One and two nucleon matrix elements from lattice QCD for precision tests of the SM in NP environments

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Lawrence Berkeley
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XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece, 28 August - 3rd September, 2016

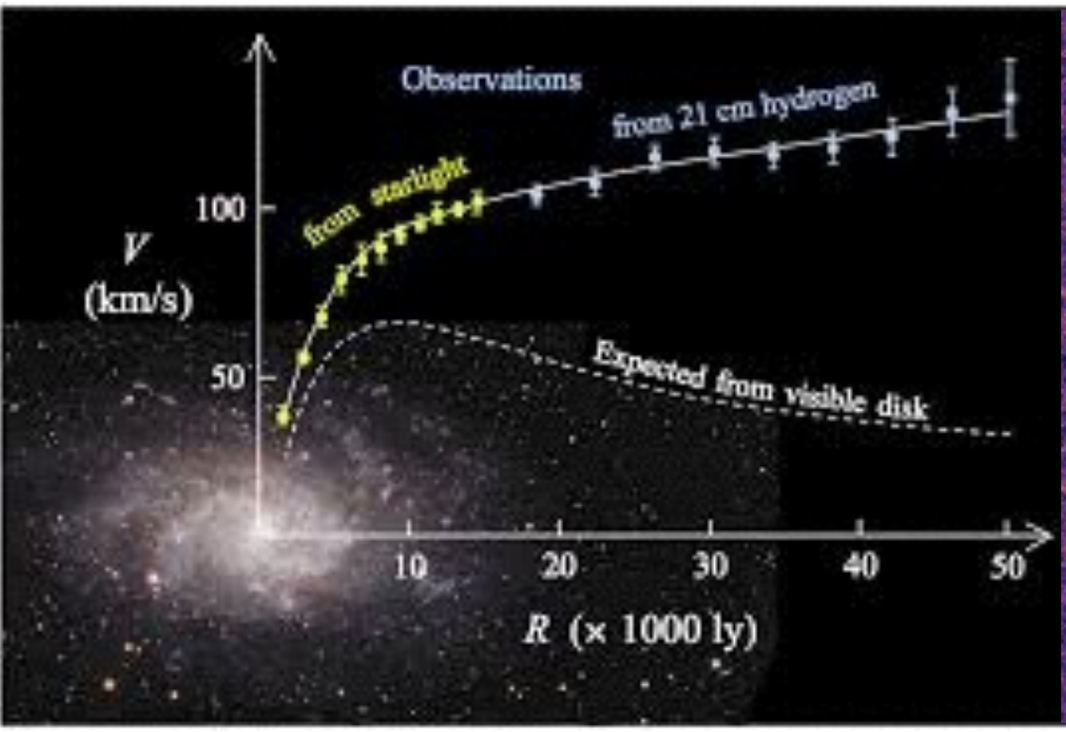
Anchoring Nuclear Physics to QCD

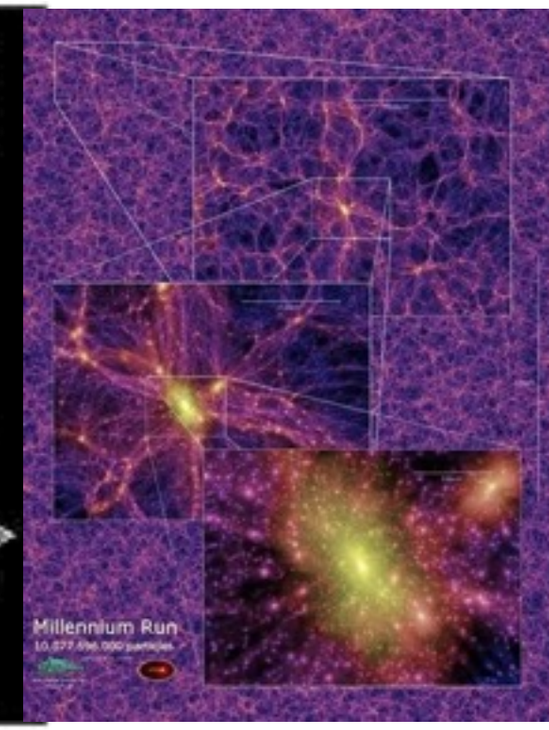
- Several low-energy, potentially high impact NP experiments whose interpretation (SM or BSM) requires a precise quantitative understanding of QCD:
  - *$0\nu\beta\beta$*
  - *EDMs in nucleons, light and heavy nuclei*
  - *direct dark matter detection*
  - *…*

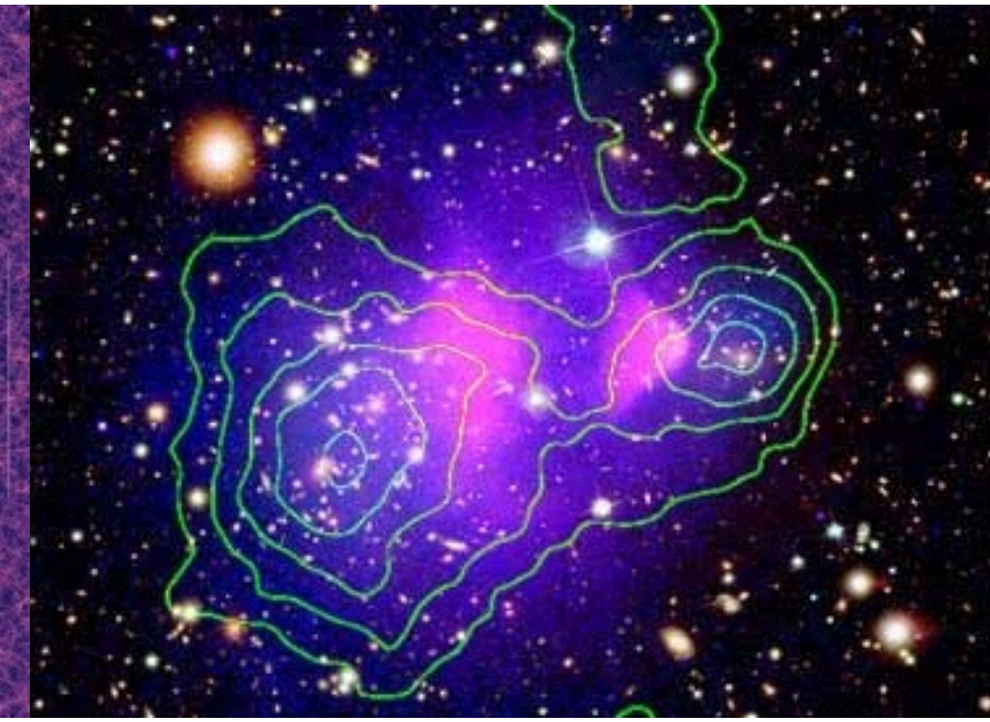
- Building a theoretical understanding relevant to these experiments requires a coordinated effort between lattice QCD + few nucleon effective theories + many body effective theories

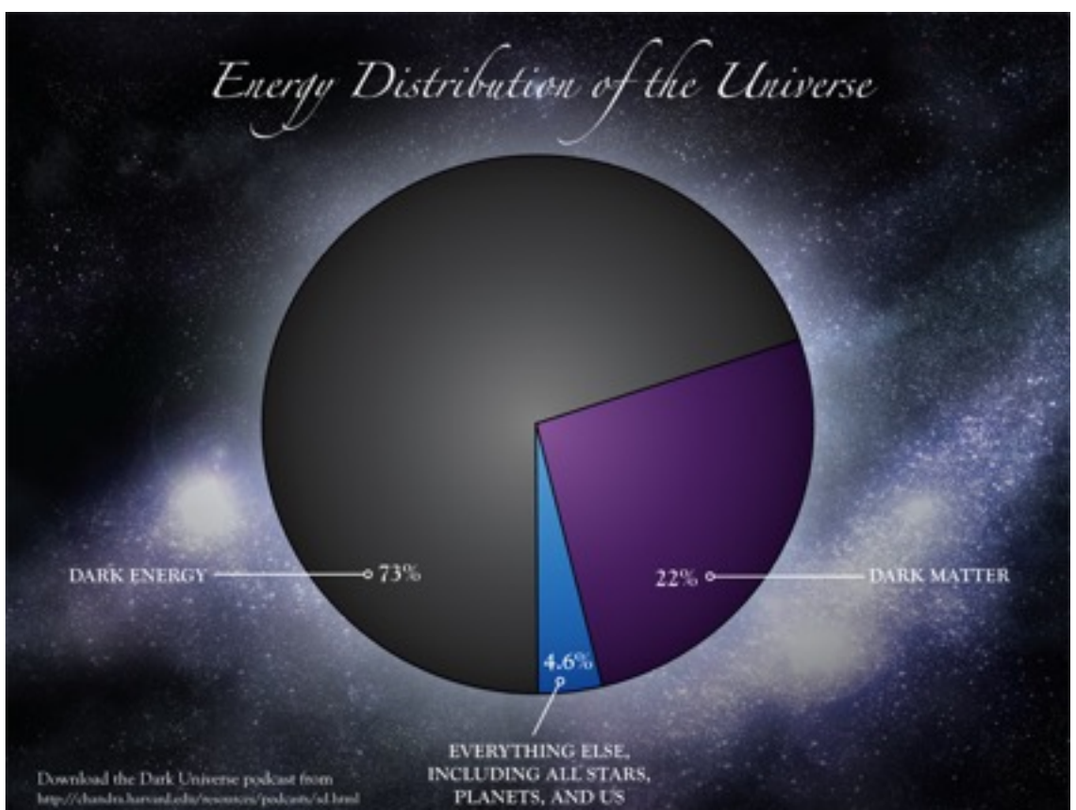
Direct Dark Matter Detection

The assumed existence of DM comes from several sources:





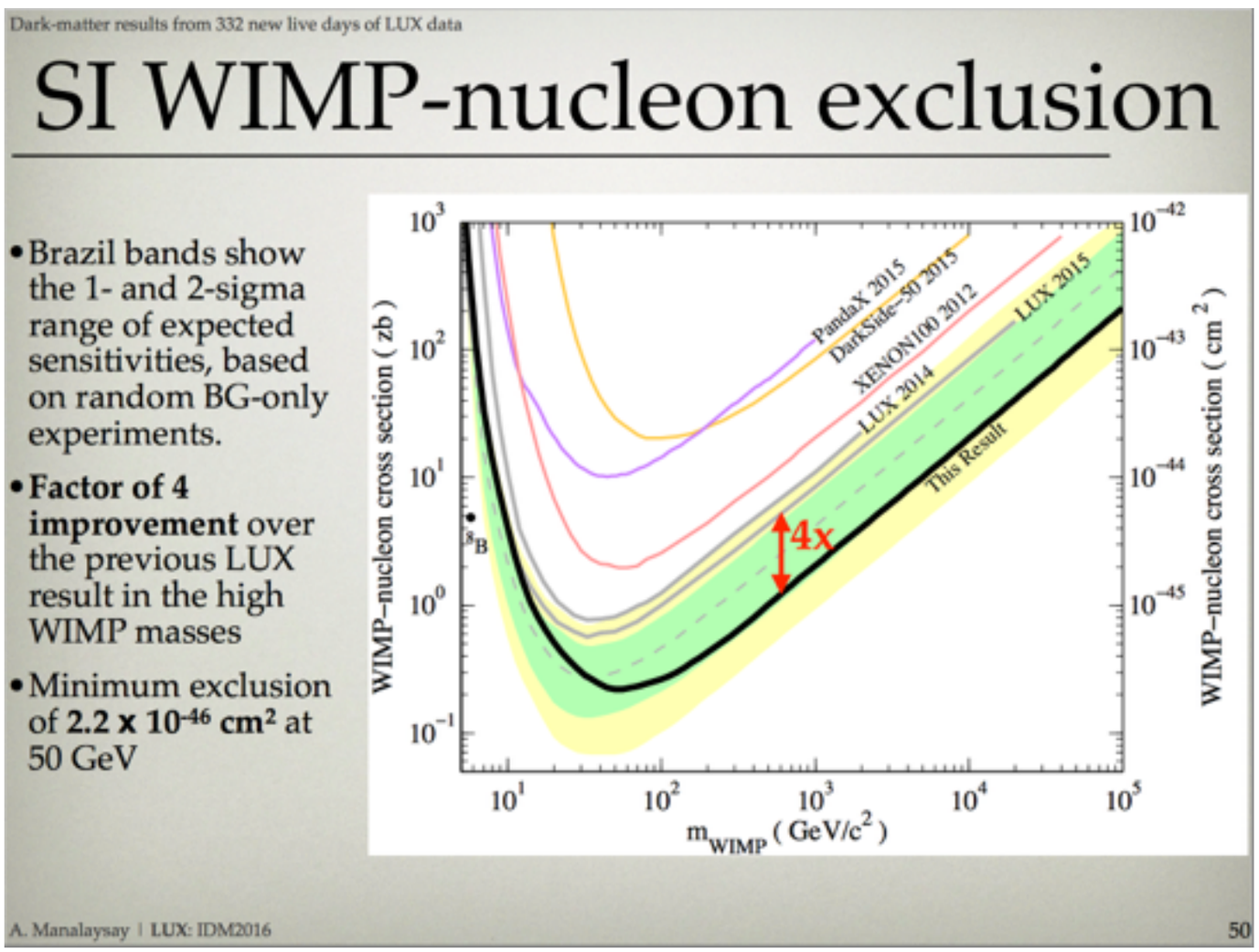




These three observations are difficult to explain with modified gravity. Cold Dark Matter is the simplest explanation consistent with all observations

Direct Dark Matter Detection

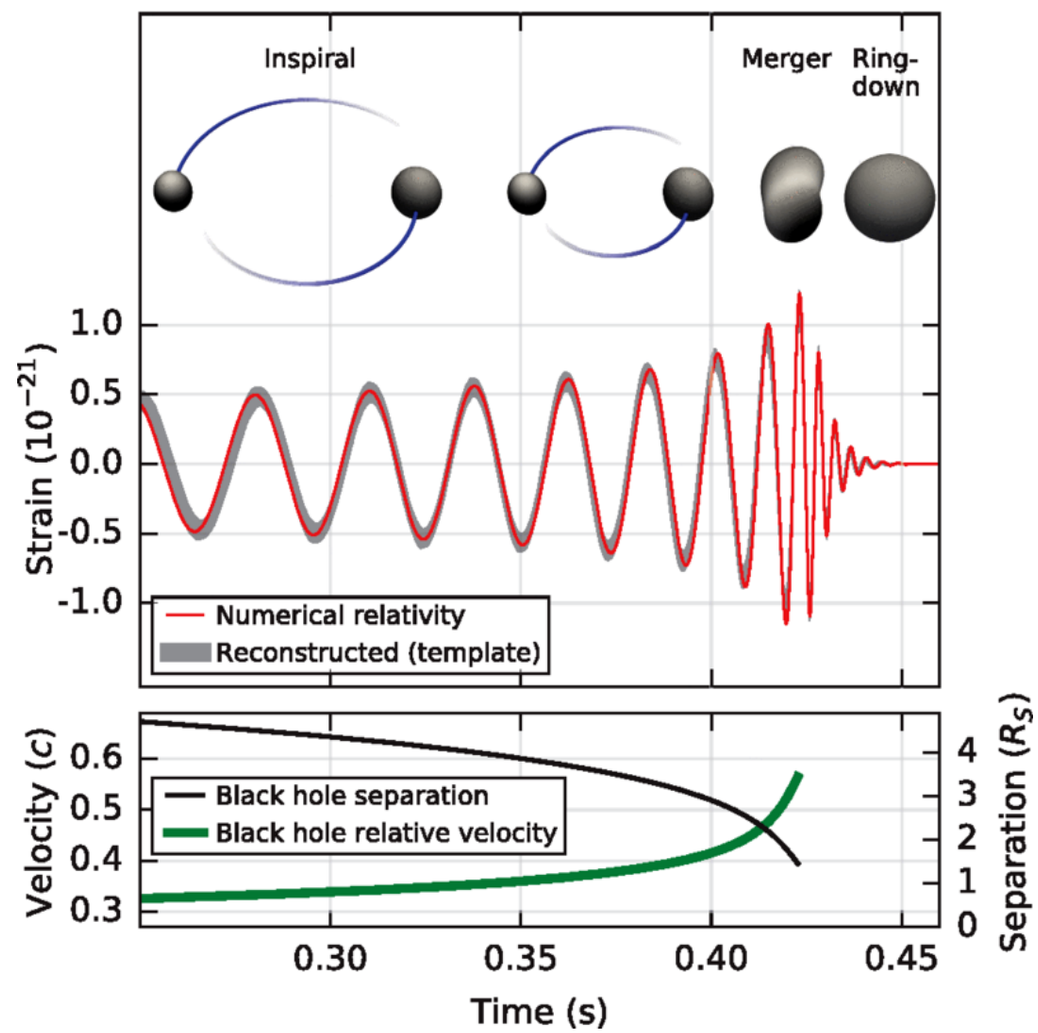
Is dark matter just primordial black holes?



LUX Dark Matter: Talk by Aaron Manalaysay

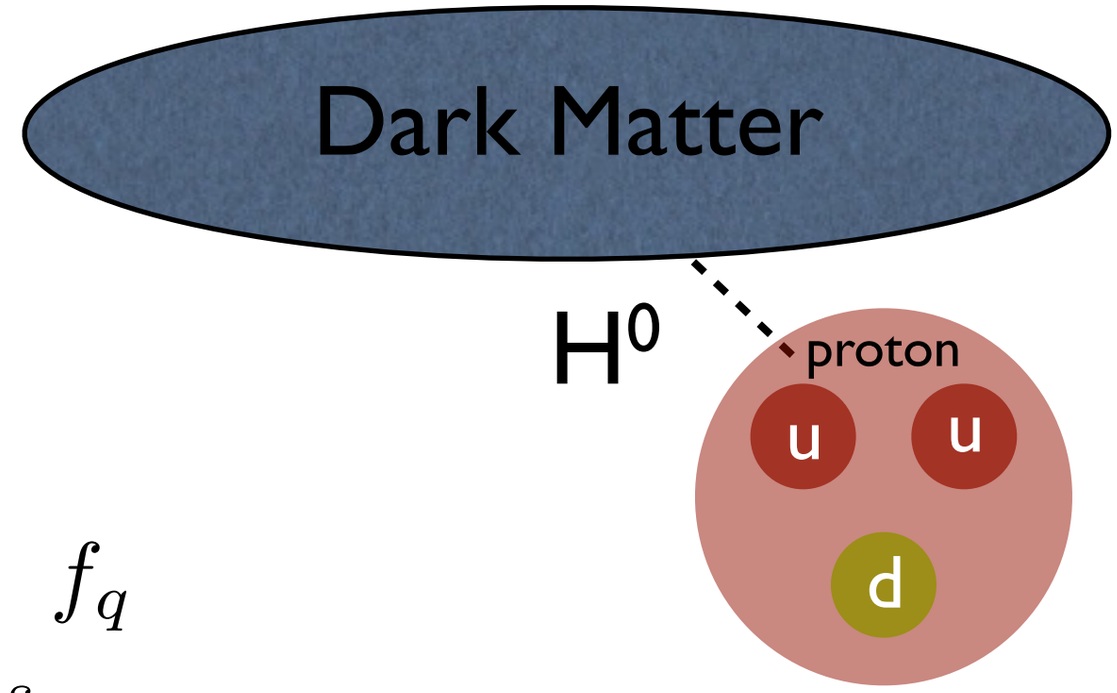
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 116, 061102

FIG. 2.



Top: Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1. The inset images show numerical relativity models of the black hole horizons as the black holes coalesce. *Bottom:* The Keplerian effective black hole separation in units of Schwarzschild radii ($R_S = 2GM/c^2$) and the effective relative velocity given by the post-Newtonian parameter $v/c = (GM\pi f/c^3)^{1/3}$, where f is the gravitational-wave frequency calculated with numerical relativity and M is the total mass (value from Table I).

If Dark Matter couples to the scalar current of the nucleon (eg via Higgs) Spin Independent cross section



$$\sigma \propto |f|^2 \qquad f = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q$$

$$f_q \equiv \frac{\langle N | m_q \bar{q} q | N \rangle}{m_N}$$

see eg. Cheung, Hall, Pinner, Ruderman JHEP 1305 (2013) 100 [arXiv:1211.4873]

with enhancement of A^2 for nucleus (Xenon)

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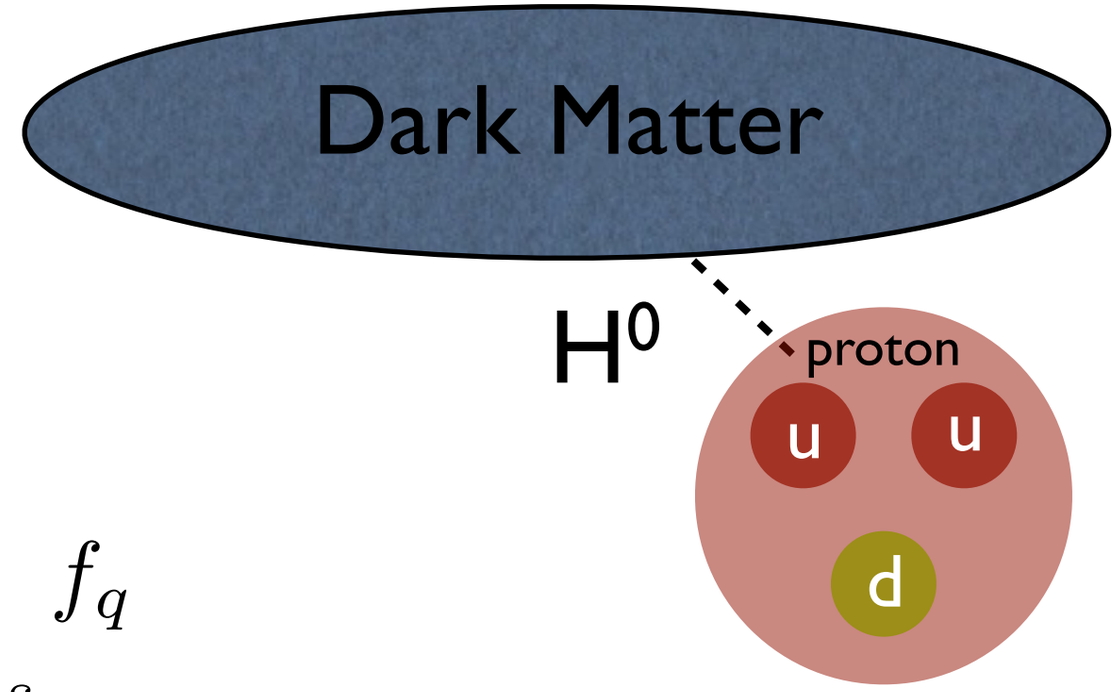

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scalar current difficult to measure experimentally

$f_{u,d}$ estimated from pion-nucleon scattering

f_s uncertainty dominates estimates of cross section

Ellis, Olive, Savage
Phys.Rev. D77 (2008)

see eg. Cheung, Hall, Pinner, Ruderman
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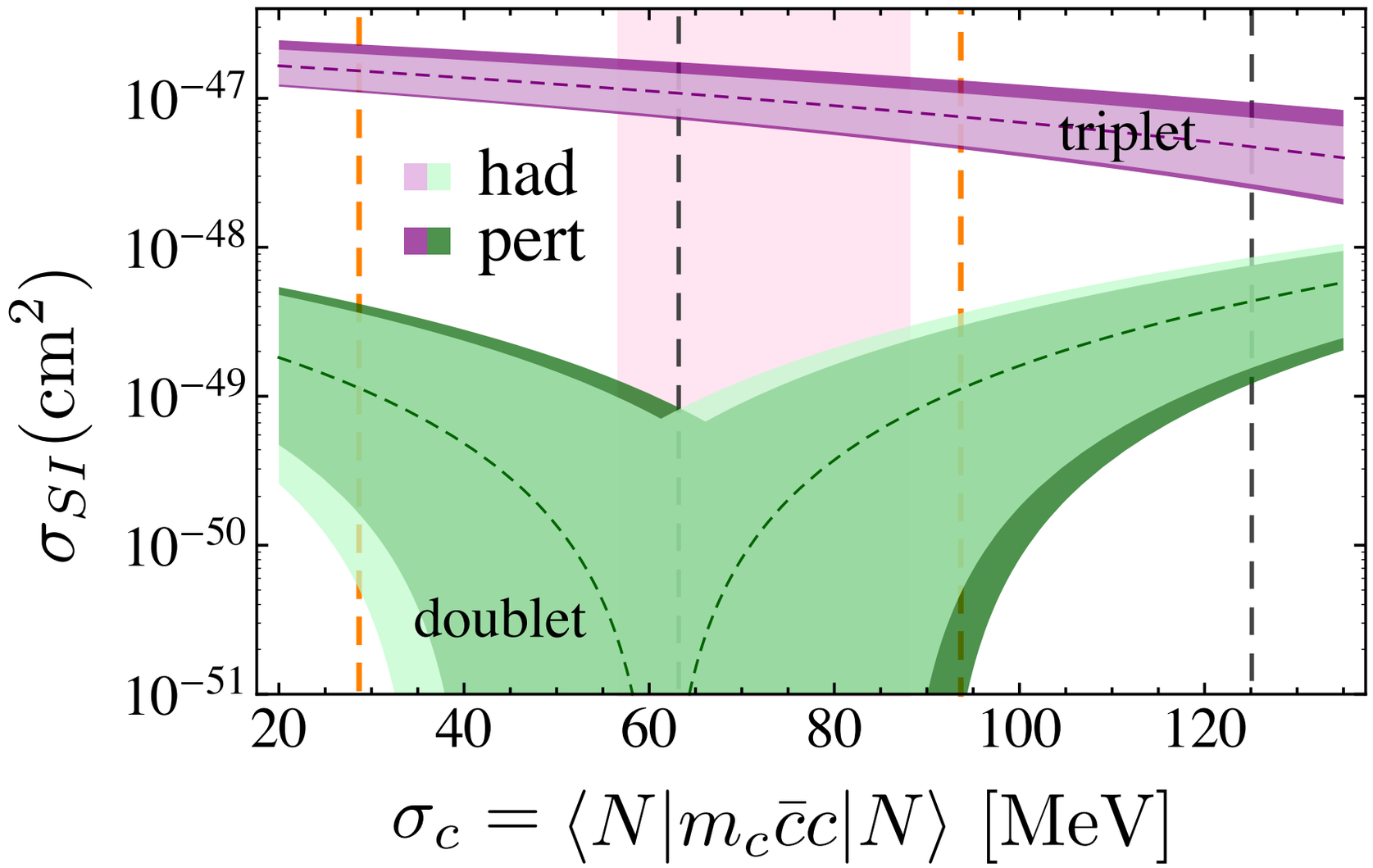
Heavy quark matrix elements



Hill & Solon
PRL 112 (2014)
arXiv:1309.4092

$$\sigma_c = 79\left(^{24}_{22}\right)\ \mathrm{MeV}$$

Abdel-Rehim et al
PRL 116 (2016)
arXiv:1601.01624

Factors of 2 normally do not seem to matter much in this business, but in some cases - there are large cancelations which are sensitive to the precise values

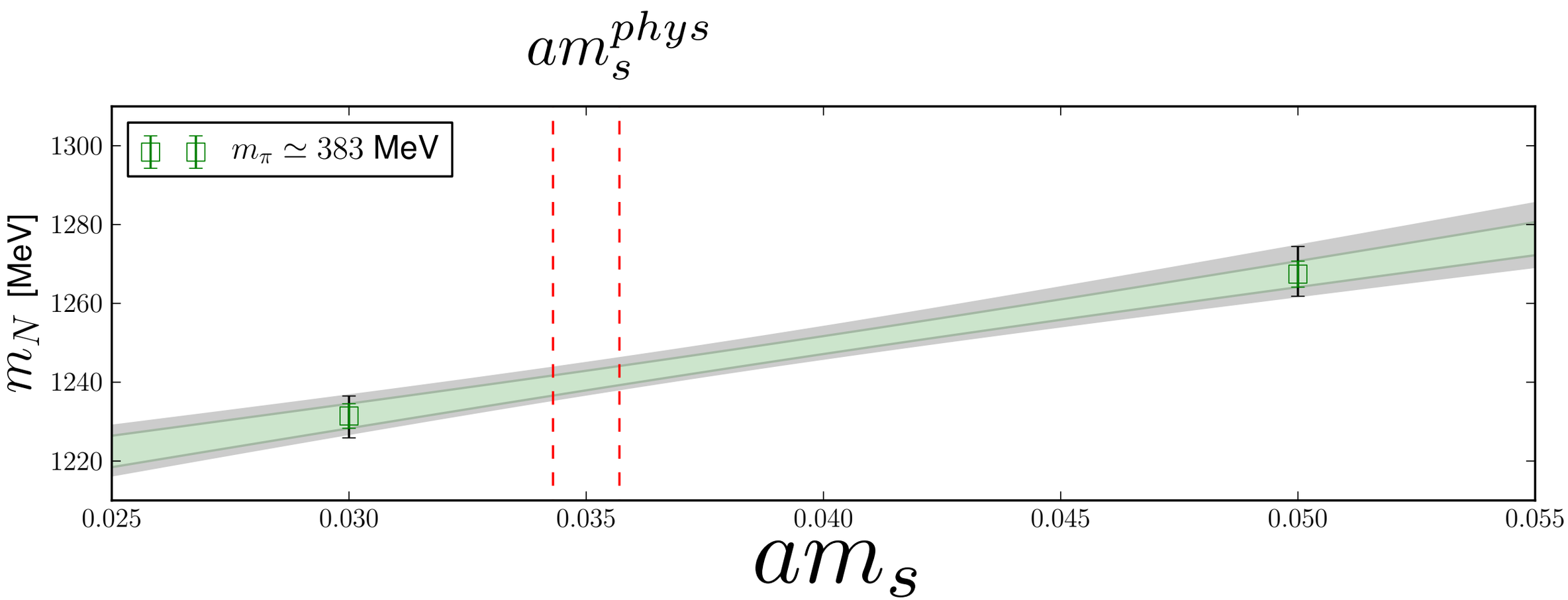
LQCD is perfect tool for such a calculation - but few results exist - need more precision

strange content of the nucleon

Parry Junnarkar and AWL
PRD 87 (2013) [1301.1114]

Lattice QCD perfect tool to compute strange content of nucleon $m_s\langle N|\bar{s}s|N\rangle$

Feynman-Hellmann Theorem $$m_q\langle N|\bar{q}q|N\rangle = m_q\frac{\partial}{\partial m_q}m_N$$



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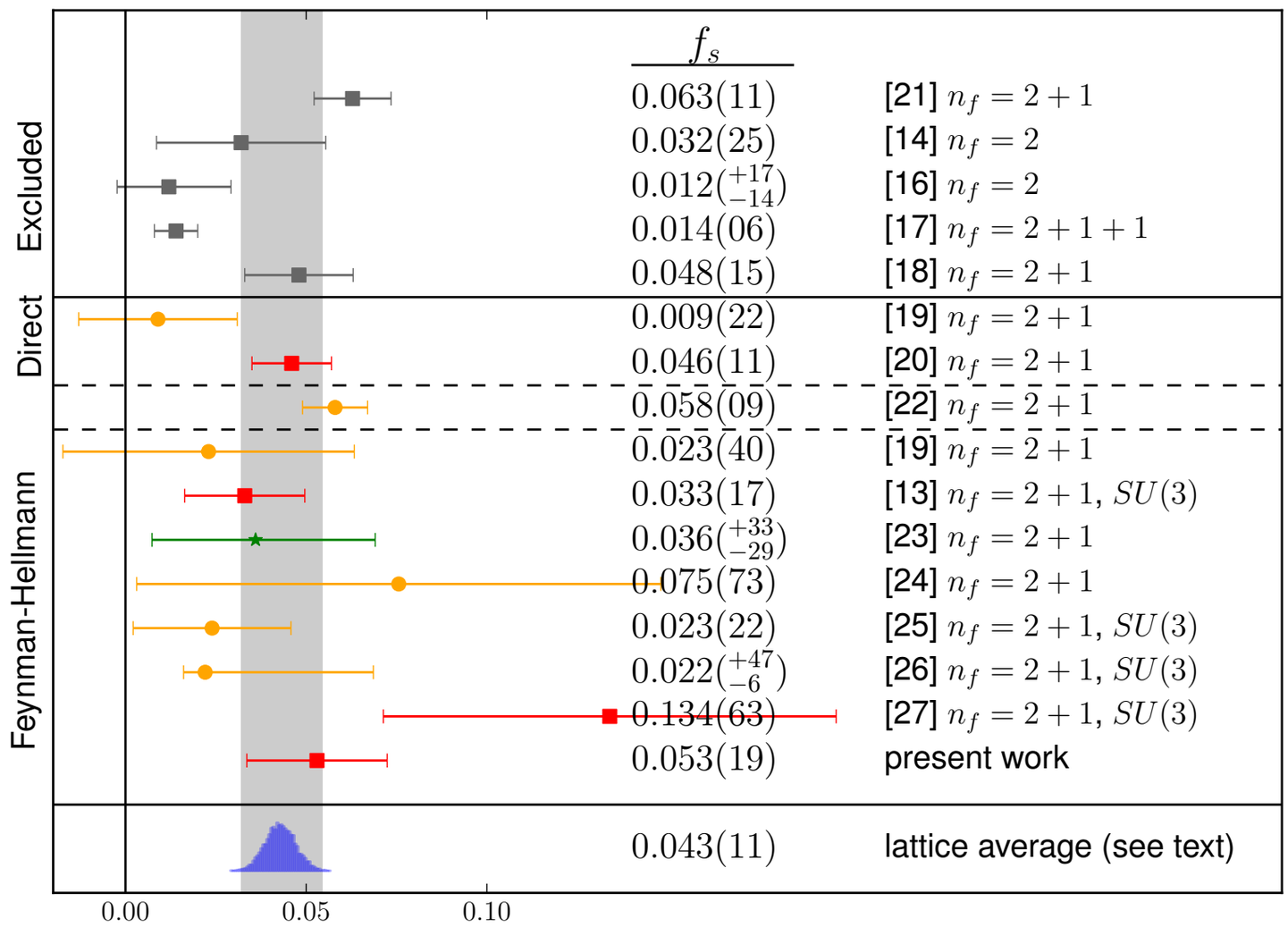

$$f_s = m_s\langle N|\bar{s}s|N\rangle/m_N$$

If Dark Matter couples to the scalar current of the nucleon (eg via Higgs) Spin Independent cross section

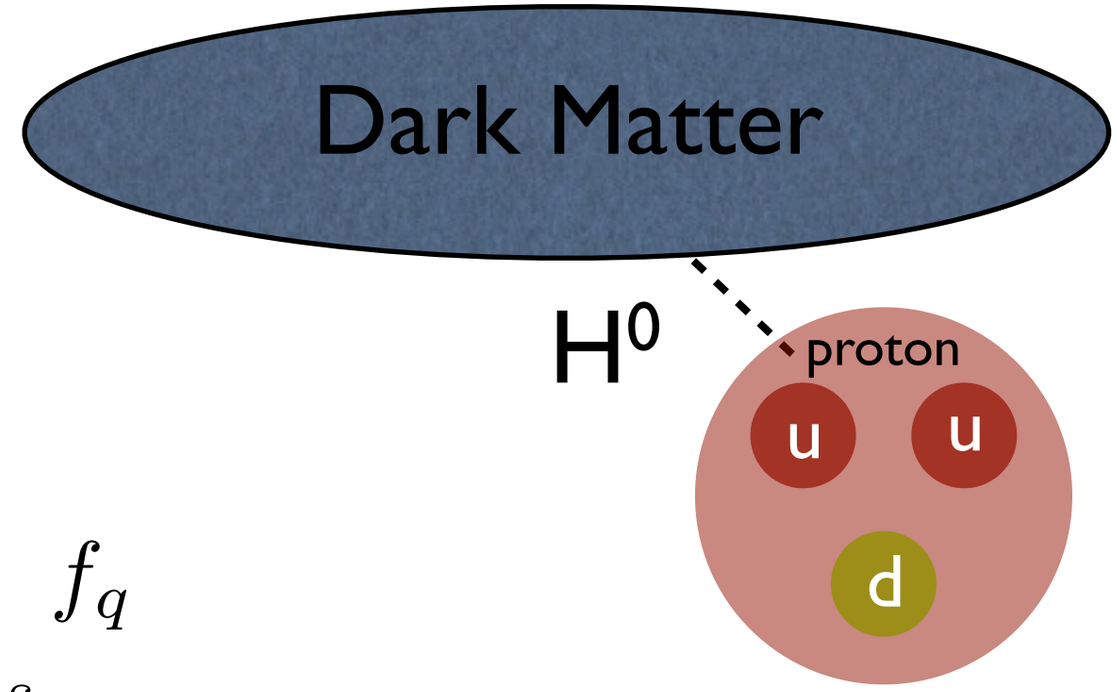

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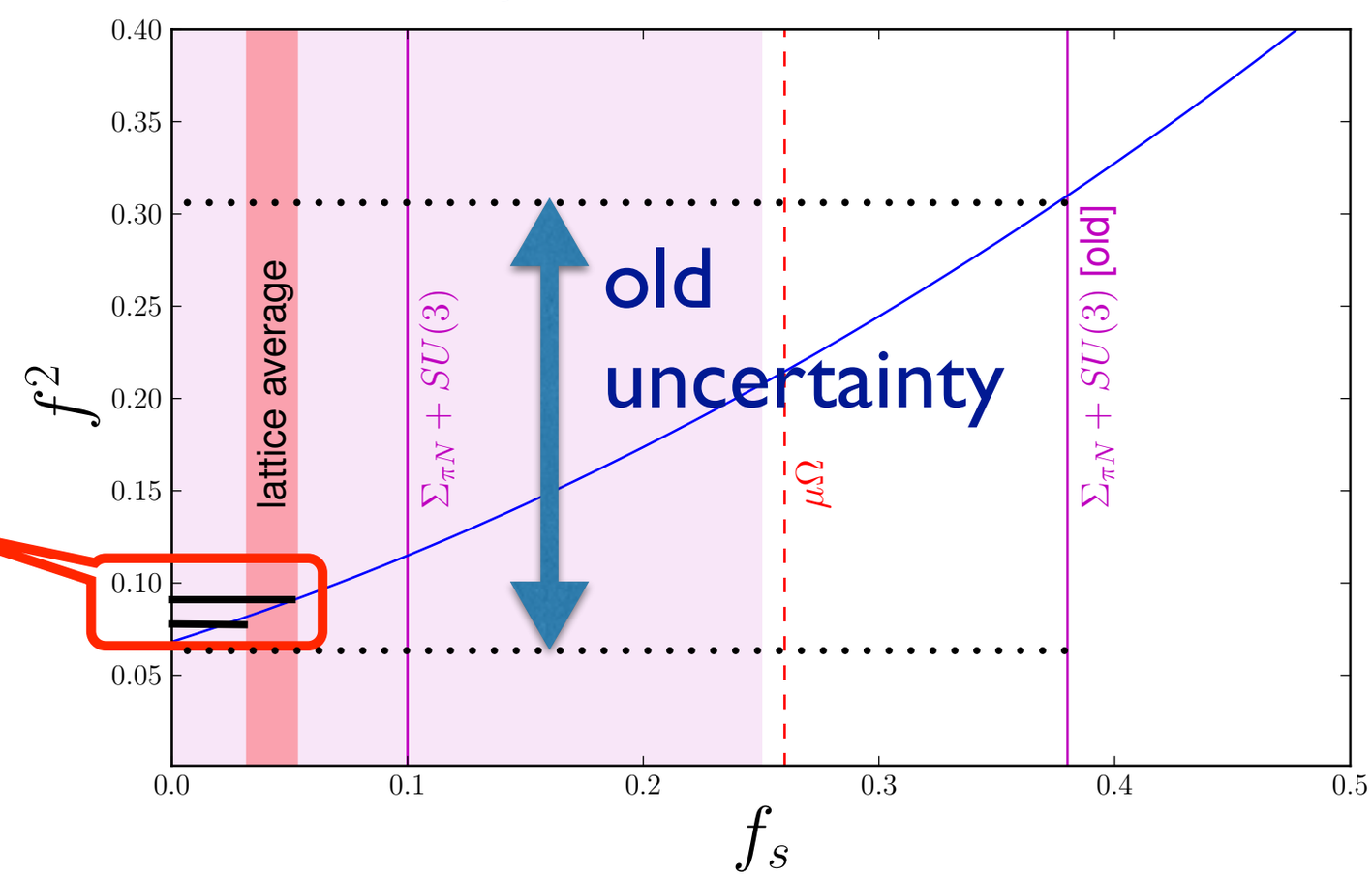
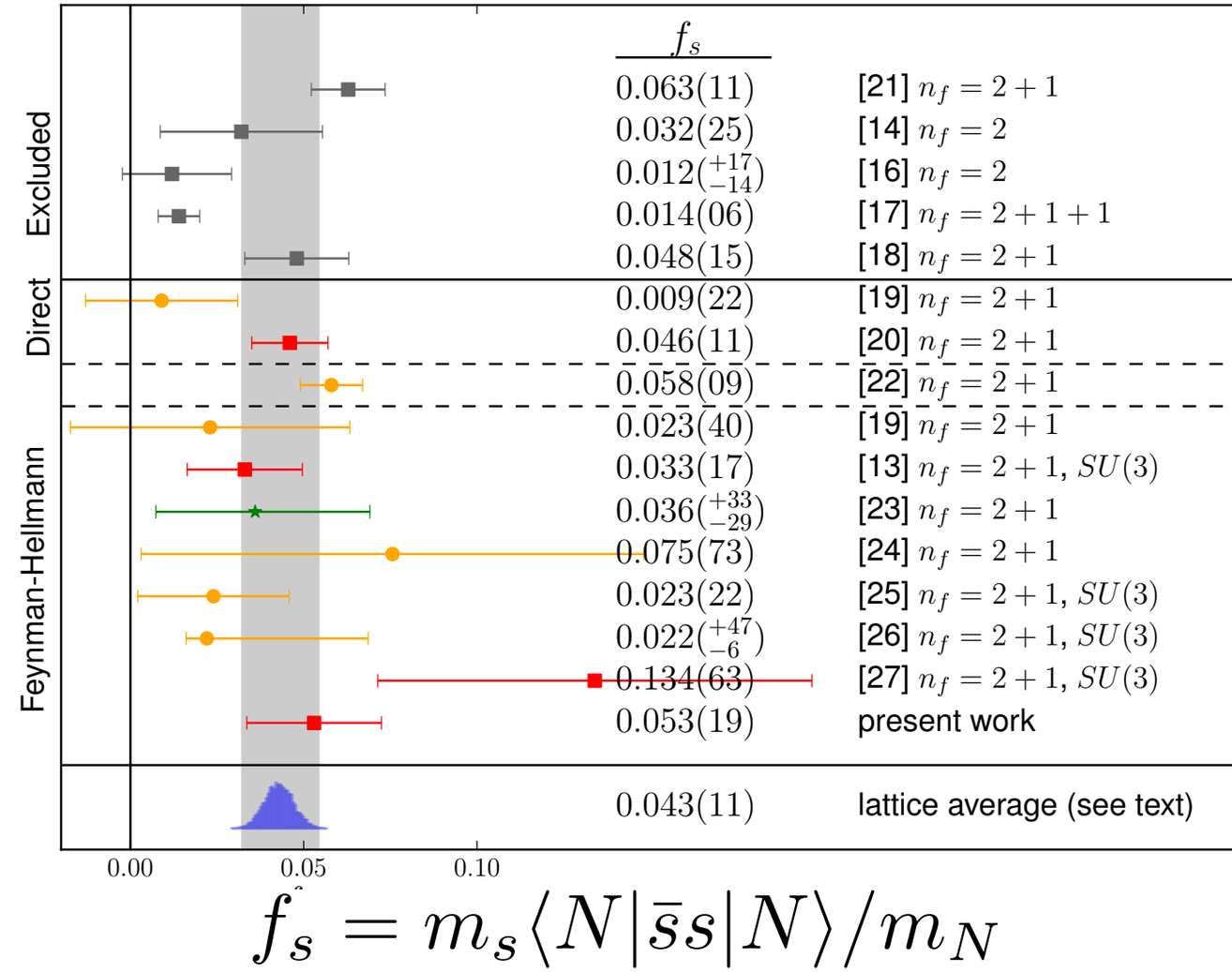
figure adapted from arXiv:1211.4873 thanks to J. Ruderman and collaborators



dramatic reduction in uncertainty of cross section

now $f_{u,d}$ gives larger uncertainty - but harder

New results from BMWc
[PRELIMINARY - lattice 2016]
and Abdel-Rehim, Alexandrou, Constantinou, Hadjiyiannakou, Jansen, Kallidonis, Koutsou and Vaquero Aviles-Casco,
Phys. Rev. Lett 116 [1601.01624]



$$f_s = m_s \langle N | \bar{s} s | N \rangle / m_N$$

BMWc: $f_s = 0.076(4)$

Abdel-Rehim et al: $f_s = 0.044(^{11}_{10})$

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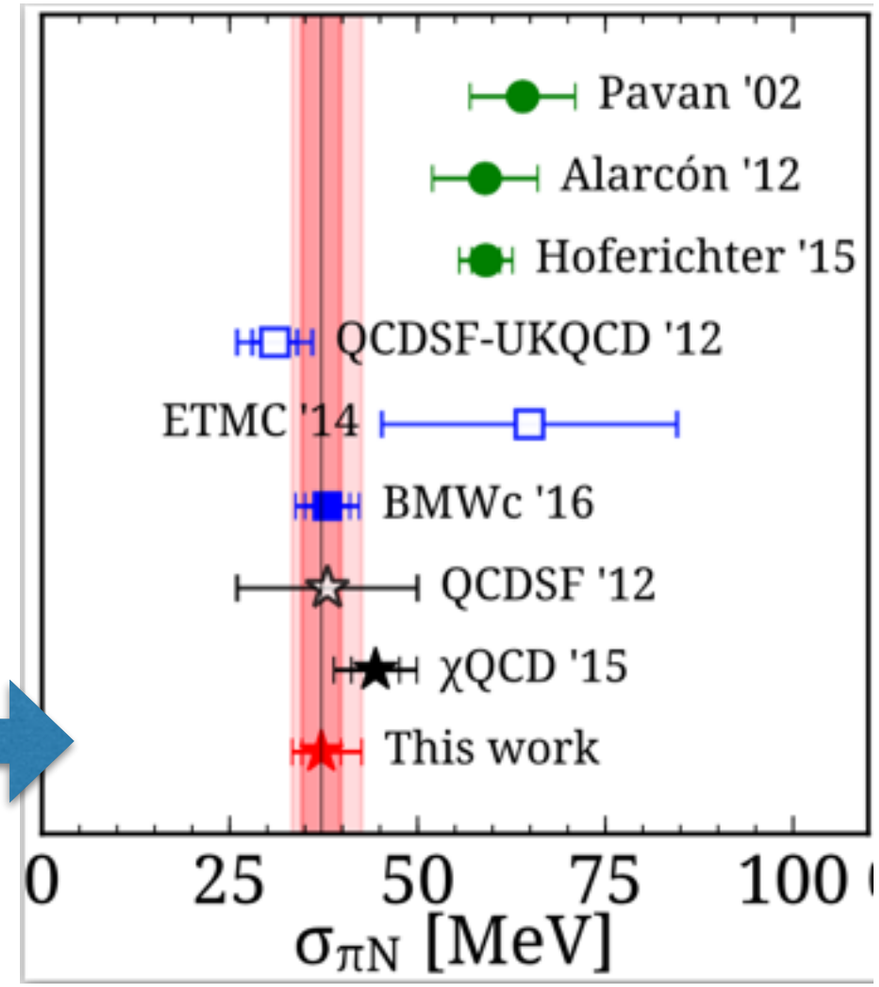

BMWc: $f_{ud}^N = 0.0517(49)(70) \rightarrow \sigma_{\pi N} = 48.5(8.0)\ \mathrm{MeV}$

Abdel-Rehim et al: $\sigma_{\pi N} = 37.2(^{5.3}_{3.9})\ \mathrm{MeV}$

Mild tension between Roy-Steiner determination and LQCD determination - BUT LQCD not competitive with uncertainty (yet)

$$\sigma_{\pi N}^{RS} = 59.1(3.5)\ \mathrm{MeV}$$

Hoferichter, Ruiz de Elvira, Kubis, Meißner
Phys.Rev.Lett. 115 (2015) 092301 [1506.04142]

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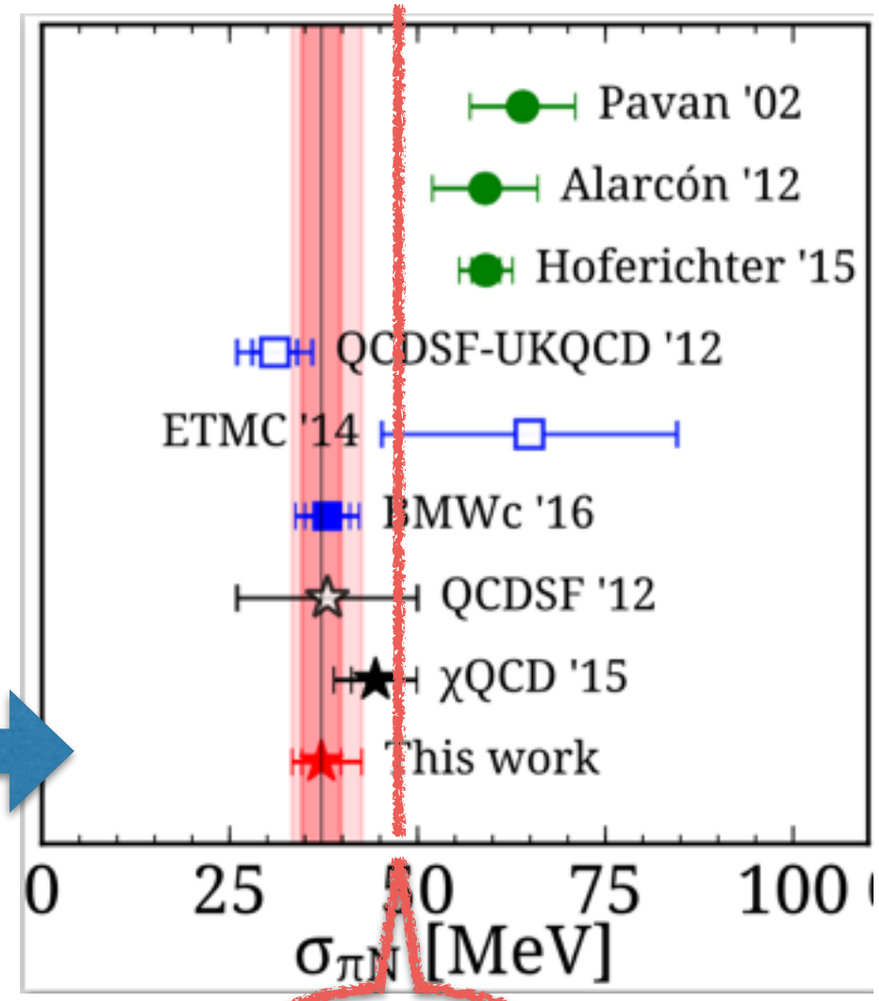

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LQCD and Chiral Physics

- Effective Field Theory (Chiral Perturbation Theory) predicts infrared (IR) corrections that are non-analytic in the light quark mass: e.g. $\ln(m_\pi^2)$ *"chiral logarithms"*
- observation of such non-analytic behavior as we vary the quark masses would provide important confidence in our LQCD calculations of basic NP quantities
- non-analytic light quark mass behavior has been observed in pion/kaon physics - but so far, no conclusive evidence of such behavior has been demonstrated for a baryon quantity
- I'll show you that the iso-vector nucleon mass provides such evidence

m_n - m_p and chiral logs

NNLO Chiral Perturbation Theory

$$2\delta = m_d - m_u$$

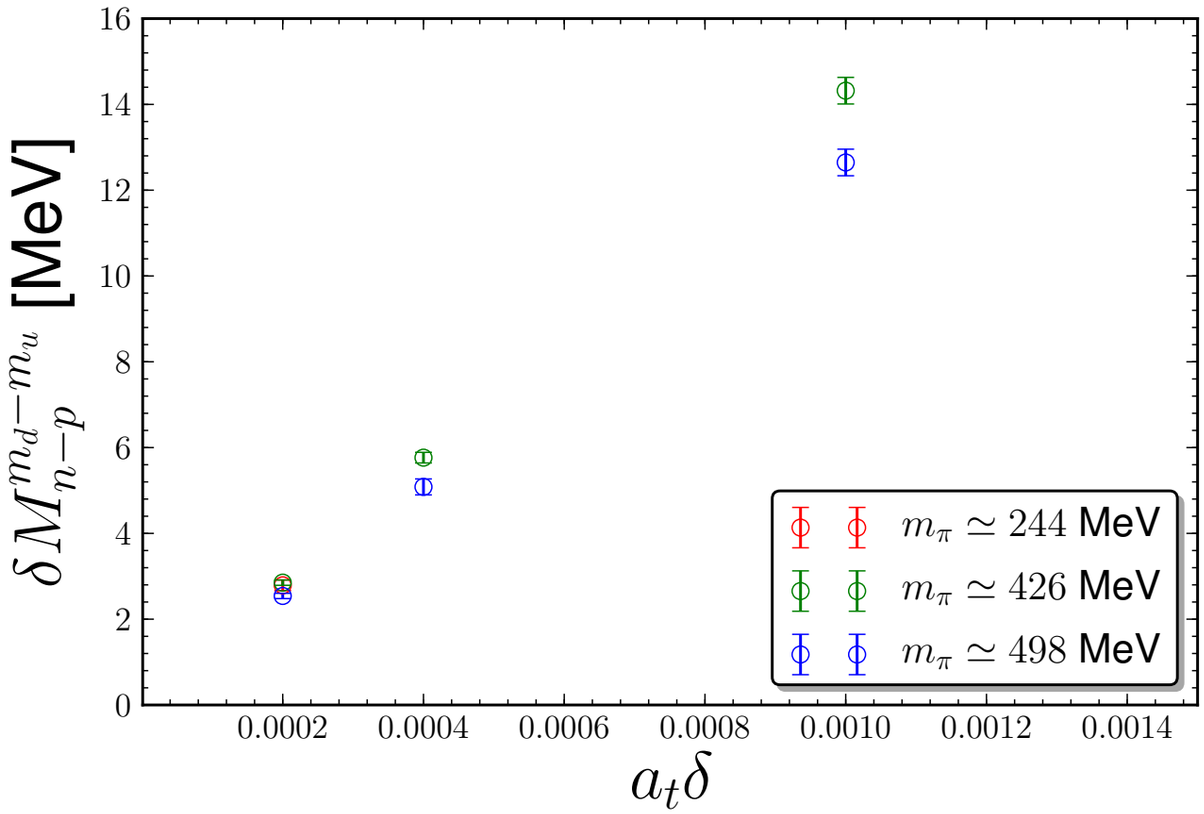
$$m_n - m_p = \delta \left\{ \alpha \left[1 - (6g_A^2 + 1) \frac{m_\pi^2}{(4\pi f_\pi)^2} \ln\left(\frac{m_\pi^2}{\mu^2}\right) \right] + \beta(\mu) \frac{2m_\pi^2}{(4\pi f_\pi)^2} \right\}$$

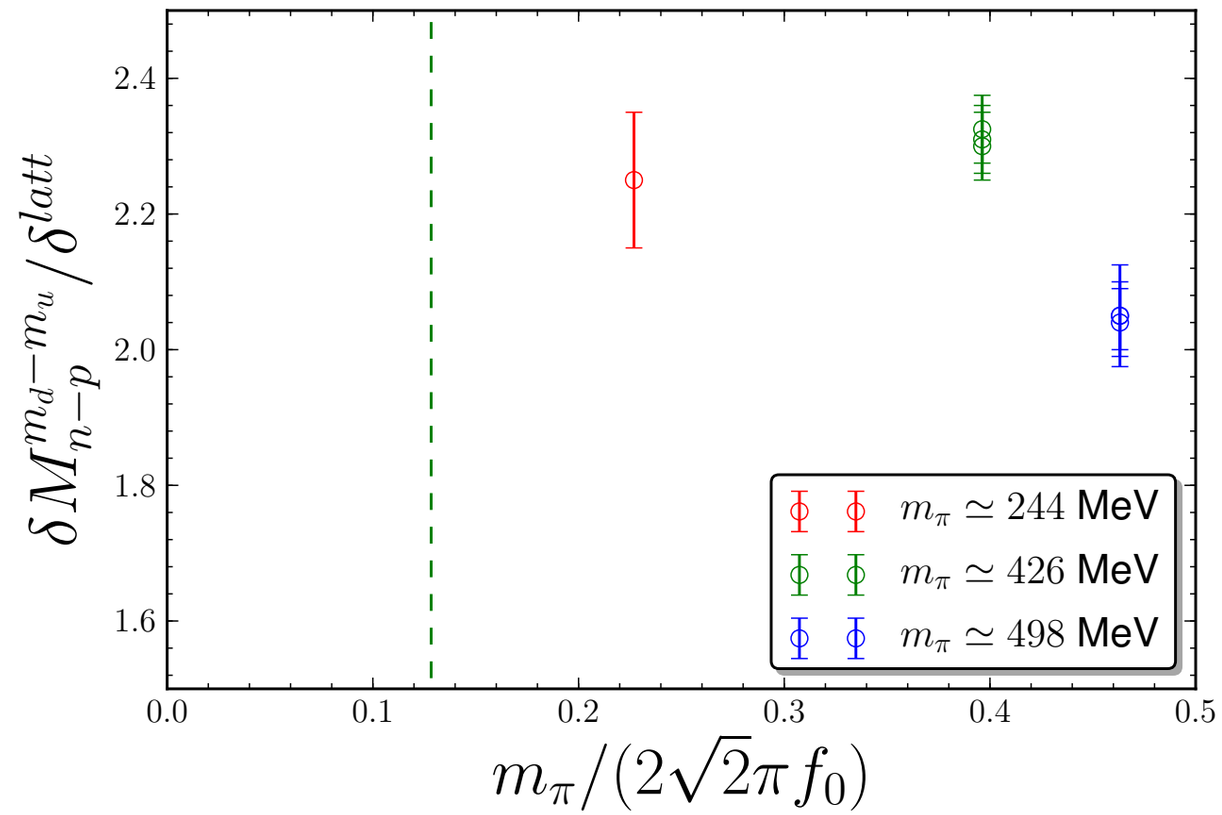
Note the very large coefficient of the log-term

α, β unknown LECs

$m_n - m_p$ and chiral logs

PRELIMINARY





slope depends slightly on pion mass

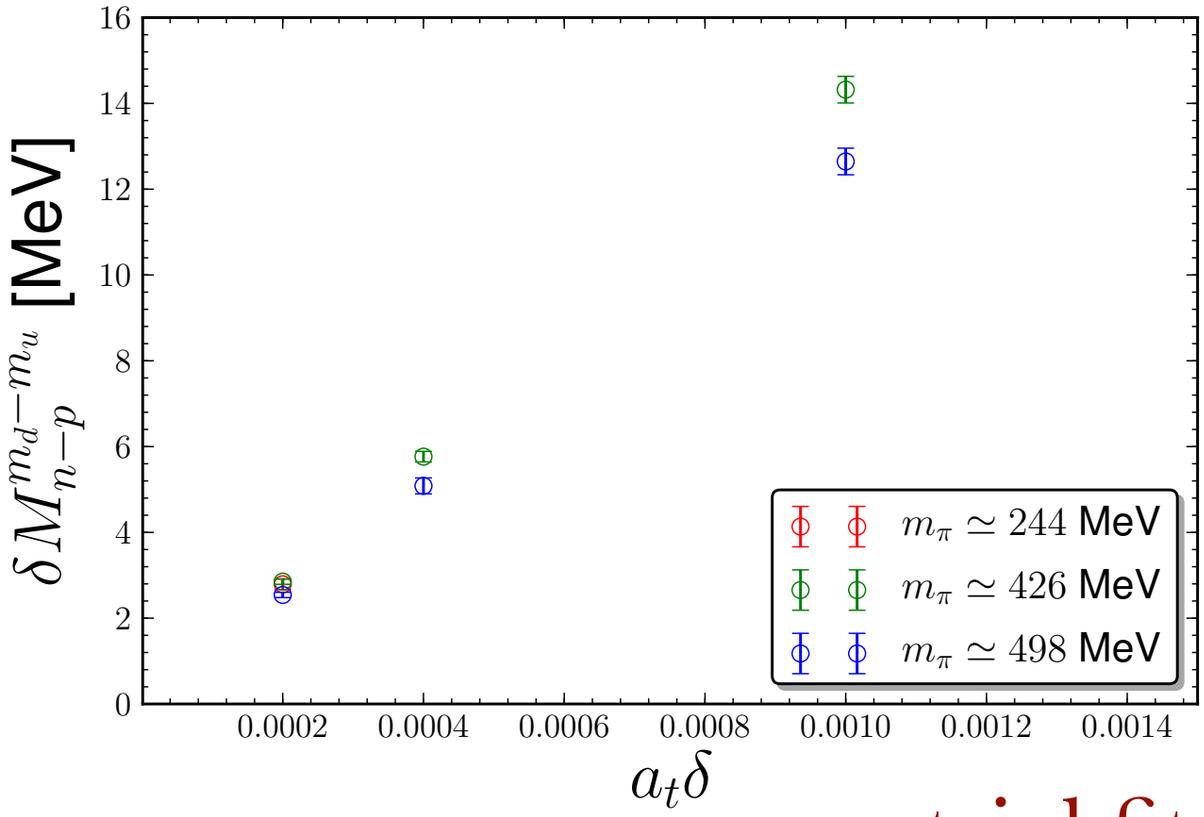
no evidence for deviations from linear δ dependence

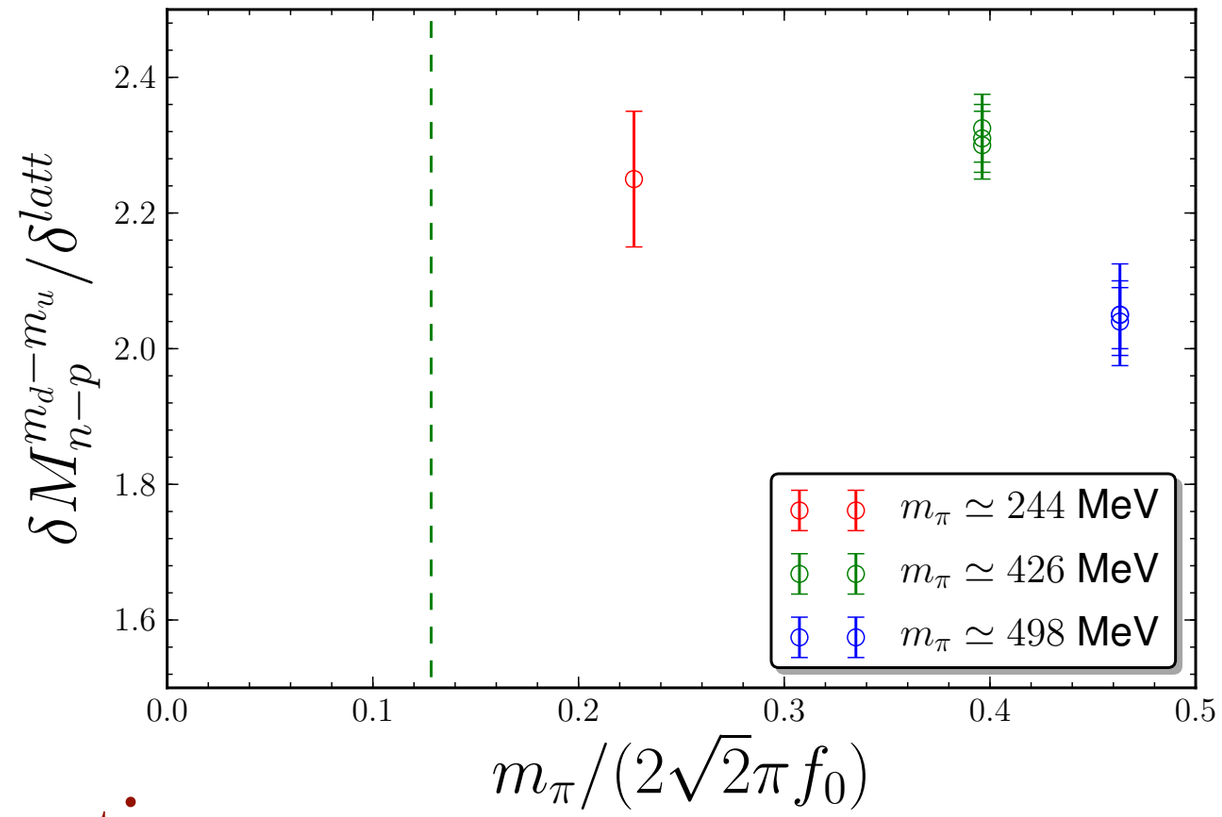
C.Aubin, David Brantley, Emanuele Mereghetti, Henry Monge Comacho, B.Tiburzi, AWL

black = has job
red = postdoc
blue = grad student

$m_n - m_p$ and chiral logs

PRELIMINARY





trial fit functions

polynomial in m_π^2

$$\delta M_{n-p}^{m_d-m_u} = \delta\left\{\alpha + \beta\frac{m_\pi^2}{(4\pi f_\pi)^2}\right\}$$

$$\chi^2/dof = 13/5 = 2.6$$

NNLO χPT

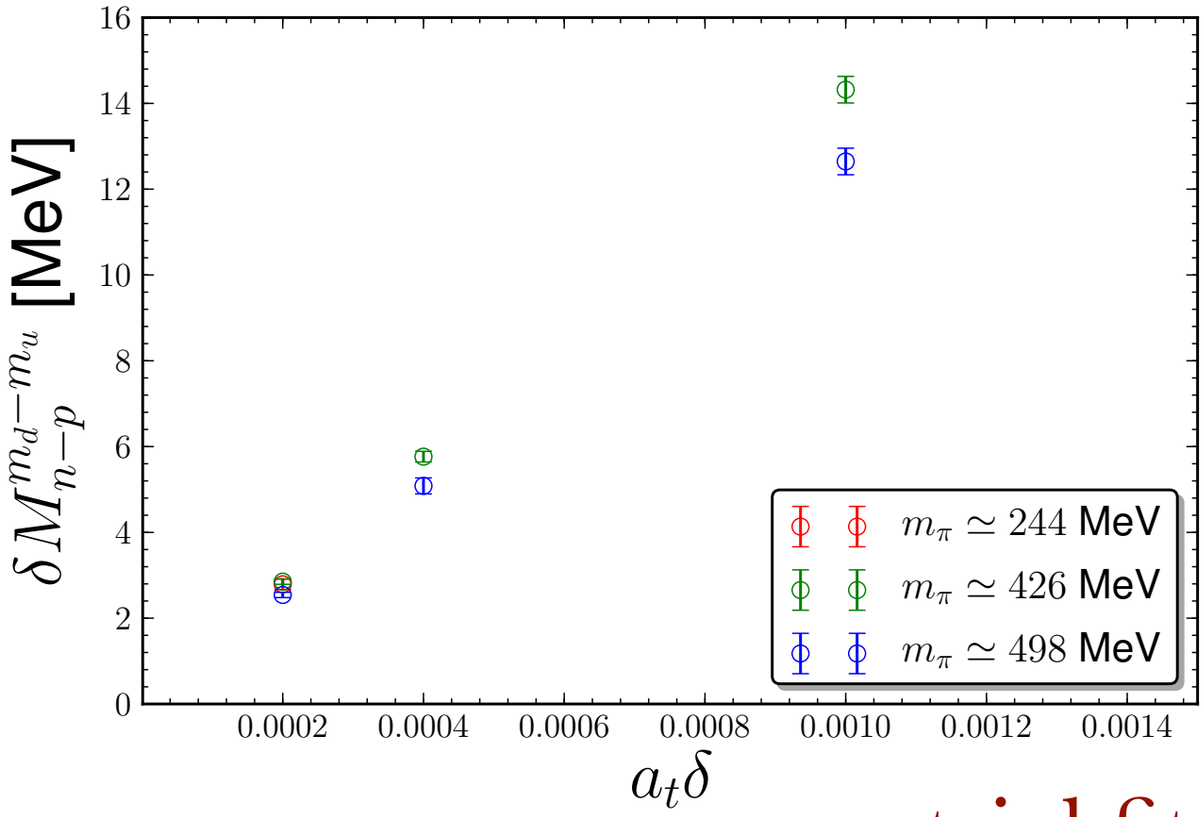
$$\delta M_{n-p}^{m_d-m_u} = \delta\left\{\alpha\left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2}(6g_A^2+1)\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + \beta(\mu)\frac{2m_\pi^2}{(4\pi f_\pi)^2}\right\}$$

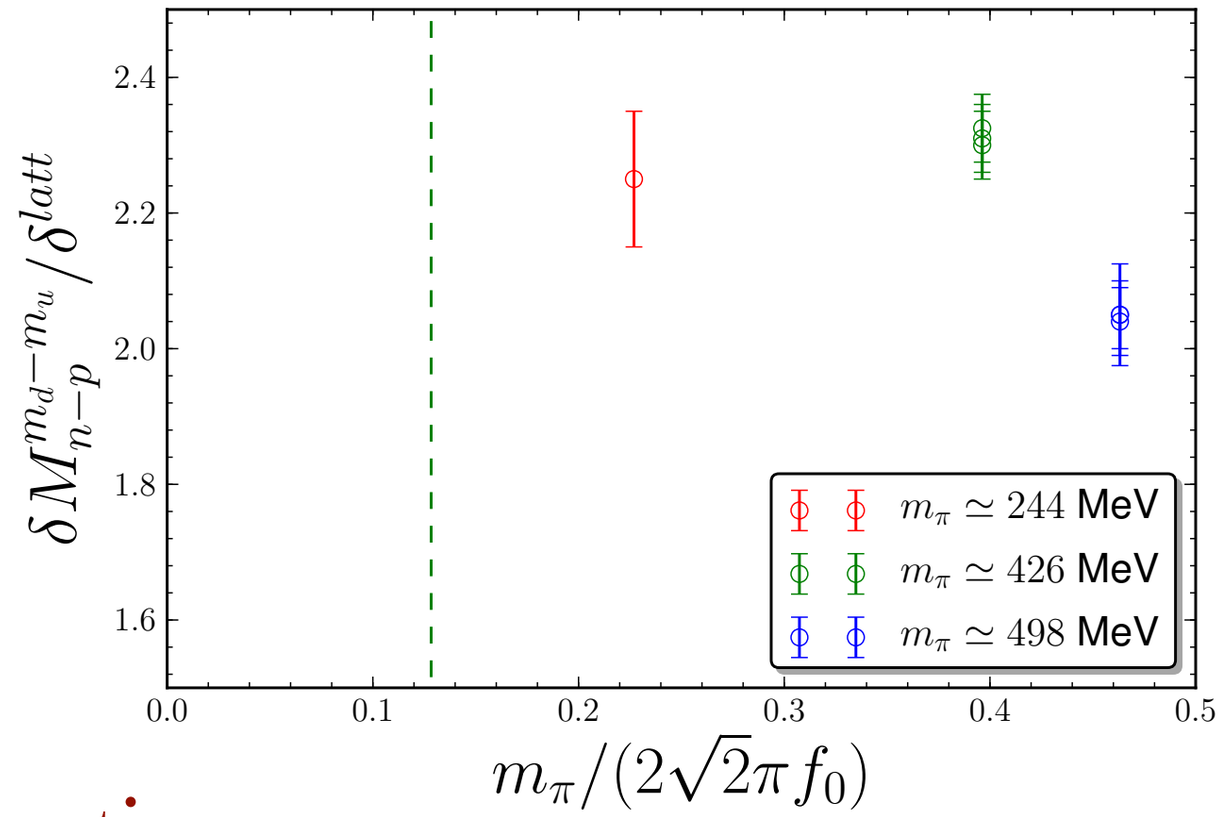
$(g_A = 1.27, f_\pi = 130$ MeV$)$

$$\chi^2/dof = 1.66/5 = 0.33$$

$m_n - m_p$ and chiral logs

PRELIMINARY





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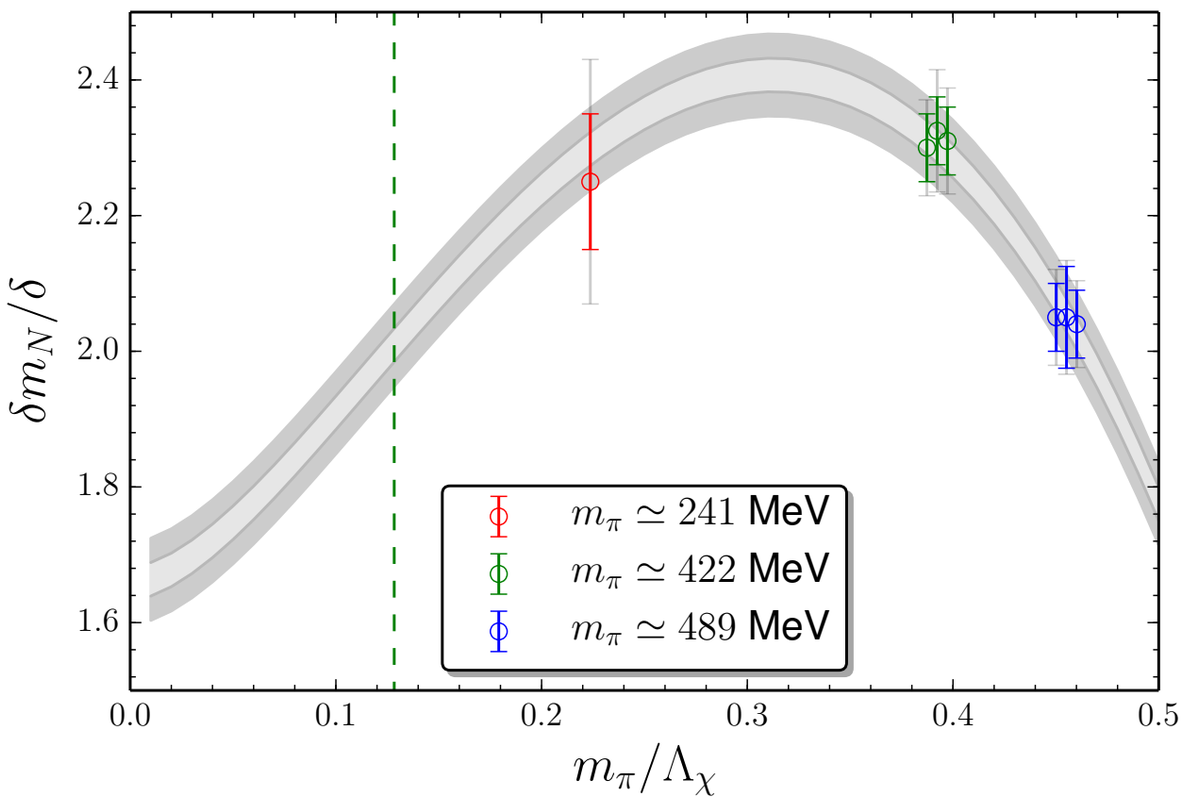
($f_\pi = 130$ MeV)

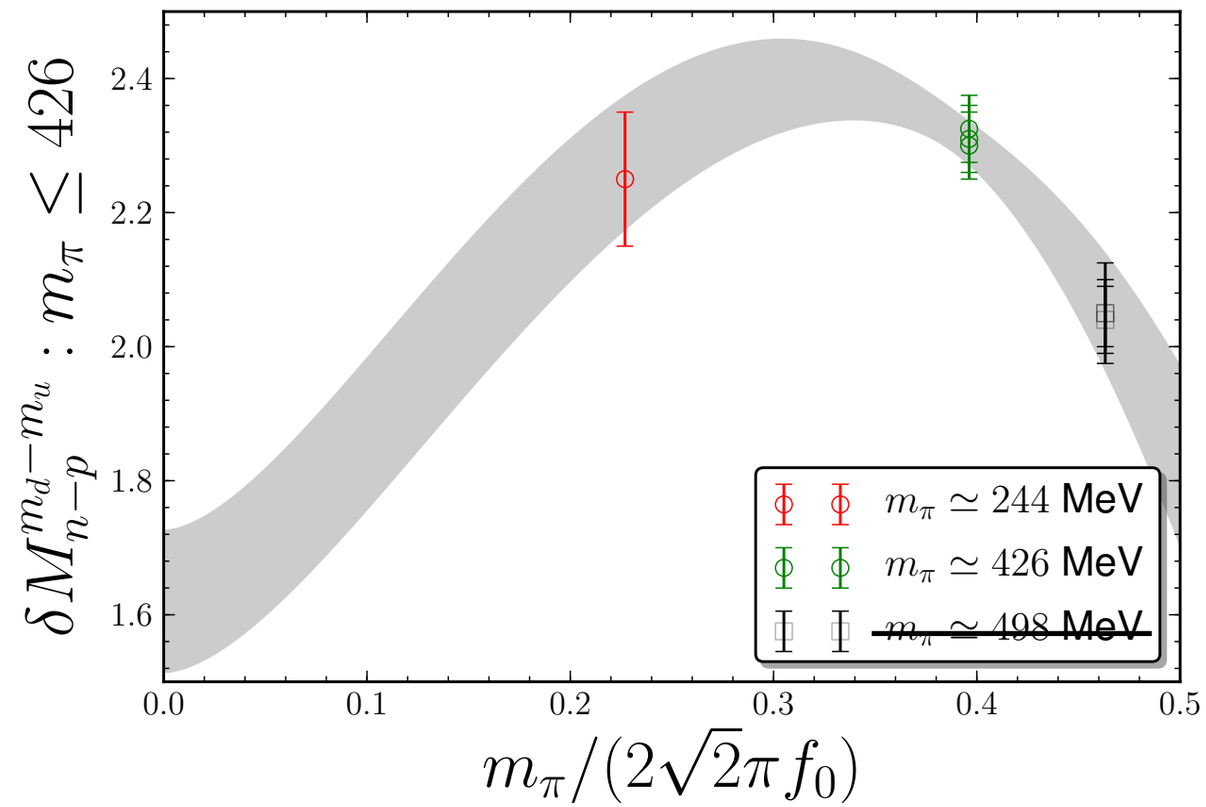
$$\chi^2/dof = 1.34/4 = 0.33$$

$\Rightarrow$ $g_A = 1.50(.29)$

$m_n - m_p$ and chiral logs

PRELIMINARY





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$(g_A = 1.27, f_\pi = 130$ MeV$)$

$$\chi^2/dof = 1.66/5 = 0.33$$

exclude heavy mass point

this is striking evidence of a chiral logarithm

m_n - m_p and chiral logs $M_{\Xi^-} - M_{\Xi^0}$ PRELIMINARY

If this story is true, we should be able to predict the behavior of the Ξ isospin splitting. The Ξ is also an iso-doublet, so the chiral Lagrangian will be identical in form, with only the LECs being different.

$$\delta M_N^{m_d - m_u} = \delta\left\{\alpha_N\left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2}(6g_A^2+1)\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + \beta_N(\mu)\frac{2m_\pi^2}{(4\pi f_\pi)^2}\right\}$$

$$g_A = 1.27$$

$$\delta M_\Xi^{m_d - m_u} = \delta\left\{\alpha_\Xi\left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2}(6g_\Xi^2+1)\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + \beta_\Xi(\mu)\frac{2m_\pi^2}{(4\pi f_\pi)^2}\right\}$$

$$g_\Xi \simeq 0.24$$

Contribution from log should be ~10 times smaller, or, rather insignificant

m_n - m_p and chiral logs $M_{\Xi^-} - M_{\Xi^0}$ PRELIMINARY

$$\delta M_N^{m_d - m_u} = \delta\left\{\alpha_N\left[1 - \frac{m_\pi^2}{(4\pi f_\pi)^2}(6g_A^2+1)\ln\left(\frac{m_\pi^2}{\mu^2}\right)\right] + \beta_N(\mu)\frac{2m_\pi^2}{(4\pi f_\pi)^2}\right\}$$

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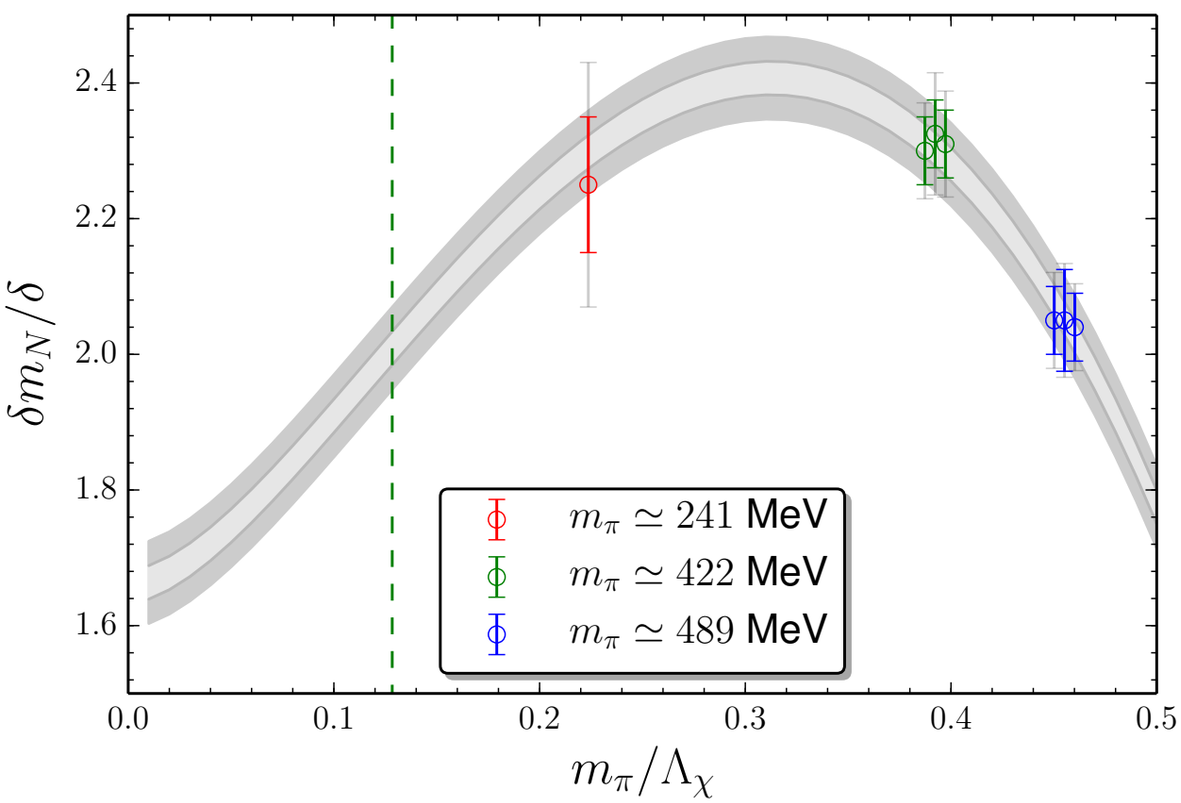
$g_A = 1.27$



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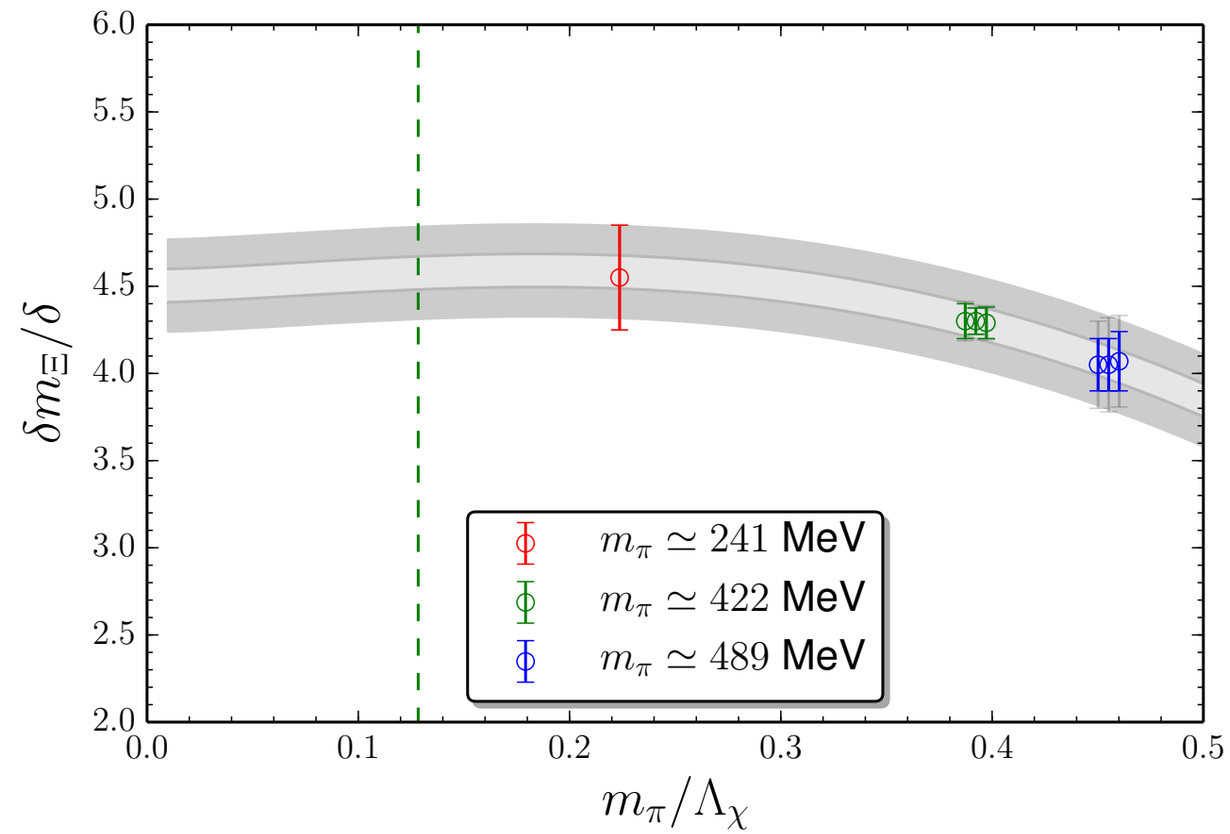
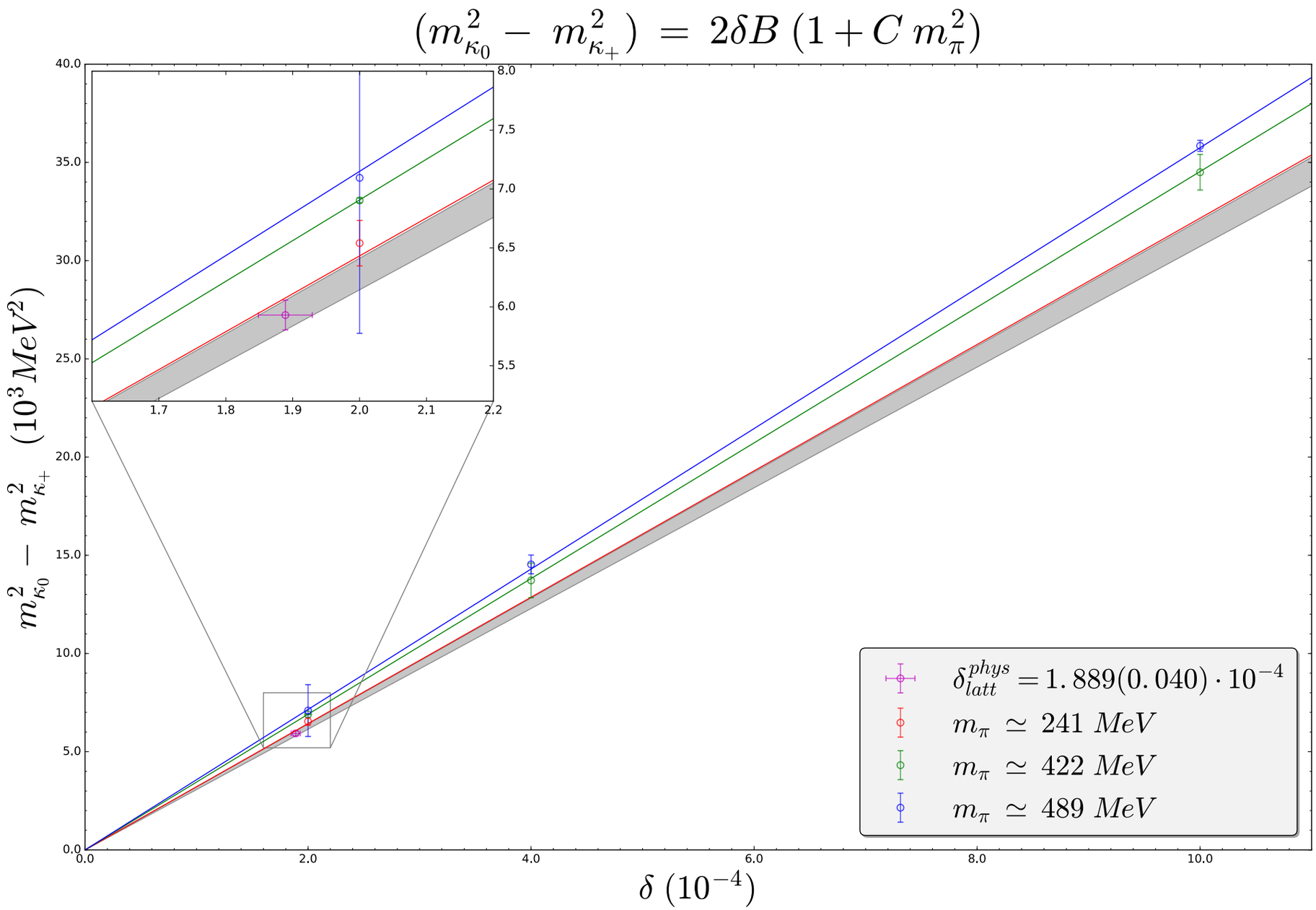


$\alpha_N = 1.66 \pm 0.06 \pm 0.09$

$\alpha_\Xi = 4.50 \pm 0.24 \pm 0.42$

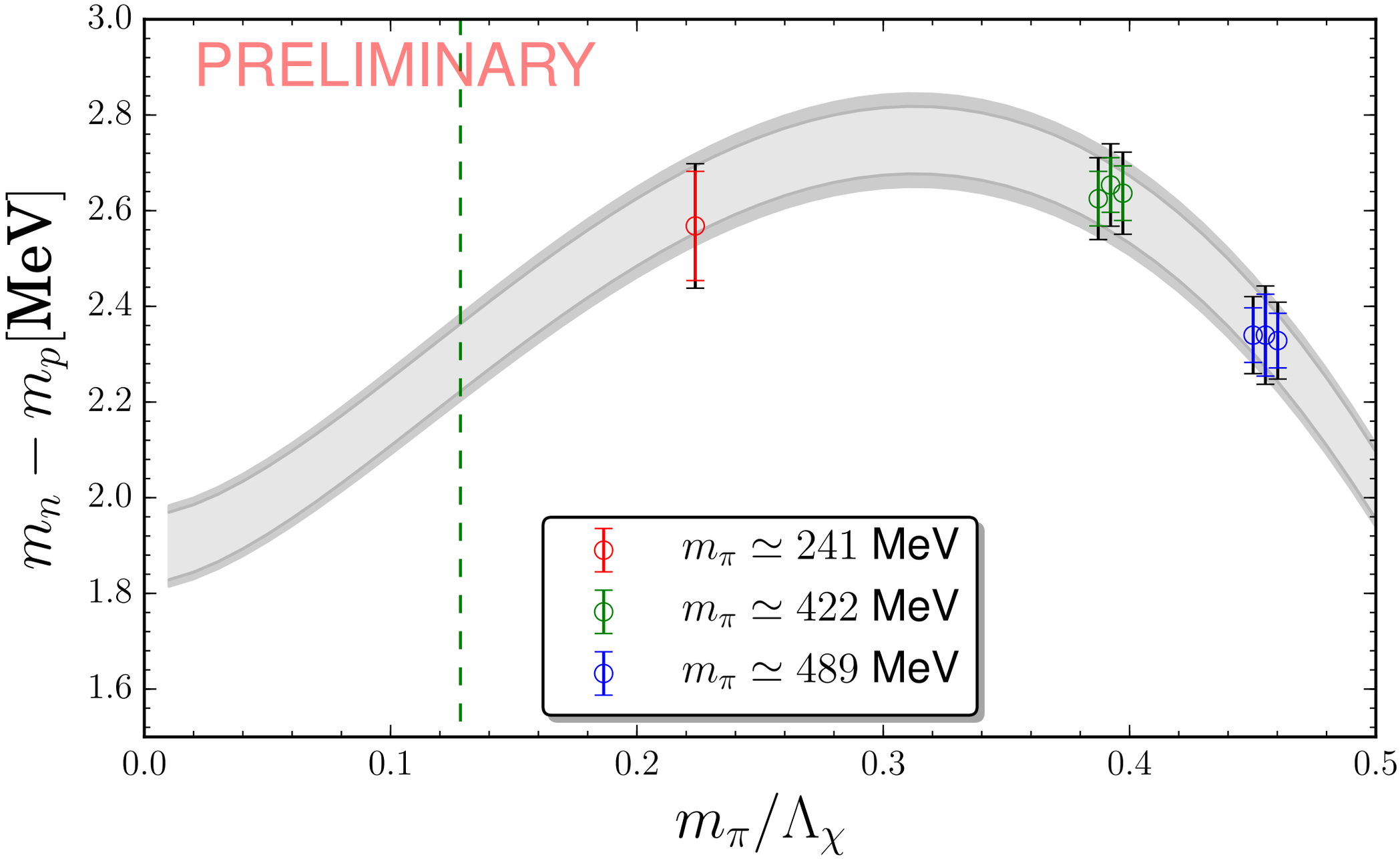
This is the first conclusive, direct evidence of a chiral-logarithm in a baryon calculation from LQCD

m_n - m_p and chiral logs $M_{\Xi^-} - M_{\Xi^0}$ PRELIMINARY



Use the (QED corrected - ala FLAG Aoki et.al. 1607.00299) Kaon splitting to determine the physical value of δ in lattice units

m_n - m_p and chiral logs $M_{\Xi^-} - M_{\Xi^0}$ PRELIMINARY



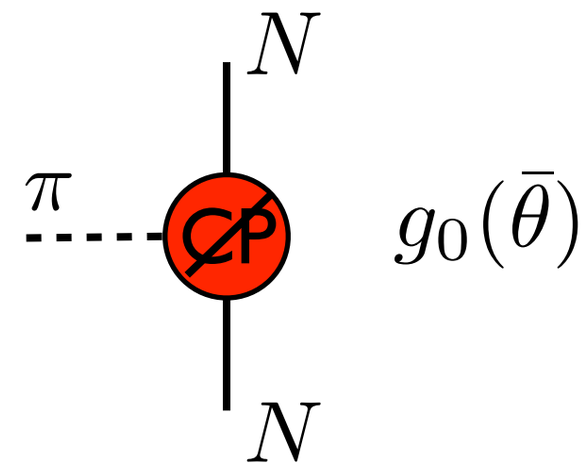
iso-vector nucleon mass splitting: CAUTION - only a single lattice spacing, so uncontrolled $\lesssim 10\%$ discretization corrections to overall height - discretization corrections to chiral-log are higher order

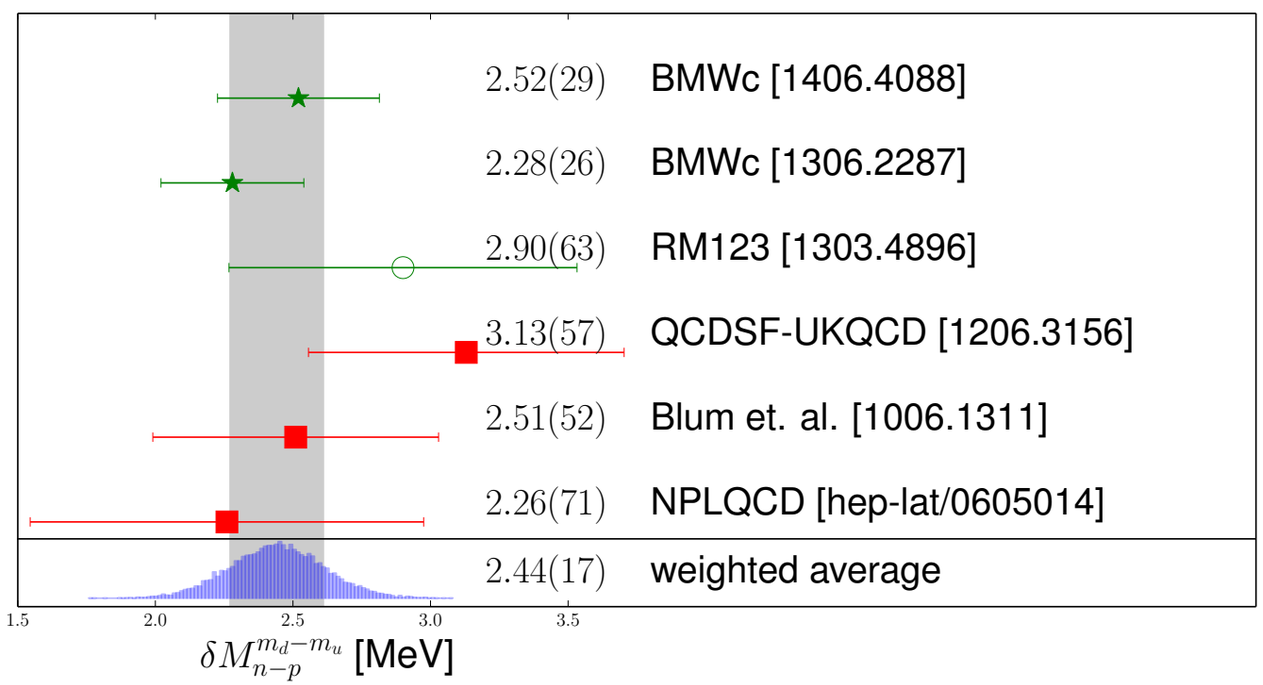
Lattice QCD for EDMs

Crewther, Di Vecchia, Veneziano, Witten
PLB 88 (1979)

$$\delta M_{n-p}^{m_d-m_u} = 2.44(17)\ \text{MeV}$$

$$\bar{g}_0 = \frac{\delta M_{n-p}^{m_d-m_u}}{m_d - m_u}\frac{2m_d m_u}{m_d + m_u}\bar{\theta} = \alpha\frac{m_d m_u}{m_d + m_u}\bar{\theta}$$





additional relations between CP-odd couplings and Octet mass splitting: ONLY nucleon mass splitting is free from large SU(3) flavor corrections

$$\frac{\bar{g}_0}{2F_\pi} = (15.5 \pm 2.0 \pm 1.6) \times 10^{-3}\bar{\theta}$$

LQCD uncertainty

SU(3) Flavor breaking uncertainty

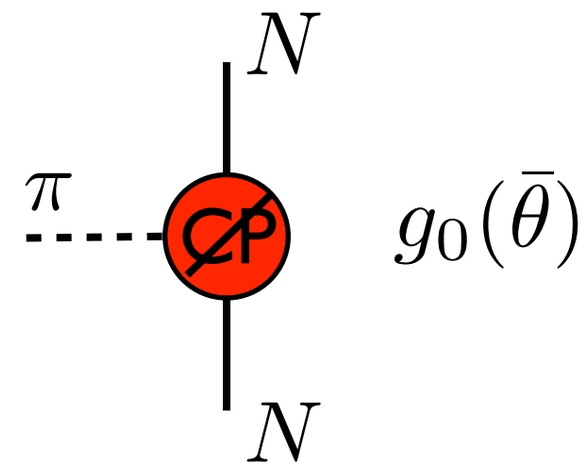
Phys. Rev. C92 (2015) [1506.06247]
Jordy de Vries,
Emanuele Mereghetti,
AWL

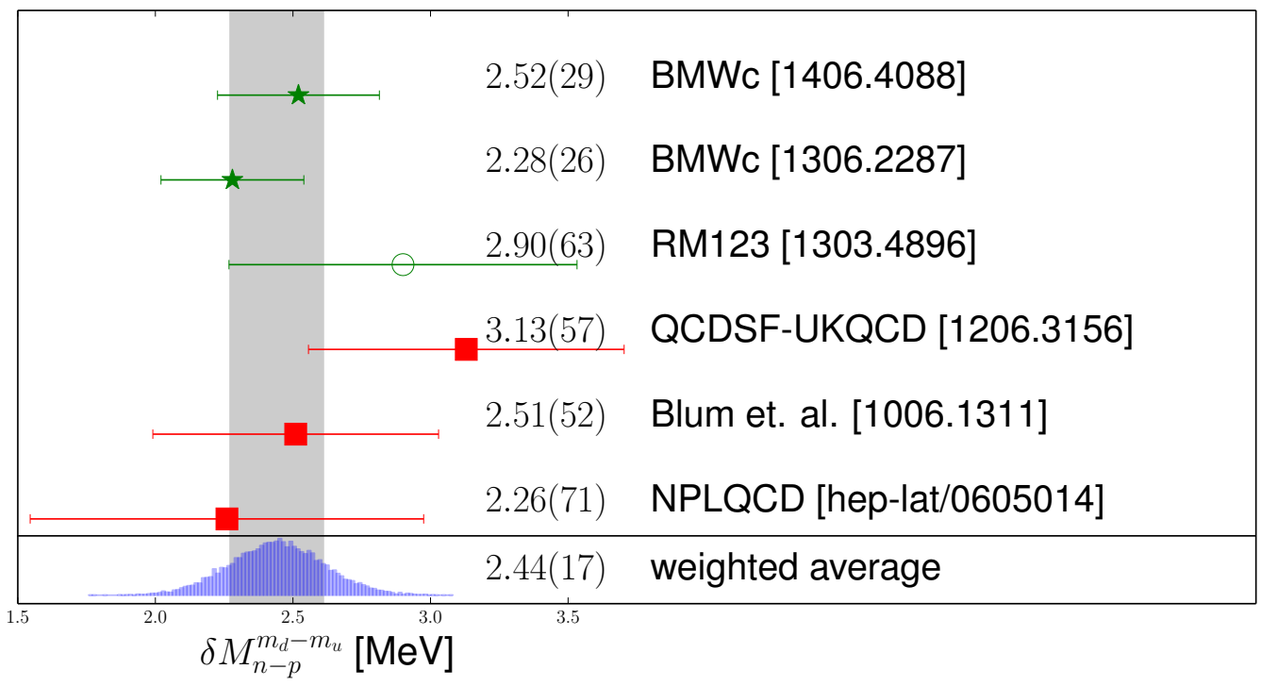
Lattice QCD for EDMs

Crewther, Di Vecchia, Veneziano, Witten
PLB 88 (1979)

$$\delta M_{n-p}^{m_d-m_u} = 2.44(17)\ \text{MeV}$$

$$\bar{g}_0 = \frac{\delta M_{n-p}^{m_d-m_u}}{m_d - m_u}\frac{2m_d m_u}{m_d + m_u}\bar{\theta} = \alpha\frac{2m_d m_u}{m_d + m_u}\bar{\theta}$$





making use of this relation to determine the CP-odd pion-nucleon coupling is how the ^{199}Hg bound on an EDM provides a competitive bound on $\bar{\theta}$

$$\frac{\bar{g}_0}{2F_\pi} = (15.5 \pm 2.0 \pm 1.6) \times 10^{-3}\bar{\theta}$$

LQCD uncertainty

SU(3) Flavor breaking uncertainty

Phys. Rev. C92 (2015) [1506.06247]
Jordy de Vries, Emanuele Mereghetti, AWL

Lattice QCD for EDMs

I just provided two examples where simple spectroscopic LQCD calculations can provide important input for interesting nucleon matrix elements:

1. quark-mass dependence of the nucleon for scalar quark matrix elements
2. iso-vector nucleon mass and the determination of the CP-odd pion-nucleon coupling

This strategy can be used to determine the would be CP-odd pion-nucleon couplings from beyond the Standard Model sources of CP-violation

M. Pospelov, A. Ritz
Annals Phys 318 (2005) [hep-ph/0504231]

Lattice QCD for EDMs

- Sources of CP-Violation in quark sector:

Operator	[Operator]	No. Operators
$\bar{\theta}$	4	1
quark EDM	6	2
quark Chromo-EDM	6	2
Weinberg (GGG)	6	1
4-quark	6	2
4-quark induced	6	1

Lattice QCD for EDMs

- Sources of CP-Violation in quark sector:

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Lattice QCD for EDMs

- Sources of CP-Violation in quark sector:

Operator	[Operator]	No. Operators
$\bar{\theta}$	4	1
quark Chromo-EDM	6	2

$$\mathcal{L}^{q}_{\not{CP}} = -\frac{g_s^2\bar{\theta}}{32\pi^2}\tilde{G}_{\mu\nu}G^{\mu\nu} - \frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5\left(\tilde{d}_0 + \tilde{d}_1\tau_3\right)G_{\mu\nu}q$$

$$\Downarrow$$

$$\mathcal{L}^{\pi N}_{\not{CP}} = -\frac{\bar{g}_0}{2F_\pi}\bar{N}\vec{\pi}\cdot\vec{\tau}N - \frac{\bar{g}_1}{2F_\pi}\bar{N}\pi_0 N - \frac{\bar{g}_2}{2F_\pi}\bar{N}\pi_0\left(\tau_3 - \frac{\tau_3}{F_\pi}\vec{\pi}\cdot\vec{\tau}\right)N$$

Computational Strategy

- Quark Chromo-EDM Operators

$$\mathcal{L}^6_{\bar{q}q} = -\frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5(\tilde{d}_0 + \tilde{d}_1\tau_3)G_{\mu\nu}q - \frac{1}{2}\bar{q}\sigma^{\mu\nu}(\tilde{c}_1\tau_3 + \tilde{c}_0)G_{\mu\nu}q$$

Computational Strategy

- Quark Chromo-EDM Operators

$$\mathcal{L}^6_{\bar{q}q} = -\frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5(\tilde{d}_0 + \tilde{d}_1\tau_3)G_{\mu\nu}q - \frac{1}{2}\bar{q}\sigma^{\mu\nu}(\tilde{c}_1\tau_3 + \tilde{c}_0)G_{\mu\nu}q$$

Symmetries ⇒

$$\bar{g}_0 = \delta_q M_N \frac{\tilde{d}_0}{\tilde{c}_1} + \delta M_N \frac{\Delta_q m_\pi^2}{m_\pi^2}\frac{\tilde{d}_1}{\tilde{c}_0}$$

$$\bar{g}_1 = -2\sigma_{\pi N}\left(\frac{\Delta_q M_N}{\sigma_{\pi N}} - \frac{\Delta_q m_\pi^2}{m_\pi^2}\right)\frac{\tilde{d}_1}{\tilde{c}_0}$$

Computational Strategy

- Quark Chromo-EDM Operators

$$\mathcal{L}^6_{\bar{q}q} = -\frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5(\tilde{d}_0 + \tilde{d}_1\tau_3)G_{\mu\nu}q - \frac{1}{2}\bar{q}\sigma^{\mu\nu}(\tilde{c}_1\tau_3 + \tilde{c}_0)G_{\mu\nu}q$$

Symmetries ⇒

$$\bar{g}_0 = \delta_q M_N \frac{\tilde{d}_0}{\tilde{c}_1} + \delta M_N \frac{\Delta_q m_\pi^2}{m_\pi^2}\frac{\tilde{d}_1}{\tilde{c}_0}$$

$$\bar{g}_1 = -2\sigma_{\pi N}\left(\frac{\Delta_q M_N}{\sigma_{\pi N}} - \frac{\Delta_q m_\pi^2}{m_\pi^2}\right)\frac{\tilde{d}_1}{\tilde{c}_0}$$

Again, all that is needed are simple spectroscopic quantities

$$\begin{aligned}
\delta M_N &= \text{nucleon mass splitting induced by } \mathcal{O} = \delta\,\bar{q}\,\tau_3\,q\,,\\
\sigma_{\pi N} &= \text{nucleon sigma-term induced by } \mathcal{O} = -\bar{m}\bar{q}q\,,\\
\delta_q M_N &= \text{nucleon mass splitting induced by } \mathcal{O} = -(\tilde{c}_1/2)\,\bar{q}\sigma^{\mu\nu}\tau_3 G_{\mu\nu}q\,,\\
\Delta_q M_N &= \text{nucleon sigma-term induced by } \mathcal{O} = -(\tilde{c}_0/2)\,\bar{q}\sigma^{\mu\nu}G_{\mu\nu}q\,,\\
\Delta_q m_\pi^2 &= \text{pion sigma-term induced by } \mathcal{O} = -(\tilde{c}_0/2)\,\bar{q}\sigma^{\mu\nu}G_{\mu\nu}q\,,
\end{aligned}$$

How can LQCD contribute?

- LBL/UCB: **Chia Cheng Chang, Amy Nicholson**, AWL,
- LLNL: **Evan Berkowitz, Enrico Rinaldi**, Pavlos Vranas
- Liverpool/Plymouth: **Nicholas Garron**
- NERSC: Thorsten Kurth
- JLab: Balint Jóo
- CCNY: Brian Tiburzi
- nVidia: Kate Clark

red = postdoc

slide (modified) from Amy Nicholson

Majorana or Dirac?

- Anything not forbidden by symmetry should occur in nature

$$\mathcal{L}_5 = -\frac{c_5}{\Lambda_{UV}} \left(\bar{L}\tilde{H}\right)\left(\tilde{H}L\right)^\dagger$$

- Why are neutrinos so light?
  - Dirac mass on its own requires fine-tuning

slide from Amy Nicholson

dim-4 operator not allowed

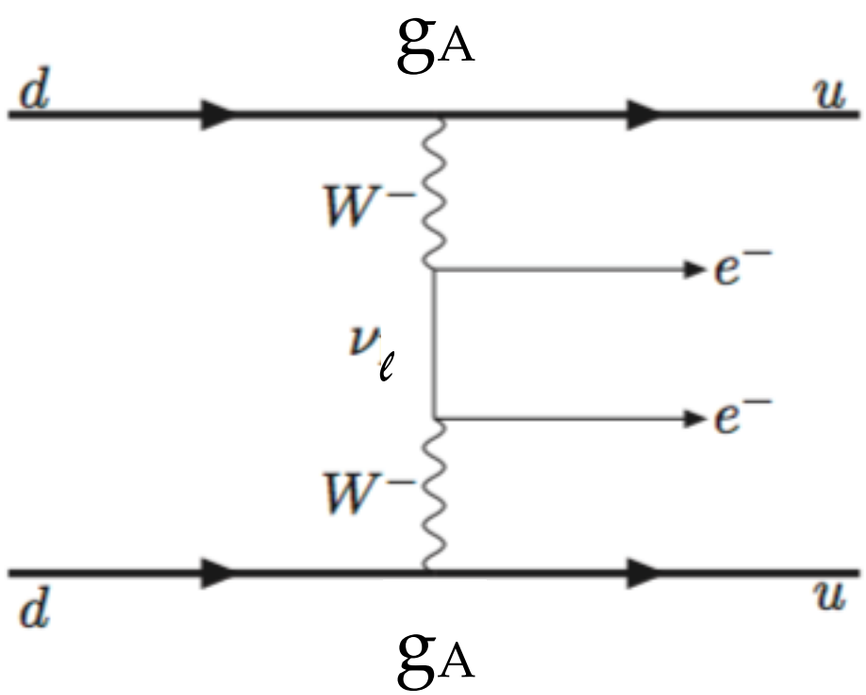
$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

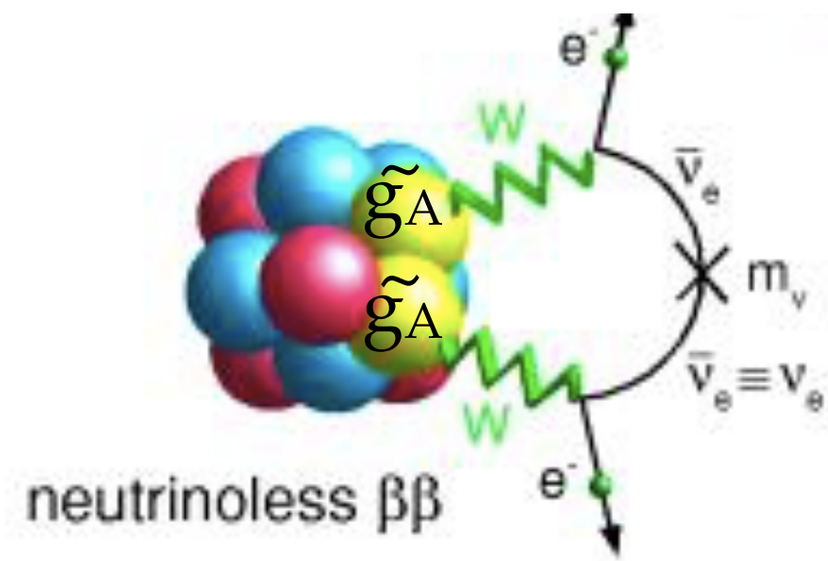
$$m_l \sim M_D^2/M_R \quad m_h \sim M_R$$

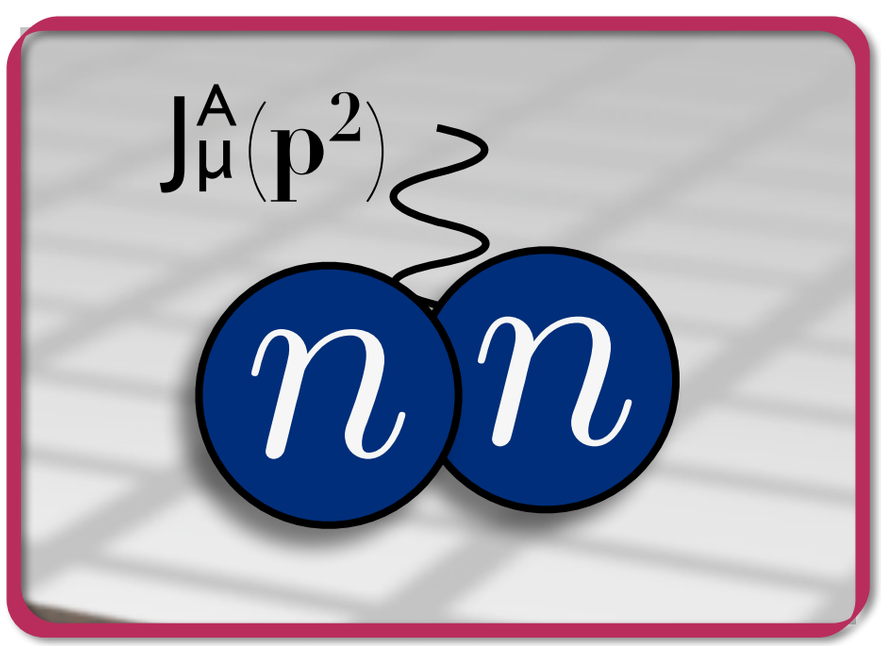
$$M_D \sim 200GeV \quad m_l \sim 0.05eV$$

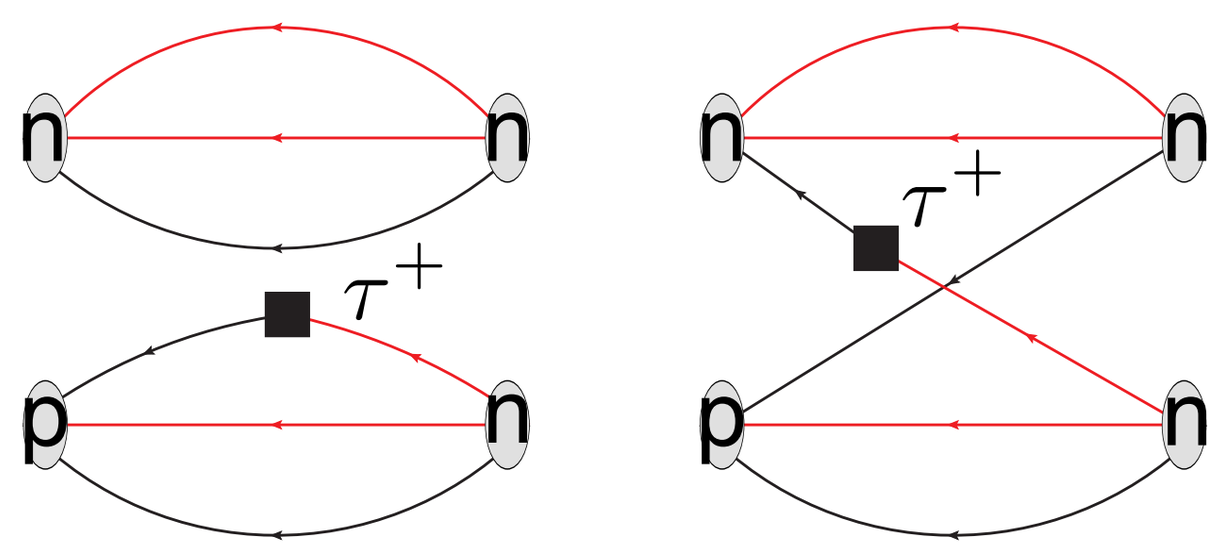
$$M_R \sim 10^{15}GeV$$

Standard picture: long-range contribution





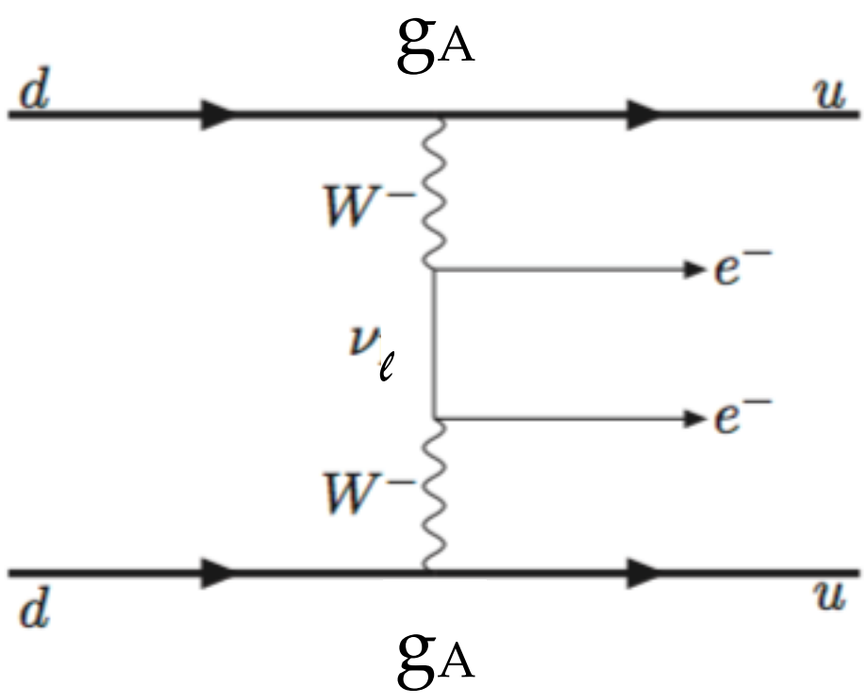


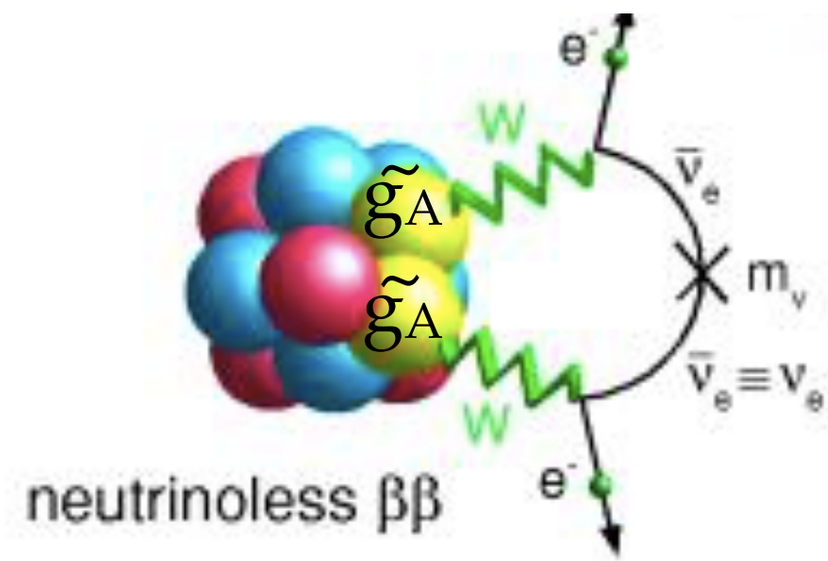


slide (modified) from Amy Nicholson

via FHT

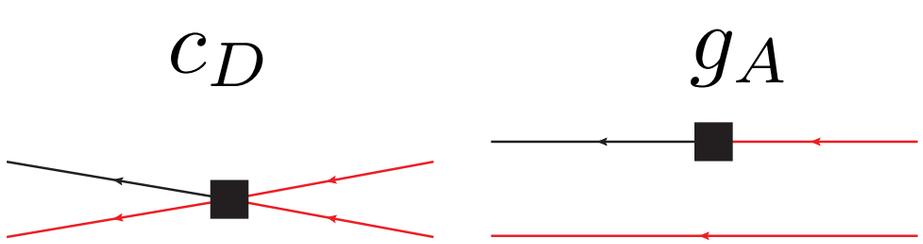
Standard picture: long-range contribution

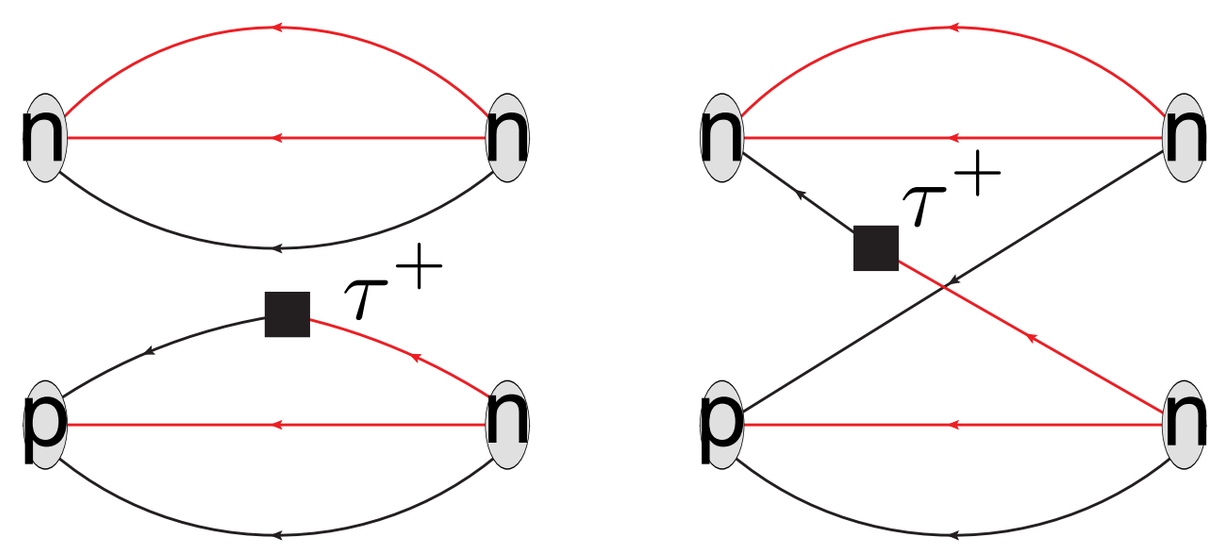




Quark Level

EFT Level



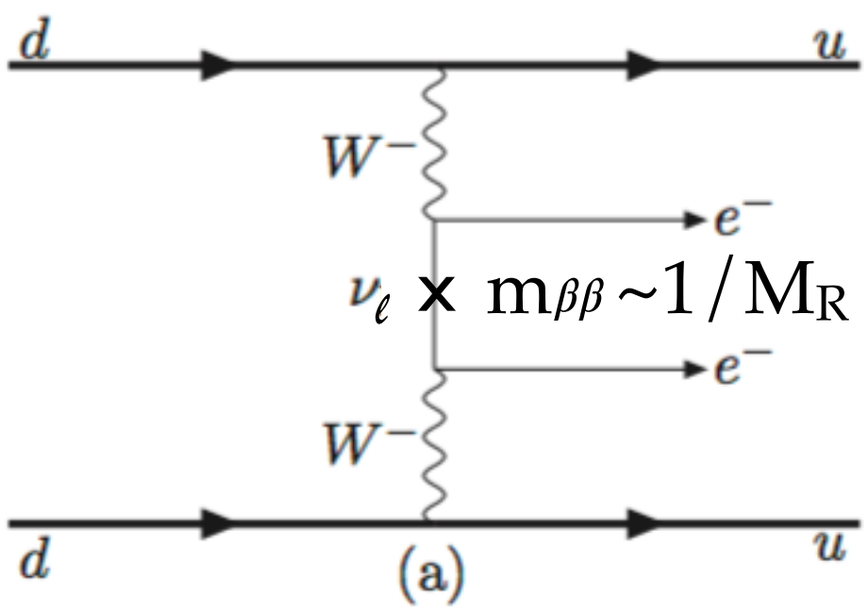


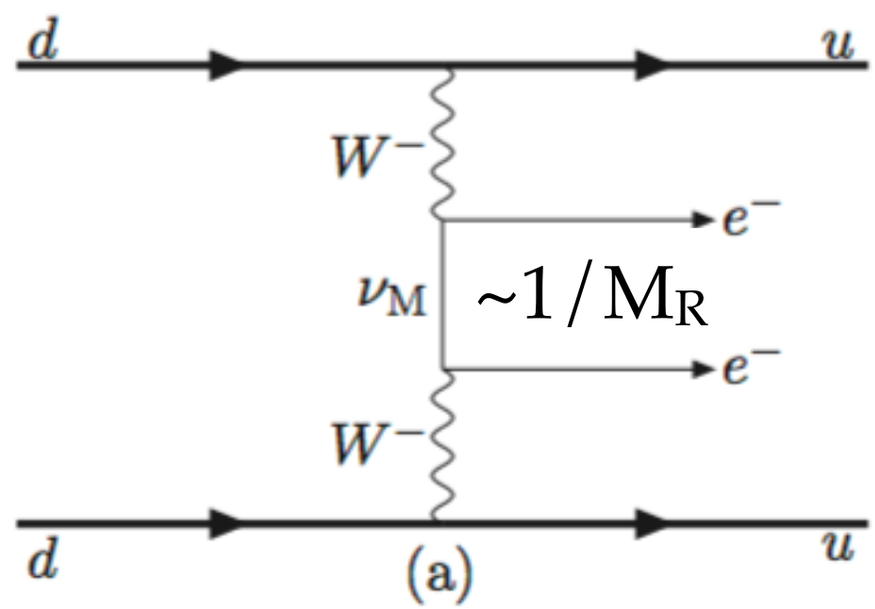
many body Nuclear Physics

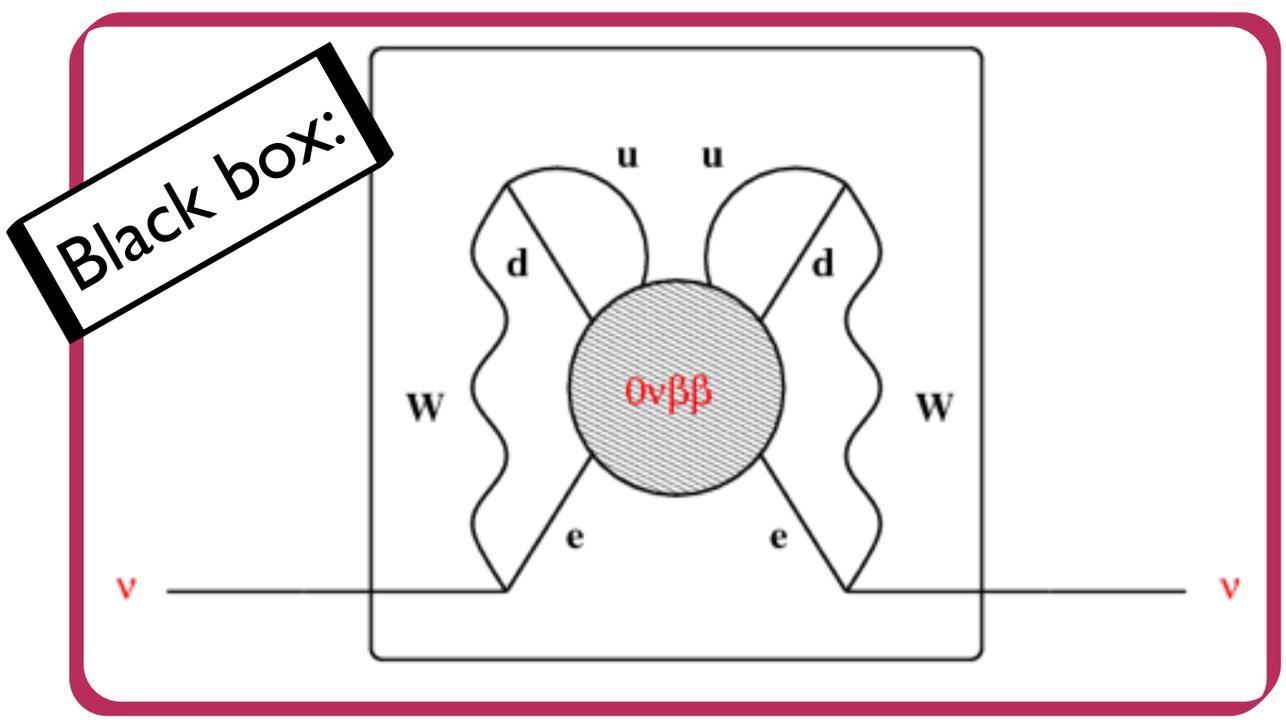
slide (modified) from Amy Nicholson

via FHT

Short-range contribution: probe for heavy physics



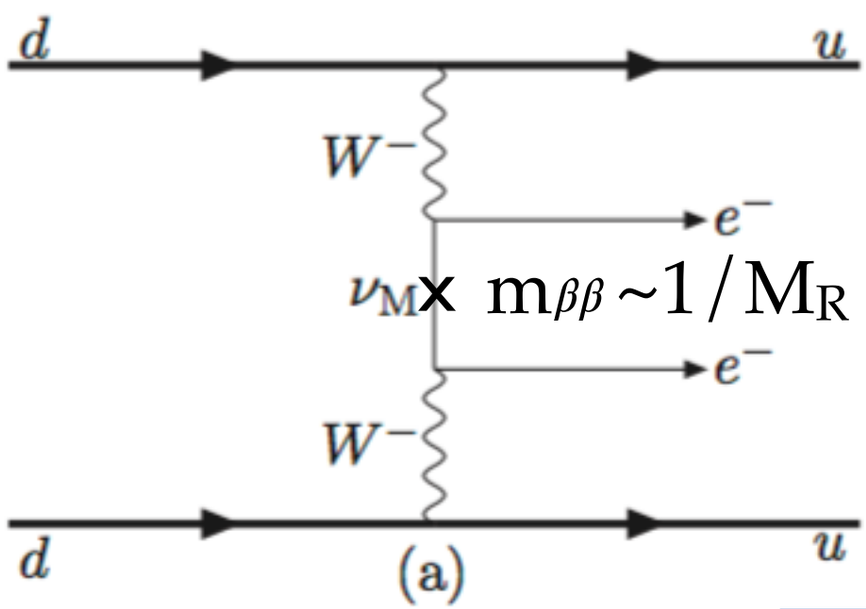




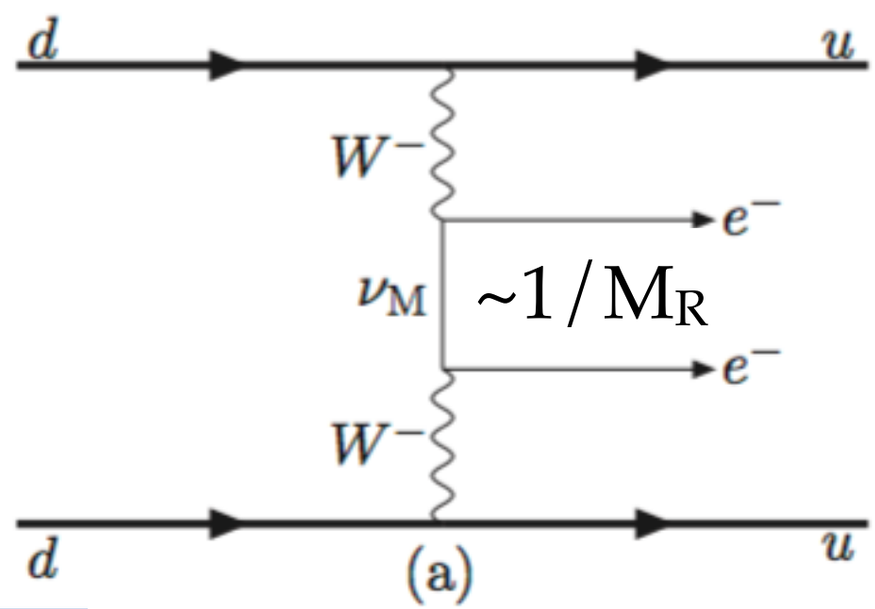
slide from Amy Nicholson

Valle & Schecter, Fig.: H. Päs, W. Rodejohann New J.Phys. 17 (2015) no.11, 115010

Short-range contribution: probe for heavy physics

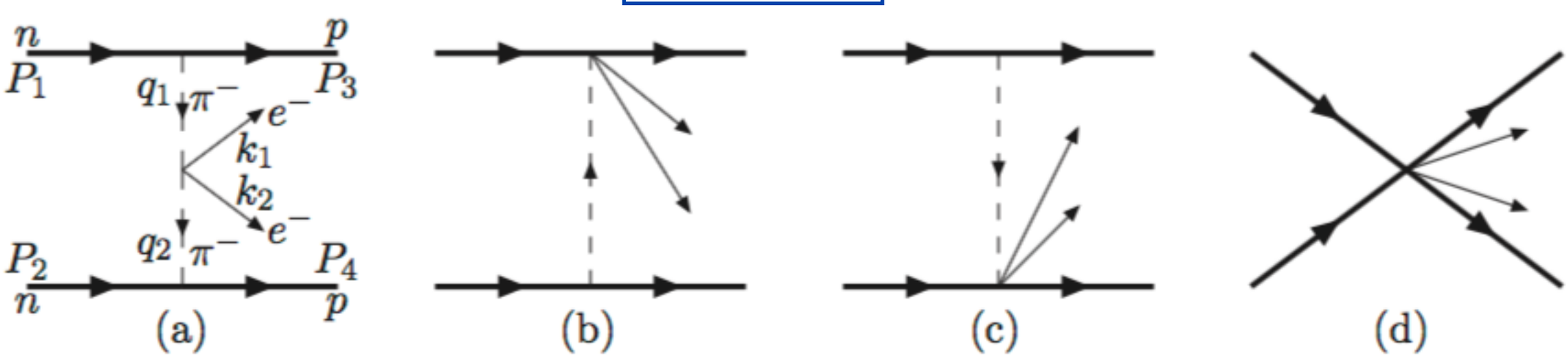


× $m_{\beta\beta} \sim 1/M_R$



$\sim 1/M_R$

Chiral EFT

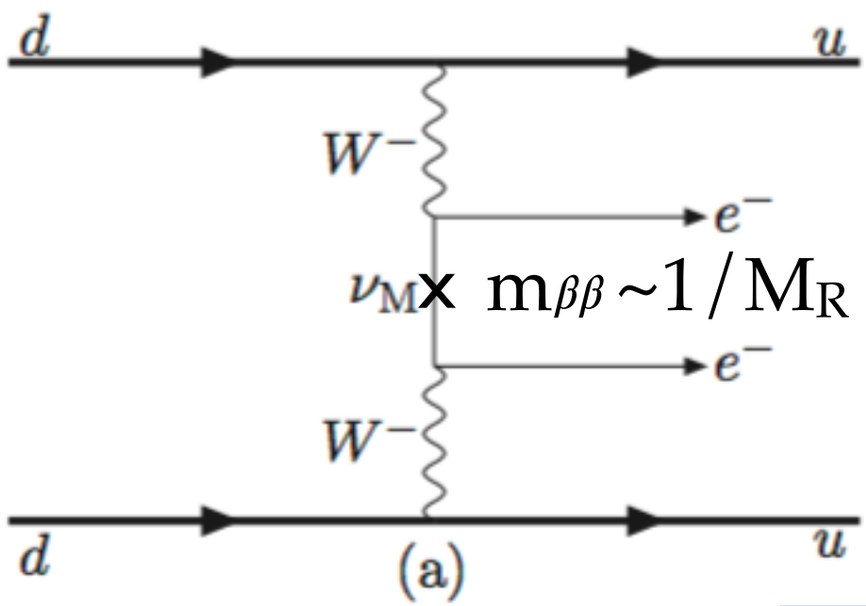


$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{0})$

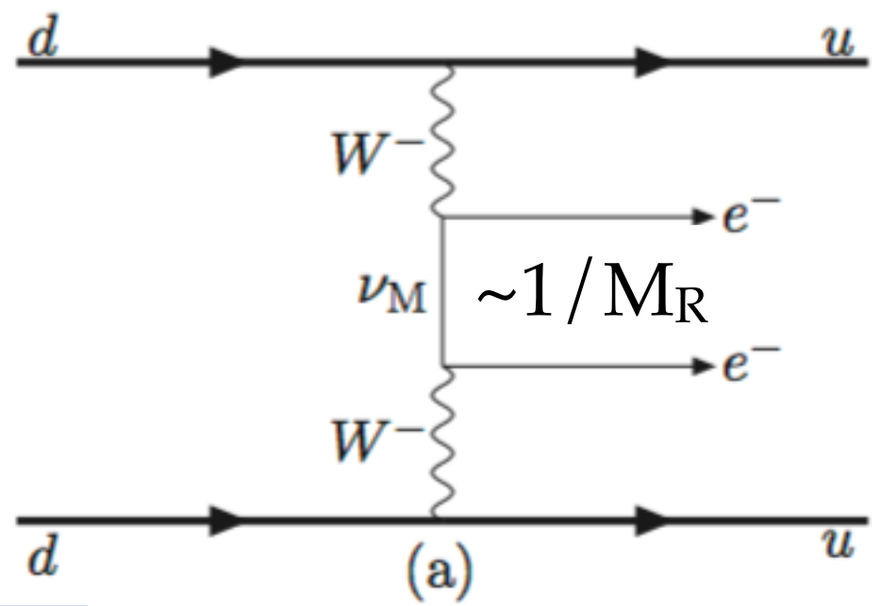
slide from Amy Nicholson

Prezeau, Ramsey-Musolf, Vogel (2003)

Short-range contribution: probe for heavy physics

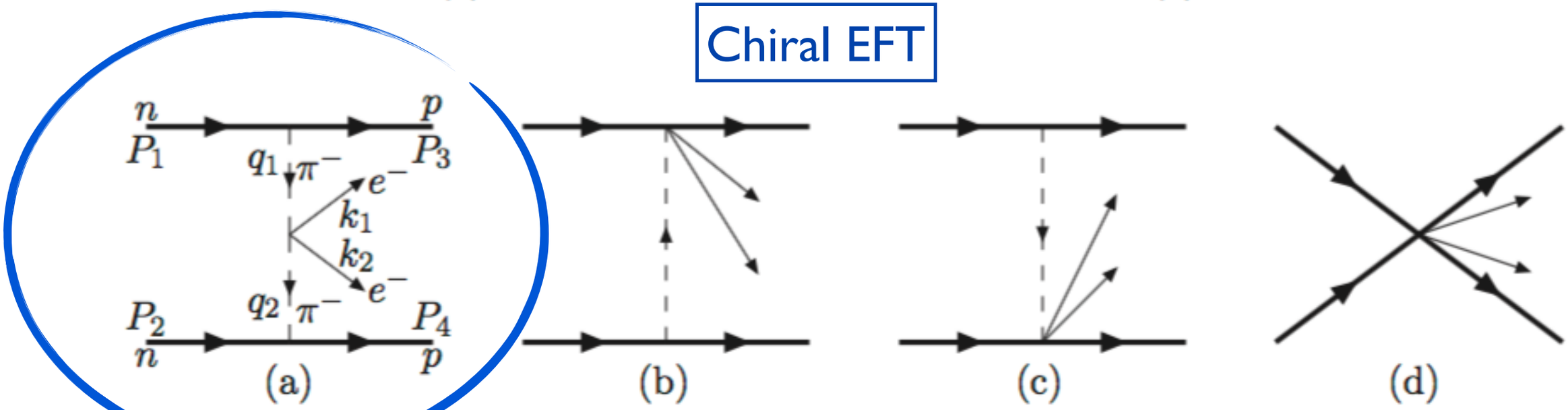


$\times\ m_{\beta\beta} \sim 1/M_R$



$\sim 1/M_R$

Chiral EFT



$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{0})$

slide from Amy Nicholson

Prezeau, Ramsey-Musolf, Vogel (2003)

slide from Amy Nicholson

Effective Lagrangian

$$\mathcal{L}^q_{0\nu\beta\beta} = \frac{G_F^2}{\Lambda_{\beta\beta}} \{ \left(o_1 \mathcal{O}^{++}_{1+} + o_2 \mathcal{O}^{++}_{2+} + o_3 \mathcal{O}^{++}_{2-} + o_4 \mathcal{O}^{++}_{3+} + o_5 \mathcal{O}^{++}_{3-} \right) \bar{e} e^c$$
$$+ \left(o_6 \mathcal{O}^{++}_{1+} + o_7 \mathcal{O}^{++}_{2+} + o_8 \mathcal{O}^{++}_{2-} + o_9 \mathcal{O}^{++}_{3+} + o_{10} \mathcal{O}^{++}_{3-} \right) \bar{e} \gamma^5 e^c$$
$$+ \left(o_{11} \mathcal{O}^{++,\mu}_{4+} + o_{12} \mathcal{O}^{++,\mu}_{4-} + o_{13} \mathcal{O}^{++,\mu}_{5+} + o_{14} \mathcal{O}^{++,\mu}_{5-} \right) \bar{e} \gamma_\mu \gamma^5 e^c + \text{h.c.} \}$$

Prezeau, Ramsey-Musolf, Vogel (2003)

- Nine operators:
  - $\pi \to \pi$: only need parity even
  - Vector operators suppressed by m_e

$$\mathcal{O}^{ab}_{1+} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_R \tau^b \gamma_\mu q_R),$$
$$\mathcal{O}^{ab}_{2\pm} = (\bar{q}_R \tau^a q_L)(\bar{q}_R \tau^b q_L) \pm (\bar{q}_L \tau^a q_R)(\bar{q}_L \tau^b q_R),$$
$$\mathcal{O}^{ab}_{3\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L)(\bar{q}_L \tau^b \gamma_\mu q_L) \pm (\bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_R \tau^b \gamma_\mu q_R),$$
$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \mp \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \pm \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R + \bar{q}_R \tau^b q_L).$$

slide from Amy Nicholson

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$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L + \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \pm \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R + \bar{q}_R \tau^b q_L).$$

slide from Amy Nicholson

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$$+ \left(o_6 \mathcal{O}^{++}_{1+} + o_7 \mathcal{O}^{++}_{2+} + o_8 \mathcal{O}^{++}_{2-} + o_9 \mathcal{O}^{++}_{3+} + o_{10} \mathcal{O}^{++}_{3-}\right) \bar{e} \gamma^5 e^c$$
$$+ \left(o_{11} \mathcal{O}^{++,\mu}_{4+} + o_{12} \mathcal{O}^{++,\mu}_{4-} + o_{13} \mathcal{O}^{++,\mu}_{5+} + o_{14} \mathcal{O}^{++,\mu}_{5-}\right) \bar{e} \gamma_\mu \gamma^5 e^c + \text{h.c.} \}$$

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$$\mathcal{O}^{ab,\mu}_{4\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L + \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R - \bar{q}_R \tau^b q_L),$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\bar{q}_L \tau^a \gamma^\mu q_L \pm \bar{q}_R \tau^a \gamma^\mu q_R)(\bar{q}_L \tau^b q_R + \bar{q}_R \tau^b q_L).$$

Calculate LECs; EFT then determines nn → pp transition via pion exchange diagram

Contractions

- Exact momentum projection at source and sink
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2

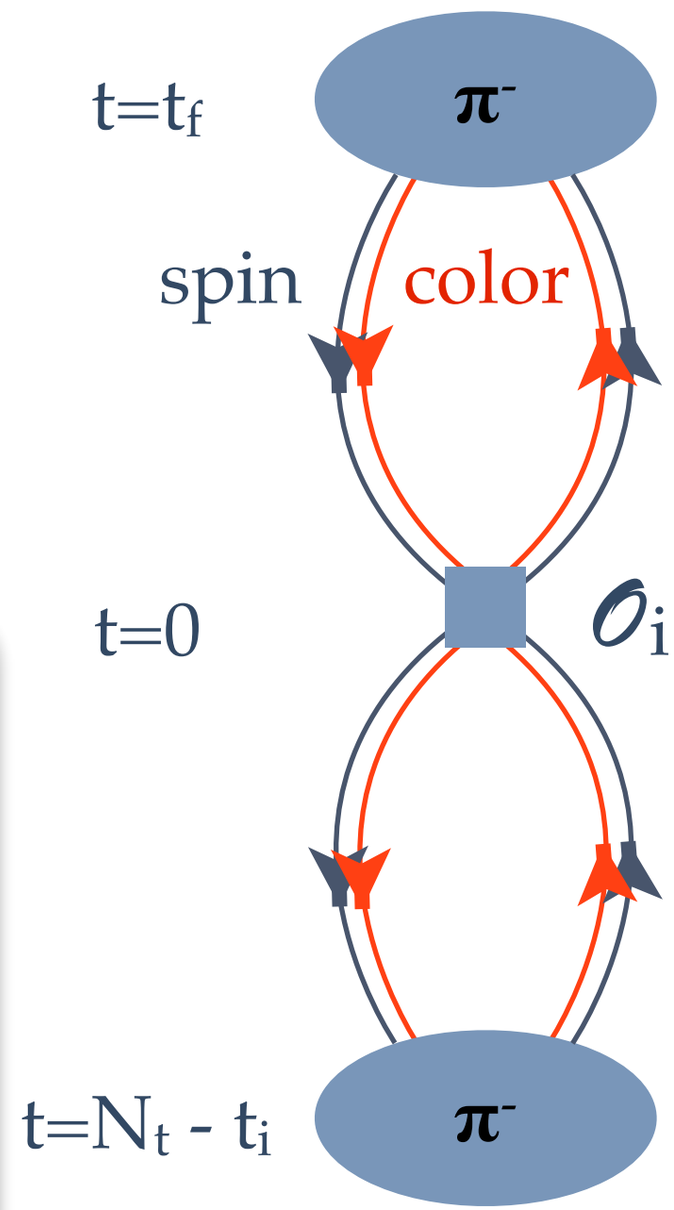
$$\mathcal{O}^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right)\left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

$$\mathcal{O}'^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right]\left[\bar{q}_R \tau^- \gamma_\mu q_R\right)$$

$$\mathcal{O}^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right)\left[\bar{q}_R \tau^- q_L\right] + \left(\bar{q}_L \tau^- q_R\right)\left[\bar{q}_L \tau^- q_R\right]$$

$$\mathcal{O}'^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right]\left[\bar{q}_R \tau^- q_L\right) + \left(\bar{q}_L \tau^- q_R\right]\left[\bar{q}_L \tau^- q_R\right)$$

$$\mathcal{O}^{++}_{3+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right)\left[\bar{q}_L \tau^- \gamma_\mu q_L\right] + \left(\bar{q}_R \tau^- \gamma^\mu q_R\right)\left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$



slide from Amy Nicholson

Contractions

- Exact momentum projection at source and sink
- Must add color mixed versions of Prezeau, Ramsey-Musolf, Vogel ops 1&2

$$\mathcal{O}^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right) \left[\bar{q}_R \tau^- \gamma_\mu q_R\right]$$

$$\mathcal{O}'^{++}_{1+} = \left(\bar{q}_L \tau^- \gamma^\mu q_L\right] \left[\bar{q}_R \tau^- \gamma_\mu q_R\right)$$

$$\mathcal{O}^{++}_{2+} = \left(\bar{q}_R \tau^- q_L\right) \left[\bar{q}_R \tau^- q_L\right] + \left(\bar{q}_L \tau^- q_R\right) \left[\bar{q}_L \tau^- q_R\right]$$

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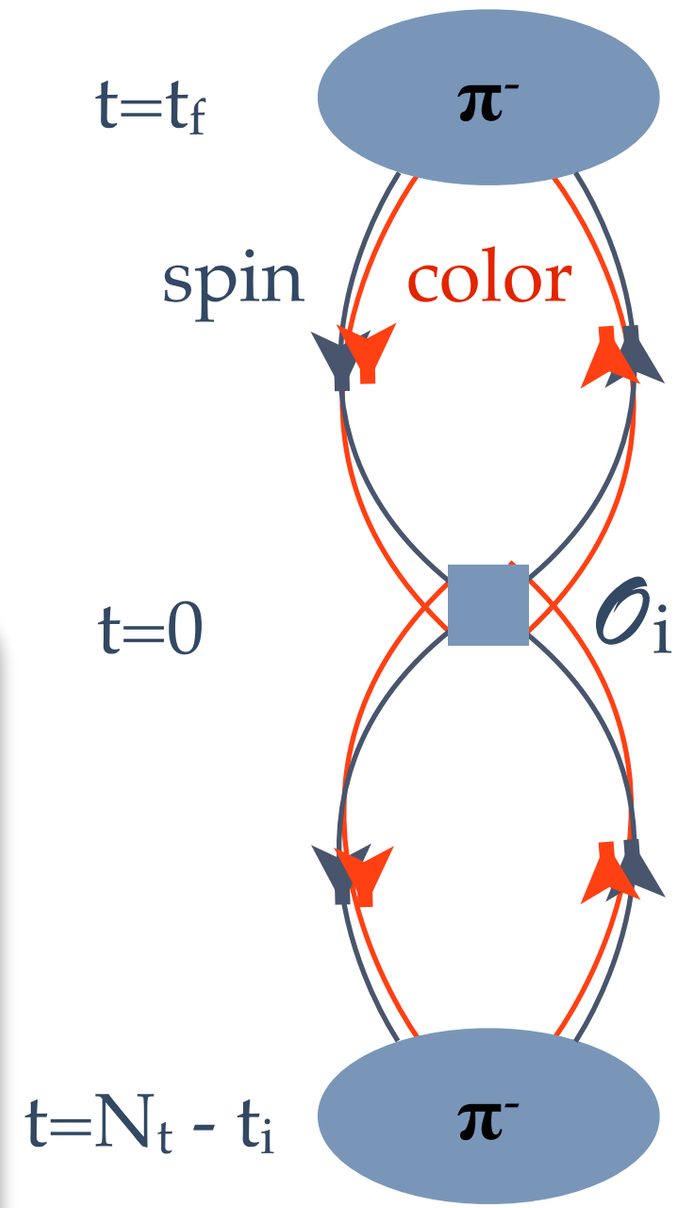


slide from Amy Nicholson

HISQ ensembles

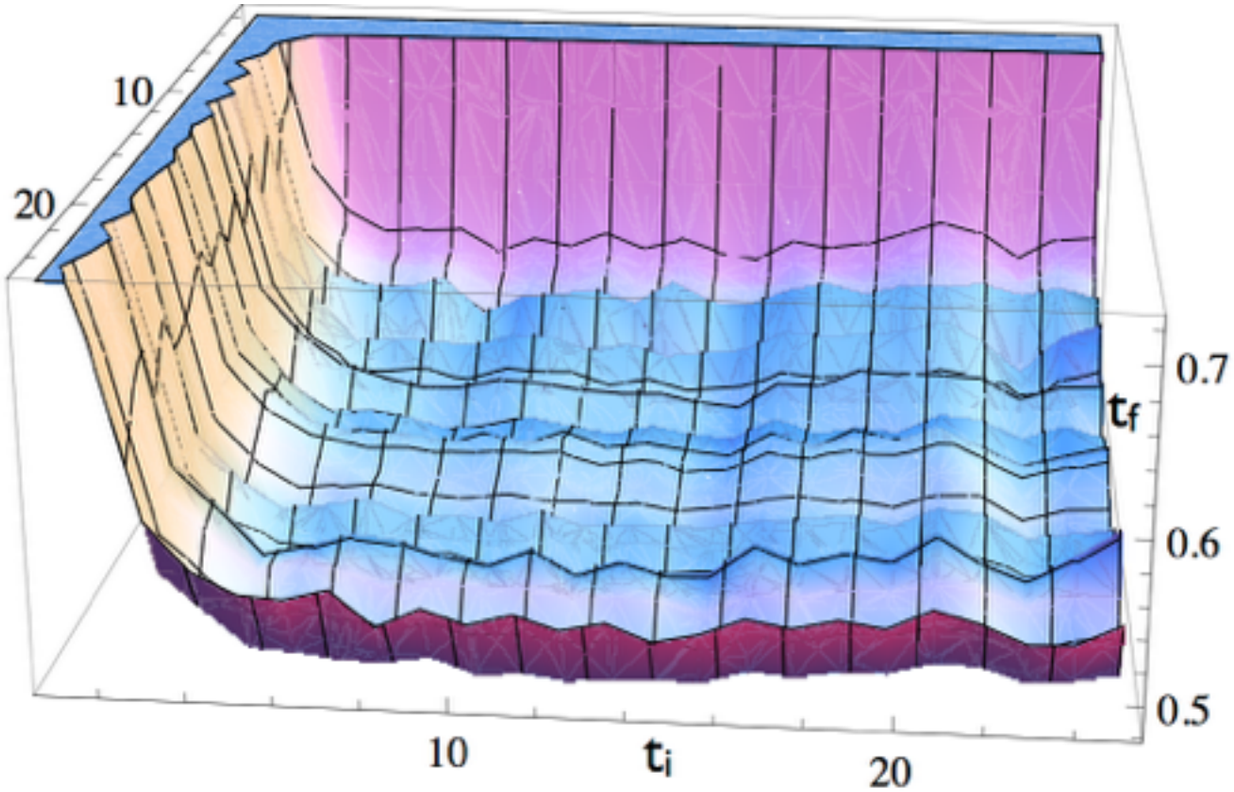
$a[fm]$: $m_\pi[MeV]$	310	220	135
0.15	$16^3 \times 48, m_\pi L \sim 3.78$	$24^3 \times 48, m_\pi L \sim 3.99$	$32^3 \times 48, m_\pi L \sim 3.25$
0.12		$24^3 \times 64, m_\pi L \sim 3.22$	
0.12	$24^3 \times 64, m_\pi L \sim 4.54$	$32^3 \times 64, m_\pi L \sim 4.29$	$48^3 \times 64, m_\pi L \sim 3.91$
0.12		$40^3 \times 64, m_\pi L \sim 5.36$	
0.09	$32^3 \times 96, m_\pi L \sim 4.50$	$48^3 \times 96, m_\pi L \sim 4.73$	

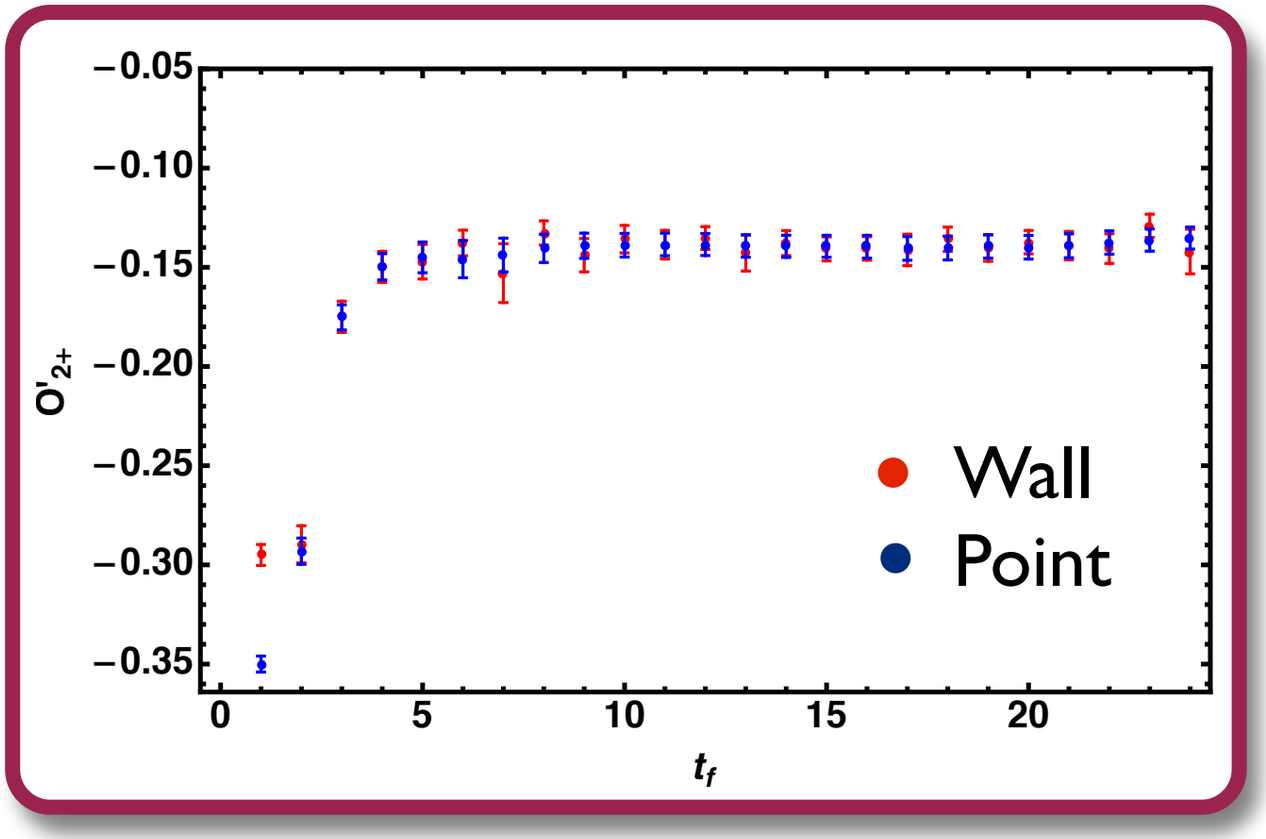
- Möbius DWF on HISQ
- Gradient flow method for smearing configs
  - $m_{res} < 0.1\ m_\ell$ for moderate L_5
- Wall + point sources for pions
- ~ 1000 cfgs, 1 source/cfg

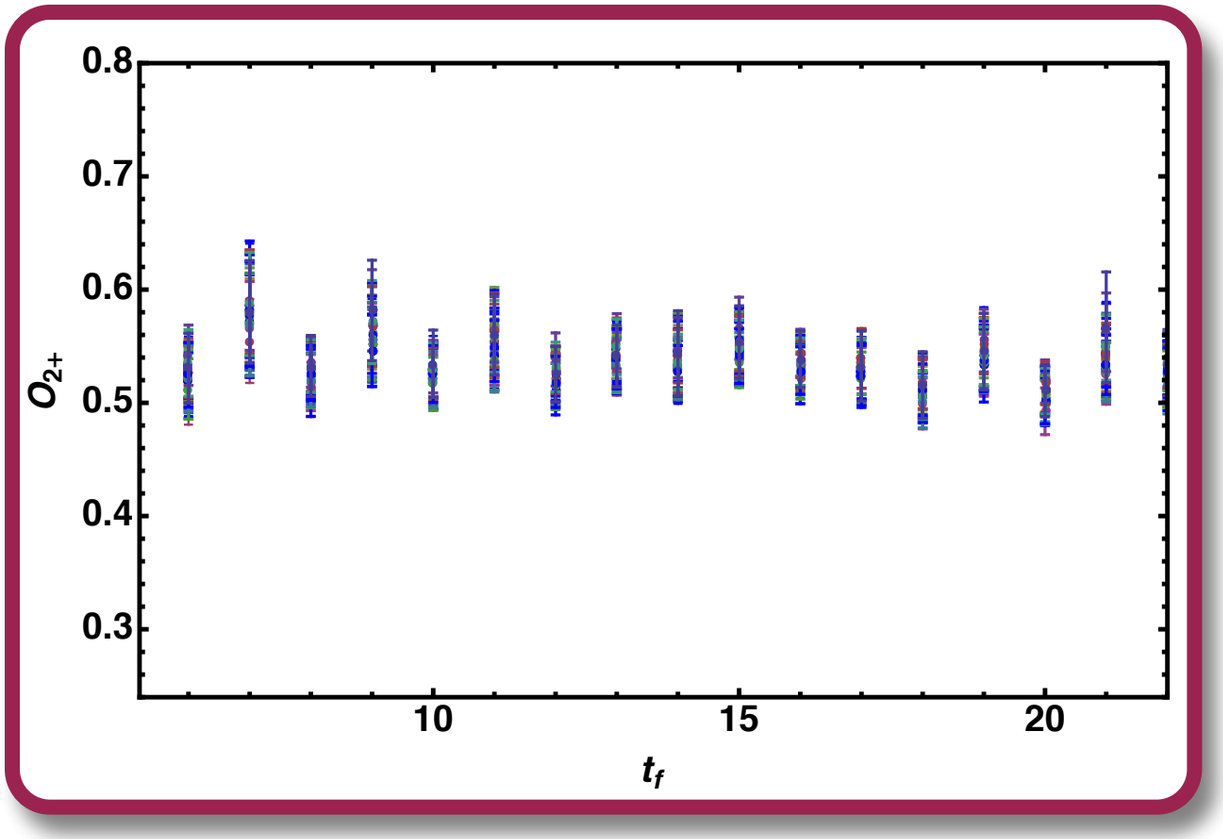
MILC Collaboration Phys. Rev. D87 (2013) 054505
Narayanan, Neuberger (2006), Luscher (2010)
K. Orginos, C. Monahan (private communication)

slide from Amy Nicholson

Signals

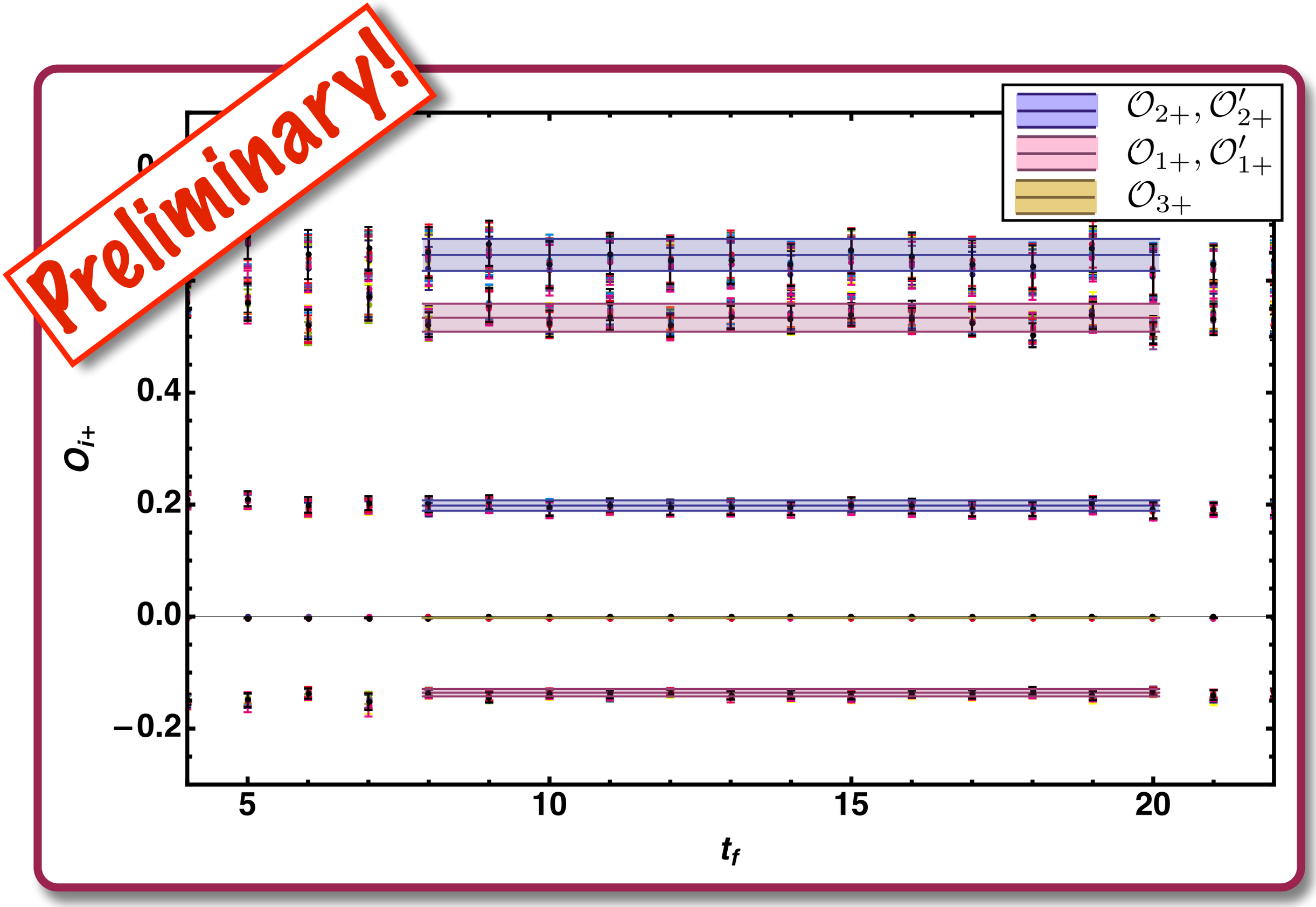




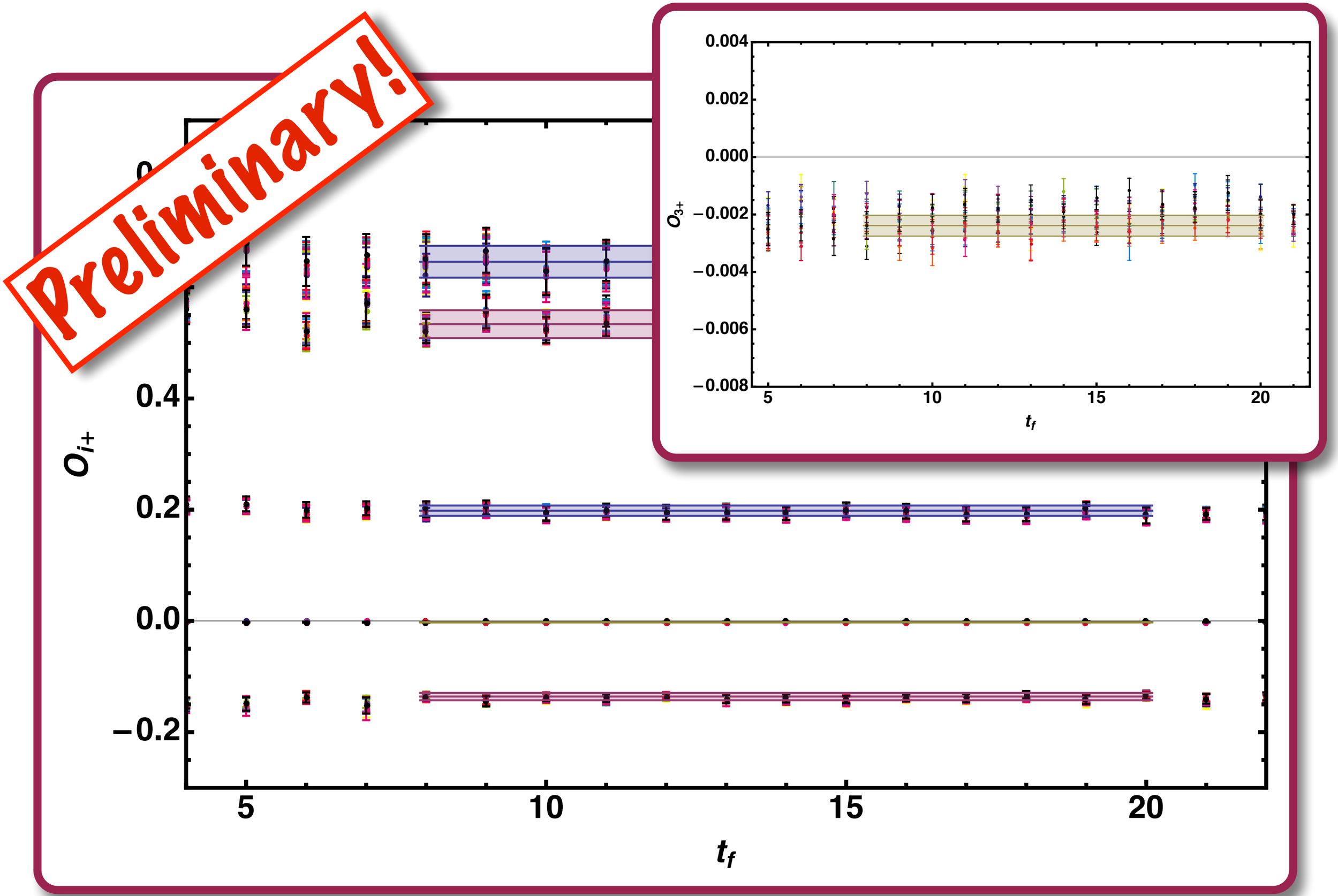


- $m_\pi \sim 135$ MeV
- L = 5.76 fm
- a = 0.12 fm

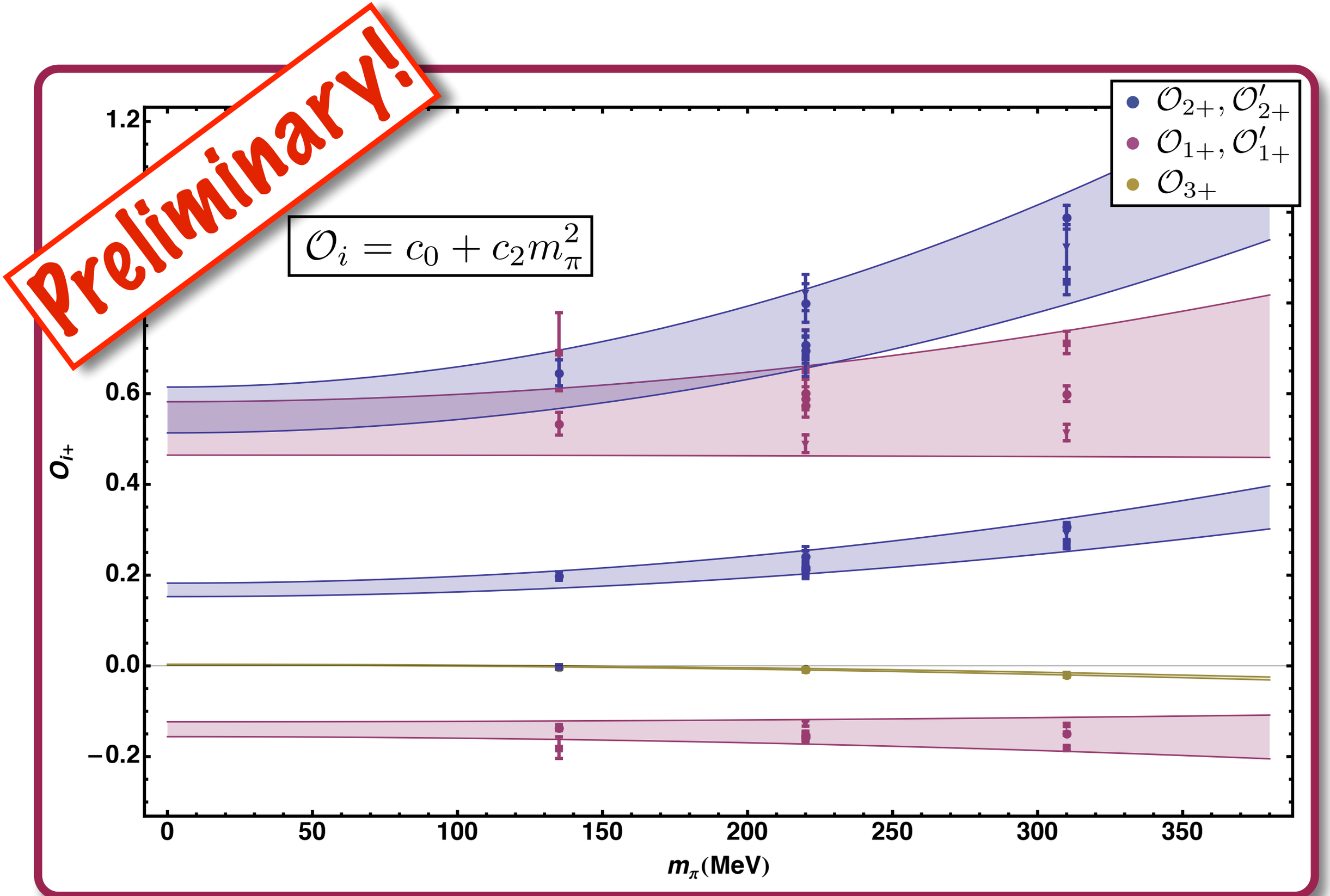
slide from Amy Nicholson



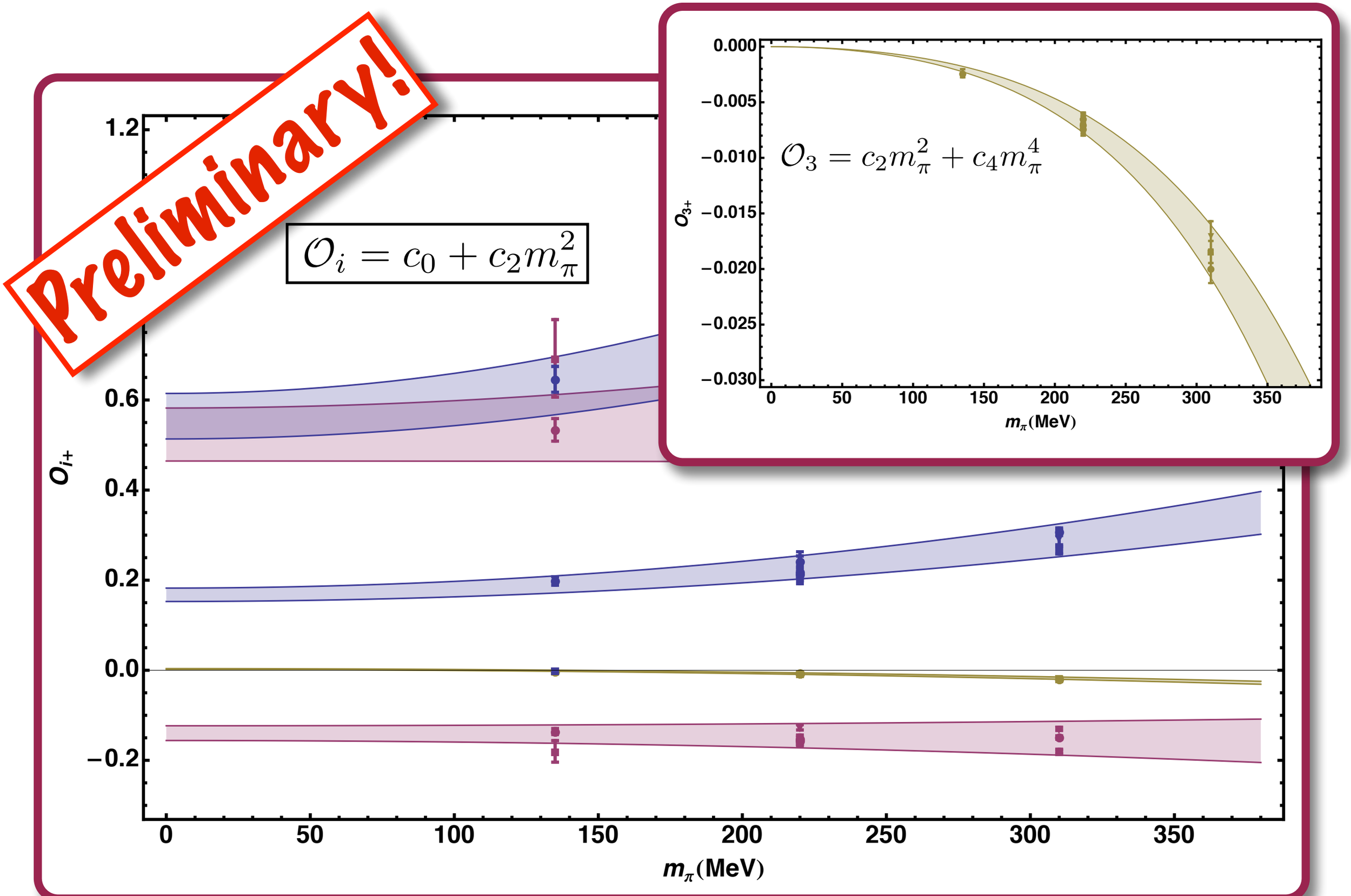
slide from Amy Nicholson



slide from Amy Nicholson

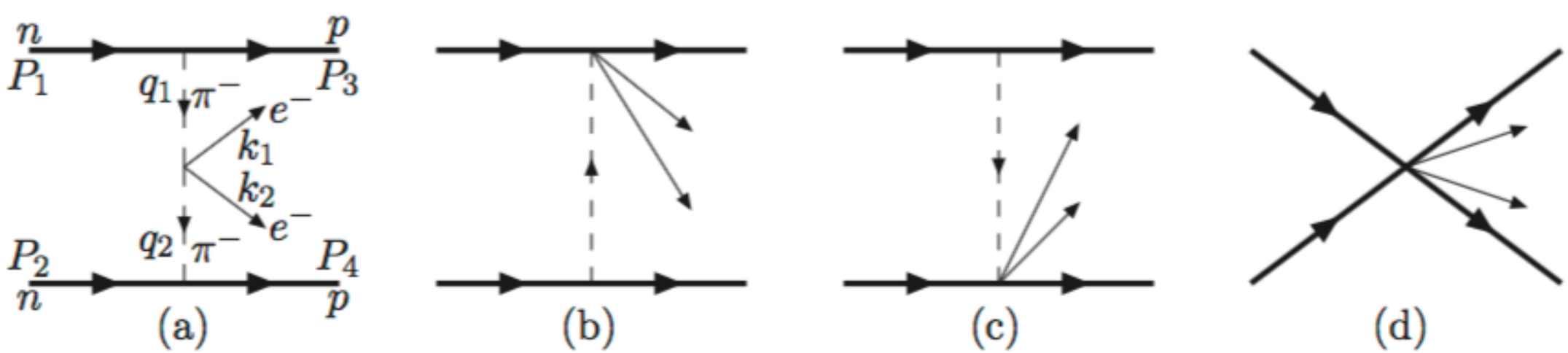


slide from Amy Nicholson



slide from Amy Nicholson

Contact operators

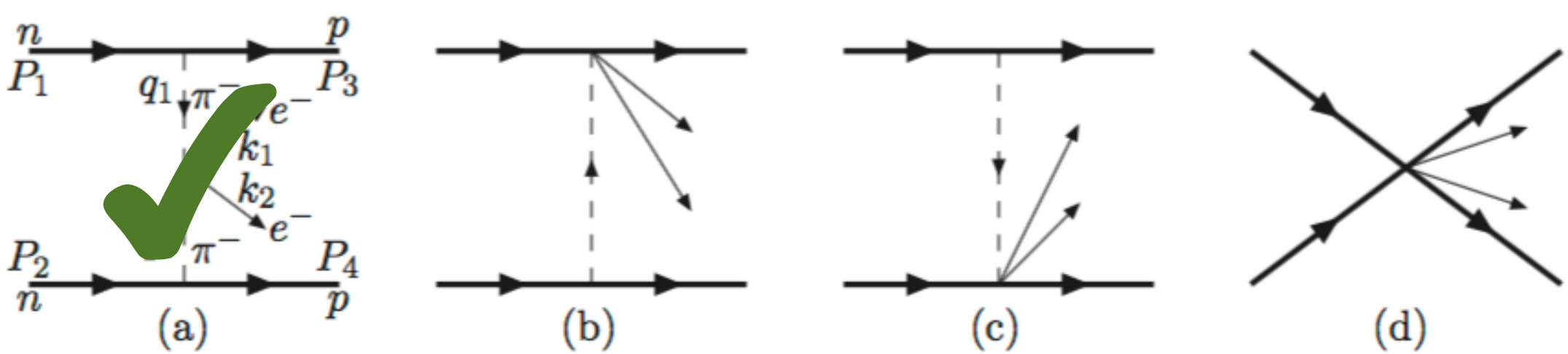


$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{0})$

slide from Amy Nicholson

Contact operators

- LO almost complete!



$\mathcal{O}(p^{-2})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{-1})$ $\mathcal{O}(p^{0})$

slide from Amy Nicholson

Contact operators

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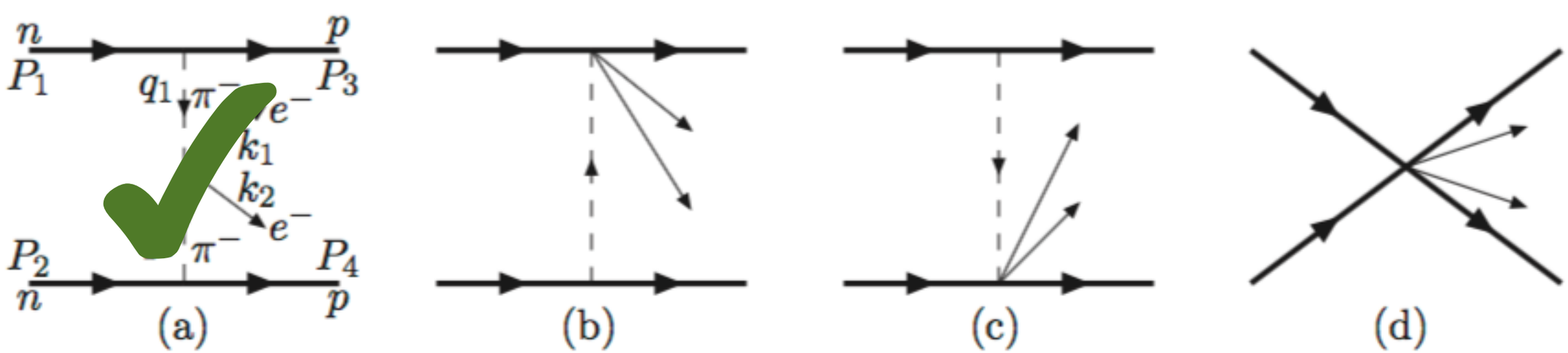
- NLO: disconnected diagrams



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slide from Amy Nicholson

Contact operators

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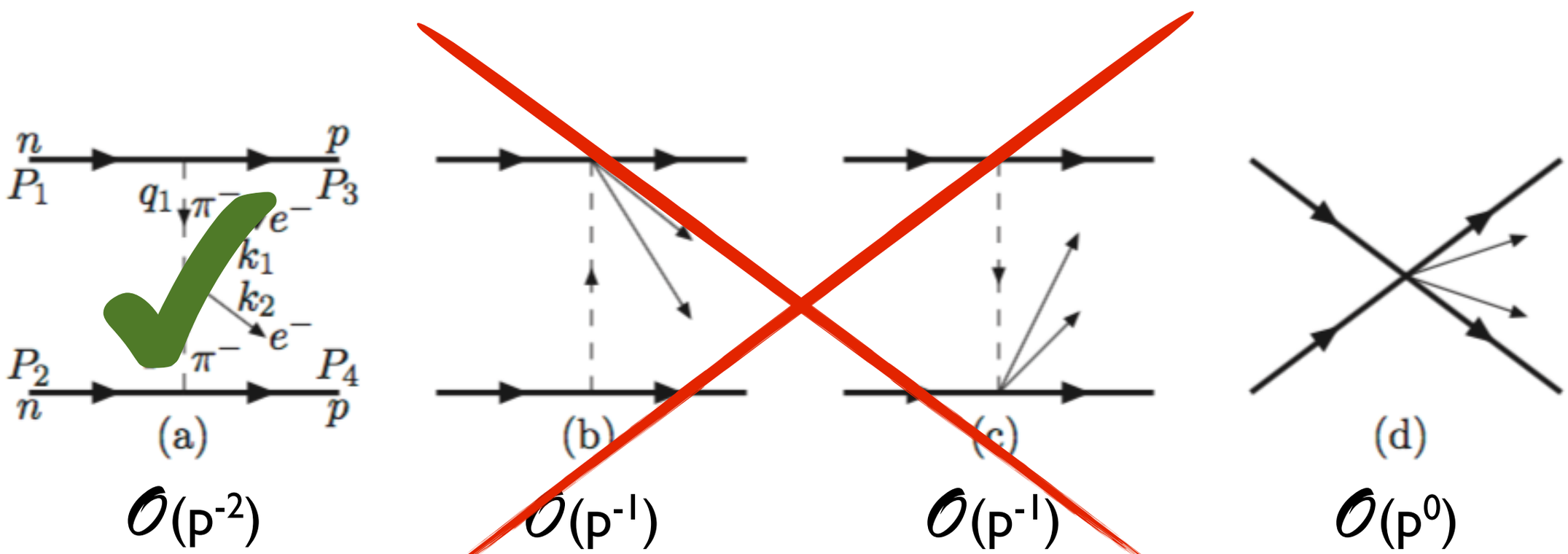
  - Don't contribute to $0^+ \to 0^+$ nuclear transitions



slide from Amy Nicholson

Contact operators

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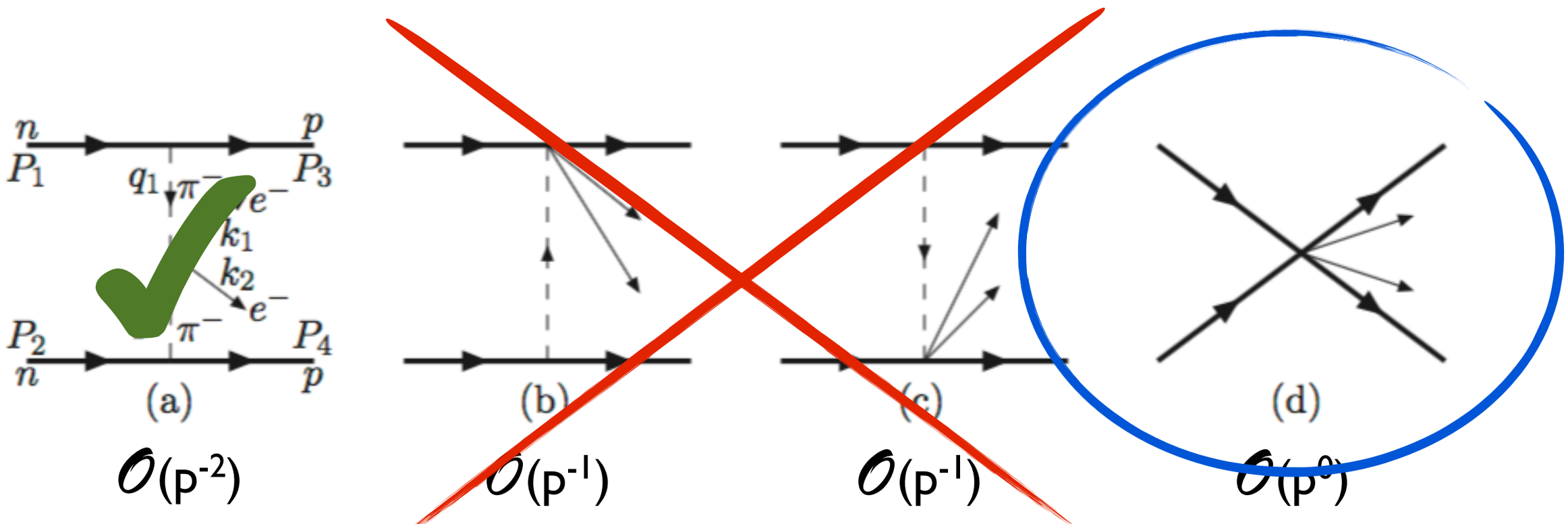
- nn → pp contact operators

  next step: similar to two-N hadronic parity violation



slide from Amy Nicholson

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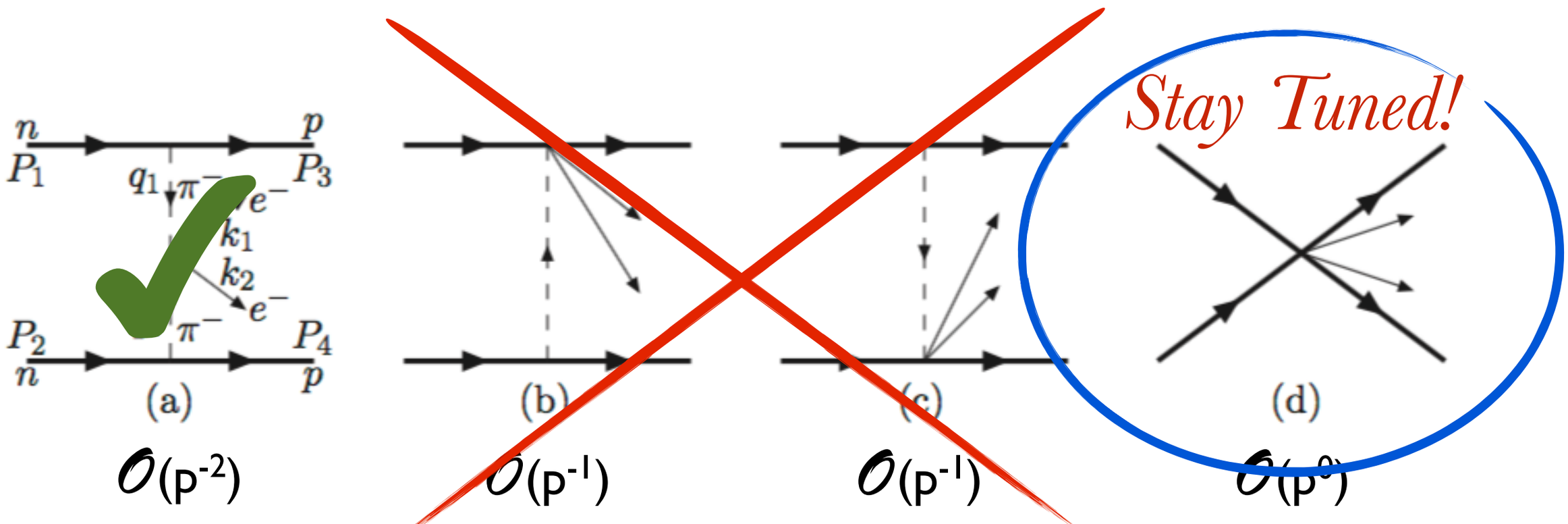


slide from Amy Nicholson

CONCLUSIONS

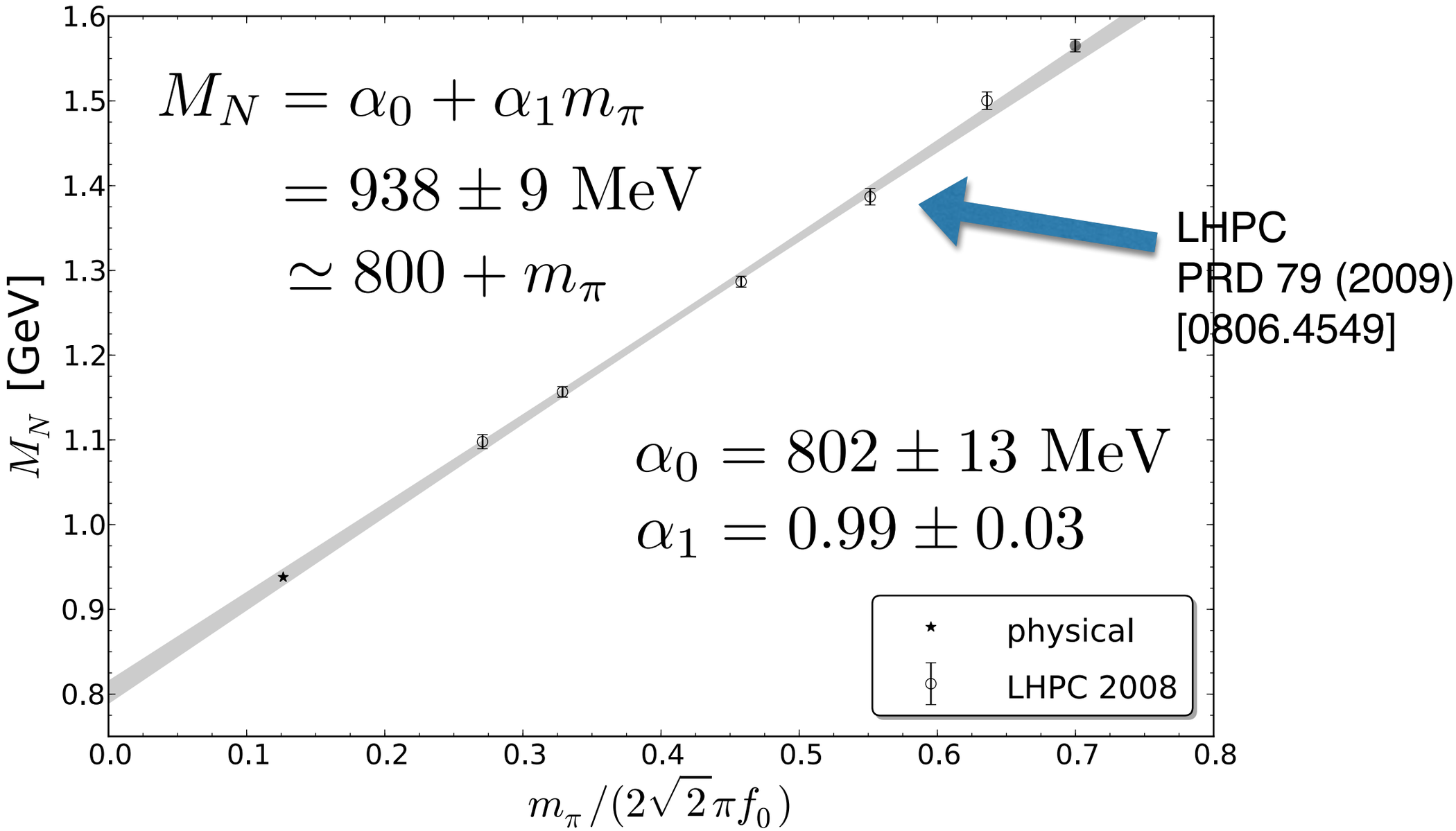
- I have provided you with a biased selection of LQCD results on nucleon matrix elements that are necessary for interpreting bounds (hopefully signals) on experiments aimed at probing the limits of the Standard Model
  - scalar quark matrix elements of the nucleon - direct dark matter detection
  - iso-vector nucleon mass and the determination of the CP-odd pion nucleon coupling for a QCD theta-term - searches for permanent EDMs in large nuclei, ^{199}Hg, ^{225}Ra, …
  - generalization to other CP-odd operators, such as the chromo-quark-EDM operators - searches for permanent EDMs
  - $\pi^- \to \pi^+$ from 4-quark—2-electron operators - planned searches for neutrinoless double beta-decay ($0\nu\beta\beta$)
- These were just a few examples. For more at this conference, see
  - Constantina Alexandrou Monday, 9:30, 16:30
  - Andreas Athenodorou Tuesday, 18:30
  - Rajan Gupta Thursday, 14:55
  - Jordy de Vries Thursday, 15:20
  - Martha Constantinou Friday, 15:20
  - Michael Wagman Friday, 16:40

Thank You

Light quark mass dependence of M_B

A.W-L Chiral Dynamics 2012 [1304.6341]

What is the status now (2012)?



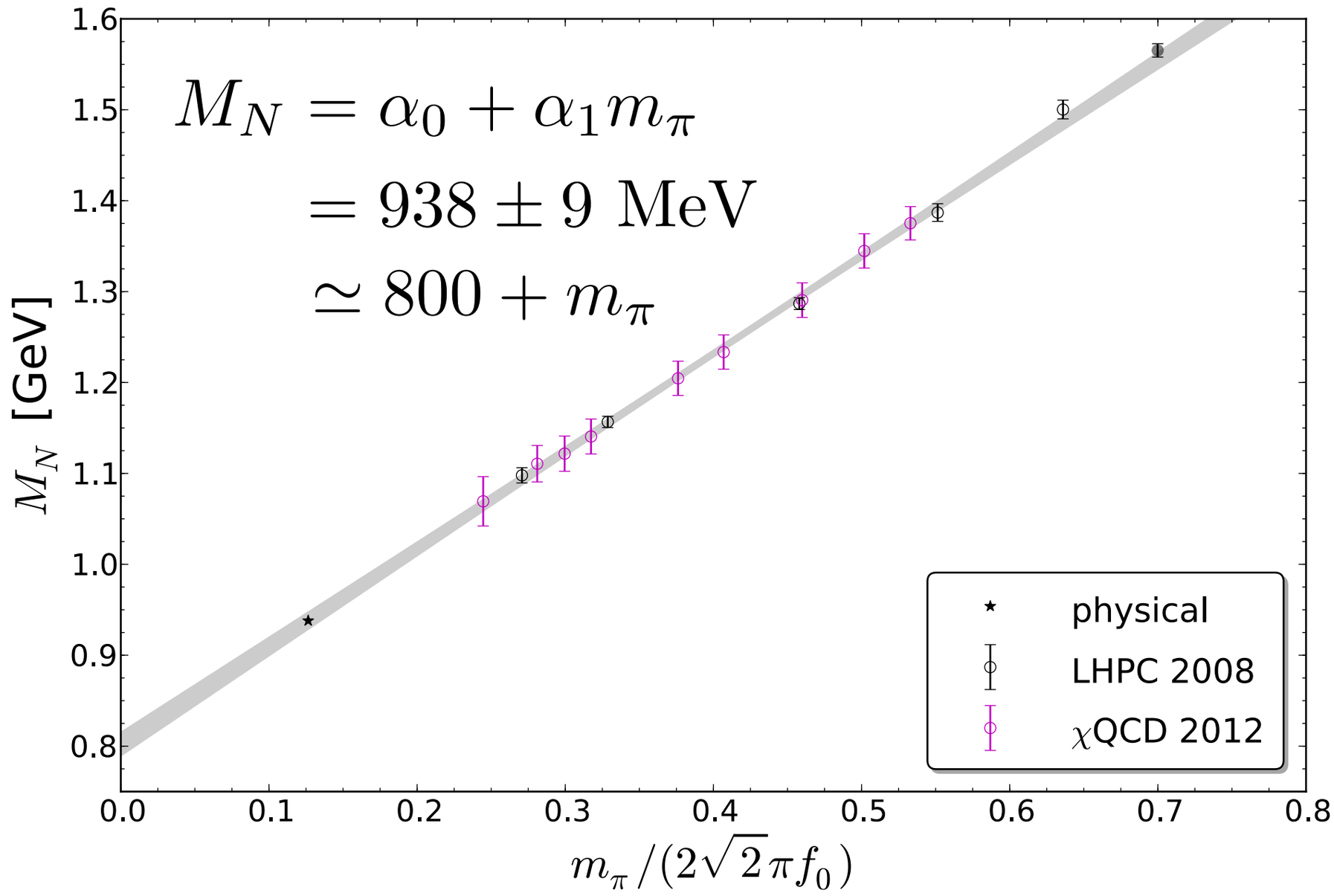
LHPC
PRD 79 (2009)
[0806.4549]

Physical point NOT included in fit

Light quark mass dependence of M_B

A.W-L Chiral Dynamics 2012 [1304.6341]

What is the status now (2012)?

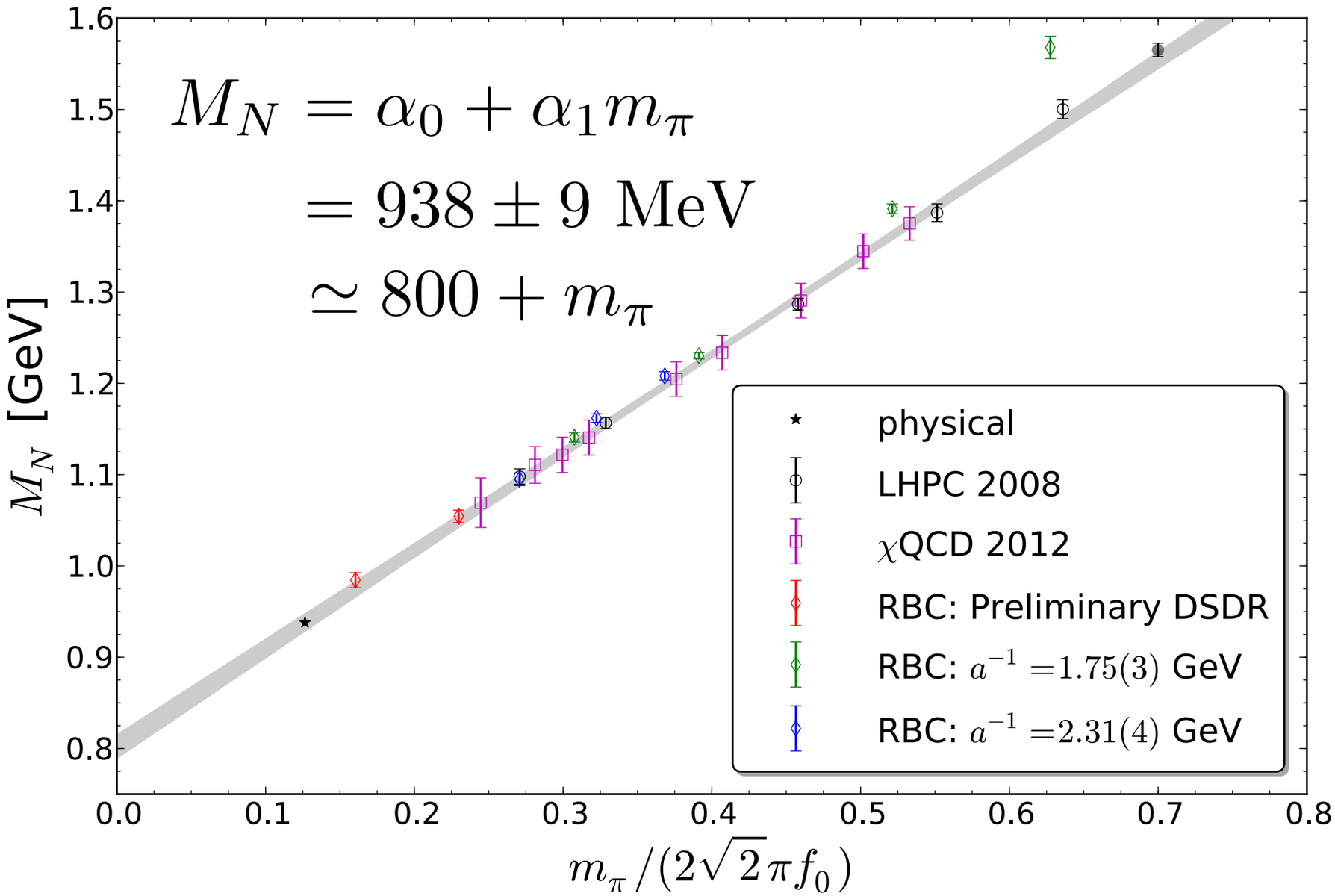


χQCD Collaboration uses Overlap Valence fermions on Domain-Wall (RBC-UKQCD) sea fermions

Light quark mass dependence of M_B

A.W-L Chiral Dynamics 2012 [1304.6341]

What is the status now (2012)?

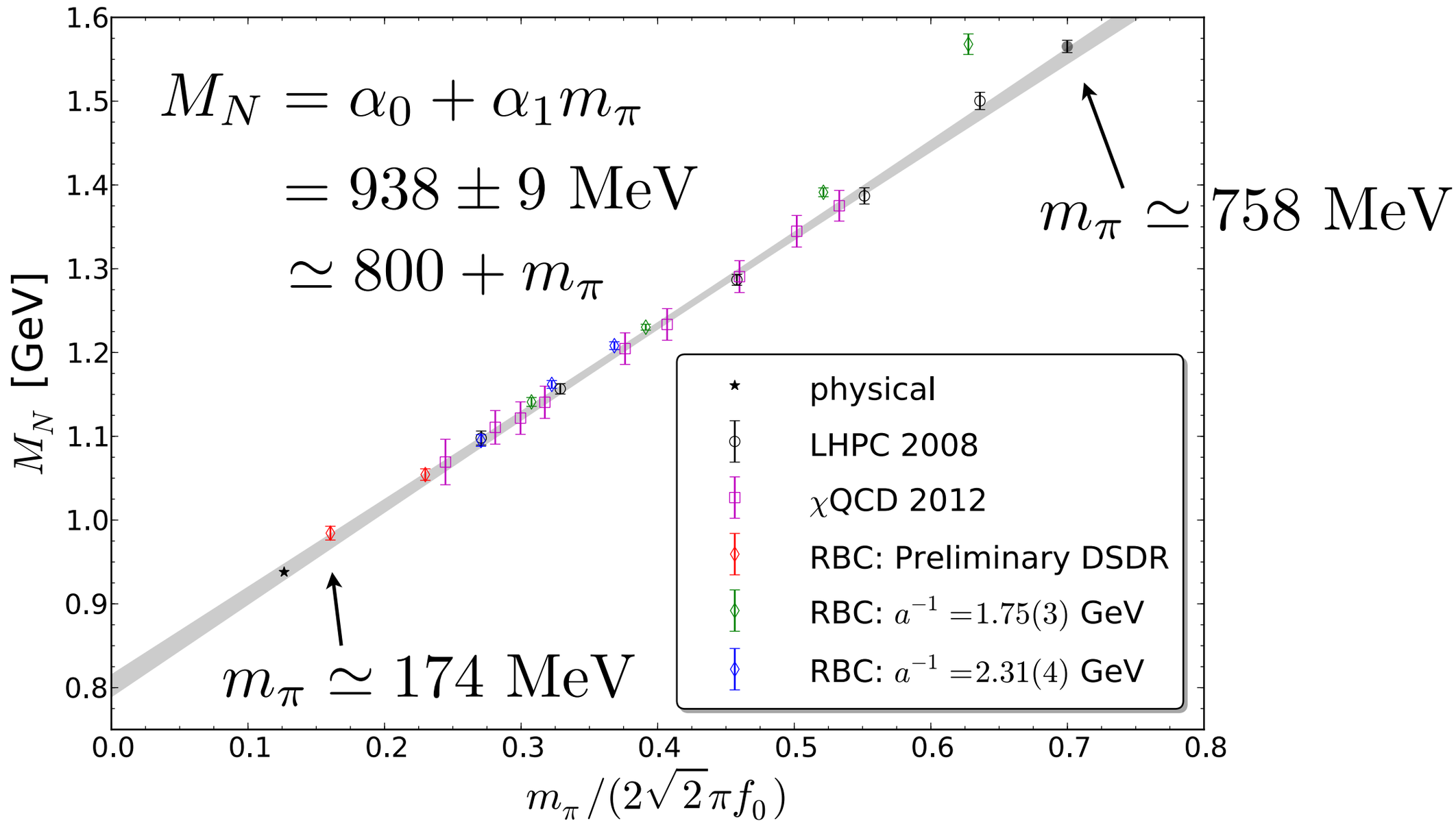


RBC-UKQCD Collaboration uses Domain-Wall valence and sea fermions

Light quark mass dependence of M_B

A.W-L Chiral Dynamics 2012 [1304.6341]

What is the status now (2012)?



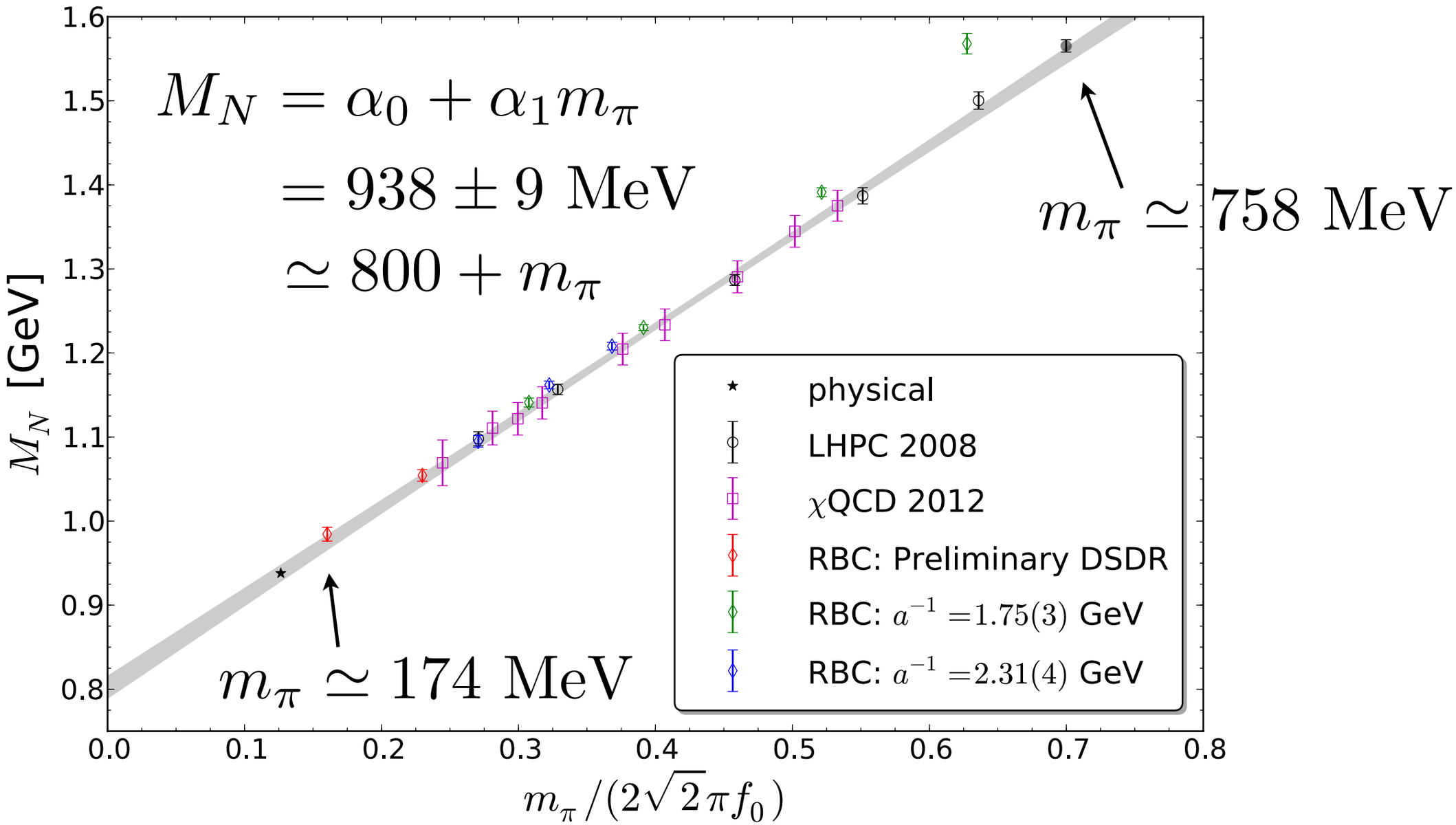
Taking this seriously yields

$$\sigma_{\pi N} = 67 \pm 4 \text{ MeV}$$

Light quark mass dependence of M_B

A.W-L Chiral Dynamics 2012 [1304.6341]

What is the status now (2012)?



Taking this seriously yields

$$\sigma_{\pi N} = 67 \pm 4 \text{ MeV}$$

I am not advocating this as a good model for QCD!