Experimental assessment of charm resonances in B->K(*)ll - theory viewpoint

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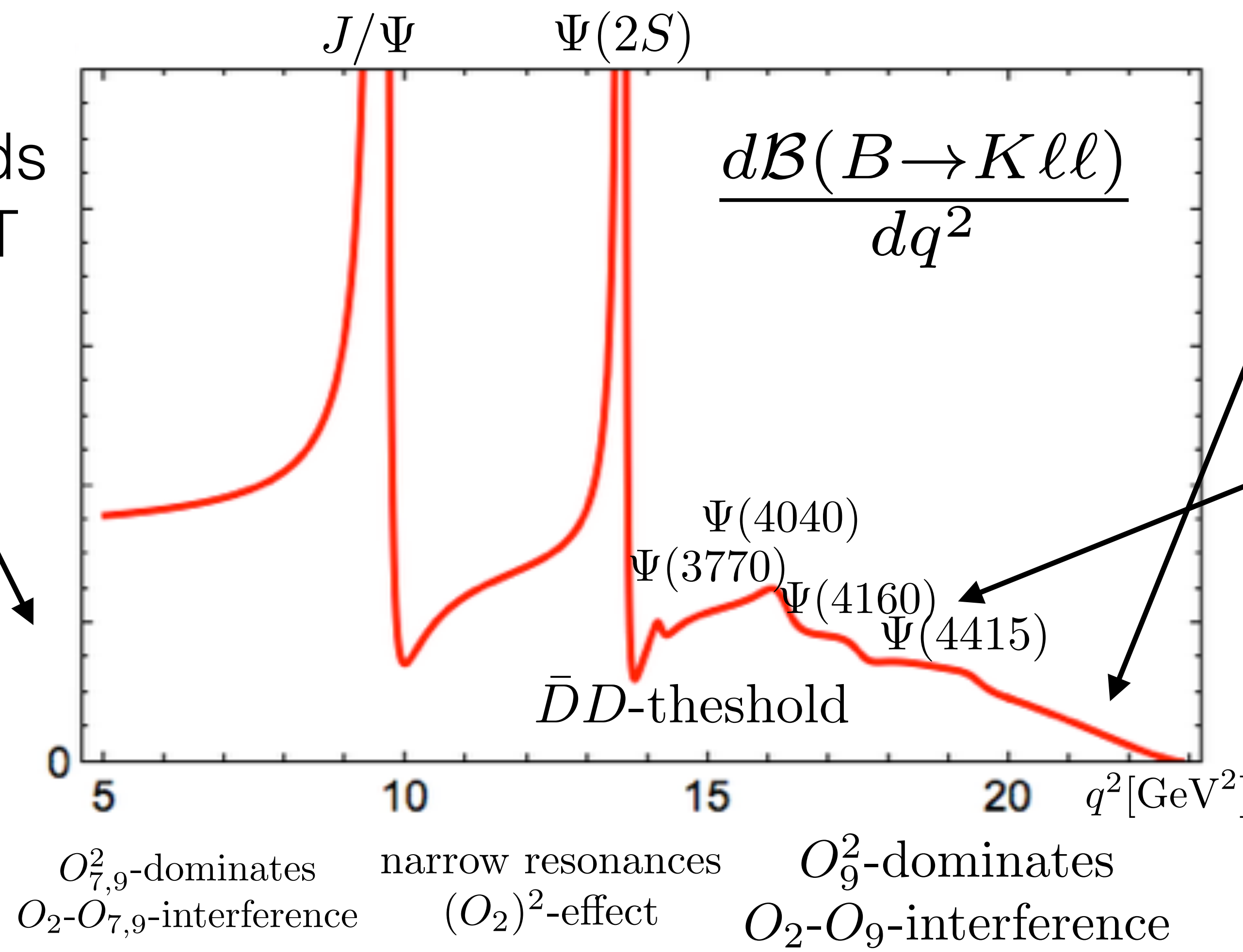
11-13 May b->sll in 2015 (Workshop-Edinburgh)

Charm resonances as a function of dilepton-pair momentum q^2

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



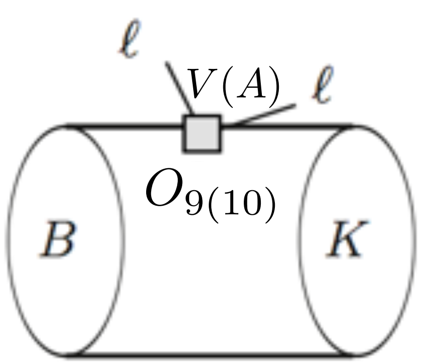
K **slow**:
- high-q^2 **"OPE"**
-**endpoint relations**

diagnostic shape for charm

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

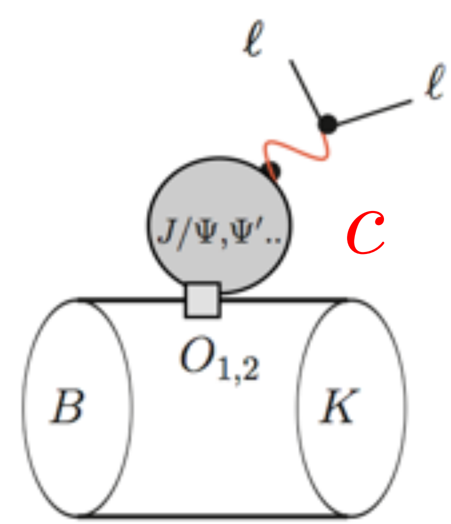
- at microscopic level

short distance (SD)



electroweak penguin (also O_7..)

Long distance (LD)



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

experimental assessment of (charm) resonances

0) introduction [3 slides]

*1) **narrow** resonances J/Ψ, Ψ(2S) [1 slide]*

*2) **broad** resonances Ψ(3770),Ψ(4040), [4 slides]*
Ψ(4160),Ψ(4415)

*3) **charm background** "continuum" DD-states [1 slide]*

4) what we have learned from LHCb-measurement
and why it is important [3 slides]

Main idea in general

- motivated **ansatz** at **amplitude**-level and then fit*
  same as experimentalists do resolve say K* in (Kπ)-data

- level of refinement of ansatz dependent on quality of data
  i.e. better data → refine ansatz
  (ansatz: fortunately we can learn a lot from e^+e^-→hadrons)

- close to the resonance the charm contribution in amplitude:

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

- main **goal**: fit for **residue** r_Ψ -phase and modulus
  question: phase with respect to what other amplitude?

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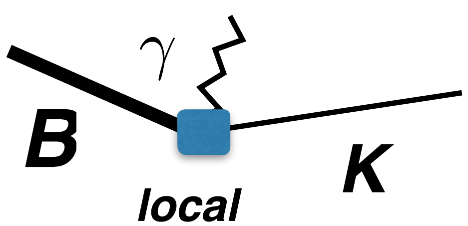
* *question of duality can only be assessed amplitude level (a priori)*

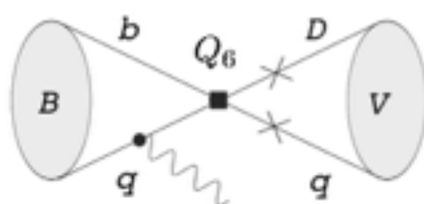
Decomposition of amplitude

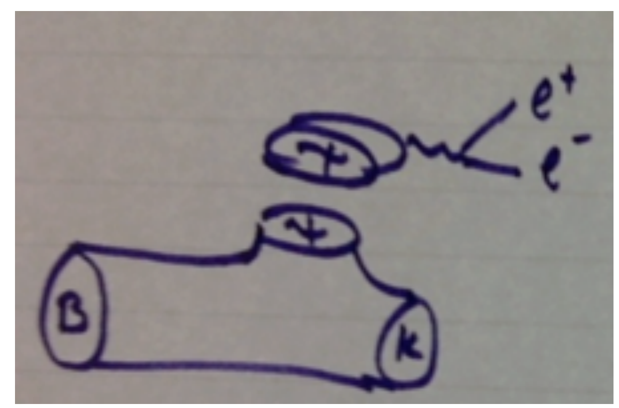
- amplitude B→Kll* decomposes into:

$$\mathcal{A}(B \to K\ell\ell) = \mathcal{A}_{non-charm} + \mathcal{A}_{c(harm)}$$

$$\mathcal{A}_{SD} + \mathcal{A}_{LD}$$







penguin (form factor) ***weak annihilation et al*** ***resonance*** ***DD-states***

- phases w.r.t. what: ideally between A) non-charm ("penguin")
  B) resonance
  C) DD-states

** first consider B→Kll — new aspect in B→K*ll : helicity amplitudes*

Best of all worlds fit all discontinuities of charm amplitude

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

$$\mathcal{A}_c(q^2) = \frac{1}{2\pi i}\int_\Gamma \frac{dt\mathcal{A}_c(t)}{t-q^2-i0} \quad \text{, module subtractions}$$
$$= \frac{1}{\pi}\int_\Gamma \frac{dt\mathrm{Disc}[\mathcal{A}_c](t)}{t-q^2-i0}$$

dispersion relation

on-shell charm

- *$e^+e^- \to$ hadrons this is the case! — one can test against partonic QCD most fundamental test of duality which **must** and does work*

- ➜ *each contribution measured helps to test QCD and for more reliable description*

1. Narrow resonances J/Ψ, $\Psi(2S)$*

- narrow: $\Gamma_\Psi/m_\Psi \simeq 10^{-4}$ since below open charm (DD-threshold)

- isolated ansatz sufficient:

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

- residue more detail: $r_\Psi \simeq \mathcal{A}(B \to K\Psi)\mathcal{A}^*(\Psi \to \ell\ell)$

  known: $|r_\Psi|$ (branching fraction)
  unknown: phase w.r.t. to penguin (please measure)*

- experimentally challenging (fine q^2-resolution …)

$$\frac{\text{resonance}}{\text{penguin}} \simeq 2 \cdot 10^3|_{q^2=m_{J/\Psi}^2}, \quad 3.3 \cdot 10^2|_{q^2=m_{\Psi(2S)}^2}$$

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* *$\Psi(2S)$ interferes with $\Psi(3770)$ — phase B partly known ..later*

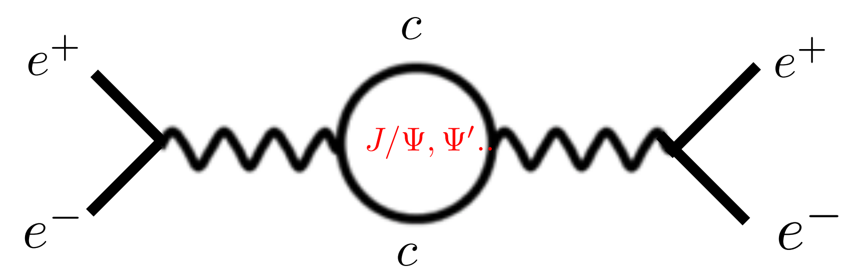
2. Broad resonances: Ψ(3770),Ψ(4040), Ψ(4160),Ψ(4415)

- at $q^2 > 4m_D^2$: DD-threshold opens

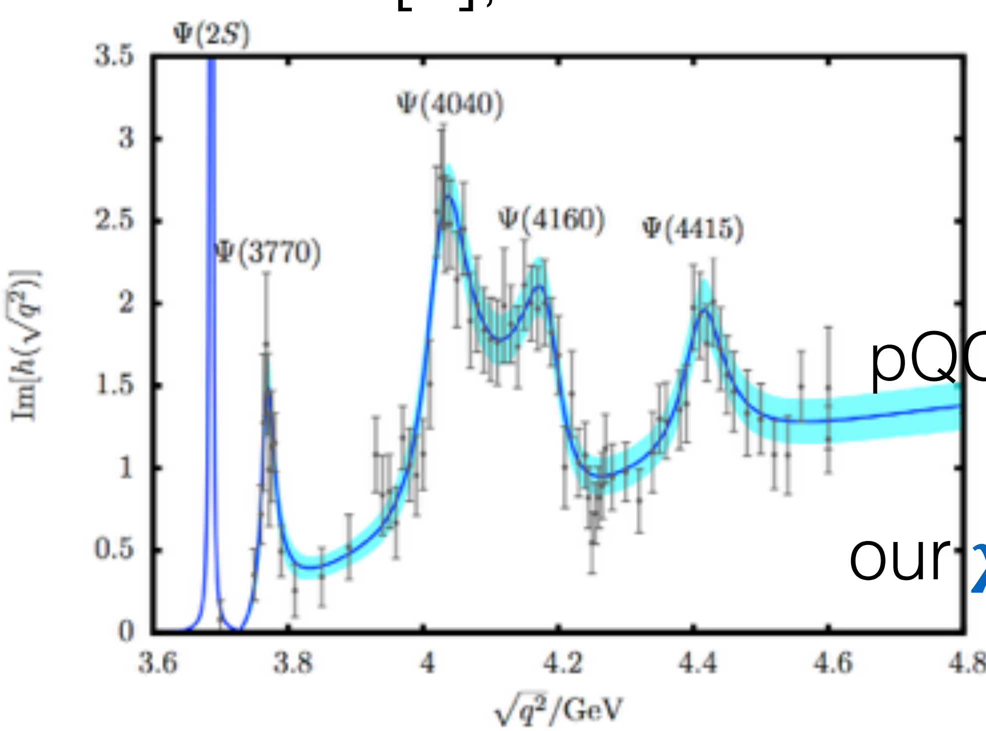
  ☞ fast decay ☞ broad resonance ☞ overlapping resonances

- learn simpler system: $e^+e^- \to$ hadrons

  Lyon and RZ 1406.0566v1



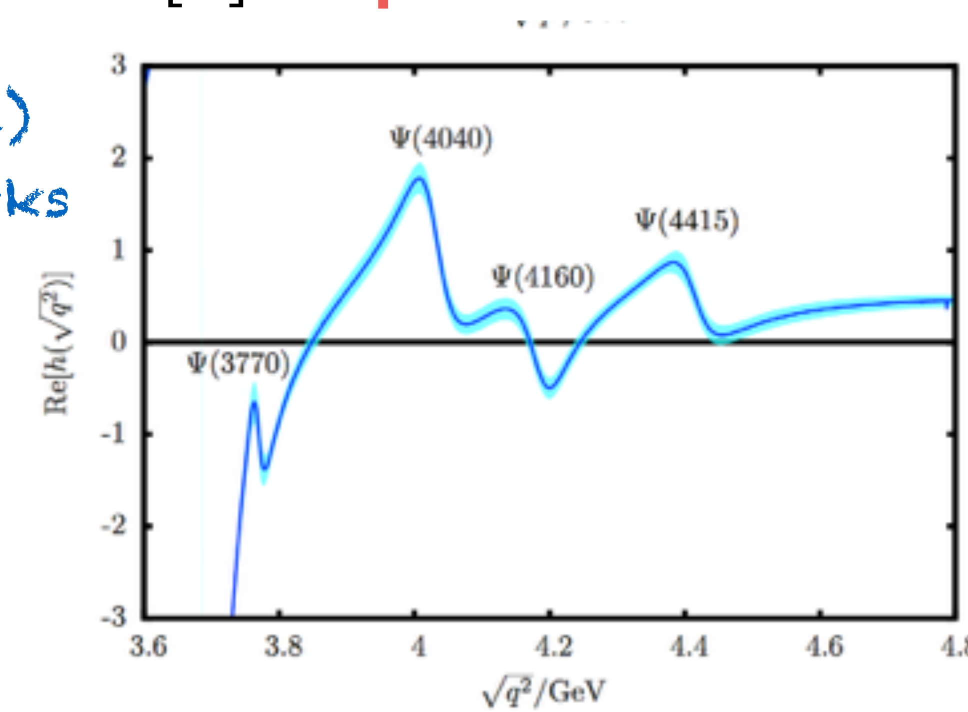
Disc ~ Im[h]; BESII-data'PLB08 → Re[h] **dispersion relation**



same as (g-2) for light quarks

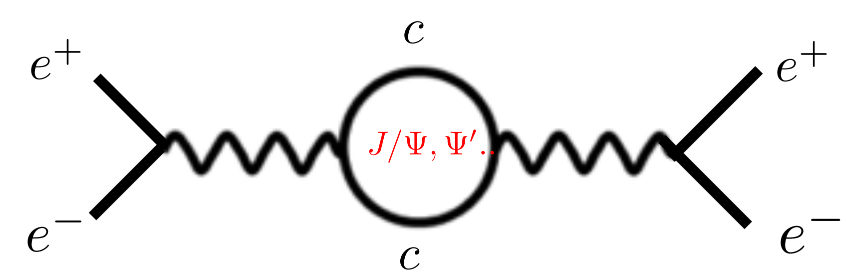
pQCD "ok"

our **χ^2/dof = 1.015**

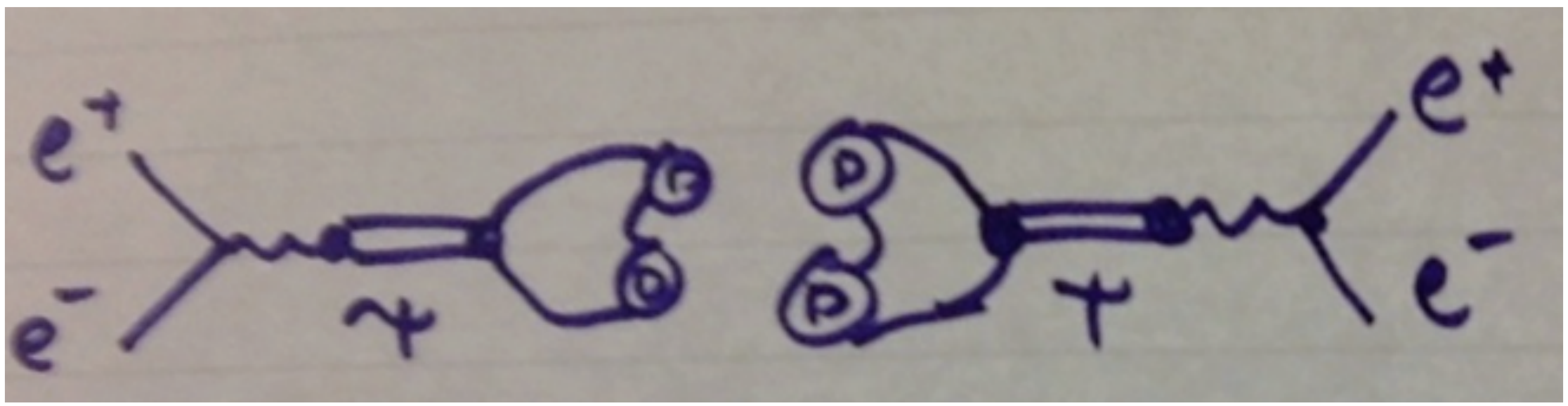


…. understanding ansatz …

- $e^+e^- \rightarrow$ hadrons is a "*dreamland*"
  spectral function positive definite!
  background: easy to model and match to pQCD at high q^2



- resonance overlap - relative interference phases



$$\mathrm{Disc}[\mathcal{A}] \sim \sum_{D\bar{D}} |\sum_{\Psi} \mathcal{A}^{\Psi \to D\bar{D}}|^2 + \mathrm{Disc}[\mathcal{A}_{\mathrm{back}}]$$

optical theorem

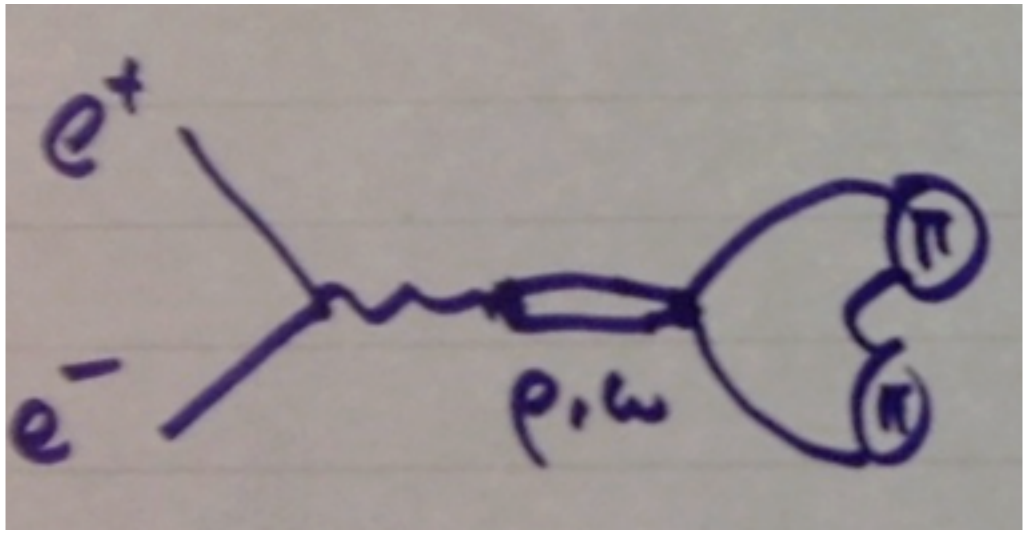
$$\mathcal{A}^{e^+e^- \to D\bar{D}}(s) \sim \frac{\mathcal{A}(\Psi \to DD)\mathcal{A}^*(\Psi \to \ell\ell)}{s - m_\Psi^2 + i m_\Psi \Gamma_\Psi(s)} e^{i\delta_\Psi}$$

…some confusions in community where phase comes from

- with phases: χ^2/dof =1 — without phases: χ^2/dof =1.4

  why is it there?

- the same phase as in pion-form factor



$$\mathcal{A}^{\gamma^* \to \pi\pi} = \frac{|r_{\rho\to\pi\pi}|}{s - m_\rho^2 + i m_\rho \Gamma_\rho(s)} + \frac{|r_{\omega\to\pi\pi}| e^{i\phi}}{s - m_\omega^2 + i m_\omega \Gamma_\omega(s)}$$

ϕ known as **Orsay phase** (of same type)

$e^+e^-\to$hadrons intermezzo finished - how does it help for B->Kll ?

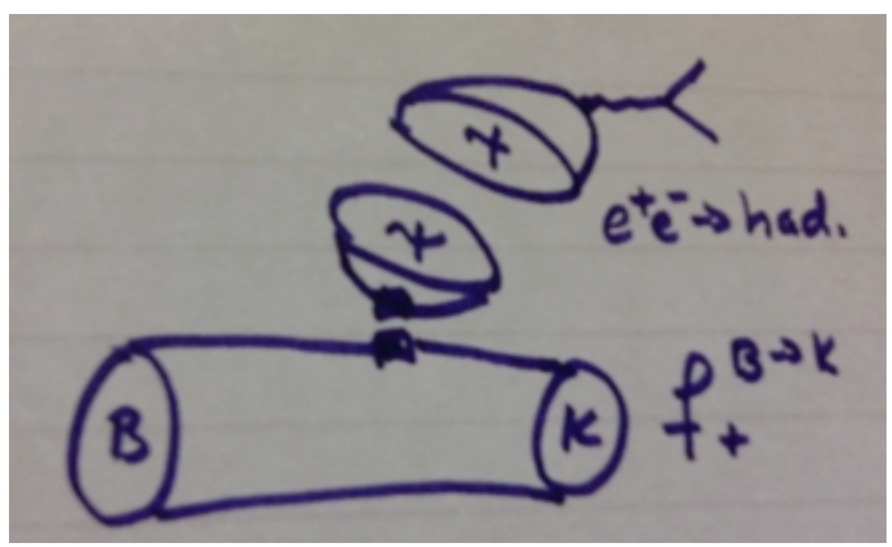
… correct for production of Ψ resonances w.r.t. naive factorisation

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

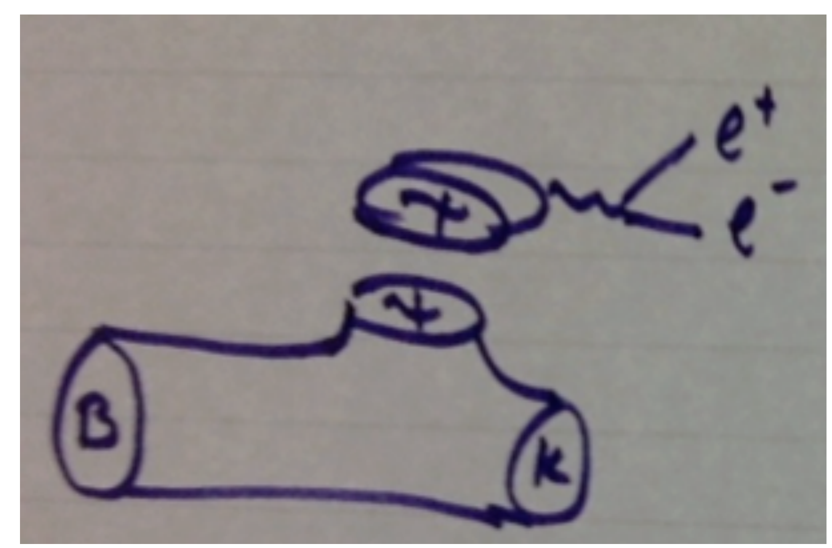
$$\mathcal{A}(B \to \Psi K)|_{\rm fac} \quad \sim \quad f_+^{B\to K}(q^2)\mathcal{A}(\Psi \to \ell\ell)$$

$$\to \quad f_+^{B\to K}(q^2) \underbrace{\eta_\Psi}_{1+\rm non-fac} \mathcal{A}(\Psi \to \ell\ell) \sim \mathcal{A}(B \to \Psi K)$$

in diagrams:



naive factorisation



full subprocess

3. future: how to get phase between resonant and non-resonant part ?

- might be difficult (not impossible) to fit charm background on top of large penguin contribution ….

- …maybe simpler: **switch off** the **penguin**

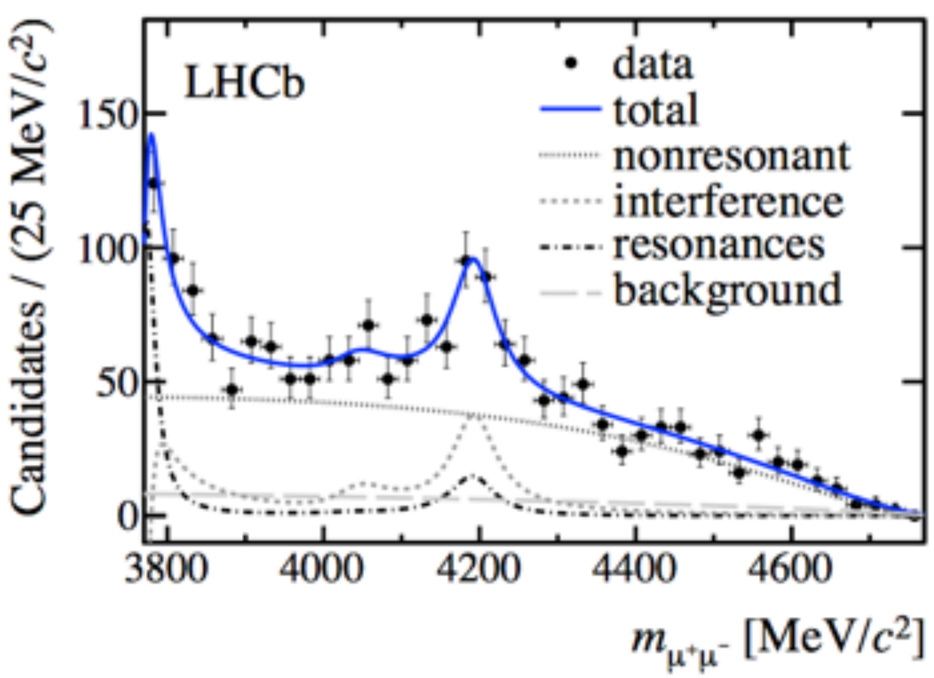
focus: directly on $b \rightarrow ccs$: $B \rightarrow DD\ K$

angular analysis (one angle) should be able to fit **smooth** open charm background beginning at DD and get relative phase w.r.t. broad charm resonances

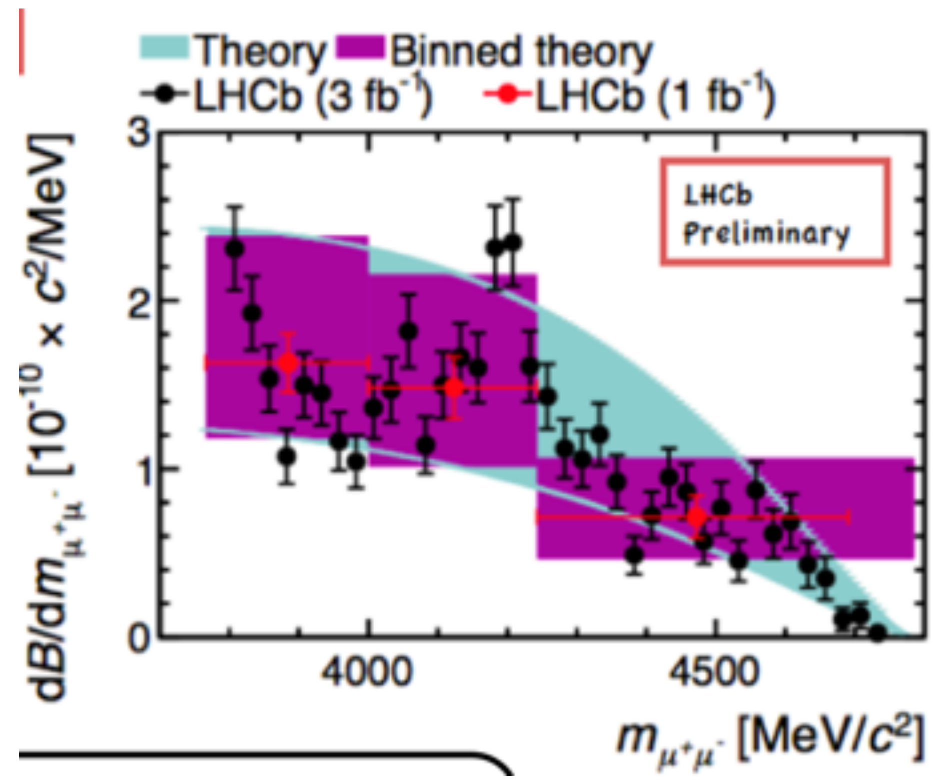
that's all I have to say here

4. Look back What did we learn from LHCb measurement

LHCb - PRL 111 (2013)

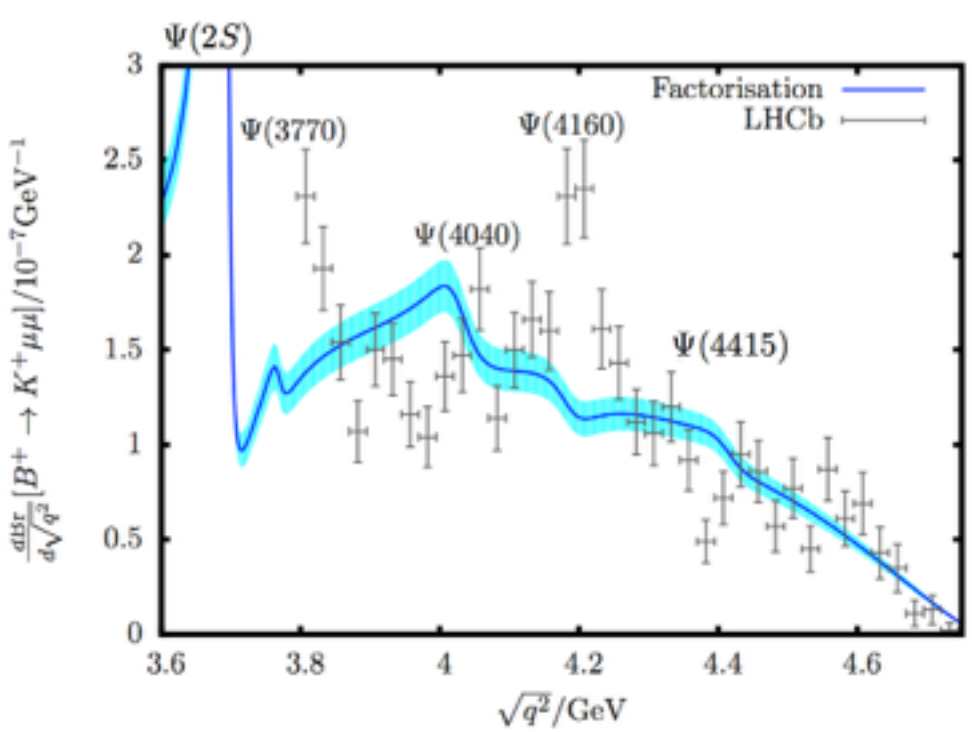


EPS-2007

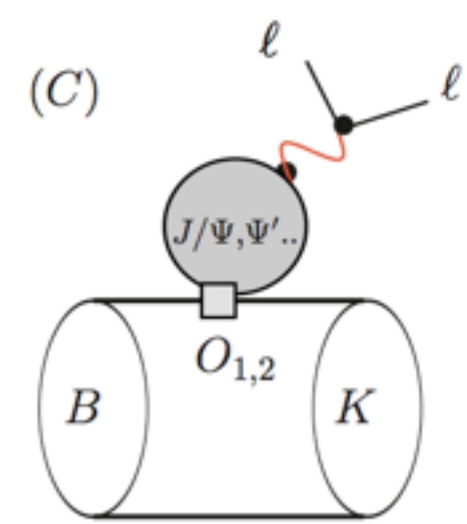


B->Kll

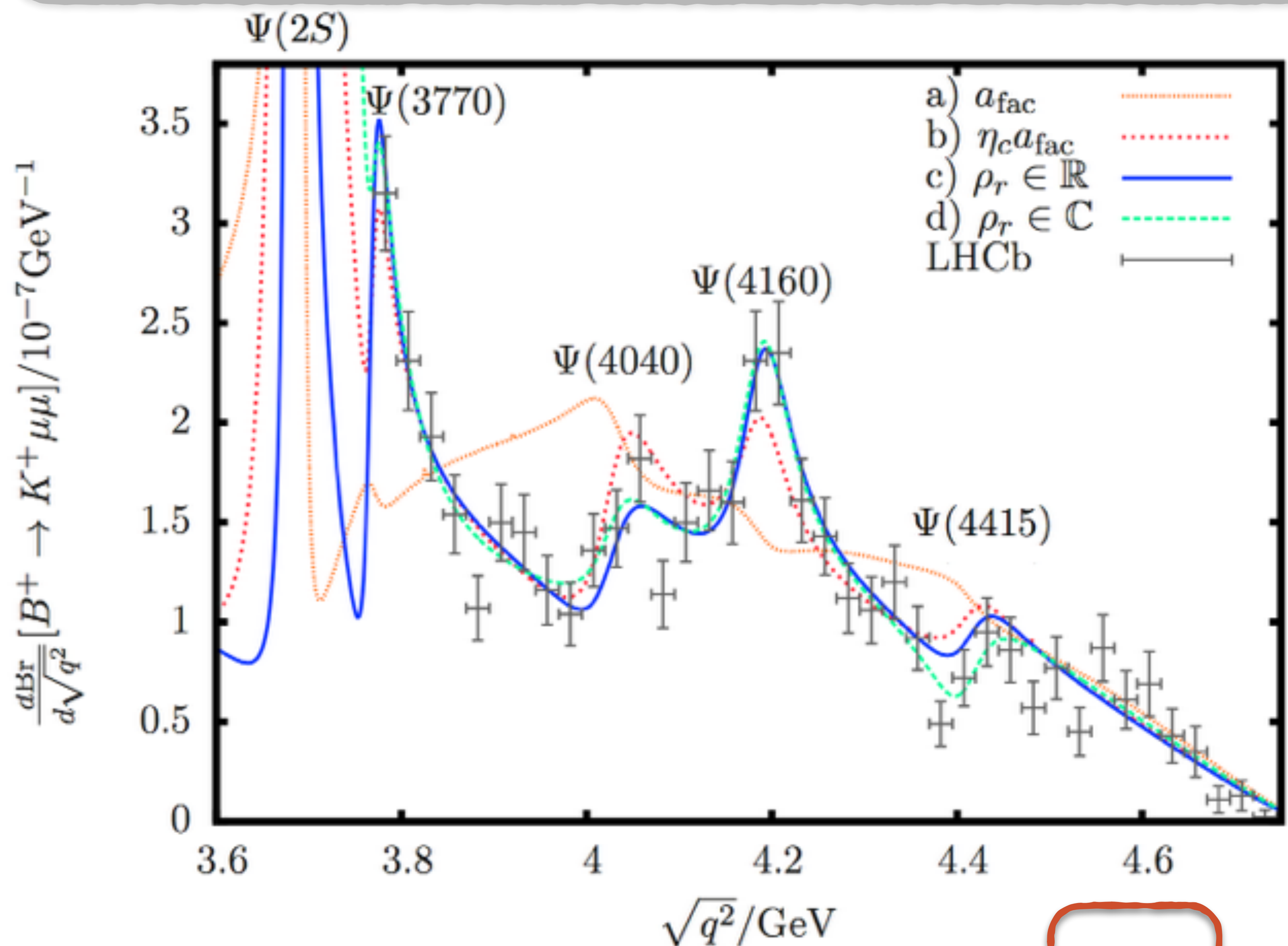
Lyon and RZ 1406.0566v1 (onwards from here)



clear failure of factorisation describing charm with (naive) factorisation



Fit for residues (non-factorisable) corrections



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 $6.4e^{-i53.3^\circ}$	-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%

added from backup slides
since discussed intensely

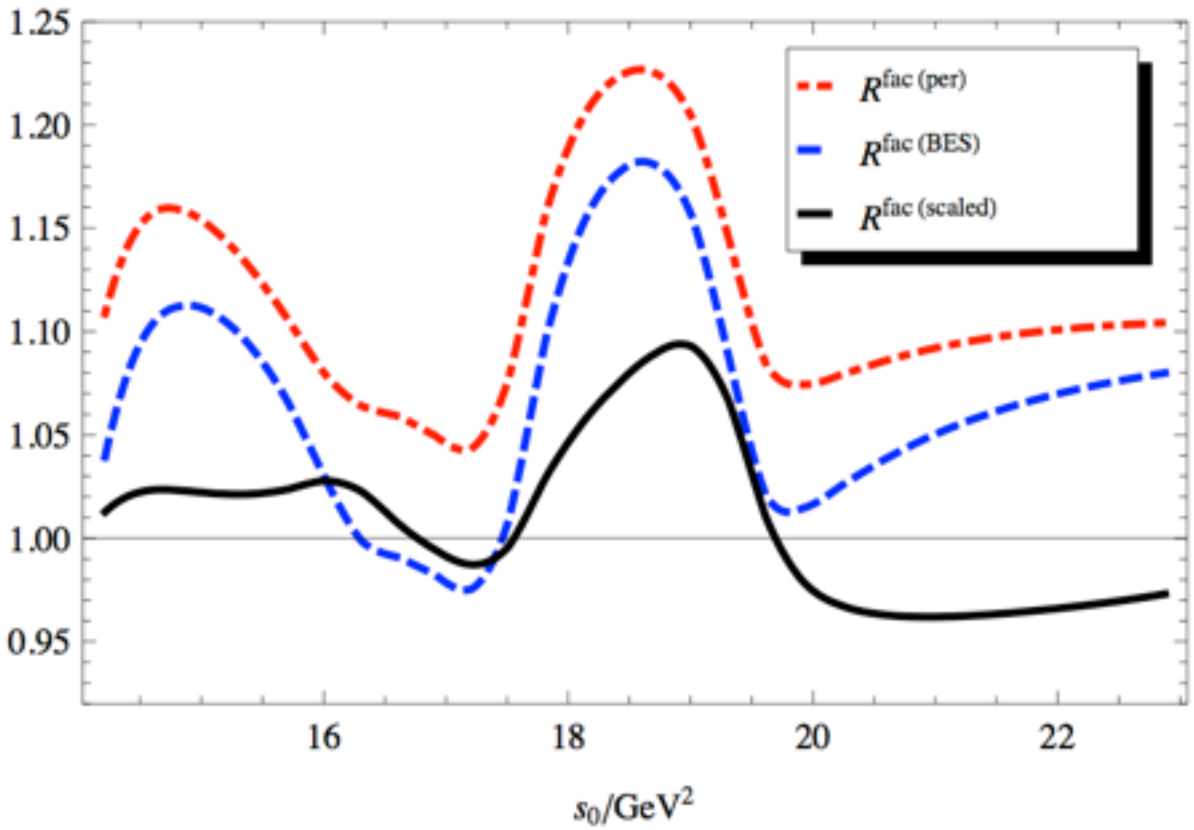
Binned Br(B→Kll) high q^2: a priori and a posteriori

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

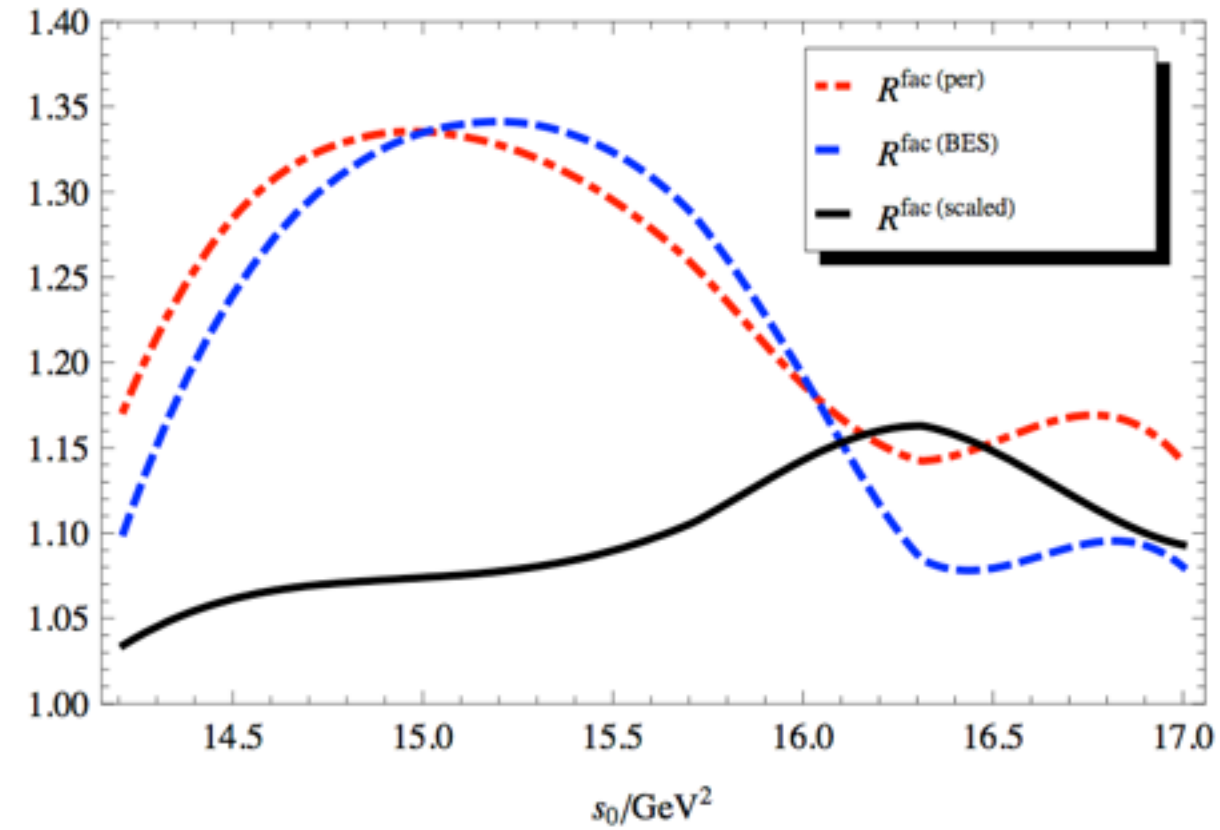
$$\frac{\mathrm{Br}(B^+ \to K^+\ell\ell)^{i),ii)}_{[s_0,s_1]}}{\mathrm{Br}(B^+ \to K^+\ell\ell)^{fit-d)}_{[s_0,s_1]}}$$

basically as good as data (by construction)

$s_1 = (m_B - m_K)^2$



$s_1 = 17\mathrm{GeV}^2$



hence duality violation are currently around 10% in practice for angular observables situation is more subtle ....

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

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

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

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

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

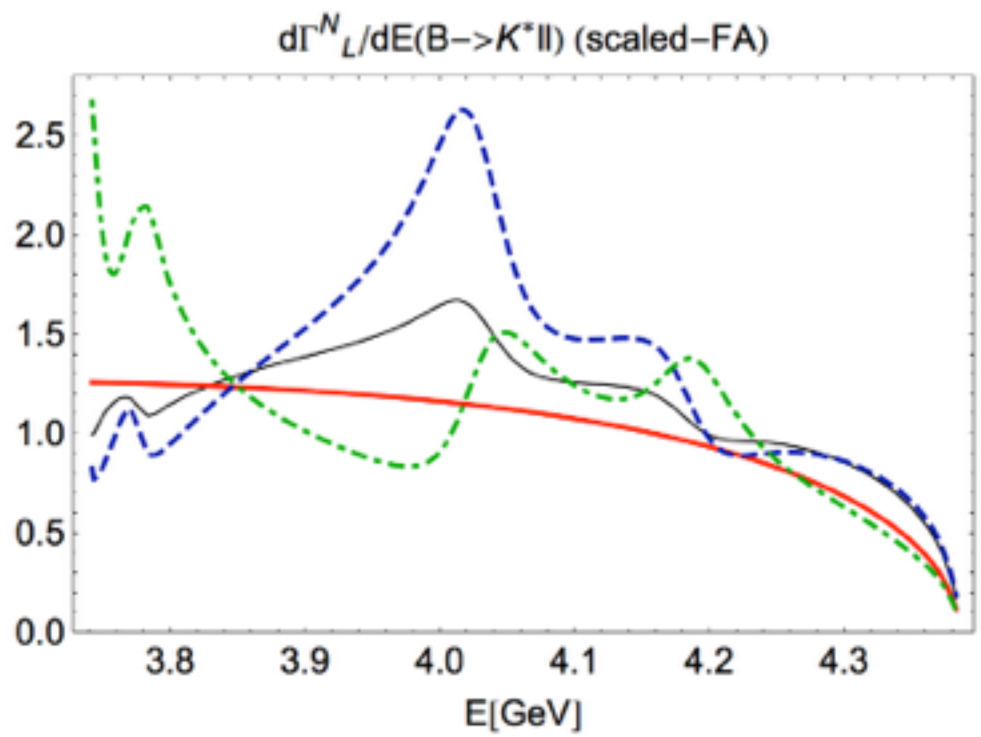
$$\frac{|H_0^V|}{|H_\parallel^V|} \stackrel{?}{\simeq} \frac{|f_0^V|}{|f_\parallel^0|} \quad \text{for some } q^2, \; f \; \text{form factor}$$

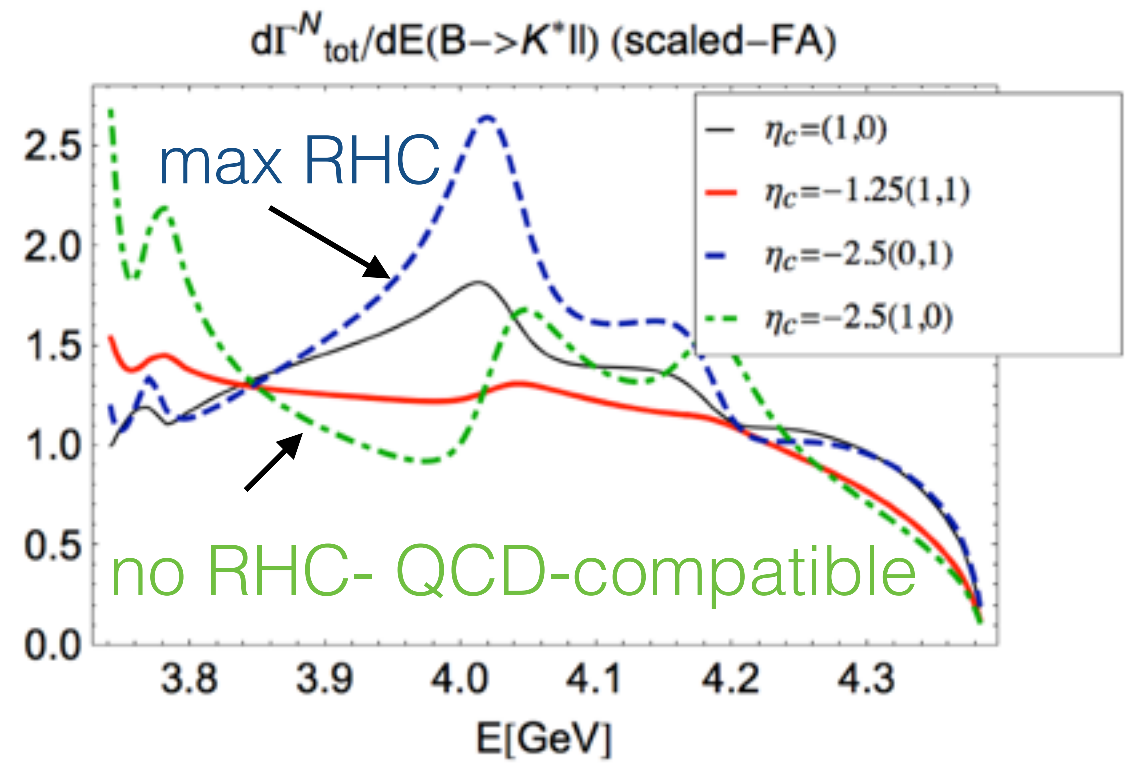
polarisation-universal

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

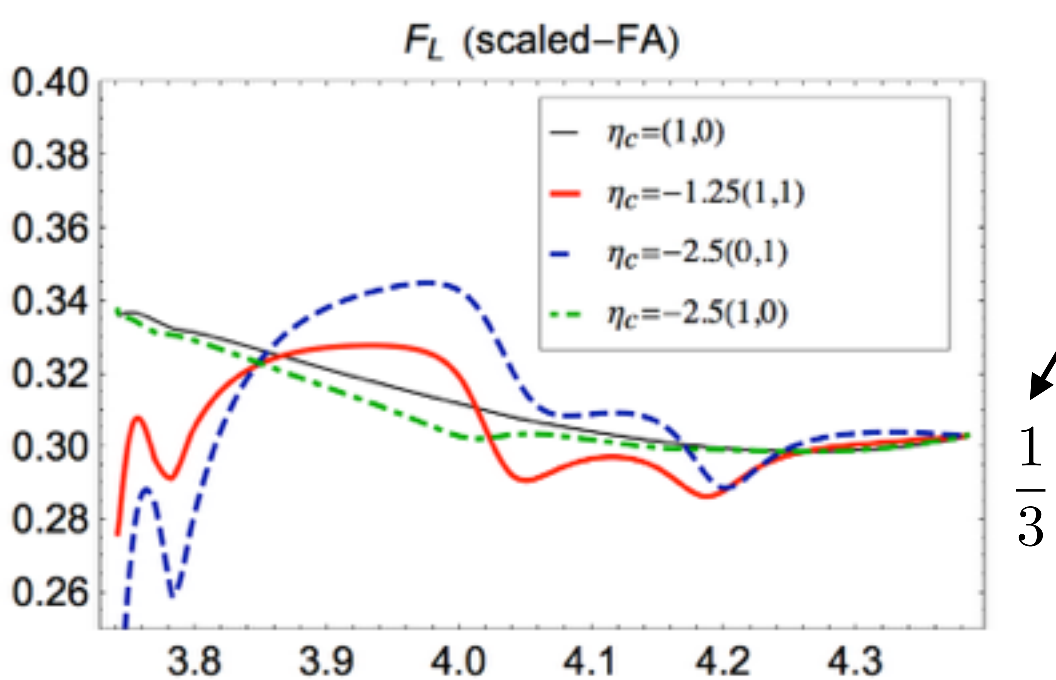
what is the pattern?

- **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



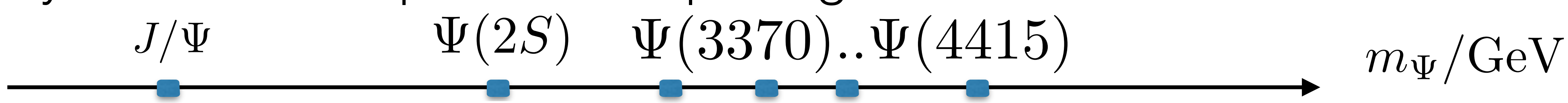
e.g. **black** and **green** curve nearly **identical** even though green curve has 2.5 as much resonances!
N.B. endpoint all curves asymptotes 1/3

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

What did we learn — (conclusions)

- modulus $r_{B\text{->}\Psi(broad)(\text{->}ll)K}$ is 2.5 times larger than factorisation

  by itself in retrospect not surprising !



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

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

- phases are all aligned negative ➜ -350% correction to fac.
  non-fac. correction/FSI alter phase
  ➜ QCD and quark hadron duality under pressure

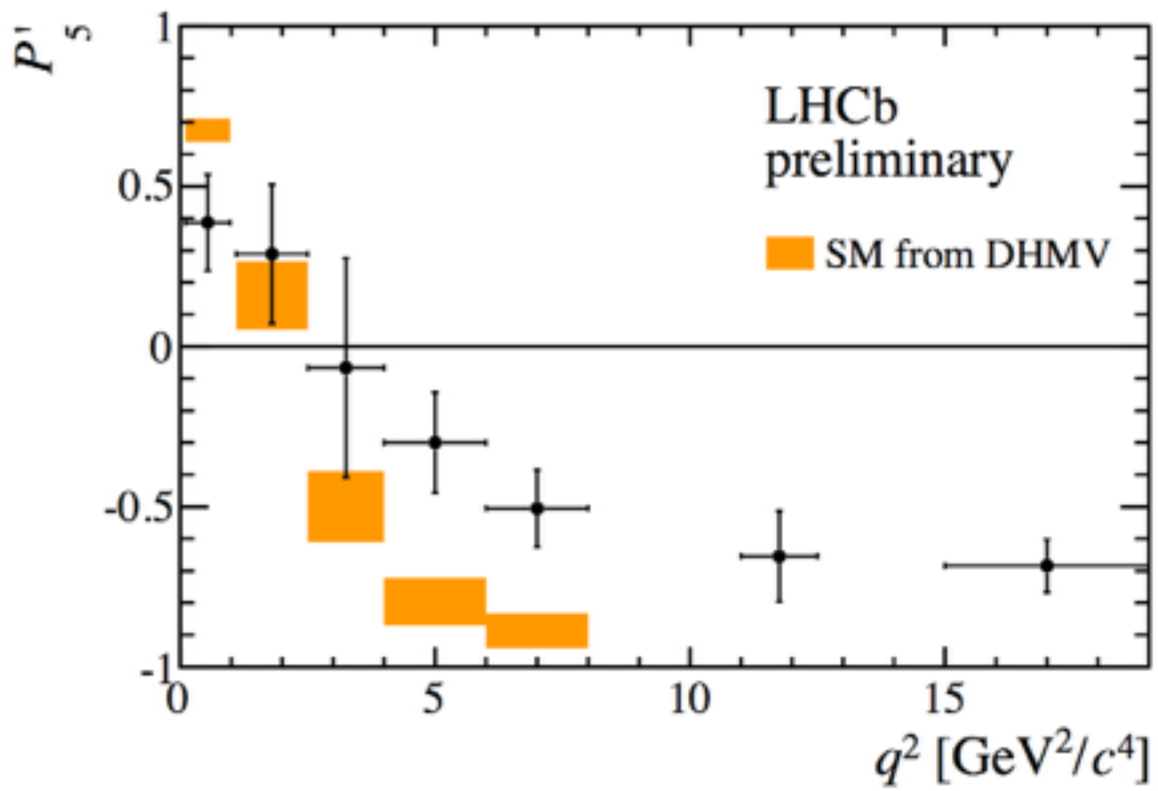
- using pQCD at high-q^2 : duality violation
  ca 10% with 1bin at high-q^2 for branching fraction
  for angular observables in B->K*ll a question to be settled ..

- we've learned a lot - please provide more data/fits
  b->ccs has wider implications in B-physics
  — some of the standard SM treatment is put into question —

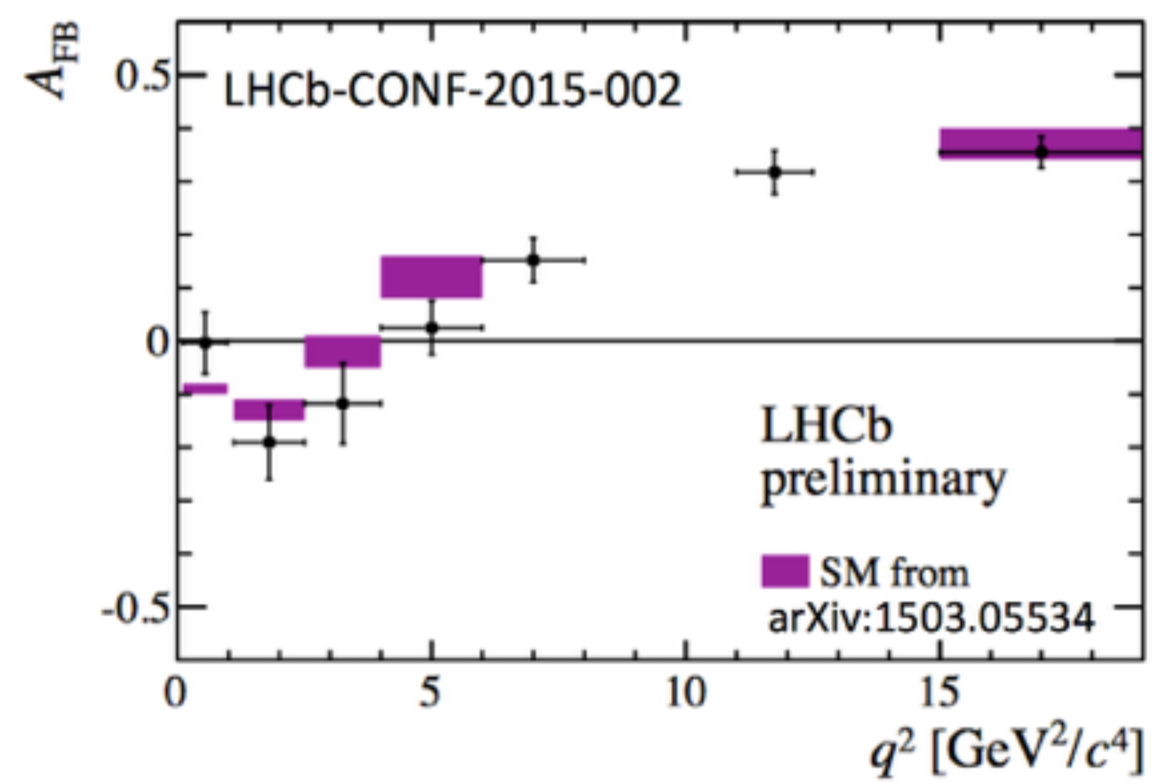
thanks for your attention

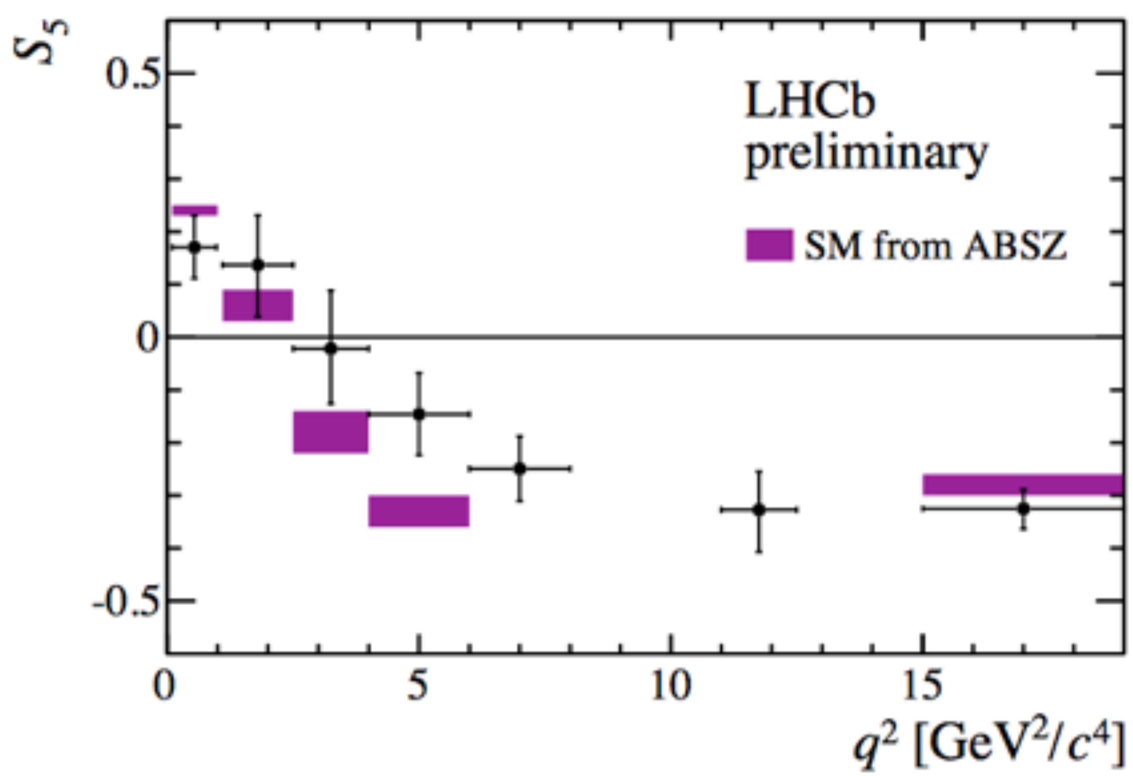
backup slides

Of current importance … anomalies B->K*ll et al



$$A_{FB} = \frac{\Gamma(\cos\theta_{B\ell^+} > 0) - \Gamma(\cos\theta_{B\ell^+} < 0)}{\Gamma(\cos\theta_{B\ell^+} > 0) + \Gamma(\cos\theta_{B\ell^+} < 0)}$$





driven by zero of helicity amplitudes

$$H_{\perp}^{L,R} = [(\mathcal{C}_9 + \mathcal{C}_{9'}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10'})] \frac{V}{M_B + M_{K^*}} + \frac{2m_b}{q^2} (\mathcal{C}_7 + \mathcal{C}_{7'}) T_1$$

$$+\mathrm{long} - \mathrm{distance}$$

- ***closer look***

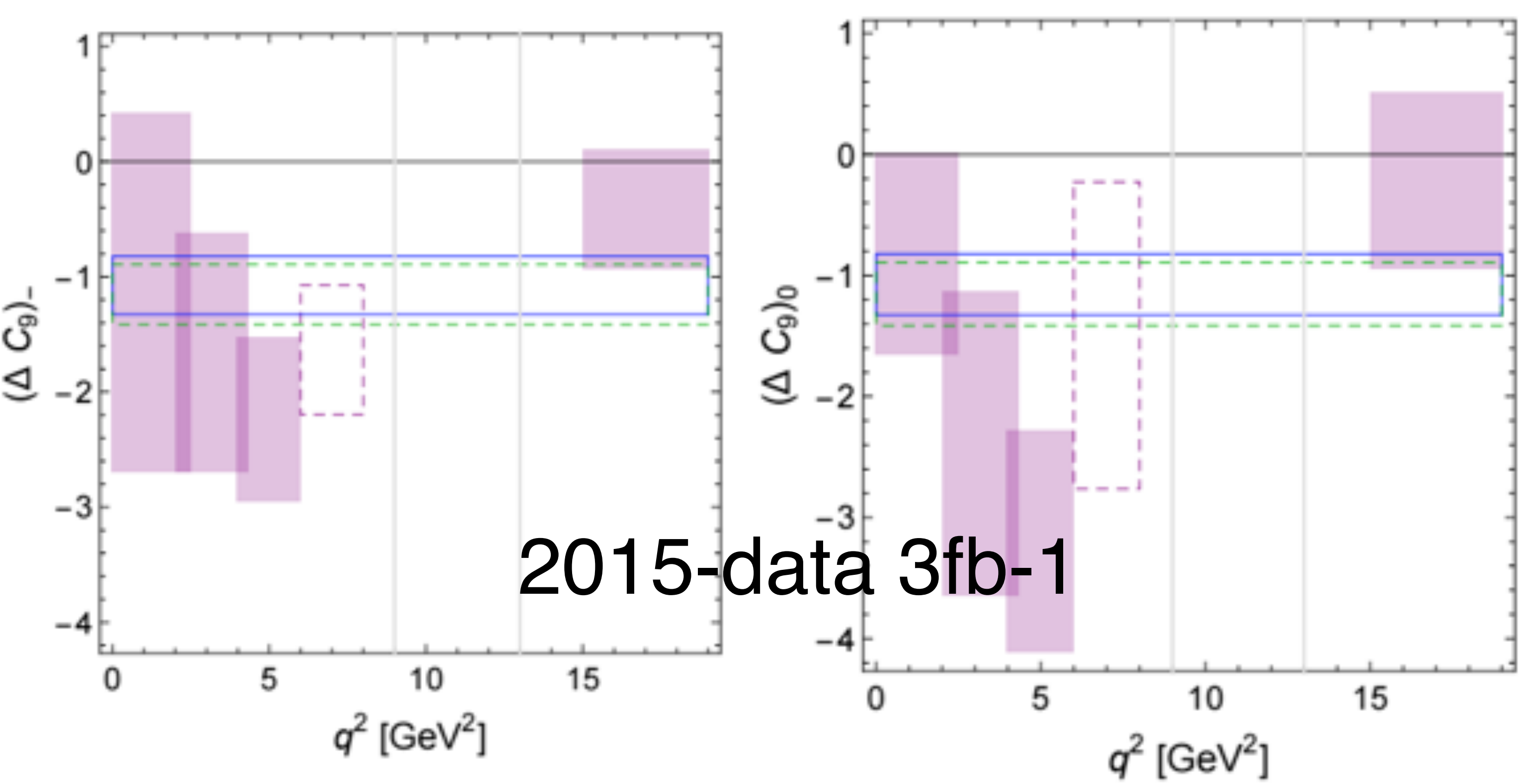
Lyon and RZ 1406.0566

a) pronounced towards J/Ψ
b) photon penguin only — C_{10} (no long-distance) not necessary
c) high q^2 charm very pronounced (tomorrow)

altogether suggests (at least a large part) in P_5' et al is due to charm

- ***Moriond 2015 data ….***

Straub's talk Moriond'15



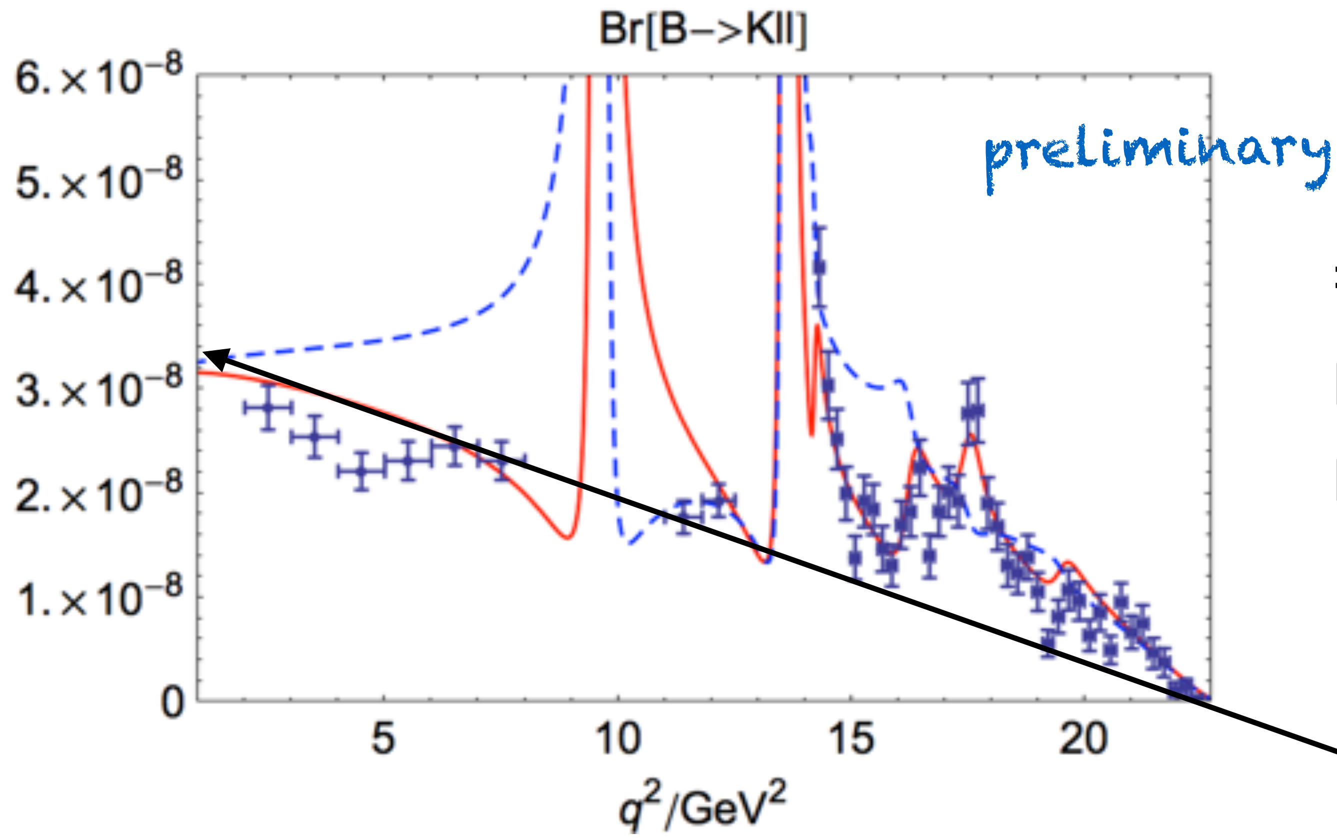
- effect same sign as in naive fac. in "-" versus "0" helicity
- <u>my comment</u>: that's what B→ J/Ψ K* experimental angular analysis predicts for J/Ψ,Ψ(2S)-contributions

— implication for high q^2-observables —

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

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

- ratio of Br(B→Kll) using
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  vs data as function lower bin bdry s_0

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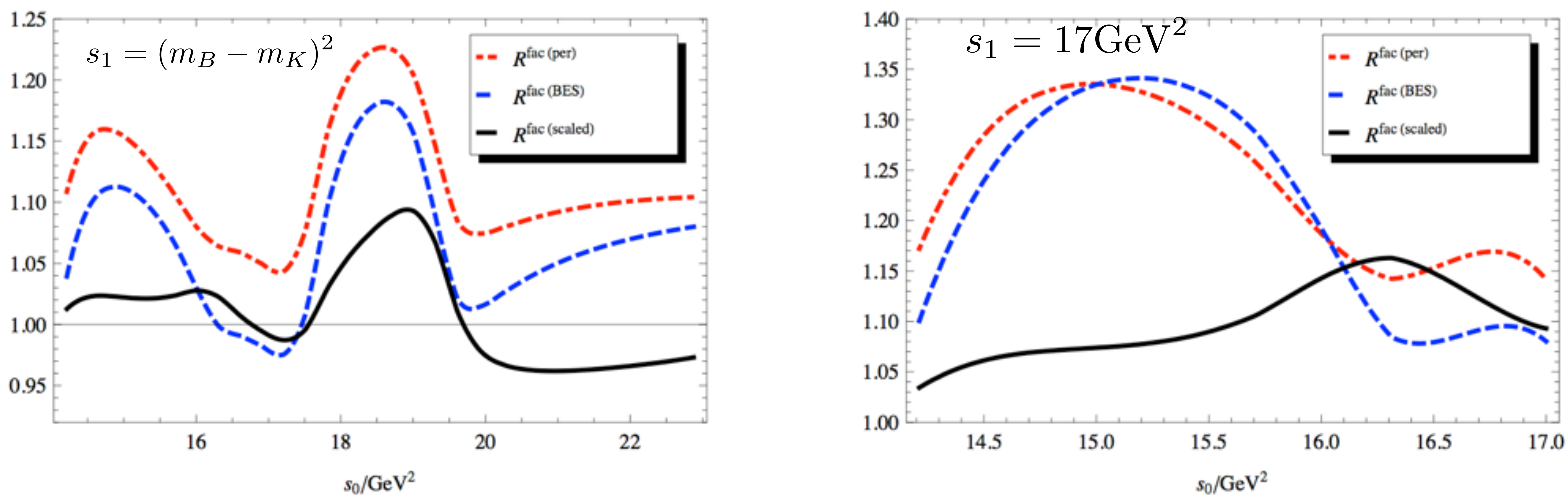

for angular observables issue more subtle as their can be cancellations in ratio ……..

right-handed currents (RHC) vs non-universal polarisation in B→K*ll

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

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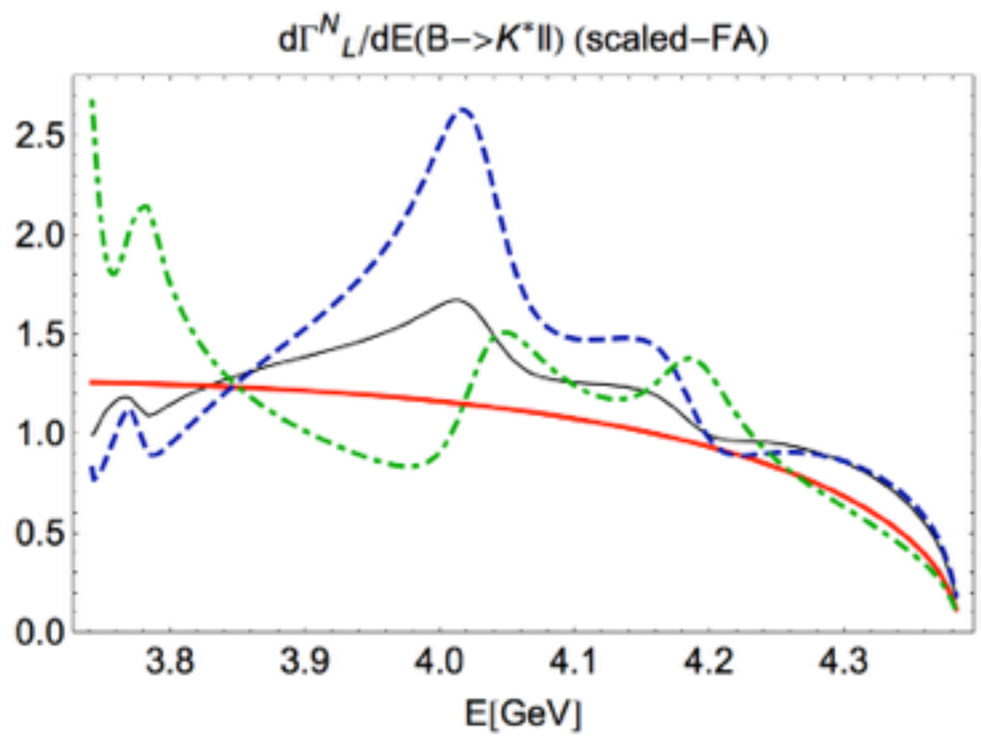
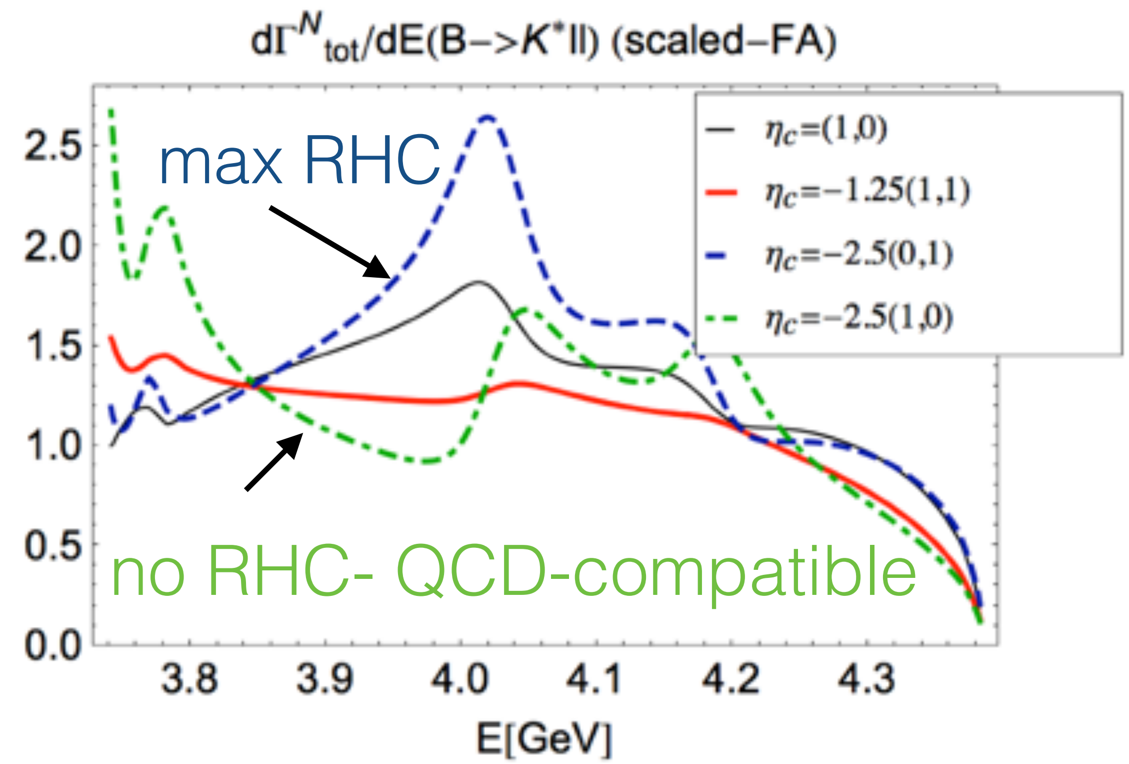
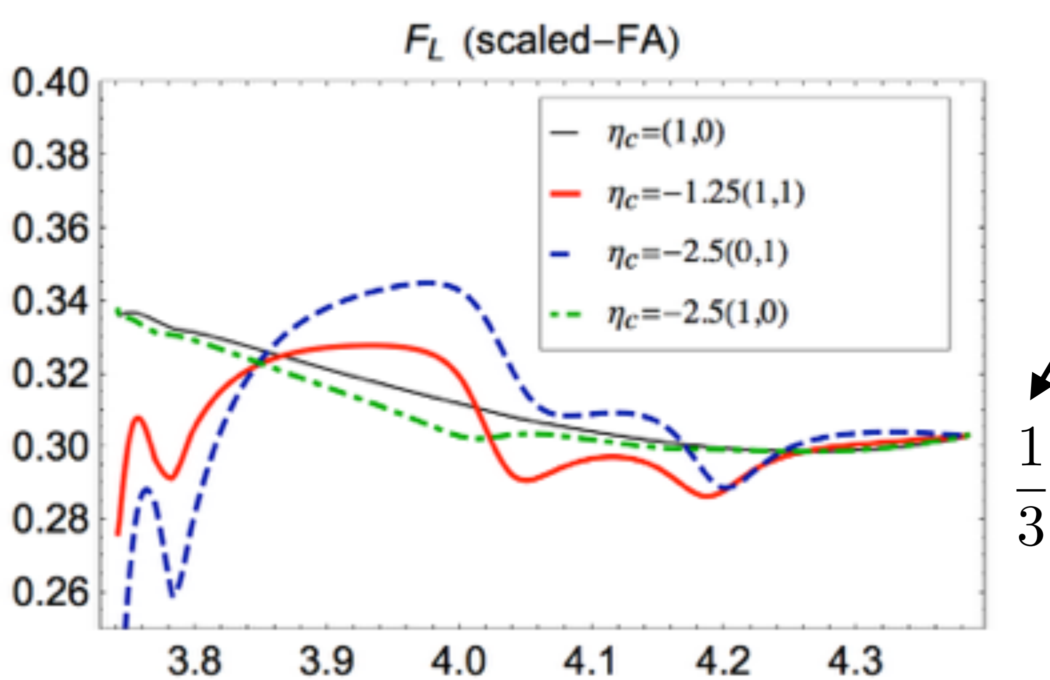




- **if polarisation universal** and **no RHC** then resonance effect minimal in class of observables Hiller and RZ'13



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

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

assessment from theory viewpoint

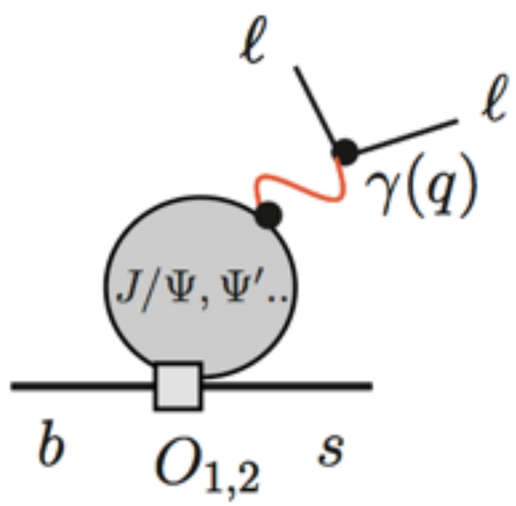
is it or isn't it all that surprising?

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

very brief

a) how large are partonic non-fac. corrections

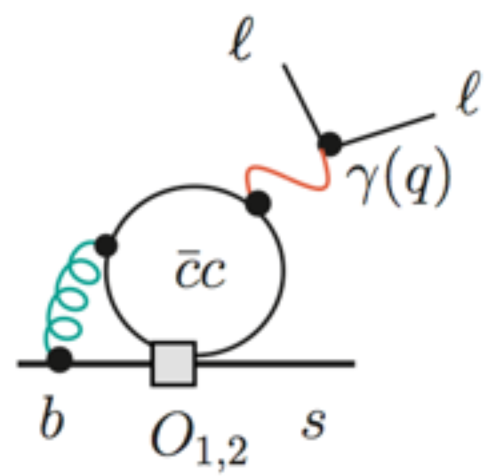
- from pQCD alone not chance to resolve locally in q^2
- at high q^2: q^2 is a large scale can integrate out charm quarks so-called high-q^2 "OPE" Grinstein,Pirjol'04 Beylich,Buchalla,Feldmann'11



factorisation (BESII)

Lyon RZ'14

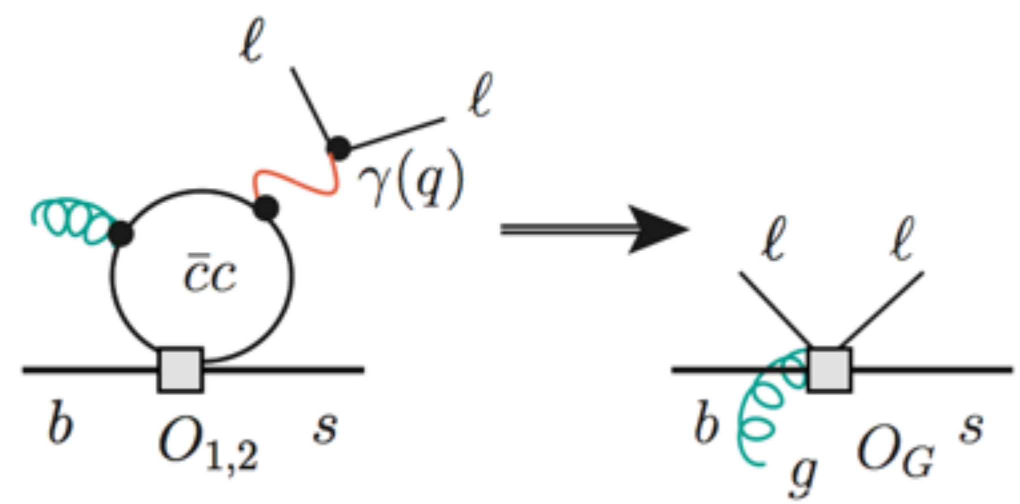
100% in our units



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)

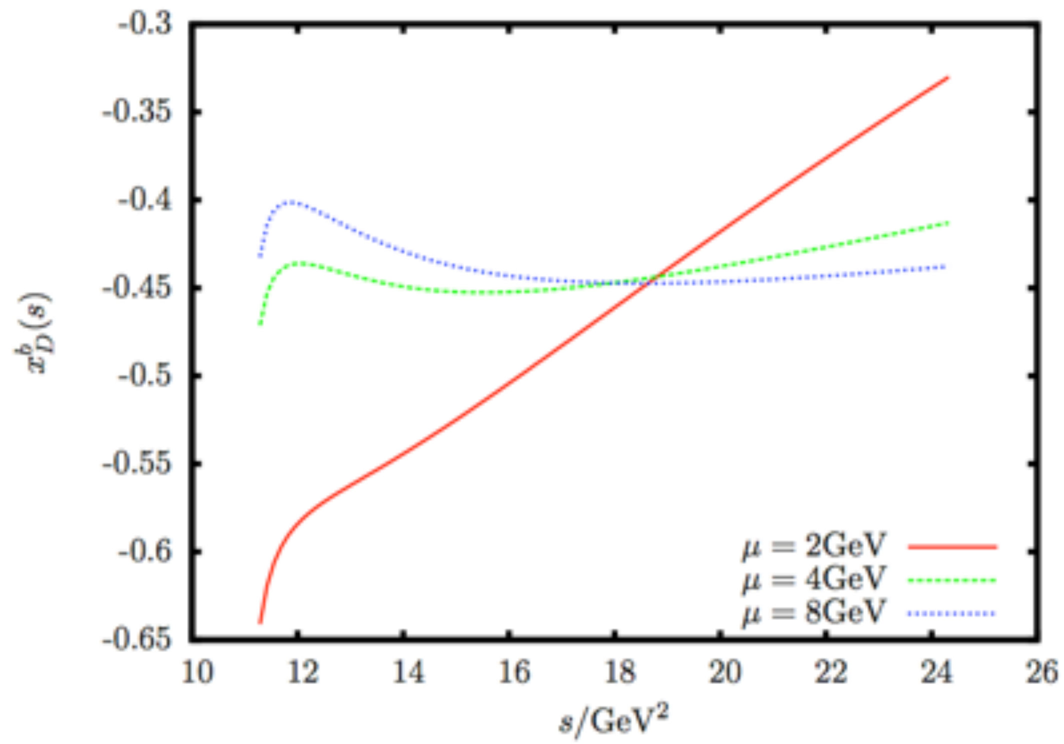


dim-5 spectator & soft gluon

Beylich,Buchalla,Feldmann'11

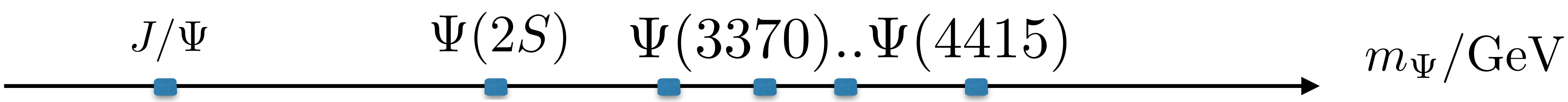
small O(2%) QCDF
consistent dim. suppression

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



b) factorisation as a function of m_Ψ

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



$|\eta_{J/\Psi K}| \simeq 1.42$ $\quad |\eta_{\Psi(2S)K}| \simeq 1.82$ $\quad$ *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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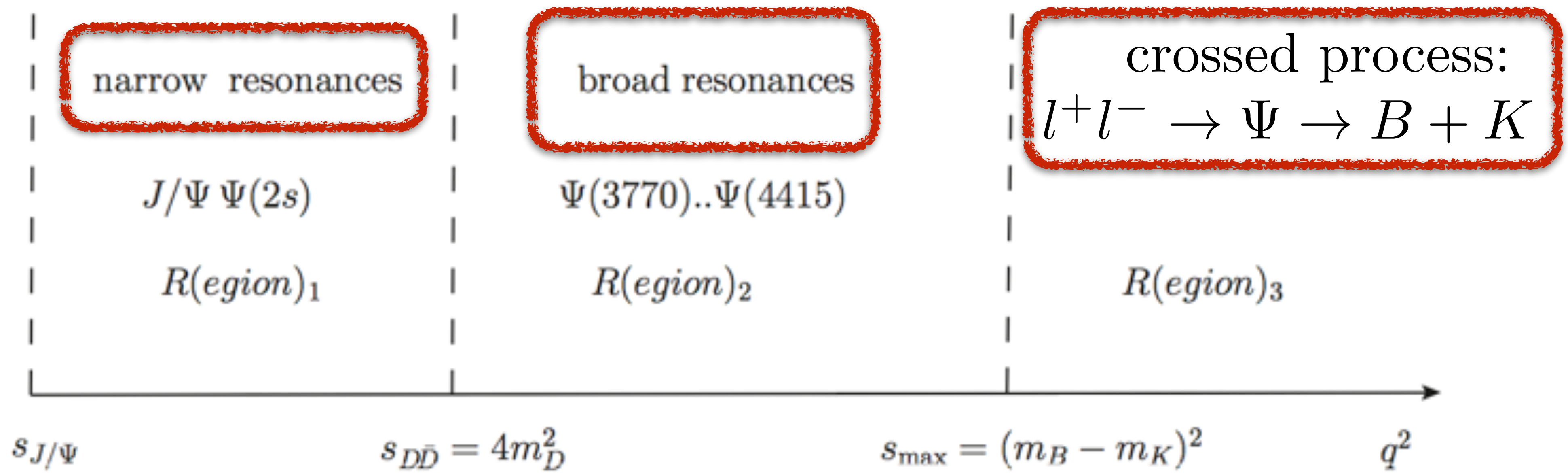
[1] *qhd-(violation) sometimes (Shifman et al) means OPE-violating term - here different usage*

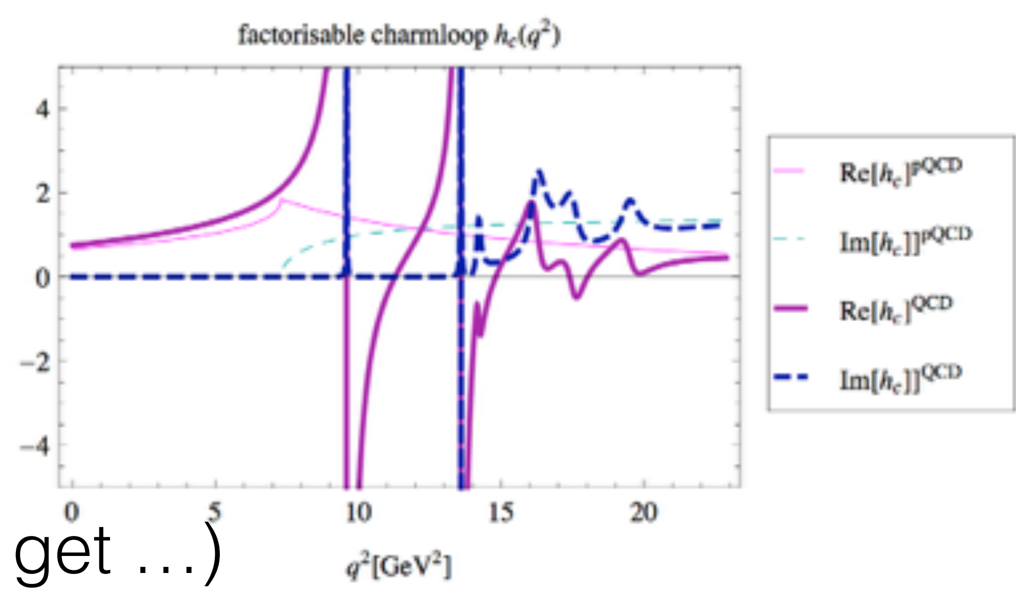
[2] *not valid for decay rate (in this form) in general*
unless can write rate in terms of amplitude (e.g. inclusive decays)

- 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-$\int$ 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