$D_{s0}(2590)^+$:
A conventional or exotic state?

Ahmad Jafar Arifi

Exotics and exotic phenomena in heavy-ion collision (ExHIC), APCTP

Sept 29 - Oct 1, 2022

A conventional or exotic state?

General questions

—> How to distinguish them?

—> What observables?

—> Would there be a mixing between them?

—> What is the proper way?

—> How good is the prediction?

—> The conventional model? Exotic state scenario?

—> What is the ambiguity of the model?

—> Model-independent relation?

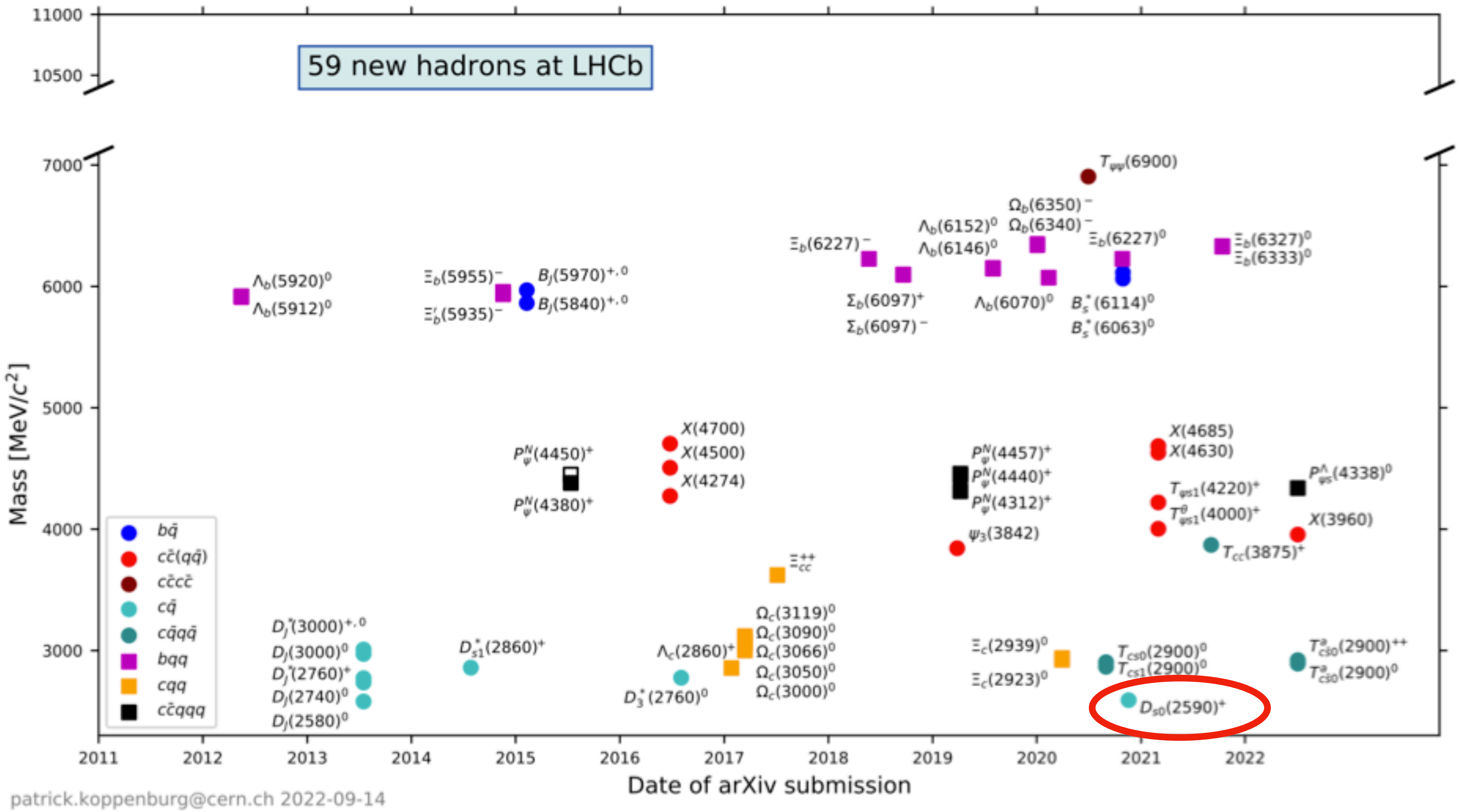
Contents

apctp

$D_{s0}(2590)^+$

$$M = 2591 \pm 6 \pm 7 \text{ MeV}$$
$$\Gamma = 89 \pm 16 \pm 12 \text{ MeV}$$

$$J^P = 0^-$$



LHCb, Phys. Rev. Lett. 126, 122002 (2021)

Theoretical calculations

$$M_{exp} = 2591 \text{ MeV} \qquad \Gamma_{exp} = 89 \text{ MeV}$$

- **Quark model**

—> Ds(2590) is a strong candidate of a radially excited state.

—> Predicted mass is 80-100 MeV larger.

—> Screened potential [PRD 105, 074037 (2022)]

—> Dressed meson (coupled channel: D*K) —> reduce the mass

—> Comp: $c\bar{s}$ (46%), D^*K (44%) [PLB 827, 136998 (2022)]

—> Comp: D^*K (10%) [PRD 104, 094051 (2021)]

—> Predicted decay width is also small~ 20 MeV. [PRD 105, 056006 (2022)]

—> Nonrelativistic model & Harmonic Oscillator WF

—> Simply fit the γ parameter to reproduce the width??

Quark model

- **Questions**

  —> Does the bad prediction always indicate the exotics?

  —> E.g. Roper resonance $N(1440)$ & $\Lambda(1405)$,

  —> What about the intrinsic problem in QM?

  —> Relativistic effect? Approximation? Higher Fock?

  —> Is the QM good for Excited state? Multi-quark state?

  —> Large ambiguity?

- **What can we do with QM?**

  —> Do a systematic study for various quark flavor contents

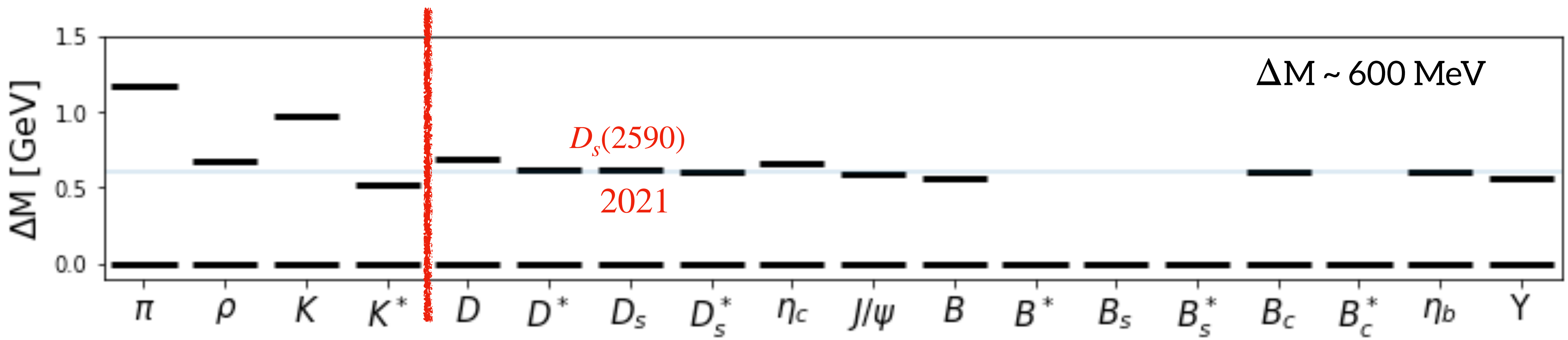
  —> Extract some patterns or systematics

  —> Look more closely at the problem

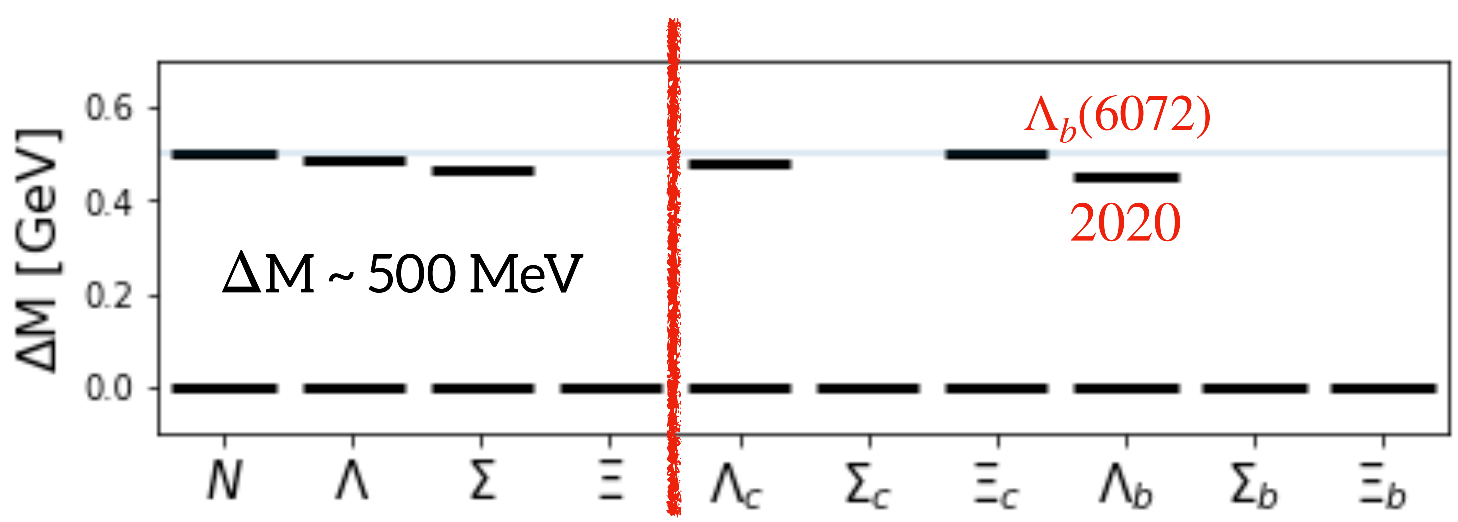
apctp

Radial excitation

Meson



Baryon

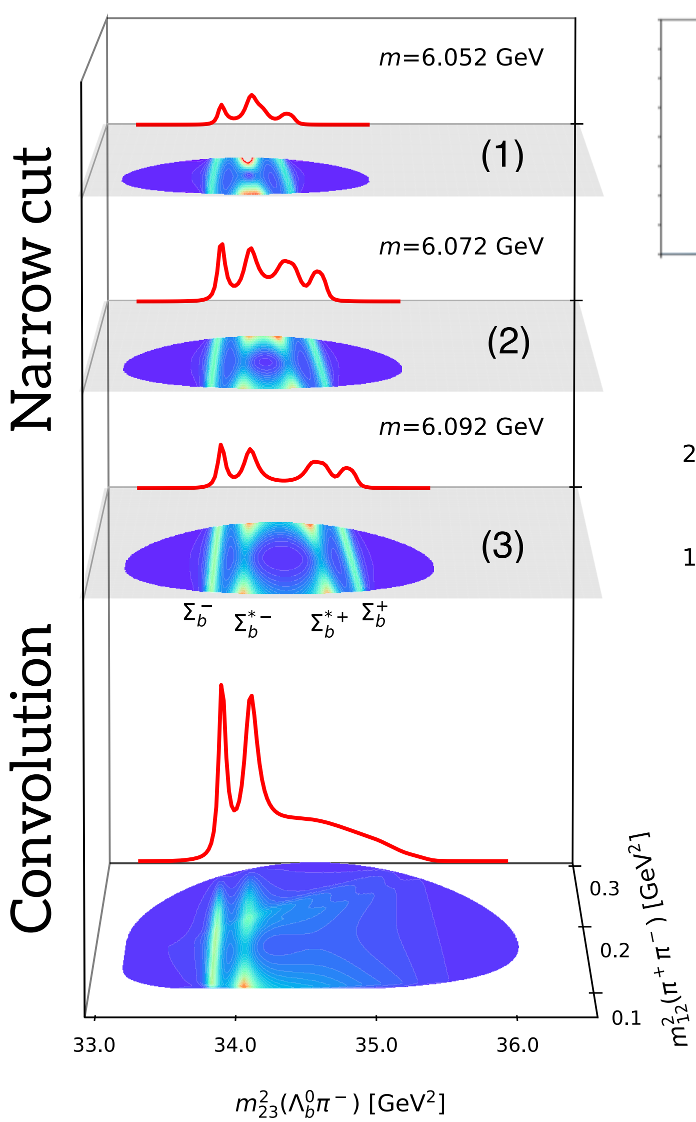


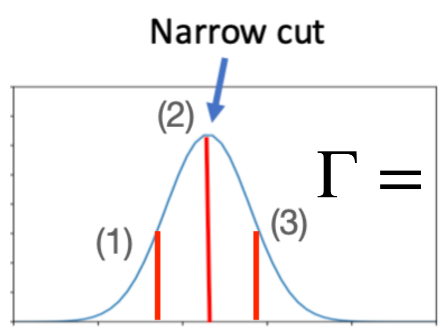
- **Similar mass gap**
  —> internal structure?
  —> can be studied in HIC??

apctp

Some of my previous works

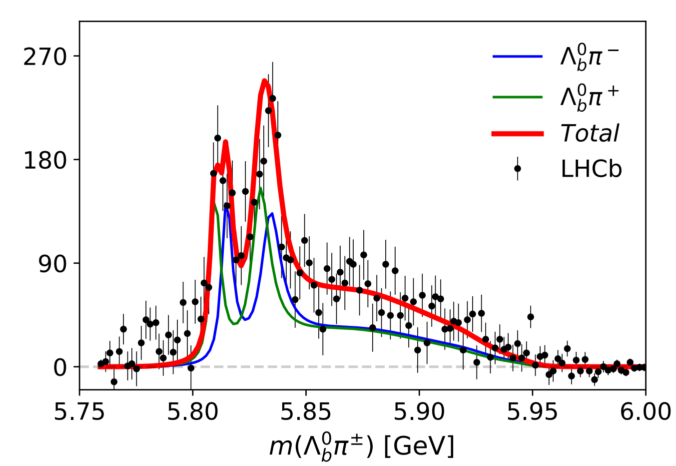
- **Dalitz plot analysis**
  - —> Spin-parity determination
  - —> $\Lambda_b(6072)$: LHCb (2020)
  - —> $\Lambda_c(2765)$: Belle (??)





$\Gamma = 72$ MeV

$J^P = 1/2^+$



Invariant mass plot

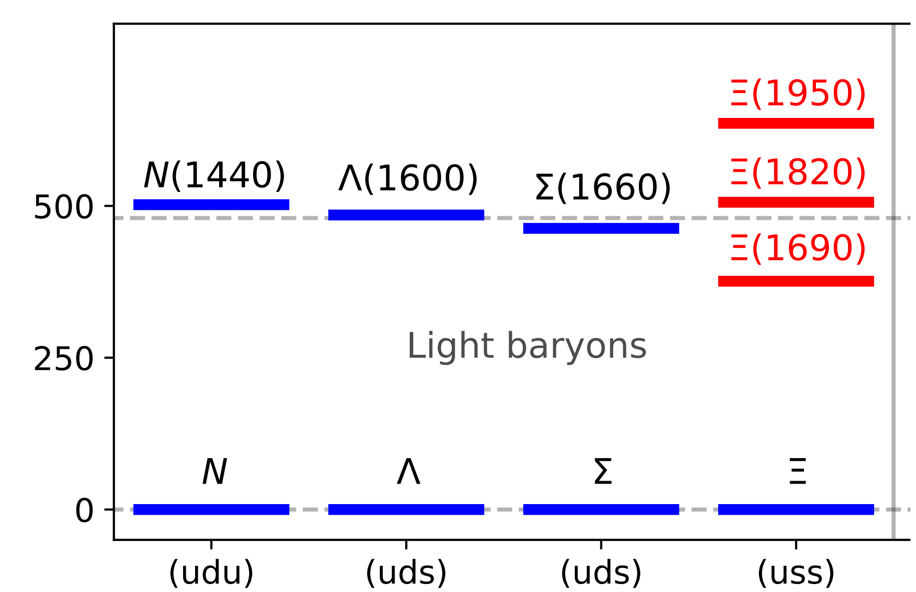
[PRD 101, 111502(R) (2020)]

- **Quark model**
  - —> Estimate the decay width
  - —> Shortcoming (1 oder smaller)
  - —> Relativistic correction?

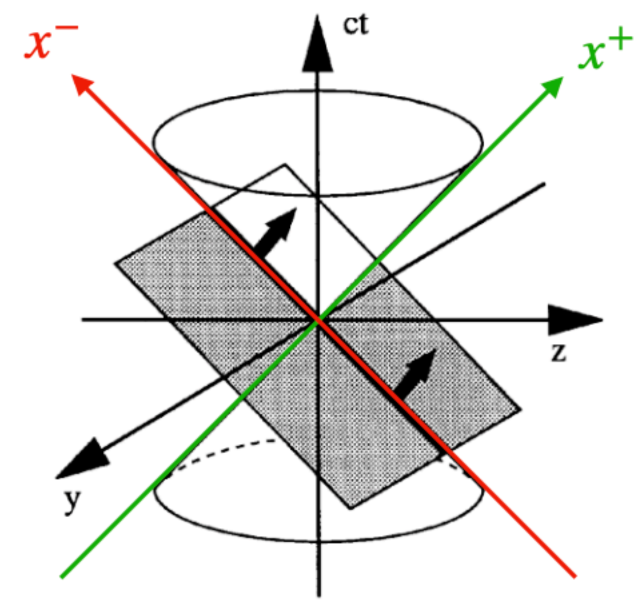
[PRD 103, 094003 (2021)]

- —> Missing $\Xi(1/2^+)$ baryon
- —> Studying the decay pattern

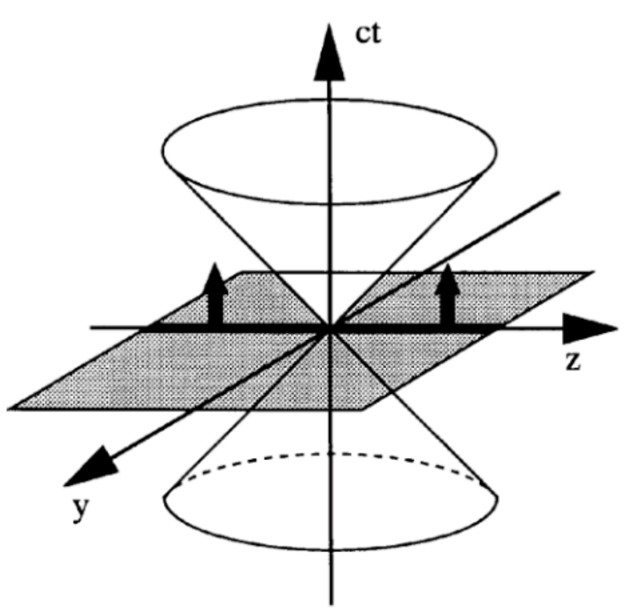
[PRD 105, 094006 (2022)]



Light-front quark model



$$x^+ = x^0 + x^3$$



$$x^0$$

- **Light-front dynamics**
  - —> natural choice for relativistic objects
  - —> dynamics becomes simpler
  - —> widely used in the field of hadron structure
  - —> Exotics?? HIC??
- **Constituent quark model**
  - —> Meson as a bound state of $Q\bar{Q}$
  - —> Higher Fock state??
- **Light-front wave function**
  - —> Compute observables from this LFWF

Light-front quark model

Chueng-Ryong Ji, Ho-meoyng Choi, Yongseok Oh

- **Some details**
  —> Based on variational principle
  —> WF: Gaussian basis, Cornel potential
  —> Good description for the ground state
  —> Successfully predict many observables

$$\frac{\partial M}{\partial \beta} = 0$$

- **Extension to radial excitation**
  —> But, it was not so easy at first.
  —> Cannot describe the decay constant.

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

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

$$f_{\Upsilon(1S)} = 689\ \mathrm{MeV}$$
$$f_{\Upsilon(2S)} = 497\ \mathrm{MeV}$$

$$f_{\Upsilon(2S)} < f_{\Upsilon(1S)}$$

apctp

Wave function of 1S and 2S states

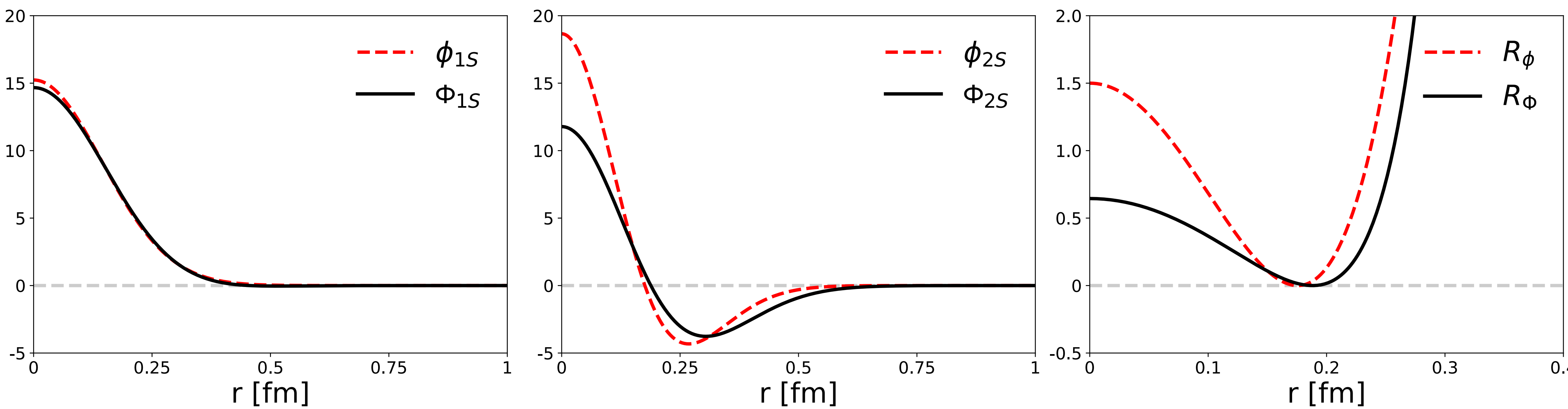
<> Minimal mixing

—> The same β for 1S and 2S states

—> keep orthogonality

—> doesn't change the 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

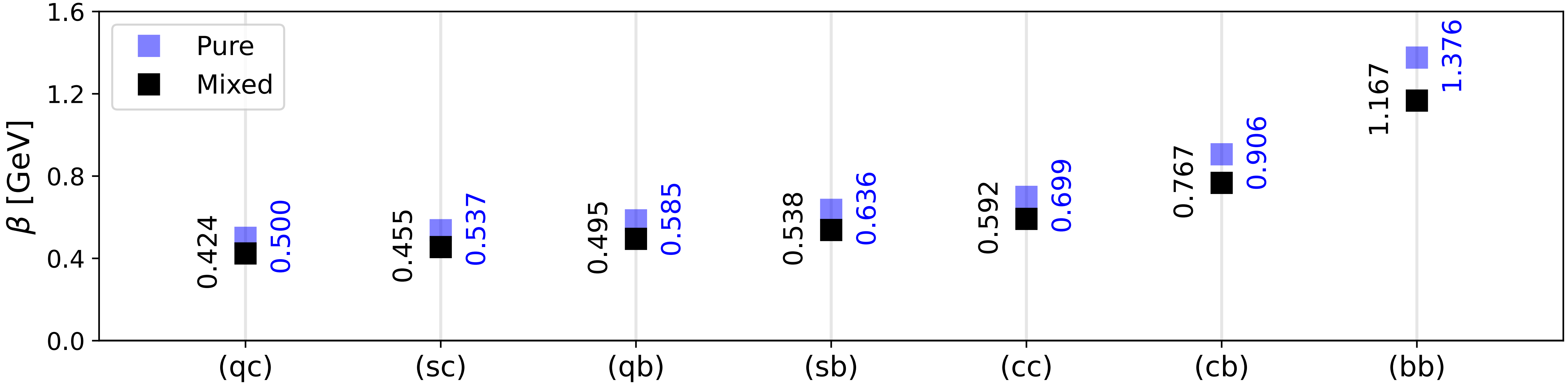
—> $\theta = 12^\circ,\ |\cos\theta|^2 = 95.7\ \%$

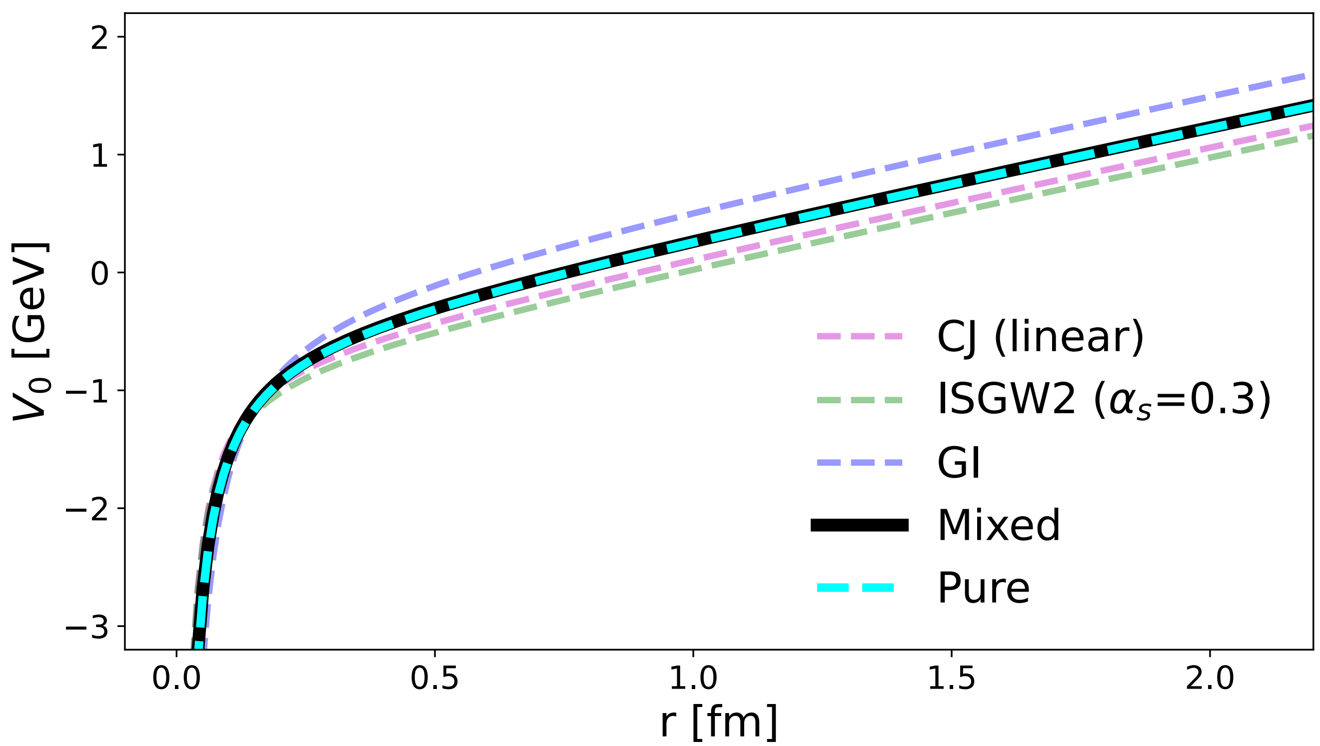
<> Huge impact to observables.

—> Mass spectra, decay constants, etc

apctp

Variational and potential parameters





<> In the mixed scenario:

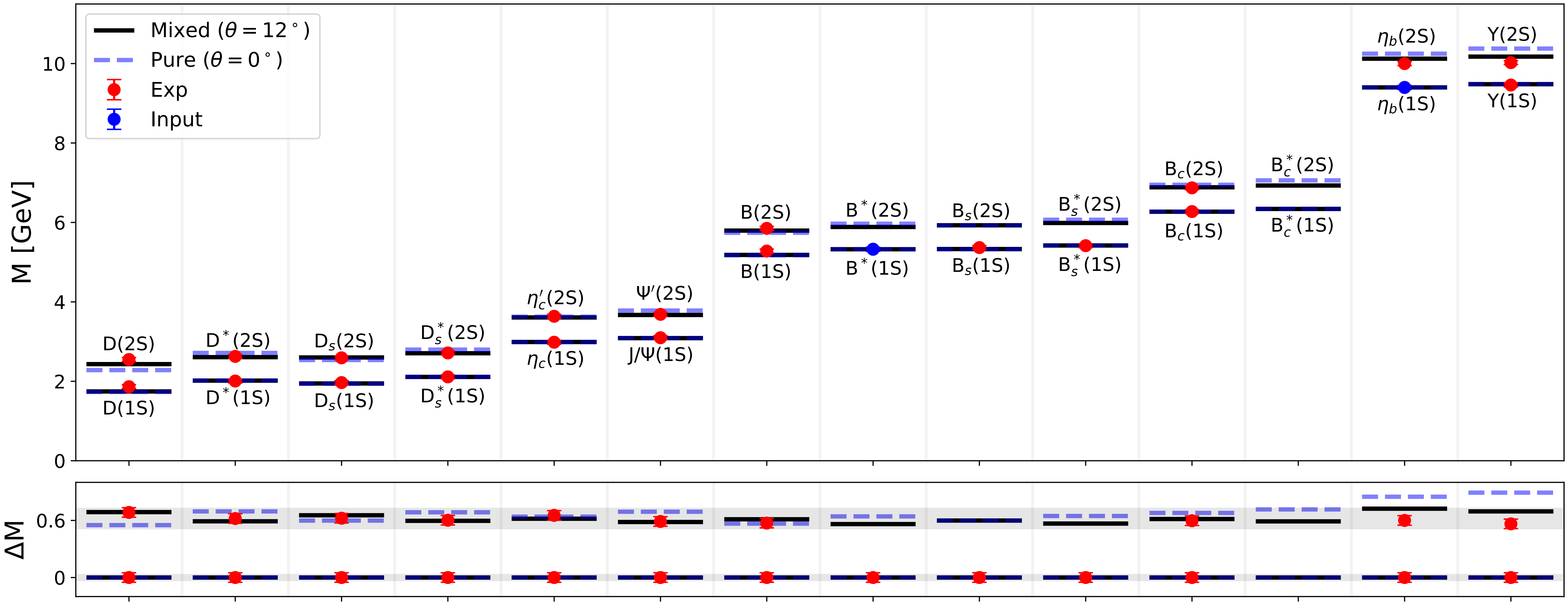
—> use the same quark mass.

—> β systematically decrease.

—> Potential look the same.

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

Mass spectra and gaps



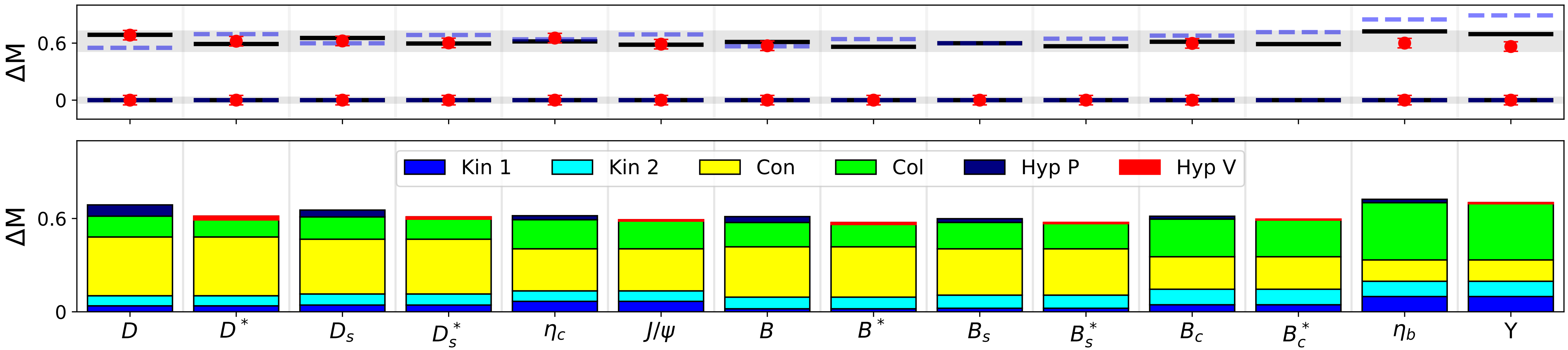
$$V_{q\bar{q}} = a + br - \frac{4\alpha_s}{3r} + \frac{2}{3}\frac{\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}}}{m_q m_{\bar{q}}}\nabla^2 V_{\rm Coul}$$

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

<> Similar mass gap around 600 MeV

<> $D_s(2590)$ is well described.

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

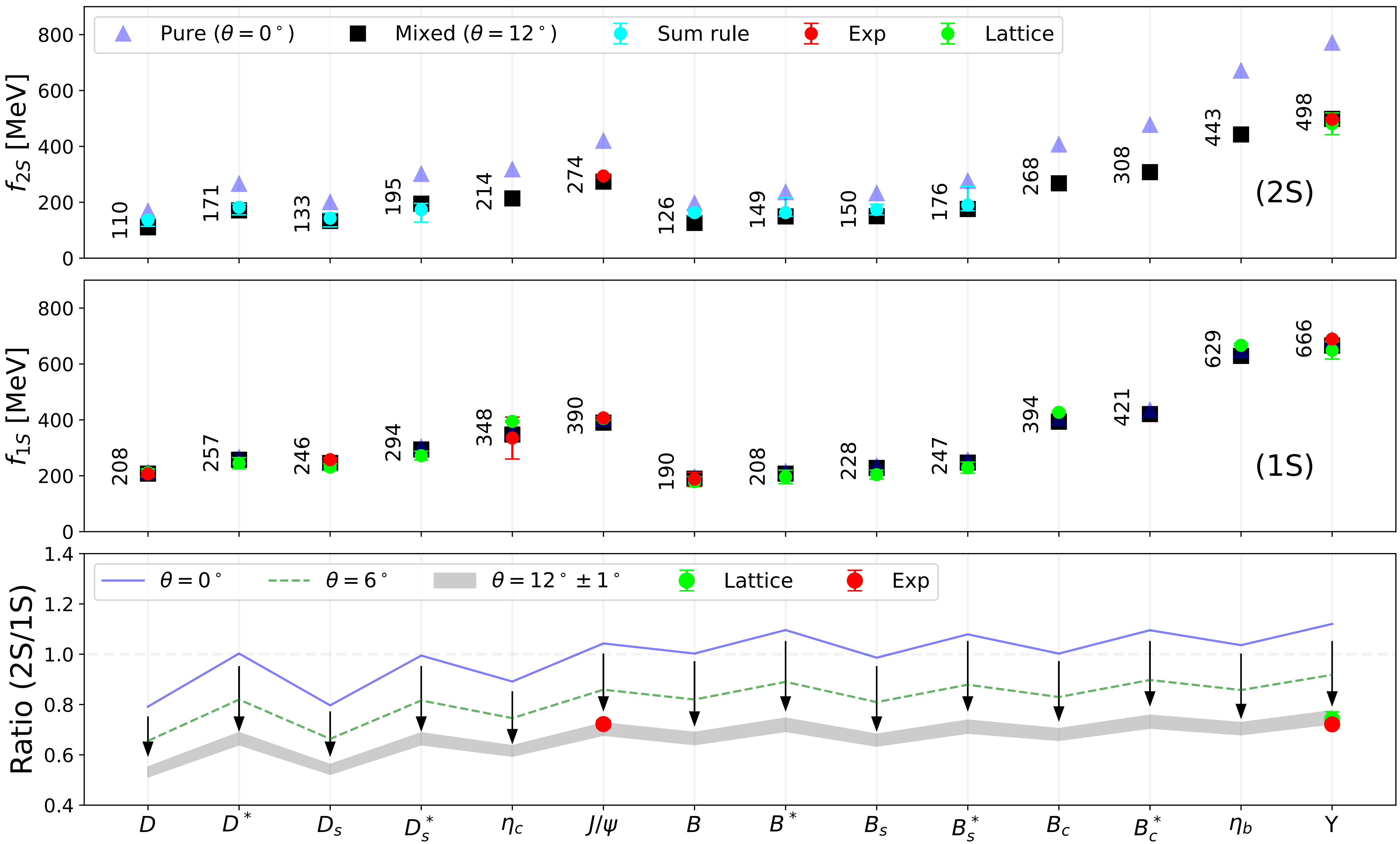
—> $\Delta M_P > \Delta M_V$

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

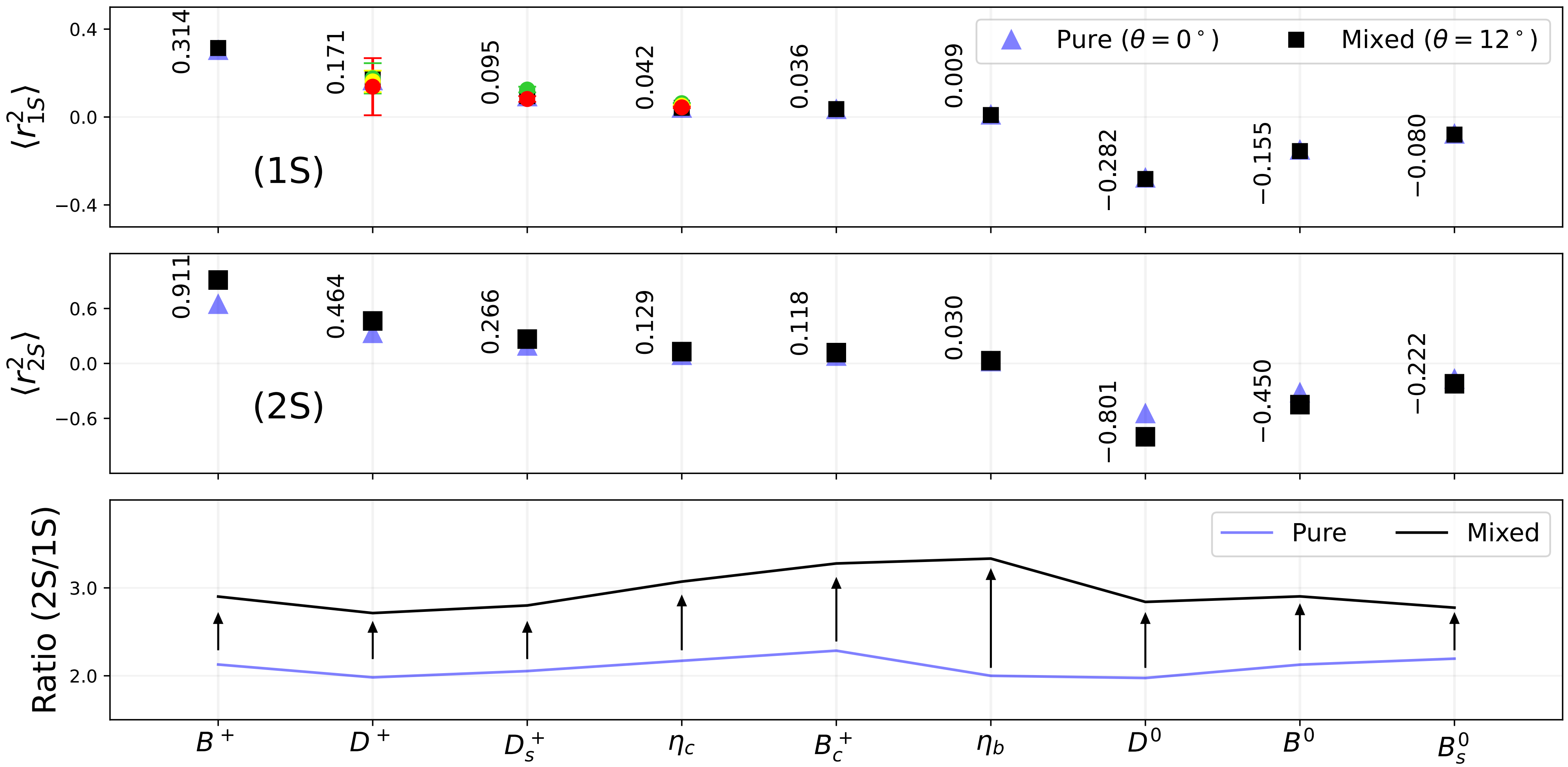
—> $\theta_c \approx 6^\circ$

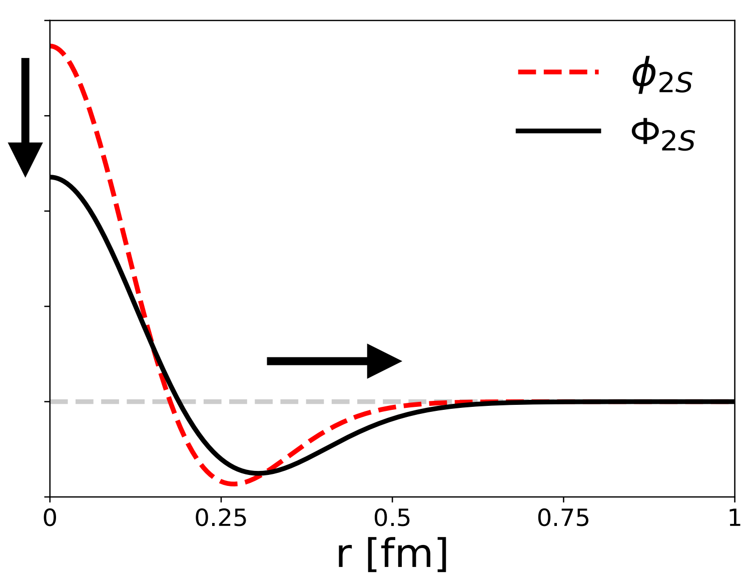
apctp

Decay constant



Charge radius





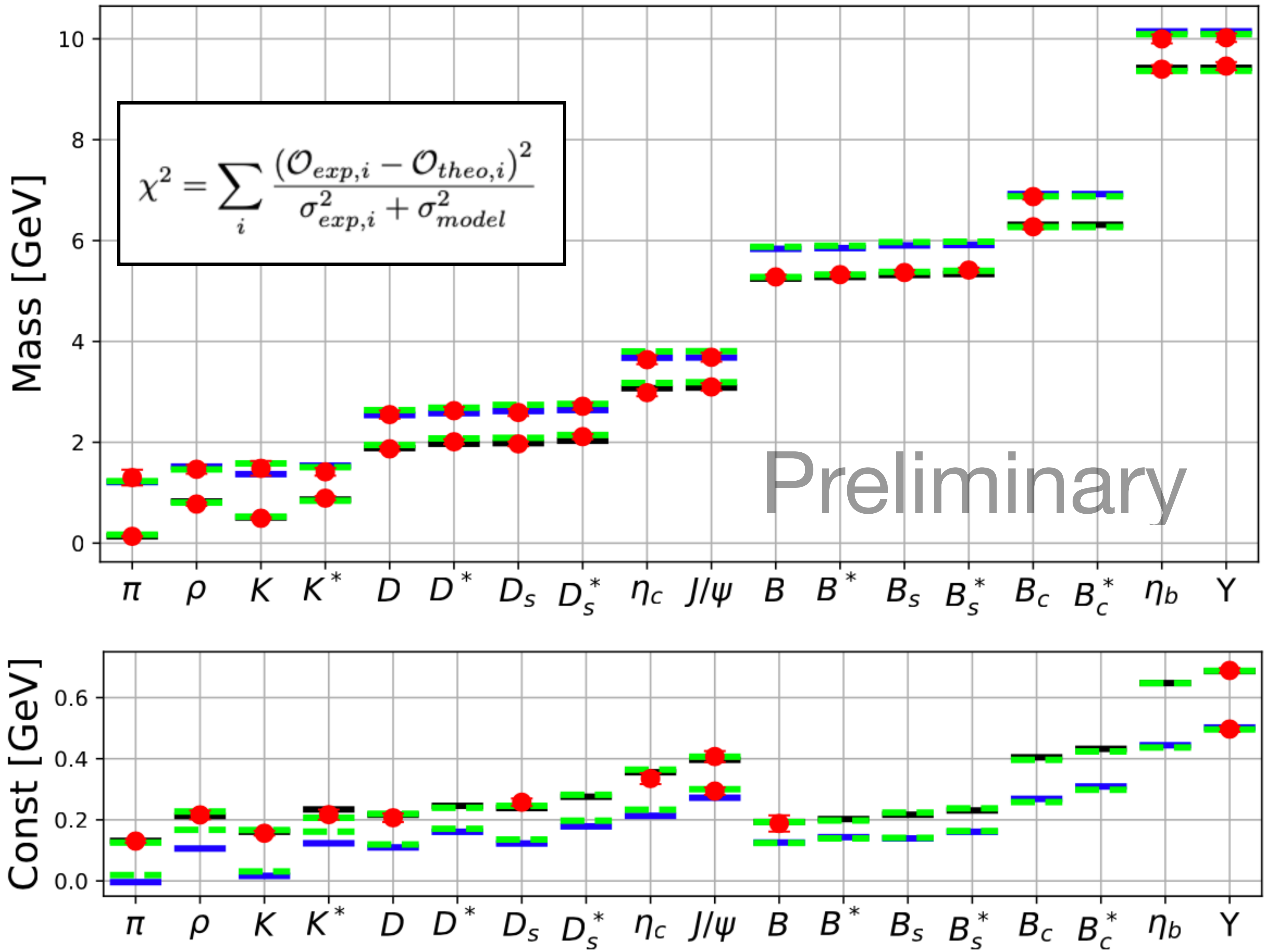
<> With mixing:

—> The 2S state decay constants decrease

—> The 2S state charge radii increase

<> Measuring radius in HIC??

A global fit: light to heavy meson



$\sigma^b_{model} = 0.7\,\%$

$\theta = 12.9(5)$

$\sigma^c_{model} = 2.0\,\%$

$\theta = 10(1)$

$\sigma^q_{model} = 3.6\,\%$

$\theta = 2(8)$

$\sigma_{model} = \lambda \sigma^i_{model}$

$\lambda = 1.2$

$\theta = 12.6(5)$

Summary

- Radial excitation of hadrons
  —> Mass gap, decay constant, radius, etc.
  —> Study in HIC?

- Knowledge of meson and baryon in quark model
  —> important for the study of multi-quark state

- Light-front quark model
  —> Extension to the radial excitation
  —> With the obtained LFWF,
  we will predict various observables

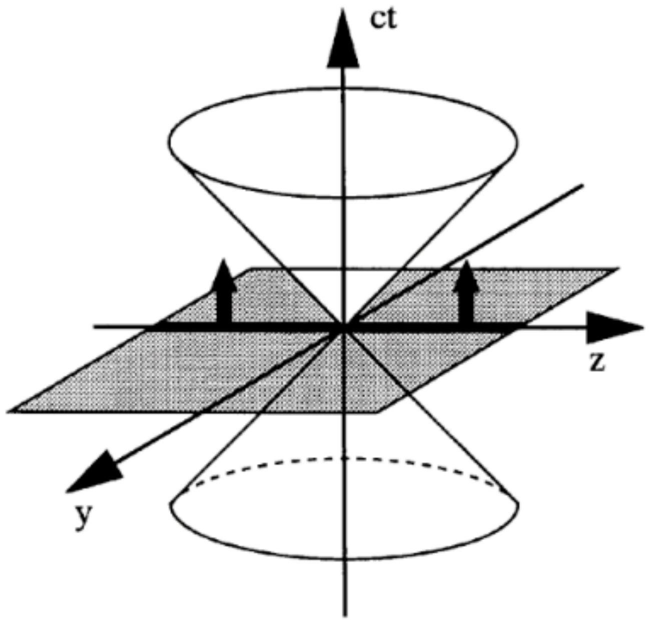
- Looking at the application of LFQM in exotics, Tcc, etc.

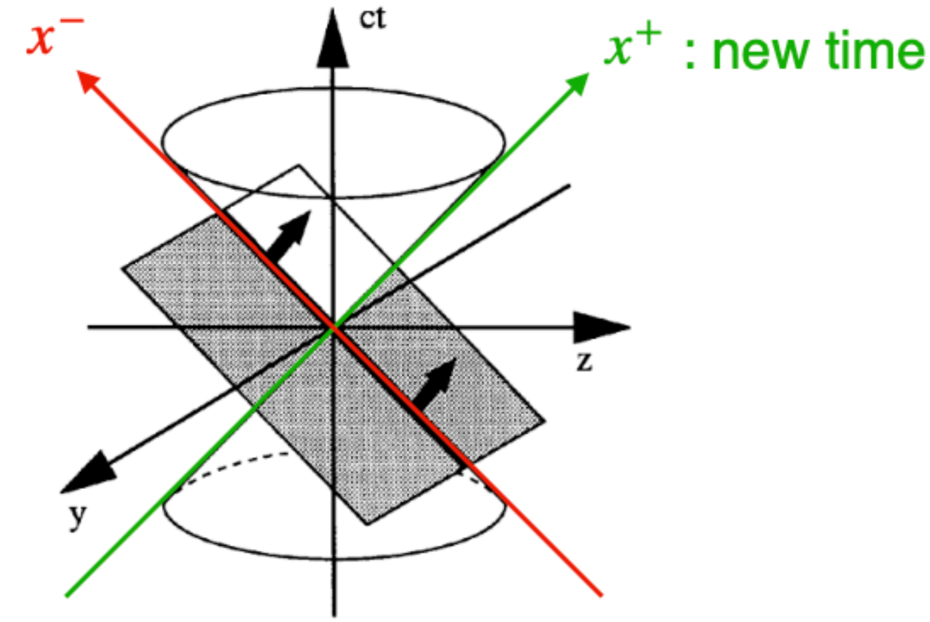
Thank you very much

https://ajarifi.github.io

Instant Form Dynamics (IFD) vs Light-front Dynamics (LFD)

Dirac proposed Light-Front Dynamics (LFD) (1949)





	Instant form	Light-Front form
Time	x^0	$x^+ = x^0 + x^3$
Space	x^1, x^2, x^3	$x^- = x^0 - x^3, \;\; \mathbf{x}_\perp = (x^1, x^2)$
Hamiltonian	p^0	$p^- = p^0 - p^3$
Momentum	p^1, p^2, p^3	$p^+ = p^0 + p^3, \;\; \mathbf{p}_\perp = (p^1, p^2)$
Product	$x \cdot p = x^0 p^0 - \mathbf{x} \cdot \mathbf{p}$	$x \cdot p = (x^+ p^- + x^- p^+)/2 - \mathbf{x}_\perp \cdot \mathbf{p}_\perp$
Vacuum	very complex	can only contain zero-mode excitations

Yongwoo's slide