flavor anomalies
and the extra-dimension option

Pietro Colangelo
INFN – Bari, Italy

based on

P. Biancofiore, F. De Fazio, PC: PRD 89 (2014) 09501
P. Biancofiore, F. De Fazio, E. Scrimieri, PC: EPJ C 75 (2015) 134

Helmholtz International Summer School
Quantum Field Theories at the Limits:
from Strong Fields to Heavy Quarks
BLTP - JINR, Dubna, Russia
18-30 July 2016

Outline:

- tensions in the flavor sector
- possible NP scenarios
- custodially protected Randall-Sundrum 5D model
- few results
- role of flavor correlations

small tensions accumulated in flavor observables

Ali at this School

$$B\left(B_s^0 \to \mu^+\mu^-\right) = \left(2.8^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$B\left(B_d^0 \to \mu^+\mu^-\right) = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$$

LHCb & CMS
1411.4413

$$\overline{B}\left(B_s^0 \to \mu^+\mu^-\right)_{SM} = \left(3.65 \pm 0.23\right) \times 10^{-9}$$
$$B\left(B_d^0 \to \mu^+\mu^-\right)_{SM} = \left(1.06 \pm 0.09\right) \times 10^{-10}$$

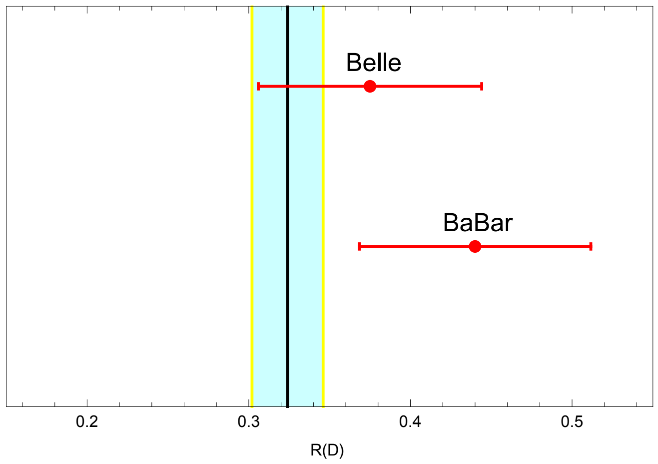
Bobeth et al,
PRL 112 (2014) 101801

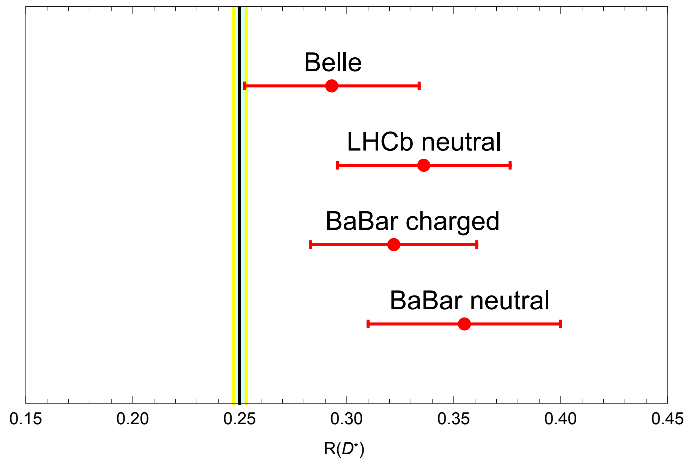
$B(B_d \to \mu^+ \mu^-)$ higher than in SM?

small tensions accumulated in flavor observables

described at this School

R(D*)=*B*(B →D* τ ν)/*B*(B →D* μ ν)
R(D)=*B*(B →D τ ν)/*B*(B →D μ ν)

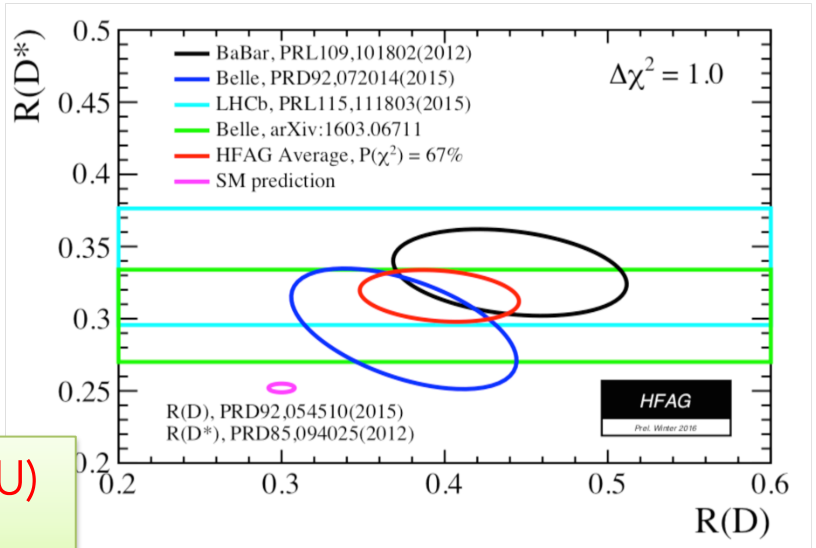




$$\mathcal{R}^0(D)|_{\rm SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell)}\bigg|_{\rm SM} = 0.324 \pm 0.022.$$

$$\mathcal{R}^0(D^*)|_{\rm SM} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell)}\bigg|_{\rm SM} = 0.250 \pm 0.003.$$

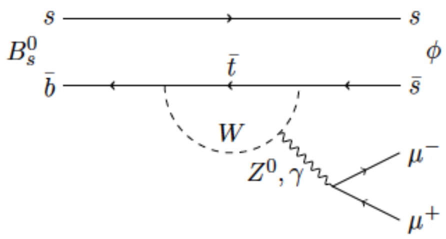
Biancofiore, De Fazio, PC, PRD 87, 074010

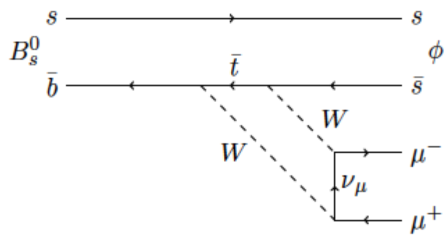


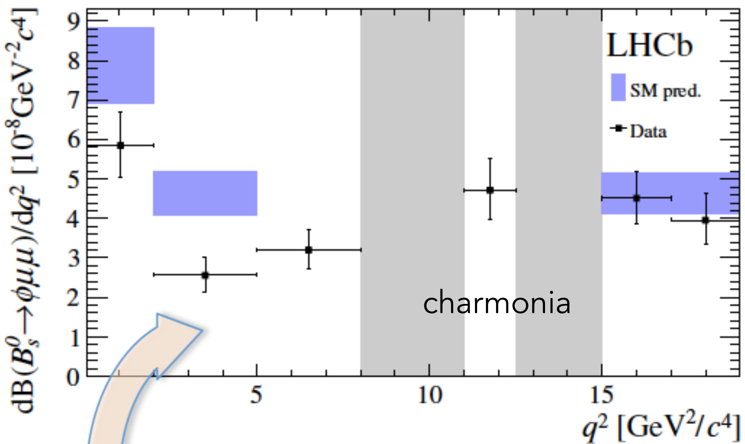
violation of Lepton Flavor Universality (LFU) in the 2nd-3rd generation?

small tensions accumulated in flavor observables

$B(B_s \to \phi \underbrace{\mu^+ \mu^-}_{q^2})$







LHCb 1506.08777

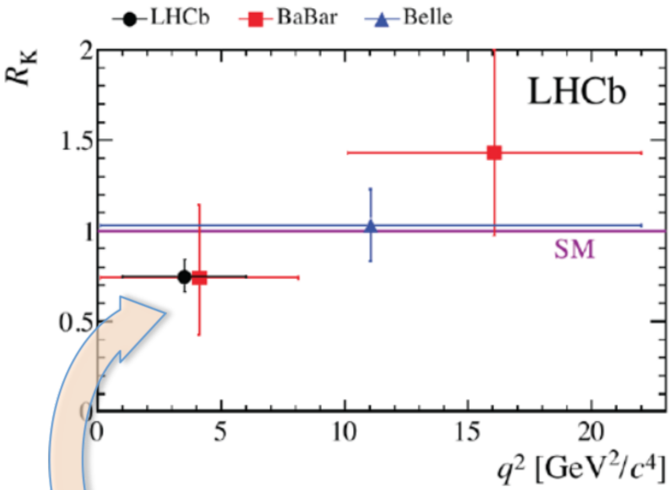
in the first two bins of q^2 [1-6 GeV^2]: deviation of 3.5 σ

hadronic uncertainties or “new physics” effects?

small tensions accumulated in flavor observables

described at this School

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+\to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+\to K^+e^+e^-]}{dq^2} dq^2},$$



LHCb PRL (2014) 151601

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}).$$

violation of LFU in the 1st-2nd generation?

small tensions accumulated in flavor observables

- $\boxed{\begin{array}{ll} V_{ub}\big|_{incl} \ \text{vs} \ V_{ub}\big|_{excl} & (\approx 3\sigma) \\ V_{cb}\big|_{incl} \ \text{vs} \ V_{cb}\big|_{excl} & (\approx 3\sigma) \end{array}}$

- $\boxed{(g-2)_\mu \qquad (\approx 3.5\sigma)}$

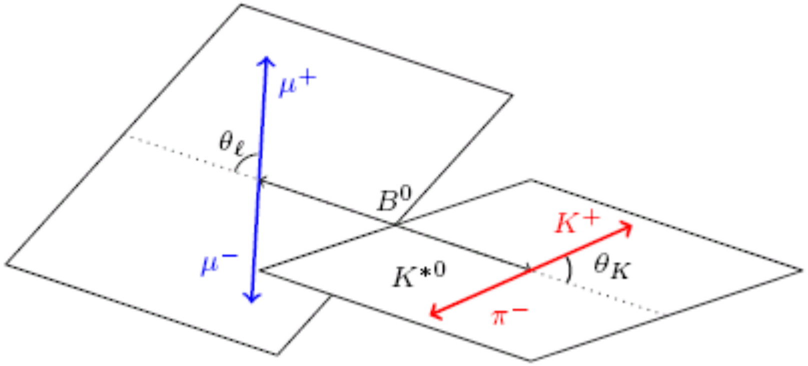
- $\boxed{\varepsilon'/\varepsilon \qquad (\approx 2-3\sigma \text{ above the SM result})}$

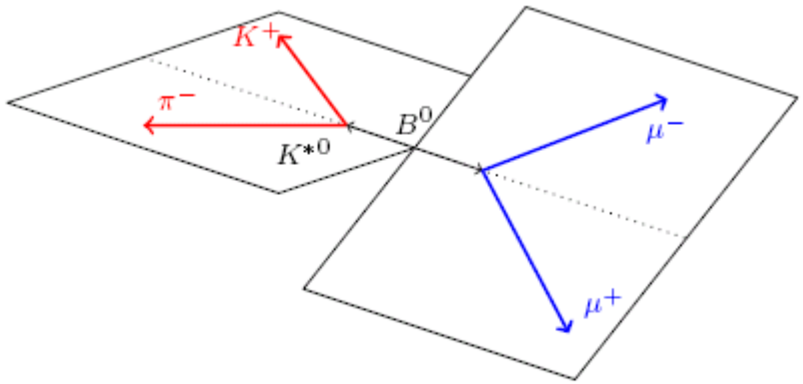
- $h \to \tau\mu$ hints for a non zero result - but new CMS measurement (2016) towards zero

  Leonardo at this School

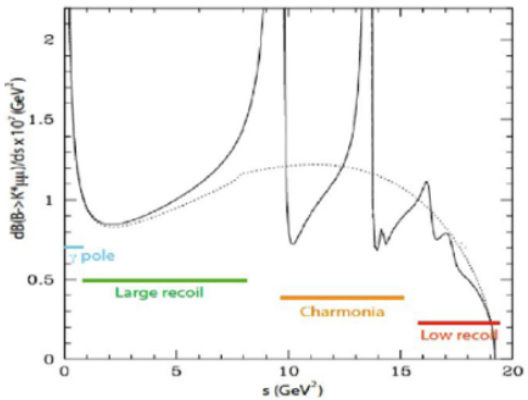
angular distributions in B → K* (K π) μ+ μ-

Sinha at this School





$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



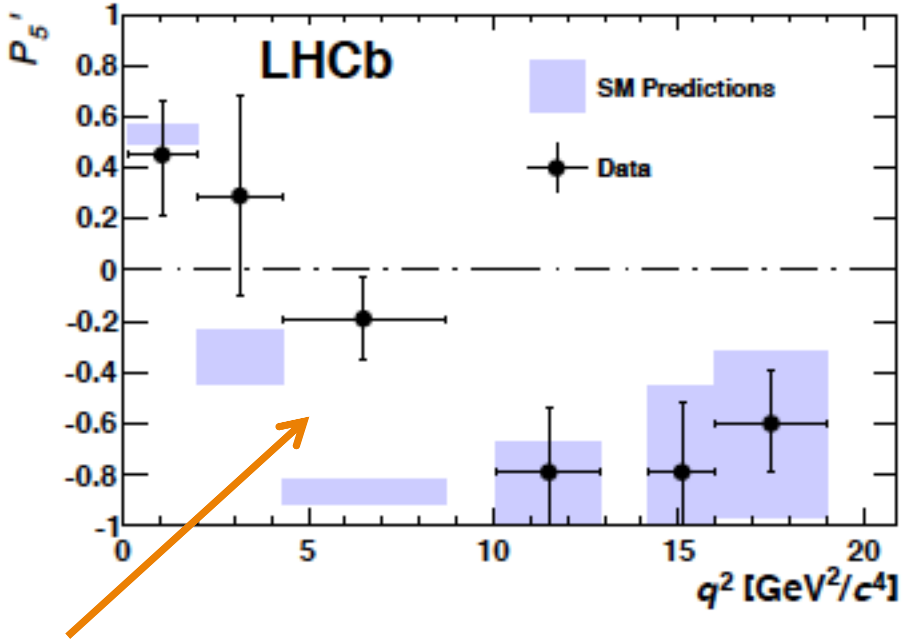
$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.}$$

mild (?) form factor dependence

Descotes, Matias, Virto, …

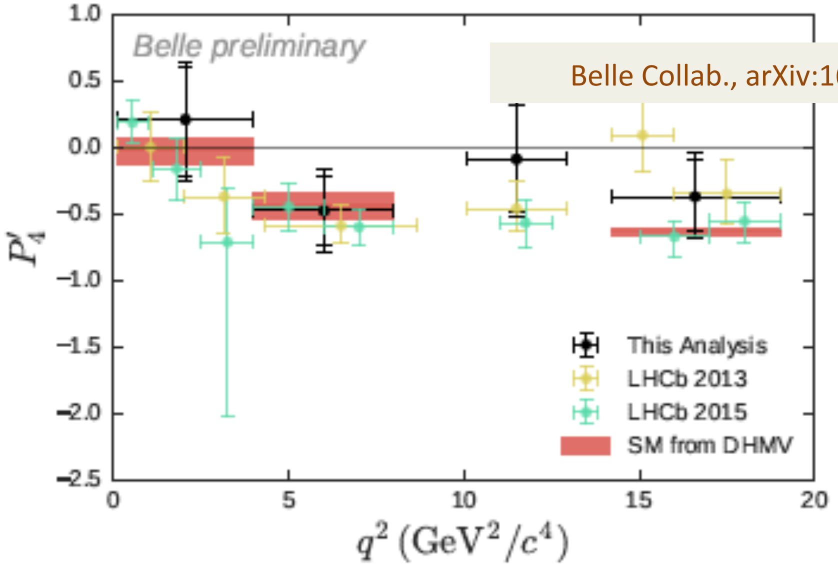
observables in $B \rightarrow K^* \mu^+ \mu^-$

LHCb
PRL 111 (2013) 191801

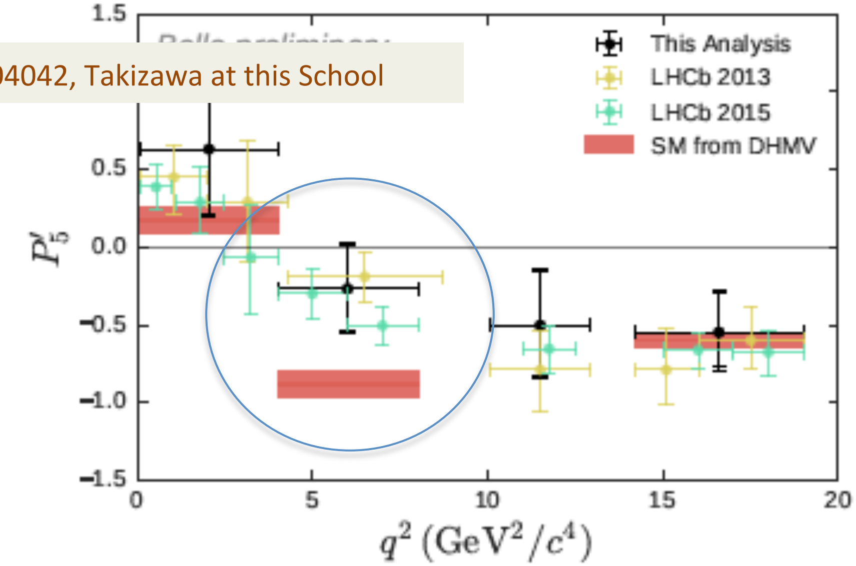


discrepancy in two bins of q^2

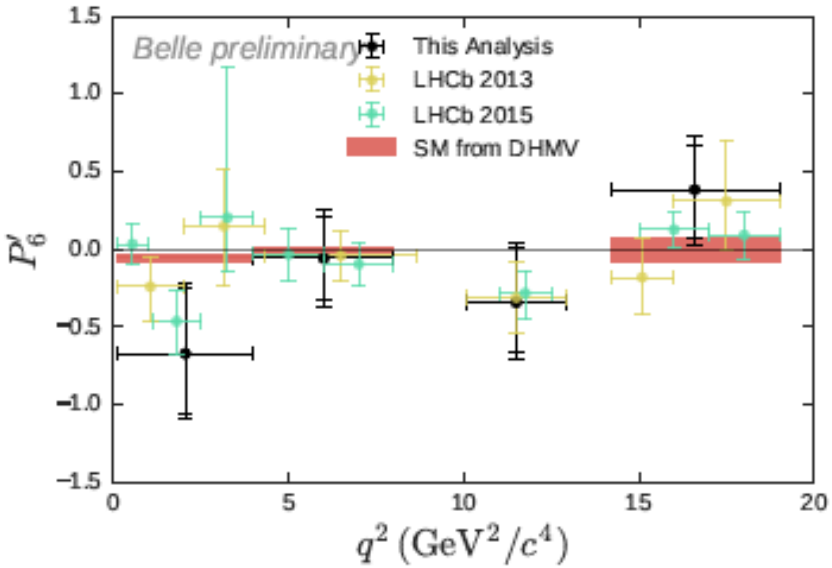
Belle Collab., arXiv:1606.04042, Takizawa at this School



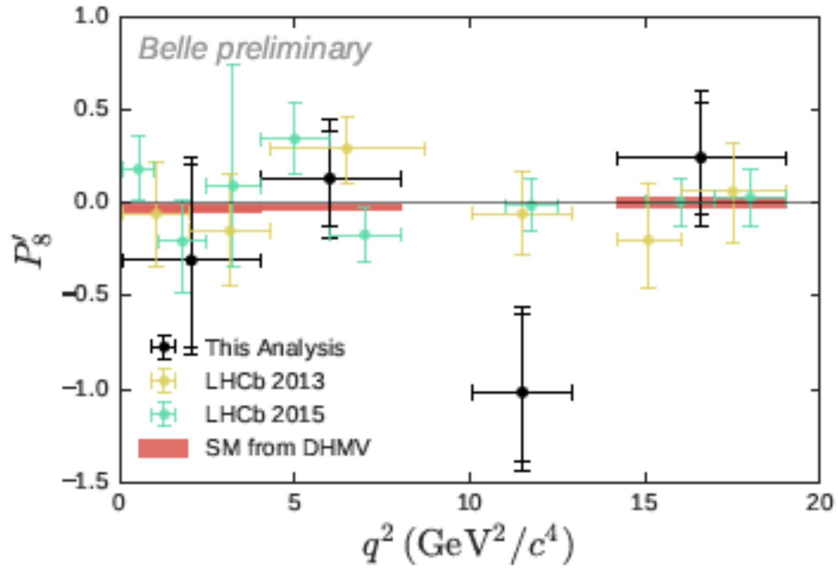
(a)Result for P_4'



(b)Result for P_5'



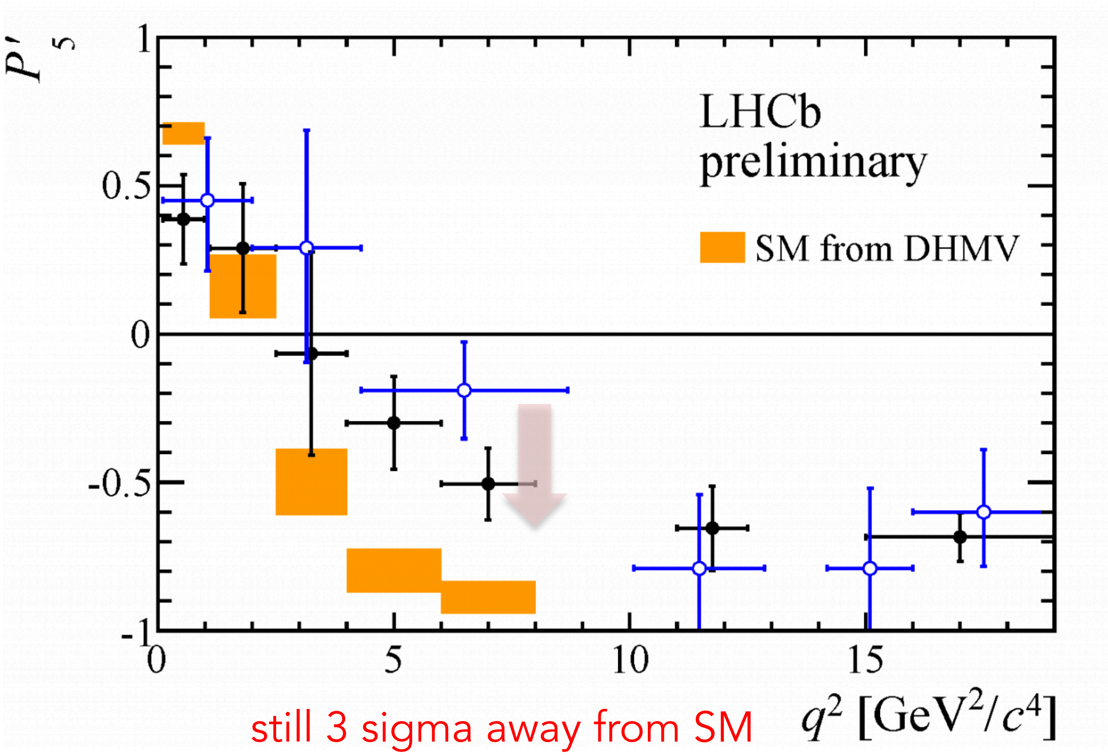
(c)Result for P_6'



(d)Result for P_8'

observables in $B \to K^* \mu^+ \mu^-$

LHCb 2015



still 3 sigma away from SM

underestimated SM effects? (hadr. uncertainty?)

$B \to K^* \mu^+ \mu^-$

$$H^{eff} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^* \left\{C_1 O_1 + C_2 O_2 + \sum_{i=3,..,6} C_i O_i + \sum_{i=7,..,10,P,S} [C_i O_i + C_i' O_i']\right\}$$

mostly relevant

$$O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_{L\alpha} \sigma^{\mu\nu} b_{R\alpha}) F_{\mu\nu}$$
$$O_7' = \frac{e}{16\pi^2} m_b (\bar{s}_{R\alpha} \sigma^{\mu\nu} b_{L\alpha}) F_{\mu\nu}$$

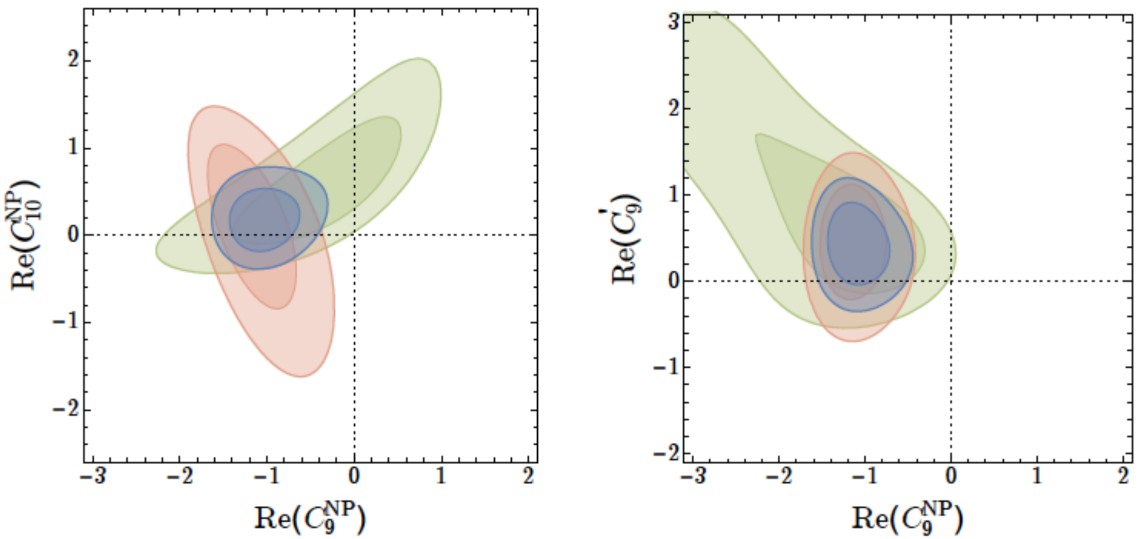
$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha})\, \bar{\ell}\gamma_\mu \ell$$
$$O_9' = \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha})\, \bar{\ell}\gamma_\mu \ell$$
$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}_{L\alpha} \gamma^\mu b_{L\alpha})\, \bar{\ell}\gamma_\mu \gamma_5 \ell$$
$$O_{10}' = \frac{e^2}{16\pi^2} (\bar{s}_{R\alpha} \gamma^\mu b_{R\alpha})\, \bar{\ell}\gamma_\mu \gamma_5 \ell\,.$$

if the anomaly is due to NP, how large should be the NP contributions to the relevant Wilson coefficients C_i?

global fits from b->s measurements

Altmannshofer, Straub 1503.06199

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$



LHCb & upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb^{-1} recorded during Run 2) and for the LHCb Upgrade (50 fb^{-1}). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Important role of BELLE II

tensions should be considered within possible NP realizations

discussed today: the extra-dimension option

main motivation: hierarchy

RS_c model

concrete models -> precise correlations among the observables

tensions should be considered within possible NP realizations

discussed today: the extra-dimension option

main motivation: hierarchy

RS_c model

not of a simple model

concrete models -> precise correlations among the observables

tensions should be considered within possible NP realizations

discussed today: the extra-dimension option

main motivation: hierarchy

RS_c model

not of a simple model

concrete models -> precise correlations among the observables

interesting correlations found in RS_c

simple introduction to extra dimensions

why extra dimensions?

first proposal

- 1914 G. Nordstrom
- 1921 T. Kaluza; 1926 O. Klein

idea: unification of gravity and electromagnetism could be achieved in 5 dimensions

- String theory (incorporating both gauge theories and gravitation) requires 6 or 7 extra spatial dimensions

today

- address the hierarchy problem
- provide dark matter candidates
- coupling unification
- ....

Arkani-Hamed, Dimopoulos, Dvali
Antoniadis
Randall, Sundrum
Dienes, Dudas, Gherghetta
...

massless scalar field in 5D

$$S=\int d^4x\int_{y_1}^{y_2} dy\ \ \frac{1}{2}\partial_A\Phi(x,y)\partial^A\Phi(x,y)$$

y_1, y_2 arbitrary $\quad$ A = 0,1,2,3,5

Try $\quad \Phi(x,y)=\sum_n \phi_n(x)\chi_n(y)$ $\quad$ and assume $\int_{y_1}^{y_2} dy\, \chi_n(y)\,\chi_m(y)=\delta_{nm}$

If $\quad \left[\chi_m\partial_y\chi_n\right]_{y_1}^{y_2}=0$ $\quad$ and $\quad \left(\partial_y^2+m_n^2\right)\chi_n=0 \quad \forall n,m$

$$\Rightarrow \quad \boxed{S=\int d^4x \quad \sum_n \frac{1}{2}\left(\partial_\mu\phi_n\partial^\mu\phi_n-m_n^2\phi_n^2\right) \qquad \mu=0,1,2,3}$$

in 4D there is a tower of states with mass m_n (KK modes)

possible BC

$$\begin{cases} \chi_m\Big|_{y_1}^{y_2}=0 & \text{Dirichlet BC} \\ \partial_y\chi_n\Big|_{y_1}^{y_2}=0 & \text{Von Neumann BC}\end{cases}$$

massless scalar field in 5D

$$\left(\partial_y^2 + m_n^2\right)\chi_n = 0 \qquad \Rightarrow \qquad \chi_n = A_n e^{im_n y} + B_n e^{-im_n y}$$

Analogy with quantum mechanics:

- The solution of the Schroedinger equation for the free particle is

$$\psi = Ae^{ipy} + Be^{-ipy}$$

Therefore $m_n \leftrightarrow p$

- If the particle moves along an infinite axis (non compact space) p has continuous values

- If the particle is confined in a box $0 \le y \le \pi L$ (compact space)

$$\psi(0) = \psi(\pi L) = 0 \qquad \Rightarrow \qquad p = n\frac{\pi}{L}$$

$$\psi \approx \sin\left(\frac{n\pi y}{L}\right)$$

absence of zero mode

$\boxed{\text{massless scalar field in 5D}}$

Similar situation in 5D: we consider that the 5th dimension y is $-\pi R \leq y \leq \pi R$

with periodic boundary conditions (geometry= unidimensional sphere S^1)

$$\chi_n(-\pi R) = \chi_n(\pi R) \qquad \Rightarrow \qquad m_n = \frac{n}{R}$$

$$\chi_n \approx A_n \cos\left(\frac{ny}{R}\right) + B_n \sin\left(\frac{ny}{R}\right) \longrightarrow \text{there is a zero mode}$$

- combine the geometry S^1 with a parity operation for $y \in [-\pi R, \pi R]$:

$$Z_2 : y \rightarrow -y$$

- require that χ_n have definite behaviour under Z_2

$$\Rightarrow \begin{cases} \chi_n \approx \cos\left(\frac{ny}{R}\right) \longrightarrow \text{even under } Z_2\text{, satisfies } \partial_y \chi_n \Big|_{-\pi R}^{\pi R} = 0 \\ \chi_n \approx \sin\left(\frac{ny}{R}\right) \longrightarrow \text{odd under } Z_2\text{, satisfies } \chi_n \Big|_{-\pi R}^{\pi R} = 0 \end{cases}$$

Geometry S^1/Z_2 $\longrightarrow$ orbifold

compactified extra dimensions

three main scenarios:

- Large extra dimensions (ADD)
- Universal extra dimension (UED)
- Warped extra dimensions (RS)

Large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali

Proposed as a possible solution to the hierarchy problem

★ Scale of weak interactions set by the Fermi constant

$$G_F = \frac{1}{(\sqrt{2}v^2)} \cong 1.166\times10^{-5} \quad \text{GeV}^{-2}$$

→ Higgs vev $v \approx 246 \quad \text{GeV}$

★ Gravitation: Newton constant

$$G_N = \frac{1}{(\sqrt{2}M_{Pl}{}^2)} \cong 6.7\times10^{-39} \quad \text{GeV}^{-2}$$

→ Planck mass $M_{Pl} \approx 10^{19} \quad \text{GeV}$

why such a hierarchy?

Is M_{Pl} the fundamental scale?

In D=4 $$F = G\frac{m_1 m_2}{r^2}$$

with $$G = \frac{1}{4\pi M_{Pl}^2}$$

In D=4+n $$F = G^{(n)}\frac{m_1 m_2}{r^{n+2}}$$

$$G^{(n)} = \frac{1}{4\pi M^{n+2}}$$

Matching at r=R $$G^{(n)}\frac{m_1 m_2}{R^{n+2}} = G\frac{m_1 m_2}{R^2} \Rightarrow G = \frac{G^{(n)}}{R^n}$$

$$\boxed{M_{Pl}^2 = R^n M^{n+2}}$$

fundamental scale no more M_{Pl} but M

for suitable values of R and n it could be M=O(TeV)

Large extra dimensions

M=O(TeV) ->

$$n = 1 \quad \Rightarrow \quad R \cong 10^{11} \ m$$ ➡ Too large!

$$n = 2 \quad \Rightarrow \quad R \cong 1 \ \mu m$$

in this scenario $n \geq 2$

SM fields do not feel the effects of large extra dimensions
and are confined to a 3-brane
Gravity is allowed to propagate in the bulk

Large extra dimensions: collider signatures

- real emission of gravitons and their KK excitations

$$\left\{ \begin{array}{l} e^+e^- \to \gamma(Z) + G_{(n)} \\ p\bar{p}(pp) \to g + G_{(n)} \\ Z \to f\bar{f} + G_{(n)} \end{array} \right.$$

the produced graviton behaves as a stable,
non interacting particle and thus appears as missing energy in the detector

- virtual graviton exchange in 2 → 2 scattering.

deviations in cross sections and asymmetries in SM processes such as $e^+e^- \to f\bar{f}$

Also possible to observe processes like $gg \to \ell^+\ell^-$

↳ the analysis of the angular distribution of the final states could signal the spin-2 nature of the intermediate state

Universal extra dimensions

Appelquist, Cheng, Dobrescu
PRD 64 (01) 035002

Universal Extra Dimensions are compact dimensions of size $R^{-1} \approx TeV$
accessible to all SM fields

KK parity $(-1)^j$ (j=KK number) conservation in the equivalent 4D theory

- no vertices involving a single non zero KK mode
  $\longrightarrow$ no tree level contribution to the EW observables

- non zero KK modes may be produced at colliders only
  in groups of 2 or more

Appelquist-Cheng-Dobrescu model (ACD): a single ED

- A single additional parameter: 1/R
- Minimal extension of the SM in 4+1 dimensions containing:

  - KK excitations of the SM fields
  - KK modes having no SM partner

under P_5 fields having a correspondent in the SM are even: the zero mode is the SM field

fields without SM partner : odd under P_5

unwanted fields (fermions with the wrong chirality and the 5th component of gauge fields) can be projected out

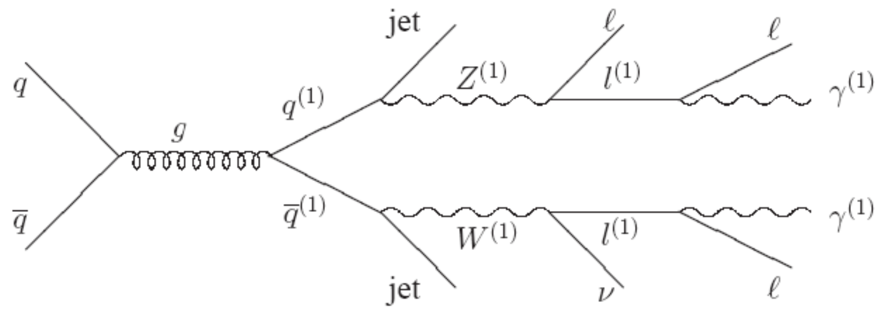
Universal extra dimensions: signatures at hadron colliders

Discovery of KK modes

Since masses are roughly $\approx \frac{n}{R}$ particles with $n \geq 3$ would be heavy and difficult to detect

→ modes with n=1 and n=2

1-modes may be produced in pairs at colliders



→ escapes detection
dark matter candidate

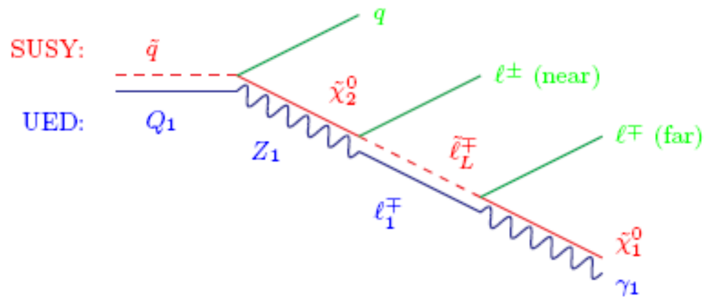
problem: how to distinguish these processes from SUSY :
1-modes are analogous to superpartners in SUSY
(KK parity resambles R parity …)

ED vs SUSY

	SUSY	ED
number of predicted partners	1 superpartner for each SM particle	tower of KK states (though cross sections for the production of higher modes are kinematically suppressed)
spin of partners	differs of ½	SM particles and their KK partners have the same spin
couplings	the same as for SM particles	the same as for SM particles
collider signature	missing energy (in models with a WIMP LSP)	missing energy

common features

example: twin processes



SUSY: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\ell^\pm\tilde{\ell}^\mp \to q\ell^+\ell^-\tilde{\chi}_1^0$

UED: $Q_1 \to qZ_1 \to q\ell^\pm\tilde{\ell}_1^\mp \to q\ell^+\ell^-\gamma_1$

same observed final state $q\ell^+\ell^-\not{E}_T$

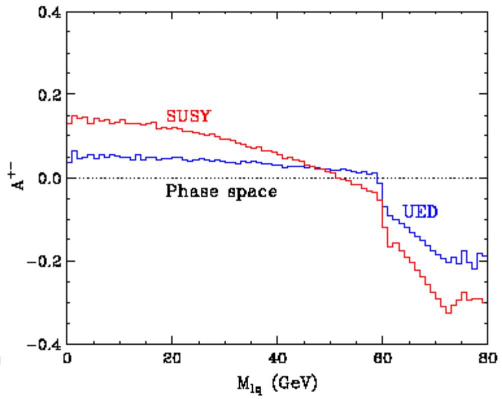
proposal

Barr, PLB 596 (04) 205
Datta et al., PRD 72 (05) 096006
Smillie and Webber, JHEP 510 (05) 69

consider the charge asymmetry $A^{+-} = \frac{s^+ - s^-}{s^+ + s^-}$ $\qquad s^\pm = \frac{d\sigma}{d(m_{\ell_\pm q})}$

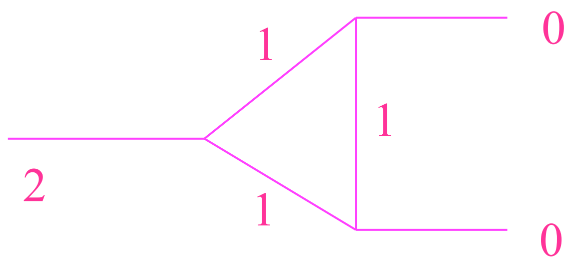
shape slightly different in the two cases

challenging!

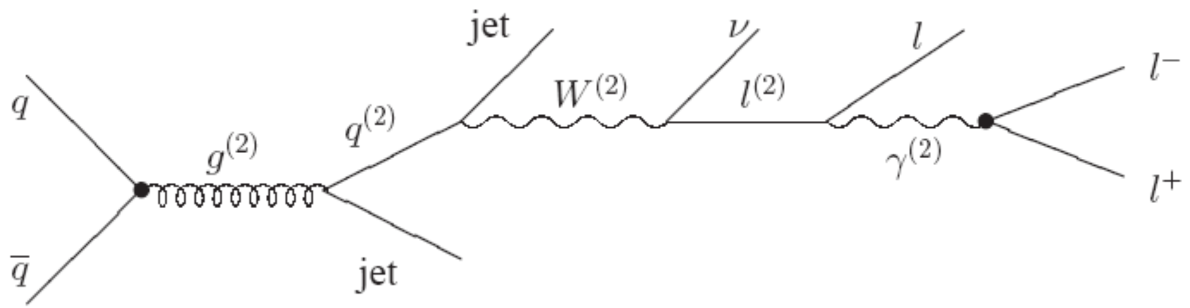


2-modes

They may be pair produced as the 1-modes
However, unlike them, they can decay into SM particles at 1 loop



The loop-induced coupling 2-0-0 allows 2-modes to be singly produced in the s-channel



$g^{(2)}$ could be observed as a narrow resonance.
However, one should discover several almost degenerate KK gauge boson resonances

UED vs SUSY: signatures at high energy lepton colliders

example: UED $e^+e^- \to \mu_1^+\mu_1^- \to \mu^+\mu^-\gamma_1\gamma_1$

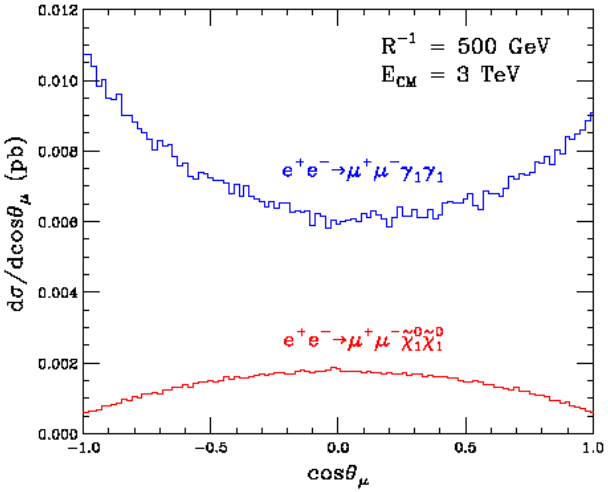
SUSY $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

for $\frac{1}{R} = 500 \quad \mathrm{GeV} \qquad \sqrt{s} = 3 \quad \mathrm{TeV}$

differential cross section as a function of the muon scattering angle

$$\left.\left(\frac{d\sigma}{d\cos\vartheta}\right)\right|_{UED} \approx 1 + \cos^2\vartheta$$

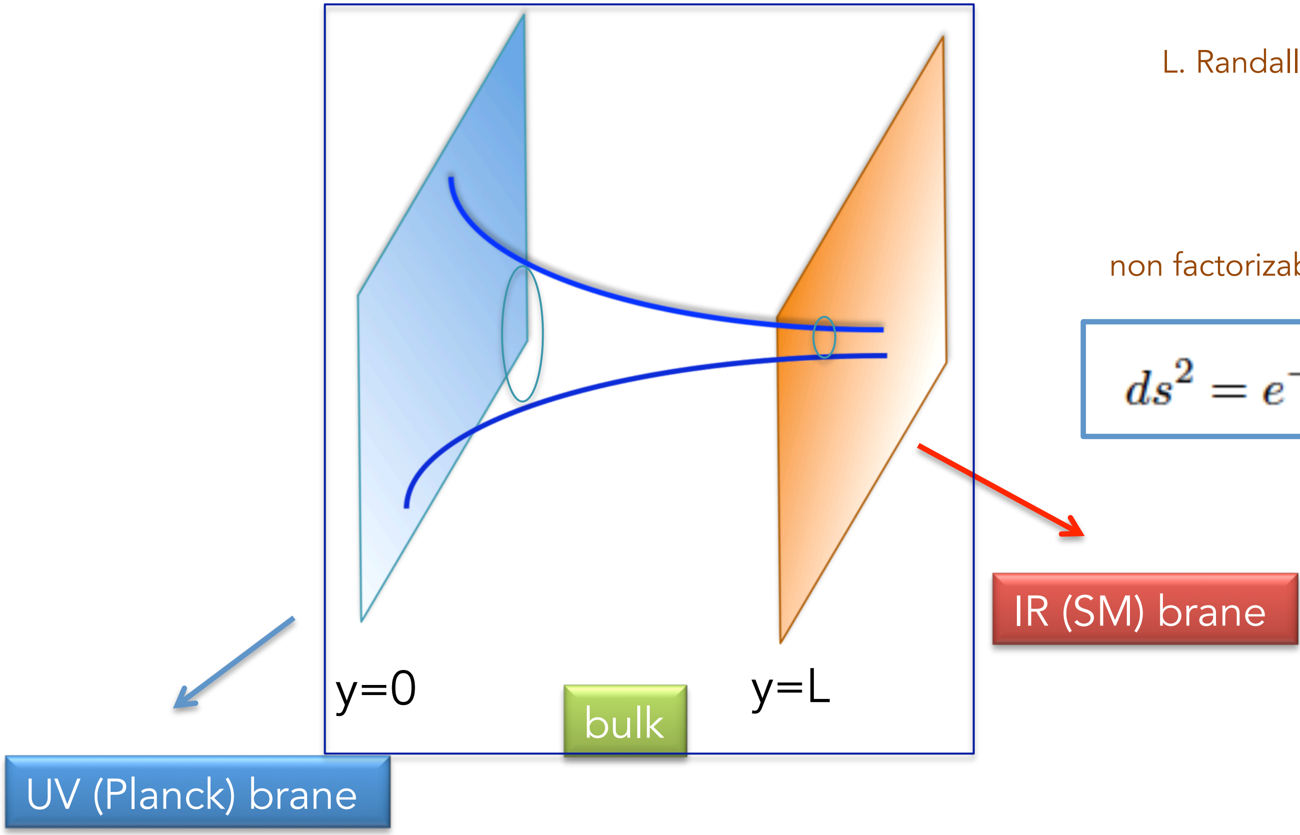
$$\left.\left(\frac{d\sigma}{d\cos\vartheta}\right)\right|_{SUSY} \approx 1 - \cos^2\vartheta$$



M. Battaglia et al., hep-ph/0507284

b-> s processes in warped extra dimensions

geometry of the RS model: 4 (x^μ) +1 (y) dimensions



L. Randall, R. Sundrum, PRL 83 (99) 8370

non factorizable geometry

$$\boxed{ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2}$$

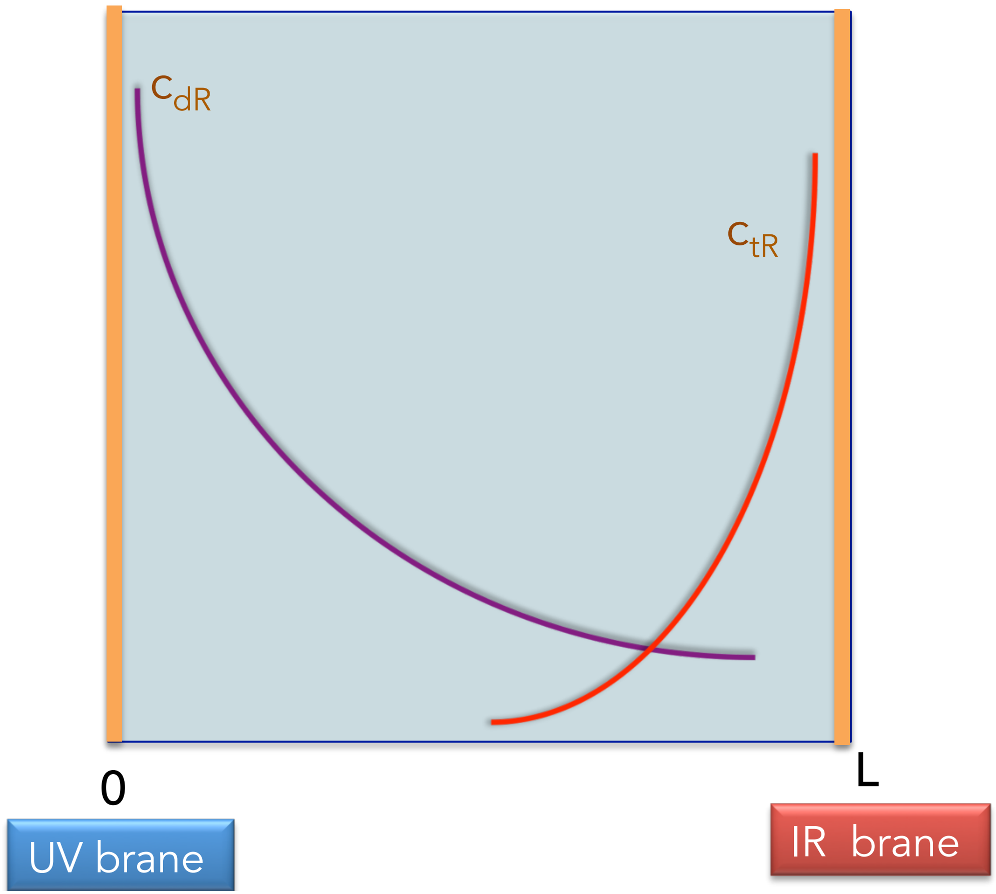
$$k \approx O(M_{Pl})$$

$$k\, e^{-kL} \approx O(TeV)$$

$$kL = Log\left(\frac{M_{Pl}}{M_{EW}}\right) \approx 37$$

- all fields propagate in the bulk, Higgs localized close to or on the IR brane
- solution of the hierarchy problem via geometry
- produces patterns in fermion masses and mixing

bulk Higgs considered, eg, in Archer et al, JHEP 1501 (2015) 060



fermion localization in the extra dimension depends exponentially on O(1) bulk mass parameters c

overlap with a Higgs localized on IR exponentially small for light quarks
O(1) for top

custodially protected RS_c

Agashe et al PLB641 (06) 62
Carena et al NPB 759 (06) 202
Cacciapaglia et al PRD75 (07) 015003
Blanke et al JHEP 0903 (09) 001
Casagrande et al JHEP 1009 (09) 014

extended gauge group: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{L,R}$

implies a mirror action of the two SU(2) groups

pros:
- prevents large Z couplings to left-handed fermions
- consistent with electroweak precision observables without large fine-tuning
- masses of Kaluza-Klein of a few TeV (within the LHC reach)

S, T, U parameters (Peskin-Takeuchi)

modified in NP models

in terms of vacuum polarization amplitudes

$$\gamma \sim\!\bullet\!\sim \gamma = i\, e^2\, \Pi_{QQ}\, g^{\mu\nu} + \cdots$$

$$Z \sim\!\bullet\!\sim \gamma = i\, \frac{e^2}{cs}\, (\Pi_{3Q} - s^2\, \Pi_{QQ})\, g^{\mu\nu} + \cdots$$

$$Z \sim\!\bullet\!\sim Z = i\, \frac{e^2}{c^2 s^2}\, (\Pi_{33} - 2s^2\, \Pi_{3Q} + s^4\, \Pi_{QQ})\, g^{\mu\nu} + \cdots$$

$$W \sim\!\bullet\!\sim W = i\, \frac{e^2}{s^2}\, \Pi_{11}\, g^{\mu\nu} + \cdots$$

$$\alpha S \equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)]\ ,$$

$$\alpha T \equiv \frac{e^2}{s^2 c^2 m_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)]\ ,$$

$$\alpha U \equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)]\ .$$

modification of the Peskin-Takeuchi parameters

In RS without custodial protection:

$$S = \frac{2\pi v^2}{M_{KK}^2}\left(1 - \frac{1}{kL}\right) \qquad T = \frac{\pi v^2}{2\cos^2\theta_W M_{KK}^2}\left(\underbrace{kL - \frac{1}{2kL}}_{\simeq 37}\right)$$

large correction to the T parameter expected
(T quantifies the strength of weak isospin breaking)

RS with custodial protection

$$S = \frac{2\pi v^2}{M_{KK}^2}\left(1 - \frac{1}{kL}\right) \qquad T = -\frac{\pi v^2}{4\cos^2\theta_W M_{KK}^2}\frac{1}{2kL}$$

T suppressed

compact ED -> tower of Kaluza-Klein (KK) excitatios for each particle

SM particles identified with zero-modes

boundary conditions on the branes distinguish particles with a SM counterpart from those without it

Neumann BC on both branes (++) -> zero-modes (SM states)

Neumann BC on the IR brane + Dirichlet BC on the UV brane-> no zero-modes

enlarged Higgs sector

Higgs field H(x,y) transforms as a bidoublet under $SU(2)_L$ x $SU(2)_R$

$$H(x,y) = \begin{pmatrix} \frac{\pi^+}{\sqrt{2}} & -\frac{h^0 - i\pi^0}{2} \\ \frac{h^0 + i\pi^0}{2} & \frac{\pi^-}{\sqrt{2}} \end{pmatrix}$$

$\Rightarrow$ two charged & two neutral components

KK decomposition $$H(x,y) = \frac{1}{\sqrt{L}} \sum_k H^{(k)}(x) h^{(k)}(y)$$

only h^0 has a non vanishing vev v=246.22 GeV

localization on the IR brane fulfilled by choosing

$$h(y) \equiv h^{(0)}(y) \simeq e^{kL} \delta(y - L)$$

extended gauge group -> new gauge bosons

$SU(2)_L \rightarrow W_L^{a,\mu}$

$SU(2)_R \rightarrow W_R^{a,\mu}$

$U(1)_X \rightarrow X^\mu$

charged

$$W^{\pm}_{L(R)\mu} = \frac{W^1_{L(R)\mu} \mp i W^2_{L(R)\mu}}{\sqrt{2}}$$

neutral: two-step mixing

$W_R^3 + X$

$$Z_{X\mu} = c_\phi W^3_{R\mu} - s_\phi X_\mu$$
$$B_\mu = s_\phi W^3_{R\mu} + c_\phi X_\mu$$

$$c_\phi = \cos\phi = \frac{g}{\sqrt{g^2 + g_X^2}}$$
$$s_\phi = \sin\phi = \frac{g_X}{\sqrt{g^2 + g_X^2}}$$

$W_L^3 + B$

$$Z_\mu = c_\psi W^3_{L\mu} - s_\psi B_\mu$$
$$A_\mu = s_\psi W^3_{L\mu} + c_\psi B_\mu$$

$$c_\psi = \cos\psi = \frac{1}{\sqrt{1 + s_\phi^2}}$$
$$s_\psi = \sin\psi = \frac{s_\phi}{\sqrt{1 + s_\phi^2}}$$

gauge bosons after mixing

- gluons $G_\mu(++)$
- charged bosons $W_L^{\pm}(++)$ and $W_R^{\pm}(-+)$
- neutral bosons $A(++),\, Z(++)$ and $Z_X(-+)$

+ KK towers

further mixing occurs between zero-modes and higher KK states

$$\begin{pmatrix} W^{\pm} \\ W_H^{\pm} \\ W'^{\pm} \end{pmatrix} = \mathcal{G}_W \begin{pmatrix} W_L^{\pm(0)} \\ W_L^{\pm(1)} \\ W_R^{\pm(1)} \end{pmatrix}$$

$$\begin{pmatrix} Z \\ Z_H \\ Z' \end{pmatrix} = \mathcal{G}_Z \begin{pmatrix} Z^{(0)} \\ Z^{(1)} \\ Z_X^{(1)} \end{pmatrix}$$

gauge boson profiles

KK decomposition

$$V_\mu(x,y) = \frac{1}{\sqrt{L}} \sum_{n=0}^{\infty} V_\mu^{(n)}(x) f_V^{(n)}(y)$$

free action

$$S_{\text{gauge}} = \int d^5x \sqrt{G} \left(-\frac{1}{4} F_{MN} F^{MN} \right)$$

- eqs of motion derived
- solutions depend on the BC
- provide the gauge boson profiles

fermions

ordinary fermions in suitable representations of the enlarged gauge group together with new massive fermions

quark mass eigenstates obtained upon rotation of the flavor eigenstates

4 rotation matrices:
$U_{L,R}$ $D_{L,R}$ for up left- (right-) and down left- (right-) type quarks

$$V_{CKM} = \mathscr{U}_L^\dagger \mathscr{D}_L$$

one of the 4 matrices can be eliminated in favor of the CKM
the others enter in the Feynman rules of neutral and charged current interactions

fermions

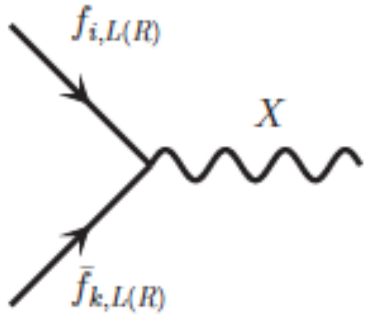
- left-handed fermions + new fermions transform as bi-doublets under $SU(2)_L$ x $SU(2)_R$
- right-handed up-type quarks are singlets
- right-handed down-type quarks + leptons + new fermions placed in multiplets transforming as $(3,1) \oplus (1,3)$ under $SU(2)_L$ x $SU(2)_R$
- electric charge $Q = T^3_L + T^3_R + Q_X$

$$\xi^i_{1L} = \begin{pmatrix} \chi^{u_i}_L(-+)_{5/3} & q^{u_i}_L(++)_{2/3} \\ \chi^{d_i}_L(-+)_{2/3} & q^{d_i}_L(++)_{-1/3} \end{pmatrix}_{2/3},$$

$$\xi^i_{2R} = u^i_R(++)_{2/3},$$

$$\xi^i_{3R} = T^i_{3R} \oplus T^i_{4R} = \begin{pmatrix} \psi'^i_R(-+)_{5/3} \\ U'^i_R(-+)_{2/3} \\ D'^i_R(-+)_{-1/3} \end{pmatrix}_{2/3} \oplus \begin{pmatrix} \psi''^i_R(-+)_{5/3} \\ U''^i_R(-+)_{2/3} \\ D^i_R(++)_{-1/3} \end{pmatrix}_{2/3}$$

tree-level FCNC in RS_c model



$$-i\bar{f}_k \Delta^{ik}_{L(R)} \gamma_\mu P_{L(R)} f_i X^\mu$$

X= $A^{(1)}$ (1st KK of the γ)
 Z, Z_H , Z′ (from mixing of 0- and 1-modes)
 $G^{(1)}$ (1st KK of the g)

FCNC involving quarks other than top suppressed

many ingredients

FIRST WITCH
Round about the cauldron go;
In the poison'd entrails throw.
Toad, that under cold stone
Days and nights has thirty-one
Swelter'd venom sleeping got,
Boil thou first i' the charmed pot.

ALL
Double, double toil and trouble;
Fire burn, and cauldron bubble.

SECOND WITCH
Fillet of a fenny snake,
In the cauldron boil and bake;
Eye of newt and toe of frog,
Wool of bat and tongue of dog,
Adder's fork and blind-worm's sting,
Lizard's leg and owlet's wing,
For a charm of powerful trouble,
Like a hell-broth boil and bubble.

ALL
Double, double toil and trouble;
Fire burn and cauldron bubble.

THIRD WITCH
Scale of dragon, tooth of wolf,
Witches' mummy, maw and gulf
Of the ravin'd salt-sea shark,
Root of hemlock digg'd i' the dark,
Liver of blaspheming Jew,
Gall of goat, and slips of yew
Silver'd in the moon's eclipse,
Nose of Turk and Tartar's lips,
Finger of birth-strangled babe
Ditch-deliver'd by a drab,
Make the gruel thick and slab:
Add thereto a tiger's chaudron,
For the ingredients of our cauldron.

ALL
Double, double toil and trouble;
Fire burn and cauldron bubble.

SECOND WITCH
Cool it with a baboon's blood,
Then the charm is firm and good.

Macbeth, act 4, scene 1

modified Wilson coefficients in RS$_c$ model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

$$\Delta C_9' = \left[\frac{\Delta Y_s'}{\sin^2(\theta_W)} - 4\Delta Z_s'\right]$$

$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)} ,$$

$$\Delta C_{10}' = -\frac{\Delta Y_s'}{\sin^2(\theta_W)} ,$$

$$\Delta Y_s = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_L^{bs}(X) ,$$

$$\Delta Y_s' = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_R^{bs}(X) ,$$

$$\Delta Z_s = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_L^{bs}(X) ,$$

$$\Delta Z_s' = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_R^{bs}(X) .$$

$$H^{eff} = -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^*\left\{C_1O_1 + C_2O_2 + \sum_{i=3,..,6} C_iO_i + \sum_{i=7,..,10,P,S}[C_iO_i + C_i'O_i']\right\}$$

$$O_9 = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\,\bar{\ell}\gamma_\mu\ell$$

$$O_9' = \frac{e^2}{16\pi^2}(\bar{s}_{R\alpha}\gamma^\mu b_{R\alpha})\,\bar{\ell}\gamma_\mu\ell$$

$$O_{10} = \frac{e^2}{16\pi^2}(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\,\bar{\ell}\gamma_\mu\gamma_5\ell$$

$$O_{10}' = \frac{e^2}{16\pi^2}(\bar{s}_{R\alpha}\gamma^\mu b_{R\alpha})\,\bar{\ell}\gamma_\mu\gamma_5\ell .$$

modified Wilson coefficients in RS_c model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

$$\Delta C_9' = \left[\frac{\Delta Y_s'}{\sin^2(\theta_W)} - 4\Delta Z_s'\right]$$

$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)}\,,$$

$$\Delta C_{10}' = -\frac{\Delta Y_s'}{\sin^2(\theta_W)}\,,$$

$$\Delta Y_s = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_L^{bs}(X)\,,$$

$$\Delta Y_s' = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_R^{bs}(X)\,,$$

$$\Delta Z_s = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_L^{bs}(X)\,,$$

$$\Delta Z_s' = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_R^{bs}(X)\,.$$

Blanke et al, JHEP 0903 (09) 108
Albrecht et al, JHEP 0909 (09) 064

couplings of new heavy particles to leptons

modified Wilson coefficients in RS$_c$ model

$$\Delta C_9 = \left[\frac{\Delta Y_s}{\sin^2(\theta_W)} - 4\Delta Z_s\right]$$

$$\Delta C_9' = \left[\frac{\Delta Y_s'}{\sin^2(\theta_W)} - 4\Delta Z_s'\right]$$

$$\Delta C_{10} = -\frac{\Delta Y_s}{\sin^2(\theta_W)} ,$$

$$\Delta C_{10}' = -\frac{\Delta Y_s'}{\sin^2(\theta_W)} ,$$

$$\Delta Y_s = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) + \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_L^{bs}(X) ,$$

$$\Delta Y_s' = -\frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_L^{\ell\ell}(X) - \Delta_R^{\ell\ell}(X)}{4M_X^2 g_{SM}^2}\Delta_R^{bs}(X) ,$$

$$\Delta Z_s = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_L^{bs}(X) ,$$

$$\Delta Z_s' = \frac{1}{V_{tb}V_{ts}^*}\sum_X \frac{\Delta_R^{\ell\ell}(X)}{8M_X^2 g_{SM}^2 \sin^2(\theta_W)}\Delta_R^{bs}(X) .$$

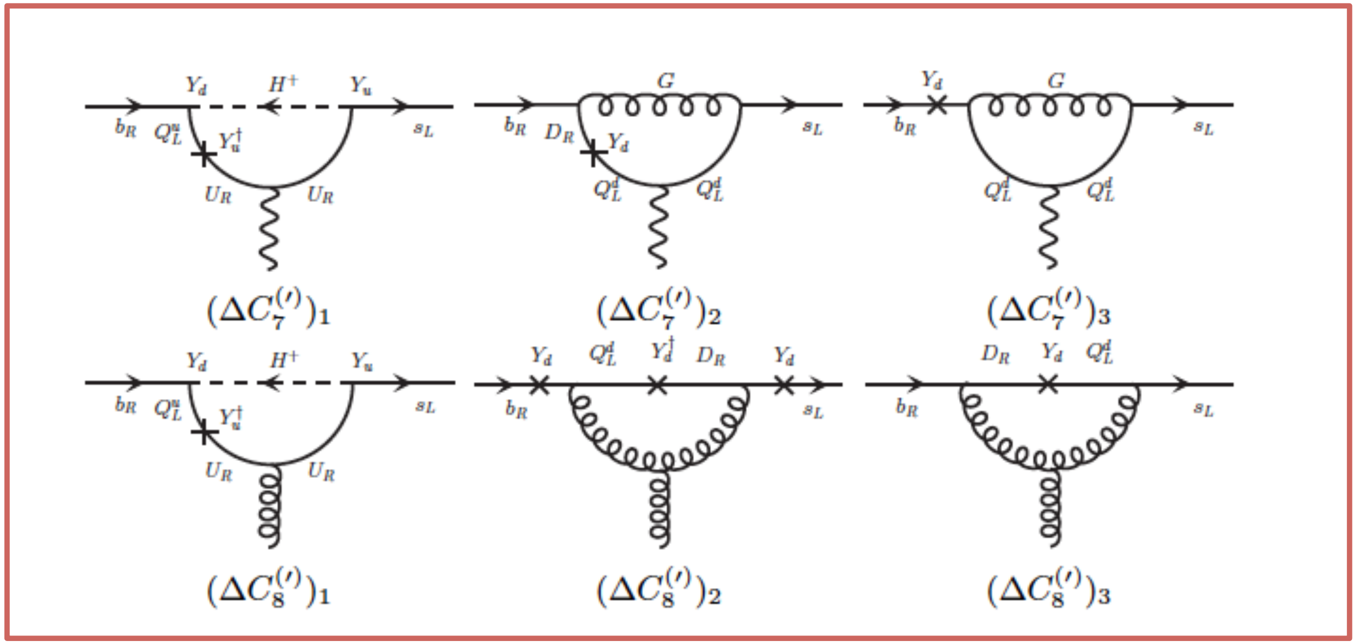
Blanke et al, JHEP 0903 (09) 108
Albrecht et al, JHEP 0909 (09) 064

couplings of new heavy particles to leptons

couplings to quarks

modified Wilson coefficients in RS_c

new contributions to $C_{7,8}$



Biancofiore, De Fazio, PC, in the effective 4D theory
PRD 89 (2014) 09501

Blanke et al. in 5D
Malm, Neubert, Schmell in 5D, arXiv:1509.02539

parameters

KK decomposition:

$$F(x,y) = \frac{1}{\sqrt{L}} \sum_k F^{(k)}(x) f^{(k)}(y)$$

4D fields

5D profiles

fermion profiles (0-mode)

$$f^{(0)}(y,c) = \sqrt{\frac{(1-2c)kL}{e^{(1-2c)kL}-1}}\, e^{-cky}$$

bulk mass

bulk mass parameters are the same for left-handed fermions of the same generation
$(u\ d)_L$ $(c\ s)_L$ $(t\ b)_L$ $(e\ \nu_e)_L$ $(\mu\ \nu_\mu)_L$ $(\tau\ \nu_\tau)_L$

parameters

4D Yukawas

$$Y_{ij}^{u(d)} = \frac{1}{\sqrt{2}}\frac{1}{L^{3/2}}\int_0^L dy\, \lambda_{ij}^{u(d)} f^{(0)}_{q_L^i}(y) f^{(0)}_{u_R^j(d_R^j)}(y) h(y)$$

5D Yukawa matrices

constraints:
$\lambda^{u,d}$ should reproduce
- quark masses
- CKM elements

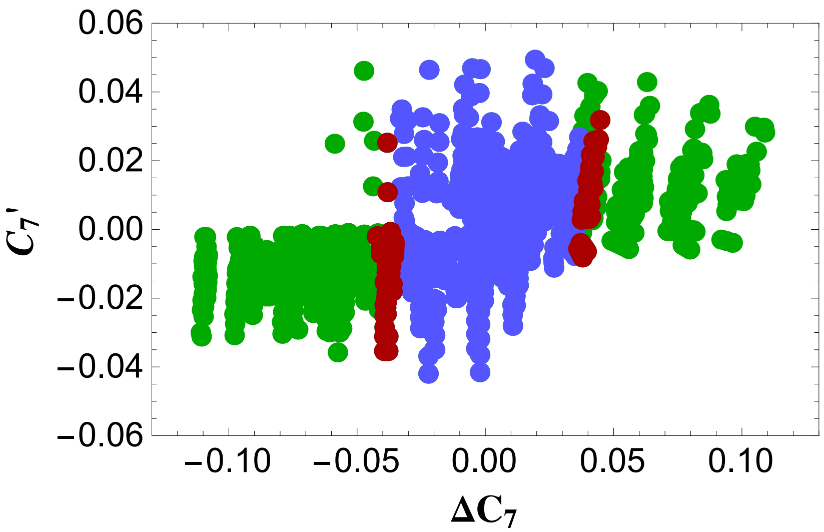
$$m_u = \frac{v}{\sqrt{2}}\frac{det(\lambda^u)}{\lambda^u_{33}\lambda^u_{22} - \lambda^u_{23}\lambda^u_{32}}\frac{e^{kL}}{L} f_{u_L} f_{u_R}$$

$$m_c = \frac{v}{\sqrt{2}}\frac{\lambda^u_{33}\lambda^u_{22} - \lambda^u_{23}\lambda^u_{32}}{\lambda^u_{33}}\frac{e^{kL}}{L} f_{c_L} f_{c_R}$$

$$m_t = \frac{v}{\sqrt{2}}\lambda^u_{33}\frac{e^{kL}}{L} f_{t_L} f_{t_R} \ ,$$

quark rotation matrices depend on $\lambda^{u,d}$

additional contraints with respect to previous analyses



constraints from V_{us} and V_{ub}

constraints from $V_{cb}$and V_{ub}

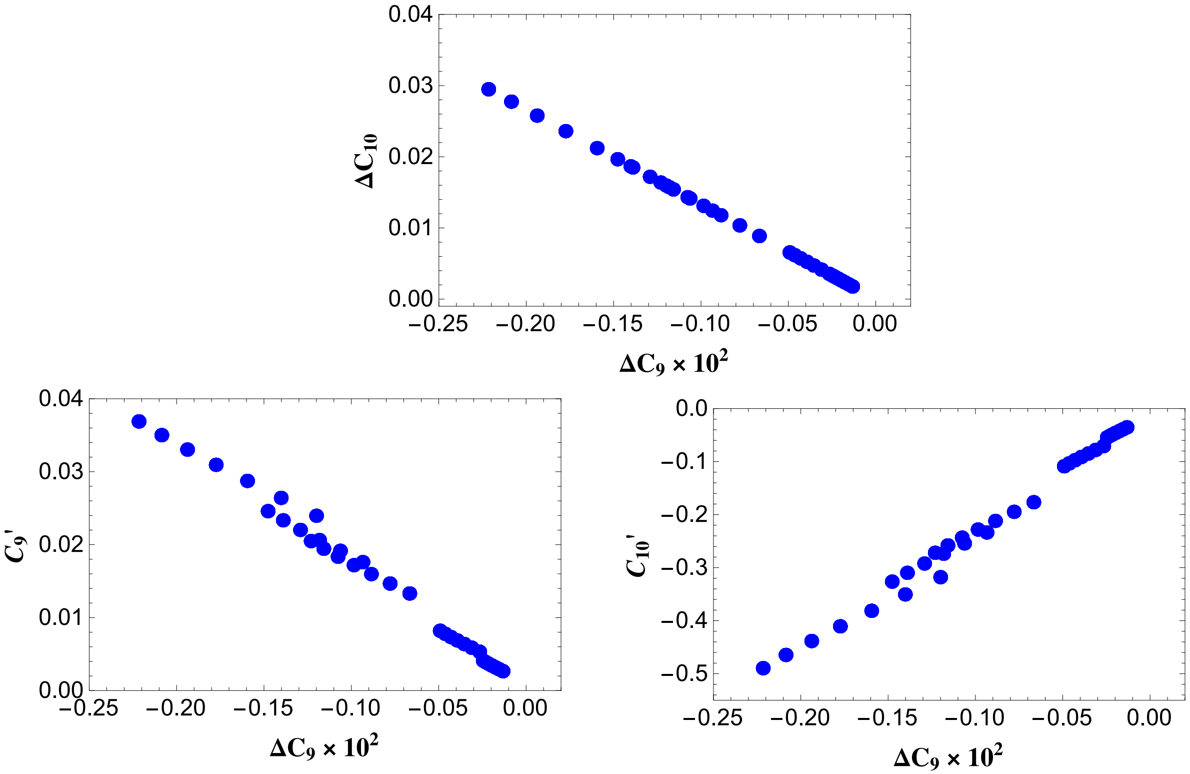
constraints from Brs

$$B(B \to X_s\gamma)_{exp} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

$$B(B \to K^*\mu^+\mu^-)_{exp} = (1.02^{+0.14}_{-0.13} \pm 0.05) \times 10^{-6}$$

Heavy Flavor Averaging Group (HFAG) 2015

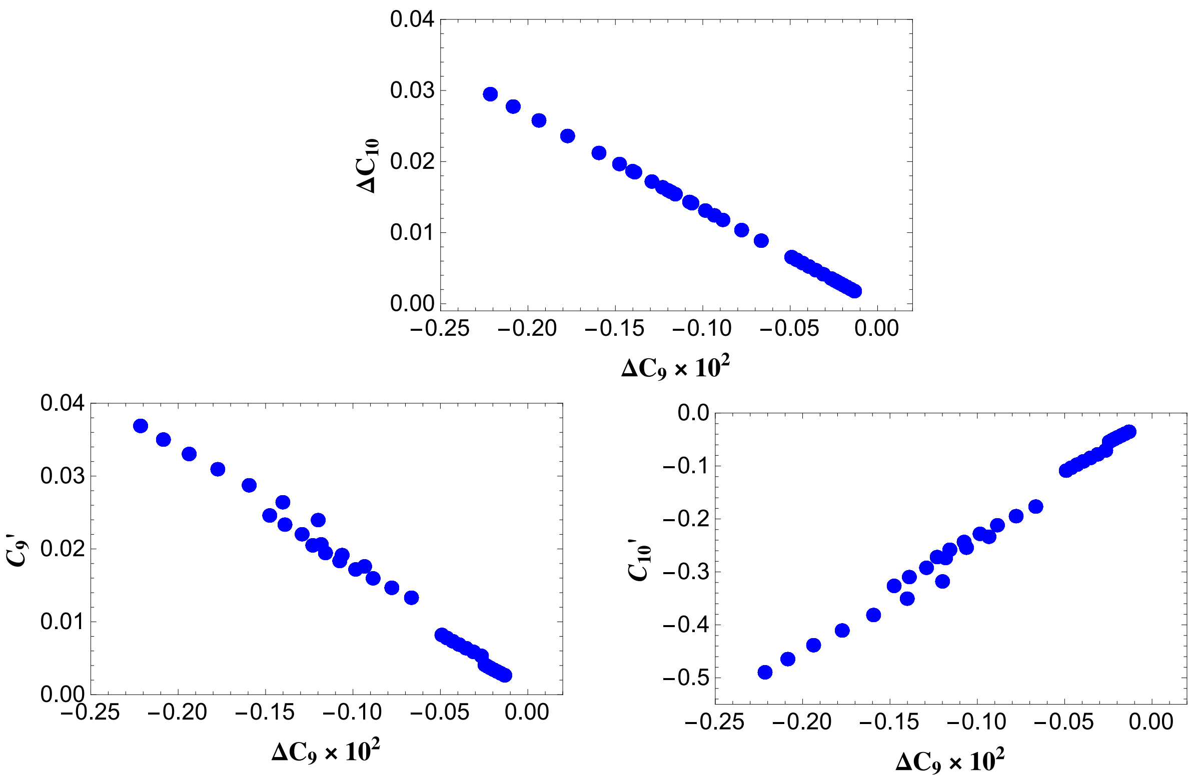
results



largest deviations from SM:

$$
\begin{aligned}
|\Delta C_7|_{max} &\simeq 0.046 \\
|\Delta C_7'|_{max} &\simeq 0.05 \\
|\Delta C_9|_{max} &\simeq 0.0023 \\
|\Delta C_9'|_{max} &\simeq 0.038 \\
|\Delta C_{10}|_{max} &\simeq 0.030 \\
|\Delta C_{10}'|_{max} &\simeq 0.50
\end{aligned}
$$

results

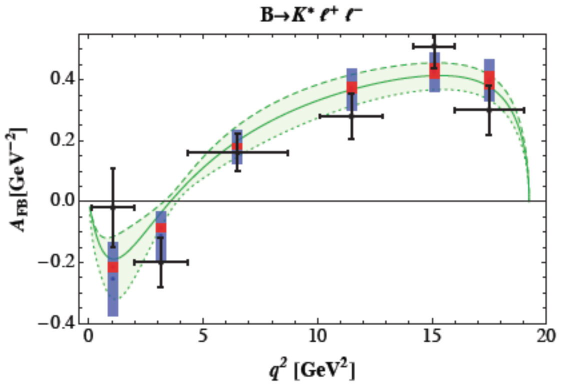


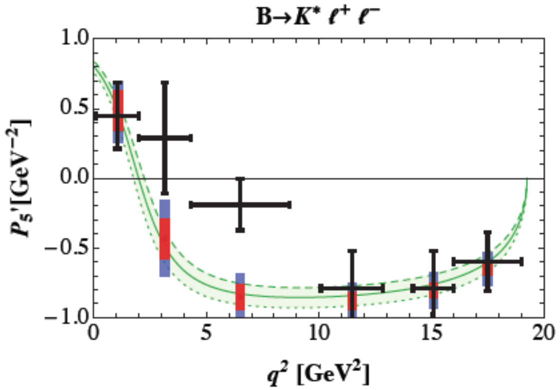
largest deviations from SM:

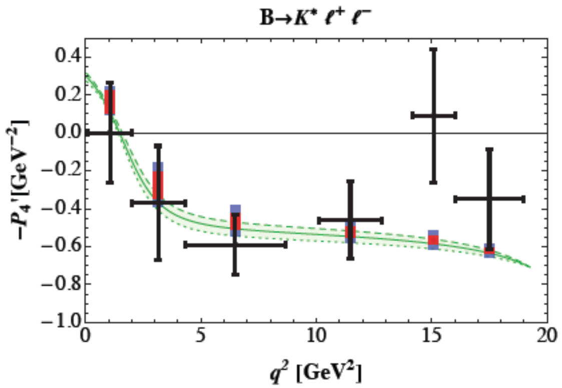
$$
\begin{aligned}
|\Delta C_7|_{max} &\simeq 0.046 \\
|\Delta C_7'|_{max} &\simeq 0.05 \\
|\Delta C_9|_{max} &\simeq 0.0023 \\
|\Delta C_9'|_{max} &\simeq 0.038 \\
|\Delta C_{10}|_{max} &\simeq 0.030 \\
|\Delta C_{10}'|_{max} &\simeq 0.50
\end{aligned}
$$

not enough to accommodate the P'_5 anomaly

results for B → $K^* \mu^+ \mu^-$







SM
including uncertainty on form factors (FF)
(LCSR + lattice)

RS_c
uncertainty reflects only
the variation of input parameters

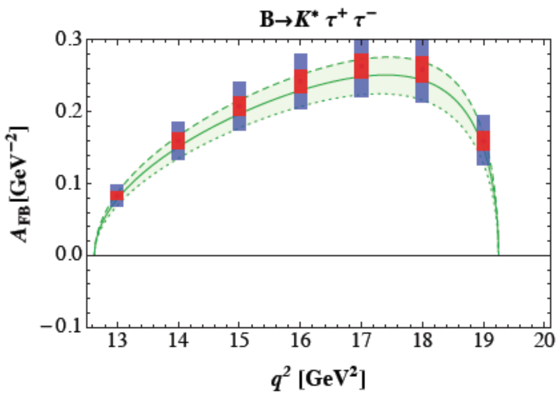
RS_c
uncertainty from
the variation of input parameters & FF

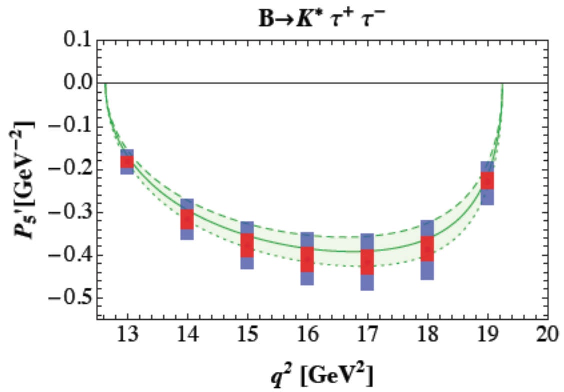
LHCb

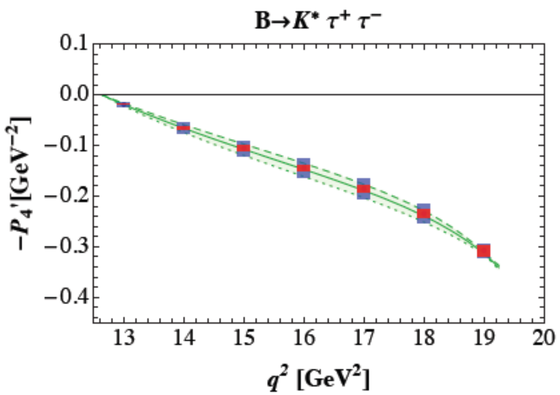
- deviations from SM hidden by the hadronic uncertainties
- anomaly in P'_5 not explained

P. Biancofiore, F. De Fazio, PC, PRD 89, 09501

τ in the final state



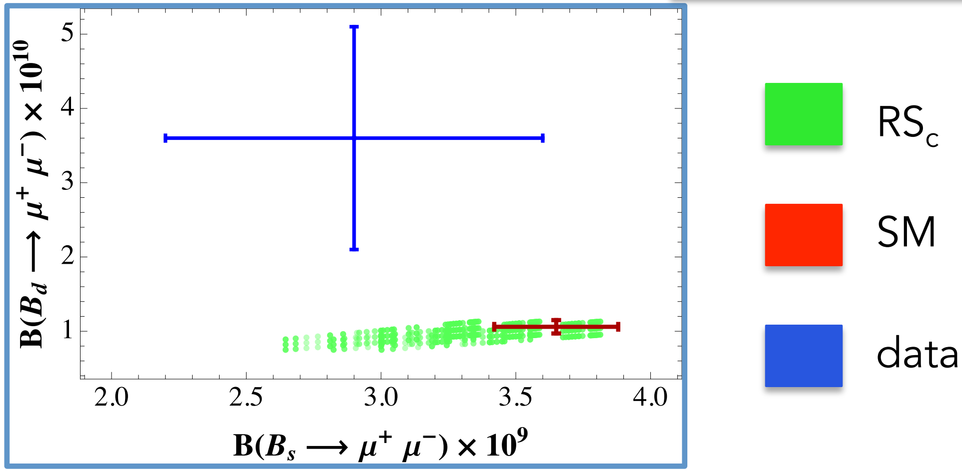




P. Biancofiore, F. De Fazio, PC, PRD 89, 09501

$B_{s,d} \to \mu^+ \mu^-$

modification versus SM: $C_{10} \to C_{10} - C_{10}'$



- in a region of the parameter space the SM result is reproduced
- the allowed range in RS_c is larger than in SM

$$B(B_s \to \mu^+\mu^-)\Big|_{RS} \in [2.64 - 3.83] \times 10^{-9}$$

$$B(B_d \to \mu^+\mu^-)\Big|_{RS} \in [0.70 - 1.16] \times 10^{-10}$$

- Br for B_d still lower than exp

P. Biancofiore, F. De Fazio, PC, PRD 89, 09501

B -> $K^{(*)} \nu \bar{\nu}$

$$H_{eff} = C_L O_L + C_R O_R$$

$$O_L = (\bar{b}s)_{V-A}(\bar{\nu}\nu)_{V-A}$$

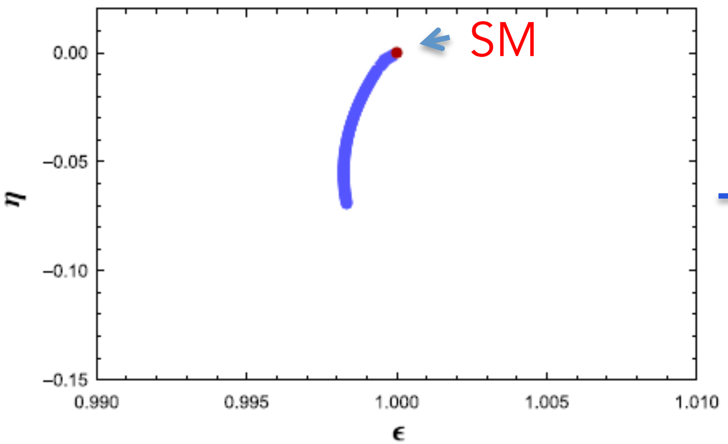
$$O_R = (\bar{b}s)_{V+A}(\bar{\nu}\nu)_{V-A}$$

the relative weight can be assessed using

$$\epsilon^2 = \frac{|C_L|^2 + |C_R|^2}{|C_L^{SM}|^2}\,, \qquad \eta = -\frac{\mathrm{Re}\,(C_L C_R^*)}{|C_L|^2 + |C_R|^2}$$

SM: $(\epsilon, \eta)_{SM} = (1, 0)$

RSc:



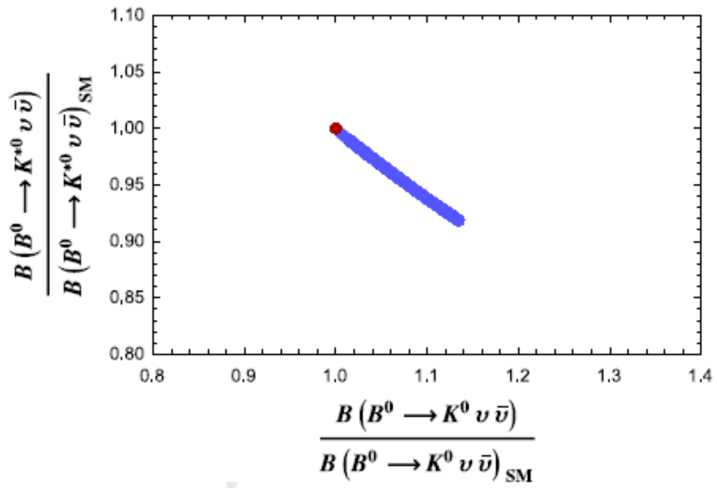
η deviates from 0

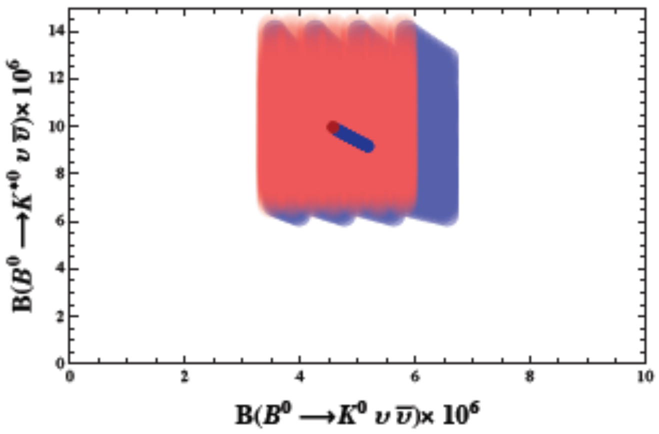
P. Biancofiore, F. De Fazio, E. Scrimieri, PC: EPJ C 75, 134

similar correlation in Buras, De Fazio, Girrbach, JHEP 1302 (2013) 116

Buras et al., JHEP 1502 (2015) 184

B -> K$^{(*)}$ ν $\bar{\nu}$





$$\mathcal{B}(B^0 \to K^0 \nu\bar{\nu})_{SM} = (4.6 \pm 1.1) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})_{SM} = (10.0 \pm 2.7) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^0 \nu\bar{\nu})_{RS} \in [3.45 - 6.65] \times 10^{-6}$$

$$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})_{RS} \in [6.1 - 14.3] \times 10^{-6}$$

Belle

$$\boxed{\begin{aligned} \mathcal{B}(B^+ \to K^+\nu\bar{\nu}) &< 5.5 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^0_S\nu\bar{\nu}) &< 9.7 \times 10^{-5} \\ \mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}) &< 4.0 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) &< 5.5 \times 10^{-5} \ . \end{aligned}}$$

BaBar

$$\boxed{\begin{aligned} \mathcal{B}(B^+ \to K^+\nu\bar{\nu}) &< 1.6 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^0\nu\bar{\nu}) &< 4.9 \times 10^{-5} \\ \mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}) &< 6.4 \times 10^{-5} \\ \mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) &< 12 \times 10^{-5} \ , \end{aligned}}$$

P. Biancofiore, F. De Fazio, E. Scrimieri, PC: EPJ C 75, 134

observables in B -> $K^{(*)} \nu \bar{\nu}$

integrated K* polarization fractions

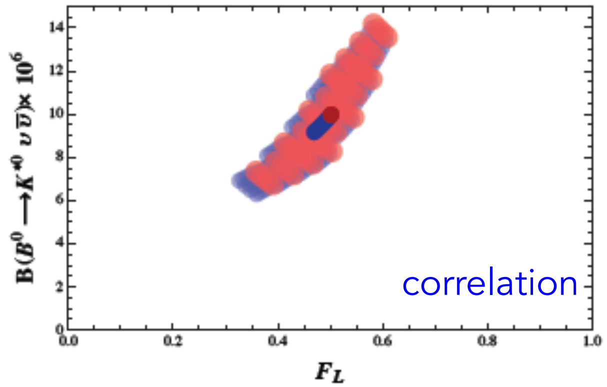
$$F_{L,T} = \frac{1}{\Gamma} \int_0^{1-\bar{m}^2_{K^*}} ds_B \, \frac{dF_{L,T}}{ds_B} \, .$$

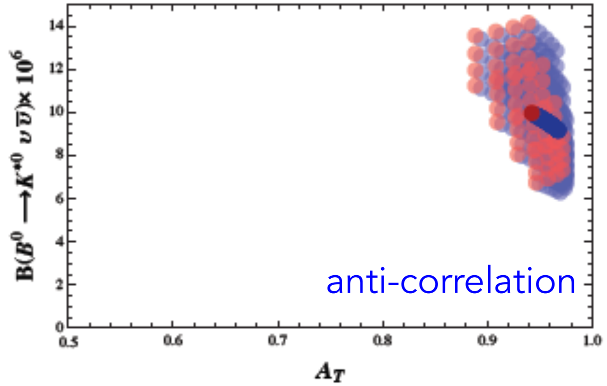
ratio of BRs of K mode and K* mode with transversely polarized K*

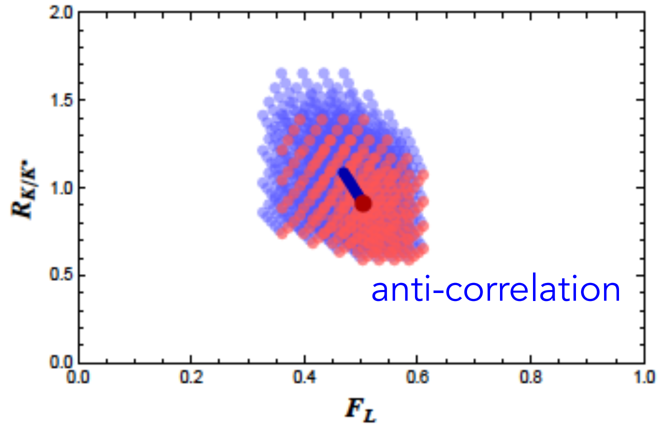
$$R_{K/K^*} = \frac{\mathcal{B}(B \to K \, \nu\bar{\nu})}{\mathcal{B}(B \to K^*_{h=-1} \, \nu\bar{\nu}) + \mathcal{B}(B \to K^*_{h=+1} \, \nu\bar{\nu})}$$

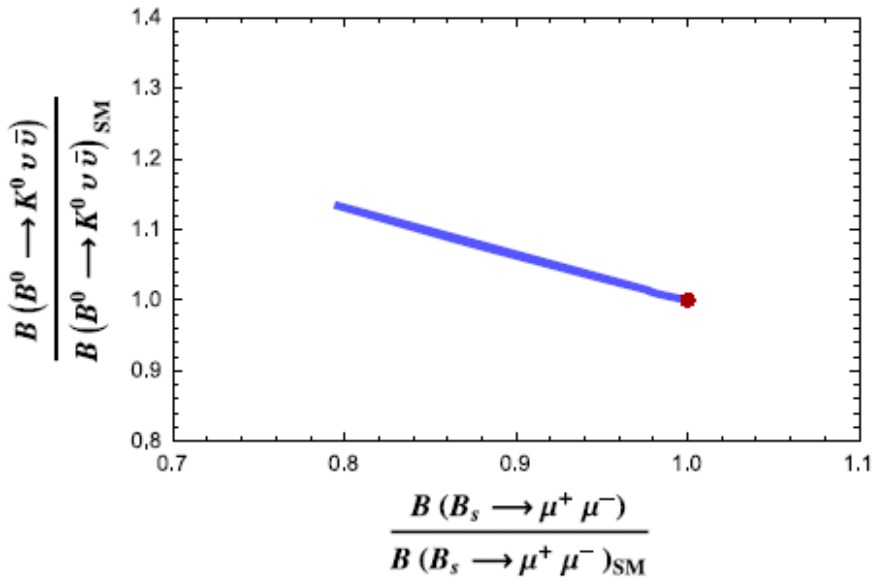
transverse asymmetry

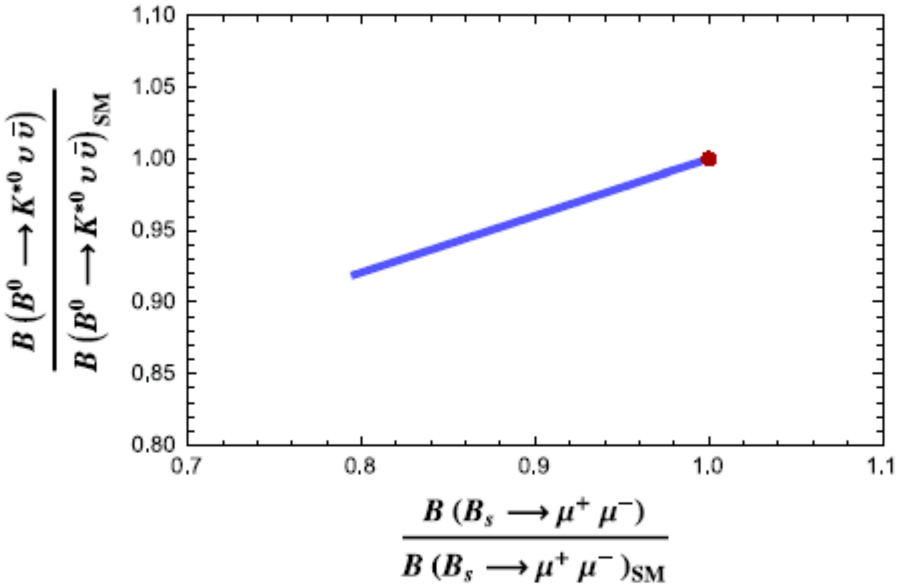
$$A_T = \frac{\mathcal{B}(B \to K^*_{h=-1} \, \nu\bar{\nu}) - \mathcal{B}(B \to K^*_{h=+1} \, \nu\bar{\nu})}{\mathcal{B}(B \to K^*_{h=-1} \, \nu\bar{\nu}) + \mathcal{B}(B \to K^*_{h=+1} \, \nu\bar{\nu})} \, ,$$







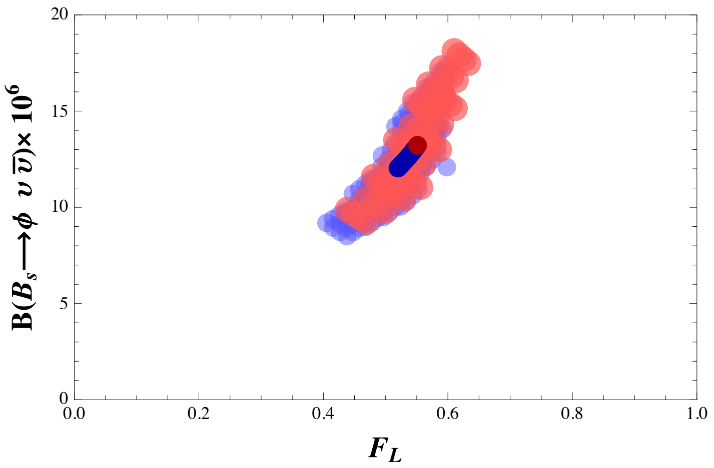

1,4
1,3
1,2
1,1
1,0
0,9
0,8
0.7
0.8
0.9
1.0
1.1
$\frac{B(B^0 \longrightarrow K^0 \nu \bar{\nu})}{B(B^0 \longrightarrow K^0 \nu \bar{\nu})_{SM}}$
$\frac{B(B_s \longrightarrow \mu^+ \mu^-)}{B(B_s \longrightarrow \mu^+ \mu^-)_{SM}}$


1,10
1,05
1,00
0,95
0,90
0,85
0,80
0.7
0.8
0.9
1.0
1.1
$\frac{B(B^0 \longrightarrow K^{*0} \nu \bar{\nu})}{B(B^0 \longrightarrow K^{*0} \nu \bar{\nu})_{SM}}$
$\frac{B(B_s \longrightarrow \mu^+ \mu^-)}{B(B_s \longrightarrow \mu^+ \mu^-)_{SM}}$

$B_s \to \phi \nu \bar{\nu}$

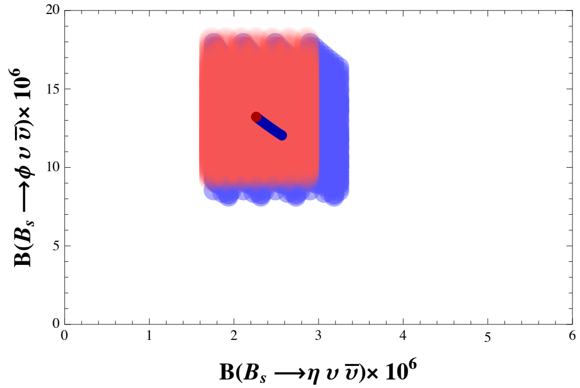
integrated ϕ polarization fractions

$$F_{L,T} = \frac{1}{\Gamma} \int_0^{1-\hat{m}^2_{K^*}} ds_B \, \frac{dF_{L,T}}{ds_B} \, .$$

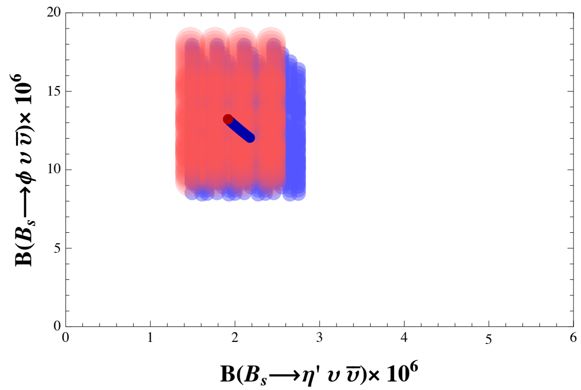


$B_s \to (\phi, \eta, \eta', f_0)\ \nu\bar{\nu}$

$$\mathcal{B}(B_s \to \eta\nu\bar{\nu})_{SM} = (2.3 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(B_s \to \eta'\nu\bar{\nu})_{SM} = (1.9 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(B_s \to \phi\nu\bar{\nu})_{SM} = (13.2 \pm 3.3) \times 10^{-6}$$

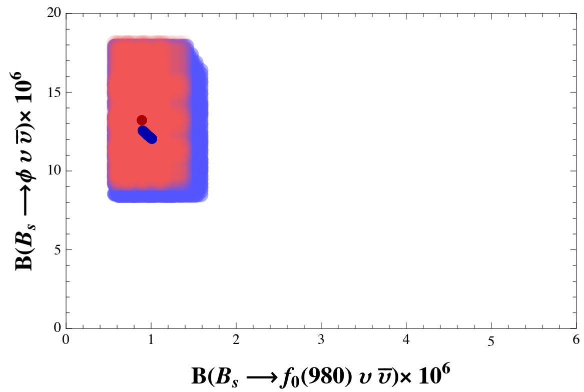


$$\mathcal{B}(B_s \to \eta\nu\bar{\nu})_{RS} \in [1.7 - 3.3] \times 10^{-6}$$
$$\mathcal{B}(B_s \to \eta'\nu\bar{\nu})_{RS} \in [1.5 - 2.8] \times 10^{-6}$$
$$\mathcal{B}(B_s \to \phi\nu\bar{\nu})_{RS} \in [8.4 - 18.0] \times 10^{-6}\ .$$



important role of $f_0(980)$ in rare $B_{(s)}$ decays

$$\mathcal{B}(B_s \to f_0(980)\nu\bar{\nu})_{SM} = (8.95 \pm^{2.9}_{2.5}) \times 10^{-7}$$
$$\mathcal{B}(B_s \to f_0(980)\nu\bar{\nu})_{RS} \in [5 - 17] \times 10^{-7}\ .$$



$B_{(s)} \to f_0(980)$ FF by LCSR

F. De Fazio, W. Wang, PC, PRD 81, 074001

Conclusions

small tensions accumulating in various flavor observables, although individually not enough significant, seem altogether to point to deviations from SM

correlations among the observables are specific of the BSM realisations

I have shown the changes induced in a particular NP model: RS_c

- small deviations obtained for the Wilson coefficients in b->s processes in RS_c not enough to accommodate the present anomaly in B->K* $\mu^+ \mu$

- role of modes with τ

- precise multiple correlation patterns among different observables

- important role of b -> s $\nu\nu$ modes (Belle II)

We do not know if Nature has chosen this particular way of extending the Standard Model:
We have to scrutinize all measurable implications in this as well as in the other possible NP scenarios