The Brown Muck of B^0 and B_s^0 Mixing: Beyond the Standard Model

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Outline

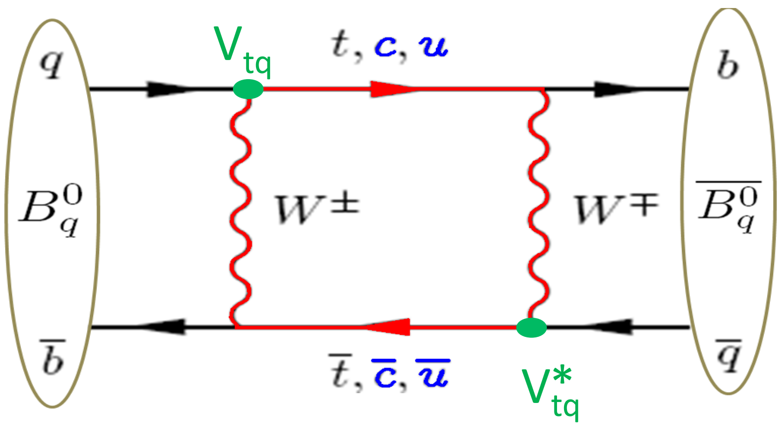
- Motivation
- Calculation
  - mixing & role of lattice QCD (LQCD)
  - mixing operators
  - the lattice calculation
- Preliminary BSM results
- Outlook

Motivation

- mixing sensitive to new physics
  - SM contributions suppressed: loop, GIM, Cabibbo
- hints of new physics
- experimental precision of mixing measurements

Mixing sensitive to new physics

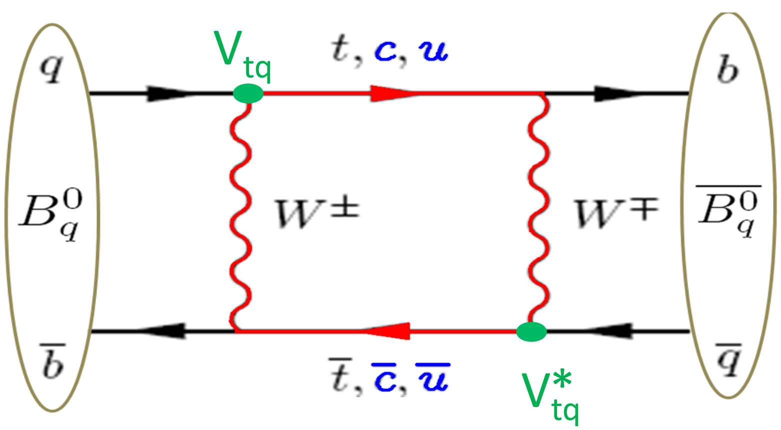
SM suppression: loop, GIM, Cabibbo

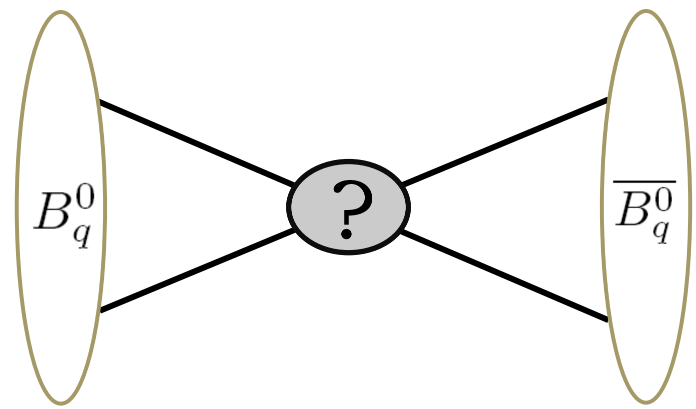


Mixing sensitive to new physics

SM suppression: loop, GIM, Cabibbo

…opens door for BSM contributions





some possibilities: [Buras et al, arXiv:0910.1032, hep-ph]

- SUSY flavor models: ? $\supseteq$ squarks, gluinos, …
- Little Higgs (extended weak gauge group): ? $\supseteq$ W_H, Z_H, …
- Randall-Sundrum (warped extra dims): ? $\supseteq$ KK particles, …

Motivation

- mixing sensitive to new physics

- hints of new physics
  - UT tension: 3σ [Lunghi, Soni arXiv:1104.2117, hep-ph]

    2-3σ [Laiho, Lunghi, Van de Water arXiv:0910.2928, hep-ph]
  - B mixing: UT*fit* 3σ [arXiv:0803.0659, hep-ph]

    DØ 3.9σ [arXiv:1106.6308, hep-ex]
  - $B_s^0 \to \mu^+\mu^-$: CDF [arXiv:1107.2304, hep-ex]

    correlated w/ NP in B mixing [Golowich et al, PRD83, 2011]

- experimental precision of mixing measurements

Motivation

- mixing sensitive to new physics

- hints of new physics

- experimental precision of mixing measurements: < 1 %

$$\Delta M_d = 0.507 \pm 0.003(\text{stat}) \pm 0.003(\text{syst})\ \text{ps}^{-1}$$ [PDG, J.Phys G37, 1 (2010)]

$$\Delta M_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$$ [CDF, PRL 97, 242003 (2006)]

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Mixing basics

- Two state system with decay

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

- off diagonal terms $\Longrightarrow$ mixing with frequency ΔM

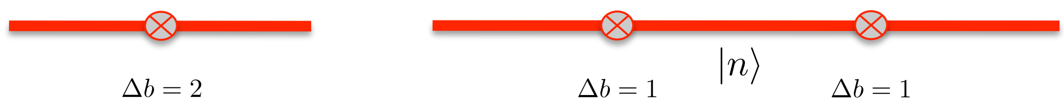
$$\Delta M = 2|M_{12}|\left[1 + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)\right]$$

- Transition matrix element: $M_{12} - \frac{i}{2}\Gamma_{12} = \langle B^0|\mathcal{H}_{\rm mix}|\bar{B}^0\rangle$

Mixing basics

- Stationary state perturbation theory: $\mathcal{H}_{\text{mix}} = \mathcal{H}^{\Delta b=0} + \mathcal{H}^{\Delta b=1} + \ldots$

$$M_{12} - \frac{i}{2}\Gamma_{12} = \langle B^0|\mathcal{H}^{\Delta b=2}|\bar{B}^0\rangle + \sum_n \frac{\langle B^0|\mathcal{H}^{\Delta b=1}|n\rangle\langle n|\mathcal{H}^{\Delta b=1}|\bar{B}^0\rangle}{E_n - M_B}$$



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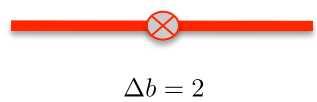
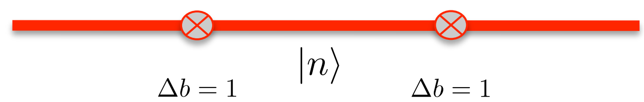
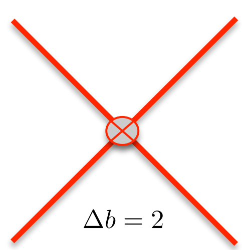
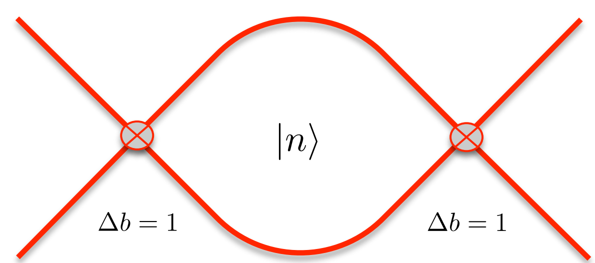




- transition to parton level via OPE

$$M_{12} - \frac{i}{2}\Gamma_{12} = \sum_i C_i \langle B^0|\mathcal{O}_i^{\Delta b=2}|\bar{B}^0\rangle + \sum_n {\sum_{j,k}}' \frac{C_j' C_k' \langle B^0|\mathcal{O}_j^{\Delta b=1}|n\rangle\langle n|\mathcal{O}_k^{\Delta b=1}|\bar{B}^0\rangle}{E_n - M_B} + \cdots$$





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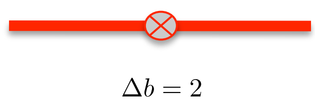
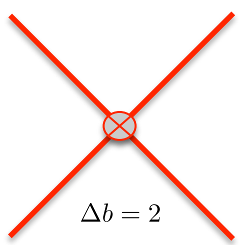


- transition to parton level via OPE

$$M_{12} = \sum_i C_i \langle B^0 | \mathcal{O}_i^{\Delta b=2} | \bar{B}^0 \rangle + \ldots$$



justified for...
- SM B mixing
- NP models w/ heavy mediators

questionable for...
- SM D mixing
- NP models w/ light mediators

Role of LQCD

$$\Delta M_d = 0.507 \pm 0.003(\mathrm{stat}) \pm 0.003(\mathrm{syst})\ \mathrm{ps}^{-1}$$

$$\Delta M_s = 17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}^{-1}$$

experiment

SM: $$\Delta M_q = \underbrace{\left(\frac{G_F^2 M_W^2 S_0}{4\pi^2 M_{B_q}}\right)\eta_B(\mu)}_{\text{know / calc in PT}} \; \underbrace{|V_{tb}V_{tq}^*|^2}_{\text{want}} \; \underbrace{\langle B_q^0|\mathcal{O}^{\Delta b=2}(\mu)|\bar{B}_q^0\rangle}_{\text{LQCD}}$$

Role of LQCD

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experiment

BSM: $$\Delta M_q = \sum_i \underbrace{C_i(\mu)}_{\text{model dep}} \underbrace{\langle B_q^0 | \mathcal{O}_i^{\Delta b=2}(\mu) | \bar{B}_q^0 \rangle}_{\text{LQCD}}$$

Role of LQCD

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$\Delta\Gamma_s$ $(\Delta\Gamma_d \approx 0)$ can also be expressed as a function of $\langle B^0|\mathcal{O}_i(\mu)|\bar{B}^0\rangle$, though experimental errors are larger

$$|\Delta\Gamma_s| = 0.076^{+0.059}_{-0.063}(\mathrm{stat}) \pm 0.006(\mathrm{syst})\ \mathrm{ps}^{-1}$$

[CDF, PRL 100, 121803, 2008]

The goal of this work

$$\Delta M_d = 0.507 \pm 0.003(\mathrm{stat}) \pm 0.003(\mathrm{syst})\ \mathrm{ps}^{-1}$$

$$\Delta M_s = 17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}^{-1}$$

experiment

BSM: $$\Delta M_q = \sum_i \underbrace{C_i(\mu)}_{\text{model dep}} \underbrace{\boxed{\langle B_q^0 | \mathcal{O}_i^{\Delta b=2}(\mu) | \bar{B}_q^0 \rangle}}_{\text{LQCD}}$$

alternatively…

bag parameter, $B_{B,i}$: $\langle B^0 | \mathcal{O}_i | \bar{B}^0 \rangle = \mathfrak{c}_i f_B^2 B_{B,i}$

mixing parameter, β_i : $\beta_i = f_B \sqrt{B_{B,i}}$

Mixing operators

- 5 (hadronic ME's of) operators form complete basis

SM

$$\mathcal{O}_1 = (\bar{b}^\alpha \gamma_\mu L q^\alpha)\, (\bar{b}^\beta \gamma_\mu L q^\beta)$$

$$\mathcal{O}_2 = (\bar{b}^\alpha L q^\alpha)\, (\bar{b}^\beta L q^\beta)$$

$$\mathcal{O}_3 = (\bar{b}^\alpha L q^\beta)\, (\bar{b}^\beta L q^\alpha)$$

BSM

$$\mathcal{O}_4 = (\bar{b}^\alpha L q^\alpha)\, (\bar{b}^\beta R q^\beta)$$

$$\mathcal{O}_5 = (\bar{b}^\alpha L q^\beta)\, (\bar{b}^\beta R q^\alpha)$$

Mixing operators

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- Current status: BSM bag parameter precision quoted ~10%
  - quenched, static limit of HQET, linear χPT

[Becirevic *et al.*, arXiv:0110091, hep-lat (2001)]

Generic lattice calculation

- start with VEV (continuum, Euclidean): $\langle \Omega | A[\psi, \bar{\psi}, U] | \Omega \rangle$
  - Wick contract: $A[\psi, \bar{\psi}, U] \to A[(\not{D} + m)^{-1}, U]$

Generic lattice calculation

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  - Wick contract: $A[\psi, \bar{\psi}, U] \to A[(\not{D} + m)^{-1}, U]$
- path integral representation of VEV

$$\langle \Omega | A | \Omega \rangle = \frac{\int d[\psi] d[\bar{\psi}] d[U] \;\; A[(\not{D} + m)^{-1}, U] \;\; e^{-S[\psi, \bar{\psi}, U]}}{\int d[\psi] d[\bar{\psi}] d[U] \;\; e^{-S[\psi, \bar{\psi}, U]}}$$

  - Berezin integration

$$\langle \Omega | A | \Omega \rangle = \frac{\int d[U] \;\; A[(\not{D} + m)^{-1}, U] \;\; e^{-S[U] + \ln[\det(\not{D} + m)]}}{\int d[U] \;\; e^{-S[U] + \ln[\det(\not{D} + m)]}}$$

"jumping off point" for lattice calculation

Generic lattice calculation

Numerically evaluate

$$\langle \Omega | A | \Omega \rangle = \frac{\int d[U]\ A[(\not{D} + m)^{-1}, U]\ e^{-S[U] + \ln[\det(\not{D}+m)]}}{\int d[U]\ e^{-S[U] + \ln[\det(\not{D}+m)]}}$$

discretize $S[\psi, \bar{\psi}, U]$

$$\int d^4x \to \sum_{x,y,z,t}$$

$$\partial_\mu \psi(x) \to \frac{\psi(x + a\hat{\mu}) - \psi(x)}{a}$$

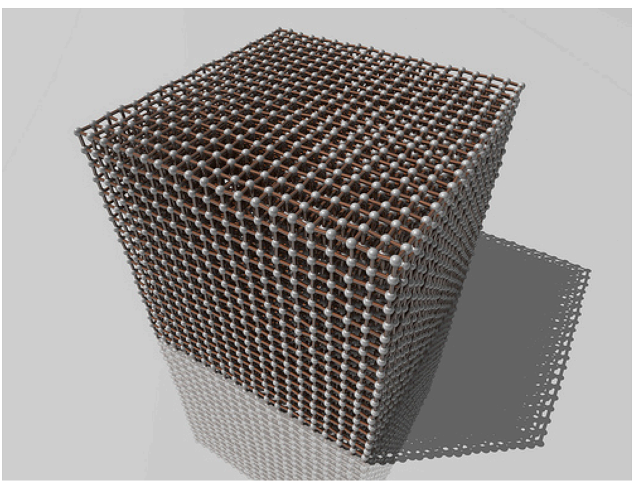
$$\int d[U]\ f(U) \to \sum_n f(U_n)$$

$$\vdots$$

Generic lattice calculation

Numerically evaluate

$$\langle\Omega|A|\Omega\rangle = \frac{\int d[U]\ A[(\not{D}+m)^{-1}, U]\ e^{-S[U]+\ln[\det(\not{D}+m)]}}{\int d[U]\ e^{-S[U]+\ln[\det(\not{D}+m)]}}$$



<u>importance sampling</u>

generate $\{U_n\}$ with probability distribution
$e^{-S[U]+\ln[\det(\not{D}+m)]}$

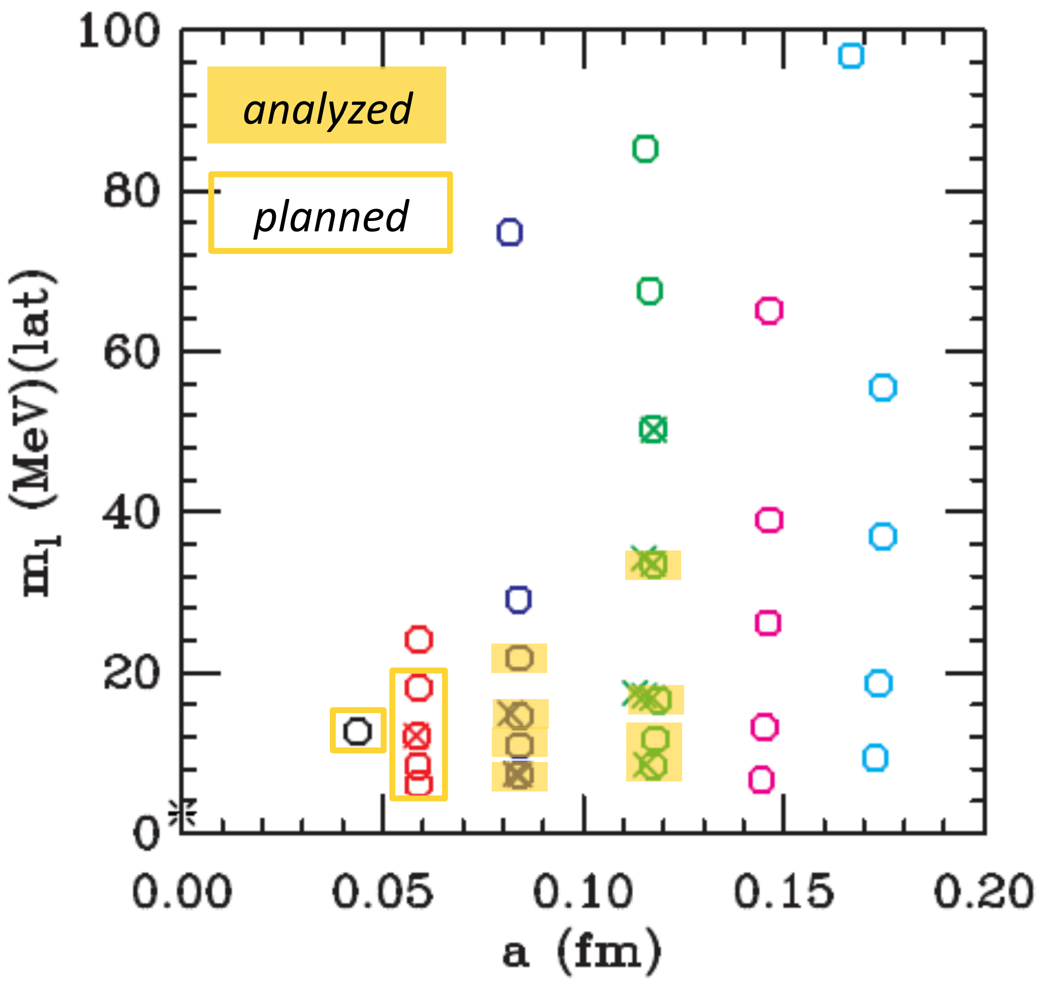
$$\langle\Omega|A|\Omega\rangle \approx \frac{1}{N}\sum_{n=1}^{N} A(U_n)$$

Generating data: gauge config's

[Bazavov *et al.*, MILC, RMP 82, 1349 (2010)]

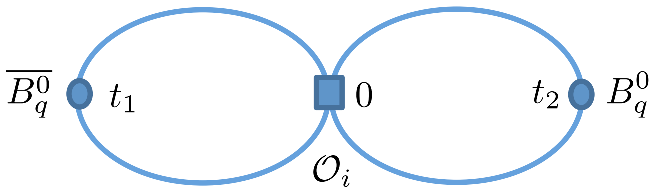
MILC

- 2+1 sea quarks
- with $\mathcal{O}(1000)$ terms in sum $\frac{1}{N}\sum_{n=1}^{N} A(U_n)$
- Symanzik, tadpole improved glue
- rooted, asqtad, staggered sea quarks

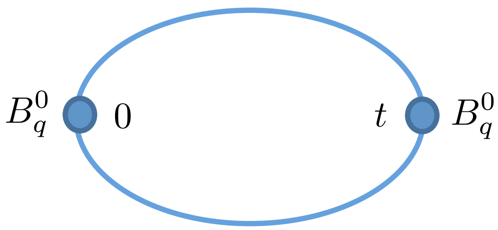


physical m_s
unphysical m_s
physical $m_{u,d}$

Generating data: correlation fn's

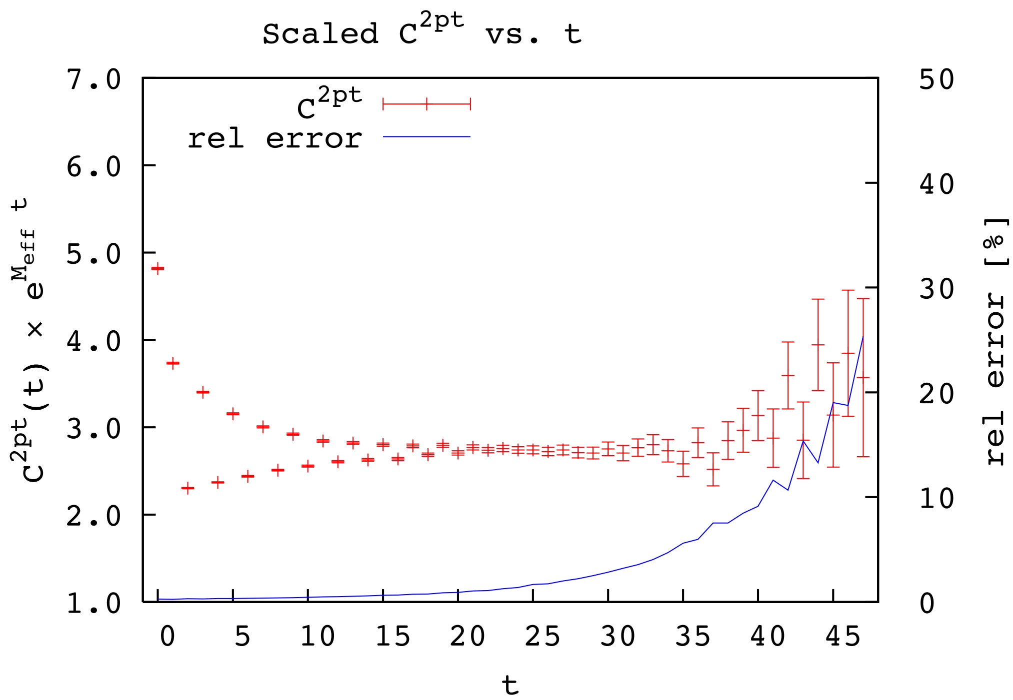


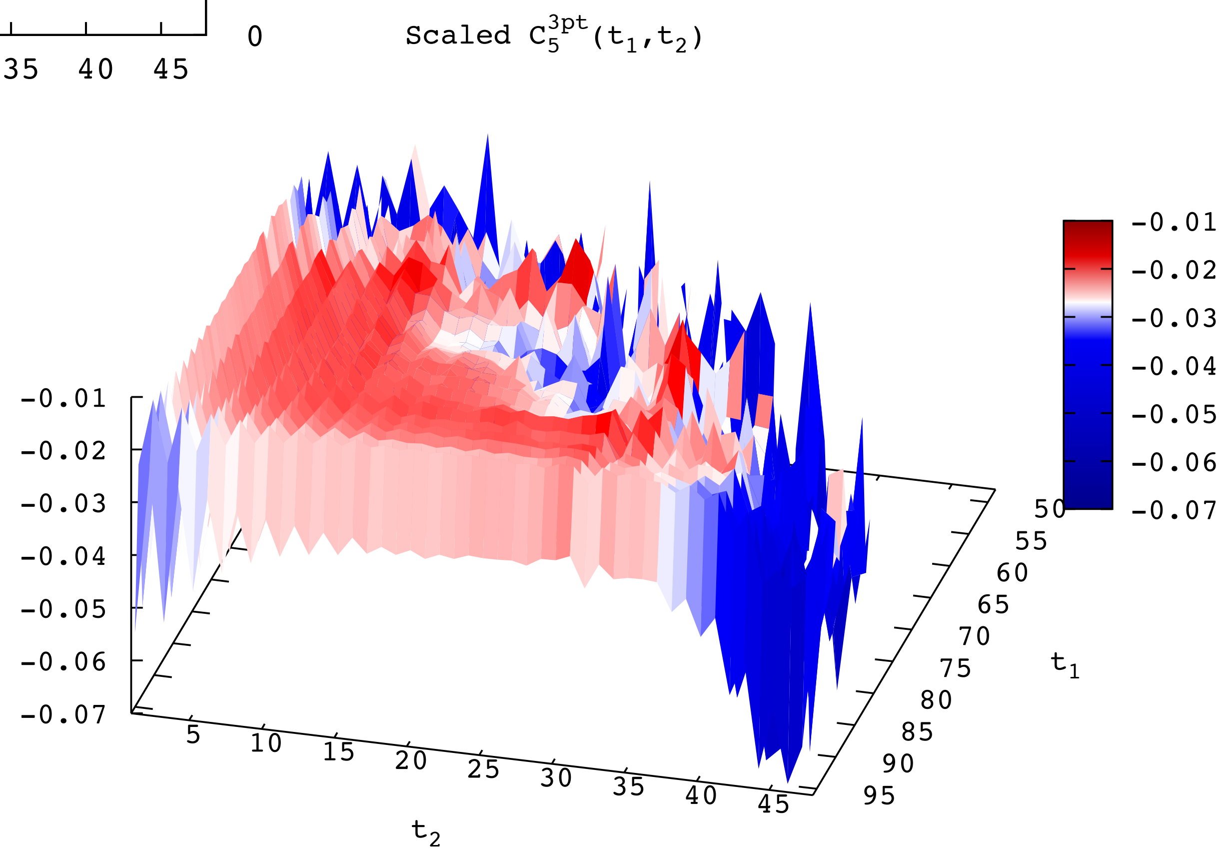
$$C_i^{3pt}(t_1,t_2) = \langle T\{(\bar{q}\gamma_5 b)_{t_2}(\mathcal{O}_i)_0(\bar{q}\gamma_5 b)_{t_1}\}\rangle$$



$$C^{2pt}(t) = \langle T\{(\bar{q}\gamma_5 b)_t(\bar{b}\gamma_5 q)_0\}\rangle$$

- asqtad staggered light valence quark
  - range of (7 or 8) masses
- Fermilab valence bottom quark





$a \approx 0.09$ fm

$40^3 \times 96$

$am_l^{\rm sea} = 0.0031$

$am_s^{\rm sea} = 0.031$

$am_l^{\rm val} = 0.0261$

$\kappa_b = 0.0976$

Fitting

- Know time dependence of correlation fn's
  [Wingate et al, PRD 67, 054505 (2003)]

$$\mathbb{C}^{2pt}(t) = \sum_{n=0}^{\infty} \frac{Z_n^2}{2M_n} (-1)^{n(t+1)} \left(e^{-M_n t} + e^{-M_n (T-t)}\right)$$

$$\mathbb{C}_N^{3pt}(t_1, t_2) =$$

$$\sum_{n,m=0}^{\infty} \frac{\langle B_n | \mathcal{O}_N | \bar{B}_m \rangle Z_n Z_m}{4 M_n M_m} (-1)^{n(t_1+1)+m(t_2+1)} \left(e^{-M_n |t_1|} + e^{-M_n (T-|t_1|)}\right) \left(e^{-M_m t_2} + e^{-M_m (T-t_2)}\right)$$

- Fit 2 & 3pt data to extract ME
  - simultaneous
  - Bayesian [Lepage, arXiv:hep-lat/0110175]

Fitting

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  - renormalization
  - continuum and chiral extrapolation
  - error budget
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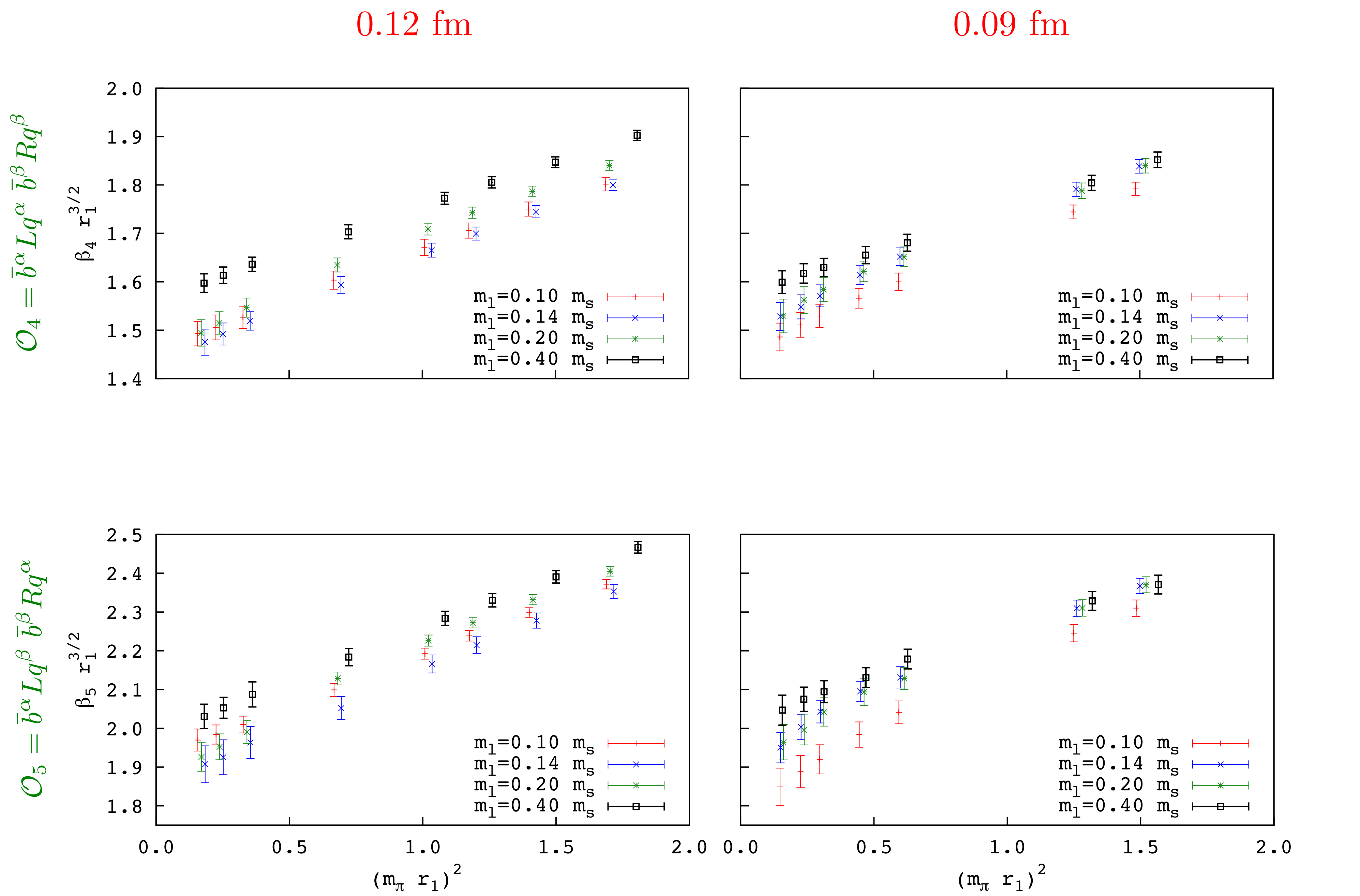

0.12 fm
0.09 fm
$\mathcal{O}_4 = \bar{b}^\alpha L q^\alpha \, \bar{b}^\beta R q^\beta$
$\mathcal{O}_5 = \bar{b}^\alpha L q^\beta \, \bar{b}^\beta R q^\alpha$
$\beta_4 \, r_1^{3/2}$
$\beta_5 \, r_1^{3/2}$
$(m_\pi \, r_1)^2$
m_l=0.10 m_s
m_l=0.14 m_s
m_l=0.20 m_s
m_l=0.40 m_s

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Renormalization

- 1-loop perturbative matching [Gamiz and Kronfeld]

$$\langle B|\mathcal{O}_4|\bar{B}\rangle_R = (1+\alpha_s\zeta_{44})\langle B|\mathcal{O}_4|\bar{B}\rangle_{\mathrm{lat}} + \alpha_s\zeta_{45}\langle B|\mathcal{O}_5|\bar{B}\rangle_{\mathrm{lat}}$$

and similarly for $\langle B|\mathcal{O}_5|\bar{B}\rangle_R$, run to b quark mass

  – ζ_{ij} : calculated to one loop

  – $\alpha_s = \alpha_V(2/a)$ [Lepage and Mackenzie, PRD 48:2250, 1993]

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Continuum & chiral extrapolation

- partially quenched, staggered, χPT
  - pq, continuum [Detmold and Lin, arXiv:0612028, hep-lat, 2006]
  - staggered [Bernard, Laiho and Van de Water, collaboration notes, 2011]

- NLO expression

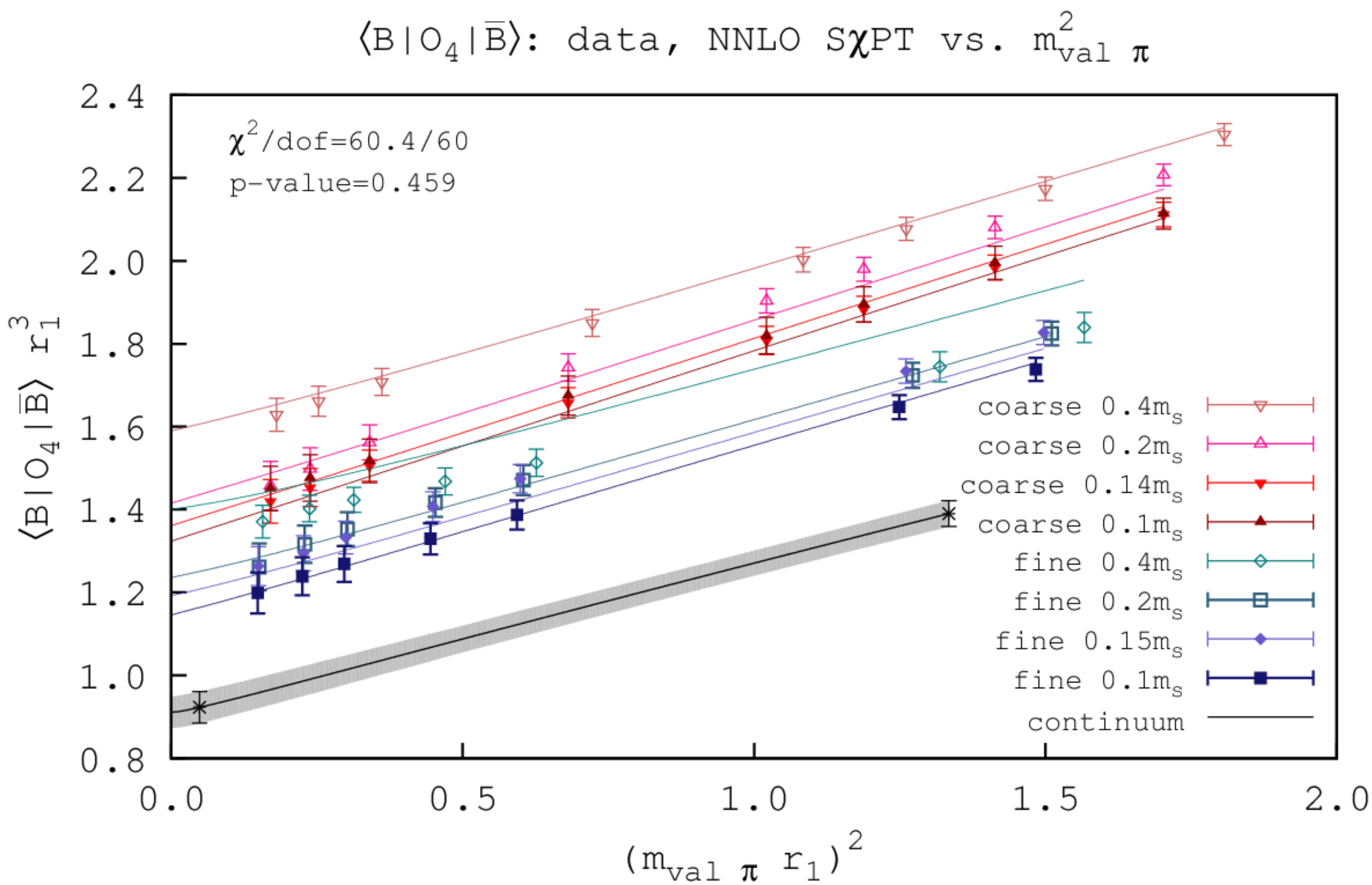
$$\mathrm{ME} = b(1 + \mathcal{T} + \mathcal{W}) + b'\mathcal{Q} + c_0 m_x + c_1(2m_l + m_s) + c_2 a^2$$

- NNLO terms included in fit

$$\boxed{m_x a^2,} \quad \cancel{m_x^2,} \quad \cancel{2m_l^2 + m_s^2} \quad \cancel{a^4,}$$

$$\cancel{(2m_l + m_s)a^2} \quad \cancel{(2m_l + m_s)^2} \quad \boxed{m_x(2m_l + m_s)}$$

Preliminary BSM results, $\langle B|\mathcal{O}_4|\bar{B}\rangle$



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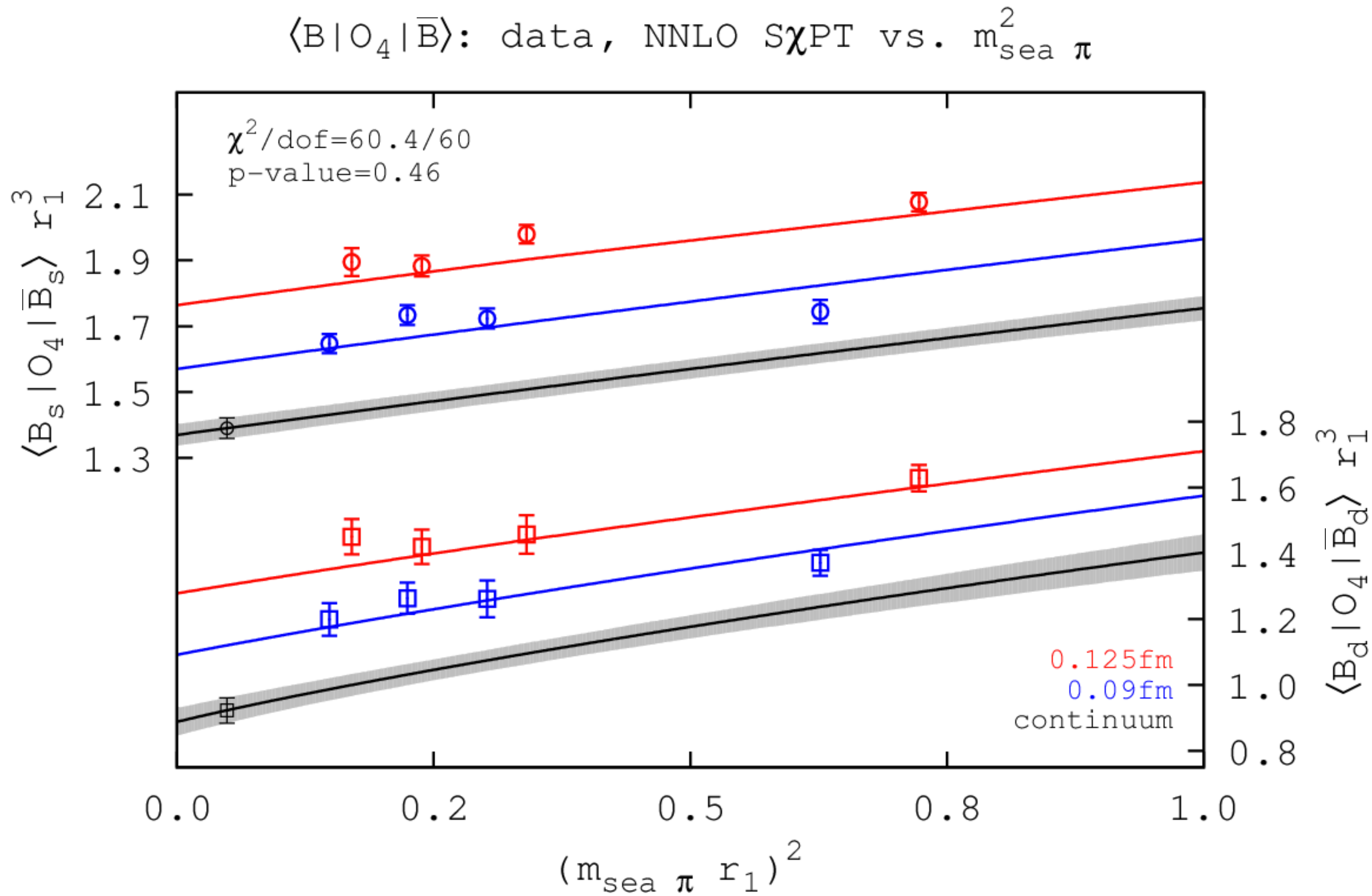
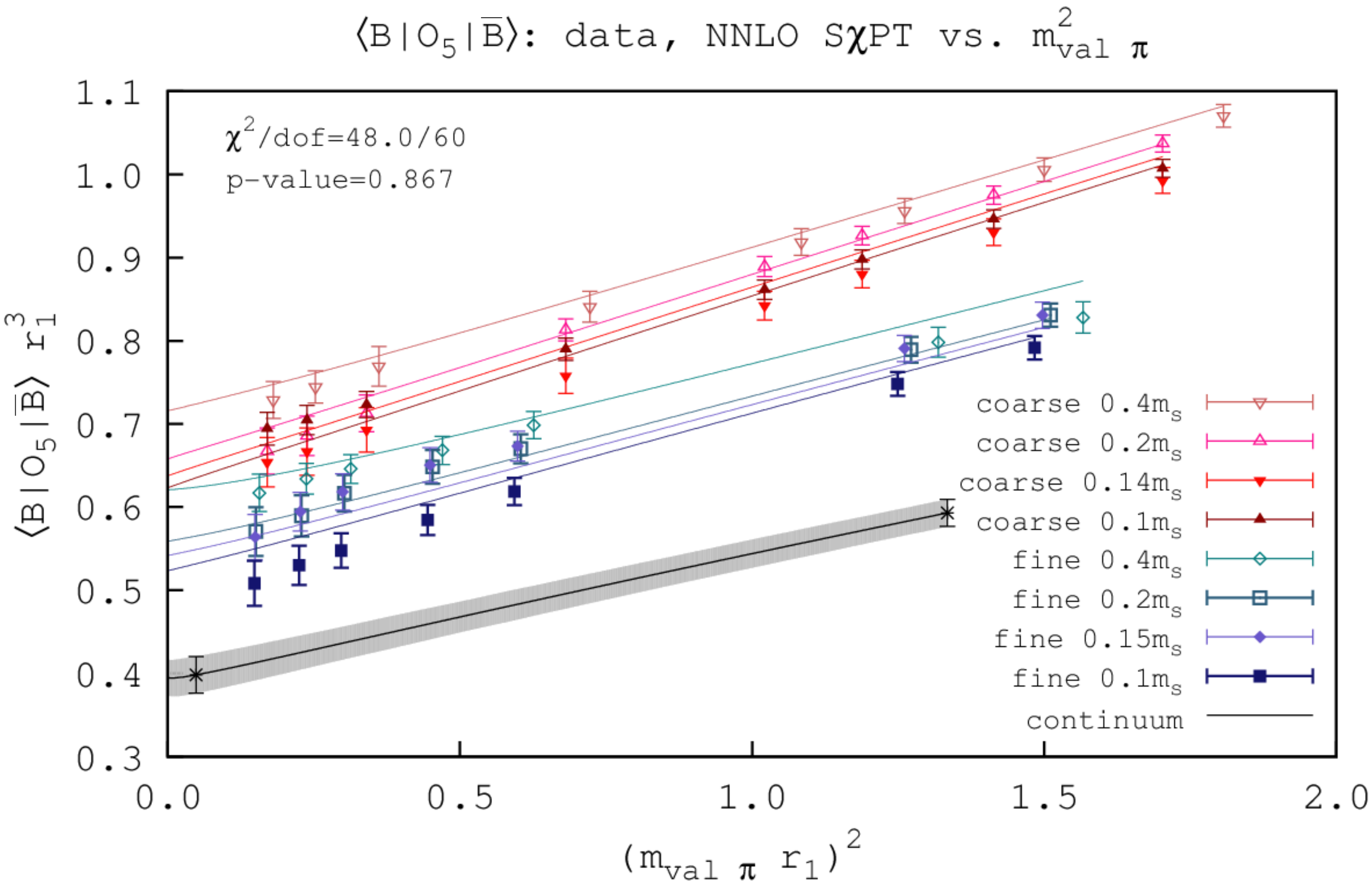
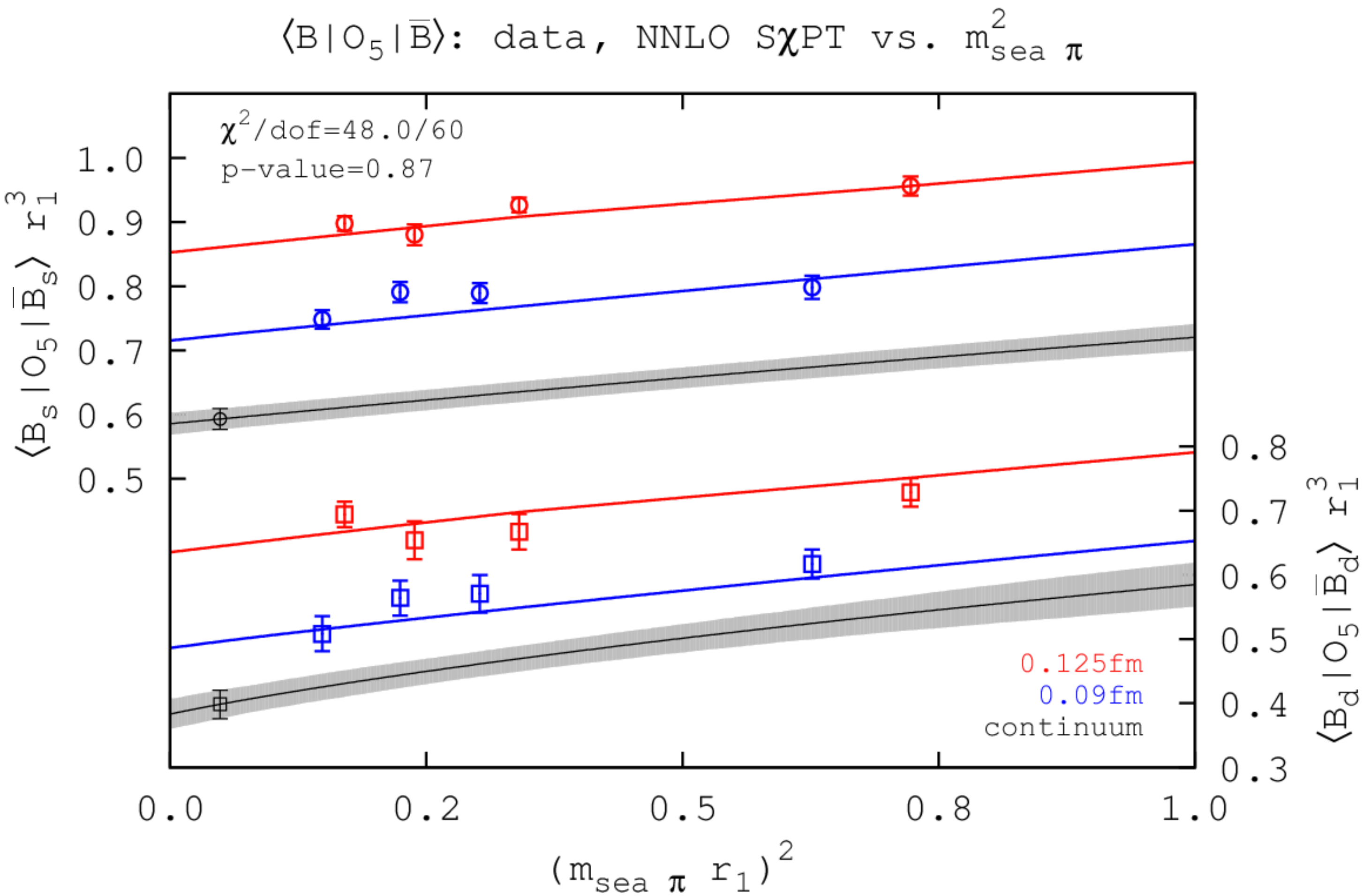


Preliminary BSM results, $\langle B|\mathcal{O}_5|\bar{B}\rangle$



Preliminary BSM results, $\langle B|\mathcal{O}_5|\bar{B}\rangle$



Preliminary BSM results

	$\langle B_q^0 \vert \mathcal{O}_4 \vert \bar{B}_q^0 \rangle \; r_1^3$	$\langle B_q^0 \vert \mathcal{O}_5 \vert \bar{B}_q^0 \rangle \; r_1^3$
B_d^0	$0.923(38)$ 4.1%	$0.398(22)$ 5.5%
B_s^0	$1.390(31)$ 2.2%	$0.593(16)$ 2.7%

Errors are statistical and determined by bootstrap.

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Error budget

Source of Error [%]	†Previous	Expected
scale (r_1)	6.0	2.1
light quark masses	0.6	0.6
$g_{B^*B\pi}$	0.6	< 0.6
κ_b	2.2	~ 1.7
χPT $\oplus$ light quark discretization	0.8	< 0.8
heavy quark discretization	4.0	~ 2.7
matching (1-loop perturbation theory)	~ 8.0	~ 5.0
finite volume effects	≤ 1.0	< 1.0
Total (syst)	11.1	~ 6.5

† [Evans et al, PoS (Lattice 2008), 052] and [Evans et al, PoS (Lattice 2009), 245]

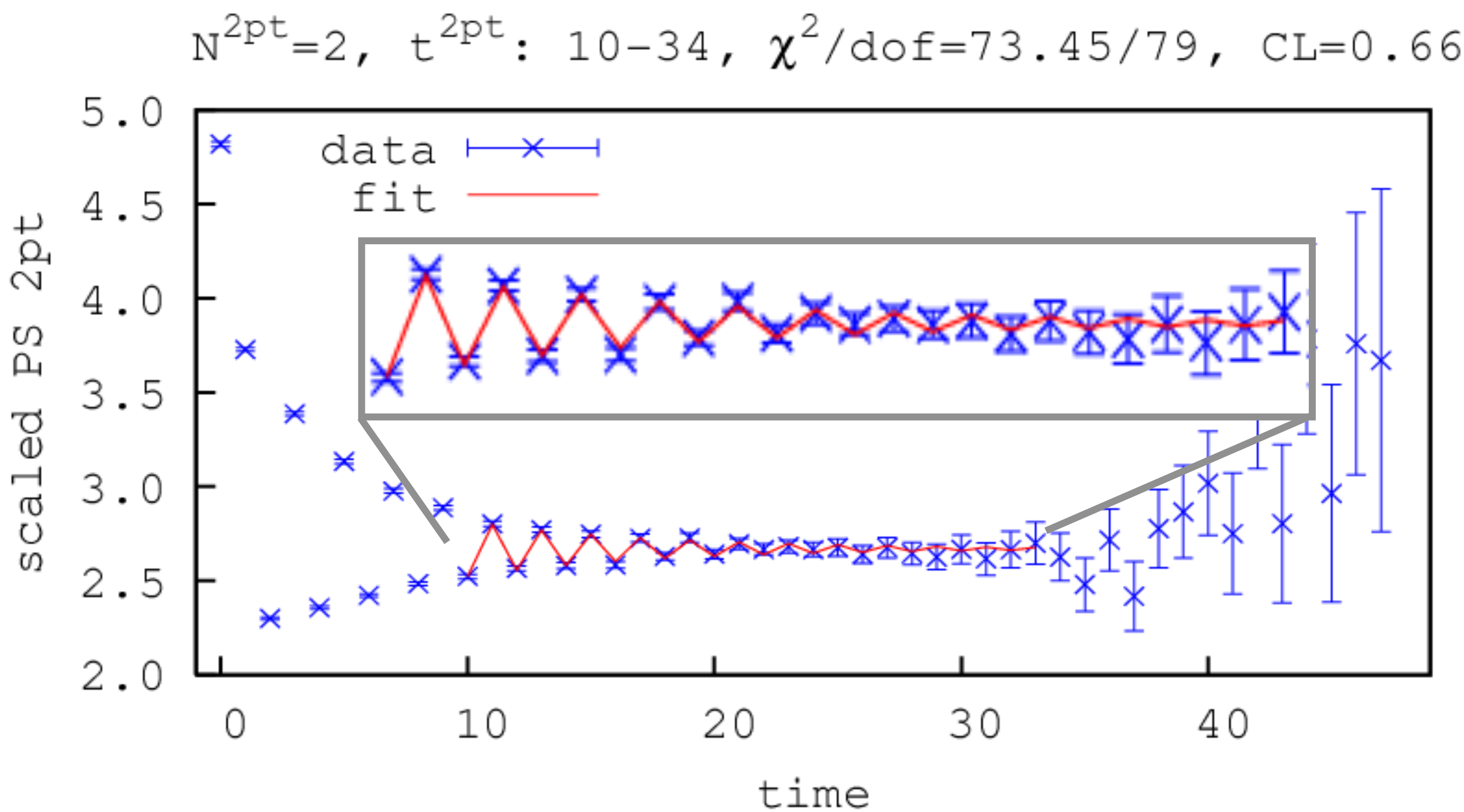
Outlook

- add data at finer lattice spacing
  - 0.06 fm, 0.045 fm
  - re-evaluated continuum and chiral extrapolation will allow more thorough determination of errors

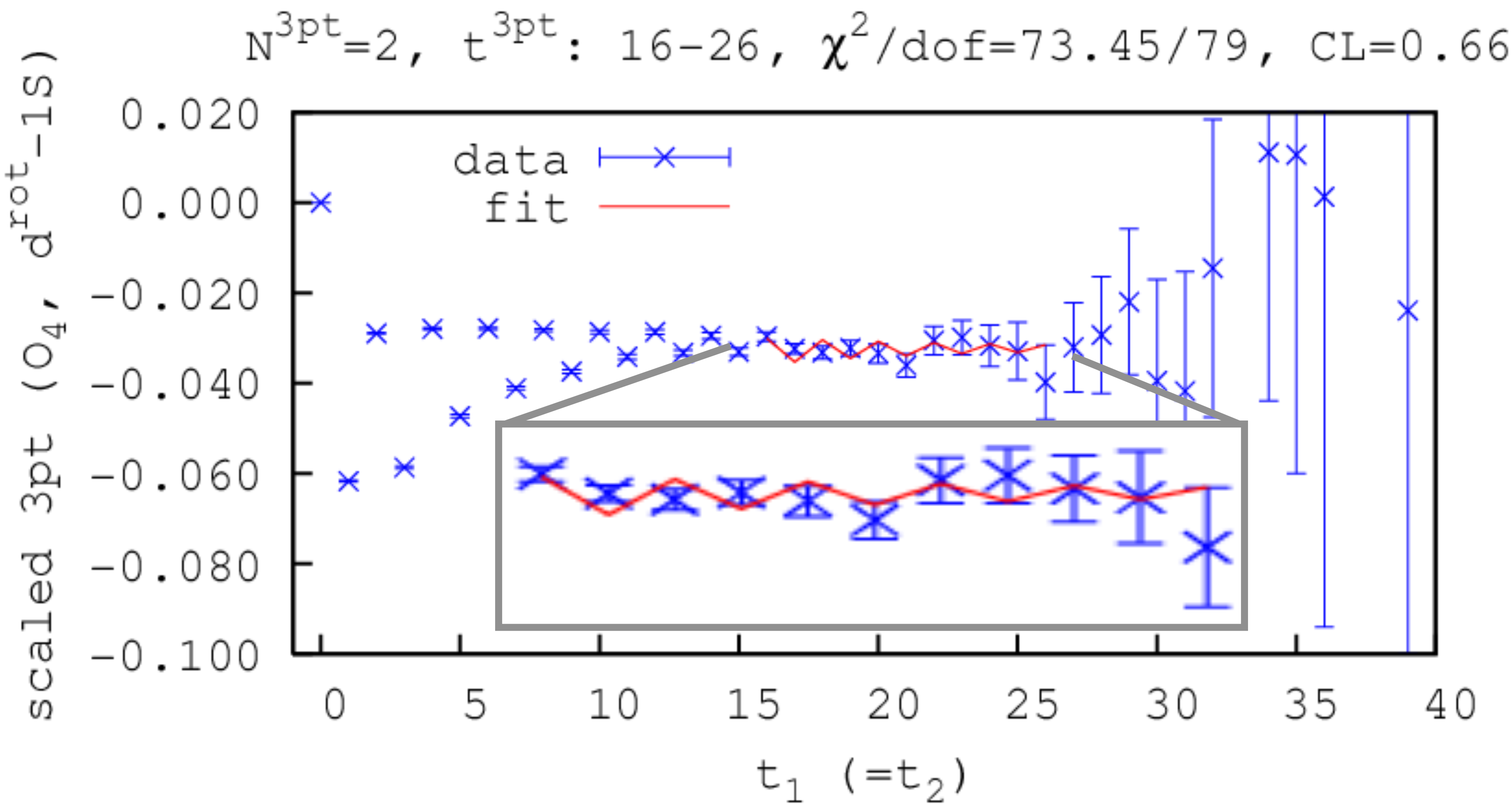
- coordinating with decay constant project to allow extraction of bag parameter

first calculation of BSM mixing parameters in 10 yrs backup slides.

Simultaneous fit: 2pt correlator

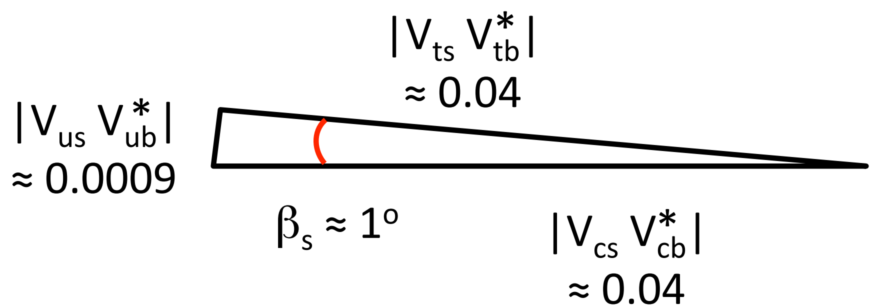


Simultaneous fit: 3pt correlator



Definitions

- $\Delta M = M_H - M_L$
- $\Delta\Gamma = \Gamma_L - \Gamma_H$
- $\phi_s^{J/\psi\phi}$ ($= -2\ \beta_s$):

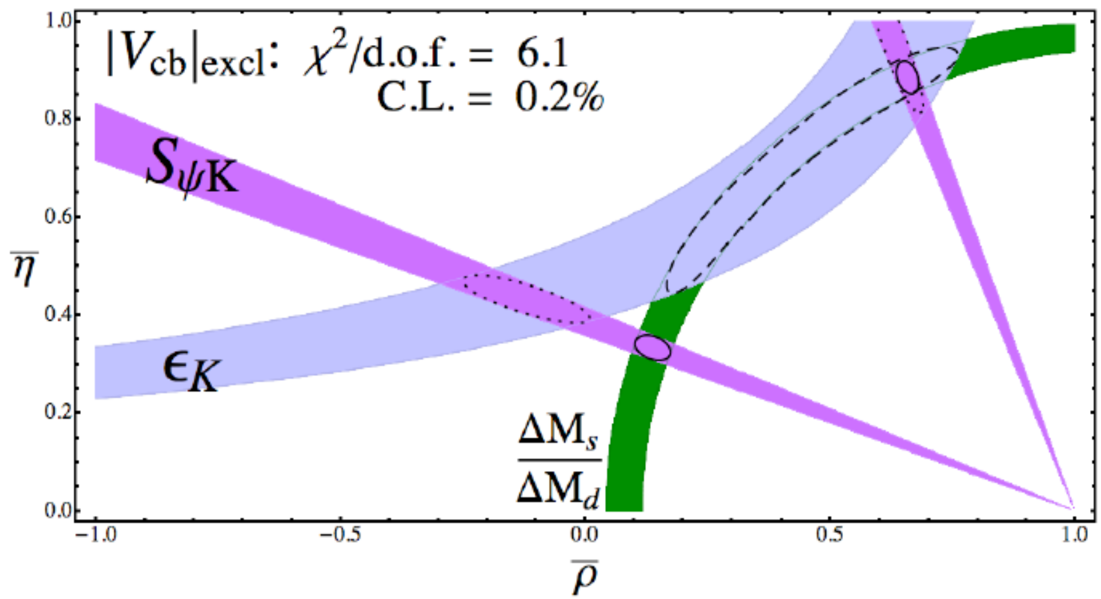


- $$A_{SL}^{s} = \frac{\Gamma(\bar{B} \rightarrow \mu^{+}D^{-}) - \Gamma(B \rightarrow \mu^{-}D^{-})}{\Gamma(\bar{B} \rightarrow \mu^{+}D^{-}) + \Gamma(B \rightarrow \mu^{-}D^{-})}$$
- $$A_{SL}^{\mu\mu} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

[DØ, arXiv:0609014, hep-ex] and [CDF public note 9015]

UT tension

[Laiho, Lunghi and Van de Water, arXiv:0910.2928, hep-ph]



solid: ε_K omitted

dashed: $S_{\psi K}$ omitted

dotted: $\Delta M_s/\Delta M_d$ omitted

→ (2-3)σ tension

UT*fit*: B_s mixing

- model independent NP analysis: $$\frac{\langle B_s|H_{\rm eff}^{\rm full}|\overline{B_s}\rangle}{\langle B_s|H_{\rm eff}^{\rm SM}|\overline{B_s}\rangle} = 1 + \frac{A_s^{\rm NP}}{A_s^{\rm SM}} e^{2i\phi_s^{\rm NP}}$$

- measured quantities (expt_i)
  - ΔM_s, A_{SL}^{s}, $A_{SL}^{\mu\mu}$, $\tau(B_s)$, $\Delta\Gamma_s$, ϕ_s

- related to A_s^{NP}/A_s^{SM}, ϕ_s^{NP} and SM/QCD input

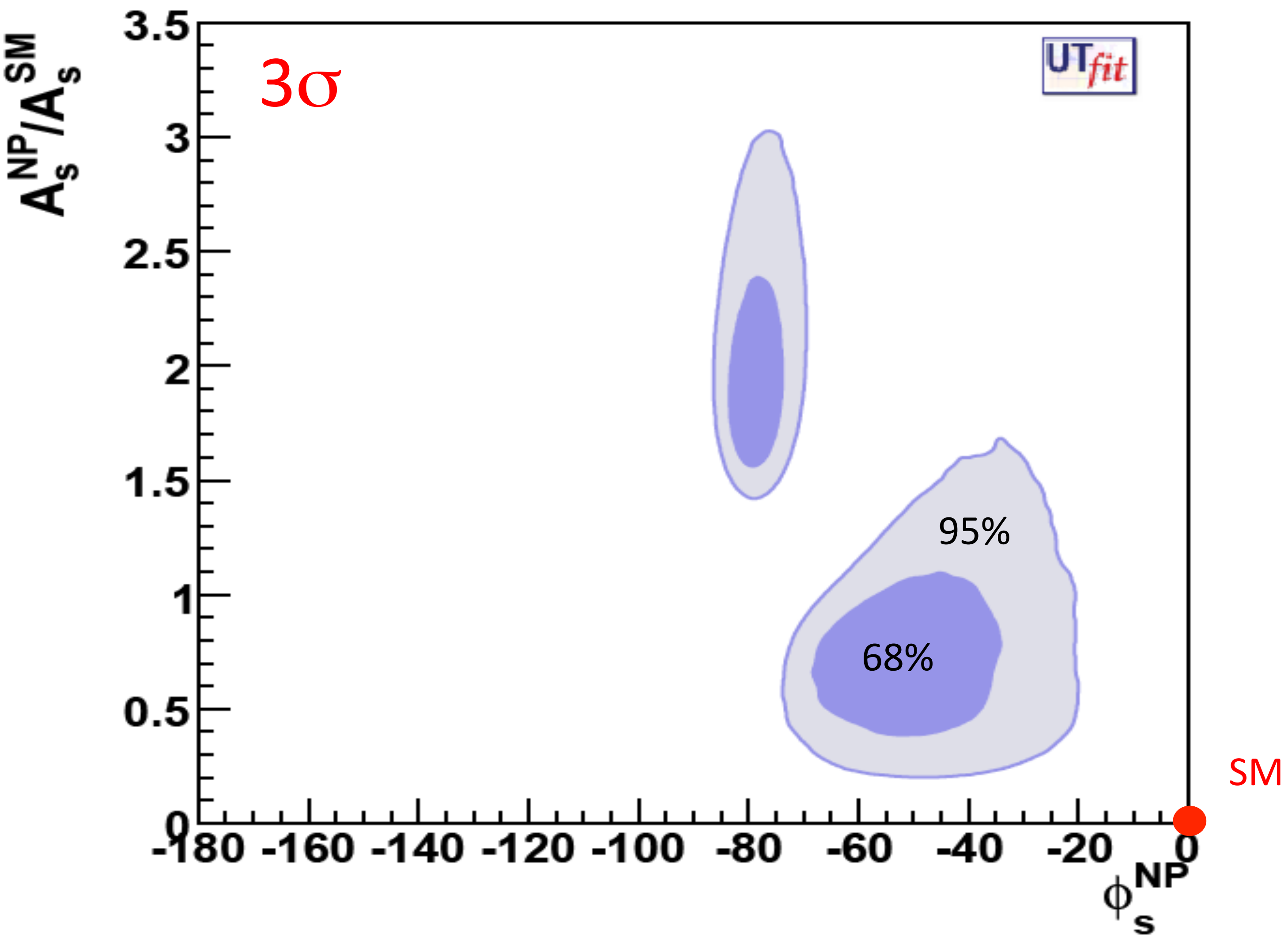
$$\text{expt}_i = \text{fn}_i\,(\,A_s^{NP}/A_s^{SM},\ \phi_s^{NP},\ \text{SM/QCD input}\,)$$

- A_s^{NP}/A_s^{SM}, ϕ_s^{NP} simultaneously fit to expt_i , SM/QCD input

[Ut*fit* Collaboration, arXiv:0803.0659, hep-ph]

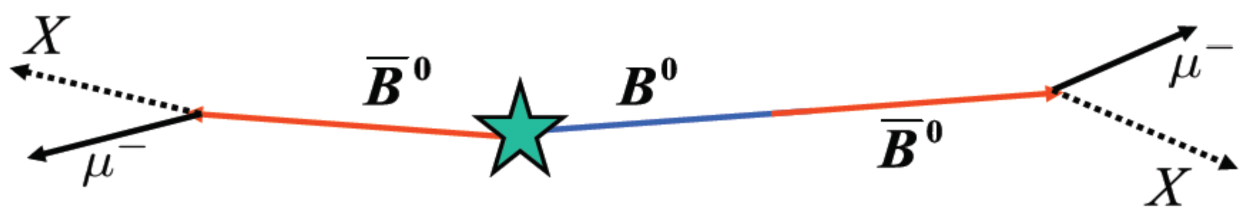
UT*fit*: B_s mixing

[Ut*fit* Collaboration, arXiv:0803.0659, hep-ph]

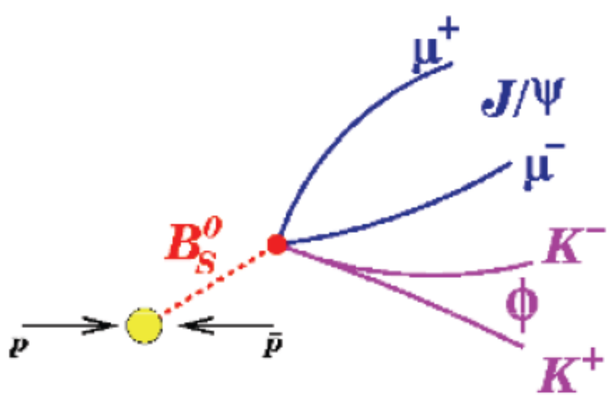


DØ / CDF: B_s mixing

- DØ: $b \longrightarrow \mu^- X$ [G. Brooijmans (DØ), FPCP 2010]

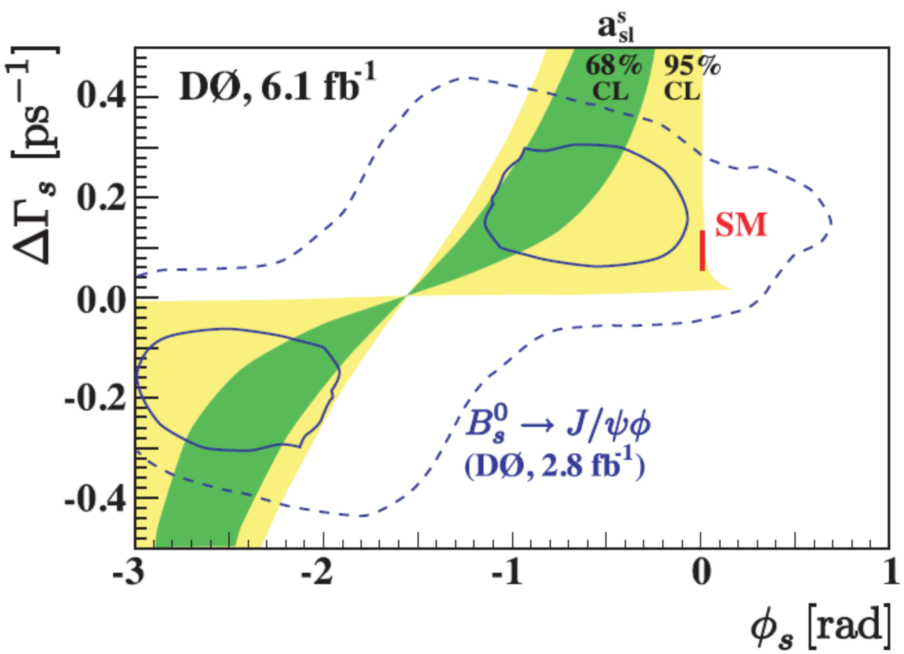


- CDF: $Bs \longrightarrow J/\psi\phi$ [L. Oakes (CDF), FPCP 2010]



DØ / CDF: B_s mixing

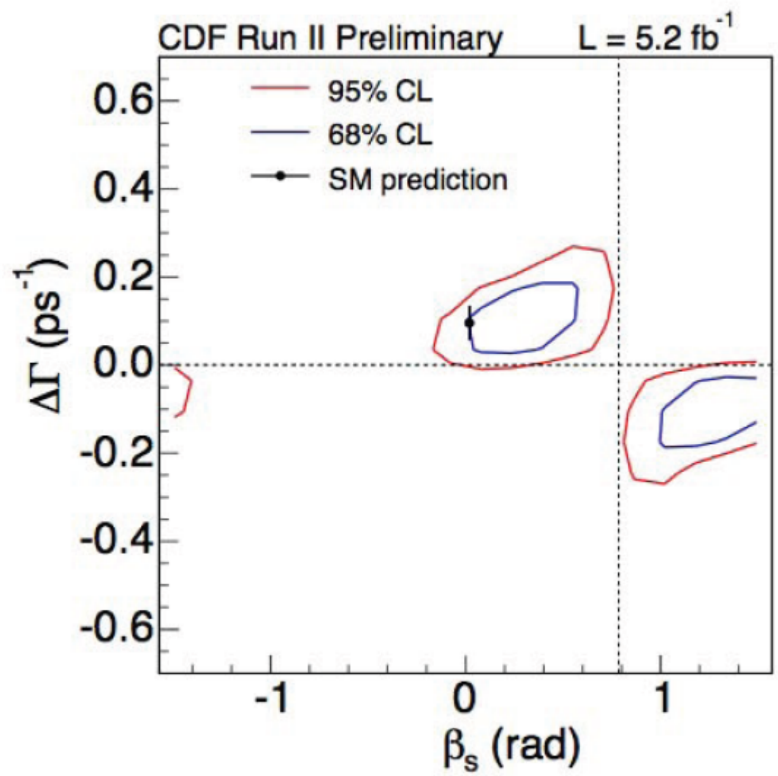
3.2σ



note: $\phi_s = -2\beta_s$

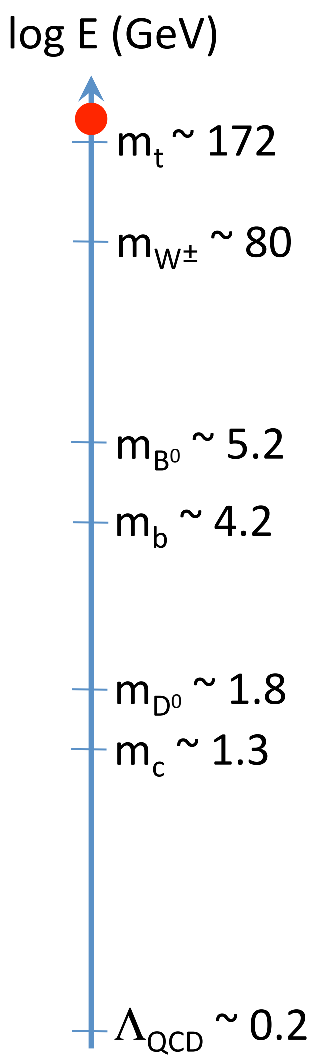
[DØ, arXiv:1005.2757, hep-ex]

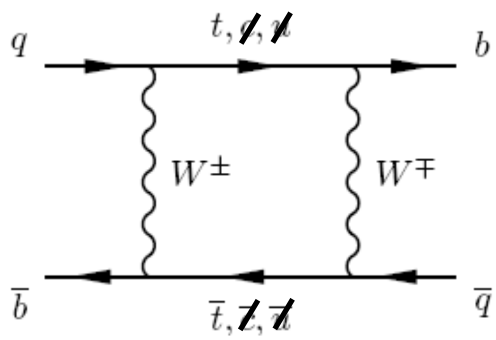
0.8σ

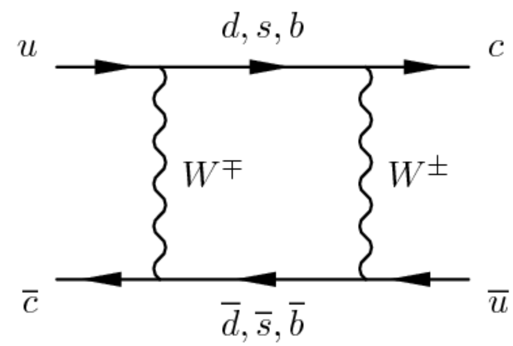


[L. Oakes (CDF), FPCP 2010]

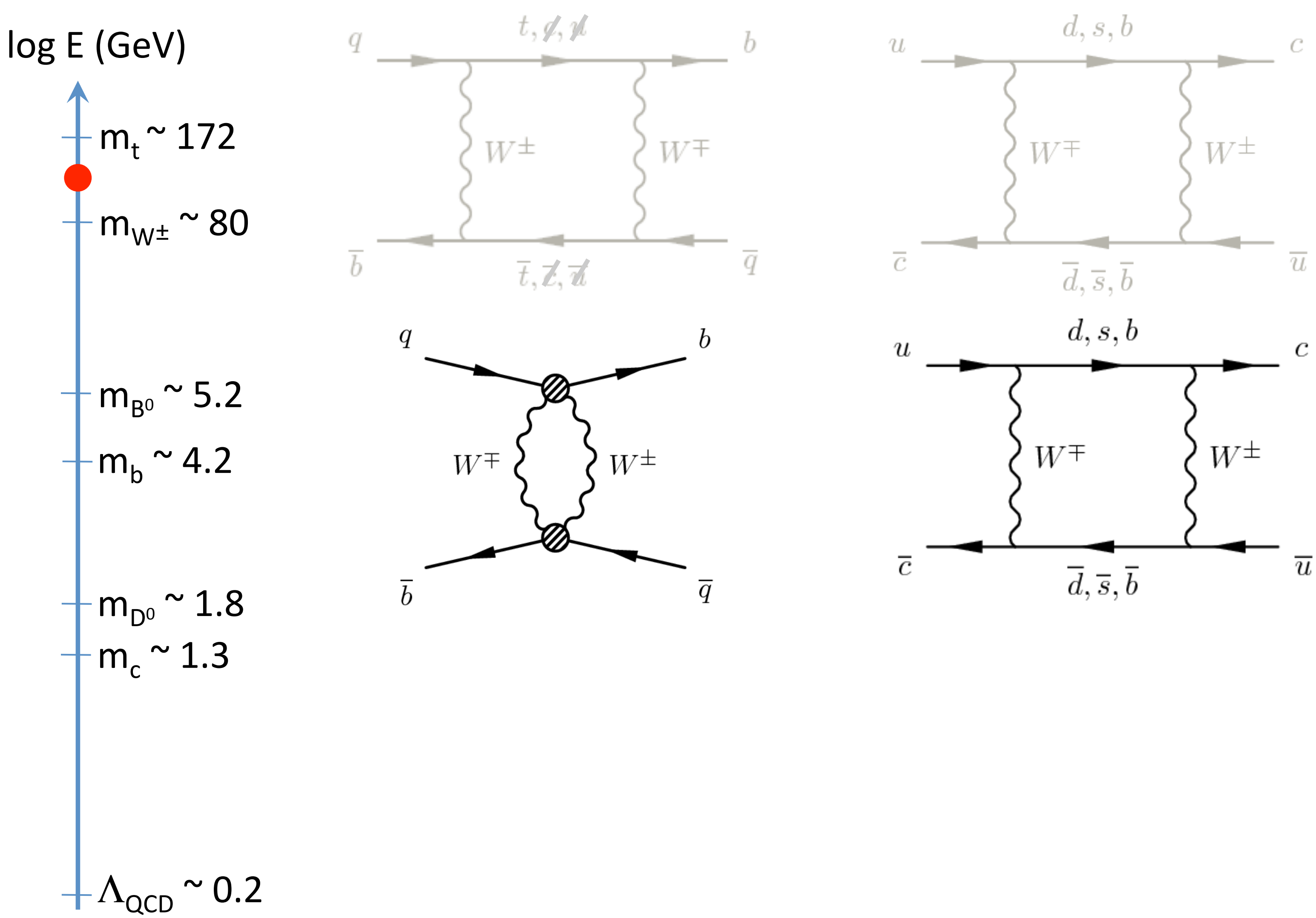
Neutral meson mixing: an effective 4q interaction



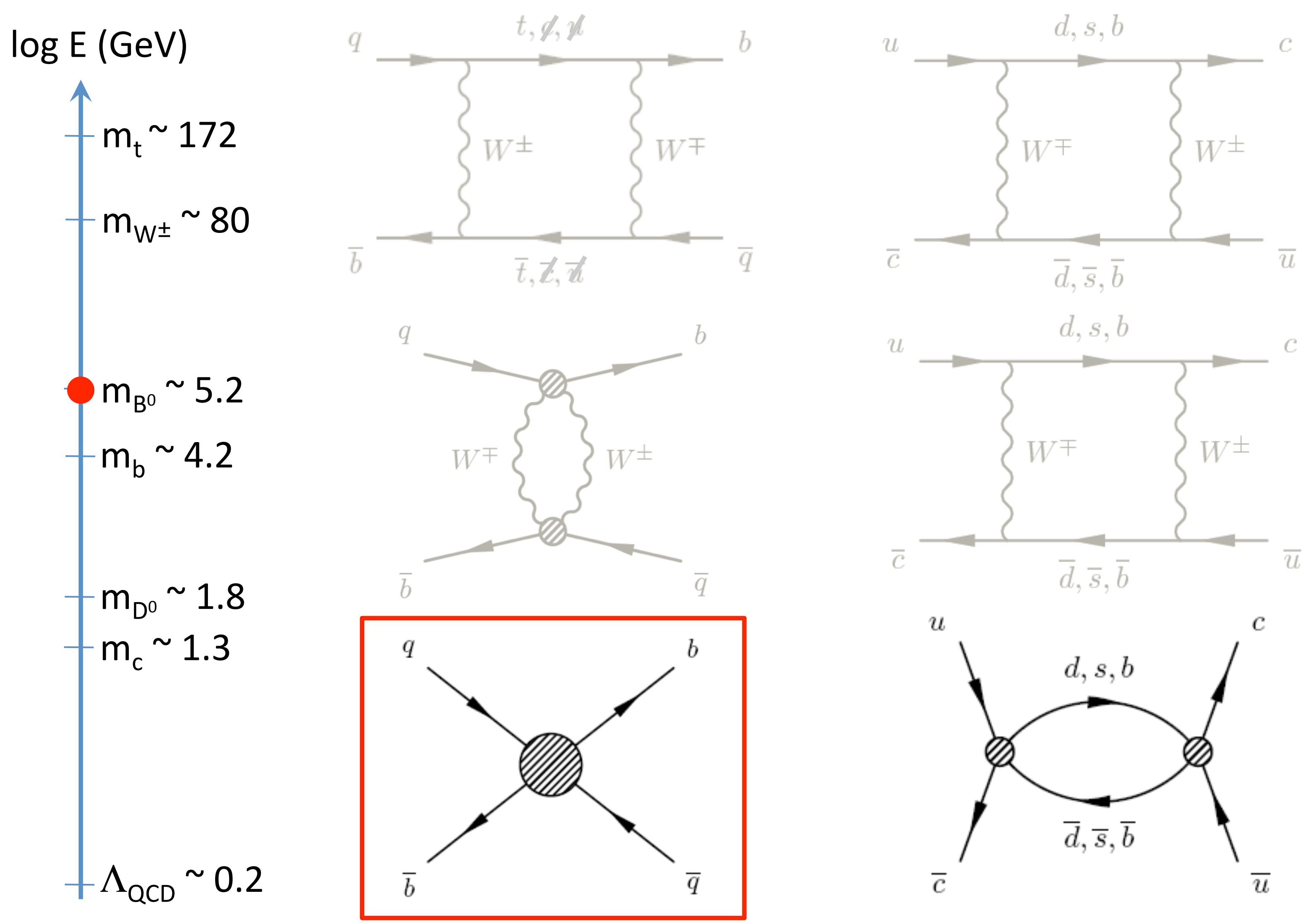




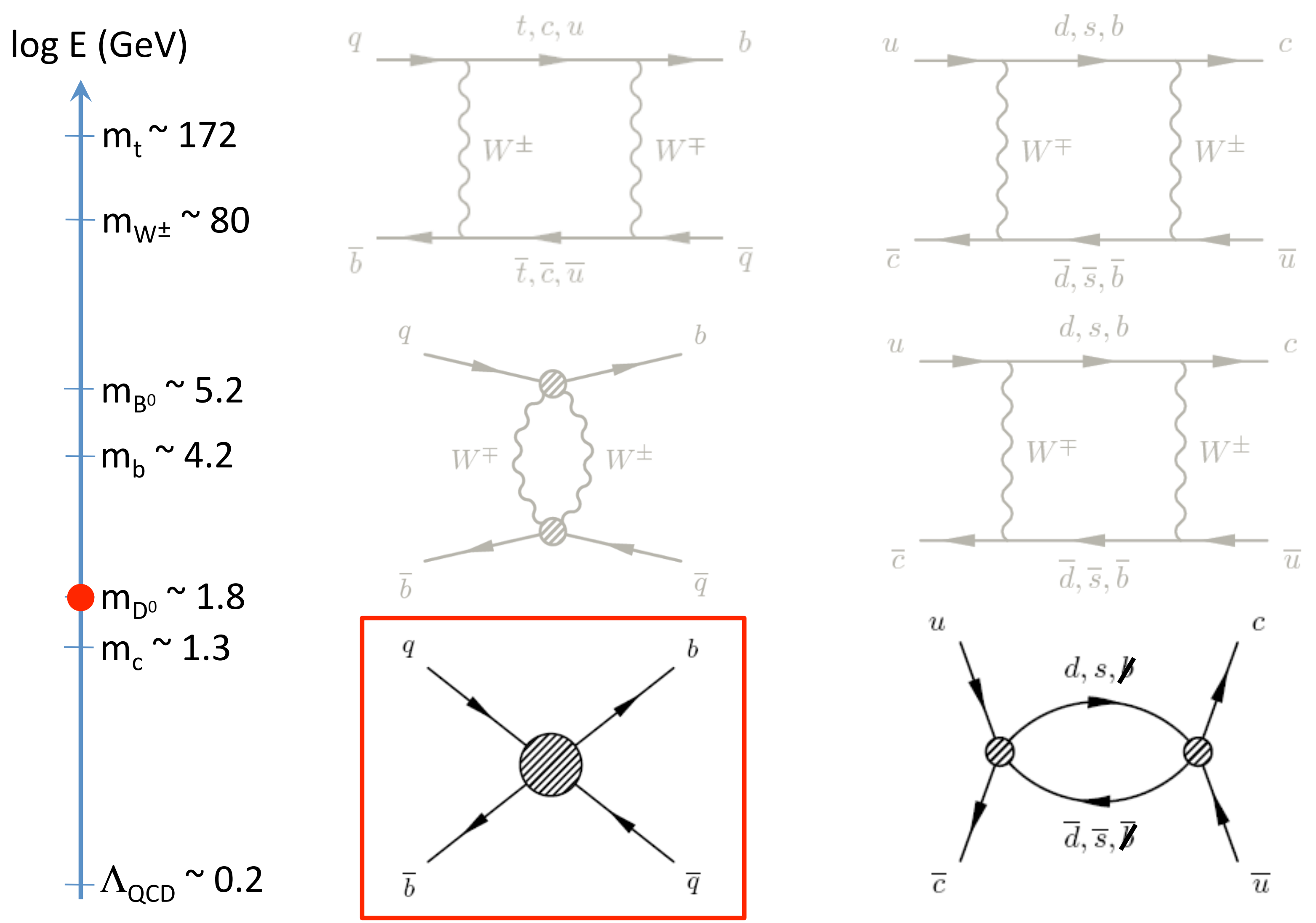
Neutral meson mixing: an effective 4q interaction



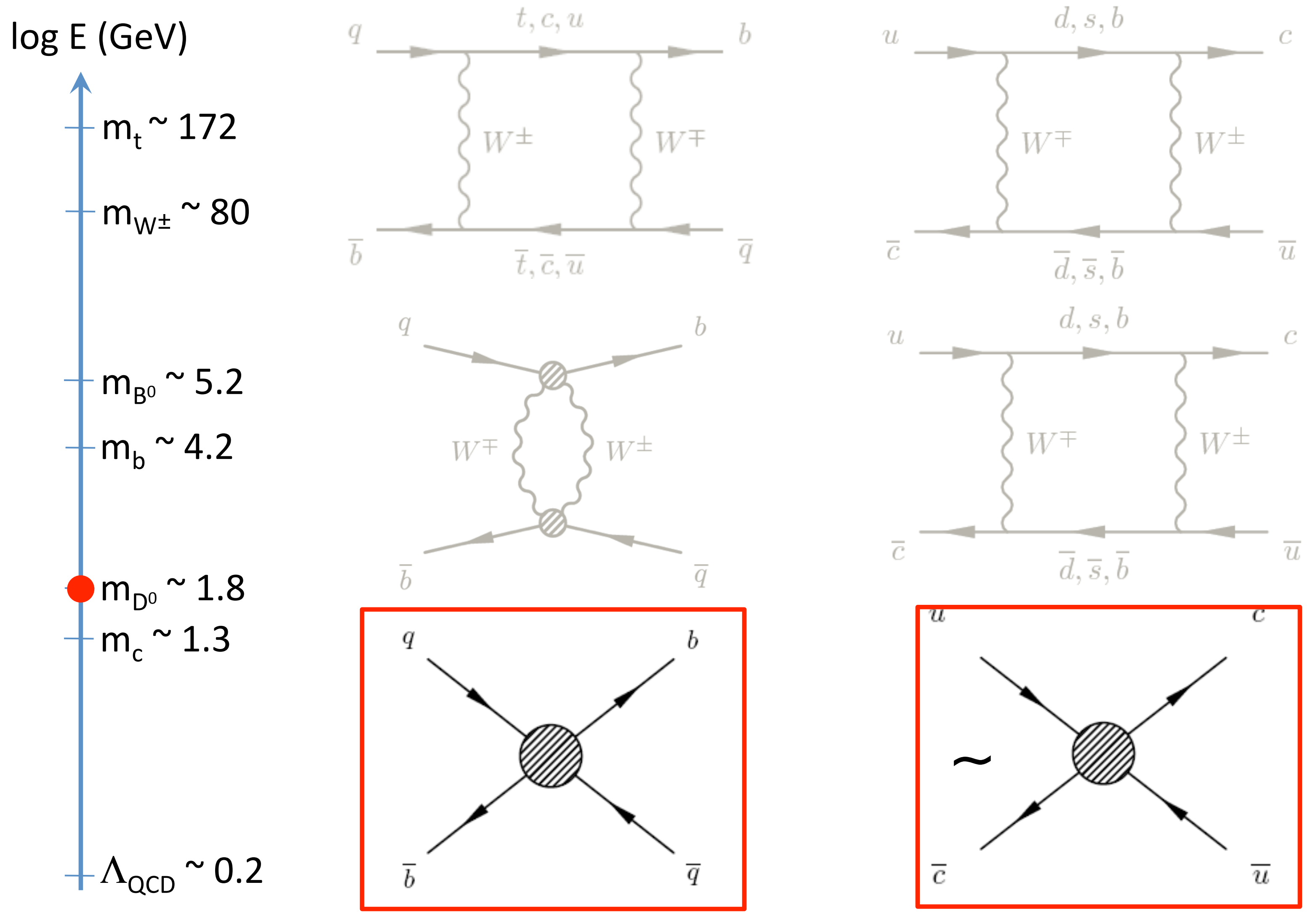
Neutral meson mixing: an effective 4q interaction



Neutral meson mixing: an effective 4q interaction



Neutral meson mixing: an effective 4q interaction



Mixing operators

The 20 local, 4 quark, dim 6, LI, color singlet, $\Delta b = 2$ mixing operators

$$\mathcal{O}_1 = (\gamma_\mu L)[\gamma_\mu L] \qquad \mathcal{O}_2 = (L)[L]$$

$$\mathcal{O}_3 = (L][L) \qquad \mathcal{O}_4 = (L)[R]$$

$$\mathcal{O}_5 = (L][R) \qquad \mathcal{O}_6 = (\gamma_\mu L)[\gamma_\mu R]$$

$$\mathcal{O}_7 = (\gamma_\mu L][\gamma_\mu R) \qquad \mathcal{O}_8 = (R)[R]$$

$$\mathcal{O}_9 = (R][R) \qquad \mathcal{O}_{10} = (\gamma_\mu R)[\gamma_\mu R]$$

$$\mathcal{O}_{11} = (\gamma_\mu R][\gamma_\mu R) \qquad \mathcal{O}_{12} = (\gamma_\mu L][\gamma_\mu L)$$

$$\mathcal{O}_{13} = (\sigma_{\mu\nu})[\sigma_{\mu\nu}] \qquad \mathcal{O}_{14} = (\sigma_{\mu\nu}][\sigma_{\mu\nu})$$

$$\mathcal{O}_{15} = (\gamma_\mu R)[\gamma_\mu L] \qquad \mathcal{O}_{16} = (\gamma_\mu R][\gamma_\mu L)$$

$$\mathcal{O}_{17} = (R)[L] \qquad \mathcal{O}_{18} = (R][L)$$

$$\mathcal{O}_{19} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu})[\sigma_{\rho\tau}] \qquad \mathcal{O}_{20} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu}][\sigma_{\rho\tau})$$

Mixing operators

commuting quark fields

$$\mathcal{O}_1 = (\gamma_\mu L)[\gamma_\mu L]$$
$$\mathcal{O}_2 = (L)[L]$$
$$\mathcal{O}_3 = (L][L)$$
$$\mathcal{O}_4 = (L)[R]$$
$$\mathcal{O}_5 = (L][R)$$
$$\mathcal{O}_6 = (\gamma_\mu L)[\gamma_\mu R]$$
$$\mathcal{O}_7 = (\gamma_\mu L][\gamma_\mu R)$$
$$\mathcal{O}_8 = (R)[R]$$
$$\mathcal{O}_9 = (R][R)$$
$$\mathcal{O}_{10} = (\gamma_\mu R)[\gamma_\mu R]$$
$$\mathcal{O}_{11} = (\gamma_\mu R][\gamma_\mu R)$$
$$\mathcal{O}_{12} = (\gamma_\mu L][\gamma_\mu L)$$
$$\mathcal{O}_{13} = (\sigma_{\mu\nu})[\sigma_{\mu\nu}]$$
$$\mathcal{O}_{14} = (\sigma_{\mu\nu}][\sigma_{\mu\nu})$$
$$\cancel{\mathcal{O}_{15} = (\gamma_\mu R)[\gamma_\mu L]}$$
$$\cancel{\mathcal{O}_{16} = (\gamma_\mu R][\gamma_\mu L)}$$
$$\cancel{\mathcal{O}_{17} = (R)[L]}$$
$$\cancel{\mathcal{O}_{18} = (R][L)}$$
$$\mathcal{O}_{19} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu})[\sigma_{\rho\tau}]$$
$$\mathcal{O}_{20} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu}][\sigma_{\rho\tau})$$

Mixing operators

commuting quark fields, Fierz

$$\mathcal{O}_1 = (\gamma_\mu L)[\gamma_\mu L] \qquad \mathcal{O}_2 = (L)[L]$$

$$\mathcal{O}_3 = (L][L) \qquad \mathcal{O}_4 = (L)[R]$$

$$\mathcal{O}_5 = (L][R) \qquad \cancel{\mathcal{O}_6 = (\gamma_\mu L)[\gamma_\mu R]}$$

$$\cancel{\mathcal{O}_7 = (\gamma_\mu L][\gamma_\mu R)} \qquad \mathcal{O}_8 = (R)[R]$$

$$\mathcal{O}_9 = (R][R) \qquad \mathcal{O}_{10} = (\gamma_\mu R)[\gamma_\mu R]$$

$$\cancel{\mathcal{O}_{11} = (\gamma_\mu R][\gamma_\mu R)} \qquad \cancel{\mathcal{O}_{12} = (\gamma_\mu L][\gamma_\mu L)}$$

$$\cancel{\mathcal{O}_{13} = (\sigma_{\mu\nu})[\sigma_{\mu\nu}]} \qquad \cancel{\mathcal{O}_{14} = (\sigma_{\mu\nu}][\sigma_{\mu\nu})}$$

$$\cancel{\mathcal{O}_{15} = (\gamma_\mu R)[\gamma_\mu L]} \qquad \cancel{\mathcal{O}_{16} = (\gamma_\mu R][\gamma_\mu L)}$$

$$\cancel{\mathcal{O}_{17} = (R)[L]} \qquad \cancel{\mathcal{O}_{18} = (R][L)}$$

$$\mathcal{O}_{19} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu})[\sigma_{\rho\tau}] \qquad \mathcal{O}_{20} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu}][\sigma_{\rho\tau})$$

Mixing operators

commuting quark fields, Fierz, parity (ME's)

$\mathcal{O}_1 = (\gamma_\mu L)[\gamma_\mu L]$

$\mathcal{O}_2 = (L)[L]$

$\mathcal{O}_3 = (L][L)$

$\mathcal{O}_4 = (L)[R]$

$\mathcal{O}_5 = (L][R)$

$\cancel{\mathcal{O}_6 = (\gamma_\mu L)[\gamma_\mu R]}$

$\cancel{\mathcal{O}_7 = (\gamma_\mu L][\gamma_\mu R)}$

$\mathcal{O}_8 = (R)[R] = \mathcal{O}_2$

$\mathcal{O}_9 = (R][R) = \mathcal{O}_3$

$\mathcal{O}_{10} = (\gamma_\mu R)[\gamma_\mu R] = \mathcal{O}_1$

$\cancel{\mathcal{O}_{11} = (\gamma_\mu R][\gamma_\mu R)}$

$\cancel{\mathcal{O}_{12} = (\gamma_\mu L][\gamma_\mu L)}$

$\cancel{\mathcal{O}_{13} = (\sigma_{\mu\nu})[\sigma_{\mu\nu}]}$

$\cancel{\mathcal{O}_{14} = (\sigma_{\mu\nu}][\sigma_{\mu\nu})}$

$\cancel{\mathcal{O}_{15} = (\gamma_\mu R)[\gamma_\mu L]}$

$\cancel{\mathcal{O}_{16} = (\gamma_\mu R][\gamma_\mu L)}$

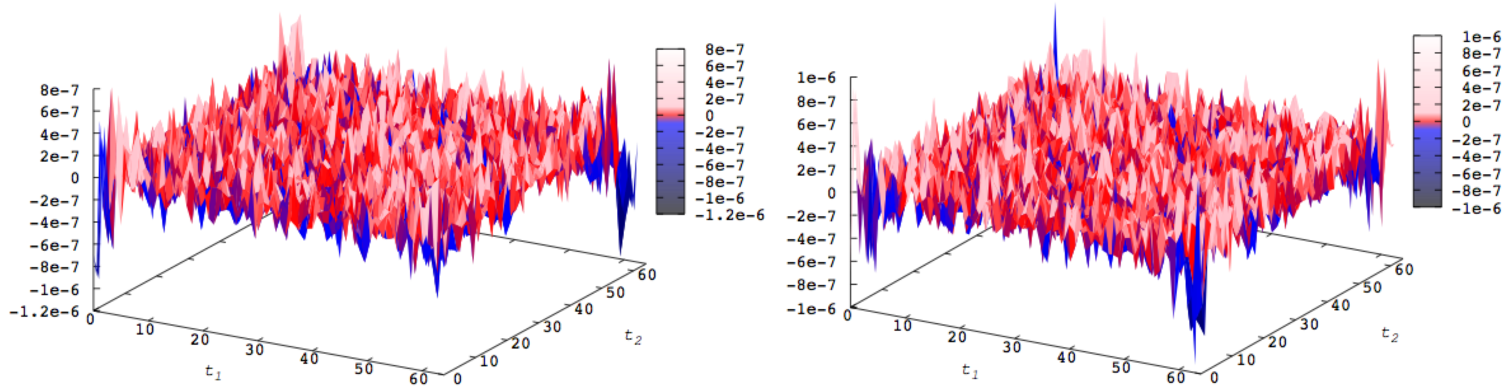
$\cancel{\mathcal{O}_{17} = (R)[L]}$

$\cancel{\mathcal{O}_{18} = (R][L)}$

$\cancel{\mathcal{O}_{19} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu})[\sigma_{\rho\tau}]} \quad = 0$

$\cancel{\mathcal{O}_{20} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu}][\sigma_{\rho\tau})} \quad = 0$

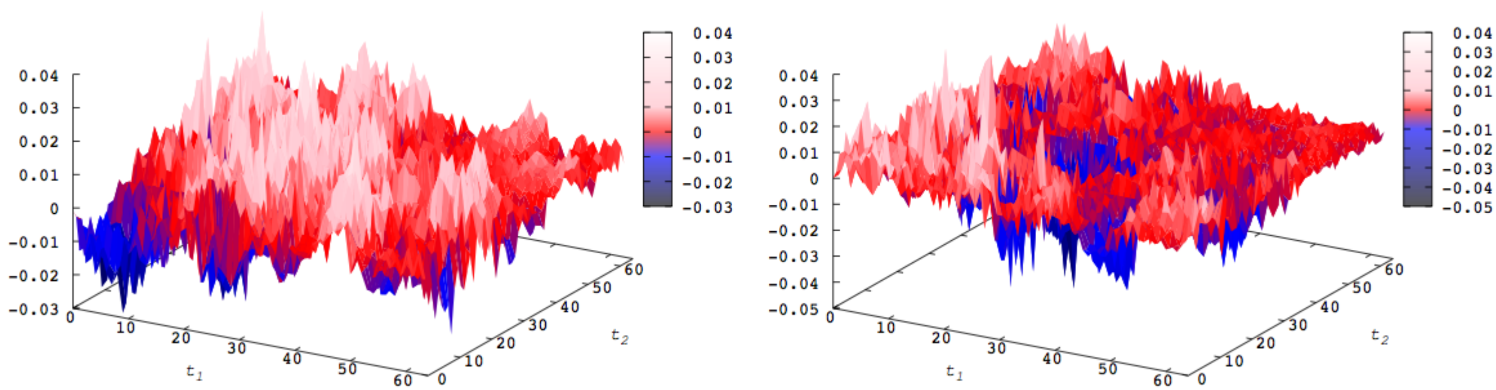
Mixing operators



(a) Difference in σ between $\mathcal{O}_4$ and $\mathcal{F}(\mathcal{O}_4)$.

(b) Difference in σ between $\mathcal{O}_{13}$ and $\mathcal{F}(\mathcal{O}_{13})$.

Figure 1: The difference between data generated for operators $\mathcal{O}_{4,13}$ and data generated for their Fierz transformations is nearly exact, with differences around one-millionth of a σ. The same is true for $\mathcal{O}_{5-7,14}$.

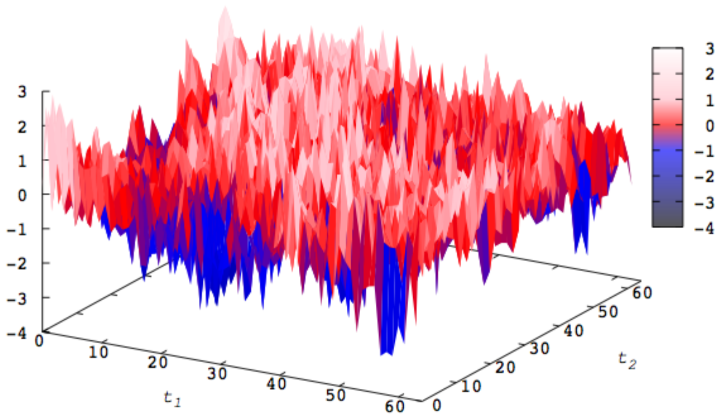


(a) Difference in σ between $\mathcal{O}_2$ and $\mathcal{F}(\mathcal{O}_2)$.

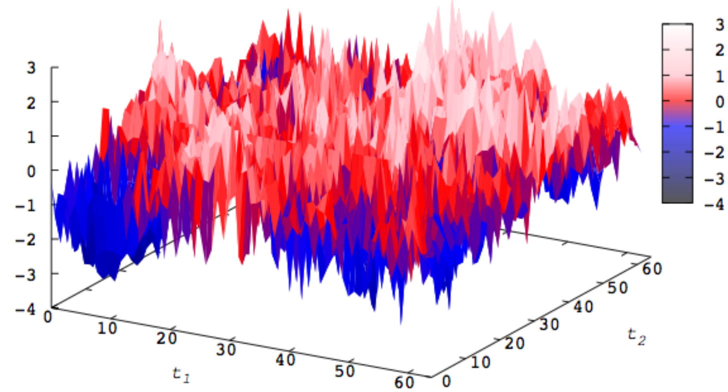
(b) Difference in σ between $\mathcal{O}_9$ and $\mathcal{F}(\mathcal{O}_9)$.

Figure 2: The difference between data generated for operators $\mathcal{O}_{2,9}$ and data generated for their Fierz transformations differs by $\sim 10^{-2}\sigma$. The same is true for $\mathcal{O}_{3,8,19,20}$.

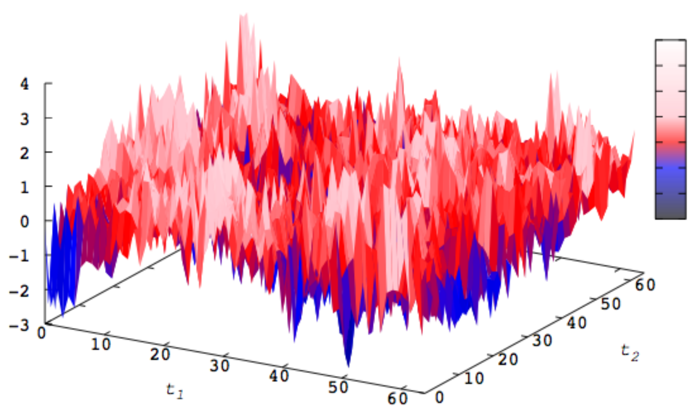
Mixing operators



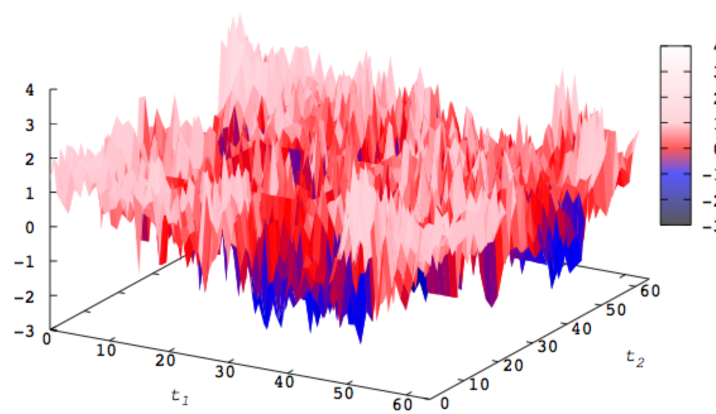
(a) Difference in σ between $\mathcal{O}_1$and $P(\mathcal{O}_1)$.



(b) Difference in σ between $\mathcal{O}_3$ and $P(\mathcal{O}_3)$.



(c) Difference in σ between $\mathcal{O}_{11}$ and $P(\mathcal{O}_{11})$.



(d) Difference in σ between $\mathcal{O}_{20}$ and $P(\mathcal{O}_{20})$. By parity, $\mathcal{O}_{20} = 0$.

The calculation: generating data

Fermion doubling: discrete Dirac eqn $\longrightarrow$ 16 poles

- 15 extra fermions with $p_\mu \approx \pi/a$

- Approach for handling them depends on mass
  - heavy quarks: Wilson quarks (explicit χSB)
  - light quarks (maintain χ symmetry)
    - sea: rooted, staggered (non-local, oscillating states)
    - valence: naïve (local interpolating operators)

The calculation: generating data, gauge configurations

MILC collaboration

- 2+1 sea quarks
- Generated with importance sampling, ie. with probability distribution

$$exp(-S[U_i] + \ln\left[det(\not{\Delta} + m)\right])$$

- Sea quarks
  - rooted staggered
  - AsqTad improved, $\mathcal{O}\left(a^4, \alpha_s a^2\right)$
- Gluons
  - Symanzik, tadpole improved, $\mathcal{O}\left(a^4, \alpha_s a^2\right)$

The calculation: extracting results, fitting the data

- Bayesian fitting

$$\chi^2 = \sum_{t_1,t_2} (f_{t_1}(\{p\}) - \bar{d}_{t_1})\ (\sigma^2_{t_1 t_2})^{-1}\ (f_{t_2}(\{p\}) - \bar{d}_{t_2})\ + \sum_n \frac{(p - \hat{p}_n)^2}{\hat{\sigma}^2_n}$$

- Considerations
  - time range of data to fit
  - number of states to include in fit

$$C^{PS}_{2pt}(t) \quad = \quad \sum_n \left(\frac{|Z^-_n|^2}{2E^-_n}\, e^{-E^-_n t} - (-1)^t \frac{|Z^+_n|^2}{2E^+_n}\, e^{-E^+_n t} \right)$$

  - choice of priors and widths

Rooted, staggered, AsqTad

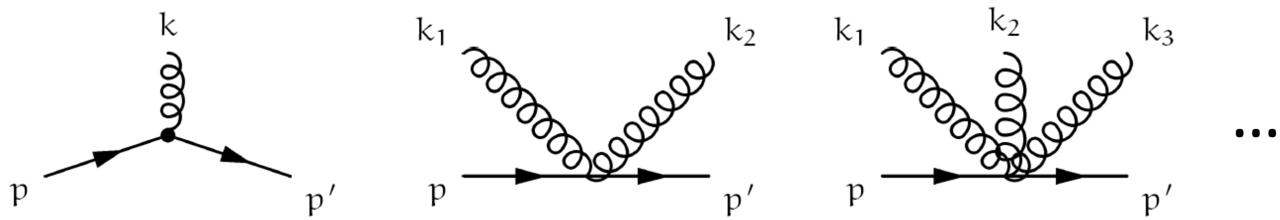
- sea quarks

$$\langle \Omega | X | \Omega \rangle = \frac{\int [dU]\ X((\not{D} + m)^{-1}, U)\ e^{-S[U] + \ln det(\not{D} + m)}}{\int [dU]\ e^{-S[U] + \ln det(\not{D} + m)}}$$

  - AsqTad = a squared, tadpole improved
  - staggered (Kogut & Susskind) spin diagonalize quark action (keep only 1 of 4 components)
    - reduces quarks from 16 to 4
  - rooted takes ¼ root of $det(\not{D} + m)$
    - reduces quarks from 4 to 1

Tadpole Improvement

- Using gauge link $U_{x,\mu} = e^{iagG_\mu(x)}$, expansion in a gives a tower of vertices



- UV modes give "tadpoles"
  – integrating out UV modes, giving

$$U_\mu \to u_0\, e^{iagA_\mu^{\mathrm{IR}}} \approx u_0\,(1 + iagA_\mu^{\mathrm{IR}})$$

- Tadpole improvement uses U_μ/u_0
  – u_0 measured on lattice as mean field value of links

Symanzik Improved glue

- Start with Wilson's gauge action
- Add terms to action to cancel order (a^2) effects
  - coeffecients determined by perturbation theory at one loop (Lüscher and Weisz)
  - lattice action viewed as eff. theory, higher order terms are irrelevant operators
- Resulting errors are $\mathcal{O}\left(a^4, \alpha_s a^2\right)$

Wilson, SW, Fermilab interpretation

- Wilson: add dim 5 term that gives "extra" fermions mass
- SW: add another dim 5 term to cancel O(a) error from the Wilson term ("clover action")
- Fermilab interpretation: matches improvement coefficients to HQET
  - action valid for all masses (ie. ma > 1)
- errors $\mathcal{O}\left(\frac{\alpha_s \Lambda_{QCD}}{m_b}, \frac{\Lambda_{QCD}^2}{m_b^2}\right)$

Naïve AsqTad

- valence quarks

$$\langle\Omega|X|\Omega\rangle = \frac{\int [dU]\ X((\not{D}+m)^{-1}, U)\ e^{-S[U]+\ln det(\not{D}+m)}}{\int [dU]\ e^{-S[U]+\ln det(\not{D}+m)}}$$

  – naïve = retain locality, deal with "doublers"
    - eases building interpolating operators

  – AsqTad = a squared, tadpole improved

FIRST EVIDENCE OF NEW PHYSICS IN $b \leftrightarrow s$ TRANSITIONS

(**UT***fit* Collaboration)

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M. Pierini,[1‖] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

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[6] *Dipartimento di Fisica, Università di Genova and INFN, I-16146 Genova, Italy*
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[8] *INFN, Sezione di Bologna, I-40126 Bologna, Italy*

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

Fermilab-Pub-10/114-E

Evidence for an anomalous like-sign dimuon charge asymmetry

(The D0 Collaboration*)

(Dated: May 16, 2010)

We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\overline{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A, we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\rm sl} = -0.00957 \pm 0.00251$ (stat) $\pm\, 0.00146$ (syst). This result differs by 3.2 standard deviations from the standard model prediction $A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

PACS numbers: 13.25.Hw; 14.40.Nd

Observation of $B_s^0 - \bar{B}_s^0$ Oscillations

(CDF Collaboration)

We report the observation of B_s^0-$\bar{B}_s^0$ oscillations from a time-dependent measurement of the B_s^0-$\bar{B}_s^0$ oscillation frequency Δm_s. Using a data sample of 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61 500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s^0-$\bar{B}_s^0$ oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8}, which exceeds 5σ significance. We measure $\Delta m_s = 17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ \mathrm{ps}^{-1}$ and extract $|V_{\mathrm{td}}/V_{\mathrm{ts}}| = 0.2060 \pm 0.0007(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d + \mathrm{theor})$.

DOI: 10.1103/PhysRevLett.97.242003 PACS numbers: 14.40.Nd, 12.15.Ff, 12.15.Hh, 13.20.He