



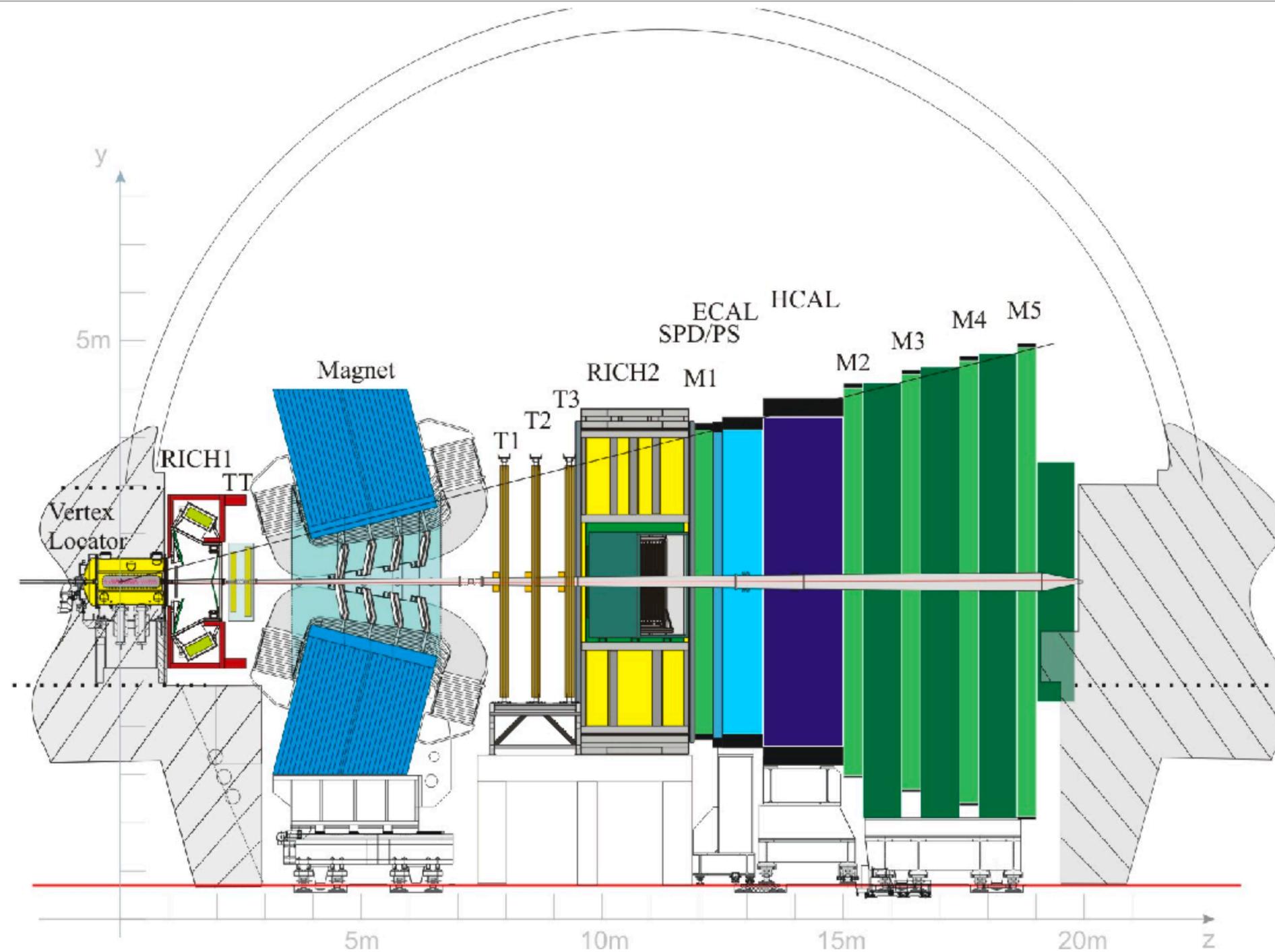
The Dark Sector @ LHCb

Adrián Casais Vidal (MIT, LHCb collaboration)

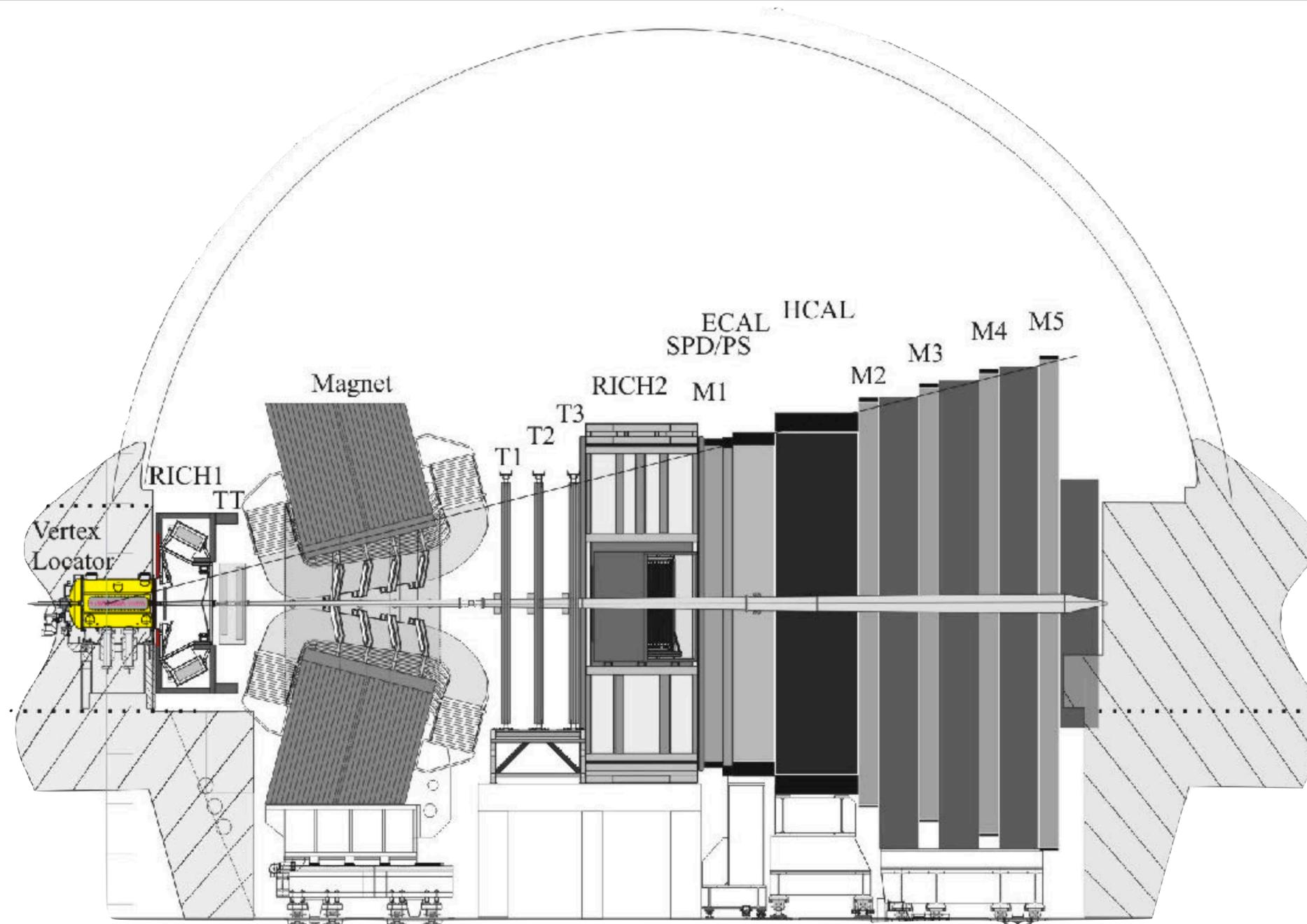
October 17th, 2024. Belle II Physics Week - KEK (Tsukuba)



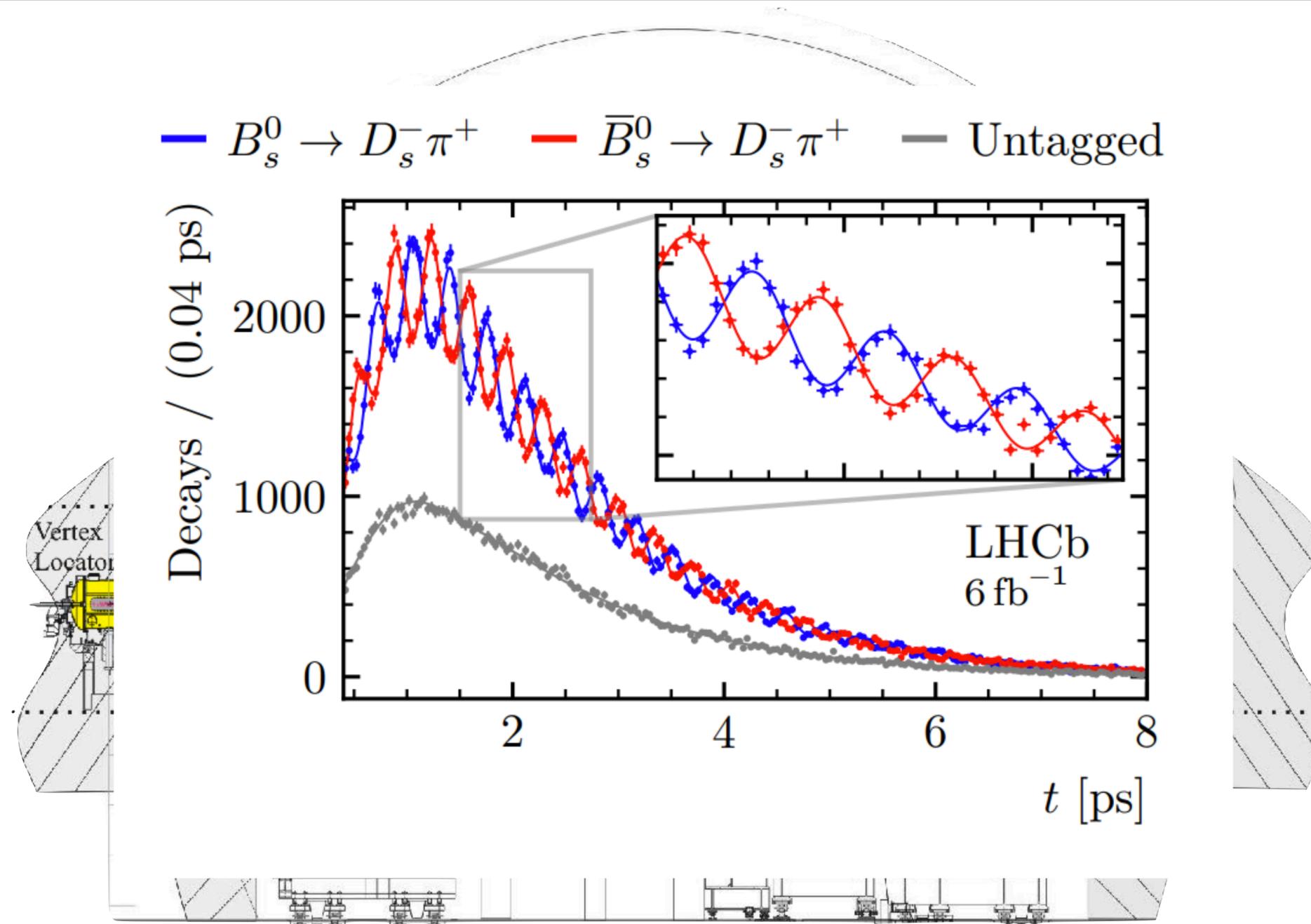
The LHCb experiment



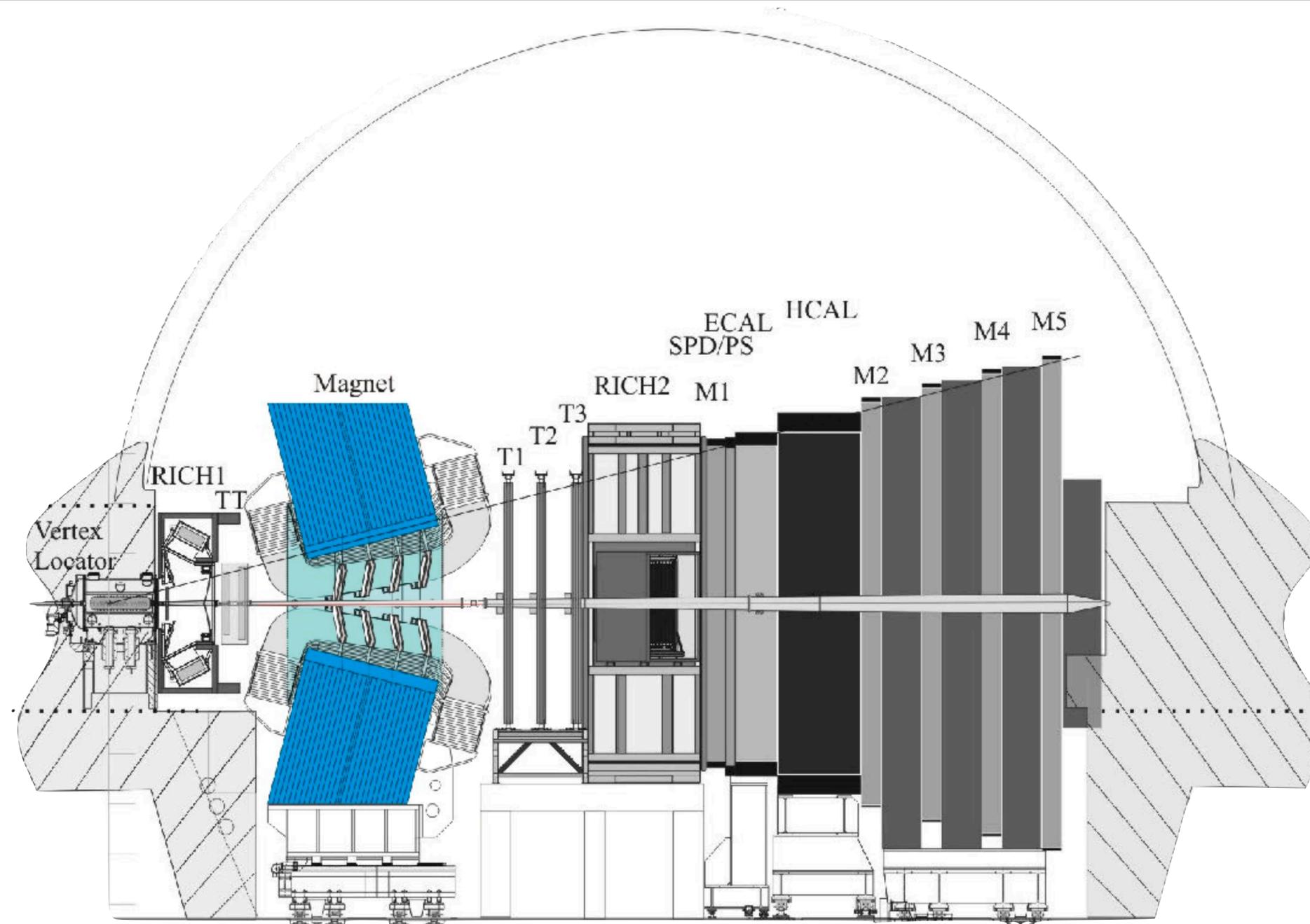
The LHCb experiment



The LHCb experiment

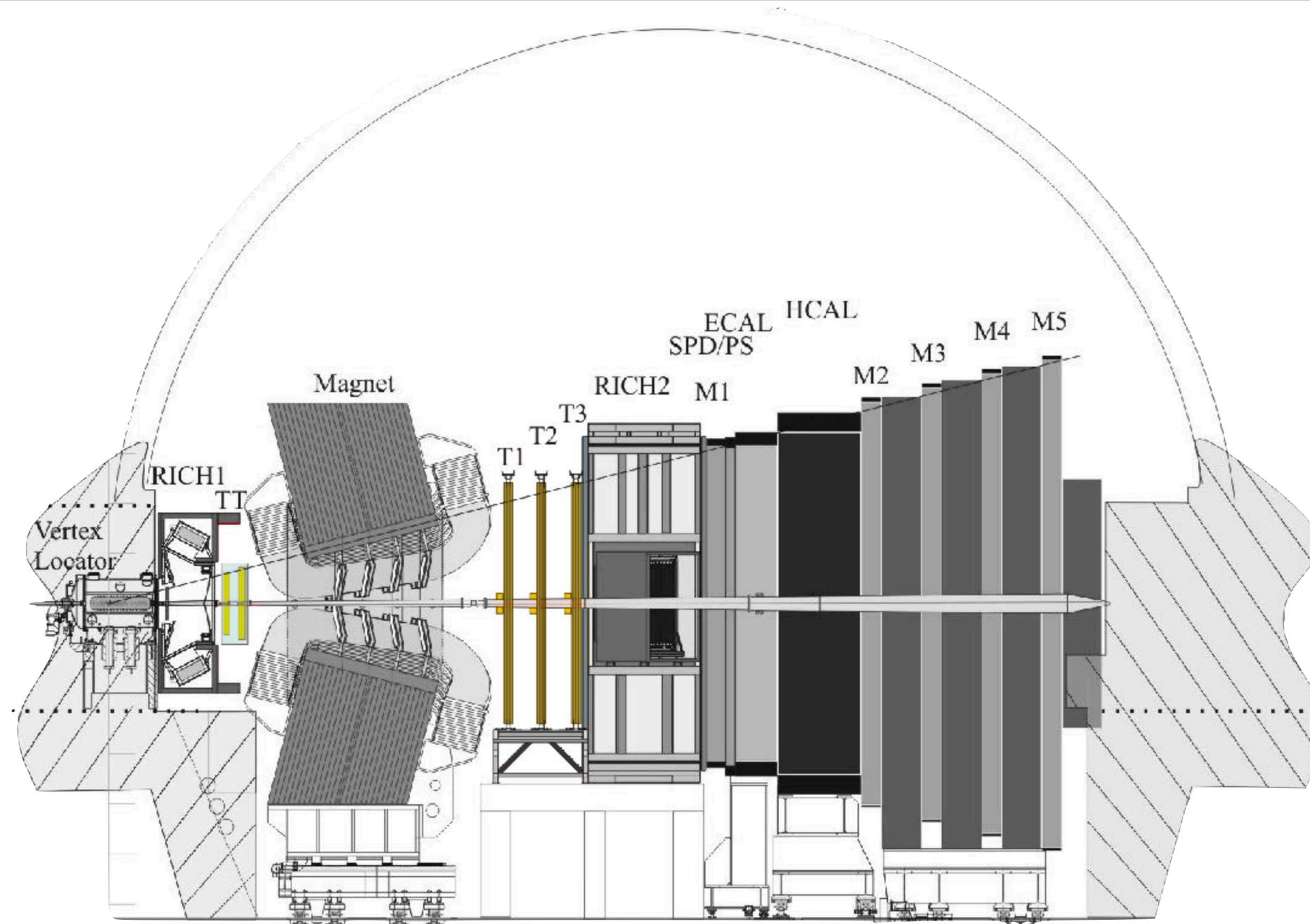


The LHCb experiment

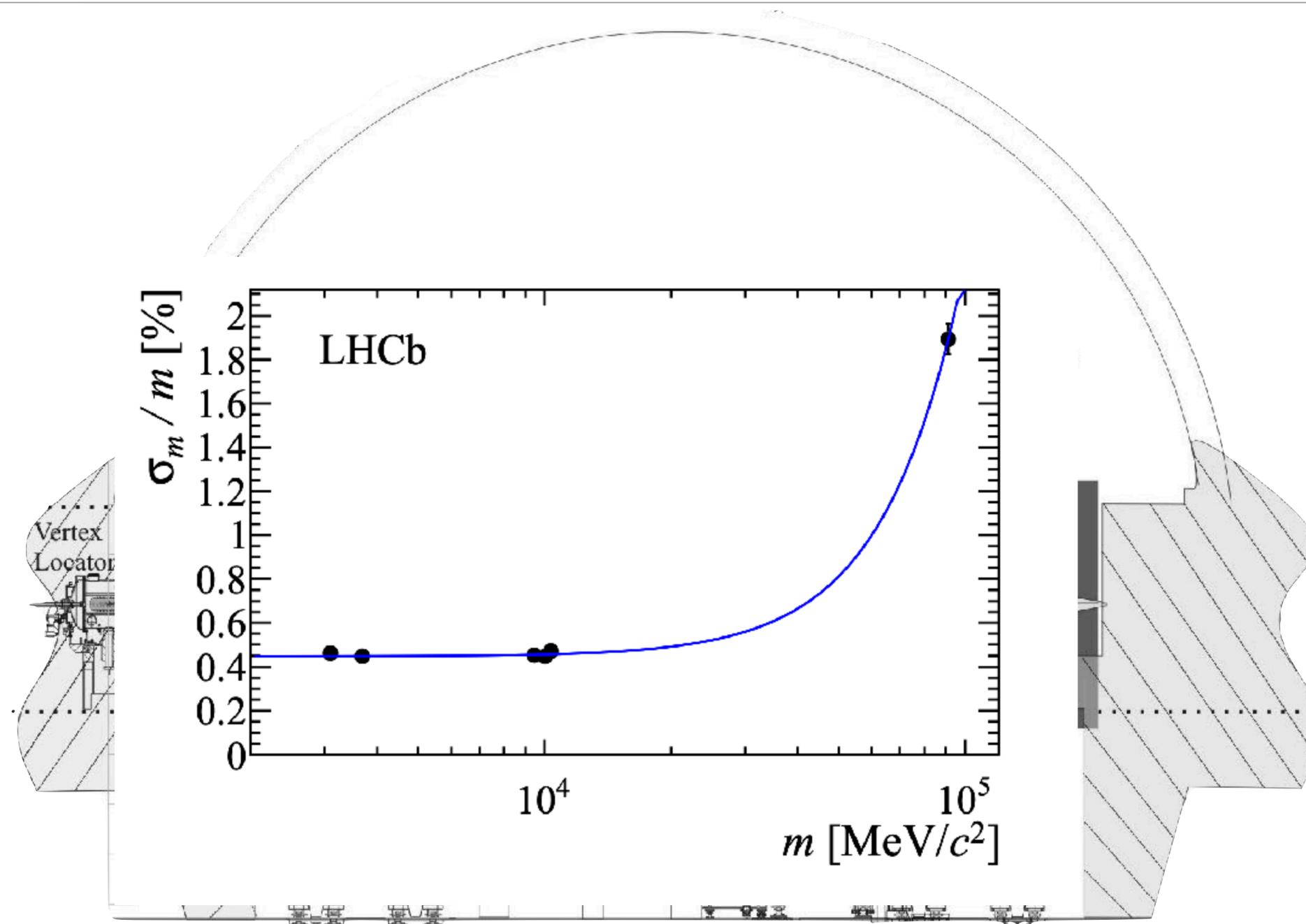


Magnet: provides the bending power to measure the momentum and charge of the charged particles

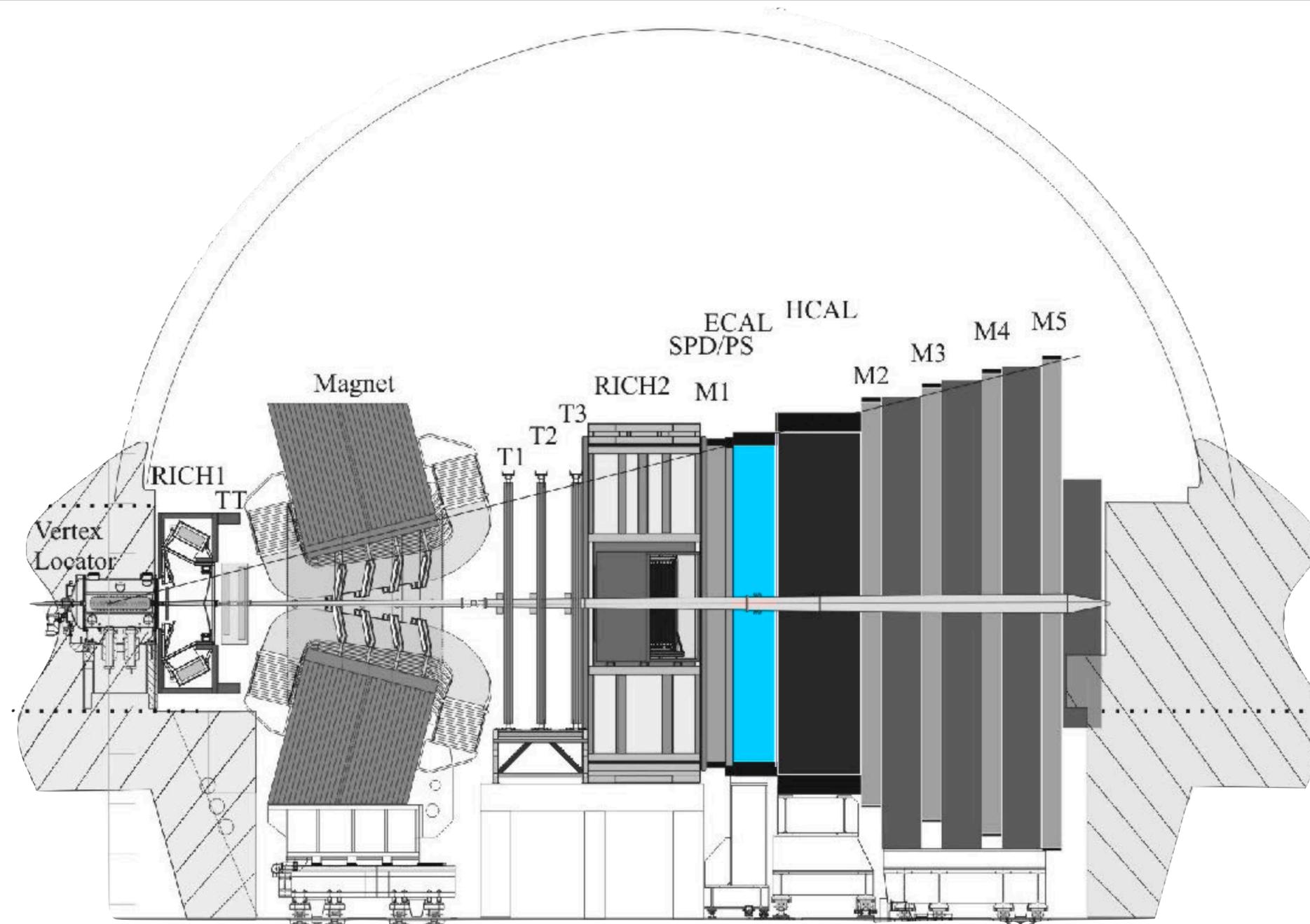
The LHCb experiment



The LHCb experiment

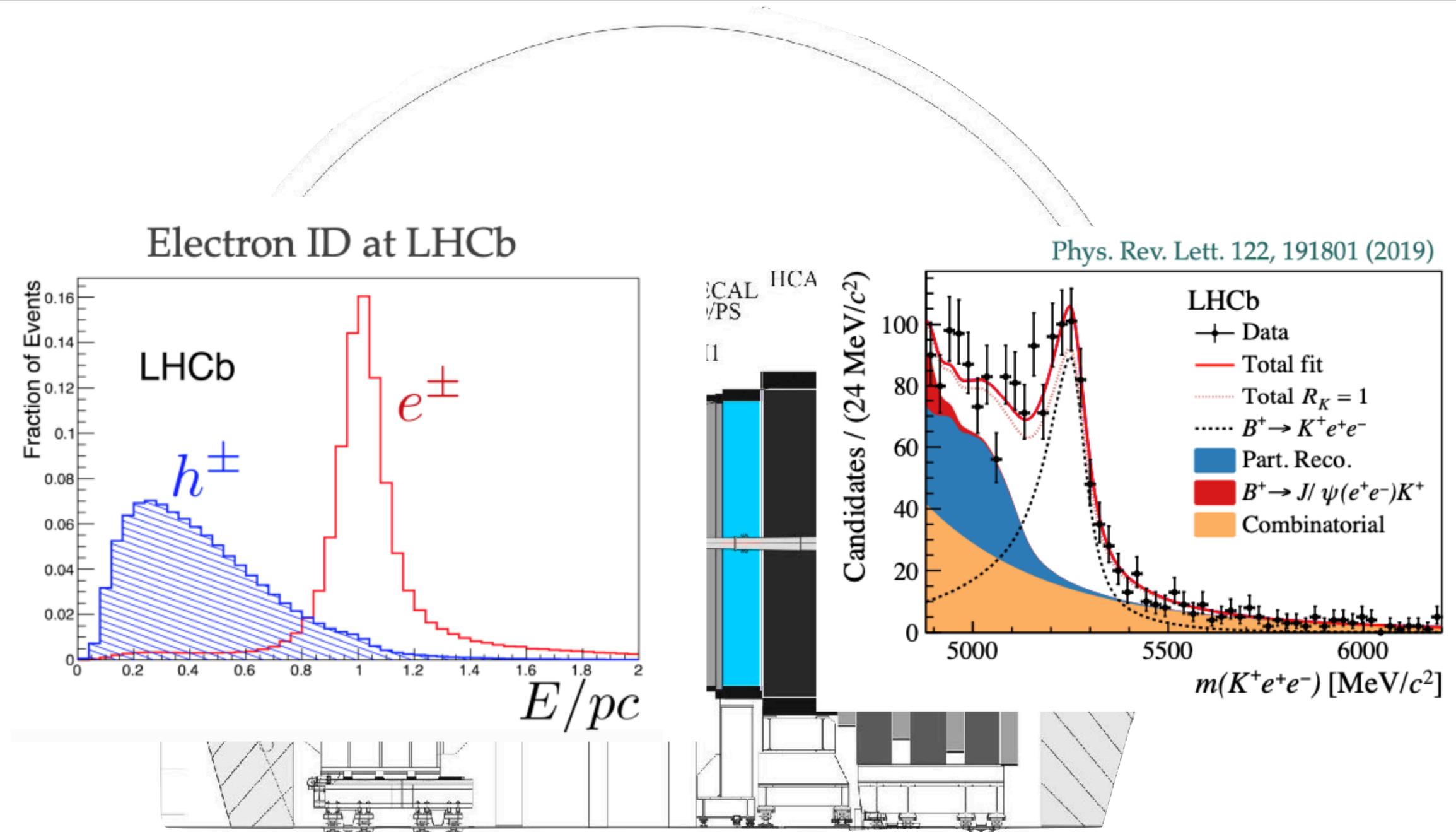


The LHCb experiment



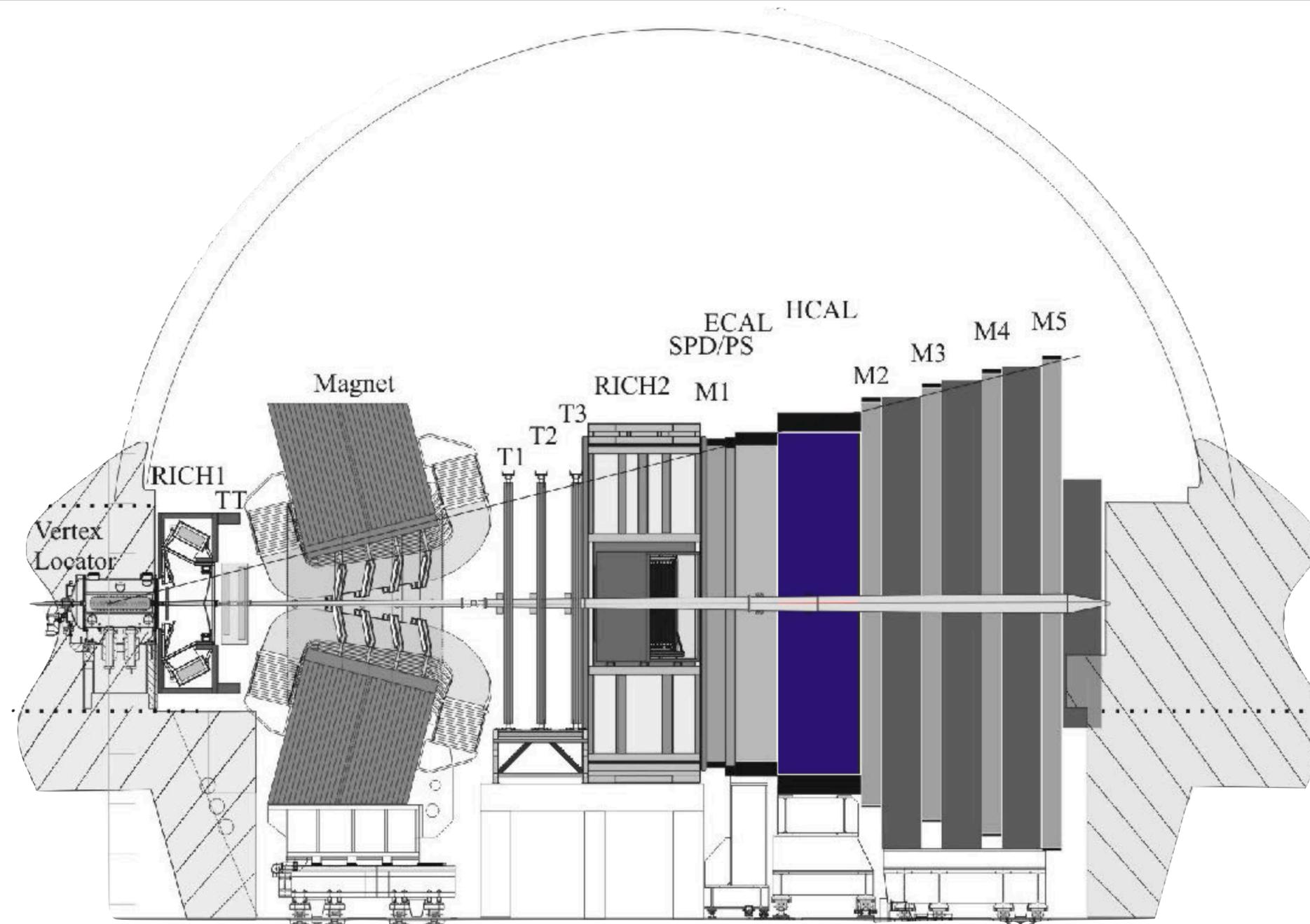
ECAL: identifies electrons and photons by measuring the energy of the EM shower they produce

The LHCb experiment



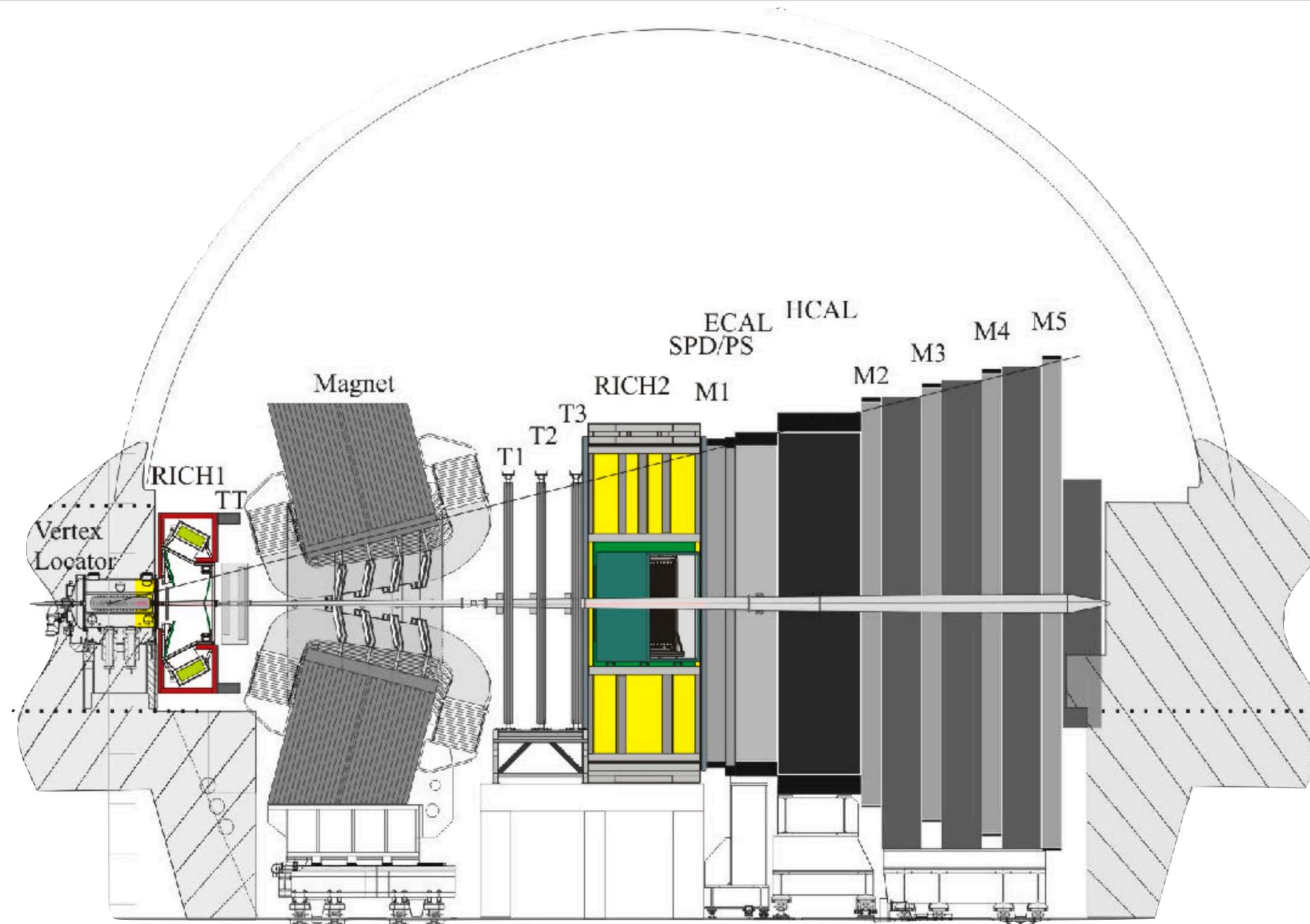
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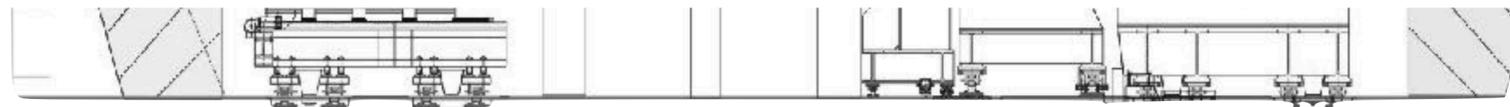
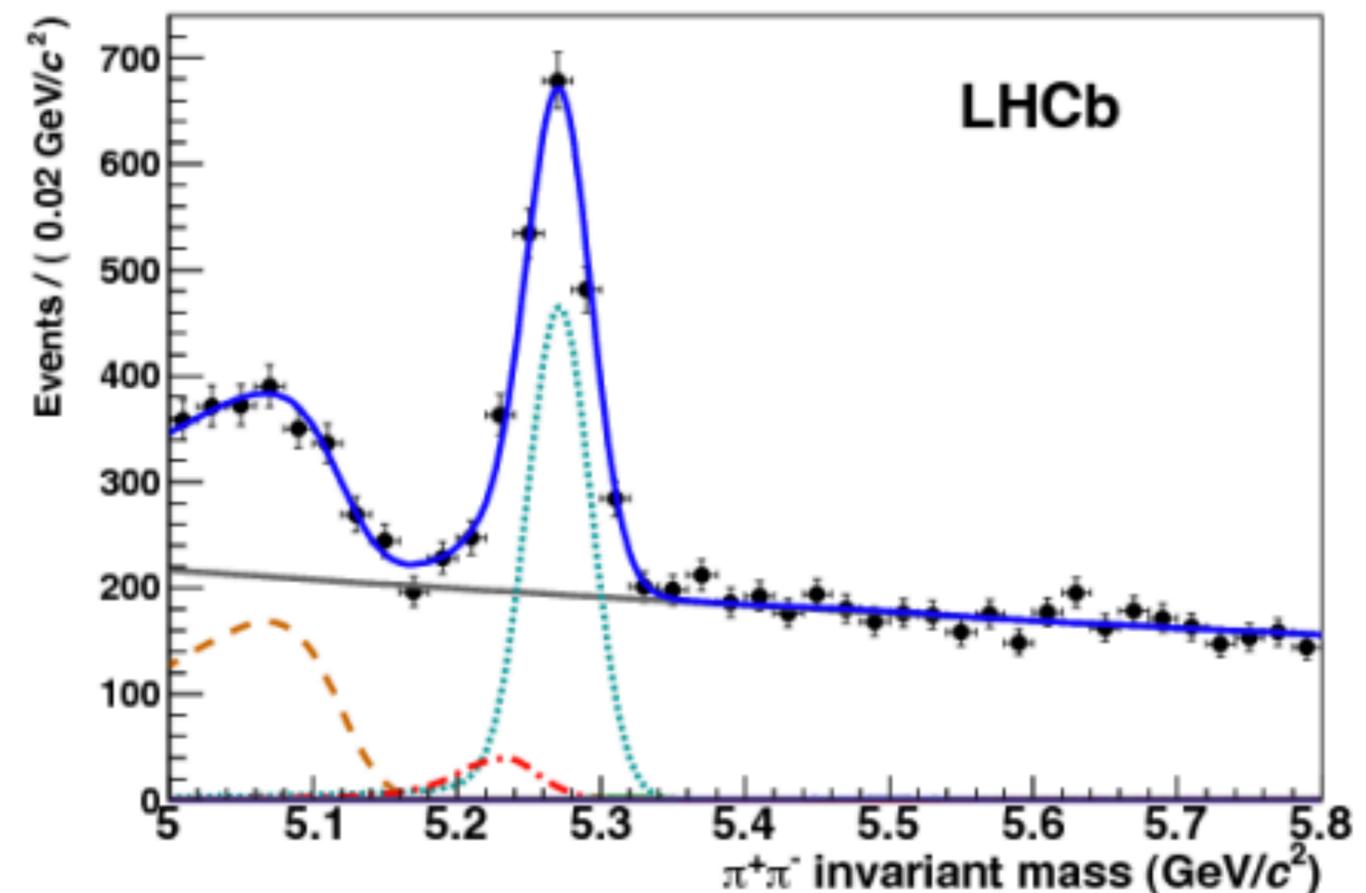
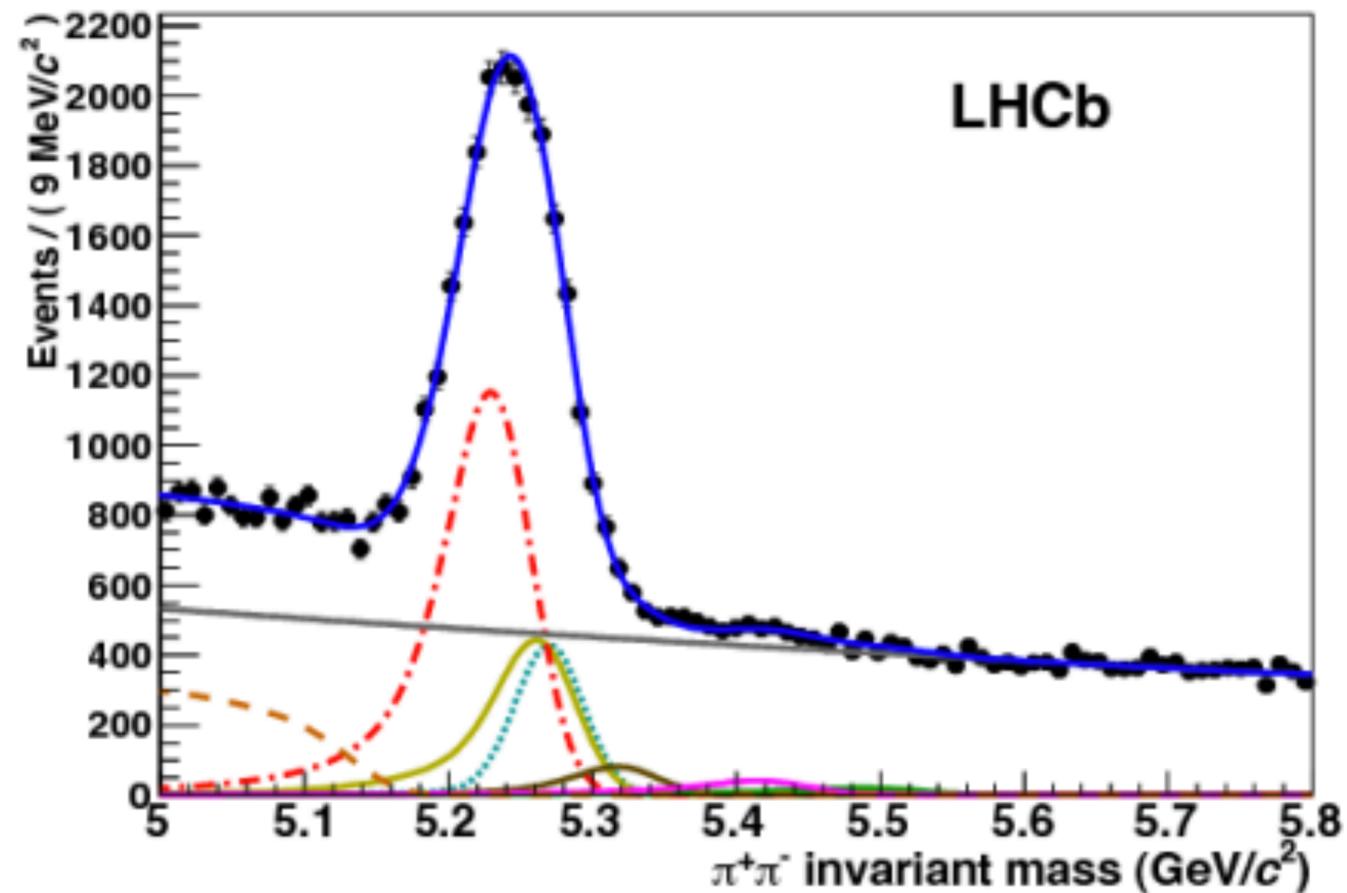
HCAL: helps identify hadrons and provides a veto for those that could fake electrons or

The LHCb experiment



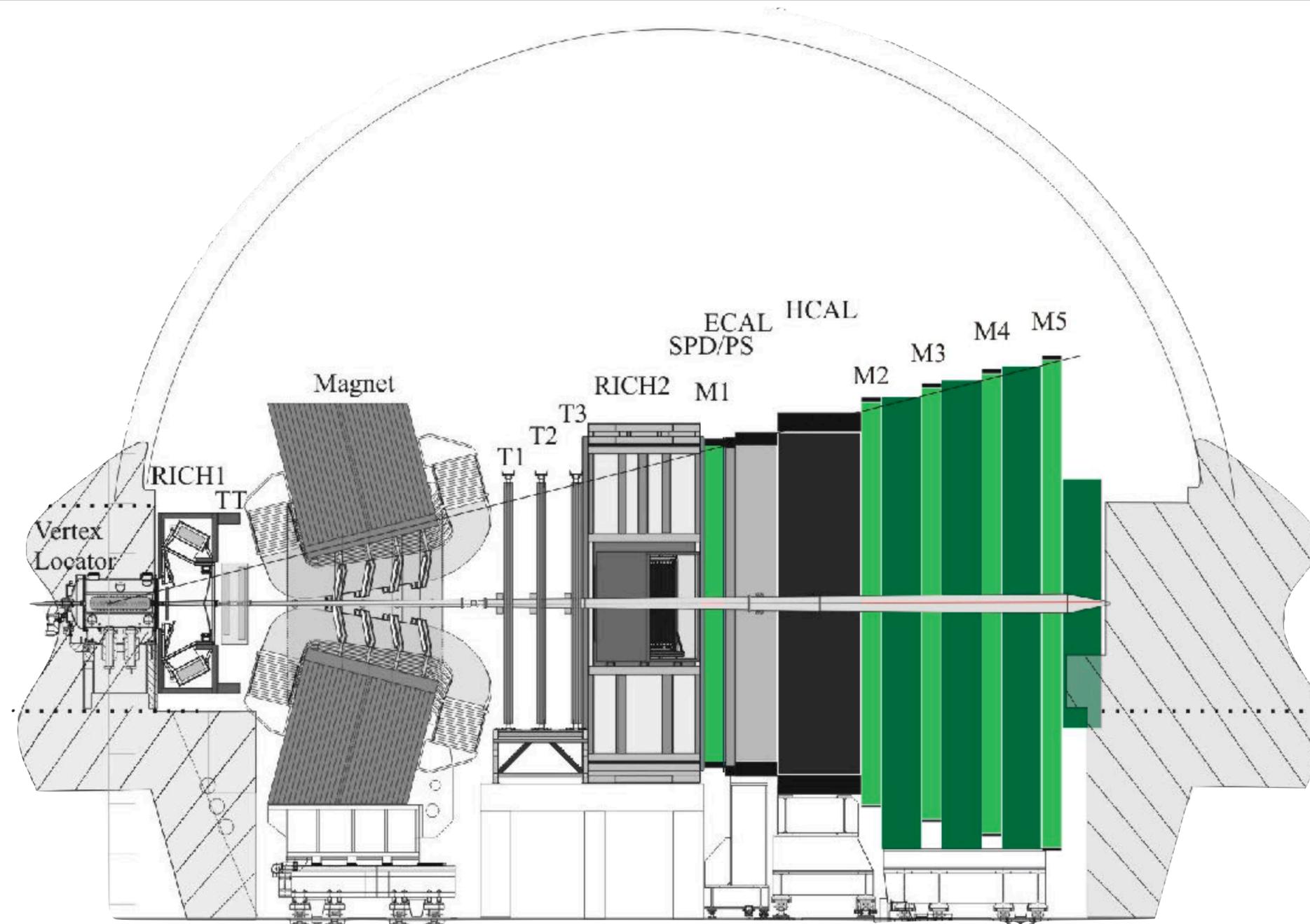
RICH: identify charged particles by measuring their Cherenkov light

The LHCb experiment



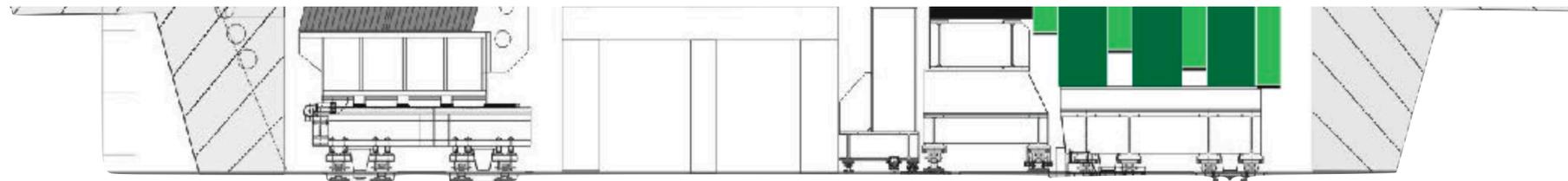
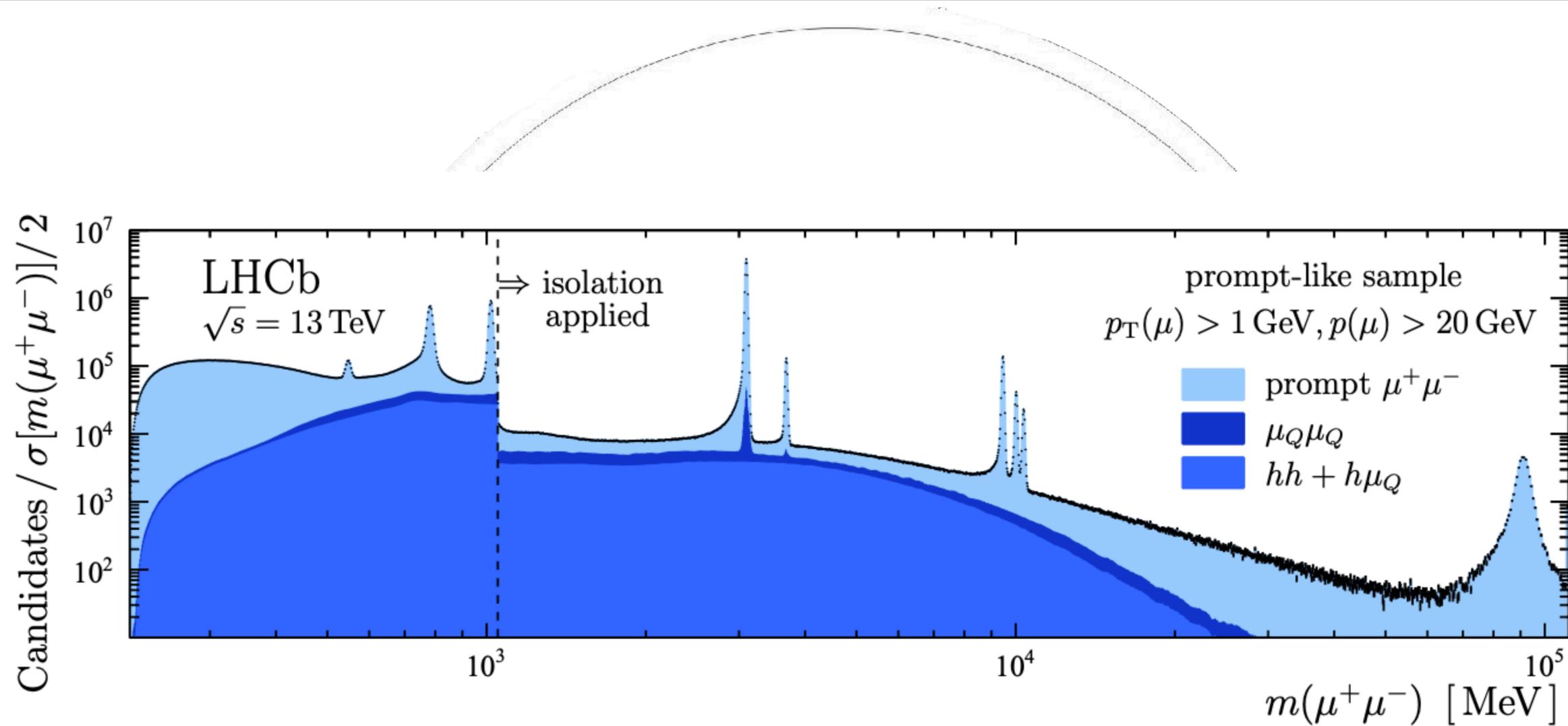
RICH: identify charged particles by measuring their Cherenkov light

The LHCb experiment



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

The LHCb experiment

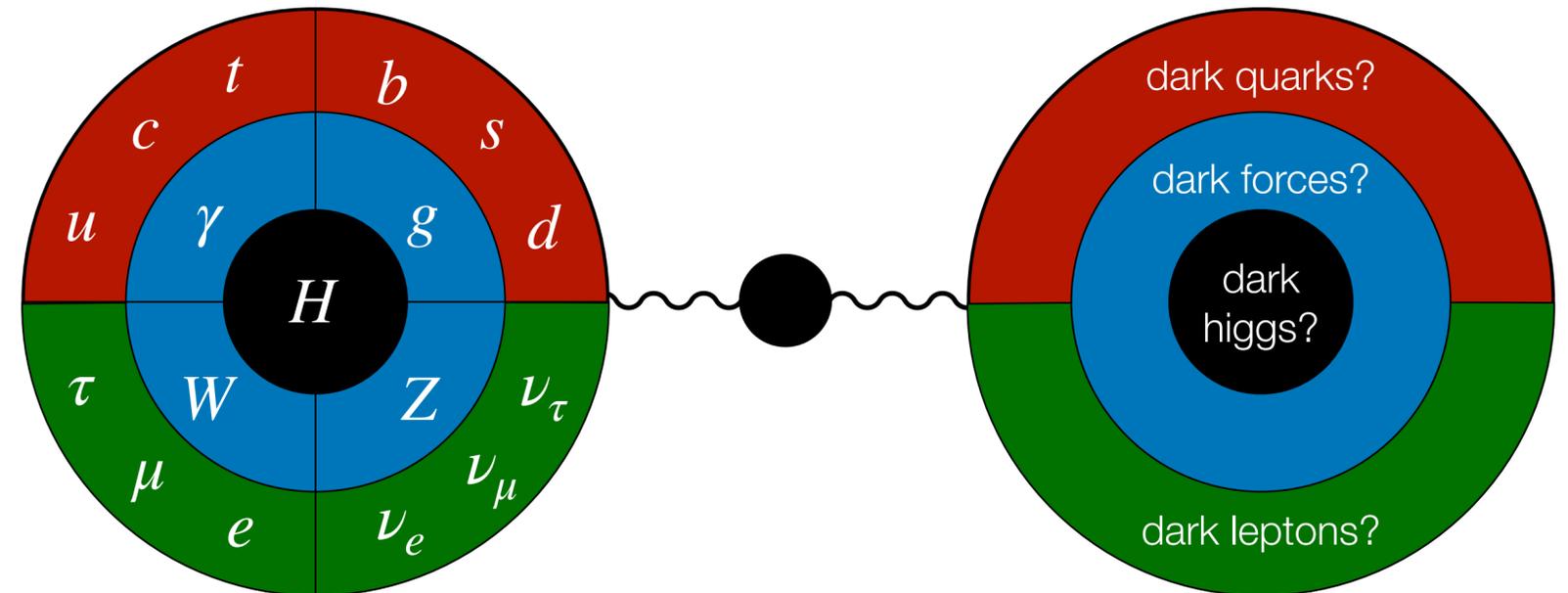


MUON stations: identify muon leptons, the most penetrating charged particles.

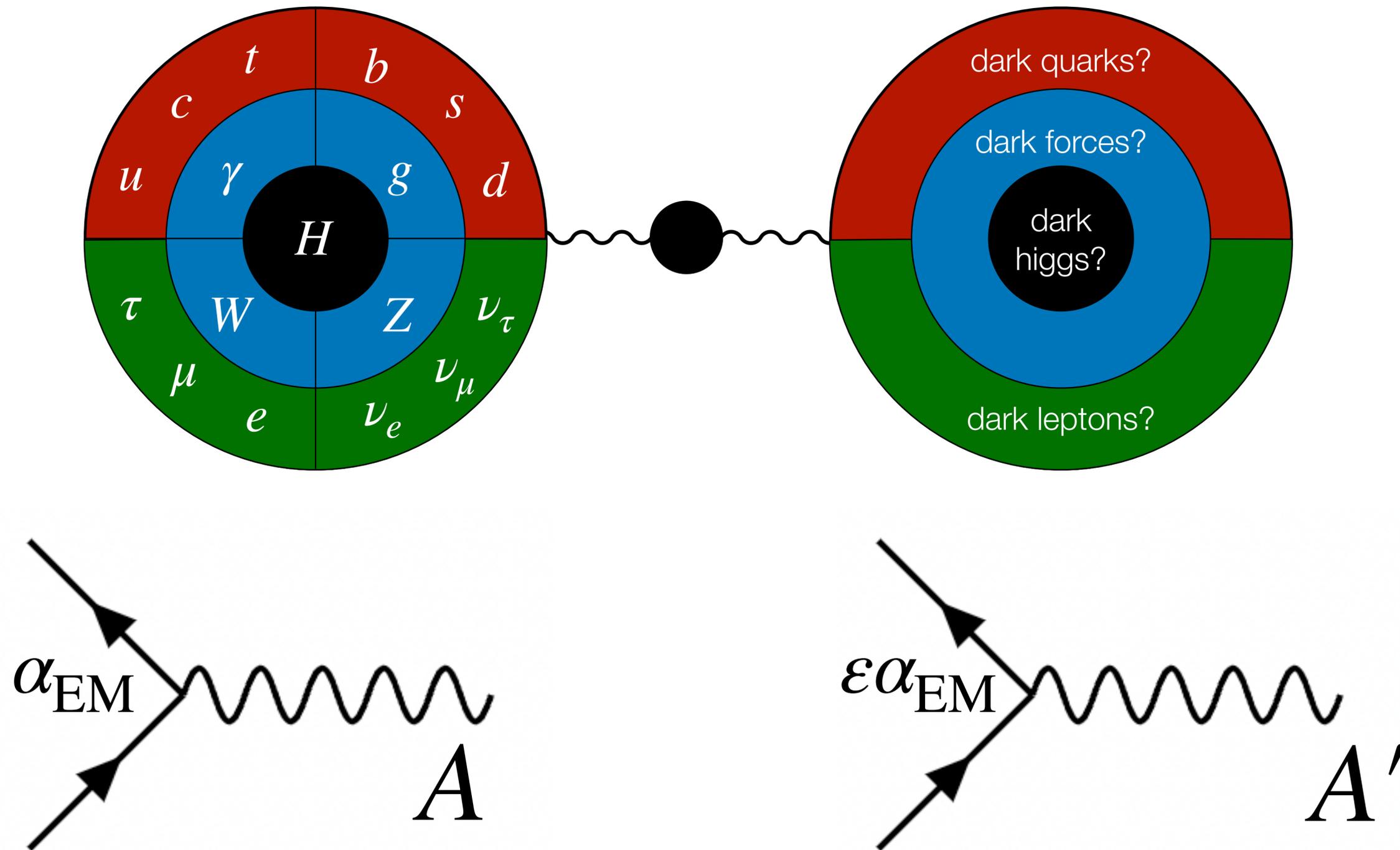
Dark sectors

- 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) : $y_N L H N$



Dark photons

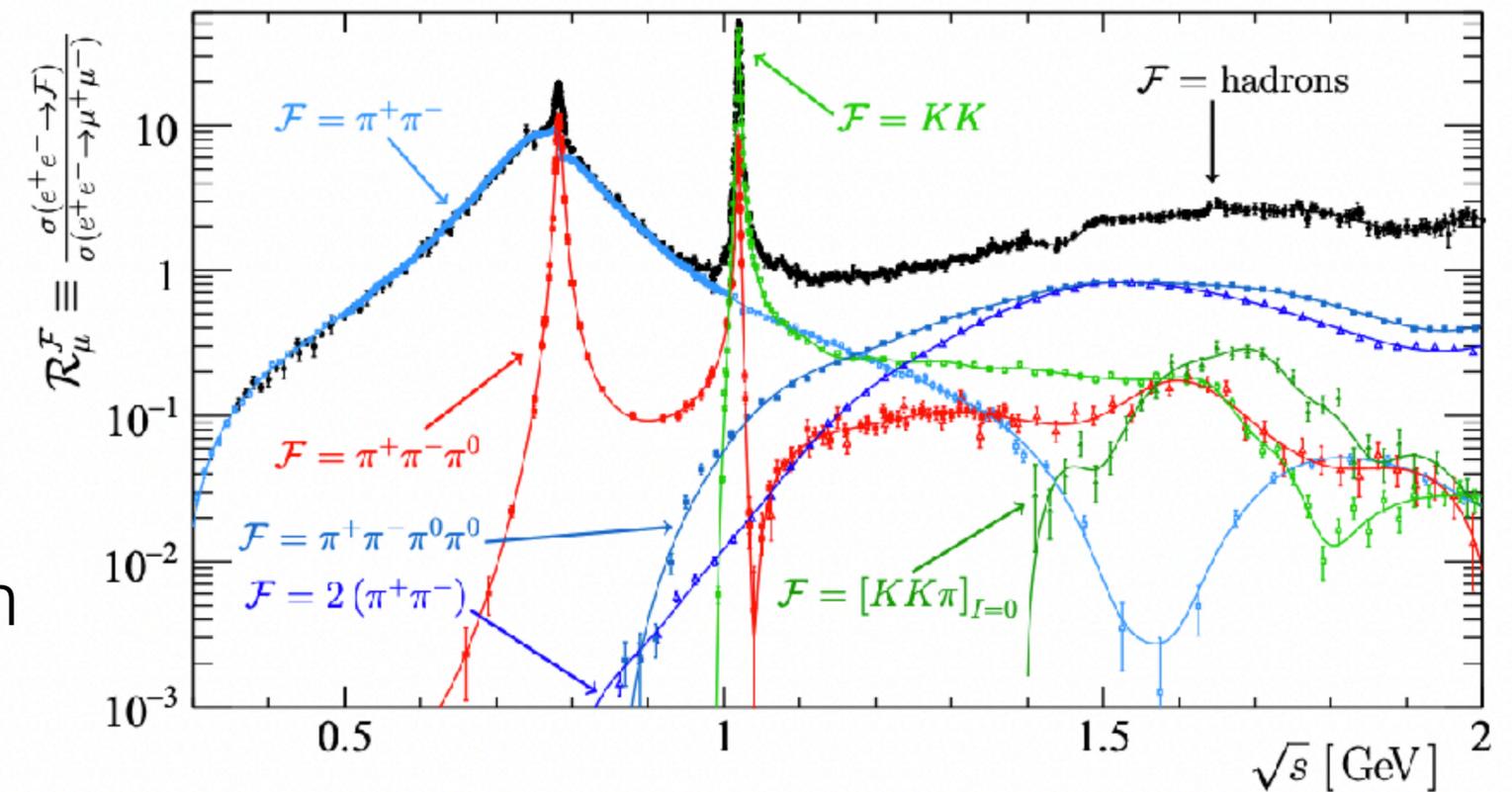


Dark photons: main production mechanisms [PRL 116 (2016) 25, 251803]

Relevant production term in pp collisions:

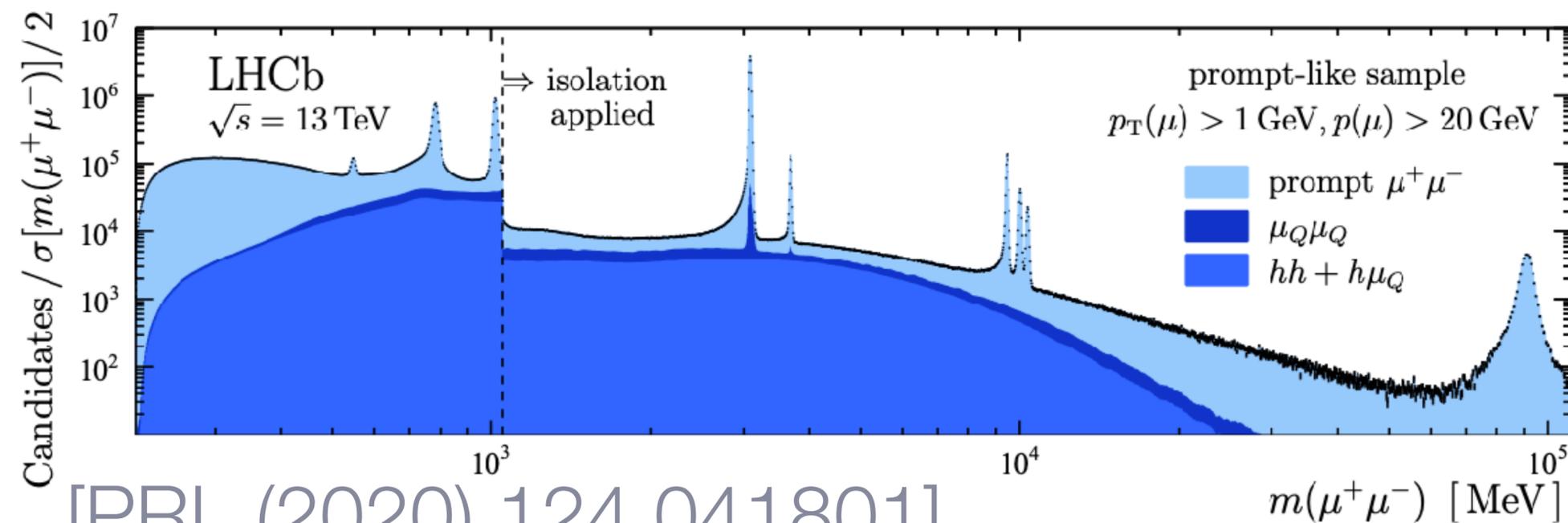
$$\frac{S_{\text{DP}}}{B_{\text{EM}}} \propto \frac{\epsilon^2 m_{A'}}{\alpha_{\text{EM}} \sigma_{\mu\mu} (N_\ell + \mathcal{R}_\mu)}$$

- Normalize wrt prompt muon production
- Take EM current to hadrons (\mathcal{R}_μ) directly from data



[JHEP 06 (2018) 004]

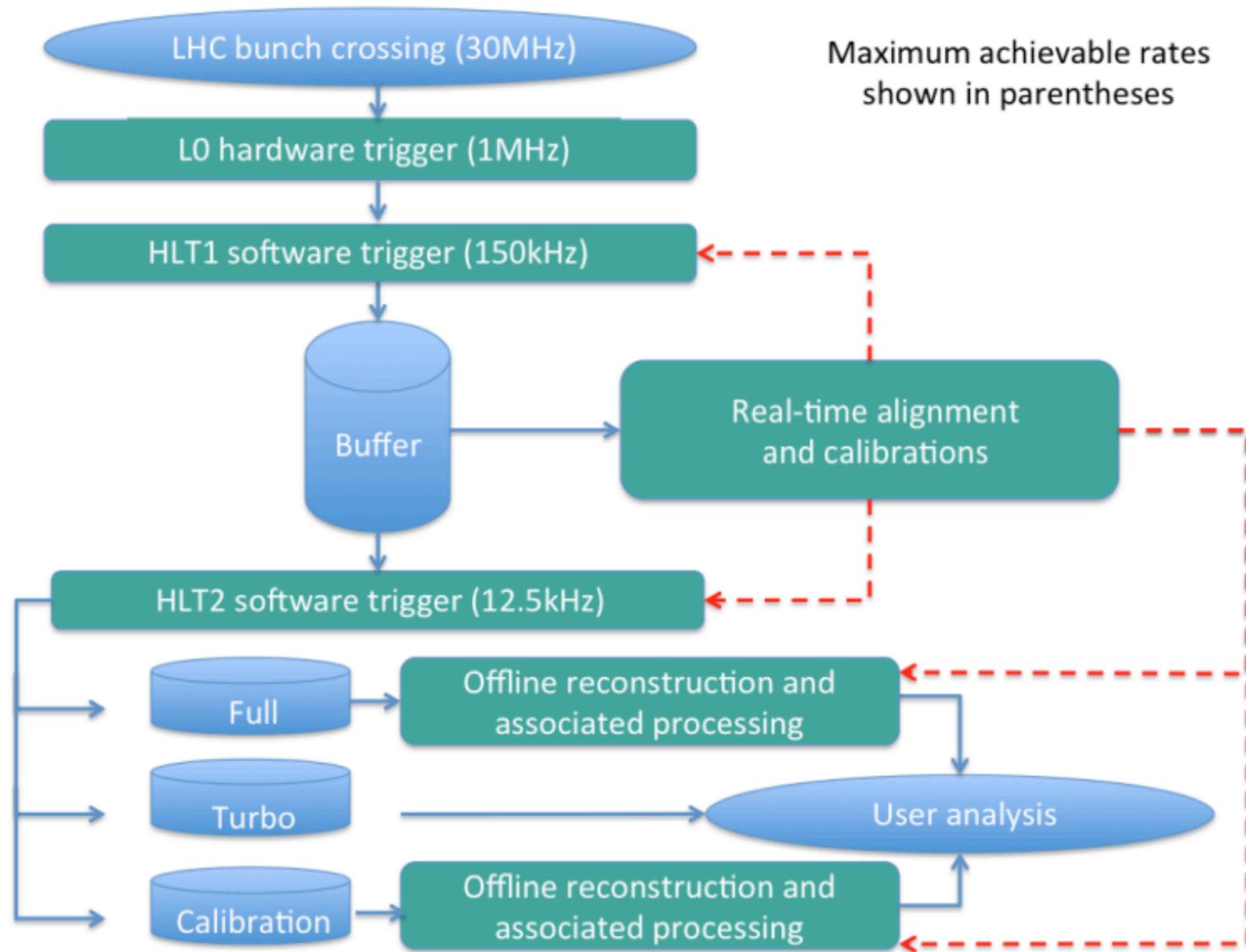
- A' produced in meson decays for m
- $m(A') < 1 \text{ GeV}$
- Drell-Yan afterwards



[PRL (2020) 124 041801]

Searches for Dark Photons

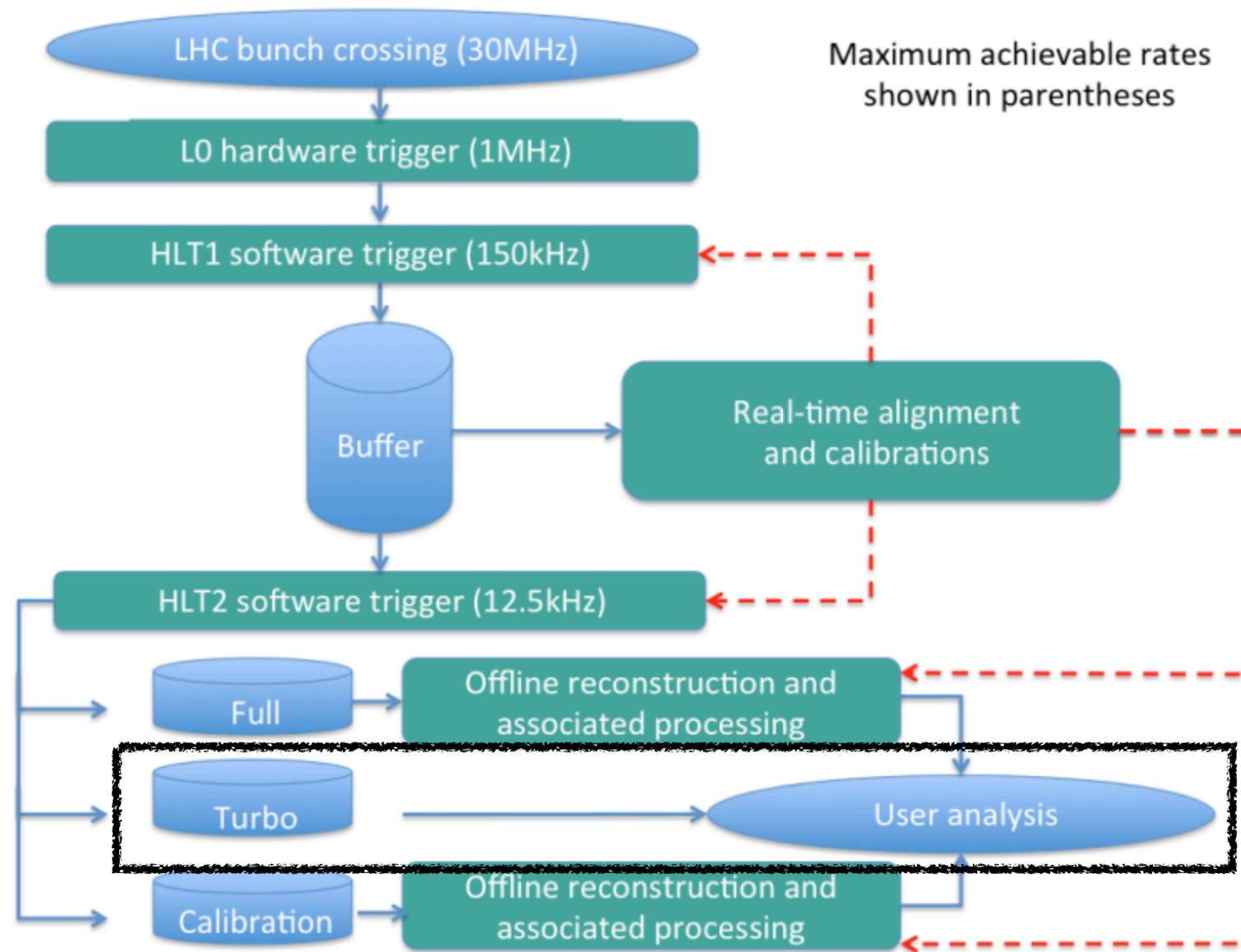
[Comput.Phys.Commun. 208 (2016) 35-42]



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

Searches for Dark Photons

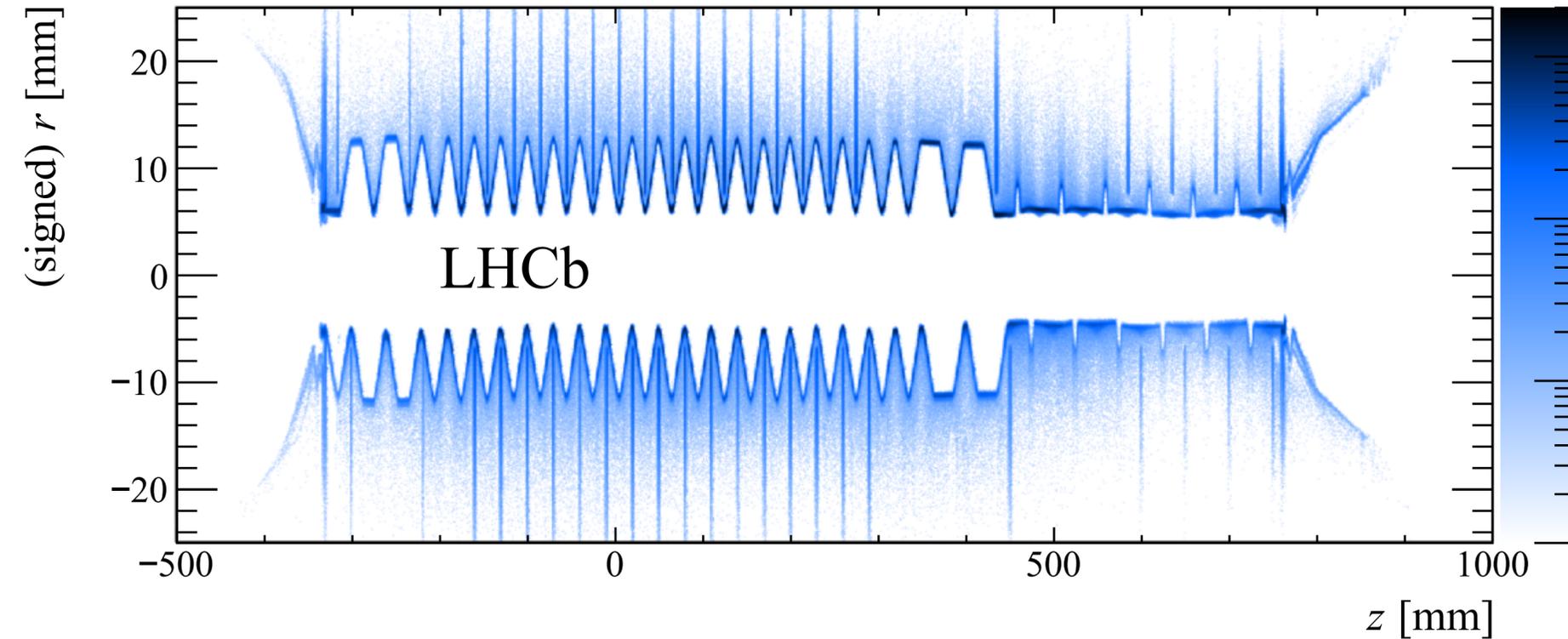
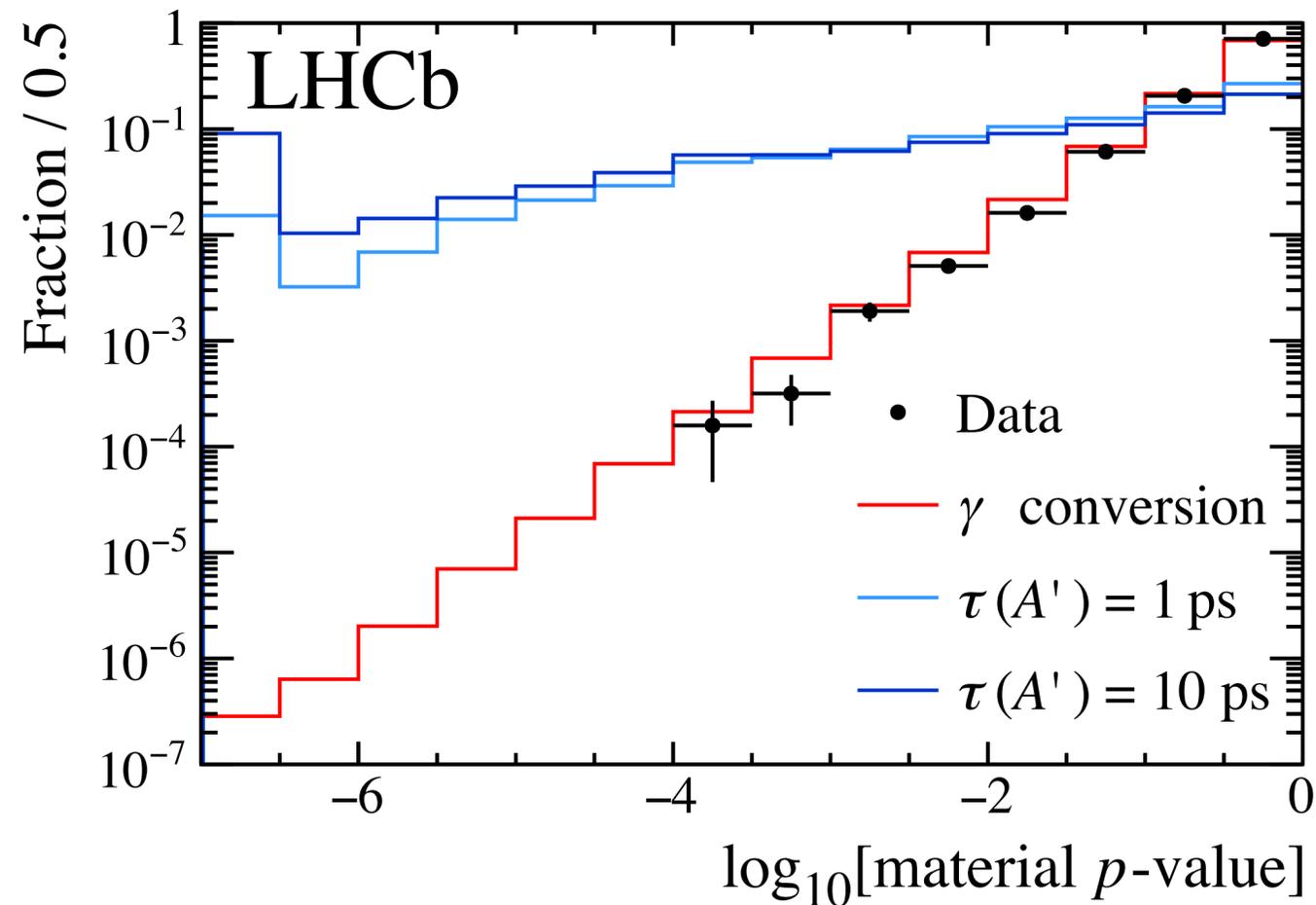
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Material interaction backgrounds

[JINST 13, P06008 (2018)]

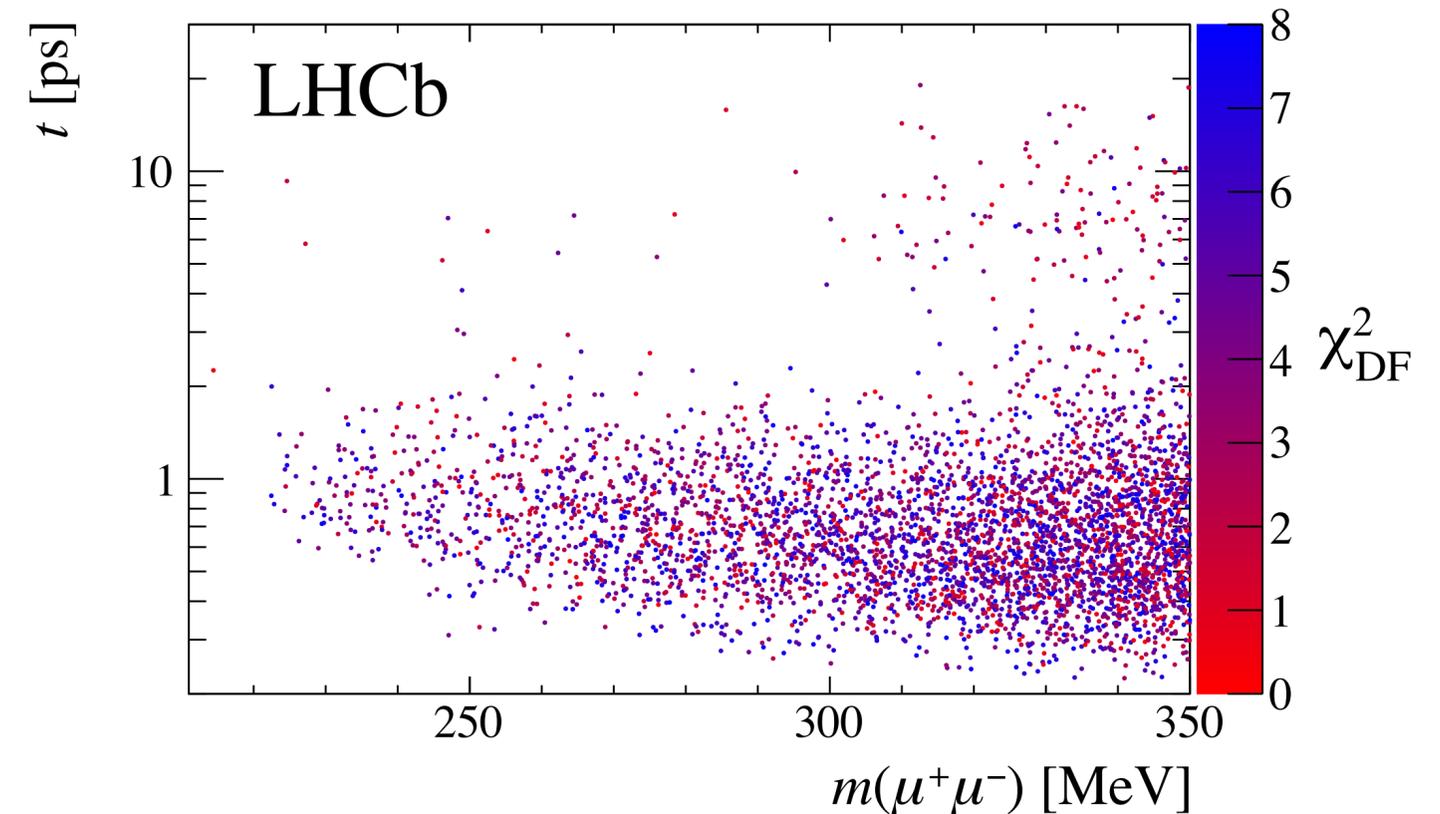
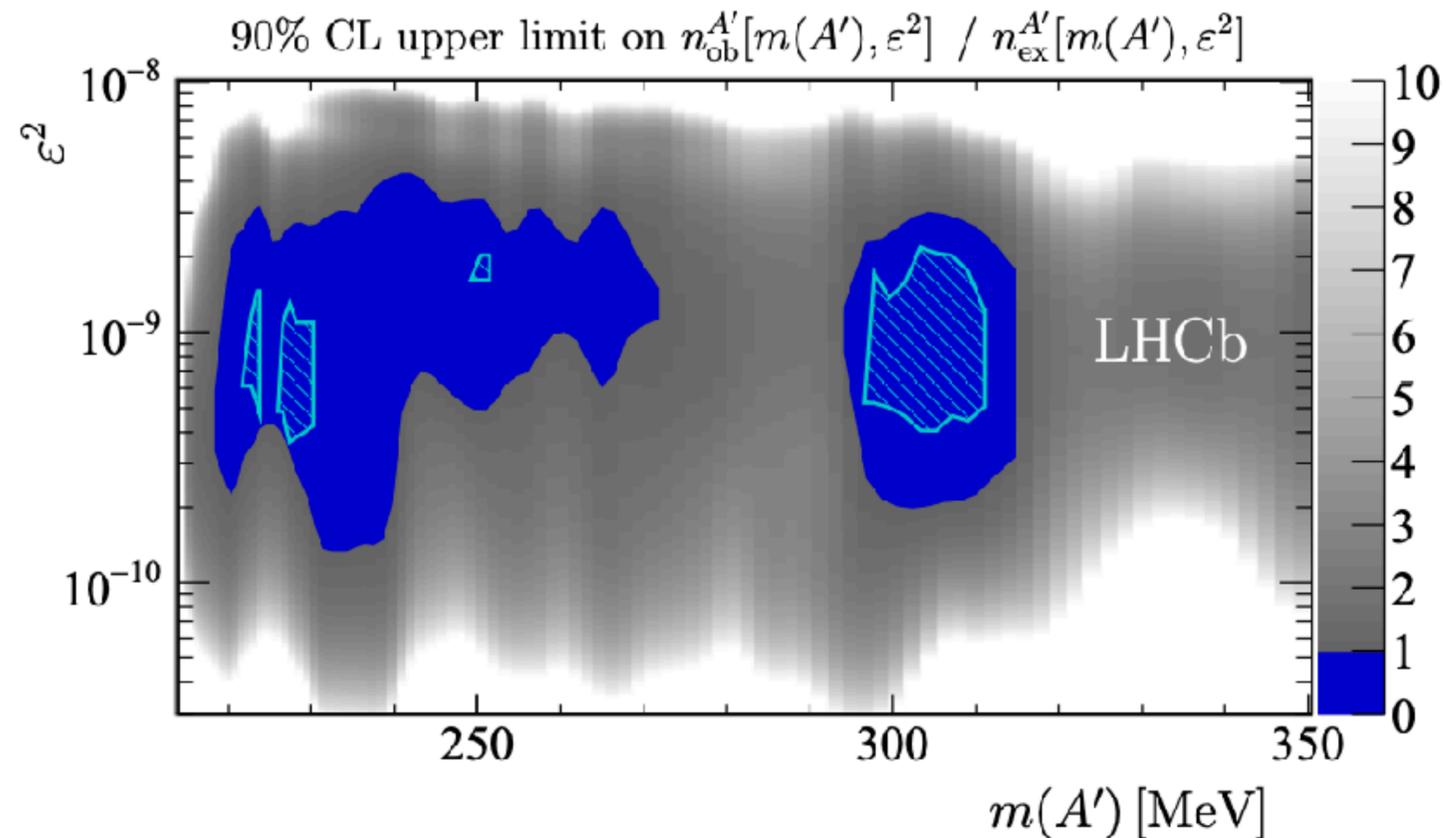


- Method to identify particles created in secondary vertices in interaction with VELO
- Three dimensional map produced from data sample of secondary hadronic interactions

Dark Photons: displaced search

[PRL (2020) 124 041801]

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

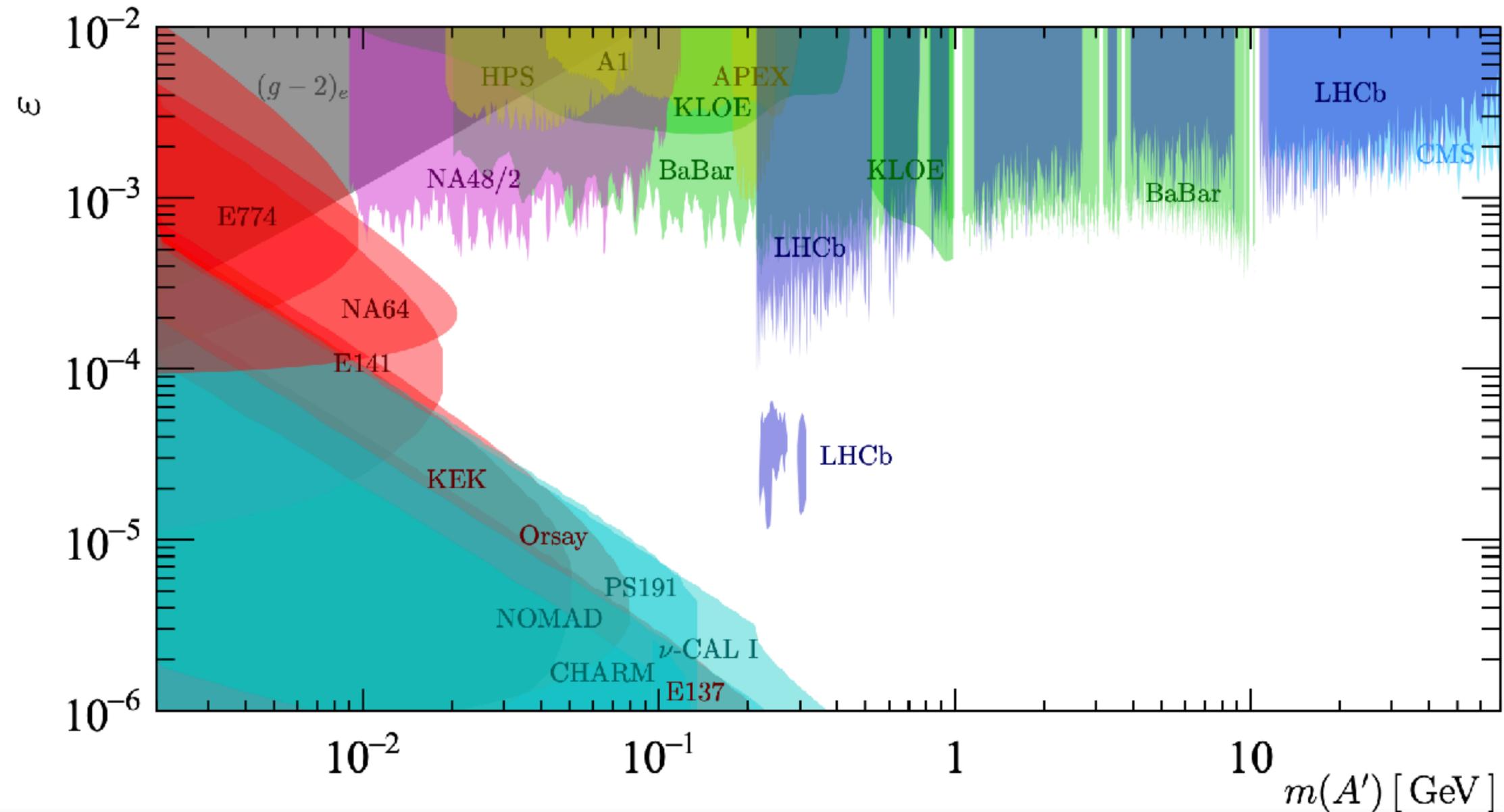


- **No significant excess found** - small parameter space region excluded:
 - First limit ever **not from beam dump**.

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 $214 < m(\mu\mu) < 350 \text{ MeV}$



Dark photons

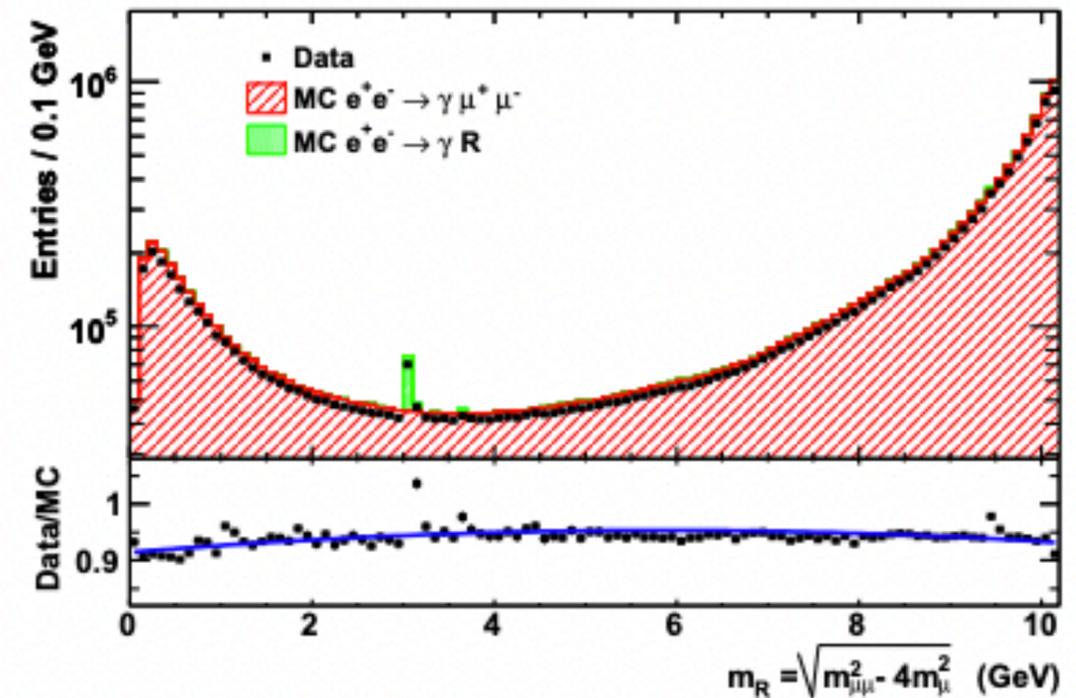
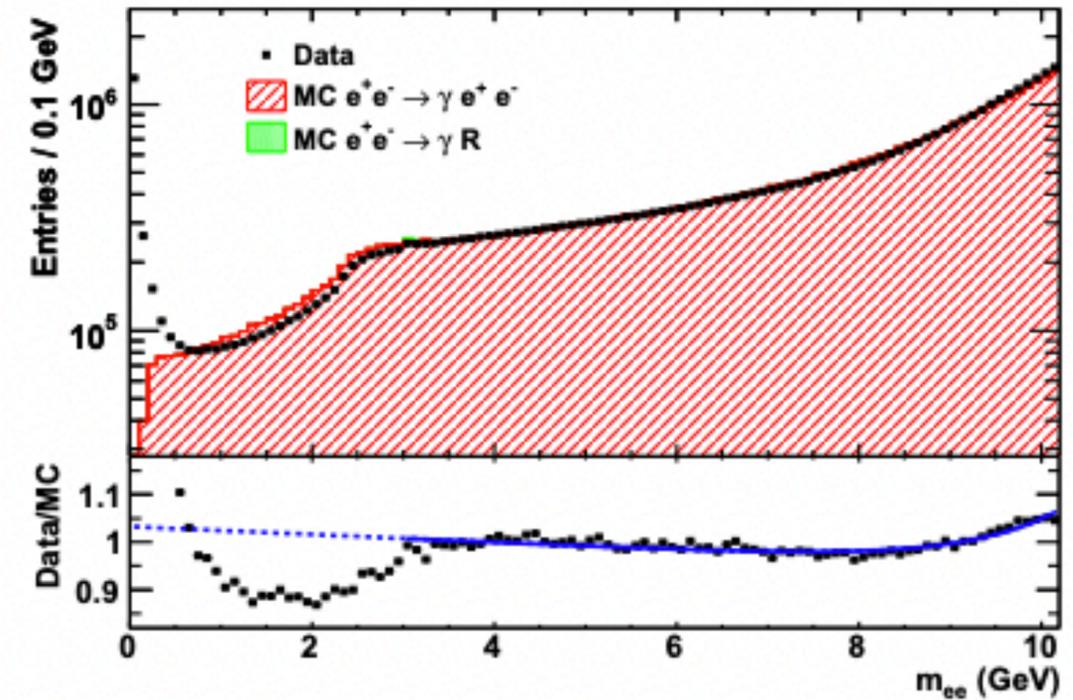
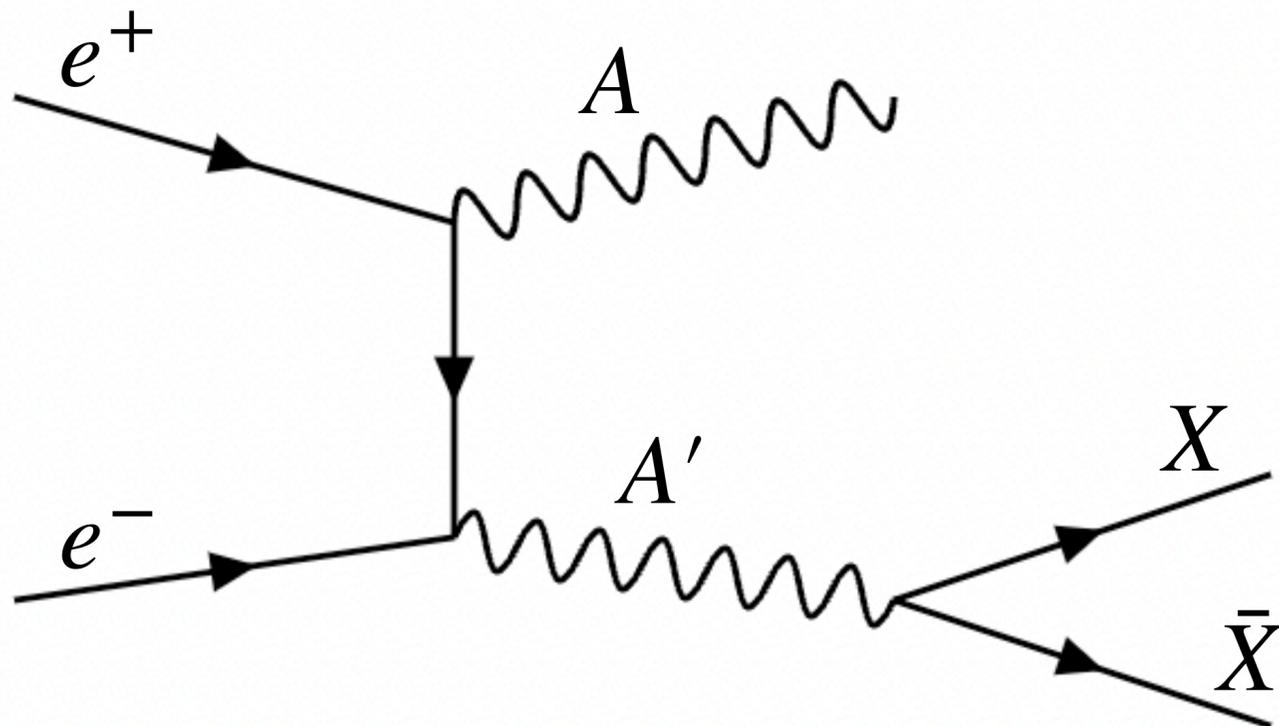
[PRL 113 (2014) 20, 201801]

Easy to make calculations:

- QED with a mass effect
- A' mixes A with a small coupling ε

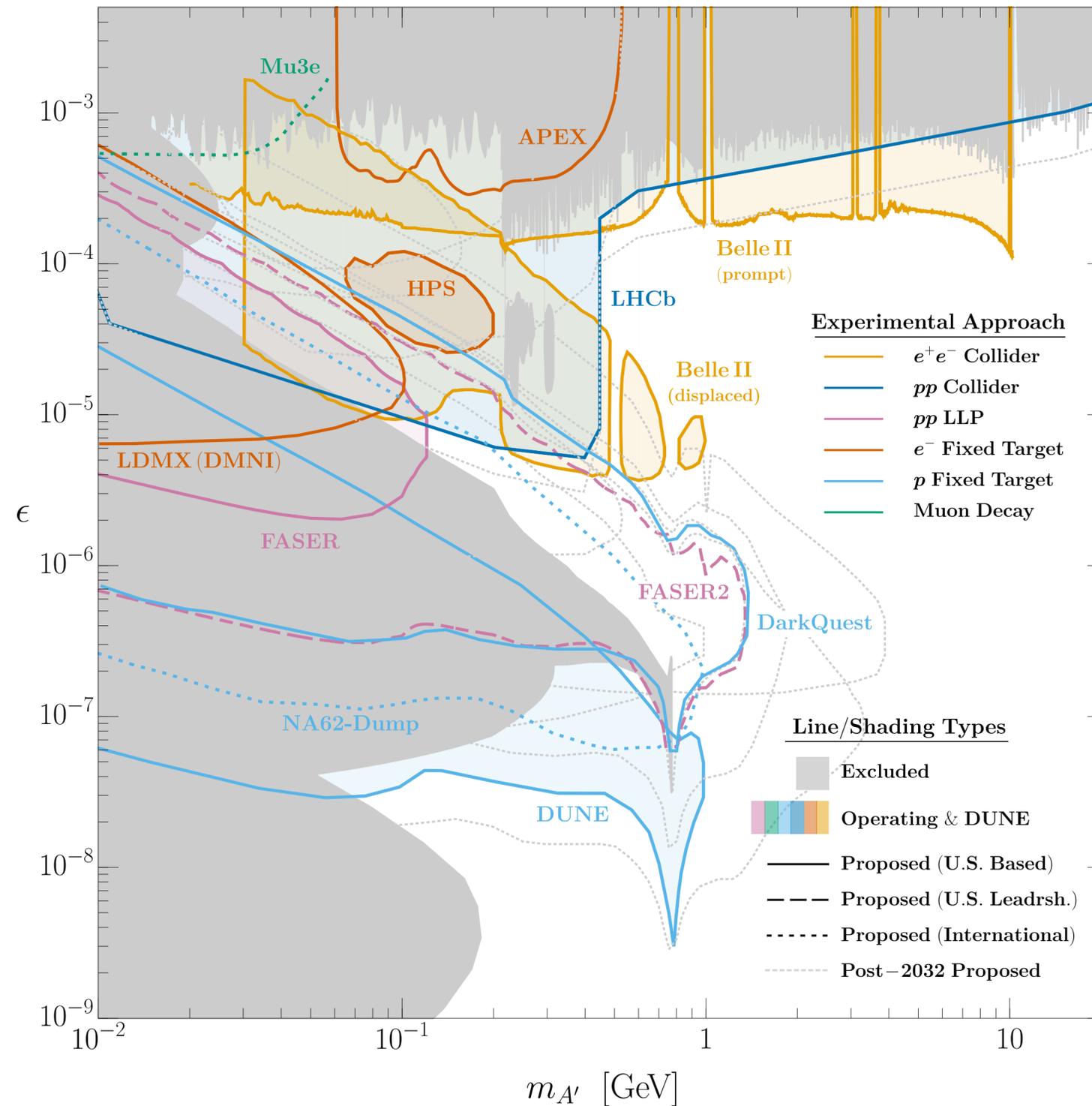
Only back of the envelope calculation is needed in e^+e^-

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



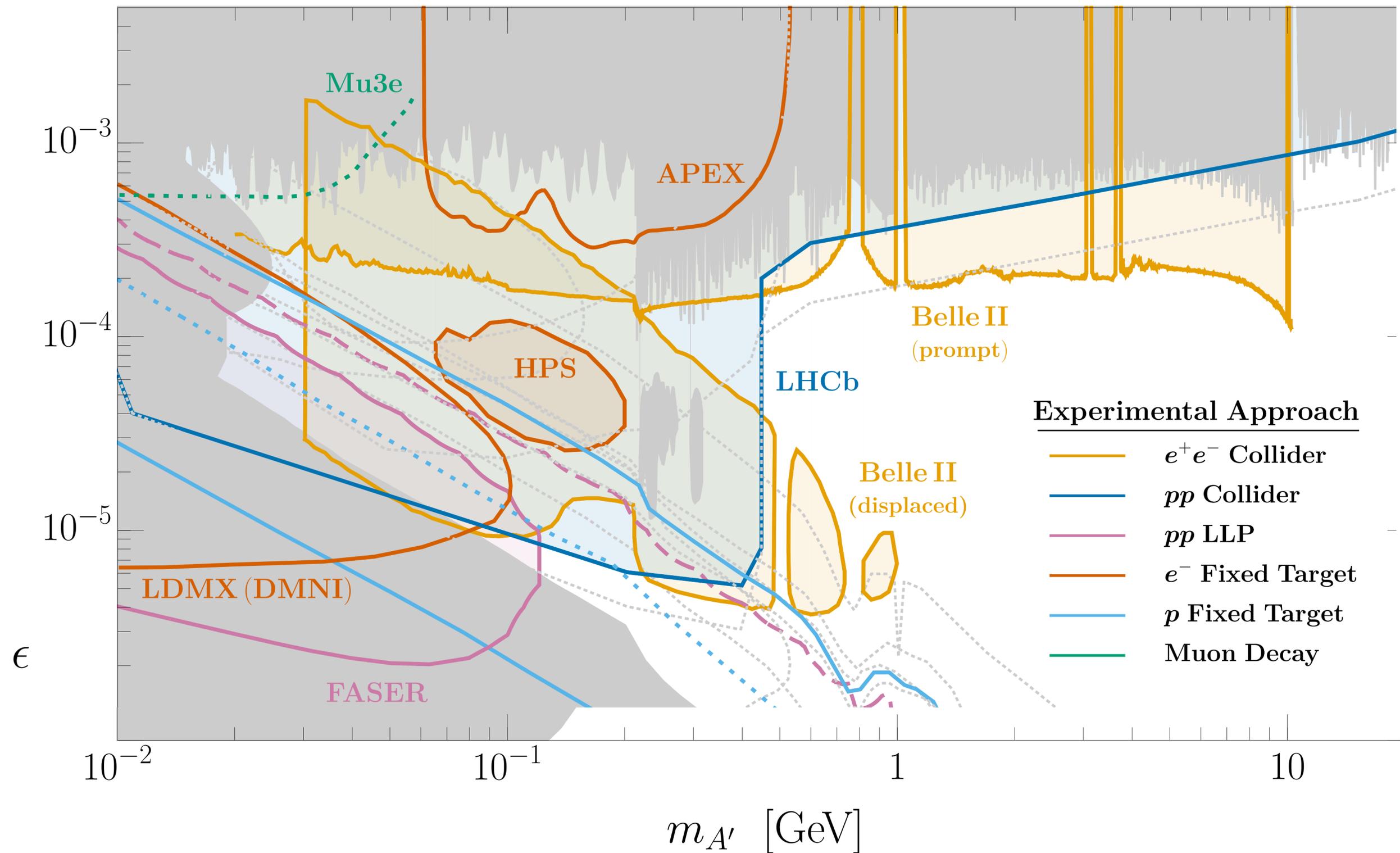
Dark photons: the fog of war

[2209.04671]



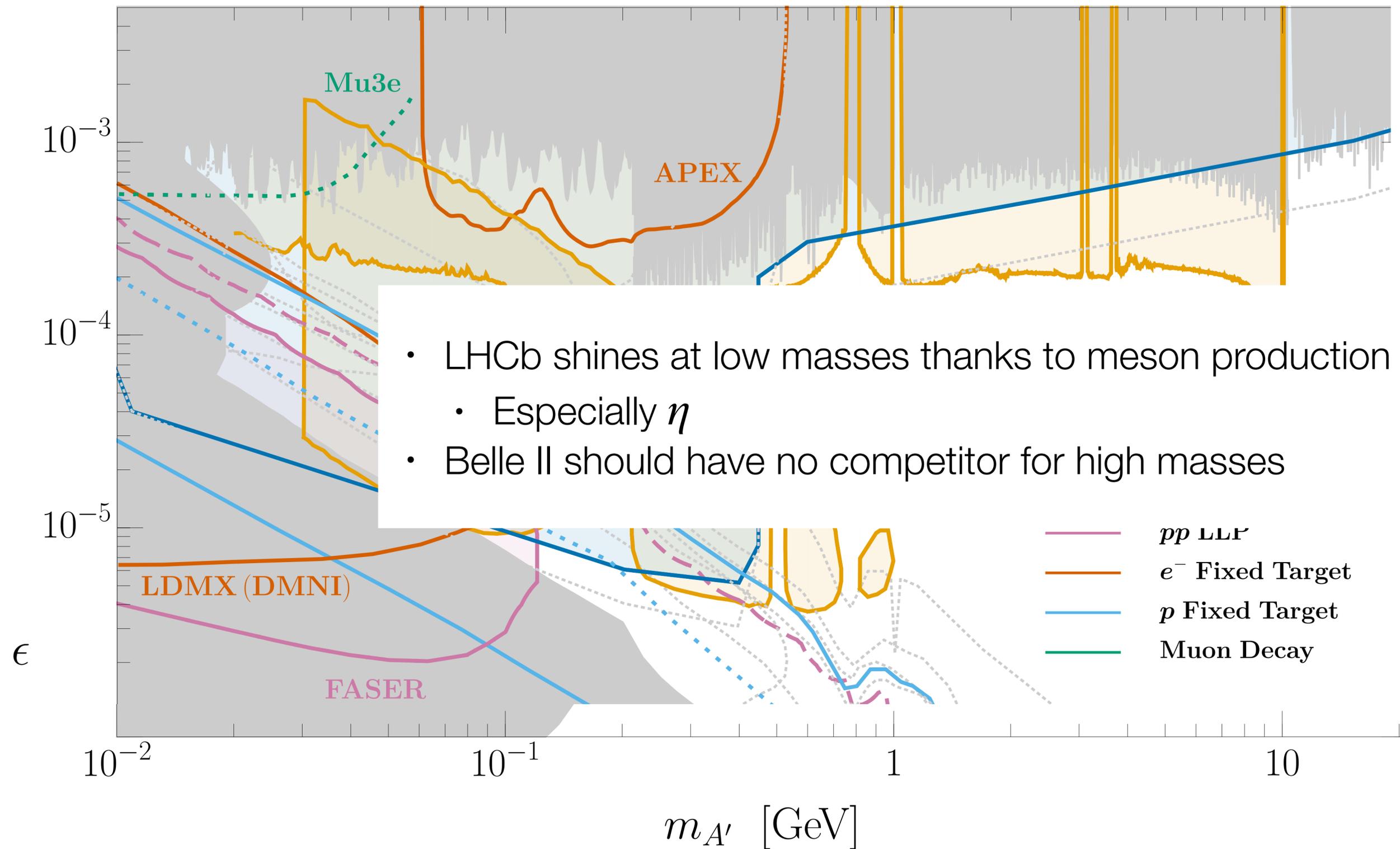
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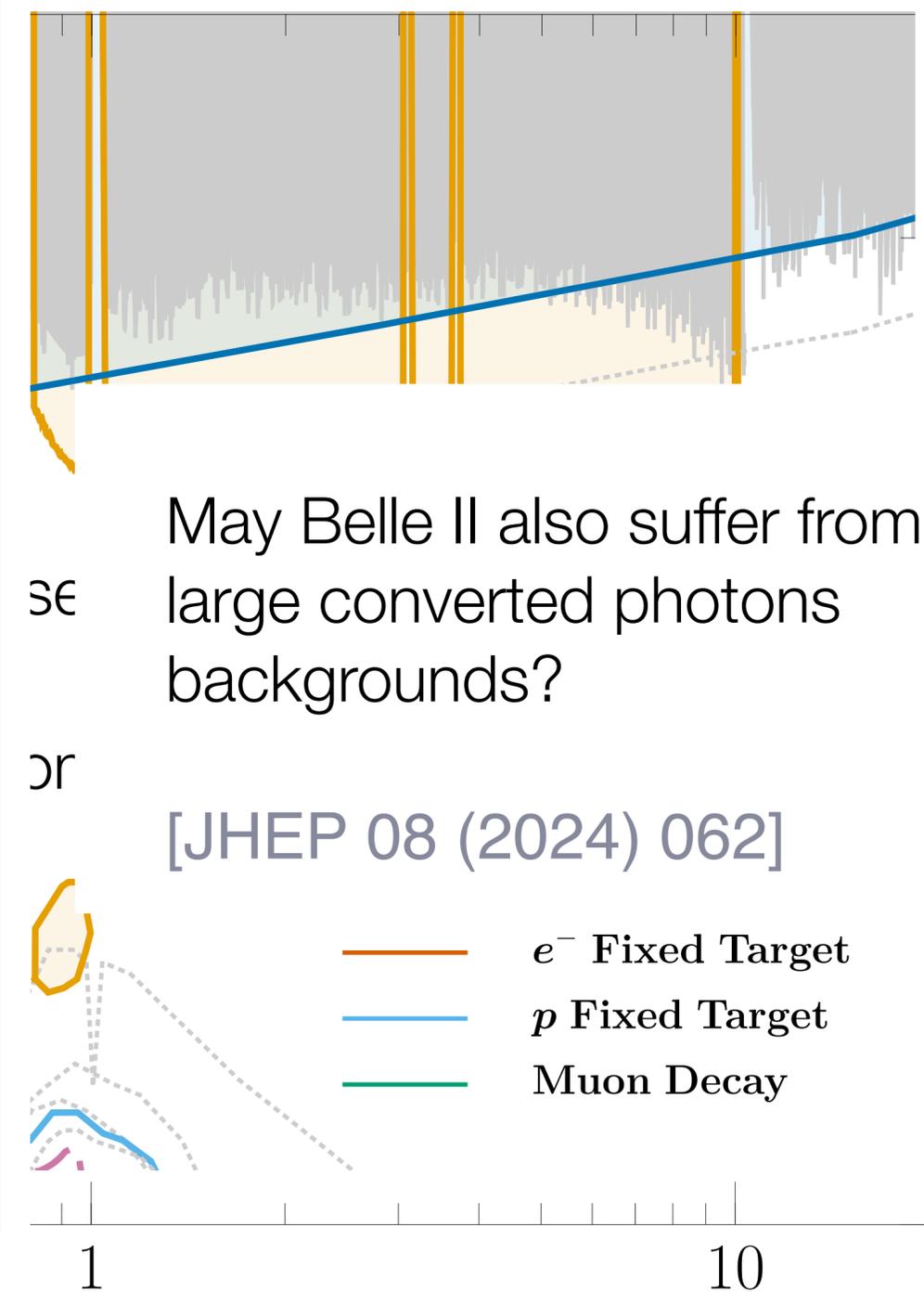
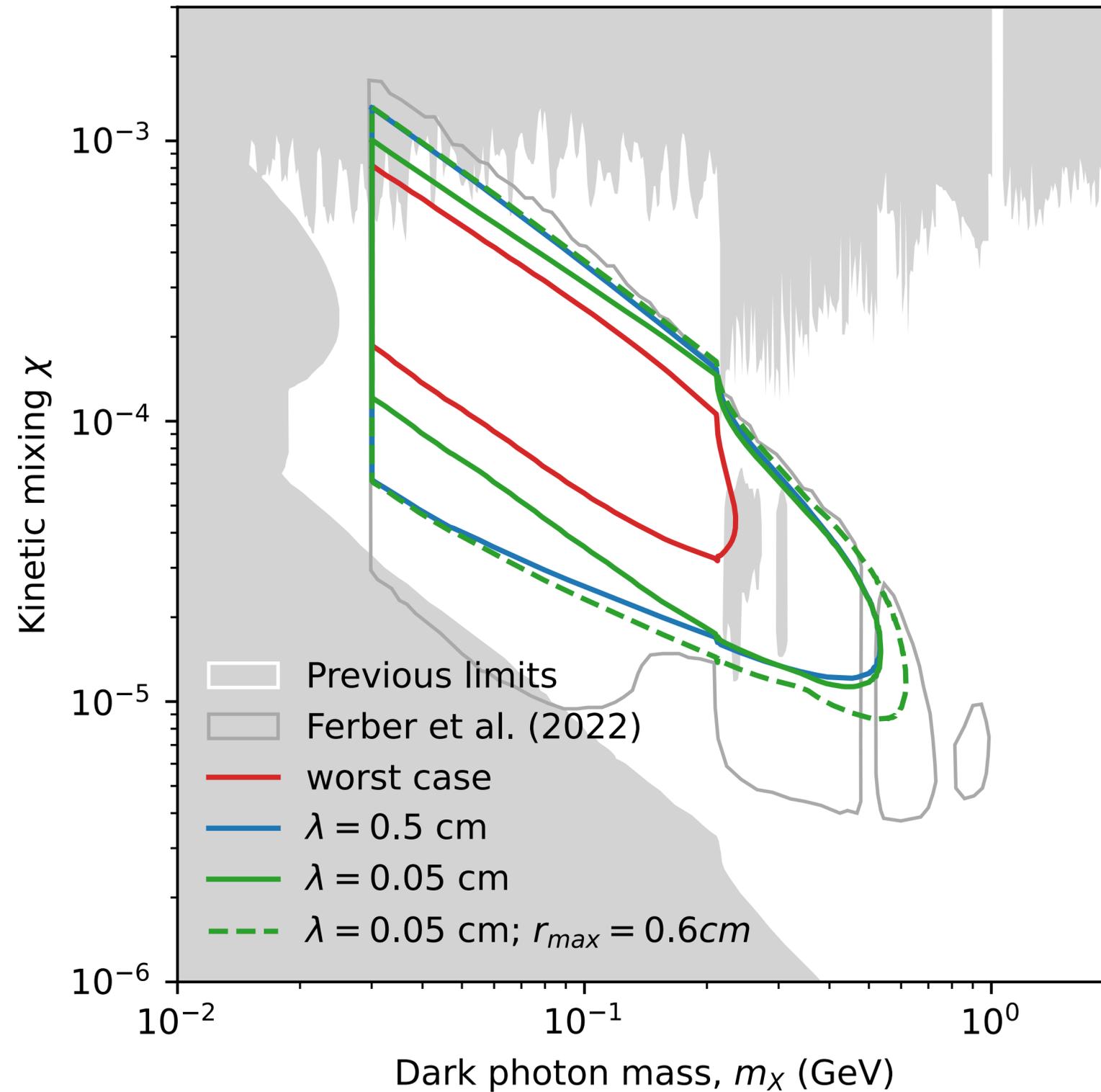
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Dark photons: the food of war

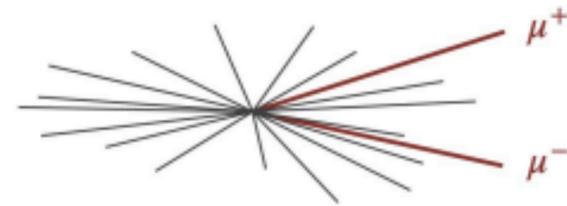
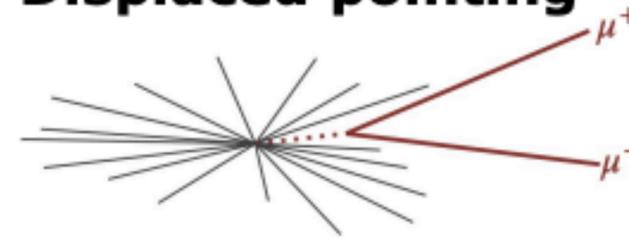
[2209.04671]



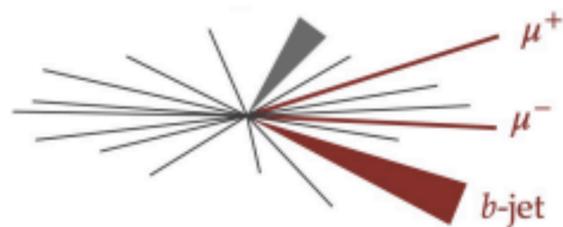
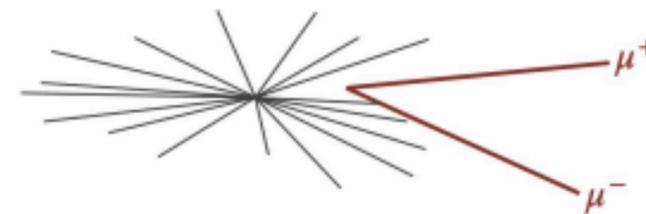
Dimuon resonances: model independent

[JHEP 10 (2020) 156]

+ no isolation
requirement
+ non-zero width
considered

Inclusive Prompt**Displaced pointing**

+ non-zero width
considered

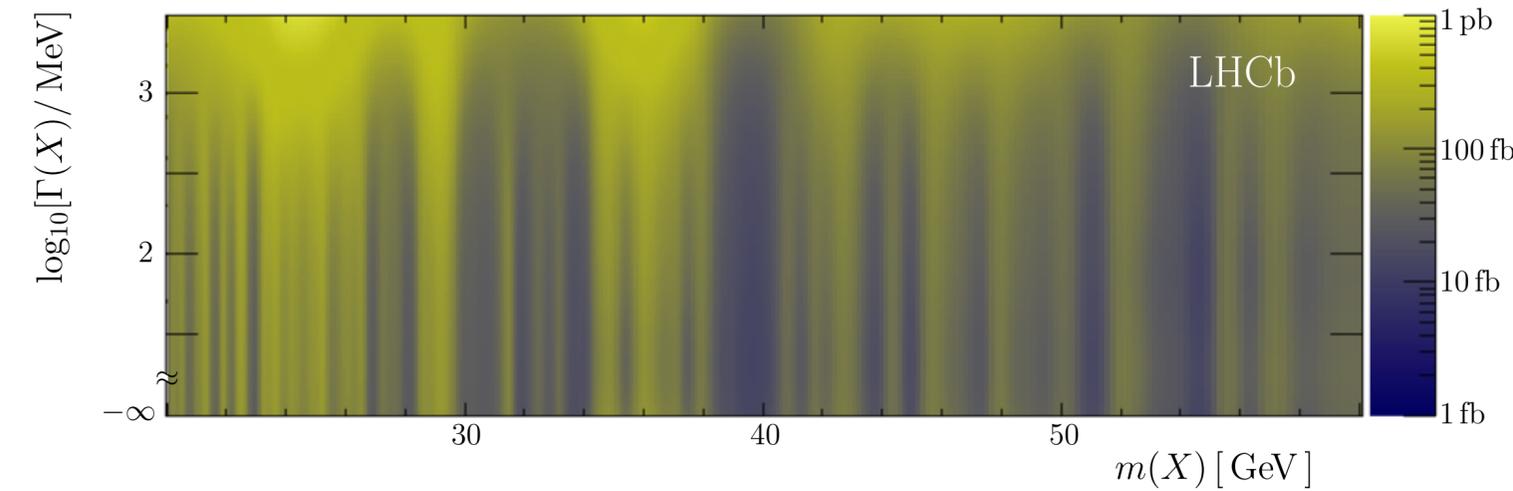
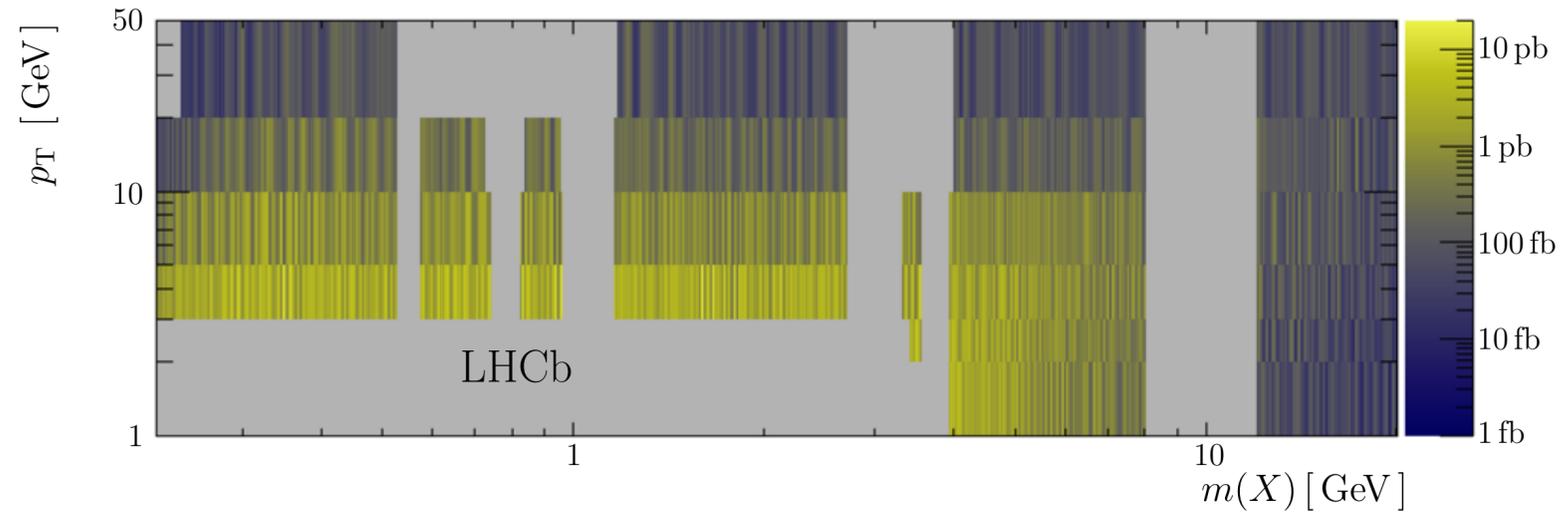
Prompt + b-jet**Displaced non-pointing**

- Model independent searches allowing for different topologies

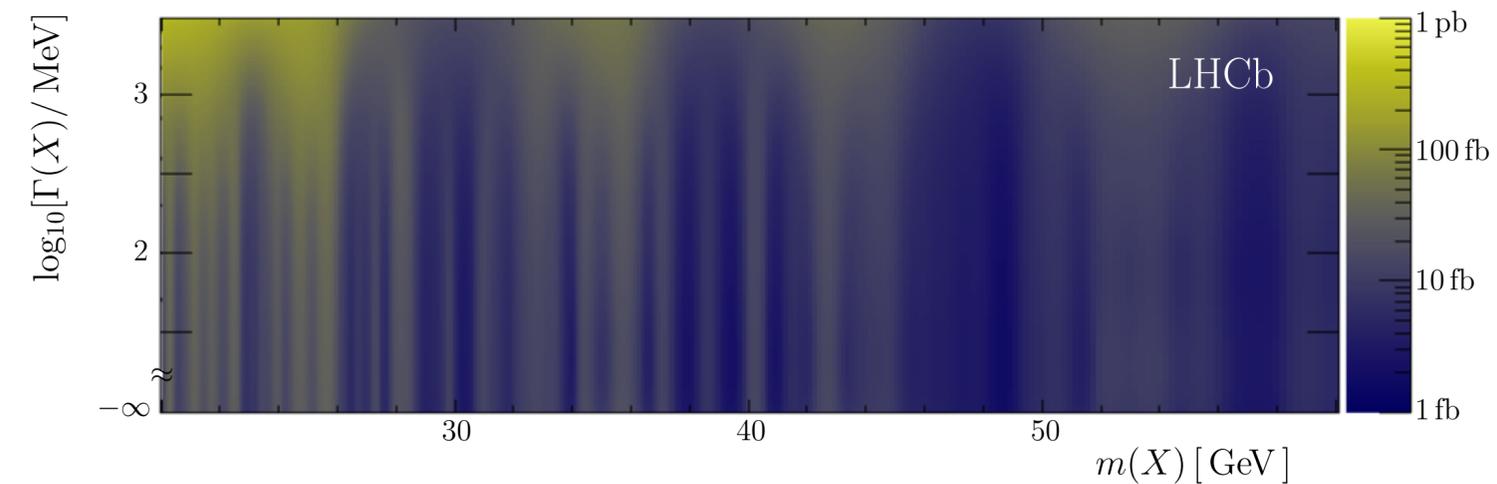
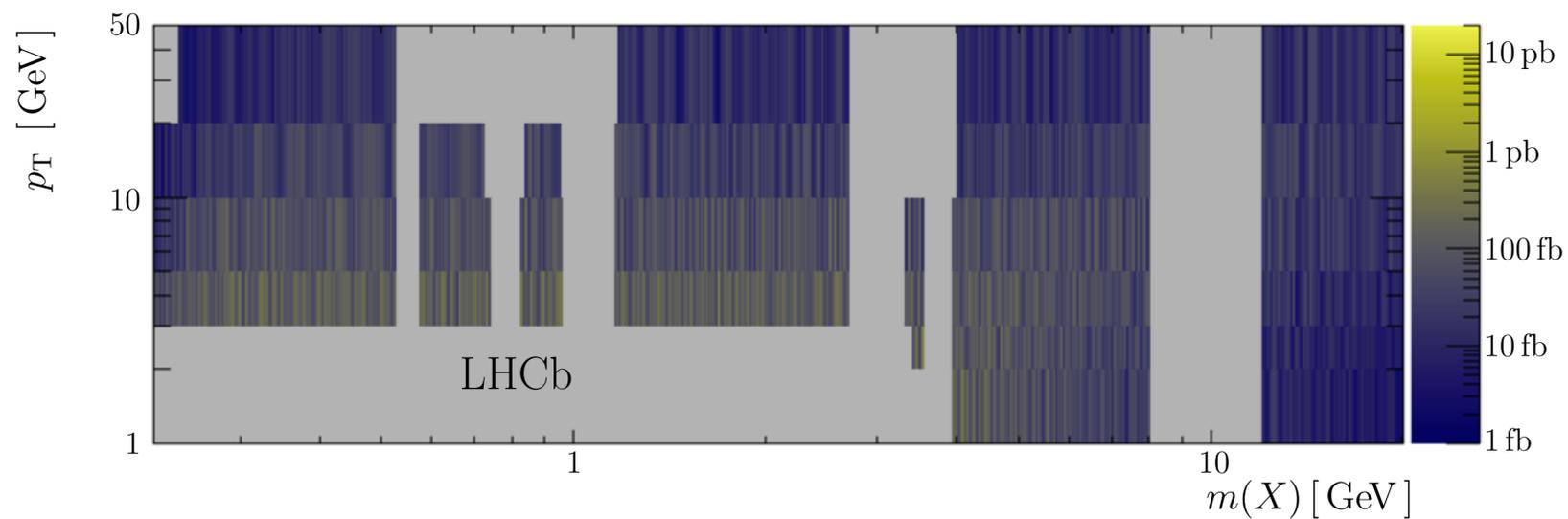
Dimuon resonances: model independent

[JHEP 10 (2020) 156]

- Prompt inclusive



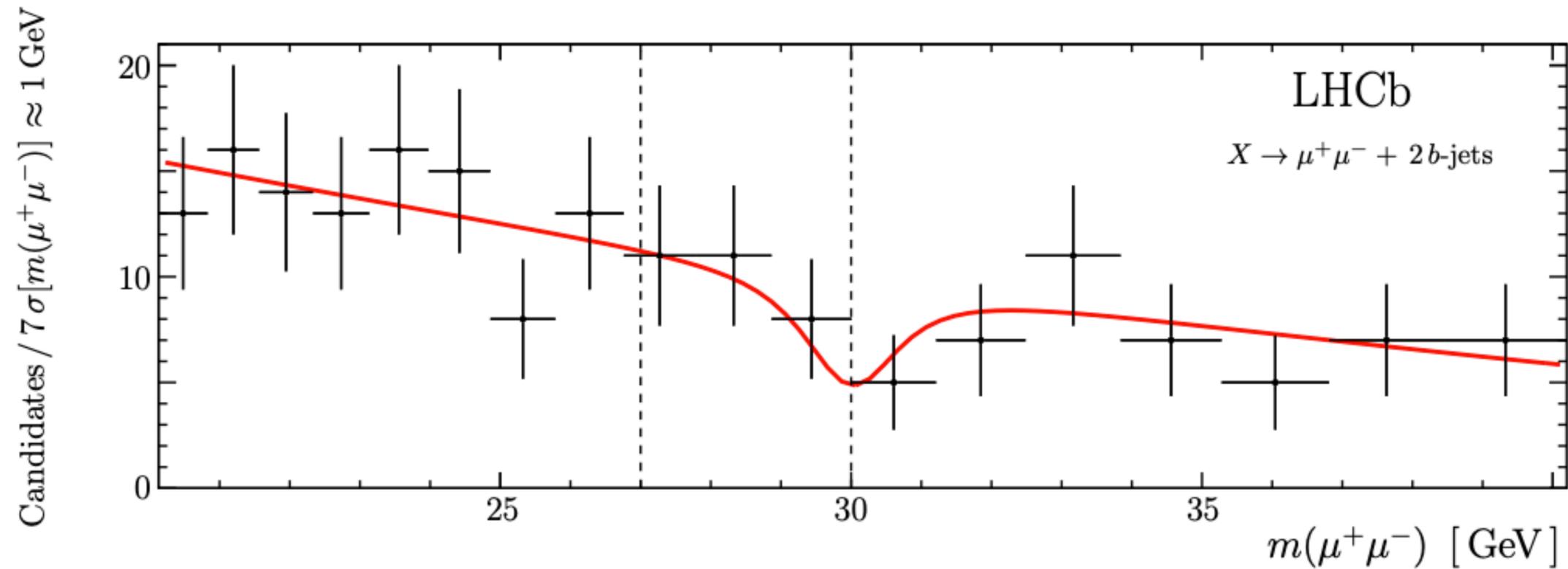
- Prompt beauty associated



- Non-negligible width considered for higher masses

Dimuon resonances: model independent

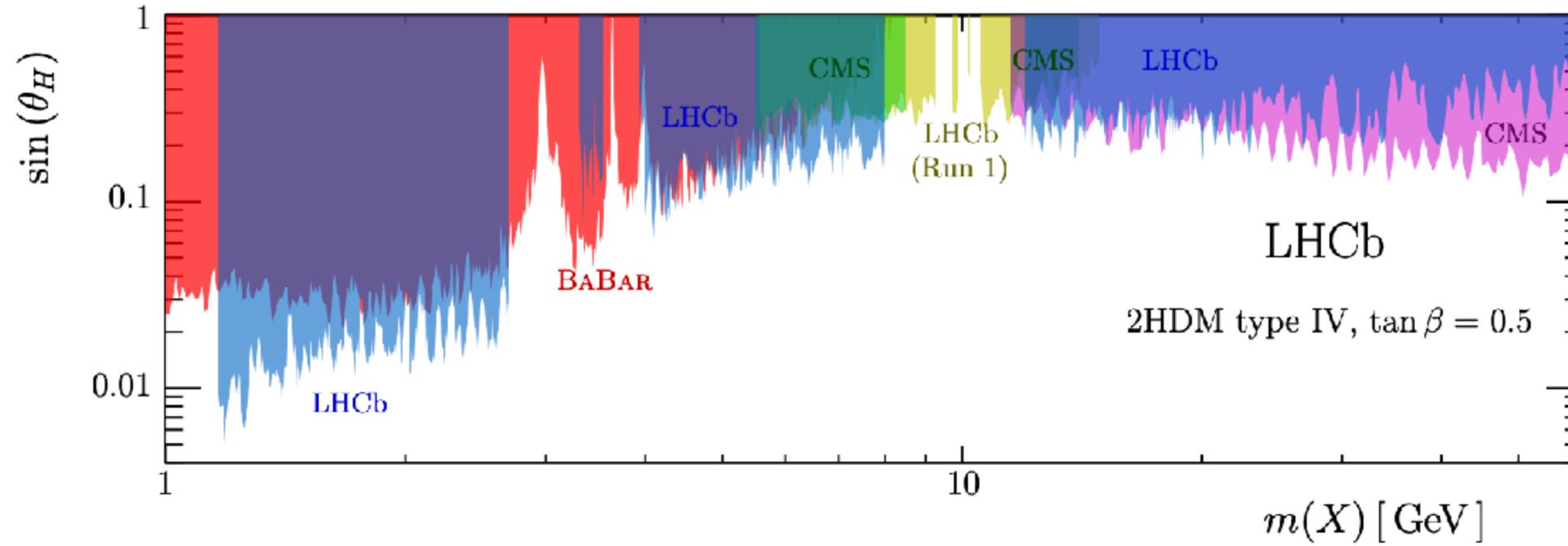
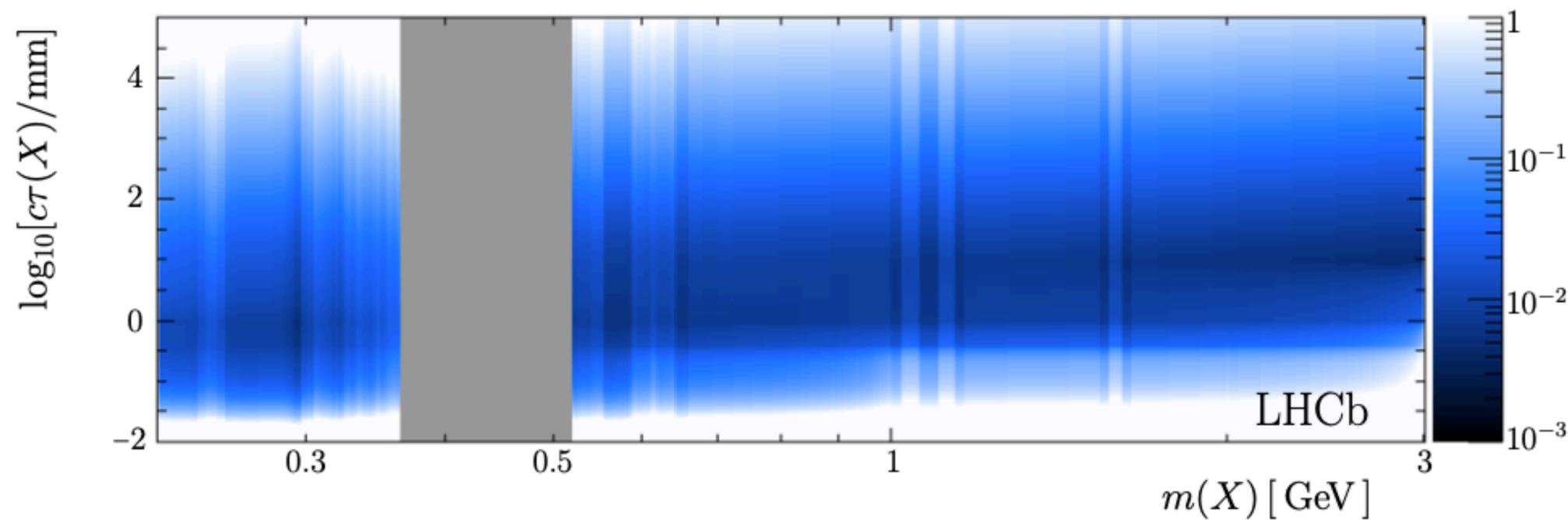
[JHEP 10 (2020) 156]



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

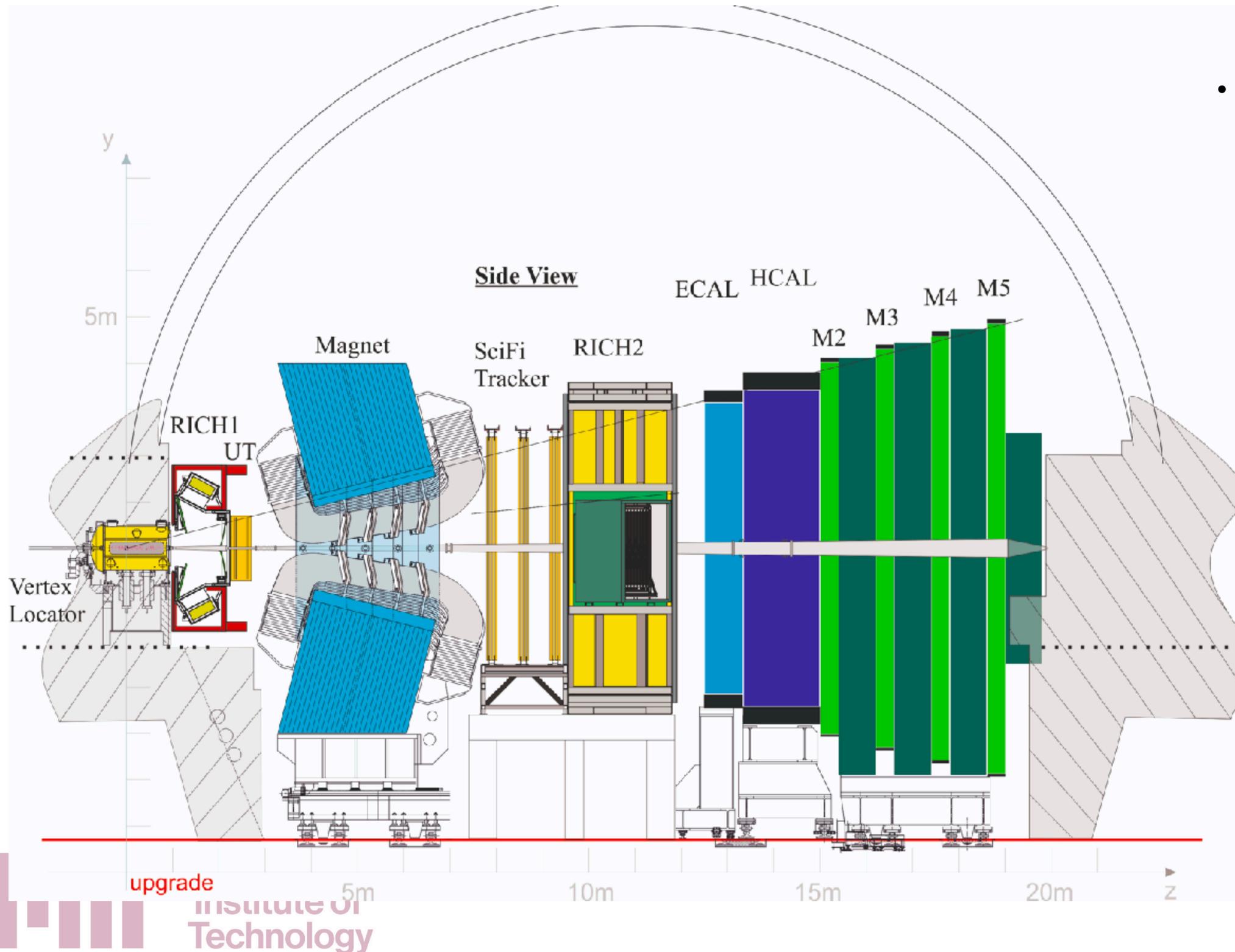
Dimuon resonances

[JHEP 10 (2020) 156]

2HDM: $X - H$ mixing angle $\gamma - Z_{HV}$ kinetic mixing

The upgraded LHCb detector

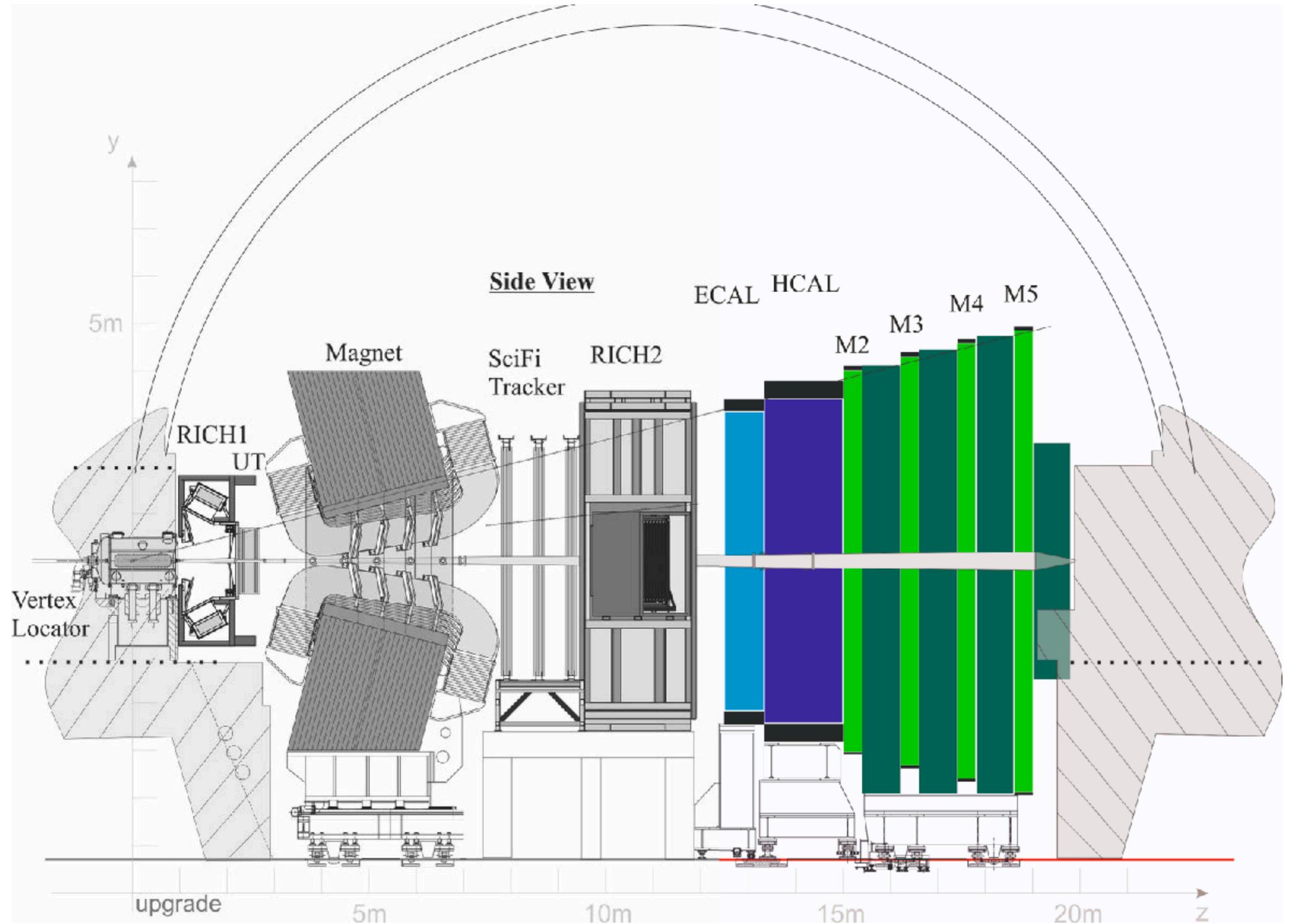
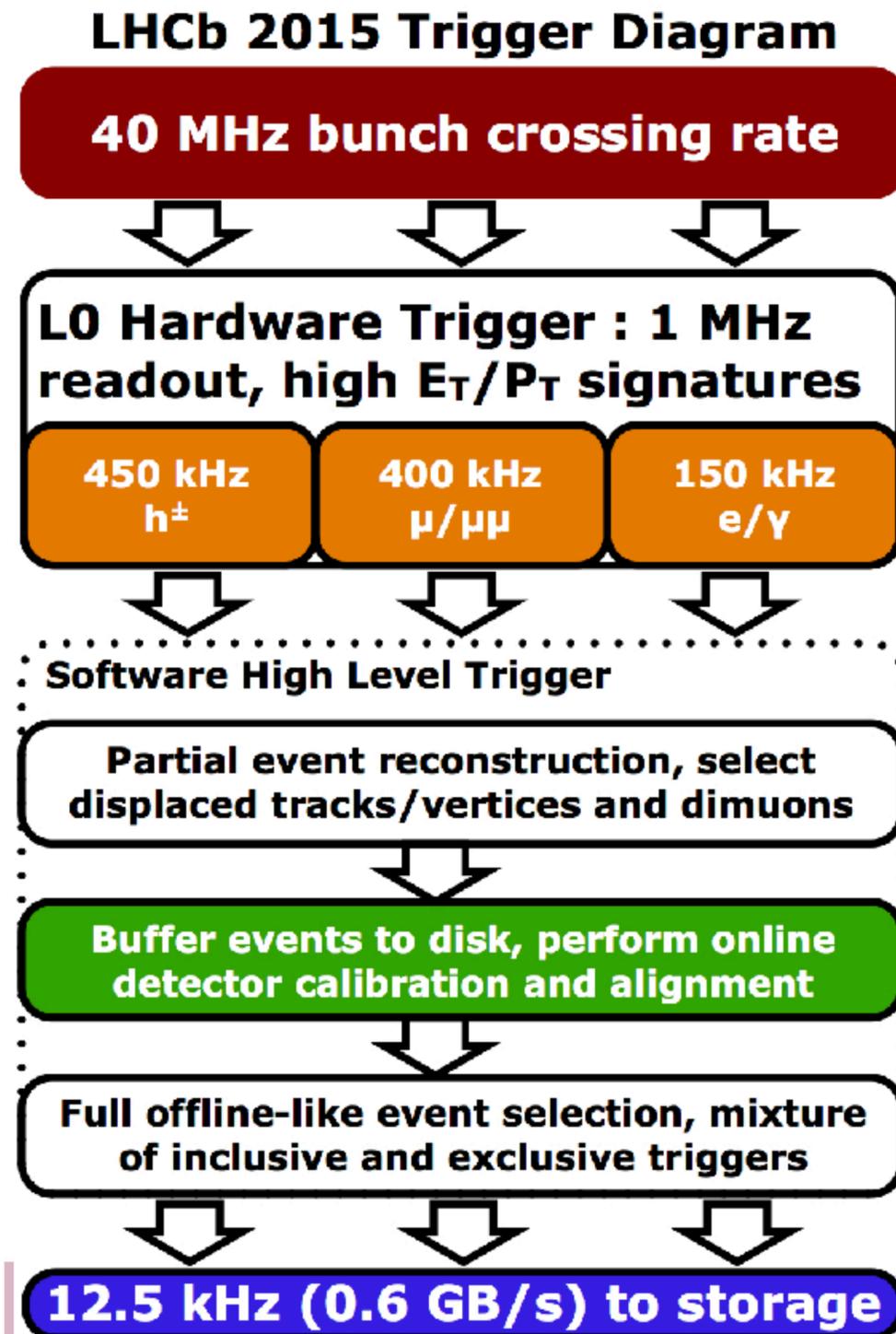
[JINST 19 (2024) 05, P05065]



- 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

The upgraded dataflow

[LHCb-FIGURE-2020-016]



The upgraded dataflow

[LHCb-FIGURE-2020-016]

LHCb Upgrade Trigger Diagram

**30 MHz inelastic event rate
(full rate event building)**



Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections



Buffer events to disk, perform online detector calibration and alignment

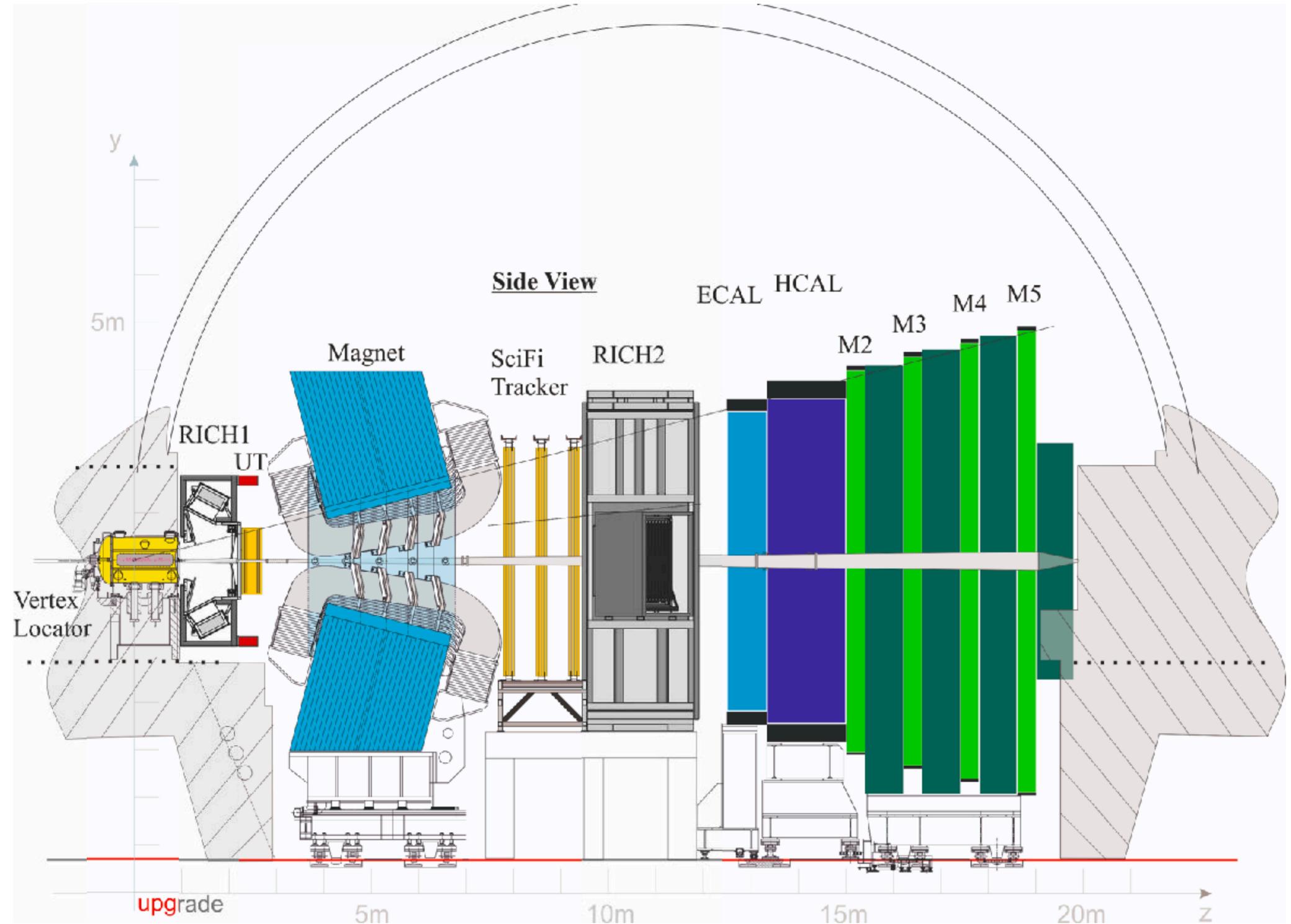


Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers



2-5 GB/s to storage



The upgraded dataflow

[LHCb-FIGURE-2020-016]

LHCb Upgrade Trigger Diagram

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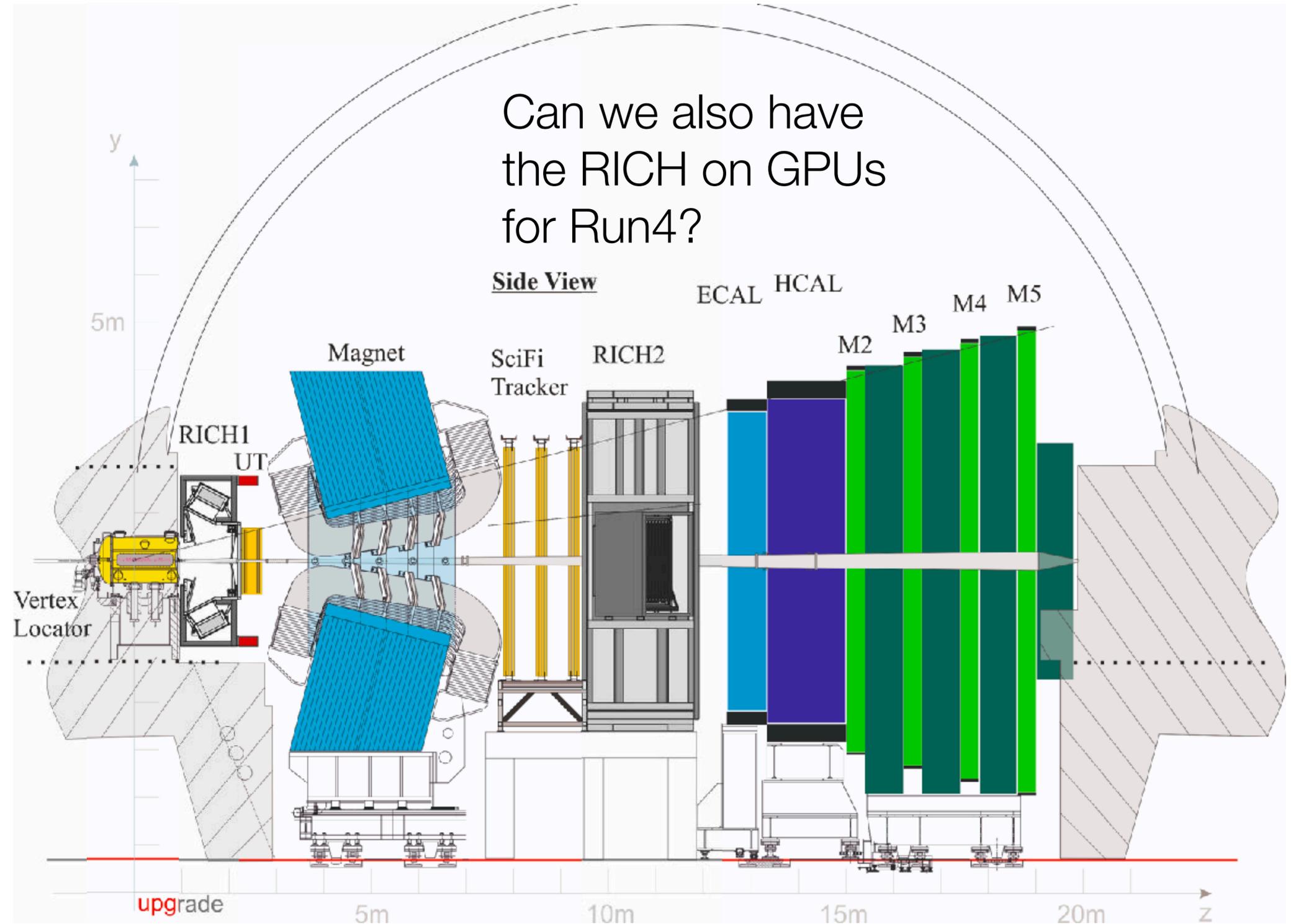


Add offline precision particle identification and track quality information to selections

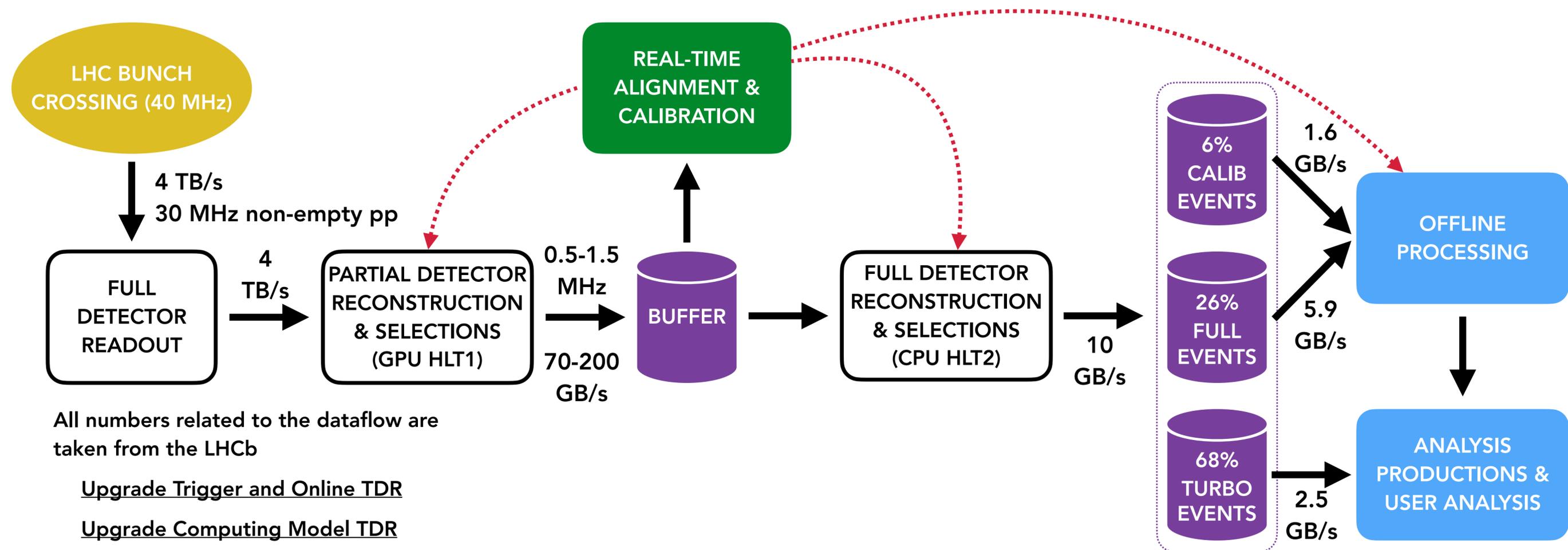
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers



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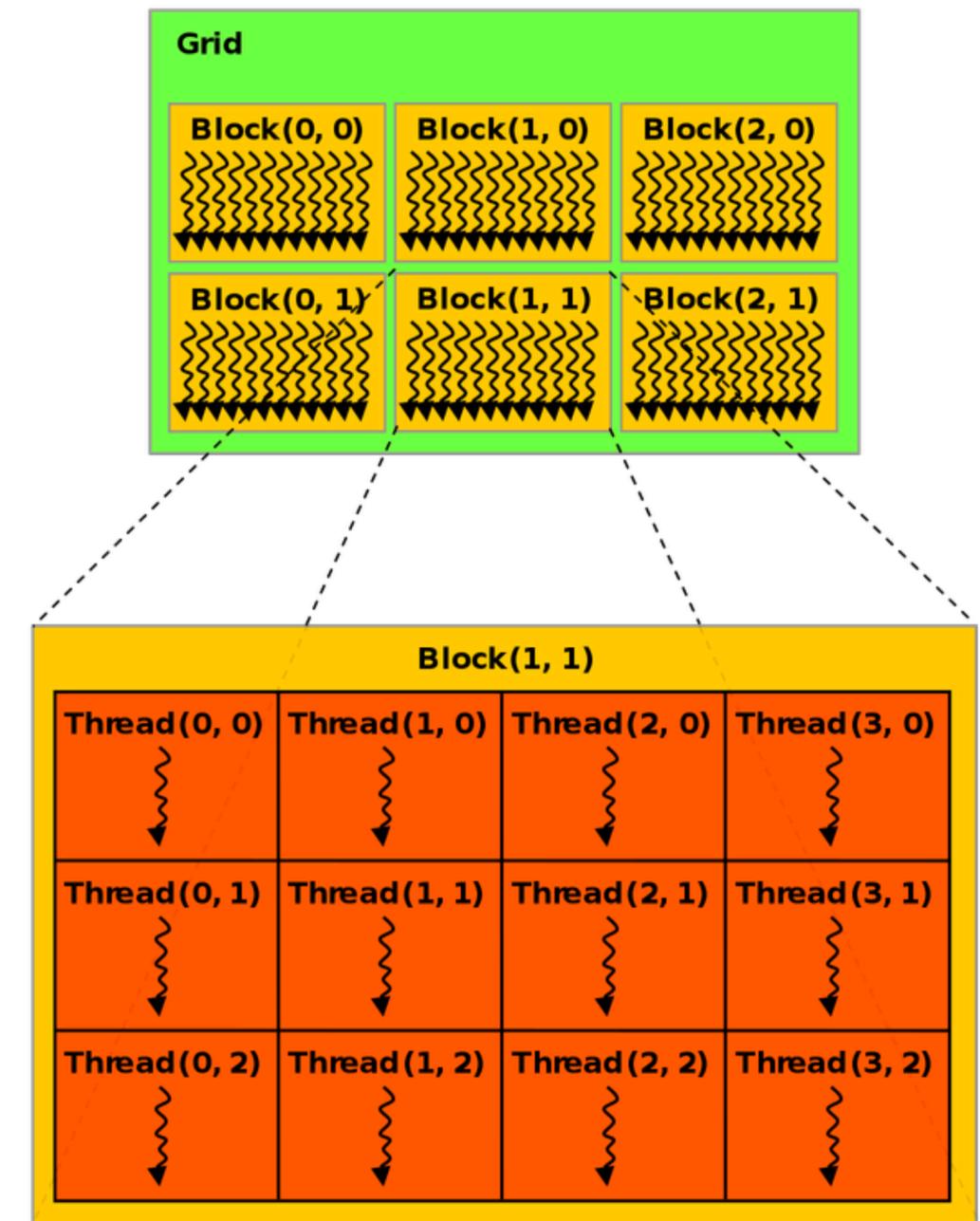


Allen: a GPU High Level Trigger for LHCb [Comput.Softw.Big Sci. 4 (2020) 1, 7]



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]

```

1 struct point3D {
2     float x;
3     float y;
4     float z;
5 };
6 struct point3D points[N];
7 float get_point_x(int i) { return points[i].x; }

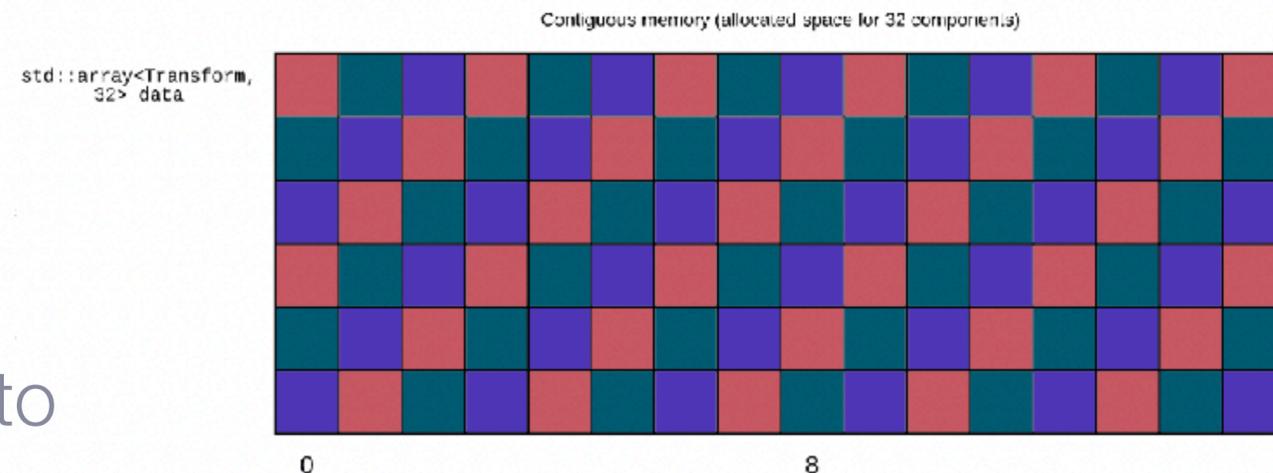
```

```

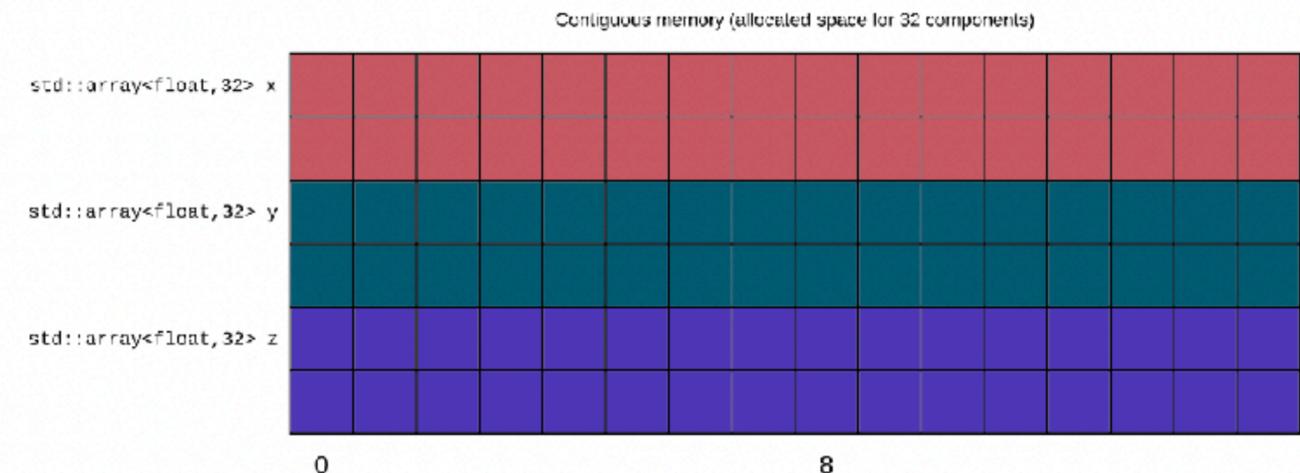
1 struct pointlist3D {
2     float x[N];
3     float y[N];
4     float z[N];
5 };
6 struct pointlist3D points;
7 float get_point_x(int i) { return points.x[i]; }

```

AOS layout



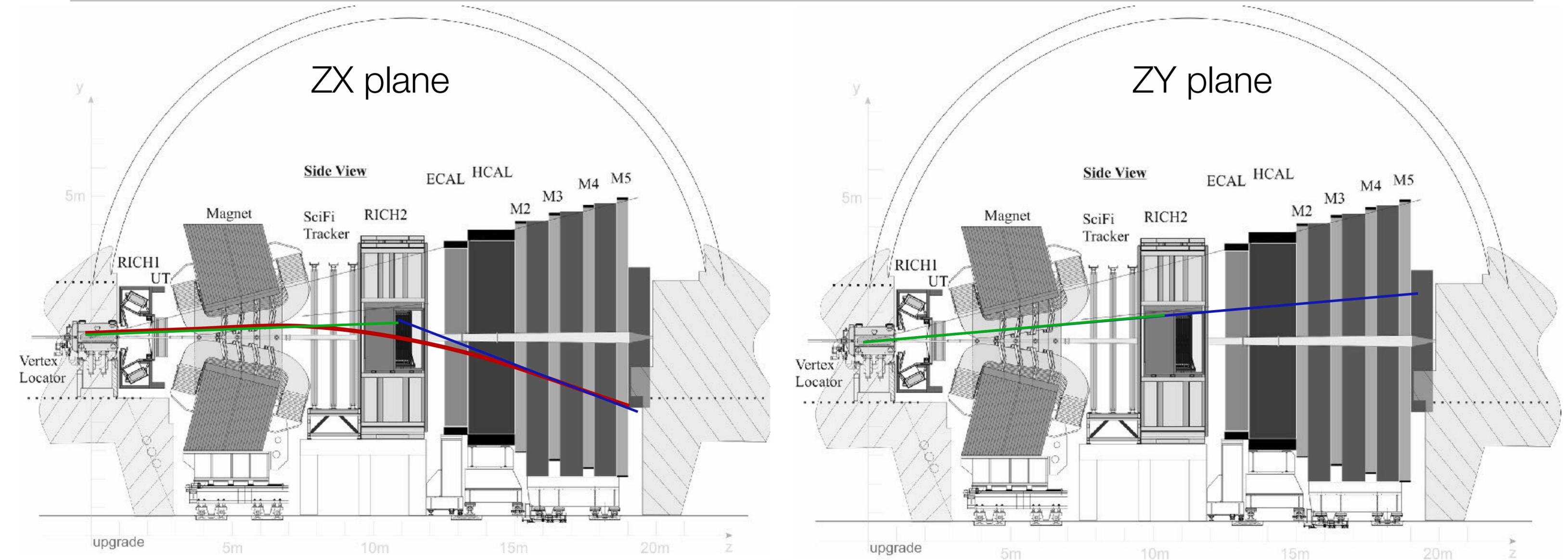
SOA layout



Thanks to
Renato
Quagliani for
the diagrams

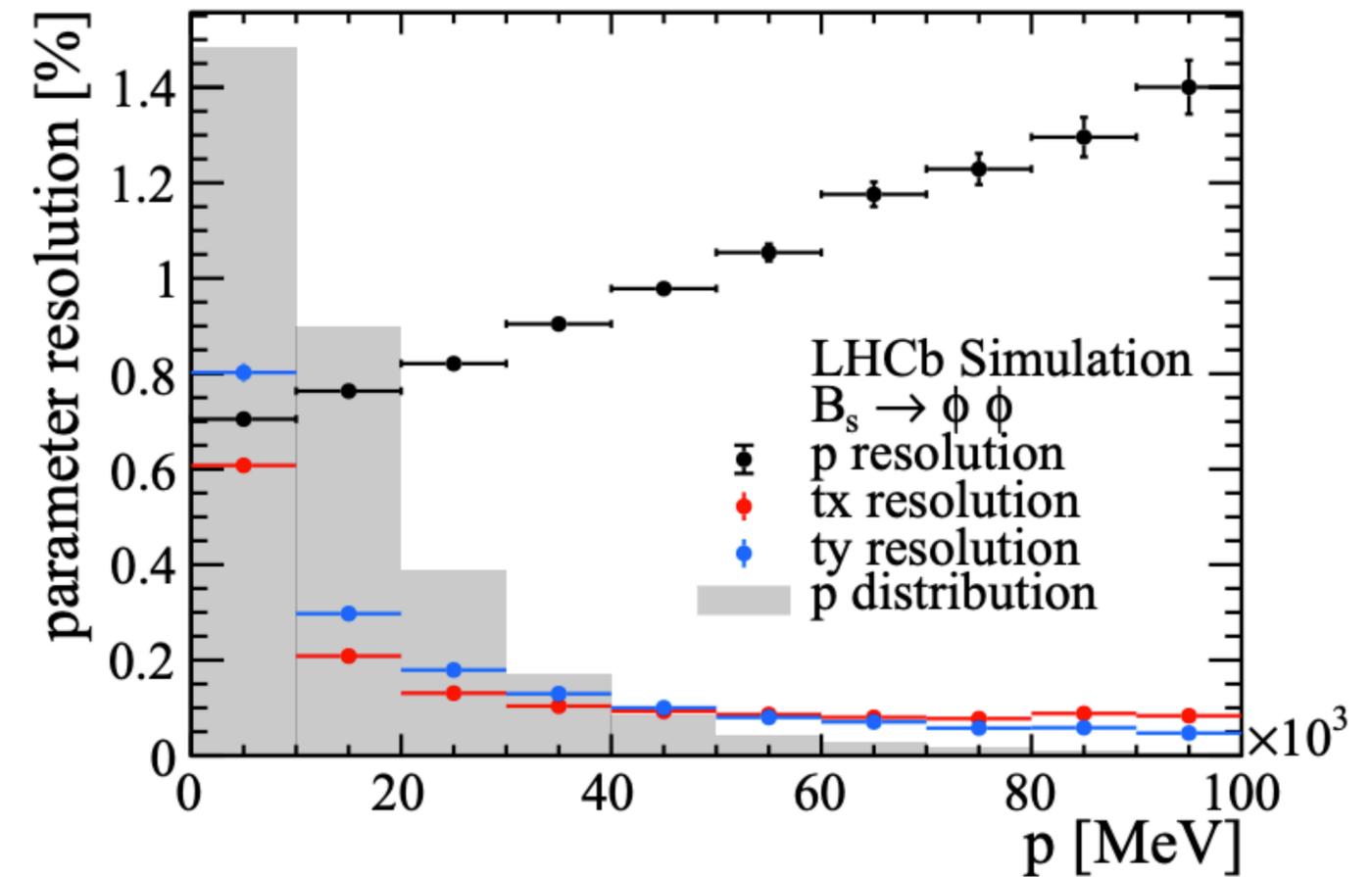
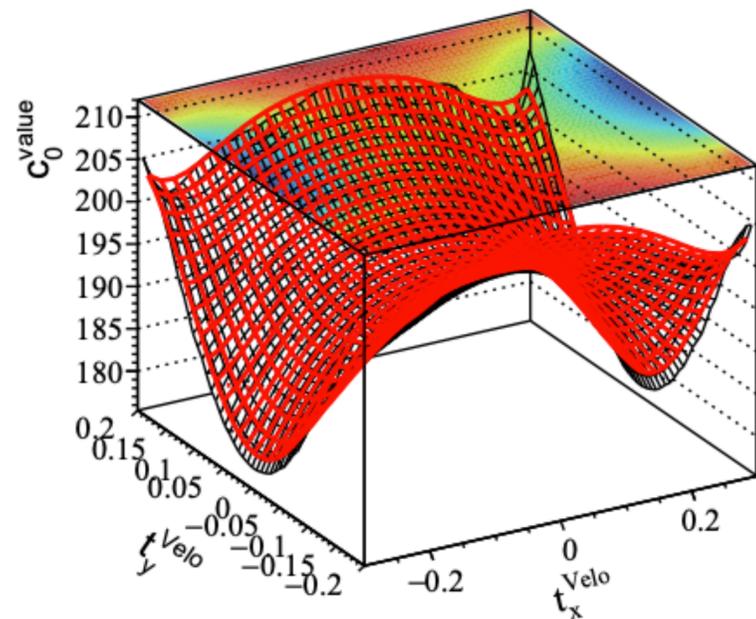
- Contiguous memory access: structure of arrays (SoA)
 - Structure of "BIG" arrays that hold information of a bunch of events
- Adequate when a lot of memory is being written/read at the same time
- Block Index + Thread Index \rightarrow Position in the array

A track through LHCb



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

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



- Basic idea:

- Expand $\int |\vec{B} \times d\vec{l}|_x = \sum_0^4 c_i (\Delta t)^i$

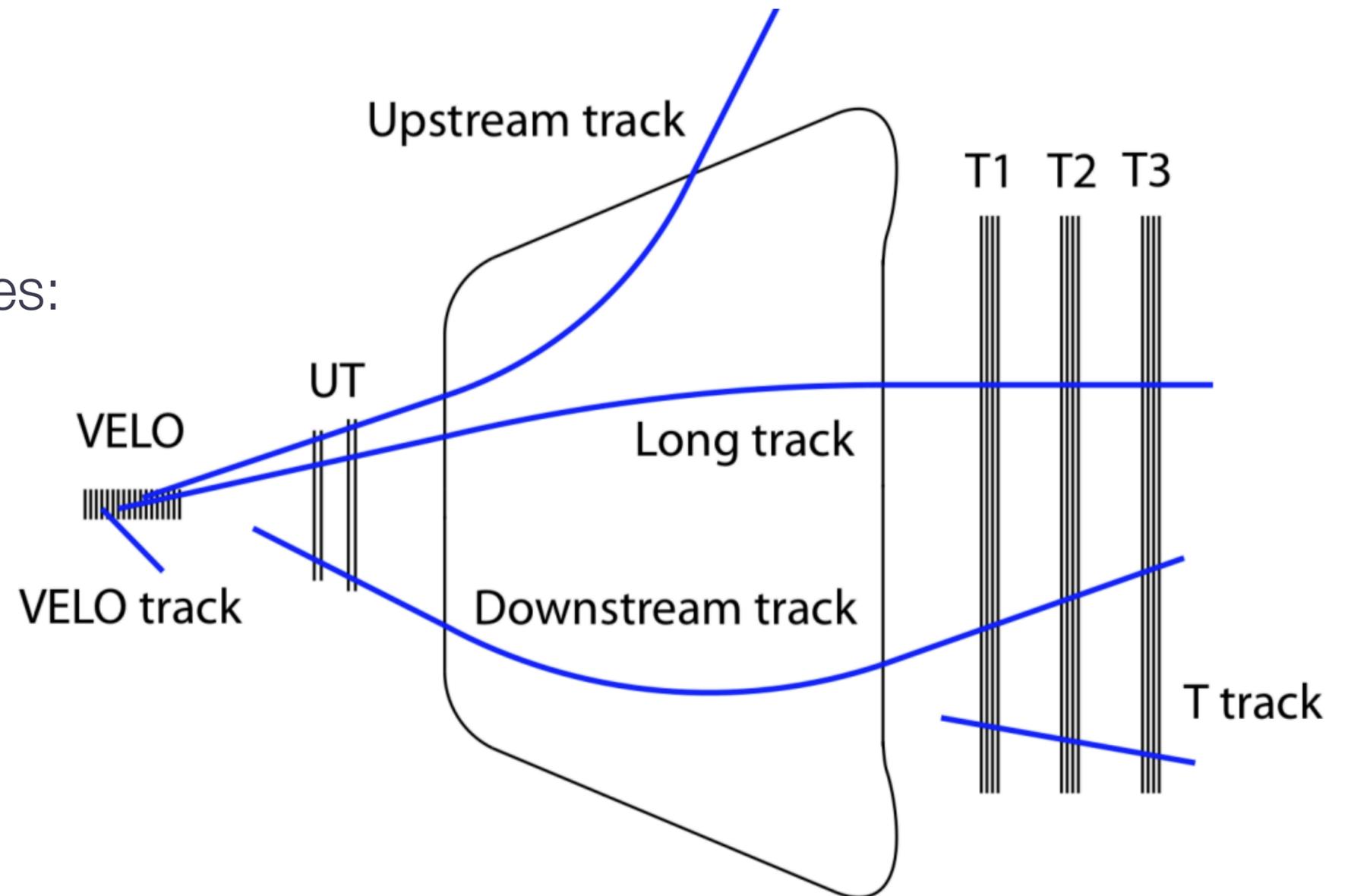
- Obtain a **map** by fitting the coefficients to **polynomials** such that:

$$c_i = c_i(t_{x,m}, t_{y,m})$$

Downstream tracks

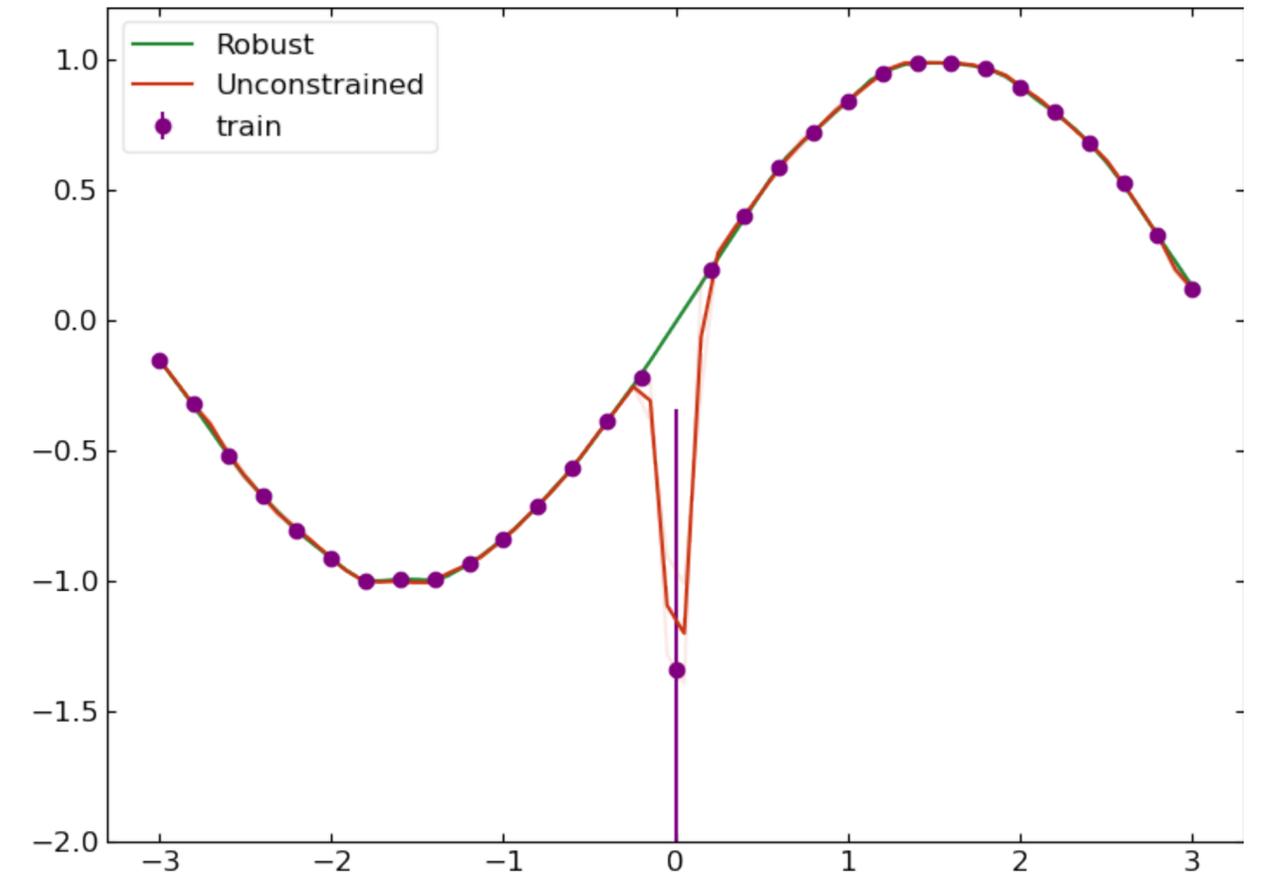
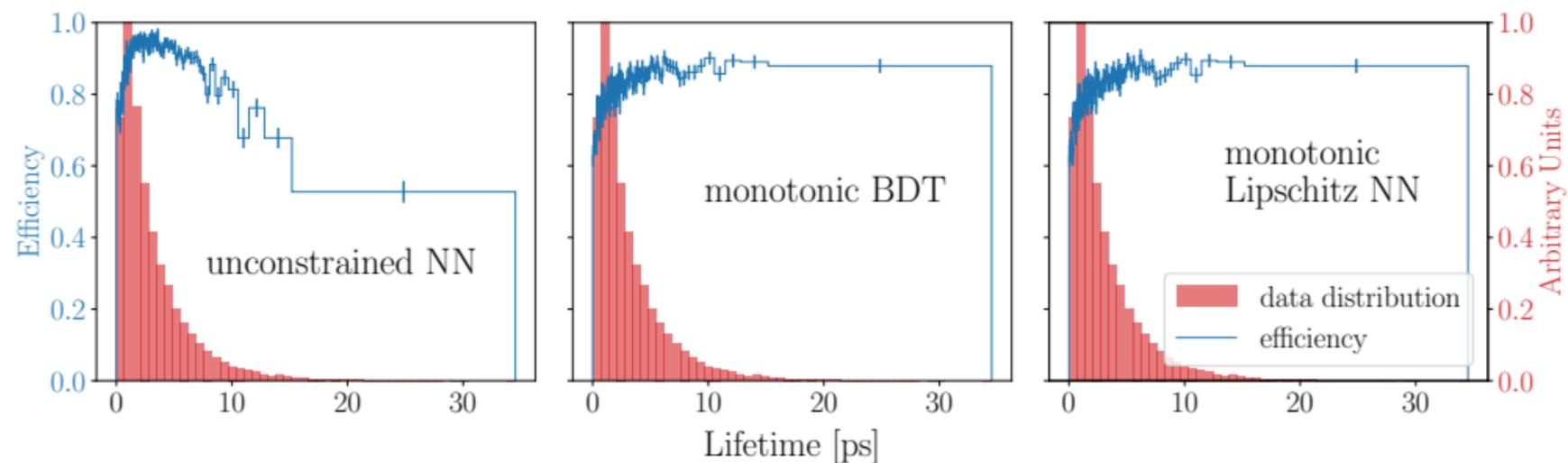
[Eur.Phys.J.C 84 (2024) 6, 608]

- 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, Λ



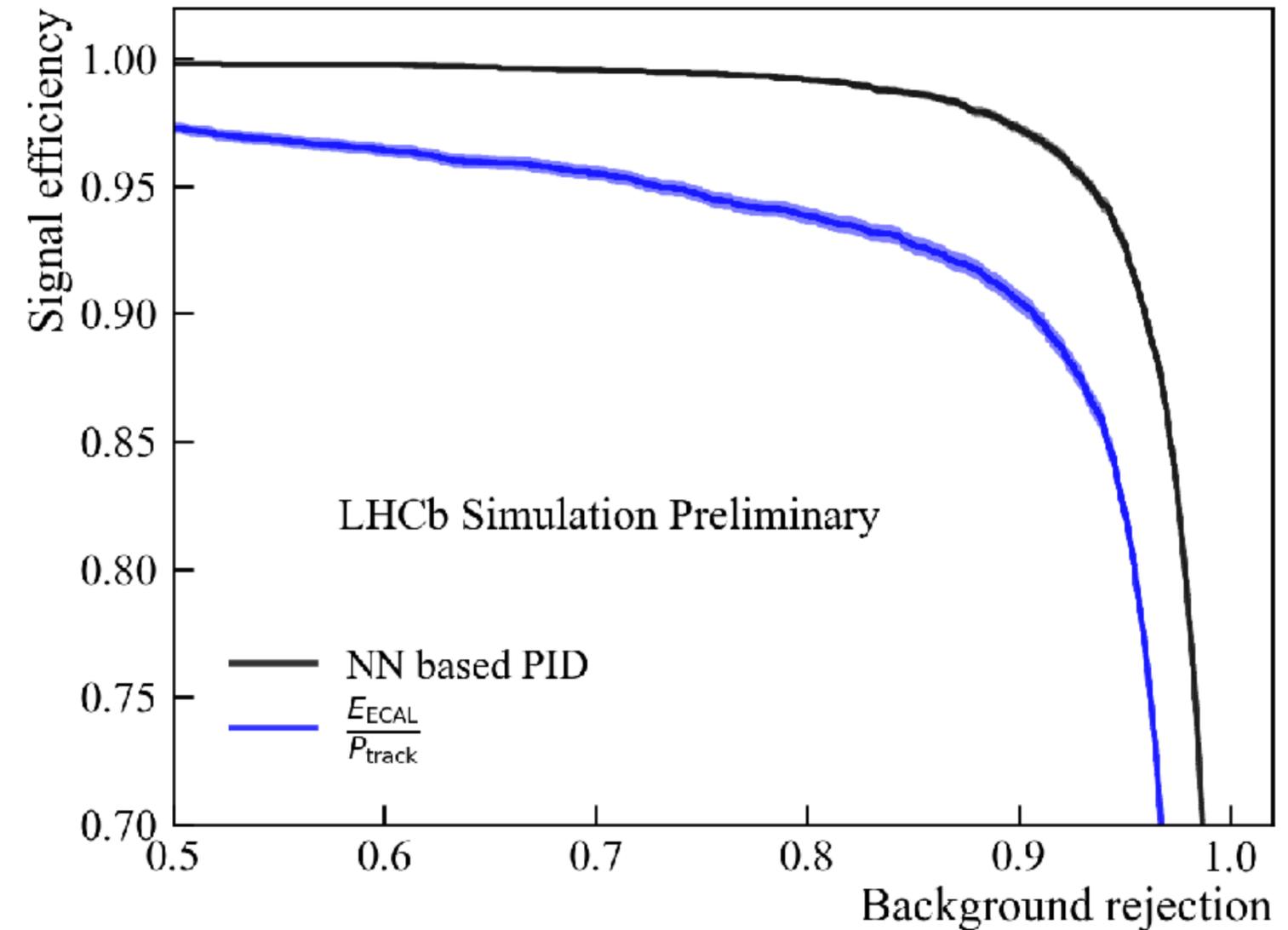
Lipschitz constrained NN [\[Mach.Learn.Sci.Tech. 4 \(2023\) 3, 035020\]](#)

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



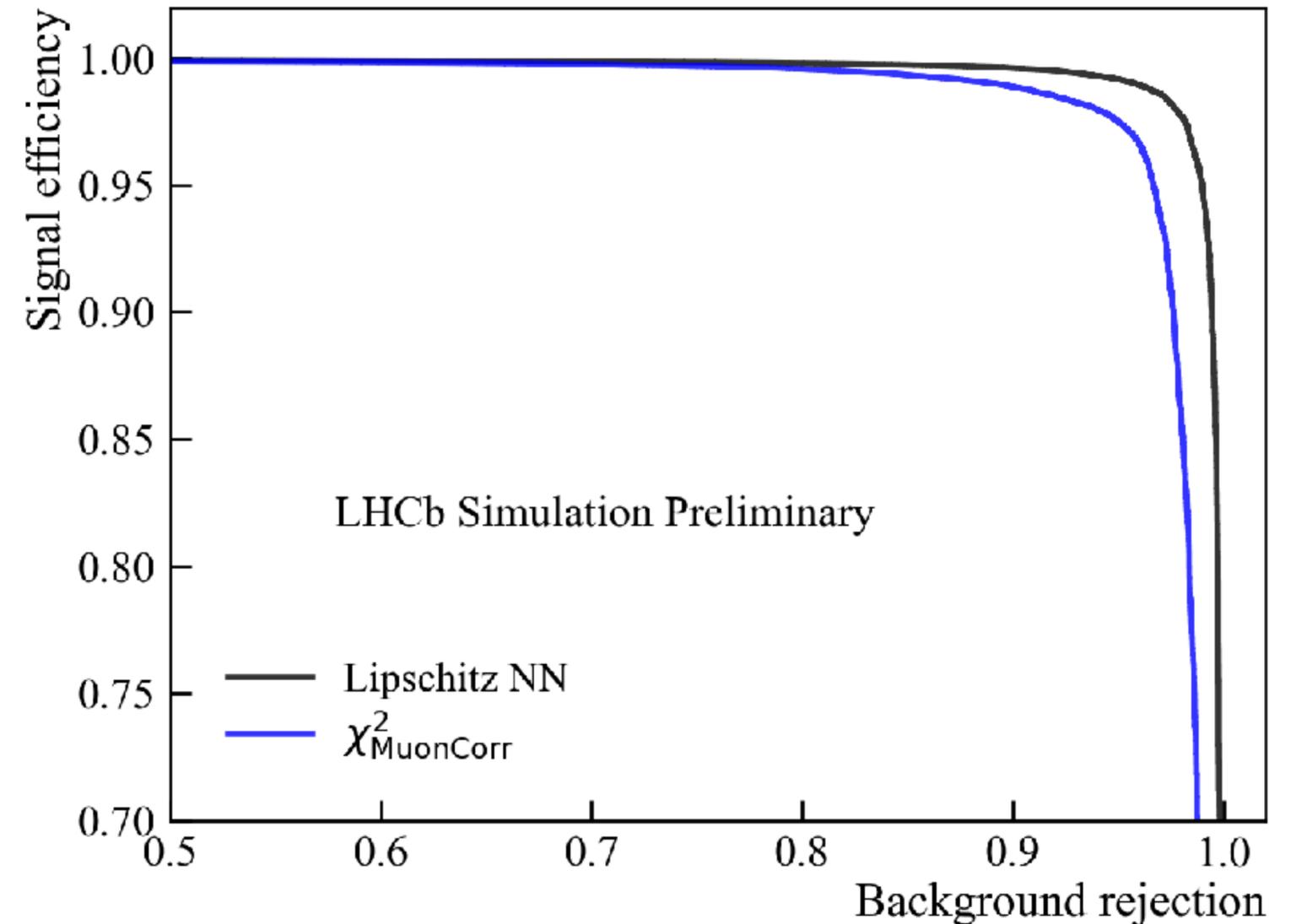
Dark Photons: Run 3, PID in real time

- Dedicated electron ID using Lipschitz constrained Neural Network
- Reconstruction of electron features at HLT1
 - $\frac{E_{\text{ECAL}}}{P_{\text{track}}}$
 - 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

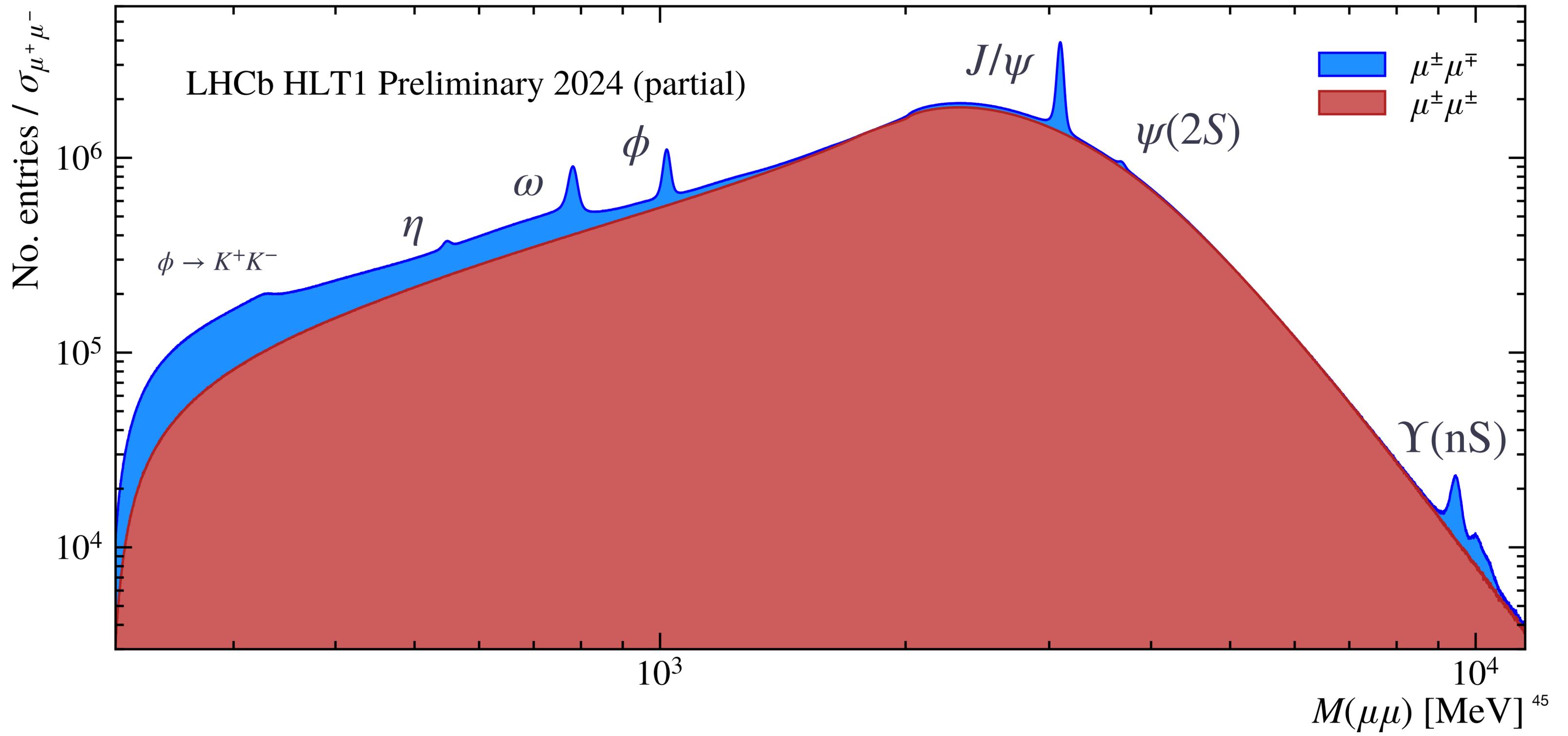


Dark Photons: Run 3, PID in real time

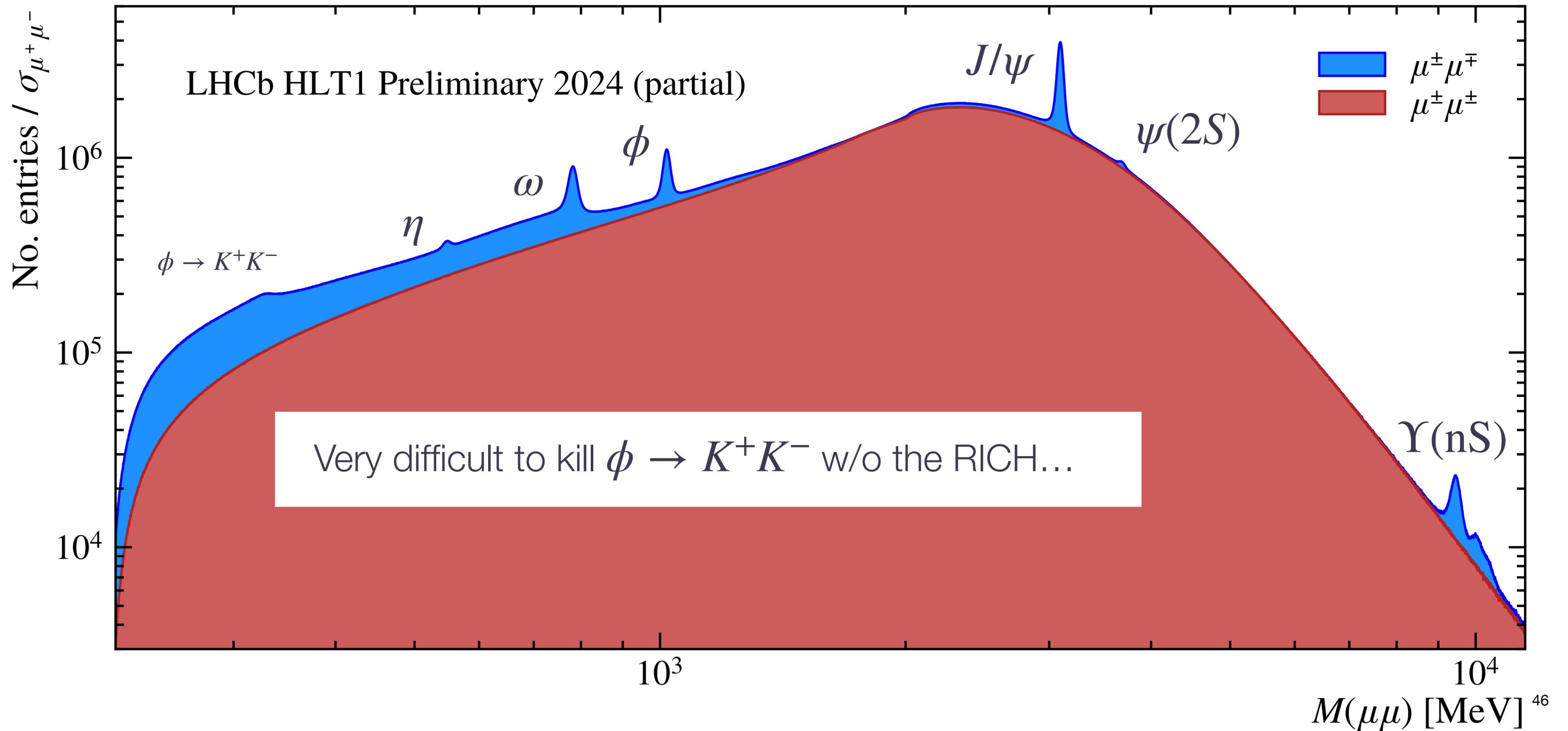
- Dedicated electron ID using Lipschitz constrained Neural Network
- Reconstruction of muon features at HLT1
 - Dispersion of hits around track extrapolation
 - Match between muon segment and track
 - Timing features
 - Hit reconstruction pattern distribution
- 50% improvement wrt baseline muonID
 - χ^2_{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



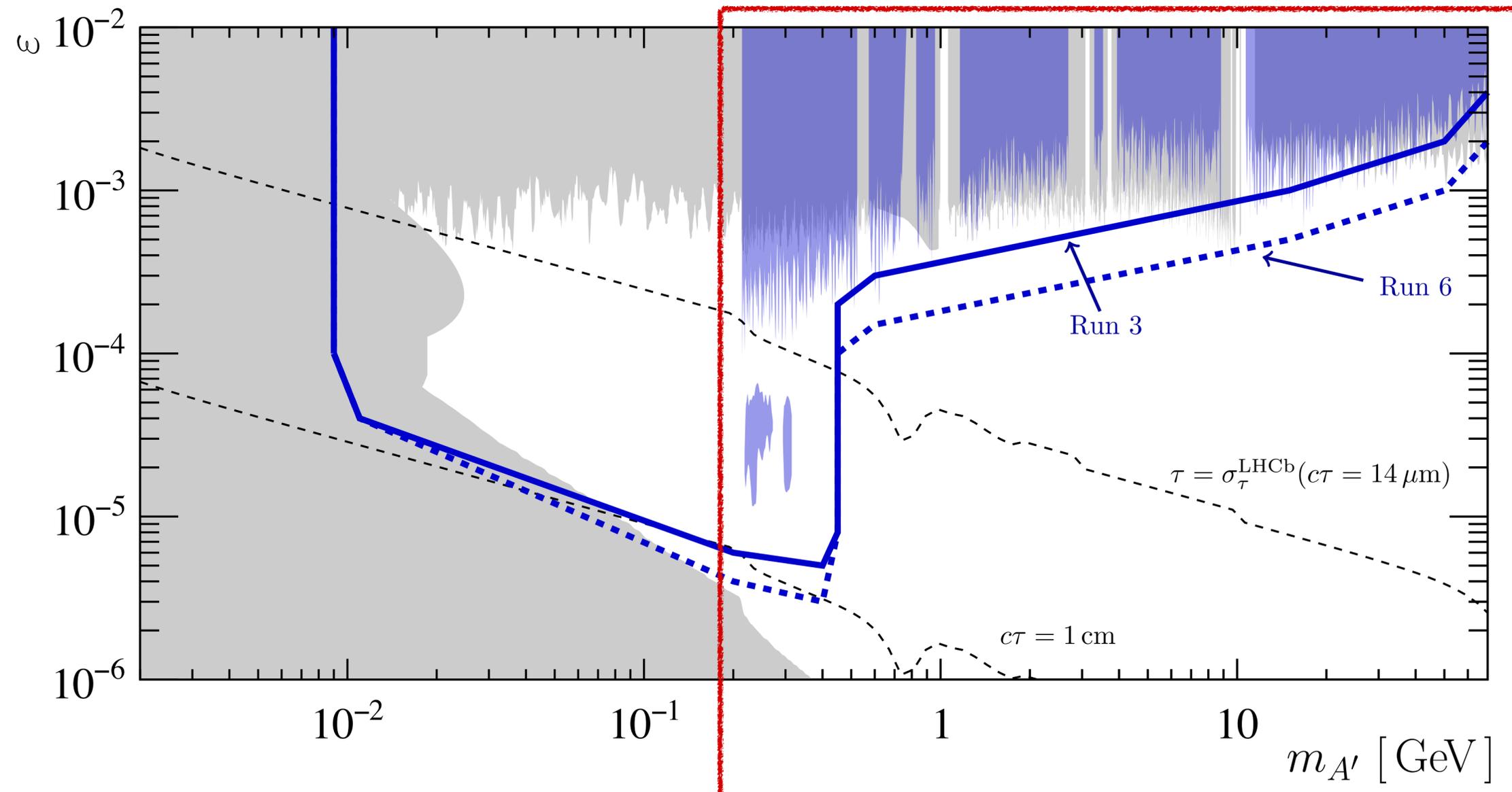
Dark Photons: Run 3, PID in real time



Dark Photons: Run 3

[2203.07048]

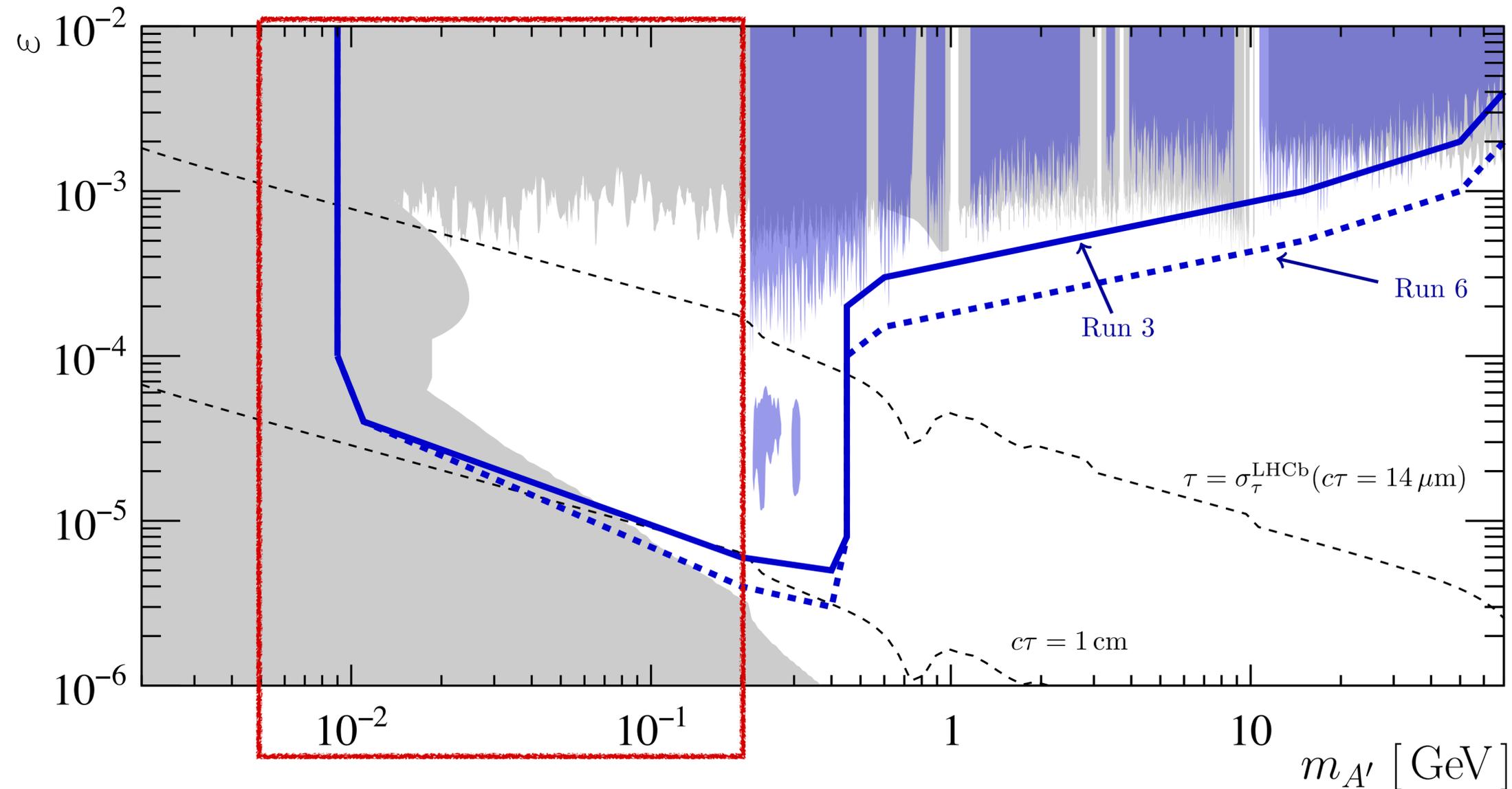
- Better reach for the dimuon search: expected to improve LHCb Run 2 result
 - During Run3 we can take all the Run2 data in \sim a couple of months



Dark Photons: Run 3

[2203.07048]

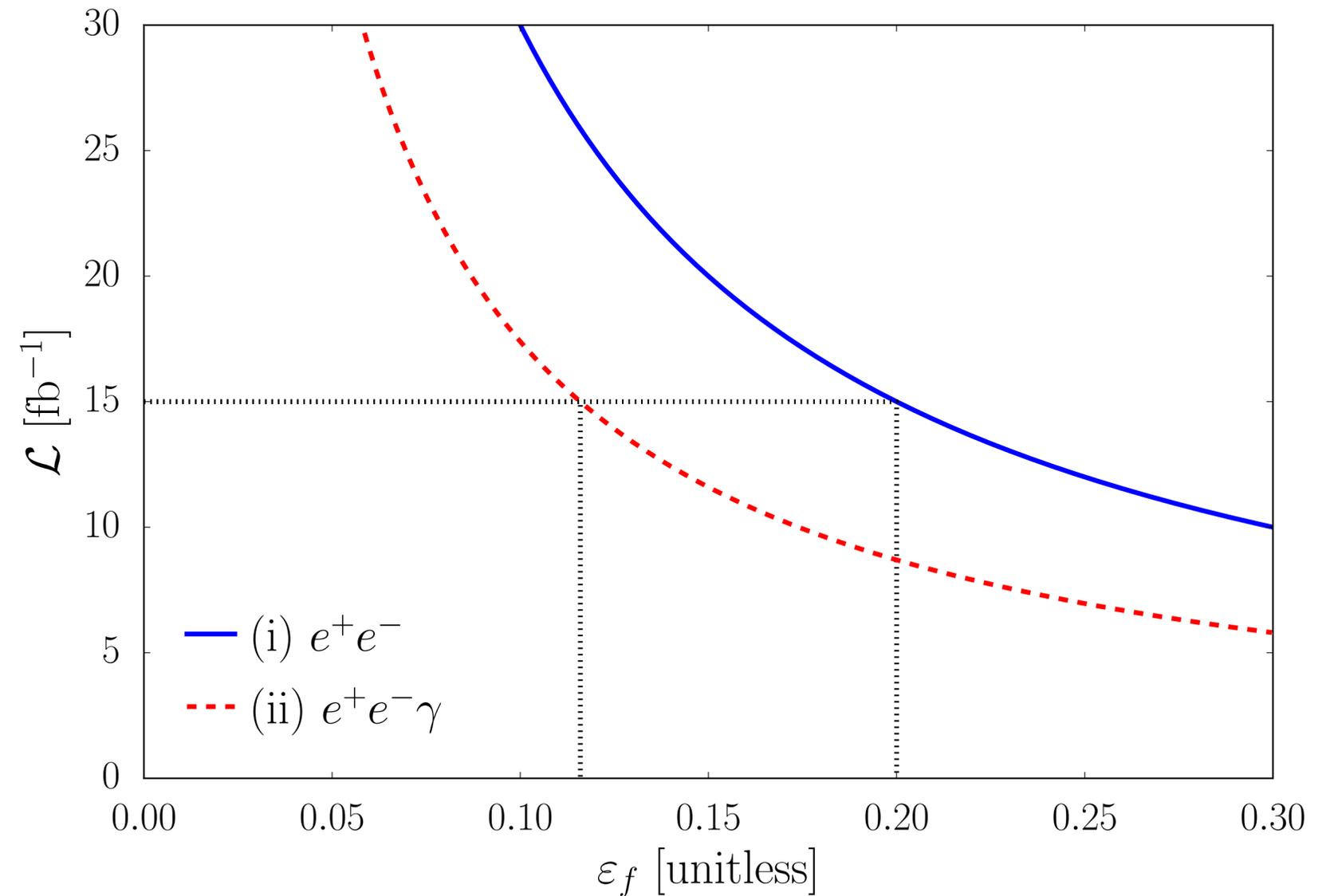
- Serious sensitivity below the 2μ threshold: dielectron channel
 - Exploit the largely produced $\pi^0/\eta \rightarrow e^+e^-\gamma$ to easily normalise



True muonium

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

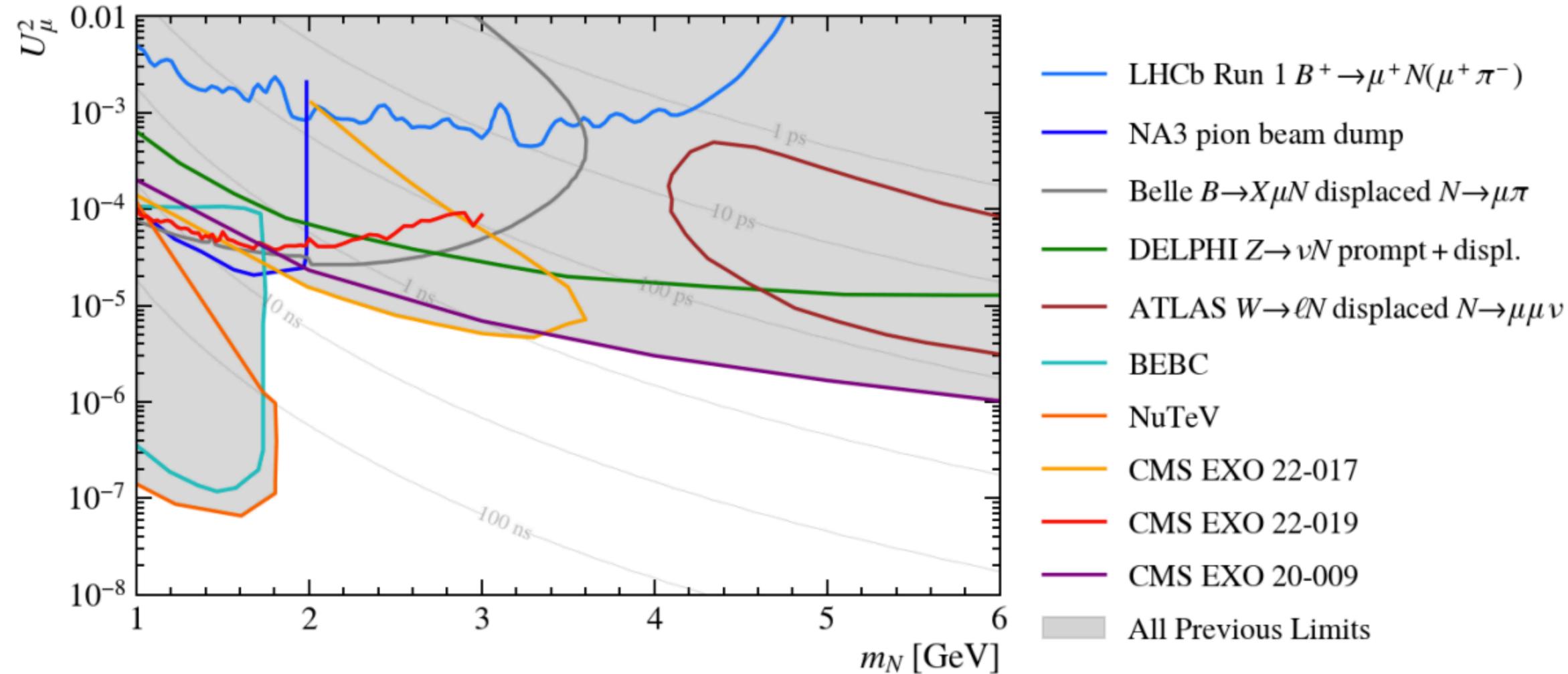
- Standard Model bound state
 - Very clear QED prediction
 - Never observed
- Same final state as a $A' \rightarrow e^+e^-$
 - Mainly produced as $\eta \rightarrow \gamma \mathcal{T} \mathcal{M}$
- Discovery potential using the full Run 3
 - Two decay channels: $e^+e^- \gamma$ and e^+e^-



New results coming soon: Dark Scalars, ALPs and HNLs

Heavy Neutral Leptons

[PRL 112 (2014) 13, 131802]

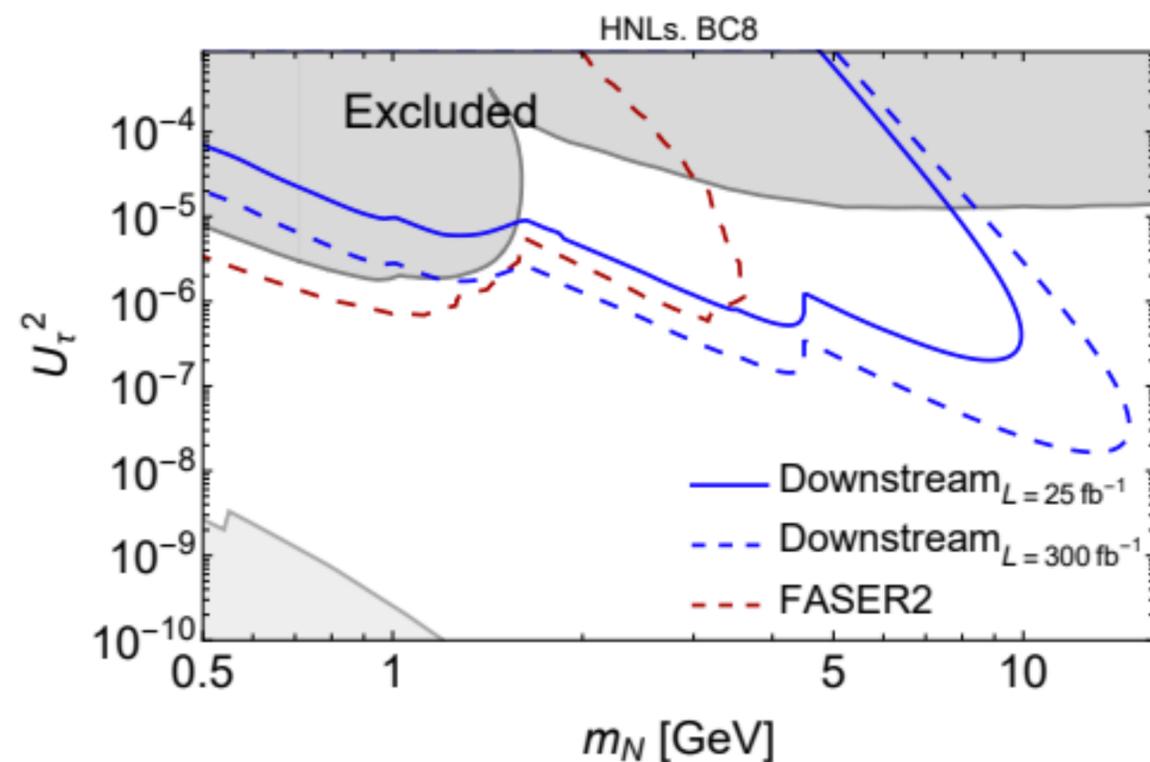
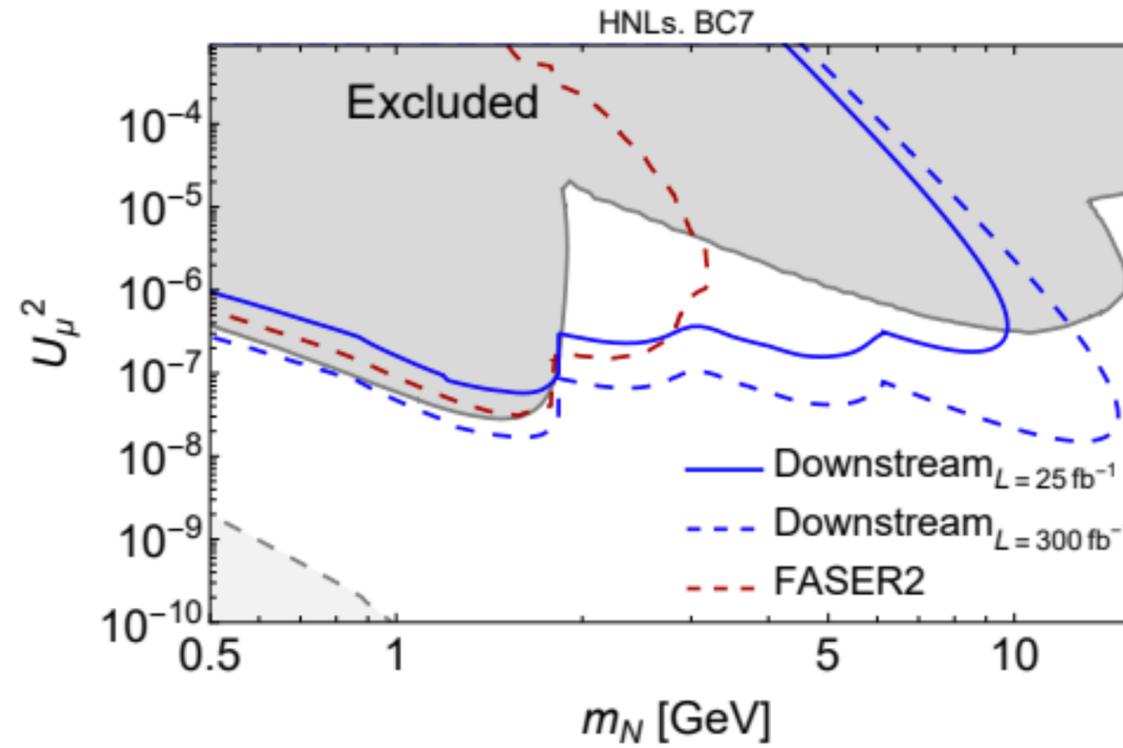
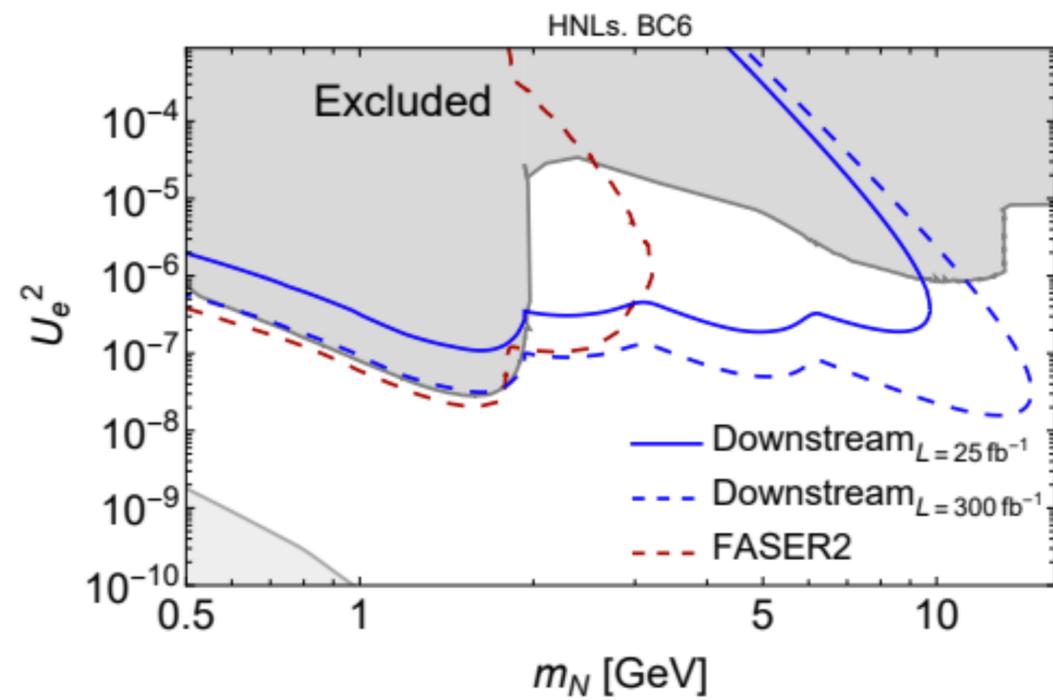


- Thanks to **Spencer Collaviti** for the nice plot

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

Heavy Neutral Leptons

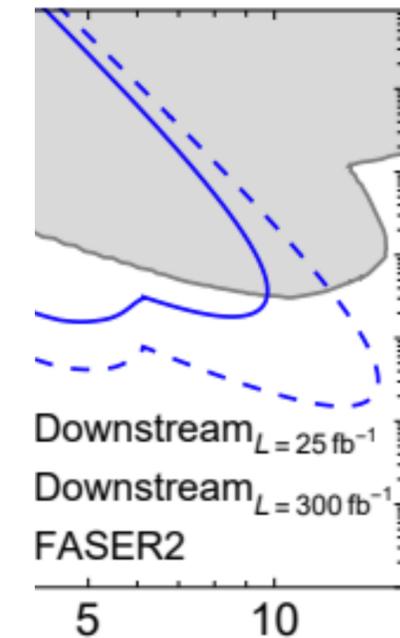
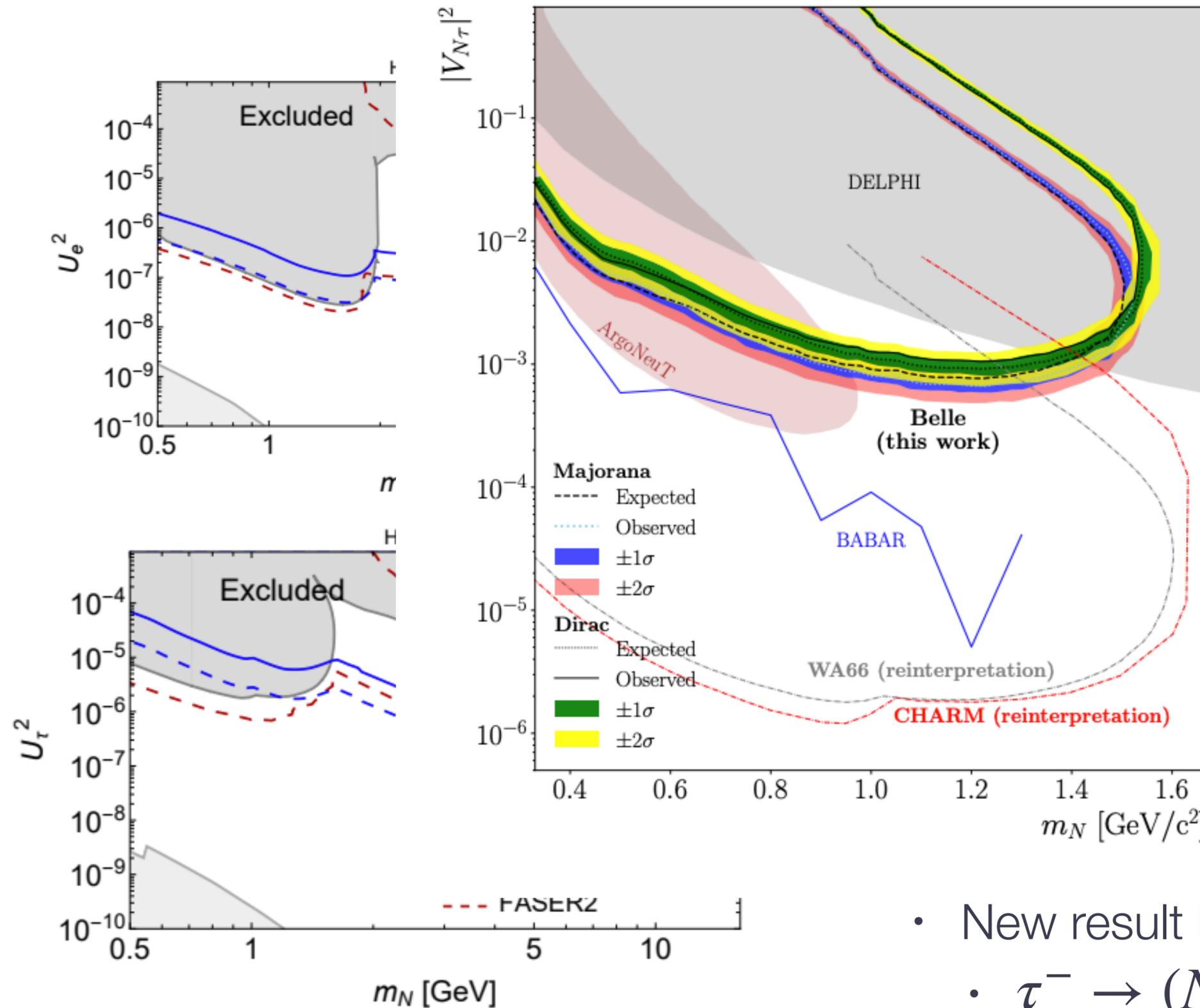
[Eur.Phys.J.C 84 (2024) 6, 608]



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

Heavy Neutral Leptons

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

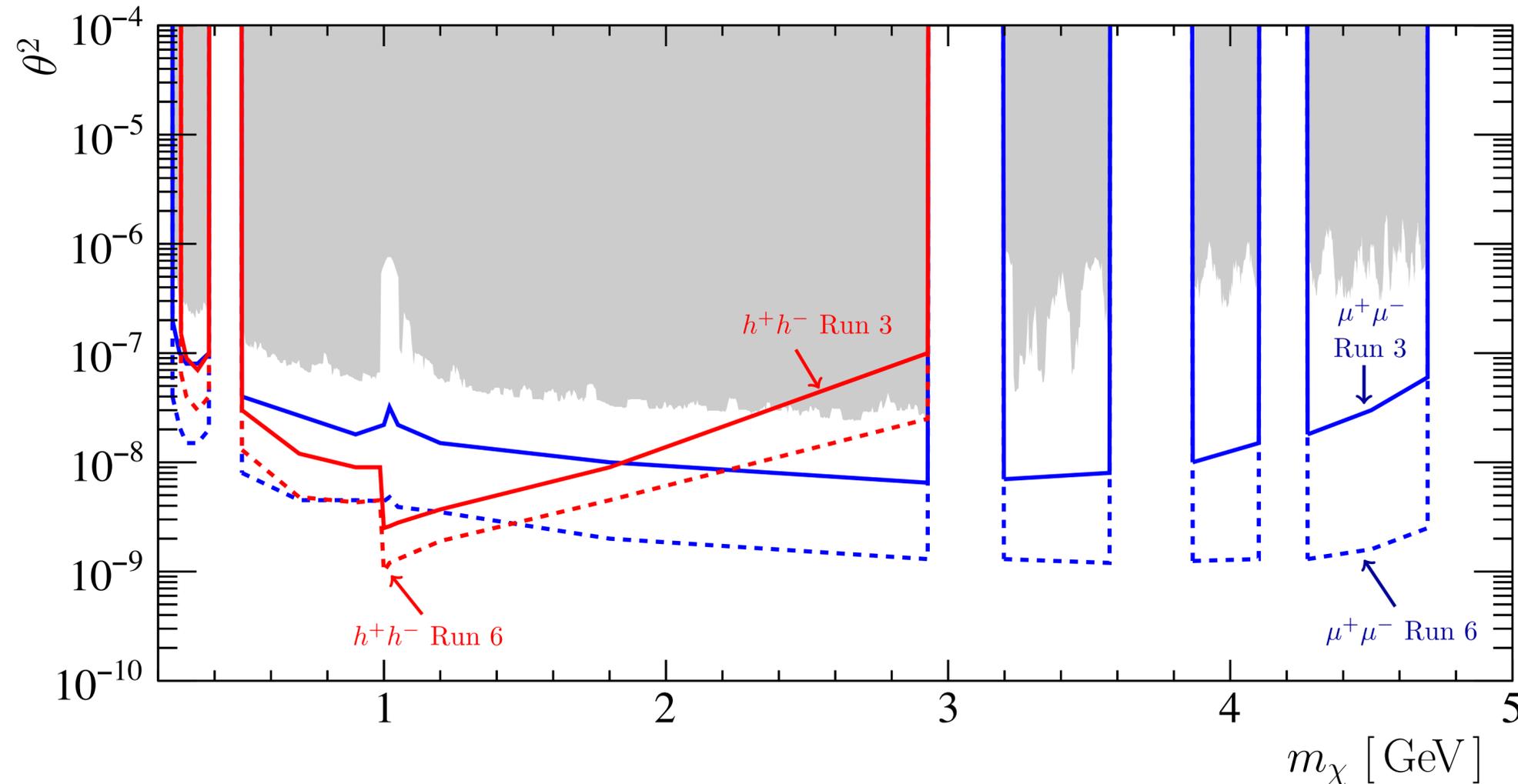


spects using Downtream
at the trigger level

- New result by Belle II: [PRD 109 \(2024\) 11, 11](#)
- $\tau^- \rightarrow (N \rightarrow \nu_\tau \mu^+ \mu^-) \pi^-$

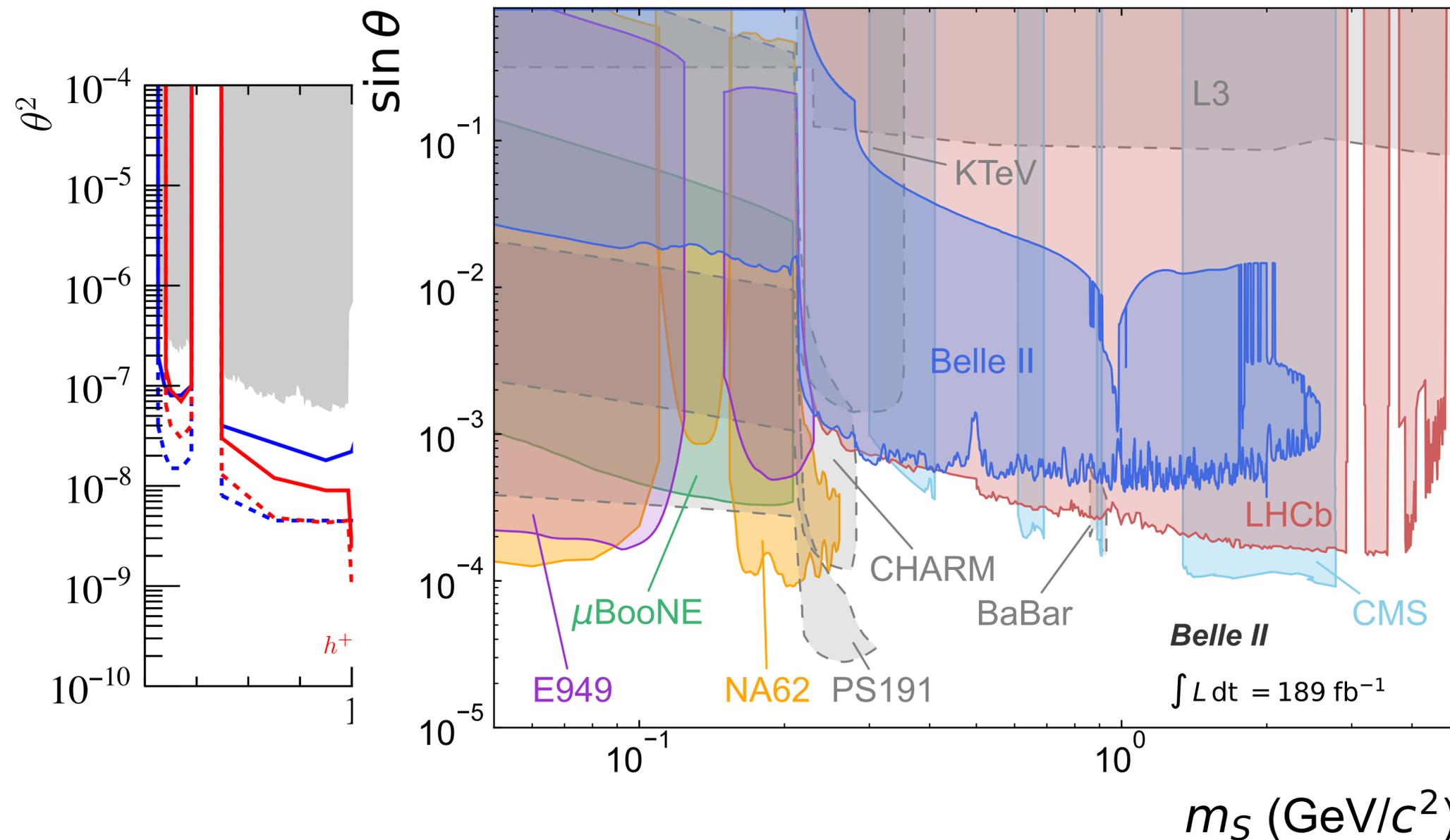
Coming up next: Higgs portal

[2203.07048]



- Dark scalar coupling to the Higgs via mixing angle: θ
- $B \rightarrow K\chi$ 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

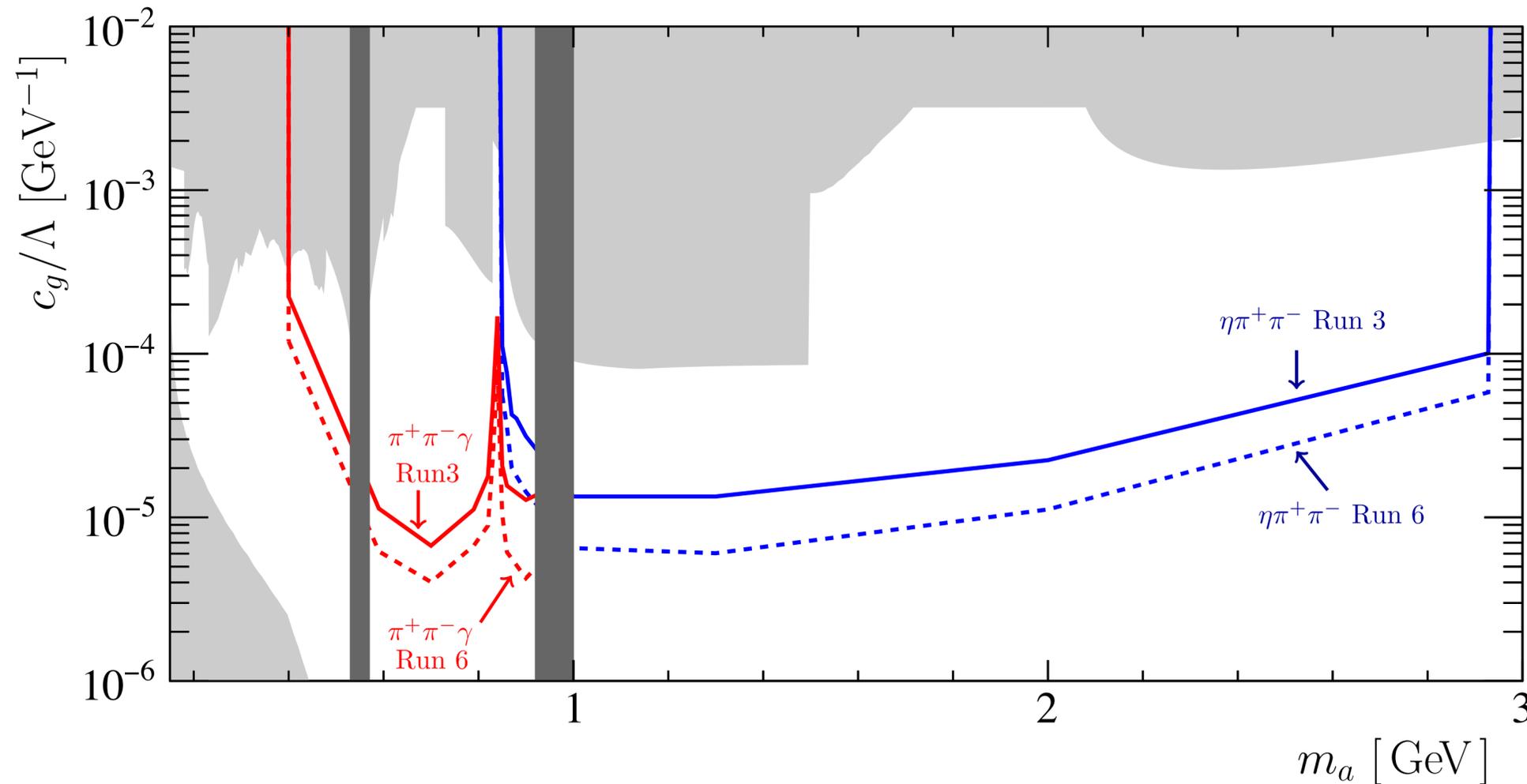
Coming up next: Higgs portal [2203.07048, PRD 108 (2023) 11, L111104]



- Dark scalar coupling to the Higgs via mixing angle: θ
- $B \rightarrow K\chi$ decays
 - Penguin decay enhancement thanks to the **top** quark mass
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ALPs coupled to gluons

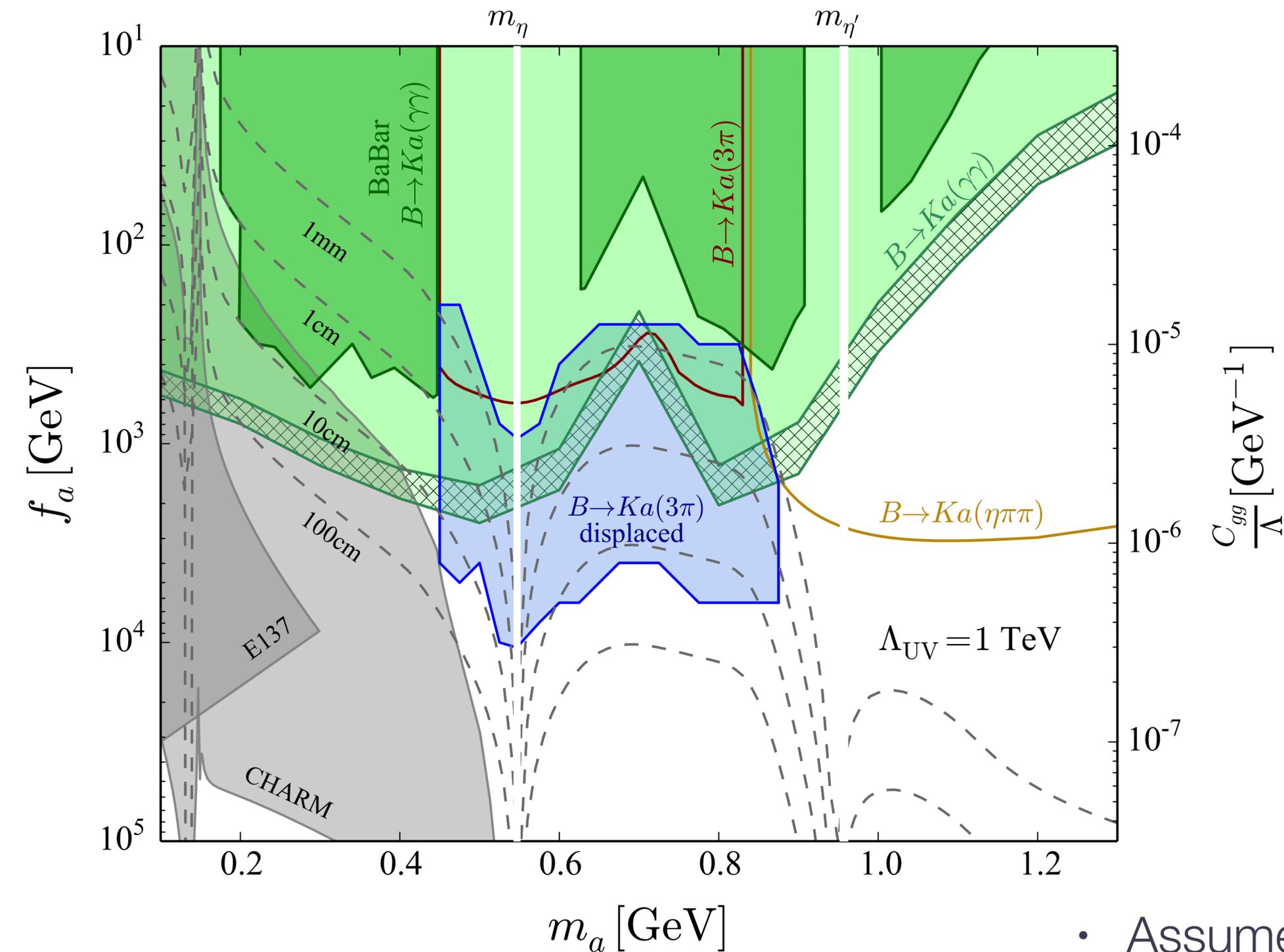
[PRL (2019) 123 031803, 2203.07048]



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

ALPs coupled to gluons: Belle II

[PRD 105 (2022) 7, L071701]

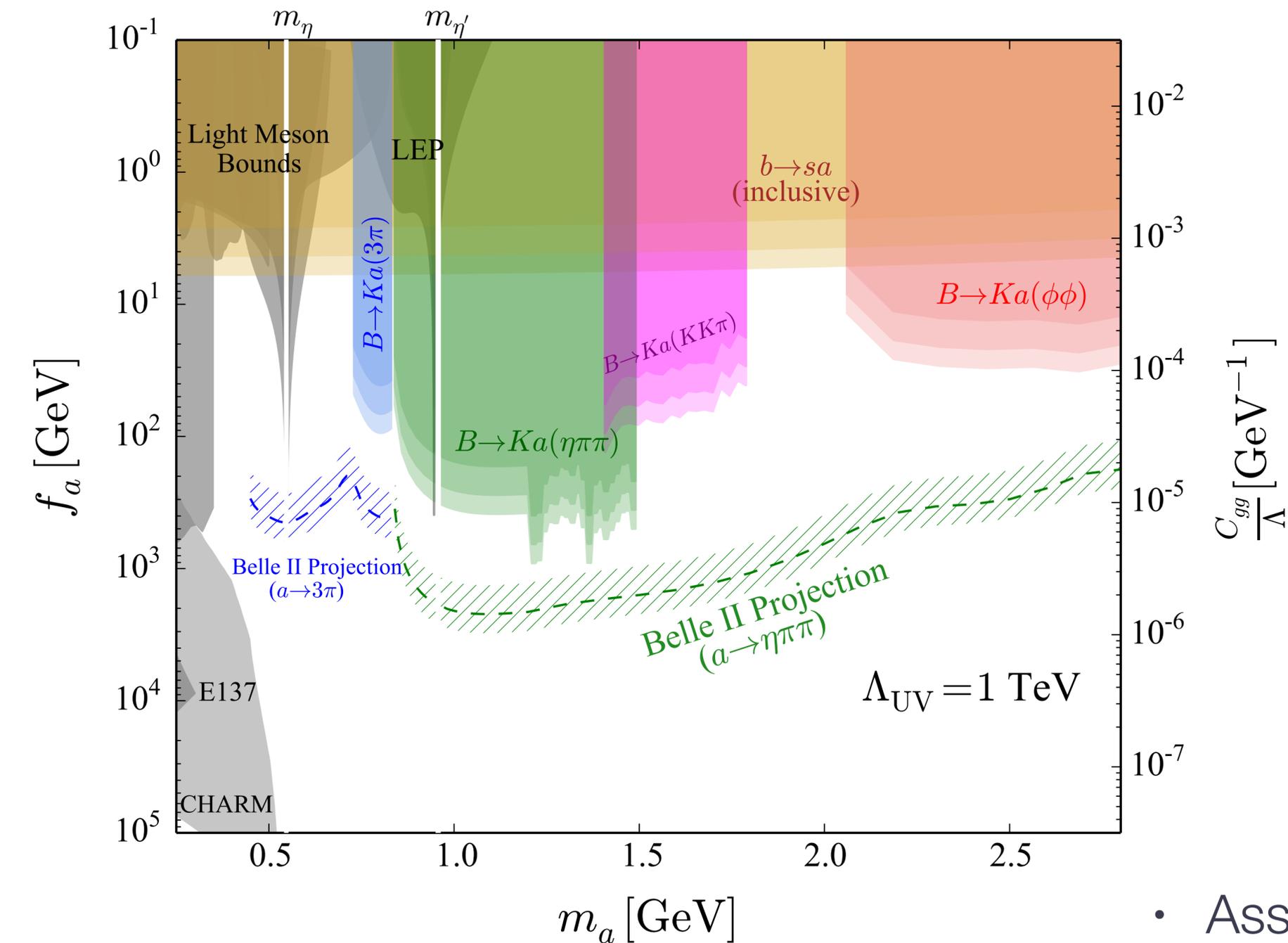


- Belle II prospects for displaced $a \rightarrow \pi^+ \pi^- \pi^0$
 - Narrower width for $m_a < 1.2$ GeV

- Assumes $5.5 \times 10^{10} B\bar{B}$ pairs

ALPs coupled to gluons: Belle II

[PRD 104 (2021) 5, 055036]

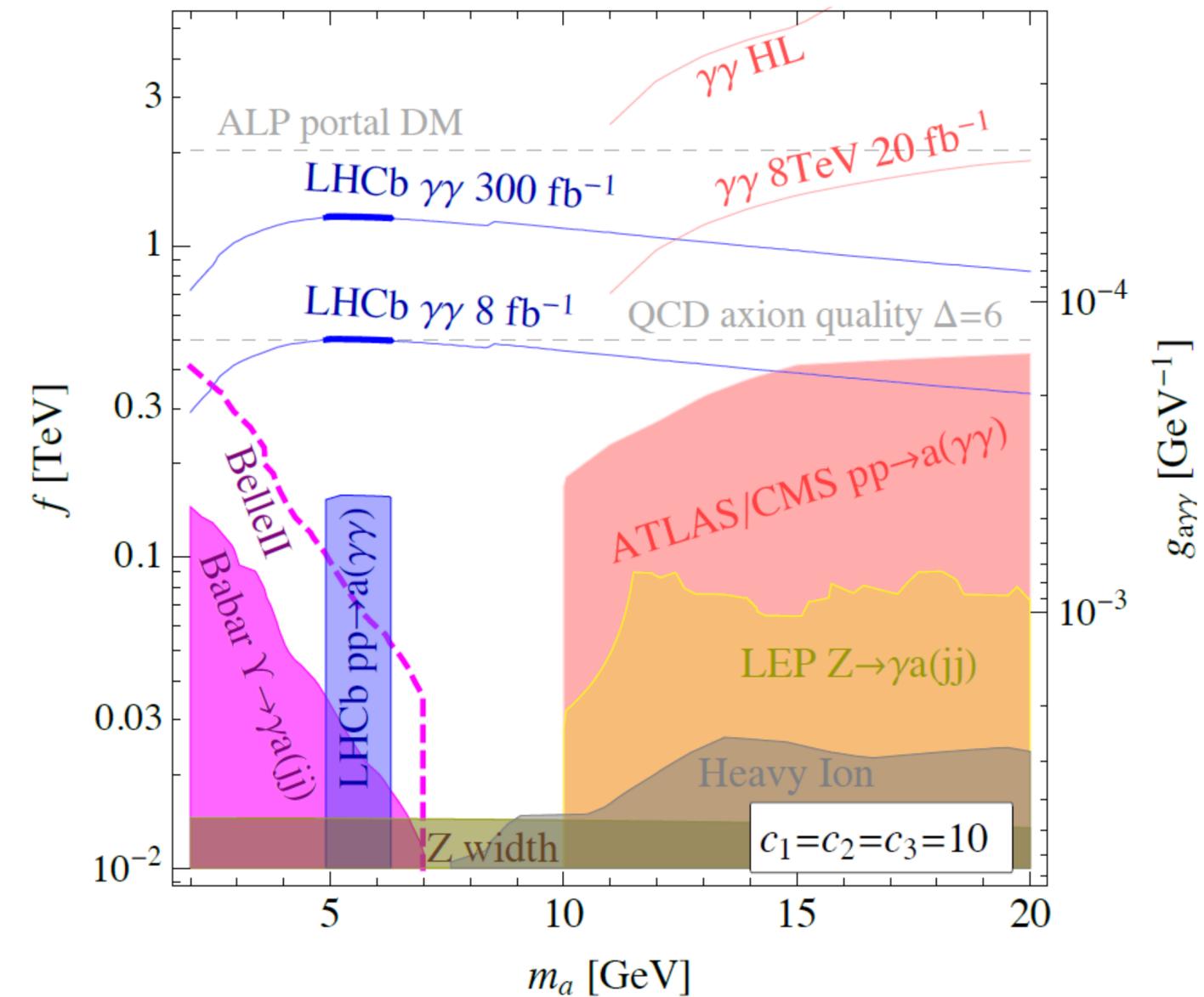


- Assumes 5.5×10^{10} $B\bar{B}$ pairs

ALP $\rightarrow \gamma\gamma$

[JHEP 1901 (2019) 113]

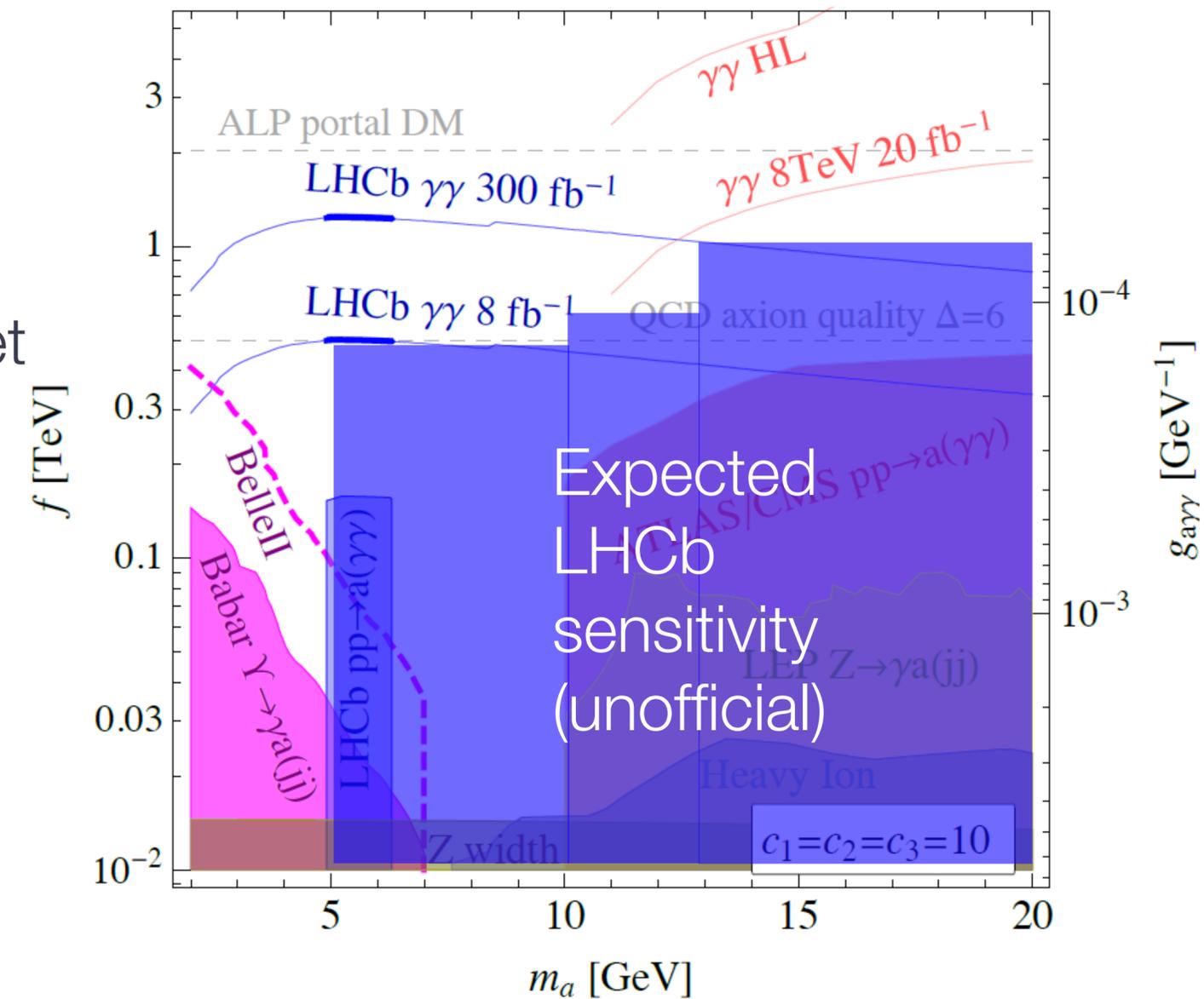
- ALPs produced by gluon fusion decaying to $\gamma\gamma$
- Light ALPs not reachable for ATLAS and CMS
- Current **best limits** in mass gap done with **80 pb⁻¹**
 - Result with the full 2018 dataset coming up VERY soon.
 - We expect to **improve** projected sensitivity
- First LHCb analysis using only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



ALP $\rightarrow \gamma\gamma$

[JHEP 1901 (2019) 113]

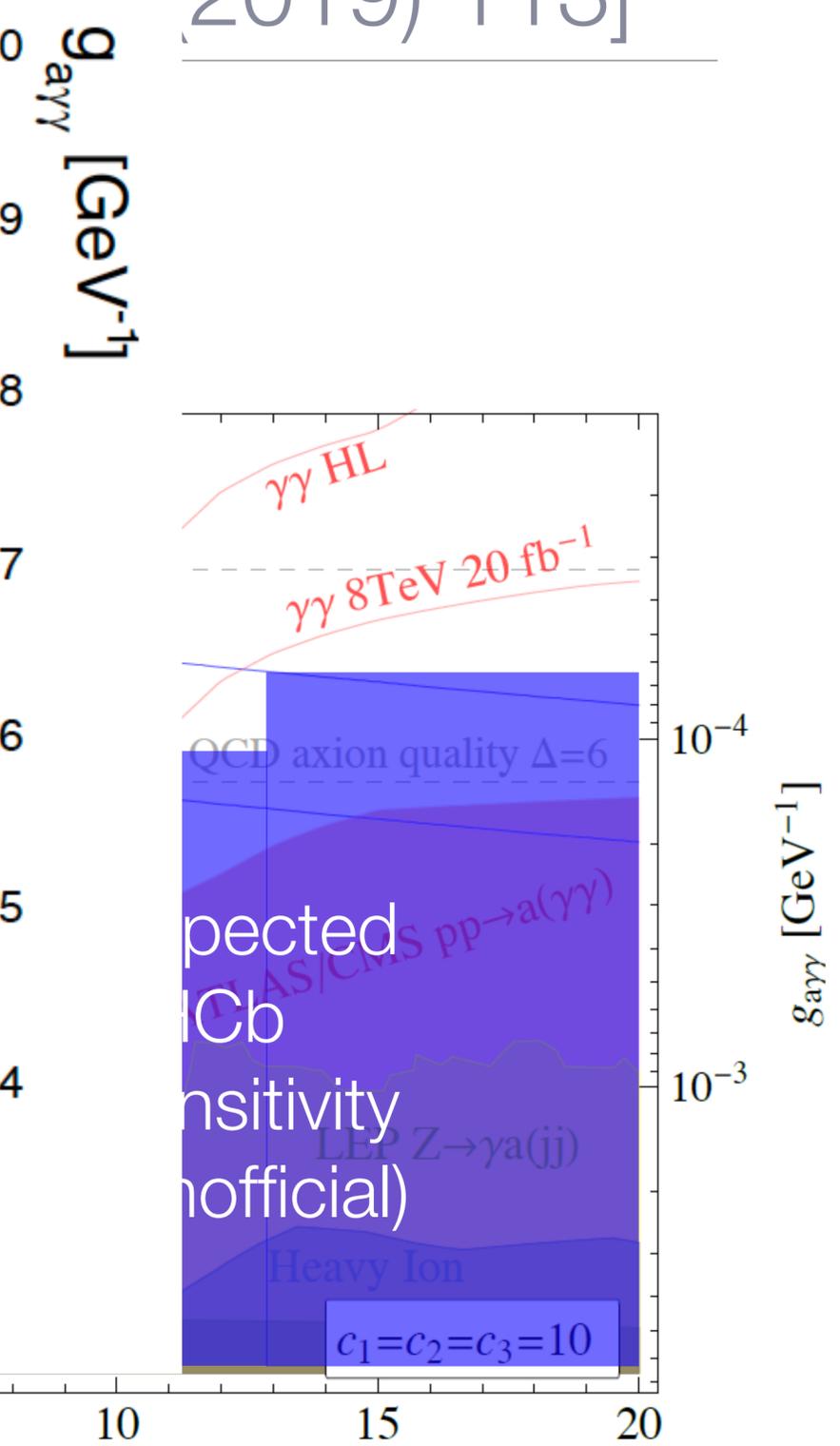
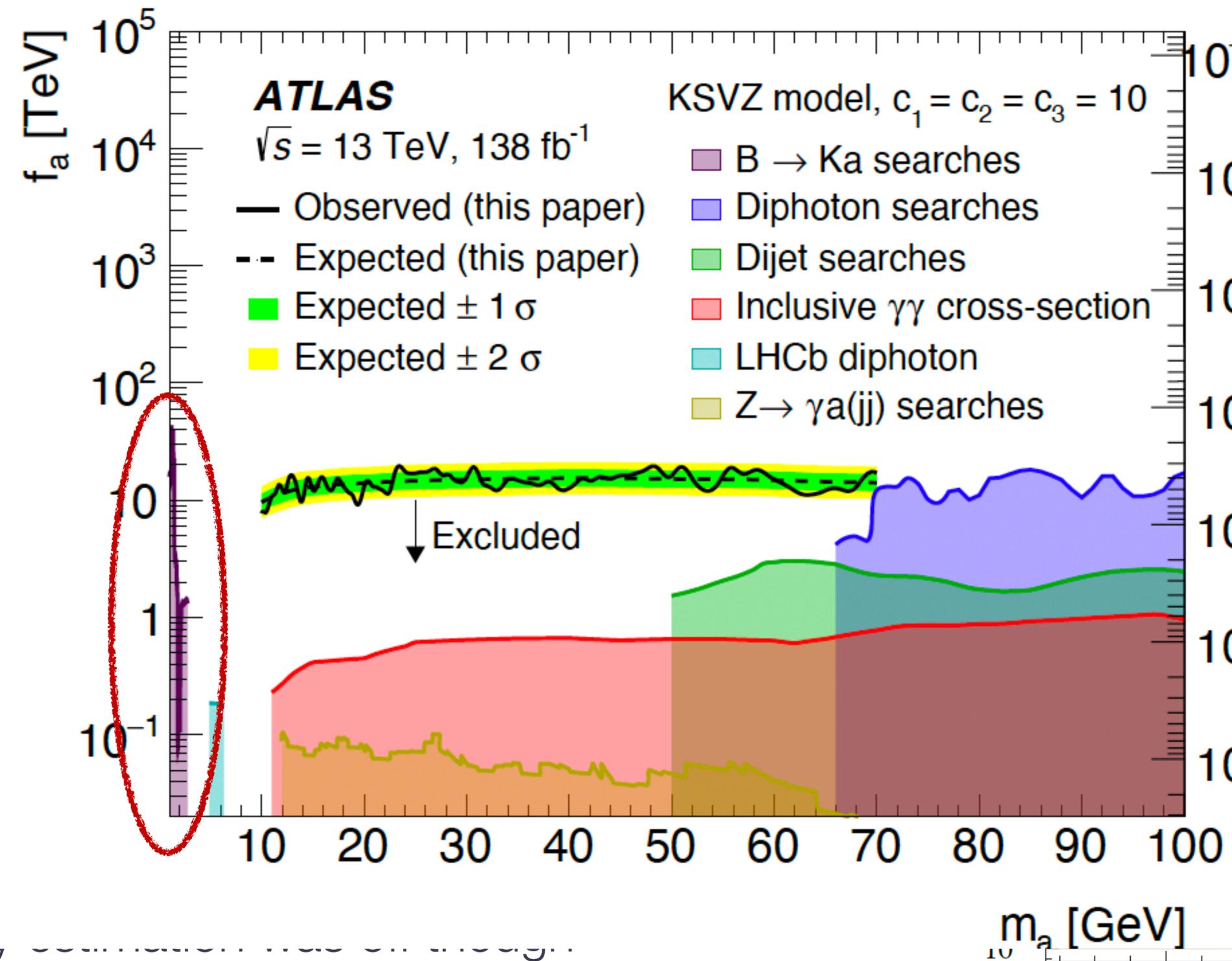
- Major challenges:
 - Unefficient HLT1 with no dedicated ECAL reco
 - ECAL dynamic range penalty: $E_T \lesssim 12 \text{ GeV}$
 - Huge load of $\pi^0 \rightarrow \gamma\gamma$ background
 - Non-negligible amount of material before the magnet
 - $\sim 0.4X_0 \rightarrow 50\%$ of diphotons convert before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



ALP →

[2019) 113]

- Major challenge
- Unefficient
- ECAL dy
- Huge loss
- Non-negligible
- ~ 0 .
- magn
- Resolution
- Improvement
- Major background
- Efficiency



- **ATLAS updated their result**
- **Belle II can improve BaBar limits on the lower mass region**

Take home

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

BACKUP

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

- **Event selection:**

- Hardware trigger stage:
 - $p_T(\mu) > 1.8 \text{ GeV} \parallel p_T(\mu_1)p_T(\mu_2) > 1.5 \text{ (GeV)}^2$
- Software trigger stage:
 - MuonID criteria
 - Good quality vertex
- Offline:
 - Dimuon isolation strategy
- Long-lived (prompt) search:
 - $p_T(\mu) > 0.5 \text{ (1.0) GeV}$
 - $p(\mu) > 10 \text{ (20) GeV}$
 - Inconsistency (consistency) with origin at the PV

- **Prompt search misRECO backgrounds:**

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

- **Displaced search backgrounds:**

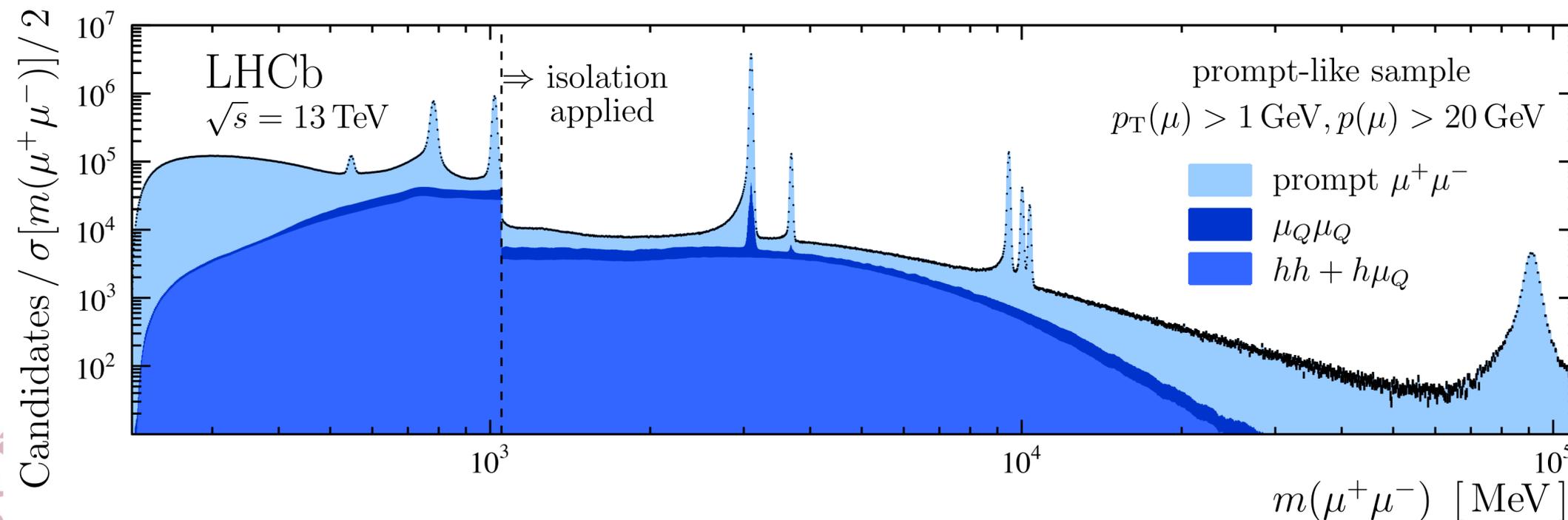
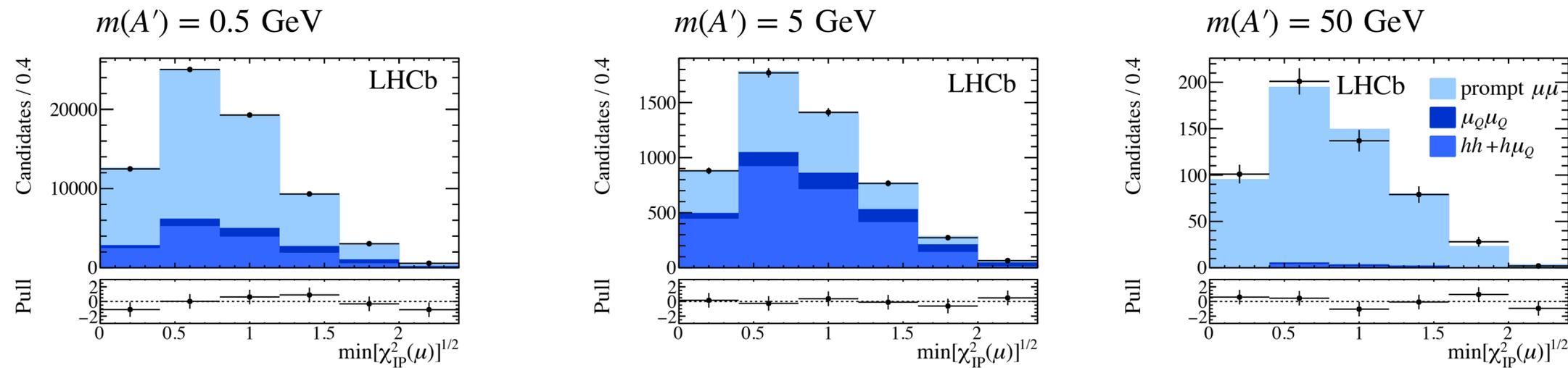
- Photon conversions to $\mu^+\mu^-$ in the VELO (matter veto strategy in the back-up)
- b-hadron decays with two muons produced in the decay chain
- Low mass tail from $K_s^0 \rightarrow \pi^+\pi^-$ where both pions misidentified as muons

Dark Photons: prompt search

[PRL (2020) 124 041801]

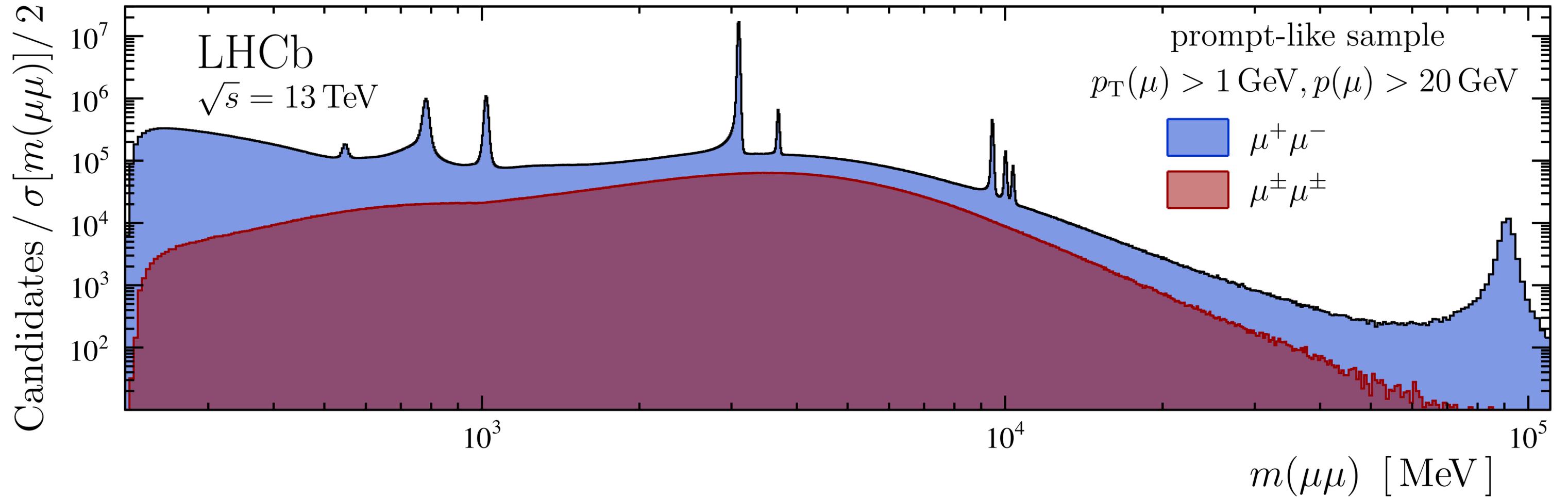
Using templates
for $\min[\chi_{IP}^2]$ and χ_{VF}^2
(small mass dependence)

- | | | |
|---|---------------------|---------------------------------------|
|  | 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) |



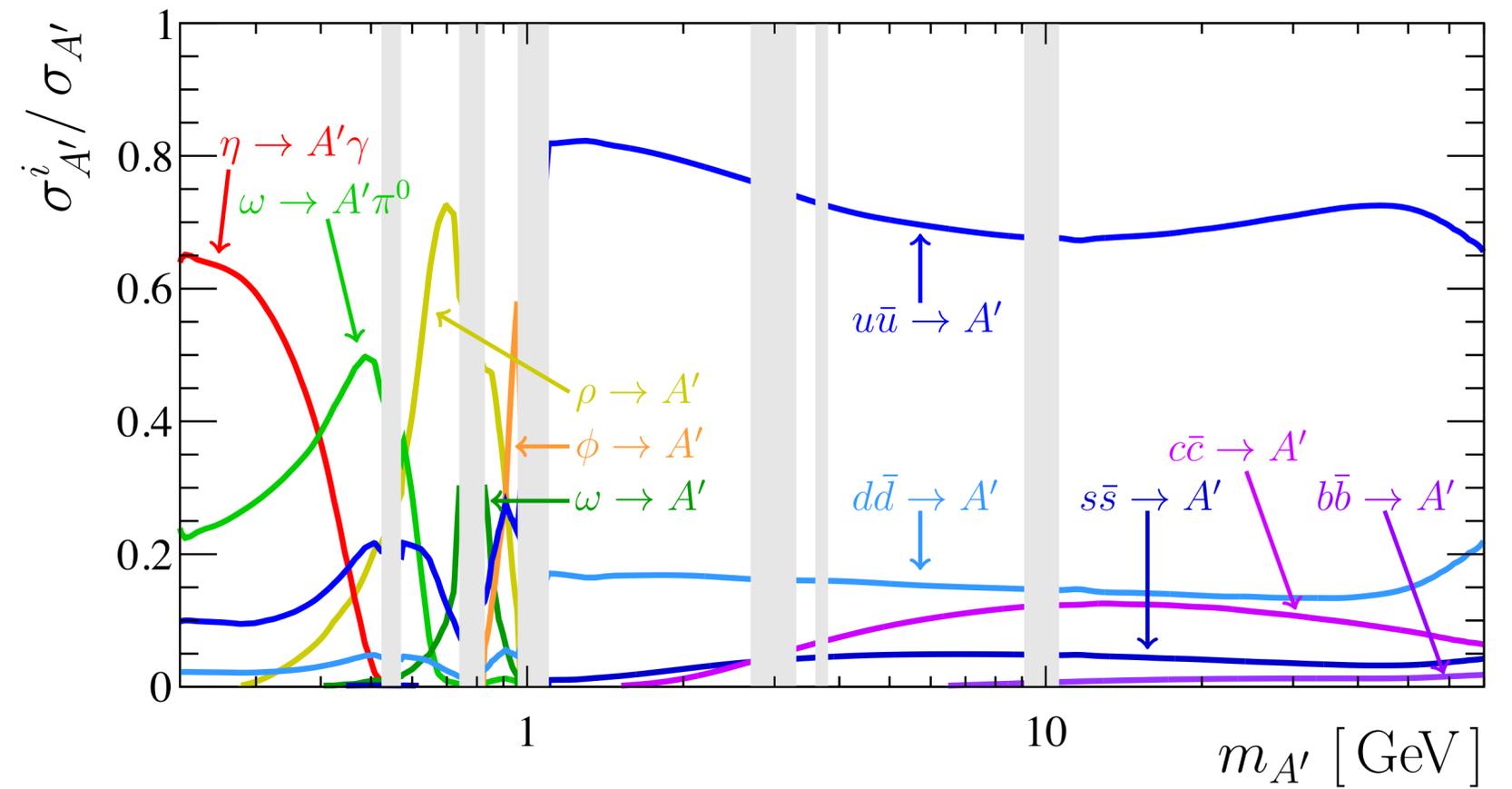
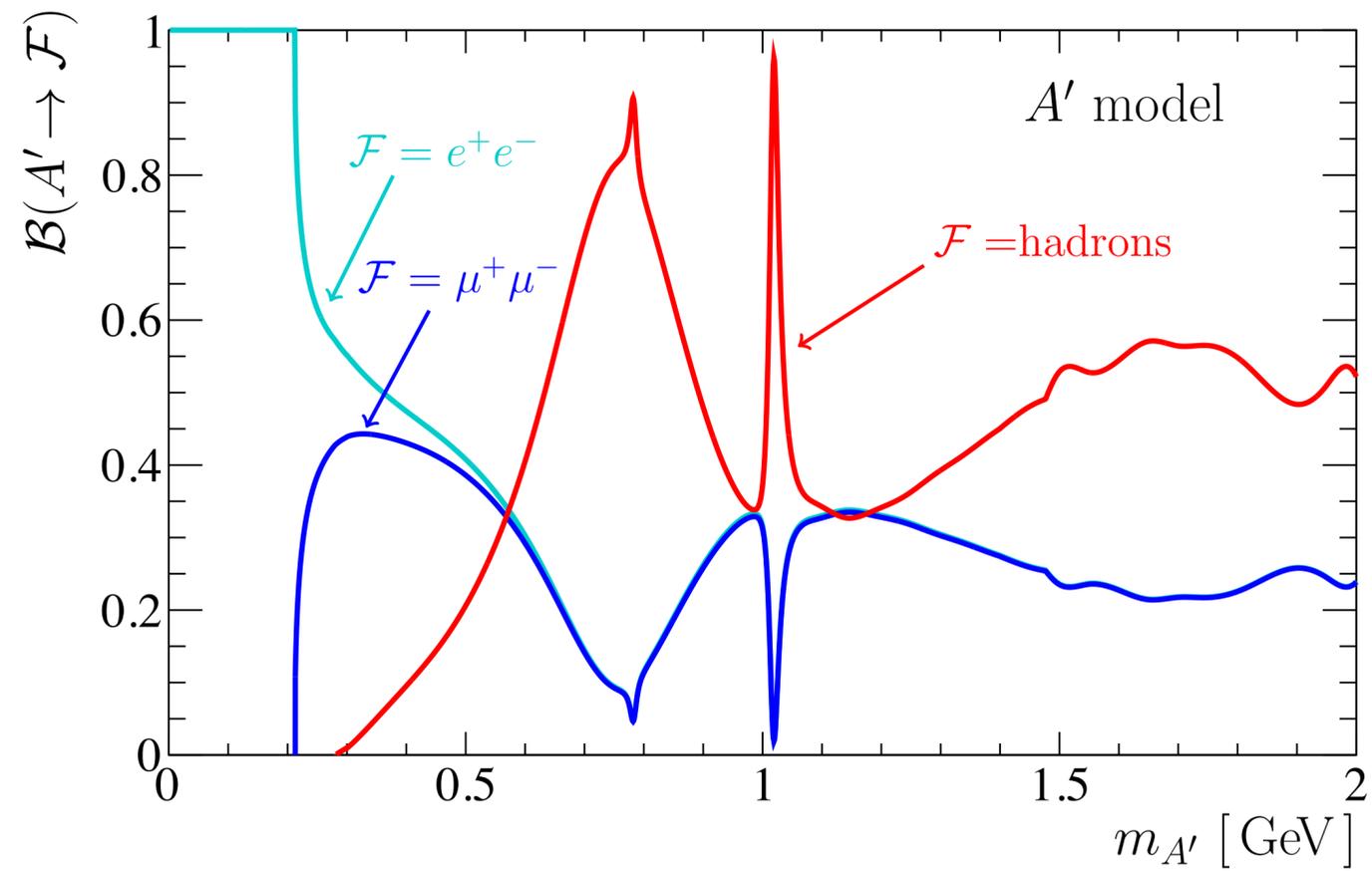
Dark Photons: prompt search

[PRL 120 (2018) 6, 061801]

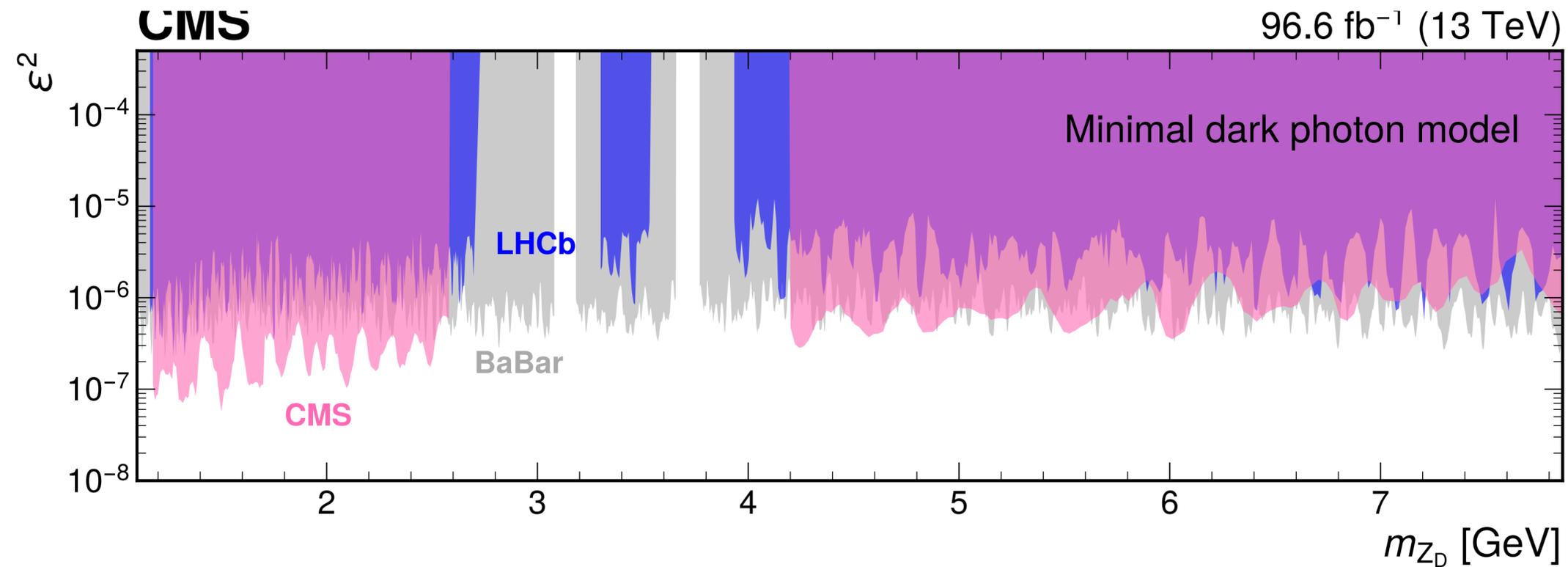
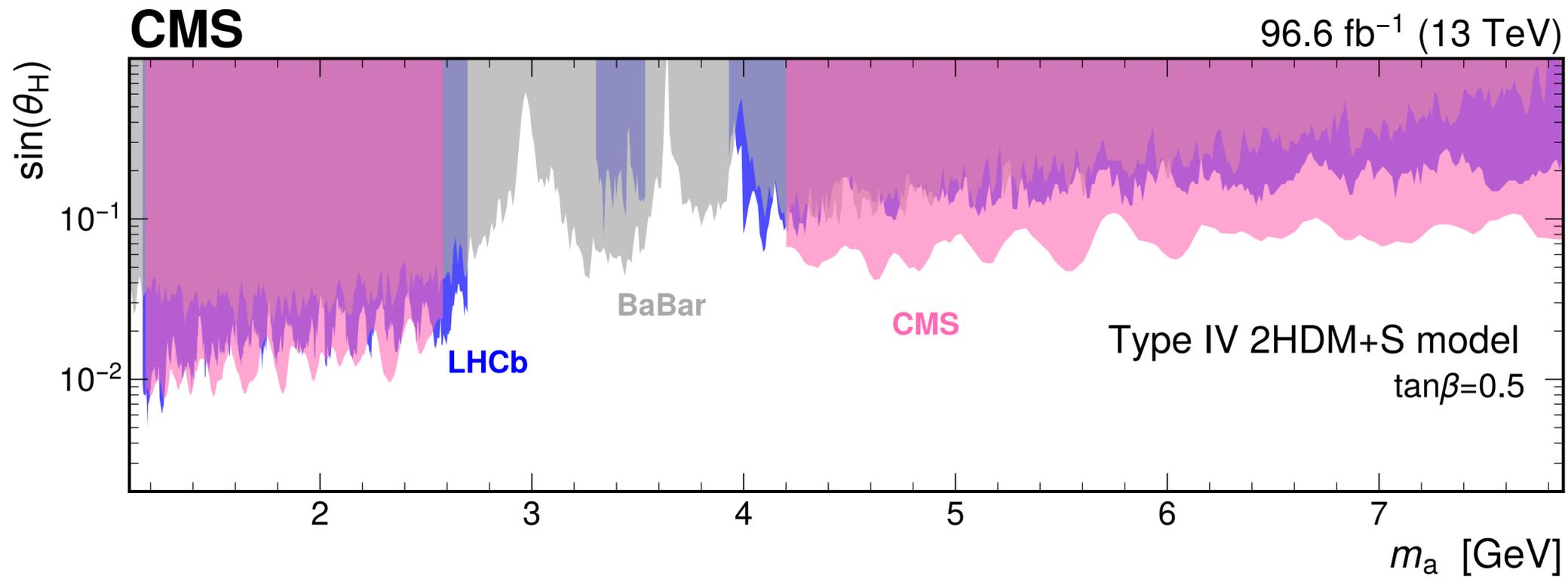


Dark Photons

[JHEP 06 (2018) 004]

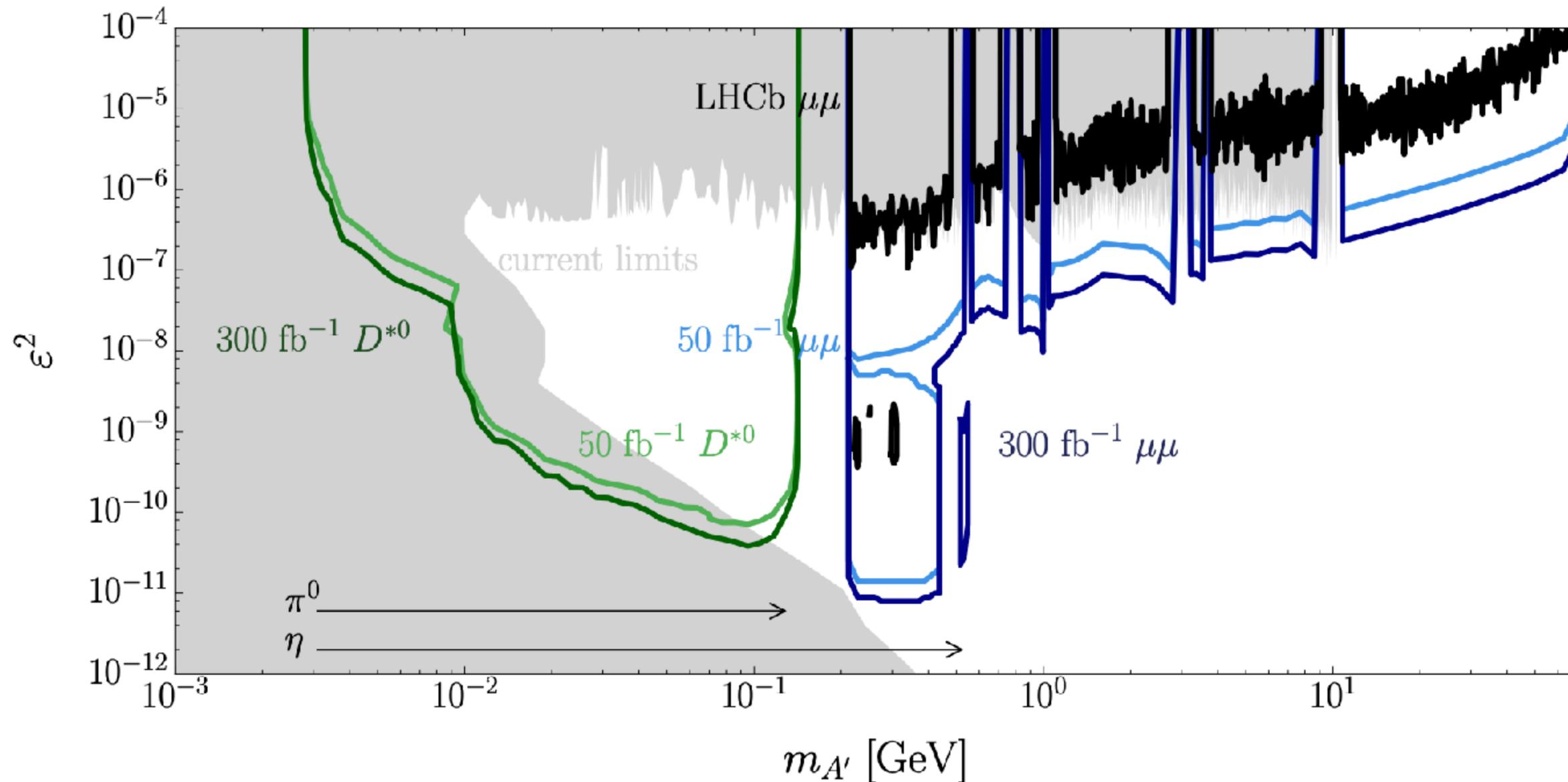


Dark Photons: latest updates from CMS

[\[JHEP 12 \(2023\) 070\]](#)

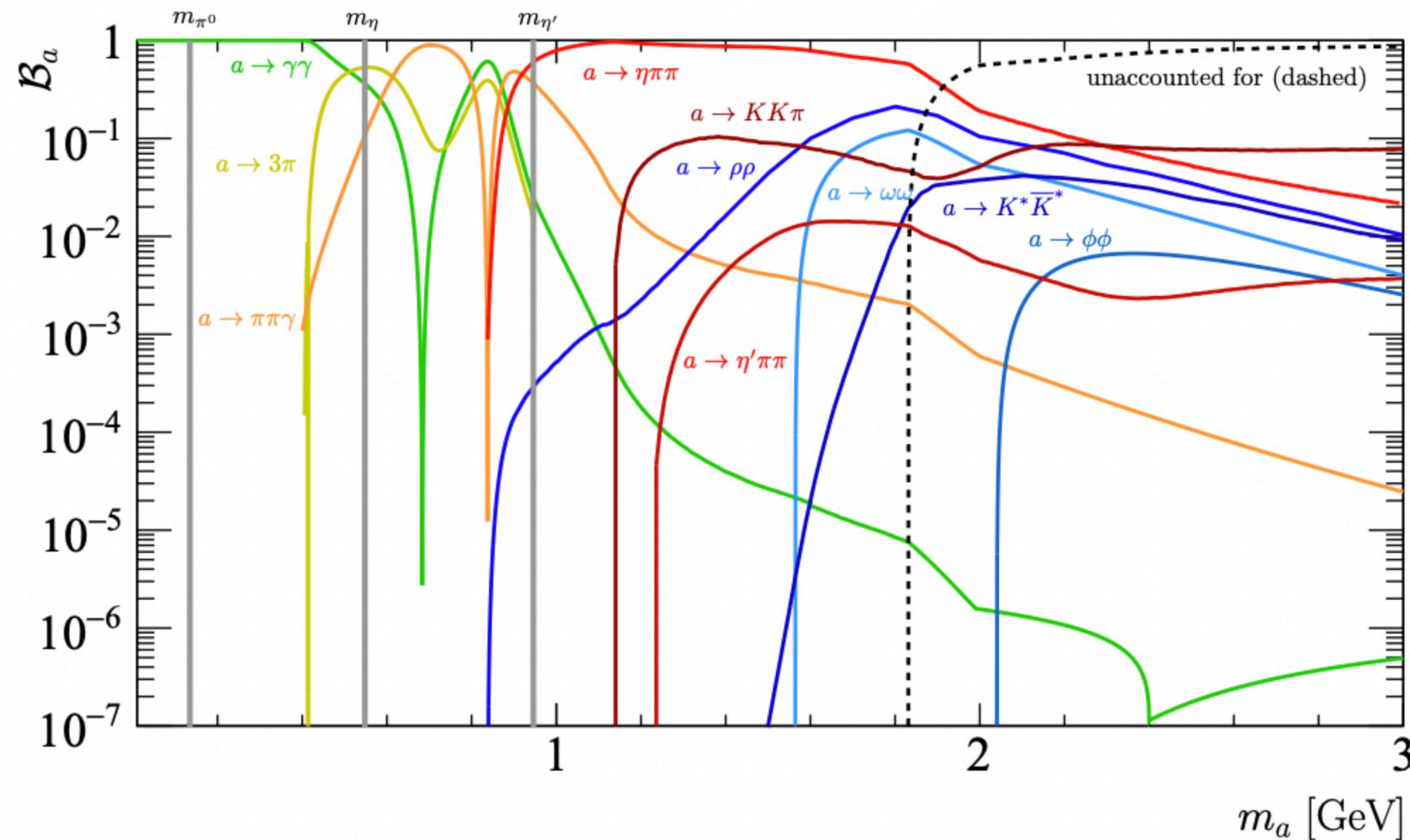
Dark Photons: Run 3

[2203.07048]



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

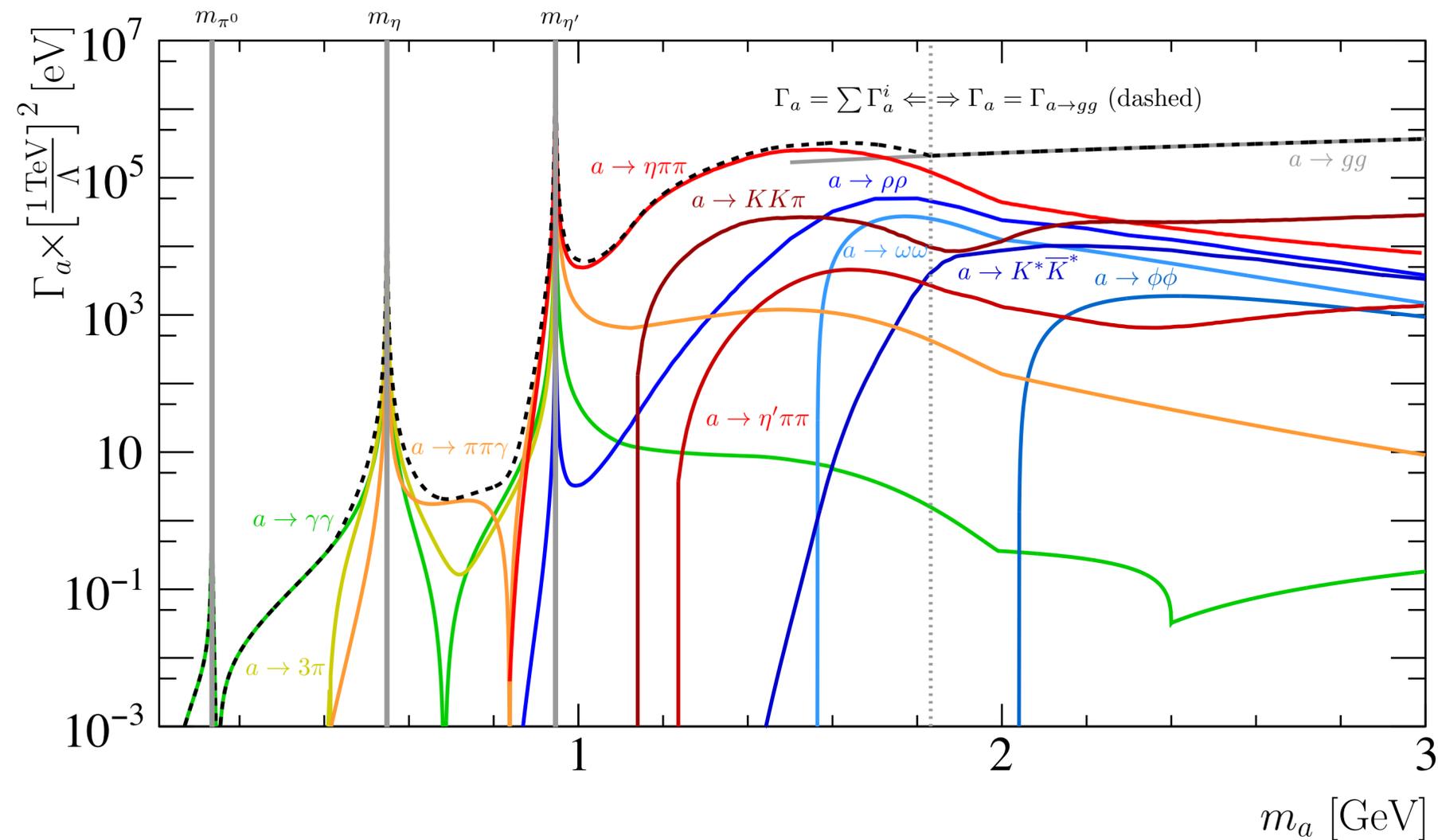
ALPs coupled to gluons

[PRL (2019) 123 031803]

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

ALPs coupled to gluons

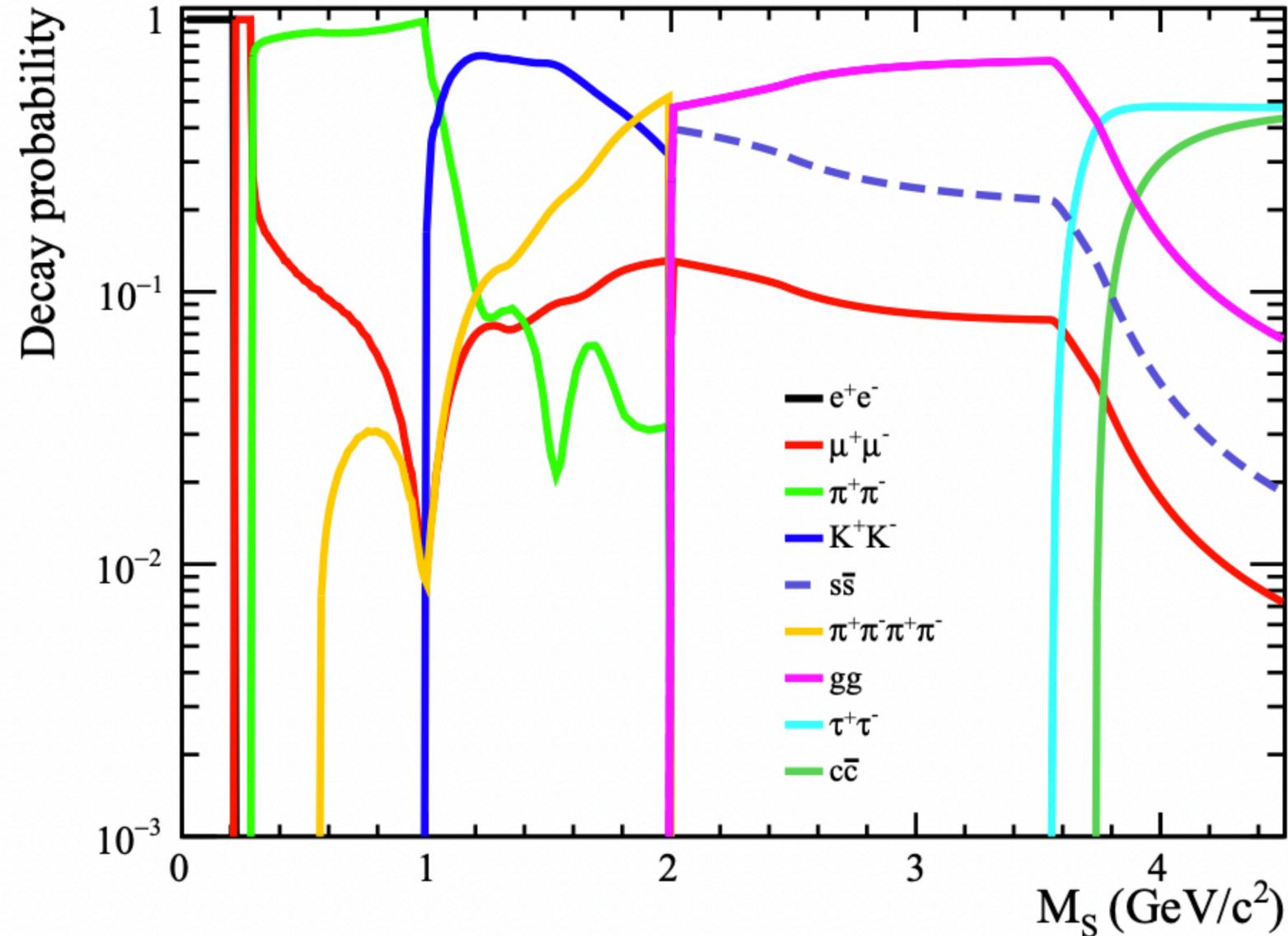
[PRL (2019) 123 031803]



- Similar to HP:
 - Enhancement for $B \rightarrow K^{(*)}a$ decays
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 - $a \rightarrow \pi^+\pi^-\pi^0$
- Current limits:
 - BaBar recast of η and η' spectra
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Coming up next: Higgs portal

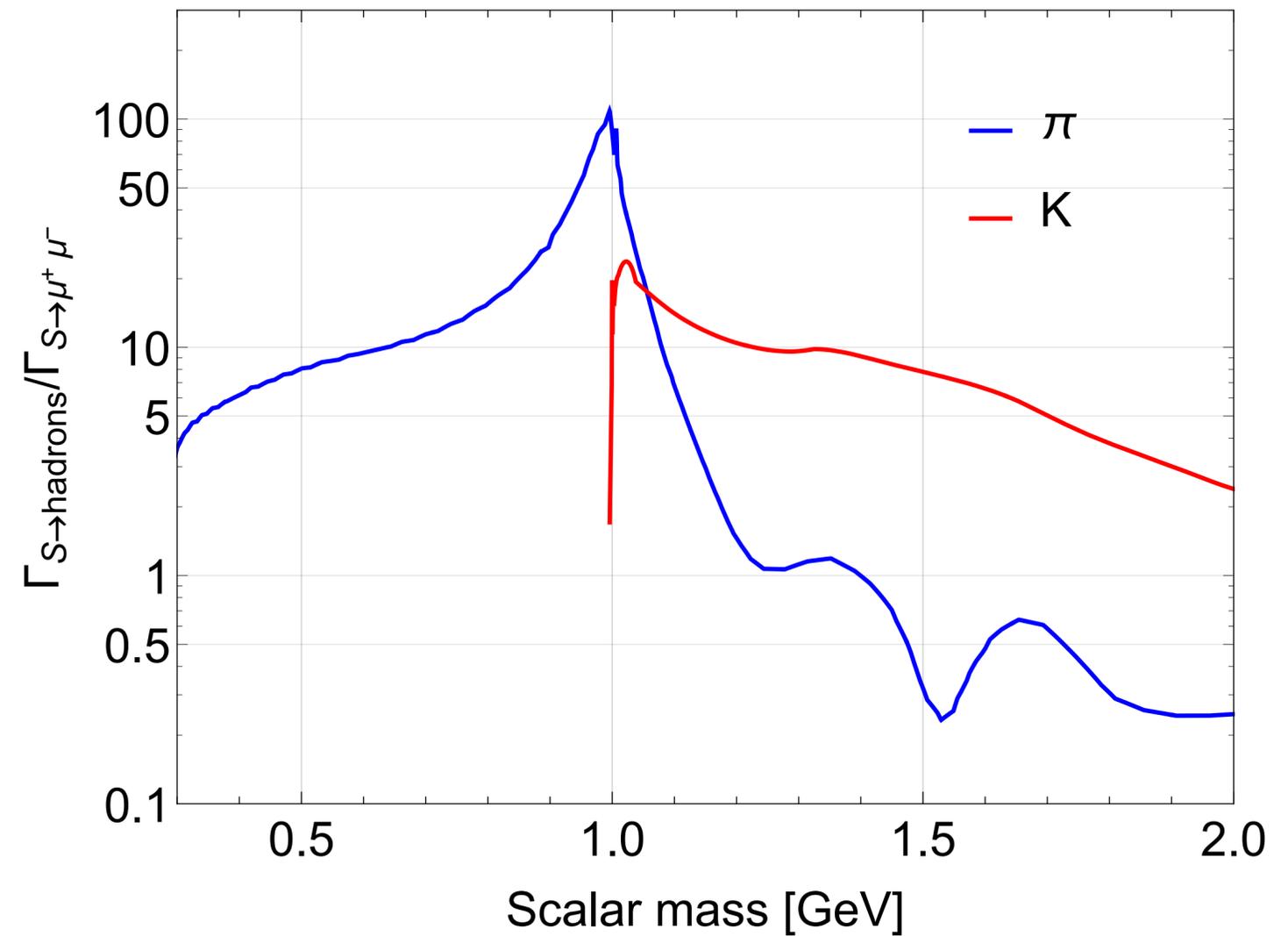
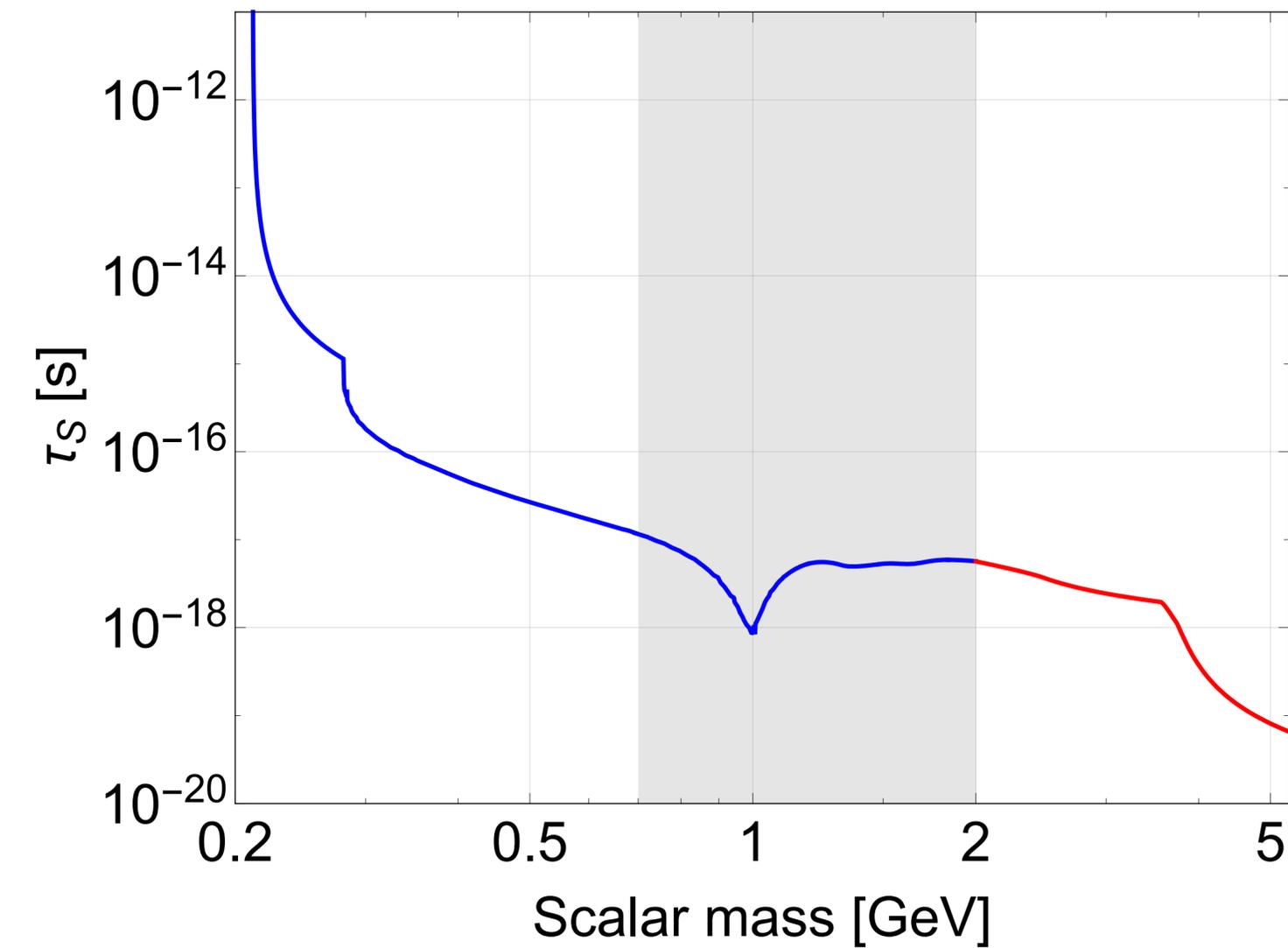
[JHEP 11 (2019) 162]



- Dark scalar coupling to the Higgs via mixing angle: θ
- $B^0 \rightarrow K^*\chi$ 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

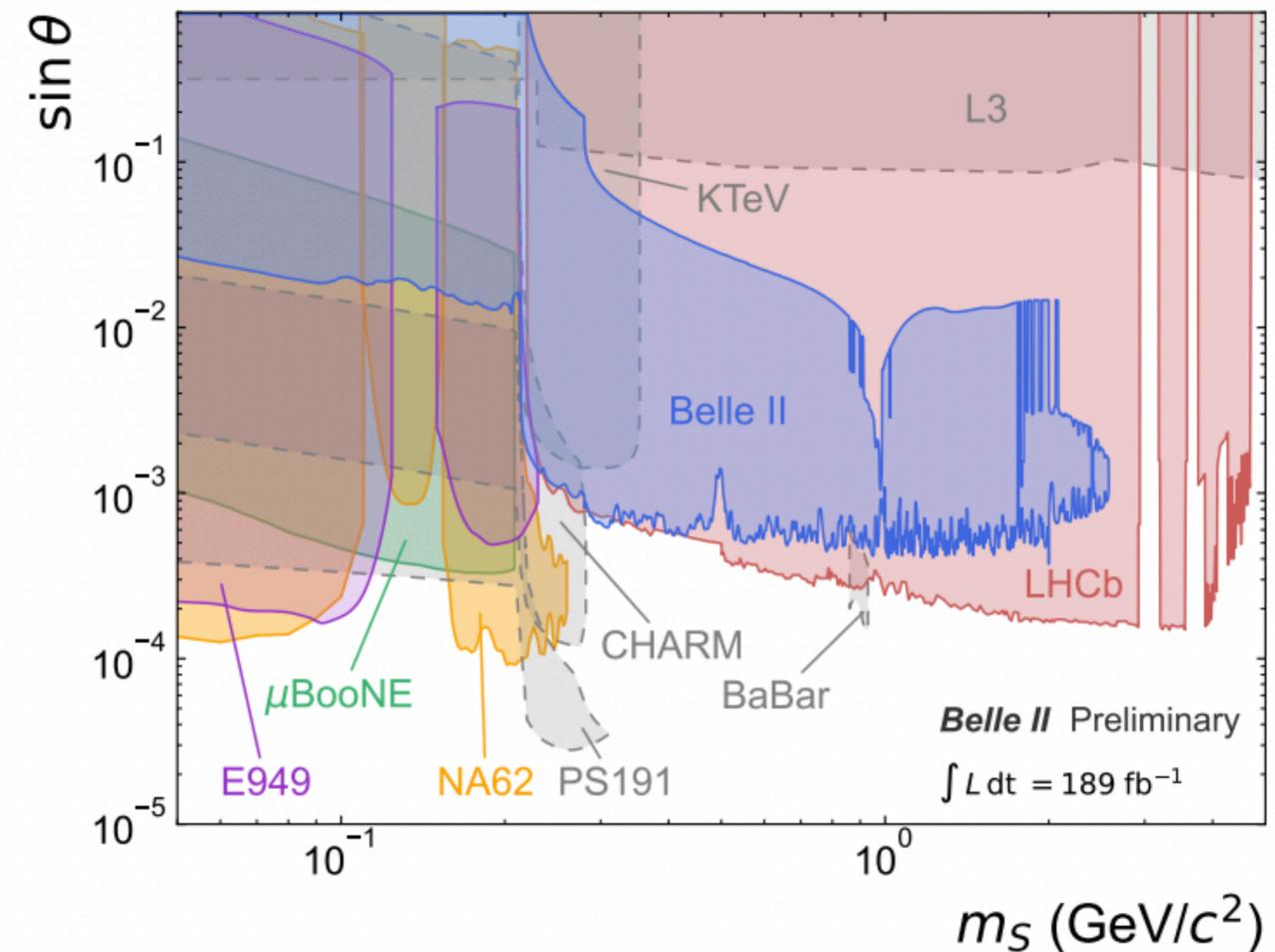
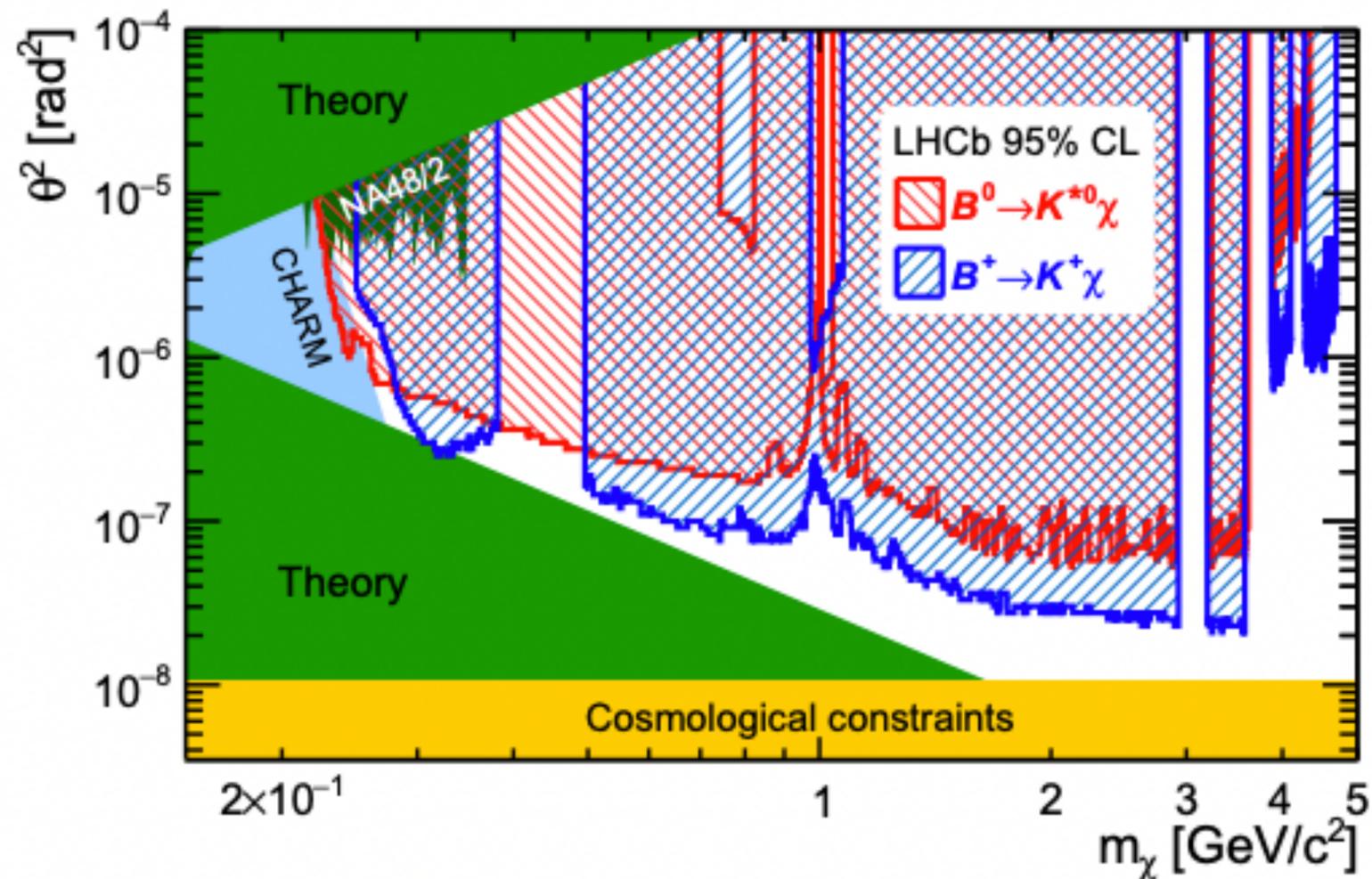
[JHEP 11 (2019) 162]



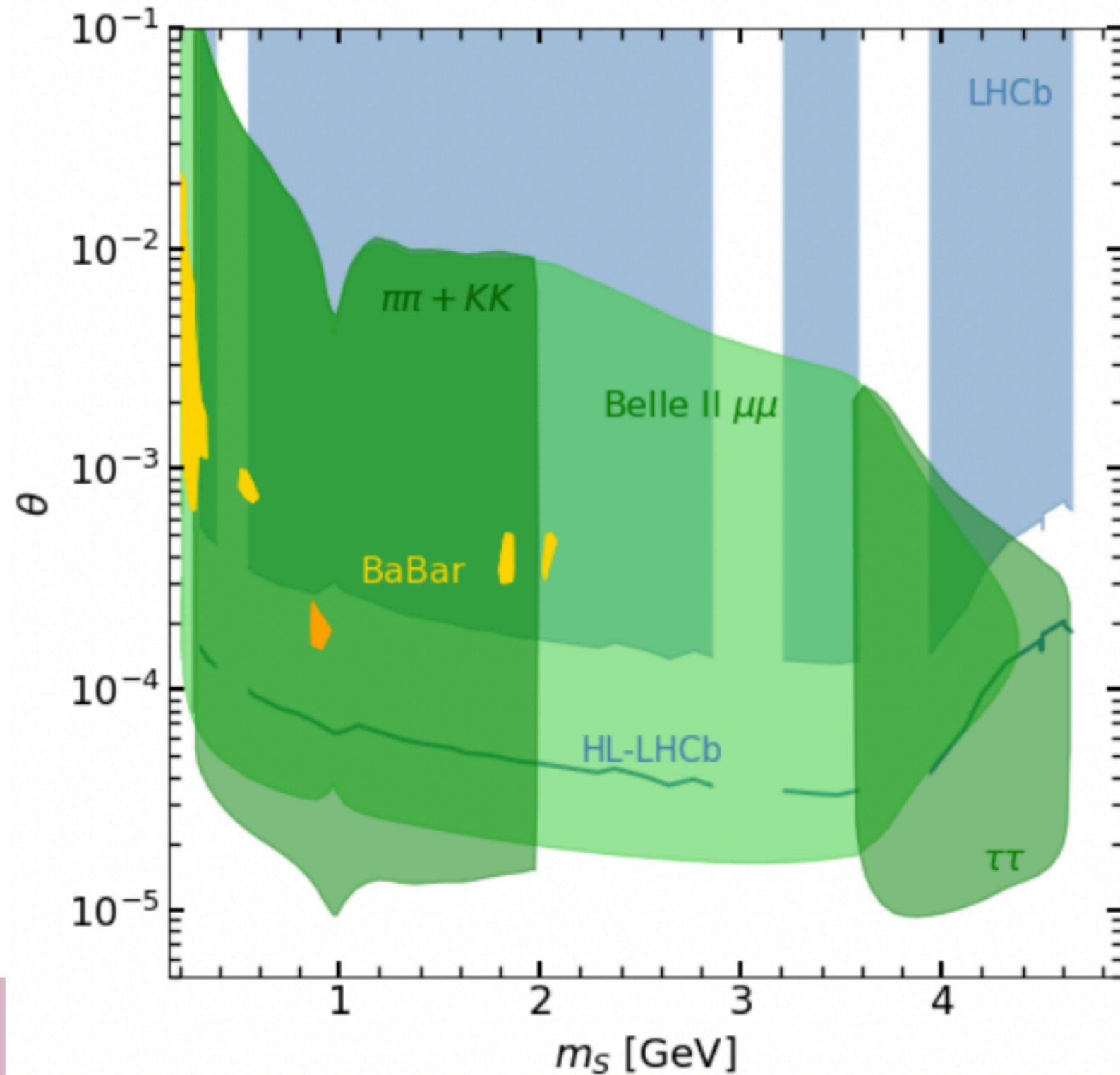
Higgs portal: The Run 1 result

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

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



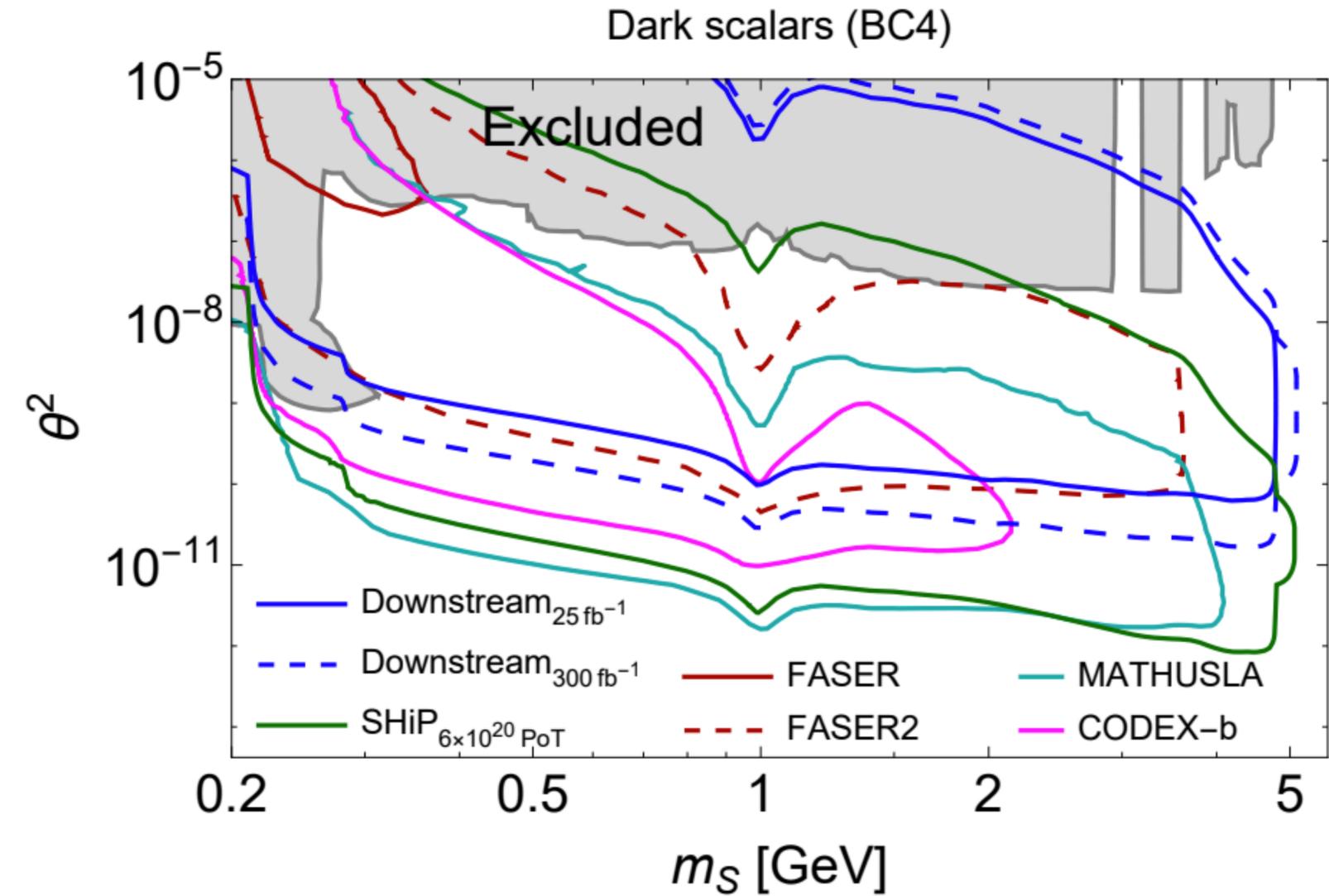
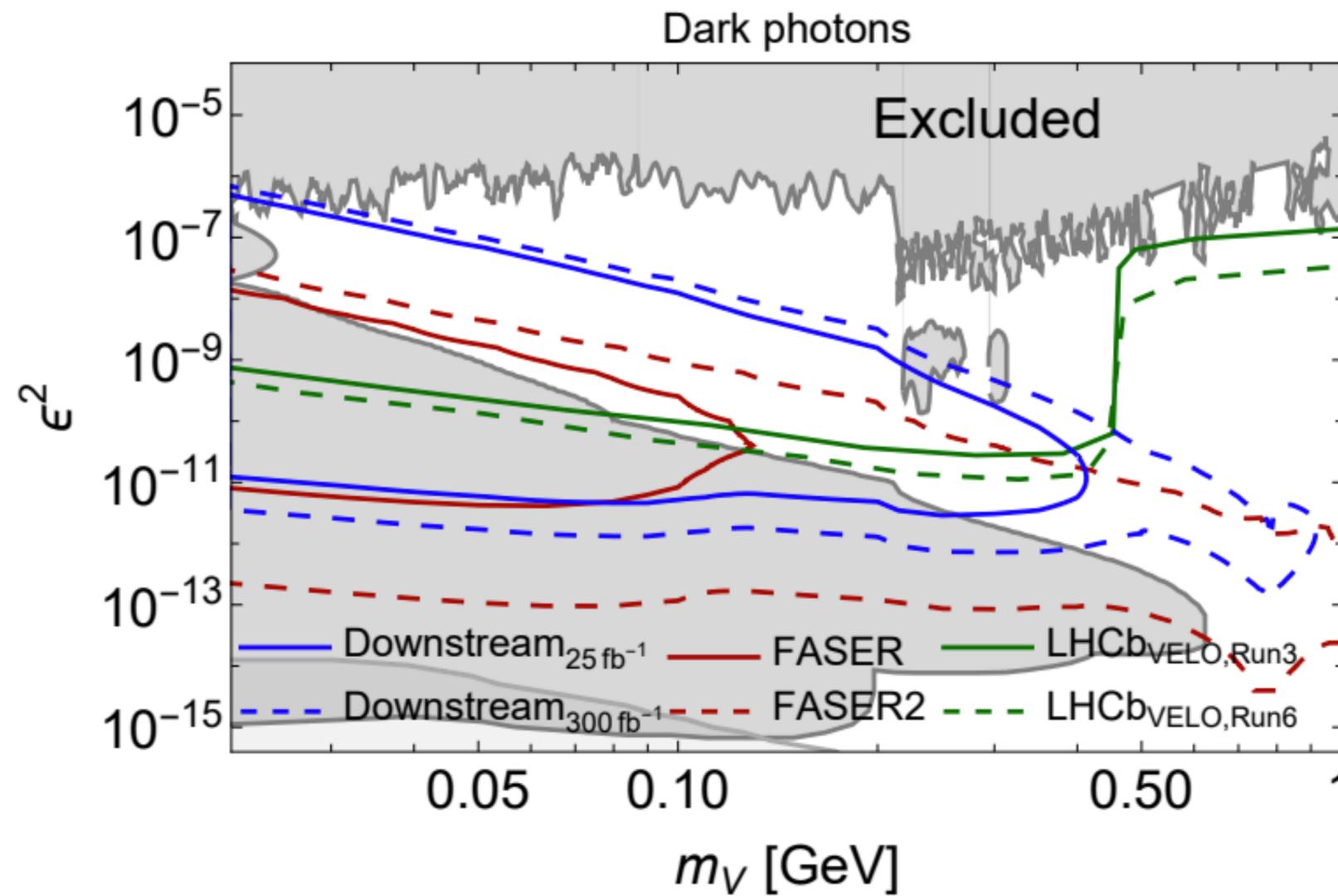
Coming up next: Higgs portal [\[PRD 101 \(2020\) 9, 095006\]](#)



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

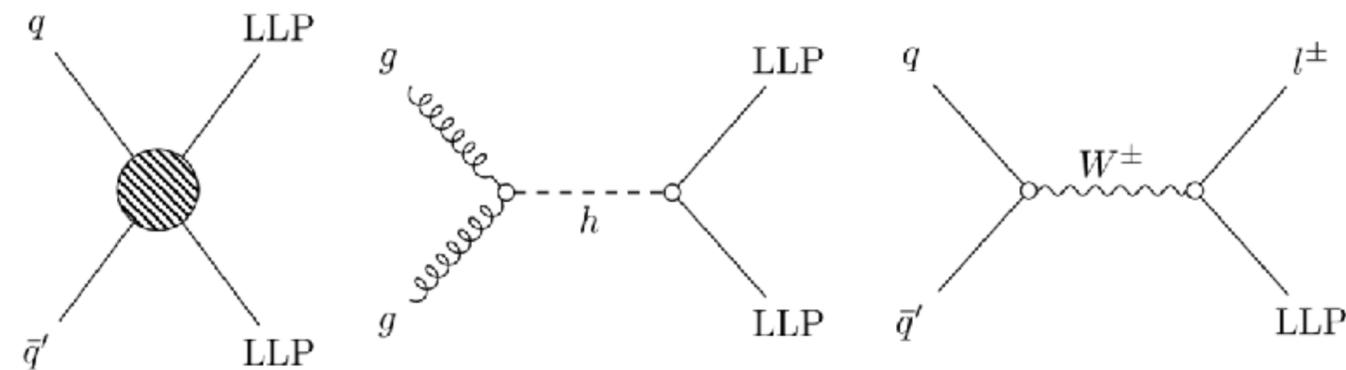
Dark Scalar: Downstream tracks

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



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

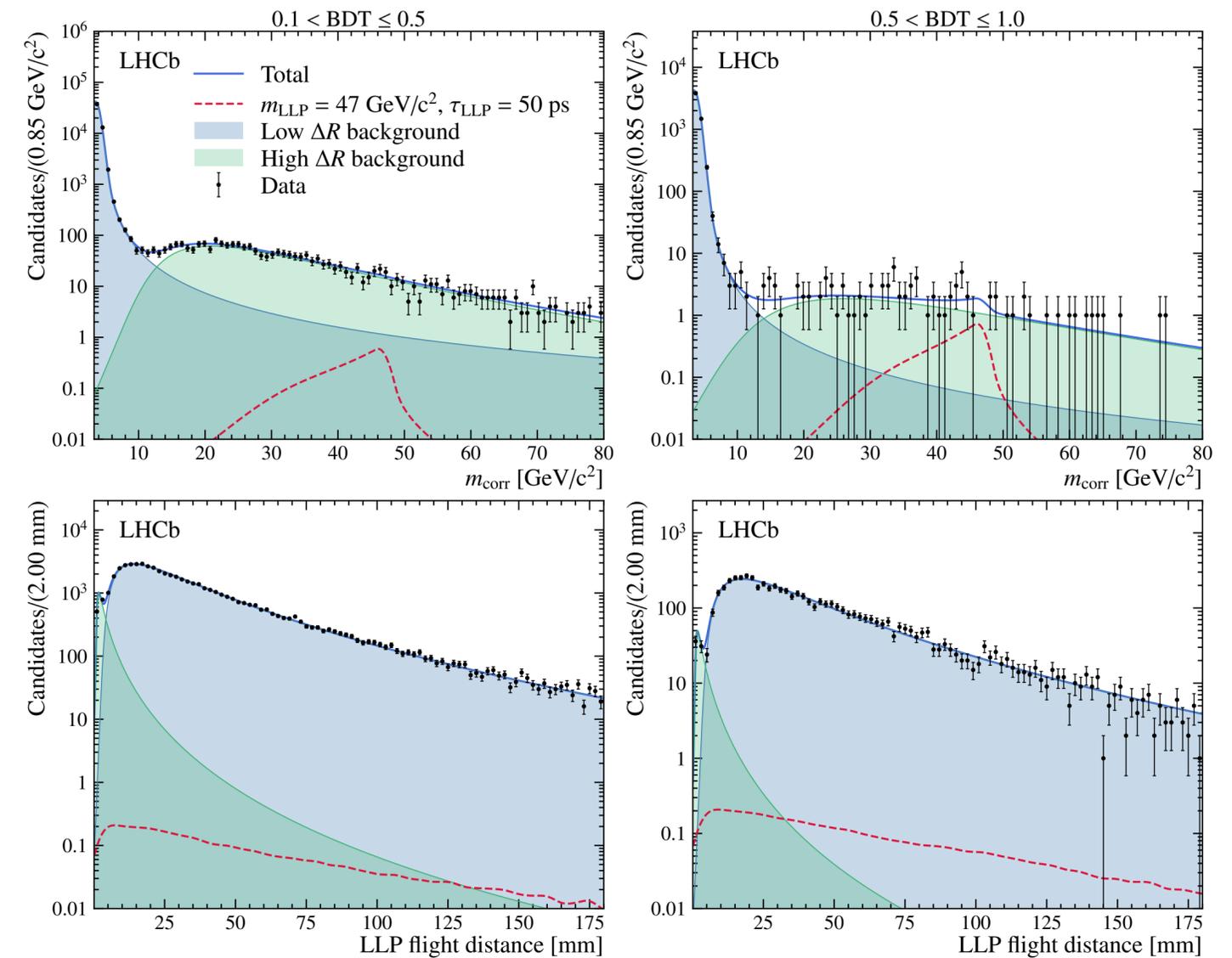
- Massive particles with with long lifetimes in BSM models:
 - Direct pair production (DPP)
 - Higgs decay (HIG)
 - Charged currents (CC)
- Results of this analysis can be interpreted as:
 - Neutralino $\tilde{\chi}_0^1$ in R-parity-violating SSM
 - Right-handed neutrino N
- Dataset: 5.38 fb^{-1} of run 2 data (2016-2018) at $\sqrt{s}=13 \text{ TeV}$
- Parameter space searched in:
 - $m \in [7,50] \text{ GeV}$
 - $\tau \in [2,50] \text{ ps}$



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

Signal yield:

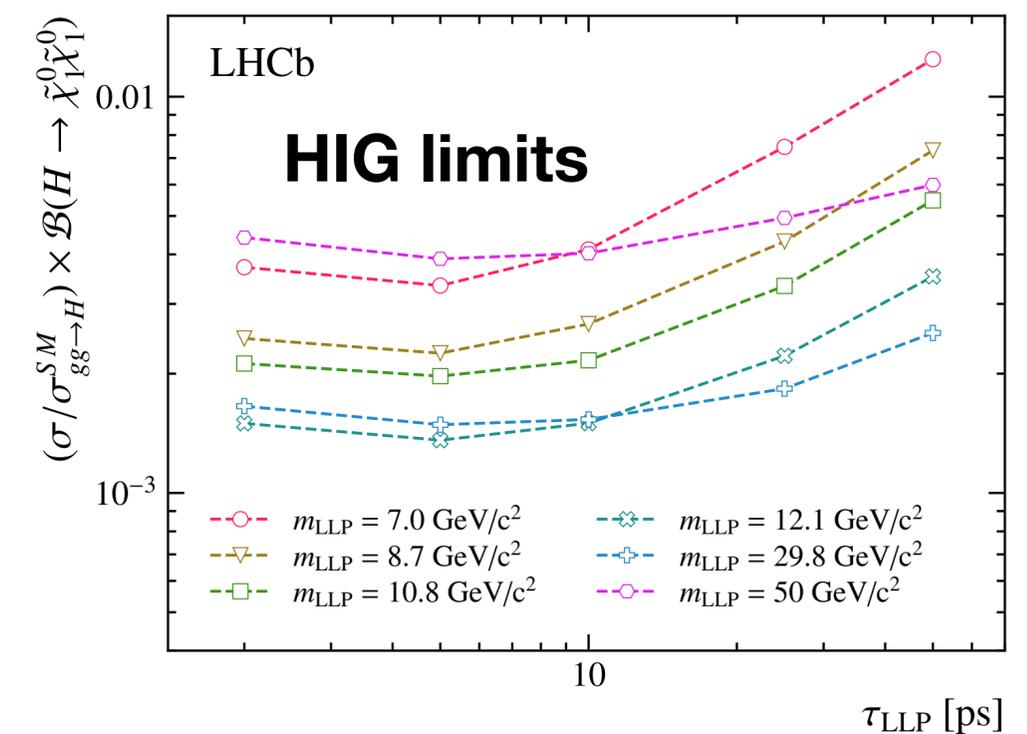
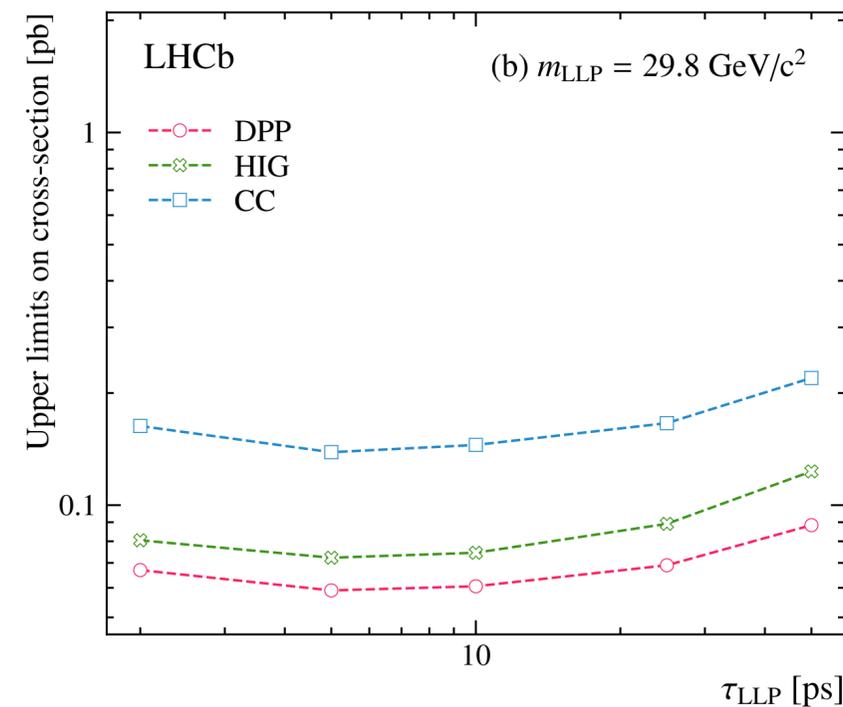
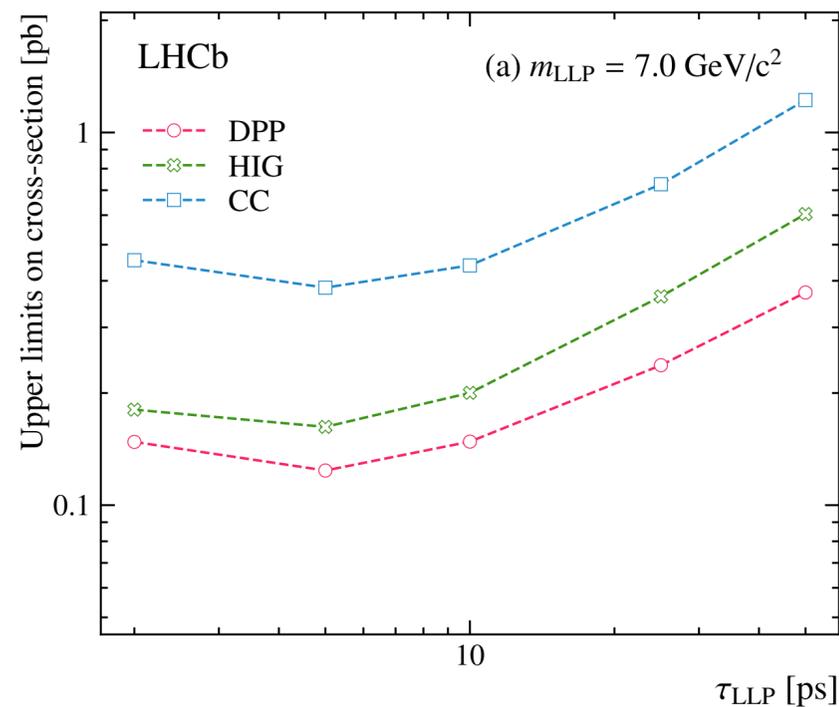
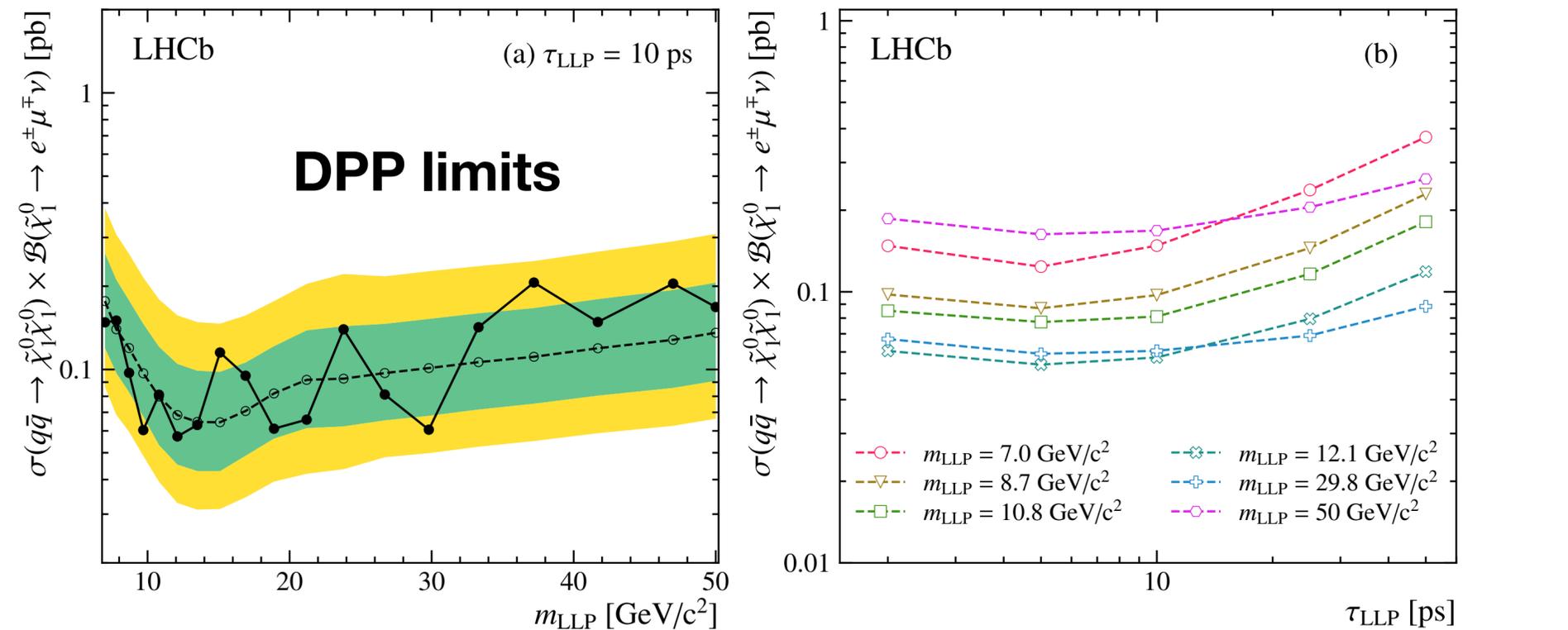
- Two components of $b\bar{b} \rightarrow e^\pm \mu^\mp X$ background
 - $\Delta R < 1$: short flight distance
 - $\Delta R > 1$: long flight distance
- Simultaneous maximum likelihood fit:
 - Corrected mass and flight distance
 - Background PDF parameters free
 - Signal PDF parameters fixed from simulation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



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

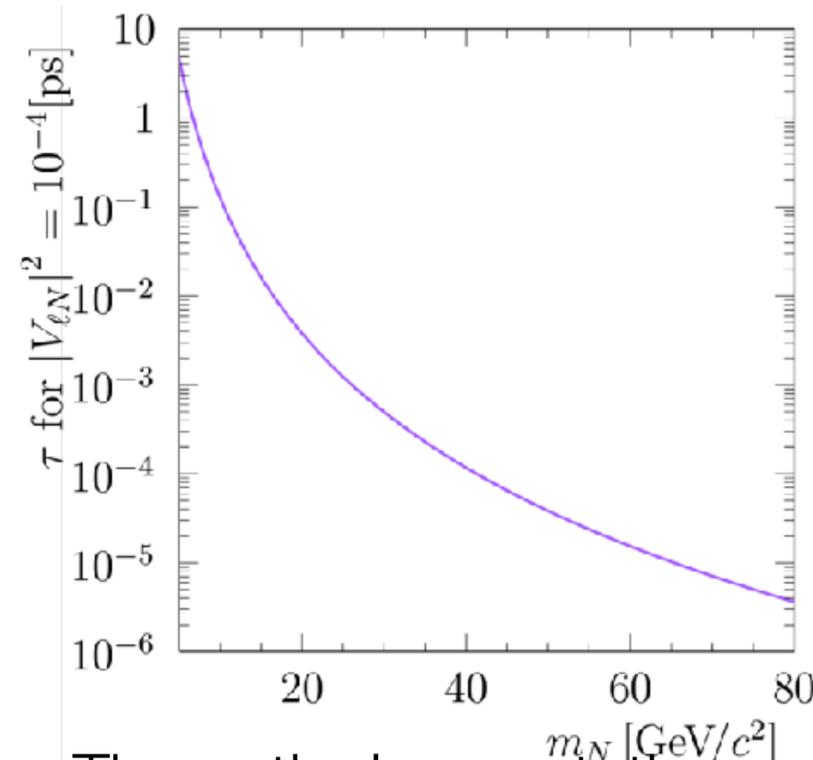
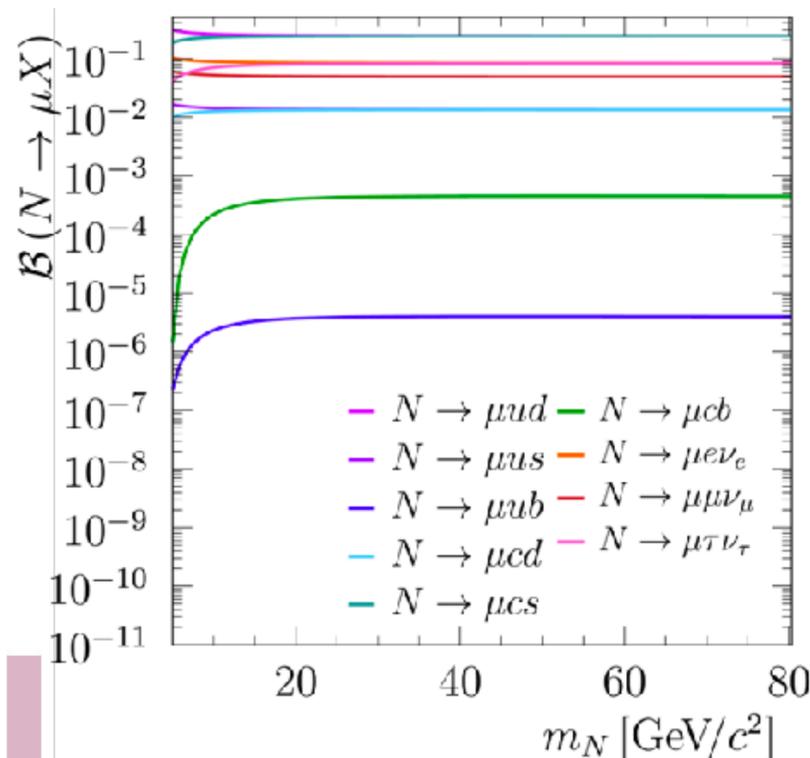
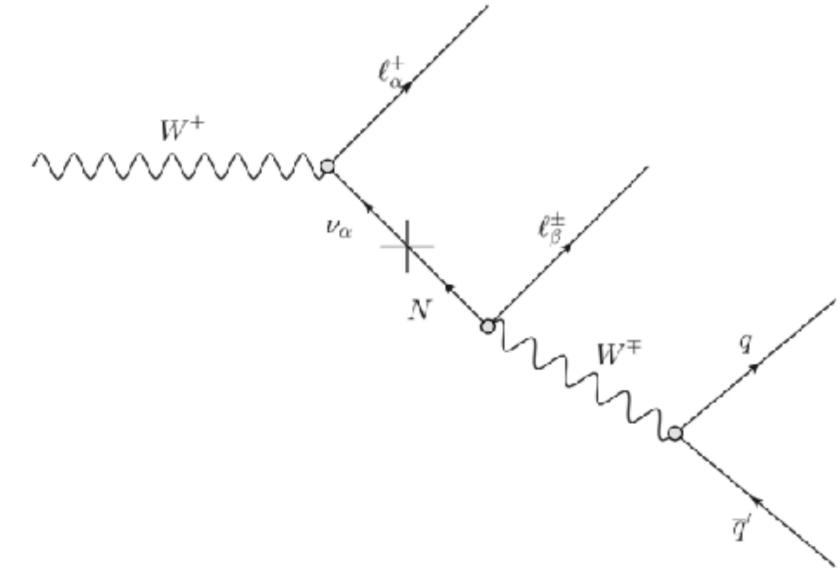
Results

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



HNL searches in $W^+ \rightarrow \mu^+ \mu^\pm jet$ [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 $N \rightarrow \mu^\pm q \bar{q}'$ decay
 - Both same-sign and different-sign muons final state
 - This allows HNL to have Majorana nature !



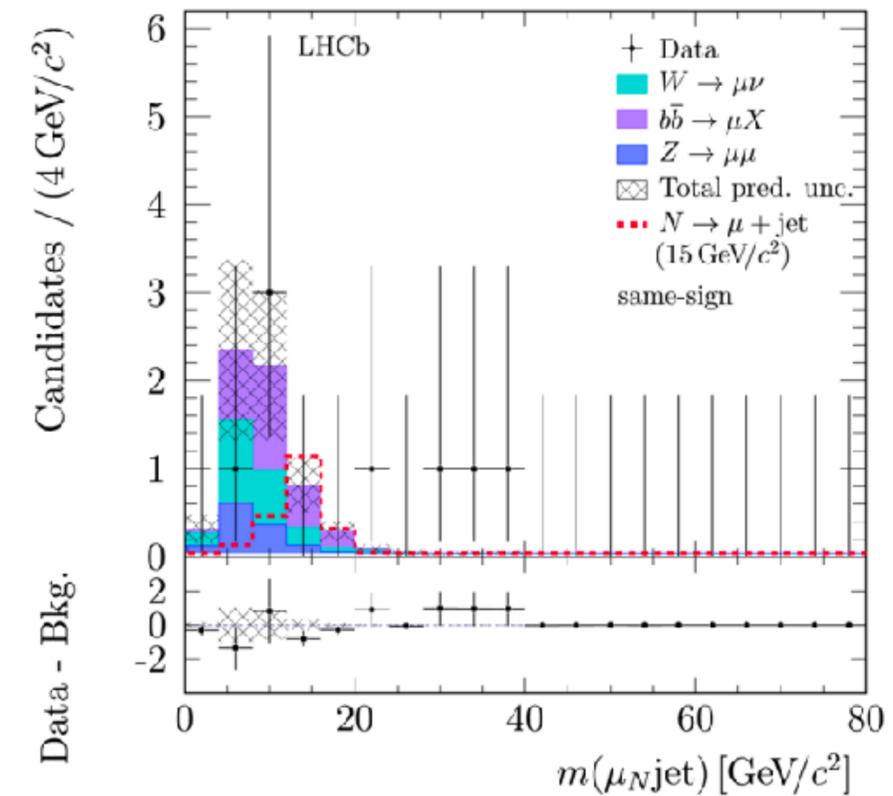
- Dataset: 3.0 fb^{-1} of run 1 data (2011-2012) at $\sqrt{s}=7,8 \text{ TeV}$
- Parameter space searched in:
 - $m \in [5,50] \text{ GeV}$
 - HNLs typically prompt in the mass window

- Theoretical expectation

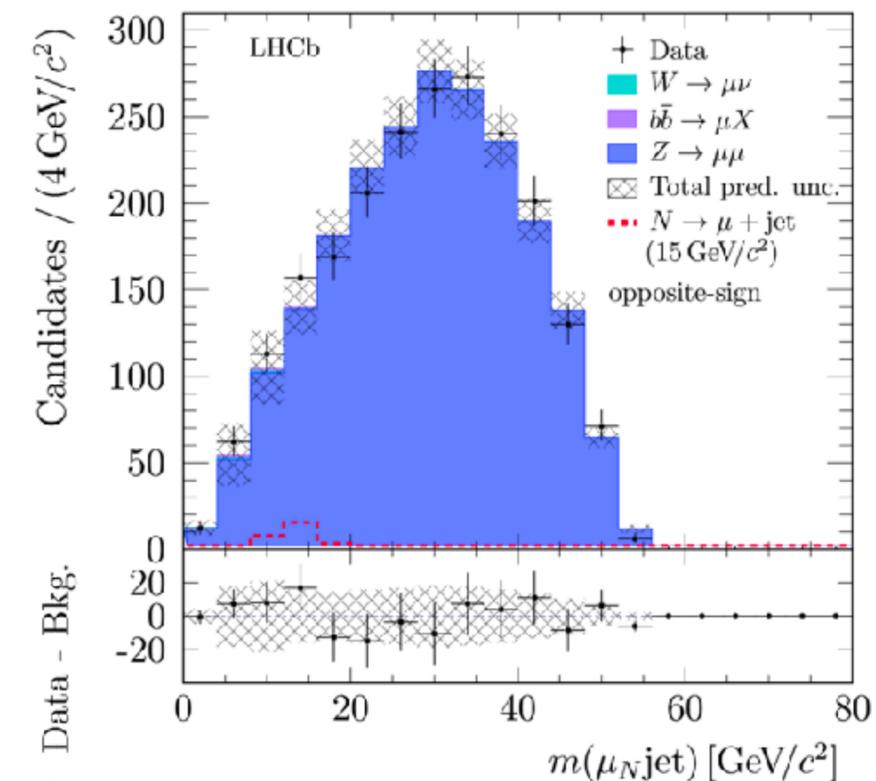
HNL searches in $W^+ \rightarrow \mu^+ \mu^\pm jet$ [Eur. Phys. J. C **81**, 248 (2021)]

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

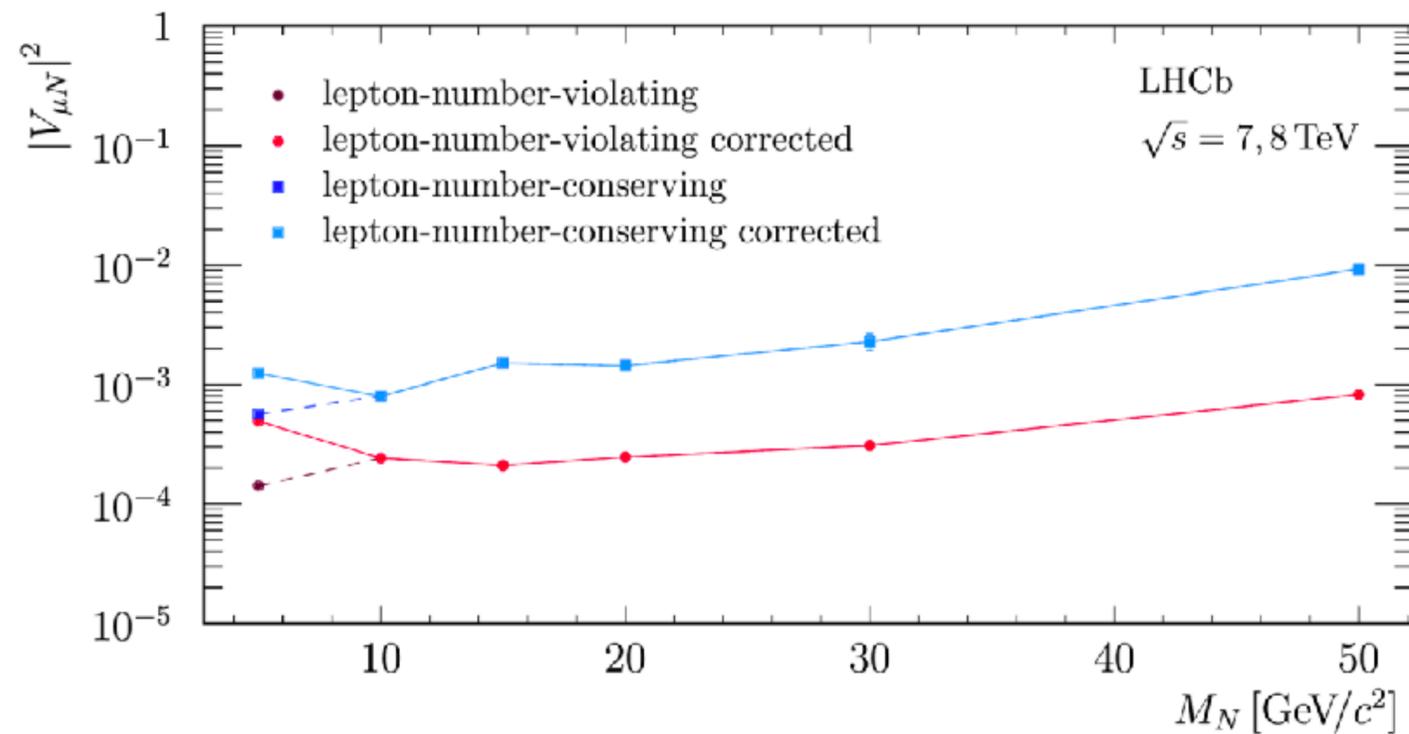


Opposite sign

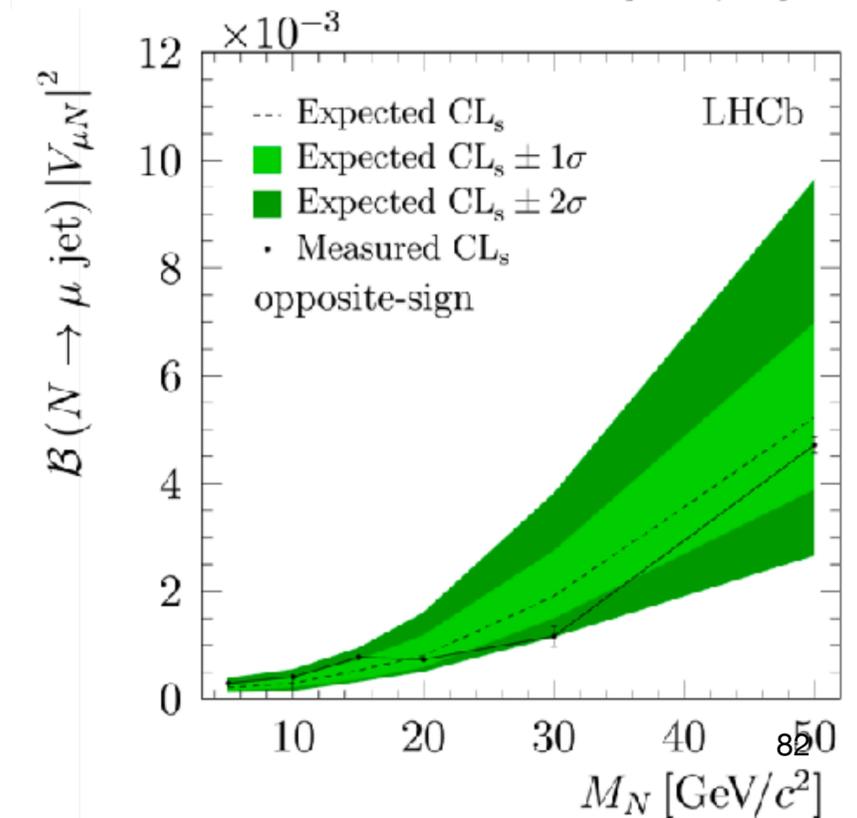
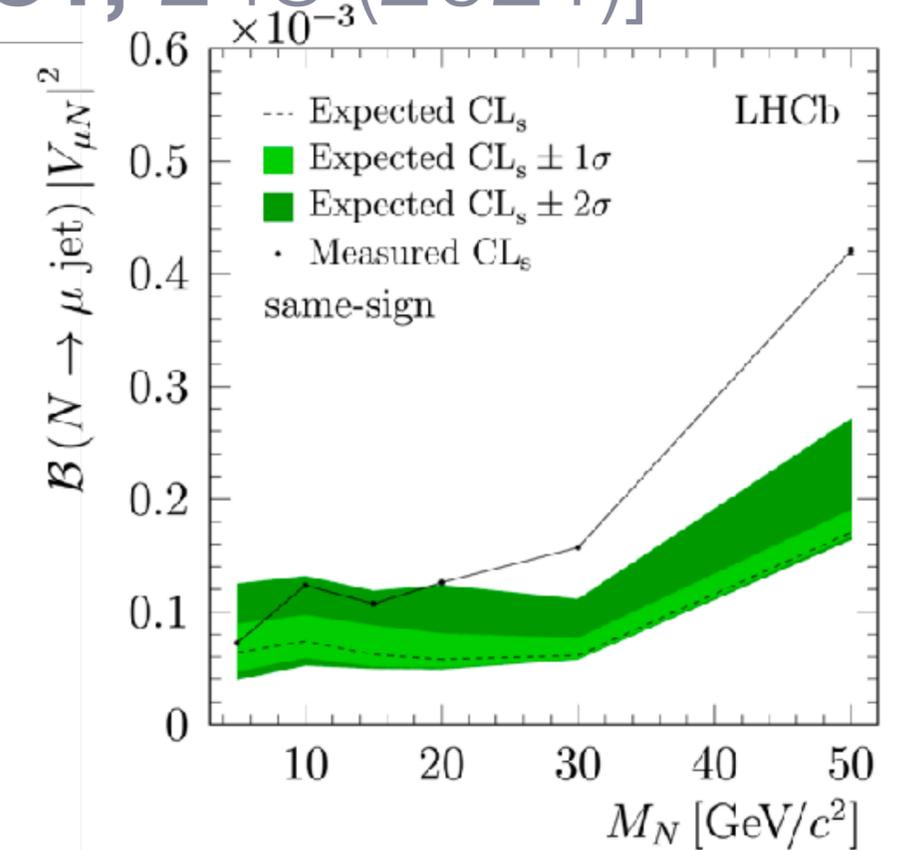
HNL searches in $W^+ \rightarrow \mu^+ \mu^\pm jet$ [Eur. Phys. J. C **81**, 248 (2021)]

Results

- No significant excess found
- Upper limits on branching fraction ($\mathcal{B}(N \rightarrow \mu jet) | V_{\mu N}|^2$) 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



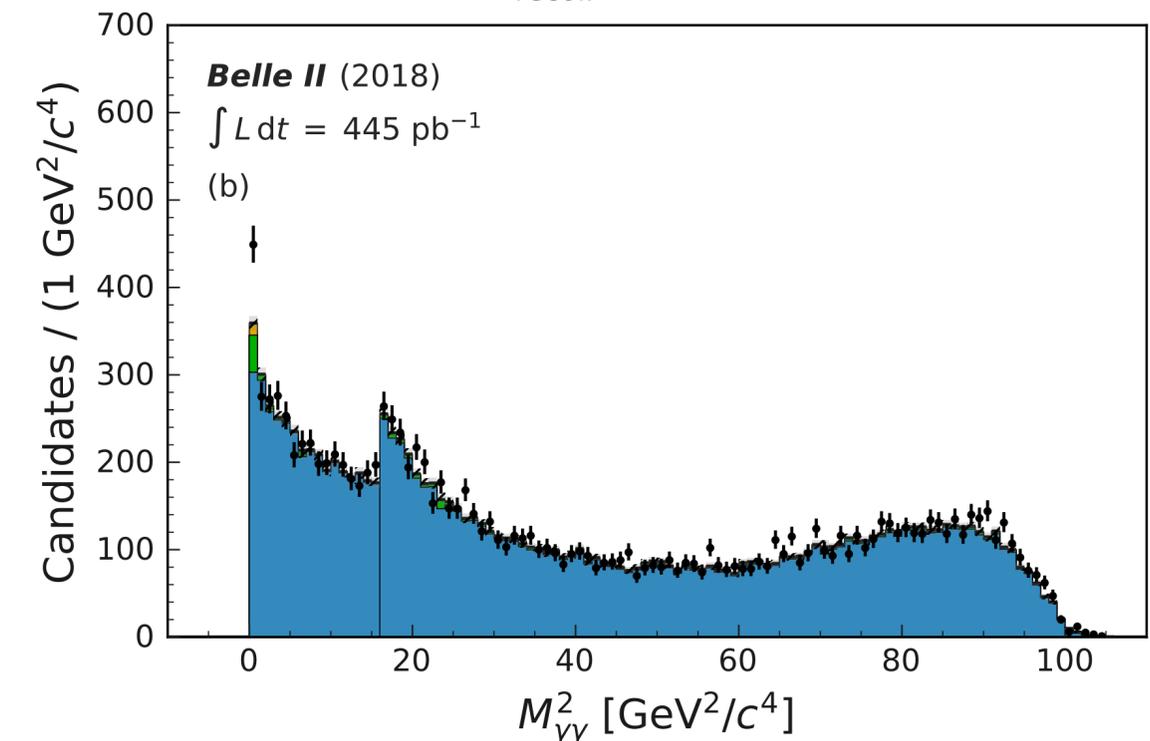
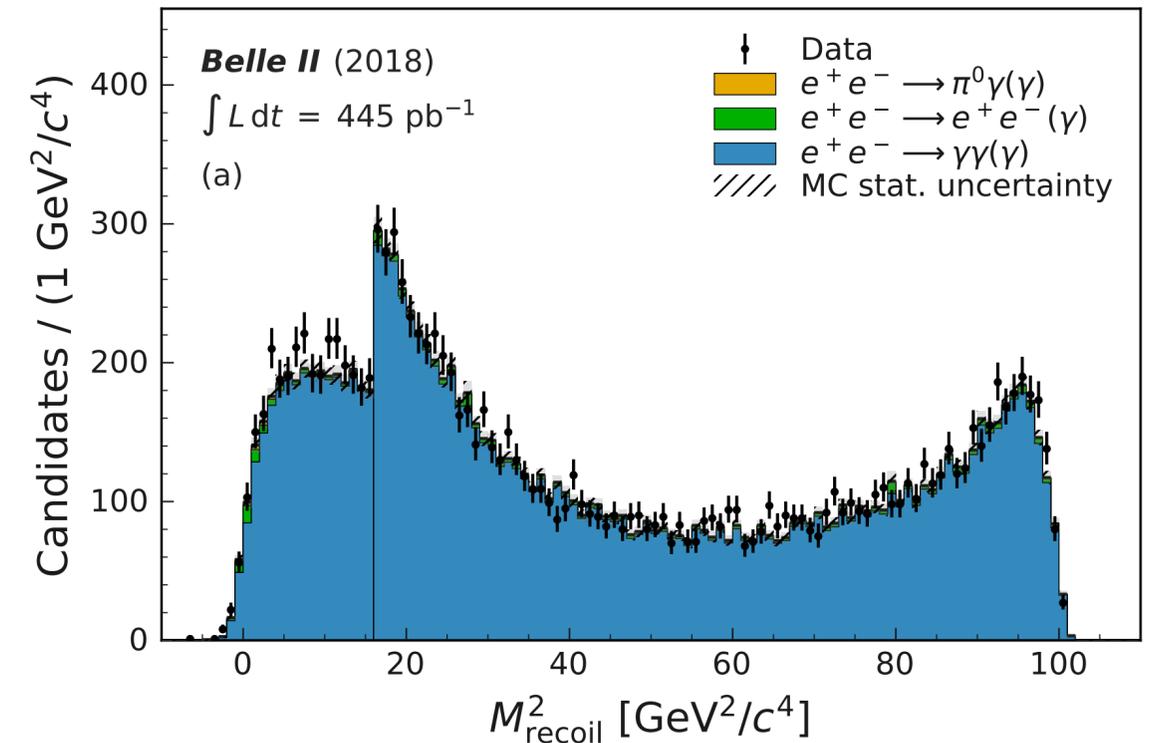
- Lower mass coupling limit corrected because of non-negligible lifetime



Belle II: $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$

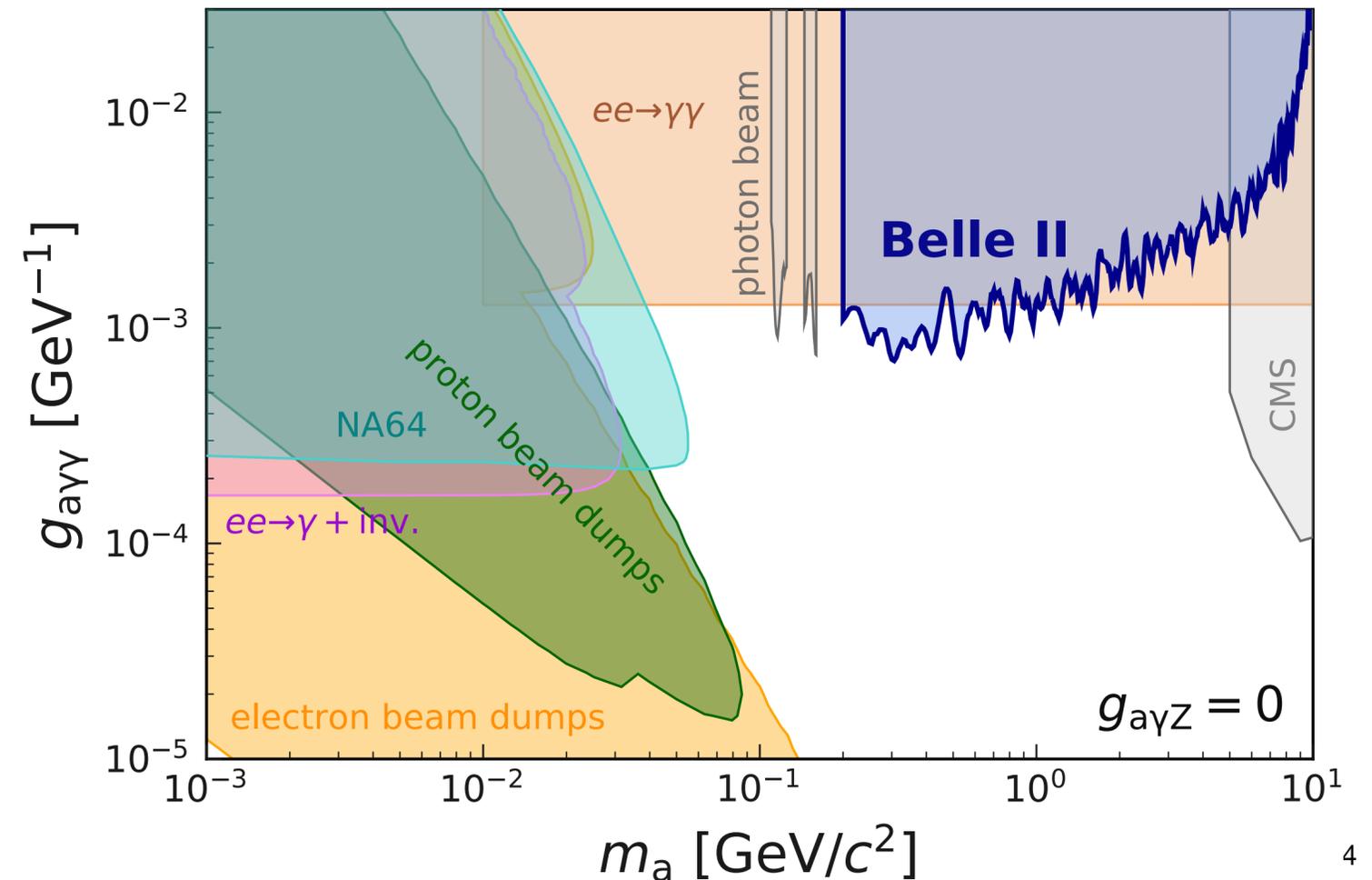
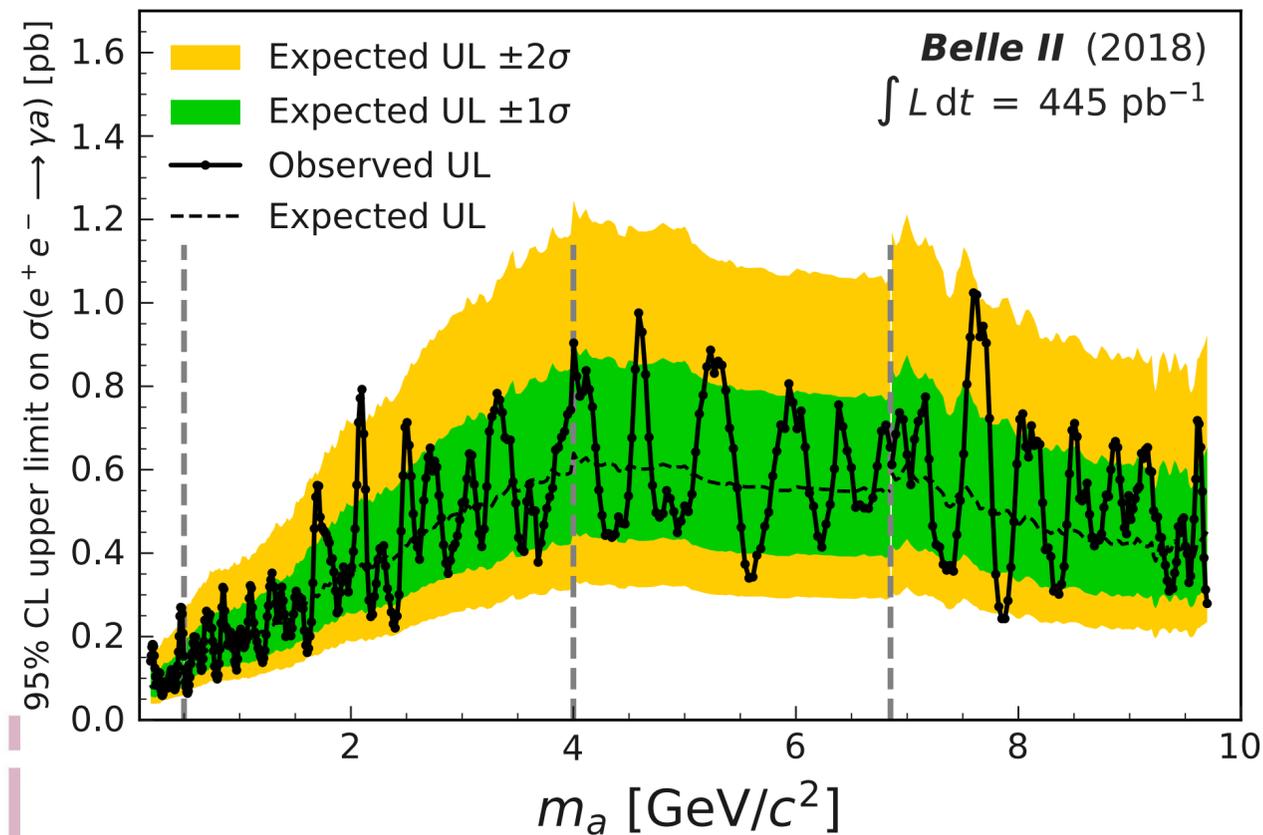
[[Phys. Rev. Lett. 125, 161806](#)]

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



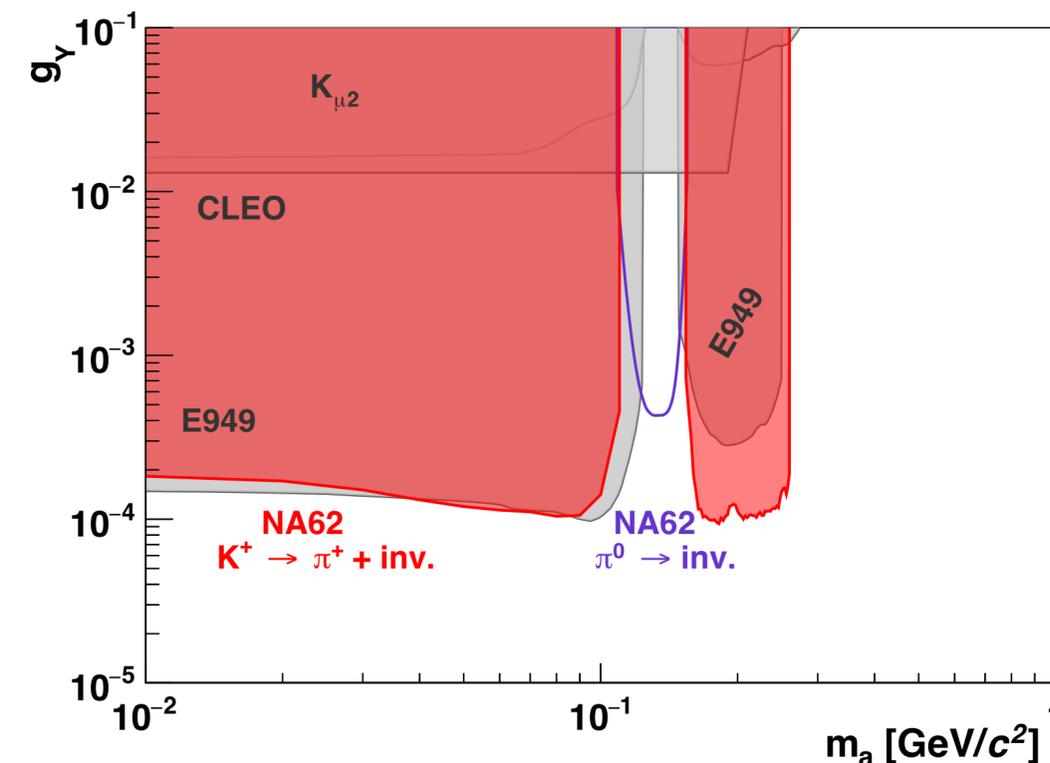
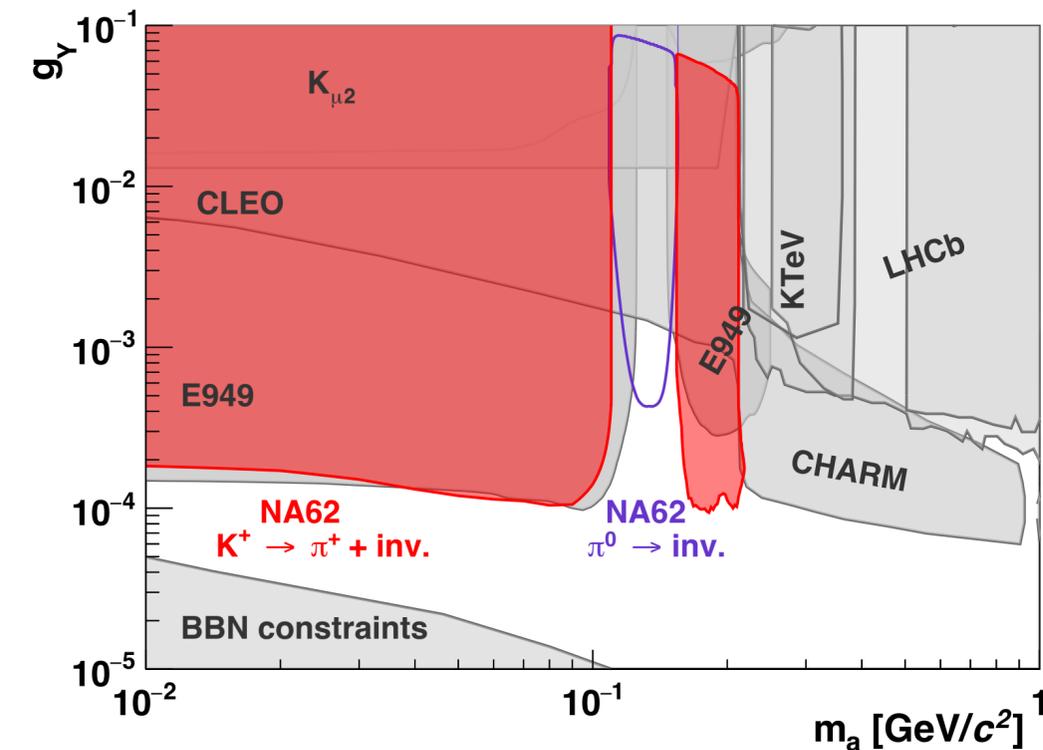
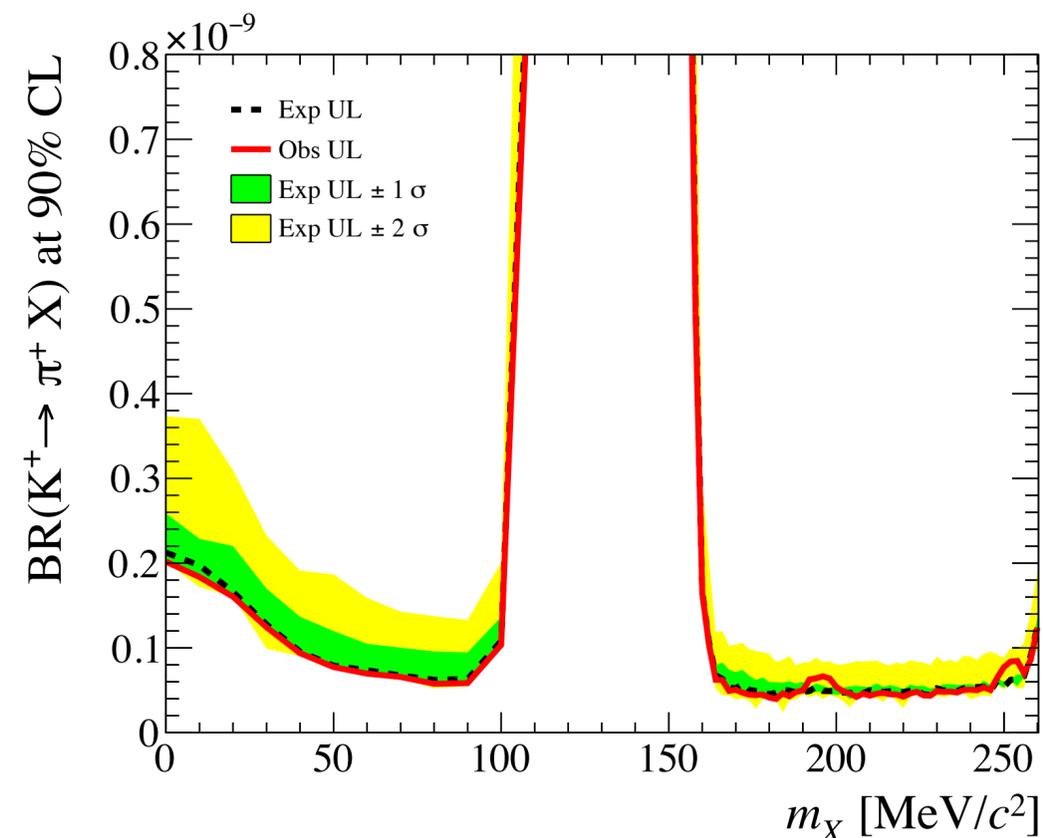
Belle II: $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$ [Phys. Rev. Lett. 125, 161806]

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



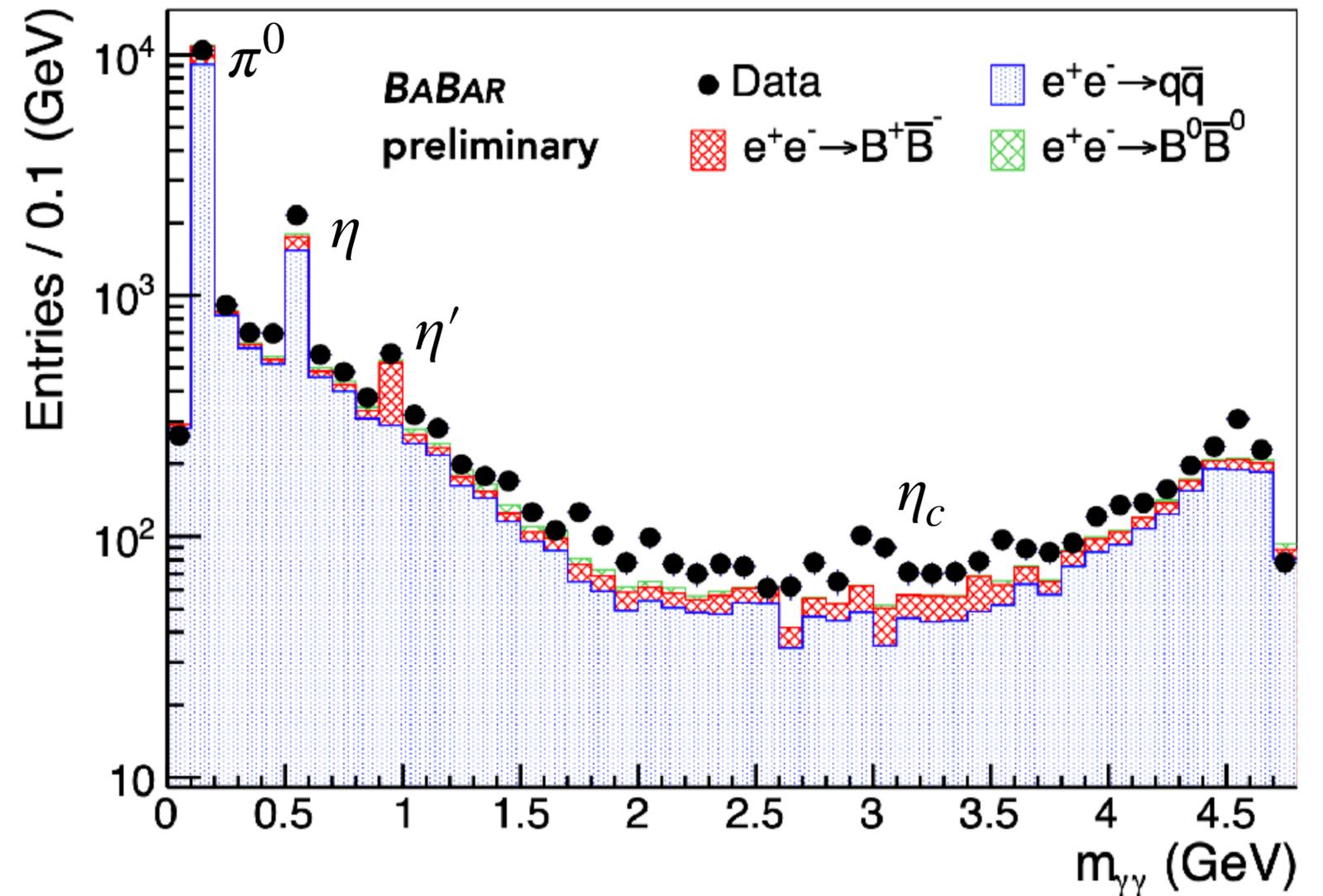
NA62: $K^+ \rightarrow \pi^+ a$, $a \rightarrow$ invisible [JHEP 03 (2021) 058]

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



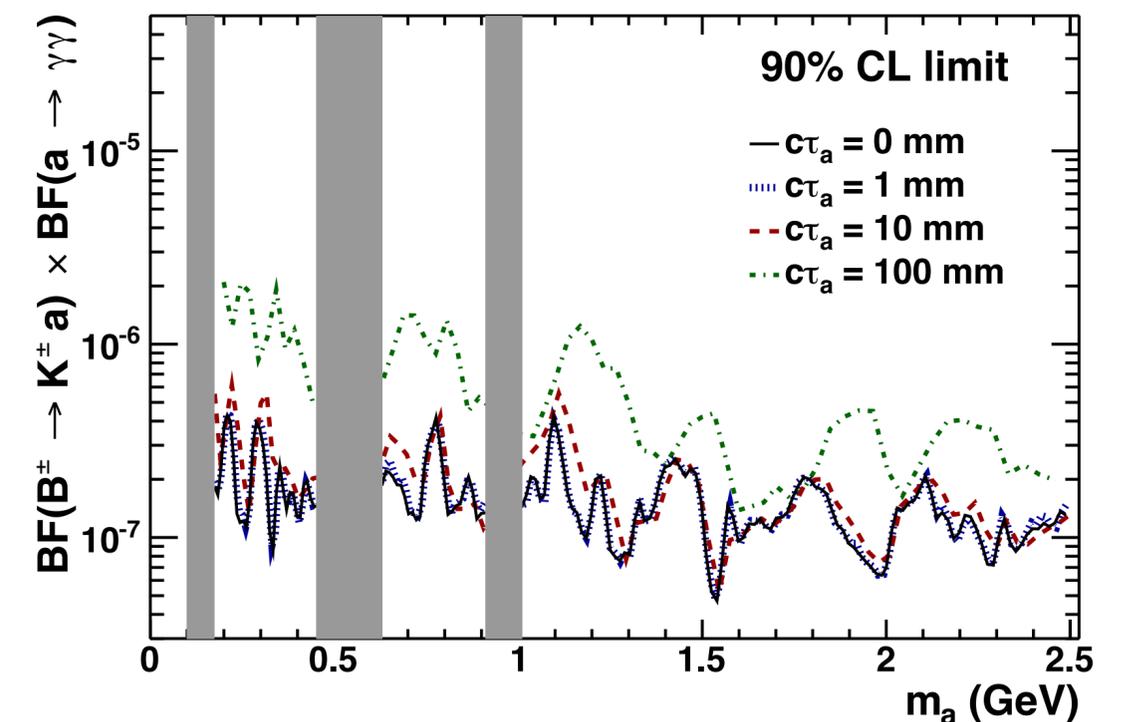
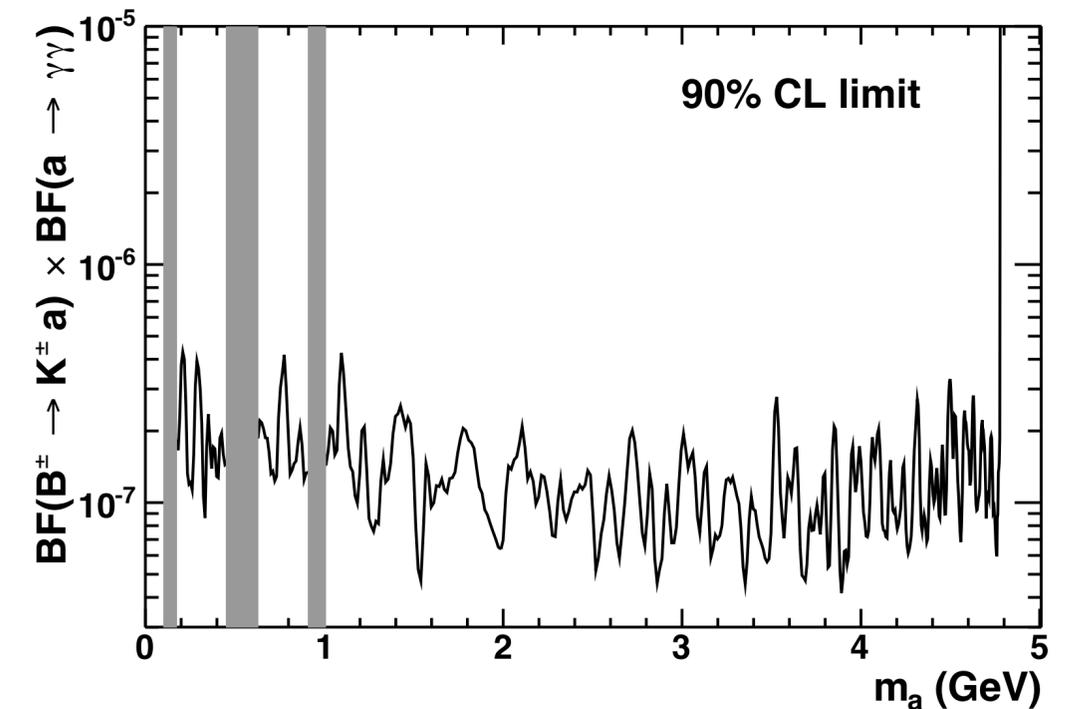
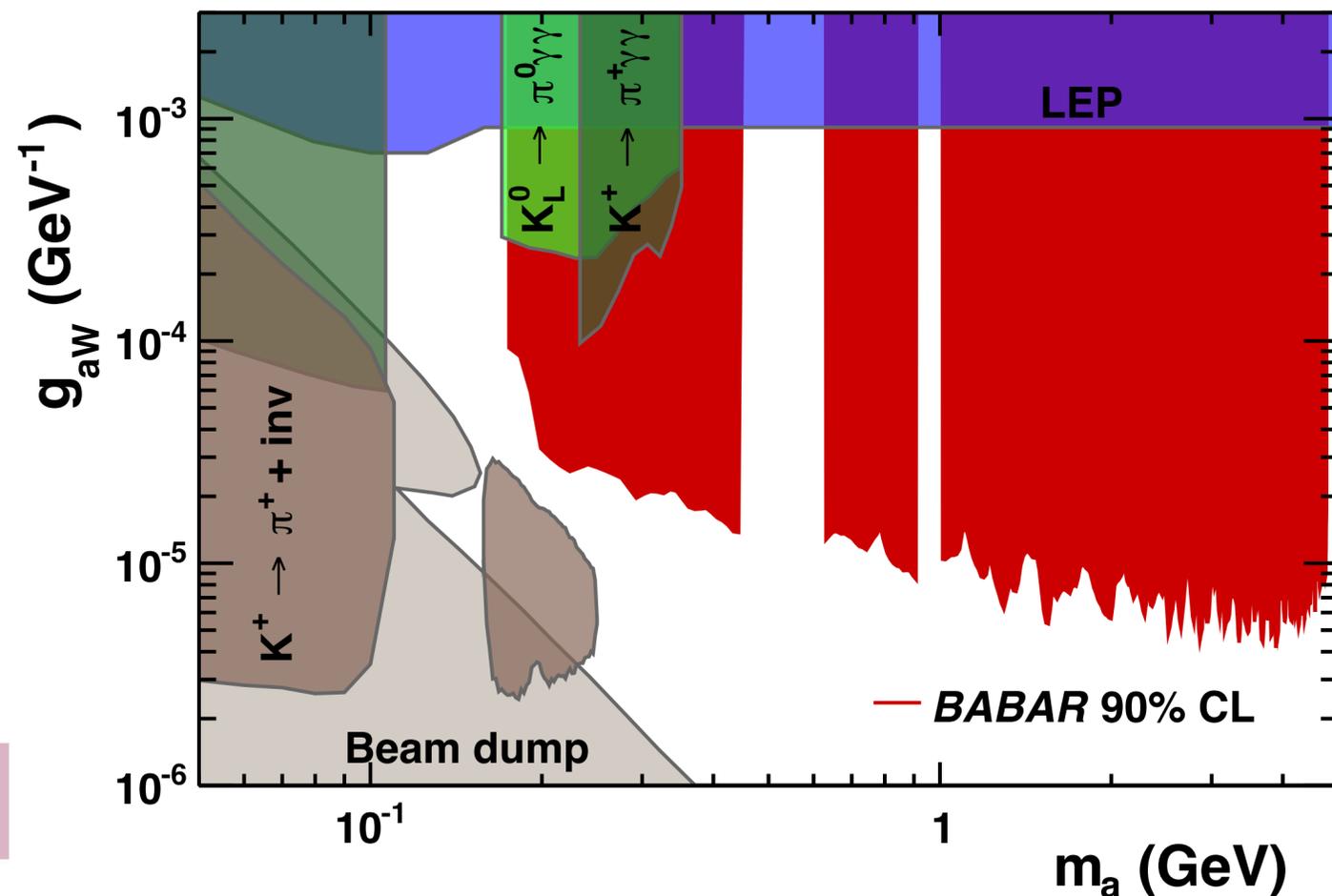
BaBar: $B^\pm \rightarrow K^\pm a, a \rightarrow \gamma\gamma$ [PRL 128 (2022) 13, 131802]

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



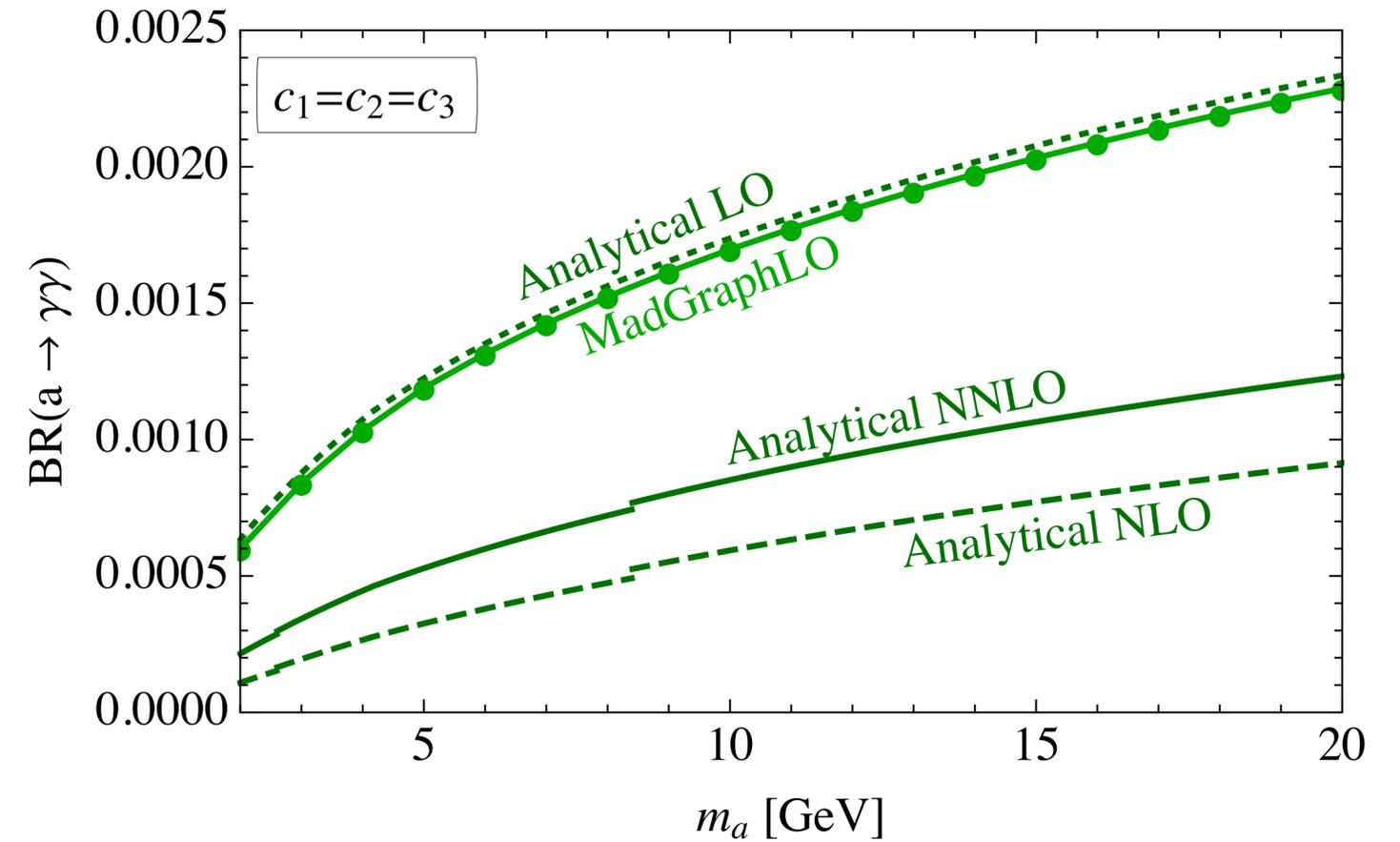
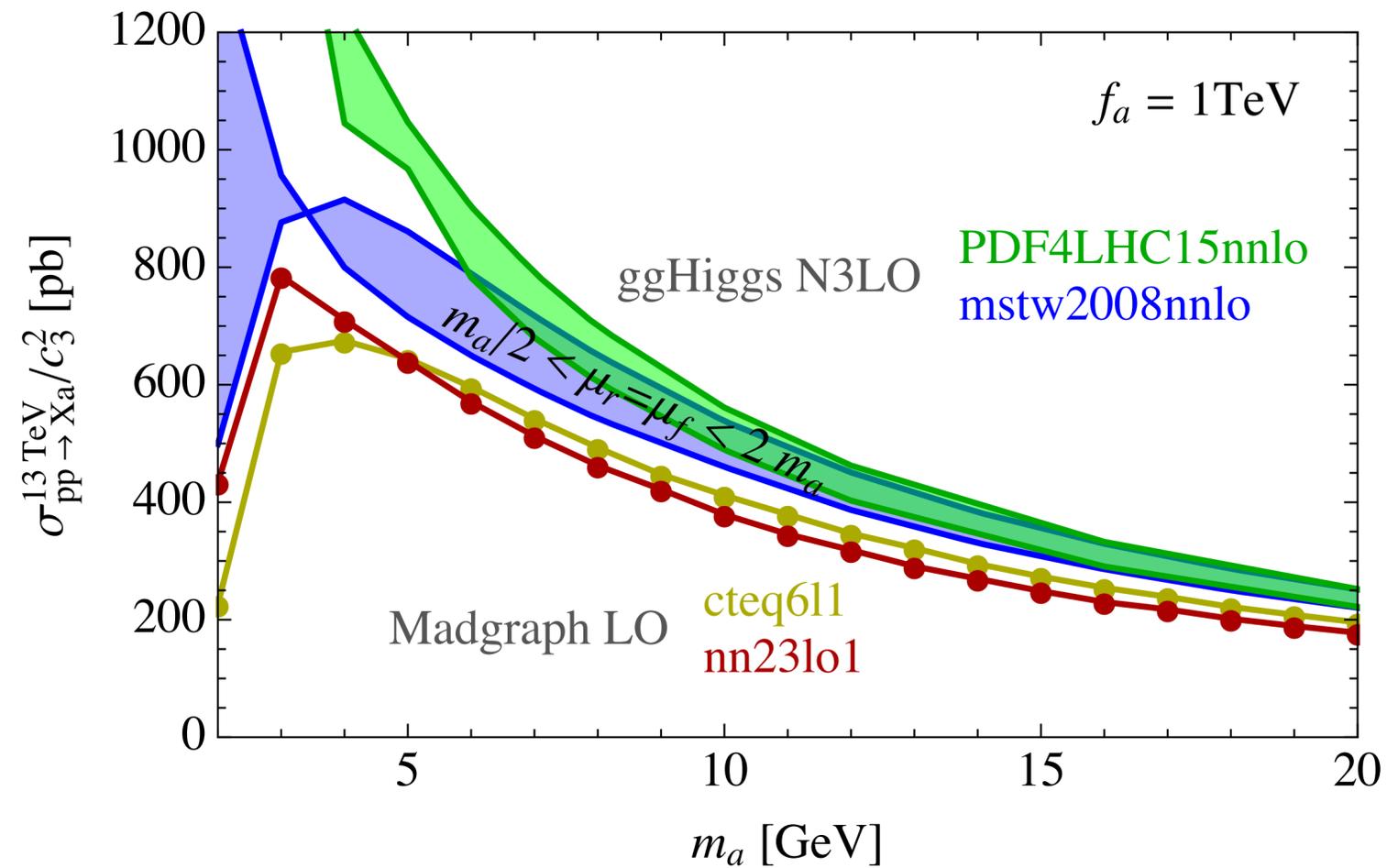
BaBar: $B^\pm \rightarrow K^\pm a, a \rightarrow \gamma\gamma$ [PRL 128 (2022) 13, 131802]

- Unbinned maximum likelihood fit to $m_{\gamma\gamma}$
- 90 % CL limits placed for prompt and long lived ALPs on $\text{BF}(B^\pm \rightarrow K^\pm a, a \rightarrow \gamma\gamma)$
- $\text{BF}(\tau)$ 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 $\rightarrow \gamma\gamma$

[JHEP 1901 (2019) 113]



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