Strange quark content of the nucleon and dark matter searches

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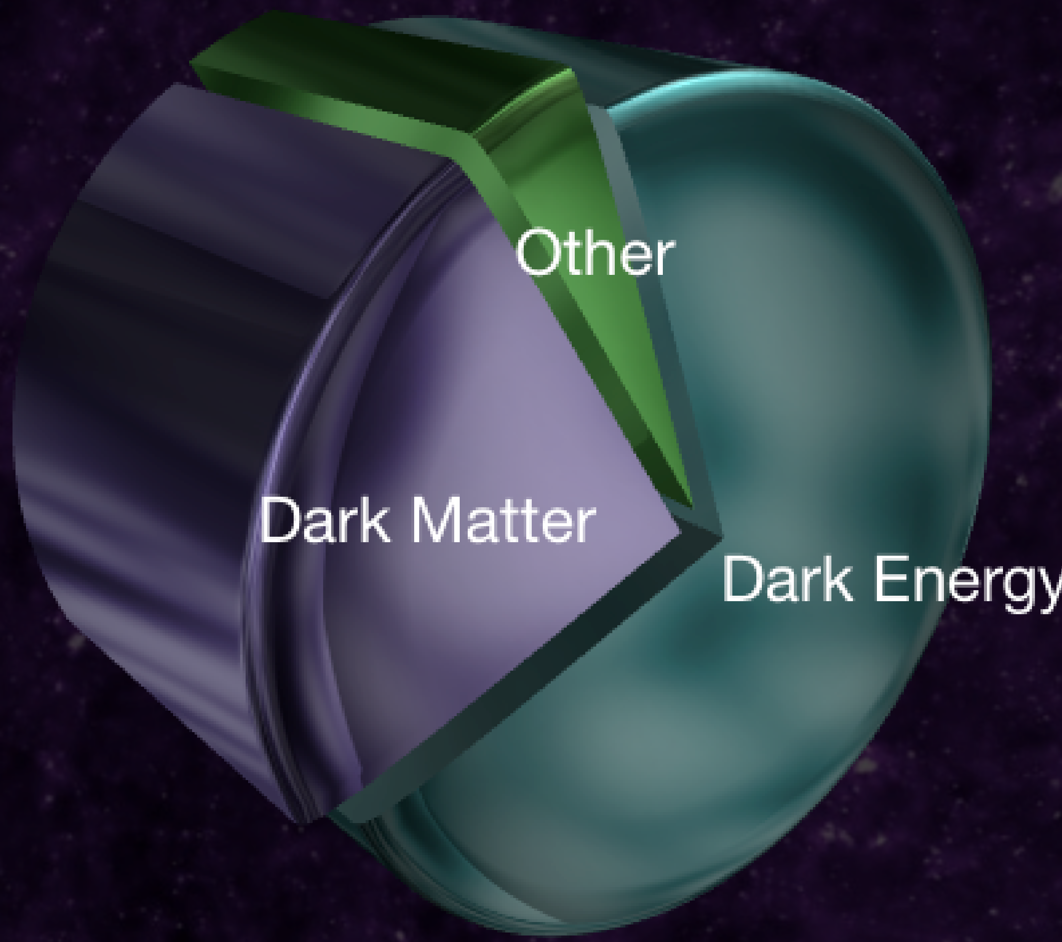
Lattice 2012
Cairns, Australia

Special Research Centre for the Subatomic Structure of Matter

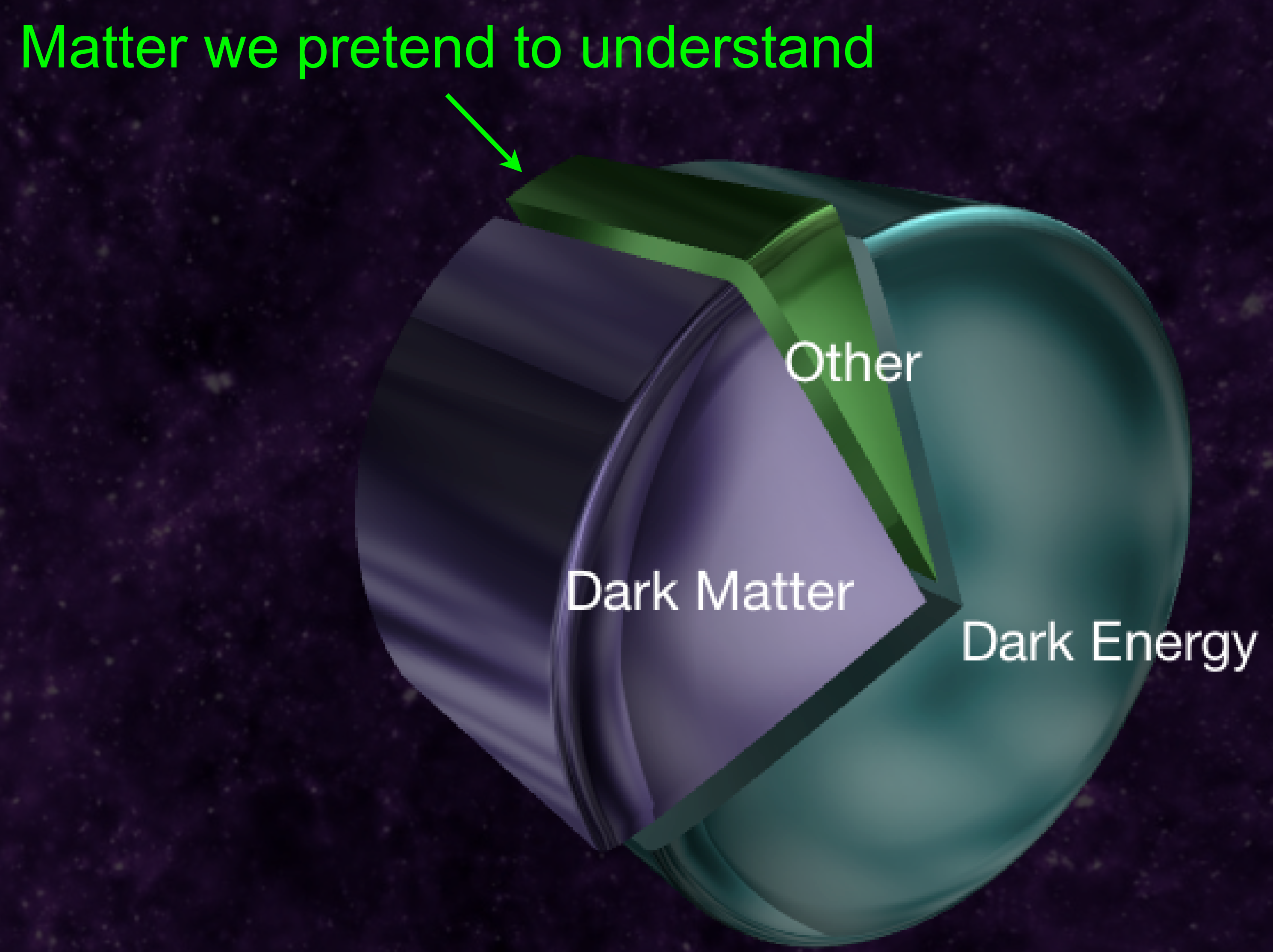
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

The University of Adelaide

Energy budget of the universe

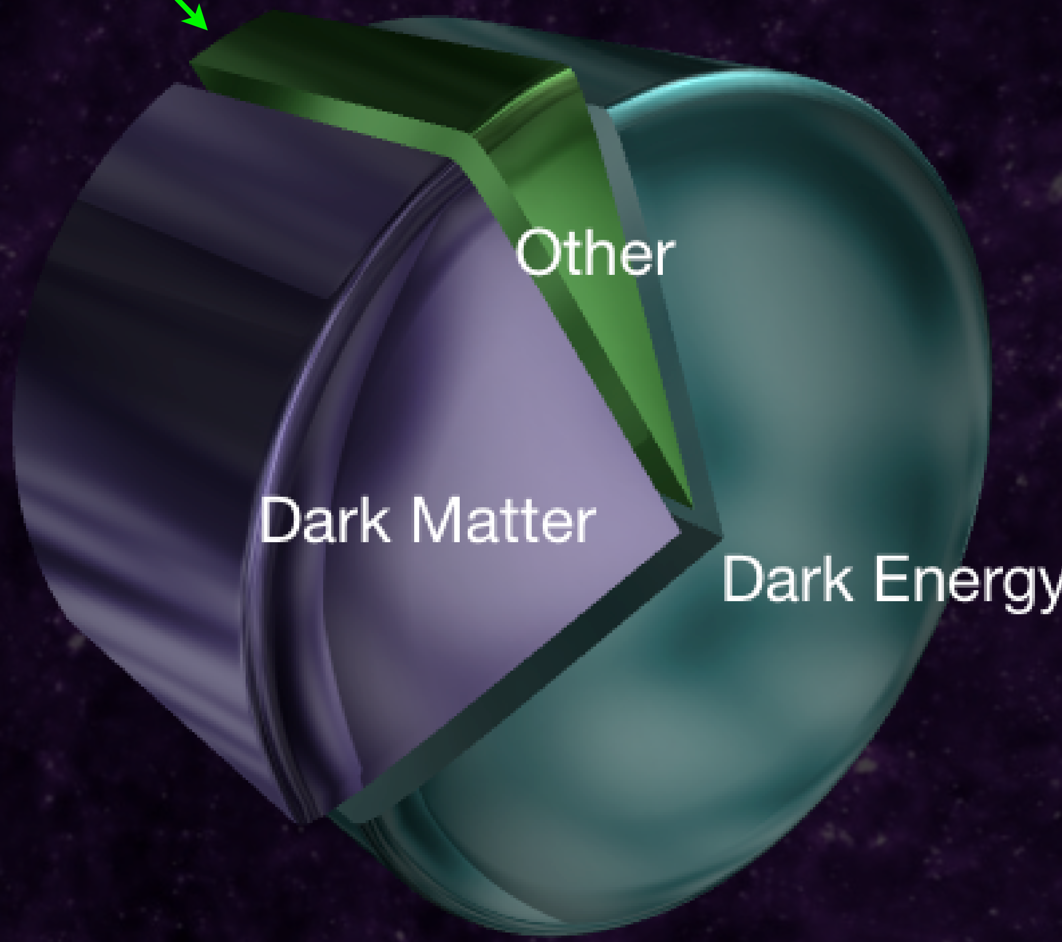


Energy budget of the universe



Energy budget of the universe

Matter we pretend to understand

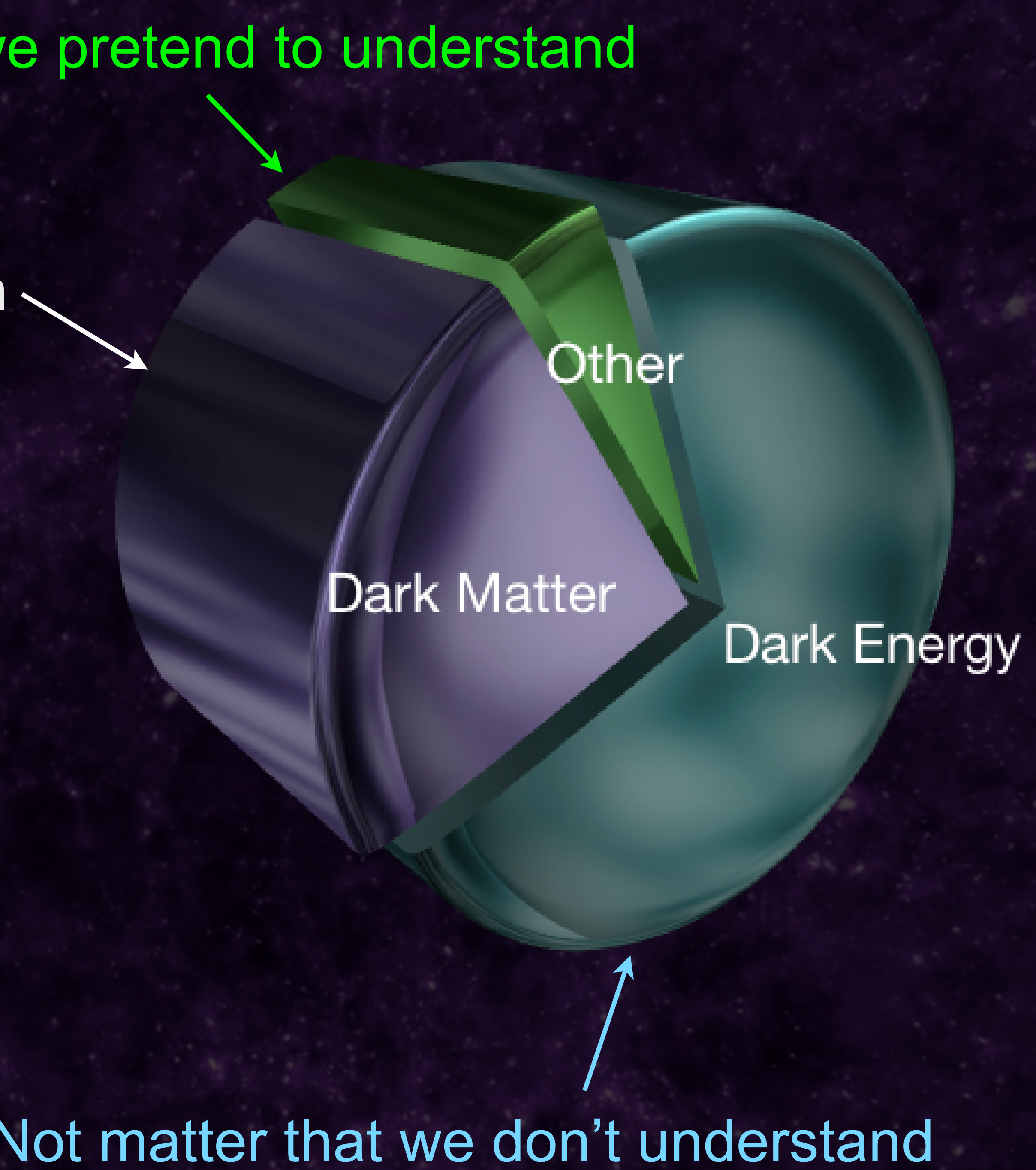


Not matter that we don’t understand

Energy budget of the universe

Energy budget of the universe

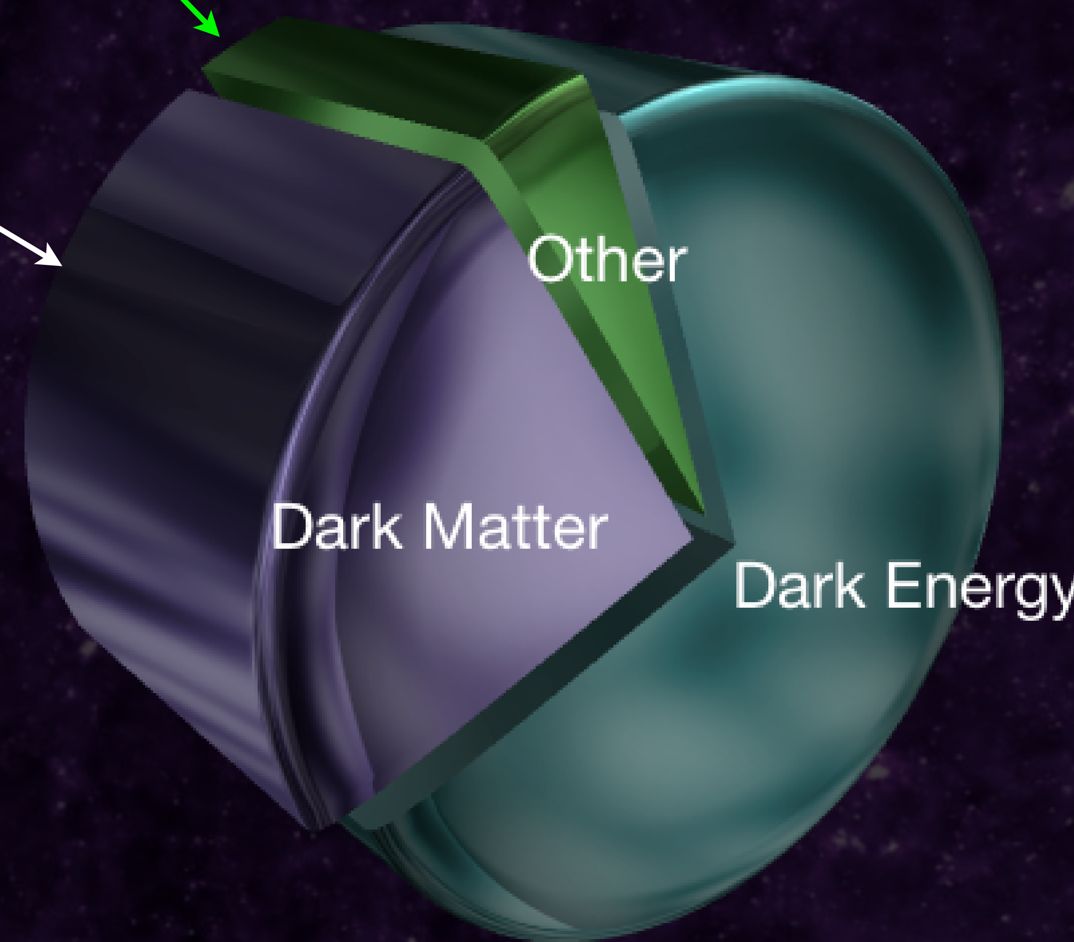
- Matter we hope to understand soon
- Strong evidence that this is made up of weakly-interacting massive particles: “WIMPs”



Energy budget of the universe

Matter we pretend to understand

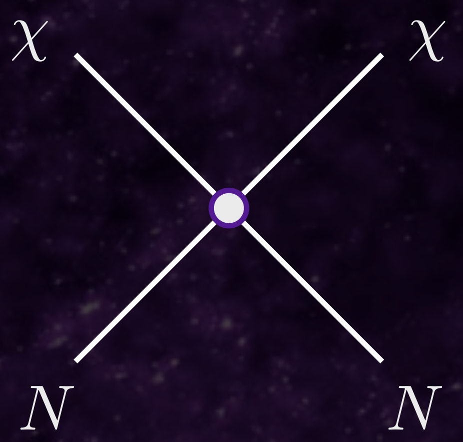
- Matter we hope to understand soon
- Strong evidence that this is made up of weakly-interacting massive particles: “WIMPs”
- eg. possible candidate: supersymmetry is not maximally broken in nature



Not matter that we don’t understand

Direct detection of dark matter

- Build a big underground detector and wait... patiently
- Of course, cross sections are small
  - but, how small?
- In practice, experiments utilise the nuclear coherence in the elastic scattering from large nuclei
- Scattering amplitude boils down to adding amplitudes from individual nucleons via contact interaction
- Spin-independent amplitude



$$\sim \overline{\chi}\chi\overline{N}N$$

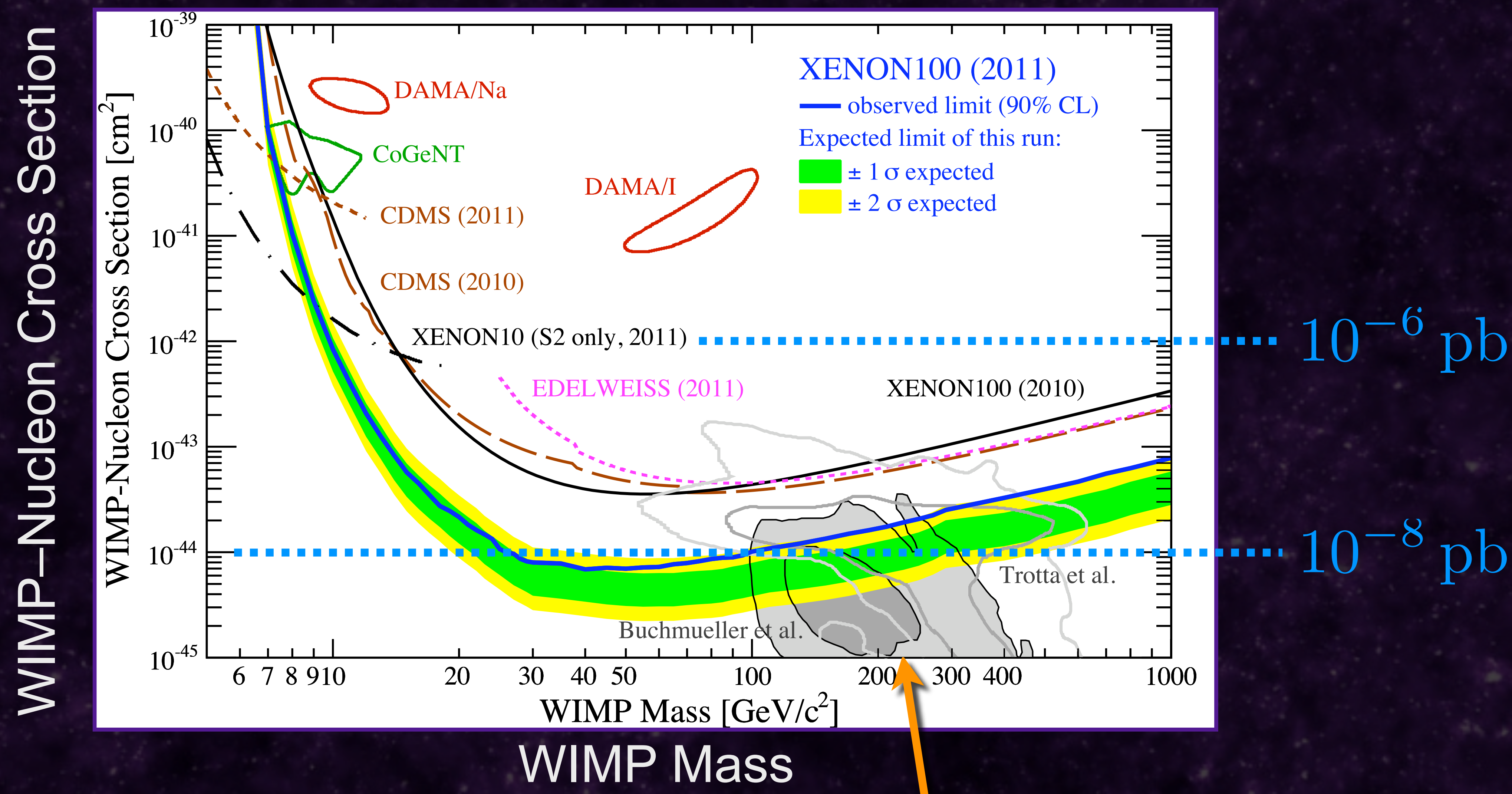
scattering amplitude

$$\mathcal{M} \sim \sum_q C_q \langle N|m_q\bar{q}q|N\rangle$$

interaction governed by nucleon “sigma terms”

XENON100 cross section limits

XENON100, PRL(2011)

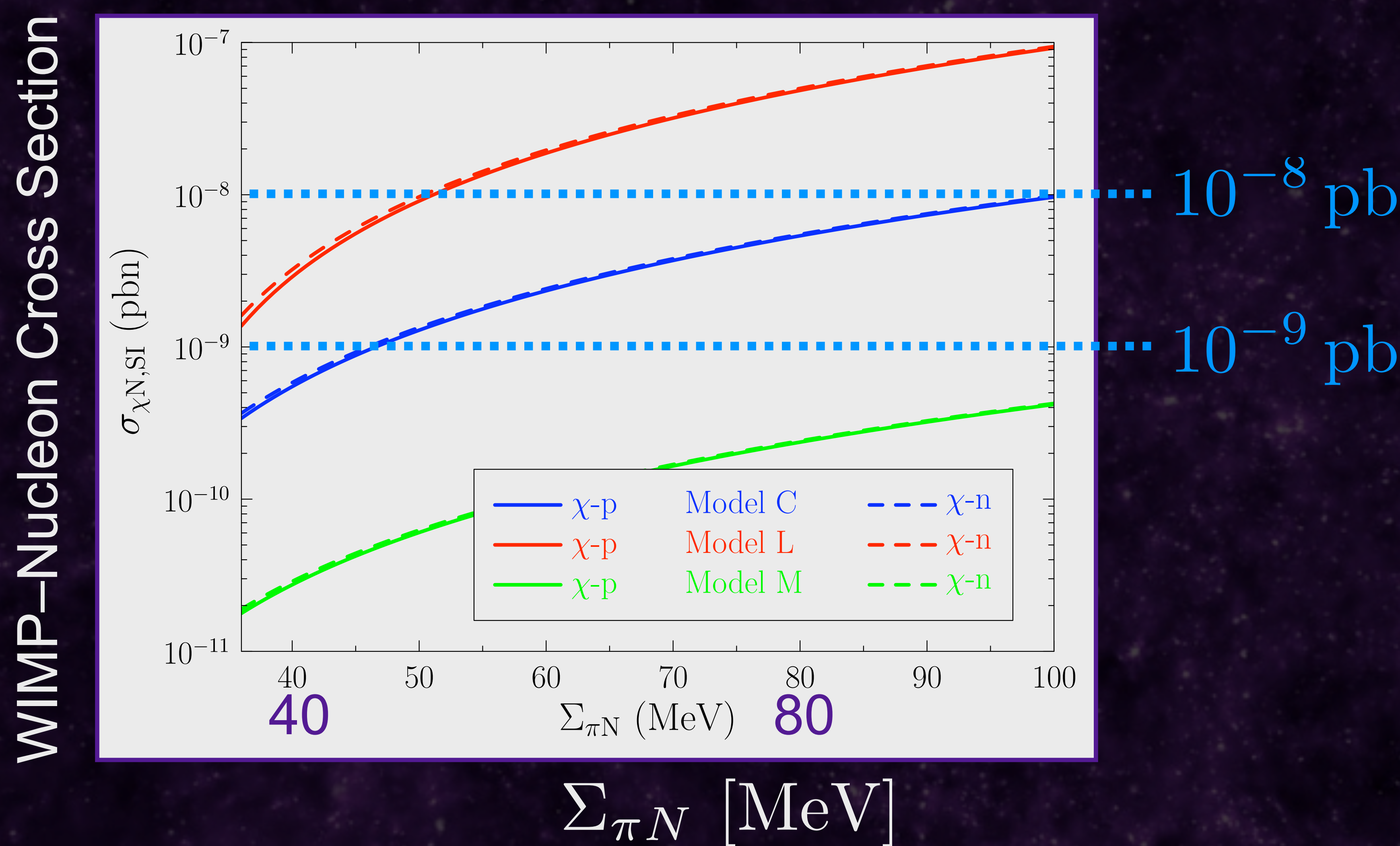


Expected cross sections for neutralino in CMSSM

Significant uncertainty from nucleon sigma terms

Sigma terms drive uncertainty

- Eg. CMSSM: Ellis, Olive & Savage, PRD2008
  - Benchmark models show variation over an order of magnitude with respect to variation of



- Uncertainty is largely driven by the poorly constrained extraction of the strangeness sigma term

Early extraction of strangeness sigma term

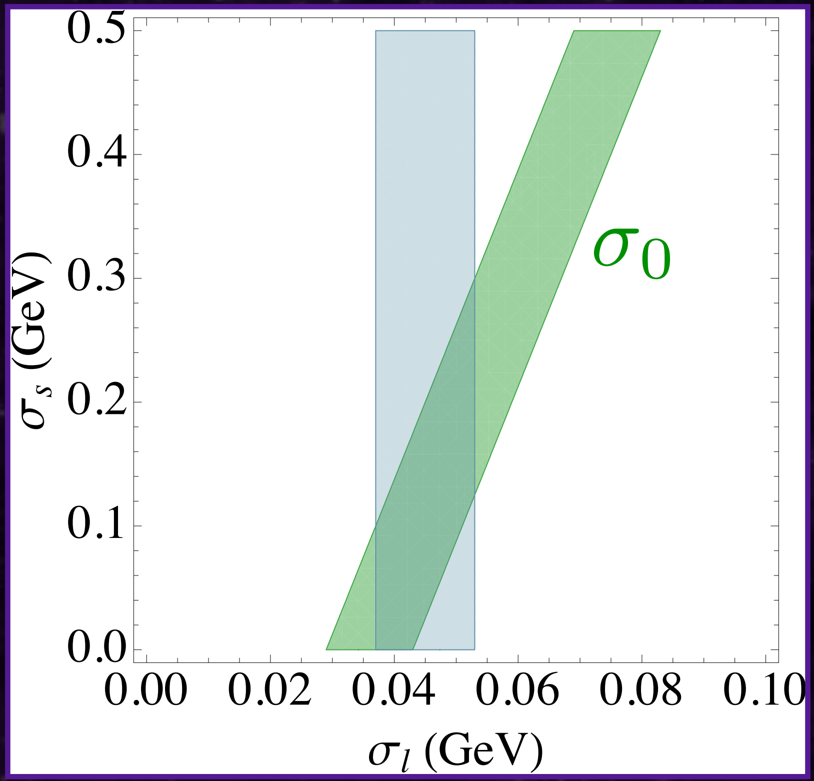
- Strangeness sigma term $\sigma_s \equiv m_s \langle N|\bar{s}s|N\rangle$
- Observed baryon mass spectrum can estimate non-singlet quantity
  $\sigma_0 \equiv \hat{m}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$
  - First-order SU(3) breaking:
  $$\sigma_0 \simeq \hat{m}\frac{m_\Xi + m_\Sigma - 2m_N}{m_s - \hat{m}} = 26\,\mathrm{MeV}$$
  - Improved EFT estimate:

  Borasoy & Meißner (1997)
  $\sigma_0 \simeq 36 \pm 7\,\mathrm{MeV}$
- Strangeness then related to $\Sigma_{\pi N}$:
  $$\sigma_s = \frac{m_s}{2\hat{m}}\left(\Sigma_{\pi N} - \sigma_0\right)$$
- Of course, $\Sigma_{\pi N}$ has seen it's own challenges over the years:

$$\Sigma_{\pi N} = \begin{cases} 45 \pm 8\,\mathrm{MeV} & \text{Gasser et al. (1991)} \\ 64 \pm 7\,\mathrm{MeV} & \text{GWU (2002)} \\ 59 \pm 7\,\mathrm{MeV} & \text{Alarcon et al. (2012)} \end{cases}$$

Strong dependence on Sigma-piN

Gasser *et al*. (1991)

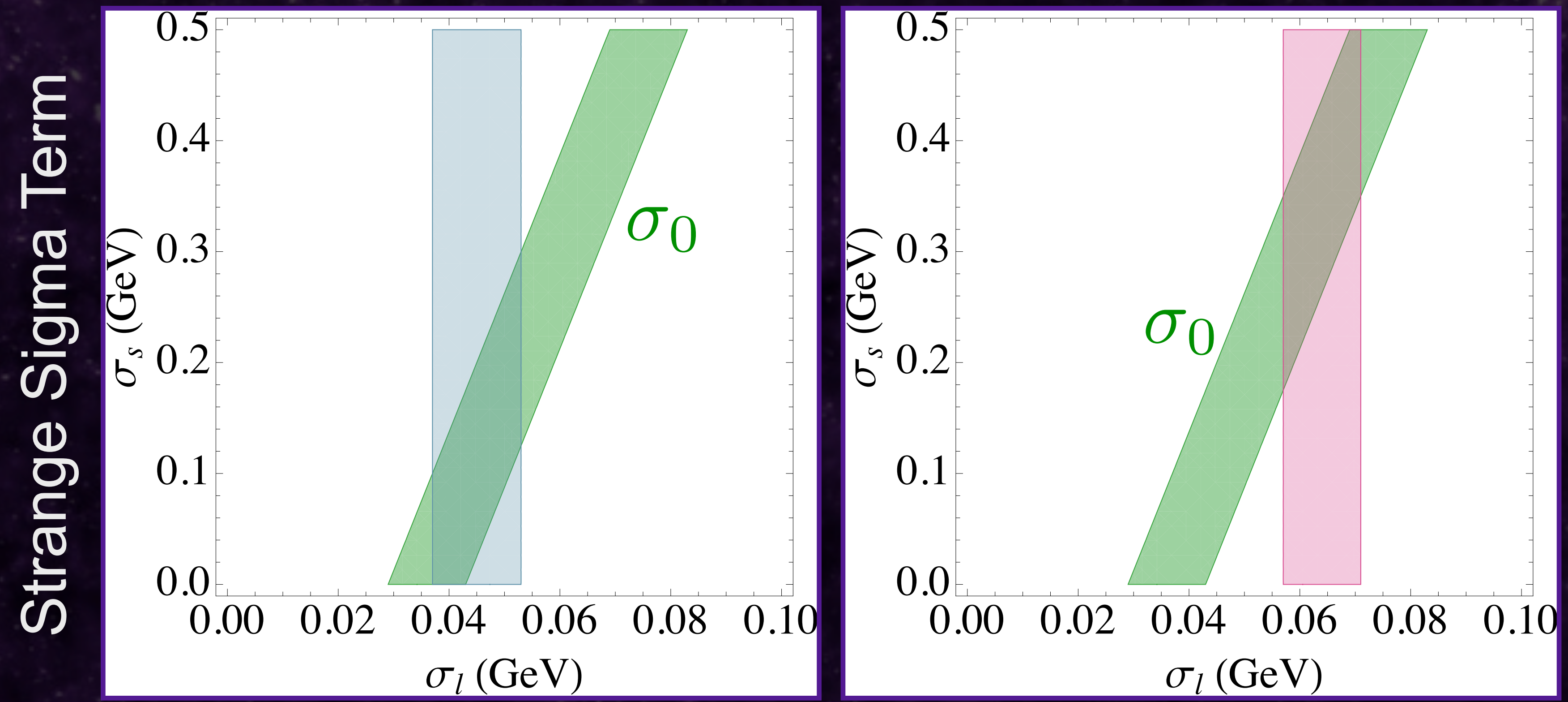


Strange Sigma Term

Light-quark Sigma Term

Strong dependence on Sigma-piN

Gasser *et al.* (1991) GWU (2002)



Light-quark Sigma Term

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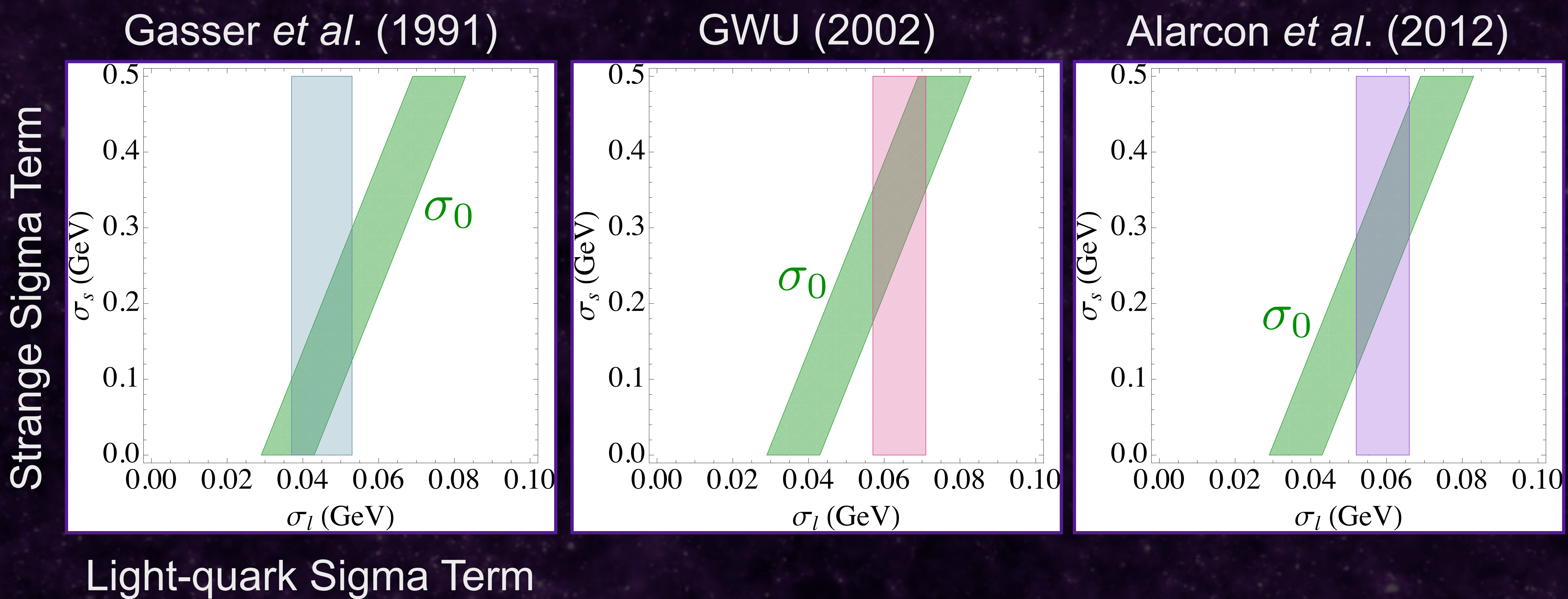
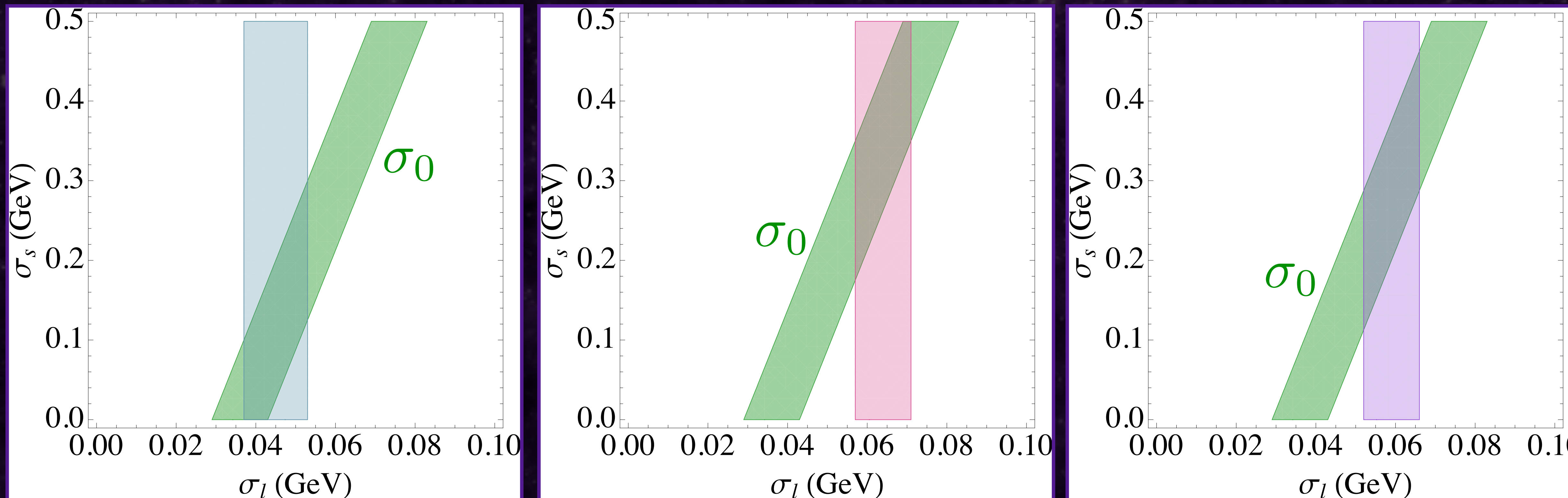


Strong dependence on Sigma-piN

Gasser *et al.* (1991) | GWU (2002) | Alarcon *et al.* (2012)

Strange Sigma Term



Light-quark Sigma Term

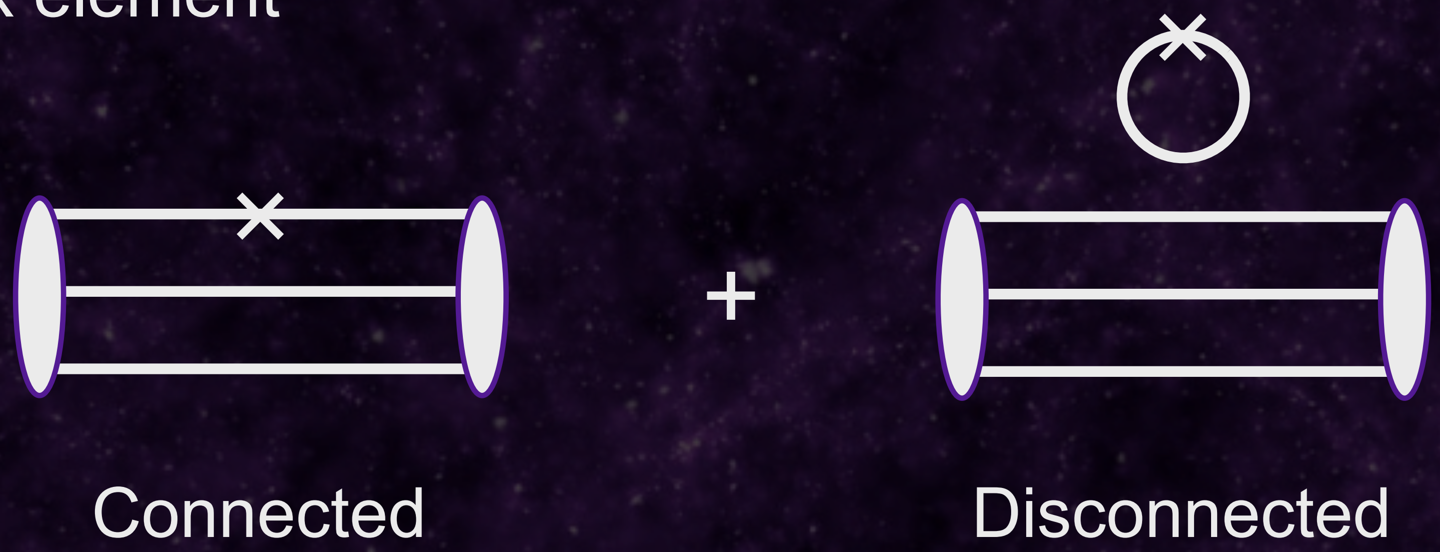
Even if $\Sigma_{\pi N}$ perfect $\Delta\sigma_s = \frac{m_s}{2\hat{m}}\Delta\sigma_0 \sim 90\,\mathrm{MeV}$

Resolution: Lattice QCD

Two common lattice QCD techniques

- **Direct:**

  3-point matrix element



- Ratio with 2-point correlator (at large Δt) isolates relevant matrix element
  - Disconnected diagrams notoriously difficult
  - Scalar current couples to vacuum ⇒ requires vacuum subtraction

Two common lattice QCD techniques

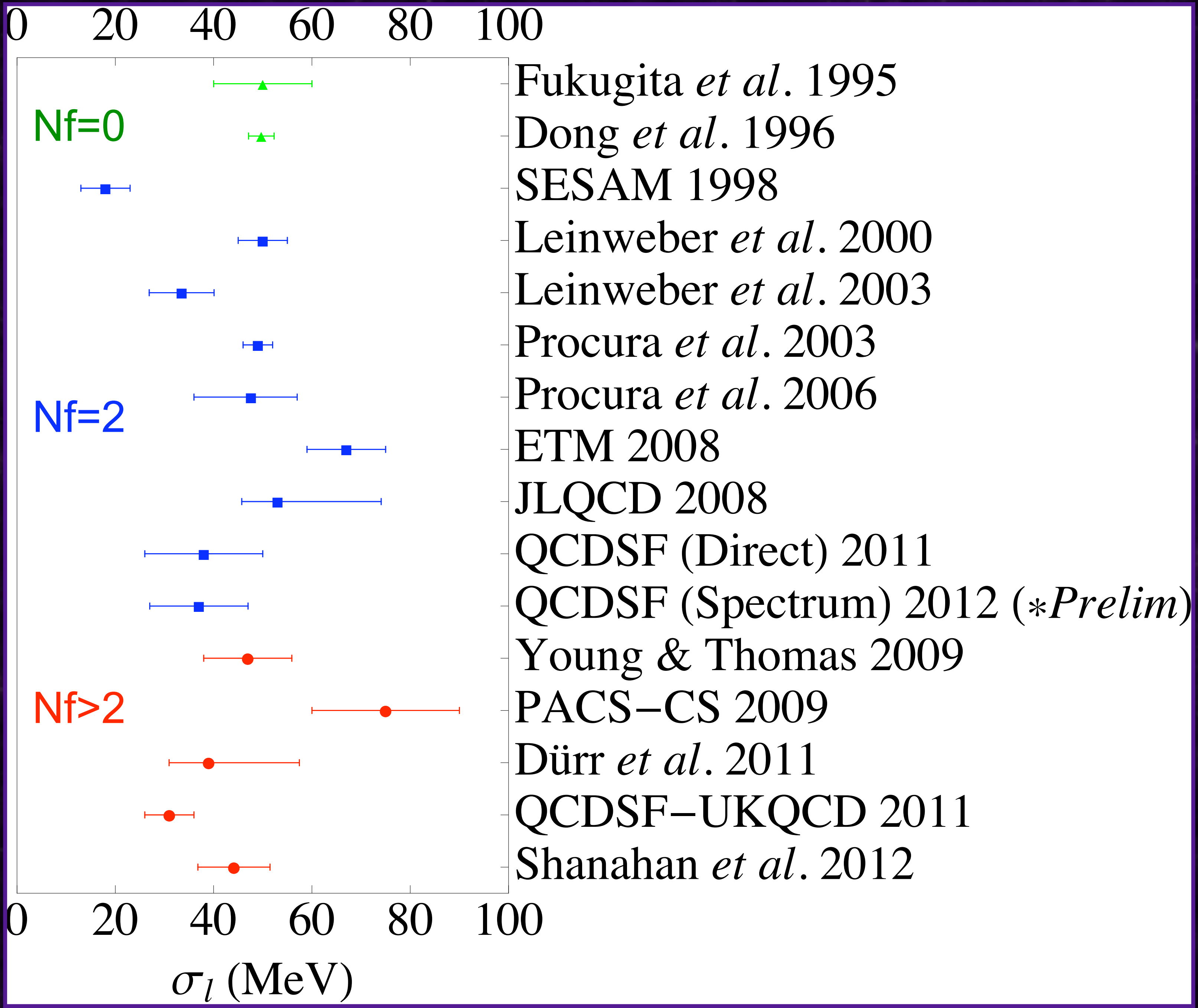
- **Spectrum / Feynman-Hellmann:**

  Differentiate quark-mass dependence

$$\sigma_q = \langle N | m_q \bar{q} q | N \rangle = m_q \frac{\partial M_N}{\partial m_q}$$

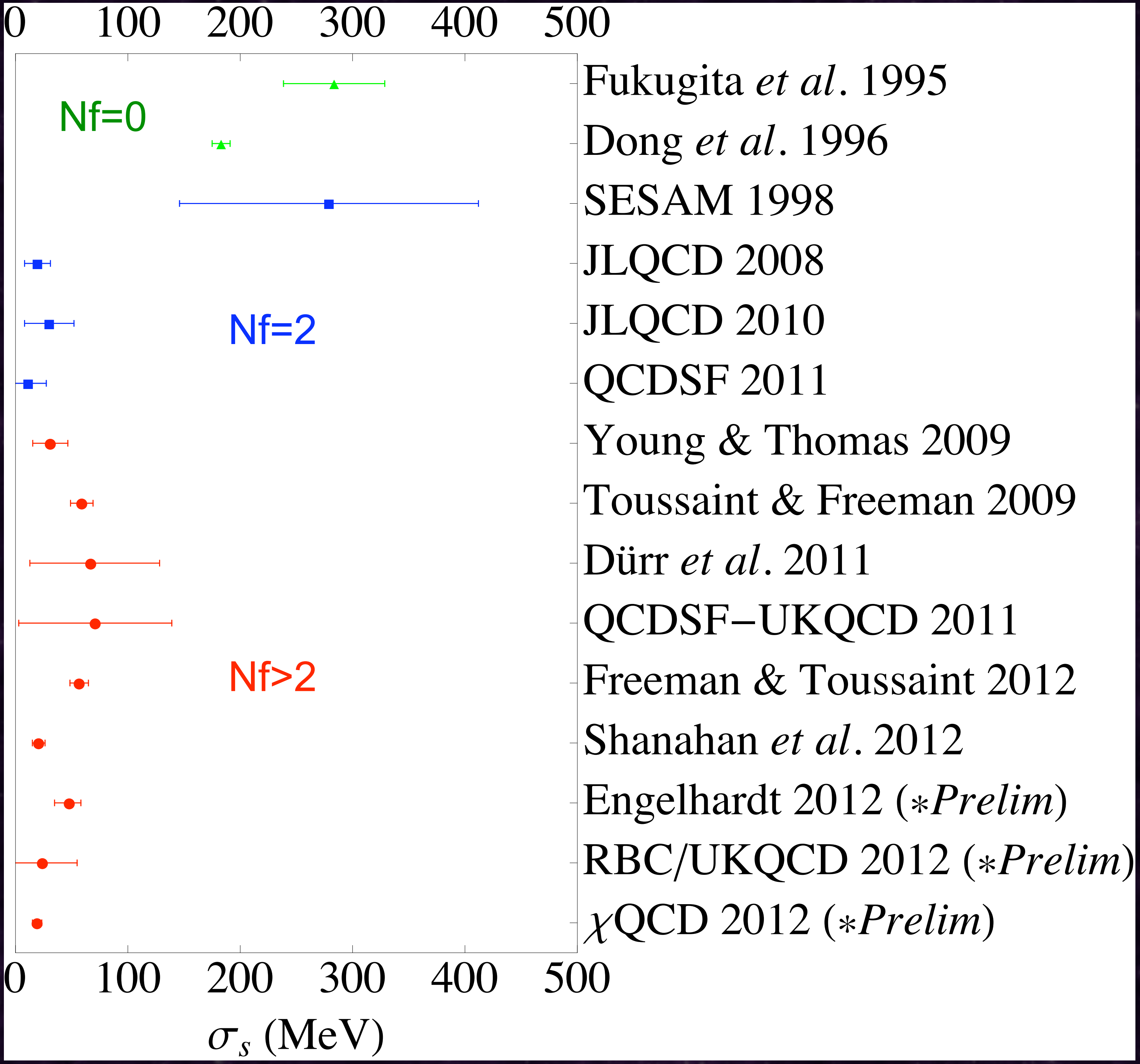
- Isolation of quark-mass dependence of baryon masses can resolve sigma terms
  - Require substantial variation of both light and strange quark masses
  - Challenge to parameterize a robust description of lattice results appropriate for extrapolation to physical point

Light-quark sigma term in lattice QCD

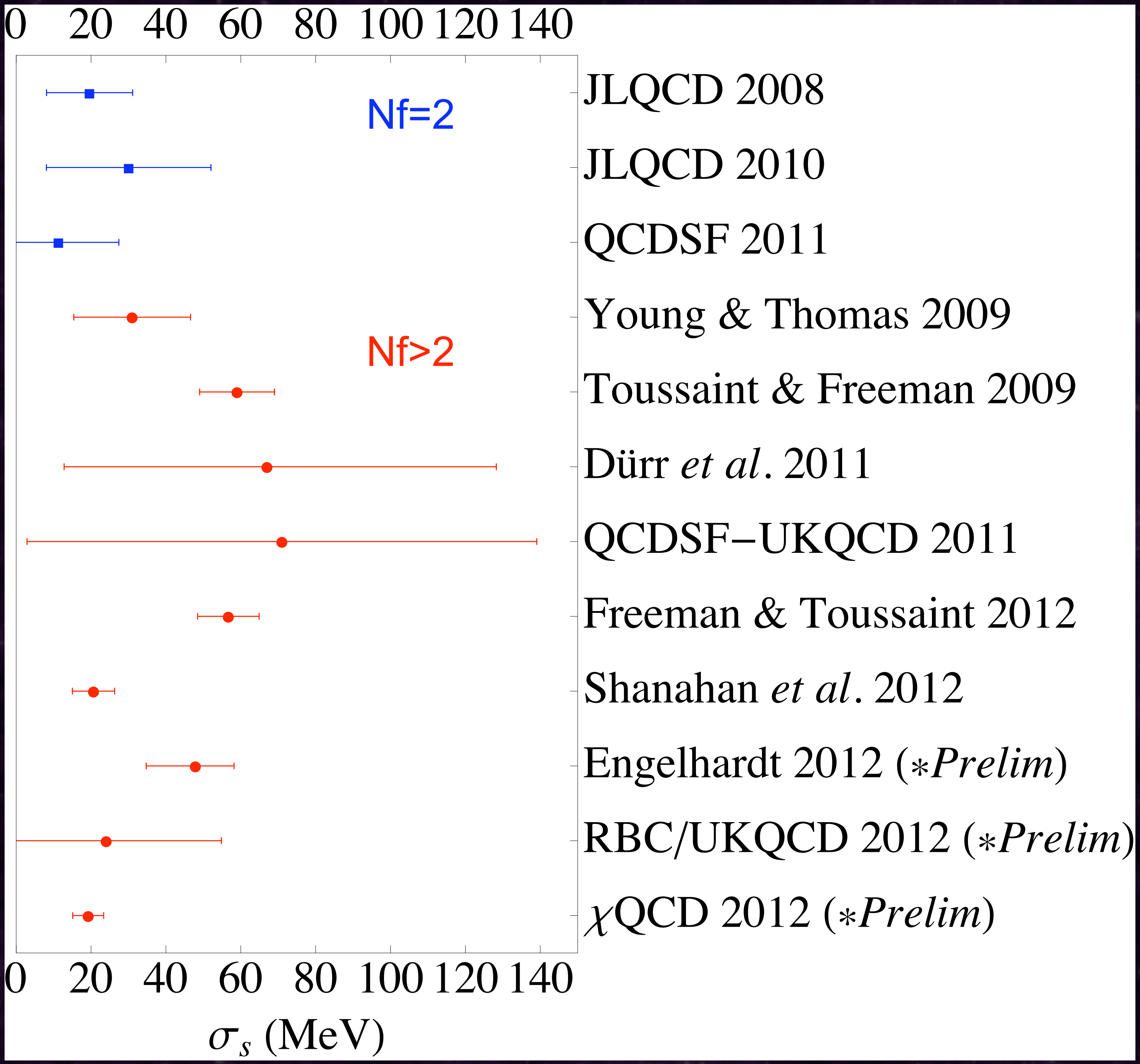


$\Sigma_{\pi N}$

Strange-quark sigma term in lattice QCD



Strange-quark sigma term in lattice QCD



Lattice QCD selected highlights

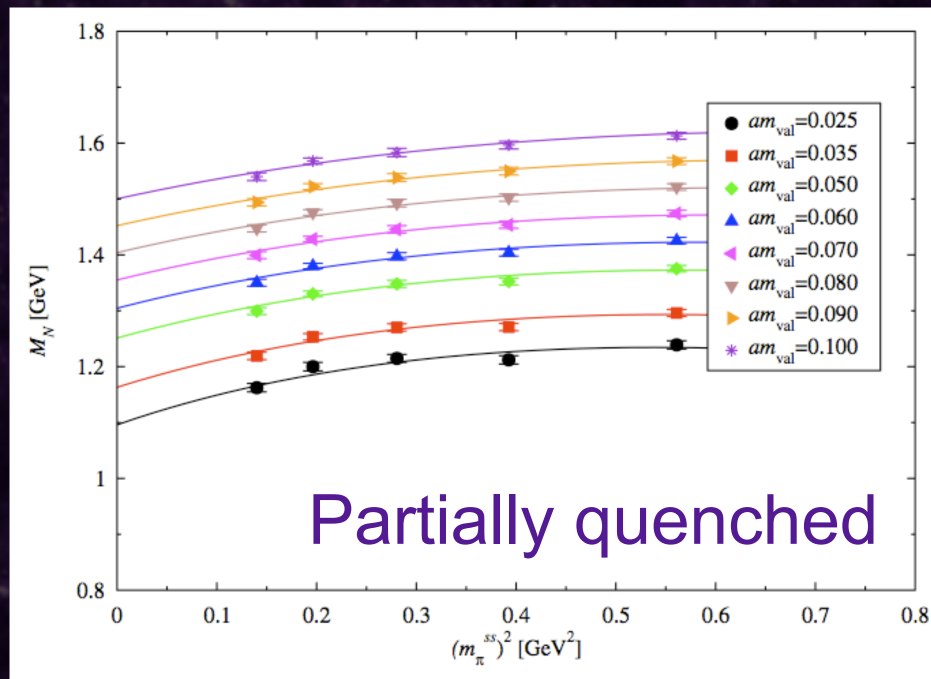
Apologies to those I don't have time to cover

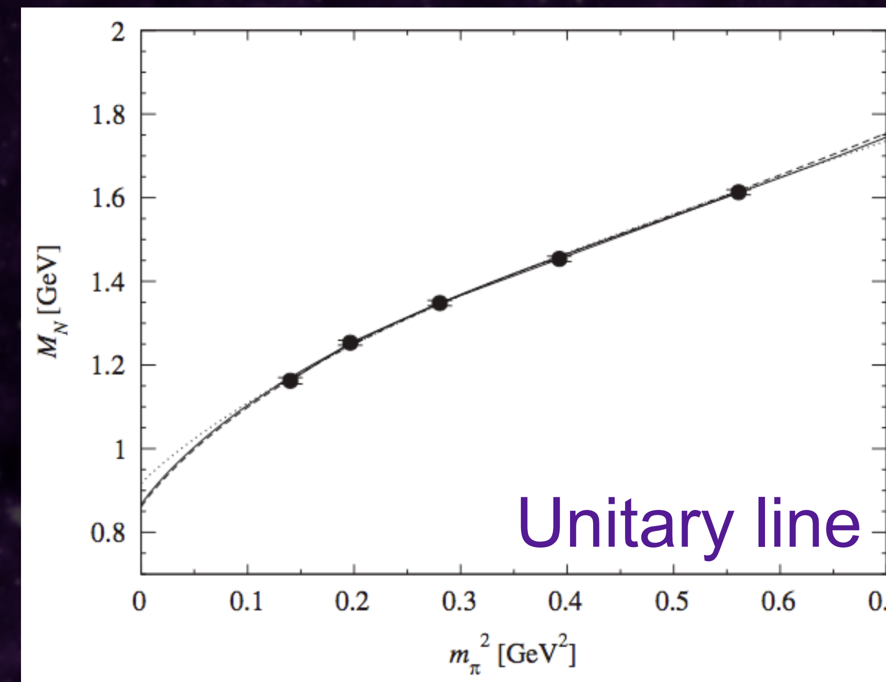
And thanks to all who wrote to me

Renewed interest thanks to JLQCD

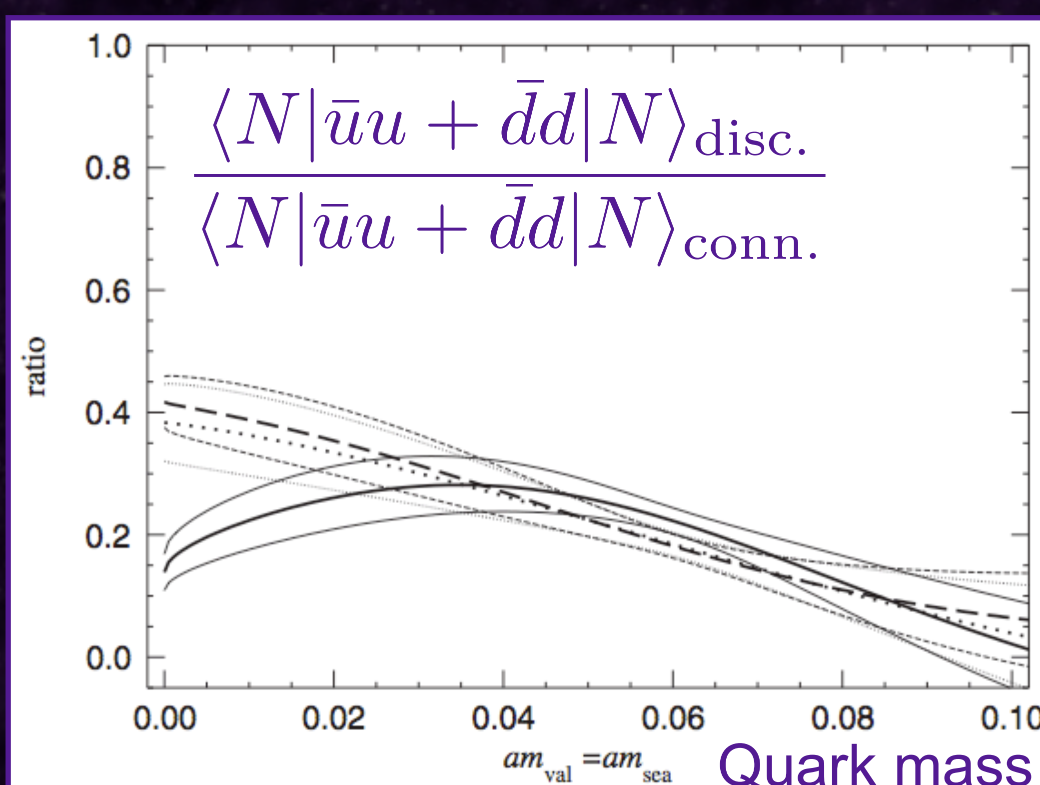
PRD(2008)

Nucleon mass





Pion mass (squared)



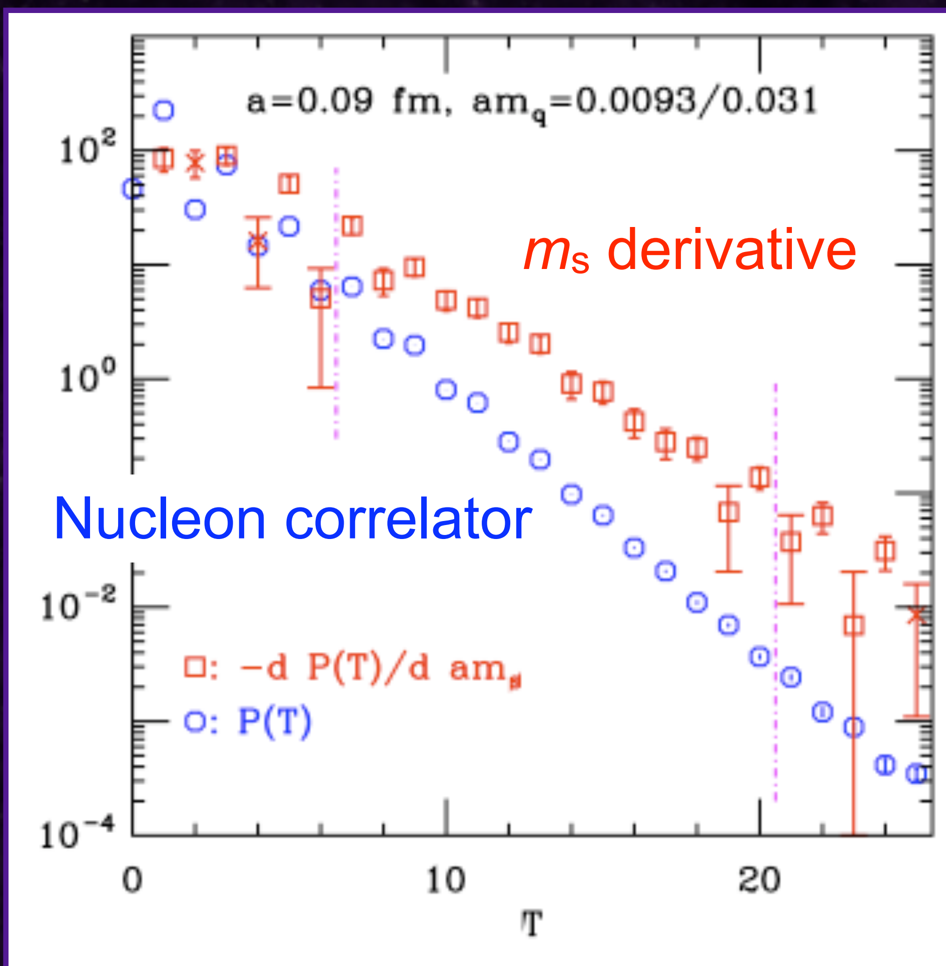
- 2-flavour overlap
- Feynman-Hellmann
- Ratio: disconnected/connected
  ⇒ estimate *y*-parameter

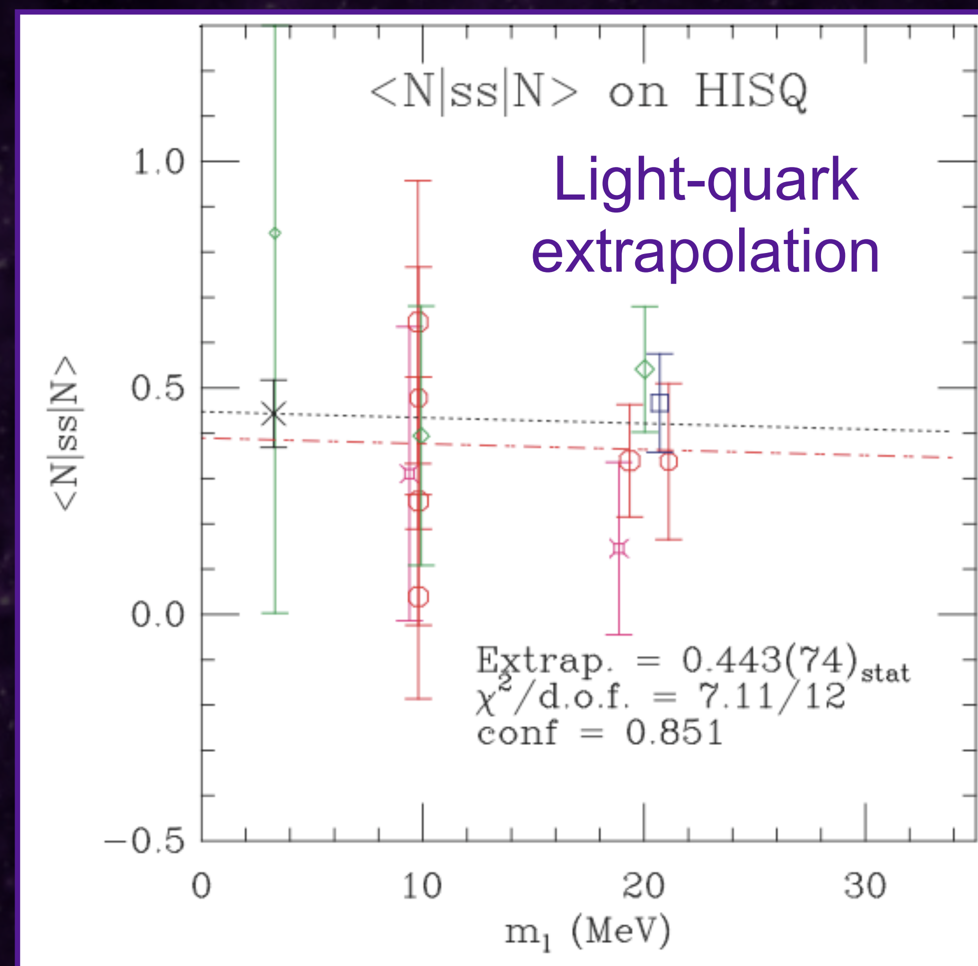
$$y = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u+\bar{d}d|N\rangle} \simeq 0.030 \pm 0.018$$

Toussaint & Freeman (MILC)

PRL(2009) & 1204.3866

- Asqtad & HISQ
- "Hybrid method": Application of the Feynman-Hellmann relation as applied directly to the nucleon correlator
- Stochastic reweighting of the nucleon mass

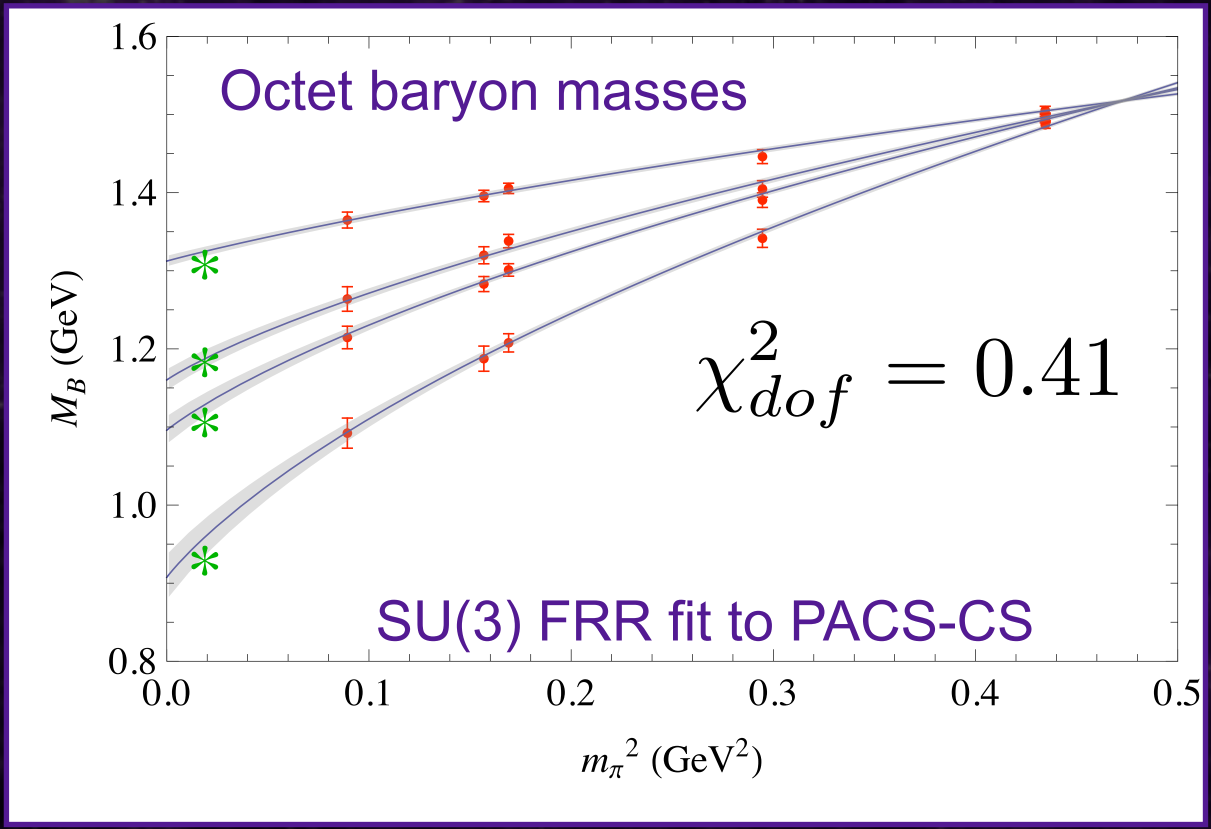




Latest result $\sigma_s = 57^{+5}_{-7}\,\mathrm{MeV}$

Shanahan–Thomas–Young

Shanahan, Monday
arXiv:1205.5365 & PRD(2010)



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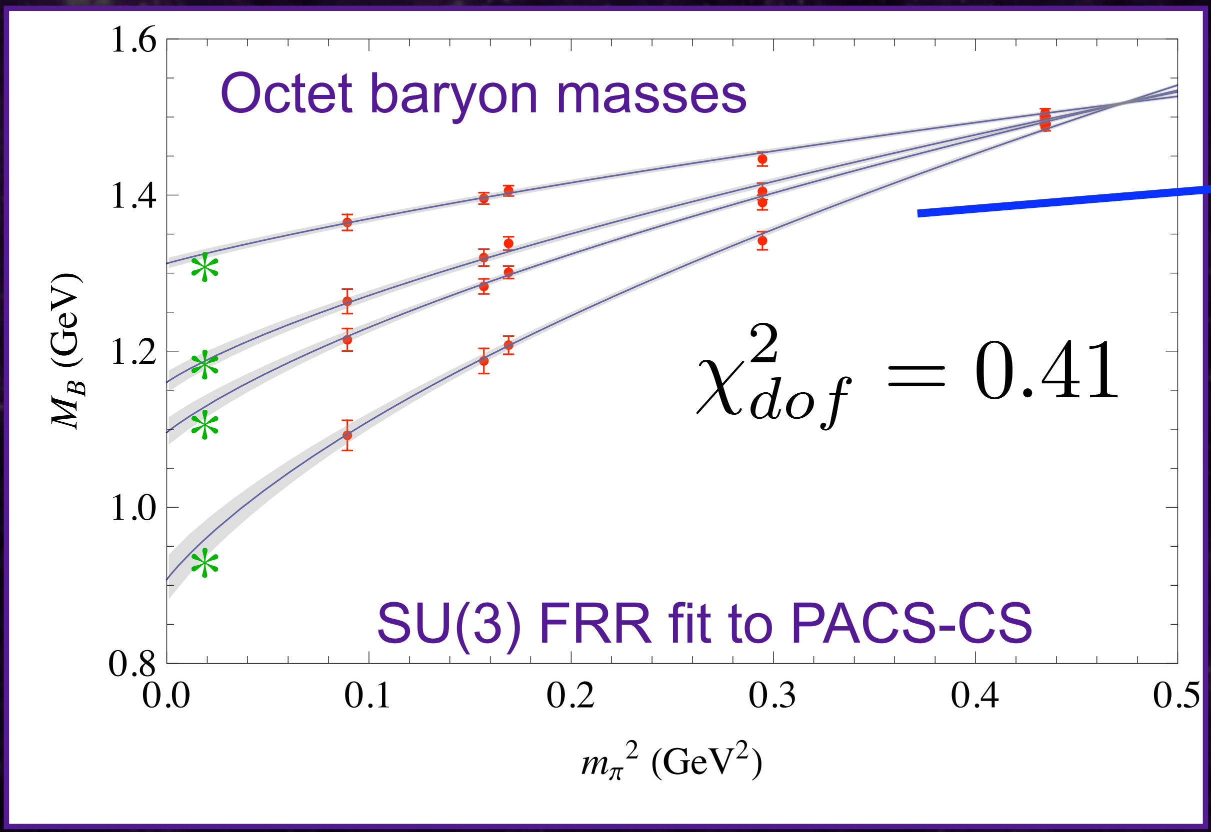

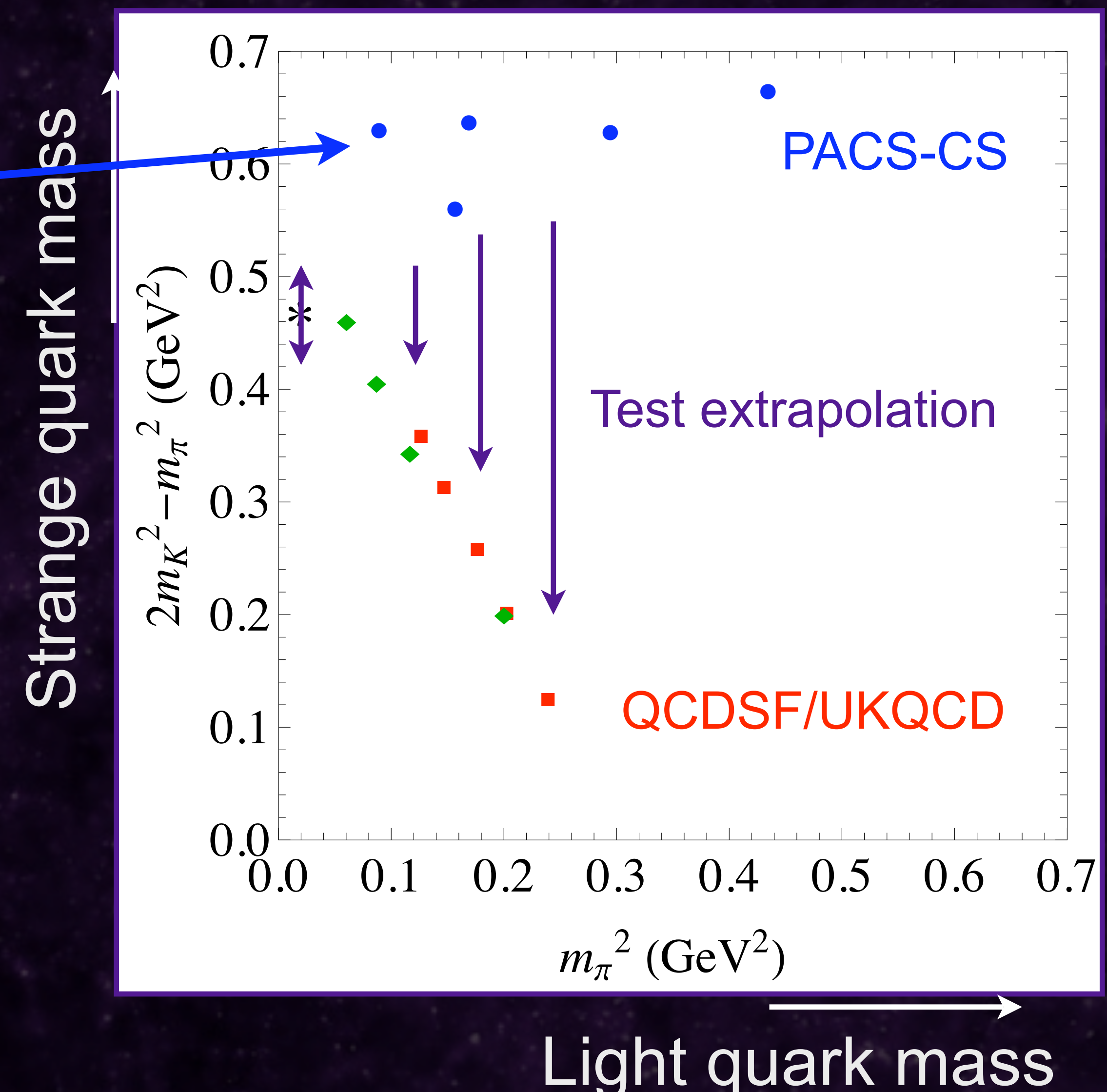

Shanahan–Thomas–Young

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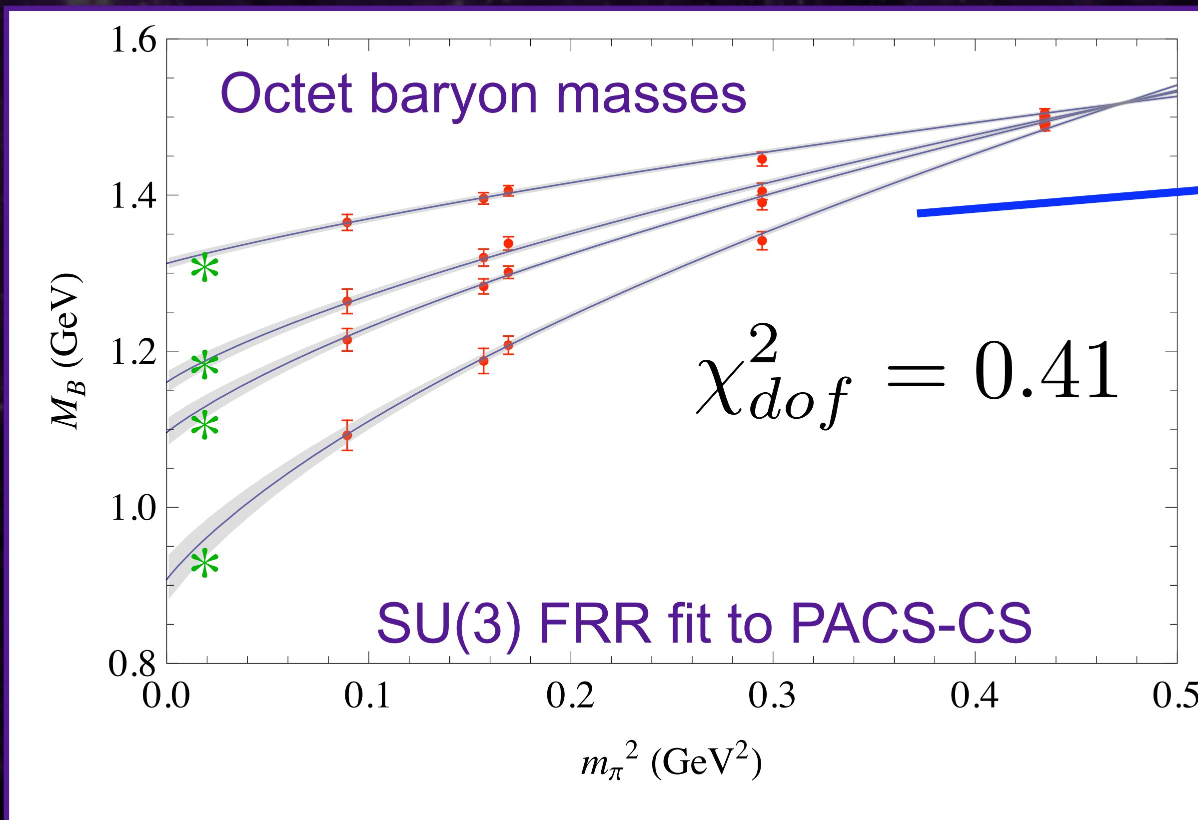

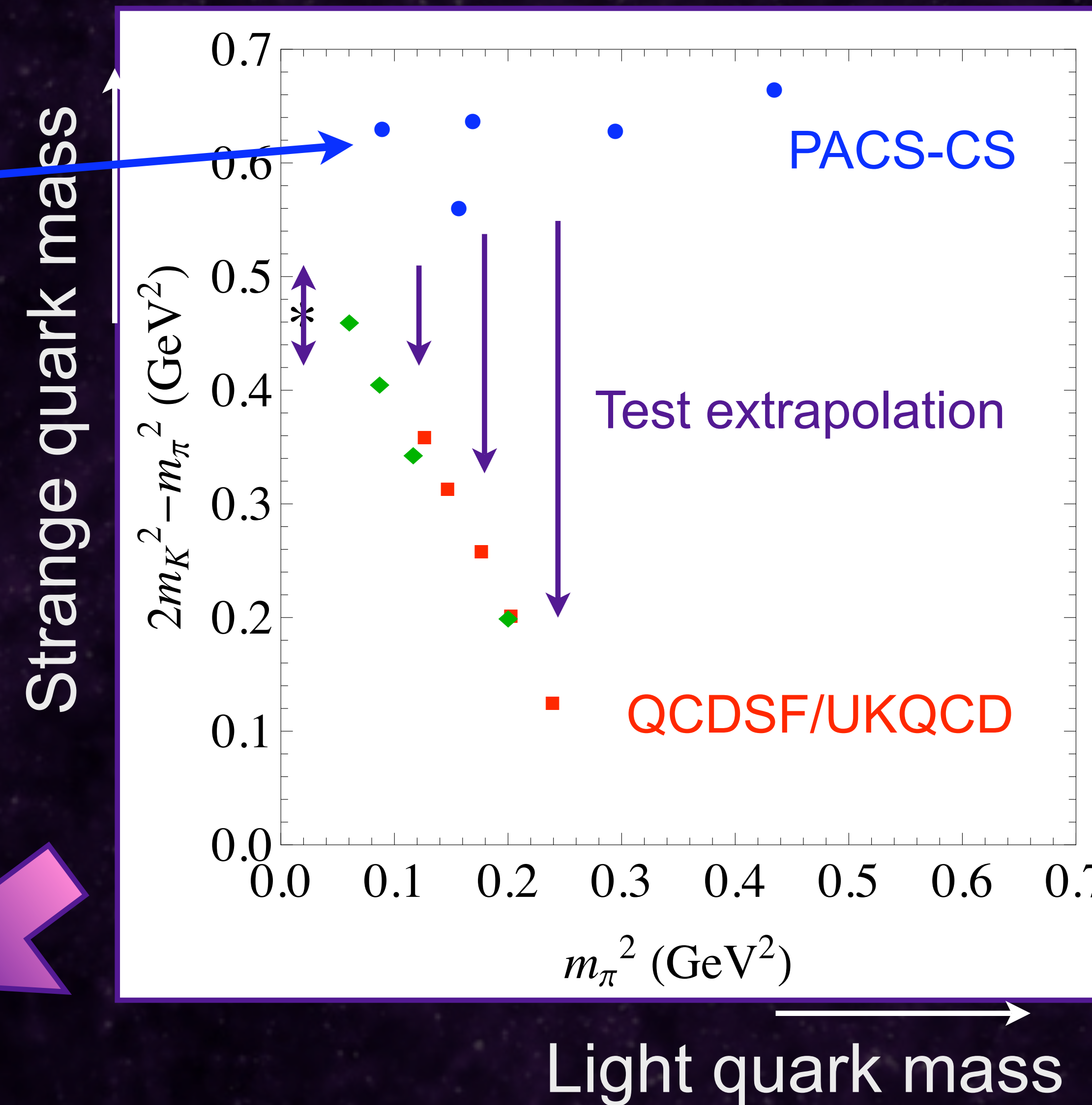

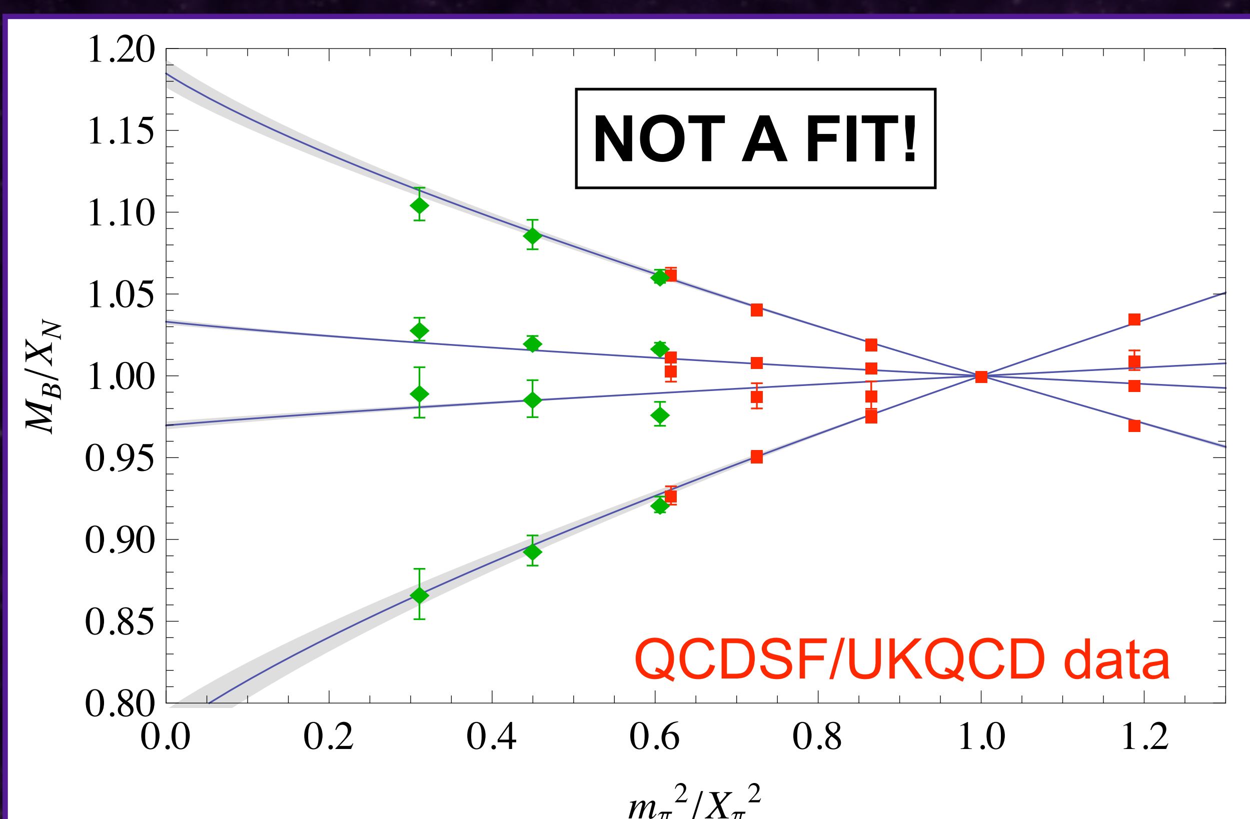

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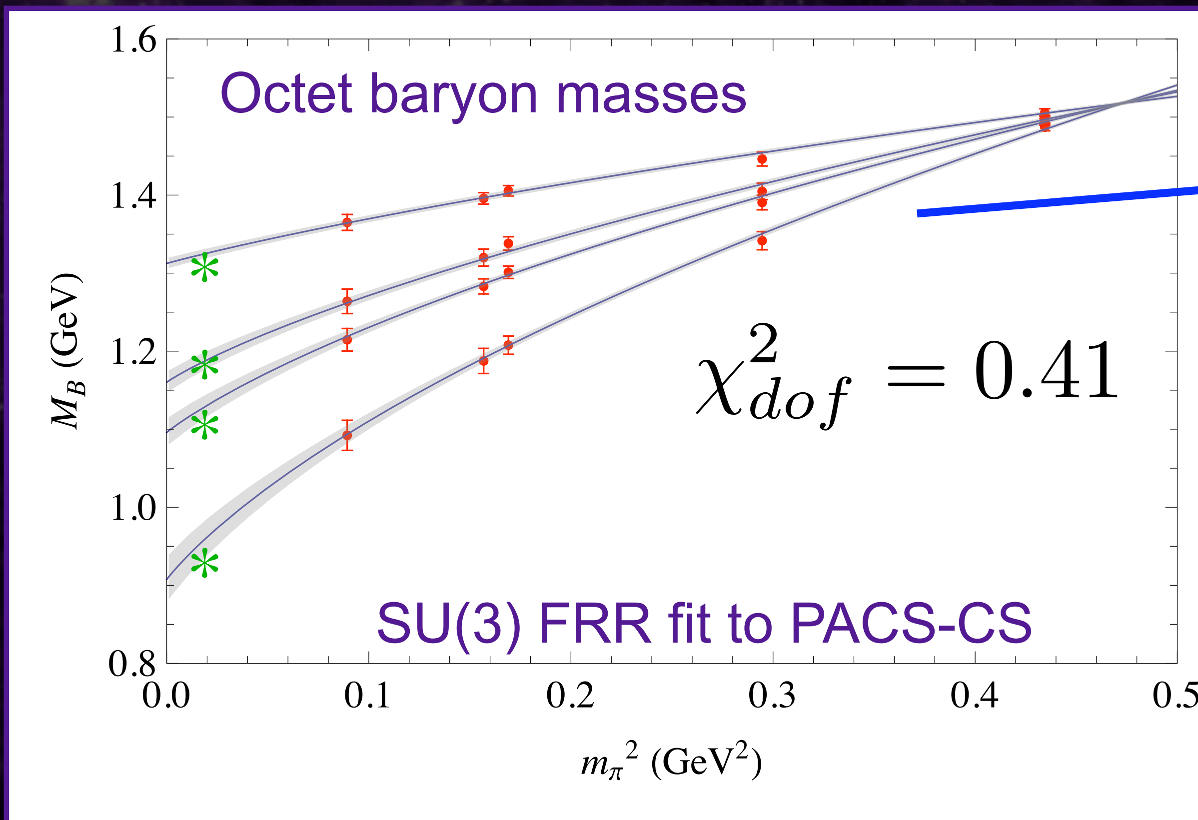
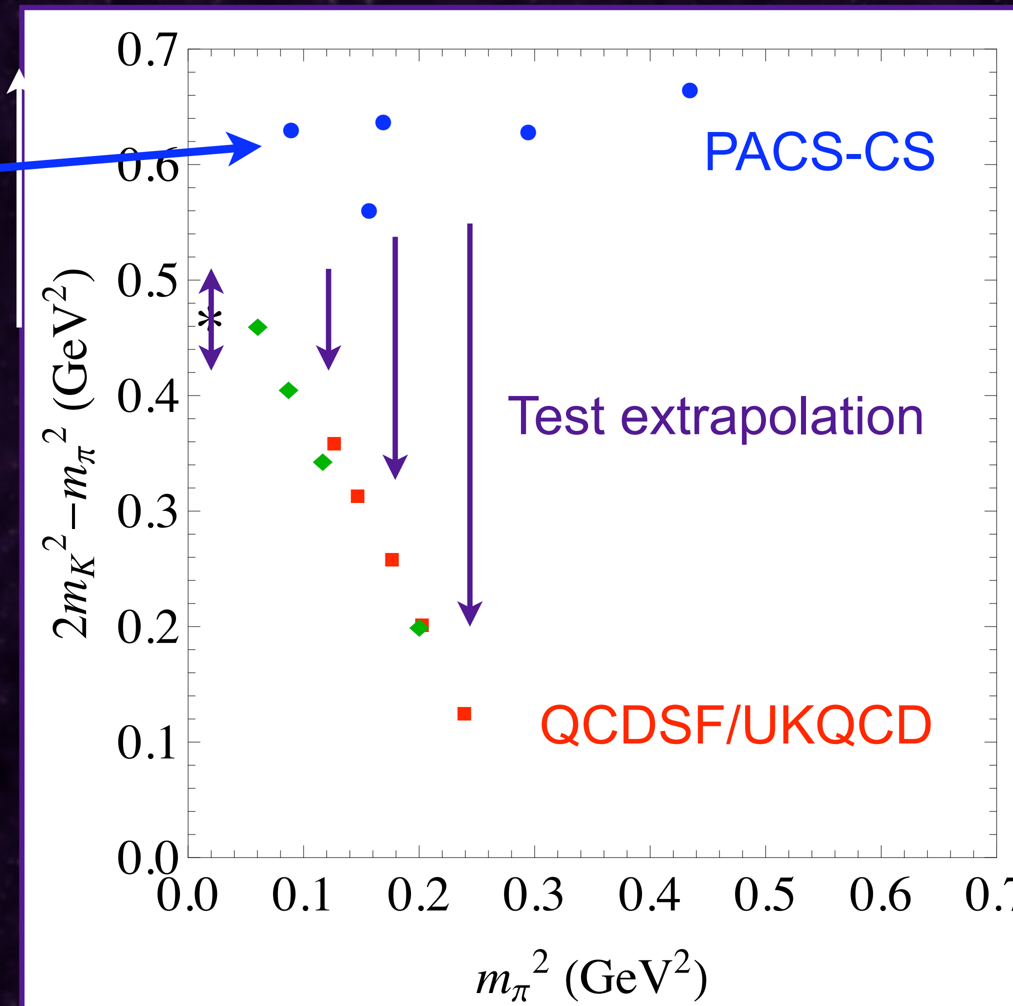
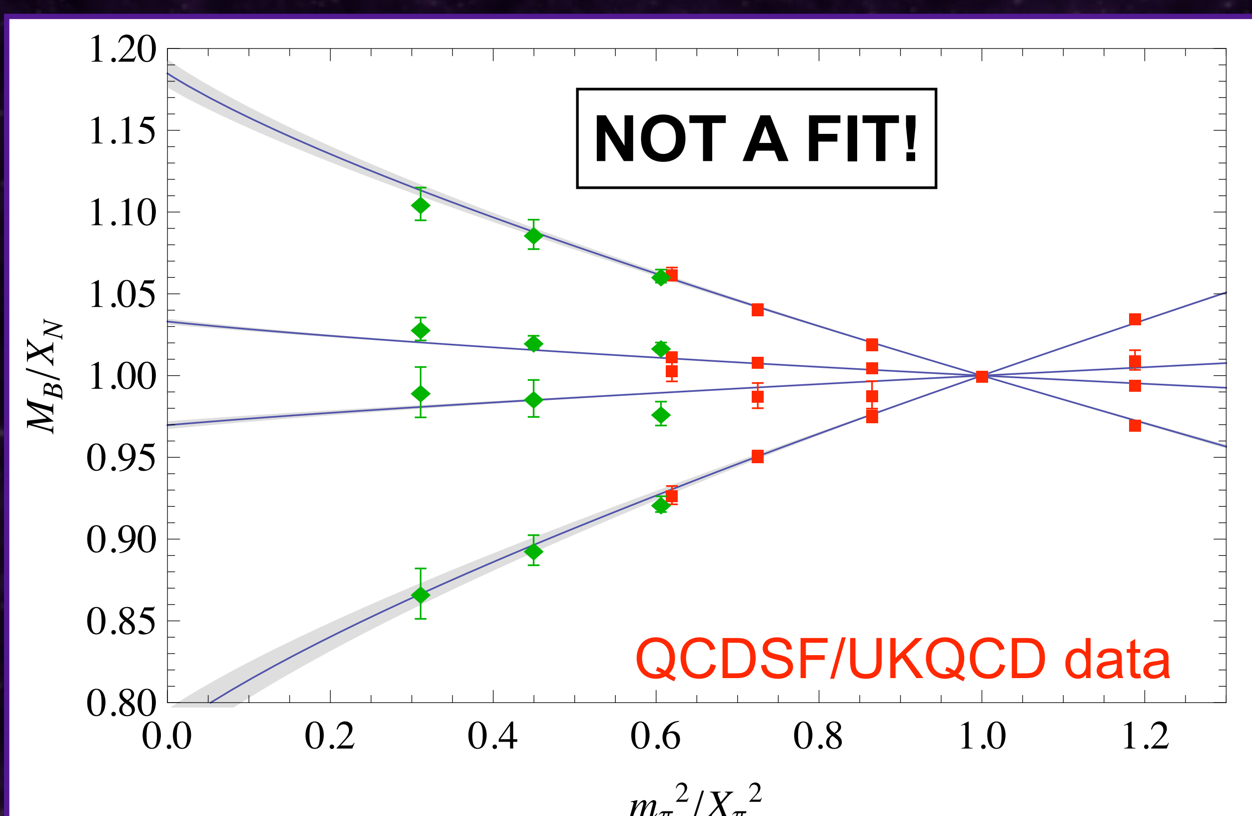


Strange quark mass



Light quark mass



$$\sigma_s = 21 \pm 6\,\mathrm{MeV}$$

Further developments

- **Direct calculations**:
  - QCDSF [1111.1600, PRD(2012)] — Careful analysis of operator mixing for Wilson fermions
  - Engelhardt [1011.6058, prelim] — Mixed action results soon!
  - ETMC [V. Drach, Monday; 1202.1480] — Investigating excited-state contamination
  - Boston U. [M. Cheng, Monday] — In progress
  - χQCD [M. Gong, Monday, prelim] — Overlap on DWF, low-mode averaging

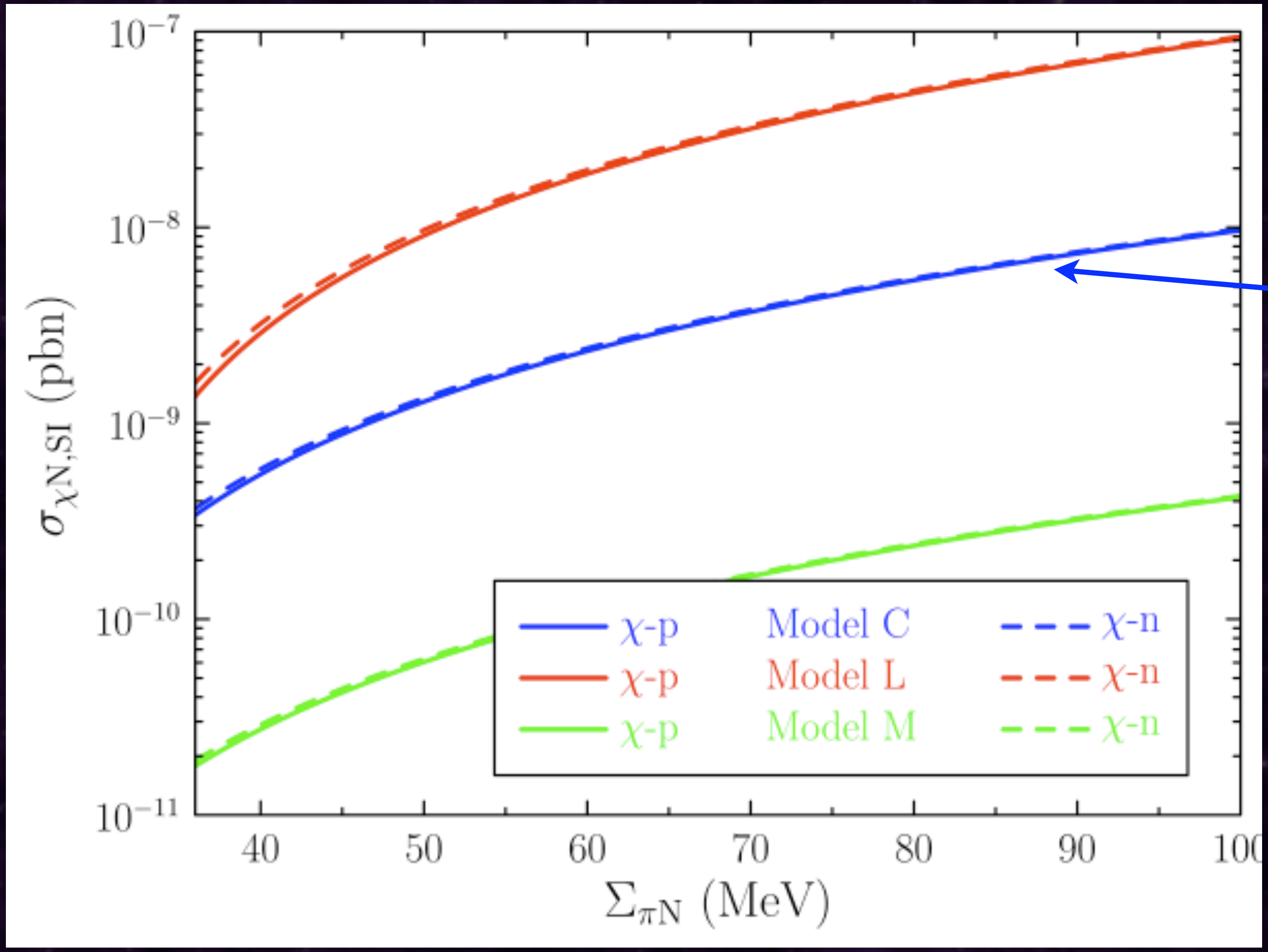
- **Spectrum / Feynman–Hellman**:
  - BMW [1109.4265, PRD(2012)] — Extensive quark-mass coverage, light pions
  - QCDSF/UKQCD [1110.4971, PRD(2012)] — Flavour expansion, novel quark-mass trajectory
  - RBC/UKQCD [C. Jung, Monday, prelim] — Strange-mass reweighting

Impact on dark matter searches

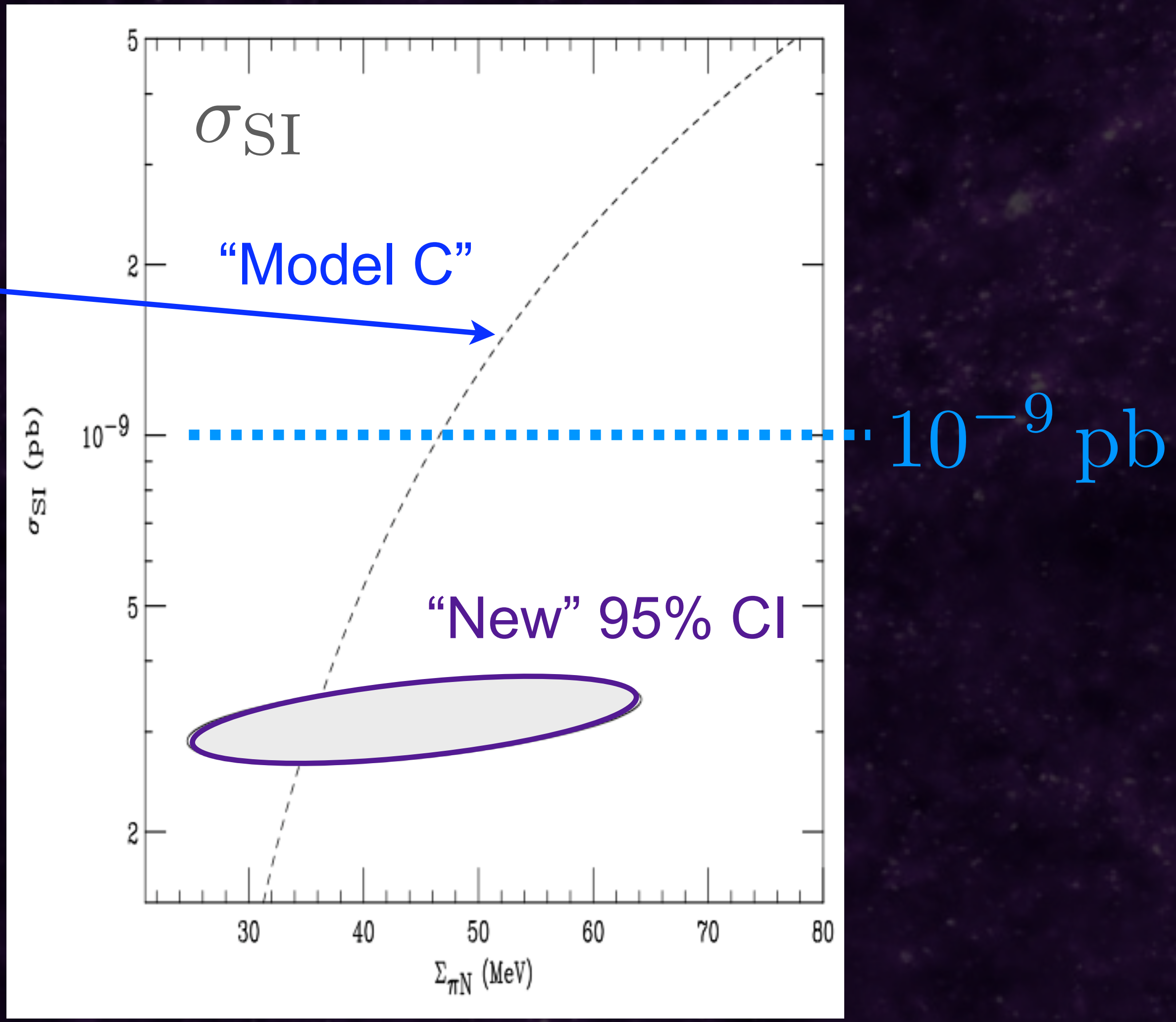
Implications for dark matter cross sections

- Suppose a (constrained) scenario where supersymmetry is not maximally broken by nature ⇒ Neutralino dark matter candidate

WIMP–Nucleon Cross Section



CMSSM: Ellis, Olive & Savage

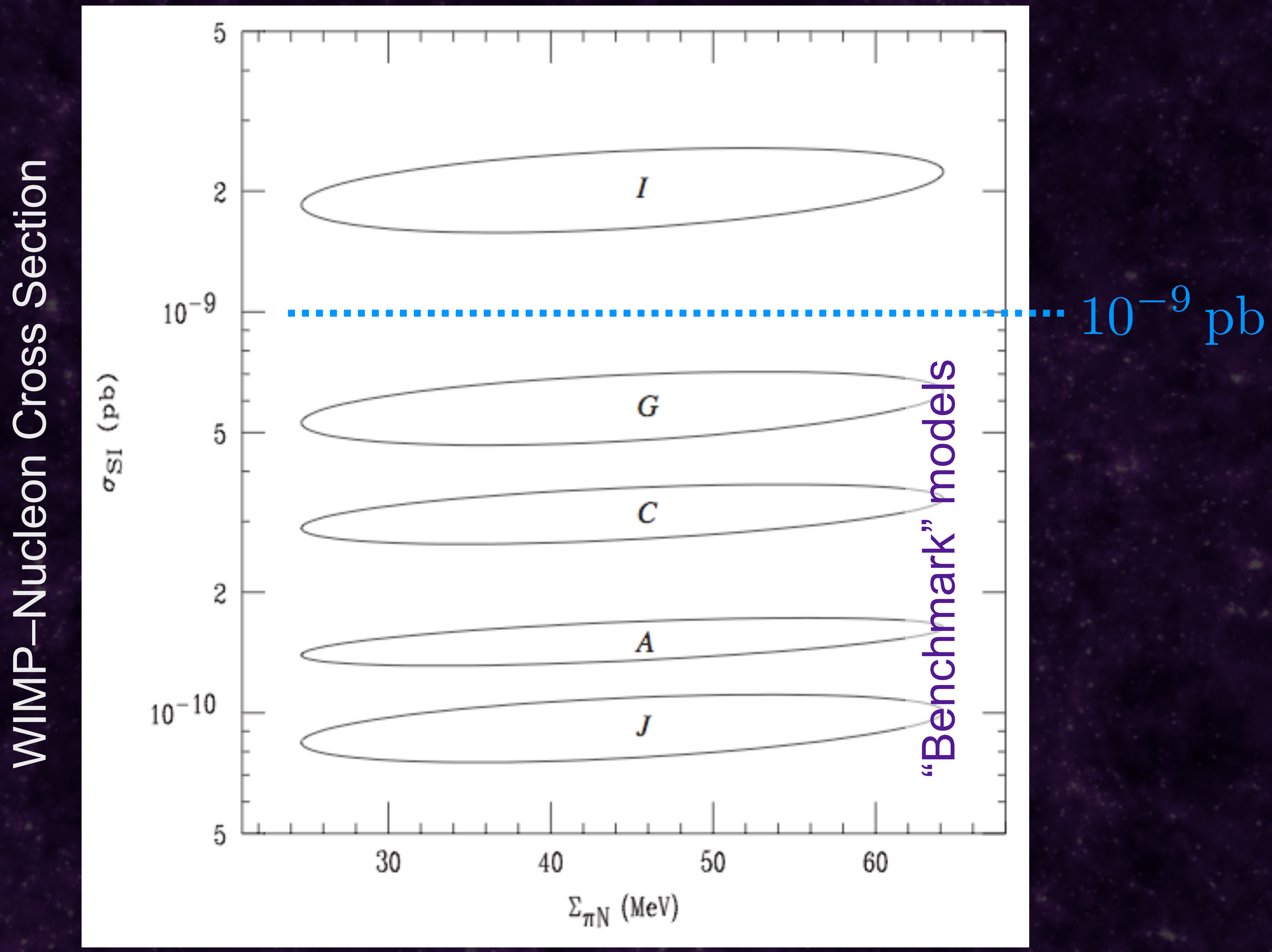


Giedt, Thomas & Young, PRL(2009)

- **Lattice QCD inputs dramatically improve cross section estimates**

Discrimination among candidate models

- Distinct cross sections for a variety of CMSSM (pre-LHC) “benchmark” models

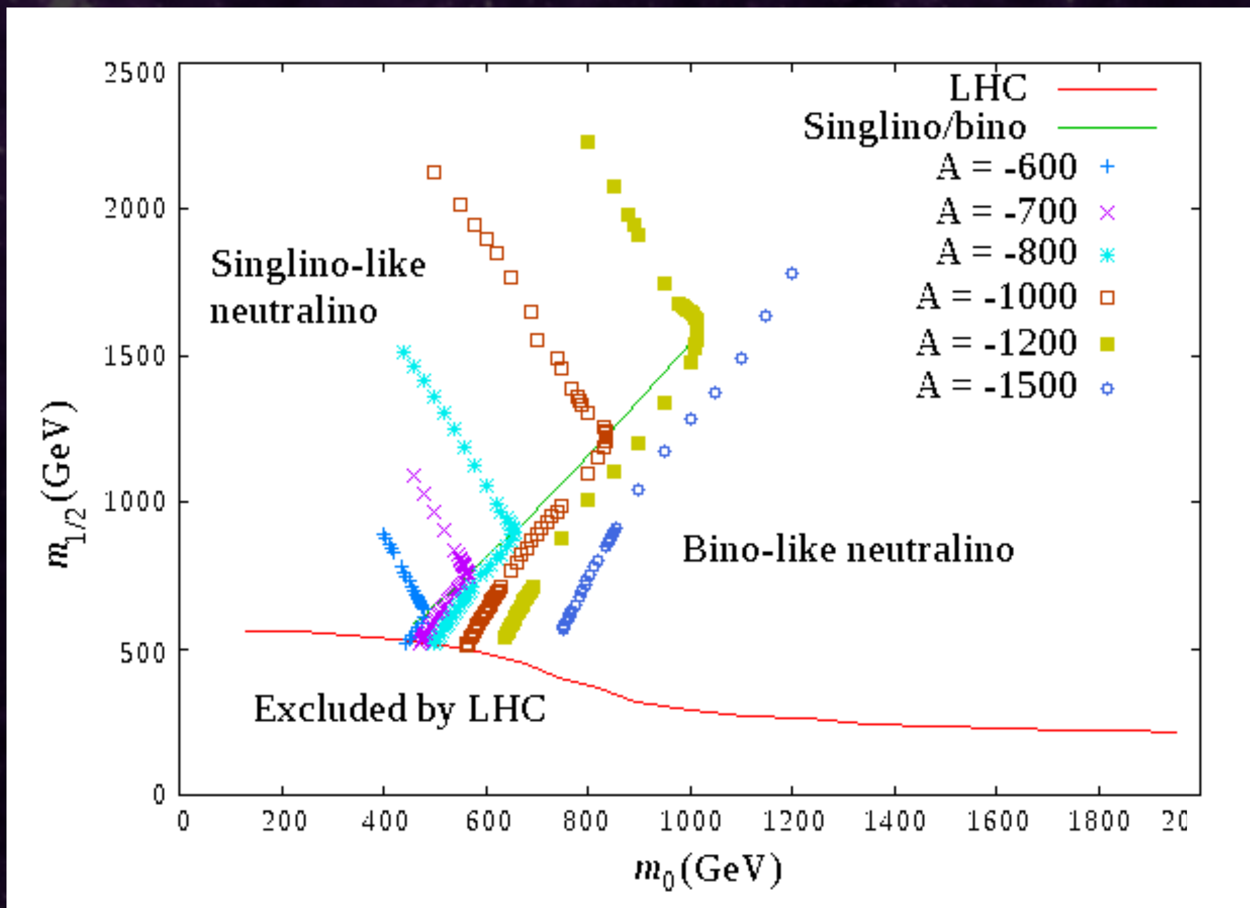


Giedt, Thomas & Young, PRL(2009)

Dark matter candidates in cNMSSM

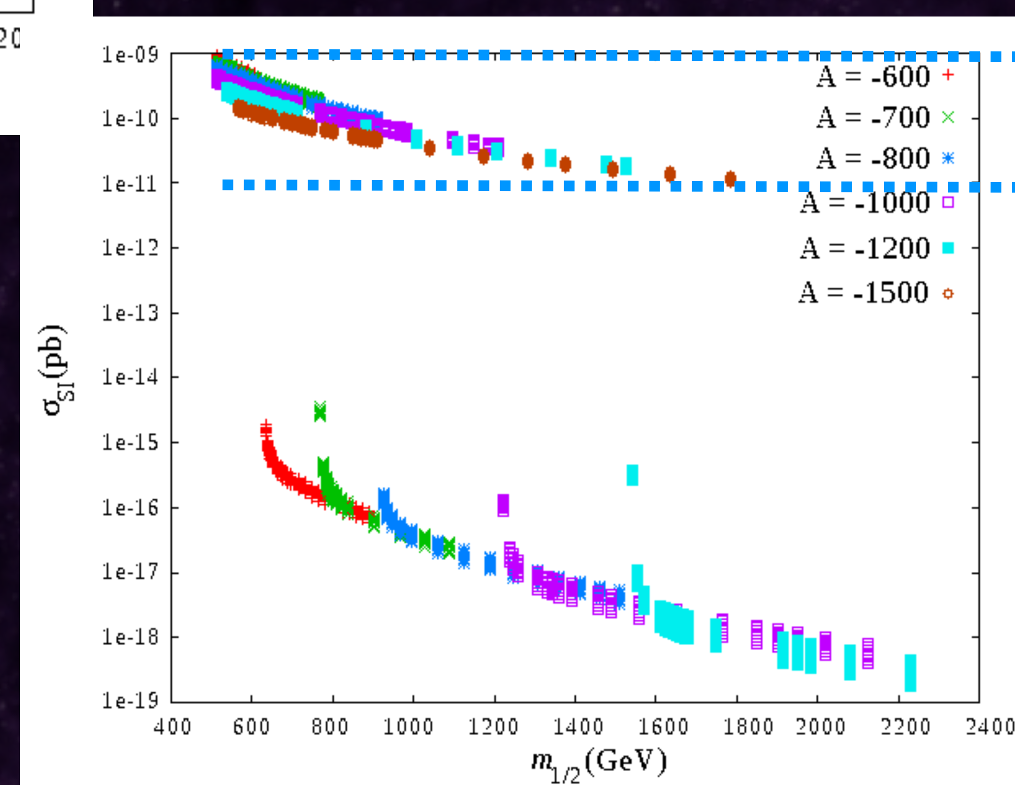
Underwood et al. 1203.1092

Universal gaugino mass



Universal scalar mass

SI cross section



10^{-9} pb

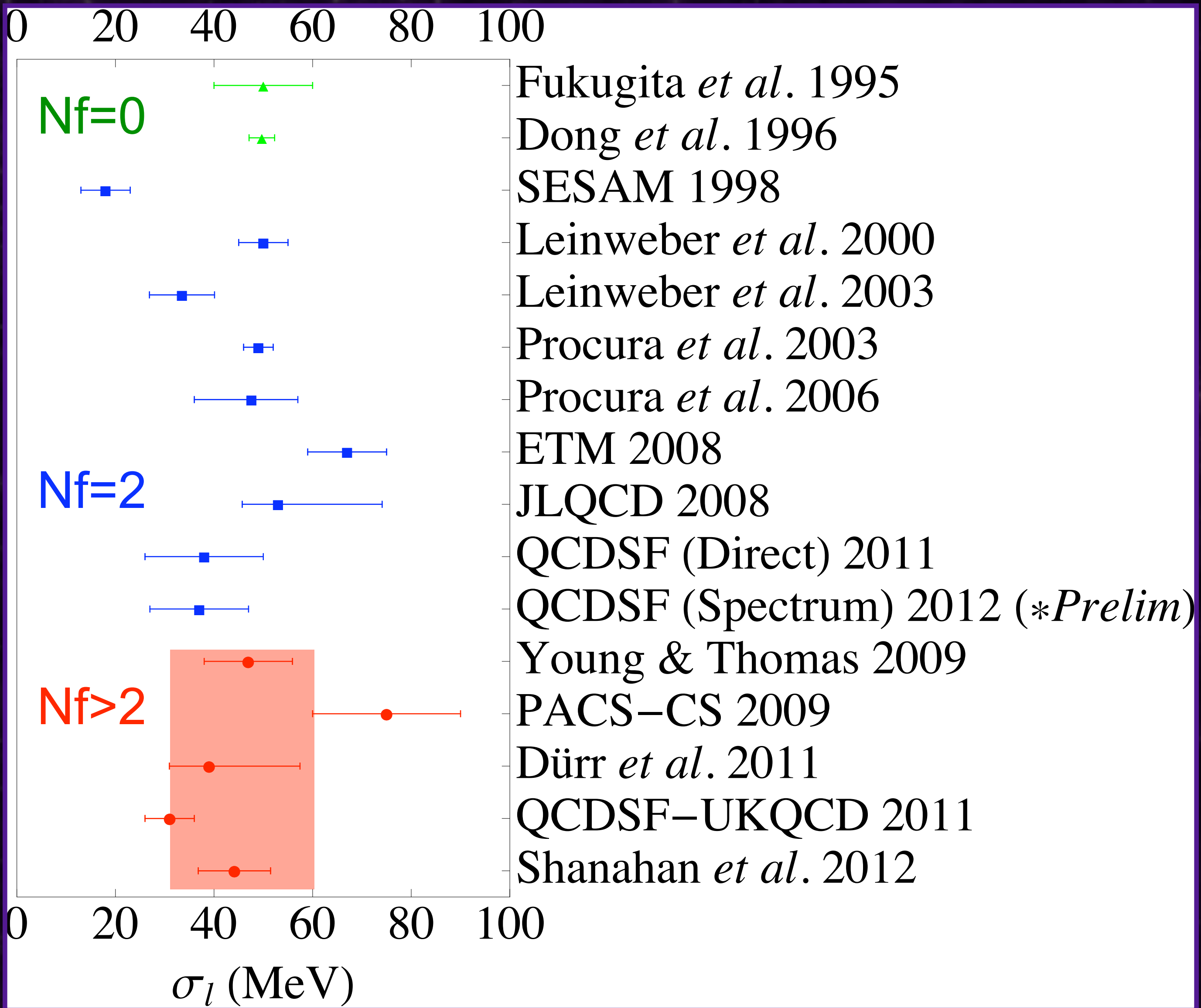
10^{-11} pb

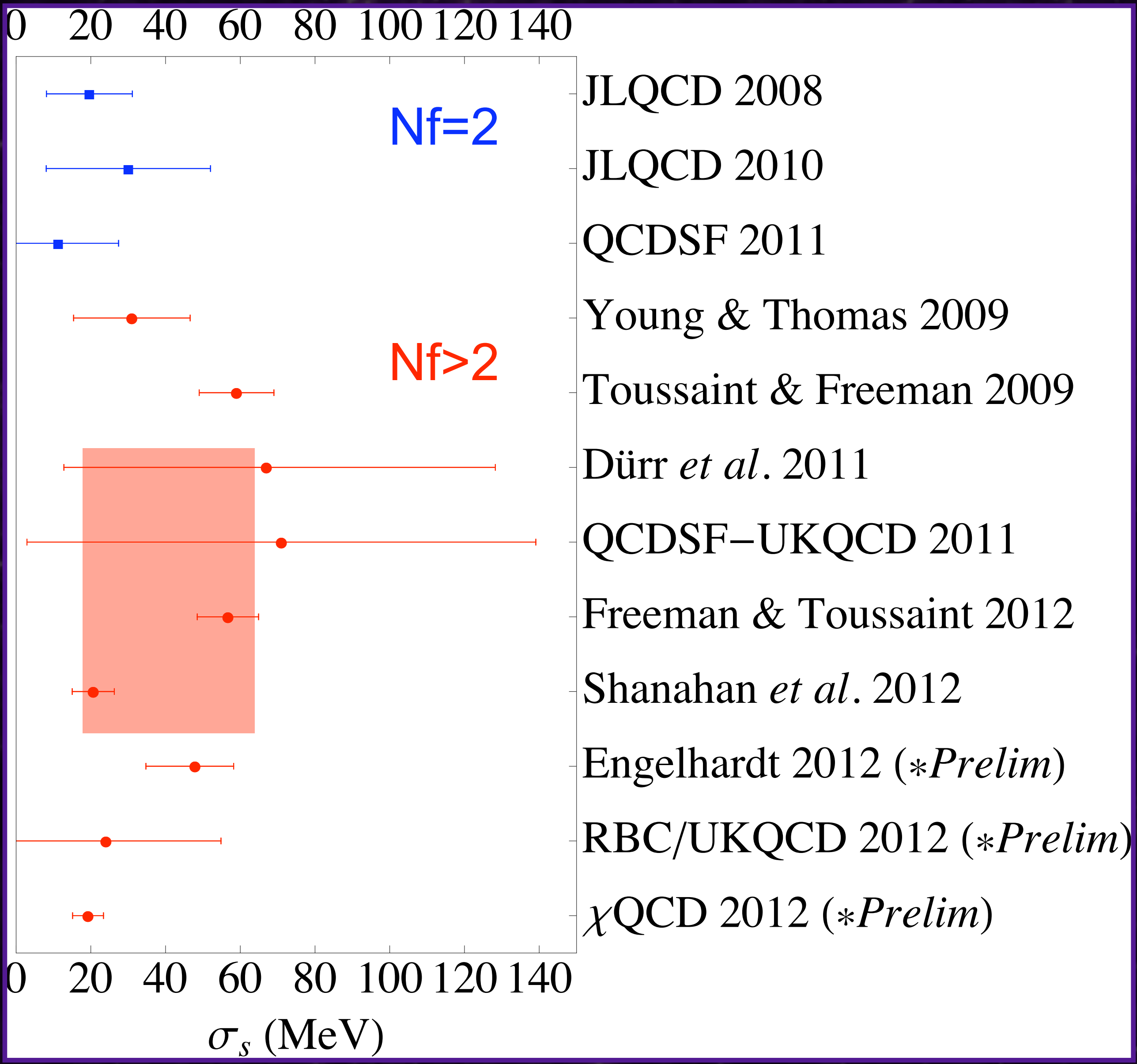
Universal gaugino mass

- Indicative parameter scans with latest WMAP, LHC & sigma terms

Comparison with early work

Sigma term estimates



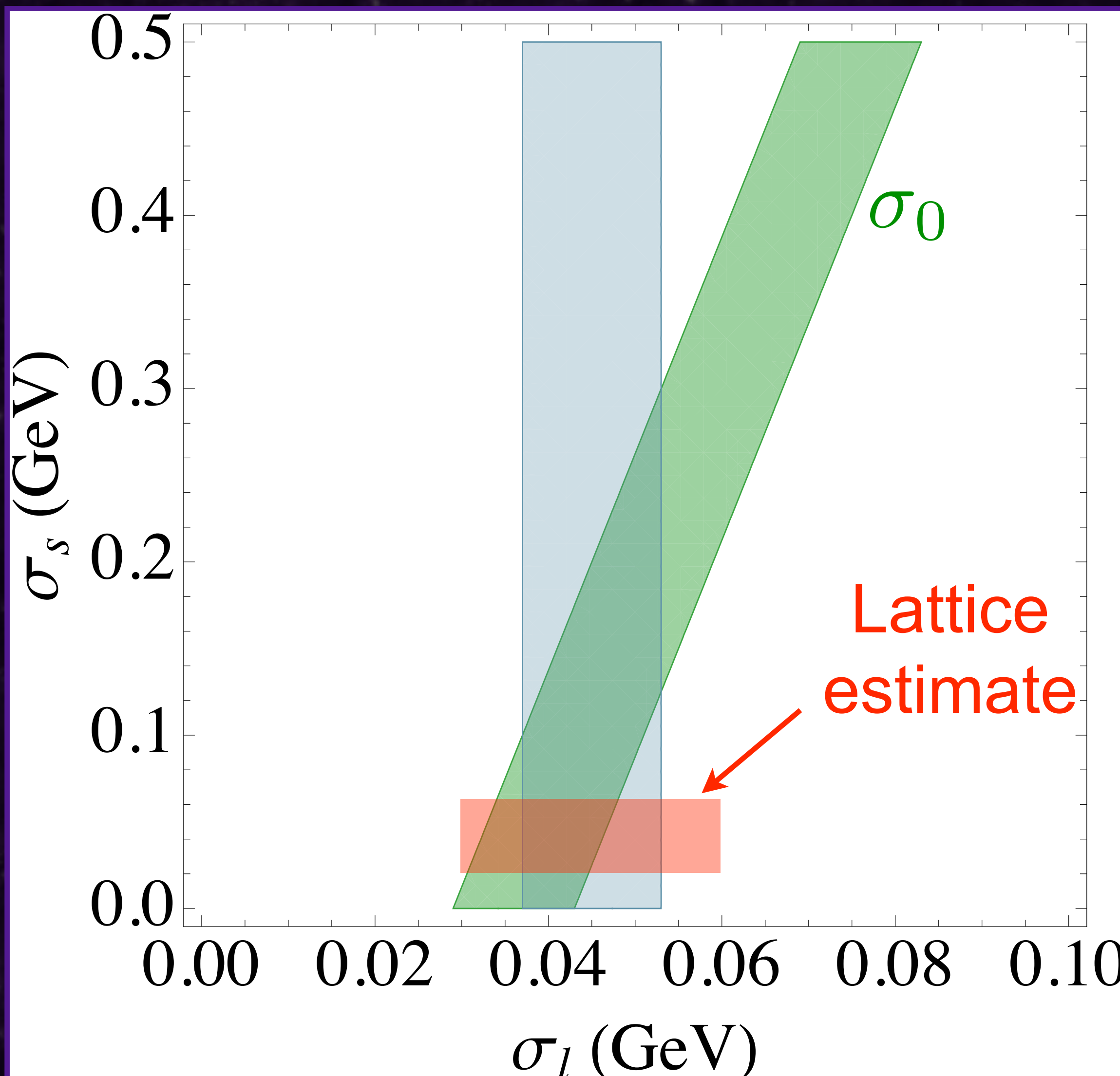


Conservative eye-ball best estimates

Comparison with early work

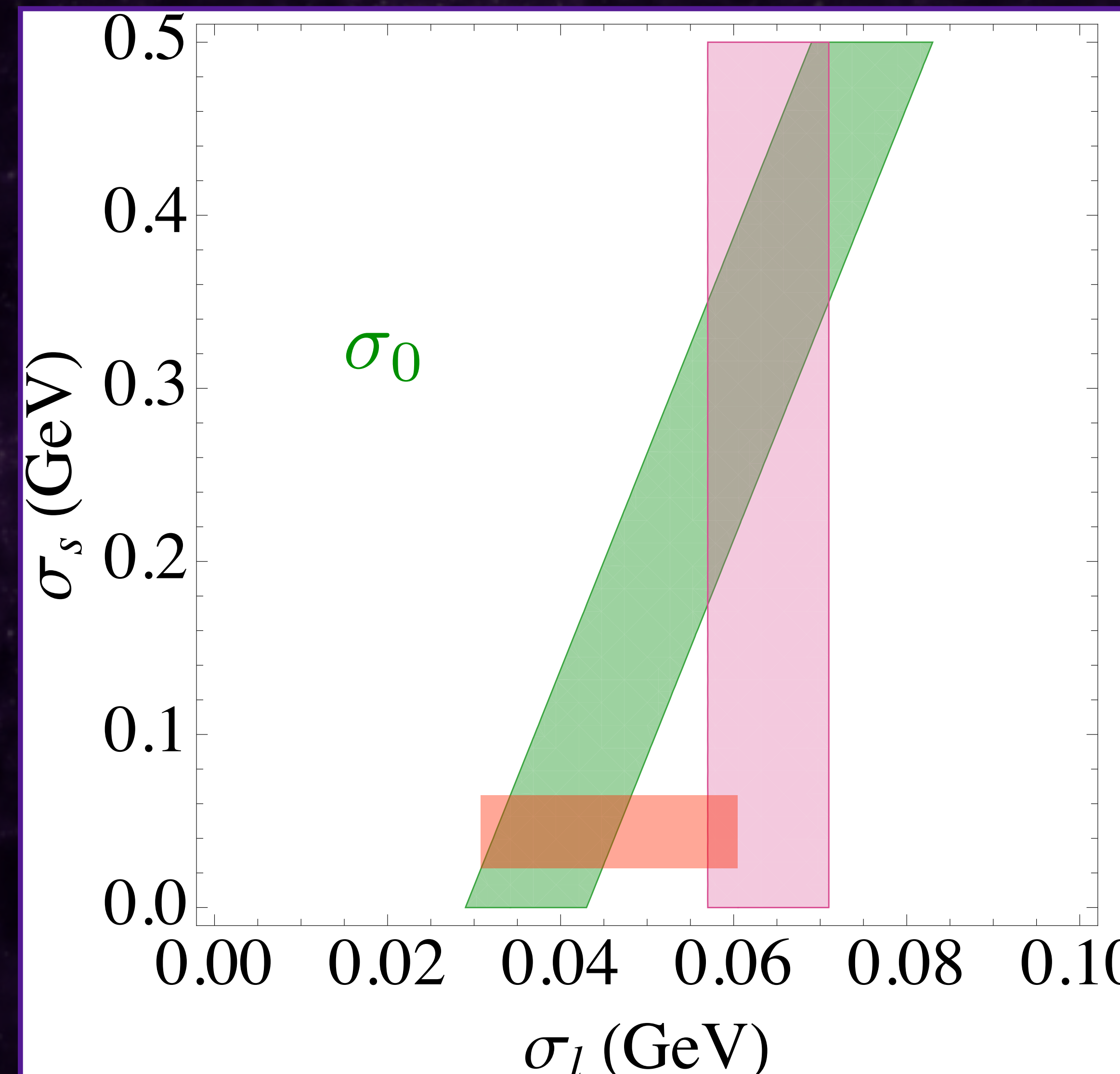
Gasser *et al.* (1991)

Strange Sigma Term



Light-quark Sigma Term

GWU (2002)



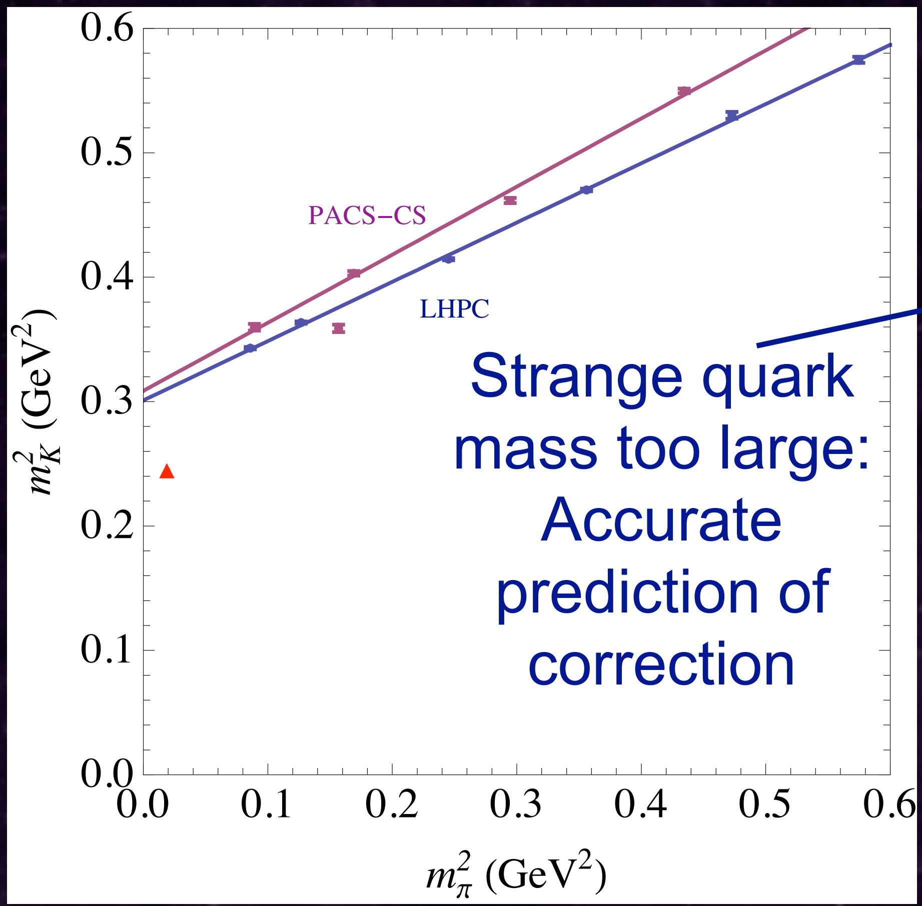
Summary

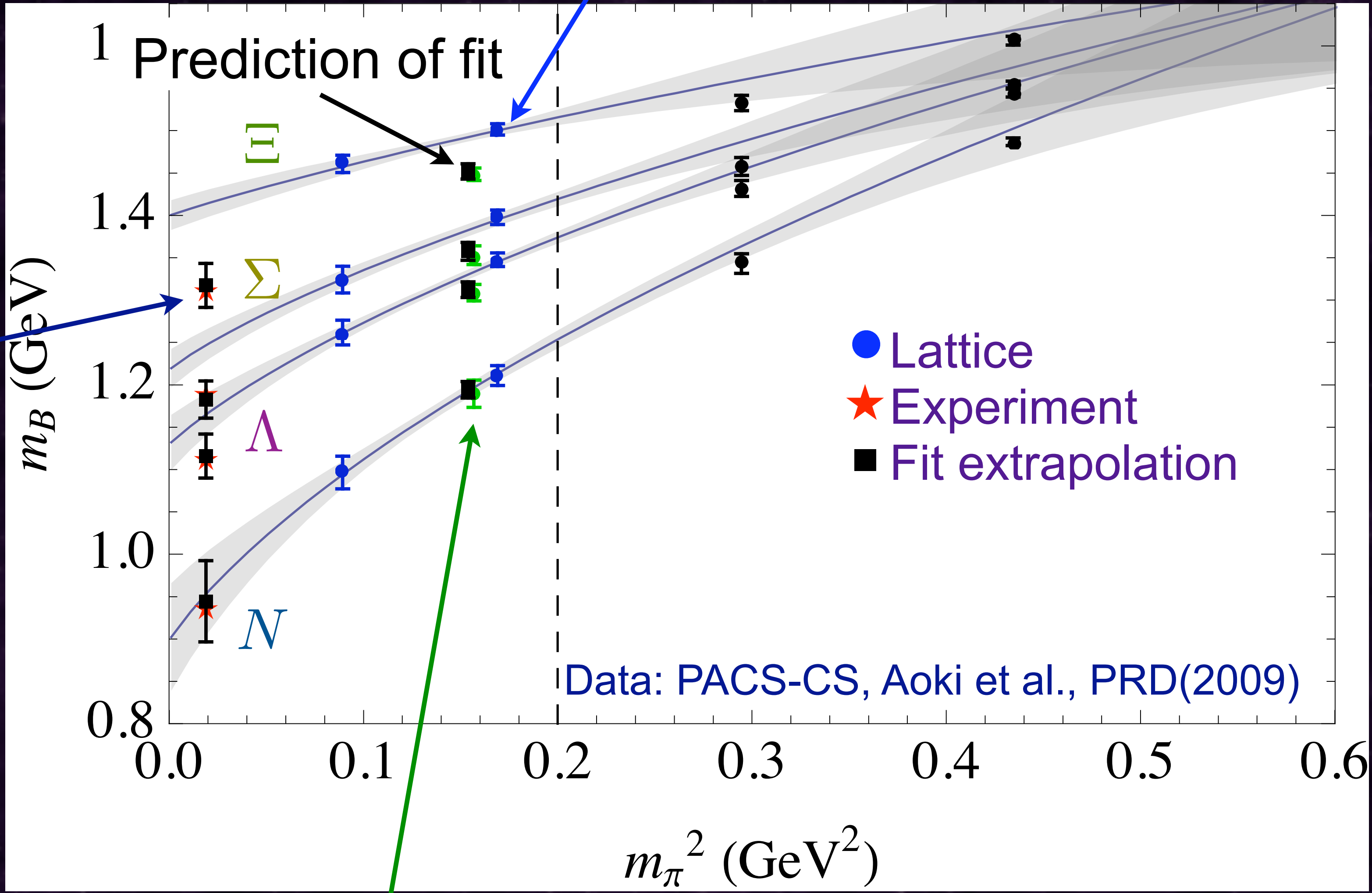
- Prospect of a near-term discovery of a quarter of the universe's energy budget
- Direct detection sensitivity largely dependent upon nucleon sigma terms
- Phenomenological extraction of sigma terms is outdated
  - **Lattice QCD is the superior tool**
  - [*we look forward to ironing out discrepancies in the near future*]
- Strangeness is much smaller than early estimates
- Current results are already able to offer significant discrimination power among candidate dark matter models

Modern lattice QCD: 2+1-flavour dynamical

- Can now independently study the dependence on the light- and strange-quark masses
  3-flavour chiral expansion: Young & Thomas PRD(2010)

Fit to just the blue points

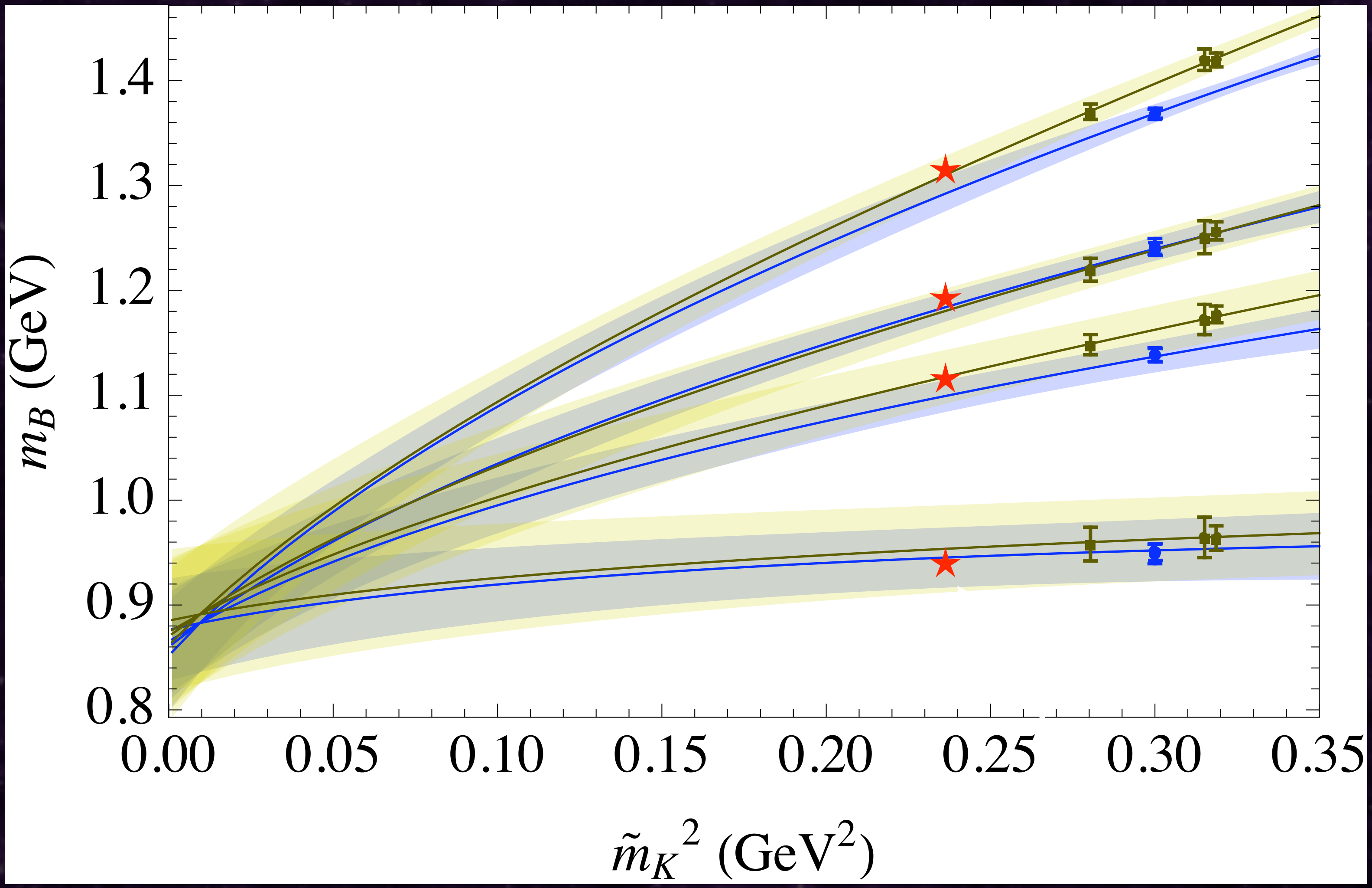




PACS-CS have an additional run with a different strange quark mass

Strange-quark mass dependence

- Extrapolate points to physical light-quark masses

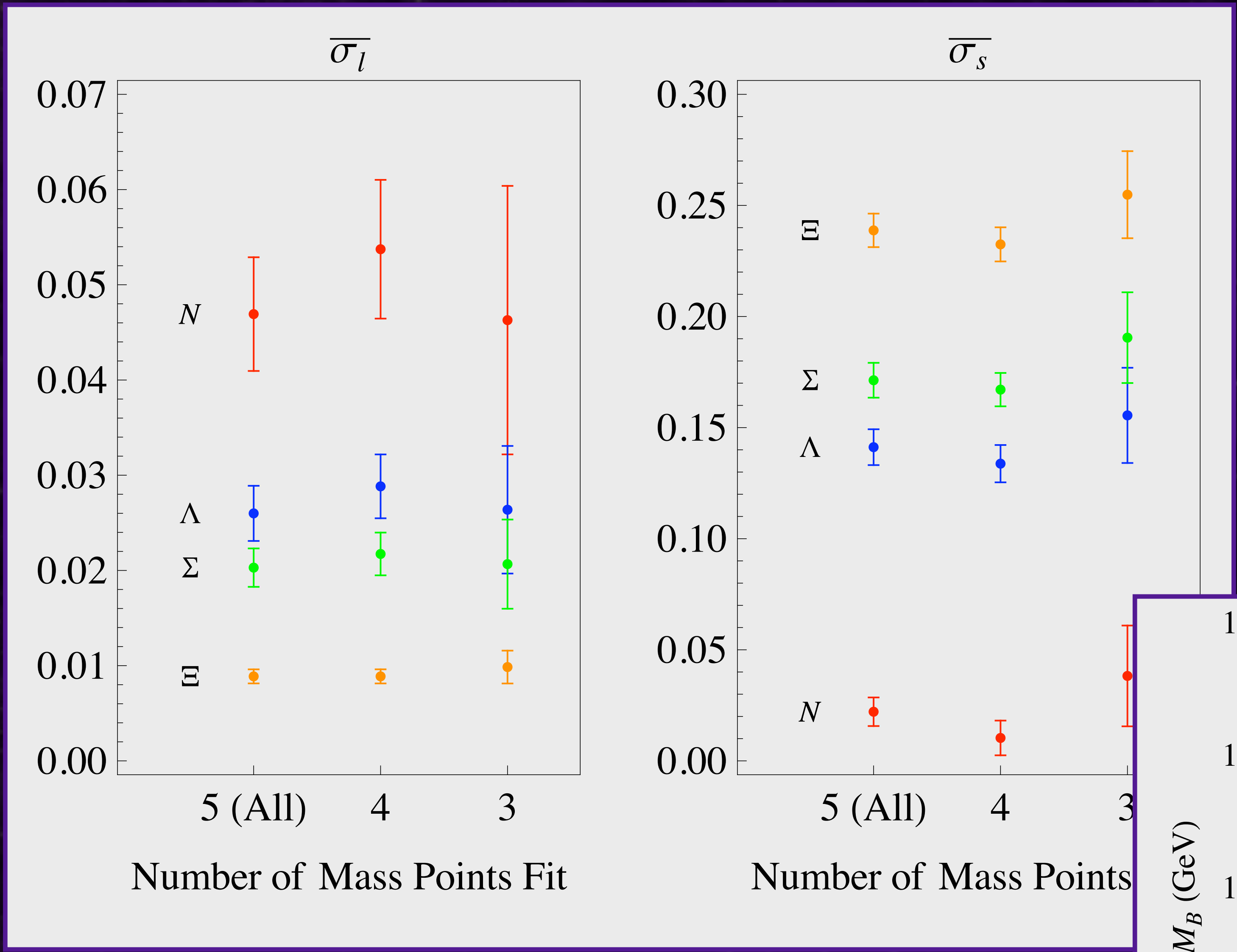


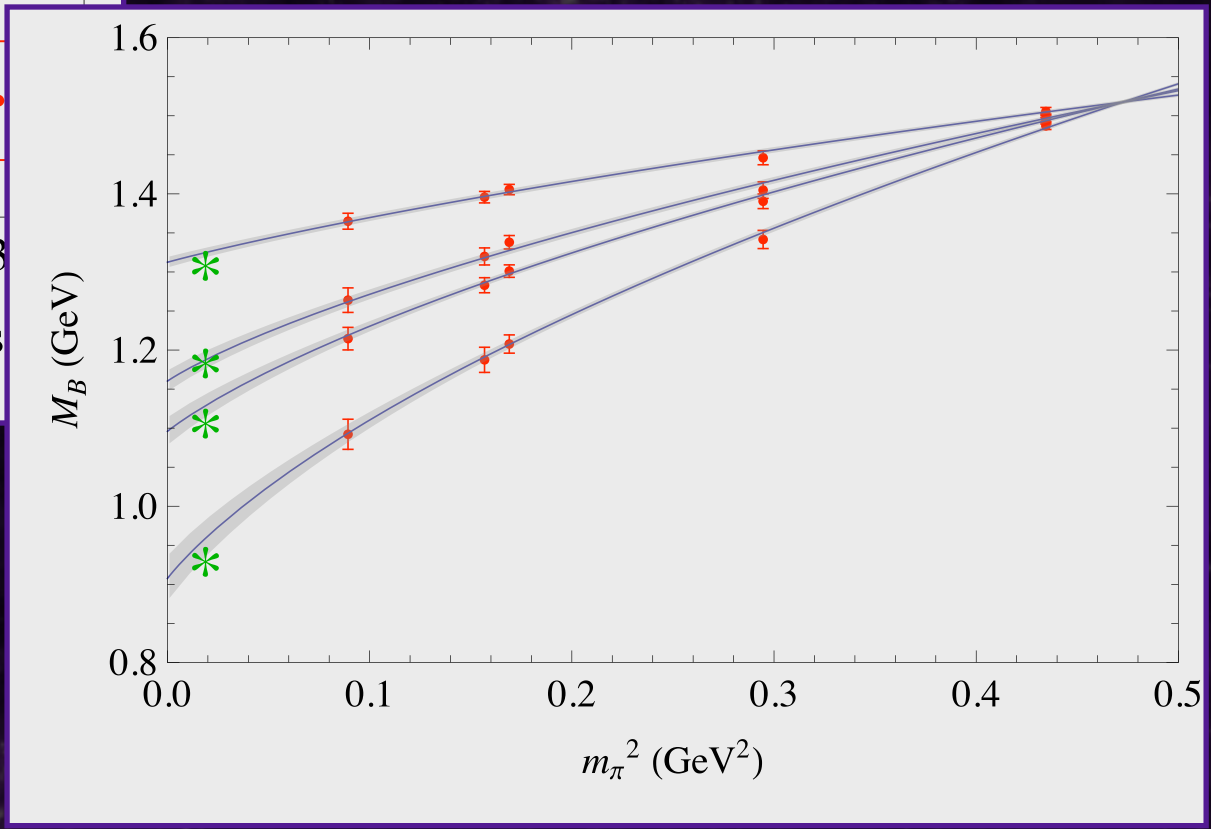
Strangeness sigma term is just local derivative at this point

Improving sigma terms

Shanahan et al. arXiv:1205.5365

- Fit full PACS-CS data set



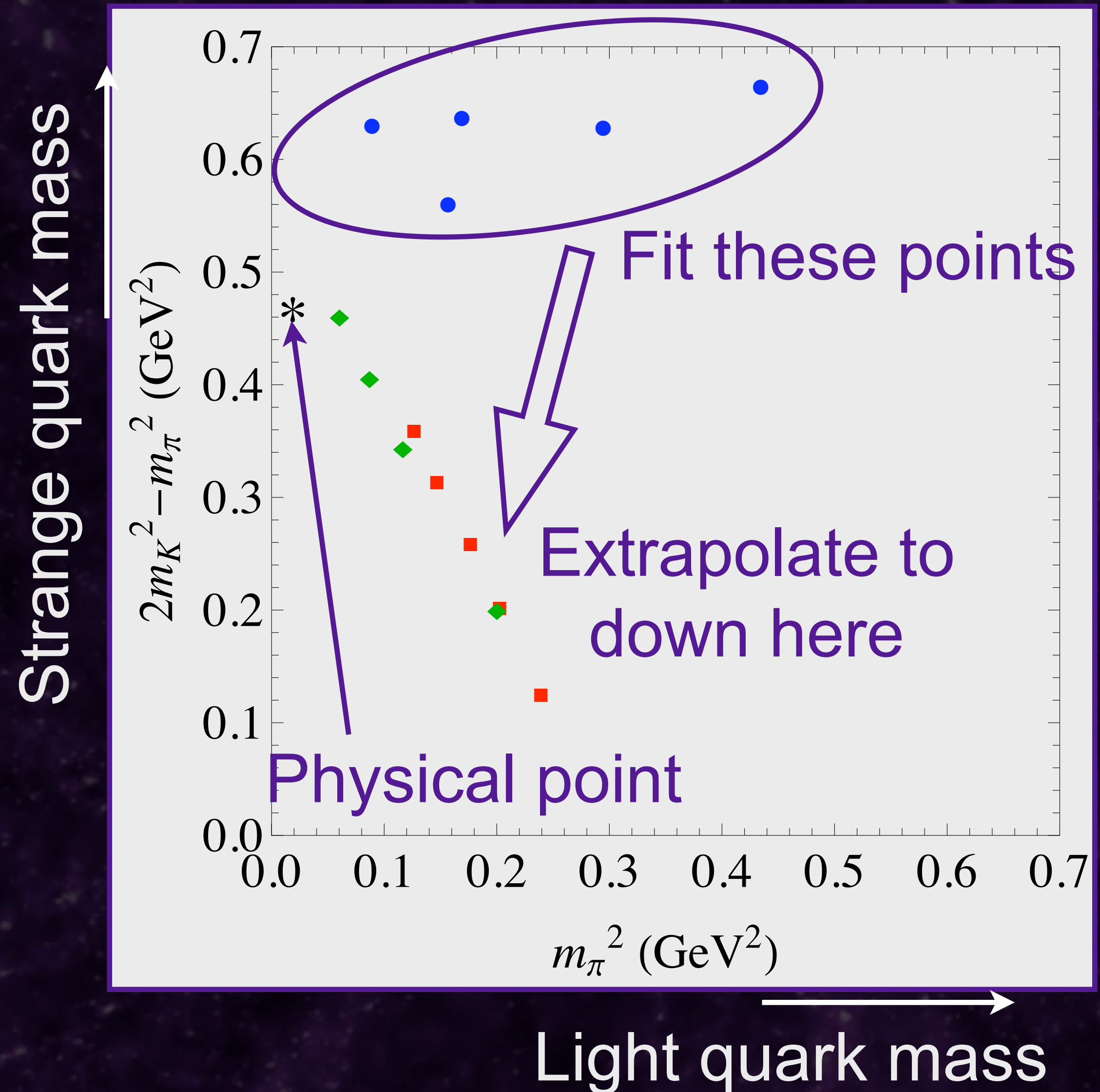


- Robust stability of fit results!

Improving sigma terms

Shanahan et al. arXiv:1205.5365

- Important new test: Extrapolate a LONG way in the strange quark mass
  NEW lattice results: QCDSF/UKQCD, Bietenholz et al. PRD(2011)



New strange sigma term determination: $\boxed{\sigma_s = 21 \pm 6\,\mathrm{MeV}}$

Improving sigma terms

Shanahan et al. arXiv:1205.5365

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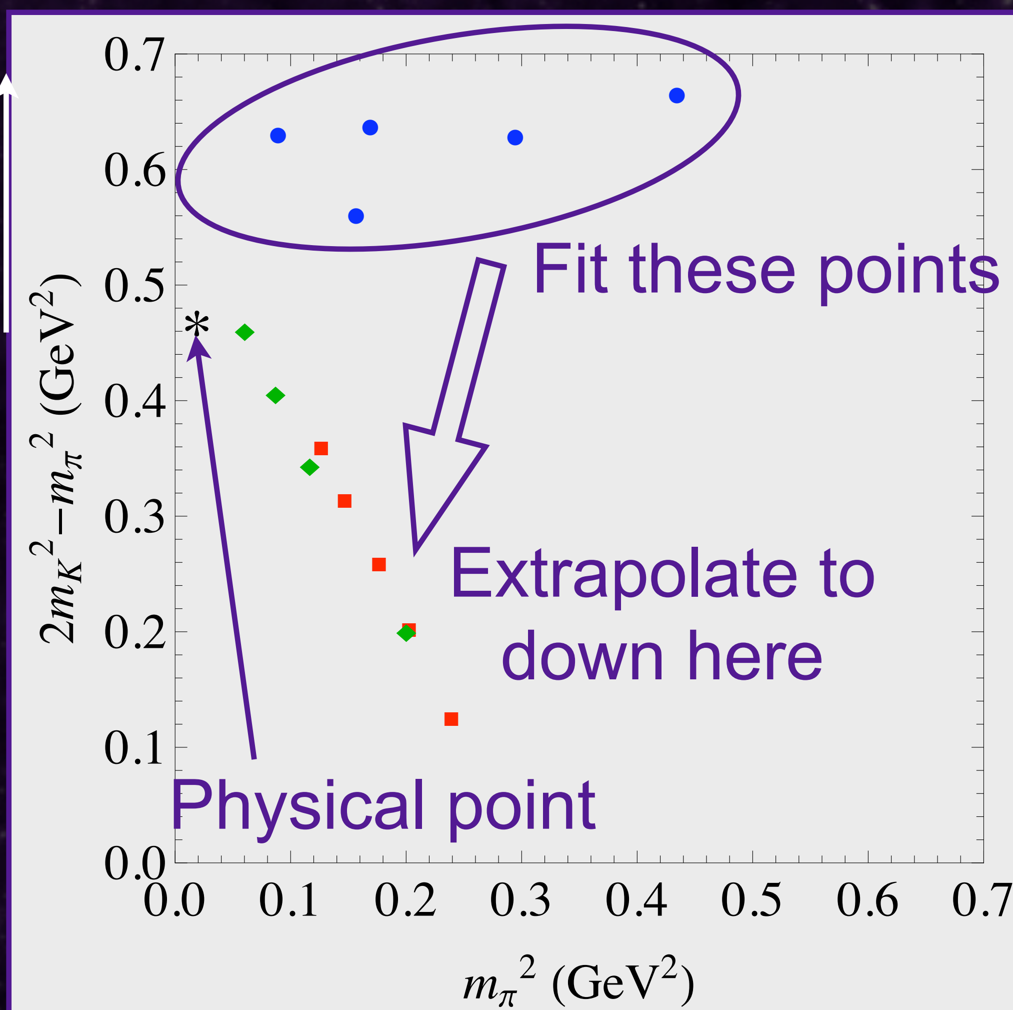
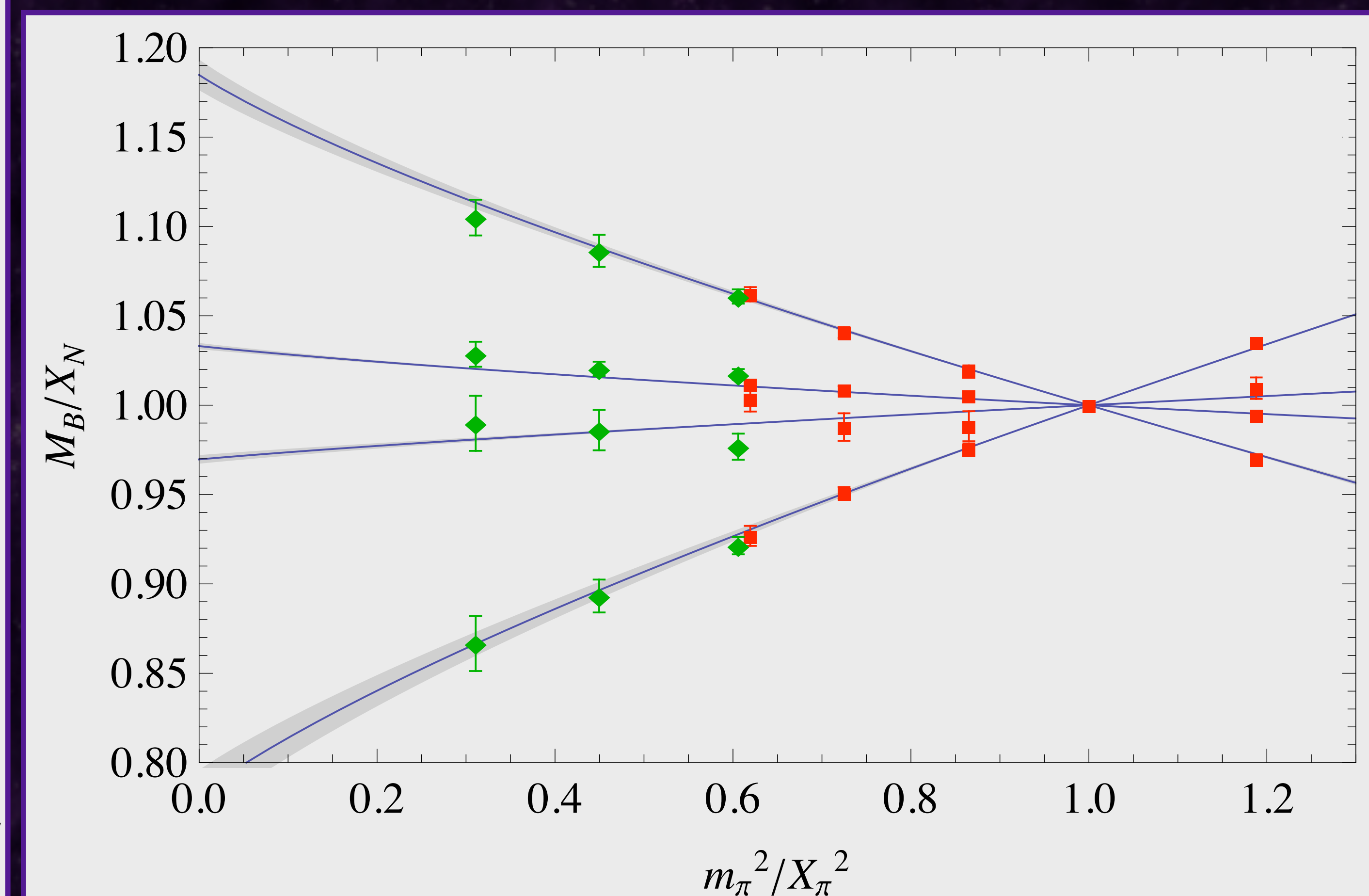
Strange quark mass





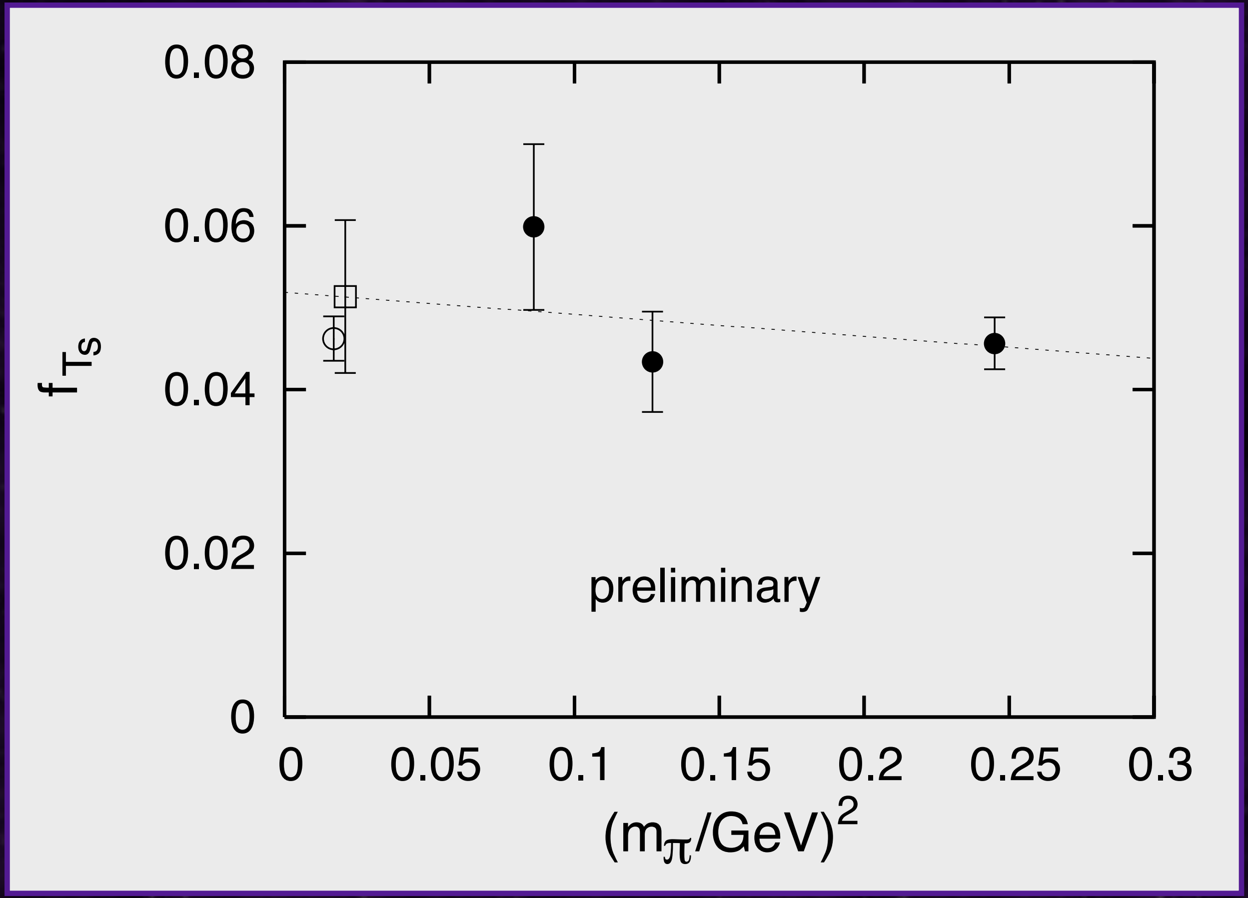
Light quark mass

New strange sigma term determination: $\sigma_s = 21 \pm 6\,\mathrm{MeV}$

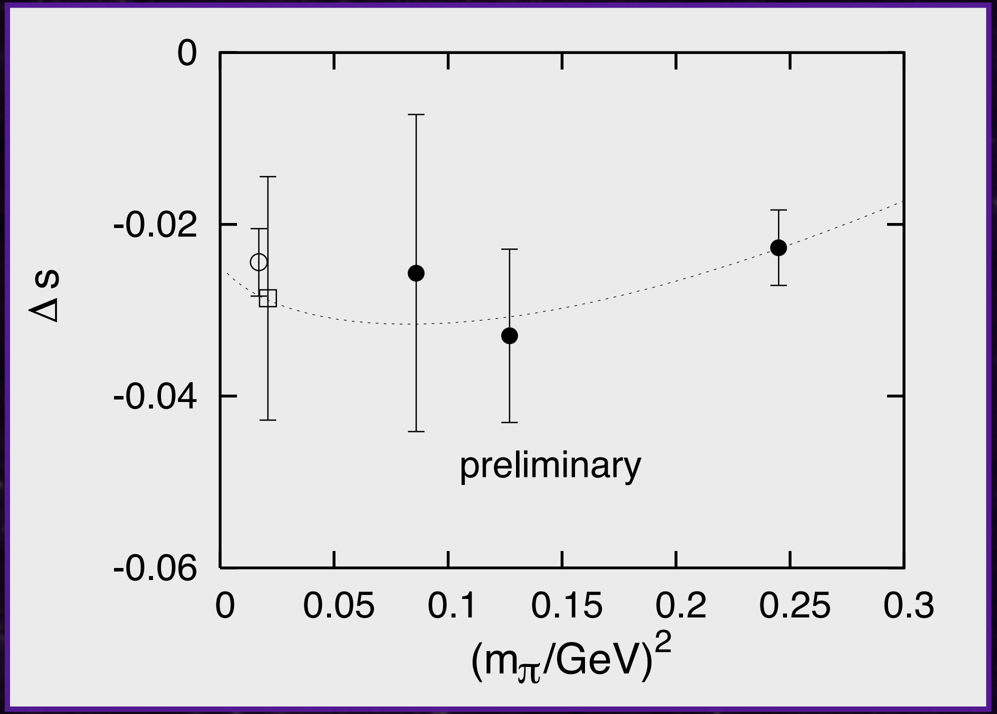
Engelhardt

- Hybrid action: DWF on Staggered (2+1): 20^3x64, a=0.124 fm
- Direct 3-point function

Strangeness scalar content



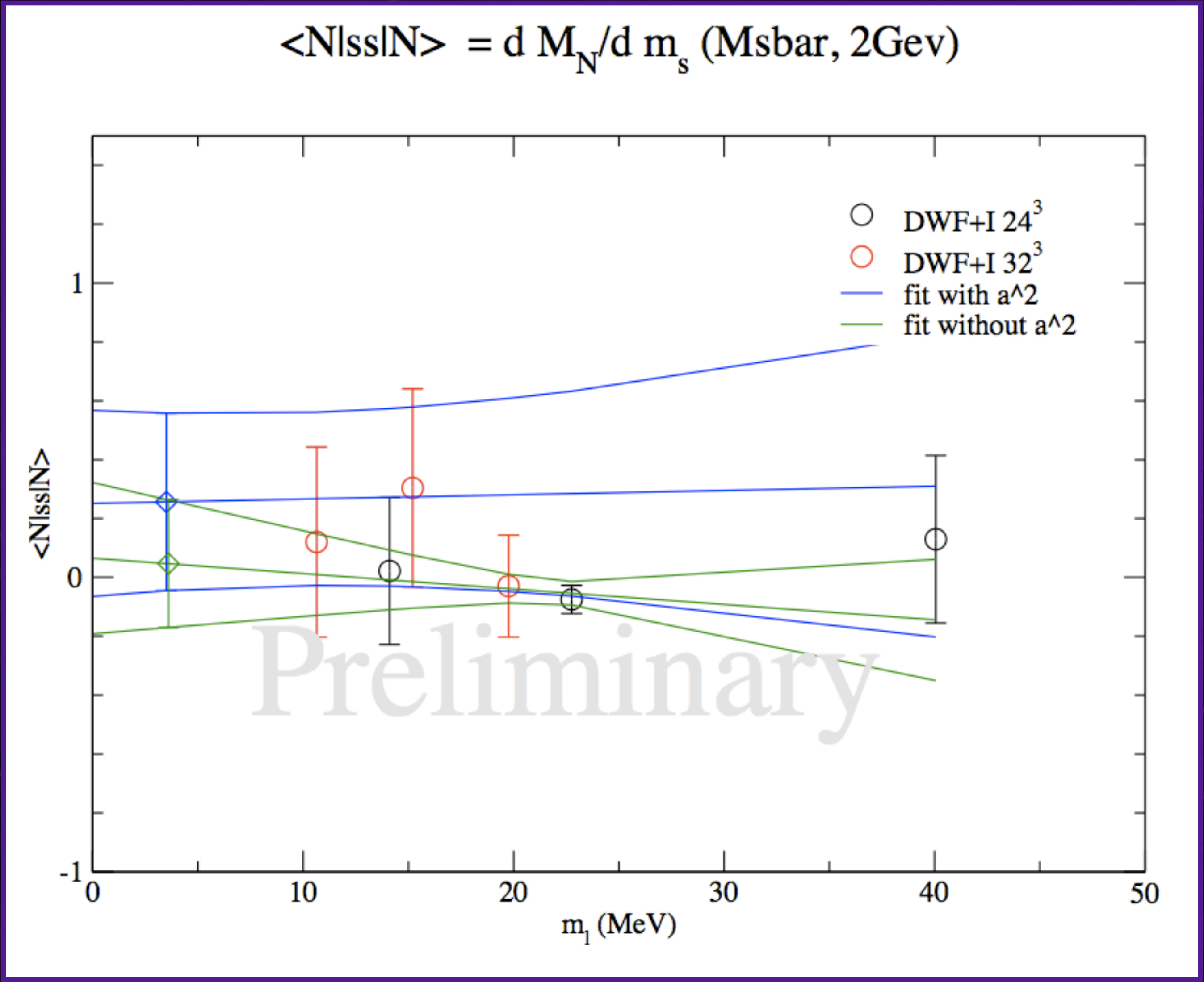
Strangeness spin content



RBC/UKQCD

C. Jung, Monday

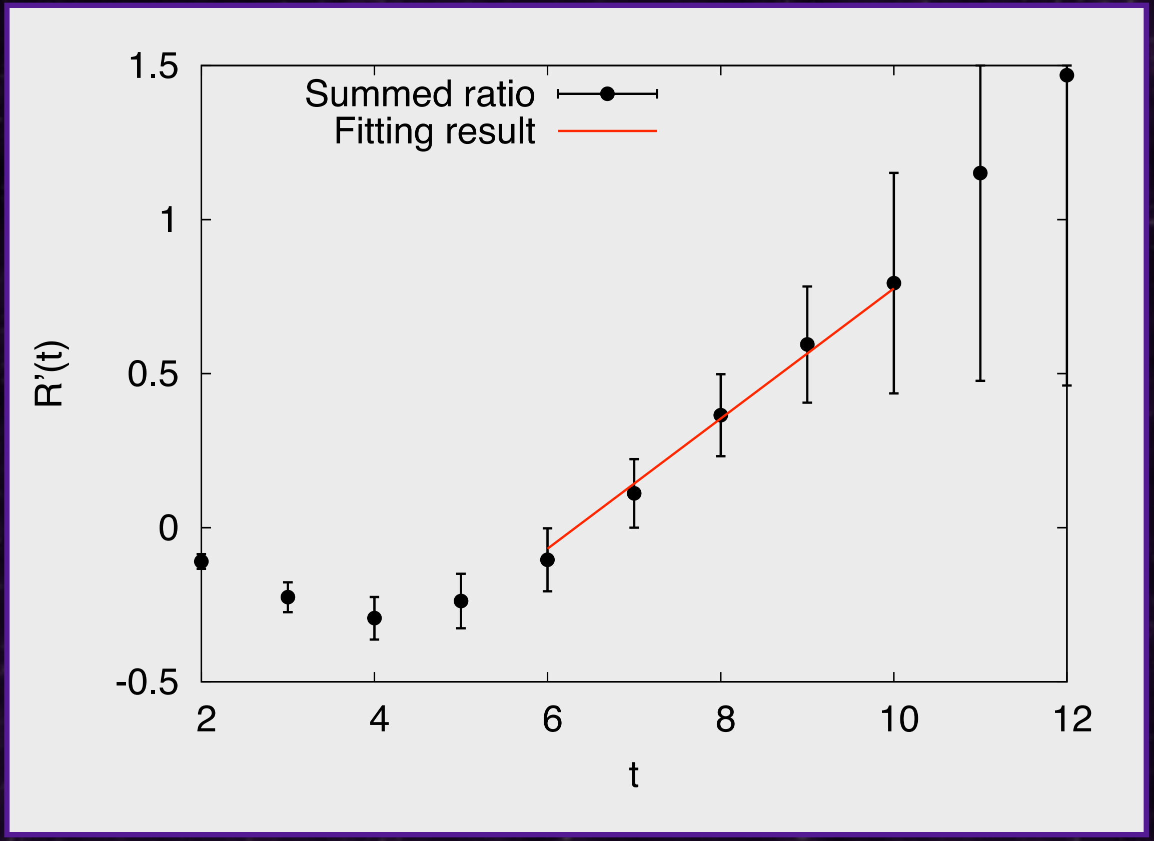
- 2+1 DWF+Iwasaki:
  - 32^3x64x16, a=0.087 fm
  - 24^3x64x16, a=0.114 fm
- Feynman-Hellman + reweighting

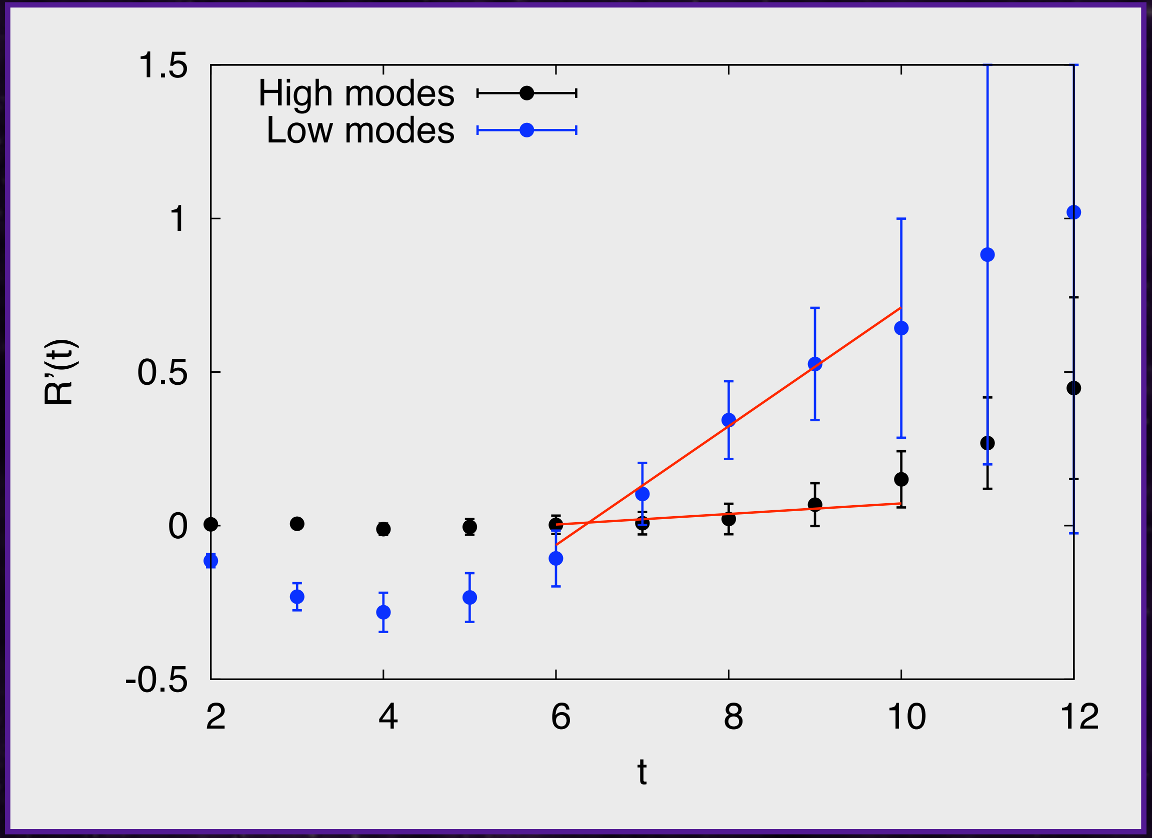


χQCD

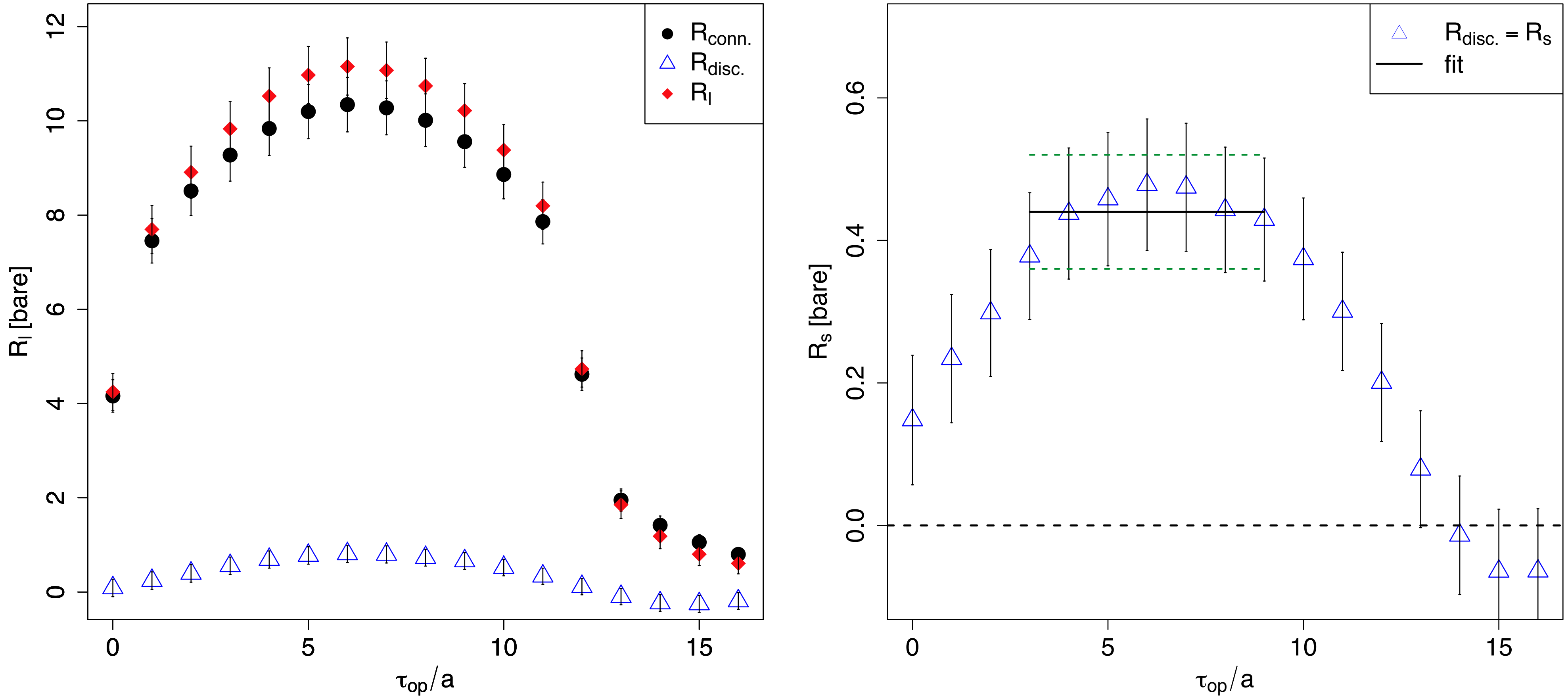
M. Gong, Monday; *see* 1204.0685

- Hybrid: Overlap on 2+1 DWF
  - 24^3x64x16, a=0.114 fm
- Direct: 3-pt function
  - “Low-mode substitution technique”





Direct calculation of σ-terms

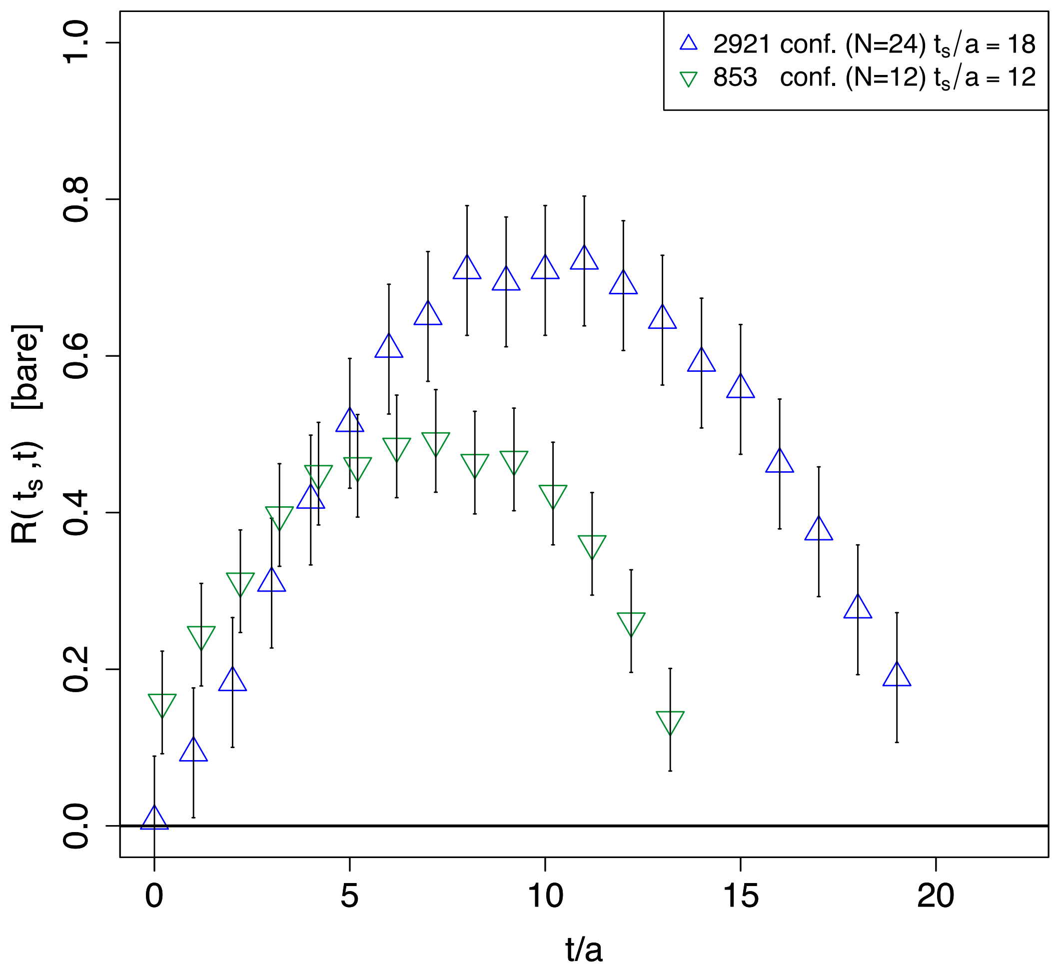


- Twisted mass fermions offers two main advantage :
  - $\rightarrow$ efficient noise reduction technique
  - $\rightarrow$ multiplicative renormalization
- Results on one twisted mass ensemble $m_\pi = 380$ MeV, $a \sim 0.078$ fm , L 2.5 fm, source-sink separation : $t_s \sim 1$ fm (mixed action setup for the strange quark)
- Statistically accurate results without eigenmode preconditionning

see [arXiv:1202.1480] for details

Systematic effects : Excited states contamination

- Dedicated study of excited states contamination of the sigma terms :
  - $\rightarrow$ large statistic : compare $t_s \sim 0.95$ fm and $t_s \sim 1.4$ fm
  - $\rightarrow$ disconnected contribution increase by a factor ~ 2 both in the light and strange sector
  - $\rightarrow$ Illustration in the strange sector



Systematic effects : Excited states contamination

- Fixed pion mass and fixed lattice spacing computation of the y_N parameter :
  - $\rightarrow$ Cancelation of the contribution of excited states
  - $\rightarrow$ grey band indicates the result obtained for $t_s \sim 0.95$ fm
  - $\rightarrow$ $y_N \sim 0.10(2)$ in agreement with other lattice group
  - $\rightarrow$ Important input for phenomenology but still requires further study e.g at lighter pion masses