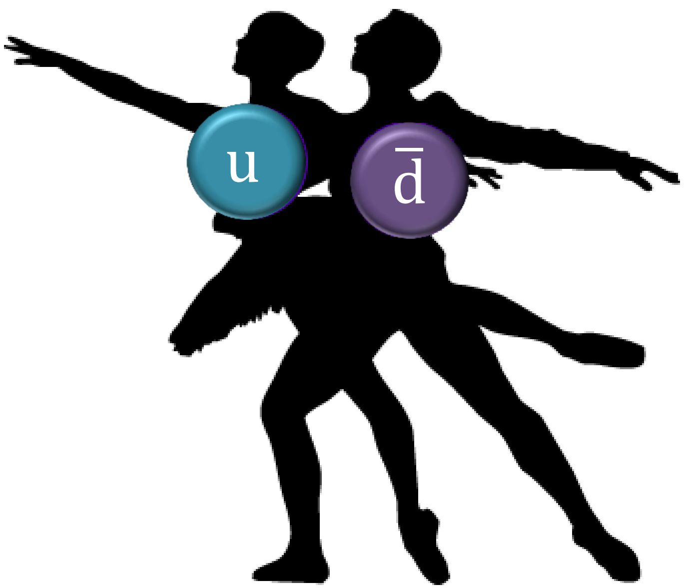
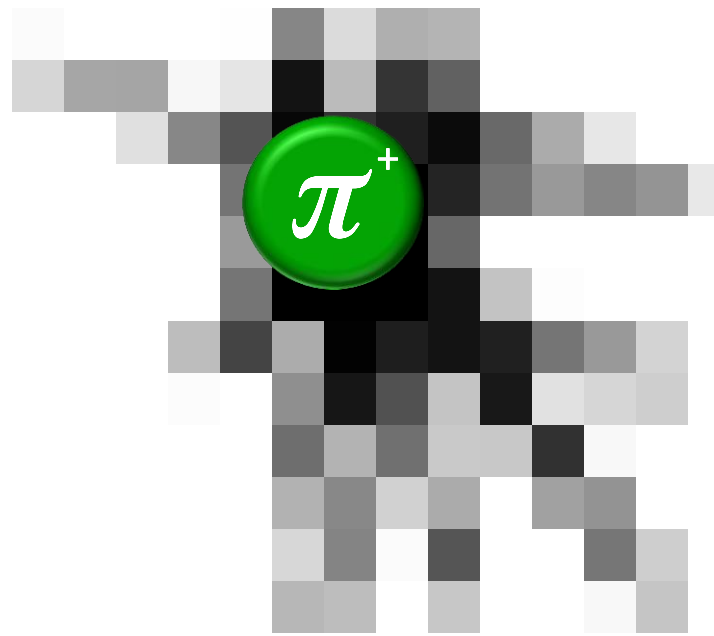
The SM and beyond at LHCb

Thomas Nikodem





Outline

- Why LHCb?
- Insides in LHCb ←
- Angular Measurement

Lifetime Measurement

1. Why not rely on simulation

2. Data driven method to measure decay time resolution

3. Recap

4. Data driven method to measure decay time dependent reconstruction efficiency (Tag and Probe)

5. Fit

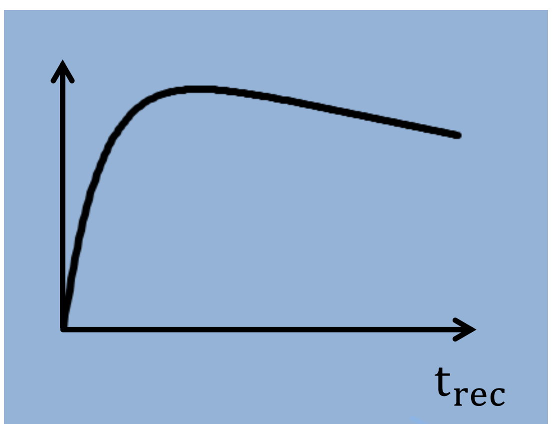
Recap

Current World averages

B^-	1.519 ± 0.005 ps
B^+	1.638 ± 0.004 ps
[illegible]	[illegible]

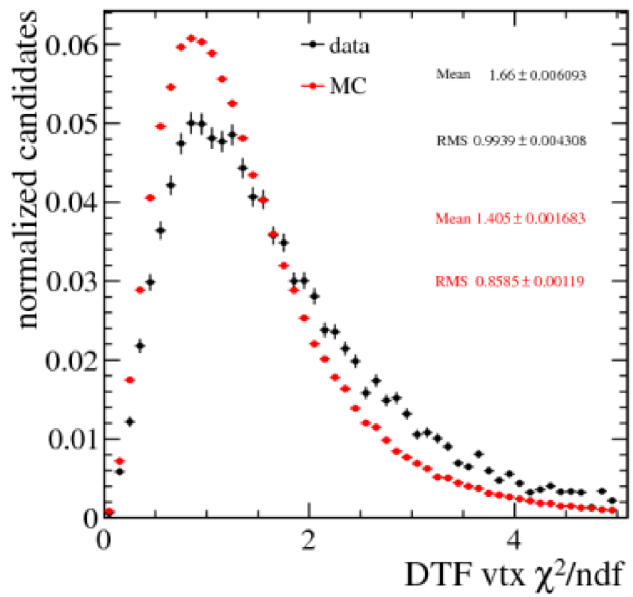
0.2% relative error!

What we fit

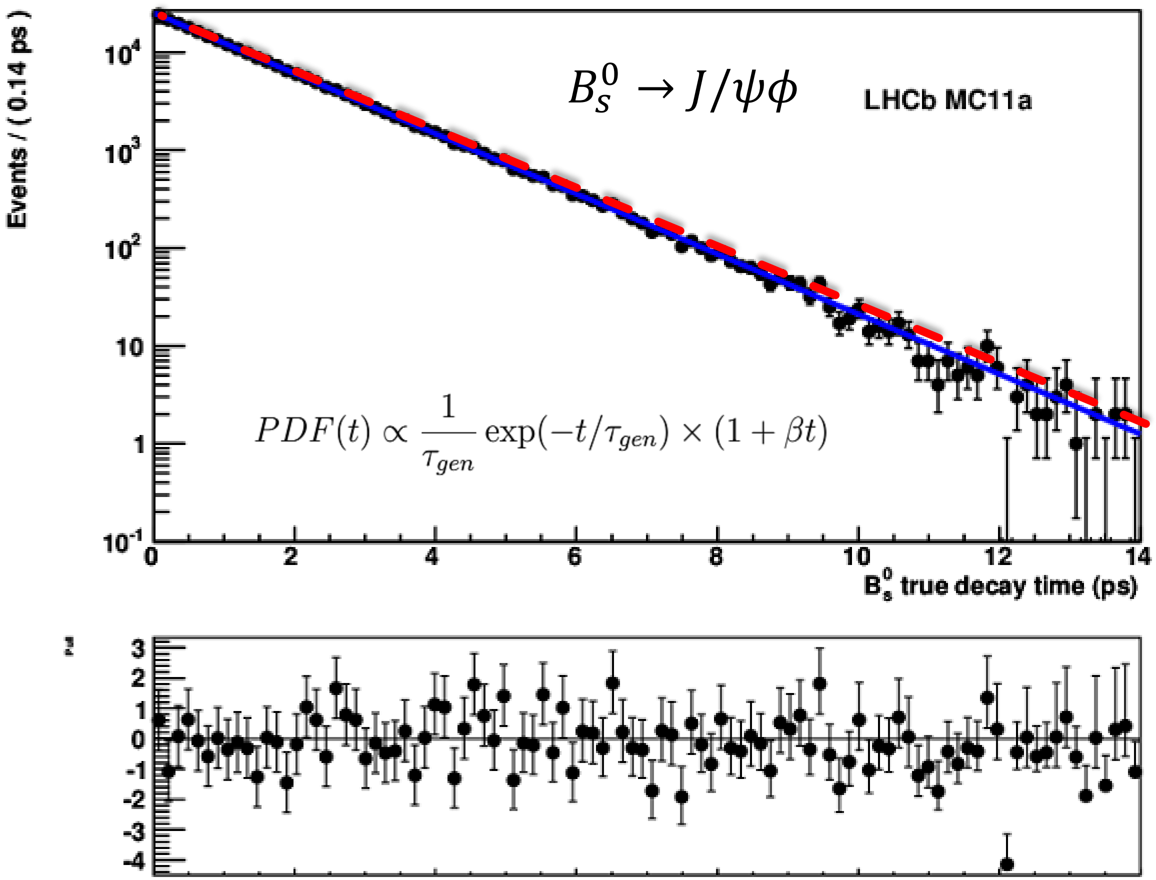


$$PDF = \exp(-t/\tau) \otimes Res(t,t') \cdot Acc(t')$$

Why we don't want to trust simulation

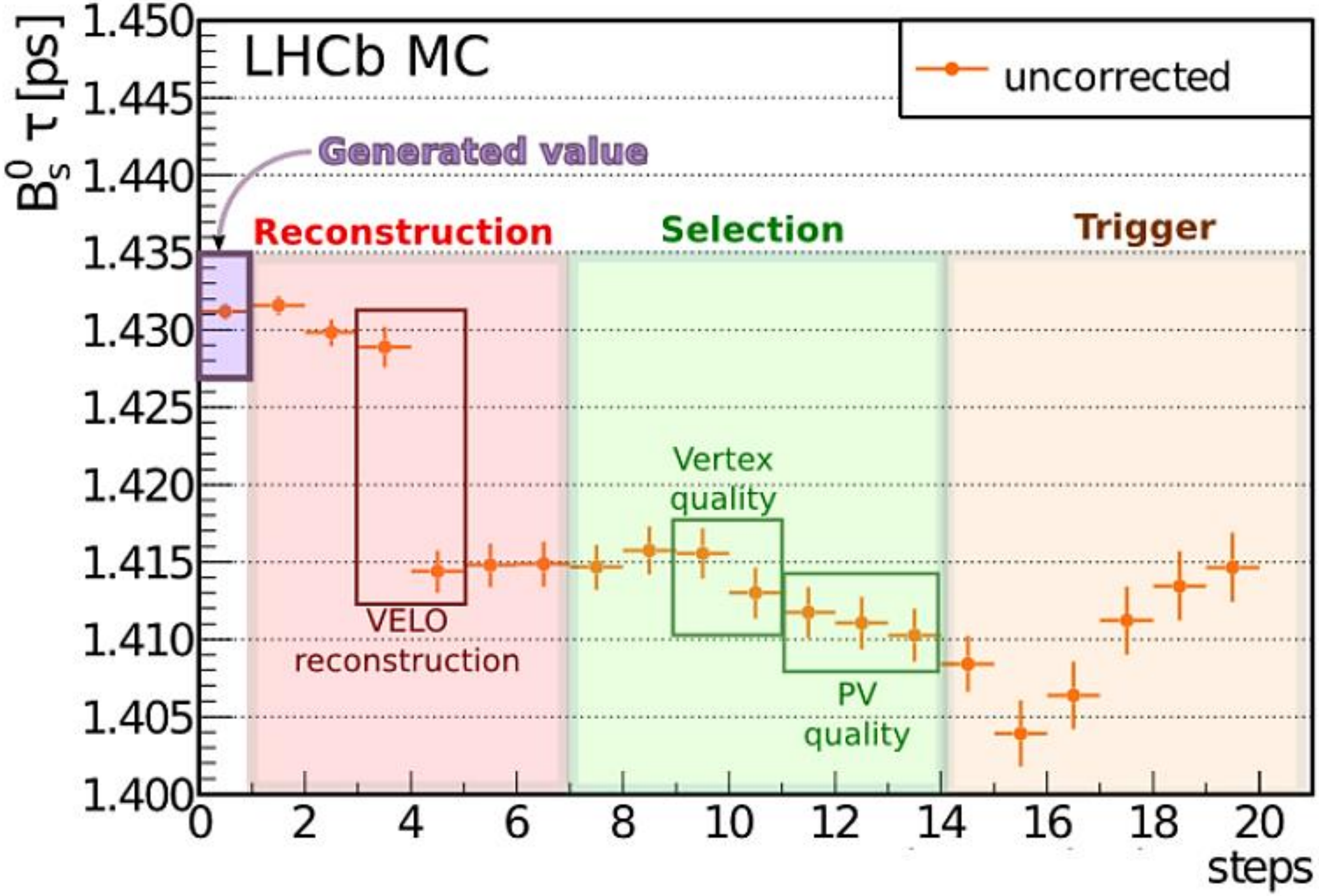


Decay Time Acceptance



$$\beta \sim \mathcal{O}(10^{-2})\text{ps}^{-1} \to \Delta\tau \sim 20 \text{ fs}$$

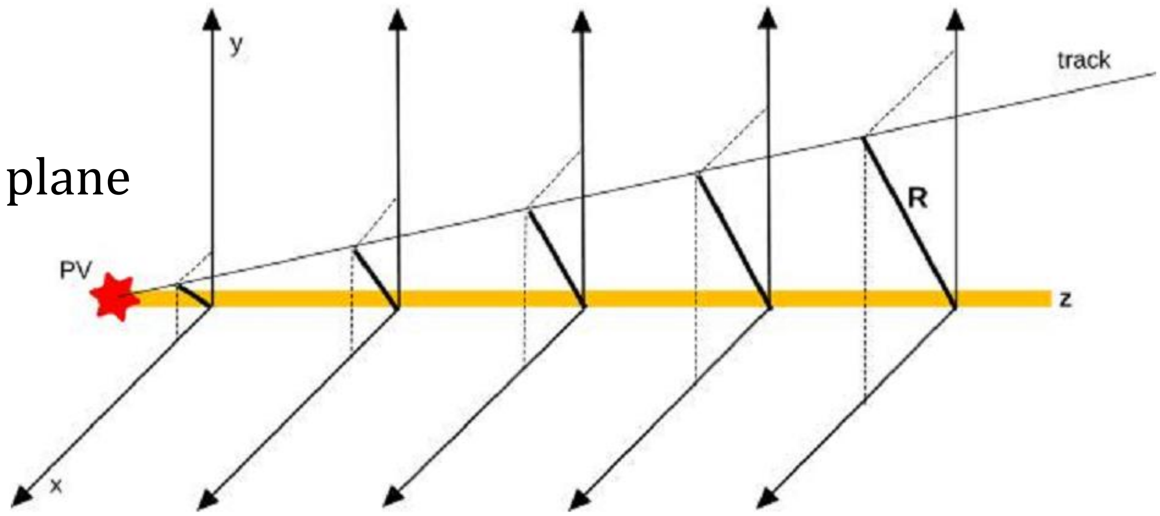
Measured lifetime after different Selection and Reconstruction steps



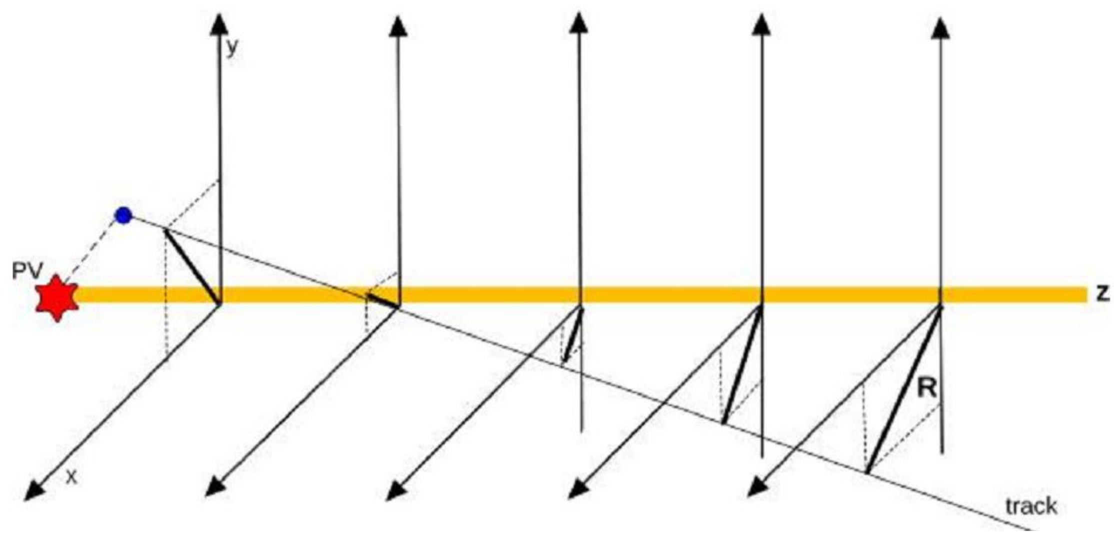
Reconstruction in the VELO

Track from origin

- straight line in R-z plane
- same ϕ

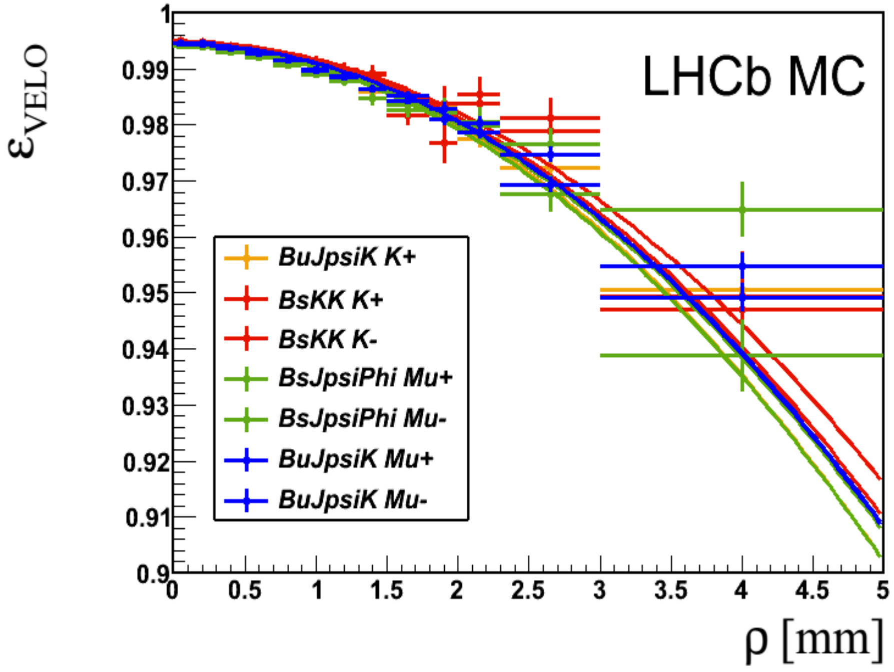


Track from B decay

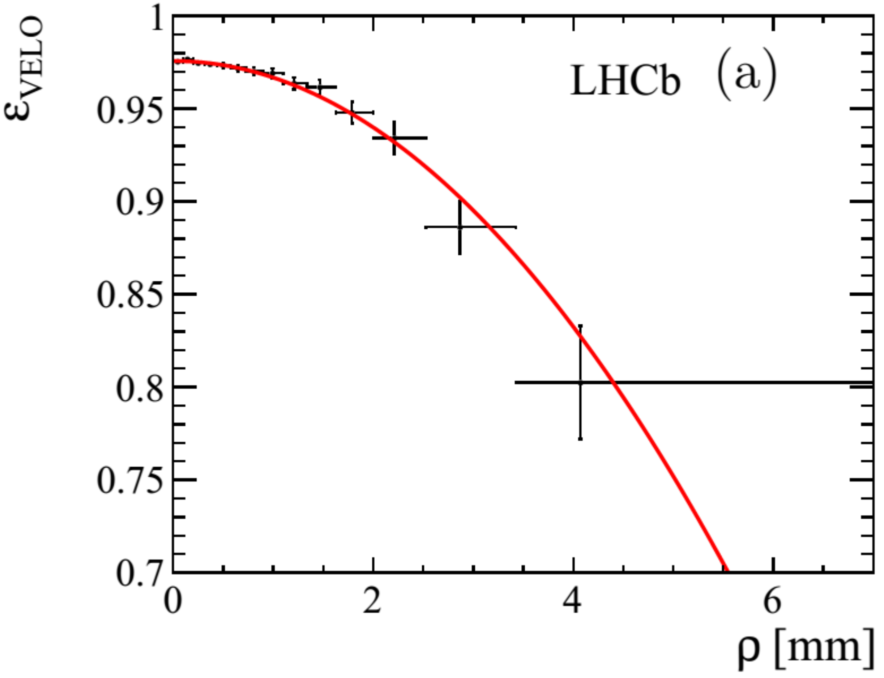


VELO reconstruction efficiency

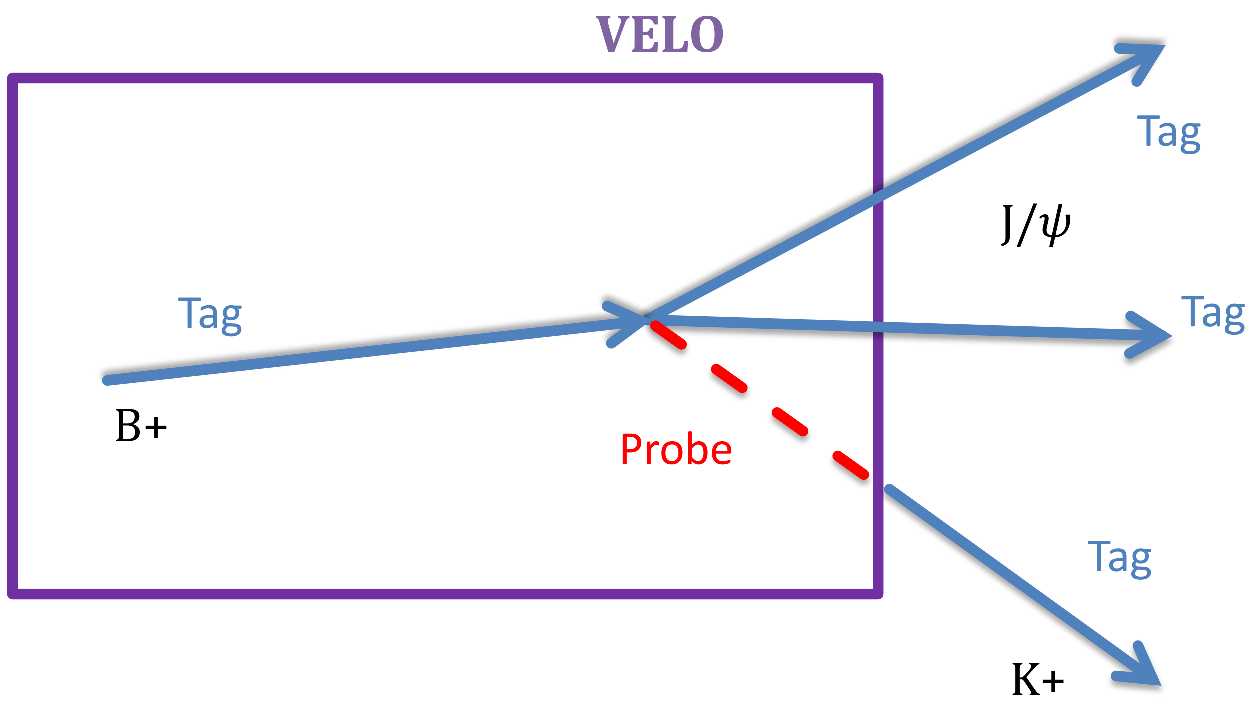
Simulation



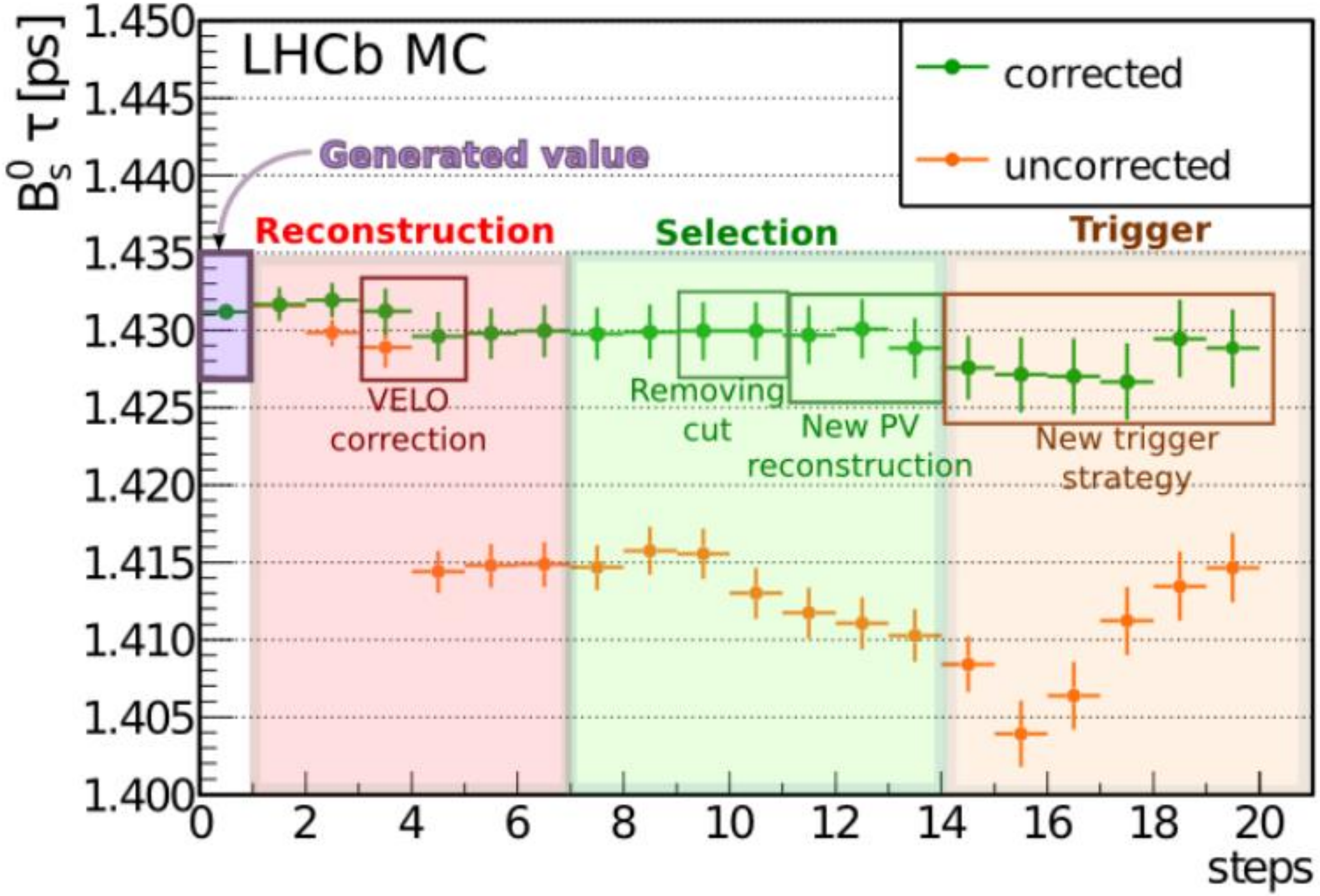
Data

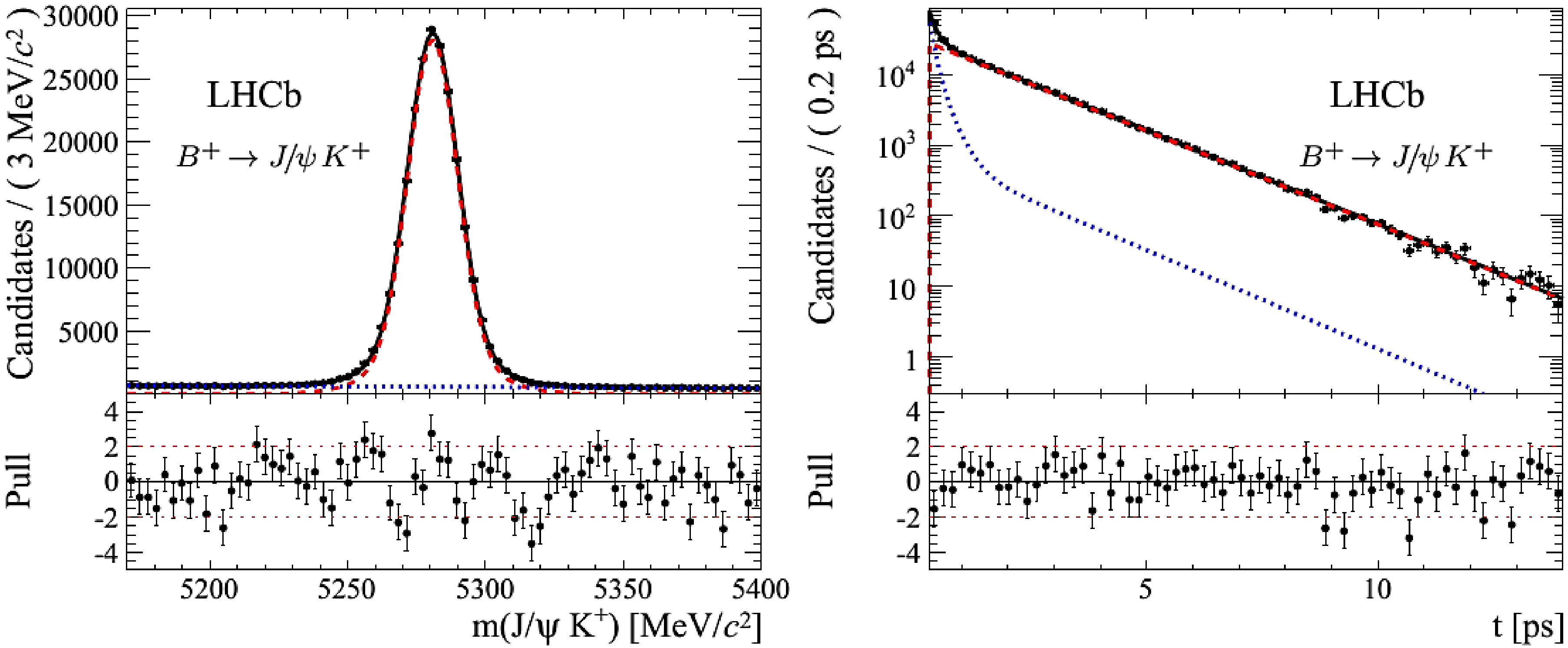


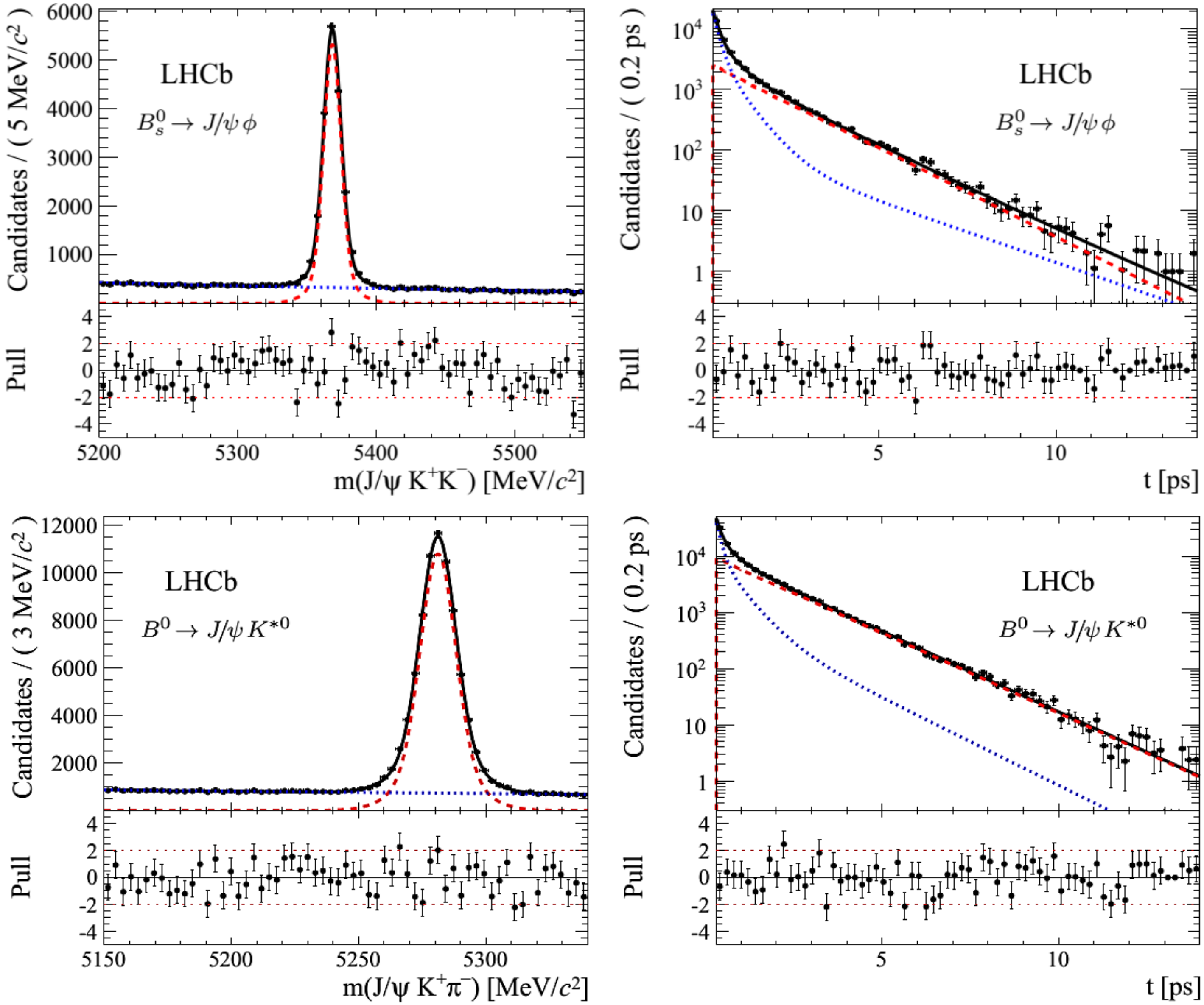
Tag and Probe

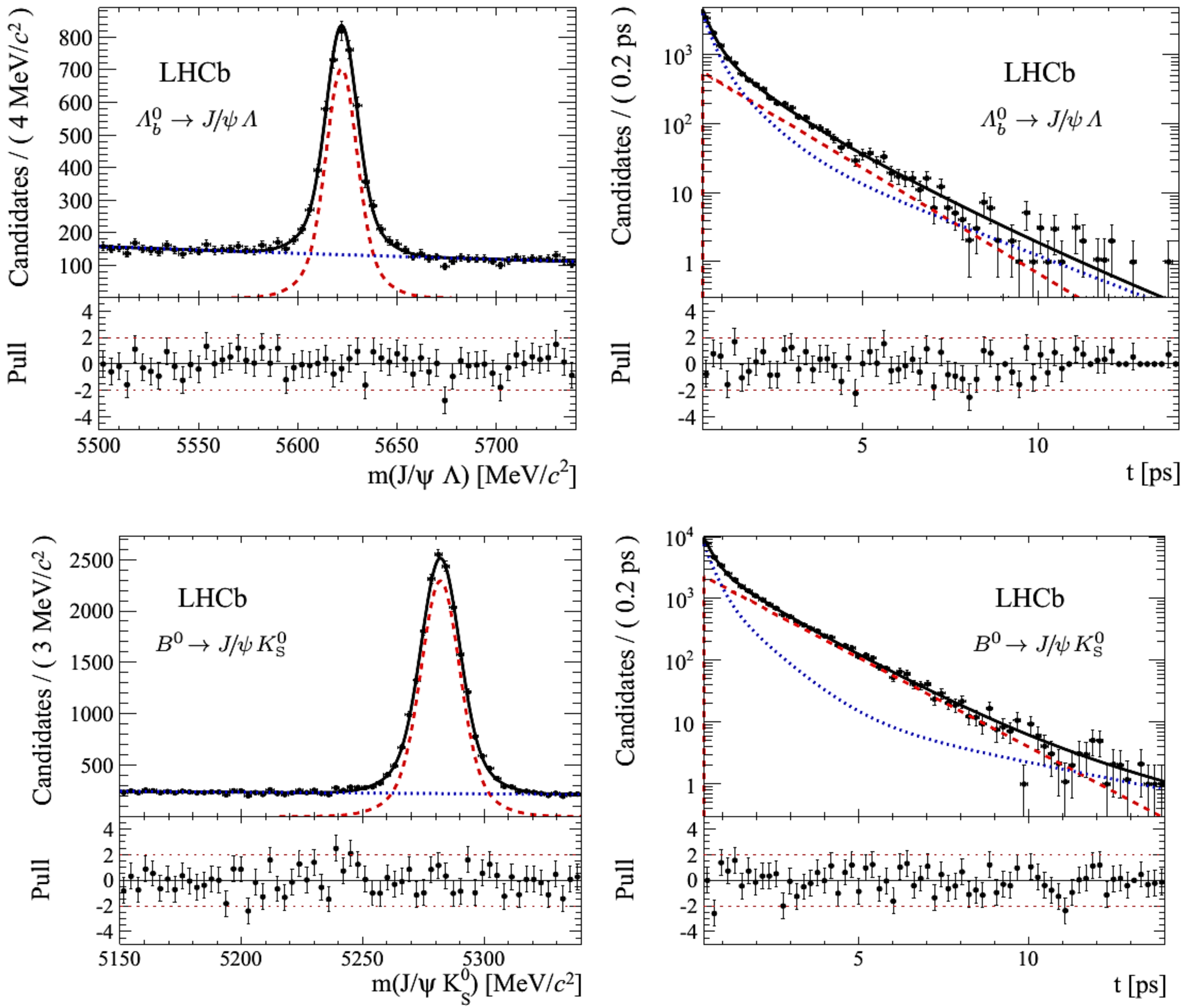


Corrected Lifetime acceptance




LHCb
$B^+ \to J/\psi K^+$
Candidates / (3 MeV/c^2)
Pull
m(J/ψ K$^+$) [MeV/c^2]
LHCb
$B^+ \to J/\psi K^+$
Candidates / (0.2 ps)
Pull
t [ps]


LHCb
$B_s^0 \to J/\psi\,\phi$
Candidates / (5 MeV/c^2)
Pull
m(J/ψ K⁺K⁻) [MeV/c^2]
LHCb
$B_s^0 \to J/\psi\,\phi$
Candidates / (0.2 ps)
t [ps]
LHCb
$B^0 \to J/\psi\,K^{*0}$
Candidates / (3 MeV/c^2)
m(J/ψ K⁺π⁻) [MeV/c^2]
LHCb
$B^0 \to J/\psi\,K^{*0}$
Candidates / (0.2 ps)
t [ps]



LHCb
$\Lambda_b^0 \to J/\psi\,\Lambda$
Candidates / (4 MeV/c^2)
Pull
m(J/ψ Λ) [MeV/c^2]
Candidates / (0.2 ps)
t [ps]
$B^0 \to J/\psi\,K_S^0$
Candidates / (3 MeV/c^2)
m(J/ψ K_S^0) [MeV/c^2]

Lifetime	LHCb 1 fb^{-1}	World average (2013)
τ_{B^+}	1.637 ± 0.005 ps	1.641 ± 0.008 ps
$\tau_{B^0 \to J/\psi K^*}$	1.524 ± 0.007 ps	1.519 ± 0.007 ps
$\tau_{B^0 \to J/\psi K_S}$	1.499 ± 0.014 ps	1.519 ± 0.007 ps
$\tau_{B_s^0 \to J/\psi\phi}$	1.480 ± 0.012 ps	1.429 ± 0.088 ps
$\tau_{\Lambda_b^0}$	1.415 ± 0.027 ps	1.429 ± 0.024 ps

	Ratio	LHCb 1 fb^{-1}	Theory
Test HQE	τ_{B^+} / τ_{B^0}	1.074 ± 0.005 ± 0.003	$1.04^{+0.05}_{-0.02}$
	$\tau_{\Lambda_b^0} / \tau_{B^0}$	0.929 ± 0.018 ± 0.004	0.935 ± 0.054
	$\tau_{B_s^0 \to J/\psi\phi} / \tau_{B^0}$	0.971 ± 0.009 ± 0.004	-
Test CPT	τ_{B^+} / τ_{B^-}	1.002 ± 0.004 ± 0.002	1
	$\tau_{B^0} / \tau_{\bar{B}^0}$	1.000 ± 0.008 ± 0.009	1
	$\tau_{\Lambda_b^0} / \tau_{\bar{\Lambda}_b^0}$	0.940 ± 0.035 ± 0.006	1

Outline

- Why LHCb?
- Insides in LHCb
- Angular Measurement ←

Example from the past: $e^+e^- \rightarrow \mu^+\mu^-$

W. Bartel et al.: New Results on $e^+e^- \rightarrow \mu^+\mu^-$

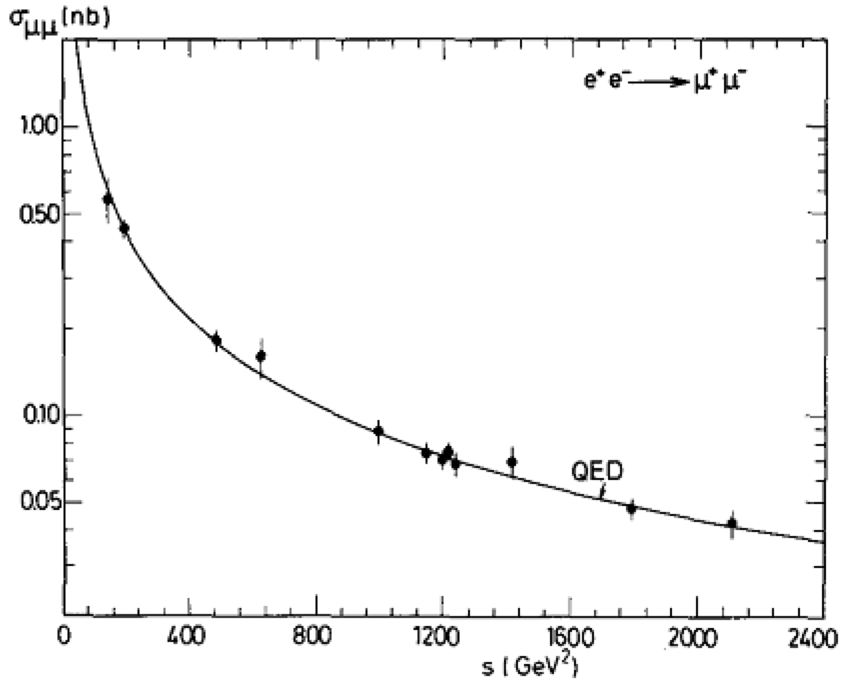


Fig. 1. Total cross section for $e^+e^- \rightarrow \mu^+\mu^-$ as a function of s, corrected for QED contributions up to order α^3

Example from the past: $e^+e^- \rightarrow \mu^+\mu^-$

$$A_{\mu\mu} = (\#F - \#B)/(\#F + \#B)$$

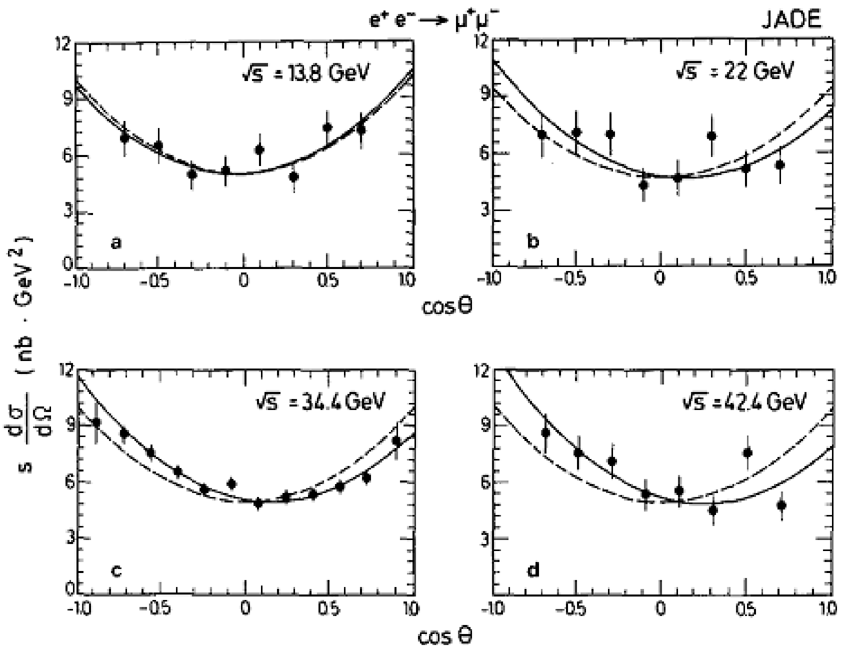


Fig. 2a–d. Angular distributions for $e^+e^- \rightarrow \mu^+\mu^-$ corrected for QED contributions to order α^3 for 4 cm energies. The full lines are fits allowing for an asymmetry, the dashed lines are symmetric fits

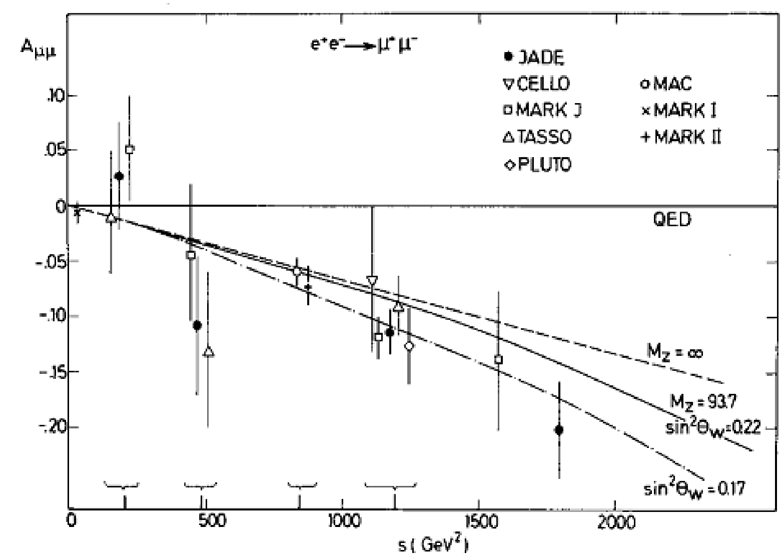


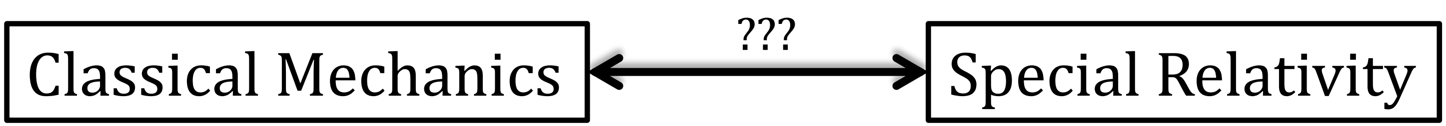
Fig. 4. $A_{\mu\mu}$ as a function of s. Data from JADE are shown together with data from SPEAR, PEP and other PETRA experiments. Note that the data taken by several detectors at the same energy were slightly displaced in s. The full line is the prediction of the Standard Model with $\sin^2\theta_w = 0.22$, and $M_Z = 93.7$ GeV; the dash-dotted line with $\sin^2\theta_w = 0.17$ and the same Z-mass

Today: m(Z) = 91187,6 ± 2,1 MeV

One can also obtain good constraints on the Z mass leaving $\sin^2\theta_w$ fixed: $M_Z = (82^{+6}_{-4})$ GeV for the JADE data and for all data $M_Z = 86 \pm 3$ GeV. This indirect method yields values which are in agreement with the results from the UA1 and UA2 experiments as shown in Fig. 5b.

What is an effective theory?

- What is the interesting physics?



Goal

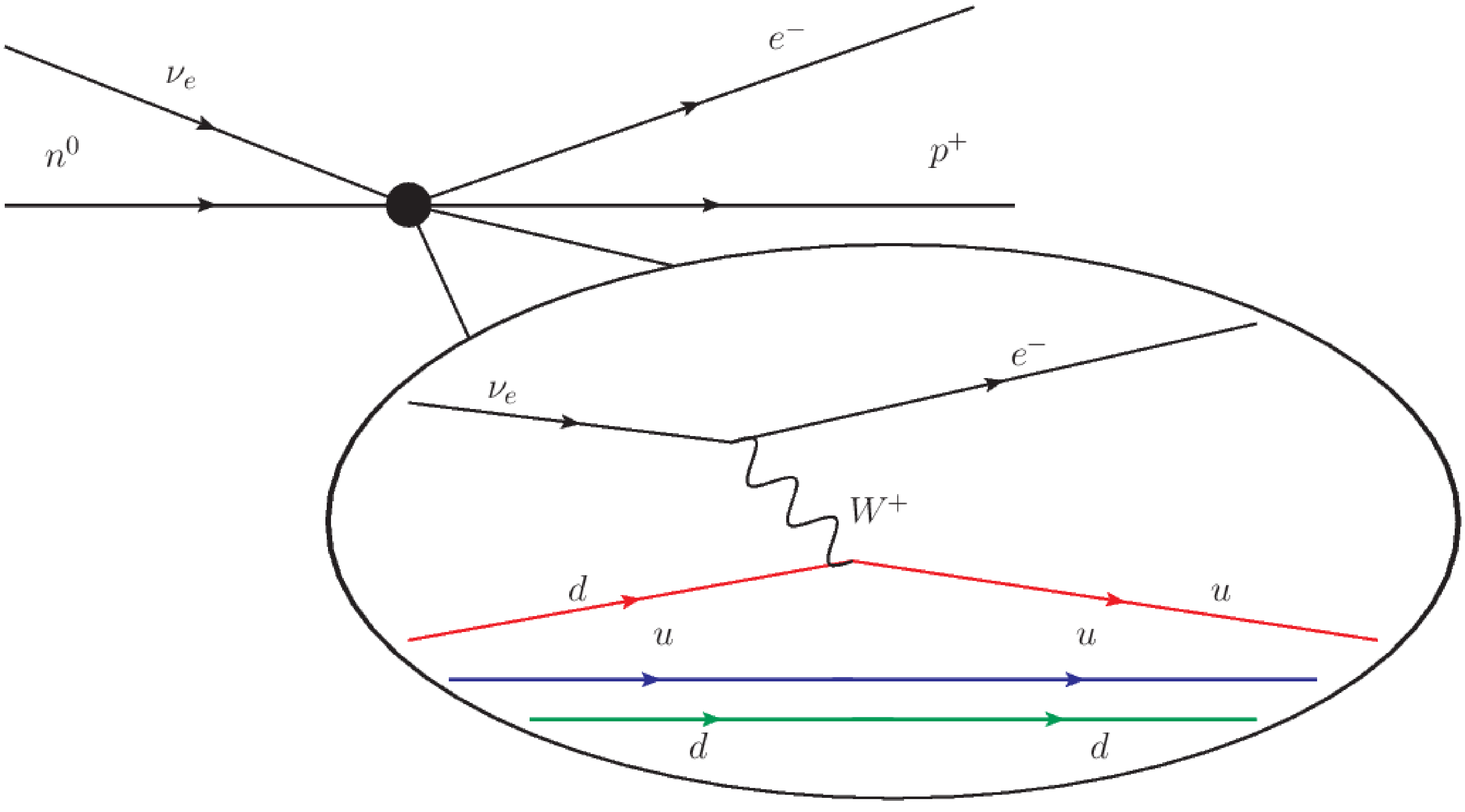
- Simplest necessary framework
- Captures essential physics
- In principle, can be corrected in arbitrary precision

→ Power expansion of special relativity

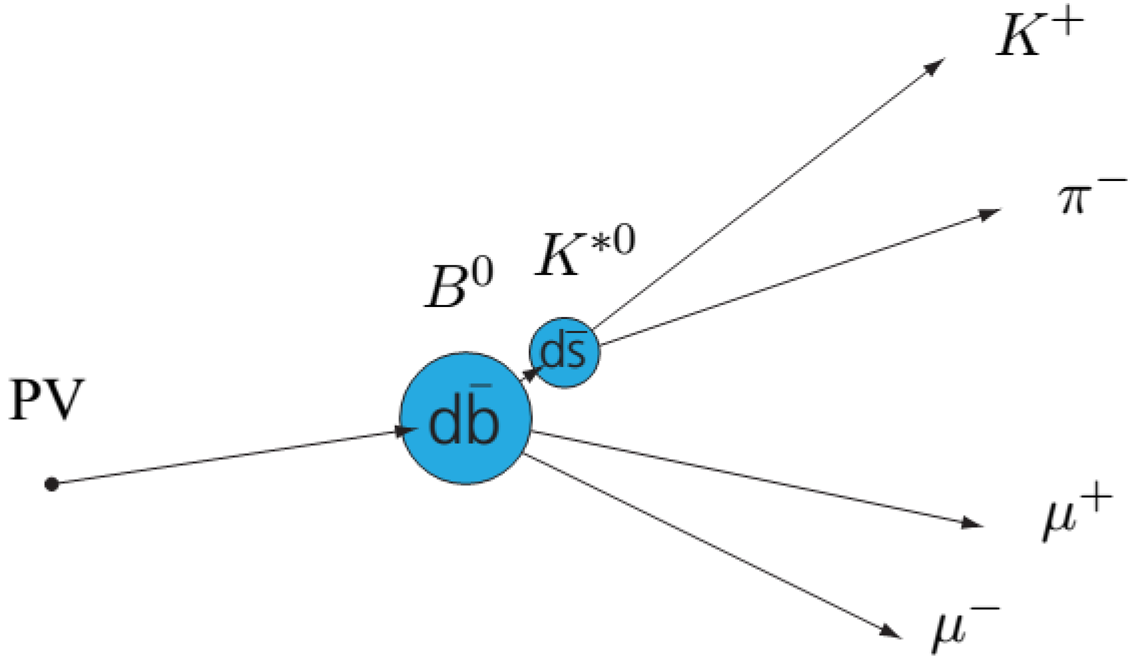
Way to go

- Determine relevant degrees of freedom
- to get low energy properties of SM "integrate" out heavy particles
- To describe physics at scale m^2 we do not need to know what is going on at $\Lambda^2 \gg m^2$
- One approach: expansion m^2/Λ^2

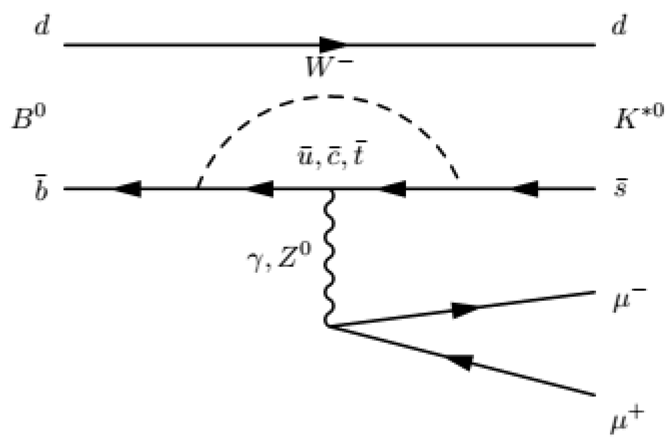
Beta decay

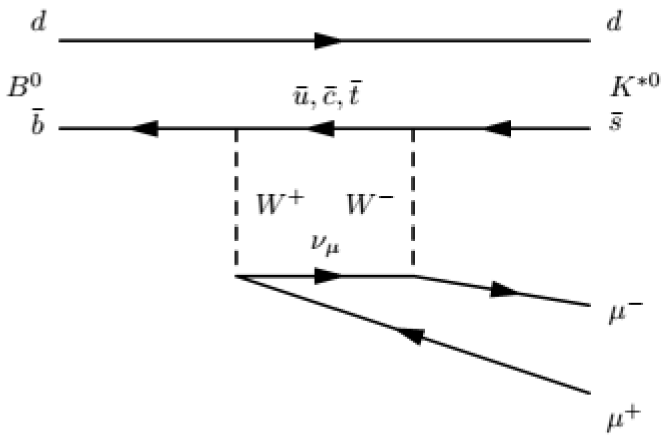


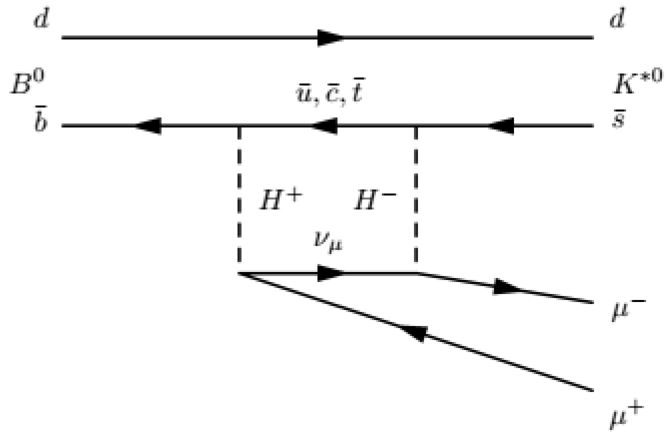
The decay of this lecture



Feynman Diagrams

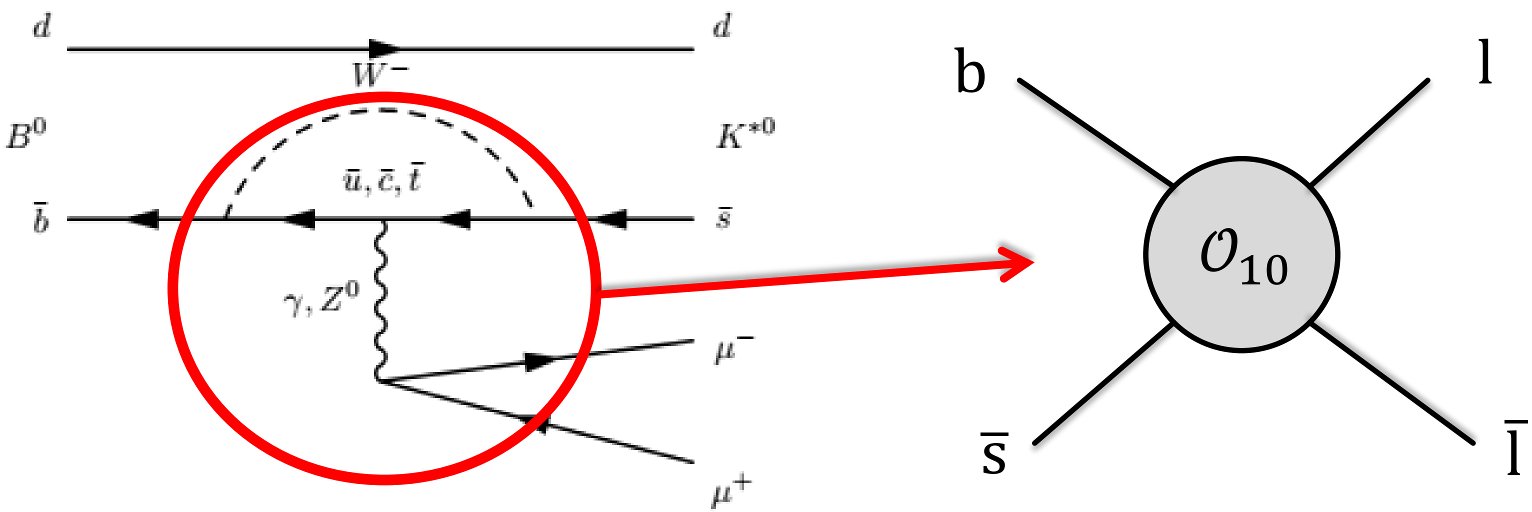




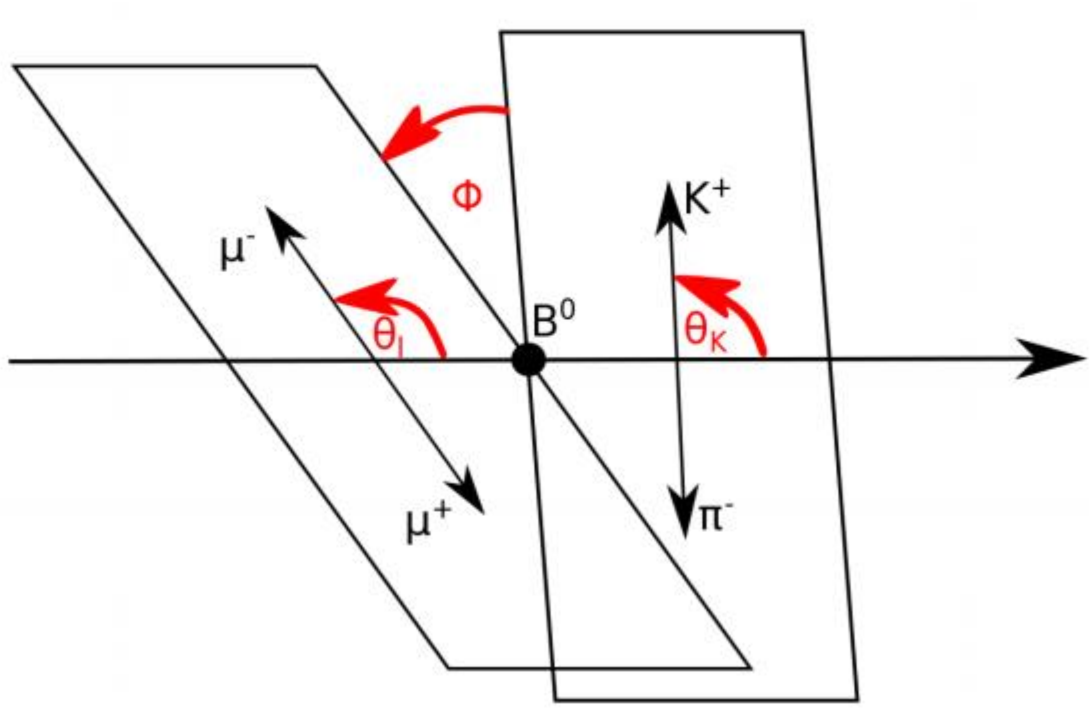


Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$



Angle definition (one of many)



Differential decay rate

$$
\begin{aligned}
\Gamma(\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-) \sim\ & J_1^s \sin^2\theta_K + J_1^c \cos^2\theta_K \\
& + (J_2^s \sin^2\theta_K + J_2^c \cos^2\theta_K)\cos 2\theta_\ell \\
& + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\Phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\Phi \\
& + J_5 \sin 2\theta_K \sin\theta_\ell \cos\Phi \\
& + J_6^s \sin^2\theta_K \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\Phi \\
& + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\Phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\Phi
\end{aligned}
$$

Js → Amplitudes

$$J_1^s = \frac{3}{4}\left\{\frac{(2+\beta_\mu^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\mu^2}{q^2}\Re(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*})\right\}$$

$$J_1^c = \frac{3}{4}\left\{|A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\Re(A_0^L A_0^{R*}\right]\right\}$$

$$J_2^s = \frac{3\beta_\mu^2}{16}\left\{|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right\}$$

$$J_2^c = -\frac{3\beta_\mu^2}{4}\left\{|A_0^L|^2 + (L\to R)\right\}$$

$$J_3 = \frac{3\beta_\mu^2}{8}\left\{|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right\}$$

$$J_4 = \frac{3\beta_\mu^2}{4\sqrt{2}}\left\{\Re(A_0^L A_\parallel^{L*}) + (L\to R)\right\}$$

$$J_5 = \frac{3\sqrt{2}\beta_\mu}{4}\left\{\Re(A_0^L A_\perp^{L*}) - (L\to R)\right\}$$

$$J_6 = \frac{3\beta_\mu}{2}\left\{\Re(A_\parallel^L A_\perp^{L*}) - (L\to R)\right\}$$

$$J_7 = \frac{3\sqrt{2}\beta_\mu}{4}\left\{\Im(A_0^L A_\parallel^{L*}) - (L\to R)\right\}$$

$$J_8 = \frac{3\beta_\mu^2}{4\sqrt{2}}\left\{\Im(A_0^L A_\perp^{L*}) + (L\to R)\right\}$$

$$J_9 = \frac{3\beta_\mu^2}{4}\left\{\Im(A_\parallel^{L*} A_\perp^L) + (L\to R)\right\}$$

Amplitudes → Wilson Coefficients

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

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

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

$$A_t = \frac{N}{\sqrt{q^2}}\sqrt{\lambda}\left\{2(\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}}) + \frac{q^2}{m_\mu}(\mathbf{C_P^{eff}} - \mathbf{C_P^{\prime eff}})\right\}\mathbf{A_0(q^2)}$$

$$A_S = -2N\sqrt{\lambda}(\mathbf{C_S} - \mathbf{C_S})\mathbf{A_0(q^2)}$$

Wilson coefficients $C_{7,9,10,S,P}^{(\prime)\text{eff}}$

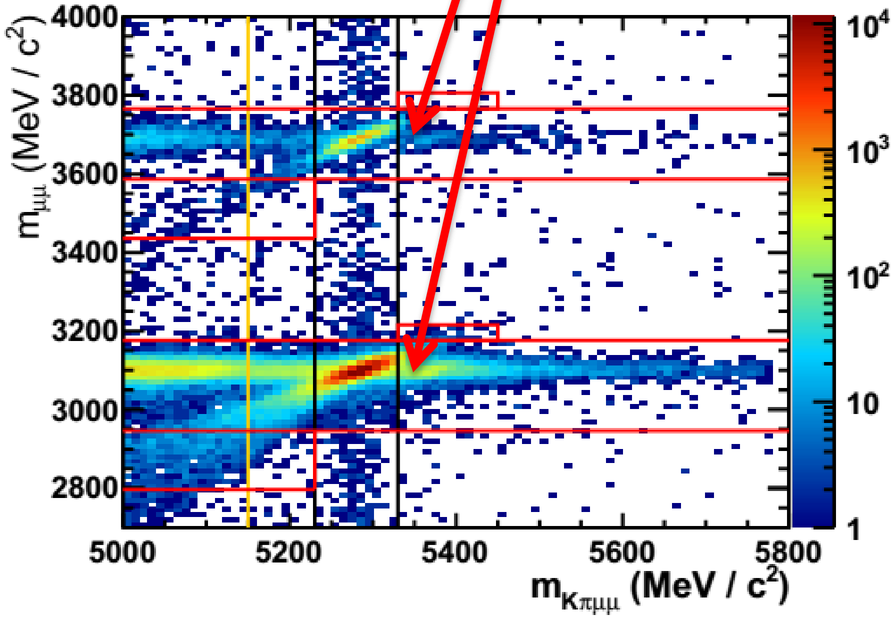
Seven form factors: $V(q^2),\ A_{0,1,2}(q^2),\ T_{1,2,3}(q^2)$

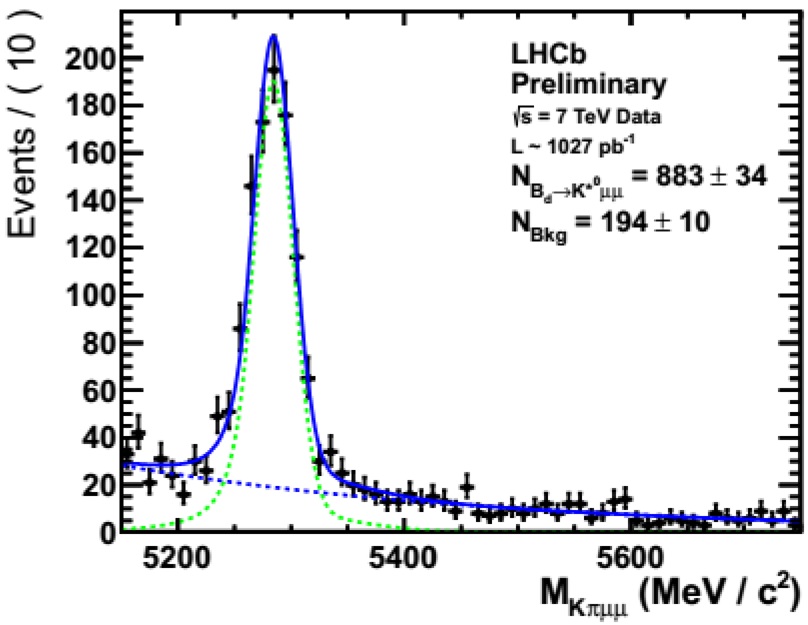
Now to the experiment

Showing analysis with 2011 data.
2012 data under study at the moment.

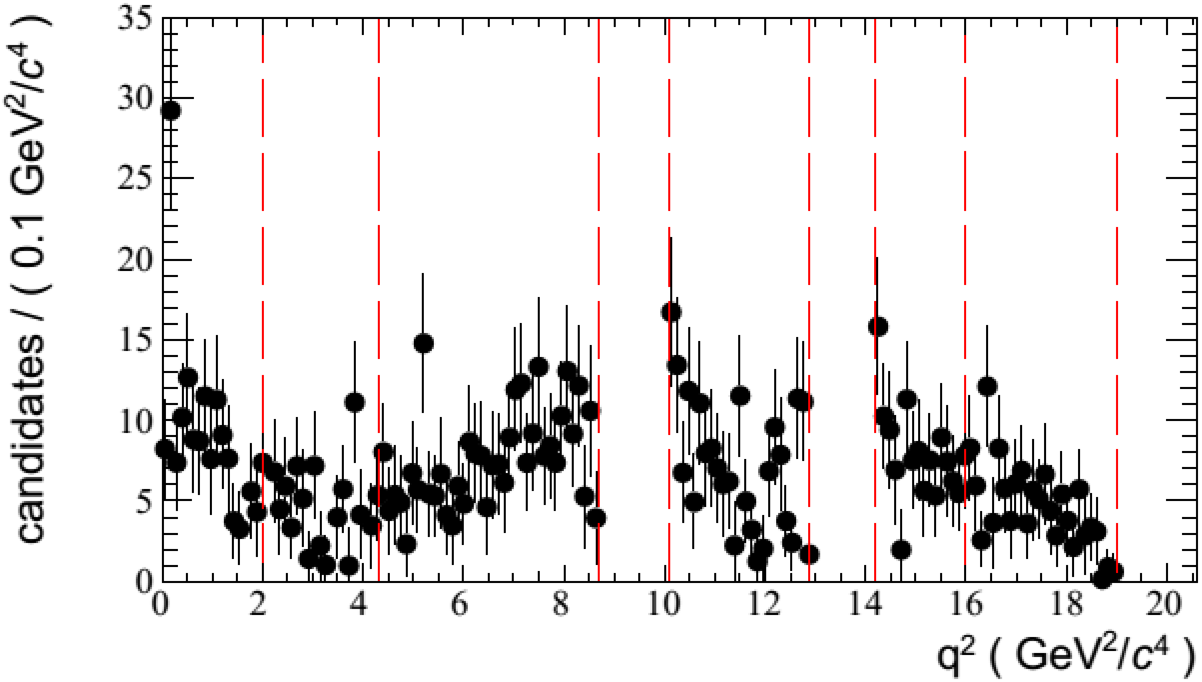
Mass spectrum

Nice peaks, but for this analysis this is the background!



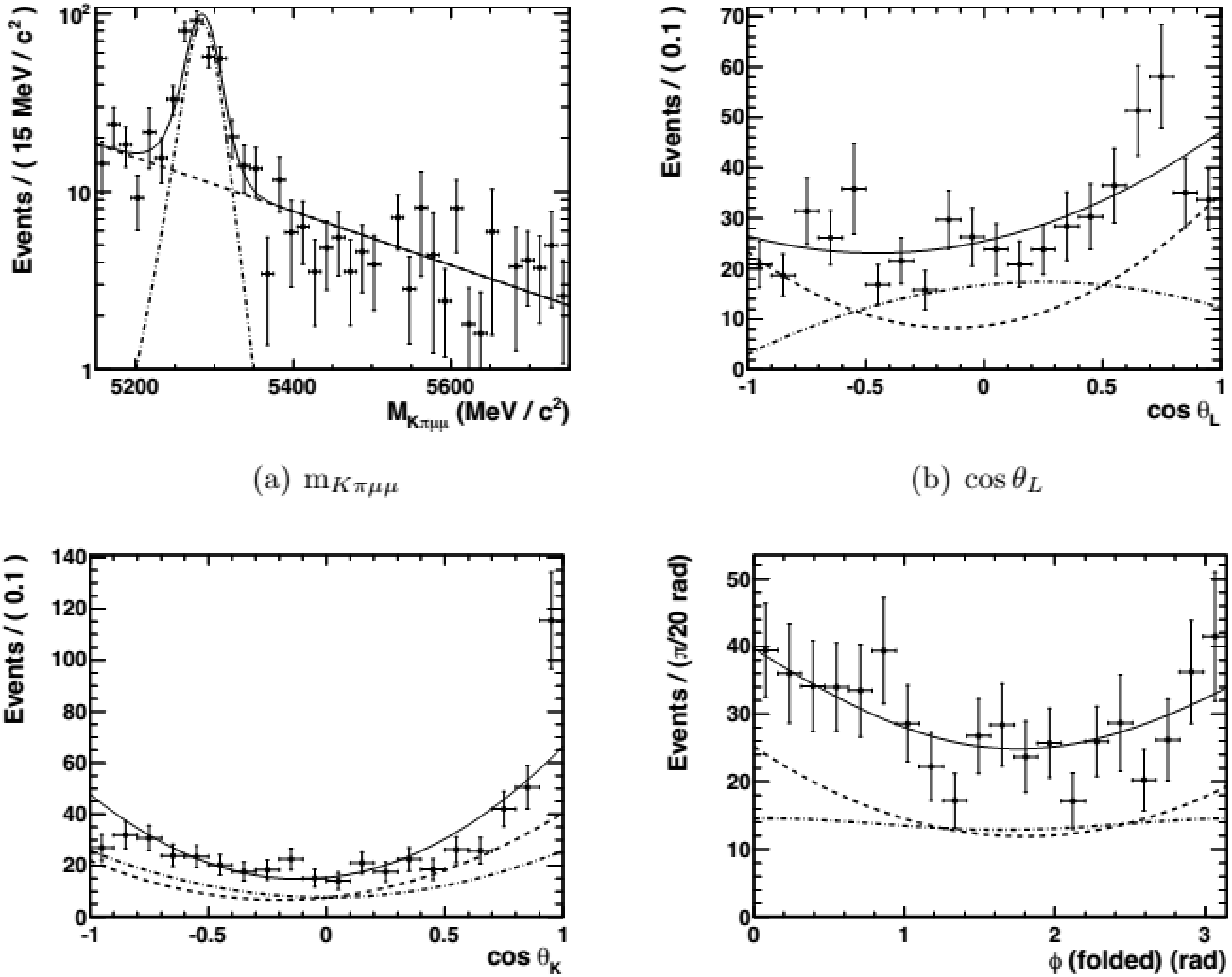


DiMuon invariant mass squared q^2



Doing analysis in bins of q^2

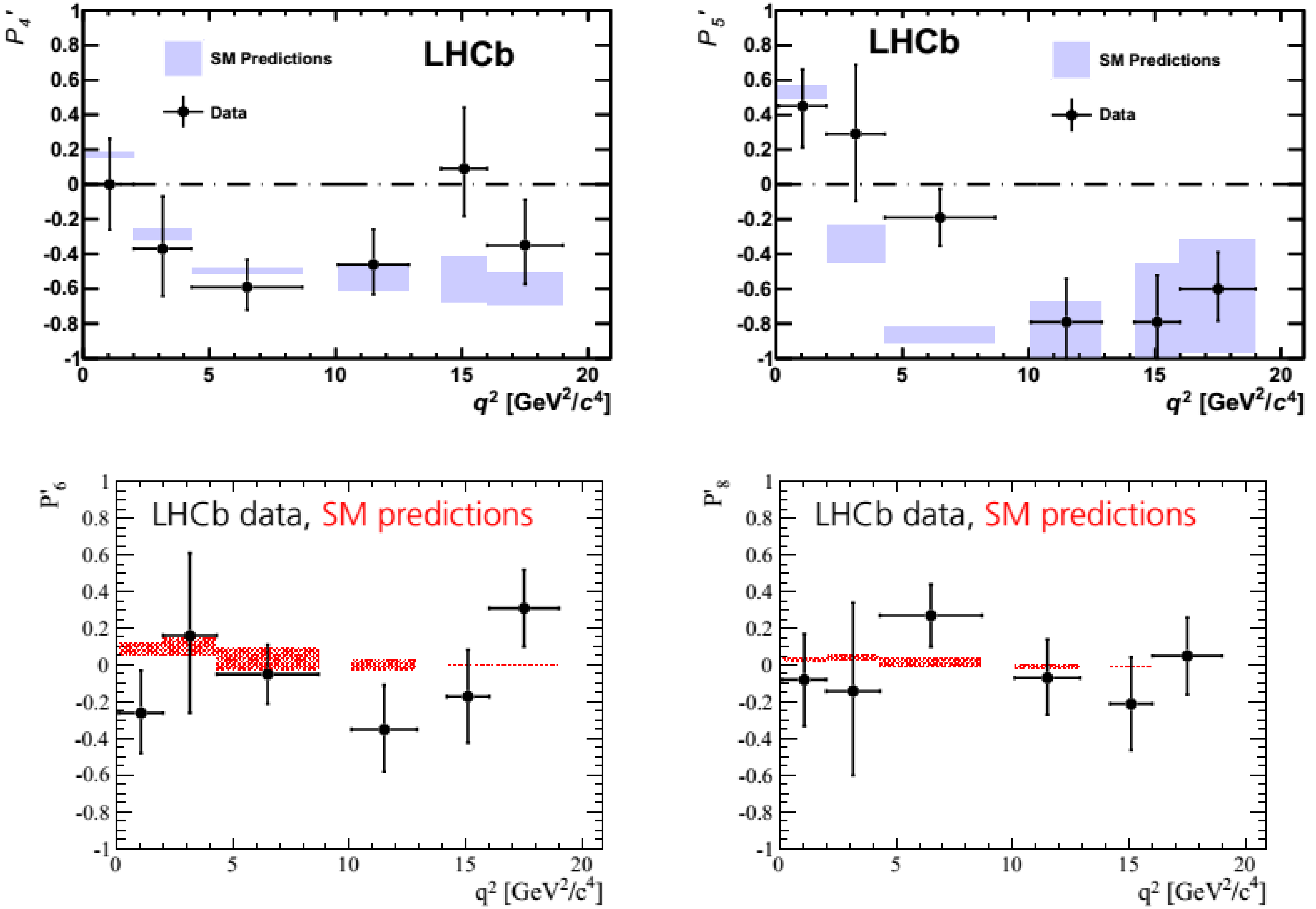
Projections of the angles



(a) $m_{K\pi\mu\mu}$ (b) $\cos\theta_L$

$$q^2 = 4.3 - 8.68\,\mathrm{GeV}^2/c^4$$

Results



LHCb
SM Predictions
Data
P_4'
P_5'
q^2 [GeV^2/c^4]
LHCb data, SM predictions
P'6
P'8

What could it be?

- statistical fluctuation
  (1 of 24 bin: probability 0.5%)
- unknown background
- something else unknown
- underestimation of theory uncertainty
  (in large discussion)
- New Physics …

What, if it would be the Wilsons?

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(C_7^\gamma Q_7^\gamma + C_9^\ell Q_9^\ell + C_{10}^\ell Q_{10}^\ell \right) + \text{h.c.}\,,$$

with

$$Q_7^\gamma = \frac{e}{(4\pi)^2} m_b (\bar{s}_L \sigma_{\alpha\beta} b_R) F^{\alpha\beta}\,,$$ — photon penguin

$$Q_9^\ell = \frac{e^2}{(4\pi)^2} (\bar{s}_L \gamma_\alpha b_L) \left(\bar{\ell}\gamma^\alpha \ell\right)\,,$$

$$Q_{10}^\ell = \frac{e^2}{(4\pi)^2} (\bar{s}_L \gamma_\alpha b_L) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right)\,.$$

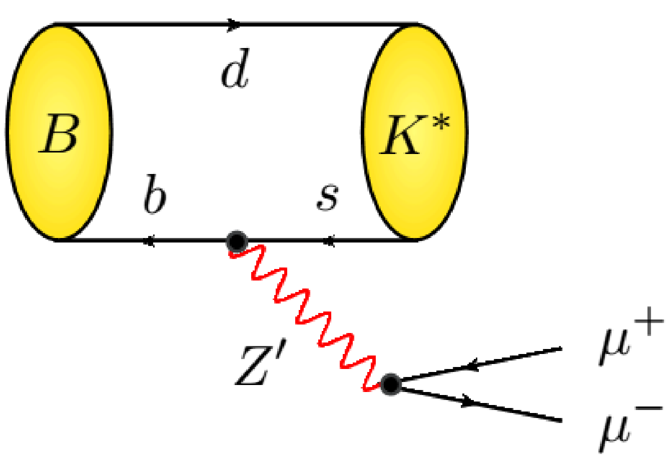
Q_9^ℓ, Q_{10}^ℓ — ew. penguin

One simple NP scenario:

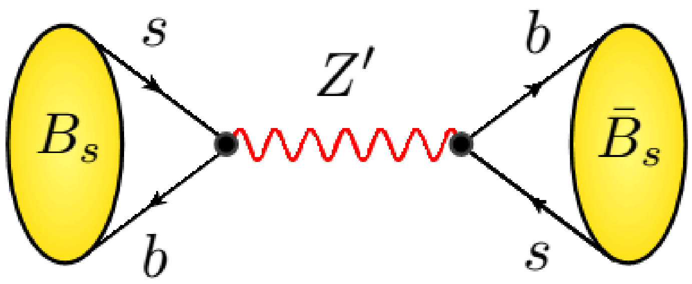
$$\Delta C_7^\gamma \sim 0\,, \qquad \Delta C_9^\ell \sim -1.5\,, \qquad \Delta C_{10}^\ell \sim 0\,.$$

Z'

Additional decay amplitude:



Would also affect Bs mixing:



An explicit Z'-boson explanation of the $B \to K^* \mu^+ \mu^-$ anomaly

Rhorry Gauld,[1] Florian Goertz[2] and Ulrich Haisch[3]

Employing $\alpha = \alpha(M_Z) \simeq 1/128$, $s_W^2 = s_W^2(M_Z) \simeq 0.23$ and $M_W \simeq 80.4\,\text{GeV}$, it hence follows that the 68% confidence level (CL) range

$$\Delta C_9^\ell \in [-1.9, -1.3]\,, \tag{4.4}$$

found in [7] from a fit to the present $b \to s\gamma, \mu^+\mu^-$ data, can be achieved for Z'-boson masses

$$M_{Z'} \in [5.7, 6.9]\ \text{TeV}\,. \tag{4.5}$$

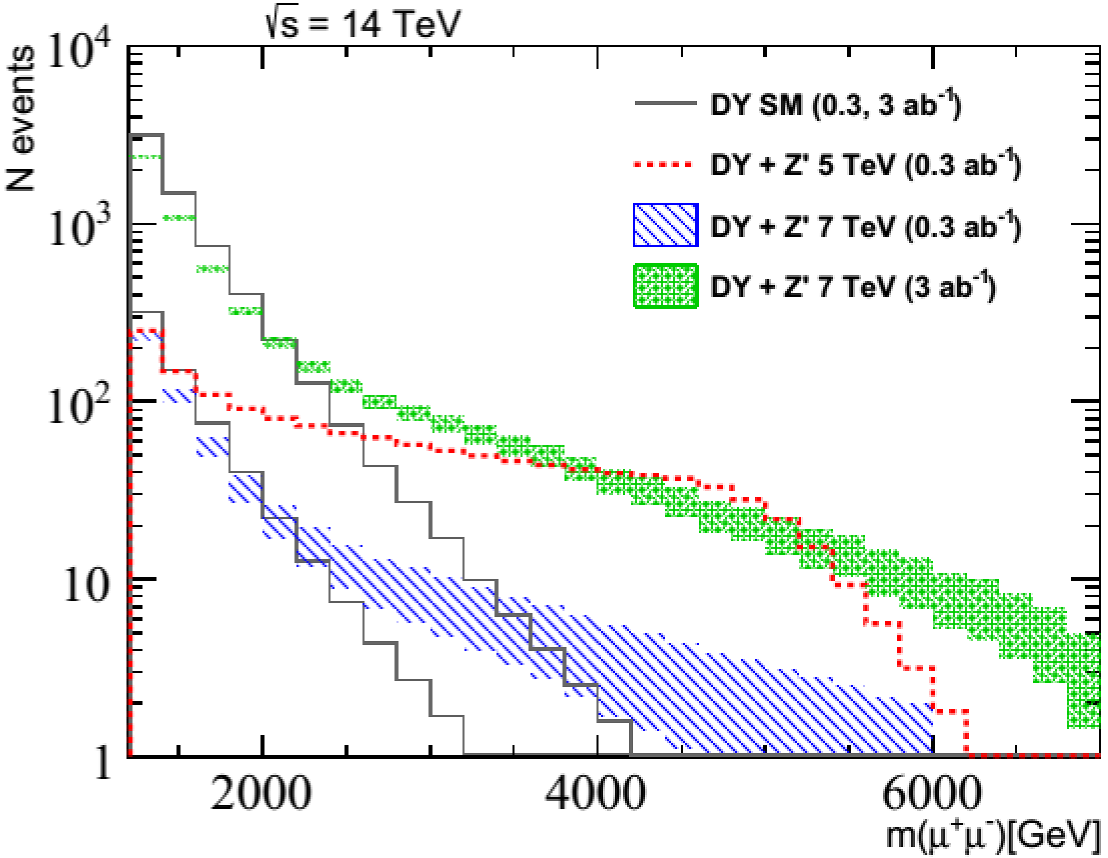
Such large Z'-boson masses lead to new-physics effects of

$$\Delta C_7^\gamma = \mathcal{O}(10^{-4})\,, \tag{4.6}$$

i.e. negligible corrections with respect to $(C_7^\gamma)_{\text{SM}} \simeq -0.19$ [22]. Likewise, the Z'-boson contributions to the semi-leptonic axial-vector operator are very small, amounting to

$$\Delta C_{10}^\ell \in [0.04, 0.05]\,. \tag{4.7}$$

Direct Search for Z’



Current limit $M_{Z'} > 3.9\,\text{TeV}$.

Summary

- Angular measurements:
  - precise theory calculations
  - precise measurements

- b-s transitions good place to look for New Physics

- Deviation from theory found. New analysis with 2x more data on the way.