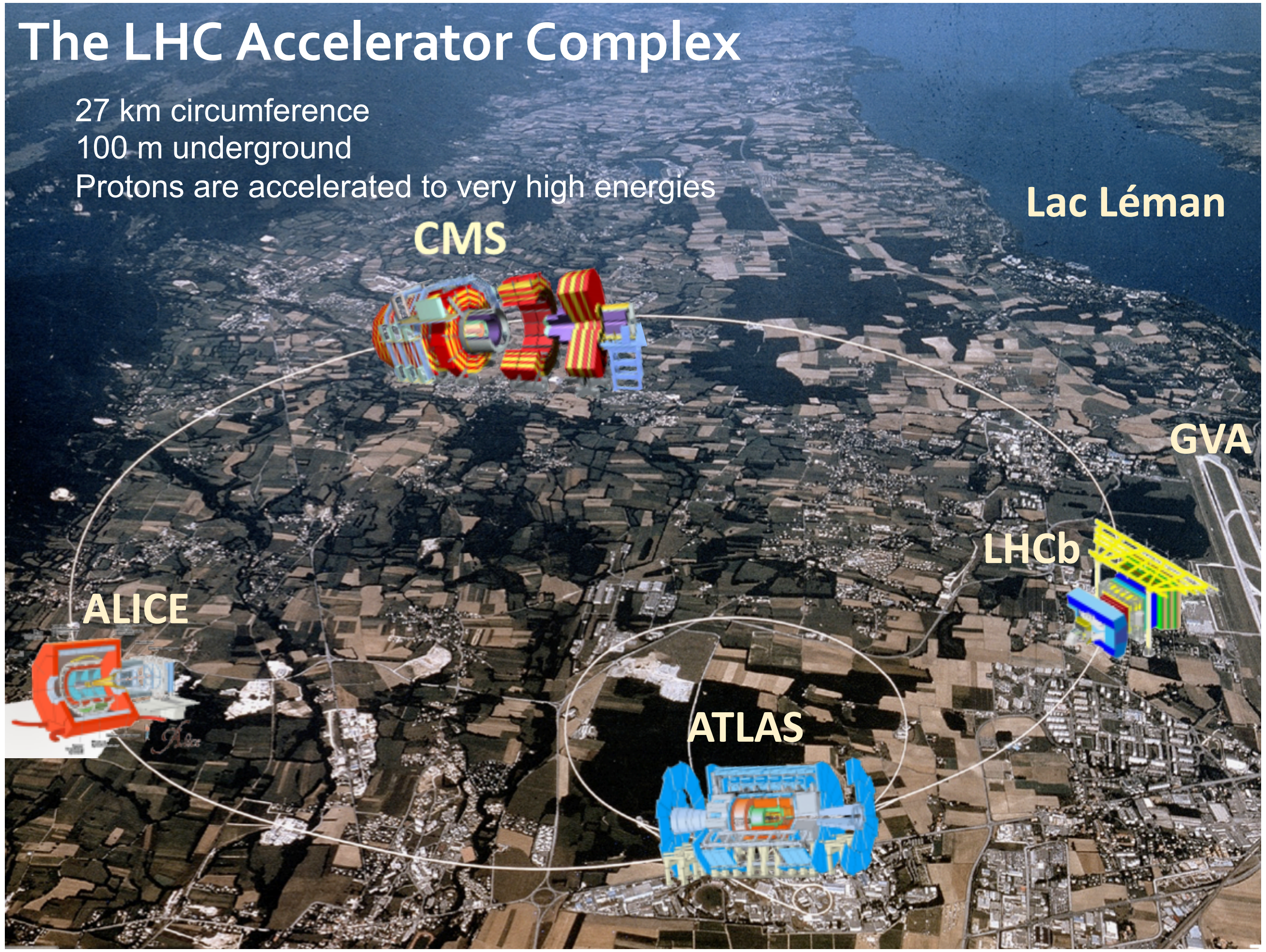
Approved for construction in 1994

Started stable operation in 2009

Planned to run till ~2040

Basically like a star for astrophysicists

⇒ need to explore all possibilities it provides!

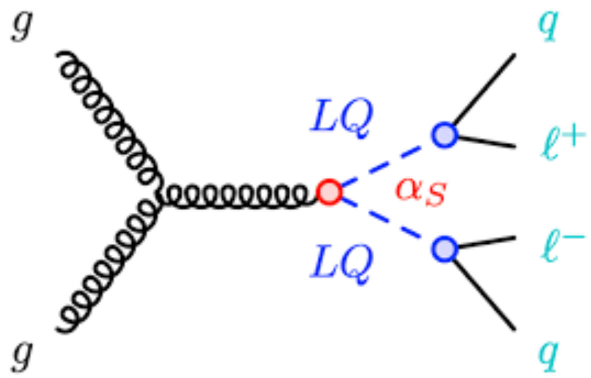


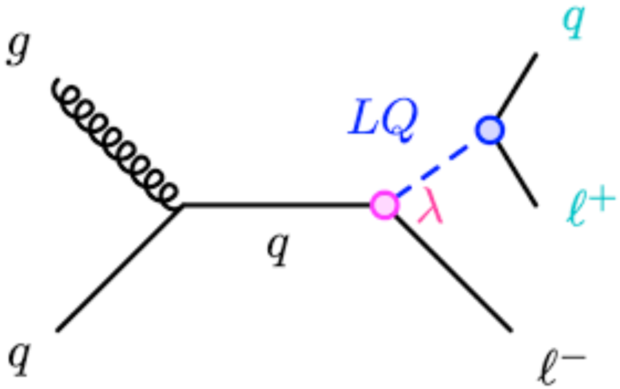
The LHC Accelerator Complex

27 km circumference
100 m underground
Protons are accelerated to very high energies

Energy frontier: heavy particles search

- New particles can be produced in *pp* collisions:

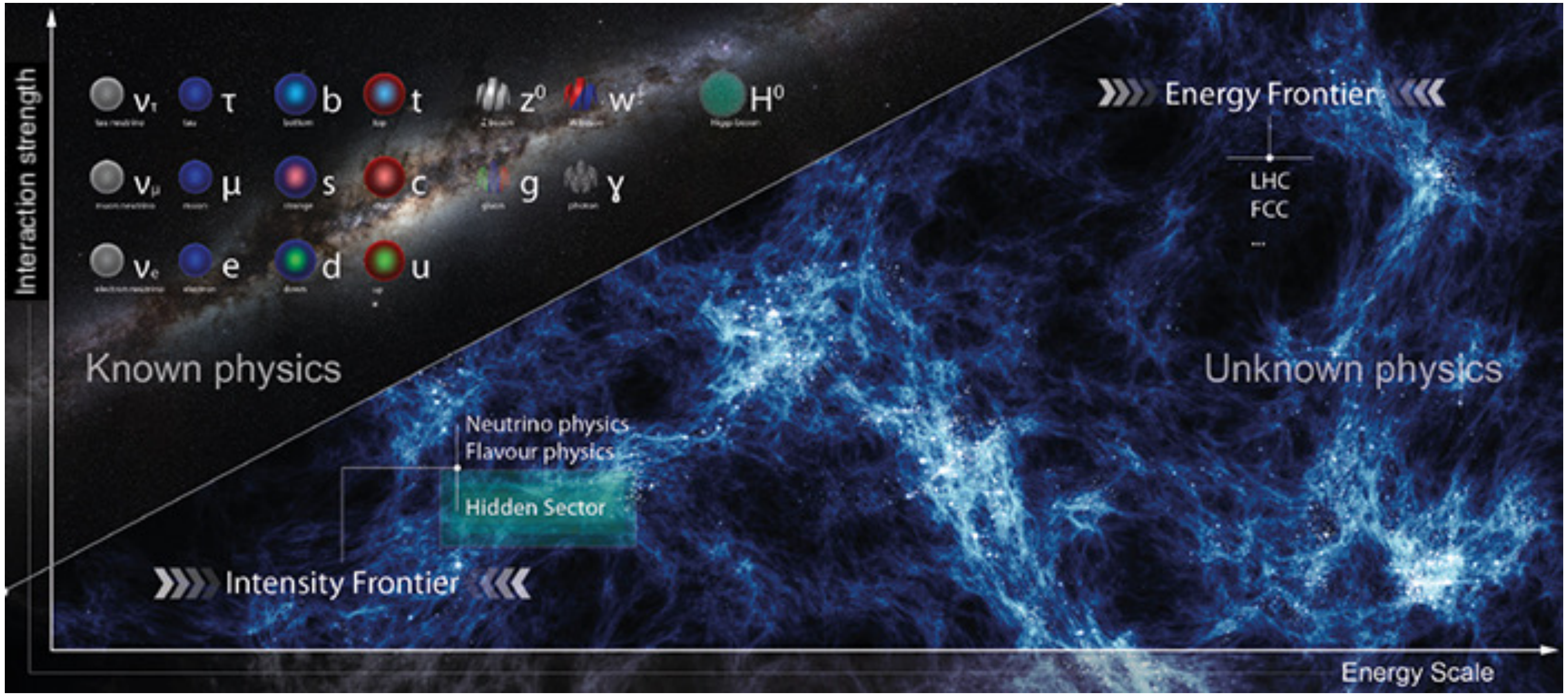




4π general-purpose detector

  - need high enough energy of colliding beams
  - can require a lot of data if the production rate is low
  - searched for with general-purpose ATLAS and CMS experiments

Research goals: global picture



New particles are too heavy to be produced

Look for modification of rare processes

New particles couple too feebly to SM

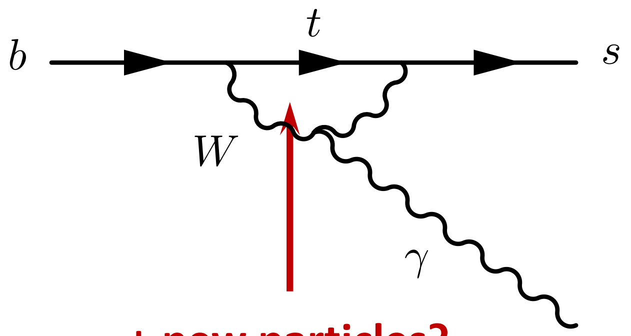
Search for new long-lived particles (LLPs)

Precision measurements track record

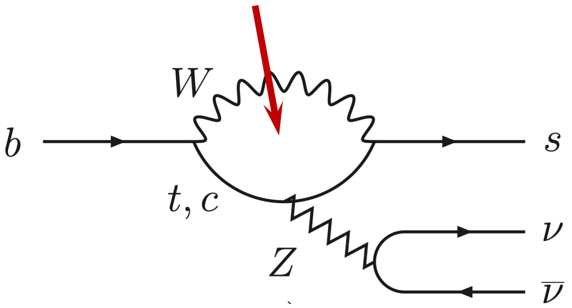
- Uncertainty principle in the works:
  - heavy particles affect lower energy processes: can probe very high scales in SM-suppressed transitions
- High-scale mass sensitivity in suppressed processes:
  - Absence of $K_L \to \mu\mu \Rightarrow$ charm quark (Glashow, Iliopulos, Maiani, 1970)
  - $\epsilon_K \Rightarrow$ existence of 3rd generation (t, b quarks) (Kobayashi, Maskawa, 1973)
  - $\Delta m_K \Rightarrow m_c \sim 1.5\ \text{GeV}$ (Gaillard, Lee; Vainshtein, Khriplovich, 1974)
  - $\Delta m_B \Rightarrow m_t \gtrsim 100\ \text{GeV}$ (direct bound in 1987: 23 GeV) ⇒ large CPV and FCNC
- Now smallness of neutrino masses is the guide?
- And/or scout for other “anomalies”!

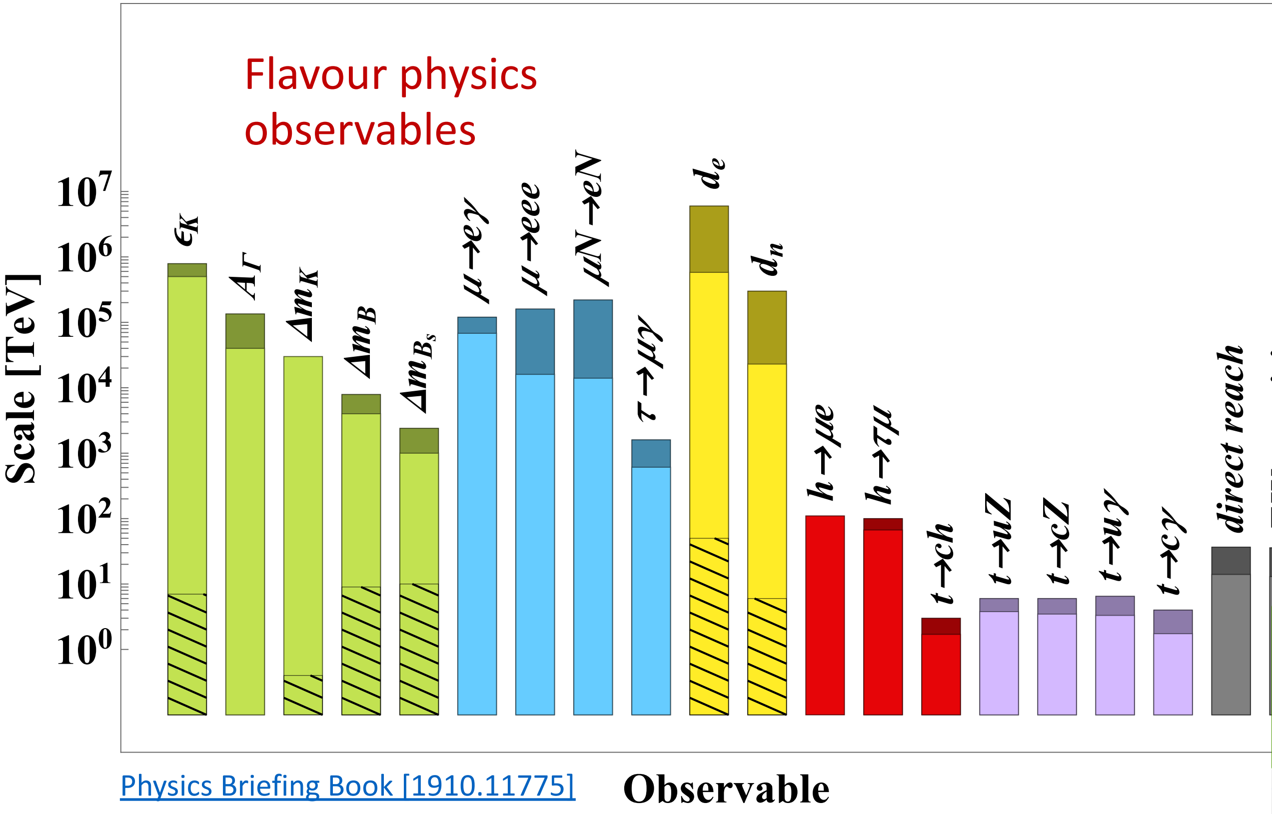
Rare processes – test-ground for unknown

Precision:
happening now



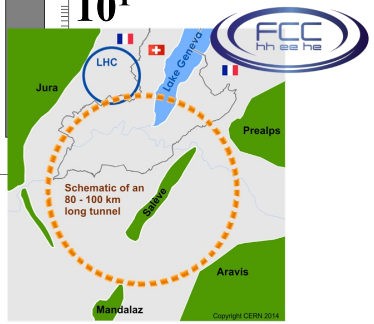
+ new particles?





Flavour physics
observables

[Physics Briefing Book [1910.11775]]

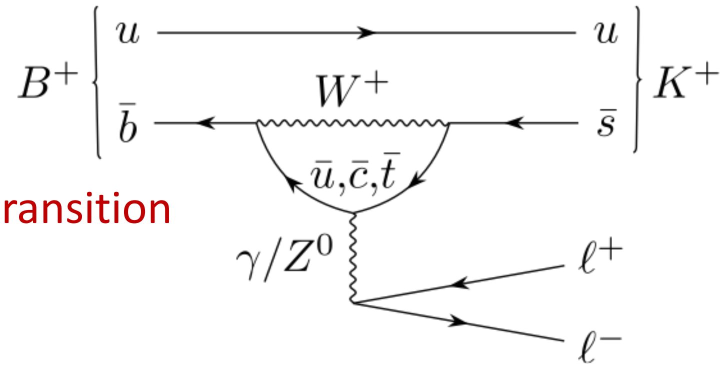


Far, far in the future…

Energy frontier ⇔ precision measurements

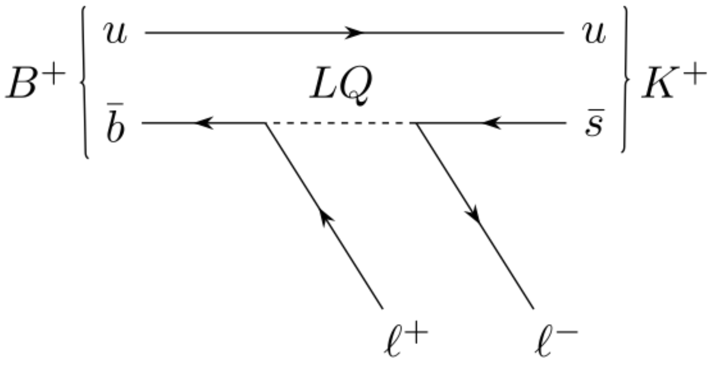
- Recent new hopes:

Standard model:



b→*sℓℓ* loop transition

New interaction: leptoquark LQ



- the $B^+ \rightarrow K^+\ell^+\ell^-$ decay is very suppressed in the SM (10^{-8} of all B^+ decays)
- requires a dedicated detector able to fish out such a rare process from the very high-rate proton collision data – LHCb!

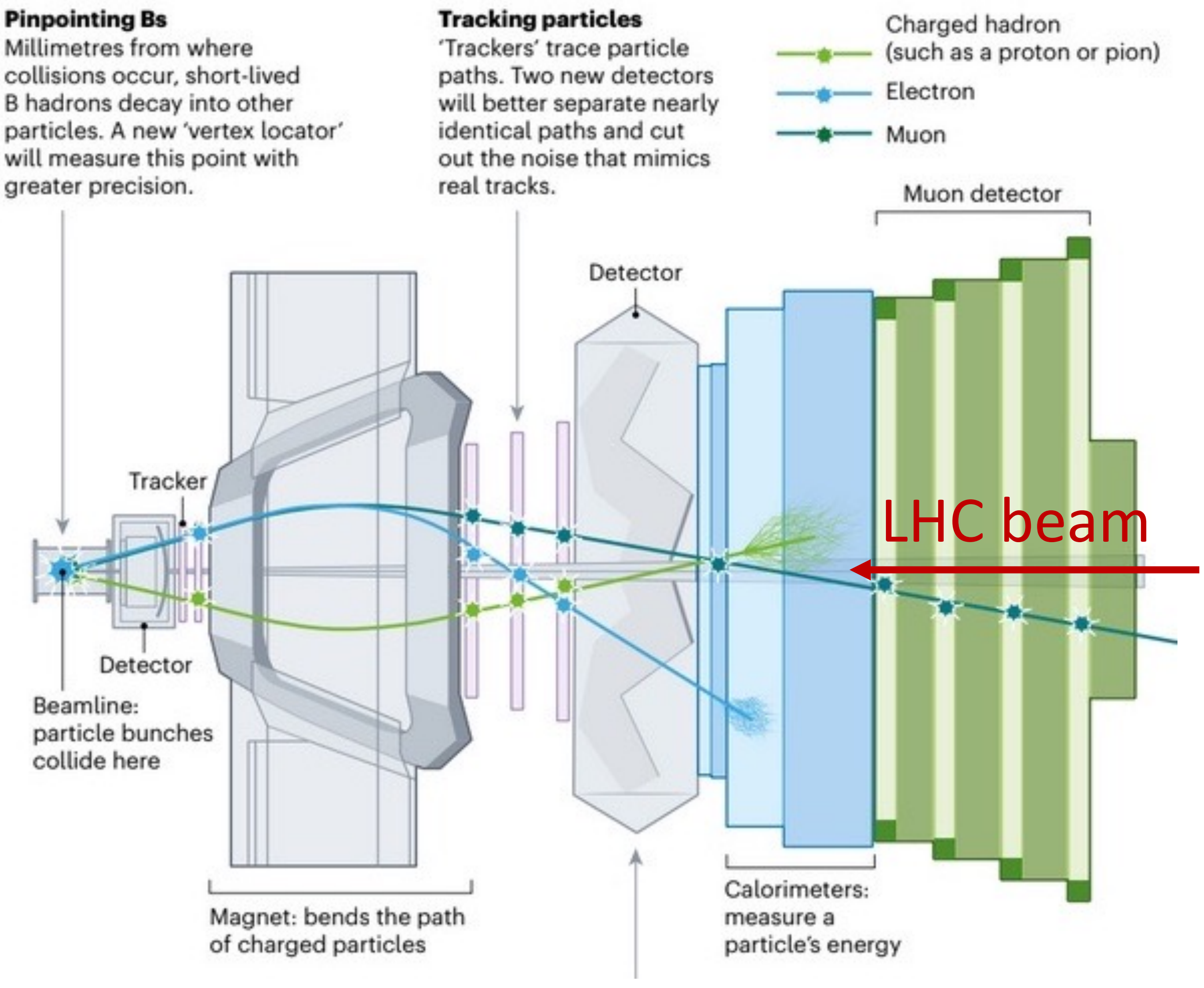
LHCb detector

Forward detector optimized for *b* hadrons

Should operate in a very busy environment

Composed of:

- precise vertex detector to distinguish pp collision point and hadron decay vertices
- tracker and magnet to measure momenta of charged particles
- calorimeter to identify electrons and photons and measure their energy
- Cherenkov detectors to distinguish between species of charged particles
- muon detector to identify muons



Pinpointing Bs
Millimetres from where collisions occur, short-lived B hadrons decay into other particles. A new 'vertex locator' will measure this point with greater precision.

Tracking particles
'Trackers' trace particle paths. Two new detectors will better separate nearly identical paths and cut out the noise that mimics real tracks.

Beamline: particle bunches collide here

Magnet: bends the path of charged particles

Calorimeters: measure a particle's energy

LHCb: top view

Credits: CERN

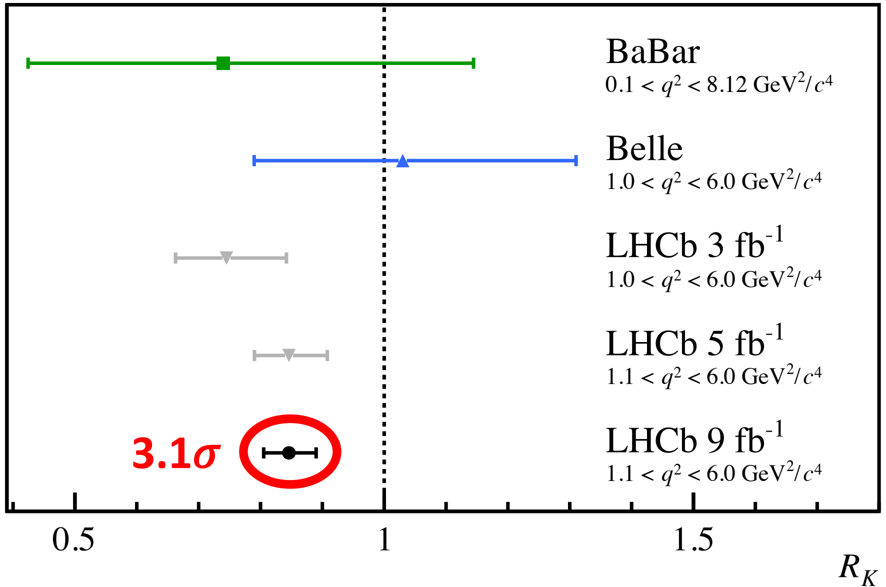
Lepton universality tests

- for theoretically precise observables, construct ratios:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

- R_K should be equal to 1 in the SM
- but decays to muons looked suppressed – a hint towards *lepton universality violation or possible new interaction*!

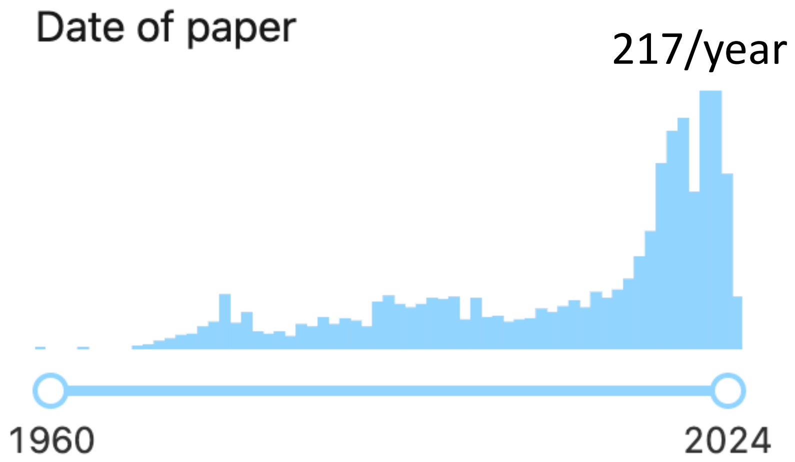
$B^\pm$ decays to $K^\pm\mu^+\mu^-$ look suppressed wrt $K^\pm e^+e^-$



Nature Phys. 18 (2022) 3

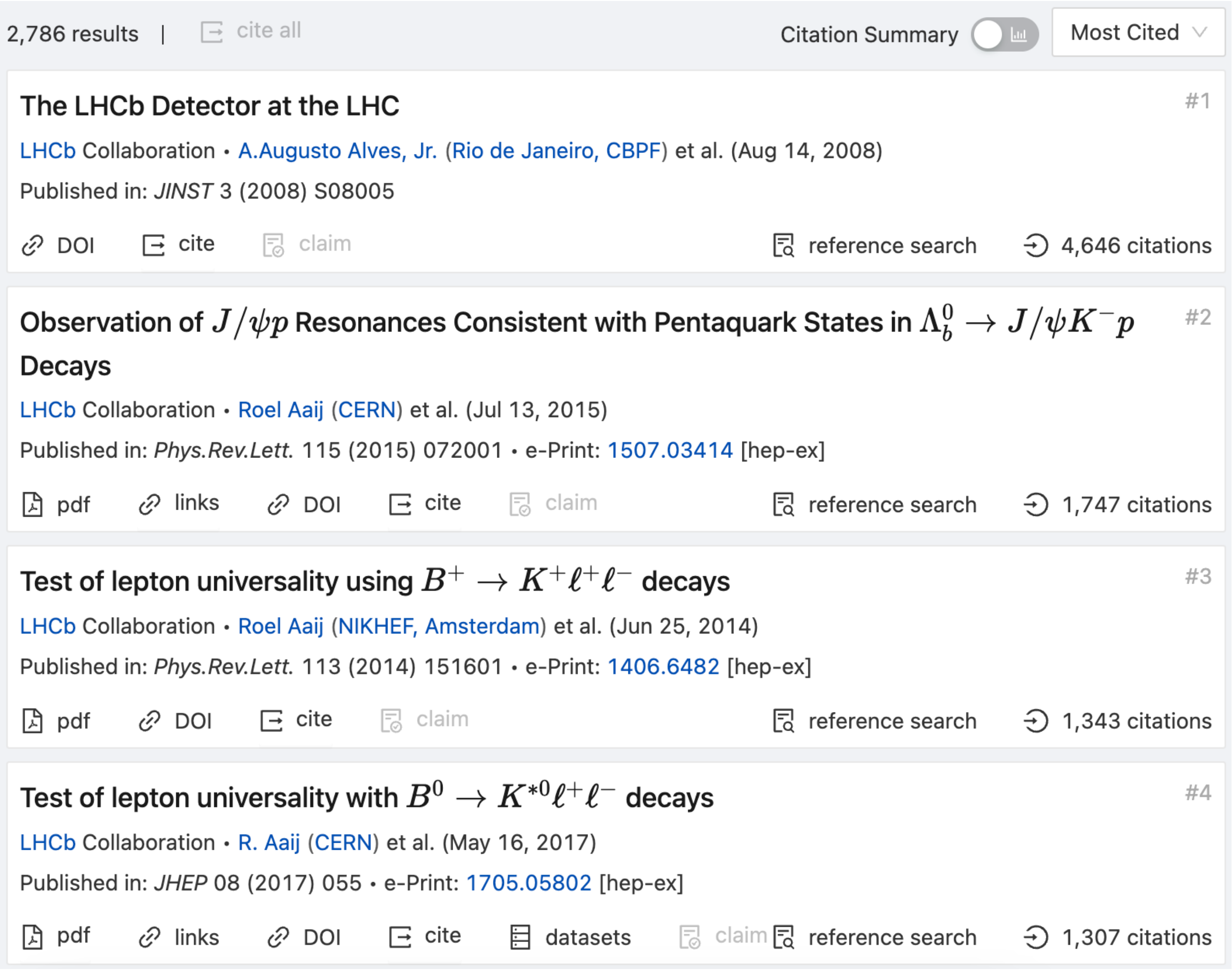
Tests of lepton universality

All “lepton universality” papers:



- over 2k papers in total
- over 94k citations

LHCb papers ranked by citation number as of May 2024


2,786 results | cite all   Citation Summary   Most Cited

The LHCb Detector at the LHC #1

LHCb Collaboration • A.Augusto Alves, Jr. (Rio de Janeiro, CBPF) et al. (Aug 14, 2008)

Published in: *JINST* 3 (2008) S08005

DOI cite claim reference search 4,646 citations

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays #2

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: 1507.03414 [hep-ex]

pdf links DOI cite claim reference search 1,747 citations

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays #3

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 25, 2014)

Published in: *Phys.Rev.Lett.* 113 (2014) 151601 • e-Print: 1406.6482 [hep-ex]

pdf DOI cite claim reference search 1,343 citations

Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays #4

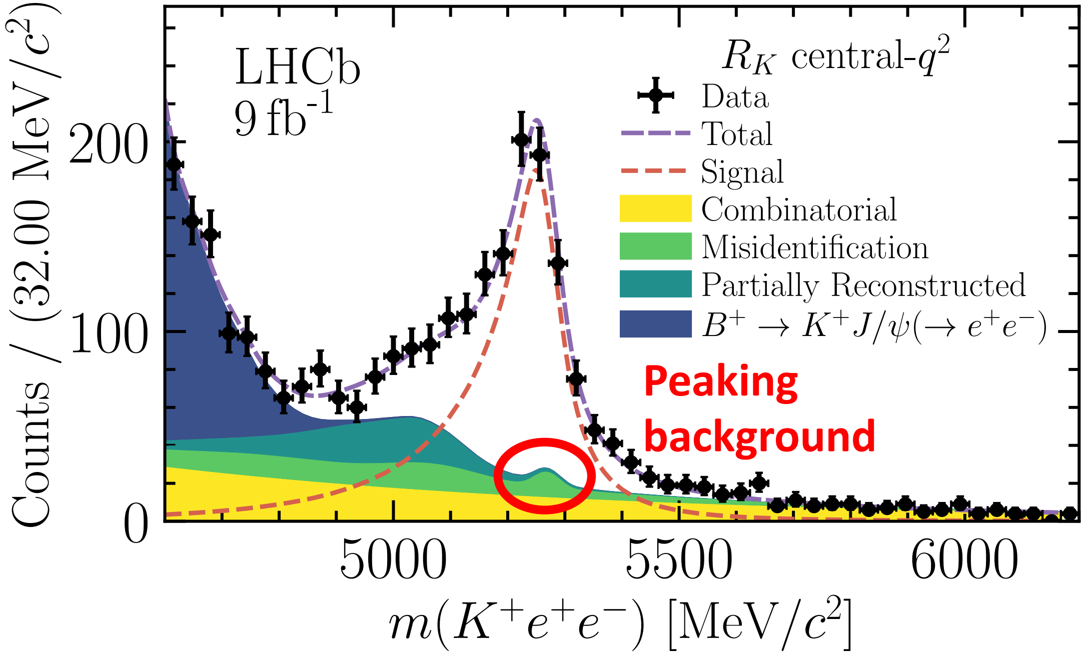
LHCb Collaboration • R. Aaij (CERN) et al. (May 16, 2017)

Published in: *JHEP* 08 (2017) 055 • e-Print: 1705.05802 [hep-ex]

pdf links DOI cite datasets claim reference search 1,307 citations

Lepton universality restored in $b \to s\ell\ell$ ratios

Reconstructed B^+ mass in $K^+e^+e^-$ mode

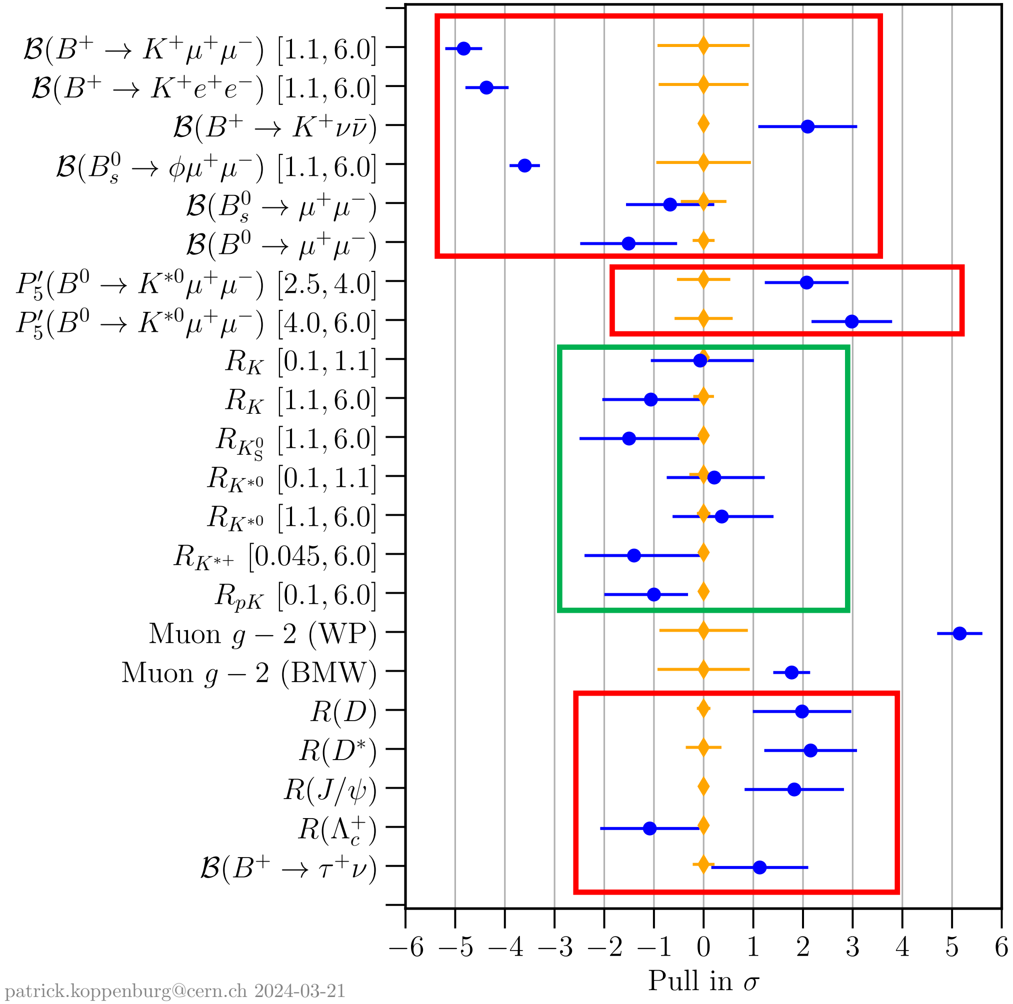


- new combined analysis finalized at the end of 2022
- hadron to electron misidentification appeared to be important
- proposed a dedicated data-driven method to reliably estimate this background
- the new measurement is consistent with the SM within 0.2σ

PRL 131 (2023) 051803, PRD 108 (2023) 032002
https://actu.epfl.ch/news/lepton-universality-restored/

Lepton puzzles are not over

Orange: theory unc.; blue: experiment



b→sℓℓ rates

*b→s**μμ*** angular

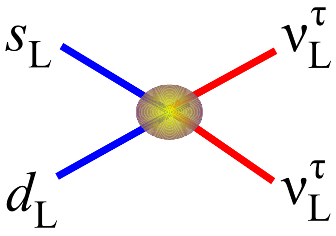
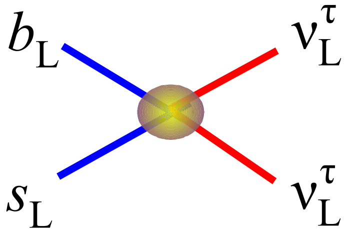
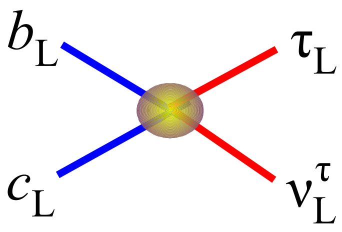
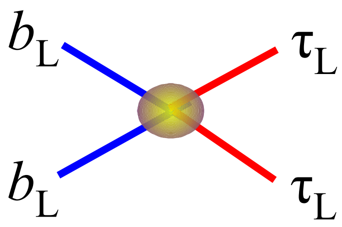
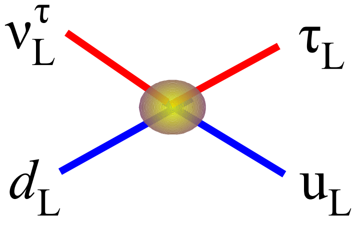
b→sℓℓ ratios
(back to SM)

*b→c**τ**ν*

- other observables in the *b→sℓℓ* transitions exhibit tensions with the SM
- some enhancement of *b→c**τ**ν* decays *vs* *b→c**μ**ν*
- follow-up and complementary measurements are in the works!

patrick.koppenburg@cern.ch 2024-03-21

Special attention to the third generation

$C \times \lvert V_{ts} \rvert \lvert V_{td} \rvert$	$C \times \lvert V_{ts} \rvert$	$C \times \lvert V_{cb} \rvert$	C	$C \times \lvert V_{ub} \rvert \lvert V_{td} \rvert$
				
$B(K^+ \to \pi^+ \nu\nu)$	$B(B^+ \to K^+ \nu\nu)$	$R[D^{(*)}]$	$\sigma(pp \to \tau\tau)$	$\sigma(\nu^\tau N \to N'\tau)$

excess over SM prediction

excess over SM prediction

excess over SM prediction

Gino Isidori

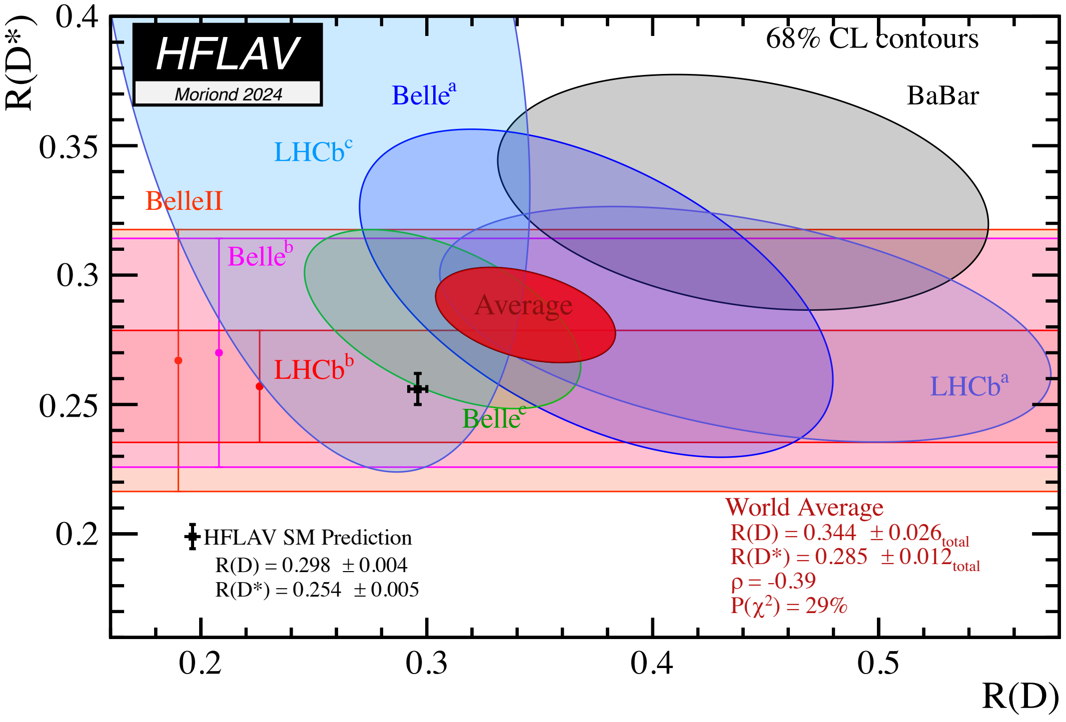
Flavor observables

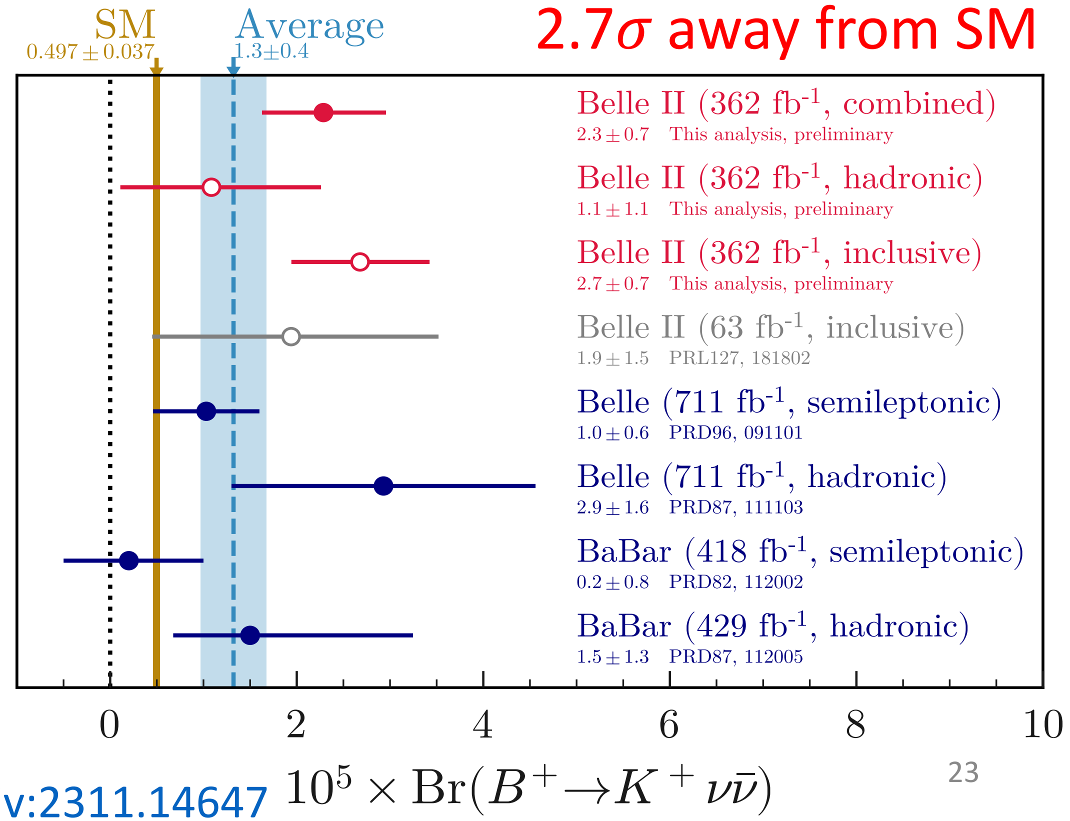
- persisting anomalies in R(D) and R($D*$) and recent enhanced evidence for $B^+ \to K^+ \nu\bar{\nu}$ motivate BSM models coupled to 3rd generation

R(D) and R($D*$): 3.2σ away from SM

$B^+ \to K^+ \nu\bar{\nu}$:

2.7σ away from SM



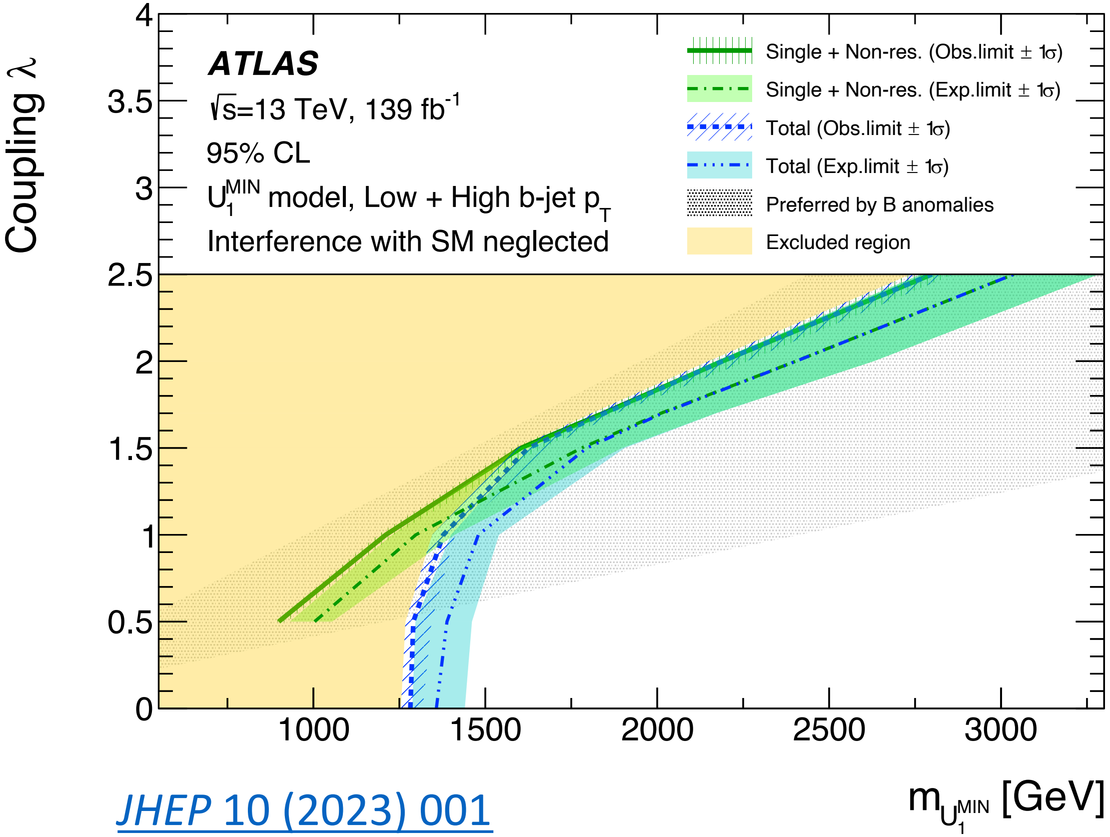


HFLAV

arXiv:2311.14647

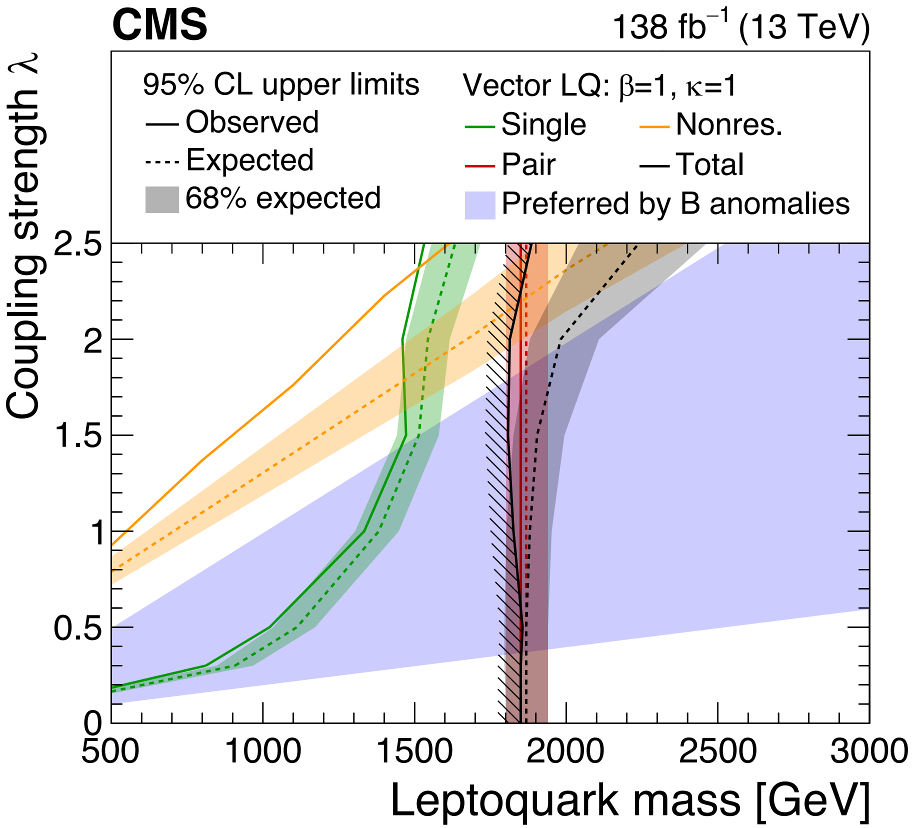
Direct pp→$\tau\tau$ production

1σ away from SM



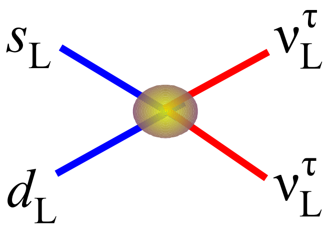
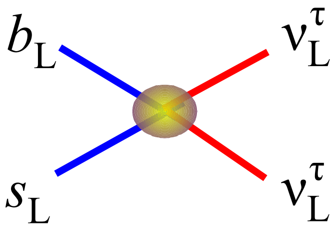
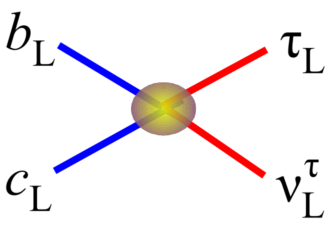
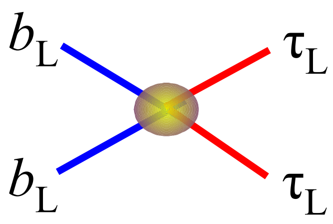
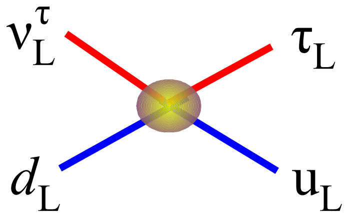
JHEP 10 (2023) 001

2.8σ away from SM



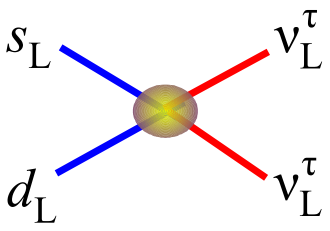
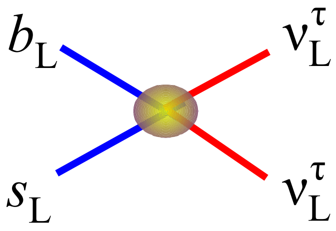
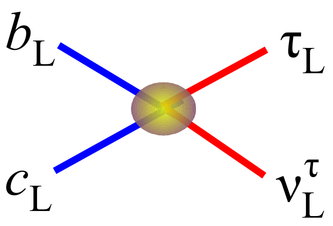
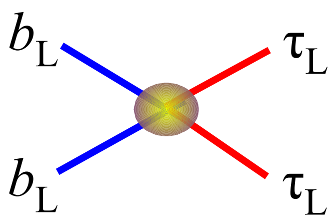
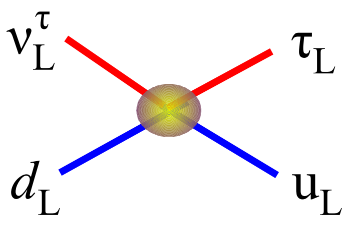
arXiv:2308.07826

Prospects with existing facilities

$C \times \lvert V_{ts} \rvert \lvert V_{td} \rvert$	$C \times \lvert V_{ts} \rvert$	$C \times \lvert V_{cb} \rvert$	C	$C \times \lvert V_{ub} \rvert \lvert V_{td} \rvert$
				
$B(K^+ \to \pi^+ \nu\nu)$	$B(B^+ \to K^+ \nu\nu)$	$R[D^{(*)}]$	$\sigma(pp \to \tau\tau)$	$\sigma(\nu^\tau N \to N'\tau)$
Now [NA62]:	Now [Belle-II]:	Now [HFLAV]:	Now [ATLAS]:	Now:
$\Lambda > 1.7$ TeV	$\Lambda > 1.3$ TeV	$\Lambda > 0.6$ TeV	$\Lambda > 1.2$ TeV	–
$\delta B = 5\%$ [HIKE]:	$50\,ab^{-1}$ [Belle-II]:	$50\,ab^{-1}$ [Belle-II]:	$3\,ab^{-1}$ [HL-LHC]:	$\delta\sigma = 5\%$ [*future* ?]:
$\Lambda > 4.7$ TeV	$\Lambda > 3.6$ TeV	$\Lambda > 1.2$ TeV	$\Lambda > 1.7$ TeV	–

Gino Isidori

Prospects and alternatives

$C \times \lvert V_{ts}\rvert\lvert V_{td}\rvert$	$C \times \lvert V_{ts}\rvert$	$C \times \lvert V_{cb}\rvert$	C	$C \times \lvert V_{ub}\rvert\lvert V_{td}\rvert$
				
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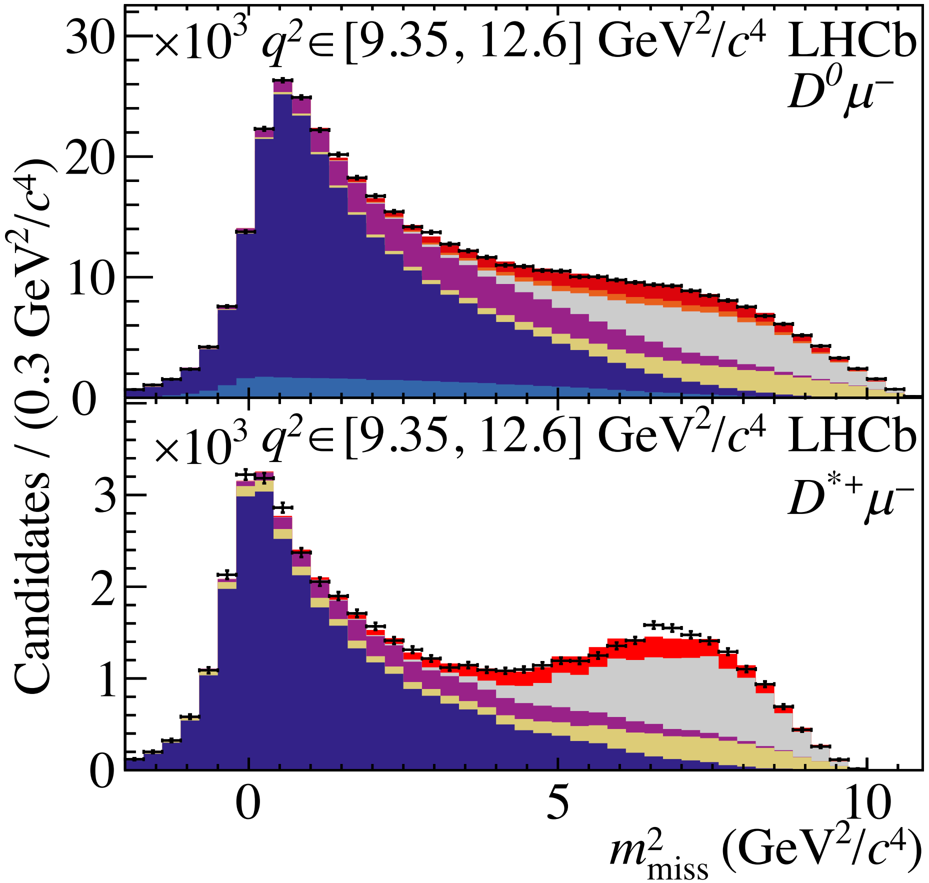
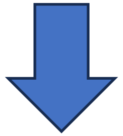
Now [NA62]:	Now [Belle-II]:	Now [HFLAV]:	Now [ATLAS]:	Now:
$\Lambda > 1.7$ TeV	$\Lambda > 1.3$ TeV	$\Lambda > 0.6$ TeV	$\Lambda > 1.2$ TeV	–
~~$\delta B = 5\%$ [HIKE]:~~	$50\,ab^{-1}$ [Belle-II]:	$50\,ab^{-1}$ [Belle-II]:	$3\,ab^{-1}$ [HL-LHC]:	$\delta\sigma = 5\%$ [*future* ?]:
~~$\Lambda >$ [illegible] TeV~~	$\Lambda > 3.6$ TeV	$\Lambda > 1.2$ TeV	$\Lambda > 1.7$ TeV	**SND @ SHiP ?**

LFU tests: $b\rightarrow c\tau\nu$ to $b\rightarrow c\ell\nu$ ratios



PRL 131 (2023) 111802

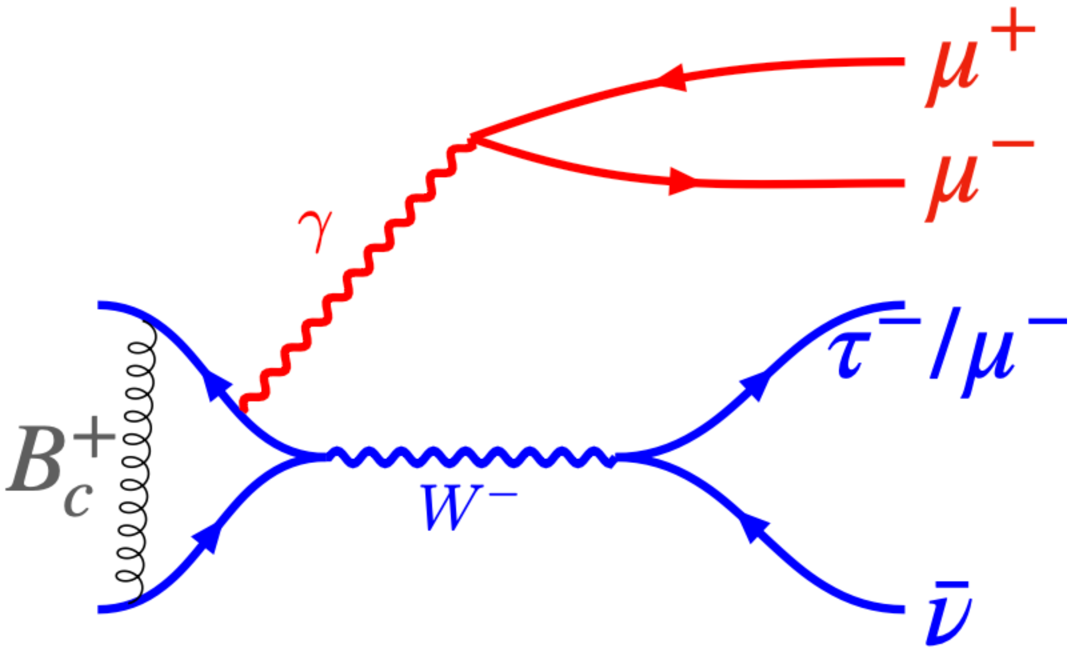
- tensions up to 3σ with theory
- measurement which is hard to control



- can go for complementary channels governed by the same transition:
  - $B^+_{(c)}\rightarrow\ell\nu\gamma^*(\rightarrow\ell'\ell')$
- or sensitive to the same new physics:
  - $b\rightarrow s\tau\tau$
- Neither of those observed to date

$B \to 3\ell\nu$: ingredients

Start with $\gamma^* \to \mu\mu$



- Soft muon handling and validation of γ^* MC simulation:
    - discover and study $J/\psi \to \mu\mu\gamma^*(\mu\mu)$
    - ⇒ done!
- Soft muon/decay in flight separation:
    - develop dedicated muon ID algorithm
    - develop data-driven residual decays in flight estimation
    - discover and study $B^+ \to K^+ J/\psi\gamma^*(\mu\mu)$
    - ⇒ in preparation

J/ψ→4μ observation

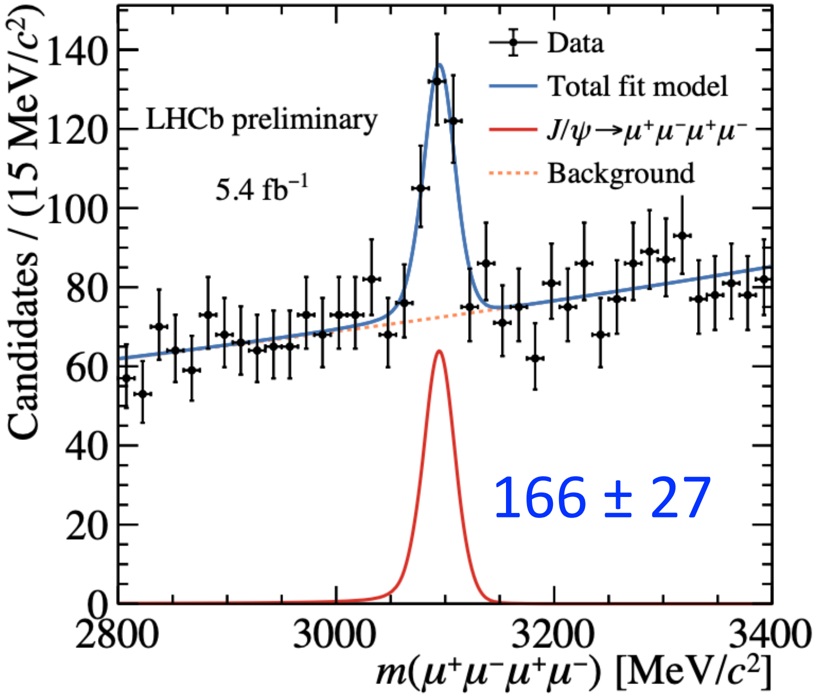
- $J/\psi \to 4\mu$ observed in both samples with large significance ($\gg 5\sigma$)

$$R_{BR} = (1.89 \pm 0.17 \pm 0.09) \times 10^{-5}$$

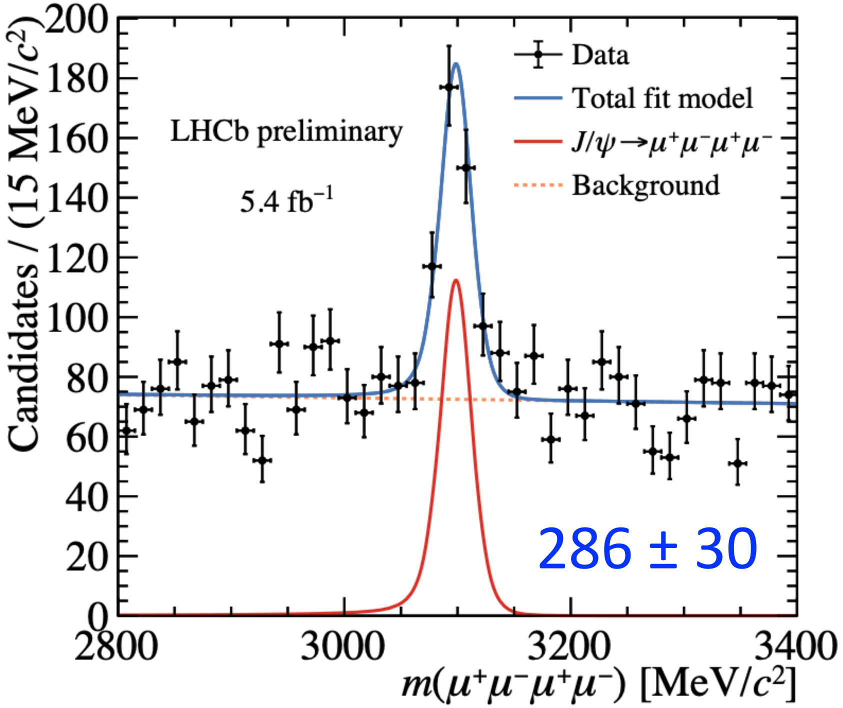
$$\mathcal{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (11.3 \pm 1.0 \pm 0.5 \pm 0.1) \times 10^{-7}$$

- most precise measurement to date
- consistent with the SM prediction at the level of 1.4σ

Prompt



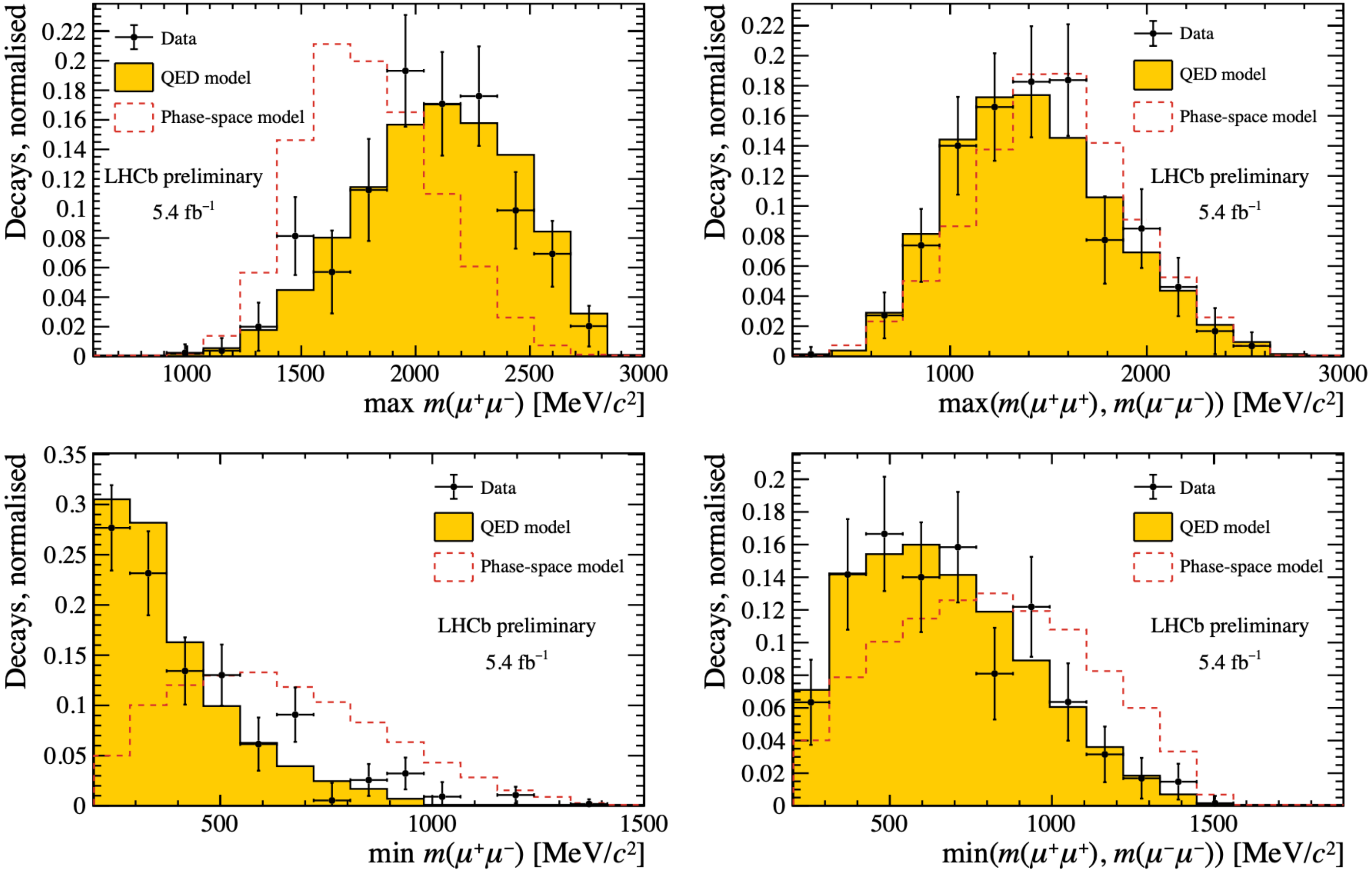
Secondary



LHCb-CONF-2024-001

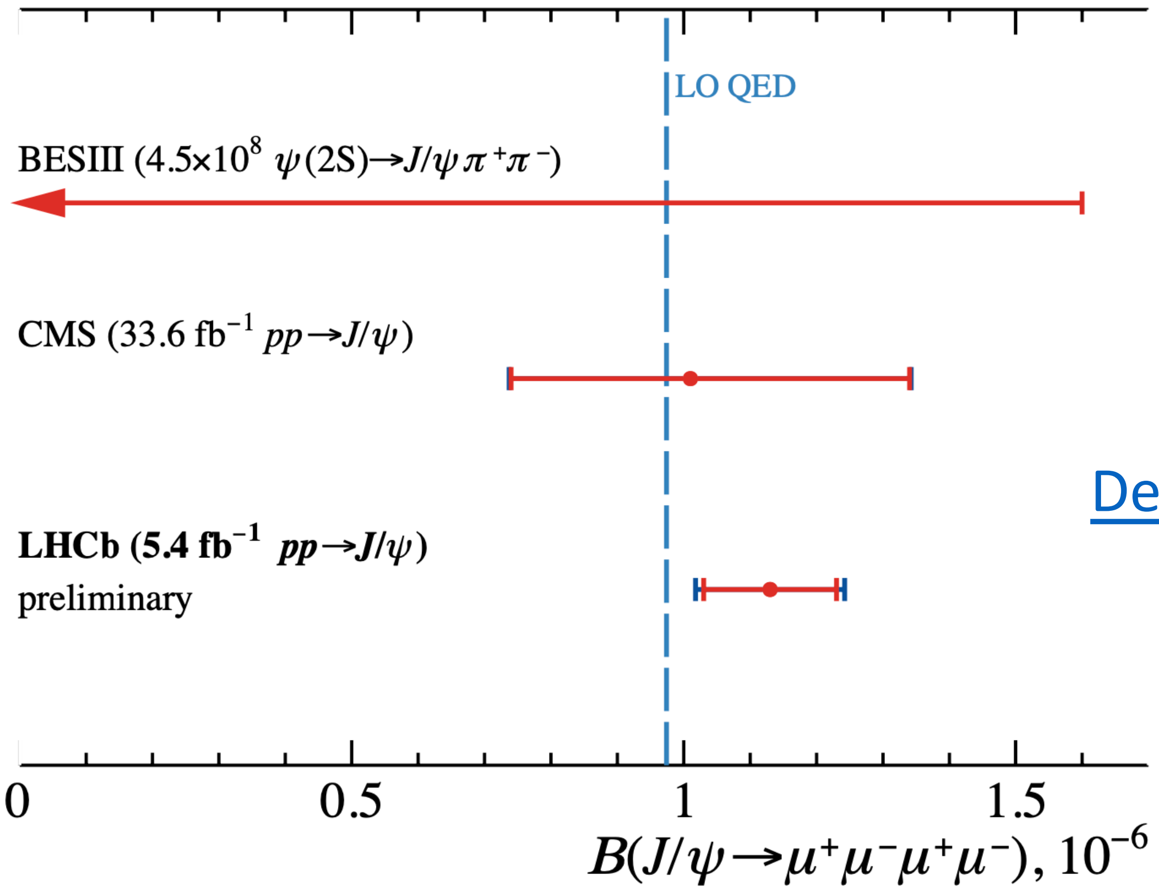
Kinematic distributions: $\gamma^*(\mu\mu)$ in data and simulation

Secondary



- size of the sample allows to study kinematic distributions
- found to be consistent with the LO QED model, provided by BES III colleagues
- PHSP model significantly differs

Existing $J/\psi \to 4\mu$ measurements summary

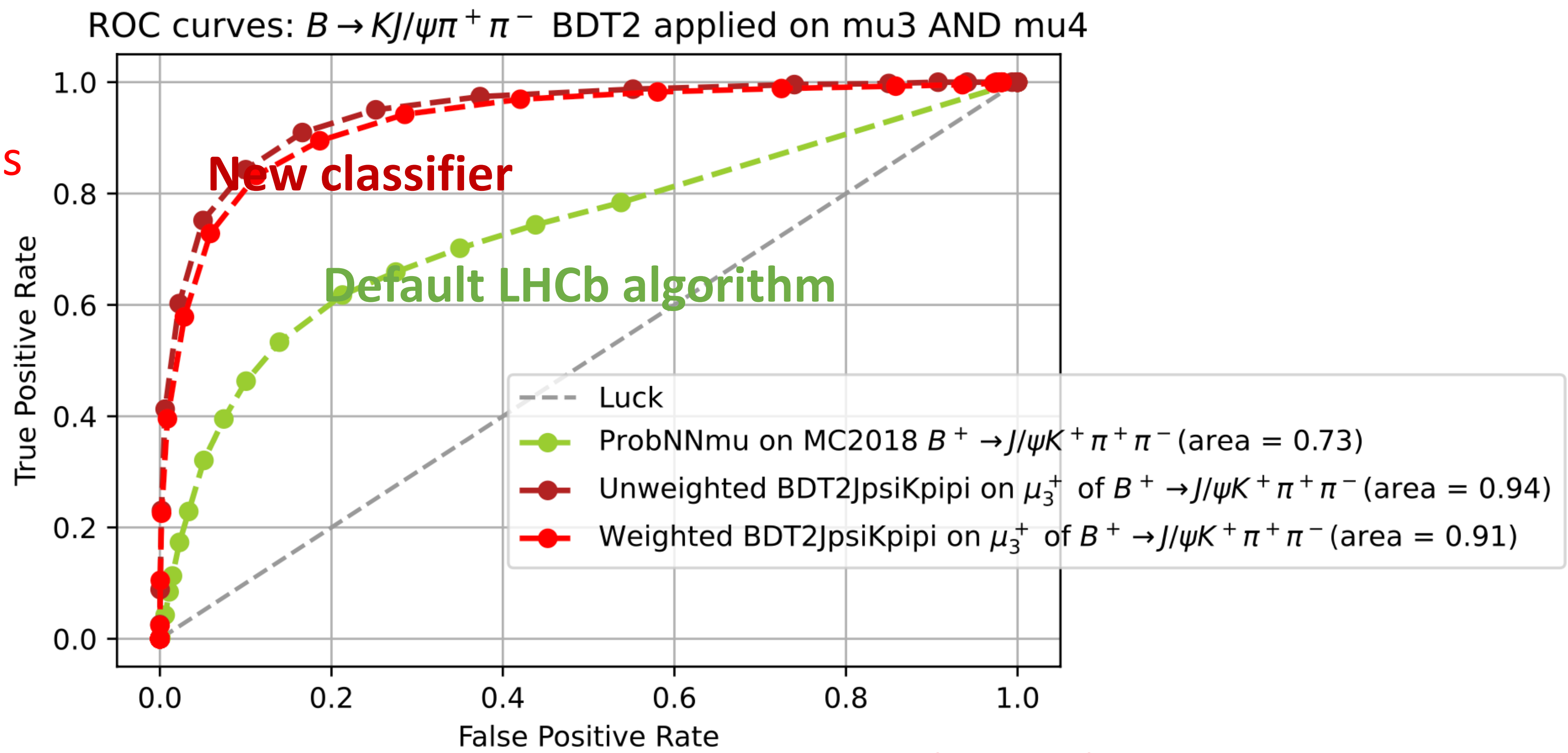


Dedicated LHCb public page

LHCb-CONF-2024-001

Next steps: muon identification improvement

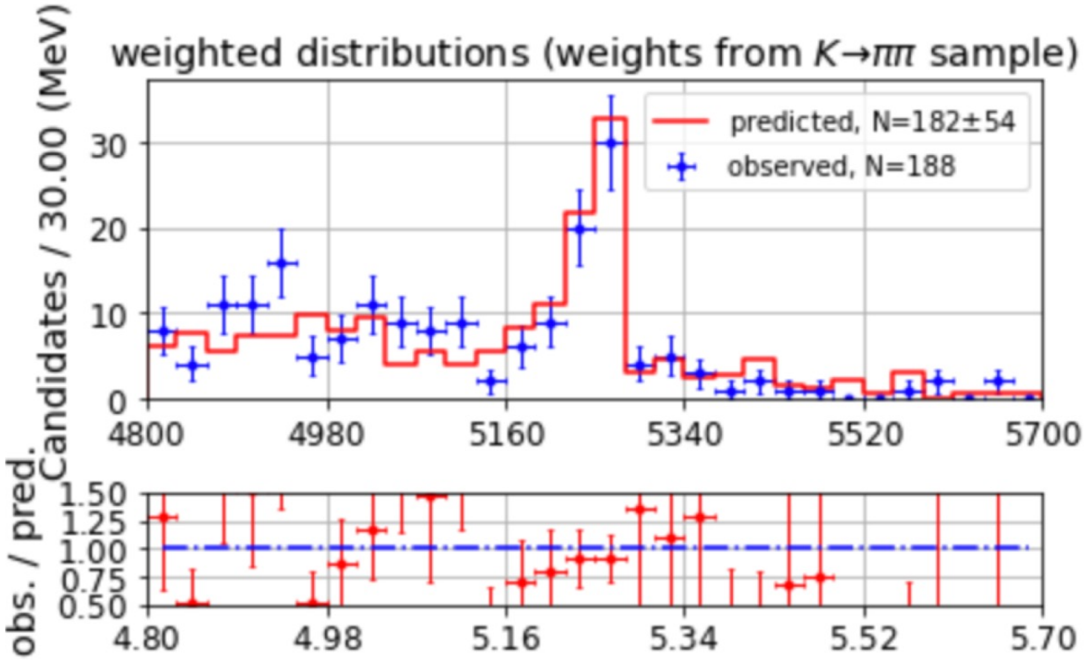
soft muons



pions with signal in muon system (isMuon)

Residual decays-in-flight estimation

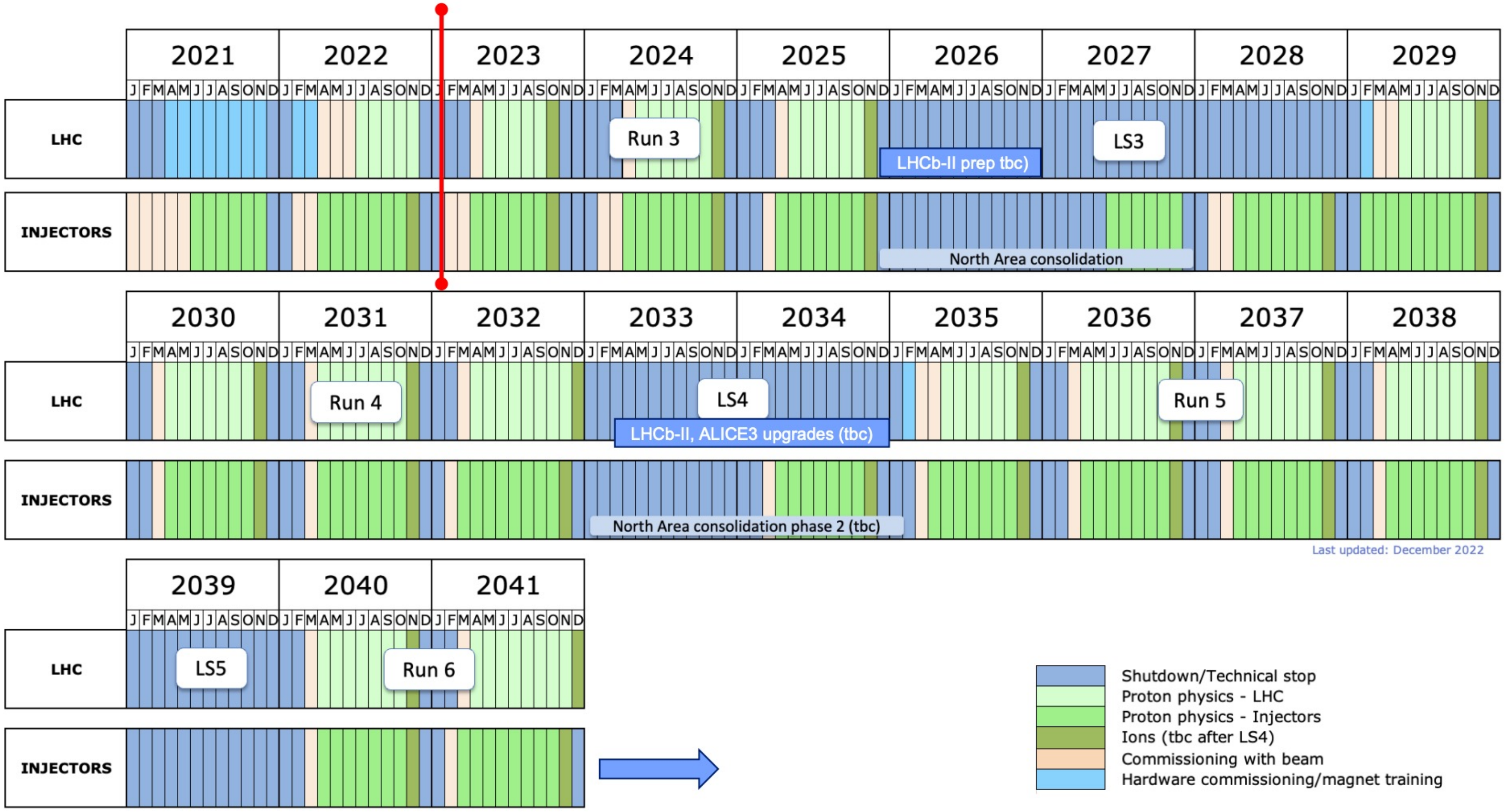
$B^+ \to K^+ J/\psi \gamma^*(\mu\mu)$ control sample



- Control sample (blue points):
  - both muons satisfy isMuon
  - one passes new classifier
  - second fails it
- Red line:
  - prediction of the blue distribution from the sample with both muons failing new classifier (isMuon=1)
  - weights measured in $K_S \to \pi^+\pi^-$

Excellent control of the residual muon misID shape and yield!
⇒ vital for $3\ell\nu$ measurements and anomalies validation

LHC star is shining for another 20 years



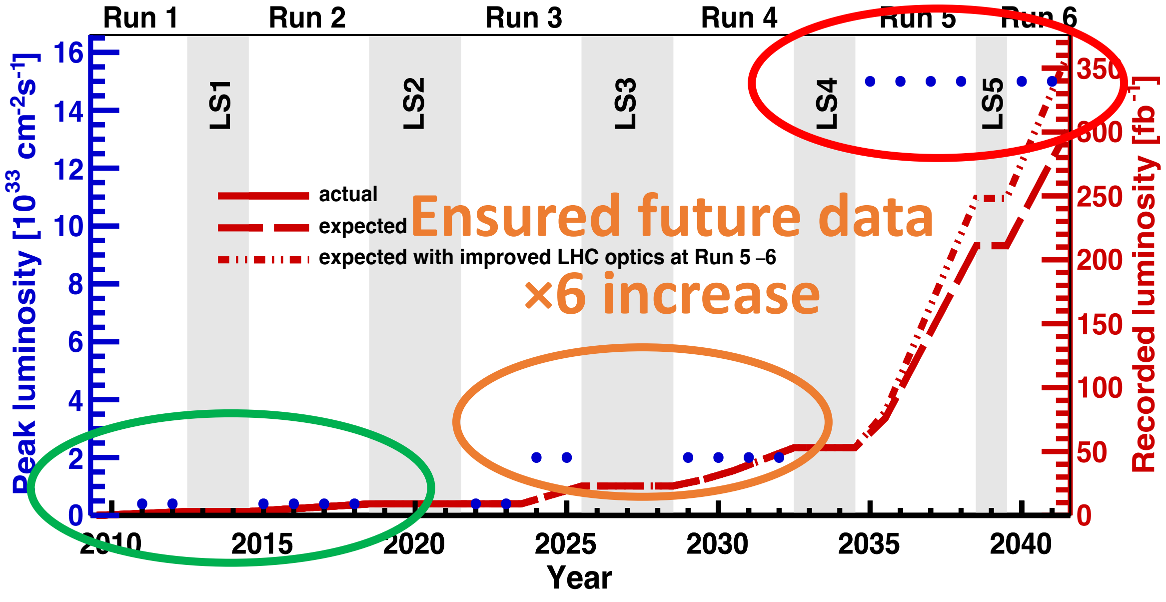
LHC Chamonix workshop'2023

LHCb endeavor till 2041

- precision era and LHCb intensity frontier is just starting
- plus an ambitious plan to take data at even higher collision rate after 2030!
- LHCb precision era is the chance to find the next energy scale and to better motivate a new large-scale facility beyond the LHC

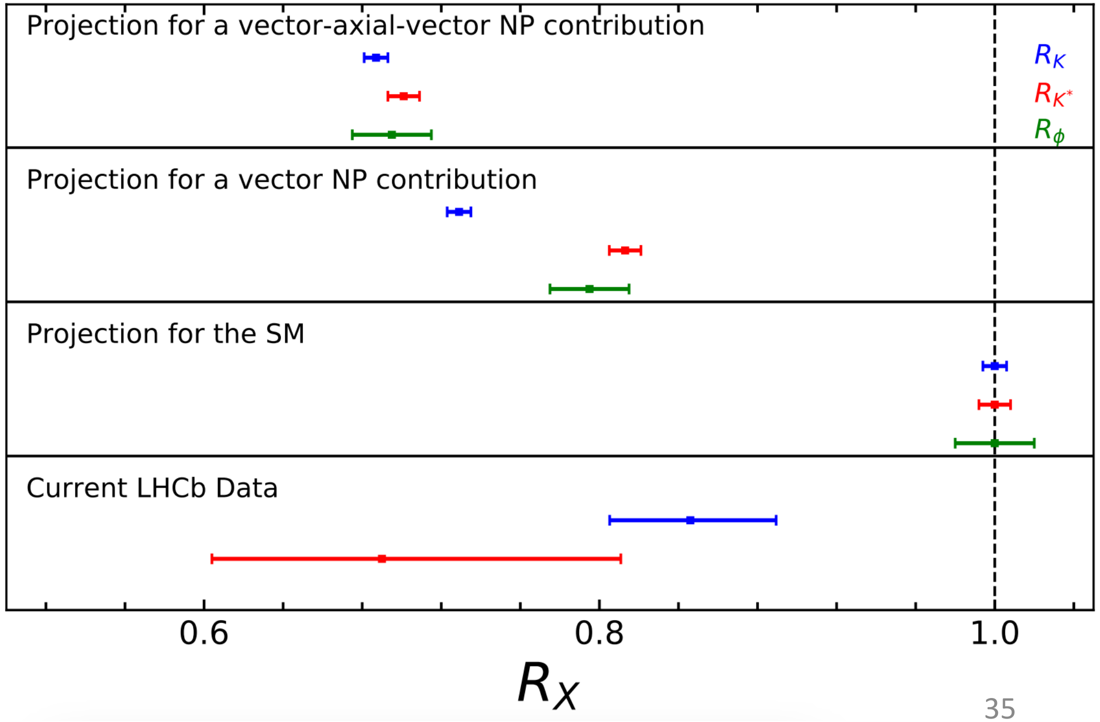
Design future data
×40 increase

Upgrade I *Upgrade II*



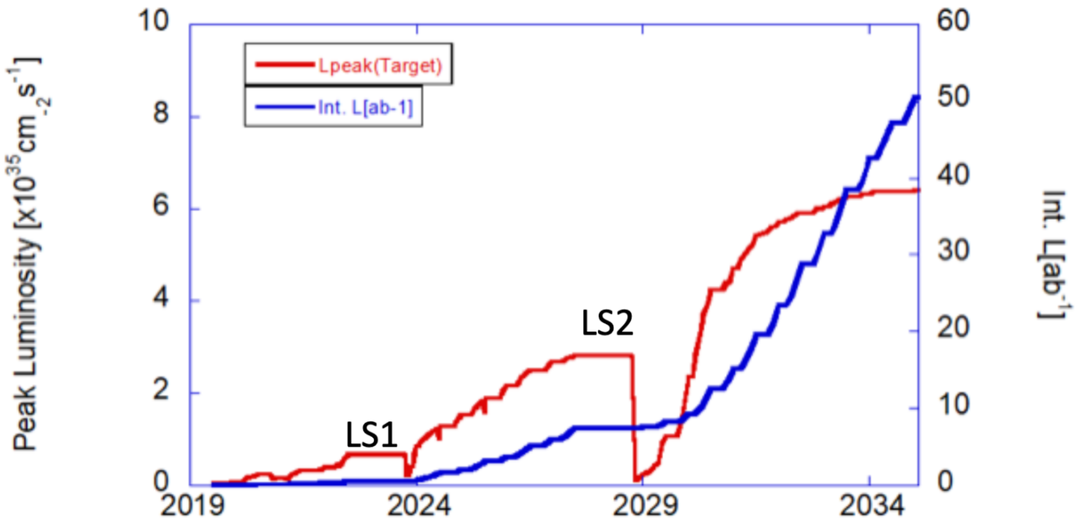
Ensured future data
×6 increase

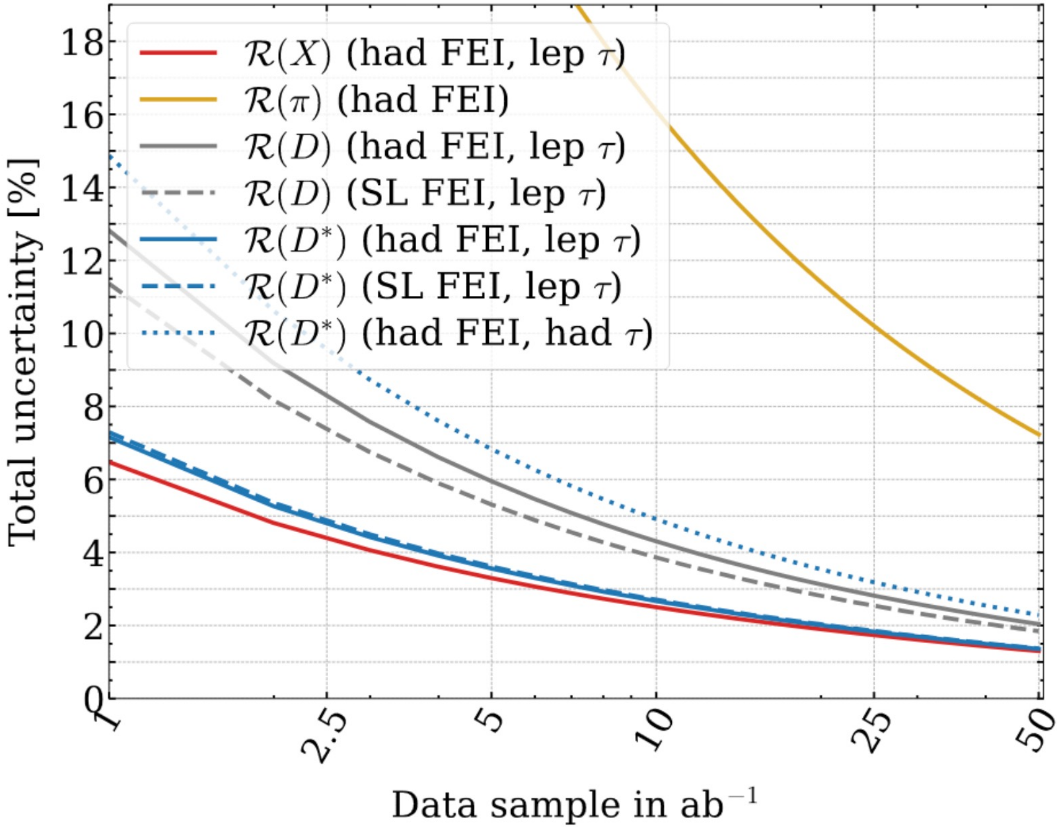
Recorded data



7th workshop on LHCb Upgrade II

LHCb not alone: a highlight of Belle II prospects

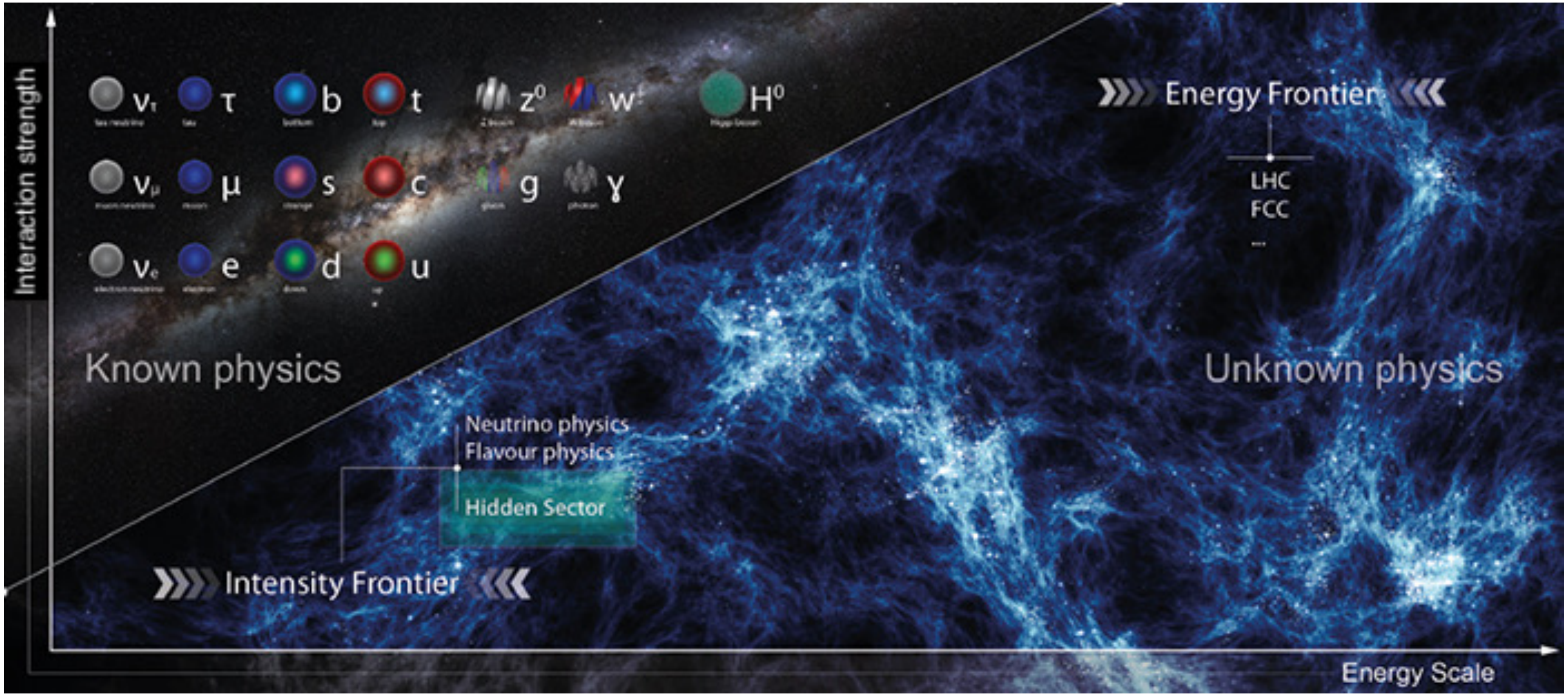




- high hope to observe $B^+ \to \mu^+\nu$ and significantly improve $B^+ \to \tau^+\nu$ measurement: both to 10% precision
  - use inclusive tagging developed for $B^+ \to K^+\nu\bar{\nu}$
  - also include radiative modes $B^+ \to \mu^+\nu\gamma$

Timeline allows to inform future energy frontier!

Other frontiers to tackle: intensity frontier



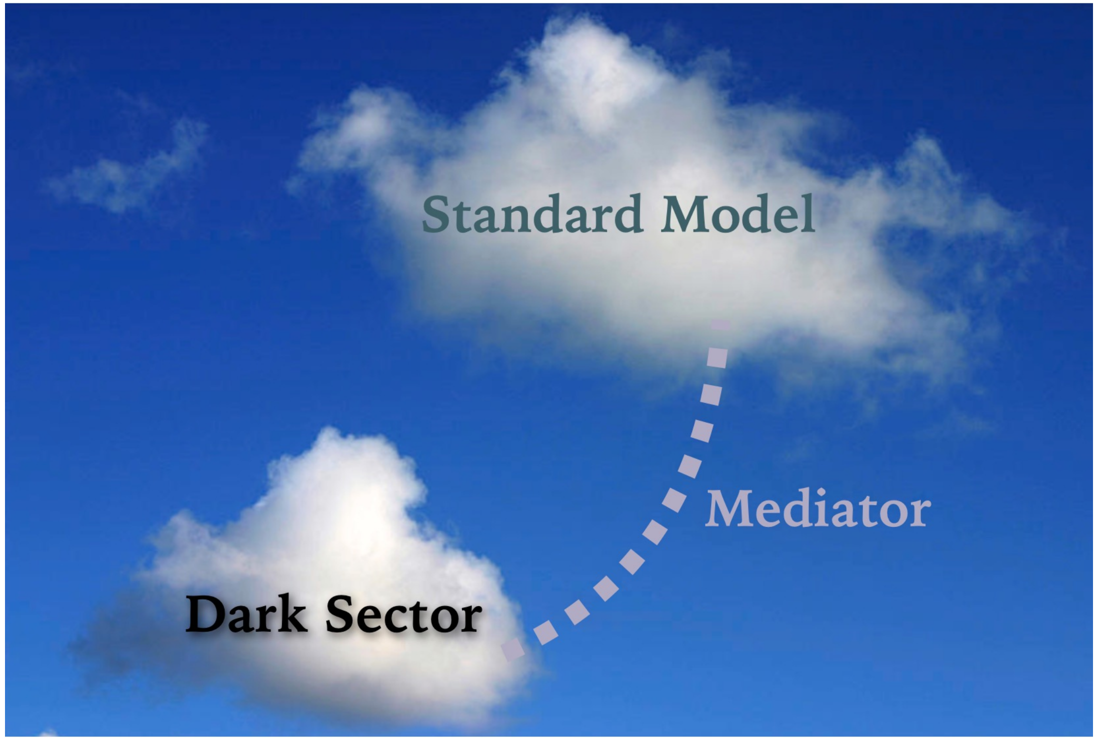
New particles are produced too rarely

⇒ SHiP *Search for Hidden Particles* ? HiLumi HL-LHC PROJECT ?

New particles are too heavy to be produced ⇒ new accelerator FCC hh ee he ?

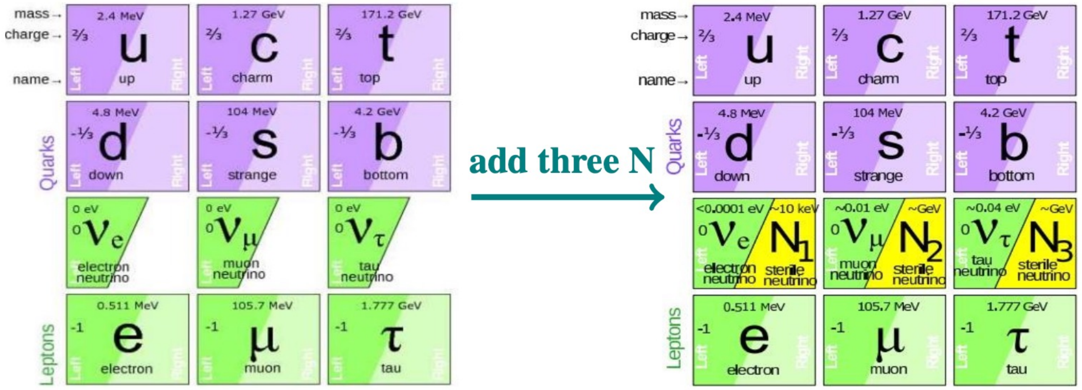
Feebly interacting particles (FIPs)

- “new physics” is cornered by precision measurements and lack of discoveries in direct searches
- can put it into **“dark sector”** which talks with the SM via feeble interaction – much less constrained
- detectors are made of ordinary matter ⇛ no direct signal from such particles, but exploration of *unusual signatures*:
  - very long-lived particles
  - delayed signals
  - anomalous energy deposits
  - …



Heavy neutral leptons (or neutrinos)

- right-handed neutrinos N are an example of "dark sector"

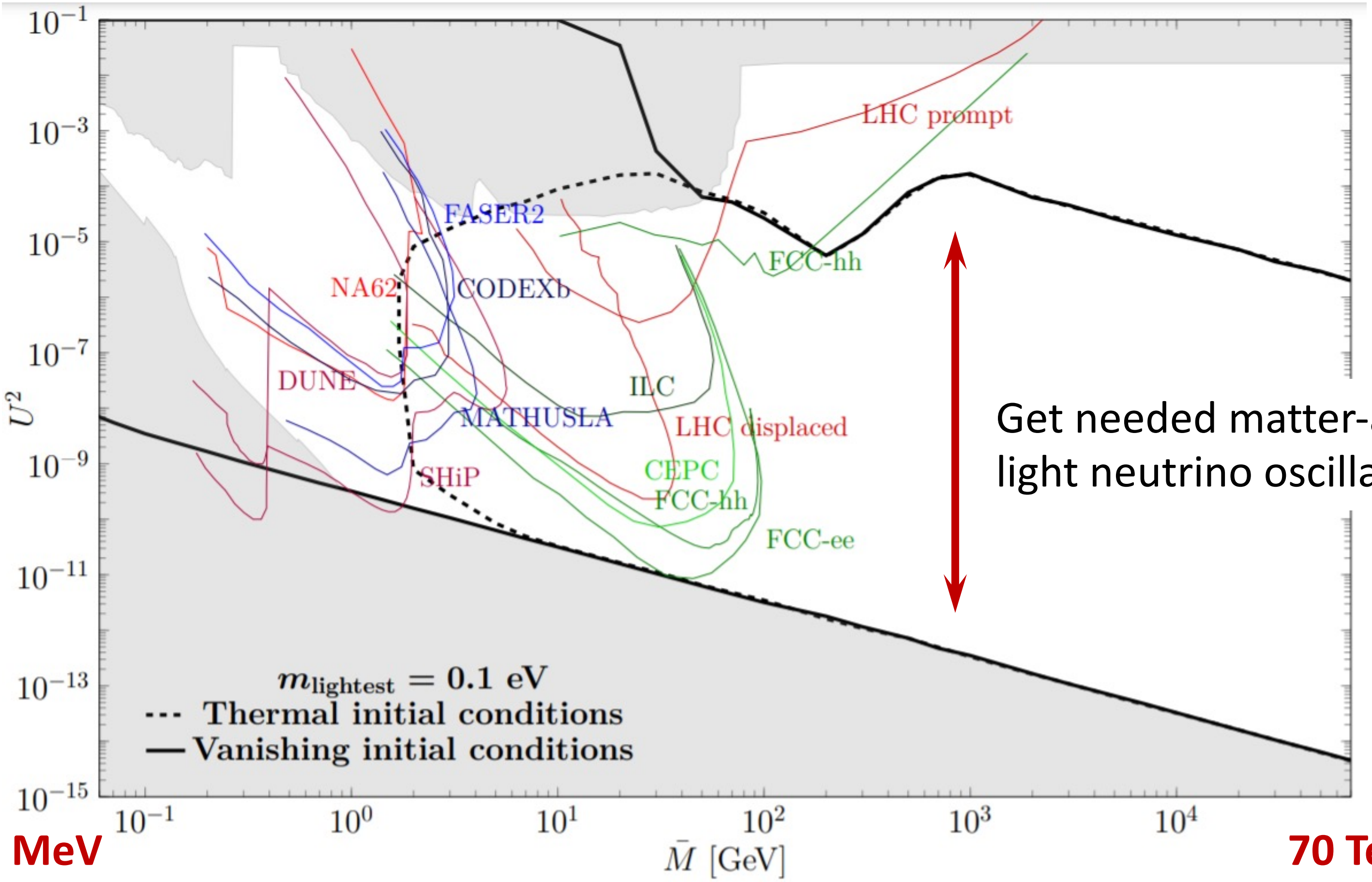


M. Shaposhnikov et al

- νMSM – a minimal extension of the SM with adding N_1, N_2, N_3
- provides a **dark matter particle N_1**:
  - very long-lived, decays as $N_1 \to \nu\gamma$
  - *debated indirect evidence from astroparticle observations exists*
- N_2 and N_3 can explain **matter dominance of the Universe**
- N_2 and N_3 can be found with conventional detectors at colliders

Viable HNL parameter space for testable leptogenesis

$$U^2 = \sum_\alpha U_\alpha^2$$



Get needed matter-antimatter asymmetry + light neutrino oscillation data w/o fine-tuning

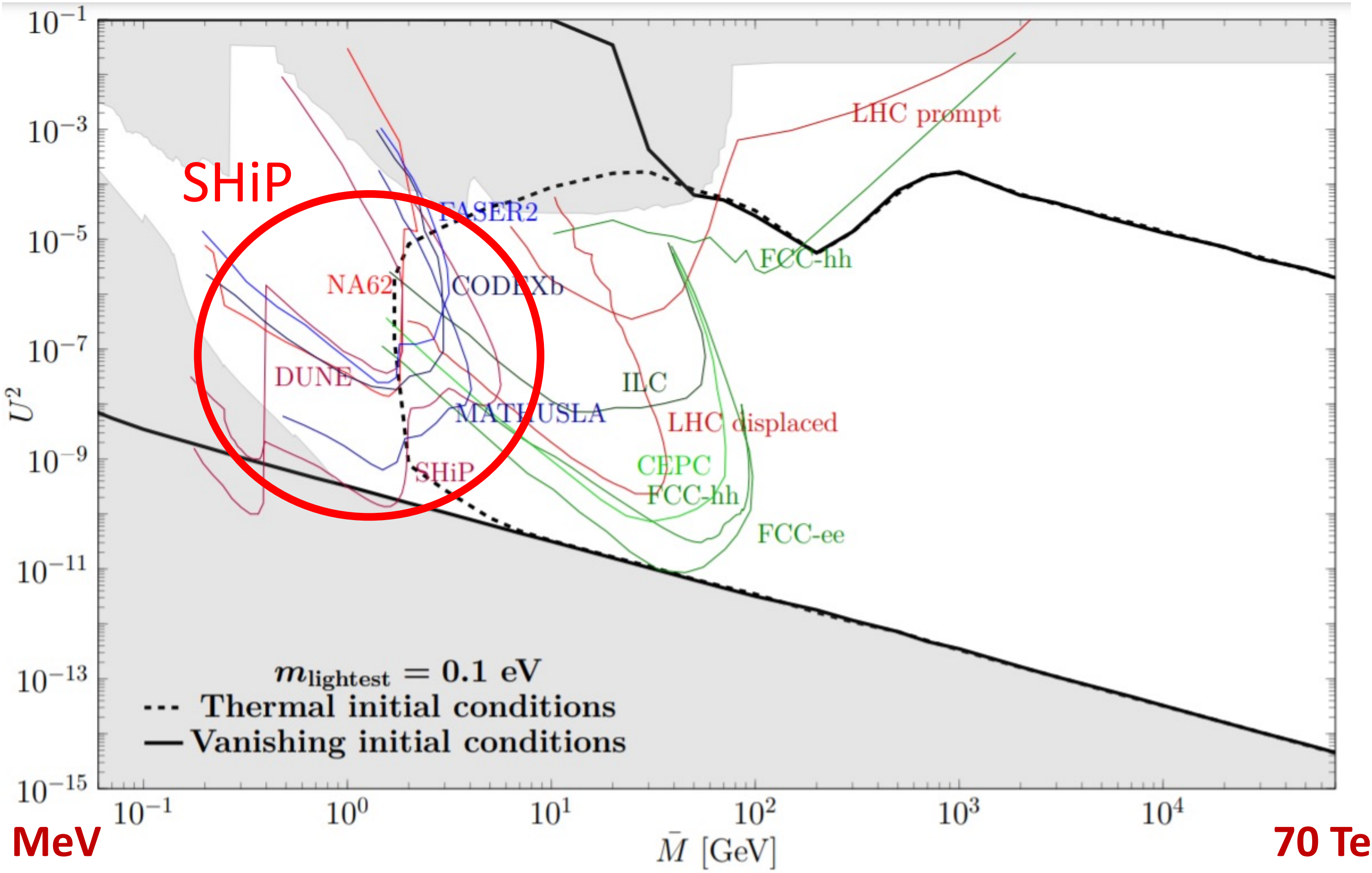
50 MeV

70 TeV

[Phys.Rev.Lett. 128 (2022) 051801](): Drewes, Georis and Klaric

SHiP: to be or not to be?

$$U^2 = \sum_\alpha U_\alpha^2$$



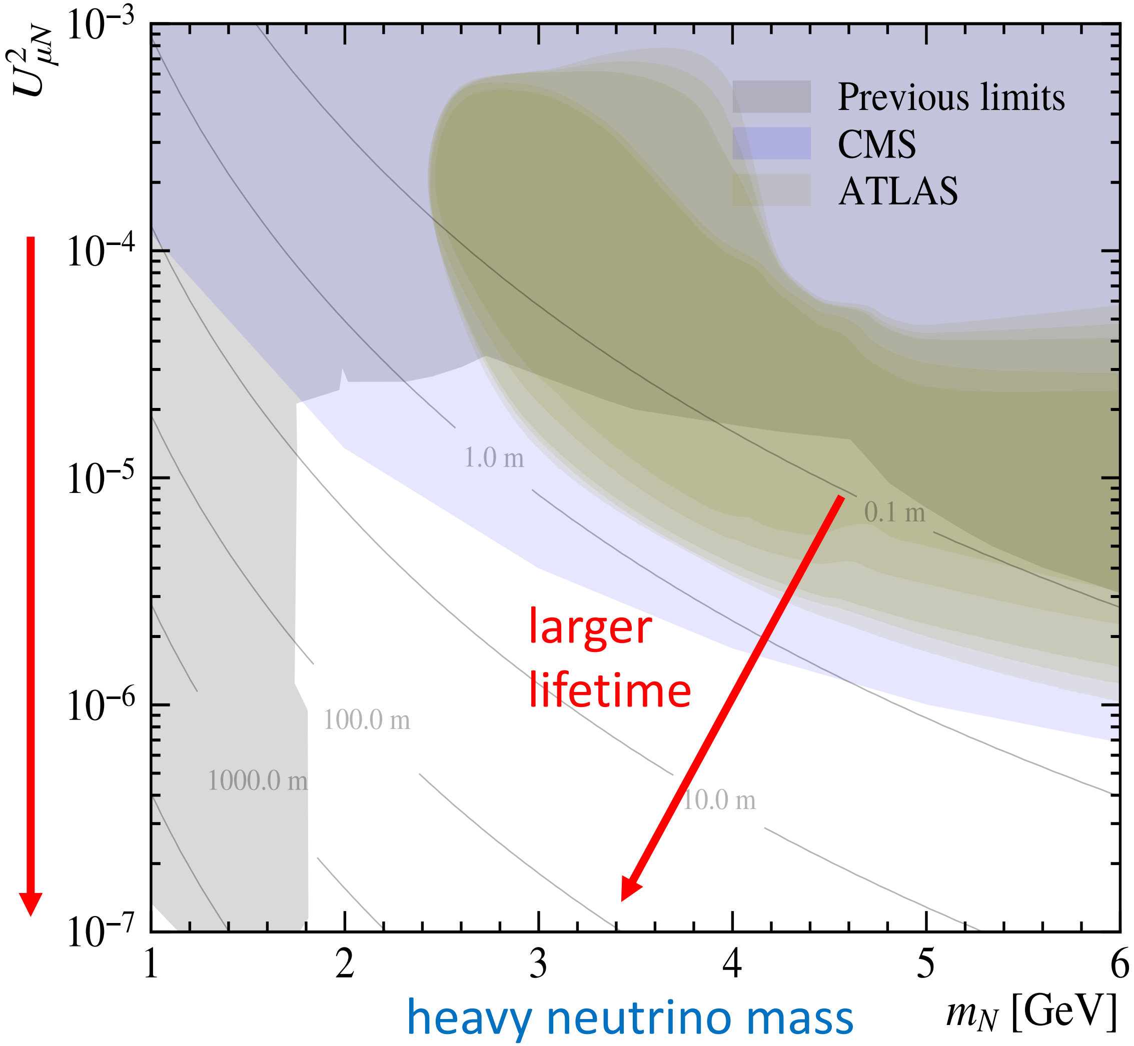
50 MeV

70 TeV

Even if there is FCC, SHiP is the only one closing fully allowed gap below 5 GeV (?)

Possible parameter space of heavy neutrinos

feeble interaction:
mixing with
active neutrinos



larger
lifetime

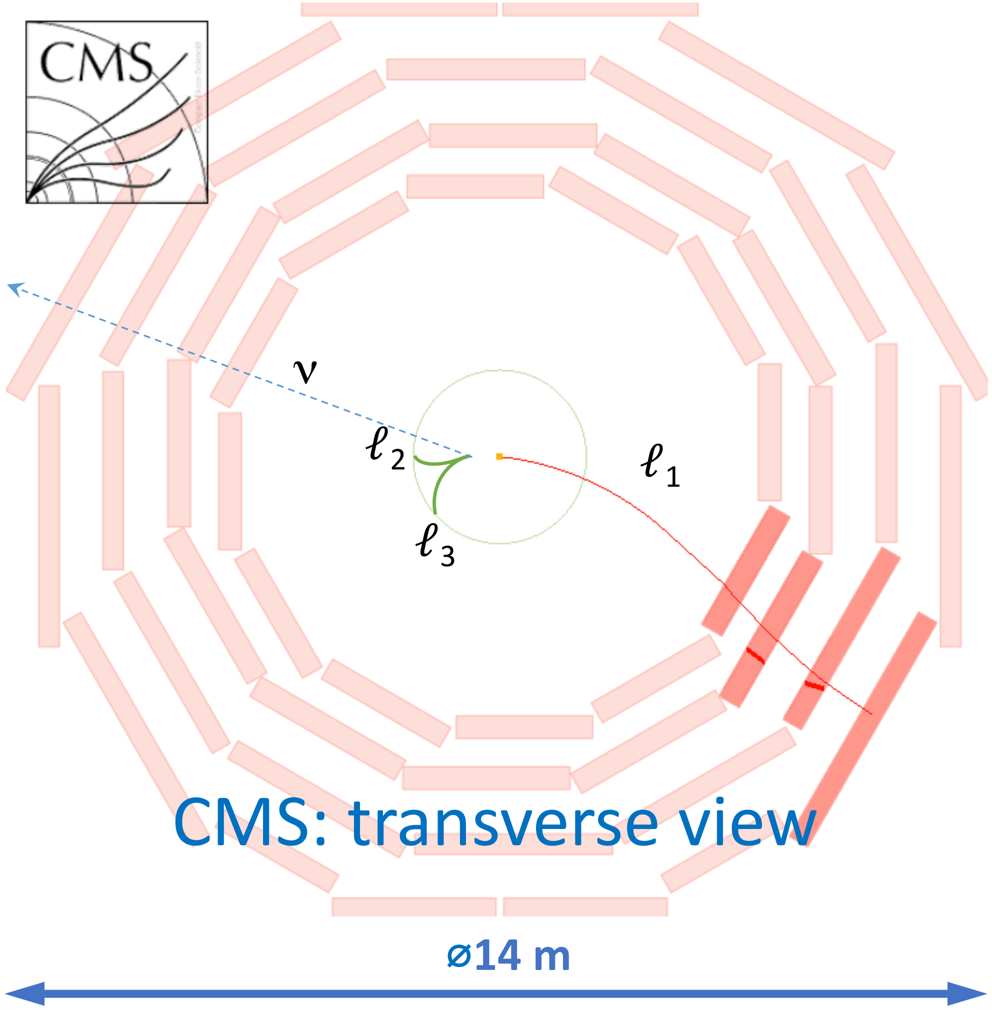
more rare
production

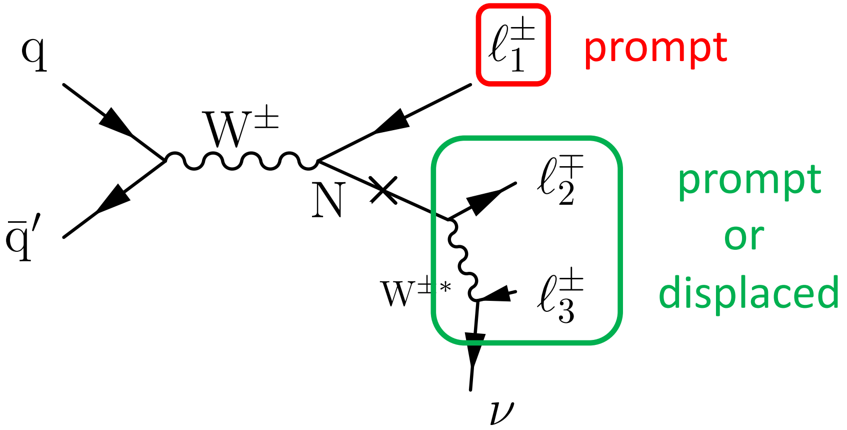
heavy neutrino mass

- value of mixing with active neutrinos is constrained from below by very low masses of SM ν
- can be as low as 10^{-12}
- exploring all allowed parameter space is not possible with just one instrument

European Research Council
Established by the European Commission

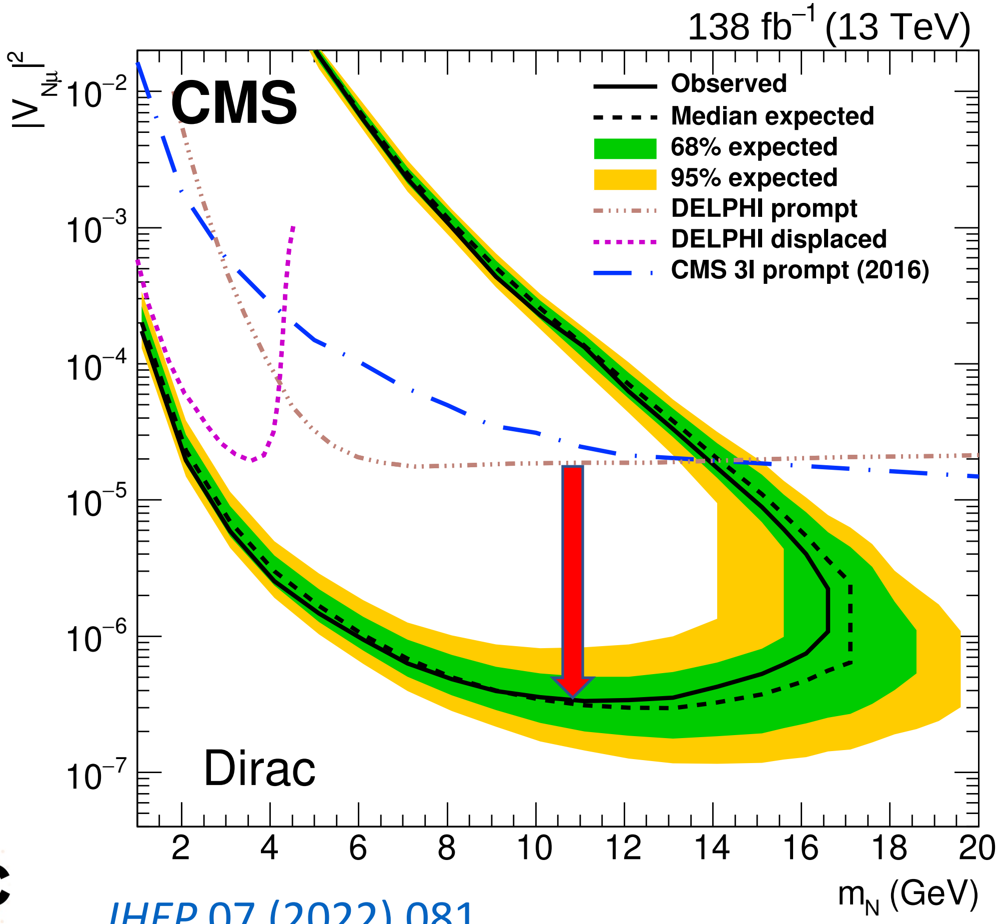
N_2 or N_3 signatures in the detector





- produced as SM neutrinos – in electroweak decays of SM particles
- decays either close to production point (prompt) or after having travelled some distance (displaced)

Long-lived N search with CMS



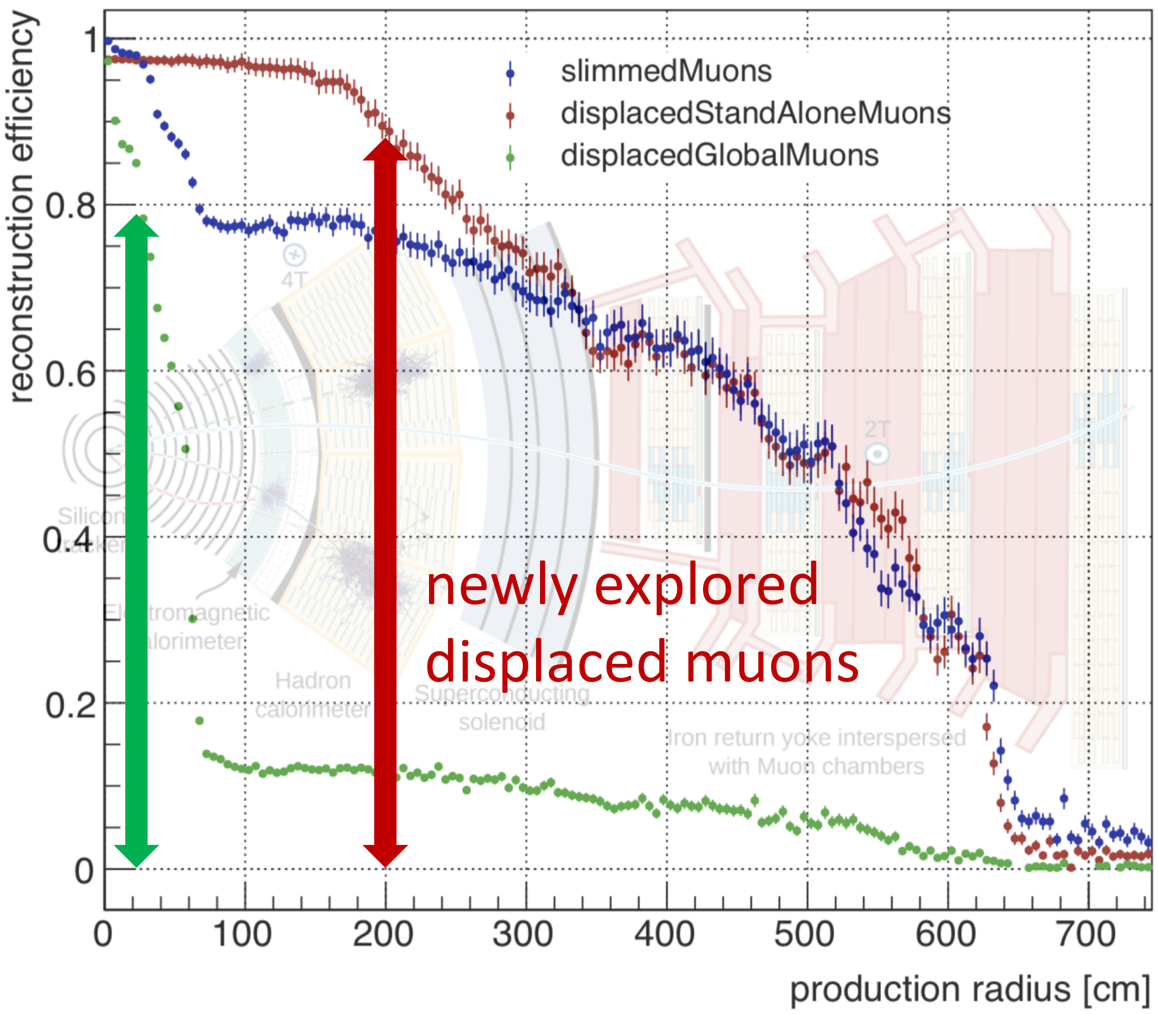
JHEP 07 (2022) 081

- developed a dedicated search at CMS with displaced leptons
- needed to use unconventional reconstruction techniques and develop new background estimation methods
- improvement by 2 orders of magnitude over the previous results

European Research Council
Established by the European Commission

Pushing the detector capabilities

$p_T > 10$ GeV; $|\eta| < 2.4$



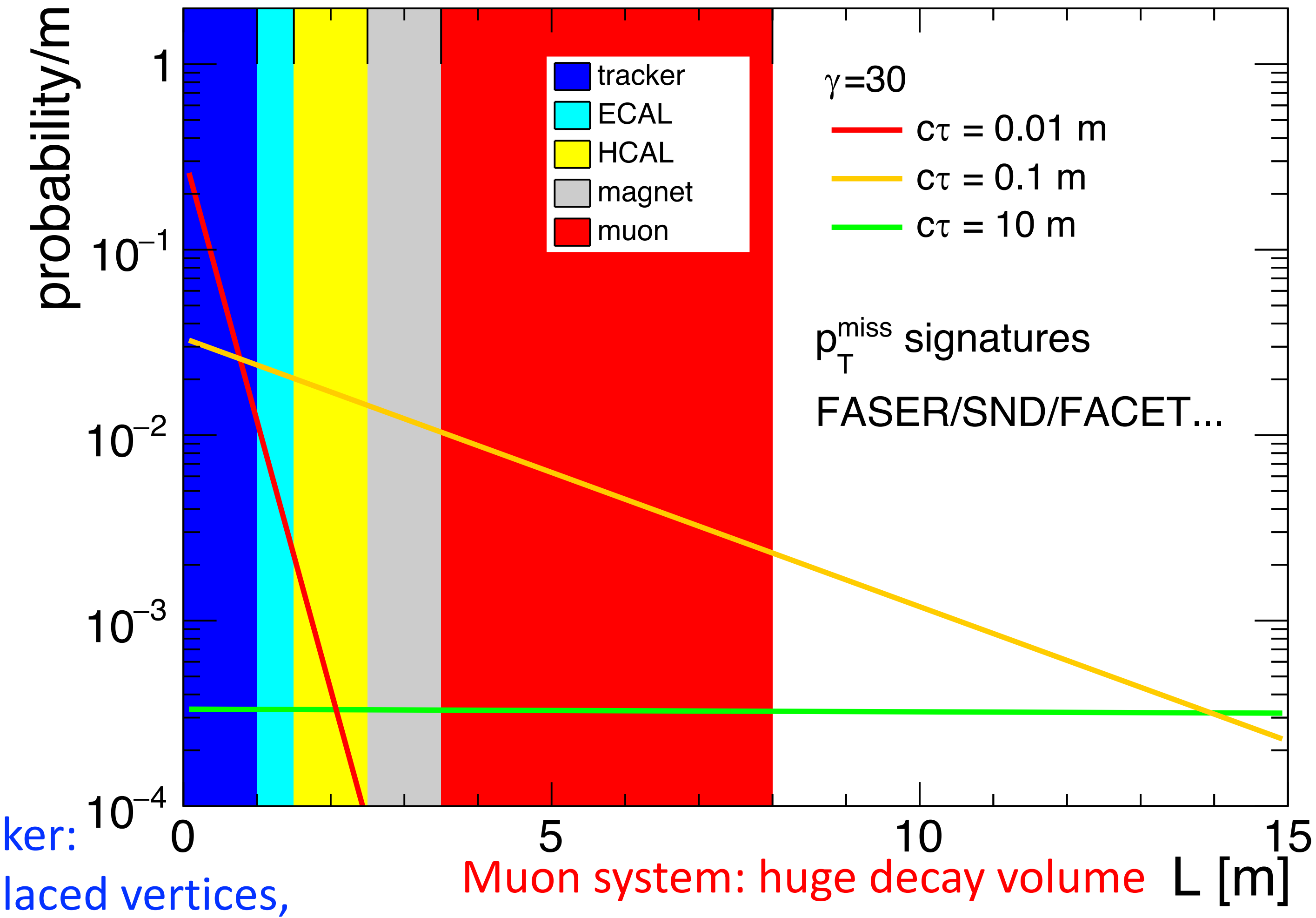
currently used displaced muons

newly explored displaced muons

- now exploring much larger decay volume: up to several m
- using the muon detectors only – the longest and the farthest from the collision point

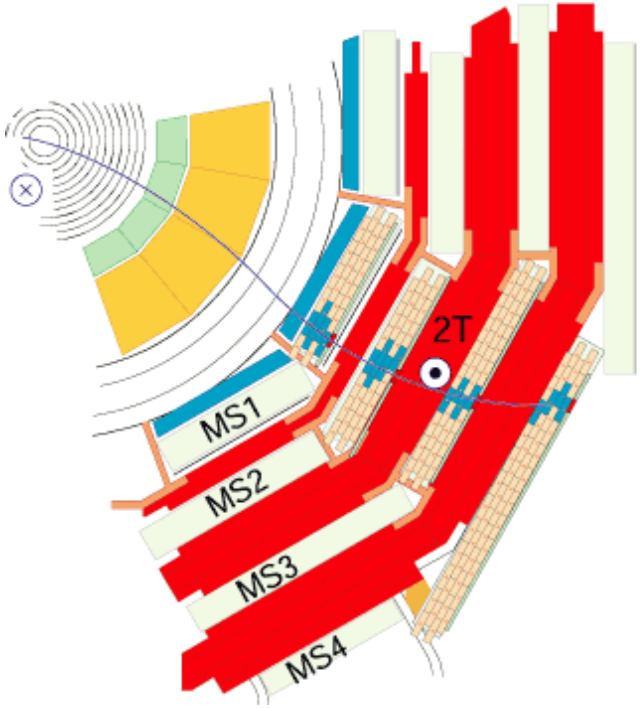
European Research Council
Established by the European Commission

Limitations for existing LHC experiments



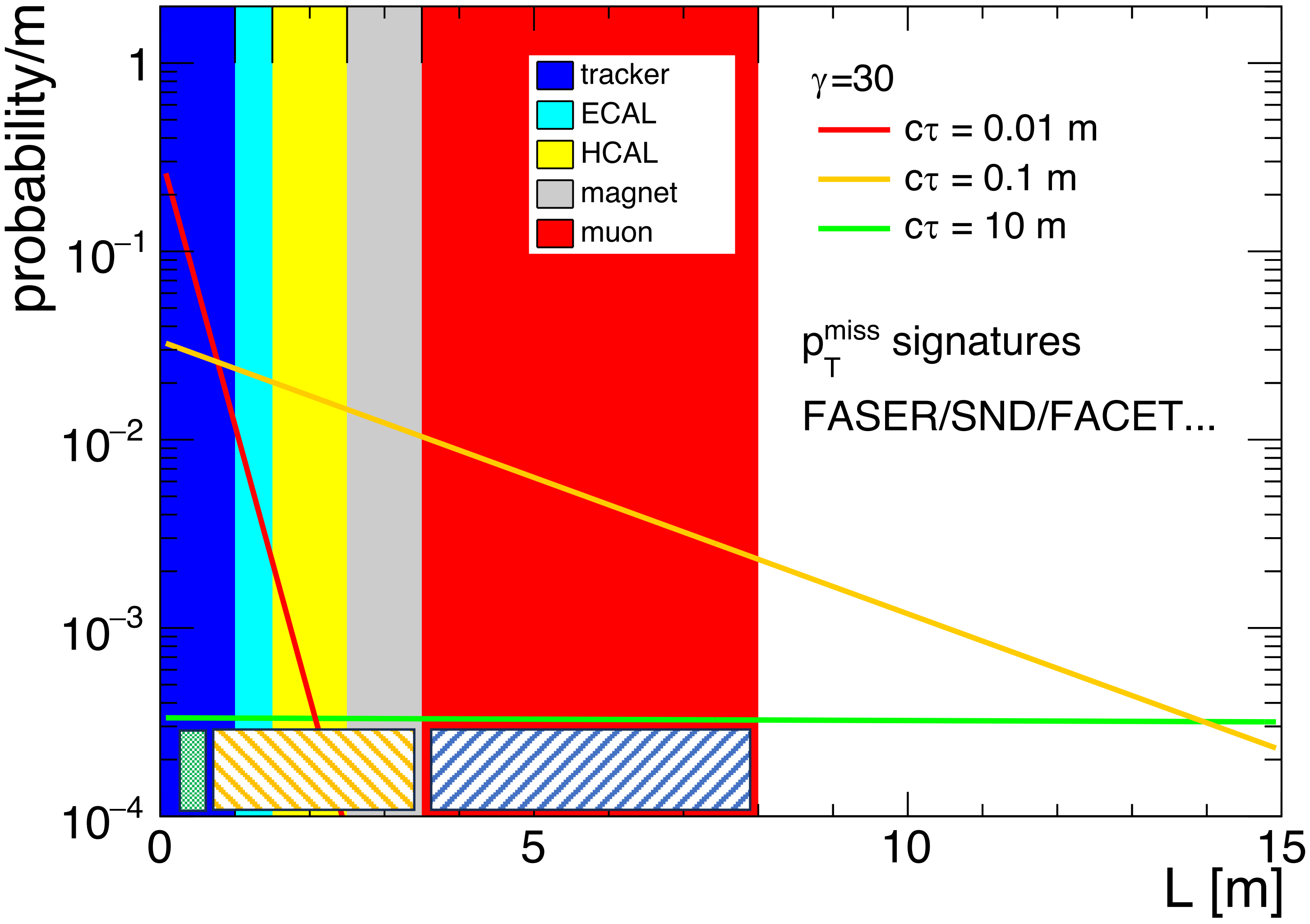
Tracker: displaced vertices, O(1 m)

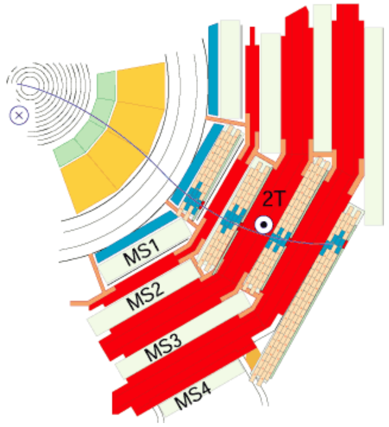
Muon system: huge decay volume and shielding with other detectors O(5 m)



- next unconventional step: use muon system to look for large energy deposits!

Decay volume for HNLs @ LHC

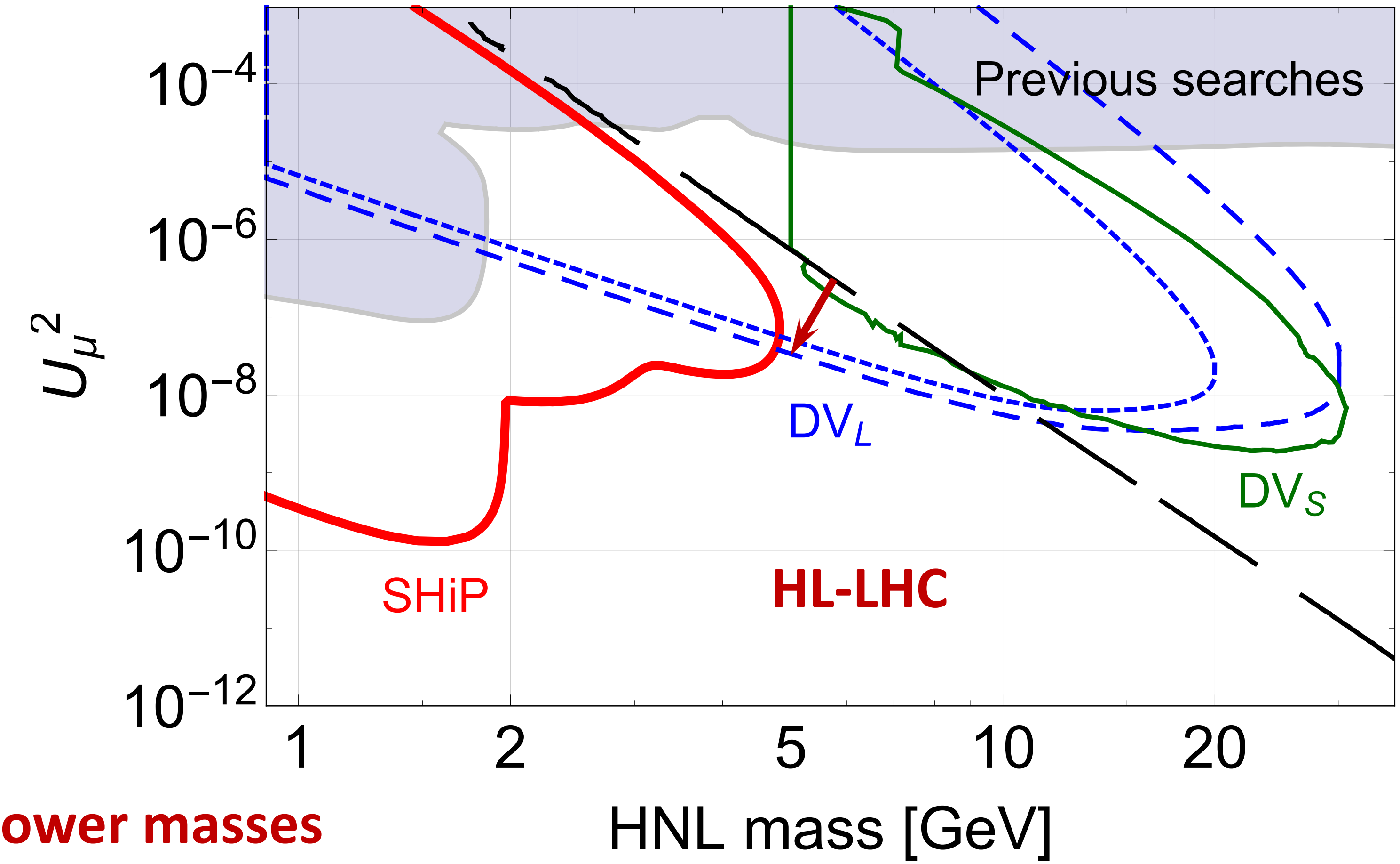




Decay volume of

- displaced vertices
- standalone muons
- muon detector showers

Displaced vertices in the tracker *vs* with standalone muons @ LHC



Sensitivity of

- displaced vertices (DV$_S$)
- standalone muons (DV$_L$)
- muon detector showers

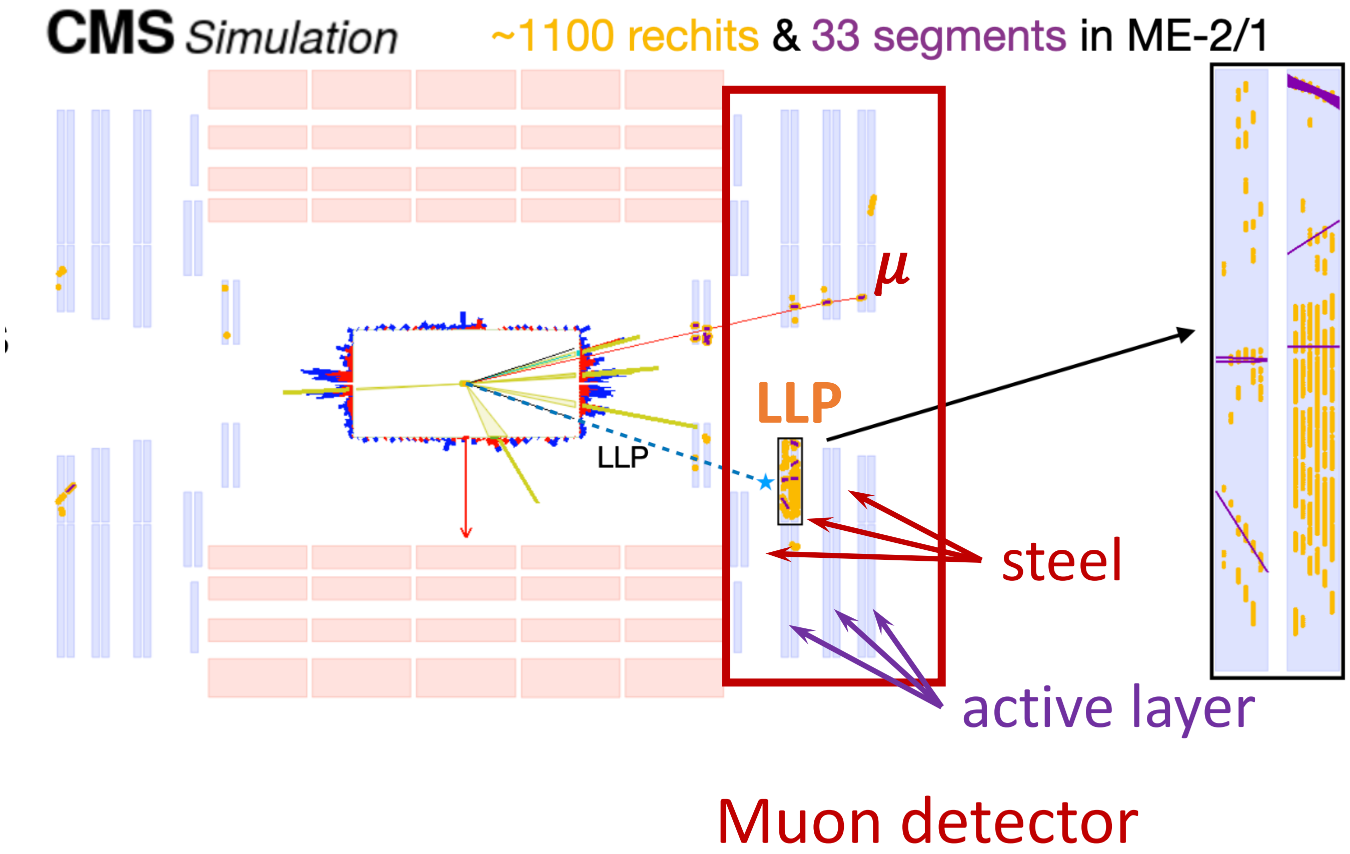
Lower masses

Lower couplings

Phys.Rev.D 100 (2019) 075015

Muon detector showers (MDS) @ CMS

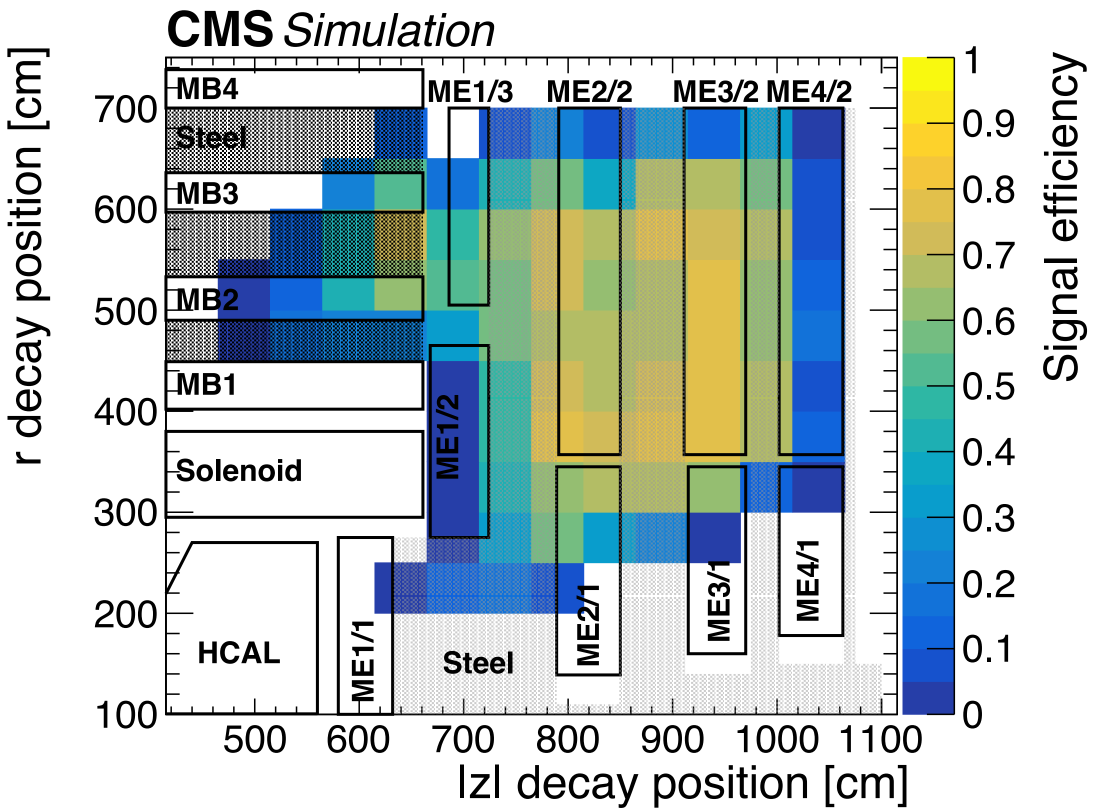
Example event display of a LLP signal event



- FIP traverses the detector and decays in the muon system
    - signal is proportional to the FIP energy rather than its mass
- muon detector acts as a sampling calorimeter
- low SM background as only muons typically survive there
- muons have much lower hit multiplicity than FIP-induced hadronic/EM shower – clear signature for a trigger

CMS-DP-2022-062

Muon detector showers (MDS): ATLAS/CMS

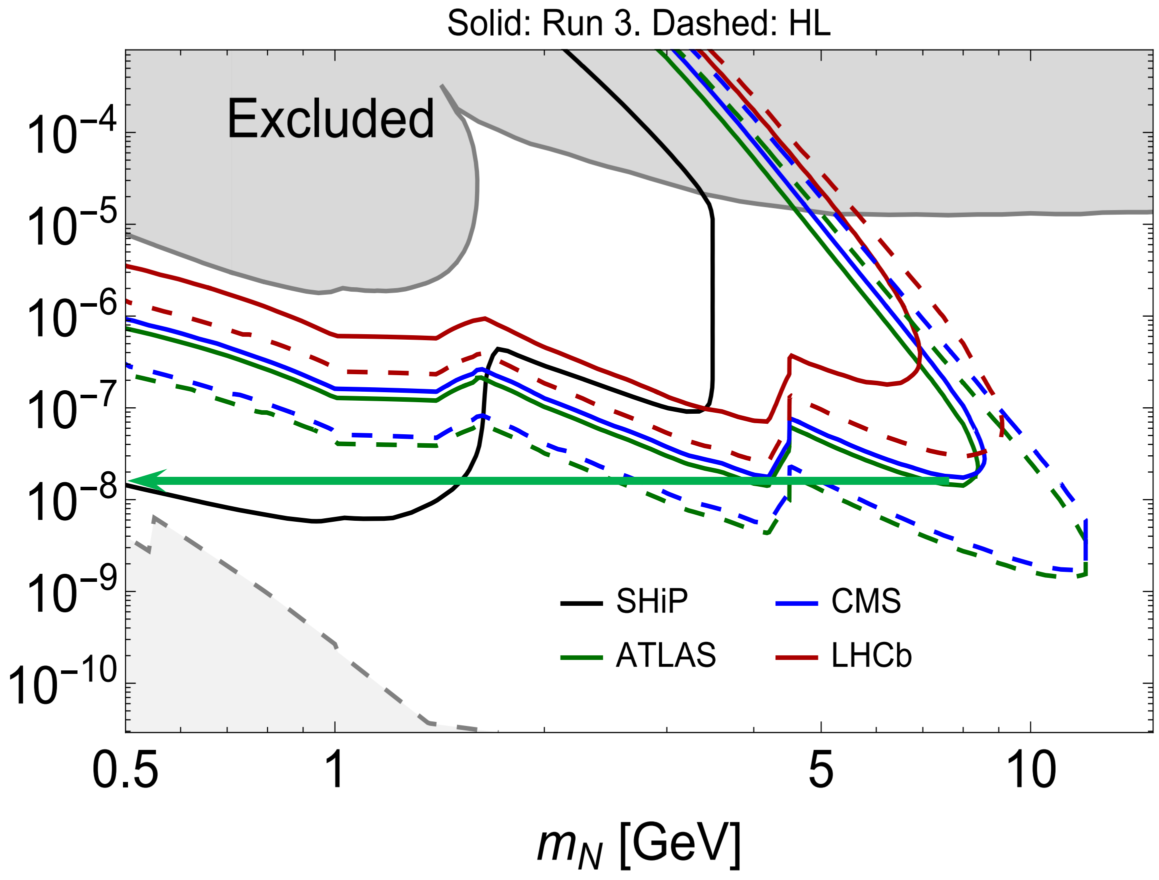


- signature sensitive to **all visible non-muonic decays (no final state suppression)**
- efficiency depends on the decay vertex and FIP energy:
  - if decay happens at the beginning of steel layer, the shower can be absorbed before reaching the sensitive layer
- → in future detectors, can optimize absorber thickness to be also sensitive to a typical spectrum of FIPs (e.g. at the FCC-ee/-hh)

Phys.Rev.Lett. 127 (2021) 261804

Phys.Rev.D 106 (2022) 032005

If triggering on MDS is accessible at (HL-)LHC



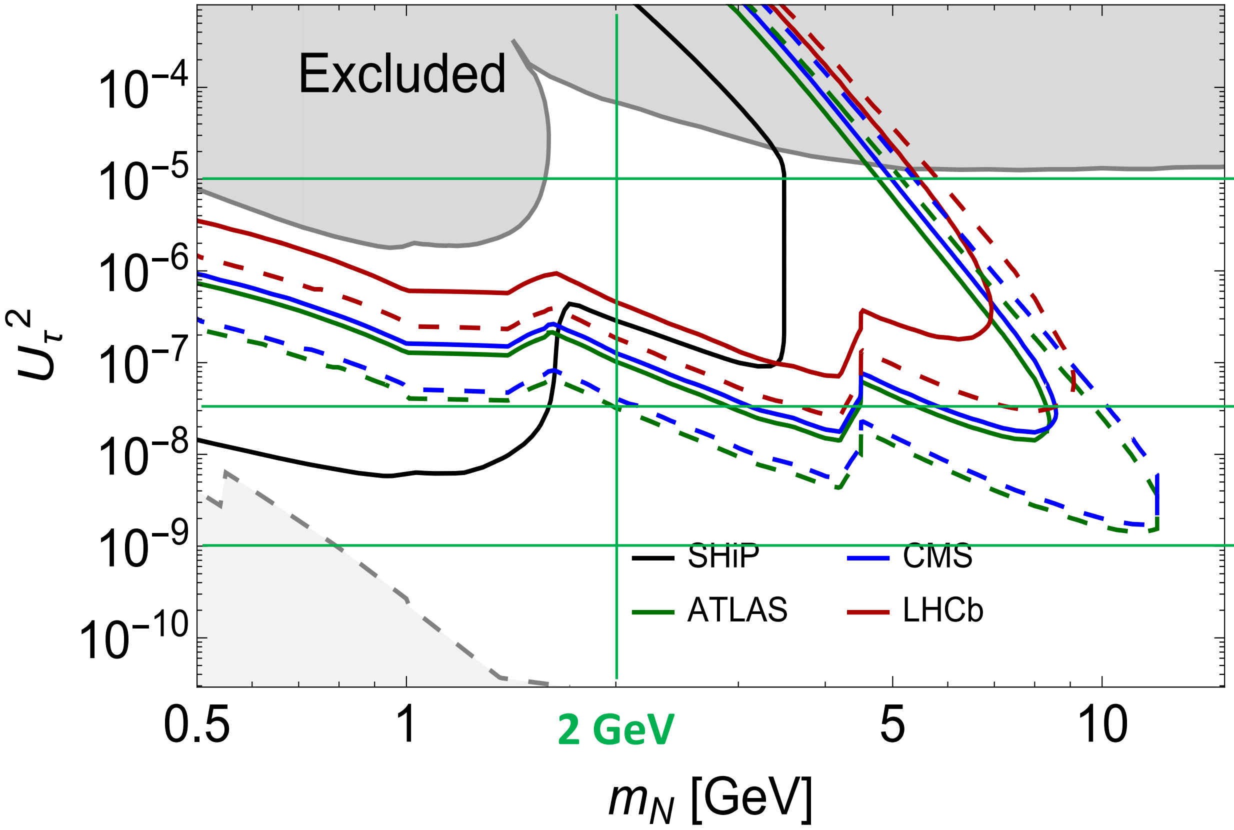
- Back-of-an-envelope estimate for HNLs in τ-dominant scenario:
  - HNLs produced in W, Z, B, D decays
  - coupling only to tau
  - visible decays within muon system (endcaps for CMS)
  - assume 70% detection eff-cy
- Sensitivity of 10^{-8} with Run 3 data!
- 2-3 orders of magnitude better than existing results

PoS LHCP2022 (2023) 094

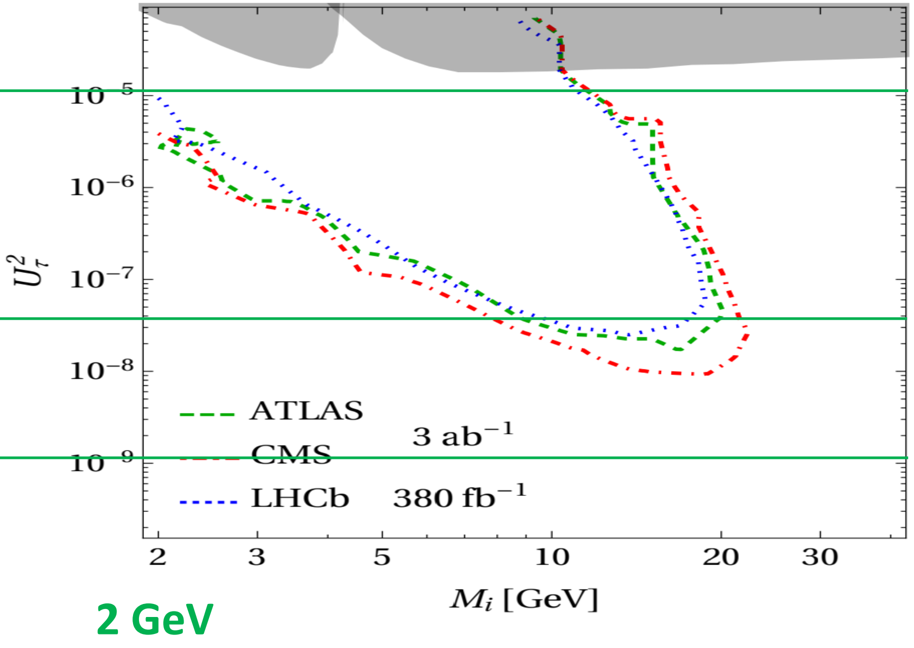
If triggering on MDS is accessible at (HL-)LHC

At low masses ×$10^{2\text{-}3}$ better than projections with more conventional techniques

Solid: Run 3. Dashed: HL



Displaced vertex search projection



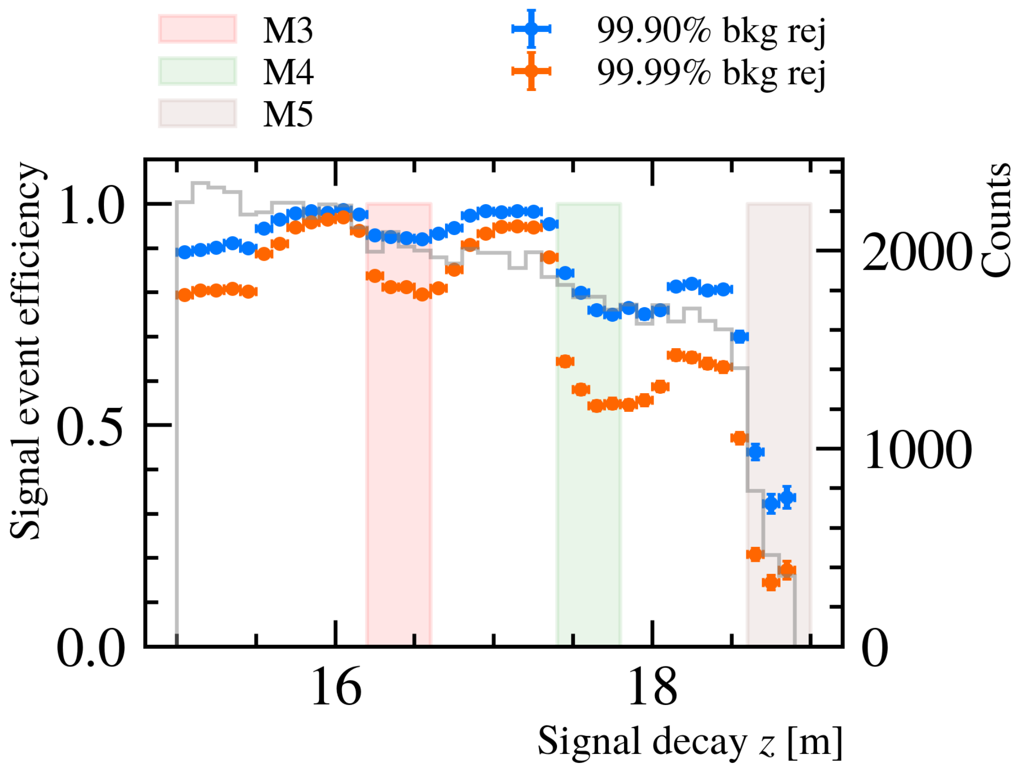
PoS LHCP2022 (2023) 094

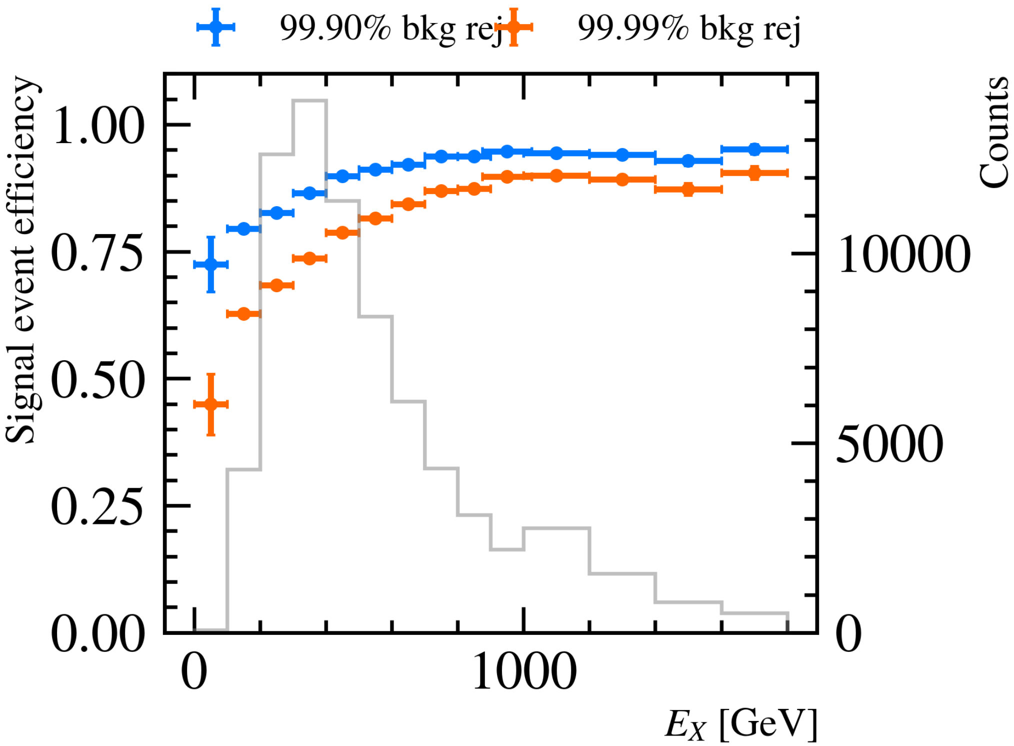
Rept.Prog.Phys. 85 (2022) 024201

Muon detector showers in LHCb HLT2

Profit from the absence of hardware trigger in LHCb

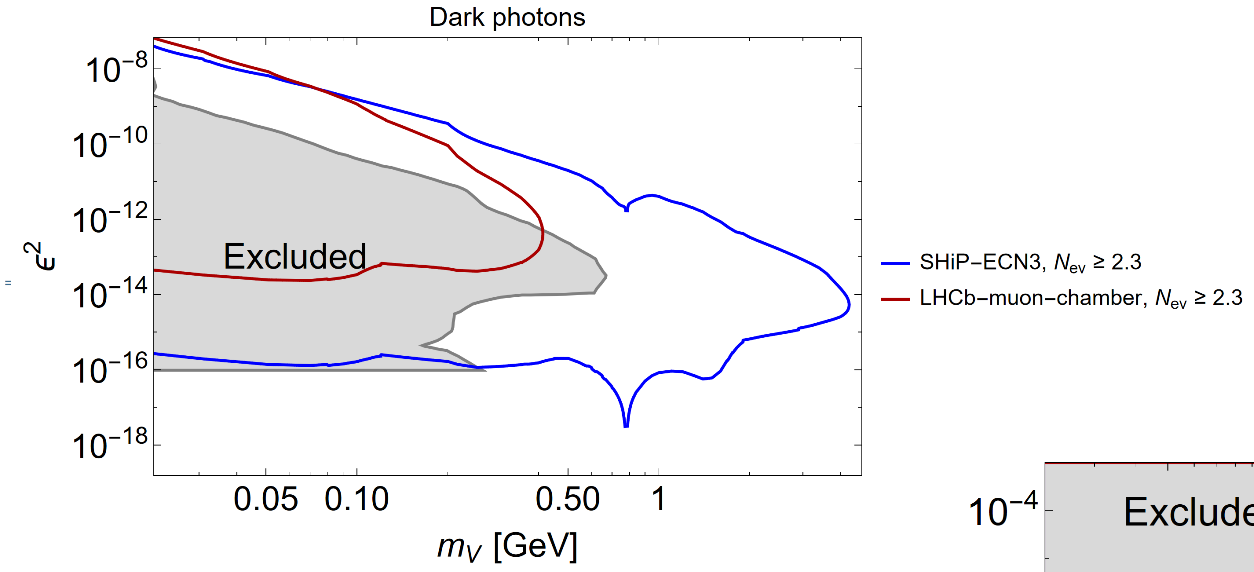
Put anomaly detection based on normalized autoencoder directly into HLT:



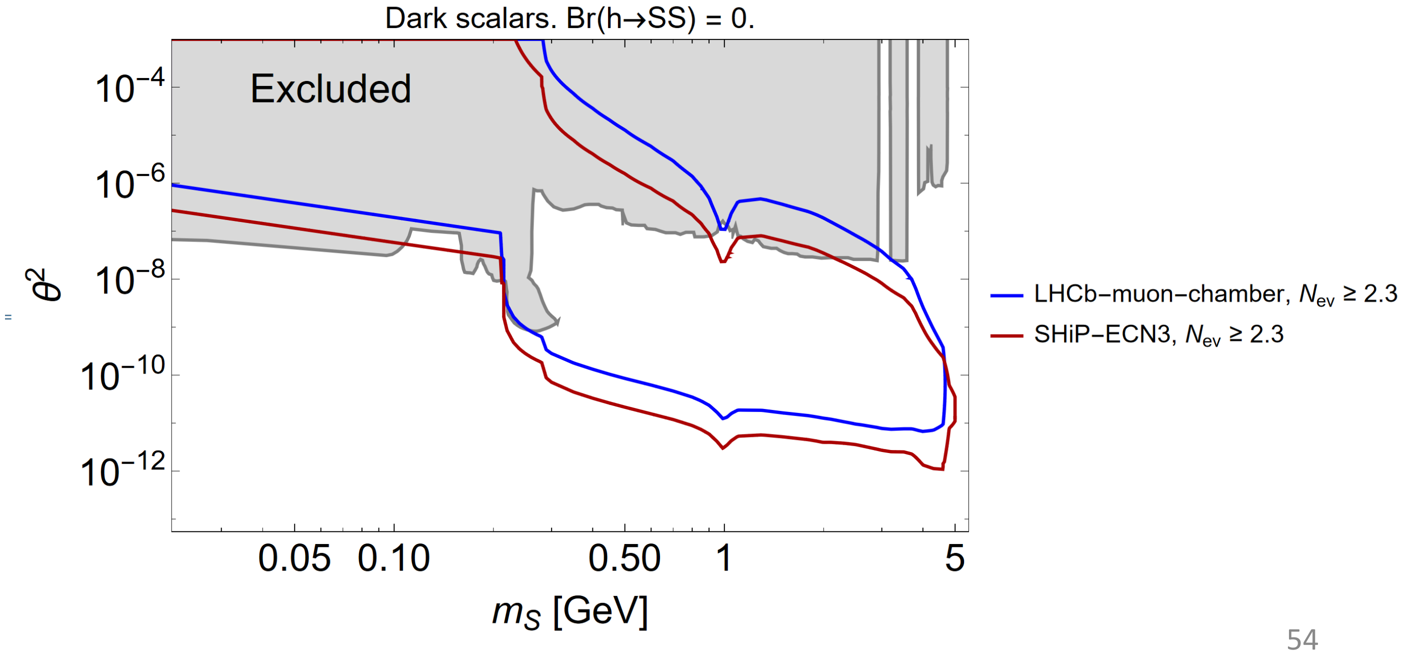


LHCb FIGURE in preparation

Potential LHCb sensitivity to other LLPs

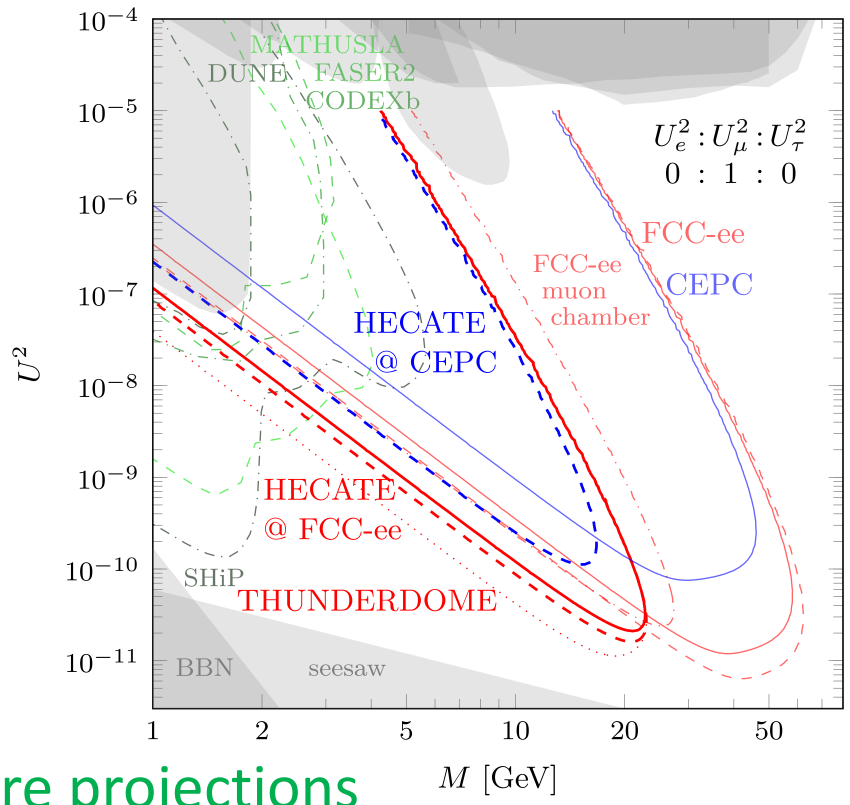


- LHCb offers unique possibilities for low-mass FIPs produced in the forward regime!



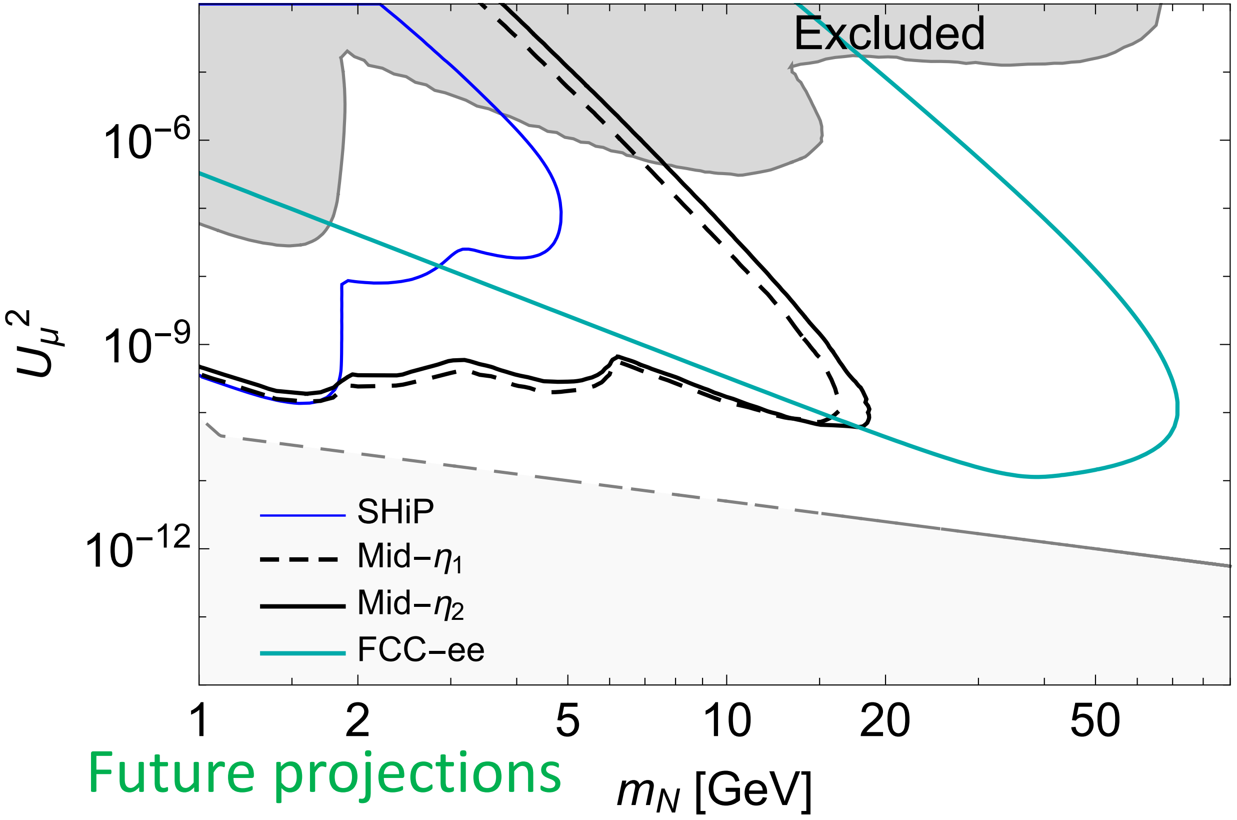
Very far in the future: HNLs at FCC-ee/-hh

FCC-ee *Eur. Phys. J. C* 81 (2021) 6



Future projections

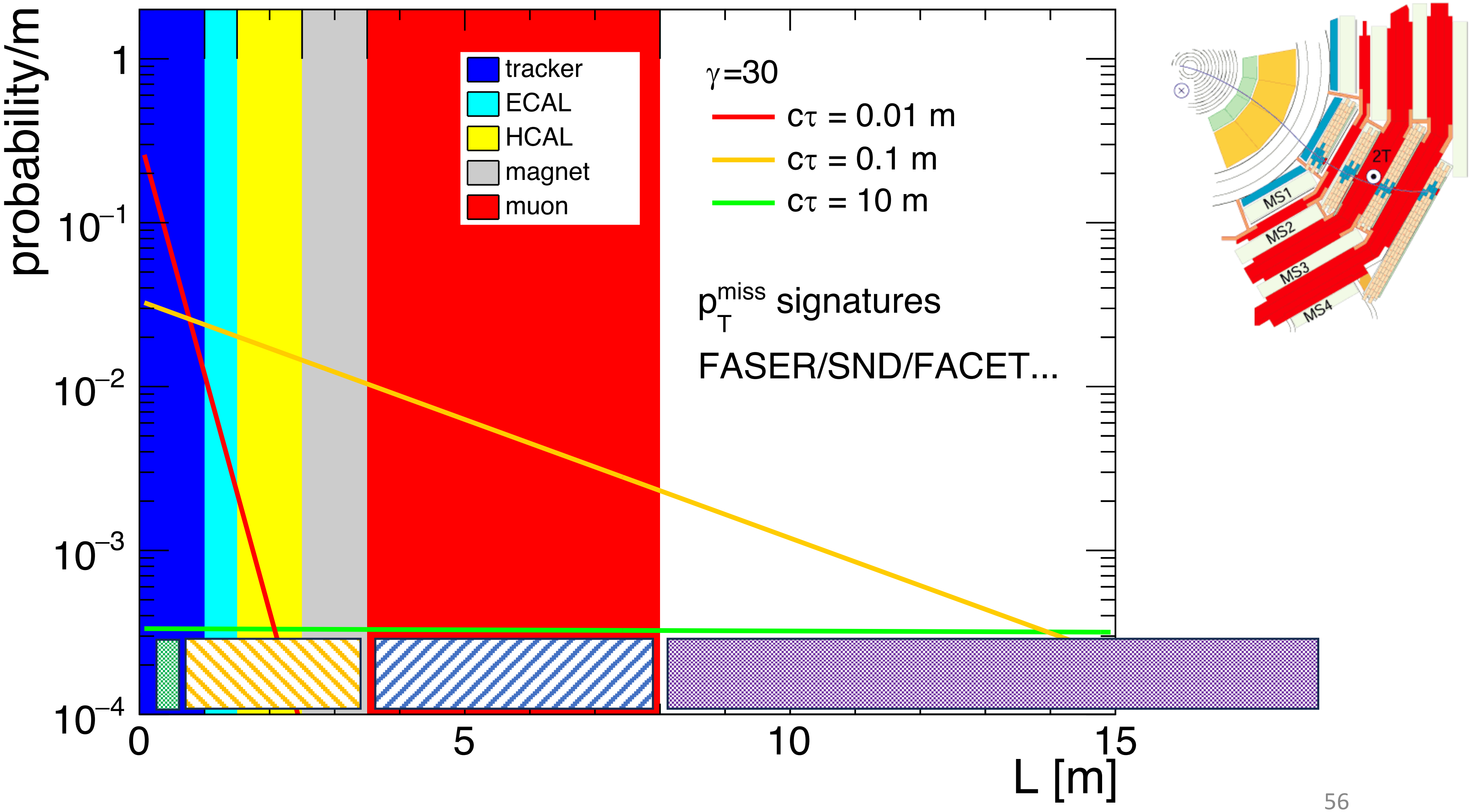
FCC-hh *JHEP* 01 (2023) 042



Future projections

Proposals for the LLP detectors on the walls of the FCC experimental caverns

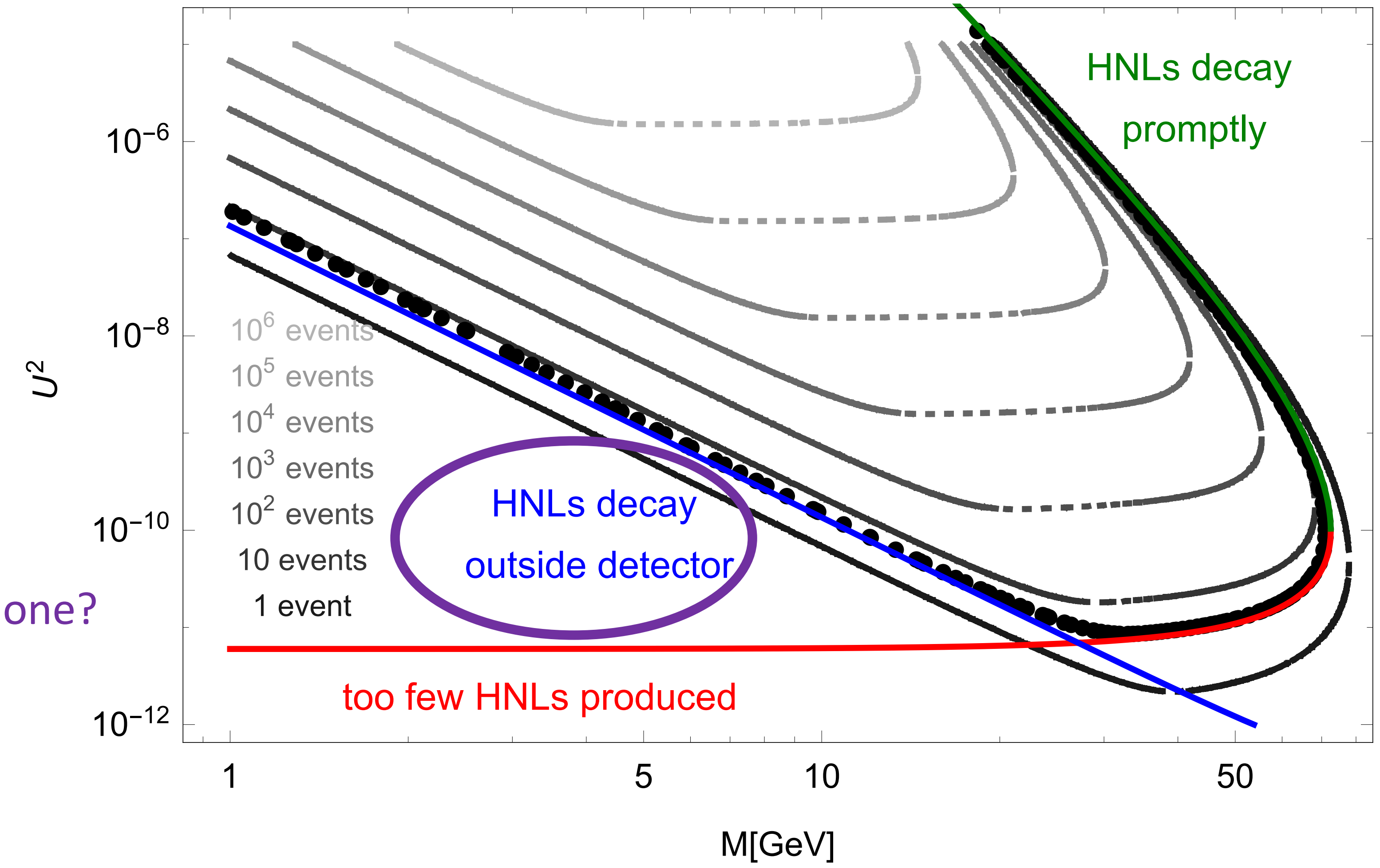
Another subdetector usage for HNLs @ LHC ?



Decay volume of

- displaced vertices
- standalone muons
- muon detector showers
- **missing particle?**

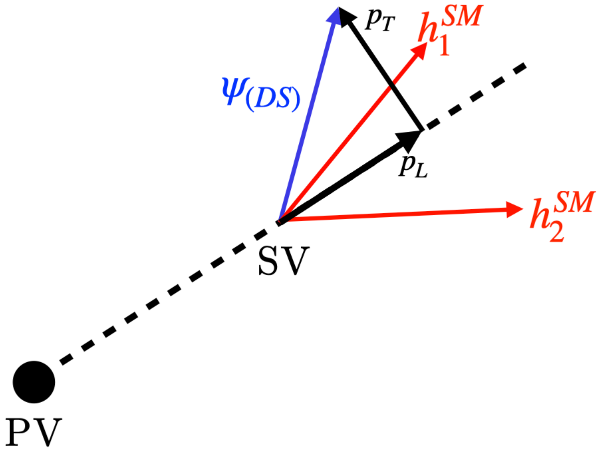
HNLs escaping detector



Can smth be done?

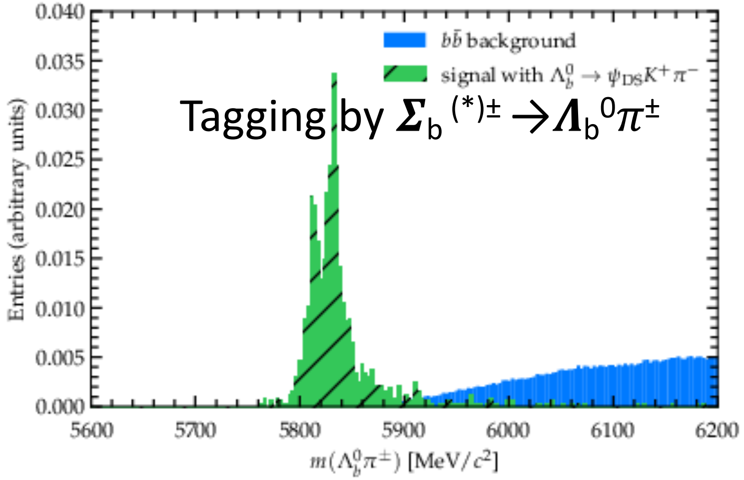
PoS ICHEP2022 (2022) 608

“Stable” low-mass particles: $\mathbf{P_T^{miss}}$ @ LHCb



Proposal to use fully reconstructed decay vertices to infer missing particles:

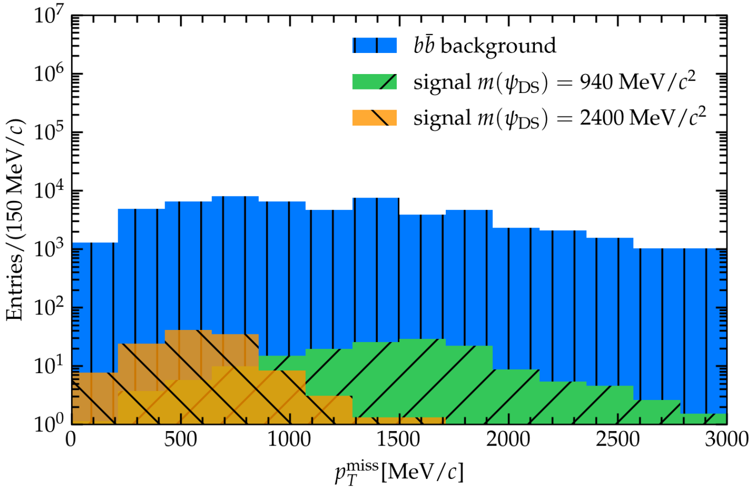
- non-hermetic detector but excellent vertex resolution
- look for missing momentum in hadron decays!
- get access to much lower masses: 1-5 GeV



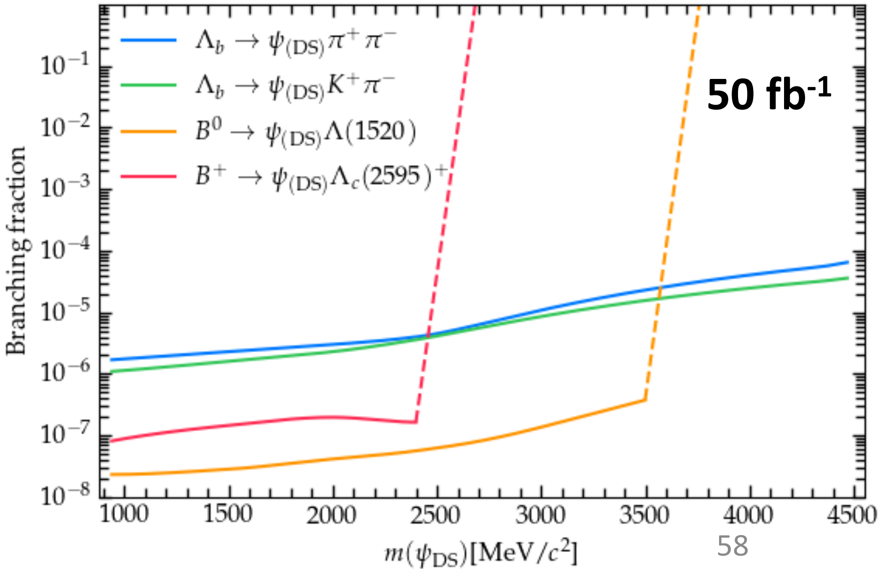
Tagging by $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$

Eur.Phys.J.C 81 (2021) 964

p_T^{miss} in hadron decays



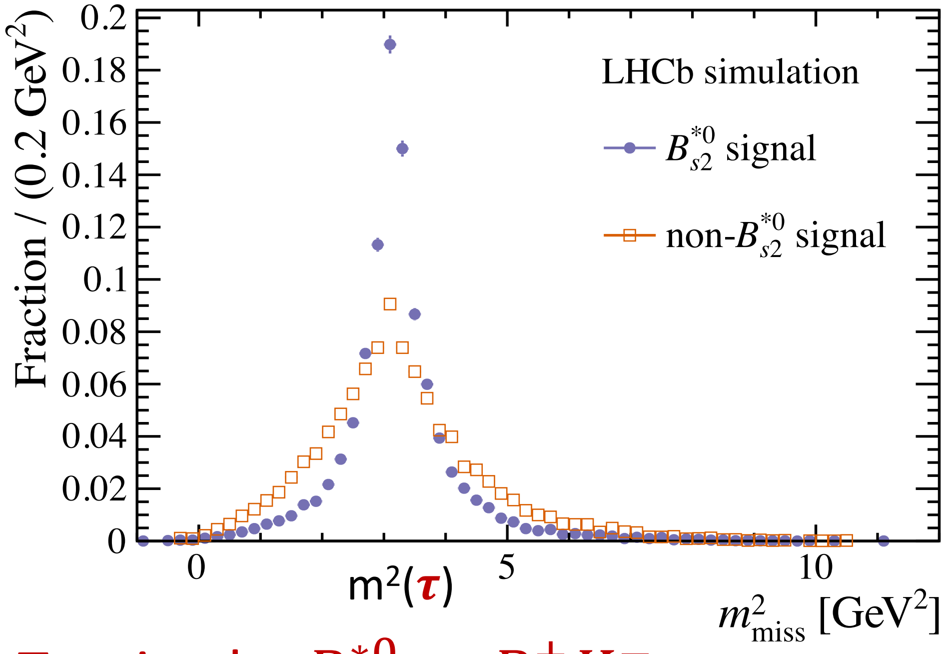
Systematic uncertainty is a challenge!



50 fb^{-1}

Science fiction idea: M_{miss} ?

Looking for $B^+ \to K^+ \mu^- \tau^+$

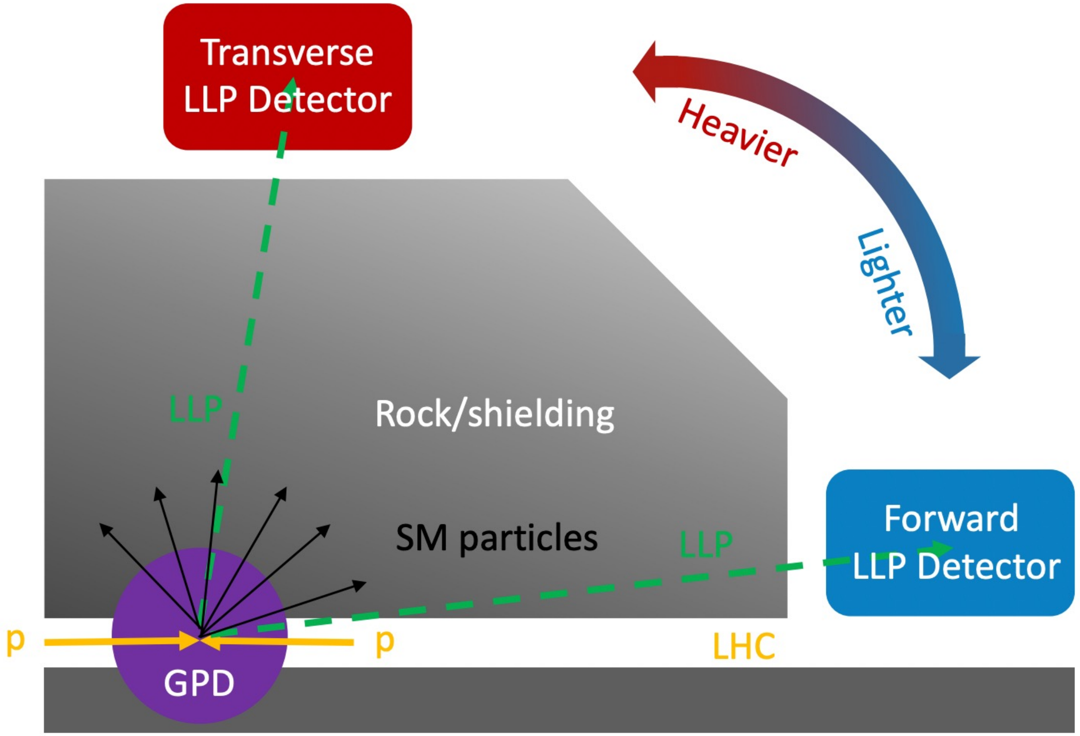


Tagging by $B_{s2}^{*0} \to B^+ K^-$

[JHEP 06 (2020) 129](#)

- missing mass used in the LHCb search for LFV decays with τ:
  - B^+ momentum computed from its flight direction and known $m(B^+K^-)$
  - missing τ 4-momentum is computed as $P(B^+)-B(K^+\mu^-)$
- can be applied for HNLs at FCC?
  - fully inclusive for HNL decays
  - suppressed by B_{s2} cross section
  - can consider B→D→HNL chains
  - needs hadron identification and excellent vertex resolution!

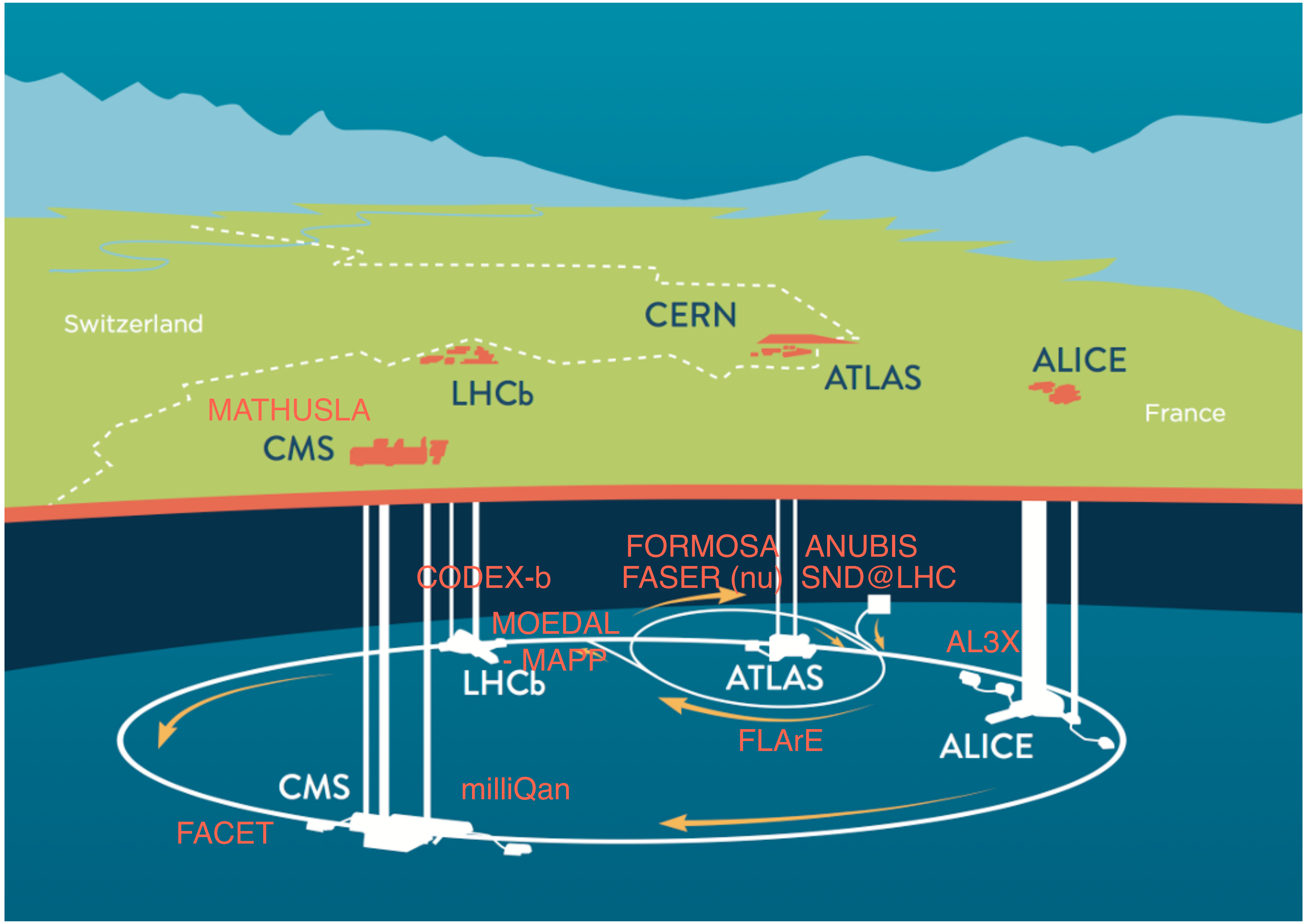
Meanwhile: new instruments proposals



- Location:
  - using available LHC interaction points
  - relying on mostly existing infrastructure
- Shielded from the collision point:
  - no SM background
  - can have large decay volume
  - no need for trigger
- Forward LLP detectors:
  - light mediators (dark photon, …)
- Transverse LLP detectors:
  - heavy mediators (H, Z, W, …)

Credits: Carl Gwilliam

Proposals and realizations

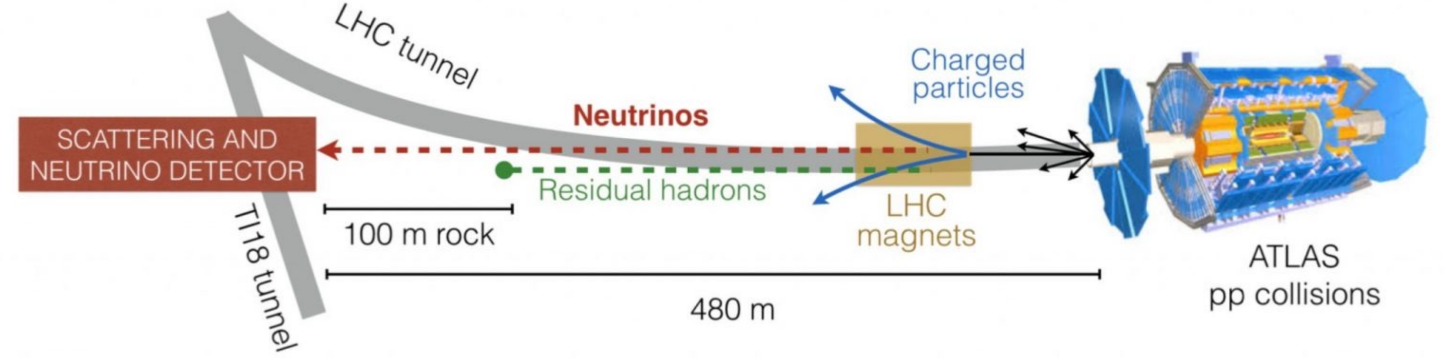


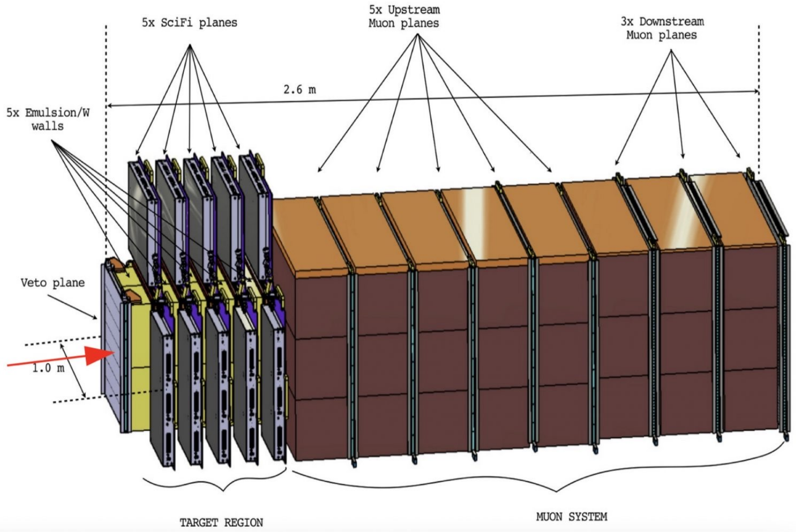
Credits: Emma Torró Pastor

- Existing:
    - FASER(ν)
    - **SND@LHC**
    - MOeDAL
    - MAPP-1
    - milliQan demonstrator
- Planned:
    - CODEX-b
    - MATHUSLA
    - MAPP-2
    - ANUBIS
    - FORMOSA
    - FLArE
    - FACET
    - milliQan
    - AL3X
    - FASER2
    - AdvSND

SND@LHC:
Scattering and Neutrino Detector at the LHC

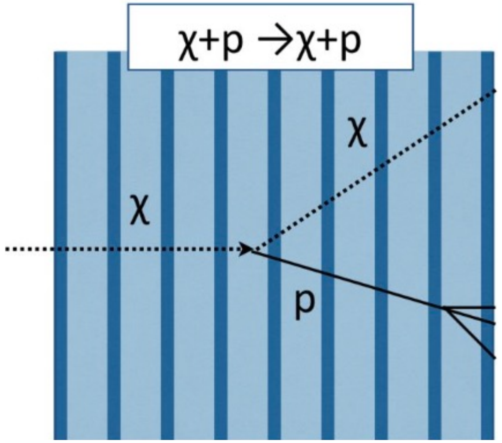
480 m from the ATLAS collision point

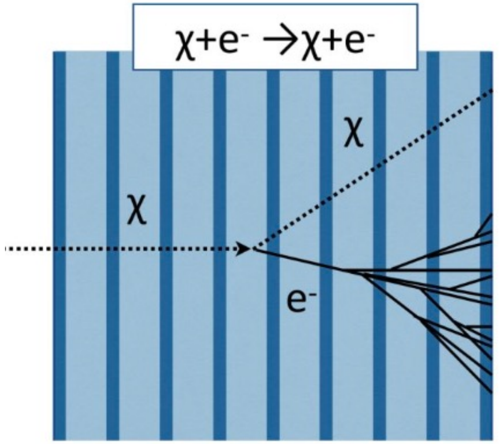




new hybrid off-axis detector for:

- SM neutrino measurement
- FIPs searches





https://snd-lhc.web.cern.ch/

SND@LHC in the tunnel

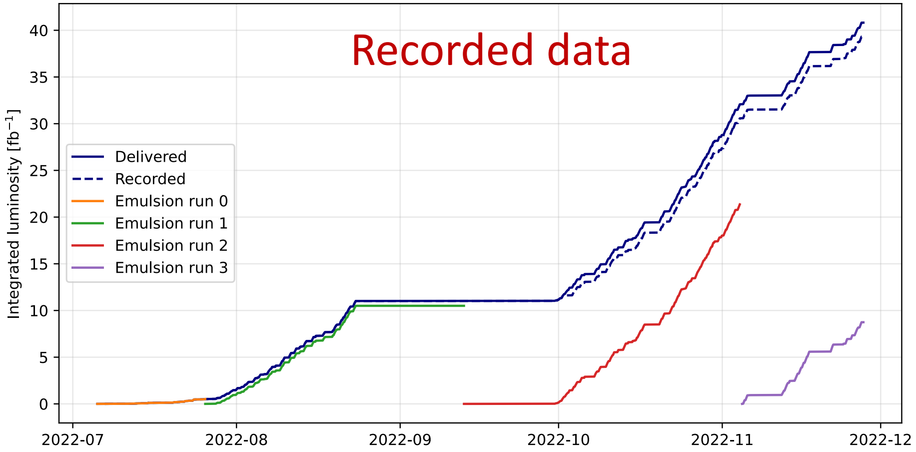
LHC

Scattering and Neutrino Detector
at the LHC

Detector in place

SciFi tracker
built at EPFL

Started data-taking in 2022



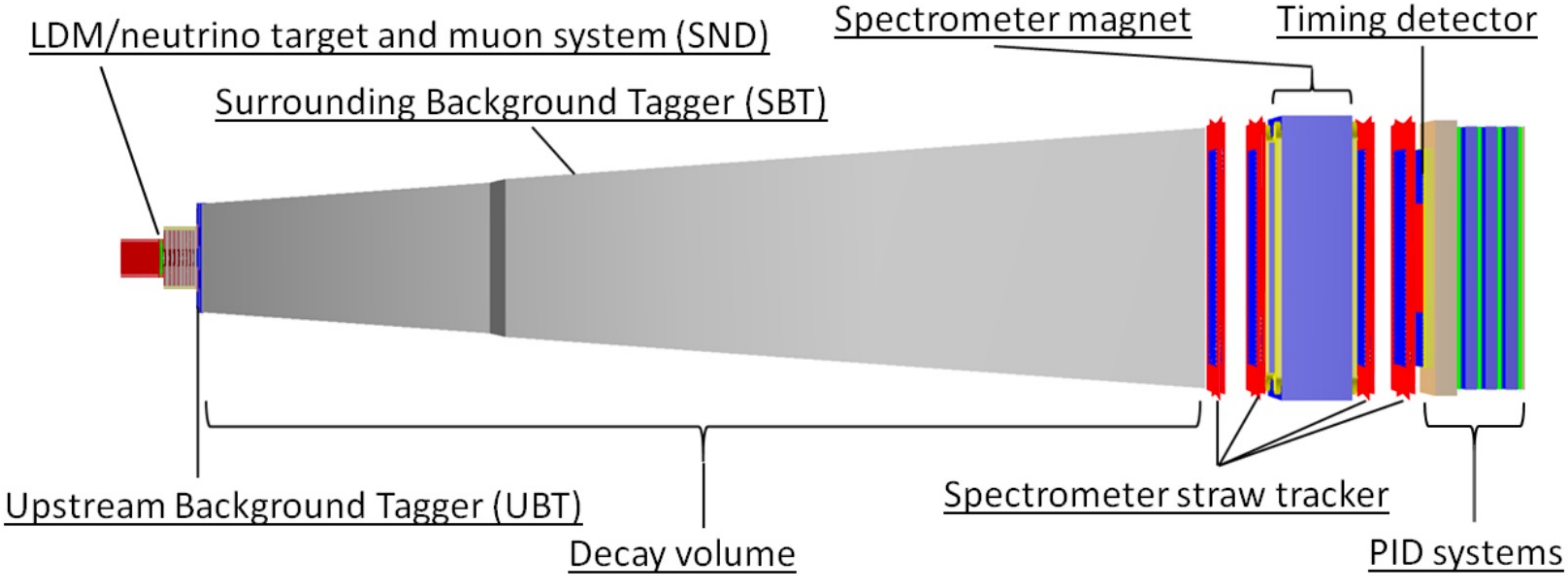
July’22

December’22

- already detected first neutrinos!
- first data are being analyzed
- data-taking planned till 2025

https://snd-lhc.web.cern.ch/

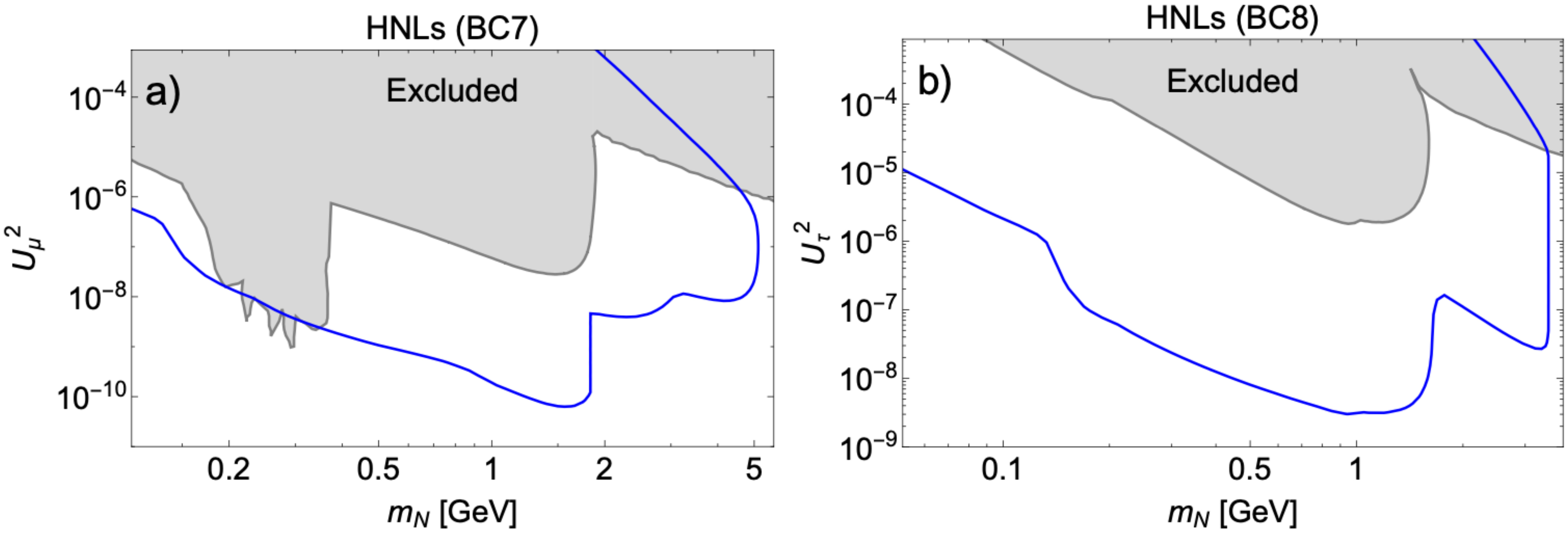
And finally:
SHiP happens!



CERN-SPSC-2023-033

SHiP sensitivity to HNLs

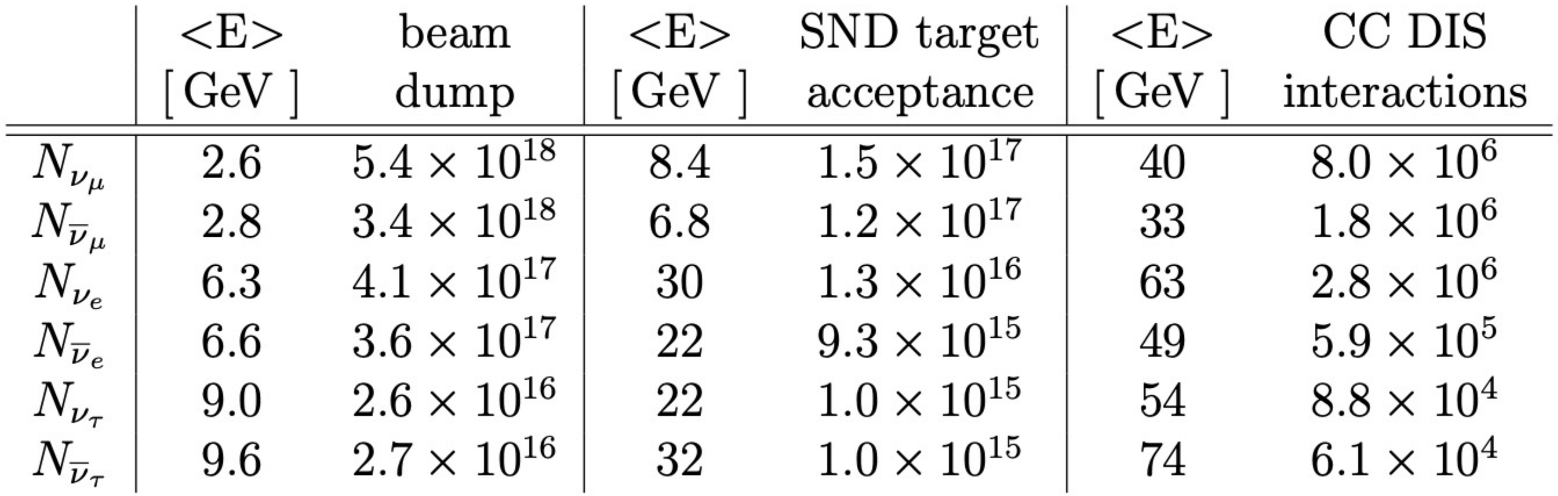
- Ultimate facility to discover HNLs (or other FIPs) with masses below 5 GeV:



CERN-SPSC-2023-033

SHiP (neutrino) physics with the SND

Expected neutrino flux and number of interactions:



	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
$N_{\overline{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
$N_{\overline{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\overline{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}

Physics programme:

- $\nu_{\tau}, \nu_{\mu}, \nu_{e}$ cross section measurement
- parton distribution functions
- V_{cd} measurement
- neutrino magnetic moment
- lepton universality
- + light dark matter searches

CERN-SPSC-2023-033

SHiP τ neutrino physics

- “double-kink” topology:
    - detector with superior vertex and tracking capabilities: emulsion or Si-based spectrometer
- event/shower shape variables:
    - ν_τ interaction vertex
    - μ momentum
    - hadronic shower energy and shape measurement
    - ⇒ absorber interleaved with tracking sensitive layers, e.g. SciFi mats

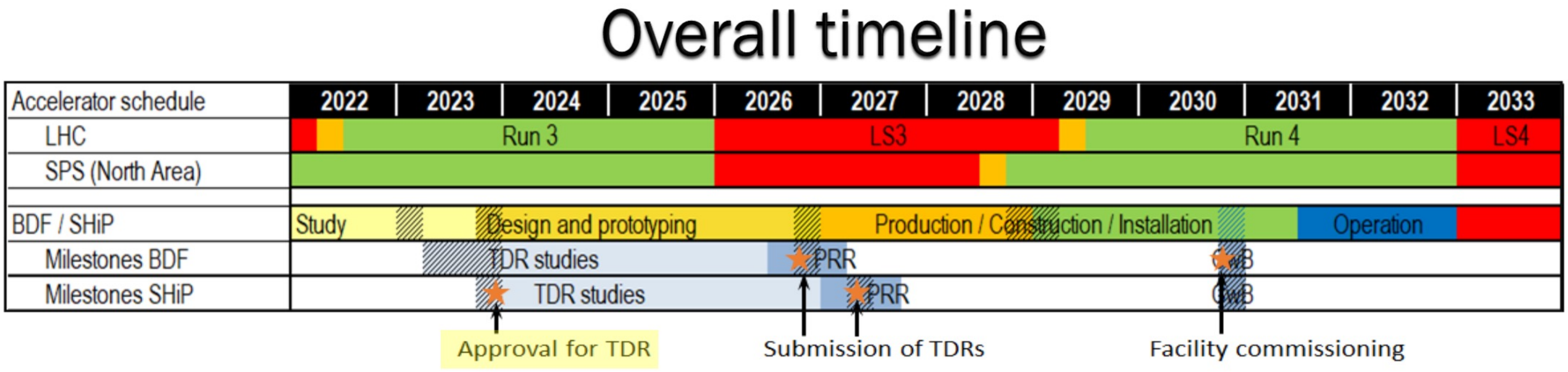
Number of reconstructed taus with emulsion:

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

⇒ relevant for NP searches and lepton universality tests!

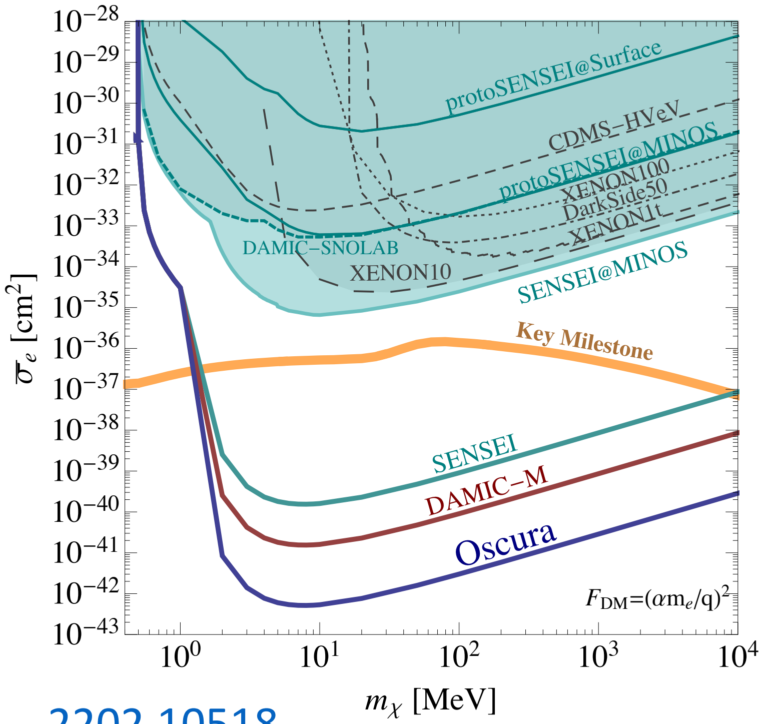
CERN-SPSC-2023-033

SHiP timeline



- planning towards SHiP realization is happening now
- expect first operation as early as 2031
- possibility to have staged approach for detector subsystems
- target of 6×10^{20} PoT is achieved in 15 years of nominal operation:
  - it is necessary that SPS delivers beams after the stop of HL-LHC

Independent source of news: Astrophysics frontier



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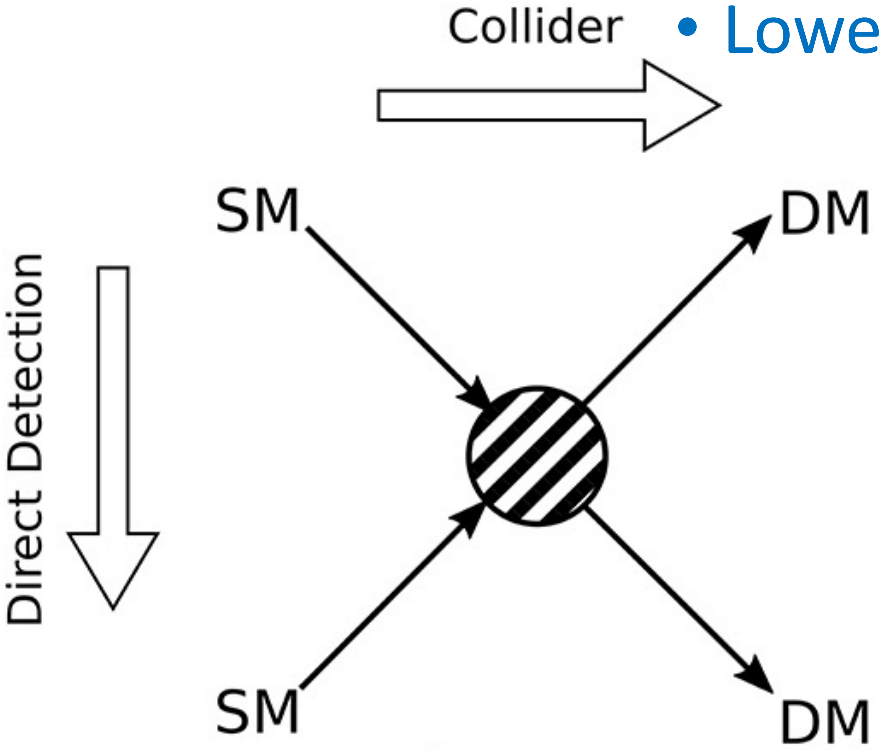
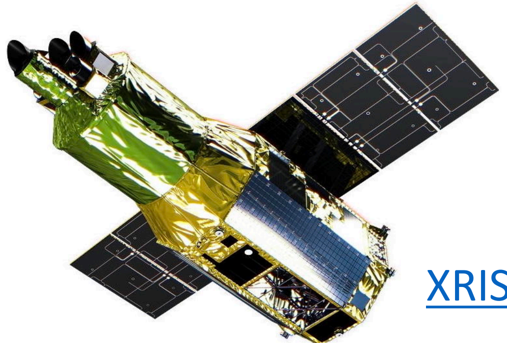
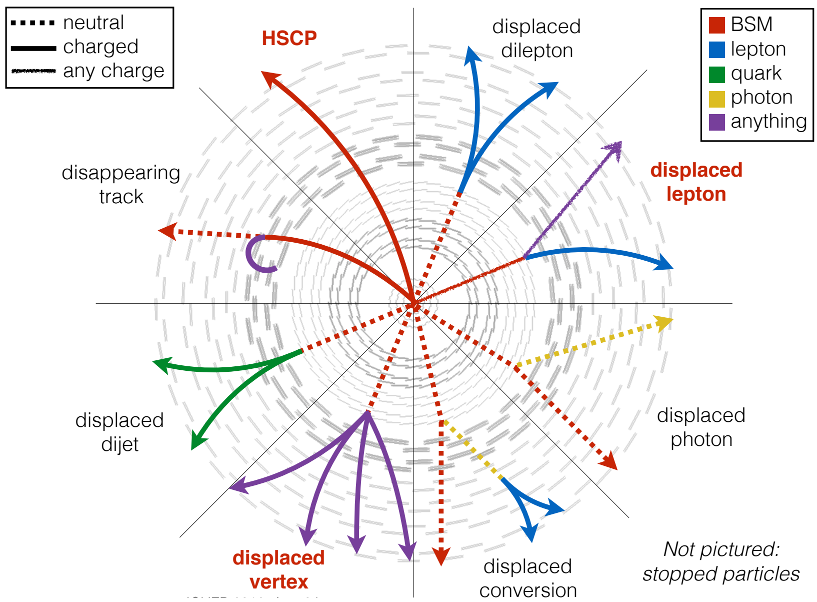


Indirect Detection

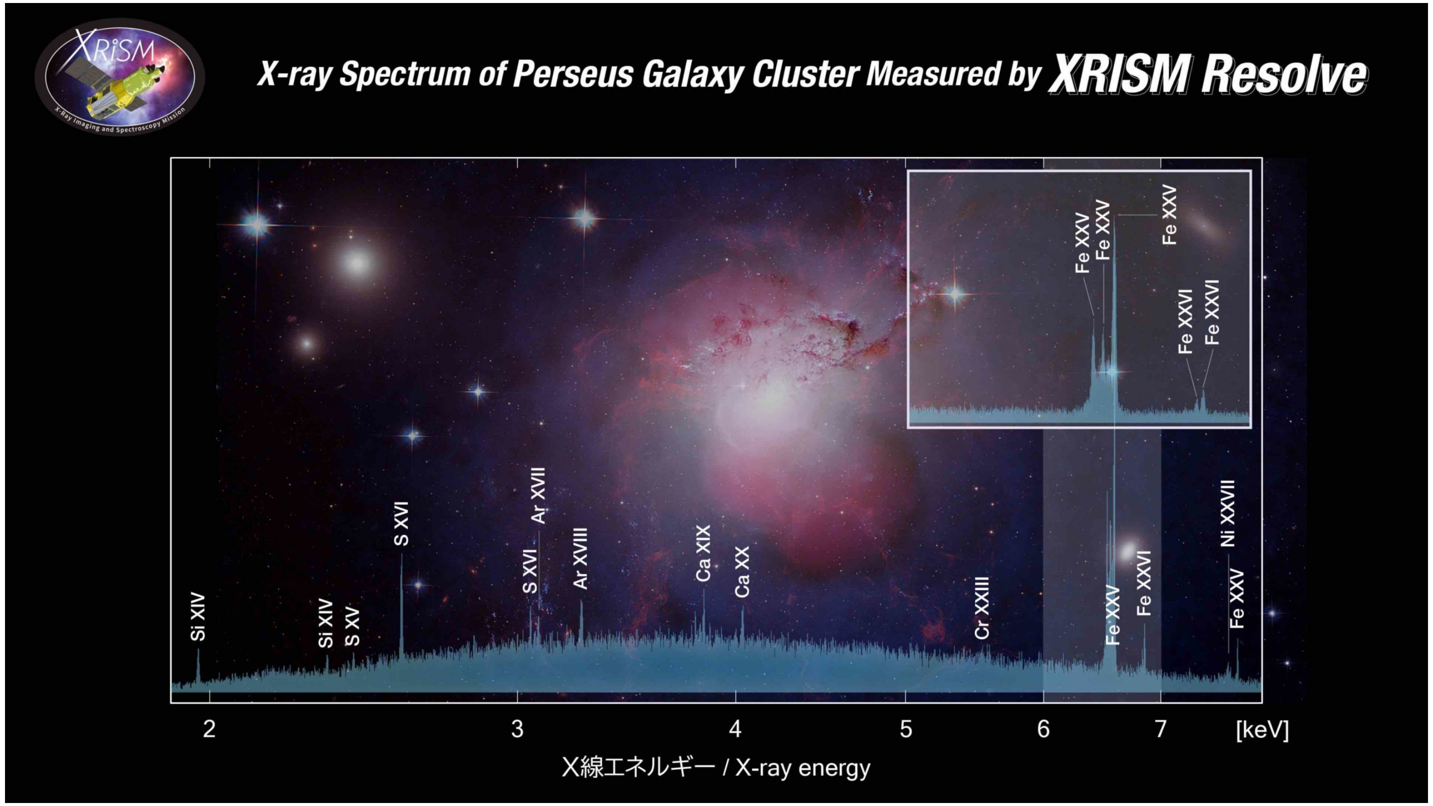
- Lower DM and mediator masses
- Long-lived mediators
- Decaying DM



XRISM



XRISM: operating in nominal phase



https://www.xrism.jaxa.jp/en/topics/news/990/

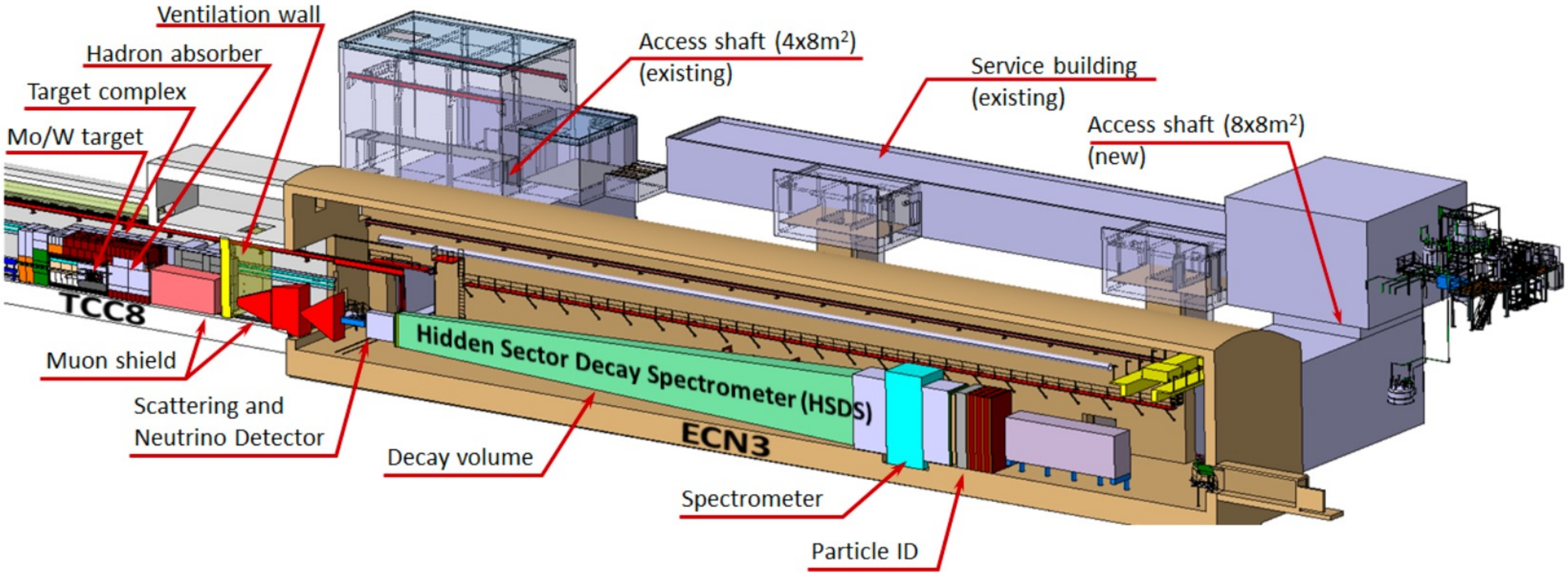
- is there a 3.5 keV line?
  - contested reports of a possible evidence of DM→$\nu\gamma$
- the answer might be around the corner already!
  - XRISM achieves 5 eV resolution in the necessary energy range

Next decade is crucial

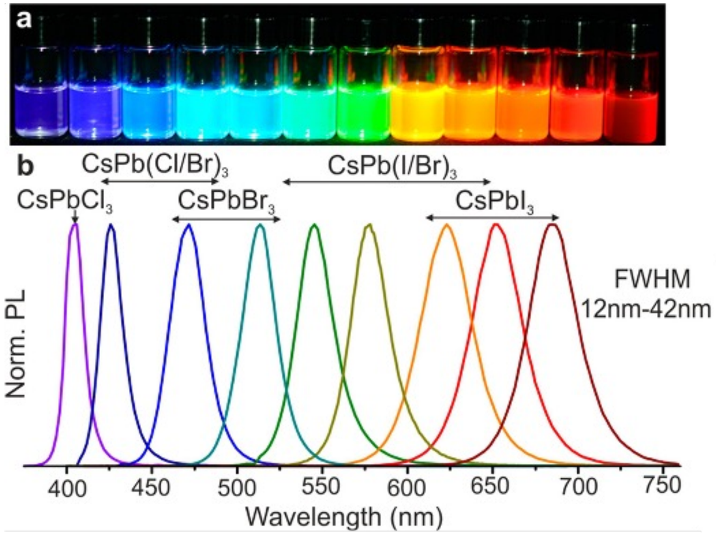
- Unique opportunity to open a window to new energy scale through precision with LHCb and Belle II experiments
- An ultimate FIP search experiment can start operating: SHiP @ ECN3
- Influx of astrophysical measurements can corner the DM mass scale
- And we have a decision on the next Higgs boson factory to make!
- While no guaranteed path to discovery, we have several promising venues to explore and to determine a new energy scale!

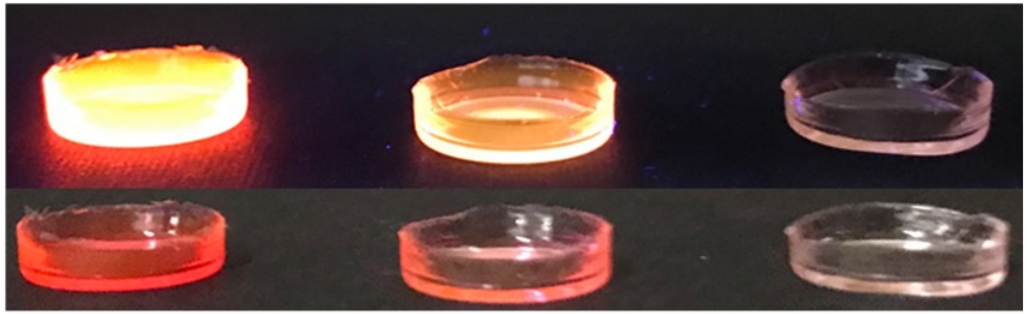
Extra slides

SHiP @ ECN3


Ventilation wall
Hadron absorber
Target complex
Mo/W target
TCC8
Muon shield
Scattering and
Neutrino Detector
Decay volume
Hidden Sector Decay Spectrometer (HSDS)
ECN3
Spectrometer
Particle ID
Access shaft (4x8m^2)
(existing)
Service building
(existing)
Access shaft (8x8m^2)
(new)

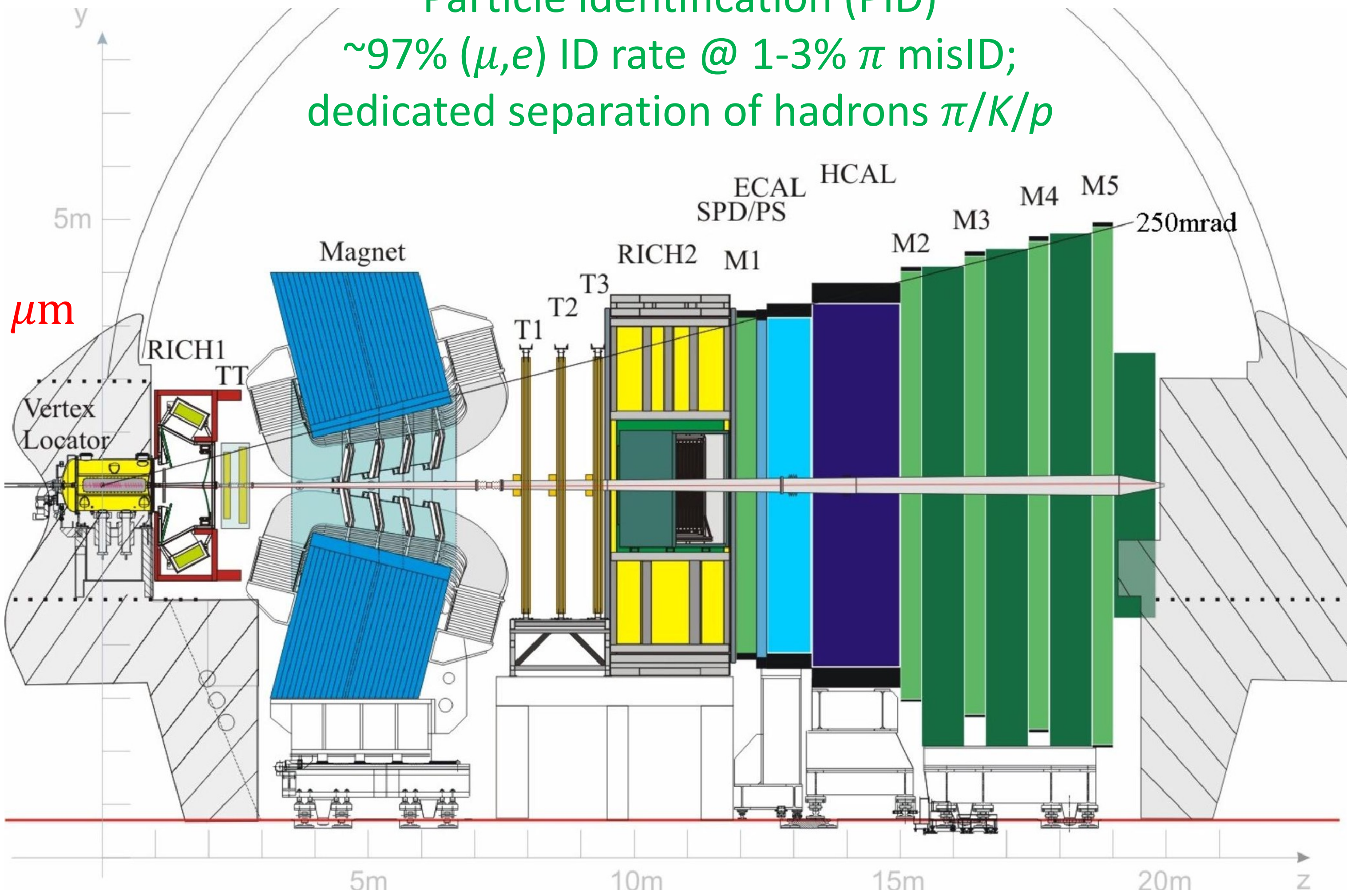
Long-term scintillator R&D





- collaboration with Kevin Sivula and Colin Jeanguenat from chemistry
- aim to develop new fast, radiation hard, high-light-yield scintillator for future applications
- they succeeded to enhance the dye-sensitized scintillators by anchoring it to the perovskite nanocrystals
- we are measuring samples light yield and attenuation length
- potentially can expand collaboration to colleagues at CERN (in the scope of ECFA DRD4)

The LHCb detector



Particle identification (PID)
~97% (μ,e) ID rate @ 1-3% π misID;
dedicated separation of hadrons $\pi/K/p$

VELO

$$\sigma_{\mathrm{IP}} = \left(15 + \frac{29}{p_{\mathrm{T}}(\mathrm{GeV})}\right)\mu\mathrm{m}$$

$2<\eta<5$

tracking system
$\sigma_p/p = 0.5...1.0\%$

ECAL

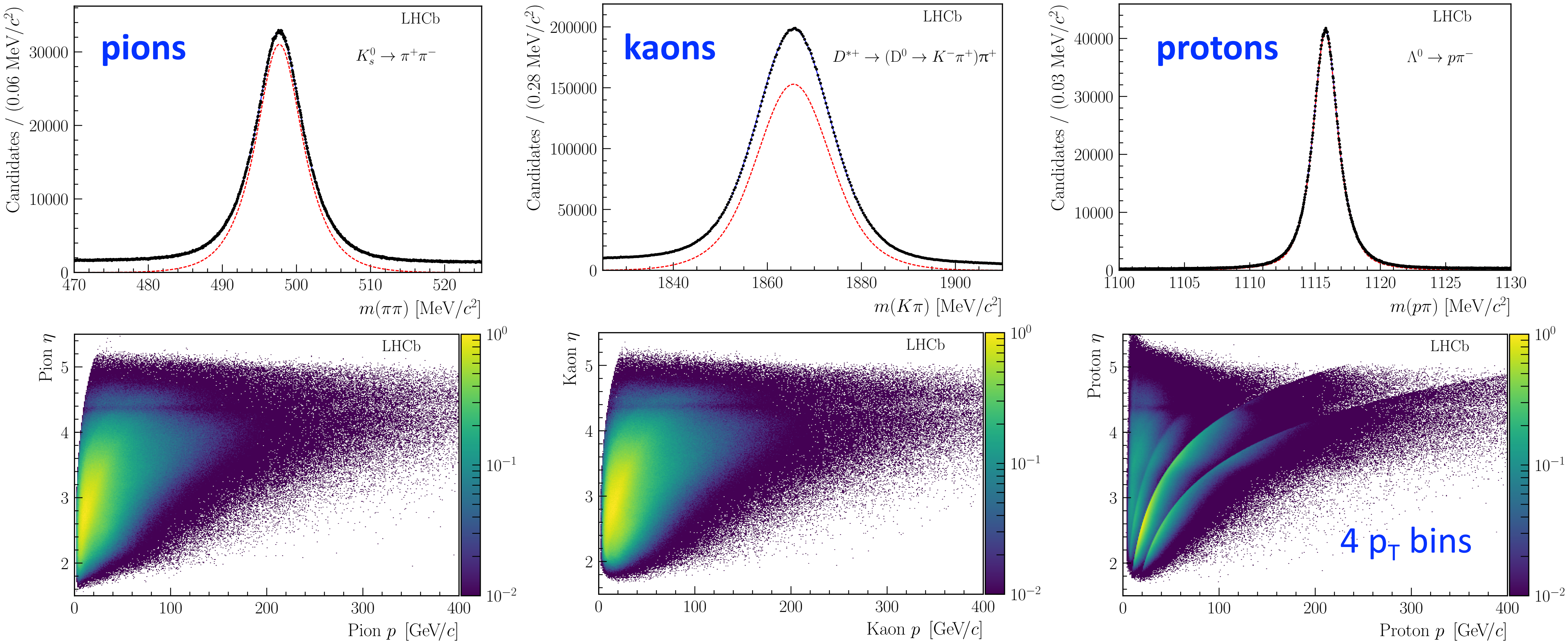
$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 1\%$$

JINST 3 (2008) S08005

EPJ Tech. Instrum. 6 (2019) 1, 1

Rare decays: background control is crucial

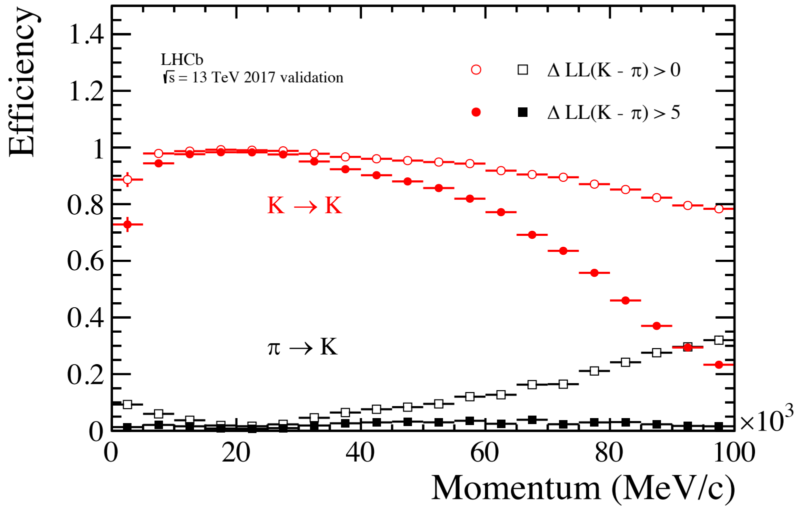
- Large calibration samples are collected with dedicated triggers and used for:
  - calibration of PID algorithms to correct MC simulation for data/MC differences
  - measurements of misidentification rates for data-driven estimates of peaking backgrounds



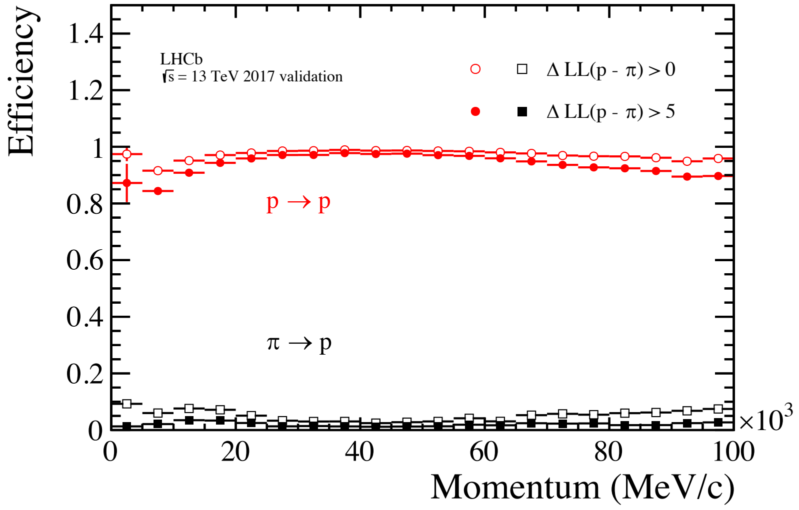
Performance of charged hadrons identification

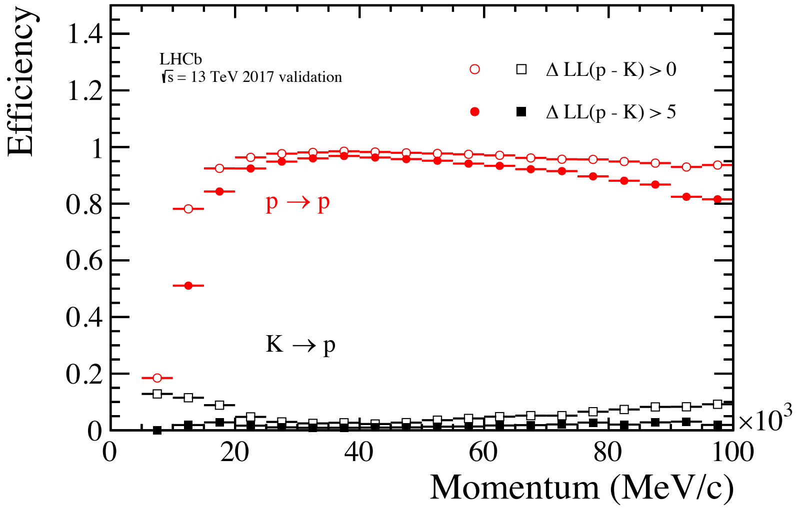
- Very good discrimination power over wide kinematic ranges for hadrons:

kaons



protons



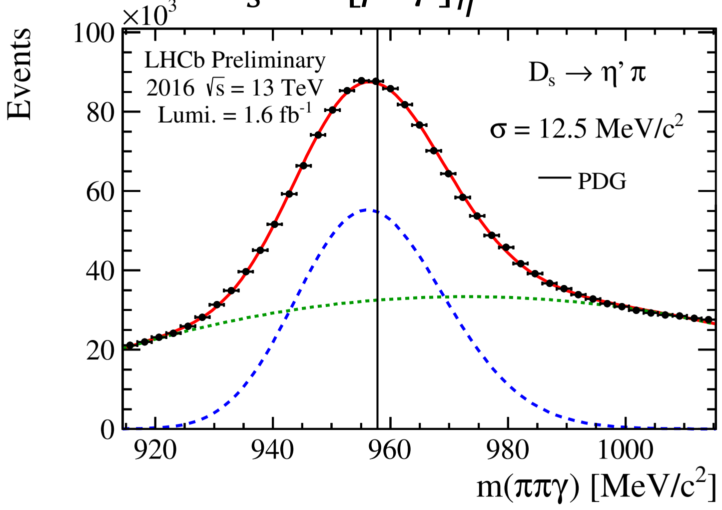


PoS LHCP2020 (2021) 047

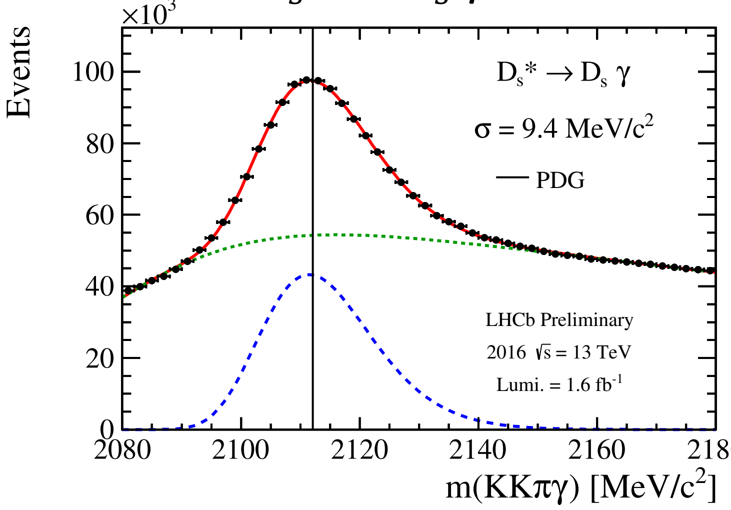
Neutral calibration samples

- multivariate classifiers combine variables describing energy deposits in the calorimeter subdetectors
- discriminate photons from hadrons, electrons and high-energy neutral pions

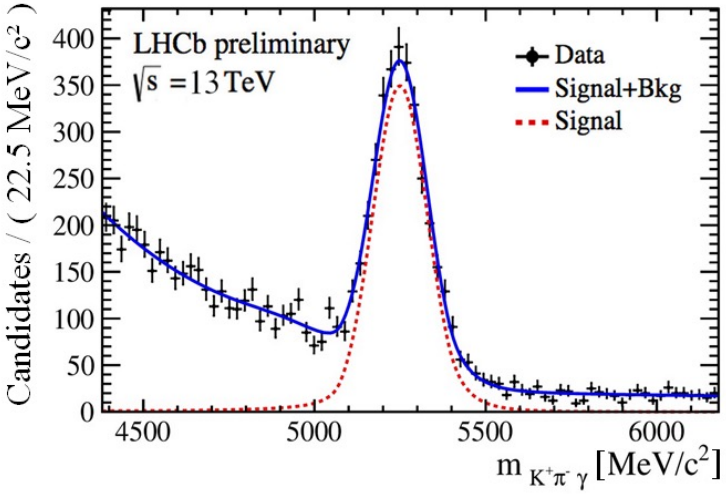
photons



$D_s^+ \to [\rho^0\gamma]_{\eta'}\pi^+$



$D_s^{*+} \to D_s^+\gamma$



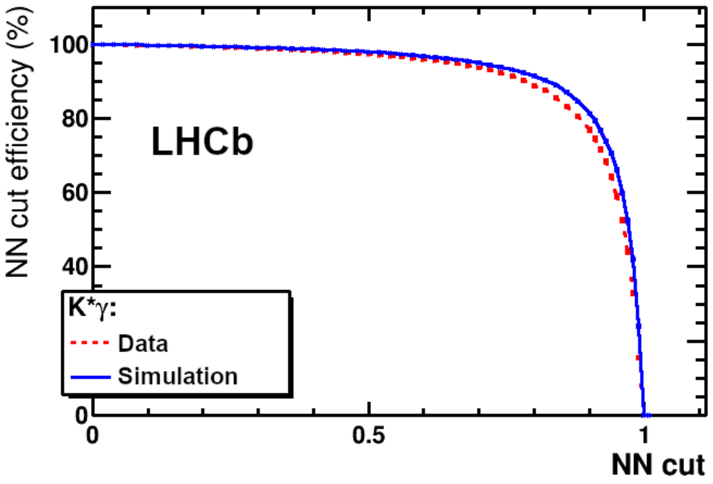
$B^0 \to K^{*0}\gamma$

PoS LHCP2020 (2021) 047

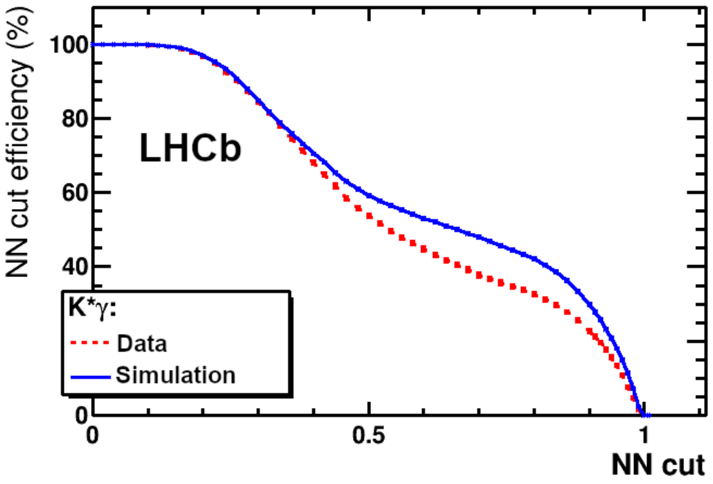
Performance of photon identification

- Three different neural networks trained with simulation to separate photon signatures from other species:
  - γ vs. hadron: IsNotH
  - γ vs. e^+e^-: IsNotE
  - γ vs. π^0: IsPhoton
- Signal: reconstructed photon candidates matching the generated photons ($B^0 \to K^{*0}\gamma$)
- Background:
  - electrons: reconstructed photons matching generated electrons ($B^0 \to K^{*0}e^+e^-$)
  - non-electromagnetic: reconstructed photons not matching to photon or electrons

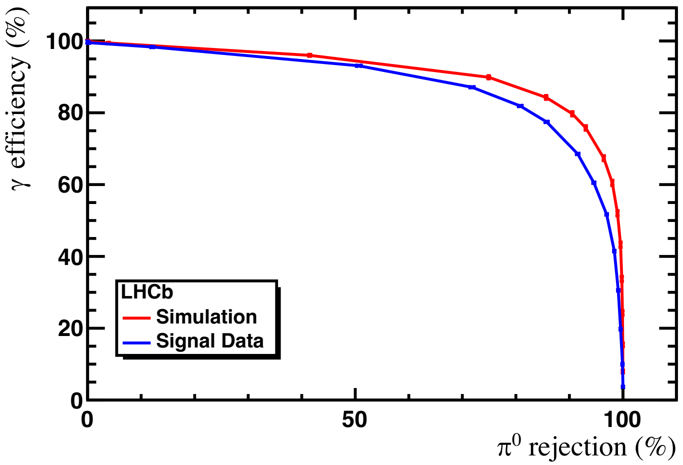
IsNotH (hadron rejection)



IsNotE (electron rejection)



IsPhoton (π^0 rejection)



arXiv:2008.11556