Measurement of *CP*-averaged observables in the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay

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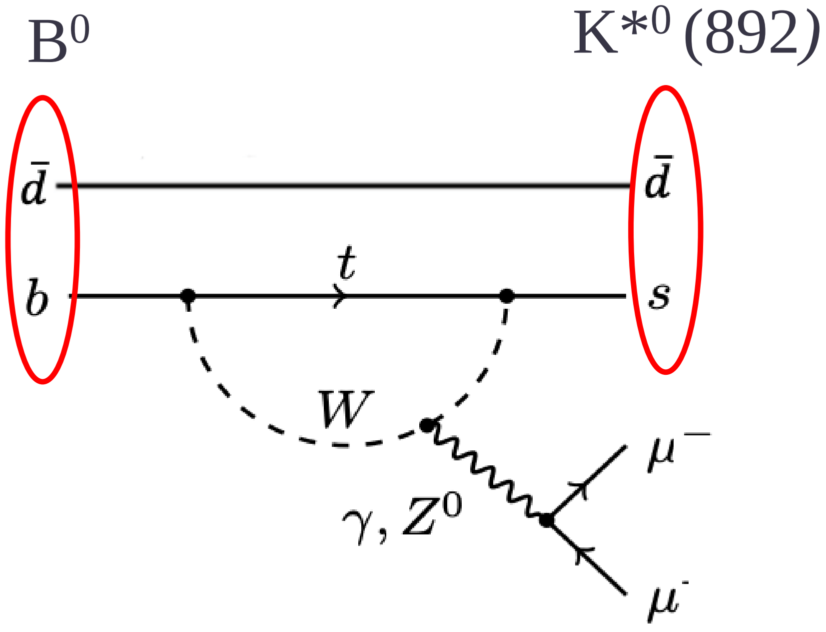
Introduction

- FCNC, rare process (BF: 10^{-7}), electroweak penguin decay at loop level
- Effects of new physics effects could show up at at loop level
- From 2013, series of anomalies appear in B meson decays of $b \to sl^+l^-$ transition
- LHCb measured the angular observables S_3 to S_9 from $B^0 \to K^{*0}\mu^+\mu^-$ decay



$B^0 \to K^{*0}\mu^+\mu^-$ Angular Distribution

- Assuming B^0 and $\overline{B^0}$ behaves similarly ("CP-averaged")
- Differential angular distribution can be expressed in terms of angular observables.
- The observables F_L, A_{FB} and S_i depend on q^2, which determines the Wilson coefficients in the decay process
- $K^{*0} \to K^+\pi^-$ decay strongly, occur in two different angular momentum configurations S-wave ($l = 0$) or P – wave ($l = 1$)
- Modified angular distribution to account for S-wave contamination in P-wave mode $K^{*0} \to K^+\pi^-$ decays.

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$

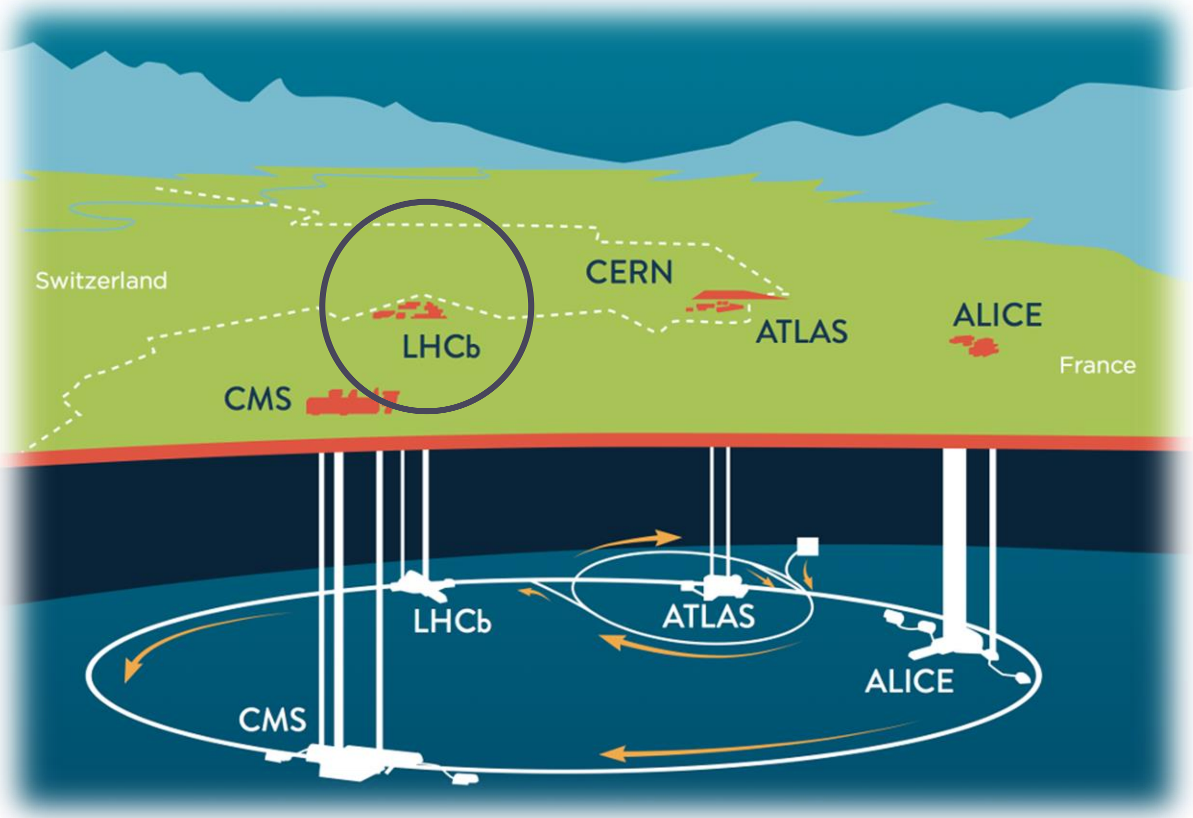
longitudinal polarisation of the K^{*0} meson

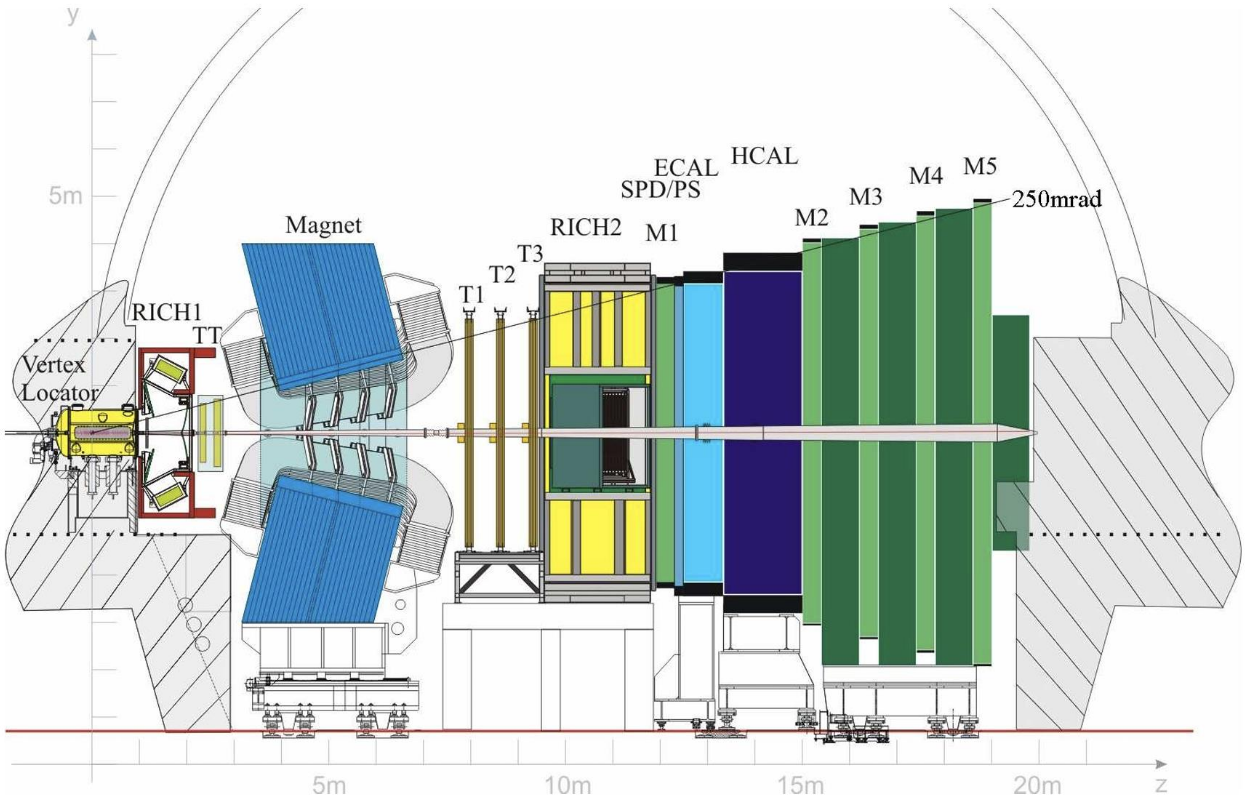
forward-backward asymmetry of the dimuon system.

CP-averaged observables.

LHCb Detector

Single-arm forward spectrometer designed for high-precision physics
Unique option to perform measurements in the forward region $2 < \eta < 5$



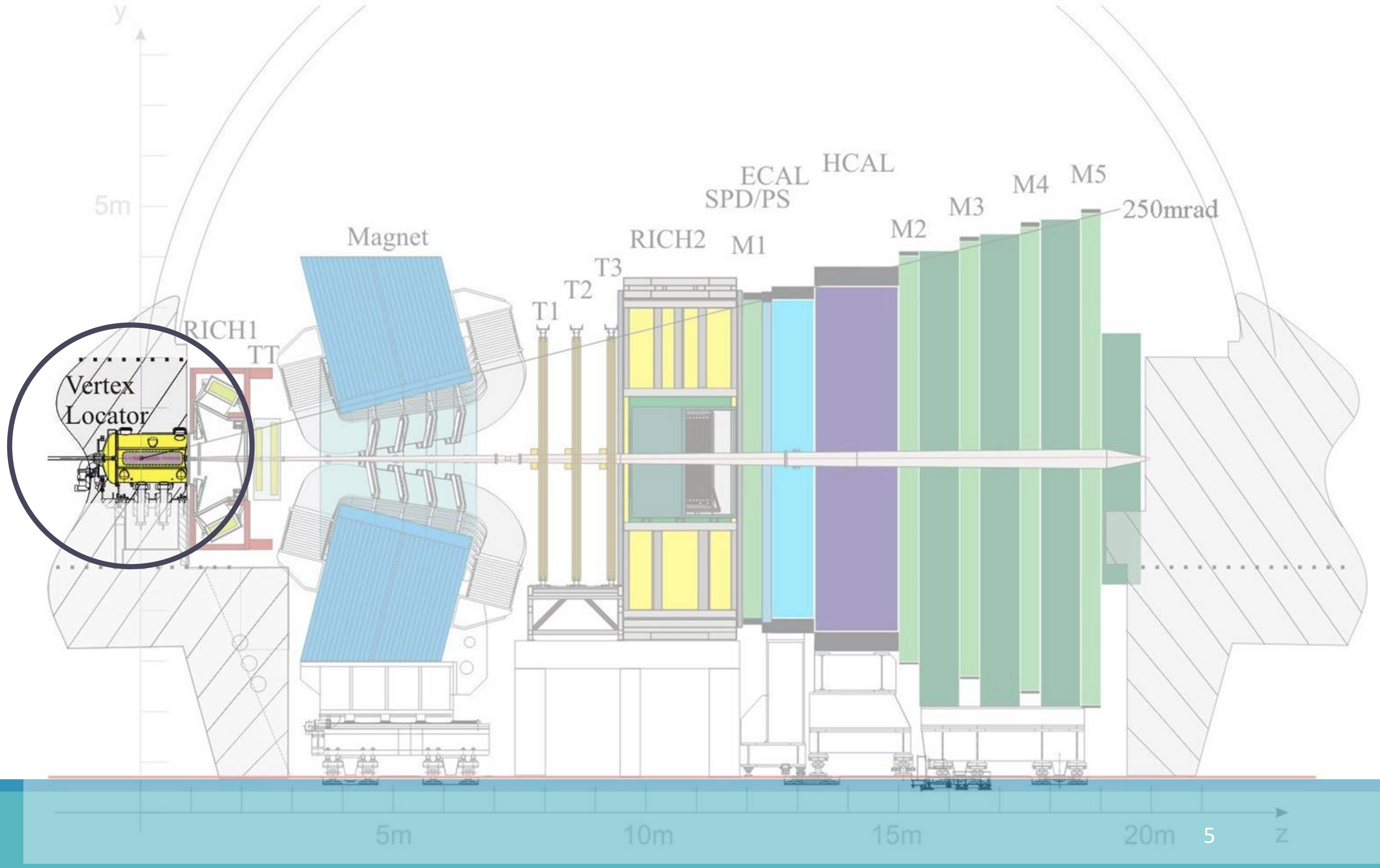


LHCb Detector

Single-arm forward spectrometer designed for high-precision physics
Unique option to perform measurements in the forward region $2 < \eta < 5$

VErtex LOcator

- ✓ Only **7 mm** distance to beam
- ✓ **Excellent** impact parameter resolution to identify **secondary** vertices
- ✓ Decay-time resolution < **50 fs** (decay-time measurement)



LHCb Detector

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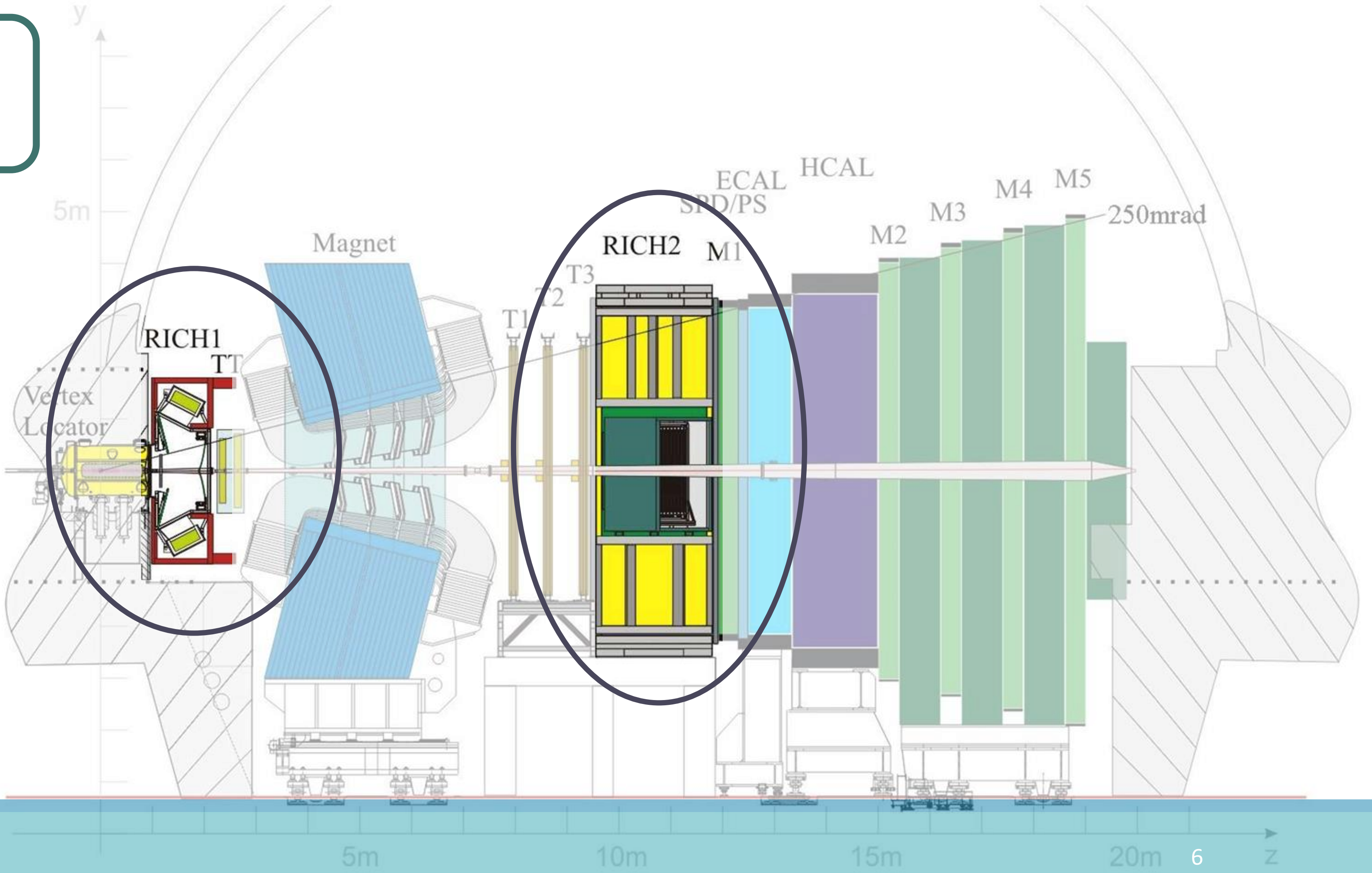
Unique option to perform measurements in the forward region $2 < \eta < 5$

Ring **I**maging **CH**erenkov

- ✓ Particle identification via **Cherenkov** angle
- ✓ **RICH1 & RICH2** work in tandem
- ✓ Charged hadron identification across $\mathbf{2 < p < 100}$ GeV/*c*



LHCb Detector

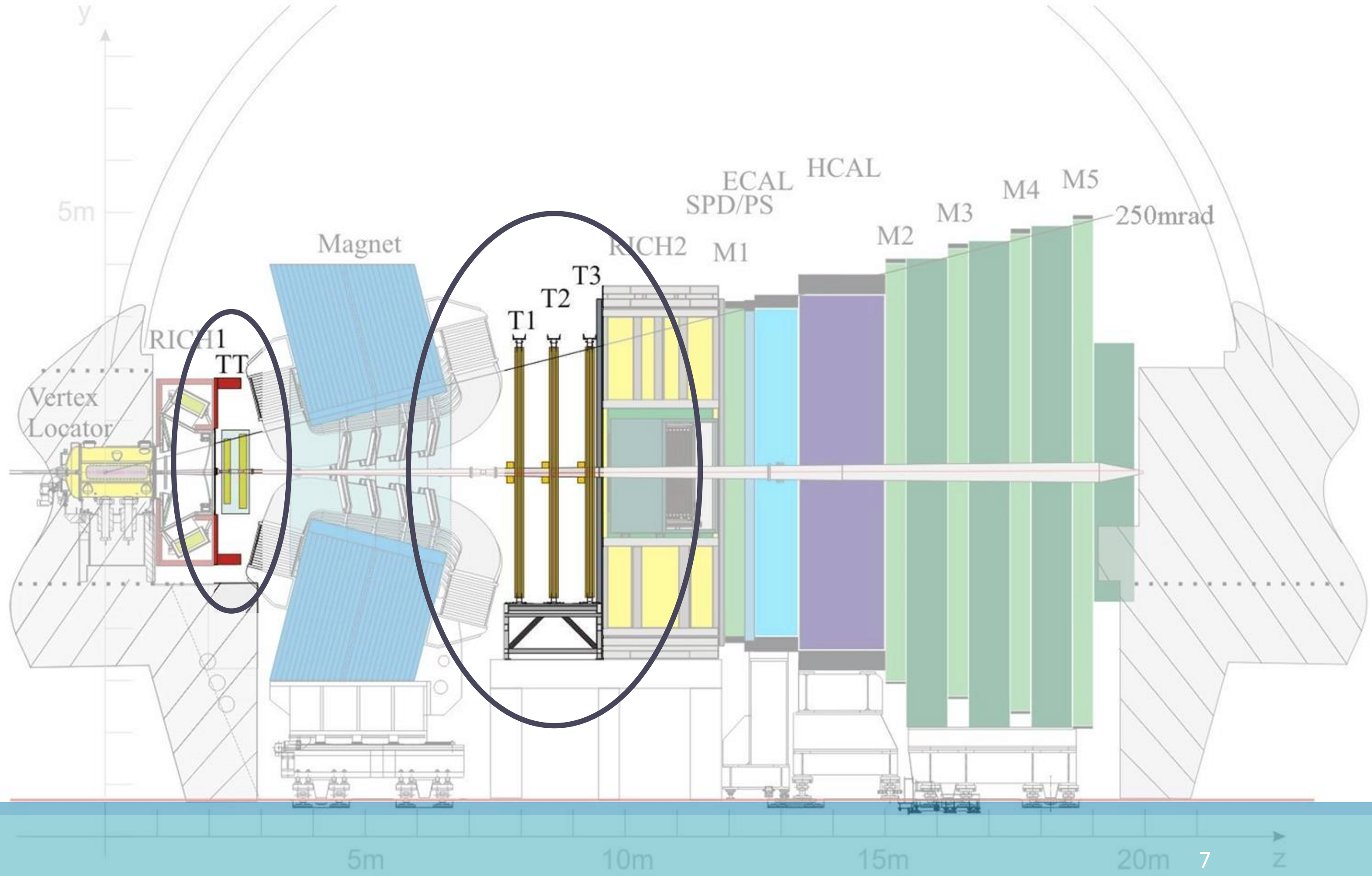
Single-arm forward spectrometer designed for high-precision physics
Unique option to perform measurements in the forward region $2 < \eta < 5$

Trackers

- ✓ Consists of:
  - ➢ Outer Tracker (T1-T3)
  - ➢ Silicon Tracker (TT)
- ✓ Precision momentum resolution

$$\delta p/p = \mathbf{0.4 - 0.6}\%$$

Excellent mass resolution

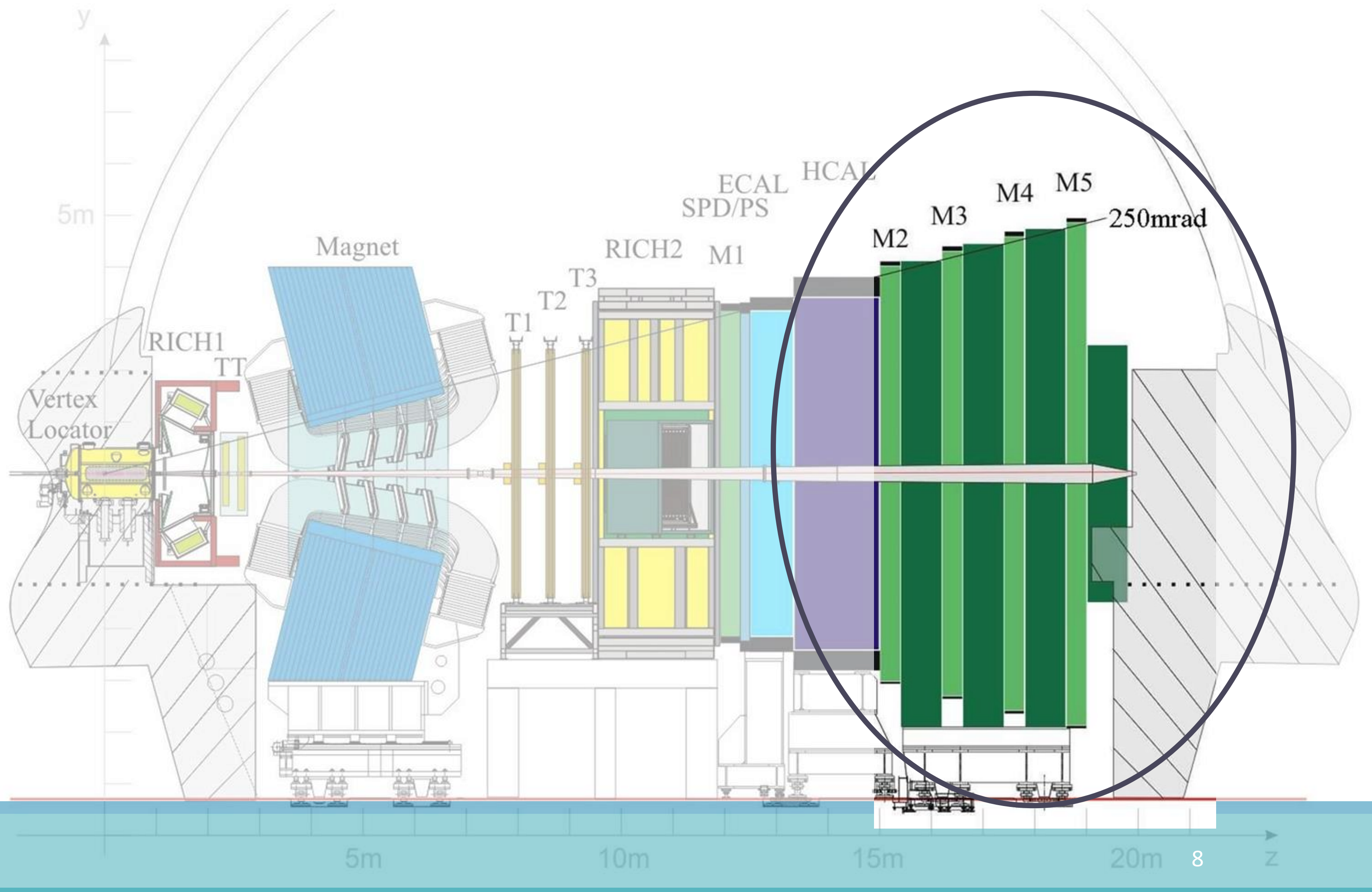


LHCb Detector

Single-arm forward spectrometer designed for high-precision physics
Unique option to perform measurements in the forward region $2 < \eta < 5$

Muon systems

- ✓ Fast information for the high-p_{T} muon trigger at the earliest level (**Level-0**)
- ✓ Muon identification for the high-level trigger (**HLT**)
- ✓ Equiped with **MWPC** and **GEMs** for a high interaction rate

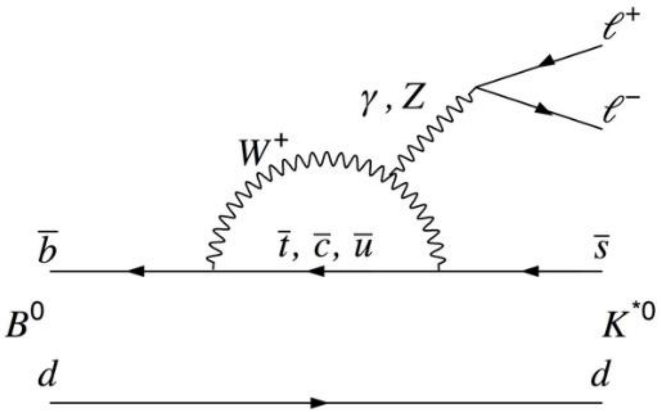


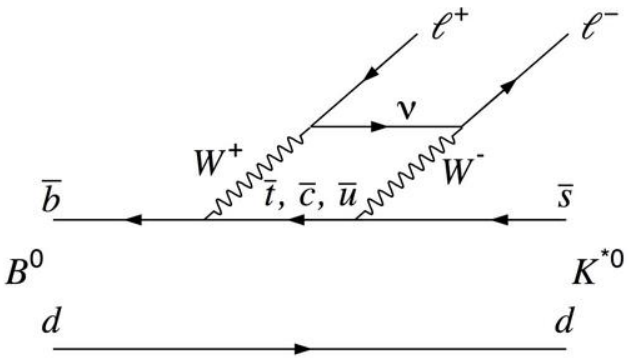
Decay Kinematics

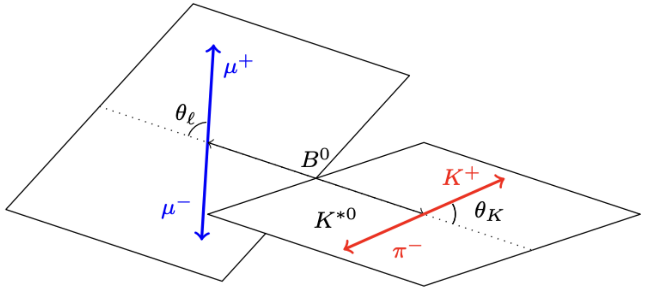
- Differential decay depending on angular distributions

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_{K^*}, \phi)$$

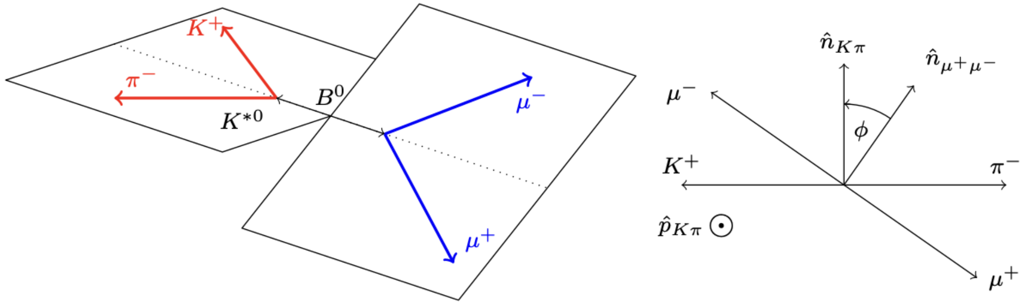
- Decay described by three angles (θ_l, ϕ, θ_K) with q^2 being the invariant squared mass of the $\mu\mu$ system



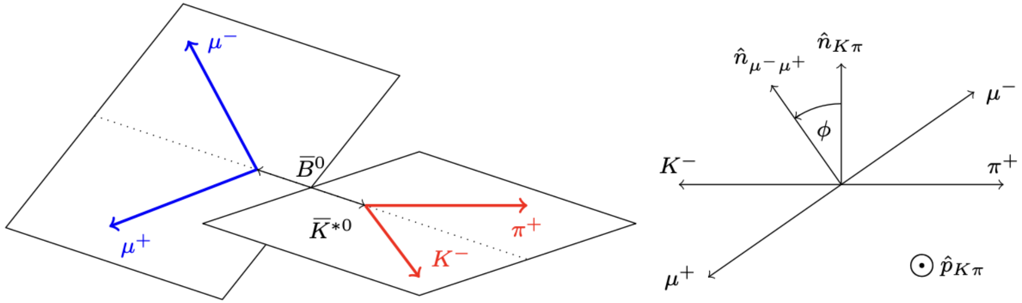




(a) θ_K and θ_ℓ definitions for the B^0 decay

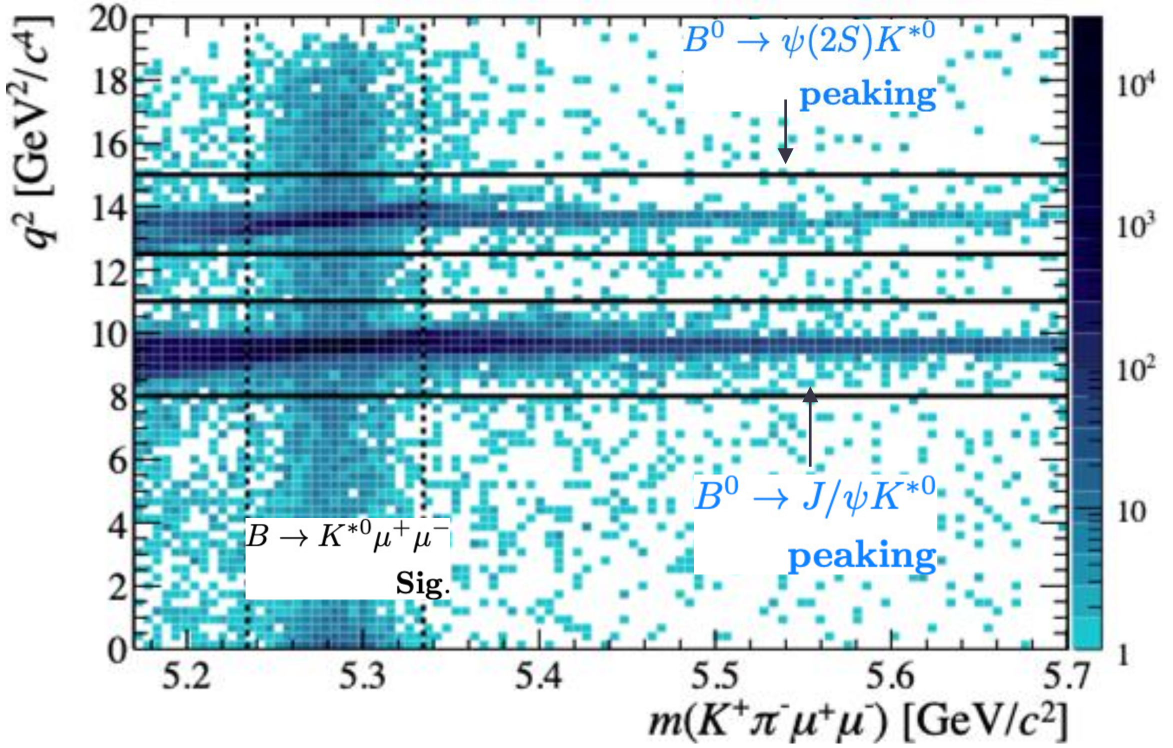


(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\bar{B}^0$ decay

Background

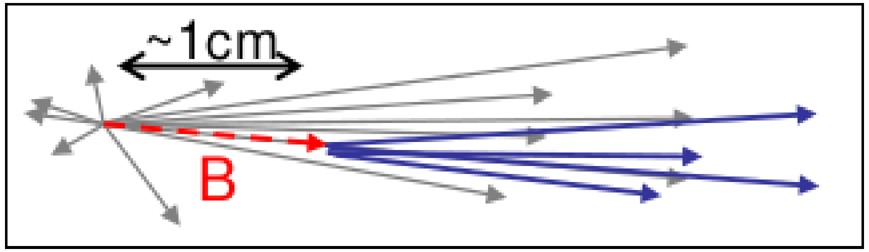


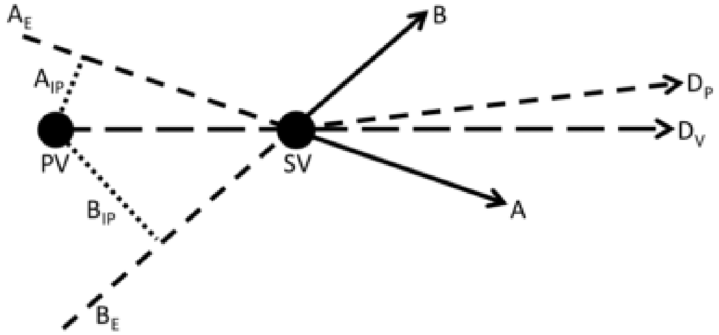
- Background component: combinatorial background + peaking backgrounds
  - non-single b-hadron decay: Smoothly distributed in m($K^+\pi^-\mu^+\mu^-$)
  - Misidentification of the final-state particles: accumulate in specific regions of the reconstructed mass

- Removal of BKGs
  - peaking bkg (Apply vetos): residual BKG (<1%), **neglectable** in the angular analysis
  - combinatorial bkg (boosted decision tree (BDT)): reject **97%** combinatorial bkg, remains 85% sig.

Selection Cuts

- Candidates are required to have
  - $5170 < m(K^+\pi^-\mu^+\mu^-) < 5700\ MeV/c^2$
  - $795.9 < m(K^+\pi^-) < 995.9\ MeV/c^2$
- The tracks are fitted to a common vertex which is required to have good quality
- The four tracks are required to originate from displaced secondary vertices





Observables

- $\boldsymbol{F_L}$ corresponds to the fraction of longitudinal polarisation of the K^{*0} meson
- $\boldsymbol{A_{FB}}$ is the forward-backward asymmetry of the dimuon system
- $\boldsymbol{S_5}$ depends on polarisation amplitudes
- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ for comparison to other studies with reduced uncertainties

Observables used for fits by varying real part of vectorial coupling strength C_9 being sensitive to new physics in the studied process

Uncertainties: Fit Bias

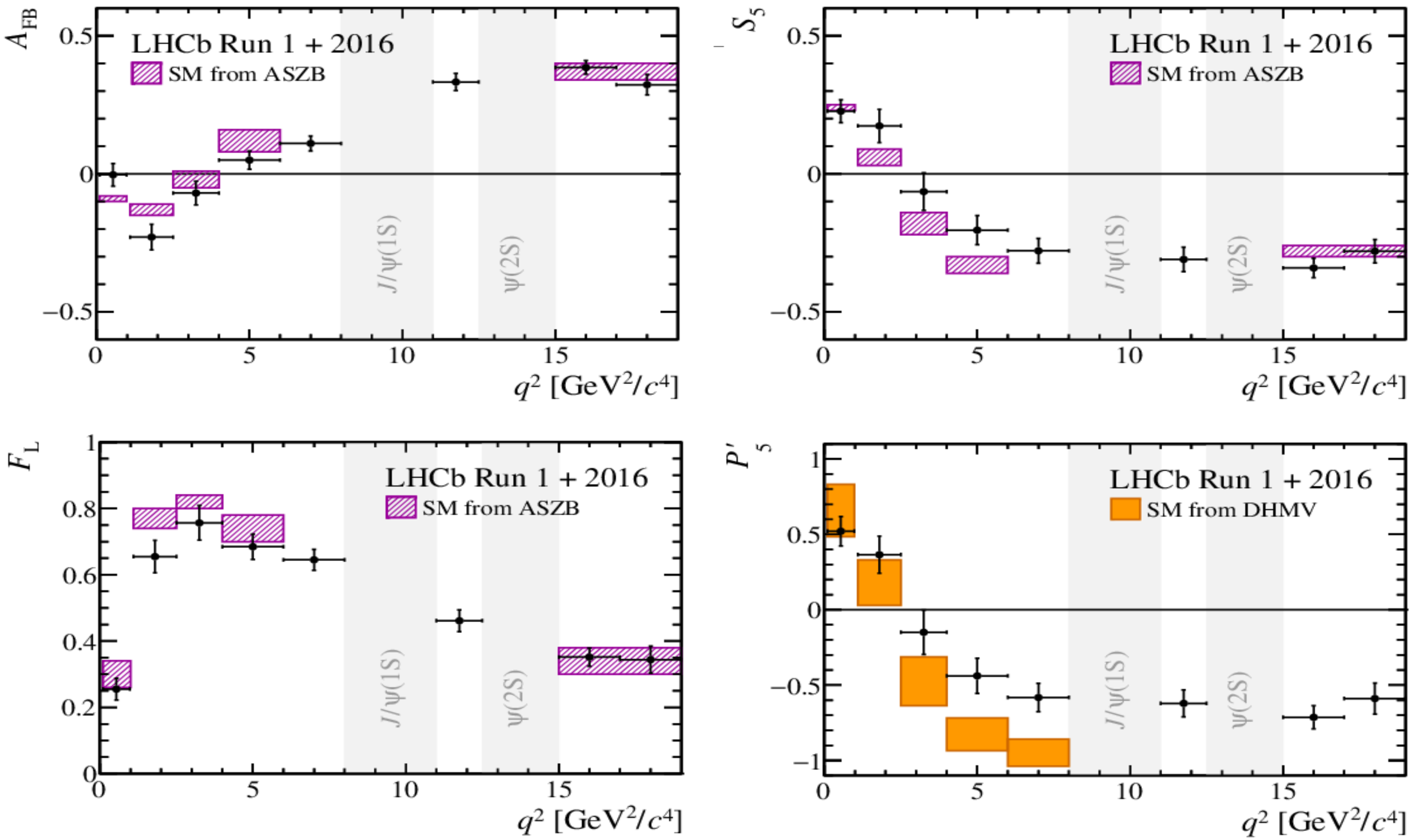
- Large number of parameters can return observable in biased way. ("do fit errors provide the correct converge")
- Biased observed are small: < 10% of statistical uncertainty
- Boundary effects in the observables contributing to biases. Significant effect comes from requiring S-wave fraction, F_S to be greater than zero
- Statistical uncertainty are corrected for under or over convergence and systematic uncertainty equal to size of the observed bias is assigned

Uncertainties: Systematics

Source	F_L	A_{FB}, S_3–S_9	P_1–P_8'
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01
Acceptance polynomial order	< 0.01	< 0.01	< 0.02
Data-simulation differences	< 0.01	< 0.01	< 0.01
Acceptance variation with q^2	< 0.03	< 0.03	< 0.09
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.02
Background model	< 0.01	< 0.01	< 0.03
Peaking backgrounds	< 0.02	< 0.02	< 0.03
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.02
$K^+\mu^+\mu^-$ veto	< 0.01	< 0.01	< 0.01
Trigger	< 0.01	< 0.01	< 0.01
Bias correction	< 0.02	< 0.02	< 0.04

- Statically dominated results and systematic uncertainties are small
- q^2 acceptance variation is the most dominant
- Peaking background and bias correction also have significant contributions to systematics

Fit Results



- Observables $\boldsymbol{A_{FB}}$, $\boldsymbol{F_L}$ and $\boldsymbol{S_5}$ compared to SM prediction based on ASZB (see [1,2]) and $\boldsymbol{P_5'}$ to SM prediction based on DHMV (see [3,4])
- No significant discrepancy for each observable separately
- Combined fit gives overall tension with SM around 3.3σ

[1]: arXiv:1503.05534, [2]: arXiv:1411.3161
[3]: arXiv:1407.8526, [4]: arXiv:1006.4945

Conclusions

- The most precise measurements of the observables to date are done by LHCb and presented in the paper. A tension with the SM of 3.3σ was observed
- The measurement is statistically limited
- Most of the observables agree individually, except the local discrepancy in the P_5' observable
- More data is required to draw conclusions about the effects of new physics

Thank You

Back up

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

- Assume B^0 and $\bar{B}^0$ behaves similarly ("CP-averaged"), angular distribution expression as:
- Quantities F_L, A_{FB}, S_i dependent on q^2 → determine Wilson coefficients.
- $K^{*0} \to K^+\pi^-$ decay strongly, occur in two different angular momentum ($l = 0$ or $l = 1$) configurations (S-wave or P-wave).

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}}$$
$$+\frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_l$$
$$+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_l)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_l + S_{15}\sin\theta_l)\sin\theta_K\cos\phi$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_l + S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi\,,$$

- Modified angular distribution to account for S-wave contamination in P-wave mode of $K^{*0} \to K^+\pi^-$ decay.
- Then… parametrize in terms of the (independent) form factors!

Interpretation of Result using EFT

- Encode the FCNC couplings using EFT in electroweak scale (Weak Effective Theory - WET):

$$\mathcal{L} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{WET}} \,.$$

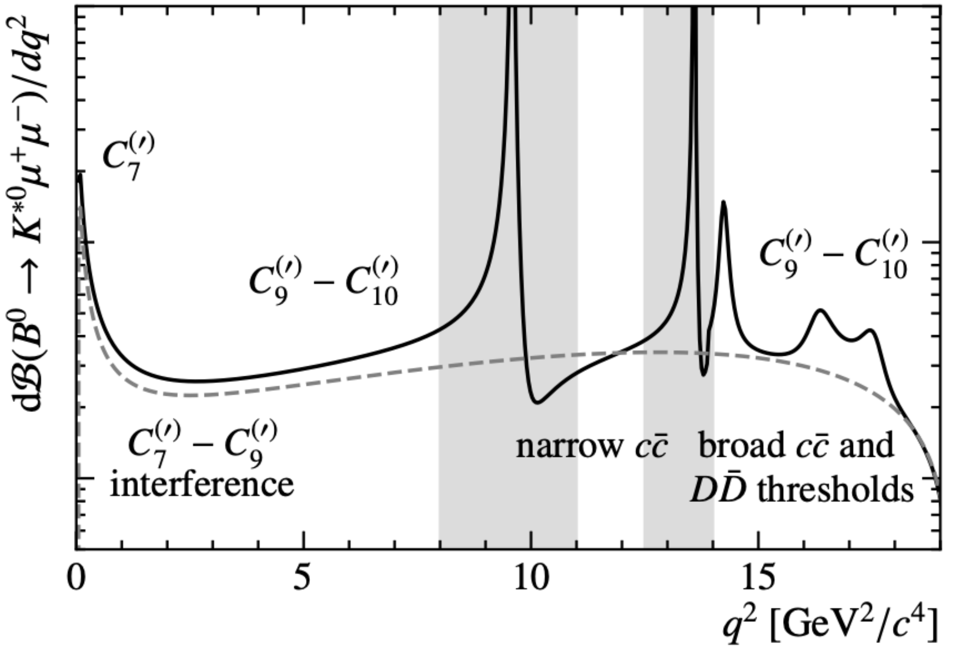
$$\mathcal{L}_{\text{WET}} = \sum_a \mathcal{C}_a \mathcal{O}_a + h.c. + \ldots$$

- Most important couplings for the process…
  - c_7, c_9, c_{10} encodes the photonic, vector and axial-vector coupling…

$$\mathcal{O}_{7(')} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e}{16\pi^2} m_b \left(\bar{s}\,\sigma^{\mu\nu} P_{R(L)} b\right) F_{\mu\nu}$$

$$\mathcal{O}_{9(')} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \left(\bar{s}\,\gamma_\mu P_{L(R)} b\right)\left(\bar{\mu}\gamma^\mu \mu\right)$$

$$\mathcal{O}_{10(')} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \left(\bar{s}\,\gamma_\mu P_{L(R)} b\right)\left(\bar{\mu}\gamma^\mu \gamma_5 \mu\right).$$



$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}\left\{\left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}')\right]\mathcal{F}_\lambda(q^2,k^2) + \frac{2m_b M_B}{q^2}\left[(\mathcal{C}_7 \pm \mathcal{C}_7')\mathcal{F}_\lambda^T(q^2,k^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2,k^2)\right]\right\}$$

Form-factor $F(q)$ enters into the amplitude…

$$\left.\frac{d\sigma}{d^2\Omega}\right|_{extended} \approx \left.\frac{d\sigma}{d^2\Omega}\right|_{pointlike} |F(q)|^2$$

More explicitly…

- Expanding the previous amplitude we see the amplitudes depend on…
  - The effective **Wilson Coefficients** c_7 (photon), c_9 (vector), c_{10} (axial-vector)
  - **Form Factors:** $V(q^2), T_{1,2,3}(q^2), A_{1,2}(q^2)$

$$A_{\perp}^{L(R)} = N\sqrt{2\lambda}\left\{\left[(C_9^{\text{eff}} + C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} + C_{10}'^{\text{eff}})\right]\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} + C_7'^{\text{eff}})T_1(q^2)\right\}$$

$$A_{\parallel}^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}})\right]\frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(C_7^{\text{eff}} - C_7'^{\text{eff}})T_2(q^2)\right\}$$

$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10}^{\text{eff}} - C_{10}'^{\text{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(C_7^{\text{eff}} - C_7'^{\text{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}T_3(q^2)\right]\right\}$$

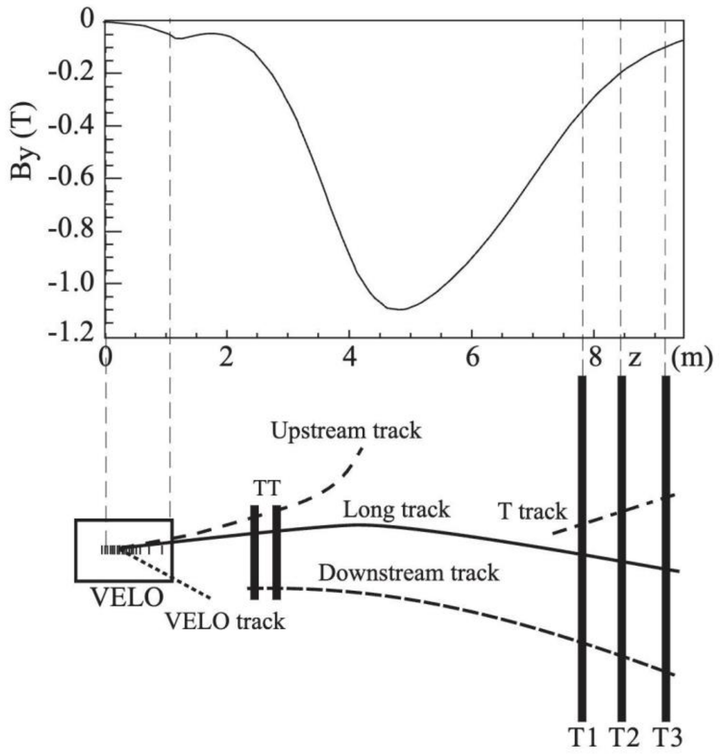
CP-averaged angular distribution

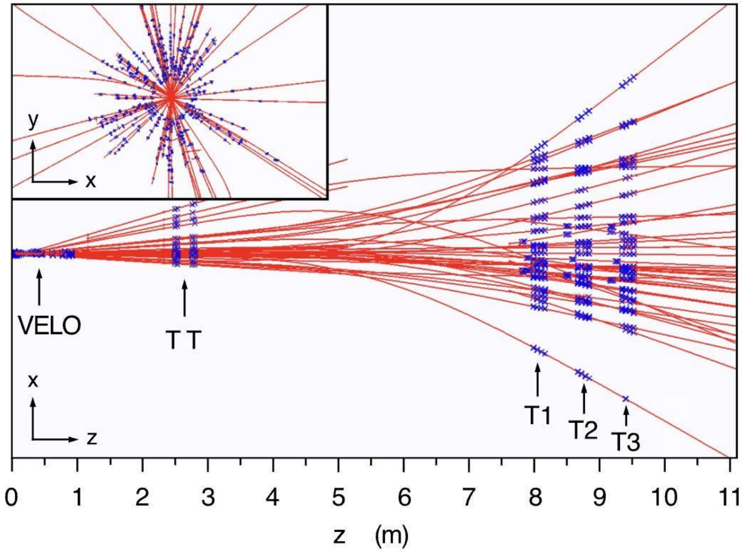
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

Uncertainties: Pseudo Experiment

- Use of pseudo experiments to validate angular analysis methods
- Generate synthetic data sets (pseudo-data) based on actual data.
- Analyze pseudo-data to extract observables.
- Assess the spread in results to estimate uncertainties.

Reconstruction Charged particle





Detector & Reconstruction