Study of the radial excitation of hadron

Ahmad Jafar Arifi

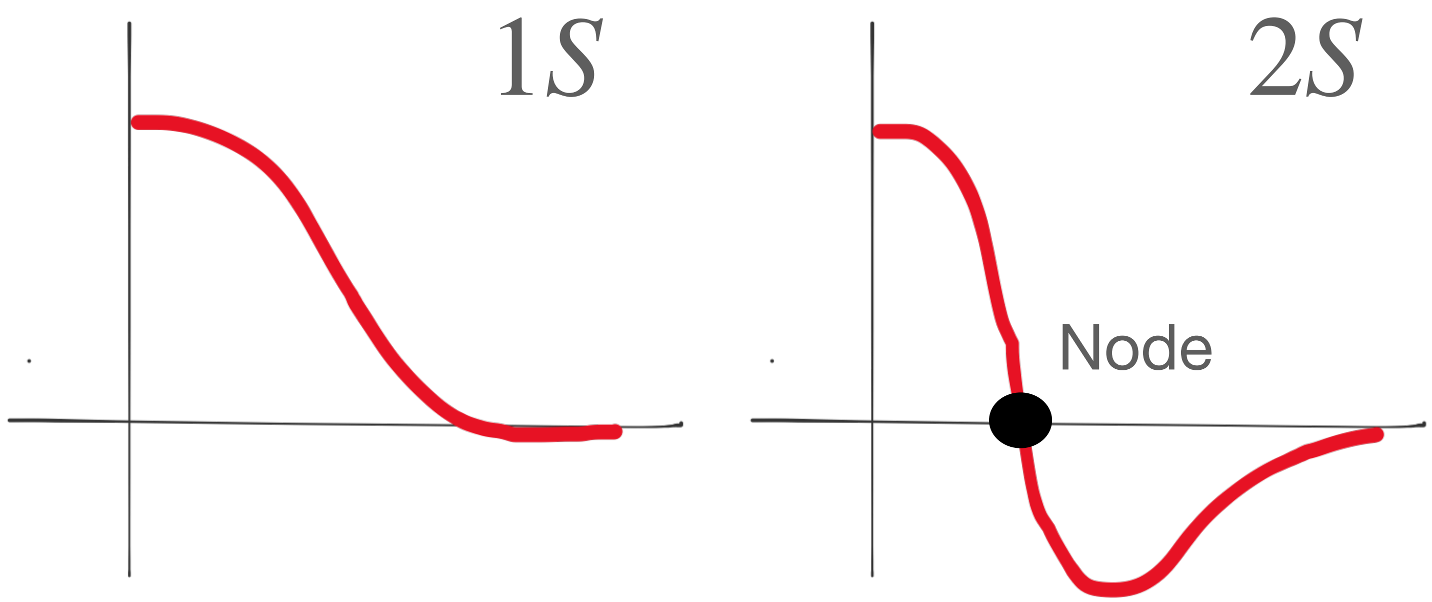
Inha HTG Workshop: Modern issues in hadron physics

Contents

- Radial excitation — **Hadron**
- Multi-body decays
  —> Dalitz plots — **Reaction**
- Light-front quark model
  —> Mass spectra,
  —> Wave-function, — **Structure**
- Global analysis
  —> Monte-Carlo Bootstrap — **Statistics**

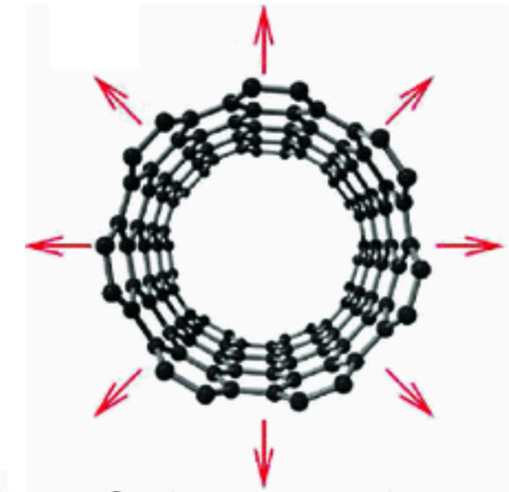
Radial excitation

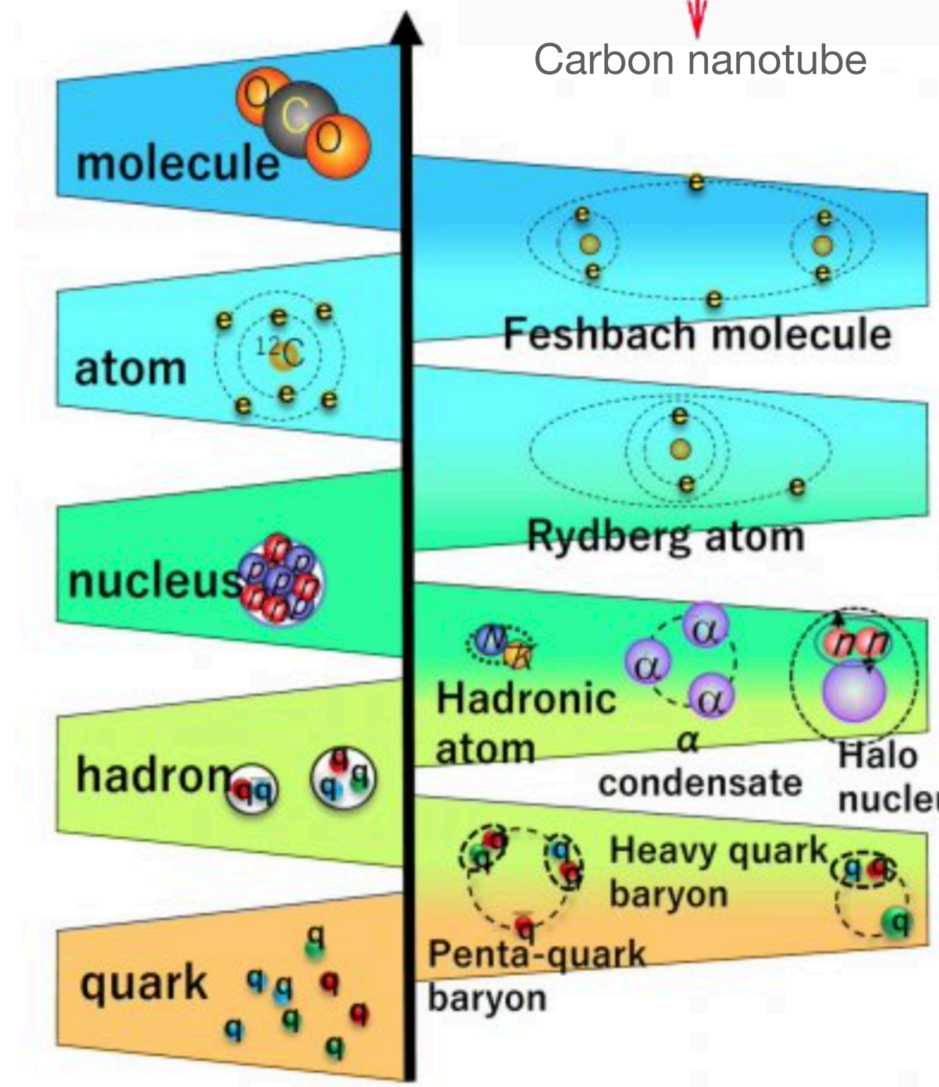
Radial excitation



- **Radial excitation**
  —> a.k.a. Breathing mode,
  —> The same spin-parity with the g. s.
  —> Has "nodal" structure,

- **Hadron**: QCD
  —> E.g. Roper resonance
  —> Puzzle: mass, decay, etc.
  —> Similar behaviors


Carbon nanotube



http://be.nucl.ap.titech.ac.jp/cluster/

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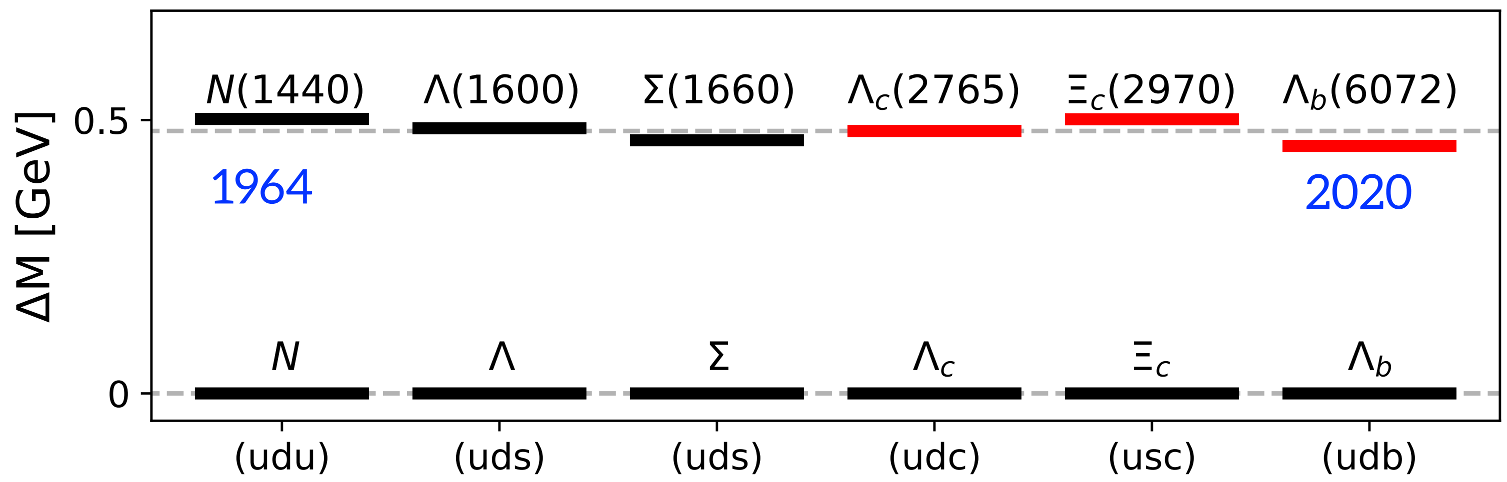
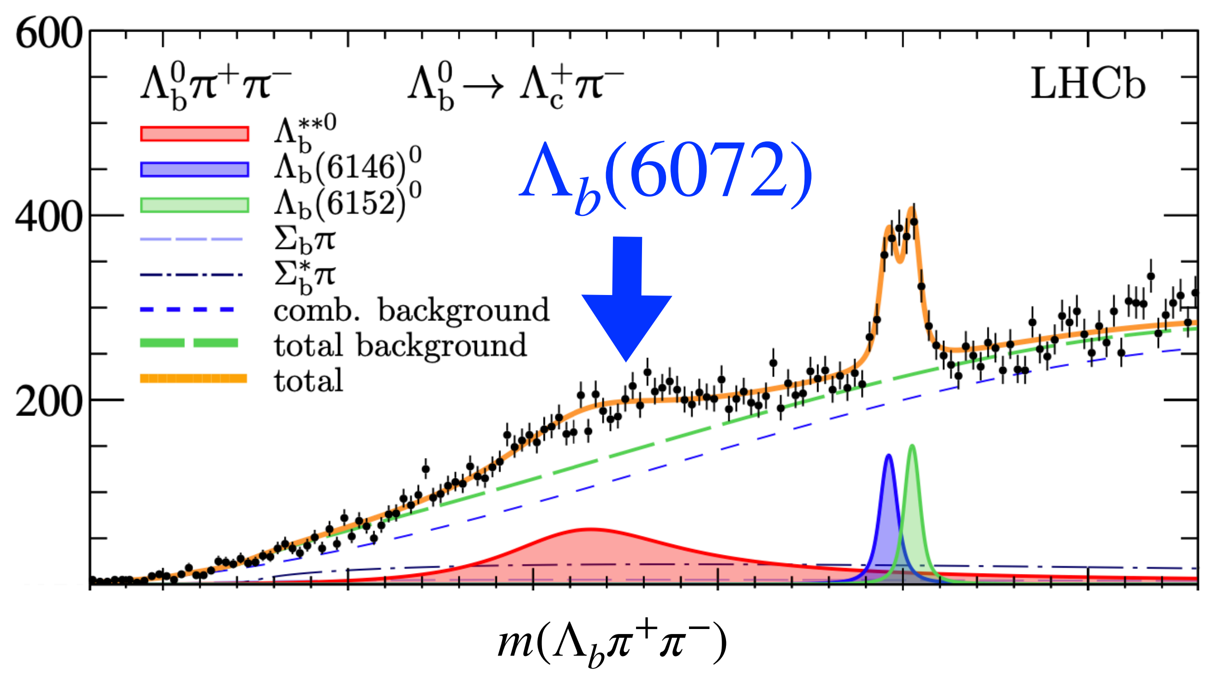
Hadrons: 1S and 2S state baryon

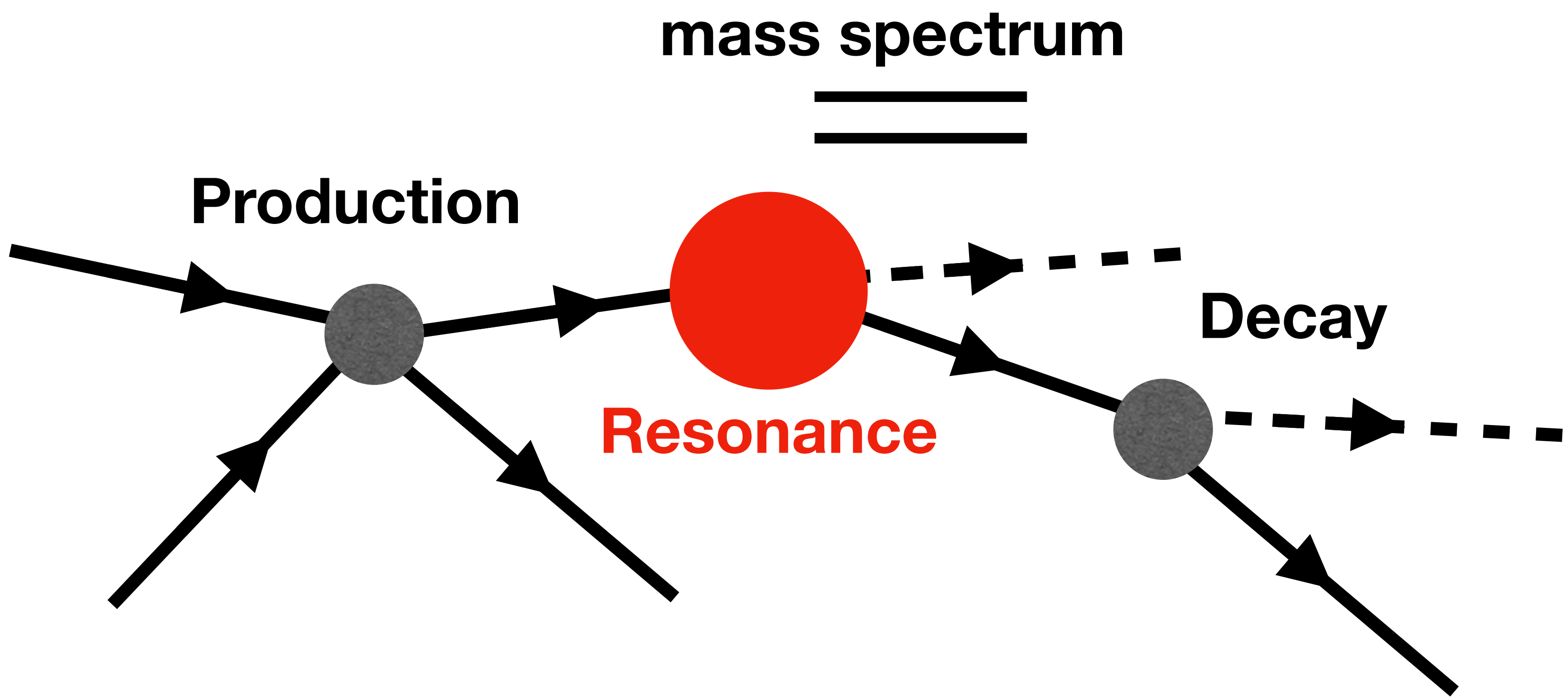


<> Similar mass gap
$\Delta M \sim 500$ MeV
Universal?
Accidental?



<> A broad resonance
($\Gamma = 72$ MeV).
Orthogonality?

Methodology



Internal structure:

—> **Production,** Cross section, polarization observables, etc

—> **Spectrum,** Mass, mass splitting, etc

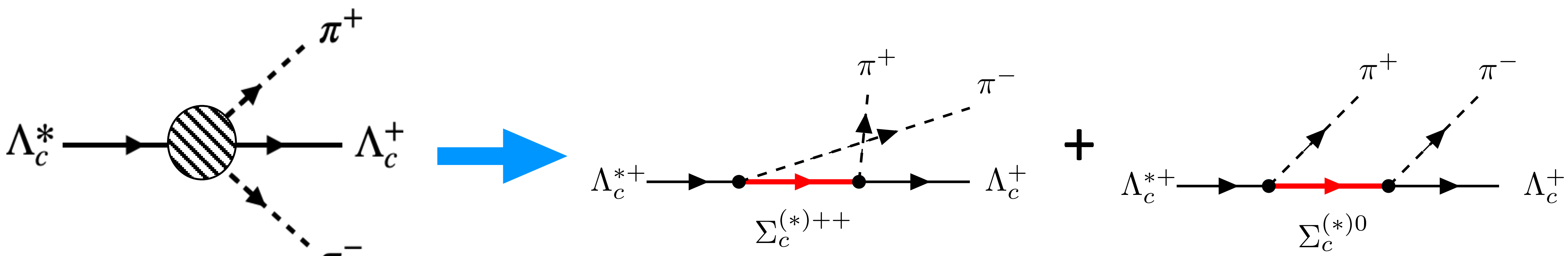
—> **Decay,** Decay rates, branching fraction, etc

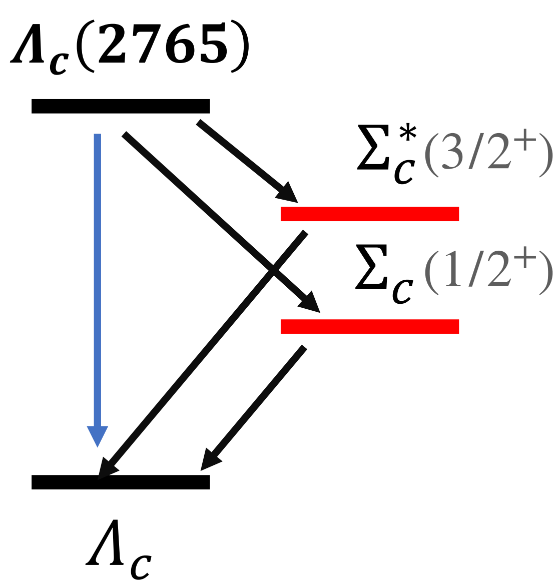
Resonance: mass, decay rate, spin, parity, isospin, etc

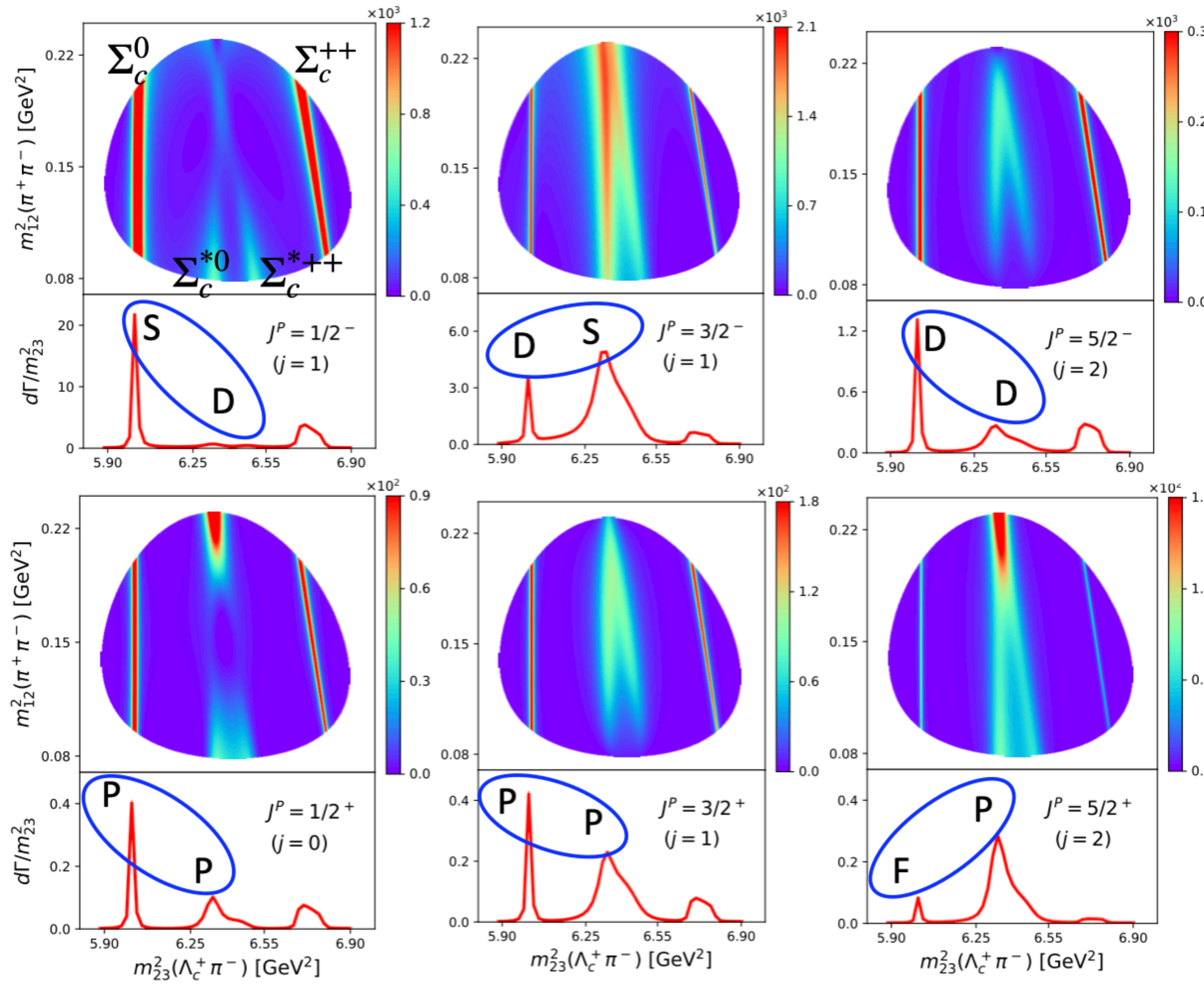
Three-body decay

Dalitz plot

Spin-parity of $\Lambda_c(2765)$



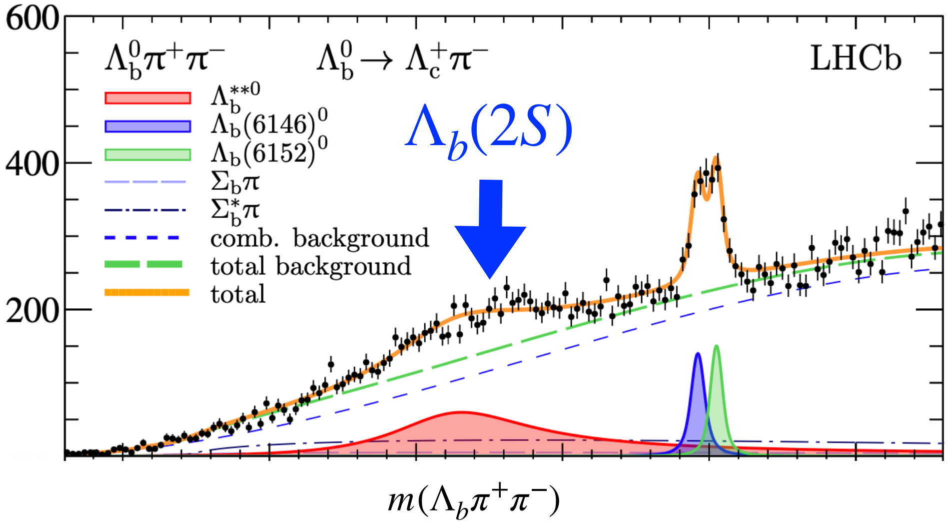


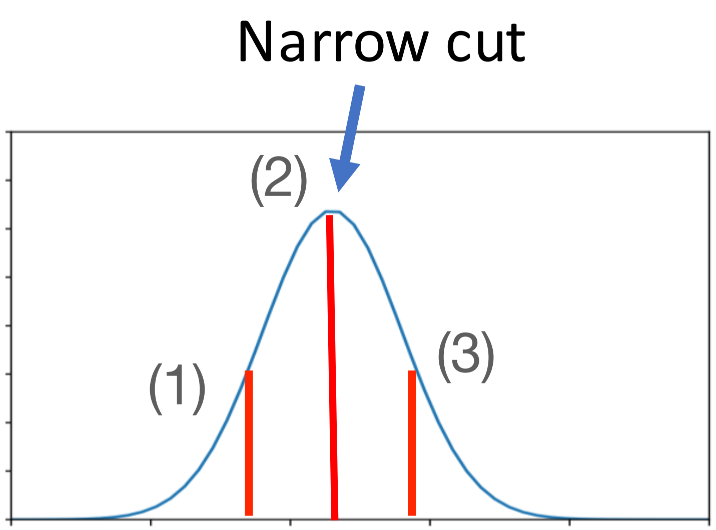


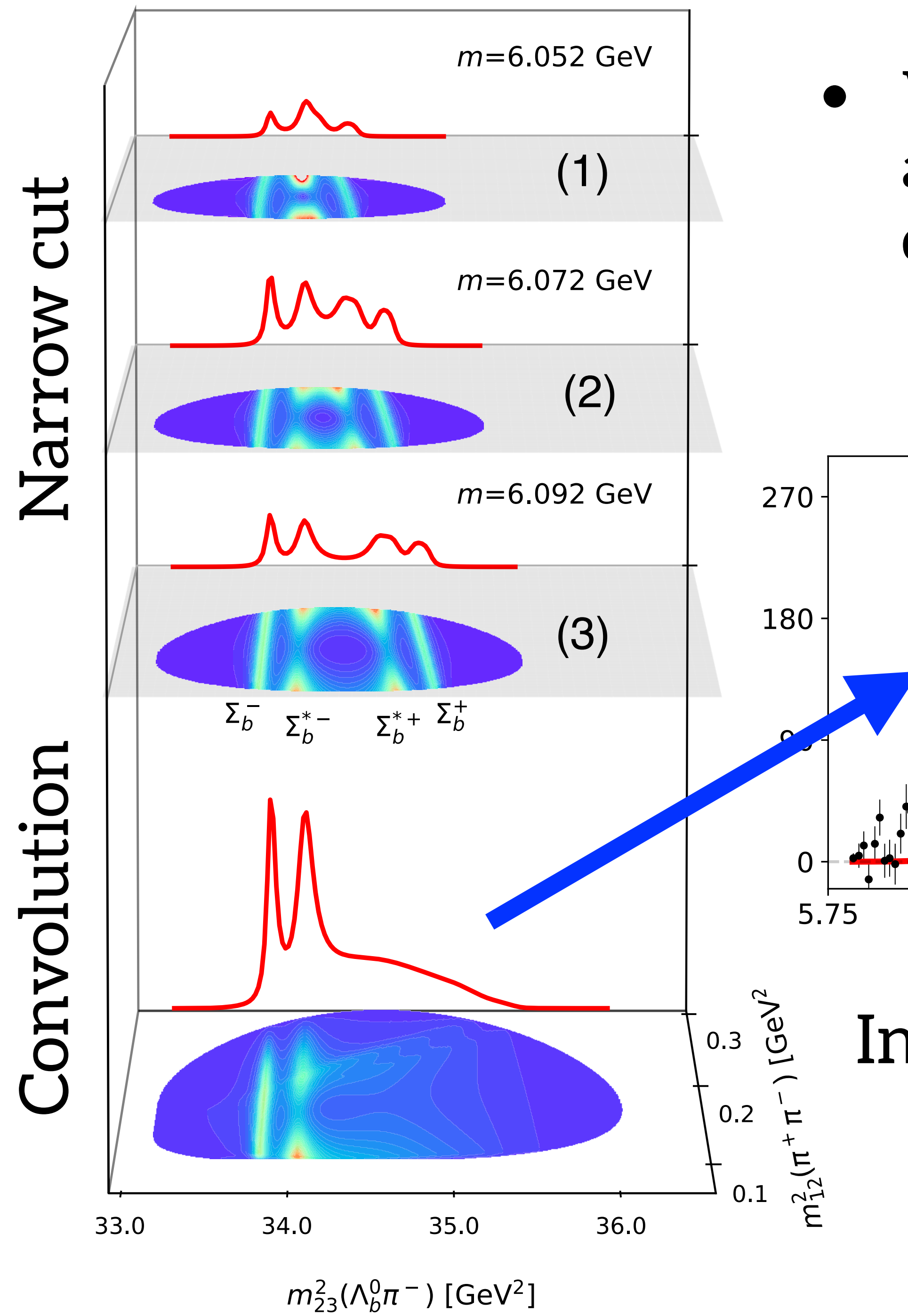
- Prediction for the Belle experiment.

Arifi, *et. al.* PRD101 094023 (2020)

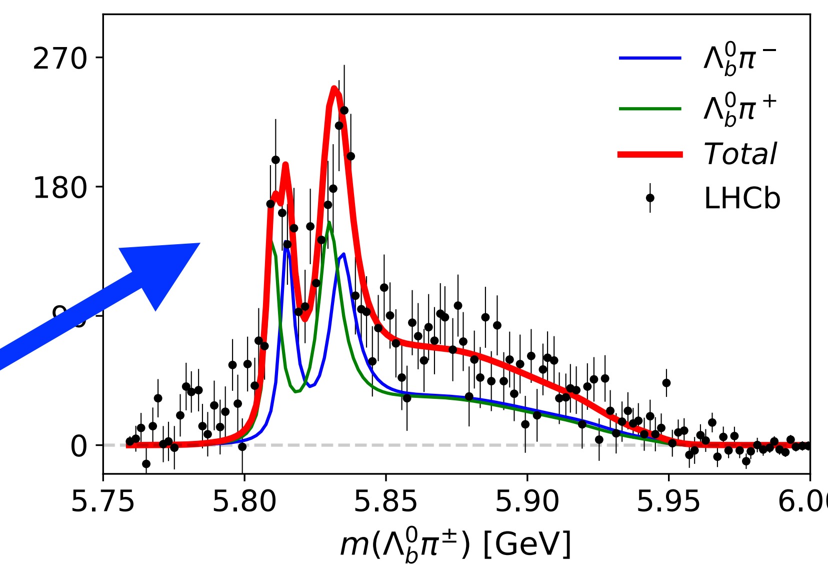
Decay of $\Lambda_b^*(6072)$







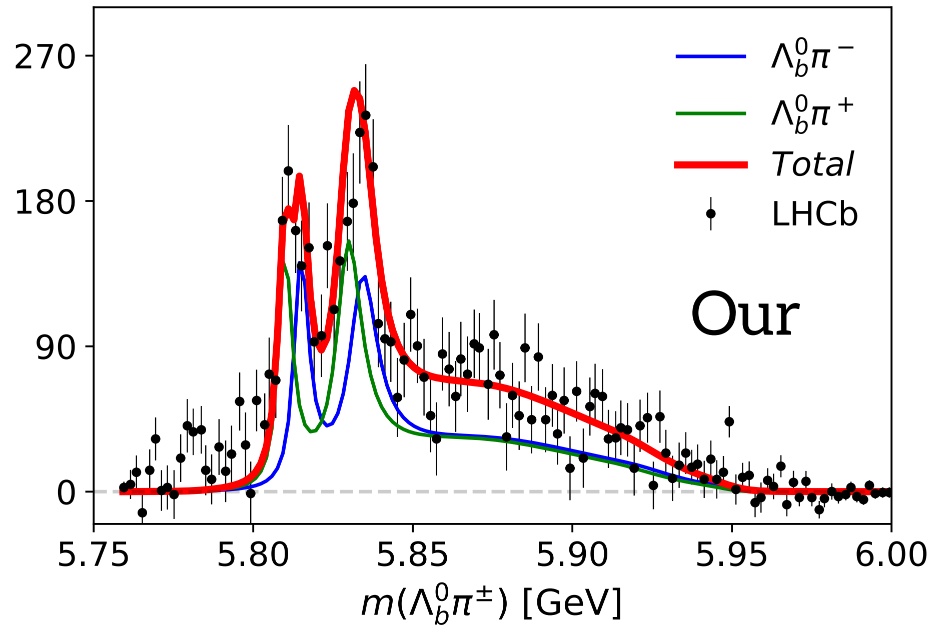
- With spin-parity 1/2+ assumption,
  data can be reproduced.

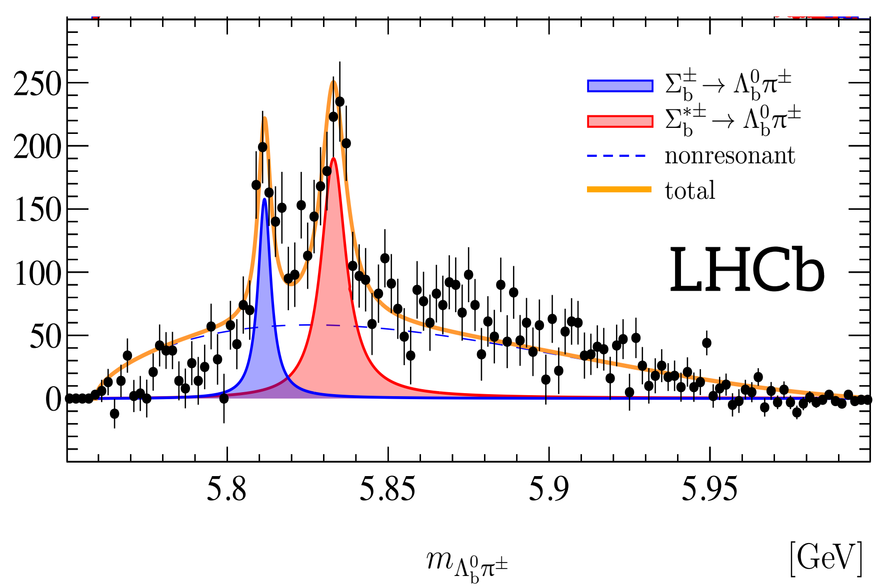


Invariant mass plot

Arifi, *et. al.* PRD101 (R) 111502 (2020)

Comparison with LHCb analysis





- Background shape is from the kinematical reflection.

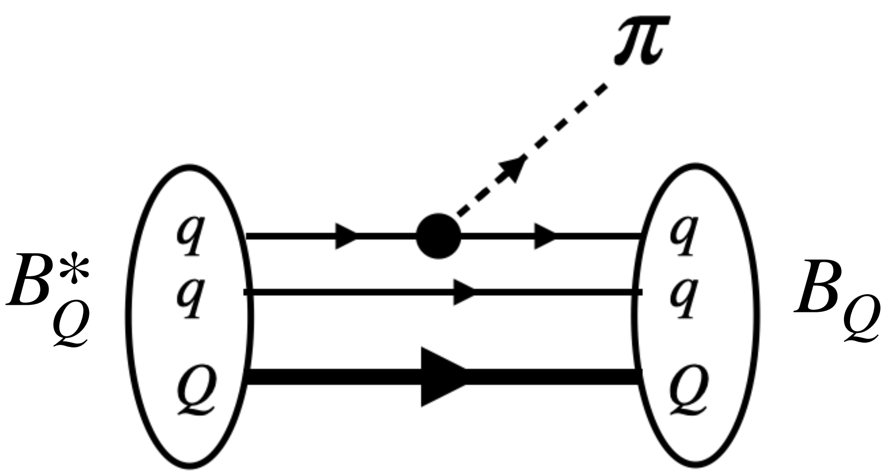
- non-resonant contribution is relatively large.

Light-front quark model

Mass spectra and wave functions

Problem of Non-rel Quark model

- Strong decay of $\Lambda_b(6072)$



[1] Wave function
—> HO (gaussian)

[2] Quark-pion interaction

$$\mathcal{L}_{\pi qq} = \frac{g_A^q}{2f_\pi} \bar{q}\gamma^\mu \gamma_5 \vec{\tau} q \cdot \partial_\mu \vec{\pi}$$

—-> Nonrelativistic expansion

$$\propto g(\sigma \cdot q - \frac{\omega}{2m} \sigma \cdot (p_i + p_f))$$

<> $\Lambda_b(6072)$ —> Γ ~ 5 MeV (narrow)

Γ_{exp} = 72 MeV

- Orthogonality of w.f. ?
- Relativistic effect?

Light-front quark model

- Constituent quark model
- Light-front dynamics

⇨ Hadrons: $q\bar{q}$, qqq

[1] Trial wave function
—> Gaussian (H.O. basis).

$$\phi_{1S}(x, \mathbf{k}_\perp) = \frac{4\pi^{3/4}}{\beta^{3/2}} \sqrt{\frac{\partial k_z}{\partial x}} e^{-\vec{k}^2/2\beta^2},$$

$$\phi_{2S}(x, \mathbf{k}_\perp) = \frac{4\pi^{3/4}}{\sqrt{6}\beta^{7/2}} \left(2\vec{k}^2 - 3\beta^2\right) \sqrt{\frac{\partial k_z}{\partial x}} e^{-\vec{k}^2/2\beta^2},$$

[2] Effective potentials
—> Cornel potential, etc

[3] Variational Parameters β
—> Fixed from mass spectra

$$M_{q\bar{q}} = \langle\Psi| [H_0 + V_{q\bar{q}}] |\Psi\rangle$$

$$\frac{\partial \langle\Psi| [H_0 + V_0] |\Psi\rangle}{\partial\beta} = 0$$

Problem!!
—> Using pure HO basis
—> Can't explain 2S decay constant.

Problem of decay constant

<> Decay constants of Upsilon (Exp)

—> f($\Upsilon(1S)$) = 689 MeV

—> f($\Upsilon(2S)$) = 497 MeV

<> If we use 2S HO wave function

—> If we use the same β parameters

—> always f($\Upsilon(2S)$) > f($\Upsilon(1S)$)

<> To solve the problem:

—> Modify the wave function

—> Simply use different β parameters

Wave function of 1S and 2S states

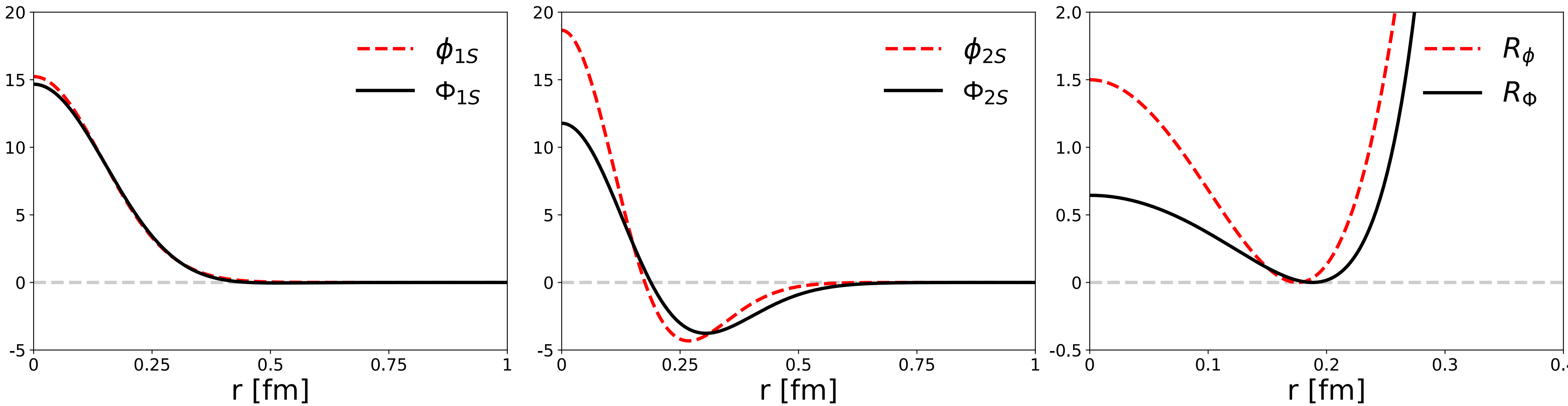
<> Minimal mixing

—> The same β for 1S and 2S states

—> keep orthogonality

—> doesn't change 1S WF

$$\begin{pmatrix} \Phi_{1S} \\ \Phi_{2S} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_{1S} \\ \phi_{2S} \end{pmatrix},$$



<> Only need a small mixing

—> $\theta = 12^\circ$

—> $|\cos\theta|^2 = 95.7\,\%\,, |\sin\theta|^2 = 4.3\,\%\,,$

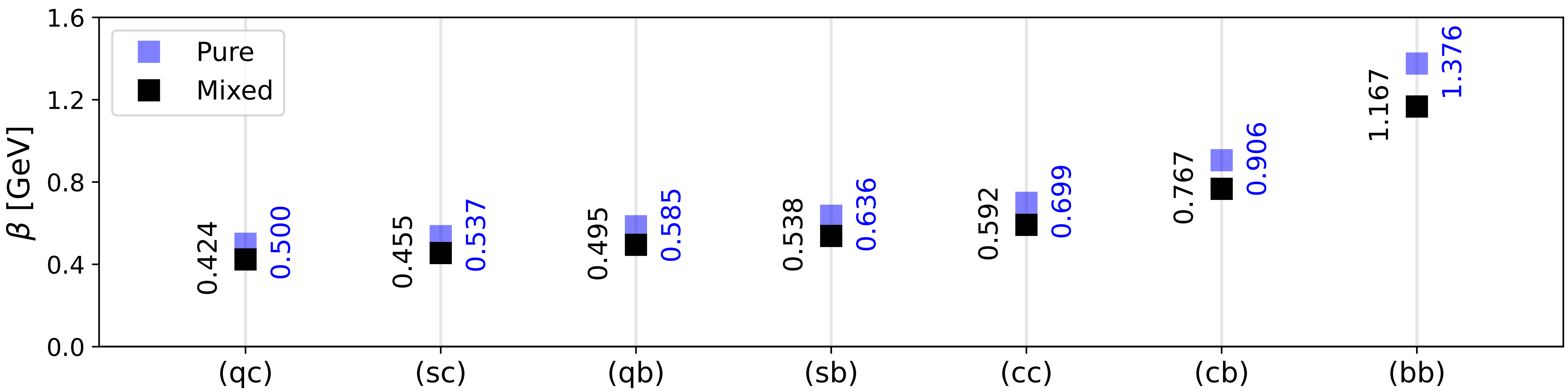
<> Huge impact to observables.

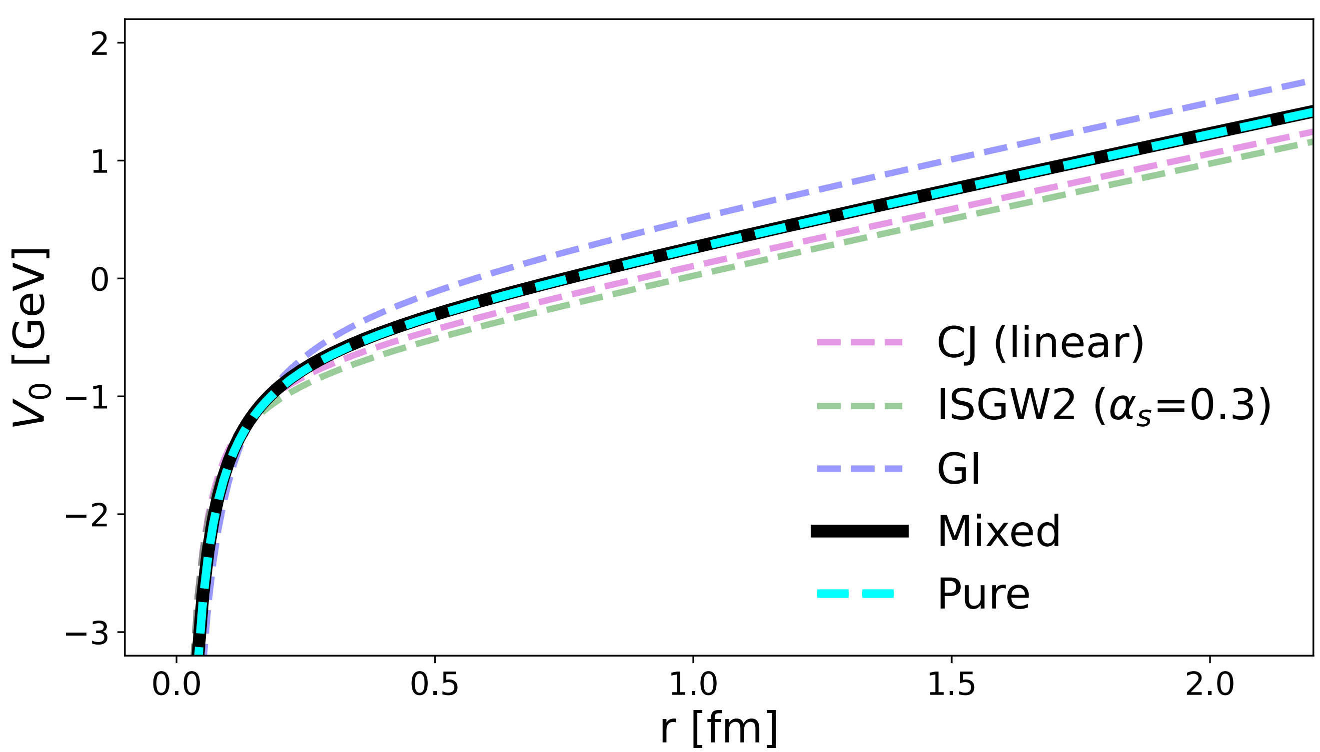
—> Mass spectra,

—> Decay constants,

—> Charge radii, etc

Variational and potential parameters





<> In the mixed scenario:

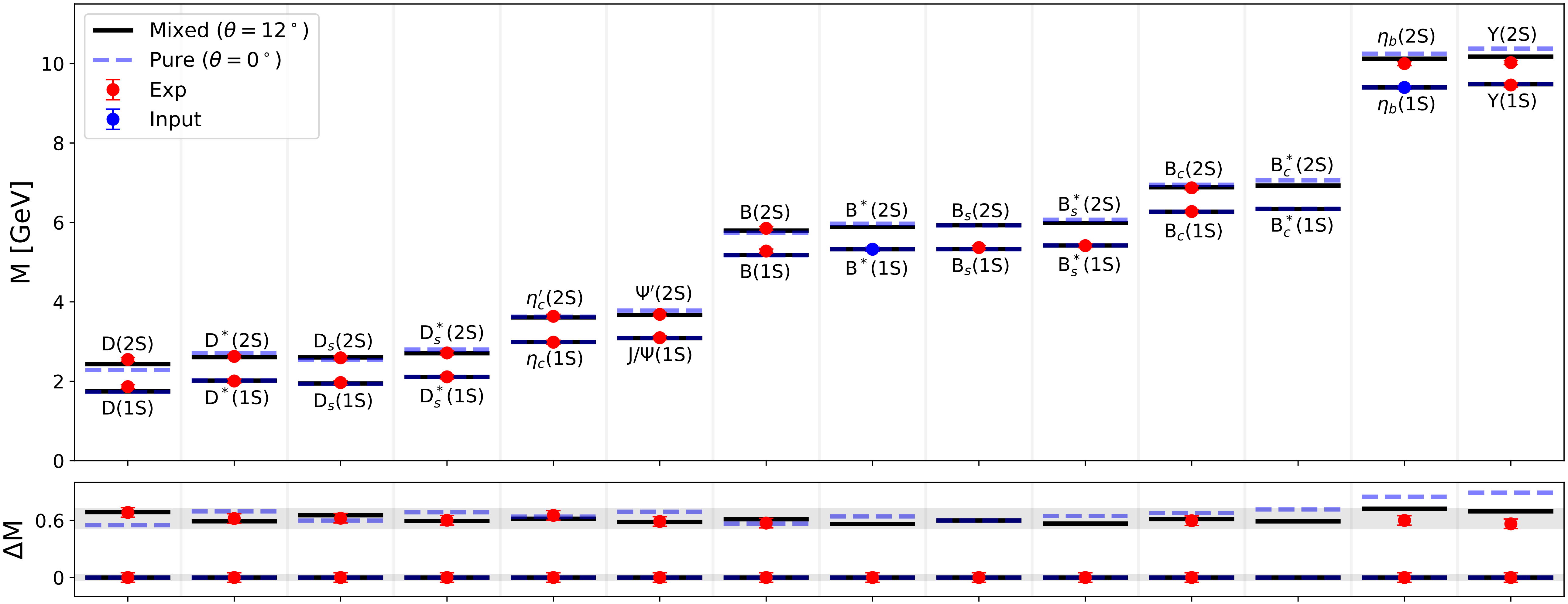
—> use the same quark mass.

—> β systematically decrease.

—> Potential look the same.

$$V_{q\bar{q}} = a + br - \frac{4\alpha_s}{3r}$$

Mass spectra and gaps



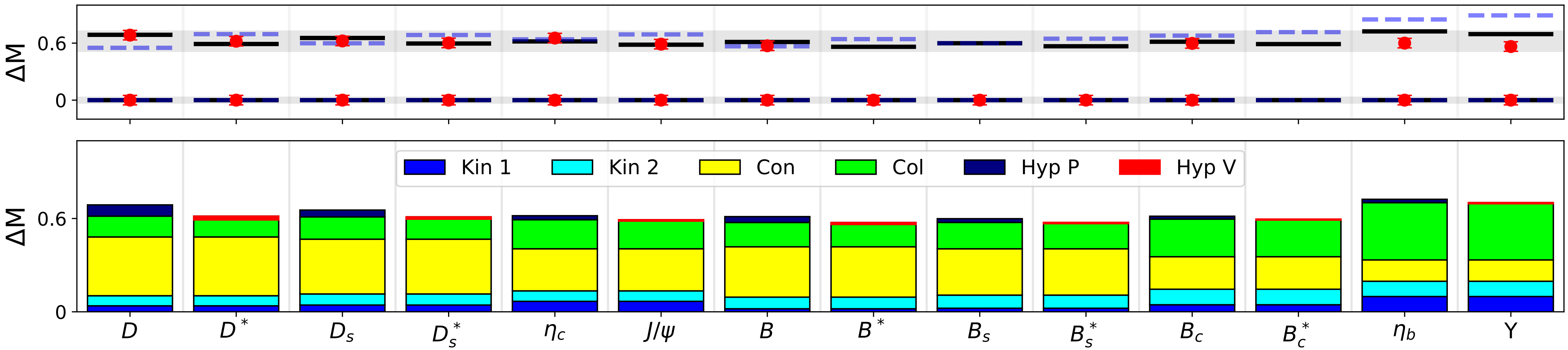
$$V_{q\bar{q}} = a + br - \frac{4\alpha_s}{3r} + \frac{2}{3}\frac{\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}}}{m_q m_{\bar{q}}}\nabla^2 V_{\text{Coul}}$$

$$M_{q\bar{q}} = \langle \Psi | \left[H_0 + V_{q\bar{q}} \right] | \Psi \rangle$$

<> Similar mass gap around 600 MeV

<> Mixed scenario
—> better agreement

Mass spectra and gaps



<> Competing contribution:

—> Confinement int

$$\Delta M_{conf} \propto \frac{1}{\beta}$$

—> Coulomb int

$$\Delta M_{colmb} \propto \beta$$

<> Hyperfine int

—> Small but, very important

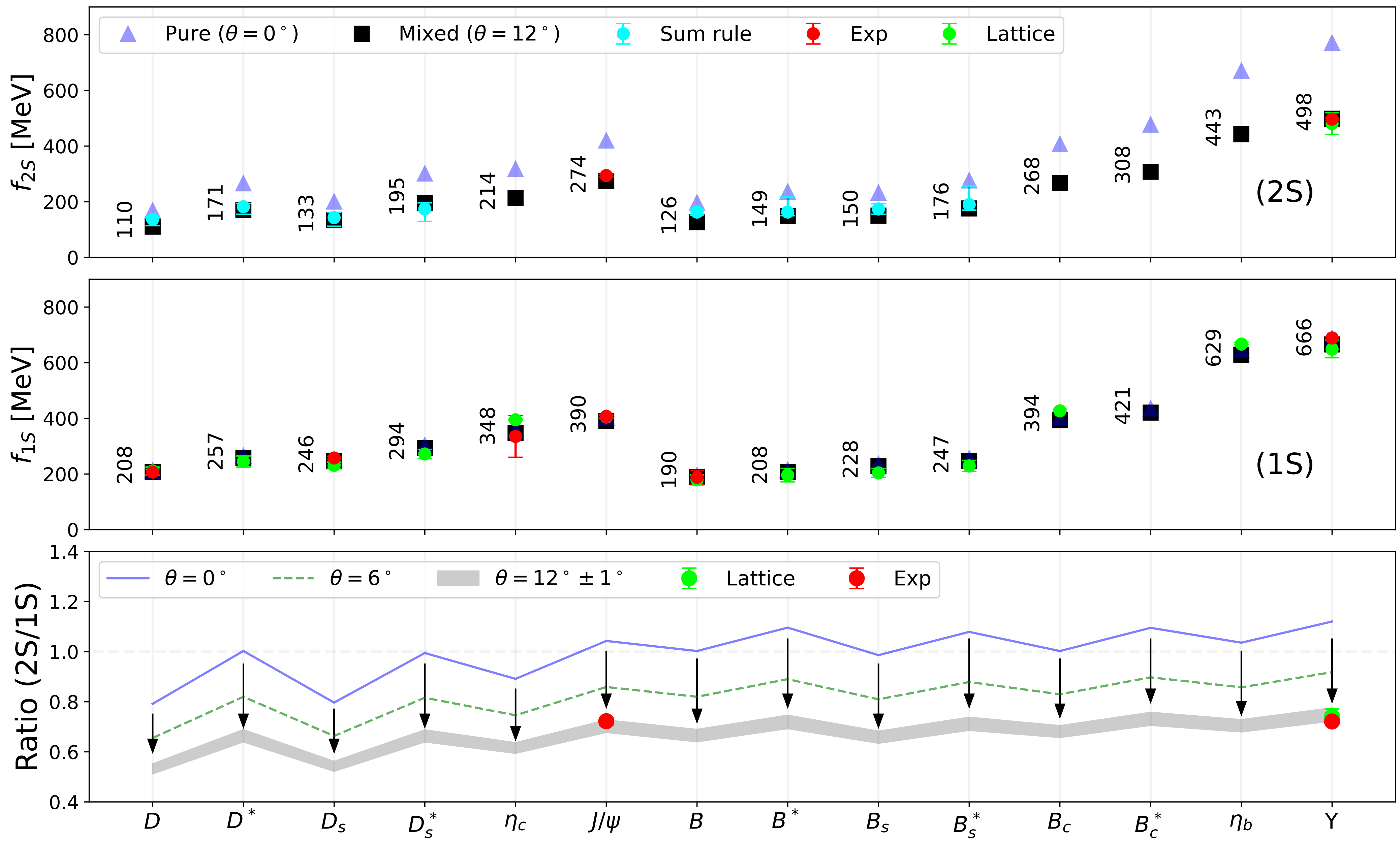
—> Mixing is needed

—> $\Delta M_P > \Delta M_V$

$$\Delta M_{hyp} \propto (S_q \cdot S_{\bar{q}})(\cos 2\theta - 2\sqrt{6}\sin 2\theta)$$

—> $\theta_c \approx 6^\circ$

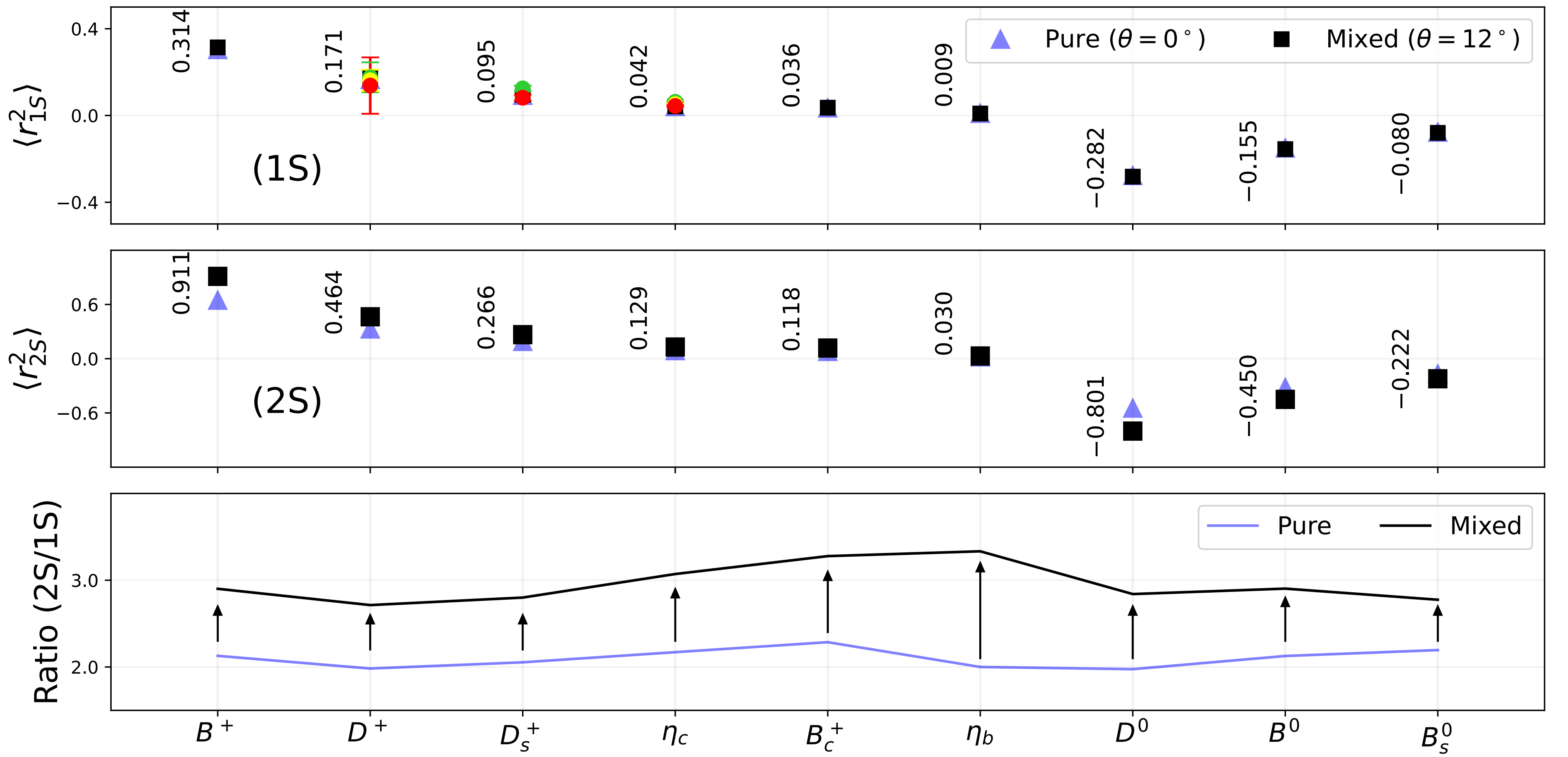
Decay constant

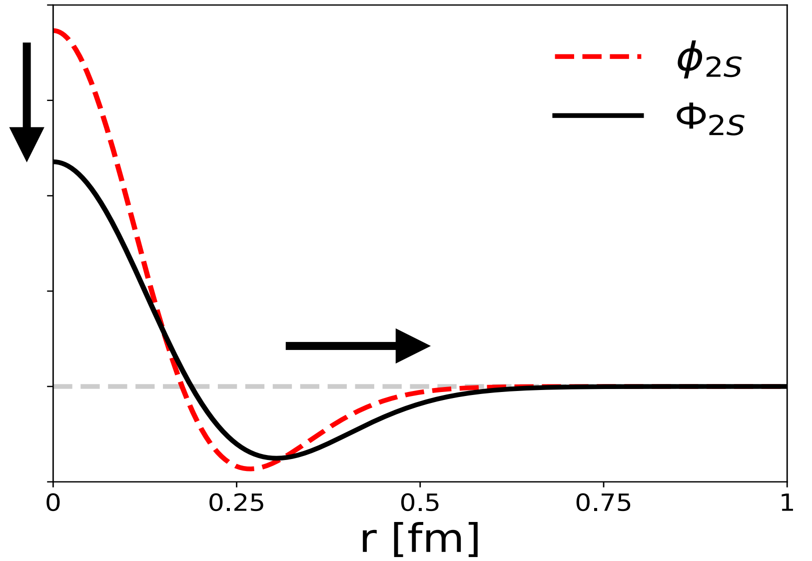


<> Related to the wave function at origin.

<> Current component independent calculation.

Charge radius





<> With mixing:

—> The 2S decay constants decrease

—> The 2S charge radii increase

Global analysis

model parameters & error analysis

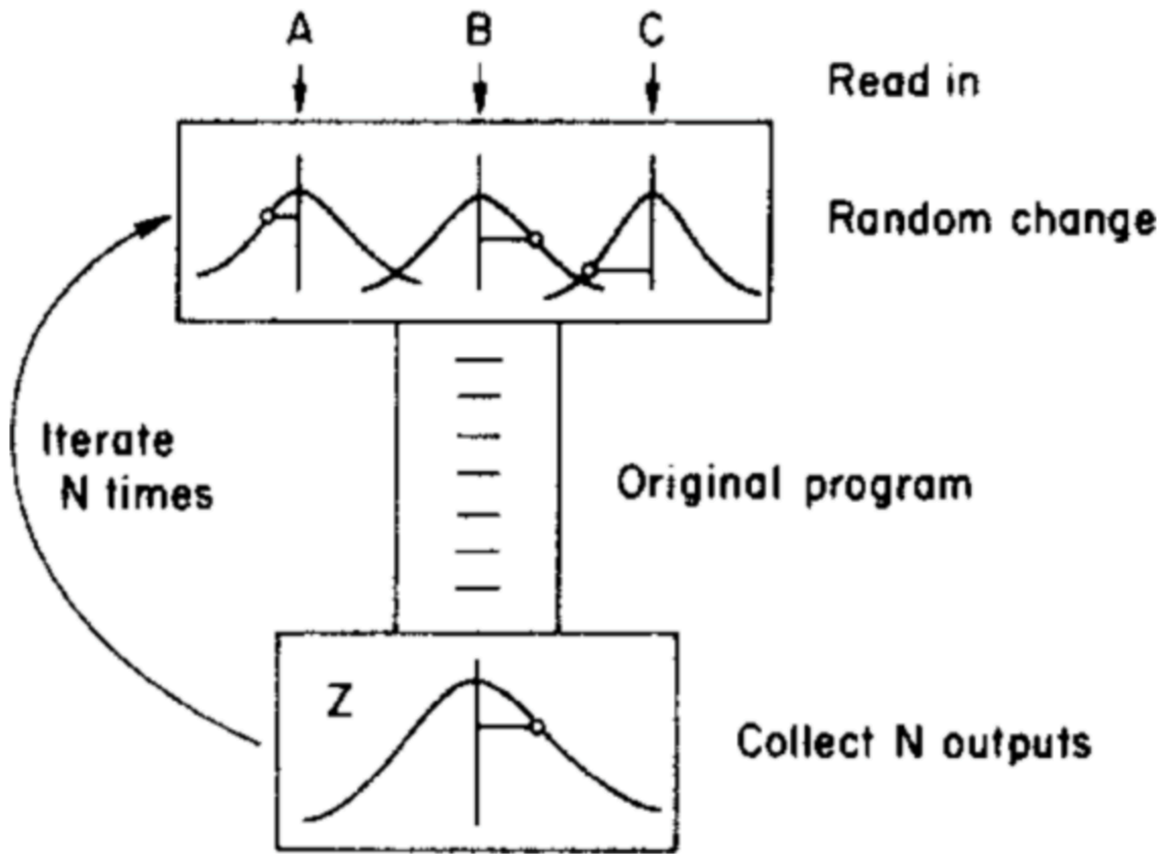
LWFW + Hamiltonian

<> Model parameters:
- Quark mass
- Beta parameters —> via variational analysis
- Potential parameters

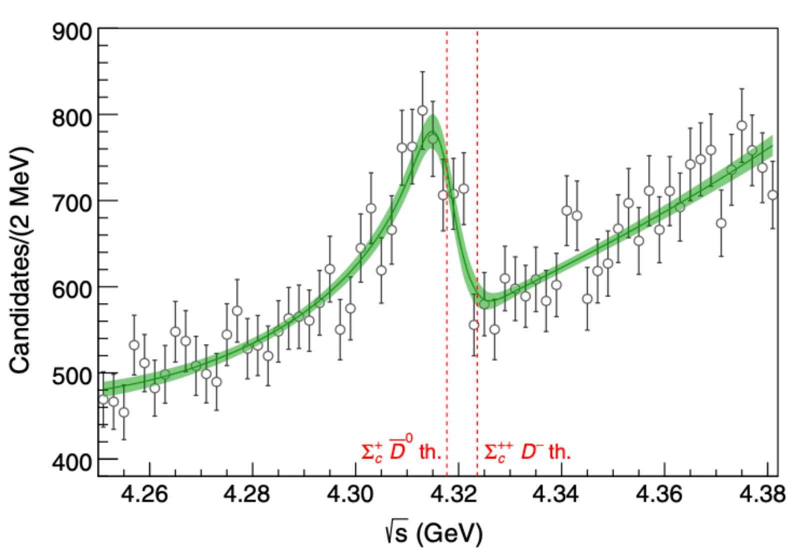
<> Parameter determination:
Previous work —> trial-error analysis
Plan —> Global fit

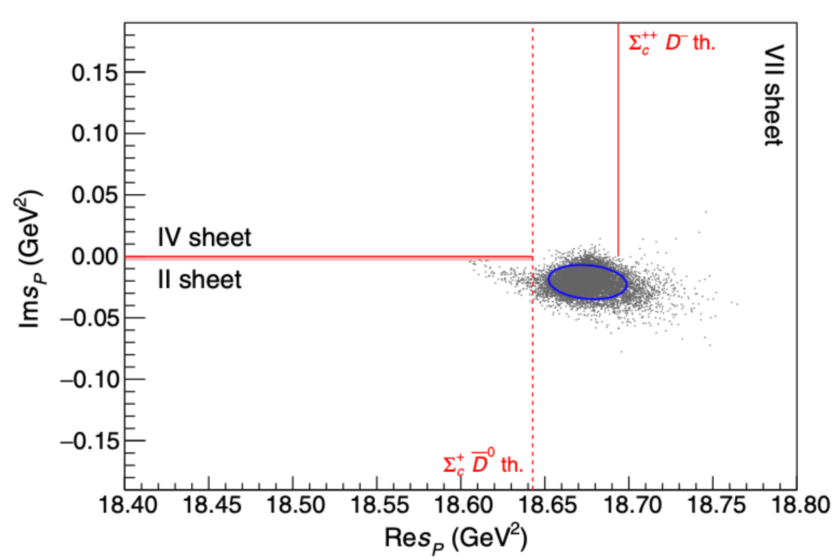
<> Fitting method (Frequentist)
—> Single fit (Minuit, Minos, Hesse)
—> Sampling (Monte-Carlo Bootstrap)

Monte-Carlo Bootstrap



<> Based on Monte-Carlo approach
—> Sampling
—> Not a single fit
—> Very expensive





<> Example:
JPAC collab
- pole determination.
- 10.000 samples.

Summary

- Numerous discoveries of hadron resonances
—> Model extension to excited state is important
—> Study of various flavor quark content
—> Radial excitation —> interesting features

- Multi-body decays
—> Extraction of resonance parameters

- Light-front quark model
—> Application to the structure and properties
—> LFWF, Hamiltonian, Higher Fock state
—> Current independent issue
—> Extension to the multi-quark states

- Global analysis/fit
—> Monte-Carlo Bootstrap/ Bayesian
—> Robust error analysis and parameter determination

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Thank you very much

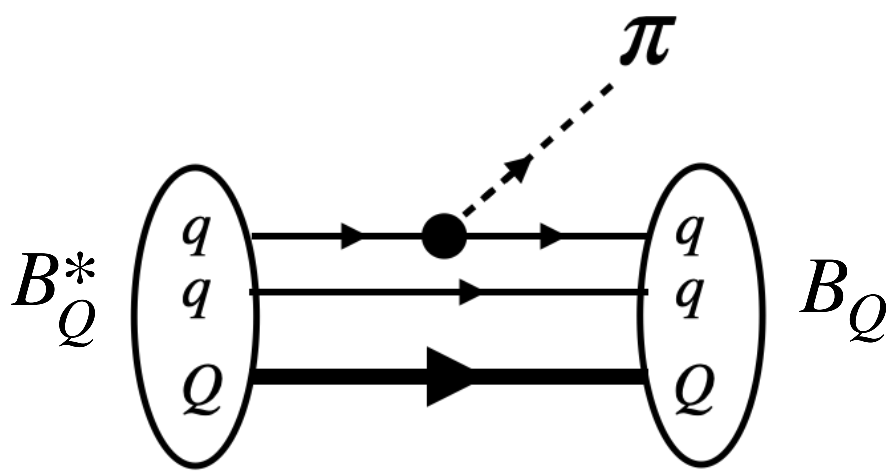
https://ajarifi.github.io

Chiral quark model

Strong decay

Strong decay of $\Lambda_b(6072)$

- **Chiral quark model (Non-relativistic)**



[1] Wave function
—> HO (gaussian)

[2] Quark-pion interaction

$$\mathcal{L}_{\pi qq} = \frac{g_A^q}{2 f_\pi} \bar{q} \gamma^\mu \gamma_5 \vec{\tau} q \cdot \partial_\mu \vec{\pi}$$

—-> Nonrelativistic expansion

$$\propto g(\sigma \cdot q - \frac{\omega}{2m} \sigma \cdot (p_i + p_f))$$

<> $\Lambda_b(6072)$ —> Γ ~ 5 MeV (narrow)
$\Gamma_{\text{exp}} = 72$ MeV

- Orthogonality of w.f. ?
- Relativistic effect?

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Relativistic correction

<> Foldy-Wouthyson-Tani trans.

$$H = \underbrace{H(1/m^0) + H(1/m)}_{\text{NR}} + \underbrace{H(1/m^2)}_{\text{RC}} + \dots$$

$$\underbrace{\overset{\text{negligible}}{\langle \Sigma_b | \, 1 \, | \Lambda_b \rangle \propto q^2} \quad \overset{\text{small}}{\langle \Sigma_b | \, p_i \, | \Lambda_b \rangle \propto q}}_{\text{NR}} \qquad \underbrace{\overset{\text{large}}{\langle \Sigma_b | \, p_i^2 \, | \Lambda_b \rangle \propto a^2}}_{\text{RC}}$$

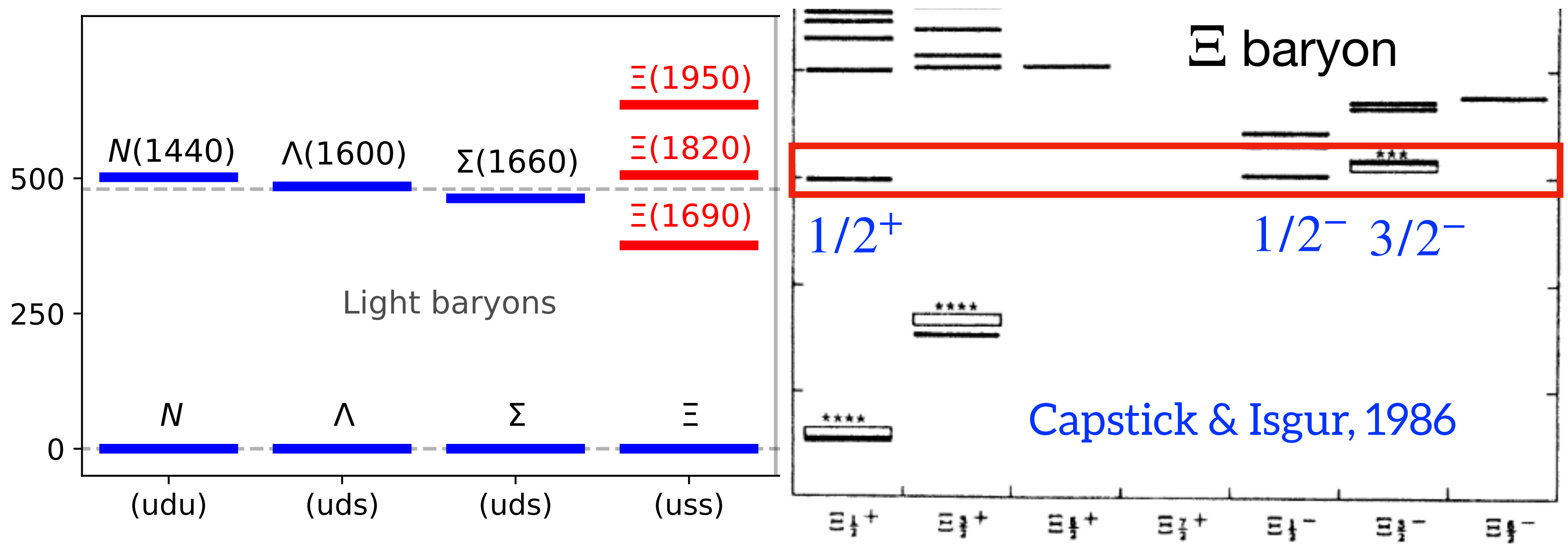
State	Multiplet	Channel	Γ_{NR}	$\Gamma_{\text{NR+RC}}$	Γ_{Exp}	
$\Sigma_b(5810)^+$	$\Sigma_b(1S, 1/2(1)^+)$	$\Lambda_b\pi$	11.9–12.3	0.62–5.11	4.83 ± 0.31	~ (−)
$\Sigma_b(5830)^+$	$\Sigma_b(1S, 3/2(1)^+)$	$\Lambda_b\pi$	20.4–21.4	1.08–8.80	9.34 ± 0.47	
$\Lambda_b(5912)^0$	$\Lambda_b(1P_\lambda, 1/2(1)^-)$	$\Sigma_b\pi$	0.001–0.003	0.001–0.003	< 0.25	~ (0)
$\Lambda_b(5920)^0$	$\Lambda_b(1P_\lambda, 3/2(1)^-)$	$\Sigma_b^*\pi$	0.004–0.008	0.004–0.009	< 0.19	
$\Lambda_b(6072)^0$	$\Lambda_b(2S_{\lambda\lambda}, 1/2(0)^+)$	$\Sigma_b\pi$	0.72–2.17	4.97–20.8		
		$\Sigma_b^*\pi$	1.08–3.00	7.81–31.5		
		Sum	1.80–5.17	12.8–52.3	72 ± 11	~ (+)

<> Large decay width of 2S states.

<> Relativistic effect is important.
—> light-front quark model

[1] Arifi et al, PRD 103 (2021), 094003

Finding the missing partner: $\Xi(2S)$



- Can be studied in J-PARC experiment
- ΔM ~ 500 MeV.
- Several states in QM, 1/2+, 1/2-, 3/2-
- $\Xi(1820)$ in PDG —> 3/2-
- Exp data —> from 1980's

How can we find it?

—> Decay pattern

—> Chiral quark model

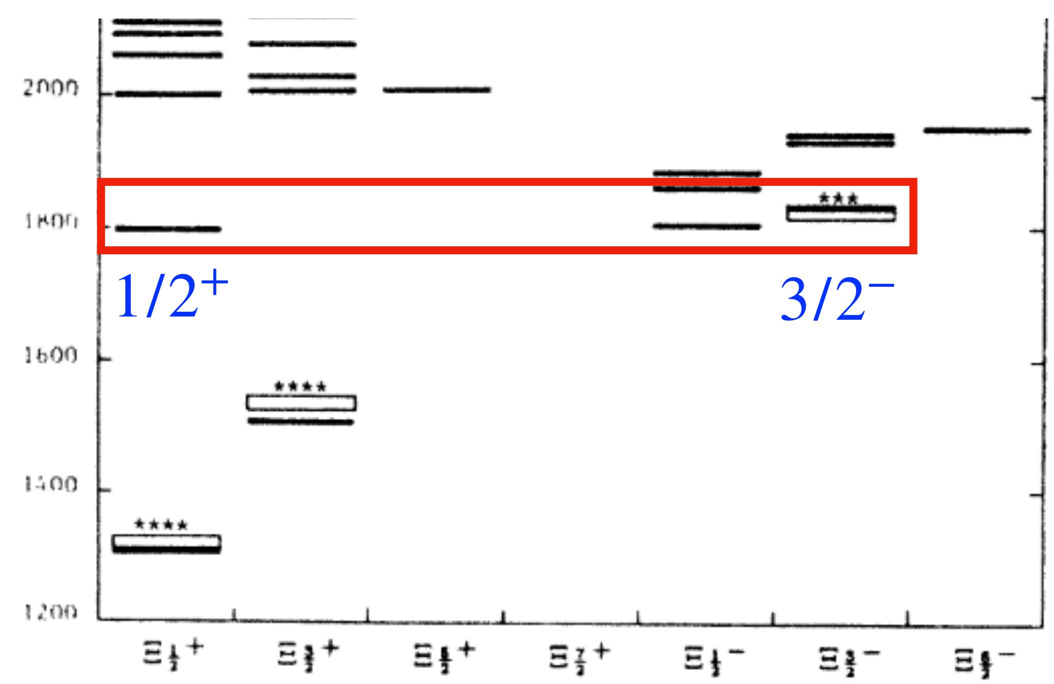
Exp status of $\Xi(1820)$

$$\Gamma_{\rm pdg} = 24 \;\pm 5 \text{ MeV}$$

LHCb, 2021	$\Gamma = 36 \;\pm 4$ MeV
BES III, 2020	$\Gamma = 17 \;\pm 15$ MeV
BES III, 2015	$\Gamma = 54.4 \;\pm 15.7$ MeV
Biagi, 1987	$\Gamma = 24.6 \pm 5.3$ MeV
Biagi, 1981	$\Gamma = 72 \pm 20$ MeV
Briefel, 1976	$\Gamma = 99 \pm 57$ MeV
Gay, 1976	$\Gamma = 21 \pm 7$ MeV
Apsel, 1970	$\Gamma = 64 \;\pm 23$ MeV

Some experiments –> $J^P = 3/2^-$.

Hypothesis:
other nearby resonance?



Inconsistencies among the data

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$\Xi(1820)$ in the quark model

			$\Xi\pi$	$\Xi^*\pi$	ΛK	ΣK	Sum
$1/2^-$	$\|70,{}^28,1,1,1/2^-\rangle$	NR NR+RC	2.5 3.9	0.7 0.5	18.3 21.5	75.3 83.1	96.7 109
	$\|70,{}^48,1,1,1/2^-\rangle$	NR NR+RC	39.3 62.4	0.2 0.1	18.3 21.5	18.8 20.8	76.6 105
	$\|70,{}^210,1,1,1/2^-\rangle$	NR NR+RC	2.5 3.9	0.7 0.5	4.6 5.4	4.7 5.2	12.4 14.9
$3/2^-$	$\|70,{}^28,1,1,3/2^-\rangle$	NR NR+RC	1.2 0.8	6.2 7.2	2.6 2.4	3.8 3.5	13.8 13.9
	$\|70,{}^48,1,1,3/2^-\rangle$	NR NR+RC	1.9 1.3	4.8 6.5	0.3 0.2	0.1 0.1	7.1 8.1
	$\|70,{}^210,1,1,3/2^-\rangle$	NR NR+RC	1.2 0.8	6.2 7.2	0.7 0.6	0.2 0.2	8.2 8.8
$1/2^+$	$\|56,{}^28,1,1,1/2^+\rangle$	NR NR+RC	0.3 4.5	0.9 8.8	0.9 3.9	17.2 64.1	19.3 81.2

Signature of the 1/2+ state:
—> Large width
—> Dominant ΣK channel
—> Ratio of $\Gamma(\Xi\pi)/\Gamma(\Xi^*\pi)$ ~ 0.5

Coupling constants in QM

—> Production of $\Xi(2S)$ in J-PARC

[1] Arifi et al, Arxiv: 2201.10427

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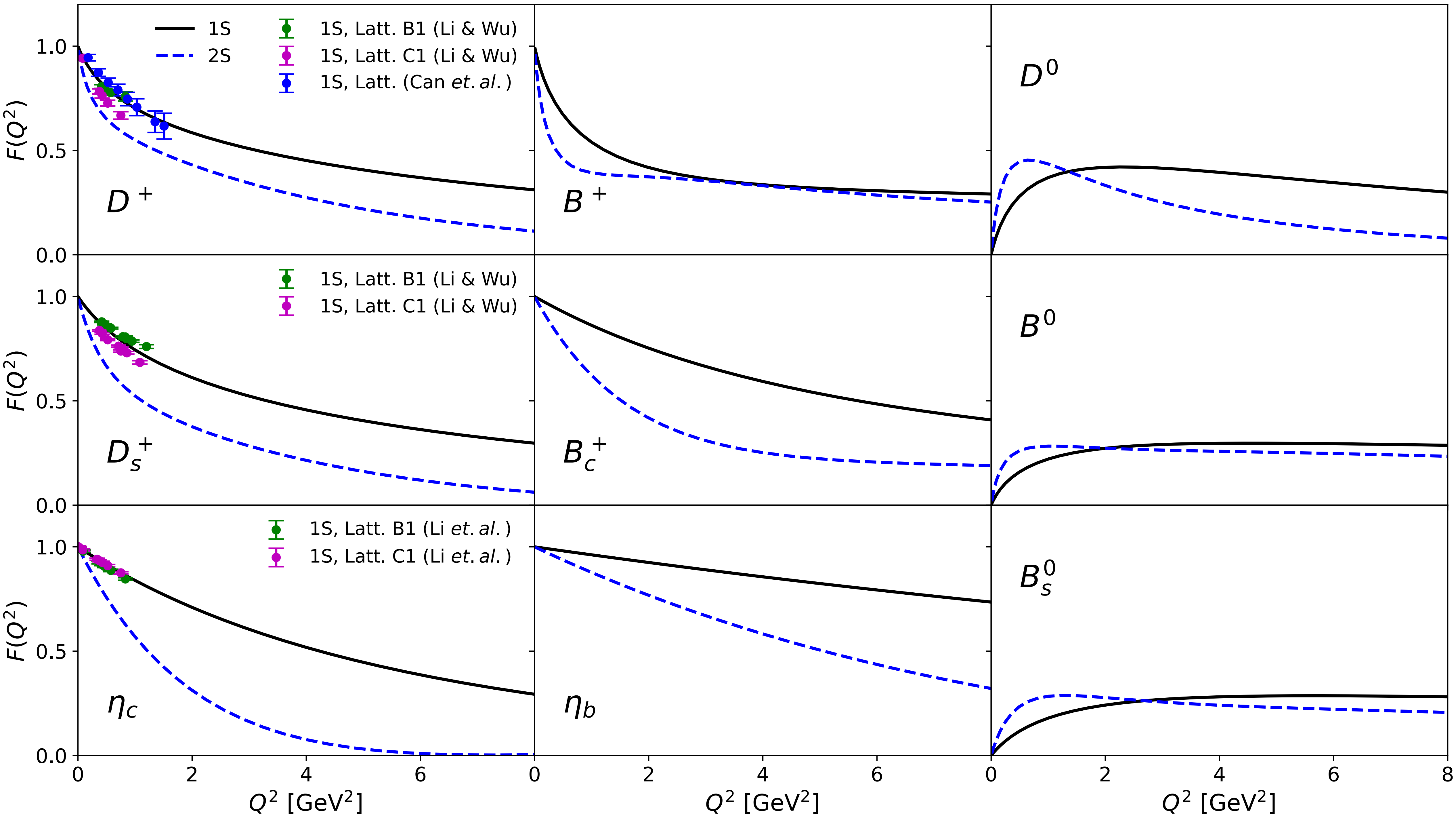
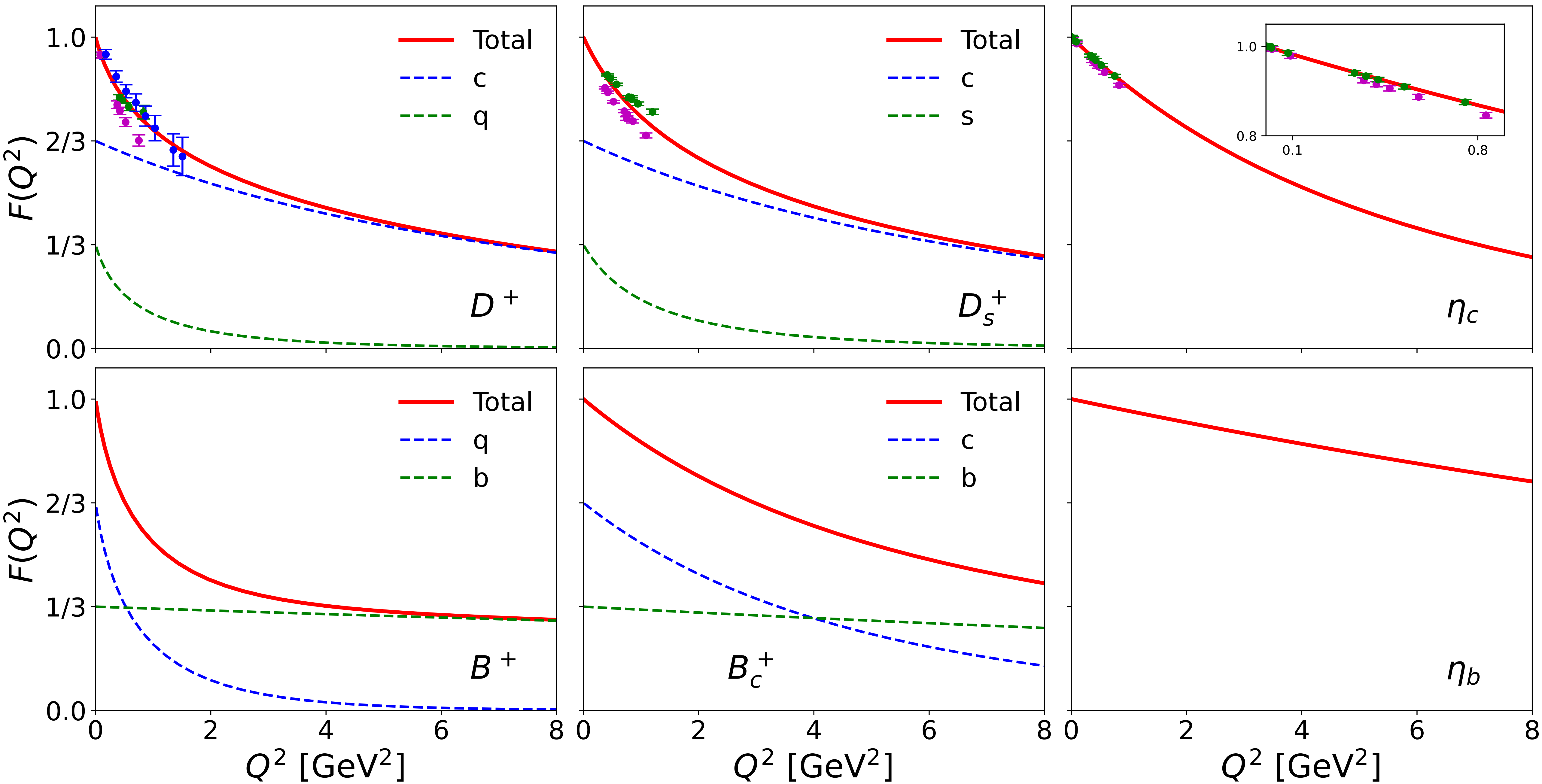
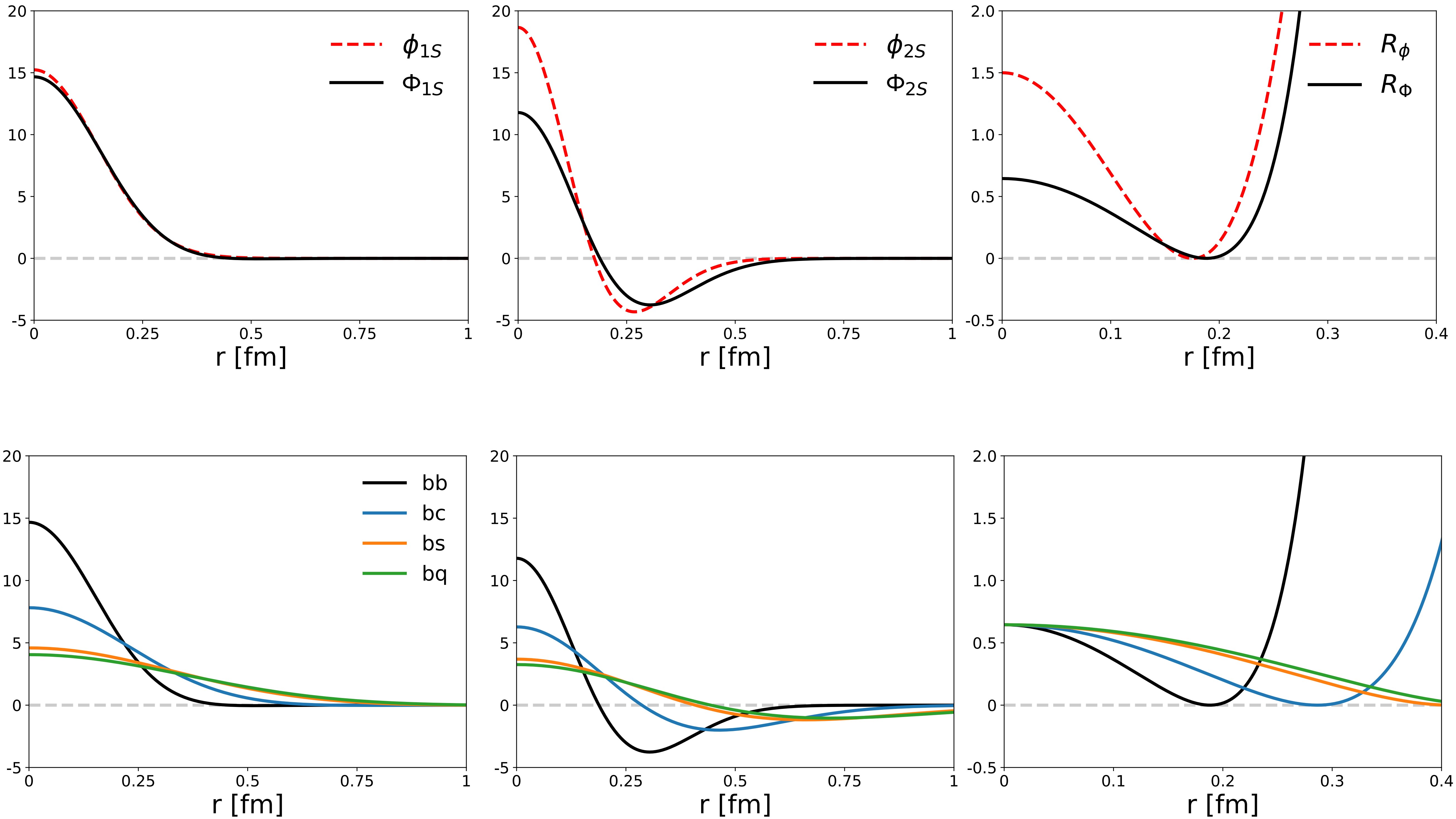
E.m. Form factor





F(Q^2)
1.0
2/3
1/3
0.0
Total
c
q
D +
Total
c
s
D_s^+
η_c
1.0
0.8
0.1
0.8
Total
q
b
B +
Total
c
b
B_c^+
η_b
0
2
4
6
8
Q^2 [GeV^2]



ϕ_{1S}
Φ_{1S}
ϕ_{2S}
Φ_{2S}
R_ϕ
R_Φ
bb
bc
bs
bq
r [fm]

$\Xi(1690)$, $?^?$

$\Gamma_{exp} < 30$ MeV

		$\Xi\pi$	$\Xi^*\pi$	ΛK	ΣK	Sum
$\vert 70,{}^2 10,1,1,1/2^- \rangle$	NR	2.0	0.002	4.1	0.6	6.7
	NR+RC	2.7	0.002	4.3	0.6	7.6
$\vert 70,{}^2 8,1,1,1/2^- \rangle$	NR	2.0	0.002	16.4	9.4	27.9
	NR+RC	2.7	0.002	17.3	9.4	29.5
$\vert 70,{}^4 8,1,1,1/2^- \rangle$	NR	32.3	0.0006	16.4	2.4	51.1
	NR+RC	42.8	0.0004	17.3	2.4	62.5
$\vert 56,{}^2 8,1,1,3/2^- \rangle$	NR	0.3	1.0	0.2	~0	1.8
	NR+RC	0.2	1.1	0.2	~0	1.6
$\vert 56,{}^2 8,2,0,1/2^+ \rangle$	NR	0.2	0.02	0.4	0.02	0.7
	NR+RC	2.3	0.3	1.3	0.1	3.9

$$R^{\Sigma^+ K^-}_{\Lambda^0 \bar{K}^0} = 0.50$$

$$R^{\Xi\pi}_{\Sigma\bar{K}} < 0.09$$

$$R^{\Xi^*\pi}_{\Sigma\bar{K}} < 0.06$$

- The most suitable state: 1/2-, Not possible to assign it as 1/2+

$\Xi(1620)$

$\Gamma_{exp} = 40 \pm 15$ MeV

		$\Xi\pi$	ΛK	Sum
$\vert 70,{}^4 8,1,1,1/2^- \rangle$	NR	24	6	30
	NR+RC	29	6	35

- Only the 1/2- state that have a sizable width.

Relativistic corrections

Kubota & Ohta, PLB 65, 374 (1976)

- Foldy-Woutysen-Tani (FWT) transformation

$$H = \beta m + \mathcal{O} + \mathcal{E},$$

Remove large-small component (odd operator).

- Unitary transformation

$$\Psi' = e^{iS}\Psi,$$

$$S = -\frac{i\beta\mathcal{O}}{2m}.$$

- Dirac equation

$$H\Psi = i\frac{\partial\Psi}{\partial t},$$

$$H' = e^{iS}\left(H - i\frac{\partial}{\partial t}\right)e^{-iS}.$$

- Expanding the Hamiltonian

$$H' = H + i[S,H] - \frac{1}{2}[S,[S,H]] - \frac{i}{6}[S,[S,[S,H]]] - \dot{S} - \frac{i}{2}[S,\dot{S}] + \frac{1}{6}[S,[S,\dot{S}]] + \dots$$

- We obtain

$$H' = \beta m + \mathcal{E}' + \mathcal{O}',$$

$$\mathcal{E}' = \mathcal{E} + \frac{1}{2m}\beta\mathcal{O}^2 - \frac{1}{8m^2}[\mathcal{O},[\mathcal{O},\mathcal{E}]] - \frac{i}{8m^2}[\mathcal{O},\dot{\mathcal{O}}],$$

$$\mathcal{O}' = \frac{\beta}{2m}[\mathcal{O},\mathcal{E}] + i\frac{\beta\dot{\mathcal{O}}}{2m} - \frac{\mathcal{O}^3}{3m^2},$$

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Pion interaction

- FWT transformation gives a correction order by order

$$H = \underbrace{H(1/m^0) + H(1/m)}_{\text{NR}} + \underbrace{H(1/m^2)}_{\text{RC}} + \ldots$$

- Hamiltonian

$$H = \beta m + \vec{\alpha}\cdot\vec{p} + g\ \partial_t \pi \gamma_5 + g\ \vec{\alpha}\cdot\vec{\nabla}\pi\gamma_5,$$

$$H = \beta m + \mathcal{O} + \mathcal{E}, \qquad \mathcal{O} = \vec{\alpha}\cdot\vec{p} + g\ \partial_t \pi\gamma_5, \quad \mathcal{E} = g\ \vec{\alpha}\cdot\vec{\nabla}\pi\gamma_5.$$

Pseudovector type

$$\mathcal{L}_{\pi q q} = -\frac{g_A^q}{2 f_\pi}\bar{q}\gamma_\mu\gamma_5\vec{\tau}q\cdot\partial^\mu\vec{\pi}$$

- Leading term up to $1/m$

$$H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} - \frac{\omega_\pi}{2m}\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i + \boldsymbol{p}_f)\right]$$

the same as obtained by non-rel reduction.

- The correction up to $1/m^2$

$$H_{RC} = \frac{g}{8m^2}\left[m_\pi^2\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i + \boldsymbol{p}_f)\times(\boldsymbol{q}\times\boldsymbol{p}_i)\right]$$

E. M. —> spin-orbit coupling

important term

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Ground state: $\Sigma_c \to \Lambda_c \pi$

Ground state	NR	NR + RC	Exp.
$\Sigma_c(2455) : 1/2^+$	4.27 - 4.34	0.35 - 1.95	1.89 MeV
$\Sigma_c(2520) : 3/2^+$	29.8 - 31.4	2.70 - 14.1	14.78 MeV
	2 x	reduced	

- Suppression of g_A^q coupling constant.
- Dominant term is $(\sigma \cdot q)$ term.
- The overlap of the wave functions is unity in wave-length limit.

$$\langle \Lambda_c | \, 1 \, | \Sigma_c \rangle \propto 1 \qquad \langle \Lambda_c | \, p_i \, | \Sigma_c \rangle \propto q \qquad \langle \Lambda_c | \, p_i^2 \, | \Sigma_c \rangle \propto a^2$$

large small large

- The relativistic correction has opposite sign.

$$H_{NR} = g\left[\boldsymbol{\sigma}\cdot\boldsymbol{q} - \frac{\omega_\pi}{2m}\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i + \boldsymbol{p}_f)\right] \quad H_{RC} = \frac{g}{8m^2}\left[m_\pi^2\boldsymbol{\sigma}\cdot\boldsymbol{q} - 2\boldsymbol{\sigma}\cdot(\boldsymbol{p}_i + \boldsymbol{p}_f)\times(\boldsymbol{q}\times\boldsymbol{p}_i)\right]$$

Negative parity state: $\Lambda_c^* \to \Sigma_c \pi$

Negative parity state	NR	NR + RC	Exp.
$\Lambda_c(2595) : 1/2^-$	1.35 - 3.16	1.36 - 3.20	2.6 MeV
$\Lambda_c(2625) : 3/2^-$	0.15 - 0.33	0.09 - 0.26	< 0.97 MeV

- In this case, the momentum is almost zero.
- The dominant term is $(\sigma \cdot p_i)$ term.

$$\langle \Sigma_c | \, 1 \, | \Lambda_c \rangle \approx q \qquad \langle \Sigma_c | \, p_i \, | \Lambda_c \rangle \approx a \qquad \langle \Sigma_c | \, p_i^2 \, | \Lambda_c \rangle \approx q \; a^2$$

small — dominant — small

- The dominance of the S-wave decay.
- The relativistic correction is rather small.

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Roper-like state: $\Lambda_c^* \to \Sigma_c \pi$

Roper-like state	NR	NR + RC	Exp.
$\Lambda_c(2765) : 1/2^+, \lambda\lambda$	2 - 5	11 - 49	73 MeV
$\Lambda_c(3136) : 1/2^+, \rho\rho$	11 - 123	314 - 1799	

- The overlap is orthogonal in the long-wavelength limit.

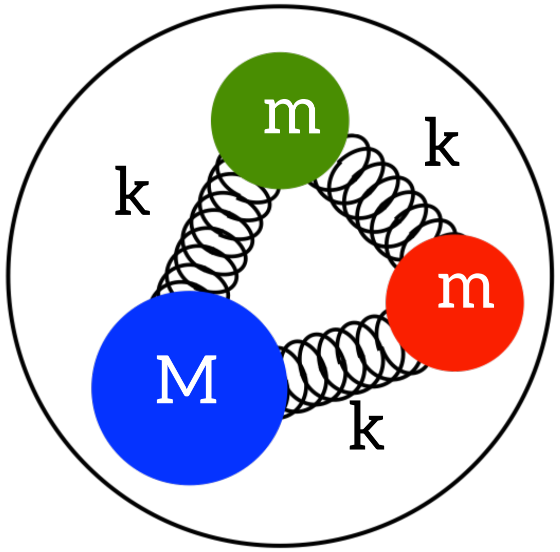
$$\langle \Sigma_c | \, 1 \, | \Lambda_c \rangle \approx q^2 \qquad \langle \Sigma_c | \, p_i \, | \Lambda_c \rangle \approx q \qquad \langle \Sigma_c | \, p_i^2 \, | \Lambda_c \rangle \approx a^2$$

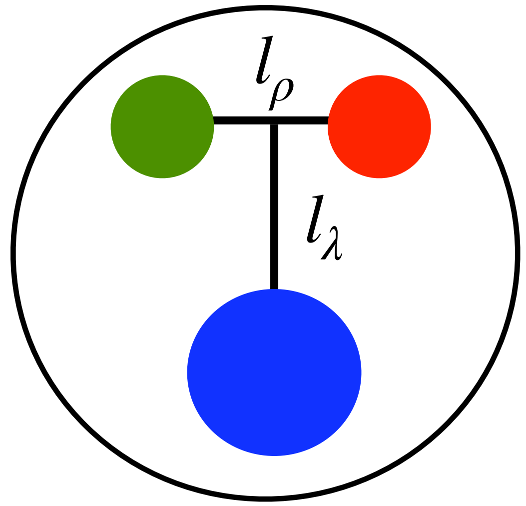
negligible small large

- The $(\sigma \cdot p_i)$ term has small contribution since it is associated to pion energy ω_π.
- The relativistic correction is quite important.

Phys. Rev. D **103**, 094003 (2021)

Wave function of heavy baryon





Harmonic Oscillator potential

M = 1.50 GeV
m = 0.35 GeV
k = 0.03 GeV^3

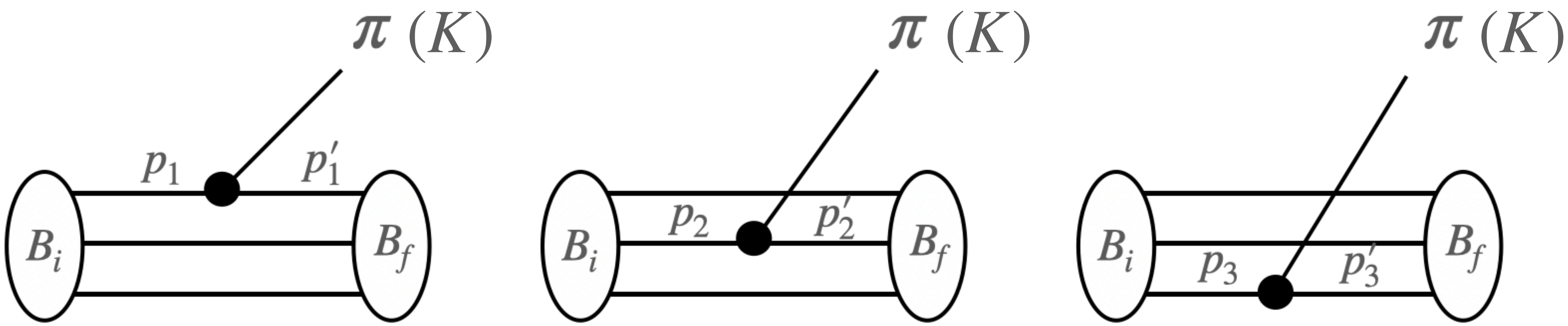
$\Rightarrow$ $\omega_\lambda = 350$ MeV

$$Y_c = \underbrace{\left[\left[\psi_{l_\lambda}(\vec{\lambda})\psi_{l_\rho}(\vec{\rho}), d\right]^j, s_c\right]^J \psi_{flavor}}_{\text{Symmetric}} \ \underbrace{\psi_{color}}_{\text{Anti-Symmetric}} \qquad J = j + s_Q$$

(Orbital: $\psi_{l_\lambda}(\vec{\lambda})\psi_{l_\rho}(\vec{\rho})$; Spin: d, s_c)

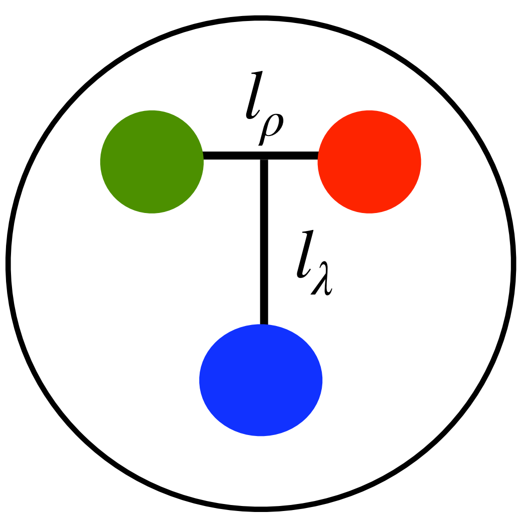
Nagahiro, *et. al.* PRD95 014023 (2017)

Ξ (or Ω) baryon decay



State
$N=0$
$\left\|56,{}^2 8,0,0,\frac{1}{2}^+\right\rangle$
$\left\|56,{}^4 10,0,0,\frac{3}{2}^+\right\rangle$
$N=1$
$\left\|70,{}^2 10,1,1,J^-\right\rangle$
$\left\|70,{}^2 8,1,1,J^-\right\rangle$
$\left\|70,{}^4 8,1,1,J^-\right\rangle$
$N=2$
$\left\|56,{}^2 8,2,0,\frac{1}{2}^+\right\rangle$
$\left\|56,{}^4 10,2,0,\frac{3}{2}^+\right\rangle$
$\left\|70,{}^2 10,2,0,\frac{1}{2}^+\right\rangle$
$\left\|70,{}^2 8,2,0,\frac{1}{2}^+\right\rangle$
$\left\|70,{}^4 8,2,0,\frac{3}{2}^+\right\rangle$

- We use SU(3) symmetry basis for the wave function.
- We take and use the averaged mass of u/d and strange quark.
- Also, we use the same interaction Lagrangian.



$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$

- Unlike heavy baryons, now λ and ρ modes are mixed.

Phys. Rev. D **87**, 094002 (2013)

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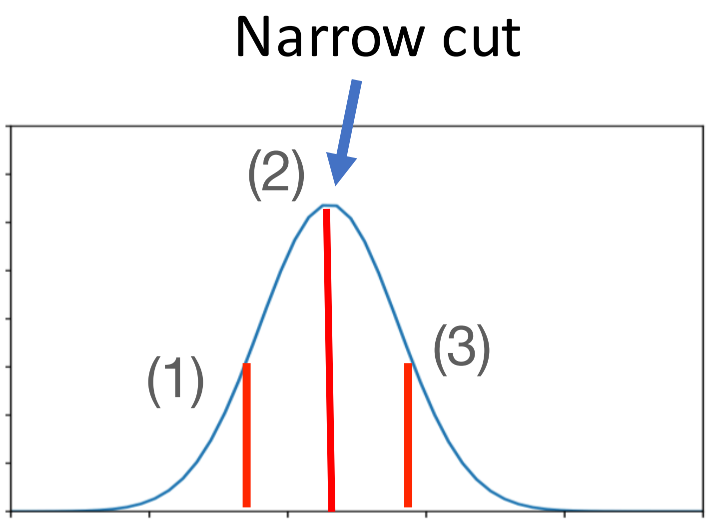
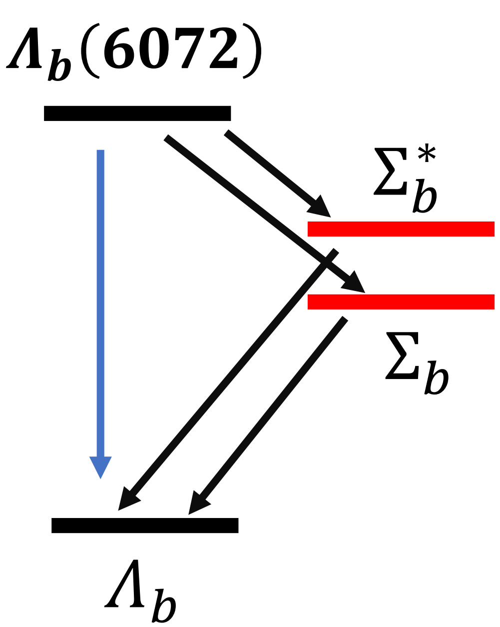
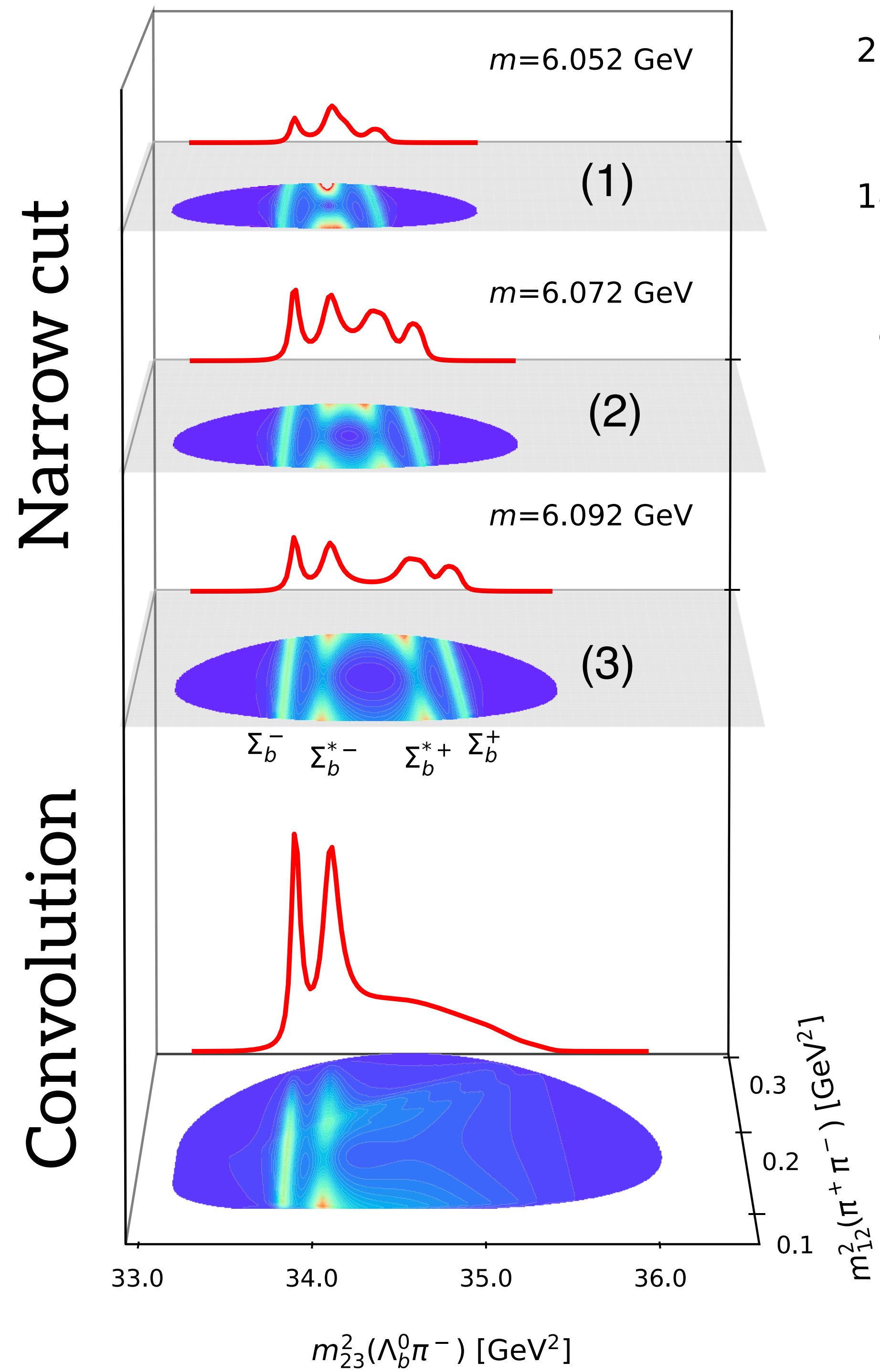
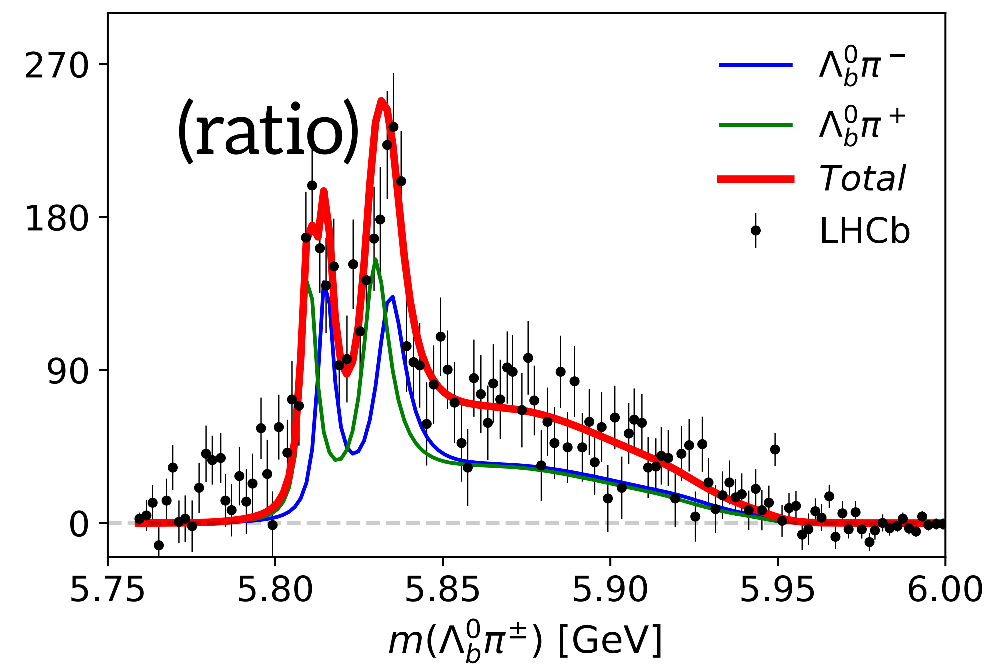
Decay of $\Lambda_b^*(6072)$

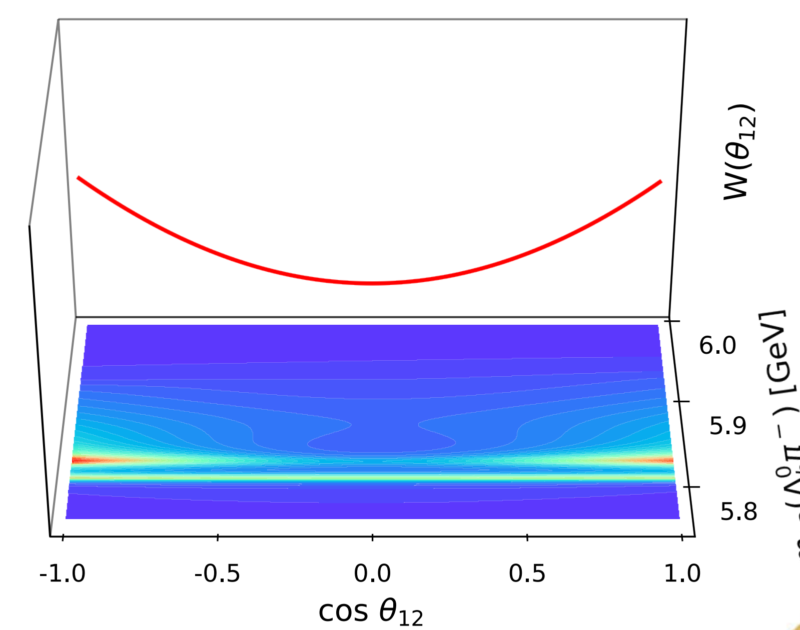








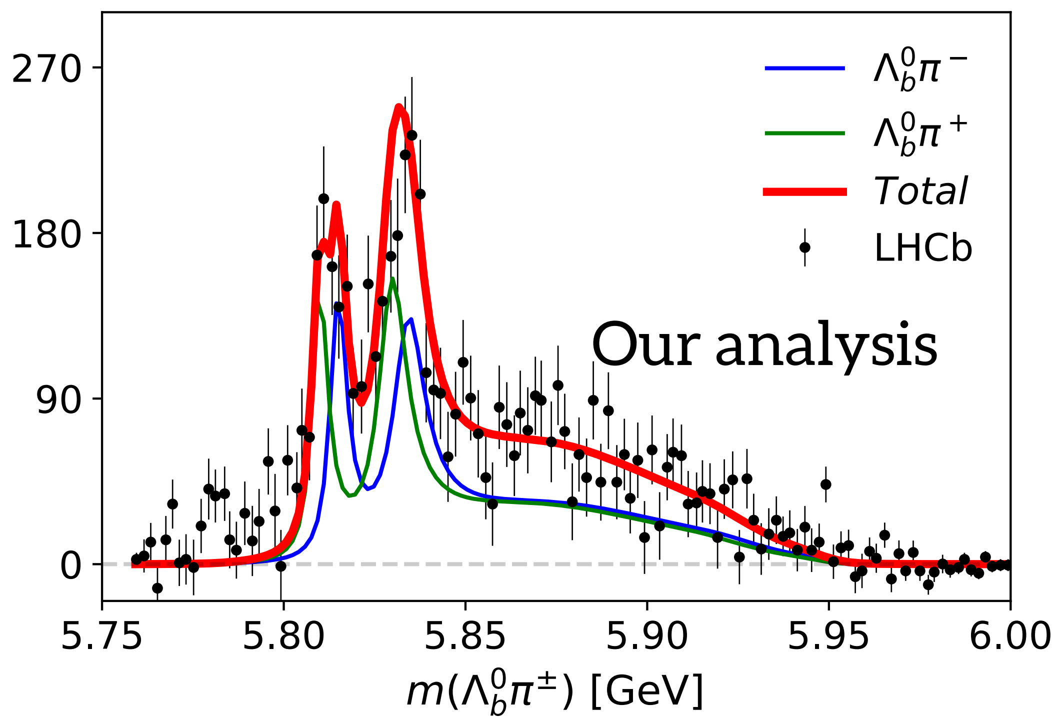
Invariant mass plot

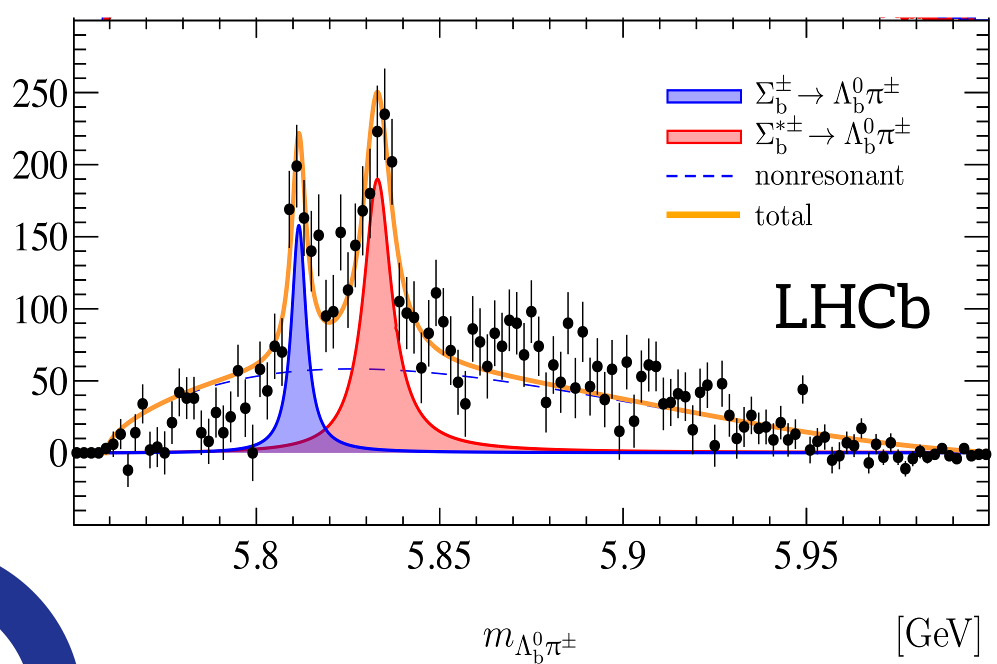


Angular correlation

Arifi, *et. al.* PRD101 (R) 111502 (2020)

LHCb analysis on $\Lambda_b^*(6072)$





- Background shape is different with the LHCb one.
- It is from the kinematical reflection.
- Sequential decay is sufficient to describe the invariant mass distribution.

- non-resonant contribution is relatively large.