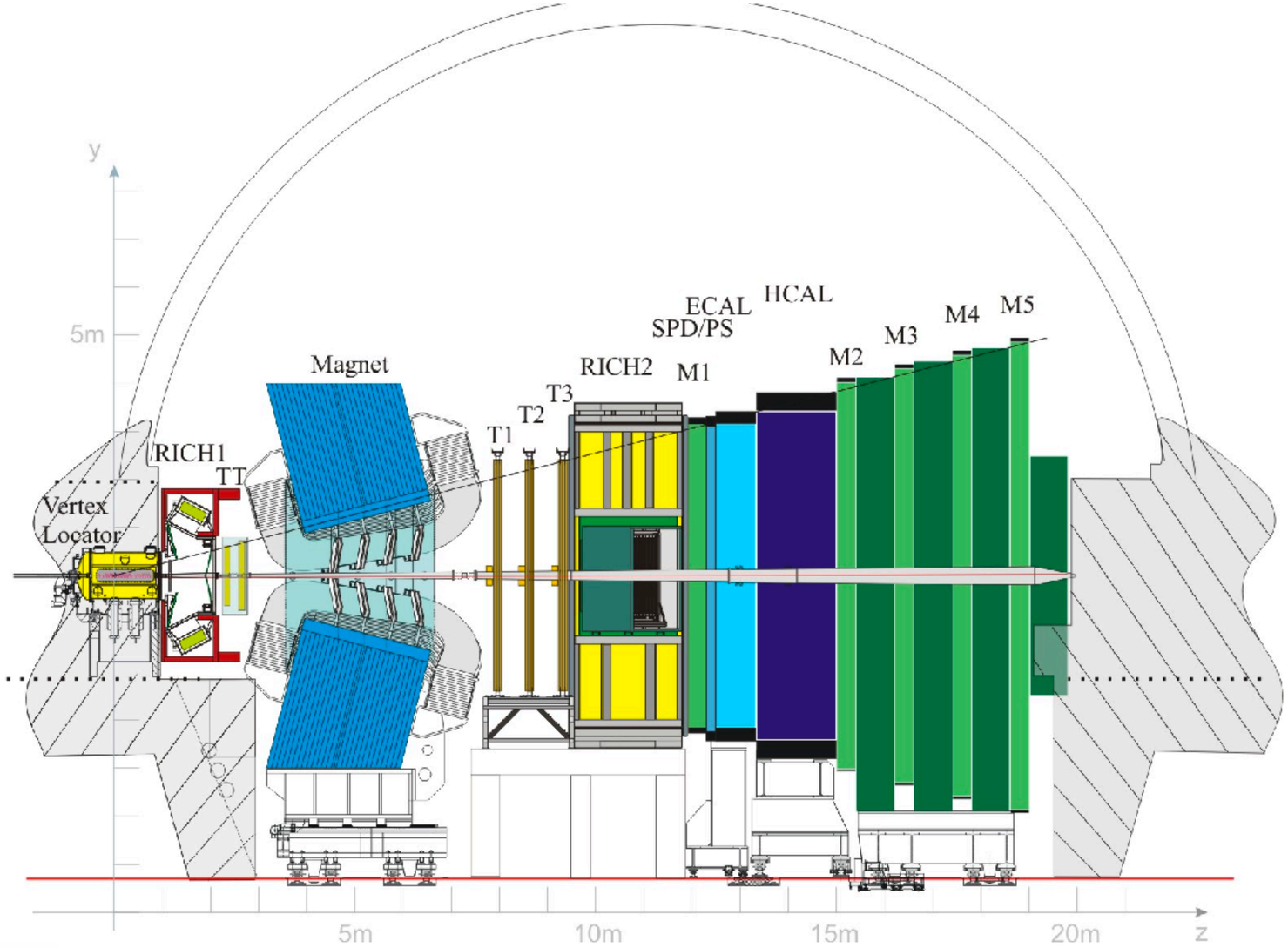

# Dark Photons @ LHCb

**Adrián Casais Vidal** (MIT, LHCb collaboration)

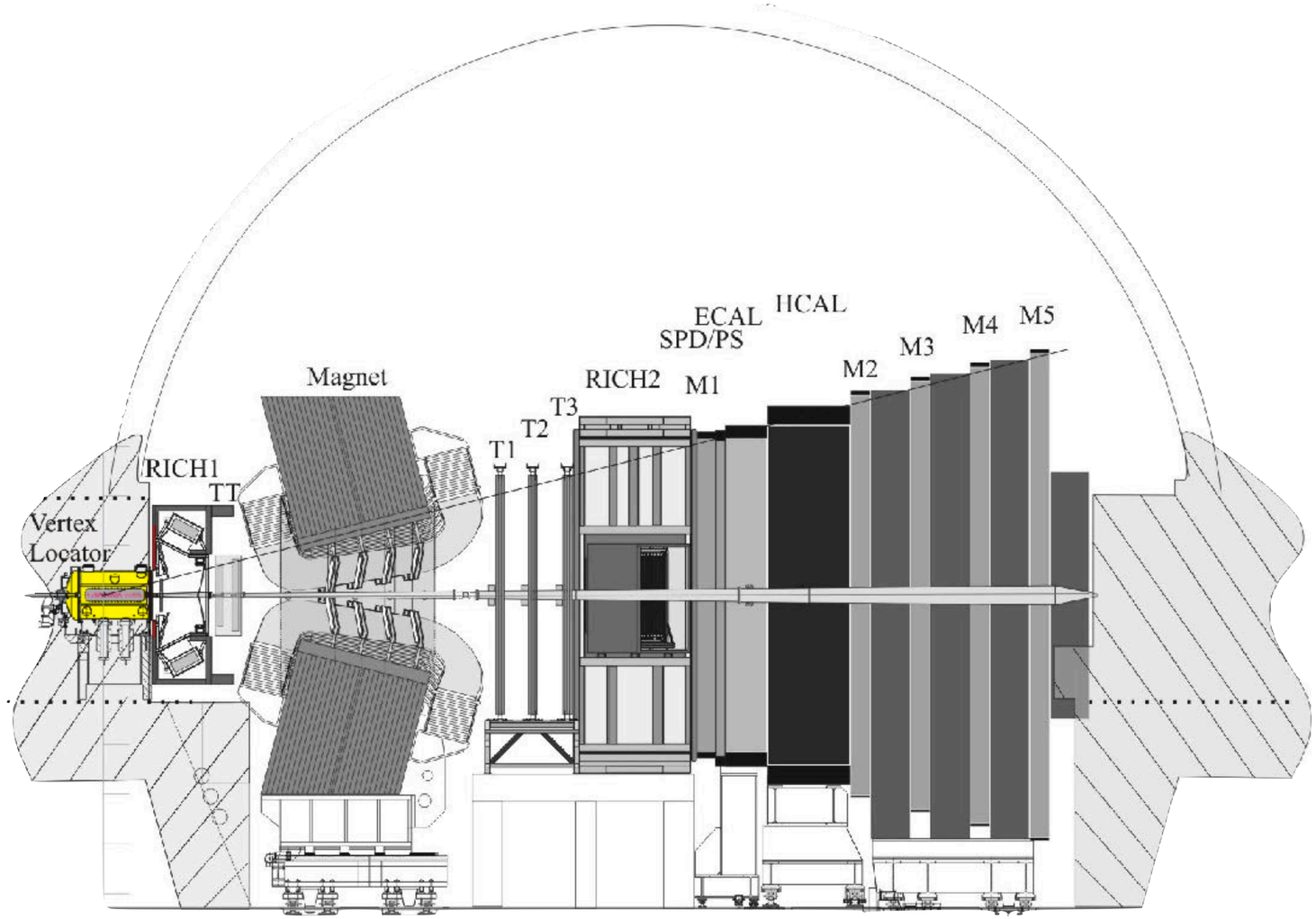
February 10th, 2025. **EPFL (Lausanne)**


# The LHCb experiment during Run2



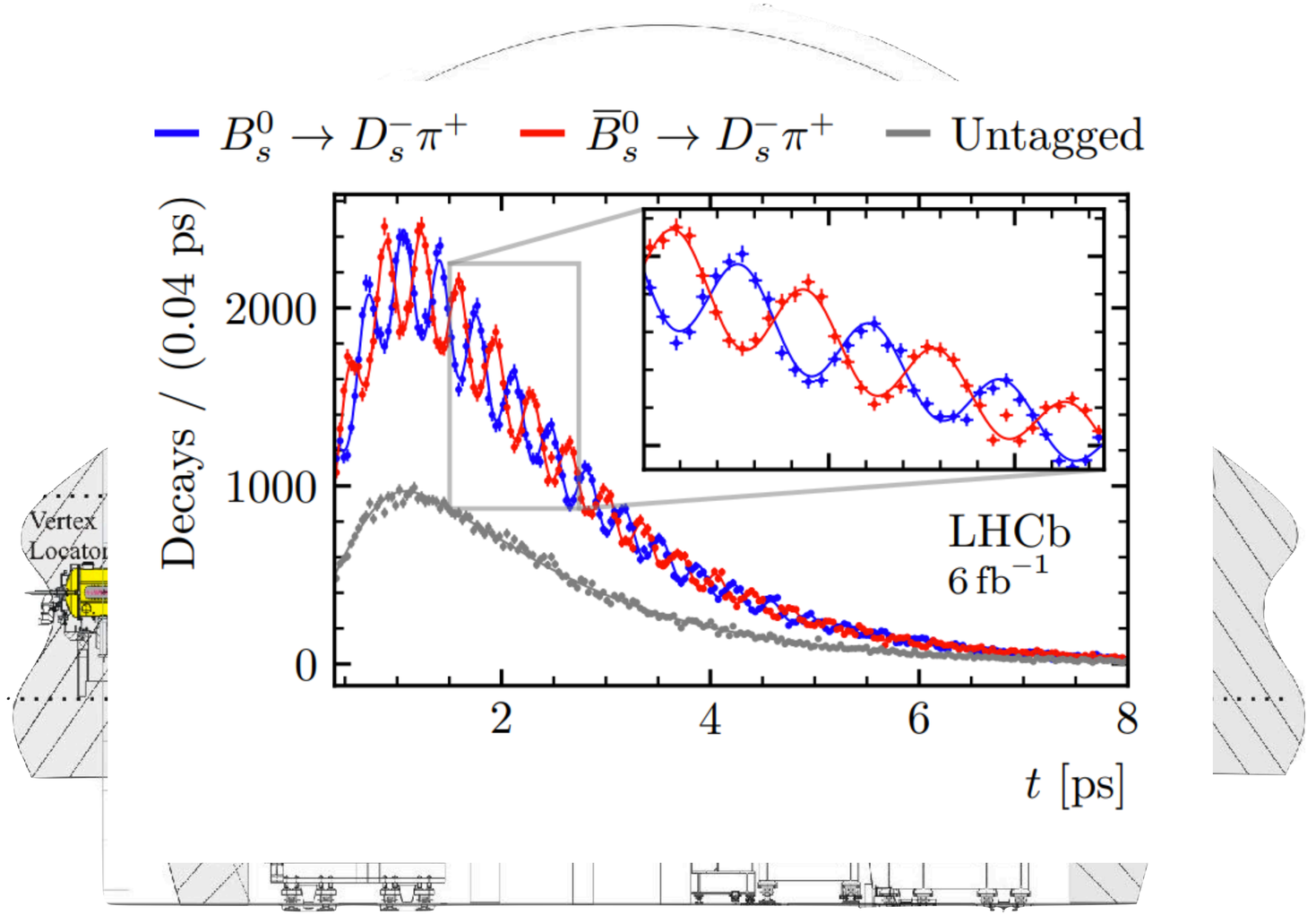

LHCb is a spectrometer in the forward region at the LHC

# The LHCb experiment during Run2




VELO: great primary/secondary vertex reconstruction

# The LHCb experiment during Run2

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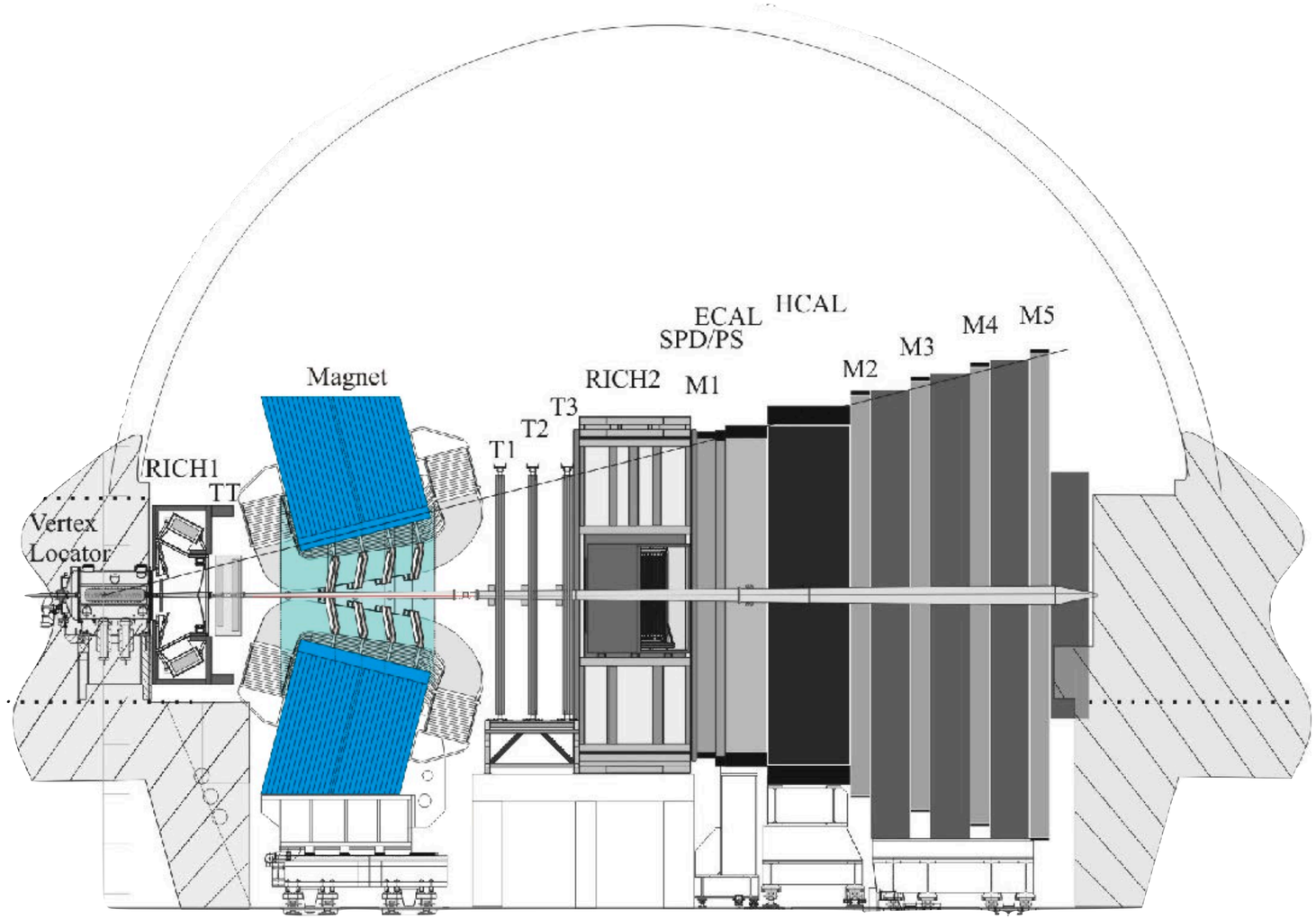
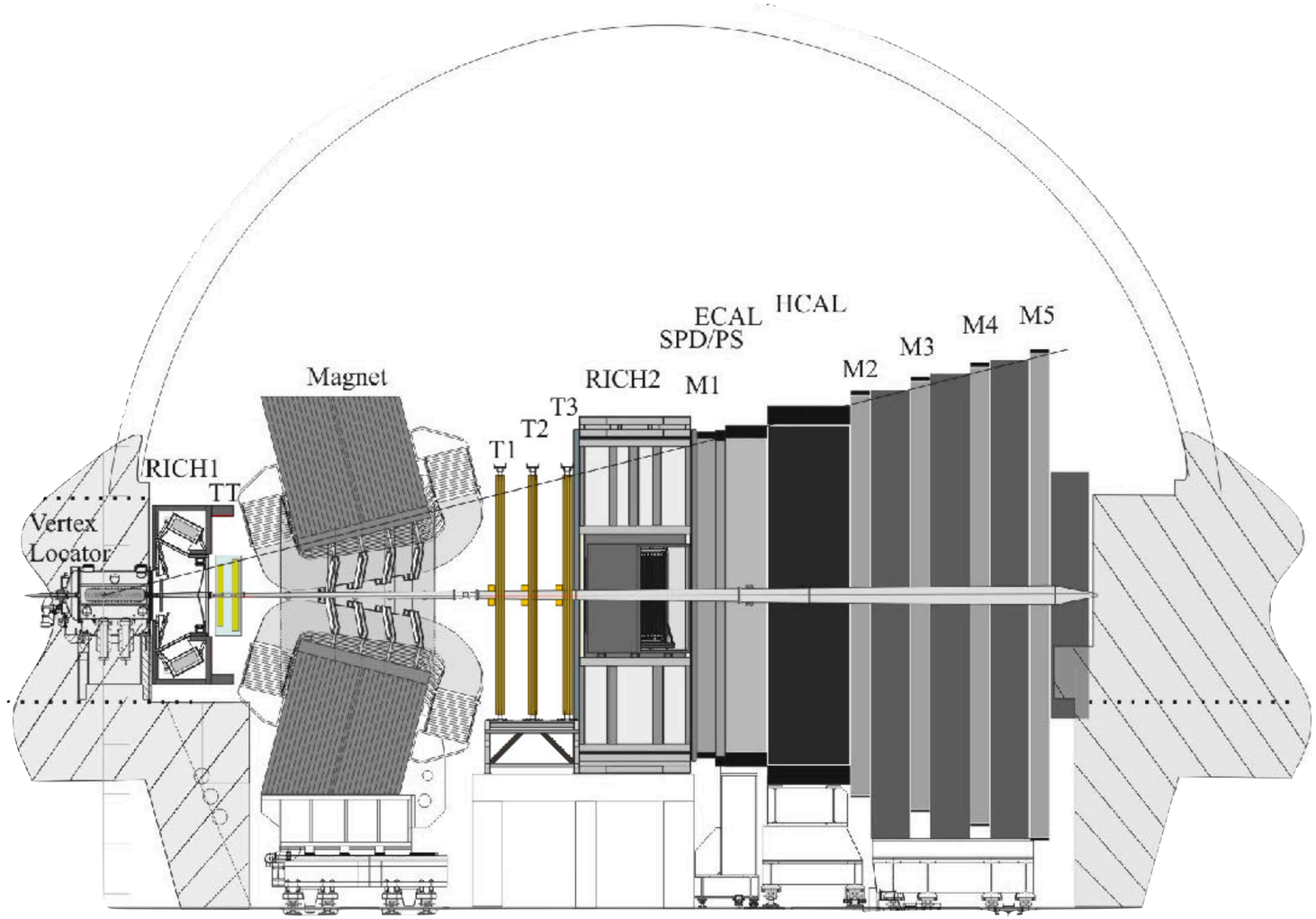


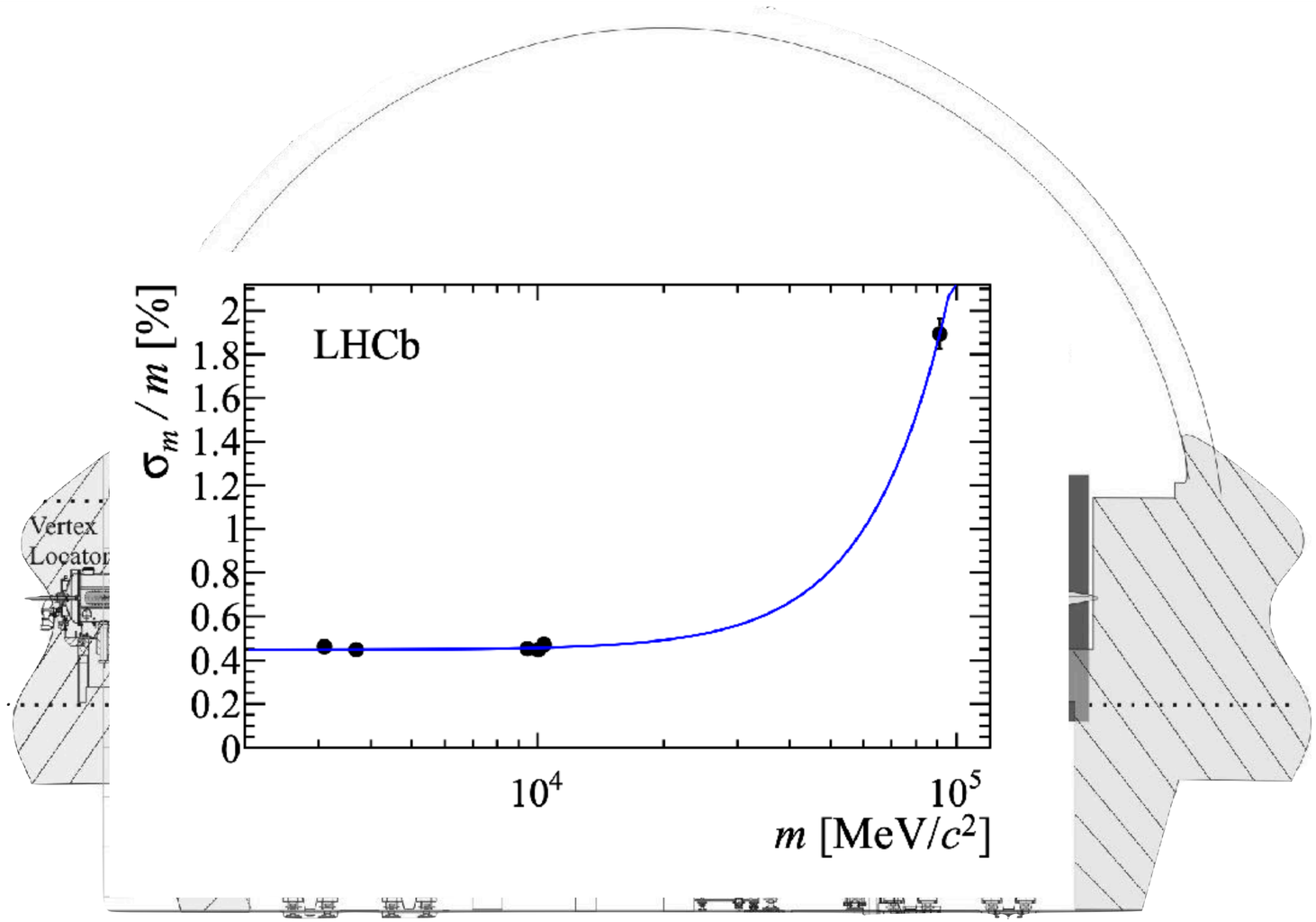

Magnet: provides the bending power to measure the momentum and charge of the charged particles

# The LHCb experiment during Run2




TT and T stations: reconstruction of charged particles

# The LHCb experiment




TT and T stations: reconstruction of charged particles

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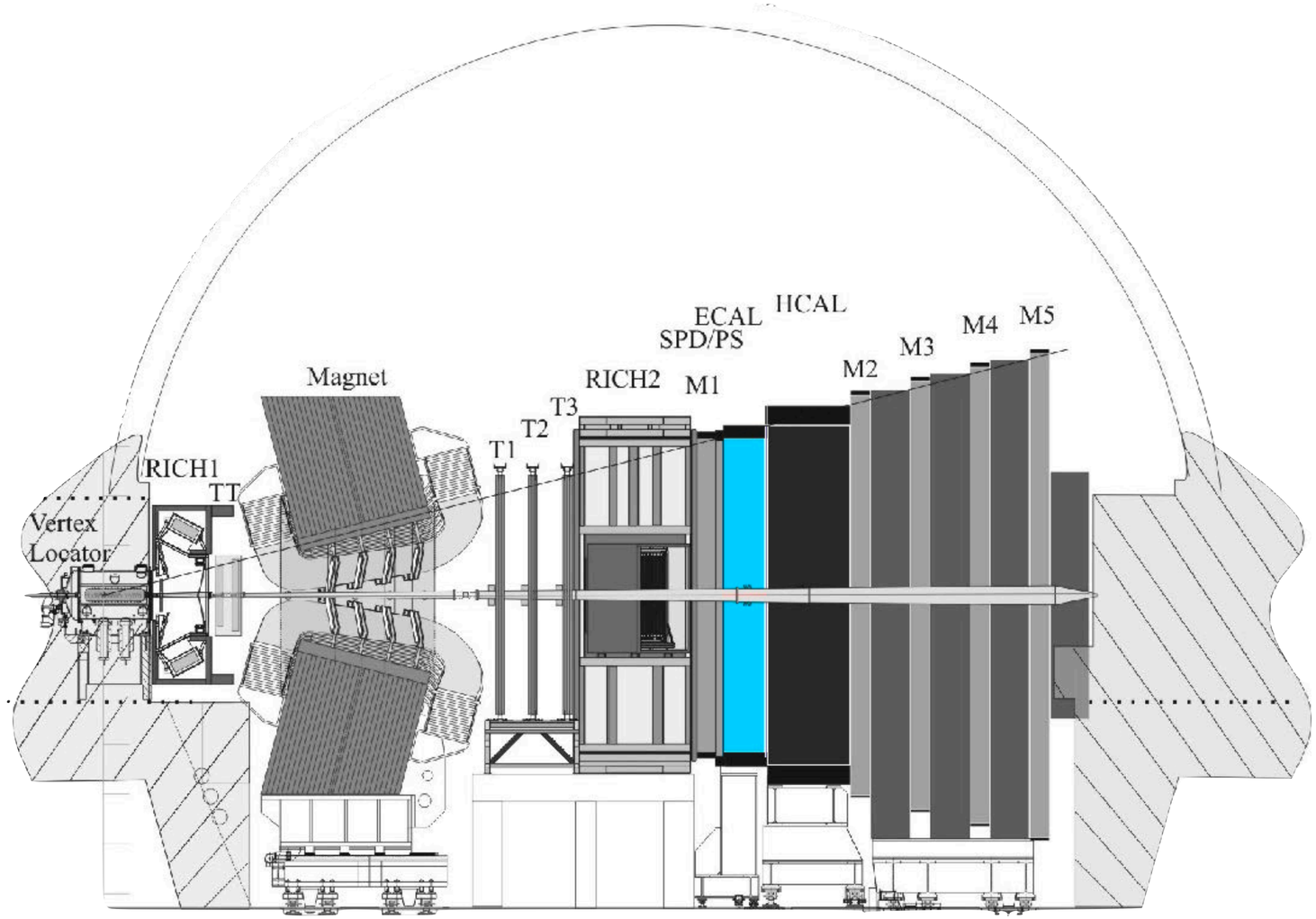


ECAL: identifies electrons and photons by measuring the energy of the EM shower they produce

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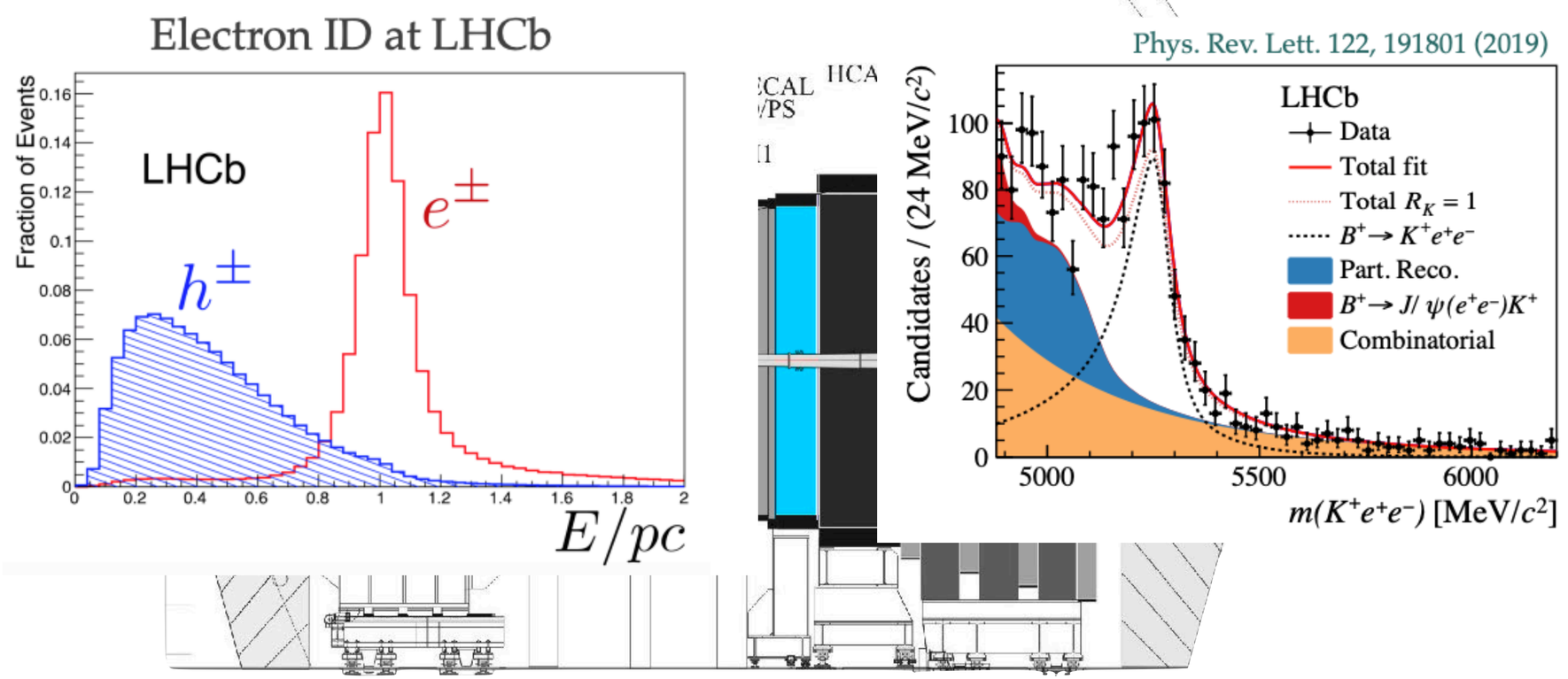
# The LHCb experiment during Run2

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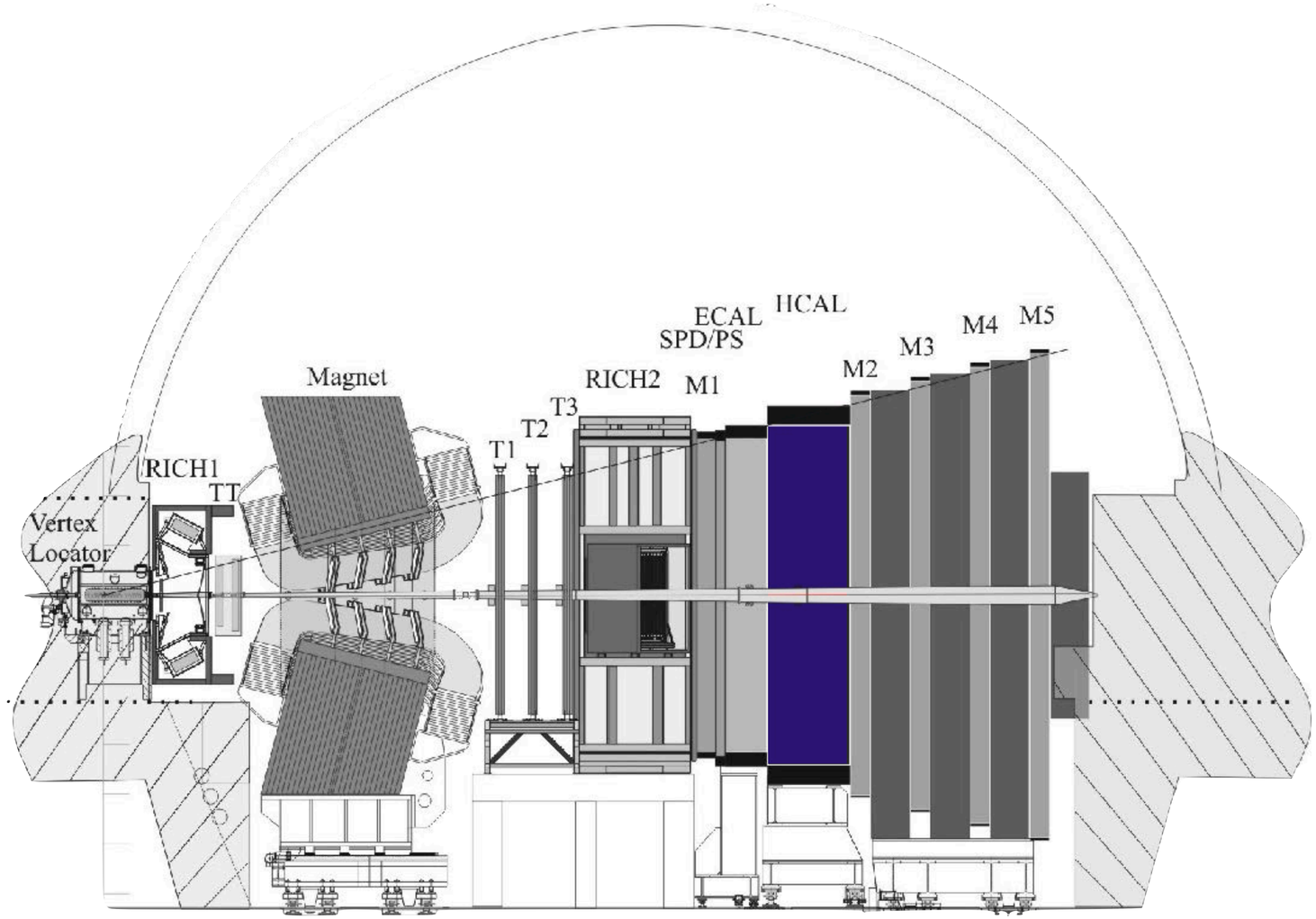
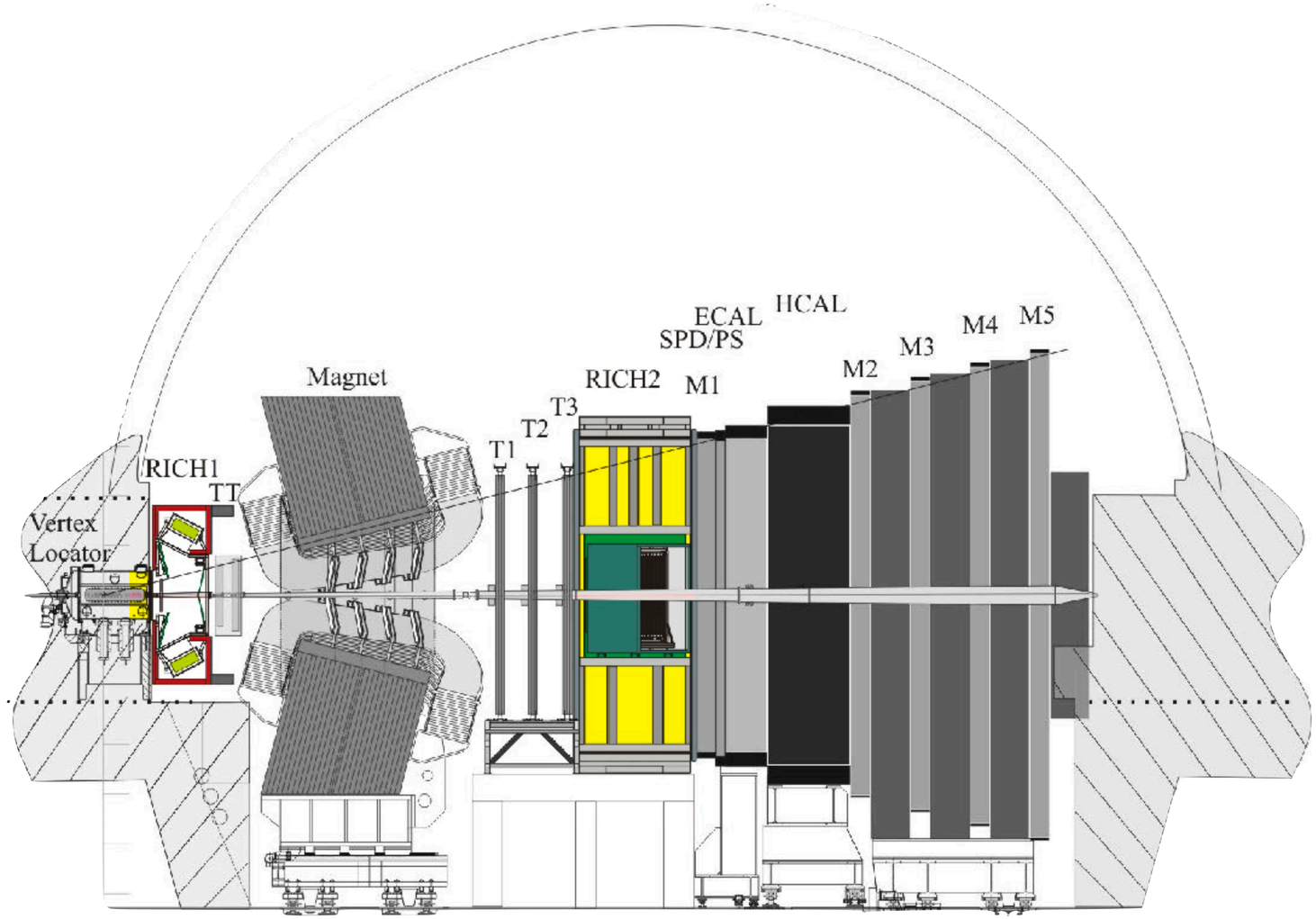



HCAL: helps identify hadrons and provides a veto for those that could fake electrons o

# The LHCb experiment during Run2




RICH: identify charged particles by measuring their Cherenkov light

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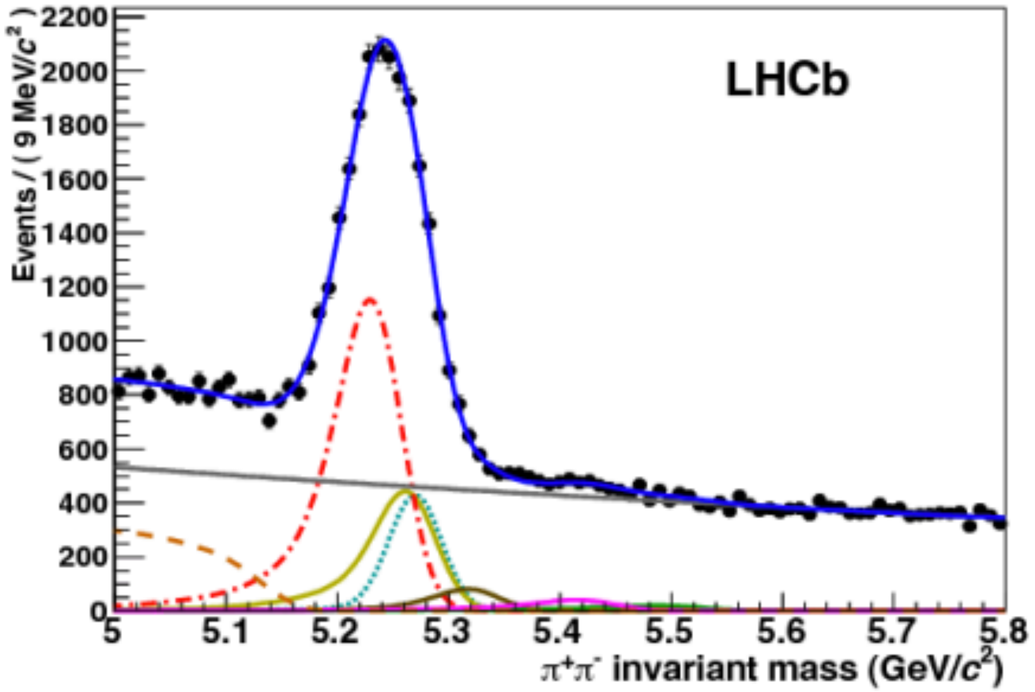


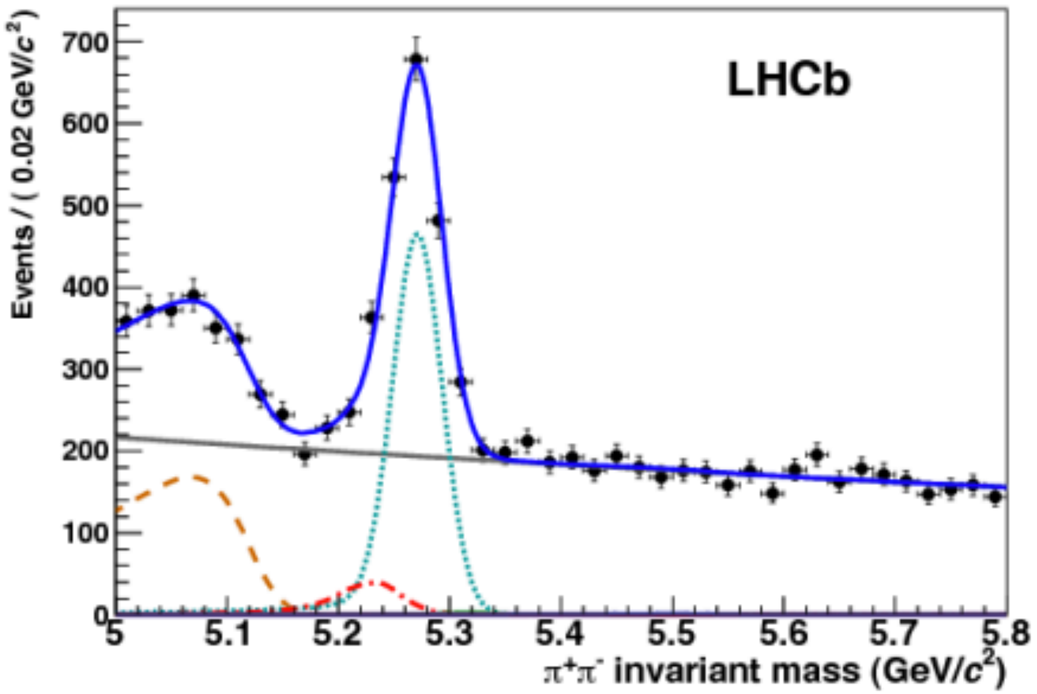


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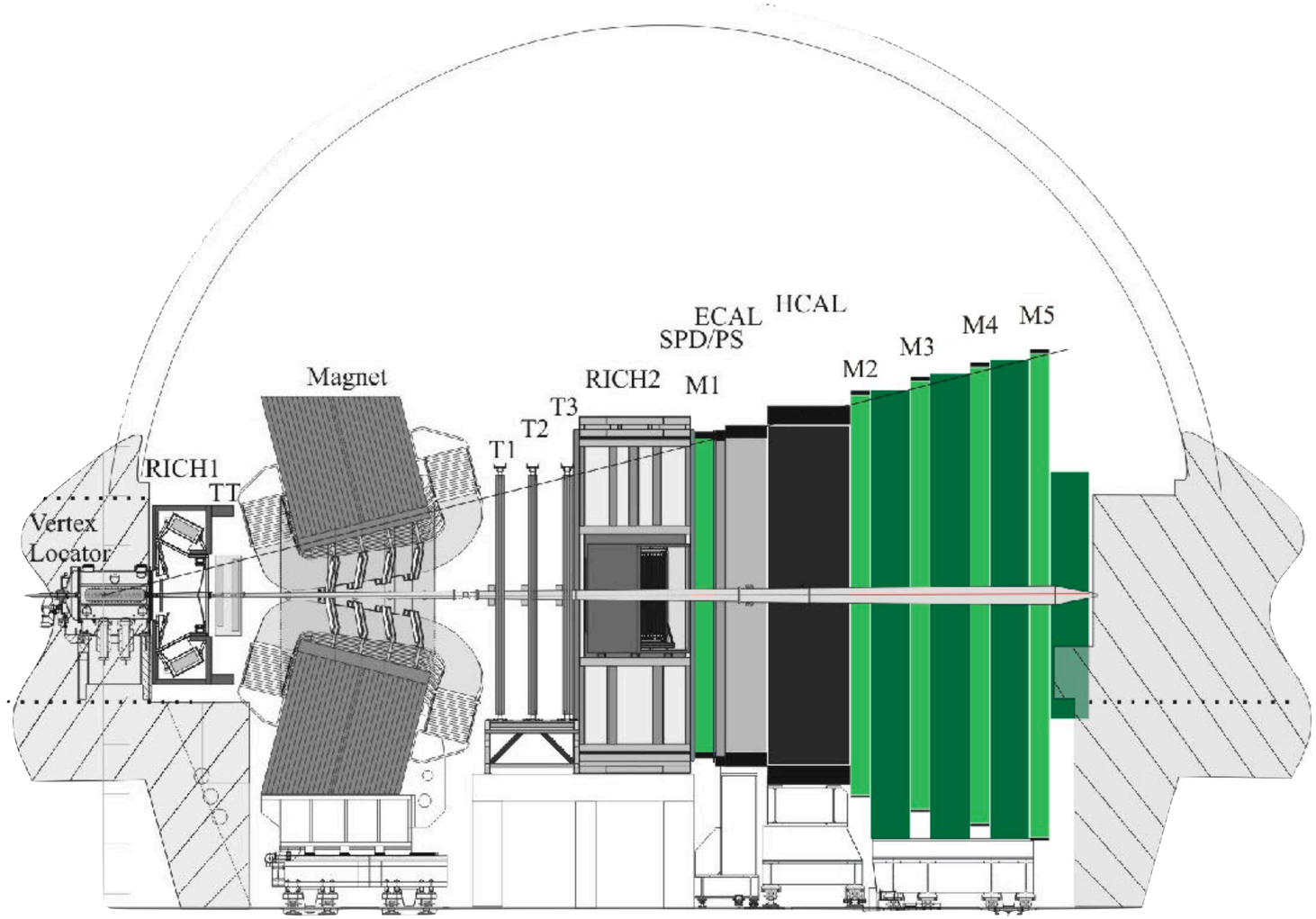


MUON stations: identify muon leptons, the most penetrating charged particles.

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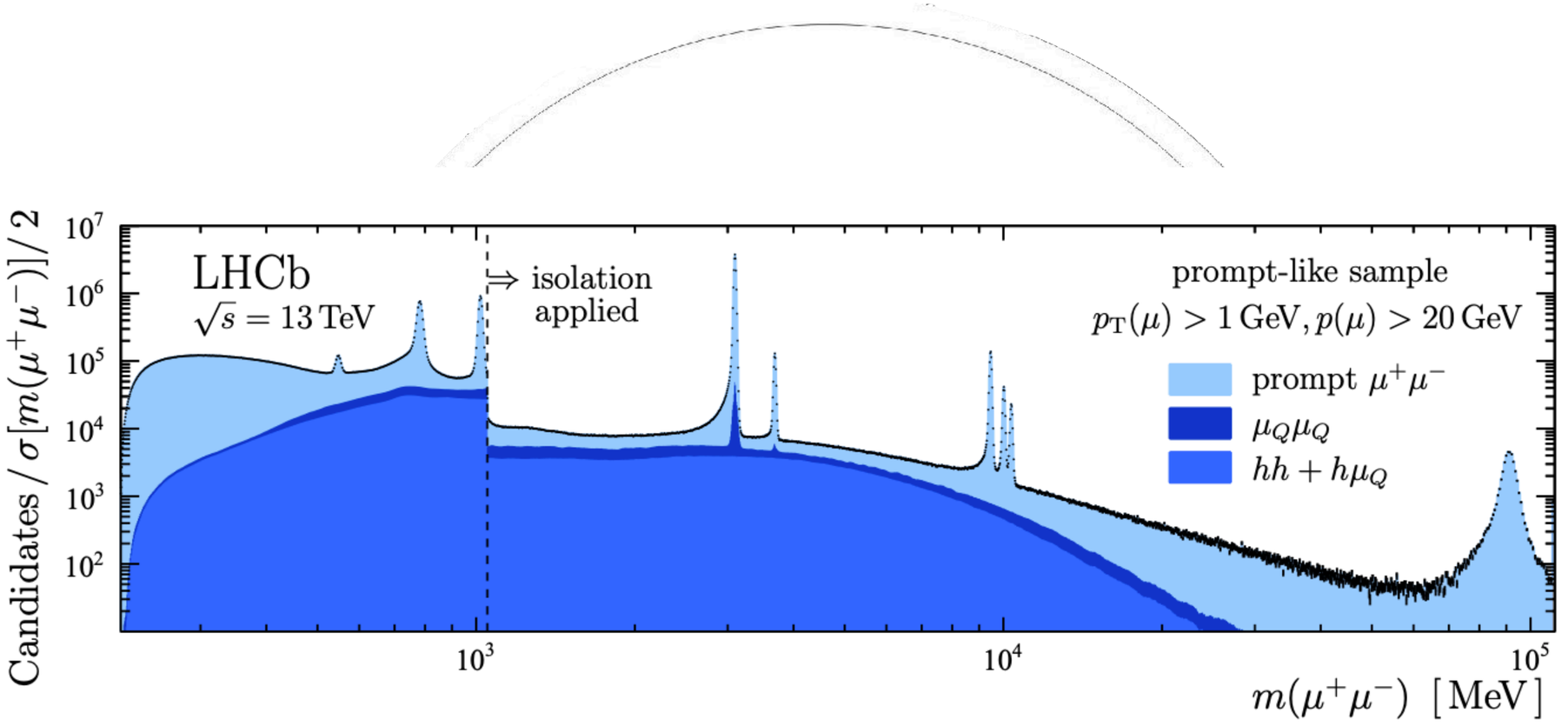


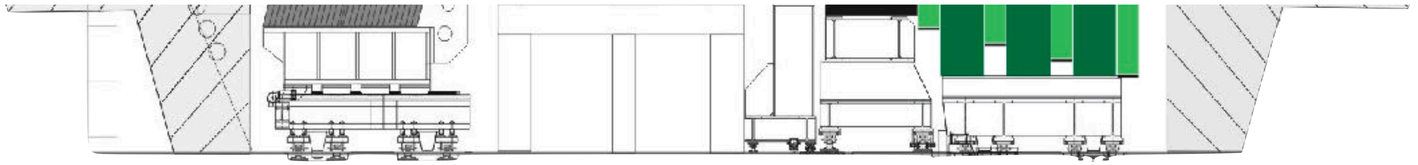

MUON stations: identify muon leptons, the most penetrating charged particles.

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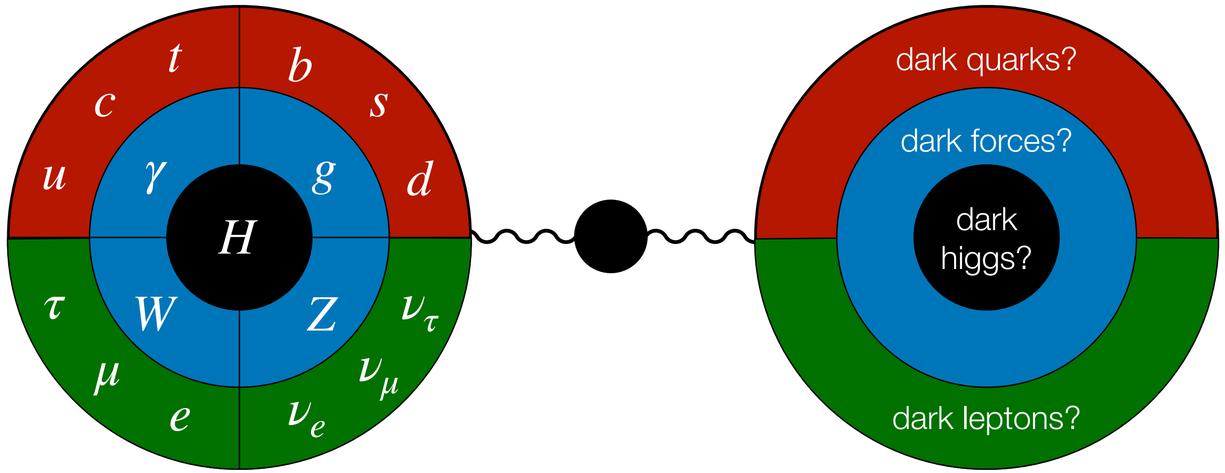
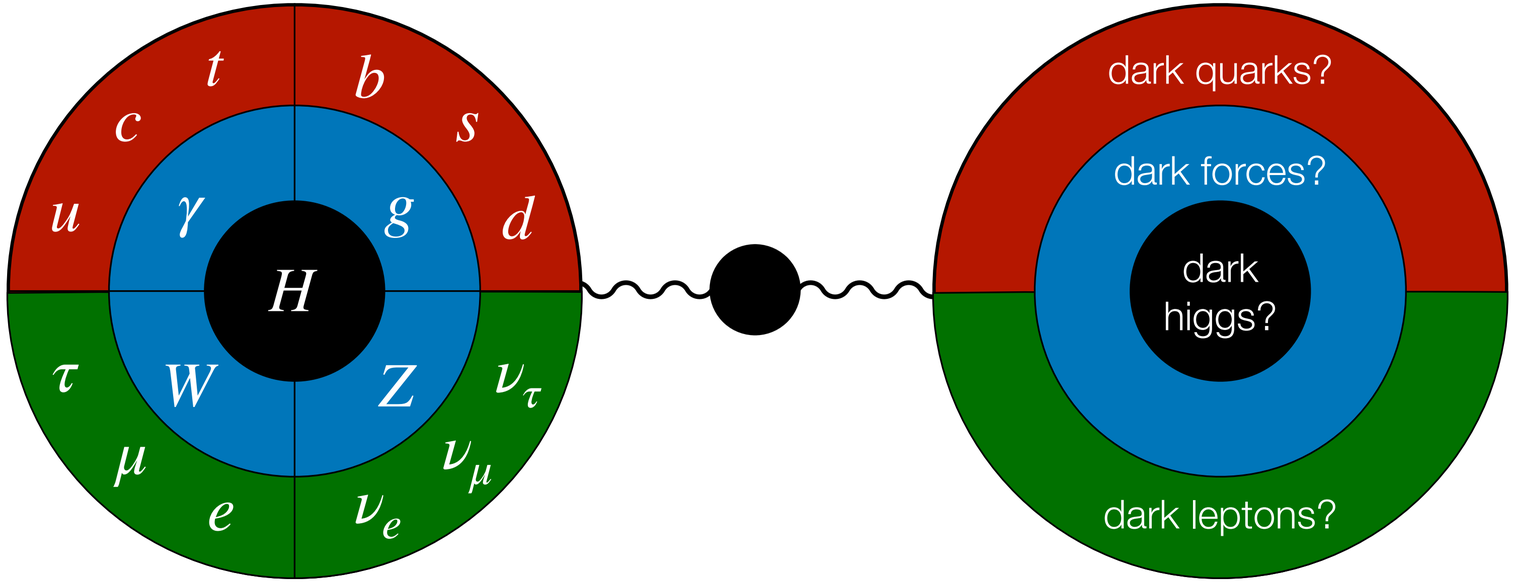
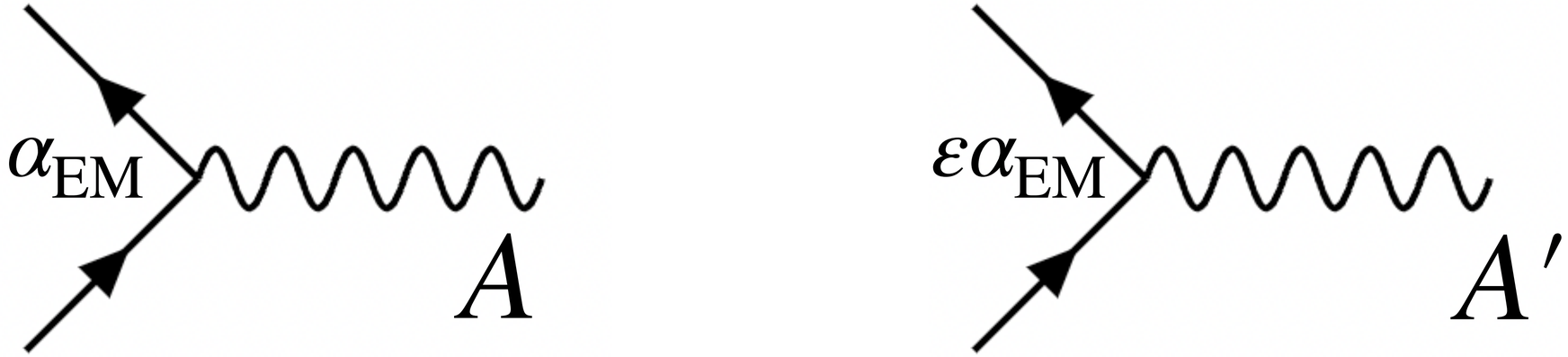
# Dark sectors

- Different Dark Sectors could communicate to SM through portals
- Portals generated by **Quantum Mechanics** between sectors that don't interact **classically**
- Examples of portals:
  - Vector portal (A'): $-\frac{\epsilon}{2\theta_W}F'_{\mu\nu}B^{\mu\nu}$
  - Scalar portal (H): $(\mu S + \lambda S^2)H^\dagger H$
  - Axion portal (a): $\frac{a}{f_a}F_{\mu\nu}\bar{F}^{\mu\nu}$
  - Neutrino portal (N) : $y_N LHN$



# Dark photons

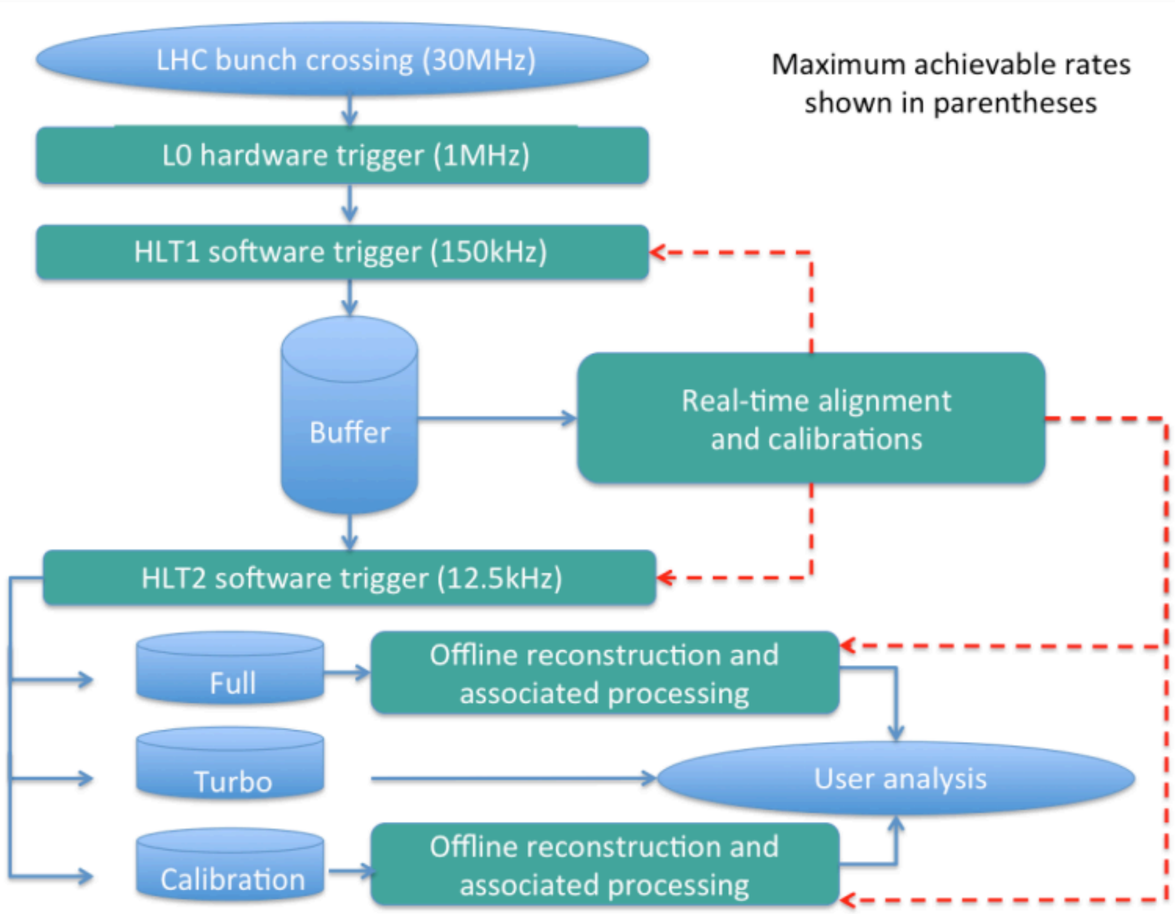



"QED" with a mass effect

# Searches for Dark Photons

[Comput.Phys.Commun. 208 (2016) 35-42]




- Novel Run 2 technique : TURBO stream
  - Not save the full event, only candidates
  - Needed to cope with the large mass window:
    - $[200\ \mathrm{MeV}, 70\ \mathrm{GeV}]$
- More novel techniques to deal with dark photons in Run 3 later in the talk

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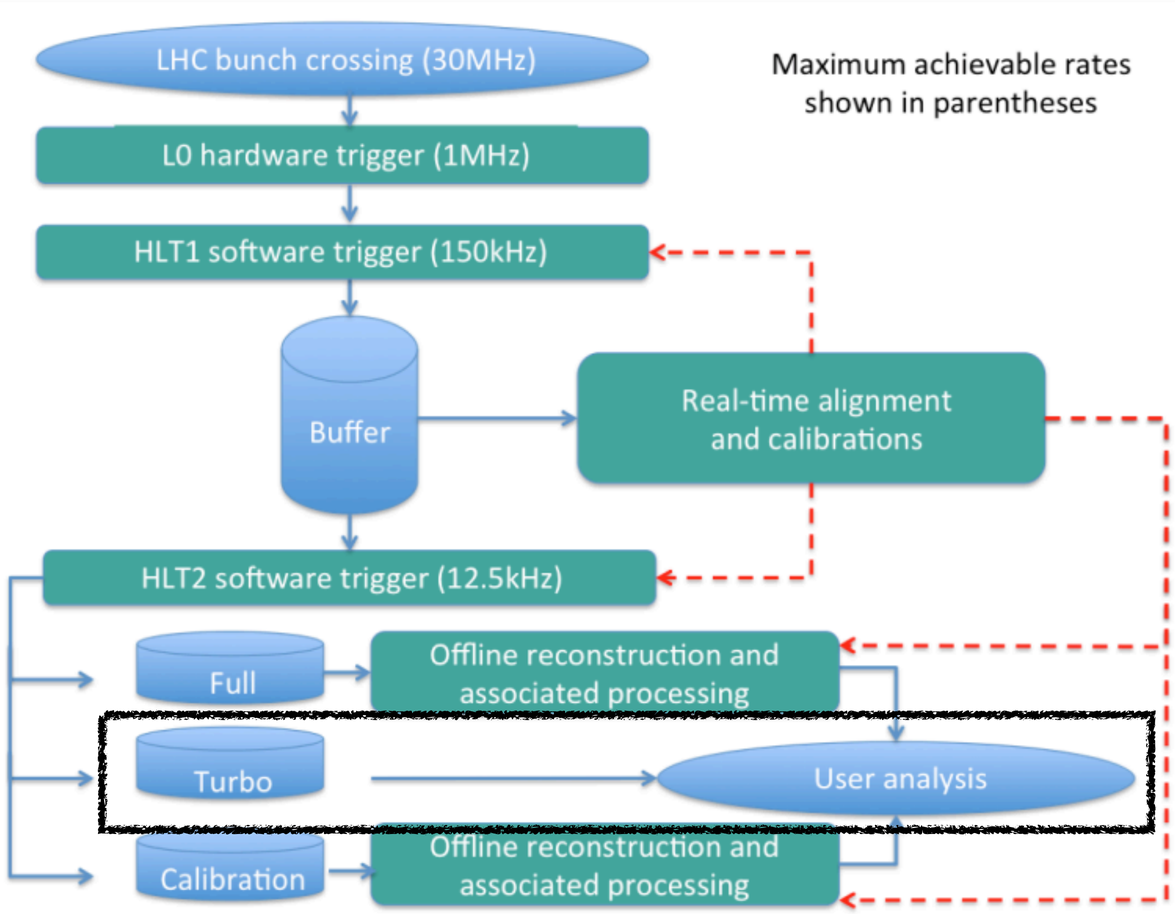


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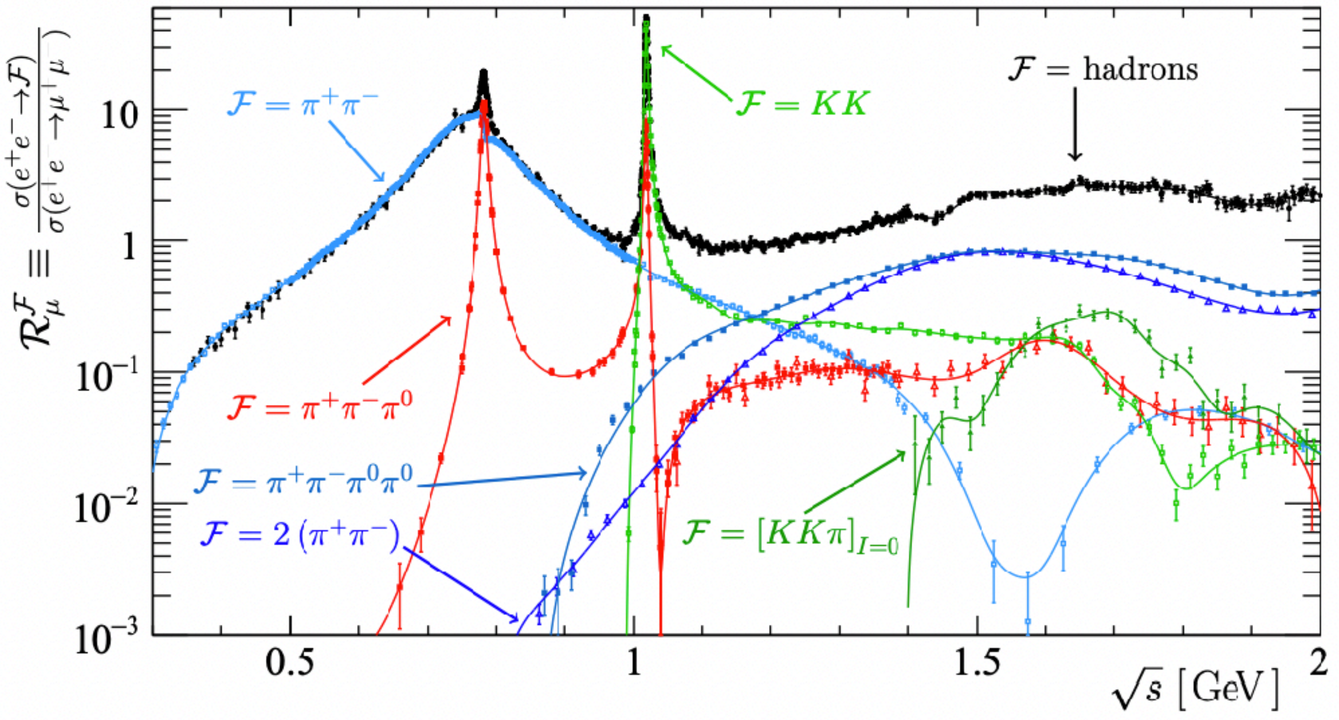
# Dark photons: main production mechanisms [PRL 116 (2016) 25, 251803]

- $A'$ mixes $A$ with a small coupling $\varepsilon$

Relevant production term in $pp$ collisions:

- $$\frac{S_{\mathrm{DP}}}{B_{\mathrm{EM}}} \propto \frac{\epsilon^2 m_{A'}}{\alpha_{\mathrm{EM}} \sigma_{\mu\mu} (N_\ell + \mathscr{R}_\mu)}$$
- Normalize wrt prompt muon production
- Take EM current to hadrons ($\mathscr{R}_\mu$) directly from data

- $A'$ produced in meson decays for $m(A') < 1\ \mathrm{GeV}$
- Drell-Yan afterwards



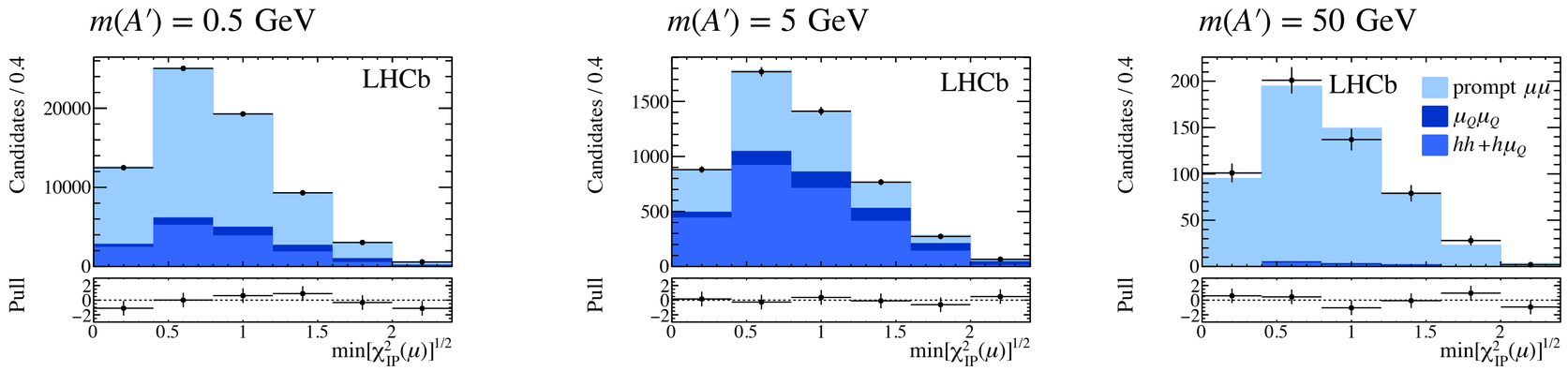

[JHEP 06 (2018) 004]

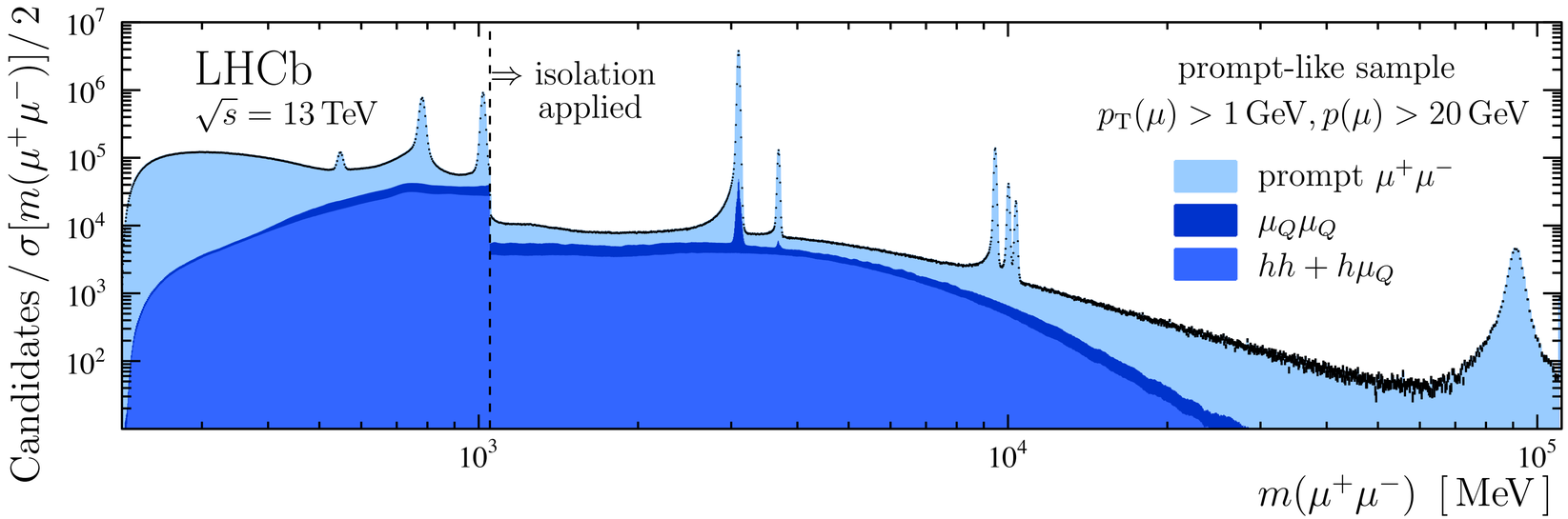
# Dark Photons: prompt search

[PRL (2020) 124 041801]

Using templates
for $\min[\chi^2_{IP}]$ and $\chi^2_{\rm VF}$
(small mass dependence)

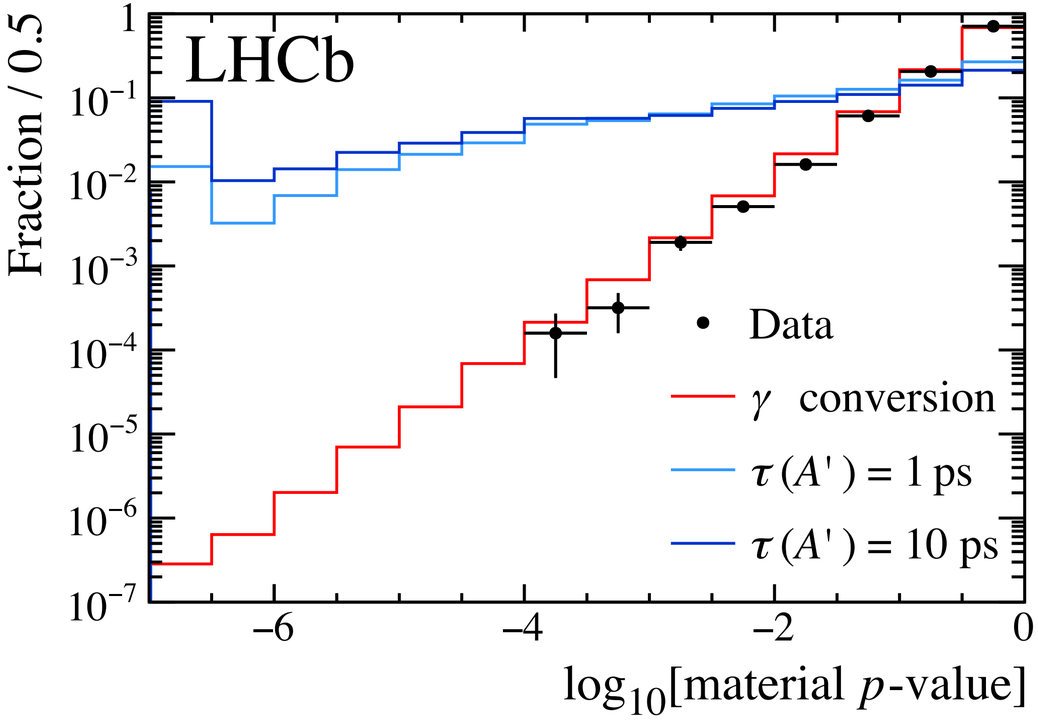
prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
$\mu_Q\mu_Q$ → from simulation (validated)
$hh + h\mu_Q$ → from same-sign dimuons (corrected)

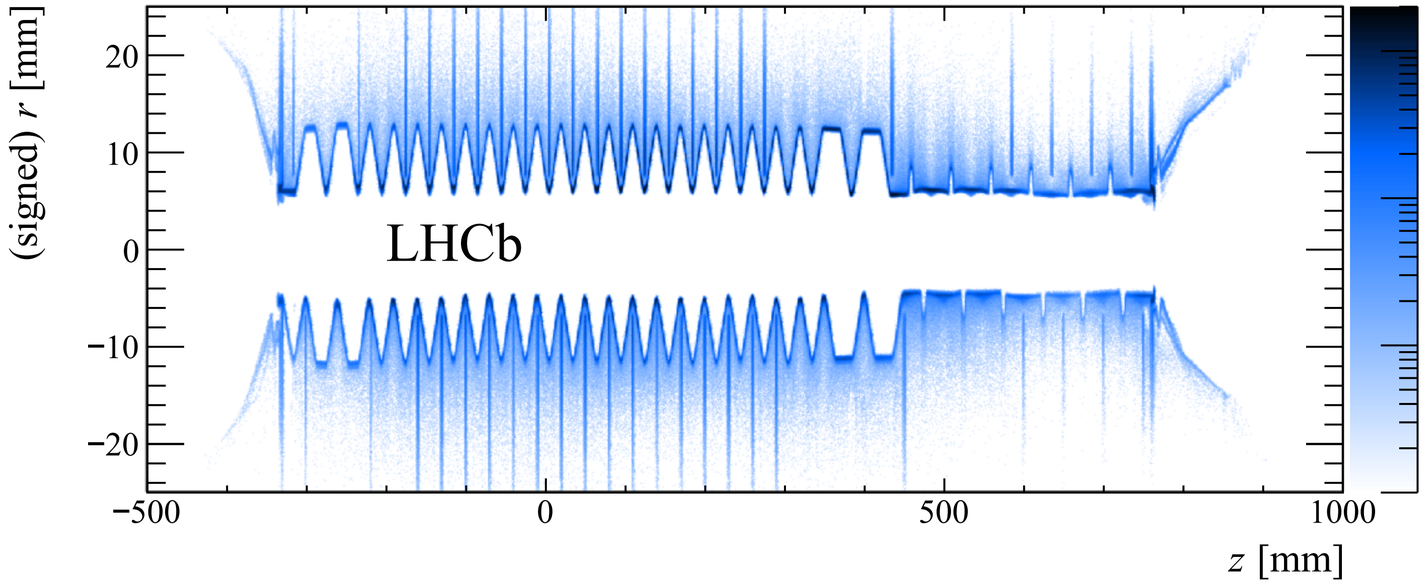


# Material interaction backgrounds

[JINST 13, P06008 (2018)]




- Method to identify particles created in secondary vertices in interaction with VELO
- Three dimensional map produced from data sample of secondary hadronic interactions

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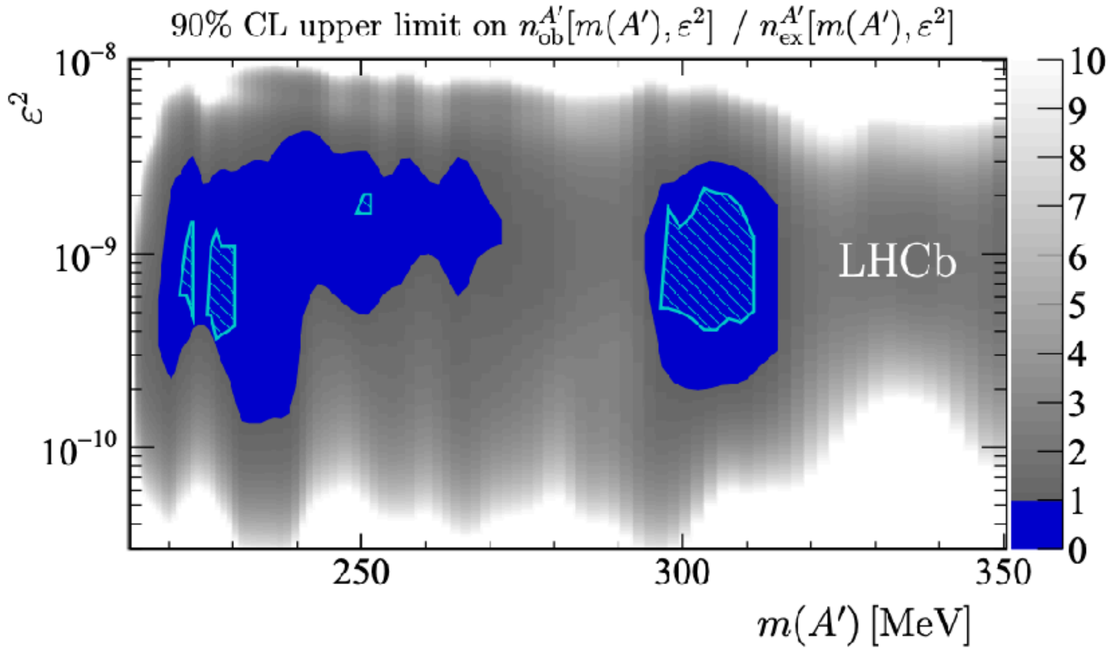
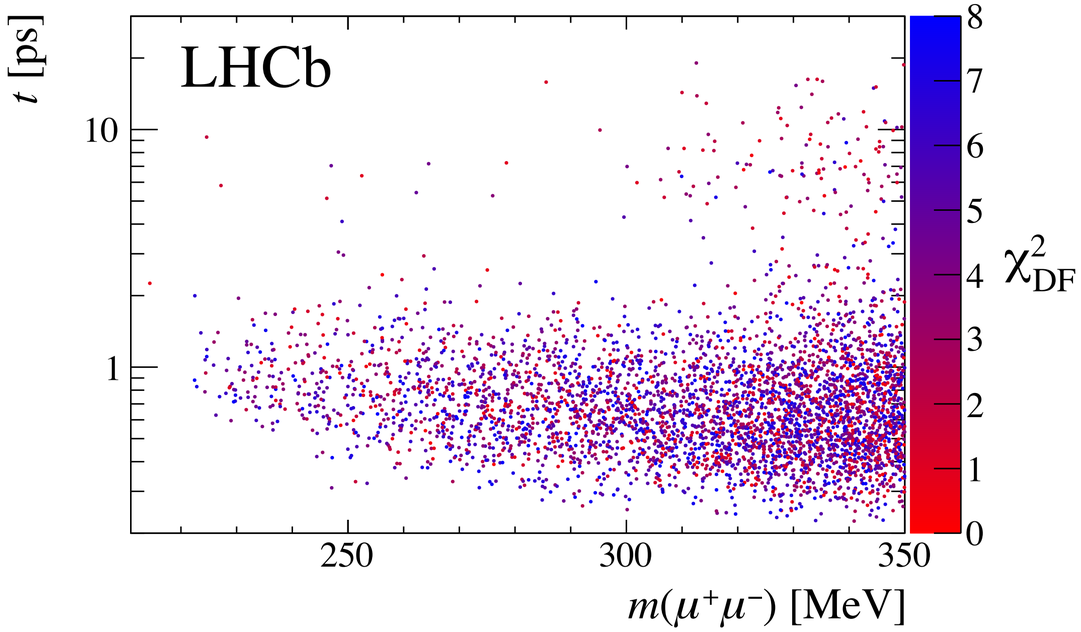
# Dark Photons: displaced search

[PRL (2020) 124 041801]

- Material background is mainly from photon conversions
- Isolation decision tree from $B_s^0 \to \mu^+\mu^-$ search:
  - Suppress events with additional number of tracks, i.e. $\mu$ from b-hadron decays.
- Fit in bins of mass and lifetime - use consistency of decay topology $\chi^2$ .



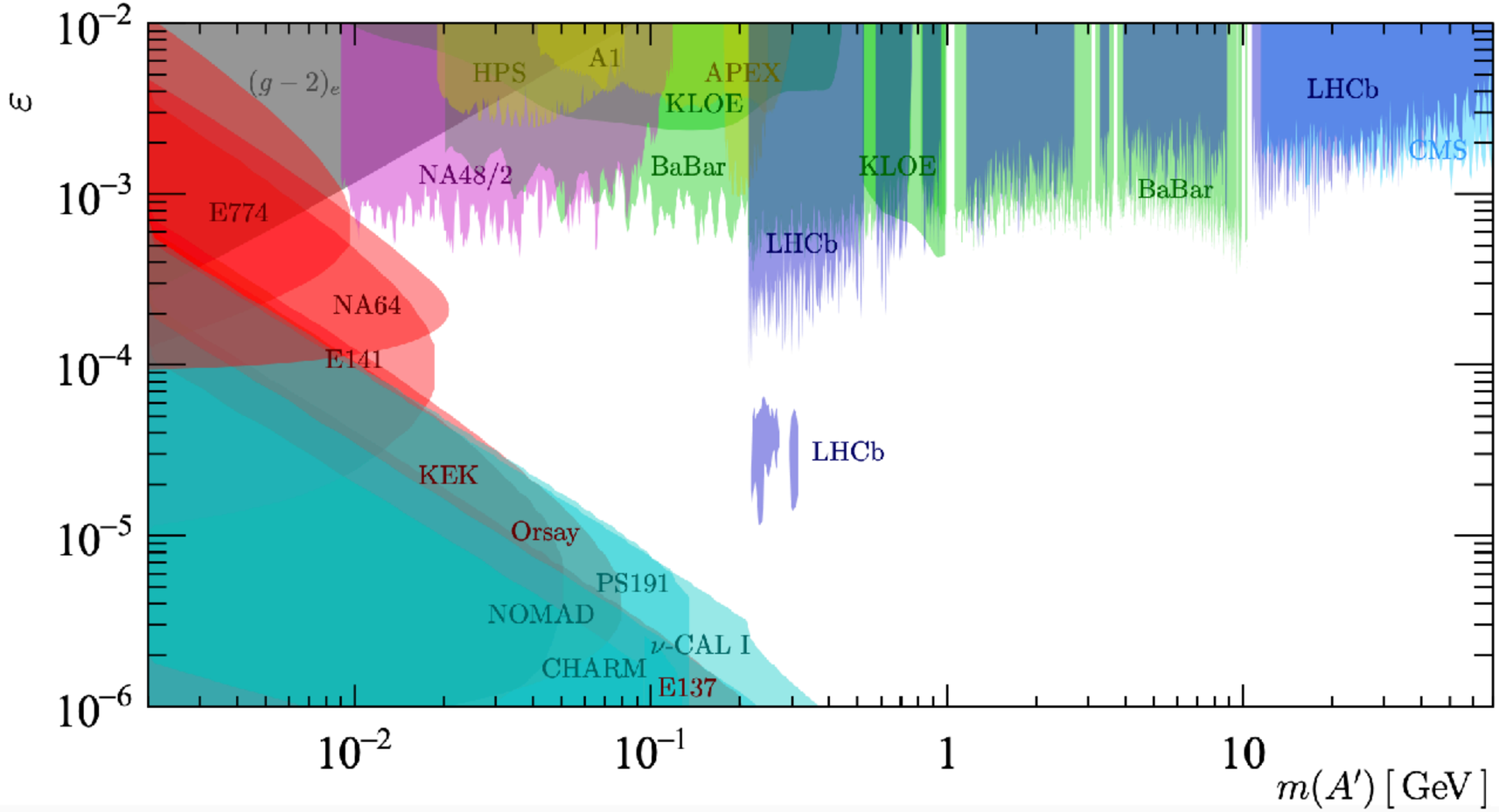




- **No significant excess found** - small parameter space region excluded:
- First limit ever **not from beam dump**.

# Dark Photons: results

[PRL (2020) 124 041801]

- Results obtained with 5.6 fb$^{-1}$ at 13 TeV
  - Prompt search in large range: $2m(\mu) < m(\mu\mu) < m(Z)$
  - Displaced search in sensitive region $214 < m(\mu\mu) < 350$ MeV

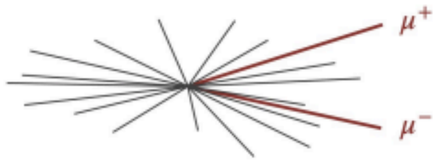


# Dimuon resonances: model independent

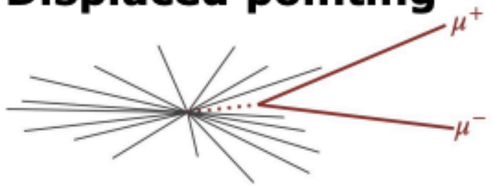
[JHEP 10 (2020) 156]

+ no isolation requirement
+ non-zero width considered

**Inclusive Prompt**

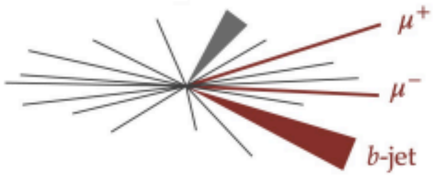



**Displaced pointing**

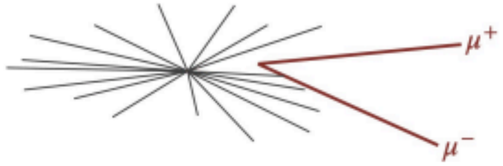



+ non-zero width considered

**Prompt + b-jet**




**Displaced non-pointing**




- Model independent searches allowing for different topologies

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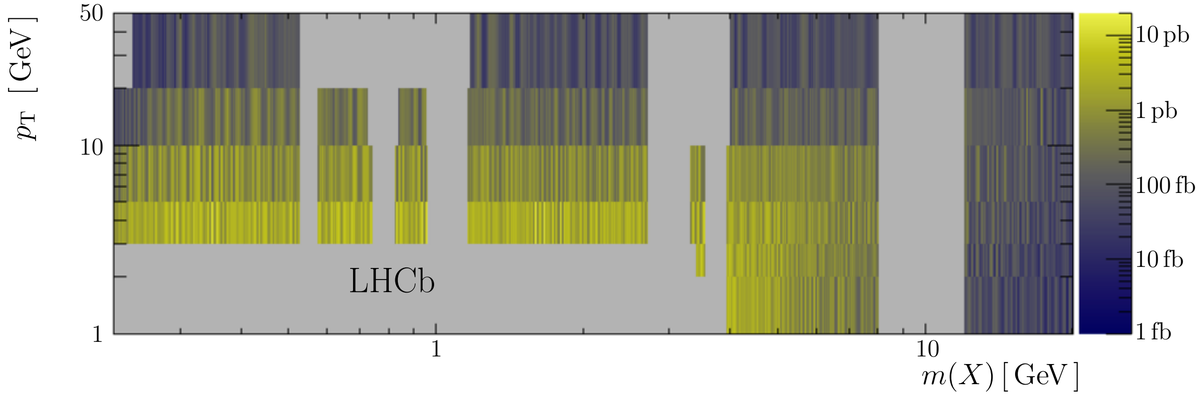
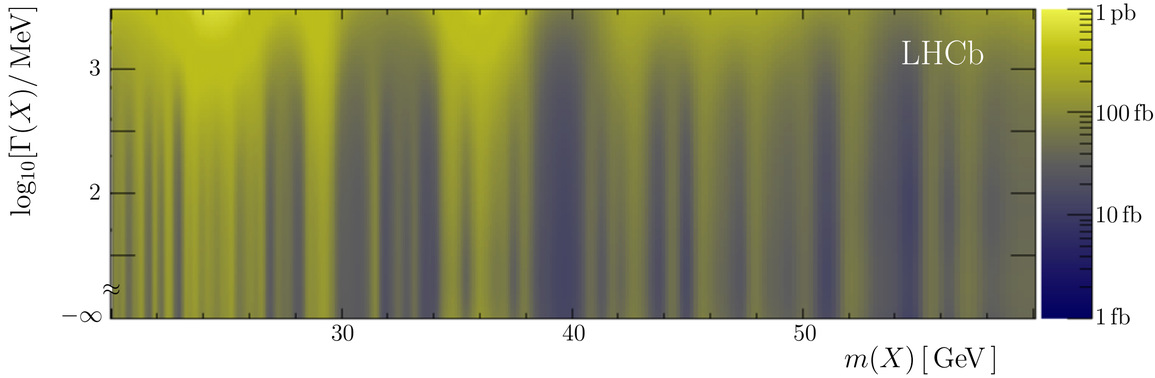
# Dimuon resonances: model independent

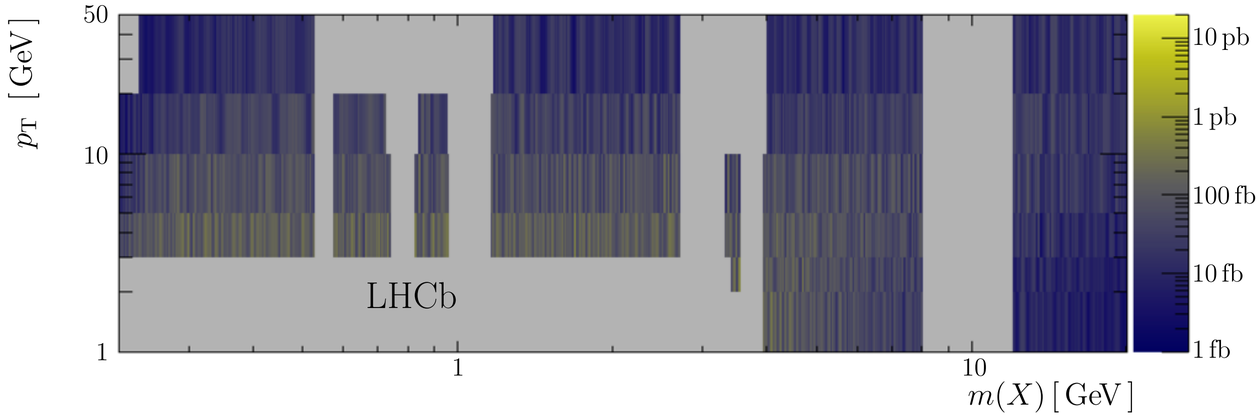
[JHEP 10 (2020) 156]

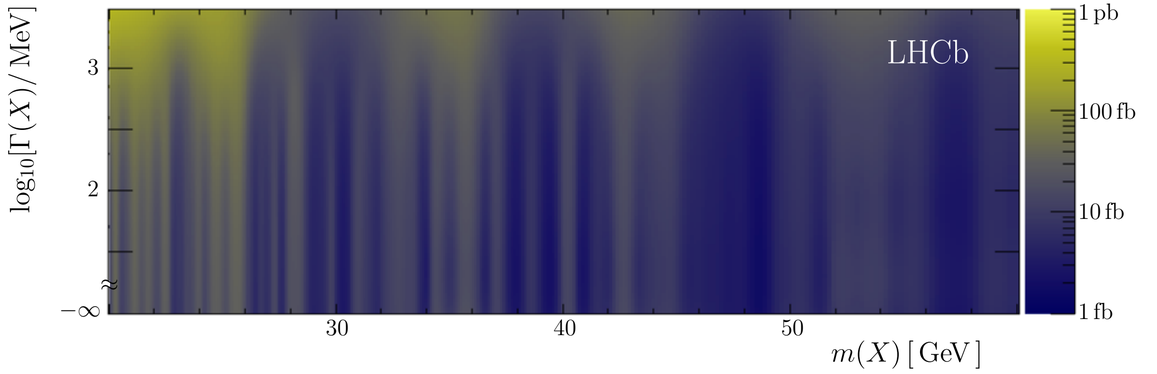
- Prompt inclusive




- Prompt beauty associated

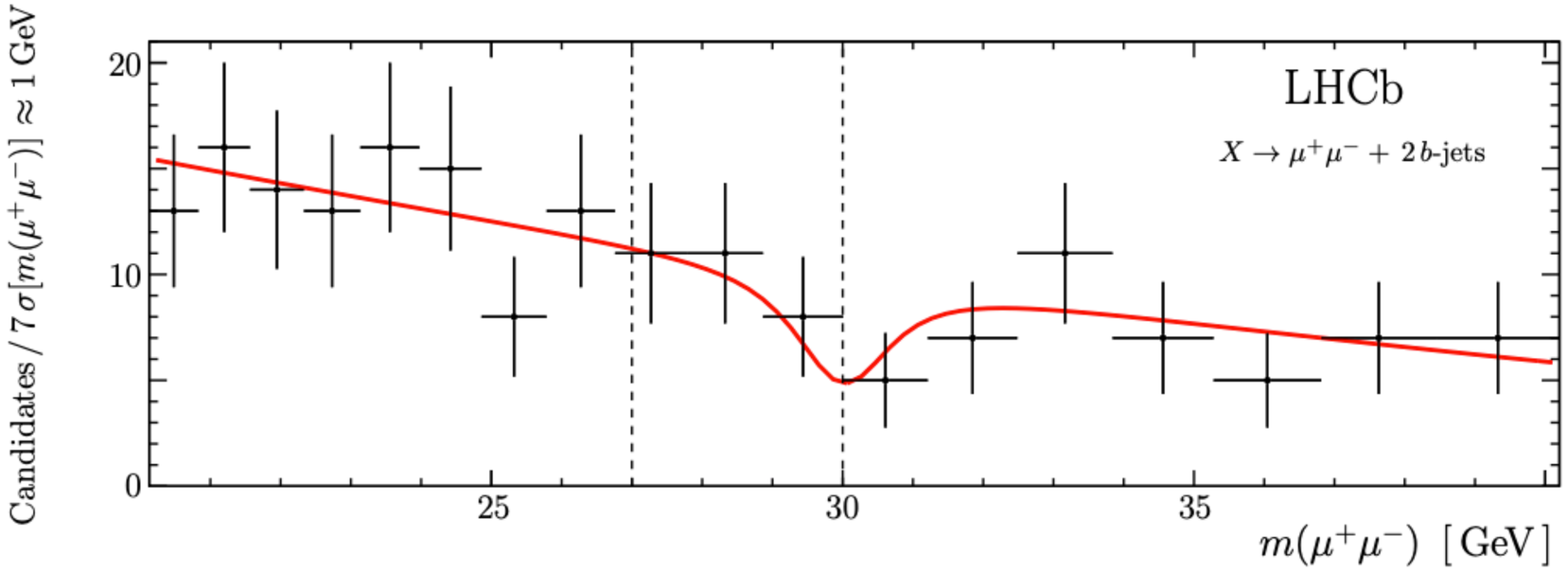



- Non-negligible width considered for higher masses

# Dimuon resonances: model independent

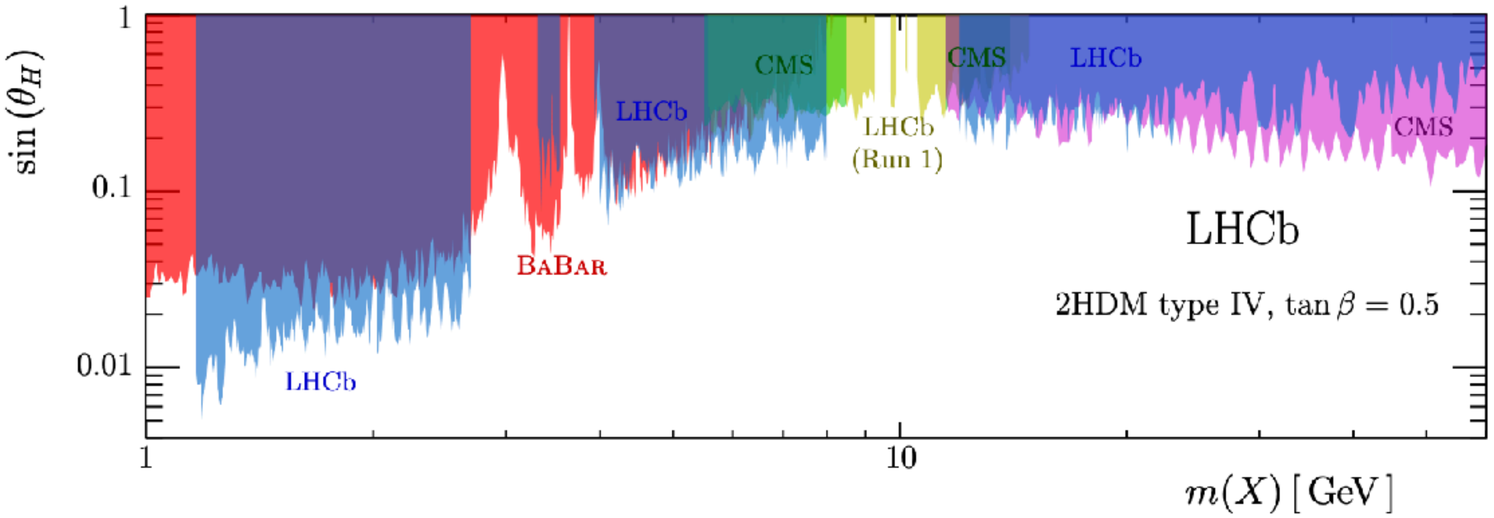
[JHEP 10 (2020) 156]



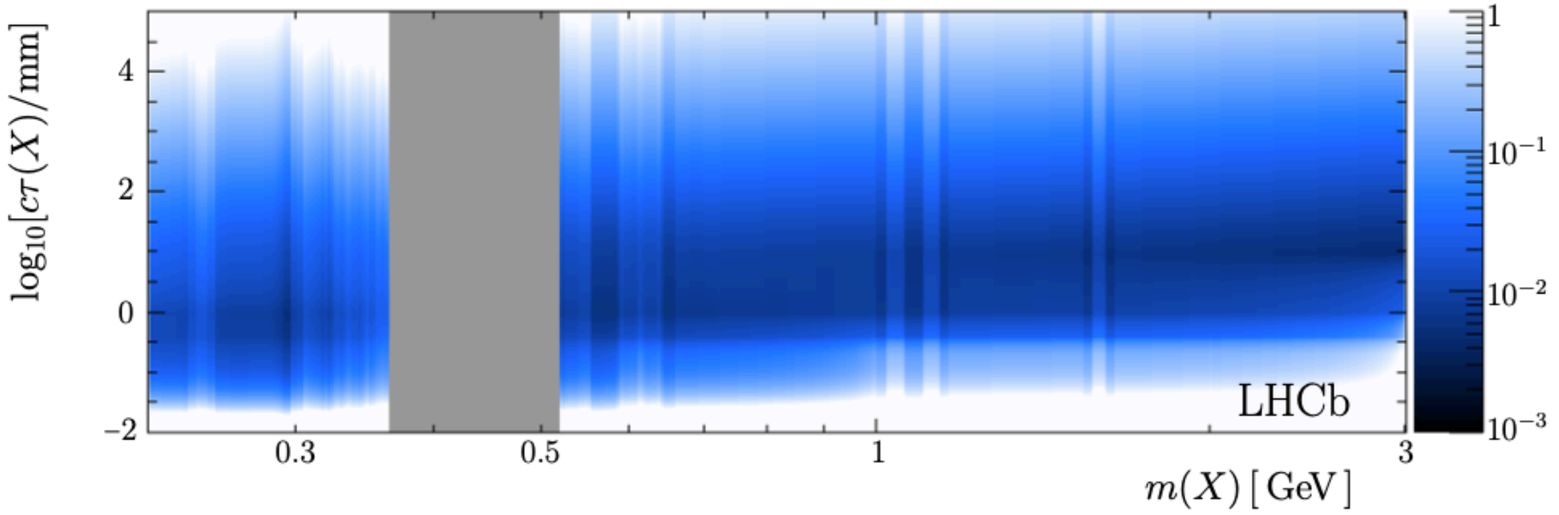

- Search for the excess found by CMS [JHEP 11 (2018) 161)] in $\mu^+\mu^- + \bar{b}b$
  - No excess found

# Dimuon resonances

[JHEP 10 (2020) 156]



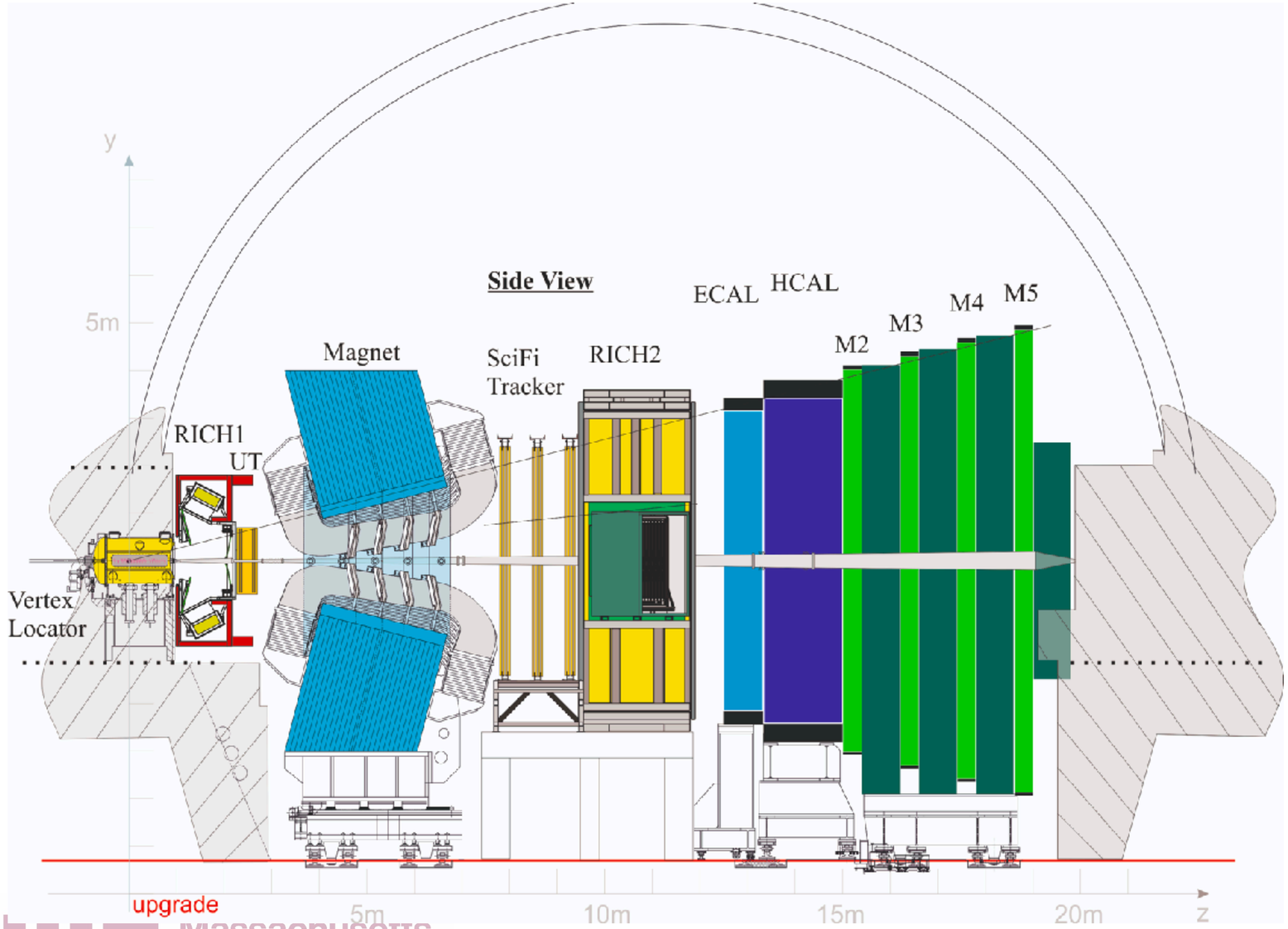

2HDM: $X - H$ mixing angle




$\gamma - Z_{\text{HV}}$ kinetic mixing

# The upgraded LHCb detector

[JINST 19 (2024) 05, P05065]




The experiment was upgraded after the end of Run 2 in 2018

- General:
  - Adapt the detector for higher occupancy and readout capacity
- Replace detectors:
  - VELO
  - Tracking:
    - UT: replaces TT
    - SciFi: replaces T-stations
    - First MUON station is removed

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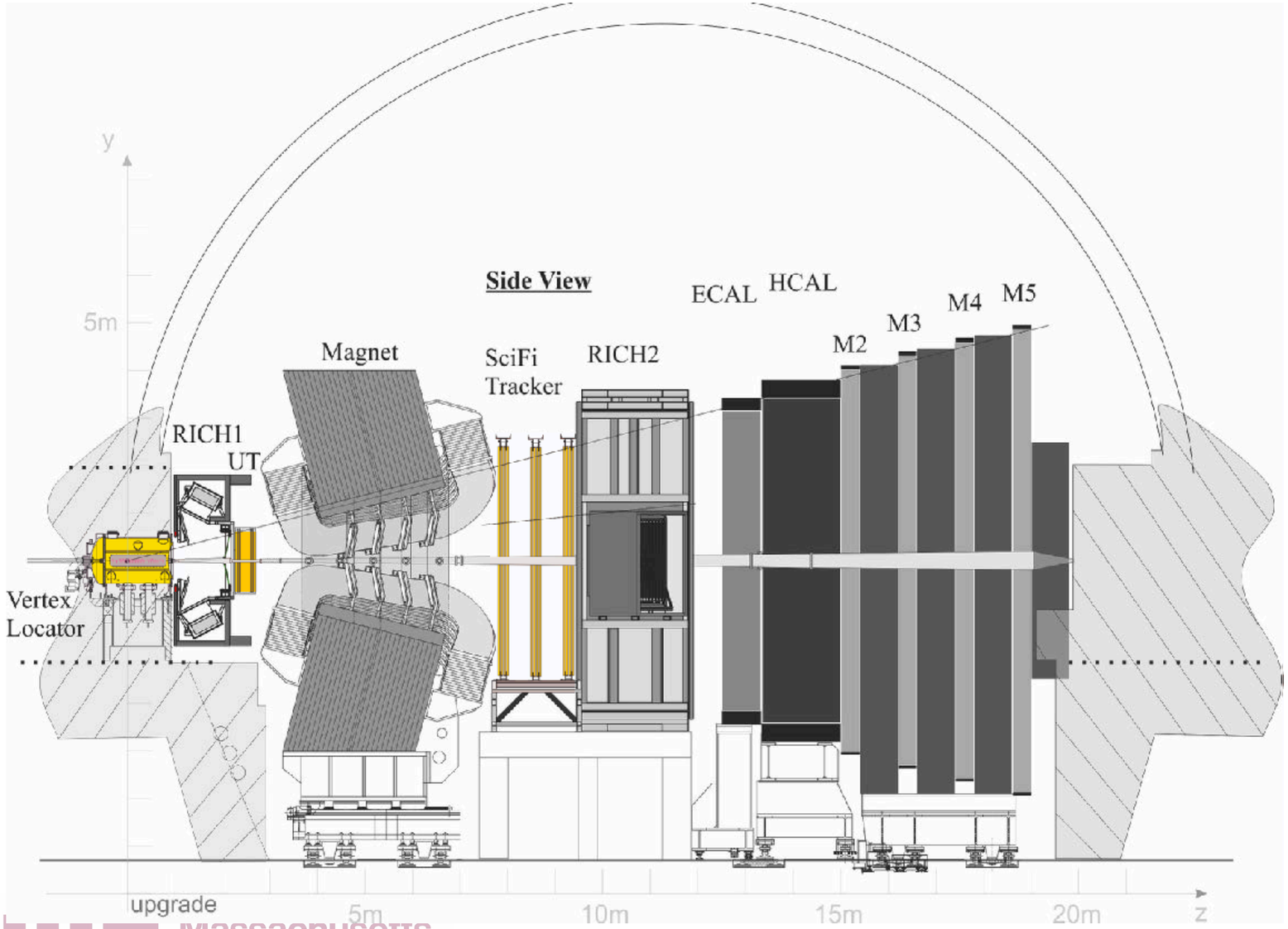


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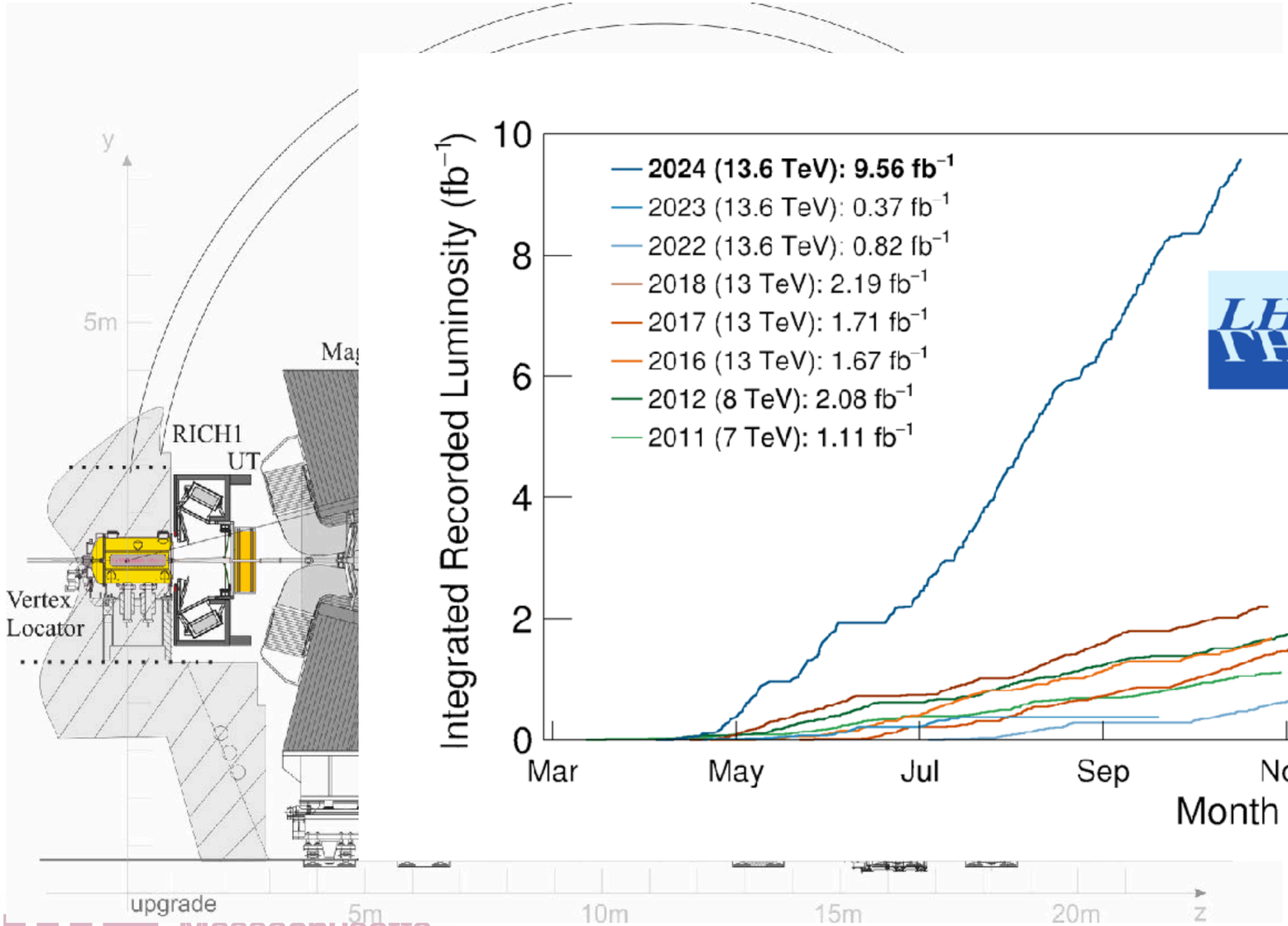





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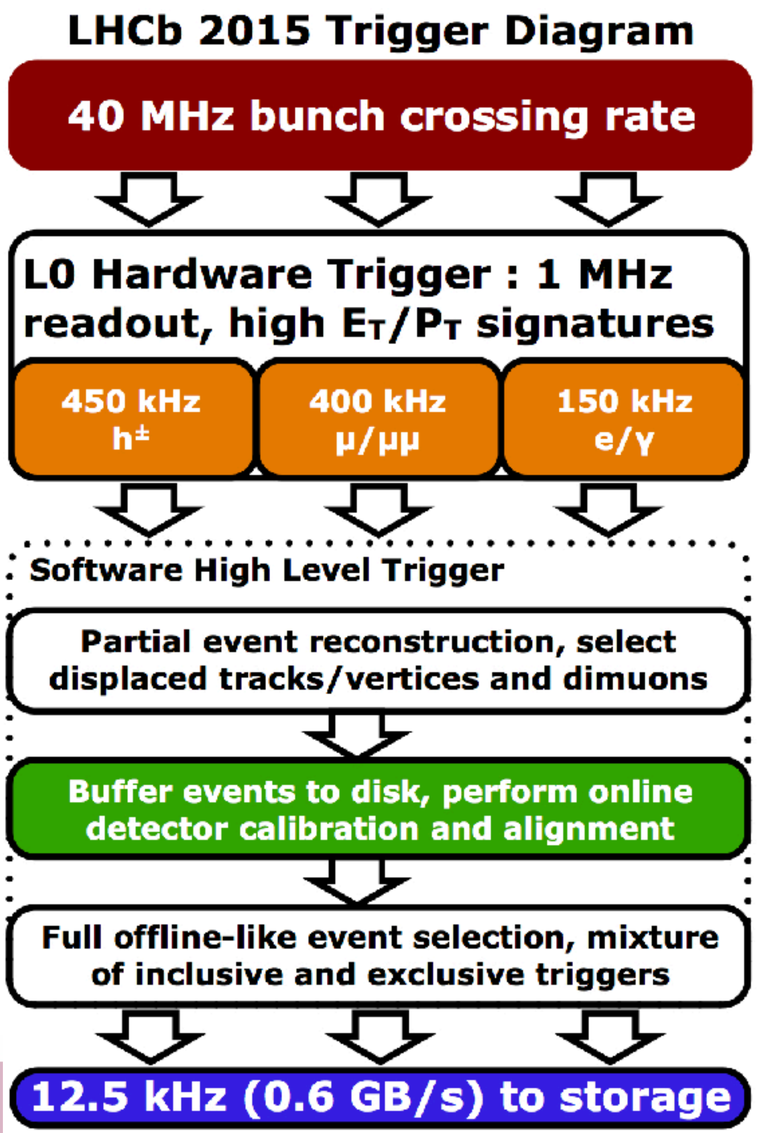
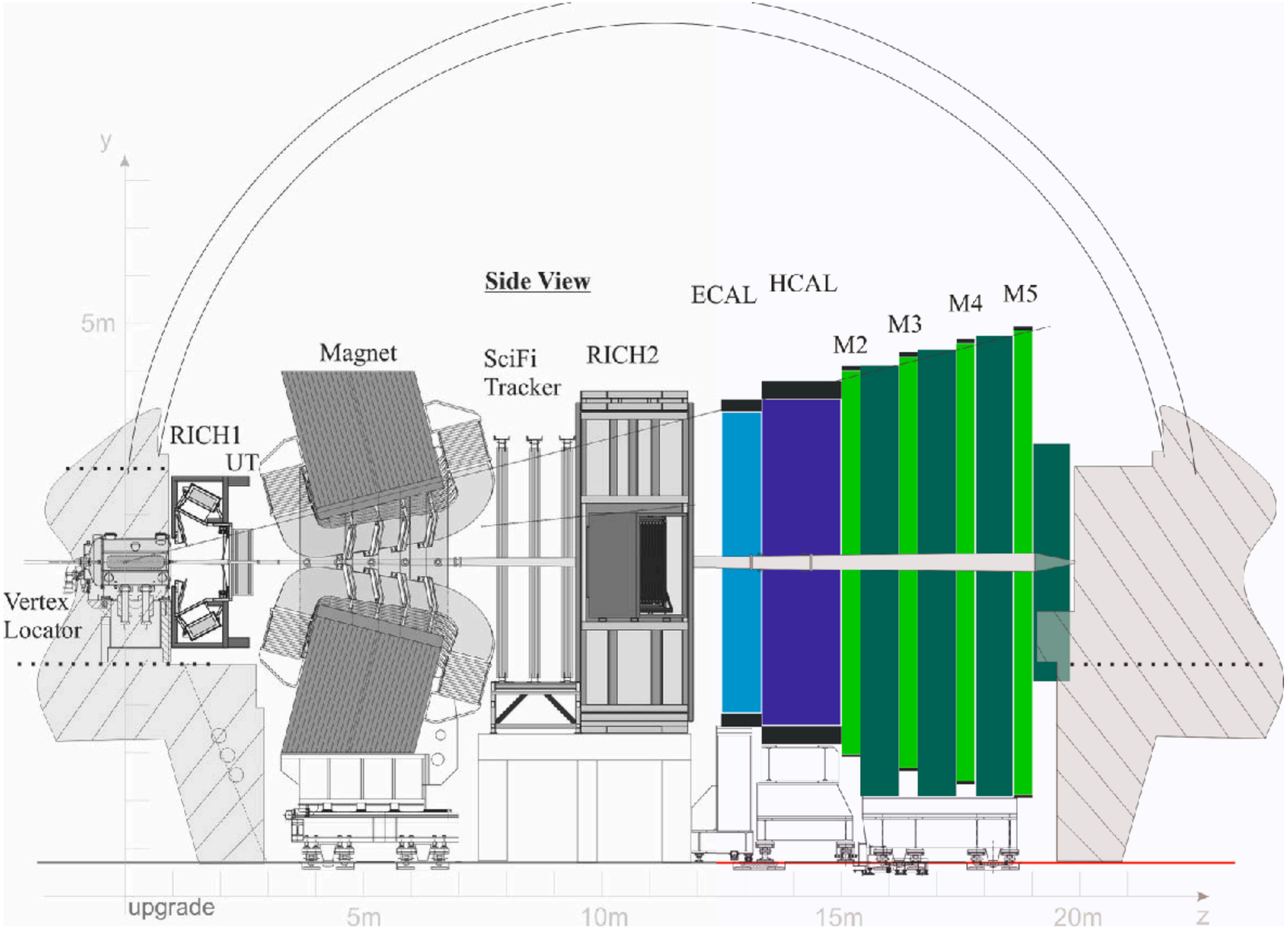
# The upgraded dataflow

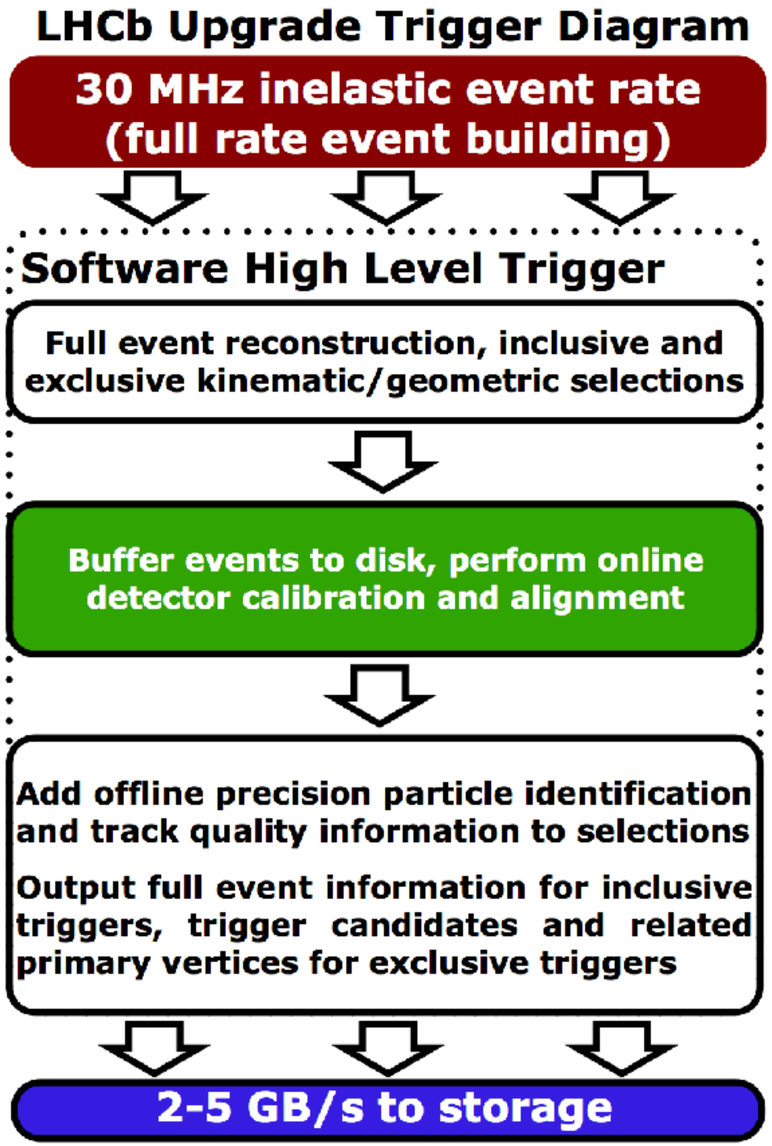
[LHCb-FIGURE-2020-016]

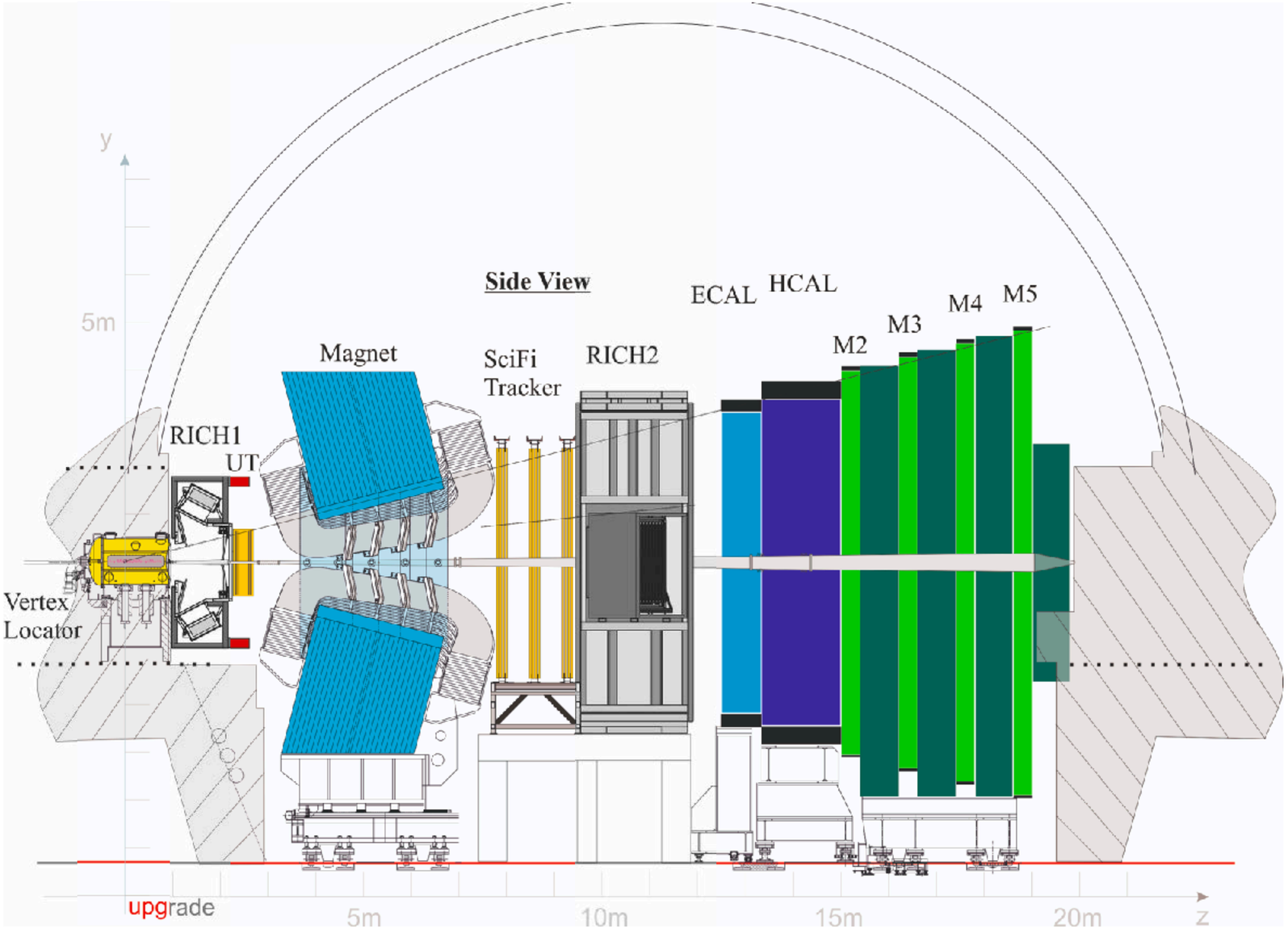


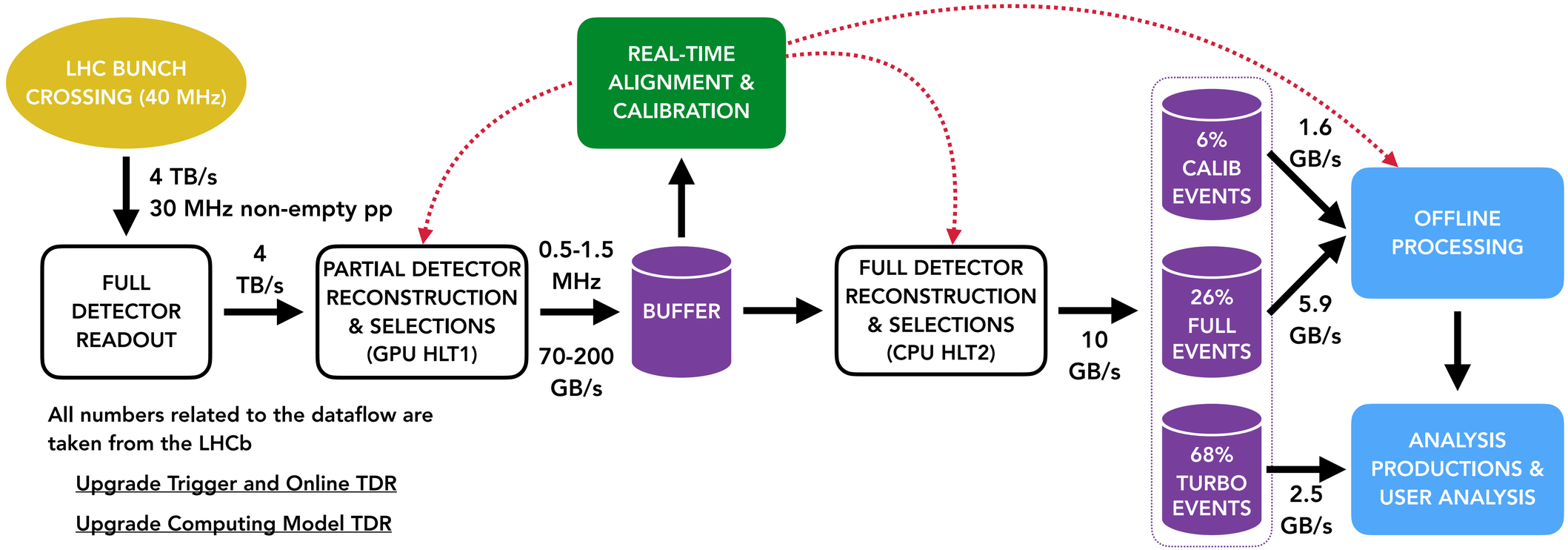
# The upgraded dataflow

[LHCb-FIGURE-2020-016]



# Allen: a GPU High Level Trigger for LHCb [Comput.Softw.Big Sci. 4 (2020) 1, 7]



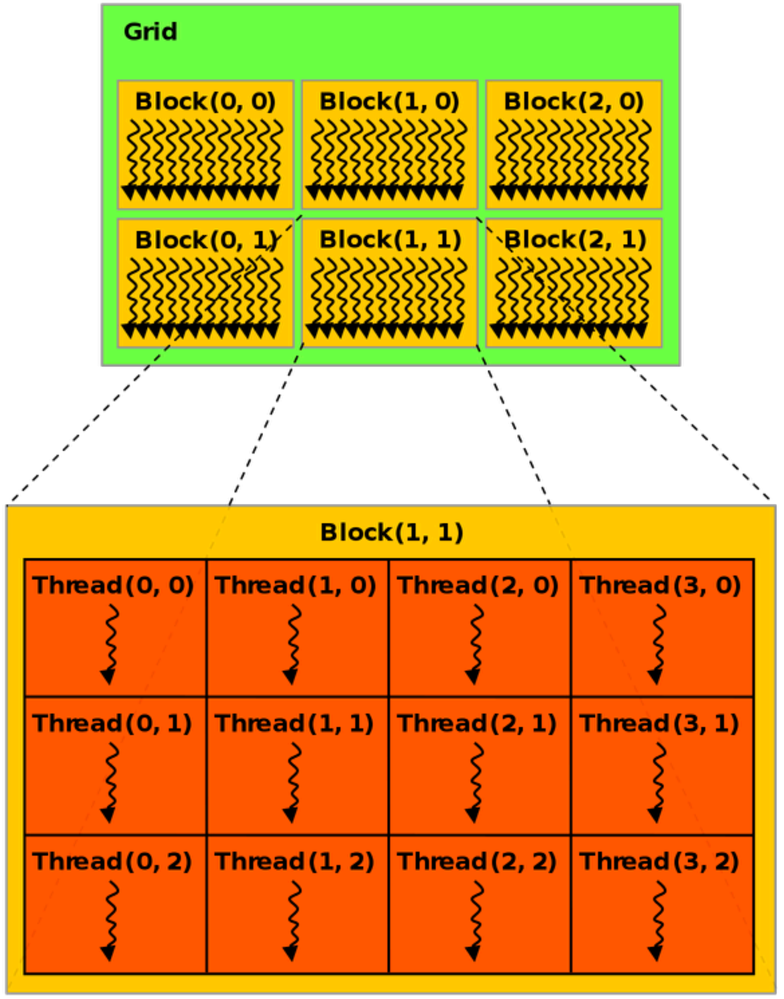

All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

# Allen: a GPU High Level Trigger for LHCb [Comput.Softw.Big Sci. 4 (2020) 1, 7]

- GPU: a LOT of threads $> \mathcal{O}(1000)$
  - Grouped in **blocks of threads**
- Parallelisation:
  - Grid $\longleftrightarrow$ Set of events
  - Event $\longleftrightarrow$ Block
  - Track $\longleftrightarrow$ Thread
- No dynamic allocation:
  - Count first write later
  - The size of the arrays are set before running each kernel
- Single precision **floats**

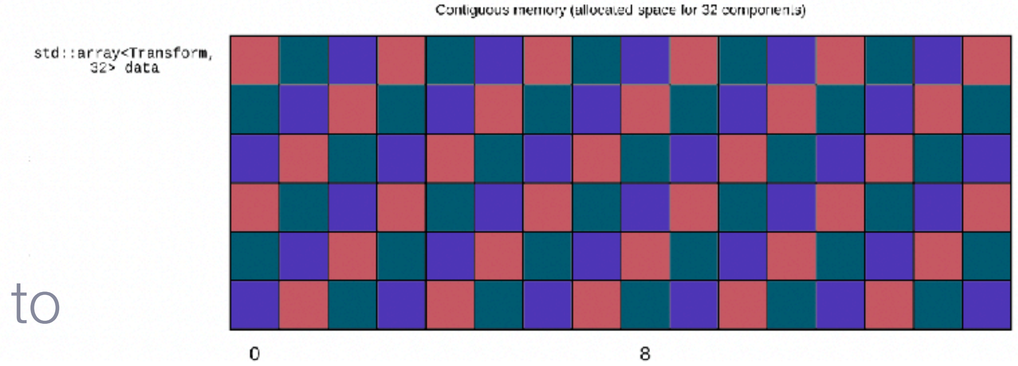


# Allen: a GPU High Level Trigger for LHCb. [Comput.Softw.Big Sci. 4 (2020) 1, 7]

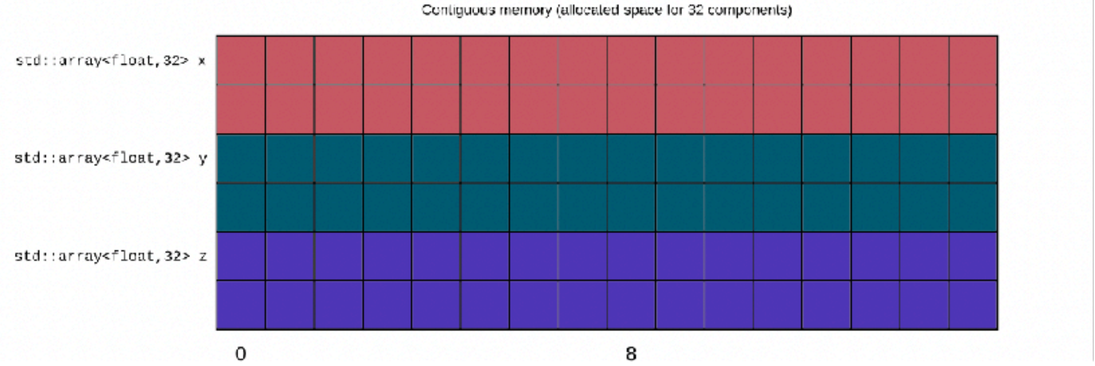
```
struct point3D {
    float x;
    float y;
    float z;
};
struct point3D points[N];
float get_point_x(int i) { return points[i].x; }
```

```
struct pointlist3D {
    float x[N];
    float y[N];
    float z[N];
};
struct pointlist3D points;
float get_point_x(int i) { return points.x[i]; }
```

**AOS layout**




**SOA layout**




Thanks to Renato Quagliani for the diagrams

- Contiguous memory access: structure of arrays (SoA)
  - Structure of "BIG" arrays that hold information of a bunch of events
- Adequate when a lot of memory is being written/read at the same time
- Block Index + Thread Index → Position in the array

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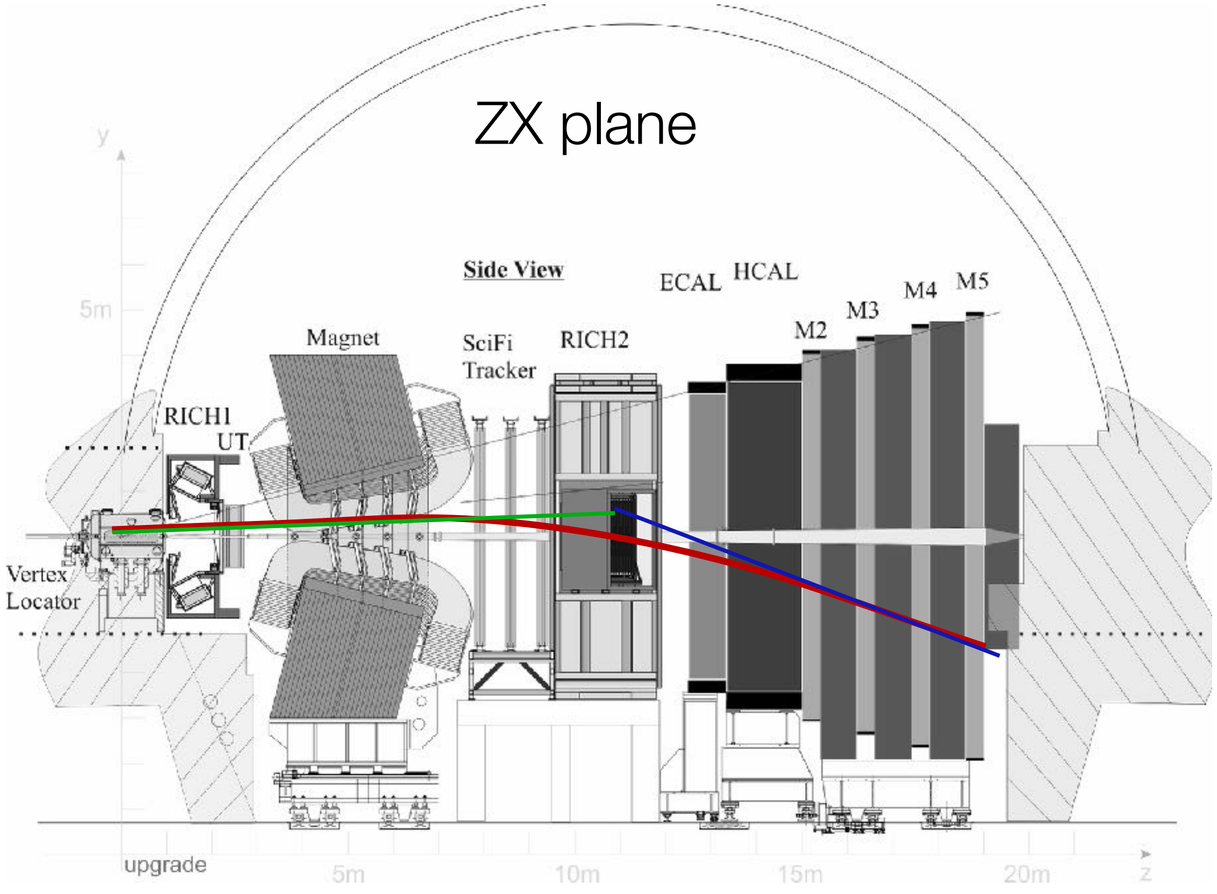
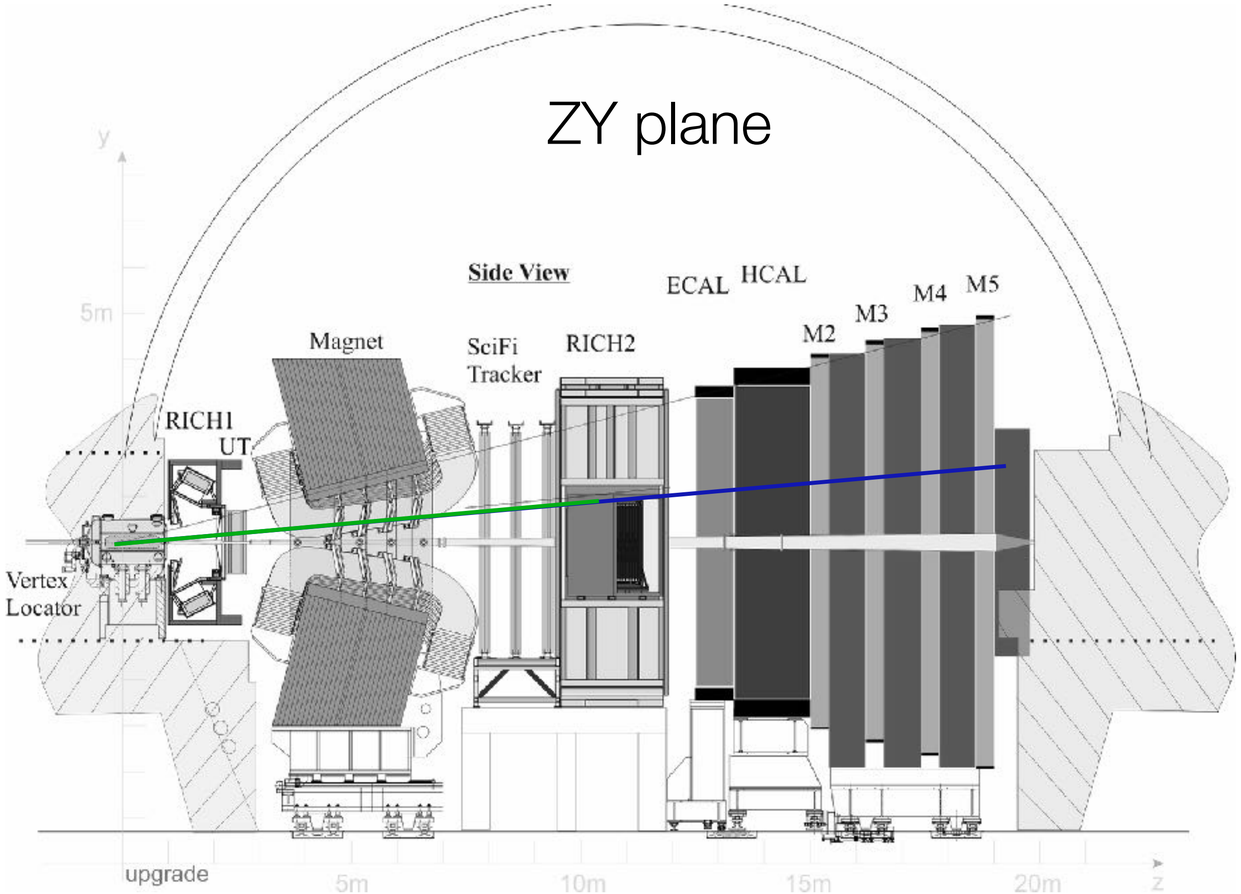
# A track through LHCb




$$\frac{q}{p} = \frac{1}{|\int d\vec{l} \times \vec{B}|} \left( \frac{t_{x,\mathrm{SciFi}}}{\sqrt{1 + t_{x,\mathrm{SciFi}}^2 + t_{y,\mathrm{SciFi}}^2}} - \frac{t_{x,\mathrm{VELO}}}{\sqrt{1 + t_{x,\mathrm{VELO}}^2 + t_{y,\mathrm{VELO}}^2}} \right)$$

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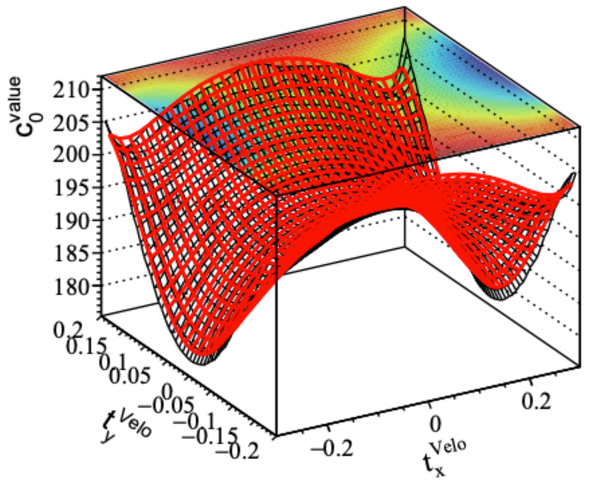
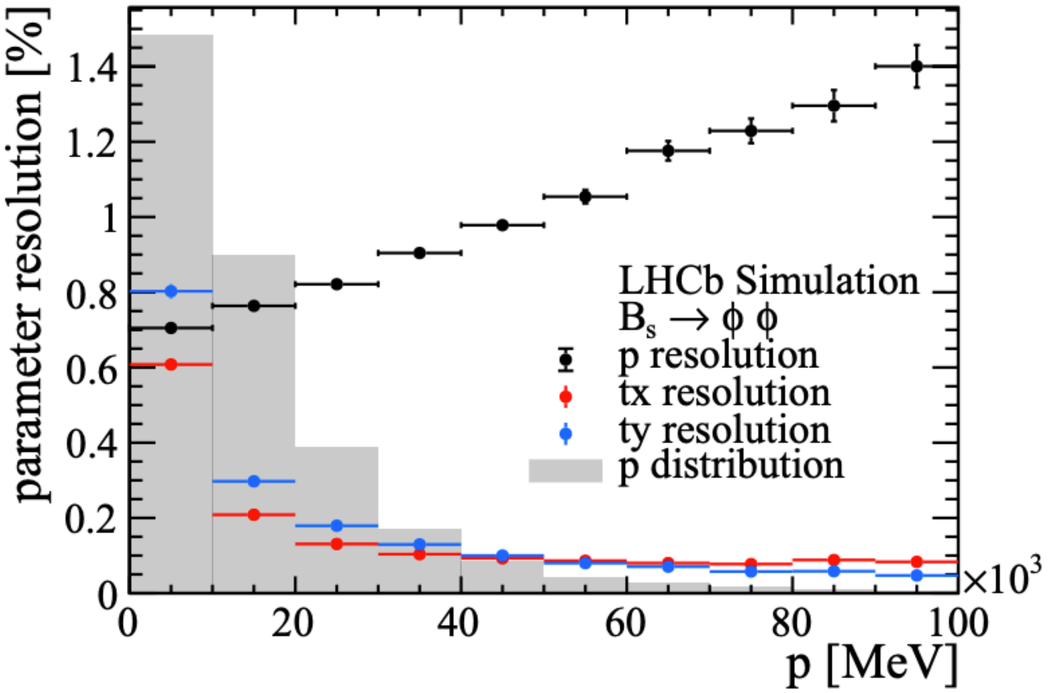
# Fast tracking: momentum parameterisation [IEEE Access 12 (2024) 114198-114211]




- Basic idea:
- Expand $\int |\,\overrightarrow{B} \times d\vec{l}\,|_x = \Sigma_0^4\, c_i(\Delta t)^i$
  - Obtain a **map** by fitting the coefficients to **polynomials** such that:
    $c_i = c_i(t_{x,m}, t_{y,m})$

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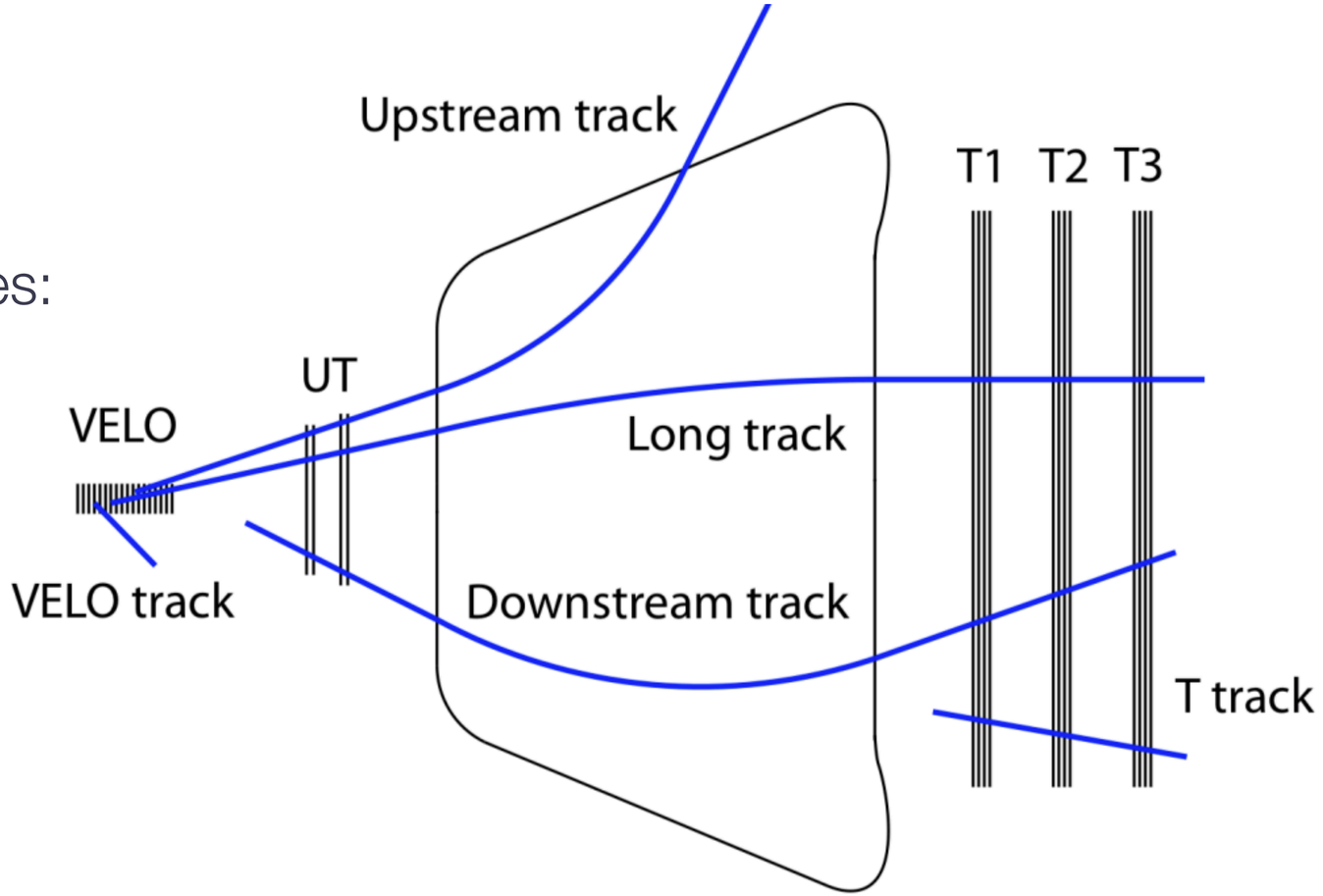
# Downstream tracks

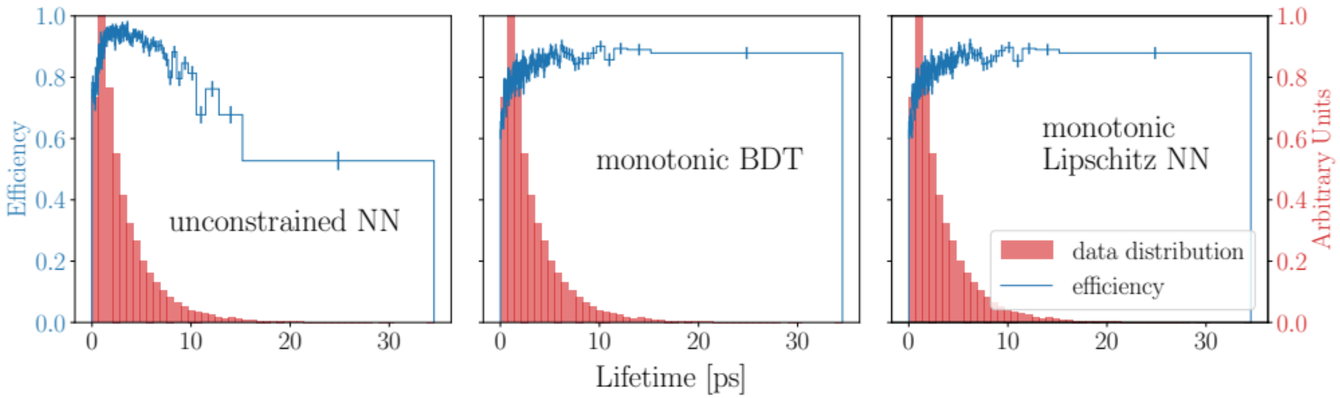
[Eur.Phys.J.C 84 (2024) 6, 608]

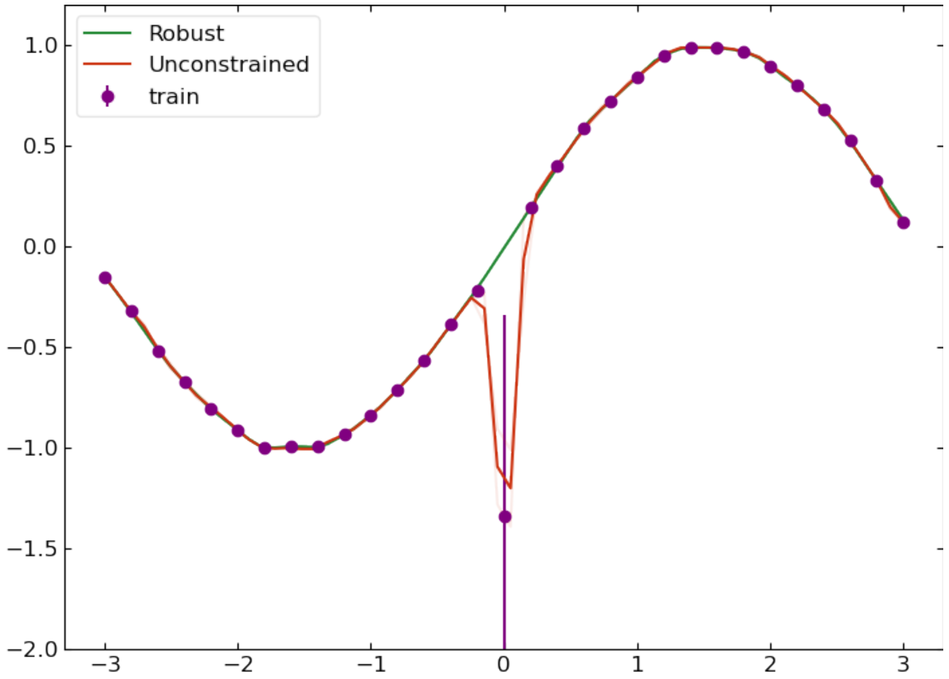
- Baseline reconstruction:
  - Long tracks (VELO + UT + SciFi)
- Alternative for very displaced signatures:
  - Downstream tracks
- Access to $\tau > 200$ ps
- More challenges:
  - Worst vertex resolution
  - Copious displaced backgrounds:
    - $K_S^0$, $\Lambda$



# Lipschitz constrained NN [Mach.Learn.Sci.Tech. 4 (2023) 3, 035020]

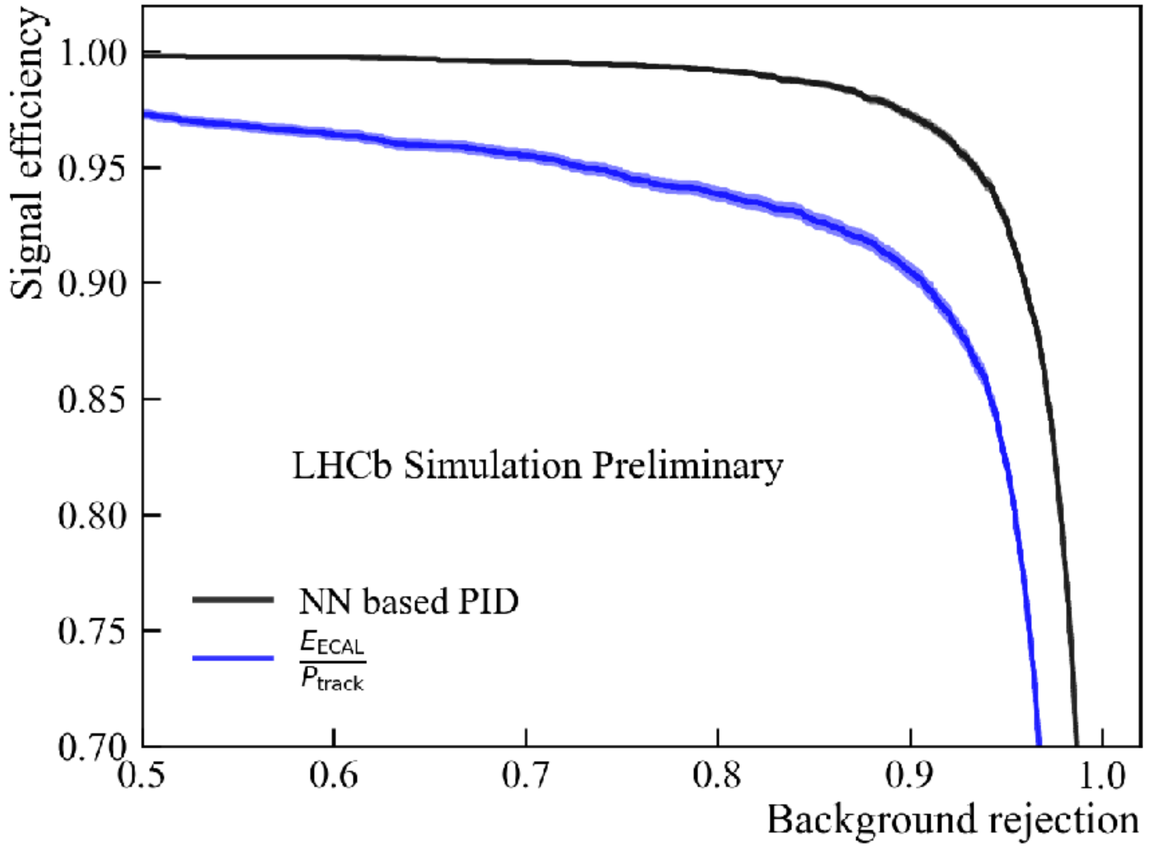
- Robustness
  - Strict bound on the slope of the function
  - Natural way of rejecting noisy outliers
- Monotonicity:
  - Trigger:
    - Especially interesting for $p_T$ and displacement



# Dark Photons: Run 3, PID in real time [LHCb-FIGURE-2024-003]

- Dedicated electron ID using Lipschitz constrained Neural Network
- Reconstruction of electron features at HLT1
  - $\frac{E_{\mathrm{ECAL}}}{P_{\mathrm{track}}}$
  - Electron cluster dispersion
  - Electron cluster barycentre
- 50% improvement wrt baseline EoP based selection
- “Hyper-turbo” selection:
  - Prompt dielectrons are saved to histograms right before the event is triggered
  - Fully reconstructed events are prescaled
  - Necessary to cope with the large amount of background

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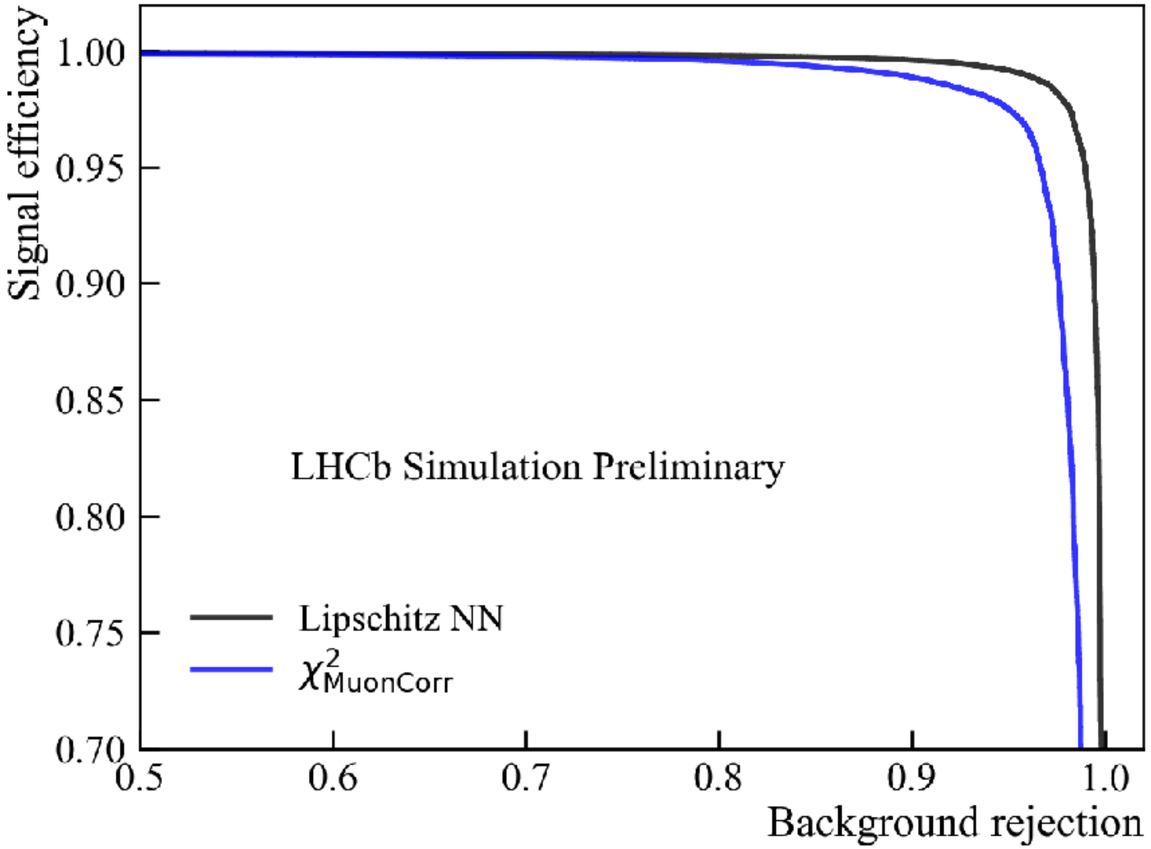
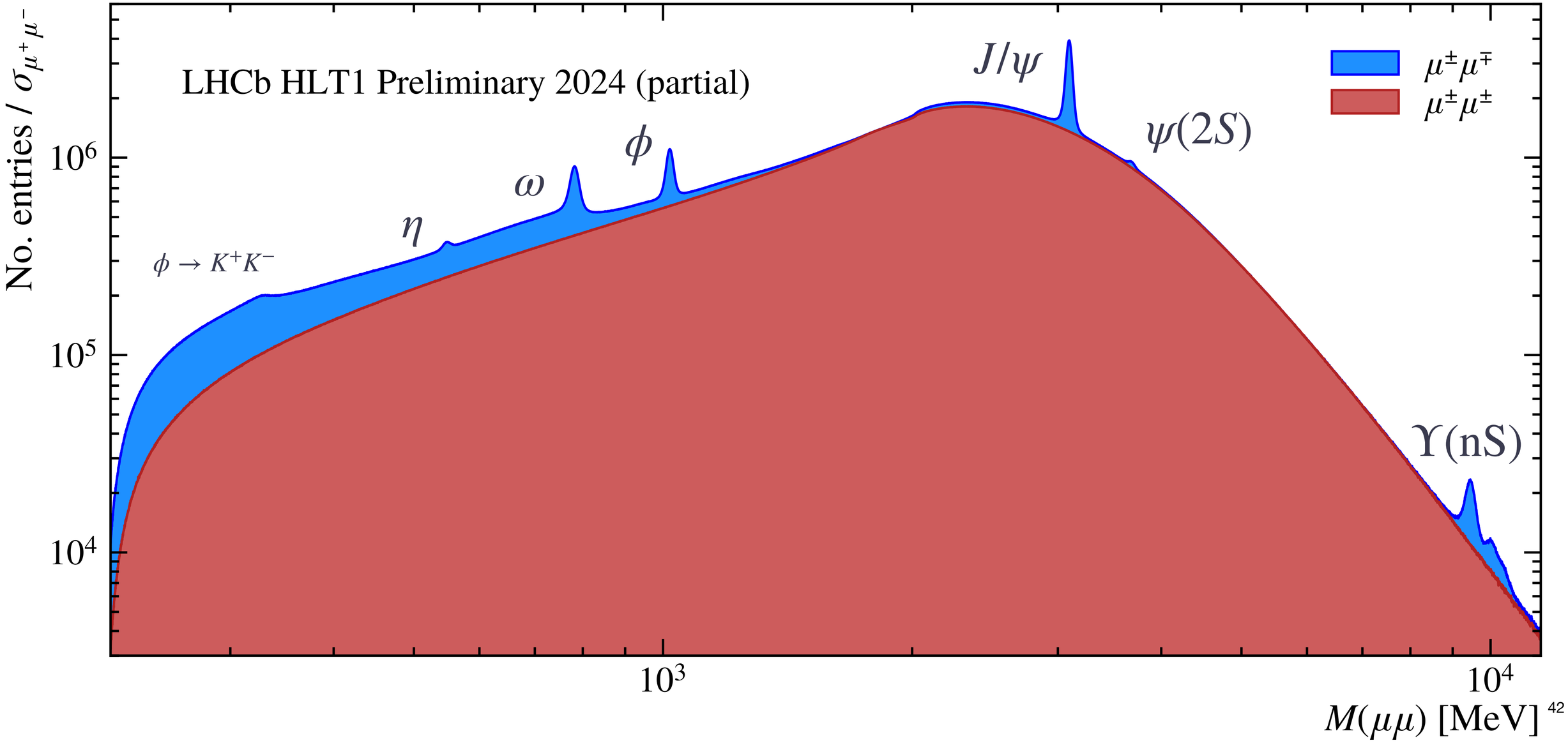
# Dark Photons: Run 3, PID in real time [LHCb-FIGURE-2024-029]

- Dedicated electron ID using Lipschitz constrained Neural Network
- Reconstruction of muon features at HLT1
  - Dispersion of hits around track extrapolation
  - Match between muon segment and track
  - Timing features
  - Hit reconstruction pattern distribution
- 50% improvement wrt baseline muonID
  - $\chi^2_{\text{Corr}}$ [JINST 15 (2020) 12, T12005]
- "Hyper-turbo" selection:
  - Prompt dimuons are saved to histograms right before the event is triggered



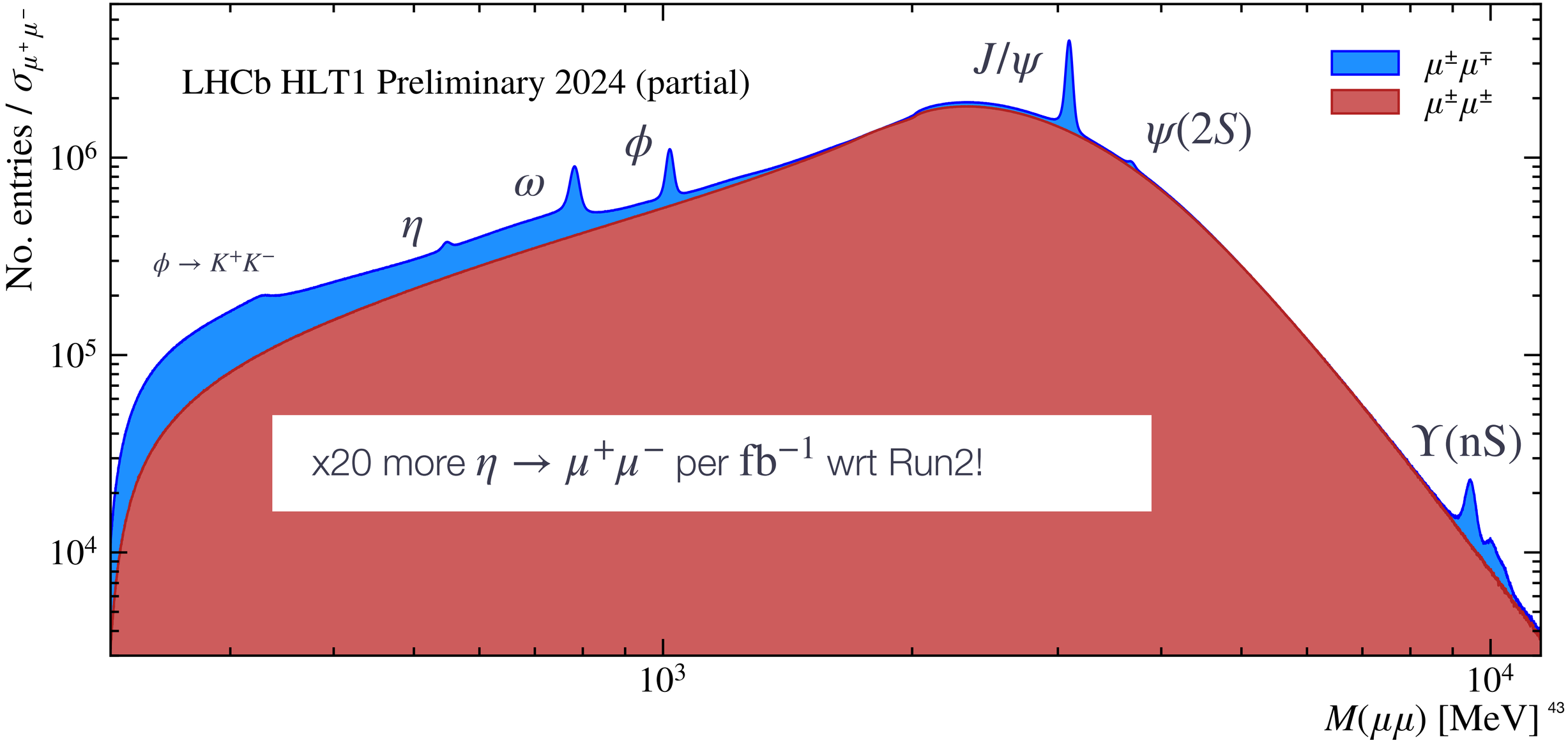
# Dark Photons: Run 3, PID in real time

[LHCb-FIGURE-2024-029]



# Dark Photons: Run 3, PID in real time

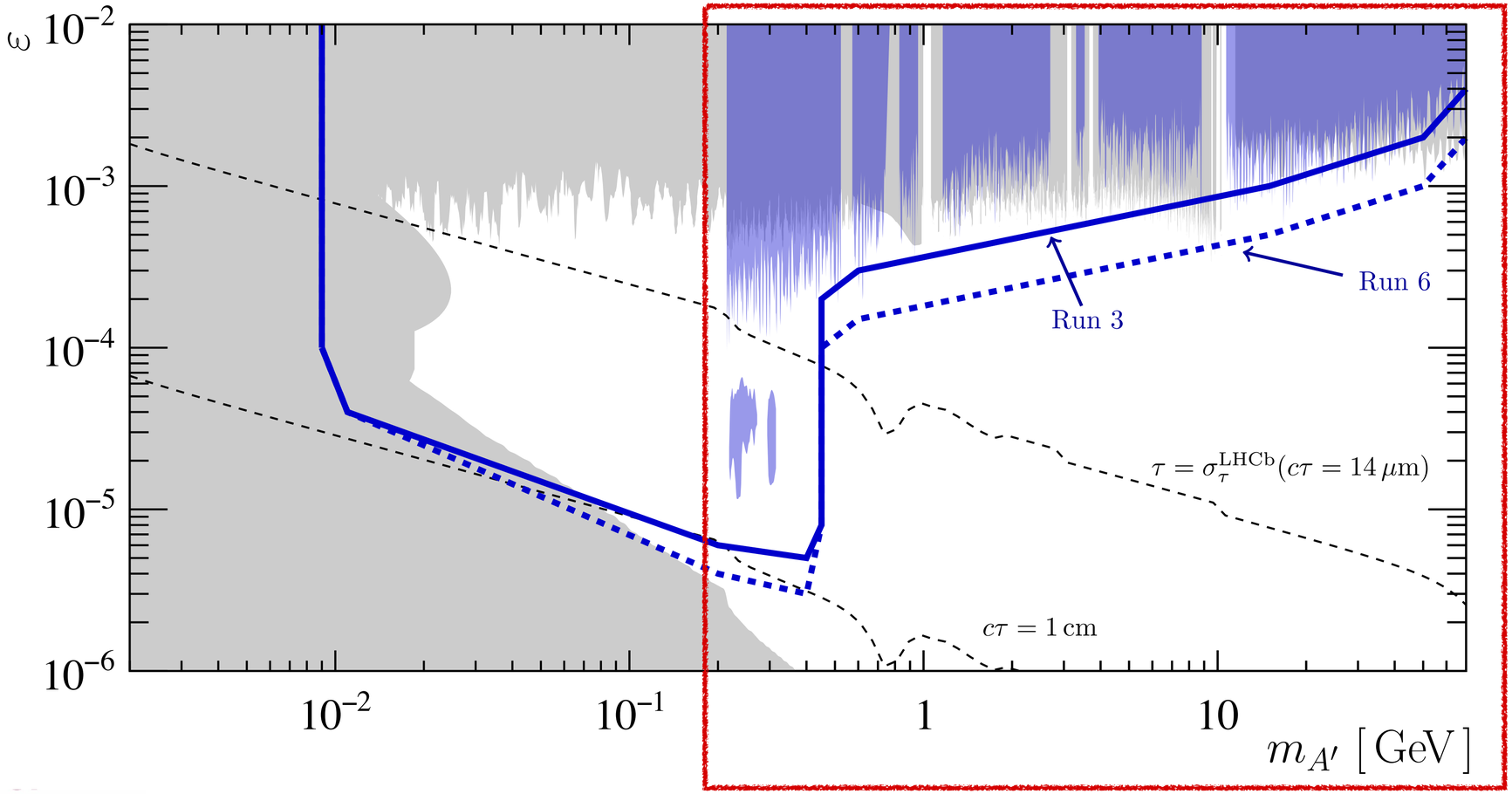
[LHCb-FIGURE-2024-029]



# Dark Photons: Run 3

[2203.07048]

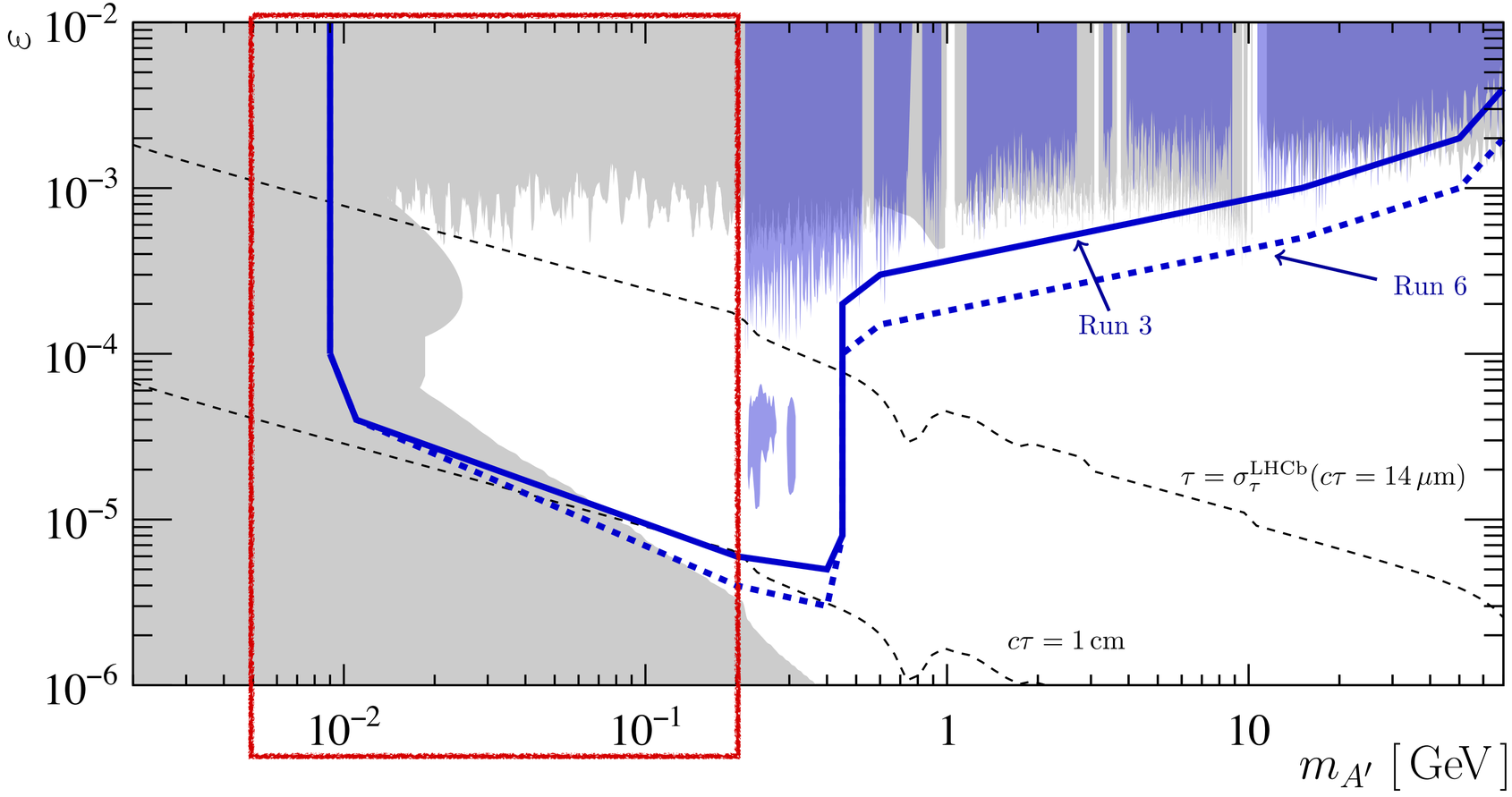
- Better reach for the dimuon search: expected to improve LHCb Run 2 result
  - During Run3 we can take all the Run2 data in ∼ a couple of months



# Dark Photons: Run 3

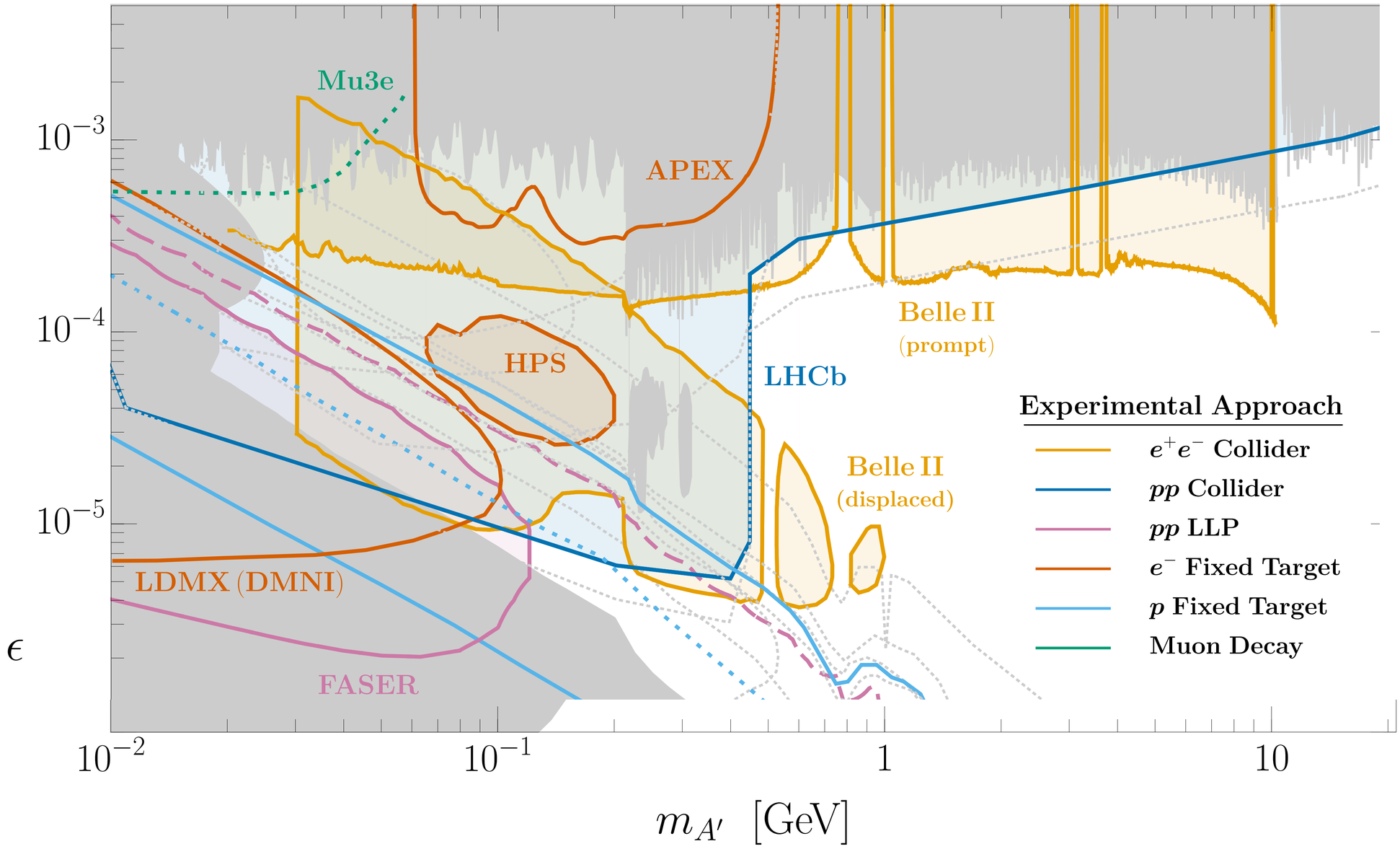
[2203.07048]

- Serious sensitivity below the $2\mu$ threshold: dielectron channel
  - Exploit the largely produced $\pi^0/\eta \to e^+e^-\gamma$ to easily normalise



# Dark photons: the fog of war

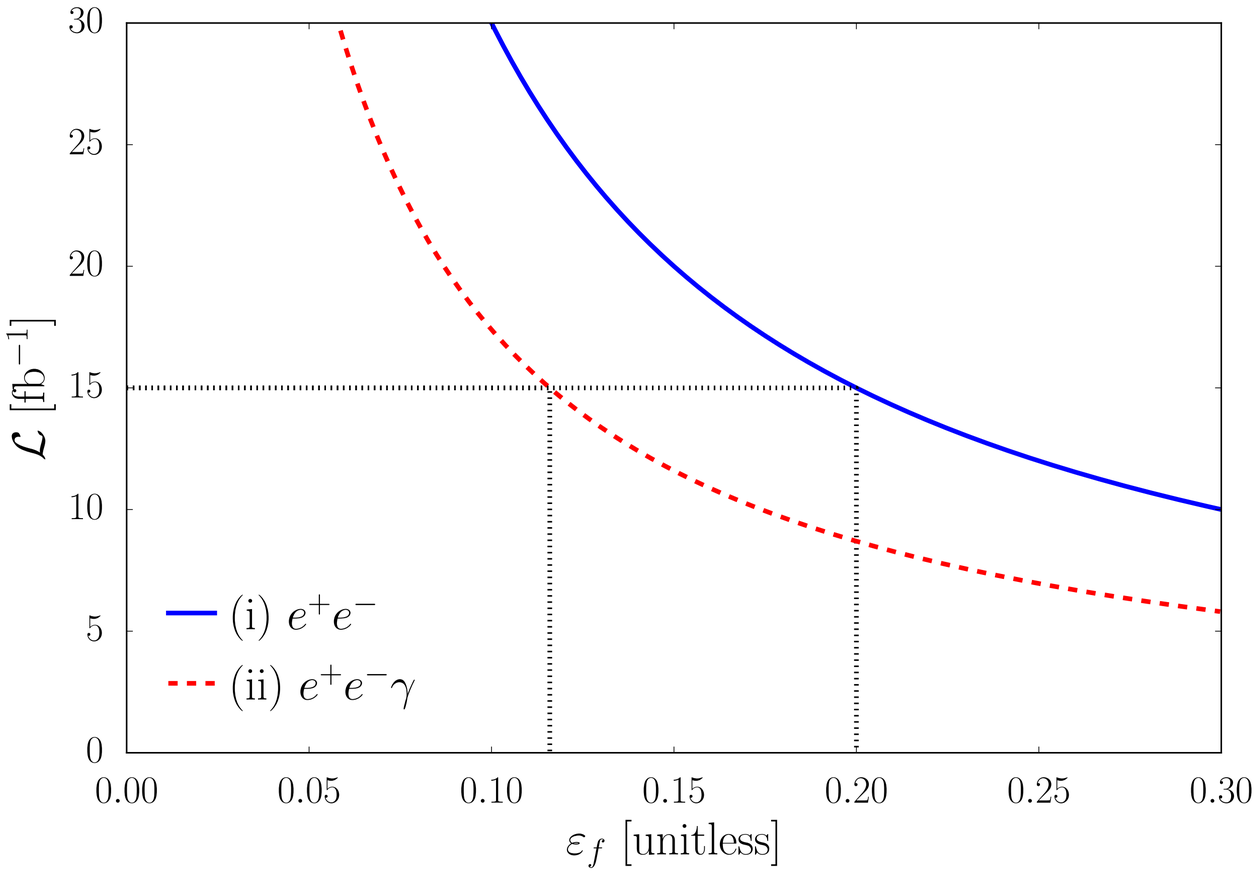
[2209.04671]



# True muonium

[Phys.Rev.D 100 (2019) 5, 053003]

- Standard Model bound state
  - Very clear QED prediction
  - Never observed
- Same final state as a $A' \to e^+e^-$
  - Mainly produced as $\eta \to \gamma\mathcal{T}\mathcal{M}$
- Discovery potential using the full Run 3
  - Two decay channels: $e^+e^-\gamma$ and $e^+e^-$

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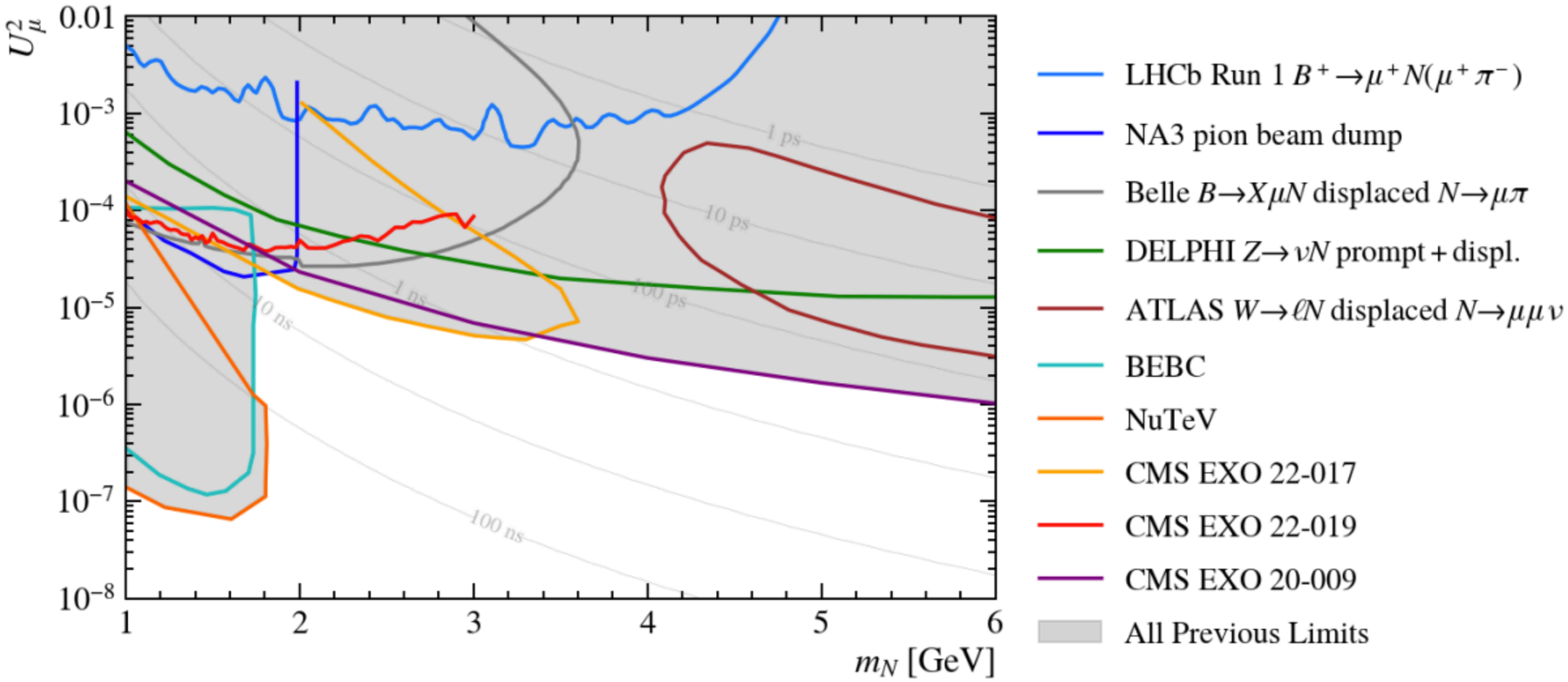
New results coming soon: Dark Scalars, ALPs and HNLs

# Heavy Neutral Leptons

[PRL 112 (2014) 13, 131802]




- Thanks to **Spencer Collaviti** for the nice plot

- Weak results coming from Run 1: $B^+ \to \mu^+ N(\mu^+ \pi^-)$
- LHCb preparing a new result using Run2 data

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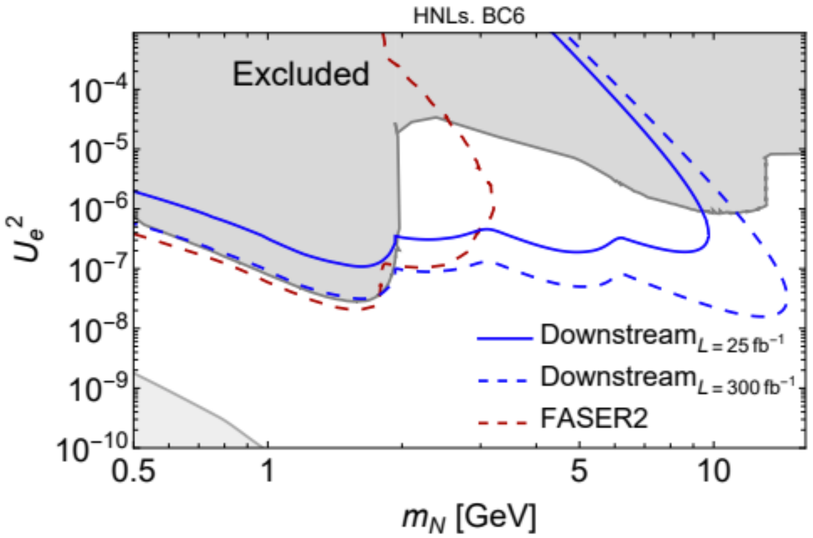
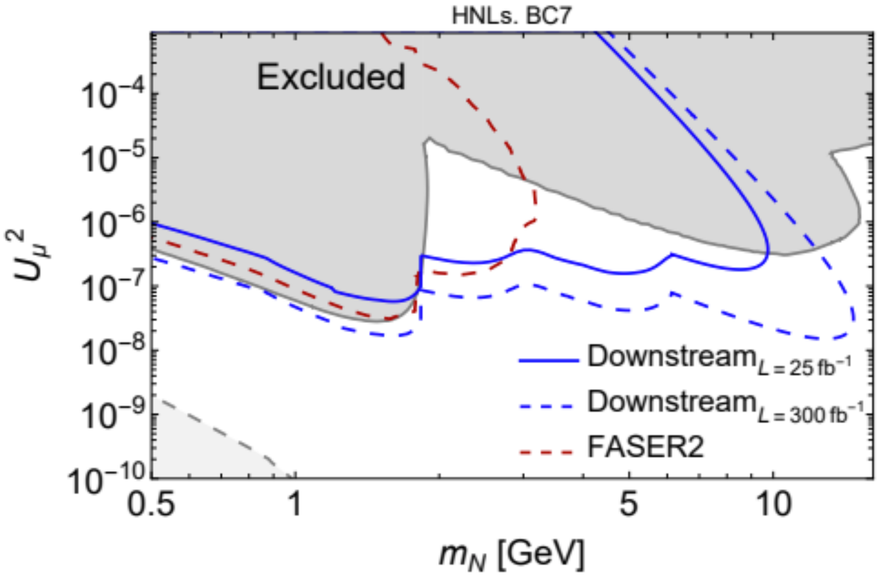
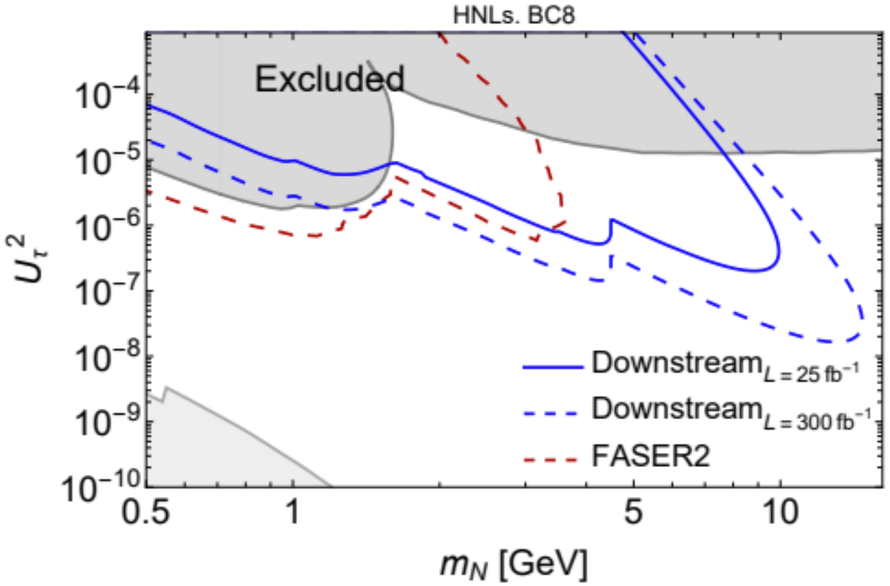
# Heavy Neutral Leptons

[Eur.Phys.J.C 84 (2024) 6, 608]



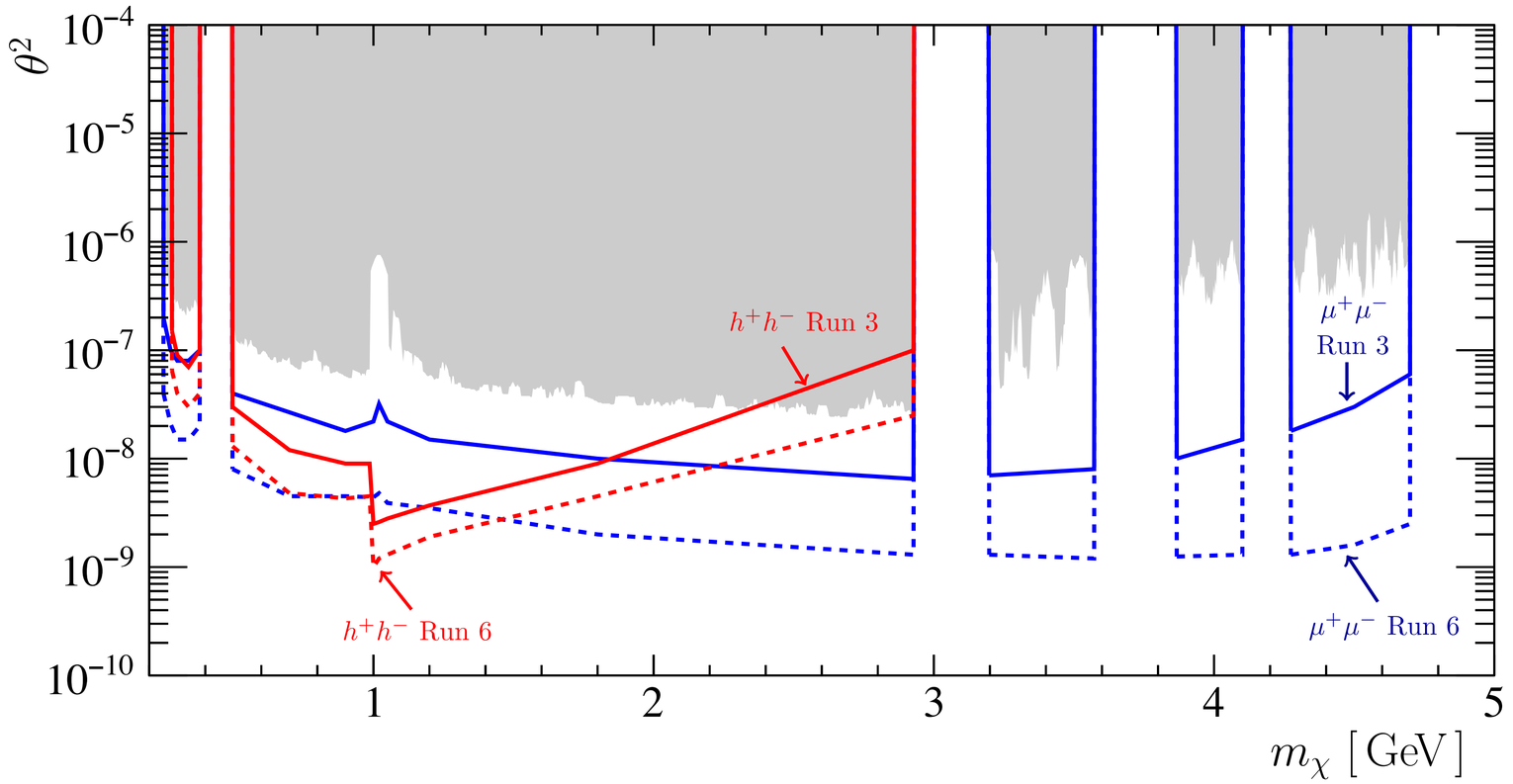




- Promising prospects using Downtream tracks
  - New thing at the trigger level

# Coming up next: Higgs portal

[2203.07048]

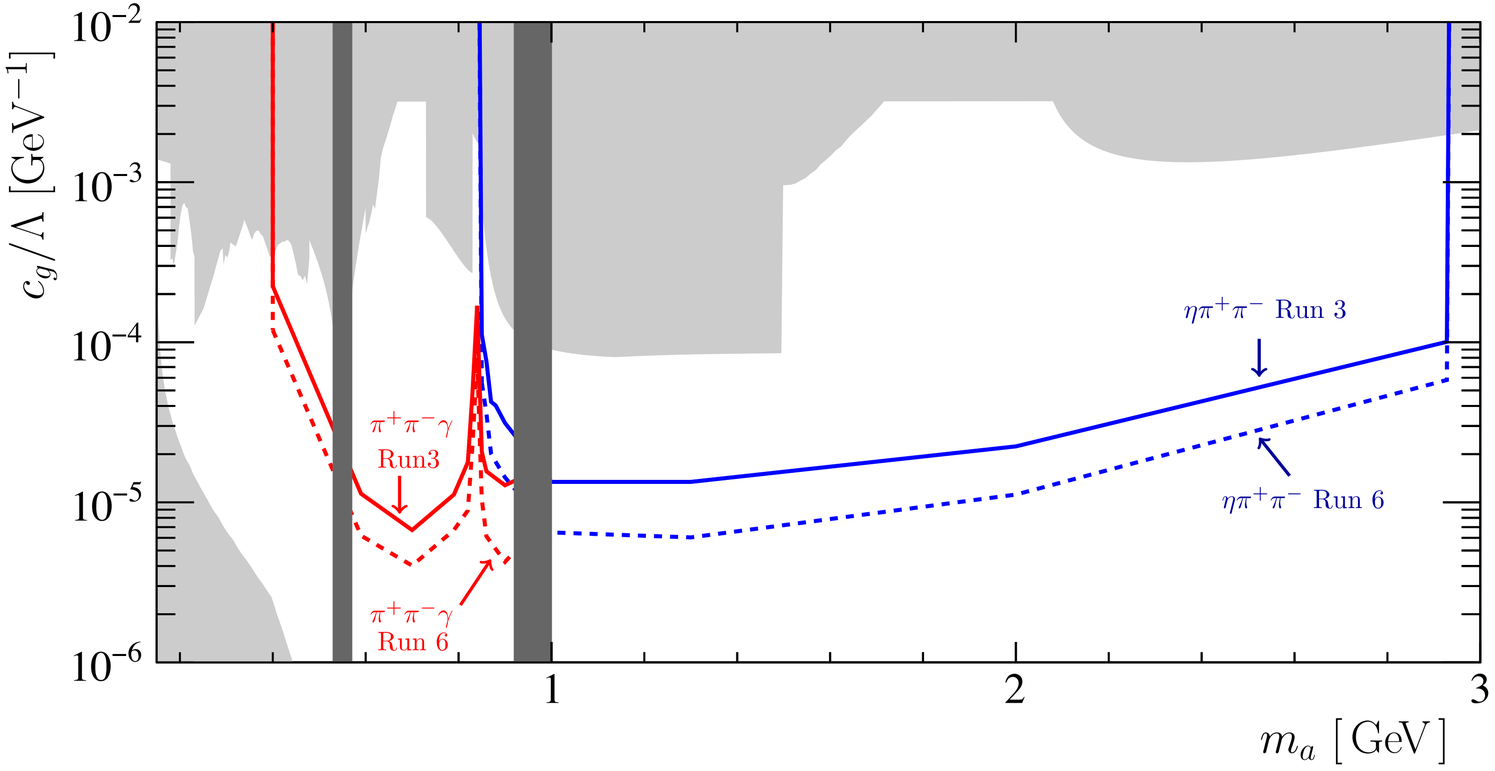



- Dark scalar coupling to the Higgs via mixing angle: $\theta$
- $B \to K\chi$ decays
  - Penguin decay enhancement thanks to the **top** quark mass
- Best limits placed by LHCb using Run 1 data
- Upgrading with **Run 2 data** now
- New strategies involving larger decay volume for Run3!

LHCb results: PRD 95 (2017) 7,071101, PRL 115 (2015) 16,161802,

# ALPs coupled to gluons

[PRL (2019) 123 031803, 2203.07048]




- Similar to Higgs Portal:
  - Enhancement for $B \to K^{(*)}a$ decays
- Gluon coupling dominates in [1,3] GeV region
- ALP to hadron decays
  - $a \to \eta\pi^+\pi^-$
  - $a \to \pi^+\pi^-\gamma$
  - $a \to \pi^+\pi^-\pi^0$
- Current limits:
  - BaBar recast of $\eta$ and $\eta'$ spectra
- We are also updating with **Run 2** data now

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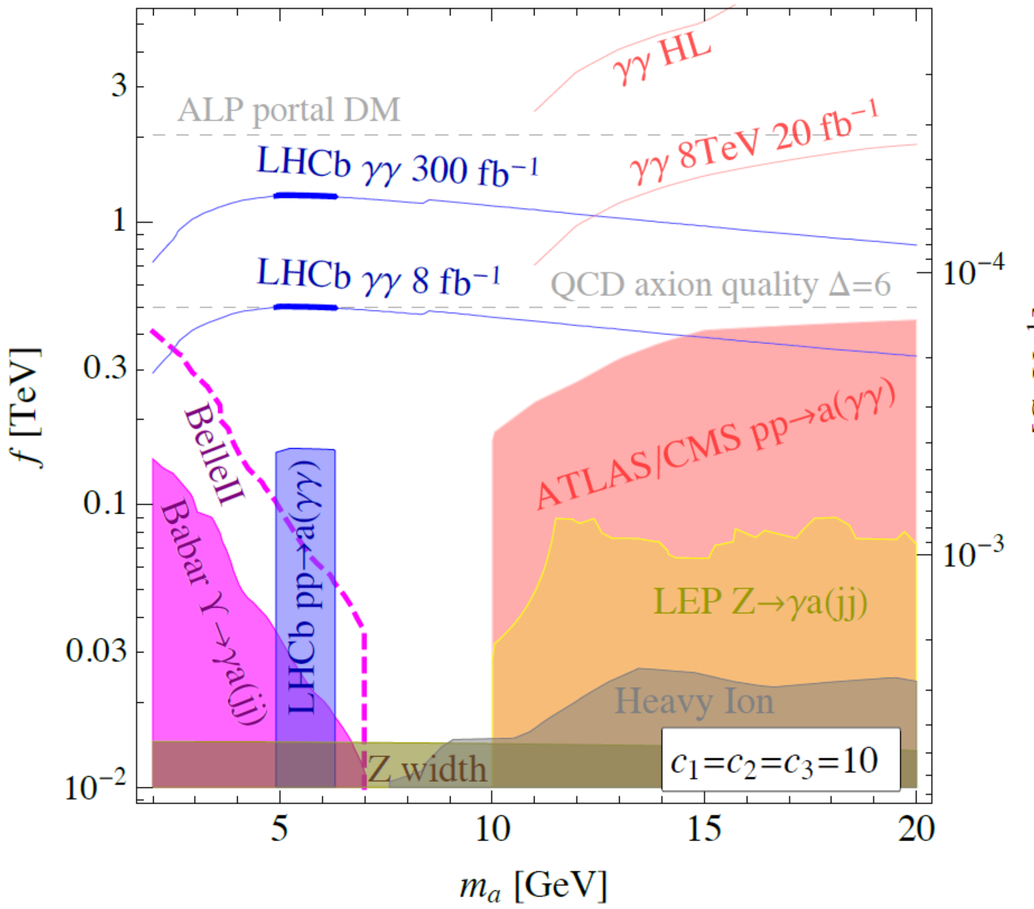
# ALP → $\gamma\gamma$

[JHEP 1901 (2019) 113]

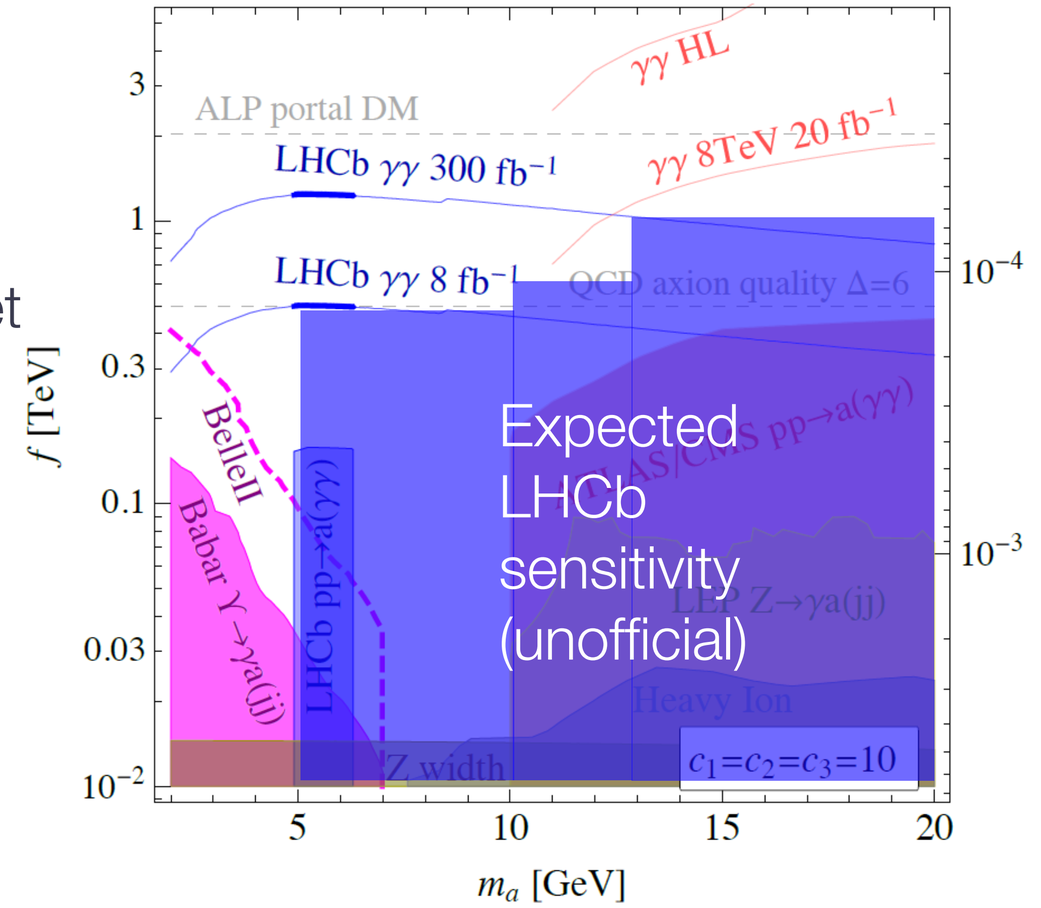
- ALPs produced by gluon fusion decaying to $\gamma\gamma$
- Light ALPs not reachable for ATLAS and CMS
- Current **best limits** in mass gap done with **80 pb$^{-1}$**
  - Result with the full 2018 dataset coming up VERY soon.
  - We expect to **improve** projected sensitivity
- First LHCb analysis using only unconverted photons



# ALP $\to \gamma\gamma$

[JHEP 1901 (2019) 113]

- Major challenges:
  - Unefficient HLT1 with no dedicated ECAL reco
  - ECAL dynamic range penalty: $E_T \lesssim 12$ GeV
  - Huge load of $\pi^0 \to \gamma\gamma$ background
  - Non-negligible amount of material before the magnet
    - $\sim 0.4X_0 \to 50\,\%$ of diphotons convert before magnet
  - Resolution $\times 10$ worse than with tracks
- Improvements since the pheno paper:
  - Major background reduction thanks to isolation
  - Efficiency estimation was off though



# Take home

- LHCb has shown world leading $A' \to \mu^+\mu^-$ results using Run 2 [2016,2018] data:
  - Prompt decays with $m(A') \in [2m(\mu),\ 1\ \mathrm{GeV}]$ and $[1\ \mathrm{GeV},\ 10\ \mathrm{GeV}]$
  - Displaced decays with $m(A') \in [2m(\mu),\ 350\ \mathrm{MeV}]$
- Very relevant updates are expected for Run3:
  - More integrated lumi for $A' \to \mu^+\mu^-$
    - Tight muon ID at first trigger level allows to soften kinematic cuts
  - $A' \to e^+e^-$ for the first time at LHCb thanks to GPU trigger
    - Dedicated electronID at first trigger level
    - Copious $\pi^0/\eta \to e^+e^-\gamma$ production
    - Store histograms before triggering allows to keep all candidates
- Stay tuned for **new results** coming from ALP and Dark Scalar too!

# BACKUP

# Searches for Dark Photons [PRL (2020) 124 041801]

- **Event selection:**
  - Hardware trigger stage:
    - $p_T(\mu) > 1.8$ GeV || $p_T(\mu_1)p_T(\mu_2) > 1.5$ (GeV)$^2$
  - Software trigger stage:
    - MuonID criteria
    - Good quality vertex
  - Offline:
    - Dimuon isolation strategy

- Long-lived (prompt) search:
  - $p_T(\mu)$ > 0.5 (1.0) GeV
  - $p(\mu)$ > 10 (20) GeV
  - Inconsistency (consistency) with origin at the PV

- **Prompt search misRECO backgrounds:**
  - Double mis ID $(hh)$ : $\mu$ as prompt hadron, most likely a pion
  - misID $(h)$ + misRECO $(\mu_Q)$: $\mu$ from b(c)-hadron decay and reconstructed as prompt
  - Double misRECO $(\mu_Q\mu_Q)$

- **Displaced search backgrounds:**
  - Photon conversions to $\mu^+\mu^-$ in the VELO (matter veto strategy in the back-up)
  - b-hadron decays with two muons produced in the decay chain
  - Low mass tail from $K_s^0 \to \pi^+\pi^-$ where both pions misidentified as muons

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# Dark photons

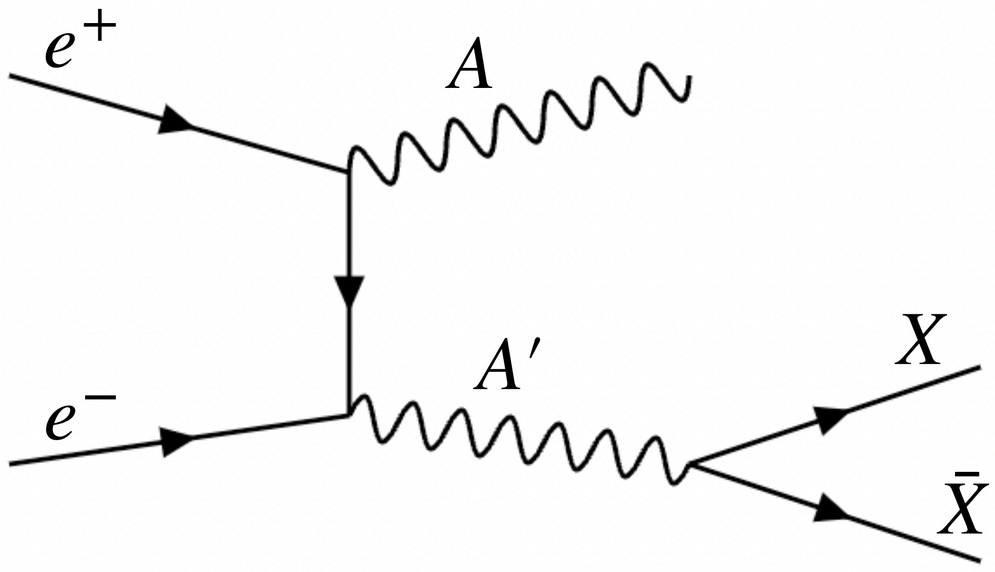
[PRL 113 (2014) 20, 201801]

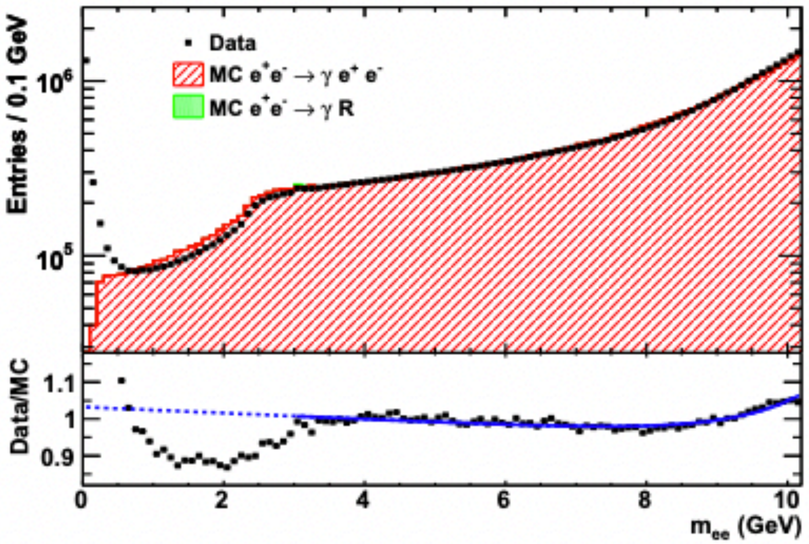
Easy to make calculations:

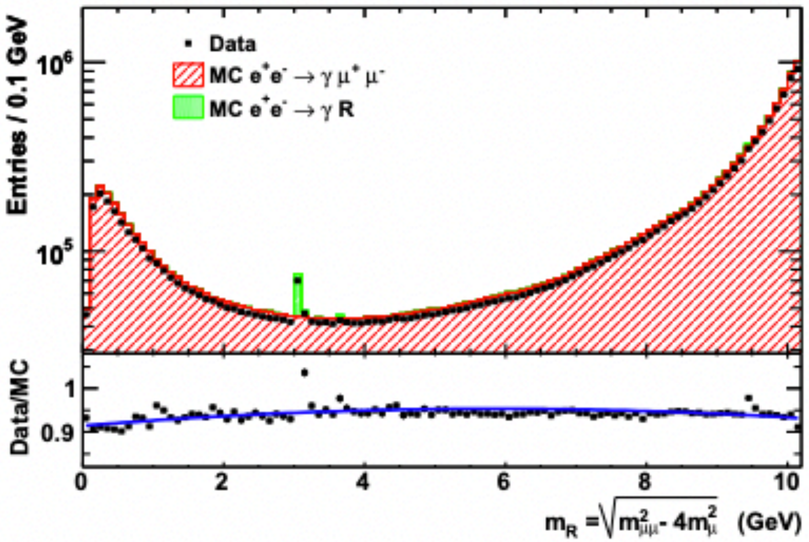
- QED with a mass effect
- $A'$ mixes $A$ with a small coupling $\varepsilon$

Only back of the envelope calculation is needed in $e^+e^-$

$$\sigma_{A'} = \frac{2\pi\varepsilon^2\alpha_{\mathrm{EM}}}{E_{\mathrm{CM}}^2} \times \mathcal{F}(\theta, m_{A'})$$

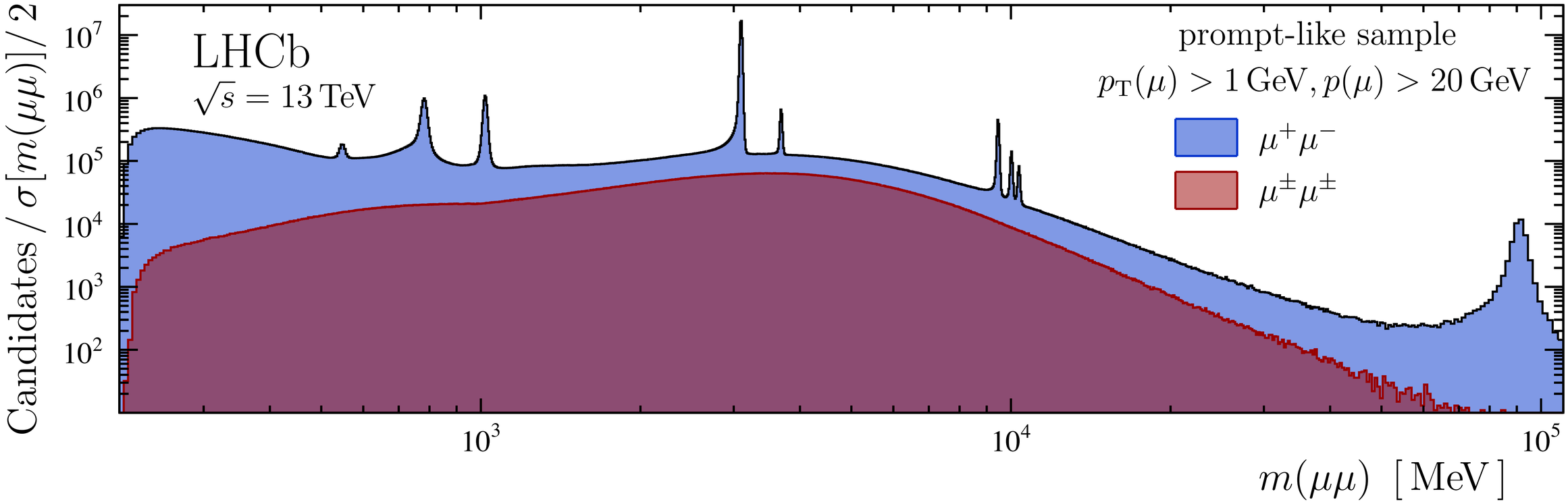


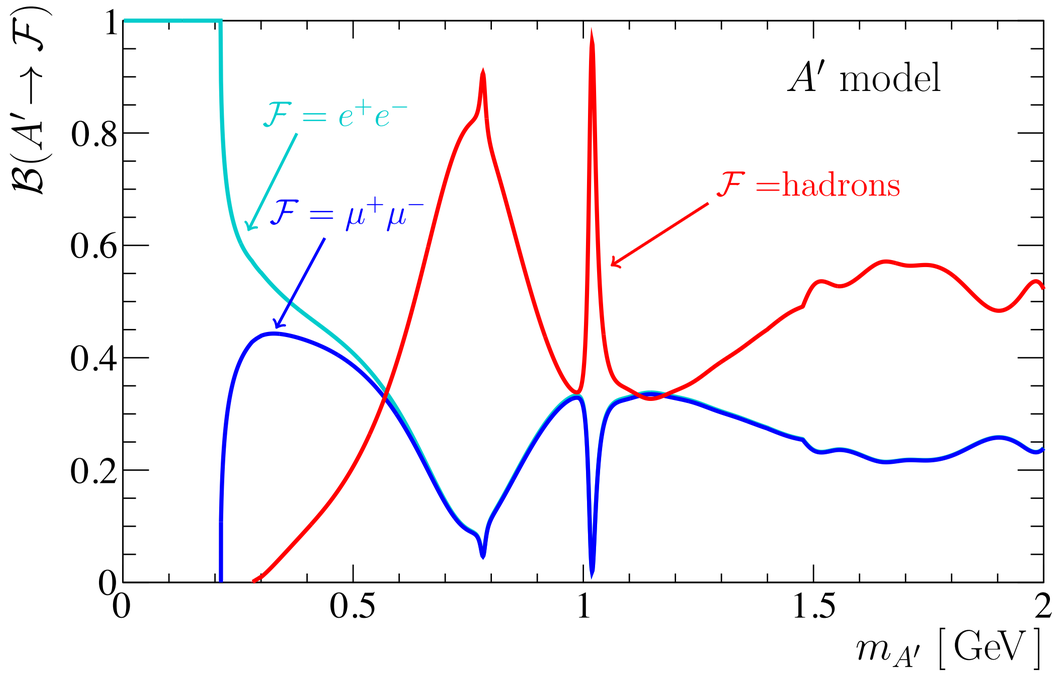
# Dark Photons: prompt search

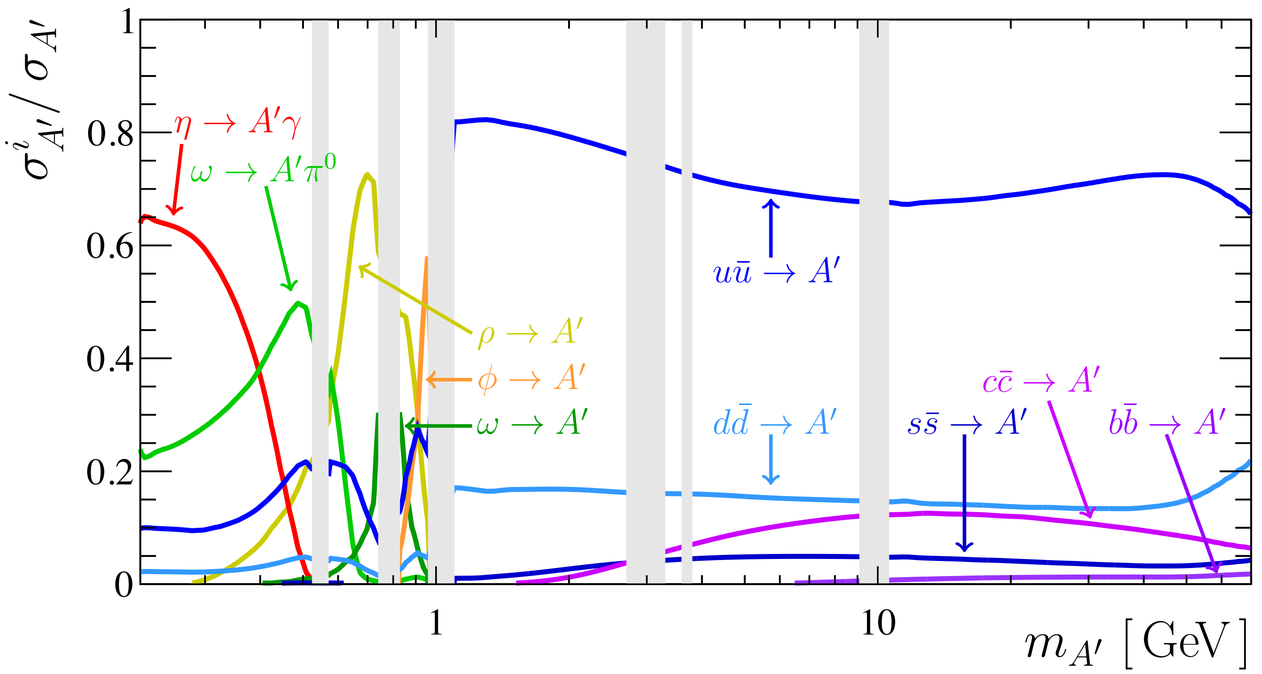
[PRL 120 (2018) 6, 061801]



# Dark Photons

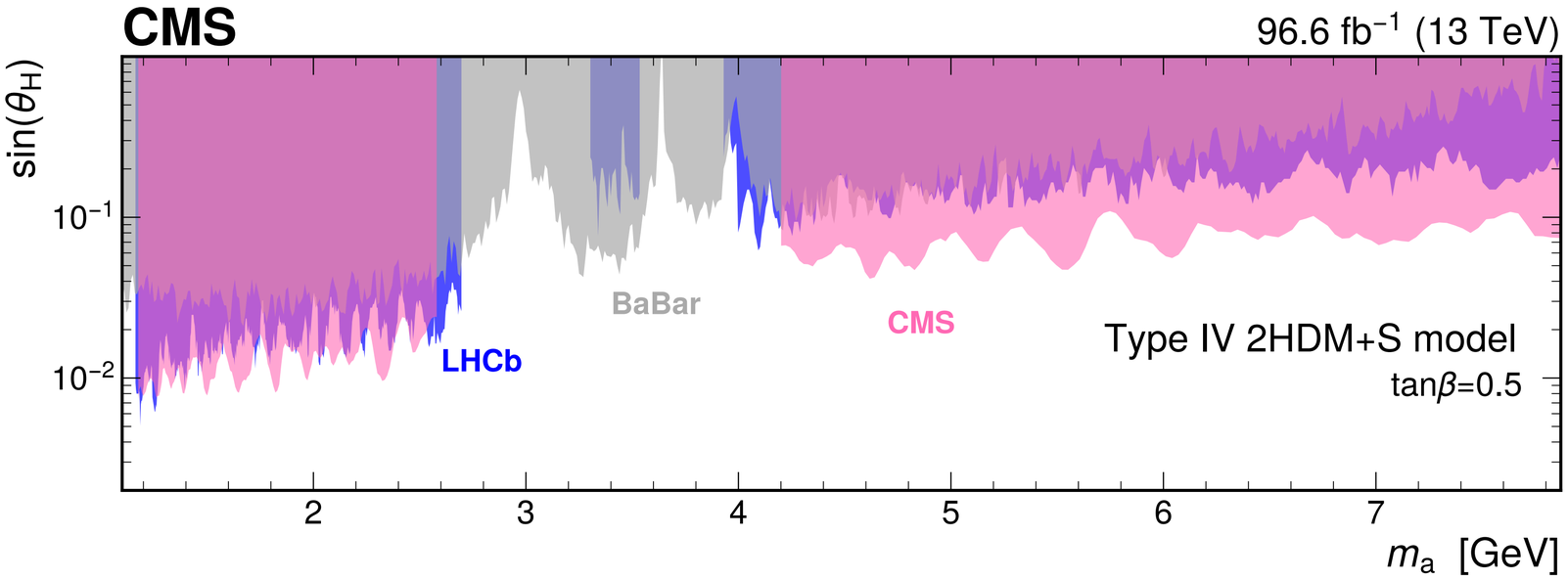
[JHEP 06 (2018) 004]

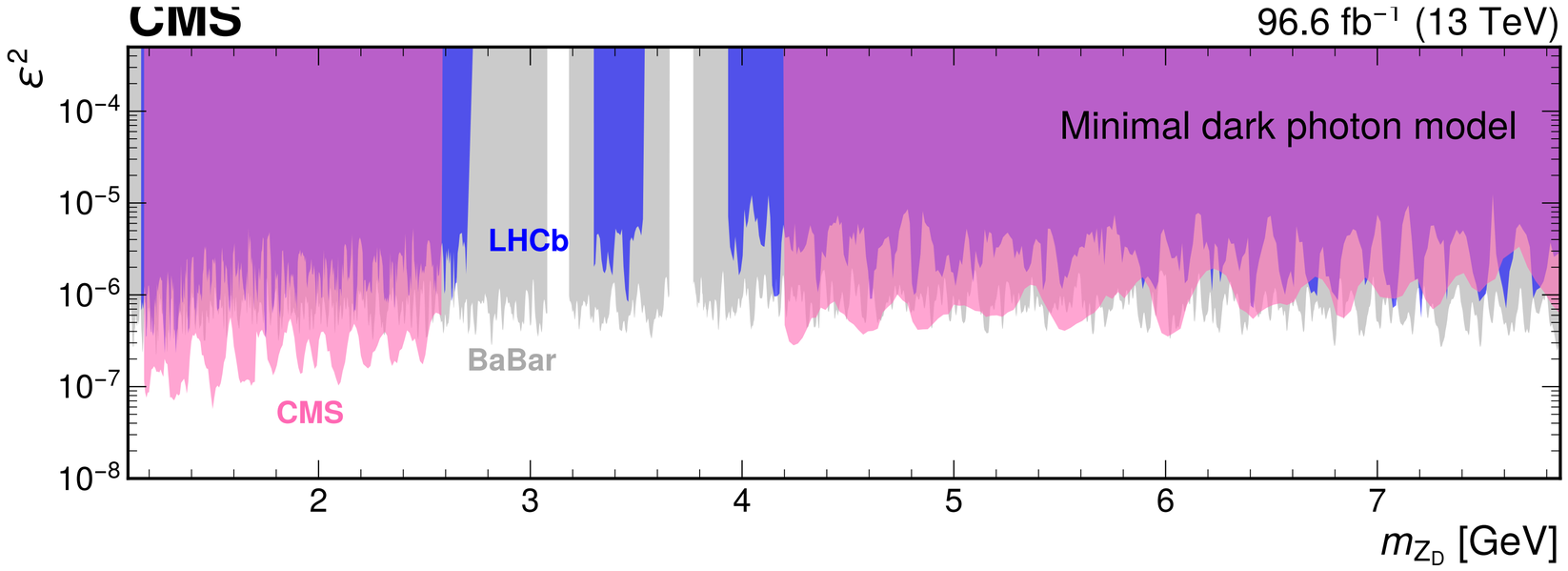


# Dark Photons: latest updates from CMS

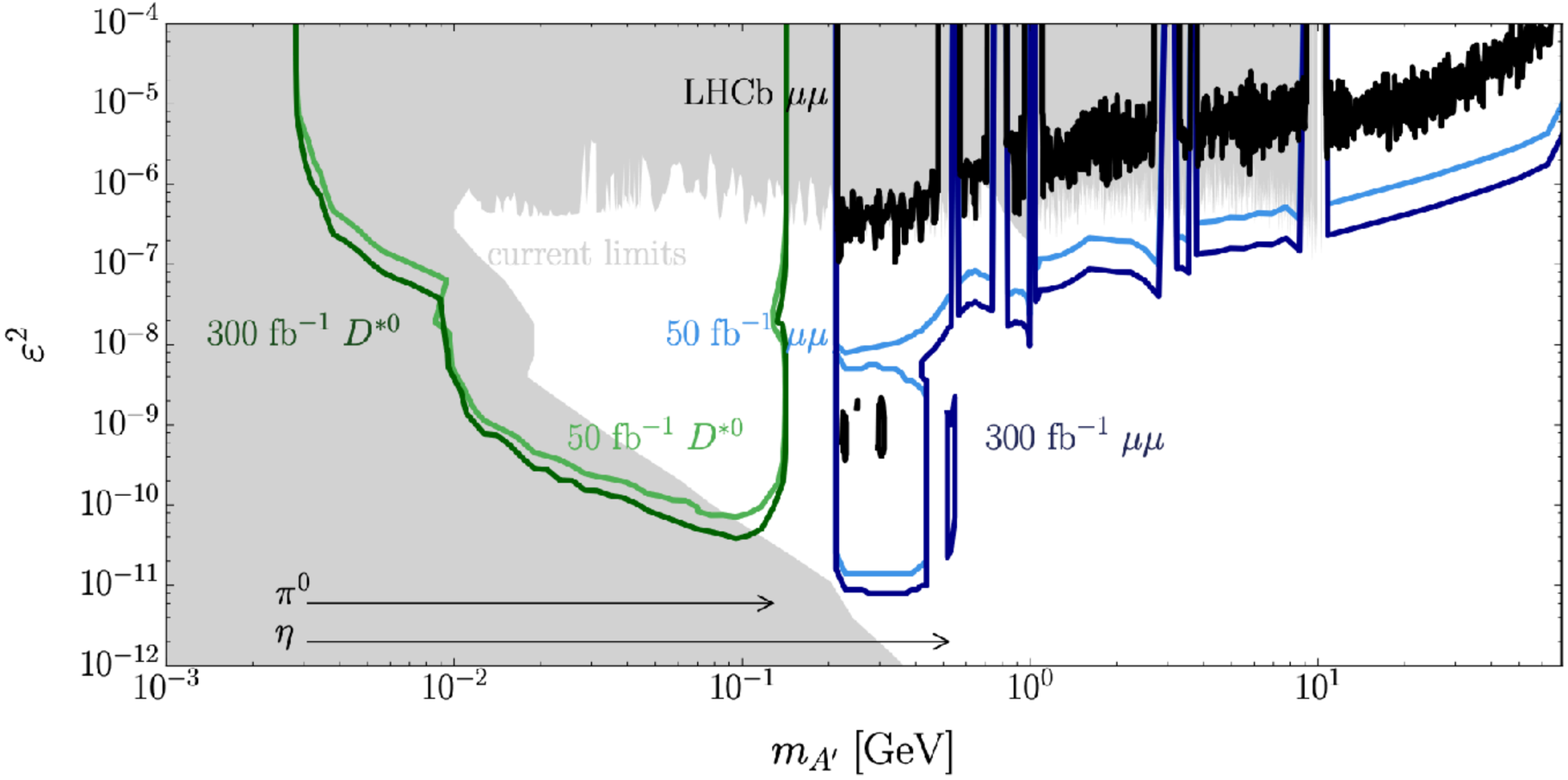
[JHEP 12 (2023) 070]



# Dark Photons: Run 3

[2203.07048]




- Extended reach through $D^* \to D^0 A'$
  - Better mass resolution through constrained decay tree
  - Easier to trigger: rely on $D^0$

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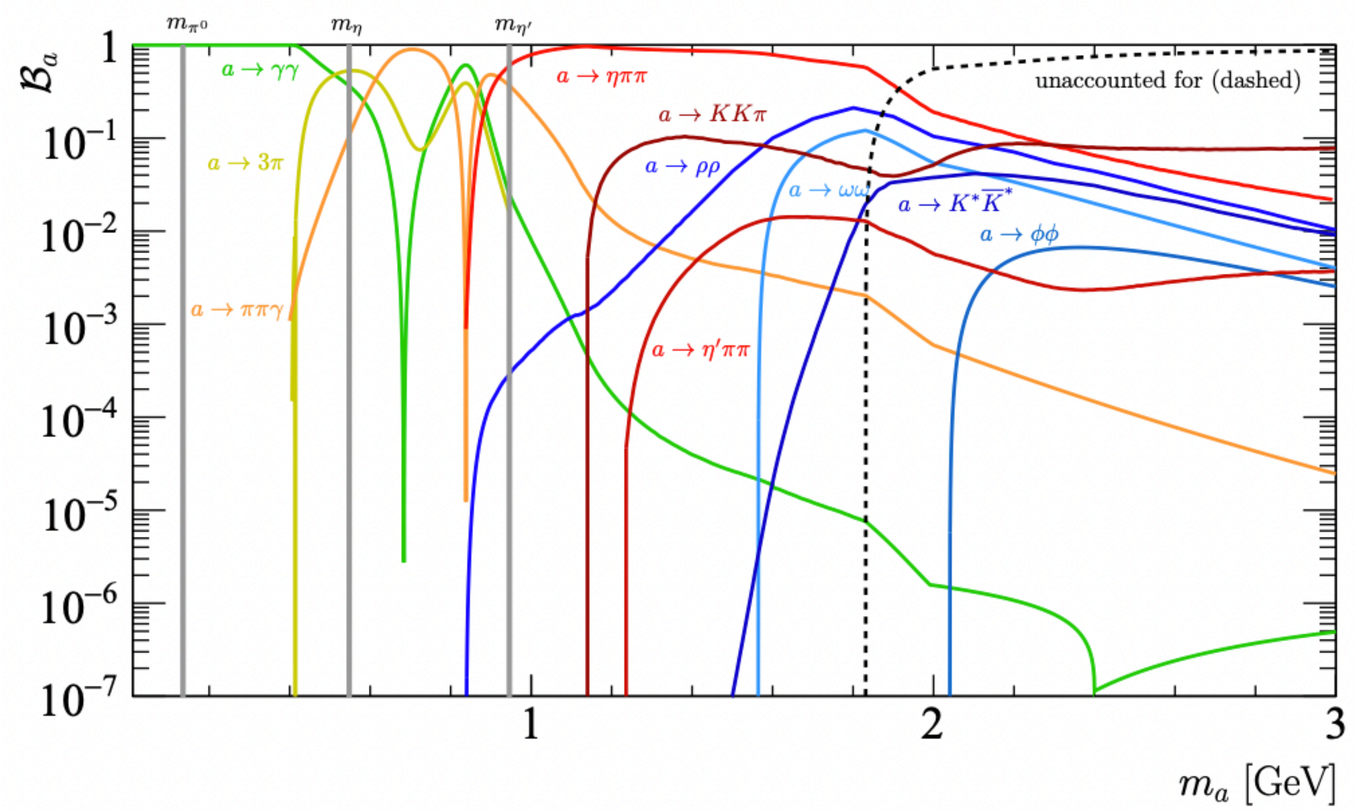
# ALPs coupled to gluons

[PRL (2019) 123 031803]




- Similar to HP:
  - Enhancement for $B \to K^{(*)}a$ decays
- Gluon coupling dominates in [1,3] GeV region
- ALP to hadron decays
  - $a \to \eta\pi^+\pi^-$
  - $a \to \pi^+\pi^-\gamma$
  - $a \to \pi^+\pi^-\pi^0$
- Current limits:
  - BaBar recast of $\eta$ and $\eta'$ spectra
- We are also updating with **Run 2** data now

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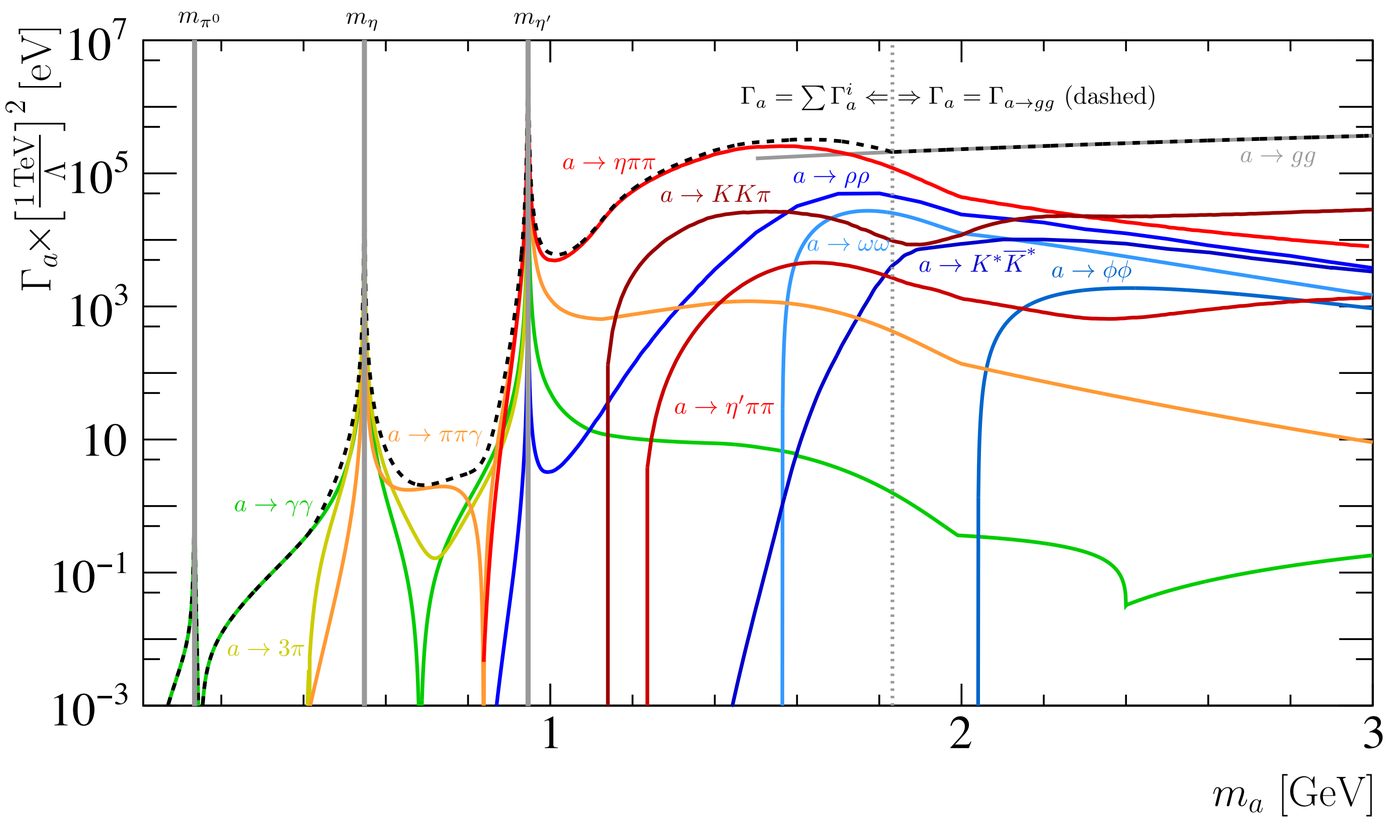
# ALPs coupled to gluons

[PRL (2019) 123 031803]




- Similar to HP:
  - Enhancement for $B \to K^{(*)}a$ decays
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  - BaBar recast of $\eta$ and $\eta'$ spectra
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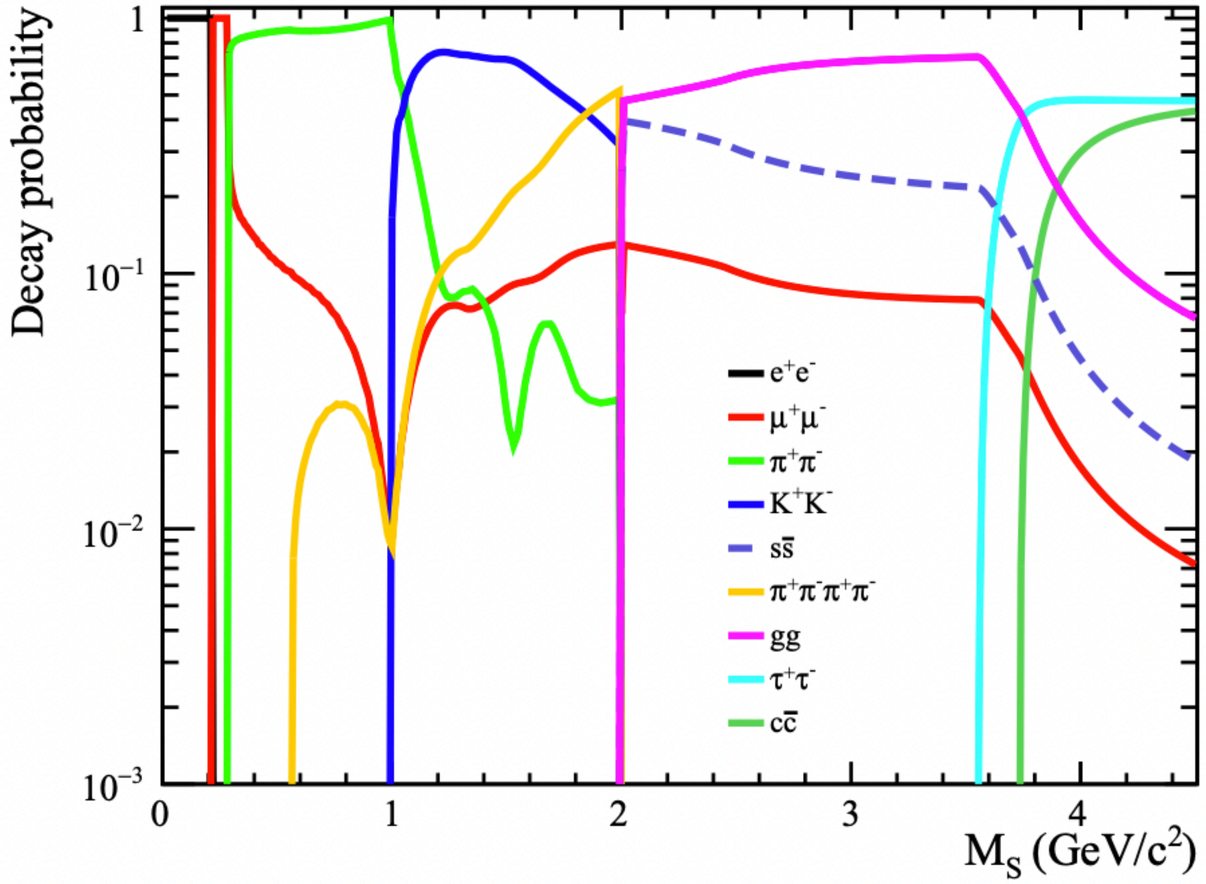
# Coming up next: Higgs portal

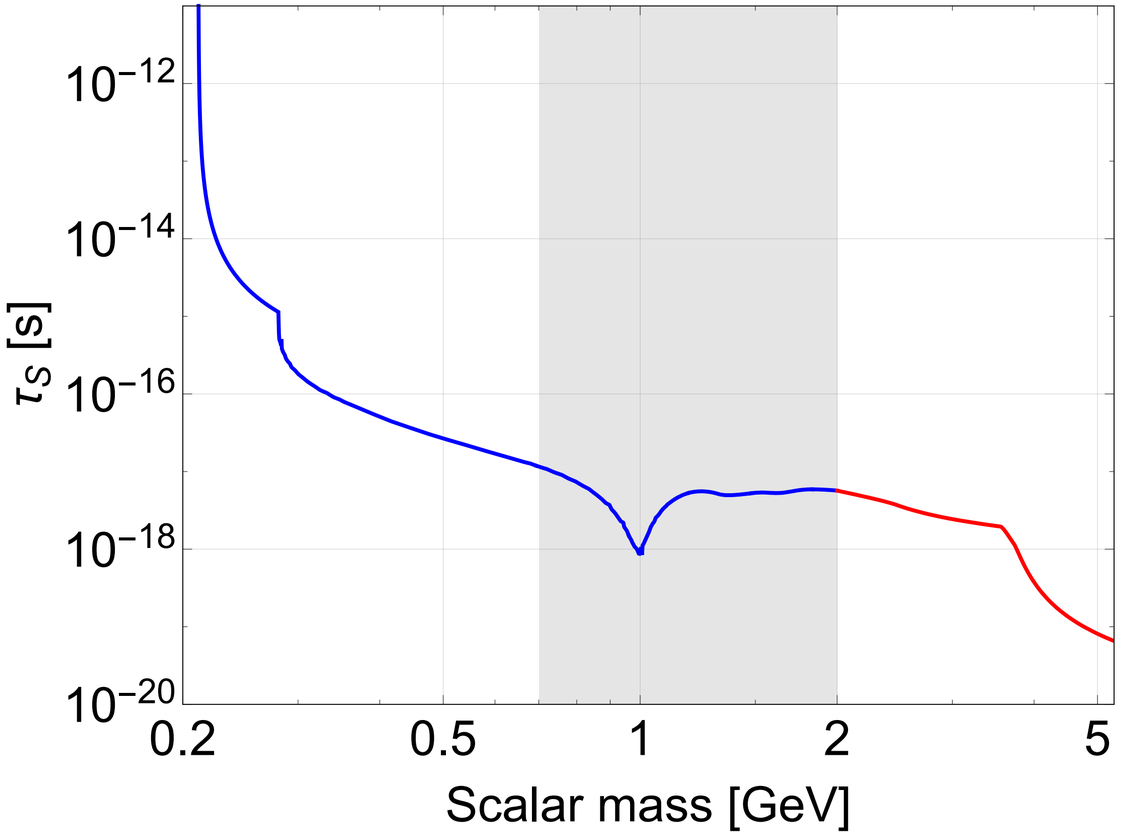
[JHEP 11 (2019) 162]

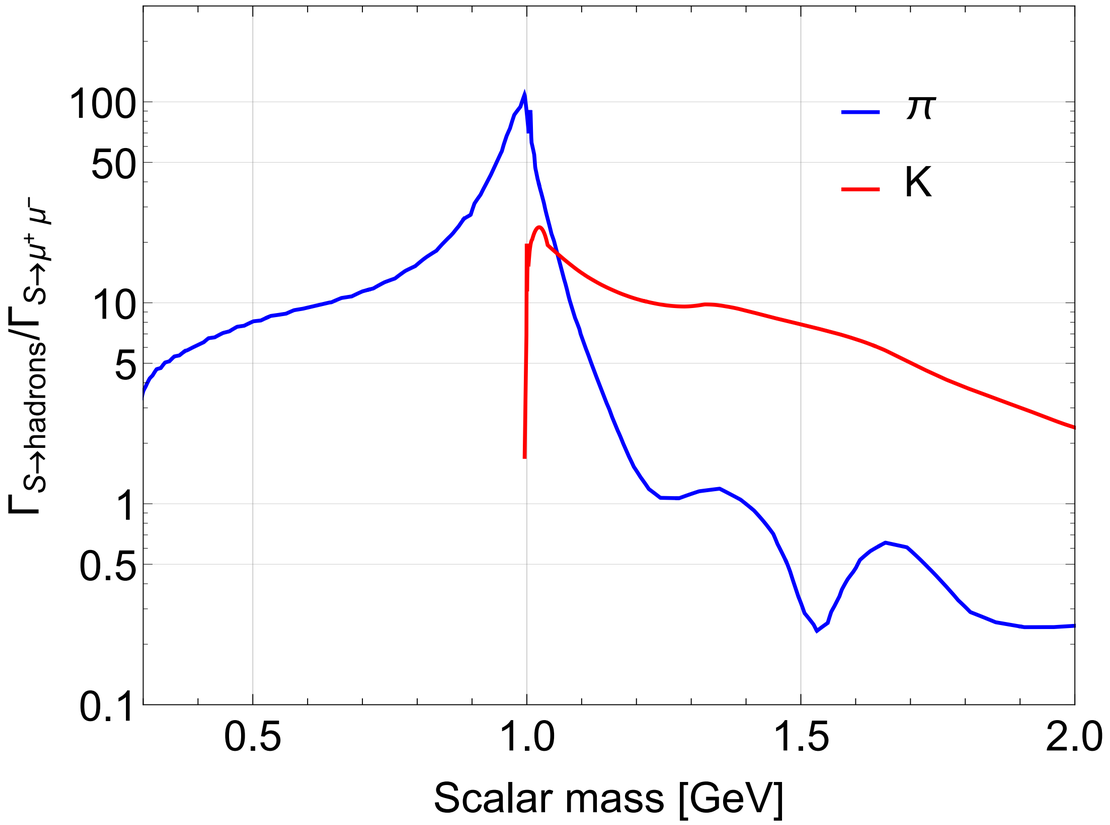



- Dark scalar coupling to the Higgs via mixing angle: $\theta$
- $B^0 \to K^*\chi$ decays
  - Penguin decay enhancement thanks to the **top** quark mass
- Best limits placed by LHCb using Run 1 data
- Upgrading with **Run 2 data** now

# Higgs portal

[JHEP 11 (2019) 162]

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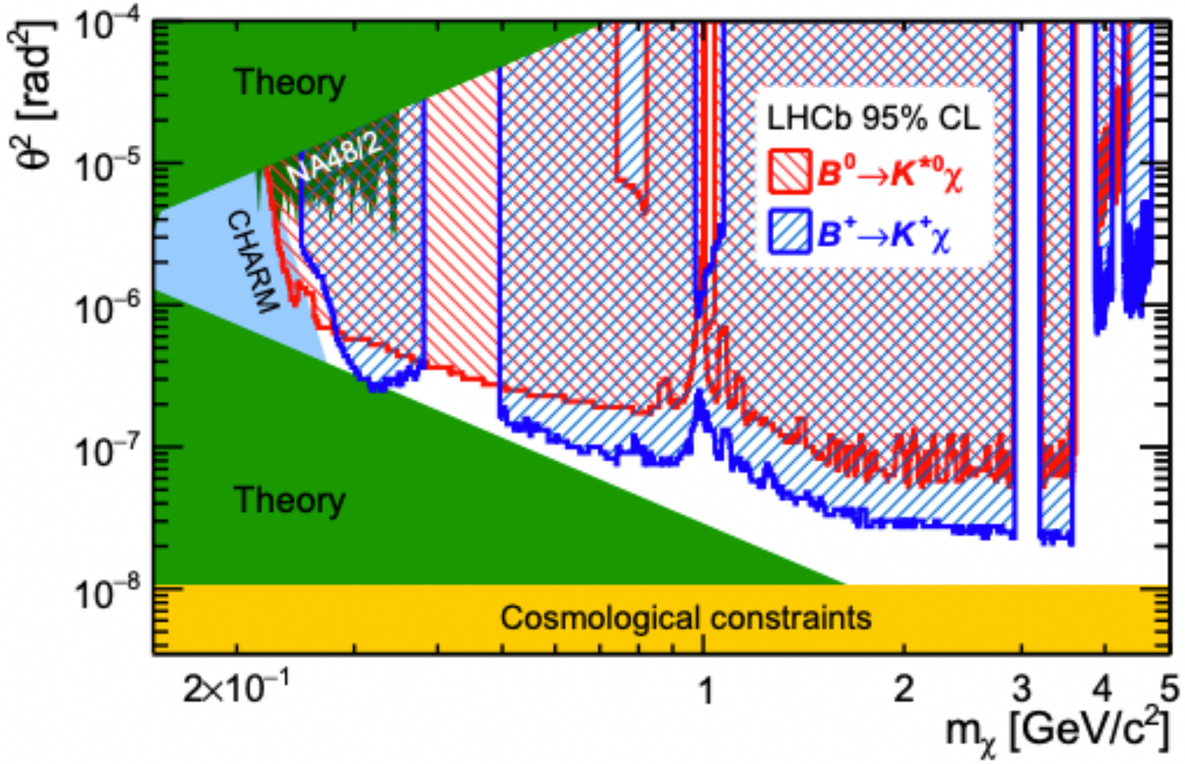
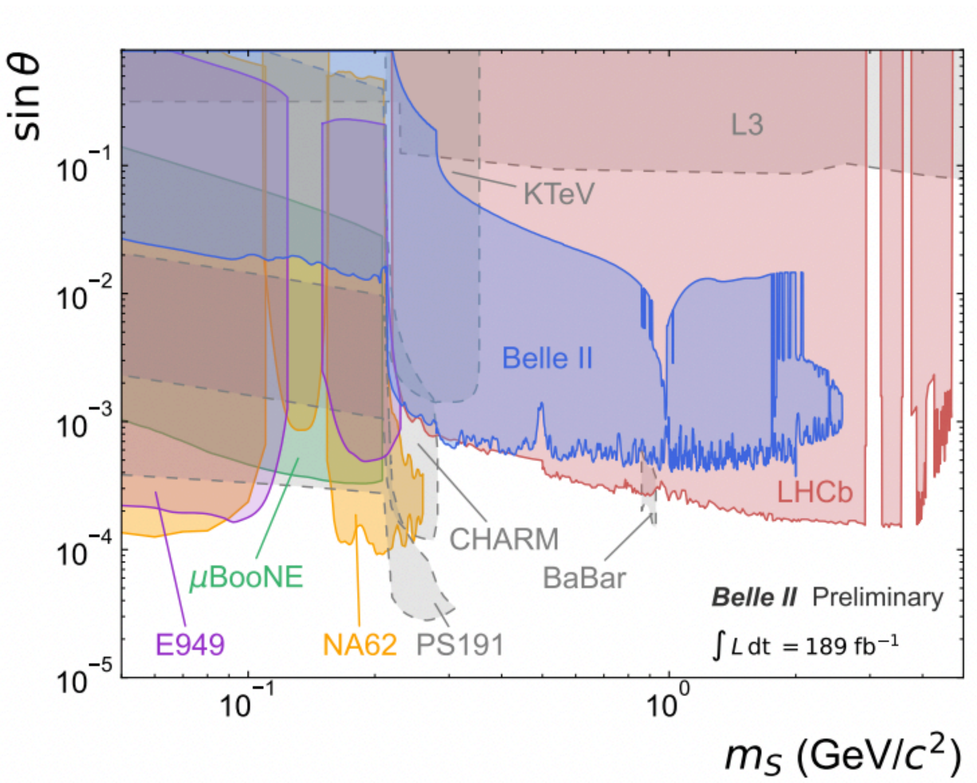
# Higgs portal: The Run 1 result

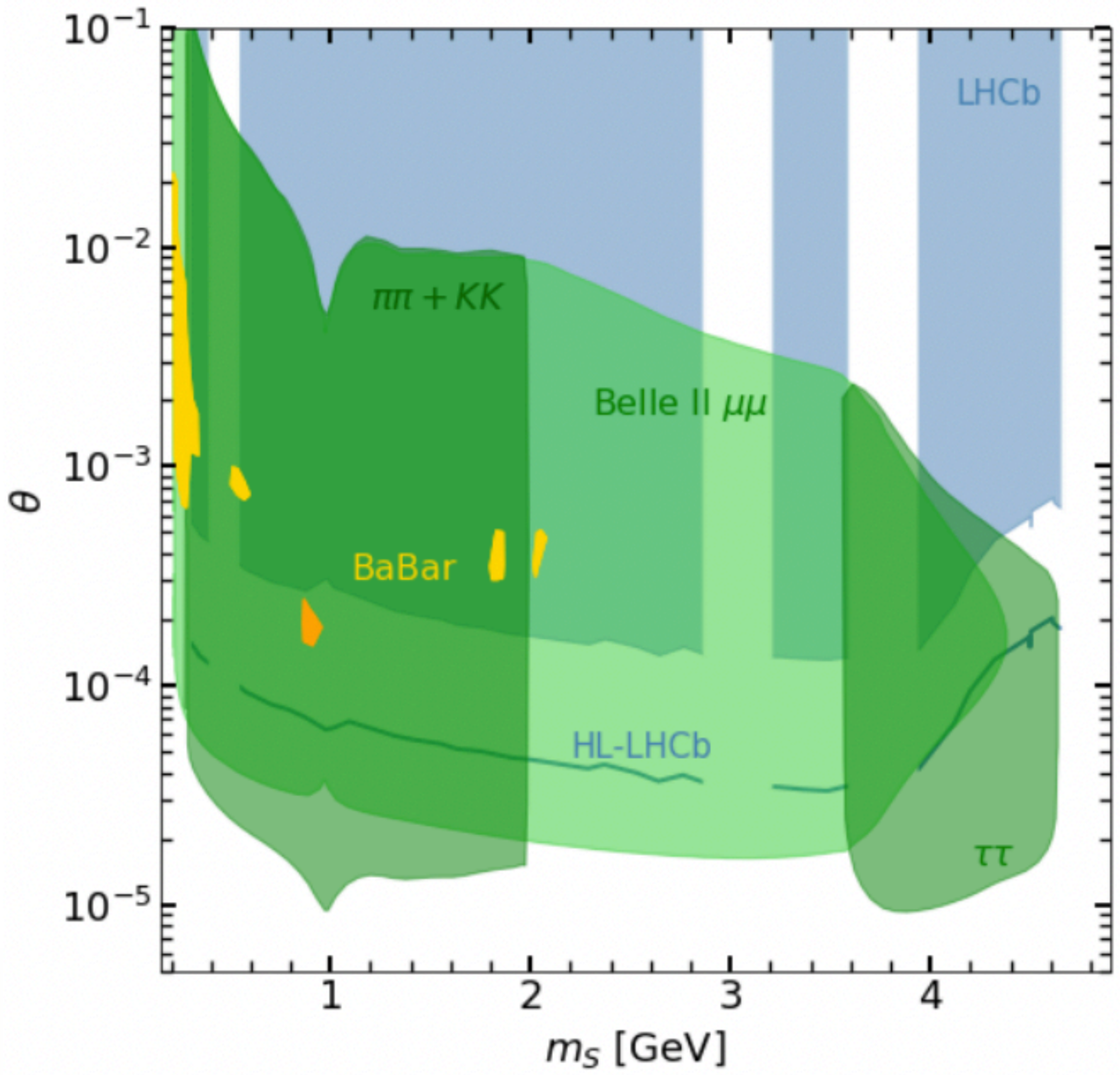
[PRD 95 (2017) 7,071101, PRL 115 (2015) 16,161802, PRD 108 (2023) 11,L111104 ]

- Dark scalar coupling to the Higgs via mixing angle: $\theta$
- $B^0 \to K^* \chi$ decays
  - Penguin decay enhancement thanks to the **top** quark mass
- Best limits placed by LHCb using Run 1 data



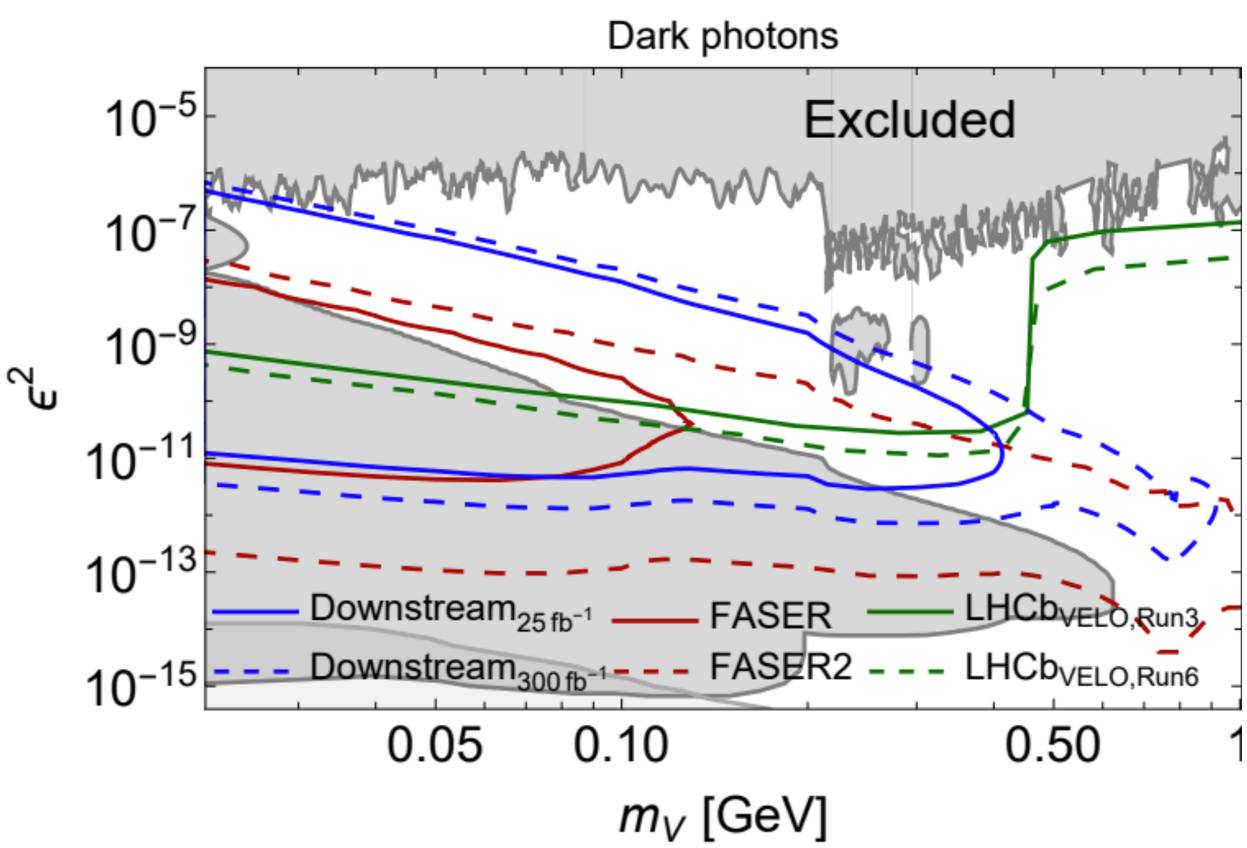
# Coming up next: Higgs portal [PRD 101 (2020) 9, 095006]

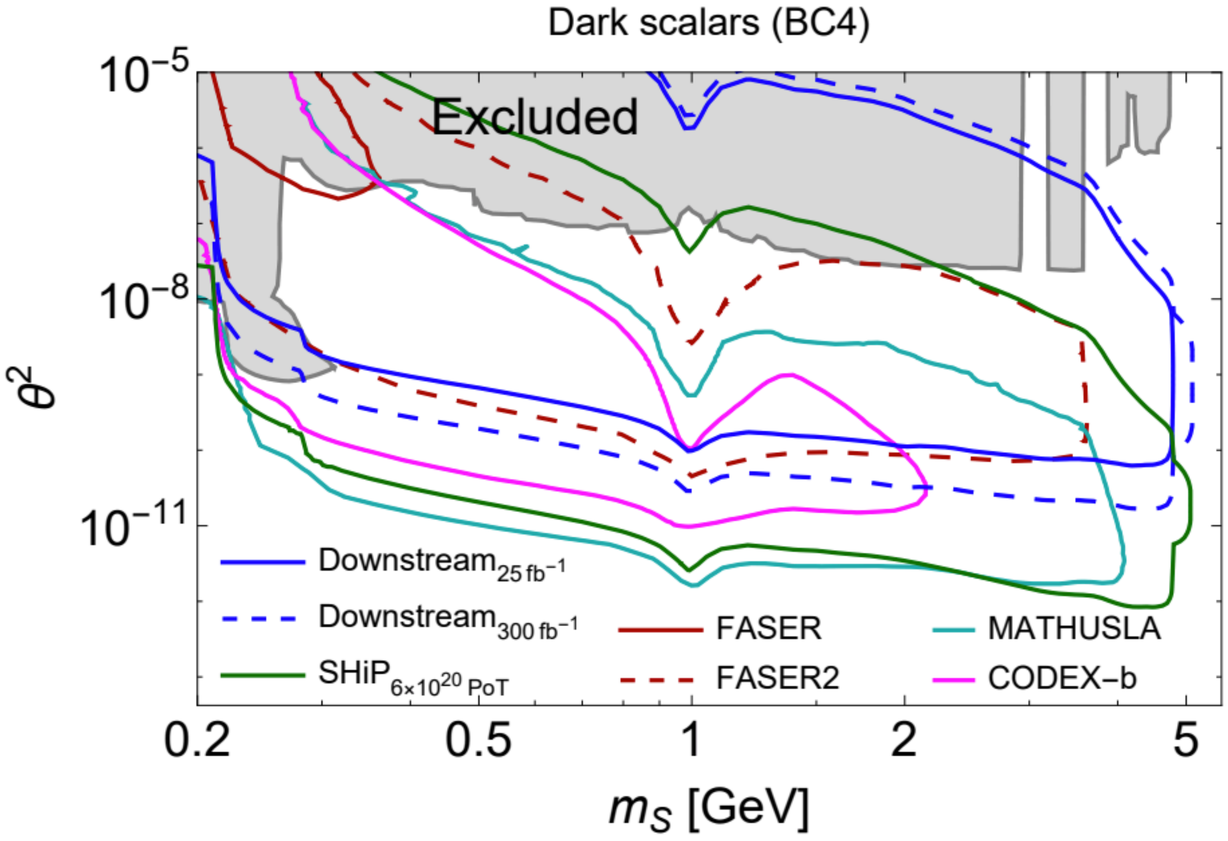



- Assuming $50\ \mathrm{ab}^{-1}$ Belle should have very strong prospects

# Dark Scalar: Downstream tracks

[Eur.Phys.J.C 84 (2024) 6, 608]

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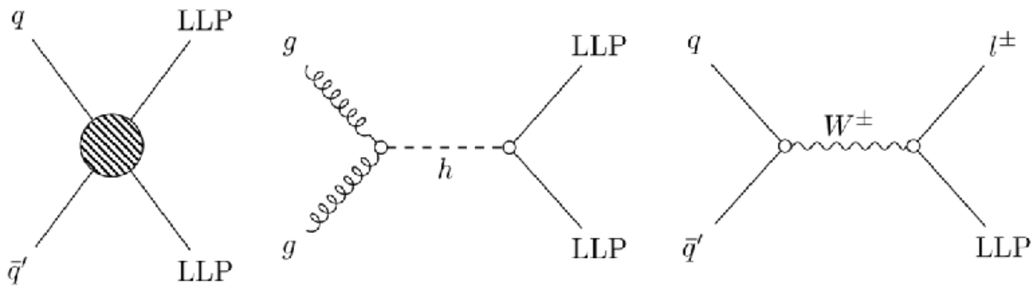
# LLP decaying to $e^{\pm}\mu^{\mp}\nu$ [Eur. Phys. J. C **81,** 261 (2021)]

- Massive particles with with long lifetimes in BSM models:
  - Direct pair production (DPP)
  - Higgs decay (HIG)
  - Charged currents (CC)
- Results of this analysis can be interpreted as:
  - Neutralino $\tilde{\chi}_0^1$ in R-parity-violating SSM
  - Right-handed neutrino N

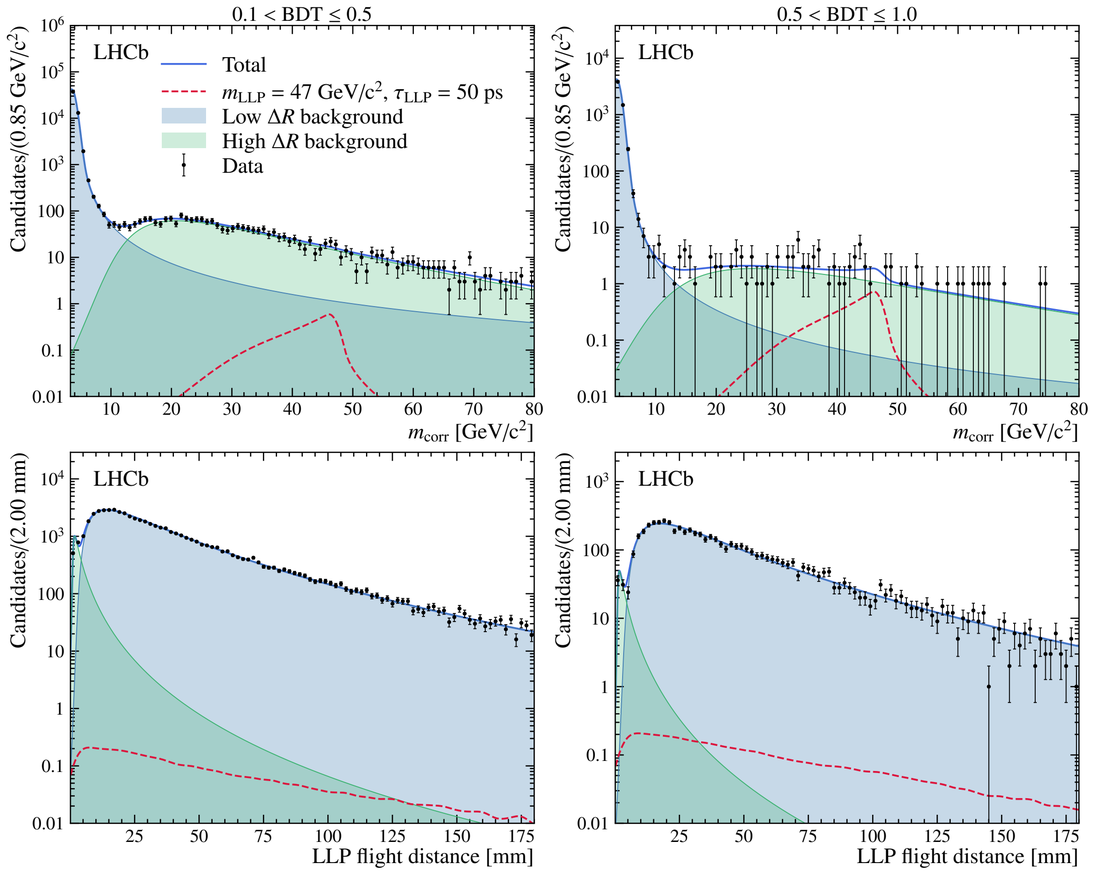
- Dataset: 5.38 fb$^{-1}$ of run 2 data (2016-2018) at $\sqrt{s}$=13 TeV
- Parameter space searched in:
  - $m \in [7,50]$ GeV
  - $\tau \in [2,50]$ ps



# LLP decaying to $e^{\pm}\mu^{\mp}\nu$ [Eur. Phys. J. C **81,** 261 (2021)]

Signal yield:

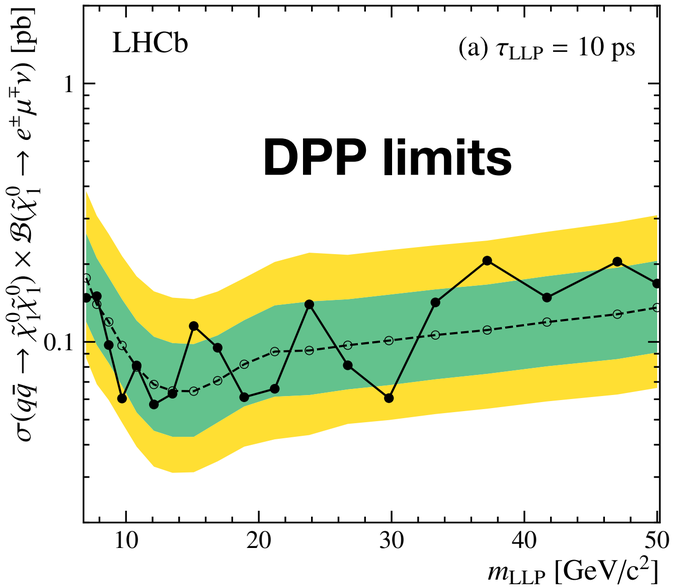
- Two componentes of $b\bar{b} \to e^{\pm}\mu^{\mp}X$ background
  - $\Delta R < 1$: shot flight distance
  - $\Delta R > 1$: long flight distance
- Simultaneous maximum likelihood fit:
  - Corrected mass and flight distance
  - Background PDF parameters free
  - Signal PDF parameters fixed from simulation
  - Signal fractions gaussian-constrained by simulation

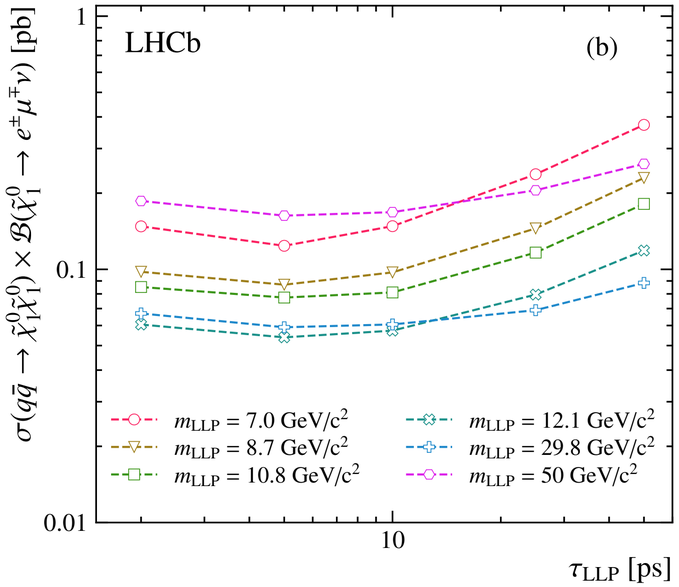


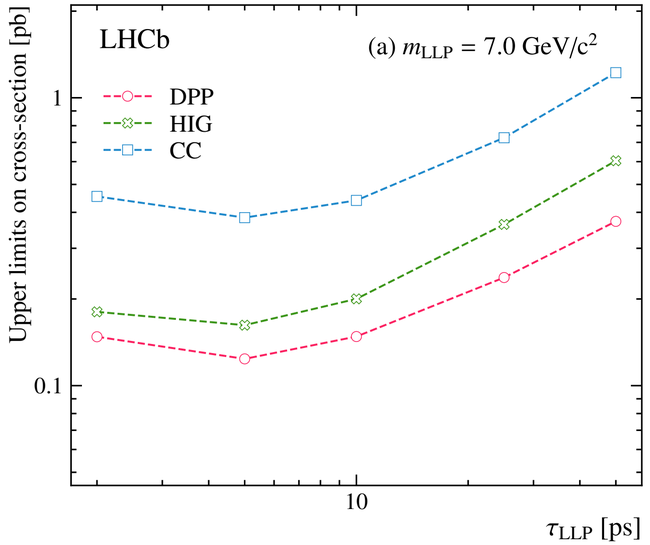
# LLP decaying to $e^{\pm}\mu^{\mp}\nu$ [Eur. Phys. J. C **81,** 261 (2021)]

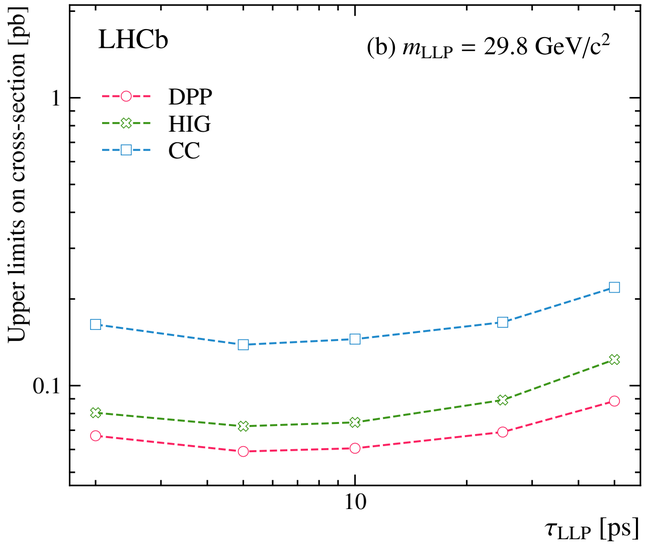
Results

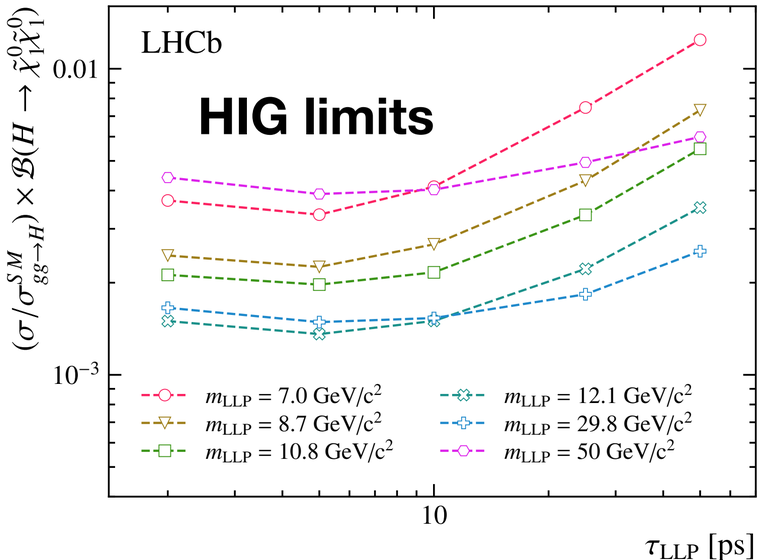
- No significant excess found
- Upper limits set at 95 % CL using CLs
- Different production mechanism probed
  - Best sensitivity for DPP mechanism



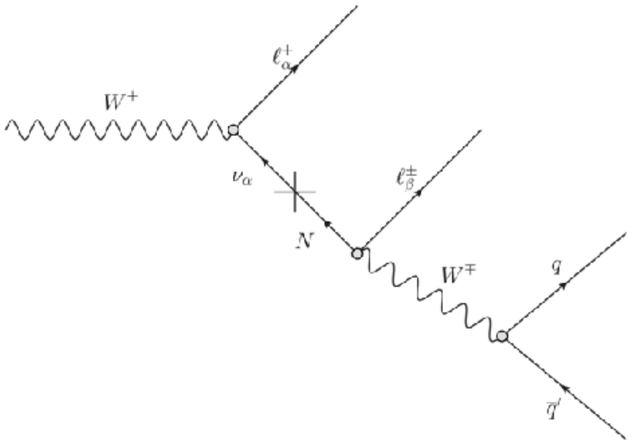



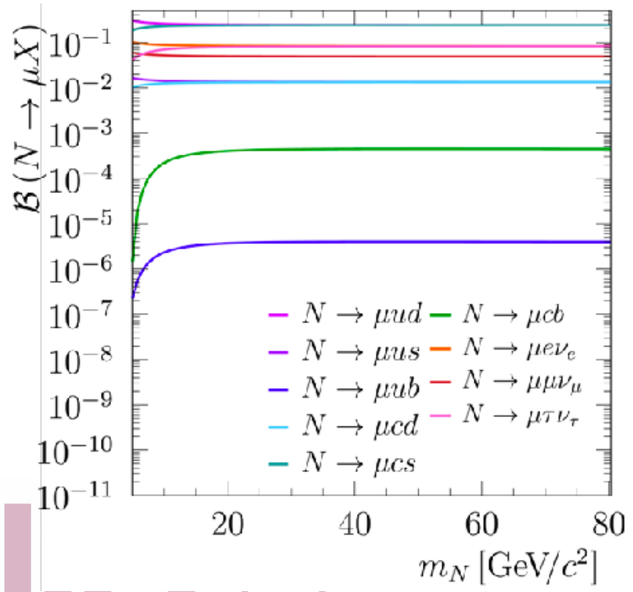



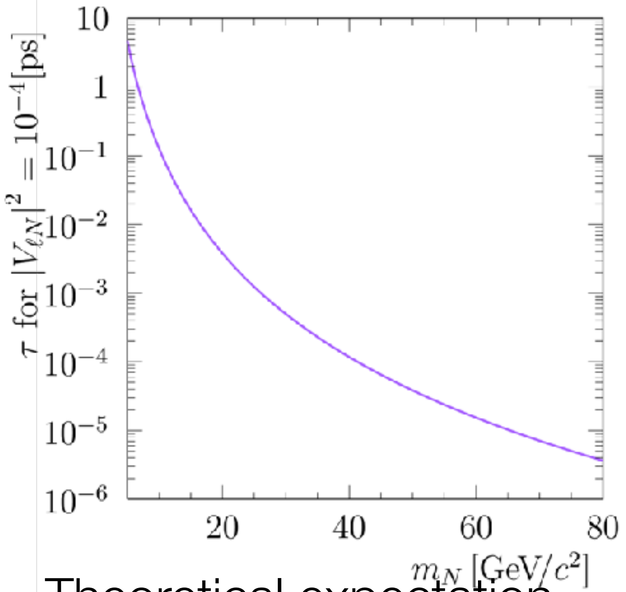



# HNL searches in $W^+ \to \mu^+\mu^\pm jet$ [Eur. Phys. J. C **81,** 248 (2021)]

- Heavy neutral leptons (HNLs): candidates to explain neutrino smallness
- Detection through mixing with SM neutrino and semileptonic decay
  - Both lepton-number-violating/-conserving scenarios
- Best sensitivity to $N \to \mu^\pm q\bar{q}'$ decay
  - Both same-sign and different-sign muons final state
  - This allows HNL to have Majorana nature !



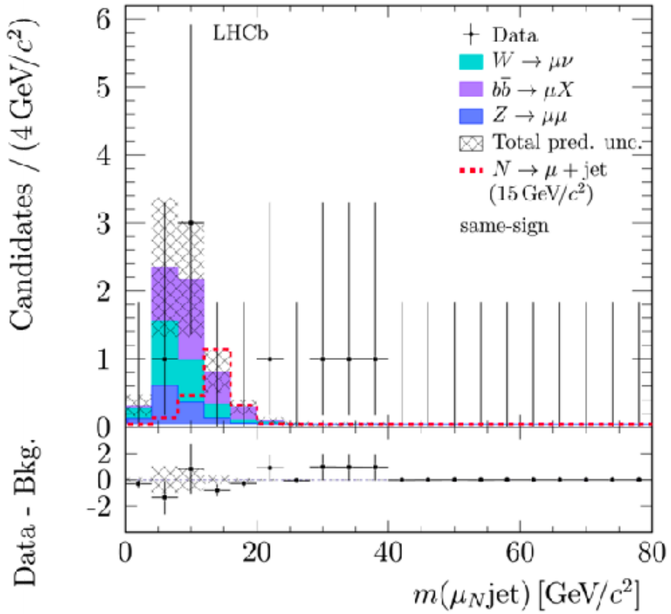

- Theoretical expectation

- Dataset: 3.0 fb$^{-1}$ of run 1 data (2011-2012) at $\sqrt{s}$=7,8 TeV
- Parameter space searched in:
  - $m \in [5,50]$ GeV
  - HNLs typically prompt in the mass window

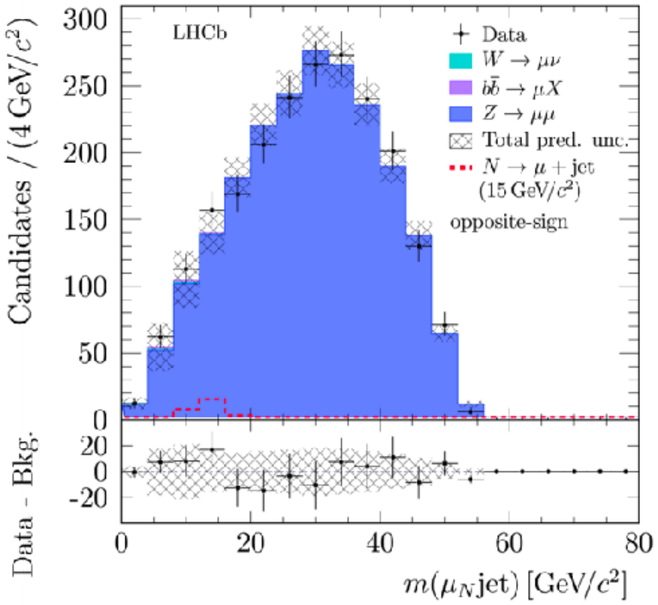
# HNL searches in $W^+ \to \mu^+\mu^\pm jet$ [Eur. Phys. J. C **81,** 248 (2021)]

Signal fit

- Binned maximum likelihood fit to the HNL mass: $m(\mu^\pm jet)$
  - Background and normalisation channel yields as well as efficiencies gaussian-constraint
- Background and normalisation channel yields taken from control regions
  - Expected background yields in signal region scaled according to simulation
- Templates taken from simulation both for signal and background




Same sign

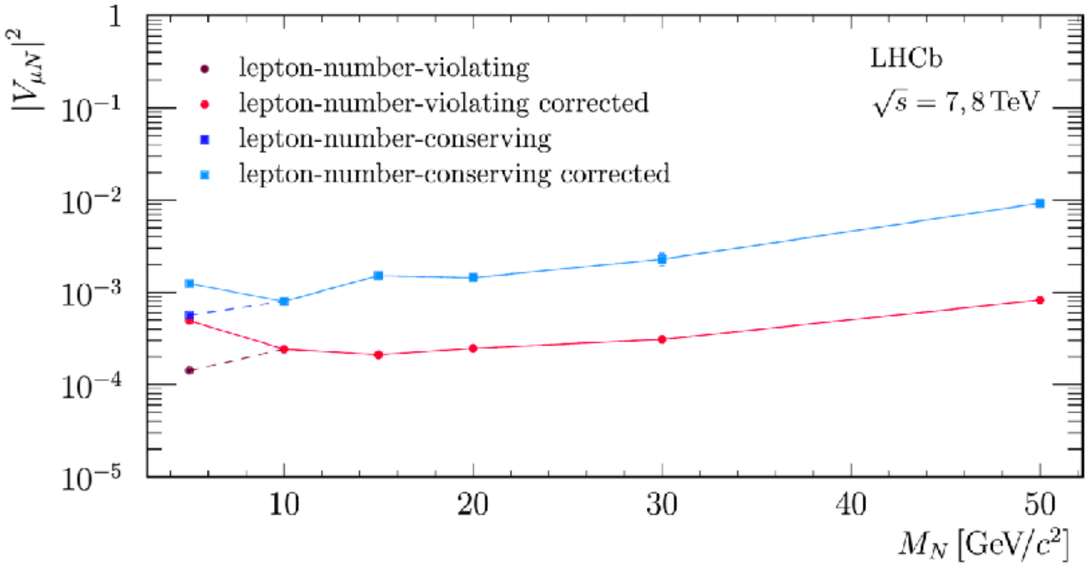


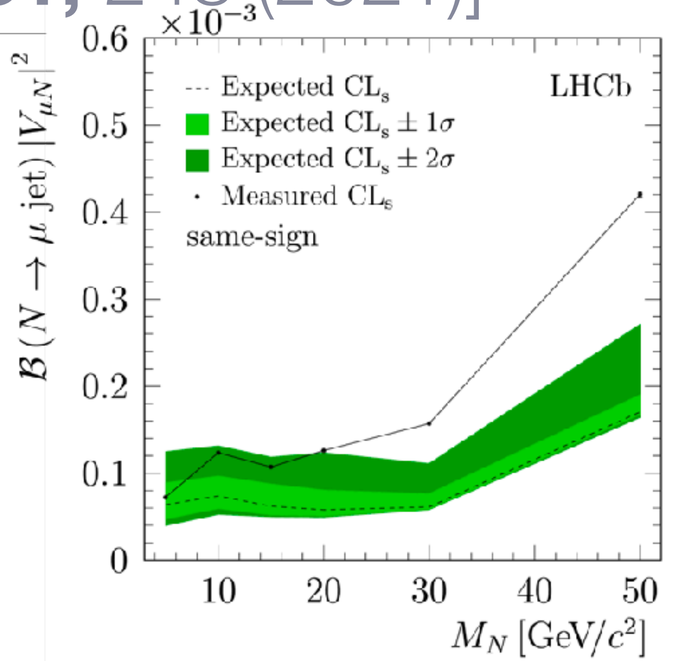

Opposite sign

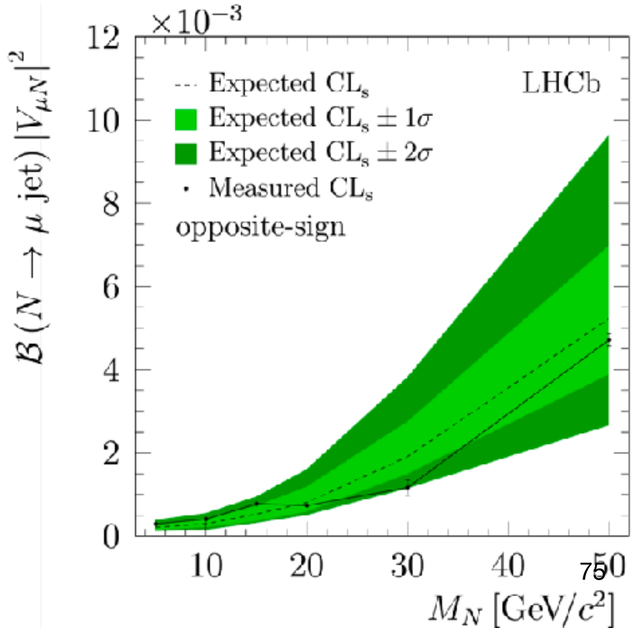
# HNL searches in $W^+ \to \mu^+\mu^\pm jet$ [Eur. Phys. J. C **81,** 248 (2021)]

Results

- No significant excess found
- Upper limits on branching fraction ($\mathcal{B}(N->\mu jet)\,|\,V_{\mu N}|^2$) are set using CLs method
  - First limit for $\mu\mu jet$ signature for $M_N < 20$ GeV
  - First lepton-number-conserving limits for prompt HNL



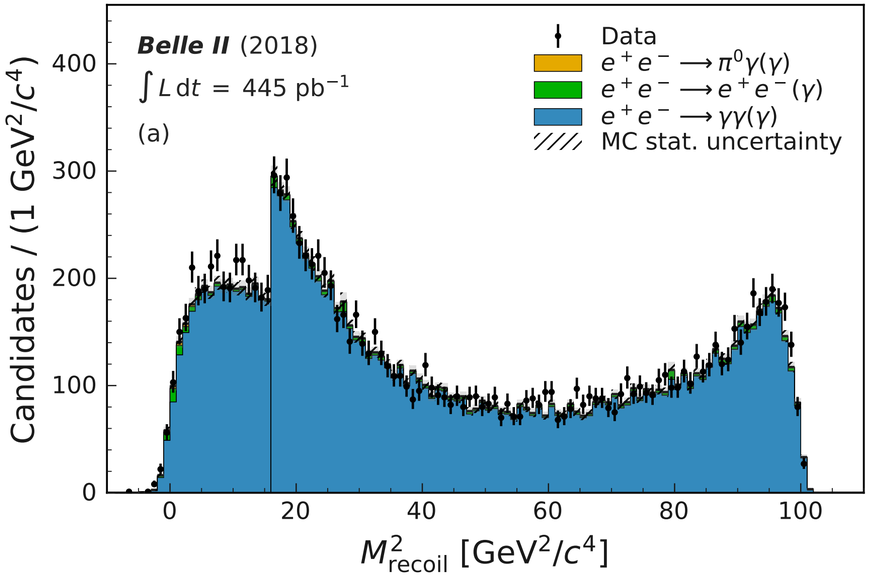



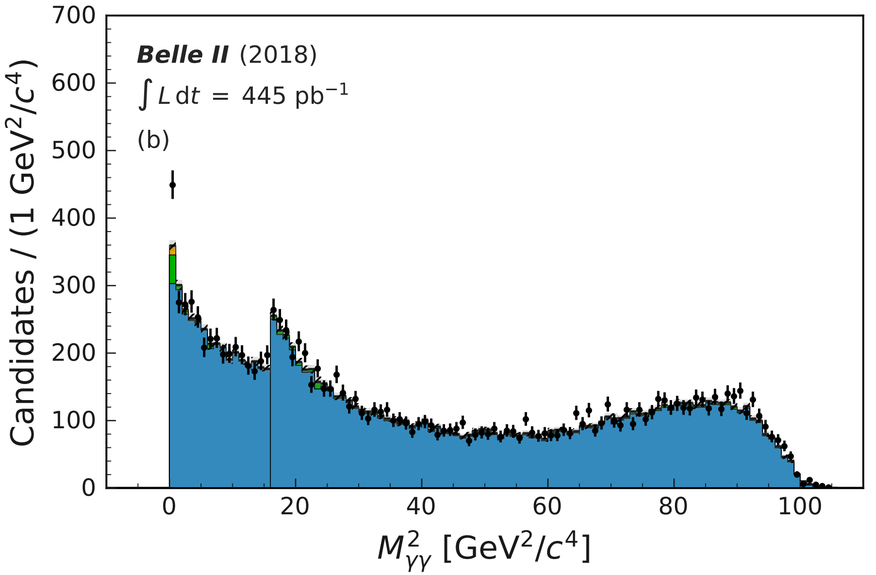




- Lower mass coupling limit corrected because of non-negligible lifetime

# Belle II: $e^+e^- \to \gamma a, a \to \gamma\gamma$ [Phys. Rev. Lett. 125, 161806]

- Dataset: $445\ \mathrm{pb}^{-1}$ from 2018 pilot run
- Search for ALPs produced together with a $\gamma$
- Signature:
  - 3 isolated photons
- Selection:
  - $0.88\sqrt{s} \leq M_{\gamma\gamma\gamma} \leq 1.03\sqrt{s}$
- Backgrounds:
  - $e^+e^- \to \gamma\gamma\gamma$
  - $e^+e^- \to e^+e^-\gamma$
- Binned extended maximum likelihood fits:
  - $m_a \in [0.2,\ 6.85]\ \mathrm{GeV}$ to the $M^2_{\gamma\gamma}$ distribution
  - $m_a \in [6.85,\ 9.7]\ \mathrm{GeV}$ to the $M^2_{\mathrm{recoil}}$ distribution

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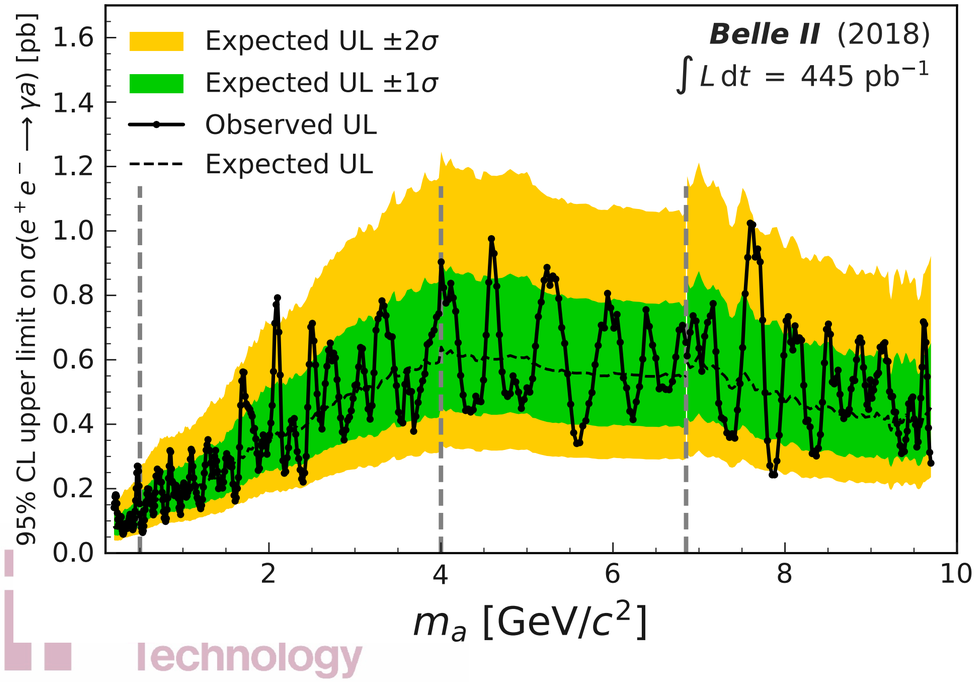
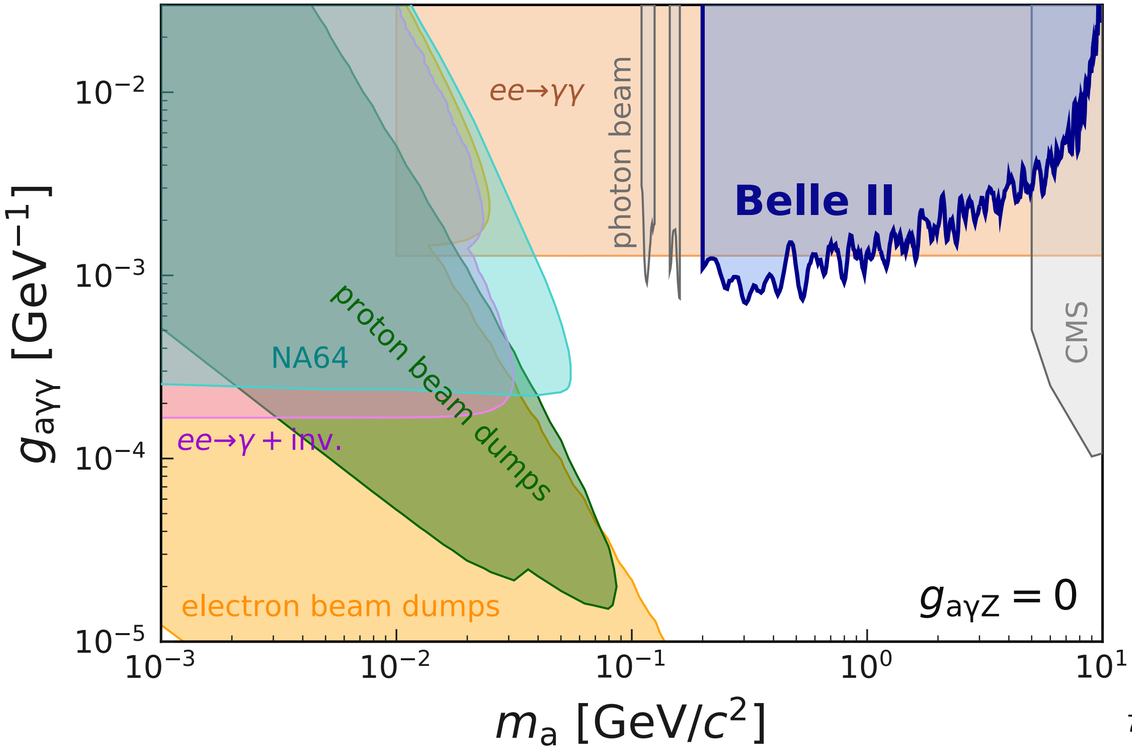
# Belle II: $e^+e^- \to \gamma a, a \to \gamma\gamma$ [Phys. Rev. Lett. 125, 161806]

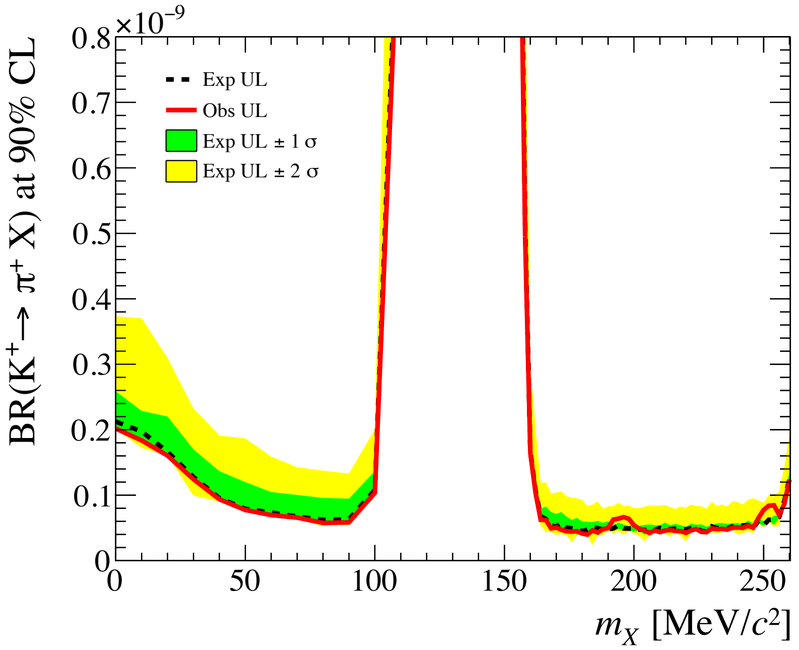
- Binned extended maximum likelihood fits over the mass range
  - $m_a \in [0.2,\ 6.85]\ \mathrm{GeV}$ to the $M^2_{\gamma\gamma}$ distribution
  - $m_a \in [6.85,\ 9.7]\ \mathrm{GeV}$ to the $M^2_{\mathrm{recoil}}$ distribution
- $95\ \%\,\mathrm{CL}$ upper limits on the signal cross section translated into $g_{a\gamma\gamma}$

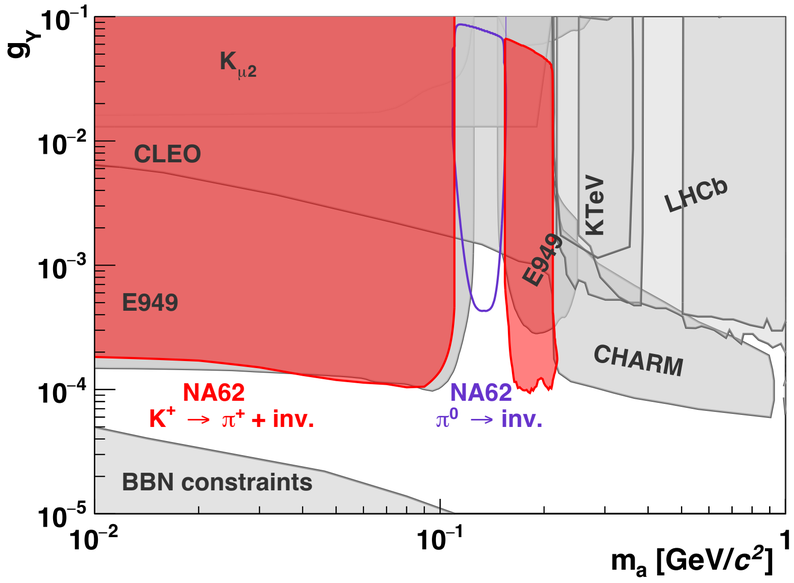


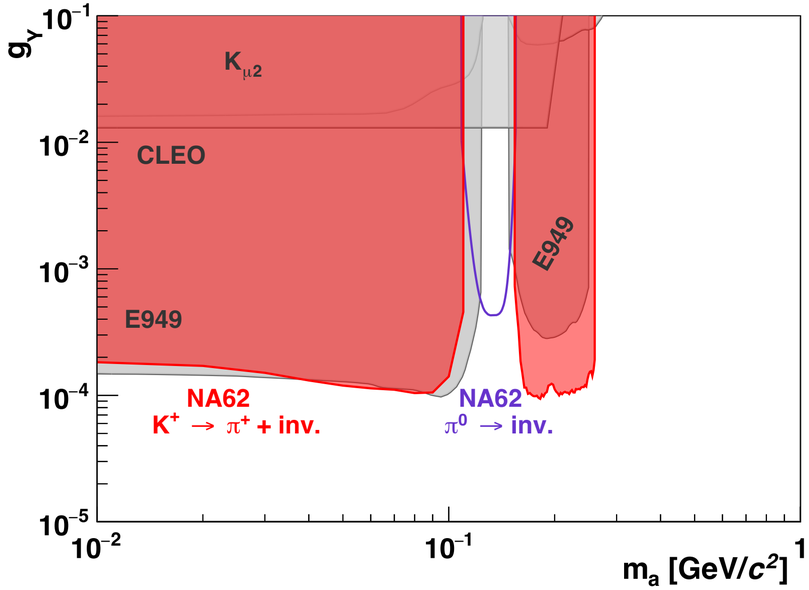



# NA62: $K^+ \to \pi^+ a,\ a \to$ invisible [JHEP 03 (2021) 058]

- Frequentist hypothesis test with $m^2_{\text{miss}}$ as observable
  - Unbinned profile likelihood ratio test statistic
  - Two compatible events found at $m_X = 196,\ 252$ MeV
- Upper limits on $\text{BR}(K^+ \to \pi^+ X)$ using $\text{CL}_\text{s}$ method at 90 % CL
  - Two category limits on the coupling to ALPs derived from those
    - ALPs decaying to visible particles
    - ALPs decaying invisibly



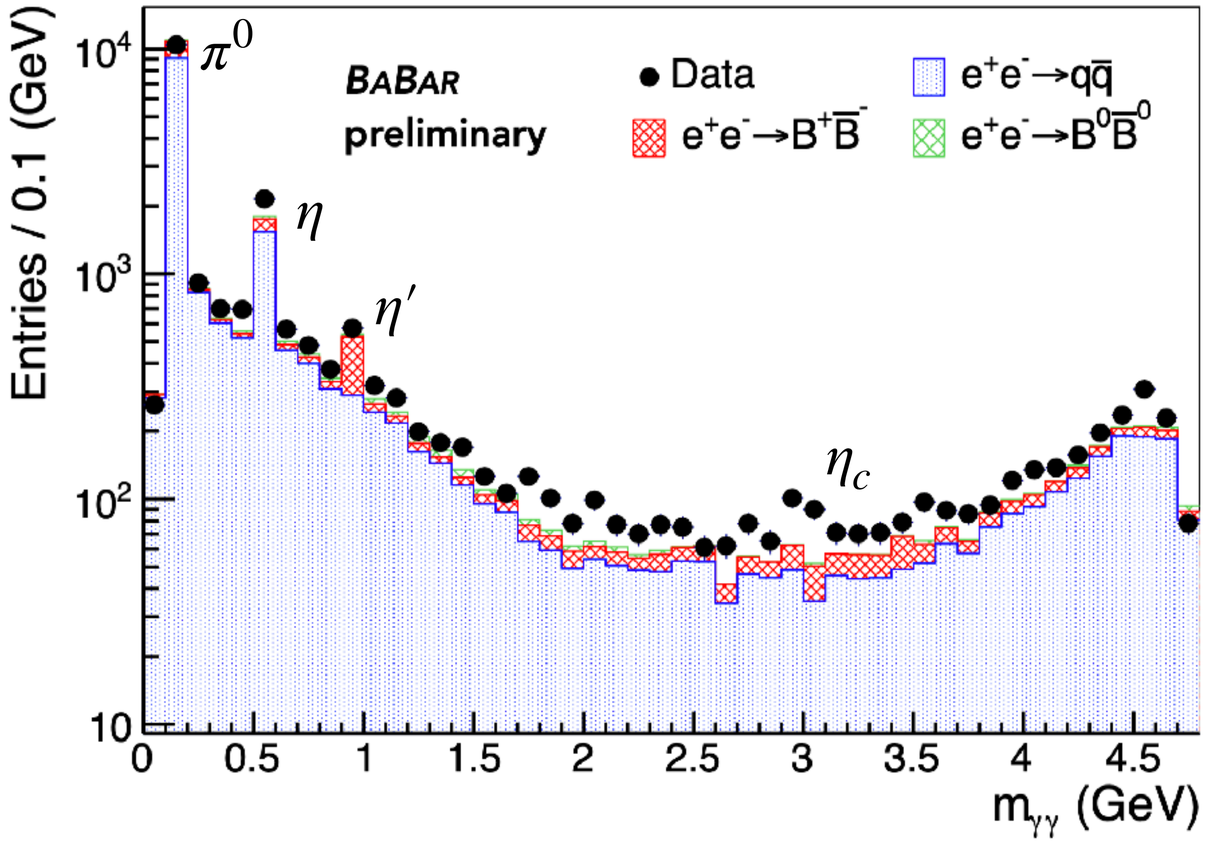



# BaBar: $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$

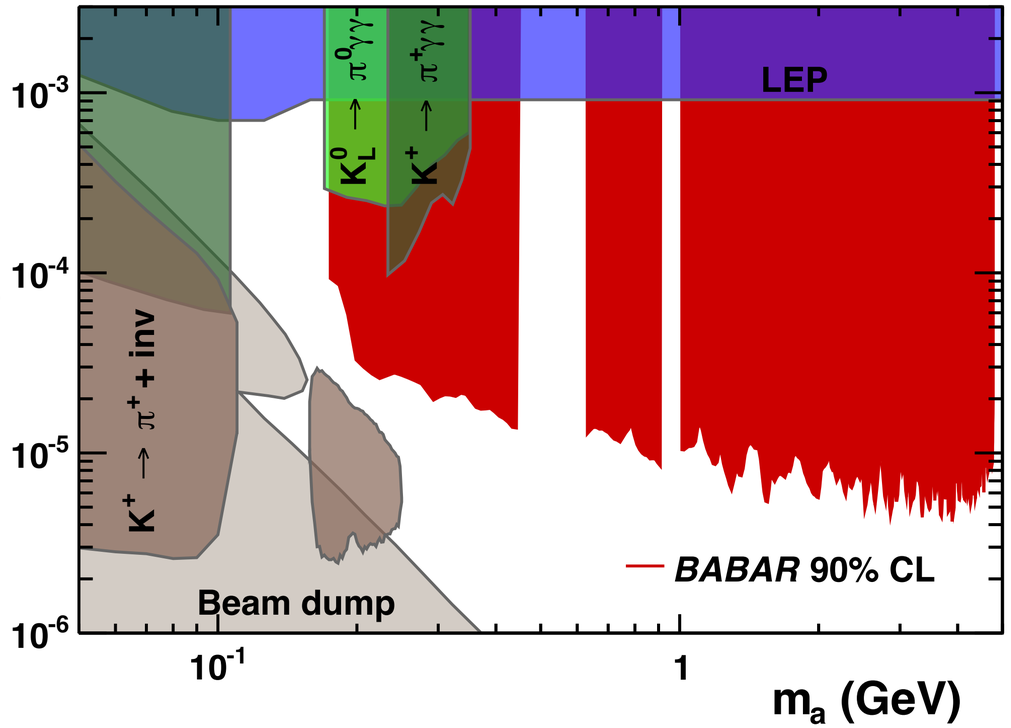
[PRL 128 (2022) 13, 131802]

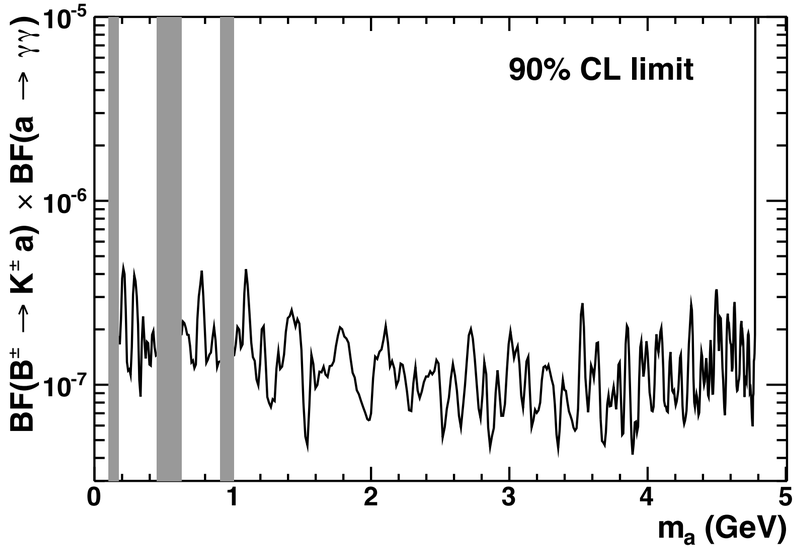
- Search for ALPs in $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ channel
  - Bump hunt for a narrow peak
- Final results waiting:
  - Blind analysis using only $8\ \%$ of total data
- Prompt search for
  - $m_a \in [0.1,\ 4.78]\ \mathrm{GeV}$
- Displaced search for:
  - $m_a < 2.5\ \mathrm{GeV}$
  - $c\tau_a = 1,\ 10,\ 100\ \mathrm{mm}$
- Main backgrounds:
  - $e^+e^- \to q\bar{q}\ (q = u,\ d,\ s,\ c)$
  - $e^+e^- \to B\bar{B}$
  - Peaking resonances: $\pi^0,\ \eta,\ \eta'$

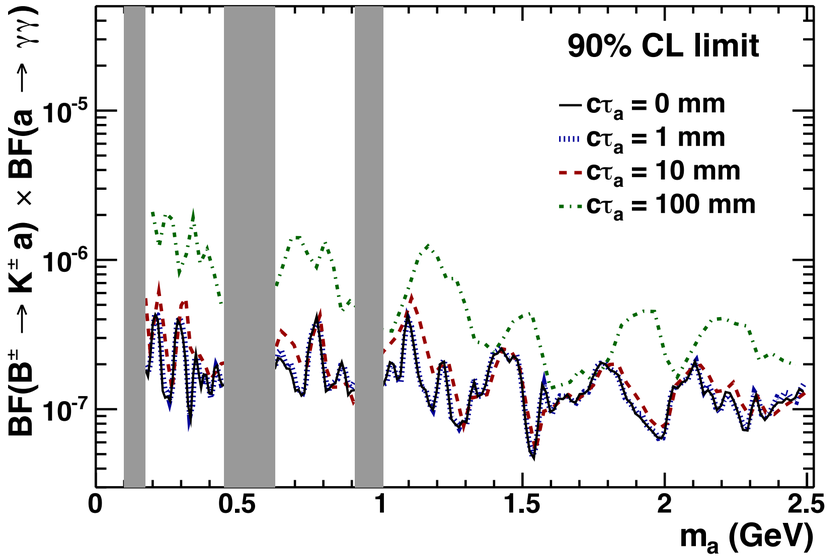


# BaBar: $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ [PRL 128 (2022) 13, 131802]

- Unbinned maximum likelihood fit to $m_{\gamma\gamma}$
- $90\ \%\ \mathrm{CL}$ limits placed for prompt and long lived ALPs on $\mathrm{BF}(B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma)$
- $\mathrm{BF}(\tau)$ used to set limits on coupling to vector boson $W$
  - Improving current bounds by many orders of magnitude !
- Signature to also be covered by Belle II in the near future as reported in EPS conference ! (this dates of 2021, didn't find the result!)

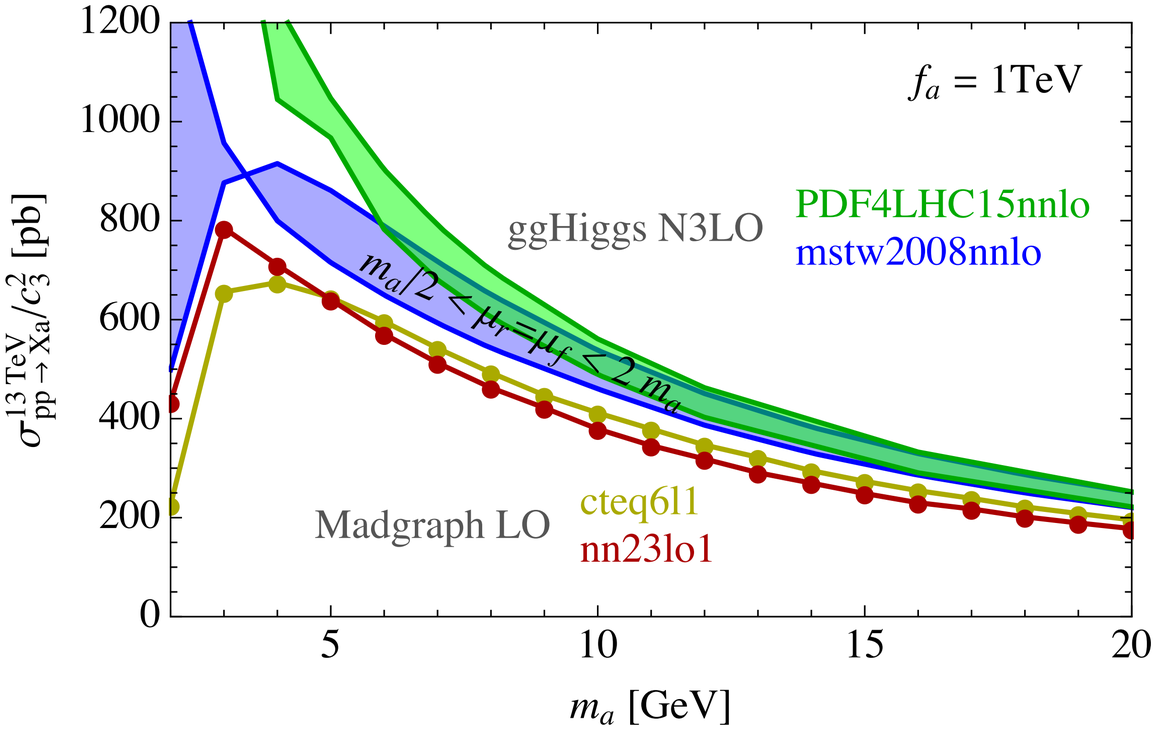


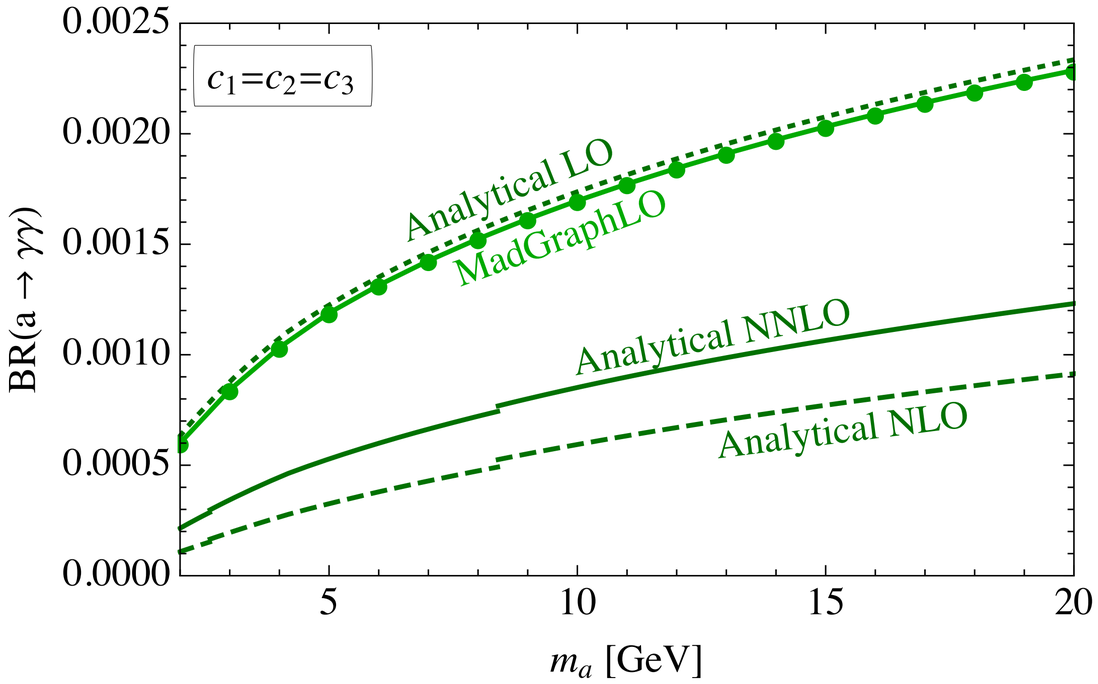



# ALP → $\gamma\gamma$

[JHEP 1901 (2019) 113]




- Production cross-section in $pp$ collisions and decay BR with perturbative calculations