Hadron spectrum and light pseudoscalar decay constants

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Lattice 2010, Villasimius
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SFB
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Outline

This review will cover recent results on

- Light quark QCD spectrum
  - Ground states
  - Excited states
- Decay constants f_π and f_K

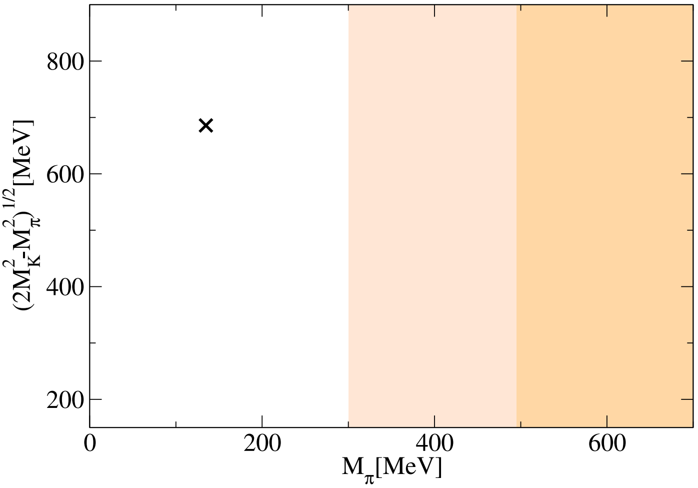
I will discuss where we stand with respect to

- Reaching the physical point
- Taking the continuum limit
- Taking the infinite volume limit

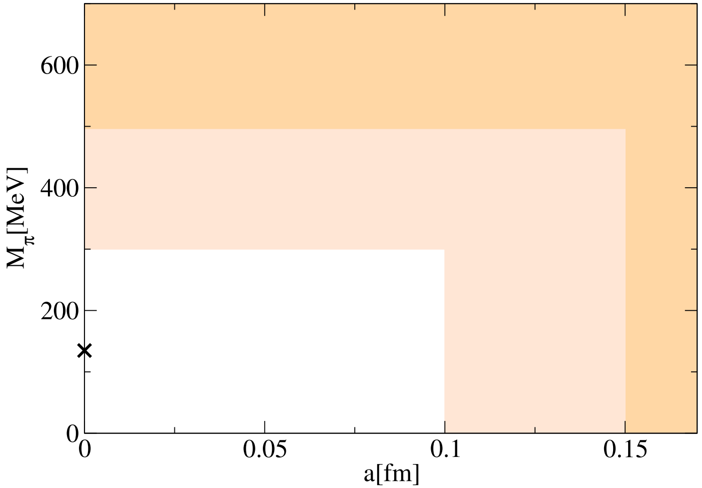
I will discuss what needs to be done to further increase accuracy

Light flavors: ☞J .Laiho (Sat) Heavy flavors: ☞J. Heitger (Fri)

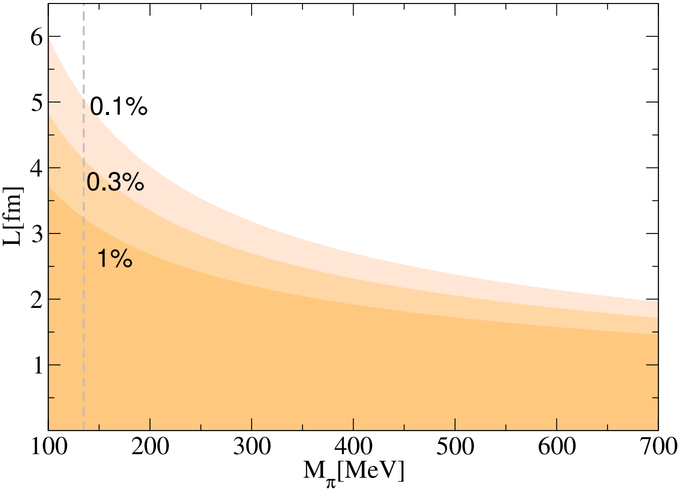
Reaching the physical point



Taking the continuum limit



Taking the infinite volume limit

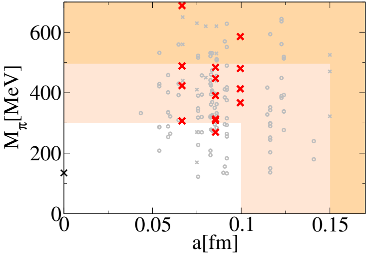


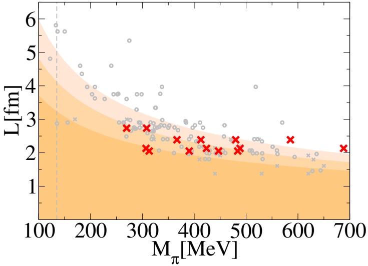
Error on m_π from χPT (Collangelo, Durr, Haefeli, ’05)

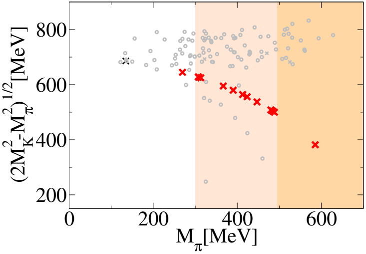
ETMC 2 Flavor (Alexandrou et. al. '09)

Gauge	Ferm.	N_f
Symanzik	TM	2

$a \to 0$	χ	FV	FV Res	Flavor
2	✓	✓	✗	✓



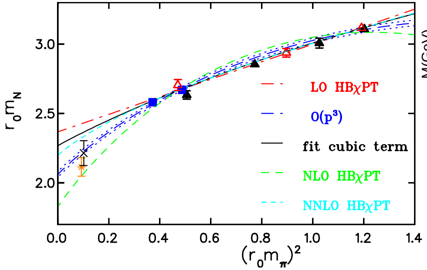


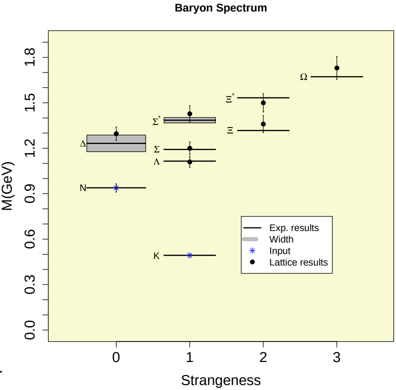


ETMC Baryon Spectrum

- Different chiral forms for different baryons
- 2 lattice spacings for continuum extrapolation
- Flavor breaking: π, Ξ

☞V. Drach(Tue)



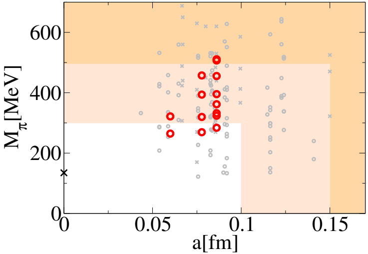


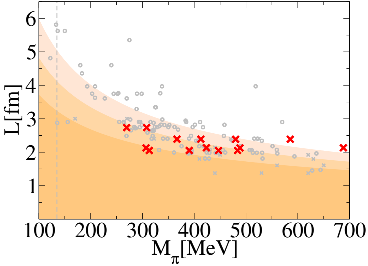
ETMC 2+1+1 Flavor (Baron et. al. '10)

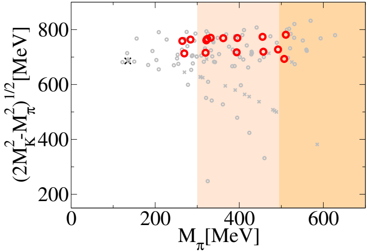
Gauge	Ferm.	N_f
Iwasaki	TM	2+1+1

$a \to 0$	χ	FV	Flavor
3	✓	✗	✓

☞S. Reker (Mon)



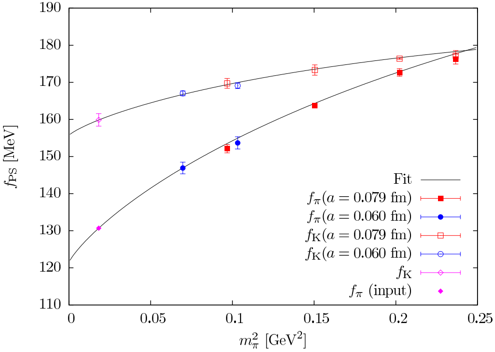




ETMC Decay Constants

- $N_f = 2+1+1$
- Scale set by f_π / m_π
- NLO χ fits
- NNLO for systematic error
- f_0=121.14(8)(19)MeV

- $f_K / f_\pi = 1.210(18)$
  from $N_f = 2$
  (Blossier et. al. '09)
- preliminary $2+1+1$:
  $f_K / f_\pi = 1.22(1)$
  ☞C. Urbach (Mon)

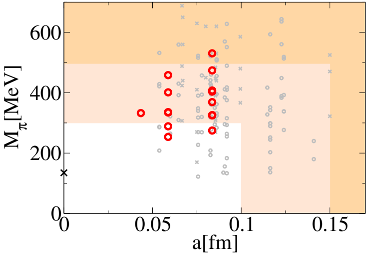


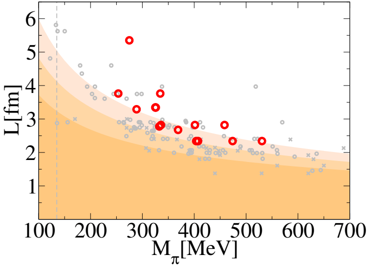
☞Plenary by G. Herdoiza(Mon)

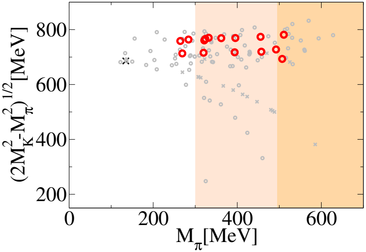
MILC (Bazavov et. al. '09)

Gauge	Ferm.	N_f
Symanzik	Asqtad	2+1

$a \to 0$	χ	FV	FV Res	Taste
3	✓	✓	✗	✓







MILC (Bazavov et. al. '09)

Gauge	Ferm.	N_f
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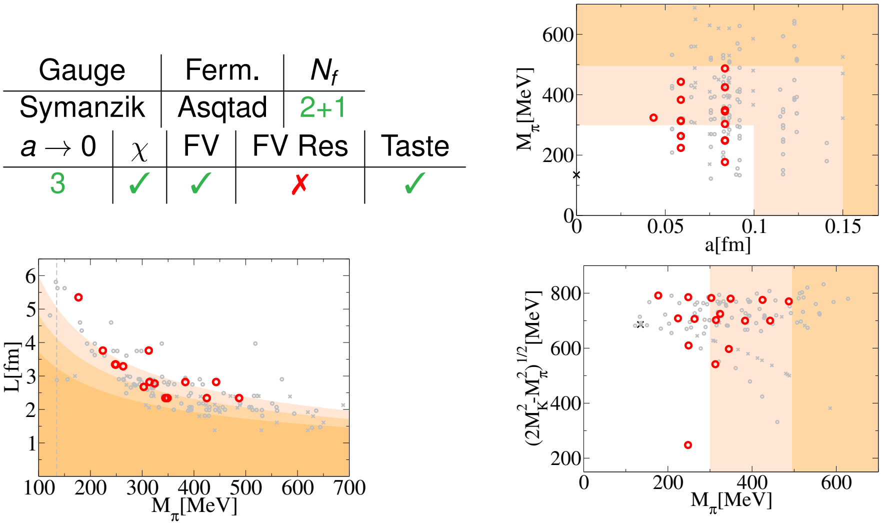
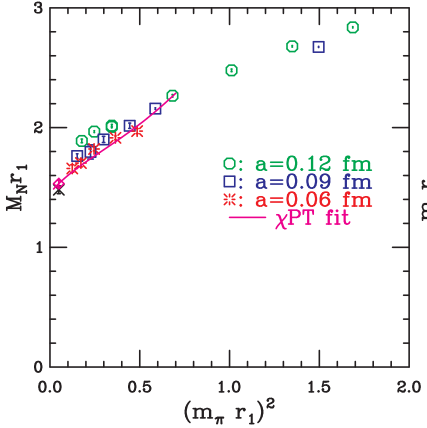
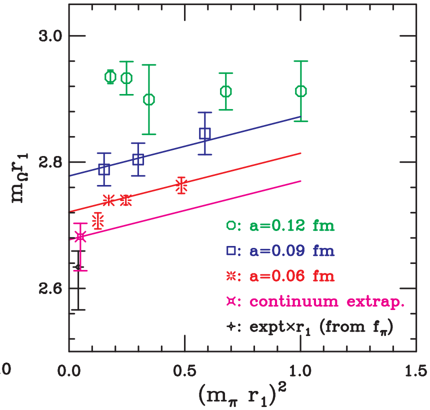
$a \to 0$	χ	FV	FV Res	Taste
3	✓	✓	✗	✓



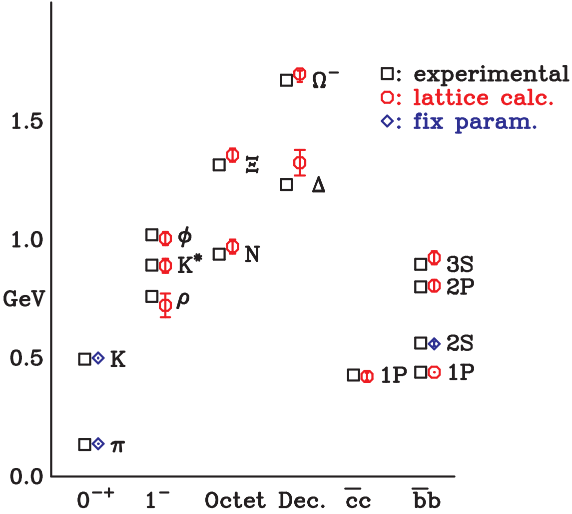
MILC Baryon Spectrum

- Different fit strategies for different baryons
- Relatively large discretization effects





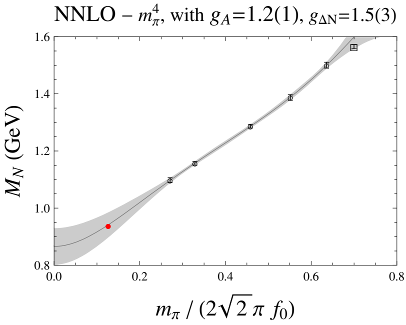
MILC Baryon Spectrum

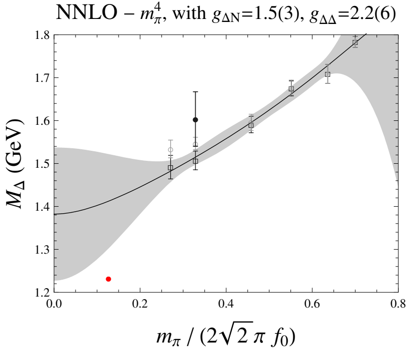


η' would be interesting for conceptual reasons (check staggered anomaly)

LHP Baryon Spectrum (Walker-Loud et. al. '09)

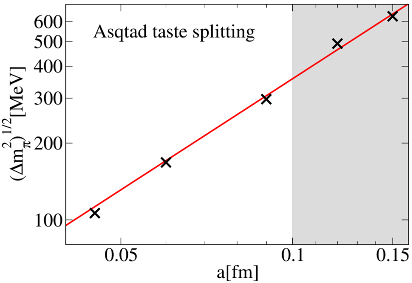
- DW on Asqtad, $a \approx 0.12$fm ensemble
- SU(2)/SU(3) HBχ PT, FV corrections





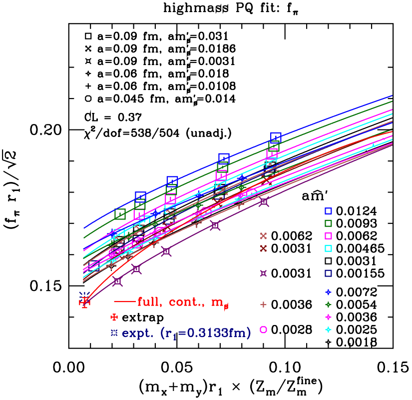
MILC Decay Constants Setup

- Partially quenched $N_f = 2 + 1$ ensembles
- Cascaded fits:
  - Fix SU(3) LECs with $m < 0.6 m_s^{\text{phys}}$ (N^2LO)
  - Use LECs and add analytic N^3LO, N^4LO to fit full set
- Crosscheck with SU(2) for light quark observables (up to N^2LO)
- Scale set by r_1
- Taste splitting $\sqrt{\Delta m_\pi^2} < m_\pi^{\text{phys.}}$ for finest lattices



MILC Decay Constants

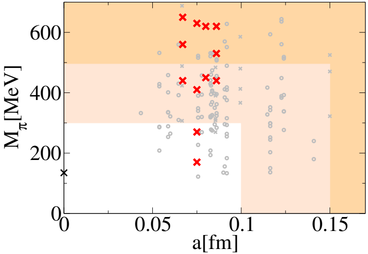
- $f_\pi = 129.2(4)(1.4)\text{MeV SU(3)}$
  $f_\pi = 130.2(1.4)\binom{2.0}{1.6}\text{MeV SU(2)}$
- $f_K = 156.1(4)\binom{2.0}{1.6}\text{MeV}$
- $f_K/f_\pi = 1.197(2)\binom{3}{7}$
- $f_3 = 118.0(3.6)(4.6)\text{MeV}$
- $f_2 = 123.0(5)(7)\text{MeV}$
  $f_2 = 123.8(1.4)\binom{1.0}{3.7}\text{MeV}$

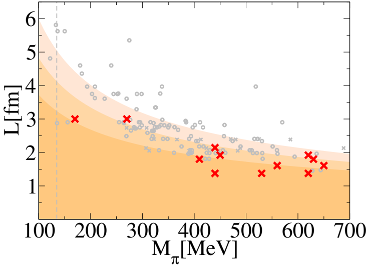


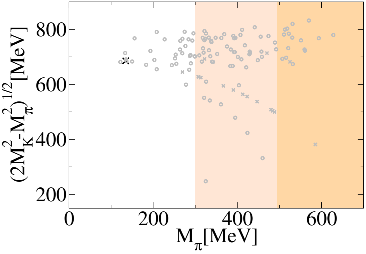
QCDSF 2 Flavor

Gauge	Ferm.	N_f
Symanzik	SLiNC	2

$a \to 0$	χ	FV	FV Res
3	✓	✓	✓



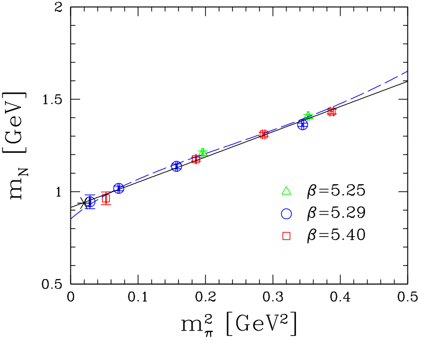




QCDSF $N_f = 2$ Baryon Spectrum

- Minimal discretization effects
- Best fit of nucleon $\propto m_\pi^2$

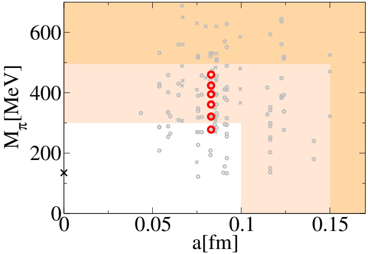
☞G. Schierholz (Mon)

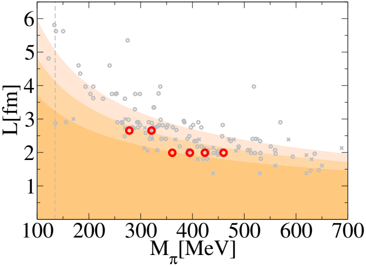


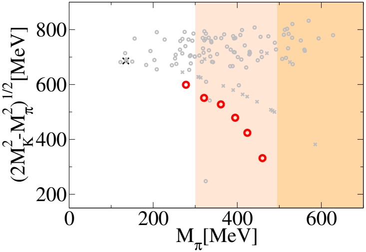
QCDSF 2+1 Flavor (Bietenholz et. al. '10)

Gauge	Ferm.	N_f
Symanzik	SLiNC	2+1

$a \to 0$	χ	FV	FV Res
✗	✓	✗	✗



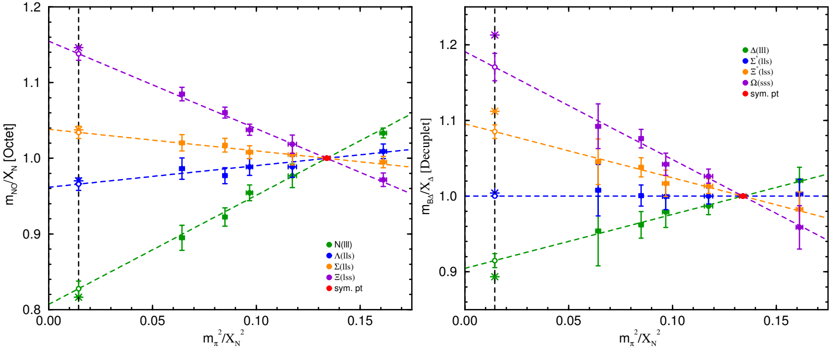




QCDSF Baryon Spectrum

- χ limit with fixed singlet quark mass (LO): $2m_K^2 + m_\pi^2 = \text{const}$
- Gell-Mann Okubo linear fit

☞P. Rakow, R. Horsley (Tue)



QCDSF Decay Constants

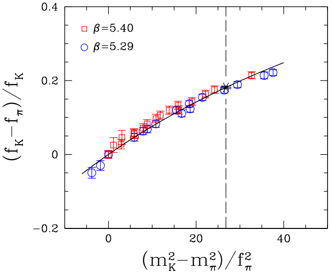
- $N_f = 2$
- Scale set by m_N
- Finite volume, continuum
- Preliminary:

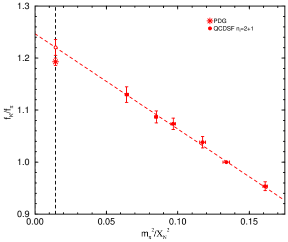
  $f_K/f_\pi = 1.222(6)$

  ☞G. Schierholz (Mon)

- $N_f = 2 + 1$
- Scale set by $X_N \equiv m_{\text{Octet}}$
- No systematics yet
- Preliminary:

  $f_K/f_\pi = 1.221(15)$

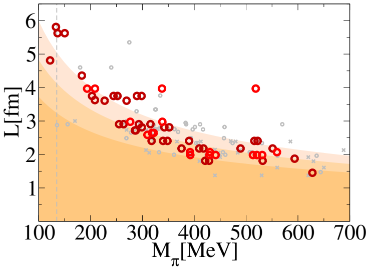


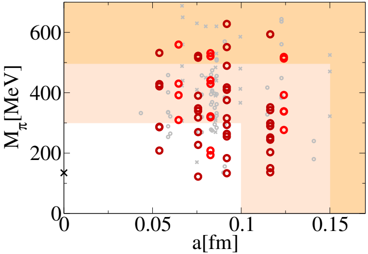


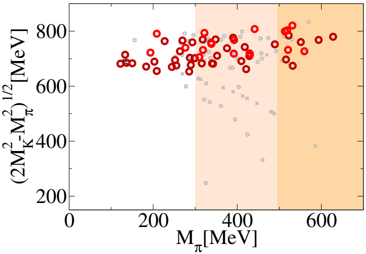
BMW (Durr et.al. '08, Durr et.al. '10)

Gauge	Ferm.	N_f
Symanzik	Clover	2+1

$a \to 0$	χ	FV	FV Res
3	✓	✓	✓

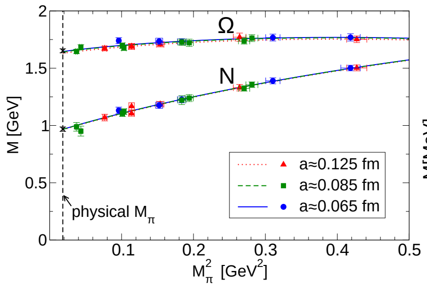


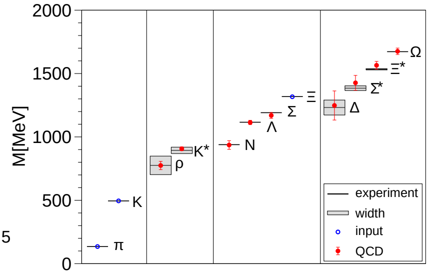




BMW Baryon Spectrum (Durr et.al. '08)

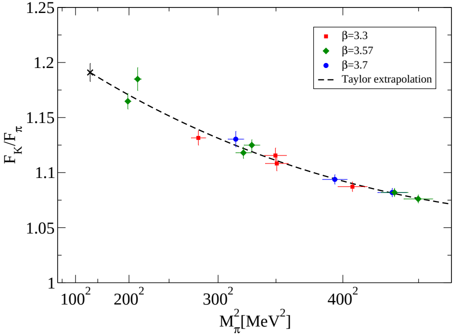
- 3 lattice spacings for continuum extrapolation
- Non-relativistic heavy baryon χPT and Taylor χ fits
- Resonances: ground state FV energy shift

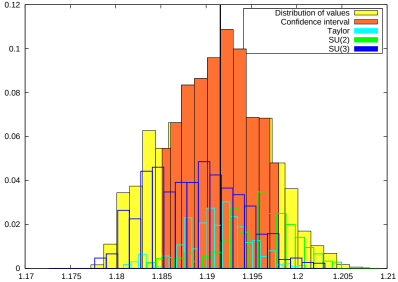




BMW Decay Constants (Durr et.al. '10)

- SU(2), SU(3) and Taylor χ fits
- Full error analysis
- f_K/f_π=1.192(7)(6)

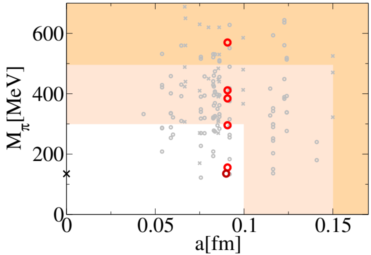


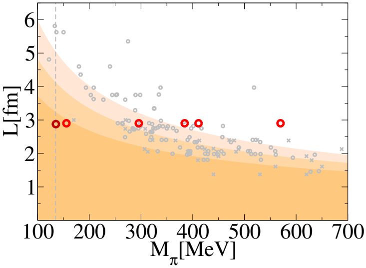


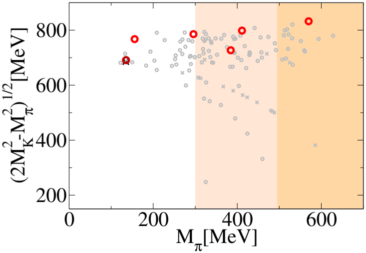
PACS-CS (Aoki et. al. ’09, Aoki et. al. ’10)

Gauge	Ferm.	N_f
Iwasaki	Clover	2+1

$a \to 0$	χ	FV	FV Res
✗	✓	✗	✗

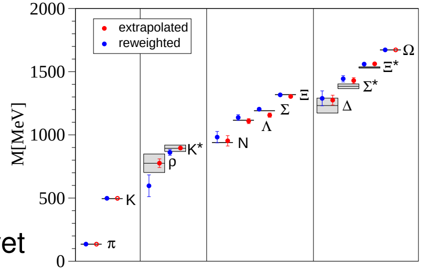






PACS-CS Baryon Spectrum and Decay Constants

- Reweighted to physical point
- 1 lattice spacing
- $m_\pi L \sim 1.97$



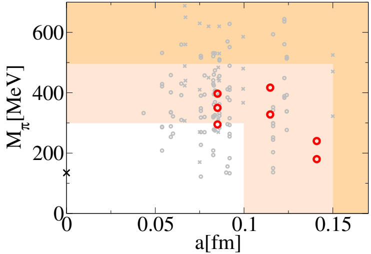
- No treatment of resonant states yet
  - Still good agreement with resonance spectrum
  - Small V: minimum momentum $p_{\mathrm{min}} \equiv \frac{2\pi}{L} > m_\rho^{\mathrm{phys}}/2$
- Decay constants:

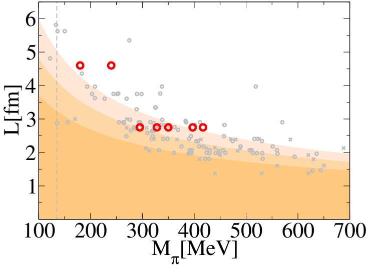
	reweighted	extrapolated
f_π[MeV]	124.1(8.5)(0.8)	134.0(4.2)
f_K[MeV]	165.5(3.4)(1.0)	159.4(3.1)
f_K/f_π	1.333(72)	1.189(20)

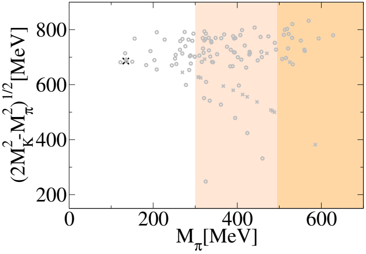
RBC/UKQCD

Gauge	Ferm.	N_f
Iwasaki	DW	2+1

$a \to 0$	χ	FV	FV Res
3	✓	✓	✗



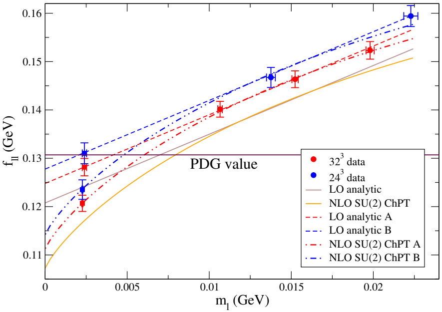


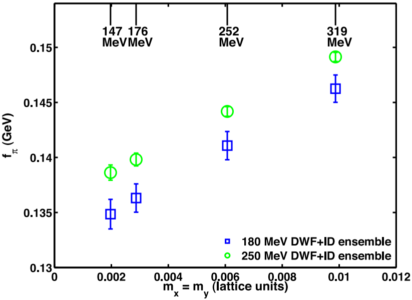


RBC/UKQCD Decay Constants ☞C. Kelly(Tue)

- Continuum, FV, Ω scale
- SU(2) and Taylor fits
- (Prelim. DSDR gauge)

- $f_\pi = 122(2)(5)_\chi(2)_{\mathrm{FV}}\mathrm{MeV}$
- $f_K = 147(2)(4)_\chi(1)_{\mathrm{FV}}\mathrm{MeV}$
- $f_K/f_\pi = 1.208(8)(23)_\chi(14)_{\mathrm{FV}}$

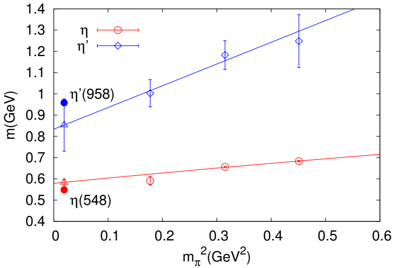


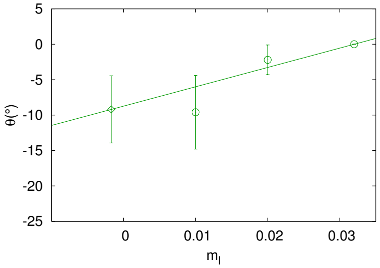


RBC/UKQCD η and η'

- $a \approx 0.11$fm, $m_\pi \sim 400 - 700$MeV
- 2-state operators, compute masses and mixing angle

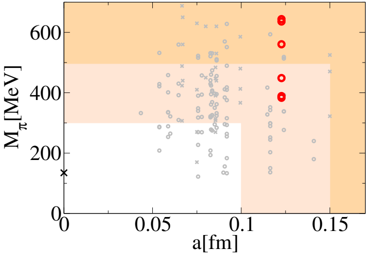
	m_η[MeV]	$m_{\eta'}$[MeV]	$\theta[°]$
RBC/UKQCD	583(15)	853(123)	-9.2(4.7)
Expt.	548	958	

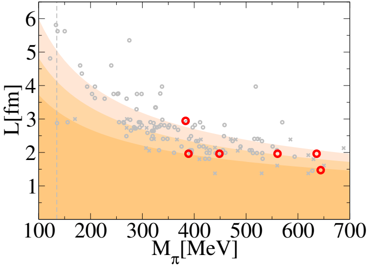


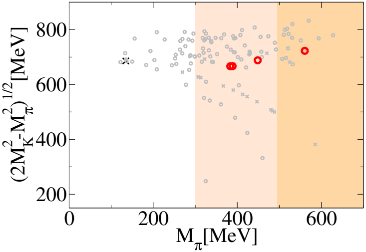


Hadron Spectrum Collaboration (Bulava et. al. '10)

Gauge		Ferm.		N_f
Symanzik		Aniso Clover		2+1
$a \to 0$	χ	FV	FV Res	
✗	✗	✗	✗	

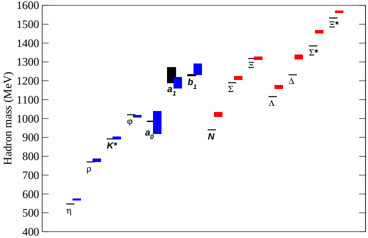


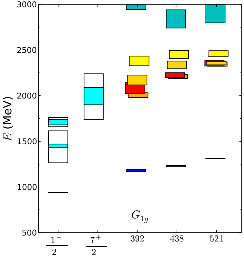


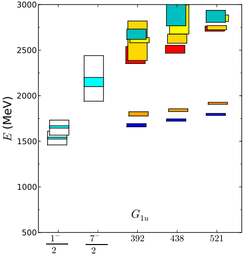


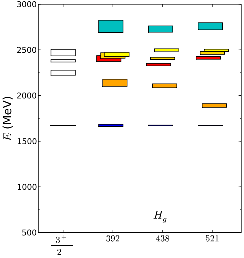
HSC (Excited) Hadron Spectrum

- Anisotropic lattices ($16^3 \times 128$)
- Variational method
- Need for multi-hadron interpolating operators





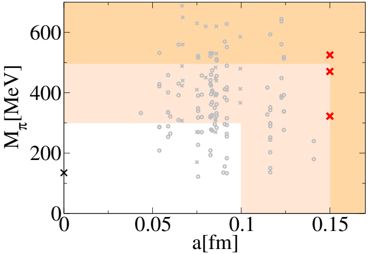


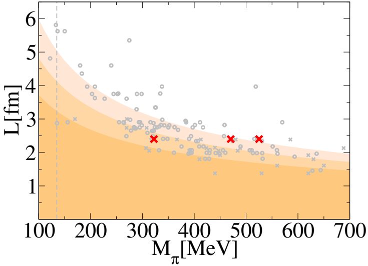


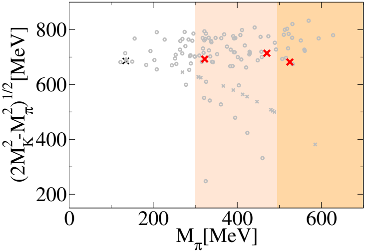
BGR (Engel et. al. '10)

Gauge	Ferm.	N_f
Symanzik	CI	2

$a \to 0$	χ	FV	FV Res
✗	✓	✗	✗



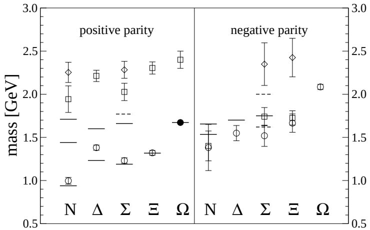


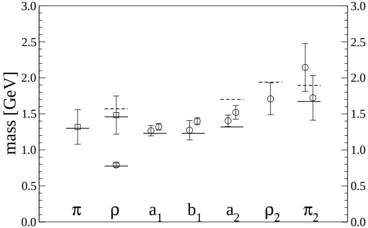


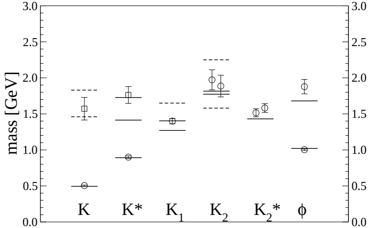
BGR (Excited) Hadron Spectrum

- Variational method
- Reasonable ground states
- Weak signals for excited and scattering states
- Finite volume effects

☞G. Engel (Mon)





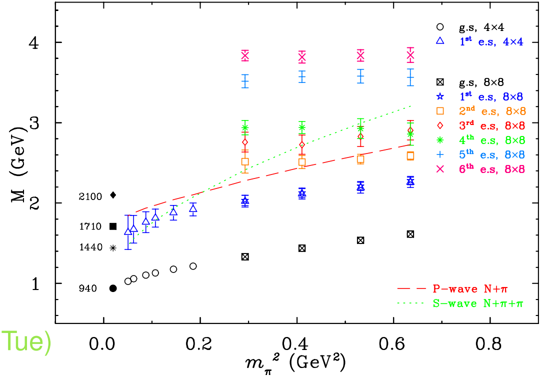


CSSM Nucleon Excitations (Mahbub et. al. ’10)

Gauge	Ferm.	N_f
DBW2	FLIC	0

$a \to 0$	χ	FV	FV Res
✗	✓	✗	✗

- Variational method (up to 8×8)
- $16^3 \times 32$, $a \sim 0.13$fm
- Signal for 3 excited states



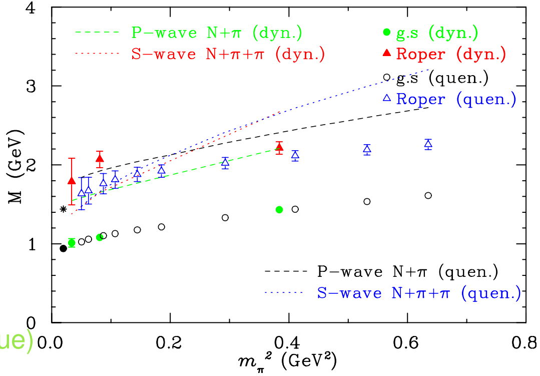
☞D. Leinweber (Tue)

CSSM Nucleon Excitations $N_f = 2 + 1$

Gauge	Ferm.	N_f
Iwasaki	FLIC on Clover	2+1

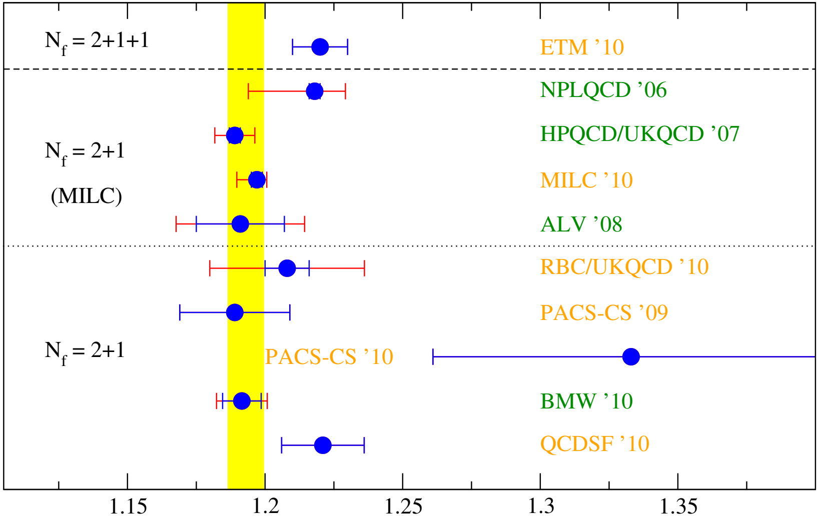
$a \to 0$	χ	FV	FV Res
✗	✓	✗	✗

- PACS-CS ensembles



☞D. Leinweber (Tue)

F_K/F_π Summary



Sources of Errors

Currently, the leading systematics for ground state masses and decay constants come from

- Reaching the physical point
- Taking the continuum limit
- Taking the infinite volume limit
- Resonances: FV interaction with scattering states

Subleading:

- QED effects
- Isospin breaking effects

Chiral Extrapolation - Interpolation

We have calculations

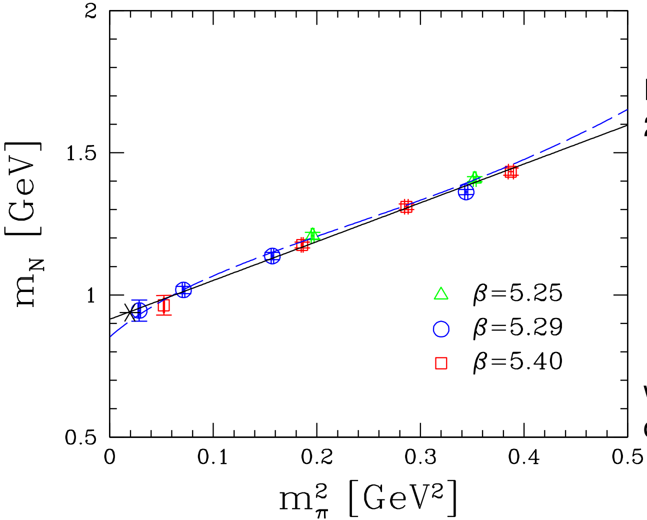
- close to the physical point ($m_\pi < 200$MeV)
  - Clover (QCDSF, PACS-CS, BMW)
  - Staggered (MILC)
  - Domain Wall (RBC)
- reweighted to the physical point (PACS-CS)

Different extrapolation methods agree

- Extrapolation is tiny
- Taylor expansion and χ PT
  - Order (N^{n}LO) depends on quality of data / external input

This is an observable dependent statement!

Chiral Extrapolation

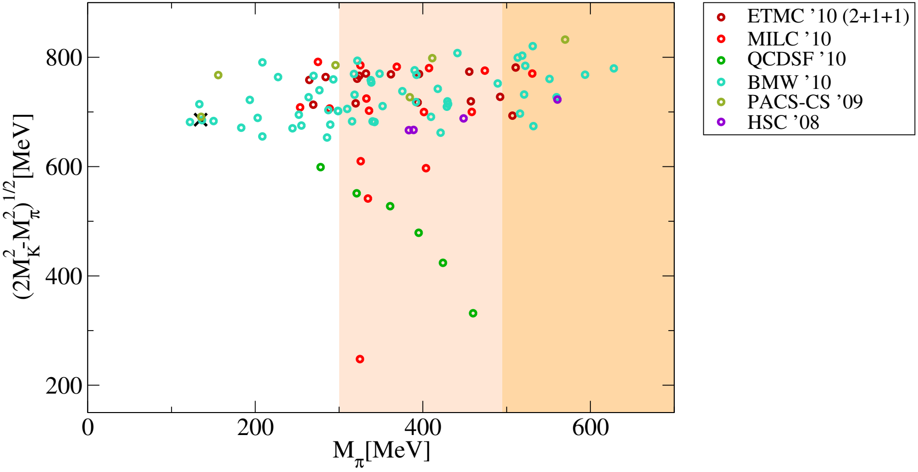


Example: QCDSF 2-flavor

which begs the question...


ARE WE THERE YET !?!
MATT GROENING

Landscape


800
600
400
200
0
200
400
600
M_π[MeV]
$(2M_K^2-M_\pi^2)^{1/2}$[MeV]
ETMC '10 (2+1+1)
MILC '10
QCDSF '10
BMW '10
PACS-CS '09
HSC '08

Finite Volume

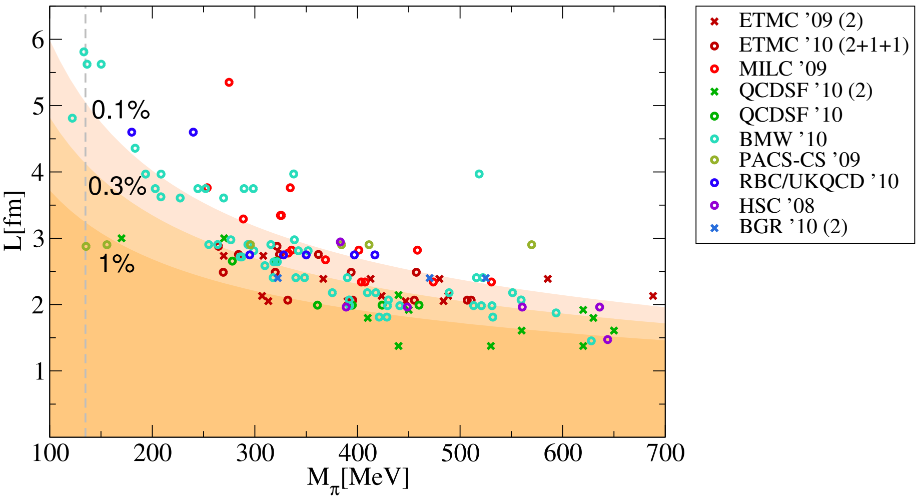
The real challenge

- Physical Point
- Infinite volume
- Continuum

In principle, infinite volume is easy for many observables:

- Leading corrections vanish exponentially in L
- ➢ Just need large enough volumes
- Carefull: This is not true for all observables!
  - Resonances: mixing with scattering states
  - FV can be usefull for determining widths etc. (Lüscher '85-'91)

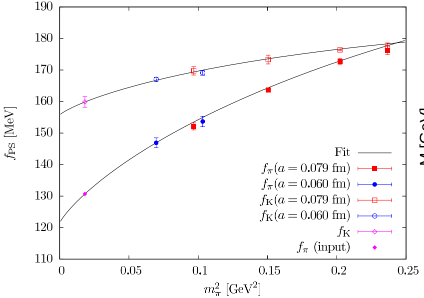
FV Landscape

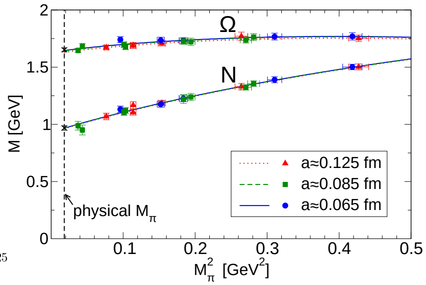


Continuum Extrapolation

Continuum extrapolation:

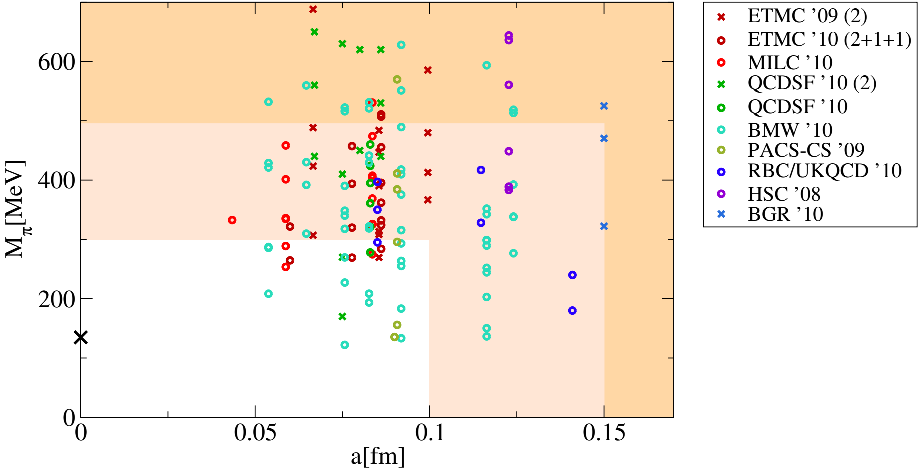
- Mild for ratios of hadron masses and decay constants
- Observable dependent
- Action dependent (interplay with flavor/taste splitting)





still extrapolation needed ➛will be leading systematics

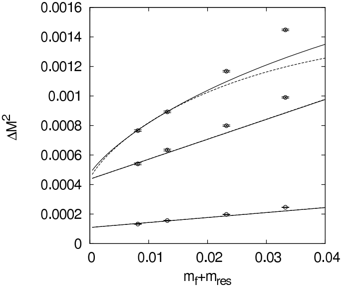
Continuum Landscape

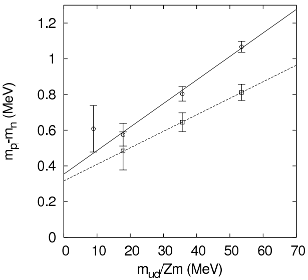


QED Effects (Blum et. al. '10)

- PQ DW, $a \approx 0.11$fm
- $16^3 \times 32$ and $24^3 \times 32$
- $m_\pi \sim 250 - 400$MeV
- Quenched, non-compact QED
- NLO χ PT

- $(m_{\pi^+} - m_{\pi^0})_{QED} = 4.50(23)$MeV
- $(m_{K^+} - m_{K^0})_{QED} = 1.33(4)$MeV
- $(m_n - m_p)_{QED} = -0.38(7)$MeV

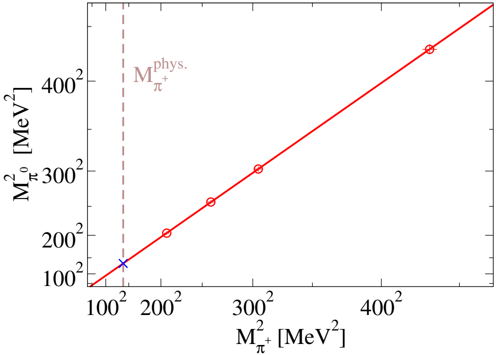




QED Effects (BMW)

- BMW Clover, $a \approx 0.115$fm
- $m_\pi \sim 200 - 400$MeV
- Quenched, non-compact QED
- Second order Taylor

- $(m_{\pi^+} - m_{\pi^0})_{QED} = 4.2(4)$MeV
- $(m_{K^+} - m_{K^0})_{QED} = 2.2(2)$MeV



- 4σ discrepancy with Blum. et. al.

☞A. Portelli(Thu)

Conclusion

Ground state light Hadron spectrum

- Reproduced to few % accuracy
- On that level: systematics under control

Light decay constants

- Lattice results in good agreement
- F_K/F_π Error competitive with experiment
- Lattice compatible with first-row unitarity

Higher precision:

- Physical point at large volume, more statistics
- Multi-state treatment of resonances

Excited state light Hadron spectrum

- Qualitative agreement
- Improve excited state treatment (scattering states, FV)

Thanks for sharing preliminary results

C. Bernard, P. Boyle, J. Carbonell, G. Herdoiza, R. Horsley, K. Jansen, C. B. Lang, R. Mawhinney, G. Schierholz, C. Urbach, A. Walker-Loud

BACKUP

Tunneling at $a \approx 0.054\text{fm}$, $m_\pi = 220\text{MeV}$