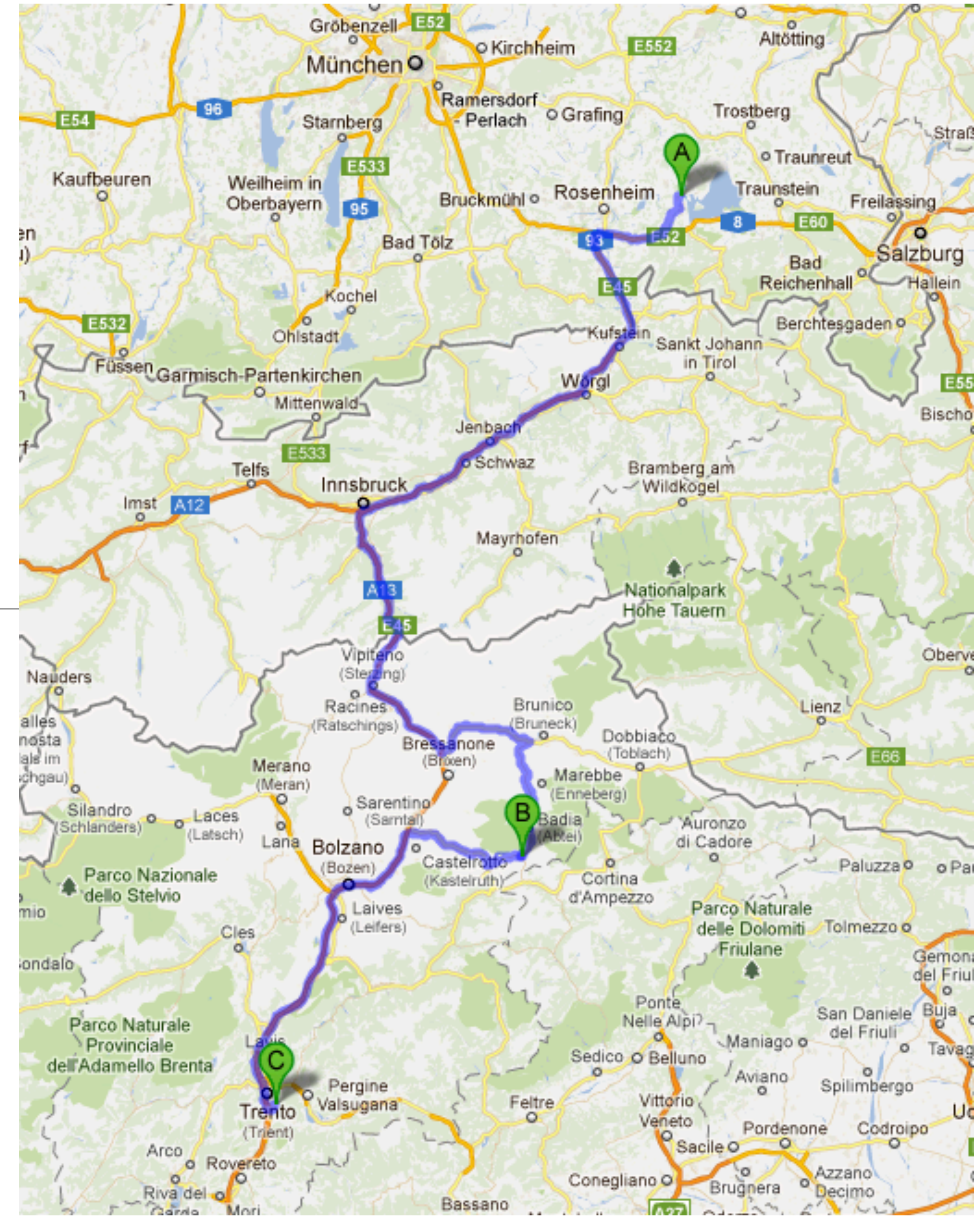
B Physics in the Standard Model

and Beyond

Andreas S. Kronfeld

Fermilab

(for the Fermilab Lattice and MILC Collaborations)



Beautiful Mesons and Baryons on the Lattice
ECT* Trento
2 April 2012

CKM Matrix

Cabibbo, *PRL* **10** (1963) 531; Kobayashi, Maskawa, *Prog. Theor. Phys.* **49** (1973) 652

- Unitary matrix connecting weak and mass eigenbases, $D_L = V_{\text{CKM}} D'_L$.
- Global symmetries reduce parameter # to 4:
  - $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, $\delta_{\text{KM}} = \arg V^*_{ub}$.
- Unitarity relations, $V^*_{ud}V_{ub} + V^*_{cd}V_{cb} + V^*_{td}V_{tb} = 0$, trace out triangles in the complex plane.
- Probed by many measurements + corresponding QCD.
- Hope to find FV and CPV BSM.

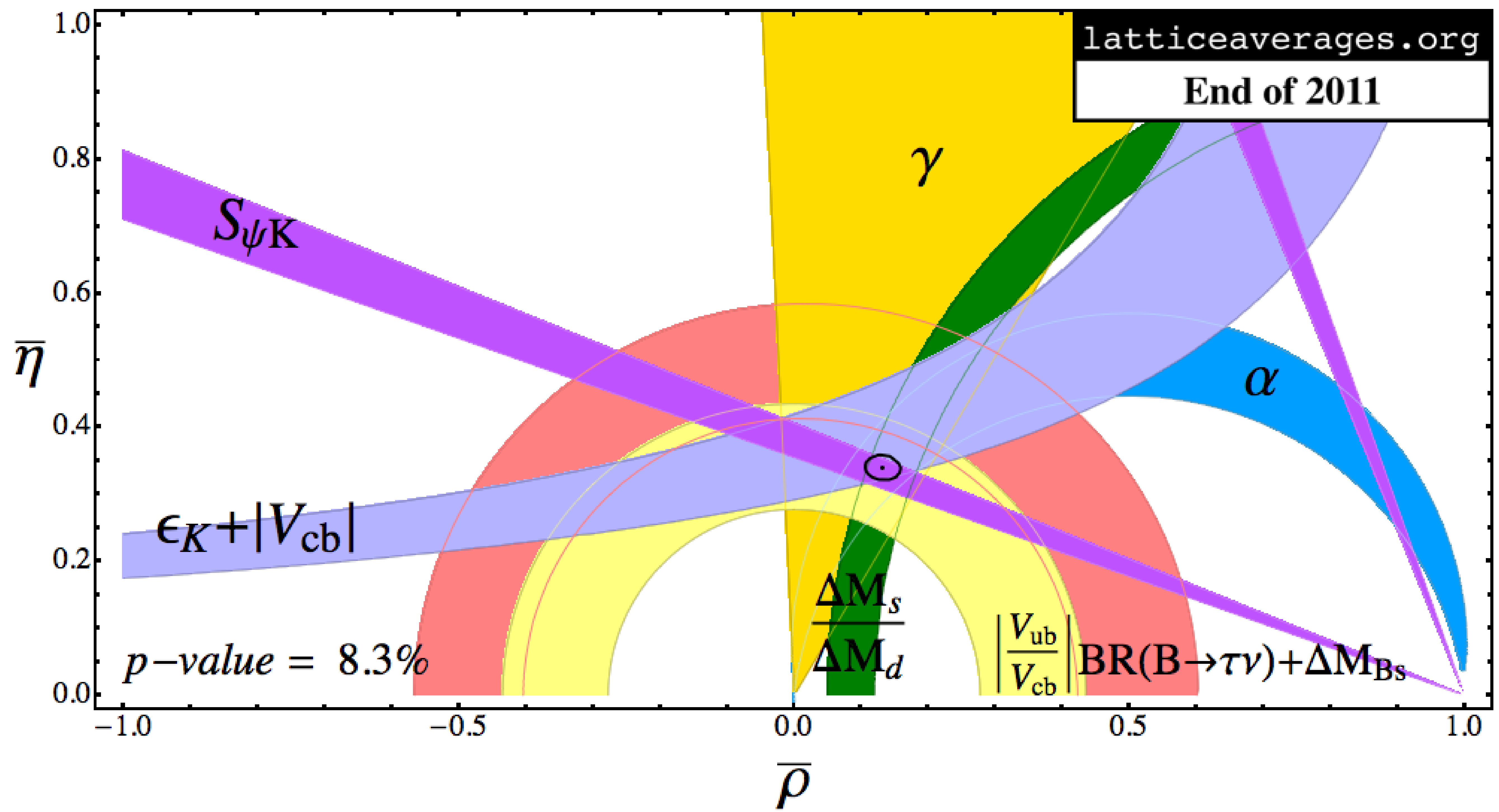
- Gold-plated lattice-QCD transitions:

$$V = \begin{pmatrix} \begin{array}{c}|V_{ud}|\\ \pi\to\ell\nu\\ n\to pe^-\bar\nu\end{array} & \begin{array}{c}|V_{us}|\\ K\to\ell\nu\\ K\to\pi\ell\nu\end{array} & \begin{array}{c}|V_{ub}|\\ B\to\tau\nu\\ B\to\pi\ell\nu\end{array} & \begin{array}{c}\arg V^*_{ub}\\ \langle K^0|\bar K^0\rangle\\ \end{array} \\ \begin{array}{c}|V_{cd}|\\ D\to\ell\nu\\ D\to\pi\ell\nu\end{array} & \begin{array}{c}|V_{cs}|\\ D_s\to\ell\nu\\ D\to K\ell\nu\end{array} & \begin{array}{c}|V_{cb}|\\ B\to D\ell\nu\\ B\to D^*\ell\nu\end{array} & \\ \begin{array}{c}|V_{td}|\\ \langle B_d|\bar B_d\rangle\end{array} & \begin{array}{c}|V_{ts}|\\ \langle B_s|\bar B_s\rangle\end{array} & \begin{array}{c}|V_{tb}|\\ (\text{no } t\bar q \text{ hadrons})\end{array} & \end{pmatrix}$$

involving tree and loop processes.

UT Triangle and Outline of the Talk

SM



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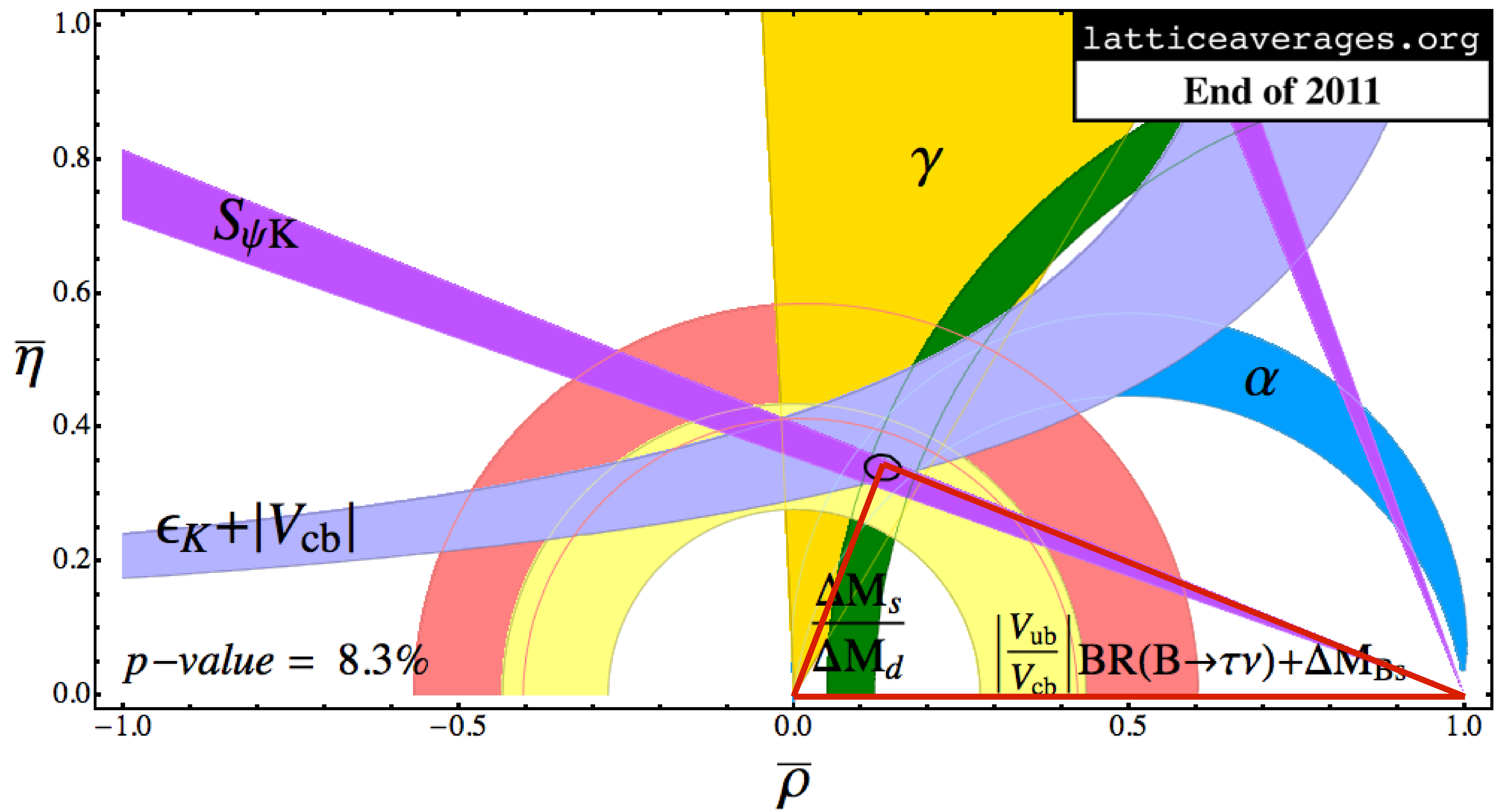

$|V_{cb}|$ normalizes triangle: $B \to D^{(*)} l \nu$

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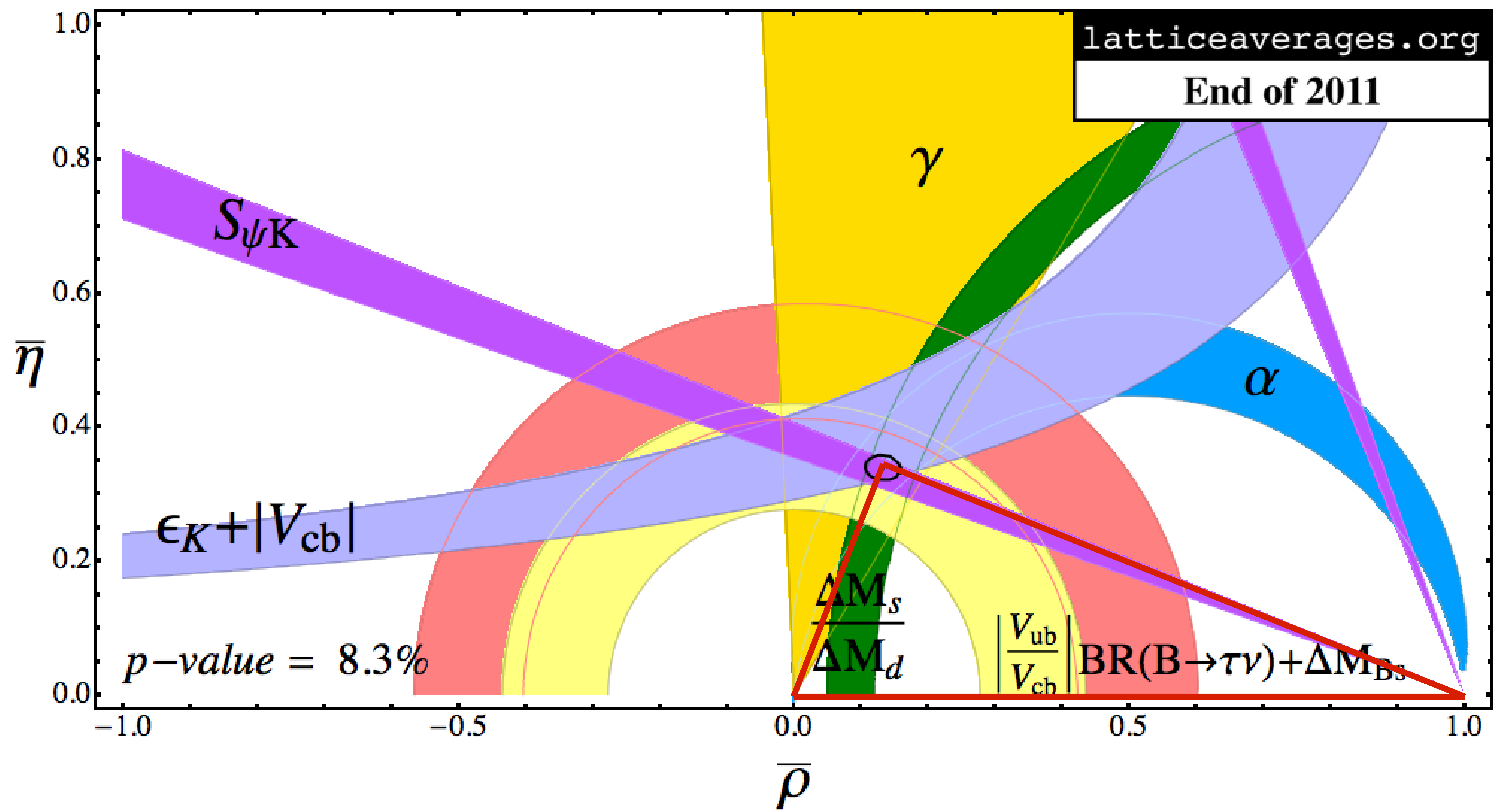

semileptonic
$|V_{ub}|$: $B \to \pi l \nu$

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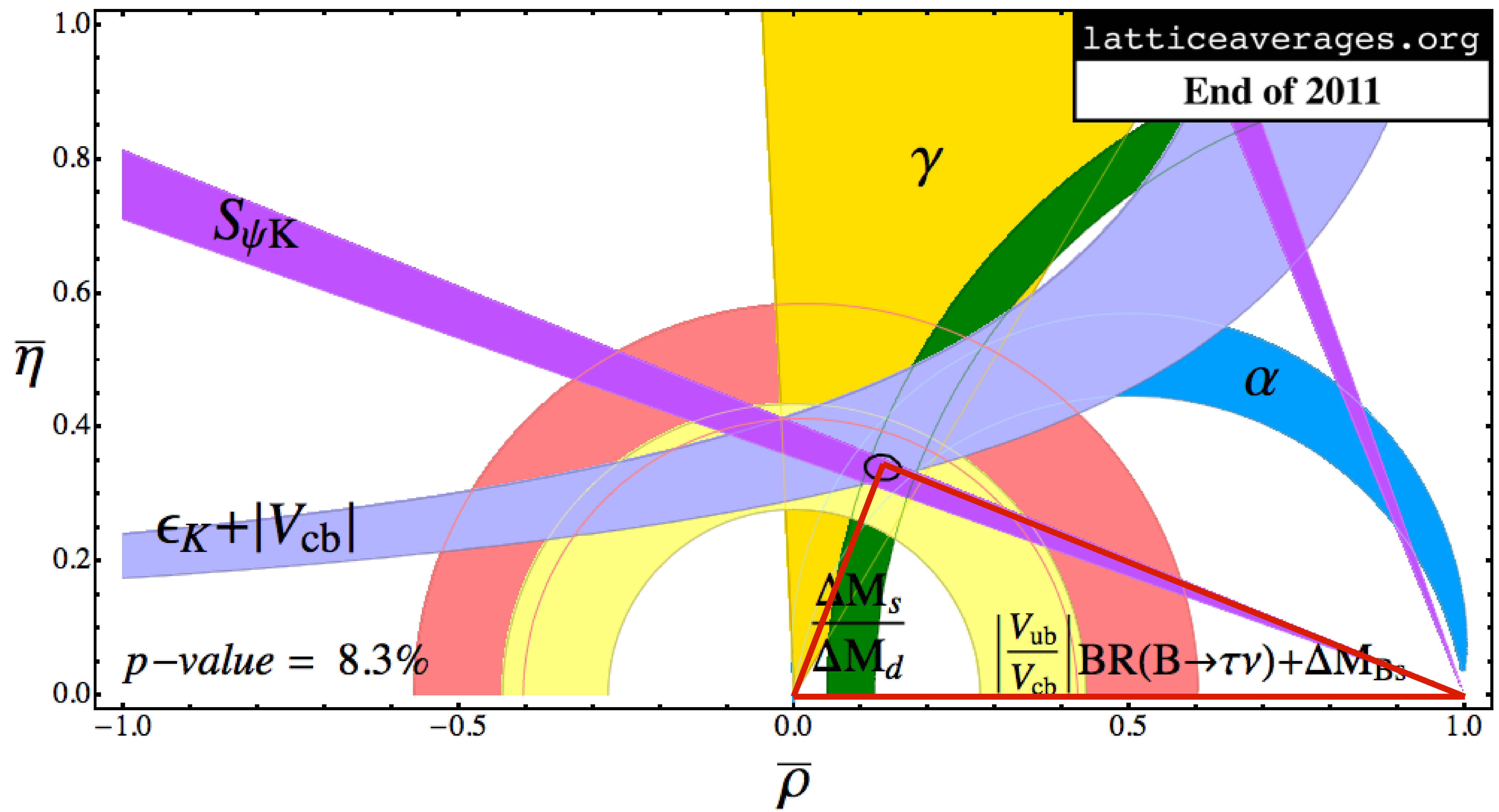

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semileptonic $|V_{ub}|$: $B \to \pi l \nu$

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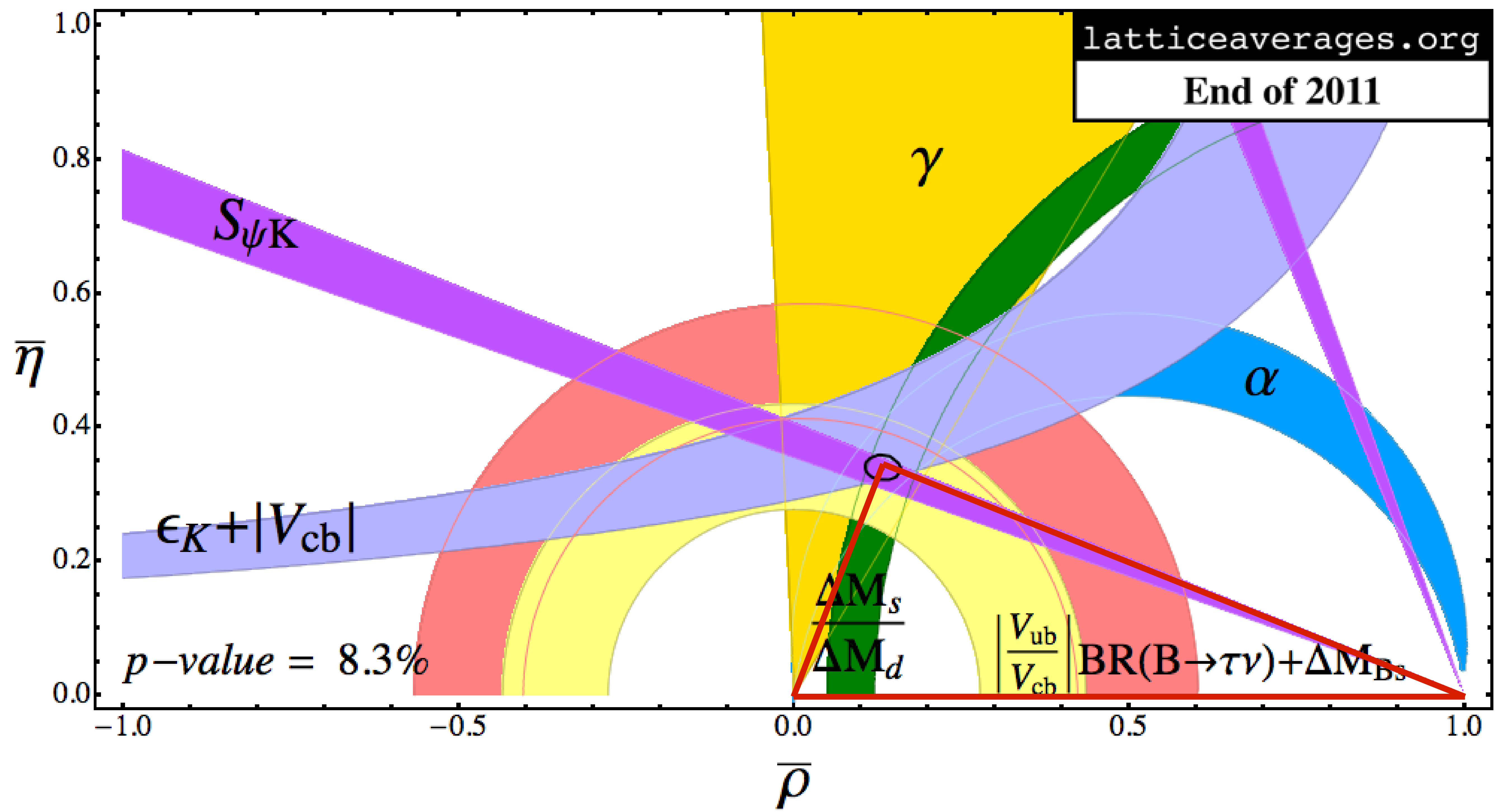
B^0-B^0 mixing



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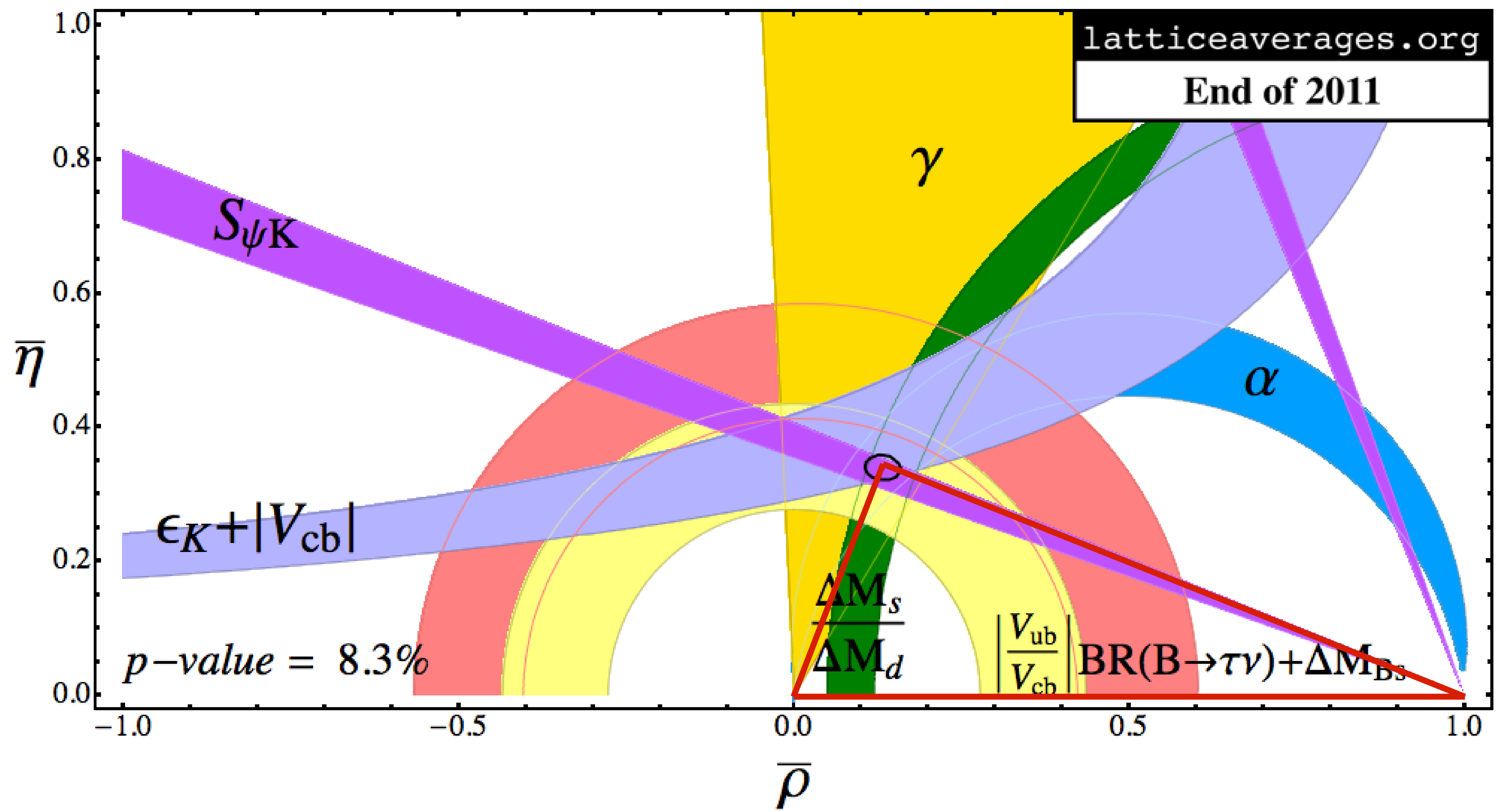

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BSM

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$B \longrightarrow Kll$

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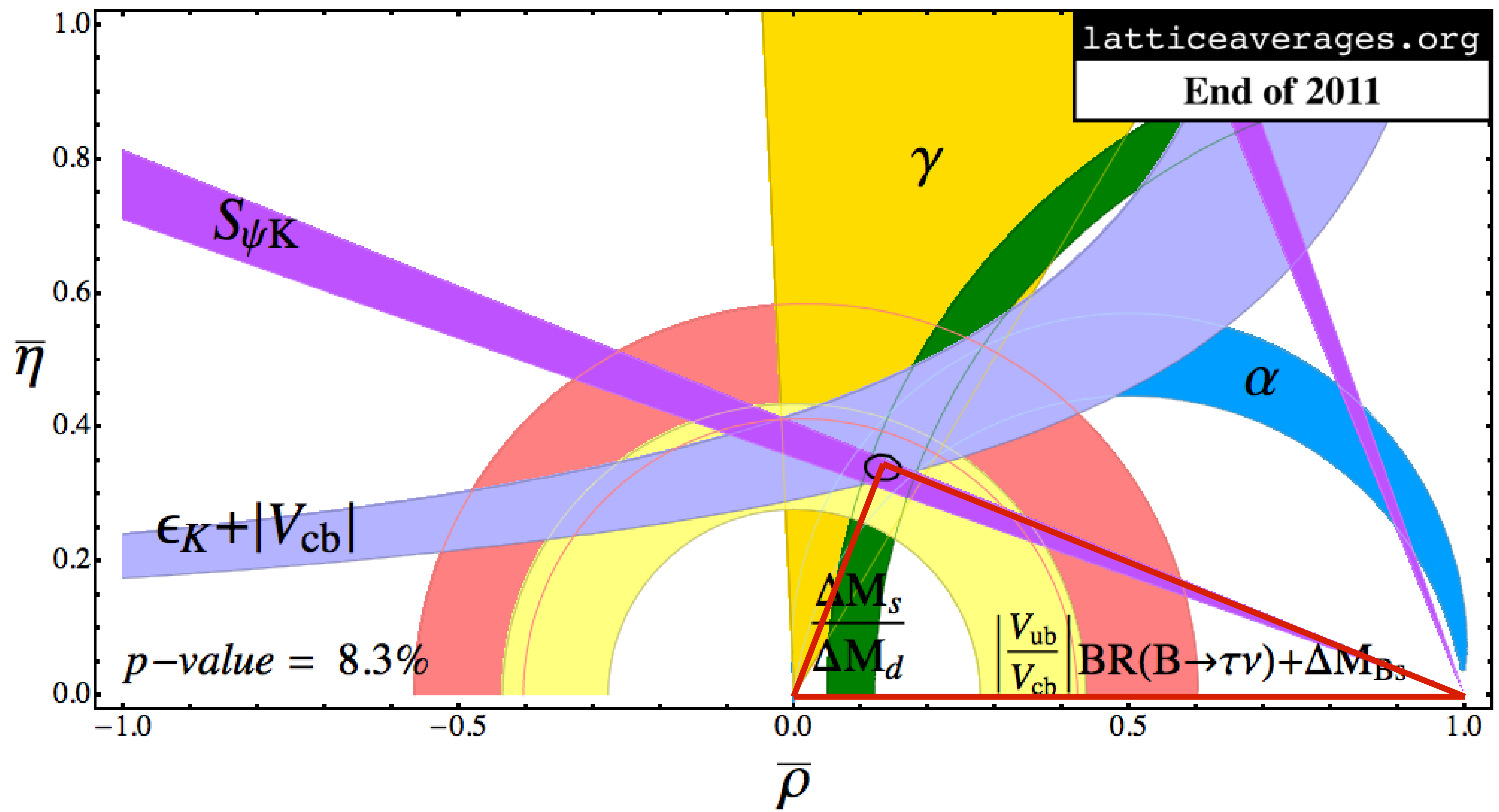

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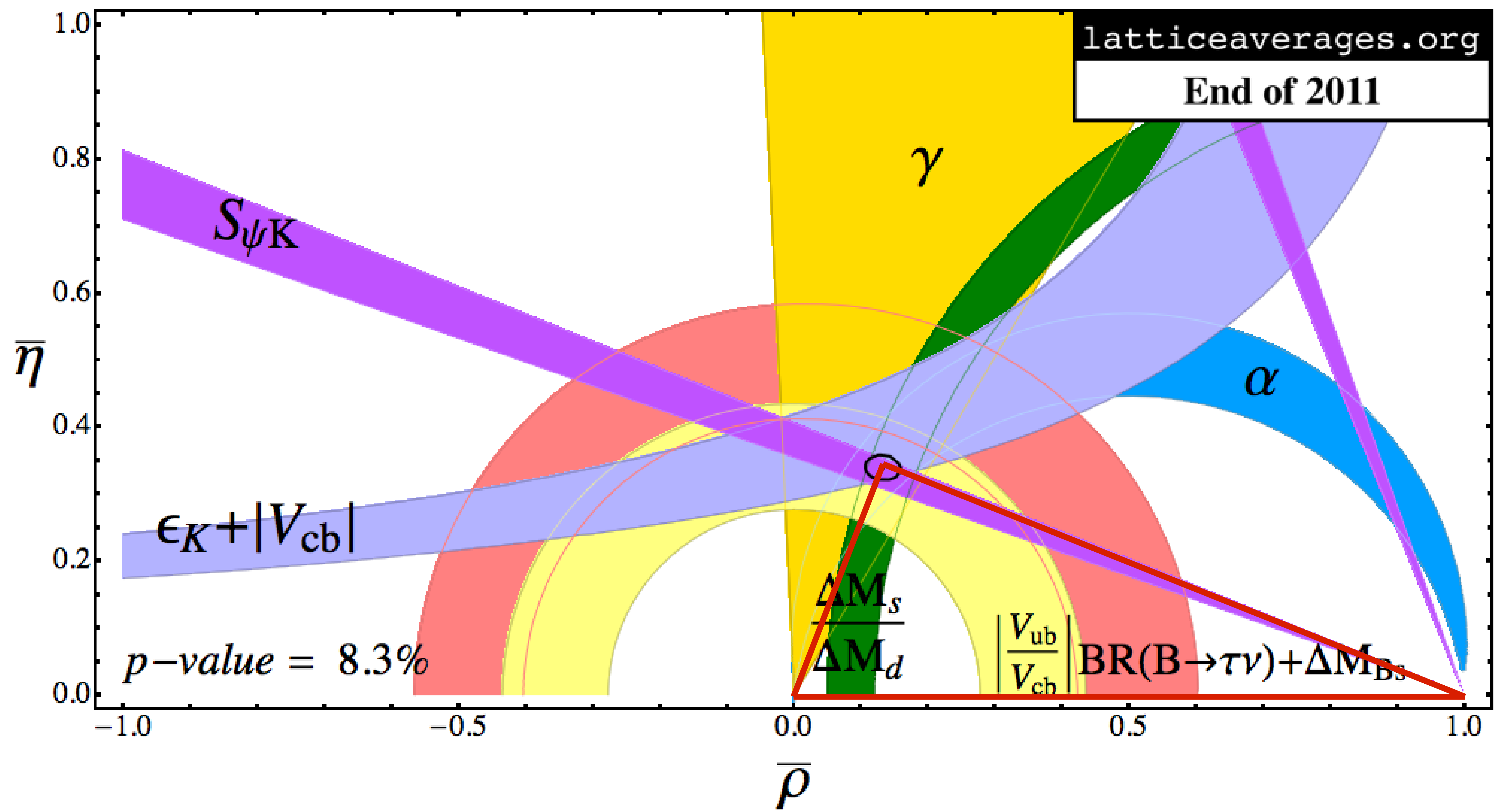

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$B \longrightarrow Kll$

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$|V_{ub}|$: $B \longrightarrow \pi l\nu$

$B_s \longrightarrow \mu\mu$ at
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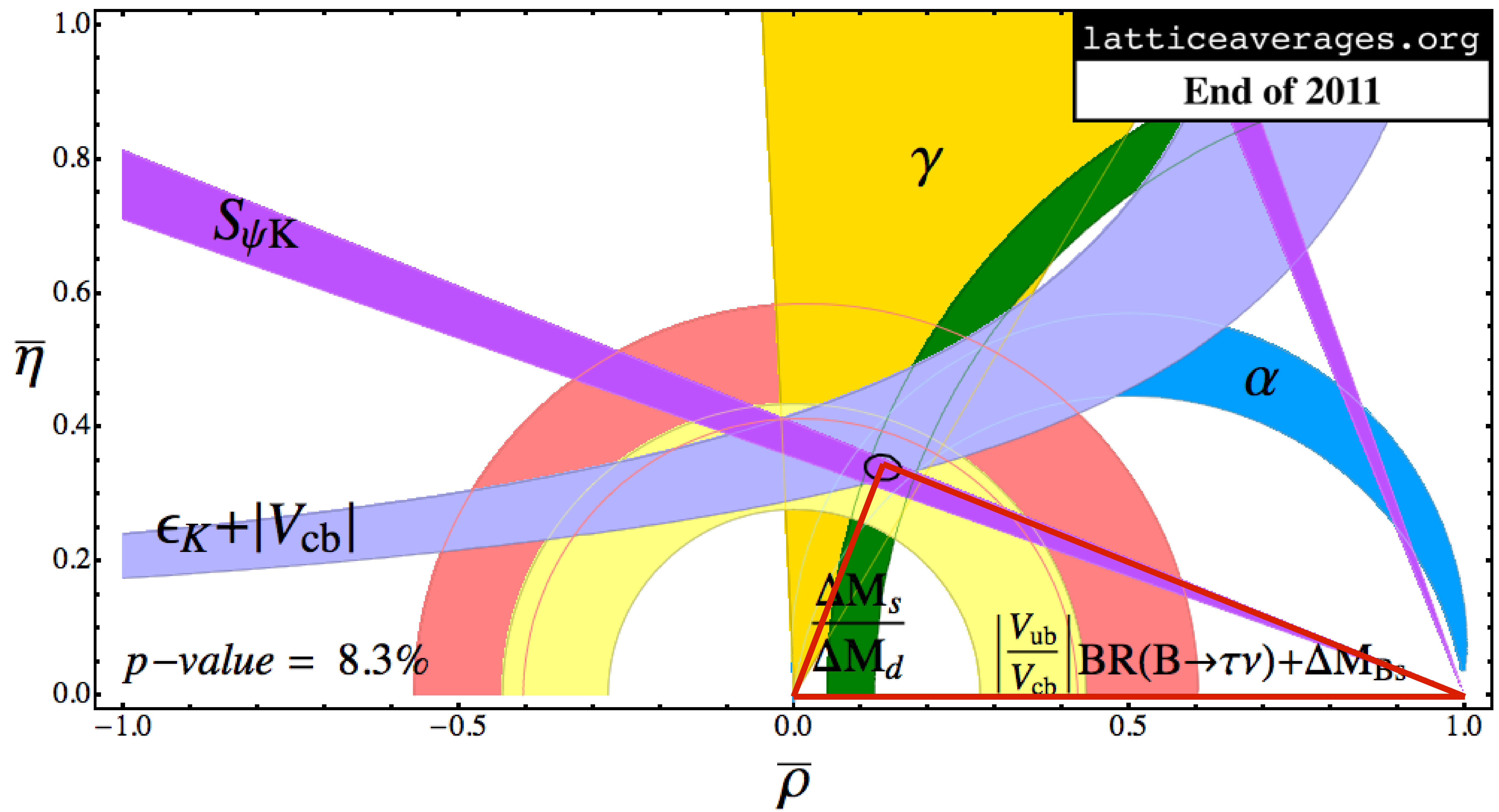

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But first … some words on the ingredients.

Actions, Ensembles, Extrapolations, Uncertainties

MILC “asqtad” Ensembles

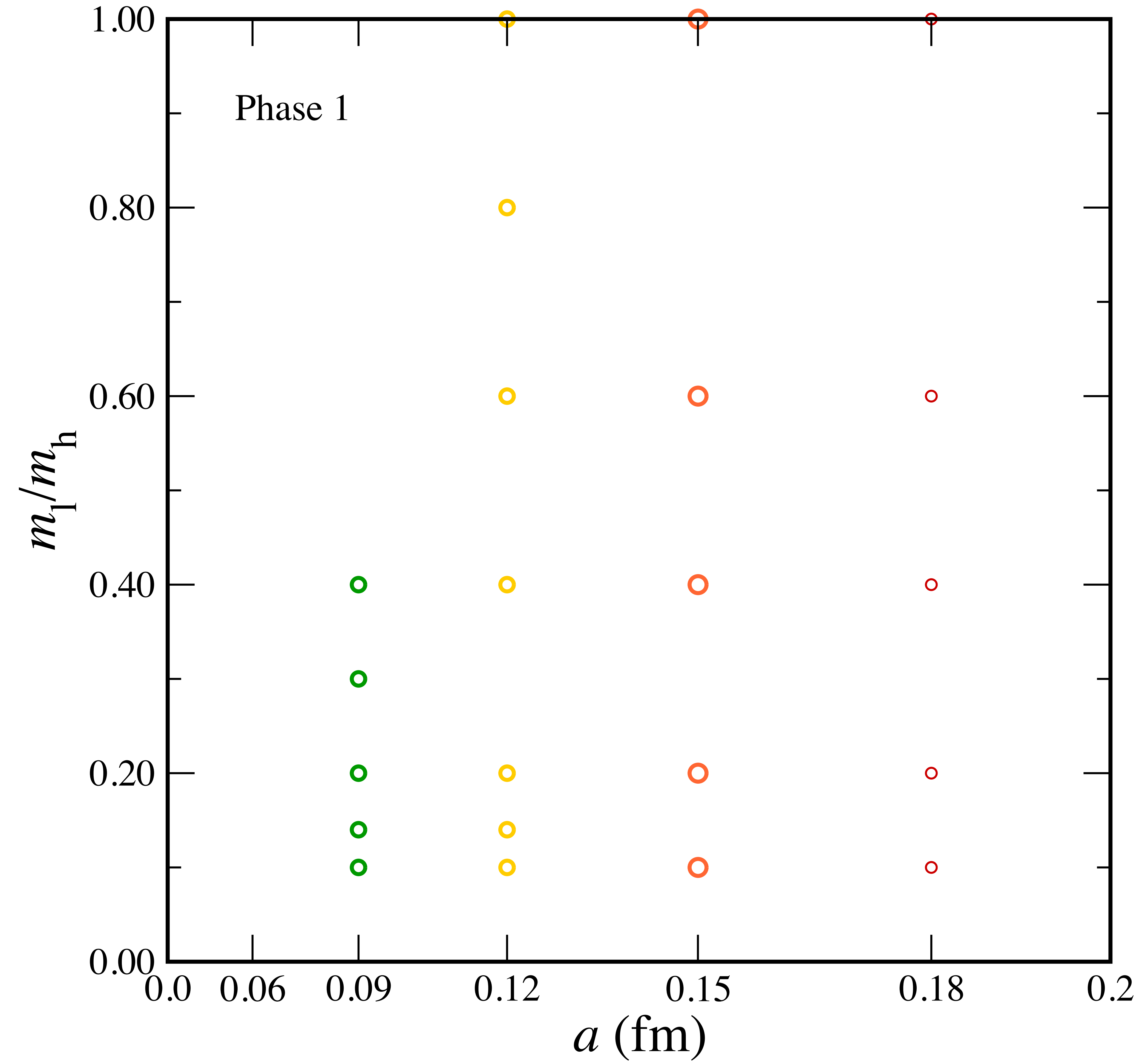
A. Bazavov *et al*., arXiv:0903.3598, and refs therein.

- Gluons: Symanzik-Weisz-Lüscher-Weisz action with gluonic $O(\alpha_s)$ corrections but not $O(n_f\alpha_s)$ (unavailable when gauge-field generation started).

- Light sea quarks: 2+1 asqtad-improved staggered, with rooted determinant [PLB **124** (1983) 99],

$$\mathrm{Det}_4^{1/2}[D+m_l]\ \mathrm{Det}_4^{1/4}[D+m_h]:$$

  - reduces number of tastes to desired value, 2+1;
  - violations of unitary and (a kind of) locality at $a \neq 0$;
  - perturbative and nonperturbative evidence that these vanish as $a \to 0$.



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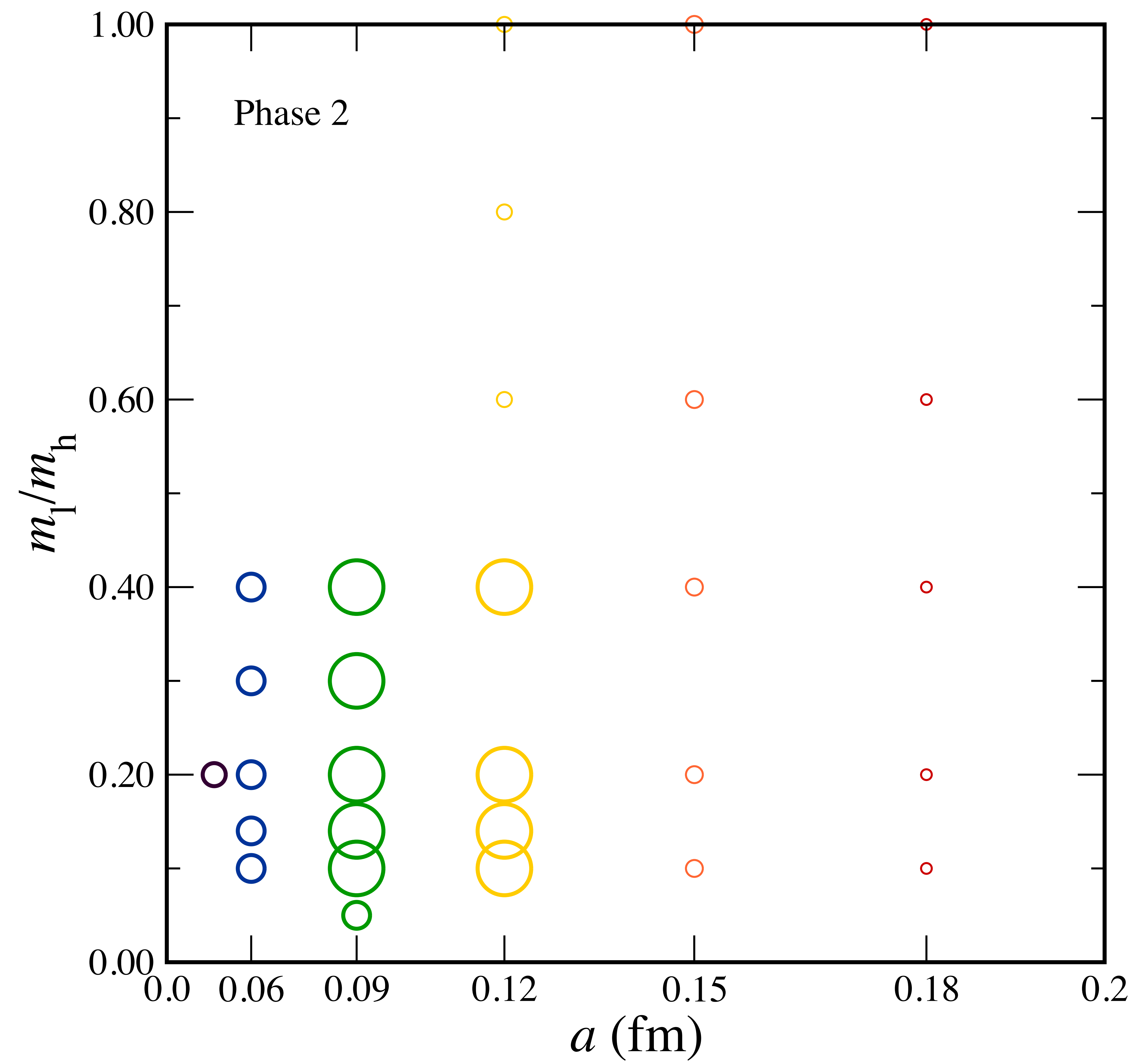


Valence-quark Actions

- Light valence quarks with asqtad-improved staggered (with suitable combinatorics in flavor-singlets).
- Heavy quarks with Sheikholeslami-Wohlert action with Fermilab interpretation [hep-lat/9604004]:
    - heavy quark is nearly stationary in heavy-light systems;
    - heavy quark orbits its partner in heavy-heavy systems;
    - Wilson-like quarks reproduced this basic feature—they have heavy-quark symmetry built in;
    - tune couplings to obtain ever-better approach to HQ limit.
- Control discretization errors with modified Symanzik effective Lagrangian or with heavy-quark effective Lagrangian [hep-lat/0002008, hep-lat/0112044, hep-lat/0112045].

Chiral Extrapolations and Light-quark Discretization Effects

- Rooted, staggered χPT takes taste splittings and taste reduction into account:

$$
\begin{aligned}
\phi_{H_q} = \phi_H^0 \Bigg[\; 1 + \frac{1}{16\pi^2 f^2}\frac{1}{2}\Bigg\{ & -\frac{1}{16}\sum_{e,\Xi}\ell(M_{eq,\Xi}^2) - \frac{1}{3}\sum_{j\in\mathcal{M}_I^{(2,x)}} \frac{\partial}{\partial M_{X,I}^2}\left[R_j^{[2,2]}(\mathcal{M}_I^{(2,x)};\mu_I^{(2)})\ell(M_j^2)\right] \\
& -\left(a^2\delta'_V \sum_{j\in\hat{\mathcal{M}}_V^{(3,x)}} \frac{\partial}{\partial M_{X,V}^2}\left[R_j^{[3,2]}(\hat{\mathcal{M}}_V^{(3,x)};\mu_V^{(2)})\ell(M_j^2)\right] + [V\to A]\right) \\
& -3g_\pi^2\frac{1}{16}\sum_{e,\Xi} J(M_{eq,\Xi},\Delta^* + \delta_{eq}) - g_\pi^2 \sum_{j\in\mathcal{M}_I^{(2,x)}} \frac{\partial}{\partial M_{X,I}^2}\left[R_j^{[2,2]}(\mathcal{M}_I^{(2,x)};\mu_I^{(2)})J(M_j,\Delta^*)\right] \\
-3g_\pi^2 & \left(a^2\delta'_V \sum_{j\in\hat{\mathcal{M}}_V^{(3,x)}} \frac{\partial}{\partial M_{X,V}^2}\left[R_j^{[3,2]}(\hat{\mathcal{M}}_V^{(3,x)};\mu_V^{(2)})J(M_j,\Delta^*)\right] + [V\to A]\right)\Bigg\} \\
& + p(m_q, m_l, m_h, a^2)\Bigg].
\end{aligned}
$$

Heavy-quark Discretization Effects

- HQET description of continuum QCD:

$$\begin{aligned}\langle L|v\cdot\mathcal{V}|B\rangle &= -C_{V_\parallel}\langle L|\bar{q}h_v|B_v^{(0)}\rangle - B_{V1}\langle L|v\cdot Q_{V1}|B_v^{(0)}\rangle - B_{V4}\langle L|v\cdot Q_{V4}|B_v^{(0)}\rangle \\ &- \mathcal{C}_2 C_{V_\parallel}\int d^4x\langle L|T\,\mathcal{O}_2(x)\bar{q}h_v|B_v^{(0)}\rangle^\star - \mathcal{C}_{\mathcal{B}} C_{V_\parallel}\int d^4x\langle L|T\,\mathcal{O}_{\mathcal{B}}(x)\bar{q}h_v|B_v^{(0)}\rangle^\star \\ &+ O(\Lambda^2/m^2)\end{aligned}$$

- HQET description of lattice gauge theory (if fermions compatible with heavy-quark symmetry):

$$\begin{aligned}\langle L|v\cdot V_{\mathrm{lat}}|B\rangle &= -C_{V_\parallel}^{\mathrm{lat}}\langle L|\bar{q}h_v|B_v^{(0)}\rangle - B_{V1}^{\mathrm{lat}}\langle L|v\cdot Q_{V1}|B_v^{(0)}\rangle - B_{V4}^{\mathrm{lat}}\langle L|v\cdot Q_{V4}|B_v^{(0)}\rangle \\ &- \mathcal{C}_2^{\mathrm{lat}} C_{V_\parallel}^{\mathrm{lat}}\int d^4x\langle L|T\,\mathcal{O}_2(x)\bar{q}h_v|B_v^{(0)}\rangle^\star - \mathcal{C}_{\mathcal{B}}^{\mathrm{lat}} C_{V_\parallel}^{\mathrm{lat}}\int d^4x\langle L|T\,\mathcal{O}_{\mathcal{B}}(x)\bar{q}h_v|B_v^{(0)}\rangle^\star \\ &- K_{\sigma\cdot F} C_{V_\parallel}^{\mathrm{lat}}\int d^4x\langle L|T\,\bar{q}i\sigma F q(x)\bar{q}h_v|B_v^{(0)}\rangle^\star + O(\Lambda^2 a^2 b(ma))\end{aligned}$$

Semileptonic Decays $B \to D^{(*)} l\nu$ for $|V_{cb}|$

arXiv:0808.2519, arXiv:1011.2166; arXiv:1111.0677

Semileptonic Form Factors & $|V_{cb}|$

- Inclusive $B \to X_c l\nu$ + OPE + HQE leads to a determination with (quoted) 1–1.5% error.
- To compete, need to exploit heavy-quark symmetry to control all uncertainties.
- Double ratios (Hashimoto *et al.*, 1999, 2001):

$$\mathcal{R}_+ = \frac{\langle D|\bar{c}\gamma^4 b|\bar{B}\rangle\langle\bar{B}|\bar{b}\gamma^4 c|D\rangle}{\langle D|\bar{c}\gamma^4 c|D\rangle\langle\bar{B}|\bar{b}\gamma^4 b|\bar{B}\rangle}$$

$$\mathcal{R}_{A_1} = \frac{\langle D^*|\bar{c}\gamma^j\gamma^5 b|\bar{B}\rangle\langle\bar{B}|\bar{b}\gamma^j\gamma^5 c|D^*\rangle}{\langle D^*|\bar{c}\gamma^4 c|D^*\rangle\langle\bar{B}|\bar{b}\gamma^4 b|\bar{B}\rangle}$$

- Matrix elements, form factors, and rate:

$$\frac{\langle D^*|\bar{c}\gamma^\mu b|B\rangle}{\sqrt{m_B m_{D^*}}} = h_V(w)\,\varepsilon^{\mu\nu\rho\sigma}v_B^\nu v_{D^*}^\rho \varepsilon_\alpha^{*\sigma}$$

$$\frac{\langle D^*|\bar{c}\gamma^\mu\gamma^5 b|B\rangle}{\sqrt{m_B m_{D^*}}} = ih_{A_1}(w)\,(1+w)\varepsilon^{*\mu} - i\left[h_{A_2}(w)\,v_B^\mu + h_{A_3}(w)\,v_{D^*}^\mu\right]\varepsilon^*\cdot v_B$$

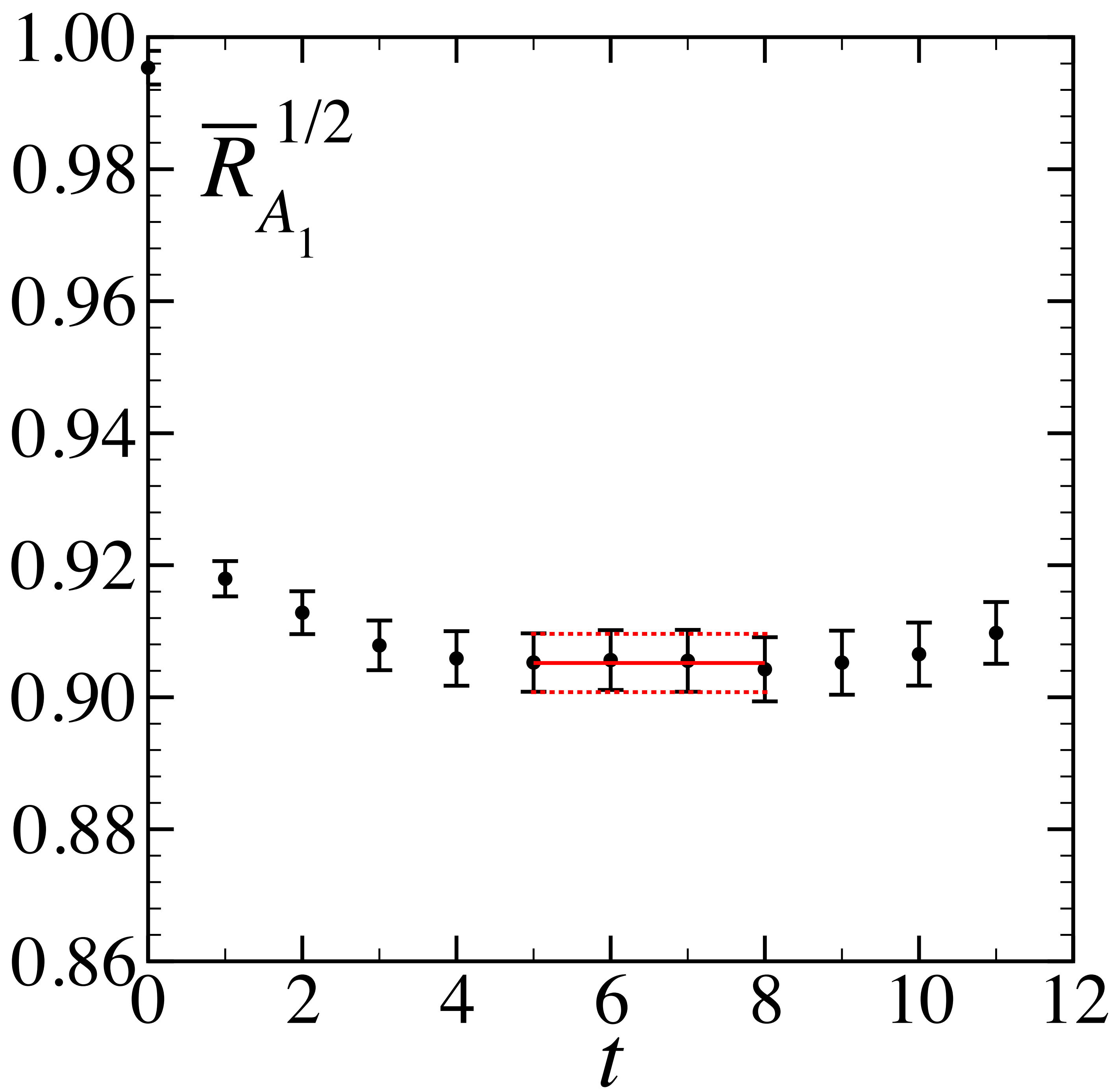
$$\frac{d\Gamma}{dw} = \frac{G_F^2 M_{D^*}^3}{4\pi^3}(M_B - M_{D^*})^2(w^2-1)^{1/2}|V_{cb}|^2\chi(w)|\mathcal{F}(w)|^2$$

- At zero recoil, $\mathcal{F}(1) = \eta_{\text{EW}} h_{A_1}(1)$, $\eta_{\text{EW}} = 1.0066$ takes electroweak corrections (*e.g.*, box with WZ) into account.

Double Ratios

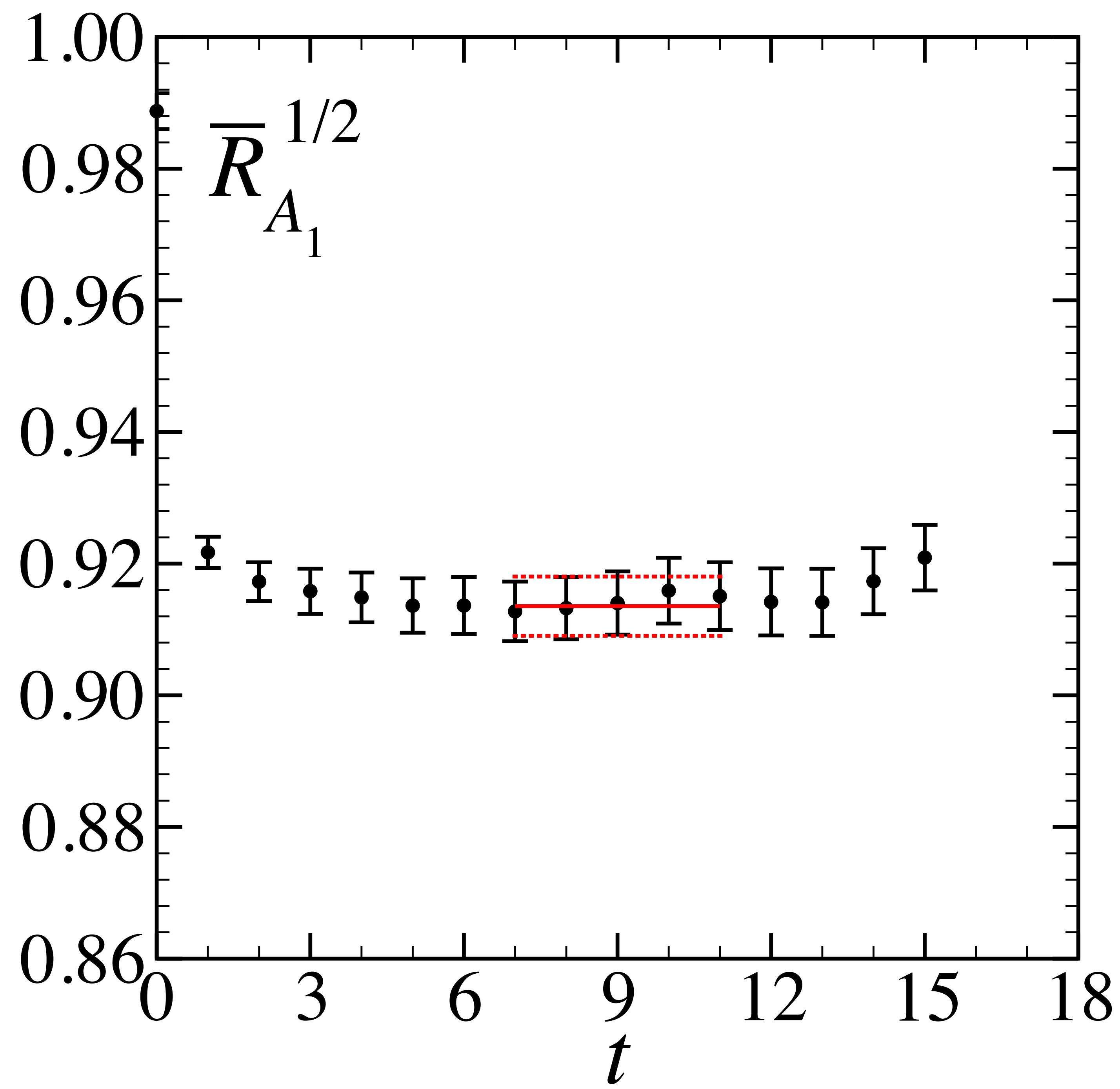
arXiv:1011.2166

coarse



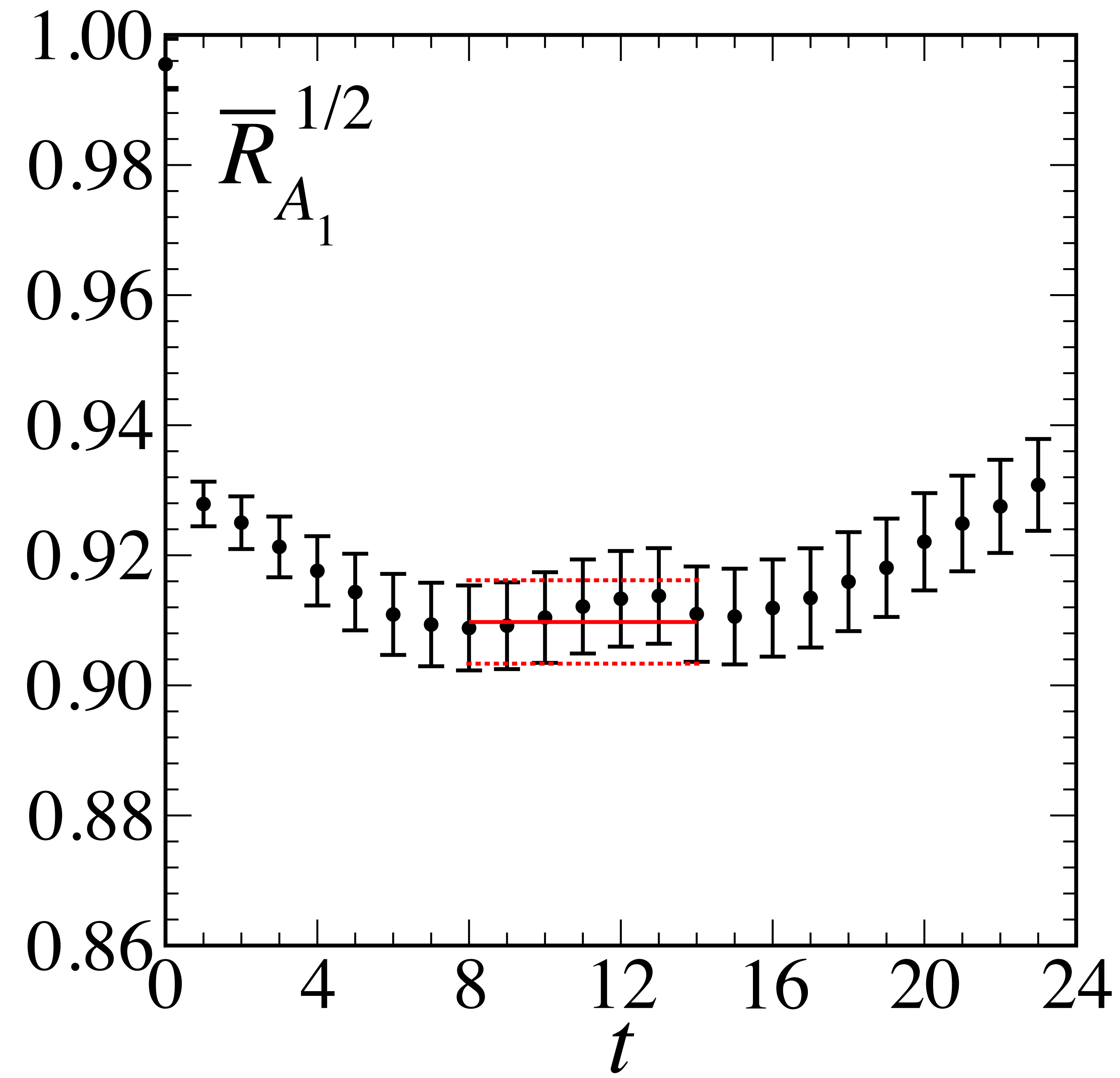
$a \approx 0.12$ fm

fine



$a \approx 0.09$ fm

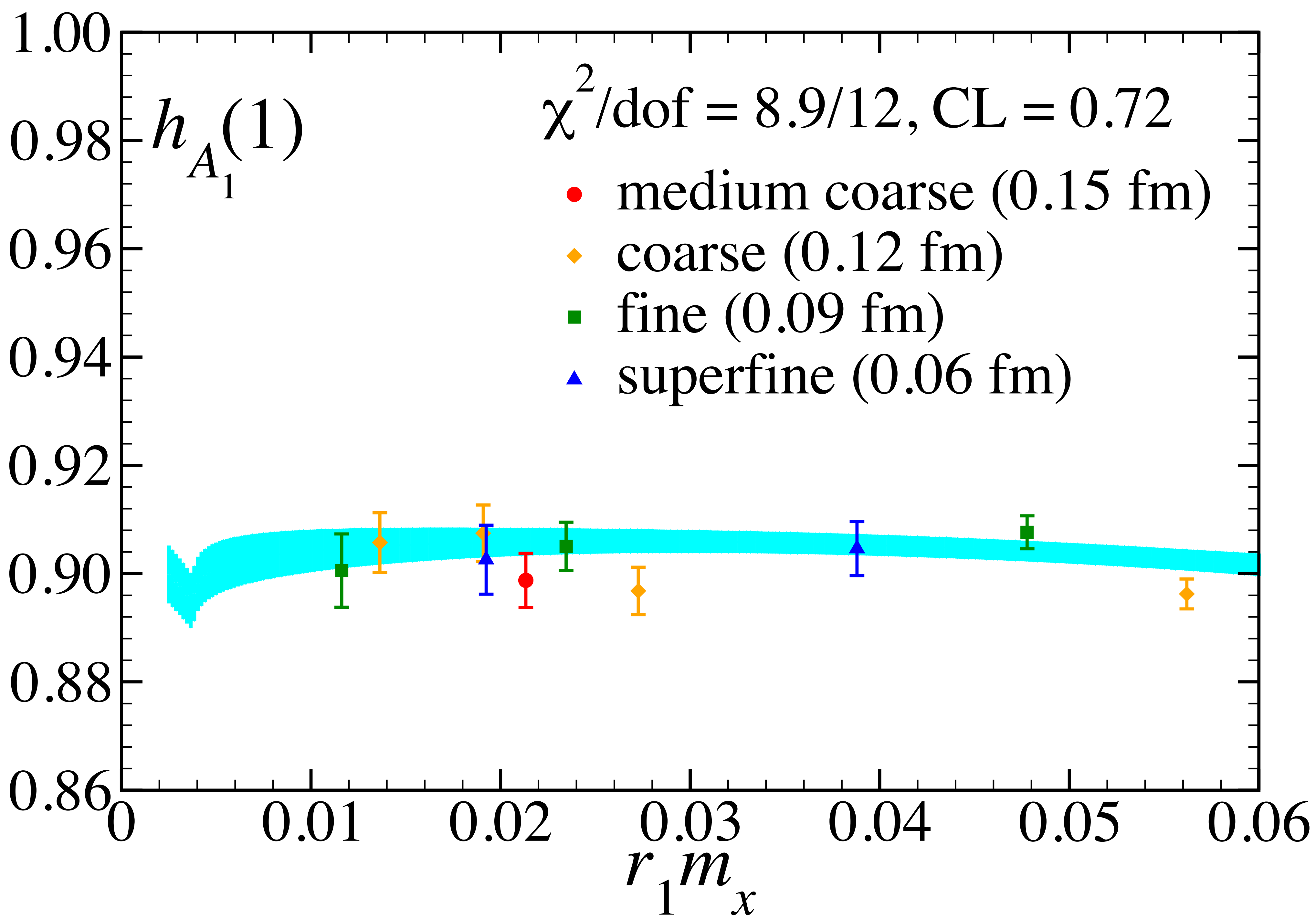
superfine



$a \approx 0.06$ fm

Chiral-Continuum Extrapolation

arXiv:1011.2166



- Latest result

$$\mathcal{F}(1) = 0.9077(51)_{\mathrm{MC}}(88)_{g_\pi}(84)_\chi(90)_{\mathrm{HQ}}(30)_Z(33)_{\kappa_{b,c}}$$

w/ measurements from Belle and *BaBar* leads to

$$|V_{cb}| = (39.7 \pm 0.9)\times 10^{-3},$$

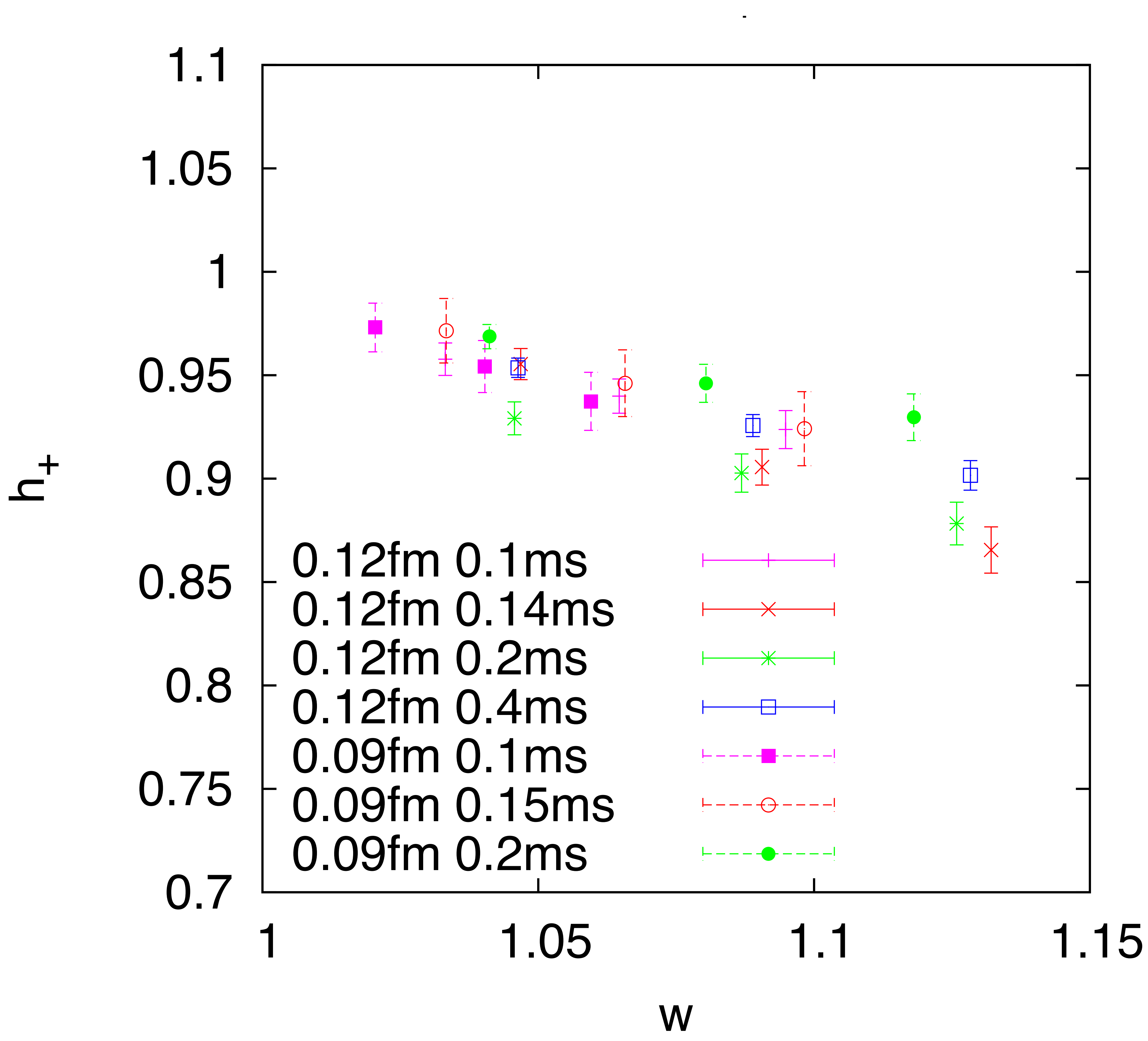
while the latest PDG.HFAG inclusive value is

$$|V_{cb}| = (41.9 \pm 0.7)\times 10^{-3},$$

representing a tension of 2σ ($p = 4\%$).

Nonzero Recoil $B \to D^{(*)} l\nu$

S.-W. Qiu *et al.* [Fermilab/MILC], arXiv:1111.0677



- Matrix elements, form factors, and rate:

$$\frac{\langle D|\mathcal{V}^\mu|B\rangle}{\sqrt{2M_D\,2M_B}} = (v+v')^\mu h_+(w) + (v-v')^\mu h_-(w),\ w = v\cdot v'$$

$$\mathcal{G}(w) = h_+(w) - \frac{M_B - M_D}{M_B + M_D} h_-(w) = \frac{2\sqrt{M_B M_D}}{M_B + M_D} f_+(q^2)$$

$$\frac{d\Gamma}{dw} = \frac{G_F^2 M_D^3}{48\pi^3}(M_B+M_D)^2(w^2-1)^{3/2}|V_{cb}|^2|\mathcal{G}(w)|^2$$

- Preliminary (Lat' 11) $h_+(w)$ data at left; need $h_-(w)$.
- Extend kinematic range $1 \le w < 1.15$ to full range $1 \le w < 1.6$ with z expansion (see below).
- Will allow complementary extraction of $|V_{cb}|$.

Semileptonic Decays $B \to \pi l \nu$ for $|V_{ub}|$

arXiv:0811.3640, BaBar, Belle

Semileptonic Form Factors & $|V_{ub}|$

arXiv:0811.3640

- Matrix elements, form factors, and rates:

$$\langle\pi|\bar{u}\gamma^\mu b|\bar{B}\rangle = f_+(q^2)\left(p_B^\mu + p_P^\mu - \frac{m_B^2 - m_P^2}{q^2}q^\mu\right) + f_0(q^2)\,\frac{m_B^2 - m_P^2}{q^2}q^\mu$$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2\,\frac{(q^2-m_\ell^2)^2\,\boldsymbol{p}_\pi^2}{q^4}\left|f_+(q^2)\right|^2 + \mathrm{O}\left(m_\ell^2\right)$$

- Chiral-continuum extrapolation with RSχPT

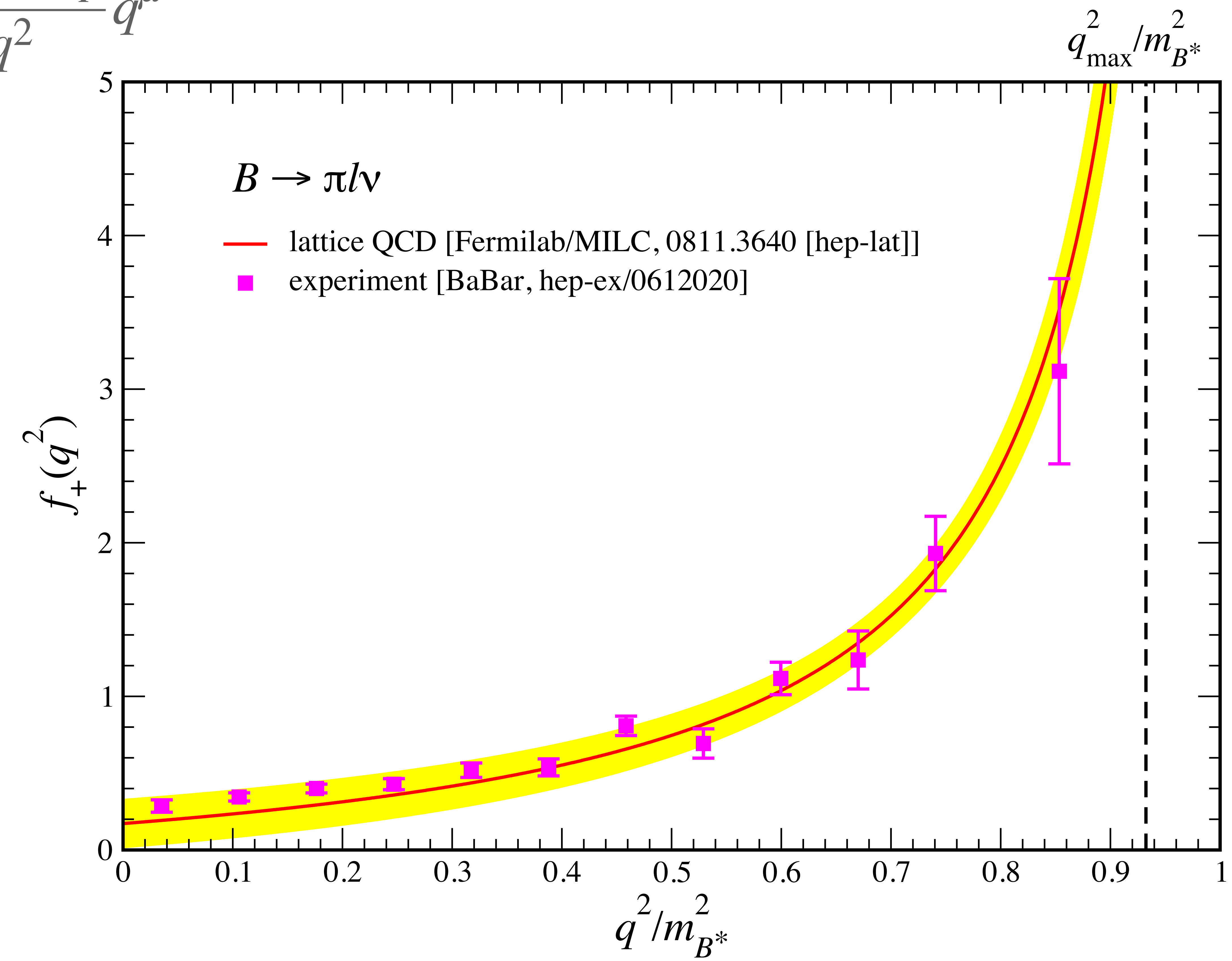
- Extrapolate to across full kinematic range using

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

$$t_\pi = (M_B \pm M_\pi)^2, \quad t_- < t_0 < t_+$$

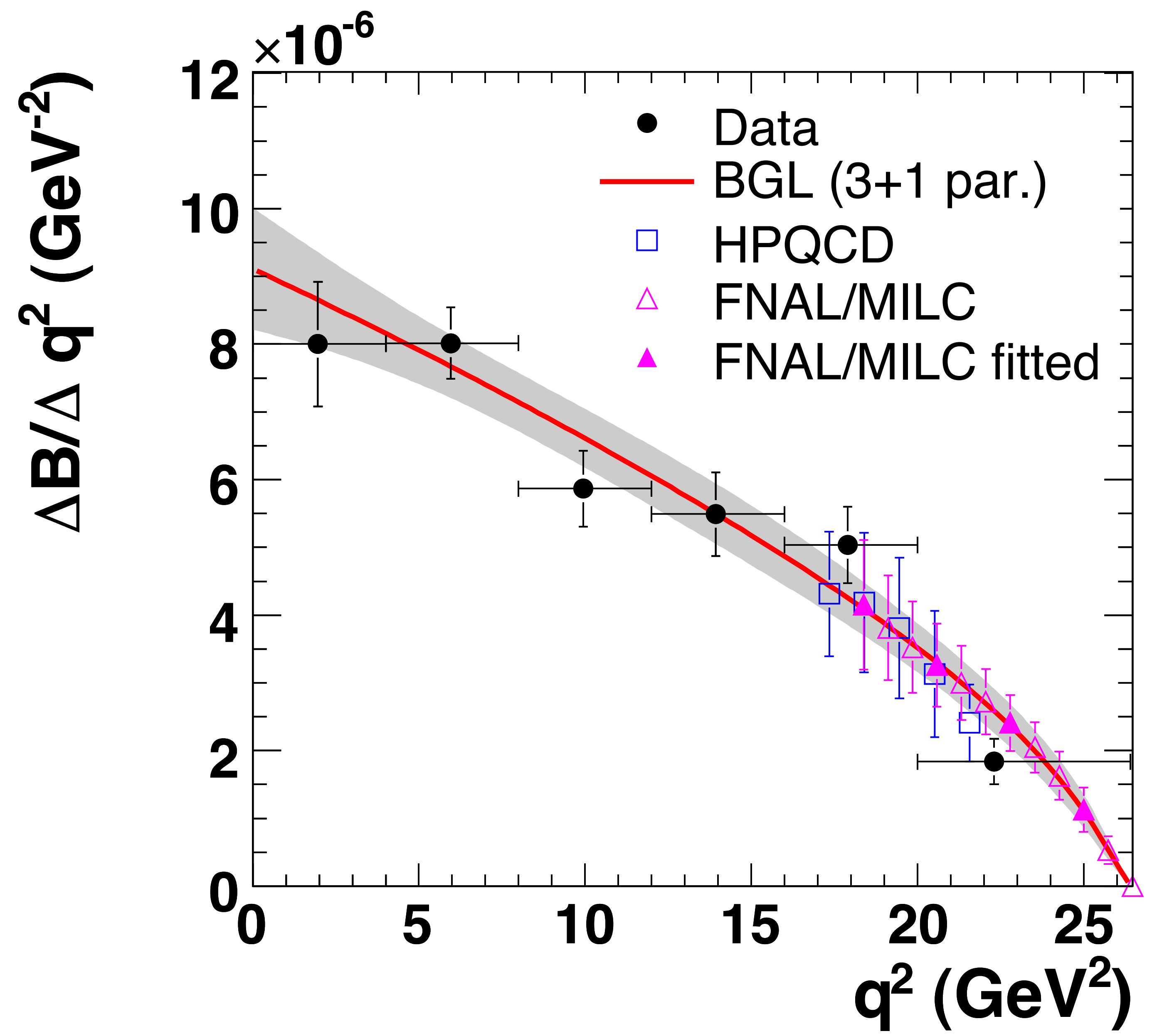
plus unitarity & analyticity.

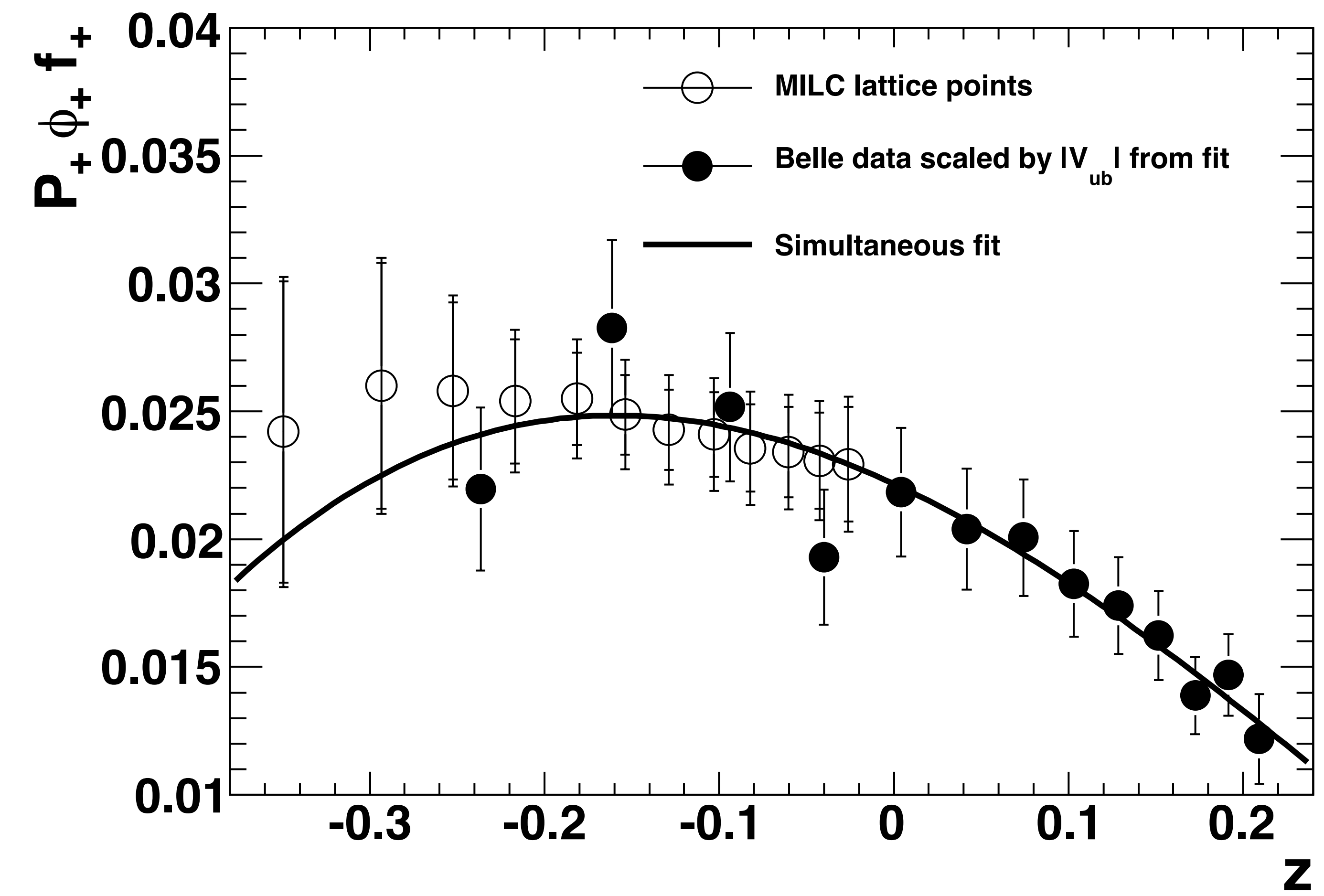
- $|V_{ub}| = (3.38 \pm 0.36)\times 10^{-3}$



Updates from B-factory Experiments

- *BaBar*, arXiv:1005.3288 simultaneous fit to their data and Fermilab/MILC calculation of $f_+(q^2)$:
  - $|V_{ub}| = (2.93 \pm 0.31)\times10^{-3}$
- Belle, arXiv:1012.0090 simultaneous fit to their data and Fermilab/MILC calculation $f_+(q^2)$::
  - $|V_{ub}| = (3.43 \pm 0.33)\times10^{-3}$





Leptonic Decay $B \to \tau\nu$ for $|V_{ub}|$

arXiv:1112.3051, arXiv:1112.3978

Decay Constants

arXiv:1112.3051

- Matrix element, decay constant and rate:

$$\langle 0|\mathcal{A}^\mu|B\rangle = ip^\mu f_B$$

$$\Gamma = \frac{G_F^2 M_B}{8\pi}|V_{ub}|^2 f_B^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{M_B^2}\right)$$

- Note helicity suppression of rate:
  - electronic decays not yet measured;
  - for D, $\ell = \mu, \tau$;
  - for B, $\ell = \tau$ only.

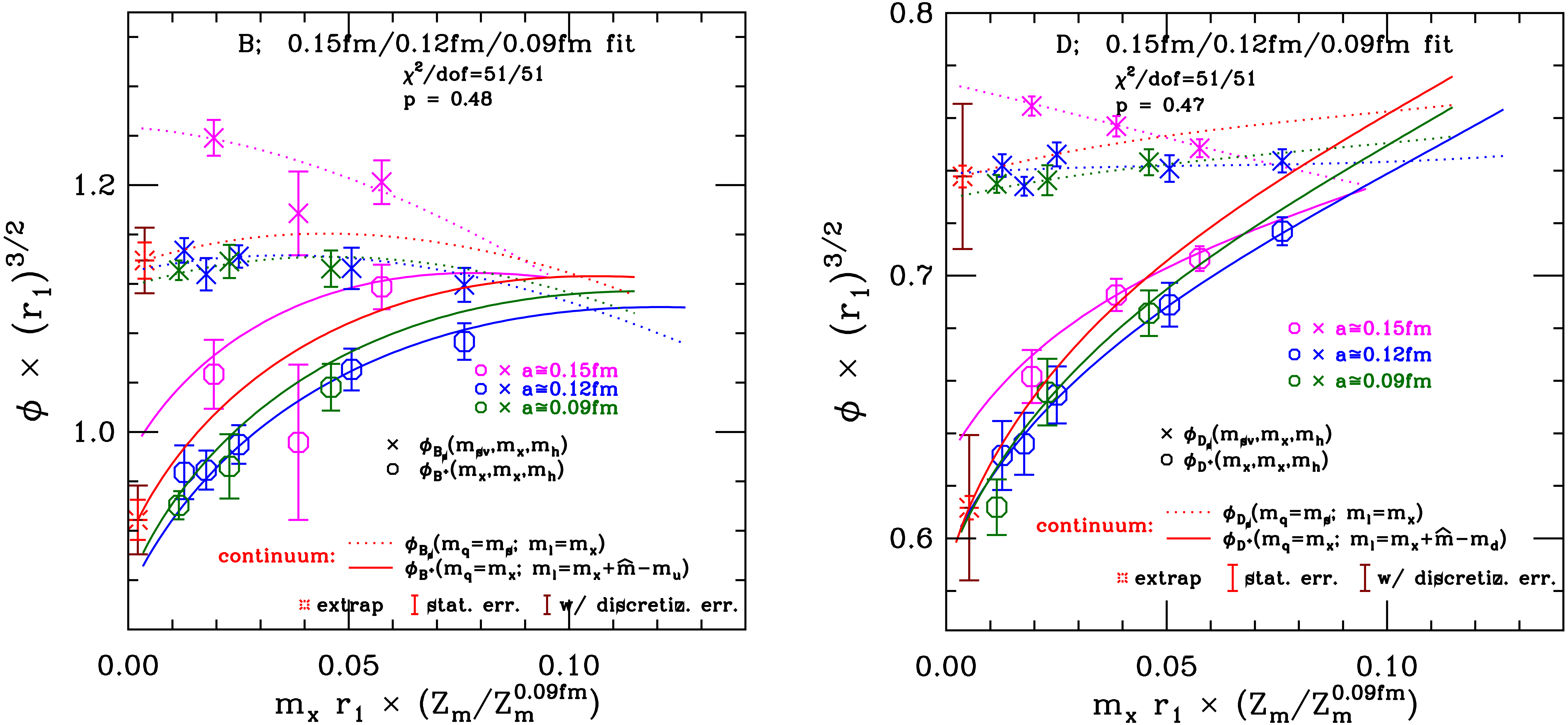
- Before, treat HQ discretization effects with naive power counting:

$$\begin{aligned}\mathtt{error}_i &= \left|\left[C_i^{\rm lat}(m_Q, m_0a) - C_i^{\rm cont}(m_Q)\right] O_i\right| \\ &= |(a\Lambda)^{n_i} f_i(m_0a)|\end{aligned}$$

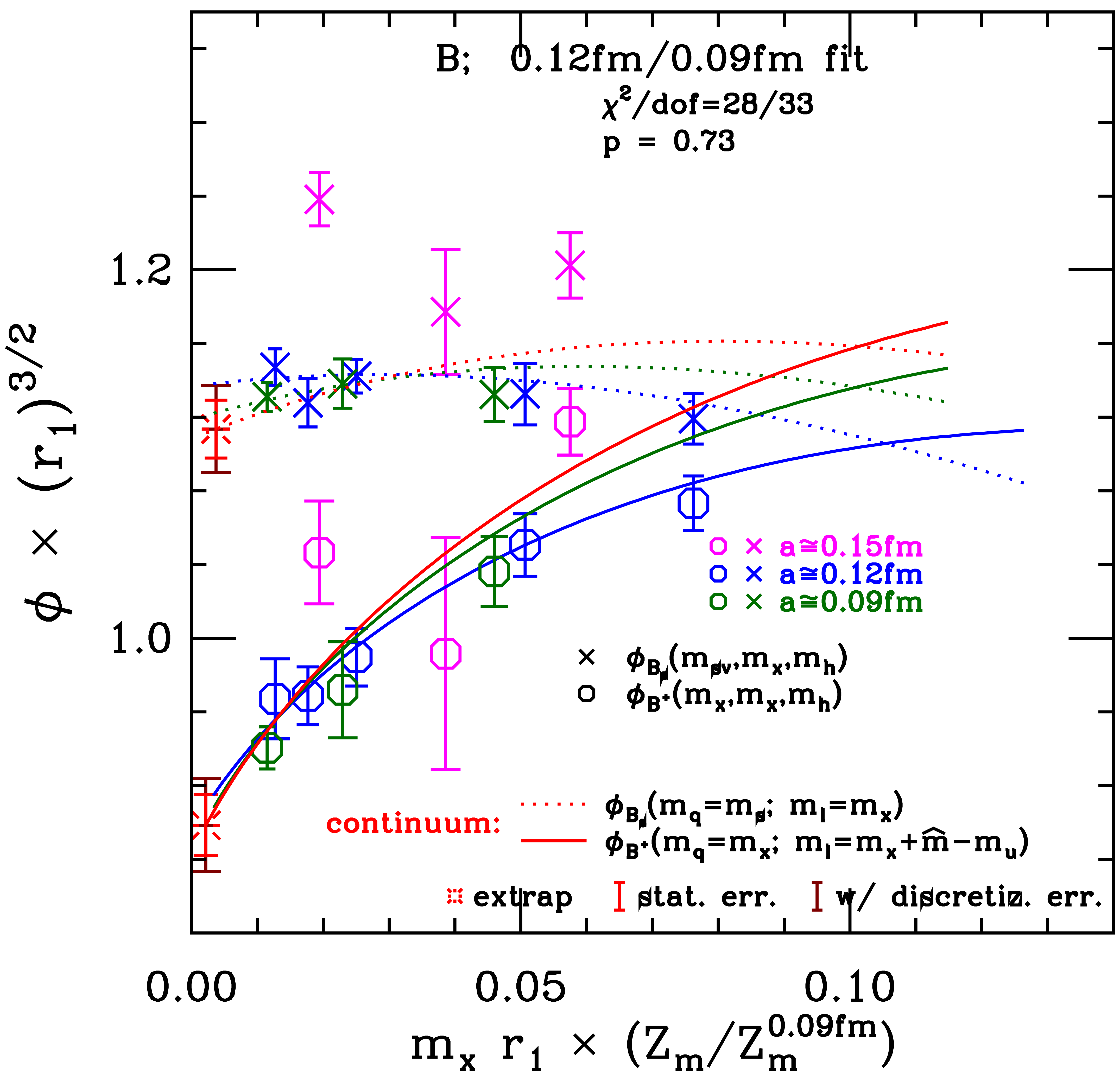
  with 500–700 MeV.

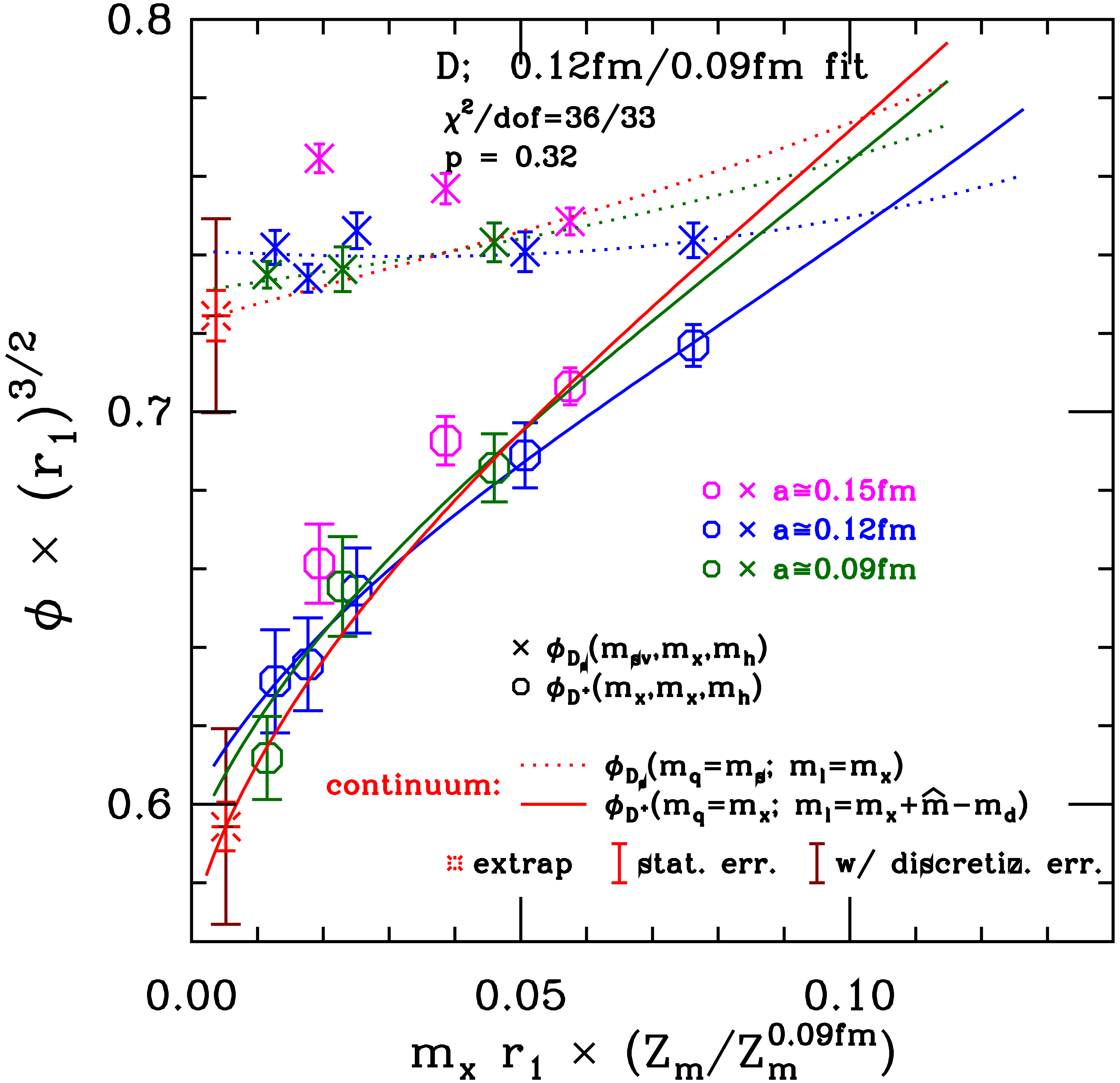
- Here, treat these functional forms with priors:
  - add these $\mathtt{error}_i$ with coefficient z_i to Ansatz for continuum extrapolation;
  - take prior for z_i to be normal(0, [multiplicity]1/2);
  - fit for z_i (and set it to 0 for χCL).

Chiral-continuum fits with all three lattice spacings

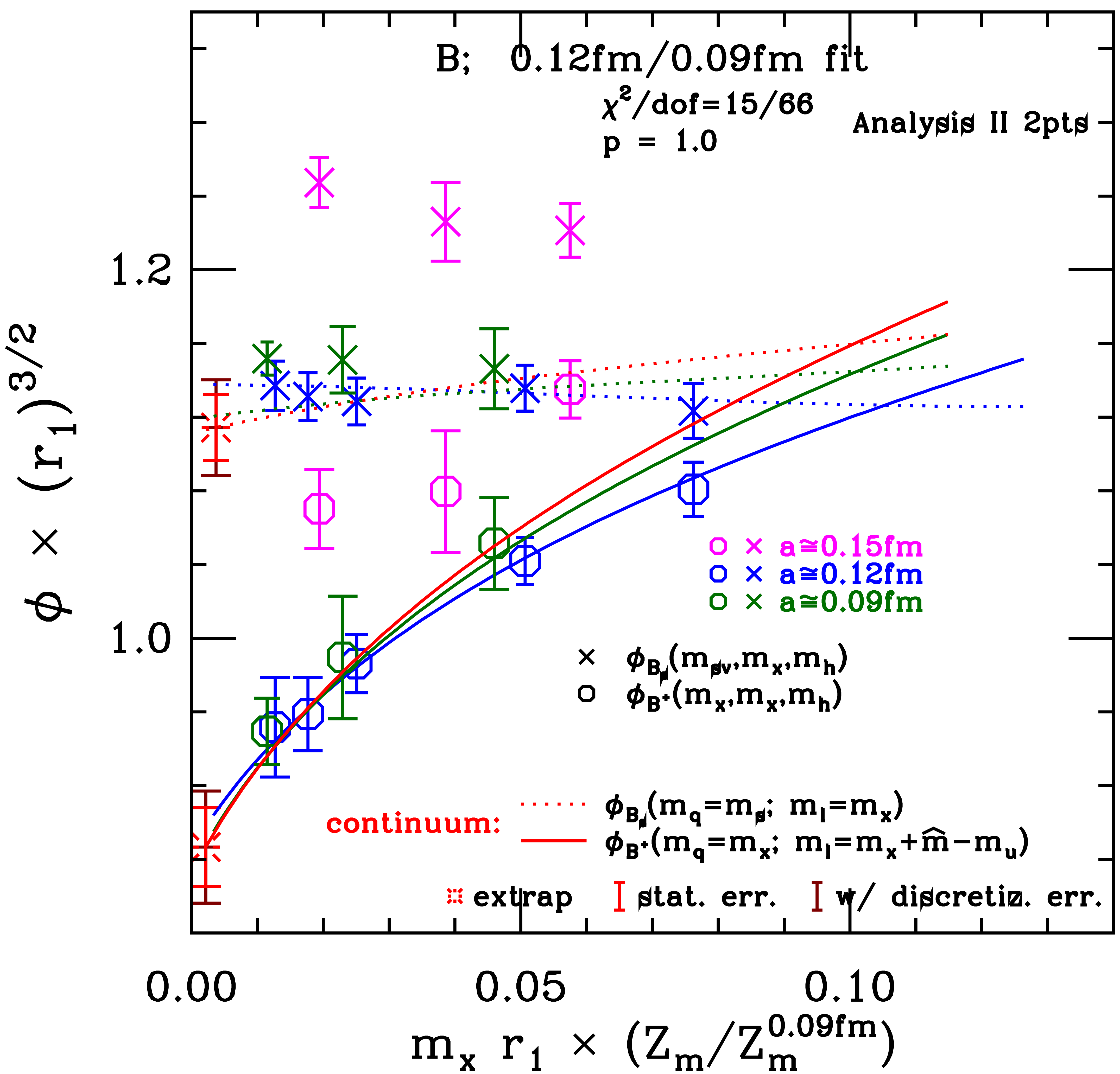


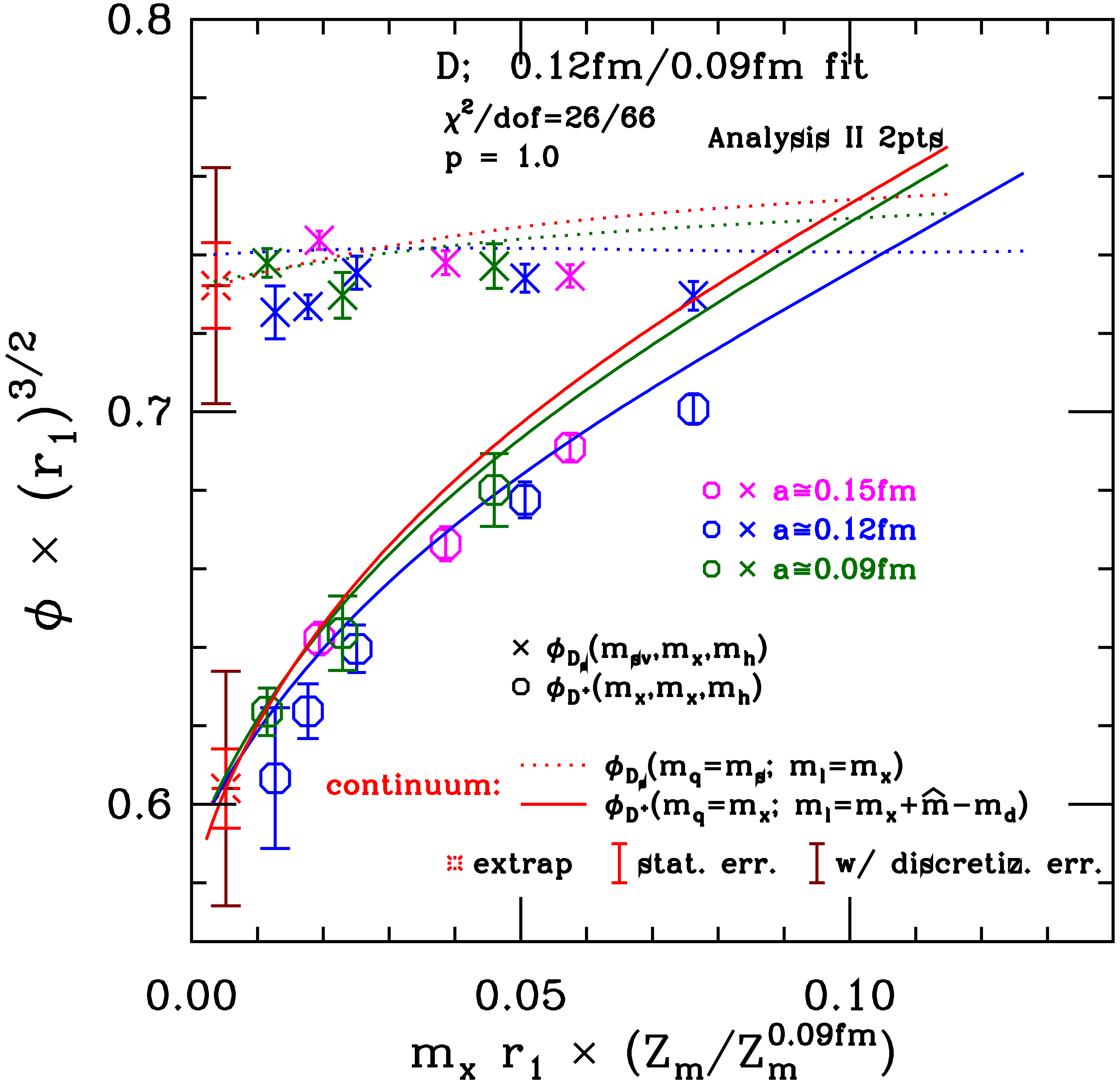
Chiral-continuum fits without medium-coarse data: central fit





Chiral-continuum fits without medium-coarse data: “2-pt Analysis II”





Results

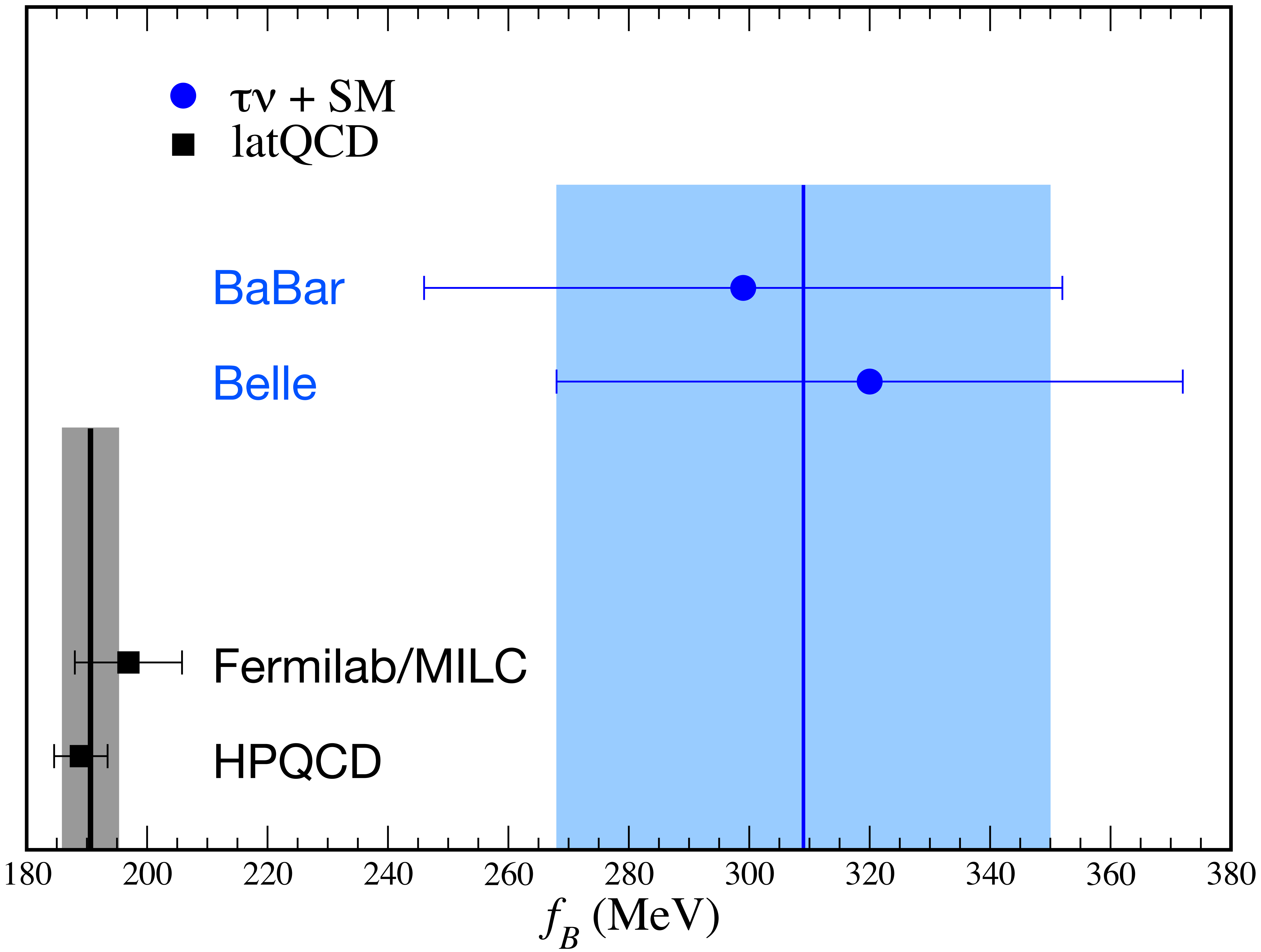
arXiv:1112.3051

- Total error budget 4–5% for decay constants, 2% for ratios (where matching and HQ discretization cancel).

$$
\begin{aligned}
f_{B^+} &= 196.9(9.1)\ \mathrm{MeV} \\
f_{B_s} &= 242.0(10.0)\ \mathrm{MeV} \\
f_{B_s}/f_{B^+} &= 1.229(0.026) \\
f_{D^+} &= 218.9(11.3)\ \mathrm{MeV} \\
f_{D_s} &= 260.1(10.8)\ \mathrm{MeV} \\
f_{D_s}/f_{D^+} &= 1.188(0.025)
\end{aligned}
$$

Tension in $B \to \tau\nu$?

$\mathrm{BR} \propto |f_B V_{ub}|^2$

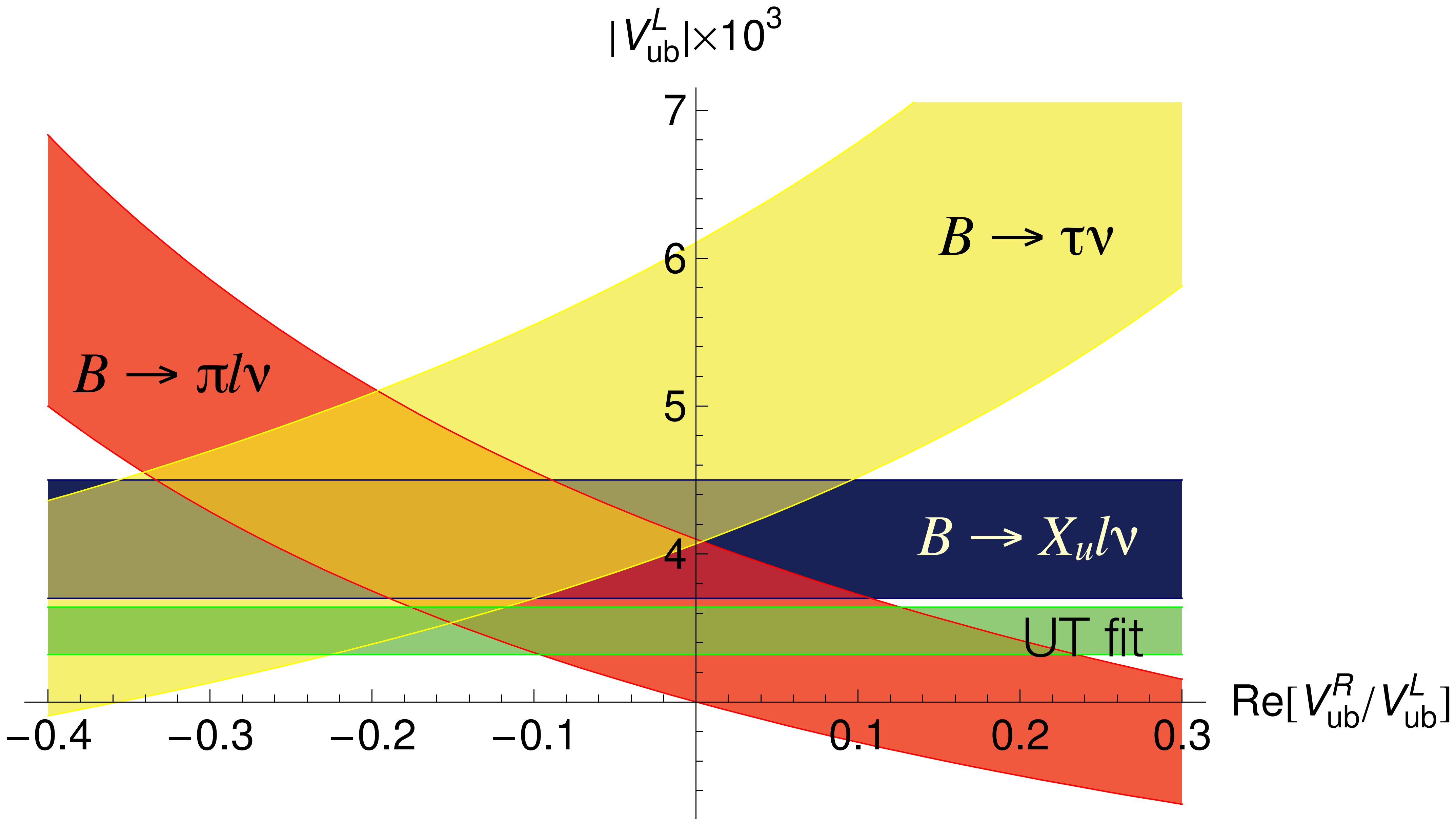


- Using $B \to \pi l \nu$ $|V_{ub}|$ to get f_B.
- New physics, *e.g.*, charged Higgs of MSSM?
  - with $A_{\mathrm{MSSM}} \sim -1.1 A_{\mathrm{SM}}$?!?

Right-Handed Currents?

Crivellin, arXiv:0907.2461

- $\mathcal{L} = V_{ub}^L \bar{u}_L \not{W} b_L + V_{ub}^R \bar{u}_R \not{W} b_R$

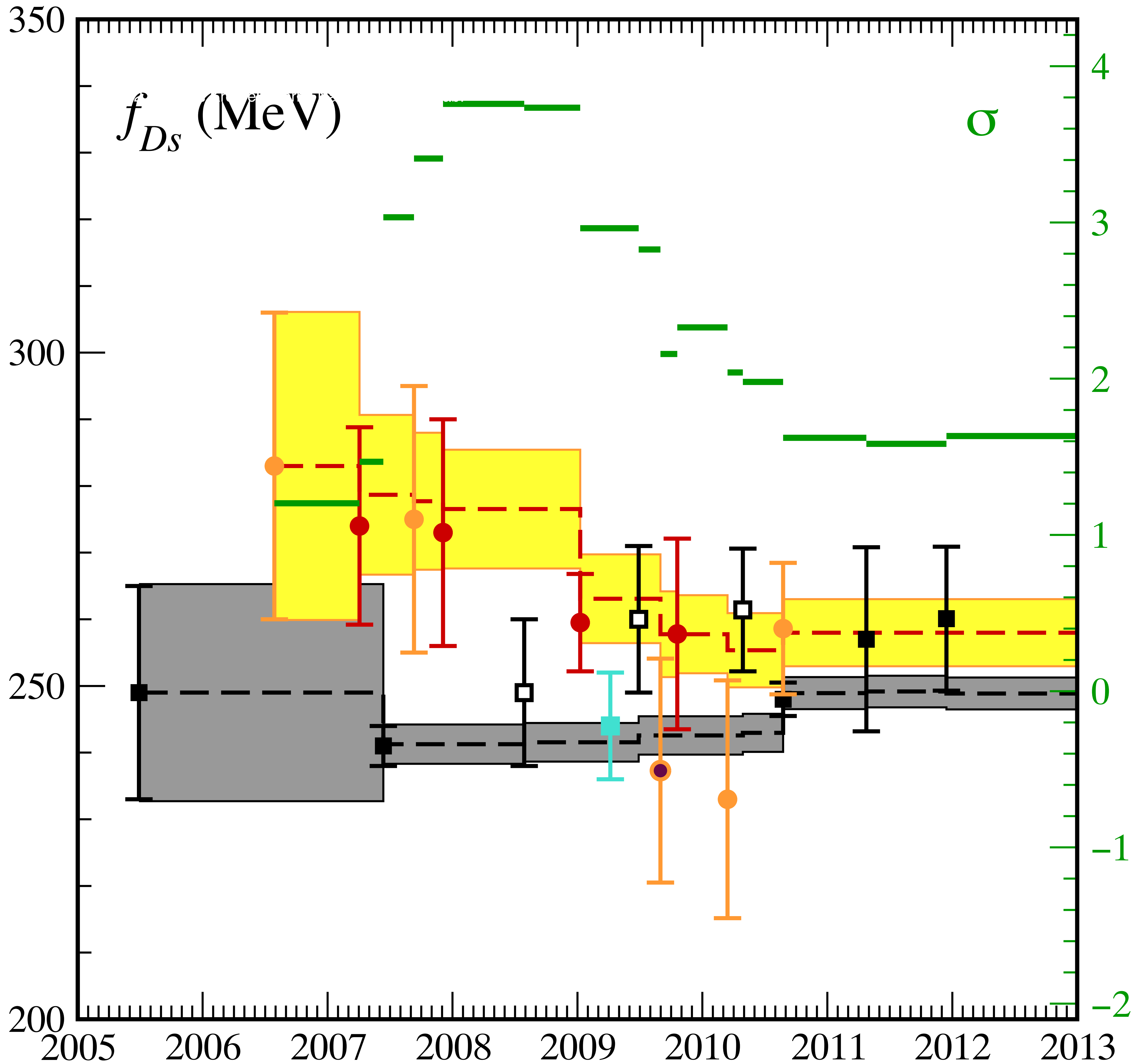


- Exclusive $(3.12 \pm 0.26)\times10^{-3}$:
  - $|V_{ub}| = |V_{ub}^L + V_{ub}^R|$
- Inclusive $(4.34 \pm 0.40)\times10^{-3}$:
  - $|V_{ub}| \approx |V_{ub}^L|$
- Leptonic $(4.95 \pm 0.55)\times10^{-3}$:
  - $|V_{ub}| = |V_{ub}^L - V_{ub}^R|$

- Realistic models?

Tension in $D_s \to l\nu$?

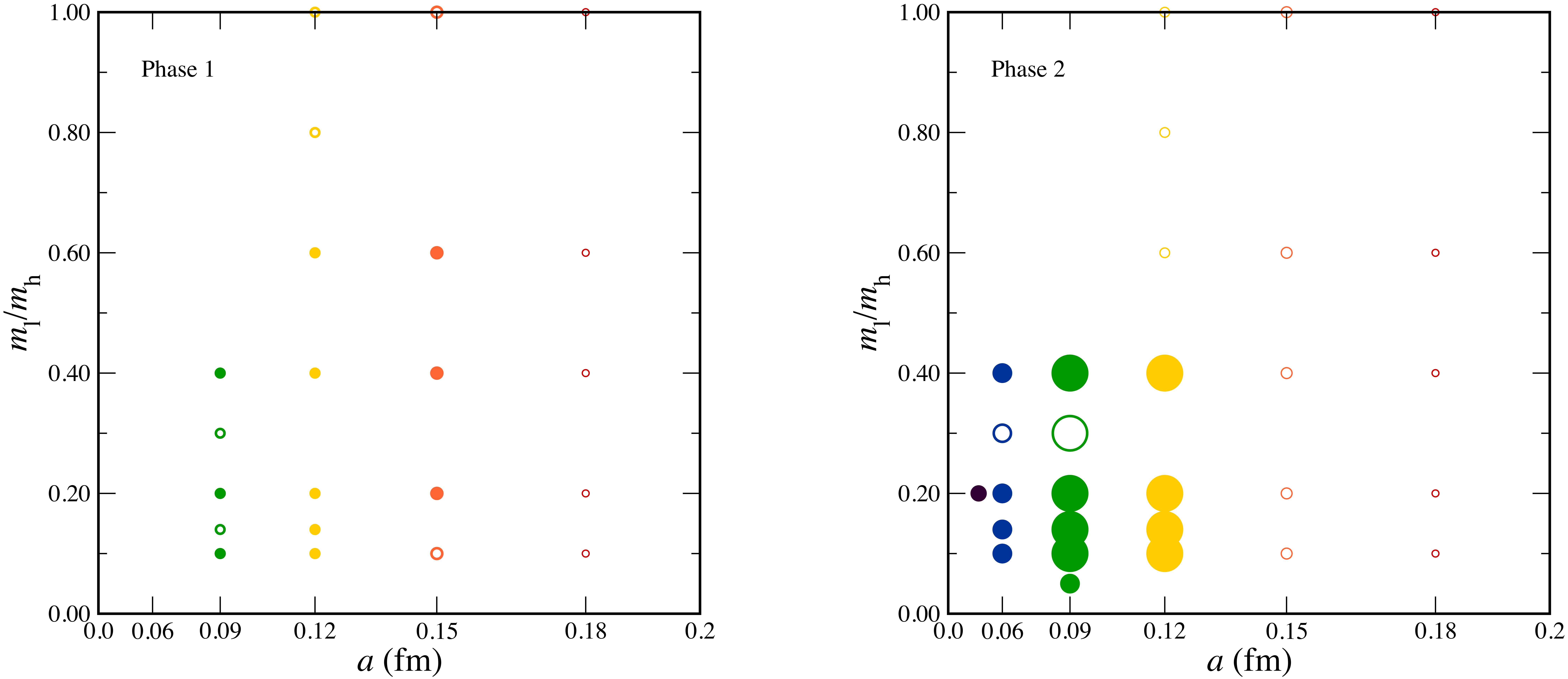
update from ASK, arXiv:0912.0543



- Gray: running lattice QCD average.
- Yellow: running experimental average.
- Orange: B factories BaBar & Belle.
- Red: charm factories CLEO (& BES3).
- Green (right y axis): running deviation in σ.
- σ is mostly experimental statistical error.

Phase 2 already underway

arXiv:1112.3978



Neutral Meson Mixing $B_q \leftrightarrow \overline{B}_q$ $(q = d, s)$ for $|V_{\mathrm{t}q}|$ or BSM?

arXiv:1112.5642

Neutral-meson Mixing

- Effective Hamiltonian, matrix elements:

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} C_i O_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i$$

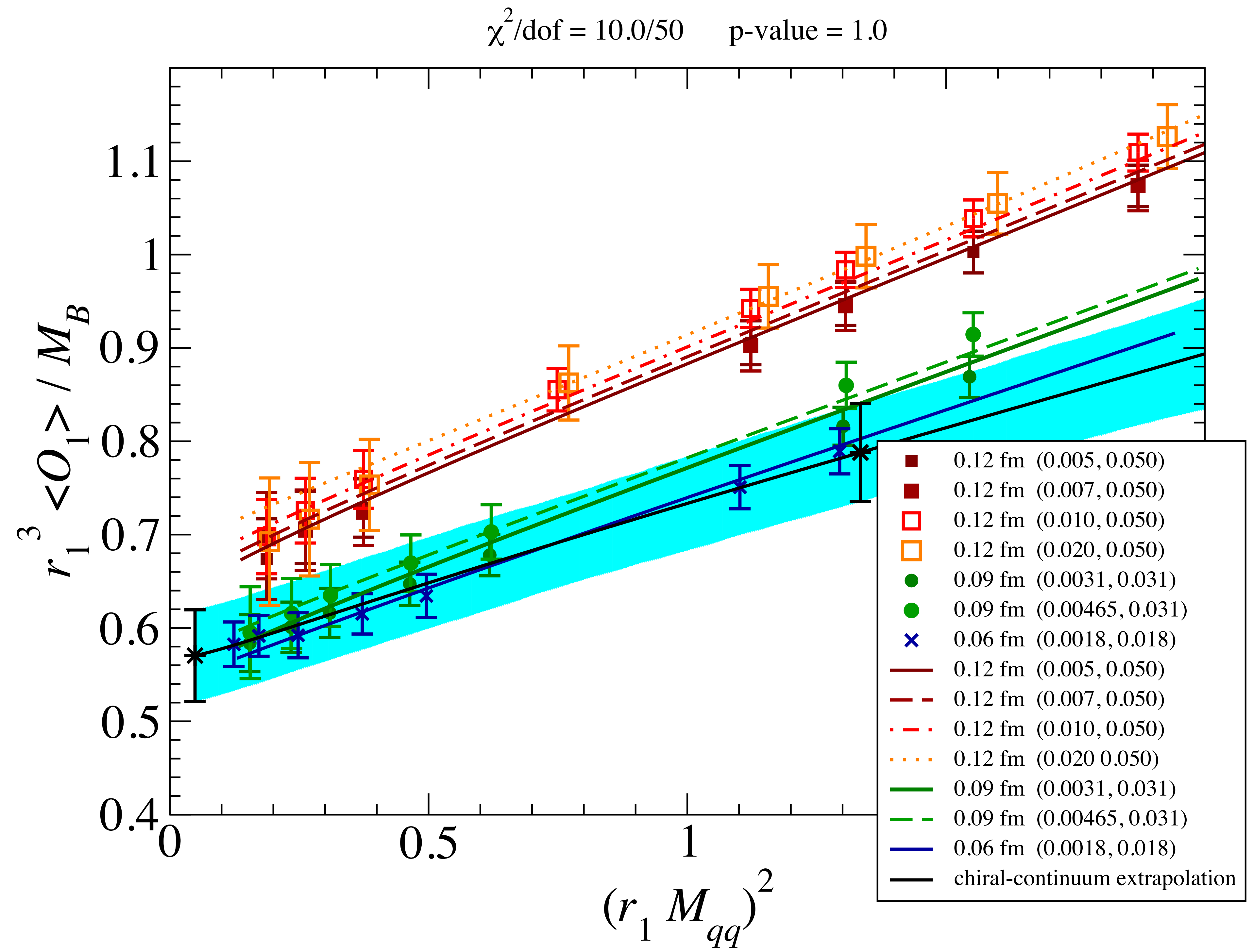
$$\begin{aligned}
O_1 &= (\bar{b}^\alpha \gamma_\mu L q^\alpha)\,(\bar{b}^\beta \gamma_\mu L q^\beta), & O_4 &= (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta R q^\beta),\\
O_2 &= (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta L q^\beta), & O_5 &= (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta R q^\alpha),\\
O_3 &= (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta L q^\alpha), & &
\end{aligned}$$

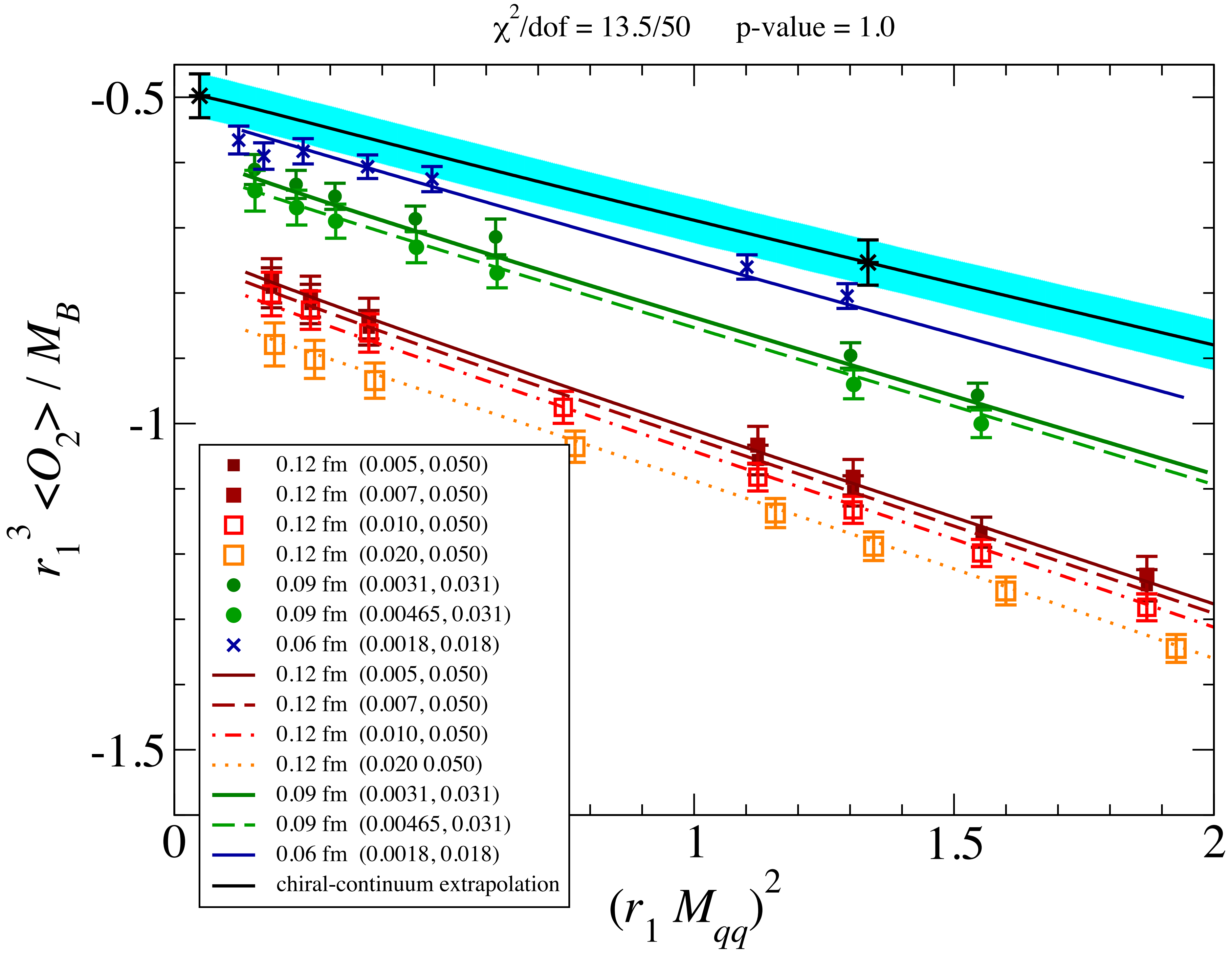
$$\langle B_q^0 | O_i | \bar{B}_q^0 \rangle(\mu) = \mathfrak{c}_i M_{B_q}^2 f_{B_q}^2 B_{B_q}^{(i)}(\mu)$$

- Mass difference (in SM):

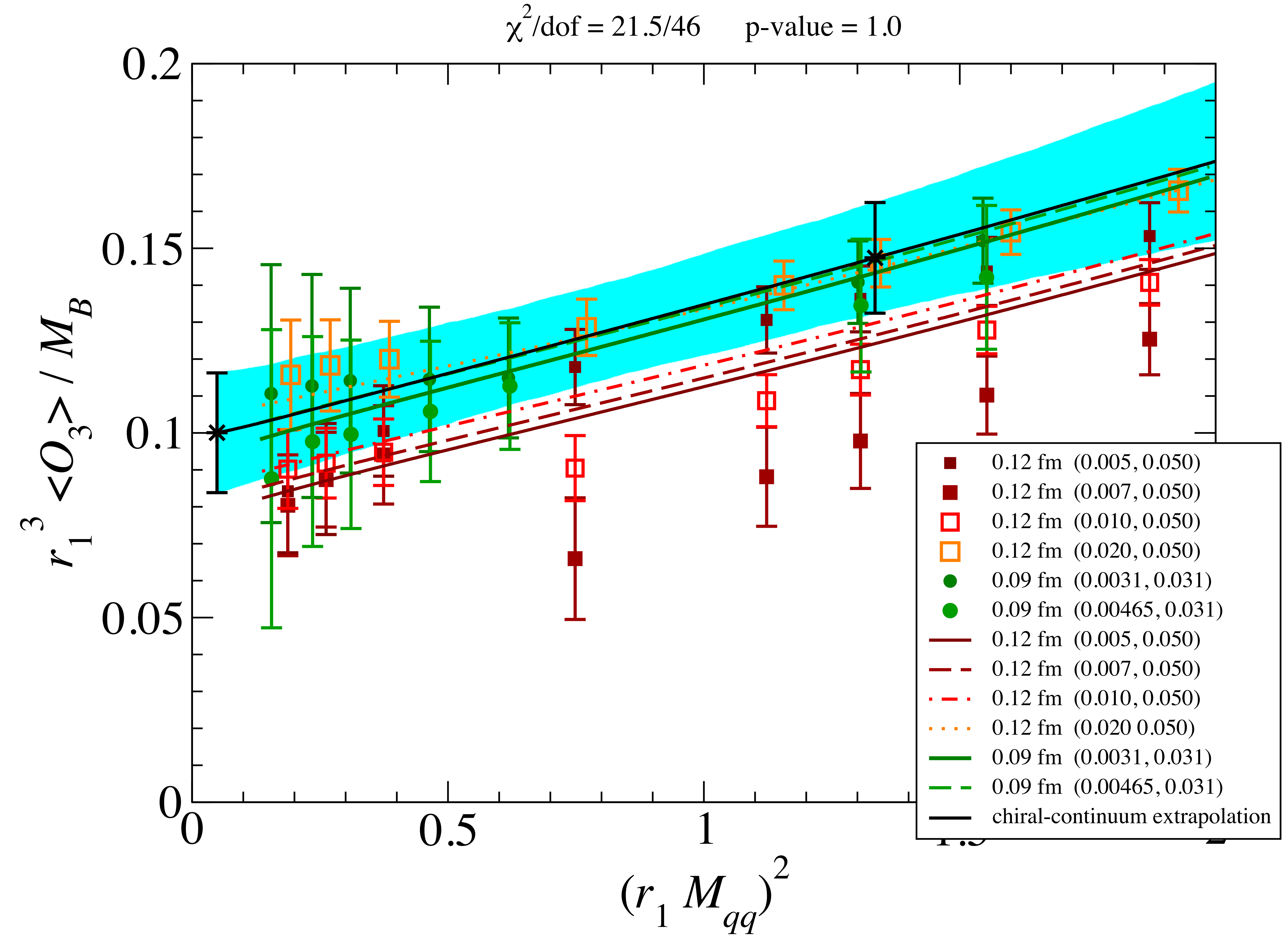
$$\Delta M_q = \frac{G_F^2 M_W^2}{4\pi^2 M_{B_q}} S_0(m_t/M_W) |V_{tb} V_{tq}^*|^2 \eta_B(\mu) \langle B_q^0 | O_1 | \bar{B}_q^0 \rangle(\mu)$$

  but non-Standard particles in loops could induce other terms.

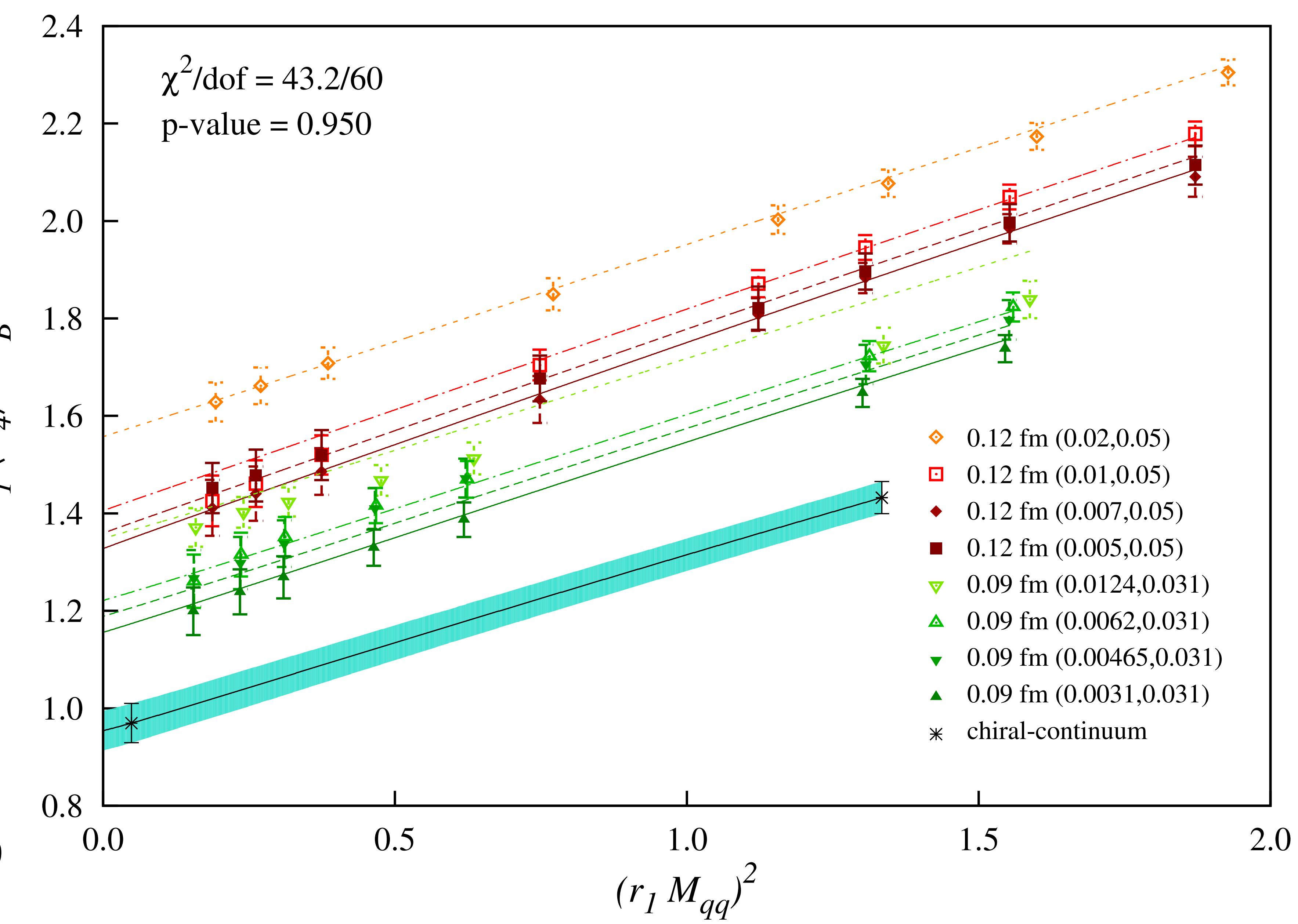




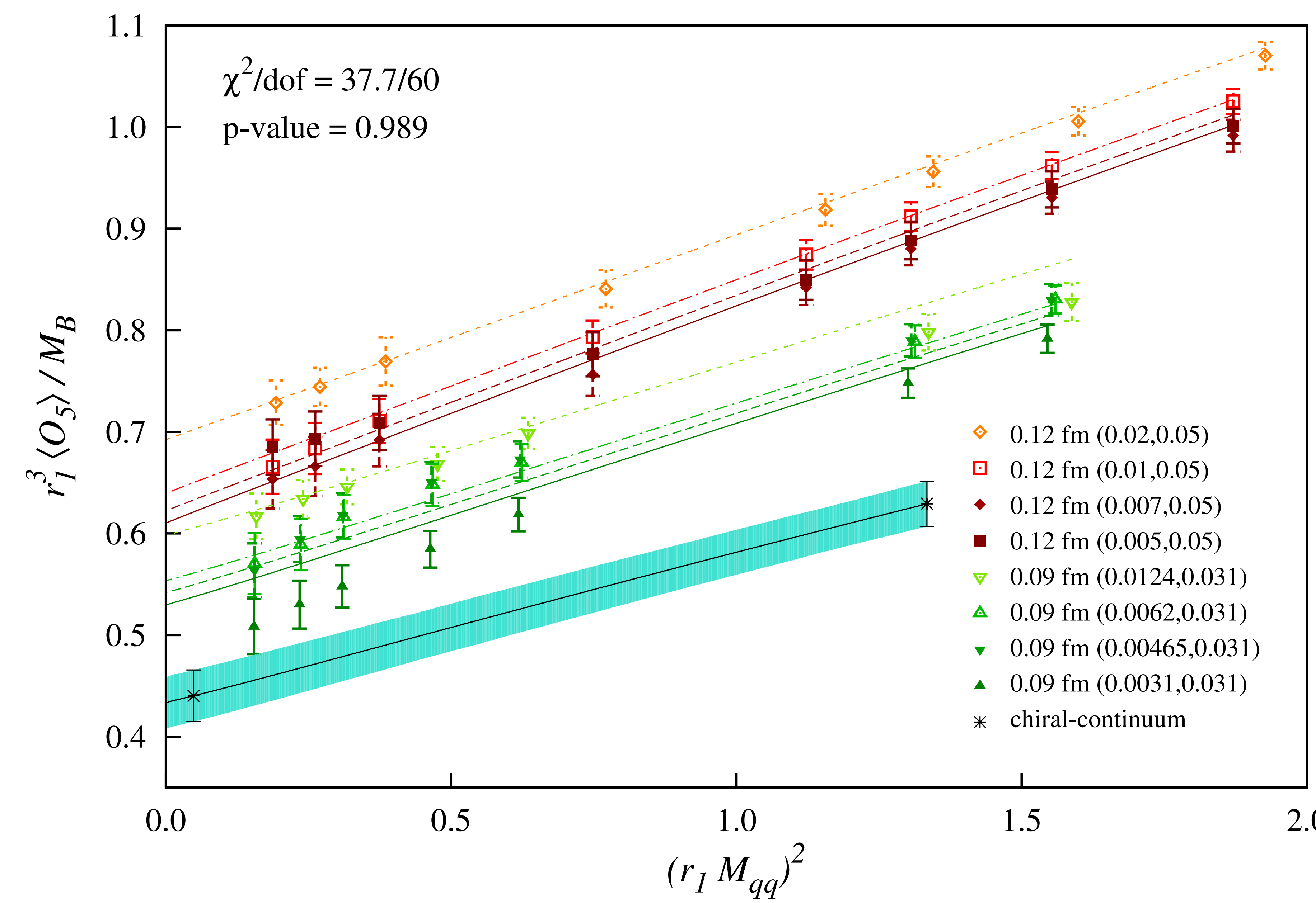
χ2/dof = 13.5/50 p-value = 1.0
r1 3 <O2> / MB
(r1 Mqq)2
0.12 fm (0.005, 0.050)
0.12 fm (0.007, 0.050)
0.12 fm (0.010, 0.050)
0.12 fm (0.020, 0.050)
0.09 fm (0.0031, 0.031)
0.09 fm (0.00465, 0.031)
0.06 fm (0.0018, 0.018)
0.12 fm (0.005, 0.050)
0.12 fm (0.007, 0.050)
0.12 fm (0.010, 0.050)
0.12 fm (0.020 0.050)
0.09 fm (0.0031, 0.031)
0.09 fm (0.00465, 0.031)
0.06 fm (0.0018, 0.018)
chiral-continuum extrapolation



χ2/dof = 21.5/46 p-value = 1.0
r1 3 <O3> / MB
(r1 Mqq)2
0.12 fm (0.005, 0.050)
0.12 fm (0.007, 0.050)
0.12 fm (0.010, 0.050)
0.12 fm (0.020, 0.050)
0.09 fm (0.0031, 0.031)
0.09 fm (0.00465, 0.031)
0.12 fm (0.005, 0.050)
0.12 fm (0.007, 0.050)
0.12 fm (0.010, 0.050)
0.12 fm (0.020 0.050)
0.09 fm (0.0031, 0.031)
0.09 fm (0.00465, 0.031)
chiral-continuum extrapolation



χ2/dof = 43.2/60
p-value = 0.950
r1 3 ⟨O4⟩ / MB
(r1 Mqq)2
0.12 fm (0.02,0.05)
0.12 fm (0.01,0.05)
0.12 fm (0.007,0.05)
0.12 fm (0.005,0.05)
0.09 fm (0.0124,0.031)
0.09 fm (0.0062,0.031)
0.09 fm (0.00465,0.031)
0.09 fm (0.0031,0.031)
chiral-continuum



χ2/dof = 37.7/60
p-value = 0.989
r1 3 ⟨O5⟩ / MB
(r1 Mqq)2
0.12 fm (0.02,0.05)
0.12 fm (0.01,0.05)
0.12 fm (0.007,0.05)
0.12 fm (0.005,0.05)
0.09 fm (0.0124,0.031)
0.09 fm (0.0062,0.031)
0.09 fm (0.00465,0.031)
0.09 fm (0.0031,0.031)
chiral-continuum

Results

arXiv:1112.5642

- We provide results for two choices of evanescent operators (appearing with dimensional regulators):

preliminary

	B_d^0		B_s^0	
$[\mathrm{GeV}^2]$	BBGLN	BJU	BBGLN	BJU
$f_{B_q}^2 B_{B_q}^{(1)}$	0.0411(75)		0.0559(68)	
$f_{B_q}^2 B_{B_q}^{(2)}$	0.0574(92)	0.0538(87)	0.086(11)	0.080(10)
$f_{B_q}^2 B_{B_q}^{(3)}$	0.058(11)	0.058(11)	0.084(13)	0.084(13)
$f_{B_q}^2 B_{B_q}^{(4)}$	0.093(10)		0.135(15)	
$f_{B_q}^2 B_{B_q}^{(5)}$	0.127(15)		0.178(20)	

preliminary

- BBGLN = Beneke, Buchalla, Greub, Lenz, Nierste; BJU = Buras, Jäger, Urban.

Rare Semileptonic Decays $B \to Kll$

Penguins and Form Factors

arXiv:1111.0981

- In the SM, $B \to Kll$ is mediated by penguins and boxes; BSM contributions could compete.

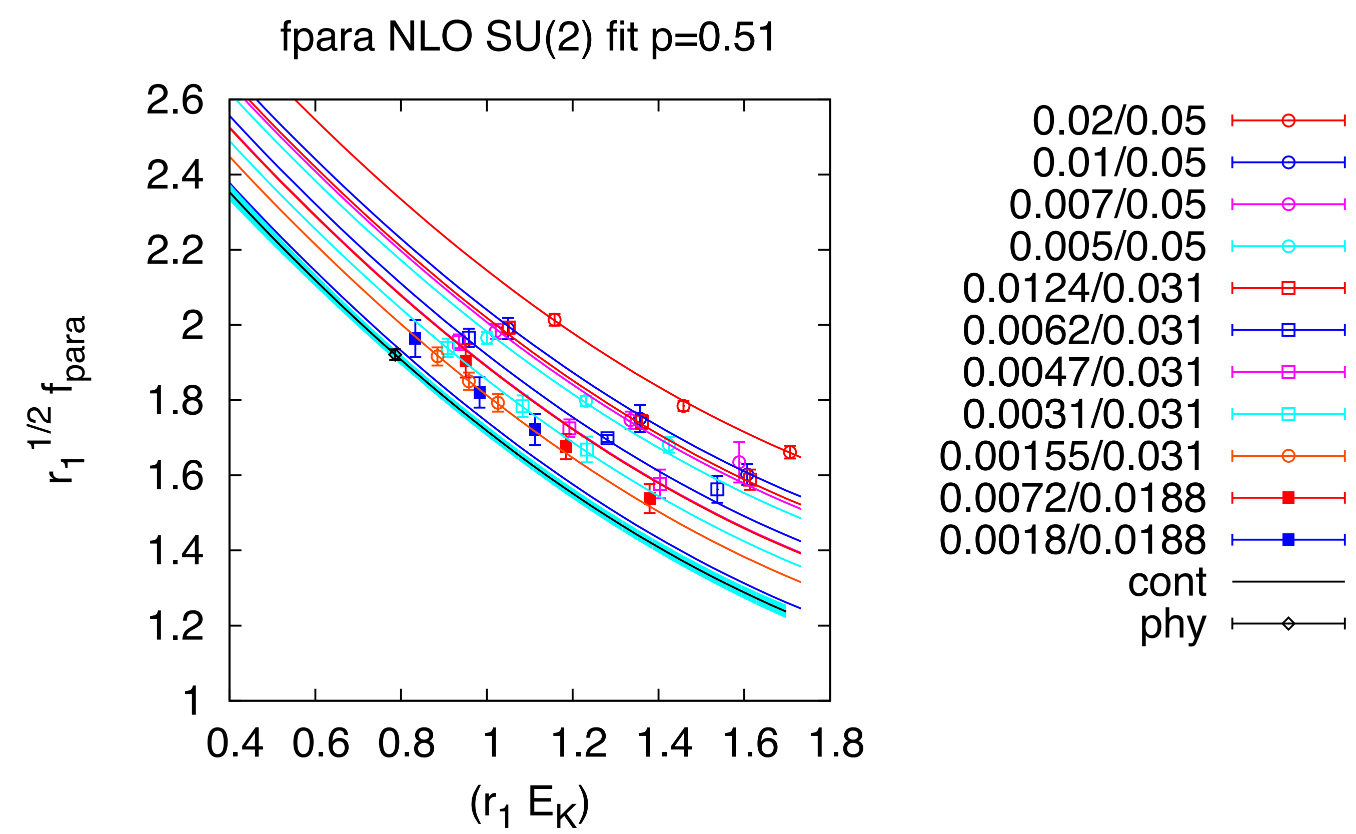
- SM vector & tensor currents lead to f_+, f_0, and f_2:

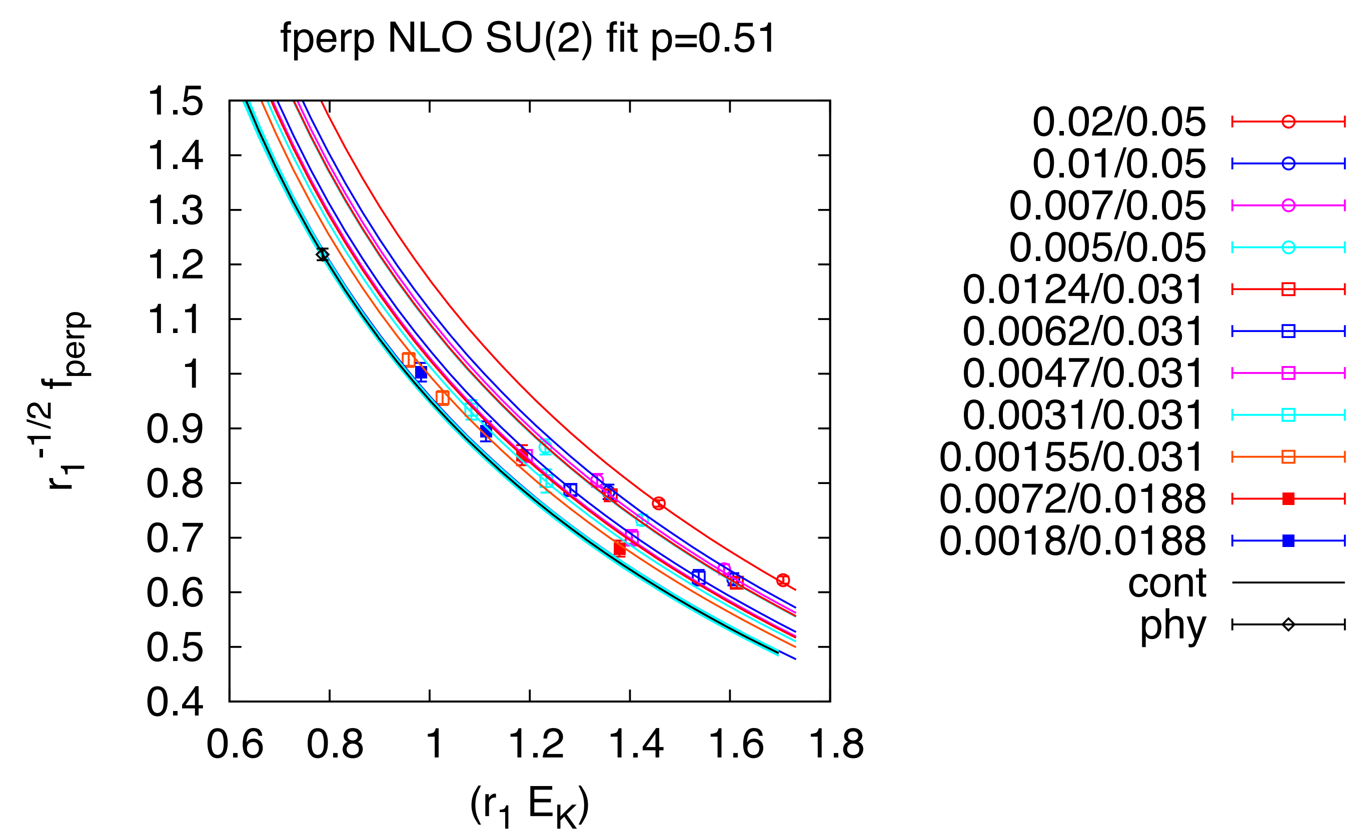
$$\langle K|\bar{s}\sigma^{\mu\nu}b|B\rangle = i(p^\mu k^\nu - p^\nu k^\mu) f_2(q^2)$$

- BSM scalar currents could arise too, f_0 again.

- Chiral extrapolation with $f_\perp$ & $f_\parallel$:

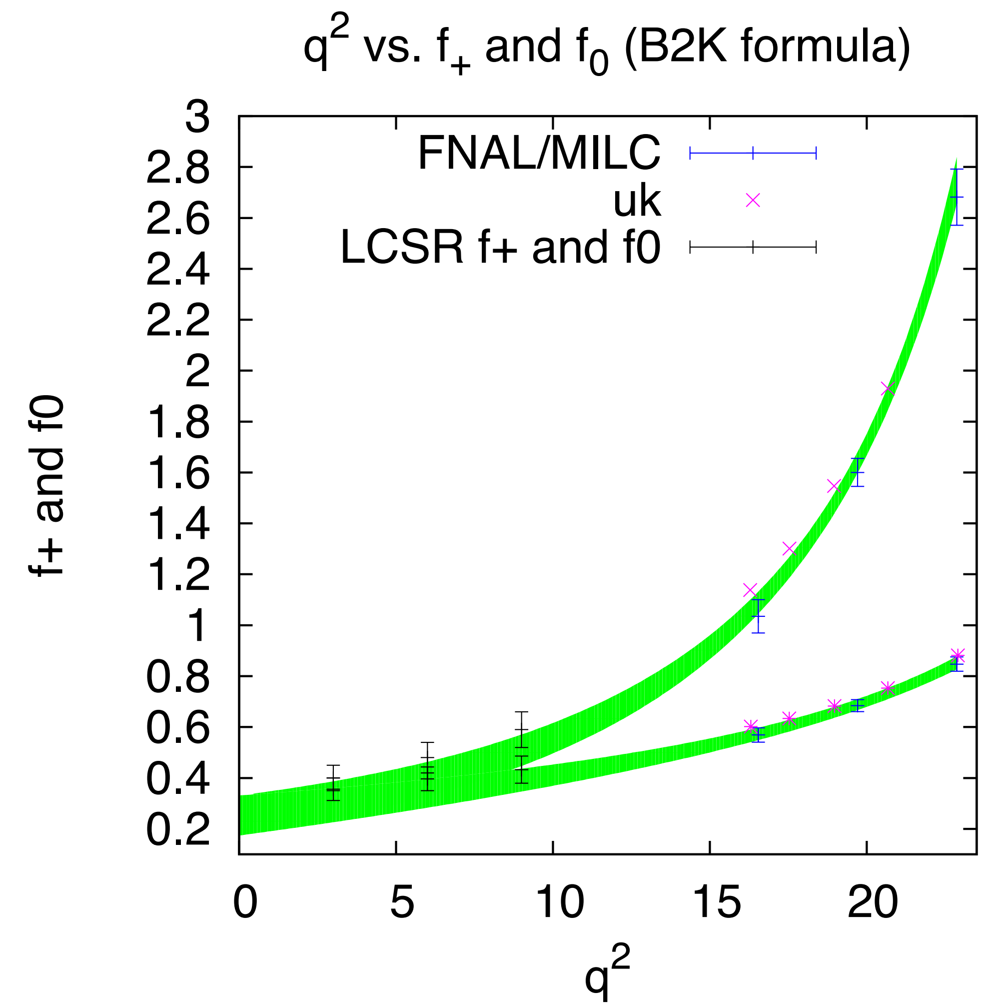
$$\langle K|i\bar{s}\gamma^4 b|B\rangle = \sqrt{2m_B} f_\parallel(q^2)$$
$$\langle K|i\bar{s}\gamma^i b|B\rangle = \sqrt{2m_B} p_K^i f_\perp(q^2)$$

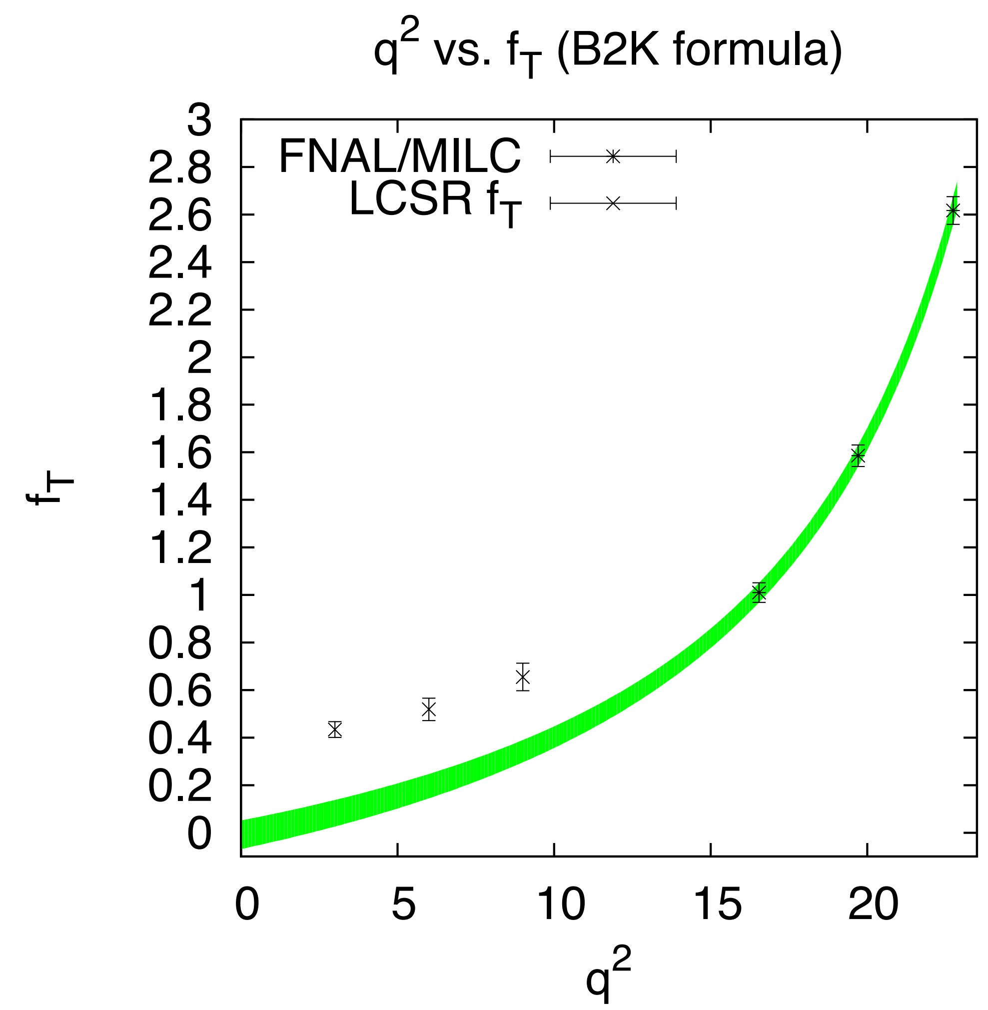




Analysis Details and Steps in Progress

- SU(2) χPT works better than SU(3).
- Since Lattice 2011, analysis for f_+ & f_2 has been fine-tuned.
- Analysis for f_2 is well underway.
- z expansion for full q^2 range (very preliminary):





very, very preliminary

Rare Leptonic Decay $B_s \to \mu^+\mu^-$ at Hadron Colliders

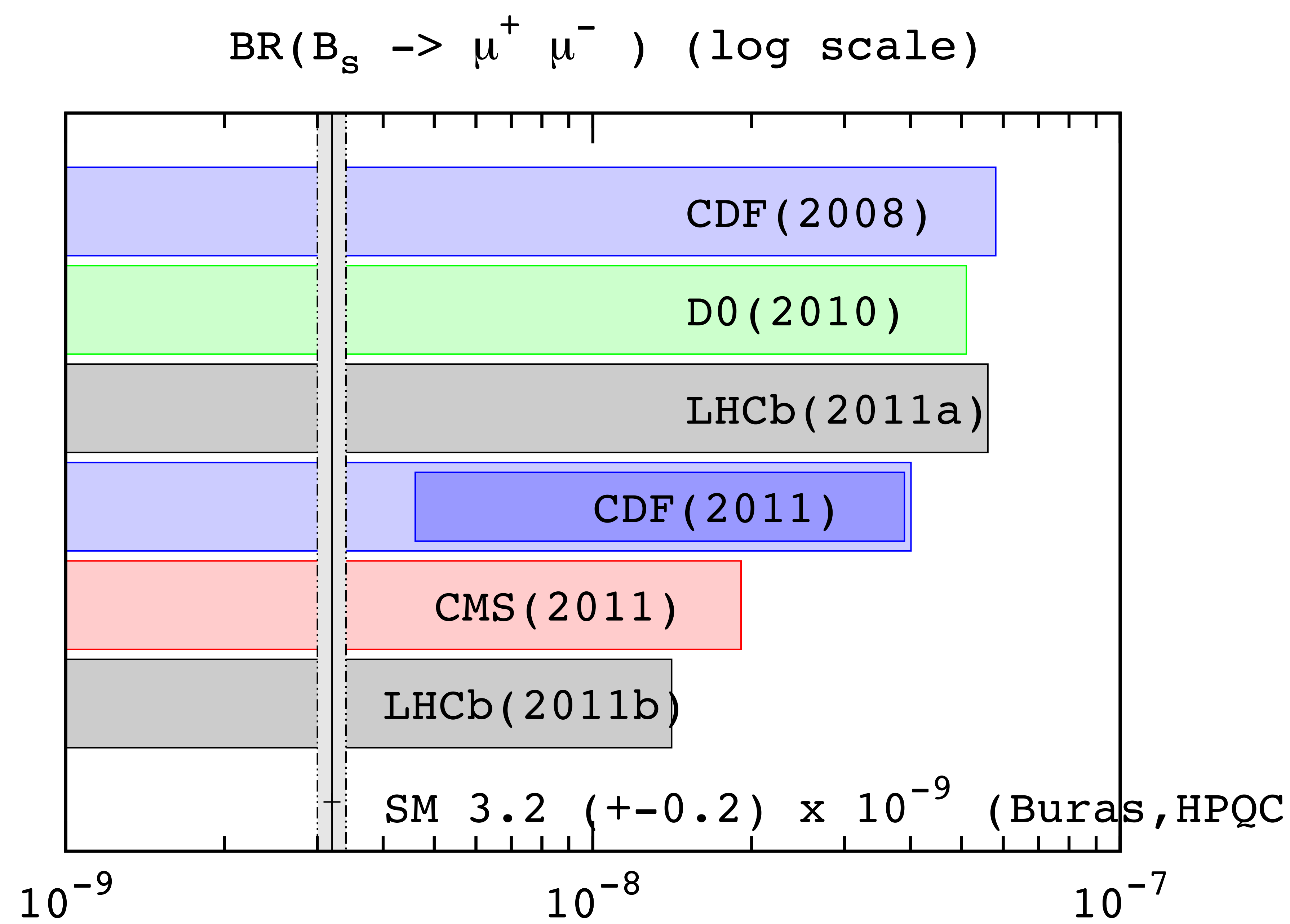
arXiv:1202.6346

Rare Decay $B_s \to \mu^+\mu^-$

- SM rate is small, $\mathrm{BR} = (3.2 \pm 0.2)\times 10^{-9}$.
- Subject of active search at hadron colliders LHC and Tevatron (02/2012 plot out of date!).
- Could be much larger in models with two Higgs doublets: BSM rate $\sim \tan^4\beta$.
- At hadron colliders, measure ratio of BRs:

$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B^0 \to X)\frac{f_d}{f_s}\frac{\varepsilon_X}{\varepsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}$$

- Thus, need f_d/f_s.



Fleischer, Serra, Tuning

arXiv:1004.3982

- CDF (and LEP experiments) used semileptonic decays.

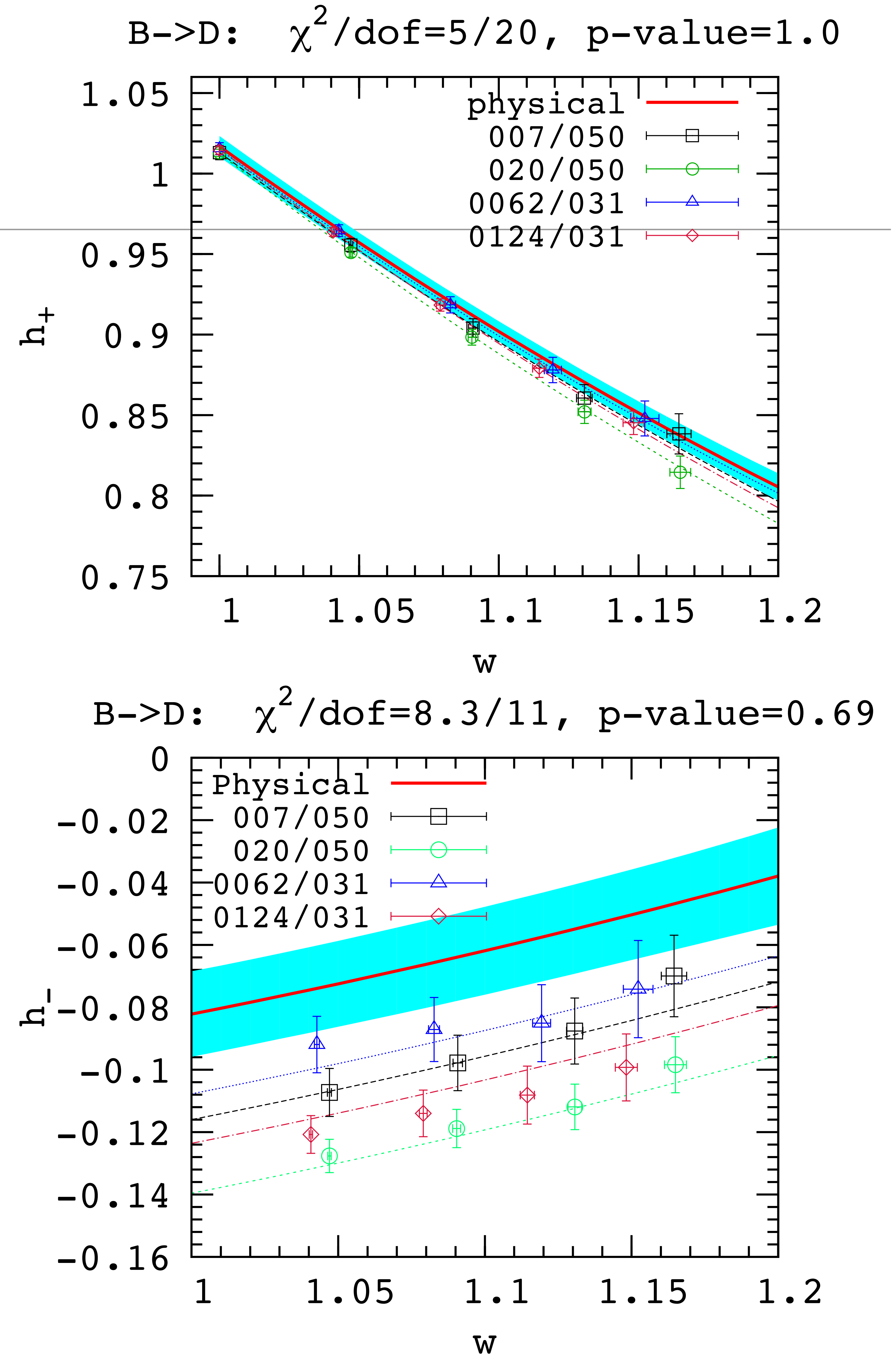
- FST proposed using hadronic decays, plus (QCD-inspired) factorization:

$$\frac{f_s}{f_d} = 0.0743 \times \frac{\tau_{B^0}}{\tau_{B_s^0}} \times \left[\frac{\varepsilon_{DK}}{\varepsilon_{D_s\pi}} \frac{N_{D_s\pi}}{N_{DK}}\right] \times \frac{1}{\mathcal{N}_a \mathcal{N}_F}$$

$$\mathcal{N}_a = \left[\frac{a_1^{(s)}(D_s^+\pi^-)}{a_1^{(d)}(D^+K^-)}\right]^2$$

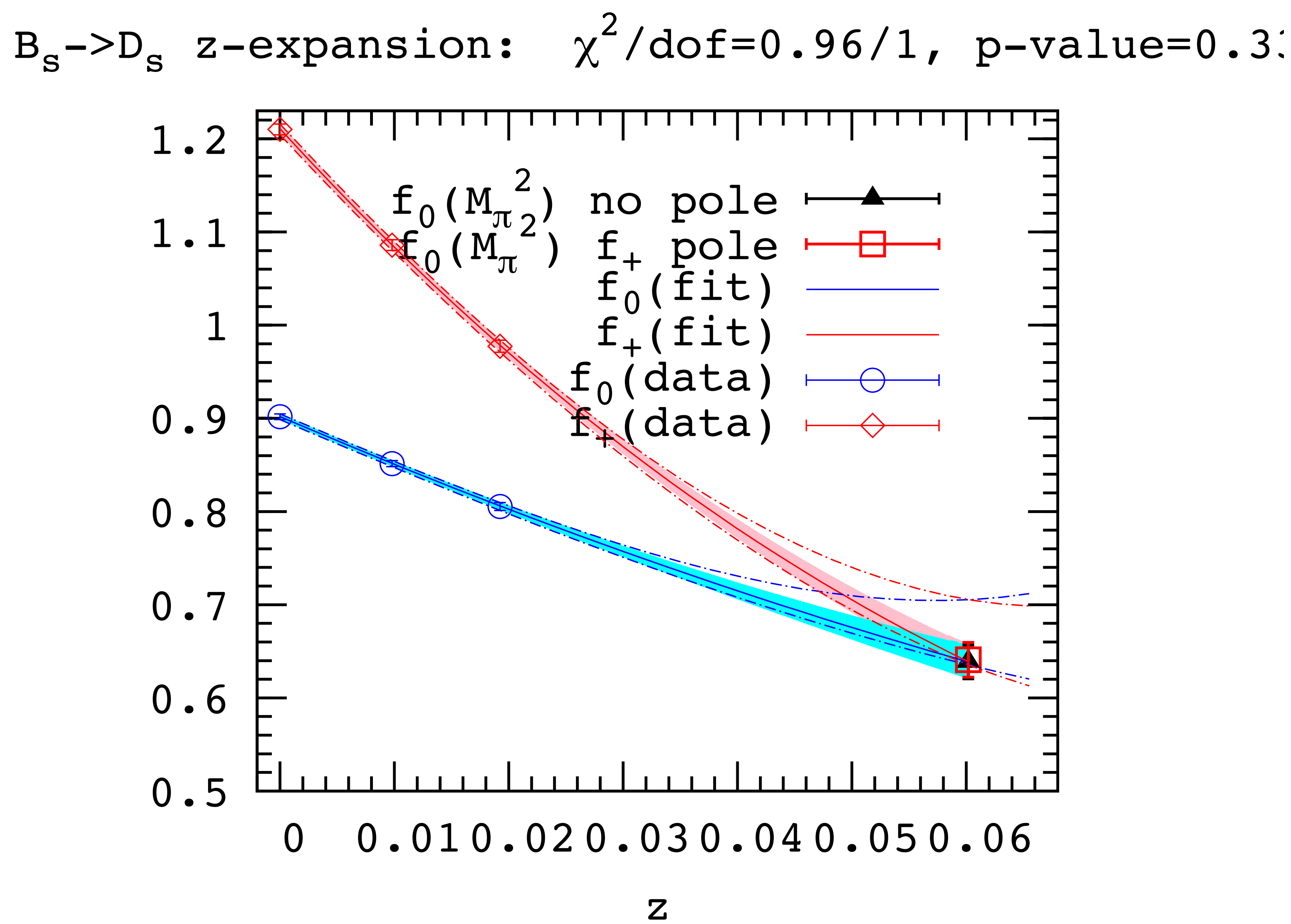
$$\mathcal{N}_F = \left[\frac{f_0^{(s)}(M_\pi^2)}{f_0^{(d)}(M_K^2)}\right]^2$$

- Same form factors as before.

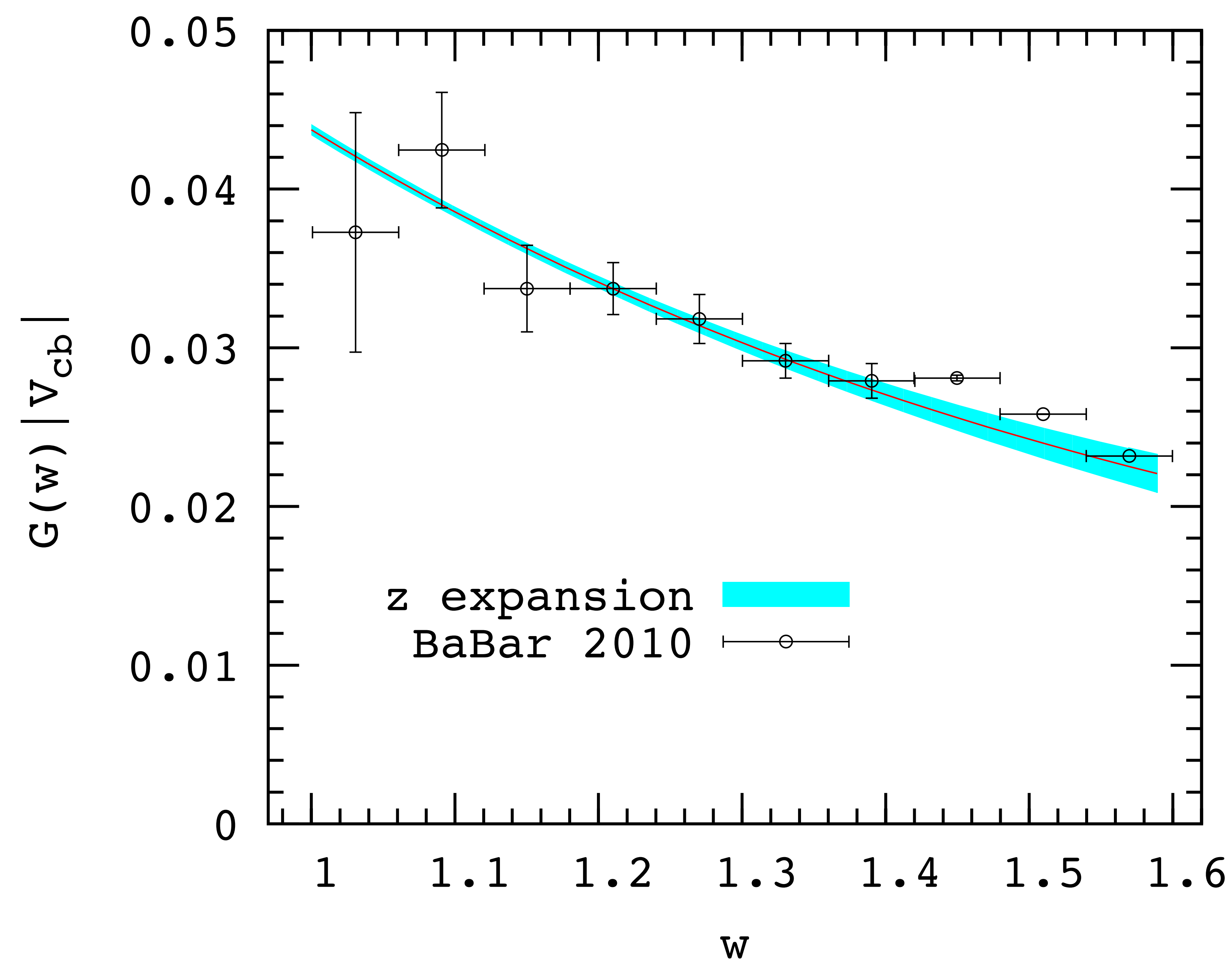


Spot checks of f_+ and Result for f_0 Ratio:

- Use z expansion to reach the small q^2 required:



- Test of results vs. BaBar data:



- Result close to unity: $\dfrac{f_0^{(s)}(M_\pi^2)}{f_0^{(d)}(M_K^2)} = 1.046(44)(15)$, consistent with other lattice-QCD form factors [HPQCD].

Outlook, Conclusions

- Belle and BaBar data warrant extension of $|V_{cb}|$ and $|V_{ub}|$ analyses for to the full asqtad statistics.
- LHC*b* experiment (and interplay with CMS & ATLAS) warrant calculations for B_s meson.
- BES 3 charm and CERN (and Fermilab?!) kaon programs make D and K physics timely (Elvira's talk).
- MILC's HISQ 2+1+1 ensembles, some with $m_\mathrm{l} = (m_\mathrm{u} + m_\mathrm{d})/2$, await.
- For these, and with an eye to future super B factories, need smaller heavy-quark discretization effects:
    - clover or OK action with nonperturbative + two-loop matching?
    - HISQ action for b quarks? with extrapolation and/or "He's so fine!" lattices?