Nucleon form factors on a (10.8fm)^4 lattice at the physical point in 2+1 flavor QCD

Y.Kuramashi for PACS Collaboration
U. of Tsukuba

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Plan of talk

- PACS Collaboration Members
- “PACS10” Configs with Physical Volume over $(10\ \mathrm{fm})^4$
- Improvements from Previous Work (arXiv:1807.03974)
- Results for Form Factors
  - − Vector Current
  - − Axial Vector Current
  - − Generalized Goldberger-Treiman Relation
    ⇒ Pseudoscalar Density
- Summary

PACS Collaboration Members

N.Ishizuka, Y.Kuramashi, Y.Namekawa, Y.Taniguchi, N.Ukita, T. Yamazaki, T.Yoshié	Tsukuba
Y.Nakamura, E.Shintani	RIKEN-CCS
K.-I.Ishikawa	Hiroshima
N.Tsukamoto, S.Sasaki	Tohoku
T.Izubuchi	BNL

"PACS10" Configs @ β=1.82 in 2+1 Flavor QCD

arXiv:1807.06237

- Wilson-clover quark action + Iwasaki gauge action
- Stout smearing with α=0.1 and N_{smear}=6
- NP C_{SW}=1.11 determined by SF
- β=1.82 ⇒ a^{-1}=2.33 GeV
- Lattice size=128^4 ⇒ (10.8 fm)^3 spatial volume
- Hopping parameters: (κ_{ud},κ_s)=(0.126117,0.124902)

  ⇒ $m_\pi \approx 135$ MeV, $m_\pi L \approx 7.5$
- Simulation algorithm
  - $(MP)^2$DDHMC w/ active link for ud quarks, RHMC for s quark
  - Block size=16 × 16 × 8 × 64
  - MP parameters: (ρ_1,ρ_2)=(0.9997,0.9940)
  - Multi-time scale integrator: (N_0,N_1,N_2,N_3,N_4)=(8,2,2,2,22)
  - trajectory length: τ=1
  - N_{RHMC}=8, $[F_{min},F_{max}]$=[0.00025,1.85]
  - Chronological inverter guess for IR parts
  - Solver: mixed precision nested BiCGStab

Measurement Details with Plateau Method (1)

2-pt correlator

$$C_{XS}(t_{\rm sink}-t_{\rm src},\boldsymbol{p}) = \frac{1}{4}{\rm Tr}\left\{\mathcal{P}_+\langle N_X(t_{\rm sink},\boldsymbol{p})\bar{N}_S(t_{\rm src},-\boldsymbol{p})\rangle\right\}$$

3-pt correlator

$$C^{\mathcal{P}_k}_{O,\alpha}(t,\boldsymbol{p}',\boldsymbol{p}) = \frac{1}{4}{\rm Tr}\left\{\mathcal{P}_k\langle N(t_{\rm sink},\boldsymbol{p}')J^O_\alpha(t,\boldsymbol{q})\bar{N}(t_{\rm src},-\boldsymbol{p})\rangle\right\}$$

Ratio of 3-pt to 2-pt correlators

$$\mathcal{R}^k_{O,\alpha}(t,\boldsymbol{p}',\boldsymbol{p}) = \frac{C^{\mathcal{P}_k}_{O,\alpha}(t,\boldsymbol{p}',\boldsymbol{p})}{C_{SS}(t_{\rm sink}-t_{\rm src},\boldsymbol{p}')}\sqrt{\frac{C_{LS}(t_{\rm sink}-t,\boldsymbol{p})C_{SS}(t-t_{\rm src},\boldsymbol{p}')C_{LS}(t_{\rm sink}-t_{\rm src},\boldsymbol{p}')}{C_{LS}(t_{\rm sink}-t,\boldsymbol{p}')C_{SS}(t-t_{\rm src},\boldsymbol{p})C_{LS}(t_{\rm sink}-t_{\rm src},\boldsymbol{p})}}$$

Measurement Details with Plateau Method (2)

- AMA is used to gain high statistical precision
- O(100) measurements/config ⇒ O(10^3～10^4) measurements so far
- 9 choices for spatial momenta:
  $\vec{n}$=(1,0,0),(1,1,0),(1,1,1),(2,0,0),(2,1,0),(2,1,1),(2,2,,0),(3,0,0),(2,2,1)
  minimum mom=2π/L～0.115 GeV thanks to L=10.8 fm
- Lattice size=128^4 ⇒ $(10.8\ \text{fm})^3$ spatial volume allows small q^2 region
- Exp smeared src/sink operators for 2-pt and 3-pt functions
- Src-sink separation: $t_{sink}-t_{src}$=10, 12, 14, 16 (～1.35 fm)
- Z_A=0.9650(68)(95), Z_V=0.95153(76)(1487) in SF scheme

PoS(LATTICE2015)271

How Large Spatial Size is Necessary?

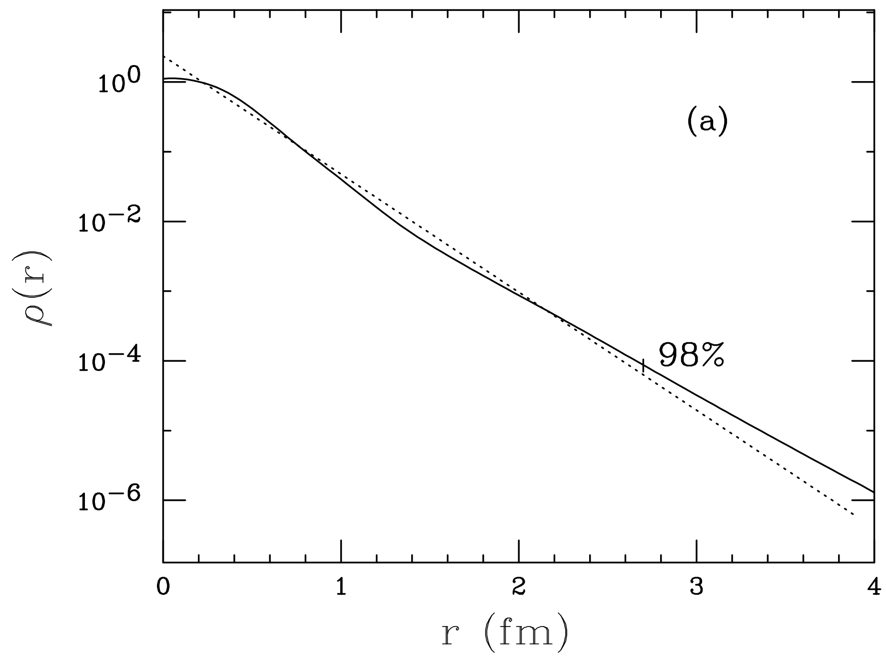
Sick, Atoms 6(2018)2

Charge RMS radius

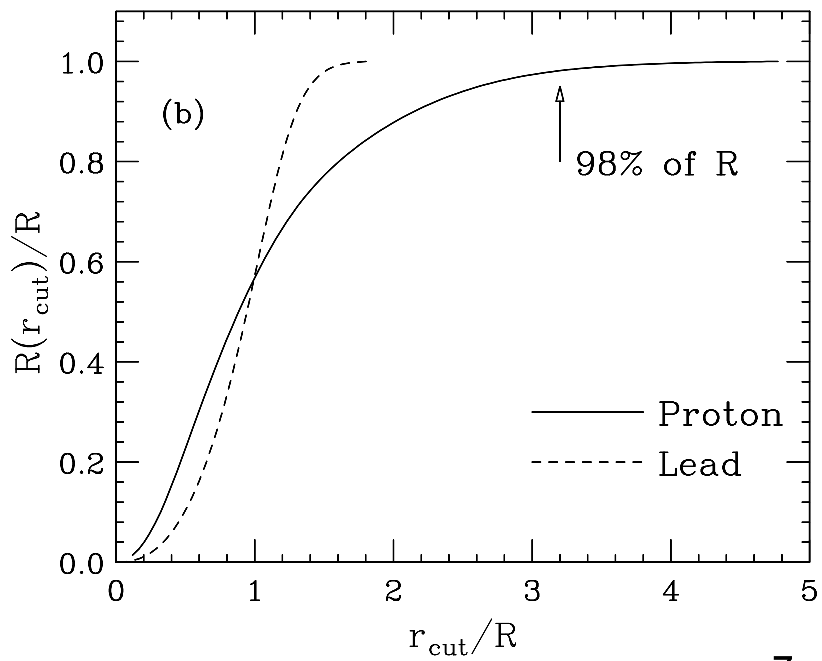
$$R^2 \equiv \int_0^\infty \rho(r)\ r^4\ 4\pi\ dr,$$

$$R(r_{cut}) = \left[\int_0^{r_{cut}} \rho(r)\ r^4\ dr\ \Big/ \int_0^\infty \rho(r)\ r^4\ dr\right]^{1/2}$$

Charge density



$R(r_{cut})$

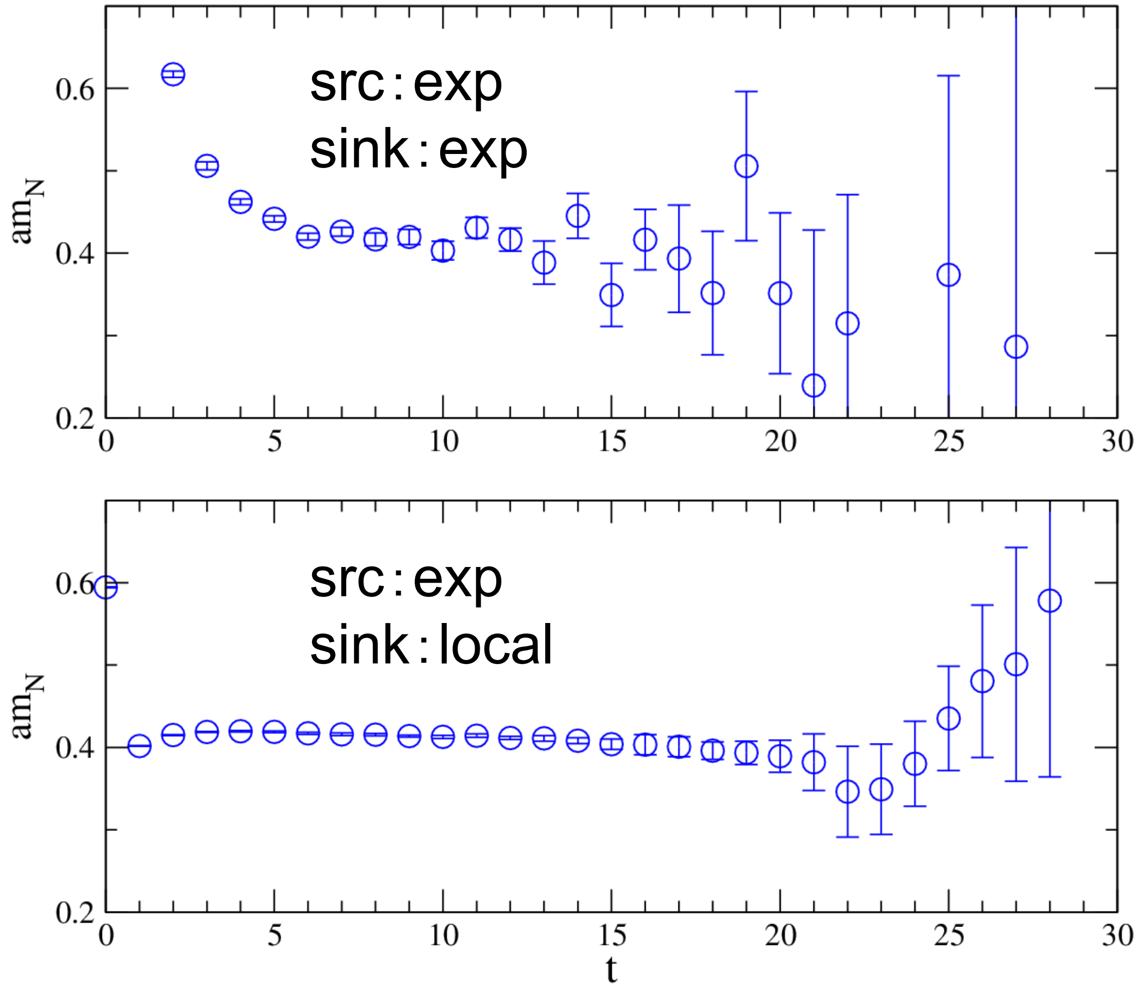


Integration up to r_{cut}=2.7fm ⇒ Only 98% of charge RMS radius

Improvements from Our Previous Work

	Lattice 2018	arXiv:1807.03974
Volume	128^4 $(10.8\ \mathrm{fm})^4$	96^4 $(8.1\ \mathrm{fm})^4$
Minimum q^2	0.013 GeV^2	0.024 GeV^2
m_π	135 MeV (physical)	146 MeV
Measurement to increase statistics	w/ AMA	w/o AMA
$t_s=\|t_{sink}-t_{src}\|$ dependence	$t_s=10, 12, 14, 16$	$t_s=15$

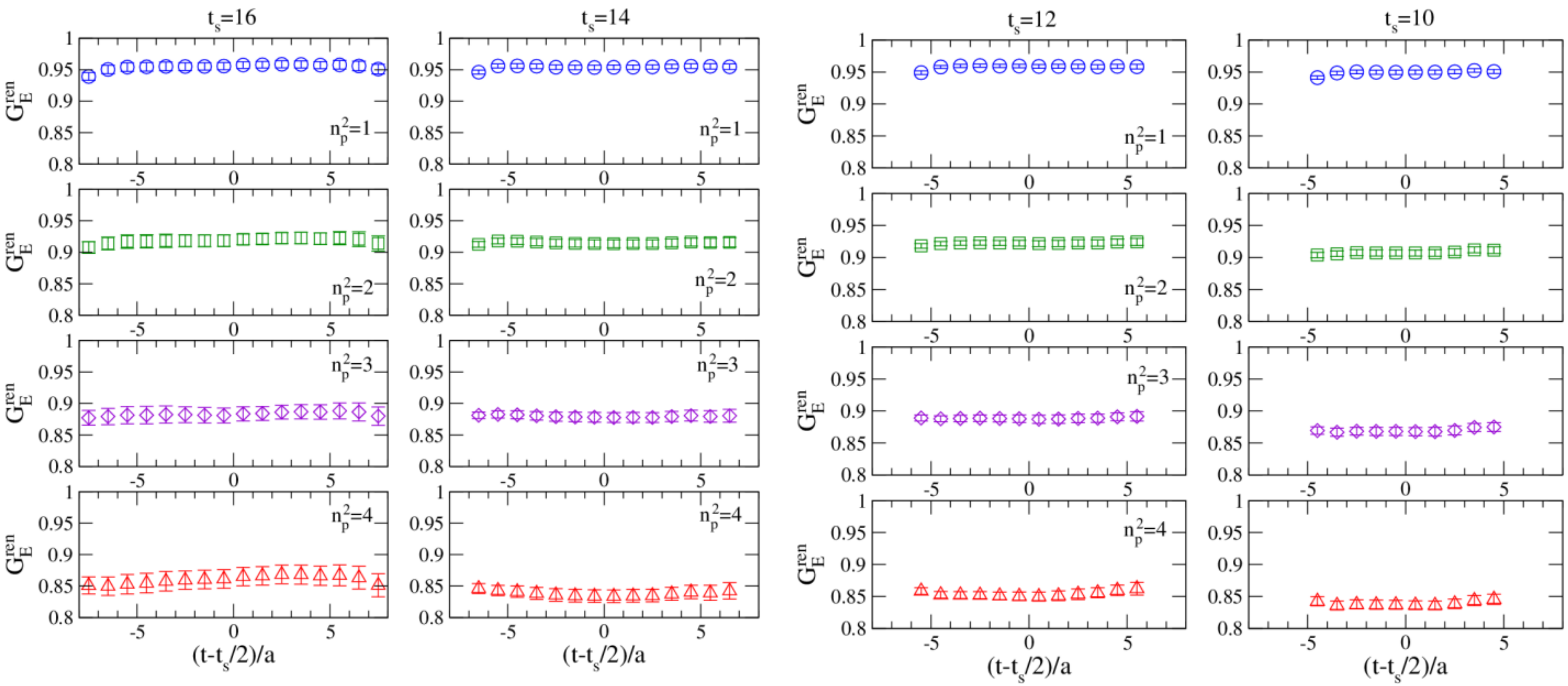
Nucleon Effective Mass



Good plateau is observed from small time slice

Isovector Electric Form Factor (1)

Ratio of 3-pt to 2-pt correlators as a function of t (location of V)

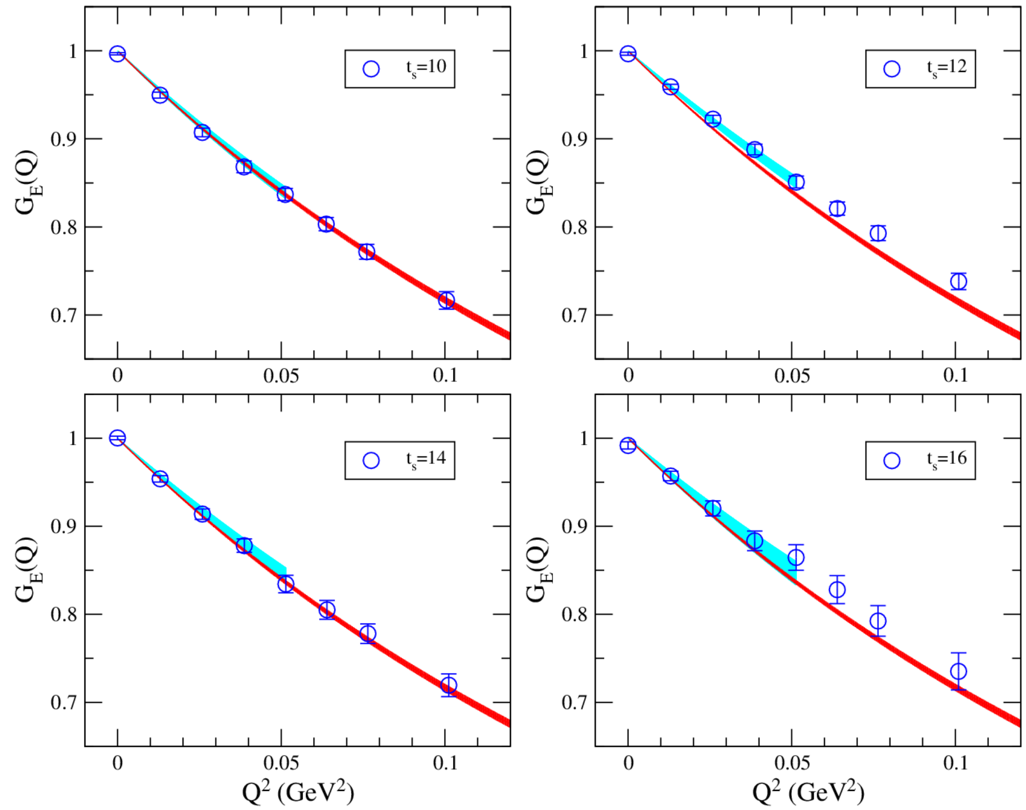


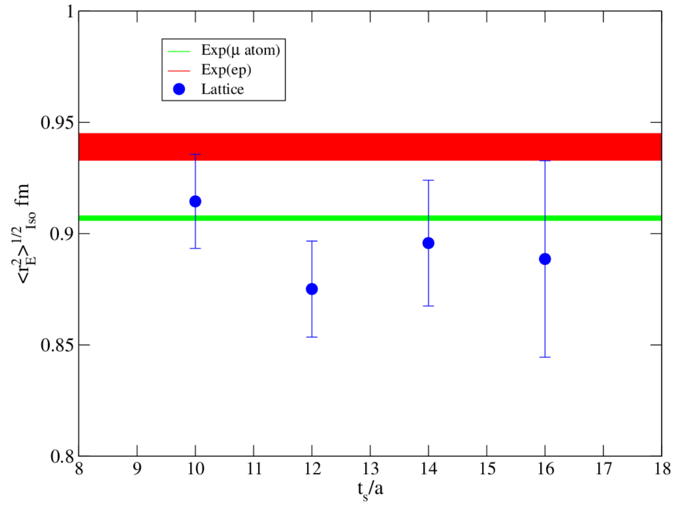
Good plateau for t_s=10, 12, 14, 16

Isovector Electric Form Factor (2)

$$G_E(q^2) = F_1(q^2) - \frac{q^2}{4m_N^2} F_2(q^2)$$

$$\langle r_E^2 \rangle = -6 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$$



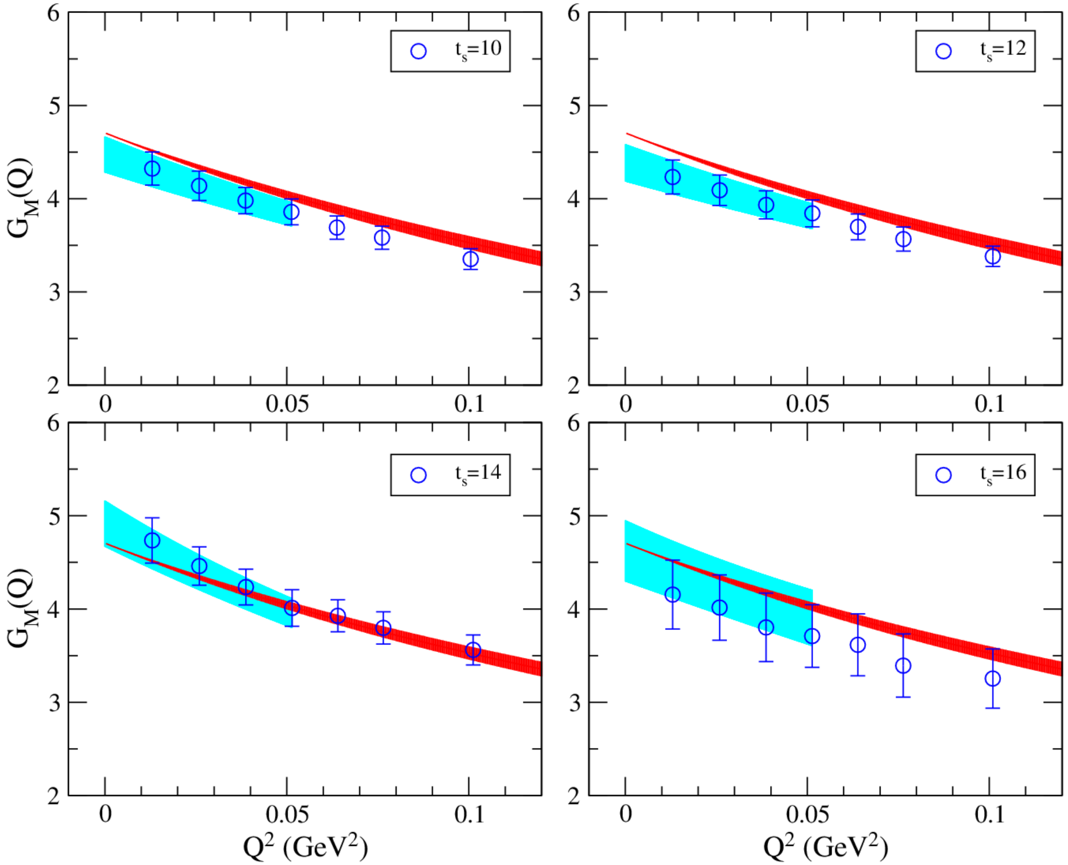


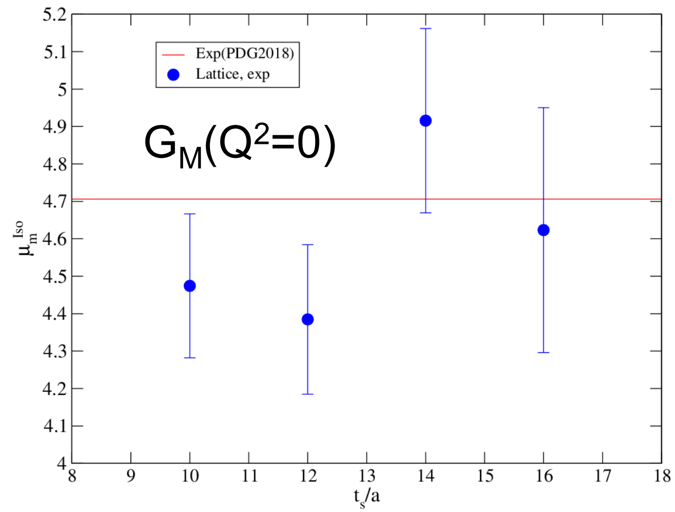
Seems to prefer μH experiment

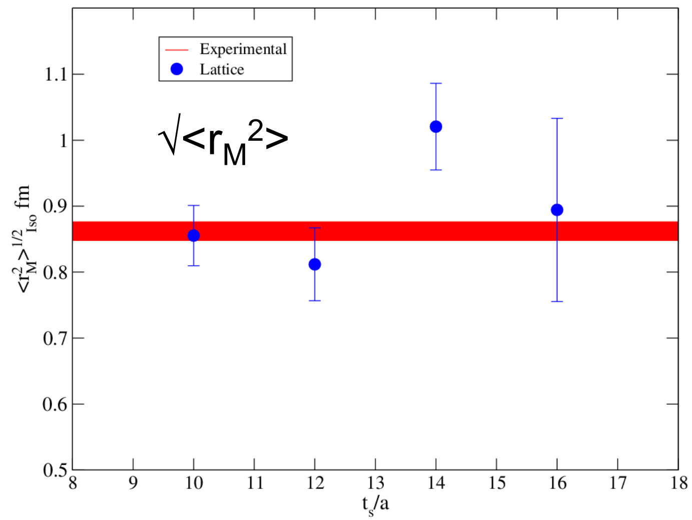
⇒ Possibility to distinguish two experimental values

Isovector Magnetic Form Factor

$$G_M(q^2) \;=\; F_1(q^2) + F_2(q^2)$$



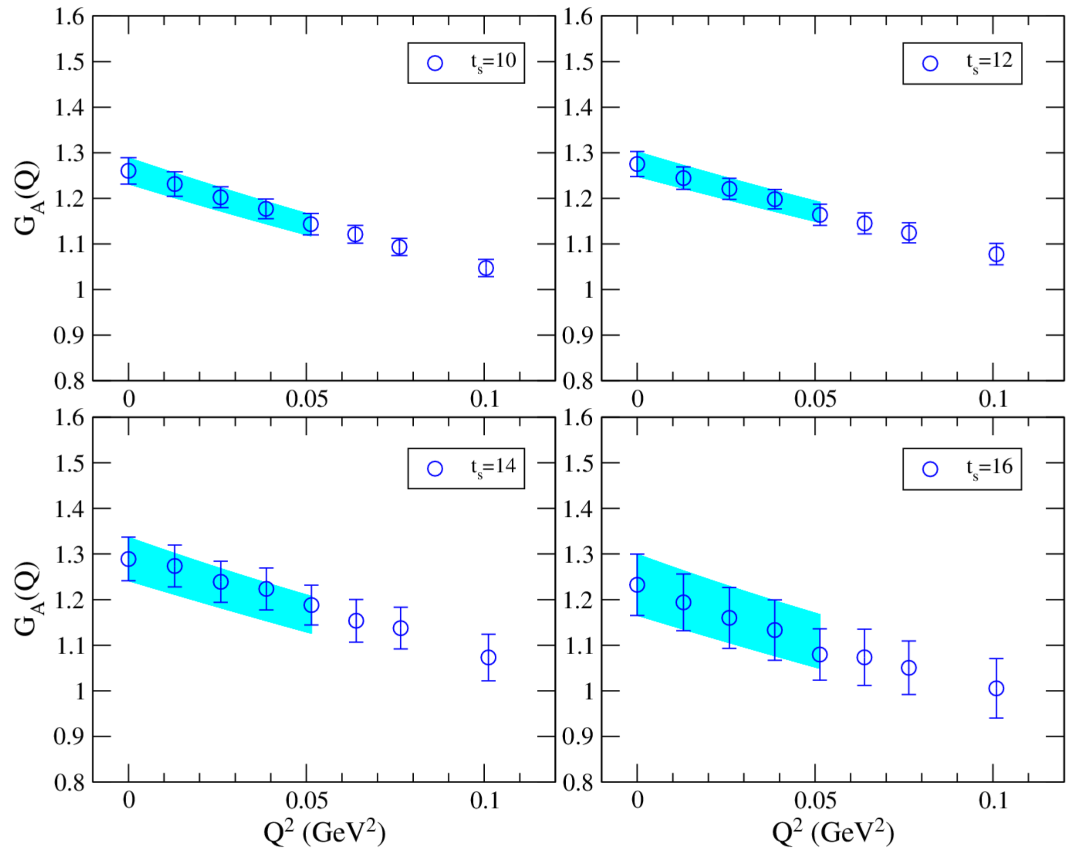


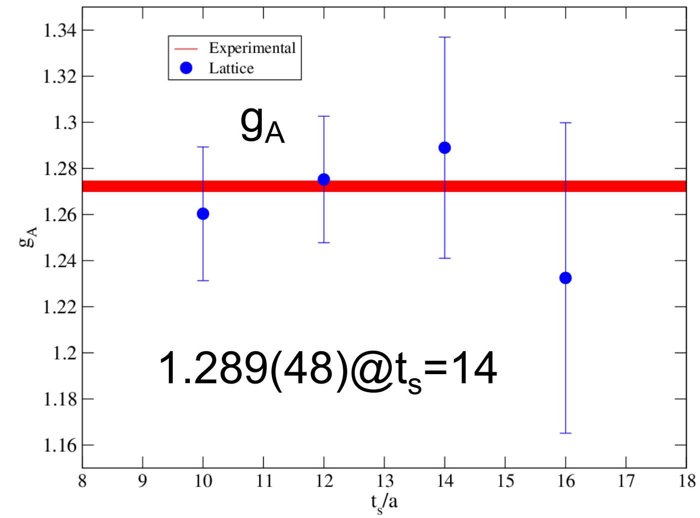


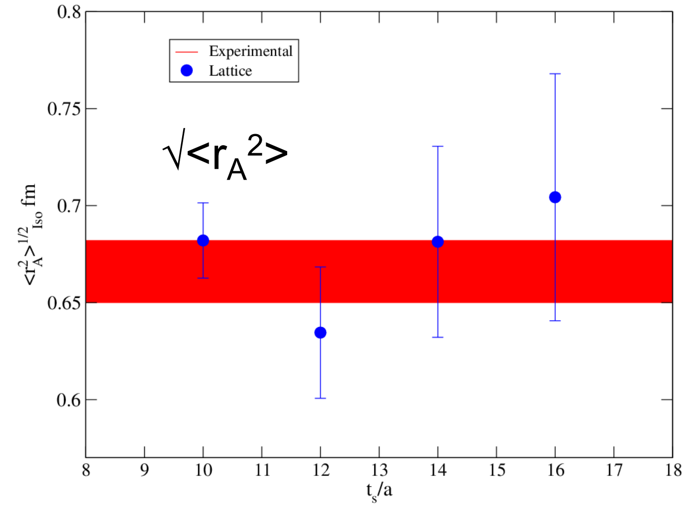
Consistent with μ_M and $\sqrt{\langle r_M^2 \rangle}$ within 2σ error

Axial Form Factor

Two form factors F_A and F_P
for axial vector current





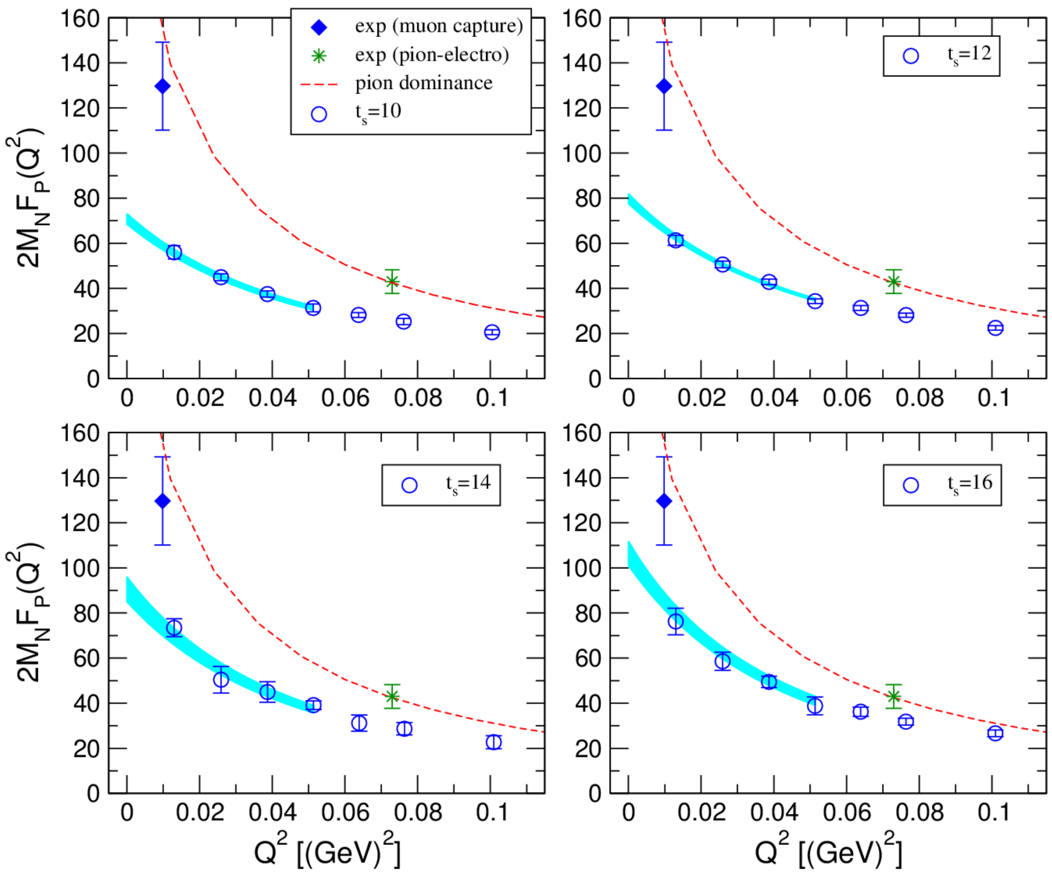


g_A is consistent with experiment being independent of t_s

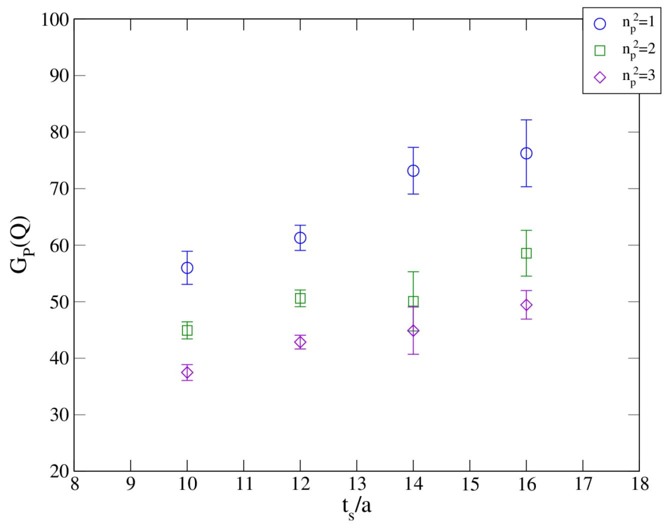
$\sqrt{<r_A^2>}$ is also consistent with experiment

Induced Pseudoscalar Form Factor F_P

Q^2 dependence of $2M_NF_P$



t_s dependence of F_P



Clear t_s dependence for F_P ⇒ Excited state contributions

※ ChPT analysis by Bär, Wed・14:00[HIS]

Generalized Goldberger-Treiman (GT) Relation

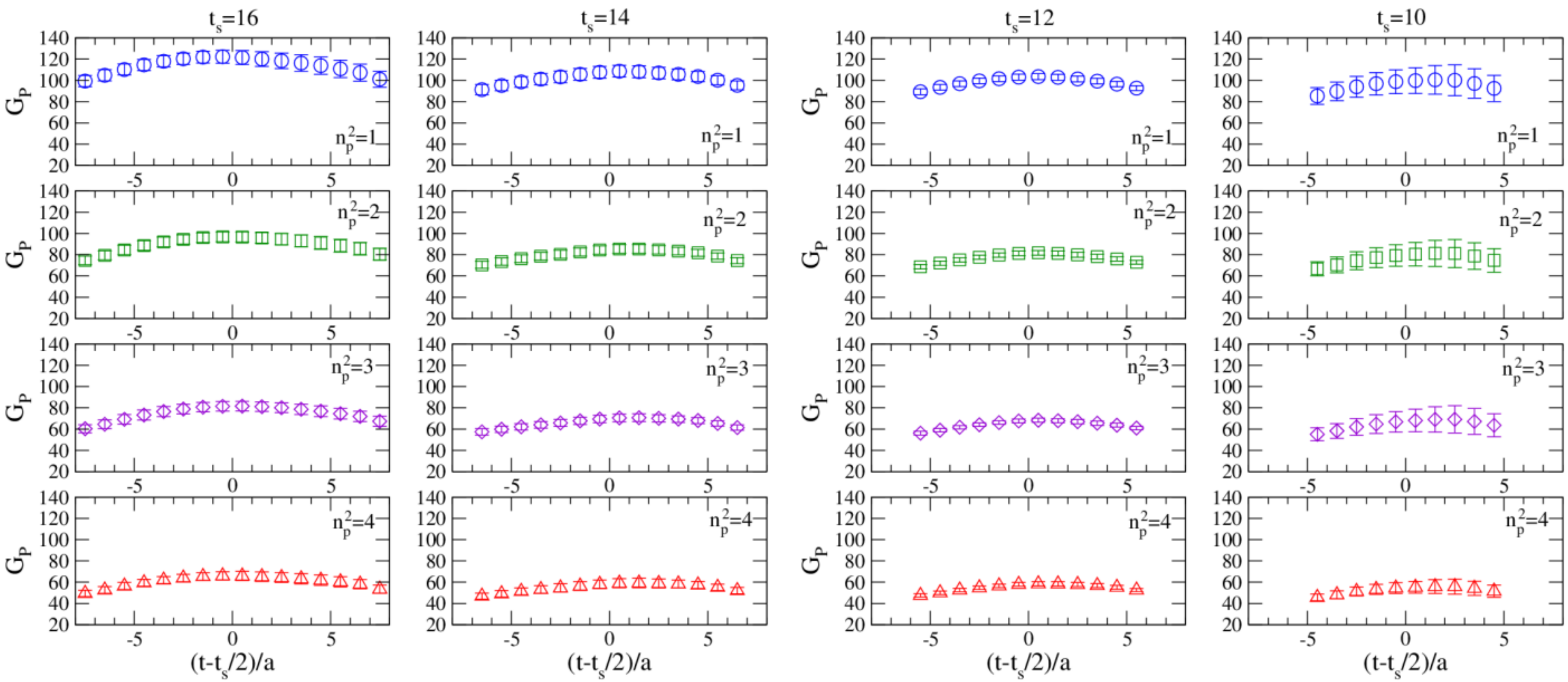
F_A and F_P are not independent

$$2M_N F_A(q^2) - q^2 F_P(q^2) = 2\hat{m} G_P(q^2)$$

⇒ Check Generalized GT relation with G_P

Pseudoscalar Form Factor G_P (1)

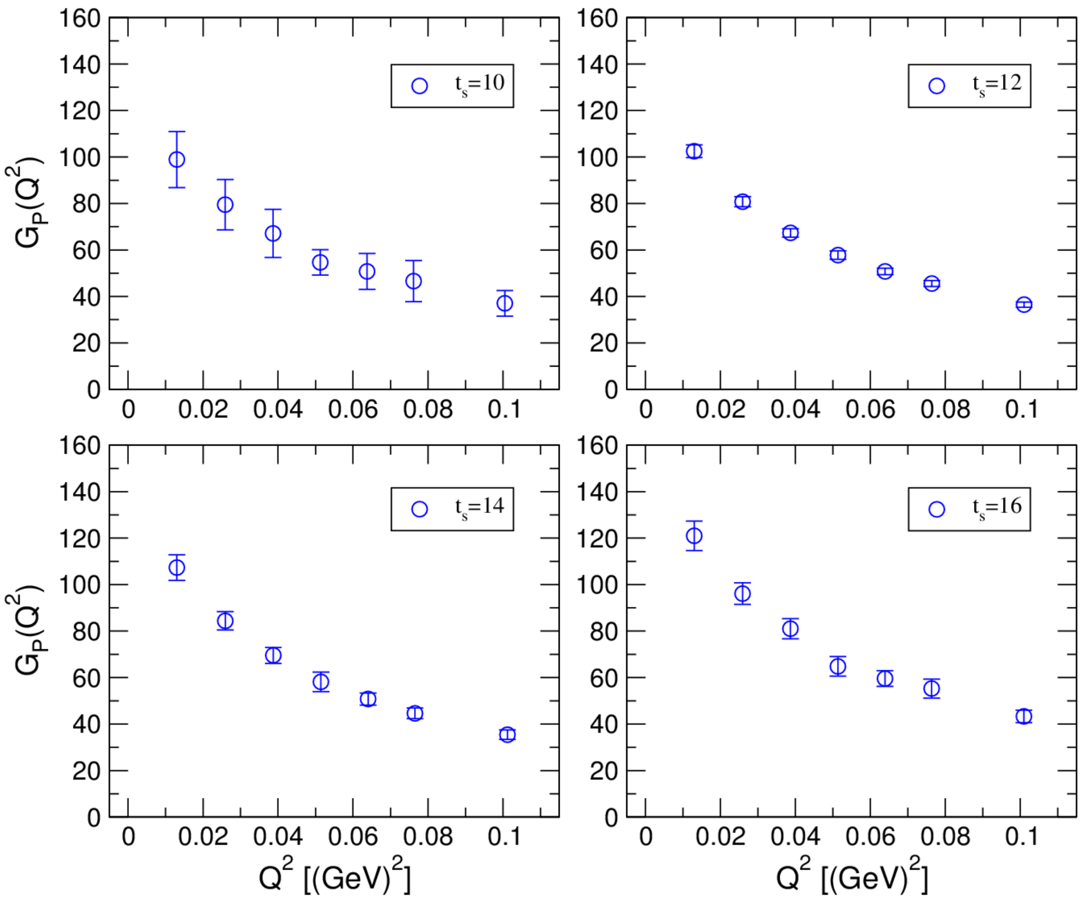
Ratio of 3-pt to 2-pt correlators as a function of t (location of P)



Mound like shape ⇒ Signal of excited state contributions

Pseudoscalar Form Factor G_P (2)

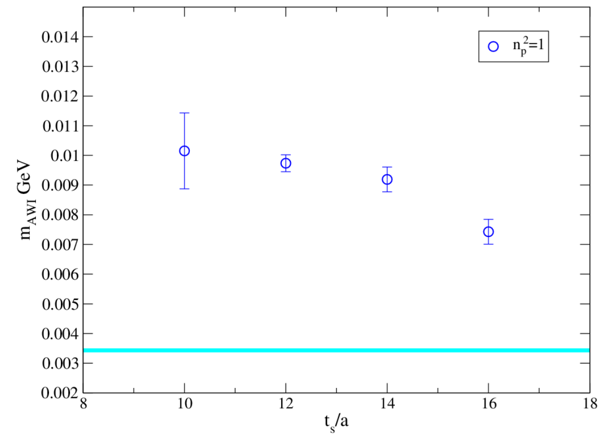
Q^2 dependence of G_P



Generalized GT relation

$$m_{\mathrm{AWTI}} = \frac{2M_N F_A^{\mathrm{ren}}(q^2) - q^2 F_P^{\mathrm{ren}}(q^2)}{2G_P(q^2)}$$

t_s dependence of m_{AWI}(GT)



m_{AWI}(GT) becomes closer to m_{AWI}(PCAC) for larger t_s

Summary

- 2+1 flavor QCD simulation at the physical point on (10.8 fm)^4 lattice
  - Large spatial volume allows investigation at small Q^2 region
- t_s dependence is systematically investigated
  - G_E, G_M and F_A show no t_s dependence
  - Clear t_s dependence is observed for F_P and G_P
- Results for G_E, G_M and F_A are consistent with experiment including g_A
- Violation of Generalized GT relation diminishes as t_s increases

BACKUP