Lepton Physics at LHCb

Preema Pais
EPFL

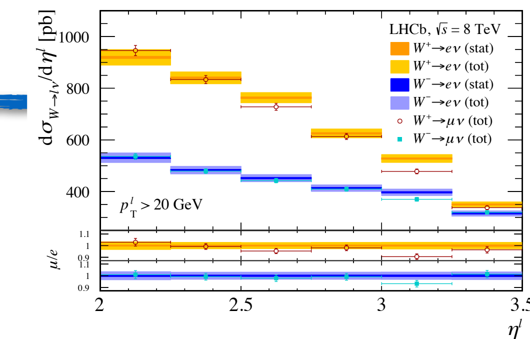
On behalf of the LHCb Collaboration

NuFact 2017
May 26, 2017
University of Uppsala

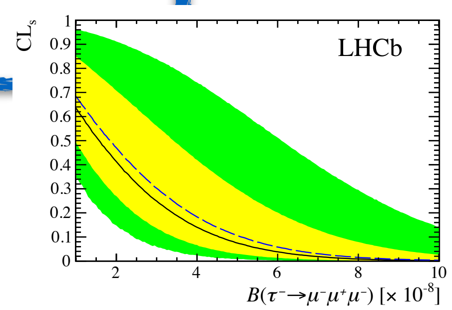
Physics with Leptons at LHCb

- Diverse physics program with leptonic and semi-leptonic final states
  - (Non-exhaustive) sampling:

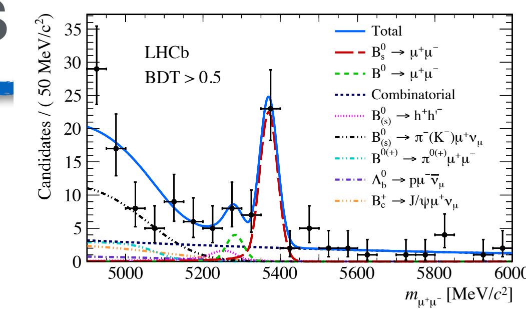
SM W,Z production measurements



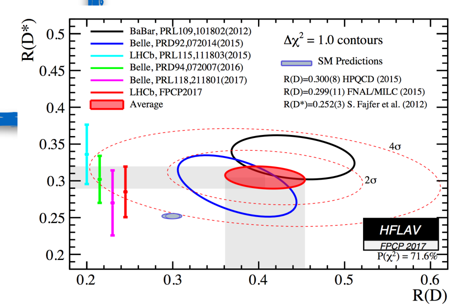
Searches for lepton flavour violation



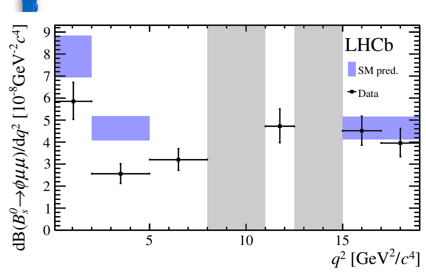
Very rare decays



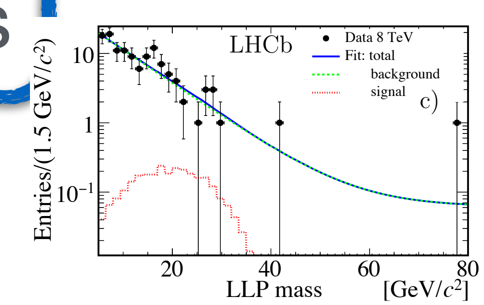
Lepton flavour universality tests



EW penguins



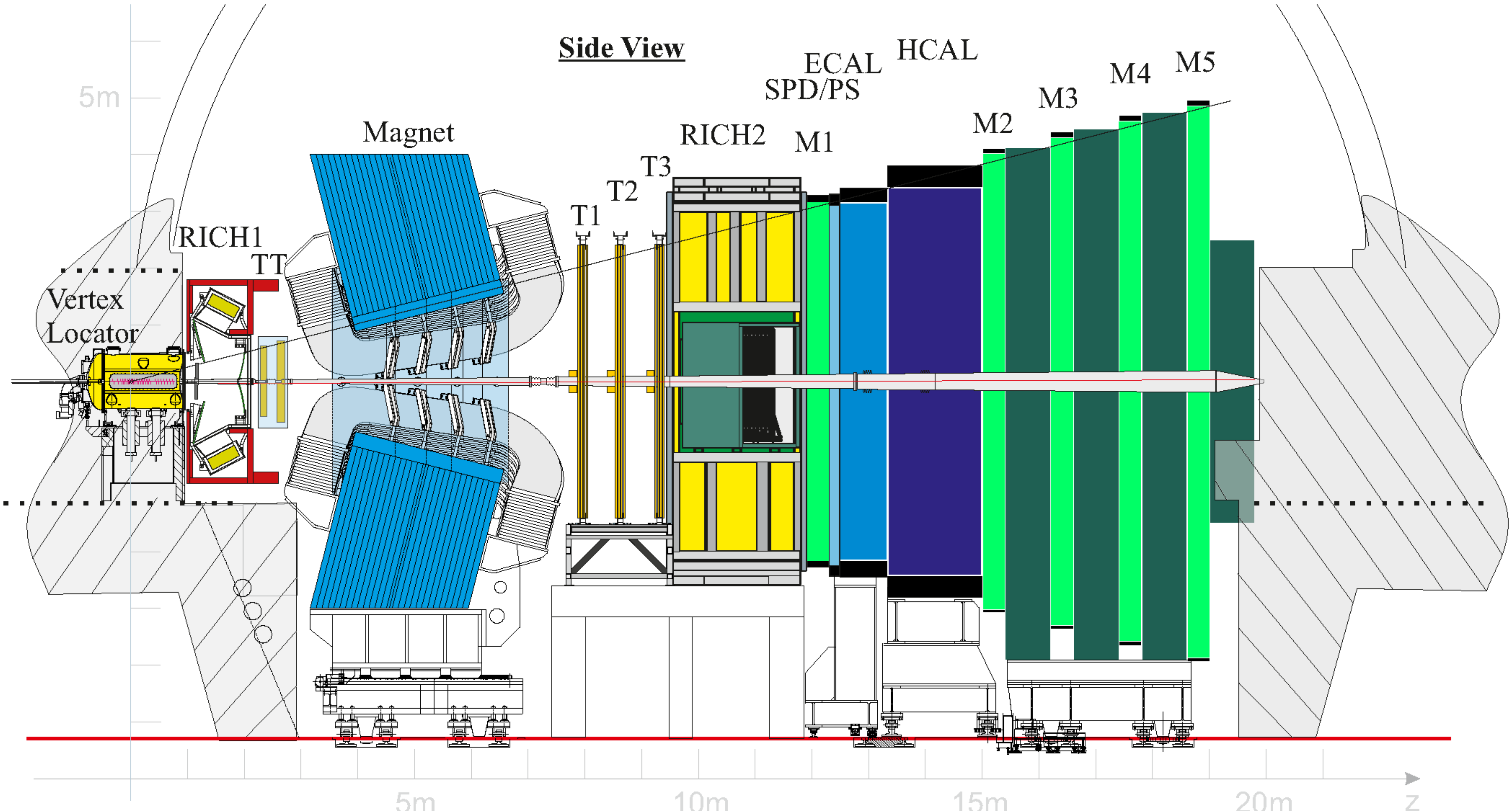
Exotica searches



Many recent results - will only cover a few in this talk!

THE LHCb DETECTOR

Single-arm spectrometer instrumented in the forward (2 < η <5) region

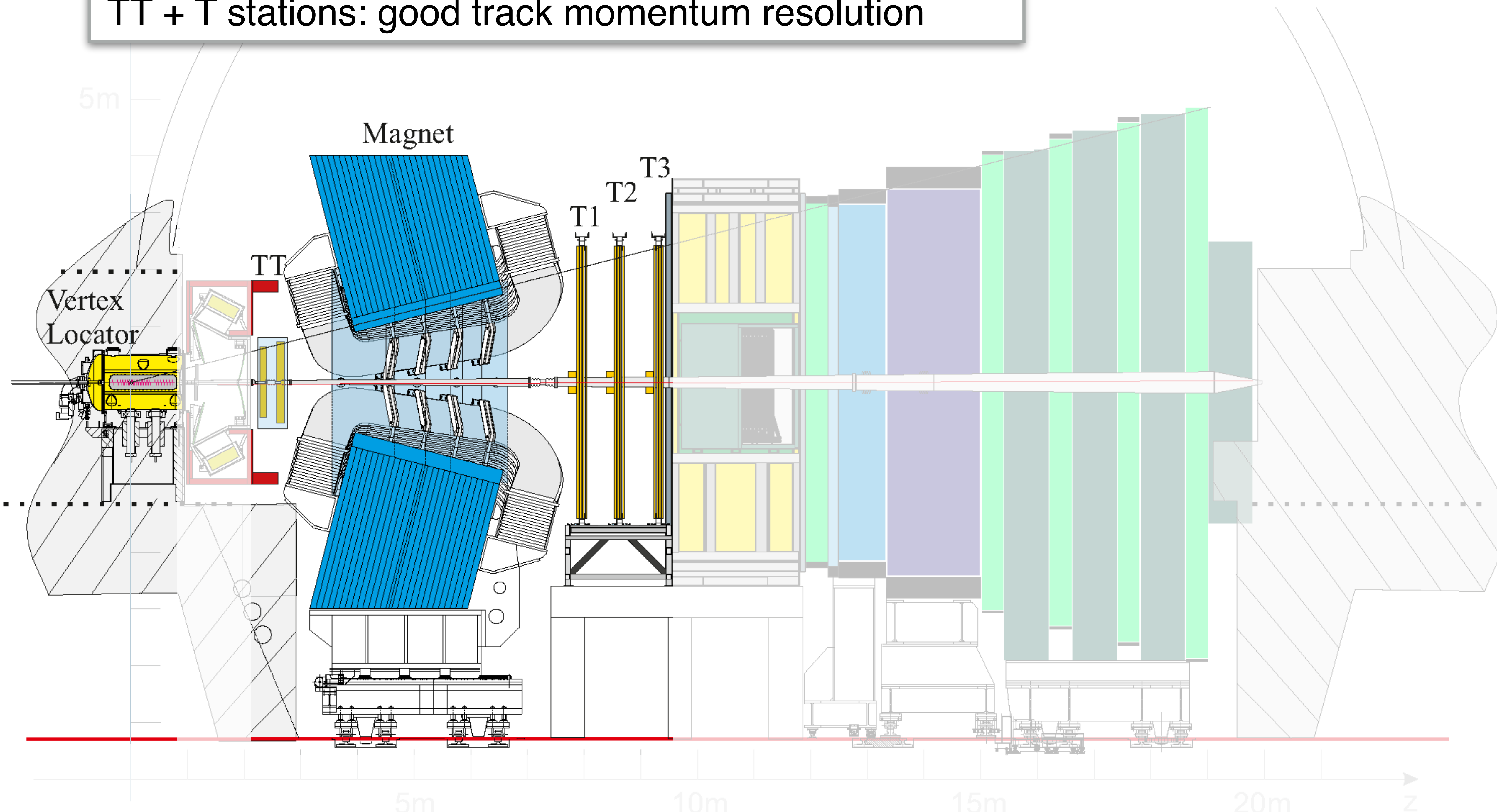


The LHCb Detector

Tracking system

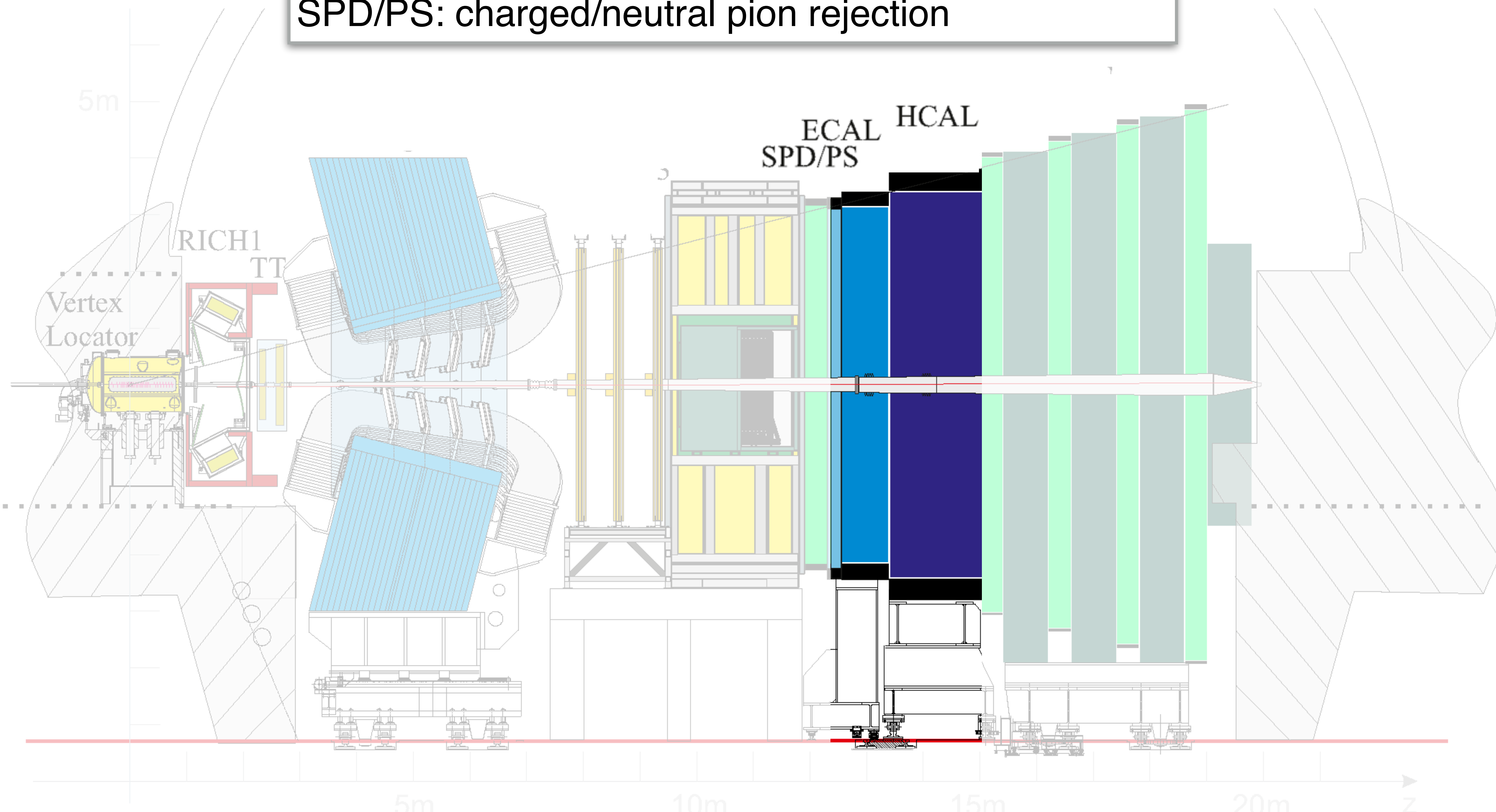
Vertex Locator(VELO): precision reconstruction + separation of primary, secondary vertices

TT + T stations: good track momentum resolution



THE LHCb DETECTOR

Calorimetry
ECAL: electron/photon reconstruction
HCAL: hadron identification
SPD/PS: charged/neutral pion rejection

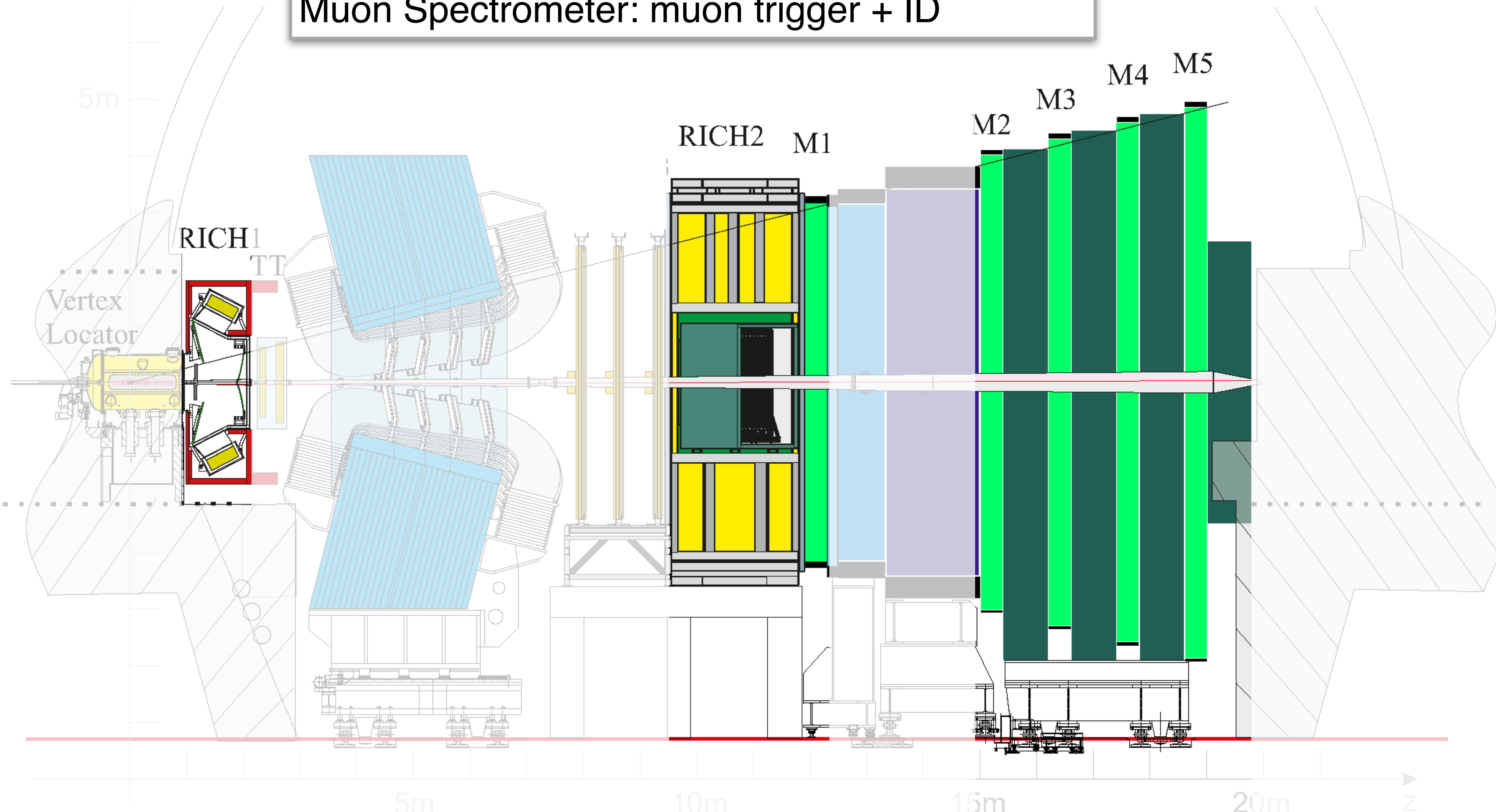


The LHCb Detector

Particle Identification

Ring Imaging Cherenkov detectors for pion, kaon identification

Muon Spectrometer: muon trigger + ID



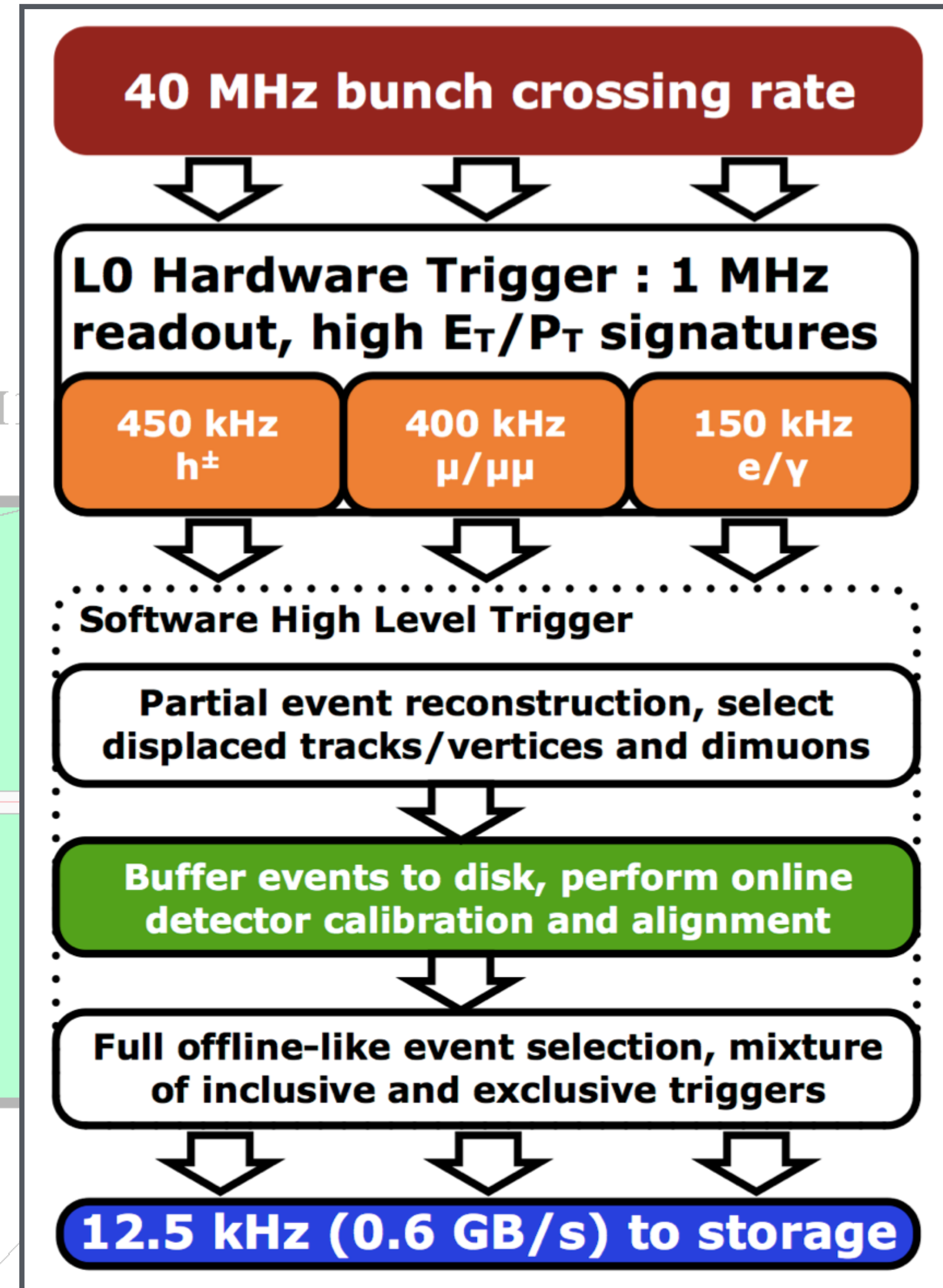
THE LHCb DETECTOR

Trigger system:

Initial hardware trigger (L0), using information from calorimeters and muon system

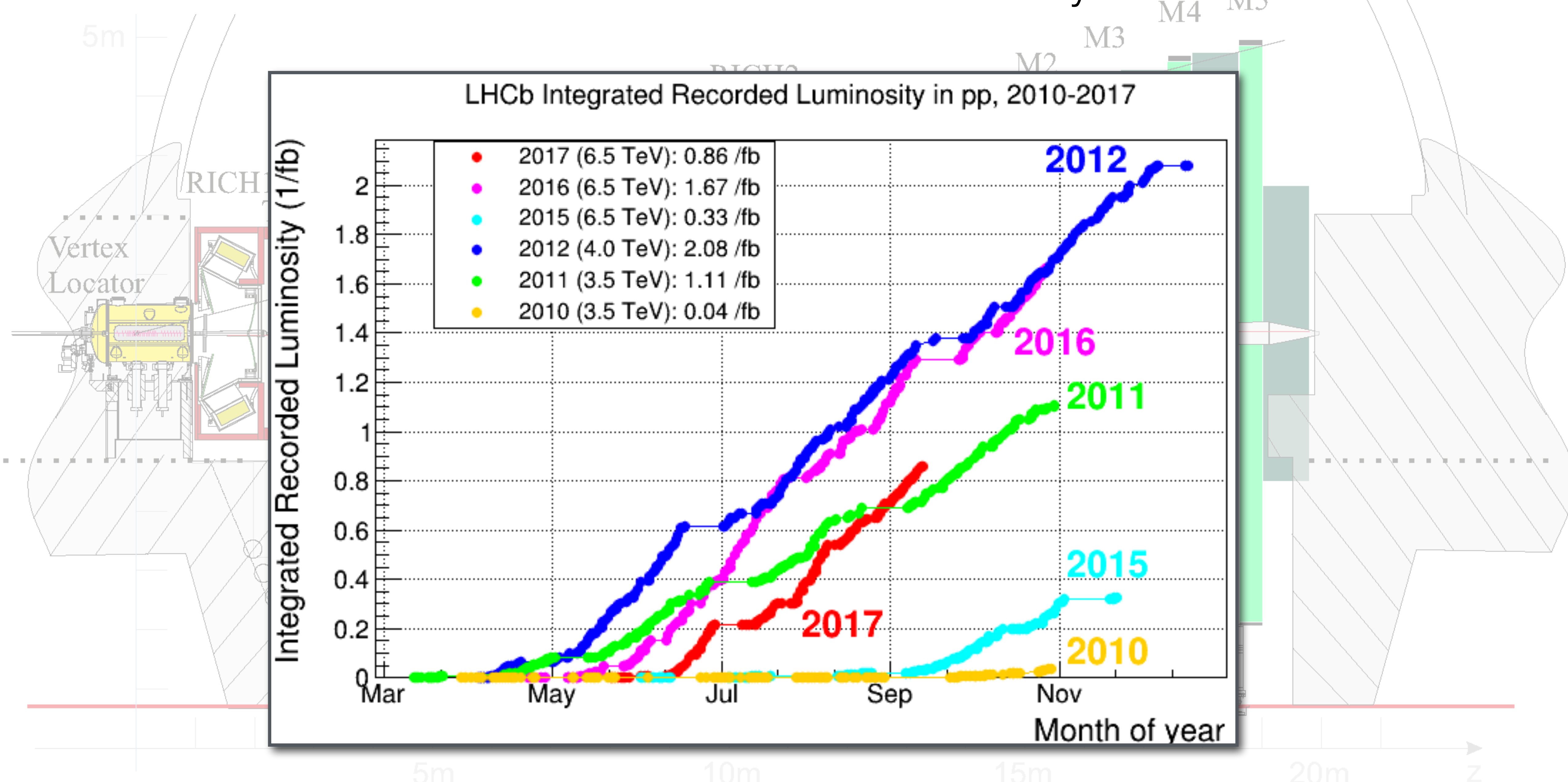
Software trigger split into two stages: fast partial event reconstruction + subsequent full reco.

Low luminosity $\Longrightarrow$ can trigger on relatively low pT objects



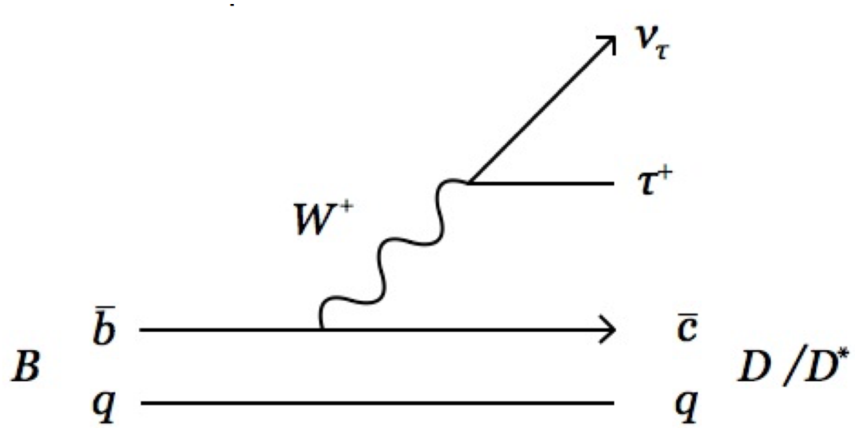
The LHCb Detector

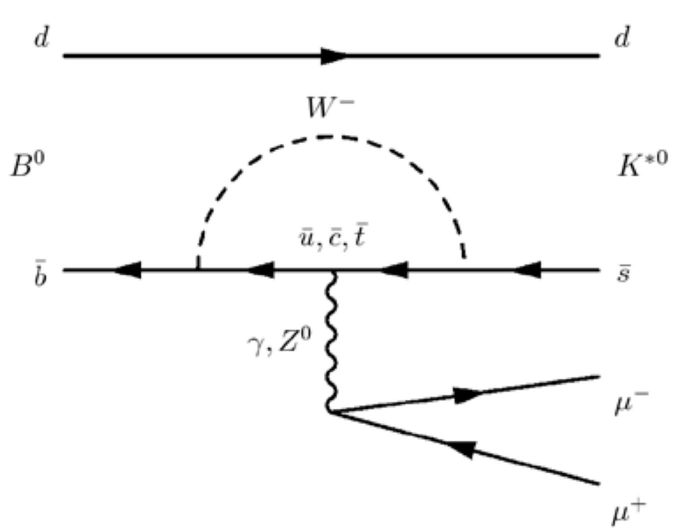
- 3 fb^{-1} collected in Run 1
  - Dataset used for all analyses shown today
- Run 2 dataset (to date) ~2.8 fb^{-1}
  - Measurements/searches with Run 2 data underway



Lepton Flavour Universality

- In the Standard Model, couplings of leptons to gauge bosons are independent of the lepton flavor
- Violation of LFU would be a clear sign of New Physics
- Semi-leptonic decays:
  - Decay rate can be factorized (weak and strong); theoretically simplified
  - Study ratio of branching fractions to cancel theoretical hadronic uncertainties
- At LHCb, measurements performed for both tree-level and loop-level processes





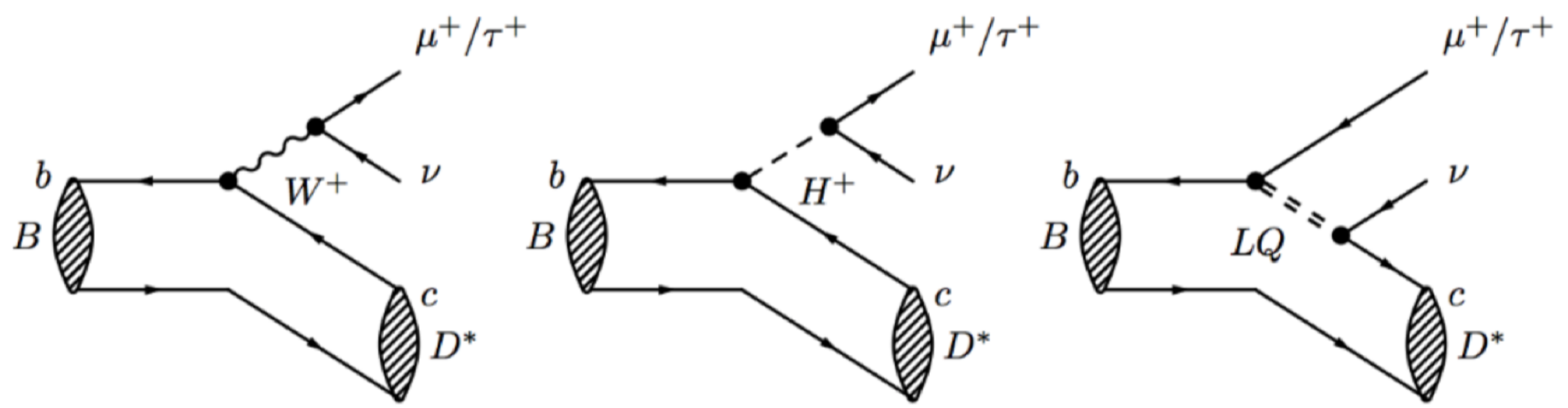
$R(D^*)$

- Search for LFU in $b \to c l \nu$ decays
- Tree-level processes; can exploit large statistics to include studies with the tauonic mode

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

  - Sensitive to NP models favouring third lepton generation (eg. charged Higgs)

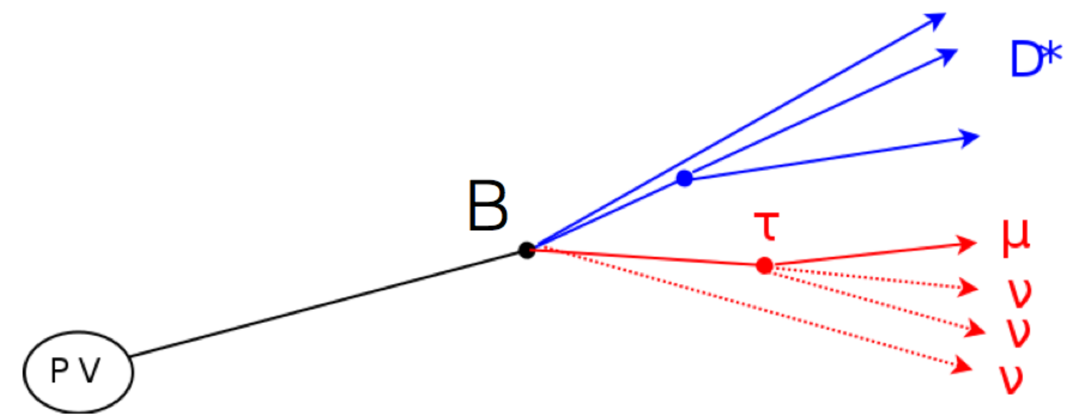
- (Precise) SM prediction = 0.252 ± 0.003 (PRD 85 (2012) 094025)
- LHCb measurements with two tau decay modes:
  - Leptonic tau decays ($\tau \to \mu\nu\nu$) - **PRL 115, 111803 (2015)**
  - Hadronic tau decays ($\tau \to \pi\pi\pi$) - **LHCB-PAPER-2017-017**



R(D*)

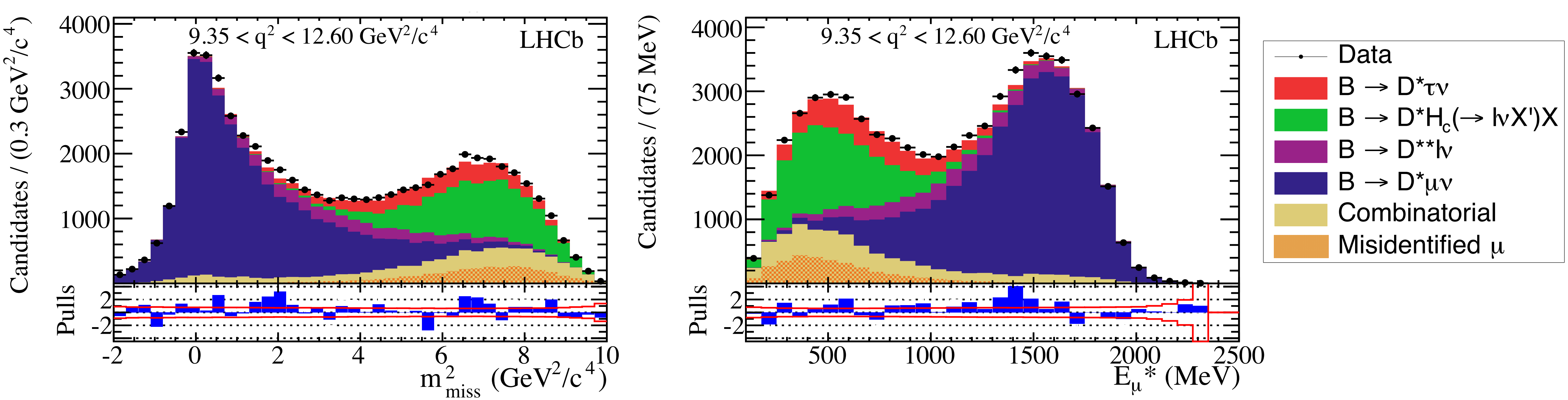
- Measurement performed with muonic tau decay
  - Experimentally very challenging! (multiple ν in the final state)
- Main backgrounds from B→D**lν and B→D*H_c(→lν)X decays; reject using isolation BDT
- Perform a 3D template fit using variables that discriminate between tauonic and muonic decays modes:
  - $q^2 = |p_B - p_{D^*}|^2$
  - E_μ^*
  - $m^2_{miss} = |p_B - p_{D^*} - p_\mu|^2$

PRL 115, 111803 (2015)



$$\mathcal{R}(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$

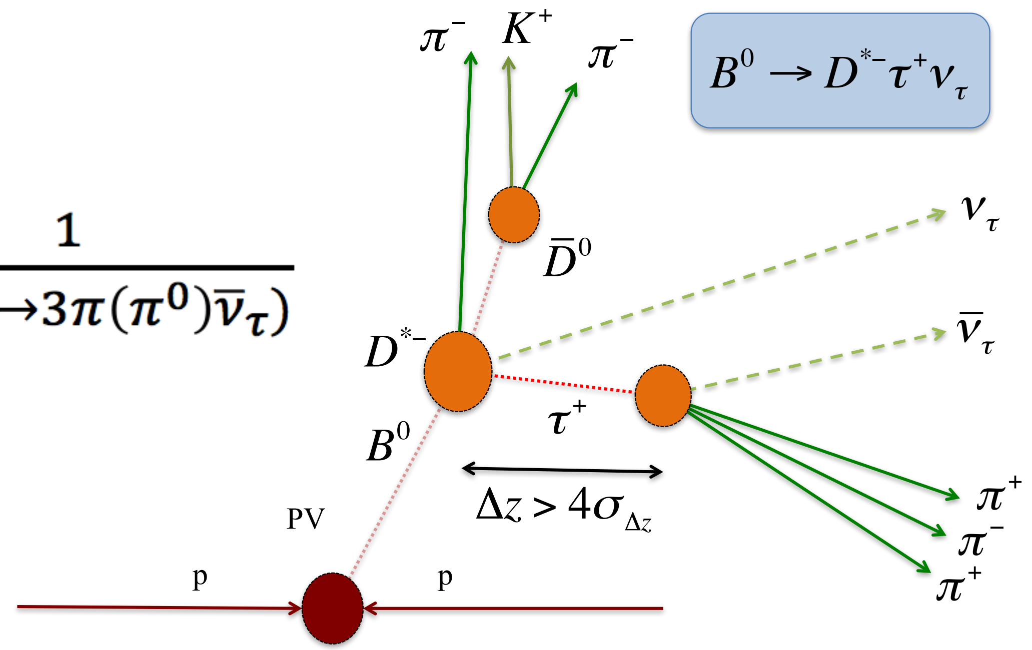
2.1σ away from SM prediction



R(D*)

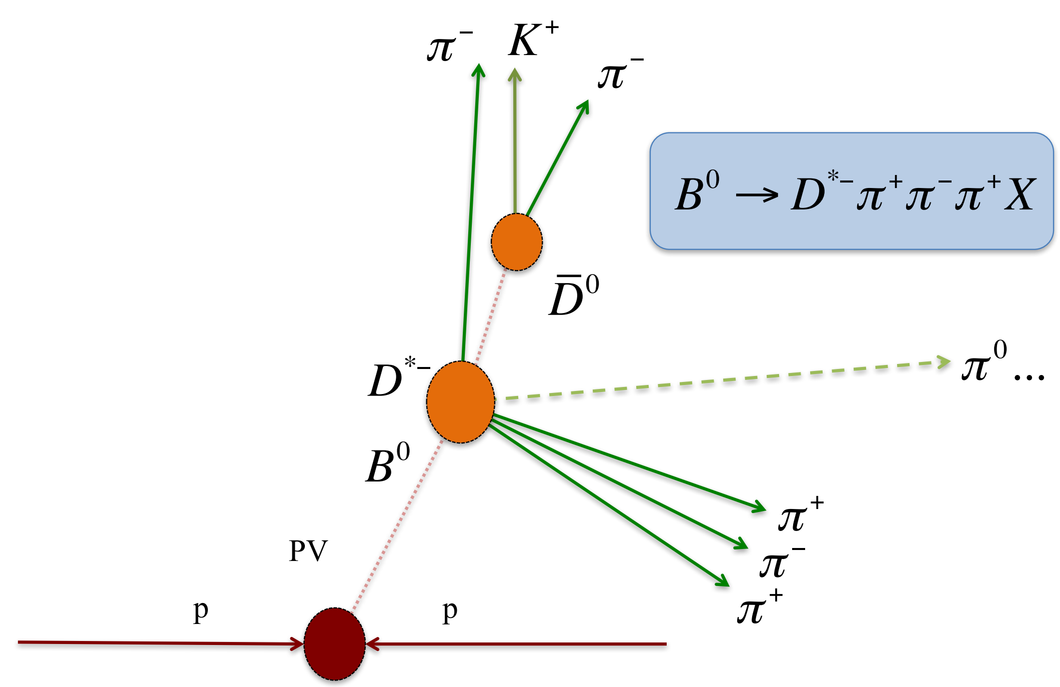
- Final state w/ three-prong hadronic tau decay: $\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\nu$ LHCB-PAPER-2017-017
- Method:
  - First measure K(D*)

$$K(D^*) \equiv \frac{Br(B^0 \to D^{*-}\tau^+\nu_\tau)}{Br(B^0 \to D^{*-}3\pi)} = \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{Br(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)}$$



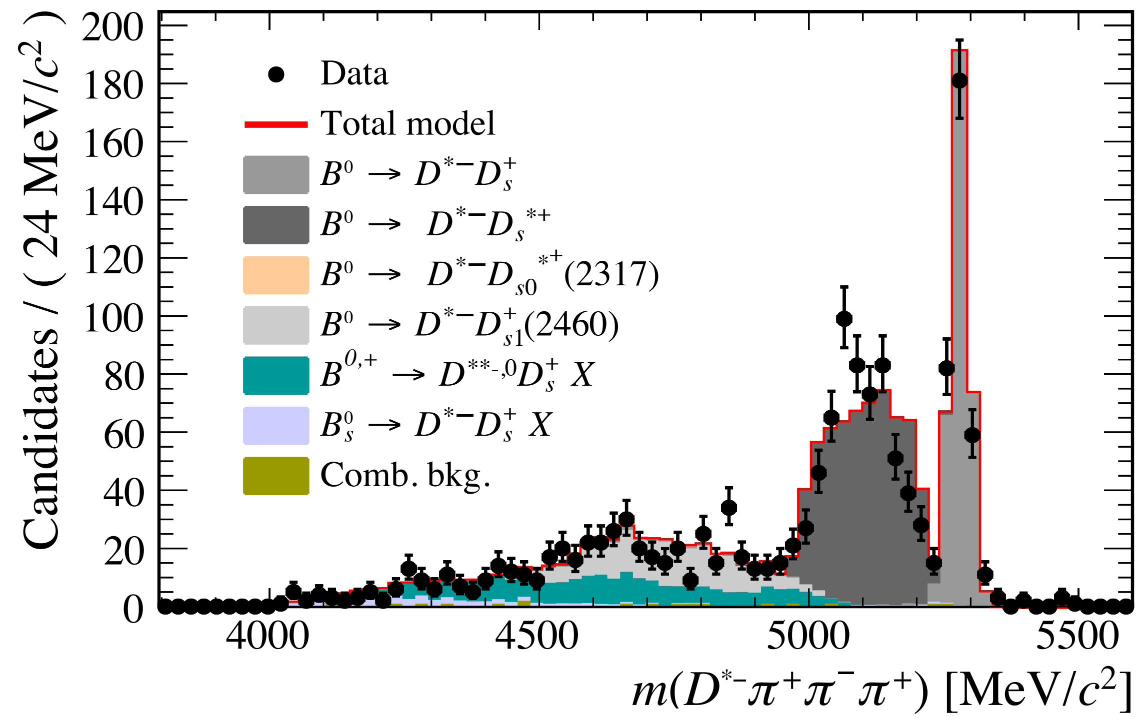
- Normalisation channel has same visible final state - systematic uncertainties cancel
- Compute ratio with muonic mode

$$R(D^*) = K(D^*) \times \frac{Br(B^0 \to D^{*-}3\pi)}{Br(B^0 \to D^{*-}\mu^+\nu_\mu)}$$



- Three charged pions allow for good tau vertex reconstruction
- However, have to contend with large background from $B \rightarrow D^*3\pi X$ (~O(100) times signal)
- Require τ decay vertex displaced from B vertex (along the beam direction) - background suppressed by ~3 orders of magnitude

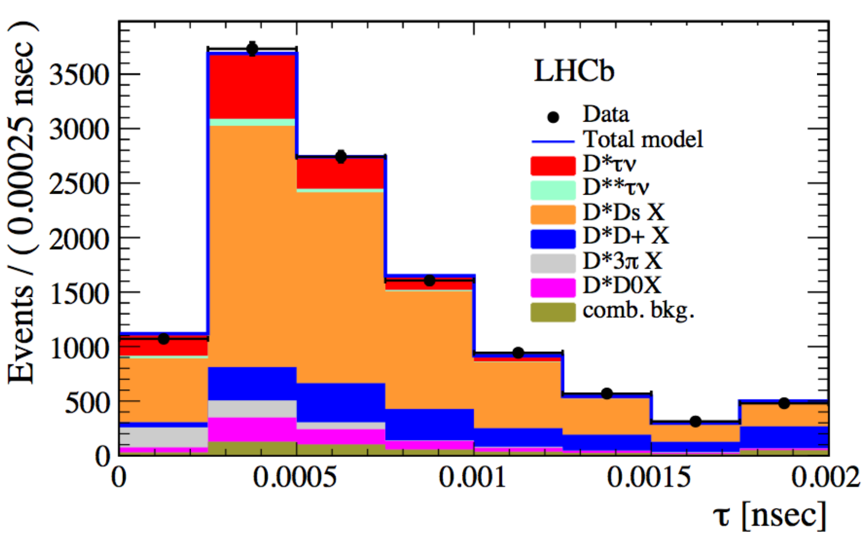
R(D*)

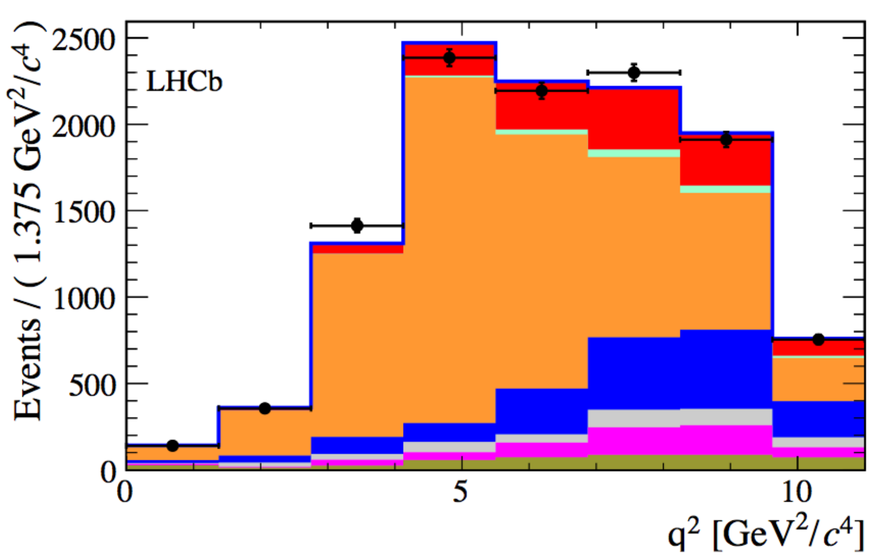


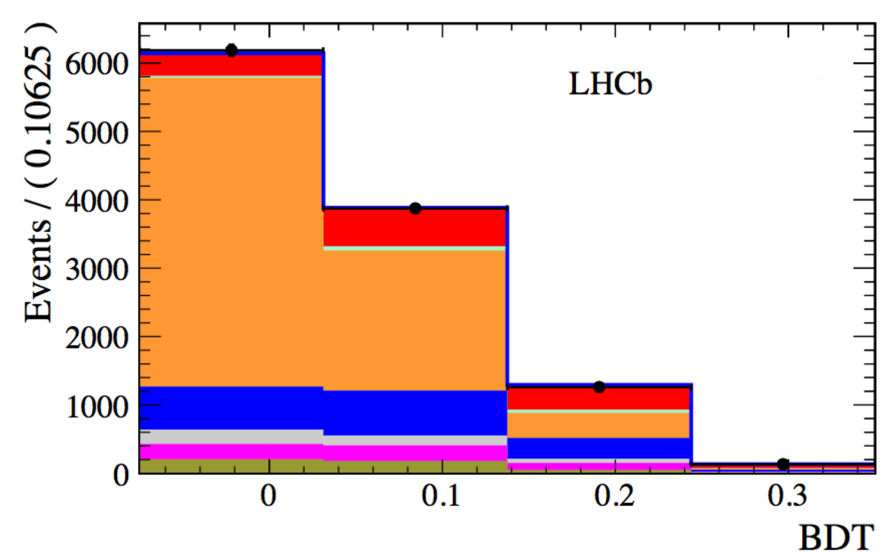
- B→D*DsX background (~O(10) times signal) controlled using data-driven techniques
- Relative yield of various contributions constrained by fit to D3π invariant mass
- Perform a 3D template fit using BDT response, q^2 and τ decay time

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.39 \pm 0.09\,(\text{stat}) \pm 0.12\,(\text{syst}) \pm 0.06\,(\text{ext})) \times 10^{-2}$$

$$\mathcal{R}(D^{*-}) = 0.285 \pm 0.019\,(\text{stat}) \pm 0.025\,(\text{syst}) \pm 0.013\,(\text{ext})$$



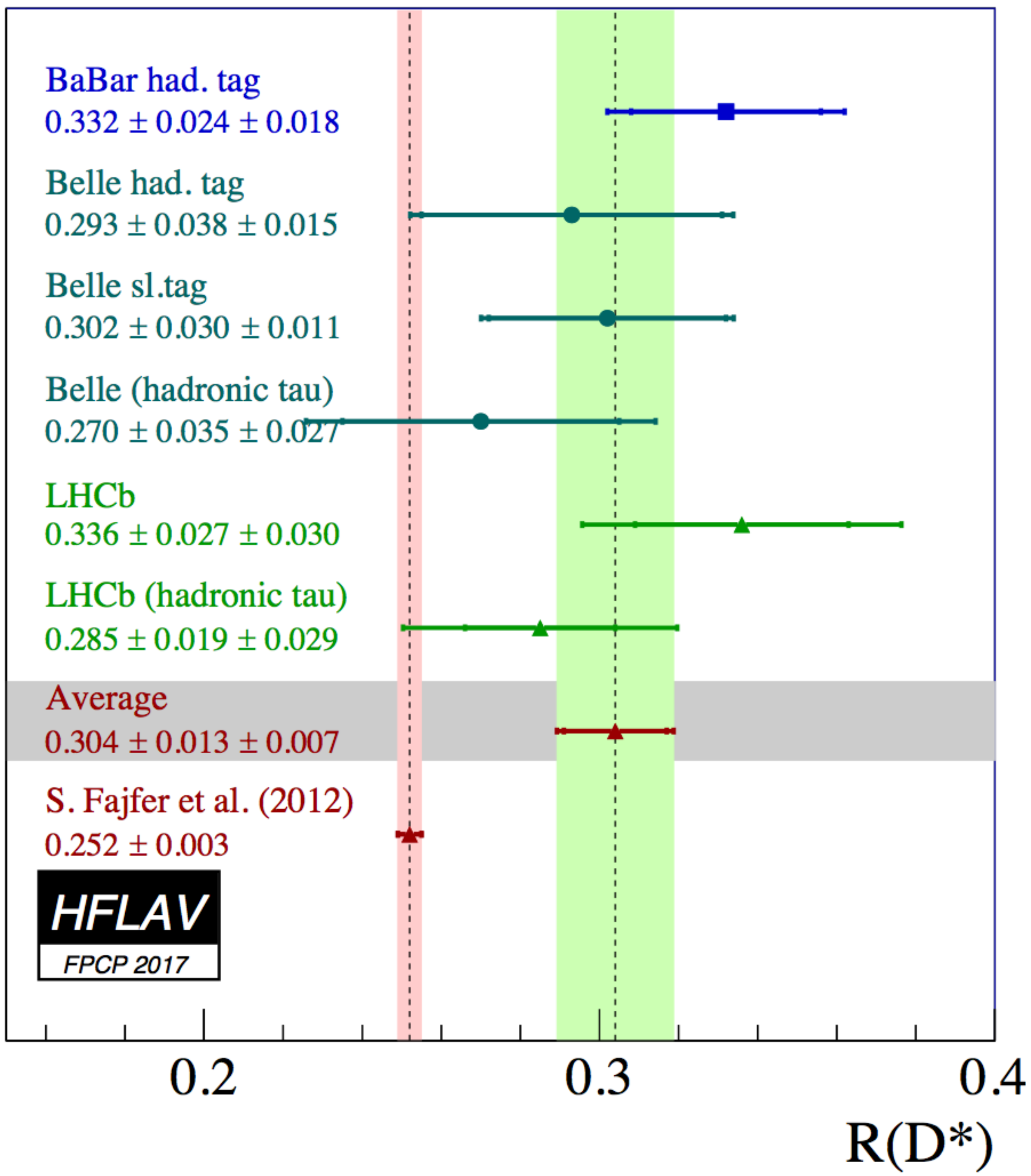




COMBINATION

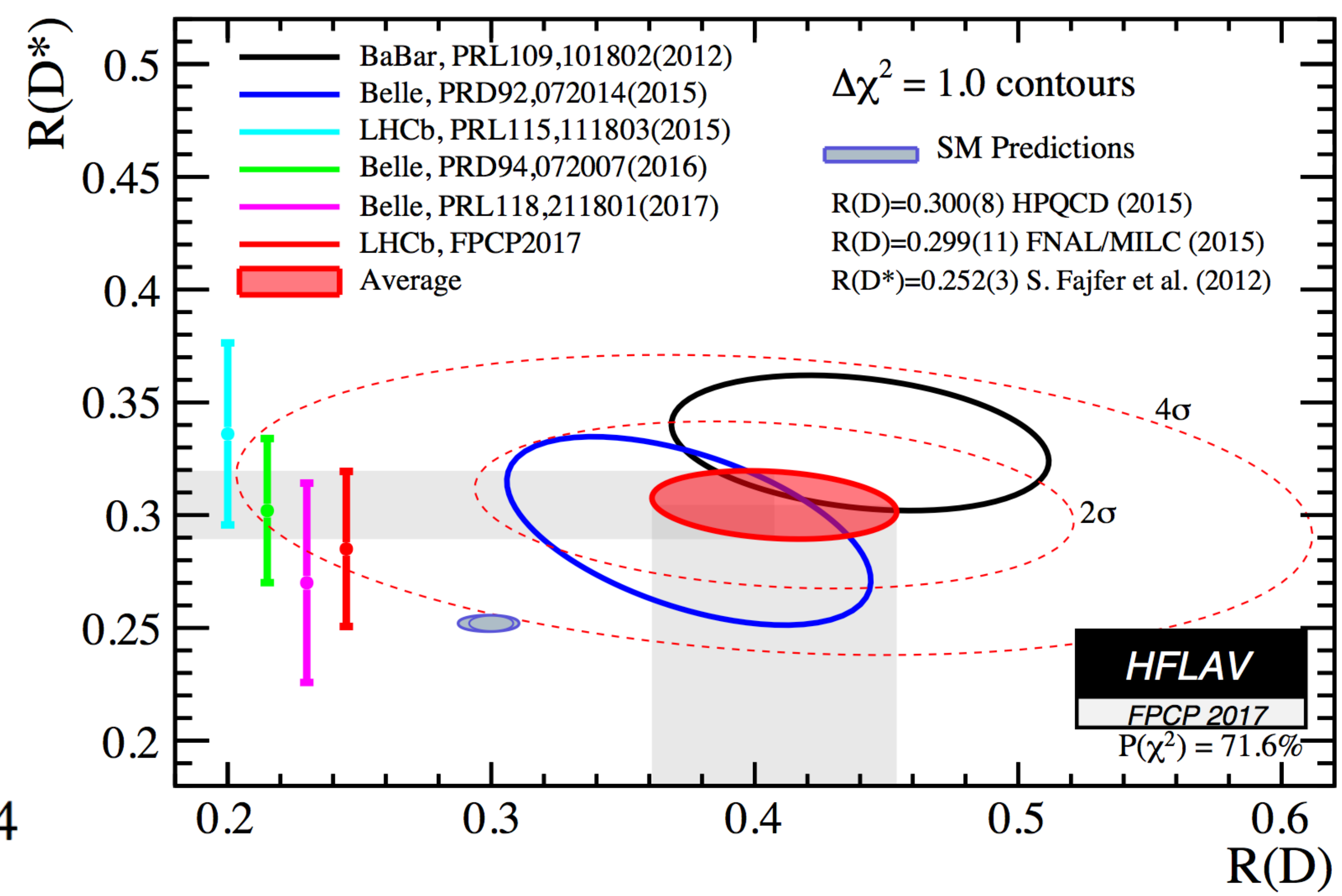
R(D*) LHCb average = 0.306 ± 0.027 (**2.1σ** from SM)

HFLAV R(D*) combination = 0.304 ± 0.015 (**3.4σ** from SM)



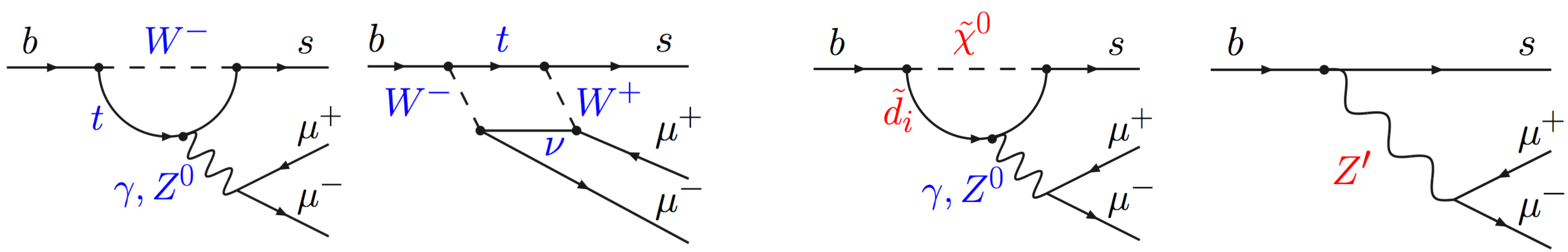
HFLAV R(D*) and R(D) combination

0.304 ± 0.015 (**4.1σ** from SM)



b→sll Transitions

- ‘Flavour-changing neutral current’ (FCNC) transitions
- Proceed via electroweak loops; suppressed in the SM
- New particles could also contribute at loop level



Potential effects observed via:

- Differential branching fraction measurements, analyses of angular distributions
- Tests of lepton flavor universality

DESCRIBING FCNC PROCESSES

Effective Hamiltonian described by an operator product expansion

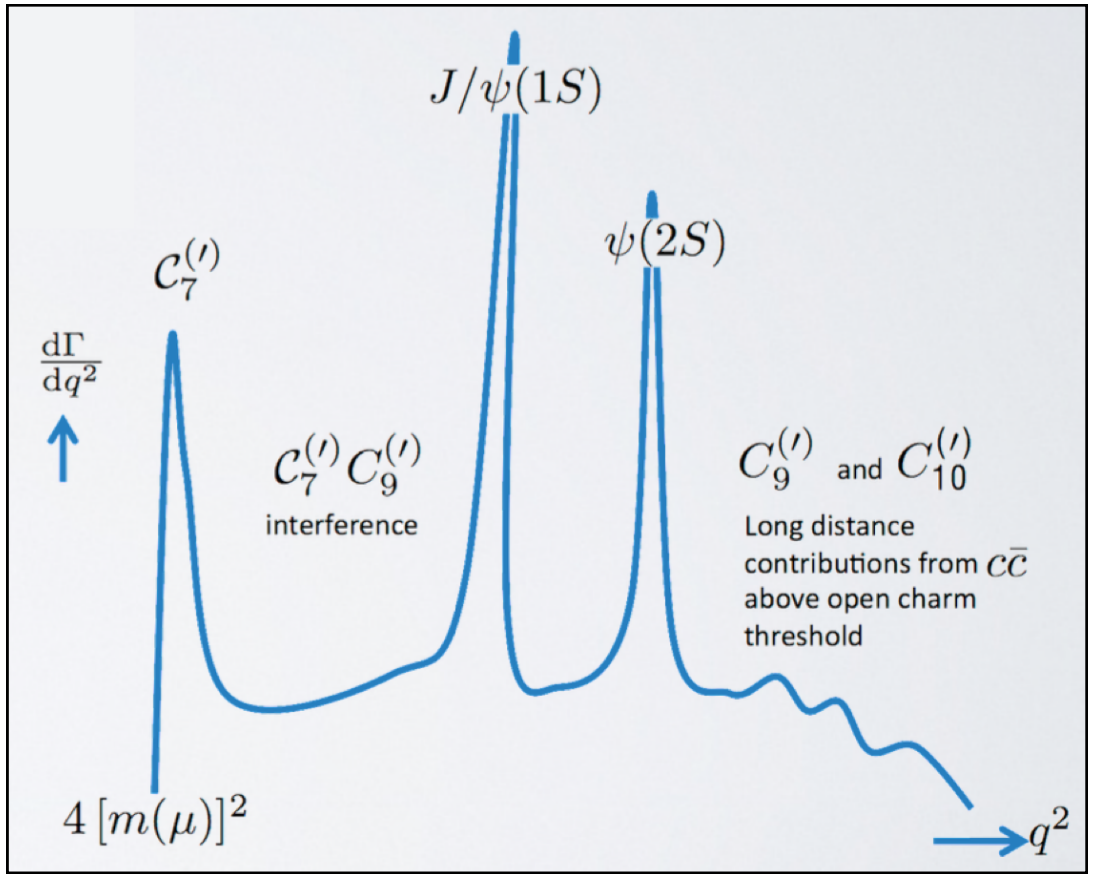
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_i [\underbrace{\mathcal{C}_i(\mu)\mathcal{O}_i(\mu)}_{\text{left handed}} + \underbrace{\mathcal{C}'_i(\mu)\mathcal{O}'_i(\mu)}_{\text{right handed (suppressed in the SM)}}]$$

Operators (O_i) - long-distance effects (non-perturbative)

Wilson coefficients (C_i) - perturbative, short-distance physics

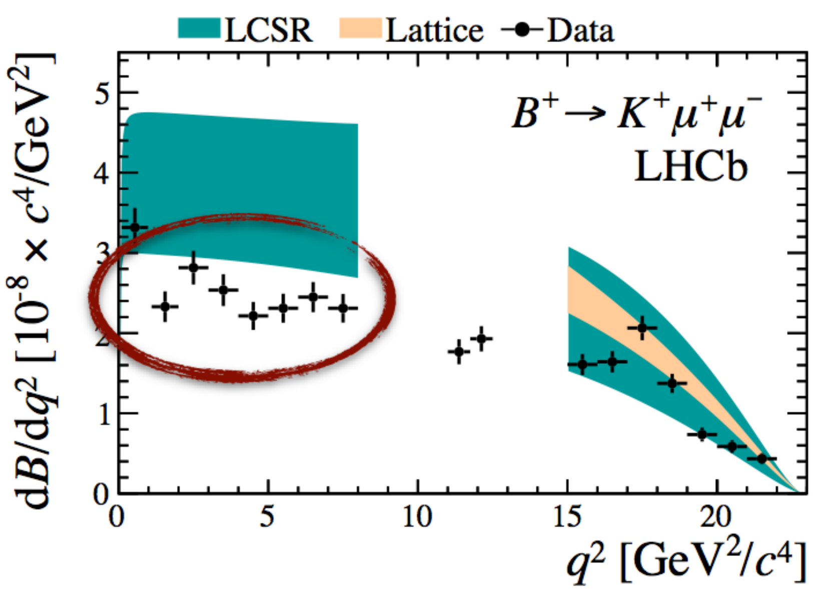
i=1, 2	Tree
i=3-6, 8	Gluon penguin
i=7	Photon penguin
i=9, 10	Electroweak penguin
i=S	Higgs (scalar) penguin
i=P	Pseudoscalar penguin

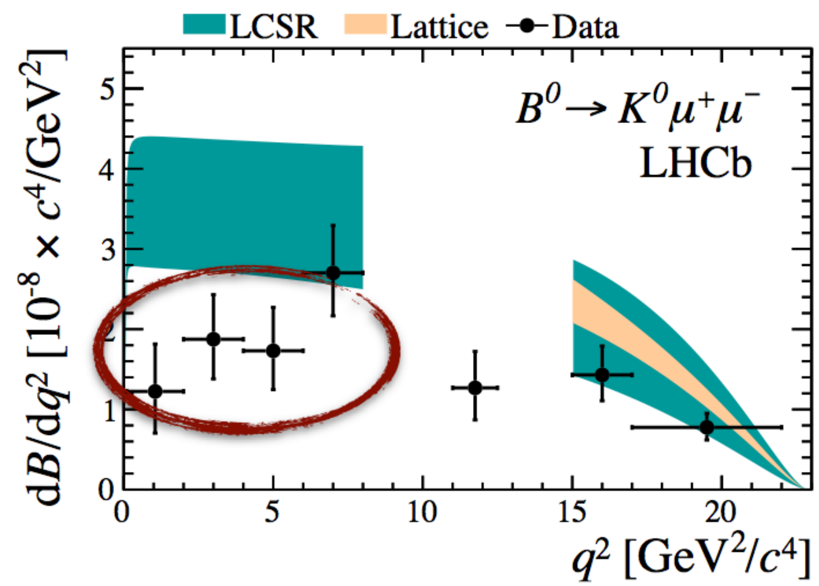
different regions of q^2 probe different processes



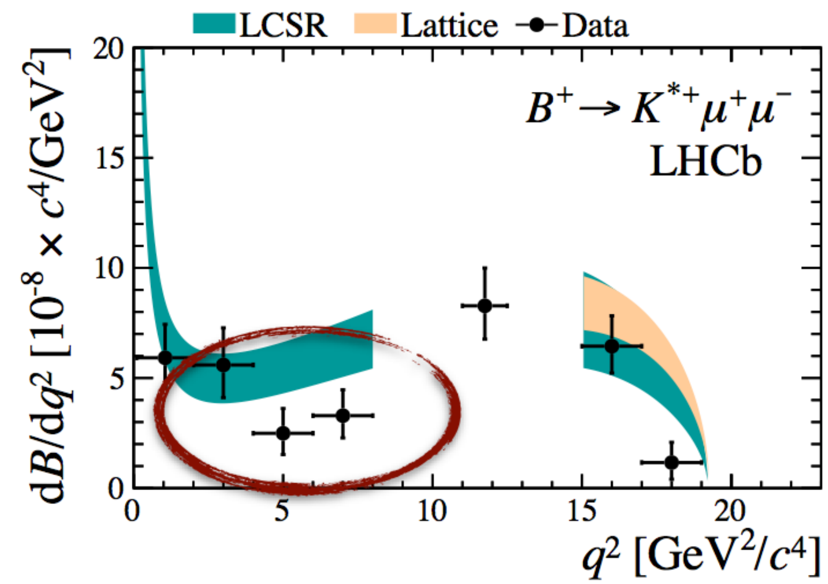
ANOMALIES IN b→sll BF MEASUREMENTS

Consistent pattern of deviations from SM predictions

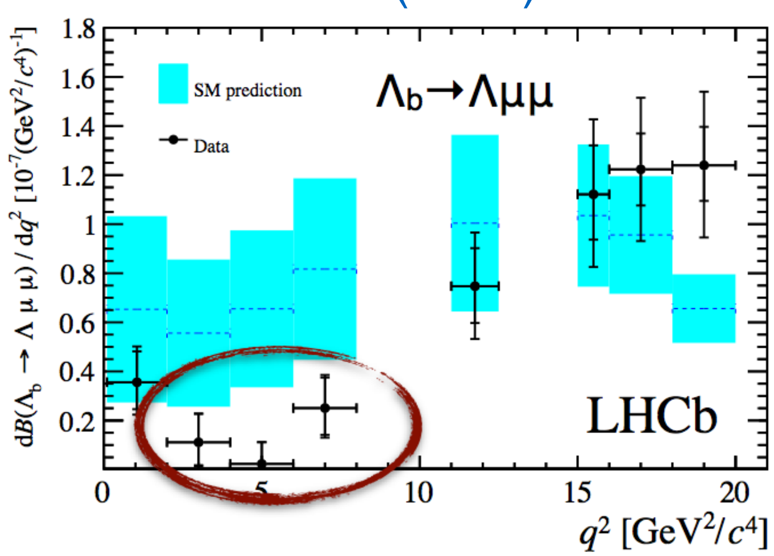




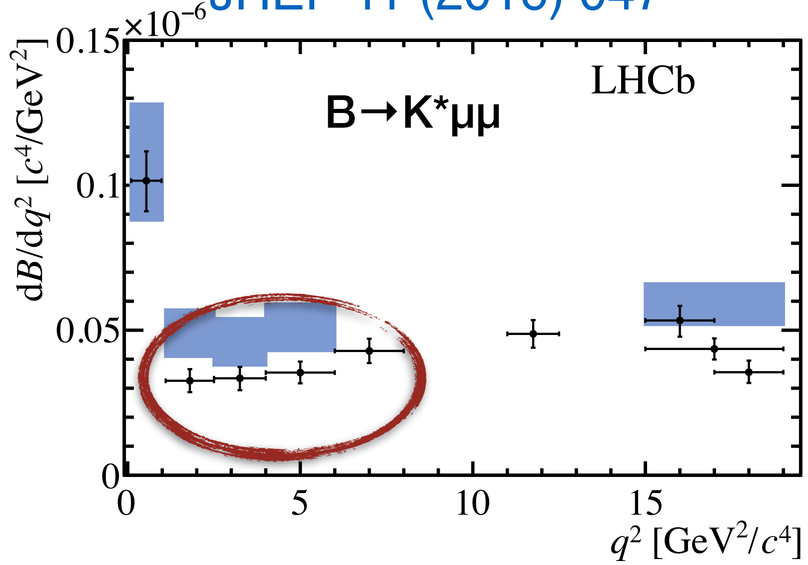
JHEP 06 (2014) 133



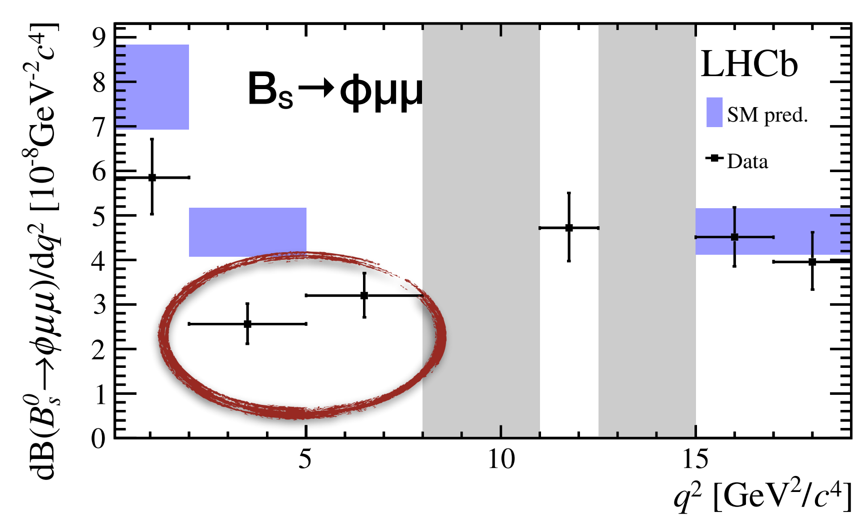
JHEP 06 (2015) 115



JHEP 11 (2016) 047



JHEP 09 (2015) 179



Are discrepancies hints of NP, or due to unaccounted-for charm loop contributions?

R(K*)

JHEP 08 (2017) 055

- Ratios of B→hll decays (with light lepton flavours) are clean probes of NP
  - Hadronic uncertainties cancel
- Analysis performed with $B^0 \to K^{*0}ll$ decays (where $K^*(892)^0 \to K^+\pi^-$) in two bins of invariant mass squared

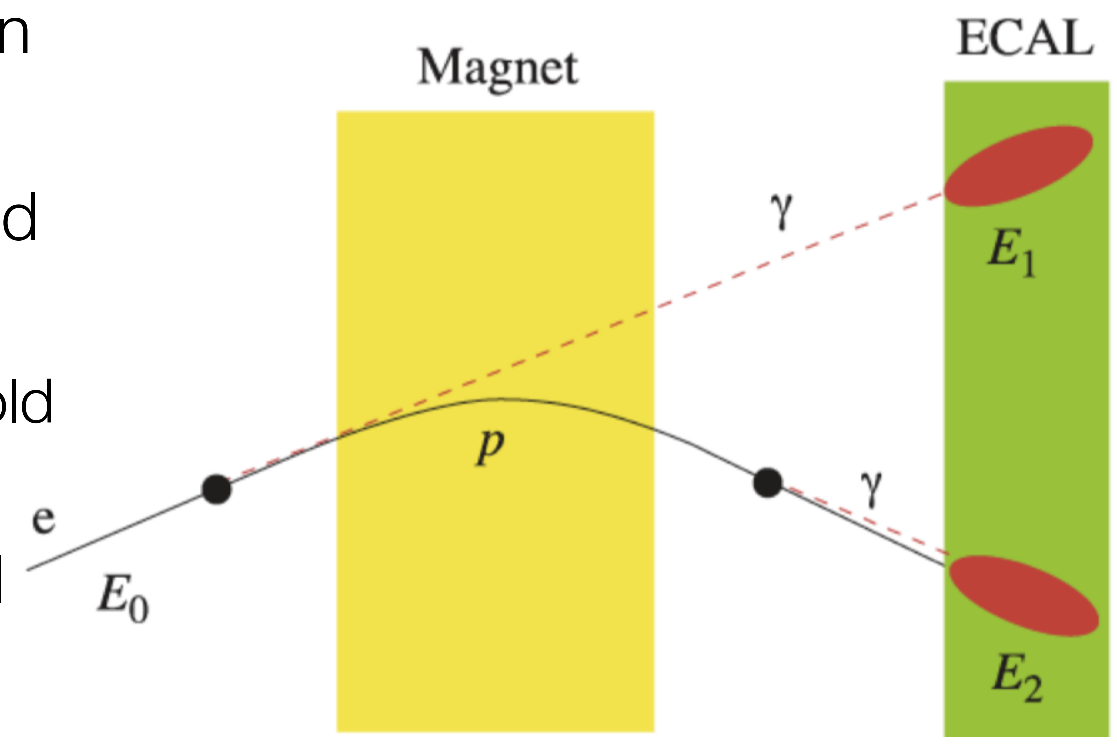
$$R_{K^{*0}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}e^+e^-)}{\mathrm{d}q^2}}$$

- Double ratio with $B^0 \to K^{*0}J/\psi$ reduces systematic uncertainties

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

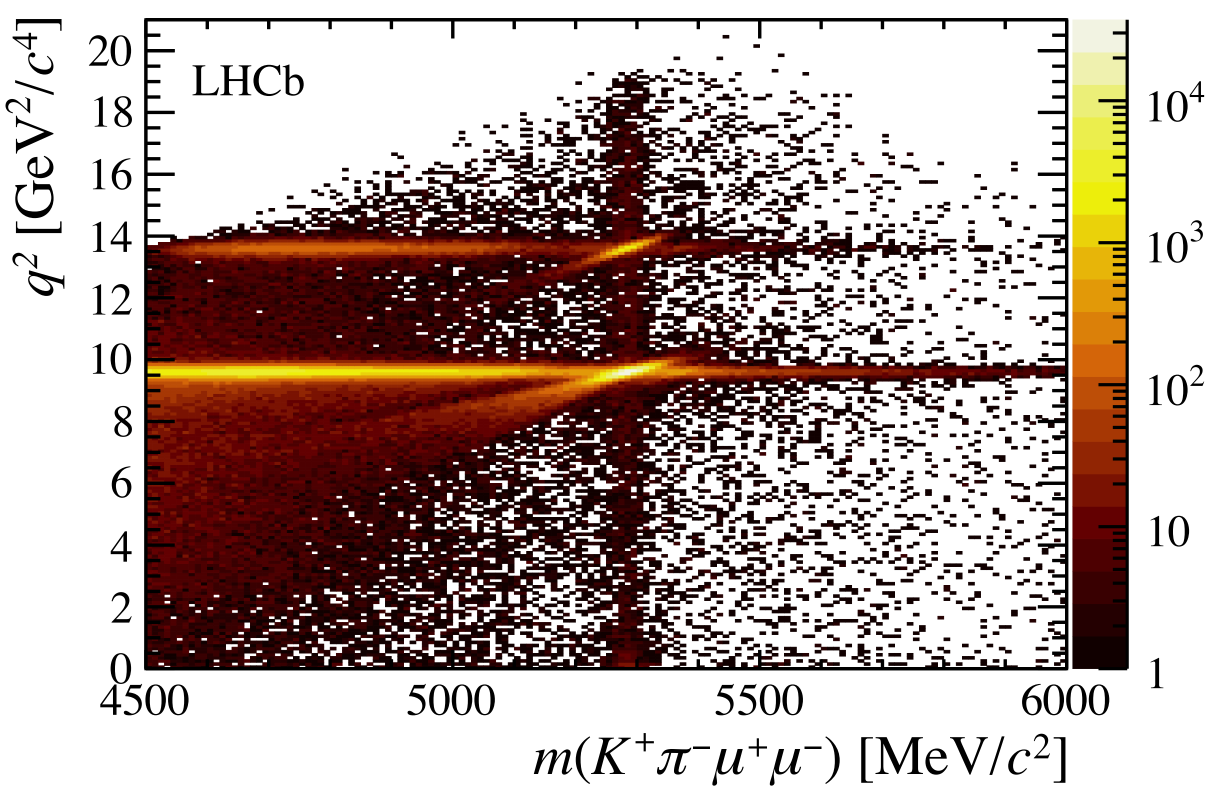
- However, extremely challenging due to differences in trigger/reconstruction for electrons and muons

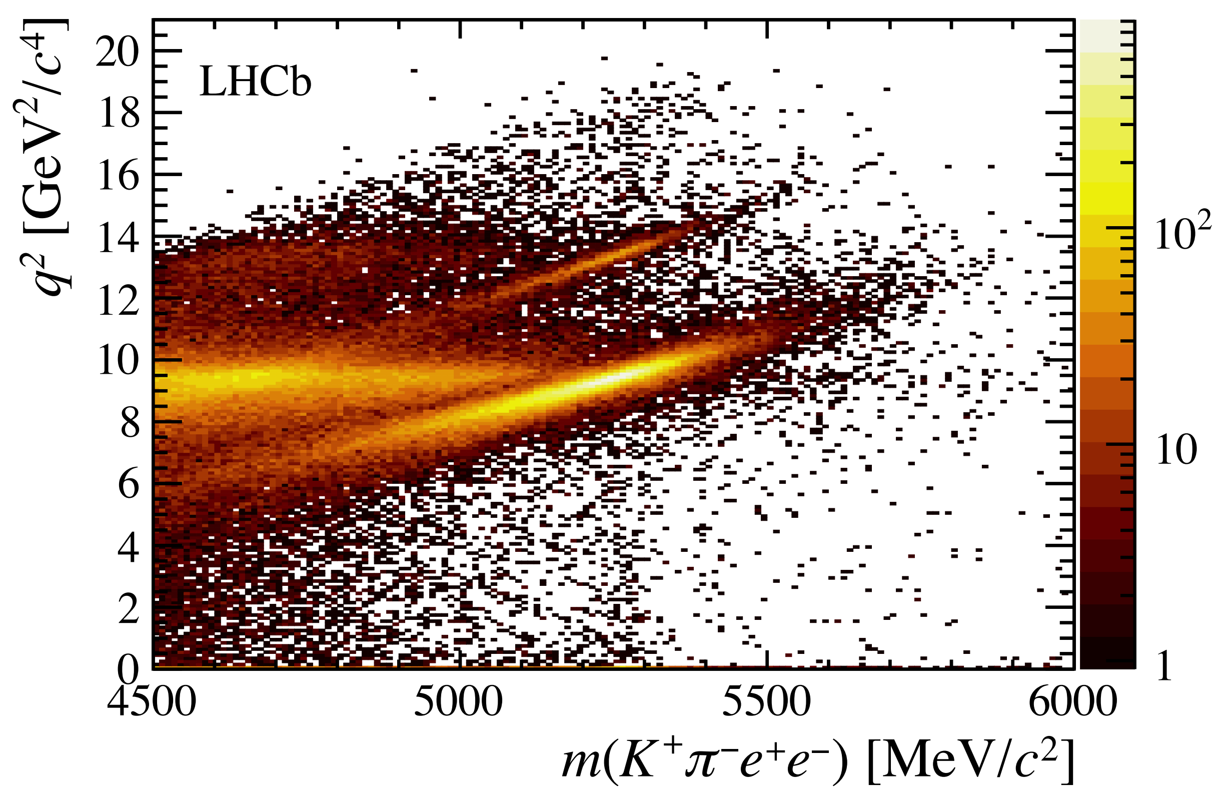
R(K*)



- Electron reconstruction challenging due to bremsstrahlung; momentum and mass resolution degraded
- Recover by adding ECAL clusters to extrapolated upstream electron track
    - Limited by calorimeter acceptance, energy threshold (E_T > 75 MeV)
- Worse B mass resolution in the electron channel

- J/ψ backgrounds leak into signal region





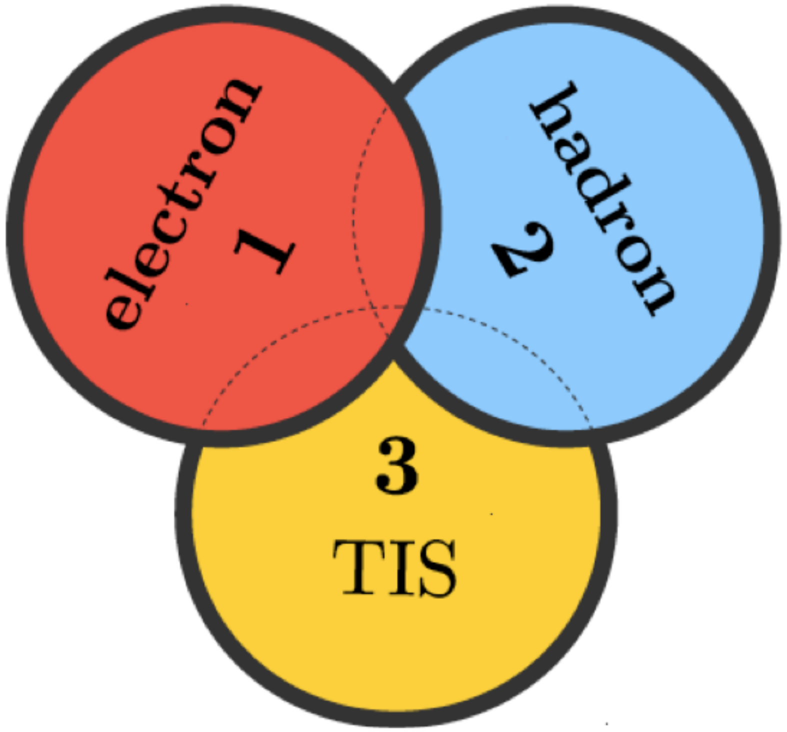
R(K*)

JHEP 08 (2017) 055

Analysis strategy:

- Keep selection as similar as possible for electron, muon channels
  - Multivariate classifier to reject combinatorial background
  - Veto for peaking backgrounds
- Signal efficiencies determined from MC, tuned with data
- Normalisation channel used to correct signal mass shapes

- Hardware trigger ET thresholds are higher for electrons than for muons (higher occupancy in the calorimeter compared to the muon spectrometer)
  - Analysis performed for three exclusive trigger categories (TIS = trigger independent of signal)

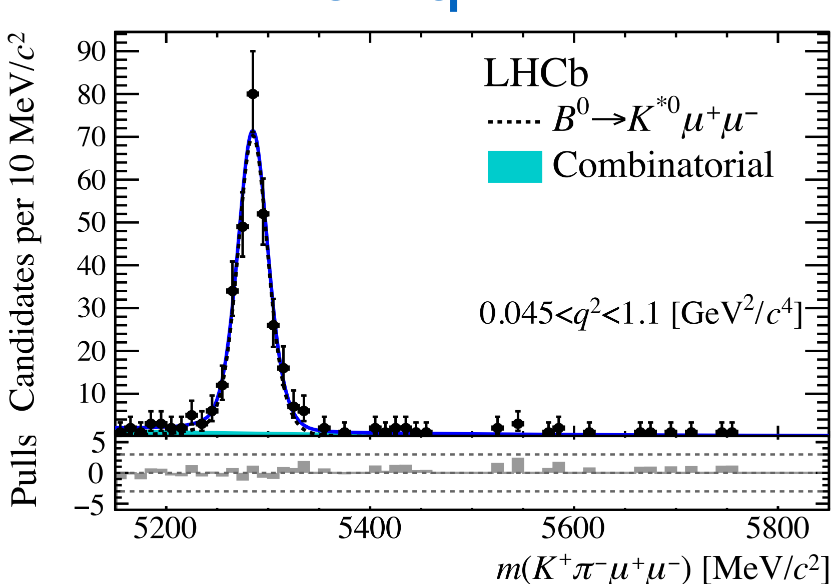


R(K*)

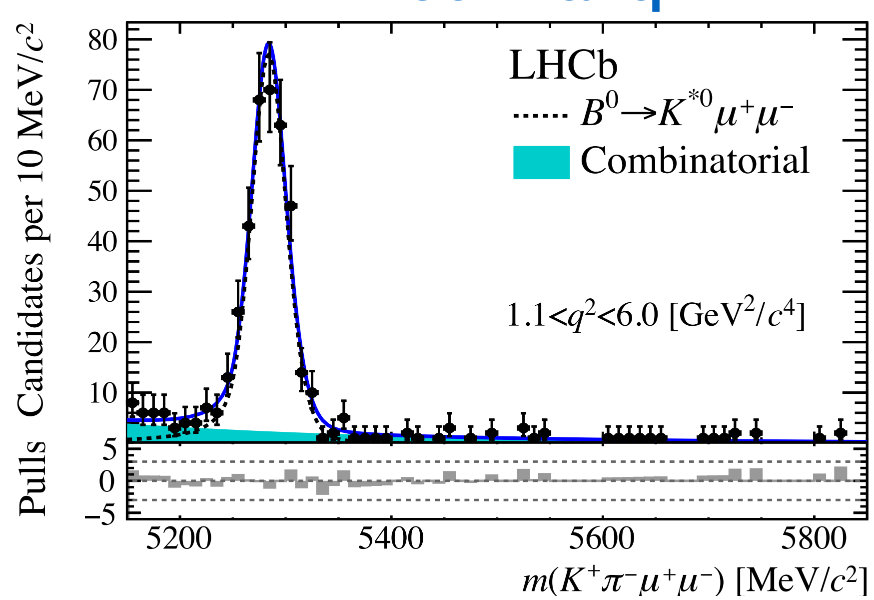
- Yields obtained from fit to the invariant mass
  - Precision dominated by statistics in electron channel

JHEP 08 (2017) 055

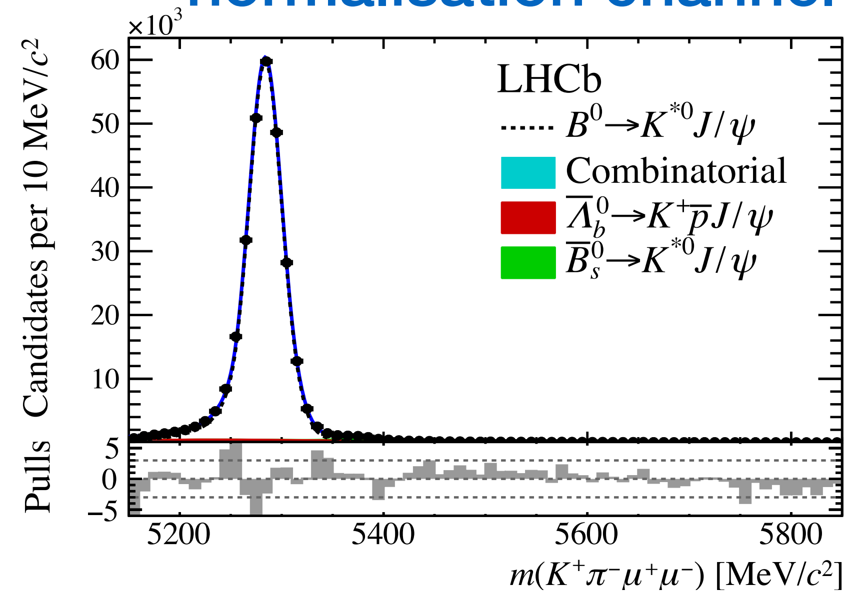
low q^2 | **central q^2** | **normalisation channel**



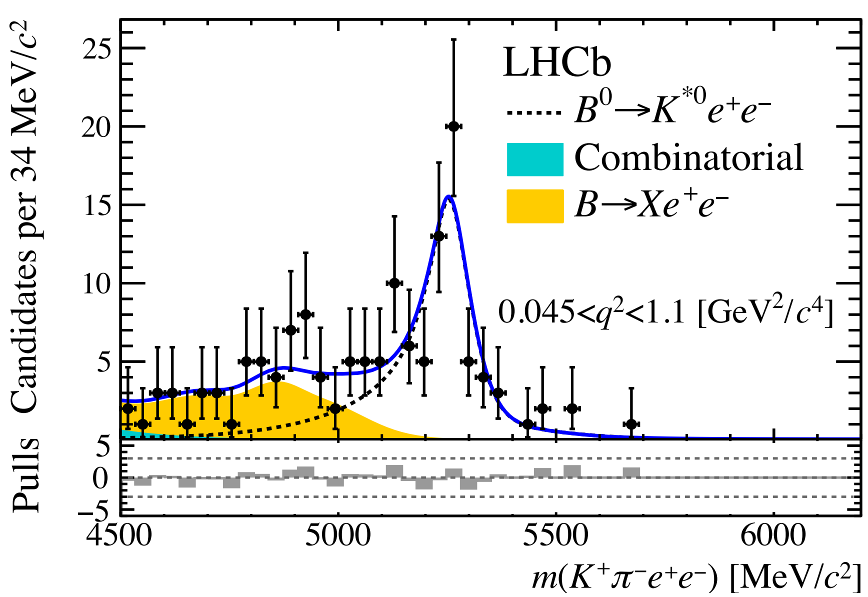
(285 ± 18)



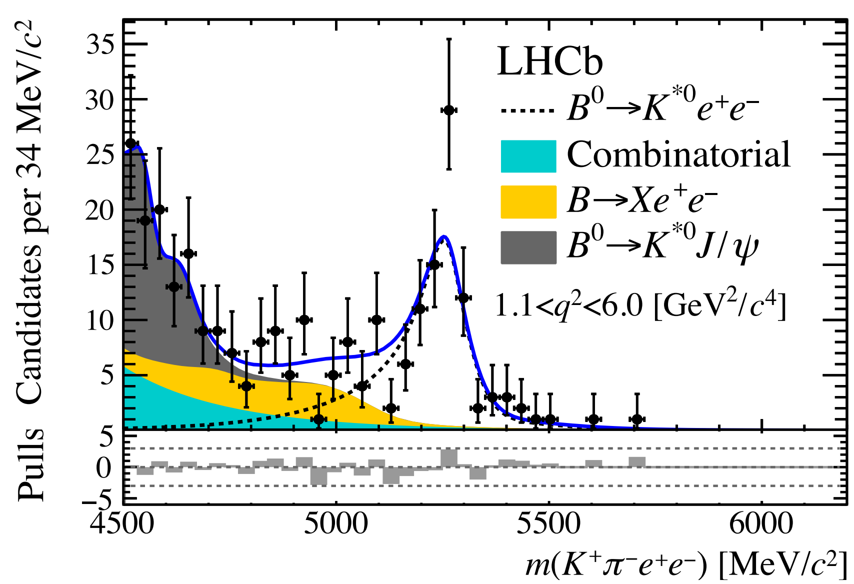
(353 ± 21)



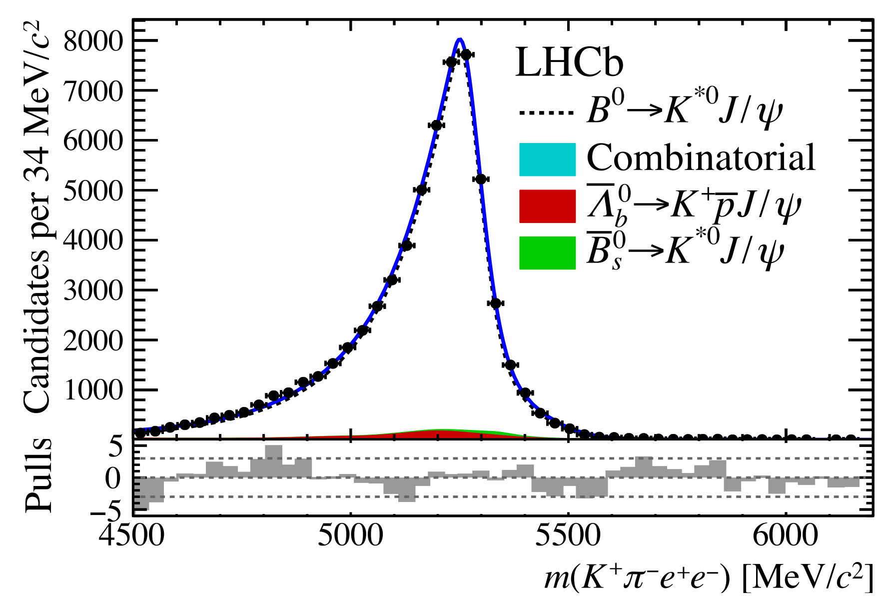
~274,000



(89 ± 11)



(111 ± 14)



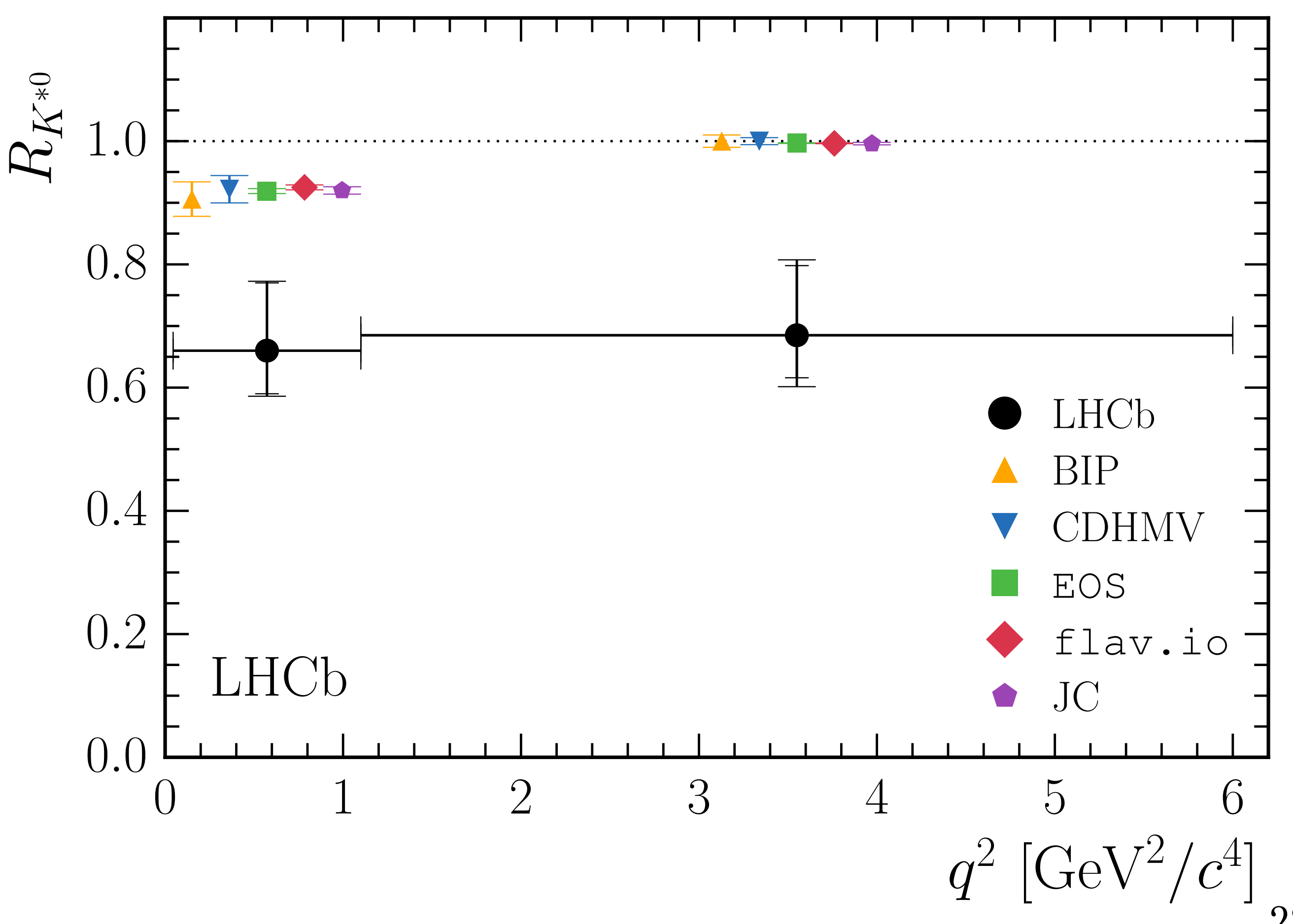
~58,000

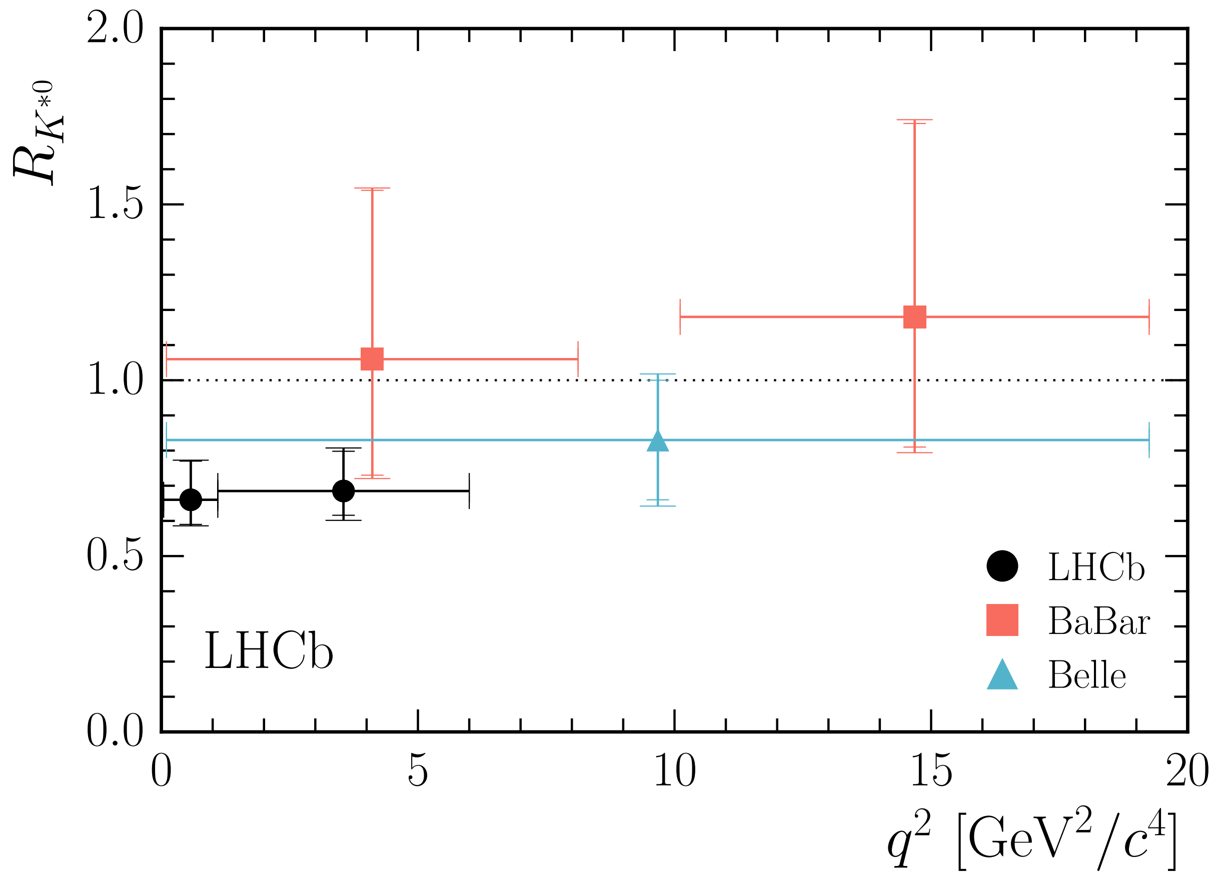
R(K*)

JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 c^4 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\,\text{GeV}^2 c^4 \end{cases}$$

- Compatible with the SM at 2.1σ - 2.3σ (2.4σ - 2.5σ) in the low (central) q^2 bin
- Measurement is statistically dominated





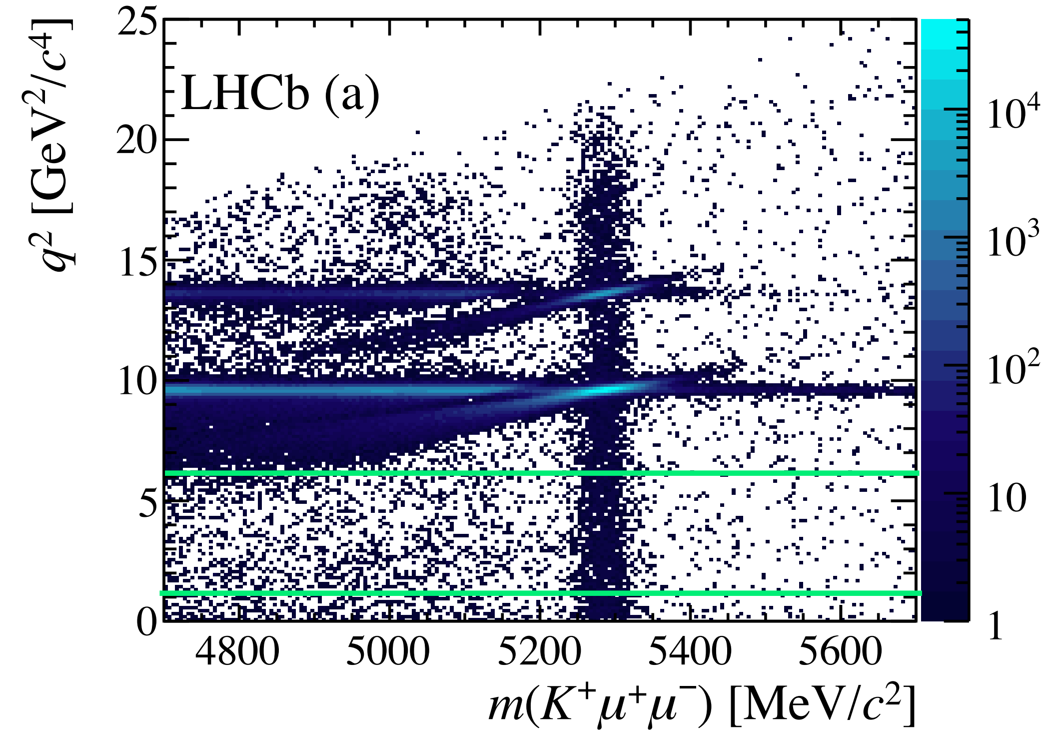
R(K)

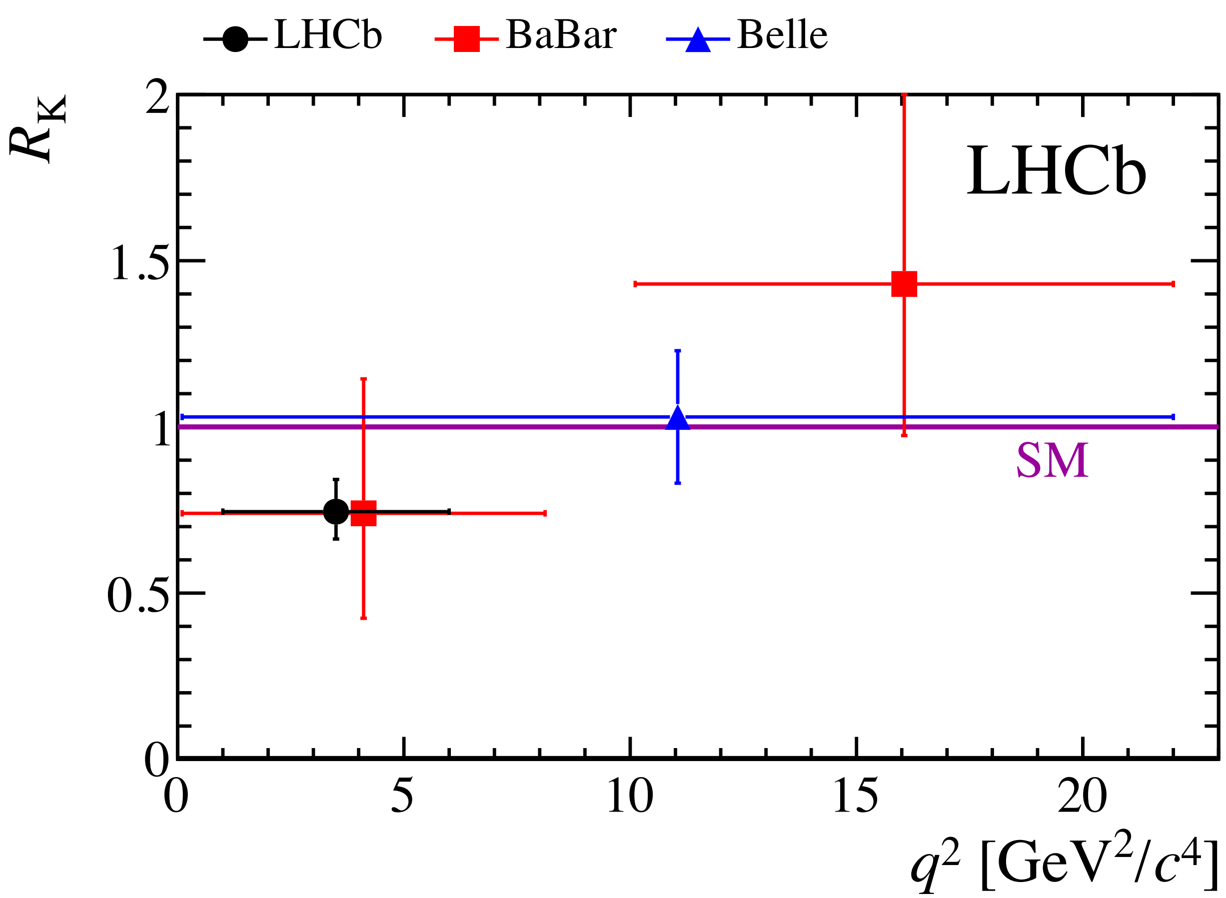
PRL 113 (2014) 151601

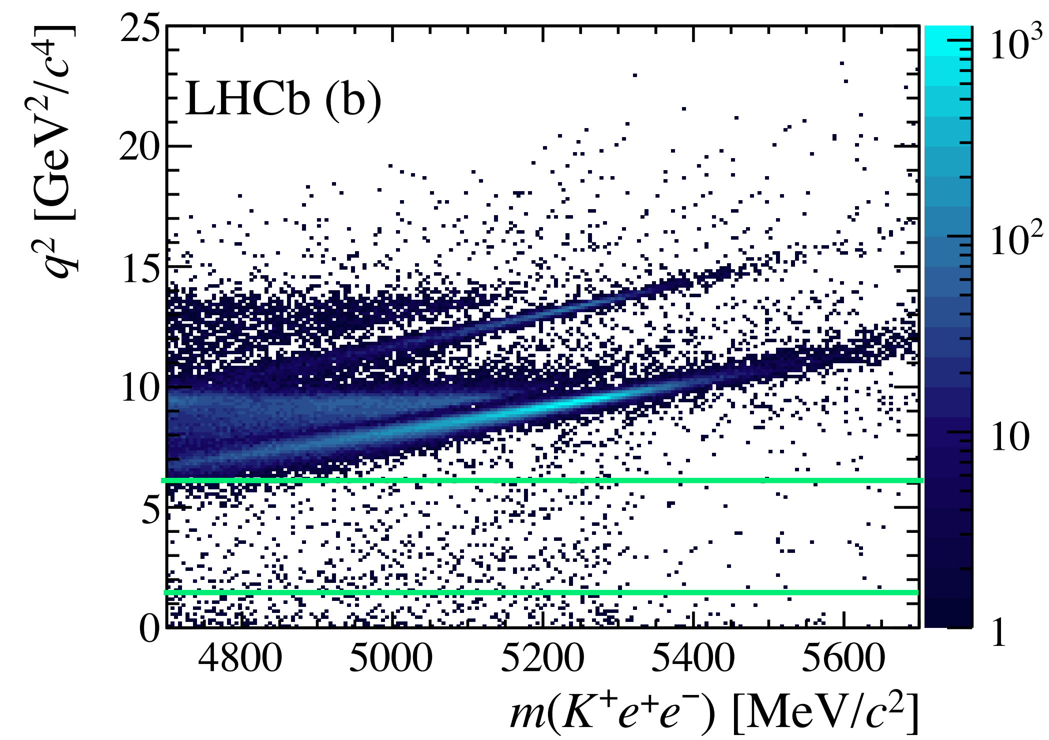
- Analysis performed with 3 fb^{-1} of data

$$R_K = \frac{\int \frac{d\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B^+ \to K^+ e^+ e^-)}{dq^2} dq^2}$$

- Signal in q^2 range [1,6] GeV^2/c^4
- R(K) value compatible with SM at 2.6σ





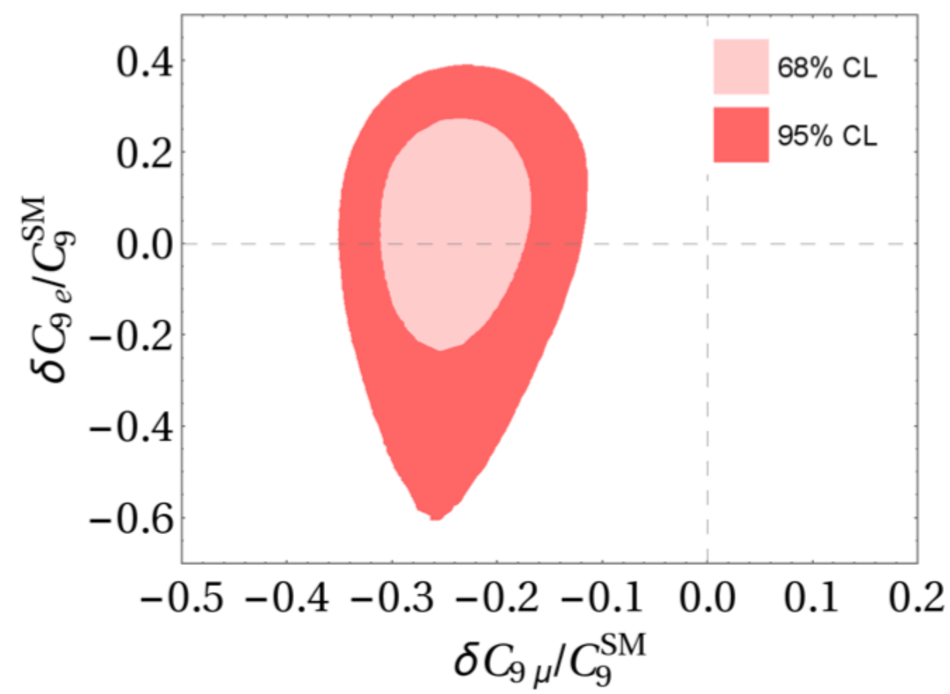


GLOBAL FITS

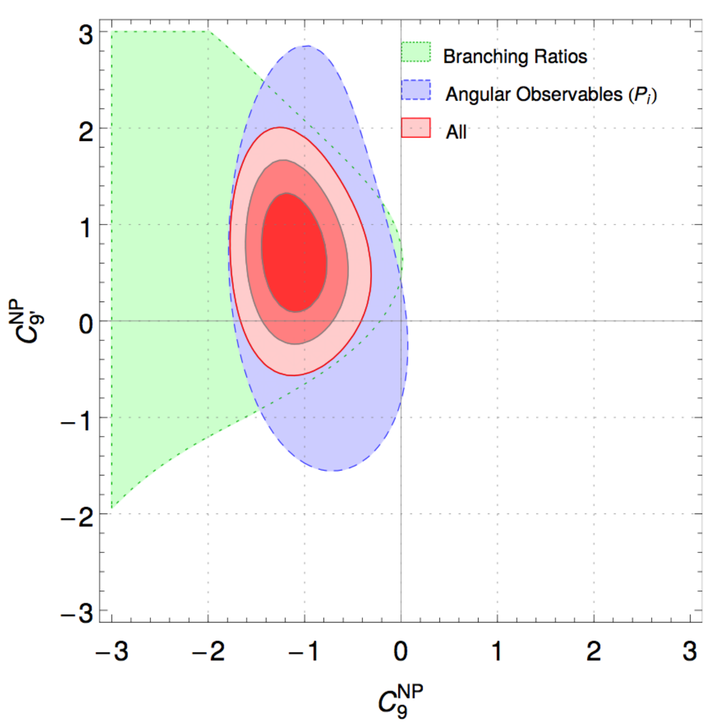
Results from b→sll, b→ll and b→sγ transitions interpreted by global fits to Wilson coefficients

- Includes ~100 observables from multiple experiments
- All fits require additional (non-SM) contribution
- NP in C_9-C_{10} favoured at ~3.5σ from R(K$^{(*)}$) results considered alone
- Adding in other results, C_9 favoured at ~5σ

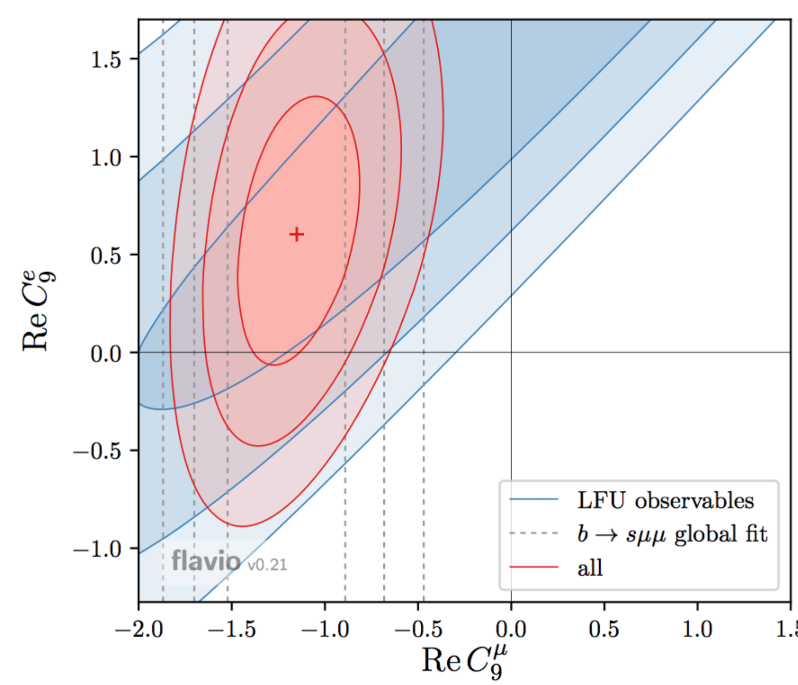
arXiV:1705.06274

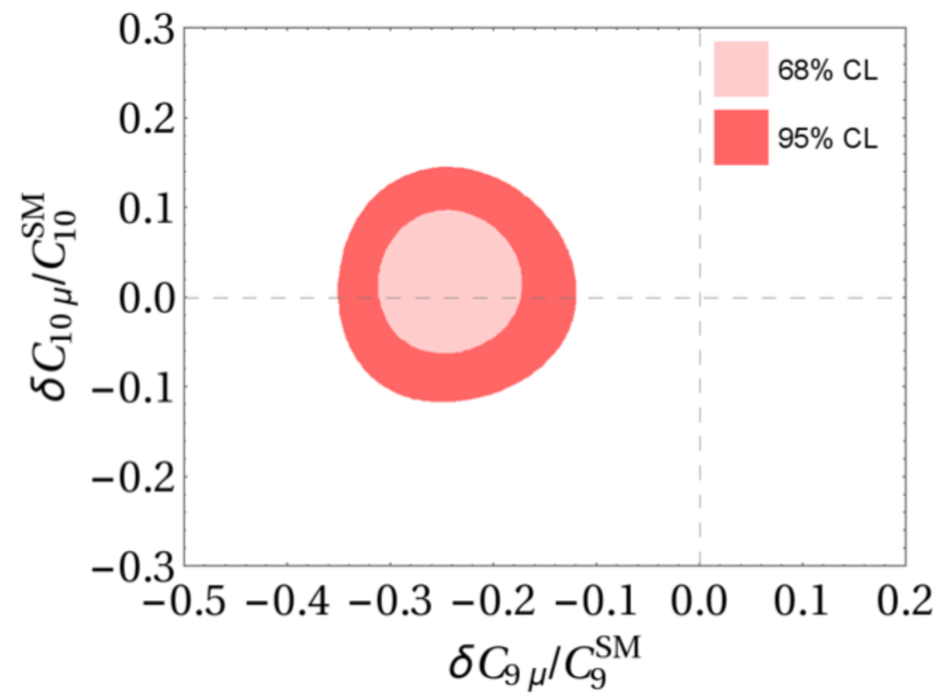


JHEP 06 (2016) 092



arXiV:1704.05435



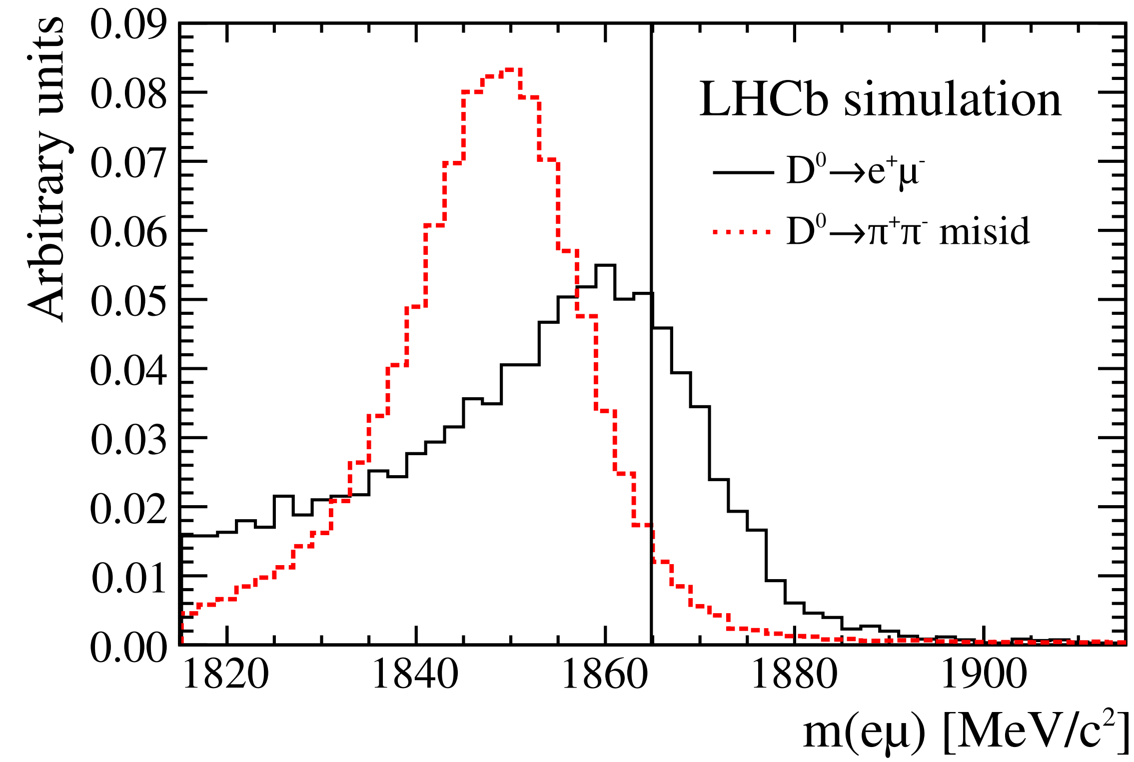


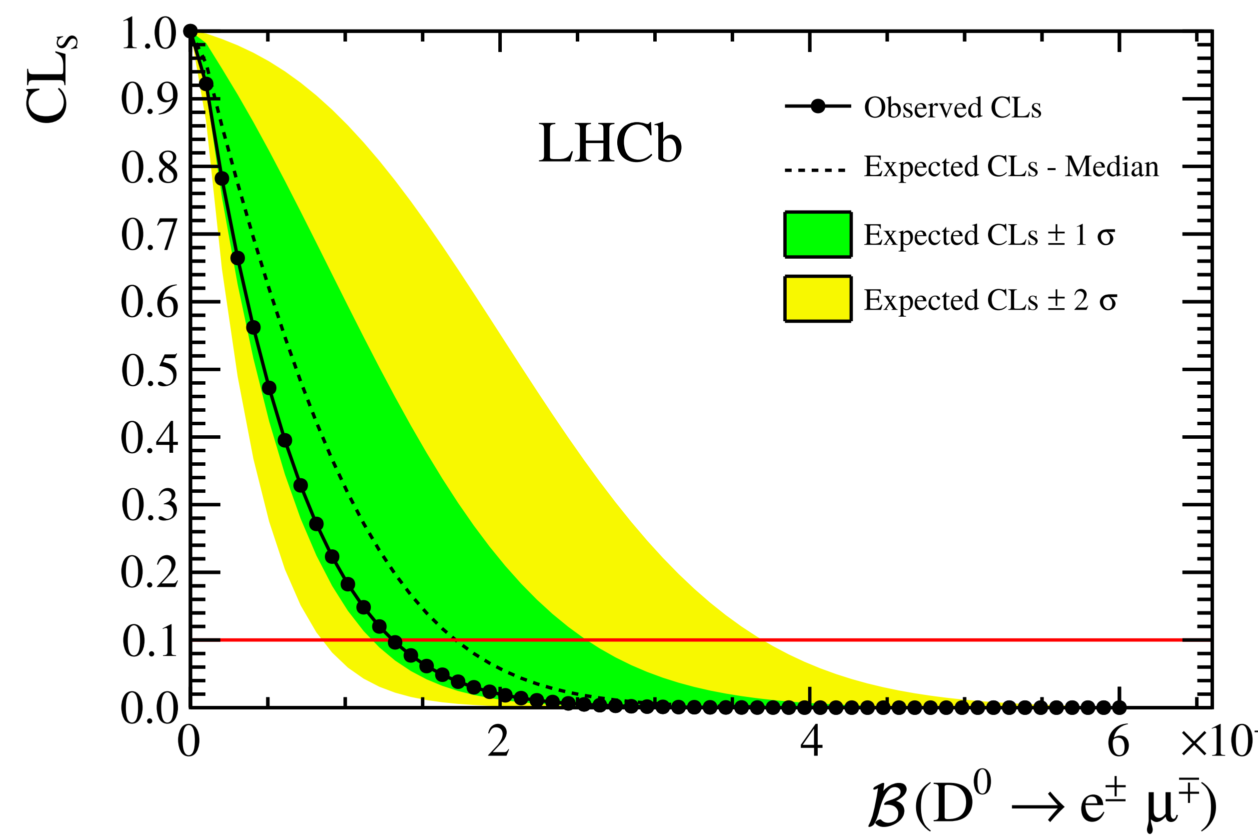
LFV in $D^0 \rightarrow e^{\pm}\mu^{\mp}$ Decays

PLB 754 (2016) 167

- Search for tagged $D^{*+} \rightarrow D^0(\rightarrow e^{\pm}\mu^{\mp})\pi^+$ decays using 3fb-1 of Run 1 data
- Normalisation channel: $D^0 \rightarrow K^{\pm}\pi^{\mp}$
- Primary background from misidentification of $D^0 \rightarrow \pi^+\pi^-$ decays
- Two-dimensional fit in m(eμ), $\Delta m(D^{*+}-D^0)$ performed
- Limits set in absence of signal:

$$\mathcal{B}(D^0 \rightarrow e\mu) < 1.3 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$
$$\mathcal{B}(B^0 \rightarrow e\mu) < 2.8 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$
$$\mathcal{B}(B_s \rightarrow e\mu) < 1.1 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$



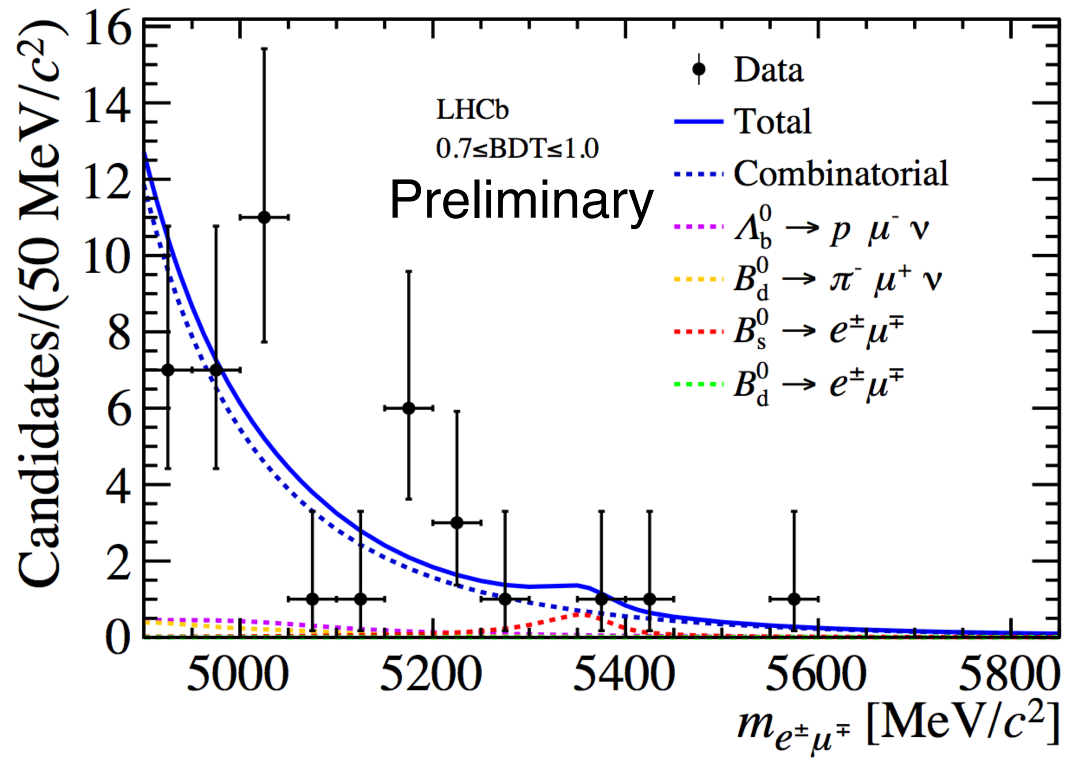


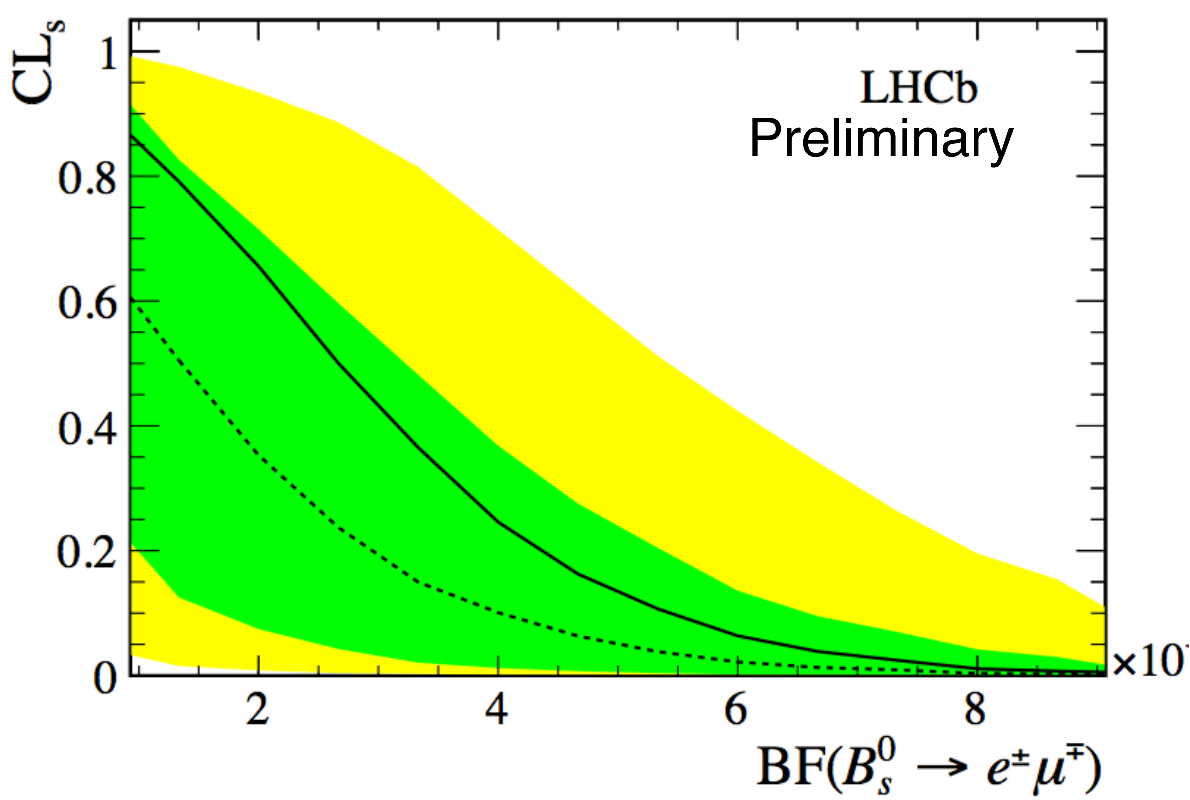
LFV in $B^0 \to e^\pm \mu^\mp$ Decays

LHCb-PAPER-2017-031
(in preparation)

- Search for $B^0 \to e^\pm \mu^\mp$ and $B^s \to e^\pm \mu^\mp$ decays using $3 fb^{-1}$ of Run 1 data
- Normalisation using $B^+ \to J/\psi K^+$ (clean final state) and $B^0 \to K^+\pi^-$ (similar topology to signal)
- Primary (peaking) background from misidentification of $B^0 \to h^+h'^-$ decays with both hadrons misidentified
- Fit to eμ invariant mass distribution yielded no excess
- Limits (world's best) set using the CLs method:

$$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.0\,(1.3) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 5.4\,(6.3) \times 10^{-9}$$



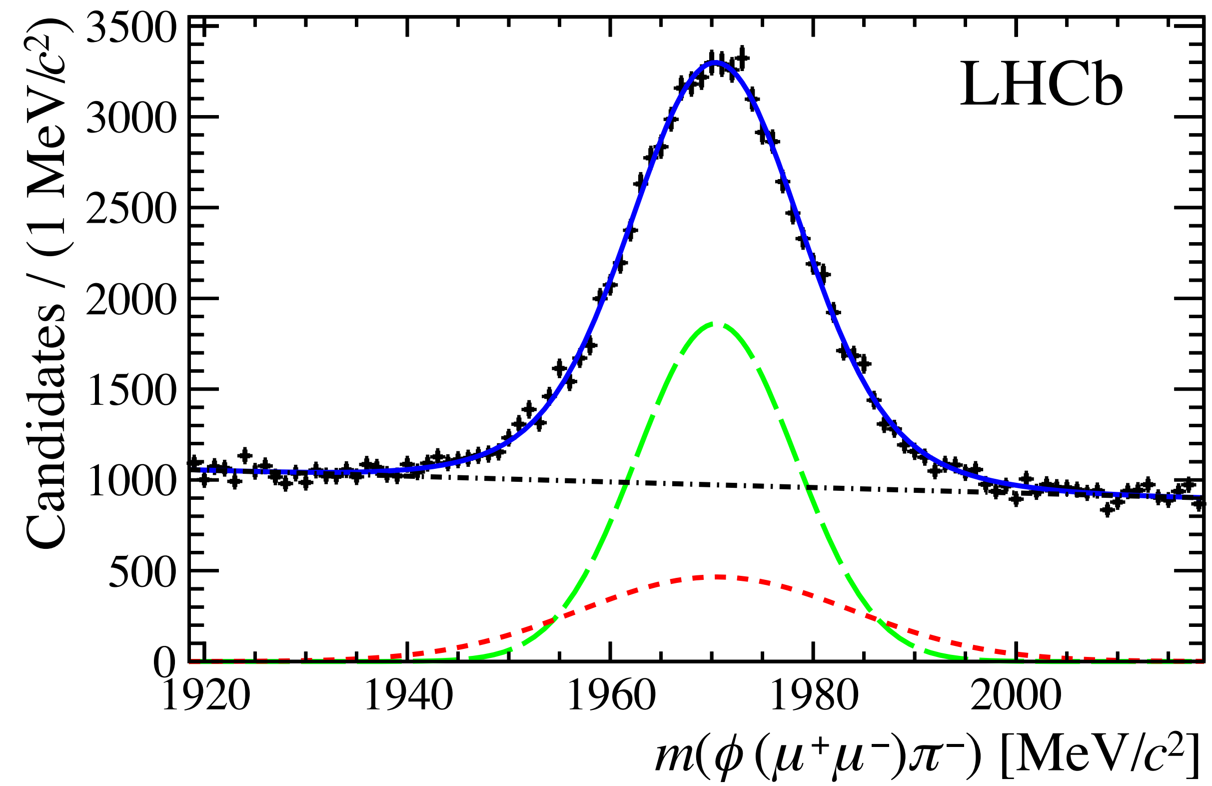


LFV in $\tau^+ \rightarrow \mu^+\mu^-\mu^+$ Decays

JHEP 02 (2015) 121

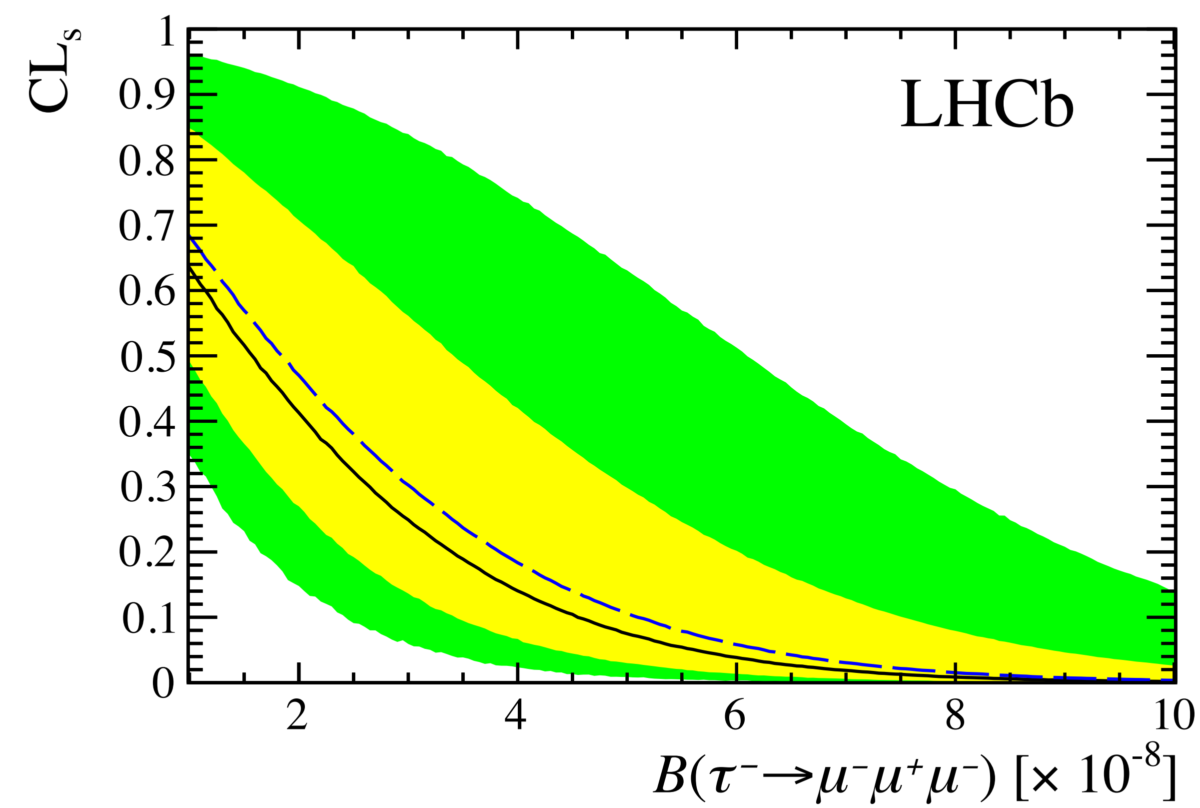
- Search for $\tau^+ \rightarrow \mu^+\mu^-\mu^+$ decays using 3fb^{-1} of Run 1 data
- Normalisation:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \mathcal{B}(D_s^- \to \phi(\to \mu\mu)\pi) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau\bar{\nu}_\tau)} \times \frac{\varepsilon_{cal}}{\varepsilon_{sig}} \times \frac{N_{sig}}{N_{cal}}$$



- Relatively clean final state
- Build three-dimensional likelihood using:
  - MVA based on PID
  - MVA based on topological variables
  - candidate invariant mass
- No signal observed; limits set on BR:

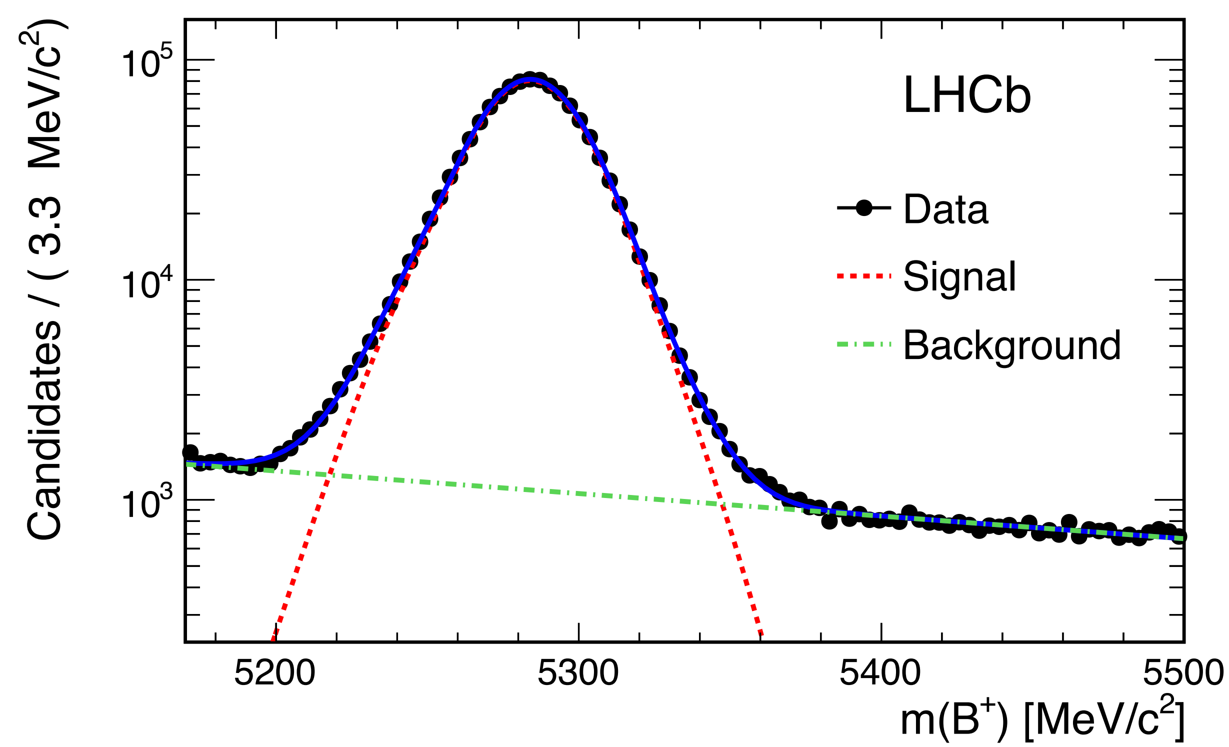
$$\mathcal{B}(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

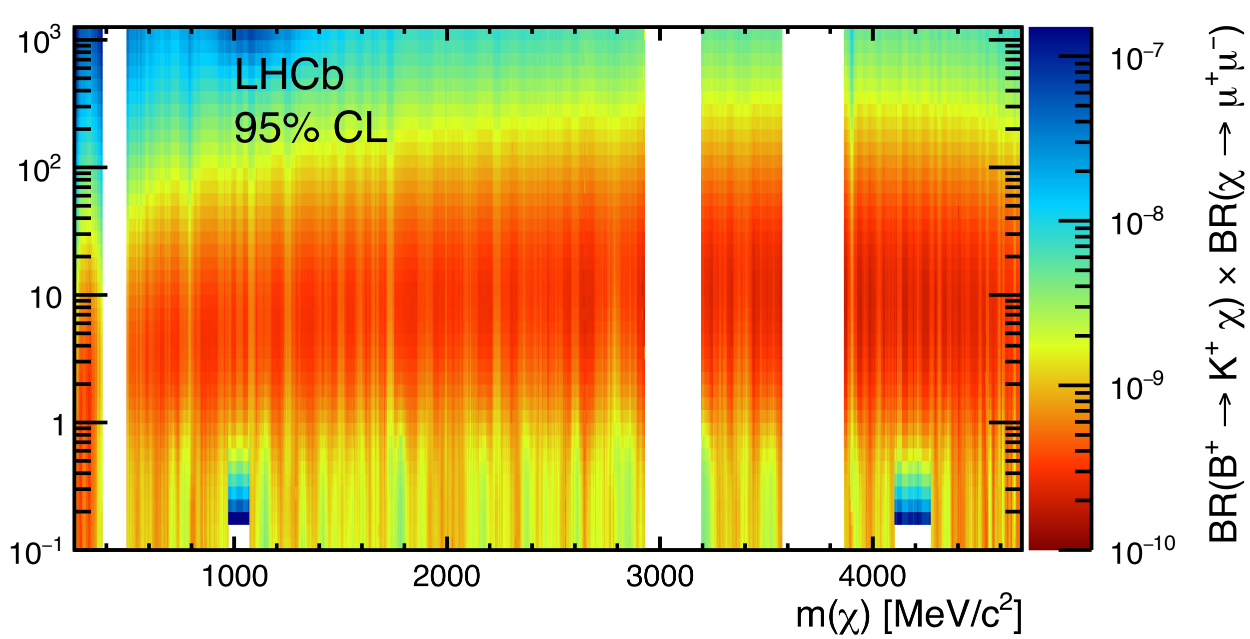


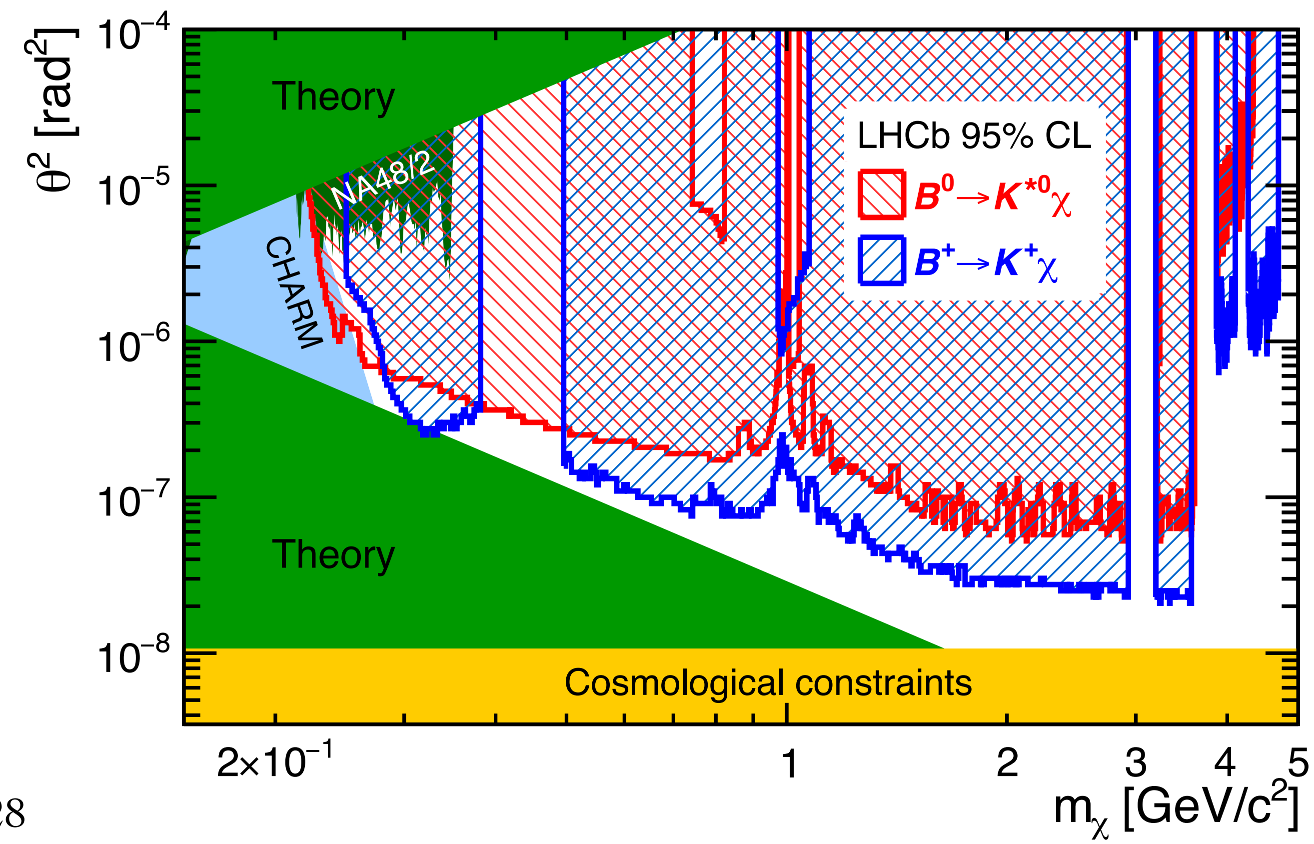
Search for long-lived scalar particles

- Search for long-lived $\chi \to \mu^- \mu^+$
  - Can be produced in $b \to s$ transitions via mixing with Higgs
- Detector signature: Narrow peak in di-muon invariant mass in $B^+ \to K^+ \mu^- \mu^+$ decays
- Normalize to $B^+ \to J/\psi\, K^+$ decays
- 95% CL set on branching fraction in absence of signal
  - Large amount of parameter space excluded in inflaton model

PRD 95, 071101 (2017)



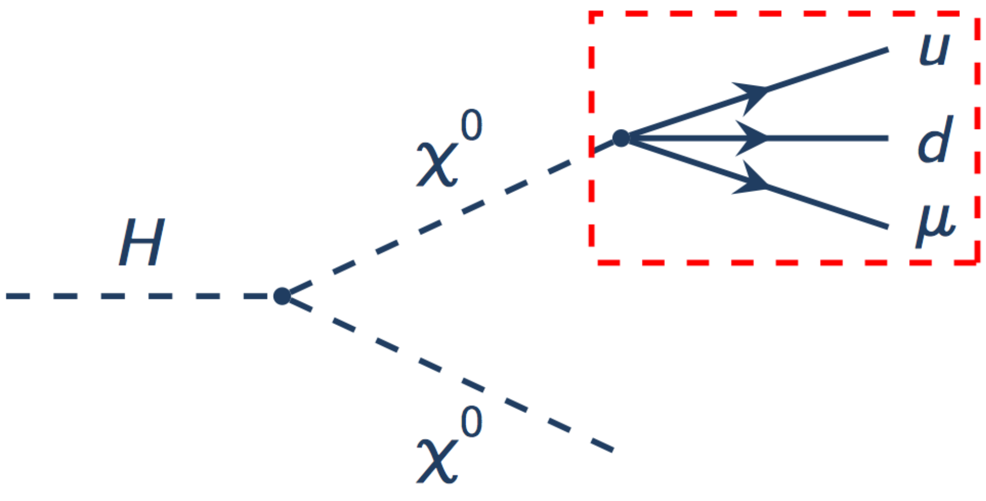


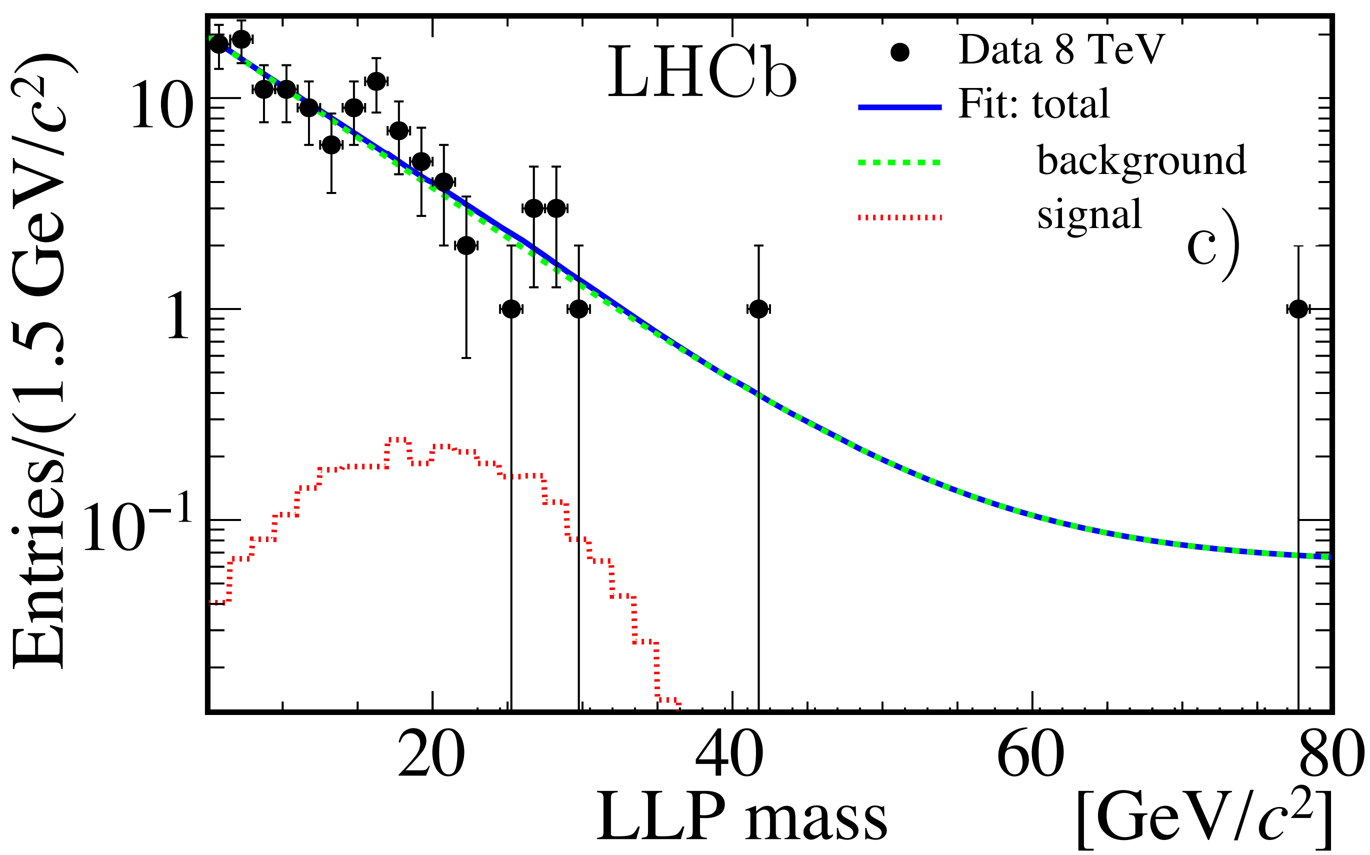


Semileptonic Decays of Long-Lived Particles

Eur.Phys.J. C (2017) 77:224

- Search for decays of long-lived mSUGRA neutralino to a muon and two quarks
- Detector signature: muon + multi-track displaced vertex
- Event selection:
  - Vertex w/ ≥ 4 tracks, significantly displaced from the IP associated to muon w/ pT > 12 GeV)
  - Veto on vertices in detector material regions
  - MVA (Multi-layer perceptron) to refine selection





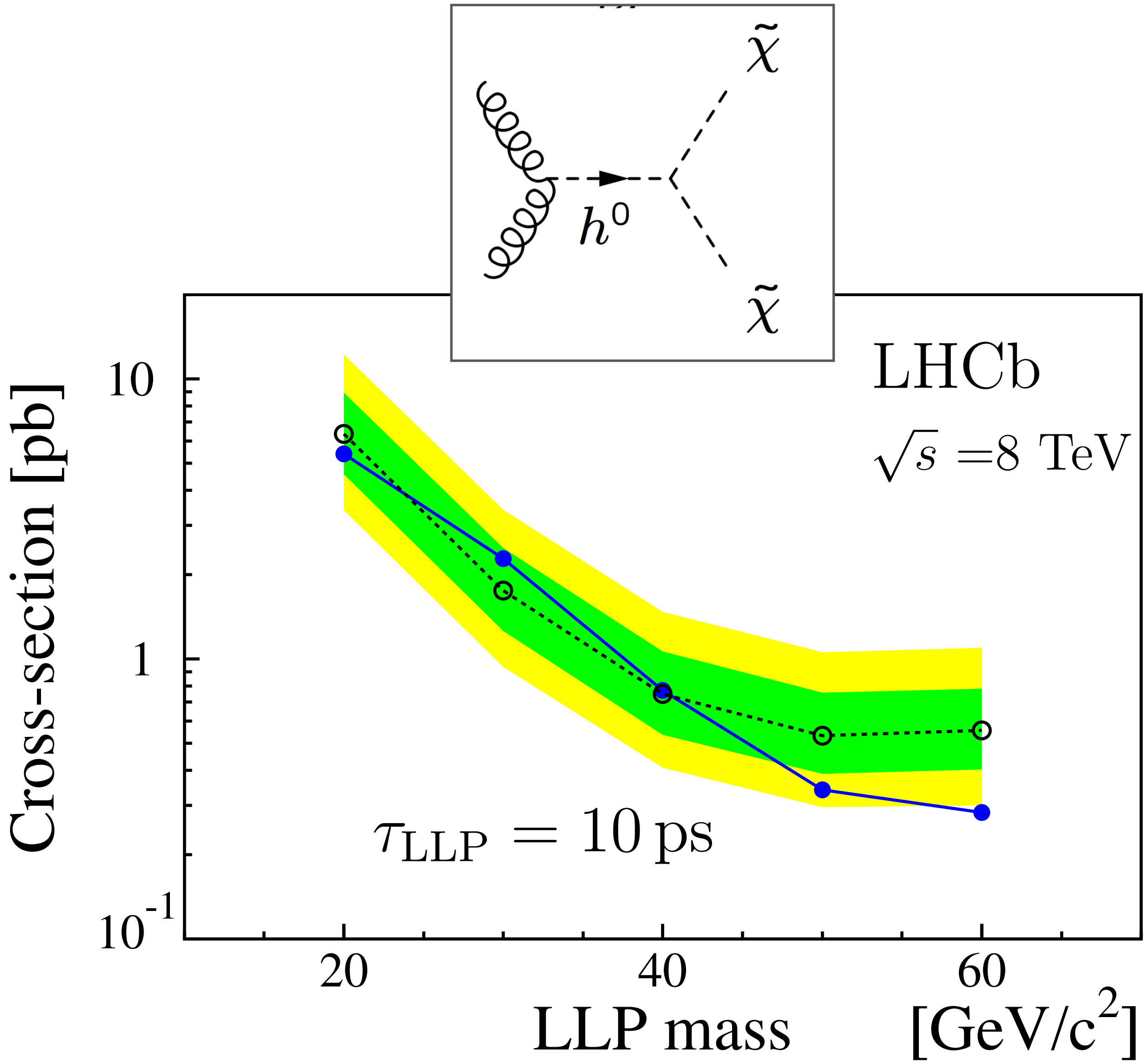
- Main backgrounds: $b\bar{b}$ decays (also W, Z decays)
- Fit LLP candidate mass with signal + background PDF
  - Simultaneous background fit on data-based control sample (selected using muon isolation variable)

Semileptonic Decays of Long-Lived Particles

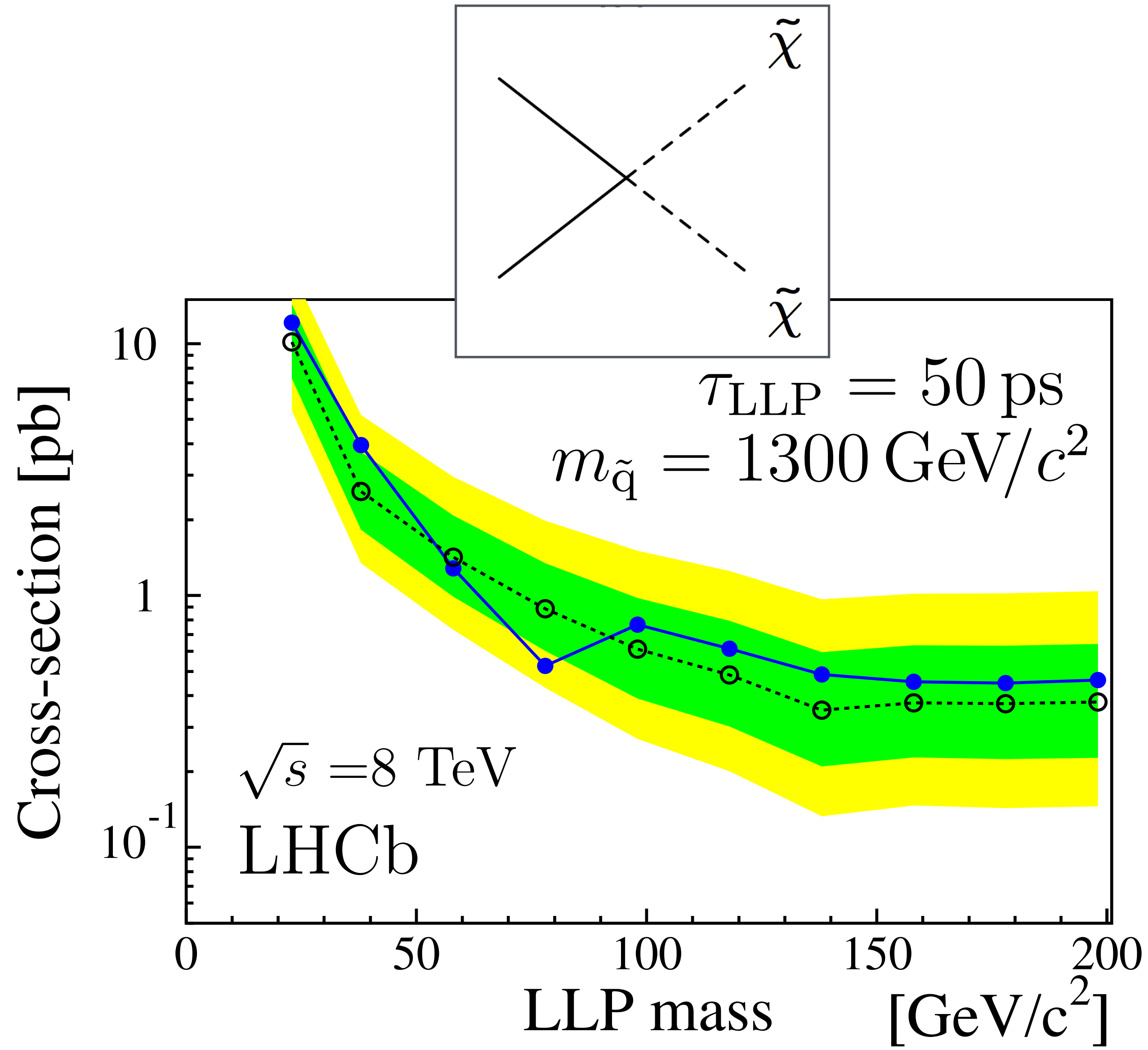
Eur.Phys.J. C (2017) 77:224

- No significant excess observed in 3fb^{-1} of data
- Results interpreted in terms of models with different production mechanisms

Higgs decay to neutralino pair



SUSY neutralino pair production



SUMMARY

- Wide variety of measurements and searches performed with the Run 1 LHCb dataset
    - No direct evidence of NP (yet) from a single measurement/search
    - Consistent anomalies seen in LFU measurements, and BF measurements, angular analyses of b→sll transitions
- LHCb Run 2 dataset collected in 2015-2016 doubles the existing statistics
    - First analyses ready, more results to come soon!

BACKUP