A look into the $f_0(980)$ through the lens of rare B meson decays

Written by Jaime del Palacio Lirola

Prof. Dr. Robert Fleischer, Dr. Keri Vos and MSc. Anders Result

VRIJE UNIVERSITEIT AMSTERDAM | UNIVERSITEIT VAN AMSTERDAM | Nikhef | UNIVERSITÄT SIEGEN

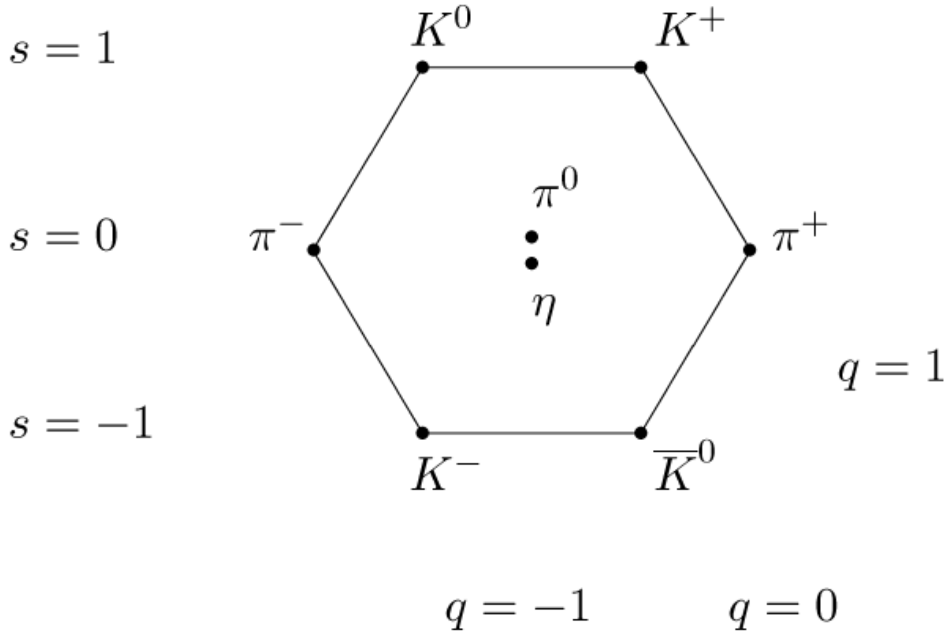
Overview

- What is the $f_0(980)$
- How do we approach it in this work
- Main results
- Conclusions

What is the $f_0(980)$

- Particle zoo in the 60's
- We solved it! The 8-fold way and the quark model

$SU(3)_f$ multiplet



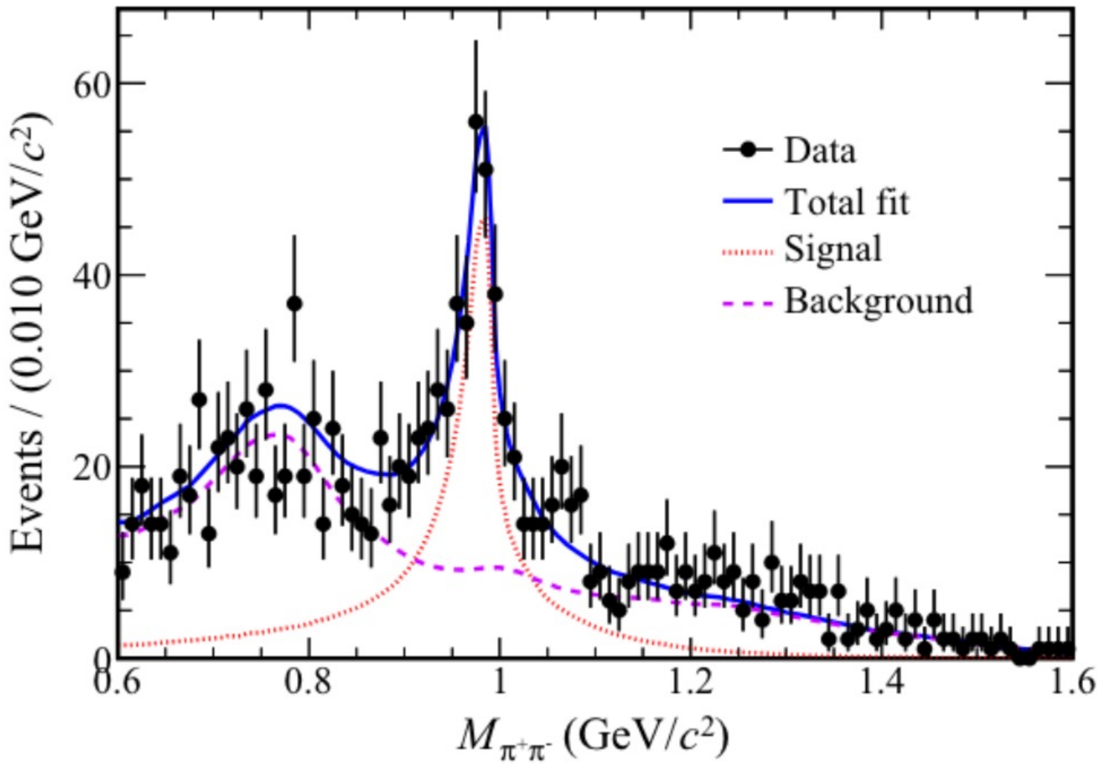
Light Unflavored Mesons (S = C = B = 0)

pi+−	PDF pdgLive	rho(1700)	PDF pdgLive
pi0	PDF pdgLive	a(2)(1700)	PDF pdgLive
eta	PDF pdgLive	a(0)(1710)	PDF pdgLive
f(0)(500)	PDF pdgLive	f(0)(1710)	PDF pdgLive
rho(770)	PDF pdgLive	X(1750)	PDF pdgLive
omega(782)	PDF pdgLive	eta(1760)	PDF pdgLive
eta'(958)	PDF pdgLive	f(0)(1770)	PDF pdgLive
f(0)(980)	PDF pdgLive	pi(1800)	PDF pdgLive
a(0)(980)	PDF pdgLive	f(2)(1810)	PDF pdgLive
phi(1020)	PDF pdgLive	X(1835)	PDF pdgLive
h(1)(1170)	PDF pdgLive	phi(3)(1850)	PDF pdgLive
b(1)(1235)	PDF pdgLive	eta(1)(1855)	PDF pdgLive
a(1)(1260)	PDF pdgLive	eta(2)(1870)	PDF pdgLive
f(2)(1270)	PDF pdgLive	pi(2)(1880)	PDF pdgLive
f(1)(1285)	PDF pdgLive	rho(1900)	PDF pdgLive
eta(1295)	PDF pdgLive	f(2)(1910)	PDF pdgLive
pi(1300)	PDF pdgLive	a(0)(1950)	PDF pdgLive
a(2)(1320)	PDF pdgLive	f(2)(1950)	PDF pdgLive
f(0)(1370)	PDF pdgLive	rho(3)(1990)	PDF pdgLive
h(1)(1380)	PDF pdgLive	pi(2)(2005)	PDF pdgLive
pi(1)(1400)	PDF pdgLive	f(2)(2010)	PDF pdgLive
eta(1405)	PDF pdgLive	f(0)(2020)	PDF pdgLive
f(1)(1420)	PDF pdgLive	a(4)(2040)	PDF pdgLive
omega(1420)	PDF pdgLive	f(4)(2050)	PDF pdgLive

f(2)(1430)	PDF pdgLive	pi(2)(2100)	PDF pdgLive
a(0)(1450)	PDF pdgLive	f(0)(2100)	PDF pdgLive
rho(1450)	PDF pdgLive	f(2)(2150)	PDF pdgLive
eta(1475)	PDF pdgLive	rho(2150)	PDF pdgLive
f(0)(1500)	PDF pdgLive	phi(2170)	PDF pdgLive
f(1)(1510)	PDF pdgLive	f(0)(2200)	PDF pdgLive
f(2)'(1525)	PDF pdgLive	f(J)(2220)	PDF pdgLive
f(2)(1565)	PDF pdgLive	omega(2220)	PDF pdgLive
rho(1570)	PDF pdgLive	eta(2225)	PDF pdgLive
h(1)(1595)	PDF pdgLive	rho(3)(2250)	PDF pdgLive
pi(1)(1600)	PDF pdgLive	f(2)(2300)	PDF pdgLive
a(1)(1640)	PDF pdgLive	f(4)(2300)	PDF pdgLive
f(2)(1640)	PDF pdgLive	f(0)(2330)	PDF pdgLive
eta(2)(1645)	PDF pdgLive	f(2)(2340)	PDF pdgLive
omega(1650)	PDF pdgLive	rho(5)(2350)	PDF pdgLive
omega(3)(1670)	PDF pdgLive	X(2370)	PDF pdgLive
pi(2)(1670)	PDF pdgLive	f(0)(2470)	PDF pdgLive
phi(1680)	PDF pdgLive	f(6)(2510)	PDF pdgLive
rho(3)(1690)	PDF pdgLive		

What is the $f_0(980)$

- What do we know:
  - Observed as a peak in $\pi\pi$, KK spectrums
  - Mass: $990 \pm 20\ MeV$
  - Width: $10 - 100\ MeV$



arXiv:2303.12927v1

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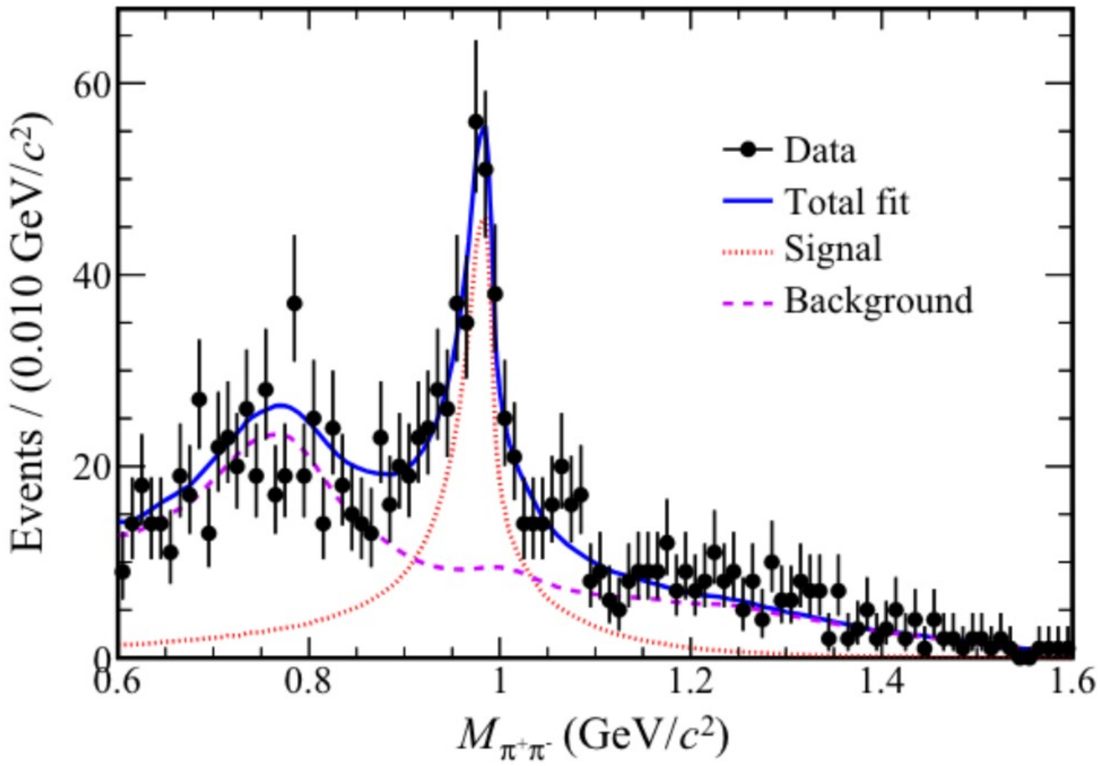

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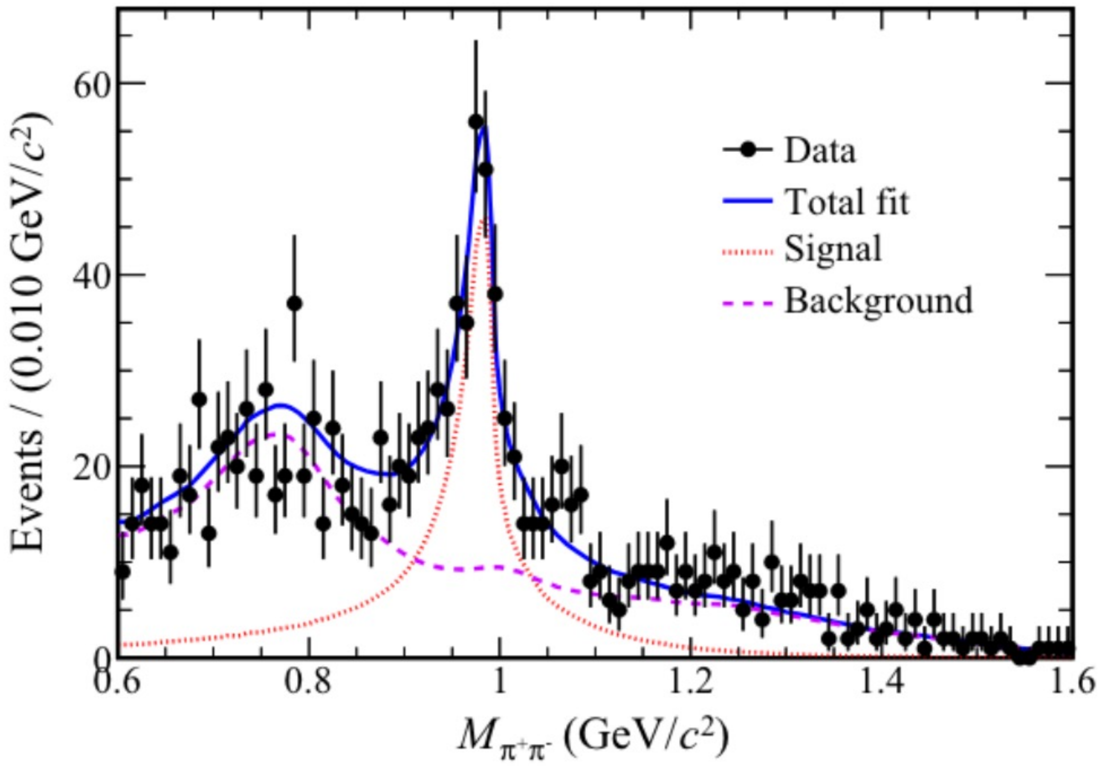
  - $I^G(J^{PC}) = 0^+(0^{++})$, in comparison η_0' has $I^G(J^{PC}) = 0^+(0^{-+})$
  - Has a strong $s\bar{s}$ component (but there is something else)



arXiv:2303.12927v1

What is the $f_0(980)$

- What if it’s a $q\bar{q}$ state?
  - Put it in a scalar octet with other measured states
  - L=1, S=1, J=0
  - Pure state? Does not seem so

$q\bar{q}$

$$\begin{pmatrix} |f_0(980)\rangle \\ |f_0(500)\rangle \end{pmatrix} = \begin{pmatrix} \cos\varphi_M & \sin\varphi_M \\ -\sin\varphi_M & \cos\varphi_M \end{pmatrix} \cdot \begin{pmatrix} |s\bar{s}\rangle \\ |n\bar{n}\rangle \end{pmatrix} \quad (1)$$

$$n\bar{n} \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

but it is not very promising experimentally

arXiv:2104.09922

What is the $f_0(980)$

- What if it's a $q\bar{q}q\bar{q}$ state?
  - Put in a scalar tetraquark octet
  - Does not require non-vanishing angular momentum
  - Describes the mass spectrum hierarchy
  - Can be expressed as:

$q\bar{q}q\bar{q}$

$$|f_0^{[0]}(980)\rangle \equiv \frac{[su]\,[\bar{s}\bar{u}] + [sd]\,[\bar{s}\bar{d}]}{\sqrt{2}}, \quad |f_0^{[0]}(500)\rangle \equiv [ud]\,[\bar{u}\bar{d}] \qquad (2)$$

$$\begin{pmatrix} |f_0(980)\rangle \\ |f_0(500)\rangle \end{pmatrix} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \cdot \begin{pmatrix} |f_0^{[0]}(980)\rangle \\ |f_0^{[0]}(500)\rangle \end{pmatrix}$$

with $|\omega| < 5$ as an upper bound with their measured masses

arXiv:0801.2288

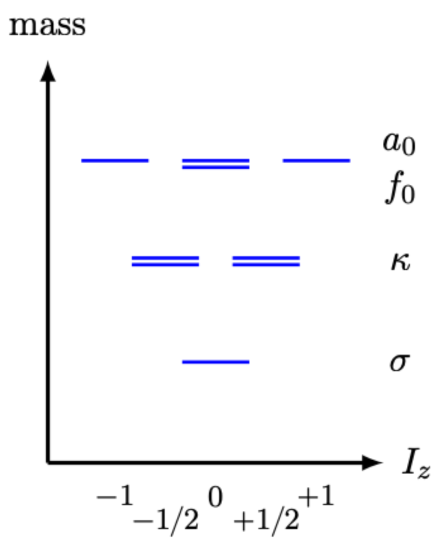


FIG. 5.1: Flavor structure and mass hierarchy for the spectrum of light scalar mesons ($J^P = 0^+$). Experimental observations (left), expectation based to the conventional $q\bar{q}$ model (center), interpretation as tetraquark states, i.e. $qq\bar{q}\bar{q}$ (right).

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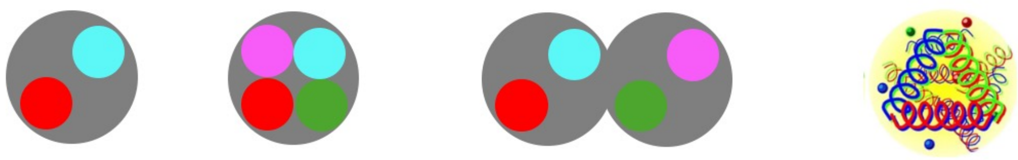
urn:nbn:de:hebis:30:3-445420

What is the $f_0(980)$

- What if it's a combinations of both?
  - It is dominated by the tetraquark component
  - Describes the mass spectrum satisfactorily (has more degrees of freedom) arXiv:0801.2288
- KK molecule has also been proposed arXiv:2001.08141
- Could also add a scalar glueball component…



$q\bar{q}$ $q\bar{q}q\bar{q}$ $(q\bar{q})(q\bar{q})$ glueball

Why the $f_0(980)$

- It is one of the lighter scalar particles
- It is common
- It is a strong candidate for an exotic quark state

- Exploring the nature of these exotic bound states could enhance our understanding of QCD

Overview

- What is the $f_0(980)$
- How do we approach it in this work (and all that is needed to do so)
- Main results
- Conclusions

We are here!

How do we approach it in this work?

$f_0(980) \rightarrow f$ or $I \rightarrow f_0(980)$

- Decays into the $f_0(980)$ to explore its nature

- Which decay do we choose?
- How do we explore it?

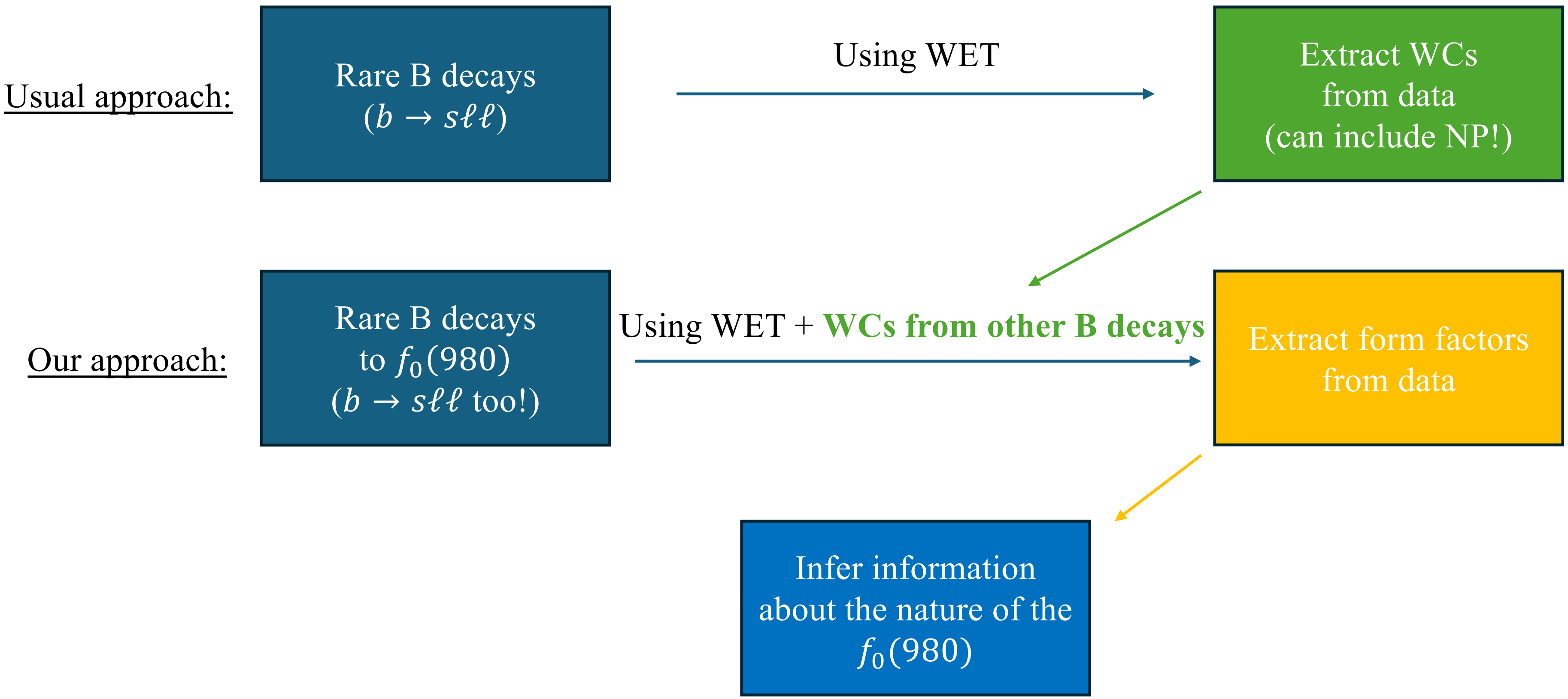
How do we approach it in this work?

- Which decay do we choose?

$$B^0_{(s)} \rightarrow f_0(980)\mu^+\mu^-$$

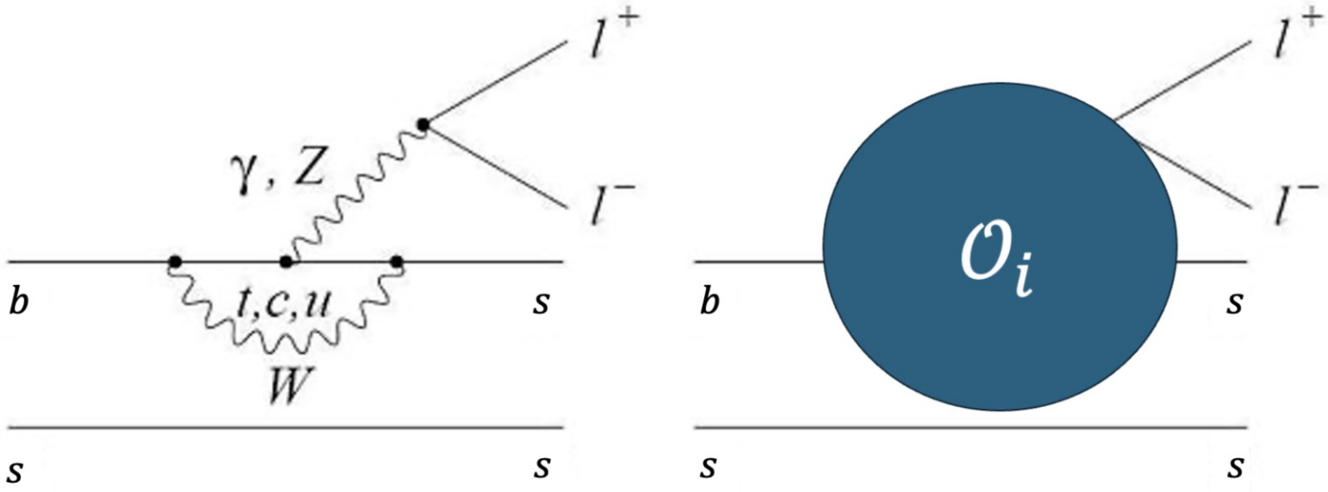
Rare B decay, with no other hadrons in the final state, muons easy to reconstruct.

Flowchart of our approach



All we need to explore the selected decay

- Weak Effective Field Theory

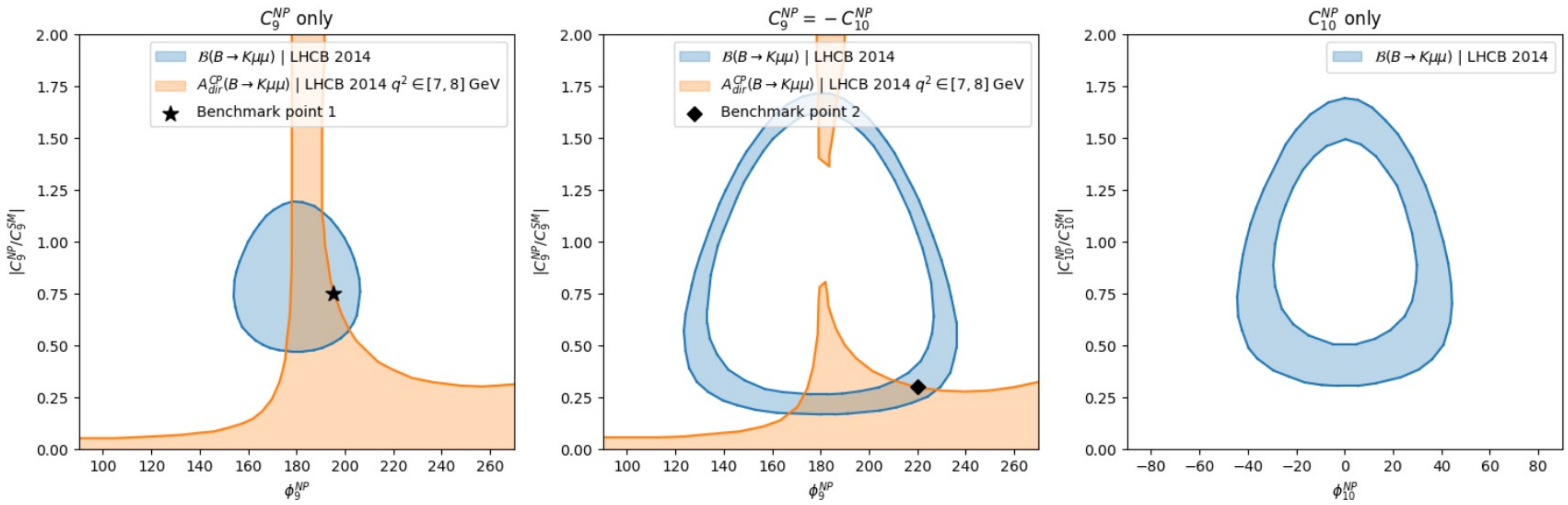


$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \mathcal{O}_i \qquad (4)$$

We will use the Wilson coefficients determined from the SM and from data on other decays with the same quark level transition.

All we need to explore the selected decay

- Current state of Wilson Coefficients
  - Come from data on other decays



$$C_i = C_i^{SM} + C_i^{NP} \quad (5)$$

Have possible weak phases!

All we need to explore the selected decay

- Form factors calculations

$$\mathcal{A} = \langle f_0(980)\mu^+\mu^- | \mathcal{H}_{eff} | B_s\rangle$$

$$\langle f_0(980)\mu^+\mu^- | \mathcal{O}_i | B_s\rangle = \langle f_0(980)| \Gamma^A | B_s\rangle \langle \mu^+\mu^- | \Gamma'_A | 0\rangle$$

$$\langle f_0(980)| s\gamma_\mu\gamma_5\bar{b} | B_s\rangle = -i \left\{ \boxed{F_1}(q^2) \left[P_\mu - \frac{m_{B_s}^2 - m_{f_0}^2}{q^2} q_\mu \right] + \boxed{F_0}(q^2) \frac{m_{B_s}^2 - m_{f_0}^2}{q^2} q_\mu \right\},$$

$$\langle f_0(980)| s\sigma_{\mu\nu}\gamma_5 q^\nu \bar{b} | B_s\rangle = -\frac{\boxed{F_T}(q^2)}{m_{B_s} + m_{f_0}} \left[q^2 P_\mu - (m_{B_s}^2 - m_{f_0}^2) q_\mu \right],$$

All we need to explore the selected decay

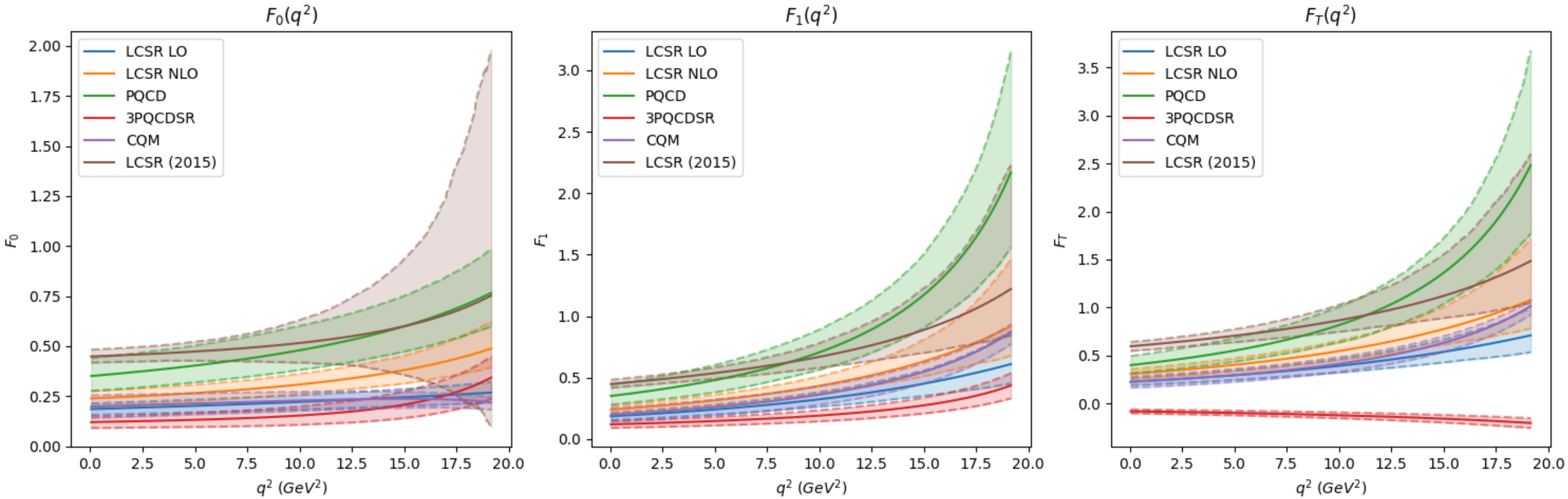
- Form factors calculations

- All assume a pure $s\bar{s}$ state and use:

  - Light Cone Sum Rules (LCSR LO, LCSR NLO, LCSR (2015))
  - Perturbative QCD (PQCD)
  - 3-point QCD Sum Rules (3PQCDSR)
  - Covariant Quark Model (CQM)

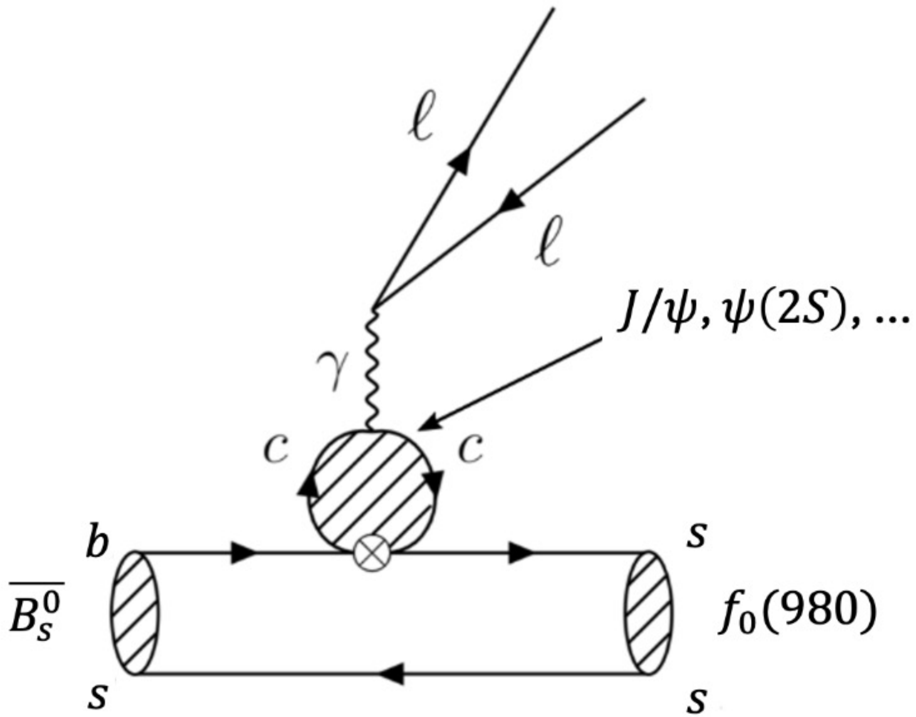
All we need to explore the selected decay

- Form factors calculations



All we need to explore the selected decay

- Long-distance effects



$$C_9^{\text{eff}} = C_9 + Y(q^2) = |C_9|e^{\delta_9} + |Y(q^2)|e^{\delta_Y(q^2)}$$

Overview

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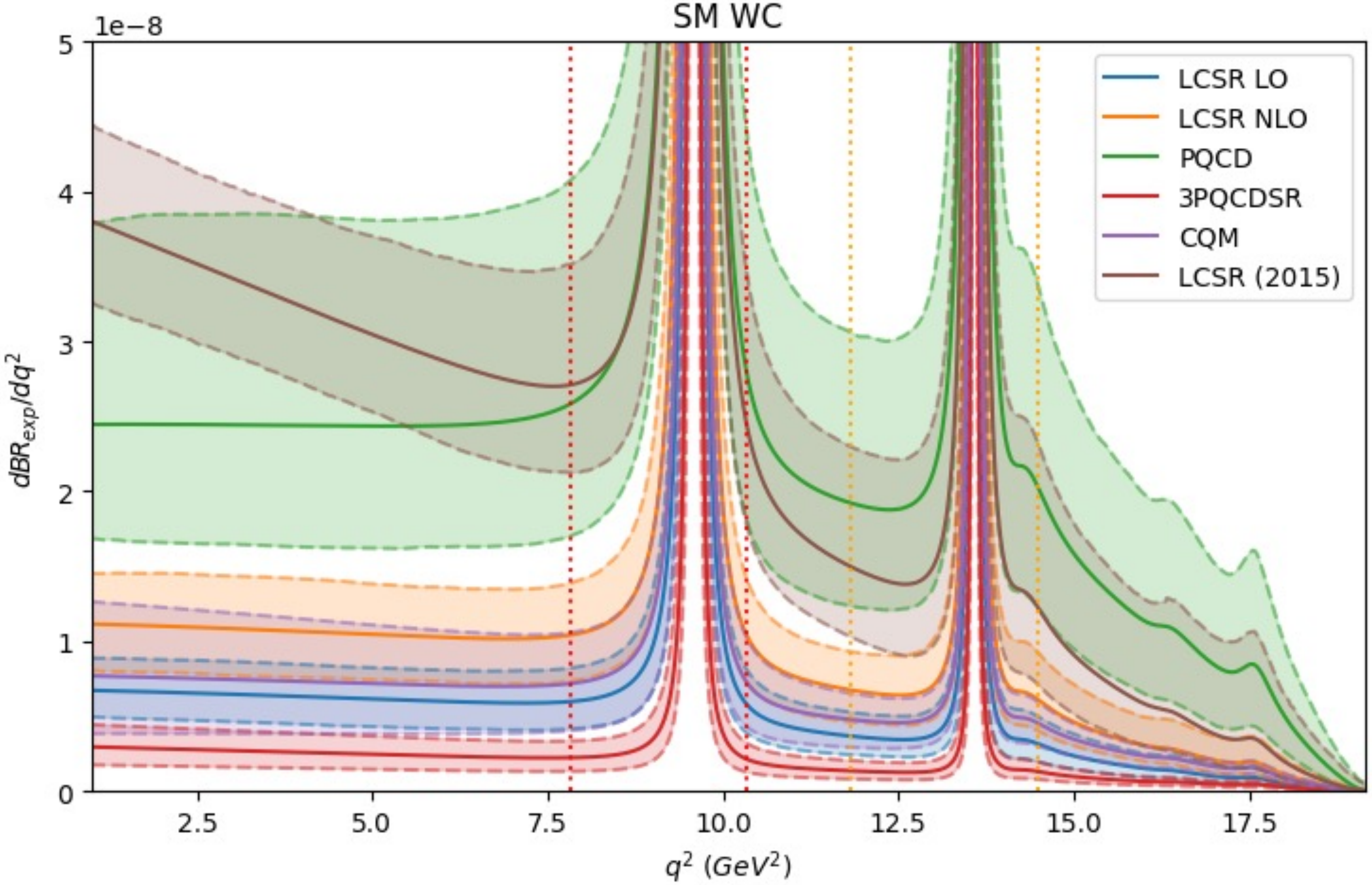
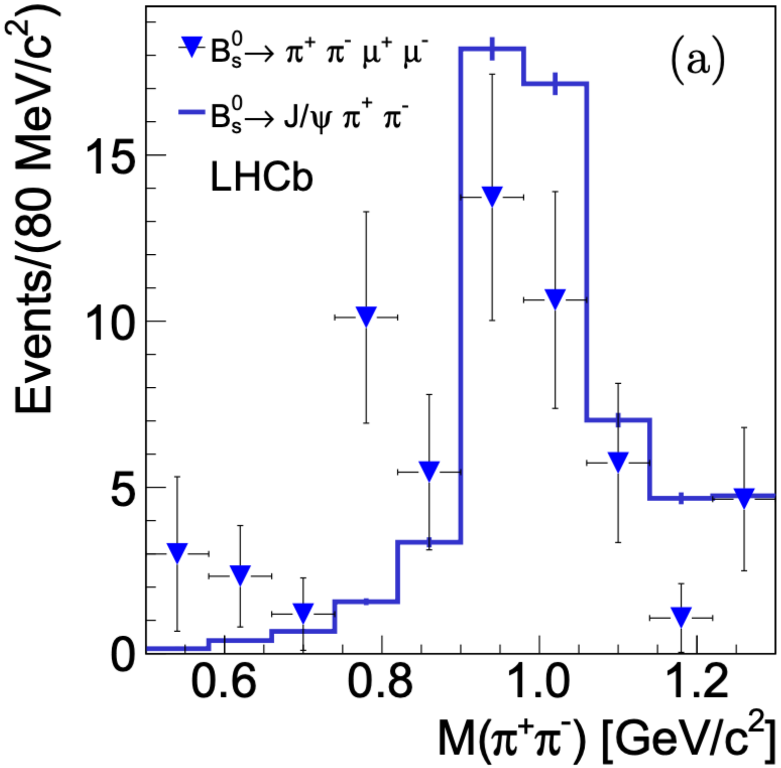
We are finally here!

Main Results

$$BR_{CP-average} = \frac{\Gamma(B_s^0 \to f_0(980)\mu^+\mu^-) + \Gamma(\overline{B_s^0} \to f_0(980)\mu^+\mu^-)}{2}\tau_{B_s}$$



Available experimental results

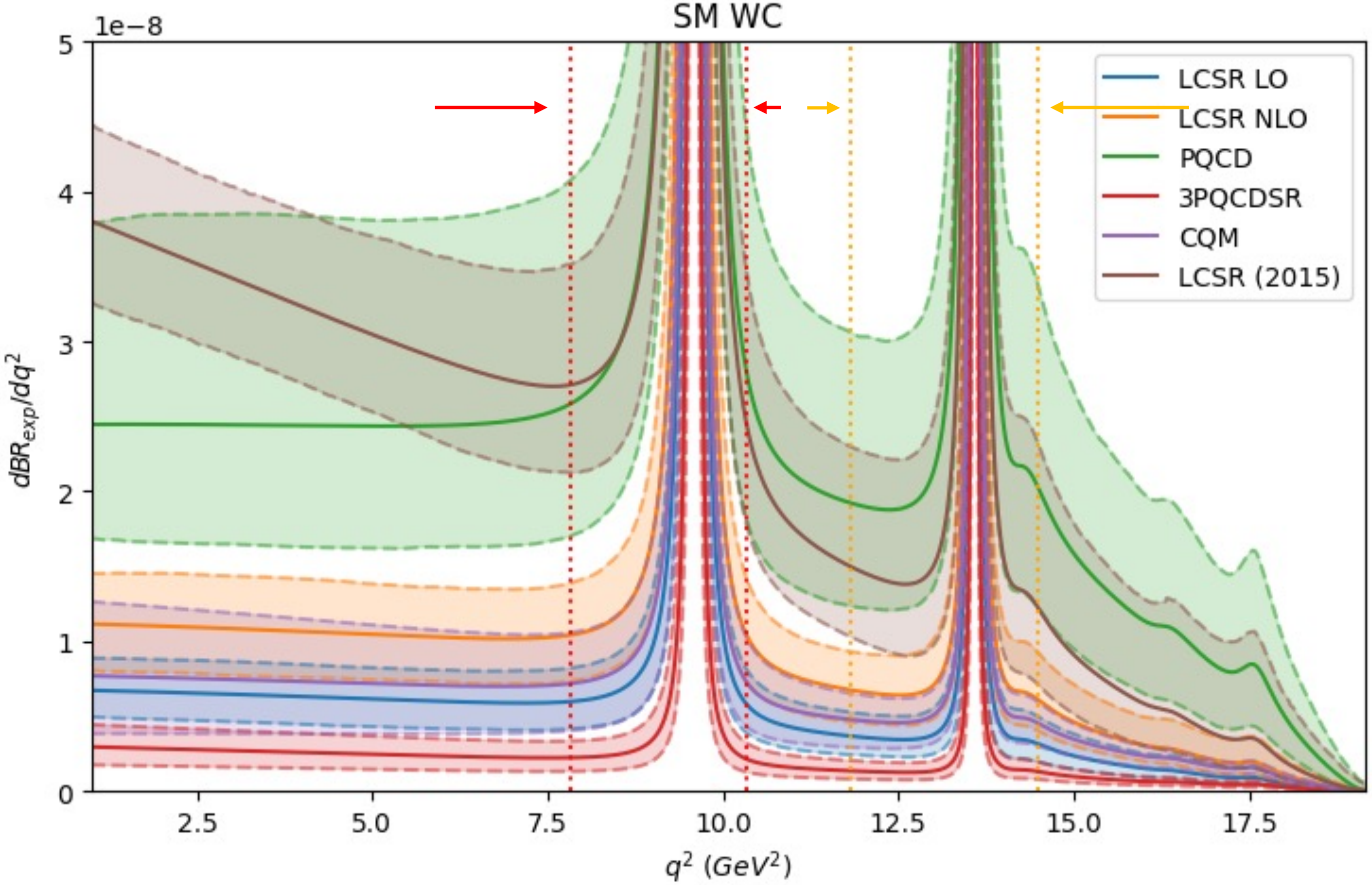


arXiv:1412.6433

$$\mathcal{B}(B_s^0 \to f_0(980)(\to \pi^+\pi^-)\mu^+\mu^- = (8.3 \pm 1.7)\times 10^{-8}$$

Main Results

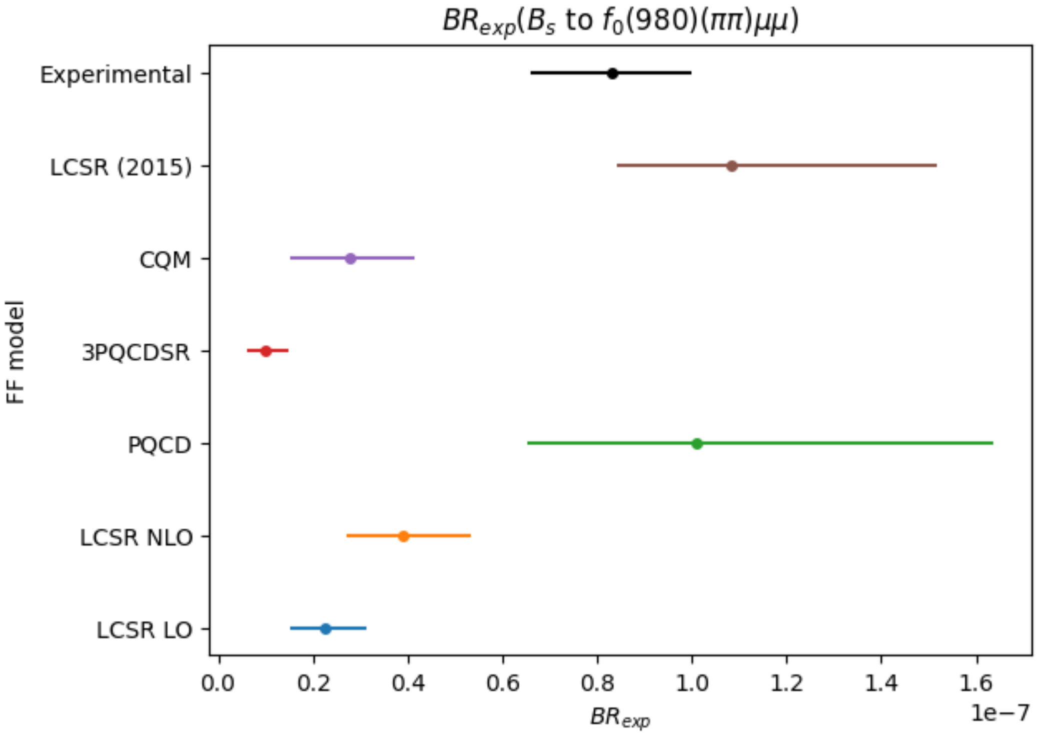
$$BR_{CP-average} = \frac{\Gamma(B_s^0 \to f_0(980)\mu^+\mu^-) + \Gamma(\overline{B_s^0} \to f_0(980)\mu^+\mu^-)}{2}\tau_{B_s}$$



Main limitations for the comparison

- Long distance effects
- $R = \frac{\Gamma(f_0 \to \pi\pi)}{\Gamma(f_0 \to \pi\pi) + \Gamma(f_0 \to KK)}$ or $\mathcal{B}(f_0 \to \pi^+\pi^-)$
- $f_0(980)$ decay constant
- Assumptions about the nature of the $f_0(980)(s\bar{s})$
- Experimental uncertainty is still big

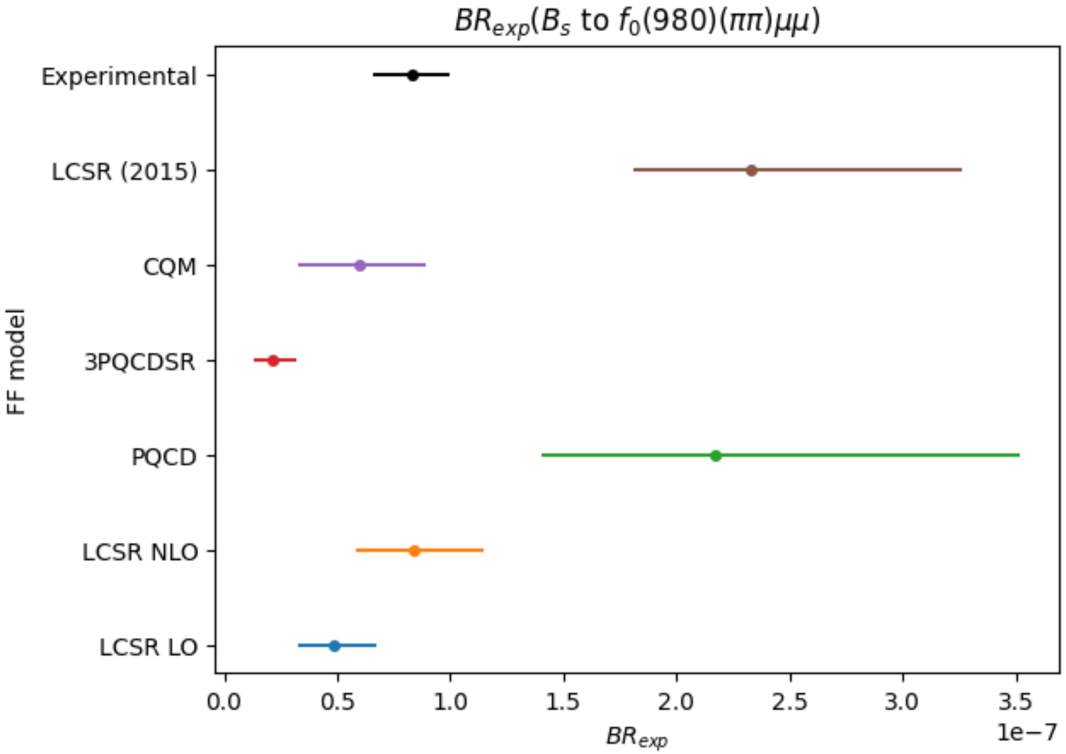
Main Results



$R = 0.52 \pm 0.12$

PHYSICAL REVIEW D **74,** 032003 (2006)

Dalitz plot analysis of the decay $B^{\pm} \to K^{\pm}K^{\pm}K^{\mp}$



$R = 0.84 \pm 0.02$

Measurement of the $\pi^+\pi^- \to K_s{}^0 K_s{}^0$ Scattering Cross Section

N. M. Cason, A. E. Baumbaugh, J. M. Bishop, N. N. Biswas, V. P. Kenney, V. A. Polychronakos, R. C. Ruchti, W. D. Shephard, and J. M. Watson

Phys. Rev. Lett. **41**, 271 – Published 31 July 1978

Main limitations for the comparison

- Long distance effects → Stay away from resonances
- $R = \frac{\Gamma(f_0 \to \pi\pi)}{\Gamma(f_0 \to \pi\pi) + \Gamma(f_0 \to KK)}$ or $\mathcal{B}(f_0 \to \pi^+\pi^-)$ → ?
- $f_0(980)$ decay constant
- Assumptions about the nature of the $f_0(980)(s\bar{s})$

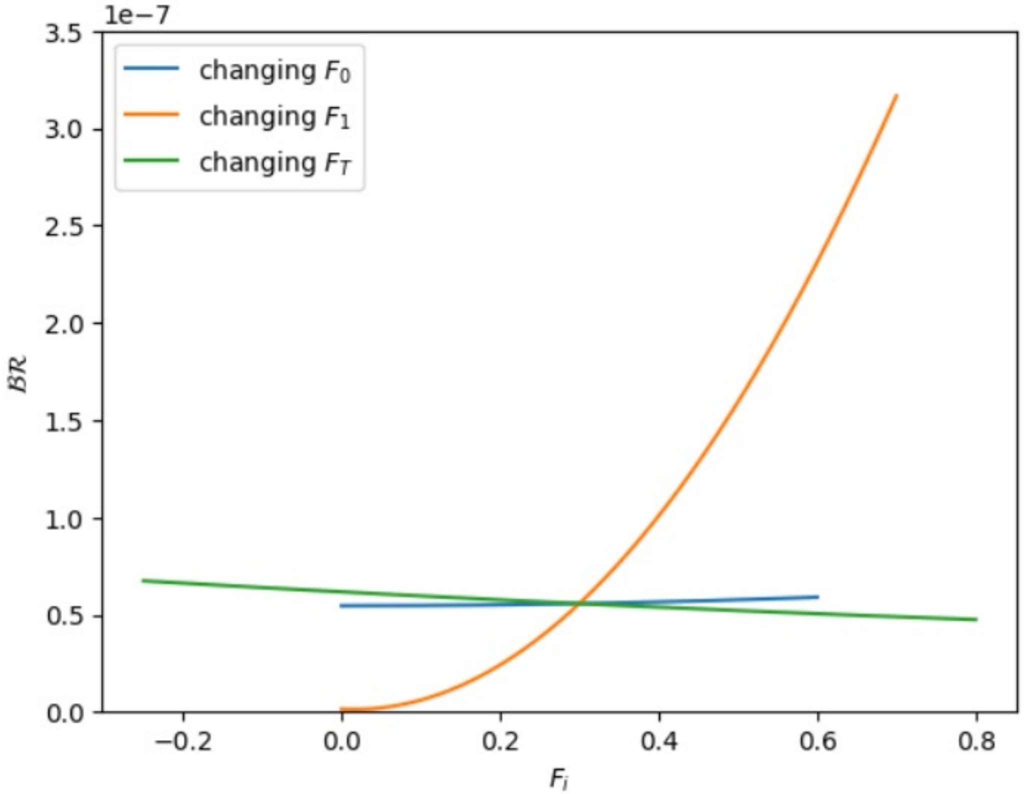
→ Extract the form factors experimentally to limit the phase space in a more agnostic way

- Experimental uncertainty is still big → Use also LHC Run 2

Main Results

- Observables vs form factors

Observables integrated in $q^2 \in [1,6] GeV^2$, and considering $F_i(q^2) = F_i$ in said range



$$\frac{m_{B_s}}{m_{B_s}+m_{f_0}}F_T(q^2) = F_1(q^2) = \frac{m_{B_s}}{2E}F_0(q^2),$$

arXiv:1002.2880v1

Conclusions

- The theoretical calculation is limited by several non-perturbative quantities, but some of them can be avoided.

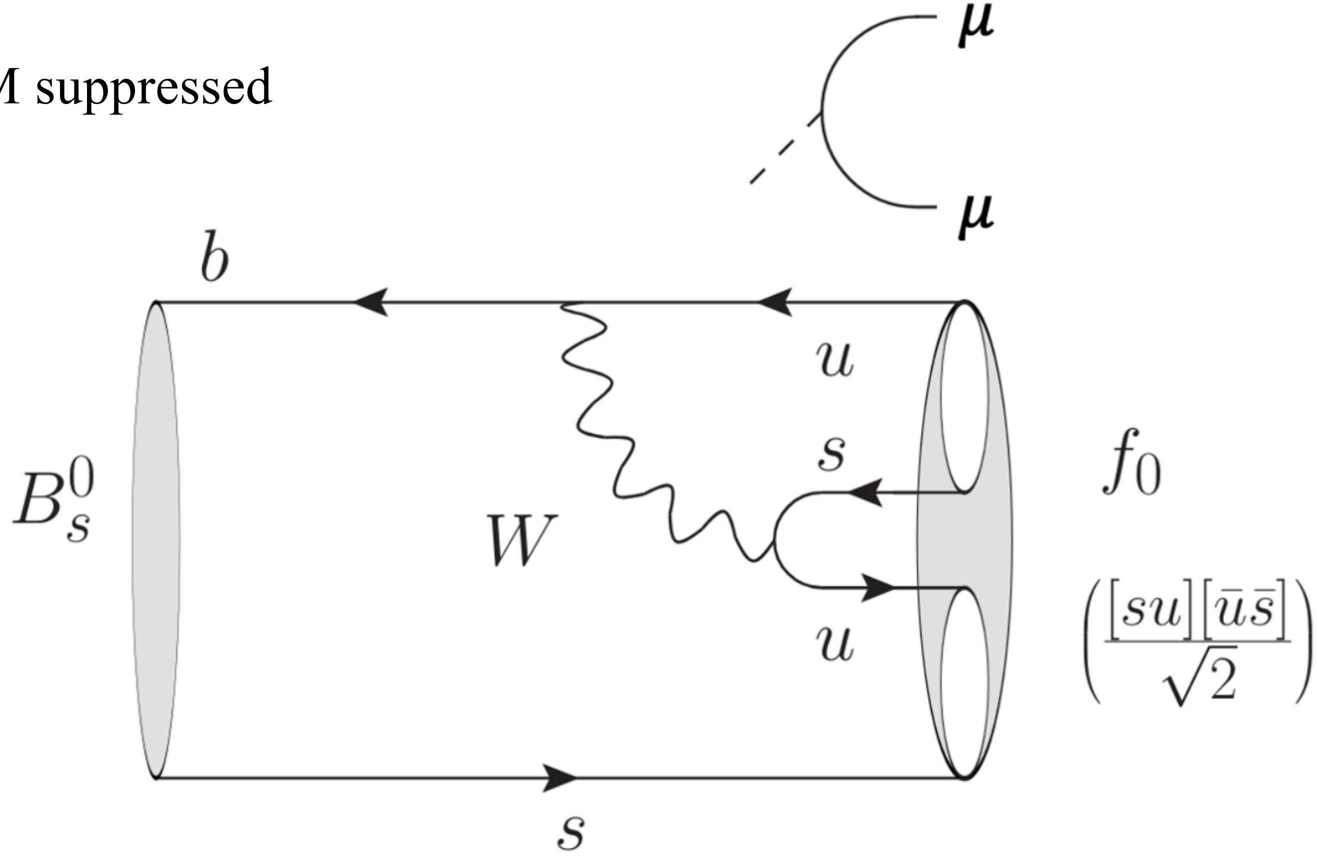
- Current results ~agree, but both theoretical and experimental values are very uncertain.

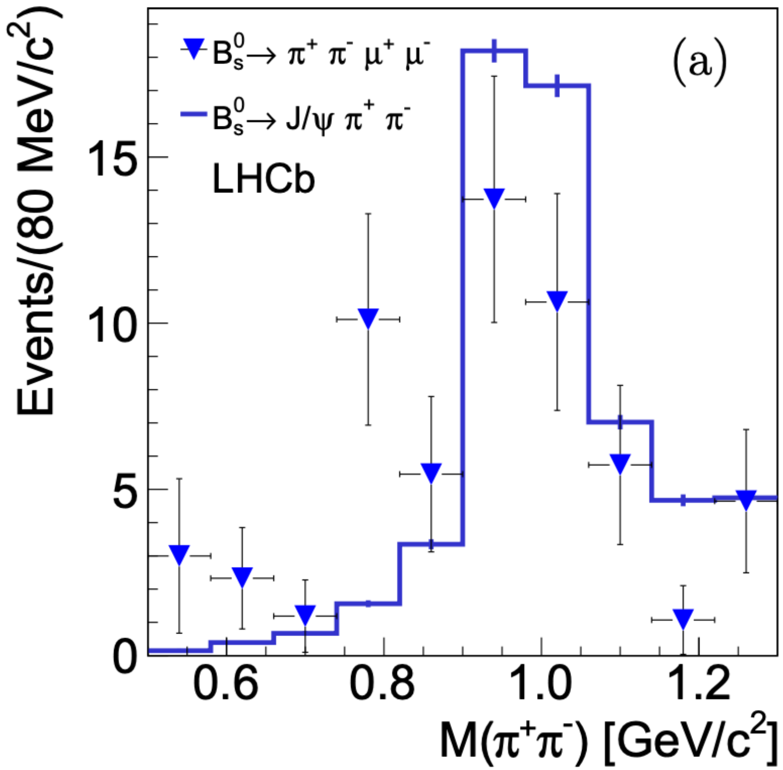
- Form factors (F_1) could be extracted from observables (BR) to limit the available phase space and guide theoretical determinations, hopefully giving some insight into the nature of the $f_0(980)$.

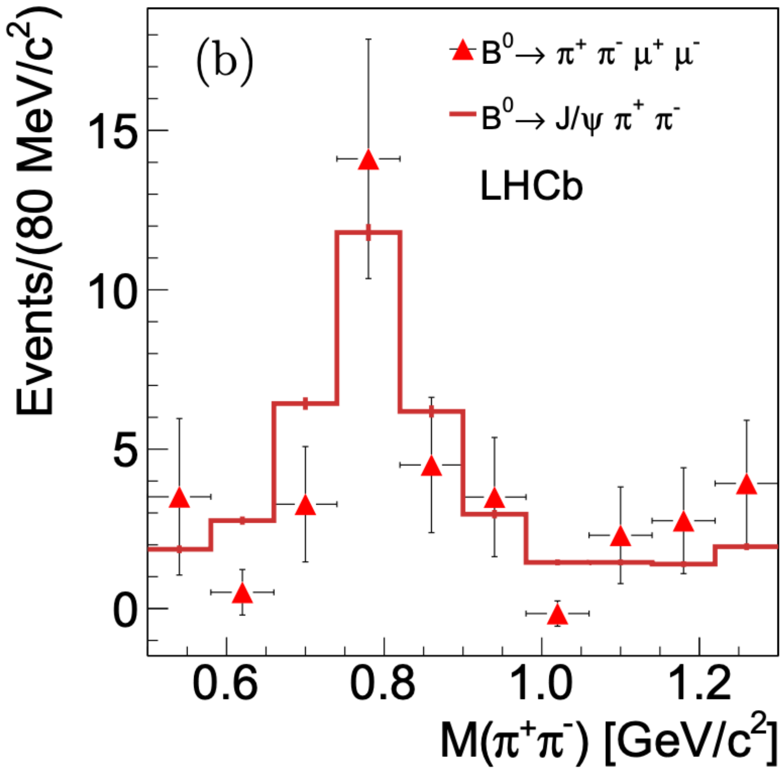
Thank you!

Extra slides

CKM suppressed







arXiv:1412.6433

PQDC approach

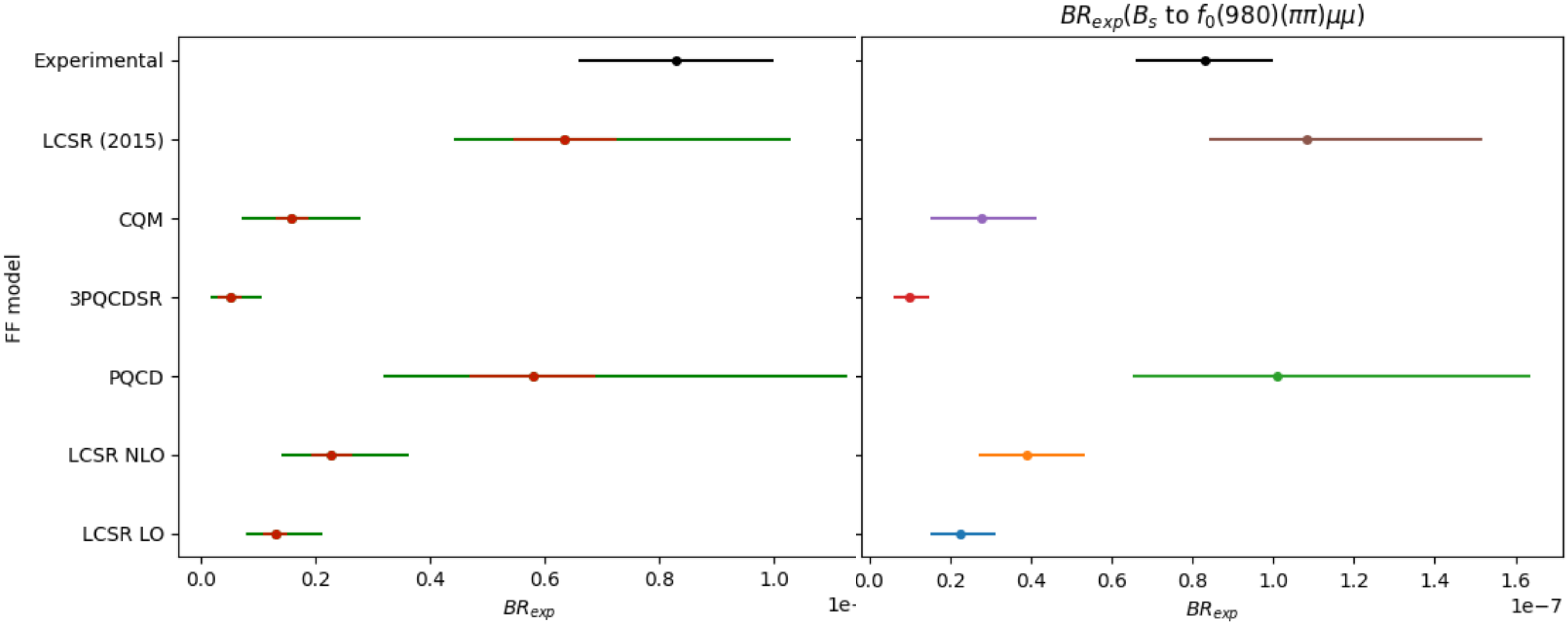
TABLE V: Form factors for $B \to S$ in scenario 1. The errors arise from the uncertainties of hadronic parameters of $B_{(s)}$ meson(f_b and ω_b), $\Lambda_{\rm QCD}$, scales(t_e^i) and the Gegenbauer moments of scalar mesons.

	$F_0(0)=F_1(0)$	$F_T(0)$	$a(F_0)$	$b(F_0)$	$a(F_1)$	$b(F_1)$	$a(F_T)$	$b(F_T)$
$B \to f_0(1370)$	$-0.30^{+0.08}_{-0.09}$	$-0.39^{+0.10}_{-0.11}$	$0.70^{+0.07}_{-0.02}$	$-0.24^{+0.15}_{-0.05}$	$1.63^{+0.09}_{-0.05}$	$0.53^{+0.14}_{-0.08}$	$1.60^{+0.06}_{-0.04}$	$0.50^{+0.08}_{-0.05}$
$B \to a_0(1450)$	$-0.31^{+0.08}_{-0.09}$	$-0.41^{+0.10}_{-0.12}$	$0.70^{+0.13}_{-0.02}$	$-0.26^{+0.24}_{-0.00}$	$1.63^{+0.08}_{-0.04}$	$0.53^{+0.13}_{-0.06}$	$1.62^{+0.04}_{-0.07}$	$0.54^{+0.03}_{-0.13}$
$B \to K_0^*(1430)$	$-0.34^{+0.07}_{-0.09}$	$-0.44^{+0.10}_{-0.11}$	$0.72^{+0.04}_{-0.04}$	$-0.18^{+0.04}_{-0.05}$	$1.65^{+0.04}_{-0.07}$	$0.57^{+0.08}_{-0.14}$	$1.61^{+0.04}_{-0.05}$	$0.52^{+0.05}_{-0.06}$
$\bar{B}_s^0 \to f_0(1500)$	$-0.26^{+0.09}_{-0.08}$	$-0.34^{+0.10}_{-0.10}$	$0.72^{+0.14}_{-0.08}$	$-0.20^{+0.10}_{-0.10}$	$1.61^{+0.13}_{-0.03}$	$0.48^{+0.27}_{-0.02}$	$1.60^{+0.06}_{-0.04}$	$0.48^{+0.09}_{-0.04}$
$\bar{B}_s^0 \to K_0^*(1430)$	$-0.32^{+0.06}_{-0.07}$	$-0.41^{+0.08}_{-0.09}$	$0.69^{+0.05}_{-0.03}$	$-0.21^{+0.11}_{-0.03}$	$1.62^{+0.06}_{-0.03}$	$0.52^{+0.14}_{-0.04}$	$1.62^{+0.01}_{-0.06}$	$0.56^{+0.00}_{-0.16}$

TABLE VI: Form factors for $B \to S$ in scenario 2, with the same error sources as the data in Table V.

	$F_0(0)=F_1(0)$	$F_T(0)$	$a(F_0)$	$b(F_0)$	$a(F_1)$	$b(F_1)$	$a(F_T)$	$b(F_T)$
$B \to f_0(1370)$	$0.63^{+0.23}_{-0.14}$	$0.76^{+0.37}_{-0.17}$	$0.70^{+0.05}_{-0.11}$	$-0.14^{+0.02}_{-0.09}$	$1.60^{+0.15}_{-0.05}$	$0.53^{+0.18}_{-0.09}$	$1.63^{+0.07}_{-0.05}$	$0.57^{+0.07}_{-0.07}$
$B \to a_0(1450)$	$0.68^{+0.19}_{-0.15}$	$0.92^{+0.30}_{-0.21}$	$0.62^{+0.05}_{-0.08}$	$-0.21^{+0.06}_{-0.02}$	$1.73^{+0.12}_{-0.07}$	$0.70^{+0.16}_{-0.11}$	$1.68^{+0.06}_{-0.04}$	$0.61^{+0.10}_{-0.02}$
$B \to K_0^*(1430)$	$0.60^{+0.18}_{-0.15}$	$0.78^{+0.25}_{-0.19}$	$0.68^{+0.07}_{-0.05}$	$-0.18^{+0.06}_{-0.01}$	$1.70^{+0.09}_{-0.07}$	$0.65^{+0.10}_{-0.10}$	$1.68^{+0.07}_{-0.04}$	$0.61^{+0.11}_{-0.02}$
$\bar{B}_s^0 \to f_0(1500)$	$0.60^{+0.20}_{-0.12}$	$0.82^{+0.30}_{-0.16}$	$0.65^{+0.04}_{-0.10}$	$-0.22^{+0.07}_{-0.02}$	$1.76^{+0.13}_{-0.08}$	$0.71^{+0.20}_{-0.08}$	$1.71^{+0.04}_{-0.07}$	$0.66^{+0.06}_{-0.10}$
$\bar{B}_s^0 \to K_0^*(1430)$	$0.56^{+0.16}_{-0.13}$	$0.72^{+0.22}_{-0.17}$	$0.67^{+0.06}_{-0.07}$	$-0.17^{+0.01}_{-0.07}$	$1.69^{+0.08}_{-0.07}$	$0.63^{+0.09}_{-0.10}$	$1.68^{+0.06}_{-0.06}$	$0.63^{+0.07}_{-0.08}$

arXiv:0811.2648v1



$$R = 0.52 \pm 0.12$$

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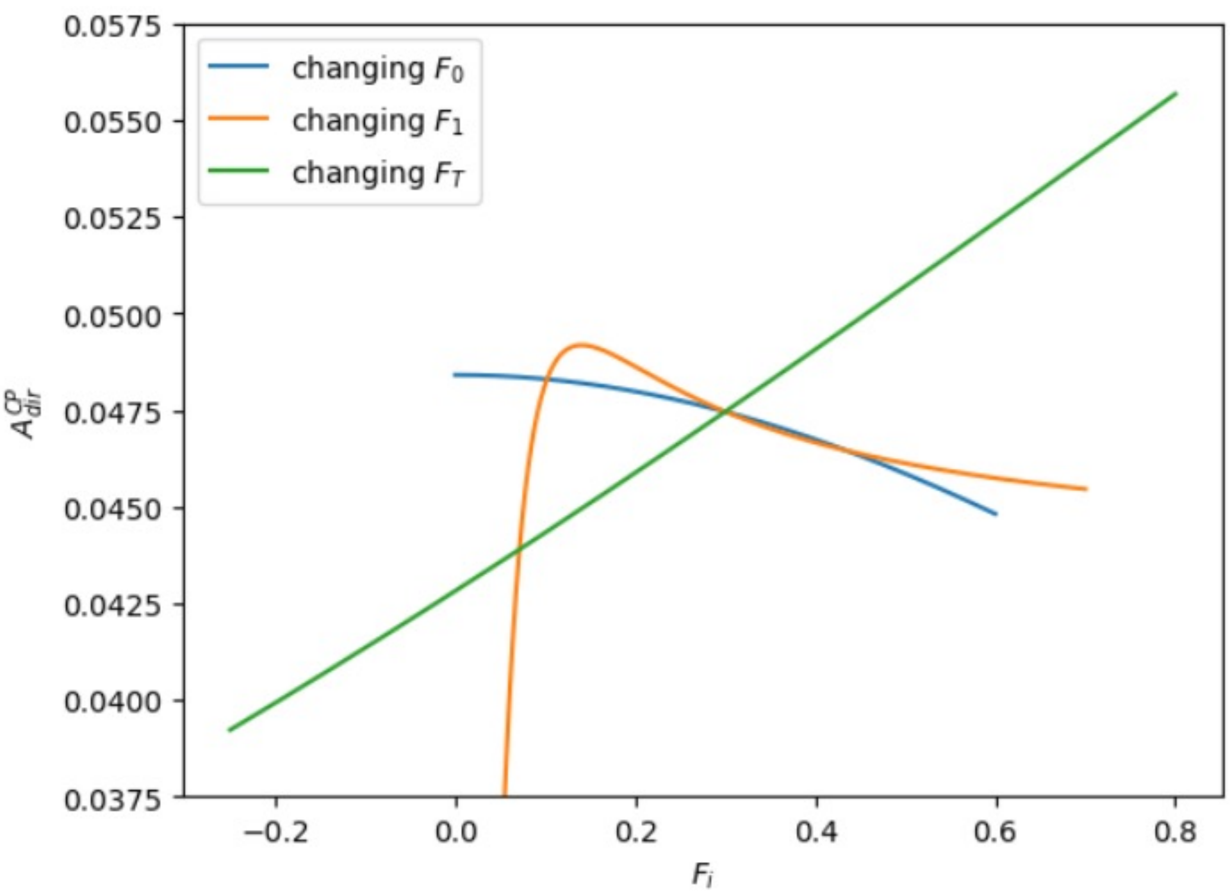
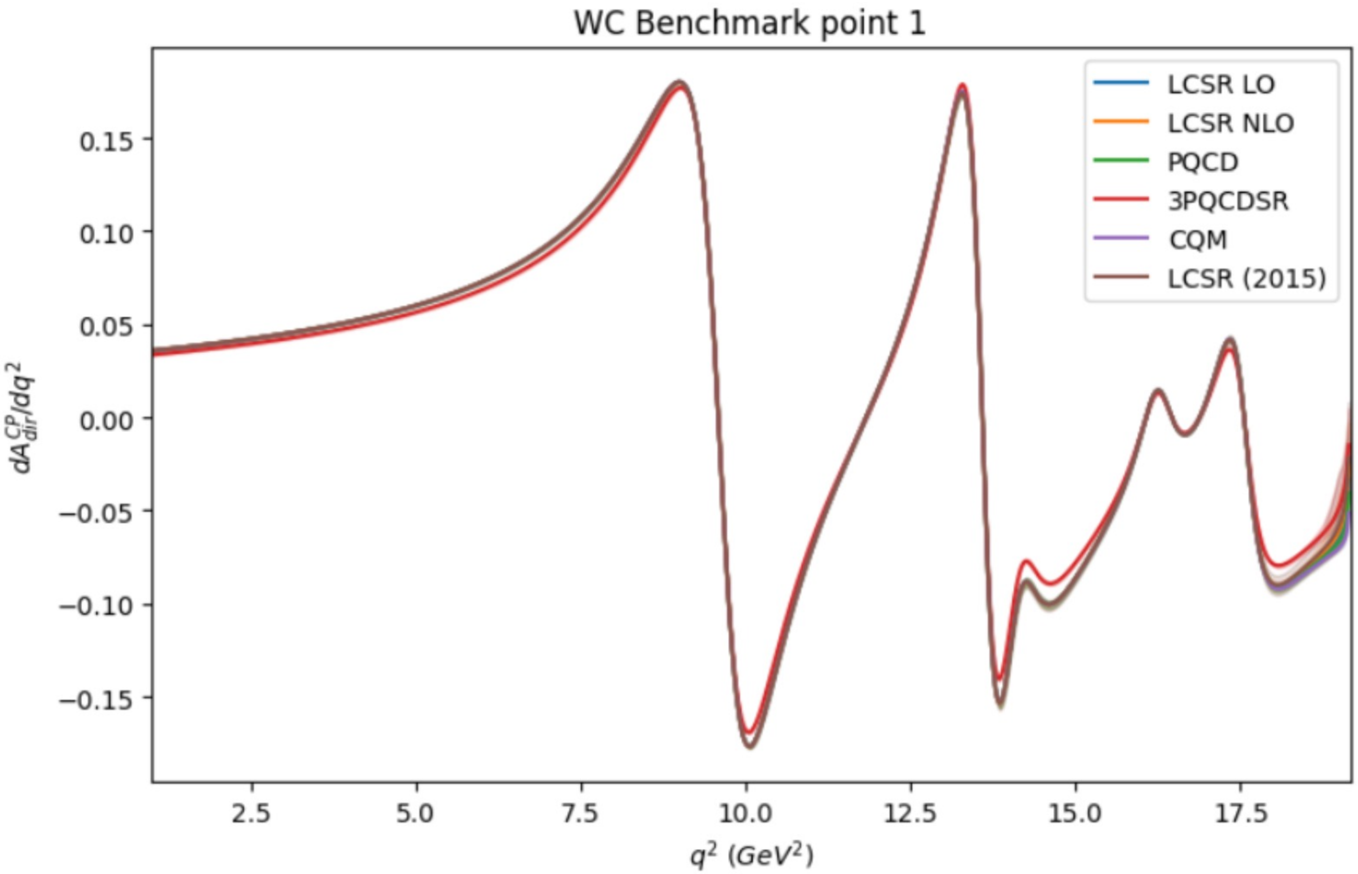
Dalitz plot analysis of the decay $B^{\pm} \to K^{\pm}K^{\pm}K^{\mp}$


changing F_0
changing F_1
changing F_T
A_{dir}^{CP}
0.0575
0.0550
0.0525
0.0500
0.0475
0.0450
0.0425
0.0400
0.0375
−0.2
0.0
0.2
0.4
0.6
0.8
F_i

Main Results

- Direct CP-violation

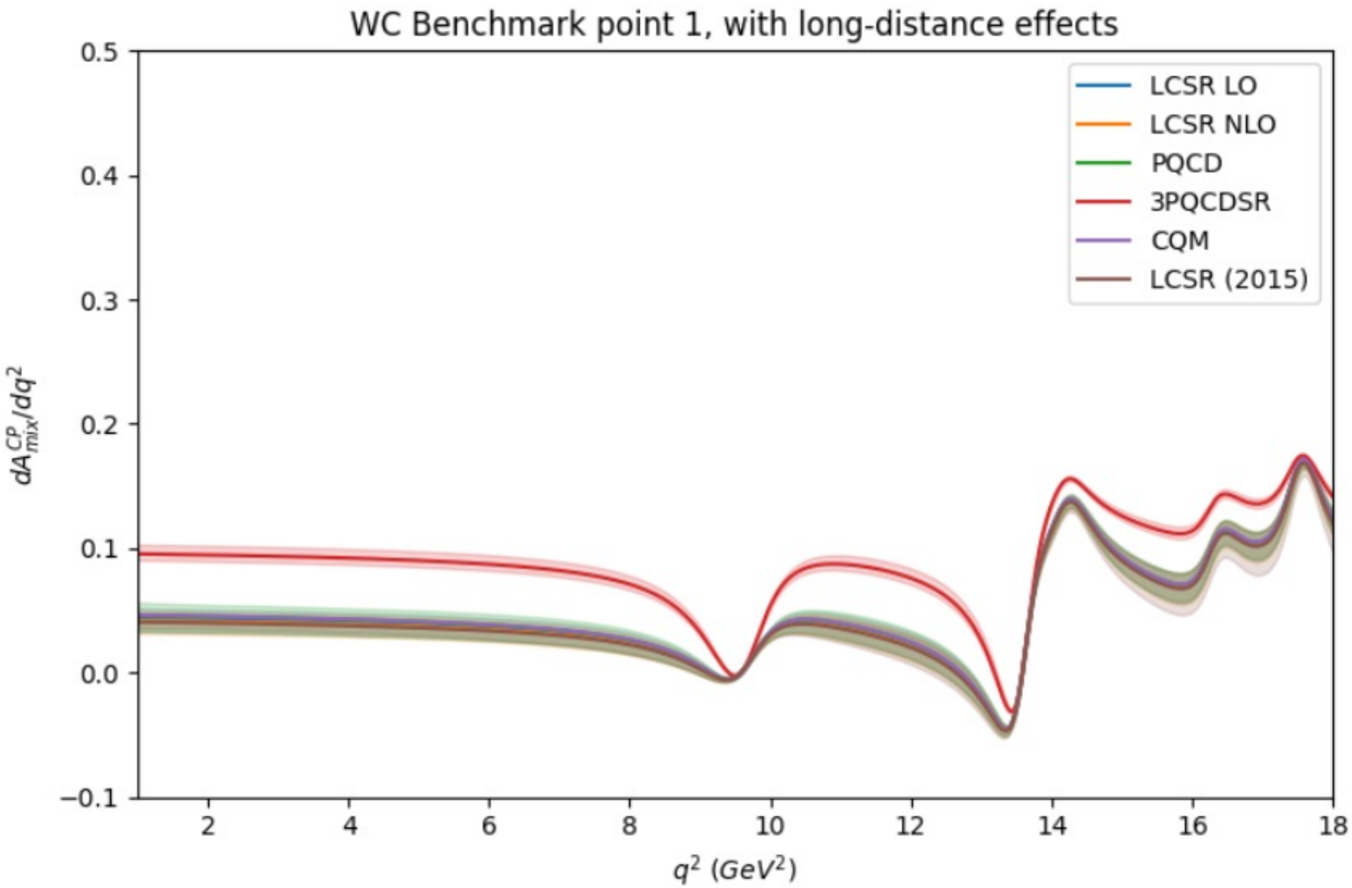
$$A_{dir}^{CP} = \frac{\Gamma(B_s^0 \to f_0(980)\mu^+\mu^-) - \Gamma(\bar{B}_s^0 \to f_0(980)\mu^+\mu^-)}{\Gamma(B_s^0 \to f_0(980)\mu^+\mu^-) + \Gamma(\bar{B}_s^0 \to f_0(980)\mu^+\mu^-)}$$



Sturdy!

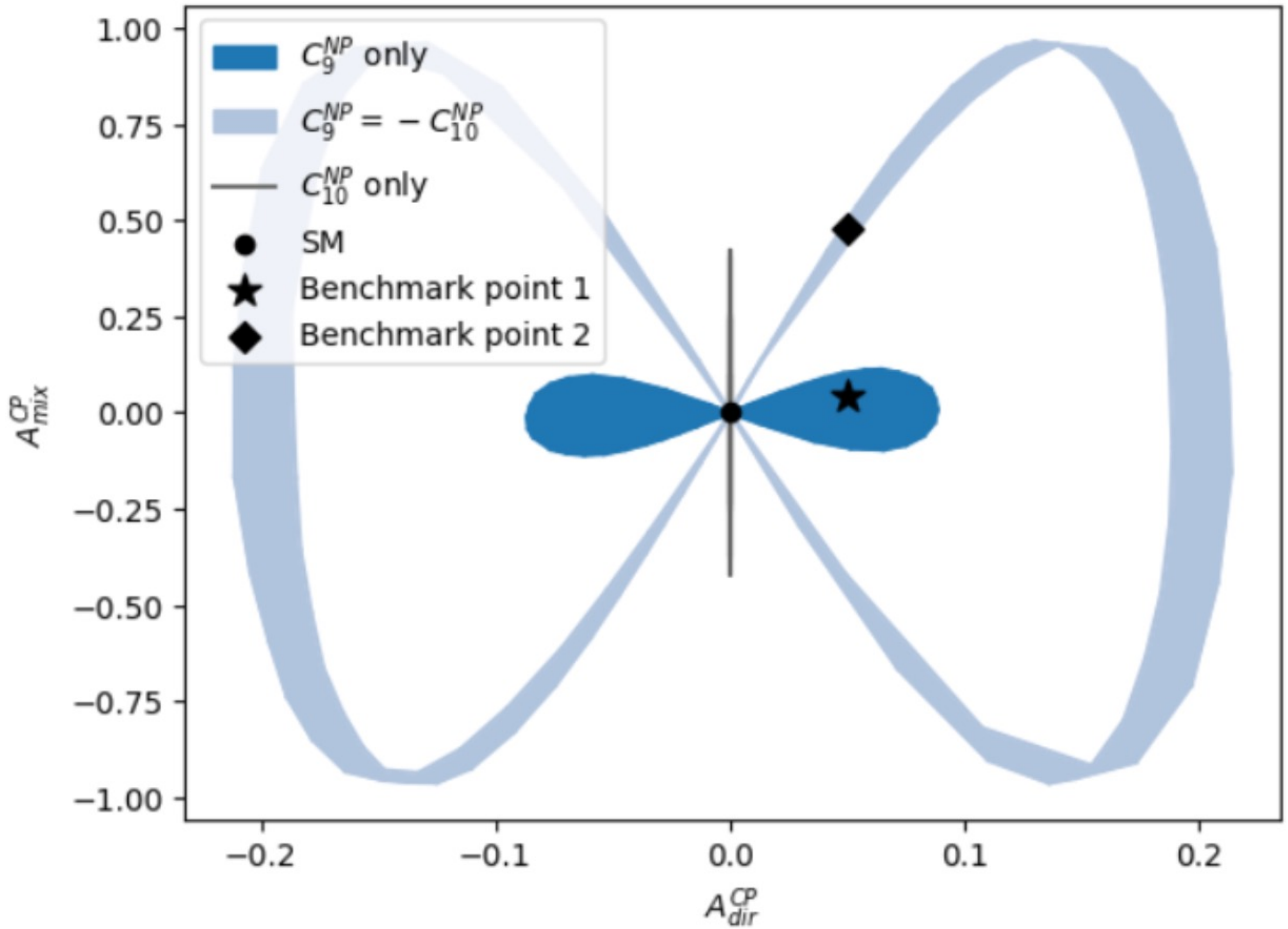
Main Results

- Mixing induced CP-violation

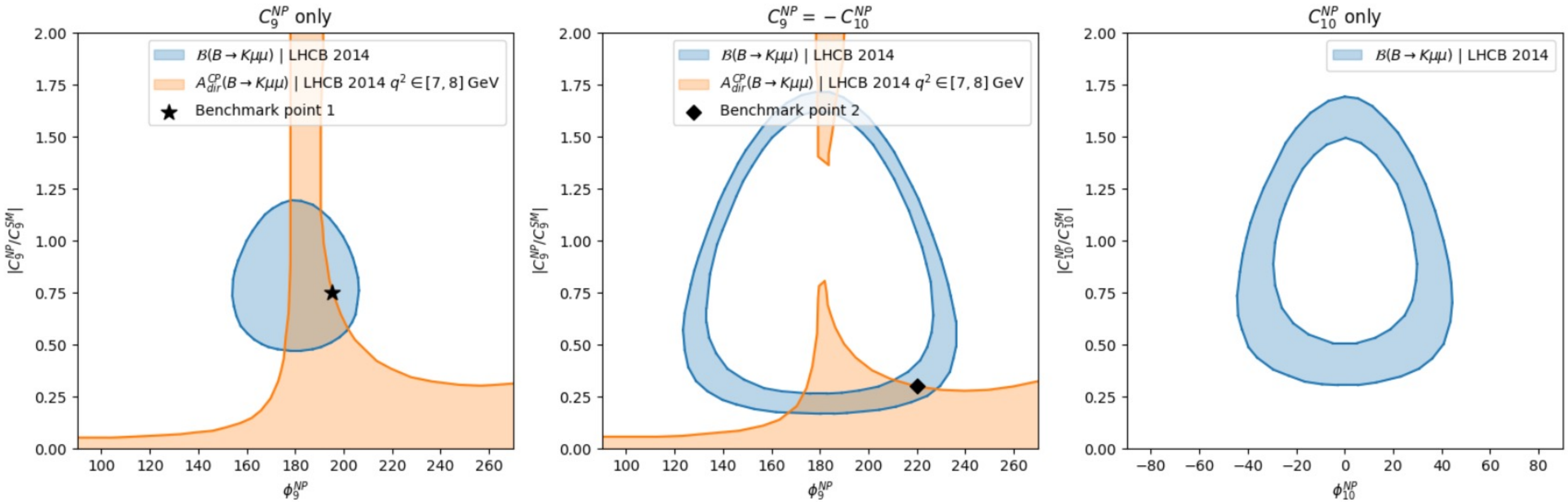


Almost sturdy!

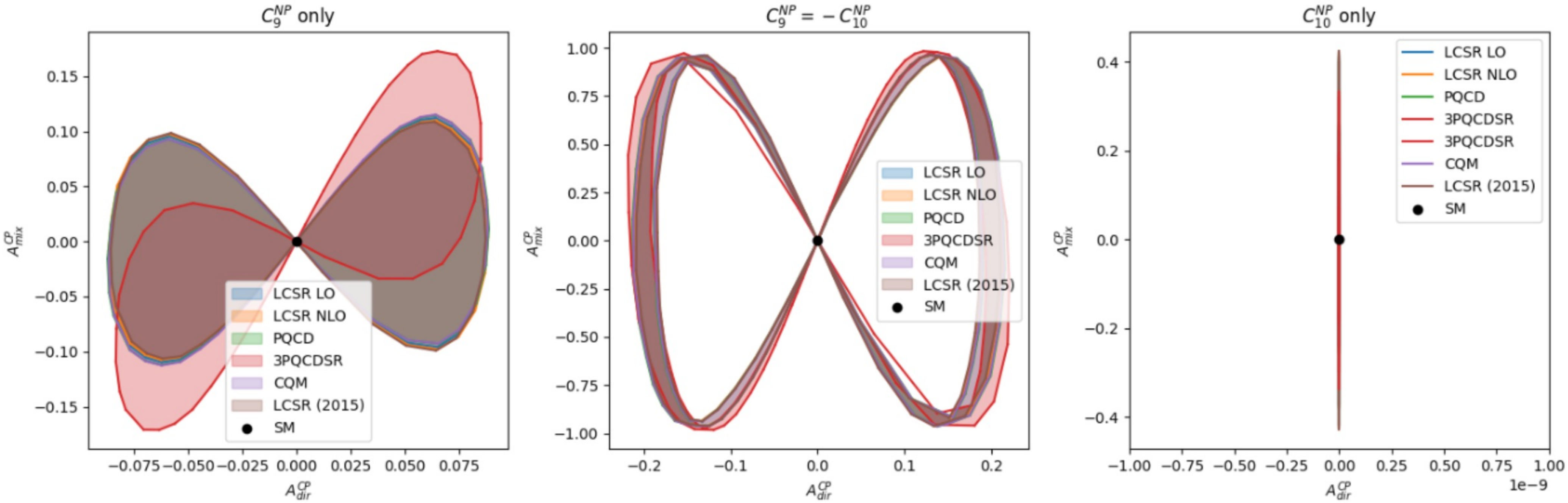
Main Results



Main Results



Main Results



- In the LCSR calculations, $F_i \propto f_{f_0}$, and they use $f_{f_0} = 180 \pm 15$ MeV
- In the PQCD calculations, $F_i \propto f_{f_0}$, and they use $f_{f_0} = 370 \pm 20$ MeV
- In the QCDSM calculations, $F_i \propto f_{f_0}^{-1}$ and they use $f_{f_0} = 370 \pm 20$ MeV
- In the LCSR (2015) calculations, $F_i \propto f_{f_0}$, and they use $f_{f_0} = 370 \pm 20$ MeV

All we need to explore the selected decay

- Direct CP-violation

$$A(\bar{B} \to \bar{f}) = e^{+i\varphi_1}|A_1|e^{i\delta_1} + e^{+i\varphi_2}|A_2|e^{i\delta_2},$$

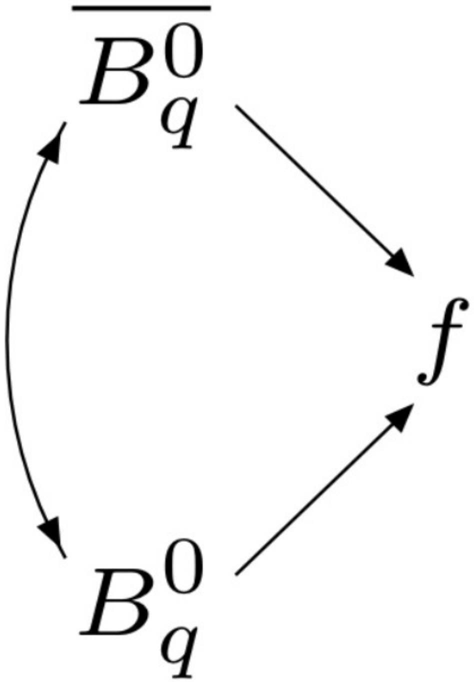
$$A(B \to f) = e^{i[\phi_{CP}(B) - \phi_{CP}(f)]}\left[e^{-i\varphi_1}|A_1|e^{i\delta_1} + e^{-i\varphi_2}|A_2|e^{i\delta_2}\right],$$

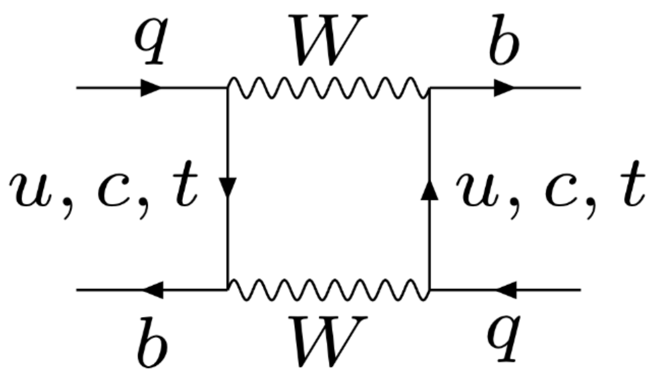
$$A_{CP}^{\rm dir} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = \frac{|A(B \to f)|^2 - |\mathcal{A}(\bar{B} \to \bar{f})|^2}{|A(B \to f)|^2 + |\mathcal{A}(\bar{B} \to \bar{f})|^2} \quad (4)$$

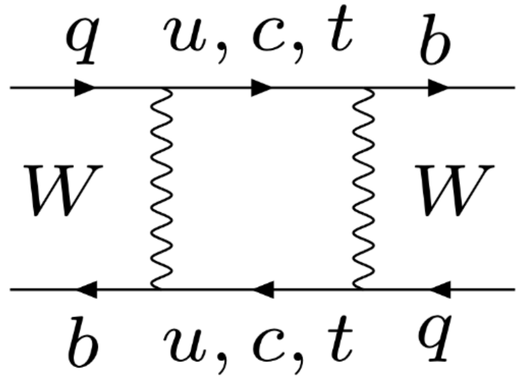
$$= \frac{2|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\varphi_1 - \varphi_2)}{|A_1|^2 + 2|A_1||A_2|\cos(\delta_1 - \delta_2)\cos(\varphi_1 - \varphi_2) + |A_2|^2}$$

All we need to explore the selected decay

- Mixing induced CP-violation







Two different amplitudes that can produce CP-violation!