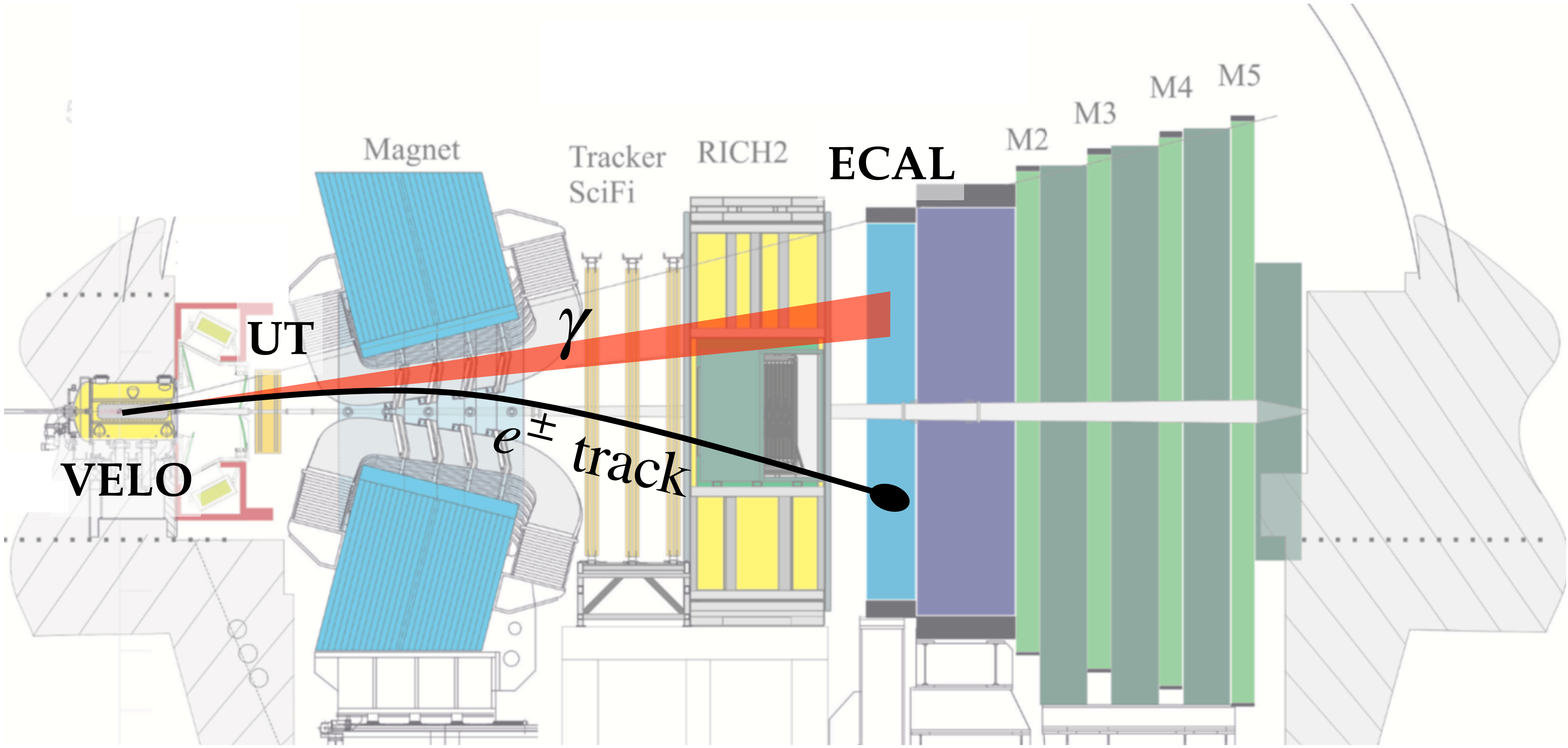


"Flavour at the crossroads" workshop

Wed 20 Apr 2022

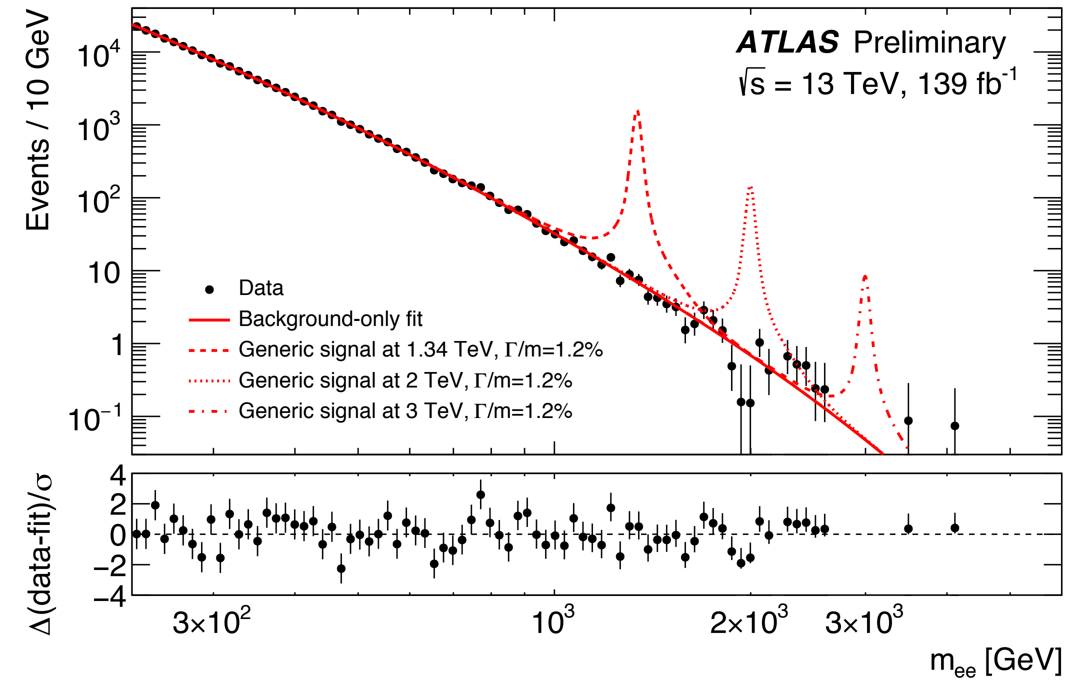
Electrons at LHCb

Martino Borsato
University of Heidelberg

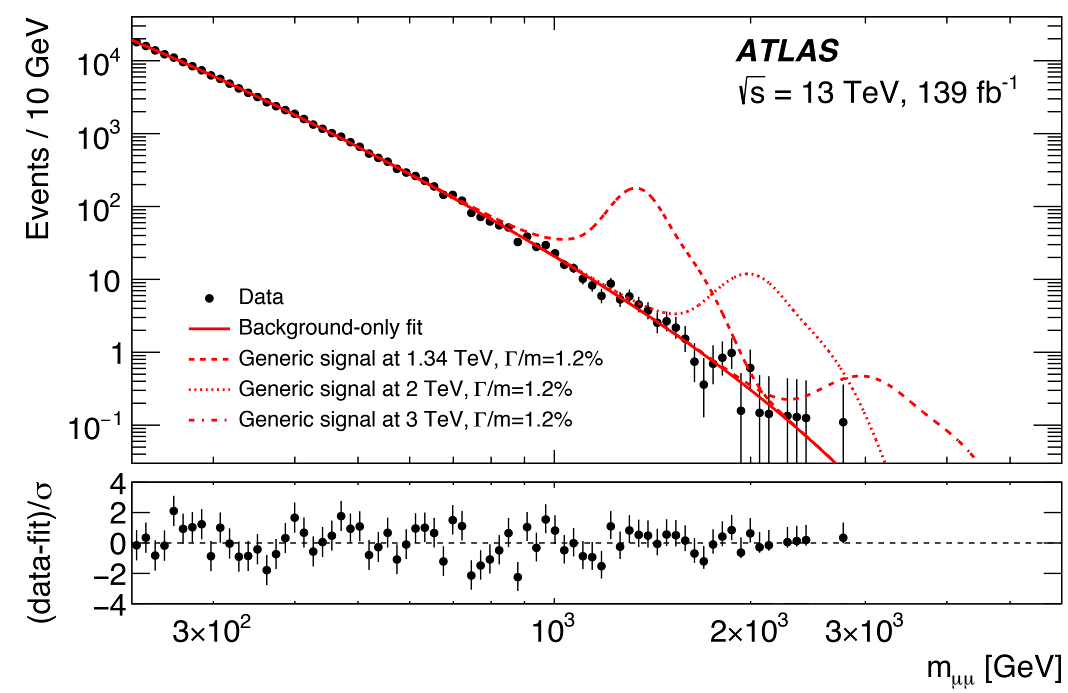
1. *How we do electrons*
2. *What we do with them*

Electrons at GPDs

- ATLAS and CMS reconstruct $e^{\pm}$ as well as $\mu^{\pm}$ (if not better)
  $\rightarrow$ True, cause they are designed mainly for higher energies
    1. Good $E(e^{\pm})$ resolution from ECal
    2. Can trigger efficiently $e^{\pm}$ in ECal despite busy LHC environment



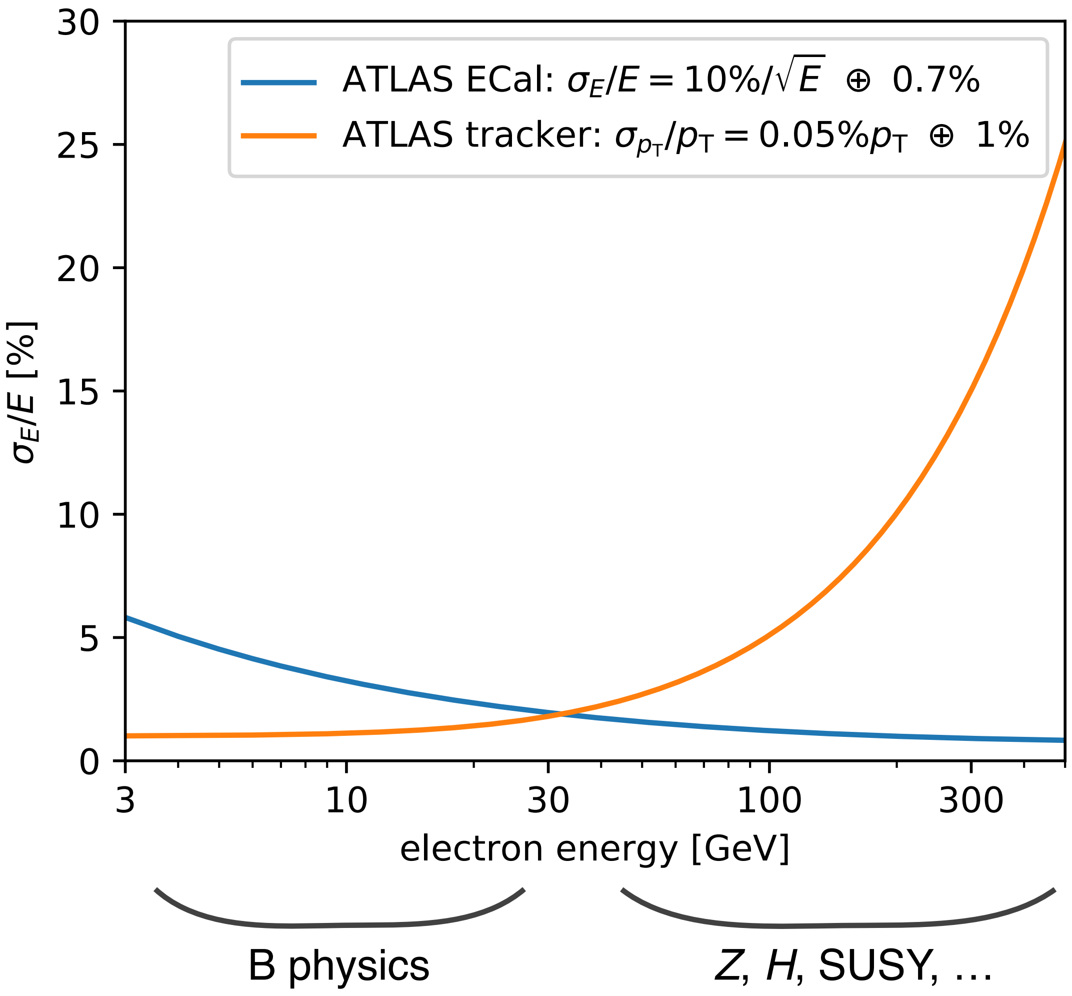
arXiv:1903.06248



arXiv:1903.06248

Electrons for B physics

- In the energy range relevant for B physics at the LHC, the electron energy is measured with the tracker, not with the ECal

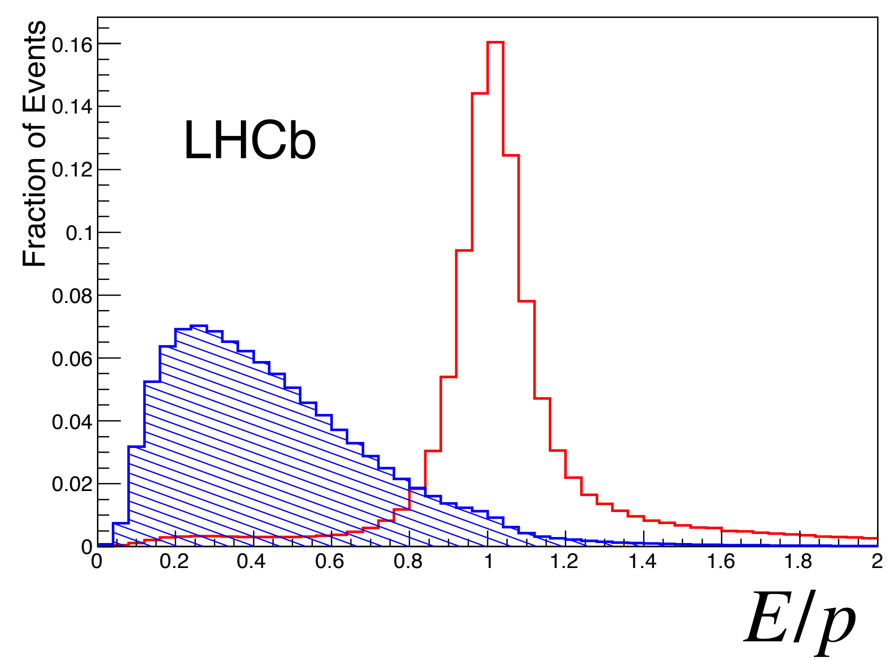


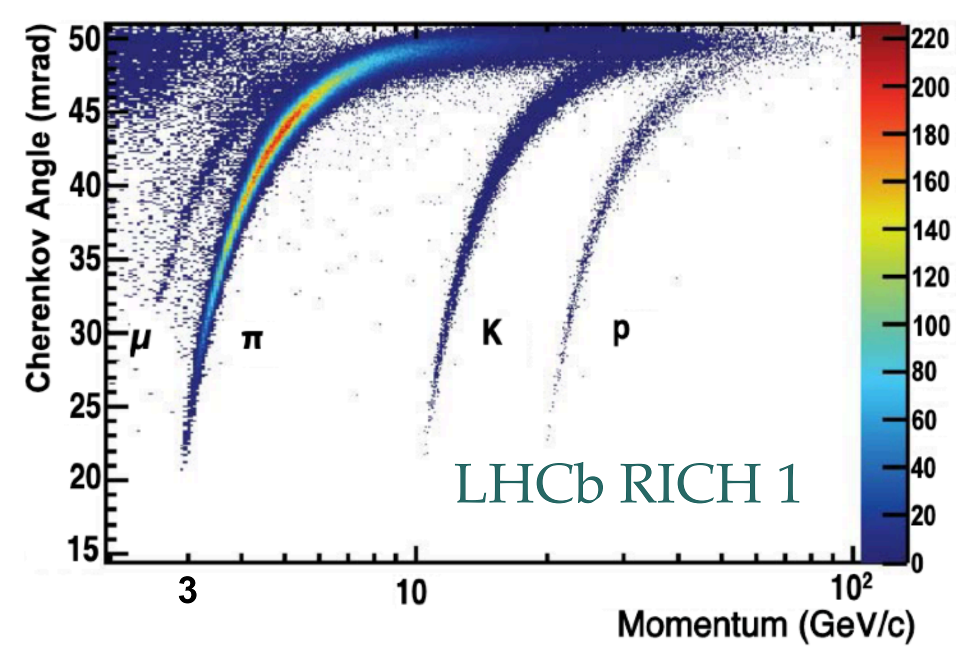
Electron identification

Int.J.Mod.Phys.A 30 (2015) 07, 1530022

- **ECal** used for electron identification and recovery of brem radiation
- At very low momentum Cherenkov light emission in RICH takes leading role

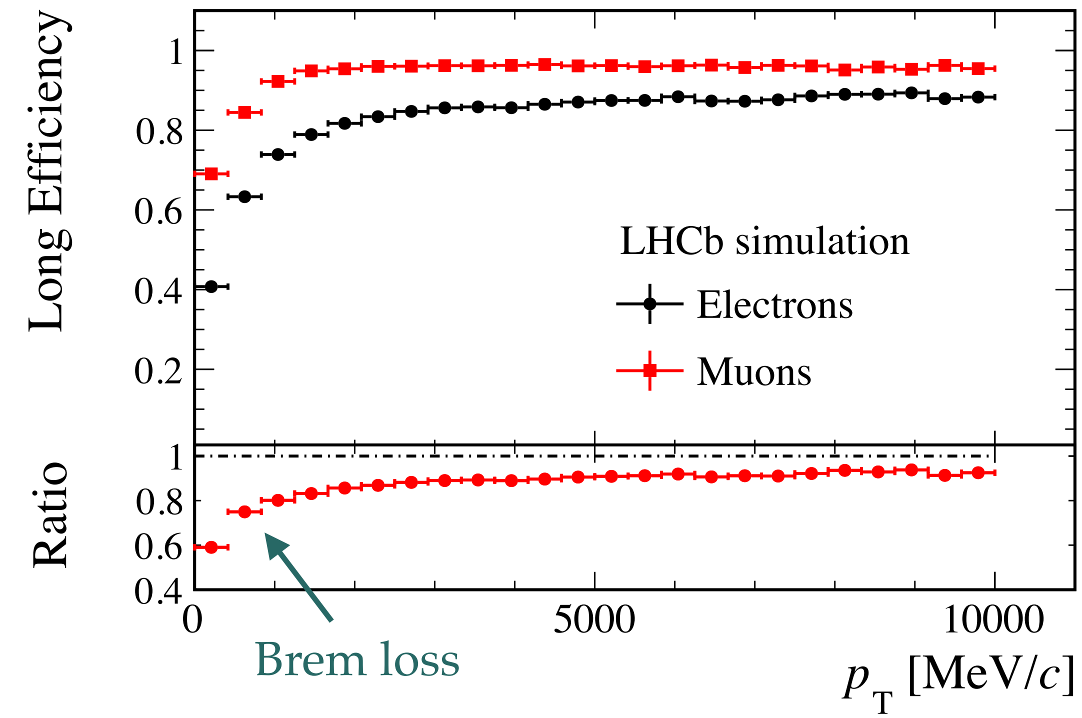
ECal electron ID





Tracking and trigger

- **Electron tracking** less efficient than muons
  - Track pattern recognition similar to muons
  - Electrons can get swept out of tracker acceptance due to brem energy loss (80% efficiency at $p_T = 1$ GeV)
- **Hardware trigger** inefficient on electrons
  - Electron threshold (ECal) higher than muons
    - $p_T(\mu^{\pm}) > 1.5 - 1.8$ GeV
    - $E_T(e^{\pm}) > 2.5 - 3.0$ GeV
  - Cannot use E/p for electron ID (no tracking)



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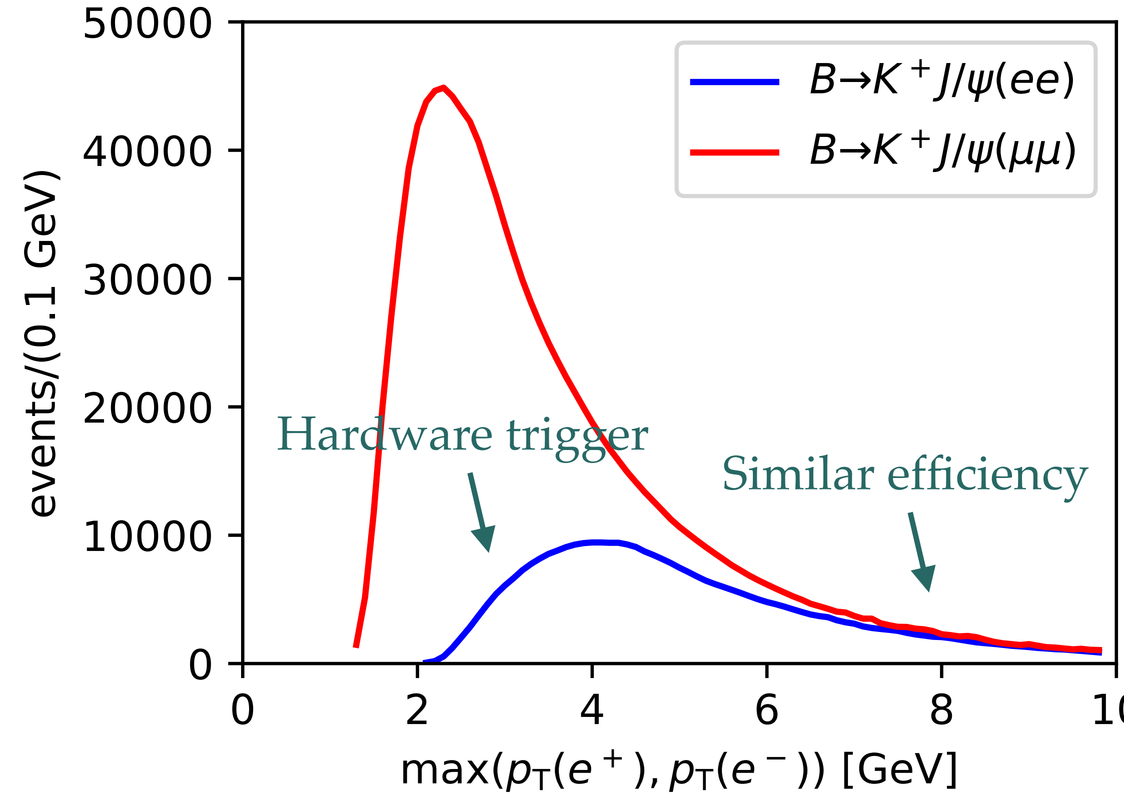

Phys. Rev. Lett. 122, 191801 (2019)

Tracking and trigger

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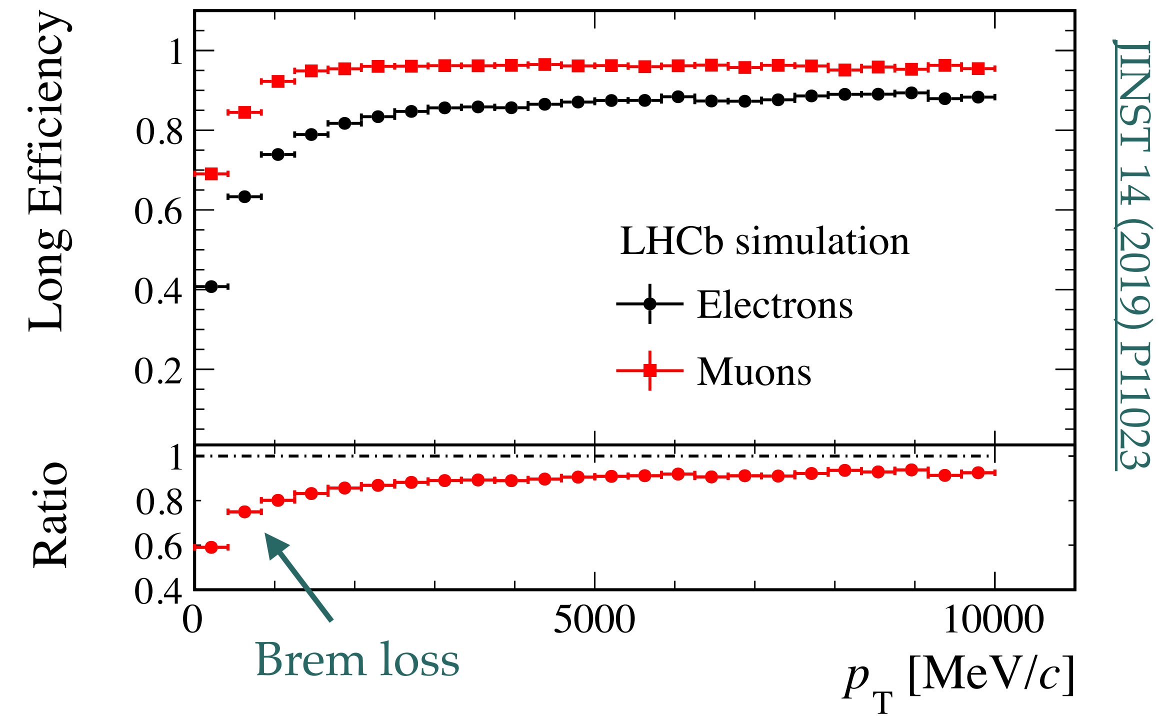
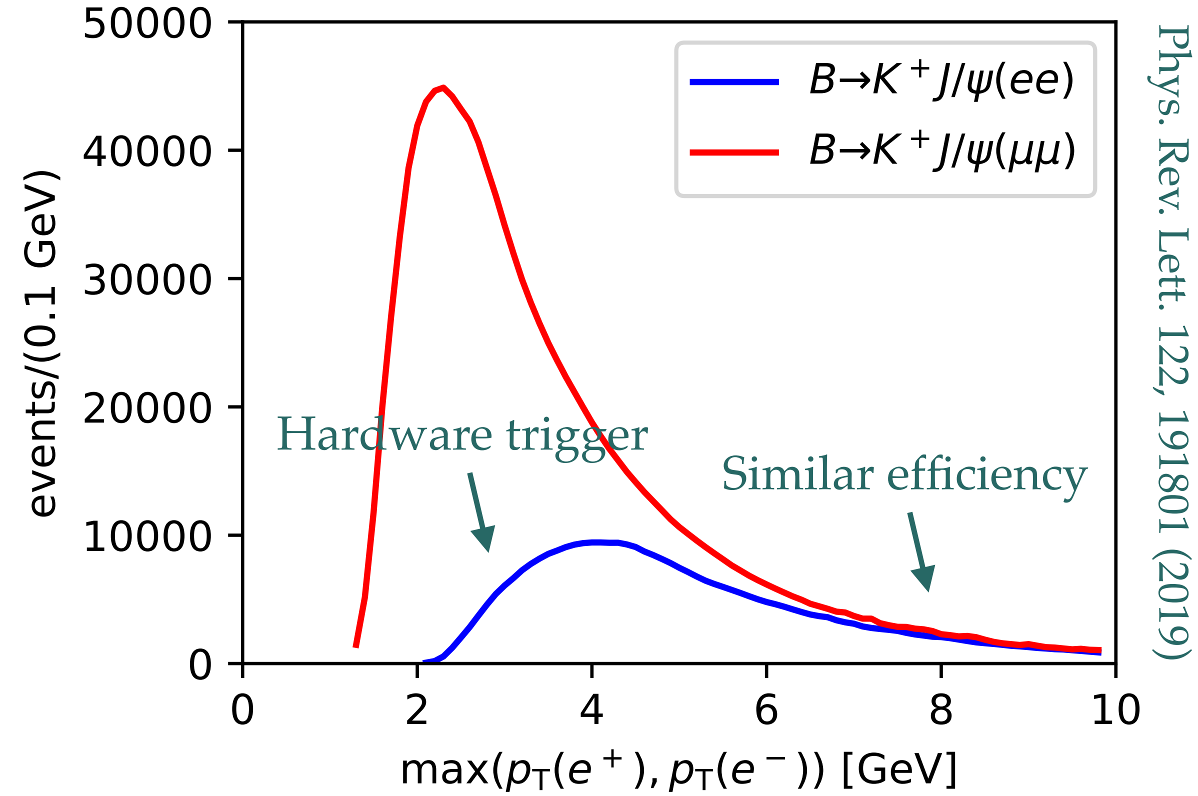


- ~~**Hardware trigger** inefficient on electrons~~
  - ~~Electron threshold (ECal) higher than muons~~
    - ~~$p_T(\mu^{\pm}) > 1.5 - 1.8$ GeV~~
    - ~~$E_T(e^{\pm}) > 2.5 - 3.0$ GeV~~
  - ~~Cannot use E/p for electron ID (no tracking)~~

LHCb Upgrade I

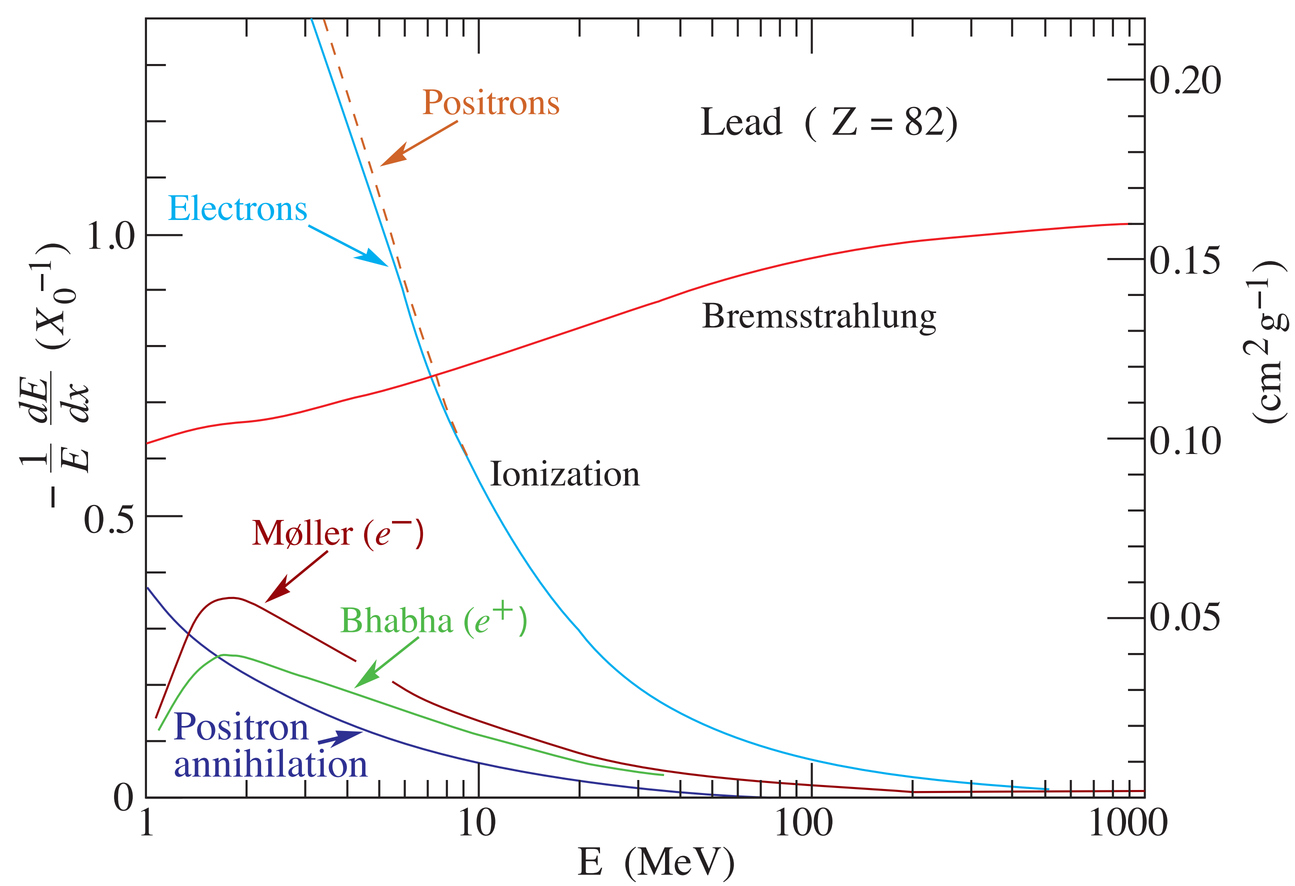
- No Hardware trigger
- Tracking in real time
  $\rightarrow$ can use E/p for ID



Bremsstrahlung

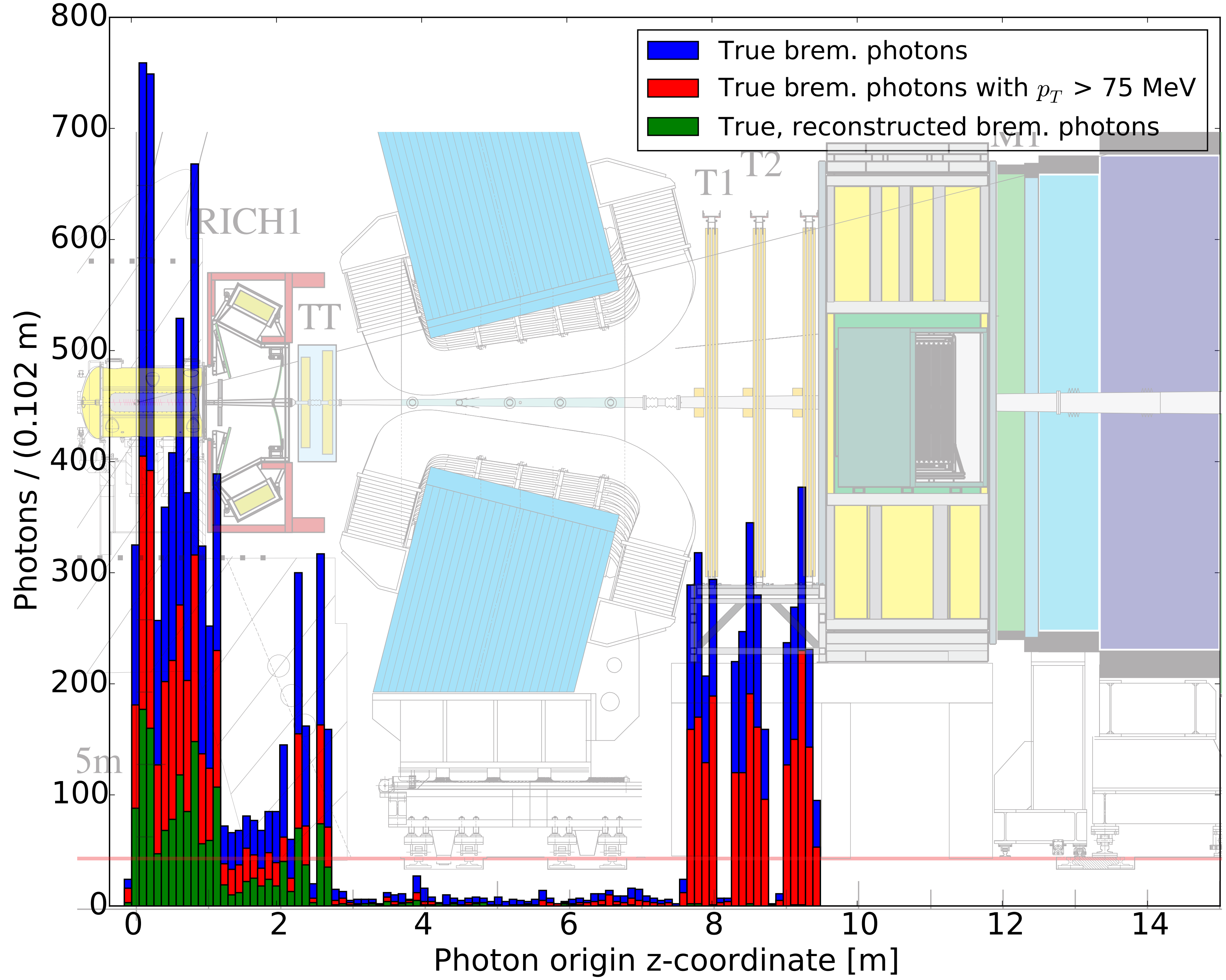
- Bremsstrahlung radiation induced by interaction with detector material
- Probability goes with E/m^2
  $\rightarrow$ mainly affecting electrons
- Energy loss due to bremsstrahlung rises linearly with $e^{\pm}$ energy
  $\rightarrow$ fractional loss roughly independent of $e^{\pm}$ energy (easier to model)

PDG



Brems emitted at LHCb

- Most brem emission due to material interaction
- If emitted before the magnet can affect momentum measurement

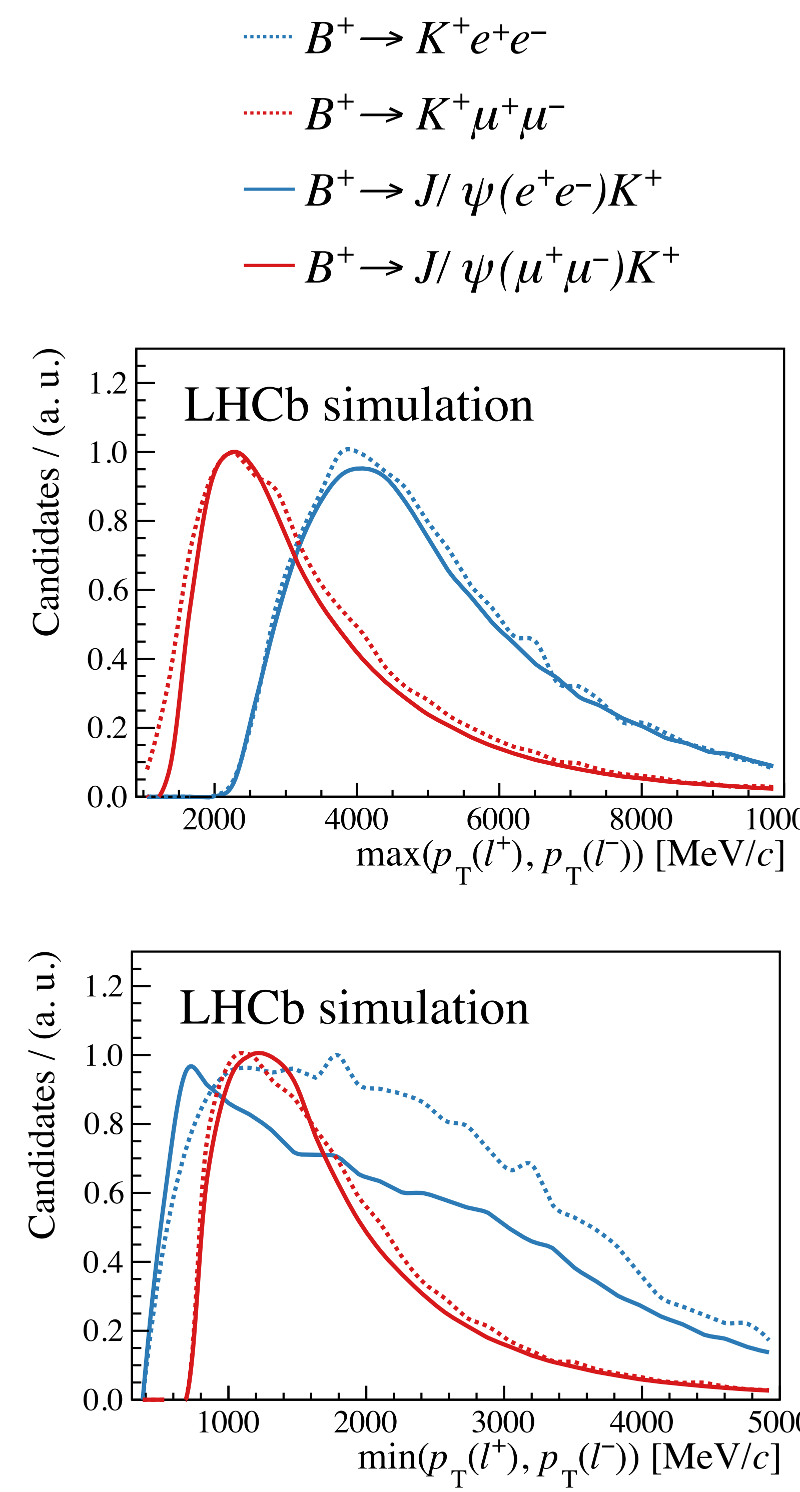


Brems emitted at LHCb

- How many brem/electron are typically emitted?
  - $E(e^{\pm}) > 10$ GeV complete screening approximation
  - Material budget before magnet: $d \simeq 38\,\%\,X_0$
  - $p_{\mathrm{T}}(e^{\pm}) \sim 3$ GeV $\Rightarrow \min(E_{\mathrm{T}}(\gamma)) = 75$ MeV $= 2.5\,\%$
  - Average number of brem emitted with at least 2.5% of the $e^{\pm}$ energy

$$< N_\gamma > = \frac{d}{X_0}\left[\frac{4}{3}\ln\left(\frac{k_{\max}}{k_{\min}}\right) - \frac{4\left(k_{\max}-k_{\min}\right)}{3E} + \frac{k_{\max}^2 - k_{\min}^2}{2E^2}\right] \simeq 1$$

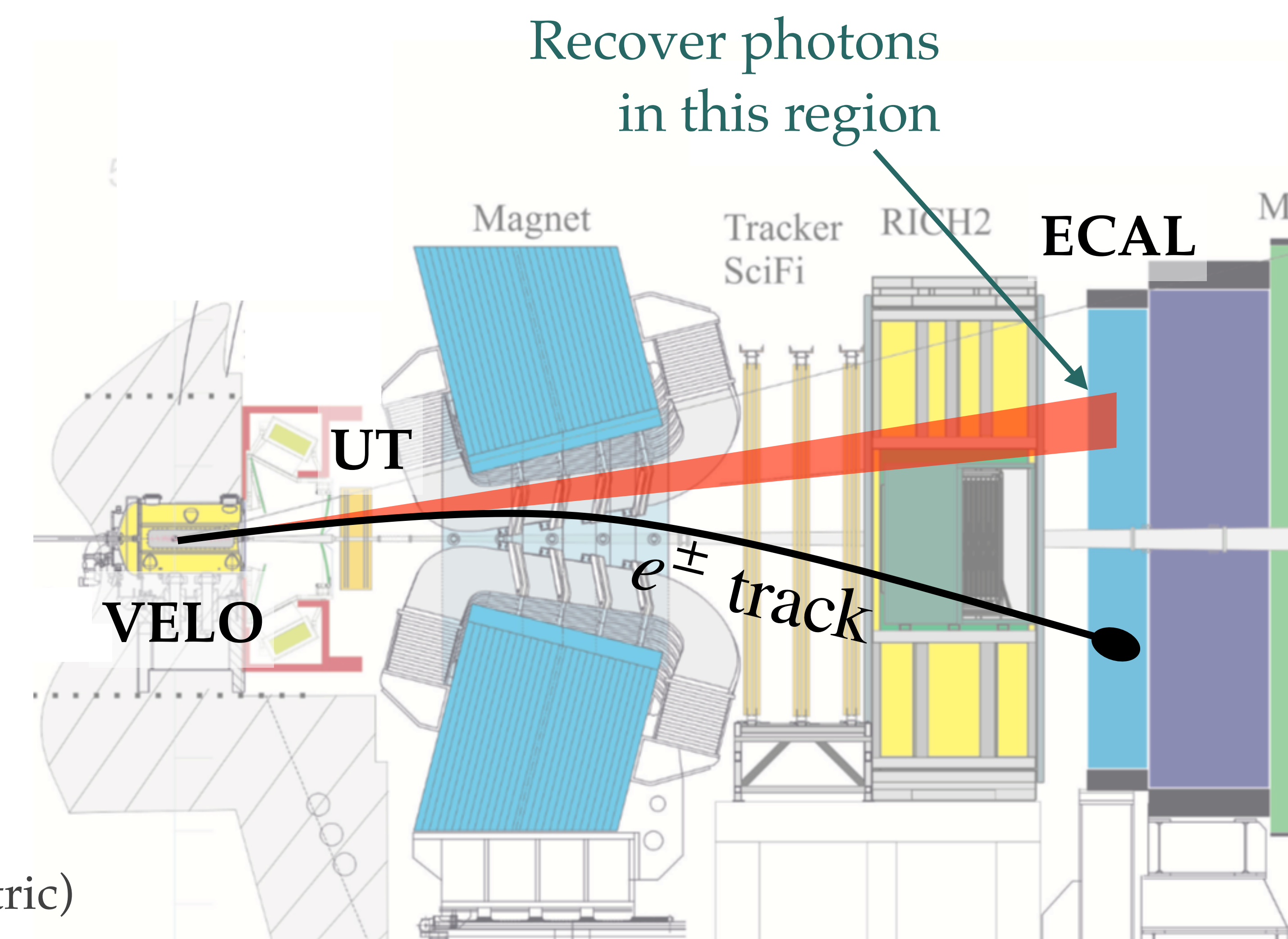
  - **At LHCb most electrons emit one energetic brem before the magnet**



Phys. Rev. Lett. 122, 191801 (2019)

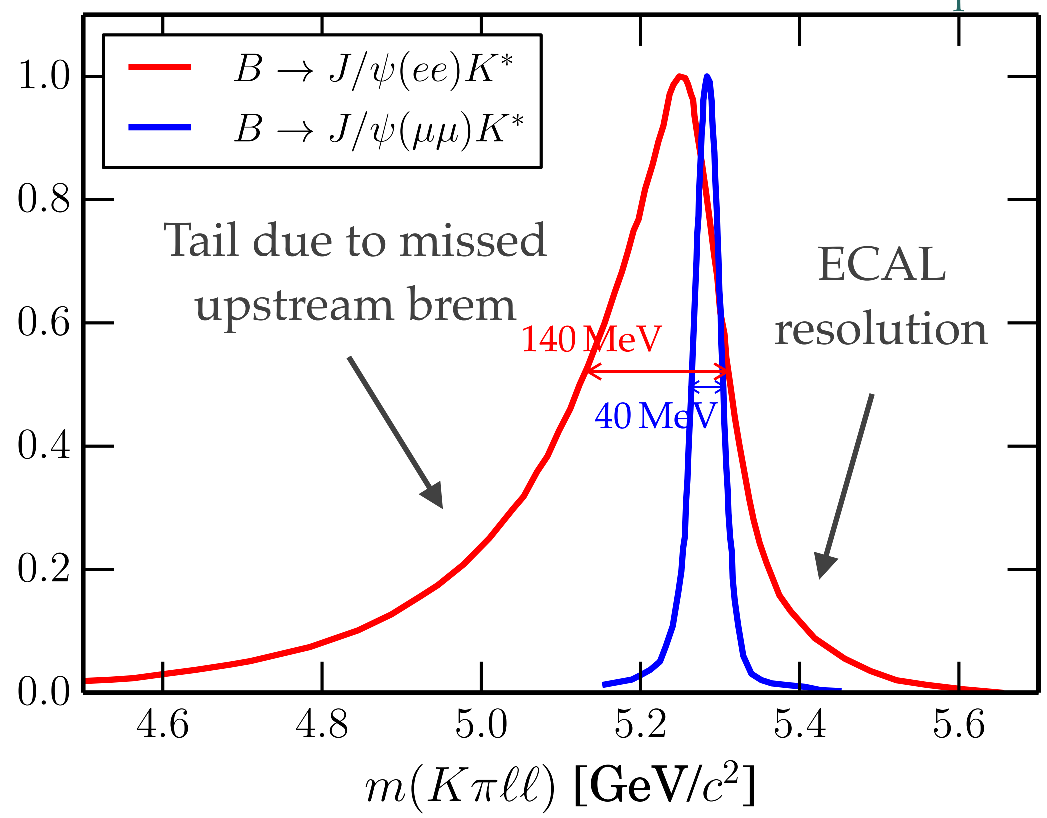
Brem recovery at LHCb

- LHCb brem recovery algorithm:
  - Extrapolate upstream $e^{\pm}$ track to the ECAL
  - Take all reconstructed neutral clusters with $E_{\mathrm{T}} > 75$ MeV
  - Add them back to electron momentum
- Main shortcomings
  - ECAL energy resolution worse than tracking resolution
  - Brem can be out of ECAL or too soft
- Electrons with brem recovered:
  - Better momentum resolution (more symmetric)
  - Better particle identification ($\pi^{\pm}$ don't emit brem)
- What if no brem is found?
  $\rightarrow$ most of the time it was missed



B mass resolution at LHCb

unofficial plot



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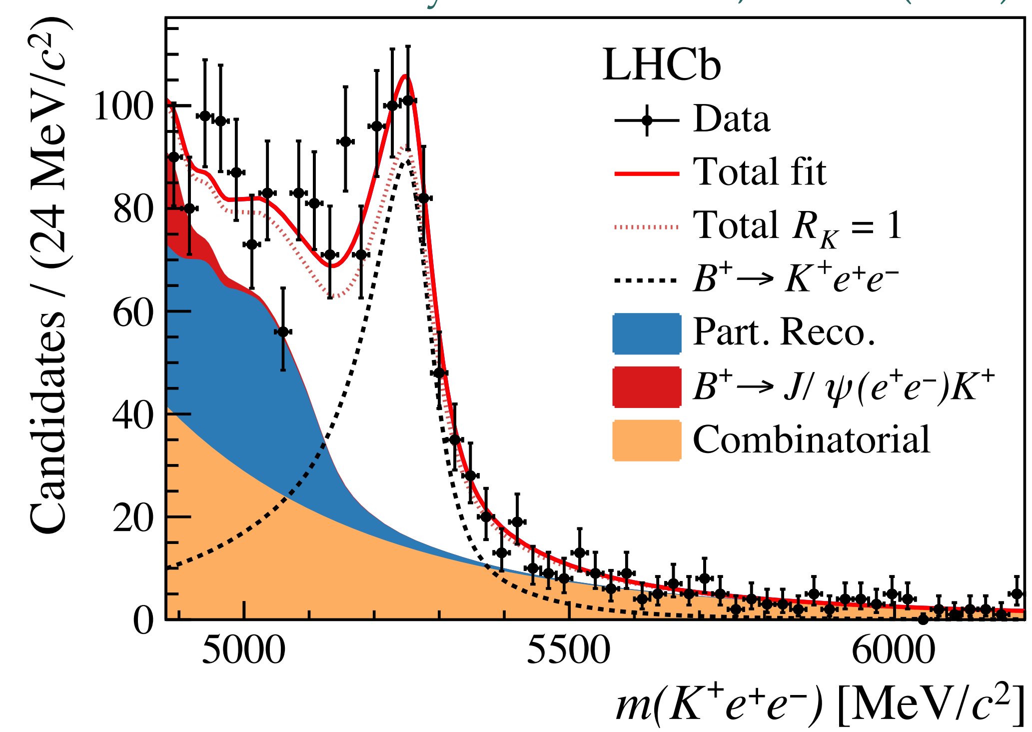

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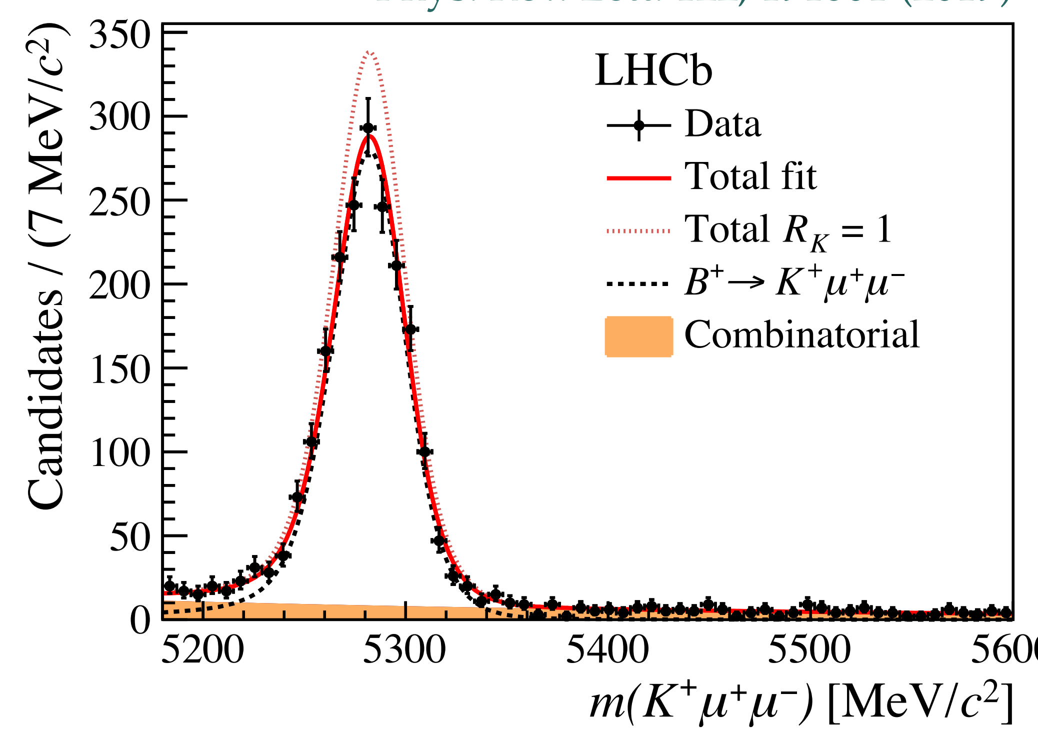
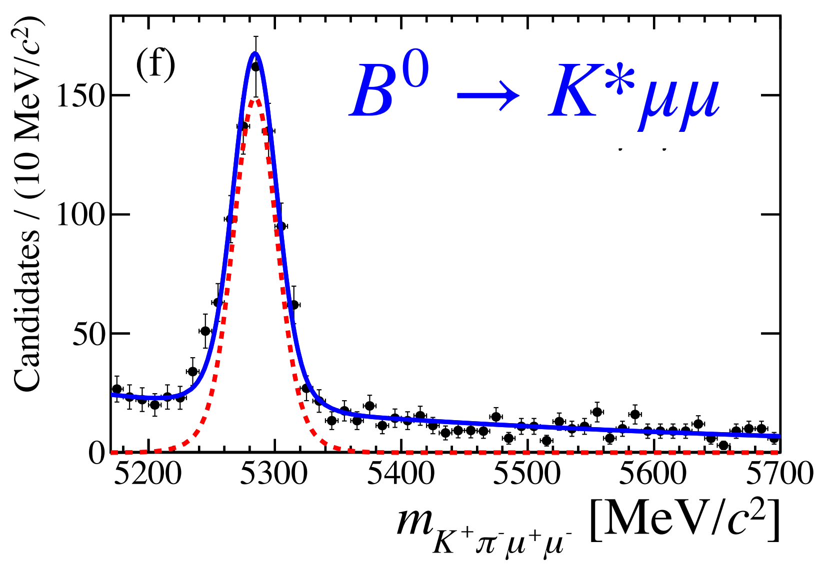


- B mass resolution essential to separate signal from partially reconstructed and combinatorial

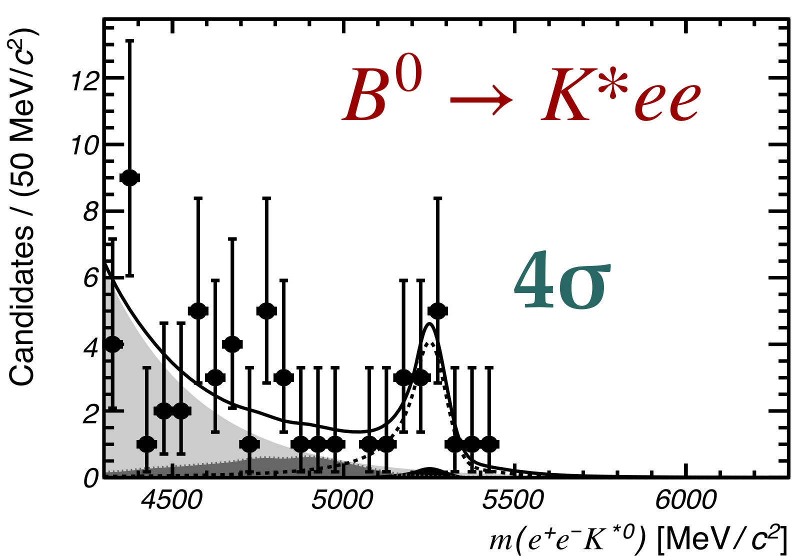
Improvements

2013 ($1\ \mathrm{fb}^{-1}$)

LHCb-PAPER-2012-011

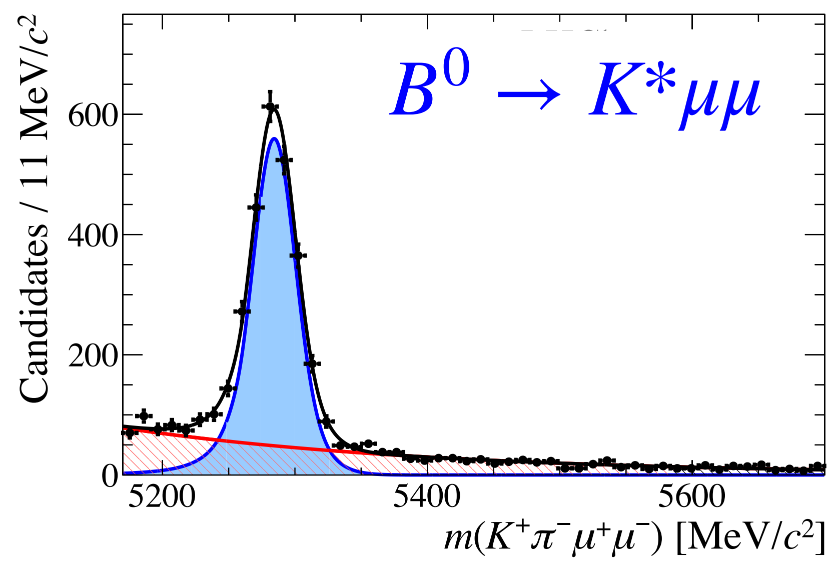


LHCb-PAPER-2013-005

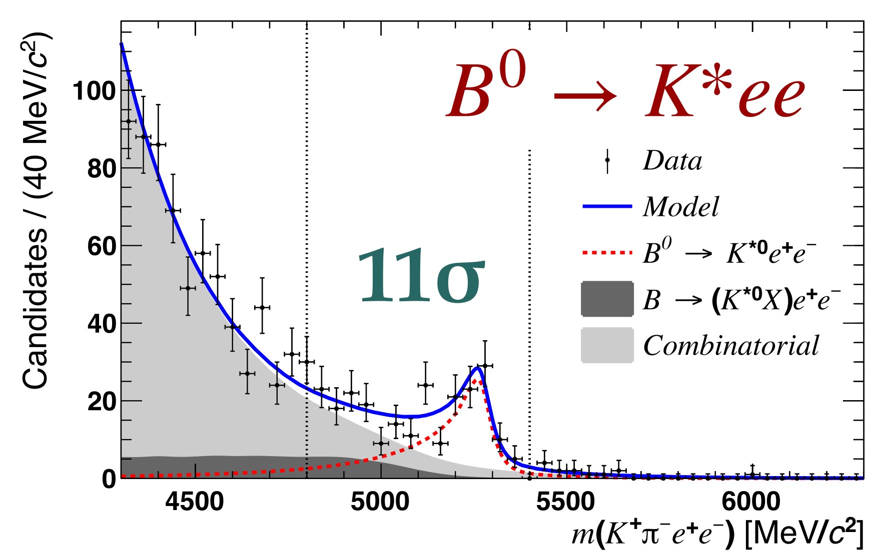


2015 ($3\ \mathrm{fb}^{-1}$)

LHCb-PAPER-2015-051

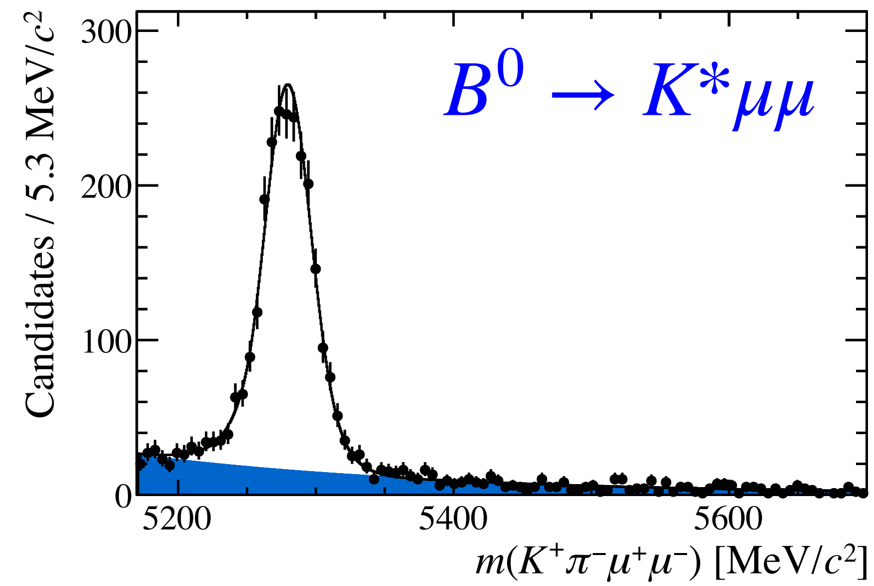


LHCb-PAPER-2014-066

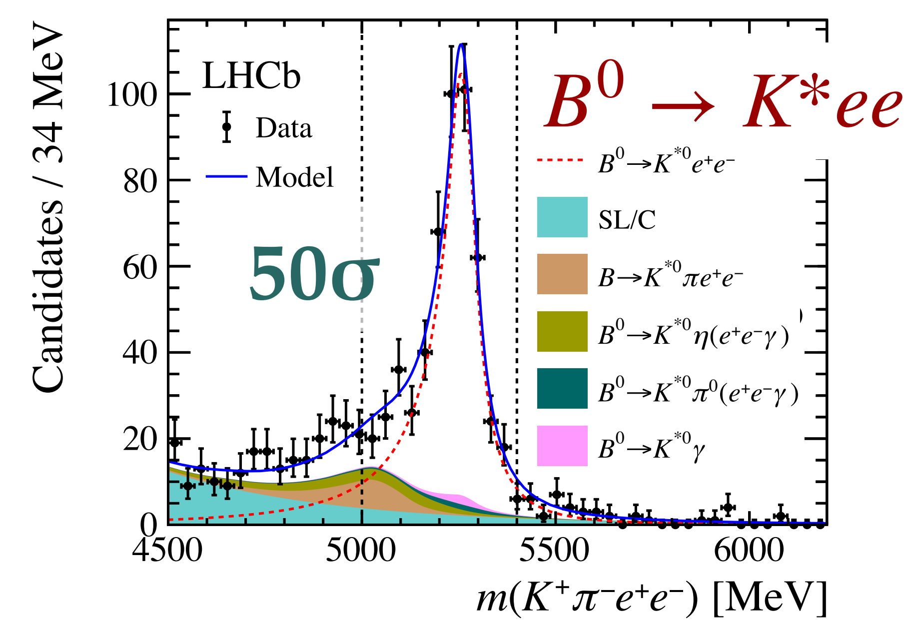


2020 ($9\ \mathrm{fb}^{-1}$)

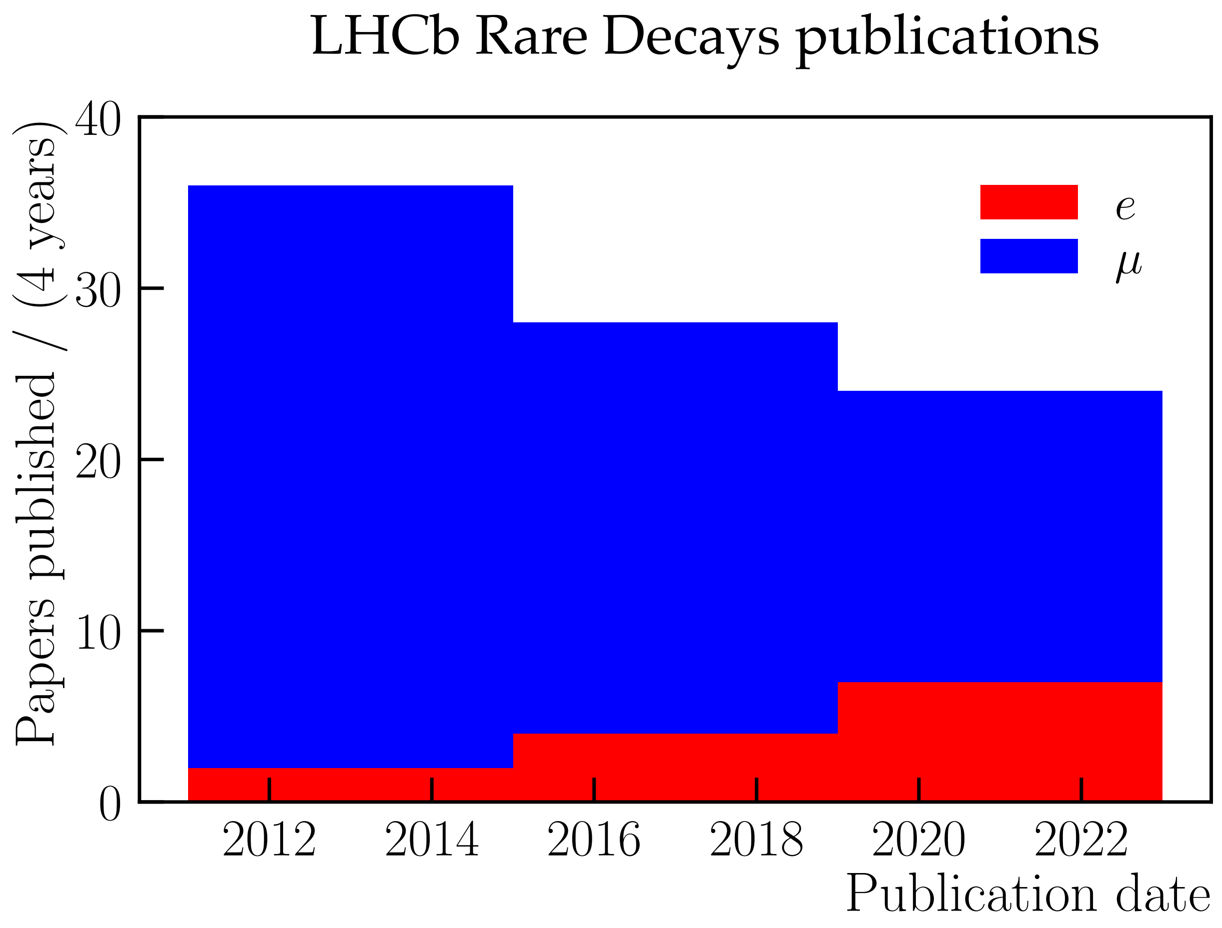
LHCb-PAPER-2020-002



LHCb-PAPER-2020-020



Publications involving electrons



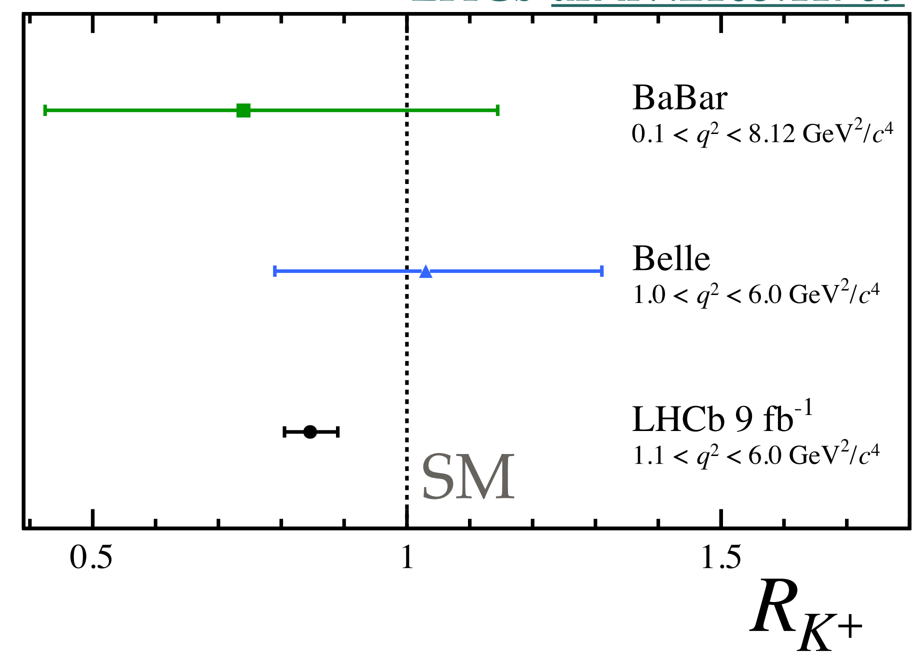
What we do with electrons?

Why electrons at LHCb?

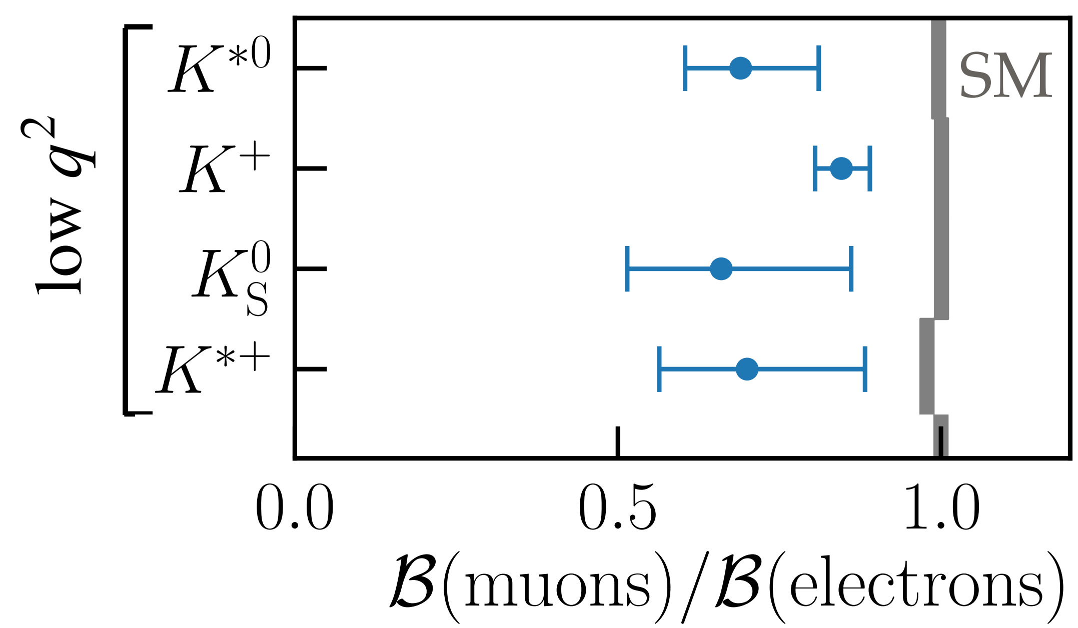
- Why **muons** rather than **electrons**?
  - **Easier reconstruction at LHCb**
  - SM gauge couplings are the same
  - Mass difference negligible $q^2 \gg m_\mu^2, m_e^2$
- Why **electrons** rather than **muons**?
  - ~~Add stat to muons~~
  - New physics couplings are different?
  - Higher rate of virtual photons $\gamma^* \to \ell\ell$

LU tests in $b \to s\ell^+\ell^-$

LHCb arXiv:2103.11769



- Results much more precise than previous experiments
- Measured in several $b \to s\ell\ell$ decay channels
  - Coherent pattern of deviations!
- If confirmed, it would be a clear sign of physics beyond the SM



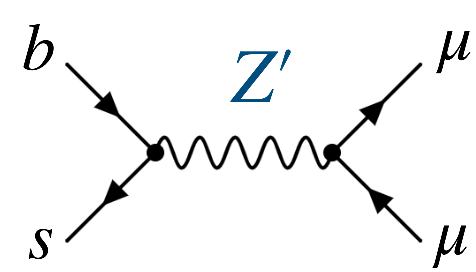
What next?

Connection to **high energy**:

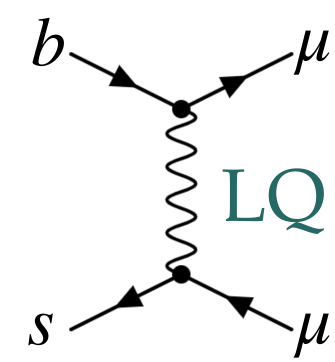
$$\frac{g_{\mathrm{NP}}^2}{\Lambda_{\mathrm{NP}}^2} \sim \frac{1}{(30\ \mathrm{TeV})^2}$$

$\rightarrow$ Could be out of reach for the LHC

Tree level candidates:



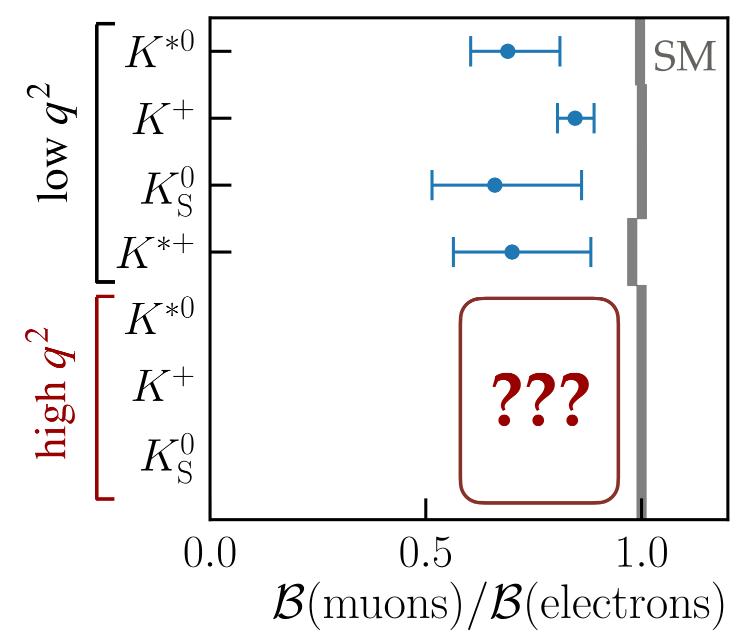
or



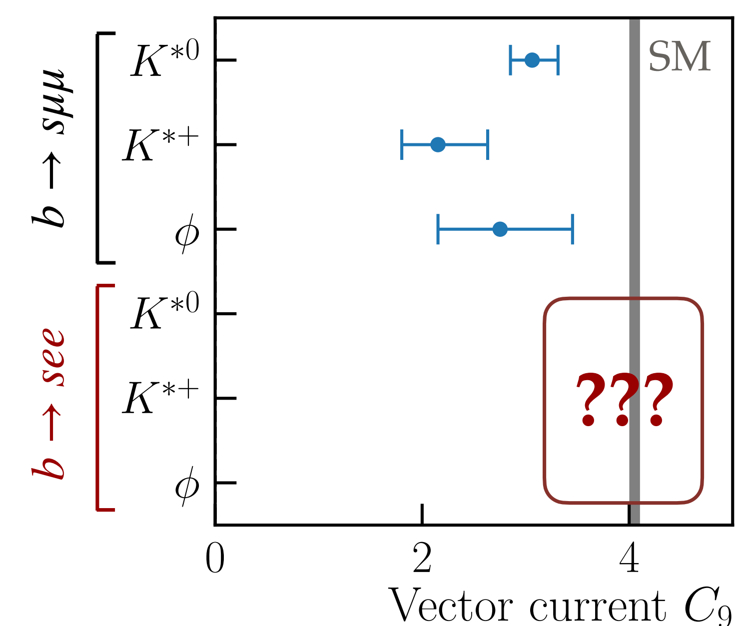
…still a lot to do at **low energy**

- Measure at other experiments
  - Results from Belle II, CMS, ATLAS might take years to reach the current LHCb sensitivity
- More measurements at LHCb
  - More decay channels ($K\pi\pi$, ϕ, $\Lambda^{(*)}$)
  - LU tests at high q^2 above $\psi(2S)$
  - $b \rightarrow see$ angular analyses
  - Searches for LFV decays ($e\mu$, $\mu\tau$, $e\tau$)

Branching ratios

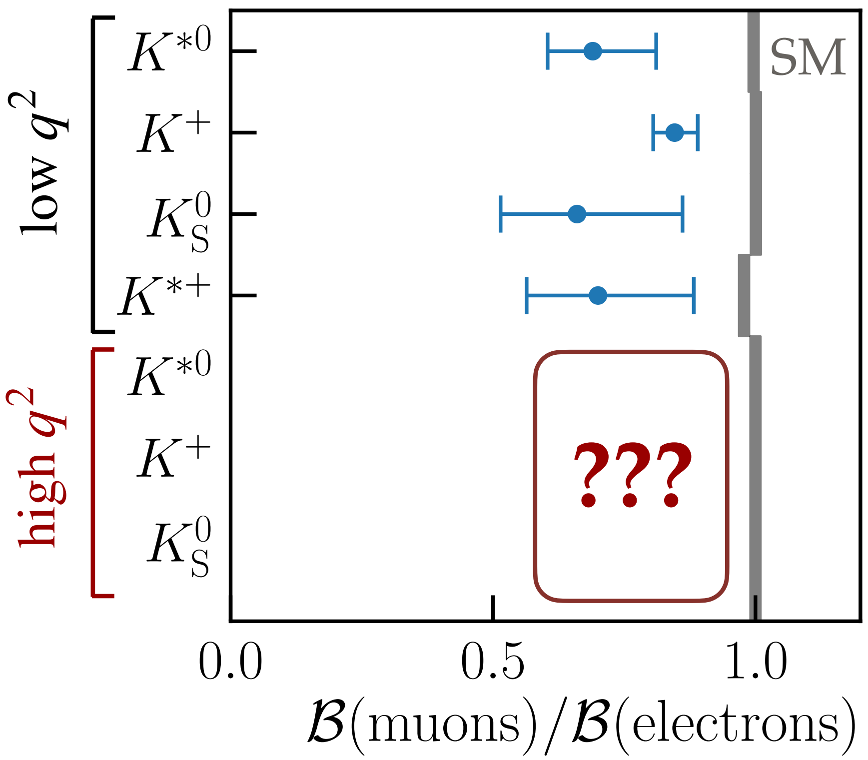


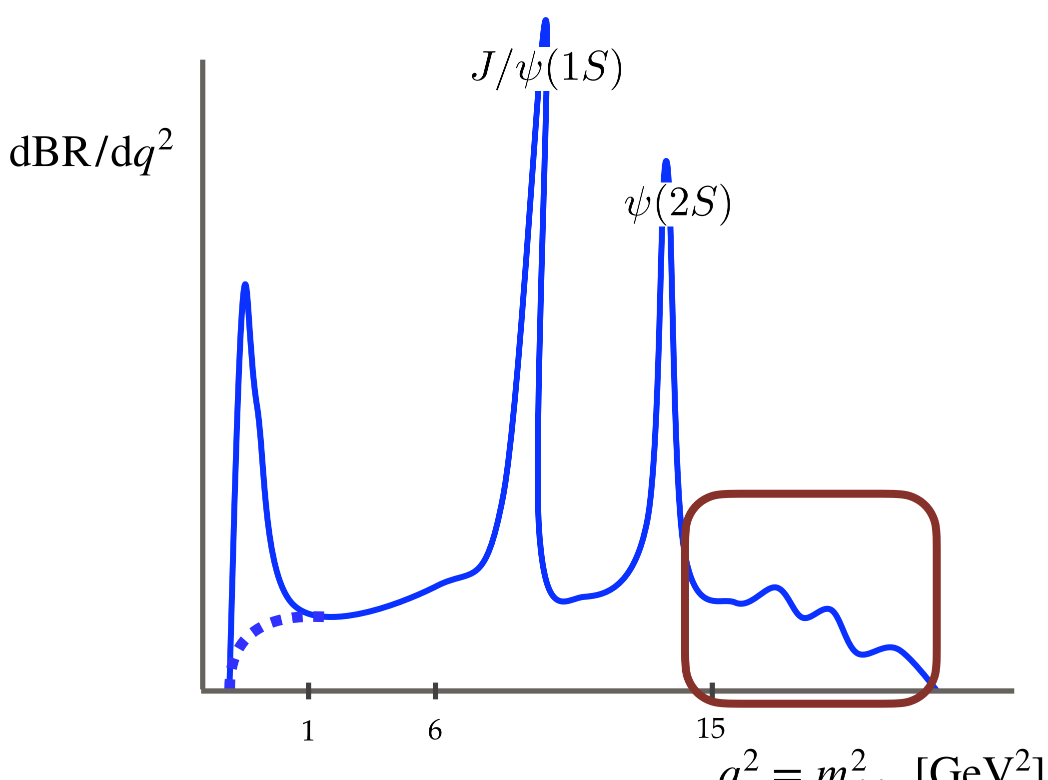
Angular analyses

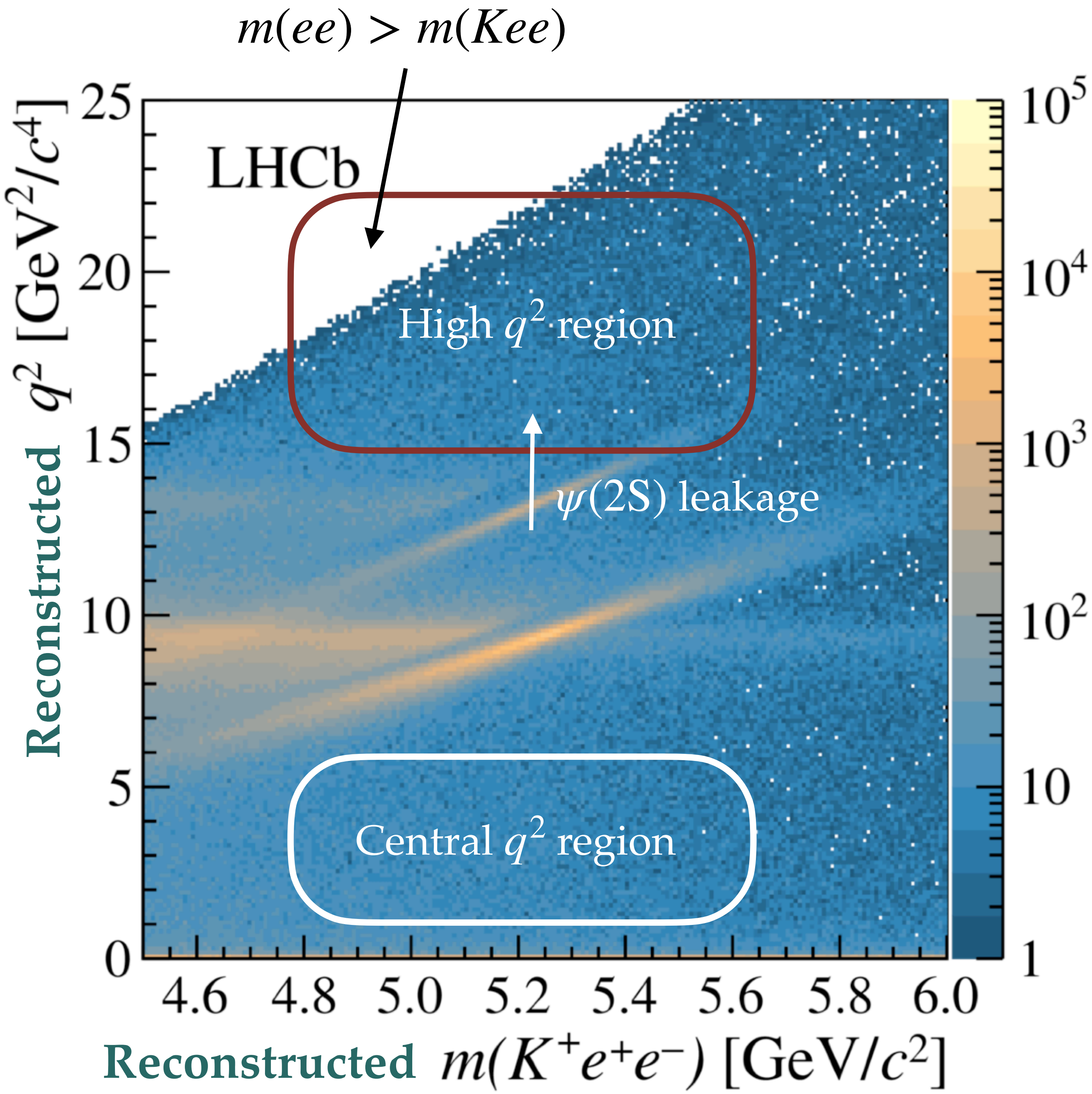


Future Prospects

High q^2

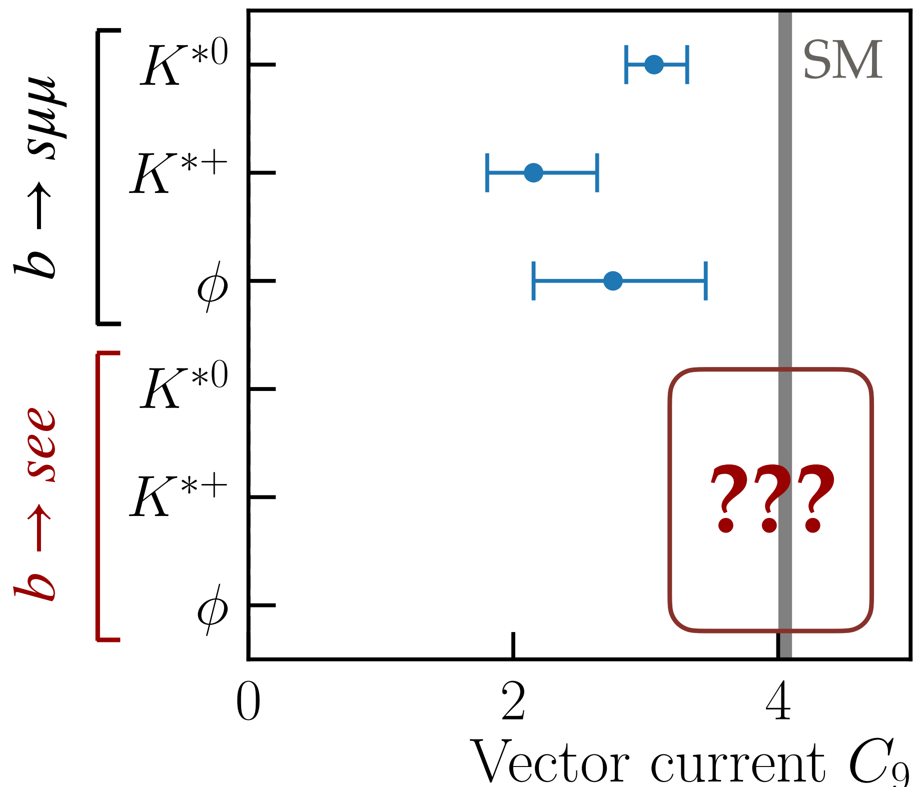






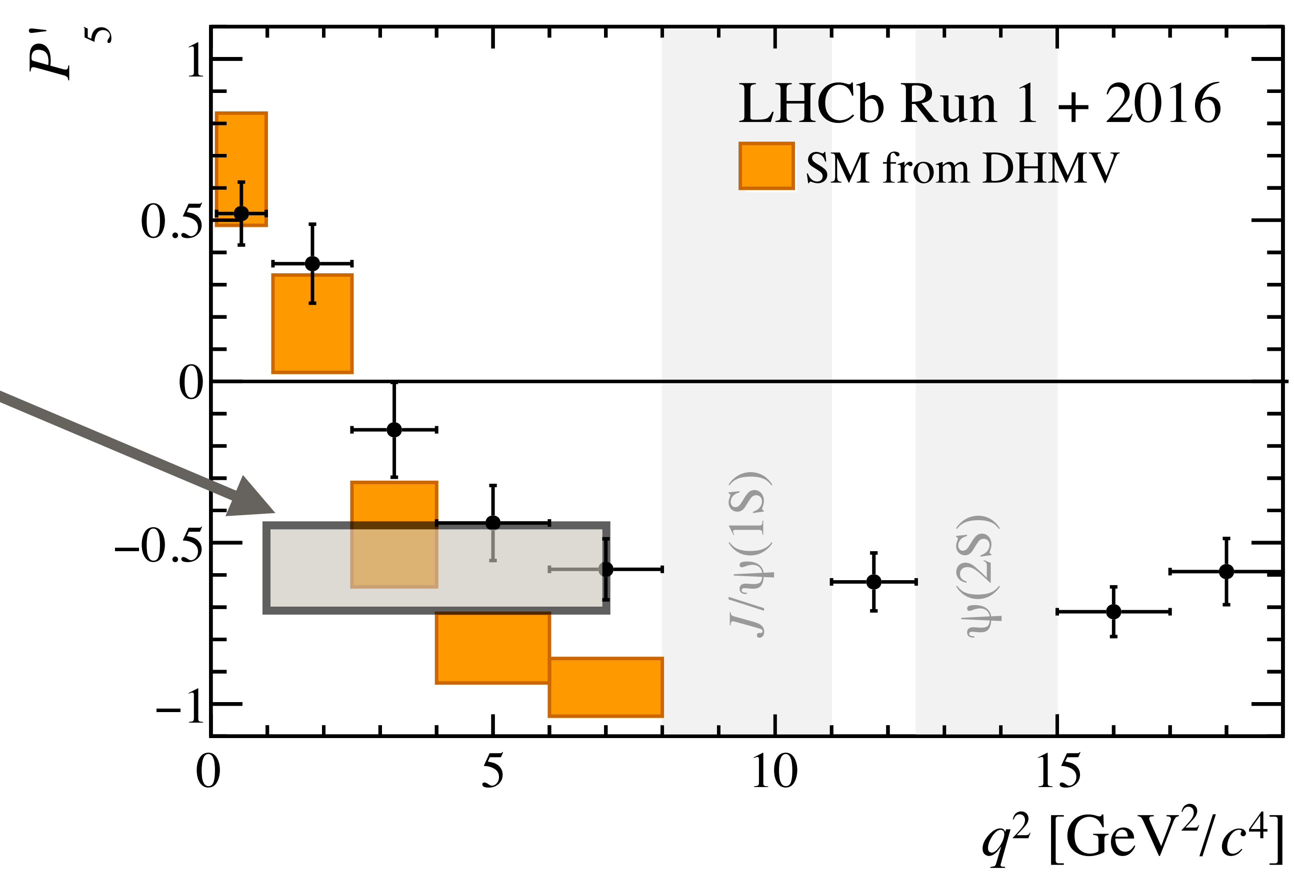
Future Prospects

$b \to see$ angular analyses



- Challenges of $b \to see$ angular analysis:
  - Angular modelling of backgrounds
  - Multi-dimensional low-stat fit
  - Hard to do fine q^2 bins (bad resolution)

Rough sensitivity of $B^0 \to K^*ee$ angular analysis in [1,7] GeV^2 bin with Run 1+2 dataset



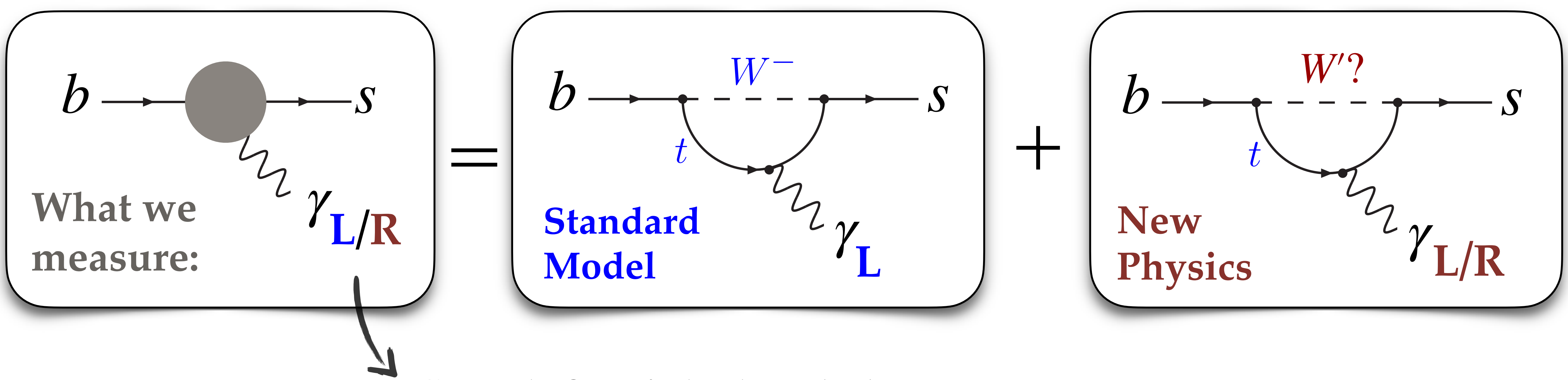
Possible improvements:

- Finer q^2 binning
- Bins at lower/higher q^2

$$Virtual\ photons\ \gamma^* \rightarrow e^+e^-$$

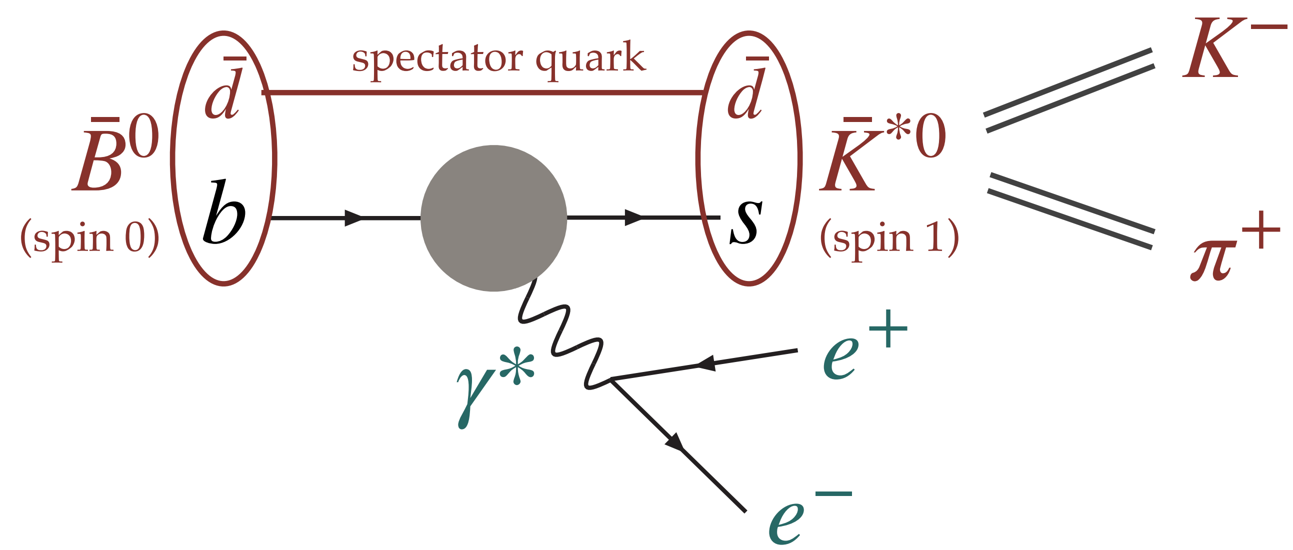
$b \to s\gamma$ with electrons

- $b \to s\gamma$ suppressed by SM symmetries
  - A golden channel of the precision frontier
  - Could receive large contributions from heavy particles



Search for right-handed current

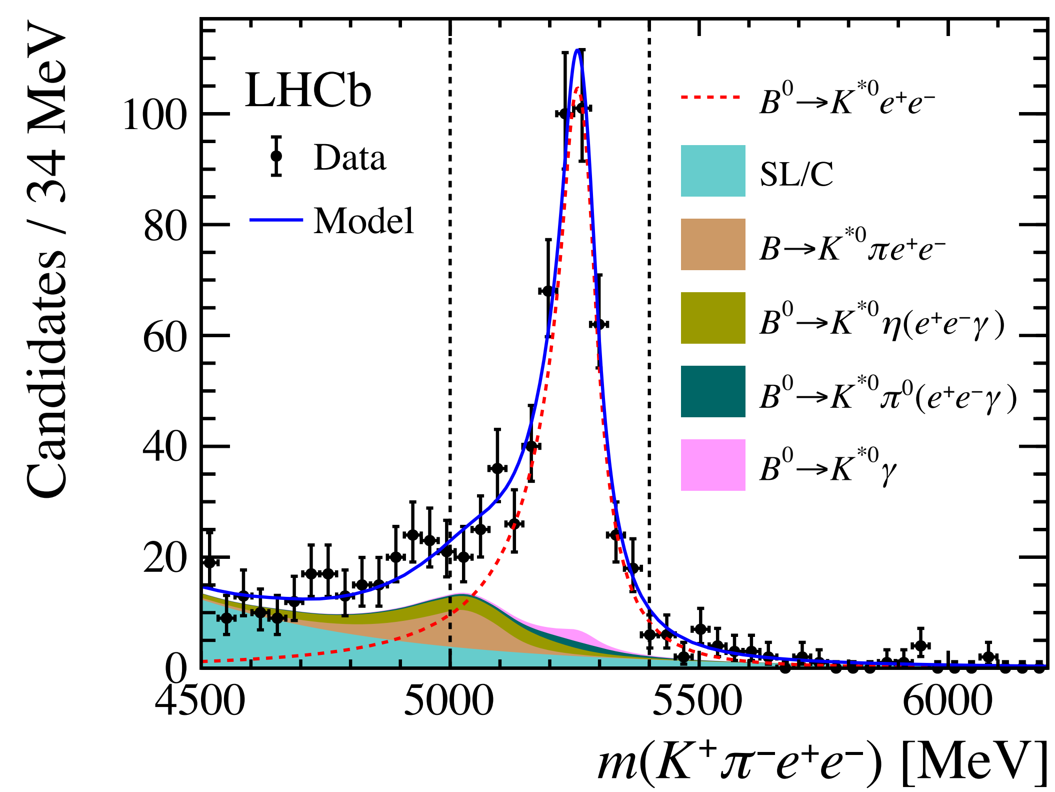
$b \to s\gamma$ in $B^0 \to K^* e^+ e^-$



- ✓ Use $\gamma^* \to e^+e^-$ to measure photon polarisation!
- ✓ Get nice $K^-\pi^+e^-e^+$ final state
- ◉ Rate lower by $\alpha_{\text{e.m.}}$

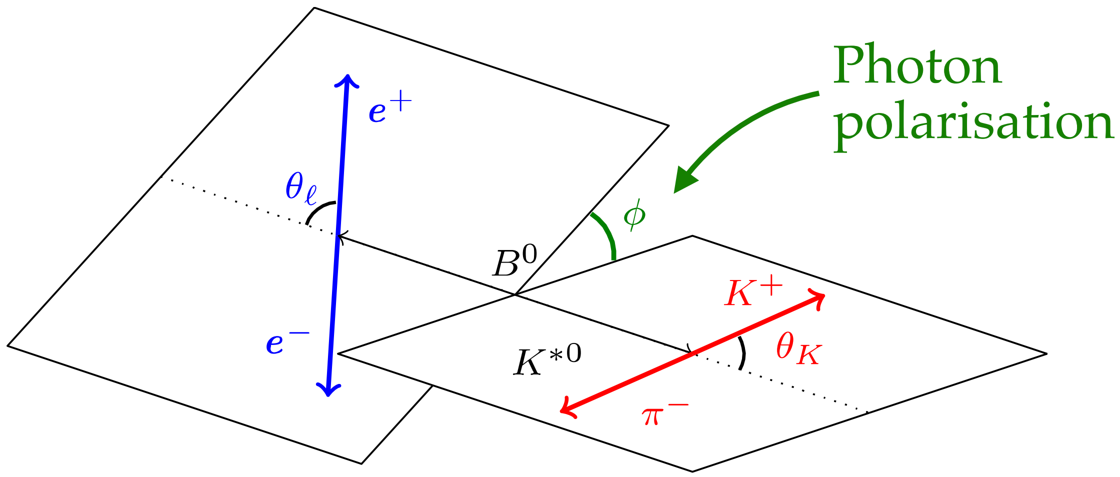
$B^0 \to K^*\gamma^*$ analysis

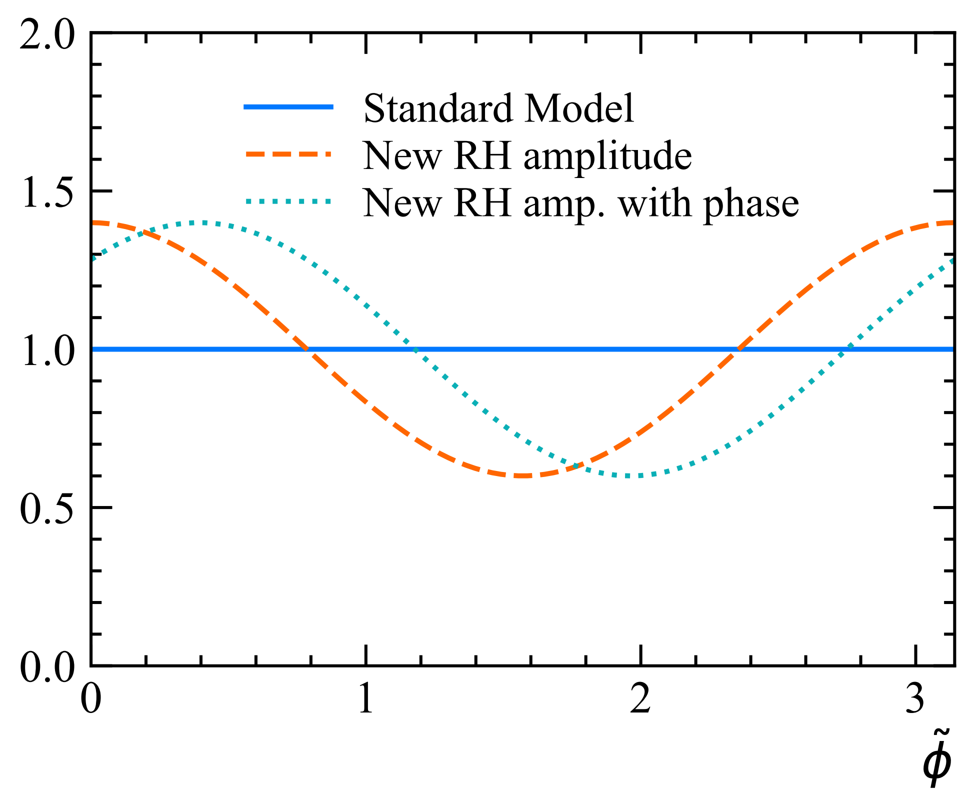
- Select $B^0 \to K^*\gamma^*$ with $\gamma^* \to e^+e^-$ requiring $m(ee) < 0.5$ GeV
  - About 500 events with LHCb dataset despite BR $\sim 2 \times 10^{-7}$

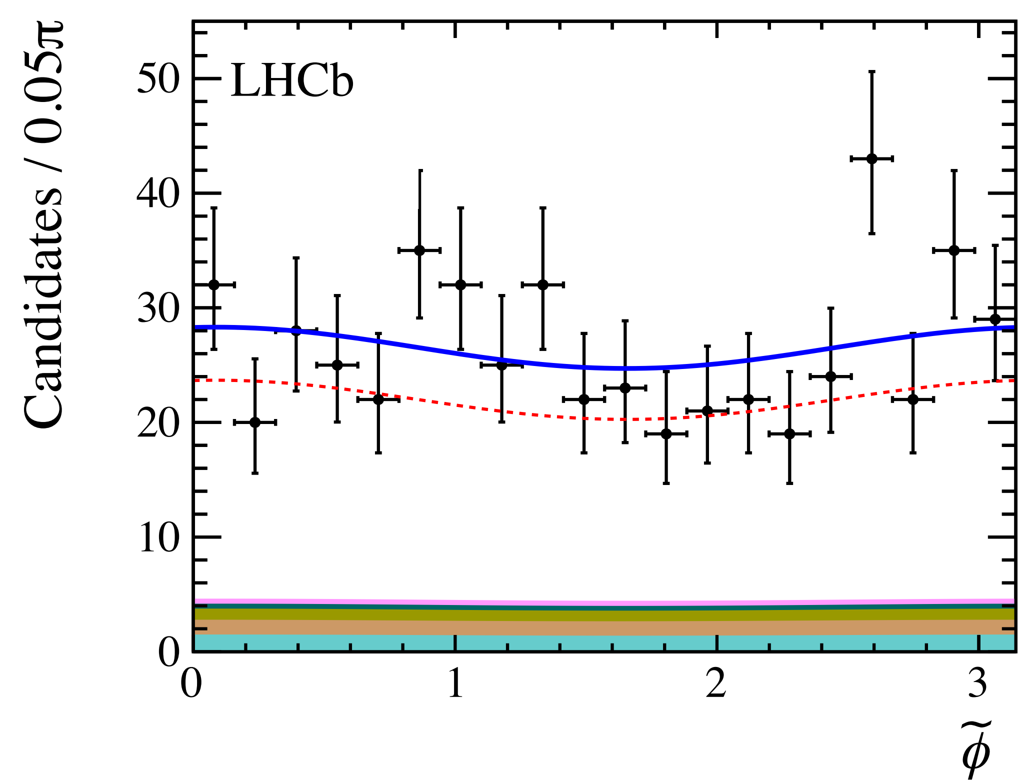


$B^0 \to K^*\gamma^*$ analysis

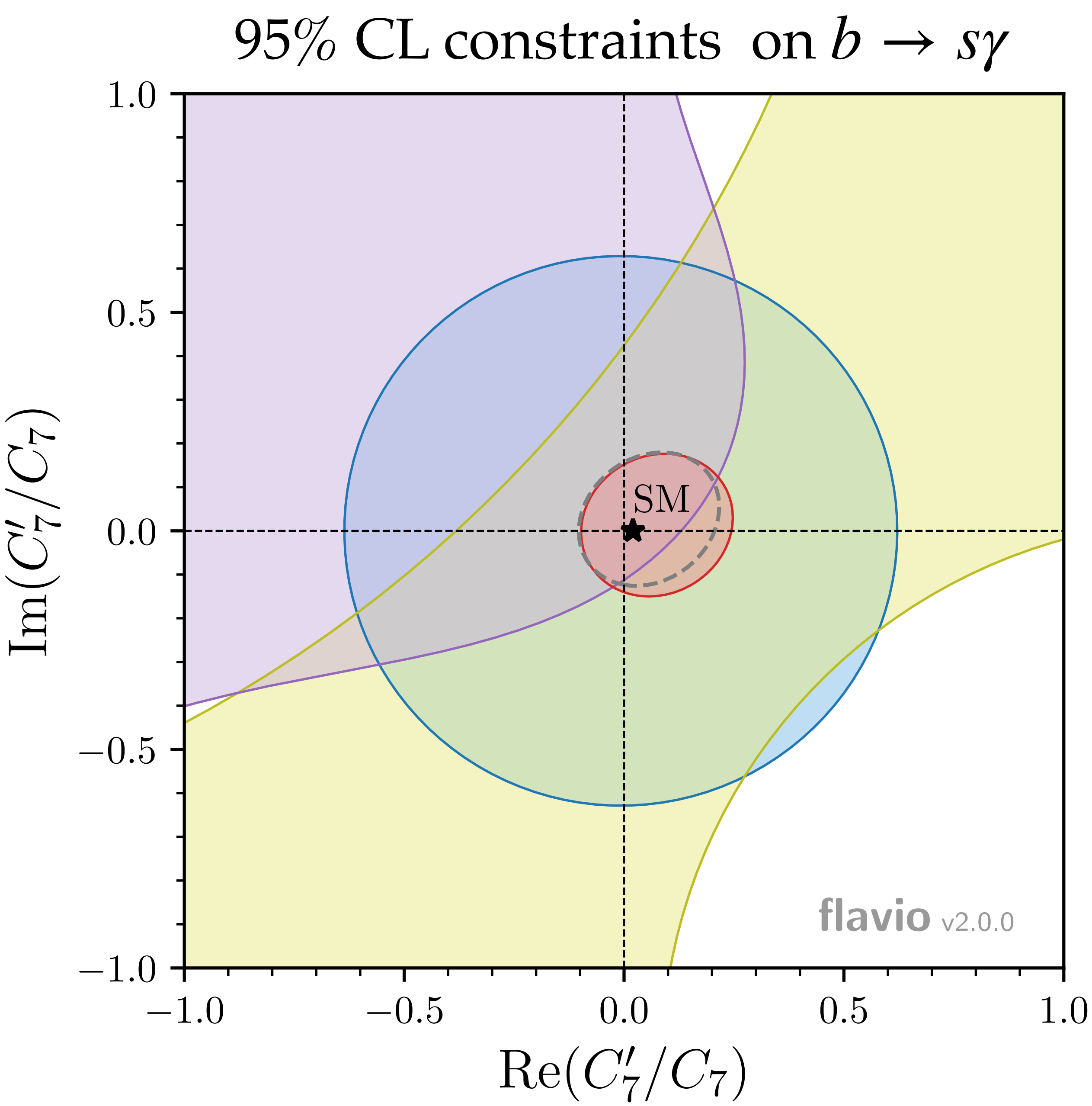
- $B^0 \to K^+\pi^-e^+e^-$ described by 3 angles
  $\rightarrow$ Full 3D angular analysis performed
- Photon polarisation measured with ϕ
  - $\cos 2\phi$ or $\sin 2\phi$ modulation would signal right-handed contribution

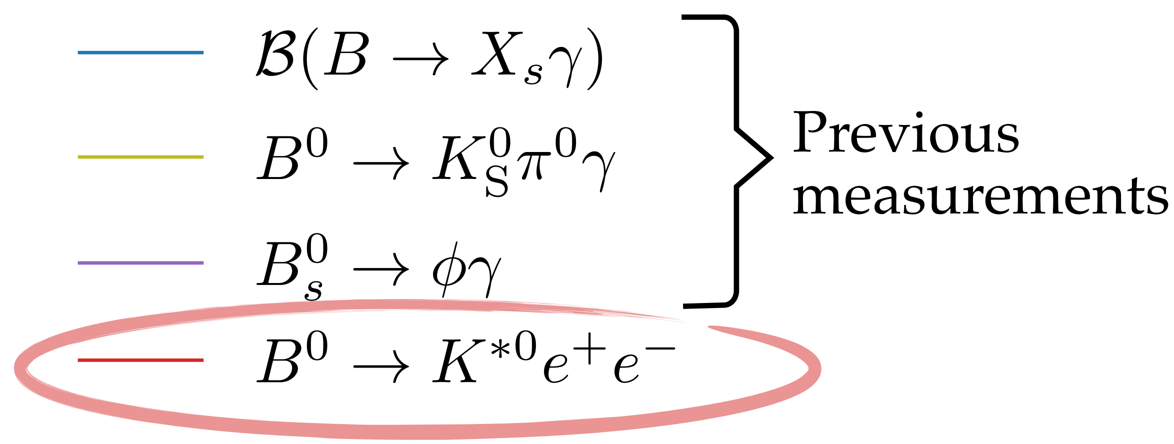






$B^0 \to K^*\gamma^*$ analysis





- Virtual-photon technique much more precise than real-photon
- Key part of the global $b \to s\ell\ell$ picture of anomalies
- **Made possible by developments in electron reconstruction at LHCb**

$C_7'/C_7 = \mathrm{RH/LH}$

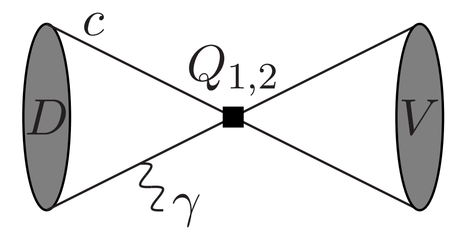
$C_7^{(\prime)}$ is $b \to s\gamma$ Wilson coefficient

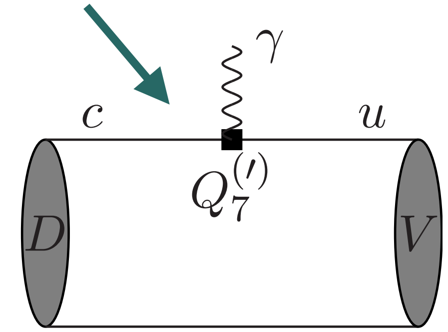
Exploring $c \to u\gamma$

- Unique sensitivity to up sector
- GIM suppressed → very sensitive to NP
  - $C_7^{bs} \simeq -0.3$ while $C_7^{cu} \simeq -10^{-3}$
  - Large contributions from LQ and SUSY
- Measure $D^0 \to V\gamma$ polarisation
  - Never done before (only BRs by Belle and BaBar)
  - Can use virtual photon technique!
- Can use data-based approach to tackle theoretical uncertainties on chirality amplitudes:
  - $\bar{K}^{*0}$ and ϕ are dominated by weak annichilation (WA)
  - Measure $\bar{K}^{*0}$ and ϕ and infer chirality predictions for ρ^0 (assuming U-spin holds)
  - $A_{L,R}^{\mathrm{SM}}\left(\rho^0\right) = A_{L,R}\left(\bar{K}^{*0}\right) \times [\text{ U-spin corrections }]$
  - Sizeable systematic related to procedure, but no measurement so far!

Anything here is NP
(SM is GIM suppressed)

Weak annihilation





Gudrun Hiller and Stefan de Boer arXiv:1802.02769
propose an analysis similar to $B_s \to \phi\gamma$

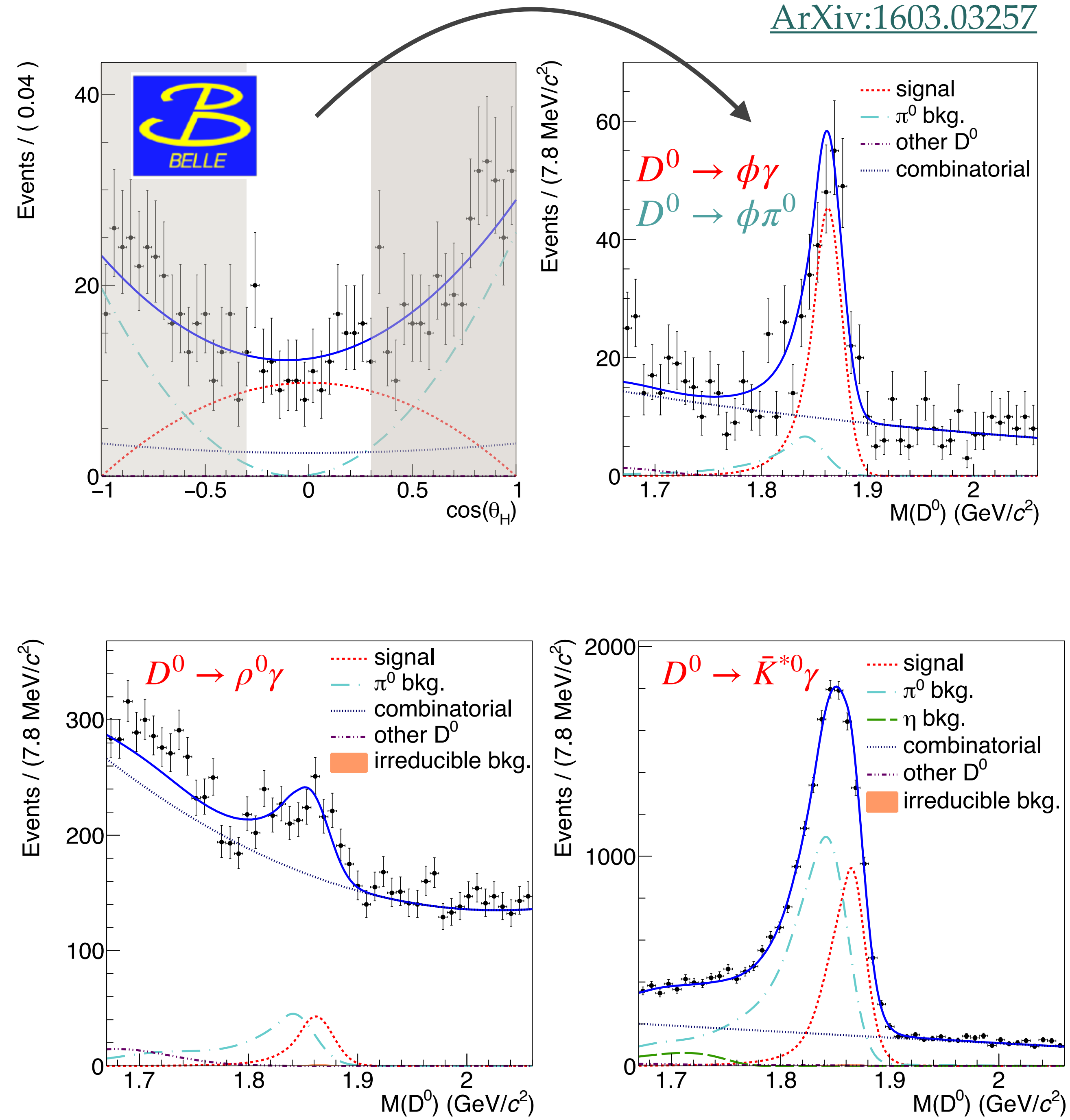
A significantly different polarisation between $\bar{K}^{*0}$ (or ϕ) and ρ^0 would be a clear sign of NP!

Future Prospects

$c \to u\gamma$ at LHCb

- Can select $D^0 \to V\gamma^*(ee)$ efficienctly in Upgrade LHCb (no trigger bottleneck)
- Challenging $D^0 \to V\pi^0(ee\gamma)$ background
  - Can fight with $\cos\theta_V$ ($F_L = 1$ instead of 0)
  - Can play with Brem adding procedure
- $B(D^0 \to K^*(K^+\pi^-)e^+e^-)_{\text{low } q^2} \simeq 2 \times 10^{-6}$
  - Expect thousands of events
- $B(D^0 \to \rho(\pi^+\pi^-)e^+e^-)_{\text{low } q^2} \simeq 1 \times 10^{-7}$
  - Hundreds of signal events
  - Hard to estimate amount of bkg
- $B(D^0 \to \phi(K^+K^-)e^+e^-)_{\text{low } q^2} \simeq 1 \times 10^{-7}$
  - Hundreds of signal events
  - Less combinatorial thanks to narrow ϕ
  - Less $\pi^0 \to ee\gamma$ according to Belle analysis

ArXiv:1603.03257



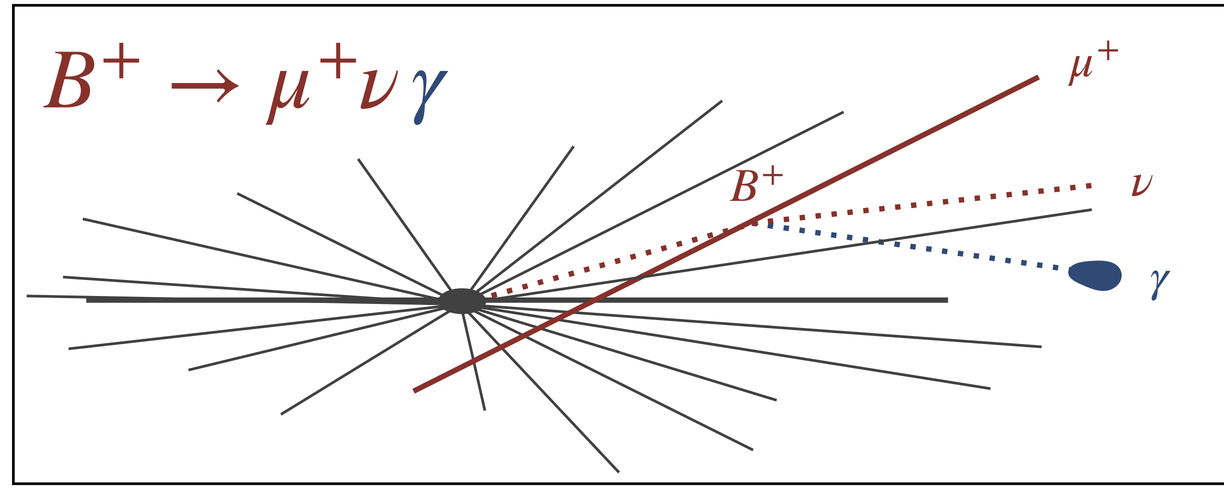
Future Prospects

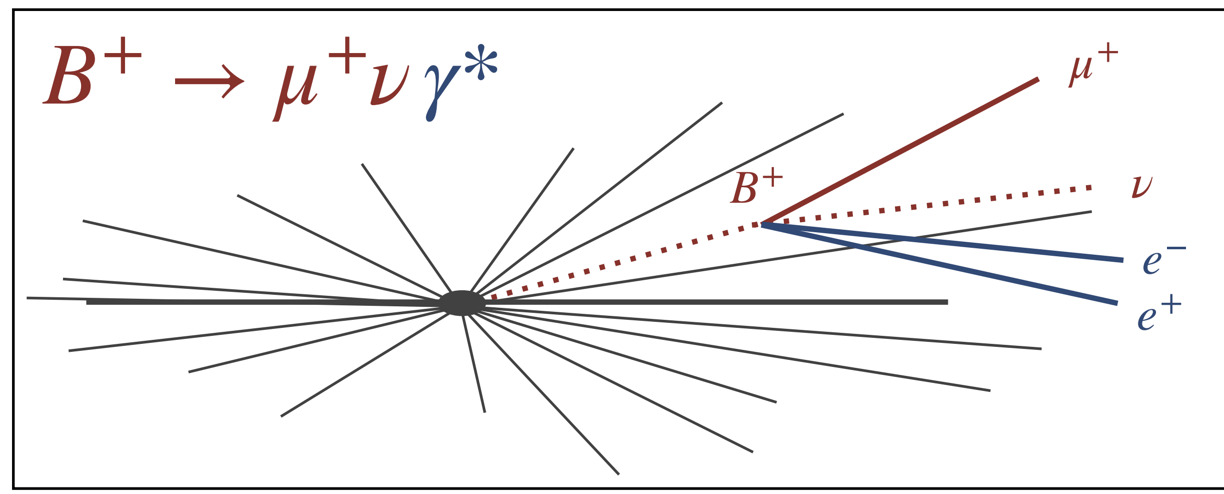
$B^+ \to \mu^+\nu\gamma$

- $B^+ \to \mu^+\nu\gamma$ unique probe of B internal structure
  - Crucial input to predictions (including those for $b \to s\ell\ell$ anomalies)
- $B^+ \to \mu^+\nu\gamma$ impossible at LHCb
  $\to$ use virtual photon $B^+ \to \mu^+\nu\gamma^*$

Eur.Phys.J.C 79 (2019) 8, 675

- LHCb searched $B \to \mu^+\nu\mu^+\mu^-$
  - $\mathrm{BR}(B^+ \to \mu^+\nu\mu^+\mu^-) < 1.6 \times 10^{-8}$
  - Harder to interpret than $B \to \mu^+\nu e^+e^-$ (two identical μ^+, large ρ, ω contribution)
- Expect $B \to \mu^+\nu e^+e^-$ to have $10\times$ larger BR
  $\to$ Could lead to first observation of $B^+ \to \mu^+\nu\gamma$





$$\mathrm{Br}\left(B^+ \to \mu^+\mu^-\mu^+\bar{\nu}_\mu\right) = \left(3.5 \pm 0.4_{\lambda_b} \pm 2.0_{\text{weak ffs}}\right) 10^{-8}$$
$$\mathrm{Br}\left(B \to e^+e^-\mu\nu_\mu\right) = \left(4.5 \pm 0.2_{\lambda_b} \pm 0.27_{\text{weak ffs}}\right) 10^{-7}$$

M.A.Ivanov and D.Melikhov, Phys.Rev.D 105 (2022) 1, 014028

Recent theory developments:
* Bharucha, Kindra, Mahajan *arXiv:2102.03193*
* Beneke, Böer, Rigatos, Keri Vos *Eur.Phys.J.C 81 (2021) 638*
* Janowski, Pullin, Zwicky *JHEP* 12 (2021) 008

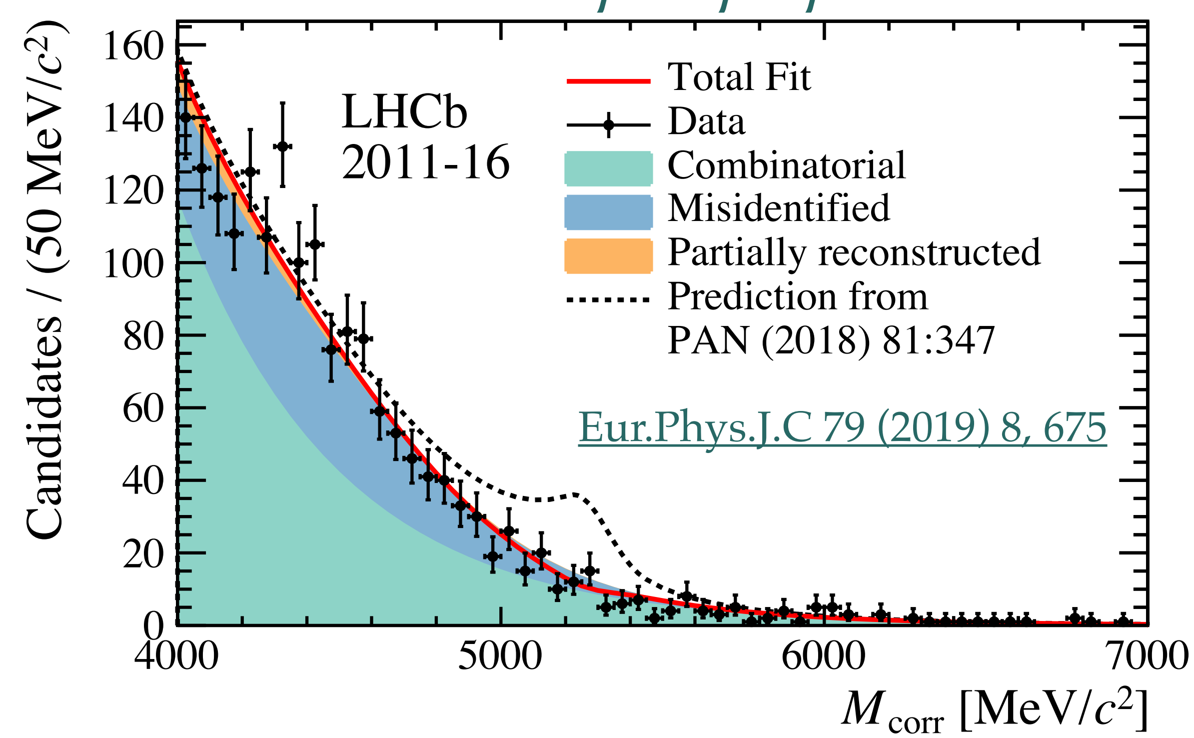
Future Prospects

$B^+ \to \mu^+\nu\gamma$

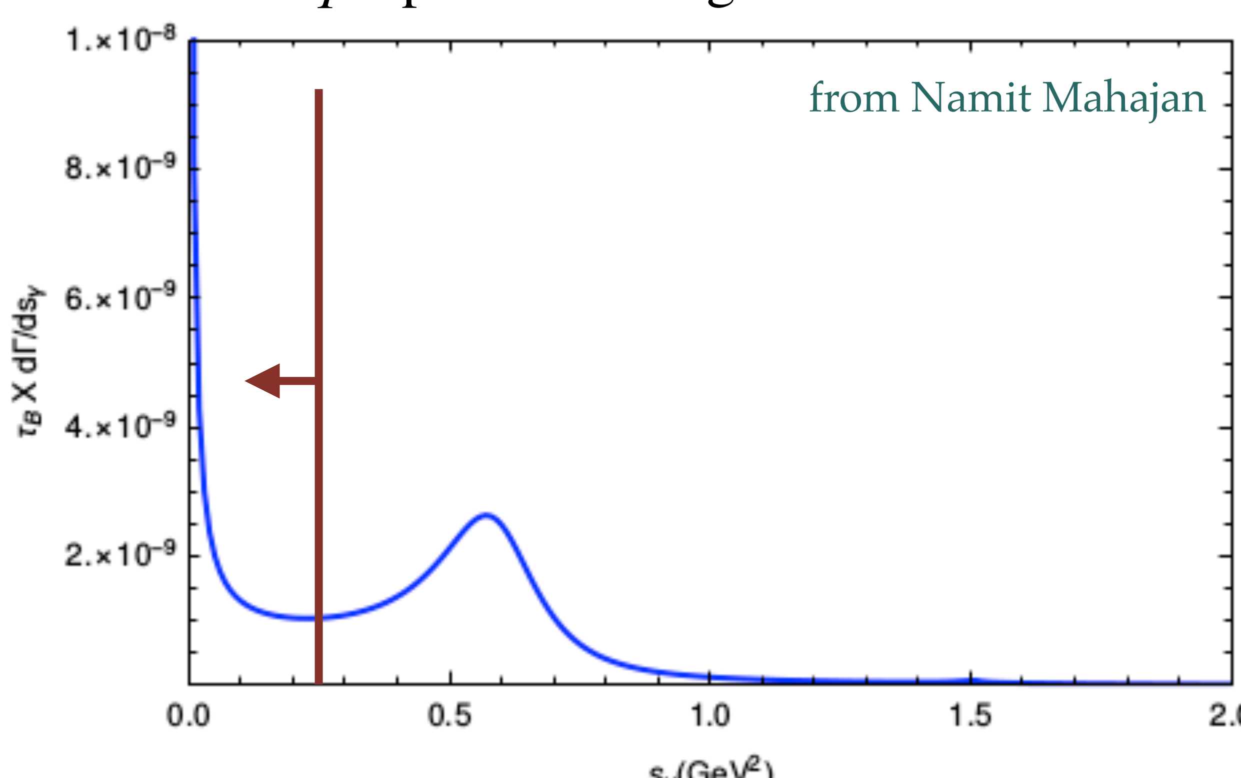
Analysis strategy

- Use corrected mass technique
  - missing brem energy should not matter
- Require $m(ee) > 20$ MeV to veto photon conversions
  - Could also search channel with converted photon, but worse vertex
- Require $q^2 < 0.25$ GeV^2
  - Removes most contributions from light mesons
- Normalise to $B^0 \to K^*\gamma$

$B^+ \to \mu^+\nu\mu^+\mu^-$



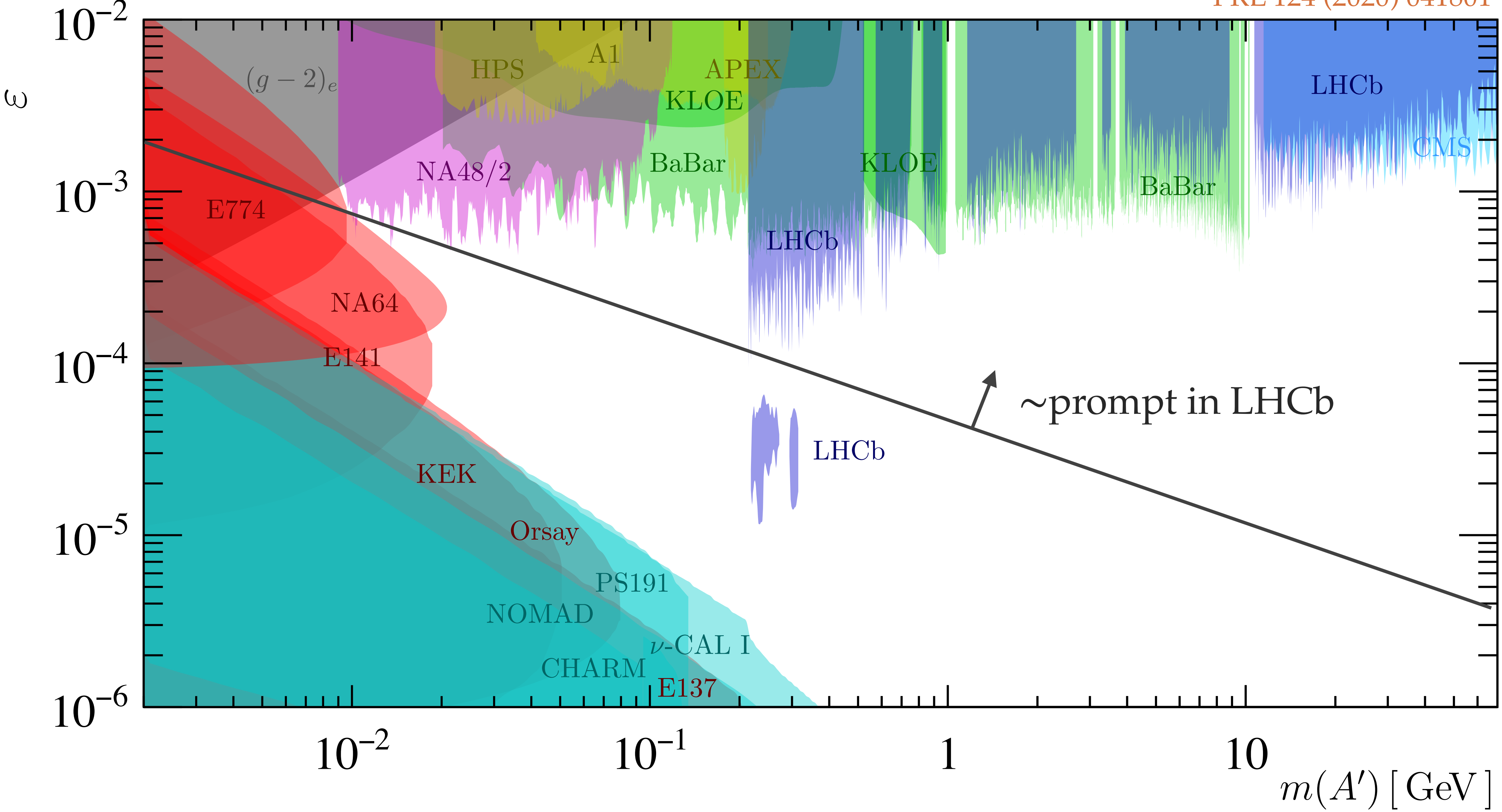
q^2 spectrum using LO form factors



Light new physics particles

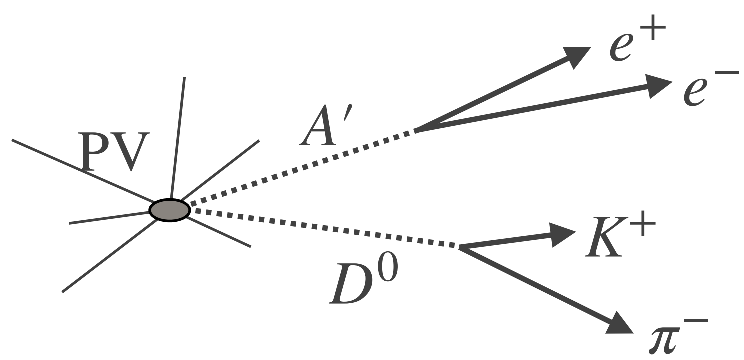
Visible Dark photons

PRL 124 (2020) 041801



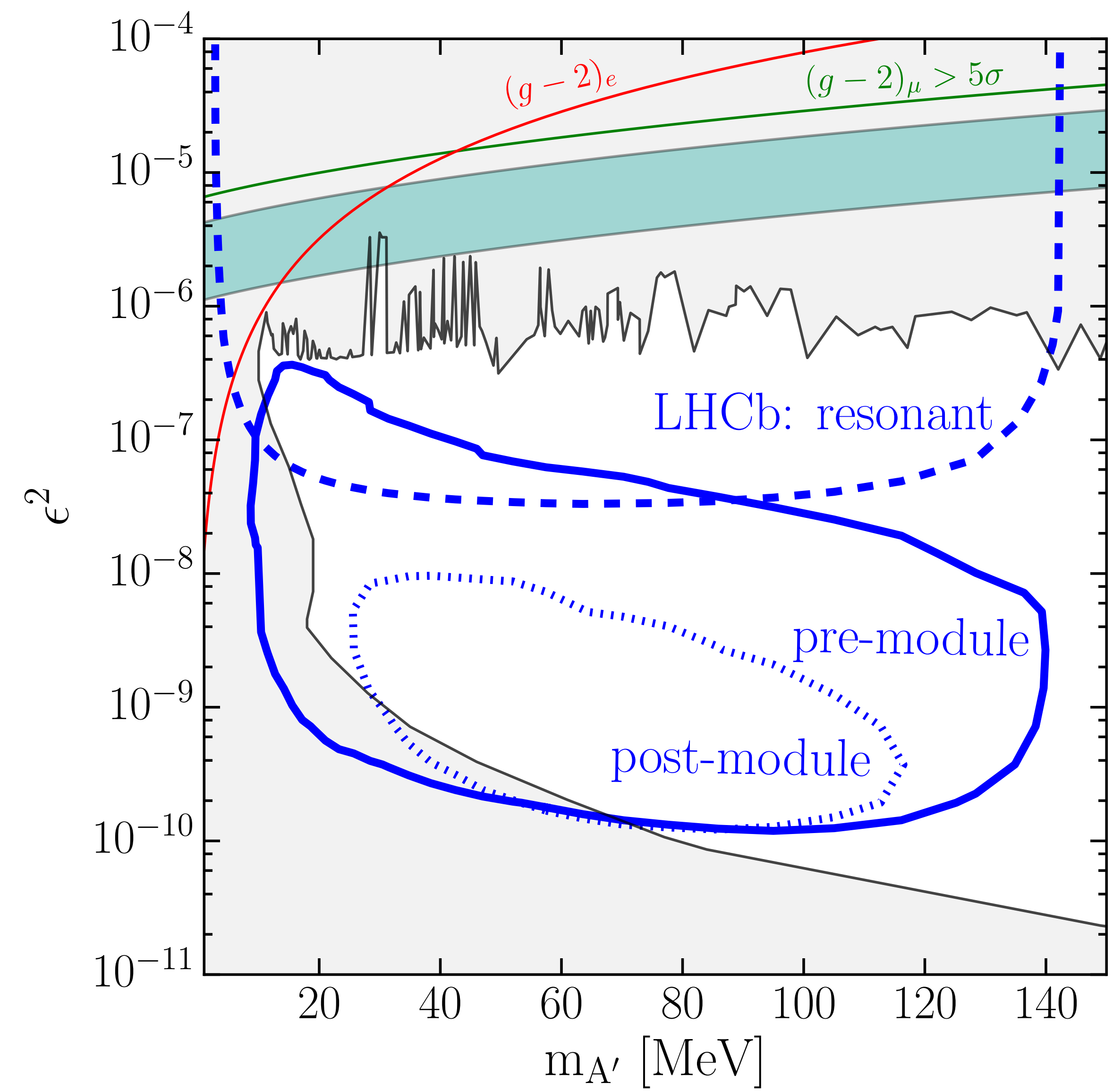
Dark Photons below $2m_\mu$

Ilten, Thaler, Williams, Xue PRD 92 no.11, 115017 (2015)



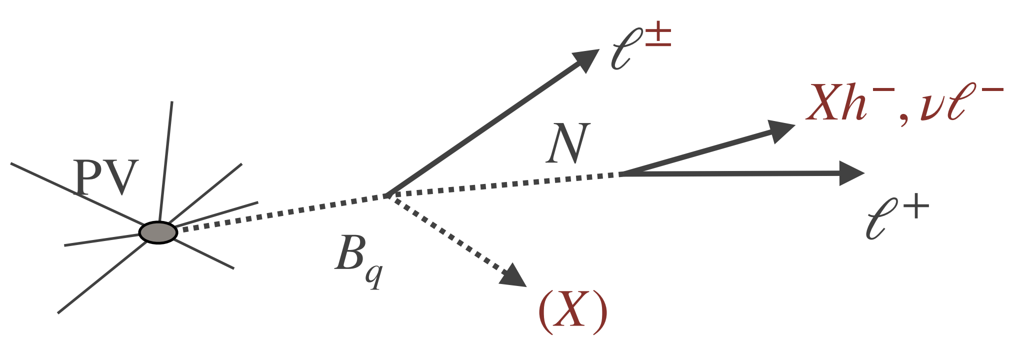
- Can cover region below $2m_\mu$ using charm decays $D^{*0} \to D^0 A'(ee)$
  - Requires upgraded trigger to select efficiently soft final state
  - Get **300×10⁹** $D^{*0} \to D^0\gamma$ **per fb⁻¹**
  - Can use $D^{(*)}$ mass constraint to correct bremsstrahlung losses
  - At these p electrons emit light in RICH while pions don't → excellent PID
  - Both displaced and prompt searches

$$\tau_{A'} \propto \frac{1}{\epsilon^2 m_{A'}}$$



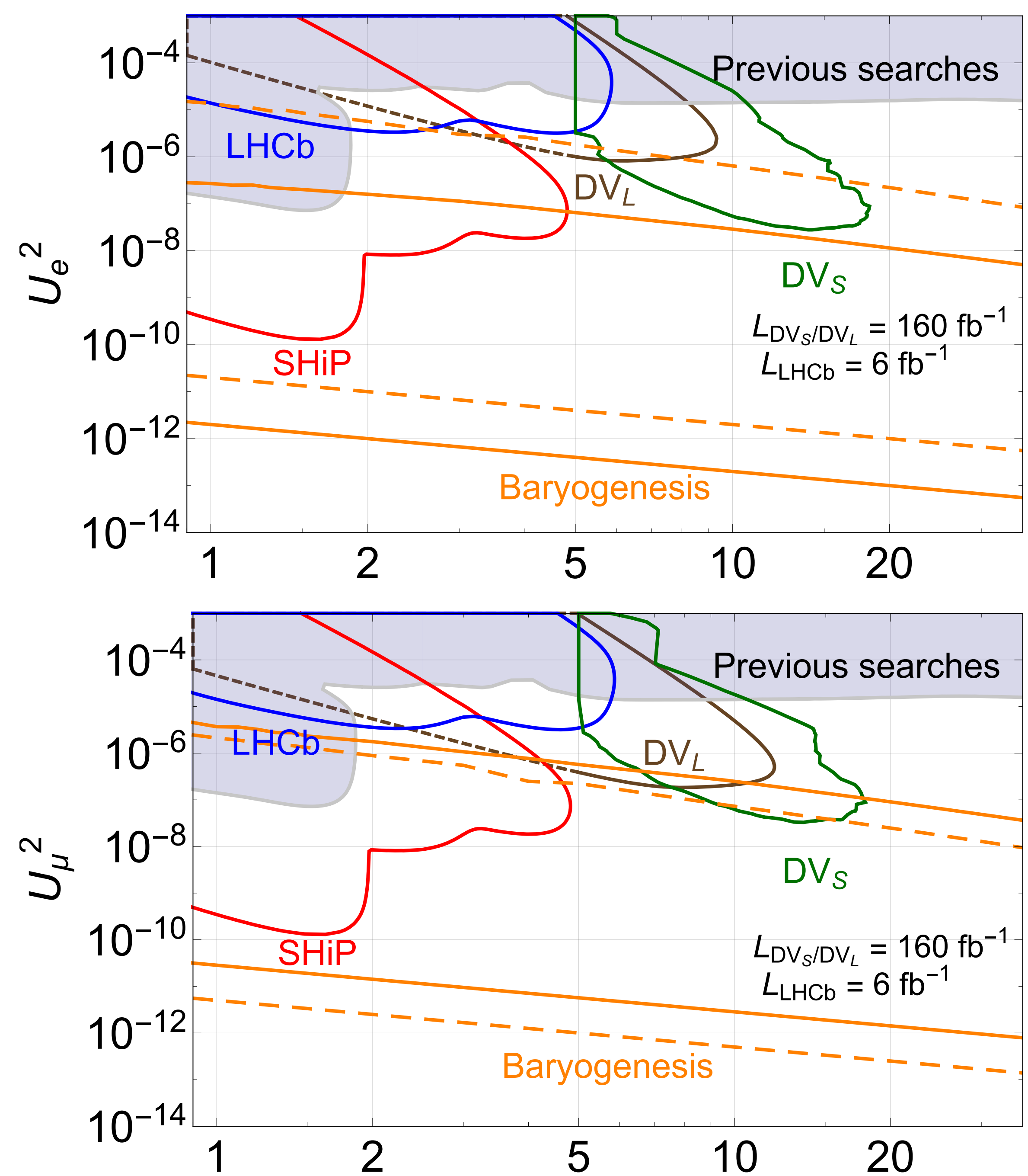
Heavy neutral leptons

- GeV-scale Heavy neutral leptons (N)
  - About 10^{11} $B \to D^{(*)}\ell\nu$ in Run 3
  - Often out of acceptance: $\tau_N \propto \dfrac{1}{U^2 m_N^5}$



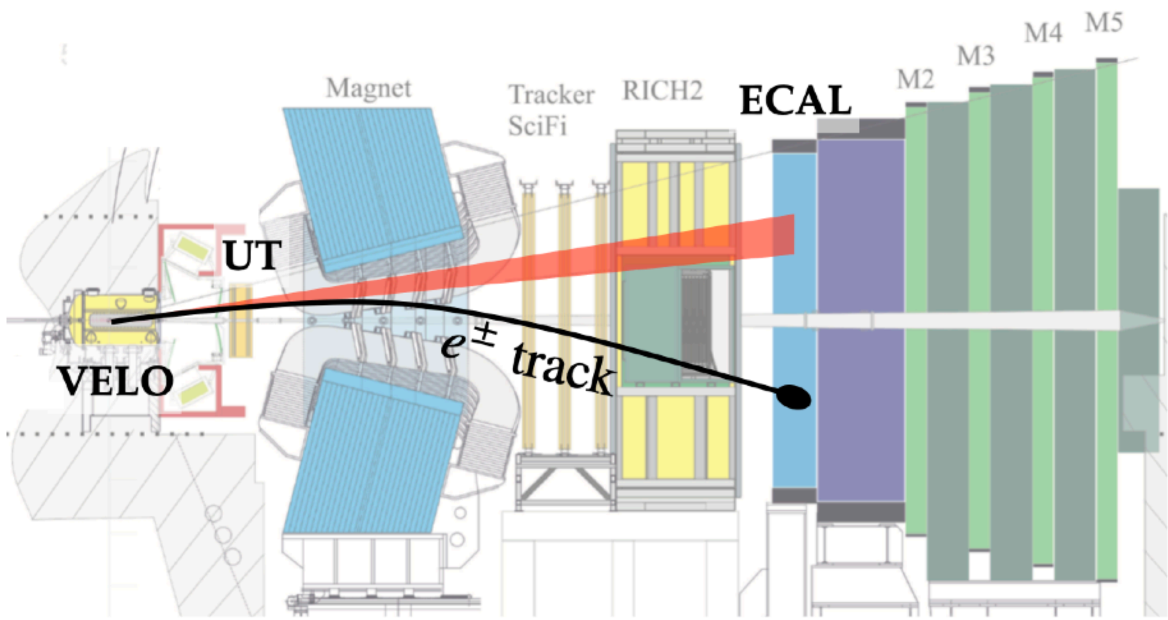
- To explore U_μ^2 and U_e^2 mixings can use:
  - $B \to D^{(*)}\mu N(\mu\pi)$ and $B_{(c)} \to \mu N(\mu\, e\nu_e)$
  - $B \to D^{(*)}eN(e\pi)$ and $B_{(c)} \to eN(e\,\mu\nu_e)$

I.Boiarska, K.Bondarenko et al, arXiv:1902.04535



Conclusions

- Doing electrons at LHCb
  - Challenging due to ID and brem
  - Great improvements in analysis techniques
  - Trigger bottleneck removed in LHCb Upgrade



- What we do with electrons
  - Growing number of lepton universality tests
  - Use $\gamma^* \to e^+e^-$ to get vertex or photon polarisation
  - Search for light particles preferring electrons due to kinematic (A') or lepton-dependent couplings (HNL)