Non-perturbative effects in $B \to K^{(*)} ll$ (charm resonances)

Lyon and RZ 1406.0566v1(v2 to appear)

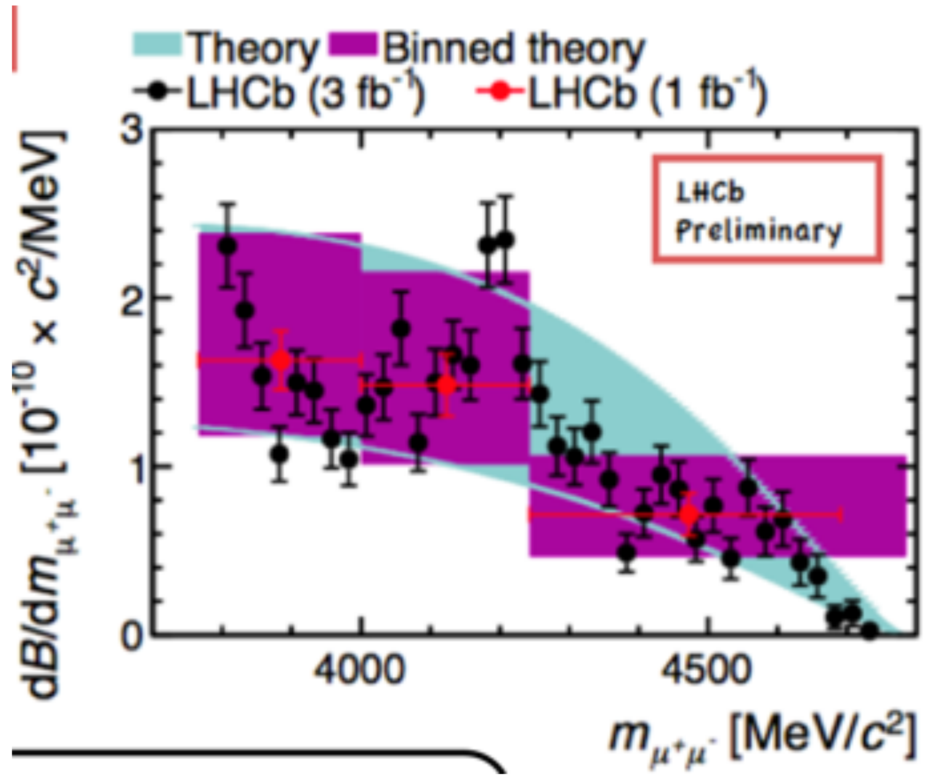
CP^3 Origins
Cosmology & Particle Physics

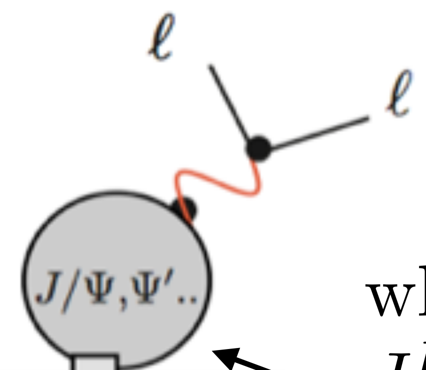
Centre for Theoretical Physics
Higgs

Roman Zwicky
Edinburgh University

8 January 2015 — The flavour of new physics (Zurich)

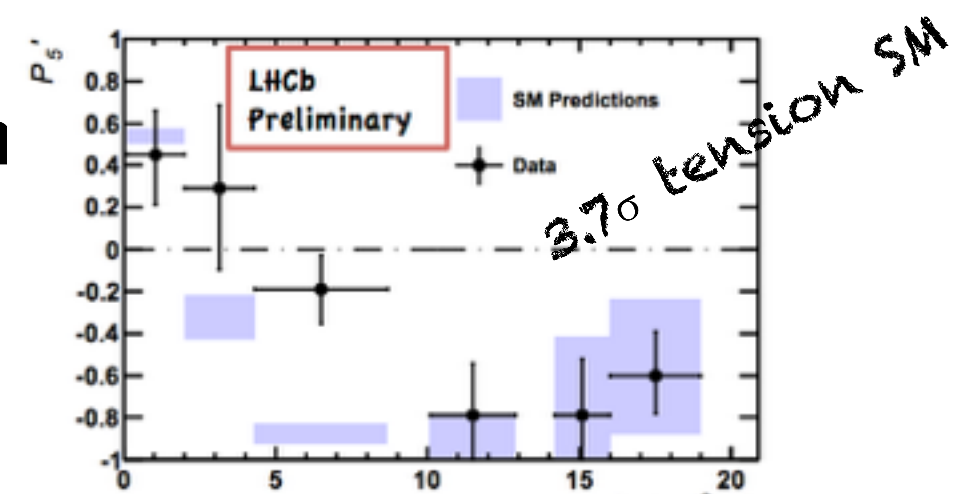
work triggered by ***LHCb measurement*** — PRL 111 (2013)





whole zoo of $J^{PC} = 1^{--}$ $c\bar{c}$−states

- very **pronounced resonance spectrum** through b->s(cc->ll)
- **is it all QCD** ? .. new bscc-physics is contrived and constrained(?)
- what are the **implications for prediction**
  is it related to 3.7σ tension SM:



structure

0) general overview

1) assessment: (naive) factorisation — fails
non-factorisable corrections

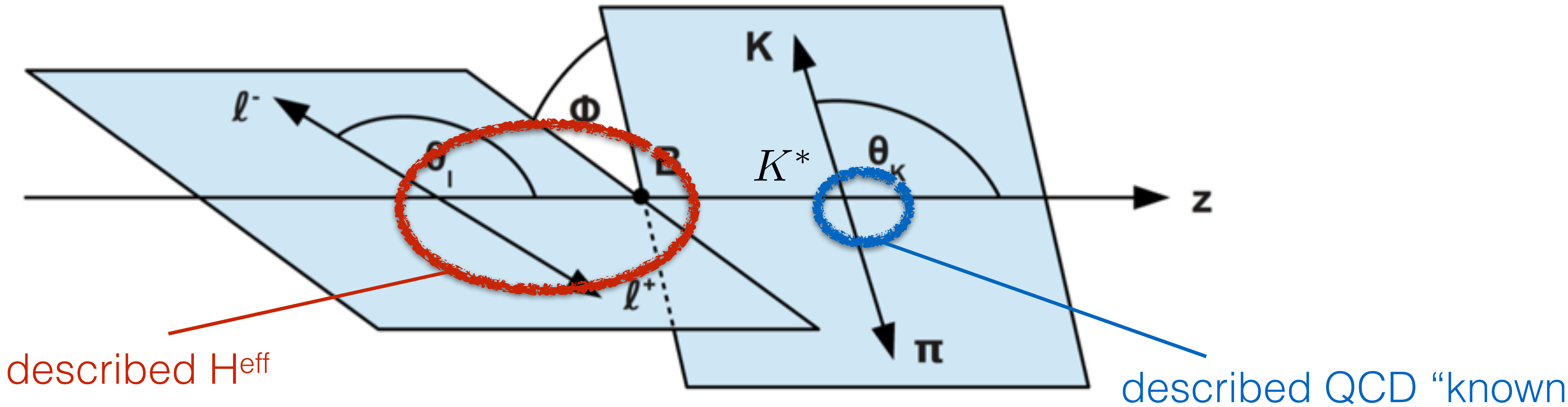
2) tension with QCD? *(semi-global quark hadron duality)*

*3) possible consequences at **low q^2***
- (yet) unknown J/Ψ-phases affect $B \to Kll$ & P_5'

*4) implications at **high q^2** (broad charm region)*
ideas to improve *(skip as dinner approaching)*

Phenomenology of B→K$^{(*)}$ll

c.f. Matias' talk



$$
\begin{aligned}
\frac{d^4\Gamma}{dq^2\,d\cos\theta_\ell\,d\cos\theta_K\,d\phi} &= (J_{1s} + J_{2s}\cos 2\theta_\ell + J_{6s}\cos\theta_\ell)\sin^2\theta_K \\
&+ (J_{1c} + J_{2c}\cos 2\theta_\ell + J_{6c}\cos\theta_\ell)\cos^2\theta_K \\
&+ (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_K\sin^2\theta_\ell \\
&+ (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K\sin 2\theta_\ell \\
&+ (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K\sin\theta_\ell\,,
\end{aligned}
$$

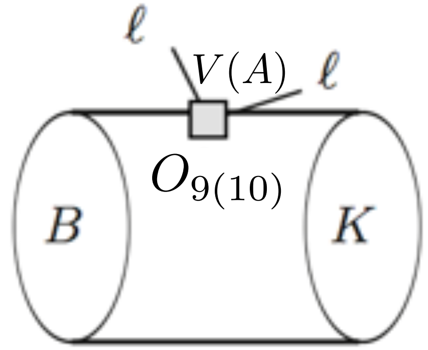
$J_i \propto H_a H_b^* \times \text{kinematics}$

for generic dim 6 H$^{\rm eff}$
12 "directions"

B→K$^{(*)}$ll under microscope

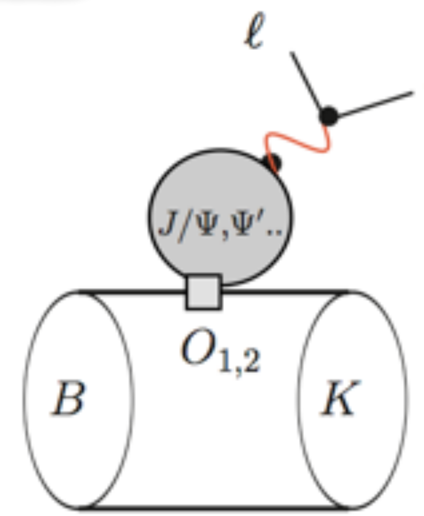
- main actors of this talk (same quantum numbers!)

short distance



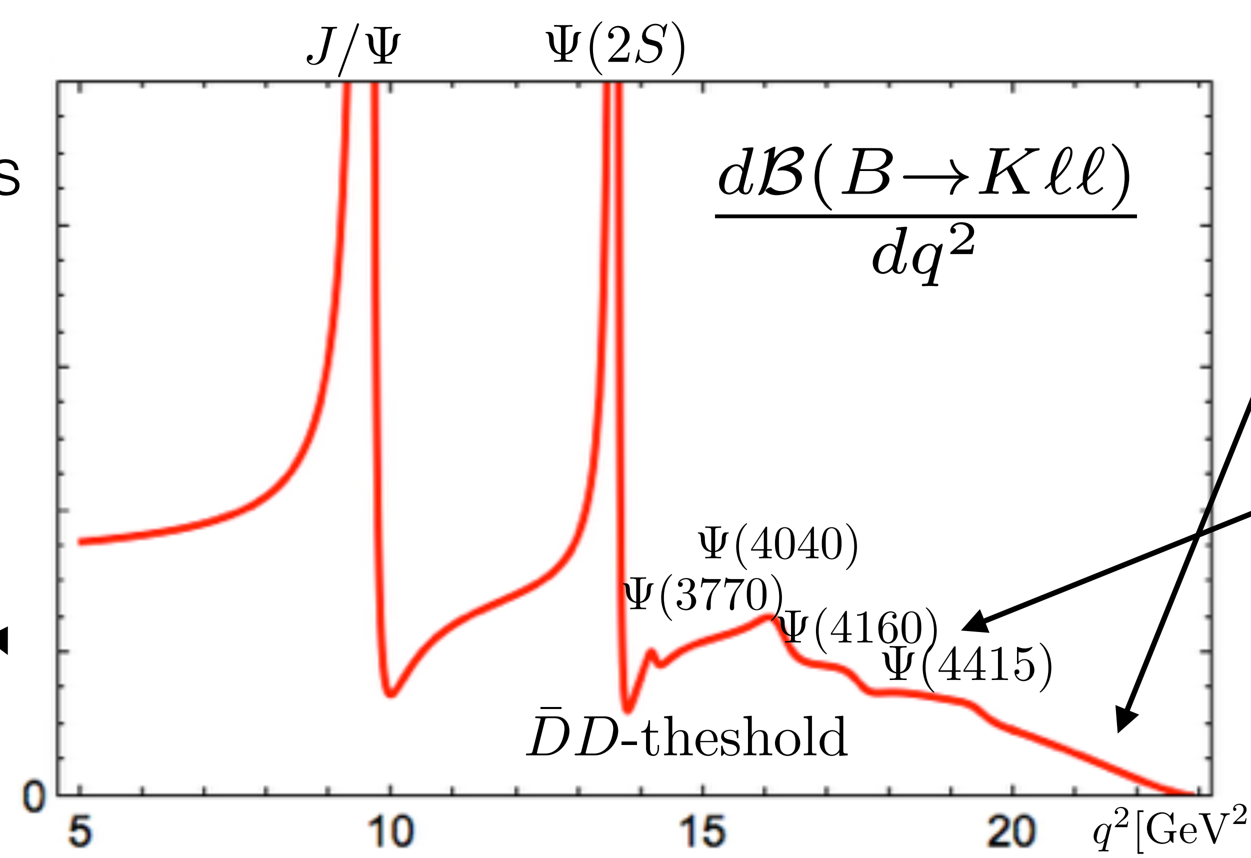
electroweak penguin (also O_7..)

Long distance



4-quark operators (also $O_{3..6}$)

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



K **slow**:
- high-q² **"OPE"**
-**endpoint relations**

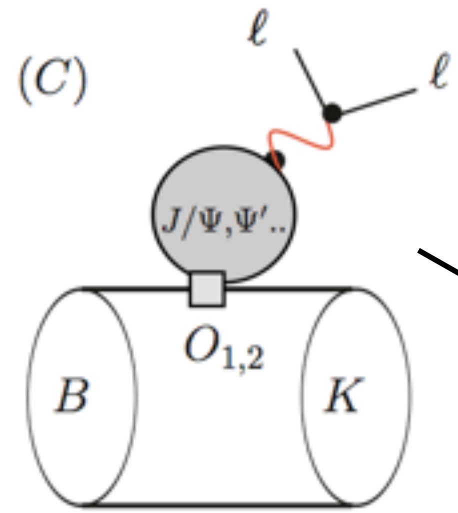
diagnostic shape for charm

$O^2_{7,9}$-dominates
O_2-$O_{7,9}$-interference

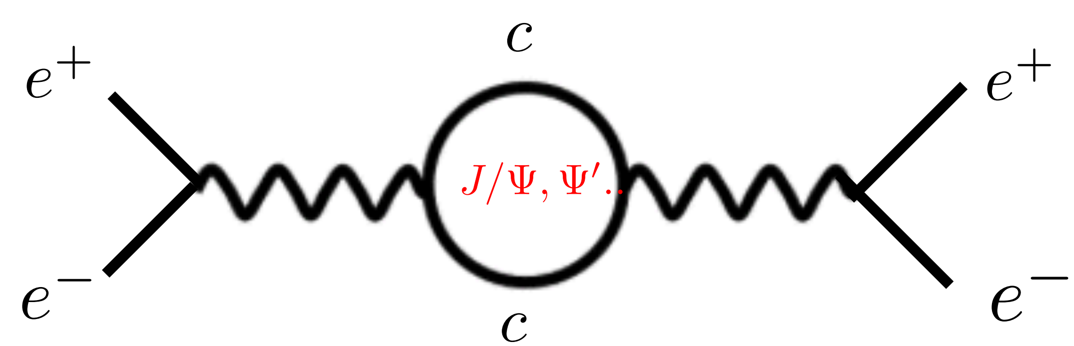
narrow resonances
$(O_2)^2$-effect

O^2_9-dominates
O_2-O_9-interference

1) assessment of (charm) resonances

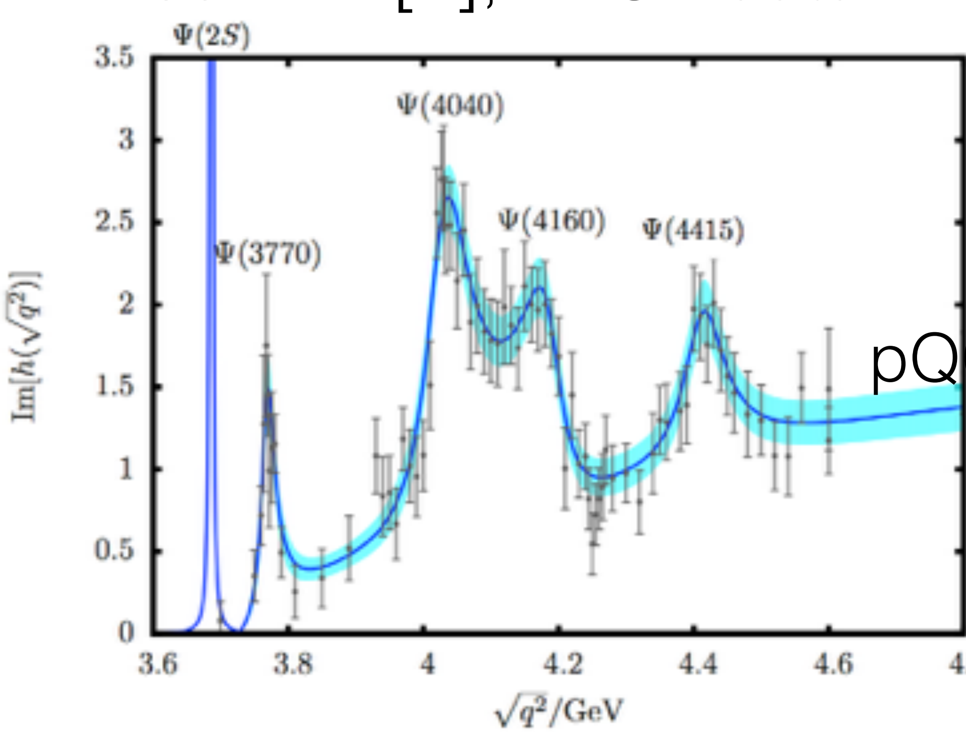


A. does (naive) factorisation describe B→Kll data?

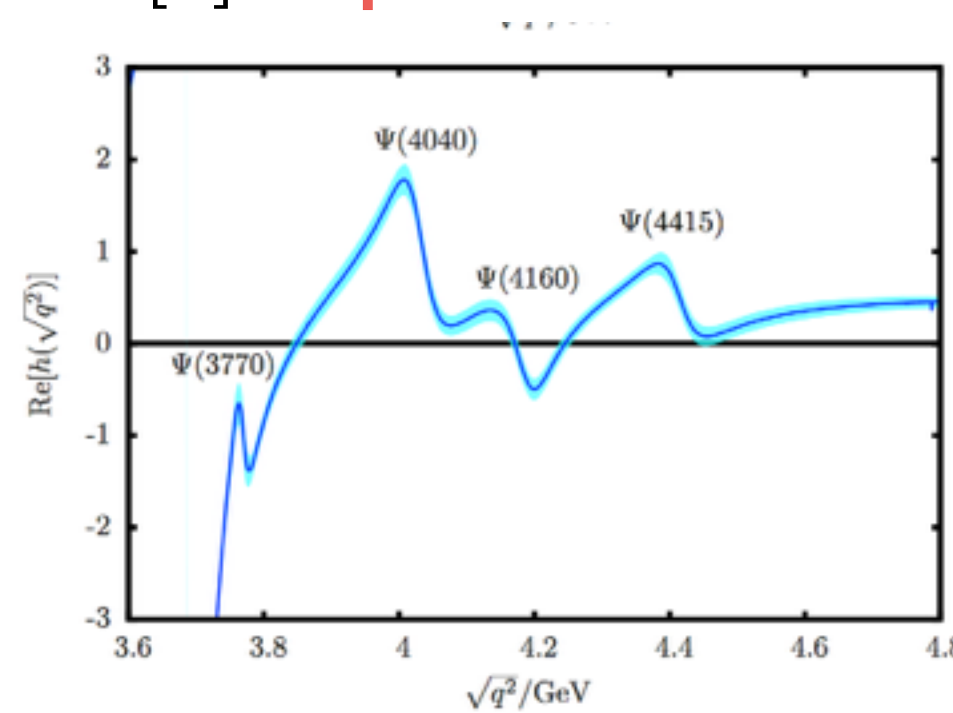


- **vac. pol. h(q²)** (for B->Kll) from $e^+e^- \to$hadrons as for (g-2)

Disc ~ Im[h]; BESII-data'PLB08 → Re[h] **dispersion relation**

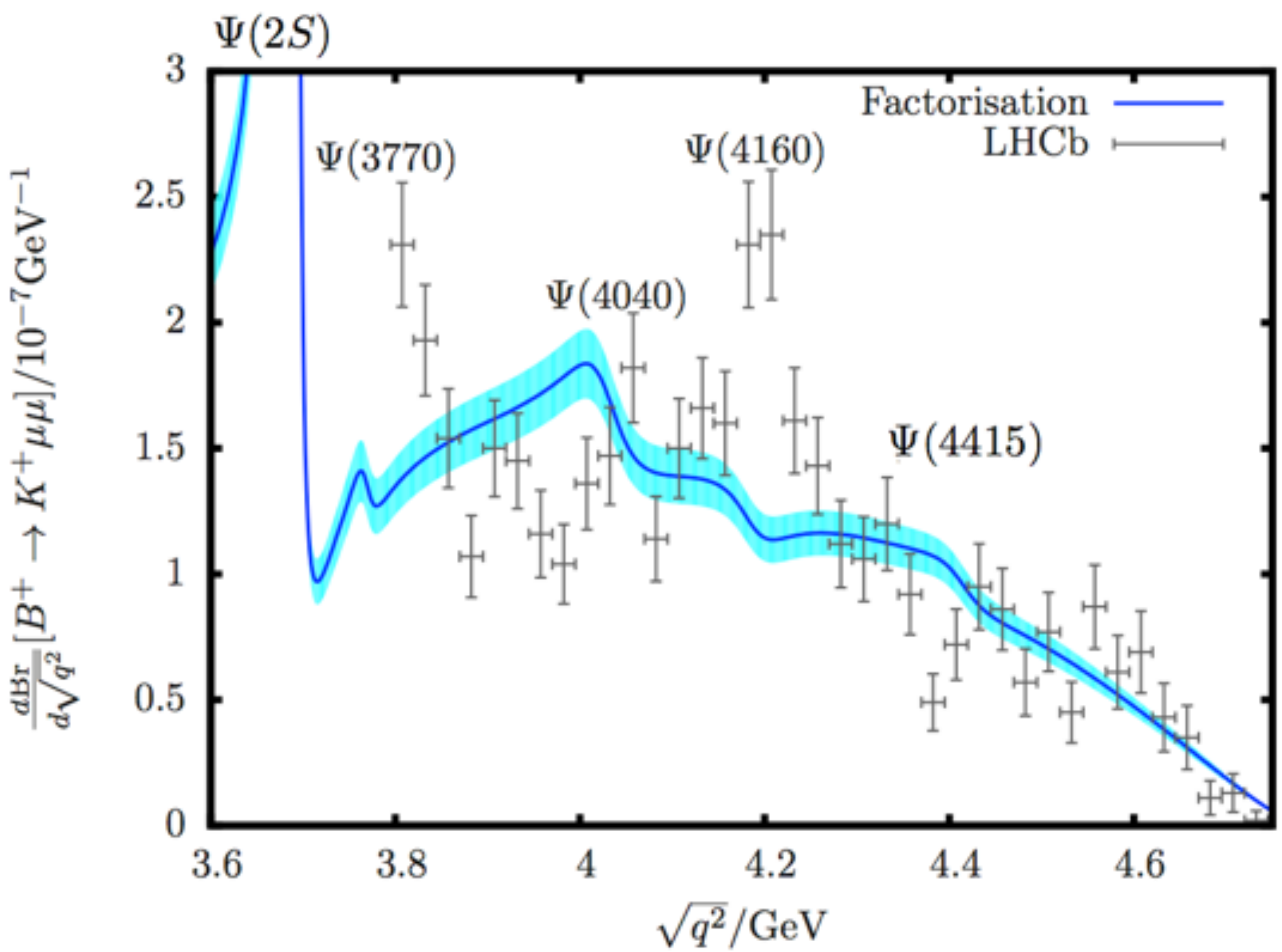


pQCD "ok"



our **χ^2/dof = 1.015**

Factorisation (BESII-data) applied to B→Kll at high q^2



clear failure of factorisation

clarifying status of factorisation of importance since:

- factorisation used estimate of "duality violations"
- perturbative factorisation used in most high-q^2 OPE predictions

B. probing non-factorisable effects

- think resonances described Breit-Wigner

N.B. 1) location of pole
& 2) residue are **physical**!

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

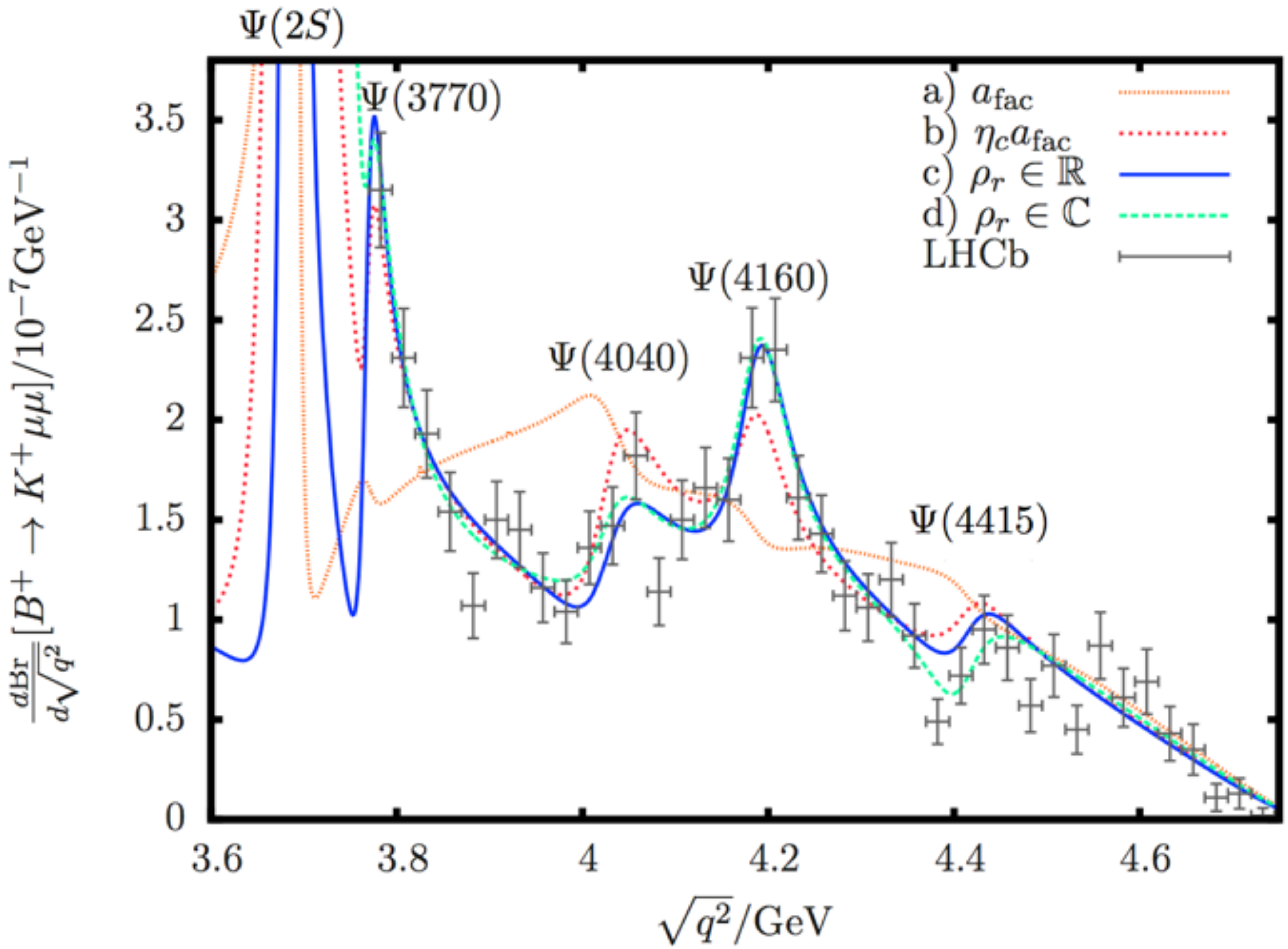
- idea: **correct** for **Ψ-production** (residue physical)

$$\begin{aligned} \mathcal{A}(B \to \Psi K)|_{\mathrm{fac}} &\sim f_+^{B\to K}(q^2)\mathcal{A}(\Psi \to \ell\ell) \\ &\to f_+^{B\to K}(q^2)\underbrace{\eta_\Psi}_{1+\mathrm{non-fac}}\mathcal{A}(\Psi \to \ell\ell) \sim \mathcal{A}(B \to \Psi K) \end{aligned}$$

- fits **η_Ψ**: b) global (scaled)fac; c) real-variable; d) complex-variable

only option d) sensible a priori

results ....



Fit	$\eta_{\mathcal{B}}$	η_c	$\eta_{\Psi(2S)}$	$\eta_{\Psi(3770)}$	$\eta_{\Psi(4040)}$	$\eta_{\Psi(4160)}$	$\eta_{\Psi(4415)}$	χ^2/d.o.f.	d.o.f.	pts	p-value
$a)$	1.02	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	3.59	99	117	$\simeq 10^{-30}$
$b)$	1.02	-2.55	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	1.334	98	117	1.5%
$c)$	0.77	$\equiv 1$	-1.3	-7.2	-1.9	-4.6	-3.0	1.169	94	117	12%
$d)$	1.00	$\equiv 1$	3.8-5.1i	-0.1-2.3i	-0.5-1.2i	-3.0-3.1i	-4.5+2.3i	1.124	89	117	20%
			$6.4e^{-i53.3^\circ}$	$2.0e^{-i92^\circ}$	$1.3e^{-i111^\circ}$	$4.3e^{-i135^\circ}$	$5.1e^{i153^\circ}$				

2) assessment from theory viewpoint

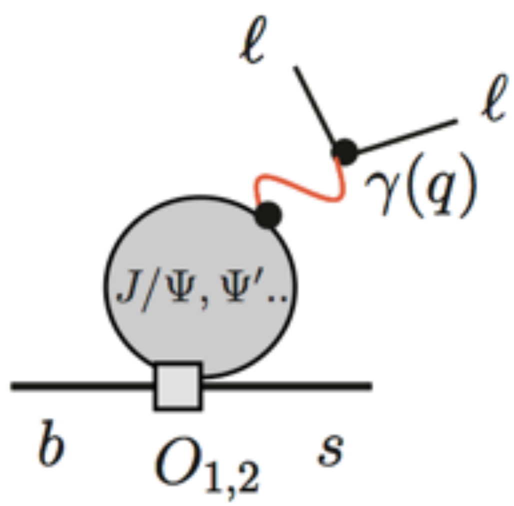
is it or isn't it all that surprising?

a) *patrons*
b) hadrons
c) linked dispersion integrals
quark hadron duality

a) how large are partonic non-fac. corrections

very brief

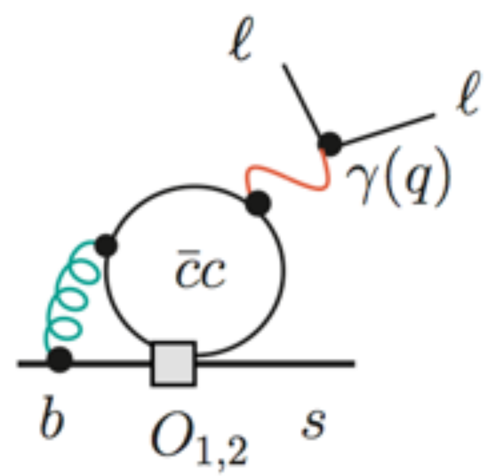
- from pQCD alone not chance to resolve locally in q^2
- at high q^2: q^2 is a large scale can integrate out charm quarks so-called high-q^2 "OPE" Grinstein,Pirjol'04 Beylich,Buchalla,Feldmann'11



factorisation (BESII)

Lyon RZ'14

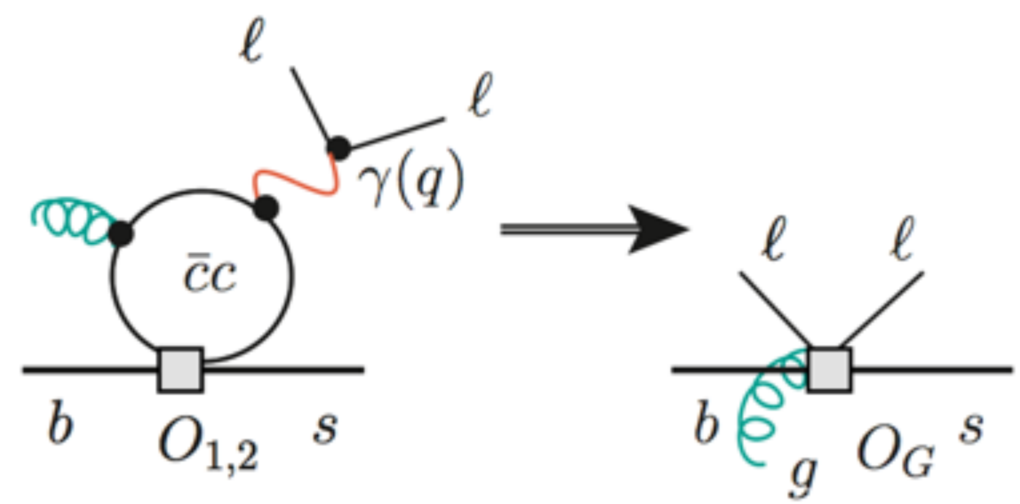
100% in our units



dim-3 vertex-corrections

Hurth, Isidori, Ghinculov, Yao'03
Greub, Pilipp, Schupach'08

roughly -50% throughout q^2-domain
N.B. large due to color-enhancement
(not repeated higher orders)

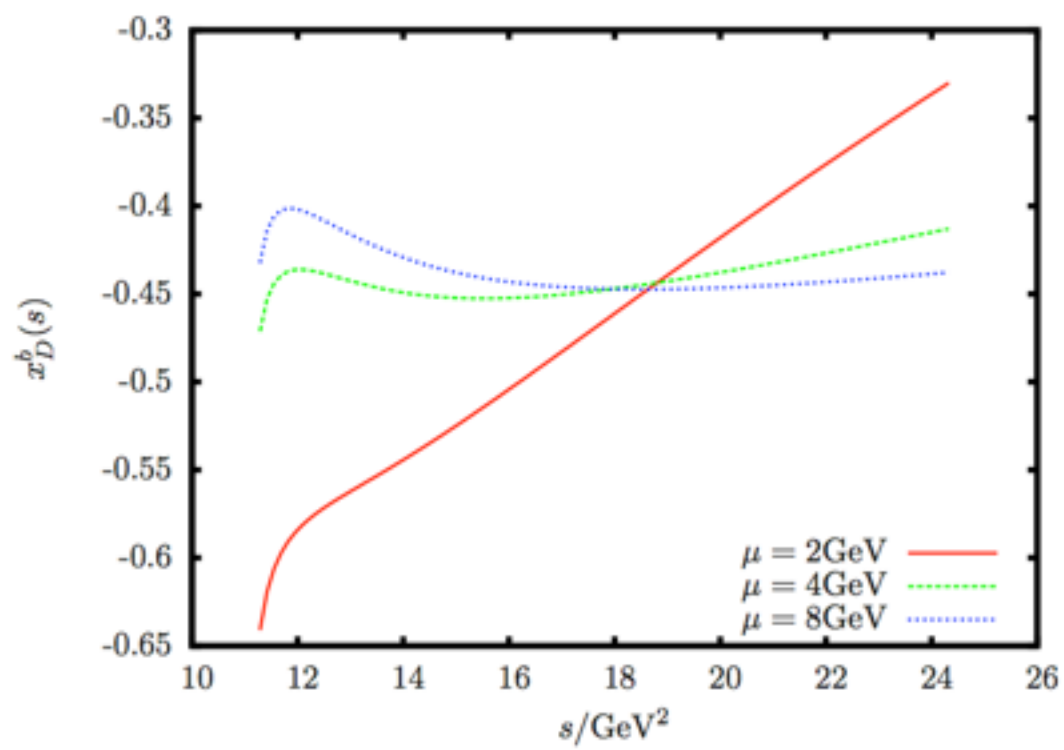


dim-5 spectator & soft gluon

Beylich,Buchalla,Feldmann'11

small O(2%) QCDF
consistent dim. suppression

- -50%-correction is nowhere near -350%



b) factorisation as a function of m_Ψ

- experimental information on B→J/ΨK$^{(*)}$ and B→Ψ(2S)K$^{(*)}$
  ⇒ quantify correction to factorisation: $\eta_\Psi = 1 + \text{non-fac}$ [1]

$J/\Psi \quad \Psi(2S) \quad \Psi(3370)..\Psi(4415) \qquad m_\Psi/\mathrm{GeV}$

$|\eta_{J/\Psi K}| \simeq 1.42 \quad |\eta_{\Psi(2S)K}| \simeq 1.82 \quad \textit{new}: \ \eta_{\Psi(broad)K} \simeq -2.5$

$|\eta_{J/\Psi K^*}| \simeq 1.03 \quad |\eta_{\Psi(2S)K^*}| \simeq 1.06$

1. whereas corrections to J/Ψ, Ψ(2S) could be 40%, 80% “only” (order of vertex corrections),
   350% correction **broad Ψ(3770) - Ψ(4415)** on **average - new result**

2. N.B magnitude 2.5 not a big surprise but that they
   i) **all have “same sign”** & ii) **sign negative**
   challenges quark-hadron duality* (nominal correction 50% learned previous slide)

is it all QCD? Can we assess it? partially through …..

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[1] *depends on “choice” of Wilson coeff. - yet ratio of η’s is well defined!*

c) dispersion relations and quark hadron duality (qhd)[1]

- amplitude $H(q^2)$ **if** know analytic structure in q^2 by Cauchy thm integral rep:

$$H(q^2) = \frac{1}{2\pi i}\int_\Gamma \frac{dt H(t)}{t-q^2-i0} \quad \text{, modulo subtractions}$$

dispersion relation

- if $H^{pQCD}(s_0) \cong H^{QCD}(s_0)$ then quark hadron duality:

$$\frac{1}{2\pi i}\int_\Gamma \frac{dt H^{pQCD}(t)}{t-q^2-i0} \simeq \frac{1}{2\pi i}\int_\Gamma \frac{dt H^{QCD}(t)}{t-q^2-i0}$$

- for amplitudes $H(q^2)$, Γ related to (in principle) experimentally accessible region[2]

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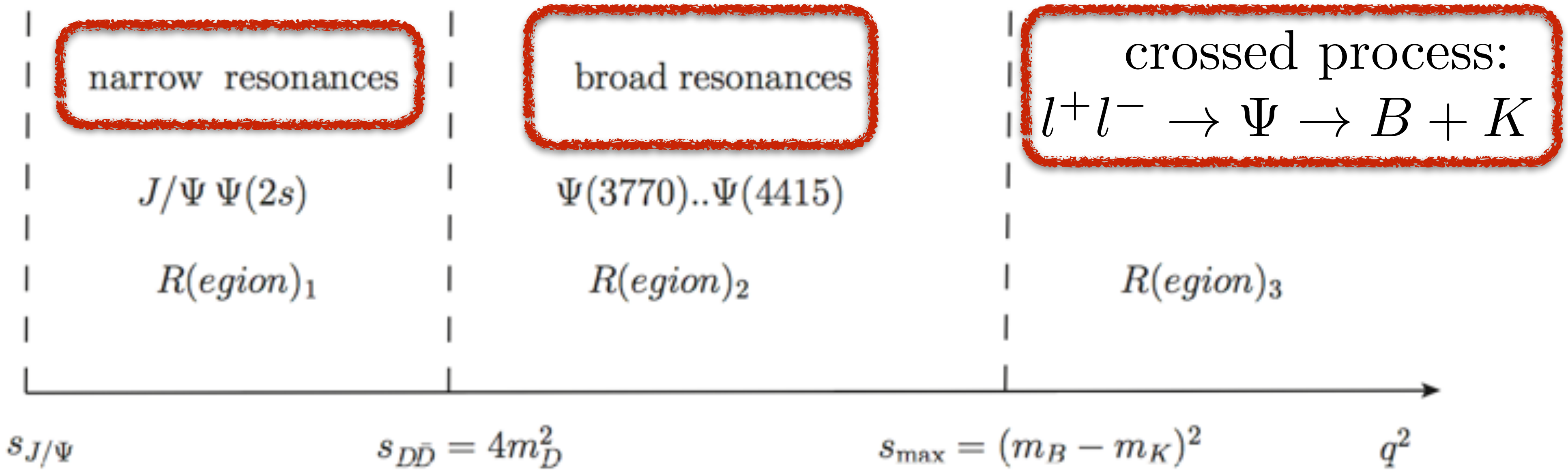
[1] *qhd-(violation) sometimes (Shifman et al) means OPE-violating term - here different usage*

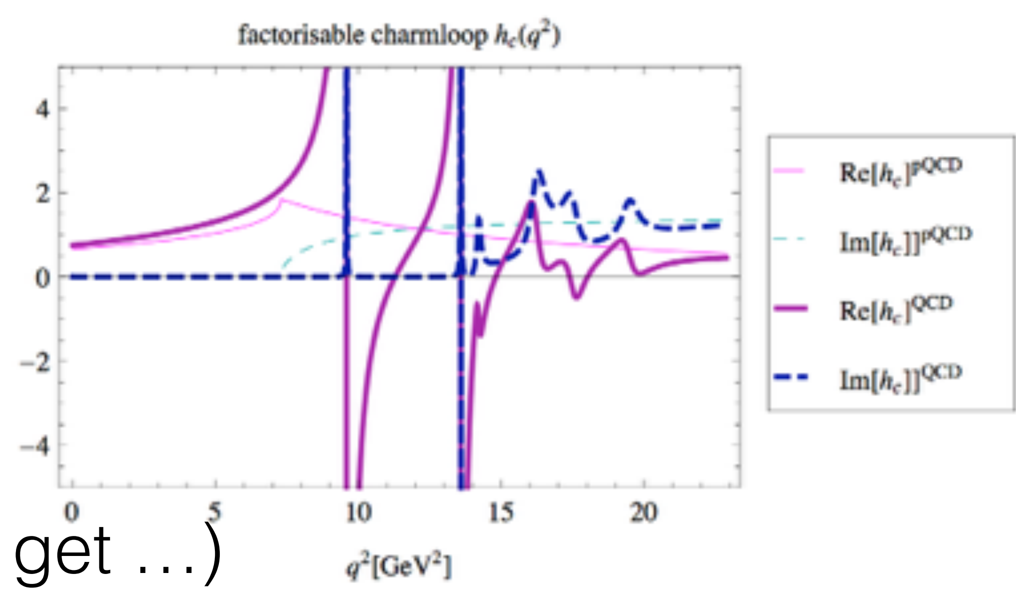
[2] *not valid for decay rate (in this form) in general*
unless can write rate in terms of amplitude (e.g. inclusive decays)

- analytic structure of charm amplitude cut starting at $4m_c^2$ poles at $m_{J/\Psi}^2$ resp.



a) **if** information in all 3 regions $\Longrightarrow$ check whether microscopic theory is compatible
b) **semi-global qhd**: approx equality of pQCD & QCD dispersion-∫ holds in (sub)region

- $e^+e^- \to \Psi \to e^+e^-$ "dreamland"
  a) information available in all regions
  b) semi-global qhd "works" in all three regions



- $B \to K\, l^+ l^-$
  a) no info available in region 3 (region 1 we may get …)
  b) region 2 semi-global qhd does not seem to hold

hence:

- a must: **check semi-global qhd region 1+2**
- if does not work:
  one possibility that region 3 (**crossed process $\Psi \to B+K$**) **compensates**

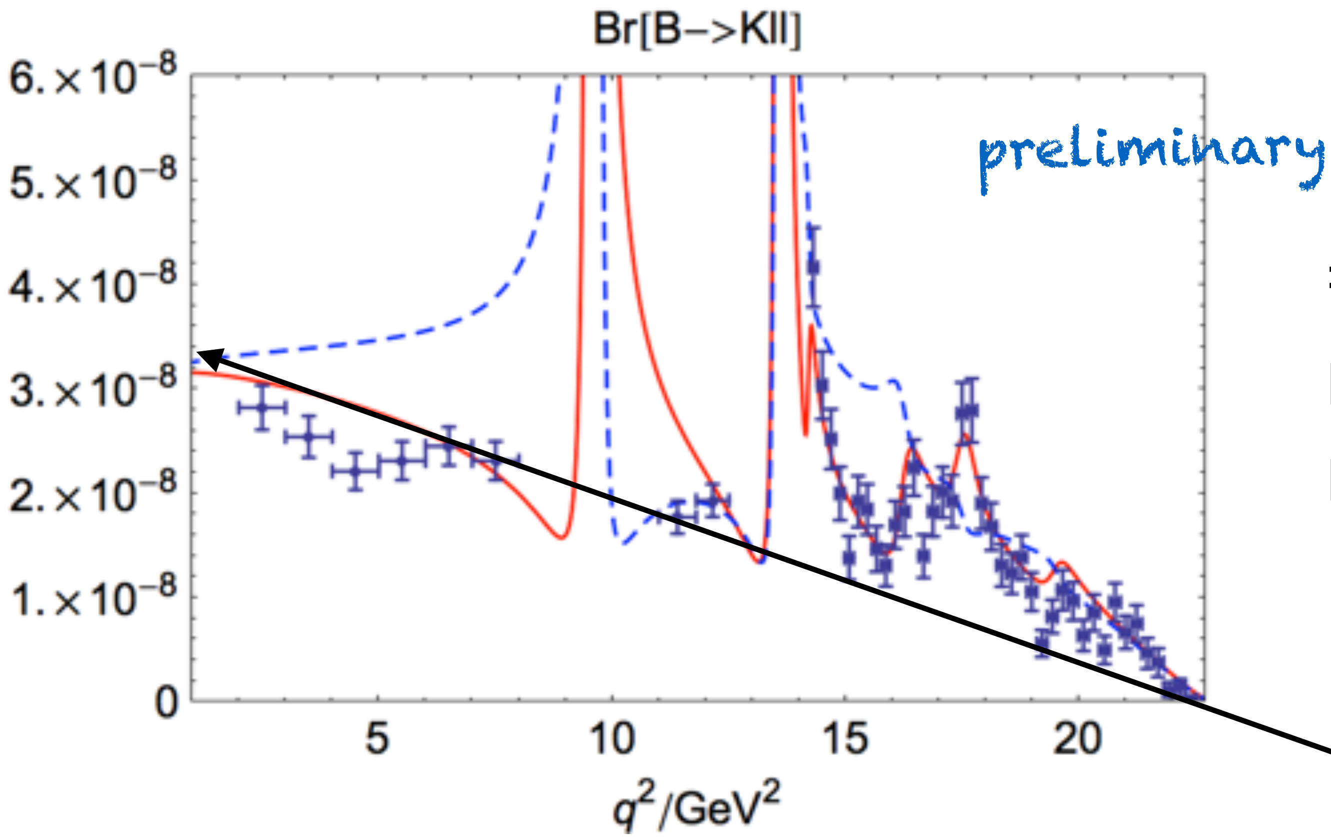
recall: region 1 phases are as of now missing
let's look at implications

3) possible consequences at low q^2
(yet) unknown $\delta_{J/\psi K^{(*)}}$-phases

the unknown J/Ψ phase

$$\eta_{J/\Psi K} = |\eta_{J/\Psi K}| e^{i\delta_{J/\Psi K}} \simeq 1.4 e^{i\delta_{J/\Psi K}}$$

- to match/fit slop of pQCD charm $\delta_{J/\psi} \simeq 0$ e.g. Khodjamirian et al'10 and others
- let's change phase to $\delta_{J/\psi K} \simeq \pi$ and compare with Br(B→Kll)



⟹ empirically $\delta_{J/\psi K} \simeq \pi$
not absurd (even slightly favoured)
not as conclusive as high q^2

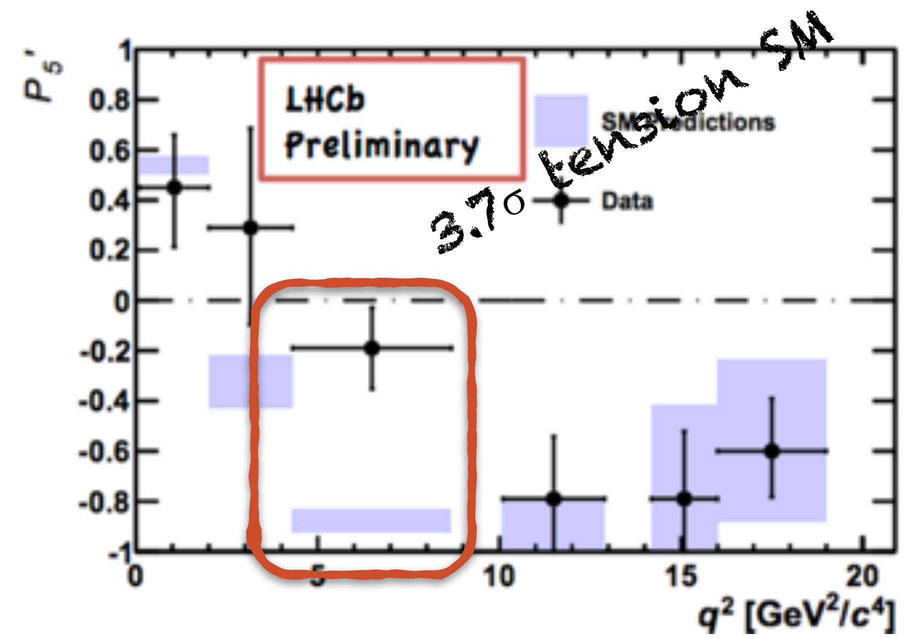
- $\delta_{J/\psi K} \simeq \pi$ matched charm amplitude to SM at $q^2 = 0$
well but then slope of charm amplitude (not to be confused with rate) has wrong sign as w.r.t. to SM ⟹ more precise data binning

possible relation to P_5'

preliminary sketch

angular observable: $P_5' \sim \mathrm{Re}[H_0 H_\perp^*]$

"form factor insensitive observables" Descotes., Matias, Ramon, Virto'12



- [4.3,8.68]-bin : LHCb: $P_5' \simeq -0.19(16)$ and SM-naive fac: $P_5' \simeq -(0.8\text{-}0.9)$
- why P_5'-anomaly could be related to charm (or SM)
  - anomaly close to J/Ψ & charm effects turn out to be large
  - only present in vector helicity amplitude (can be mediated by photon)
- similar story as for K: global phase of helicity amplitudes unknown
  $\boldsymbol{\delta_{J/\psi K^*} \simeq 0}$ to match SM used theorists
  if we take $\boldsymbol{\delta_{J/\psi K^*} \simeq \pi}$ then $\Delta P_5' \simeq -0.3$ get rather close to LHCb-value

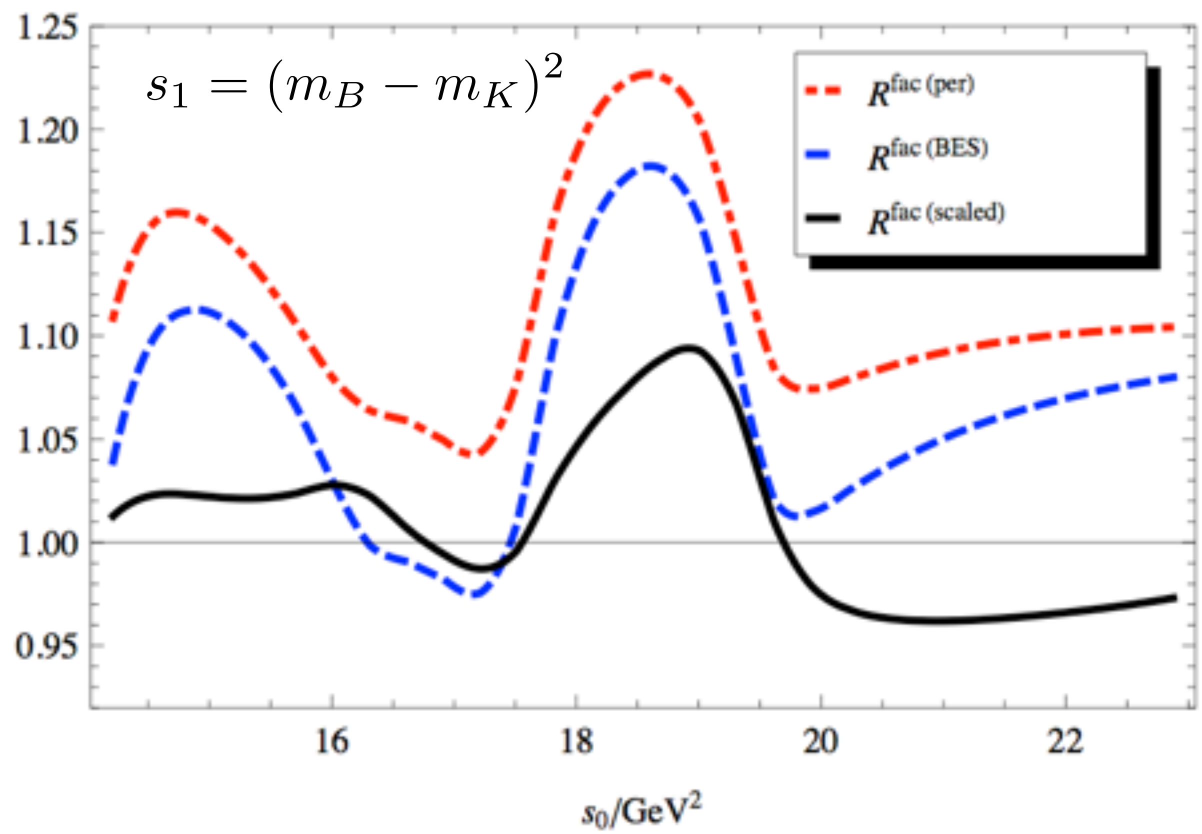
4) implication for high q^2-observables

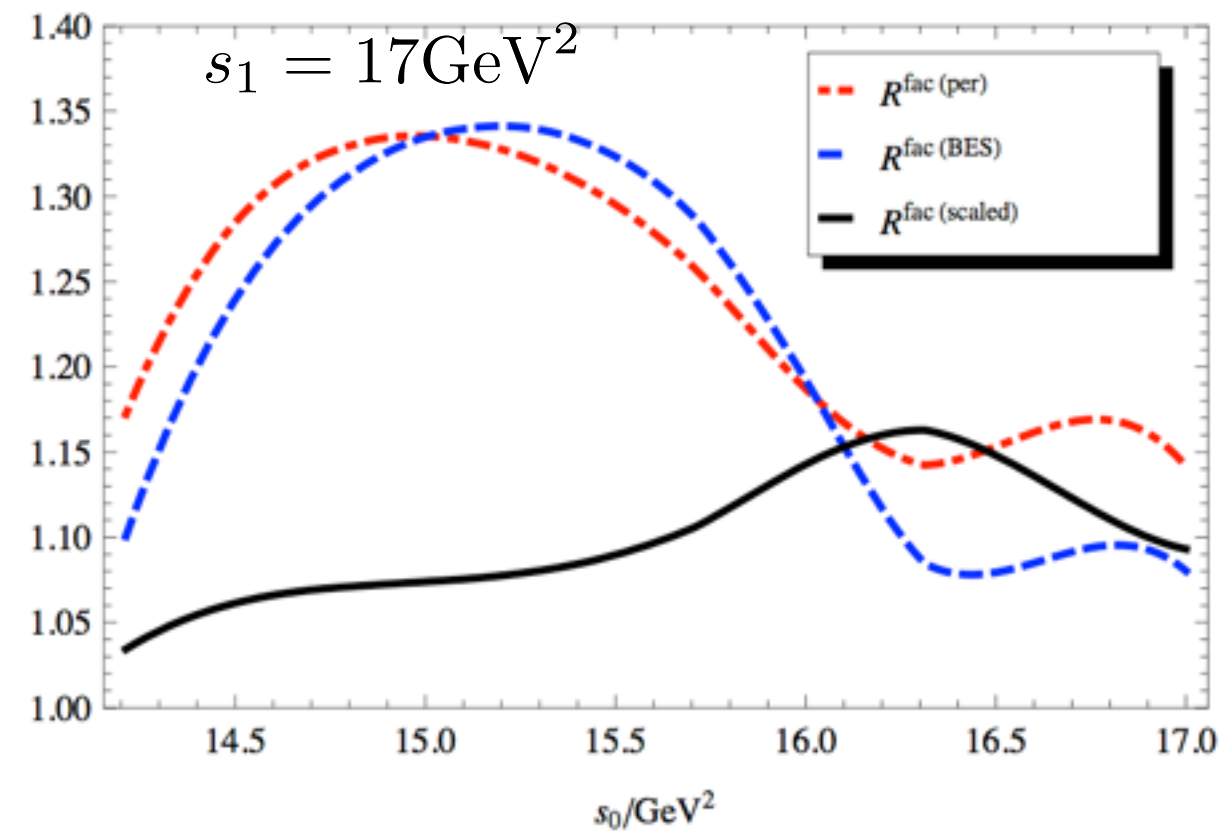
Binned Br(B→Kll) high q^2: a priori and a posteriori

- ratio of Br(B→Kll) using
  i) factorisation perturbative (no resonances)
  ii) factorisation (BES-data)
  vs data as function lower bin bdry s_0

$$\frac{\mathrm{Br}(B^+ \to K^+\ell\ell)^{i),ii)}_{[s_0,s_1]}}{\mathrm{Br}(B^+ \to K^+\ell\ell)^{fit-d)}_{[s_0,s_1]}}$$

basically as good as data (by construction)





for angular observables issue more subtle as their can be cancellations in ratio ……..

right-handed currents (RHC) vs non-universal polarisation in $B \to K^* ll$

- issue imminent from structure of **helicity amplitudes**

$$H_0^V \sim (C_9 - C_9') \, \hat{H}_0{}^V(q^2) + .. \, , \quad H_{||}^V \sim (C_9 - C_9') \hat{H}_{||}^V(q^2) + .. \, , \quad H_\perp^V \sim \sqrt{\lambda_{K^*}} (C_9 + C_9') \, \hat{H}_\perp^V(q^2) + .. \, ,$$

RHC $C_9' \neq 0$ intertwined polarisation effects $0, ||, \perp$

- **polarisation universality:** fac and non-fac depend same way on pol.

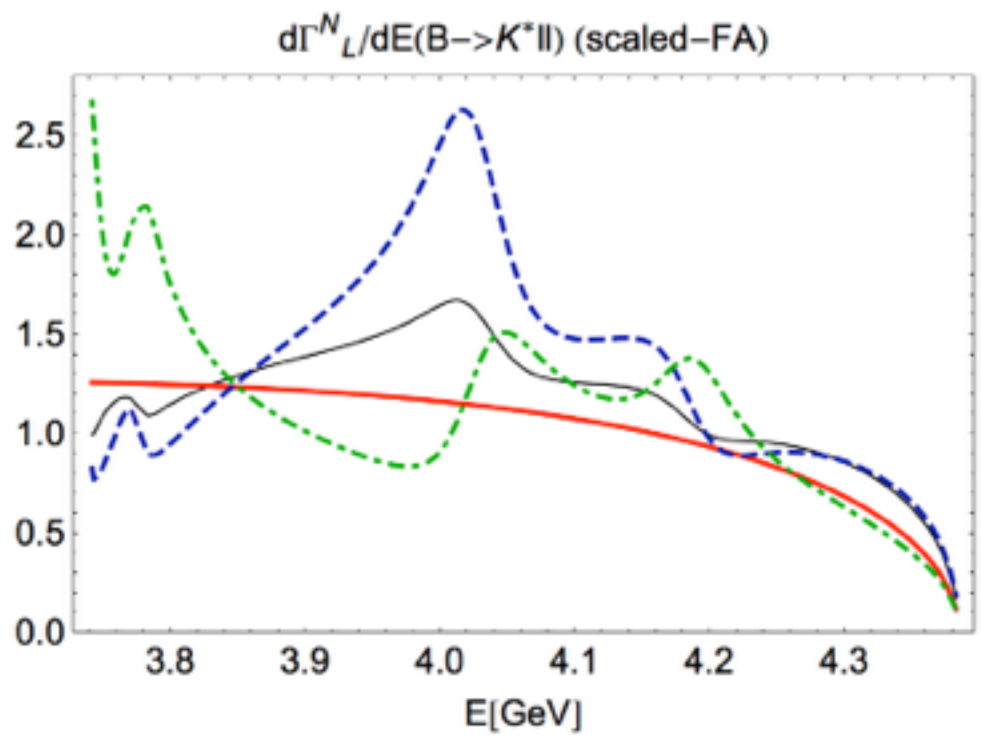
$$\frac{|H_0^V|}{|H_{||}^V|} \overset{?}{\simeq} \frac{|f_0^V|}{|f_{||}^0|} \quad \text{for some } q^2, \; f \; \text{form factor}$$

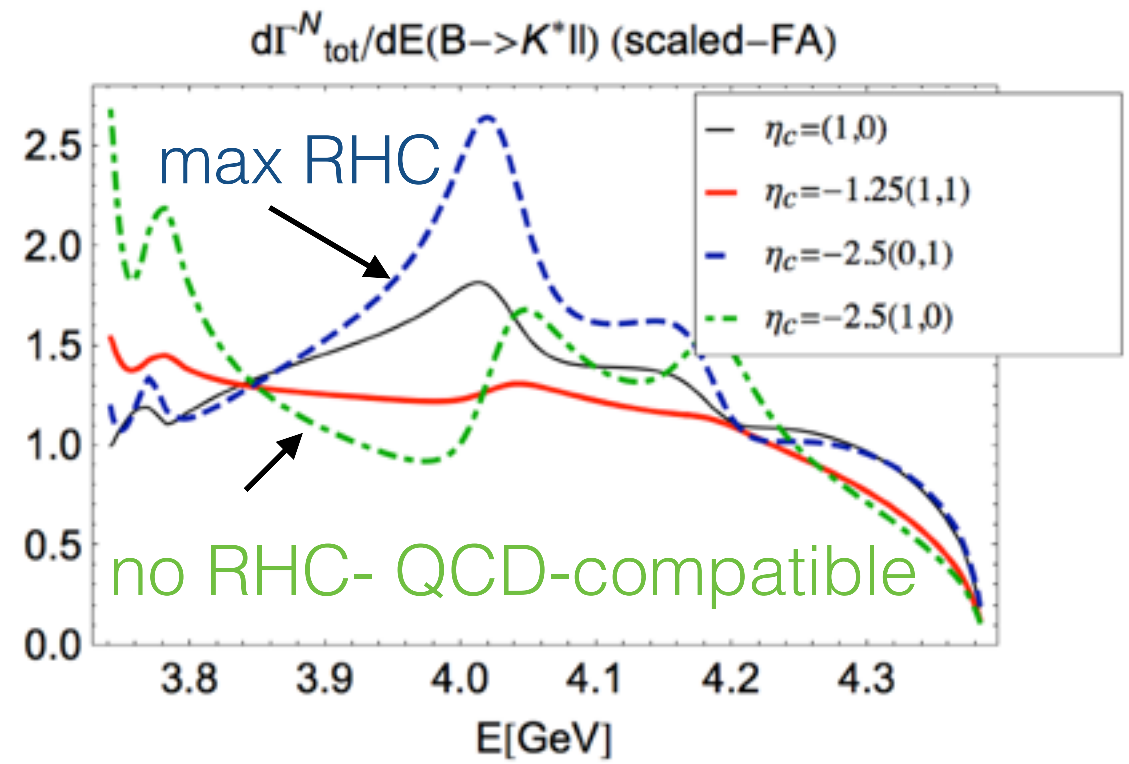
polarisation-universal

S-state: J/Ψ ok, $\Psi(2S)$ okish,
P-state: χ_{c1} broken
D-state: $\Psi(3370)$,$\Psi(4160)$? —- experimentally accessible

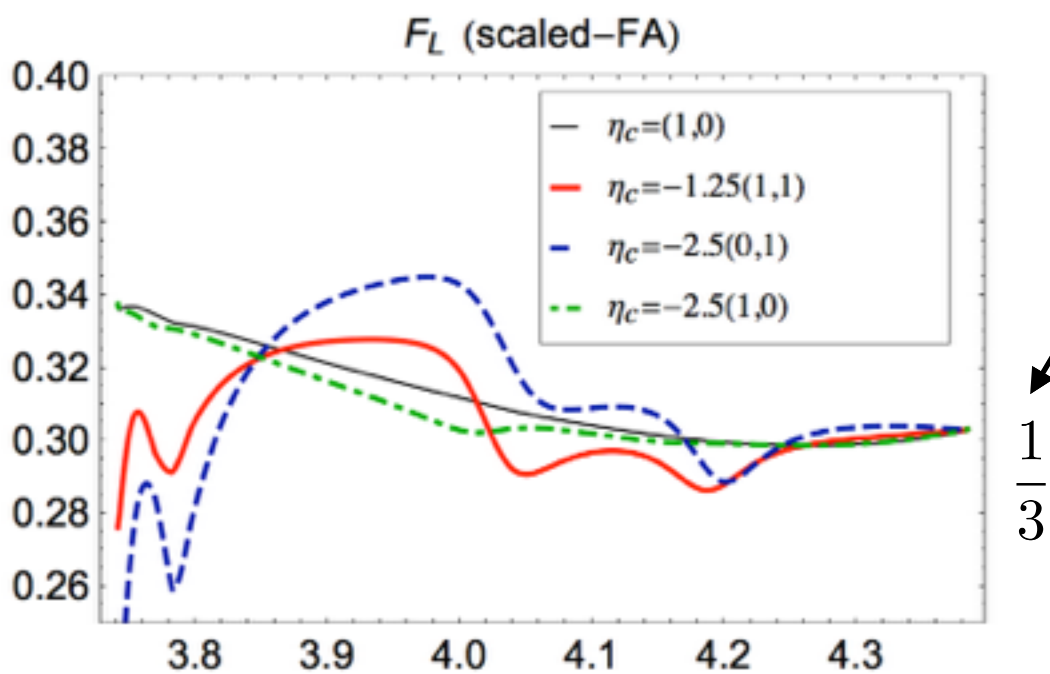
what is the pattern?

- **if polarisation universal** then $Br_{L,tot}(B \to K^* ll)$ good observable to test for right-handed currents*





- **if polarisation universal** and **no RHC** then resonance effect minimal in class of observables Hiller and RZ'13



e.g. **black** and **green** curve nearly **identical** even though green curve has 2.5 as much resonances!
N.B. endpoint all curves asymptotes 1/3

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* *assumes effect same magnitude in $B \to K^* ll$ (could be bit smaller or larger in reality)*

conclusions and summary

- General: **B→Kll** a) rich information **angles** & **q^2-shape**
  b) long distances effects to deal with

- In relation to b) long versus short-distance effects?
  If *non form factor* ***q^2-dependence ⇒ long-distance new physics****

- **factorisation** approximation **fails** spectacularly - pressure on SM(QCD)
  new physics in bscc-operators? (contrived)
  ⟹ need more experimental information, finer binning low q^2

- change in **$\delta_{J/\psi} \simeq \pi$** (empirically unknown) fits **shape** and magnitude of Br(B→Kll) low q^2 and also looks promising for P_5'

- whereas charm can explain some "anomalies"
  i) of course there is room for short-distance new physics in C_9^{eff}
  ii) progress in form factor correlations (backup) should help in searches due to use of Ward identities (e.o.m.)
  iii) charm resonances are lepton-universal ⇒ no relation to R_K

thanks for your attention

backup slides

comment on form factor correlations ....

Use of equation of motion for form factors

- Consider QCD e.o.m./Ward-identity (*study correction Isgur-Wise relations*)

Grinstein Pirjol'04

$$i\partial^\nu(\bar{s}i\sigma_{\mu\nu}(\gamma_5)b) = -(m_s \pm m_b)\bar{s}\gamma_\mu(\gamma_5)b + i\partial_\mu(\bar{s}(\gamma_5)b) - 2\bar{s}i\overleftarrow{D}_\mu(\gamma_5)b$$

- Evaluate on ⟨K*| …|B⟩ get 4 independent equations e.g.

$$T_1(q^2) - \frac{(m_b+m_s)}{m_B+m_{K^*}}V(q^2) + \mathcal{D}_1(q^2) = 0$$

- 1) any determination of form factors must satisfy e.o.m.
  2) Correlation function lattice/LCSR are compatible e.o.m. up to irrelevant contact terms

Hambrock, Hiller, Schacht, Zwicky '13
Bharucha, Straub, Zwicky'14 (to appear)

$$T_1(q^2) - \frac{(m_b + m_s)}{m_B + m_{K^*}} V(q^2) + \mathcal{D}_1(q^2) = 0$$

- 1) denote $F(q^2)^{s_0^F, M_F^2}$, s_0^F threshold, M_F^2 Borel parameter
  then compatible with eom $s_0^{T_1} = s_0^V = s_0^{\mathcal{D}_1}$ and $M_{T_1}^2 = M_V^2 = M_{\mathcal{D}_1}^2$ *
  2) observe T_1,V » D_1 (5% maximal) over q^2-range [0,15]GeV^2

- even associate 40% uncertainty to D_1 then ratio

$$r_\perp = \frac{(m_b + m_s)}{m_B + m_{K^*}} \frac{V(q^2)}{T_1(q^2)}$$ determined up to 2%

Crucial for B→K*ll pheno as determines zero of helicity amplitude ….

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* *means that s_0 and M^2 of T_1 and V highly correlated*