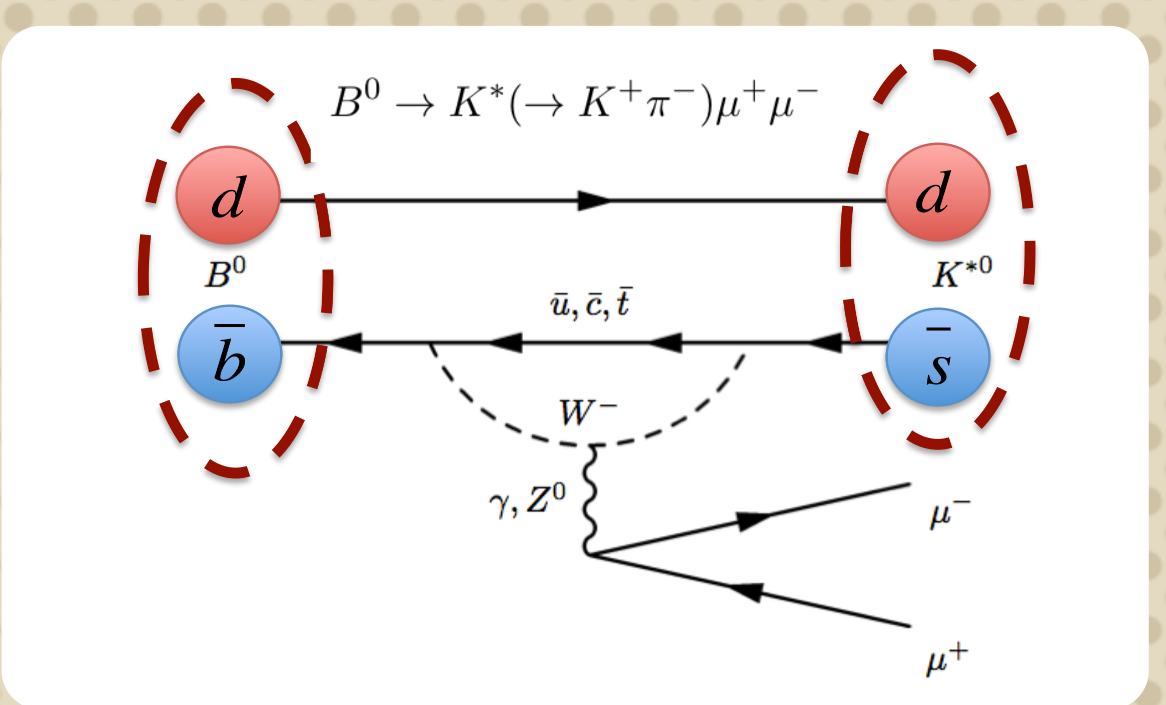
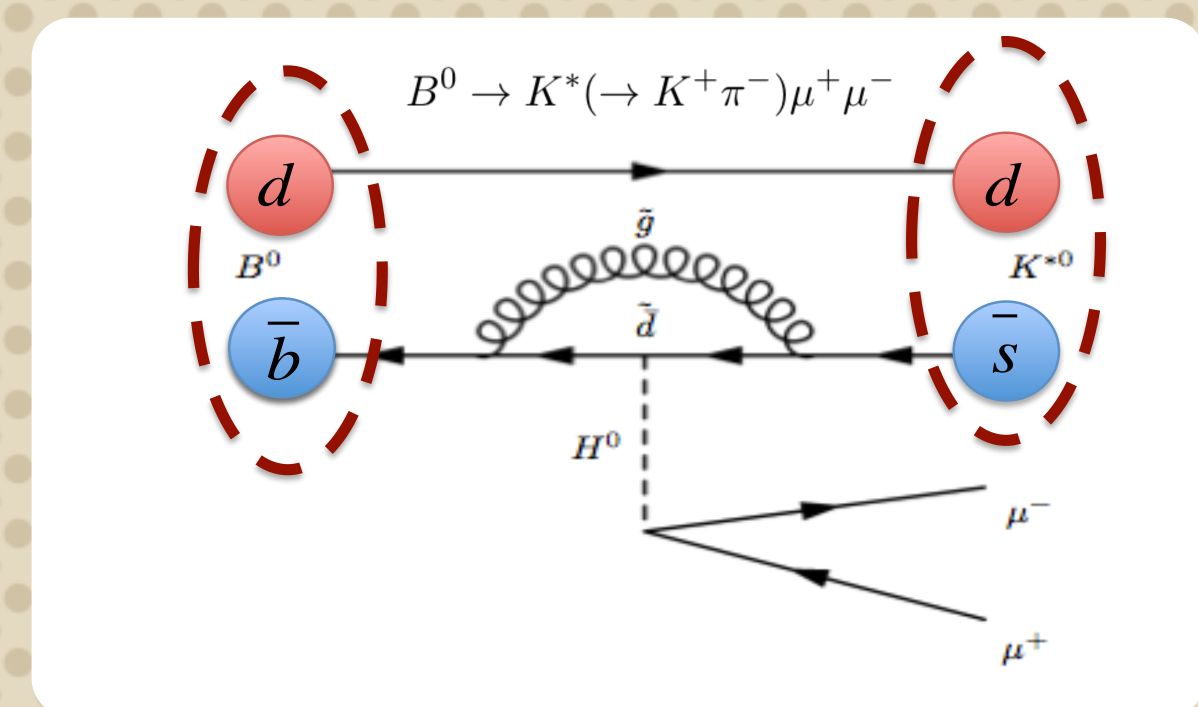
Rare decays

Weak Hamiltonian





- FCNC suppressed in the SM
- New heavy particle can contribute with competing diagrams

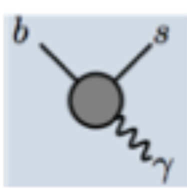
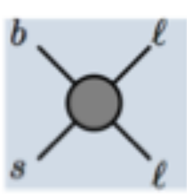
$$A(i \to f) =< f|H_{eff}|i >= -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_j (C_j < f|O_j|i > + C_j' < f|O_j'|i >) + \sum_i C_i^{NP} < f|O_i^{NP}|i >$$

- C_i are short distance Wilson coefficients
- $<f\,|O_i\,|i>$ long distance hadronization (form-factors)

Weak Hamiltonian

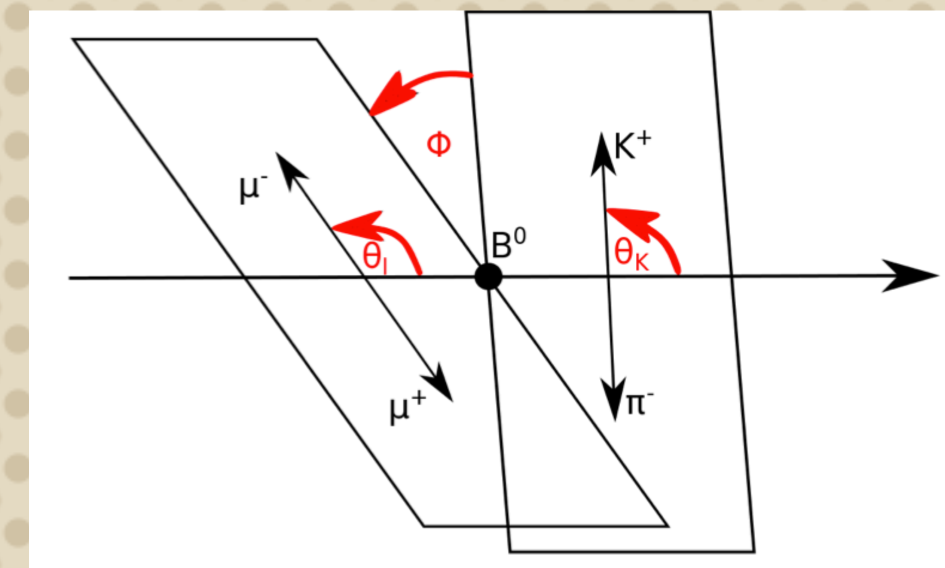
$$A(i \to f) =< f|H_{eff}|i >= -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_j (C_j < f|O_j|i > + C_j' < f|O_j'|i >) + \sum_i C_i^{NP} < f|O_i^{NP}|i >$$

- Allows to separate short and long distance contributions
- Allows to classify the NP contributions
- Combine information from different decays

	Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
	$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✓	✓	
	$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
	$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
	$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$			✓

Angular analysis of B->K*mm

The decay is described by three angles θ_ℓ, θ_K, ϕ and the dimuon invariant mass q^2



- Observables of interest:
  - F_L (longitudinal polarization fraction of the K^*)
  - The forward-backward asymmetry A_{FB}
  - The observables S_i
- Bilinear combination of the transversity amplitudes A_i
- Depend on Form-factors and Wilson coefficients

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

Amplitudes

- The decay is described by six complex amplitudes $A^{L,R}_{0,\parallel,\perp}$
- Correspond to different transversity state of the K^*
- and different (left- and right-handed) chiralities of the dimuon system

$$
\begin{aligned}
F_L &= \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2} = 1 - F_T \\
S_3 &= \frac{1}{2}\frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R \\
S_4 &= \frac{1}{\sqrt{2}}\frac{\Re(A_0^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R \\
S_5 &= \sqrt{2}\frac{\Re(A_0^{L*}A_\perp^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R \\
A_{FB} &= \frac{8}{3}\frac{\Re(A_\perp^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R \\
S_7 &= \sqrt{2}\frac{\Im(A_0^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R \\
S_8 &= \frac{1}{\sqrt{2}}\frac{\Im(A_0^{L*}A_\perp^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R \\
S_9 &= \frac{\Im(A_\perp^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R
\end{aligned}
$$

- $\Gamma = |A_\parallel|^2 + |A_0|^2 + |A_\perp|^2$
- Let's see how the amplitudes depend on Wilson coefficients and form factors

Amplitudes

$$A_{\perp}^{L,R} \propto [(C_9^{eff} + C_9^{eff\prime}) \mp (C_{10}^{eff} + C_{10}^{eff\prime}) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} + C_7^{eff\prime}) T_1(q^2)]$$

$$A_{||}^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime}) \frac{A_1(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} - C_7^{eff\prime}) T_2(q^2)]$$

$$A_0^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})] \times [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*} A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}})] +$$
$$2m_b(C_7^{eff} + C_7^{eff\prime})[(m_B^2 + 3m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2 T_3(q^2)}]$$

“Clean” observables

At low q^2 and first order

$$A_0^{L,R} \propto \left[C^+_{9\mp 10} A_{12} + C^+_7 T_{23}\right]$$
$$A_\parallel^{L,R} \propto \left[C^-_{9\mp 10} A_1 + C^-_7 T_2\right]$$
$$A_\perp^{L,R} \propto \left[C^-_{9\mp 10} V + C^-_7 T_1\right]$$

$$R_1 = \frac{T_1}{V} \sim 1$$
$$R_2 = \frac{T_2}{A_1} \sim 1$$
$$R_3 = \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}$$

$$A_\perp^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*})$$

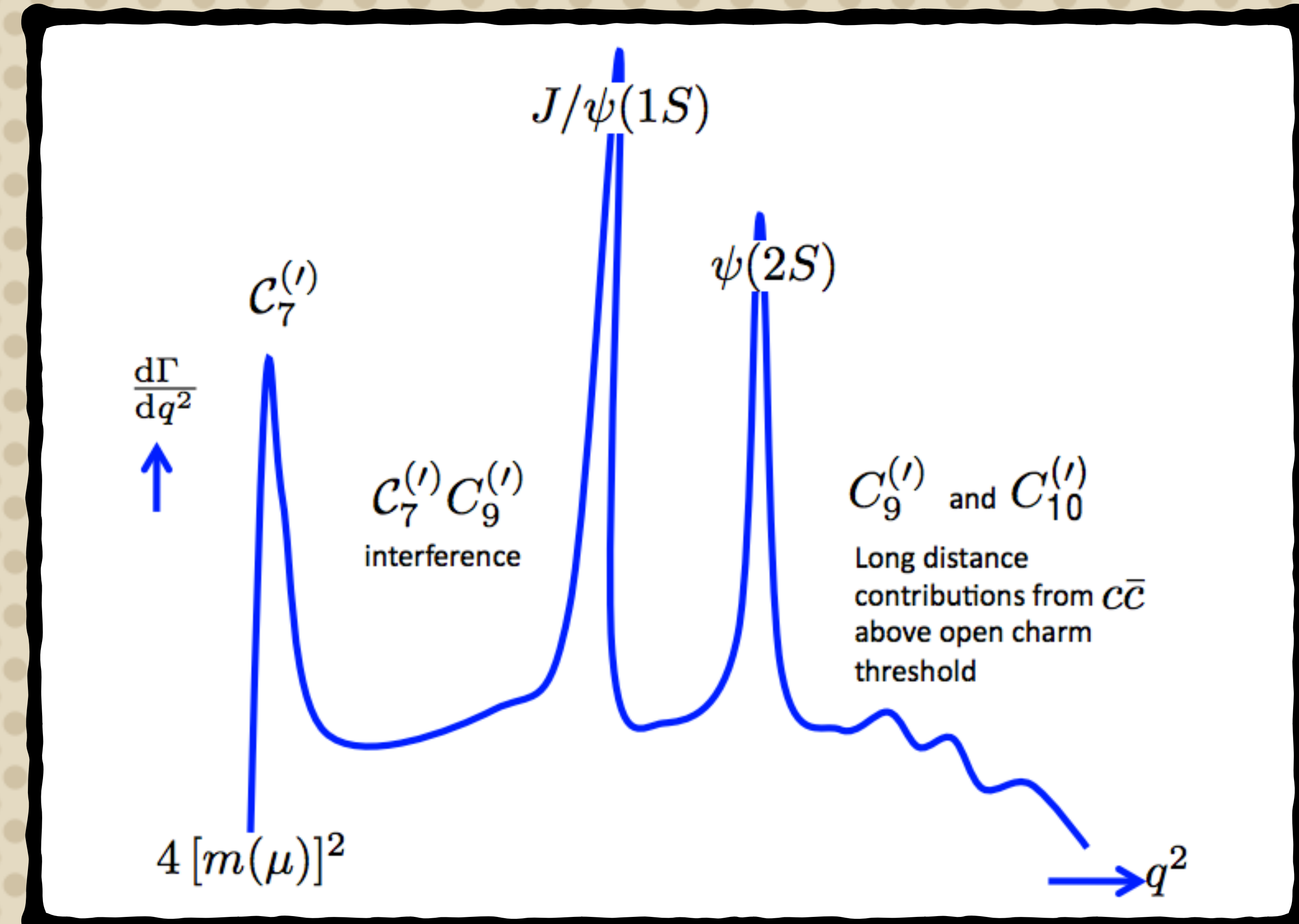
$$A_\parallel^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_\parallel(E_{K^*})$$

We now build ratios such that the same combination of FF appears in the numerator and in the denominator

$$P'_5 \propto \frac{\Re(A_0 A_\perp)}{\sqrt{|A_0|^2 \times |A_\perp|^2}}$$

the q² distribution



Analysis of 1fb^{-1}

In the analysis of 1fb^{-1} we did not have enough data to fit the full Pdf, so we used "folding" of angles to simplify the Pdf

$$\begin{aligned} \phi &\rightarrow -\phi && \text{if } \phi < 0 \\ \theta_\ell &\rightarrow \pi - \theta_\ell && \text{if } \theta_\ell < \pi/2 \end{aligned}$$

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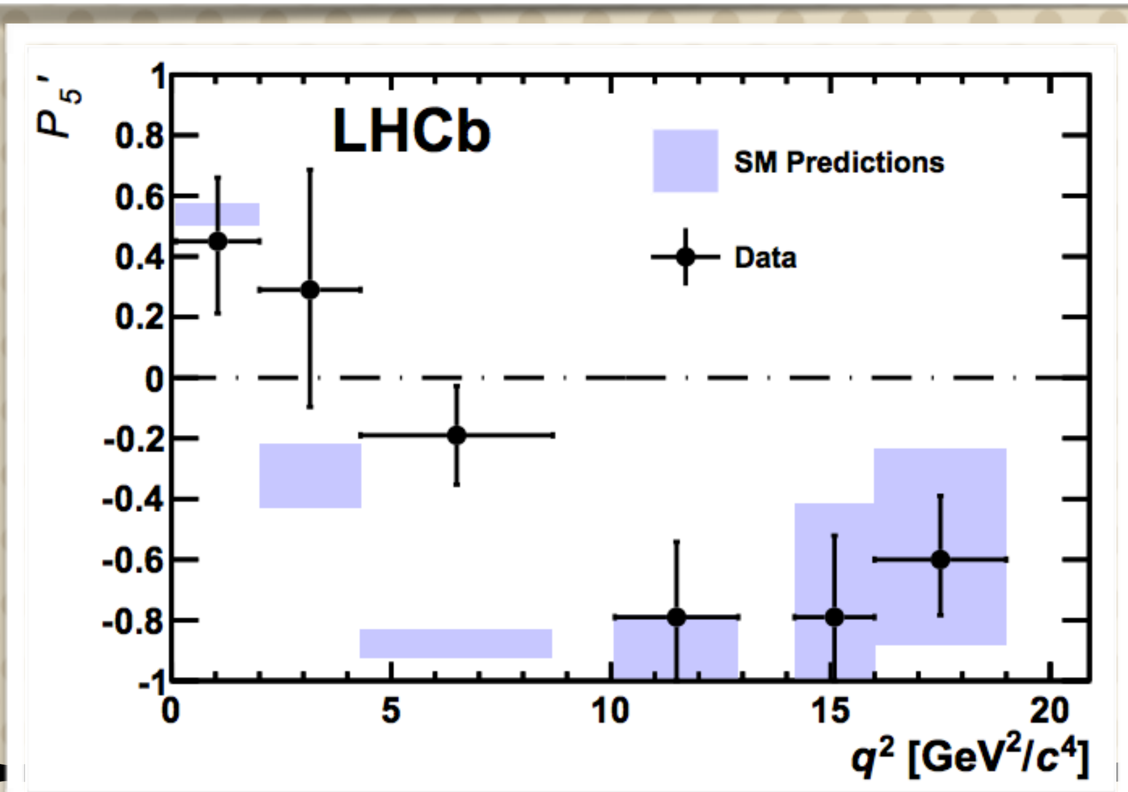
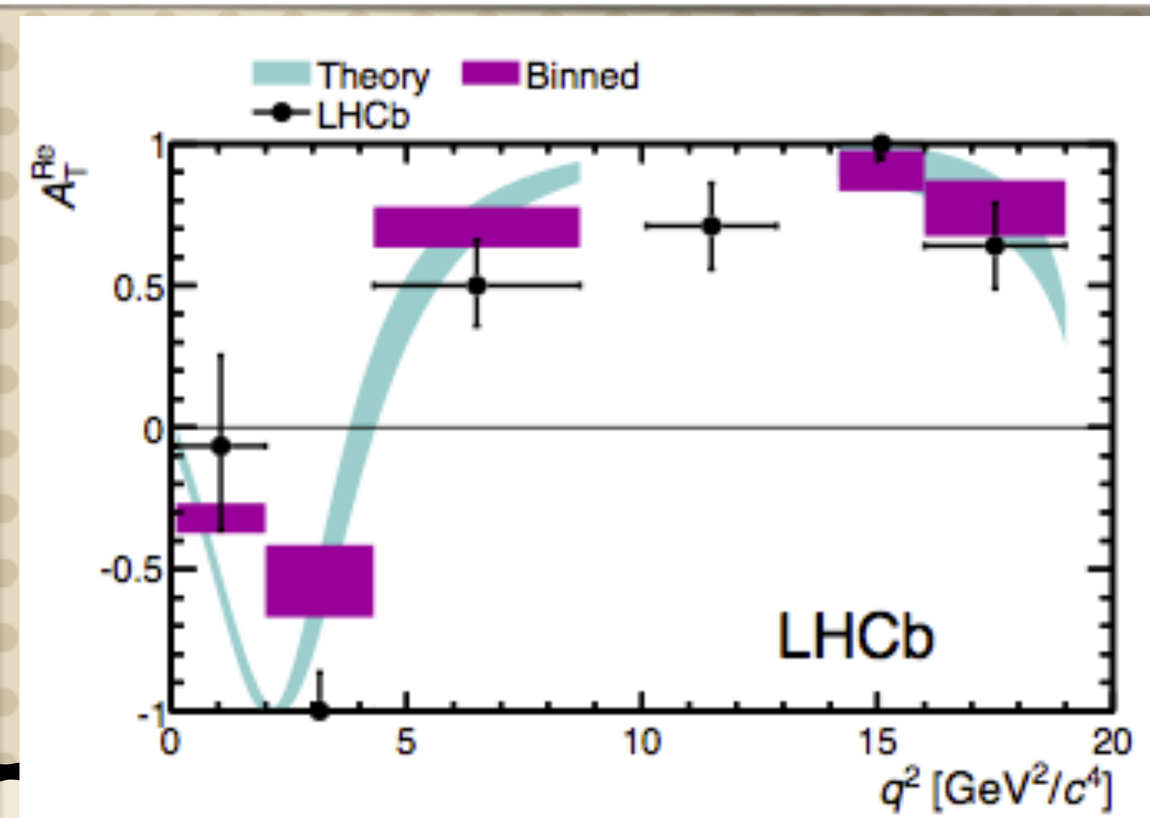
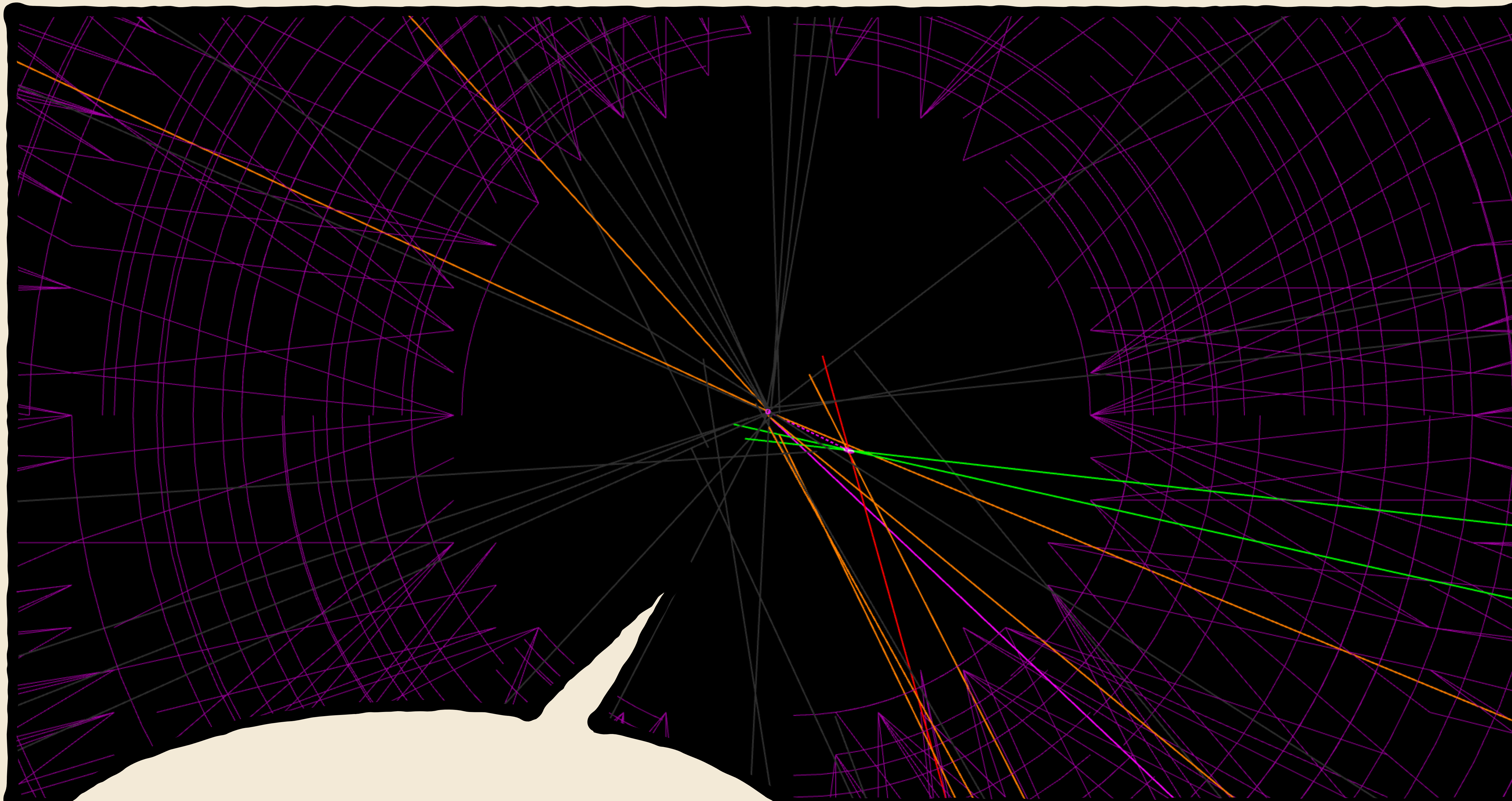
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \right. \\ \left. - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + \sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi\right]$$

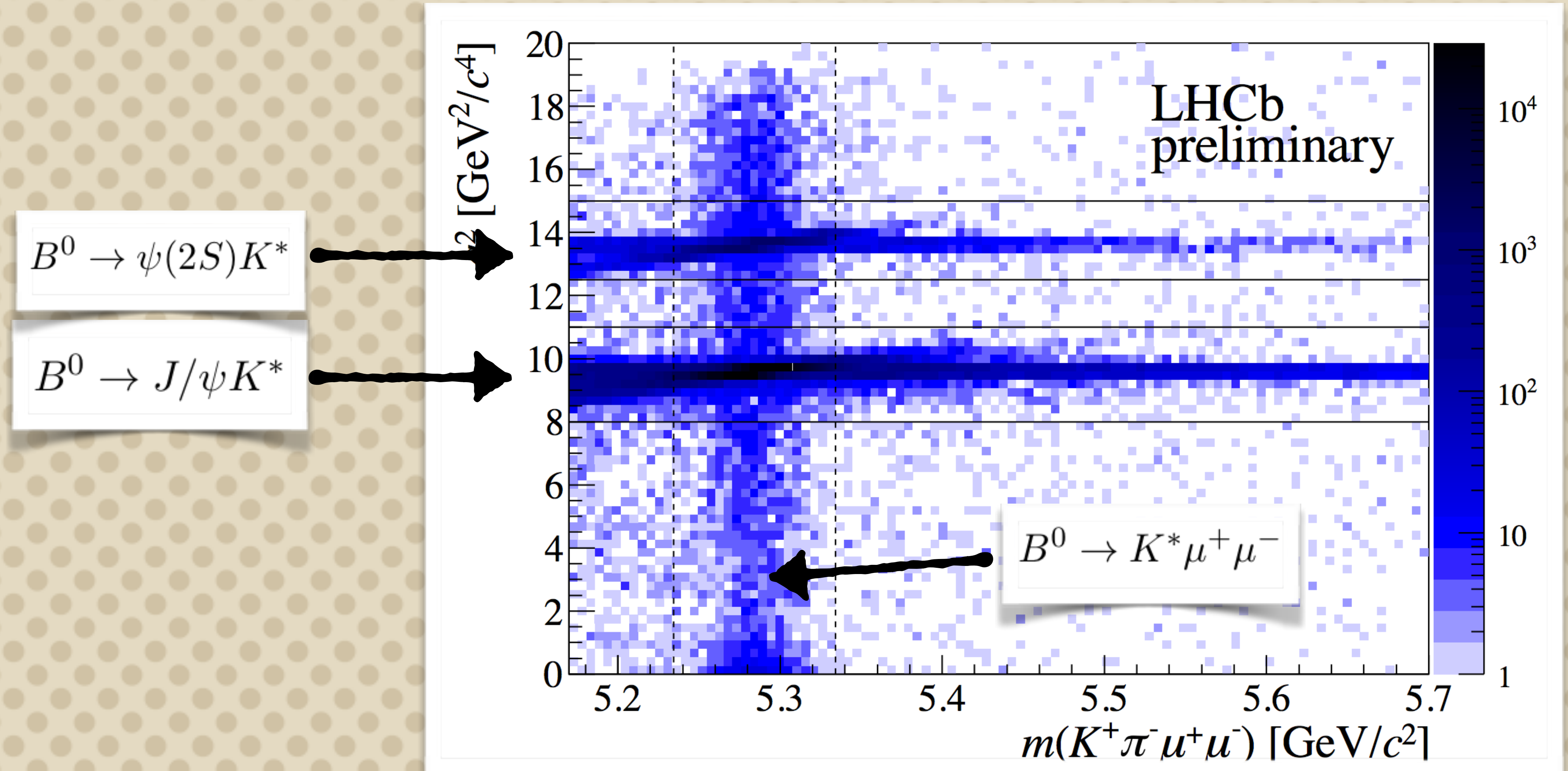






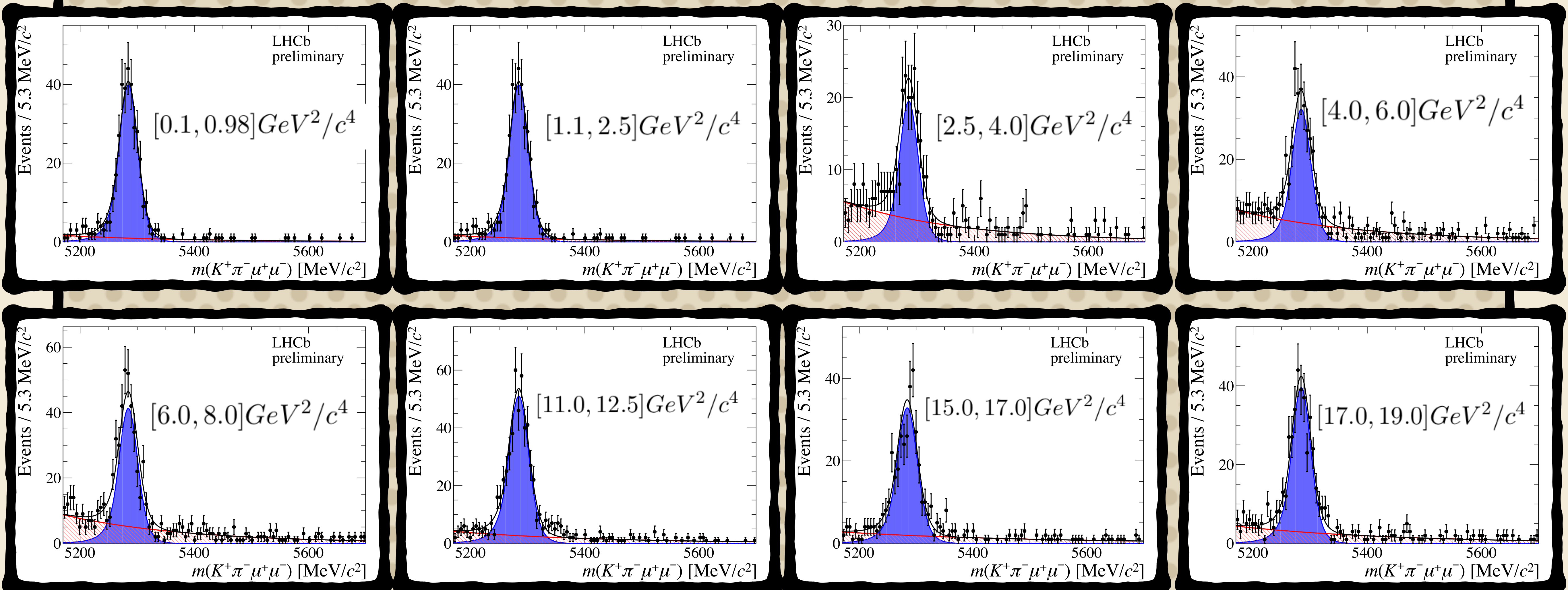
Analysis of B0—>K*mm (3fb^{-1})

Signal region



- Signal selected with BDT which combines kinematic, geometric and PID criteria
- Veto charminium resonances
- Used of charmonia as control channels

Invariant Mass fit



- Total signal yield integrated in q^2: 2398 ± 58 events
- Angular analysis performed in small q^2 bins is more sensitive to NP contributions
- High significance of the signal in all bins
- Independent angular and mass fits in each bins

Likelihood Fit

- Four dimensional fit of B-mass, angles (ϕ, θ_ℓ, θ_K) and simultaneous fit of $m(K\pi)$ (background fraction shared)

$$\log\mathcal{L} = \sum_i \log\left[\epsilon(\vec{\Omega}, q^2) f_{\rm sig}\mathcal{P}_{\rm sig}(\vec{\Omega})\mathcal{P}_{\rm sig}(m_{K\pi\mu\mu}) + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\vec{\Omega})\mathcal{P}_{\rm bkg}(m_{K\pi\mu\mu})\right] + \sum_i \log\left[f_{\rm sig}\mathcal{P}_{\rm sig}(m_{K\pi}) + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(m_{K\pi})\right]$$

- $\mathcal{P}_{sig}(\Omega) = \frac{d^3\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi}$ and $\epsilon(\Omega, q^2)$ is the signal efficiency
- $\mathcal{P}_{bkg}(\Omega)$ is modelled with three second order Chebychel polynomial and extracted from the sidebands
- $\mathcal{P}_{bkg}(m_{K\pi\mu\mu})$ is an esponential

Method of Moments

Use orthogonality of spherical harmonics to determine the coefficients

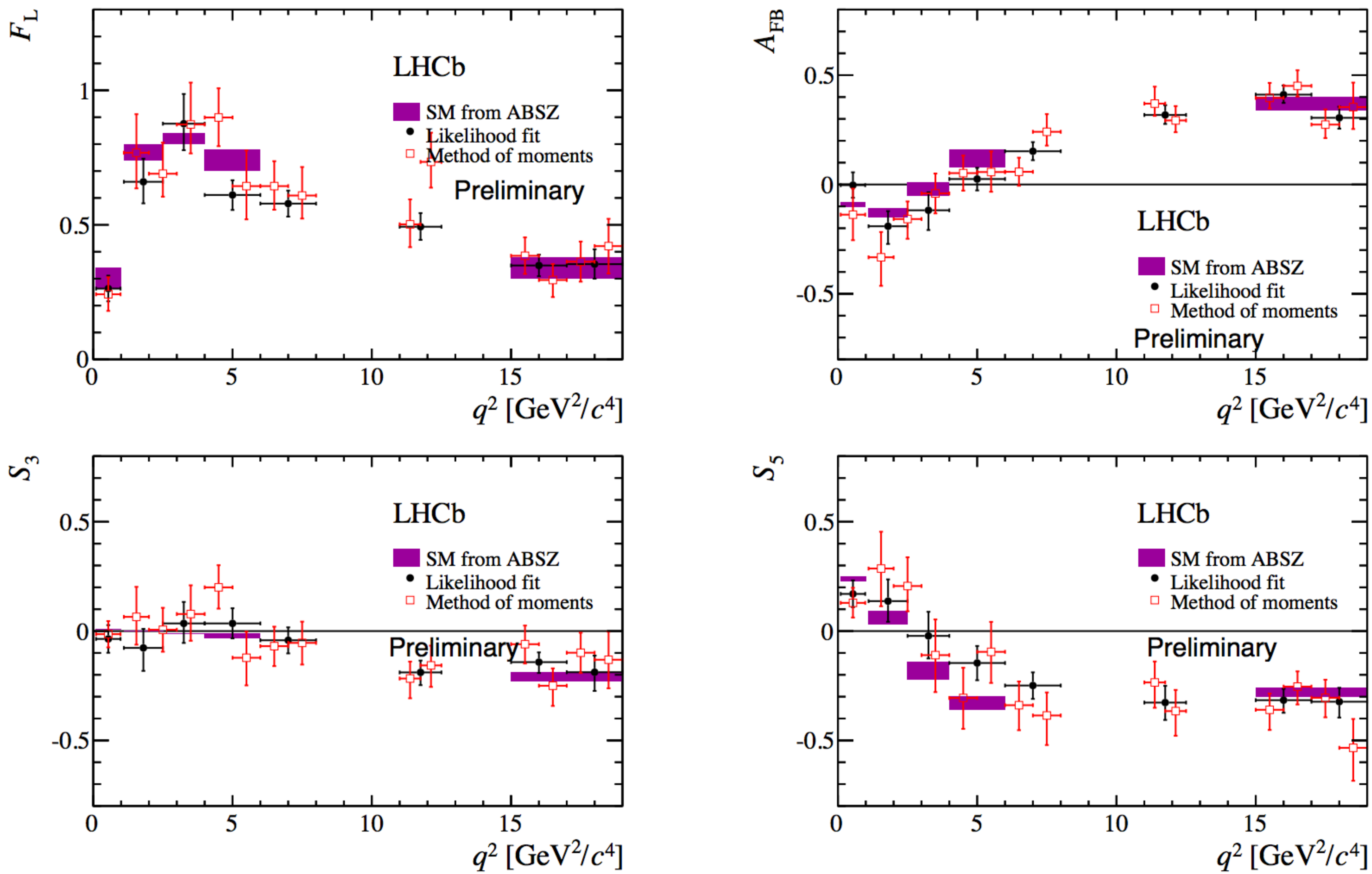
$$\int f_i(\vec{\Omega}) f_j(\vec{\Omega}) \mathrm{d}\vec{\Omega} = \delta_{ij}$$

$$M_i = \int \left(\frac{1}{\mathrm{d}(\Gamma + \bar{\Gamma})/\mathrm{d}q^2} \right) \frac{\mathrm{d}^3(\Gamma + \bar{\Gamma})}{\mathrm{d}\vec{\Omega}} f_i(\vec{\Omega}) \mathrm{d}\vec{\Omega}$$

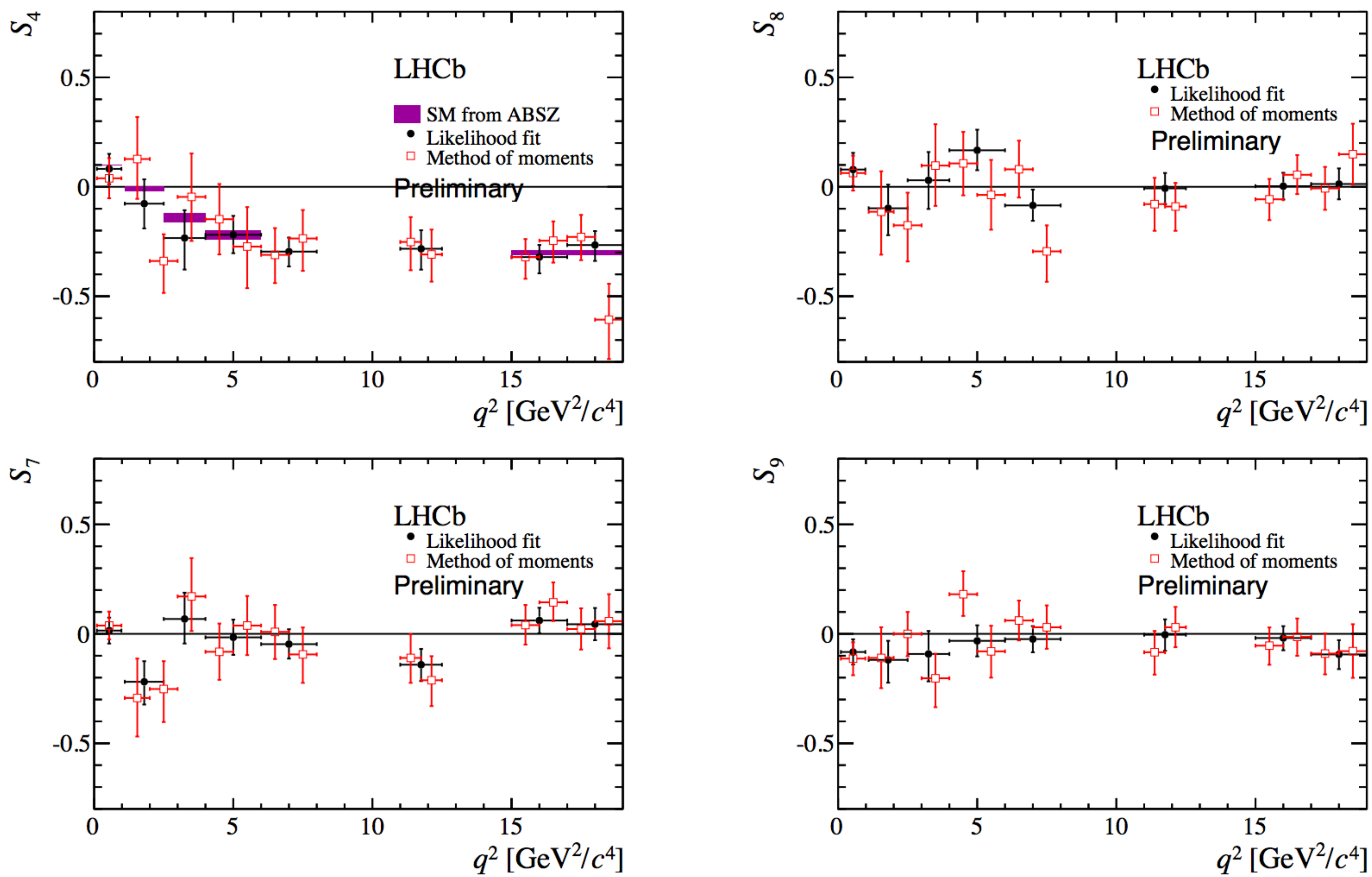
We sample the angular distribution with our data, so the integral becomes a sum over data

$$\widehat{M_i} = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\vec{\Omega}_e)$$

The weights w_e accounts for the efficiency

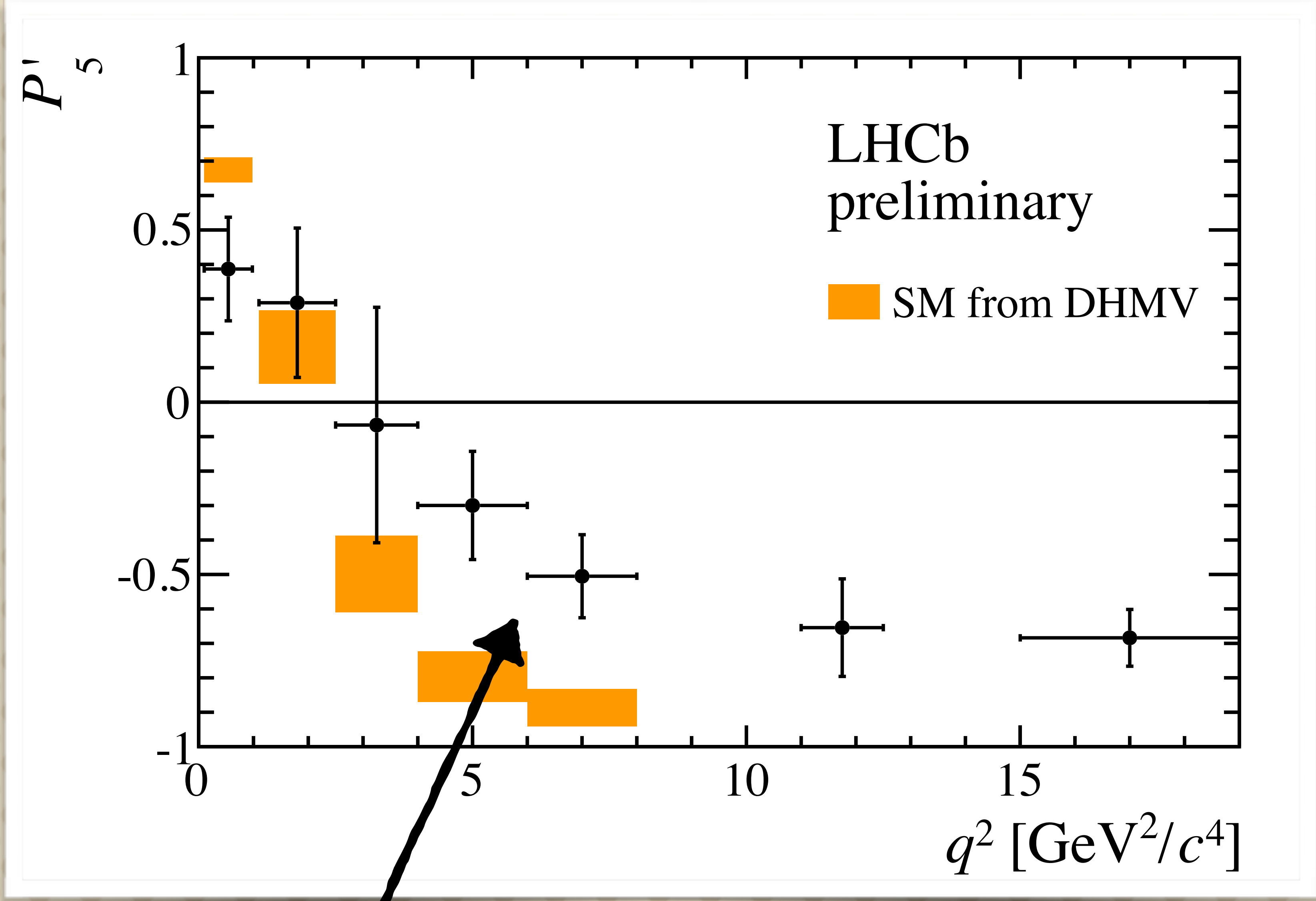


F_L
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]
A_{FB}
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]
S_3
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]
S_5
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]



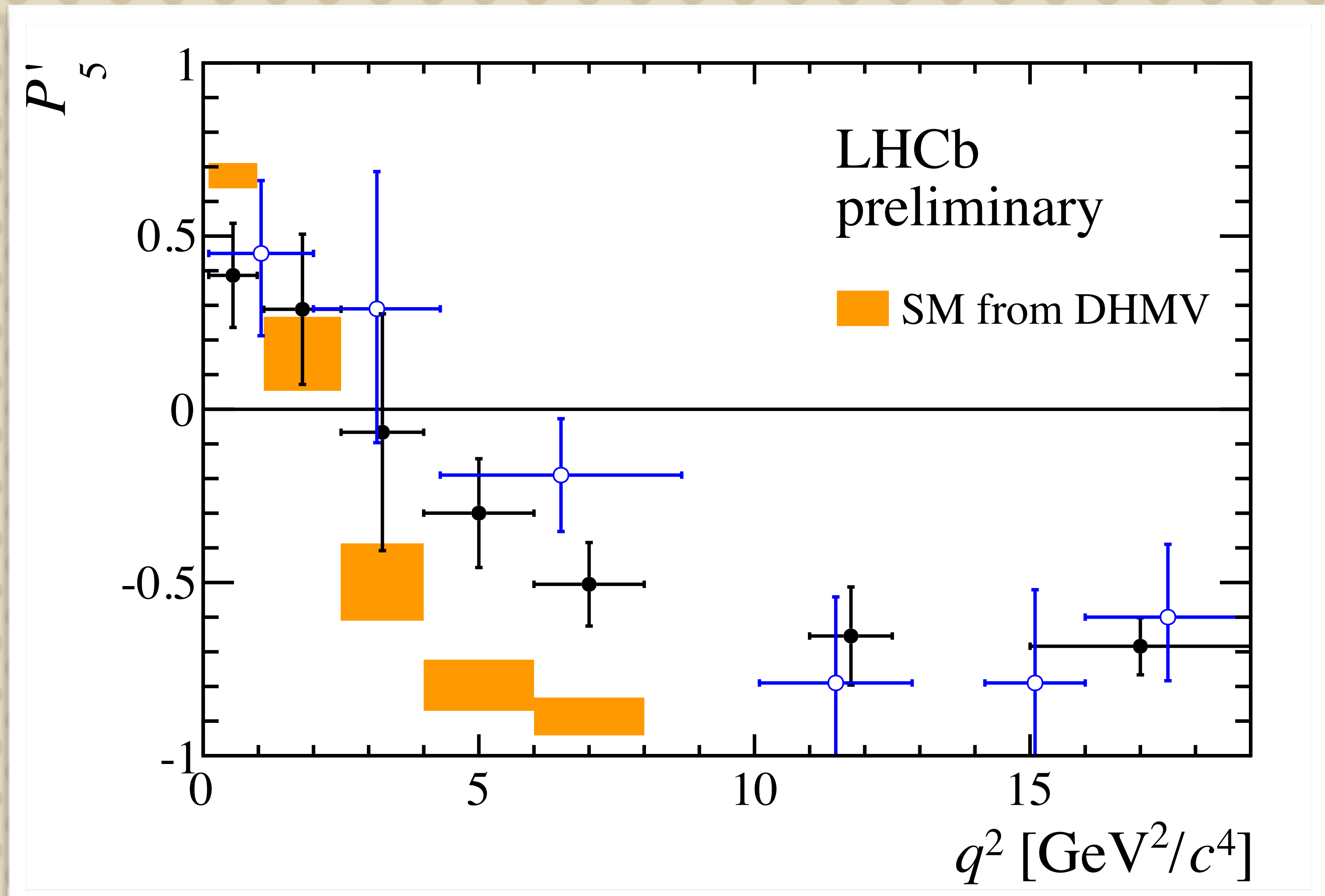
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
S_4
S_8
S_7
S_9
q^2 [GeV^2/c^4]

The K*mm anomaly persists



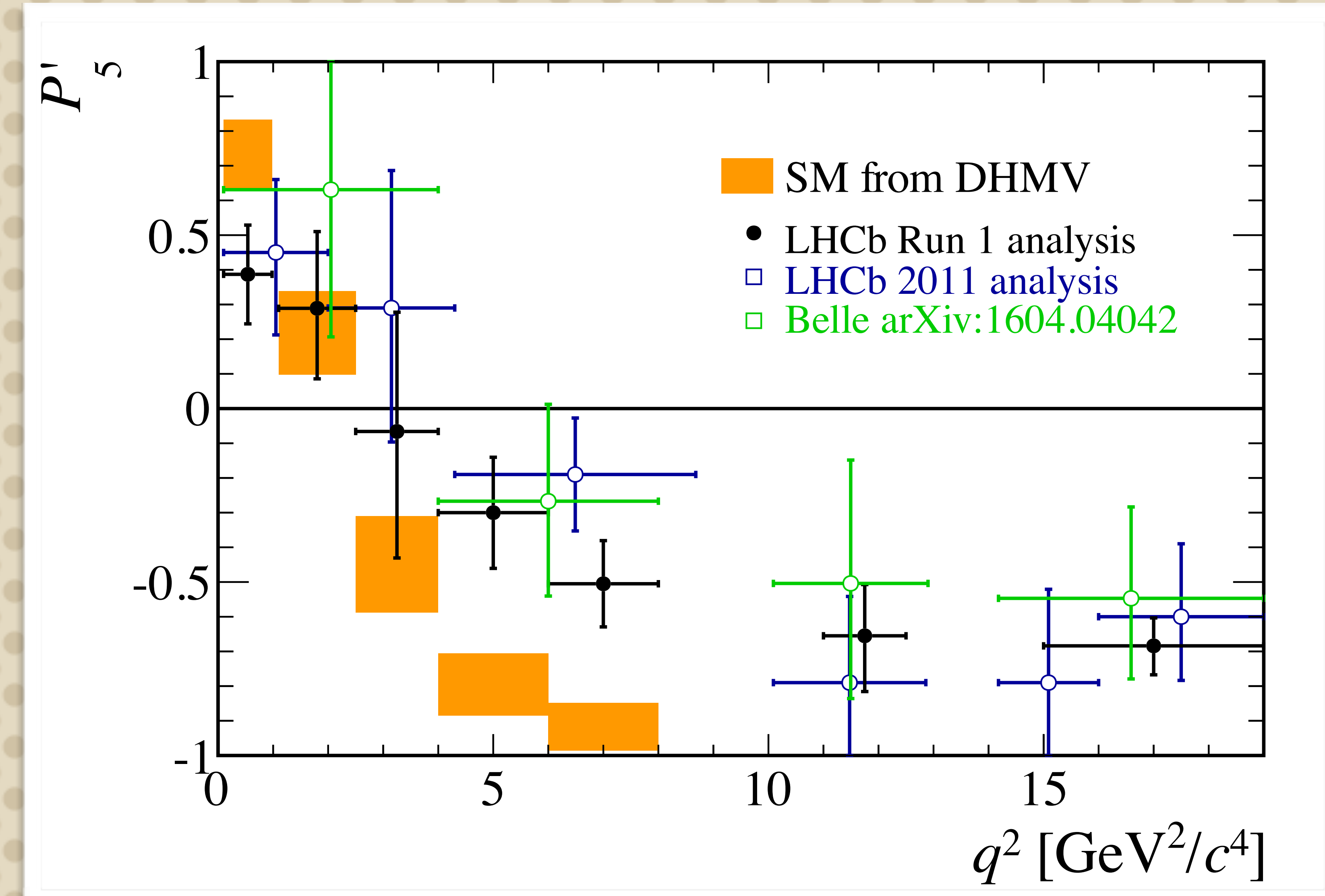
- Local discrepancy of about 3.0σ in each of these two bins

The K*mm anomaly persists

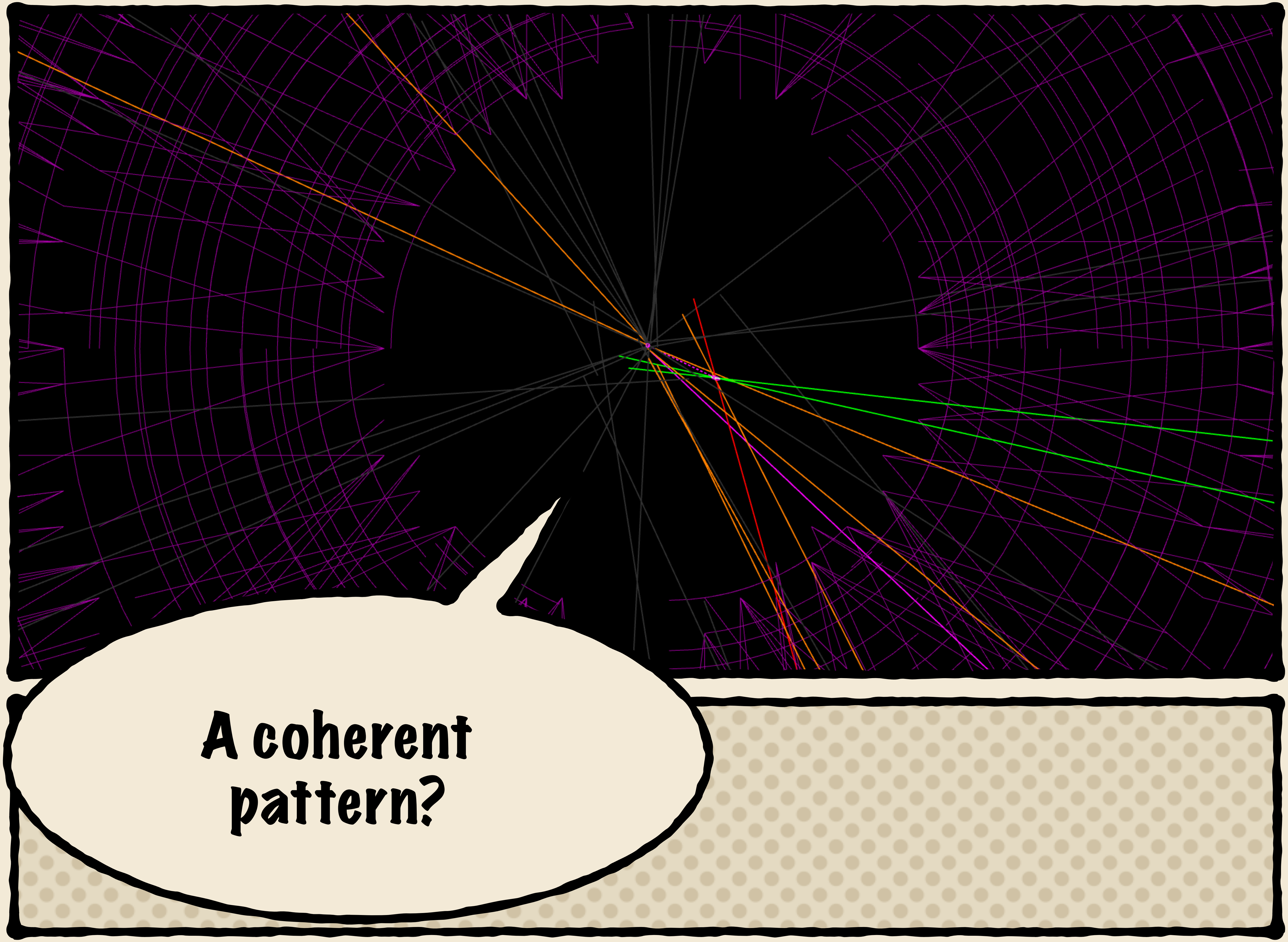


- Good agreement with the analysis of 1fb^{-1}

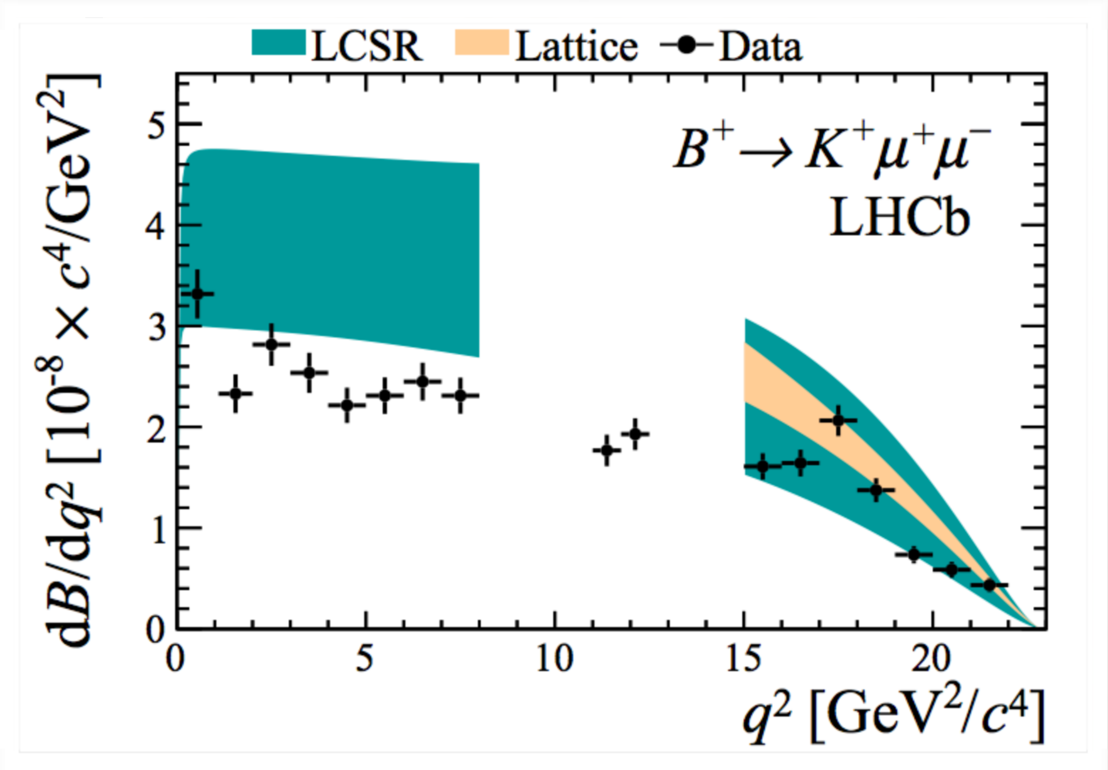
The K*mm anomaly persists

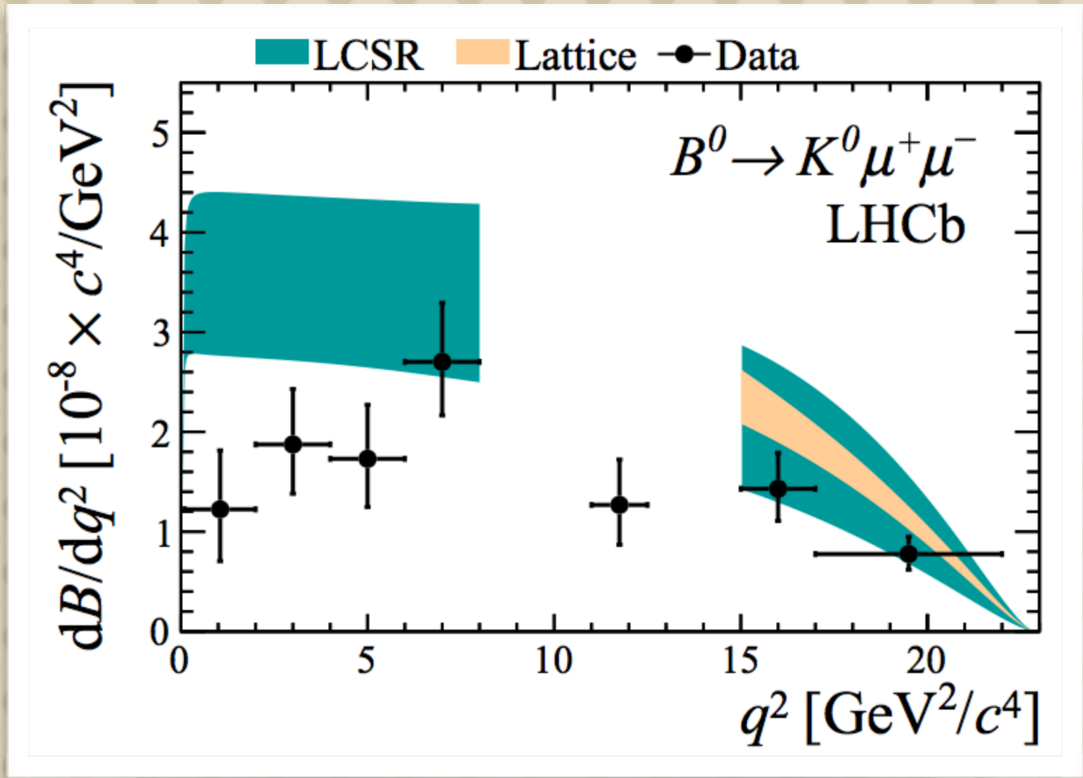


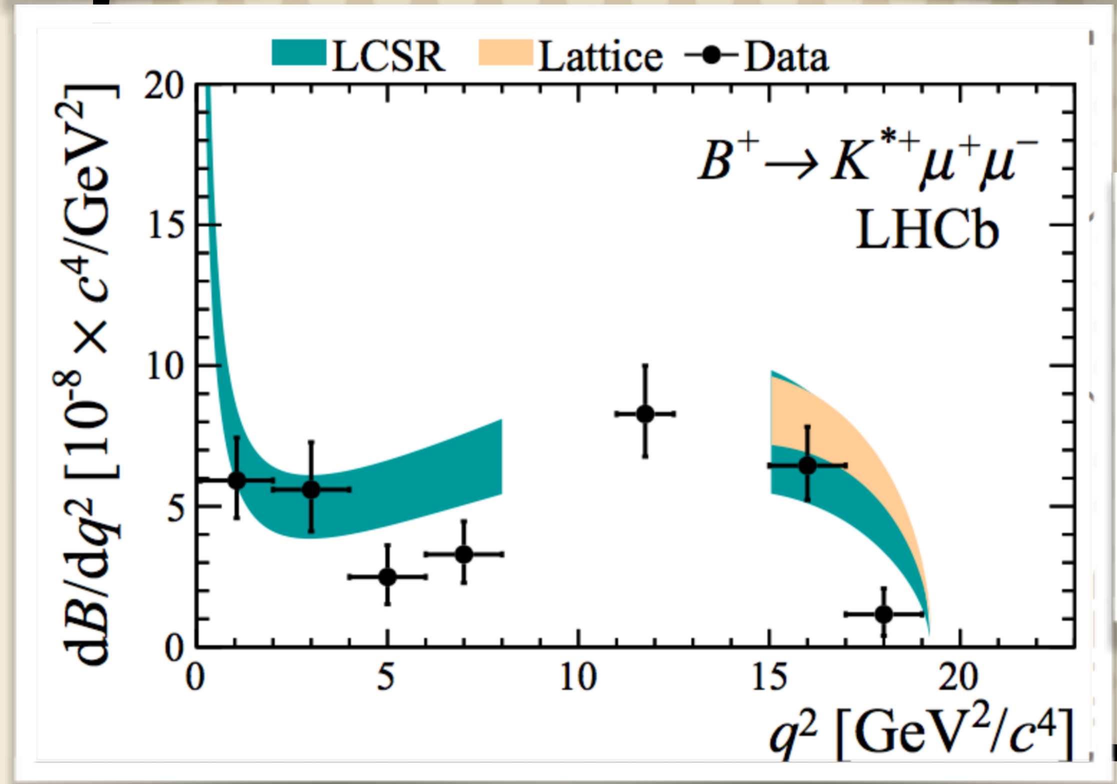
Very good agreement with the recent Belle measurement of P_5'


A coherent pattern?

A coherent pattern?



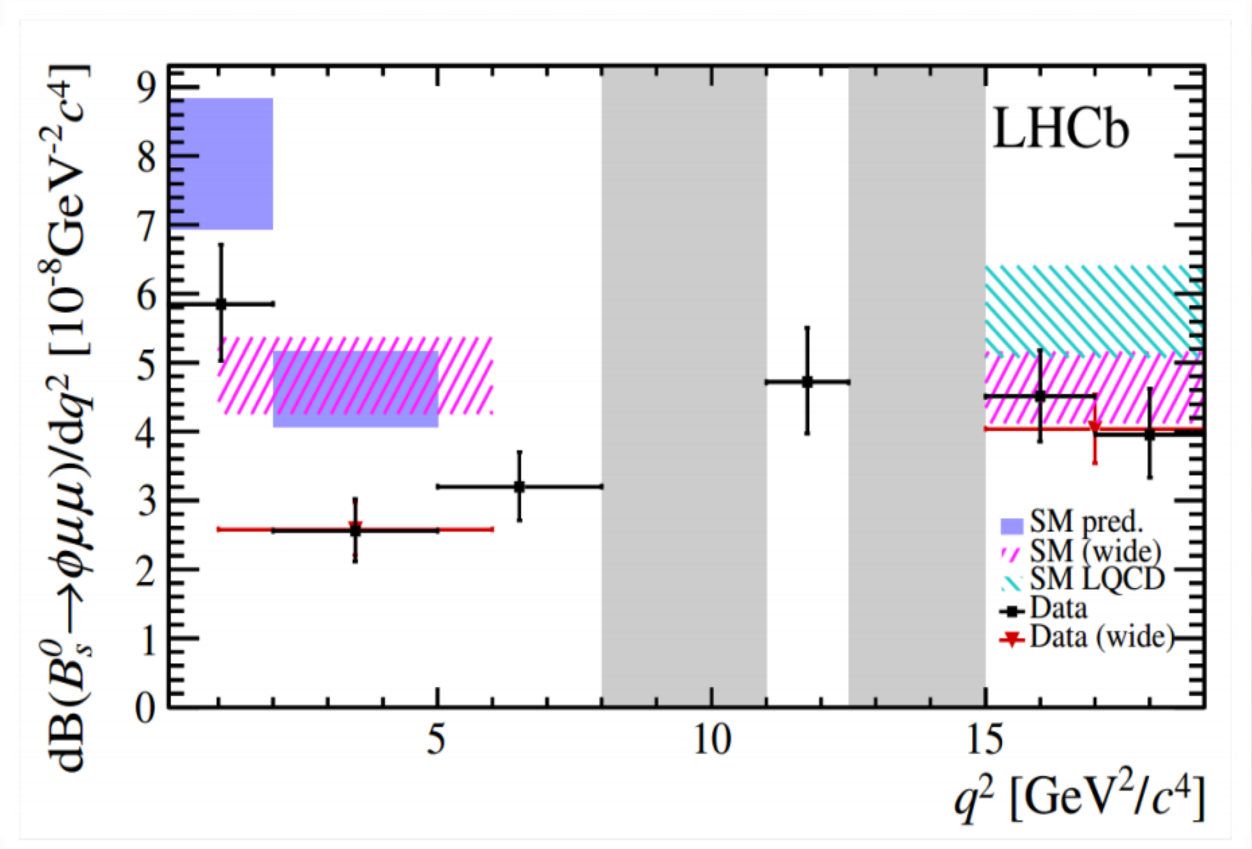


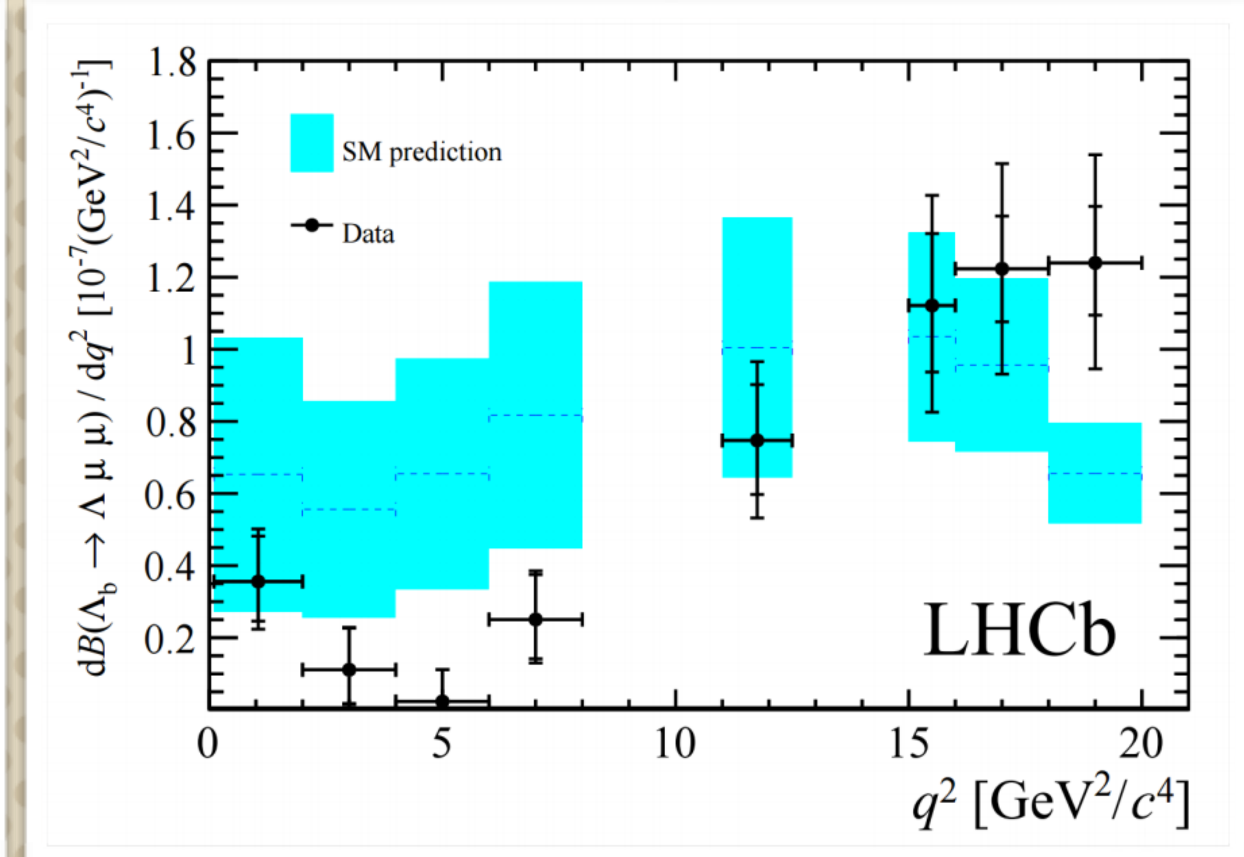


LHCb Collaboration JHEP 06 (2014) 133

- All $b \to s\mu\mu$ branching ratios are measured to be lower than SM predictions
- All these measurements are numerically consistent with a reduced C_9 Wilson coefficient

A coherent pattern?



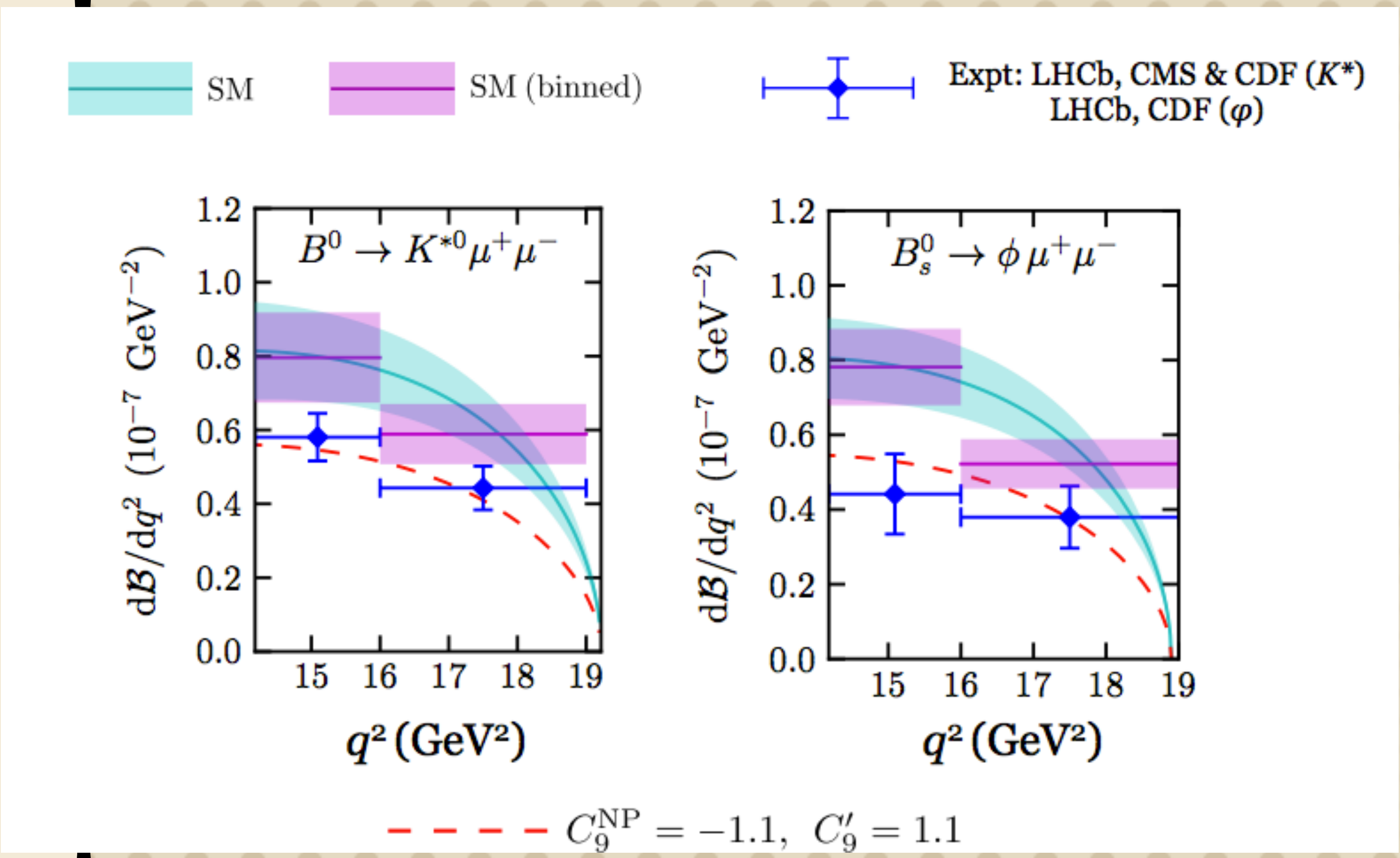


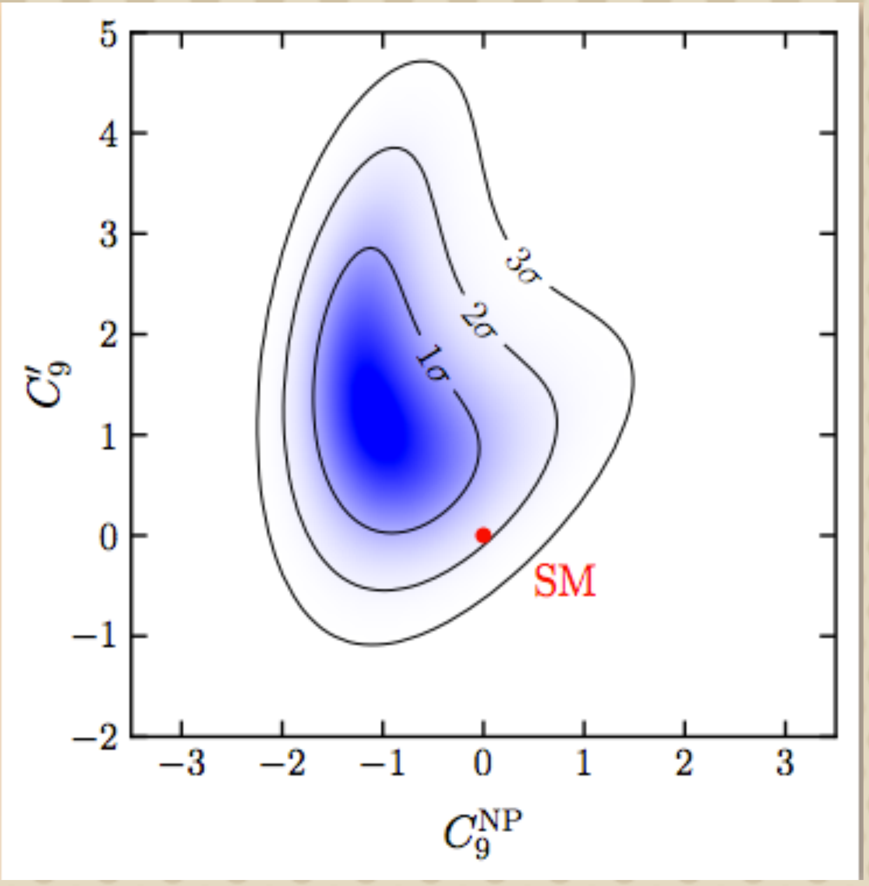
- All $b \to s\mu\mu$ branching ratios are measured to be lower than SM predictions
- All these measurements are numerically consistent with a reduced C_9 Wilson coefficient

Larger than expected deviations (even in NP scenarios)

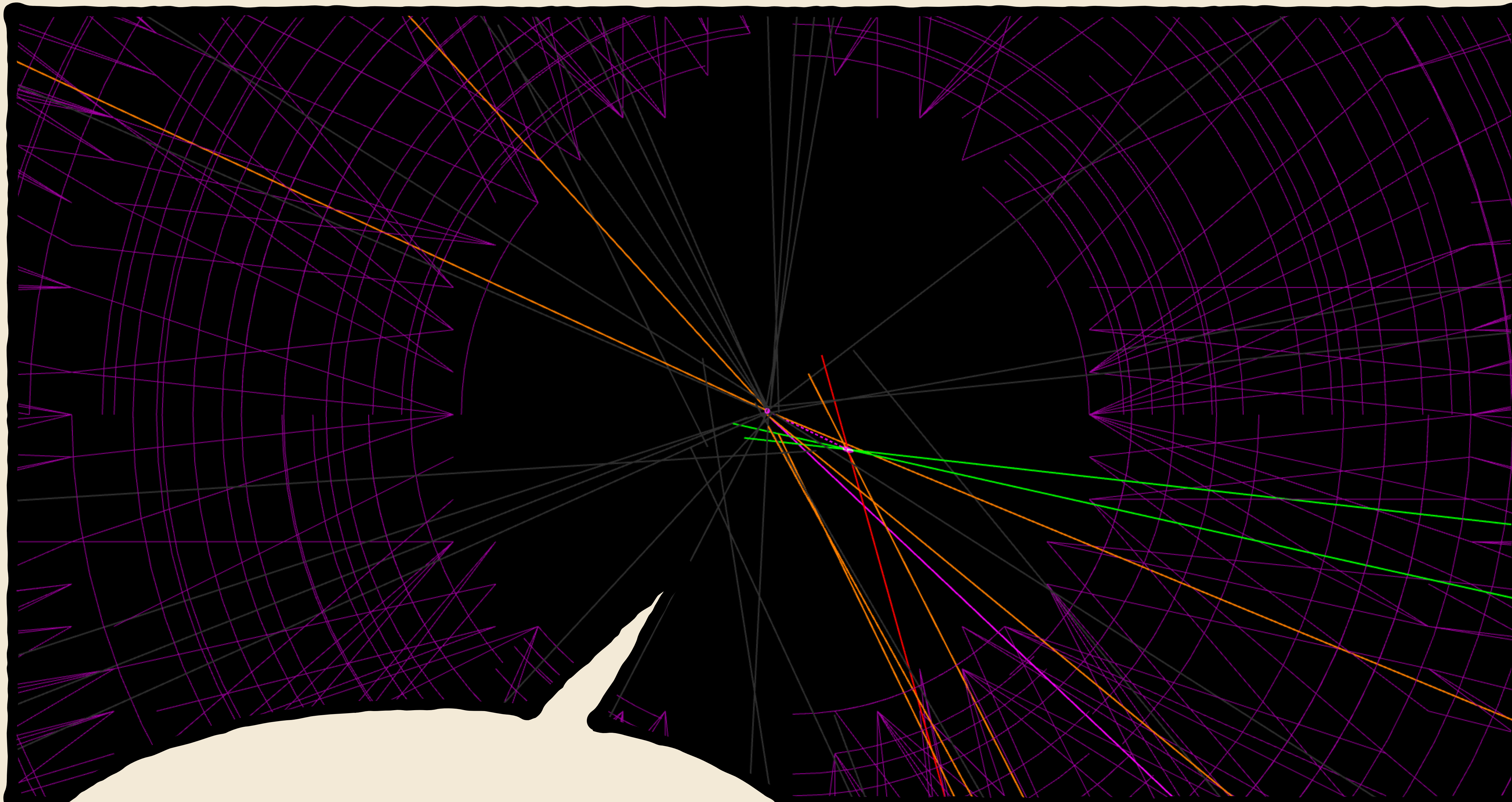
A coherent pattern?

A reduced C_9 Wilson coefficient would be visible in a number of other observables, like branching ratios



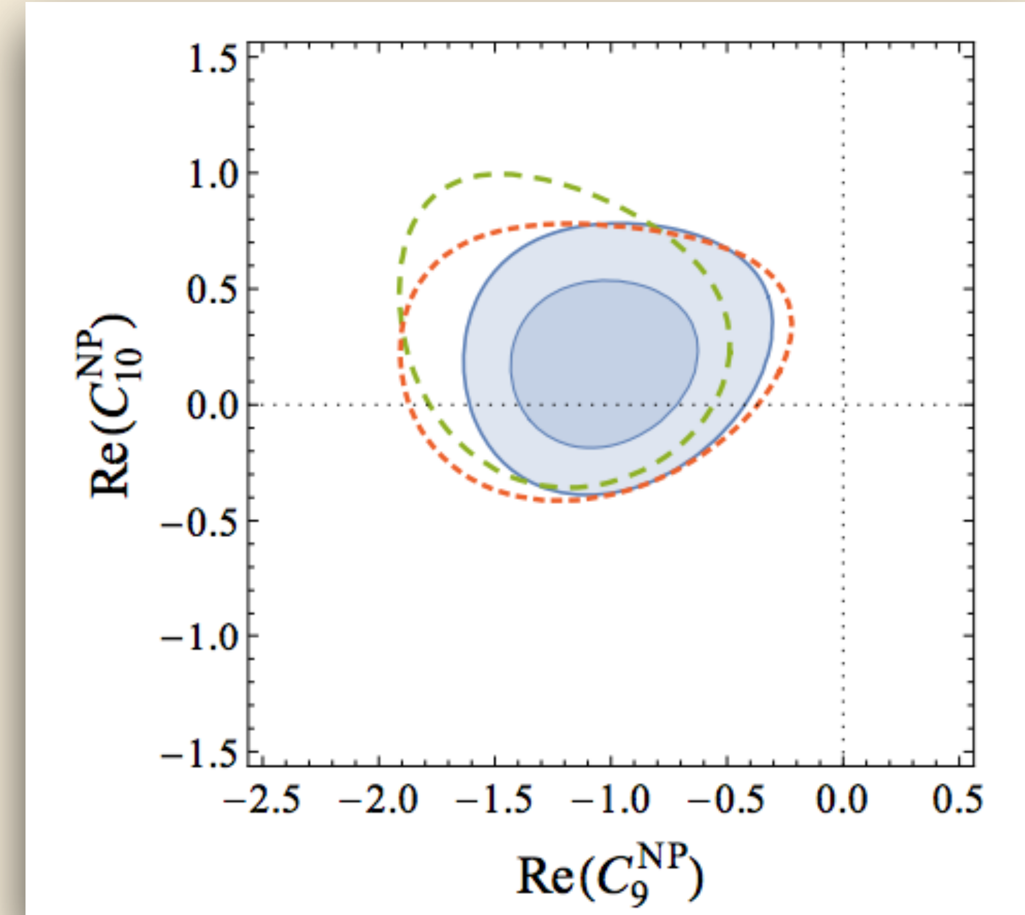


Wingate et al. Phys. Rev. Lett. 112 (2014) 212003
(high q^2 form factors from lattice QCD)



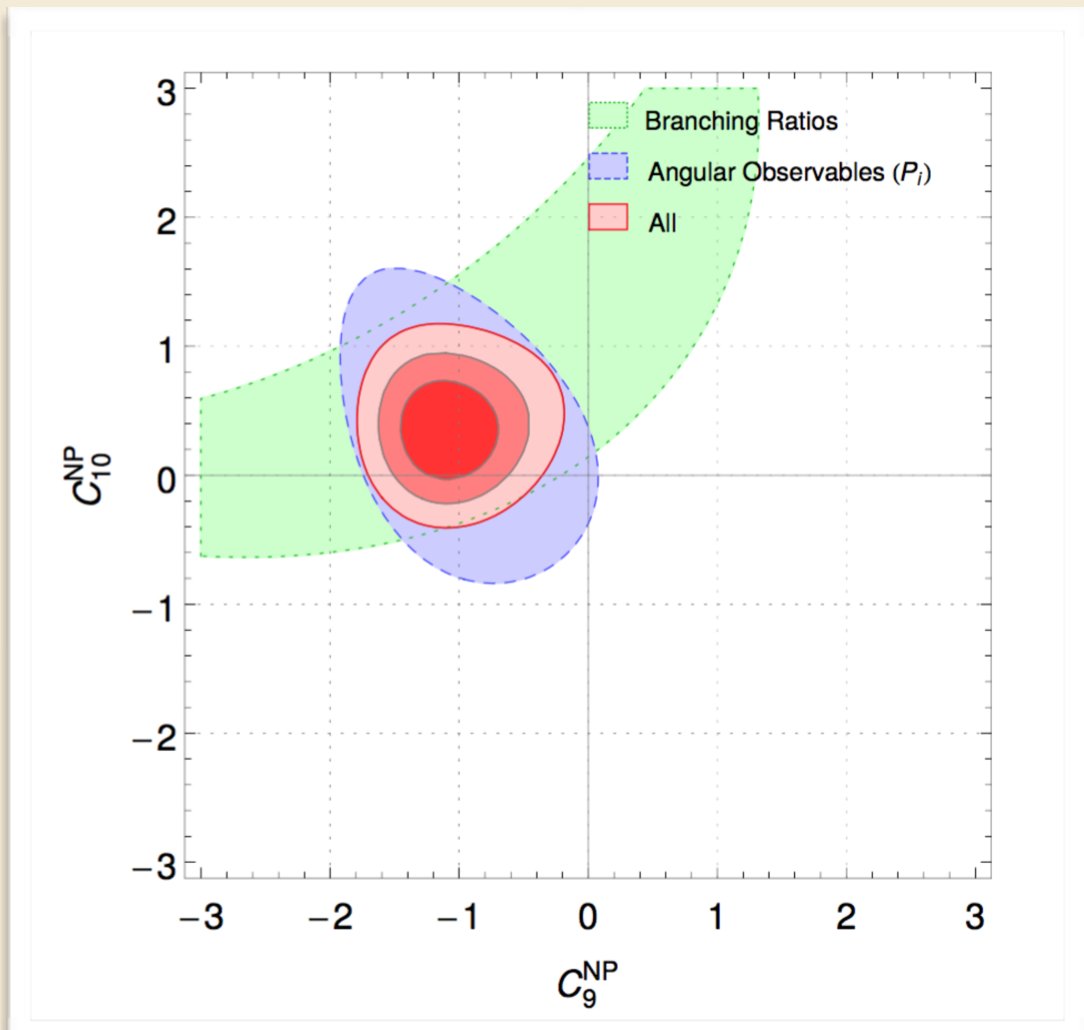
Theory Interpretation

[Altmannshofer/Straub 1411.3161 & 1503.06199]

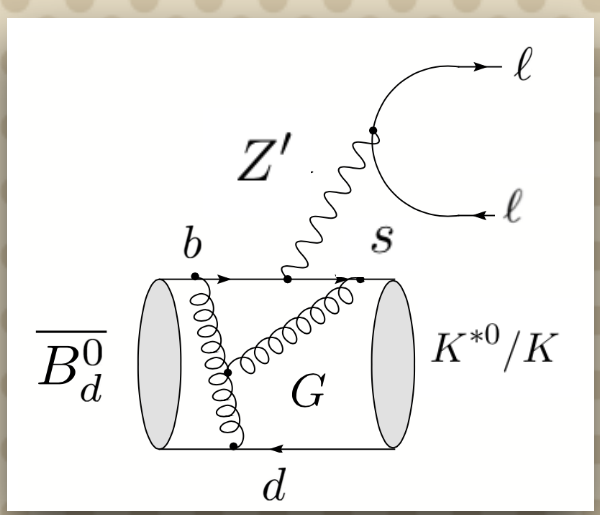


Tension with SM prediction when theory combine this measurements with many others

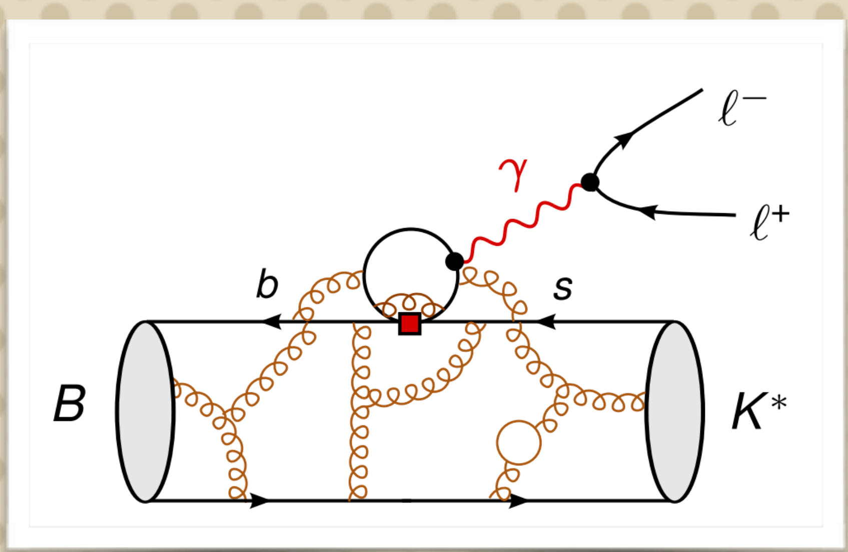
[Descotes-Genon/Hofer/Matias/Virto 1510.04239]

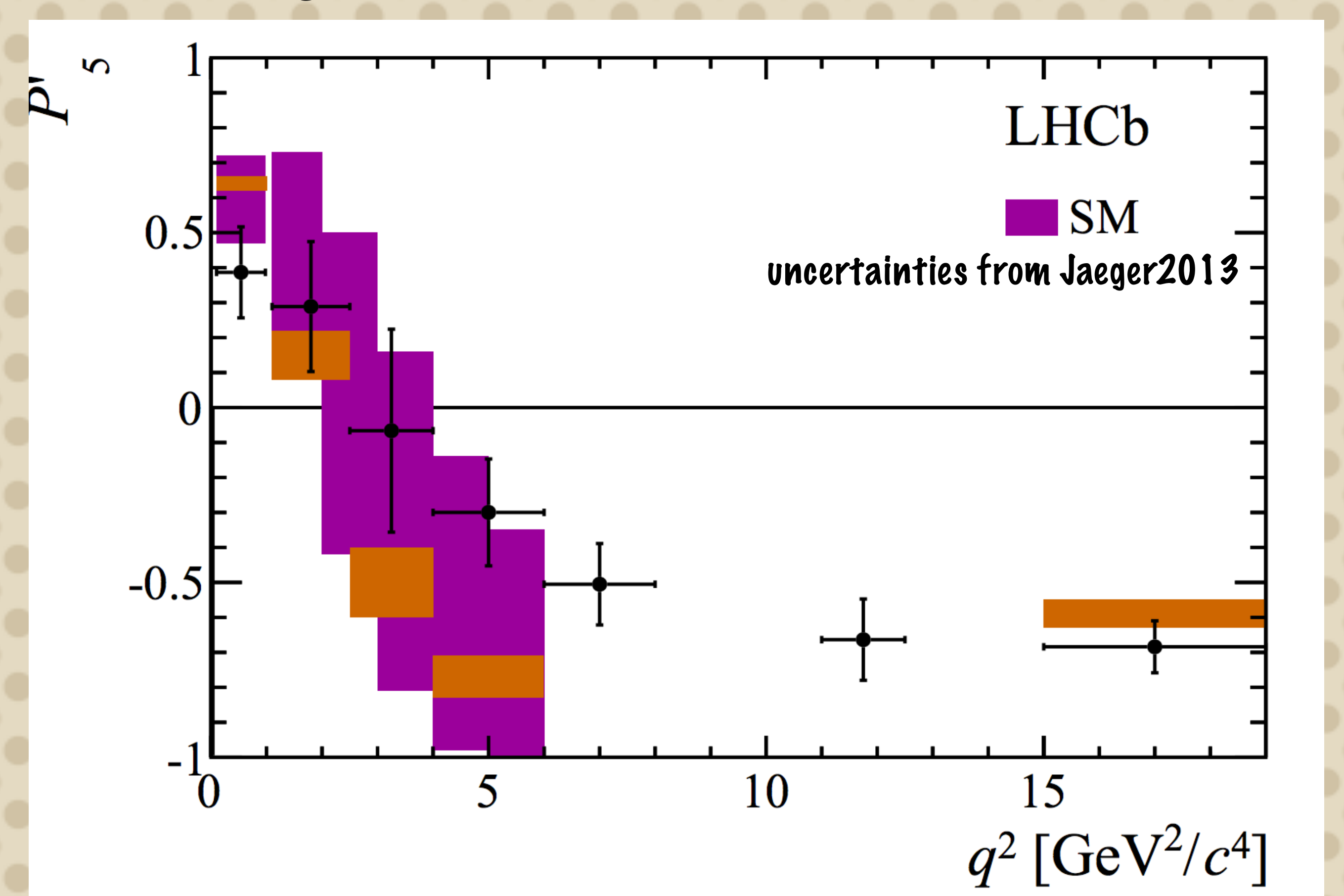


If it is a New Particle the best candidate seem to be a Z'



Charm loop effects?

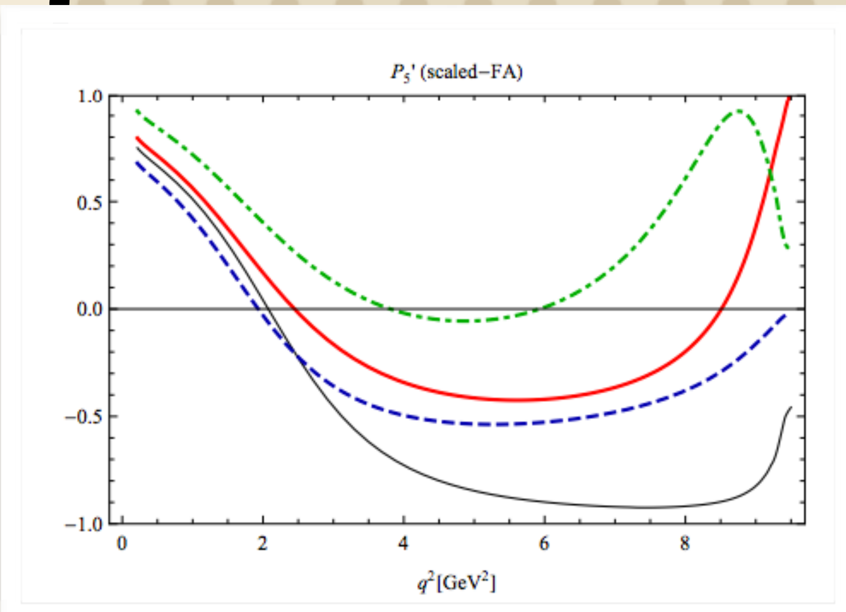




- Non factorizable contribution could be large
(Van Dyk 2013, Zwicky 2015, Silvestrini,Ciuchini 2016, ...)
- Charm loop photon mediated can give a C_9-effect
- Possibility to explained with "large" charm loop contribution

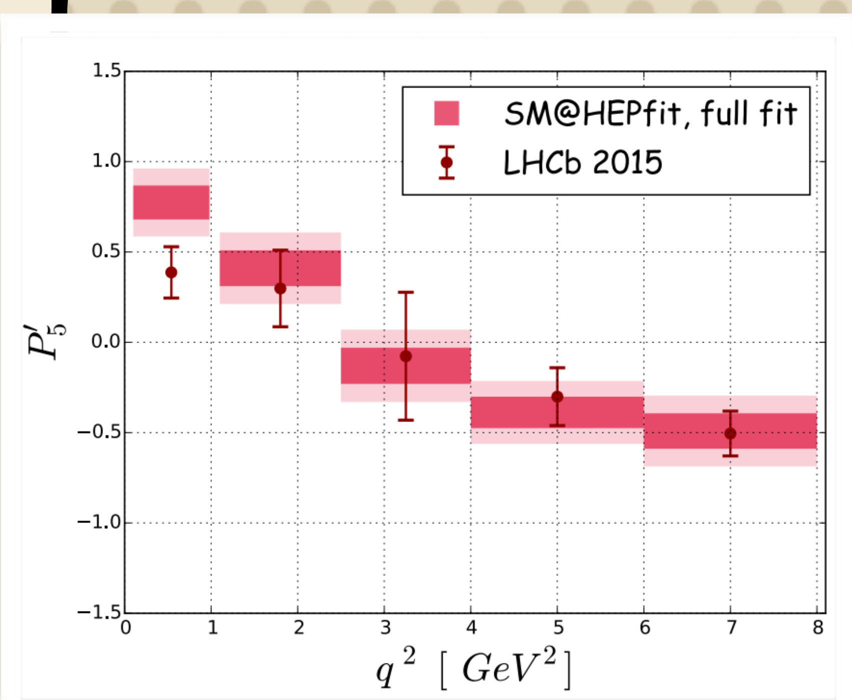
- S. Jaeger pointed to possible (soft) form factors effects

Charm loop effects?



Hadronic picture:
- Large effect from the tails of the ccbar resonances + open charm

Zwicky-Lyons 2015

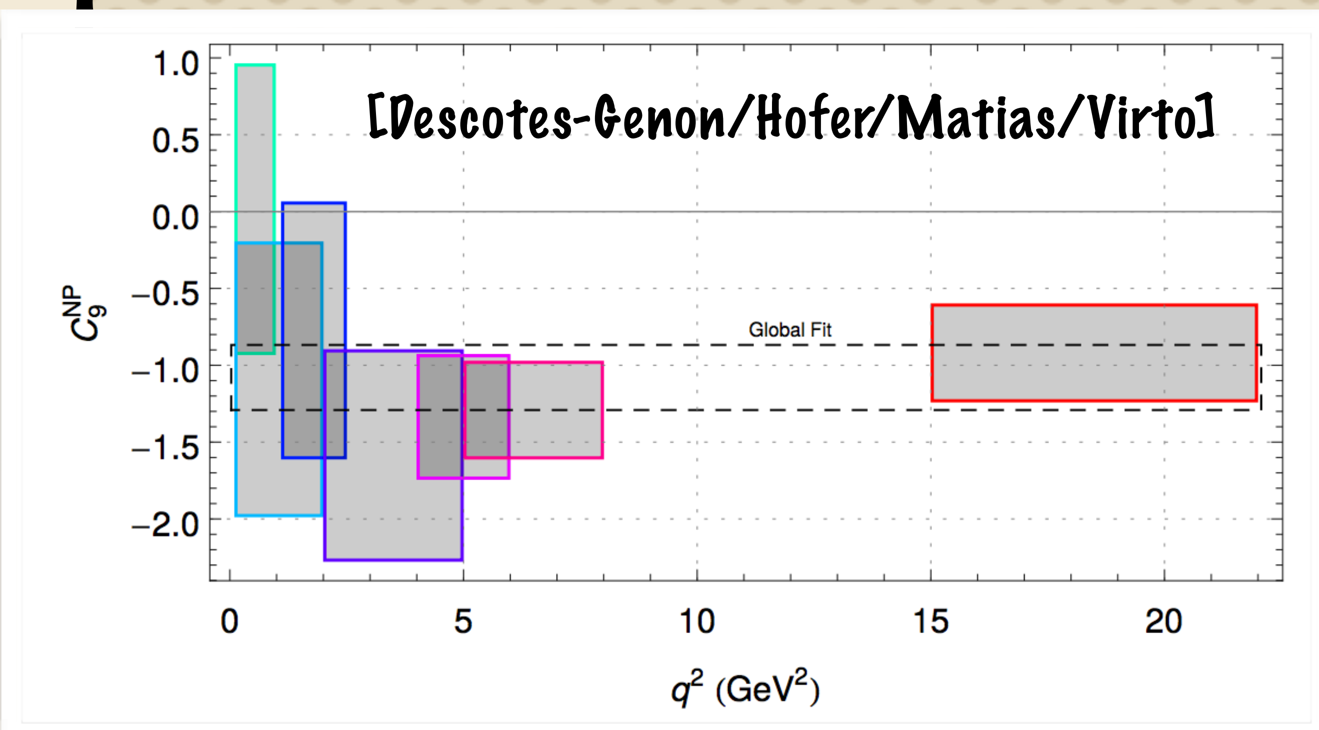


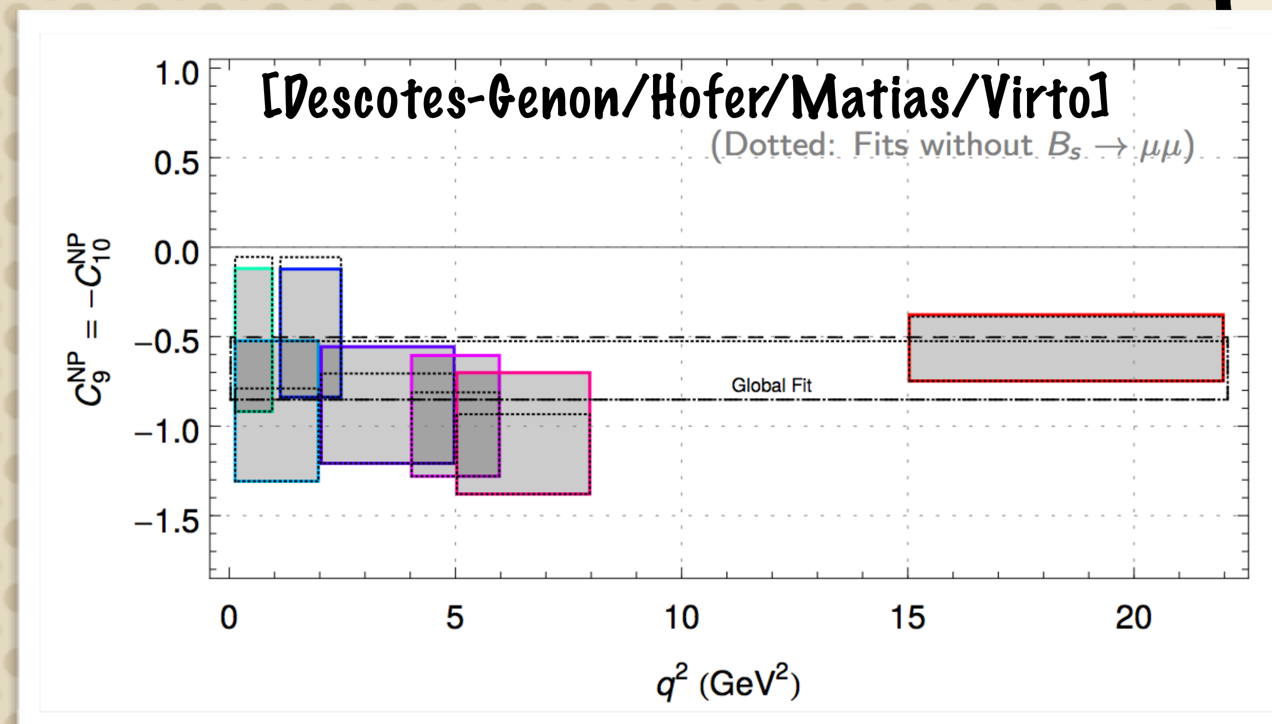
Partonic picture:
- Large effect from ccbar loop
- Adding an hadronic parameter to the fit it is possible to describe the anomaly

Silvestrini, Ciuchini et al., 2016

NP or hadronic effect?

- NP is expected to be universal for all b->smumu transitions
- NP is expected to be q^2 independent



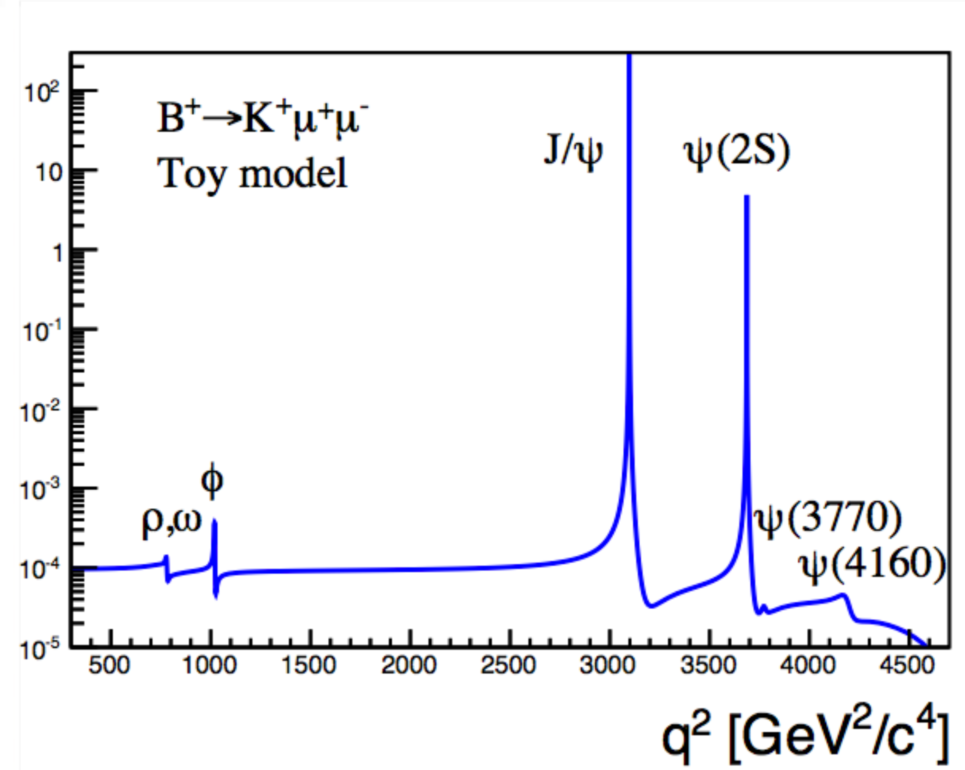


- For now we do not have evidence for process dependency or q^2 dependence

- Need more statistics

Trying to handle the ccbar-loop

Decay	% of $B^+ \to K^+\mu^+\mu^-$
Penguin	0.6 %
$B^+ \to \rho K^+$	0.0003 %
$B^+ \to \omega K^+$	0.0006 %
$B^+ \to \phi K^+$	0.003 %
$B^+ \to J/\psi\, K^+$	92 %
$B^+ \to \psi(2S) K^+$	7.3 %
$B^+ \to \psi(3770) K^+$	0.007 %
$B^+ \to \psi(4040) K^+$	~ 0 %
$B^+ \to \psi(4160) K^+$	0.005 %
$B^+ \to \psi(4415) K^+$	~ 0 %

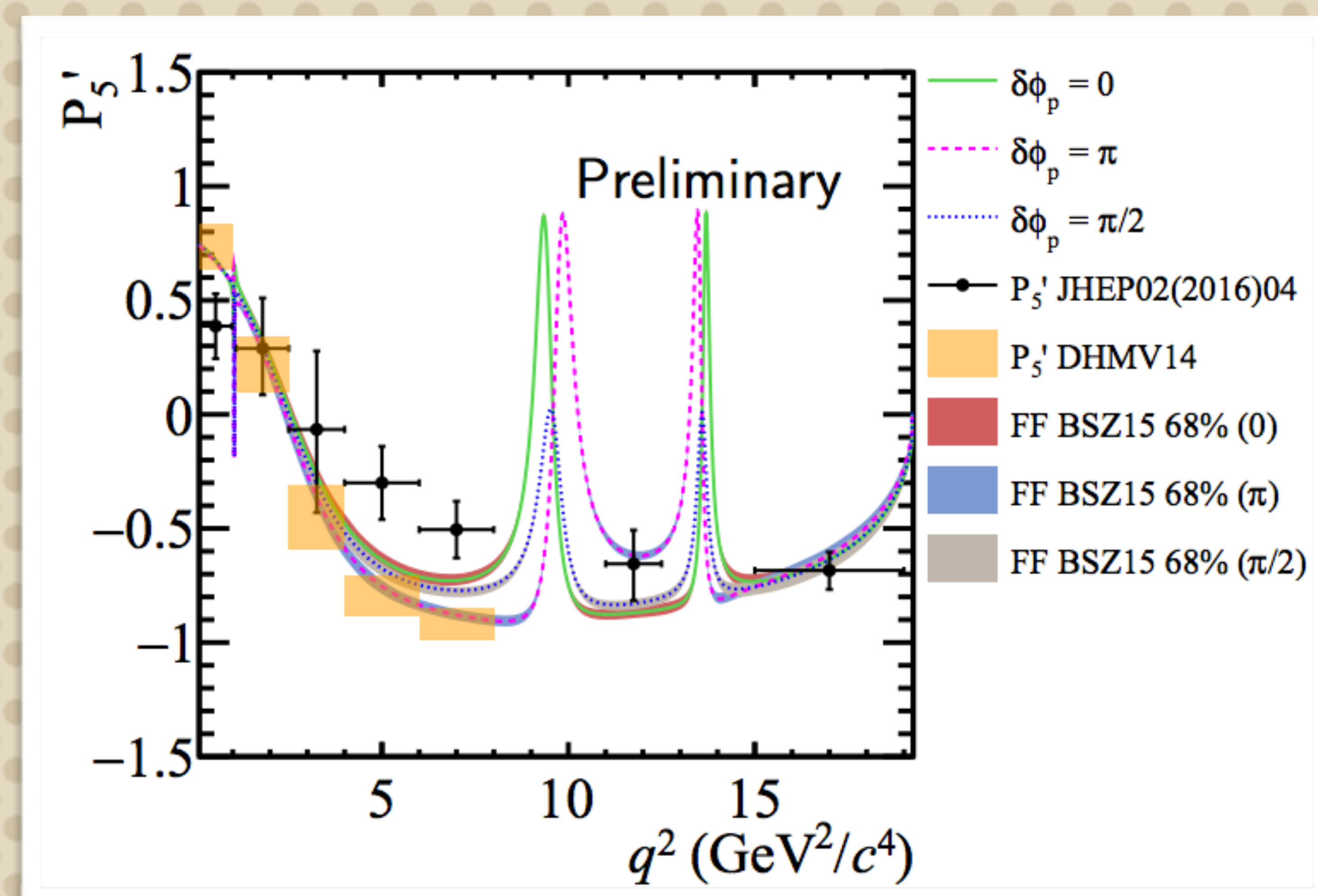


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{2^7\pi^5}|\boldsymbol{k}|\beta_+ \left\{ \frac{2}{3}|\boldsymbol{k}|^2\beta_+^2 \left|C_{10}^{\text{eff}} f_+(q^2)\right|^2 + \frac{m_l^2(M_B^2 - M_K^2)^2}{q^2 M_B^2}\left|C_{10}^{\text{eff}} f_0(q^2)\right|^2 \right.$$

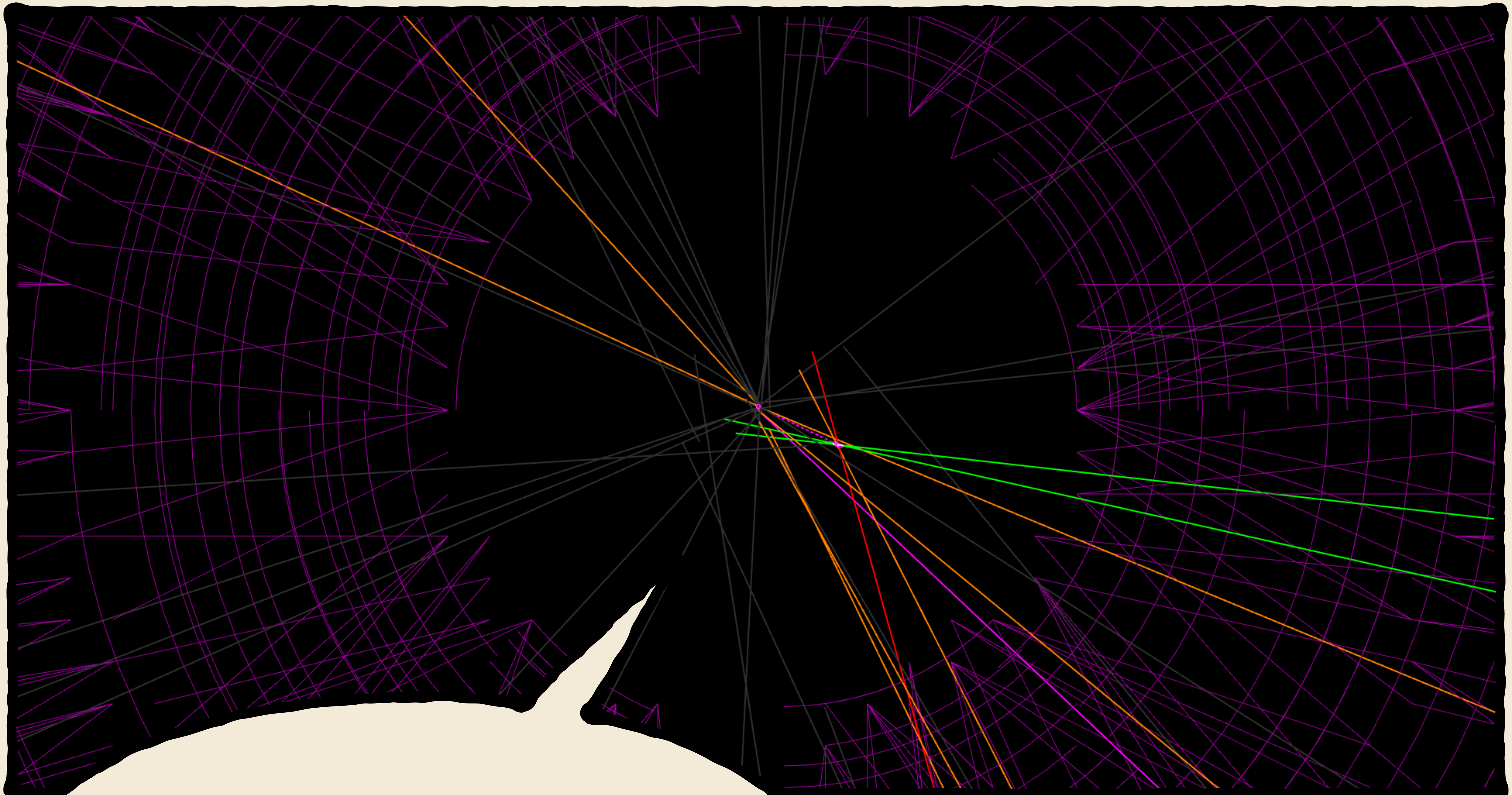
$$\left. + |\boldsymbol{k}|^2\left[1 - \frac{1}{3}\beta_+^2\right]\left|C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}}\frac{m_b+m_s}{M_B+M_K} f_T(q^2)\right|^2 \right\}$$

- Add all the resonances with BW and the try to fit for C_9

Trying to handle the ccbar-loop

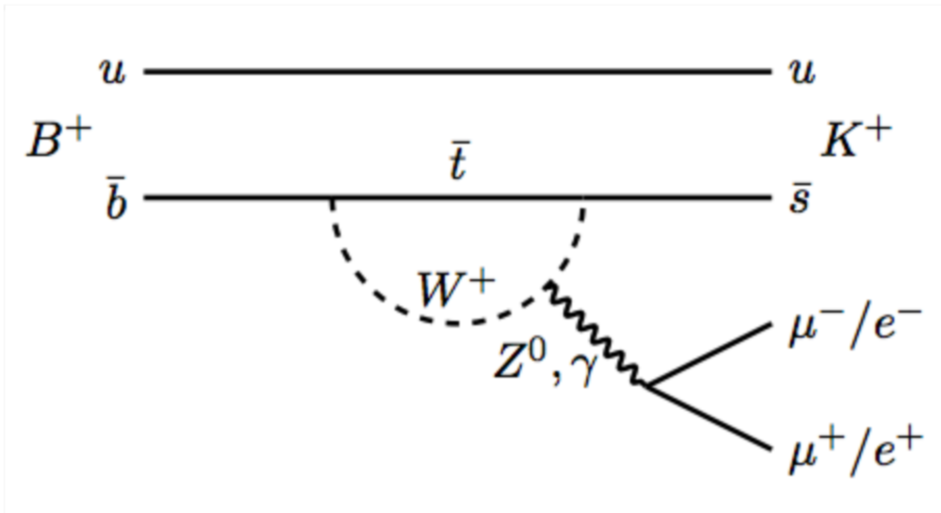


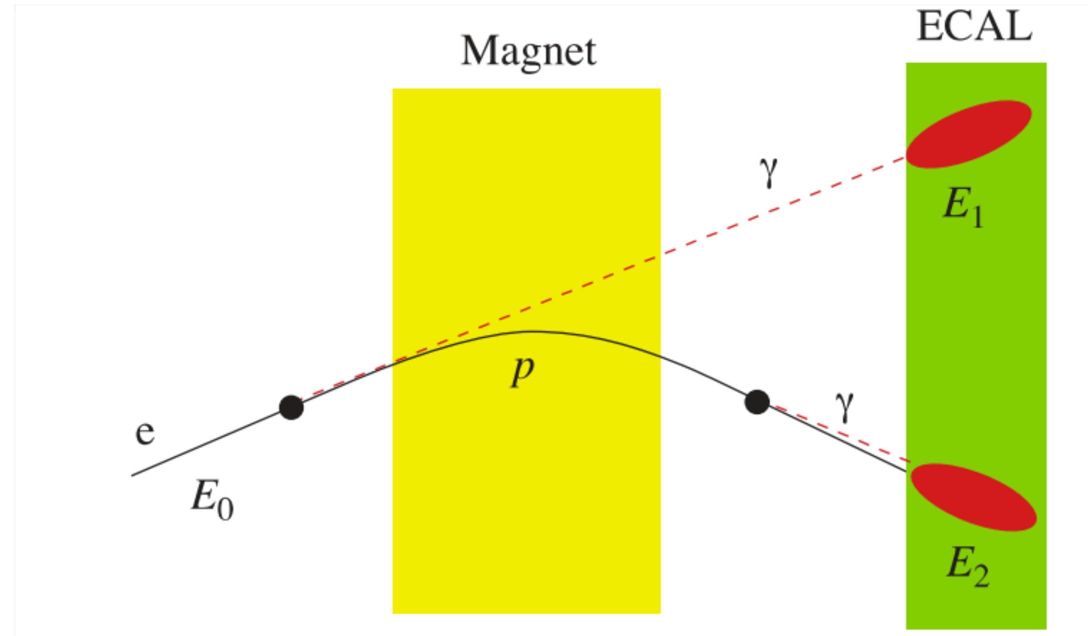
- Used SM predictions for B^0->K*mm with no charm loop
- Taking publish measurements for the resonances
- Assuming the penguin pollution having small effect on the resonances
- Contribution from open charm missing



Lepton Flavour Universality (e/mu)

R_K Anomaly





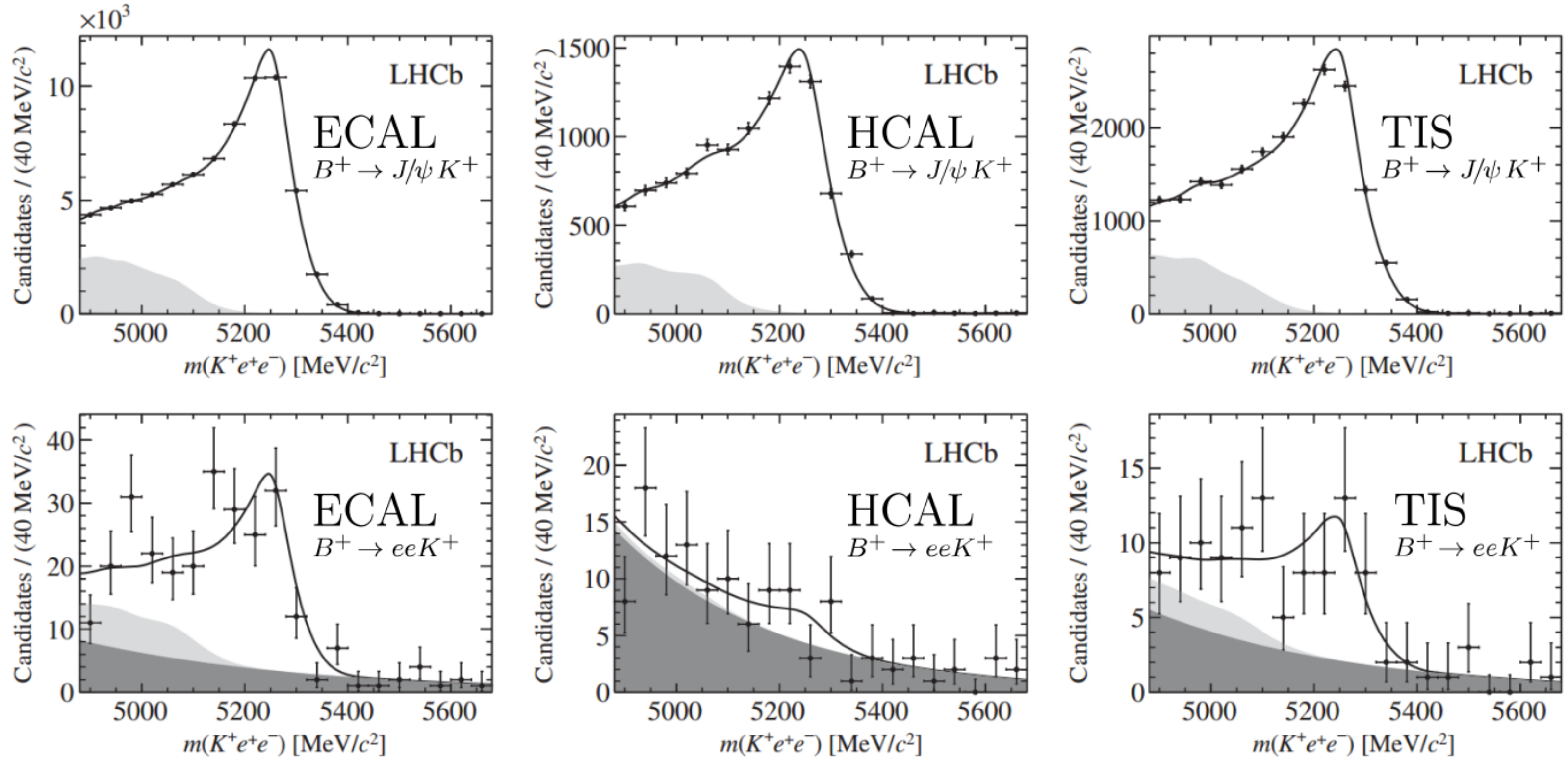
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

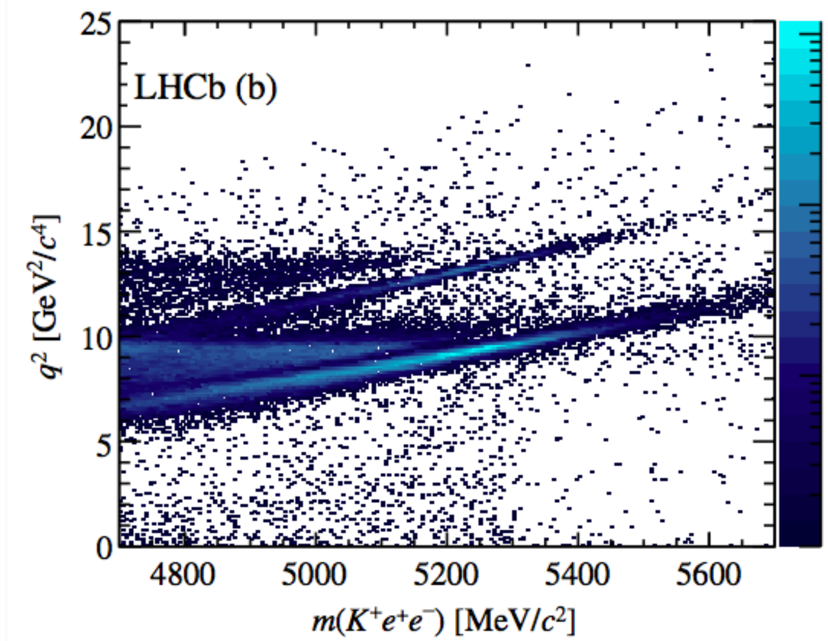
$\boxed{R_K \text{ (SM)} = 1.0003 \pm 0.0001}$ Bobeth et al., JHEP 12 (2007) 040

- Difficult bremsstrahlung recovery affects invariant mass resolution
- More complicate J/psi veto
- Harder trigger, reconstruction, PID

R_K Anomaly

LHCb: PRD 113(2014).151601





- Need to correct for q^2 migration, due to bremsstrahlung
- Total signal yield 264 events

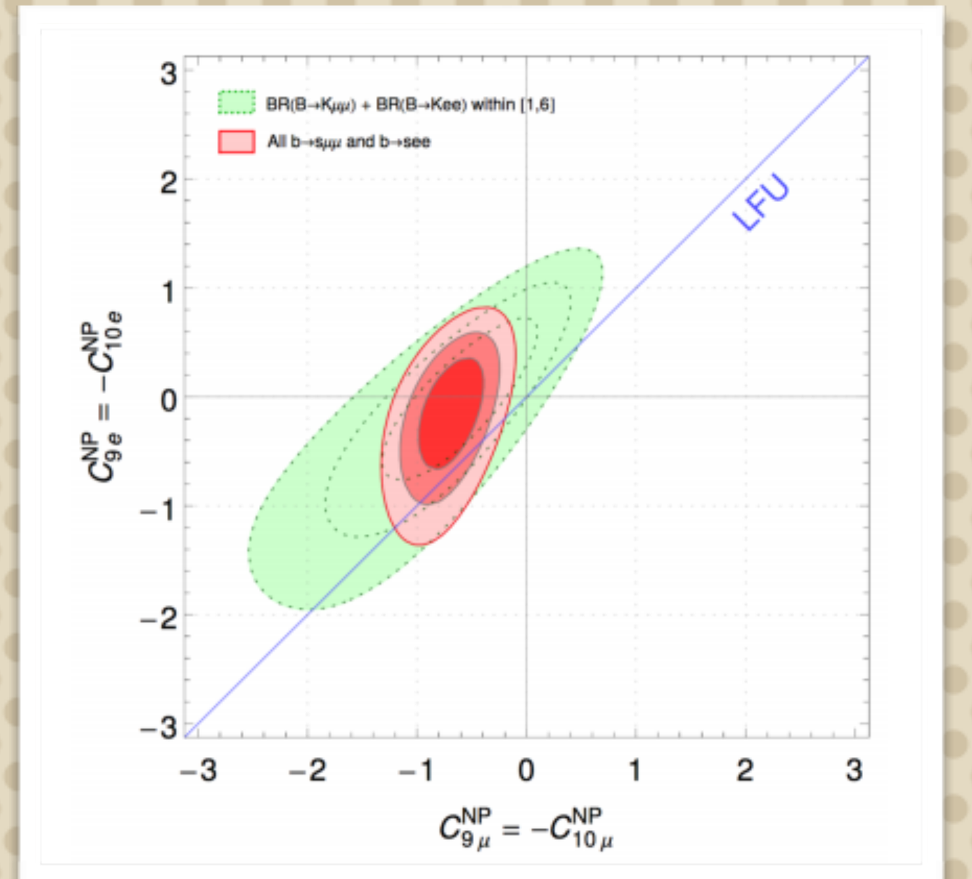
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi\,(\mu^+\mu^-))}\frac{\mathcal{B}(B^+ \to K^+ J/\psi\,(e^+e^-))}{\mathcal{B}(B^+ \to K^+e^+e^-)} =$$

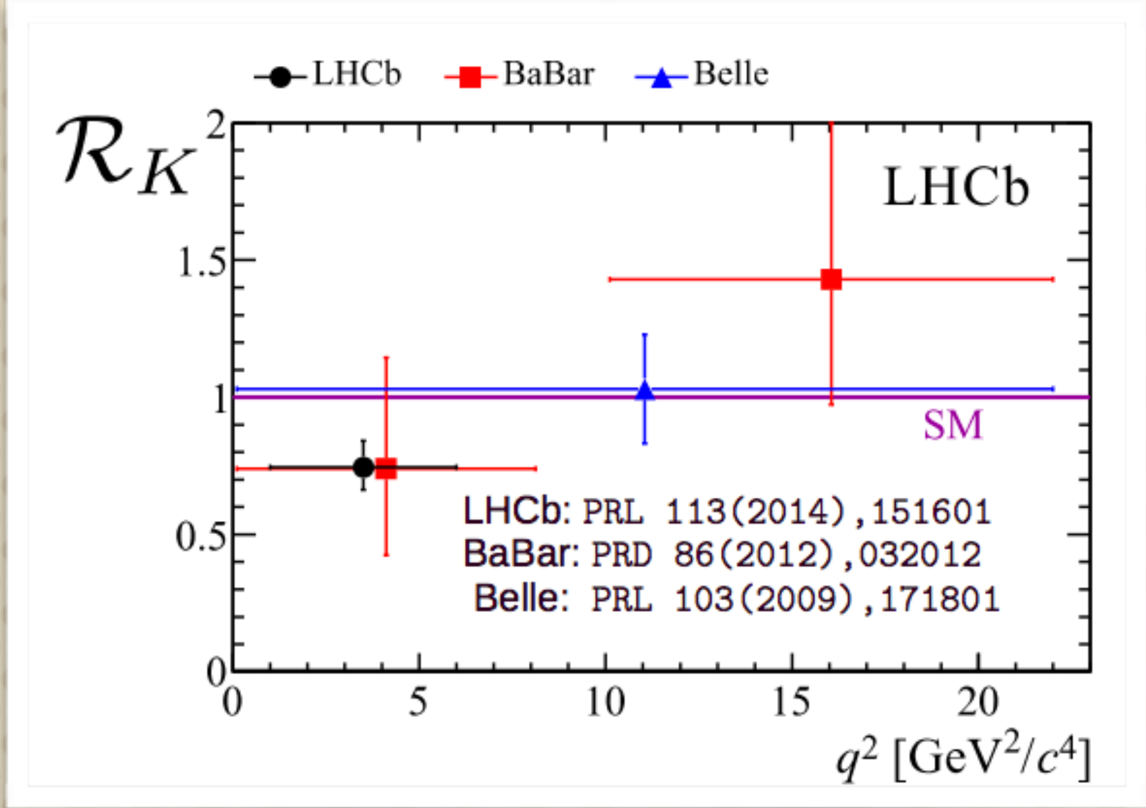
$$= \frac{N_{K^+\mu^+\mu^-}}{N_{K^+J/\psi\,(\mu^+\mu^-)}}\frac{N_{K^+J/\psi\,(e^+e^-)}}{N_{K^+e^+e^-}}\boxed{\frac{\epsilon_{K^+J/\psi\,(\mu^+\mu^-)}}{\epsilon_{K^+\mu^+\mu^-}}}\boxed{\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+J/\psi\,(e^+e^-)}}}$$

$\rightarrow$ cancel systematics

R_K Anomaly

[Descotes-Genon/Hofer/Matias/Virto]





- Intriguing deficit in muon branching ratio compatible with the effect in b->smumu analyses (2.6 sigmas from SM)
- QCD uncertainties cancel out in the ratio
- Still statistically limited... need confirmation

Leptonic B-decays

$$B^0_{(s)} \to \ell^+\ell^-$$

$$BR(B^0_{(q)} \to \ell^+\ell^-) = \frac{\tau_B G_F^4 M_W^2 sin^4\theta_W}{8\pi^5}|C_{10}V_{tb}V_{tq}^*|F_B^2 m_B m_\ell^2 \times \sqrt{1-\frac{4m_\ell^2}{m_B^2}}$$

- These decays can be predicted very cleanly since you have only one known hadronic parameter that is F_B and can be computed by lattice QCD

- In the SM the only operator which contributes is the axial-vector operator (C_{10})

- They have two suppression, one is because it is FCNC and the other is the helicity suppression

Leptonic B-decays

$$\frac{BR(B^0_{(q)} \to \tau^+\tau^-)}{BR(B^0_{(q)} \to \mu^+\mu^-)} \sim \frac{m_\tau^2}{m_\mu^2} \qquad \frac{BR(B^0_{(q)} \to \mu^+\mu^-)}{BR(B^0_{(q)} \to e^+e^-)} \sim \frac{m_\mu^2}{m_e^2}$$

- Because of Lepton Universality, the only difference between the different leptons is the mass
- The decay of taus is about 250 times more abundant than the decays into muons, but it is experimentally challenging because the taus decays before we track it
- LFU holds in the SM but not in general in other NP scenarios

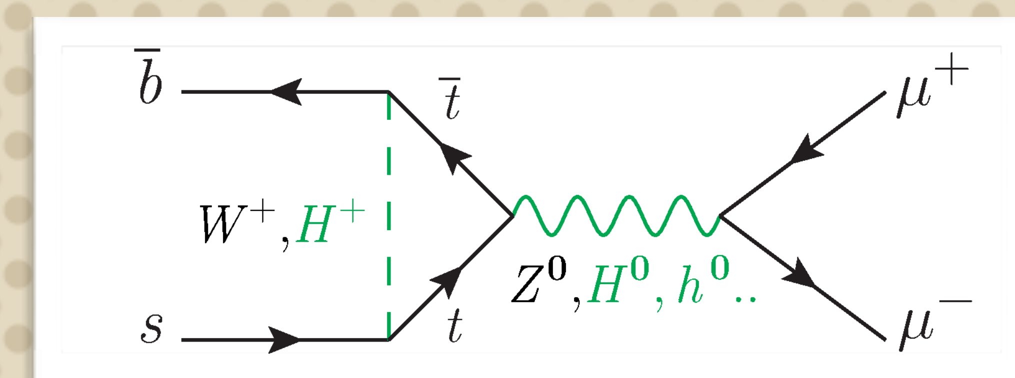
Leptonic B-decays

$$\frac{BR(B^0_{(d)} \to \mu^+\mu^-)}{BR(B^0_{(s)} \to \mu^+\mu^-} = \frac{\tau_{B^0_d}}{\tau_{B^0_s}} \frac{m_{B^0_d}}{m_{B^0_s}} \frac{F_{B^0_d}}{F_{B^0_s}} (\frac{V_{td}}{V_{ts}})^2$$

- The ratio of B_s and B_d decays into leptons depends the ratio of V_{td} and V_{ts}, of B-masses, of B-lifetime and the ratio of the bag parameters

- This is true in all Minimal Flavour Violation theories, so we can test non-MFV models

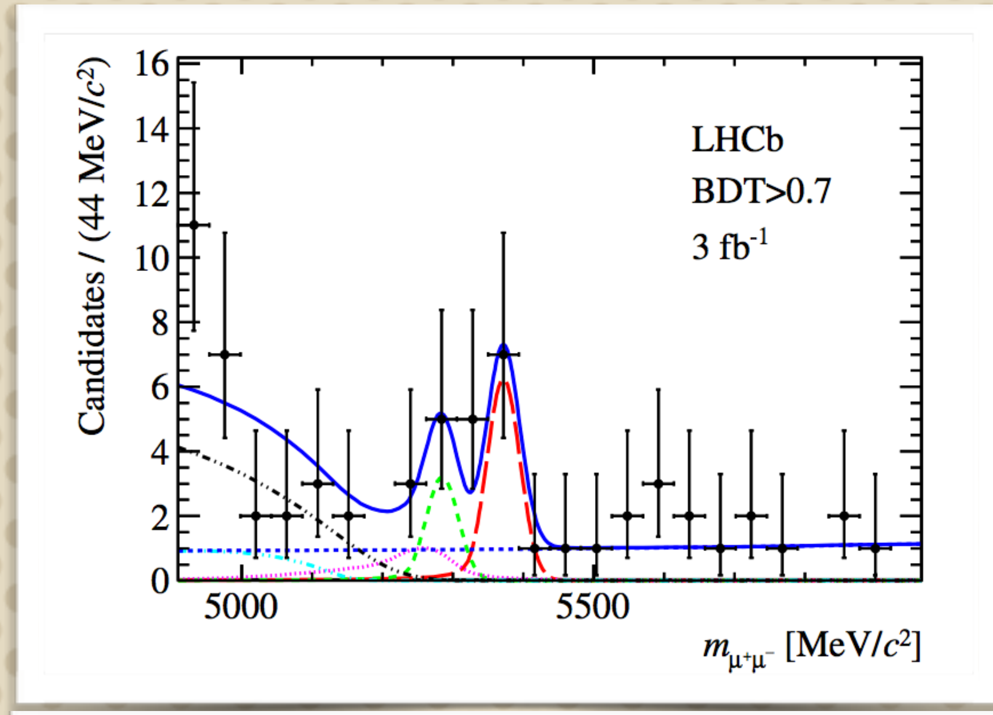
Leptonic B-decays

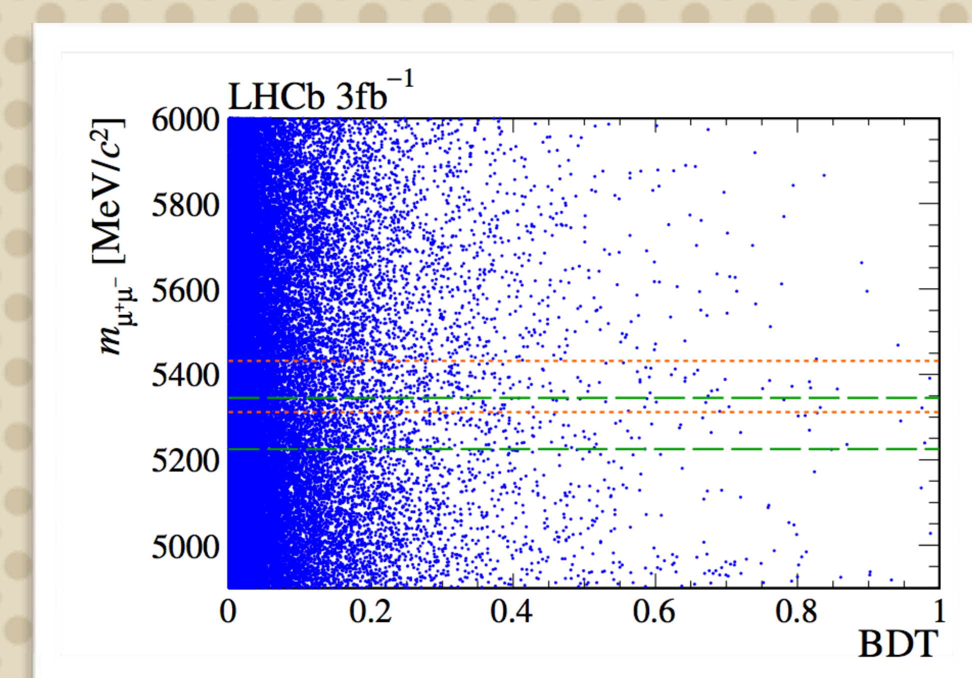


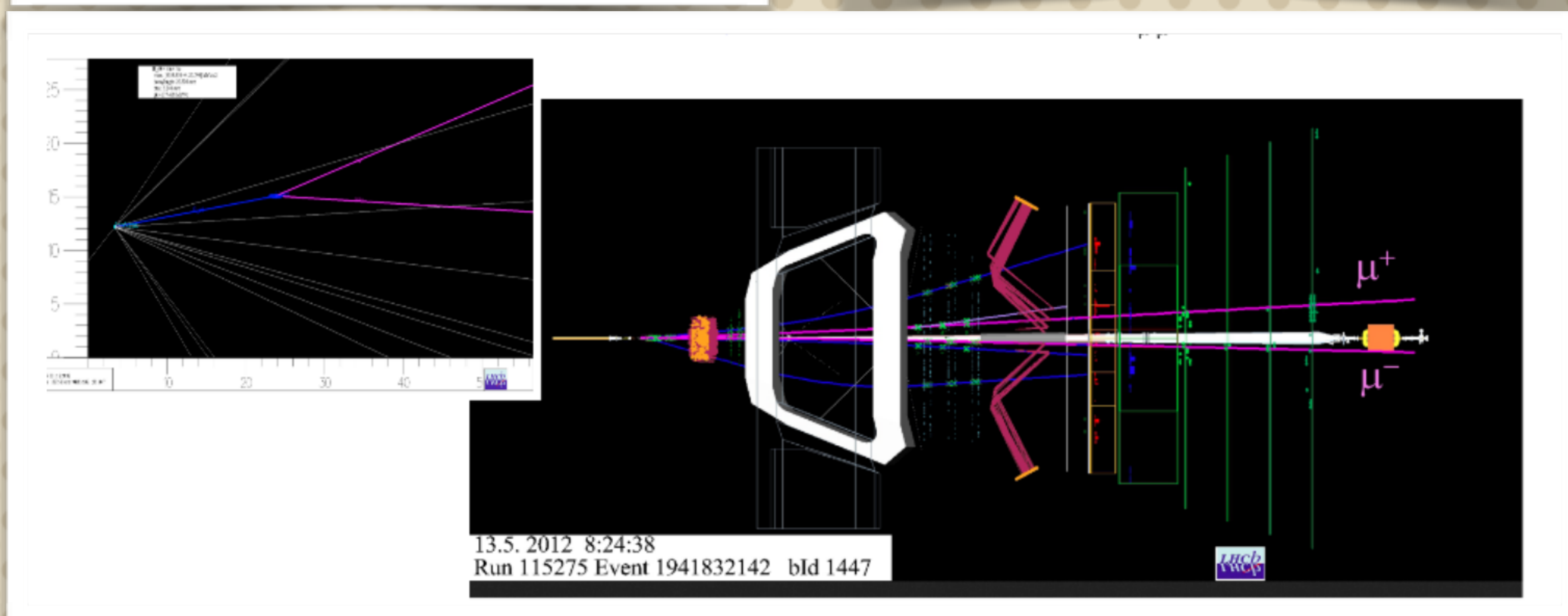
$$BR(B_s^0 \to \mu^+\mu^-) \propto (1 - \frac{4m_\ell^2}{m_B^2})|C_S - C_S'|^2 + |(C_P - C_P')^2 + 2\frac{m_\ell^2}{m_B^2}(C_{10} - C_{10}')|^2$$

- In general NP theories the operators that contribute are $O_{10}^{(')}$, $C_s^{(')}$ and $C_P^{(')}$
- Models with an extended Higgs or in general (psudo)-scalar contributions, since they do not have an helicity suppression

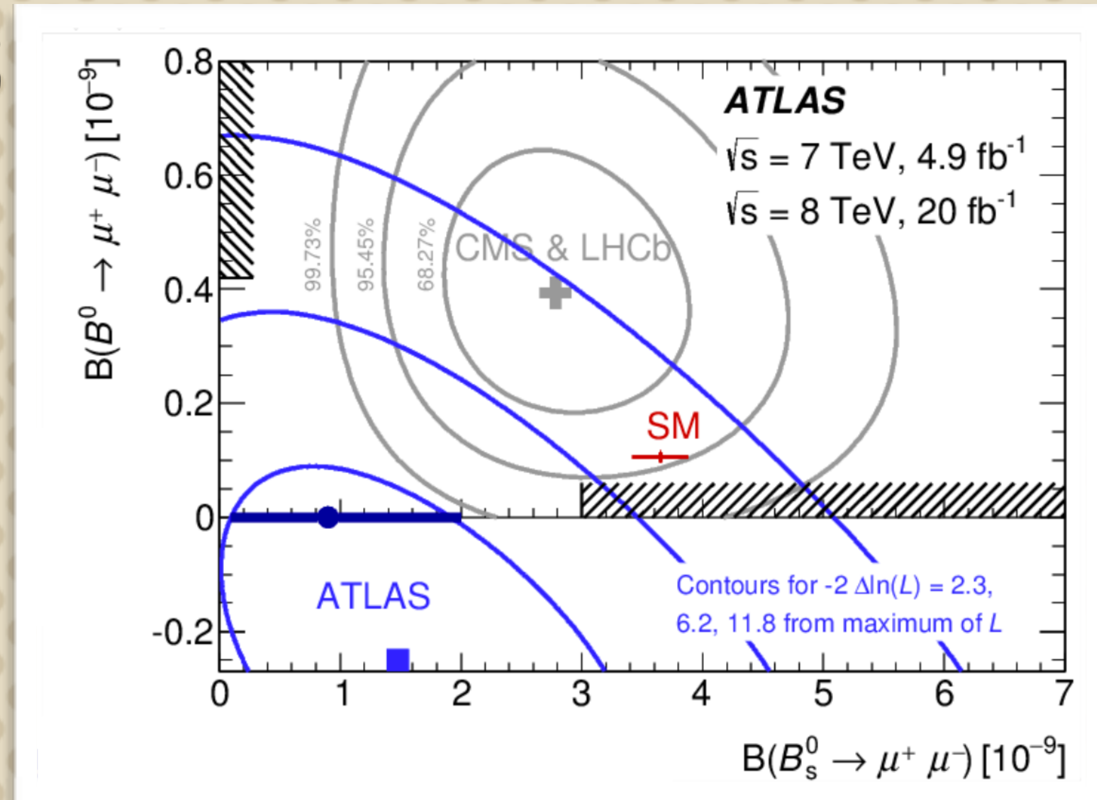
Measurements at LHCb

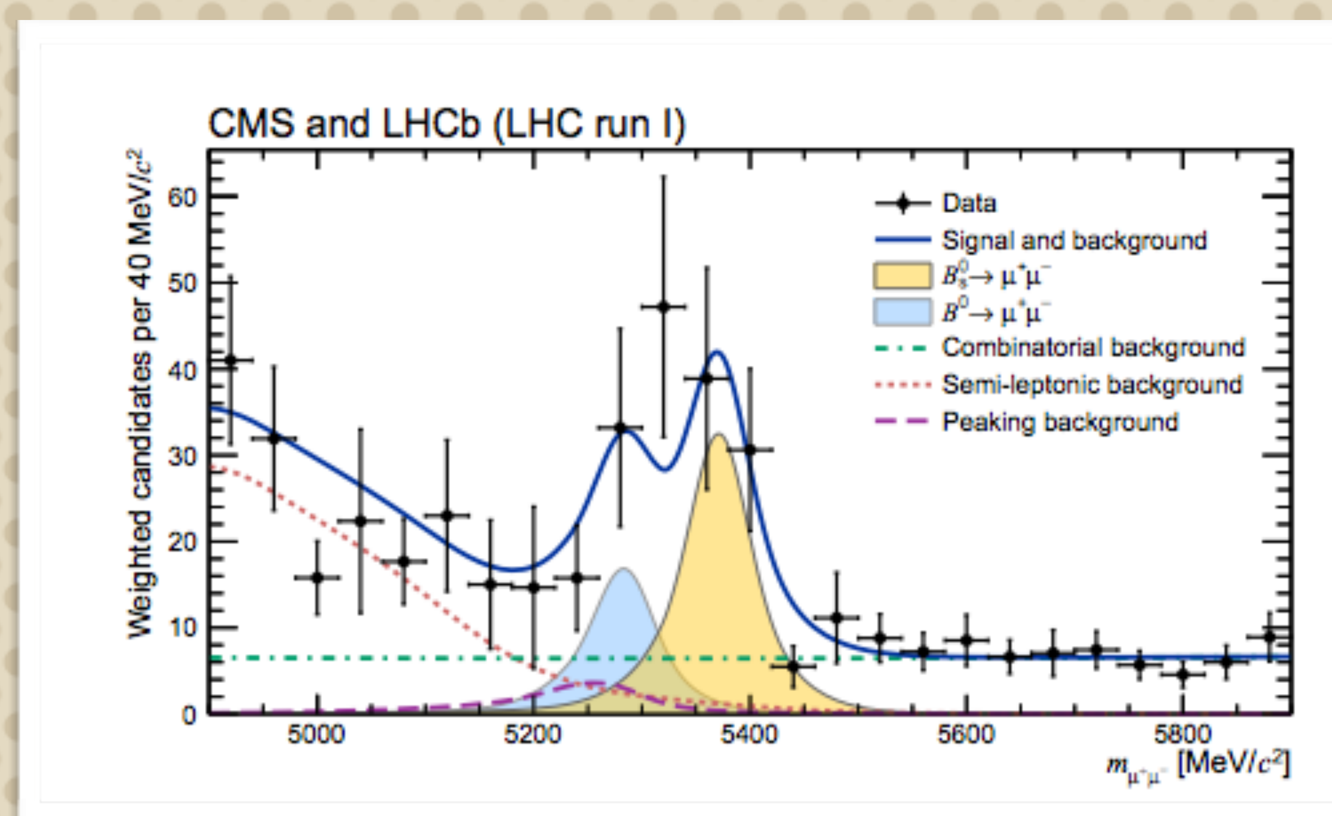






B->mm branching ratio





CMS + LHCb

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

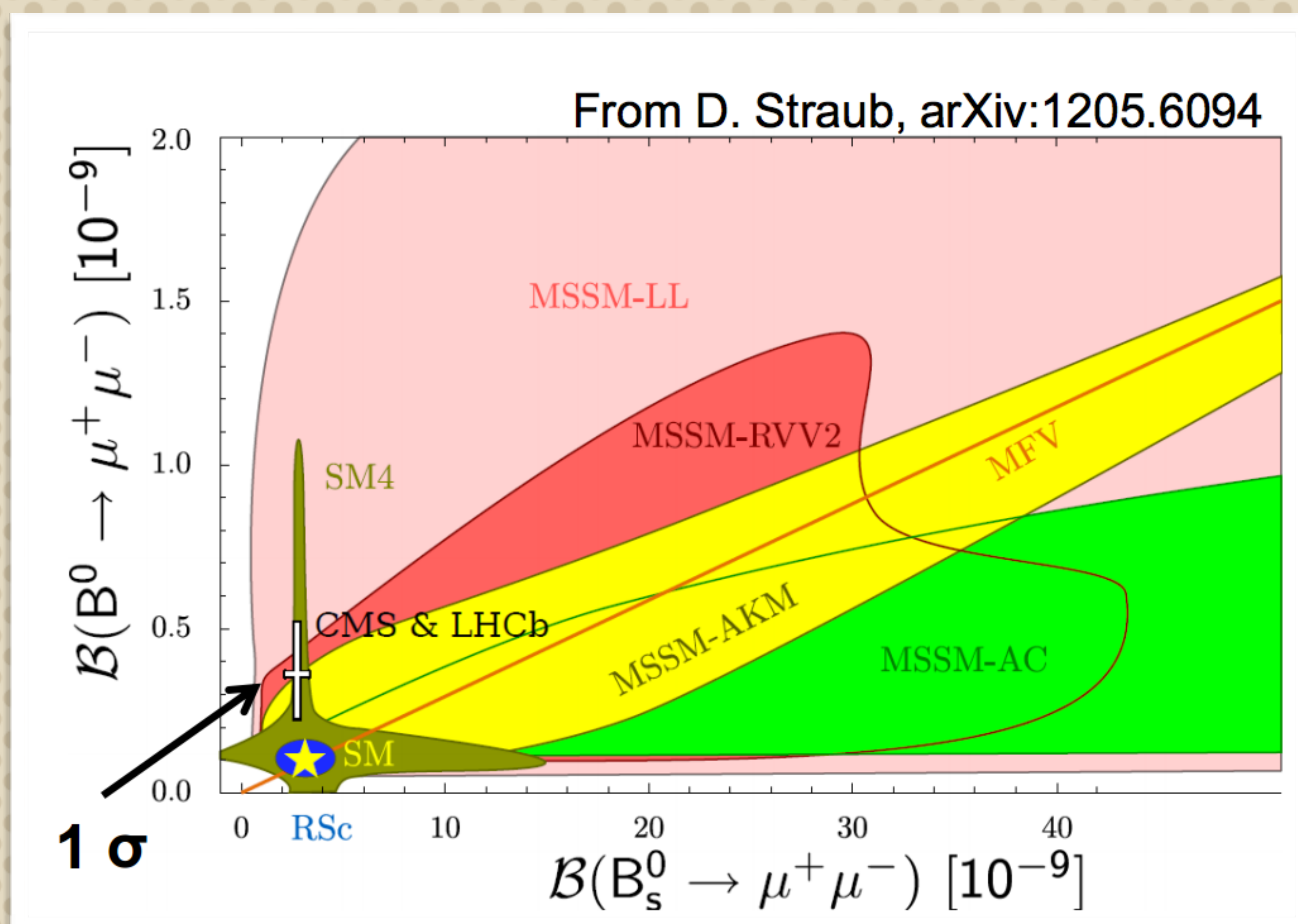
ATLAS

$$B(B^0{}_s \to \mu^+\mu^-) = 0.9\,^{+1.1}_{-0.8} \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \text{ at 95\% CL}$$

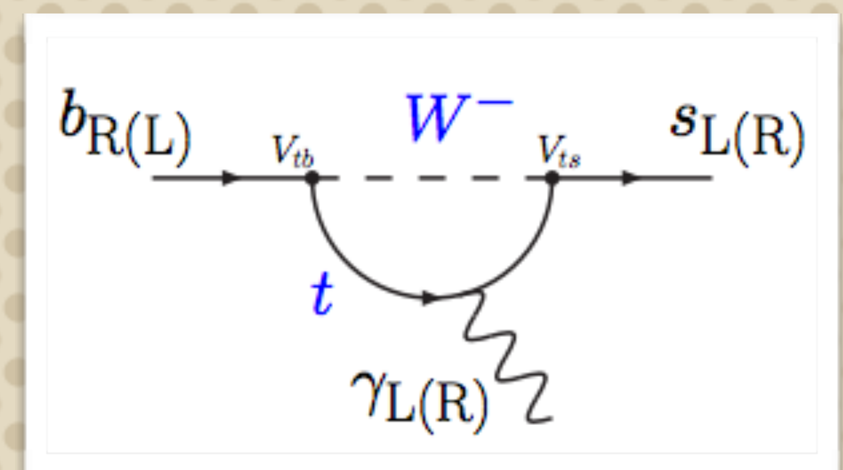
- If there is NP in C_{10} this will have to be confirmed in Bs->mm

Measurements at LHC

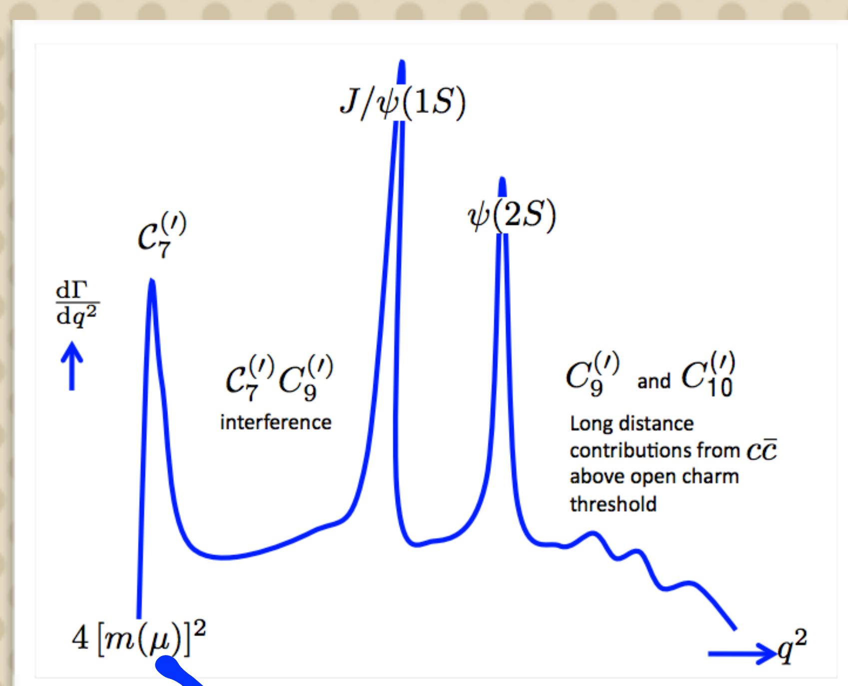


Radiative decays

Photon polarisation



- $B^+ \to K^+\pi^-\pi^+\gamma$
- $B^0 \to K^{*0}e^+e^-$
- $B_s \to \phi\gamma$
- b-baryons: $\Lambda_b \to \Lambda\gamma$, $\Xi_b \to \Xi\,\gamma$, $\Omega_b \to \Omega\gamma$



Results with 1fb^{-1}

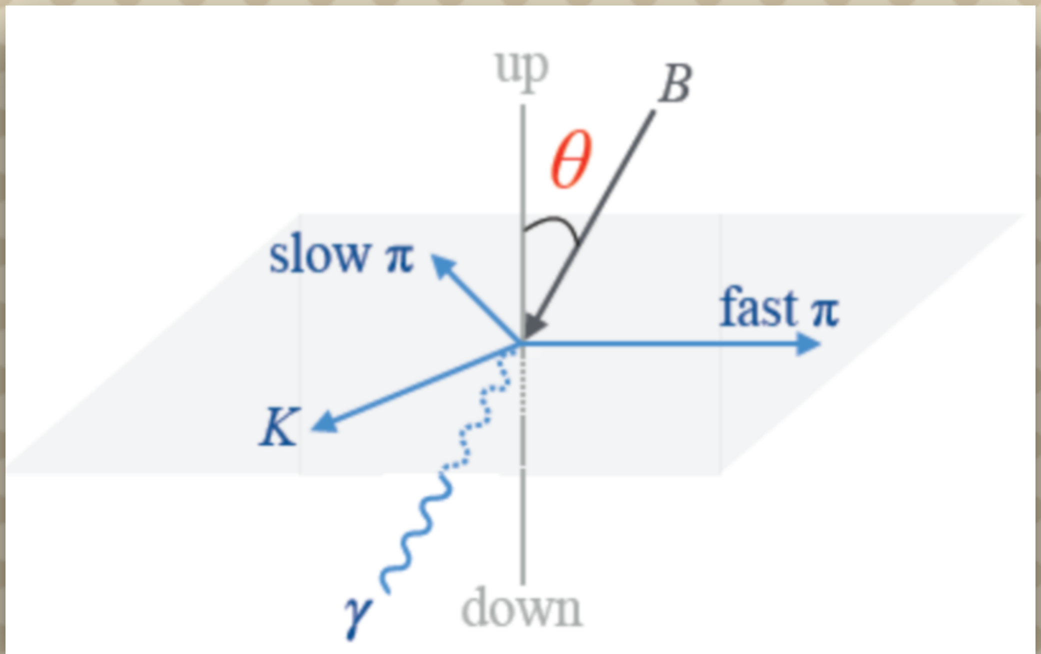
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d)$$

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\gamma) = (0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.}))\%.$$

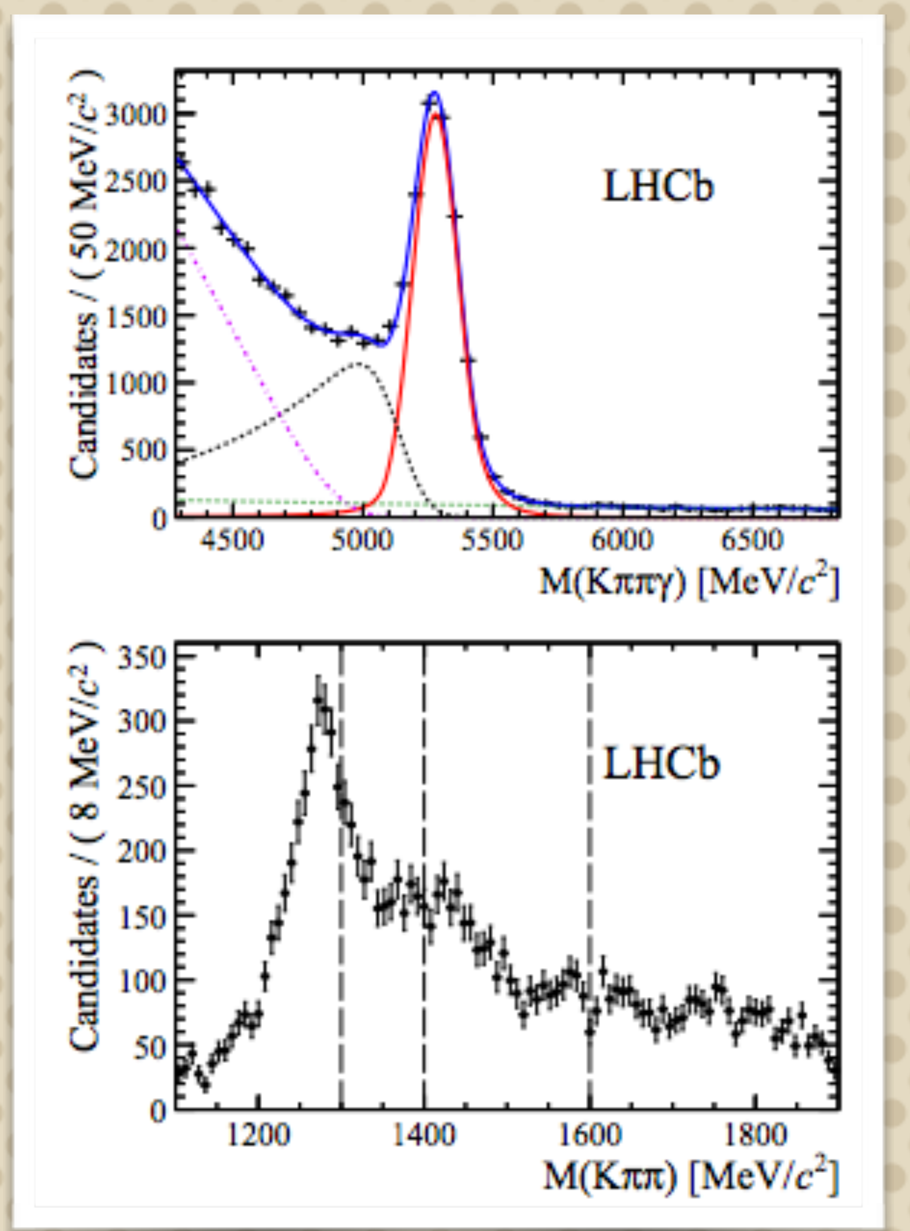
$\rightsquigarrow$ In the SM, photons from $b \to s\gamma$ decays are predominantly left-handed ($C_7/C_7' \sim m_b/m_s$) due to the charged-current interaction.

very low q^2 sensitive to photon polarization

Photon polarisation

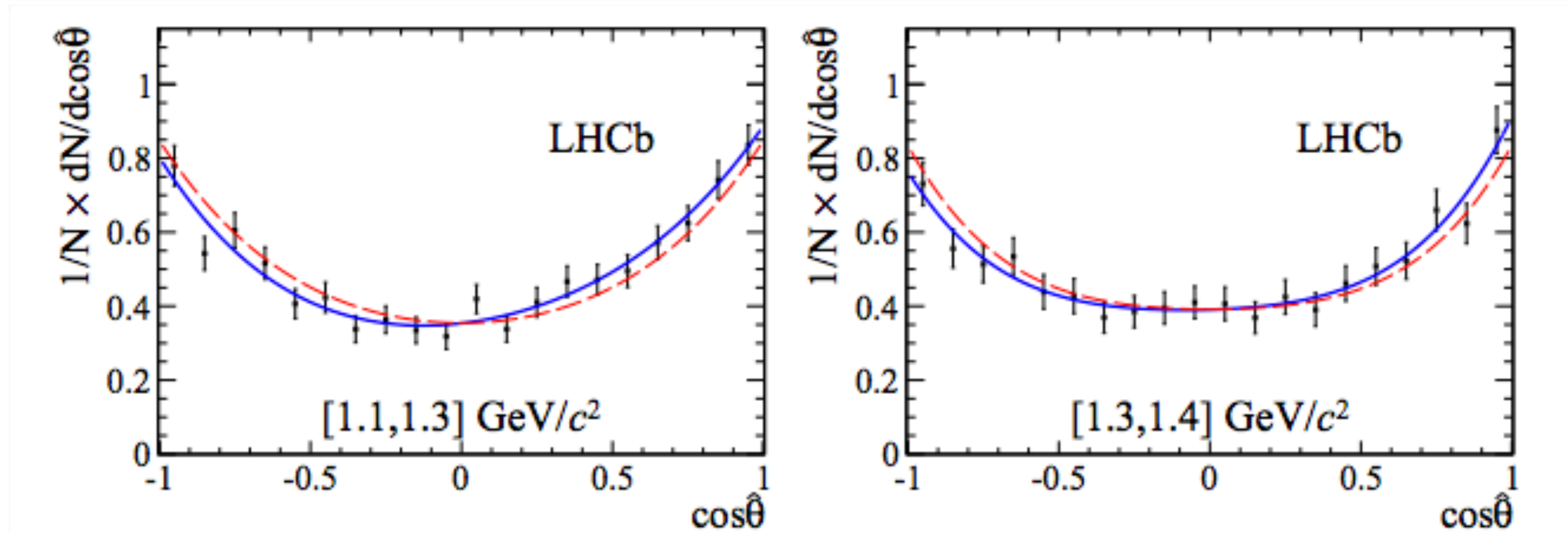


- Can infer the photon polarisation from the up-down asymmetry of the photon direction in the $K^+\pi^-\pi^+$ rest-frame. Unpolarised photons would have no asymmetry.
- This is conceptionally similar to the Wu experiment, which first observed parity violation.



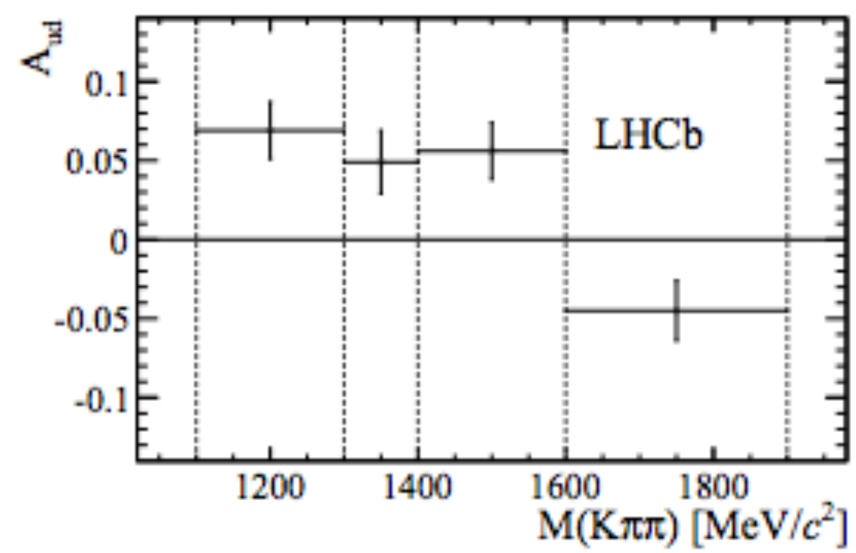
$$\mathcal{A}_{up/down} = \frac{\int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta}{\int_{-1}^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta} \propto \lambda_\gamma$$

Photon polarisation



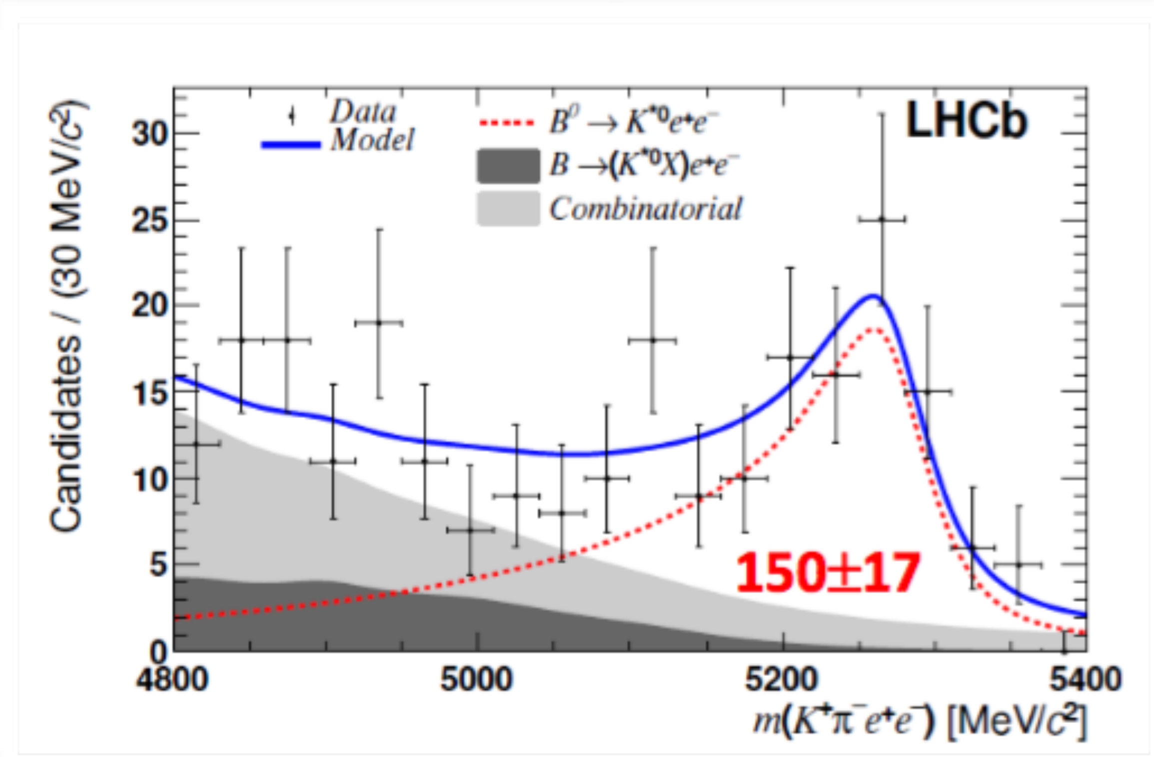
[PRL 112, 161801 (2014)]

- Combining the 4 bins, the photon is observed to be polarised at 5.2σ.
- Unfortunately you need to understand the hadronic system to know if the polarisation is left-handed, as expected in the SM.



→ First observation of photon polarisation in $b \to s\gamma$ decays

Photon polarisation



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\tilde{\phi}} =$$

$$\frac{9}{16\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \left(\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\right)\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} + (1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Re}}\sin^2\theta_K\cos\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{\mathrm{Im}}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big]$$

$$\boxed{\mathrm{A}_{\mathrm{T}}^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e(\mathcal{C}_7\mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}}$$

$$\boxed{\mathrm{A}_{\mathrm{T}}^{\mathrm{Im}}(q^2\to 0) = \frac{2\mathcal{I}m(\mathcal{C}_7\mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}}$$

access to the photon polarization information

[D. Becirevic and E. Schneider Nucl. Phys. B 854 (2012) 321]

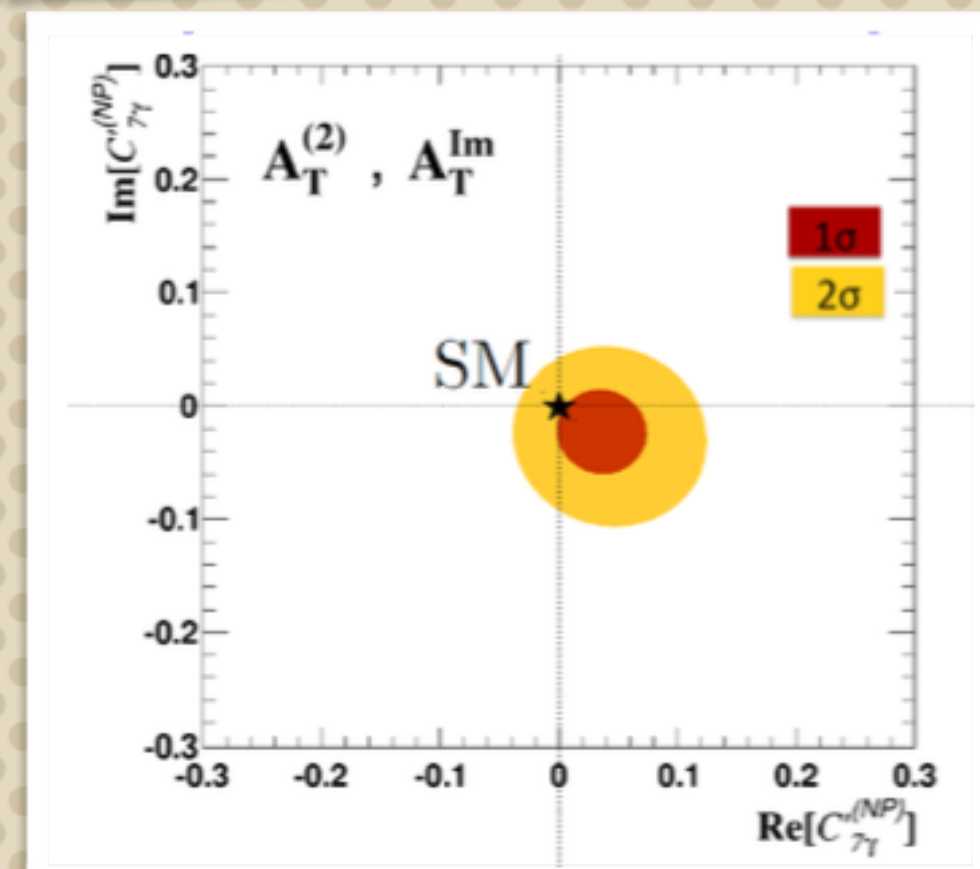
Photon polarisation

Results:

$$\begin{aligned} F_{\rm L} &= 0.16 \pm 0.06 \pm 0.03 \\ \mathrm{A}_{\rm T}^{\rm Re} &= +0.10 \pm 0.18 \pm 0.05 \\ \mathrm{A}_{\rm T}^{(2)} &= -0.23 \pm 0.23 \pm 0.05 \\ \mathrm{A}_{\rm T}^{\rm Im} &= +0.14 \pm 0.22 \pm 0.05 \end{aligned}$$

SM predictions:

$$\begin{aligned} F_{\rm L} &= 0.10^{+0.11}_{-0.05} \\ \mathrm{A}_{\rm T}^{\rm Re} &= -0.15^{+0.04}_{-0.03} \\ \mathrm{A}_{\rm T}^{(2)} &= +0.03^{+0.05}_{-0.04} \\ \mathrm{A}_{\rm T}^{\rm Im} &= (-0.2^{+1.2}_{-1.2}) \times 10^{-4} \end{aligned}$$



- Compatible with SM predictions
- Best sensitivity to C7' up to date

Inclusive

$$\mathcal{B}(B \to X_s\gamma)|_{E_\gamma>1.6\ \mathrm{GeV}} = (3.43 \pm 0.22) \times 10^{-4}$$

Measurement by CLEO, BELLE and BaBar

$$\mathcal{B}(\bar{B} \to X_s\gamma)|_{E_\gamma>1.6\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$

NLLO predictions

- Radiative decays allow to probe the operator O_7 and O_7'

- Inclusive decays are cleaner from experimental point of view, but are more difficult experimentally

- The sum of O_7 and O_7' is constrained from the b—>s gamma measurement, but to probe O_7 and O_7' separately need to an angular analysis (probing the photon polarization)

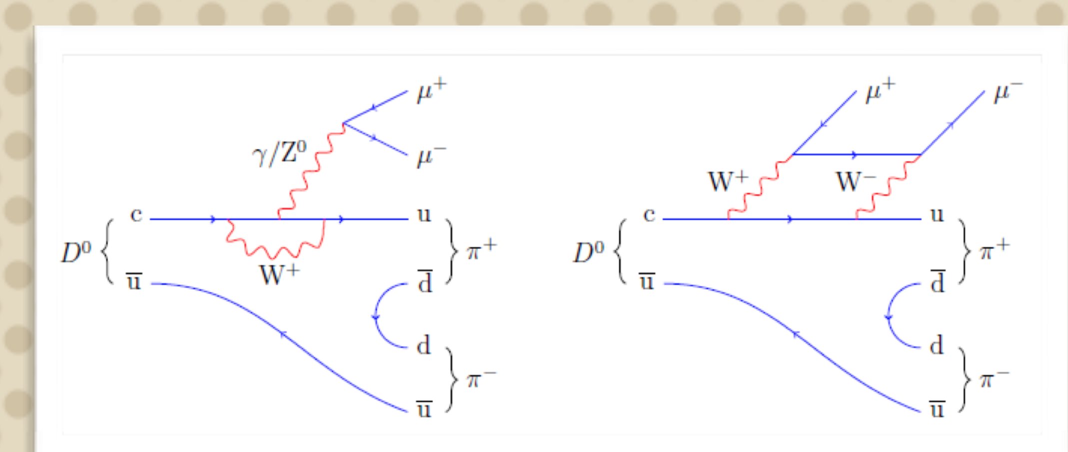
Other rare decays

Rare D-decays

FCNC in D-meson decays are more suppressed than in B-mesons

Γ_{235}	$D^0 \to \gamma\gamma$	$<2.2 \times 10^{-6}$	CL=90%	932
Γ_{236}	$D^0 \to e^+e^-$	$<7.9 \times 10^{-8}$	CL=90%	932
Γ_{237}	$D^0 \to \mu^+\mu^-$	$<1.4 \times 10^{-7}$	CL=90%	926
Γ_{238}	$D^0 \to \pi^0 e^+e^-$	$<4.5 \times 10^{-5}$	CL=90%	928
Γ_{239}	$D^0 \to \pi^0 \mu^+\mu^-$	$<1.8 \times 10^{-4}$	CL=90%	915
Γ_{240}	$D^0 \to \eta e^+e^-$	$<1.1 \times 10^{-4}$	CL=90%	852
Γ_{241}	$D^0 \to \eta \mu^+\mu^-$	$<5.3 \times 10^{-4}$	CL=90%	838
Γ_{242}	$D^0 \to \pi^+\pi^- e^+e^-$	$<3.73 \times 10^{-4}$	CL=90%	922
Γ_{243}	$D^0 \to \rho^0 e^+e^-$	$<1.0 \times 10^{-4}$	CL=90%	771
Γ_{244}	$D^0 \to \pi^+\pi^- \mu^+\mu^-$	$<3.0 \times 10^{-5}$	CL=90%	894
Γ_{245}	$D^0 \to \rho^0 \mu^+\mu^-$	$<2.2 \times 10^{-5}$	CL=90%	754
Γ_{246}	$D^0 \to \omega e^+e^-$	$<1.8 \times 10^{-4}$	CL=90%	768
Γ_{247}	$D^0 \to \omega \mu^+\mu^-$	$<8.3 \times 10^{-4}$	CL=90%	751
Γ_{248}	$D^0 \to K^-K^+e^+e^-$	$<3.15 \times 10^{-4}$	CL=90%	791
Γ_{249}	$D^0 \to \phi e^+e^-$	$<5.2 \times 10^{-5}$	CL=90%	654
Γ_{250}	$D^0 \to K^-K^+\mu^+\mu^-$	$<3.3 \times 10^{-5}$	CL=90%	710
Γ_{251}	$D^0 \to \phi \mu^+\mu^-$	$<3.1 \times 10^{-5}$	CL=90%	631
Γ_{252}	$D^0 \to \overline{K}^0 e^+e^-$	$<1.1 \times 10^{-4}$	CL=90%	866
Γ_{253}	$D^0 \to \overline{K}^0 \mu^+\mu^-$	$<2.6 \times 10^{-4}$	CL=90%	852
Γ_{254}	$D^0 \to K^-\pi^+e^+e^-$	$<3.85 \times 10^{-4}$	CL=90%	861

Predictions:



SM prediction for the BR ~10^{-9}

Rare K-decays

Γ_{23}	$K(\mathrm{L})0 \to \mu^+\mu^-$	$(6.84 \pm 0.11) \times 10^{-9}$		225
Γ_{24}	$K(\mathrm{L})0 \to e^+e^-$	$(9\ ^{+6}_{-4}) \times 10^{-12}$		249
Γ_{25}	$K(\mathrm{L})0 \to \pi^+\pi^-e^+e^-$	$(3.11 \pm 0.19) \times 10^{-7}$		206

Γ_{11}	$K(\mathrm{S})0 \to \mu^+\mu^-$	$<9 \times 10^{-9}$	CL=90%	225
Γ_{12}	$K(\mathrm{S})0 \to e^+e^-$	$<9 \times 10^{-9}$	CL=90%	249

Γ_{13}	$K(\mathrm{S})0 \to \pi^0e^+e^-$	$(3.0\ ^{+1.5}_{-1.2}) \times 10^{-9}$		230
Γ_{14}	$K(\mathrm{S})0 \to \pi^0\mu^+\mu^-$	$(2.9\ ^{+1.5}_{-1.2}) \times 10^{-9}$		177

Γ_{36}	$K^+ \to \pi^+e^+e^-$	$(3.00 \pm 0.09) \times 10^{-7}$		227
Γ_{37}	$K^+ \to \pi^+\mu^+\mu^-$	$(9.4 \pm 0.6) \times 10^{-8}$	S=2.6	172
Γ_{38}	$K^+ \to \pi^+\nu\bar{\nu}$	$(1.7 \pm 1.1) \times 10^{-10}$		227

Still more precision might give us surprises (e.g. NA62 experiment)

Conclusions and outlook

Conclusions

- Indirect searches allow to probe very high energy scales, much higher than those reachable at central colliders

- Study of b-hadrons strongly constraint BSM and test the CKM paradigm (which seems to hold... but room for NP is still left —> more precision)

- There are some intriguing discrepancies in B-physics: test of lepton universality in semileptonic and B-decays and b—>sll transitions —> more statistics, better theory understanding

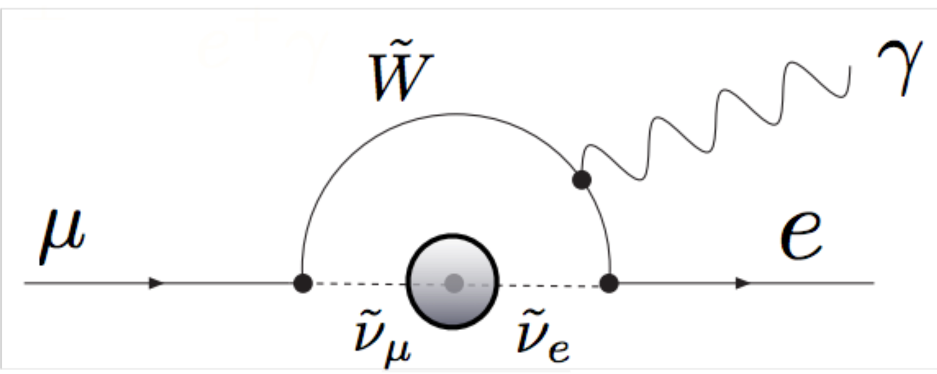
- In the next few years we will know if these discrepancies wrt SM predictions are genuine sign of NP

Backup slides

Searches for LFV decays

LFV due to neutrino oscillations

Neutrino masses induce LFV at loop level, e.g. mu—>e gamma



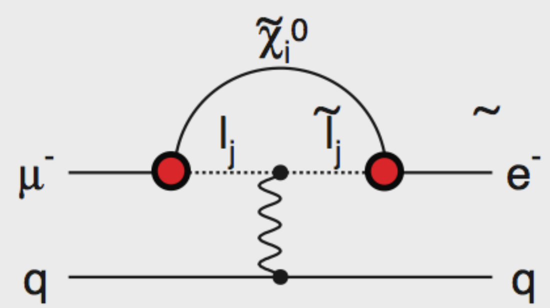
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

Because their standard-model branching ratios are far too tiny for possible detection, observation of any mode would be certain evidence of new physics. That's what makes such sensitive searches potentially transformative. *S.L. Glashow*

Mu—> e transitions

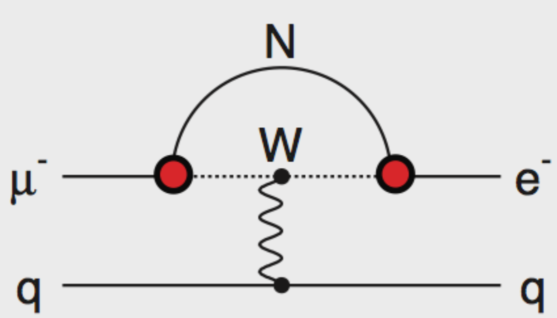
Supersymmetry

rate ~ 10^{-15}



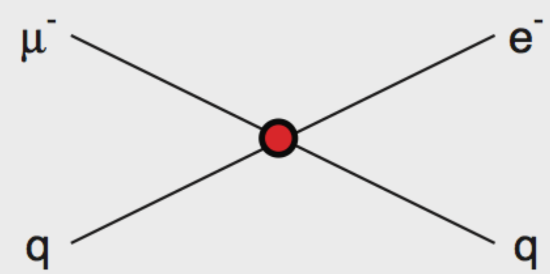
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\mathrm{x}10^{-13}$



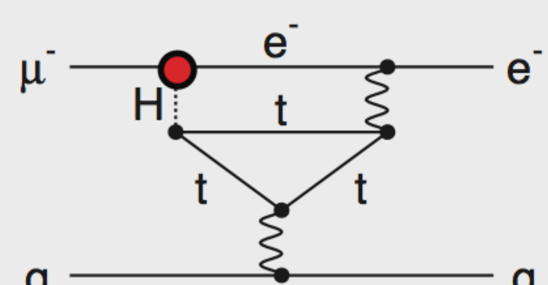
Compositeness

$\Lambda_c \sim 3000$ TeV



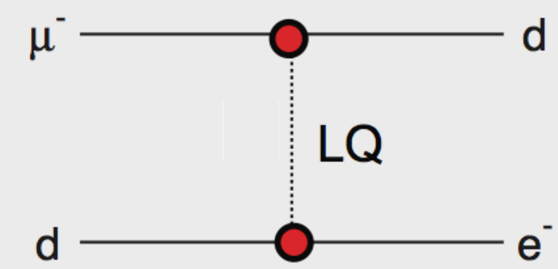
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



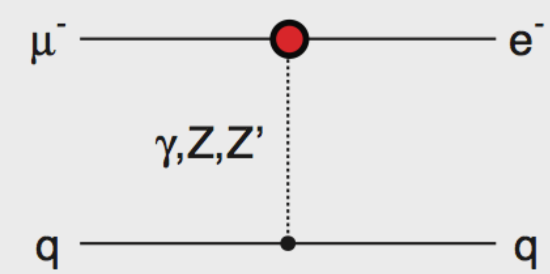
Leptoquark

$M_{LQ} =$
$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



Heavy Z’
Anomal. Z Coupling

$M_{Z'} = 3000$ TeV/c^2

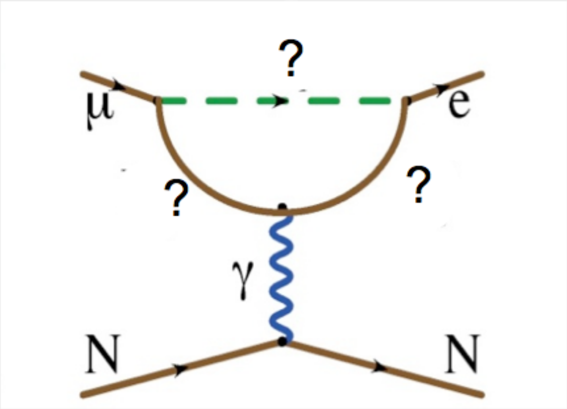


see arXiv:0801.1826

Model in dependent transition

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

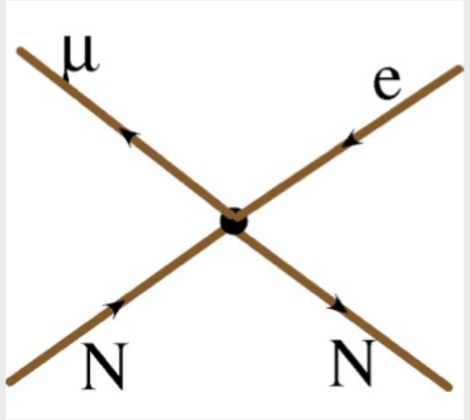
"Loops"



κ

Supersymmetry and Heavy Neutrinos

"Contact Terms"



Λ

Exchange of a new, massive particle

Contrinbute to $\mu \to e\gamma$	does not contrinbute to $\mu \to e\gamma$

m—>e gamma

- Signal: $N_{sig} = R_\mu \times \mathcal{B}(\mu \to e\gamma)$
- Physic Bkg: $N_{RD} \propto R_\mu \times \mathcal{B}(\mu \to e\gamma 2\nu)$
- Accidental Bkg: $N_{Acc} \propto R_\mu^2 \times (\Delta\Theta)^2 \times (\Delta E_\gamma)^2 \times \Delta T \times \Delta E$

Signal

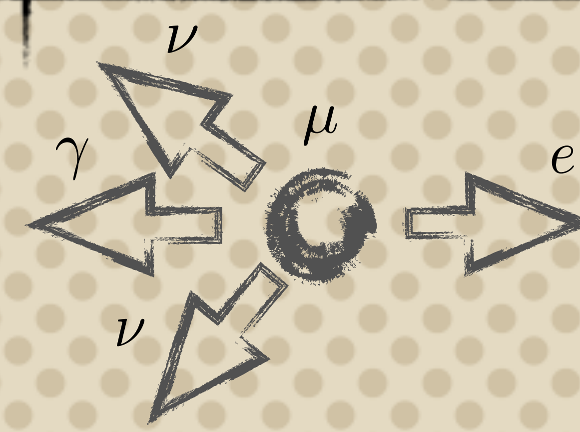
$\mu^+ \to e^+\gamma$

- $E_\gamma = E_e = 52.8 MeV$
- $\Theta_{e\gamma} = \pi$
- $T_\gamma = T_e$

Background

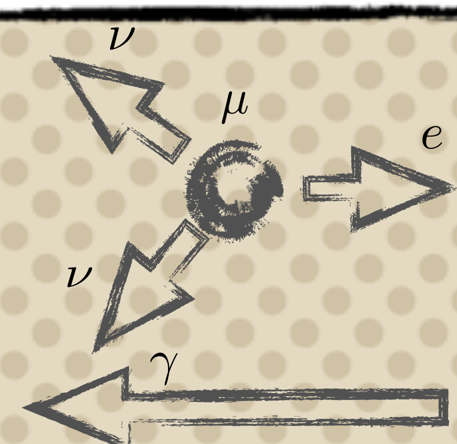
$\mu^+ \to e^+\overline{\nu}_\mu \nu_e \gamma$

Physical



$\mu^+ \to e^+\overline{\nu}_\mu \nu_e + \gamma$

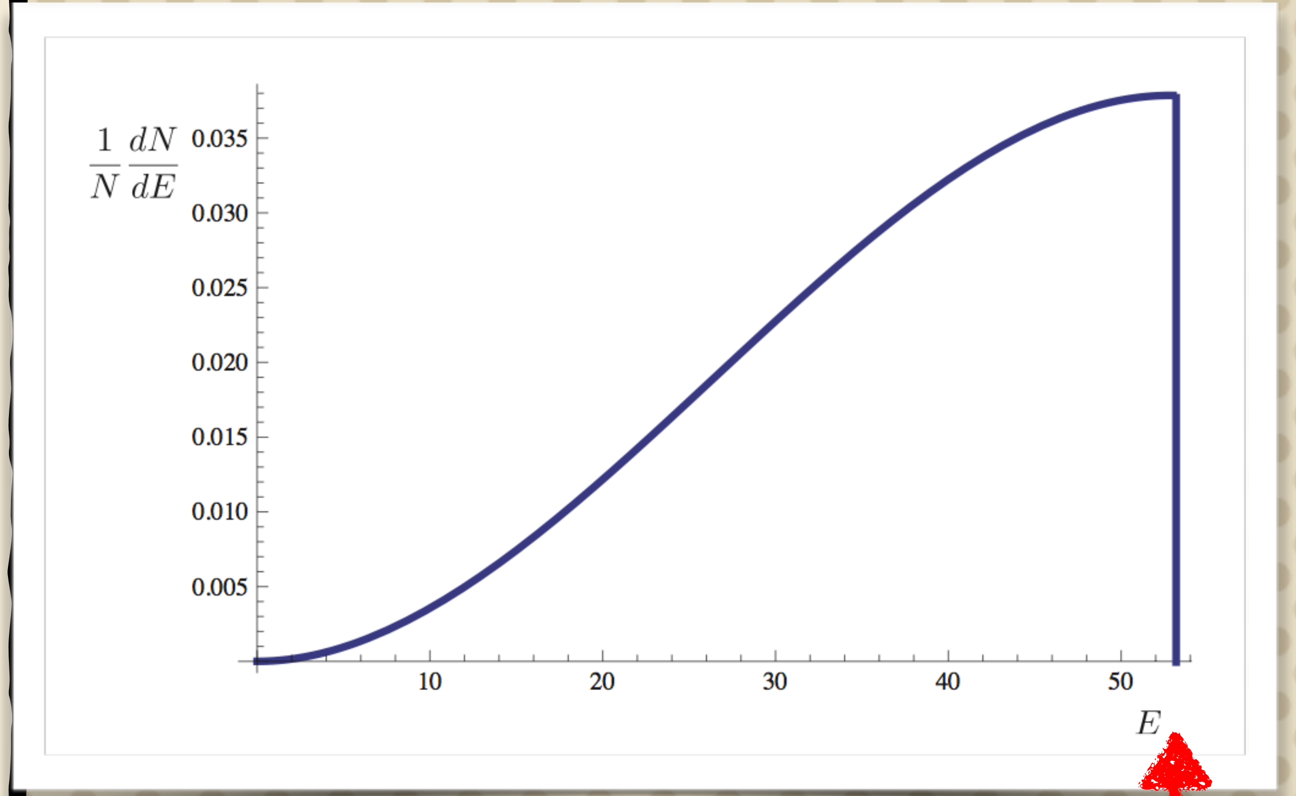
Accidental



Signal and background

- Signal: $N_{sig} = R_\mu \times \mathcal{B}(\mu \to e\gamma)$
- Physic Bkg: $N_{RD} \propto R_\mu \times \mathcal{B}(\mu \to e\gamma 2\nu)$
- Accidental Bkg: $N_{Acc} \propto R_\mu^2 \times (\Delta\Theta)^2 \times (\Delta E_\gamma)^2 \times \Delta T \times \Delta E$

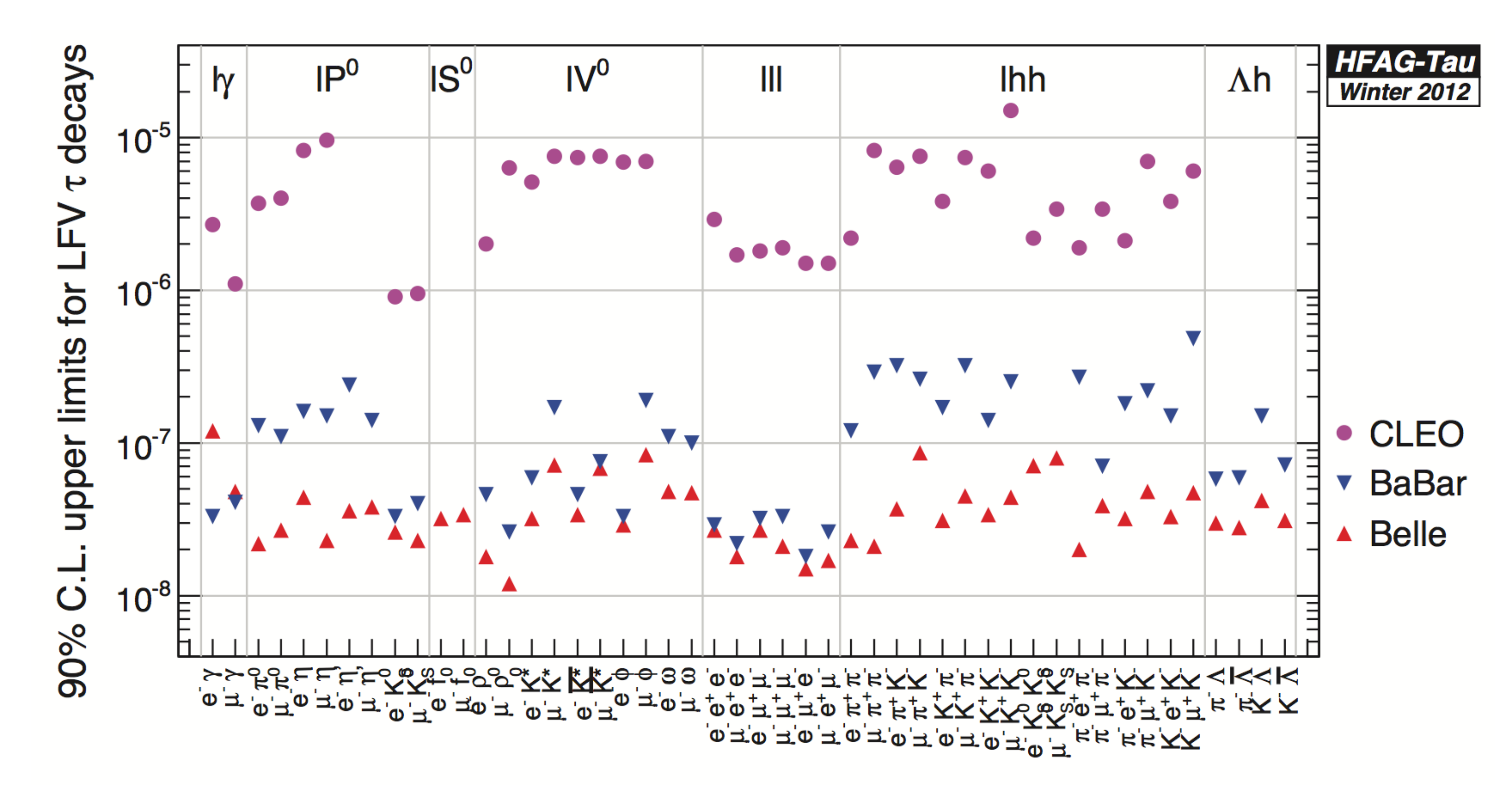
Michel spectrum



Signal region

Tau LFV decays

In general one expects τ LFV more sensitive to NP
e.g. $\tau \to 3\mu$ predicted at the level of 10^{-8} in some NP scenarios



LHCb limit with 1fb^{-1} $\mathcal{B}(\tau \to 3\mu) < 6.3 \times 10^{-8}$ @90% C.L.

World's best limit set by BELLE ($< 2.1 \times 10^{-8}$ at 95% CL)

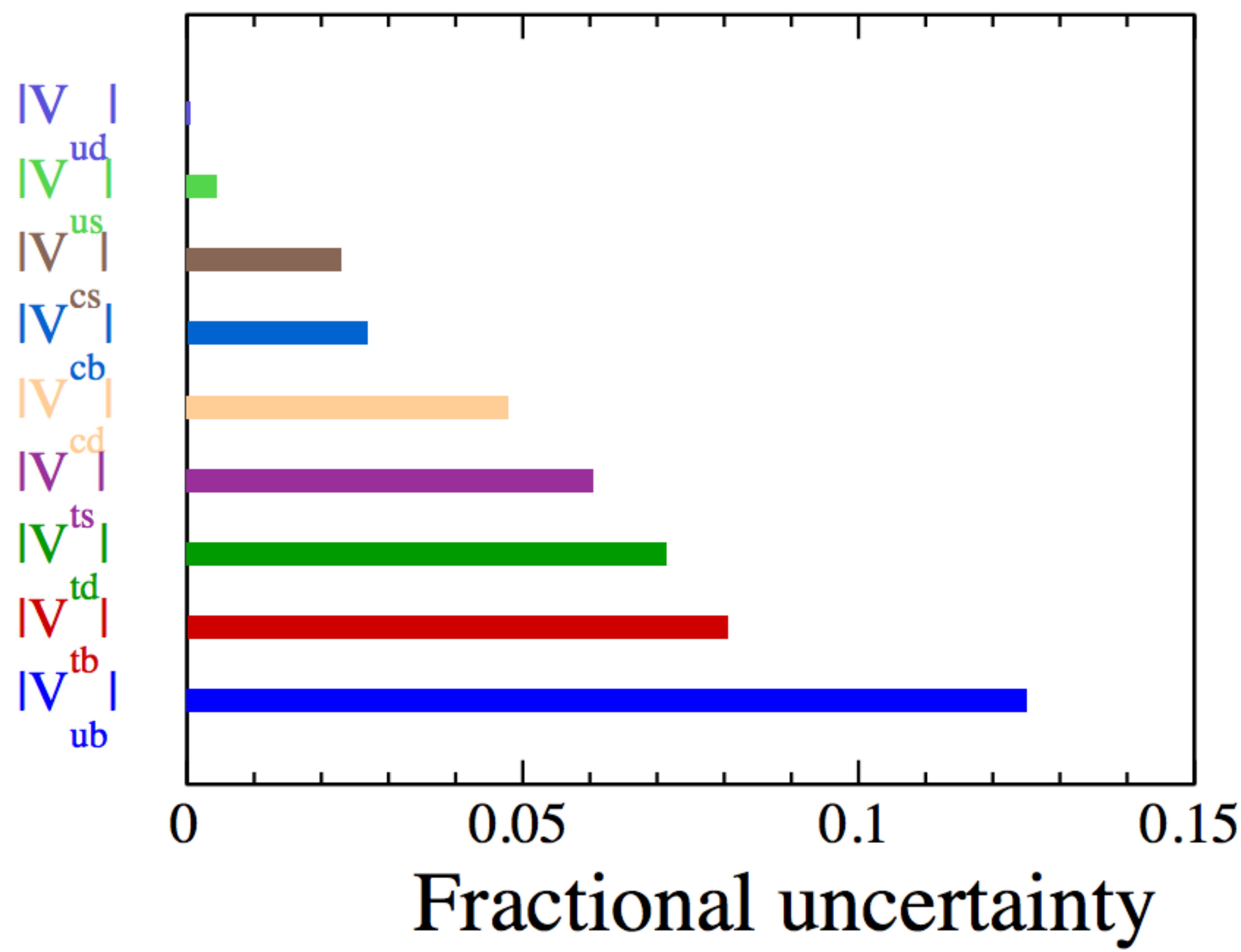
Meson LFV decays

Decays of the type $H \to e\mu h$ are sensitive to "contact models" (e.g. leptoquarks)

History of $K_L \to e\mu$

Year	90% CL	Collaboration/Lab	Reference
1966	1.0×10^{-4}	BNL	Carpenter *et al.* [1966]
1967	8.0×10^{-6}	BNL	Fitch *et al.* [1967]
1967	9.0×10^{-6}	CERN	Bott-Bodenhausen *et al.* [1967]
1988	1.1×10^{-8}	BNL	Cousins *et al.* [1988]
1988	6.7×10^{-9}	BNL	Greenlee *et al.* [1988]
1989	1.9×10^{-9}	BNL	Schaffner *et al.* [1989]
1989	2.2×10^{-10}	BNL/E791	Mathiazhagan *et al.* [1989]
1989	4.3×10^{-10}	KEK	Inagaki *et al.* [1989]
1993	3.3×10^{-11}	BNL/E791	Arisaka *et al.* [1993]
1995	9.4×10^{-11}	KEK/E137	Akagi *et al.* [1995]
1998	4.7×10^{-12}	BNL/E871	Ambrose *et al.* [1998]

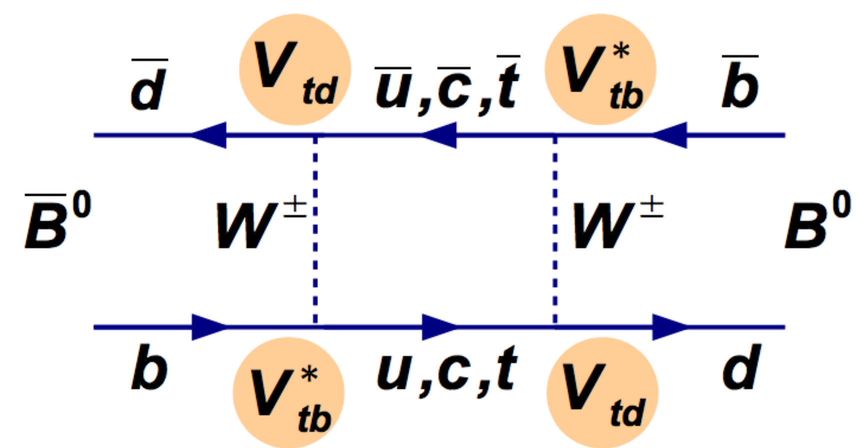
Limits of $B^+ \to h^+ e\mu$, $B^0_{(s)} \to e\mu$ at the level of 10^{-8}


|V_ud|
|V_us|
|V_cs|
|V_cb|
|V_cd|
|V_ts|
|V_td|
|V_tb|
|V_ub|
0
0.05
0.1
0.15
Fractional uncertainty

CPV in Mixing

CP violated in mixing if $\bar{a}_{mix}(t) \neq a_{mix}(t)$

- requires relative phase arg (q/p) ≠ 0 between dispersive part M_{12} and absorptive part Γ_{12} of the $B^0 \leftrightarrow \bar{B}^0$ transition amplitude:



$$\left.\begin{aligned} a_{mix}(t) &= \frac{\cos(\Delta m \cdot t) \boxed{+} \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) \boxed{+} \delta \cdot \cos(\Delta m \cdot t)} \\ \bar{a}_{mix}(t) &= \frac{\cos(\Delta m \cdot t) \boxed{-} \delta \cdot \cosh(\Delta\Gamma \cdot t/2)}{\cosh(\Delta\Gamma \cdot t/2) \boxed{-} \delta \cdot \cos(\Delta m \cdot t)} \end{aligned}\right\} \quad \delta = \frac{1-|q/p|^2}{1+|q/p|^2} \; ; \; \frac{q}{p} = -\sqrt{\frac{M^*_{12}-(i/2)\Gamma^*_{12}}{M_{12}-(i/2)\Gamma_{12}}}$$

- remember: $B^0 \leftrightarrow \bar{B}^0$ transition amplitude described by effective Hamiltonian

$$H_{12} = M_{12} - (i/2)\,\Gamma_{12}$$

  - M_{12}: transitions through off-shell intermediate states, $M_{12} \propto m_t^2 \cdot (V_{td} V^*_{tb})^2$
  - Γ_{12}: transitions through on-shell intermediate states, $\Gamma_{12} \propto m_c^2 \cdot (V_{cd} V^*_{cb})^2$
- different weak phases as required for CP violation
- $\Gamma_{12} \ll M_{12} \Rightarrow$ interference term small $\Rightarrow$ CP violation in mixing small
  - New Physics can enter in box and have significant effect

CPV in the decay

***CP* violated in decay if $A(\overline{B} \to \bar{f}) \neq A(B \to f)$**

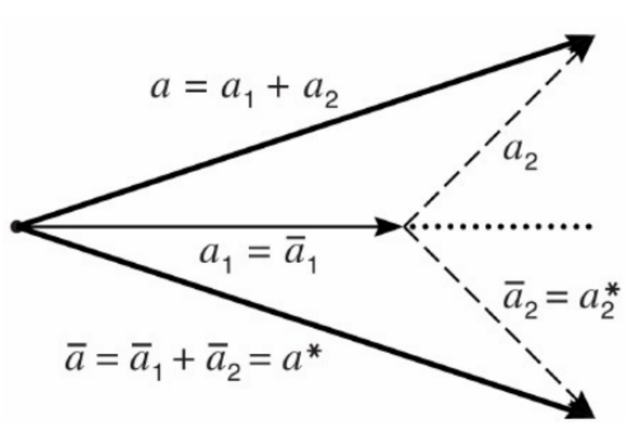
- **requires interference of (at least) two decay amplitudes with different weak phase and different strong phase leading to the same final state**

$$\left.\begin{aligned} A_f &\equiv A(B \to f) = \sum_i a_i\, e^{i(\delta_i + \phi_i)} \\ \overline{A}_{\bar{f}} &\equiv A(\overline{B} \to \bar{f}) = \sum_i a_i\, e^{i(\delta_i - \phi_i)} \end{aligned}\right\}$$

ϕ_i: weak phase, changes sign under *CP*

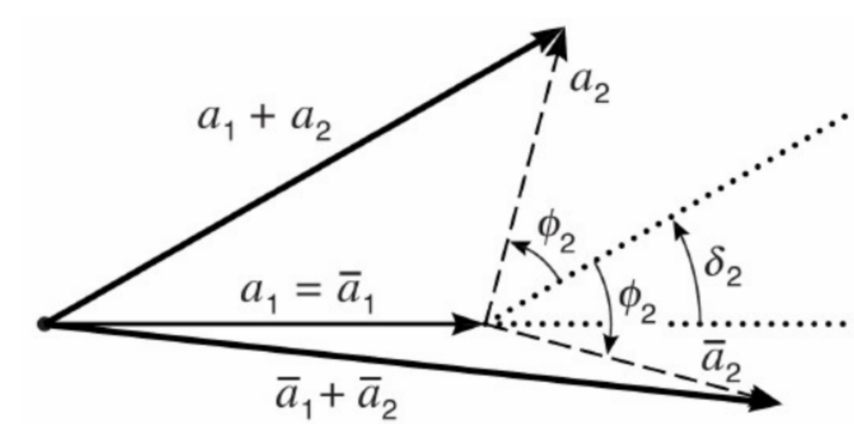
δ_i: strong phase, does not change sign under *CP*

$$|A_f|^2 - |\overline{A}_{\bar{f}}|^2 = -2 \sum_{ij} a_i a_j \cdot \sin(\phi_i - \phi_j) \cdot \sin(\delta_i - \delta_j)$$



$$\boxed{\begin{aligned} &\phi_2 \neq \phi_1 \\ &\delta_2 = \delta_1 \\ &\Rightarrow |\bar{a}| = |a| \end{aligned}}$$

$(\phi_1 = \delta_1 = 0)$



$$\boxed{\begin{aligned} &\phi_2 \neq \phi_1 \\ &\delta_2 \neq \delta_1 \\ &\Rightarrow |\bar{a}| \neq |a| \end{aligned}}$$

$(\phi_1 = \delta_1 = 0)$

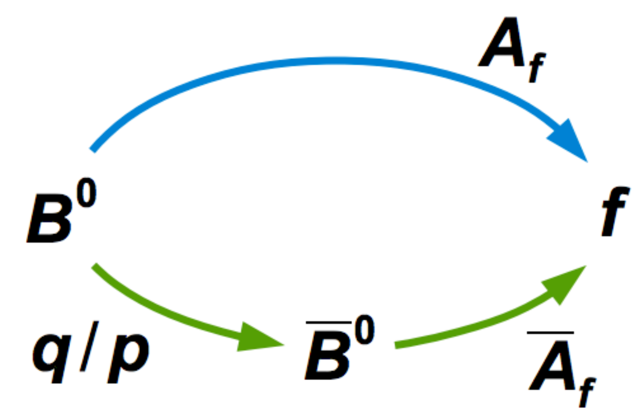
- **interference and *CP* violation can be large**
  - New Physics can enter through loops if penguin diagrams involved
- **but have to battle large theoretical uncertainties due to the strong phases**

CPV in the interference

For decays into a *CP* eigenstate *f* that is accessible to both $B^0_{(s)}$ and $\overline{B}^0_{(s)}$

- *CP* violated if

$$\mathrm{Im}\left(\lambda_f\right) \equiv \mathrm{Im}\left(\frac{q}{p}\cdot\frac{\overline{A}_f}{A_f}\right) \neq 0$$



- time-dependent decay rate asymmetry:

$$a_f(t) = \frac{N(B^0_{t=0}\to f,t) - N(\overline{B}^0_{t=0}\to f,t)}{N(B^0_{t=0}\to f,t) + N(\overline{B}^0_{t=0}\to f,t)}$$

$$\approx \frac{-C_f\cos(\Delta m\cdot t) + S_f\sin(\Delta m\cdot t)}{\cosh(\Delta\Gamma\cdot t/2) + \Omega_f\sinh(\Delta\Gamma\cdot t/2)}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\ ;\ S_f = \frac{2\cdot\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}$$

$$\Omega_f = 1 - S_f^2 - C_f^2$$

- the ideal case: asymmetries can be large and no strong phase involved
- if one single decay amplitude dominates: $\left|\overline{A}_f/A_f\right| = 1 \ \Rightarrow\ \left|\lambda_f\right| = 1$

$$a_f(t) = \frac{\mathrm{Im}(\lambda_f)\cdot\sin(\Delta m\cdot t)}{\cosh(\Delta\Gamma\cdot t/2) + \mathrm{Re}(\lambda_f)\cdot\sinh(\Delta\Gamma\cdot t/2)}$$

- in $B^0\overline{B}^0$ system: $\Delta\Gamma_d \approx 1$

$$a_f(t) = \mathrm{Im}(\lambda_f)\cdot\sin(\Delta m\cdot t)$$

CP Violation in decay

Consider $\{|P\rangle, |\bar{P}\rangle\}$ decaying into the final state $\{|f\rangle, |\bar{f}\rangle\}$

Defining

$$A_f = \langle f|P\rangle \quad A_{\bar{f}} = \langle \bar{f}|P\rangle$$
$$\bar{A}_f = \langle f|\bar{P}\rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f}|\bar{P}\rangle$$

We have CP violation in the decay if

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1 \quad \left|\frac{A_{\bar{f}}}{\bar{A}_f}\right| \neq 1$$

Then the probability of the decay of the CP conjugate

$$\Gamma(P^0 \to f) \neq \Gamma(\bar{P}^0 \to \bar{f})$$

CP Violation in mixing

CP violation in mixing occurs when the oscillation from meson to anti-meson is different than that of anti-meson to meson

$$\mathrm{Prob}(P^0 \to \bar{P}^0) \neq \mathrm{Prob}(\bar{P}^0 \to P^0)$$

These probabilities are given by

$$\wp_{P\to\bar{P}}(t) = \left|\left\langle \bar{P} | P(t) \right\rangle\right|^2 = \left|\frac{q}{p} g_-(t)\right|^2$$

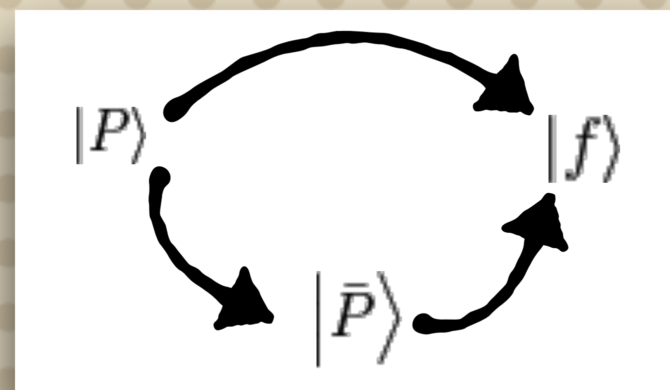
$$\wp_{\bar{P}\to P}(t) = \left|\left\langle P | \bar{P}(t) \right\rangle\right|^2 = \left|\frac{p}{q} g_-(t)\right|^2$$

So this occurs when $\left|\frac{q}{p}\right| \neq 1$

CPV in interference

Let's consider a CP eigenstate f to which P and anti-P can decay

$$f = \bar{f}$$



$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f \cos \Delta m t - 2S_f \sin \Delta m t}{2\cosh \frac{1}{2}\Delta\Gamma t + 2D_f \sinh \frac{1}{2}\Delta\Gamma t}$$

$$|A_f| = |\bar{A}_f| \quad |q/p| = 1 \quad \Rightarrow \quad |\lambda_f| = 1$$

We have CPV if

$$A_{CP}(t) = \frac{-\Im\lambda_f \sin \Delta m t}{\cosh \frac{1}{2}\Delta\Gamma t + \Re\lambda_f \sinh \frac{1}{2}\Delta\Gamma t}$$

$$\Im\lambda_f = \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$