B_s^0 and B^0 mixing in the Standard Model and beyond

…a progress report

Chris Bouchard, University of Illinois
FNAL Lattice – MILC Collaboration

Lattice 2010

Outline

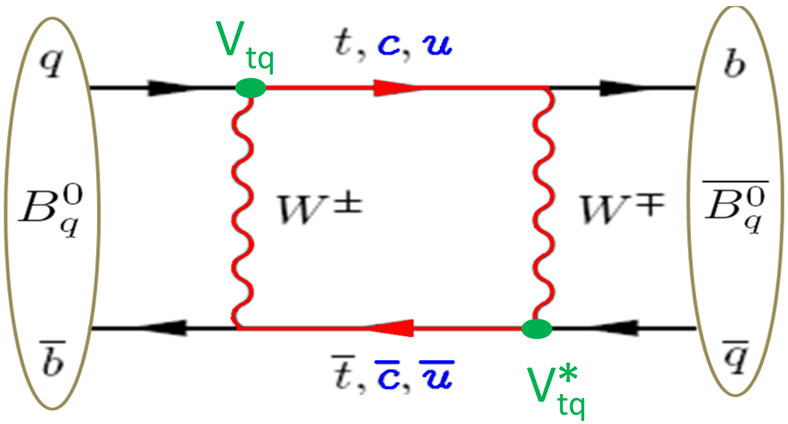
- Introduction
  - motivation
  - role of LQCD
- Calculation
  - mixing operators
  - generating data
  - fitting
- Initial results
- Outlook

Motivation

- mixing sensitive to NP
  - SM contributions suppressed: loop, GIM, Cabibbo
- hints of NP
- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

Mixing sensitive to NP

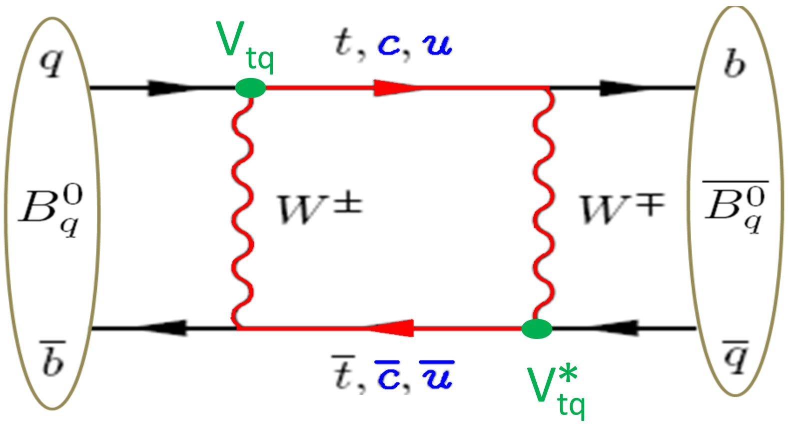
SM suppression: loop, GIM, Cabibbo

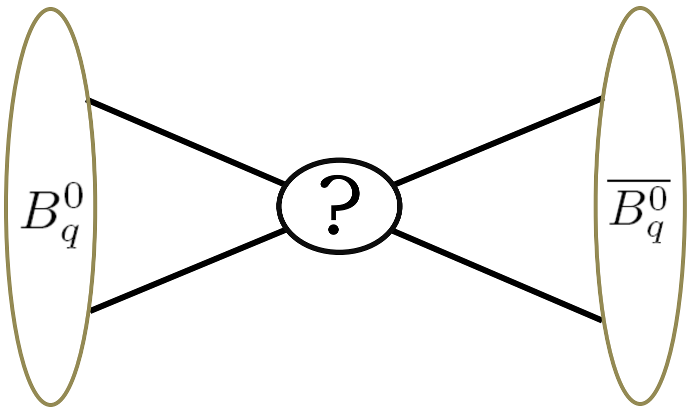


Mixing sensitive to NP

SM suppression: loop, GIM, Cabibbo

...opens door for BSM contributions





some possibilities [Buras, 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

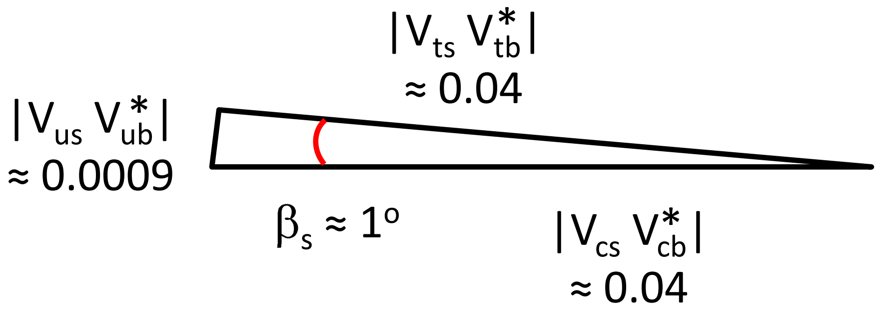
- mixing sensitive to NP
- hints of NP
  - definitions
- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

Definitions

- $\Delta M = M_H - M_L$

- $\Delta\Gamma = \Gamma_L - \Gamma_H$

- $\phi_s^{J/\psi\phi}$ ($= -2\ \beta_s$):

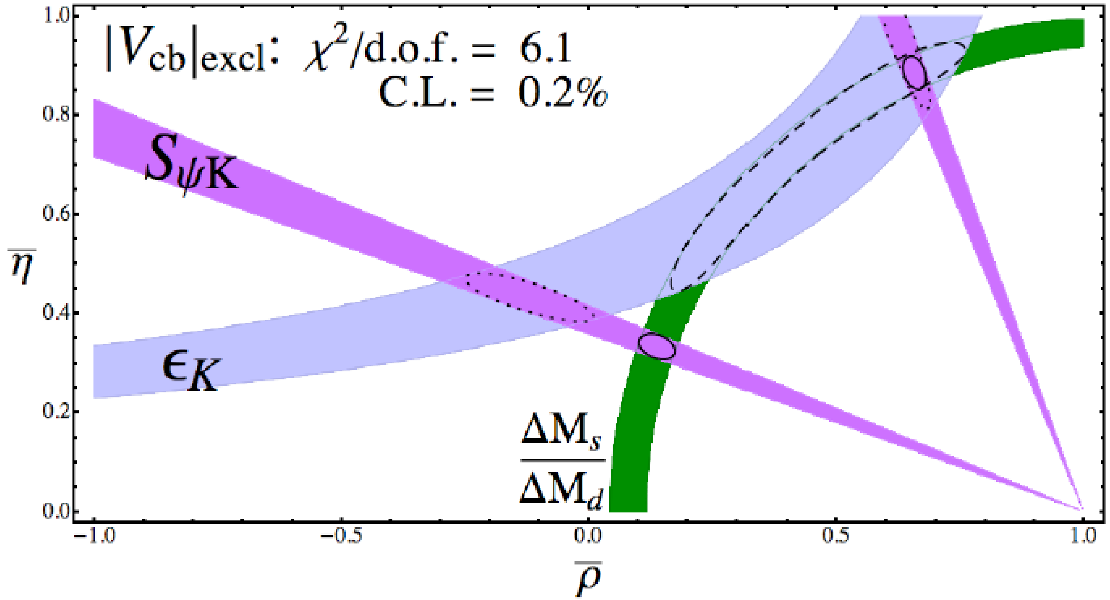


Motivation

- mixing sensitive to NP
- hints of NP
  - definitions
  - UT tension: 2-3σ [Laiho, Lunghi, Van de Water arXiv:0910.2928v2, hep-ph] [Lunghi and Soni, arXiv:0803.4340, hep-ph]
- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

UT tension

[Laiho, Lunghi and Van de Water, arXiv:0910.2928v2, hep-ph]



solid: ϵ_K omitted
dashed: $S_{\psi K}$ omitted
dotted: $\Delta M_s/\Delta M_d$ omitted

→ (2-3)σ tension

Motivation

- mixing sensitive to NP
- hints of NP
  - definitions
  - UT tension: 2-3σ [Laiho, Lunghi, Van de Water arXiv:0910.2928v2, hep-ph] [Lunghi and Soni, arXiv:0803.4340, hep-ph]
  - B_S mixing: UT*fit* 3σ [arXiv:0803.0659, hep-ph]
- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

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

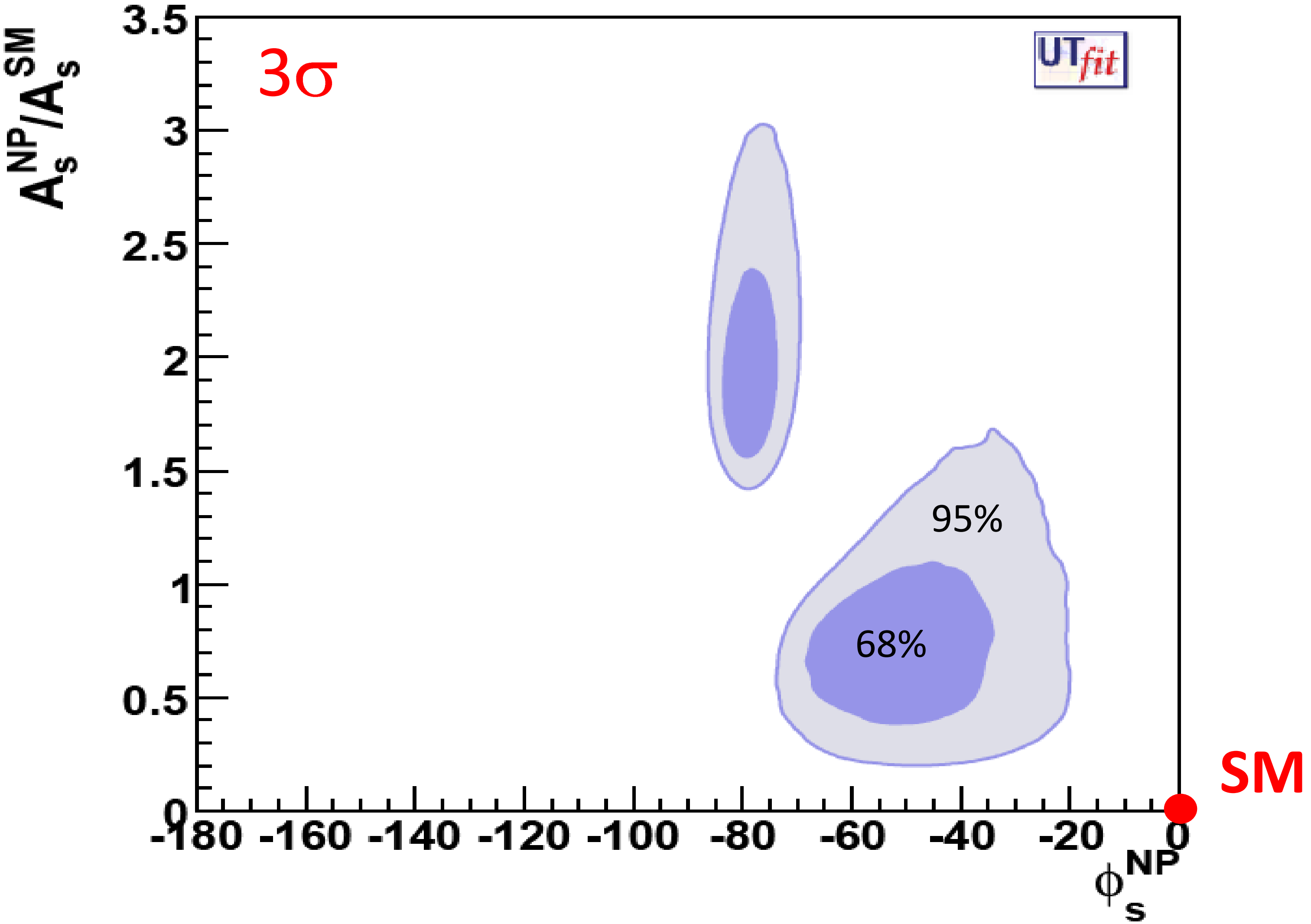
$$\text{expt}_i = \text{fn}_i\left(A_s^{NP}/A_s^{SM}, \phi_s^{NP}, \text{SM/QCD input} \right)$$

- 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]



Motivation

- mixing sensitive to NP

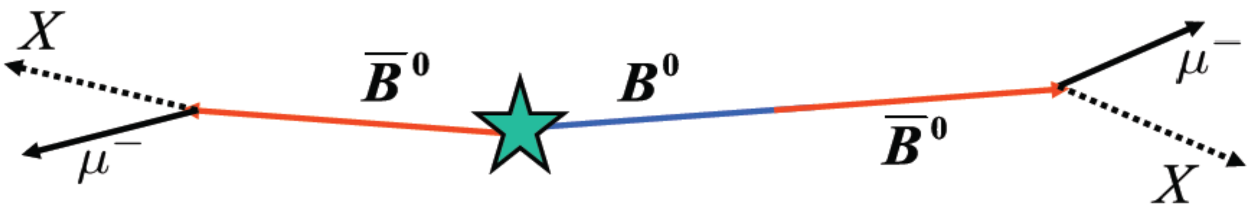
- hints of NP
  - definitions
  - UT tension: 2-3σ [Laiho, Lunghi, Van de Water arXiv:0910.2928v2, hep-ph] [Lunghi and Soni, arXiv:0803.4340, hep-ph]
  - B_S mixing: UT*fit* 3σ [arXiv:0803.0659, hep-ph]
    DØ 3.2σ [arXiv:1005.2757, hep-ex]
    CDF 0.8σ [FPCP 25 May 2010]

- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

DØ / CDF: B_s mixing

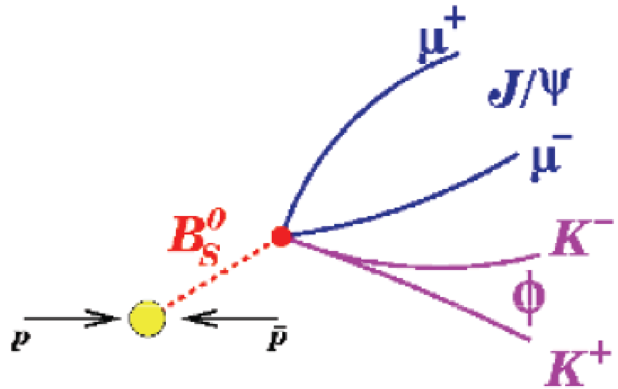
[G. Brooijmans (DØ), FPCP 2010]

$$A_{SL}^{\mu\mu} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$



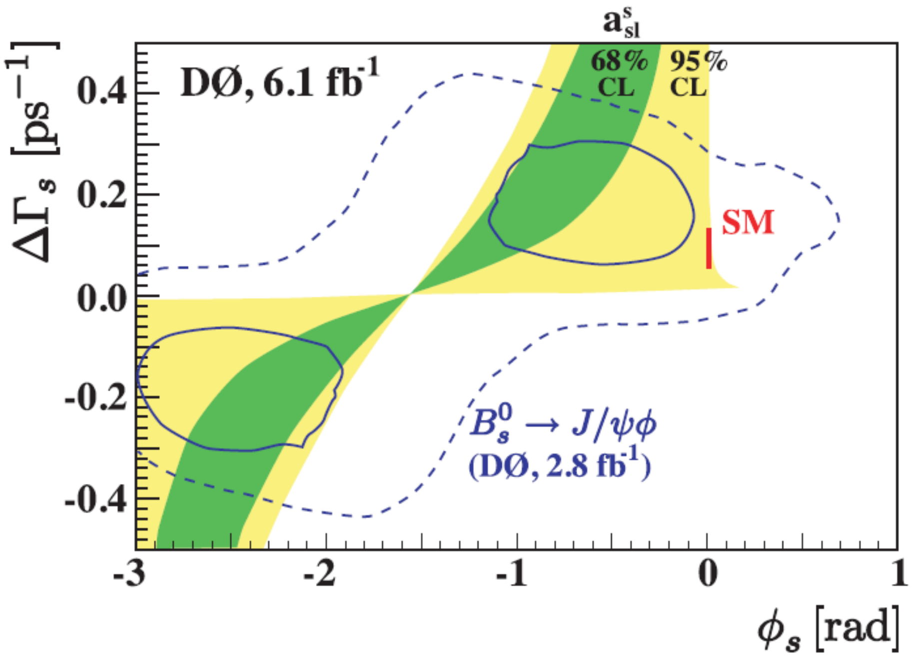
[L. Oakes (CDF), FPCP 2010]

$$A_{SL}^{S} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

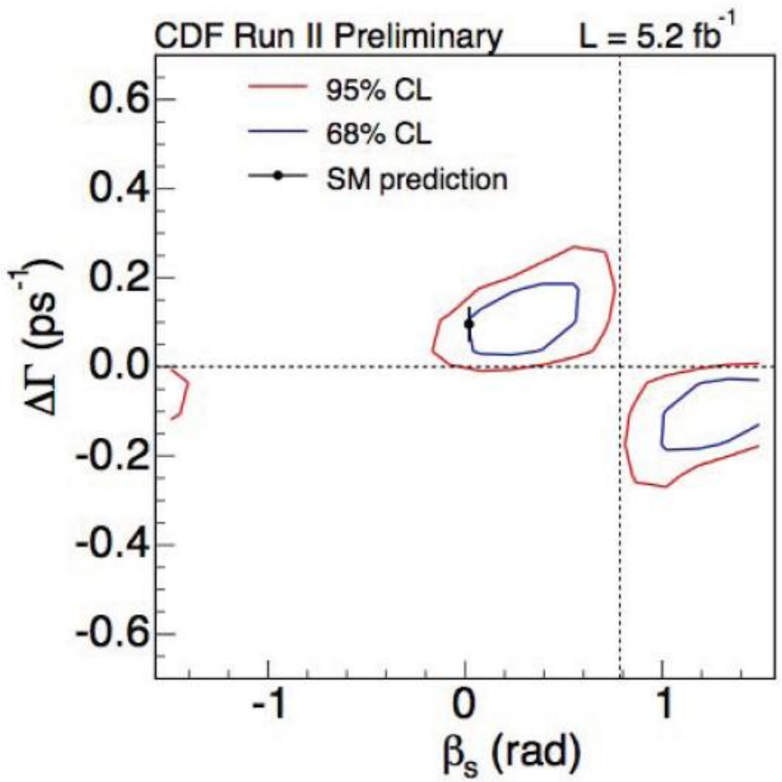


DØ / CDF: B_s mixing

3.2σ



0.8σ



note: $\phi_s = -2\beta_s$

[DØ, arXiv:1005.2757, hep-ex]

[L. Oakes (CDF), FPCP 2010]

Motivation

- mixing sensitive to NP

- hints of NP

- experimental precision in determining $|V_{td}|$ & $|V_{ts}|$

Δm_d = 0.507 ± 0.003(stat) ± 0.003(stat) ps^{-1} < 1%

Δm_s = 17.77 ± 0.10(stat) ± 0.07(syst) ps^{-1} < 0.7%

Role of LQCD

Δm_d = 0.507 ± 0.003(stat) ± 0.003(syst) ps^{-1} [PDG, PL B667, 1 (2008)]

Δm_s = 17.77 ± 0.10(stat) ± 0.07(syst) ps^{-1} [CDF, PRL 97, 242003 (2006)]

expt

SM: $$\Delta m_q = \left(\frac{G_F^2 M_W^2 S_0}{4\pi^2 M_{B_q}}\right)\eta_B(\mu) \quad \left|V_{tb}V_{tq}^*\right|^2 \quad \langle\overline{B_q^0}|\mathcal{O}(\mu)|B_q^0\rangle$$

know / calc in PT — want — LQCD

Role of LQCD

Δm_d = 0.507 ± 0.003(stat) ± 0.003(syst) ps^{-1} [PDG, PL B667, 1 (2008)]

Δm_s = 17.77 ± 0.10(stat) ± 0.07(syst) ps^{-1} [CDF, PRL 97, 242003 (2006)]

expt

SM + BSM: $$\Delta m_q = \sum_i \underbrace{C_i(\mu)}_{\text{model dep}} \underbrace{\langle \overline{B_q^0} | \mathcal{O}_i(\mu) | B_q^0 \rangle}_{\text{LQCD}}$$

Role of LQCD

Δm_d = 0.507 ± 0.003(stat) ± 0.003(syst) ps^{-1} [PDG, PL B667, 1 (2008)]

Δm_s = 17.77 ± 0.10(stat) ± 0.07(syst) ps^{-1} [CDF, PRL 97, 242003 (2006)]

expt

SM + BSM: $$\Delta m_q = \sum_i \underbrace{C_i(\mu)}_{\text{model dep}} \underbrace{\langle \overline{B^0_q} | \mathcal{O}_i(\mu) | B^0_q \rangle}_{\text{LQCD}}$$

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

$|\Delta\Gamma_s|$ = 0.076 $^{+0.059}_{-0.063}$ (stat) ± 0.006 (syst.) ps^{-1} [CDF, PRL 100, 121803, 2008]

Outline

- Introduction
  - motivation
  - role of LQCD
- Calculation
  - mixing operators
  - generating data
  - fitting
- Initial results
- Summary

Mixing operators: SUSY basis

- 5 independent operators form ''SUSY'' basis

$$\mathcal{O}_1 = (\overline{b}^{\alpha}\gamma_\mu L q^{\alpha})\ (\overline{b}^{\beta}\gamma_\mu L q^{\beta})$$
$$\mathcal{O}_2 = (\overline{b}^{\alpha} L q^{\alpha})\ (\overline{b}^{\beta} L q^{\beta})$$
$$\mathcal{O}_3 = (\overline{b}^{\alpha} L q^{\beta})\ (\overline{b}^{\beta} L q^{\alpha})$$
$$\mathcal{O}_4 = (\overline{b}^{\alpha} L q^{\alpha})\ (\overline{b}^{\beta} R q^{\beta})$$
$$\mathcal{O}_5 = (\overline{b}^{\alpha} L q^{\beta})\ (\overline{b}^{\beta} R q^{\alpha})$$

- investigating: 15 redundant operators (Fierz and parity)

Mixing operators: current status

- SM mixing parameters known to ~(3-4)%
  - 2+1 sea quarks

    [Gamiz *et al*., HPQCD, PRD80, 014503 (2009)]
    [Evans *et al*., FNAL Lattice, PoS (LAT2009) 245]
    [Witzel *et al*., RBC/UKQCD, PoS (LAT2009) 243]

- BSM mixing parameters known to ~10%
  - 2 sea quarks (4 of 5 ME's; static limit of HQET)

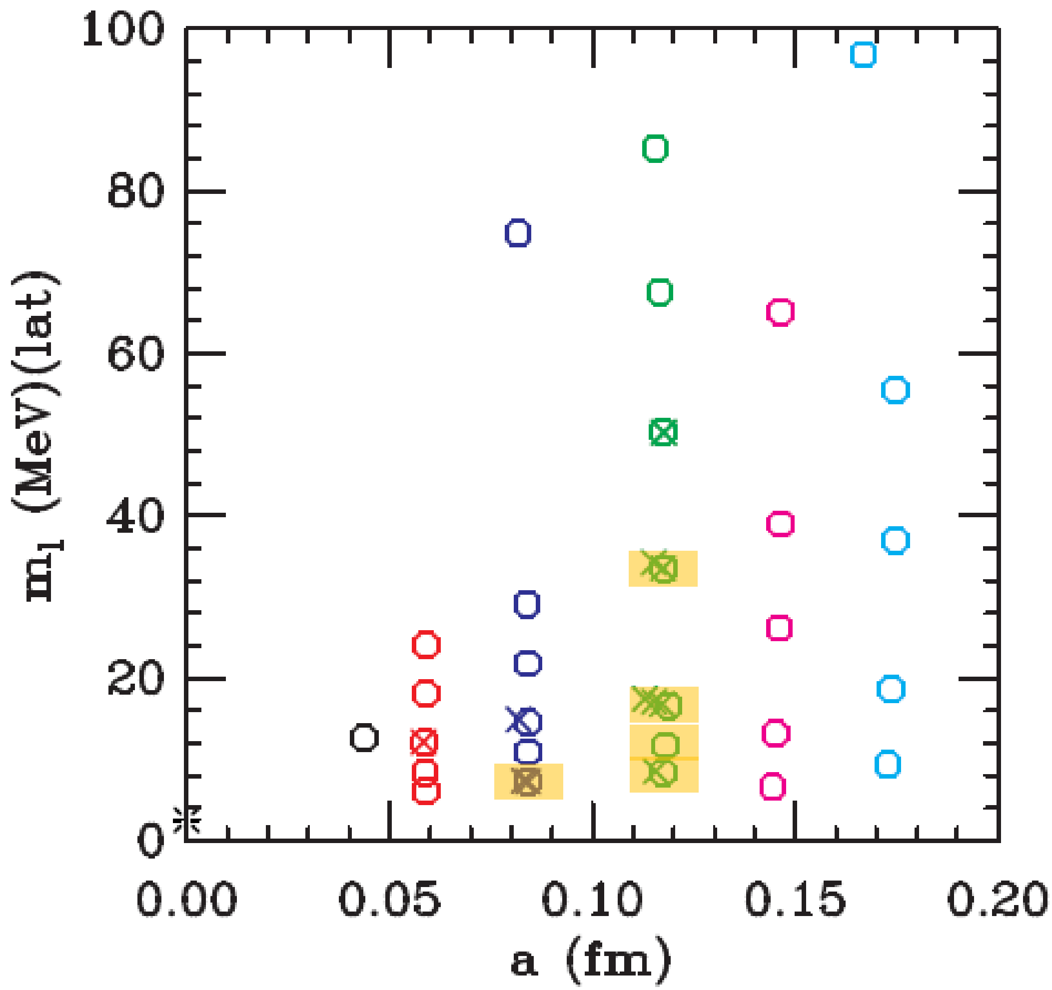
    [Gimenez and Reyes, arXiv:0010048v3, hep-lat (2000)]

  - quenched

    [Becirevic *et al*., arXiv:0110091v1, hep-lat (2001)]

Generating data: gauge config's

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



MILC

- 2+1 asqtad sea quarks

  $\mathcal{O}\left(a^4, \alpha_s a^2\right)$

- improved gluons

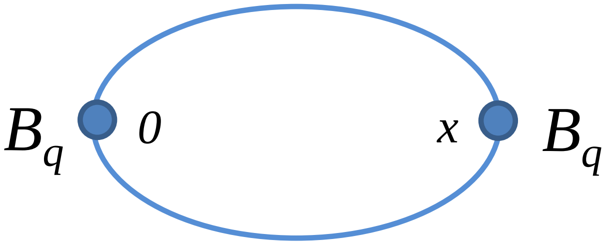
  $\mathcal{O}\left(a^4, \alpha_s a^2\right)$

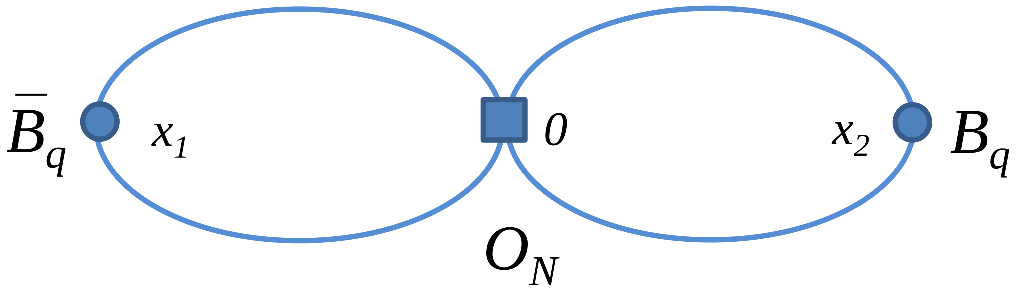
- 700-2300 cfg's (4 src's)

analyzed for this work

Generating data: correlators

- 2 & 3pt correlators

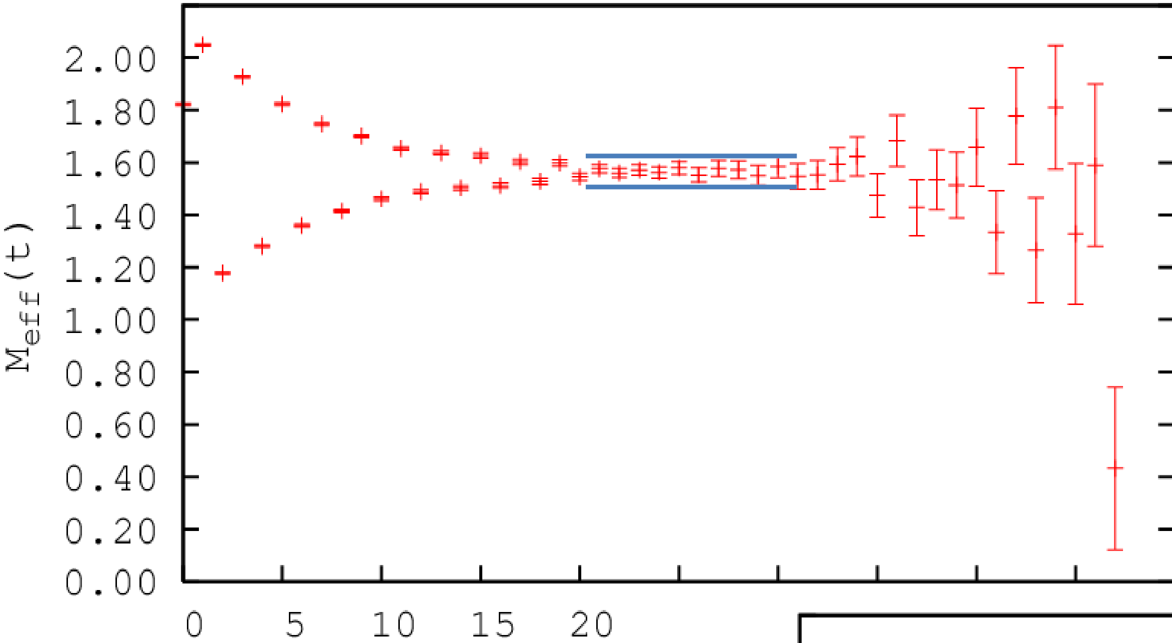




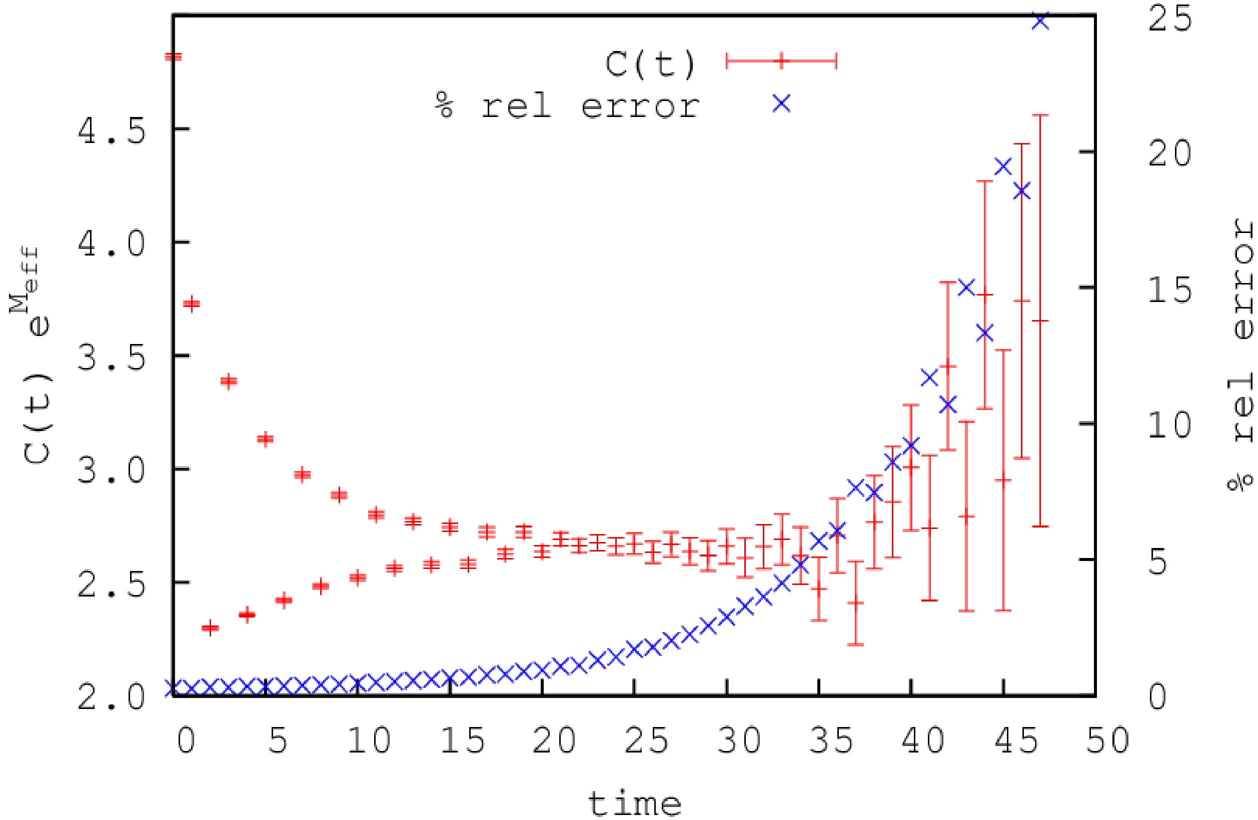
- built from lattice propagators

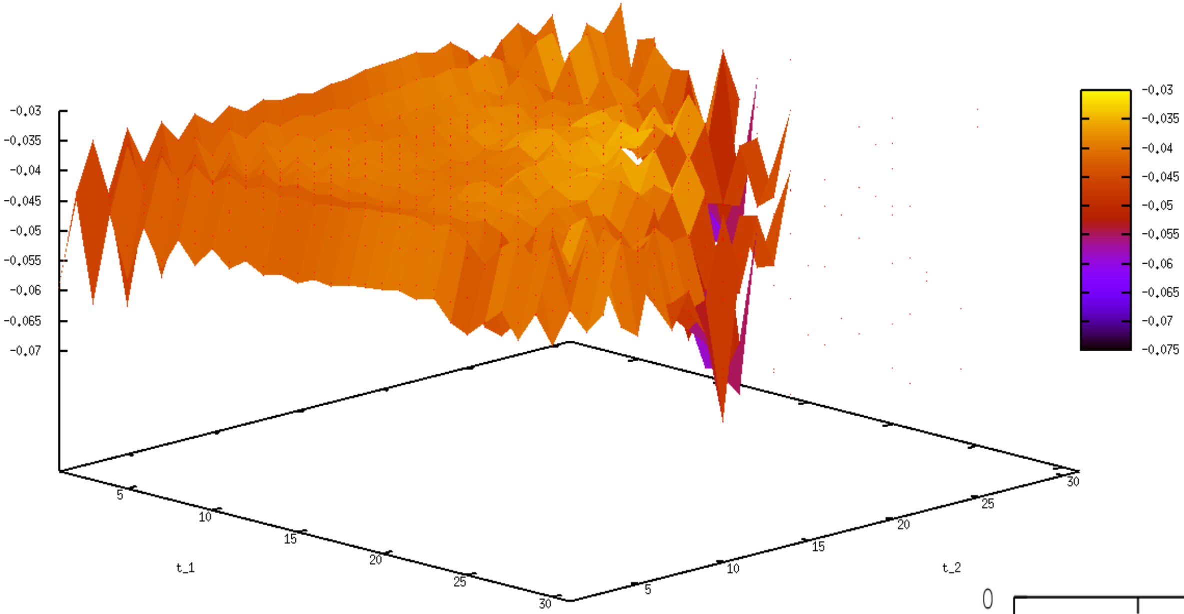
$$\langle (B_q^0)_{\vec{x},t} | (B_q^0)_{\vec{0},0} \rangle = \langle T\{ (\overline{q}\gamma_5 b)_{\vec{x},t} (q\gamma_5 \overline{b})_{\vec{0},0} \} \rangle$$

$$\langle (B_q^0)_{\vec{x}_2,t_2} | (\mathcal{O}_N)_{\vec{0},0} | (\overline{B_q^0})_{\vec{x}_1,t_1} \rangle = \langle T\{ (\overline{q}\gamma_5 b)_{\vec{x}_2,t_2} (\mathcal{O}_N)_{\vec{0},0} (\overline{q}\gamma_5 b)_{\vec{x}_1,t_1} \} \rangle$$



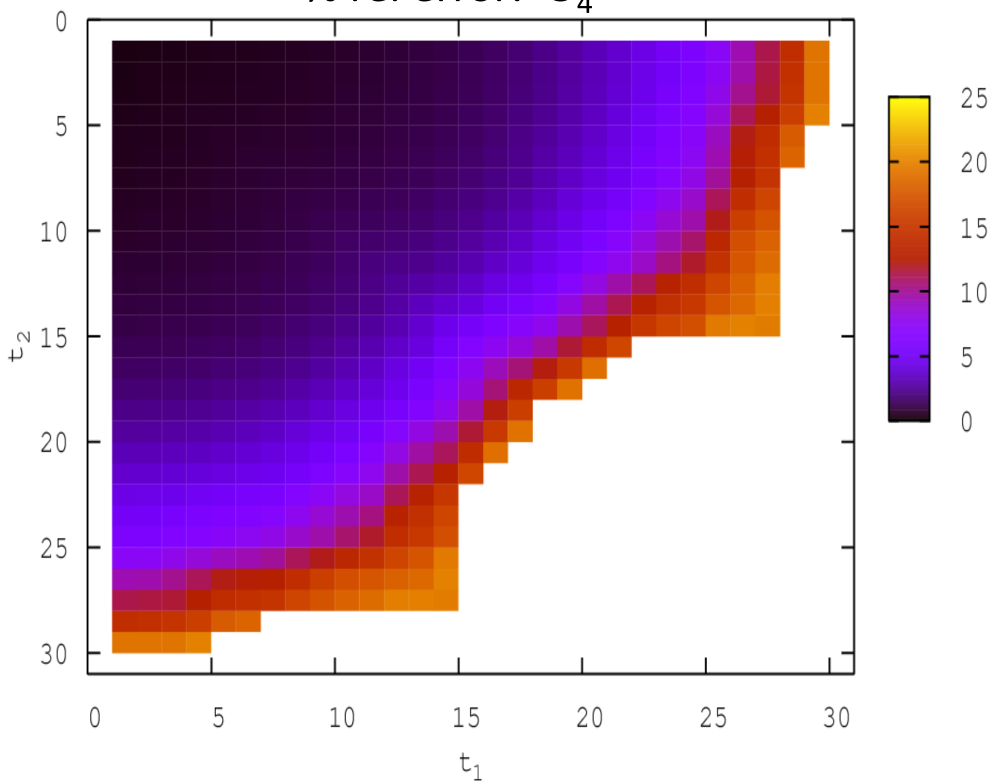
a=0.09fm
40^3x96
β=7.08
m_l(sea)=0.0031
m_s(sea)=0.031
κ_b=0.0976
m_l(val)=0.0261
PS 2pt correlator





scaled 3pt correlator: O_4

% rel error: O_4



$a=0.09$fm

40^3x96

$\beta=7.08$

$m_l(sea)=0.0031$

$m_s(sea)=0.031$

$\kappa_b=0.0976$

$m_l(val)=0.0261$

$O_4=q^\alpha L b^\alpha \, q^\beta R b^\beta$

Fitting

- Meson rest frame ($\sum_{\vec{x}_1,\vec{x}_2}$)

$$\langle (B_q^0)_t | (B_q^0)_0 \rangle = \sum_n \frac{|Z_n|^2}{2E_n} (-)^{n(t+1)} \left(e^{-E_n t} + e^{-E_n (T-t)} \right)$$

$$\langle (B_q^0)_{t_2} | (\mathcal{O}_N)_0 | (\overline{B_q^0})_{t_1} \rangle =$$

$$\sum_{n,m} \frac{\langle n | \mathcal{O}_N | m \rangle Z_n^\dagger Z_m}{4E_n E_m} (-)^{n(t_1+1)+m(t_2+1)} \left(e^{-E_n |t_1|} + e^{-E_n (T-|t_1|)} \right) \left(e^{-E_m t_2} + e^{-E_m (T-t_2)} \right)$$

- Fit 2 & 3pt correlators to extract ME
  - simultaneous
  - Bayesian
  - G. P. Lepage's Python based fitter (*lsqfit*)

Fitting

- Meson rest frame ($\sum_{\vec{x}_1,\vec{x}_2}$)

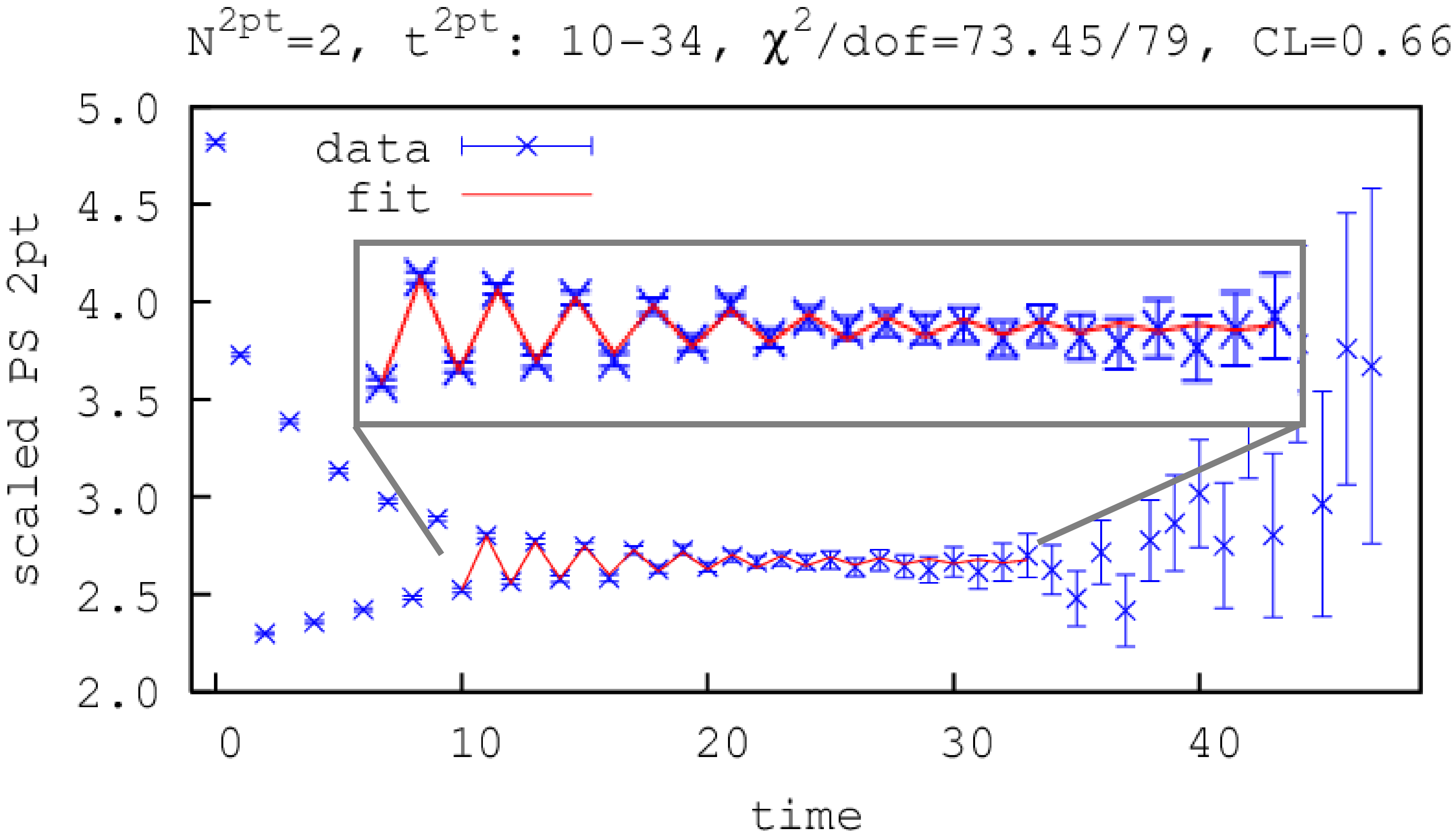
$$\langle (B_q^0)_t | (B_q^0)_0 \rangle = \sum_n \frac{|Z_n|^2}{2E_n} (-)^{n(t+1)} \left(e^{-E_n t} + e^{-E_n (T-t)} \right)$$

$$\langle (B_q^0)_{t_2} | (\mathcal{O}_N)_0 | (\overline{B_q^0})_{t_1} \rangle =$$

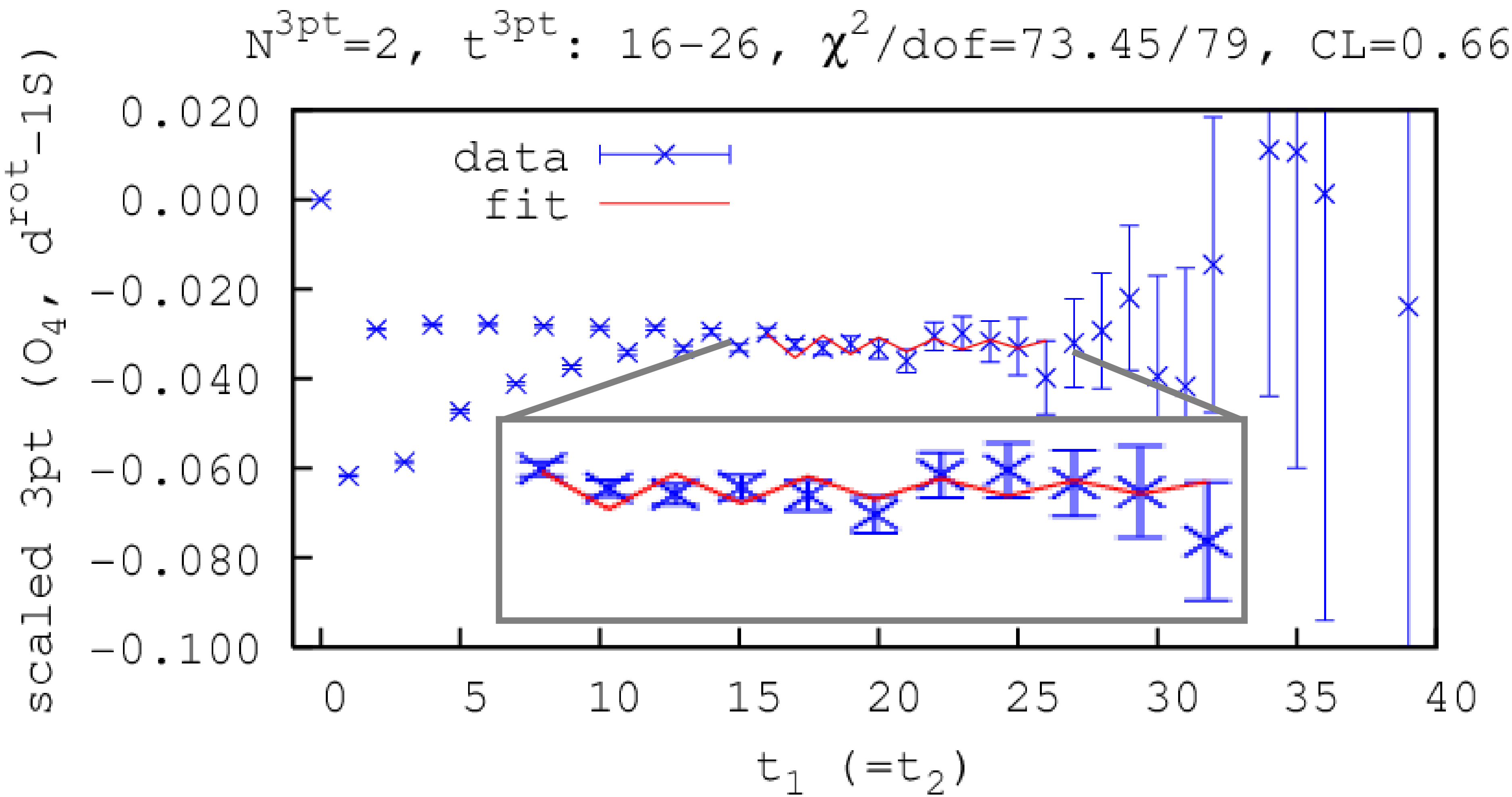
$$\sum_{n,m} \frac{\boxed{\langle n | \mathcal{O}_N | m \rangle} Z_n^\dagger Z_m}{4E_n E_m} (-)^{n(t_1+1)+m(t_2+1)} \left(e^{-E_n |t_1|} + e^{-E_n (T-|t_1|)} \right) \left(e^{-E_m t_2} + e^{-E_m (T-t_2)} \right)$$

- Fit 2 & 3pt correlators to extract ME
  - simultaneous
  - Bayesian
  - G. P. Lepage’s Python based fitter (*lsqfit*)

Simultaneous fit: 2pt correlator



Simultaneous fit: 3pt correlator



Initial results: $\beta_s^N = f_{B_s} (M_{B_s} B_{B_s}^N)^{1/2}$

- Extract "reduced matrix element", β_N

$$\langle B_q^0 | \mathcal{O}_N | \overline{B_q^0} \rangle \propto M \ \beta_N^2 \propto f^2 M^2 B_N$$

- Stat error decrease: [Evans, PhD thesis, UIUC, 2008]

<u>expected</u>

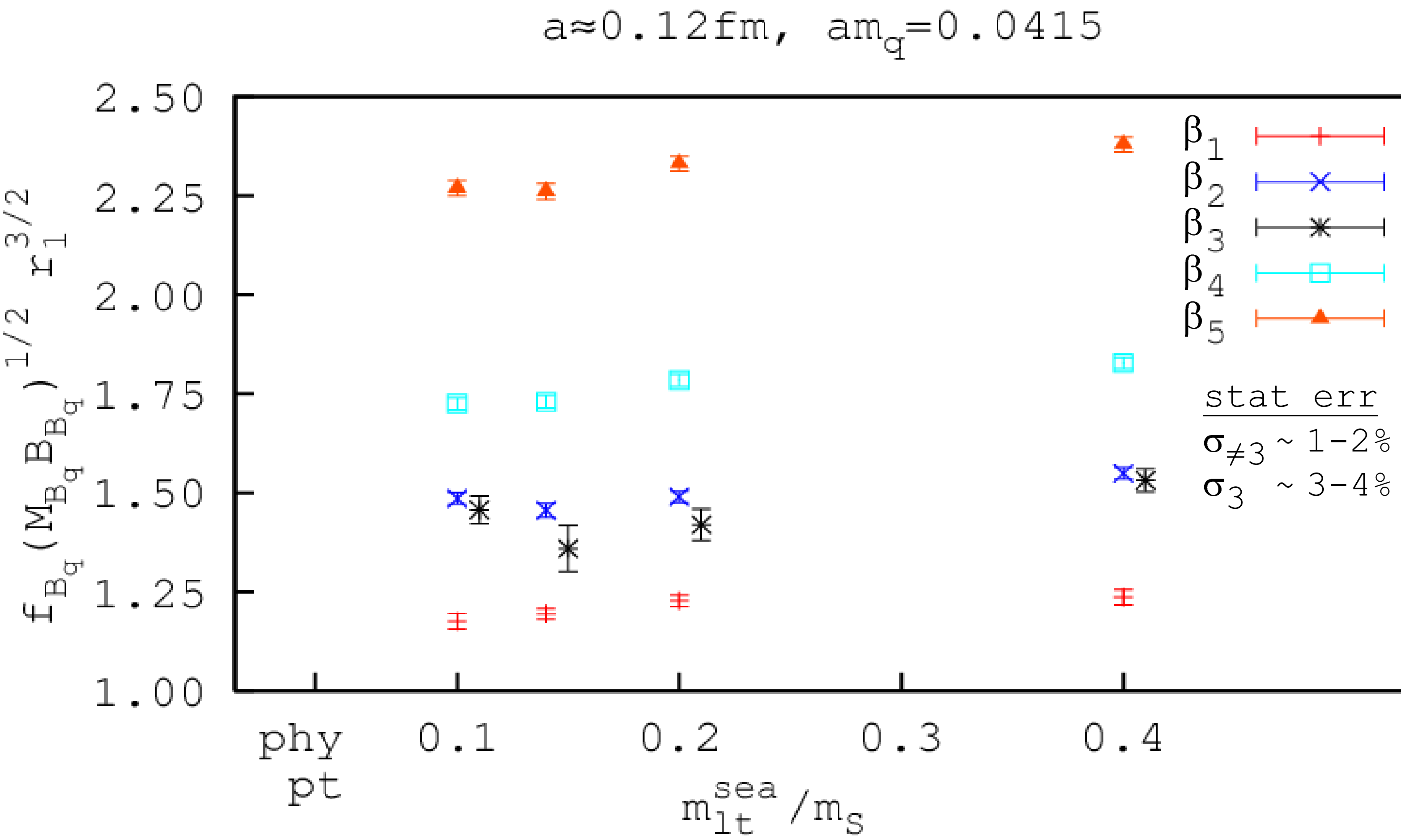
$$\sqrt{N_{\rm old}^{\rm cfg} / N_{\rm new}^{\rm cfg}} \sim 50 - 60\%$$

<u>observed</u>

β_1: 65%

β_2: 53%

Preliminary: $\beta_N = f_{B_s} (M_{B_s} B^N_{B_s})^{1/2}$



Outlook

- continue fitting
  - 0.09fm, 0.06fm, 0.045fm lattice spacings
  - range of light m_q's ($B_s^0 \longrightarrow B^0$)
  - charm heavy quark (D^0 mixing)

- implement chiPT
  - continuum [Detmold and Lin, arXiv:0612028, hep-lat, 2006]
  - staggered [Laiho and Van de Water, collaboration note, 2007]

- perturbative matching
  - hopefully similar to SM operators [Kronfeld and Gamiz]

Outlook

- continue fitting
  - 0.09fm, 0.06fm, 0.045fm lattice spacings
  - range of light m_q's $(B_s^0 \longrightarrow B^0)$
  - charm heavy quark (D^0 mixing)

- implement chiPT
  - continuum [Detmold and Lin, arXiv:0612028, hep-lat, 2006]
  - staggered [Laiho and Van de Water, collaboration note, 2007]

- perturbative matching
  - hopefully similar to SM operators [Kronfeld and Gamiz]

Outlook

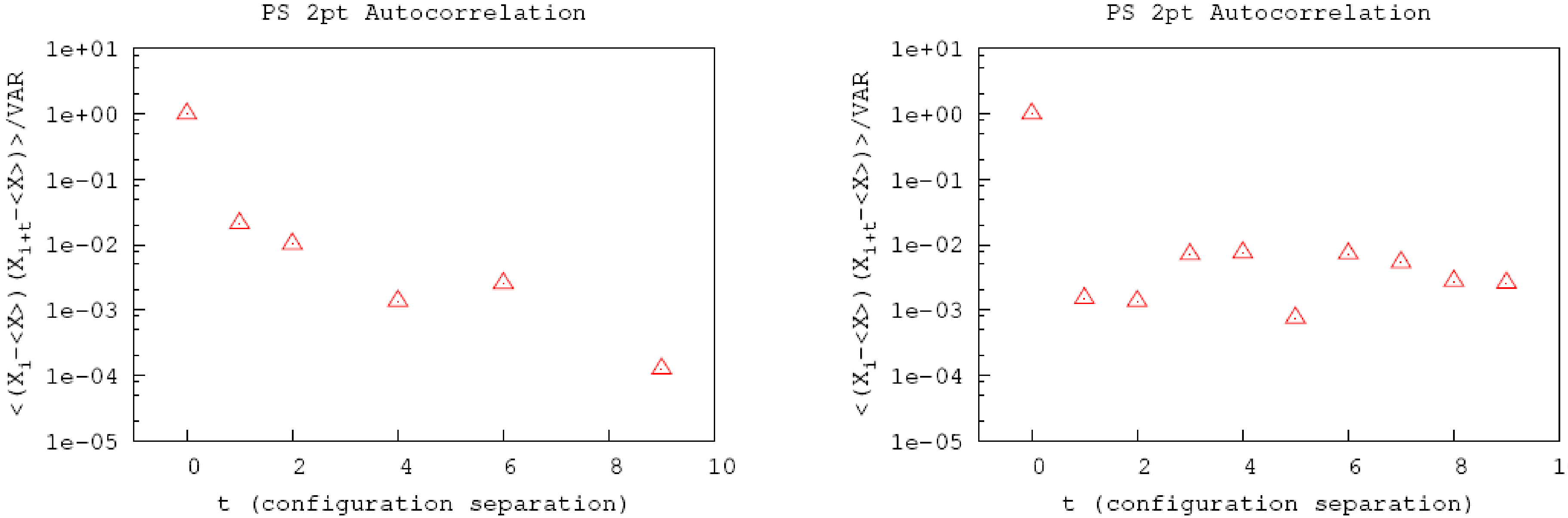
- continue fitting
  - 0.09fm, 0.06fm, 0.045fm lattice spacings
  - range of light m_q's ($B^0_s \longrightarrow B^0$)
  - charm heavy quark (D^0 mixing)

- implement chiPT
  - continuum [Detmold and Lin, arXiv:0612028, hep-lat, 2006]
  - staggered [Laiho and Van de Water, collaboration note, 2007]

- perturbative matching
  - hopefully similar to SM operators [Kronfeld and Gamiz]

LA FINE

$$\mathcal{A}(t) = (N\sigma^2)^{-1}\sum(x_{i+t} - \overline{x})(x_i - \overline{x})$$

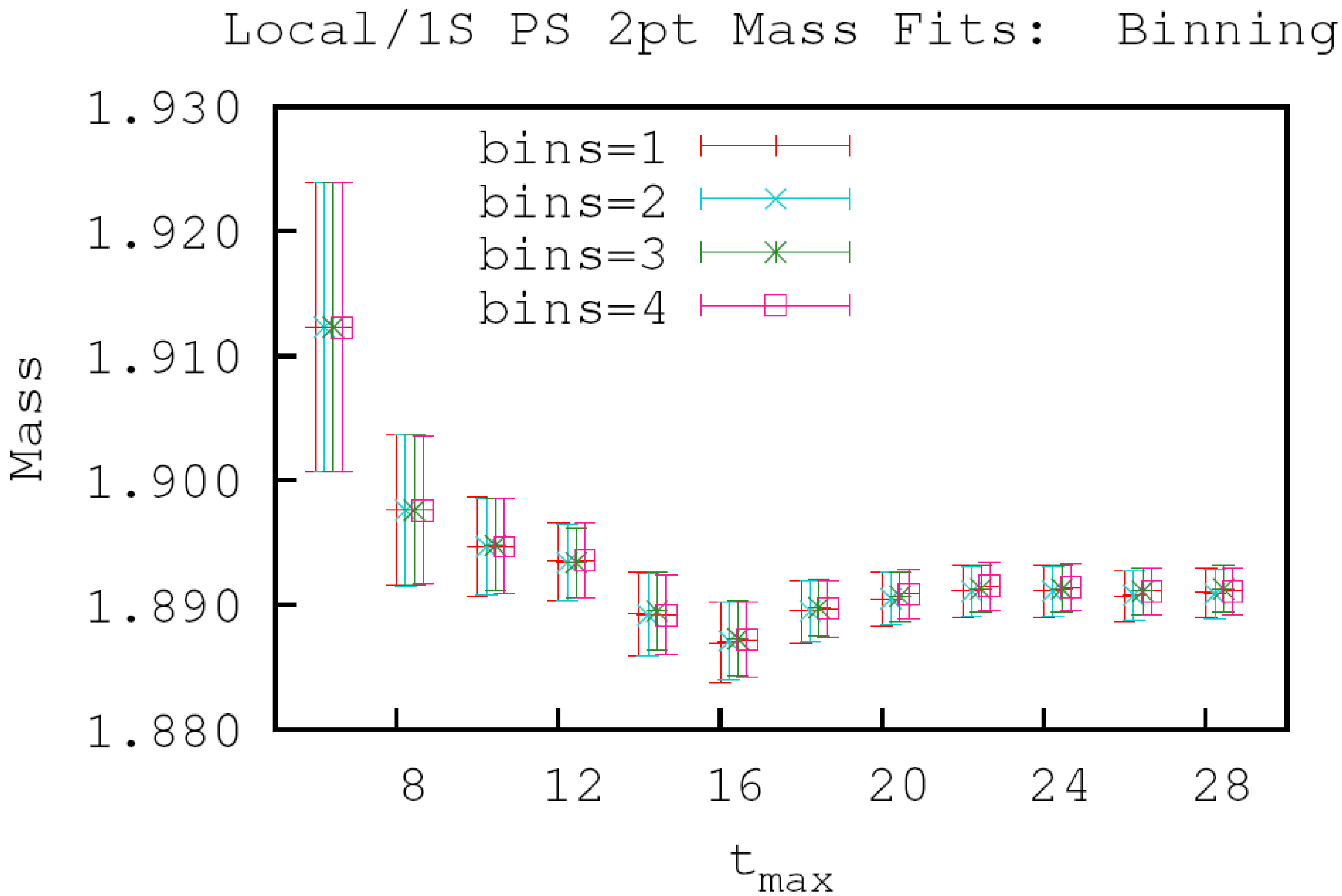


(a) Prior ensemble: No spatially randomized sources. (b) New ensemble: Spatially randomized sources.

Figure 6: Ensemble: $a = 0.12$fm, $20^3 \times 64$, $m_l/m_s = 0.12$. Missing points indicate $\mathcal{A}(t) < 0$.

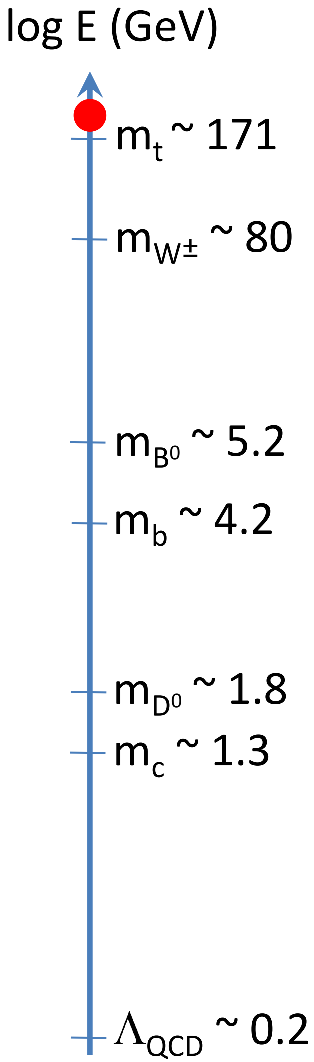
$$\tau_{exp} = -1/\text{slope}$$

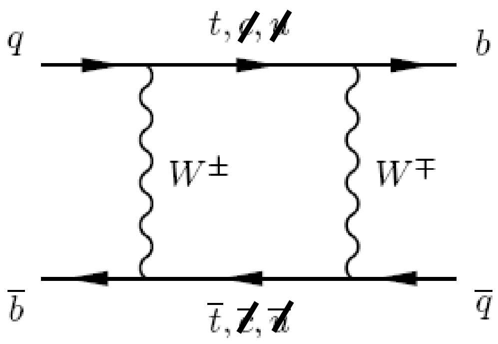
$\tau_{exp}^{old} \approx 0.44$ $\tau_{exp}^{new} \approx 0.15$

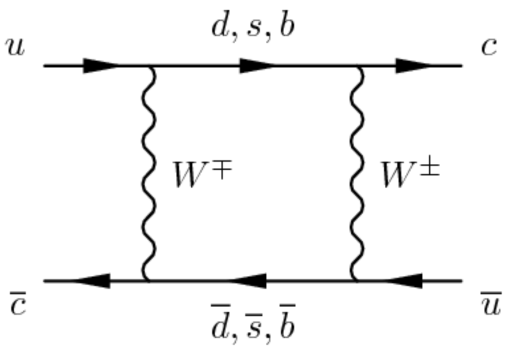


For Bs meson 2pt correlator on coarse ml=0.14ms ensemble, binning is unnecessary.

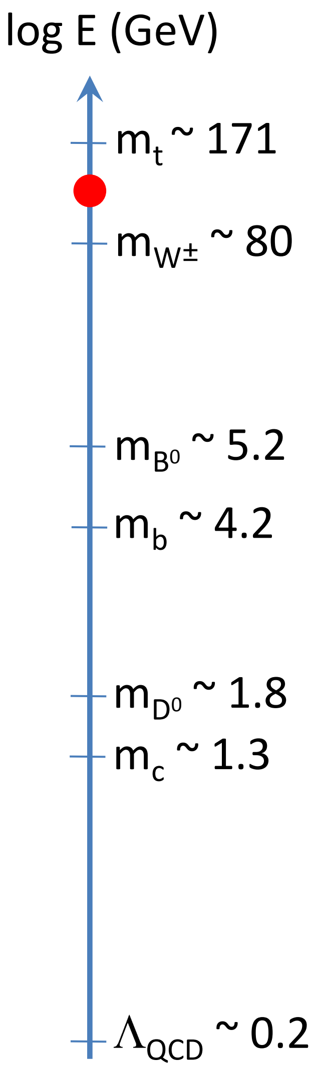
Neutral meson mixing: an effective 4q interaction

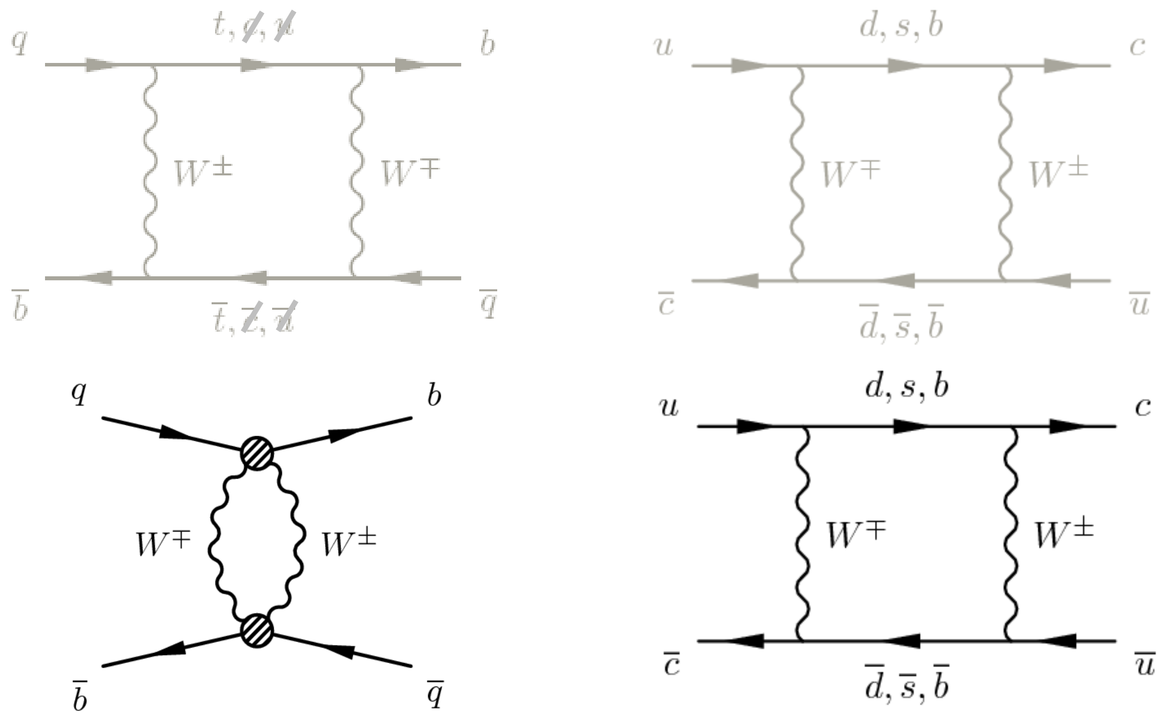




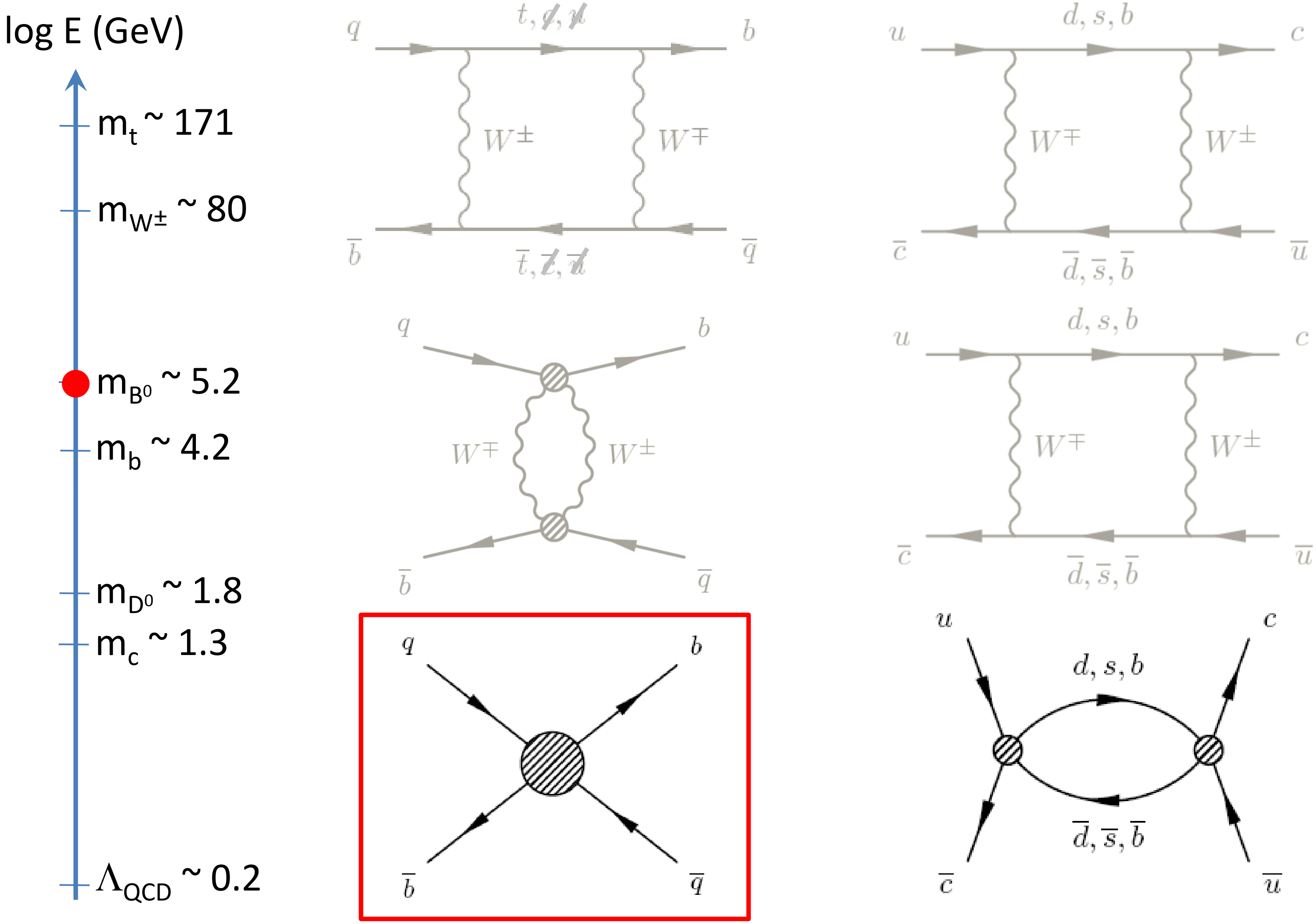


Neutral meson mixing: an effective 4q interaction

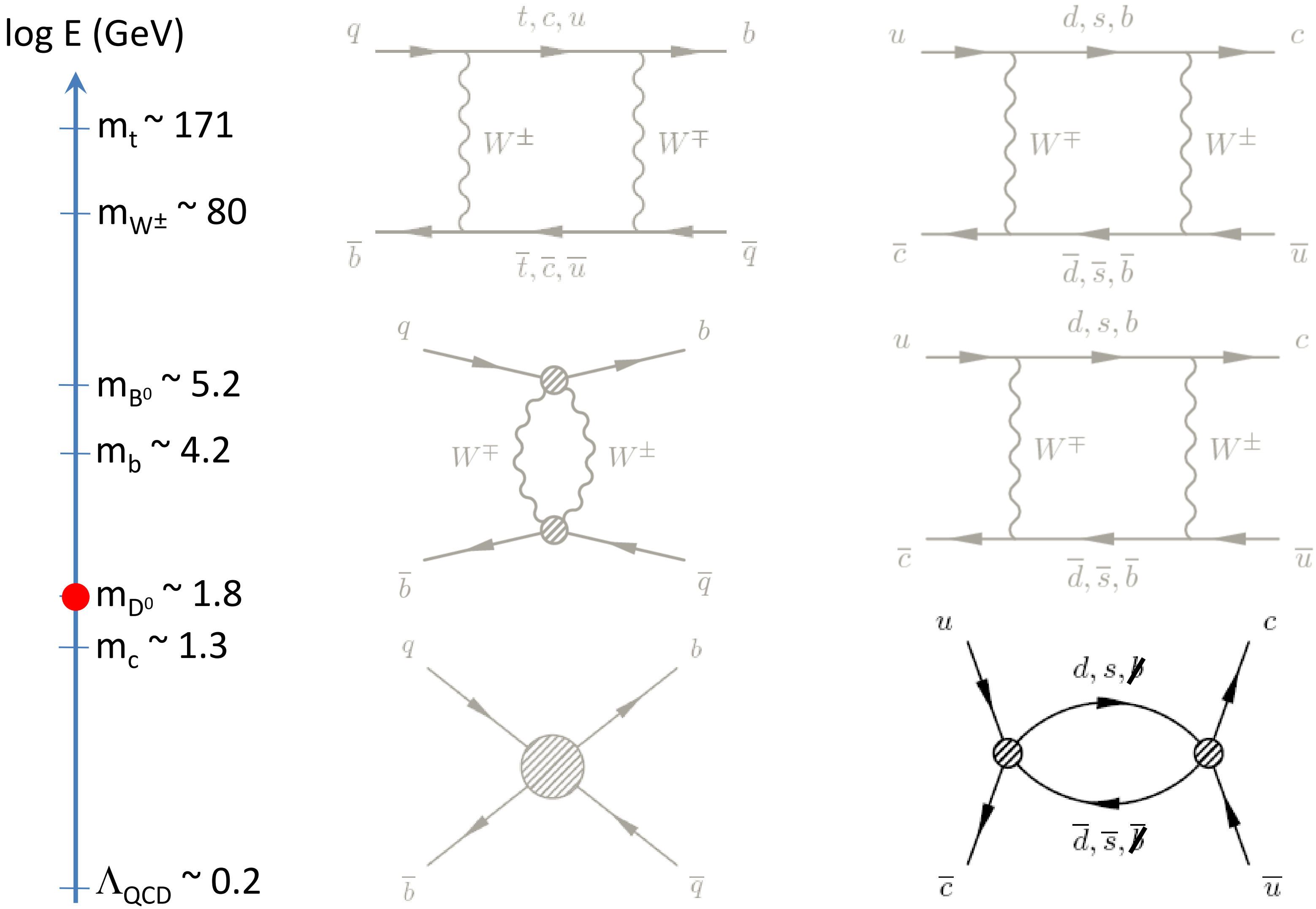




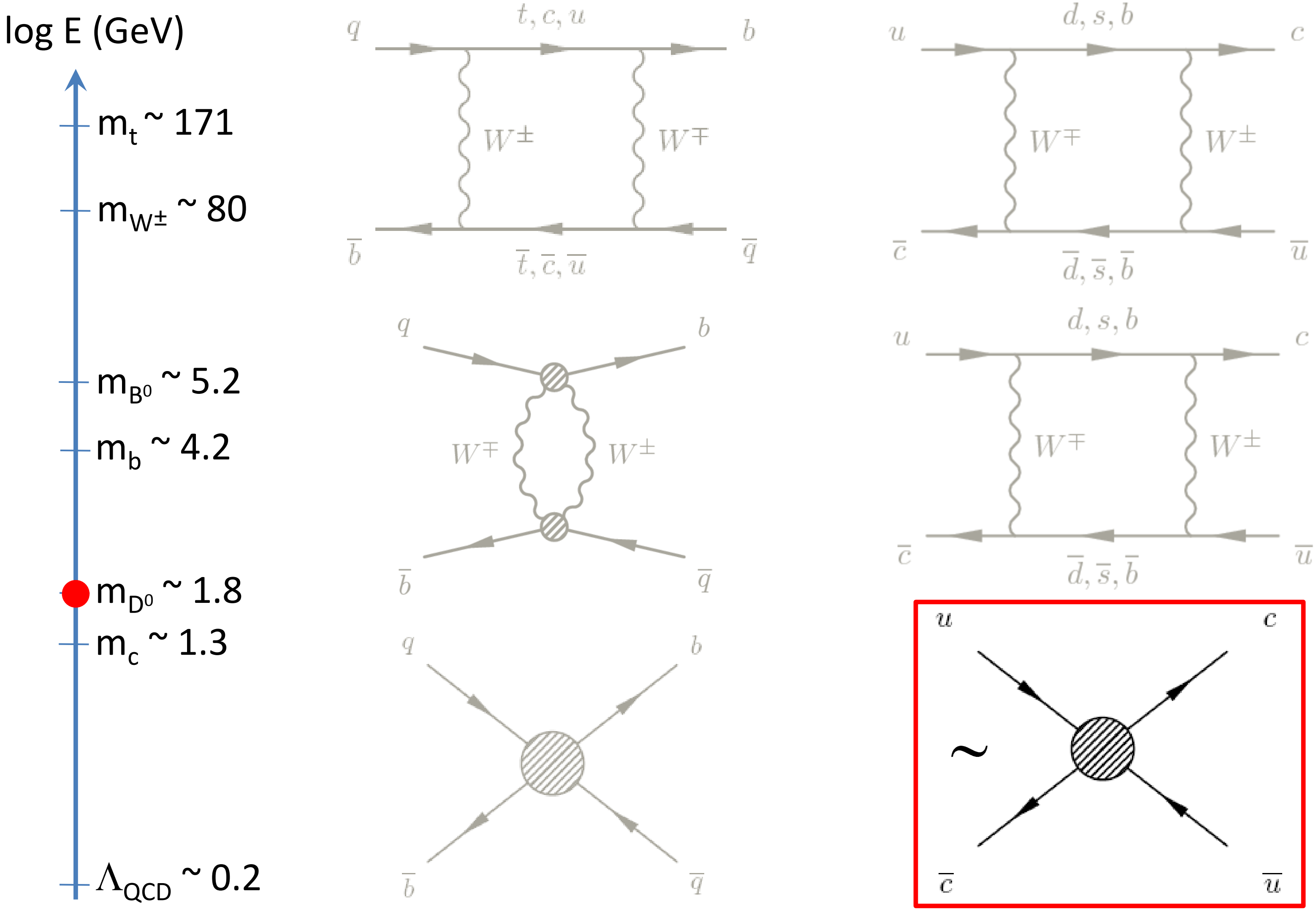
Neutral meson mixing: an effective 4q interaction



Neutral meson mixing: an effective 4q interaction



Neutral meson mixing: an effective 4q interaction



The calculation: mixing operators

- For $\langle X^0 | \mathcal{O}_i^{\Delta Q=2} | \overline{X^0} \rangle$, need all $\mathcal{O}_i^{\Delta Q=2}$ generalized BSM (Lorentz inv, color singlets)
  - examples

$$\begin{aligned} \mathcal{O}_1 &= \overline{Q}_i^{\alpha} \gamma_{\mu,ij} L_{jk} q_k^{\alpha} \, \overline{Q}_r^{\beta} \gamma_{\mu,rs} L_{st} q_t^{\beta} \\ \mathcal{O}_3 &= \overline{Q}_i^{\alpha} L_{ij} q_j^{\beta} \, \overline{Q}_r^{\beta} L_{rs} q_s^{\alpha} \end{aligned}$$

  - notation (Takahashi)

$$\overline{Q}_i^{\alpha} \gamma_{\mu,ij} L_{jk} q_k^{\alpha} \, \overline{Q}_r^{\beta} \gamma_{\mu,rs} L_{st} q_t^{\beta} \longrightarrow (\gamma_\mu L)[\gamma_\mu L]$$

$$\overline{Q}_i^{\alpha} L_{ij} q_j^{\beta} \, \overline{Q}_r^{\beta} L_{rs} q_s^{\alpha} \longrightarrow (L][L)$$

The calculation: mixing operators

- Single bilinear spin structures: $\{L, R, \gamma_\mu L, \gamma_\mu R, \sigma_{\mu\nu}\}$

- 10 Lorentz inv pairings

$$\{L\otimes L,\ L\otimes R,\ R\otimes L,\ R\otimes R,\ \gamma_\mu L\otimes\gamma_\mu L,\ \gamma_\mu L\otimes\gamma_\mu R,\ \gamma_\mu R\otimes\gamma_\mu L,\ \gamma_\mu R\otimes\gamma_\mu R,\ \sigma_{\mu\nu}\otimes\sigma_{\mu\nu},\ \epsilon_{\mu\nu\rho\tau}\,\sigma_{\mu\nu}\otimes\sigma_{\rho\tau}\}$$

- Gives 20 Lorentz inv, color singlet pairings

$$\mathcal{O}_1 = (\gamma_\mu L)[\gamma_\mu L] \qquad \mathcal{O}_6 = (\gamma_\mu L)[\gamma_\mu R] \qquad \mathcal{O}_{11} = (\gamma_\mu R][\gamma_\mu R) \qquad \mathcal{O}_{16} = (\gamma_\mu R][\gamma_\mu L)$$

$$\mathcal{O}_2 = (L)[L] \qquad \mathcal{O}_7 = (\gamma_\mu L][\gamma_\mu R) \qquad \mathcal{O}_{12} = (\gamma_\mu L][\gamma_\mu L) \qquad \mathcal{O}_{17} = (R)[L]$$

$$\mathcal{O}_3 = (L][L) \qquad \mathcal{O}_8 = (R)[R] \qquad \mathcal{O}_{13} = (\sigma_{\mu\nu})[\sigma_{\mu\nu}] \qquad \mathcal{O}_{18} = (R][L)$$

$$\mathcal{O}_4 = (L)[R] \qquad \mathcal{O}_9 = (R][R) \qquad \mathcal{O}_{14} = (\sigma_{\mu\nu}][\sigma_{\mu\nu}) \qquad \mathcal{O}_{19} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu})[\sigma_{\rho\tau}]$$

$$\mathcal{O}_5 = (L][R) \qquad \mathcal{O}_{10} = (\gamma_\mu R)[\gamma_\mu R] \qquad \mathcal{O}_{15} = (\gamma_\mu R)[\gamma_\mu L] \qquad \mathcal{O}_{20} = \epsilon_{\mu\nu\rho\tau}(\sigma_{\mu\nu}][\sigma_{\rho\tau})$$

Chiral Fierz transformations

$$(\Gamma_A)[\Gamma_B] = \sum_{C,D} \frac{1}{4} Tr[\Gamma_A \tilde{\Gamma}_C \Gamma_B \tilde{\Gamma}_D](\Gamma_D][\Gamma_C)$$

$$\mathcal{O}_1 = -\mathcal{O}_{12}$$

$$8\mathcal{O}_2 = 4\mathcal{O}_3 + 2\mathcal{O}_{14} - i\mathcal{O}_{20}$$

$$8\mathcal{O}_3 = 4\mathcal{O}_2 + 2\mathcal{O}_{13} - i\mathcal{O}_{19}$$

$$2\mathcal{O}_4 = \mathcal{O}_{16}$$

$$2\mathcal{O}_5 = \mathcal{O}_{15}$$

$$\mathcal{O}_6 = 2\mathcal{O}_{18}$$

$$\mathcal{O}_7 = 2\mathcal{O}_{17}$$

$$8\mathcal{O}_8 = 4\mathcal{O}_9 + 2\mathcal{O}_{14} + i\mathcal{O}_{20}$$

$$8\mathcal{O}_9 = 4\mathcal{O}_8 + 2\mathcal{O}_{13} + i\mathcal{O}_{19}$$

$$\mathcal{O}_{10} = -\mathcal{O}_{11}$$

$$\mathcal{O}_{13} = 6\left(\mathcal{O}_3 + \mathcal{O}_9\right) - 2\mathcal{O}_{14}$$

$$\mathcal{O}_{14} = 6\left(\mathcal{O}_2 + \mathcal{O}_8\right) - 2\mathcal{O}_{13}$$

$$\mathcal{O}_{19} = 12i\left(\mathcal{O}_3 - \mathcal{O}_9\right) - 2\mathcal{O}_{20}$$

$$\mathcal{O}_{20} = 12i\left(\mathcal{O}_2 - \mathcal{O}_8\right) - 2\mathcal{O}_{19}$$

The calculation: generating data

Fermion doubling: discrete Dirac eqn $\rightarrow$ 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: generating data, gauge configurations

a (fm)	$(L/a)^3 \times (T/a)$	m_l/m_s	# ens's	# config's
0.12	$20^3 \times 64$	0.12 – 1	11	8710
0.12	$24^3 \times 64$	0.1	1	1802
0.12	$28^3 \times 64$	0.2	1	275
0.12	$32^3 \times 64$	1	1	701
0.09	$28^3 \times 96$	0.2 – 1	6	6565
0.09	$32^3 \times 96$	0.15	1	540
0.09	$40^3 \times 96$	0.1 – 1	3	2097
0.09	$64^3 \times 96$	0.05	1	530
0.06	$48^3 \times 144$	0.2 – 0.4	3	2013
0.06	$56^3 \times 144$	0.14	1	800
0.06	$64^3 \times 144$	0.1 – 0.33	2	1309
0.045	$64^3 \times 192$	0.2	1	861

Rooted, staggered, AsqTad

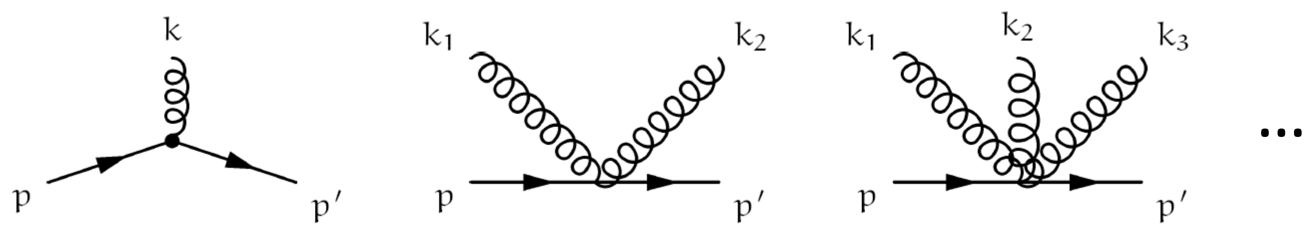
- sea quarks

$$\langle 0|\mathcal{O}|0\rangle = \frac{\int [dG_\mu]\ \mathcal{O}((\not{D}+m)^{-1}, G_\mu)\ e^{-S[G_\mu]+\ln[det(\not{D}+m)]}}{\int [dG_\mu]\ e^{-S[G_\mu]+\ln[det(\not{D}+m)]}}$$

  - AsqTad = a squared, tadpole improved
  - staggered (Kogut & Susskind) spin diagonalizes 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 α 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

$$\langle 0|\mathcal{O}|0\rangle = \frac{\int [dG_\mu]\ \mathcal{O}\left((\not{D}+m)^{-1}, G_\mu\right)\ e^{-S[G_\mu]+\ln\left[det(\not{D}+m)\right]}}{\int [dG_\mu]\ e^{-S[G_\mu]+\ln\left[det(\not{D}+m)\right]}}$$

  – naïve = retain locality in favor of ``doublers''
    - eases building interpolating operators

  – AsqTad = a squared, tadpole improved

The calculation: error budget

- Systematic errors
  - inputs (m_{quark}'s , a)
  - discretization (m_q , m_Q)
  - finite volume
  - chiral extrapolation
  - renormalization/matching (one-loop)

The calculation: extracting results, fitting the data

- Bayesian fitting

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

- Considerations
  - time range of data to fit
  - number of states to include in fit
  - choice of priors and widths

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

(**UT***fit* Collaboration)

M. Bona,[1] M. Ciuchini,[2] E. Franco,[3] V. Lubicz,[2,4] G. Martinelli,[3,5] F. Parodi,[6]
M. Pierini,[1,‖] C. Schiavi,[6] L. Silvestrini,[3] V. Sordini,[7] A. Stocchi,[7] and V. Vagnoni[8]

[1] *CERN, CH-1211 Geneva 23, Switzerland*
[2] *INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
[3] *INFN, Sezione di Roma, I-00185 Roma, Italy*
[4] *Dipartimento di Fisica, Università di Roma Tre, I-00146 Roma, Italy*
[5] *Dipartimento di Fisica, Università di Roma "La Sapienza", I-00185 Roma, Italy*
[6] *Dipartimento di Fisica, Università di Genova and INFN, I-16146 Genova, Italy*
[7] *Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex, France*
[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: $A^b_{\rm sl} = -0.00957 \pm 0.00251\ ({\rm stat}) \pm 0.00146\ ({\rm syst})$. 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