Heavy baryons in lattice QCD

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and
University of Arizona

Evidence for $\Delta S = -\Delta Q$ Currents or Charmed-Baryon Production by Neutrinos*

E. G. Cazzoli, A. M. Cnops,† P. L. Connolly, R. I. Louttit, M. J. Murtagh, R. B. Palmer, N. P. Samios, T. T. Tso, and H. H. Williams‡
Brookhaven National Laboratory, Upton, New York 11973
(Received 17 March 1975)

We report on the production by neutrinos of an event with negative strangeness. In an exposure of the Brookhaven National Laboratory 7-ft cryogenic bubble chamber to a broad-band neutrino beam 335 events were observed, one of which fits the reaction $\nu p \to \mu^- \Lambda^0 \pi^+ \pi^+ \pi^+ \pi^-$. Alternative explanations are examined and none found with a probability greater than 3×10^{-5}. The event thus represents a large violation of the $\Delta S = \Delta Q$ rule or alternatively the production and decay of a charmed baryon state. The most plausible mass for this state is found to be 2426 ± 12 MeV.

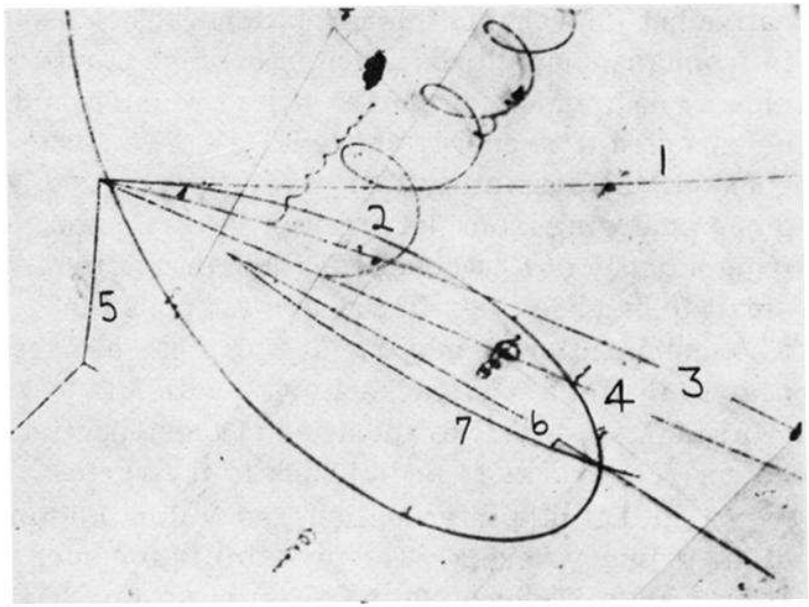
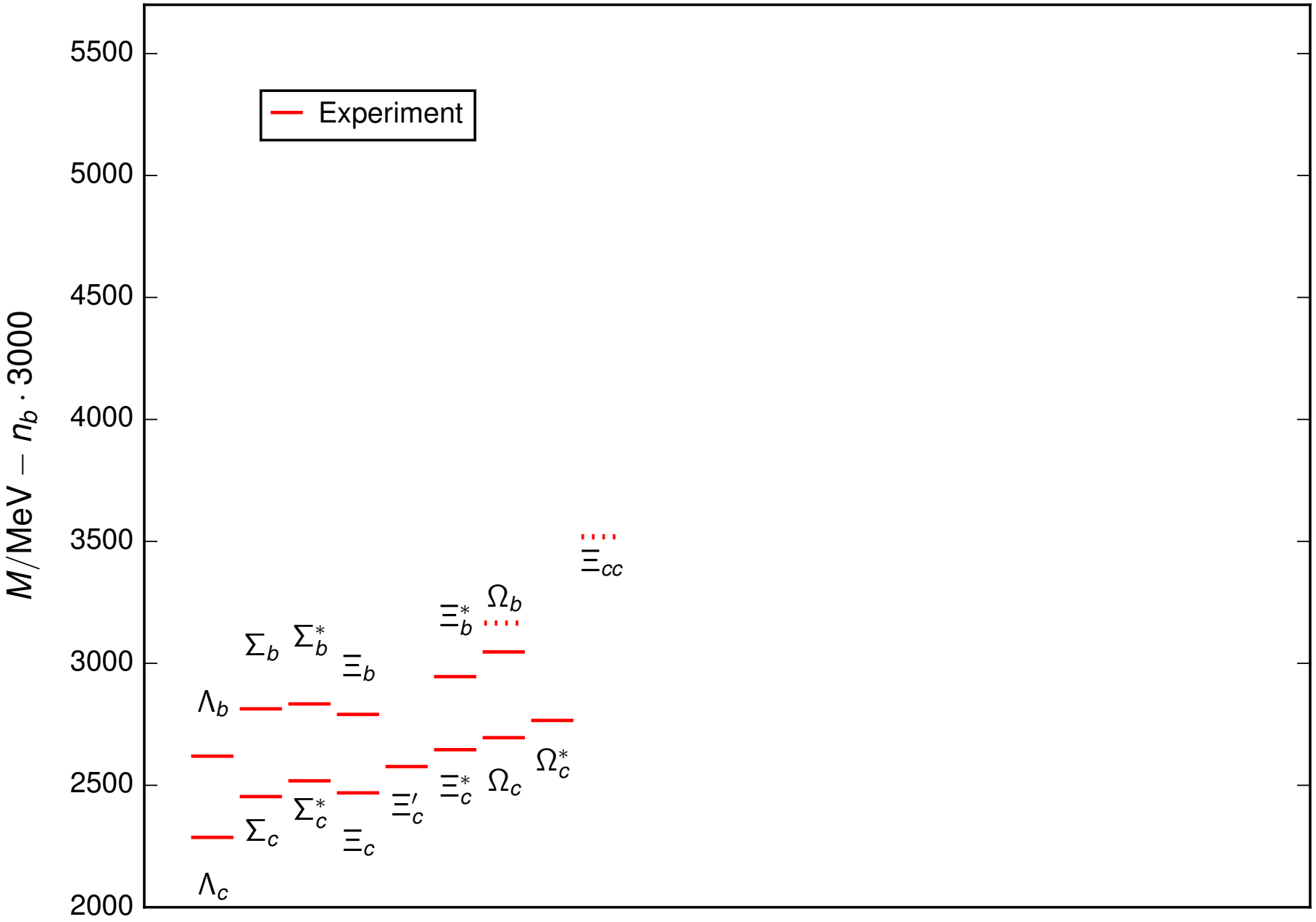
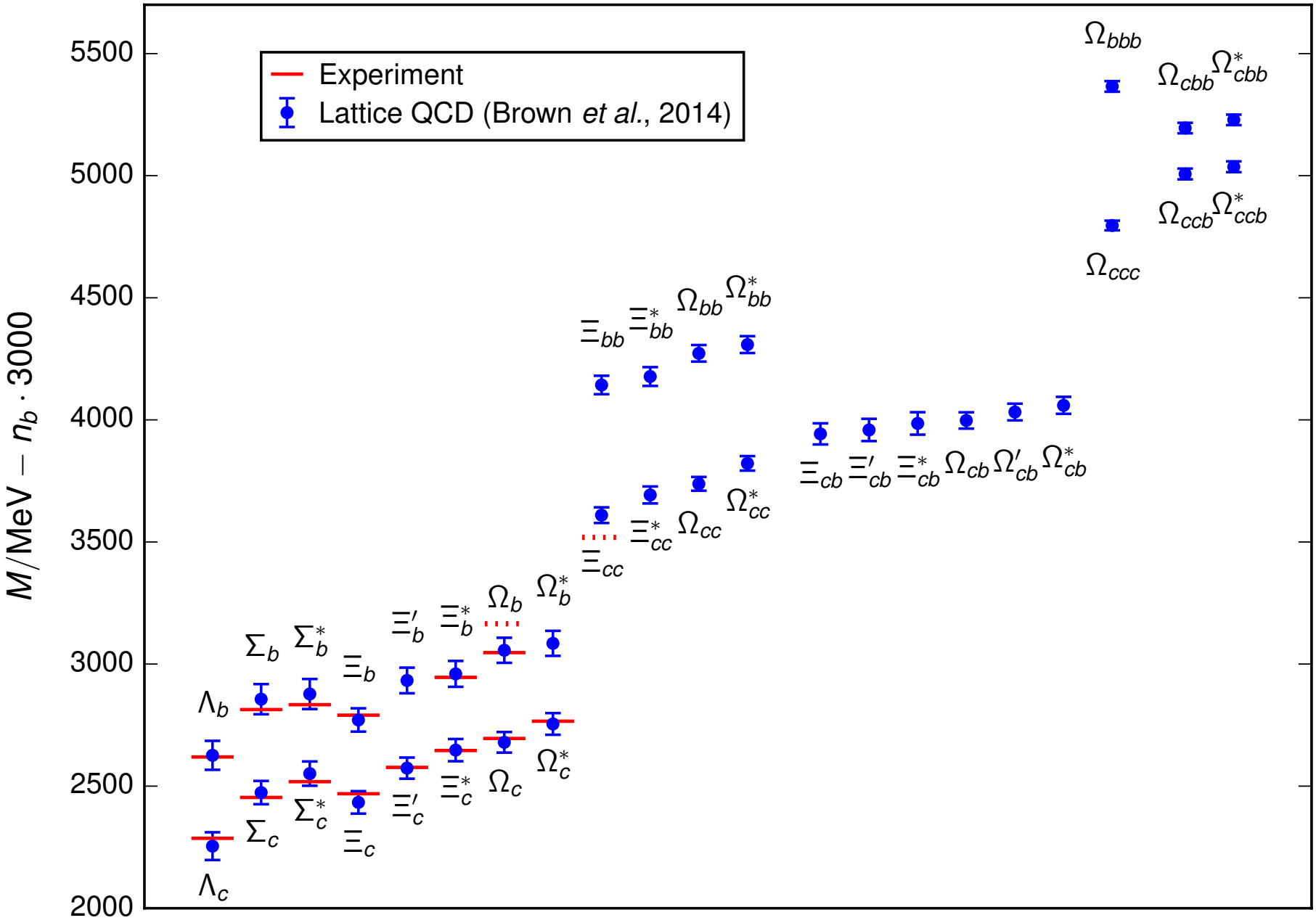


FIG. 1. View of event as seen in camera 3.


Experiment
$M/\mathrm{MeV} - n_b \cdot 3000$
5500
5000
4500
4000
3500
3000
2500
2000
Λ_c
Λ_b
Σ_c
Σ_b
Σ_c^*
Σ_b^*
Ξ_c
Ξ_b
Ξ_c'
Ξ_c^*
Ξ_b^*
Ω_c
Ω_b
Ω_c^*
Ξ_{cc}



[Brown, Detmold, Meinel, Orginos, arXiv:1409.0497]

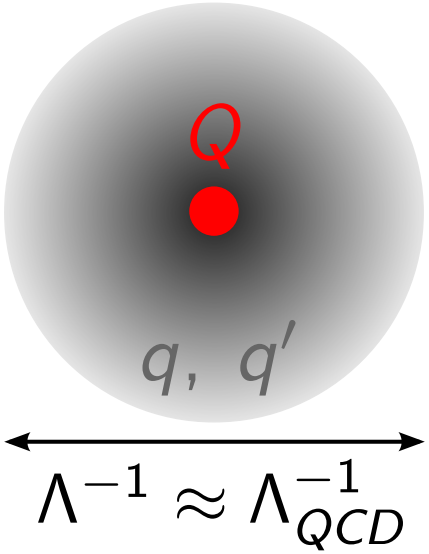
1 Heavy-quark symmetries

2 Spectroscopy

3 Strong decays

4 Weak decays

Singly heavy baryons



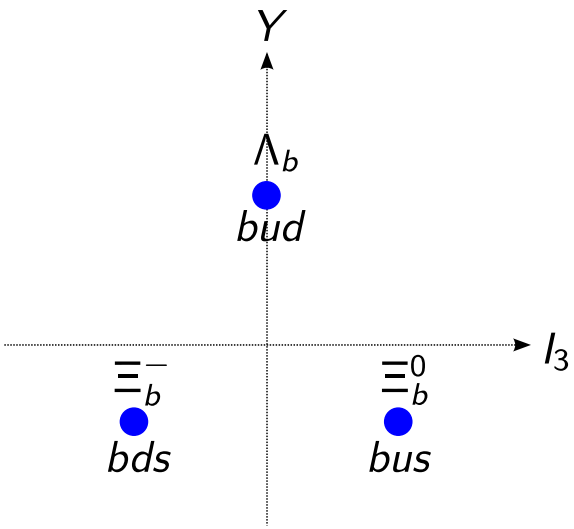
In the limit $m_Q \to \infty$

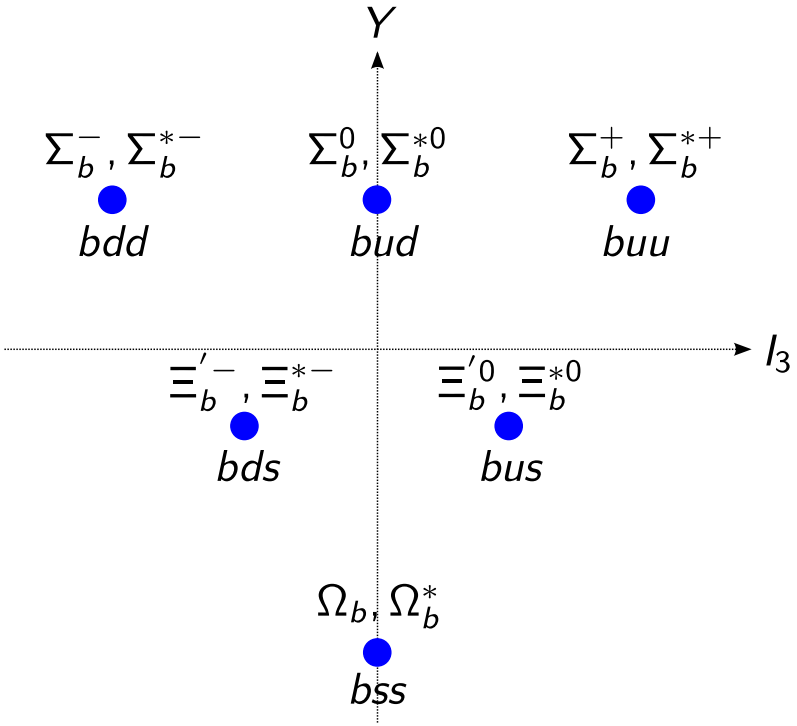
- J_{light} becomes conserved quantum number
- Interaction with heavy-quark spin vanishes

Expect corrections of order Λ/m_Q

Singly heavy baryons

Low-lying positive-parity states: $\mathbf{3} \otimes \mathbf{3} = \overline{\mathbf{3}}_A \oplus \mathbf{6}_S$

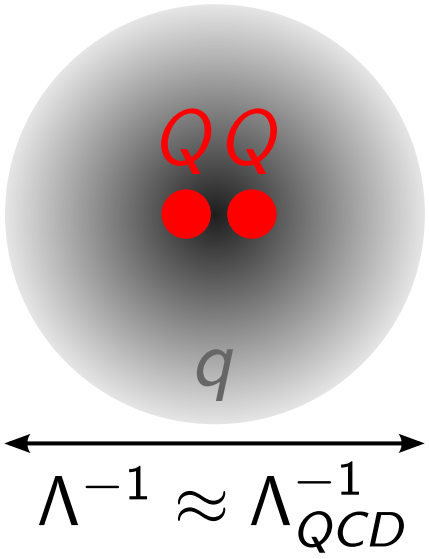




$J_{\text{light}} = 0, \;\; J^P = \frac{1}{2}^+$

$J_{\text{light}} = 1, \;\; J^P = \frac{1}{2}^+, \frac{3}{2}^+$

Doubly-heavy baryons

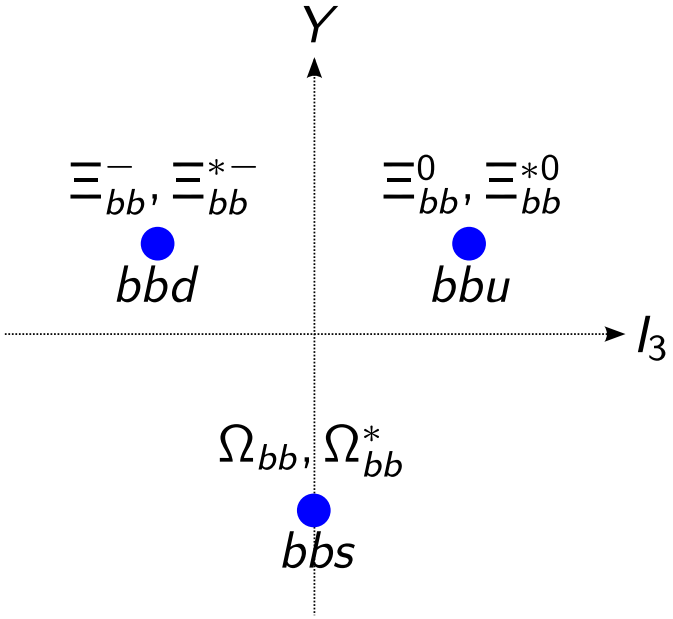


In the limit $m_Q \to \infty$

- The two heavy quarks form a point-like diquark ($\bar{\mathbf{3}}$ color source)
- J_{light} becomes conserved quantum number
- Interaction with heavy-diquark spin vanishes
- Dynamics of light degrees of freedom is the same as in a heavy-light meson [Savage and Wise, PLB 248, 177 (1990)]

Doubly-heavy baryons: equal-flavor case

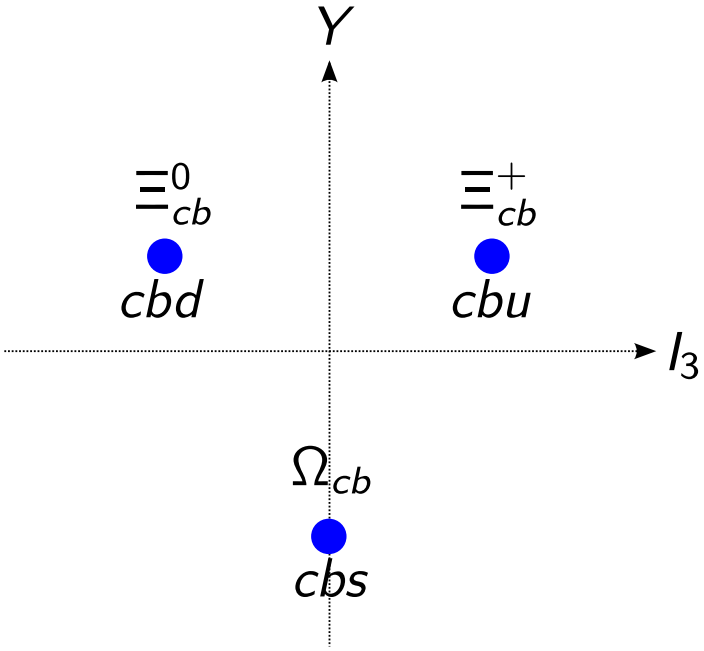
Low-lying positive-parity states: heavy diquark has $L = 0$; antisymmetric color wave function $\rightarrow$ Pauli principle implies symmetric spin wave function $\rightarrow$ $J_{\text{heavy}} = 1$

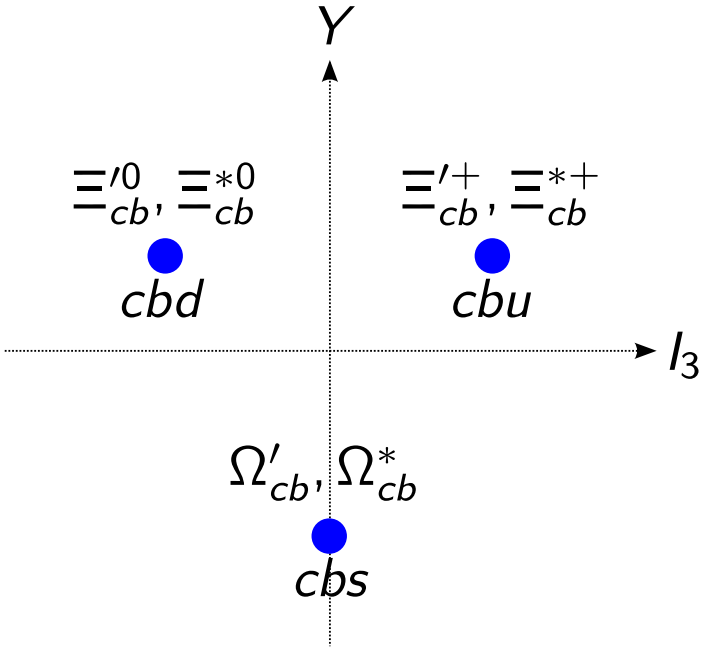


$$J_{\text{light}} = \tfrac{1}{2}, \quad J^P = \tfrac{1}{2}^+, \tfrac{3}{2}^+$$

Doubly-heavy baryons: mixed-flavor case

Now, $J_{\text{heavy}} = 0$ and $J_{\text{heavy}} = 1$ both possible with $L = 0$.

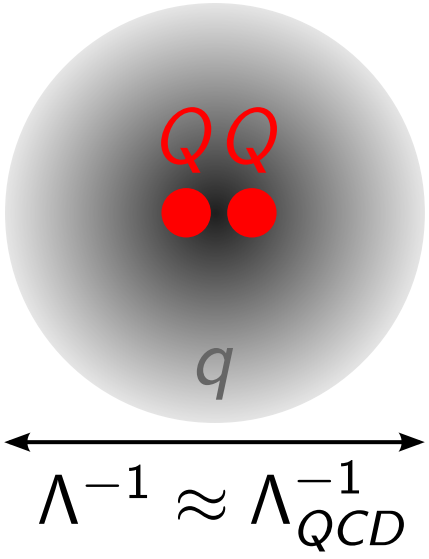




$J_{\text{heavy}} = 0, \;\; J_{\text{light}} = \frac{1}{2}, \;\; J^P = \frac{1}{2}^+$

$J_{\text{heavy}} = 1, \;\; J_{\text{light}} = \frac{1}{2}, \;\; J^P = \frac{1}{2}^+, \frac{3}{2}^+$

Doubly-heavy baryons: equal-flavor case



Prediction for hyperfine splittings in the limit $m_Q \to \infty$:

$$\frac{M(\Xi^*_{QQ}) - M(\Xi_{QQ})}{M(P^*_Q) - M(P_Q)} \to \frac{3}{4}$$

[Brambilla, Vairo, Rosch, PRD 72, 034021 (2005)]

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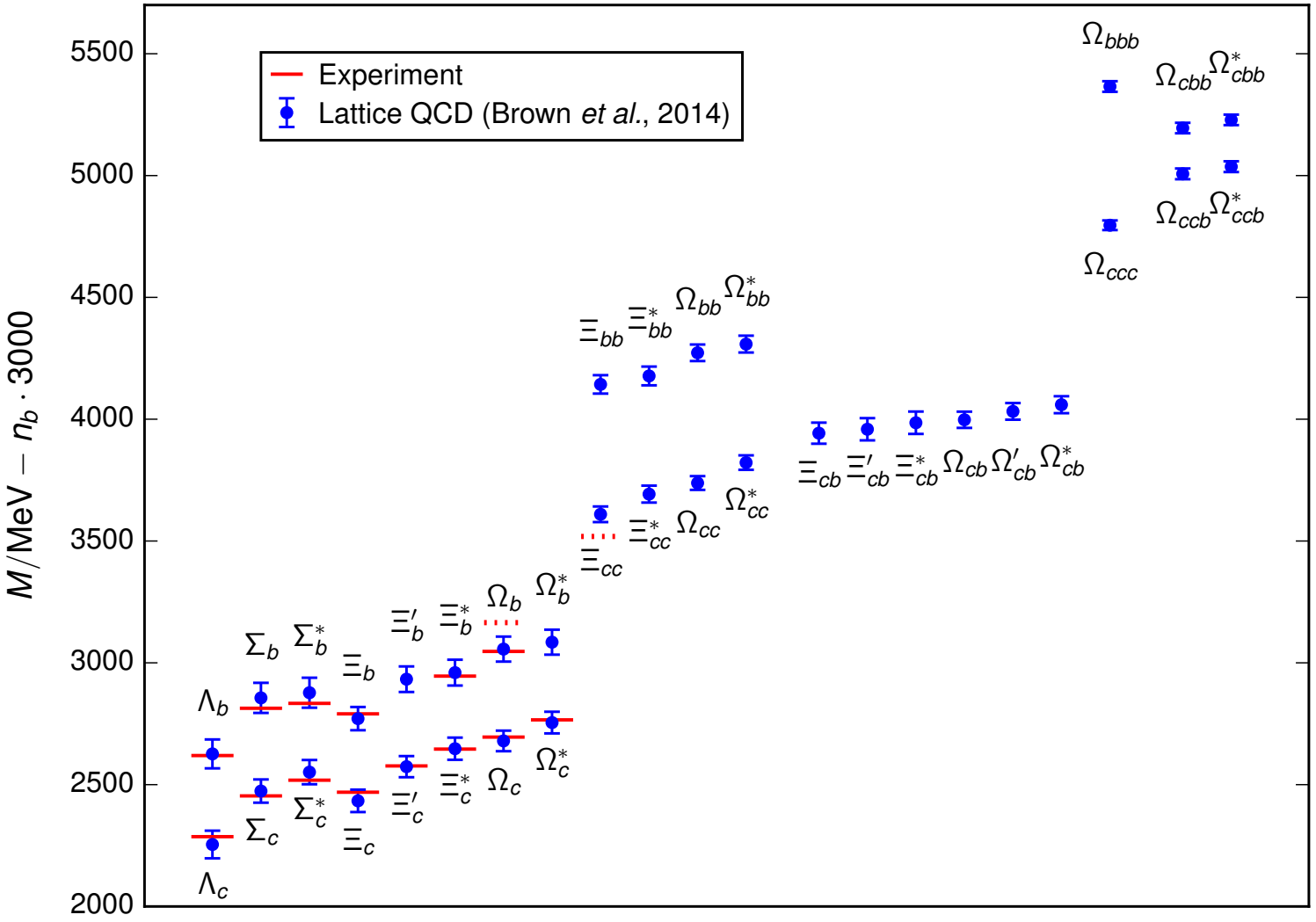


[Brown, Detmold, Meinel, Orginos, arXiv:1409.0497]

First dynamical lattice QCD calculation that includes mixed charm-bottom baryons.

Actions and parameters

- u, d, s: domain-wall fermions

  [Kaplan, PLB 288, 342 (1992); Furman and Shamir, NPB 439, 54 (1995)]

- c: relativistic heavy-quark action

  [El-Khadra, Kronfeld, Mackenzie, PRD 55, 3933 (1997)]

- b: lattice NRQCD

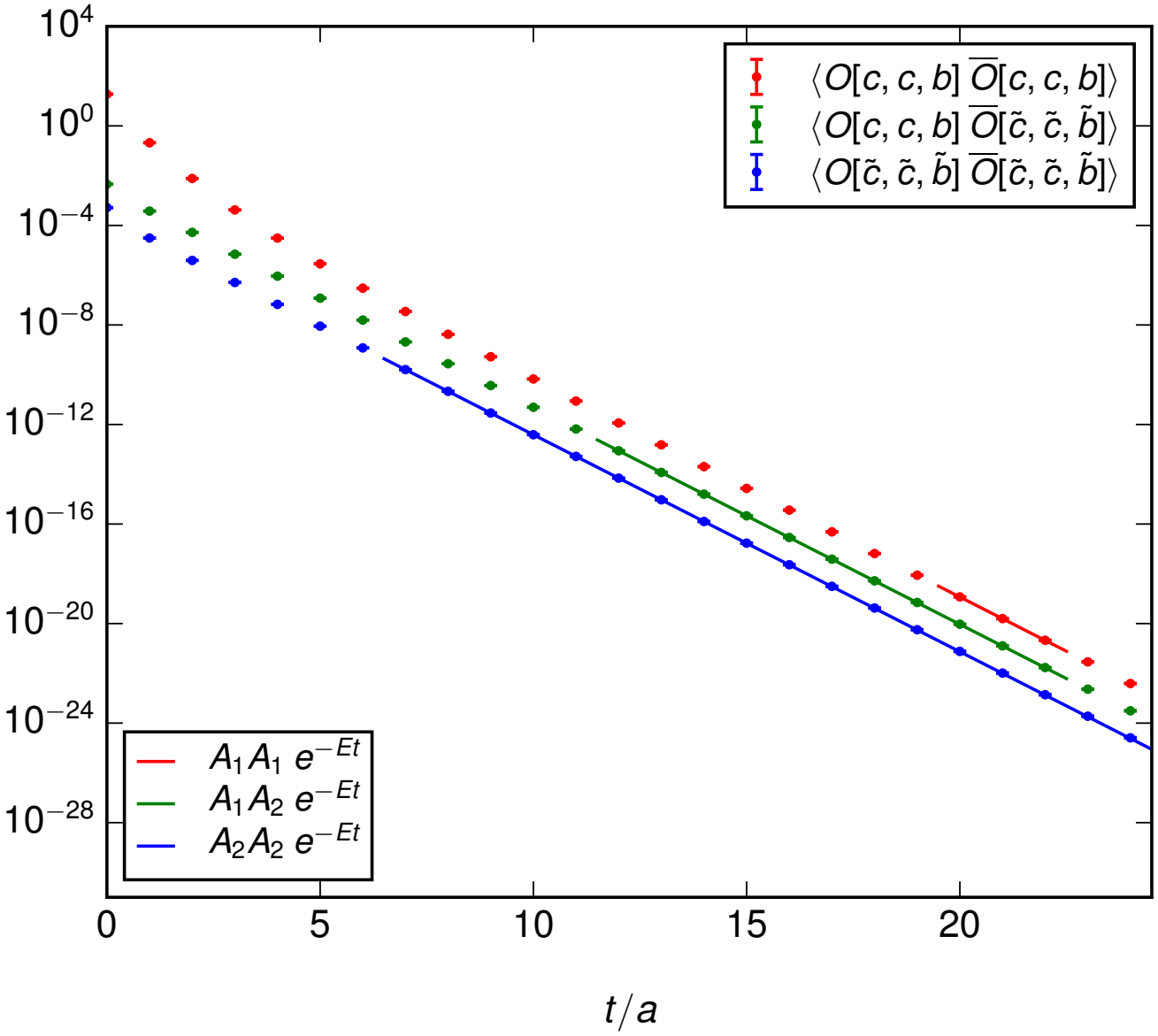
  [Lepage et al., PRD 46, 4052 (1992)]

- Gauge field configurations generated by RBC/UKQCD

  [Aoki et al. (RBC/UKQCD), PRD 83, 074508 (2011)]

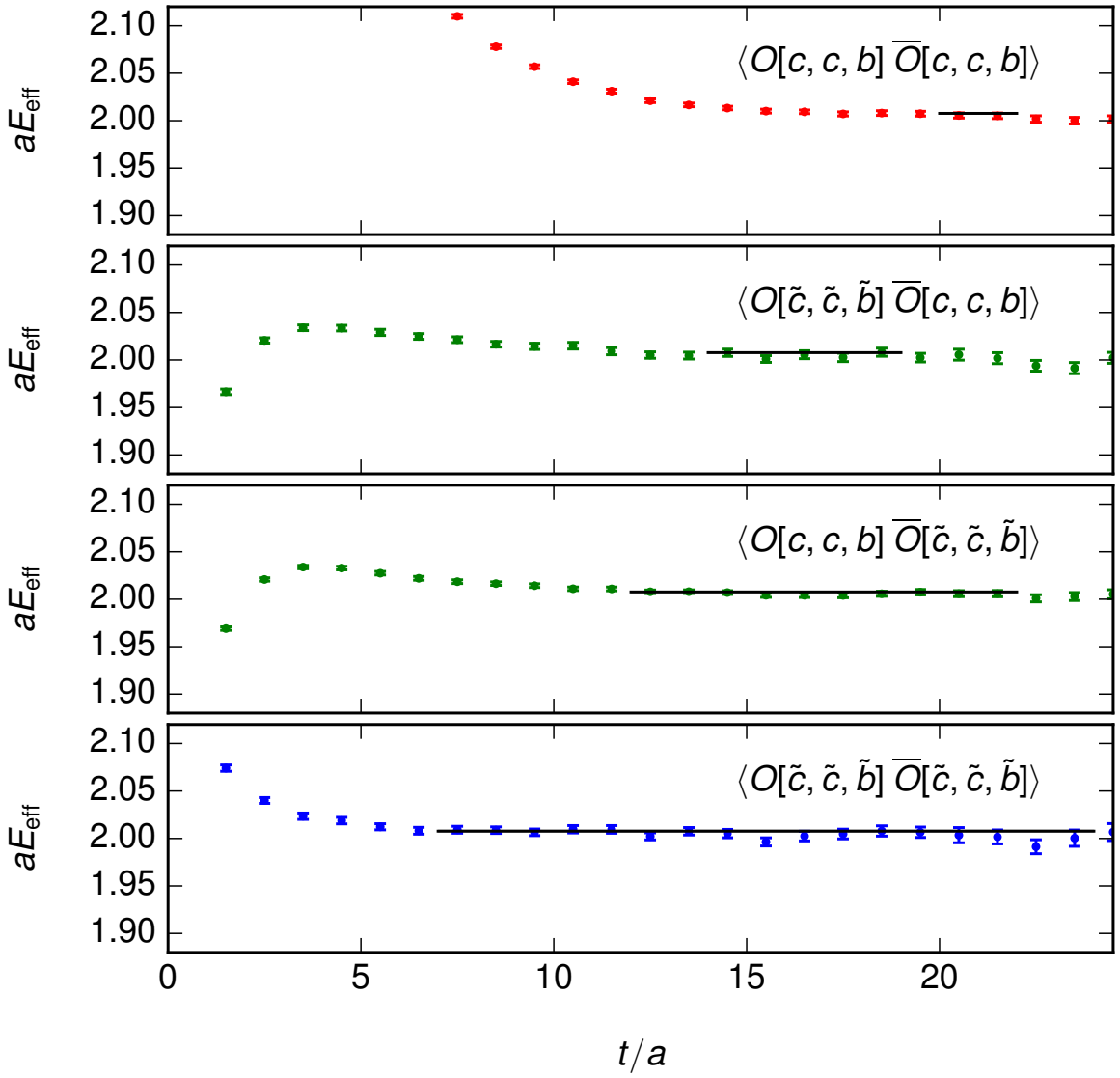
- Two lattice spacings: $a \approx 0.11$ fm, $a \approx 0.08$ fm
- Box size: $L \approx 2.7$ fm
- $m_u = m_d$
- Seven different pion masses in the range 230 ... 430 MeV (lowest three partially quenched)

Step 1: extract energies from two-point functions



Step 1: extract energies from two-point functions

$$aE_{\text{eff}}(t) = \ln\left[C(t)/C(t+a)\right]$$



Step 1: extract energies from two-point functions

For a baryon "X" with n_b bottom quarks and n_c charm quarks, we compute the subtracted energies

$$E_X^{(\mathrm{sub})} = E_X - \frac{n_c}{2}\overline{E}_{c\bar{c}} - \frac{n_b}{2}\overline{E}_{b\bar{b}}\,,$$

where

$$\overline{E}_{c\bar{c}} = \frac{3}{4}E_{J/\psi} + \frac{1}{4}E_{\eta_c}\,, \qquad \overline{E}_{b\bar{b}} = \frac{3}{4}E_{\Upsilon} + \frac{1}{4}E_{\eta_b}$$

Step 2: chiral and continuum extrapolations

Quark-mass and volume dependence predicted by NLO $SU(4|2)$ heavy-hadron chiral perturbation theory [Mehen and Tiburzi, PRD 74, 054505 (2006)]

$$
\begin{aligned}
E^{(\mathrm{sub})}_{\Xi_{cb}} &= E^{(\mathrm{sub},0)} + d_\pi^{(\mathrm{vv})}\,\frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + d_\pi^{(\mathrm{ss})}\,\frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + d_a\, a^2\Lambda^3 \\
&\quad - \frac{g_1^2}{16\pi^2 f^2}\left[\frac{4}{9}\mathcal{F}(m_\pi^{(\mathrm{vs})},0,\mu) - \frac{1}{9}\mathcal{F}(m_\pi^{(\mathrm{vv})},0,\mu)\right]
\end{aligned}
$$

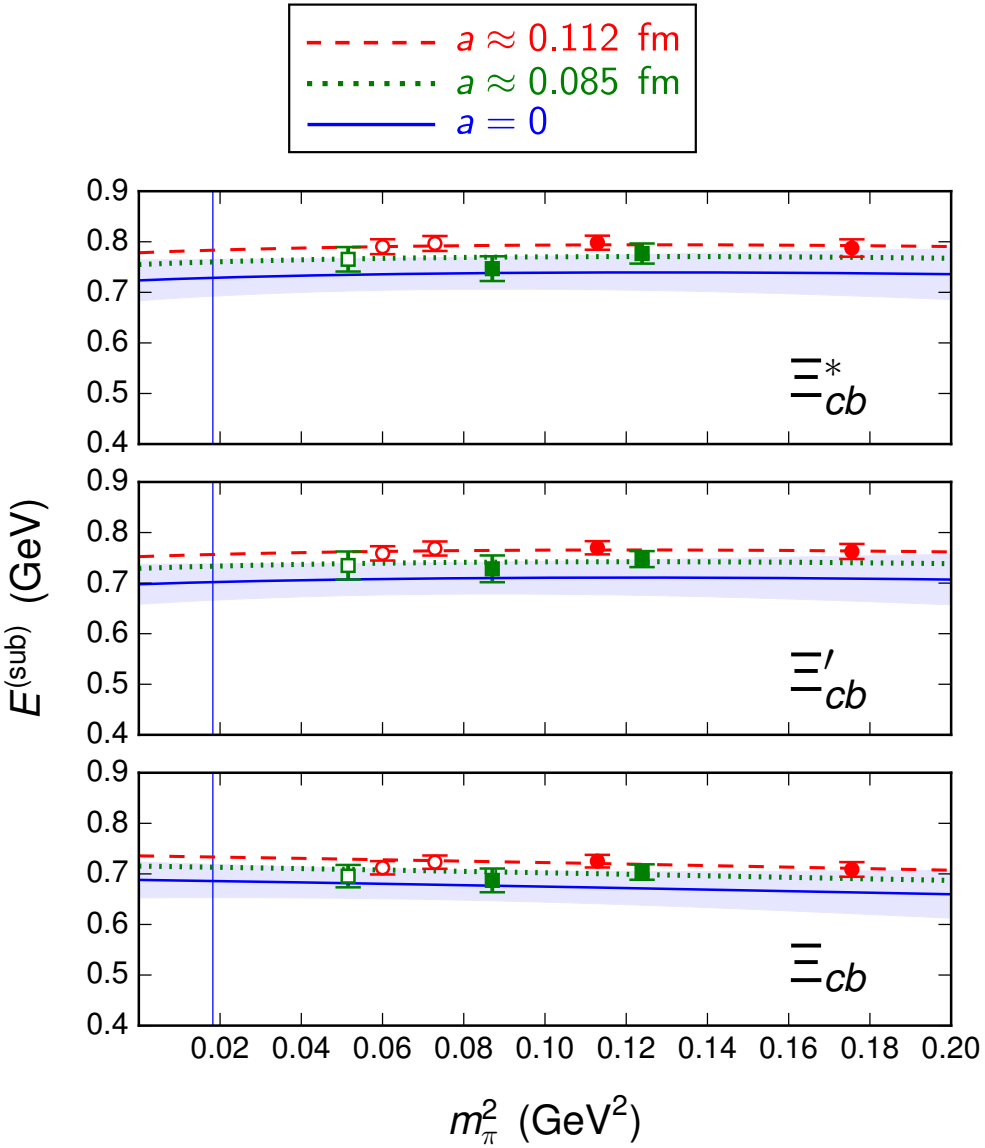
$$
\begin{aligned}
E^{(\mathrm{sub})}_{\Xi'_{cb}} &= E^{(\mathrm{sub},0)} + \Delta^{(0)} + c_\pi^{(\mathrm{vv})}\,\frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + c_\pi^{(\mathrm{ss})}\,\frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + c_a\, a^2\Lambda^3 \\
&\quad - \frac{g_1^2}{16\pi^2 f^2}\left[\frac{32}{9}\mathcal{F}(m_\pi^{(\mathrm{vs})},\Delta_*,\mu) + \frac{4}{9}\mathcal{F}(m_\pi^{(\mathrm{vs})},0,\mu) - \frac{8}{9}\mathcal{F}(m_\pi^{(\mathrm{vv})},\Delta_*,\mu) - \frac{1}{9}\mathcal{F}(m_\pi^{(\mathrm{vv})},0,\mu)\right]
\end{aligned}
$$

$$
\begin{aligned}
E^{(\mathrm{sub})}_{\Xi^*_{cb}} &= E^{(\mathrm{sub},0)} + \Delta^{(0)} + \Delta_*^{(0)} + c_\pi^{(\mathrm{vv})}\,\frac{[m_\pi^{(\mathrm{vv})}]^2}{4\pi f} + c_\pi^{(\mathrm{ss})}\,\frac{[m_\pi^{(\mathrm{ss})}]^2}{4\pi f} + c_a\, a^2\Lambda^3 \\
&\quad - \frac{g_1^2}{16\pi^2 f^2}\left[\frac{16}{9}\mathcal{F}(m_\pi^{(\mathrm{vs})},-\Delta_*,\mu) + \frac{20}{9}\mathcal{F}(m_\pi^{(\mathrm{vs})},0,\mu) - \frac{4}{9}\mathcal{F}(m_\pi^{(\mathrm{vv})},-\Delta_*,\mu) - \frac{5}{9}\mathcal{F}(m_\pi^{(\mathrm{vv})},0,\mu)\right]
\end{aligned}
$$

Axial coupling g_1 taken from separate lattice calculation

[Detmold, Lin, Meinel, PRL 108, 172003 (2012)]

Step 2: chiral and continuum extrapolations



Step 3: estimate systematic uncertainties

Evaluate fit functions at $a = 0$, $m_\pi = 135$ MeV, $L = \infty$ to obtain $E_X^{(\mathrm{sub,phys})}$.

Estimate chiral/continuum extrapolation systematic uncertainties by redoing fits with added higher-order terms (constrained to be natural-sized), and calculating

$$\sigma_{\mathrm{syst.,HO}} = \sqrt{\sigma^2_{\mathrm{NLO+HO}} - \sigma^2_{\mathrm{NLO}}}$$

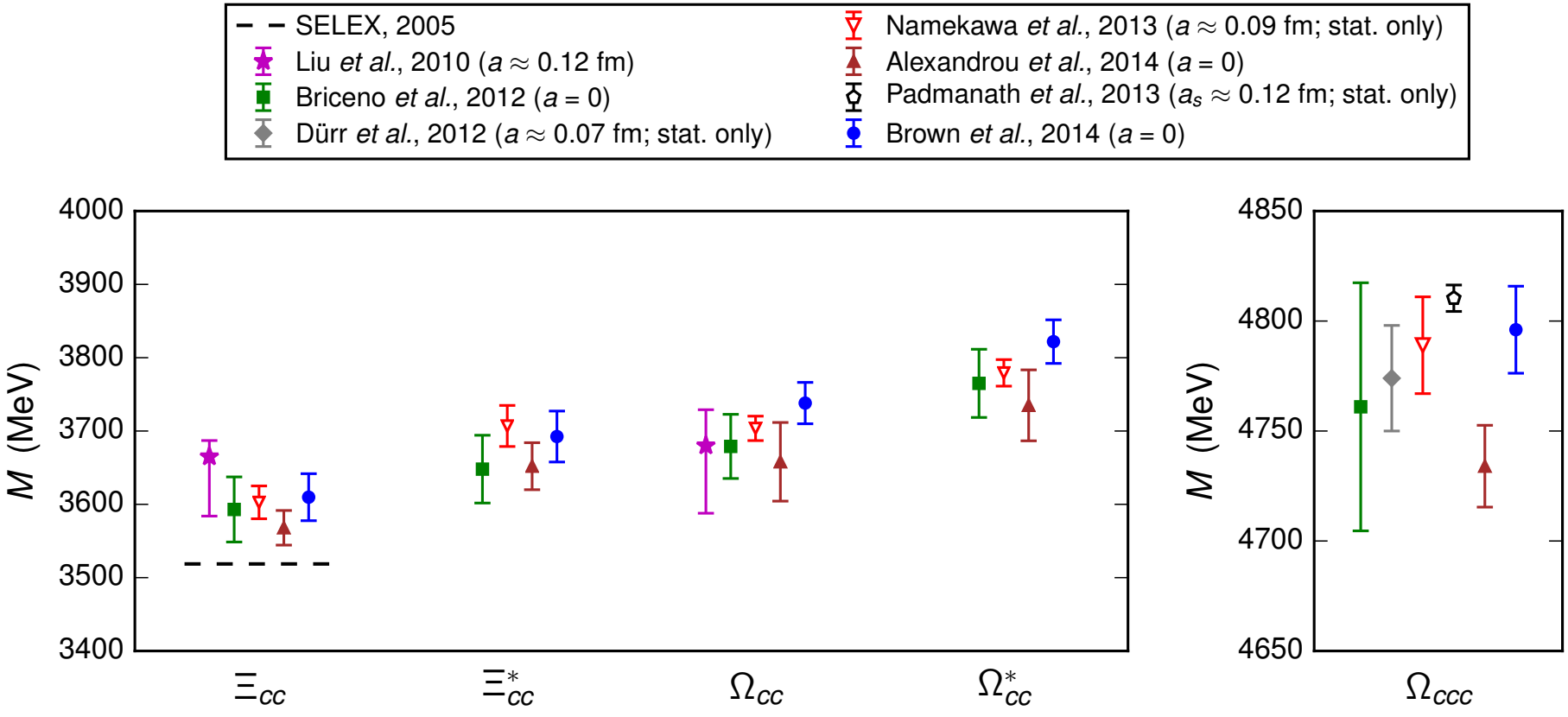
Estimate NRQCD uncertainties using power counting.

Step 4: add experimental values of subtraction term

$$M_X^{(\text{phys})} = E_X^{(\text{sub,phys})} + \left[\frac{n_c}{2}\overline{M}_{c\bar{c}} + \frac{n_b}{2}\overline{M}_{b\bar{b}}\right]_{\text{PDG}}$$

Results

Doubly charmed: lattice QCD and SELEX



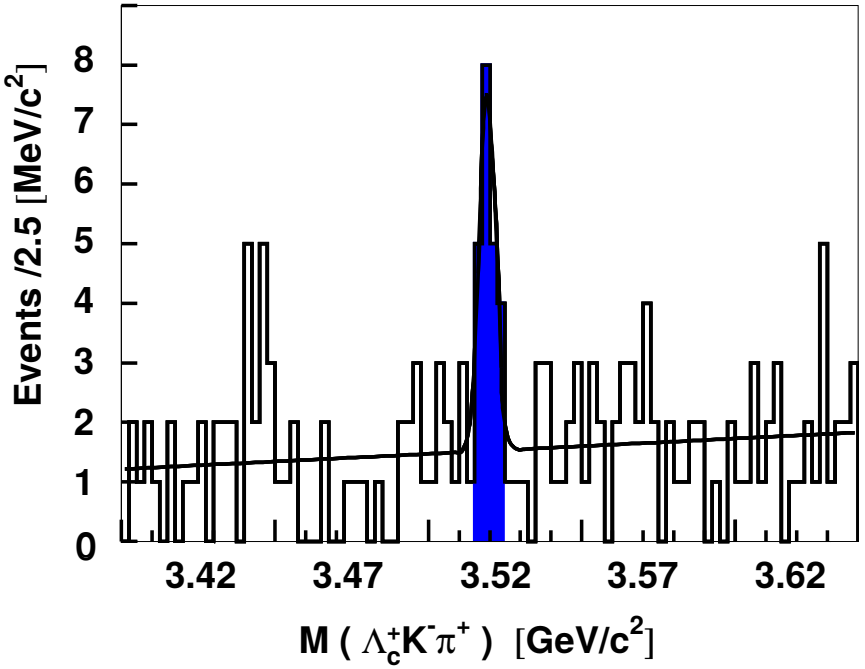
SELEX measurements

VOLUME 89, NUMBER 11 PHYSICAL REVIEW LETTERS 9 SEPTEMBER 2002

First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+}

M. Mattson,[3] G. Alkhazov,[11] A. G. Atamantchouk,[11,a] M. Y. Balatz,[8,a] N. F. Bondar,[11] P. S. Cooper,[5] L. J. Dauwe,[17]
G. V. Davidenko,[8] U. Dersch,[9,b] A. G. Dolgolenko,[8] G. B. Dzyubenko,[8] R. Edelstein,[3] L. Emediato,[19] A. M. F. Endler,[4]

We observe a signal for the doubly charmed baryon Ξ_{cc}^{+} in the charged decay mode $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ in data from SELEX, the charm hadroproduction experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of 6.3σ. The observed mass of this state is 3519 ± 1 MeV/c^2. The Gaussian mass width of this state is 3 MeV/c^2, consistent with resolution; its lifetime is less than 33 fs at 90% confidence.



SELEX measurements

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Physics Letters B 628 (2005) 18–24

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Confirmation of the doubly charmed baryon $\Xi_{cc}^{+}(3520)$ via its decay to $pD^{+}K^{-}$

Abstract

We observe a signal for the doubly charmed baryon Ξ_{cc}^{+} in the decay mode $\Xi_{cc}^{+} \to pD^{+}K^{-}$ to complement the previous reported decay $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$ in data from SELEX, the charm hadroproduction experiment at Fermilab. In this new decay mode we observe an excess of 5.62 events over a combinatoric background estimated by event mixing to be 1.38 ± 0.13 events. The mixed background has Gaussian statistics, giving a signal significance of 4.8σ. The Poisson probability that a background fluctuation can produce the apparent signal is less than 6.4×10^{-4}. The observed mass of this state is 3518 ± 3 MeV$/c^{2}$, consistent with the published result. Averaging the two results gives a mass of 3518.7 ± 1.7 MeV$/c^{2}$. The observation of this new weak decay mode confirms the previous SELEX suggestion that this state is a double charm baryon. The relative branching ratio for these two modes is 0.36 ± 0.21.
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SELEX: $m_{\Xi_{cc}^{+}} = 3518.7 \pm 1.7$ MeV

Our lattice calculation: $m_{\Xi_{cc}} = 3610 \pm 23 \pm 22$ MeV

Isospin splitting from lattice QCD+QED: $m_{\Xi_{cc}^{++}} - m_{\Xi_{cc}^{+}} = 2.16 \pm 0.11 \pm 0.17$ MeV [Borsanyi et al. (BMW), arXiv:1406.4088]

Newer searches do not find the Ξ_{cc}

Signal:

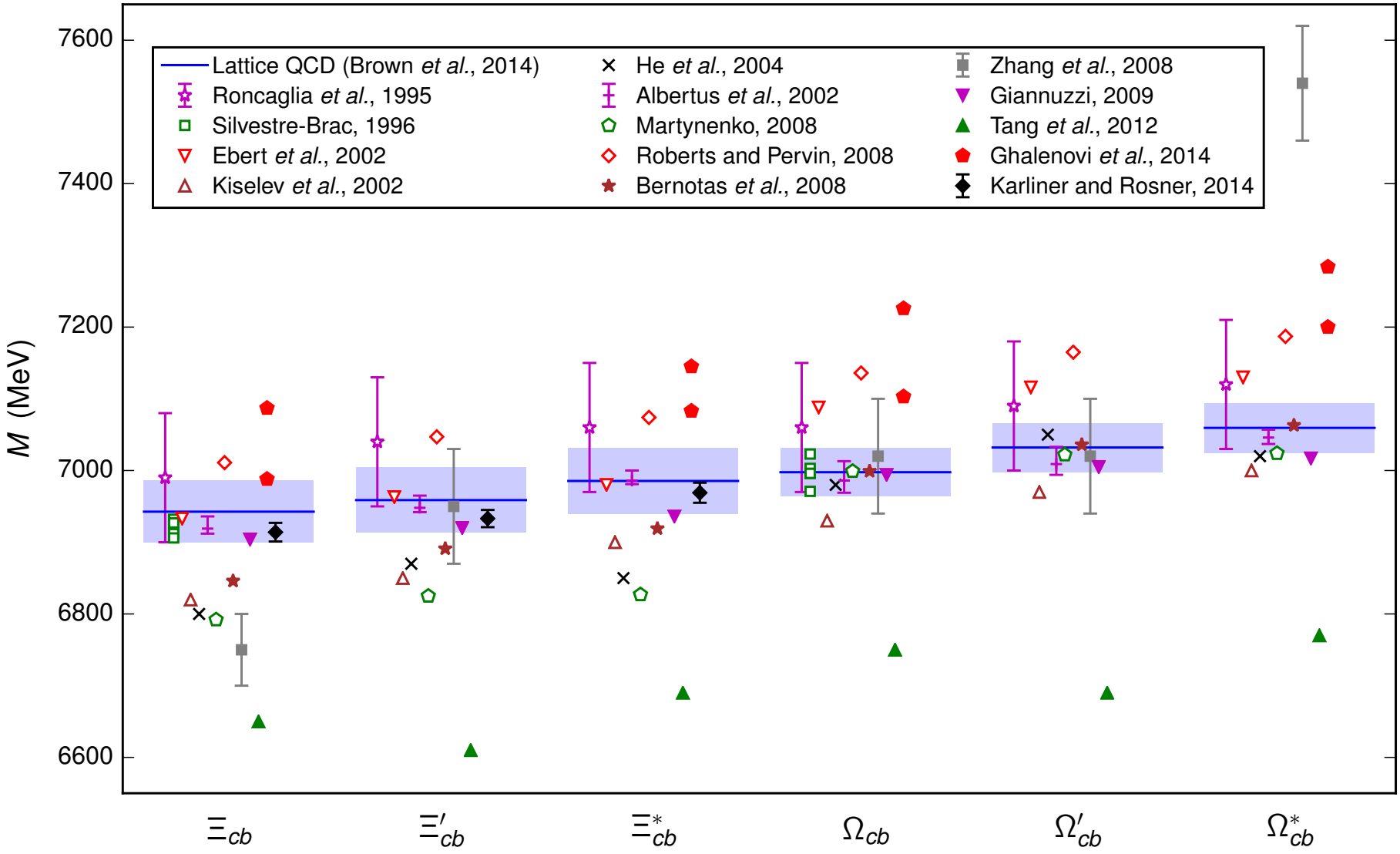
- SELEX [PRL 89, 112001 (2002)]: Σ^-, π^- beam (600 GeV) on Cu/diamond fixed target

No signal:

- FOCUS [NPPS 115, 33 (2003)]: γ ($\leq$ 250 GeV) on BeO fixed target
- BaBar [PRD 74, 011103 (2006)]: e^+e^- at $\sqrt{s} = 10.58$ GeV
- Belle [PRL 97, 162001 (2006)]: e^+e^- at $\sqrt{s} = 10.58$ GeV
- LHCb [JHEP 1312, 090 (2013)]: pp at $\sqrt{s} = 7$ TeV

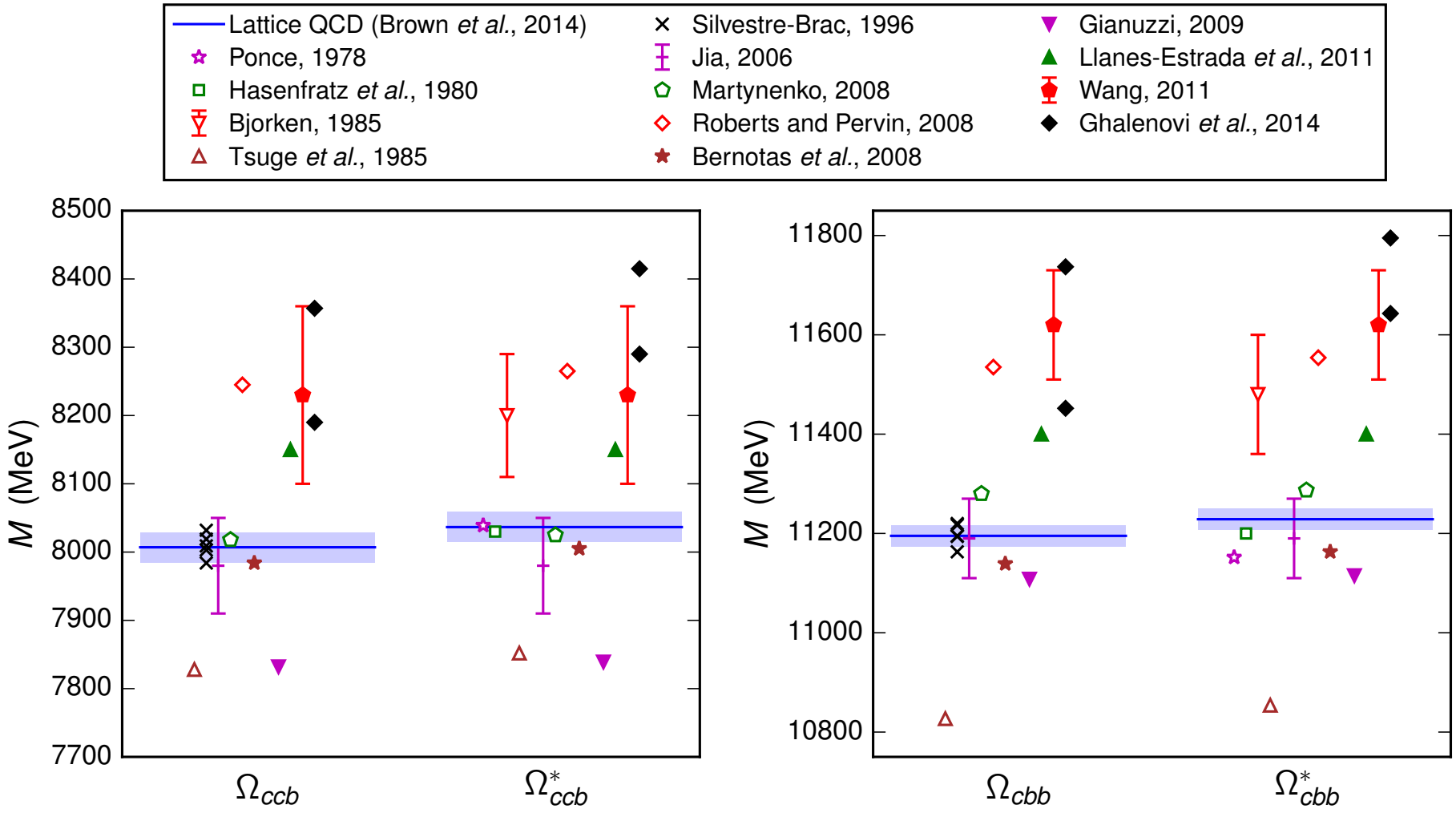
Results

Singly charmed, singly bottom: lattice QCD vs. models



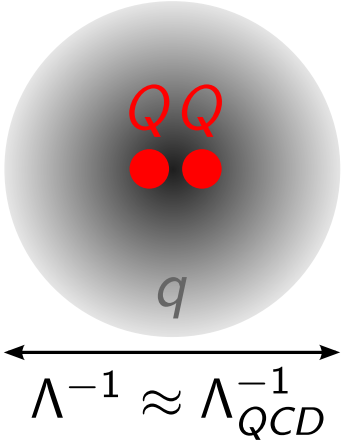
Results

Triply heavy charm-bottom: lattice QCD vs. models



Results

Prediction of heavy quark-diquark symmetry:



$$\frac{M(\Xi^*_{QQ}) - M(\Xi_{QQ})}{M(P^*_Q) - M(P_Q)} \longrightarrow \frac{3}{4} \qquad (\text{for } m_Q \to \infty)$$

[Brambilla, Vairo, Rosch, PRD 72, 034021 (2005)]

Test using lattice QCD:

Splitting	This work (MeV)	Splitting	Experiment (MeV)	Ratio
$\Xi^*_{cc} - \Xi_{cc}$	82.8(9.2)	$D^{*0} - D^0$	142.12(7)	0.58(6)
$\Omega^*_{cc} - \Omega_{cc}$	83.8(5.5)	$D^*_s - D_s$	143.8(4)	0.58(4)
$\Xi^*_{bb} - \Xi_{bb}$	34.6(7.8)	$B^* - B$	45.78(35)	0.76(17)
$\Omega^*_{bb} - \Omega_{bb}$	35.7(5.7)	$B^*_s - B_s$	48.7(2.3)	0.73(12)

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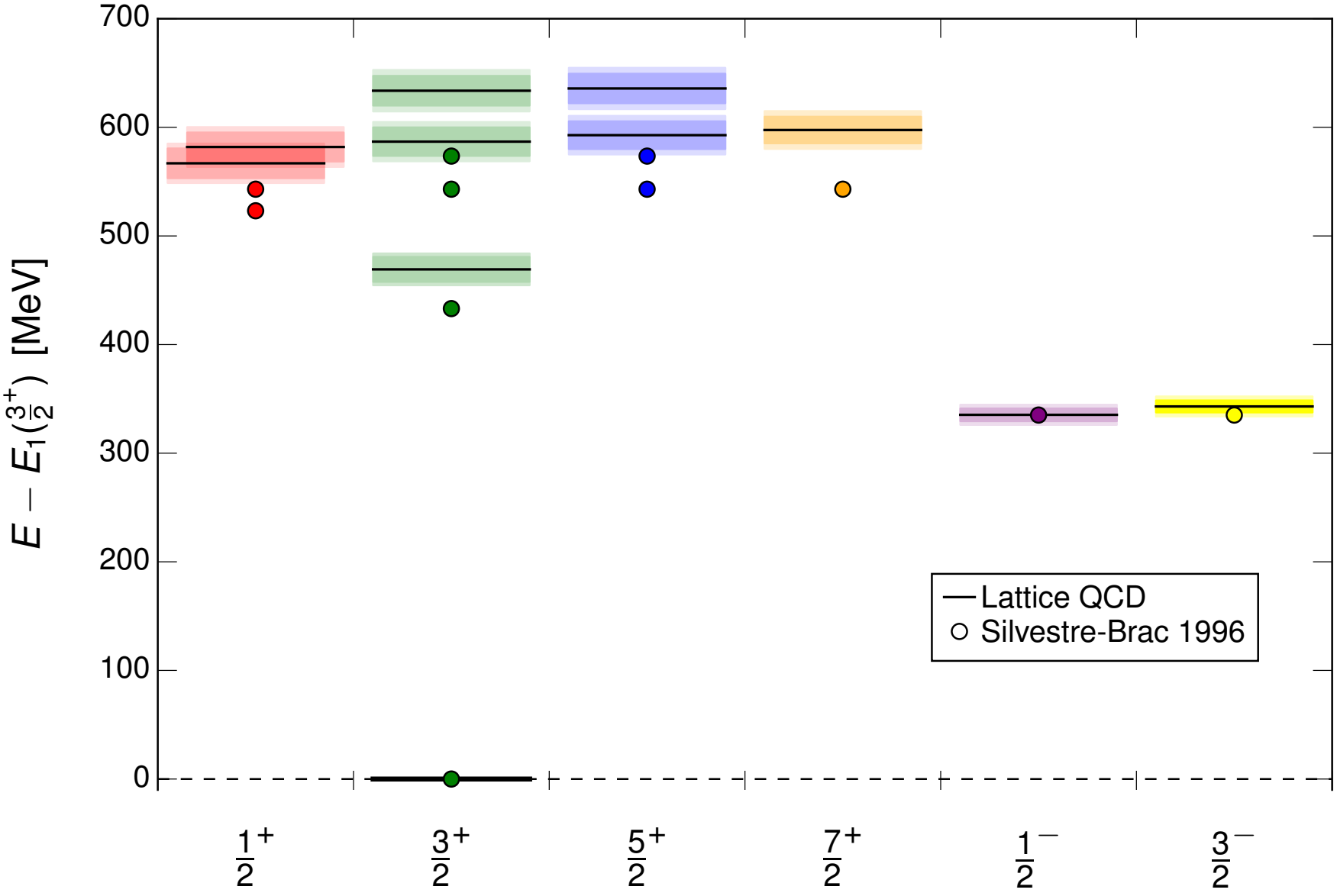
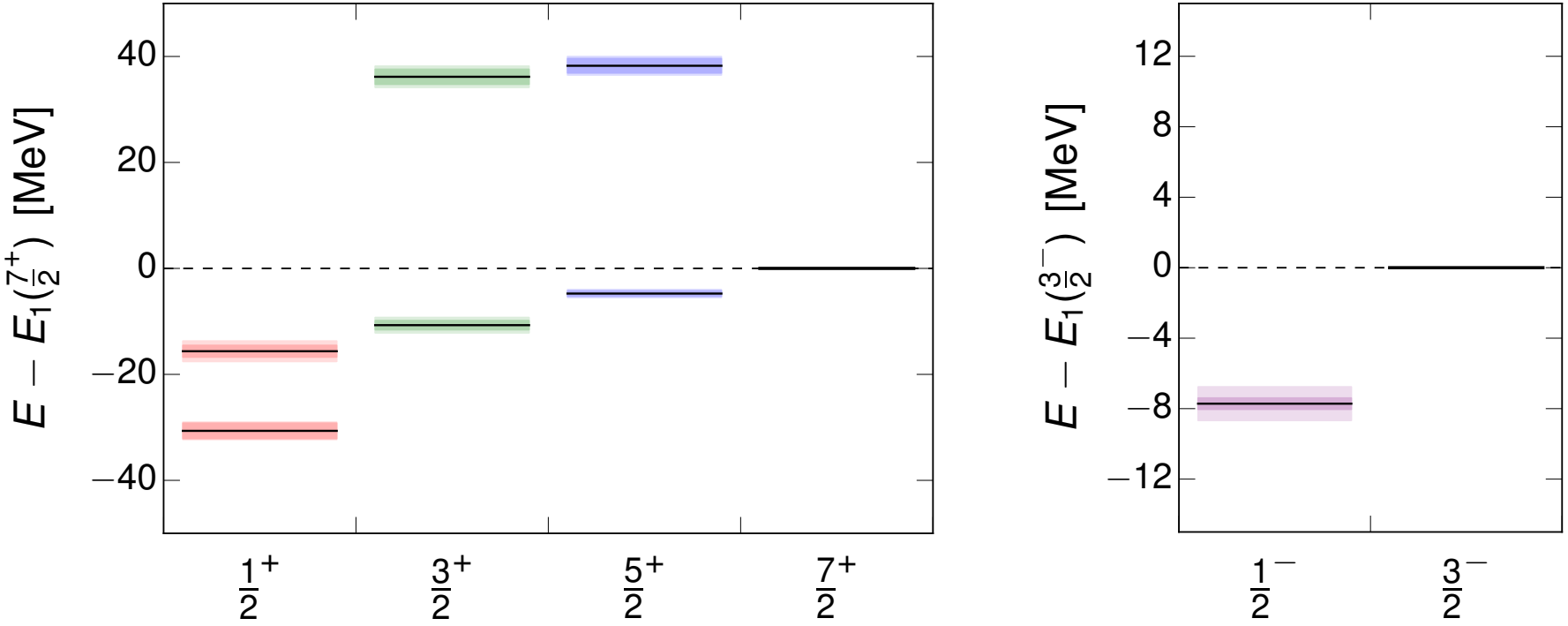
Ω_{bbb} excited states

[Meinel, PRD 85, 114510 (2012)]



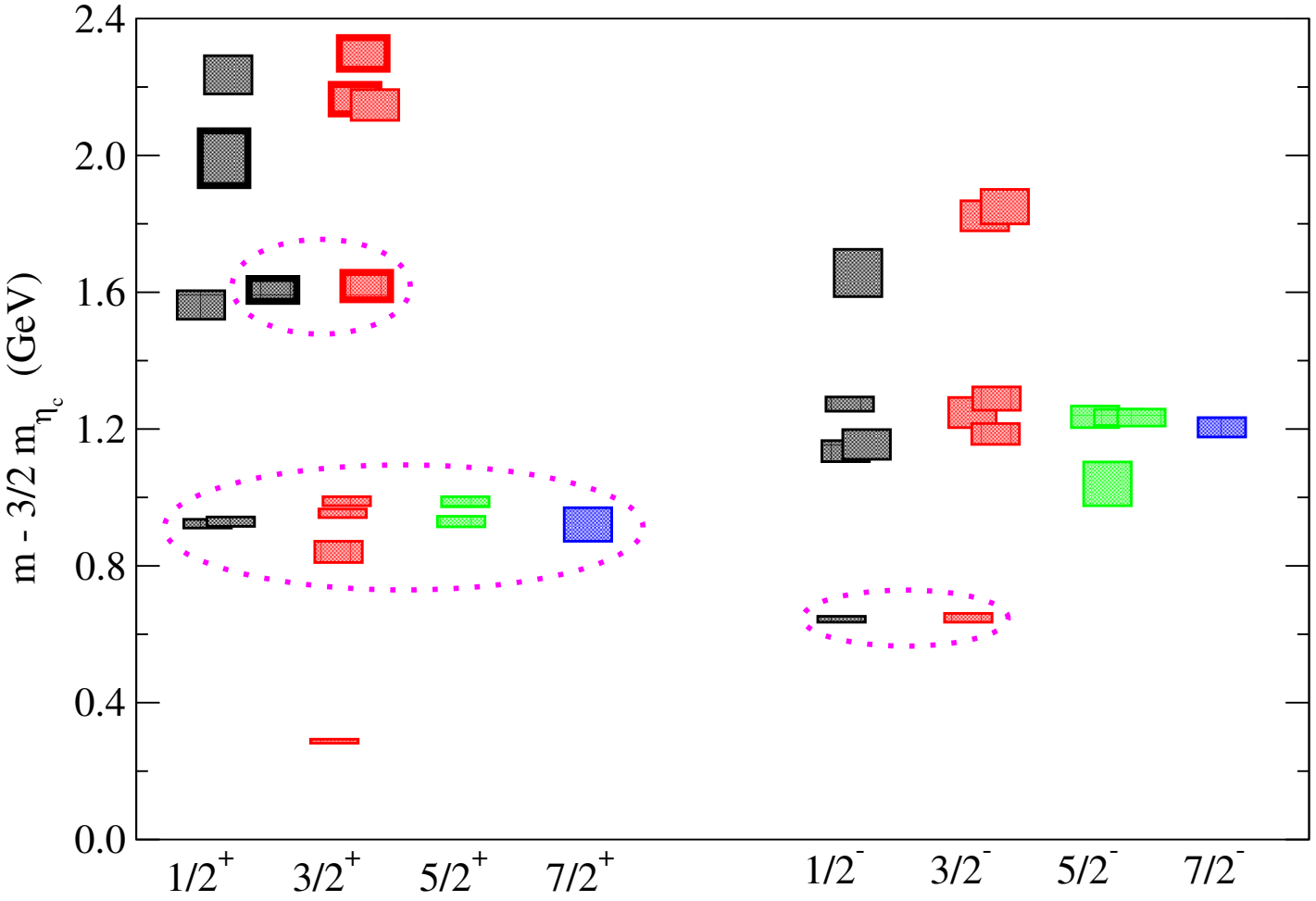
Ω_{bbb} excited states

[Meinel, PRD 85, 114510 (2012)]



Ω_{ccc} excited states

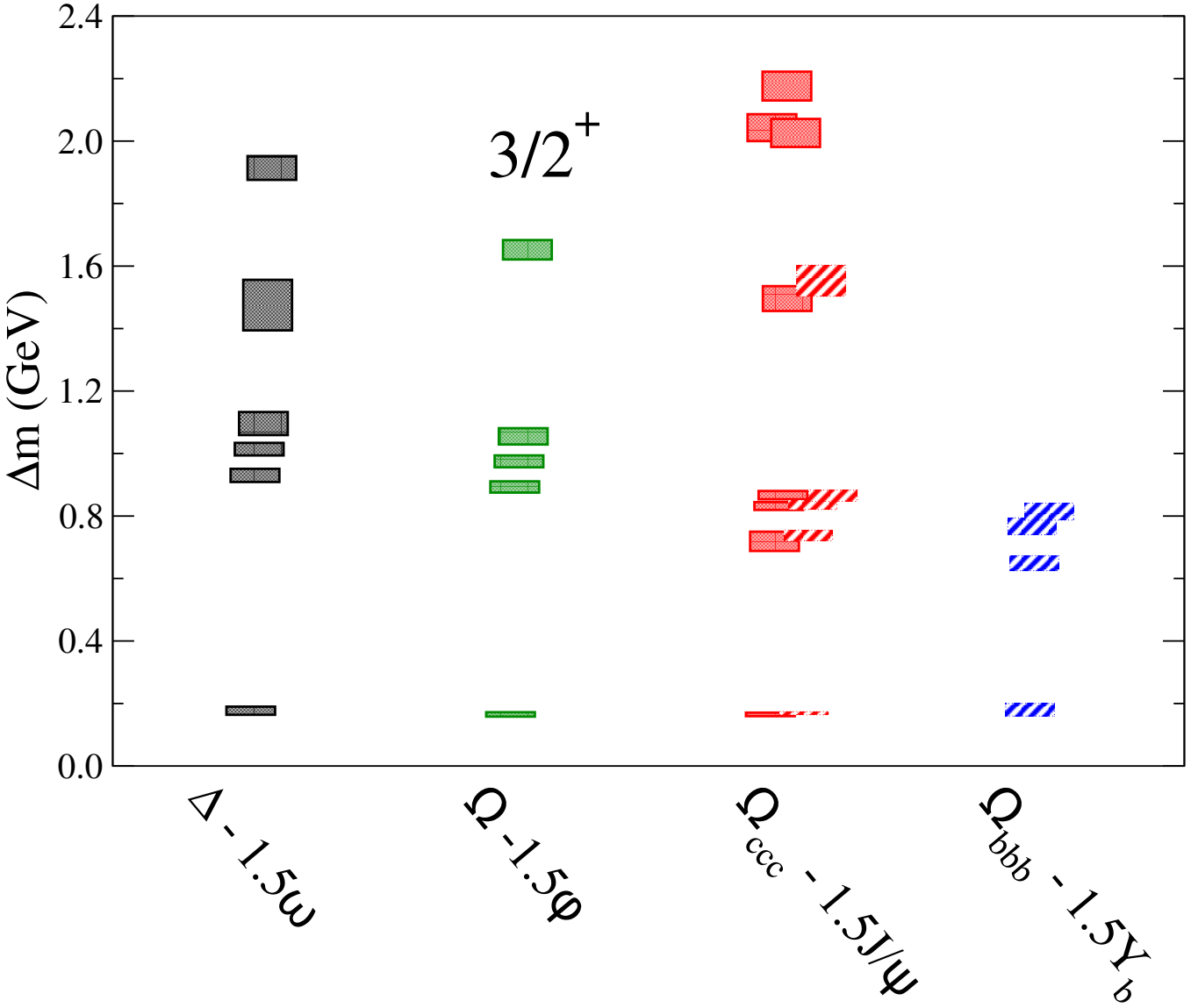
[Padmanath, Edwards, Mathur, Peardon, arXiv:1307.7022]



(only statistical uncertainties shown)

Quark-mass dependence

[Padmanath, Edwards, Mathur, Peardon, arXiv:1307.7022]



(except for Ω_{bbb}, only statistical uncertainties shown)

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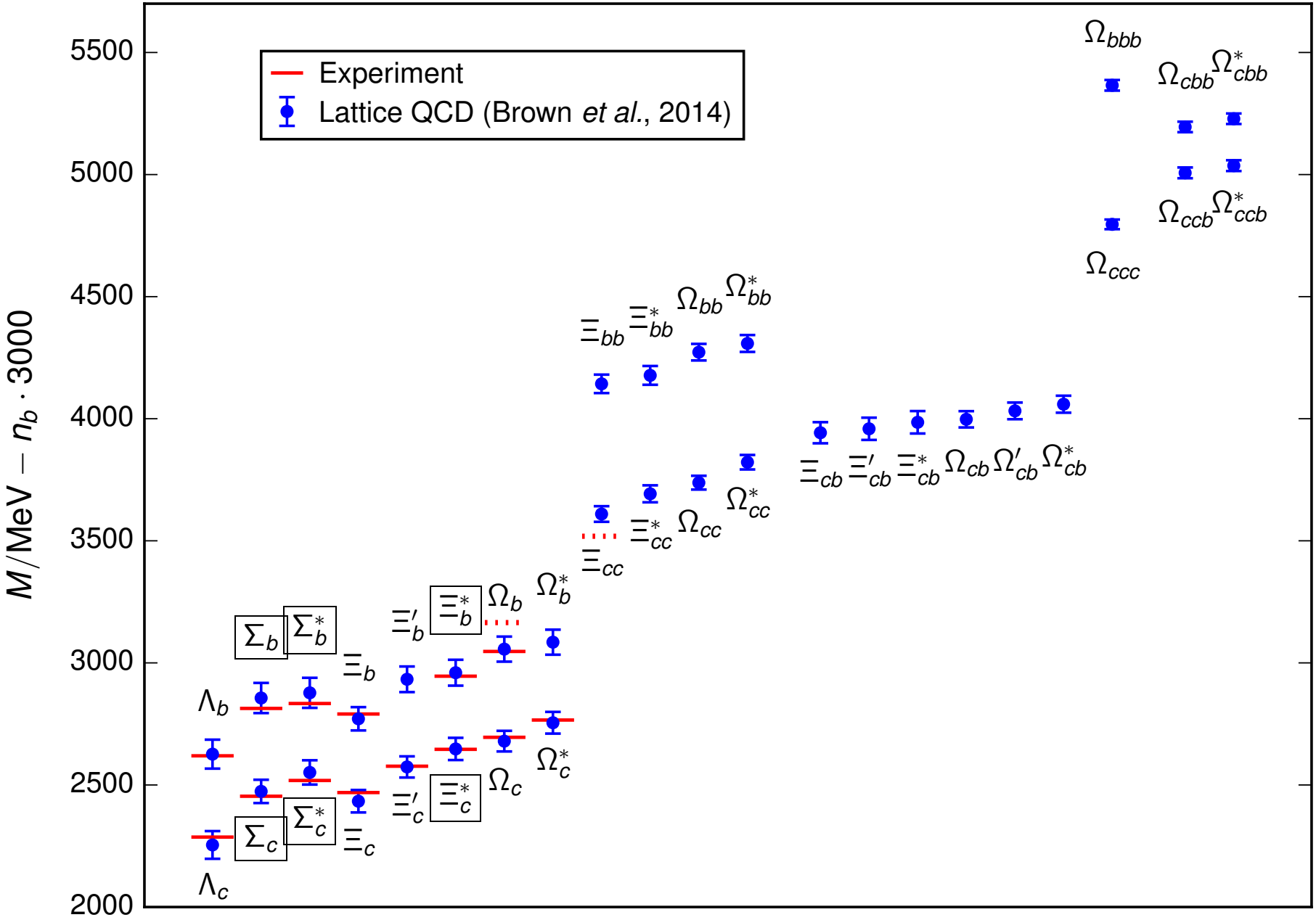
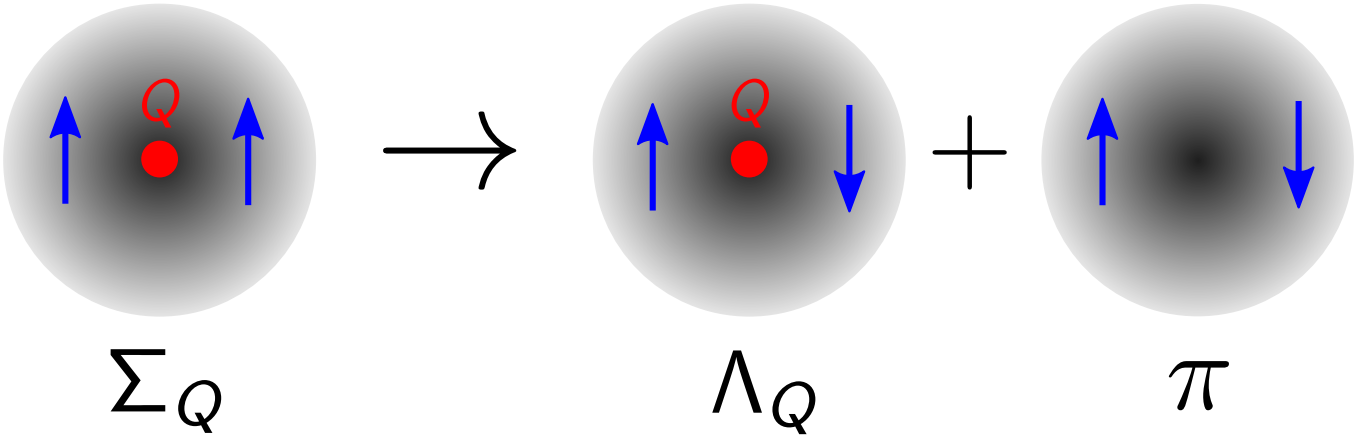
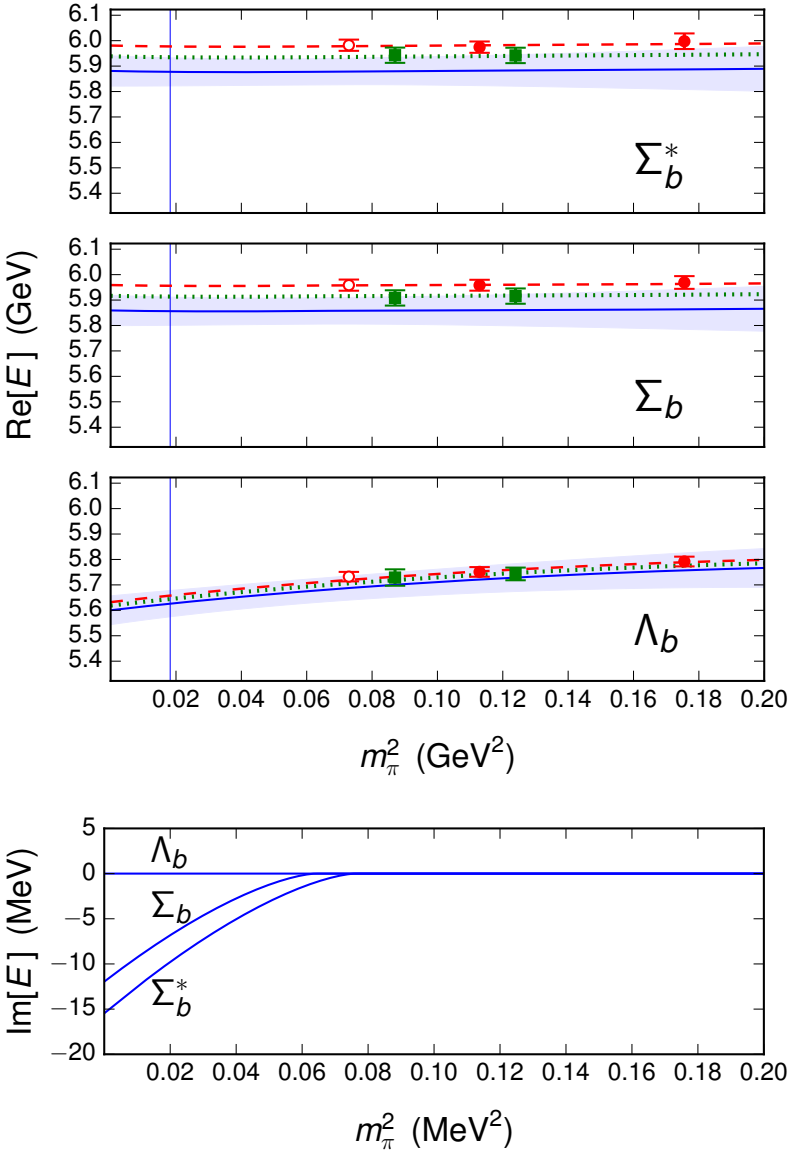

Experiment
Lattice QCD (Brown et al., 2014)
$M/\mathrm{MeV} - n_b \cdot 3000$
5500
5000
4500
4000
3500
3000
2500
2000
Λ_c
Λ_b
Σ_c
Σ_c^*
Σ_b
Σ_b^*
Ξ_c
Ξ_b
Ξ_c'
Ξ_c^*
Ξ_b'
Ξ_b^*
Ω_c
Ω_b
Ω_c^*
Ω_b^*
Ξ_{cc}
Ξ_{bb}
Ξ_{cc}^*
Ξ_{bb}^*
Ω_{cc}
Ω_{bb}
Ω_{cc}^*
Ω_{bb}^*
Ξ_{cb}
Ξ_{cb}'
Ξ_{cb}^*
Ω_{cb}
Ω_{cb}'
Ω_{cb}^*
Ω_{ccc}
Ω_{bbb}
Ω_{ccb}
Ω_{ccb}^*
Ω_{cbb}
Ω_{cbb}^*

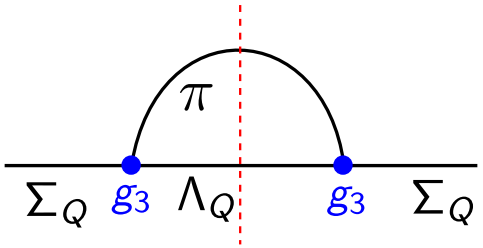
Strong decays

Schematically:



Strong decays in chiral perturbation theory





$$\Gamma[\Sigma_Q^{(*)} \to \Lambda_Q \pi] = -2\,\mathrm{Im}[E_{\Sigma_Q^{(*)}}] = \frac{g_3^2}{6\pi f^2}\left|\mathbf{p}_\pi\right|^3$$

Computing g_3 (and g_1, g_2) in lattice QCD

Matrix elements of the axial current $A_\mu = \bar{d}\gamma_\mu\gamma_5 u$:

$$\begin{aligned}
\langle P^*|A_\mu|P\rangle &= (g_1)_{\text{eff}} \times (\text{kinematic factors}), \\
\langle \Sigma_Q^{(*)}|A_\mu|\Sigma_Q^{(*)}\rangle &= (g_2)_{\text{eff}} \times (\text{kinematic factors}), \\
\langle \Sigma_Q^{(*)}|A_\mu|\Lambda_Q\rangle &= (g_3)_{\text{eff}} \times (\text{kinematic factors})
\end{aligned}$$

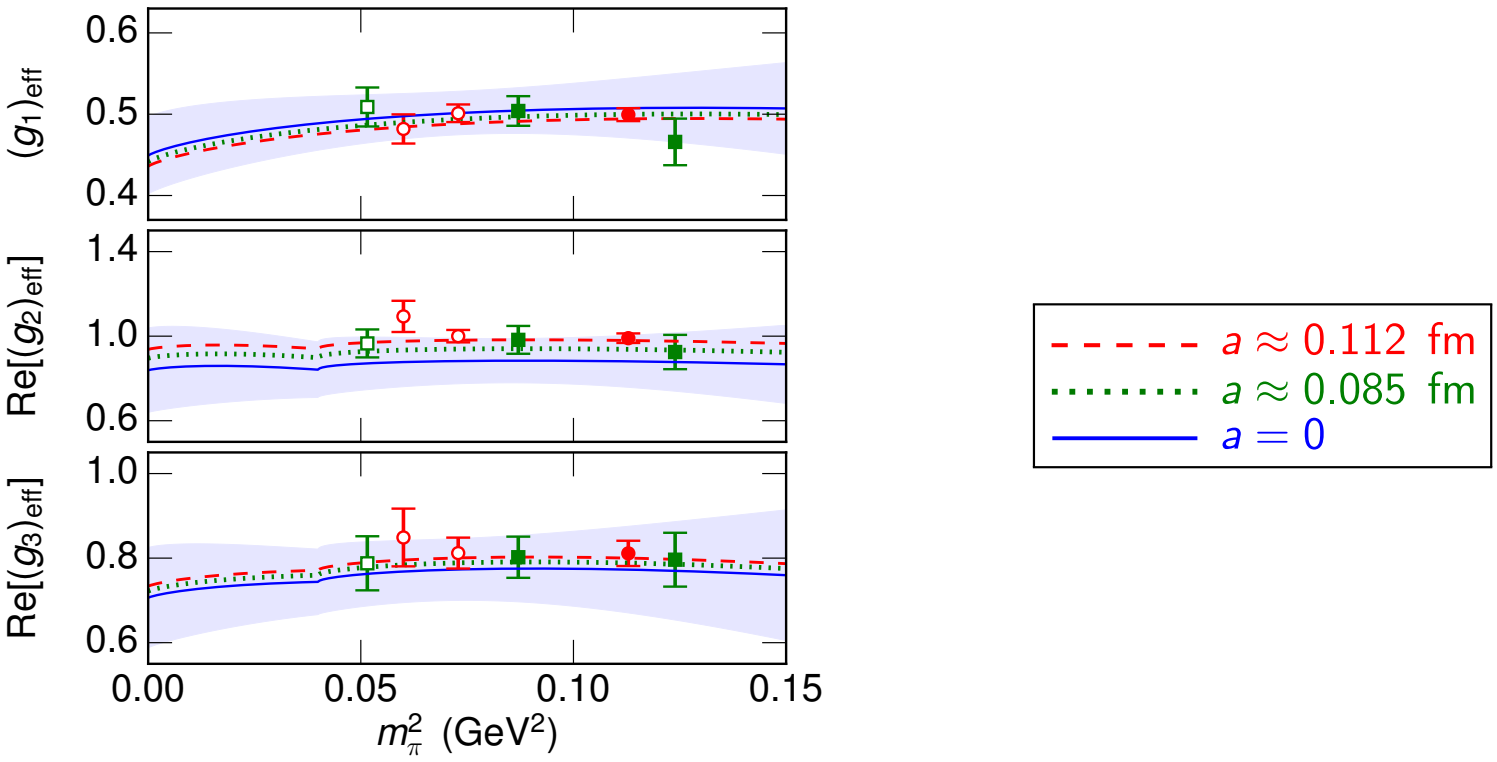
(defined in heavy-quark limit $m_Q \to \infty$).

In heavy-hadron chiral perturbation theory,

$$\begin{aligned}
(g_1)_{\text{eff}} &= g_1 + \text{NLO}, \\
(g_2)_{\text{eff}} &= g_2 + \text{NLO}, \\
(g_3)_{\text{eff}} &= g_3 + \text{NLO}.
\end{aligned}$$

[Detmold, Lin, Meinel, PRD 84, 094502 (2011)]

Computing g_3 (and g_1, g_2) in lattice QCD

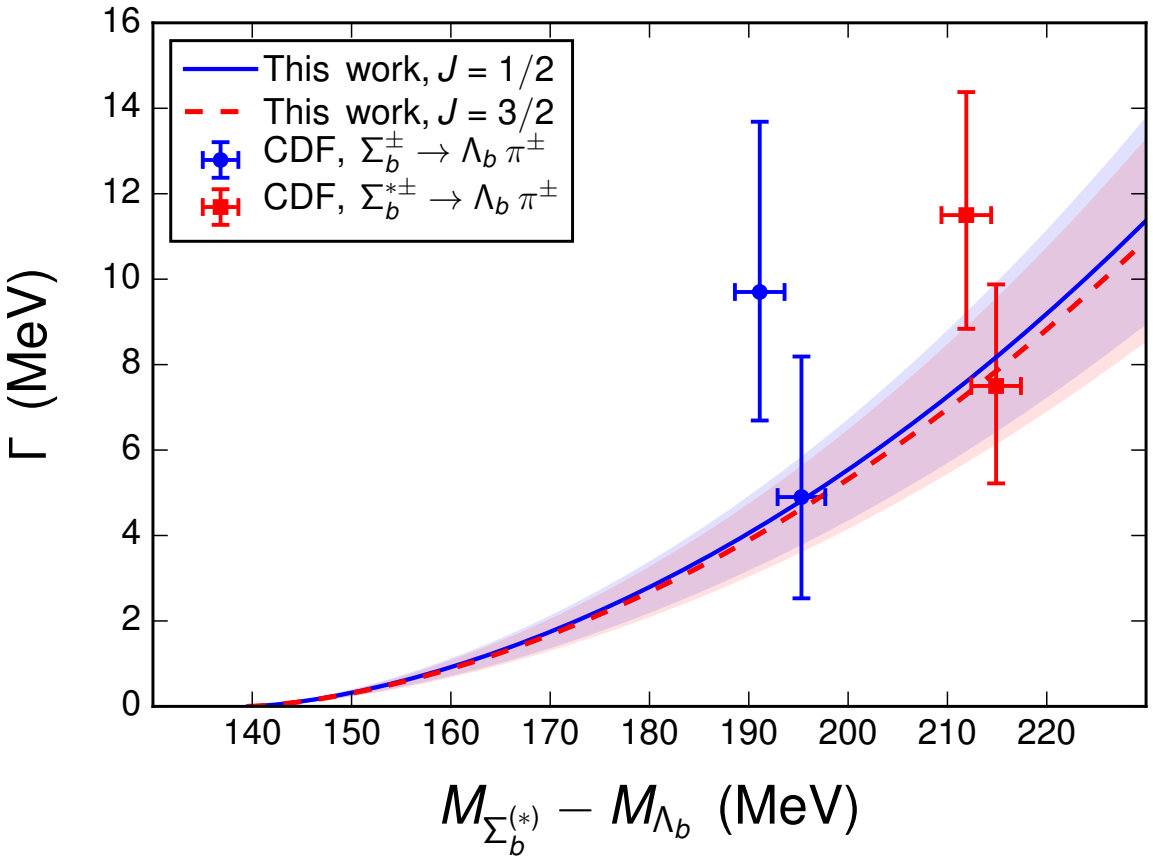


Our result:

$$
\begin{aligned}
g_1 &= 0.449 \pm 0.047 \pm 0.019 \\
g_2 &= 0.84 \pm 0.20 \pm 0.04 \\
g_3 &= 0.71 \pm 0.12 \pm 0.04
\end{aligned}
$$

[Detmold, Lin, Meinel, PRL 108, 172003 (2012); PRD 85, 114508 (2012)]

Resulting Σ_b and Σ_b^* decay widths



$\mathcal{O}(\Lambda/m_b)$ correction is included in Γ.

[Detmold, Lin, Meinel, PRL 108, 172003 (2012); PRD 85, 114508 (2012)]

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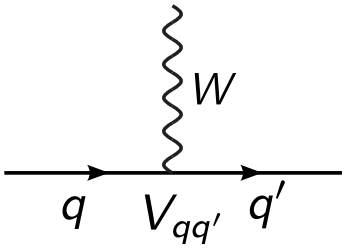
- The FCNC decay $\Lambda_b \to \Lambda\mu^+\mu^-$

Testing CKM unitarity



$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

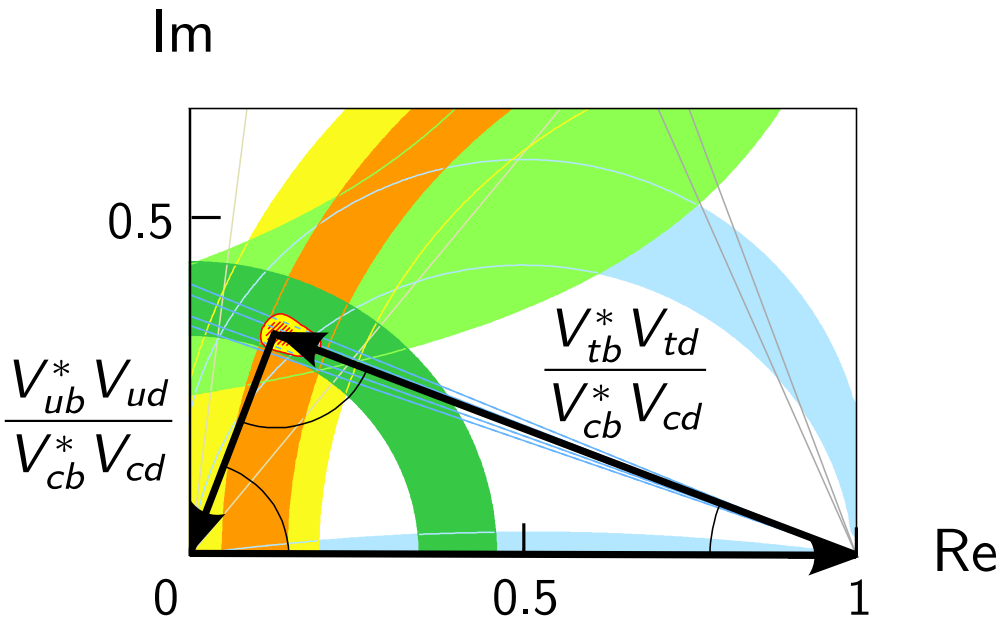
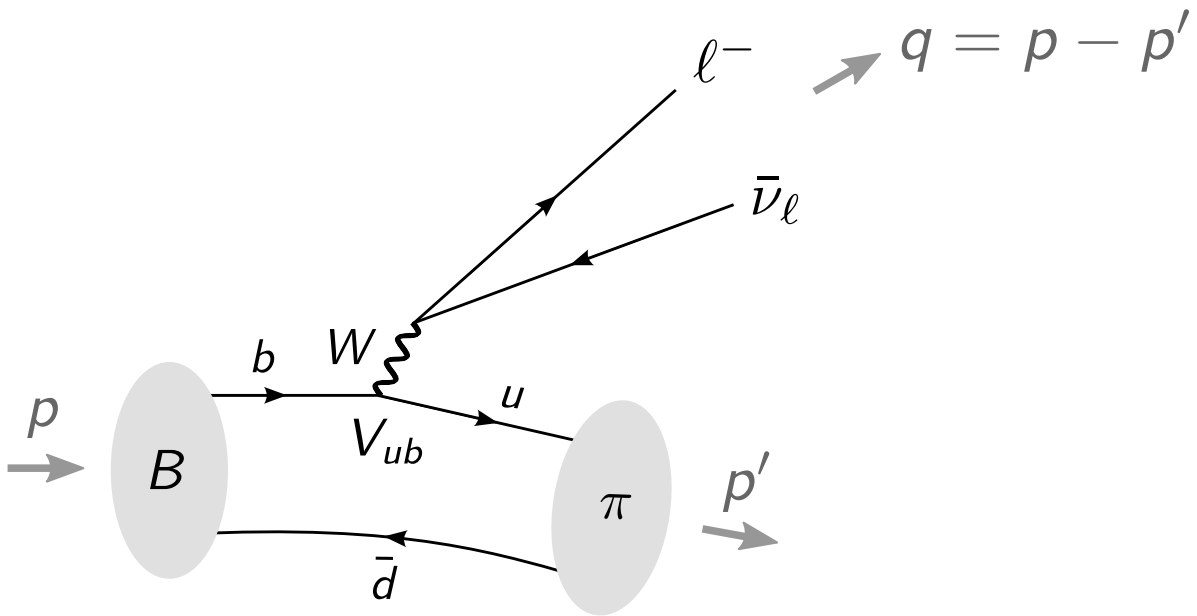


figure based on: [CKMfitter, 2013]

■ = measurement of $|V_{ub}|$

■ = measurement of ϵ_K. Constraint depends on $|V_{cb}|^4$

$B \to \pi \ell \bar{\nu}$

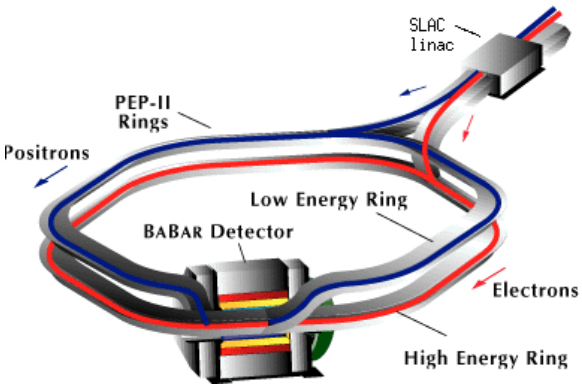


$$\langle \pi | \bar{u} \gamma^\mu b | B \rangle = \left[(p + p')^\mu - \frac{m_B^2 - m_\pi^2}{q^2} q^\mu \right] f_+(q^2) + \frac{m_B^2 - m_\pi^2}{q^2} q^\mu f_0(q^2)$$

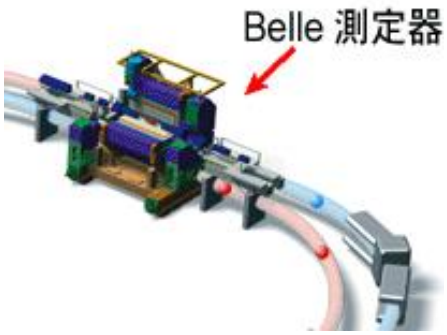
$$\langle \pi | \bar{u} \gamma^\mu \gamma_5 b | B \rangle = 0$$

$$\frac{d\Gamma}{dq^2} = \underbrace{|\eta_{\rm EW}|^2}_{\approx 1} \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |\mathbf{p}'|^3 |f_+(q^2)|^2 \qquad (\text{for } m_\ell = 0)$$

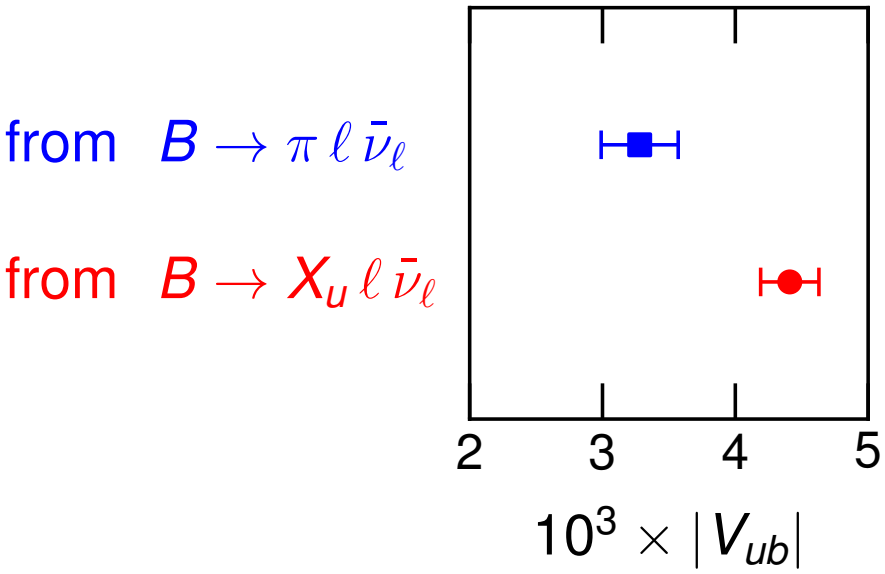
The $|V_{ub}|$ puzzle



BaBar, 1999–2008

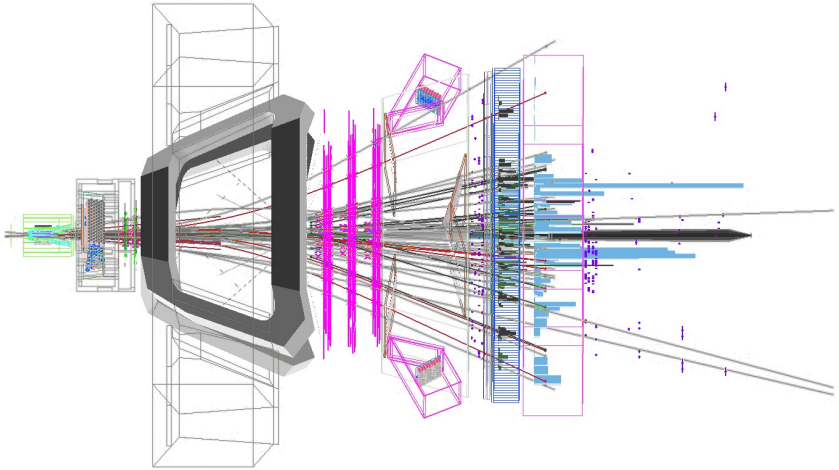


Belle, 1998–2010



[Gulez et al. (HPQCD), PRD 73, 074502 (2006); Bailey et al. (FNAL/MILC), PRD 79, 054507 (2009); Particle Data Group, 2013]

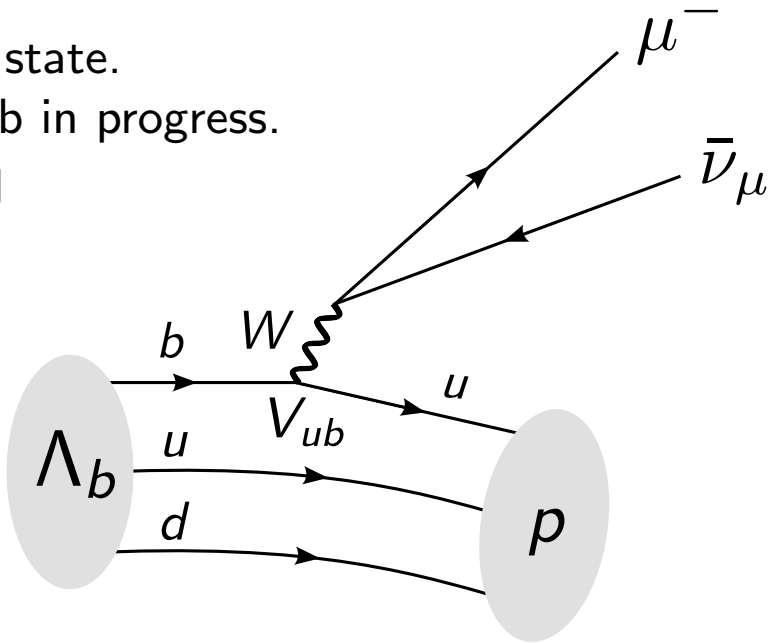
Measuring $|V_{ub}|$ at the LHC



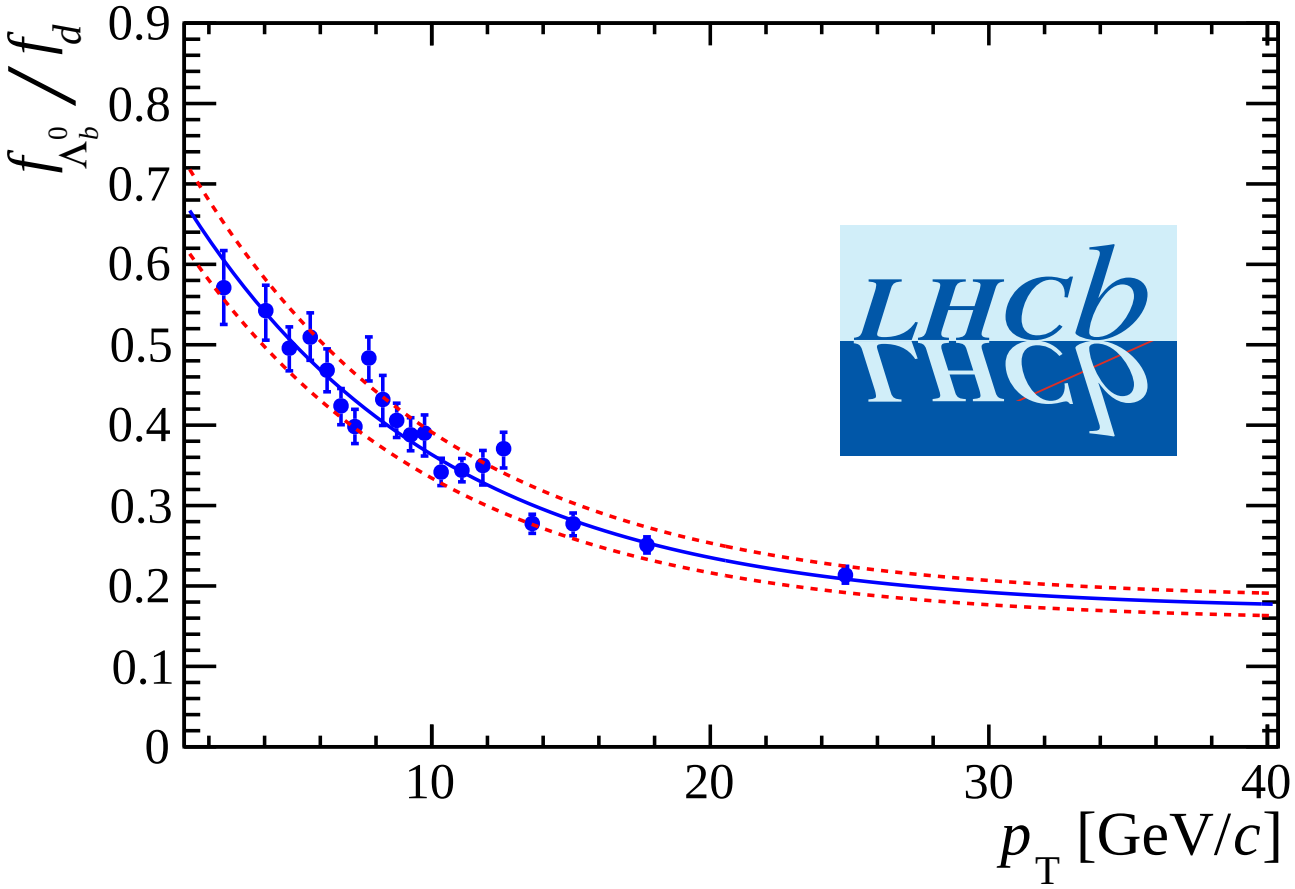
$B \to \pi\, \ell\, \bar{\nu}_\ell$:
Difficult to isolate from background because pp collisions produce many pions

$\Lambda_b \to p\, \ell\, \bar{\nu}_\ell$:
More distinctive final state.
Data analysis at LHCb in progress.

[Egede, private communication]



Λ_b production rate at the LHC



[Aaij et al. (LHCb), JHEP 08, 143 (2014)]

$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$

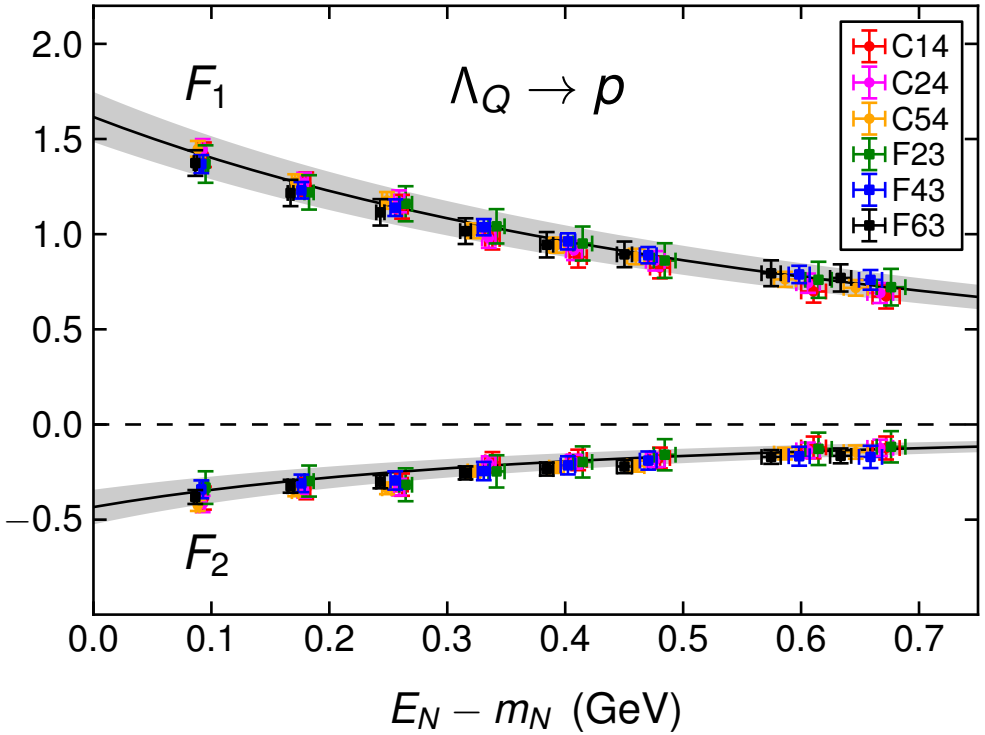
At leading order in $1/m_b$ expansion (static limit), only two form factors:

$$\langle N^+(p')|\,\bar{u}\,\Gamma\,Q\,|\Lambda_Q(v)\rangle \;=\; \bar{u}_N\,\left[F_1(p'\cdot v) + \not{v}\,F_2(p'\cdot v)\right]\,\Gamma\,u_{\Lambda_Q}$$

$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$

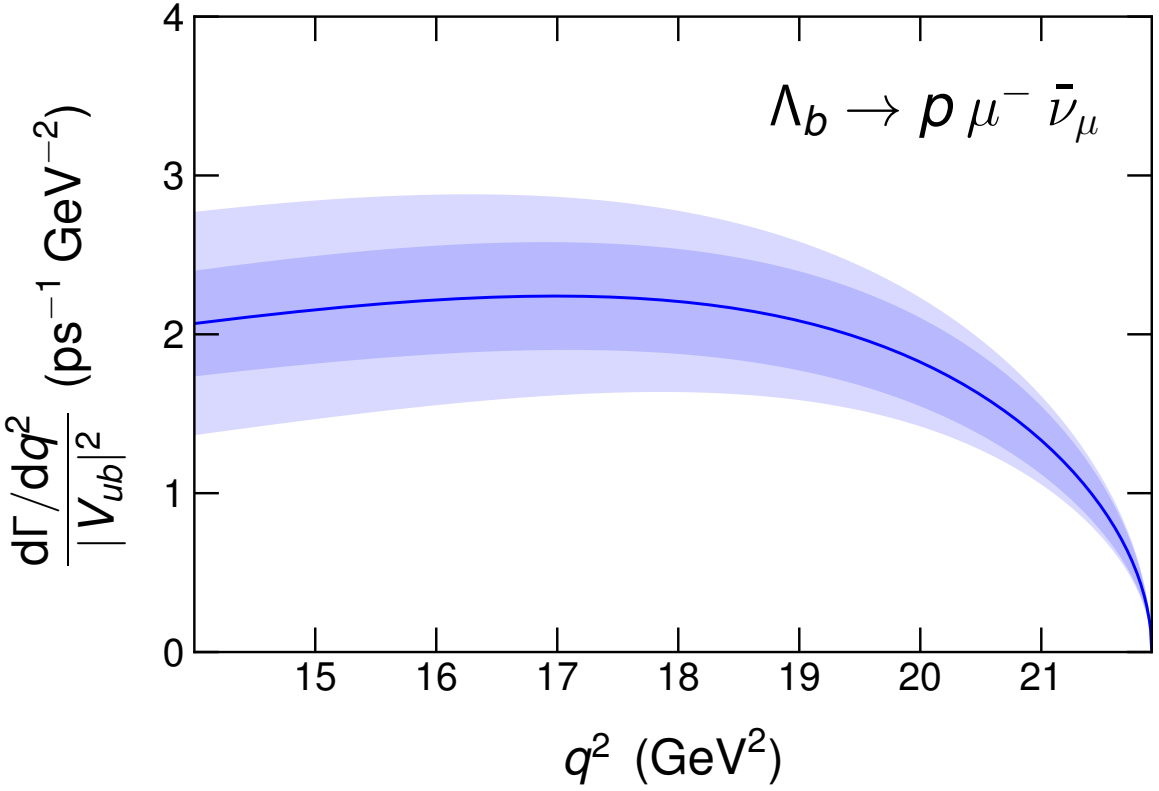
Lattice QCD calculation using domain-wall u, d, s quarks and Eichten-Hill static b quark:

[Detmold, Lin, Meinel, Wingate, PRD 88, 014512 (2013)]:



$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$

Predicted differential decay rate $/|V_{ub}|^2$:



Outer error band includes $\dfrac{\sqrt{|\mathbf{p}'|^2 + \Lambda_{\rm QCD}^2}}{m_b}$ uncertainty from static approximation

$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$

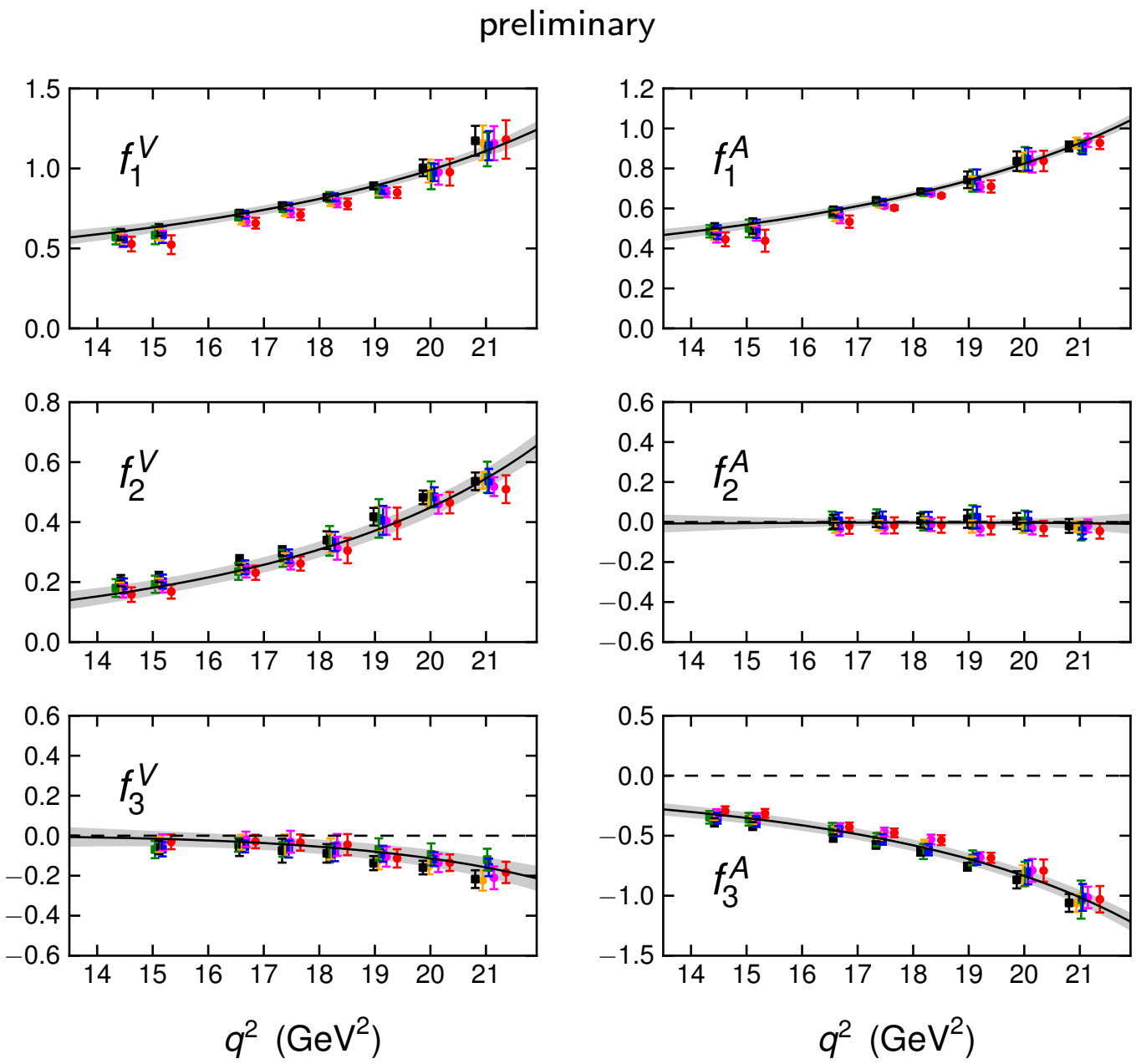
$\Lambda_b \to p$ form factors with relativistic b quarks:

$$\begin{aligned}
\langle N^+|\,\overline{u}\,\gamma^\mu\,b\,|\Lambda_b\rangle &= \overline{u}_N\big[f_1^V\,\gamma^\mu - f_2^V\,i\sigma^{\mu\nu}q_\nu/m_{\Lambda_b} + f_3^V\,q^\mu/m_{\Lambda_b}\big]u_{\Lambda_b}, \\
\langle N^+|\,\overline{u}\,\gamma^\mu\gamma_5\,b\,|\Lambda_b\rangle &= \overline{u}_N\big[f_1^A\,\gamma^\mu - f_2^A\,i\sigma^{\mu\nu}q_\nu/m_{\Lambda_b} + f_3^A\,q^\mu/m_{\Lambda_b}\big]\gamma_5\,u_{\Lambda_b}
\end{aligned}$$

Lattice QCD calculation in progress [Meinel, arXiv:1401.2685]:

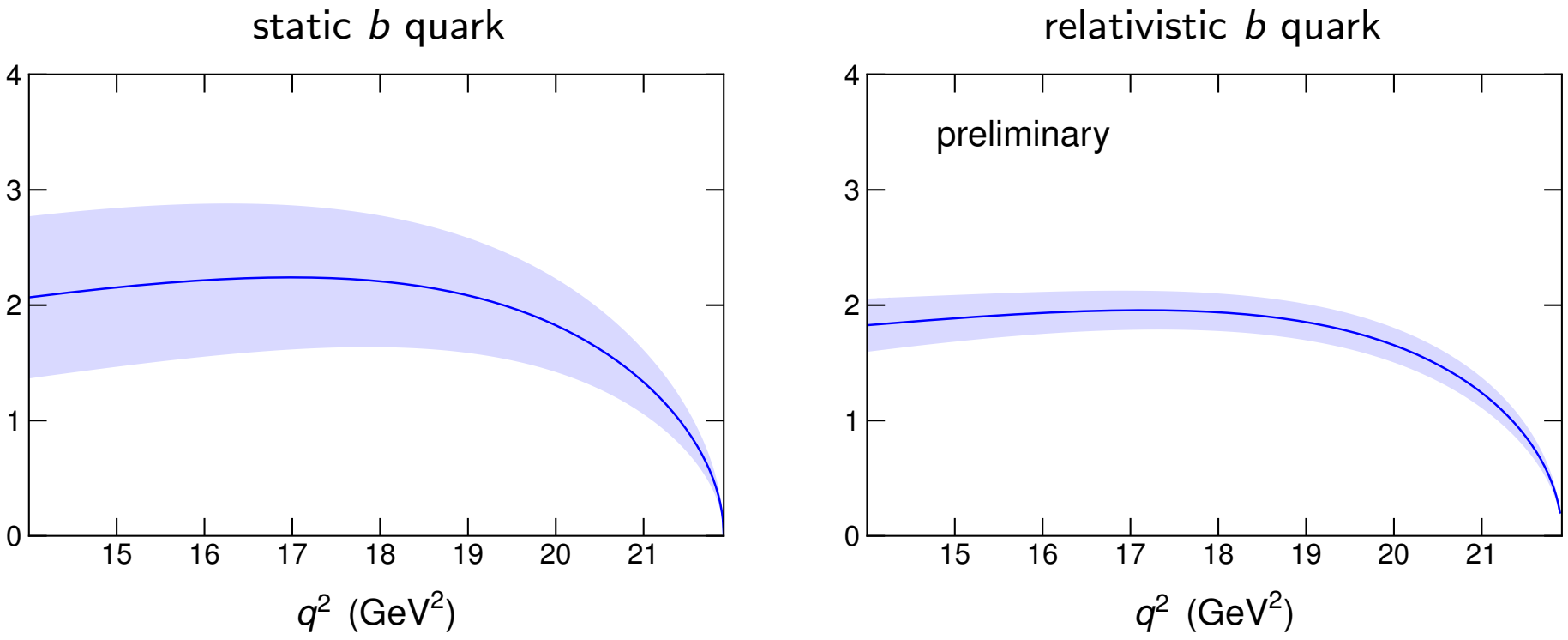
- domain-wall u, d, s quarks
- RHQ b quarks

$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$



$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$

$$\frac{\mathrm{d}\Gamma/\mathrm{d}q^2}{|V_{ub}|^2}\ (\mathrm{ps}^{-1}\,\mathrm{GeV}^{-2})$$



Total uncertainties shown.

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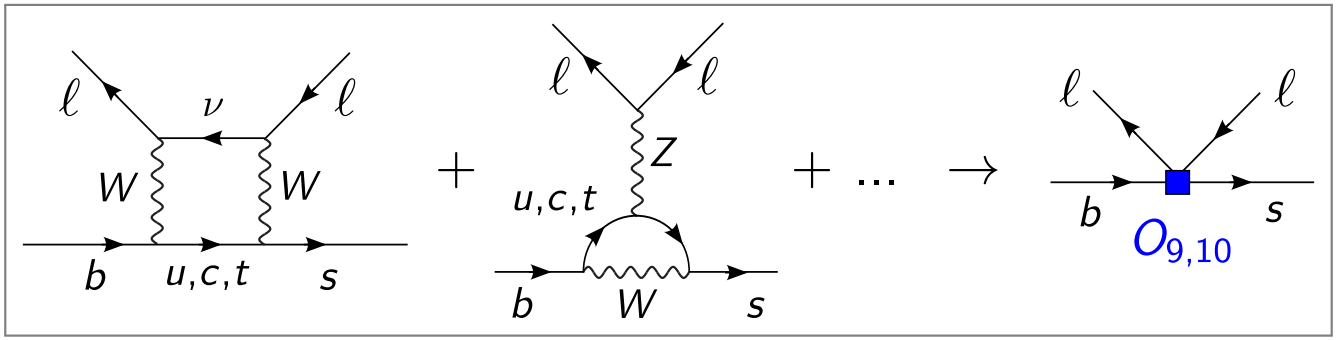
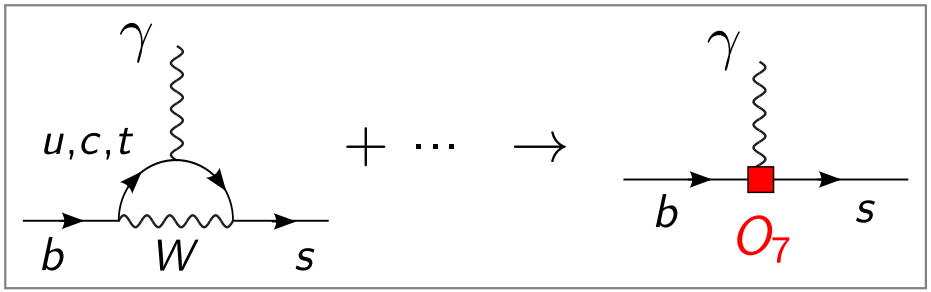
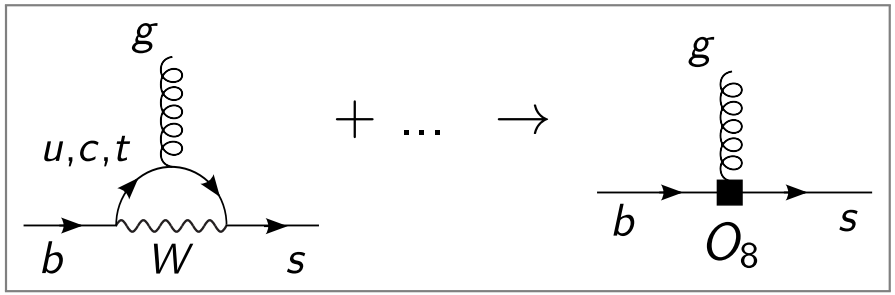
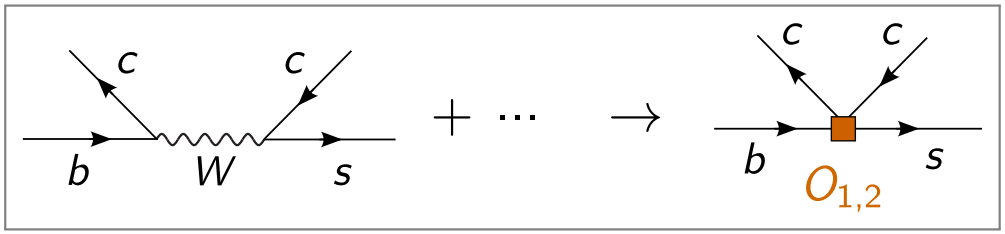
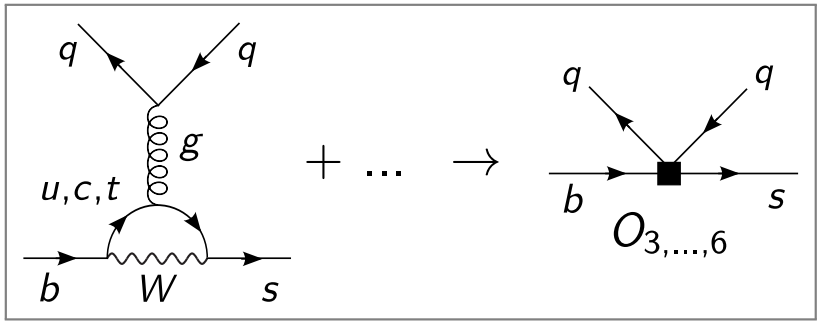
$b \to s\,\ell^+\ell^-$ decays











[Grinstein, Savage, Wise, NPB 319, 271 (1989)]

$b \to s\ell^+\ell^-$ effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i O_i + C_i' O_i' \right)$$

with

$$\begin{aligned}
O_7^{(\prime)} &= \frac{e\, m_b}{16\pi^2}\ \bar{s}\sigma^{\mu\nu} P_{R(L)} b\ \ F_{\mu\nu}^{(\text{e.m.})}, \\
O_9^{(\prime)} &= \frac{e^2}{16\pi^2}\ \bar{s}\gamma^\mu P_{L(R)} b\ \ \bar{\ell}\gamma_\mu \ell, \\
O_{10}^{(\prime)} &= \frac{e^2}{16\pi^2}\ \bar{s}\gamma^\mu P_{L(R)} b\ \ \bar{\ell}\gamma_\mu\gamma_5 \ell
\end{aligned}$$

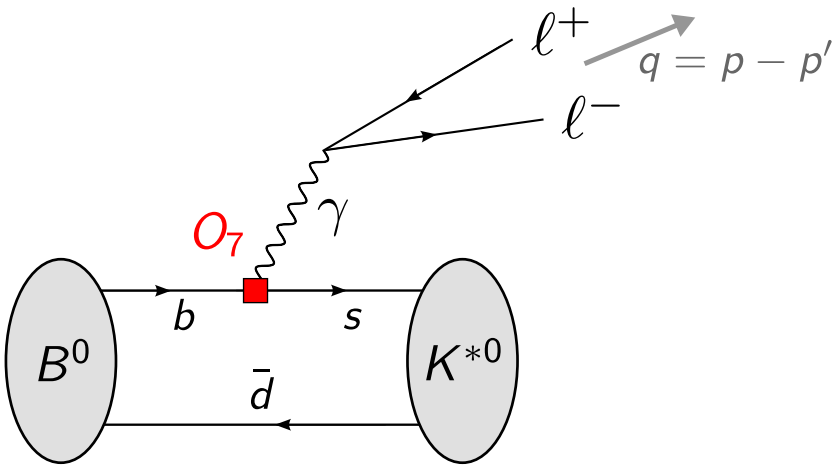
$[P_{R,L} = (1 \pm \gamma_5)/2]$

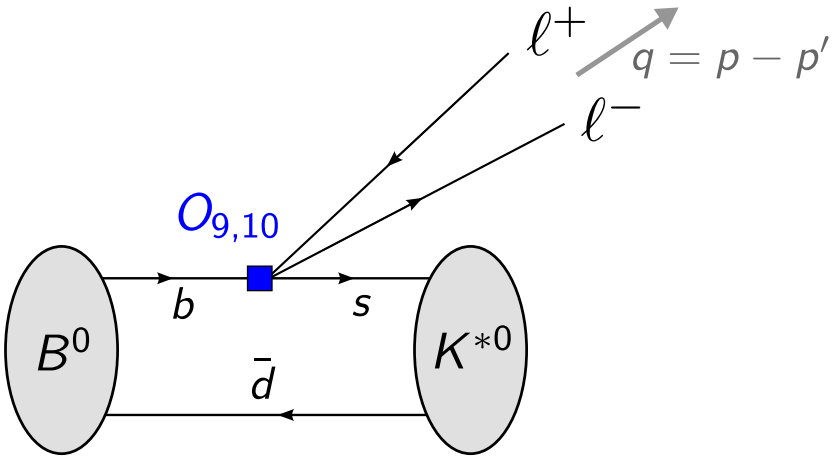
In the Standard Model, at $\mu = m_b$, to order NNLL:

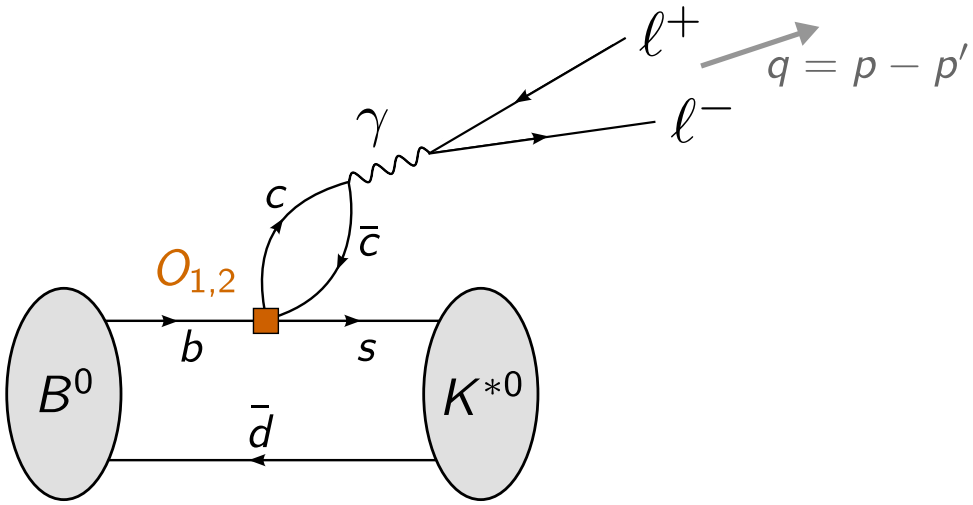
C_7	C_9	C_{10}
-0.331	4.211	-4.103
C_7'	C_9'	C_{10}'
-0.006	0	0

[Altmannshofer et al., JHEP 0901, 019 (2009)]

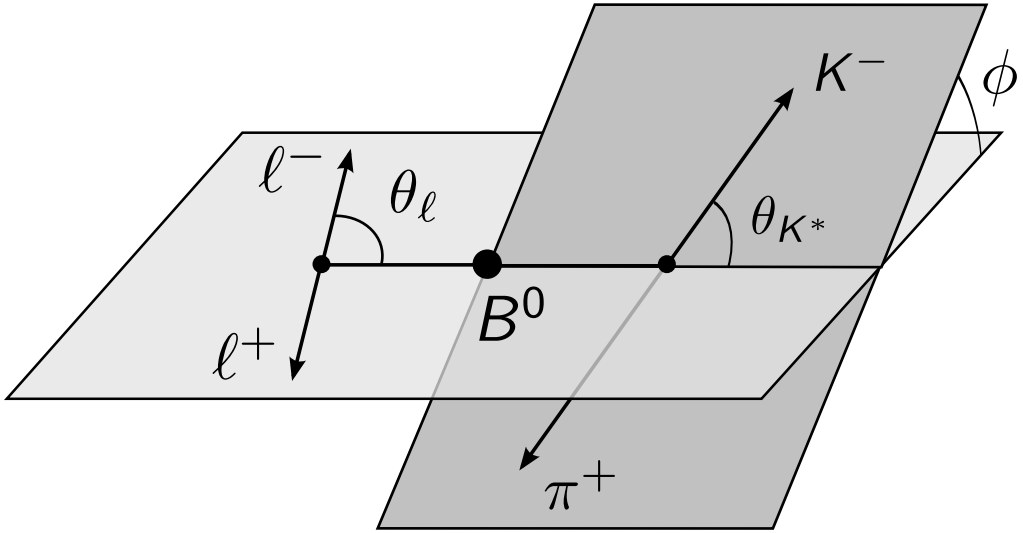
The decay $B^0 \to K^{*0}(\to K^-\pi^+)\mu^+\mu^-$







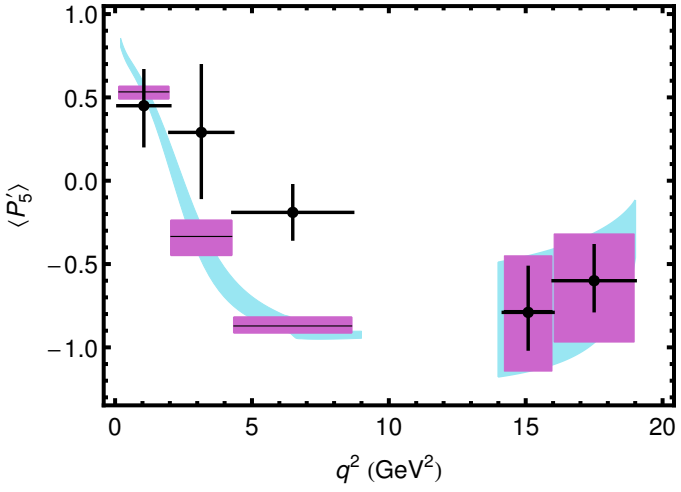
The decay $B^0 \to K^{*0}(\to K^-\pi^+)\mu^+\mu^-$



Many observables. Gives powerful constraints on Wilson coefficients.

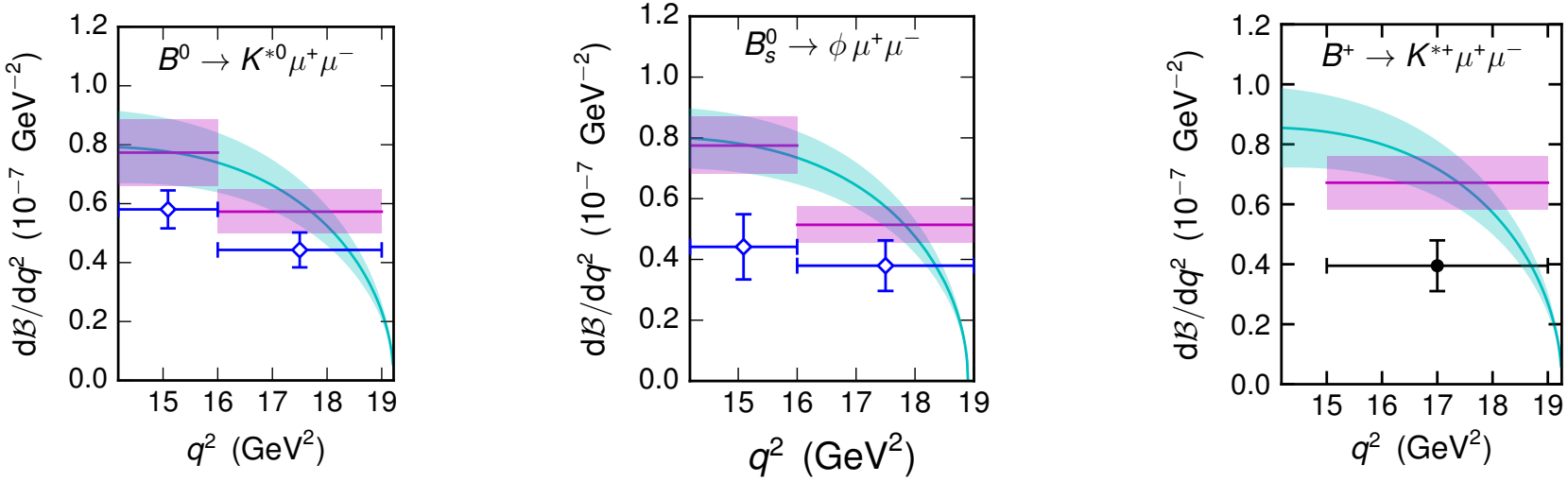
Deviations from the Standard Model?

Angular observables [Descotes-Genon, Matias, Virto, PRD 88, 074002 (2013)]:



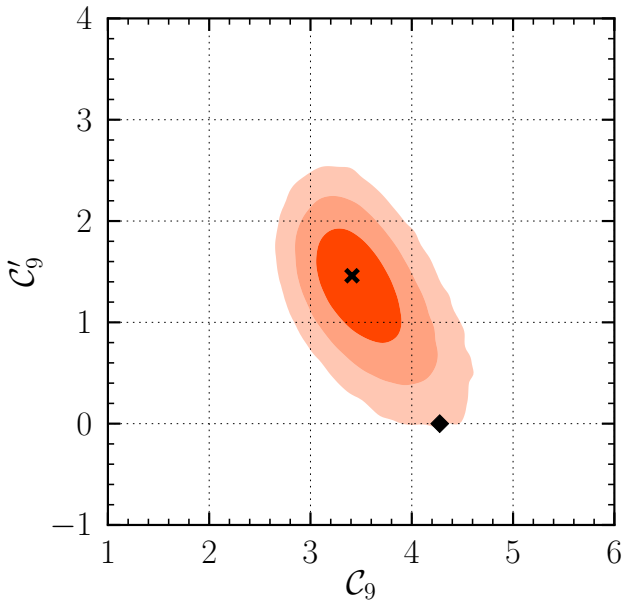
(using narrow-width approximation for K^*)

Differential decay rates [Horgan, Liu, Meinel, Wingate, PRL 112, 212003 (2014)]:



Deviations from the Standard Model?

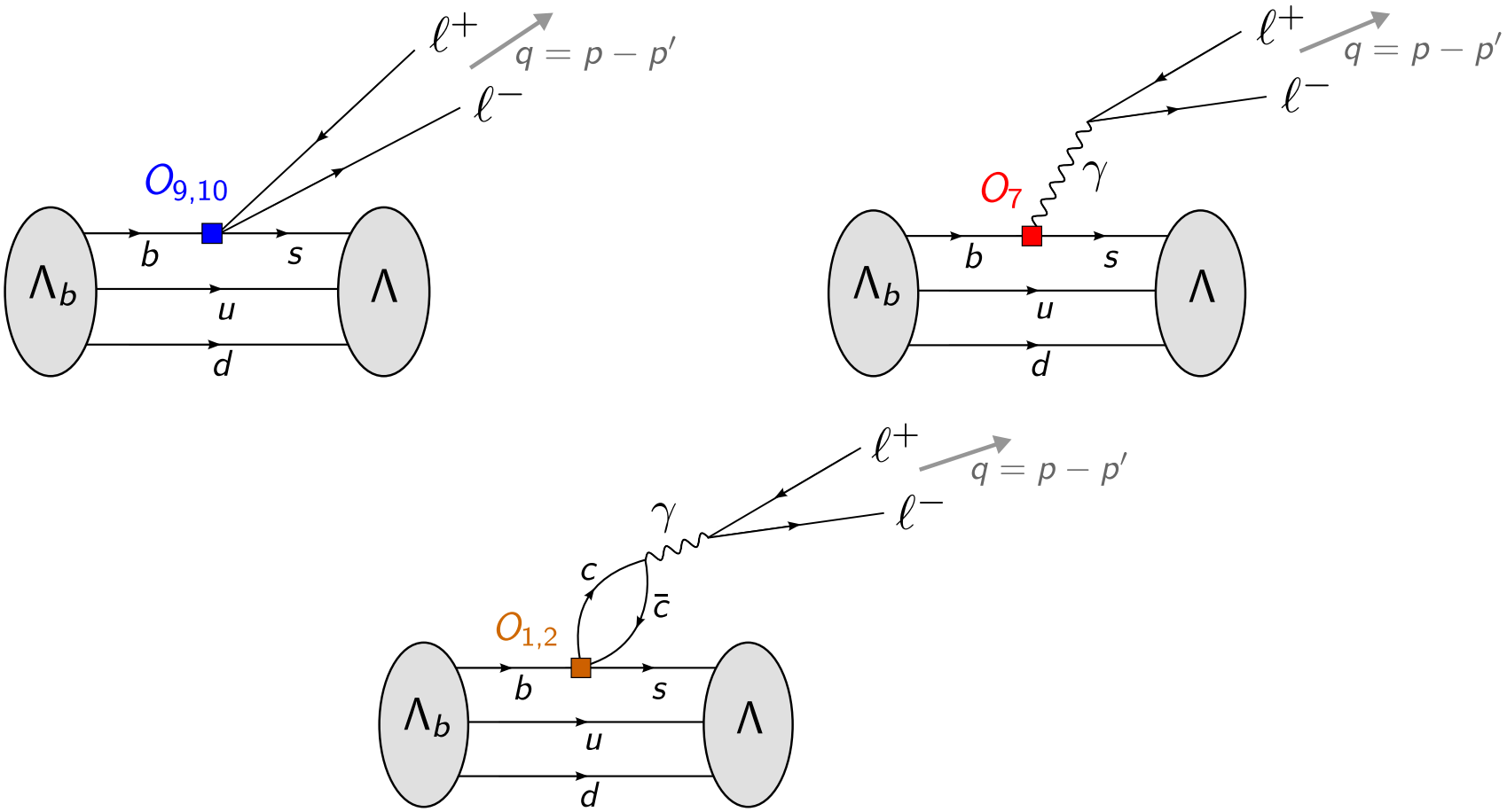
Fitting the Wilson coefficients C_9, C_9' to the data:



[Beaujean, Bobeth, Van Dyk, EPJC 74, 2897 (2014)]

- new Z' gauge boson? [Gauld, Goertz, Haisch, JHEP 1401, 069 (2014)]
- contributions from charm four-quark operators? [Lyon and Zwicky, arXiv:1406.0566]

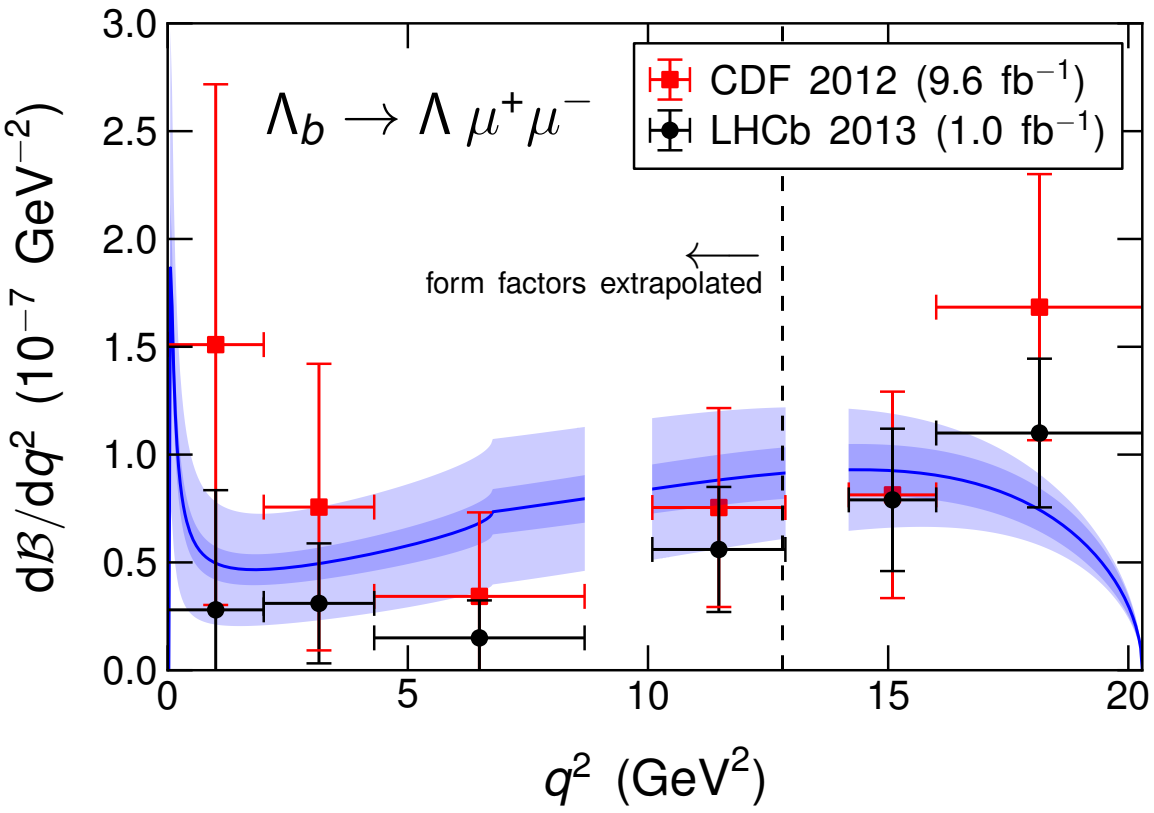
The decay $\Lambda_b \to \Lambda(\to p\,\pi^-)\,\mu^+\mu^-$



- Same or better new-physics sensitivity compared to $B^0 \to K^{*0}(\to K^-\pi^+)\mu^+\mu^-$
- Λ is stable in QCD. Narrow-width approximation is exact. $\Lambda_b \to \Lambda$ form factors are "gold-plated" quantities in lattice QCD

The decay $\Lambda_b \to \Lambda(\to p\,\pi^-)\,\mu^+\mu^-$

Using form factors from lattice QCD with static b quarks:

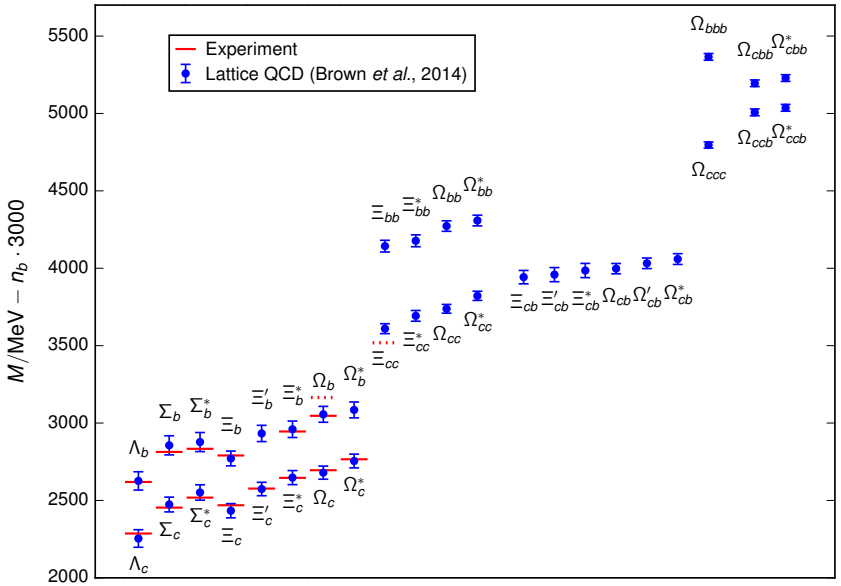
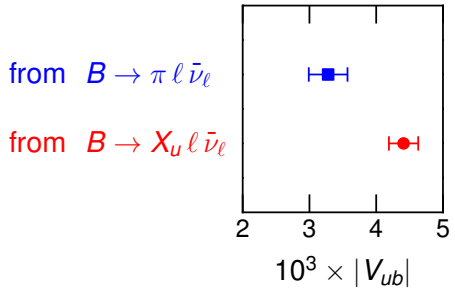
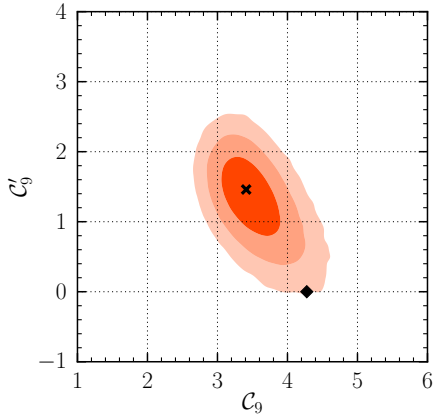


[Detmold, Lin, Meinel, Wingate, PRD 87, 074502 (2013)]

New calculation with RHQ b quarks in progress [Meinel, arXiv:1401.2685]

Updated LHCb results with 3 fb^{-1} and angular analysis are forthcoming.

Summary

Heavy baryons are interesting and useful.

- Many states remain to be discovered.
- In the absence of experimental data, lattice QCD results for doubly and triply heavy baryons provide tests of models and effective field theories.
- The decay $\Lambda_b \to p\mu\bar{\nu}$ will allow the first determination of $|V_{ub}|$ at the LHC (using form factors from lattice QCD).
- The decay $\Lambda_b \to \Lambda(\to p\,\pi^-)\mu^+\mu^-$ will test recent hints of new physics in $b \to s\mu^+\mu^-$ (using form factors from lattice QCD).