Universität Zürich[UZH]

Testing the SM symmetries in beauty and searching for dark particles

Symposium on Low Energy Experimental Particle Physics

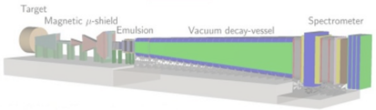
Max-Planck-Institüt Für Physik

Nico Serra - Universität Zürich

LHCb

- World's largest sample of b-hadrons
- General purpose experiment in the forward region

SHiP

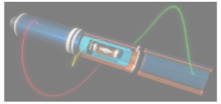


Improve Constraints On Dark Sector By Orders Of Magnitude

SND@LHC

Measure high energy neutrinos
Search for Dark Sector

Mu3e



Strongly constrain
$\mu \rightarrow 3e$

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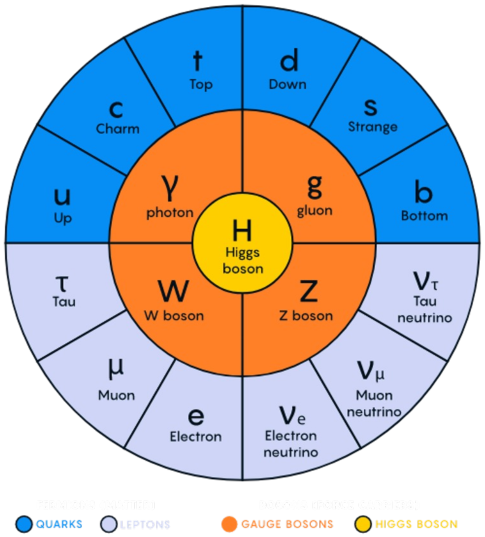
Orphans of naturalness



- The SM describes what we observe and what we do not

$$\mathcal{L} = (\mathcal{L}_{gauge} + \mathcal{L}_{\mathcal{H}iggs})_{\text{dim}\leq 4} + \sum_i \frac{\alpha_i}{(\Lambda_{\mathcal{NP}})^n} \mathcal{O}^i_{\text{dim } 4+n}$$

  - suppress FCNC, neutron EDM very small, Lepton flavour conservation, lepton universality, … → Λ_{NP} >> EW scale

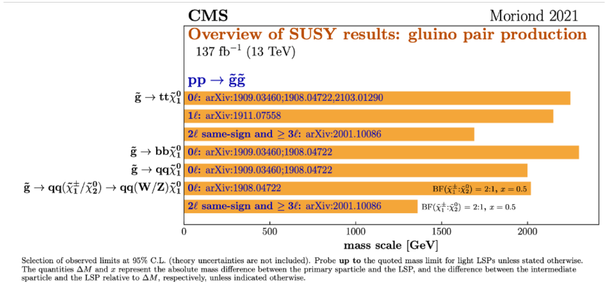
  - Higgs mass "unnaturally" small → expect Higgs mass of the order of Λ_{NP}

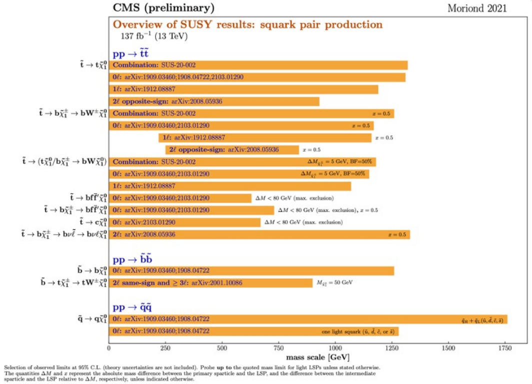
Naturalness → NP at the EW scale

Introduction

Orphans of naturalness

The LHC has found the Higgs and essentially confirmed SM predictions





- Other issues of the SM (Dark Matter, neutrino masses, baryon-antibaryon asymmetry) do not point to any specific energy scale

- Maybe NP is just slightly heavier, e.g. 10/100 TeVs (frustrated naturalness), or has a peculiar structure, or the SM is more “fundamental” than we thought (Λ_{NP} very big, e.g. Planck scale)

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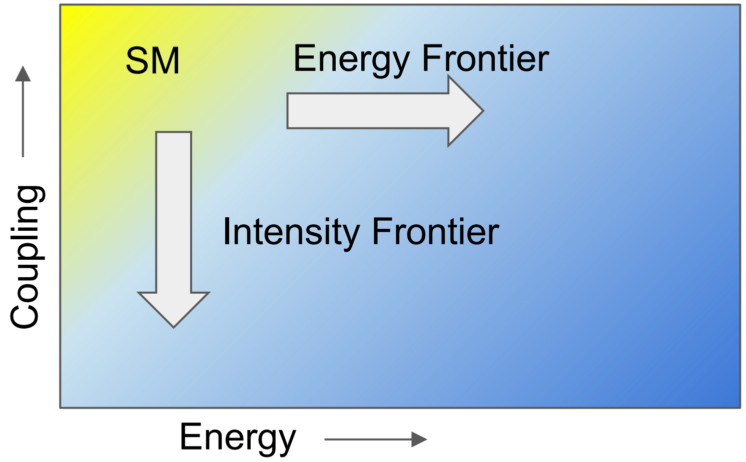
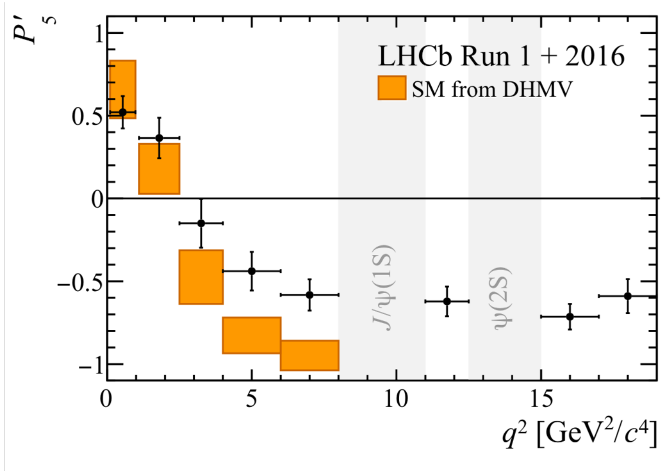
Need experimental guidance, what to do?

A lesson I learned from math economists (Genovese et al. arXiv:2202.11060) → Evaluate your expected returns and losses with a bayesian approach

- Search for NP should be as broad as possible



- Search for NP but also try to improve our SM knowledge



Introduction

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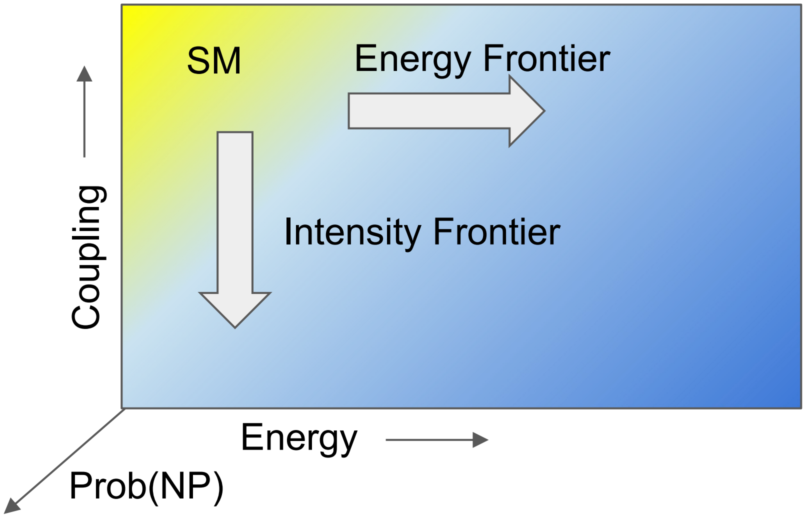

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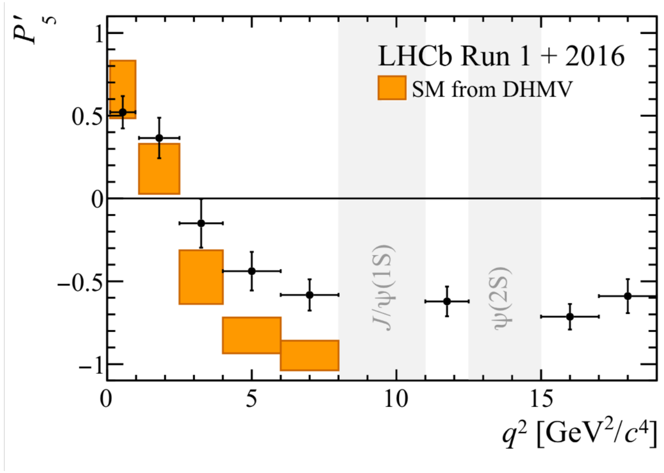
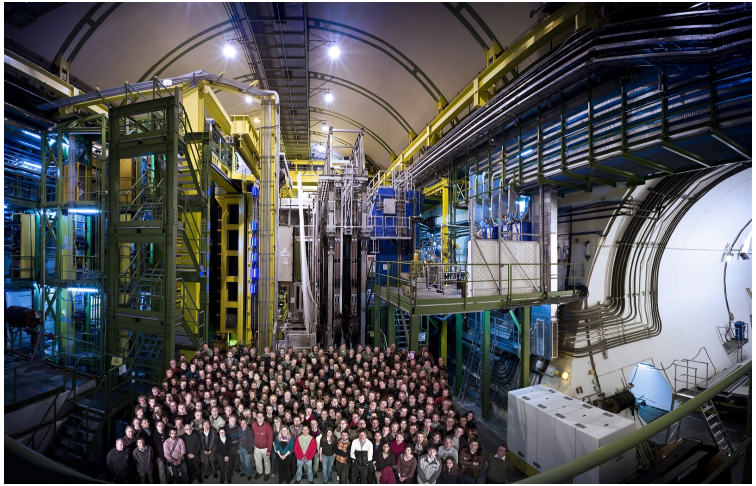


My Bayesian prior on NP

LHCb

- World's largest sample of b-hadrons
- General purpose experiment in the forward region



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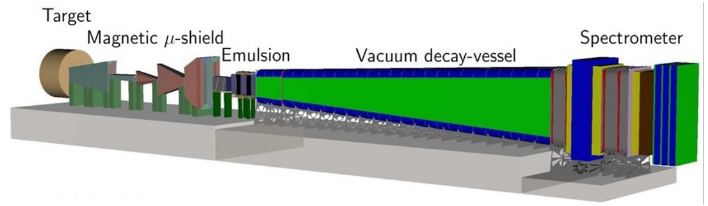
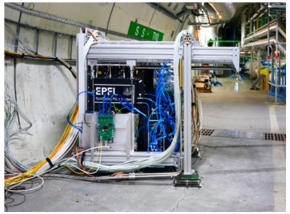


Improve constraints on Dark Sector by orders of magnitude

SND@LHC



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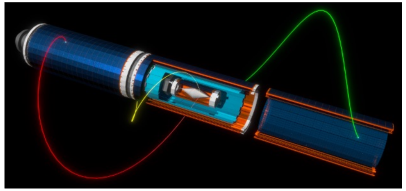

Strongly constrain
$\mu \to 3e$

The LHCb Experiment

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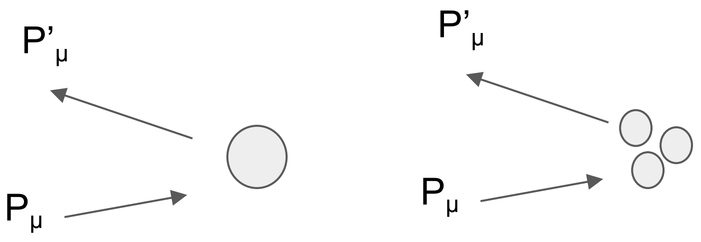
Importance of Precision measurements

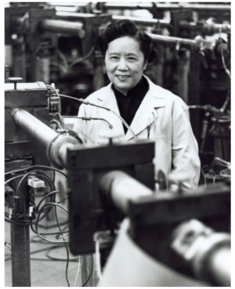


- To investigate a system you can go to short distances (high energy) or improve the precision

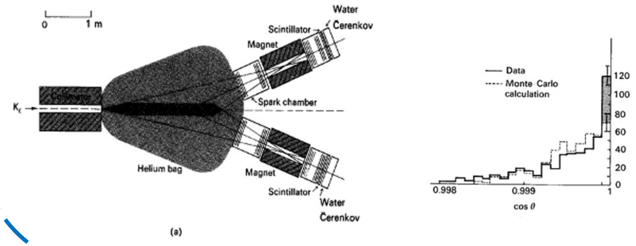
- Typically global symmetries in a system emerge at long distances are broken when you can resolve the system (e.g. parity, CPV, …)

> "Seen from far away a cow exhibit O(3) (spherical) symmetry, which is broken at short distances." R. Rattazzi

Discovery of P-violation



Discovery of CP violation

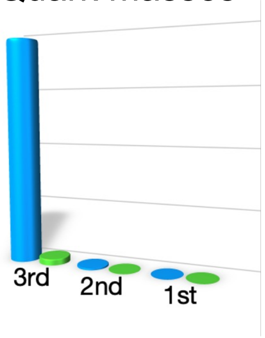


The Flavour Puzzle

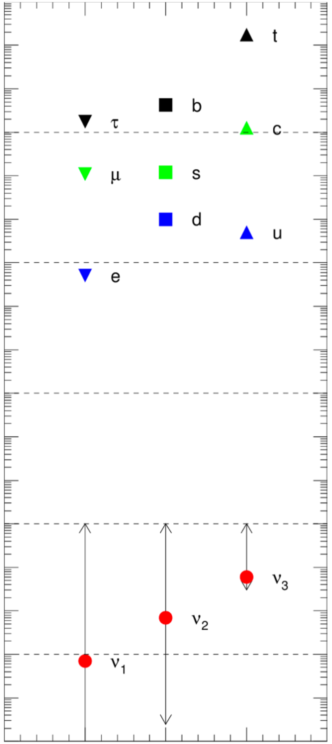
$$\mathcal{L} = (\mathcal{L}_{gauge} + \mathcal{L}_{Higgs})_{\dim \leq 4} + \sum_i \frac{\alpha_i}{(\Lambda_{NP})^n} \mathcal{O}^i_{\dim\, 4+n}$$

Flavour symmetric — Flavour not symmetric

Quark masses



- Is the UV completion of the SM "flavour symmetric"? Yukawa coupling suggest maybe not!
- Possible that NP has stronger coupling to the 3rd generation → It could alleviate the hierarchy problem (e.g. Isidori et al. 2022)



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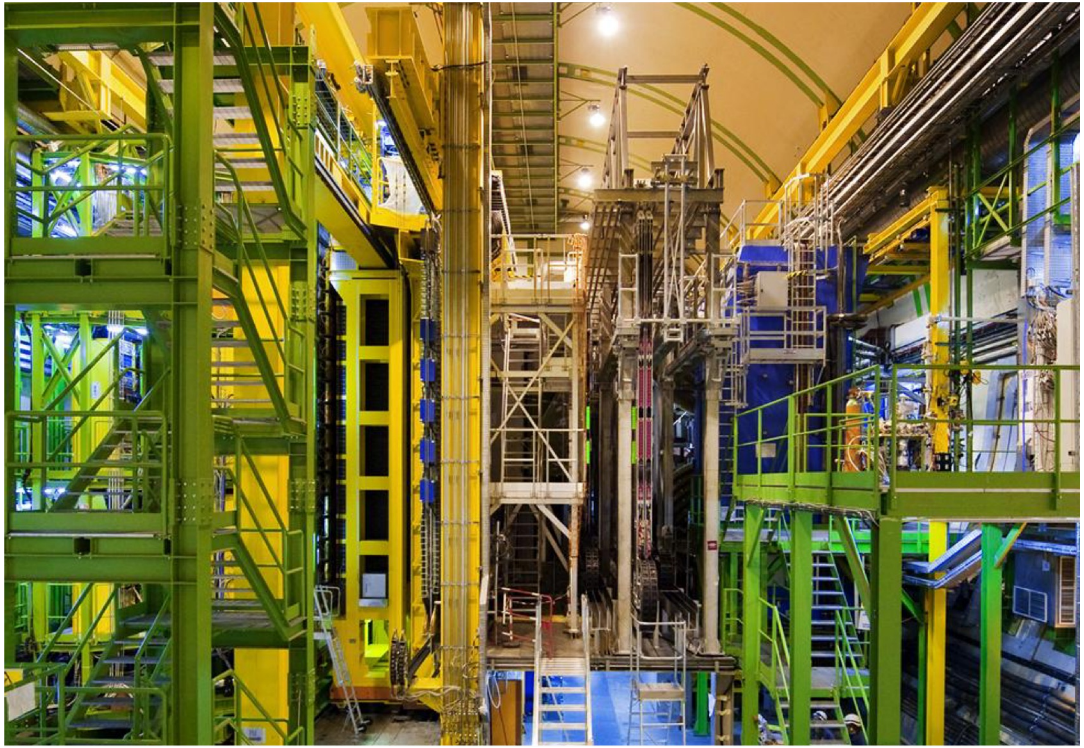
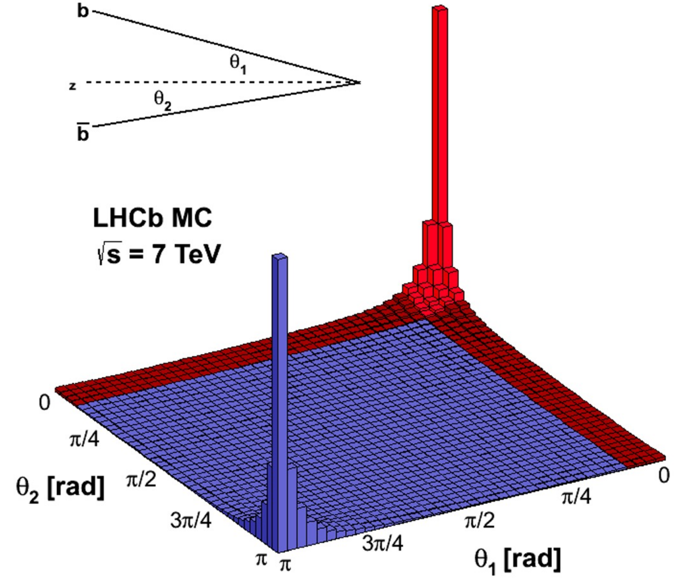
The LHCb Detector





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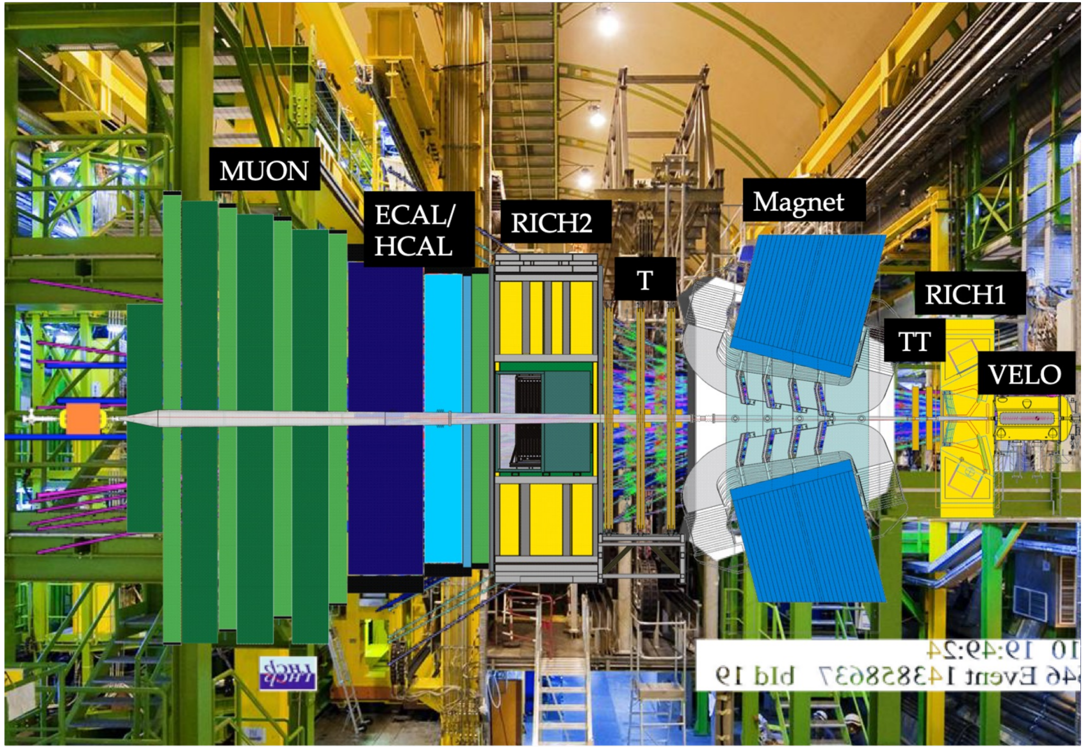
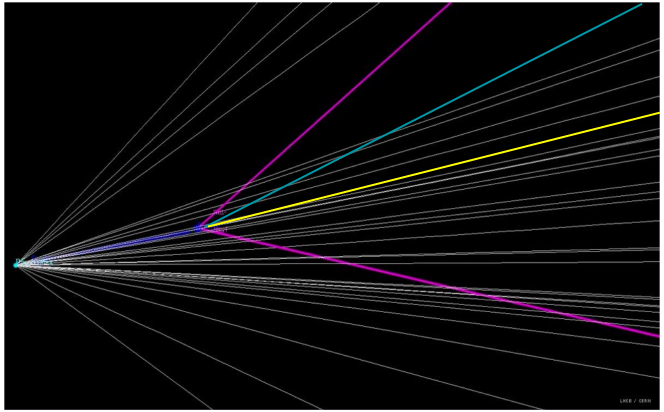


B→K*μμ Event Display



- Excellent vertex resolution
  $\sigma_{IP} = (15+29/p_t)\mu m$
- Excellent momentum resolution
  ($\delta p/p \sim 0.5\text{-}1.0$ %)
- Very good particle identification
  ($\pi \to \mu \sim 0.5\%$, good K/π/p separation)

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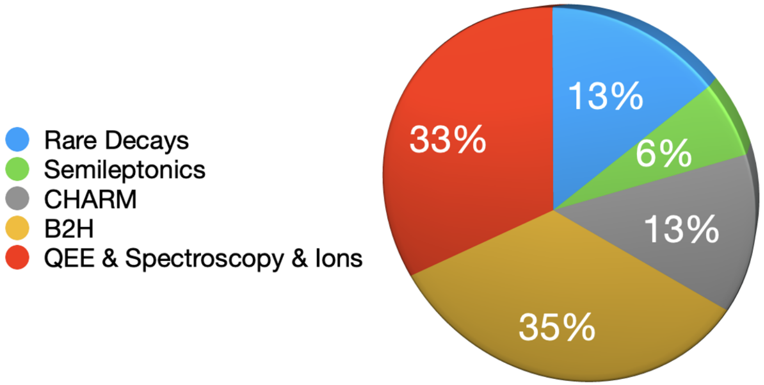
LHCb Physics

- LHCb designed and optimized to measure beauty
- World leading in “core physics case” (e.g. rare decays, CP violation, etc..)
- Also world leading far from the “core physics case” (e.g. fixed target, electroweak, spectroscopy, heavy ions, dark sector)



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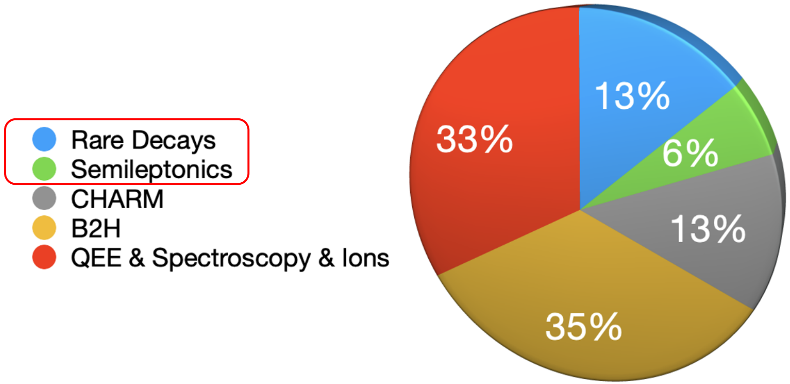
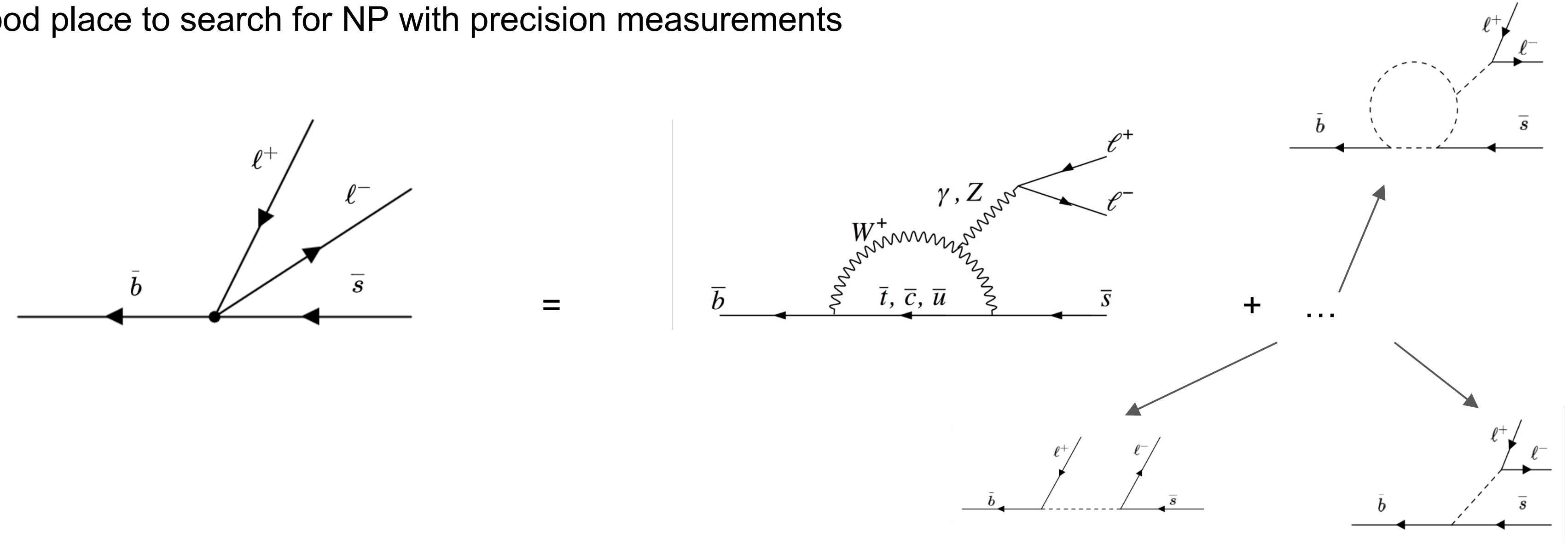


- My group involved in many analyses in several working groups
- Recently, we have focused more on rare decays and semileptonics

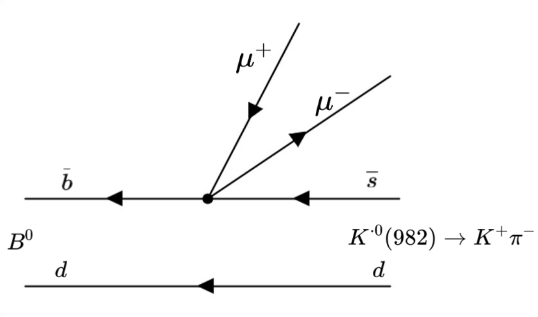
Flavour Changing Neutral Currents and Rare Decays

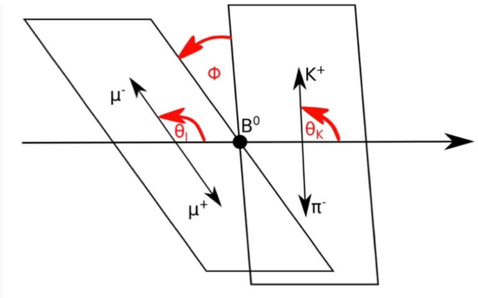
- Structure of the SM suppress FCNC (GIM Mechanism)
- Good place to search for NP with precision measurements



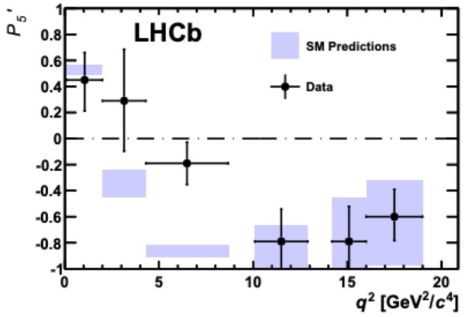
The B→K*μμ decay

Measurement of angular observables in the decays B→K*μμ exhibit discrepancies wrt SM predictions

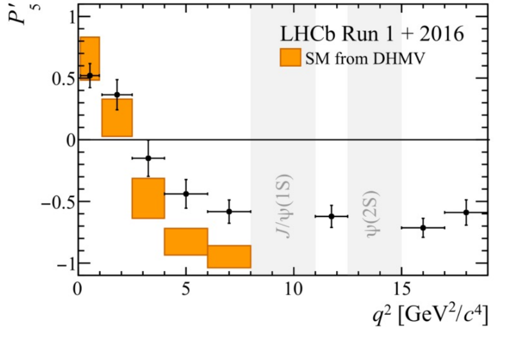




Phys.Rev.Lett. 111 (2013) 191801



Phys.Rev.Lett. 125 (2020) 1, 011802

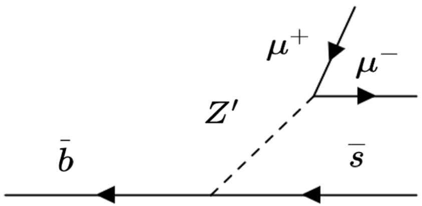


$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell - F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi + \sqrt{F_L(1-F_L)}P'_5\sin2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi + S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$

The charm loop problem

P_5' results points to a destructive interference with something unexpected:

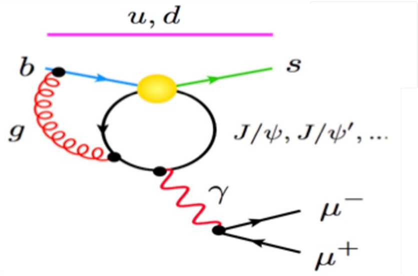
- NP hypothesis include Z' or LQ
- A SM ccbar-loop contribution much larger than predicted

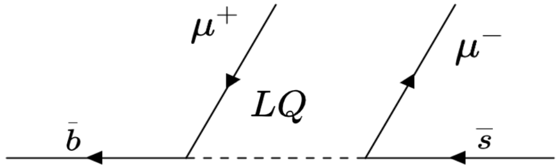


Matias et al. 2013
Haisch et al. 2013
Buras et al. 2013

Ciuchini et al., JHEP 06 (2016) 116

Lyon, Zwicky arXiv:1406.0566



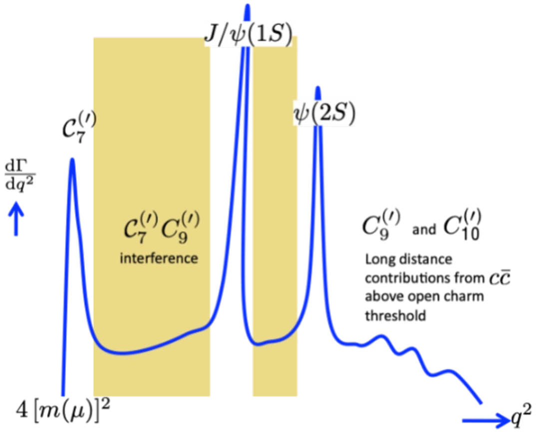


LQ solution became popular in the context of a global interpretation of the anomalies (especially with RD(*)): Greljo et al. 2015, Bauer et al. 2015, Barbieri et al. 2016… and many others

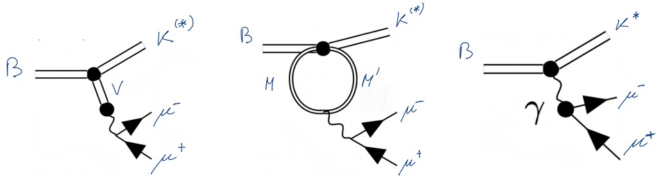
Can we disentangle these two hypotheses?

The charm loop problem - attempts to understand

Hybrid theory data-driven approaches to attempt understanding P_5'

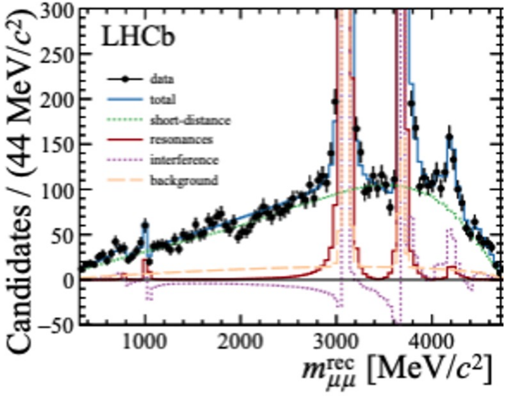


[1.1, 9.0] & [10.0, 13.0] GeV2



M. Chrzaszcz al., JHEP 10 (2019) 236
Van Dyk et al. arXiv:2206.03797

$B^+ \to K^+\mu\mu$

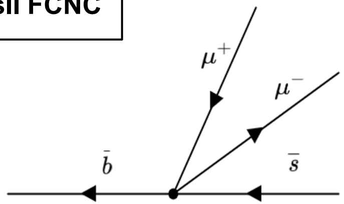


Eur.Phys.J.C 77 (2017) 3, 161

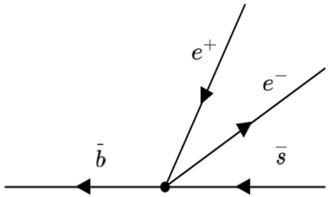
Testing Lepton Flavour Universality

- LFU accidental symmetry of the SM (robust theory prediction)
- Expect LFUV in NP, but level depends on Λ_{NP}

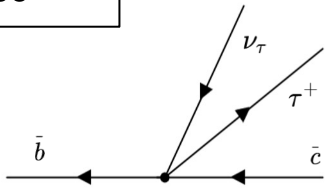
LFU tests in b→sll FCNC



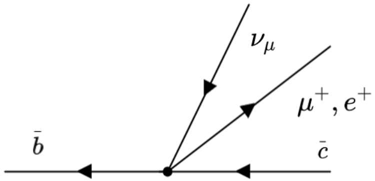
$\mathbf{R(K^{(*)})=}$



LFU tests in b→clν CC



$\mathbf{R(D^{(*)})=}$



The LHCb Experiment

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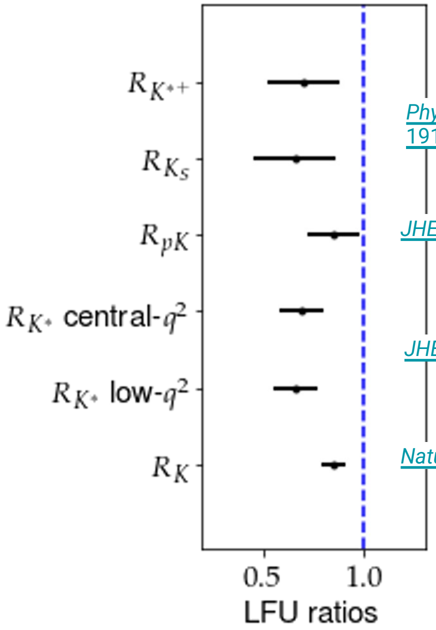
Lepton Flavour Universality Tests

- LFU Ratios of b→sμμ/b→see transitions measured to be below 1.0 (SM prediction)
- Challenging measurements at LHCb → Need more measurements and systematic checks

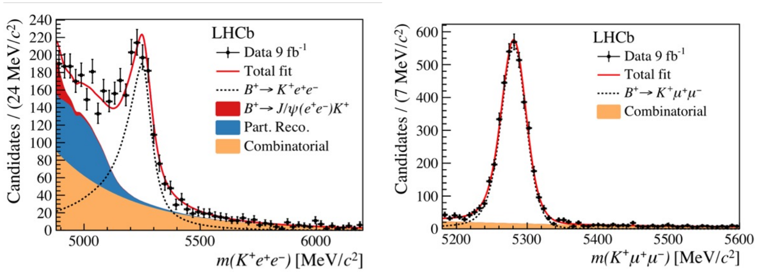


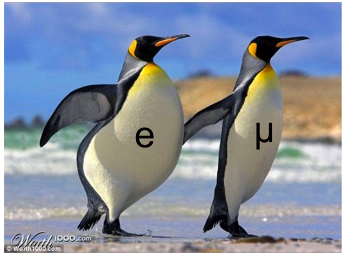
Phys.Rev.Lett. 128 (2022) 19, 191802

JHEP 05 (2020) 040

JHEP 08 (2017) 055

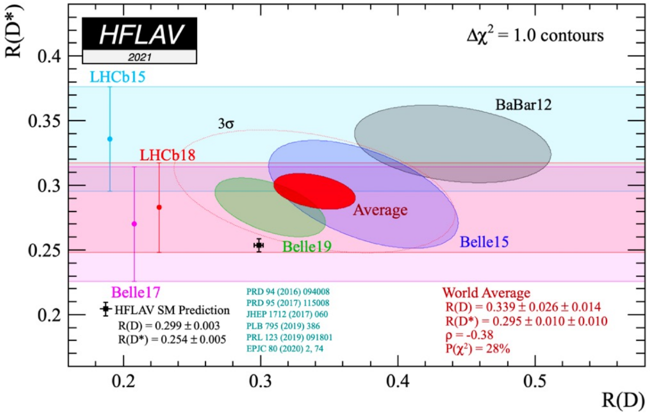
Nature Phys. 18 (2022) 3, 277-282

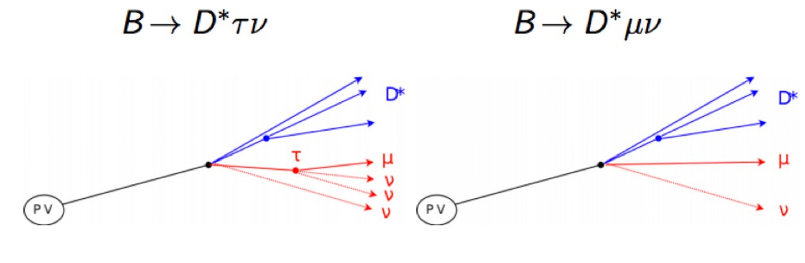




Lepton Flavour Universality Tests

Global tension wrt SM predictions at the level of 3.4σ in semileptonic decays





$$R(D^*)_{\tau\to\mu 2\nu} = 0.336 \pm 0.027 \pm 0.030$$

Phys.Rev.Lett.115,111803 (2015)

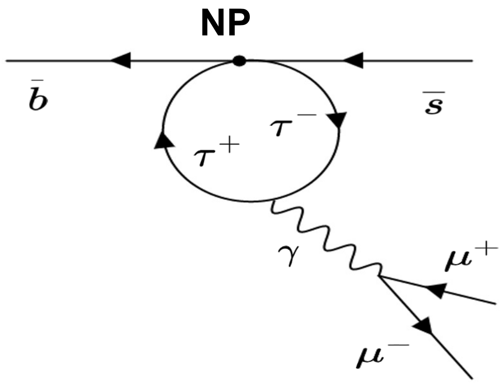
$$R(D^*)_{\tau\to 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

Phys.Rev.Lett.120,171802 (2018)

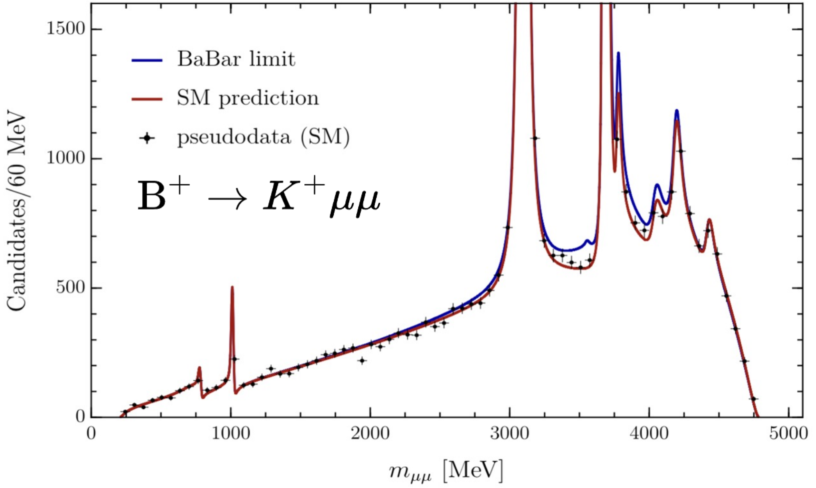
More measurements from LHCb coming soon!

Searching for b→sττ in $B^+ \to K^+ \mu\mu$ spectrum

- R($D^{(*)}$) → NP in b→cτν →SU(2)→NP in b→sττ
- NP in b→sττ would feedback into b→sμμ decays
- Effect of the same size as P_5' (Crivellin et al., Phys.Rev.Lett. 122 (2019) 1, 011805)



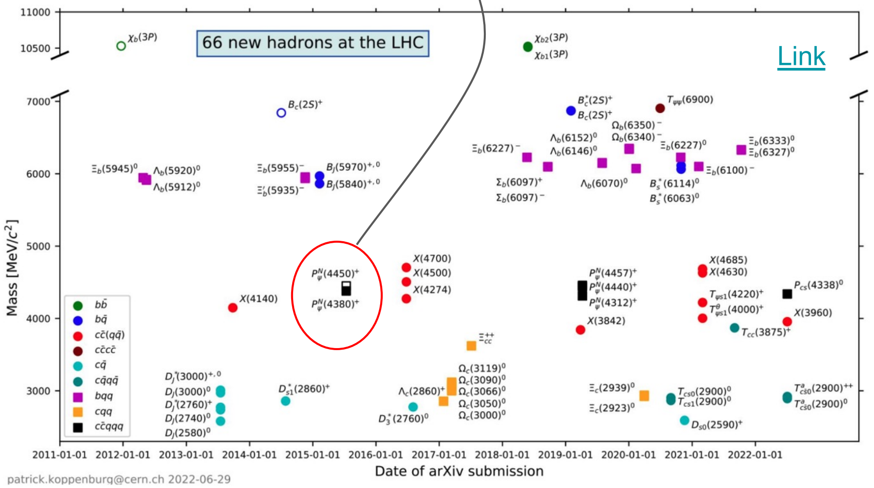
Cornella et al., Eur.Phys.J.C 80 (2020) 12,



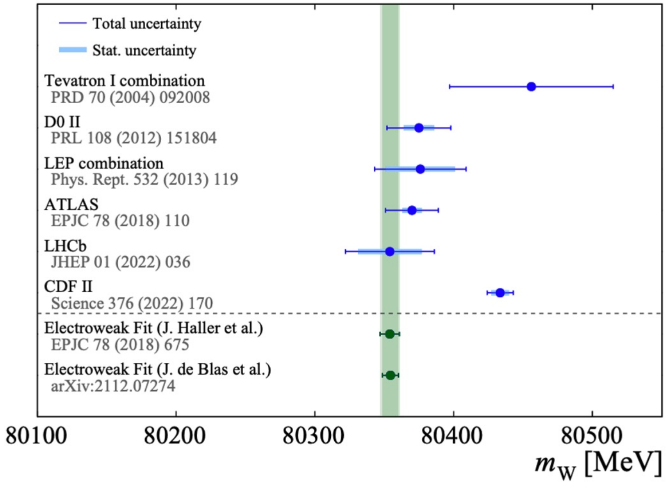
The LHCb Experiment

A general purpose detector in the forward region

LHCb discovered 59 of the 66 new hadrons, including pentaquarks ([Phys. Rev. Lett. **115**, 072001](#))!



Competitive measurement of W mass



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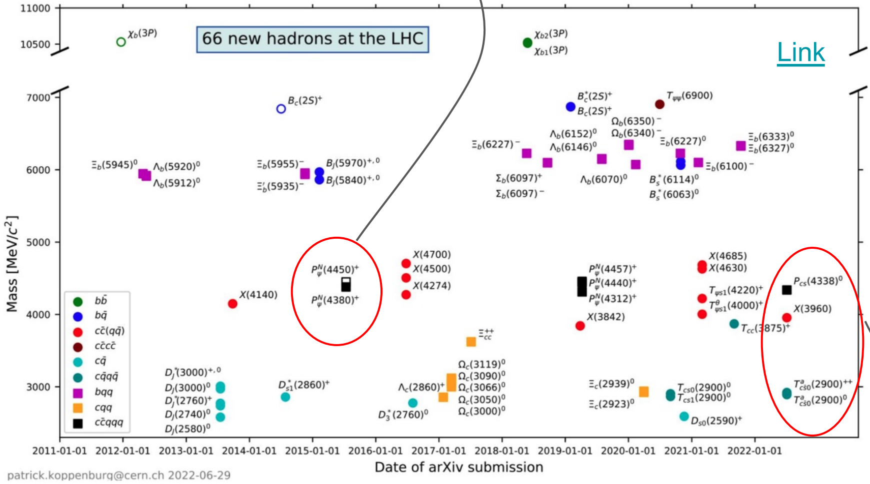
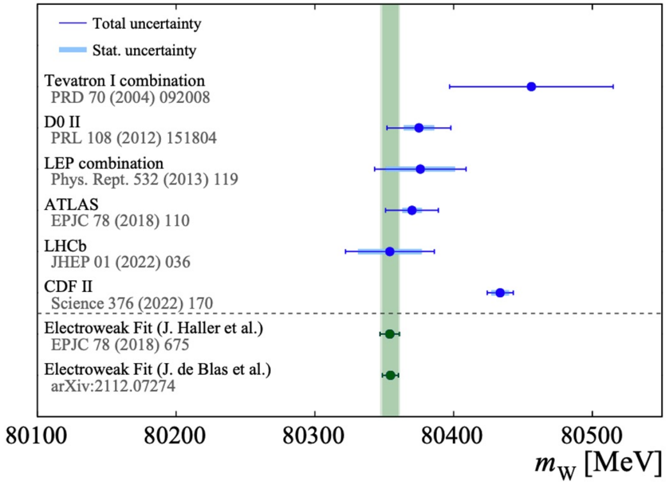


New Tetraquarks and Pentaquark observation (CERN Seminar 5th July)

Competitive measurement of W mass



The LHCb Experiment

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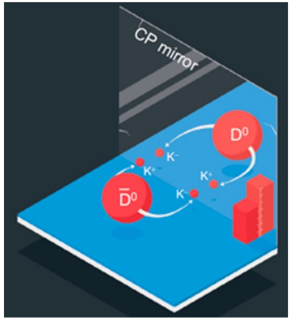
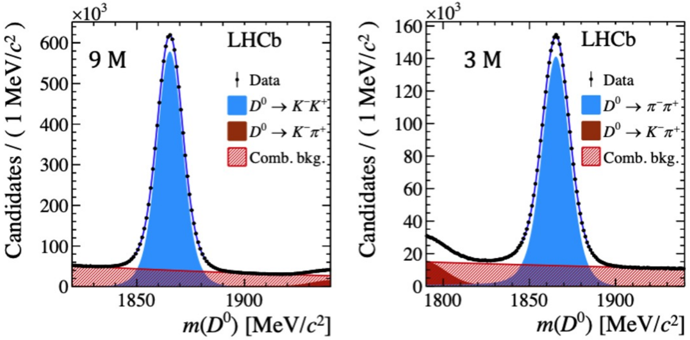
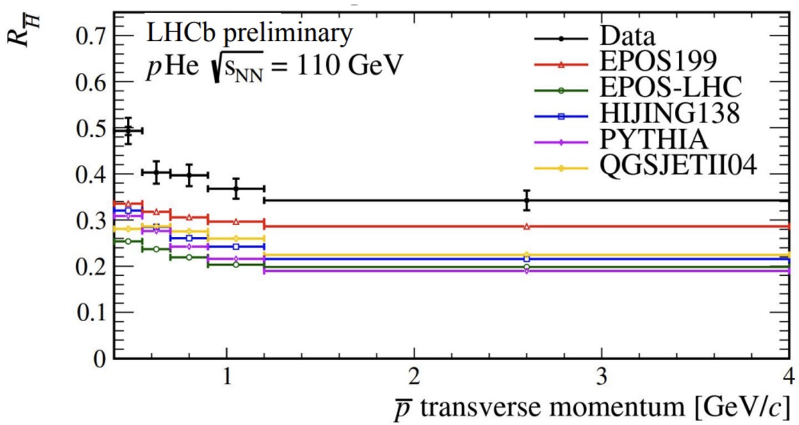
A general purpose detector in the forward region

Discovery of CP violation in charm





Antiproton production in pHe collisions input for PAMELA and AMS experiments



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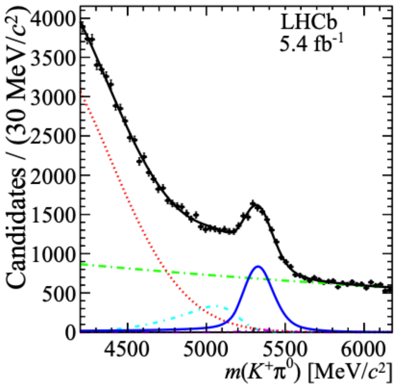
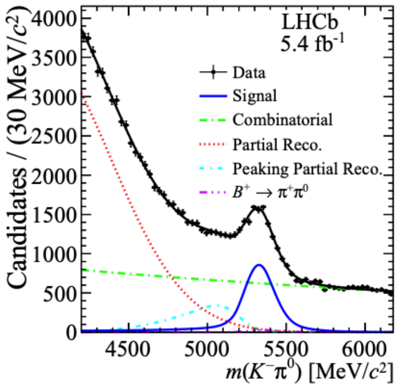
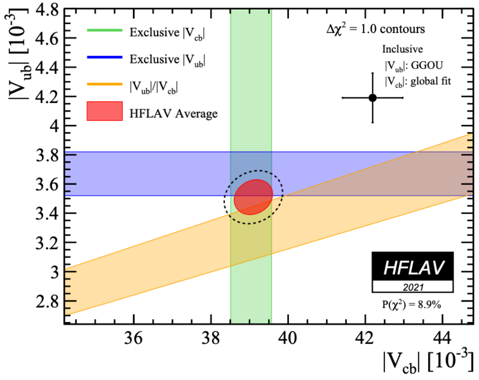
A general purpose detector in the forward region

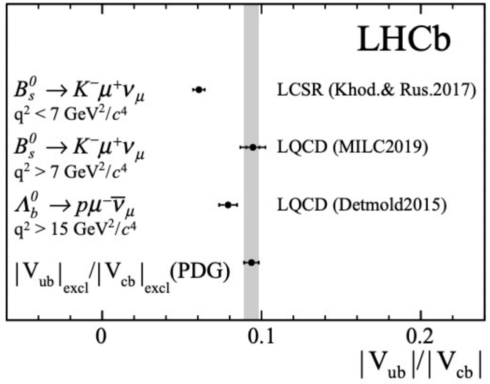
Kπ puzzle





V_{ub} puzzle





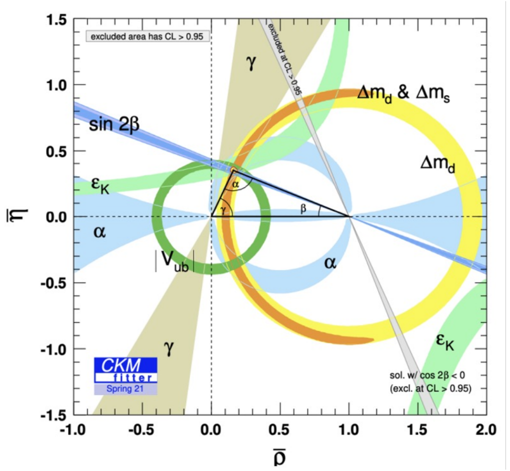
LHCb contributing to areas which previously were thought impossible at hadron colliders!

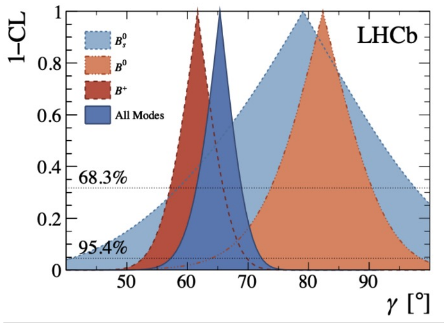
The LHCb Experiment

Universität Zürich[UZH]

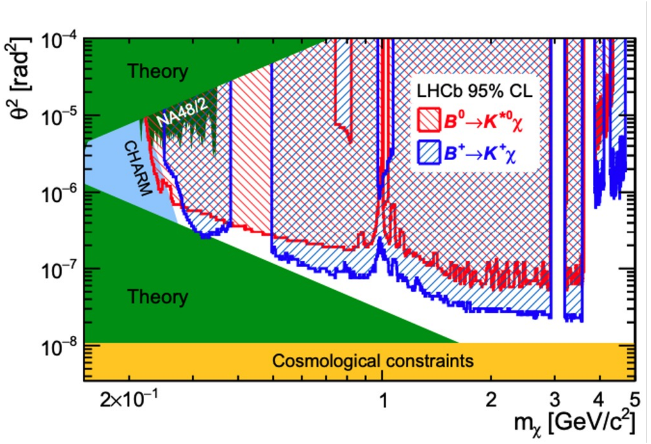
A general purpose detector in the forward region

LHCb strong contribution in measuring the CKM, e.g. gamma





Strong potential to search for hidden sector

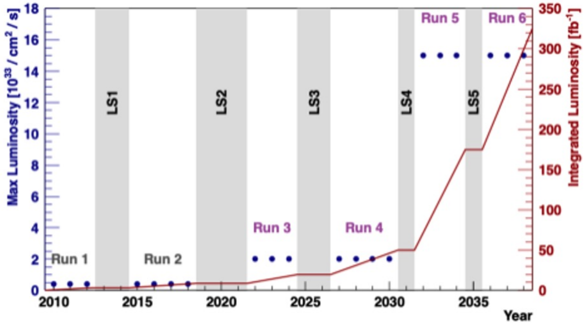


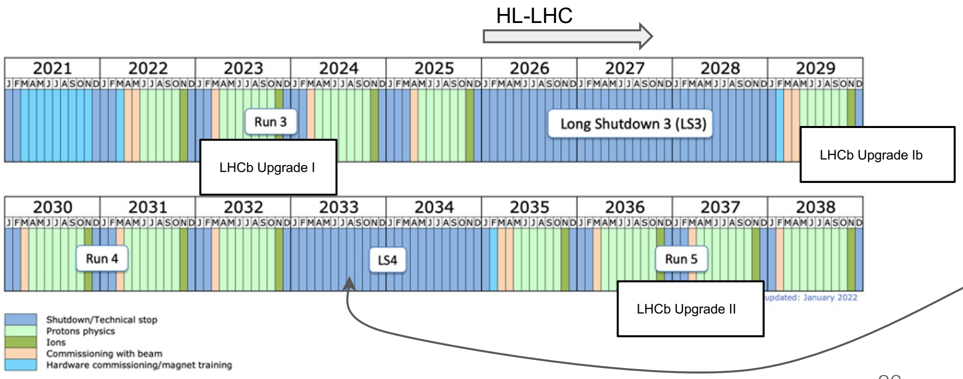
… and much much more in LHCb more than 600 publications!

LHCb Upgrades

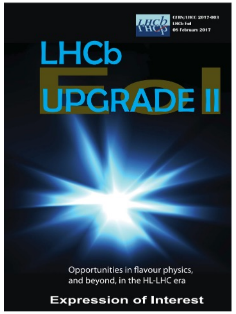
The LHCb Upgrade I & II

- LHCb Upgrade starts this year, almost an independent experiment

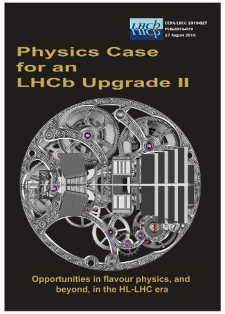




LS4 extended to accommodate LHCb Upgrade II installation



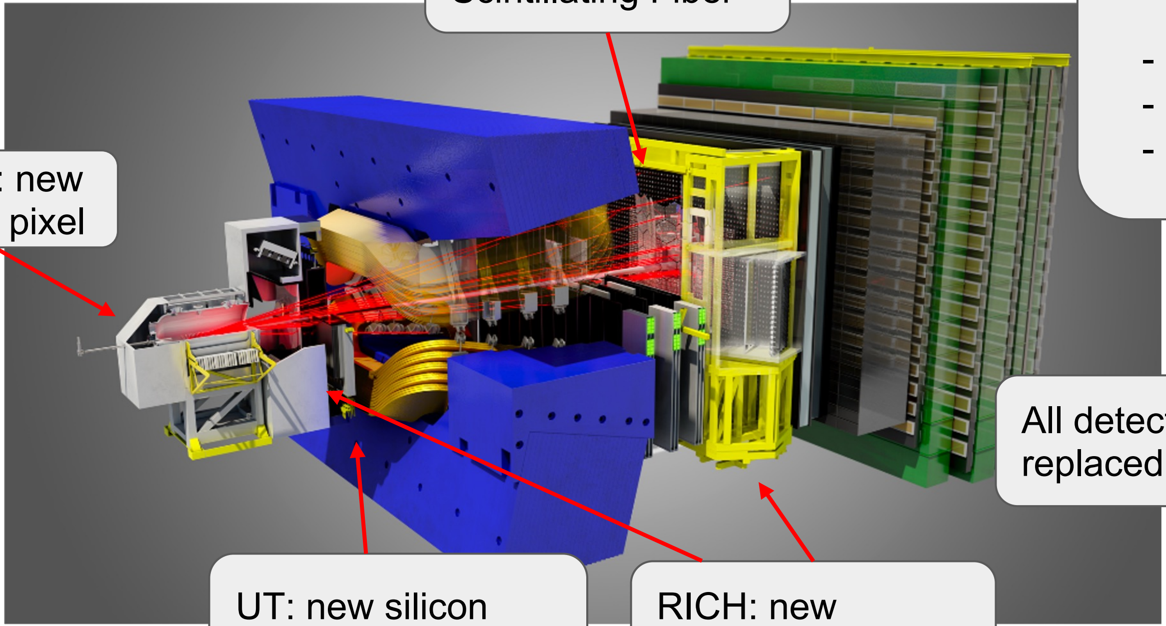
Eol LHCb Upgrade II



arXiv:1808.08865

Framework TDR

The LHCb Upgrade I



Brand New Detector (almost independent experiment):

- 40MHz readout
- Fully software trigger
- Instantaneous luminosity $2x10^{33}$ $cm^{-2}s^{-1}$

All detectors: replaced electronics

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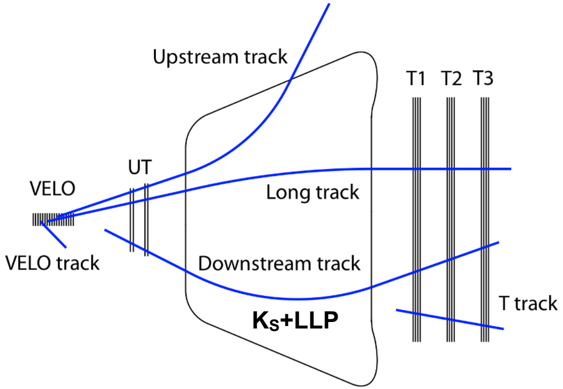
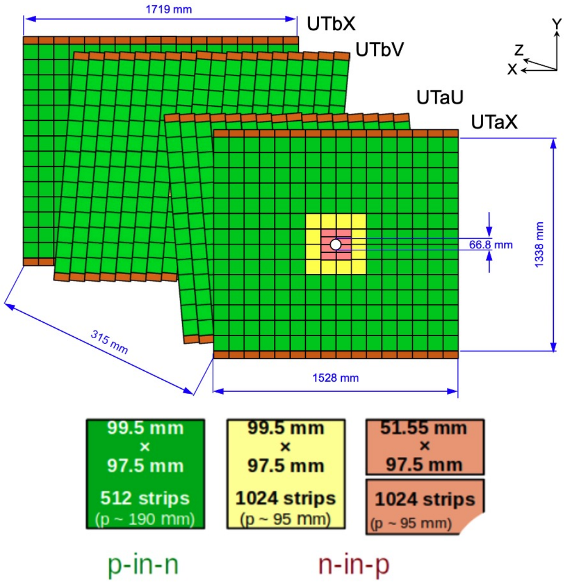
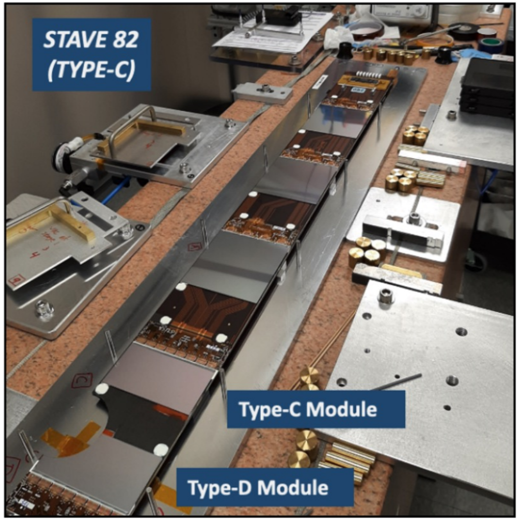
The LHCb Upgrade I - The Upstream Tracker (UT)





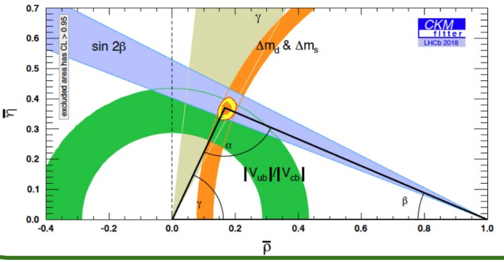


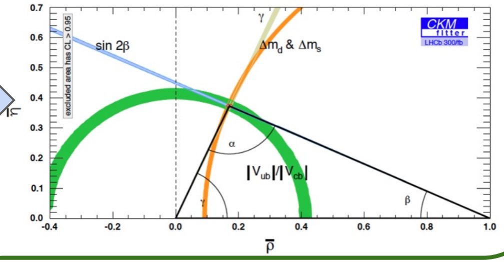
- UT key detector for trigger for online track reconstruction
- Silicon microstrip detector with finer granularity and larger acceptance than the TT
- Four detector layers ($2m^2$), light-tight, thermally isolated box
- Custom-developed readout chip (40 MHz)

LHCb Upgrades

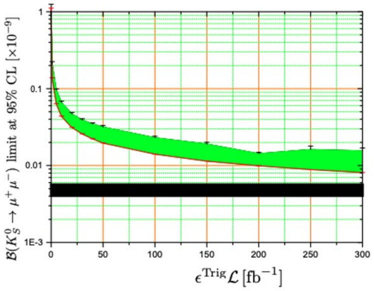
The LHCb Upgrade II - Physics Case

Strong improvement of Unitarity Triangle constraint

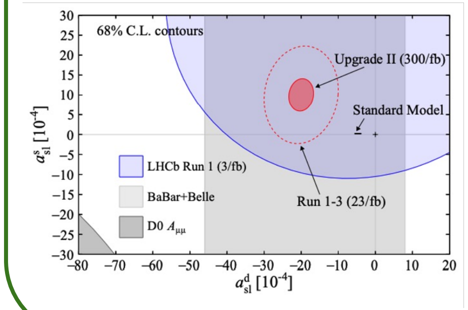




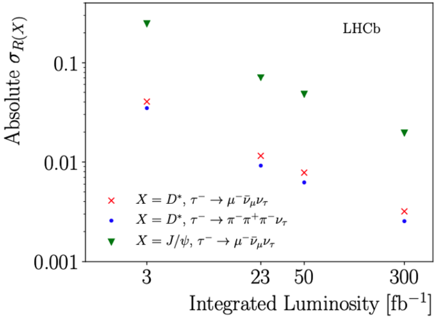
Kaon Physics



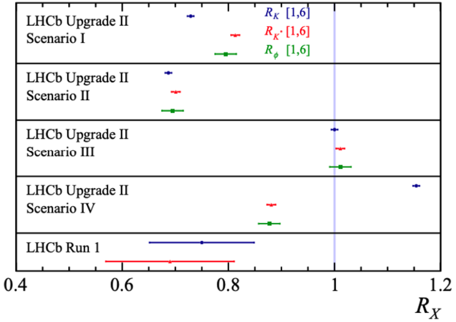
CPV with Semileptonics



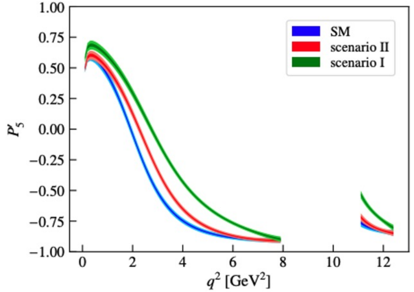
LFU tests in b→clv



LFU tests in rare decays



b→sμμ measurements



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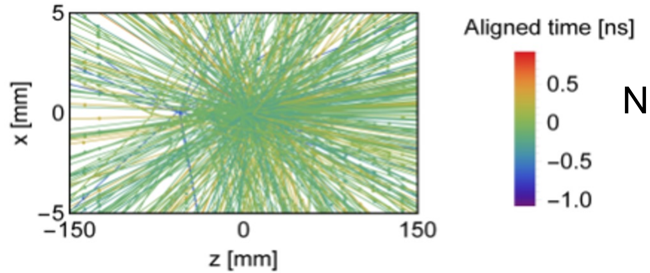
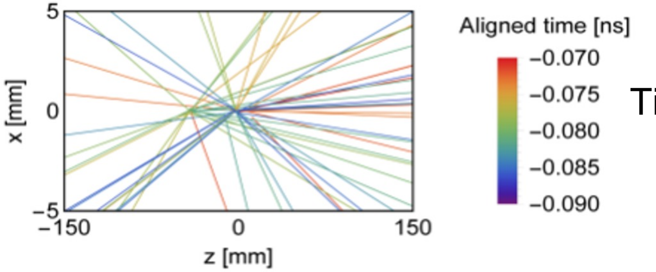
The LHCb Upgrade II

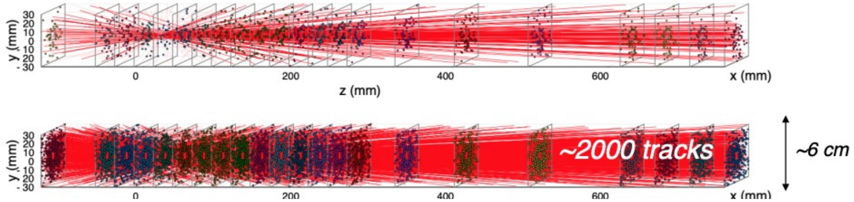
- Pileup: 6→ 42 interactions per bunch crossing
- High Granularity
- 4D tracking (few tens of ps)
- Extreme fluences ($6x10^{16}$ n_{eq}/cm^2)

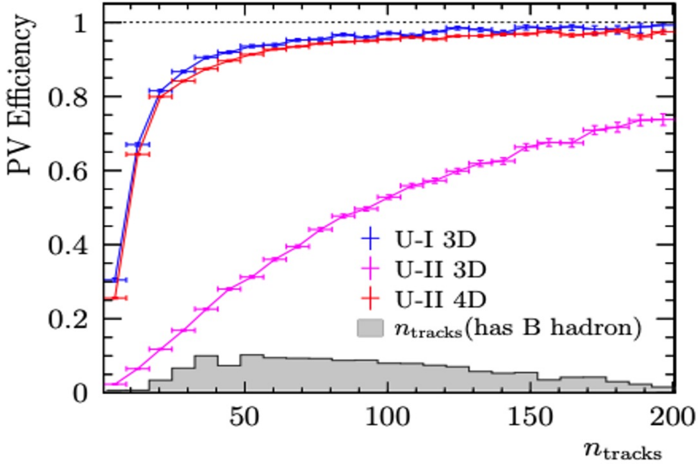


No timing



Timing (50ps)





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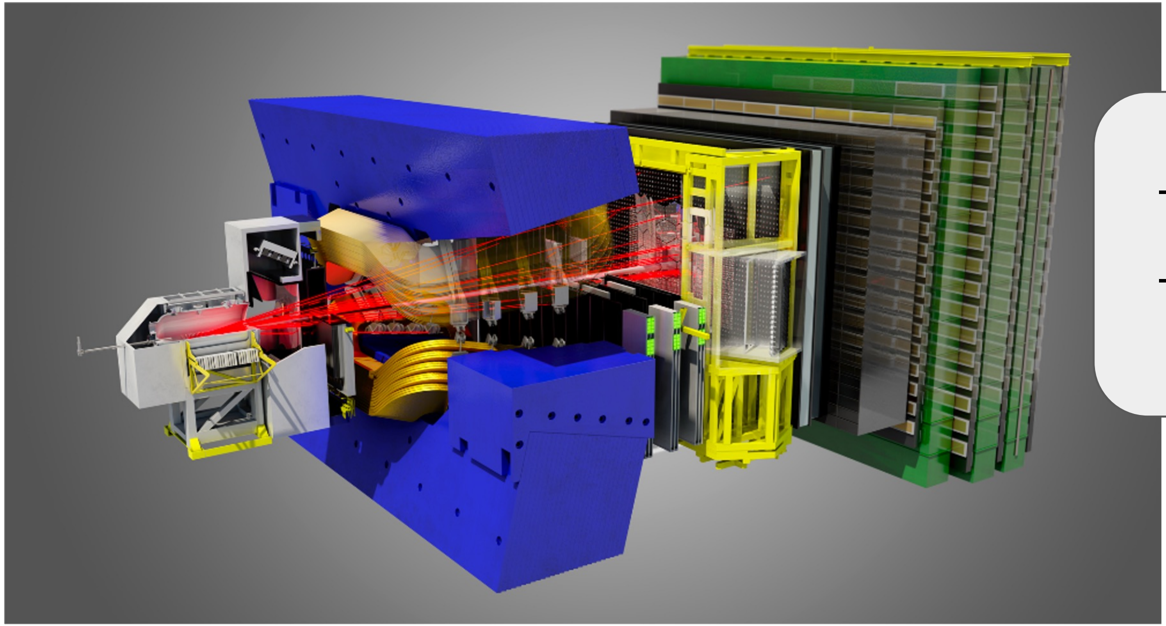
The LHCb Upgrade II



- Instantaneous luminosity up to 1.5 x10^{34} $cm^{-2}s^{-1}$
- Require excellent spatial resolution and timing

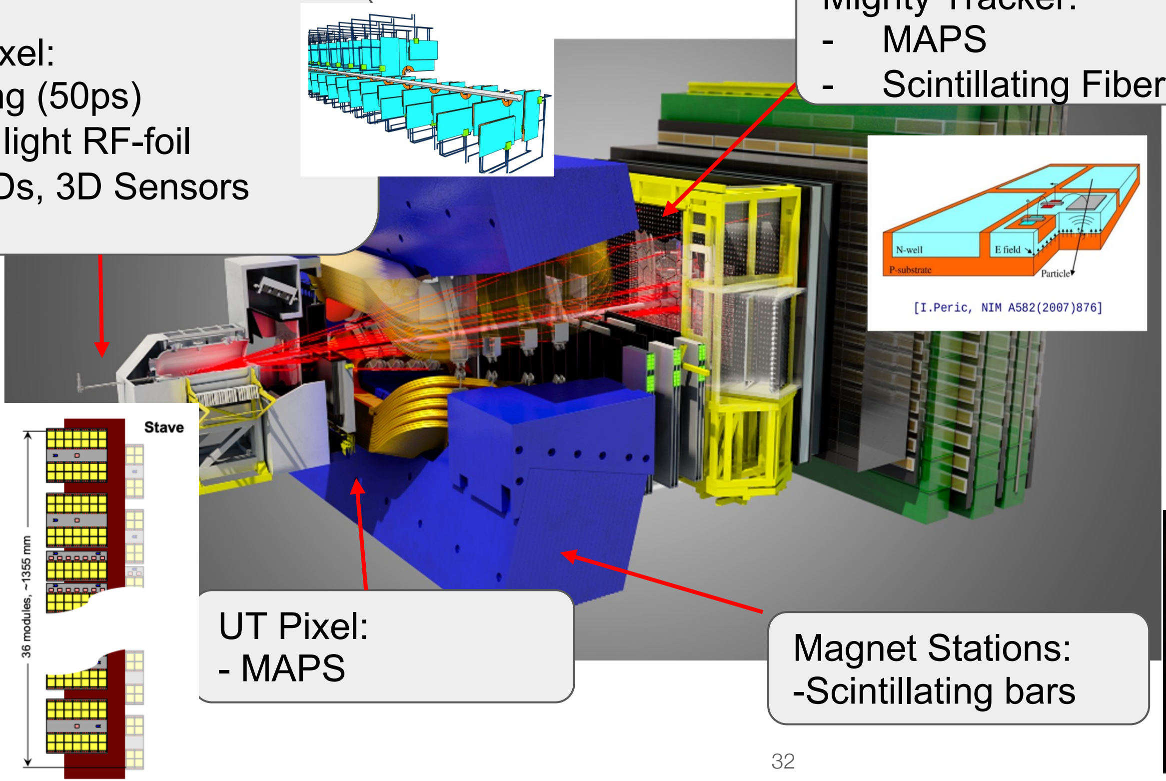
LHCb Upgrades

Universität Zürich[UZH]

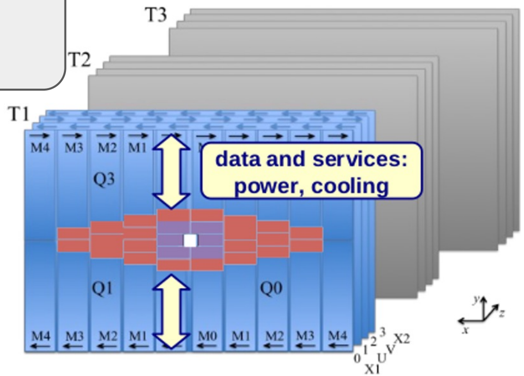
The LHCb Upgrade II

VELO Pixel:
- Timing (50ps)
- Ultra light RF-foil
- LGADs, 3D Sensors

Mighty Tracker:
- MAPS
- Scintillating Fibers



[I.Peric, NIM A582(2007)876]



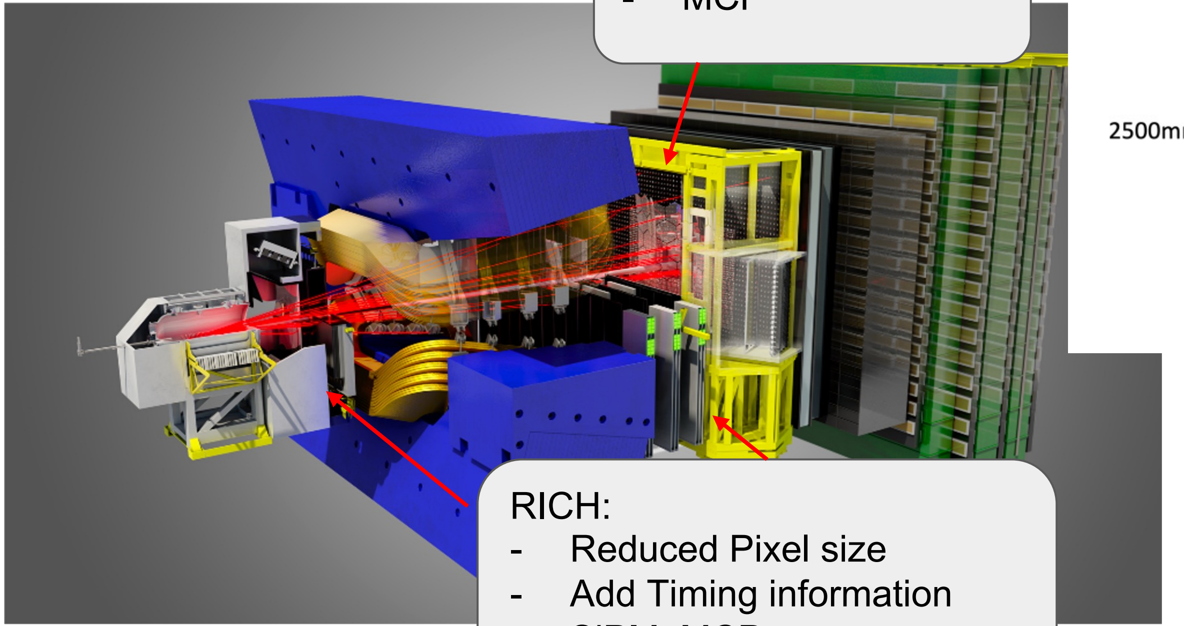
UT Pixel:
- MAPS

Magnet Stations:
-Scintillating bars

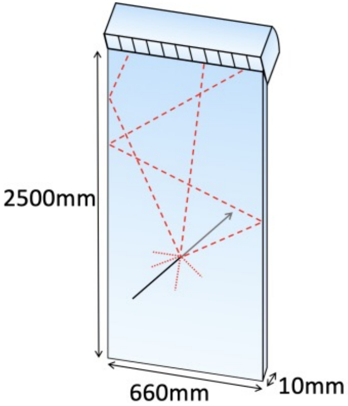
LHCb Upgrades

The LHCb Upgrade II

TORCH:
- TOF – quartz
- MCP



RICH:
- Reduced Pixel size
- Add Timing information
- SiPM, MCP



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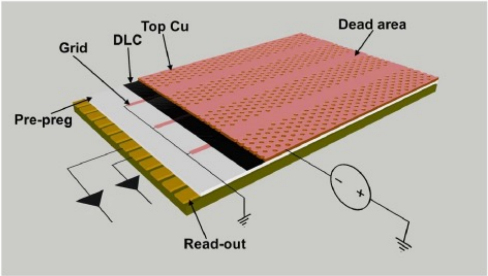
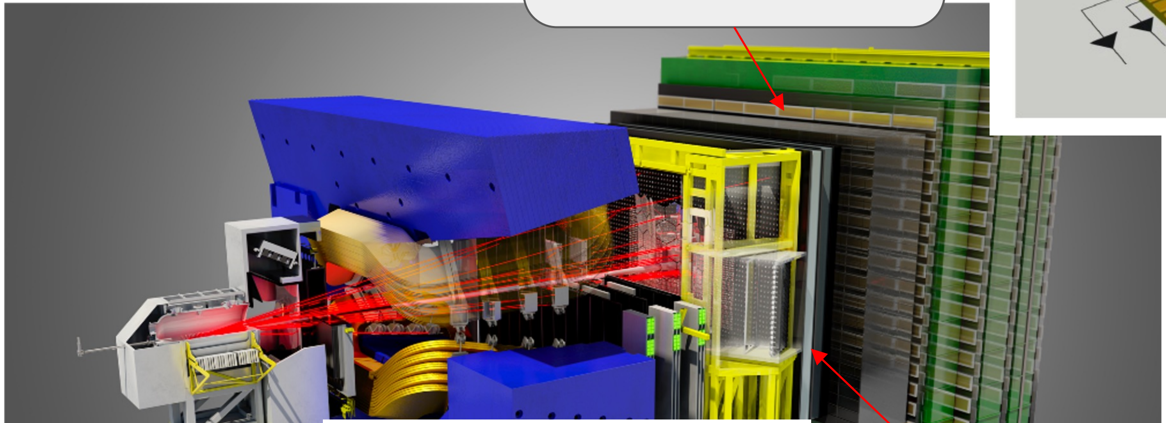
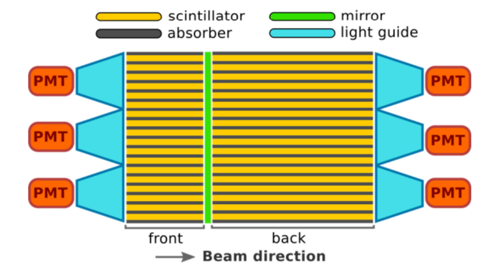
The LHCb Upgrade II

Muon:
- µRWELL (inner)
- MWPC (outer)







ECAL:
- SpaCal
- Shashlik

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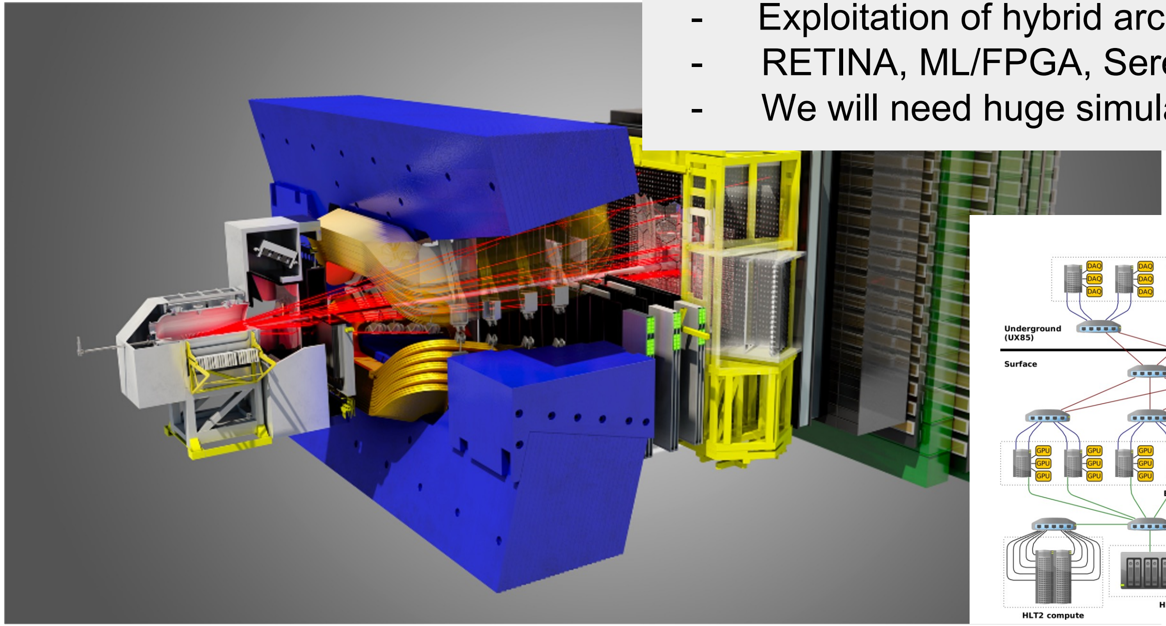
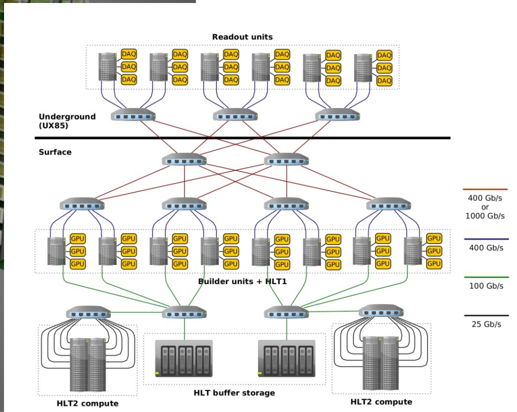
The LHCb Upgrade II

- Fully software trigger (as in Upgrade I)
- Exploitation of hybrid architectures (CPU, GPU, FPGA)
- RETINA, ML/FPGA, Serenity, IPUs
- We will need huge simulation samples





Take home messages

- Strong motivations to improve constraints on Flavour Physics

- The anomalies could be the first glimpse of NP at the TeV
  - One of the largest BR of b-decays ($b \to c\tau\nu$) can accommodate 15% well motivated NP
  - Wealth of theory work in both phenomenology and model building

- LHCb Upgrades will allow unique precision in flavour physics observables, but strong program also in spectroscopy, ion physics, dark sector etc…

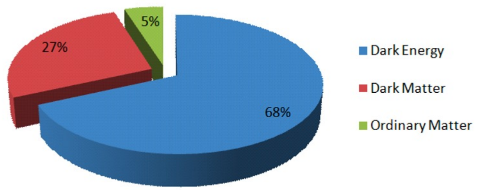
- Great opportunities for challenging hardware and computing projects in LS4:
  - Lots of R&D needed (e.g. tracking, online reconstruction)
  - Major R&D and technical challenges

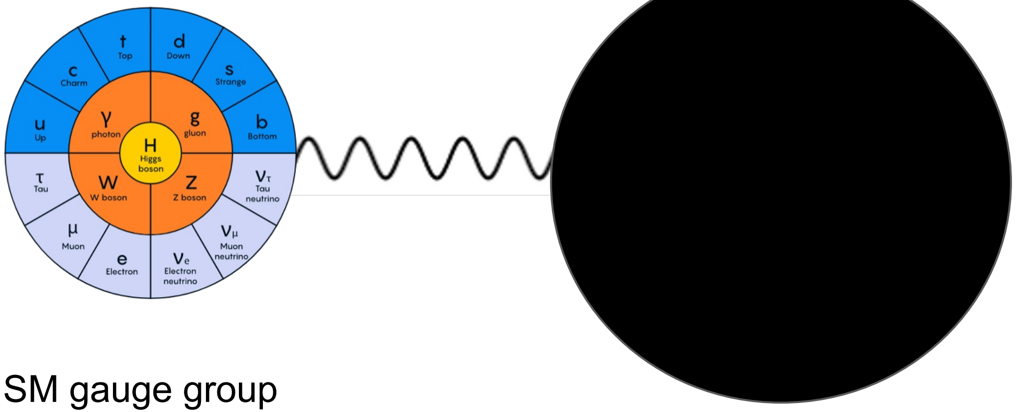
The SHiP Experiment

Universität Zürich[UZH]

Dark Sector Physics Case

$$\mathcal{L} = \mathcal{L}(\mathcal{A}_{SM}, \psi_{SM}, \mathcal{H}_{SM})_{\dim\leq 4} + \sum_i \frac{\alpha_i}{(\Lambda_{\mathcal{NP}})^n} \mathcal{O}^i_{\dim\, 4+n} + \mathcal{L}(A_{SM}, \psi_{SM}, H_{SM}, A_{DS}, \psi_{DS}, H_{DS}) + \mathcal{L}(A_{DS}, \psi_{DS}, H_{DS})$$



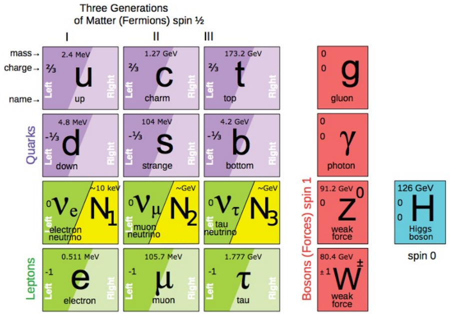


- New light hidden particles singlets under SM gauge group
- Mediator composite operator of SM and Dark Sector
- Lowest dimension SM operator makes up the portal to the Dark Sector:
  - Neutrino portal, Higgs portal, Vector Portal, Axion Portal, …

The SHiP Experiment

Universität Zürich[UZH]

Dark Sector Physics Case



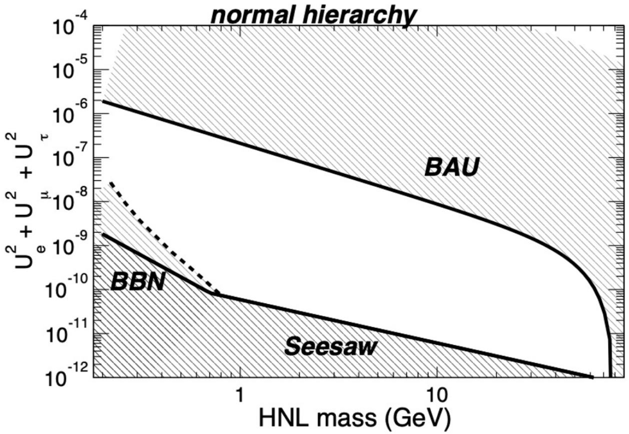
[Shaposhnikov et al. 2005 (and references therein)]

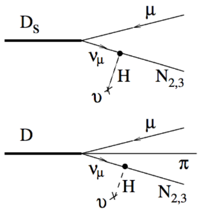
Possibility to solve SM "problems" below the EW scale (radical consequences):

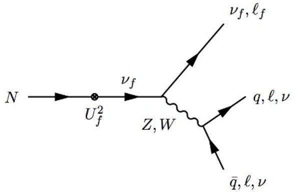
- N_1 (KeV) could be Dark Matter
- N_2,N_3 (GeV) responsible for matter-antimatter asymmetry and neutrino oscillations, partially explain smallness of neutrino masses

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.},$$

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$





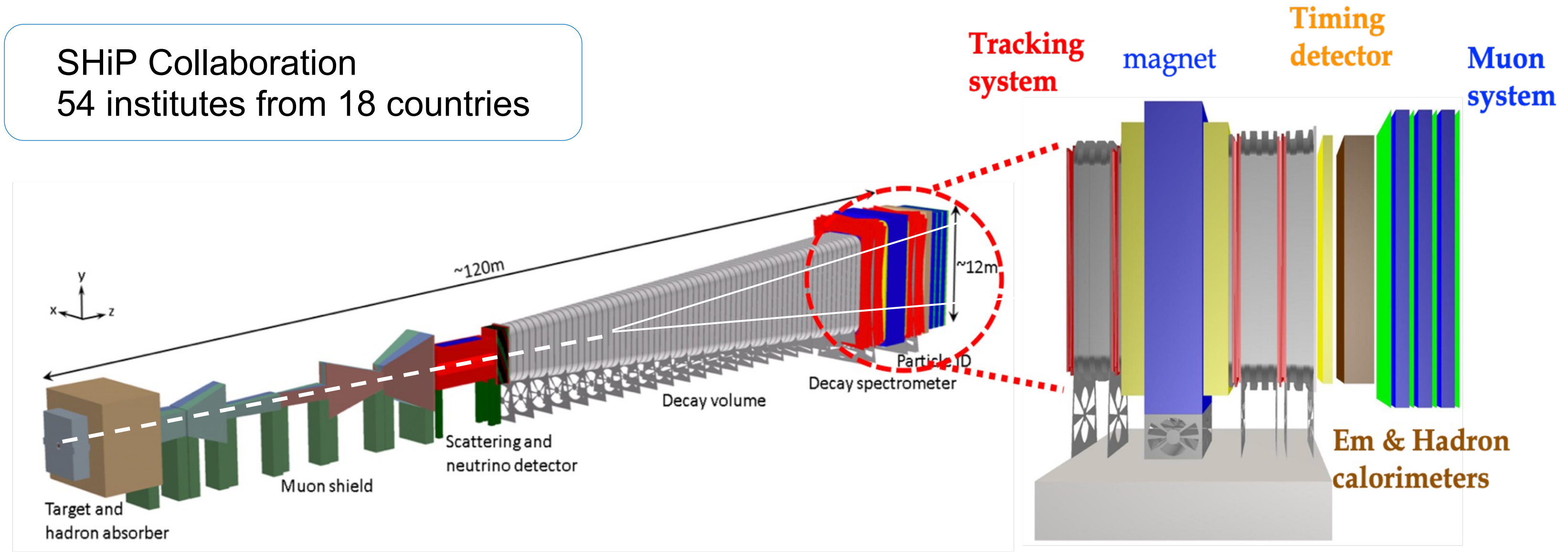


The SHiP Experiment

Universität Zürich[UZH]

General purpose experiment to search for Dark Sector

SHiP Collaboration
54 institutes from 18 countries

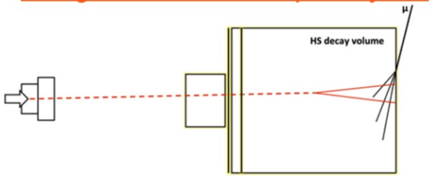


- Heavy target + hadron absorber + muon shield
- Fiducial volume with veto detectors
- Close as possible to the target to maximize accpetance

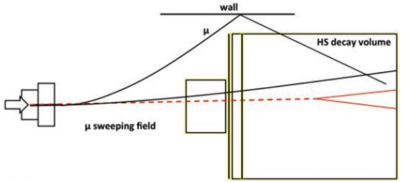
The SHiP Experiment

Backgrounds

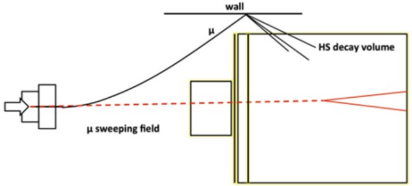
Backgrounds in 2×10^{20} pots/5 years:



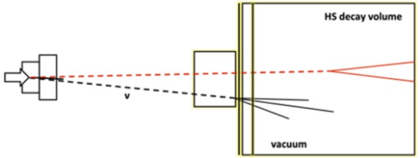
Cosmics: negligible



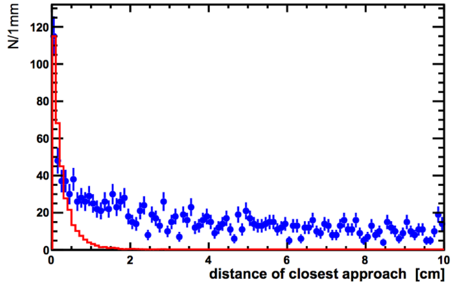
Muon combinatorial: $1.2 \times 10^{-2} \pm 1.2 \times 10^{-2}$

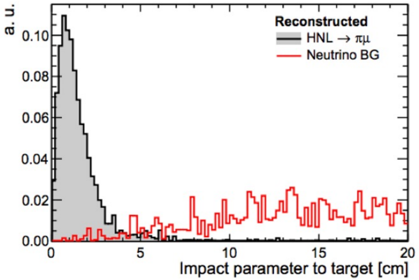


Muon DIS: 6×10^{-4}



Neutrino DIS: 0.1 (fully) / 0.3 (partial)





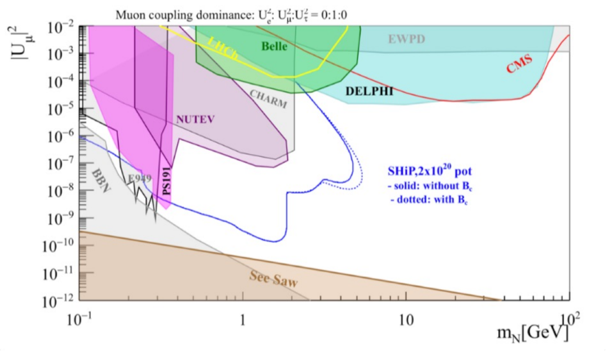
Careful design and optimization of the experiment to achieve zero background

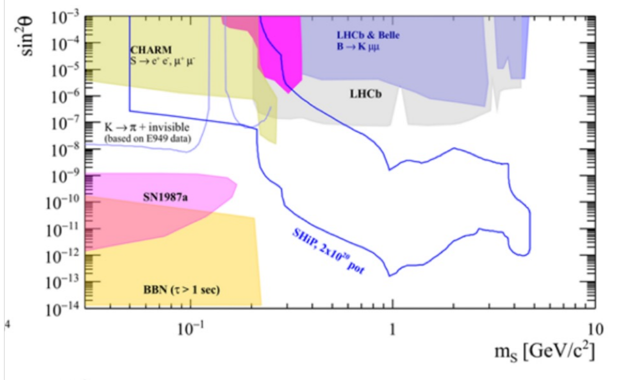
The SHiP Experiment

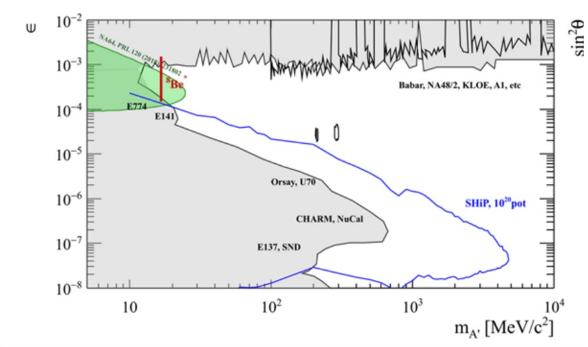
Universität Zürich[UZH]

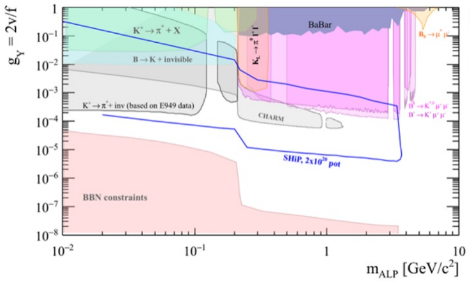
Sensitivity to Dark Sector

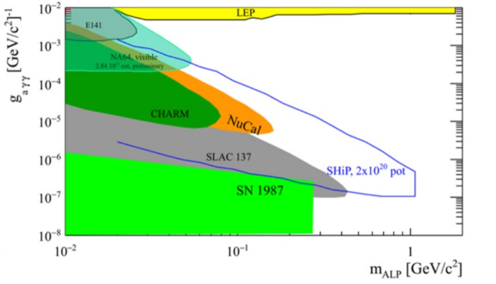
SHiP can improve current limits on Dark Sector by orders of magnitudes





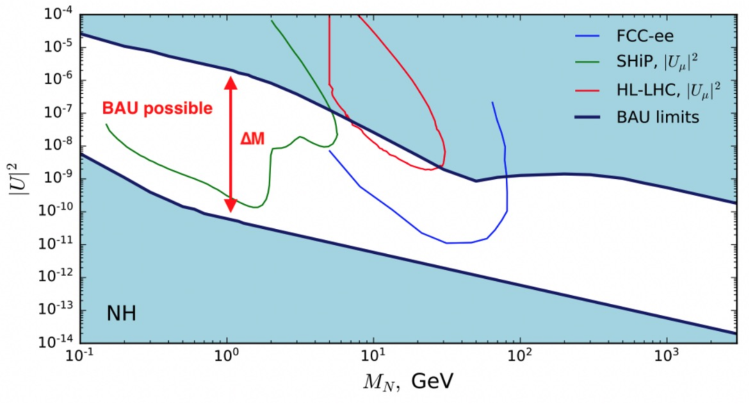






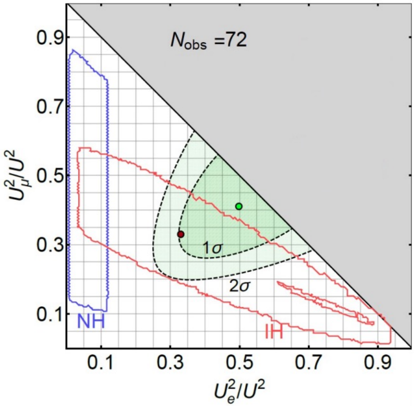
SHiP as signal exploration machine

- SHiP can discriminate different models with handful of events
  - Sensitive in the most interesting region



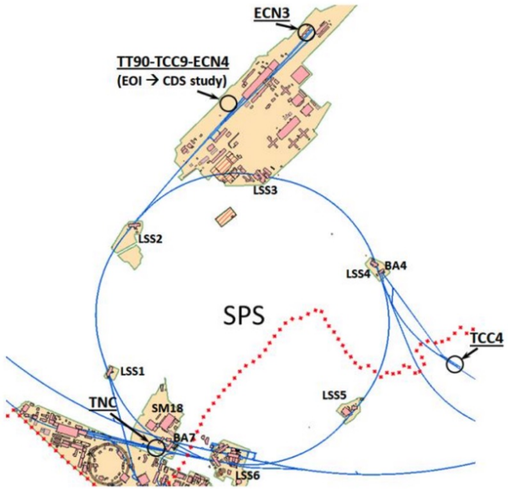
- Can probe compatibility with the BAU (100-1000) events (HNLs oscillation)

- Check if HNLs mixing pattern fits flavour oscillations



The SHiP Experiment

Status of the SHiP Experiment



- In the ESPPU 2019 the message was:
  “The physics case is great but the BDF facility is too expensive”

- We have been looking for existing locations at CERN:
  CERN-ACC-NOTE-2022-0009 ; CERN-PBC-Notes-2022-002

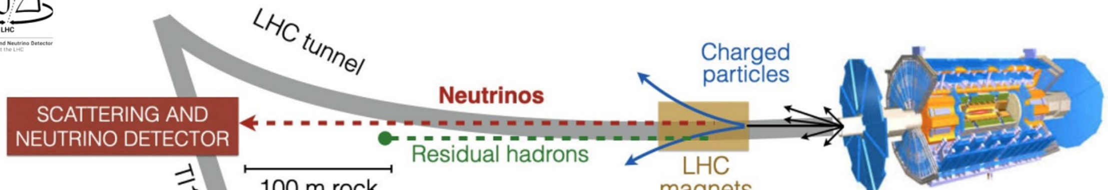
- CERN Management/PBC encouraged us to focus on ECN3:
  - Competition with HIKE
  - Decision by CERN committees and management in the first half of 2023

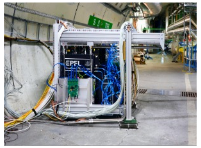
- Possibility to have a beam dump dedicated $\tau \to 3\mu$ experiment running in parasitic mode (see presentation at PBC)

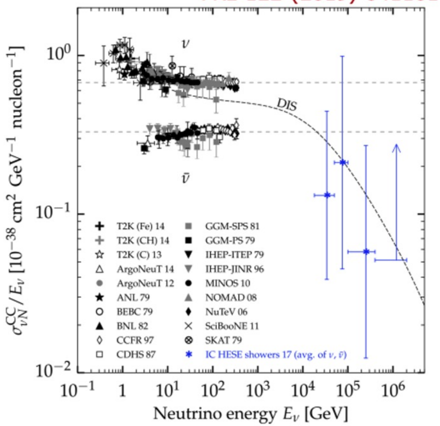
Take home messages

- Complementary possibility of new particles at low energy and small coupling
- Is the SM more fundamental than expected? → NP below the EW scale
- SHiP can to strongly constrain these models
- After SHiP several other dedicated experiments were proposed CODEXB, MATHUSLA, Shadow, … → downscope possibilities to test hidden sector

Measuring high-energy neutrinos and searching for LDM





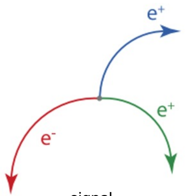


- Study production of different neutrinos flavors at TeV energies
- QCD with neutrinos: Charmed hadron yield
- ν_e/ν_τ, ν_e/ν_μ ratio for LFU test
- Search for feebly interacting particles

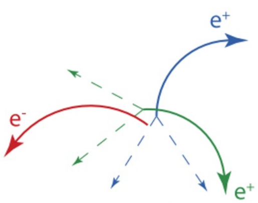
Measurement	Uncertainty Stat.	Uncertainty Sys.
$pp \to \nu_e X$ cross-section	5%	15%
Charmed hadron yield	5%	35%
ν_e/ν_τ ratio for LFU test	30%	22%
ν_e/ν_μ ratio for LFU test	10%	10%
NC/CC ratio	5%	10%

Constraining LFV

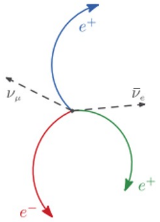
- LFV suppressed in the SM by selection rules → sensitive to high NP scale



signal



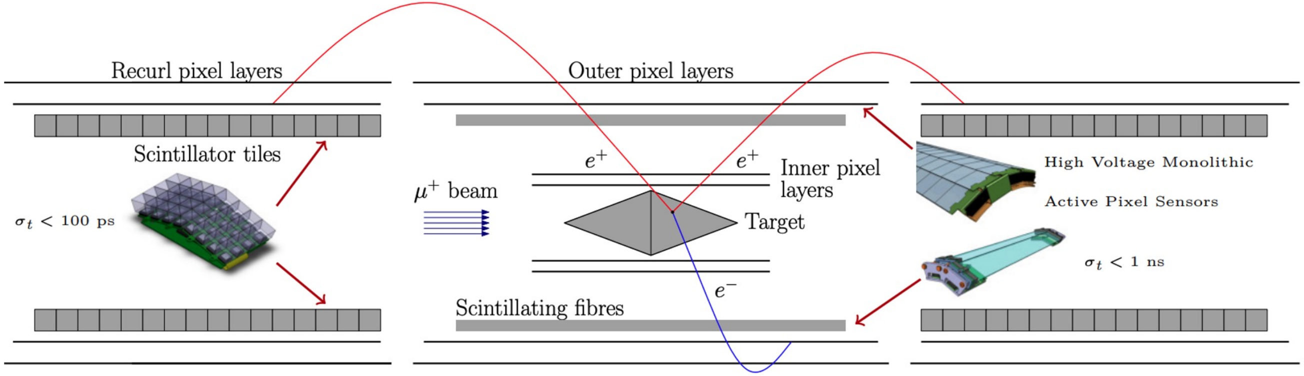
random combinations



internal conversion

$$\sum \vec{p_e} = 0$$ - Good Vertex

$$\sum E_e = m_\mu$$ - Timing



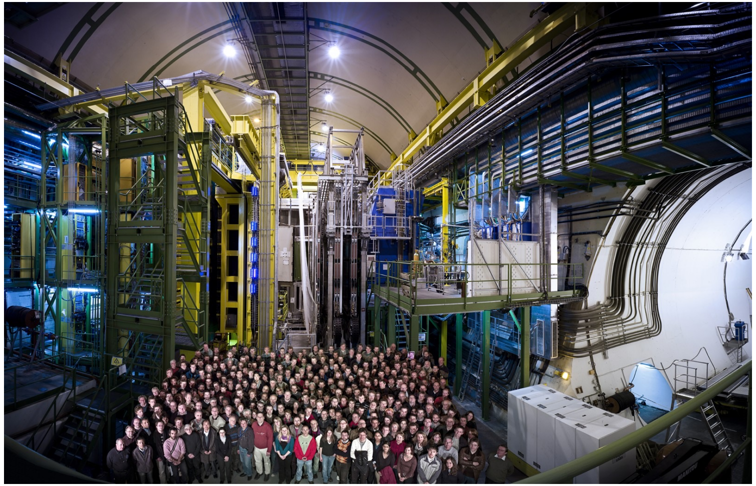
- Target stops muons
- Magnetic field 1T
- Current limit 10^{-12} SINDRUM(1988)
- Sensitivity 10^{-15} in phase I and 10^{-16} in phase II

Conclusions

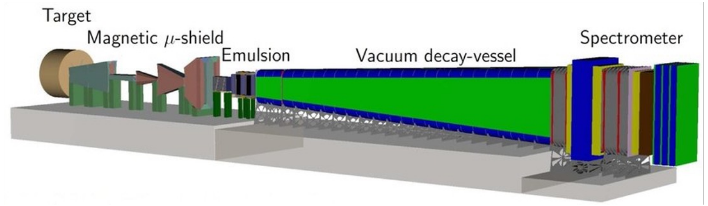
My Bayesian prior on NP

LHCb

- World's largest sample of b-hadrons
- General purpose experiment in the forward region



SHiP

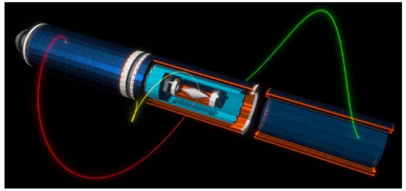


Improve Constraints On Dark Sector By Orders Of Magnitude

SND@LHC

Measure high energy neutrinos
Search for Dark Sector

Mu3e



Strongly constrain $\mu \to 3e$

Summary

- We are in a peculiar situation in HEP:
  - The SM describes well what we observe and what we do not
  - Naturalness has left us orphans
  - Maybe a revolution is coming, maybe there are some subtleties we are missing

- Strategy:
  - Test SM selection rules such as accidental symmetries and suppressed decays (such as LFU, LFV, FCNC, CPV)
  - Search for NP below the Fermi scale
  - Improve our SM knowledge

Thanks for the attention!

The door of my office in my house in Sardinia… I promised that when NP is finally discovered I will break it and replace it with the SM extension