B-physics and CP-violation introductory talk

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CENTRE FOR THEORETICAL PHYSICS · Higgs

Rencontre de Vietnam, Flavour Conference

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Overview

- 1. **Introduction**

  Generalities, CKM fits, anomalies, anarchy vs flavour symmetry

- 2. **Dynamics,** $\Delta F = 1{,}2$ and topologies

- 3. **Kinematics** angular distributions

- 4. **Dynamics II ,** IR-matrix elements

- 5. R_K**-anomaly** (testing LFU) … caveats?

- **Conclusions**

B-physics (or flavour physics)

strengths

1. many channels ⇒ **data driven approaches**
(longterm future? @ FCC, μ-collider Trifinopoulos's talk)

2 many **QFT-applications**: RGE & Wilson coeff. ⇒ SMEFT (MIsiak's talk)
non-perturbative matrix elements, lattice..

3. many **experimental techniques** at B-factories (Belle ..), collider (LHCb …)
⇒ Urquijo's talk Wednesday

4. **CP-violation**, unique in SM so far but not enough as we know
(cf. also neutrinos ⇒ Chen's talk Thursday)

- no direct detection (unless low energy model)
collider search program **model-dependent**
Fuentes-Martin & Gori's talks Tuesday &Friiday

weakness

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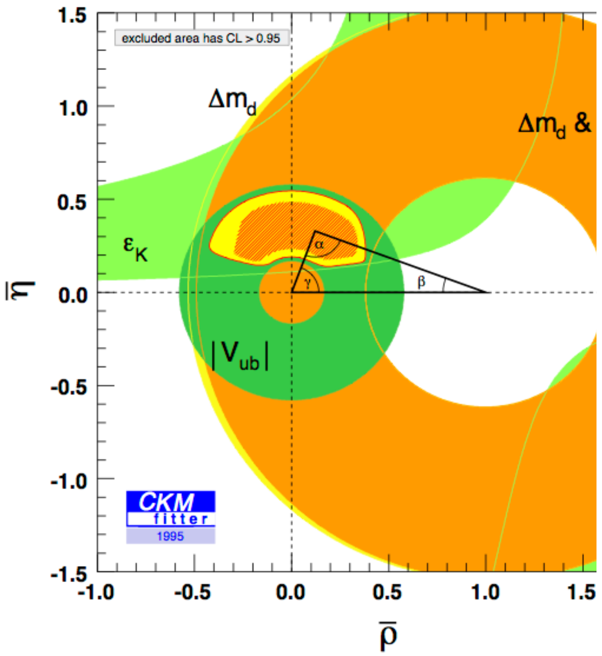
* matter also apply to K,D physics

- **persistent anomalies** around since 2014 … where?

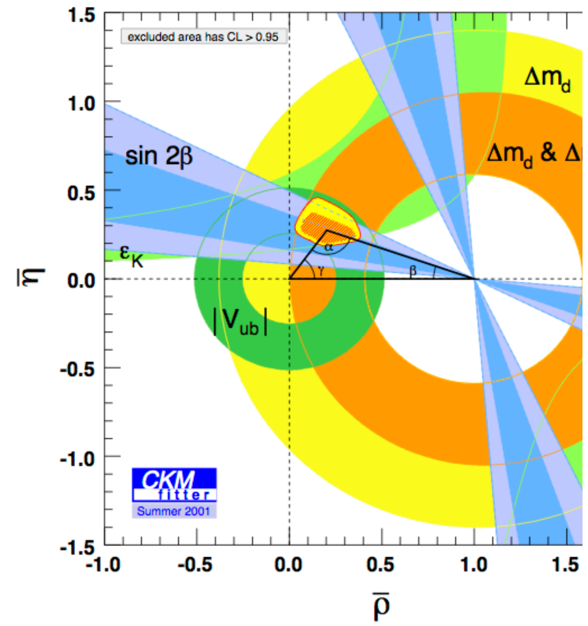
big topic

..not in the CKM mechanism

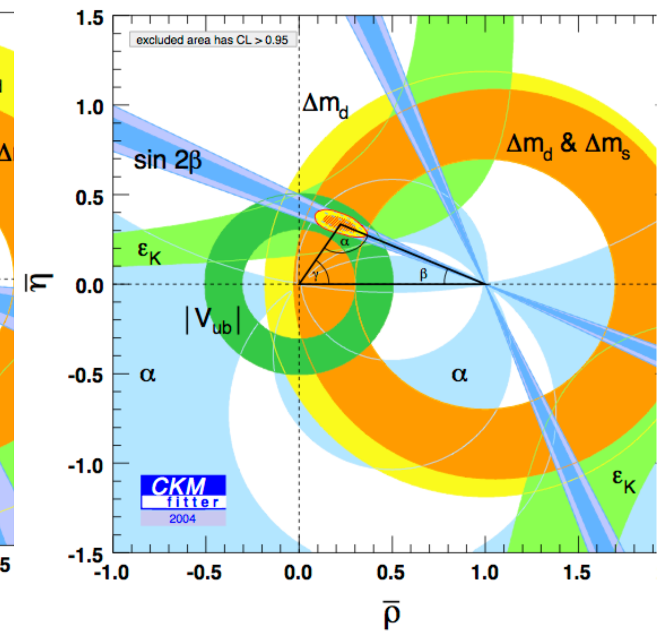
Area triangle =
strength CP-violation
NB: ca 10^3 below max.



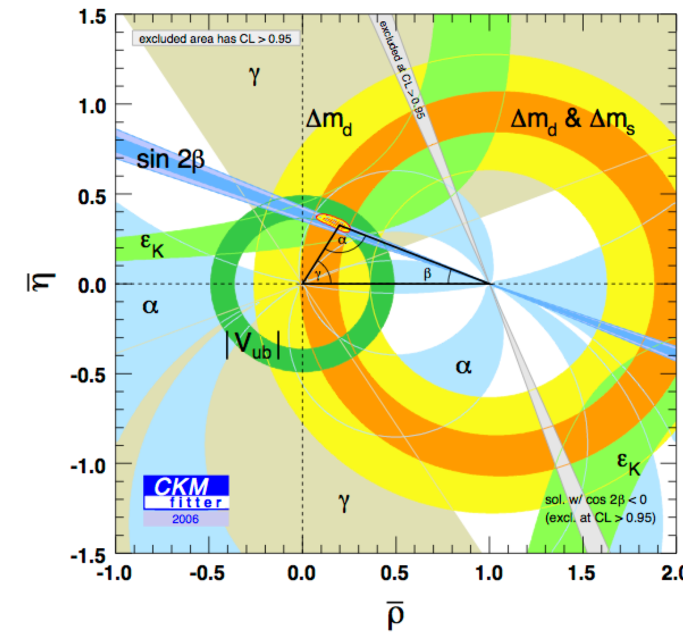
95' pre b-factory



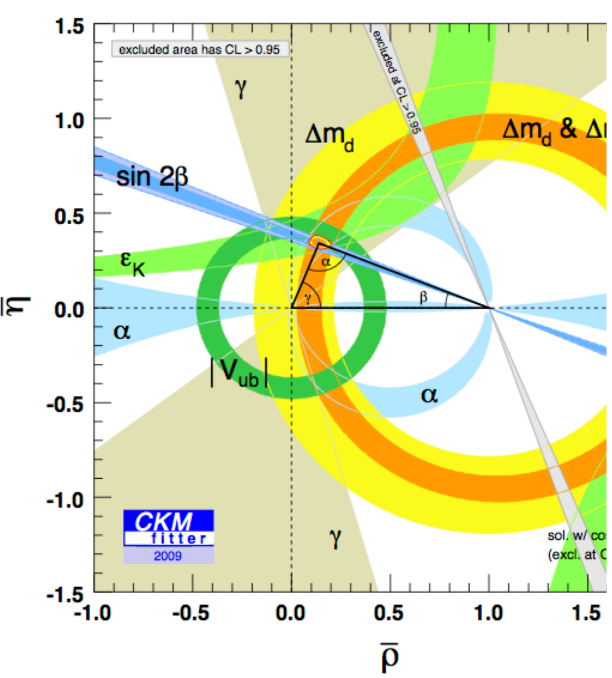
01'



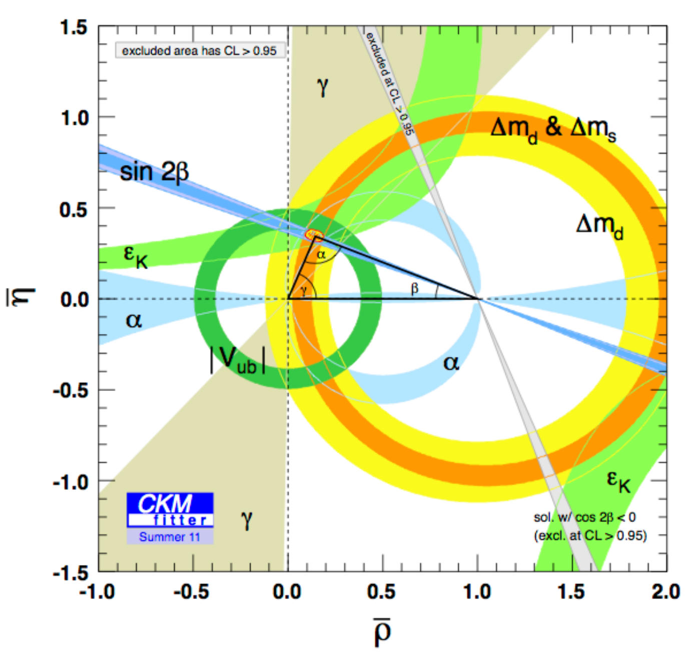
04'



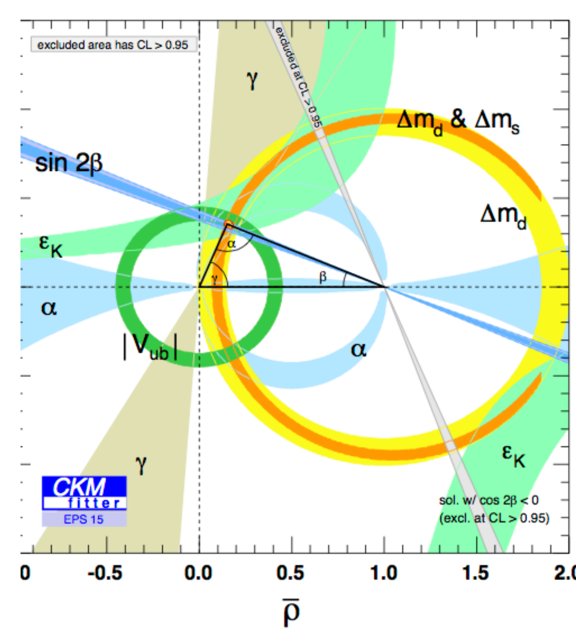
06'



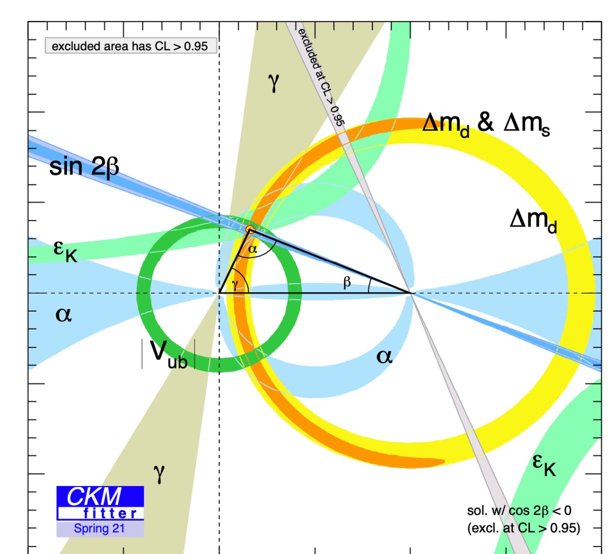
09'



11'



15'



22'

Note: here CKM-fitter also U-fit group

..in partly (un)expected places

$$R_{D^{(*)}} = \frac{\mathcal{B}[B \to D^{(*)}\tau\nu]}{\mathcal{B}[B \to D^{(*)}\ell\nu]}$$

$\ell = e, \mu$

tree-level

$|V_{\rm ub}|_{\rm excl}$ & global fit vs $|V_{\rm ub}|_{\rm incl}$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

exclusive FCNC's
$B \to K^{(*)}\ell\ell$

Angular Observables (e.g. $A_{\rm FB}$, P_5')

TD-CPV: $B_s \to \phi\gamma$

Lepton Flavour Universality Violation (LFUV) common theme

Fuentes-Martin's talk on Tuesday

New flavour physics and generic flavour structure?

- Anarchic flavour O(1) Wilson coefficients
  → most severe **constraints** from **mixing** i.e. ΔF=2

hadron	discovery	dim-6 operator	bound $\Lambda_{FV}/(10^3\text{TeV})]$
K_0	1964	$(\bar{s}d)_{\mathrm{V-A}}(\bar{s}d)_{\mathrm{V-A}}\,(\Lambda_{FV})^{-2}$	1
B_0	1999	$(\bar{b}d)_{\mathrm{V-A}}(\bar{b}d)_{\mathrm{V-A}}$	0.4
B_s	2006	$(\bar{b}s)_{\mathrm{V-A}}(\bar{b}s)_{\mathrm{V-A}}$	0.07
D_0	2007	$(\bar{c}u)_{\mathrm{V-A}}(\bar{c}u)_{\mathrm{V-A}}$	1

⇒ new flavour better have a structure! (also more likely to explain old one)

- ***N.B.*** In Lepton sector larger ΔF=1 even more constraining Λ_{FV} higher
  (since photon does not couple to ν)

ABC of Symmetry: Flavour Universality (FU) & Flavour Conservation

- **Yukawa** = 0 global symmetry: $G_F = U(3)^5 = G_q \times G_l$, $G_q = U(3)_Q \times U(3)_{UR} \times U(3)_{DR}$
  Yukawa ≠0 breaking down: $G_q = U(3)_q^3 \rightarrow U(1)_{Baryon}$

- **SM: FU-broken** : $m_u \neq m_c \neq m_t$ but not couplings $g_{weak} = g_u = g_c = g_t$

  SM: Flavour Violation (FV) by misalignment of Yukawa matrices:

  $$V_{CKM} = S_D S_U^\dagger \neq 1$$

  (i) charged FV @tree: $b \rightarrow W^* c$

  (ii) neutral FV @loop (FCNC) $b \rightarrow s\gamma$

Flavour Universality is not a symmetry of the SM

- Yet for leptons: control the breaking in terms of (mainly) kinematic factors.

2.Dynamics I

effective Hamiltonian & topologies

Make use of energy scales (eg. talk T.Becher)

ABC of Dynamics: Effective Hamiltonian

energy: $\Lambda_{\rm BSM}?$ ← m_W ← m_b ← 0

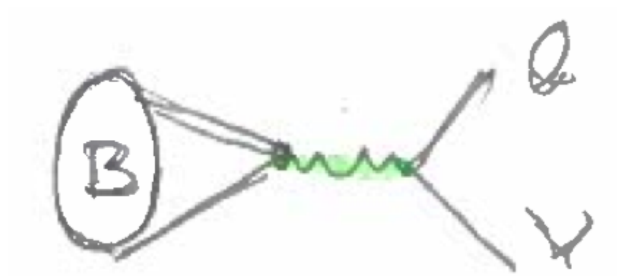
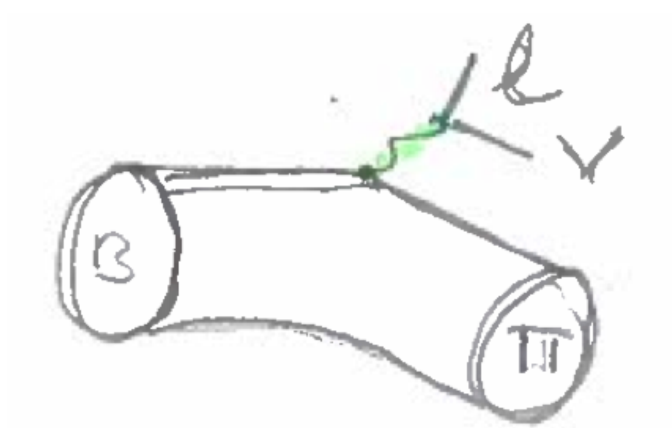
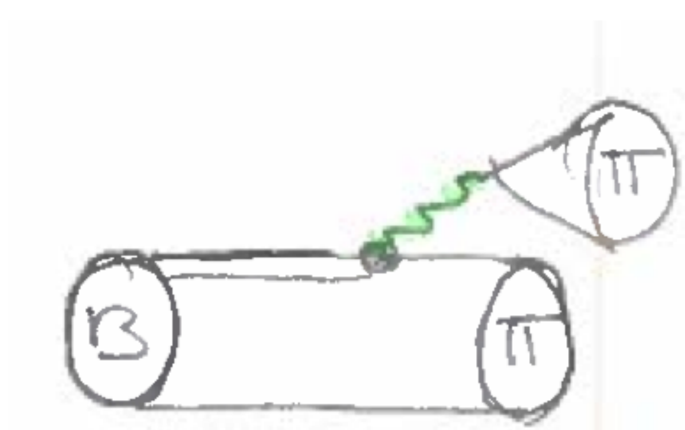
amplitude $$\mathcal{A} = \langle XYZ|H_{\rm eff}|B\rangle = \sum_i C_i(m_b)\langle XYZ|\underbrace{O_i(m_b)}_{\bar{q}_1\Gamma_1 q_2 \bar{b}\Gamma_2 q_3}|B\rangle$$

perturb. calculable
Wilson coefficient
UV physics (BSM?)
(MIsiak's talk)

M-element
IR physics (**non-perturbative**)

→ decays classified according to final state XYZ

ABC of topologies: $\Delta F=1$

final hadron	type	topology	theory	methods
0	**leptonic**		decay constant f_B	lattice sum rules (SR)
1	**semi-leptonic**		form factors	lattice, slow π LCSR, fast π
	radiative FCNC		form factors LD multi-resonance	↗ ***duality*** QCDF → Breit-Wigner
≥2	**non-leptonic**		factorisation (fast pions) pb: FSI size of Λ/m_b	QCDF: $1/m_b$

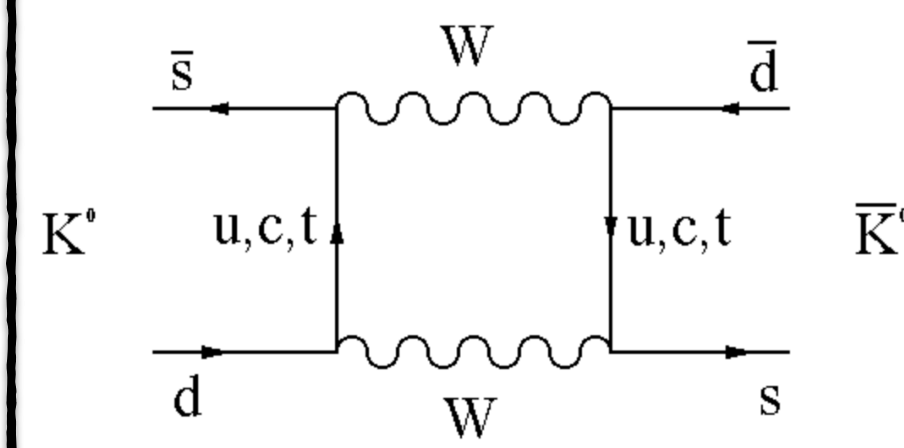
difficulty theory ↓

ABC ΔF=2 mixing

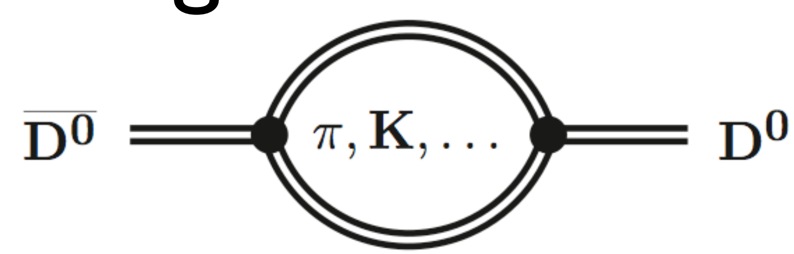
time-dependent CP-violation

- **direct CP-violation** ($\Delta F = 1{,}2$) is observable: $\mathscr{A} \propto |A_1| + |A_2|\, e^{i\phi_{weak}} e^{i\delta_{strong}}$

- K_0, D_0, B_q, B_s antiparticles mix ($\Delta F = 2$)
  time-dep. CP-violation (& CPT-tests)



short-
long-
distance



$$i\frac{d}{dt}\begin{pmatrix}|D(t)\rangle \\ |\bar{D}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|D(t)\rangle \\ |\bar{D}(t)\rangle\end{pmatrix}$$

$$7 - \text{numbers} \overset{\text{CPT}}{\rightarrow} 5 - \text{numbers}$$

$$M_{\mathrm{L}} \qquad \Delta M = M_H - M_L \qquad \delta_{\mathrm{CP}} = |p|^2 - |q|^2$$

$$\Gamma_{\mathrm{L}} \qquad \Delta\Gamma = \Gamma_H - \Gamma_L$$

flavour to mass eigenstate: $|D_{H,L}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$

- **experiment:** asymmetric B-factories to detect B_0-oscillation (1999) establishes $\Delta F = 2 \leftrightarrow (\Delta F = 1)^2$ (not superweak mechanism Wolfenstein…)

- **theory:** Operator product expansion, demands computing ….

$$\langle \bar{B} \,|\, Q_i \,|\, B \rangle = f_B^2 m_B^2 f(N_c) B_{Q_i}$$

"bag"-parameter $B_Q \sim 1 + \ldots$

Hatree-Fock app. (VFH)

….for a set of QCD (or BSM) operators

$$Q_1 = \bar{b}_i \gamma_\mu (1-\gamma^5) q_i \; \bar{b}_j \gamma^\mu (1-\gamma^5) q_j,$$

$$Q_2 = \bar{b}_i (1-\gamma^5) q_i \; \bar{b}_j (1-\gamma^5) q_j, \qquad Q_3 = \bar{b}_i (1-\gamma^5) q_j \; \bar{b}_j (1-\gamma^5) q_i,$$

$$Q_4 = \bar{b}_i (1-\gamma^5) q_i \; \bar{b}_j (1+\gamma^5) q_j, \qquad Q_5 = \bar{b}_i (1-\gamma^5) q_j \; \bar{b}_j (1+\gamma^5) q_i.$$

- Main tool: lattice QCD as matrix element static quantity However, QCD sum rules can also contribute Lenz et al' (new master integrals, progress triggered by LHC-program)

3.Kinematics (general)

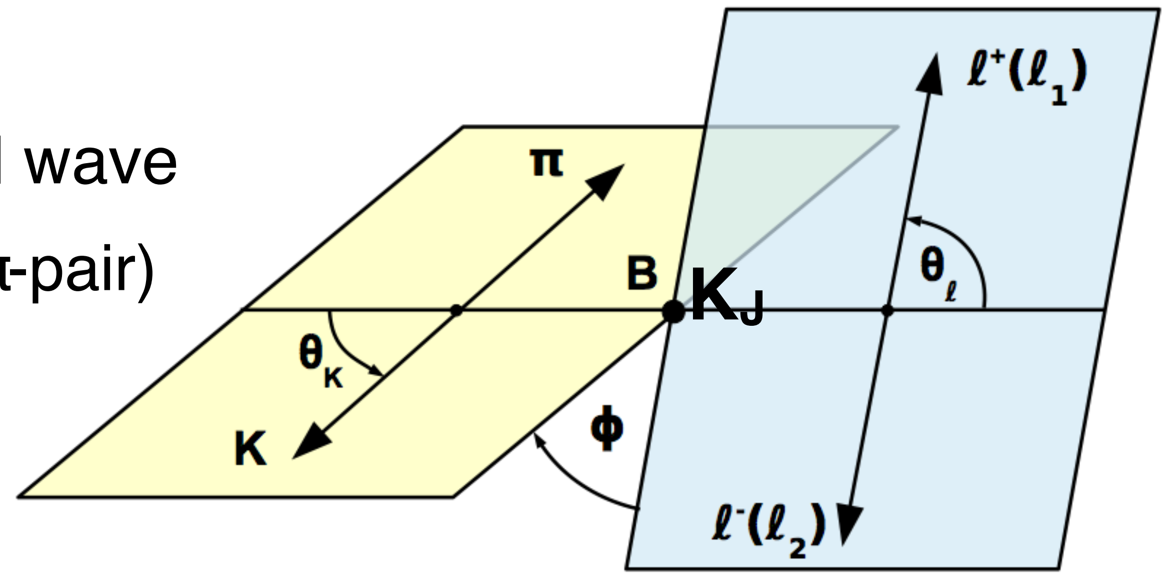
angular distributions & partial waves

independent of microscopic theory

ABC of Kinematics: Angular Distributions

- **This talk** mostly: B → V(→S$_1$S$_2$)l$_a$l$_b$ or B → Sl$_a$l$_b$ (semi-leptonic/radiative)

partial wave
l_K-(Kπ-pair)



partial wave
l_l-(ll-pair)

Heff of dim=6 with 10 operators

$$H^{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{\rm ts}V_{\rm tb}^* \sum_{i=V,A,S,P,\mathcal{T}} (C_i O_i + C_i' O_i') \ .$$

$$O_{S(P)} = \bar{s}_L b\, \bar{\ell}(\gamma_5)\ell \ , \qquad O_{V(A)} = \bar{s}_L \gamma^\mu b\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

$$O_{\mathcal{T}} = \bar{s}_L \sigma^{\mu\nu} b\, \bar{\ell}\sigma_{\mu\nu}\ell \ , \qquad O' = O|_{s_L \to s_R}$$

→ **S-** and **P-wave**

$$\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \sum_{m,l_l=0..2,l_K=0..J_K} \underbrace{G_m^{l_k,l_l}}_{|\mathcal{A}_{S,P}|^2} Y_{l_k}(\theta_K,\phi)Y_{l_l,m}(\theta_l,0)$$

12-terms known for some time

“Jacob-Wick formalism” for effective theories

Sinha et al ’99
Gratrex. Hopfer, RZ’15

... connection to dynamics

$$\frac{32\pi}{3}\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \mathrm{Re}\Big[G_0^{0,0}(q^2)\Omega_0^{0,0} + G_0^{0,1}(q^2)\Omega_0^{0,1} + G_0^{0,2}(q^2)\Omega_0^{0,2} + G_0^{2,0}(q^2)\Omega_0^{2,0} + G_0^{2,1}(q^2)\Omega_0^{2,1} + G_1^{2,1}(q^2)\Omega_1^{2,1} + G_0^{2,2}(q^2)\Omega_0^{2,2} + G_1^{2,2}(q^2)\Omega_1^{2,2} + G_2^{2,2}(q^2)\Omega_2^{2,2}\Big],$$

$$G_2^{2,2} \sim \left(H_+^V \bar{H}_-^V + H_+^A \bar{H}_-^A - 2\left(H_+^T \bar{H}_-^T + 2H_+^{T_t}\bar{H}_-^{T_t}\right)\right)$$

Hadronic helicity amplitudes e.g. $H_\lambda^{V[A]} = \langle \bar{K}^*(\lambda)|\bar{s}\gamma^\mu[\gamma_5]b|\bar{B}\rangle\epsilon^*(\lambda)_\mu$

- Pause! Goal find info on microscopic theory

Tools: (1) angular analysis (moments) extract G’s
(2) q²-dependence - disentangle short from long-distance physics

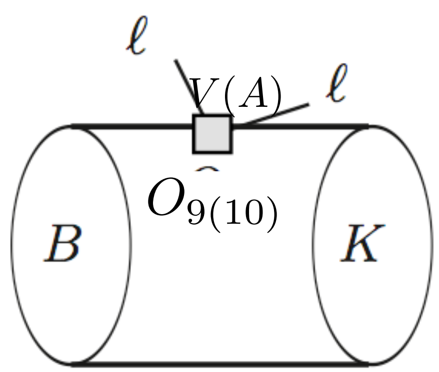
4. Dynamics II (IR)-matrix elements

- $B_d \to K^{(*)}\ell^+\ell^-$ as an example

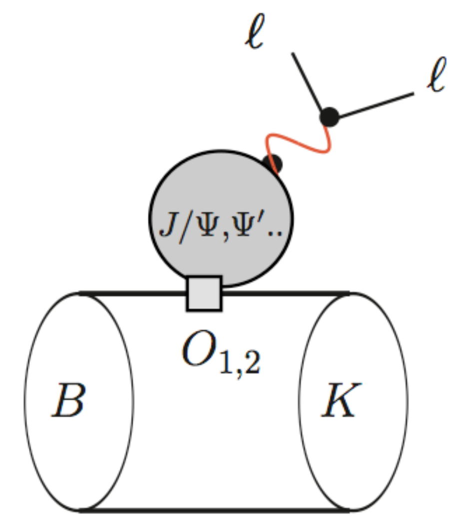
2-quark: $\bar{s}\Gamma_1 b\bar{\ell}\Gamma_2\ell$

4-quark: $\bar{s}\Gamma_1 b\bar{c}\Gamma_2 c$

short distance



long distance



form factor

long distance

- related by $SU(3)_F$ to semileptonic $B_s \to \bar{K}^{+(*)}l^+\bar{\nu}$ form factor as **no long-distance in semileptonic**, can measure ff.

$B \to K^*$ form factors as an example

q^2= momentum transfer

- form factor local m-elements (no long distance ⇒ no strong phases)
- number of form factors related group theory

$$\langle K^*(p,\eta)|\bar{s} i q_\nu \sigma^{\mu\nu}(1\pm\gamma_5)b|\bar{B}(p_B)\rangle = P_1^\mu T_1(q^2) \pm P_2^\mu T_2(q^2) \pm P_3^\mu T_3(q^2)$$
$$\langle K^*(p,\eta)|\bar{s}\gamma^\mu(1\mp\gamma_5)b|\bar{B}(p_B)\rangle = P_1^\mu \mathcal{V}_1(q^2) \pm P_2^\mu \mathcal{V}_2(q^2) \pm P_3^\mu \mathcal{V}_3(q^2) \pm P_P^\mu \mathcal{V}_P(q^2)$$

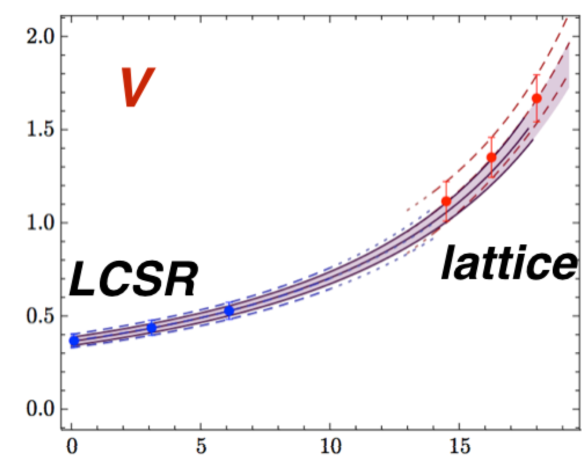
Methods

- **low q²** (large recoil) Light-cone sum rules

K*-DA: Bharucha, Straub, RZ ’15 (use of eoms - backup)
B-DA: Offen, Khodjamirian, Mannel ’06

- **high q²** (low recoil) lattice Horgan, Meinel, Wingate, Liu’13

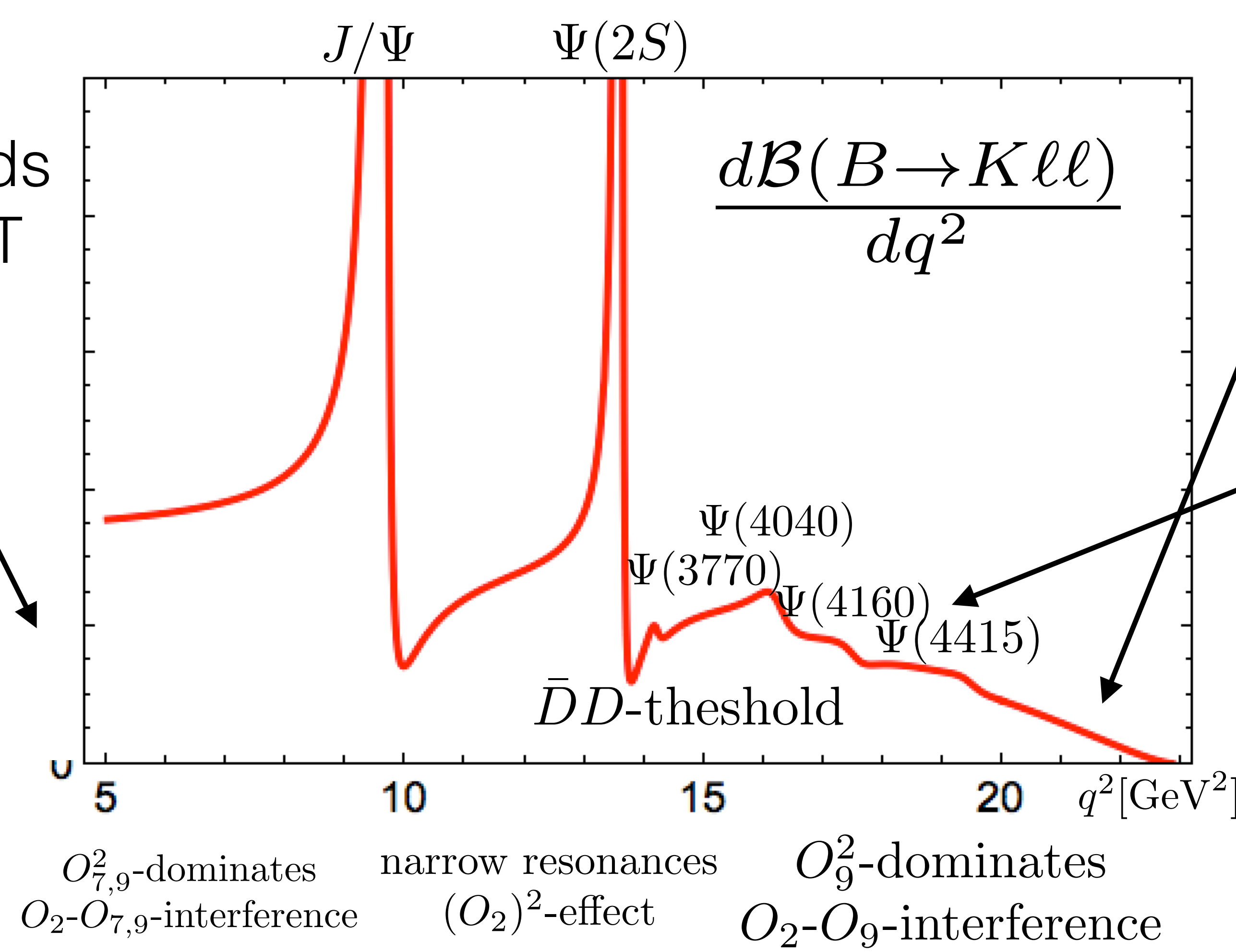
- interpolated by z-expansion →



Long distance = strong phases

- **lattice QCD impossible for B-physics**
  (low energy booming field Hansen,Dudek,.. cf.also Hashimoto's talk)
- **perturbative methods** such as QCD sum rules can deal with **multiparticle production** (local duality assumption.. some insight)
- **resonance region** only **dispersion theory** can and does work to the extent that parameters are known or can be fitted.

K **fast**:
- **light-cone** methods
LCSR, QCDF/SCET



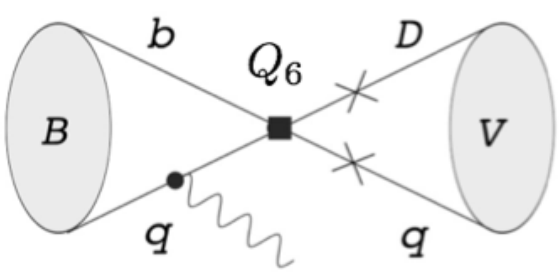
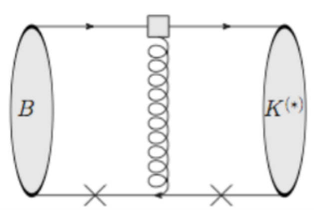
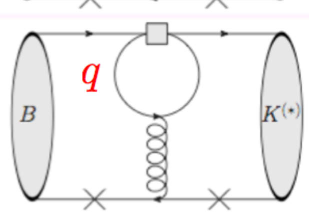
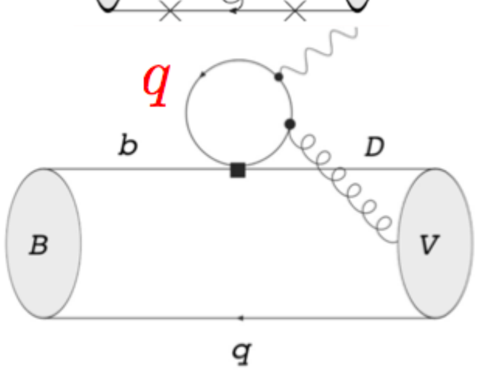
K **slow**:
- high-q^2 **"OPE"**
-**endpoint relations**

diagnostic shape for charm

"data driven approach"

long-distance brief overview status

skip as no time

	QCDF	LCSR
comments:	1) depends B-meson DA 2) at $1/m_b$ breakdown fac endpoint divergences	1) depend on spurious momentum and analytic continuation thereof 2) includes photon DA
	$1/m_b$ suppressed $O(a_s)$ accidental?	photon DA sizeable Khodjamirian et al'95 Ali Braun'95 Lyon, RZ'13
	the $1/m_b$ endpoint divergent	Dimou, Lyon, RZ'12
	idem	not done (some work)
	non-factorisable	various bits done Ball, Jones, RZ'06, Khodjamirian et al'10, ..later

Bosch, Buchalla'01

Beneke, Feldman, Seidel'01

5. R_K theoretically clean - so it seems

R_K-anomaly ..testing LFU

- simple idea: **hadronic** effects are **universal**, ought to cancel in ratios such as:

$$R_H = \frac{\int \frac{d\Gamma(B \to H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H e^+ e^-)}{dq^2} dq^2}$$

Hiller Kruger'03

$$R_K\left[1.1\text{GeV}^2, 6\text{GeV}^2\right] = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

LHCb (2103.11769)
2-3σ

- $R_K = 1 + \Delta_{QED}$ as QED does not respect LFU

What could go wrong?

- **QED-effects** due to (soft)-hard collinear logs
  $O(\alpha) \ln m_e/m_b$ 10 [20]% at $q^2 = 0$ [max q^2] in the point-like approx.

  - 1. **Structure-dependent** effects new hard-collinear logs
  - 2. **PHOTOS** (QED Monte-Carlo) not in harmony with point-like approx.
  - 3. **Resonances** impact on [1.1,6]GeV^2-bin

- **Summary** (more detail my *talk on Tuesday*) .. all positive answers
  - For 1 proof using gauge inv. Isidori, Nabeebaccus, RZ 2009.00929
  - For 2,3* checked in Isidori, Lancierini, Nabeebaccus, RZ 2205.08635

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* for 2,3 partial answers (as approximations) in Bordone, Pattori, Isidori'16

Conclusions & Summary

some of my personal impressions

- **B-physics:** well & alive in long term complementary results from Belle valuable
- **Lepton Flavour Universality**:

  1) QED-safe theory viewpoint
  2) experiment? LHCb challenging, but many crosschecks Belle cleaner, hence very valuable
  3) further testing with moments interesting as ∞-partial wave… sthg looking into …

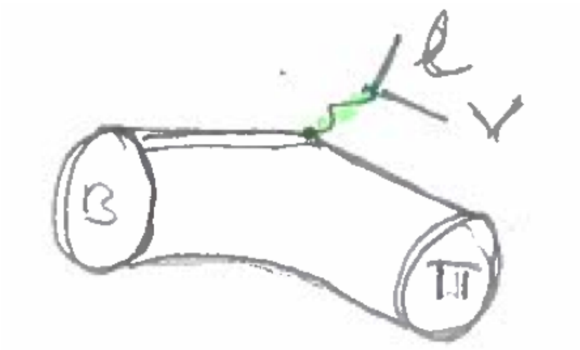
- **Far future of B-physics**
  1) theory: progress possible but takes effort .. "individuality"
  2) data-driven approaches are clearly an opportunity especially for FCC or μ-collider

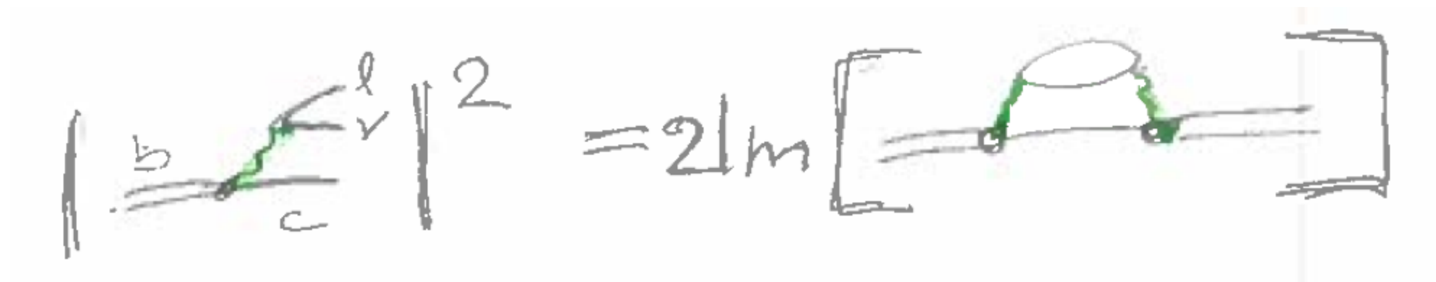
The end as time is up!

Backup

CKM-elements

exclusive vs **inclusive**





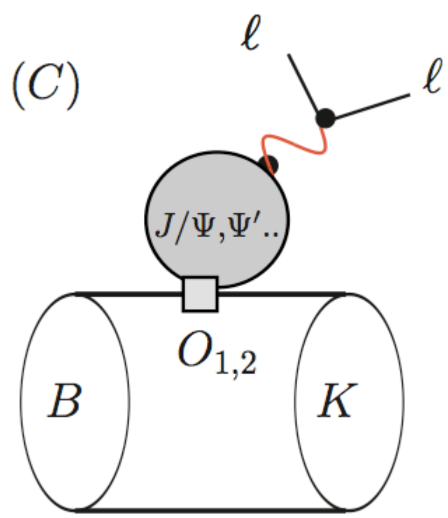
optical thm & OPE

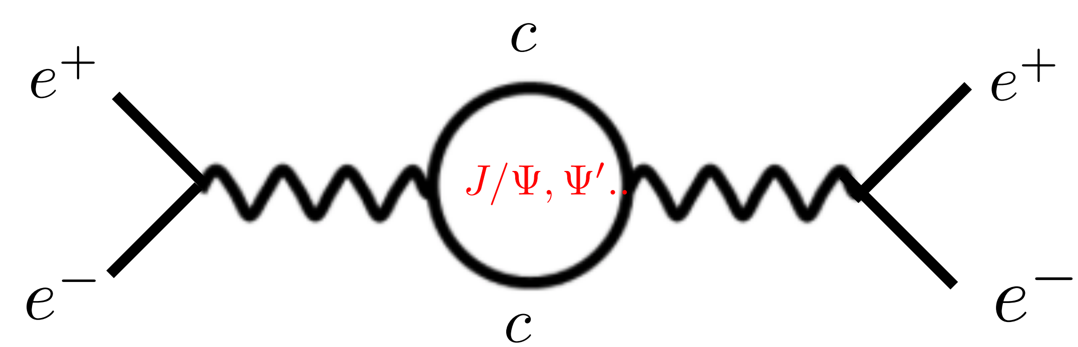
$\|V_{\rm ub}\|$	$\|V_{\rm cb}\|$	non-perturbative Input
$B \to \pi \ell \nu$	$B \to D \ell \nu$	$\Gamma[\|V(q^2)\|^2, m_\ell^2 \|S(q^2)\|^2]$
$B \to \rho \ell \nu$	$B \to D^* \ell \nu$	$\Gamma[\|V_{\pm,0}(q^2)\|^2, m_\ell^2 \|S(q^2)\|^2]$
$\Lambda_b \to \Lambda \ell \nu$		
$b \to X_u \ell \nu$	$b \to X_c \ell \nu$	universal m-elements shape function (model, fit)

Yet charm is virulent

Lyon RZ'14

- Does (naive) factorisation describe B→Kll data? Answer: **no** **ly**

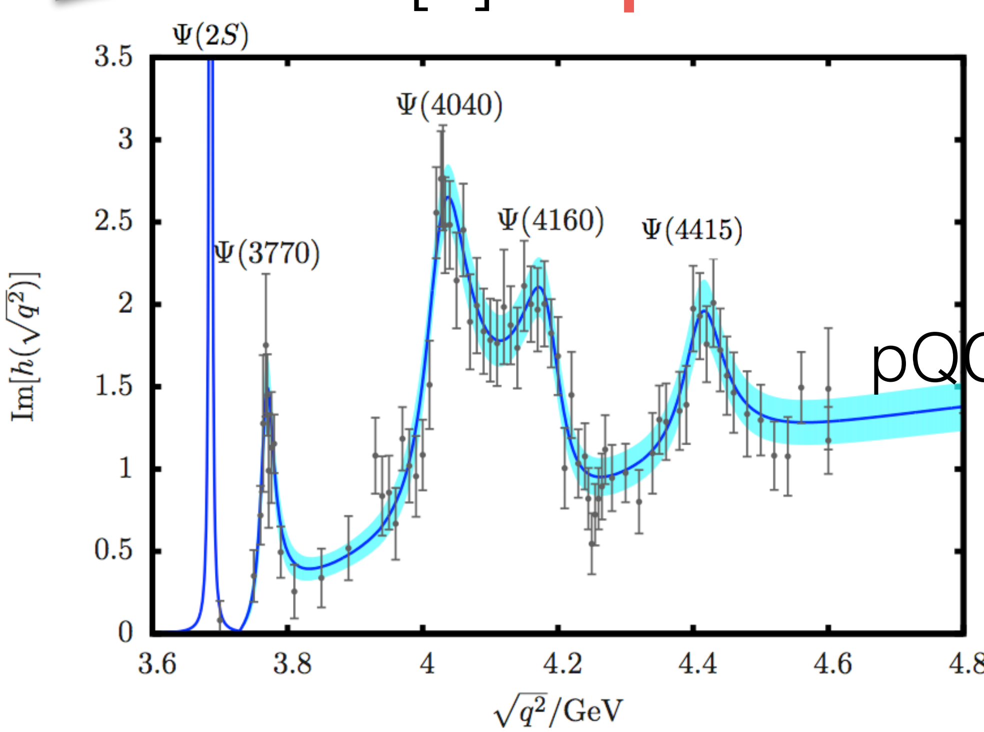




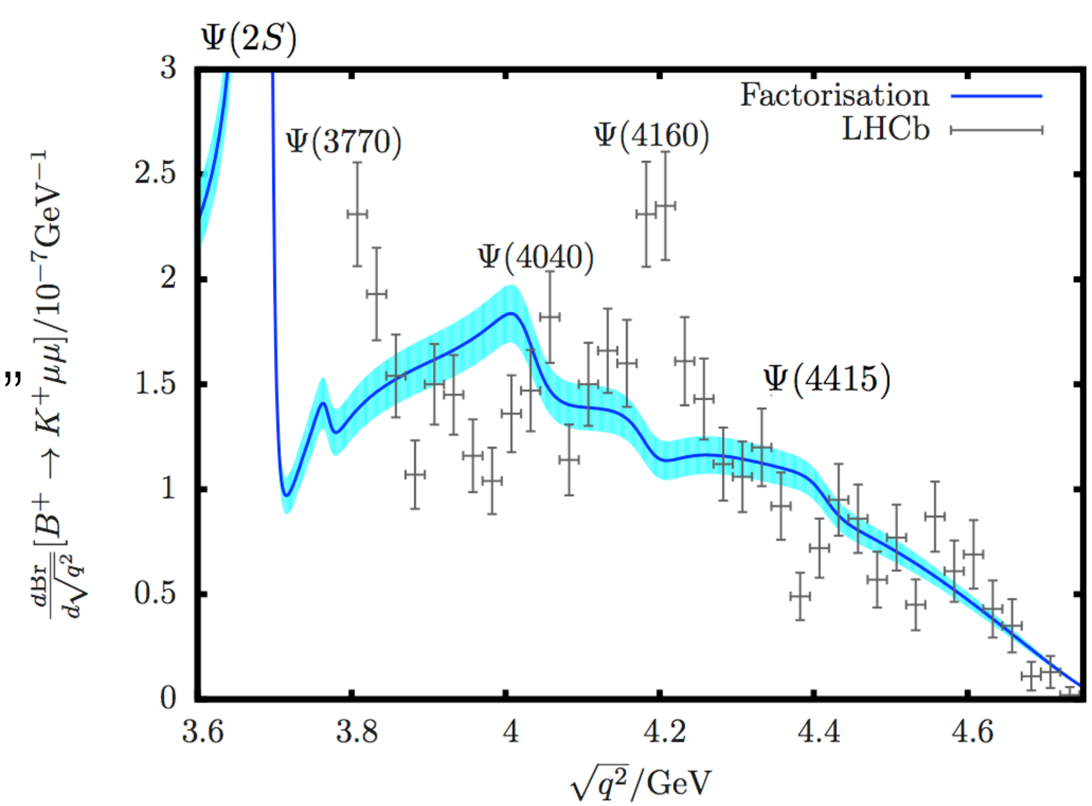
- **vac. pol. h(q²)** (for B->Kll) from e^+e^-→hadrons as for (g-2

Disc ~ Im[h]; BESII-data'PLB08

Re[h] **dispersion relation**



pQCD "ok"



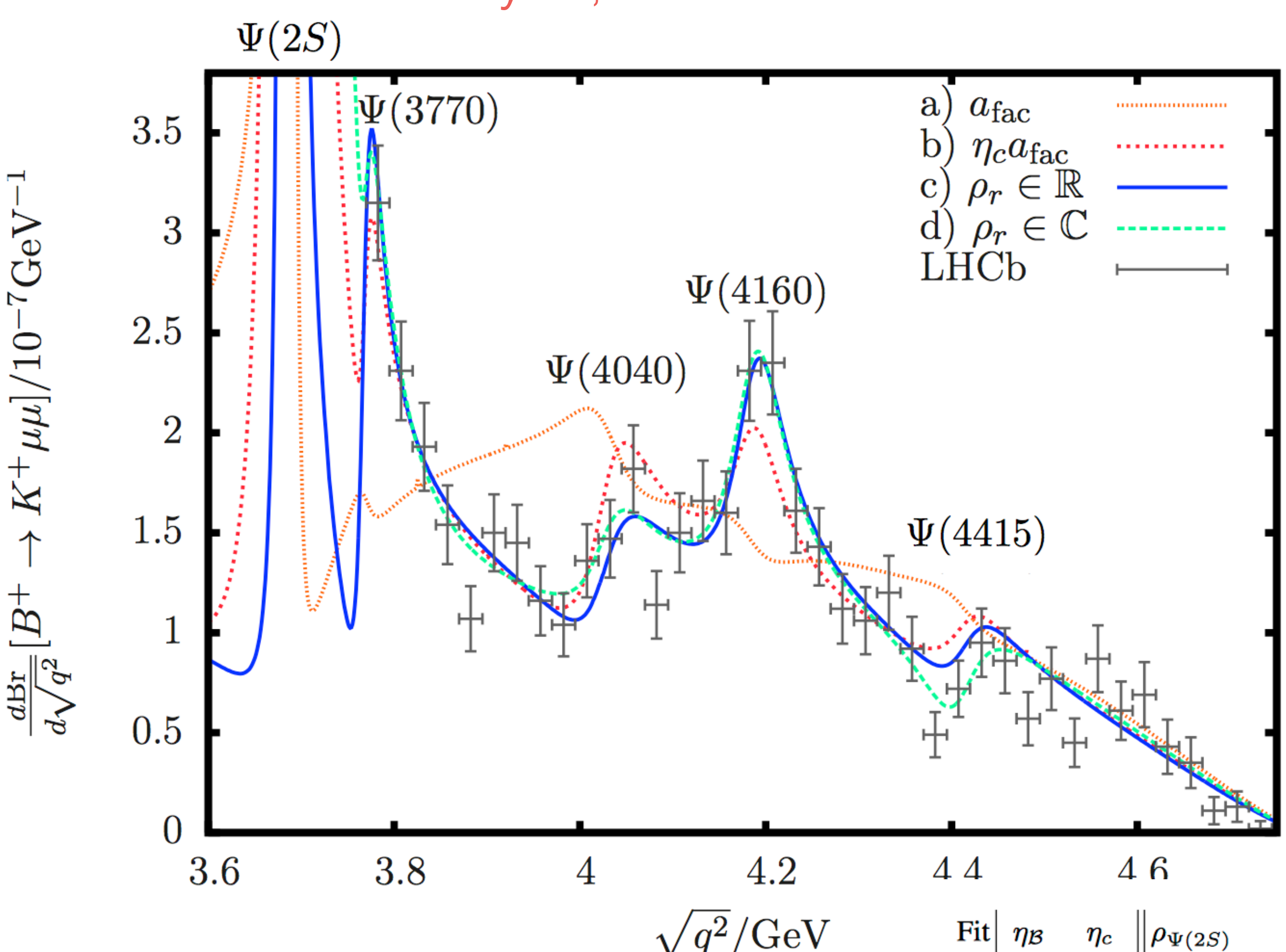
our **χ^2/dof = 1.015**

Beyond naive factorisation

- Can were understand data? Answer: **yes**
- first principles: Breit-Wigner **residues** related to amplitudes

$$\mathcal{A}(B \to K\ell\ell)|_{q^2 \simeq m_\Psi^2} = \frac{\mathcal{A}(B \to \Psi K)\mathcal{A}^*(\Psi \to \ell\ell)}{q^2 - m_\Psi^2 + i m_\Psi \Gamma_\Psi} + ..$$

Lyon, RZ '14 fit to LHCb data **broad** charmonium resonances



results:

- fit for residues large and opposite in ph
  to what people used to use for
  estimates (pQCD or e^+e^- -> hadrons)

Fit-values:

Fit	$\eta_{\mathcal{B}}$	η_c	$\rho_{\Psi(2S)}$	$\rho_{\Psi(3370)}$	$\rho_{\Psi(4040)}$	$\rho_{\Psi(4160)}$	$\rho_{\Psi(4415)}$	χ^2/d.o.f.	d.o.f.	pts	p-value
$a)$	0.98	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	3.59	99	117	$\simeq 10^{-30}$
$b)$	1.08	-2.55	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	1.334	98	117	1.5%
$c)$	0.81	$\equiv 1$	-1.3	-7.2	-1.9	-4.6	-3.0	1.169	94	117	12%
$d)$	1.06	$\equiv 1$	3.8-5.1i $6.4e^{-i53.3^\circ}$	-0.1-2.3i $2.0e^{-i92^\circ}$	-0.5-1.2i $1.3e^{-i111^\circ}$	-3.0-3.1i $4.3e^{-i135^\circ}$	-4.5+2.3i $5.1e^{i153^\circ}$	1.124	89	117	20%