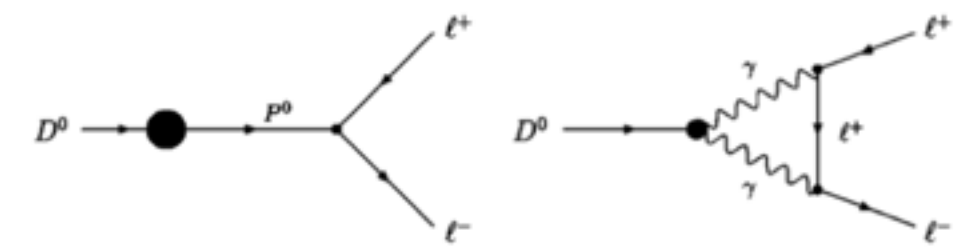
WG3 - Rare Decays - Theory Summary

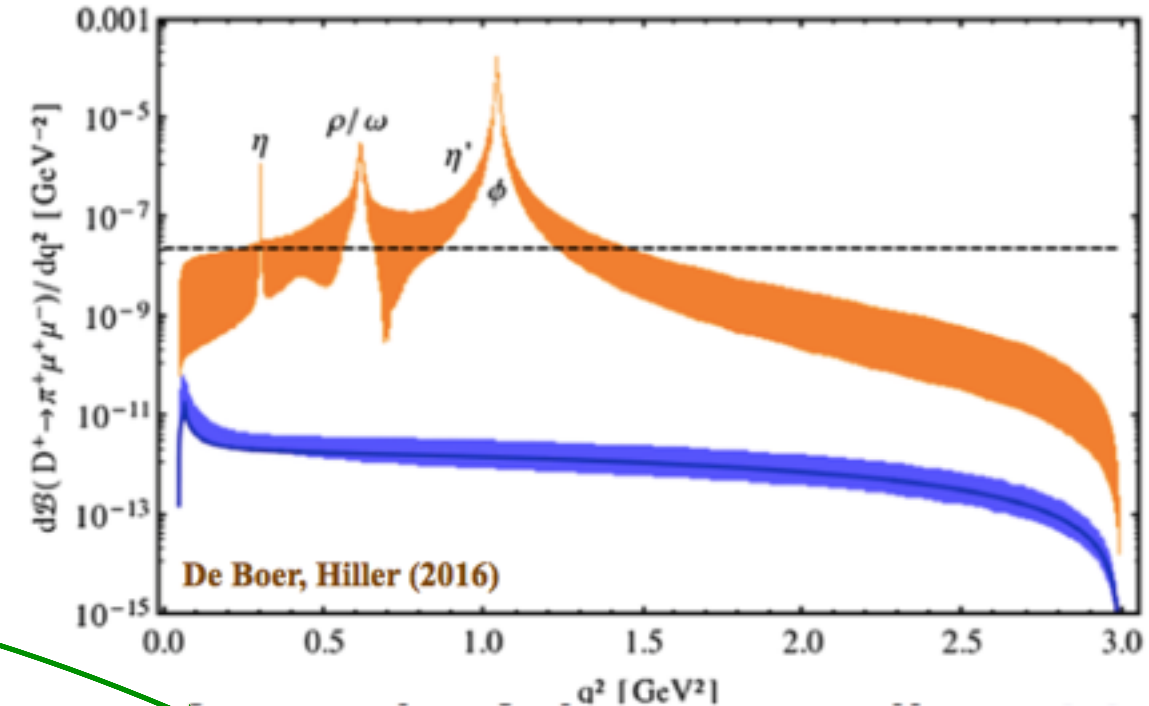
Enrico Lunghi
Indiana University

December 2, 2016
CKM 2016, TIFR-Mumbai

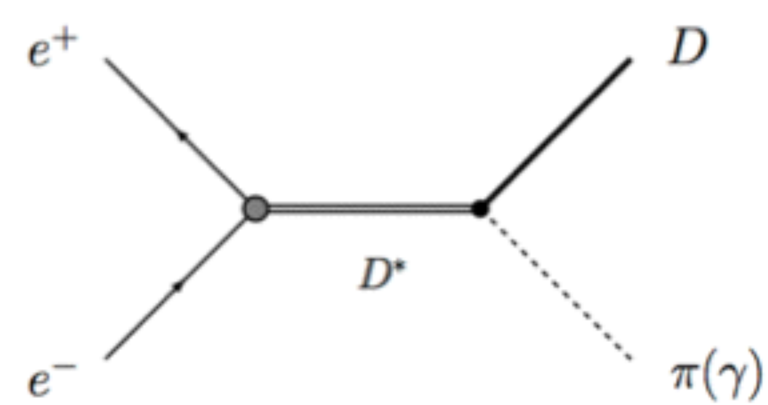
Rare D decays: theory [Petrov]

- D decays often controlled by long distance effects
  - $D\to\mu\mu$: $BR_{SD} \sim 10^{-18}$ and $BR_{LD} \sim 10^{-13}$
    correlation with D-mixing
  - $D\to(\pi,\eta,\rho,\omega,\phi,K,K^*,\pi\pi,\pi K,KK,\pi\pi\pi)$
    $BR(D\to\pi\mu\mu) \sim 10^{-12}$
    Laboratory for NP, e.g. RPV-SUSY, LQ





- $D^*(B^*)\to ee$: $BR{\sim}10^{-19}$, cannot be measured but it might be studied via resonant production!
  - $ee\to D^*(B^*)\to D\pi$
  - BEPCII (BESIII) and VEPP-2000 (Novosibirsk) can be tuned to m_{D^*/B^*}



- Lepton Flavor Violation
  - $D\to\mu e,\ \gamma\mu e,\ \pi\mu e,\ \rho\mu e,\ \ldots$
- Rare decays with missing energy
  - $D\to\nu\nu,\ \nu\nu\gamma$
  - Extremely rare but can be used to test dark matter models!

Rare K decays: theory [d'Ambrosio]

$K \to \pi\nu\nu$

Extremely rare, precisely predicted in SM:

- Amplitude $\propto V_{ts}^* V_{td}$

$K^+ \to \pi^+ \nu\nu$

- $\mathrm{BR_{SM}} = (8.22 \pm 0.27_{V_{cb}} \pm 0.29_{\text{non pert}}) \times 10^{-11}$
- Brookhaven E949 (stopped K^+): $\mathrm{BR} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

$K_L \to \pi^0 \nu\nu$: never measured

- $\mathrm{BR_{SM}} = (2.43 \pm 0.25 \pm 0.06_{\text{non pert}}) \times 10^{-11}$
- Grossman-Nir limit on BR: $\mathrm{BR}(K_L) \leq \mathrm{BR}(K^+) \times \tau_L/\tau_+ \sim 1.4 \times 10^{-9}$

Other interesting rare K decays

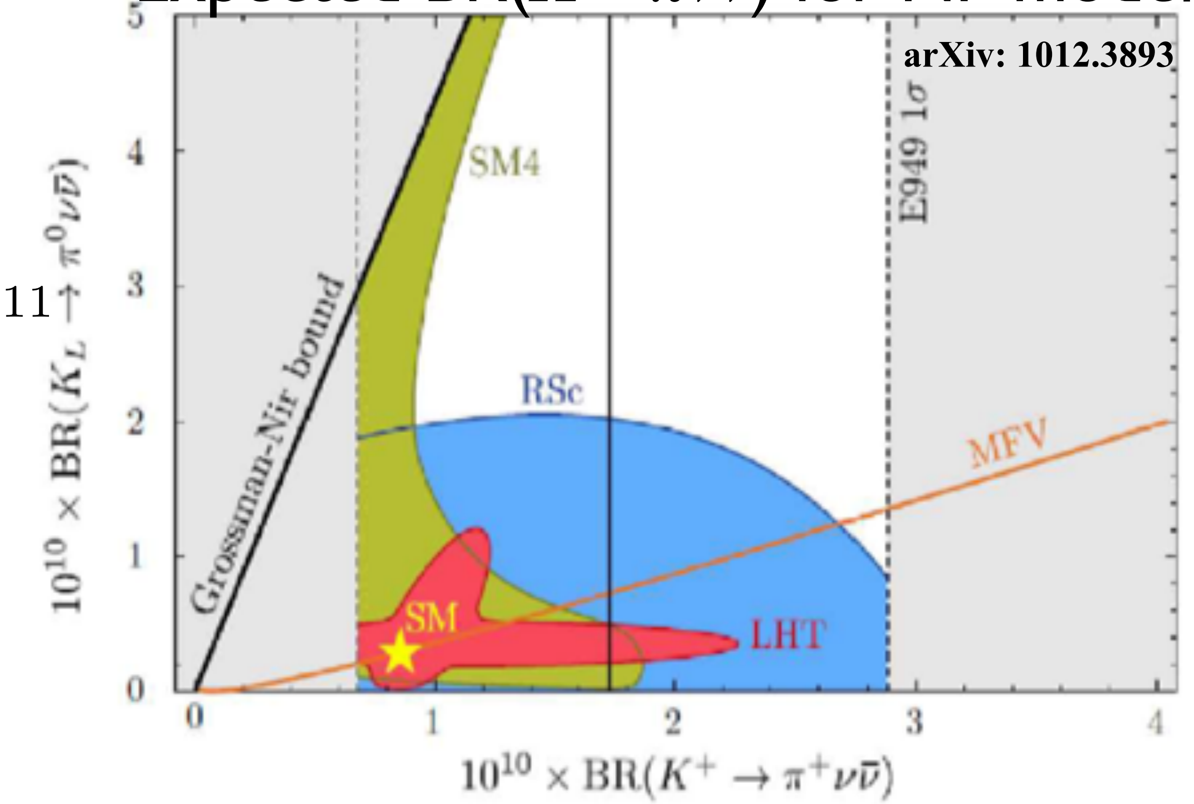
$K^+ \to \pi^+ ll$ and $K_S \to \pi^0 ll$

- Controlled by long distance effects
- Test of lepton universality

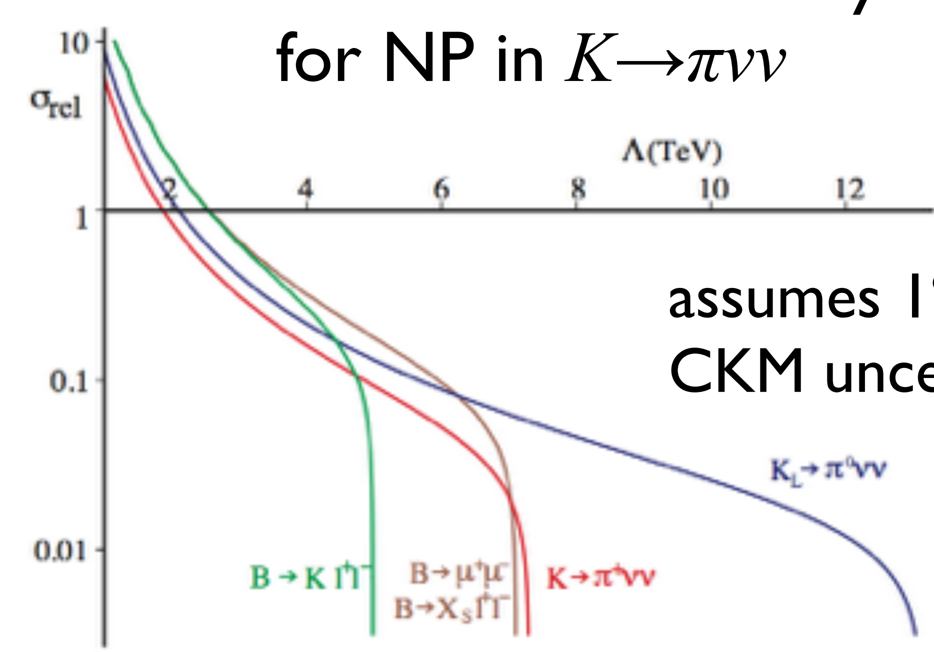
$K^+ \to \pi^+ \pi^0 \gamma$, $K_L \to \pi^+ \pi^- ee$, $K^+ \to \pi^+ \pi^0 ee$, ...

- ChiPT tests
- Direct CP violating charge asymmetry

Expected BR($K \to \pi\nu\nu$) for NP models



Mass scale sensitivity for NP in $K \to \pi\nu\nu$

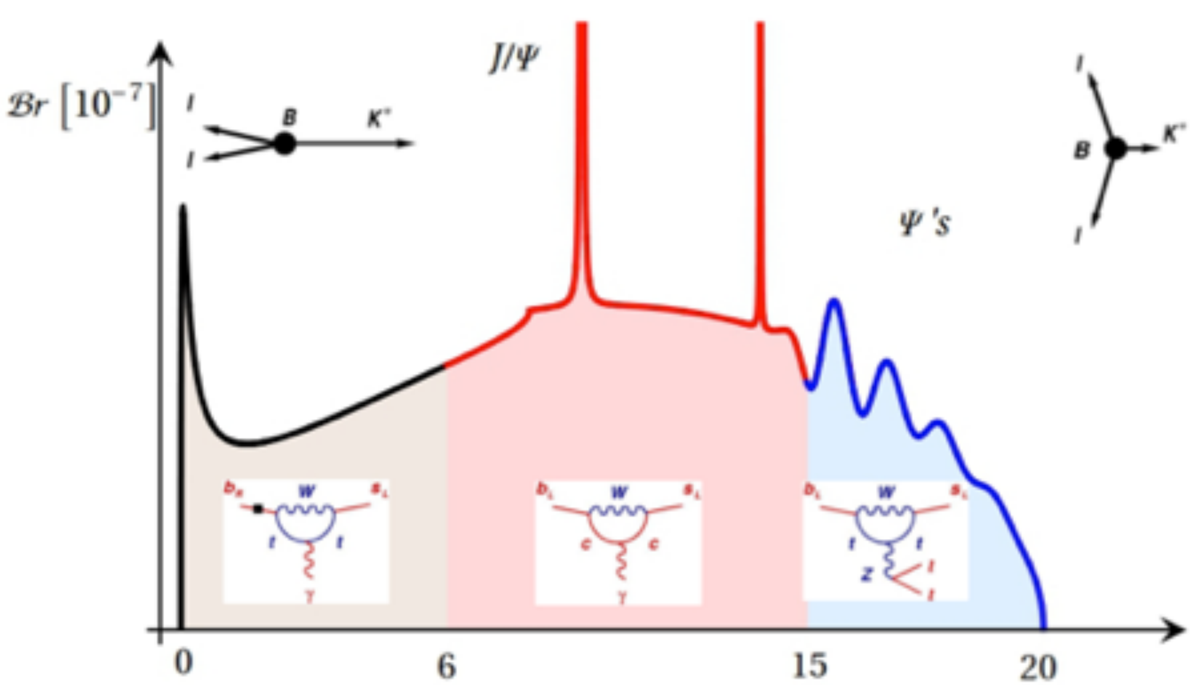


assumes 1% CKM uncertainty

NPB 645 (2002) 155

Theory of exclusive $B \to K^* ll$ decays [Camalich]

- $R_K = \mathrm{BR}(B^+ \to K^+ \mu\mu)/\mathrm{BR}(B^+ \to K^+ ee)$ is very clean
- $B_s \to \mu\mu$ is clean (depends only on f_{Bs})
- $B \to K^{(*)} ll$ can be calculated using SCET (at low-q^2) and an OPE (at high-q^2)
  - Many non-perturbative inputs are required. Form factors from lattice-QCD at high-q^2 and LCSR at low-q^2. Decay constants (f_B, f_K, f_{K^*}) from lattice-QCD. LCDA for $K^{(*)}$ from lattice-QCD. LCDA for B not well known.
  - Presence of charmonium resonances poses a problem at high-q^2. Violation of quark-hadron duality? Use experimental data (LHCb recent analysis)?
  - Both approaches receive power corrections ($O(\Lambda/m_B)$). How large?



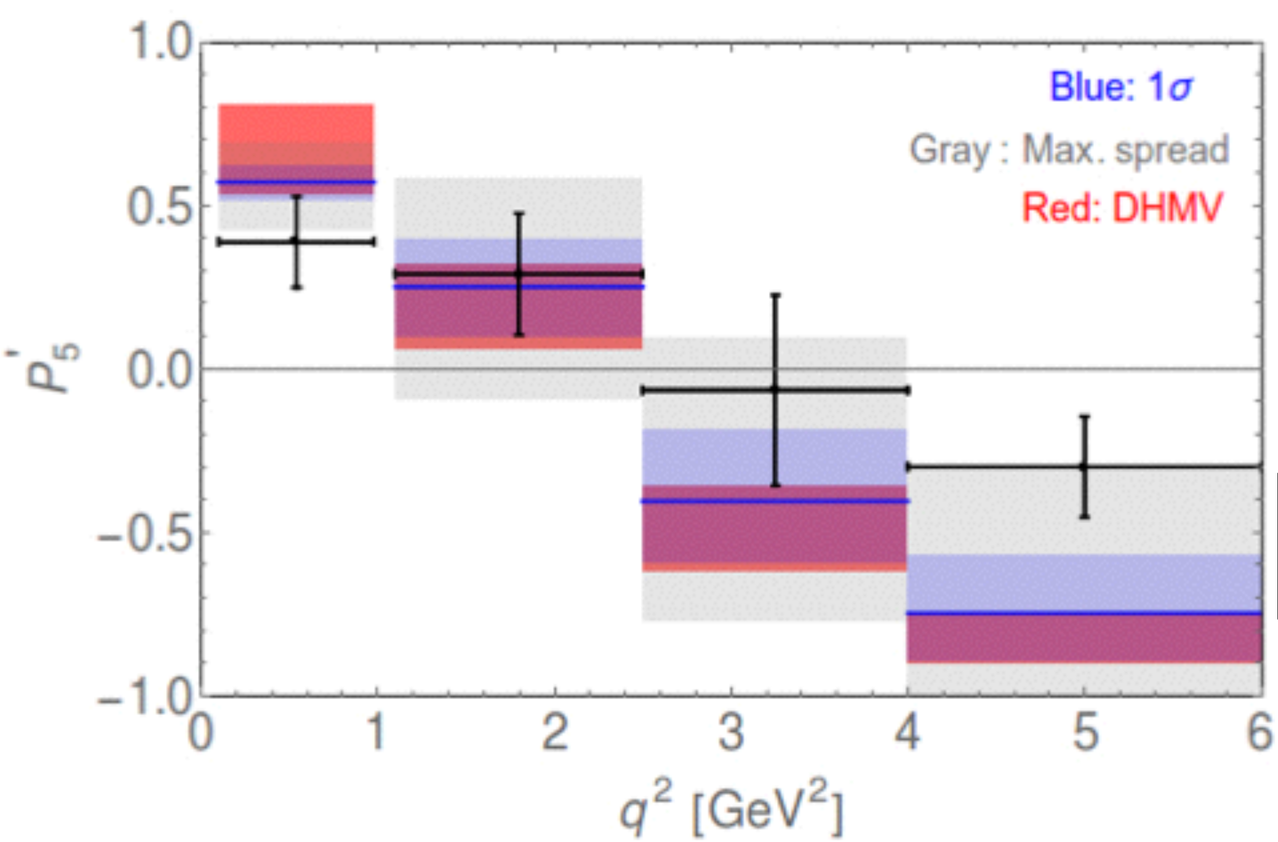
- **Large-recoil region** (low q^2)
  - **LCSR+QCDf/SCET** (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6 - 7$ GeV^2
- **Low-recoil region** (high q^2)
  - **LQCD+HQEFT + OPE** (duality violation)
  - Dominated by semileptonic operators

Theory of exclusive $B \to K^* ll$ decays [Camalich]

$$P_5' = P_5'|_\infty \Bigg(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} 2\, C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})}$$

$$+ 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \ldots \Bigg) + \mathcal{O}(\Lambda^2/m_B^2)$$

Jäger and JMC, PRD93(2016)no.1,014028



Better understanding of had. uncert. desirable!

- **Learn from LCSR** Bharucha, Straub and Zwicky, arXiv: 1503.05534
- **Charm under control?** Lyon *et al.* arXiv:1406.0566, Ciuchini *et al.* JHEP 1606 (2016)

No agreement on this in the literature
See J. Matias, J. Virto

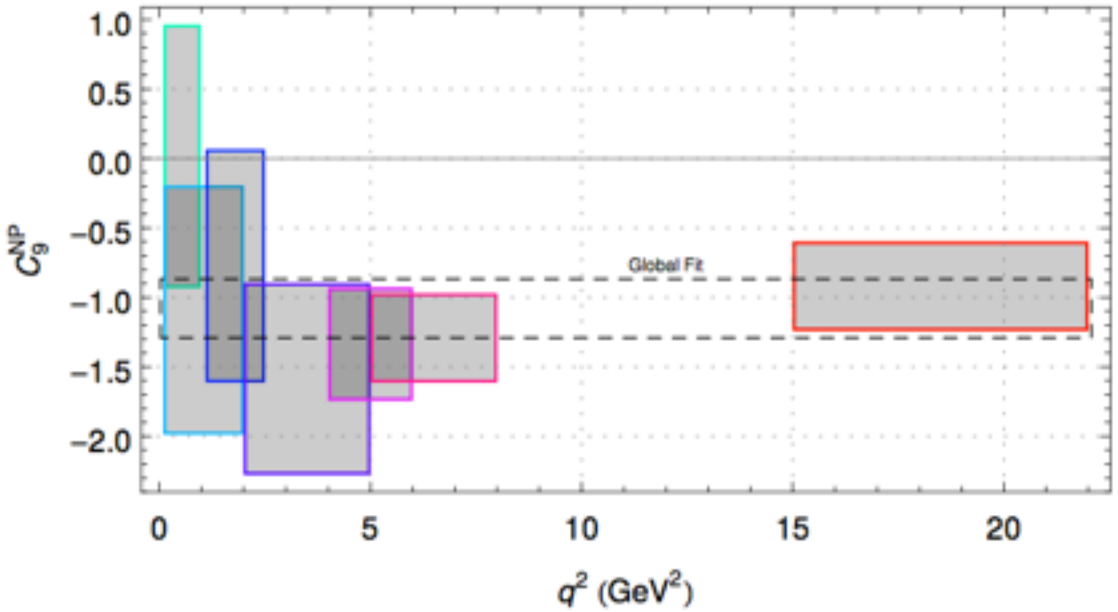
"Extraordinary claims require Extraordinary evidence"
– C. Sagan

Global fits to $b\to sll$ anomalies [Virto]

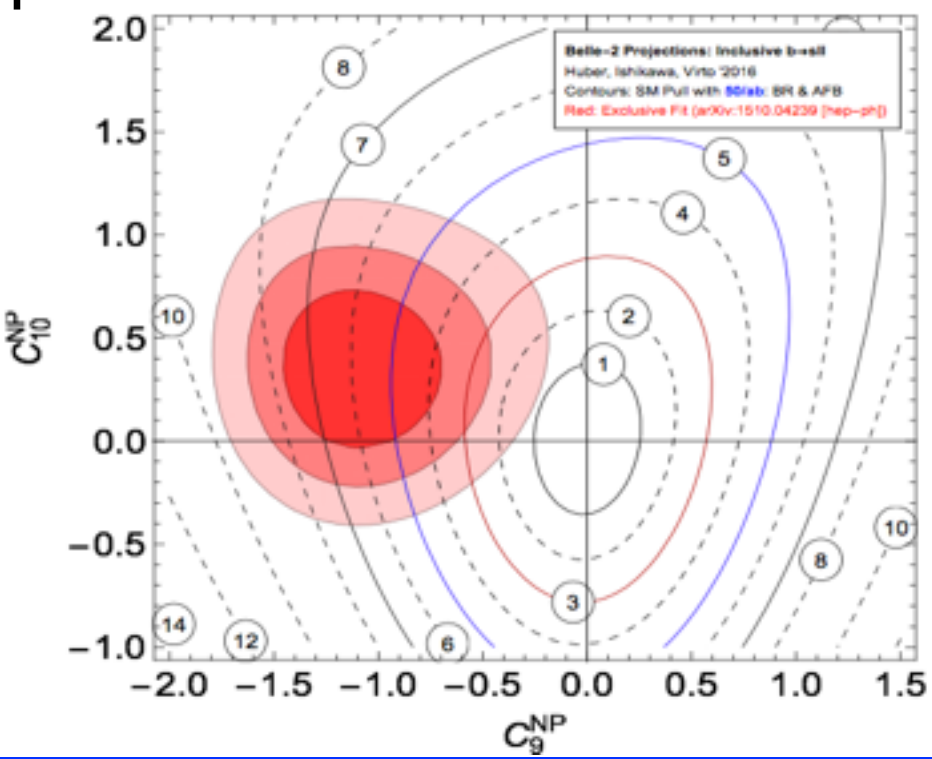
- Inclusion of ~100 observables: $B\to X_s\gamma$, $B\to X_s ll$, $B_s\to ll$, $B\to K^{(*)}\gamma$, $B\to K^{(*)}ll$, $B_s\to\phi ll$
- Main theory issues are in $B\to K^{(*)}ll$
  - low-q^2: SCET, form factors from LCSR [KMPW=Khodjamirian et al 2010], power corrections (correlated central values from KMPW+ uncorrelated 10%), long distance charm effects = [KMPW]⊗[-1,1]
    - ☛ assume that LCSR describe correctly size and sign of the power corrections
  - high-q^2: OPE, lattice QCD (HPQCD 2015 for K, Horgan et al 2013 for K*), possible quark-hadron duality violation modeled as ±10%
    - ☛ would be great to have updated results for the K* form factors
    - ☛ use experimental data to understand interference between charmonium resonances?
- Canonical fit prefers scenarios with non vanishing δC_9, $\delta C_9=-\delta C_{10}$ or $\delta C_9=-\delta C'_9$ with pulls above 4 (but $p_{SM}=17\%$)

Global fits to $b \to sll$ anomalies [Virto]

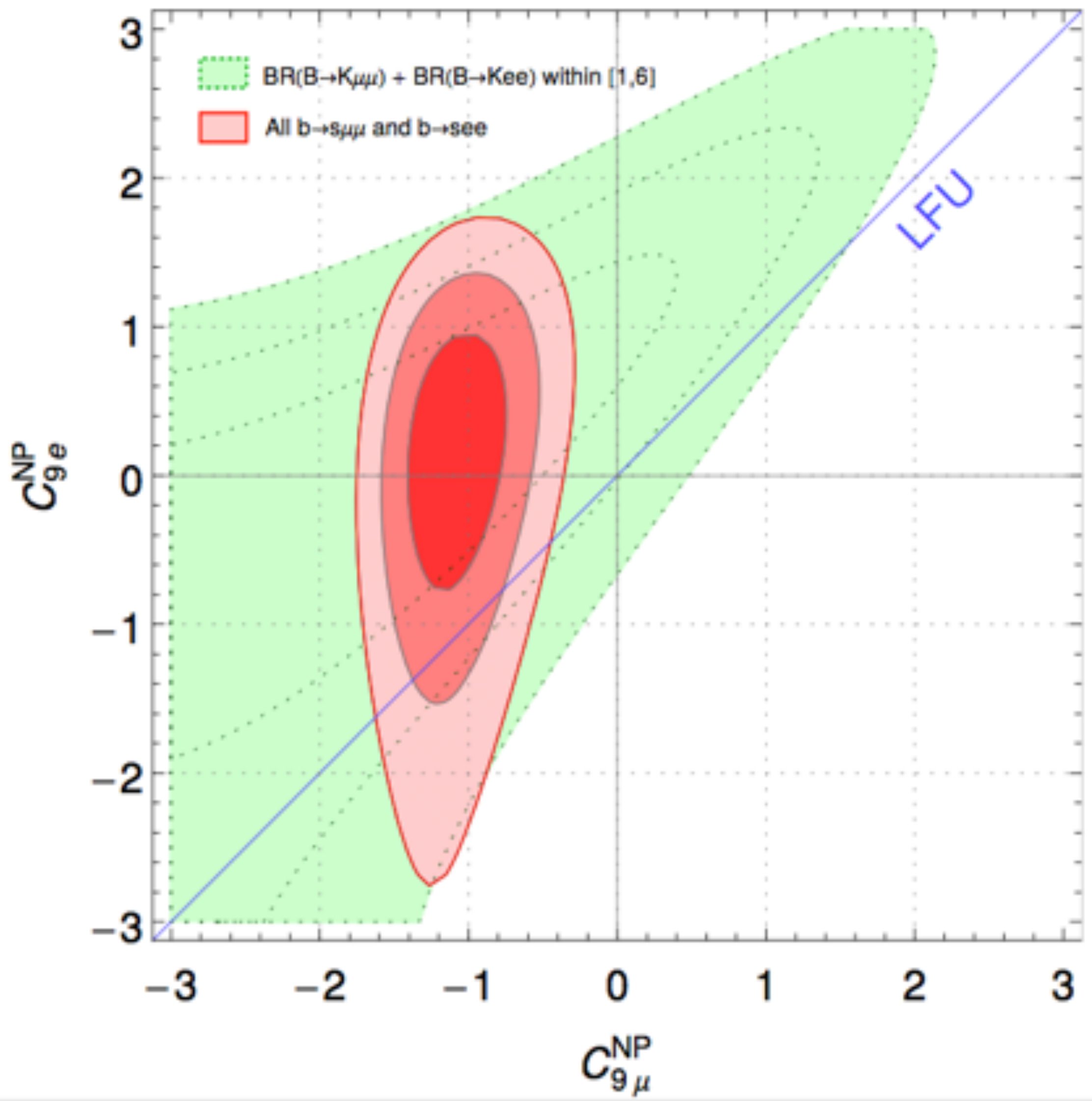
- Fit doesn't show evidence of q^2 dependence:



- Inclusive $b \to sll$ at Belle-II with 50 ab^{-1} have the potential to confirm the anomaly:

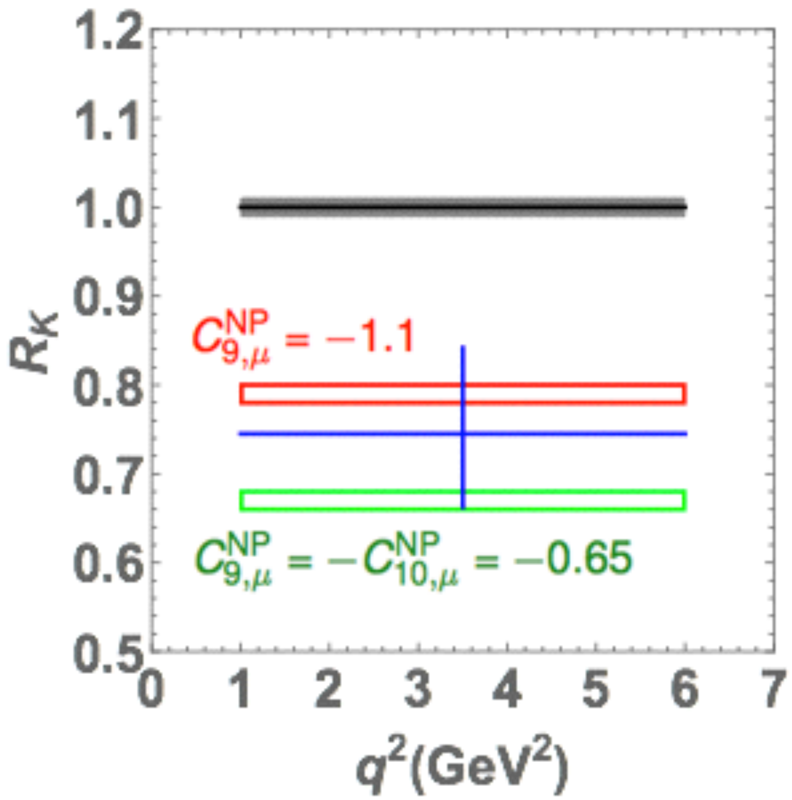


- Assumption of no NP in is supported by the fit $(\bar{s}b)(\bar{e}e)$:



Lepton Universality Violation in $B \to K^* ll$ [Matias]

- R_K alone is not sufficient to discriminate between different LFU violating scenarios:



- Can help disentangle NP effects
  - Q_5': C_9
  - $Q_{1,4}$: C_9', C_{10}' (RH currents)
  - B_5, B_{6s}: C_{10}

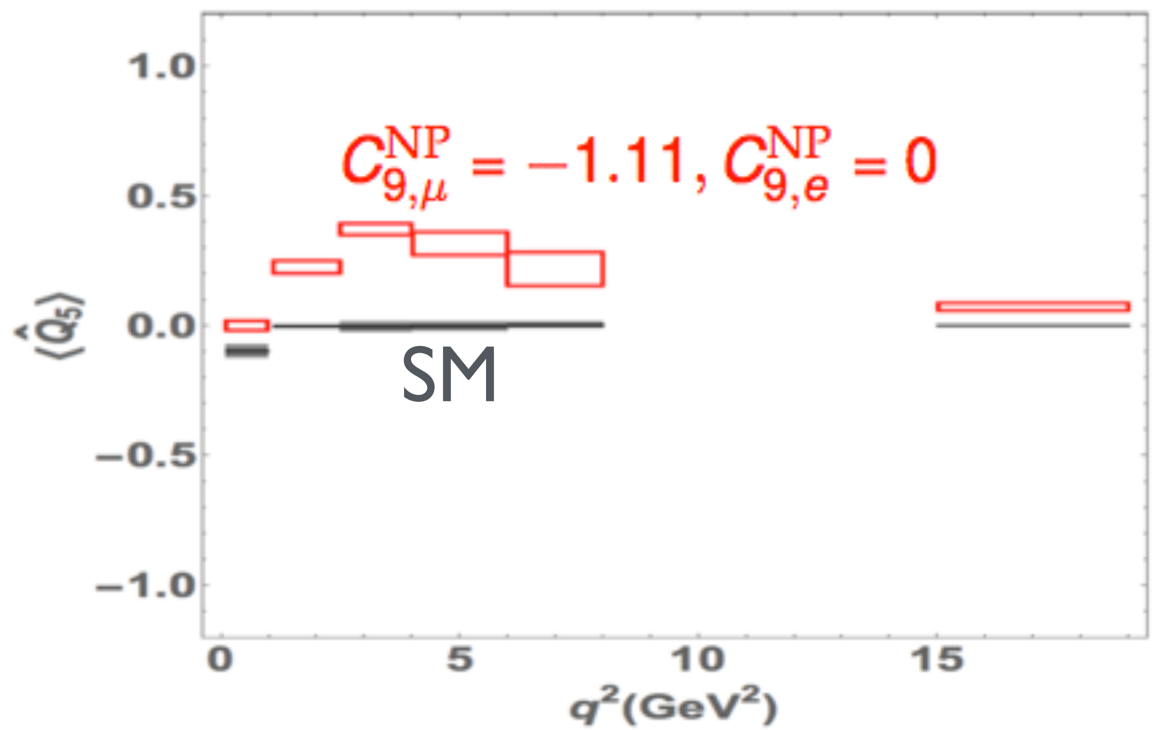
- Introduce new observables which are sensitive to $C_{i,\mu}$-$C_{i,e}$ without hadronic uncertainties

$$C_{i,\mu} = \begin{cases} C_i + \delta C_i, \; i = 10, 9', 10' \\ C_9 + \delta C_9 + \triangle C_9^{(j)} \end{cases} \qquad C_{i,e} = \begin{cases} C_i, \; i = 10, 9', 10' \\ C_9 + \triangle C_9^{(j)} \end{cases}$$

$j = \perp, \|, 0$ — same

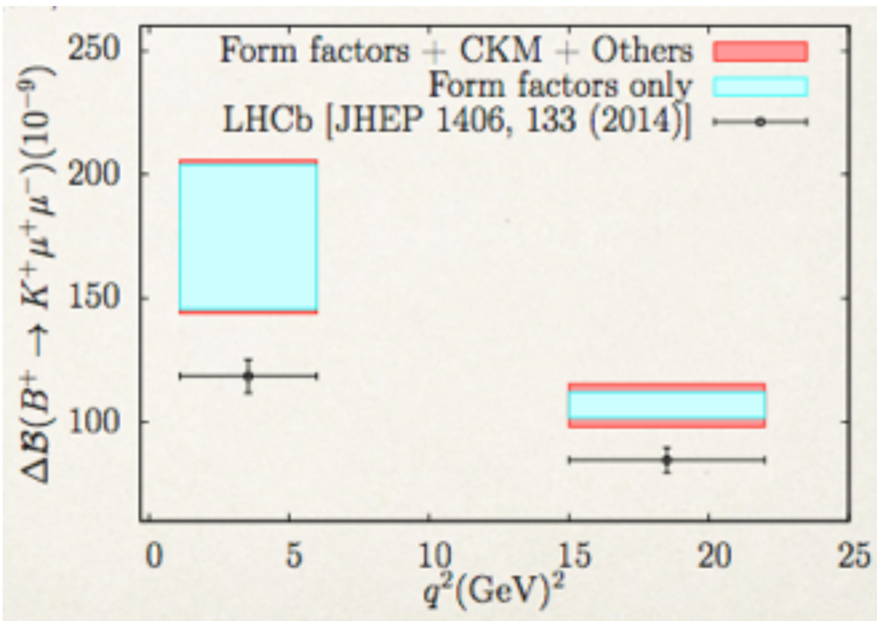
$$\langle Q_i \rangle = \langle P_i^\mu \rangle - \langle P_i^e \rangle \qquad \langle \hat{Q}_i \rangle = \langle \hat{P}_i^\mu \rangle - \langle \hat{P}_i^e \rangle$$

$$\langle B_k \rangle = \frac{\langle J_k^\mu \rangle}{\langle J_k^e \rangle} - 1 \qquad \langle \tilde{B}_k \rangle = \frac{\langle J_k^\mu / \beta_\mu^2 \rangle}{\langle J_k^e / \beta_e^2 \rangle} - 1$$

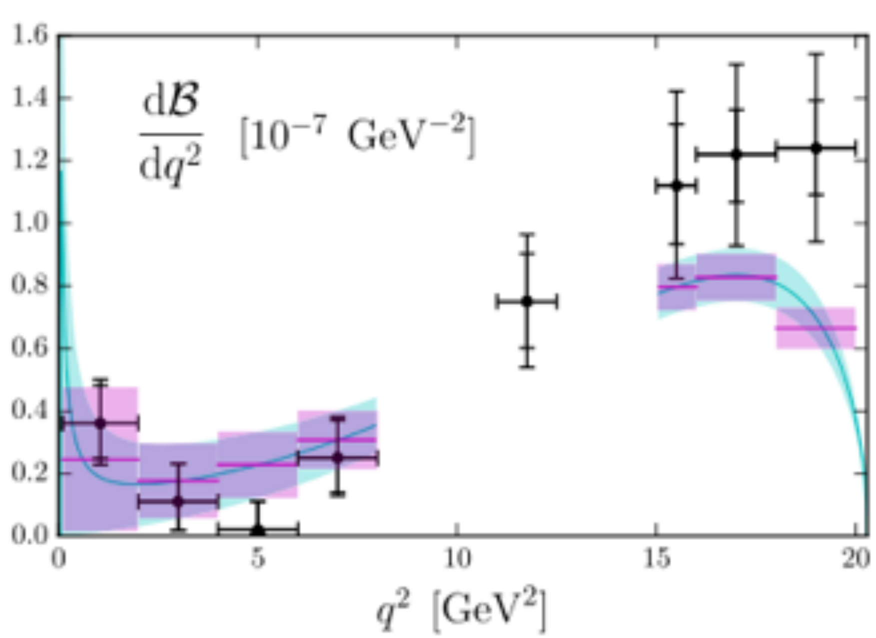


Lattice results for B decays [Wingate]

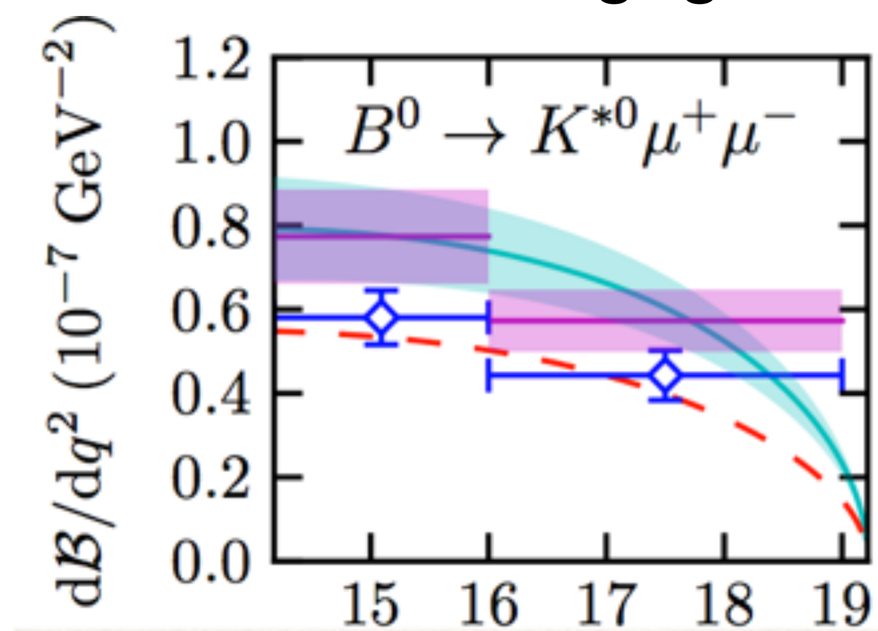
- $B \to \pi$ and $B \to K$ form factors are in excellent shape

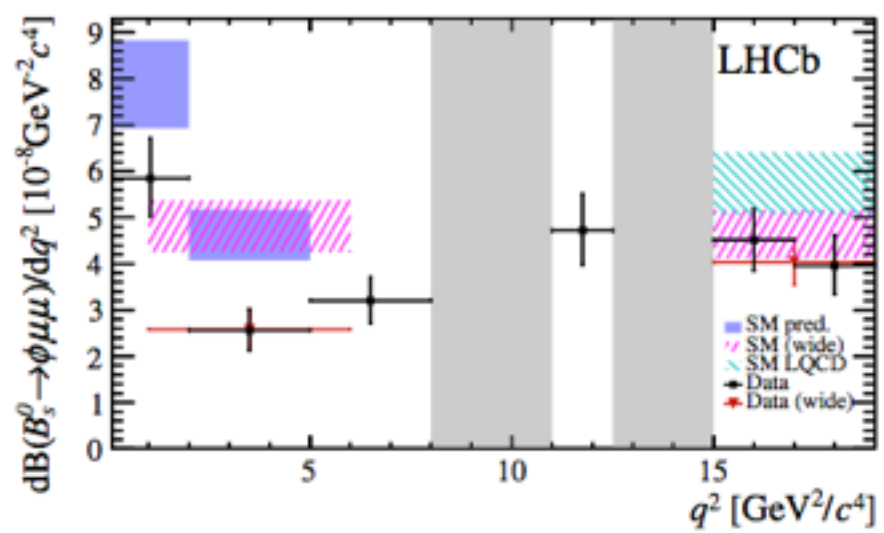


- Baryonic modes also possible: $\Lambda_b \to \Lambda$



- $B \to K^*$ and $B_s \to \phi$ form factors are much more challenging





- Work in progress on the long distance contributions in $K_S \to \pi^0 ll$ and $K^+ \to \pi^+ \nu\nu$

RH currents in $B \to K^* ll$ [Mandal]

- Look at endpoint: use exact endpoint relations, expand in $\delta = q^2_{max} - q^2$ and fit to LHCb data.

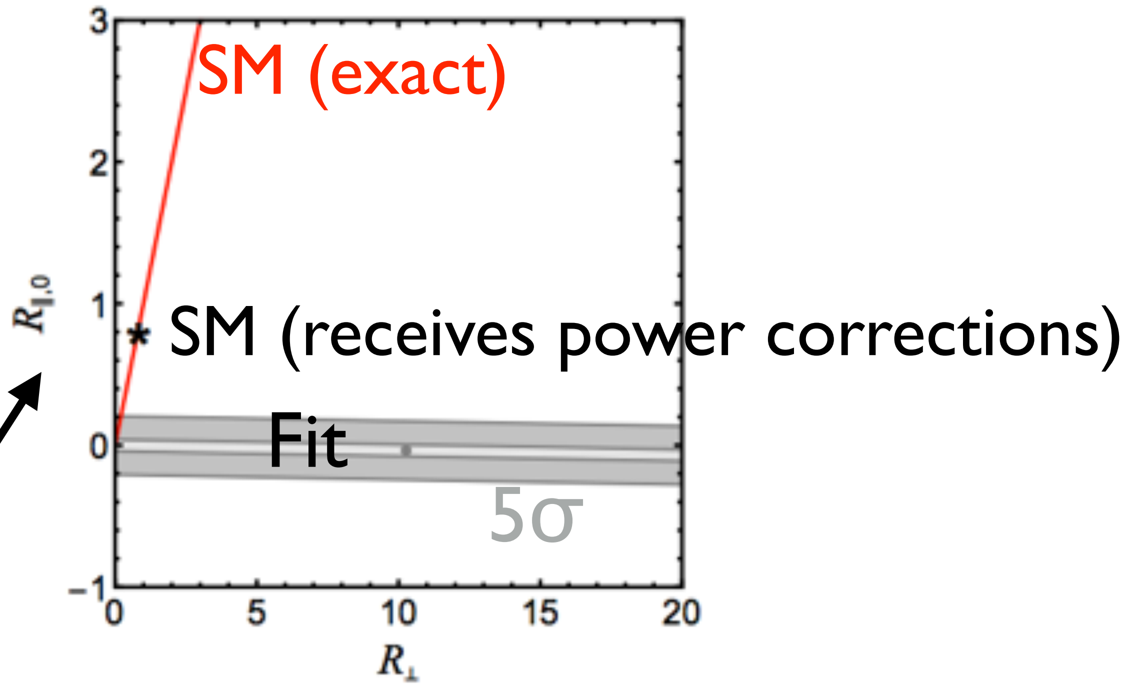
$$F_L = \frac{1}{3} + F_L^{(1)}\delta + F_L^{(2)}\delta^2 + F_L^{(3)}\delta^3$$

$$F_\perp = F_\perp^{(1)}\delta + F_\perp^{(2)}\delta^2 + F_\perp^{(3)}\delta^3$$

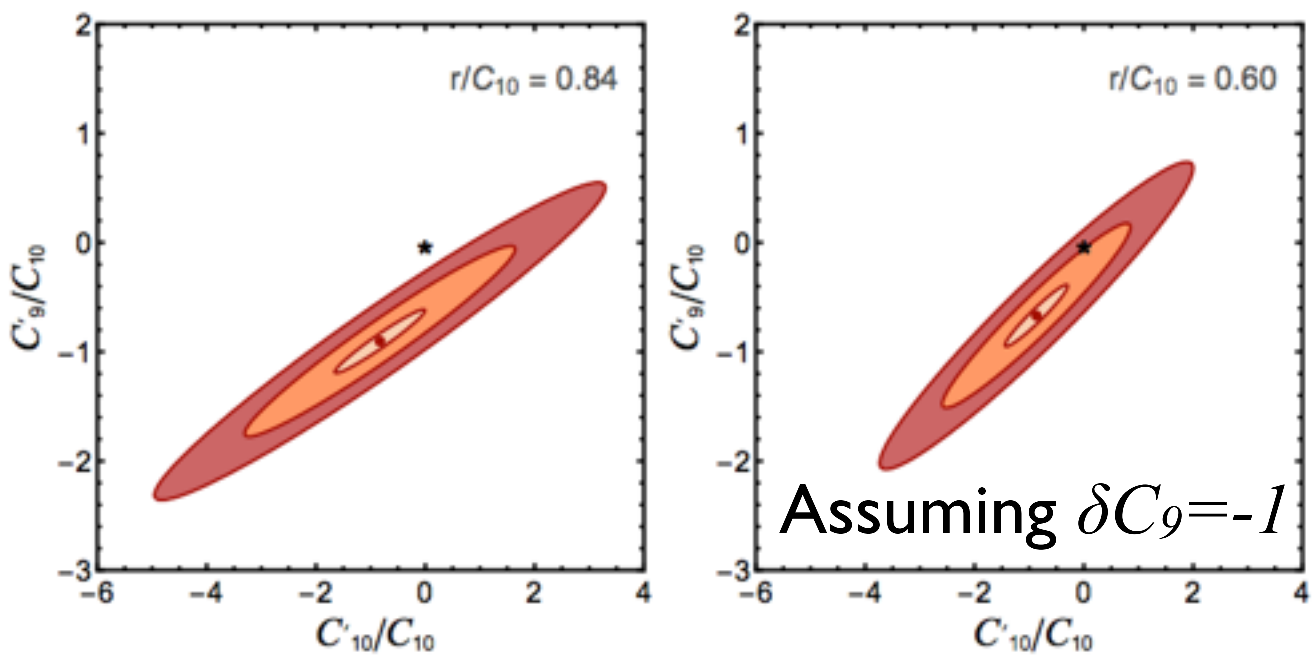
$$A_{FB} = A_{FB}^{(1)}\delta^{\frac{1}{2}} + A_{FB}^{(2)}\delta^{\frac{3}{2}} + A_{FB}^{(3)}\delta^{\frac{5}{2}}$$

$$A_5 = A_5^{(1)}\delta^{\frac{1}{2}} + A_5^{(2)}\delta^{\frac{3}{2}} + A_5^{(3)}\delta^{\frac{5}{2}},$$

	$O^{(1)}(10^{-2})$	$O^{(2)}(10^{-3})$	$O^{(3)}(10^{-4})$
F_L	-2.94 ± 1.36	12.27 ± 2.05	-5.73 ± 0.72
$F_\perp$	6.83 ± 1.75	-9.67 ± 2.59	3.77 ± 0.90
A_{FB}	-30.59 ± 2.37	26.75 ± 4.42	-4.00 ± 1.83
A_5	-16.57 ± 2.36	6.77 ± 4.18	1.94 ± 1.61



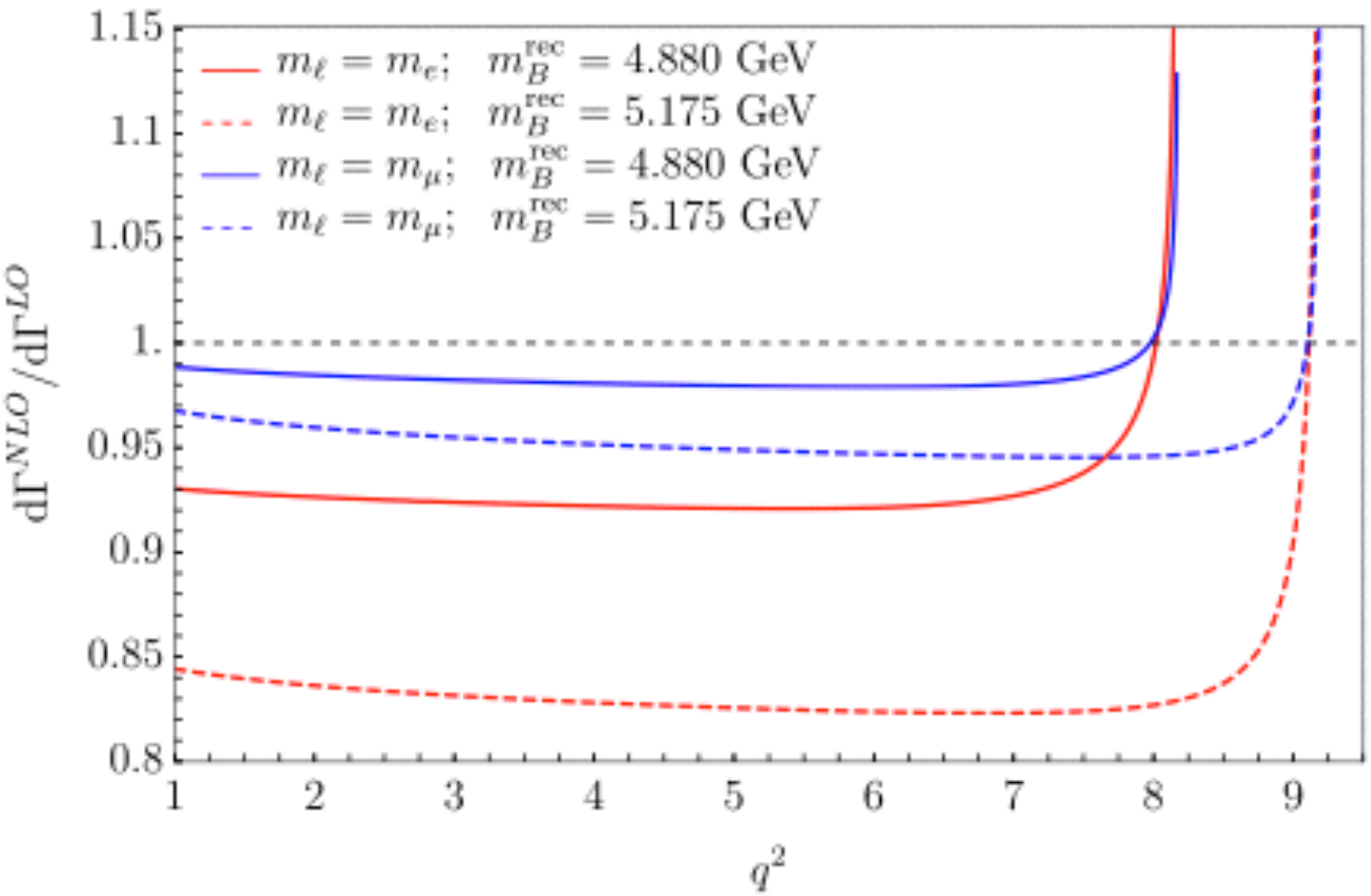
- Interpretation in terms of RH currents depend on SM prediction for r



More work on: Dependence on functional form, inclusion of experimental correlations, impact of experimental bins included in the fit

Theory of $R_{K(*)}$ [Bordone]

- How accurate is the SM prediction for $R_{K(*)}$?
- Only possible effects are related to issues with QED radiation.
- LHCb looks for radiation from final state leptons and puts it back into the q^2. This relies on EVTGEN ($b \to sll$ Monte Carlo) and PHOTOS.
- Important to check whether this procedure leads to a systematic bias.
- Some technical aspects are non trivial (e.g. need to model the J/ψ peak)
- Impact of photon radiation is large and depends on details of experimental cuts:



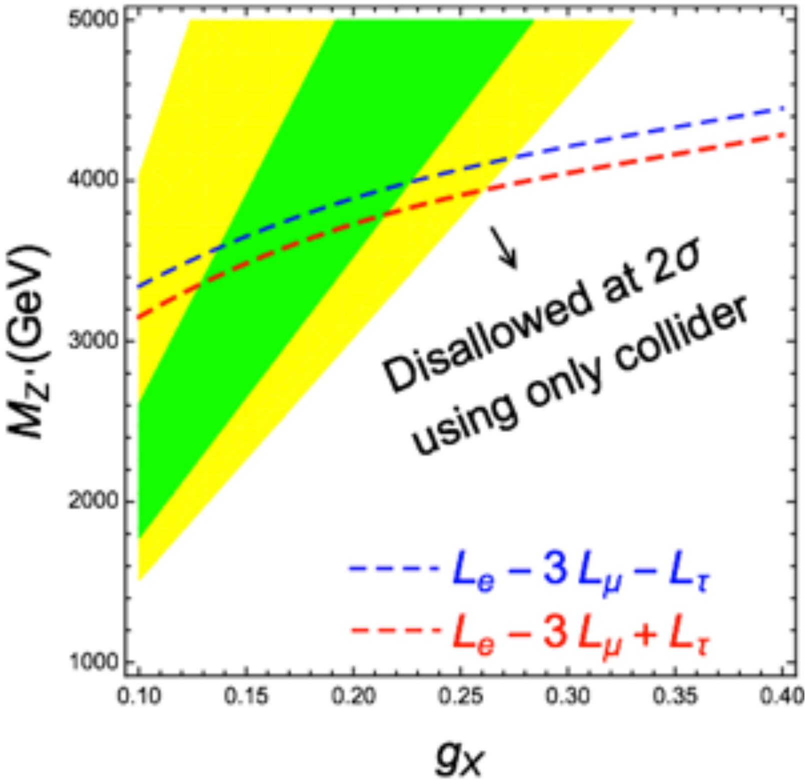
- The most important result is that this analytic procedure and PHOTOS agree within few permil

$$R_{K_{[1,6]\mathrm{GeV}^2}} = 1.00 \pm 0.01$$

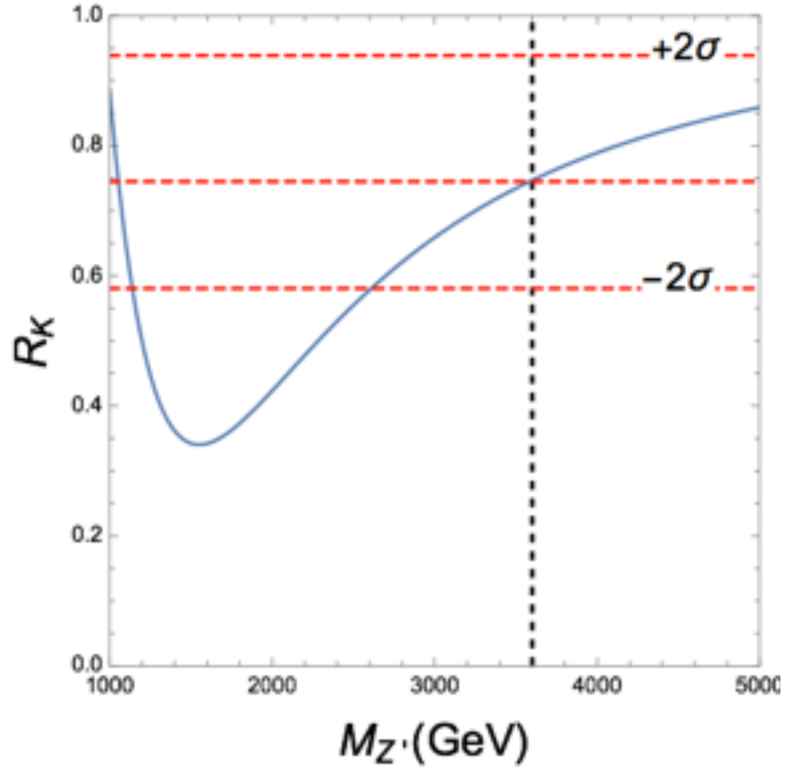
R_K in $U(1)_X$ models [Bhatia]

- Address the $b \to s$ anomalies (P_5' and R_K) and neutrino mixing in terms of a gauge boson (Z') of a new $U(1)_X$ symmetry
- After imposing all constraints (including anomaly cancellation, Bs mixing, etc..) only one possibility survives: Type-A $= Le - 3L_\mu \pm L_\tau$

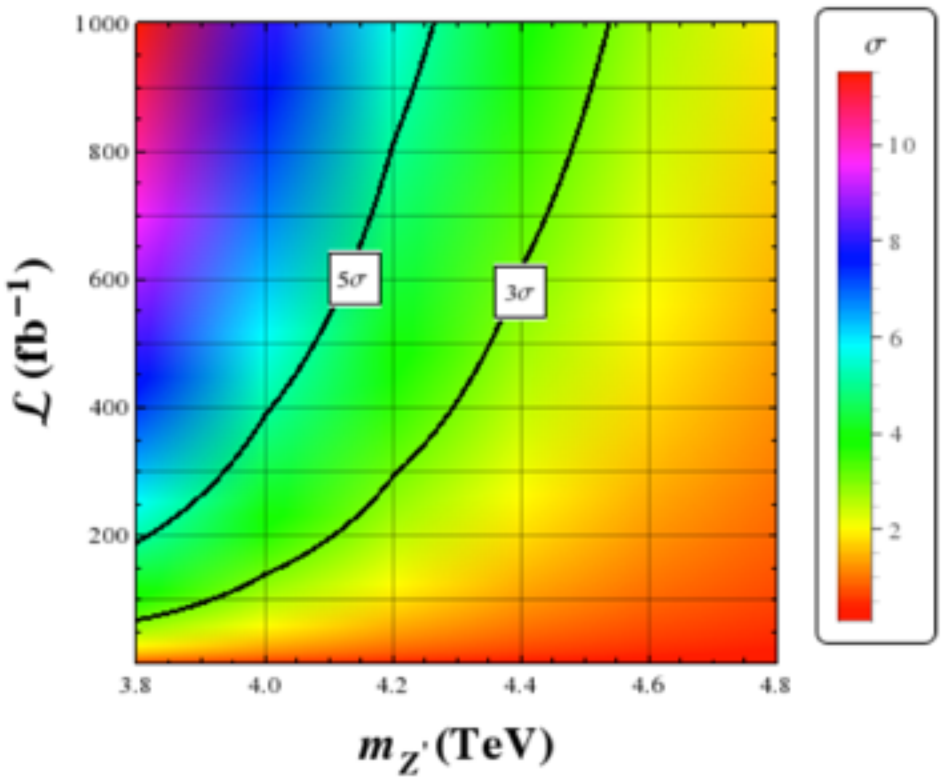
Constraint from $pp \to Z' \to \mu\mu$:



Expectations for R_K:



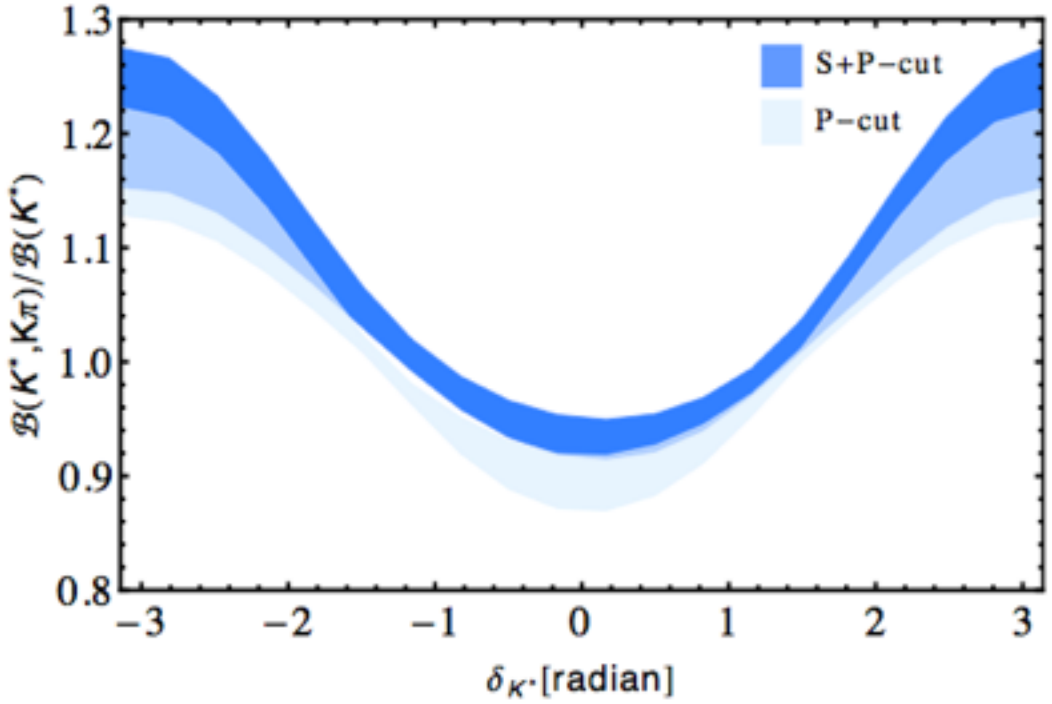
$Z' \to \mu\mu$ significance for $g_X = 0.2$:



Resonant and non-resonant effects in $B \to K^* \nu\nu$ [Das]

- $B \to K^* \nu\nu$ is controlled by form factors only (no charm effects etc…)
- Focus on backgrounds from resonant K_0^* and non-resonant $K\pi$
  - The K_0^* form factor is taken from LCSR. Its finite width is implemented with Breit-Wigner
  - Non-resonant $K\pi$ matrix elements are estimated with HHχPT and yield a non-standard θ_K dependence of the rate
- A strong phase can appear when combining resonant and non-resonant modes:

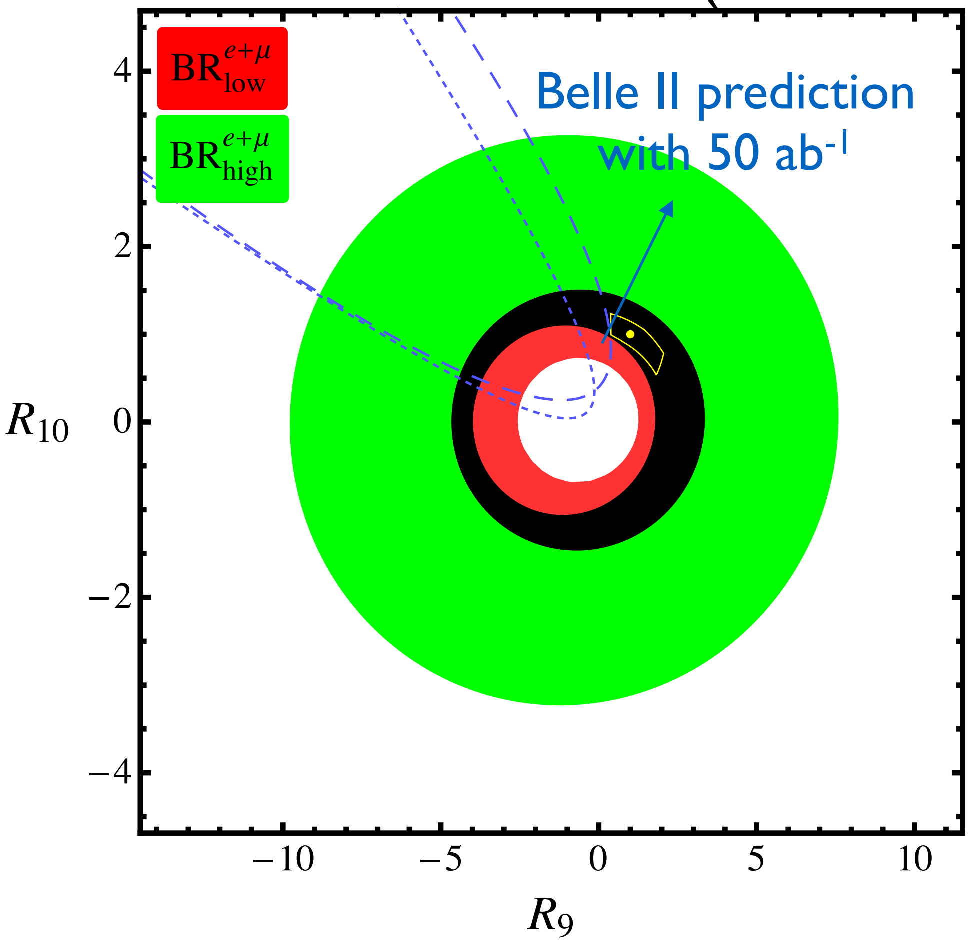
$$\frac{d^3\Gamma}{dq^2 dp^2 d\cos\theta_K} = 3\mathcal{N}(q^2)\left[|\widetilde{H_\perp} + e^{i\,\delta_{K^*}} H_\perp^{nr}|^2 + |\widetilde{H_\parallel} + e^{i\,\delta_{K^*}} H_\parallel^{nr}|^2 + |\widetilde{H_0} + e^{i\,\delta_{K^*}} H_0^{nr} + \widetilde{H_0}'|^2\right]$$



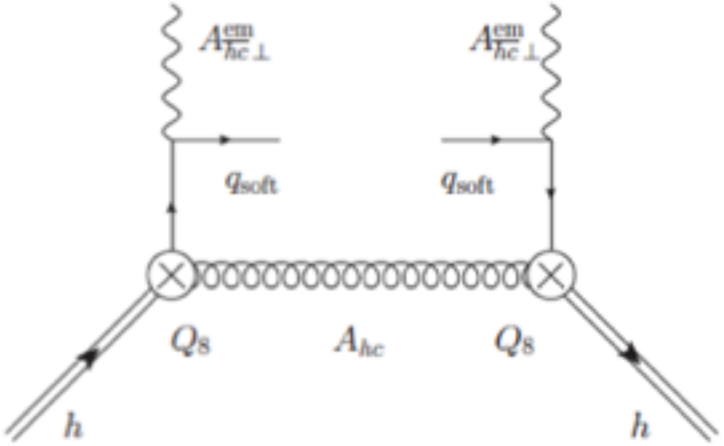
- Non-resonant and K_0^* effects can be up to 30%
- The strong phase can be extracted by looking at interference effects

Theory of inclusive $B \to X_s ll$ decays [Hurth]

- Only three observables: $\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right]$
- QED corrections enhanced by $\log(m_b/m_l)$ distort the spectrum and are included
- Local Λ^2/m_B^2 and Λ^3/m_B^3 power corrections are known
- Non-local Λ/m_B can be estimated and lead to a 5% extra uncertainty.
- Similar issues as exclusive with charmonium resonances
- Present and future ($R_i = C_i/C_i^{SM}$):



- At low-q^2, a cut on m_{X_s} is required to remove background
  - Experiments correct using a Fermi motion model
  - Effect of the cut can be calculated in SCET (work in progress)



Theory of radiative B decays [Paz]

- Inclusive $B \to X_{s,d}\gamma$ (OPE)
  - Good agreement between theory and experiment
  - Perturbatively known at NNLL ($Q_{1,2}$-Q_7 interference not calculated at physical m_c)
  - Non-perturbative effects appear at order Λ/m_b, depend on the non-local features of the B meson (shape function) and lead to a 5% uncertainty
  - Possible to use data (e.g. isosping asymmetry) to reduce some of this uncertainty
  - CP asymmetries receive large non-perturbative effects
  - Isospin difference of CP asymmetries is clean (measured by BaBar)
  - CP asymmetry on the untagged $B \to X_{s+d}\gamma$ is still almost zero due to U-spin

- Exclusive $B_{(q,s)} \to (K^*,\phi)\gamma$ and $B_{(q,s)} \to (\rho/\omega, K^*)\gamma$ (Factorization)
  - Unlike the $b \to sll$ case, the inclusive mode is well measured
  - In order to extract interesting information it is useful to consider ratios and asymmetries:

$$R^{SM}_{K^*\gamma/\phi\gamma} = 0.78 \pm 0.18 \qquad R^{exp}_{K^*\gamma/\phi\gamma} = 1.23 \pm 0.12$$

$$\bar{a}_I^{SM}(K^*\gamma) = (4.9 \pm 2.6)\% \qquad \bar{a}_I^{exp}(K^*\gamma) = (5.2 \pm 2.6)\%$$

$$\bar{a}_I^{SM}(\rho\gamma) = (5.2 \pm 2.8)\% \qquad \bar{a}_I^{exp}(\rho\gamma) = (30^{+16}_{-13})\%$$

$\pi \to l\nu$ decays in very special relativity [Jain]

- Assume Lorentz invariance violated and fundamental symmetry group is instead SIM(2) subgroup
  - Implies the existence of a **preferred direction** in space-time
- Construct effective interaction terms that violate Lorentz invariance but respect SIM(2)
  - Hadronic current in $\pi \to l\nu$ decays picks up a contribution

$$L_{VSR} = g \left(\frac{n_\mu}{n\cdot\partial}\pi^-\right)\overline{\psi}_l\gamma^\mu(1-\gamma^5)\psi_\nu + \text{h.c.}$$

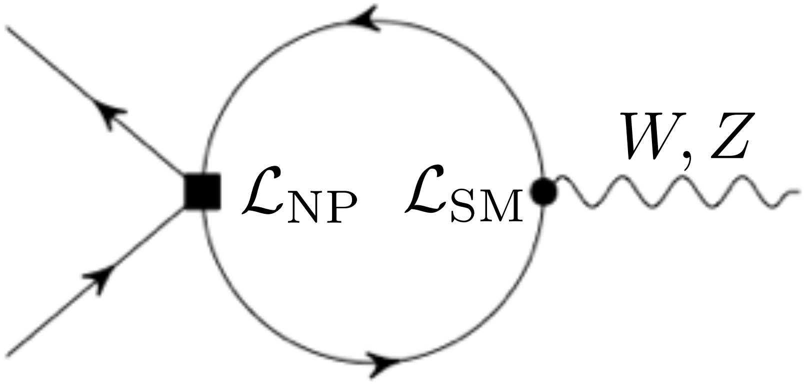
- Gives rise to **anisotropy of lepton momentum** with respect to preferred direction
  - In lab frame, anisotropy observed in distribution in azimuth ϕ
  - For $\pi \to \mu\nu$ could be $\sim 10^{-4}$, based on uncertainty for $\pi \to \mu\nu$ total partial width
- **Experimental test**
  - Look for variations as a function of sidereal time in peak position and amplitude for modulation in ϕ

Theory of LFV [Paradisi]

- The R_K anomaly suggests (via global fits) an explanation in terms of left handed operators (contribution to $Q_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$). This suggests to solve the R_D and $R_D{}^*$ anomalies in terms of $(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$.
- Assuming NP respects $SU(2)_L \otimes U(1)_Y$ there are only two coefficients:

$$\mathcal{L}_{\rm NP} = \frac{C_1}{\Lambda^2}(\bar{q}_{3L}\gamma^\mu q_{3L})(\bar{\ell}_{3L}\gamma_\mu\ell_{3L}) + \frac{C_3}{\Lambda^2}(\bar{q}_{3L}\gamma^\mu\tau^a q_{3L})(\bar{\ell}_{3L}\gamma_\mu\tau^a\ell_{3L})$$

$$= \frac{1}{\Lambda^2}[(C_1+C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu e_{Ll}) + 2C_3\left(\lambda^{ud}_{ij}\lambda^e_{kl}\,(\bar{u}_{Li}\gamma^\mu d_{Lj})(\bar{e}_{Lk}\gamma_\mu\nu_{Ll}) + h.c.\right) (C_1-C_3)\,\lambda^d_{ij}\lambda^e_{kl}\,(\bar{d}_{Li}\gamma^\mu d_{Lj})(\bar{\nu}_{Lk}\gamma_\mu\nu_{Ll}) + \cdots]$$



- After RG running ($\Lambda_{NP} \to 1\ GeV$), Z and W couplings to fermions are modified (need to impose Z-pole constraints)
- Purely leptonic and semileptonic Lagrangian modified, implying effects in
  - LFV tau decays, $\tau \to (3\mu,\ \mu\rho,\ \mu\pi)$
  - LFV B decays, $B \to K\tau\mu$
  - LFU breaking in $\tau \to l\nu\nu$: $R_\tau^{\tau/\ell_{1,2}} = \frac{\mathcal{B}(\tau\to\ell_{2,1}\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau\to\ell_{2,1}\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu\to e\nu\bar{\nu})_{\rm SM}}$

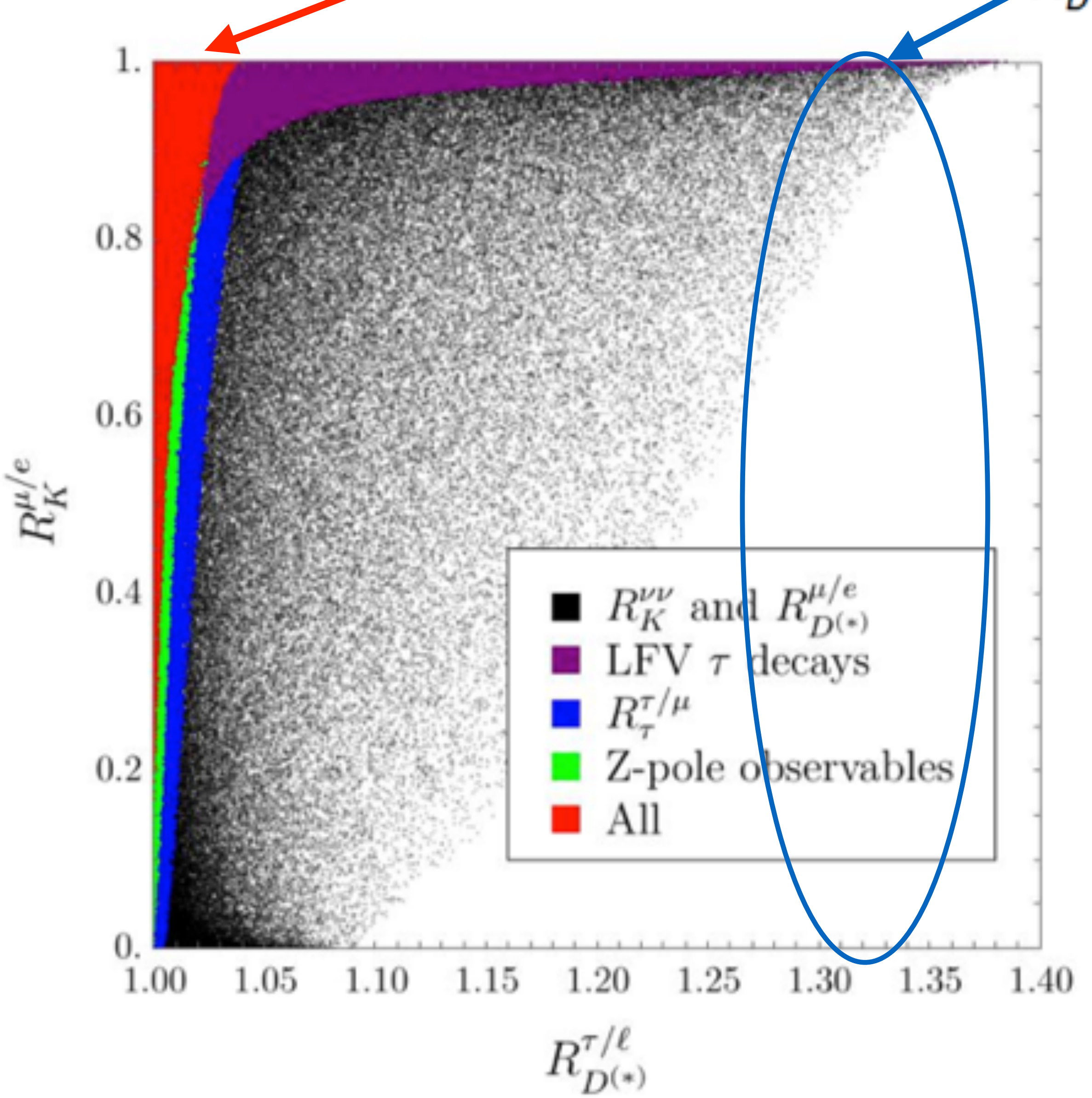
Theory of LFV [Paradisi]

- Tension between $R_{D^{(*)}}$ and R_τ: $R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030\,, \quad R_\tau^{\tau/e} = 1.0060 \pm 0.0030$ [HFAG, '14]

$$R_\tau^{\tau/\ell} \simeq 1 + 2\, c_t^{cc} \lambda_{33}^{e} \approx 1 + \frac{0.008\, C_3}{\Lambda^2(\mathrm{TeV})} \lambda_{33}^{e}$$

$$R_D^{\tau/\ell} = 1.37 \pm 0.17, \qquad R_{D^*}^{\tau/\ell} = 1.28 \pm 0.08$$

$$R_{D^{(*)}}^{\tau/\ell} \approx 1 - \frac{0.12\, C_3}{\Lambda^2(\mathrm{TeV})} \lambda_{33}^{e}$$



- Contributions generated by running effects not enough
- Need extra genuine high-scale NP effects


"I WILL NOT DIE UNTIL AMERICA IS DESTROYED"
FIDEL CASTRO
1926-2016