EW physics and LLPs at LHCb

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Swiss National Science Foundation

Outline

- EW physics:
  - Introduction
  - m_W measurement
  - Measurement of Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV 

- Long-Lived Particles (LLPs):
  - Introduction
  - Dark photon searches
  - Perspectives

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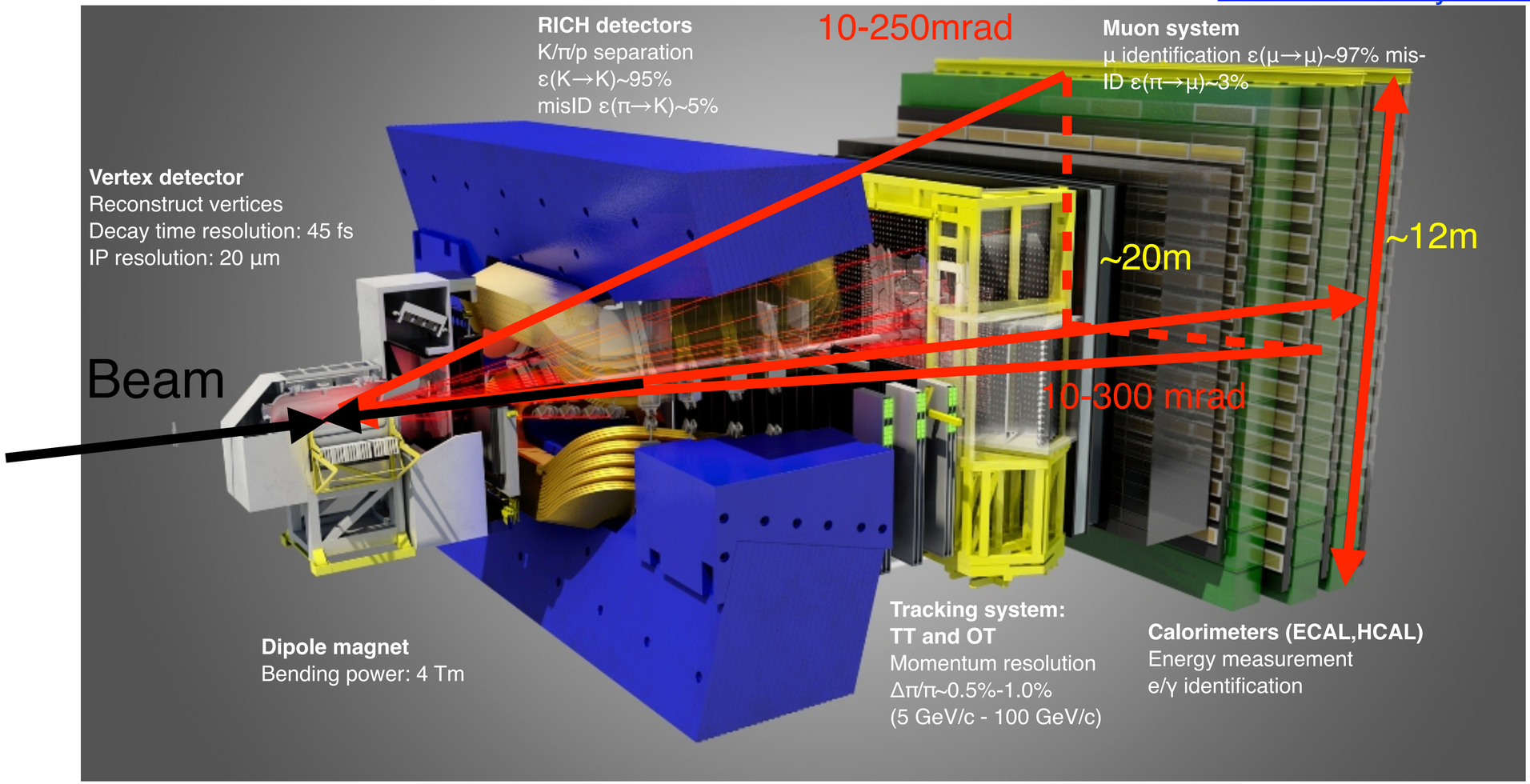
The LHCb detector

- Excellent performances of tracking and muon detector

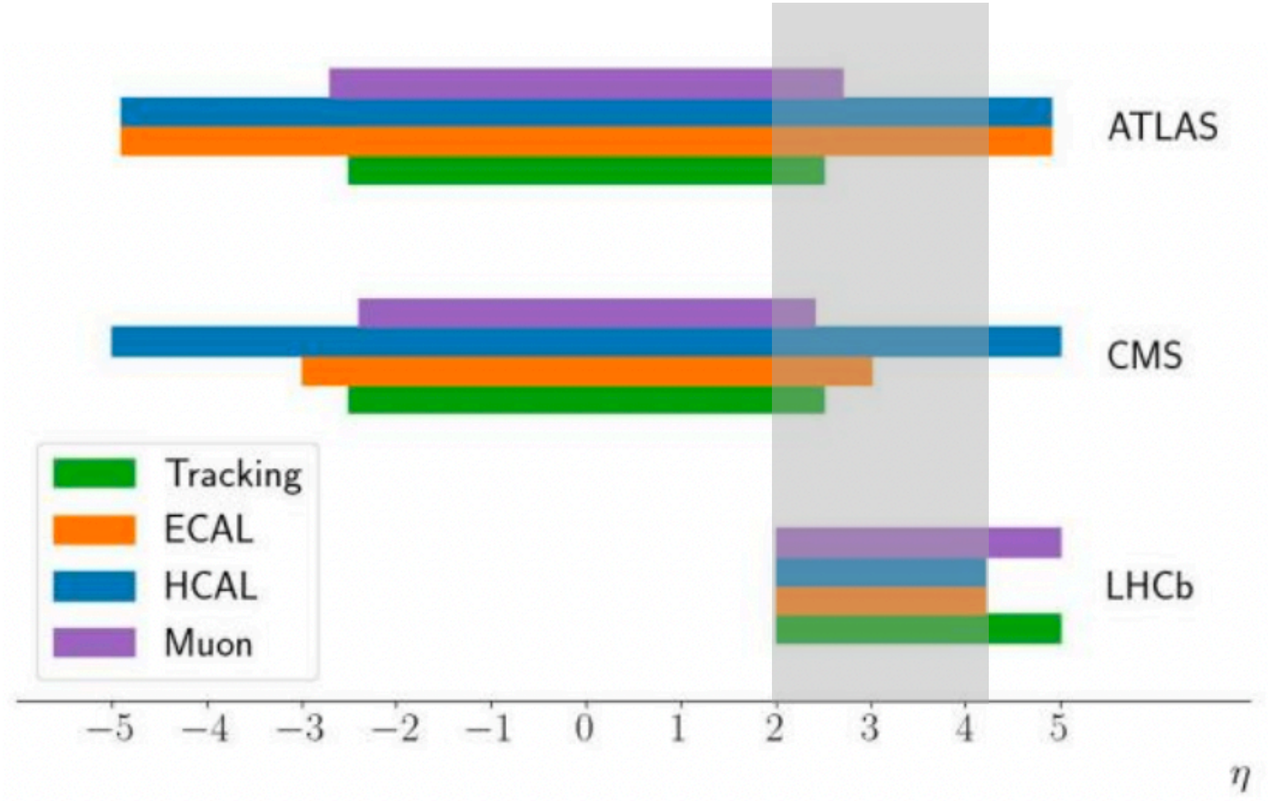
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)



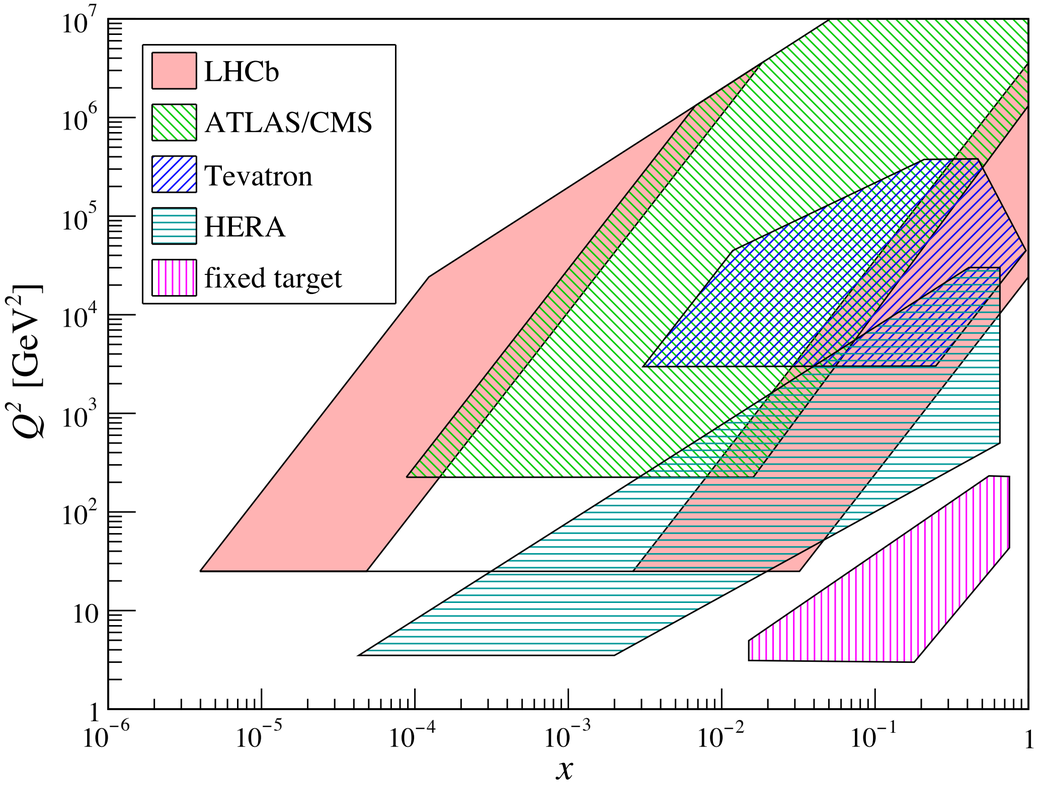
Forward acceptance —> cover complementary kinematic regions

Forward region

- Forward region: high/low-x partons involved



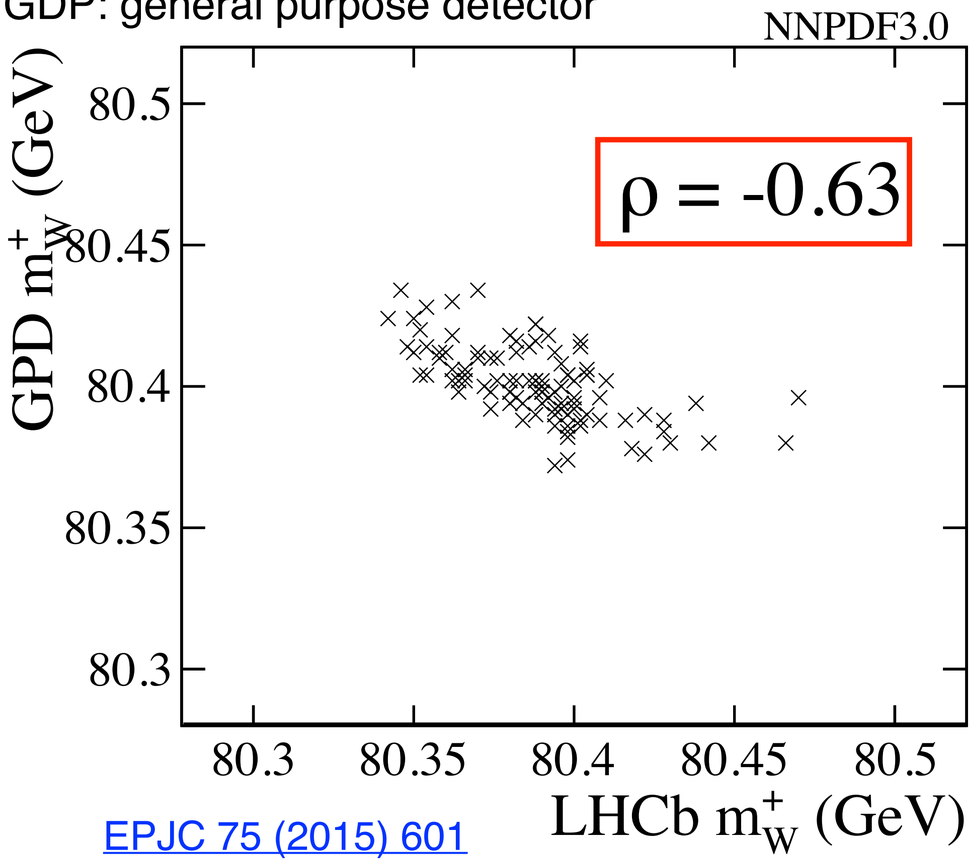
Phys. Rev. D 93 (2016) 074008



m_W measurement

- m_W is directly related to electroweak symmetry breaking in the Standard Model

GDP: general purpose detector



EPJC 75 (2015) 601

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

Δr: loop corrections

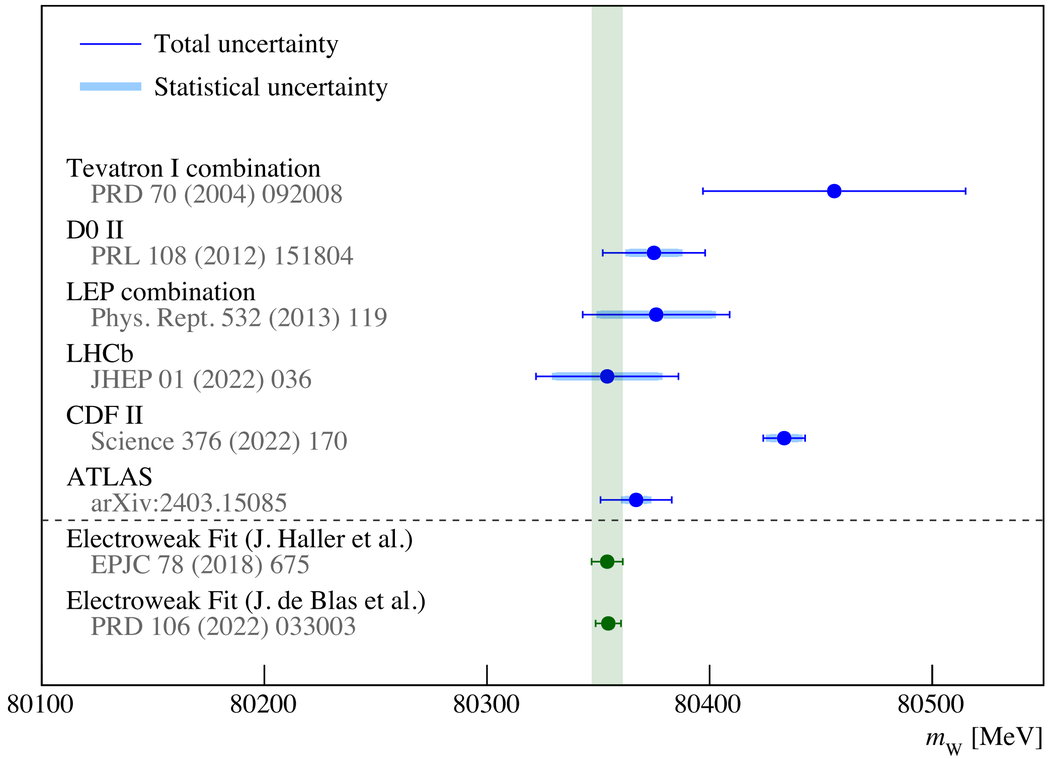
- Uncertainty from PDFs at LHCb is anticorrelated to that of ATLAS/CMS
- LHC experiments can achieve a sensitivity closer to the global EW fit (~7 MeV)

m_W measurement

$$m_W = 80354 \pm 23_{stat.} \pm 10_{exp.} \pm 17_{theory} \pm 9_{PDF}\,\text{MeV}$$ JHEP 01 (2022) 036

- LHCb achieves a precision of ~32 MeV using roughly 1/3 of the Run-II dataset
- Further of Run-II data to add —> statistical precision of ~14 MeV
- Effort now on improving the modelling and reducing the systematic uncertainties
- An overall precision ~20 MeV is achievable with all existing LHCb data

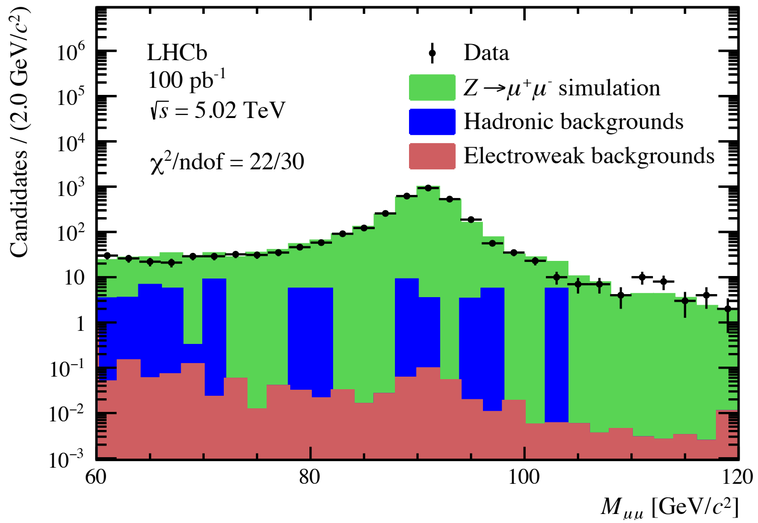
LHCb-FIGURE-2022-003

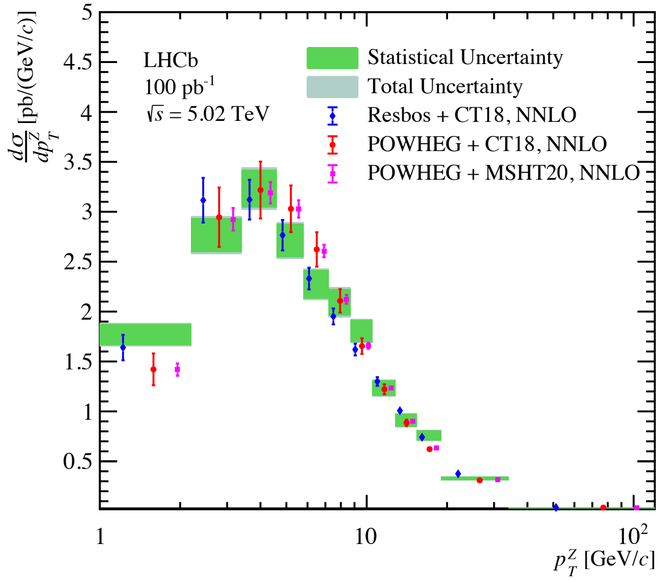


Measurement of Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV

NEW! JHEP 02 (2024) 070

- $pp \to Z \to \mu^+\mu^-$ an important channel to study the QCD and EW sectors of the SM at LHC energies
- Constraining the uncertainties of PDF
- **Performed with 2017 pp dataset of** $\sim 100\,\mathrm{pb}^{-1}$
- $2.0 < \eta < 4.5$ with transverse momentum $p_T > 20$ GeV
- Dimuon mass window $60 < m(\mu^+\mu^-) < 120$ GeV
- **General good agreement between predictions and data in observables**

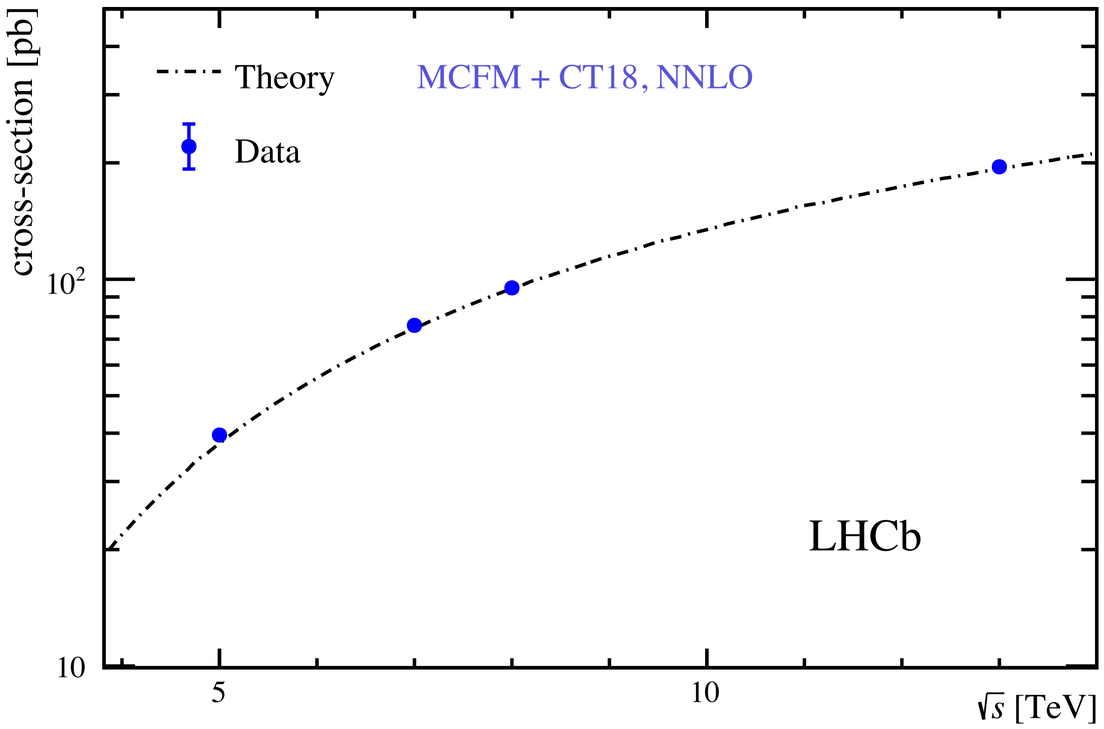


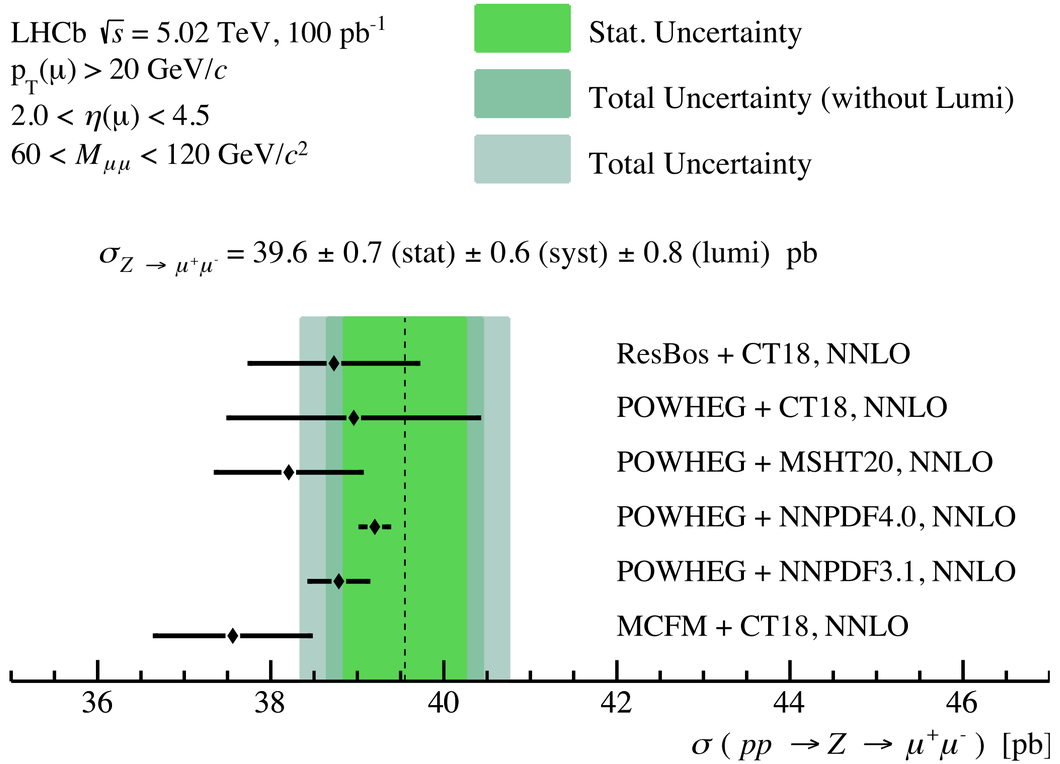


Measurement of Z boson production cross-section in pp collisions at $\sqrt{s} = 5.02$ TeV

NEW! JHEP 02 (2024) 070

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





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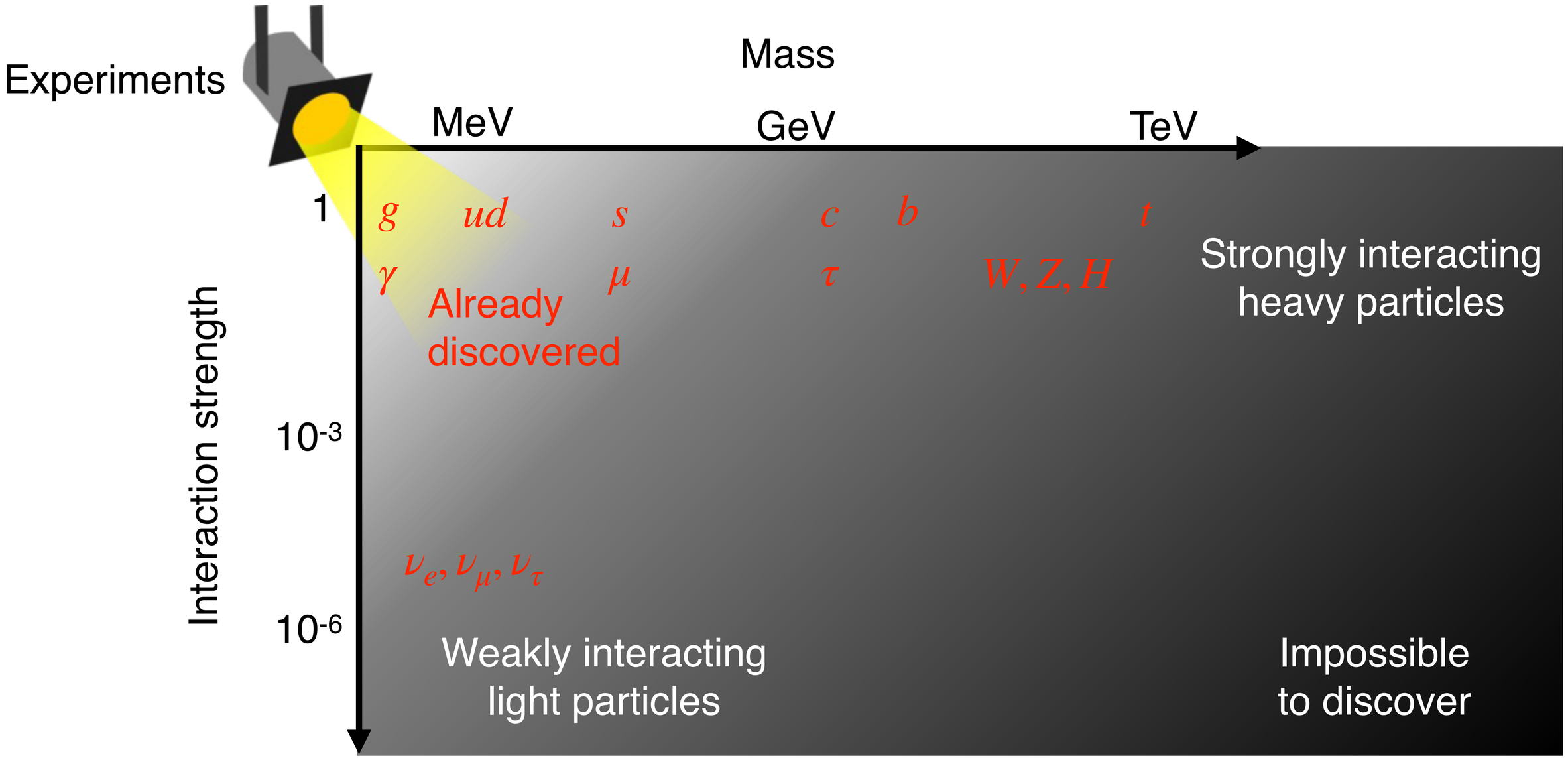
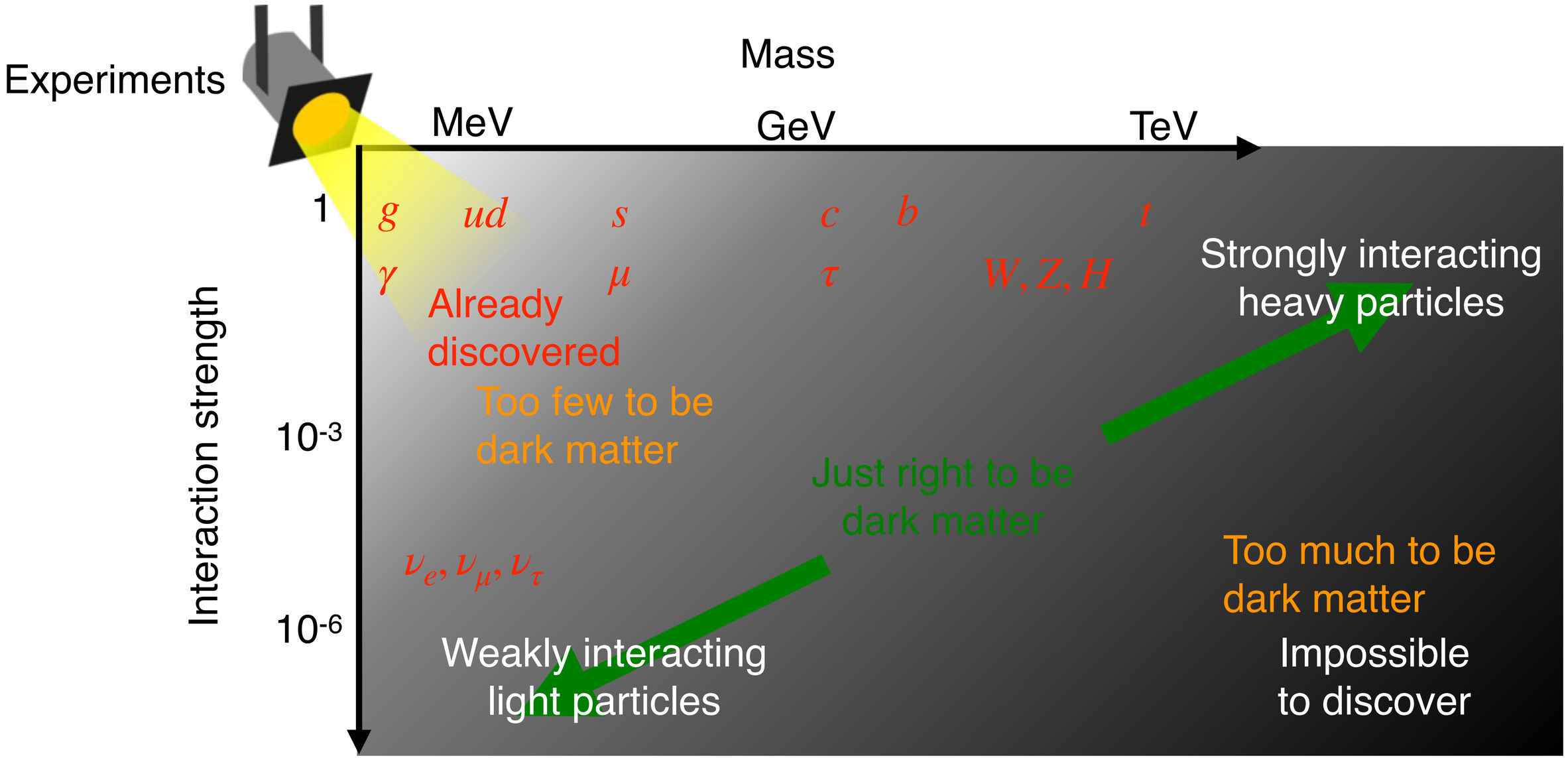
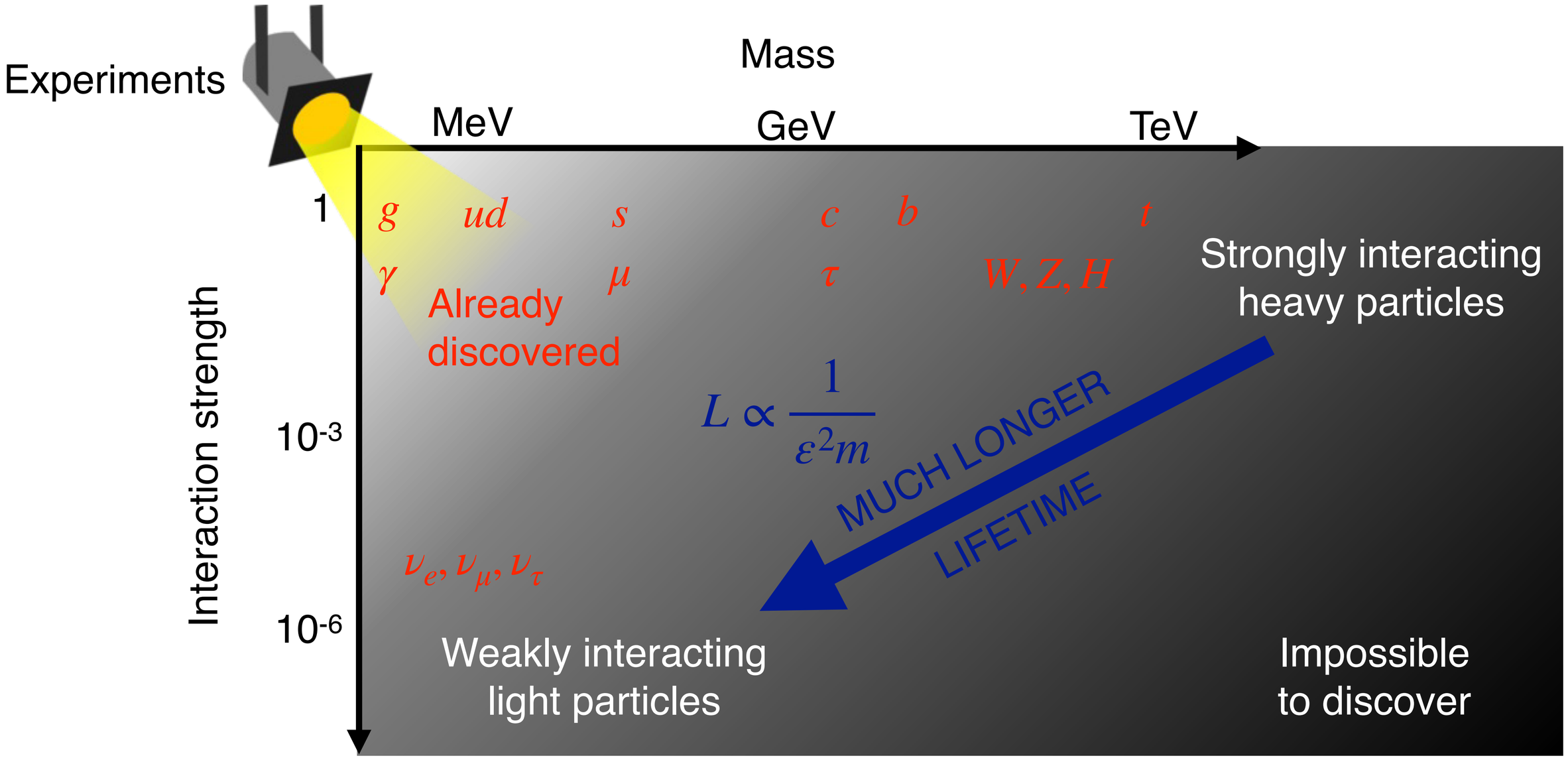
The particle landscape



The cosmological landscape



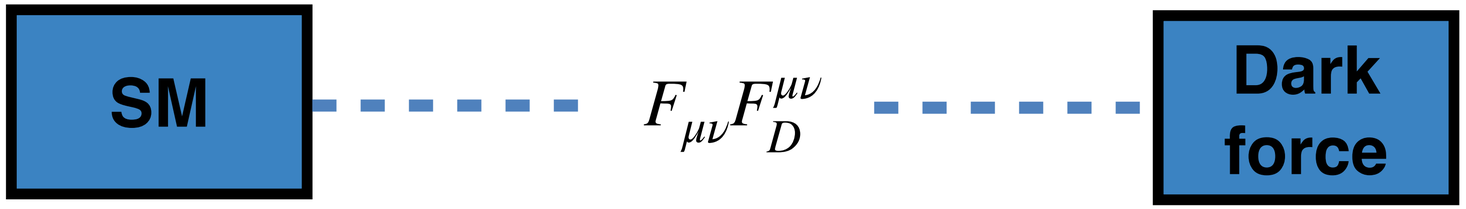
The lifetime frontier



The LLPs from light physics

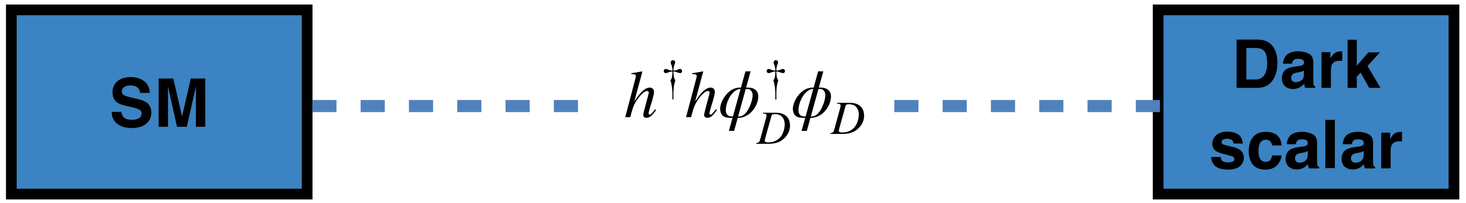
- This provides an organising principle that motivates specific examples of new, weakly interacting light particles. There are just a few options

SPIN 1



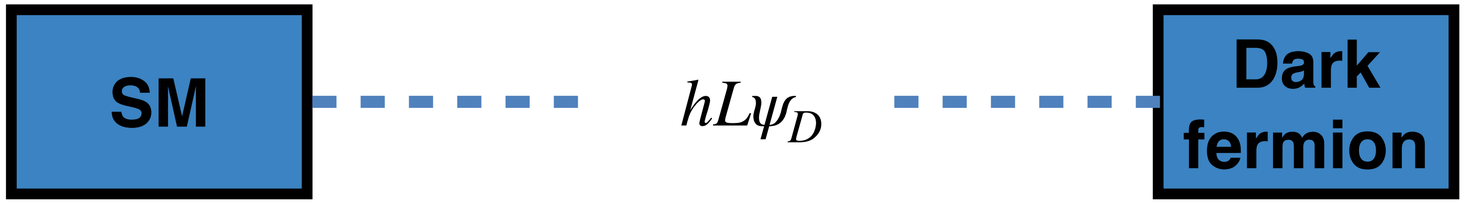
→ dark photon, couples to SM fermions with suppressed couplings proportional to charge εq_f

SPIN 0



→ dark Higgs boson, couples to SM fermions with suppressed coupling proportional to mass $m_f \sin\theta$

SPIN 1/2

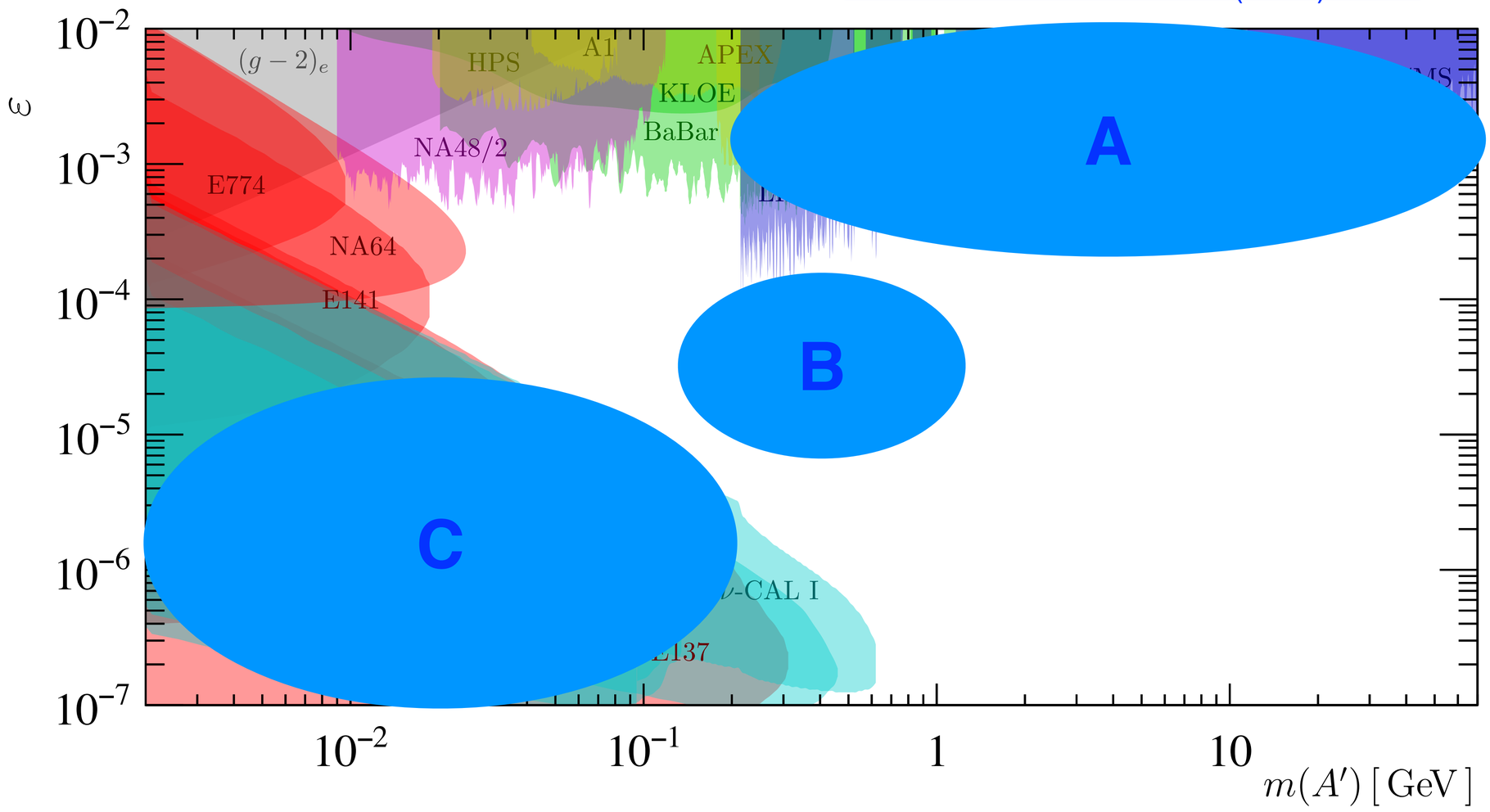


→ heavy neutral leptons, mixes with SM νs with suppressed mixing $U = \sin\theta$

Dark photons

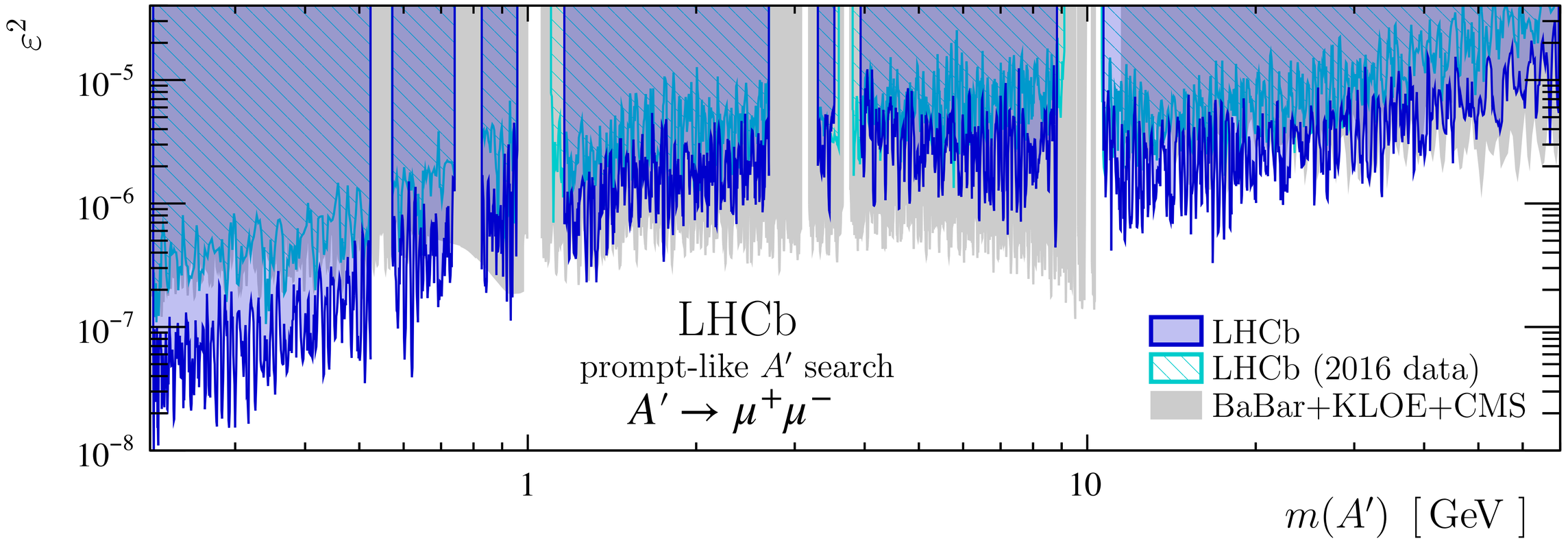
- **A**: bump hunts
- **B**: displaced vertex searches, short decay lengths
- **C**: displaced vertex searches, long decay lengths

Ann.Rev.Nucl.Part.Sci. 71 (2021) 37-58



Search for dark photons / prompt

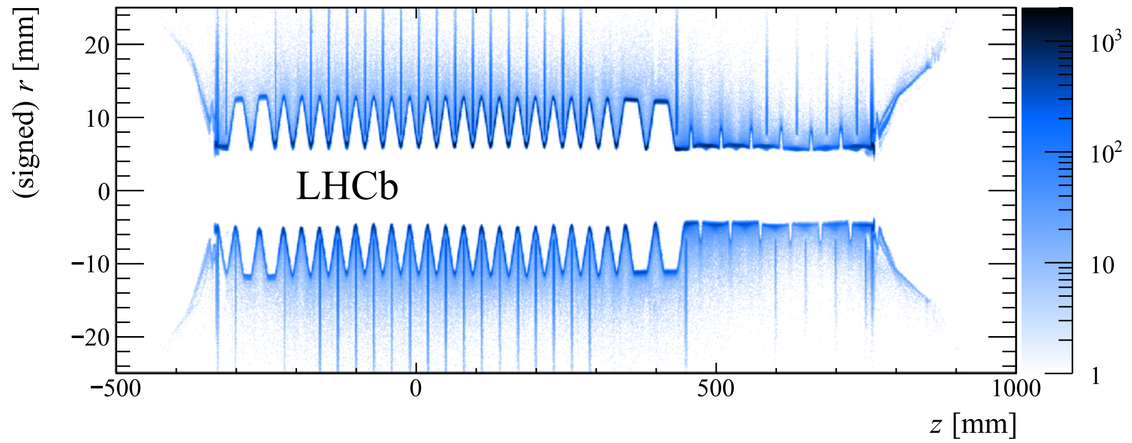
- No significant excess found - exclusion regions at 90% C.L. PRL 124 (2020) 041801
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV

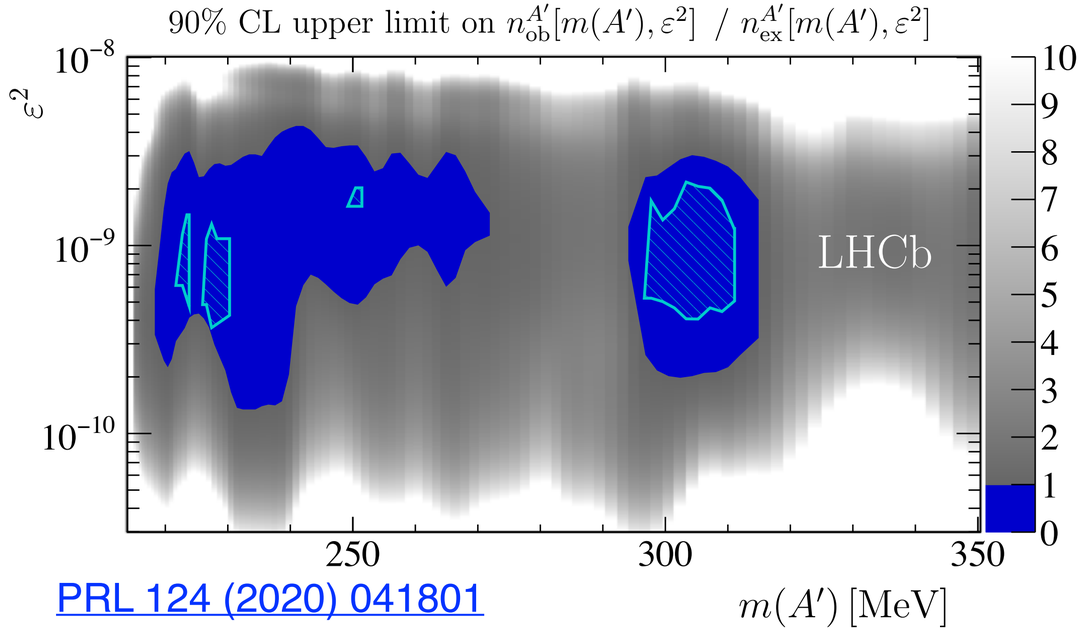


Search for dark photons / displaced

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

JINST 13, P06008 (2018)





PRL 124 (2020) 041801

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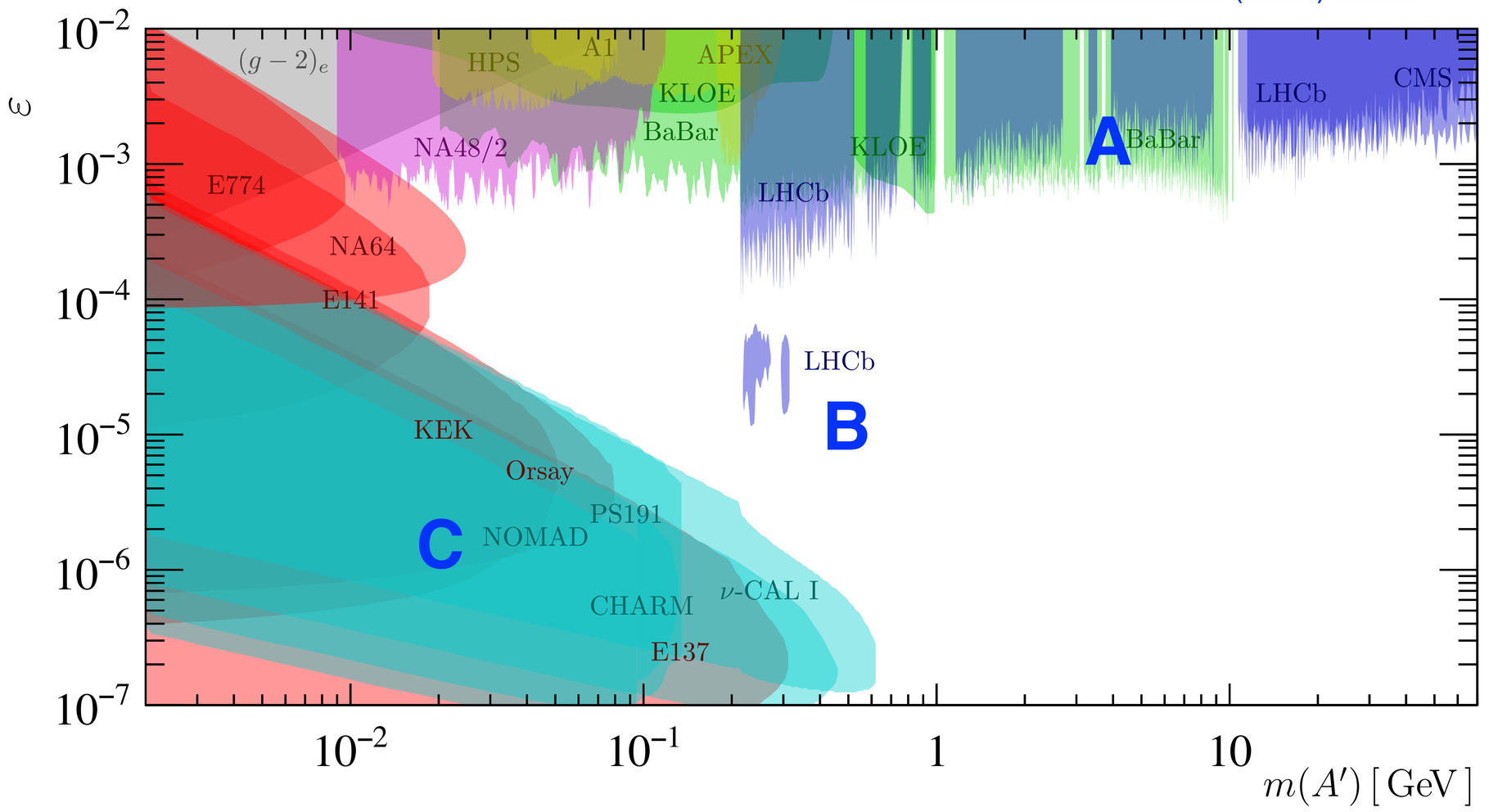
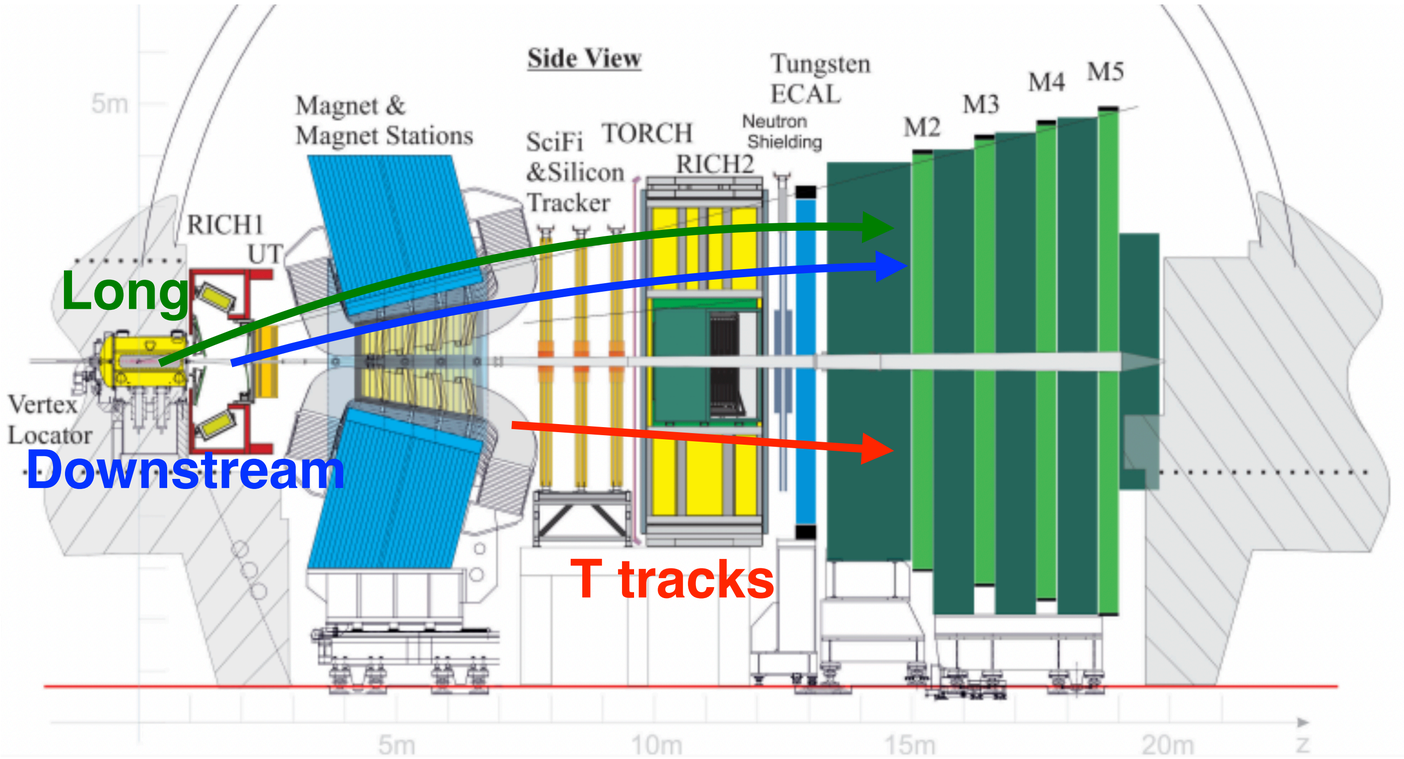
Ann.Rev.Nucl.Part.Sci. 71 (2021) 37-58



New algorithms to reconstruct Long-Lived Particles

- LHCb has undergone a major upgrade
- Fully software trigger: **great LHCb performance** for b- and c-hadron decays (long tracks)
- What about LLPs?
  - For particles with $\tau > 100\,\text{ps}$ many decays happen out of the VELO
  - **Now LHCb can trigger on decays with downstream tracks** Front.Big Data 5 (2022) 1008737
  - Sensitivity gained for hadrons and BSM particles
  - **Effort to extend searches with T tracks** NEPTUNE project arXiv:2211.10920



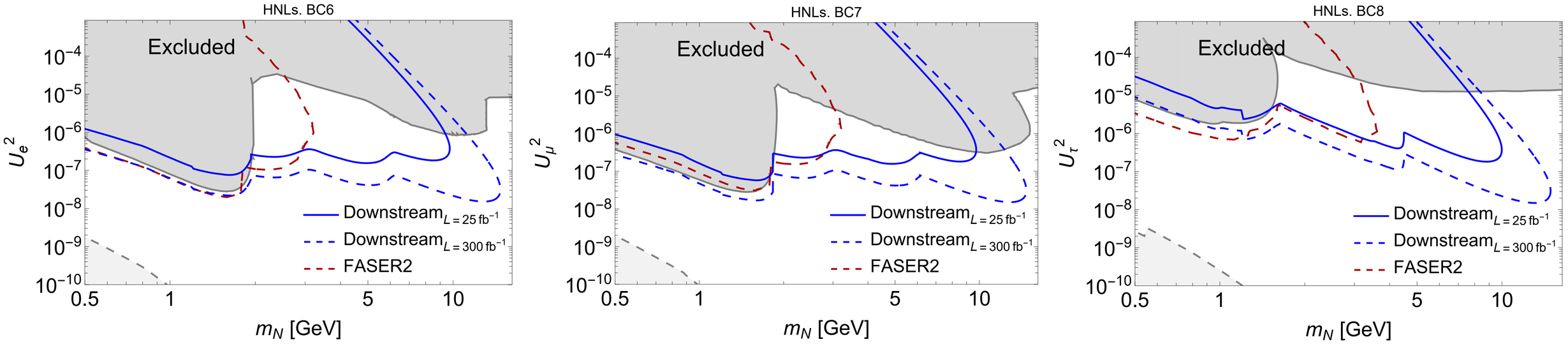
Maximum displacement

Long	$\sim 1\,\text{m}$
Downstream	$\sim 2\,\text{m}$
T tracks	$\sim 8\,\text{m}$

Heavy neutral leptons

- Downstream tracks (~2 m displacement) able to test unexplored regions able to unveil New Physics
- D/τ production ($m_N \lesssim 2\,\mathrm{GeV}$) not competitive, instead promising B ($2\,\mathrm{GeV} \lesssim m_N < m_{B_c} - m_\ell$) and W ($m_N > m_{B_c}$) production

arXiv:2312.14016

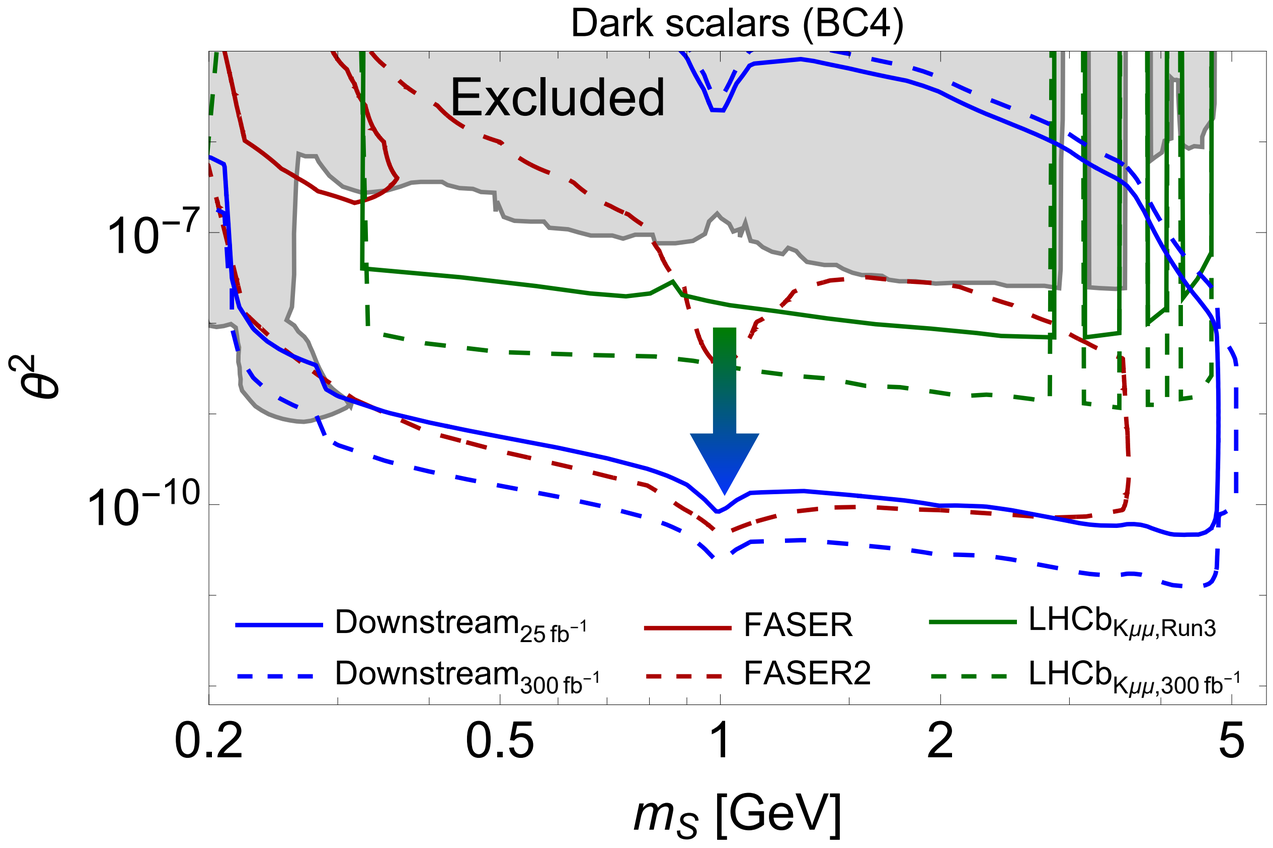


- Effort to extend searches to T tracks (~8 m displacement)

NEPTUNE project

Dark Higgs boson

- For a Higgs mediated dark scalar very similar effect on the exclusion plots. In this scenario the decay $B \to K^{(*)}\chi(\to \mu^+\mu^-)$



arXiv:2312.14016

Long
Downstream

Conclusions

LHCb has a thriving program on EW precision measurements and LLP searches

- LHCb was designed to do b-physics but during years it has extended its physics capabilities

- **LHCb will be able to tackle physics beyond its original design purpose even further than what it is already doing**:
  - **LHCb can provide very useful data to further tune the generators, understand QCD and EW effects and provide important and unique information to the PDFs global fitting**
    - Time constraints prevented to present results:
      - first measurement of the $Z \to \mu^+\mu^-$ angular coefficients at forward pseudorapidities of pp collisions -> direct access to Z polarisation [Phys. Rev. Lett. 129 (2022) 091801]
      - Search for the rare decays $W^+ \to D_s^+\gamma$ and $Z \to D^0\gamma$ [Chin.Phys.C47 (2023) 093002]
  - **Bright future for LLP direct searches with many new ideas**

- Foreseen in the future:
  - Weak mixing angle with full Run-II data
  - W boson mass with full Run-II data
  - Search for HNL in the mass range $2 \lesssim m_N \lesssim 6\,\mathrm{GeV}$

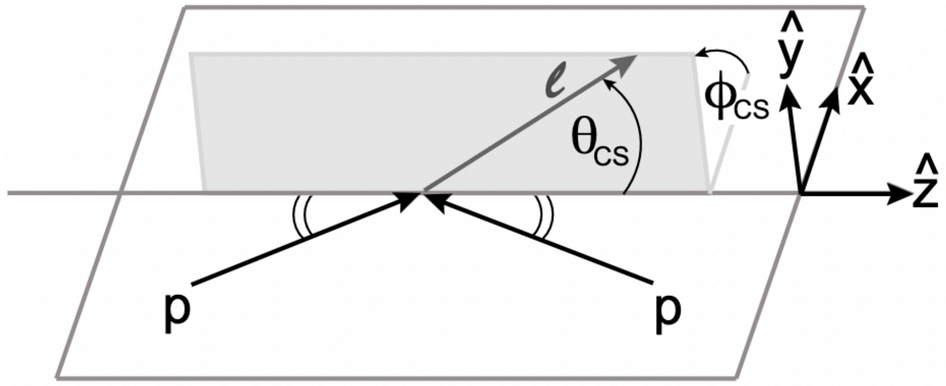
Backup

First measurement of the $Z \to \mu\mu$ angular coefficients at forward pseudorapities of pp collisions

Phys. Rev. Lett. 129 (2022) 091801

- The kinematic distribution of the final-state leptons provides a direct probe of the polarisation of the intermediate gauge boson
- Using full Run2 dataset ($5.1\ \mathrm{fb}^{-1}$)
- Dimuon angular distribution in $Z \to \mu\mu$ expressed in 8 coefficients A_i
- A_i extracted with unbinned maximum likelihood fit to muon $\cos\theta$ and ϕ
- It is the first measurement of $A_i (i = 0 - 4)$ in the forward region of *pp* collisions at 13 TeV

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

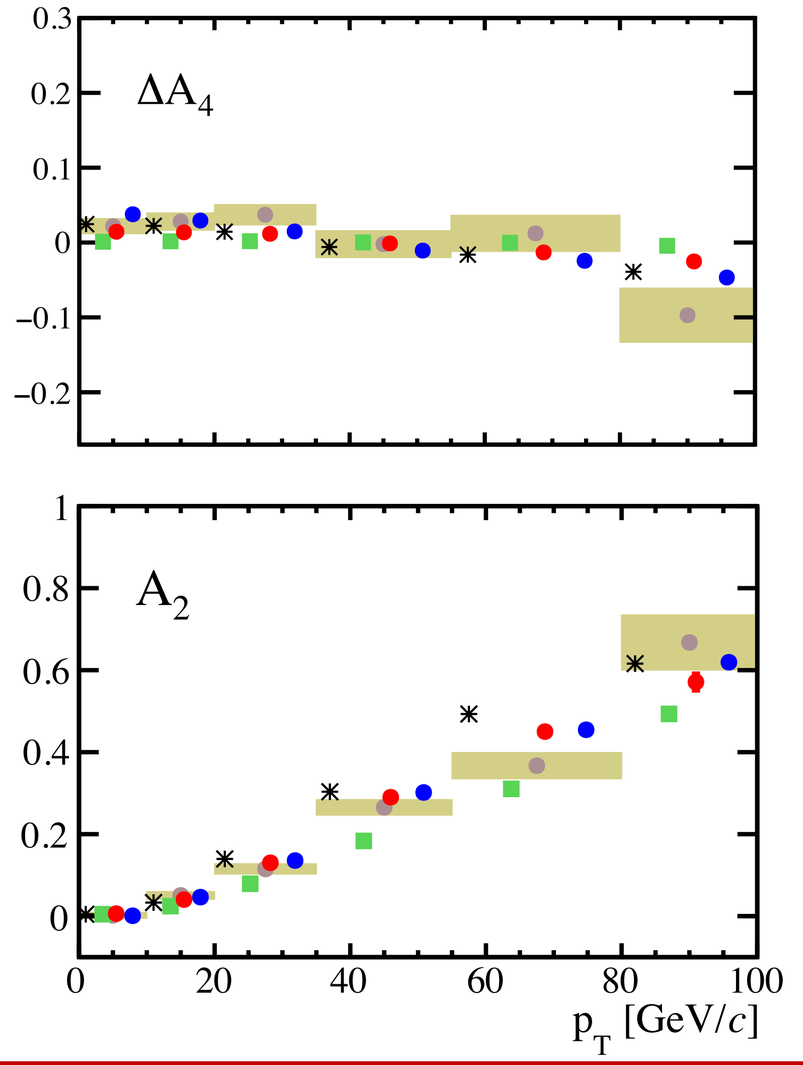


Collins Soper reference frame

First measurement of the $Z \to \mu\mu$ angular coefficients at forward pseudorapities of pp collisions

Phys. Rev. Lett. 129 (2022) 091801

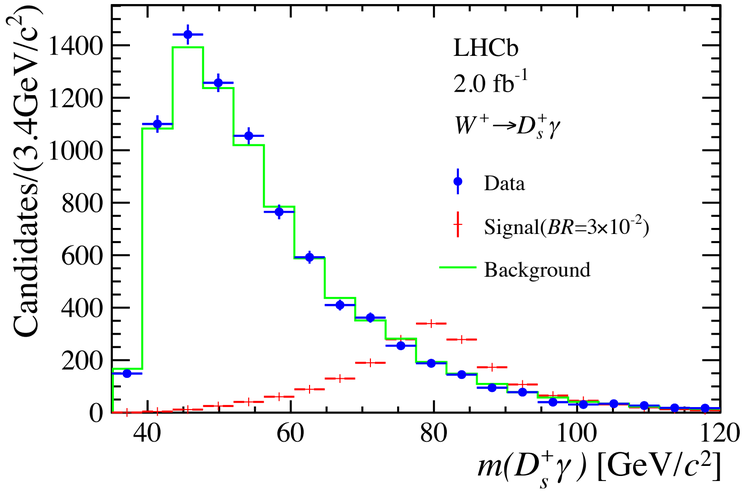
- Results as a function of transverse momentum
- $\Delta A_4 = A_4 - < A_4 >$ decouples measurement from the value of the weak mixing angle
- Compared with 4 sets of theoretical predictions
- Good agreements with predictions
- A_2 proportional to convolution of transverse-momentum-dependent PDFs:
  - This measurement can improve constraints on non perturbative partonic spin-momentum correlations within unpolarised protons

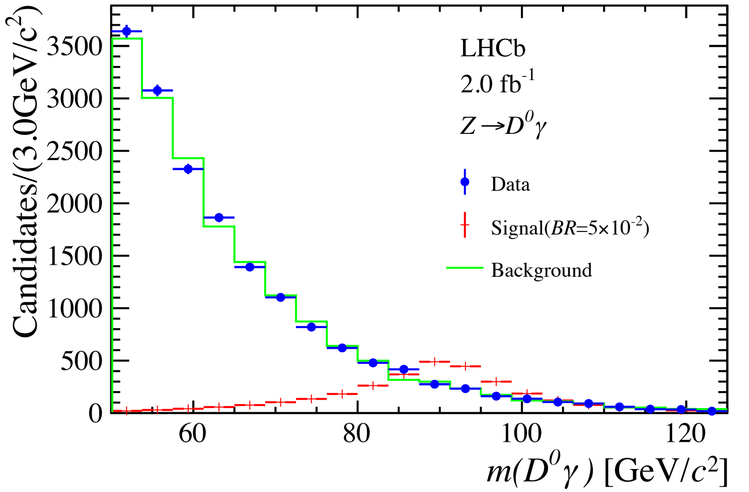


Search for the rare decays $W^+ \to D_s^+\gamma$ and $Z \to D^0\gamma$

Chin.Phys.C47 (2023) 093002

- Using $2.0\,\text{fb}^{-1}$ from pp collisions at $\sqrt{s} = 13\,\text{TeV}$
- $W \to \mu\nu$ and $Z \to \mu\mu$ as normalisation channels
- $\mathcal{B}(W \to D_s^+\gamma) < 6.5 \times 10^{-4}$, $\mathcal{B}(Z \to D^0\gamma) < 2.1 \times 10^{-3}$ at 95% CL
- Pseudomass $m(M\gamma) = \sqrt{2p^M p_T^M \frac{p^\gamma}{p_T^\gamma}(1-\cos\theta)}$ to overcome the poorly measured photon energy for transverse energies above the saturation value

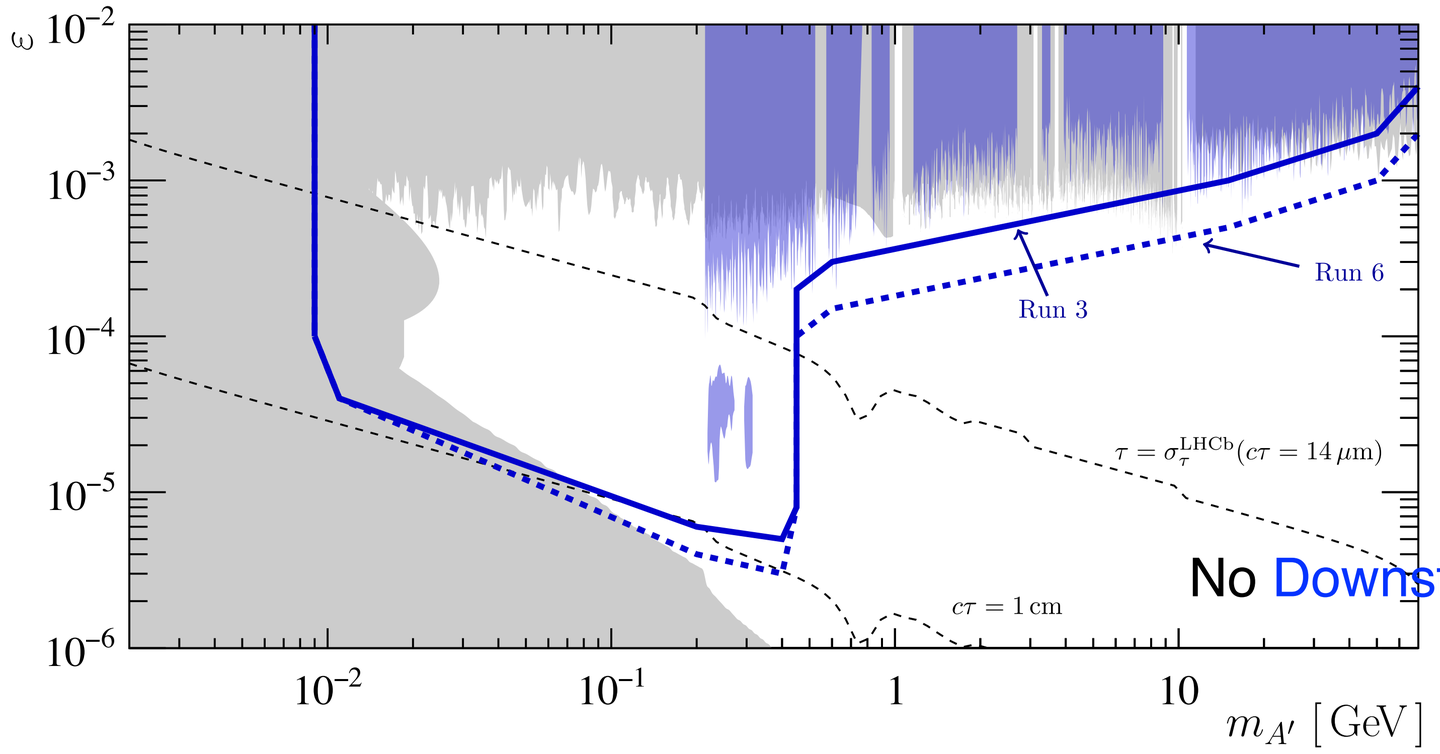




Perspectives for the search of dark photons

- Dimuon is used for higher masses, for lower masses estimations use dielectrons final states (thanks to fully software GPU triggering)
- Minimal increase with increased luminosity

arXiv:2203.07048



No Downstream or T tracks