Fitting the exotic hadron spectrum with an additional quark

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The Hypothesis:

A seventh quark exists

charge: -1/3

mass: ~2.8 GeV

The W boson connects this quark with the right-chiral component of the charm quark.

Right-chiral connection leads to Z being FCNC

arxiv:2203.03007

Topics

- Mapping exotic hadrons to mesons and baryons
  - Reproducing observed production and decay of exotic hadrons
  - Predictions testable by LHCb (and other experiments)
- Addressing experiments that rule out an additional quark
- W & Z interactions of the additional quark
- Cancelling gauge anomalies
- Theory motivation: broken supersymmetry, 3u+6d -> 3u+4d

Additional slides…

- More predictions … and possible additional evidence
- Alternative non-SM explanations for a few experiments

Mapping exotic hadrons to mesons and baryons

Properties of the quark:

charge: -1/3

mass: ~2.8 GeV

Given the symbol: "f"

Decays used in the mapping:

$$f \to c + W, \; |V_{cf}| \sim 1, \; \tau_f \sim 0.01 \; \tau_b$$

$$b \to f + Z, \; |V_{bf}^{Z}| \sim 0.03, \; |V_{bc}| \sim 0.04$$

$$Z \to d\bar{s} \quad Z \to d\bar{f} \quad Z \to s\bar{f}$$

and Hermitian conjugate decays

Exotic hadrons mapped to mesons and baryons

Proposed f-quark Mesons and Baryons

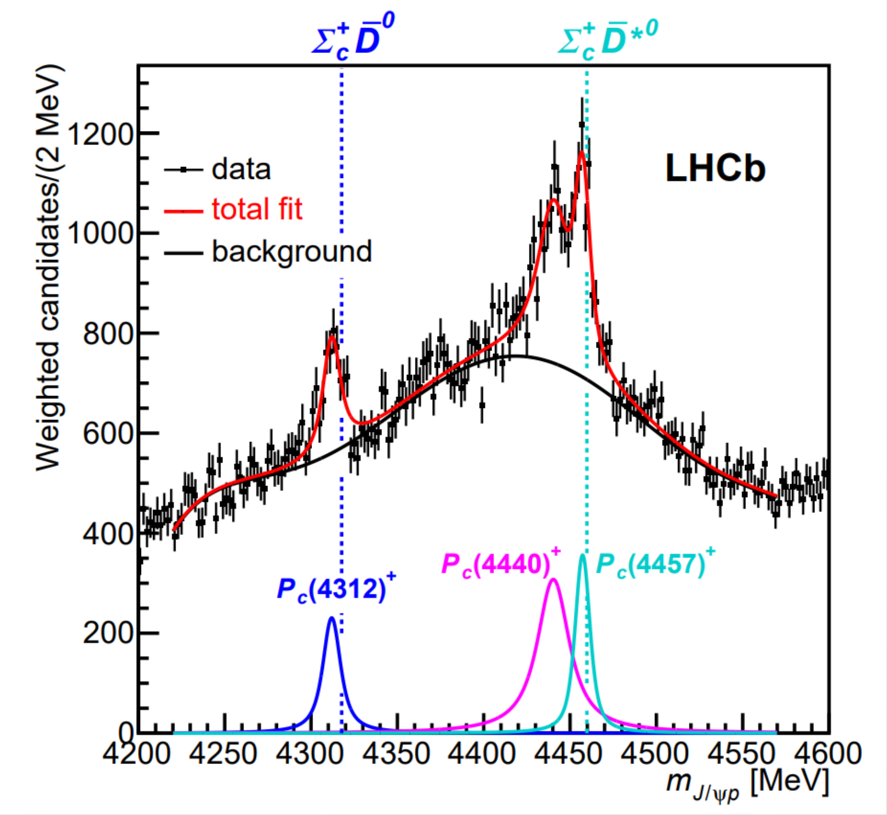
Name	QM	Quarks
$X^{\pm,0}(3250)$	1^1S_0	$f\bar{u}, u\bar{f}, f\bar{d}, d\bar{f}$
$X(3350)$	1^3S_1	$f\bar{d}, d\bar{f}$
$\chi_{c0}(3860)$	1^3P_0	$f\bar{d}, d\bar{f}$
$\chi_{c1}(3872)$	1^3P_1	$f\bar{d}, d\bar{f}$
$T_{cc}^{+}(3875)$	1^3P_1	$u\bar{f}$
$Z_c^{\pm,0}(3900)$	1^1P_1	$f\bar{u}, u\bar{f}, f\bar{d}, d\bar{f}$
$Z_{cs}^{\pm,0}(3985)$	2^1S_0	$f\bar{u}, u\bar{f}, f\bar{d}, d\bar{f}$
$X^{\pm,0}(4020)$	2^3S_1	$f\bar{u}, u\bar{f}, f\bar{d}, d\bar{f}$
$X(4160)$	1^1D_2	$f\bar{d}, d\bar{f}$
$Y(4230)$	1^3D_1	$f\bar{d}, d\bar{f}$
$\chi_{c1}(4274)$	2^3P_1	$f\bar{d}, d\bar{f}$
$Z_c^{\pm}(4430)$	2^1P_1	$f\bar{u}, u\bar{f}$
$Y(4500)$	3^3S_1	$f\bar{d}, d\bar{f}$
$\psi(4660)$	2^3D_1	$f\bar{d}, d\bar{f}$
$\chi_{c1}(4685)$	3^3P_1	$f\bar{d}, d\bar{f}$
$\chi_{c0}(4700)$	3^3P_0	$f\bar{d}, d\bar{f}$
$R(3760)$	1^3S_1	$f\bar{s}, s\bar{f}$
$X(3960)$	1^3P_0	$f\bar{s}, s\bar{f}$
$\chi_{c1}(4140)$	1^3P_1	$f\bar{s}, s\bar{f}$
$\psi(4360)$	2^3S_1	$f\bar{s}, s\bar{f}$
$R(4407)$	1^3D_1	$f\bar{s}, s\bar{f}$
$\chi_{c0}(4500)$	2^3P_0	$f\bar{s}, s\bar{f}$
$X(6600)$	1^3S_1	$f\bar{f}$
$X(6900)$	1^3P_0	$f\bar{f}$
$X(7200)$	2^3S_1	$f\bar{f}$
$P_c^{+}(4312)\ldots$	Σ_f^{+}	fuu
$P_{\psi s}^{\Lambda 0}(4459)$	Σ_f^{0}	fud
$P_{\psi s}^{\Lambda 0}(4338)$	Λ_f^{0}	fud

$$\mathrm{QM} = n^{2S+1}L_J$$

Pentaquarks

Name	Mass	Γ	J^P
$P_c^+(4312)$	4312	10	$?^?$
$P_c^+(4380)$	4380	200	$?^?$
$P_\psi^{N+}(4337)$	4337	29	$?^?$
$P_c^+(4440)$	4440	21	$?^?$
$P_c^+(4457)$	4457	6	$?^?$

Name	Mass	Γ	J^P
$P_{\psi s}^{\Lambda 0}(4338)$	4338	7	$\frac{1}{2}^-$
$P_{\psi s}^{\Lambda 0}(4459)$	4459	17	$?^?$



Motivates mass of f quark being a bit less than 2800 MeV

Pentaquark Production and Decay

$$\Xi_b^- \to P_{\psi s}^{\Lambda 0} K^- : \quad bds \underset{\text{FCNC}}{\longrightarrow} fds + Z \to fds + u\bar{u} \to fud + s\bar{u}$$

$$P_{\psi s}^{\Lambda 0} \to \Lambda\, J/\psi : \quad fud \to cud + W^- \to cud + s\bar{c} \to sud + c\bar{c}$$

$$B^- \to P_{\psi s}^{\Lambda 0} \bar{p} : \quad b\bar{u} \to f\bar{u} + Z + g \to f\bar{u} + u\bar{u} + d\bar{d} \to fud + \overline{uud}$$

$$P_{\psi s}^{\Lambda 0} \to \Lambda\, J/\psi : \quad fud \to cud + W^- \to cud + s\bar{c} \to sud + c\bar{c}$$

$$B_s^0 \to P_{\psi}^{N+} \bar{p} : \quad s\bar{b} \underset{Z}{\longrightarrow} f\bar{d} + 2g \to f\bar{d} + u\bar{u}u\bar{u} \to fuu + \overline{uud}$$

$$P_{\psi}^{N+} \to p\, J/\psi : \quad fuu \to cuu + W^- \to cuu + d\bar{c} \to uud + c\bar{c}$$

$$\Lambda_b^0 \to P_{\psi}^{N+} K^- : \quad bdu \underset{Z}{\longrightarrow} fsu + g \to fsu + u\bar{u} \to fuu + s\bar{u}$$

$$P_{\psi}^{N+} \to p\, J/\psi : \quad fuu \to cuu + W^- \to cuu + d\bar{c} \to uud + c\bar{c}$$

Predicted Pentaquark decays to 1 c quark

Isospin triplets: positively charged

$$\Lambda_b^0 \to P_c^+ K^- : \quad P_c^+ \to p D^{*0}$$

(or replace K^- with K^{*-}, π^- or ρ^-)
replace D^{*0} with D^0

For neutral members, substitutions like $K^- \Rightarrow K^0$ or $\pi^- \Rightarrow \pi^0$ and $p \Rightarrow \Lambda$

Also $\boxed{\Lambda_b^0 \to P_c^+ \pi^- : \quad P_c^+ \to \Lambda_c^+ p \bar{p}}$

Look for existing pentaquarks … and the following predicted new fuu baryons:

$$\text{mass},\ J^P : \sim 3870, \tfrac{1}{2}^+, \sim 4065, \tfrac{3}{2}^+, \sim 4260, \tfrac{3}{2}^-$$

Isospin singlets:

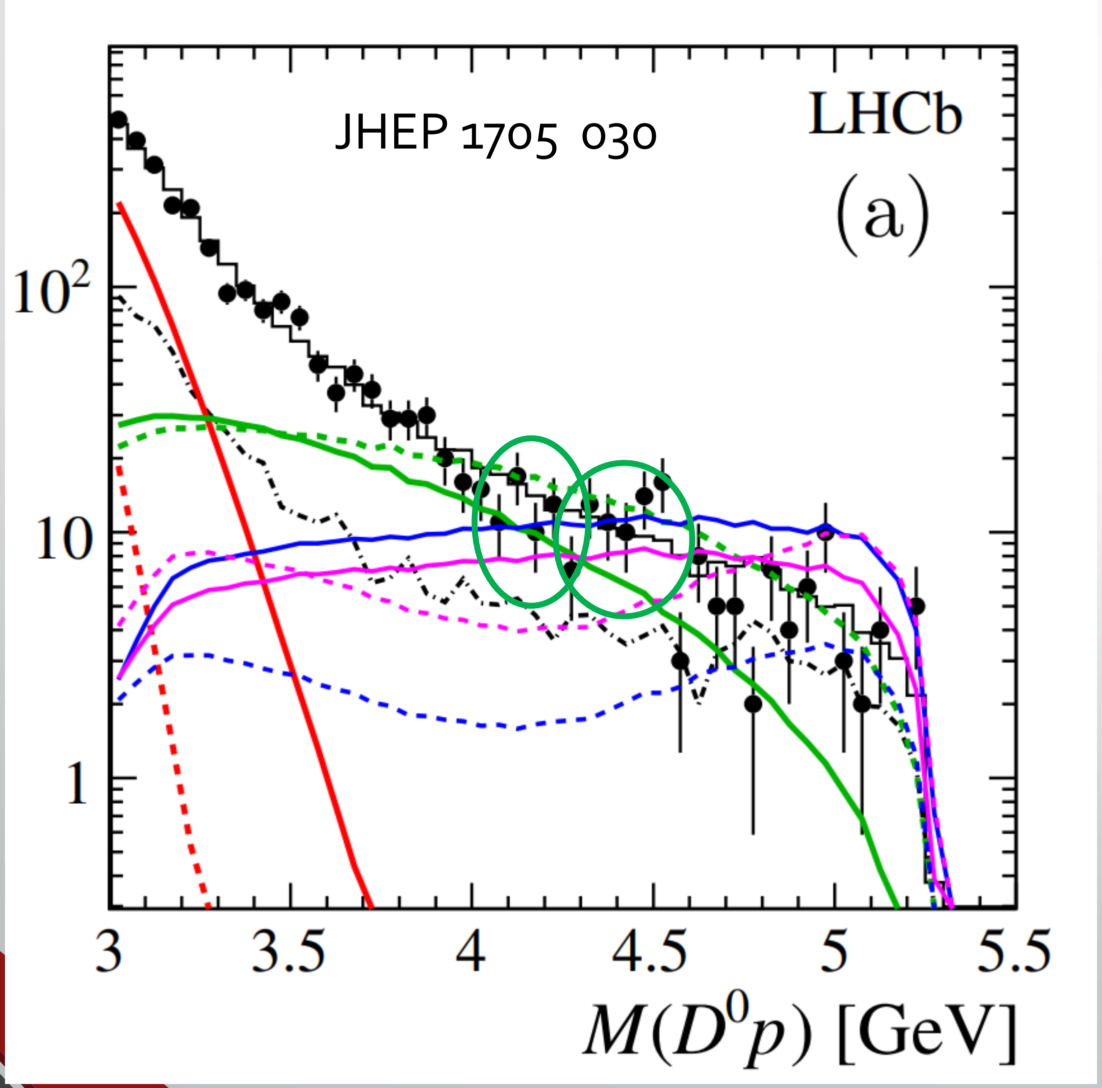
$B^- \to P_{\psi s}^{\Lambda 0} \bar{p} : \quad P_{\psi s}^{\Lambda 0} \to \Lambda D^{*0}$: Belle: arxiv:1108.4271

Look for $P_{\psi s}^{\Lambda 0}(4338)$ and $\sim 3795, \tfrac{1}{2}^+, \sim 4060, \tfrac{1}{2}^-, \sim 4085, \tfrac{1}{2}^-, \sim 4200, \tfrac{3}{2}^-$

LHCb has studied this in arxiv:1804.09617

Has LHCb seen evidence of a predicted decay?

Predicted: $\Lambda_b^0 \to P_c^+ \pi^- : \quad P_c^+ \to p D^0$



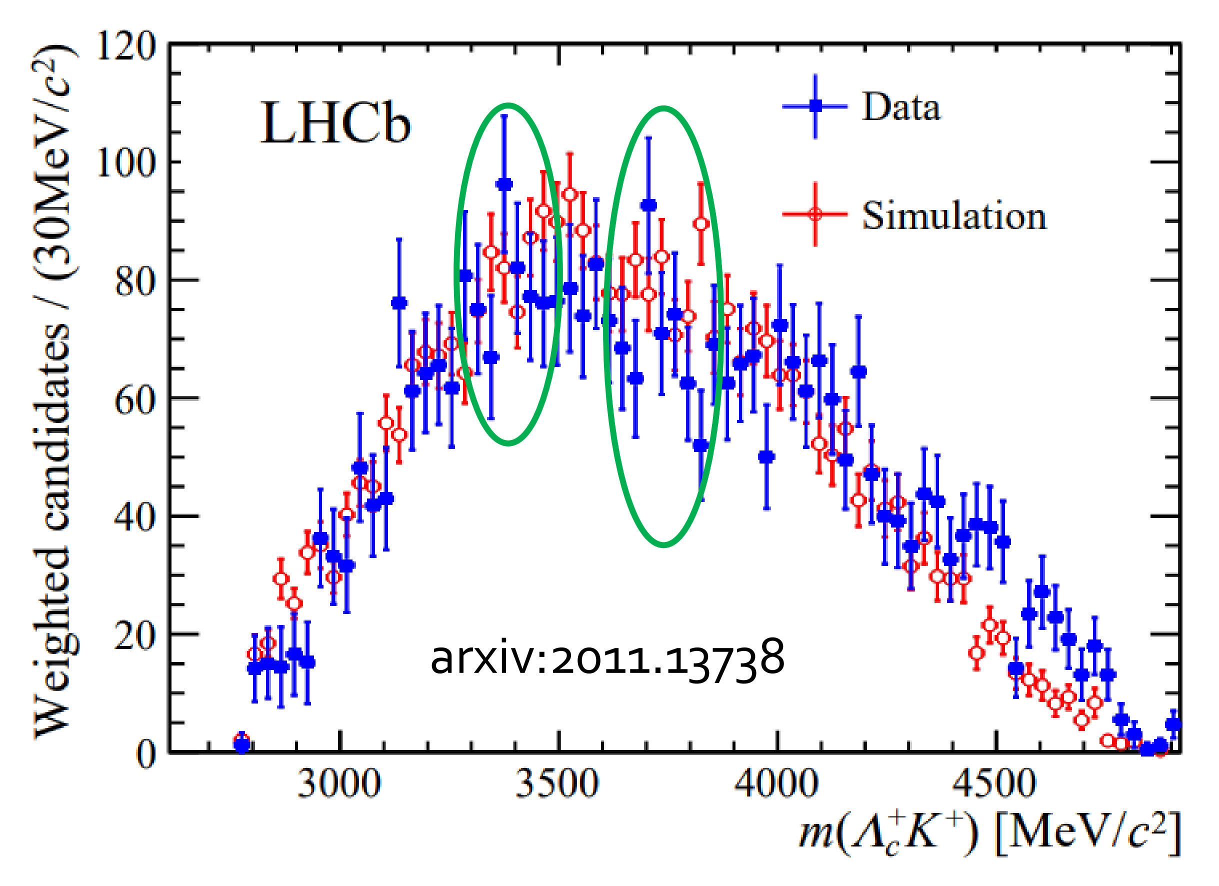
Could this be mapped to existing pentaquarks?

Other lower mass predictions?

Hints of the predicted Pc^+(3870) and (4260)?

$$\Lambda_b^0 \to P_c^+\pi^- : \quad bdu \to fdu + g \to fdu + u\bar{u} \to fuu + d\bar{u}$$

$$P_c^+ \to \Lambda_c^+K^+K^- : \quad fuu \to cuu + W^- + g \to cuu + d\bar{u} + s\bar{s} \to cdu + s\bar{u} + u\bar{s}$$



When just looking at invariant mass of $\Lambda_c^+K^+$ could there be hints of $\Lambda_c^+K^+K^-$ resonances at

3870, 1/2^+?

4260, 3/2^-?

Hadrons decaying to J psi pairs

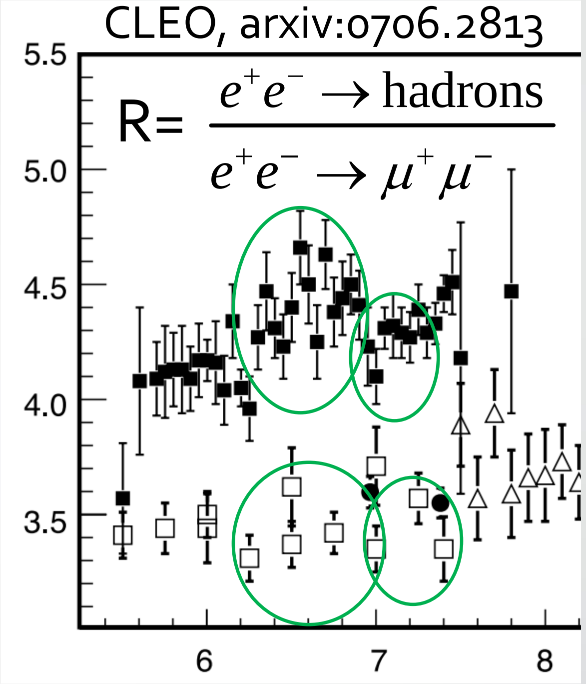
Wide resonances,
must be strong decays

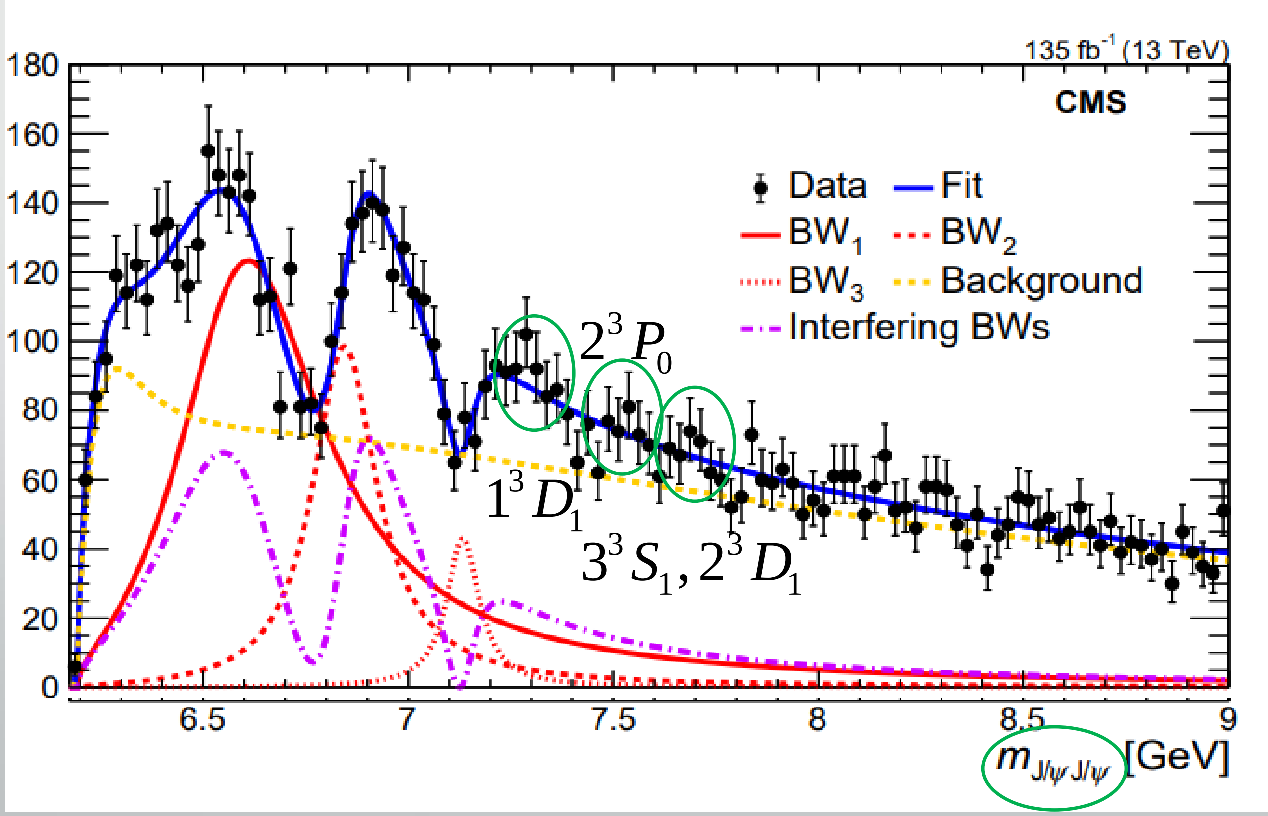
$c\bar{c}c\bar{c} \to c\bar{c} + c\bar{c}$

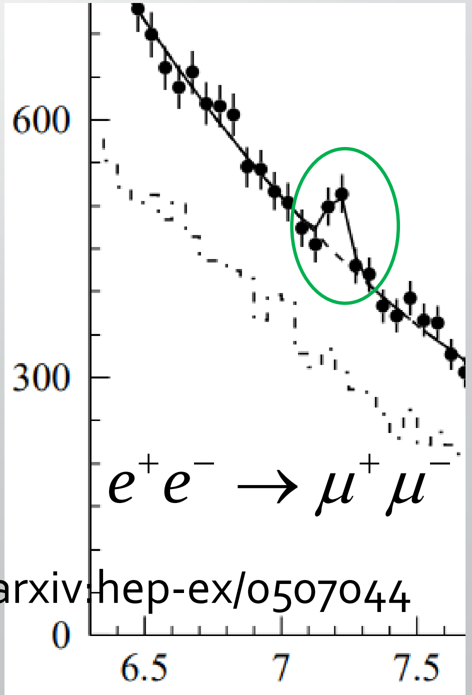
$f\bar{f} \to f\bar{u} + u\bar{f}$

$f\bar{f} \to c\bar{c} + c\bar{c}$

Name	Mass	Γ	J^{PC}
$X(6600)$	6638	440	$?^{??}$
$X(6900)$	6847	191	0^{++}
$X(7200)$	7134	97	$?^{??}$







ffbar Production and Decay

$$g,\gamma \to X(6900)\ldots: \quad g,\gamma \to f\bar{f}$$

$$X(6900)\ldots \to J/\psi\, J/\psi: \quad f\bar{f} \underset{W}{\to} c\bar{c} + g \to c\bar{c} + c\bar{c}$$

This decay is analogous to $\Upsilon \underset{W}{\to} J/\psi\, J/\psi$

But in the "CKM" matrix $\left|V_{cf}\right|^4 \sim 40,000\left|V_{cb}\right|^4$

ffbar meson predictions

Look at pairs of $\psi(2S)$

$$X \to \psi(2S)\psi(2S): \quad f\bar{f} \underset{W}{\to} c\bar{c} + g \to c\bar{c} + c\bar{c}$$

New invariant masses: **~7500 and ~7700 MeV**,
corresponding to bumps seen in the $J/\psi\, J/\psi$ chart

Also strong decays

$$X(6600)\ldots \to X^{+}(3250)\, X^{-}(3250): \quad f\bar{f} \to f\bar{u} + u\bar{f}$$

$$X(6600)\ldots \to X^{0}(3250)\, \bar{X}^{0}(3250): \quad f\bar{f} \to f\bar{d} + d\bar{f}$$

X(3250) (in PDG meson listings: Further States)

1993: PAN 56 1358 A.N. Aleev et al. (BIS-2 Collab.) Translated from YAF 56 100.

$$X^+(3250) \to \Lambda\bar{p}K^+\pi^+ : \quad u\bar{f} \to u\bar{u} + W^+ + 3g \to u\bar{u} + u\bar{d} + s\bar{s}u\bar{u}d\bar{d}$$

$$X^+(3250) \to \bar{\Lambda}pK^-\pi^+ : \quad u\bar{f} \to u\bar{u} + W^+ + 3g \to u\bar{u} + u\bar{d} + s\bar{s}u\bar{u}d\bar{d}$$

$$X^+(3250) \to p\bar{p}K_S^0K^+ : \quad u\bar{f} \to u\bar{u} + W^+ + 3g \to u\bar{u} + u\bar{d} + s\bar{s}u\bar{u}d\bar{d}$$

$$X^0(3250) \to \Lambda\bar{p}K^+ : \quad d\bar{f} \to d\bar{u} + W^+ + 2g \to d\bar{u} + u\bar{d} + s\bar{s}u\bar{u}$$

and Hermitian conjugate decays

Look for events with $\left(\Lambda\bar{p}K^+\pi^+\right)\left(\Lambda\bar{p}K^+\pi^-\right)$ or h.c.

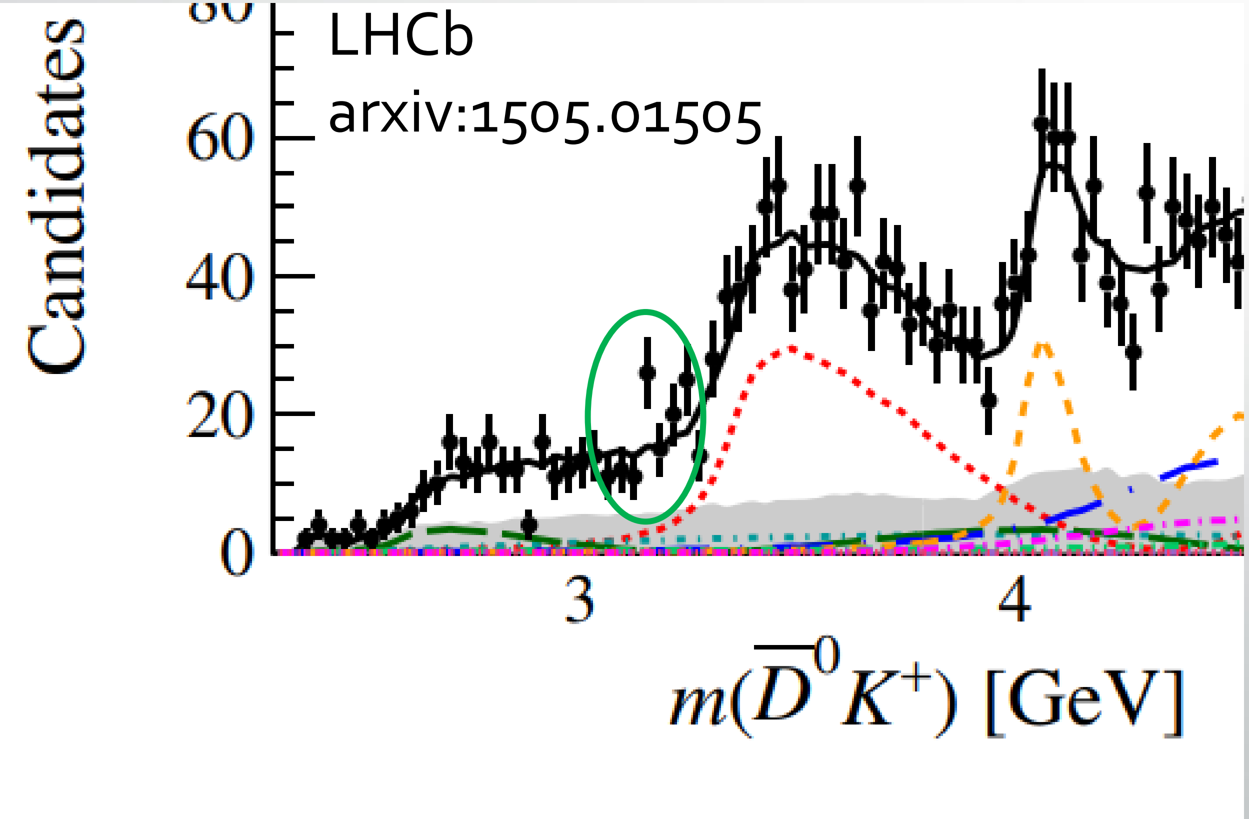
Look for invariant mass peaks at ~3250 for hadrons in the parentheses (alternatively without the pions for neutral X pairs)

For those events with 3250 invariant masses, look for peaks in the invariant mass of a pair of 3250s. See if they are at 6600, 6900, 7200, etc.

Has LHCb seen a hint of the charged 3250?

$$B^0 \to X^+(3250)\pi^- : \quad d\bar{b} \to d\bar{f} + Z \to d\bar{f} + u\bar{u} \to u\bar{f} + d\bar{u}$$

$$X^+(3250) \to \bar{D}^0 K^+ : \quad u\bar{f} \to u\bar{c} + W^+ \to u\bar{c} + u\bar{s}$$



Alternative search for strong decay of X(6600), X(6900) ...?

Look for

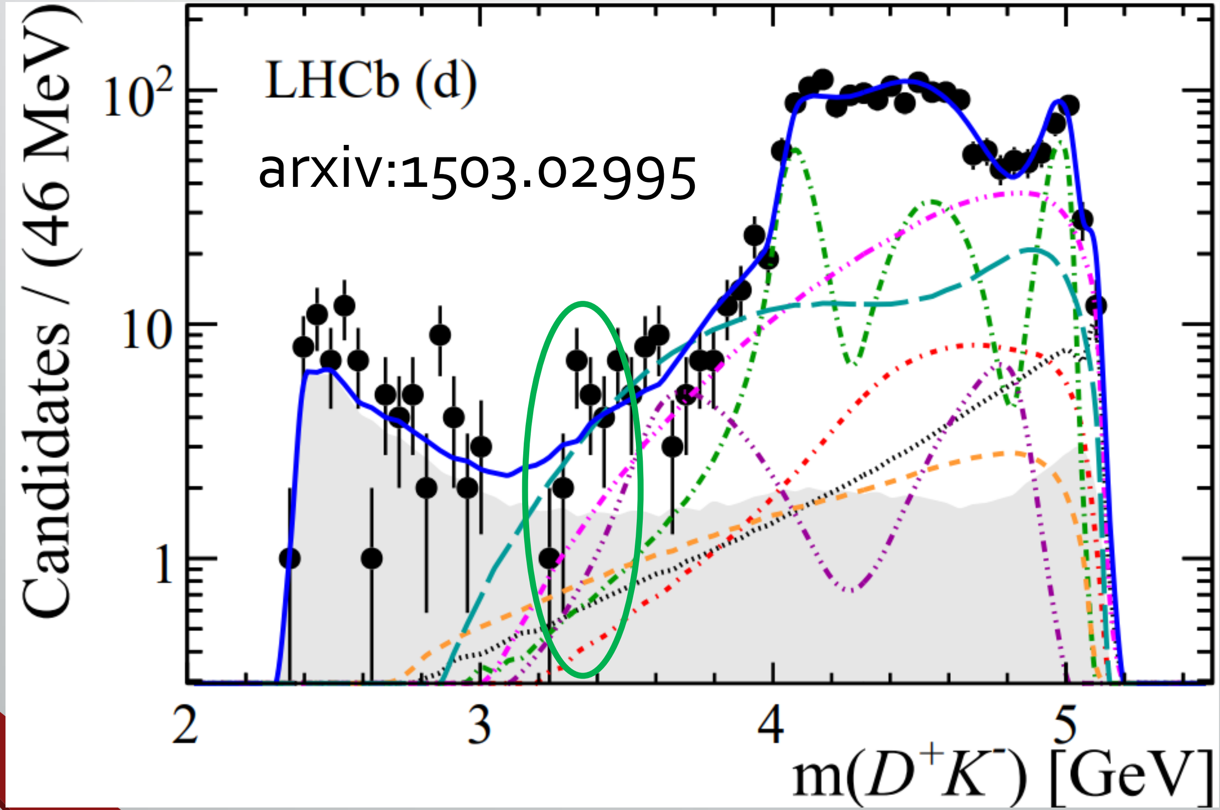
$$X(6600) \to X^+(3250)\, X^-(3250)$$

$$X^+(3250) \to \bar{D}^0 K^+$$

And maybe a hint of the neutral 3250?

$$B^- \rightarrow X^0(3250)\pi^- : \quad b\bar{u} \rightarrow f\bar{u} + Z \rightarrow f\bar{u} + d\bar{d} \rightarrow f\bar{d} + d\bar{u}$$

$$X^0(3250) \rightarrow D^+K^- : \quad f\bar{d} \rightarrow c\bar{d} + W^- \rightarrow c\bar{d} + s\bar{u}$$



Alternative search for strong decay of X(6600), X(6900) ...?

Look for

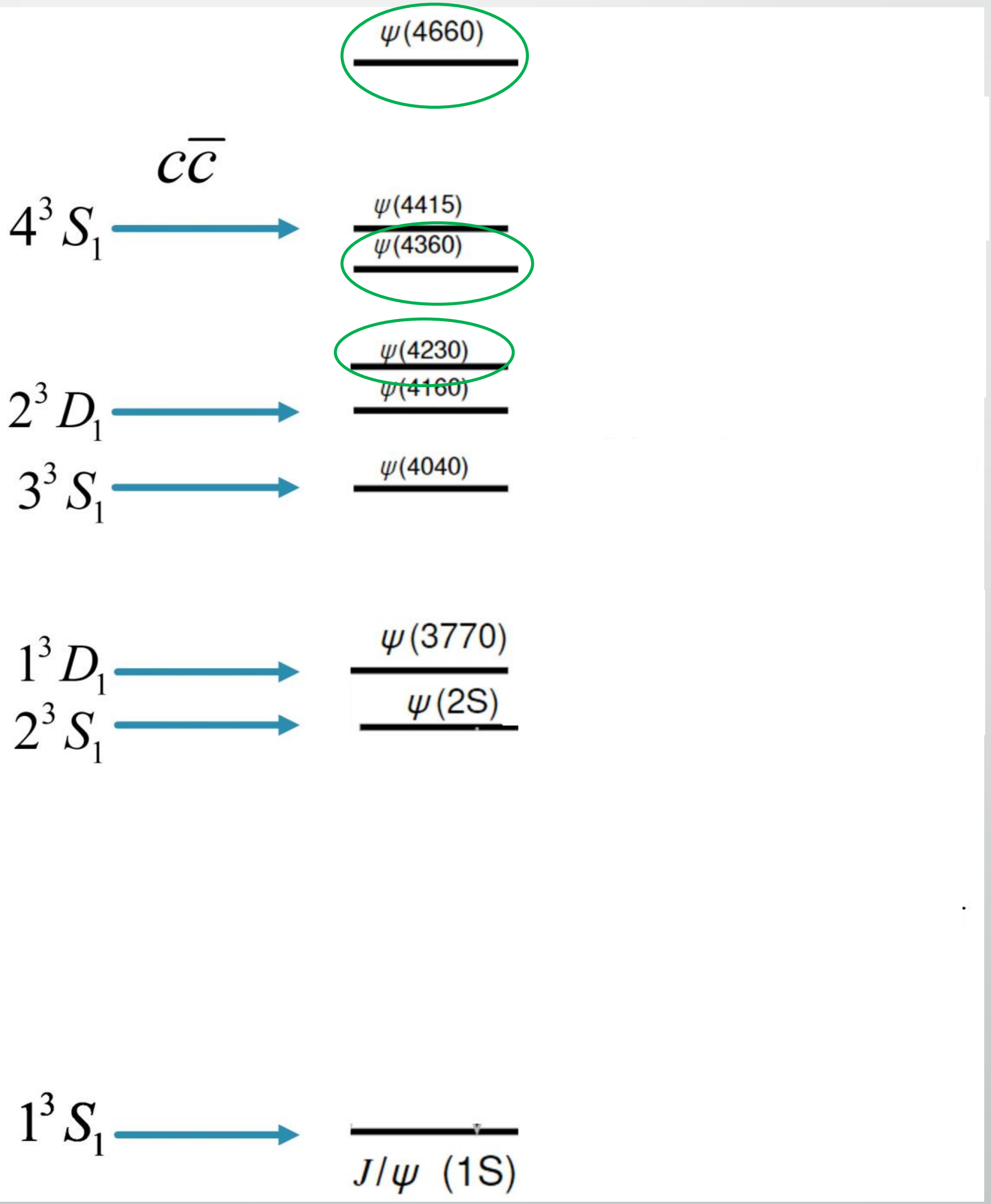
$$X(6600) \rightarrow X^0(3250)\bar{X}^0(3250)$$

$$X^0(3250) \rightarrow D^+K^-$$

$J^{PC} = 1^{--}$ mesons

seen in e^+e^- collisions

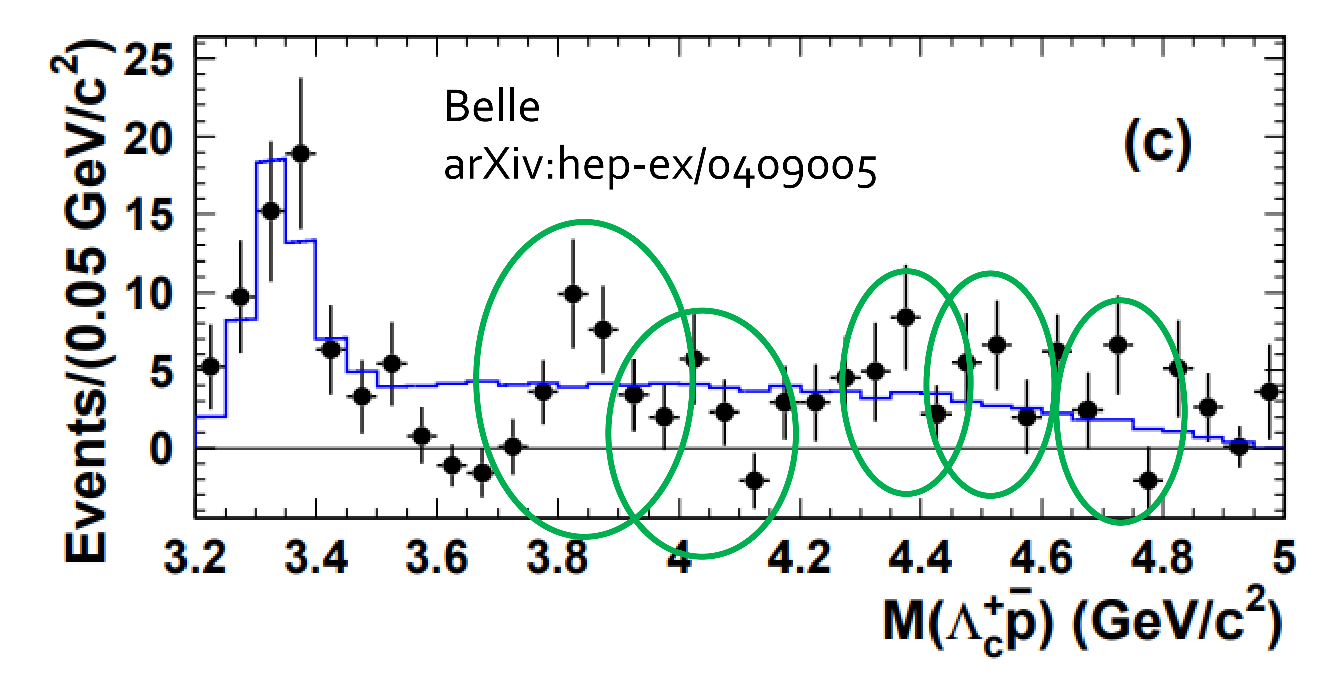
- Mesons in the diagram are in PDG listings for the charmonium system
- Model enables $Z \to f\bar{d}$ and $Z \to f\bar{s}$
- 4500, 4407, 3760 are in BESIII publications
- The J^{PC} of $X(3350)$ and $X^0(4020)$ are not determined
- Mass spacings for are somewhat similar to those for charmonium



Observation of X(3350)

$$B^- \to X\pi^- : \quad b\bar{u} \to f\bar{u} + Z \to f\bar{u} + d\bar{d} \to f\bar{d} + d\bar{u}$$

$$X \to \Lambda_c^+ \bar{p} : \quad f\bar{d} \to c\bar{d} + W^- + g \to c\bar{d} + d\bar{u} + u\bar{u}$$



This was considered an observation of X(3350), mapped here as the $1^{--}\ 1^3S_1$ meson of $f\bar{d}$

But it could also have been an observation of the $0^{++}\ 1^3P_0$ meson of $f\bar{d}$ at ~3860

And maybe also of the $1^{--}\ 2^3S_1$ meson of $f\bar{d}$: $X^0(4020)$

2^3P_0 ? 3^3S_1 ? 3^3P_0 ?

Down, up, strange mesons

Proposed $f\bar{d}$ and $d\bar{f}$ Mesons

Name	Mass	Γ	J^{PC}	QM	Δm_c	Δm_b
$X(3250)$	3250	45	$?^{??}$	1^1S_0	1385	2030
$X(3350)$	3350	70	$?^{??}$	1^3S_1	1343	1975
$\chi_{c0}(3860)$	3862	201	0^{++}	1^3P_0	1519	1836
$\chi_{c1}(3872)$	3872	1.2	1^{++}	1^3P_1	1460	1854
$Z_c^0(3900)$	3887	28	1^{+-}	1^1P_1	1465	1839
$Z_{cs}^0(3985)$	3993	8	$?^{??}$	2^1S_0	1444	1978
$X^0(4020)$	4024	13	$?^{?-}$	2^3S_1	1397	
$X(4160)$	4153	136	2^{-+}	1^1D_2		
$\psi(4230)$	4223	49	1^{--}	1^3D_1	1463	
$\chi_{c1}(4274)$	4286	51	1^{++}	2^3P_1		
$Y(4500)$	4485	111	1^{--}	3^3S_1		
$\psi(4660)$	4630	72	1^{--}	2^3D_1		
$\chi_{c1}(4685)$	4684	126	1^{++}	3^3P_1		
$\chi_{c0}(4700)$	4694	87	0^{++}	3^3P_0		

Proposed $f\bar{u}$ and $u\bar{f}$ Mesons

Name	Mass	Γ	J^{PC}	QM	Δm_c	Δm_b
$X(3250)$	3250	45	$?^{??}$	1^1S_0	1385	2030
$T_{cc}^{+}(3875)$	3875	0.4	$1^{+?}$	1^3P_1	1463	1851
$Z_c^{\pm}(3900)$	3887	28	1^{+-}	1^1P_1	1465	1839
$Z_{cs}^{\pm}(3985)$	3983	13	$?^{??}$	2^1S_0	1434	1988
$X^{\pm}(4020)$	4024	13	$?^{?-}$	2^3S_1	1397	
$Z_c^{\pm}(4430)$	4478	181	1^{+-}	2^1P_1		

.

Proposed $f\bar{s}$ and $s\bar{f}$ Mesons

Name	Mass	Γ	J^{PC}	QM	Δm_c	Δm_b
$R(3760)$	3766	22	1^{--}	1^3S_1	1648	1655
$X(3960)$	3956	43	0^{++}	1^3P_0	1639	
$\chi_{c1}(4140)$	4147	19	1^{++}	1^3P_1	1687	
$\psi(4360)$	4372	115	1^{--}	2^3S_1	1658	
$R(4407)$	4407	128	1^{--}	1^3D_1		
$\chi_{c0}(4500)$	4474	77	0^{++}	2^3P_0		

,

Three arguments against the proposed quark

1. The quark was not seen in precision e+e- to Z experiments at LEP/SLD.
2. The model doubles the coupling of the Z boson with the right-chiral charm quark, but LEP/SLD experiments established the charm-Z coupling to be the same as the Standard Model.
3. Inclusive hadronic cross sections fit the data with the known quarks

Lifetime of the f quark

First calculate lifetime of f quark

Heavy quark effective theory zeroth order:

$$\frac{\tau_f}{\tau_b} \approx \frac{m_b^5 \left(\left| V_{cb}^{+} \right|^2 + 3 \left| V_{cb}^{-} \right|^2 \right)}{m_f^5 \left(\left| V_{cf}^{+} \right|^2 + 3 \left| V_{cf}^{-} \right|^2 \right)} \approx 1\%$$

Main reason: the new quark has stronger interactions with the W boson

$$\left| V_{cb}^{+} \right| \approx 0.04 \qquad \left| V_{cf}^{+} \right| \approx \left| V_{cf}^{-} \right| \approx 1$$

Lifetime: ~0.02 ps

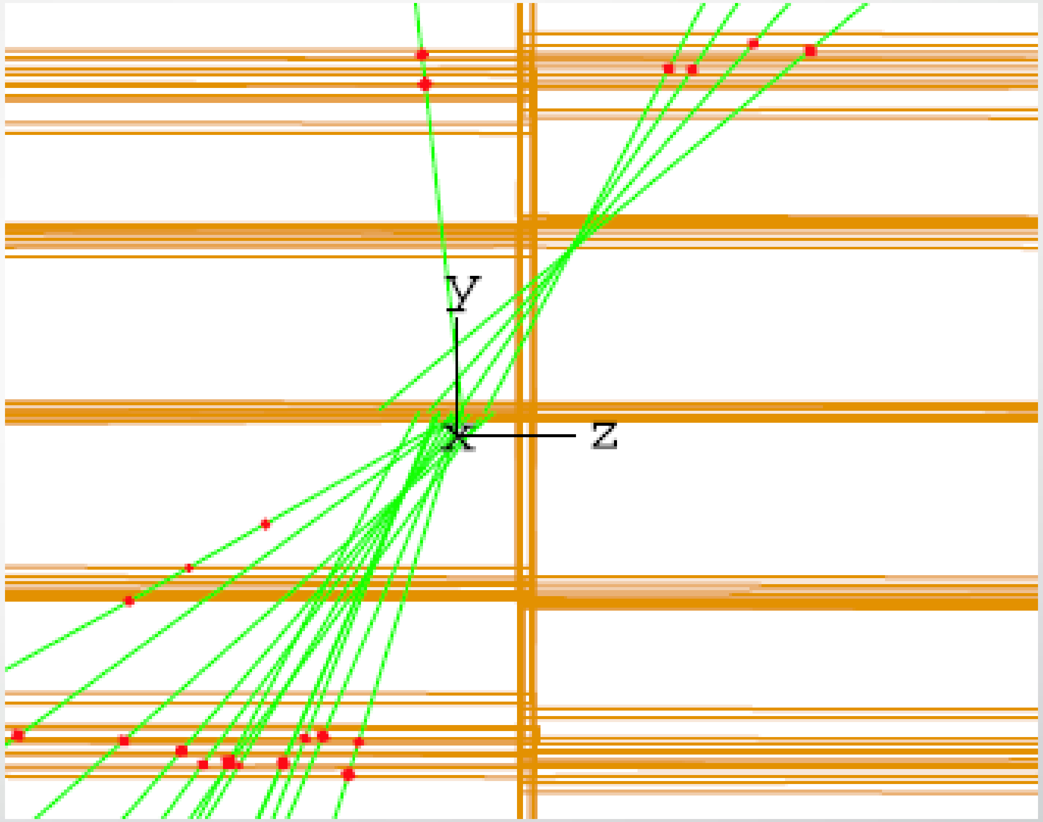
Secondary vertex tagging at LEP & SLD

Experimental Resolution:
~20-70 microns

Lifetime of b quark: ~1.6 ps
Impact parameter: ~300 microns

Lifetime of c quark: ~.5 - 1 ps
Impact pmtr: ~100-200 microns

Lifetime of f quark: ~0.016 ps
Impact parameter: ~3 microns



b -> c and c-> s vertices were seen

An f -> c vertex would not have been seen

f quarks would have been lumped with c quarks

Effective Z-charm coupling

Z-c coupling

	$V_{c\bar{c}}^{V}$	$V_{c\bar{c}}^{A}$
$7q$	$1-\frac{4}{3}x$	0
SM	$\frac{1}{2}-\frac{4}{3}x$	$-\frac{1}{2}$

~no FCNC with c

$$V_{c\bar{c},eff}^{V} \approx V_{c\bar{c}}^{V} + P_f V_{f\bar{f}}^{V} + 2\sum_q P_q V_{q\bar{f}}^{V}$$

$$V_{c\bar{c},eff}^{A} \approx V_{c\bar{c}}^{A} + P_f V_{f\bar{f}}^{A} + 2\sum_q P_q V_{q\bar{f}}^{A}$$

P_q is the probability that this survives tagging, cuts, etc.

Partial widths: $\left(V_{c\bar{c},eff}^{V}\right)^2 + \left(V_{c\bar{c},eff}^{A}\right)^2$ Asymmetry: $2V_{c\bar{c},eff}^{V} V_{c\bar{c},eff}^{A} \Big/ \left(\left(V_{c\bar{c},eff}^{V}\right)^2 + \left(V_{c\bar{c},eff}^{A}\right)^2\right)$

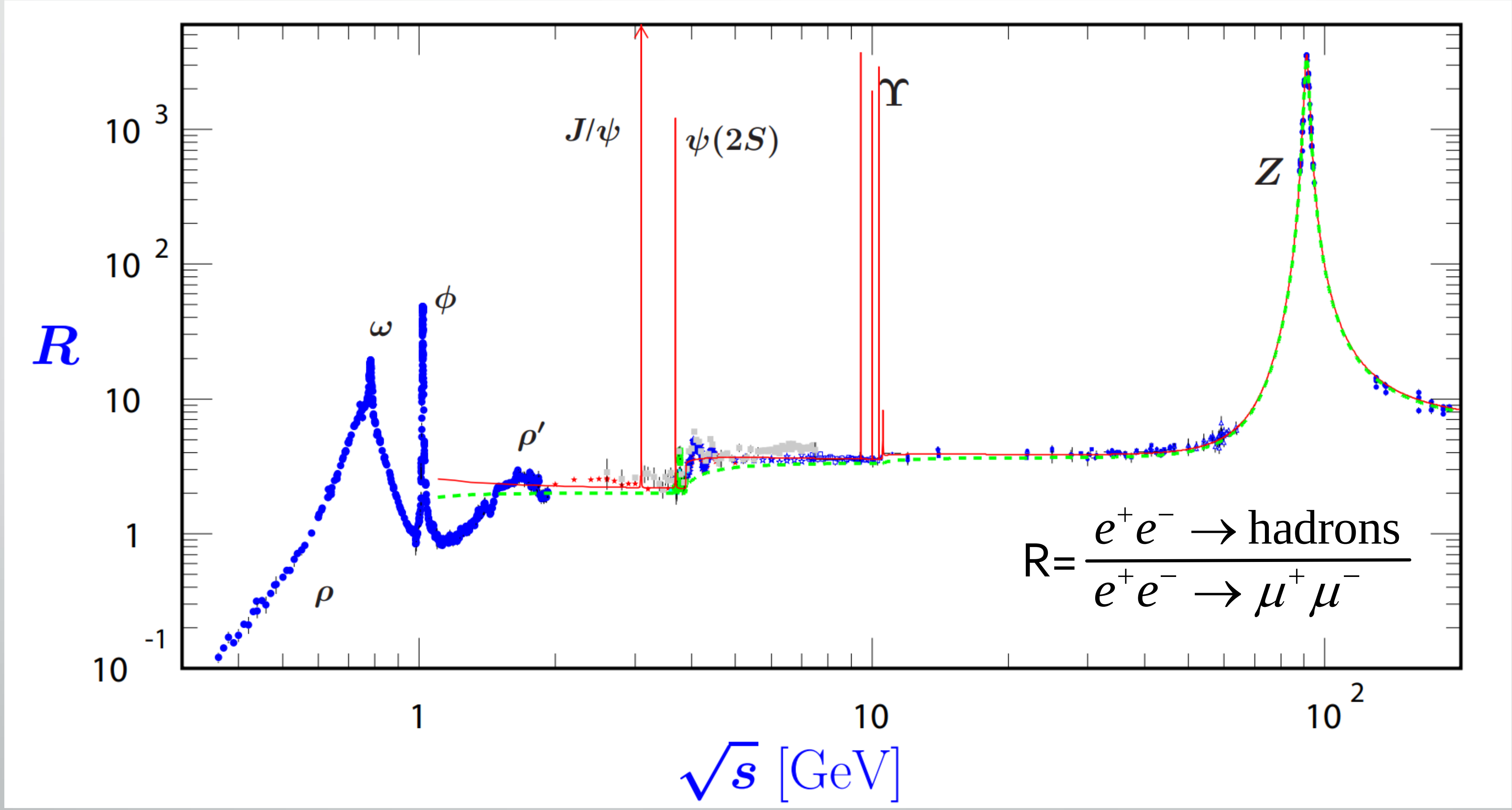
$P_f = P_b = 1,\; P_s = P_d = 0.5$ reproduces SM partial widths and the data

$P_f = P_b = 46\%,\; P_s = P_d = 23\%$ reproduces SM asymmetry and the data

This is consistent with:

- the best tags for c events were ones that counted c quarks or D mesons
- asymmetry used tags like opposite hemisphere charge, lepton charge

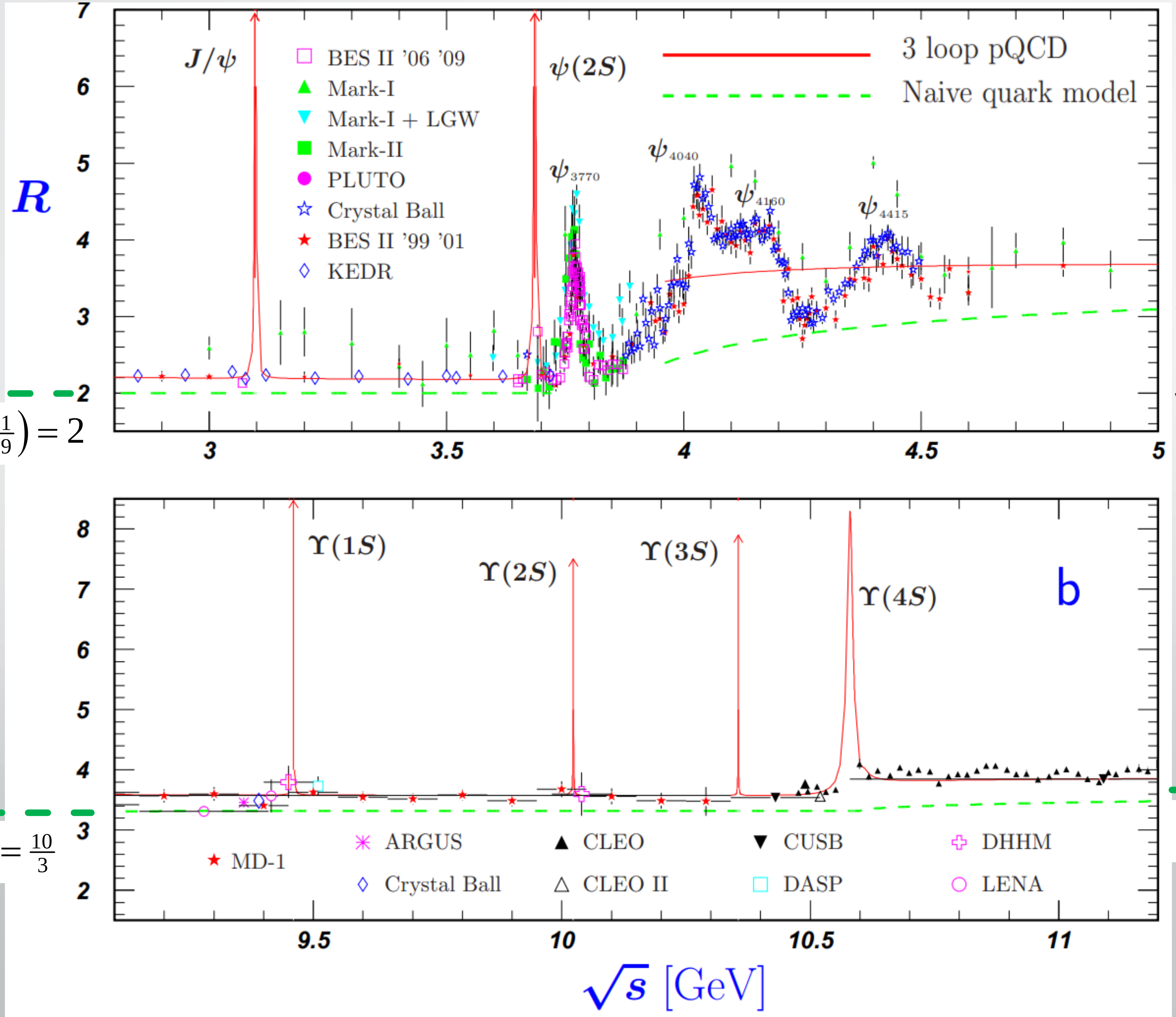
Inclusive Hadronic Cross Section - PDG



PDG R Graph showing quark levels

u,d,s

$$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}\right)=2$$



It will be hypothesized calculations may be missing an effect that would lower R by 1/3

Adding an f quark would add 1/3 to R

u,d,s,c

$$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9}\right)=\frac{10}{3}$$

u,d,s,c,b

$$3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}+\frac{4}{9}+\frac{1}{9}\right)=\frac{11}{3}$$

Complete sets of states for inclusive cross sections

The calculation of the inclusive cross section adds exclusive cross sections over a complete set of orthogonal final states

It has been argued that:

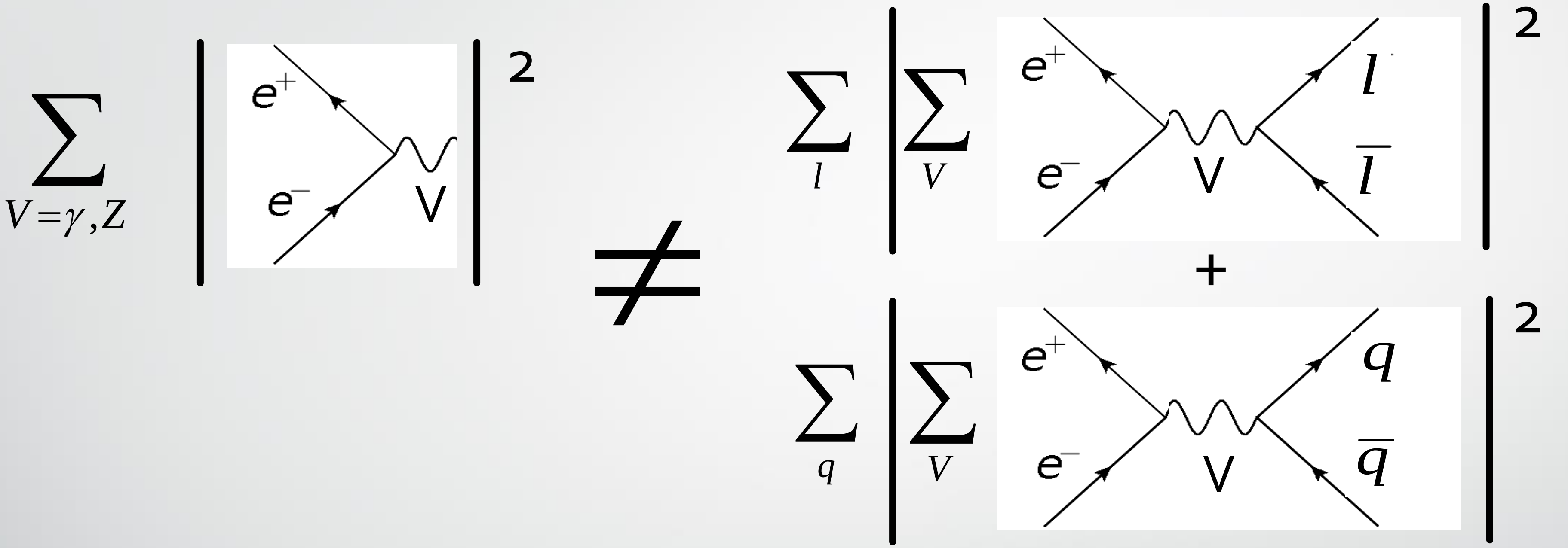
- Any complete set of orthogonal states can be used; they will all generate the same answer
- The final states in the complete set do not need to be observable

The argument appears to be incorrect, at least for some cases.

Two complete sets of final states

Set (a): photon & Z

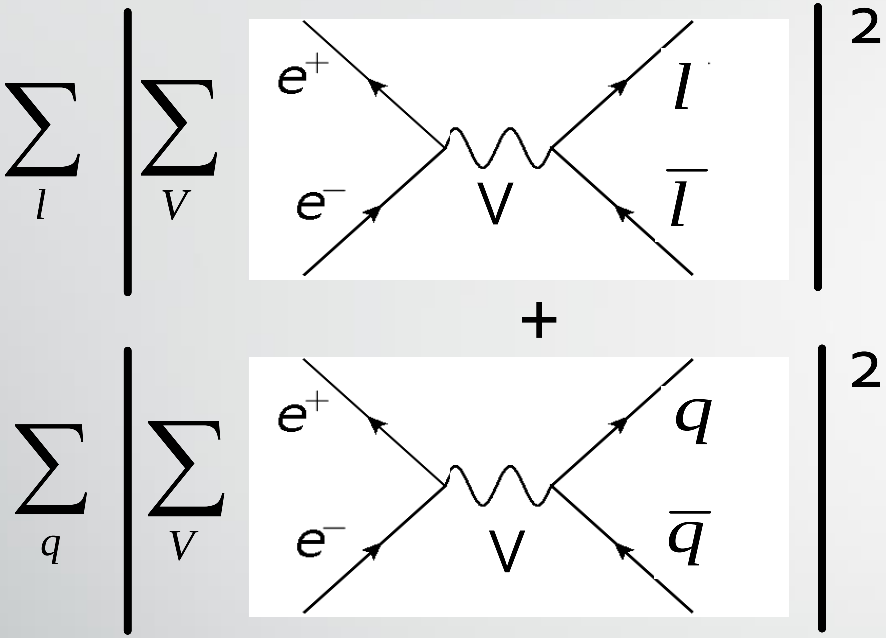
Set (b): lepton and quark pairs



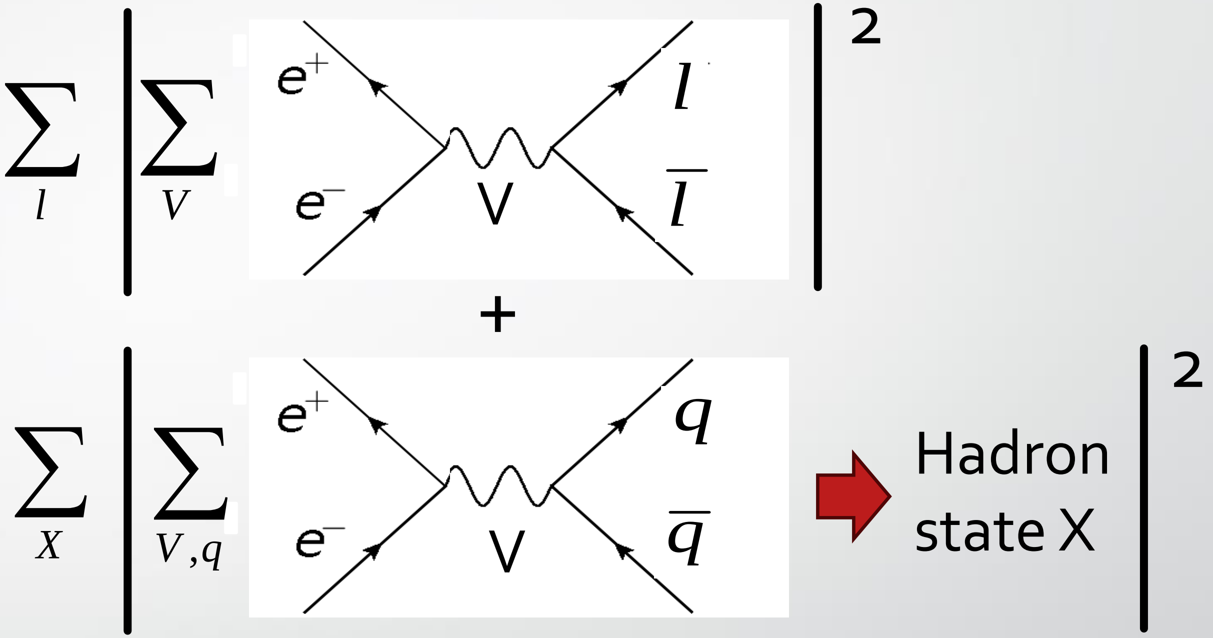
- When using set (a), the photon and Z boson are treated as orthogonal final states, so there is no interference between them.
- When using set (b), interference between the photon and Z boson is included, since each can lead to the same final state
- Sets (a) and (b) generate different results
- Set (b) reproduces inclusive lepton data. Set (a) does not.

Another complete set of final states

Set (b): lepton and quark pairs

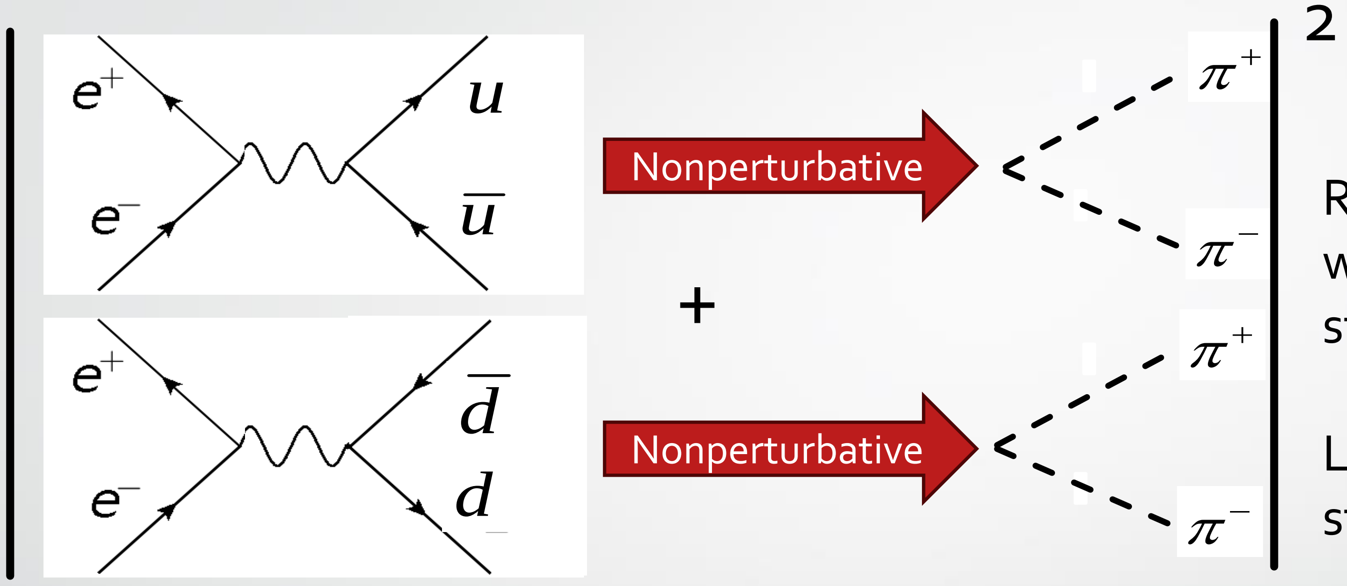


Set (c): lepton pairs and hadrons



If there are hadronic states X in set (c) that could have been produced by different flavor quark pairs created by V, then interference between those quark-pair intermediate states must be considered in the set (c) calculation.

Example “set (c)” final state: 2 pions



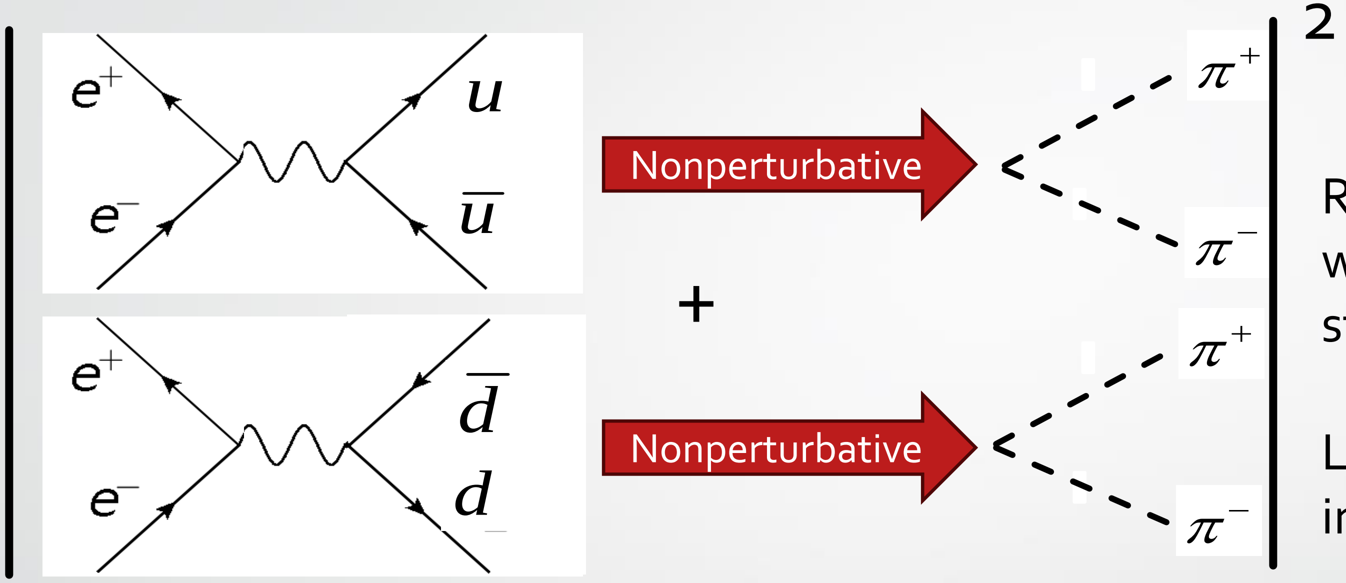
Replace pions with two jets with no net beauty, charm, strangeness, baryon number

Large class of interfering states

If complete set (c) is being used for calculation of the inclusive cross section (hadron states instead of q qbar states), then interference between these two diagrams must be taken into account for this hadronic state X.

An inclusive cross section calculation using set (c) would be different than one using set (b).

Is the interference significant?



Replace pions with two jets with no net beauty, charm, strangeness, baryon number

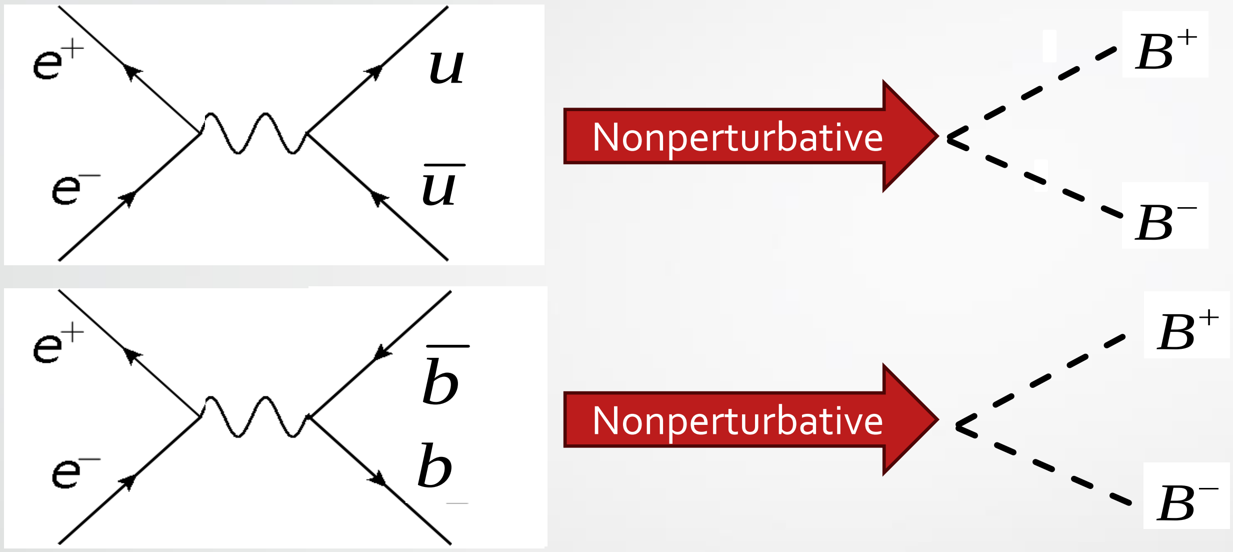
Large class of significantly interfering states

From isospin symmetry, the nonperturbative parts above should be the same (even if they can't be calculated analytically).

The difference between neglecting interference and including it is:

$$C\left(\left(\frac{2}{3}\right)^2+\left(\frac{1}{3}\right)^2\right) \text{ vs. } C\left(\frac{2}{3}-\frac{1}{3}\right)^2$$

Interference for heavy quarks?



Negligible since $2m_b \gg \Lambda_{QCD}$

Almost all the contribution $2m_u \ll \Lambda_{QCD}$

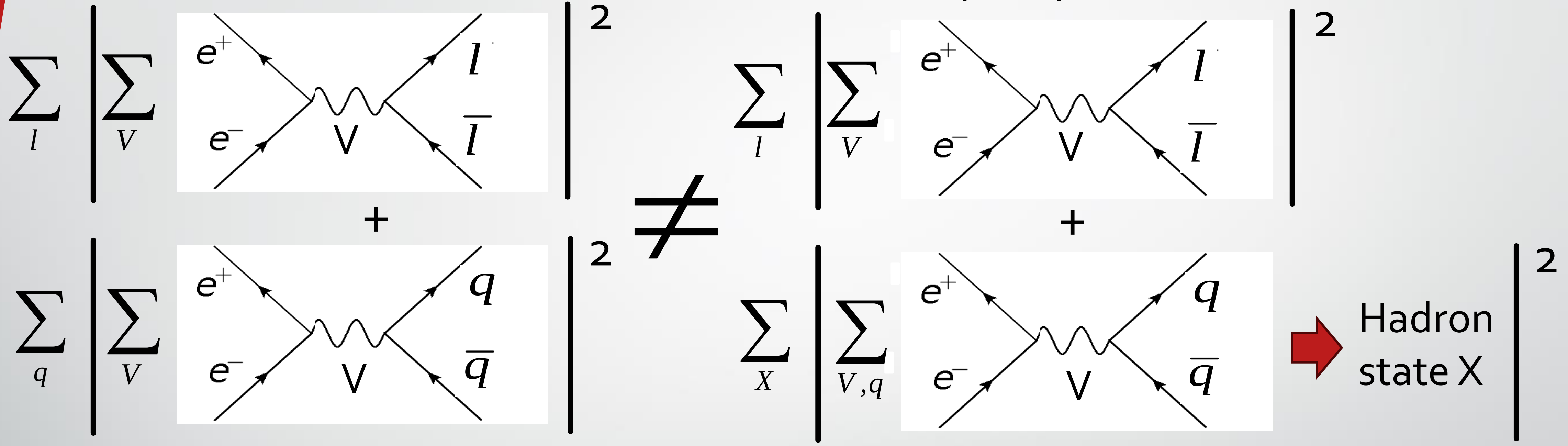
Inteference of this kind involving the heavy quarks is neglible.

So for heavy quarks, calculations using set (b) and set (c) should generate the same result, so might as well use set (b) for heavy quarks

Comparing complete sets of final states

Set (b): lepton and quark pairs

Set (c): lepton pairs and hadrons



There are hadronic states X in set (c) that could have been produced by either a u ubar or a d dbar intermediate state

Interference between those intermediate states must be considered

The set (c) calculation has not been performed

A set (c) calculation would generate different results than set (b)

- Due to up-down interference, inclusive cross section calculation results would be different using complete sets of states (b) vs. (c)
- Based on other examples, it is best to use a complete set of observable states: set (c)
- Therefore, the usual calculation of inclusive cross sections is incorrect: set (b)

Hypothesis for a set c inclusive cross section calculation

- Given that the R generated by u ubar is 4/3 and by d dbar is 1/3, it is plausible that if a set (c) calculation incorporating interference was performed, it could generate an R value for both of ~4/3, rather than ~5/3.
- If so, after including 3-loop pQCD corrections, this new cross section calculation would under-predict the measured R values by ~1/3.
- If there was an additional heavy quark with charge -1/3, that would contribute an additional ~1/3 to the R value and reproduce the data.

It would be interesting to find some way to do the set (c) calculation.

W & Z interactions of the additional quark

Modified W boson interactions

Add a fourth generation of down-type quark.

$$\begin{pmatrix} \bar{u}_{L1} & \bar{u}_{L2} & \bar{u}_{L3} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \gamma^{\mu} \begin{pmatrix} d_{L1} \\ d_{L2} \\ d_{L3} \\ d_{L4} \end{pmatrix} g W_{\mu} + h.c.$$

$$+ \begin{pmatrix} \bar{u}_{R1} & \bar{u}_{R2} & \bar{u}_{R3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \gamma^{\mu} \begin{pmatrix} d_{R1} \\ d_{R2} \\ d_{R3} \\ d_{R4} \end{pmatrix} g W_{\mu} + h.c.$$

Both the 1st and 4th generation down-type quark have right-chiral W interactions

Two R and two L connections means gauge anomalies are cancelled for W

Modified "CKM" Matrix

Vector (+) and Axial Vector (-) versions

$$V_{CKM}^{\pm} = V_R^U \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} V_R^{D\dagger} \pm V_L^U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} V_L^{D\dagger}$$

Unitary matrices that translate to quark mass eigenstates

$$M_D = \begin{pmatrix} -0.0338 & 0.0137 & 0.0246 & -0.0527 \\ -0.0252 & -0.0725 & -0.0636 & -0.0804 \\ 0.1054 & 1.4894 & -3.8554 & 0.1329 \\ 1.4717 & -0.0800 & 0.2408 & 2.3052 \end{pmatrix}$$

$$M_U = \begin{pmatrix} 0.00131 & -0.00191 & 0.0122 \\ 0.6493 & 1.1126 & -5.3477 \\ 1.7379 & -1.0843 & 171.94 \end{pmatrix},$$

$$|V_{\mathrm{CKM}}^{+}| = \begin{pmatrix} 0.9745 & 0.2239 & 0.0043 & 0.0094 \\ 0.2323 & 0.9661 & 0.0388 & 0.9720 \\ 0.0088 & 0.0402 & 0.9973 & 0.0619 \end{pmatrix}$$

$$|V_{\mathrm{CKM}}^{-}| = \begin{pmatrix} 0.9742 & 0.2252 & 0.0042 & 0.0093 \\ 0.2165 & 0.9805 & 0.0394 & 1.0278 \\ 0.0144 & 0.0349 & 0.9974 & 0.0621 \end{pmatrix}$$

This choice of mass matrices can reproduce all normal CKM data

It also helps with the vector vs. axial 3-sigma difference in V_us

Quark couplings to the Z boson by generation

$$Zq\overline{q}$$

Up-type quarks

Gen	g_L	g_R
1	$-\frac{2}{3}x$	$\frac{1}{2}-\frac{2}{3}x$
2	$\frac{1}{2}-\frac{2}{3}x$	$\frac{1}{2}-\frac{2}{3}x$
3	$\frac{1}{2}-\frac{2}{3}x$	$-\frac{2}{3}x$
SM	$\frac{1}{2}-\frac{2}{3}x$	$-\frac{2}{3}x$

$x=\sin^2\theta_W$

Down-type quarks

Gen	g_L	g_R
1	$\frac{1}{3}x$	$-\frac{1}{2}+\frac{1}{3}x$
2	$-\frac{1}{2}+\frac{1}{3}x$	$\frac{1}{3}x$
3	$-\frac{1}{2}+\frac{1}{3}x$	$\frac{1}{3}x$
4	$\frac{1}{3}x$	$-\frac{1}{2}+\frac{1}{3}x$
SM	$-\frac{1}{2}+\frac{1}{3}x$	$\frac{1}{3}x$

Z boson coupling depends on the generation

Quark gauge anomalies cancel for Z boson:
For every L interaction, there is an R interaction

Example Z Mixing Matrix

$$V_{ZD}^{L} = V_{L}^{D} \begin{pmatrix} \frac{1}{3}x & 0 & 0 & 0 \\ 0 & -\frac{1}{2}+\frac{1}{3}x & 0 & 0 \\ 0 & 0 & -\frac{1}{2}+\frac{1}{3}x & 0 \\ 0 & 0 & 0 & \frac{1}{3}x \end{pmatrix} V_{L}^{D\dagger} = \begin{pmatrix} 0.0520 & -0.1093 & -0.0030 & 0.0032 \\ -0.1093 & -0.3972 & -0.0003 & 0.0147 \\ -0.0030 & -0.0003 & -0.4210 & -0.0304 \\ 0.0032 & 0.0147 & -0.0304 & 0.0749 \end{pmatrix}$$

- Since the diagonal elements are not the same, the Z boson mixes flavors
- There are 4 mixing matrices for U vs. D and L vs. R
- For the mass matrices that fit CKM data, most off-diagonal elements of the Z mixing matrices are very small, no appreciable FCNC
- $V_{f\bar{b}}^{L}, V_{f\bar{s}}^{L}, V_{f\bar{d}}^{L}, V_{d\bar{s}}^{A}$ are significant, non-negligible FCNC
- Non-negligible $V_{f\bar{b}}^{L}$ facilitates $b \to f \to c$ and could help with the 3 sigma difference between inclusive vs. exclusive measurements of CKM V_{cb}

Cancelling gauge anomalies

- In the Standard Model, quark gauge anomalies are cancelled by leptons
- In this model, quark gauge anomalies cancel among themselves
- A full theory should have additional right-handed leptons, so that gauge anomalies also cancel separately among leptons
- These right-handed leptons can include neutrinos needed for neutrino mixing (Twisted Superfields: arxiv:2112.04469)

"Twisted Superfields"

A theory with broken supersymmetry

- Supersymmetry helps solve the hierarchy problem (Why doesn't the Higgs Boson have a much larger mass?)
- But supersymmetry predicts a lot of new particles that are not observed, since no existing particles can be N=1 superpartners with each other: **HLS**
- Breaking supersymmetry can allow existing particles to be superpartners with each other: **quarks can be "superpartners" of the gauge bosons**
- 3 key features of supersymmetry
  - ~~Invariance to global superspace translations~~
  - Invariance to local superspace gauge transformations
  - Holomorphic superpotential

Twisted superfields break supersymmetry to allow this

Twisted Superfields for U(3)xU(3)

Real twisted superfield $V \square \begin{pmatrix} A_1^\mu & q_{VL}^\dagger, q_{VR} \\ q_{VL}, q_{VR}^\dagger & A_2^\mu \end{pmatrix}$

gluons are in A_1^μ, W^μ is in A_2^μ

Each q is a 3x3 matrix with 3 colors, and 3 flavors (1 up-type, 2 down-type)

Adjoint twisted superfield $\Phi \square \begin{pmatrix} \phi_1 & q_{\Phi R} \\ q_{\Phi L} & \phi_2 \end{pmatrix}$ $\Psi_{1F} \square \begin{pmatrix} \varphi_{1F} \\ l_{LF} \end{pmatrix}$ $\Psi_{2F} \square \begin{pmatrix} q_{\varphi RF} \\ \varphi_{2F} \end{pmatrix}$

And 3 flavors of fundamental and conjugate representation fields (1 u 2 d)

No gauge anomaly – like Supersymmetric QCD

Adding up quarks: $3u_L,\ 3u_R,\ 6d_L,\ 6d_R \rightarrow 3u_L,\ 3u_R,\ 4d_L,\ 4d_R$

Symmetry breaking to SU(3) x SU(2) x U(1)^2 gives unification-scale masses to 2 quarks, leaving the 7 quarks and the CKM matrices discussed earlier

Summary

- Hypothesis: A fourth down-type quark exists
  - It has a mass of ~2.8 GeV
  - The W boson connects this quark with the right-chiral component of the charm quark
  - The right-left combo generates FCNC with the Z boson
- The quark explains the mass, spin, parity, production and decay processes of most exotic hadrons
- Inclusive cross sections and precision electroweak measurements do not definitively rule it out
- Predictions have been made for where to find more mesons and baryons
- Many published papers have charts that could be evidence of the predictions
- In the theory, gauge anomalies cancel separately among quarks

Look for resonances in existing LHCb data?

In each decay below, look at invariant masses in parentheses:

- arxiv:1804.09617 $\Lambda_b^0 \to (\Lambda_c^+ p\bar{p})\pi^-,\ \Lambda_b^0 \to (\Lambda_c^+ \bar{p}\pi^-)p$
- arxiv:2011.13738 $\Lambda_b^0 \to (\Lambda_c^+ K^+ K^-)\pi^-,\ \Lambda_b^0 \to (\Lambda_c^+ K^- \pi^-)K^+$ (2nd: fsd baryon)
- arxiv:1109.6831 $\bar{B}^0 \to (D^+\pi^-\pi^-)\pi^+,\ \bar{B}_s^0 \to (D_s^+\pi^-\pi^-)\pi^+,\ B^- \to (D^0\pi^+\pi^-)\pi^-$
  $\bar{B}^0 \to (D^+\pi^-)\pi^-\pi^+,\ \bar{B}_s^0 \to (D_s^+\pi^-)\pi^-\pi^+,\ B^- \to (D^0\pi^-)\pi^+\pi^-$
  $\Lambda_b^0 \to (\Sigma_c^0\pi^+)\pi^-,\ \Lambda_b^0 \to (\Sigma_c^0\pi^-)\pi^+,\ \Lambda_b^0 \to (\Sigma_c^{++}\pi^-)\pi^-$
- Phys Rev Lett 108, 161801 $B^- \to (D^0\pi^+\pi^-)K^-,\ B^- \to (D^0K^-\pi^+)\pi^-$
- Phys Rev D87, 112009 $B^0 \to (\bar{D}^0K^+)\pi^-,\ B_s^0 \to (\bar{D}^0\pi^+)K^-$
- arxiv:1704.07581 $B^+ \to (D^{*-}K^+)\pi^+$
- arxiv:1803.06444 $B^+ \to (D^{(*)-}l^+\nu)\pi^+,\ B^0 \to (\bar{D}^{(*)0}l^+\nu)\pi^-$
- arxiv:1704.08497 $B^0 \text{ or } B_s^0 \to (p\bar{p}h^+)h^-,\ h \text{ is } K \text{ or } \pi$
  $B^0 \text{ or } B_s^0 \to (\bar{p}h^+h^-)p,\ h \text{ is } K \text{ or } \pi$

Questions?

Additional slides
- more experimentally testable predictions
- more possible evidence of these predictions in published papers
- non-SM explanations for some experiments (e.g. forward Z+c)

arxiv:2203.03007

More experimentally testable predictions
… and possible sightings

3872 Production and Decay

$$B^+ \to \chi_{c1}(3872)K^+ : \quad u\bar{b} \to u\bar{f} + Z \to u\bar{f} + d\bar{s} \to d\bar{f} + u\bar{s}$$

$$\chi_{c1}(3872) \to \bar{D}^0 D^0 \pi^0 : \quad d\bar{f} \to d\bar{c} + W^+ + g \to d\bar{c} + c\bar{d} + u\bar{u}$$

Decay from valence quarks exchanging a W boson

$$\chi_{c1}(3872) \to J/\psi\, \omega \text{ or } \bar{D}^0 D^{*0} : \quad d\bar{f} \underset{W}{\to} c\bar{c} + g \to c\bar{c} + u\bar{u}$$

Assume $\chi_{c1}(3872) \to J/\psi\, \pi^+\pi^-$ is mostly from $\chi_{c1}(3872) \to J/\psi(\omega \text{ or } \rho^0)$

Same decay mechanism as above W exchange.

If there is a $\chi_{c1}^+(3872) = u\bar{f}$, it cannot decay by W boson exchange.

This explains no significant signal in $\chi_{c1}^+(3872) \to J/\psi\, \pi^+\pi^0$

$\chi_{c1}^{+}(3872)$ Expected Production and Decay

$$B^{+} \to \chi_{c1}^{+}(3872)\pi^{0}: \quad u\bar{b} \to u\bar{f} + Z \to u\bar{f} + u\bar{u}$$

$$B^{0} \to \chi_{c1}^{+}(3872)\pi^{-}: \quad d\bar{b} \to d\bar{f} + Z \to d\bar{f} + u\bar{u} \to u\bar{f} + d\bar{u}$$

Expected decay

$$\chi_{c1}^{+}(3872) \to \bar{D}^{0}D^{0}\pi^{+} \text{ or } \bar{D}^{0}D^{+}\pi^{0}: \quad u\bar{f} \to u\bar{c} + W^{+} + g$$

If the $\bar{D}^{0}$ did a $\bar{D}^{0} \to D^{0}$ fluctuation and then decayed,

this would look just like decays seen for $T_{cc}^{+}(3875)$

Why not a much larger signal for $T_{cc}^{+}(3875) \to \bar{D}^{0}D^{0}\pi^{+}$?

Predicted 3872+ decays to 1 c quark

$$B^+ \to \chi_{c1}^+(3872)\pi^0 \qquad B^0 \to \chi_{c1}^+(3872)\pi^-$$

$$\chi_{c1}^+(3872) \to D_s^- K^+ \pi^+ : \quad u\bar{f} \to u\bar{c} + W^+ + g \to u\bar{c} + u\bar{d} + s\bar{s}$$

$$\chi_{c1}^+(3872) \to \bar{D}^0 \pi^0 \pi^+ : \quad u\bar{f} \to u\bar{c} + W^+ + g \to u\bar{c} + u\bar{d} + u\bar{u}$$

$$\chi_{c1}^+(3872) \to D^- \pi^+ \pi^+ : \quad u\bar{f} \to u\bar{c} + W^+ + g \to u\bar{c} + u\bar{d} + d\bar{d}$$

$\bar{B}^0 \to \chi_{c1}^-(3872)\pi^+$ with χ_{c1}^- having h.c. decays

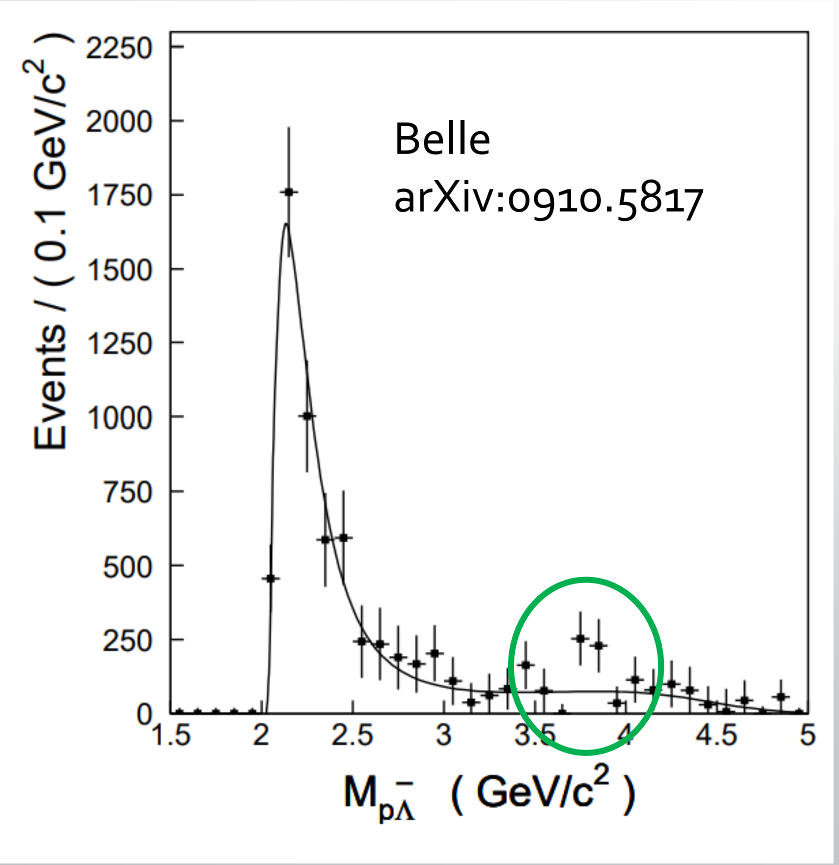
LHCb has measured $\bar{B}^0 \to D^+ \pi^- \pi^- \pi^+$ 1109.6831.pdf (arxiv.org)

Check invariant mass of $D^+ \pi^- \pi^-$?

A predicted decay to 3860+

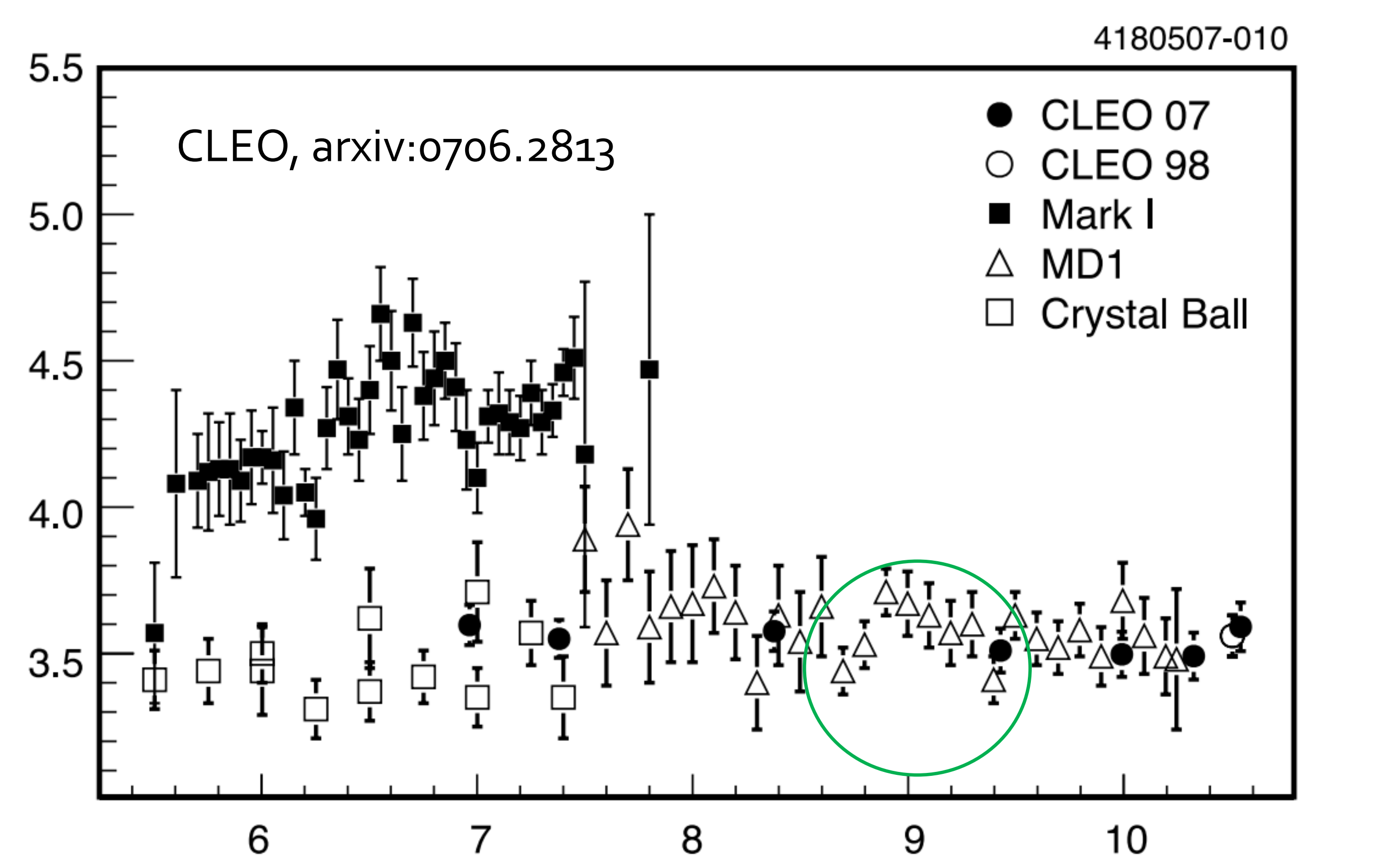
$$B^+ \to \chi_{c0}^+(3860)\pi^+\pi^- : \quad u\bar{b} \to u\bar{f} + Z + g \to u\bar{f} + d\bar{d}u\bar{u}$$

$$\chi_{c0}^+(3860) \to \bar{\Lambda}p : \quad u\bar{f} \to u\bar{s} + Z + g \to u\bar{s} + d\bar{d}u\bar{u}$$



All mass combinations of $\bar{\Lambda}p\pi^+\pi^-$ were studied, and there was no mention of any structure in any other mass combination.

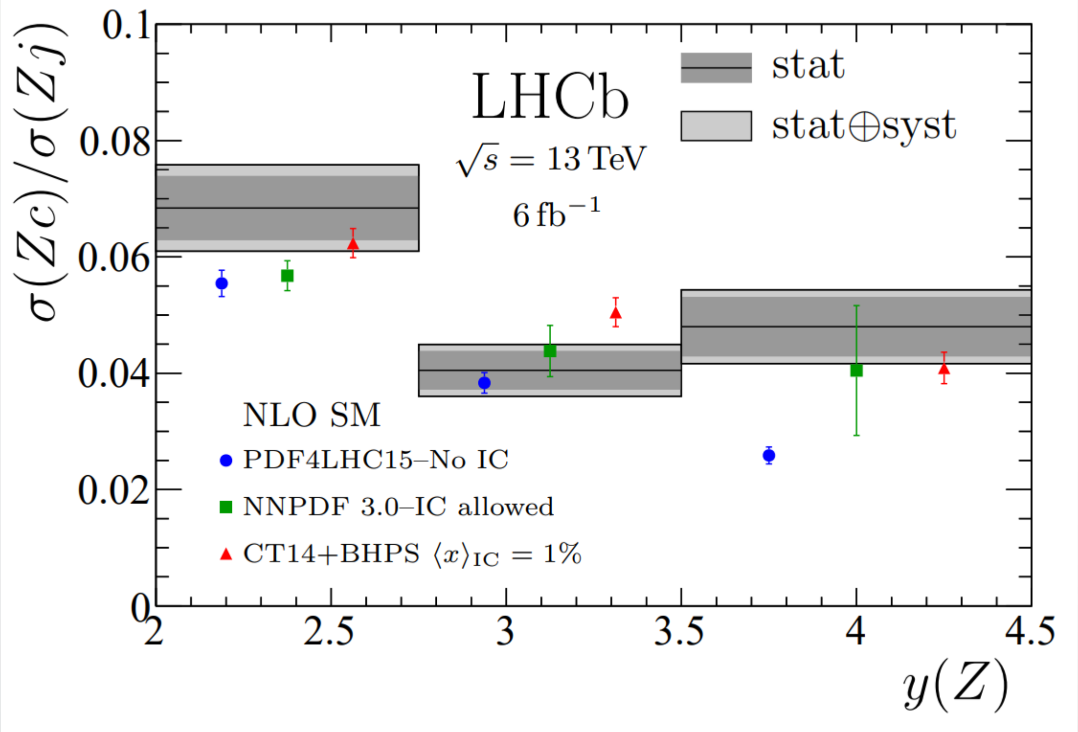
Look for f bbar mesons in e+e-?

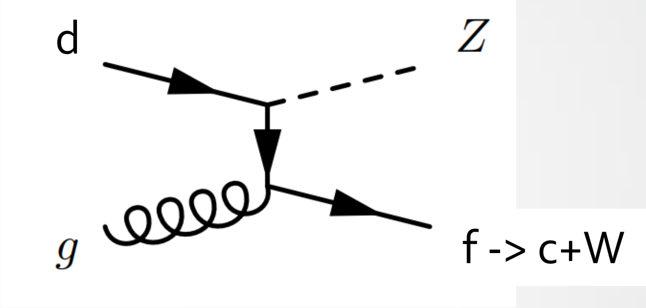


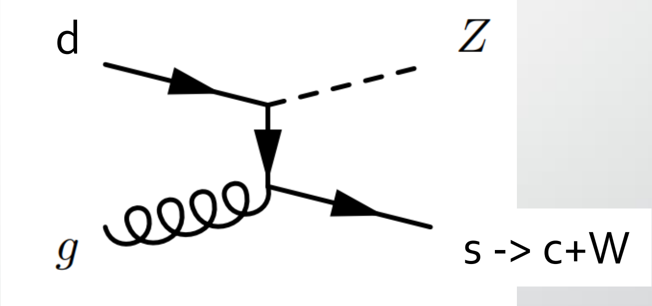
$$f\bar{b}\left(3^3S_1\,?\right) \to X\left(3250\right) + B_1\left(5721\right)$$

Alternative non-SM explanations for a few experiments

Forward Z + c jet data







Data only reproduced by Standard Model with PDFs that have significant intrinsic charm

This model has two additional ways that valence d quarks can produce Z + c jet.
It is possible this model could reduce or eliminate the need for intrinsic charm.

Suggestion: Measure forward Z + c jet in heavy ion collisions where there are more neutrons. This model would predict much more than intrinsic charm models

Charm abundance is larger than most event generators

science 2.0
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W And Charm - Twice As Many As Predicted

By Tommaso Dorigo | August 15th 2010 08:14 AM | Print | E-mail

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Tommaso Dorigo

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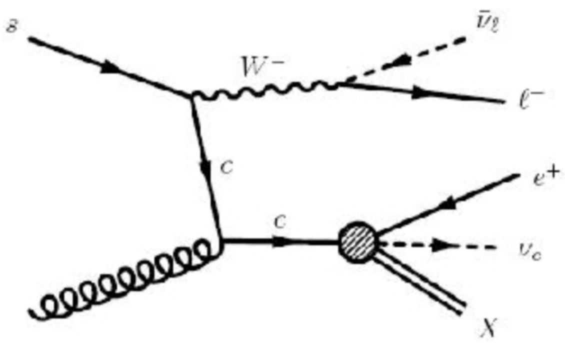
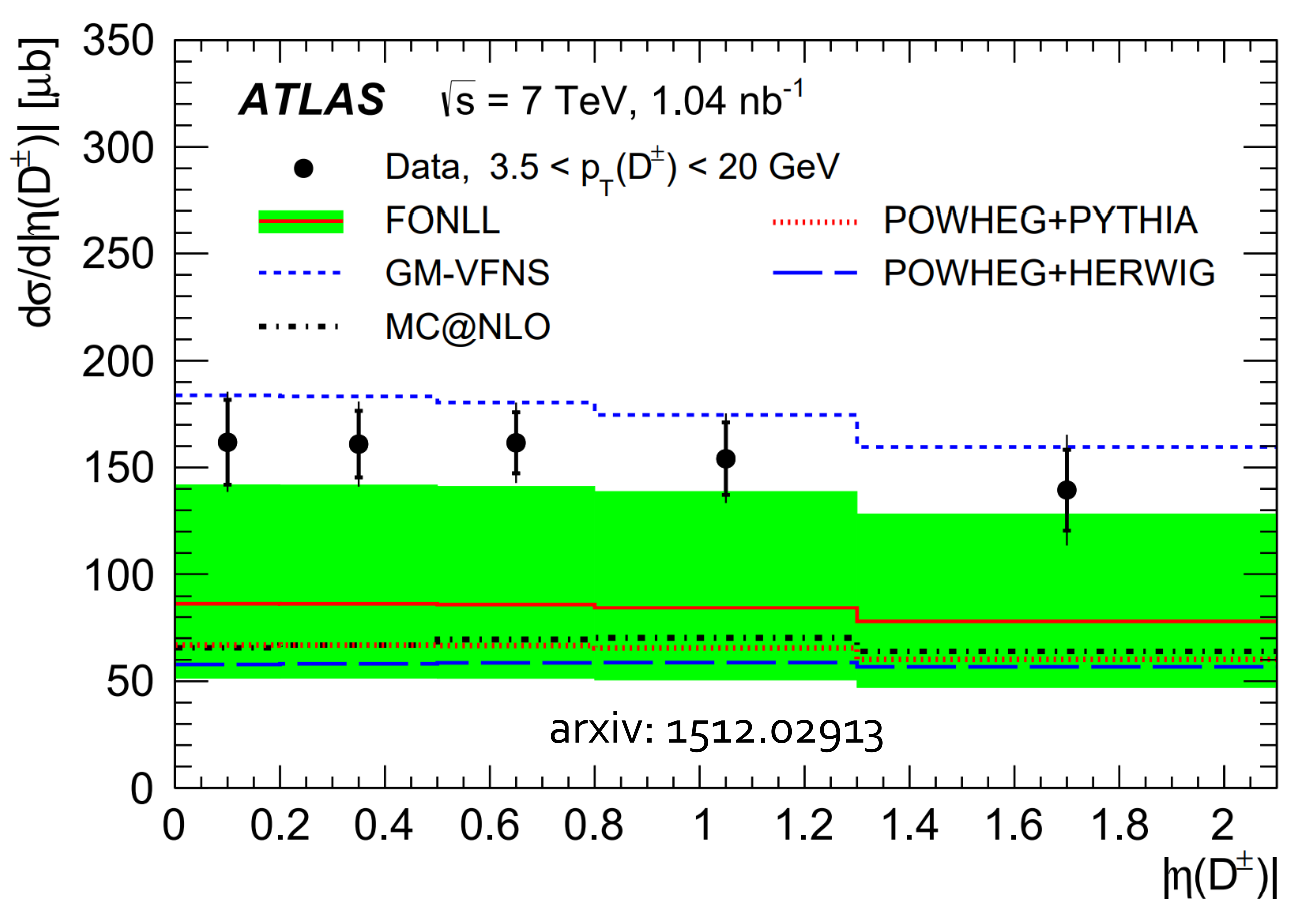
W bosons have been thoroughly studied at the Tevatron collider. Discovered by the UA1 experiment at the CERN SppS proton-antiproton collider in 1984, these particles have since been produced also in electron-positron collisions at LEP II (in pairs), and recently at the Large Hadron Collider. But the CDF and DZERO experiments have some of the most precise measurements of the physics of these particles, thanks to their now very large datasets.

A question that has always caused headaches in experimentalists and theorists concerning W production is how large a fraction of these particles is produced in association with heavy-flavour quarks -charm and bottom ones. These heavier brothers of up, down and strange quarks are not contained in the colliding protons and antiprotons in significant amounts, and their observation together with a W boson in the final state of a collision is the result of a very distinct class of Feynman diagrams. For charm the typical process is the one shown on the right, where charm originates from a strange quark in the proton being transmuted by the weak interaction vertex which produces the W.





The model's FCNC mechanisms could help explain the excess of charm seen in high energy collisions with intrinsic charm or doubling the strange content of the proton

Weak Radiative Hyperon Decay Puzzle

$$\Sigma^+ \to p\gamma$$

2009.12552.pdf (arxiv.org)

In hadronic field theory, the only allowed parity-violating interaction term is:

$$\left[\bar{\psi}_p i\sigma_{\mu\nu}\gamma_5\psi_{\Sigma^+} - \bar{\psi}_{\Sigma^+} i\sigma_{\mu\nu}\gamma_5\psi_p\right] q^\mu A^\nu$$

In the limit of flavor SU(3) being a good symmetry, this vanishes and these decays show little or no parity violation.

For baryon magnetic moments, flavor SU(3) has been shown to be a very good symmetry, but in $\Sigma^+ \to p\gamma$ decays, parity is strongly violated

Data implies: Flavor SU(3) is a good symmetry for the EM interaction
Flavor SU(3) is badly broken for the weak interaction.

In this model: the d and s quarks have the same electric charge
d and s quarks have opposite chirality of weak interactions

Papers on arXiv

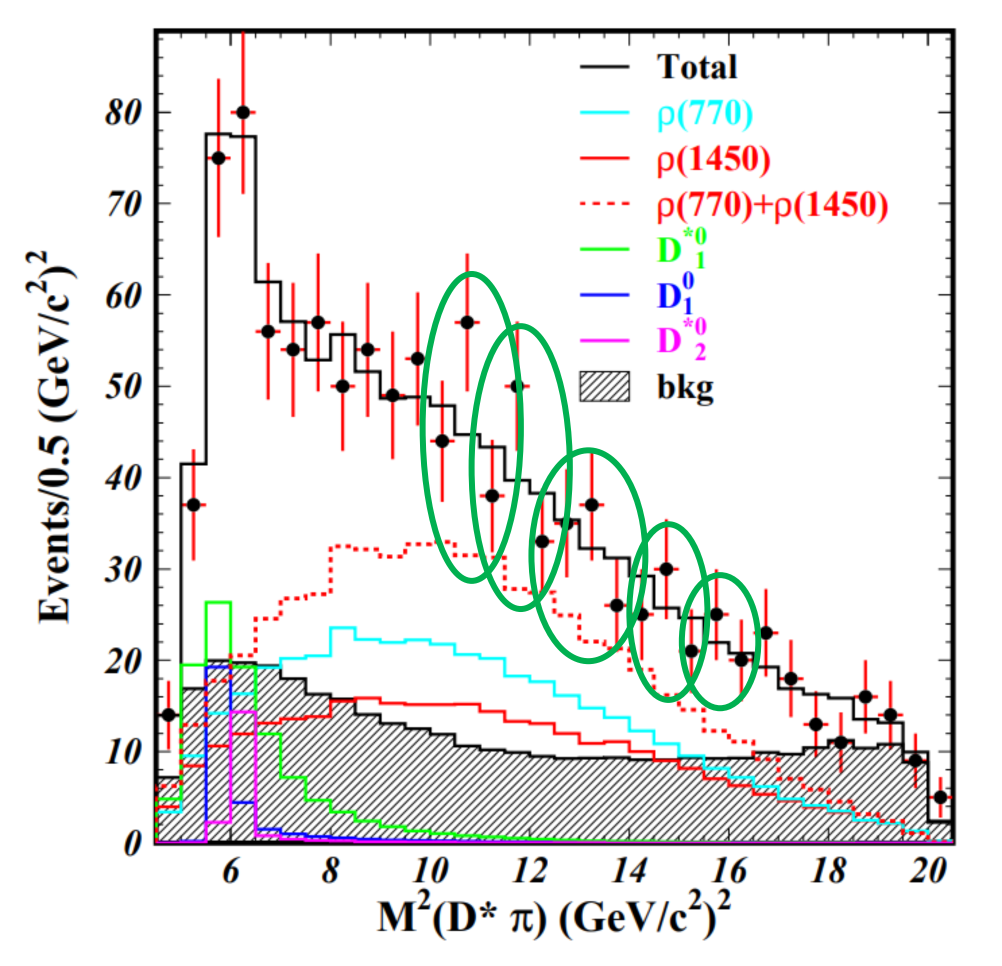
arxiv:2203.03007
arxiv:2112.04469

schapman@chapman.edu

Hints of Predicted f quark decays Invariant mass data

Hints of f meson resonances?

Belle, arxiv:1505.03362



$$\bar{B}^0 \to X^0 \omega : \quad X^0 \to D^{*+}\pi^-$$

$f\bar{d}$

3250

3350

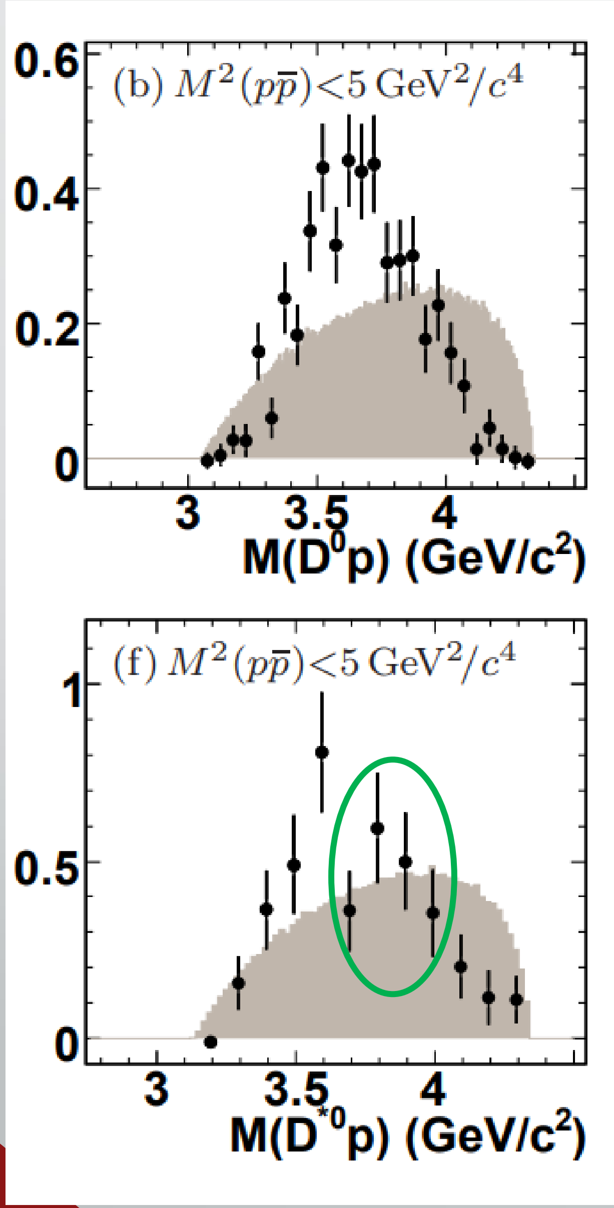
3860, the predicted 1^3P_0 meson

3985

$f\bar{s}$

3600 1^1S_0 meson ?

BaBar, arxiv:1111.4387



Hint of predicted Pc+(3870)?

$$\bar{B}^0 \to P_c^+ \bar{p} : \quad P_c^+ \to D^{*0} p$$

A larger hint of 3870 resonance is seen in D* events relative to D events

The decay $\frac{1}{2}^+ \to 0^{-+}\ \frac{1}{2}^+$ is suppressed relative to $\frac{1}{2}^+ \to 1^{--}\ \frac{1}{2}^+$

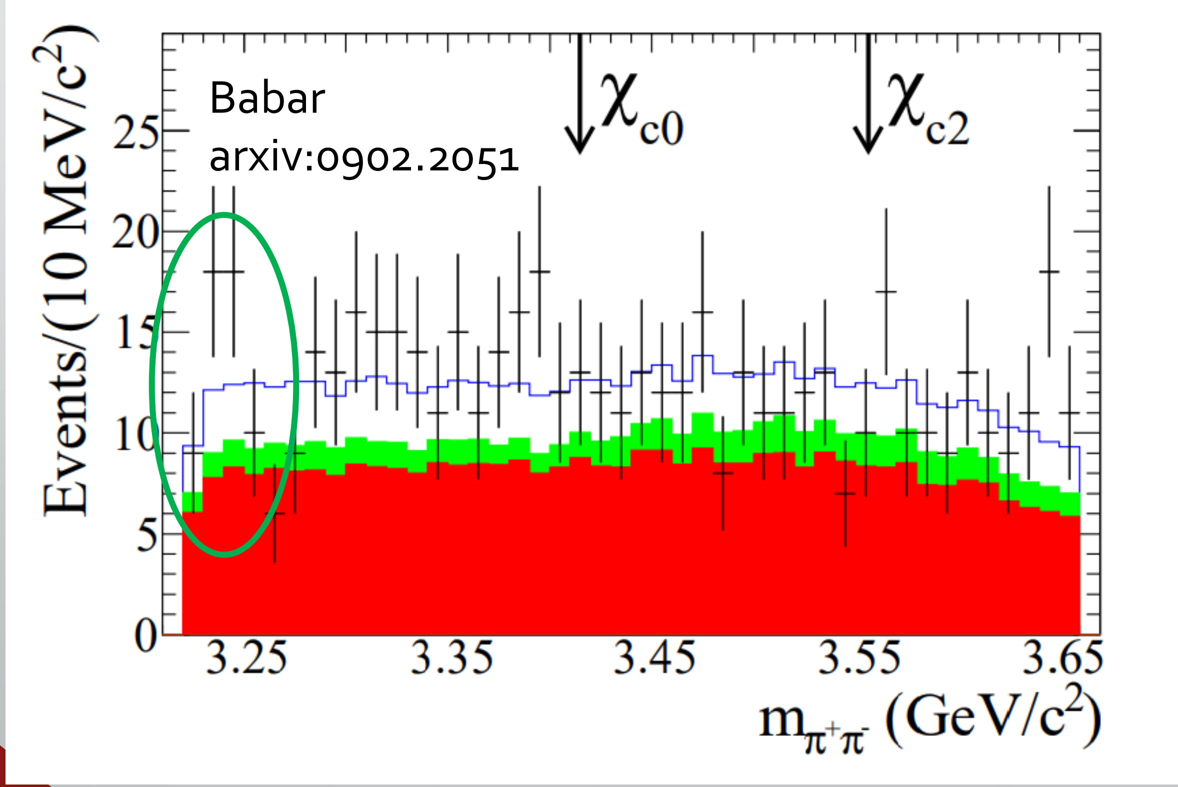
Hint of 3250?

In this model $X(3250)$ is mapped to the 1^1S_0 $J^{PC}=0^{-+}$ meson of $d\bar{f}$

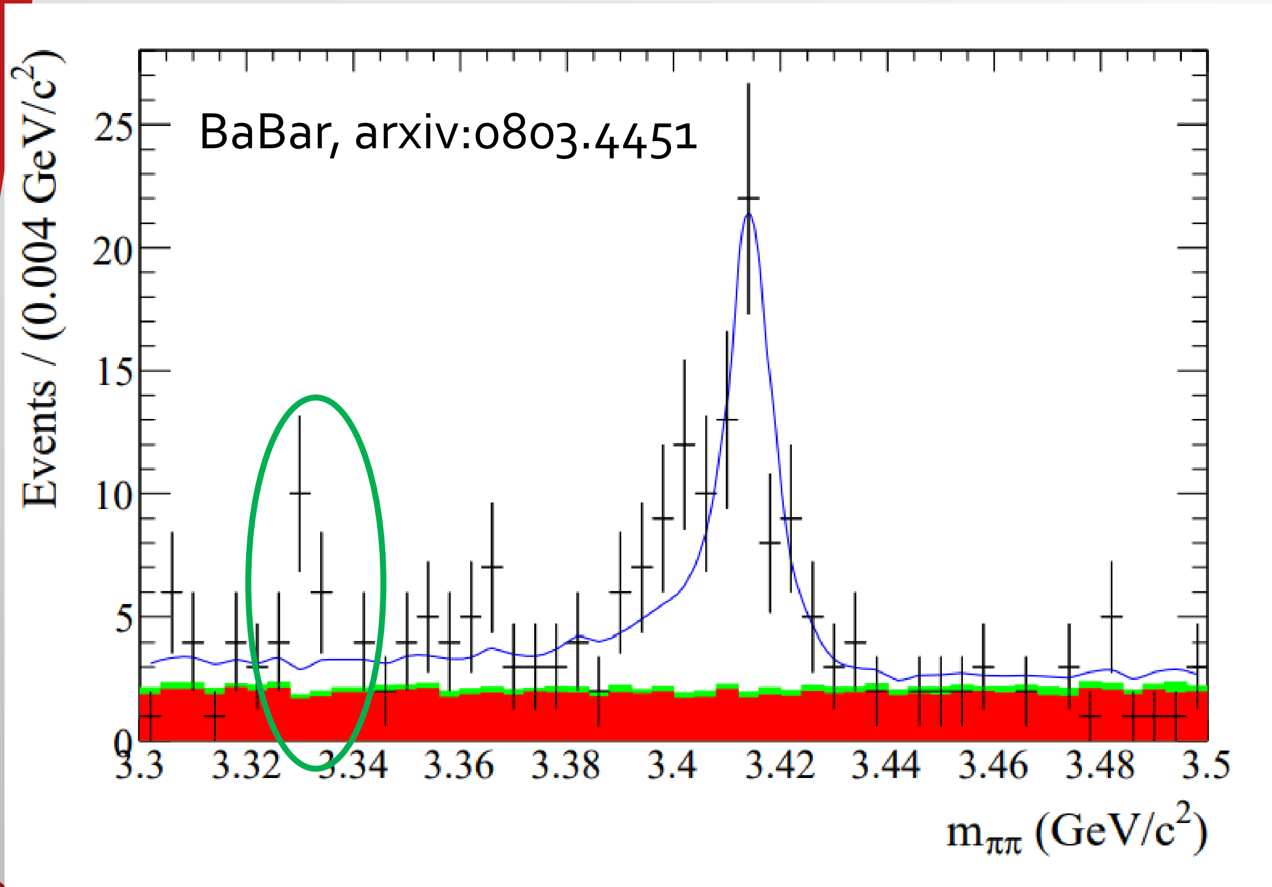
$$B^+ \to X(3250)\pi^+ : \quad u\bar{b} \to u\bar{f} + Z \to u\bar{f} + d\bar{d} \to d\bar{f} + u\bar{d}$$

$$X(3250) \to \pi^+\pi^- : \quad d\bar{f} \to d\bar{u} + W^+ \to d\bar{u} + u\bar{d}$$

$$|V_{uf}| \sim 0.009$$



Hint of 3350?



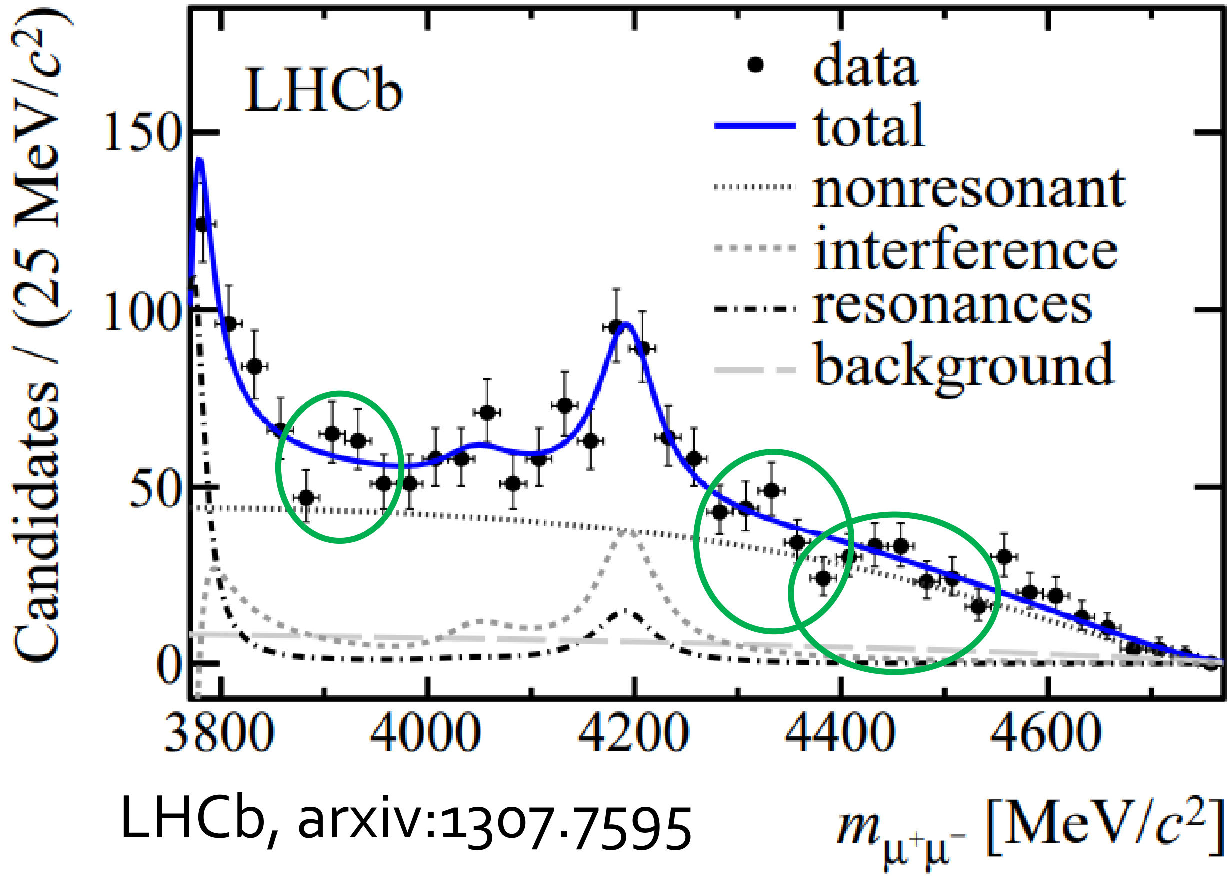
$$B^- \to XK^- : X \to \pi^+\pi^-$$

Even larger invariant mass in K- pi+? Not shown in that range in the paper.

Hints of $s\bar{f}$ mesons?

$$B^+ \to XK^+ : \; u\bar{b} \to u\bar{f} + Z \to u\bar{f} + s\bar{s} \to s\bar{f} + u\bar{s}$$

$$X \to \mu^+\mu^- : \; s\bar{f} \to Z \to \mu^+\mu^-$$



LHCb, arxiv:1307.7595

3960?

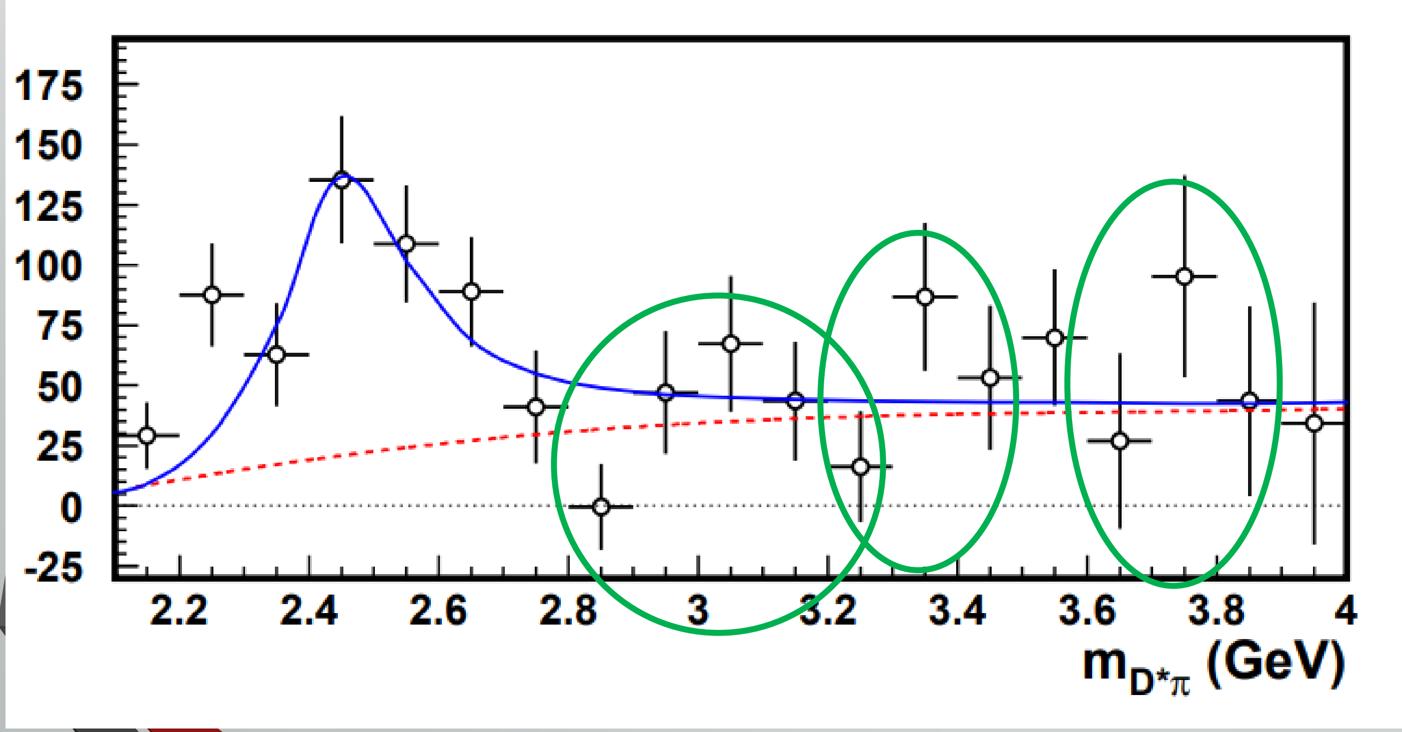
4360?

4407?

Hints of 3250, 3350 and 3860?

BaBar, hep-ex/0604009

$$\bar{B}^0 \to D^{*+}\omega\pi^-$$

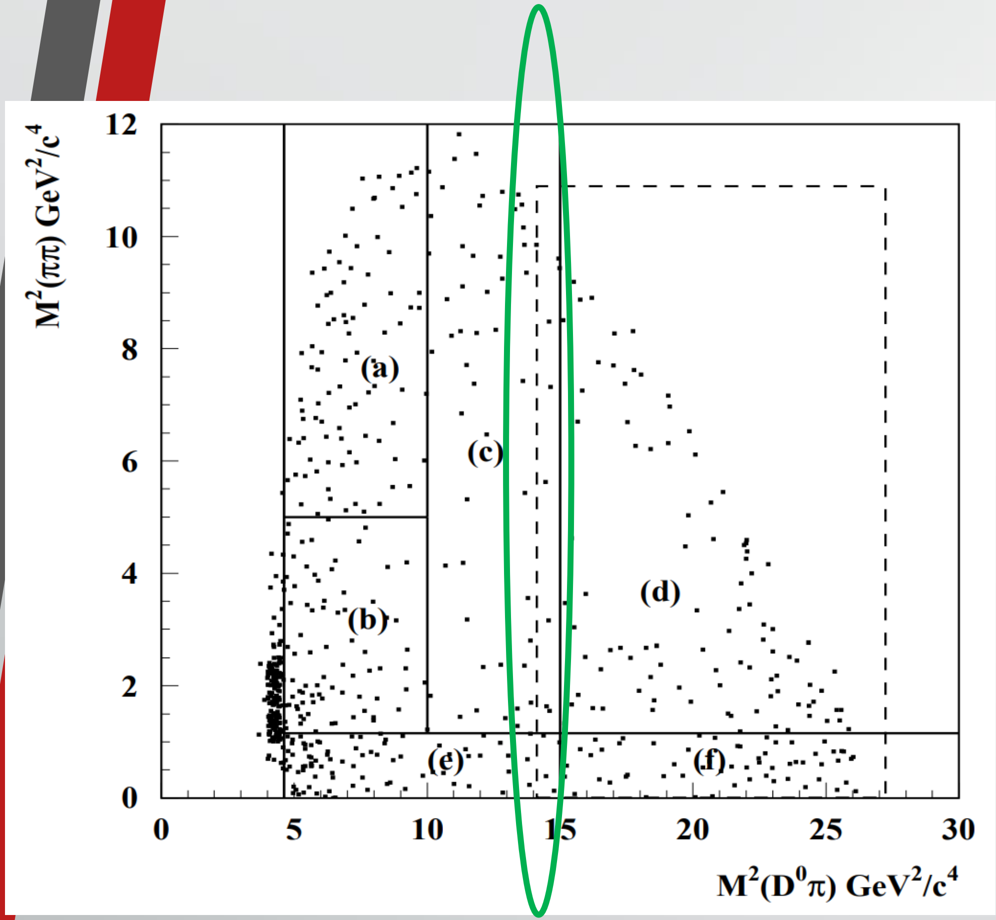


The peaks are consistent with

$$\bar{B}^0 \to X\omega : X \to D^{*+}\pi^-(\gamma)$$

for 3250, 3350, and 3860, but where 3250 and 3860 decays also include a soft photon

Hint of charged X(3860) 1^3P_0 meson?



Belle 2002, arxiv:hep-ex/0211022

looked at $\bar{B}^0 \rightarrow D^0\pi^+\pi^-$ and also with D*o

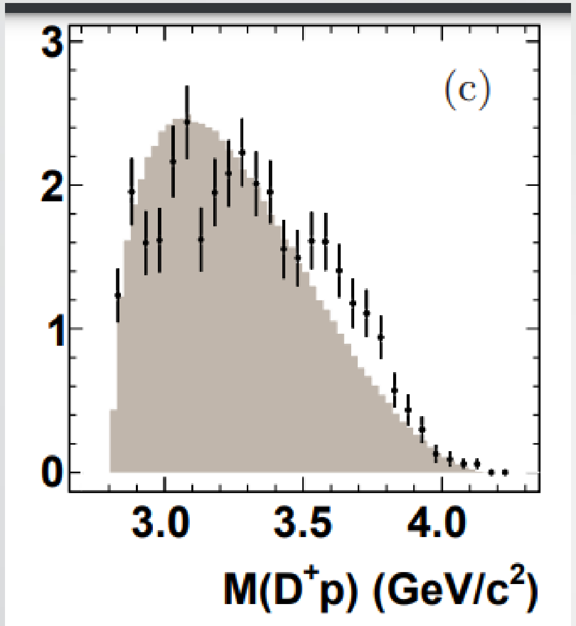
A meson with an f quark cannot have positive charge, so cannot decay to $D^0\pi^+$

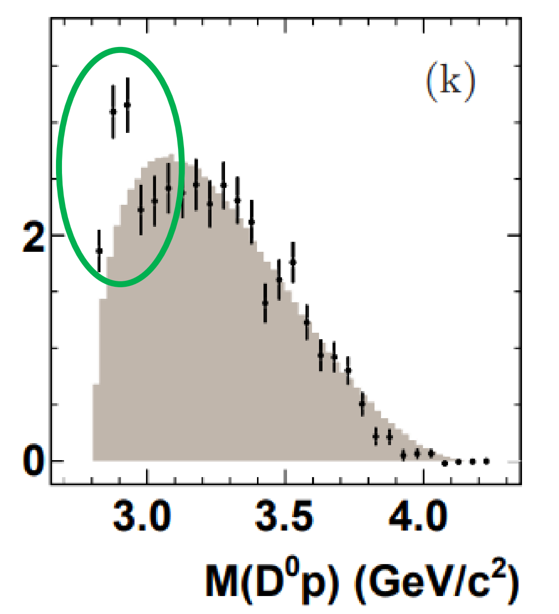
But $f\bar{u} \rightarrow D^0\pi^-$ is OK

Squinting, it looks like there might be more dots where needed for $D^0\pi^-$ to make a 3860
… and maybe to make a 3350.

Hints of Predicted f quark decays
Partial Invariant mass data

BaBar, arxiv:1111.4387





Hint of X(3860) 1^3P_0 state?

$\bar{B}^0 \to D^+ p\bar{p}\pi^-$

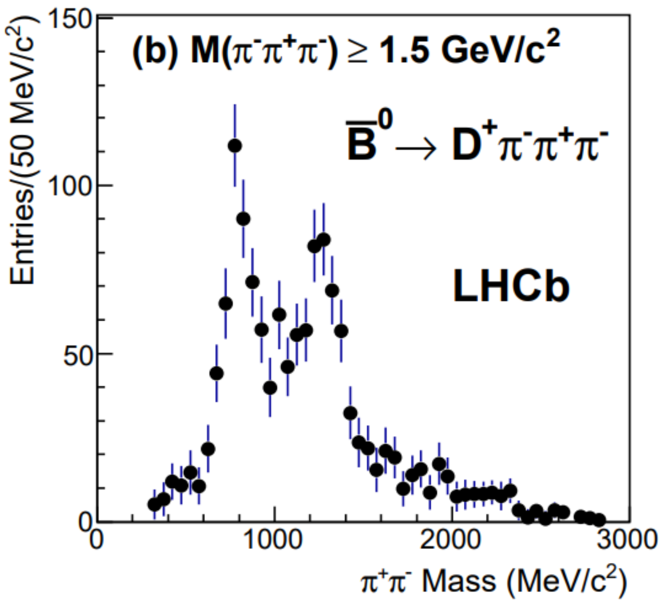
$B^- \to X\pi^- : \quad X \to D^0 p\bar{p}$

A meson with an f cannot have positive charge, so cannot decay to $D^+ p\bar{p}$

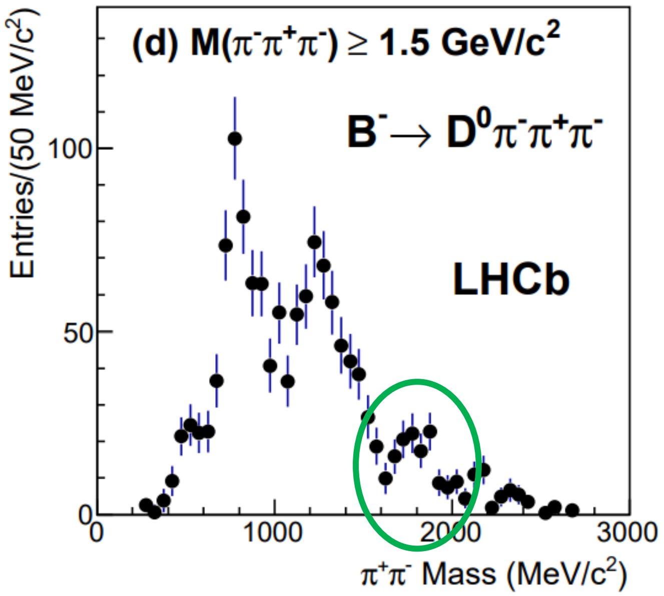
But $f\bar{d} \to D^0 p\bar{p}$ is OK

A bump in the bottom but not in the top graph is consistent with the above X(3860) allowed decays

$D^0 p\bar{p}$ invariant mass would be interesting



LHCb, arxiv:1109.6831



Hint of X(3860) 1^3P_0 state?

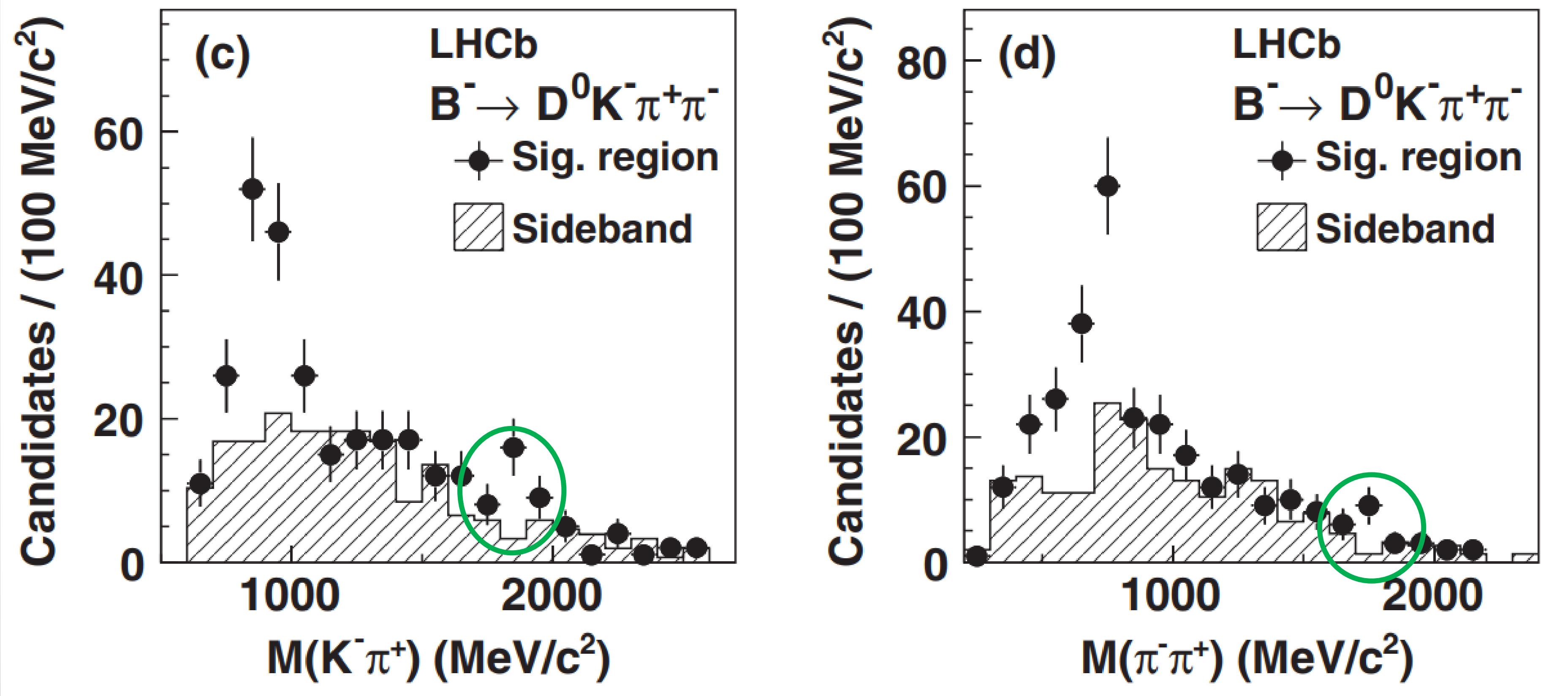
A meson with an f cannot have positive charge, so cannot decay to $D^+\pi^+\pi^-$

But $f\bar{d} \to D^0\pi^+\pi^-$ is OK

A bump in the bottom but not in the top graph is consistent with the above X(3860) allowed decays

$D^0\pi^+\pi^-$ invariant mass would be interesting

Hint of X(3860) 1^3P_0 state?

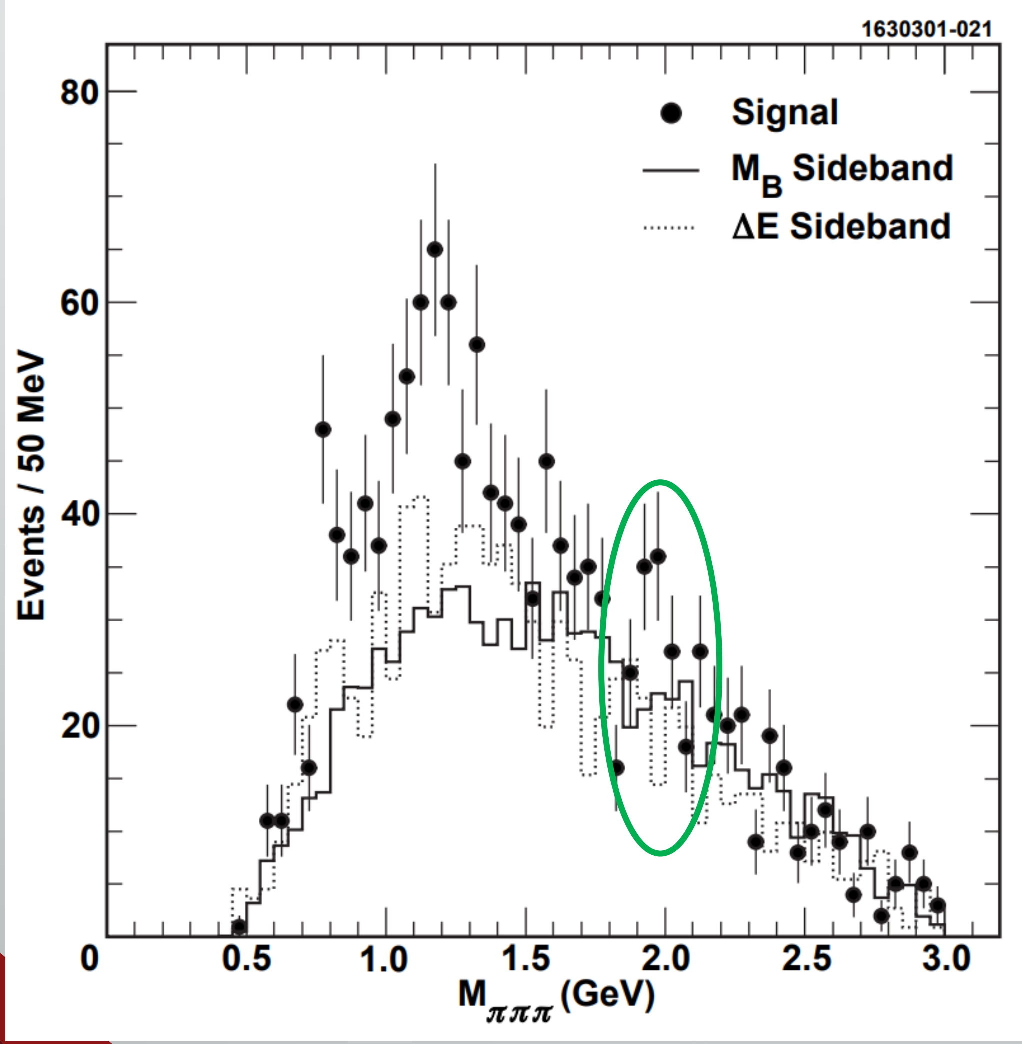


LHCb, 10.1103/PhysRevLett.108.161801

$D^0K^-\pi^+, \ D^0\pi^-\pi^+$ invariant masses would be interesting

Hint of 4020?

CLEO, hep-ex/0103021



$$B^- \to D^{*0}\omega\pi^-$$

The invariant mass is of the 3 pions that make the omega

The omega peak below 2 GeV could be consistent with

$$B^- \to X(4020)\pi^- : X(4020) \to D^{*0}\omega$$

$D^{*0}\omega$

invariant mass would be interesting