Strange quarks and the detection of dark matter

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International School of Nuclear Physics
33rd Course
From Quarks and Gluons to Hadrons and Nuclei
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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

University *of* Adelaide

The direct search for dark matter

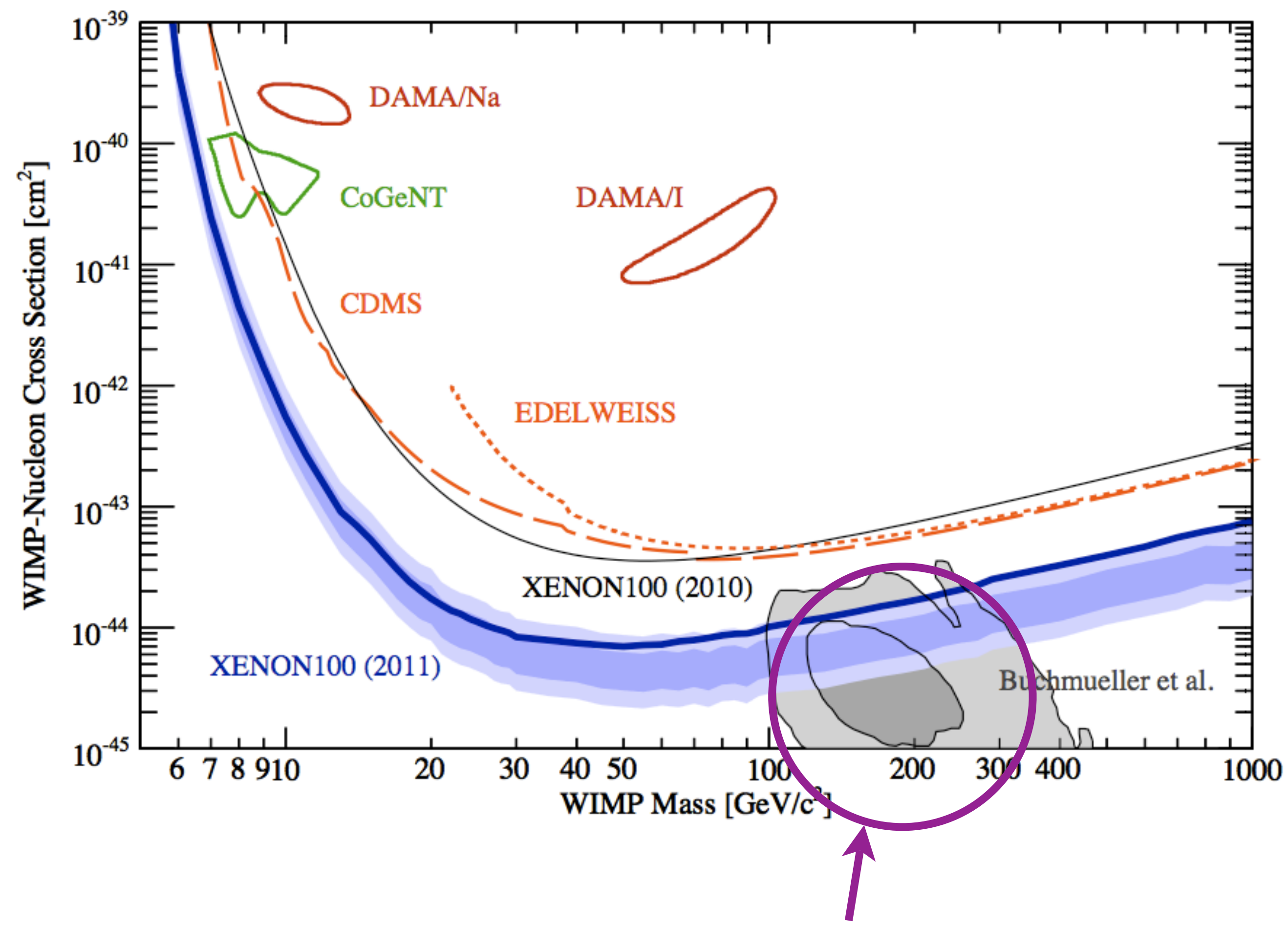
- "Dark Matter Results from 100 Live Days of XENON100 Data" arXiv:1104.2549

The New York Times

Particle Hunt Nets Almost Nothing; the Hunters Are Almost Thrilled

April 13, 2011

Ozier Muhammad/The New York Times



CMSSM

Today... convince you this CMSSM blob is too "high"

CMSSM: Constrained Minimal Supersymmetric Standard Model

WIMP-Nucleon cross section

- The Constrained MSSM (CMSSM):

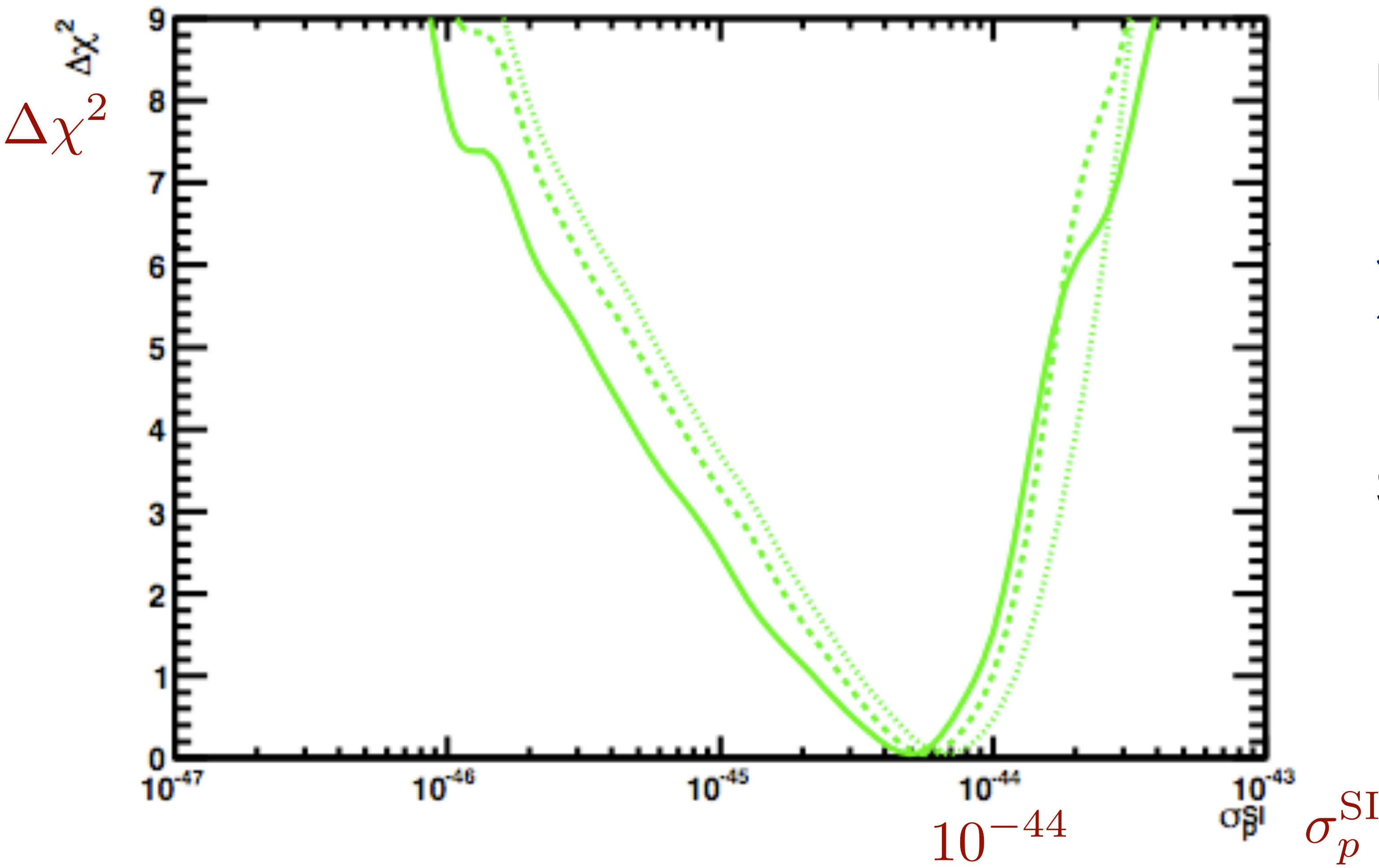
Eur. Phys. J. C (2011) 71: 1634
DOI 10.1140/epjc/s10052-011-1634-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Implications of initial LHC searches for supersymmetry

O. Buchmueller[1], R. Cavanaugh[2,3], D. Colling[1], A. De Roeck[4,5], M.J. Dolan[6], J.R. Ellis[4,7], H. Flächer[8], S. Heinemeyer[9], G. Isidori[10], K. Olive[11,a], S. Rogerson[1], F. Ronga[12], G. Weiglein[13]



Using: $\Sigma_{\pi N} = 64\,\mathrm{MeV}$

$\Sigma_{\pi N} = 45\,\mathrm{MeV}$
⇒ reduction in cross section by factor ~3 to 4

Why are we so sensitive to $\Sigma_{\pi N}$?

Spin-independent neutralino cross section

see eg. Ellis, Olive & Savage, PRD77:065026(2008)

- Scalar neutralino–quark contact interaction

$$\mathcal{L}_{SI} = \sum_i \alpha_{3i} \bar{\chi}\chi \bar{q}_i q_i$$

α_{3i} depend on model (eg. CMSSM) evolved down to low-energy scale

- Cross section $\sigma^p_{SI} \propto |f_p|^2$

$$\frac{f_p}{M_p} = \sum_{q=u,d,s} \bar{\sigma}_{pq} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f^p_{TG} \sum_{q=c,b,t} \frac{\alpha_{3q}}{m_q}$$

Nucleon scalar quark content $\bar{\sigma}_{pq} = \dfrac{m_q}{M_N} \langle N | \bar{q} q | N \rangle$

$$\Sigma_{\pi N} = M_N(\bar{\sigma}_{pu} + \bar{\sigma}_{pd}) = \begin{cases} 45 \pm 8\,\mathrm{MeV} & \text{Gasser et al. (1991)} \\ 64 \pm 7\,\mathrm{MeV} & \text{GWU (2002)} \end{cases}$$

$$f^p_{TG} = 1 - \sum_{q=u,d,s} \bar{\sigma}_{pq}$$

Trace anomaly:
Shifman, Vainstein & Zakharov, PLB(1978)

The missing ingredient

- Strangeness scalar content $\bar{\sigma}_{ps} = m_s \langle N|\bar{s}s|N\rangle / M_N$
- Commonly used quantity

$$\sigma_0 \equiv \hat{m}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

- some algebra

$$\Rightarrow \bar{\sigma}_{ps} = \frac{m_s}{2\hat{m}} \left(\Sigma_{\pi N} - \sigma_0\right) / M_N$$

- Use Feynman-Hellmann relation $m_q \langle N|\bar{q}q|N\rangle = m_q \frac{\partial M_N}{\partial m_q}$
- First-order breaking in SU(3) baryon masses

$$\sigma_0 \simeq \hat{m} \frac{m_\Xi + m_\Sigma - 2m_N}{m_s - \hat{m}} = 26\,\mathrm{MeV}$$

- With higher-order terms in chiral expansion

$$\sigma_0 \simeq 36 \pm 7\,\mathrm{MeV} \qquad \Rightarrow \sigma_{ps} = \begin{cases} 110 \pm 130\,\mathrm{MeV} & [\Sigma_{\pi N}(1)] \\ 350 \pm 120\,\mathrm{MeV} & [\Sigma_{\pi N}(2)] \end{cases}$$

Lattice QCD can probe scalar matrix elements

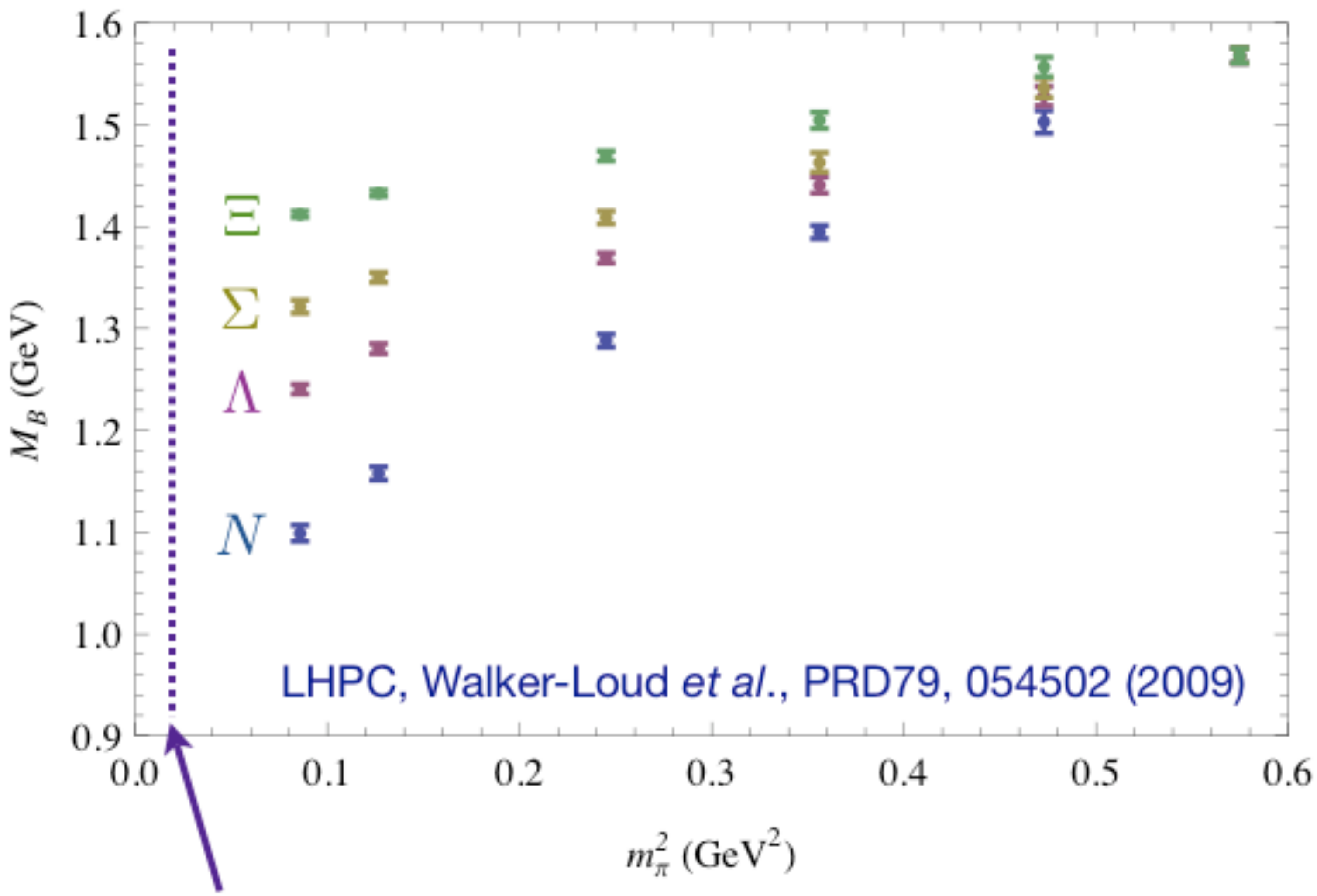
- Can directly probe matrix elements in 3-pt correlation functions
  - See talks:
    - *Alexandrou, Bali*
- *Here*: Parameterise quark mass dependence and use Feyman–Hellmann relation

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

2+1-flavour lattice results

Dynamical : $m_u = m_d$ & m_s

Octet baryon masses



Physical pion mass

- State-of-the-art lattice results approaching the physical domain

Chiral EFT: SU(3) expansion to $m_q^{3/2}$

- Chiral EFT is low-energy effective theory of QCD
- Only way to perform chiral extrapolation consistent with the chiral symmetries and symmetry breaking of QCD

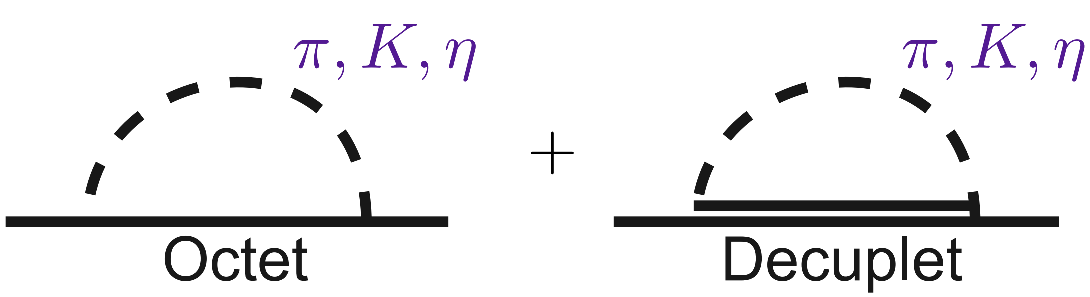
Octet baryon masses

4 free parameters (at this order)

— 1 Overall mass scale M_0

— 3 Linear perturbation in quark masses $\alpha_M, \beta_M, \sigma_M$

Chiral nonanalytic contributions come with *model-independent* coefficients



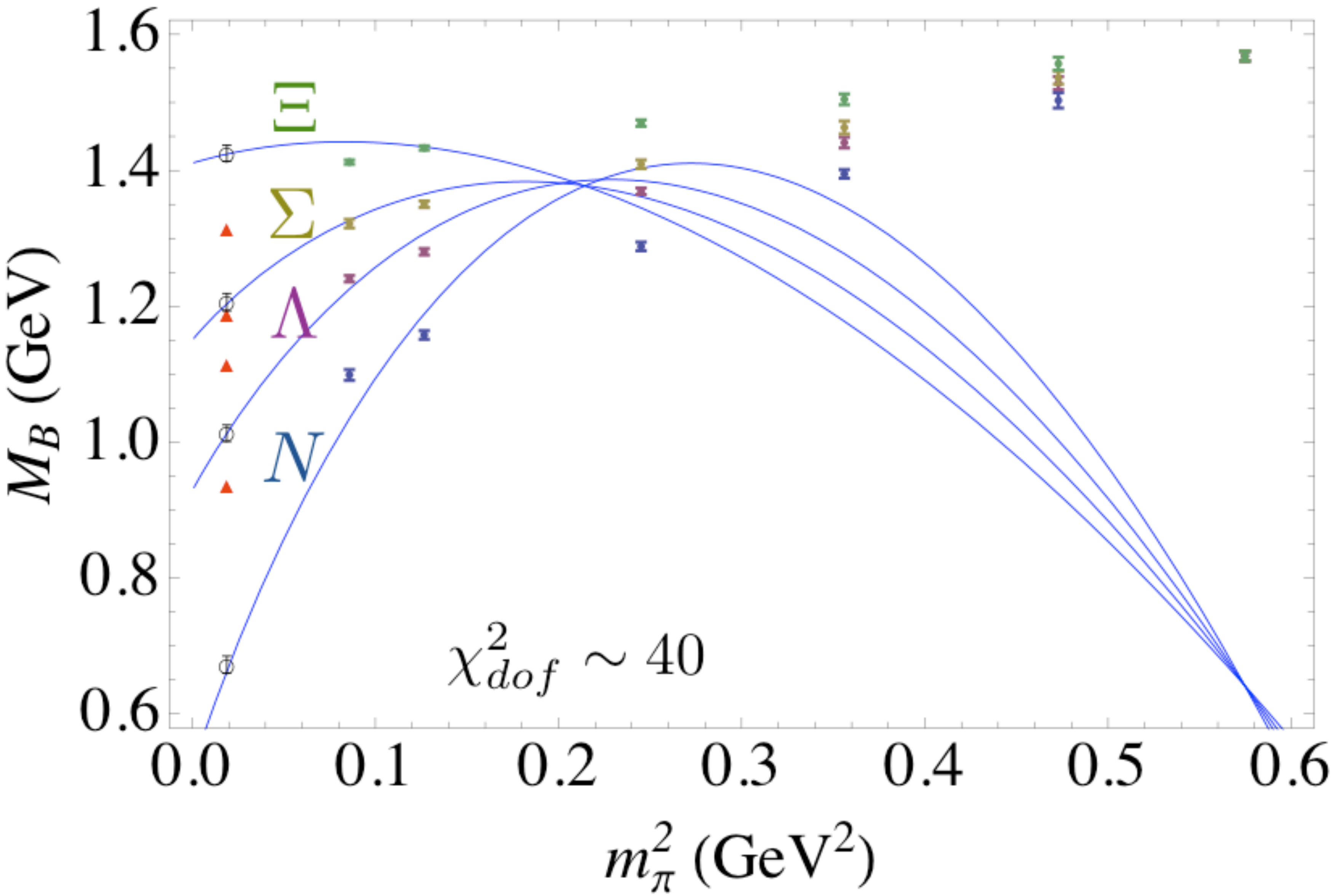
Inputs: $g_A = 1.267, D \simeq \frac{3}{5} g_A, F \simeq \frac{2}{5} g_A, \mathcal{C} \simeq -2D, f_\pi \simeq 0.087\,\mathrm{GeV}$

$\pm 15\%$ $\pm 15\%$ $\pm 15\%$ $\pm 5\%$

Corrections to the linear expansion

$$\frac{2}{\pi}\int dk \frac{k^4}{k^2+m^2} \xrightarrow{R} m^3$$

- Poorly converging



Finite Range Regularization (FRR)

- Suppress ultraviolet contributions to loop integrals from scale beyond the validity of the EFT
- Maintain renormalization such that scale dependence is removed to working order

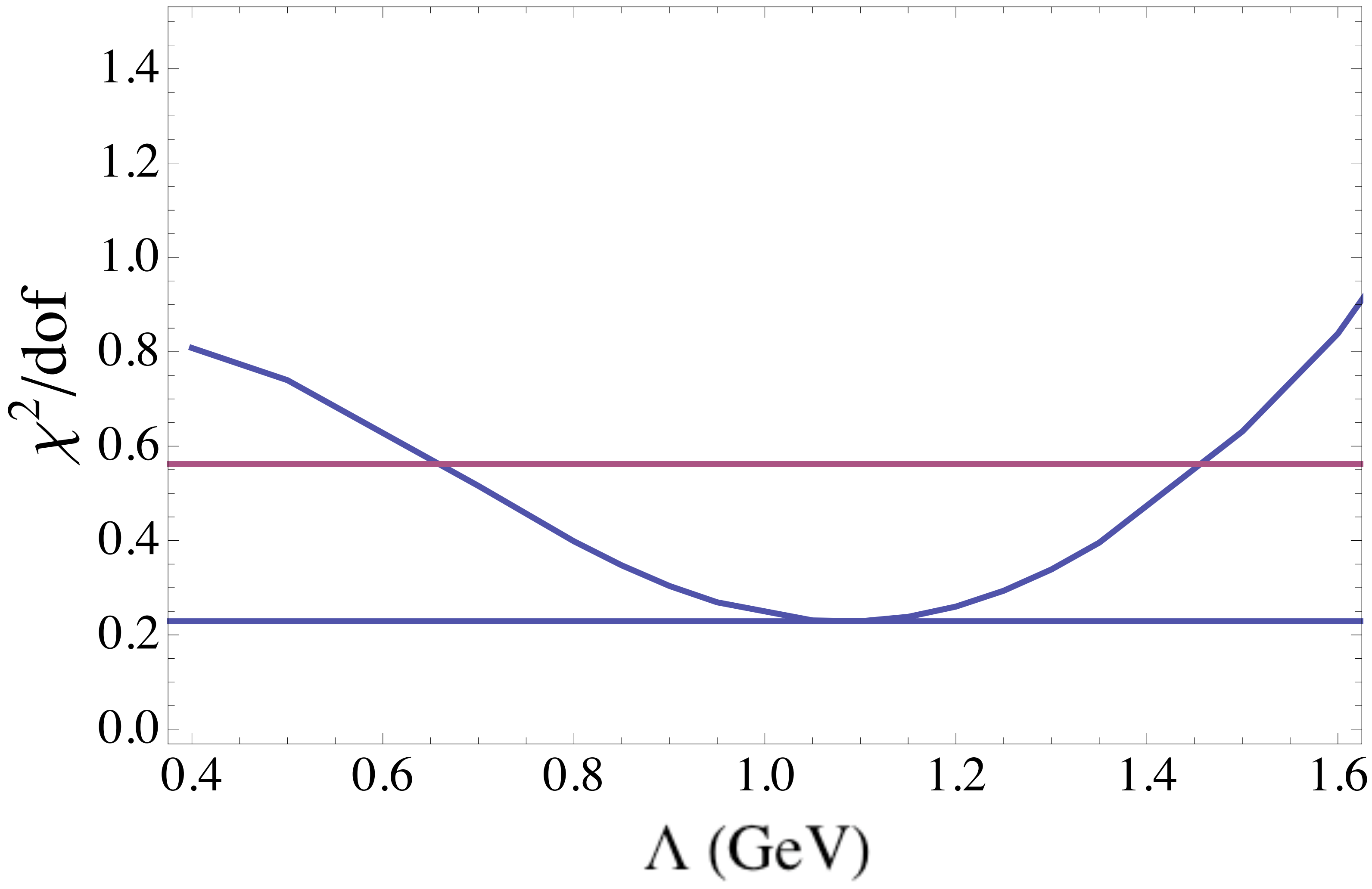
Text book
$$\frac{2}{\pi}\int dk \frac{k^4}{k^2+m^2} \xrightarrow{R} m^3$$

FRR
$$\frac{2}{\pi}\int dk \frac{k^4}{k^2+m^2}\theta(\Lambda^2-k^2) \xrightarrow{R} m^3\,\frac{2}{\pi}\arctan\frac{\Lambda}{m}$$

Donoghue, Holstein & Borasoy, PRD59,036002(1999)
Leinweber *et al.*, PRD61,074502(2000)
Young, Leinweber & Thomas, PPNP 50,399(2003)
Leinweber, Thomas & Young, PRL92,242002(2004)

Lattice results "choose" regularisation scale

- Lattice results prefer a regularisation scale of order 1 GeV (Dipole)



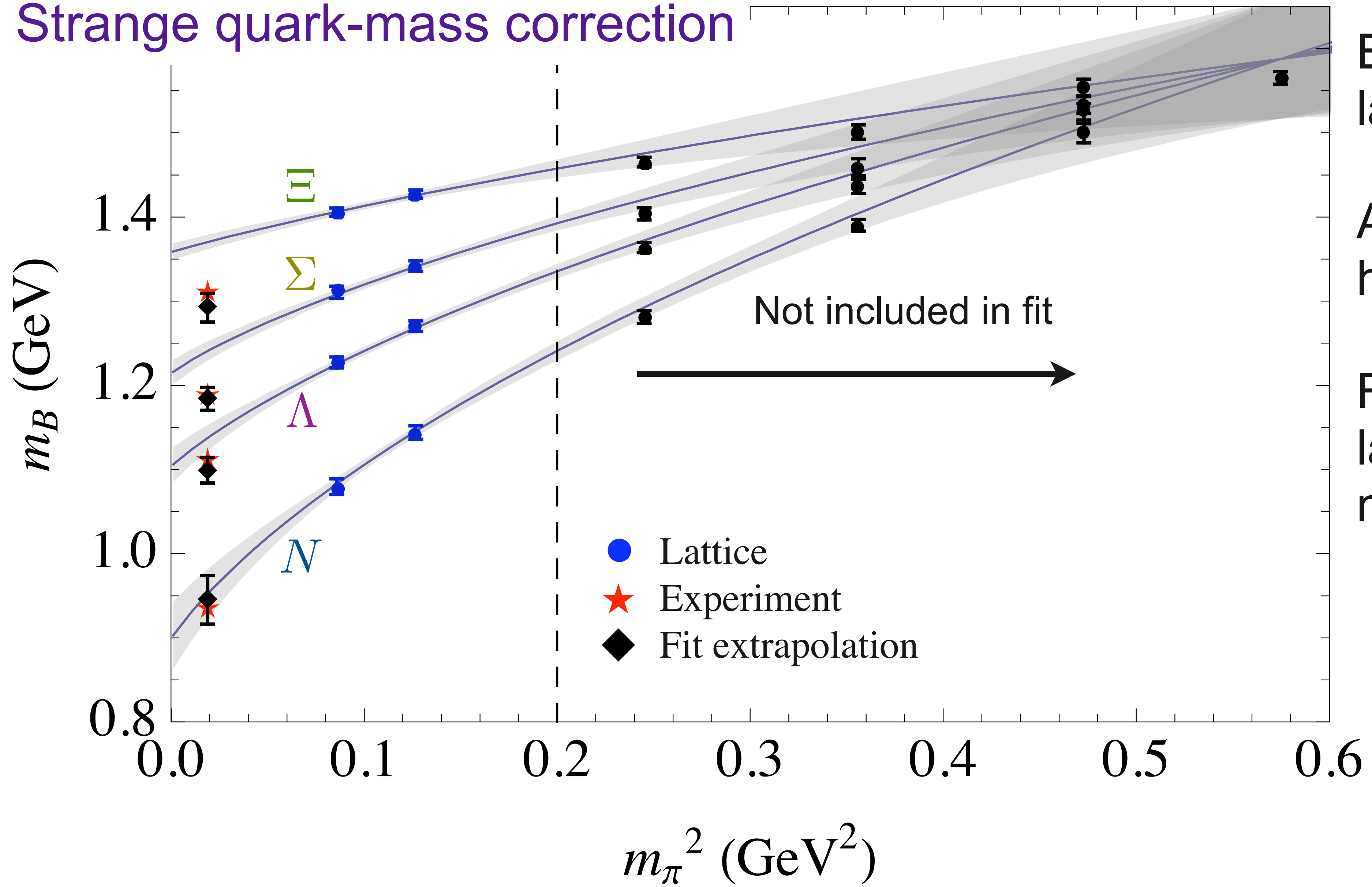
*New development: preferred scale is **not** input from phenomenology*

Young & Thomas, PRD(2010)

Fit to 8 LHPC points

$m_s^{latt} \sim 1.3 m_s^{phys}$

Strange quark-mass correction



Excellent description of lattice results

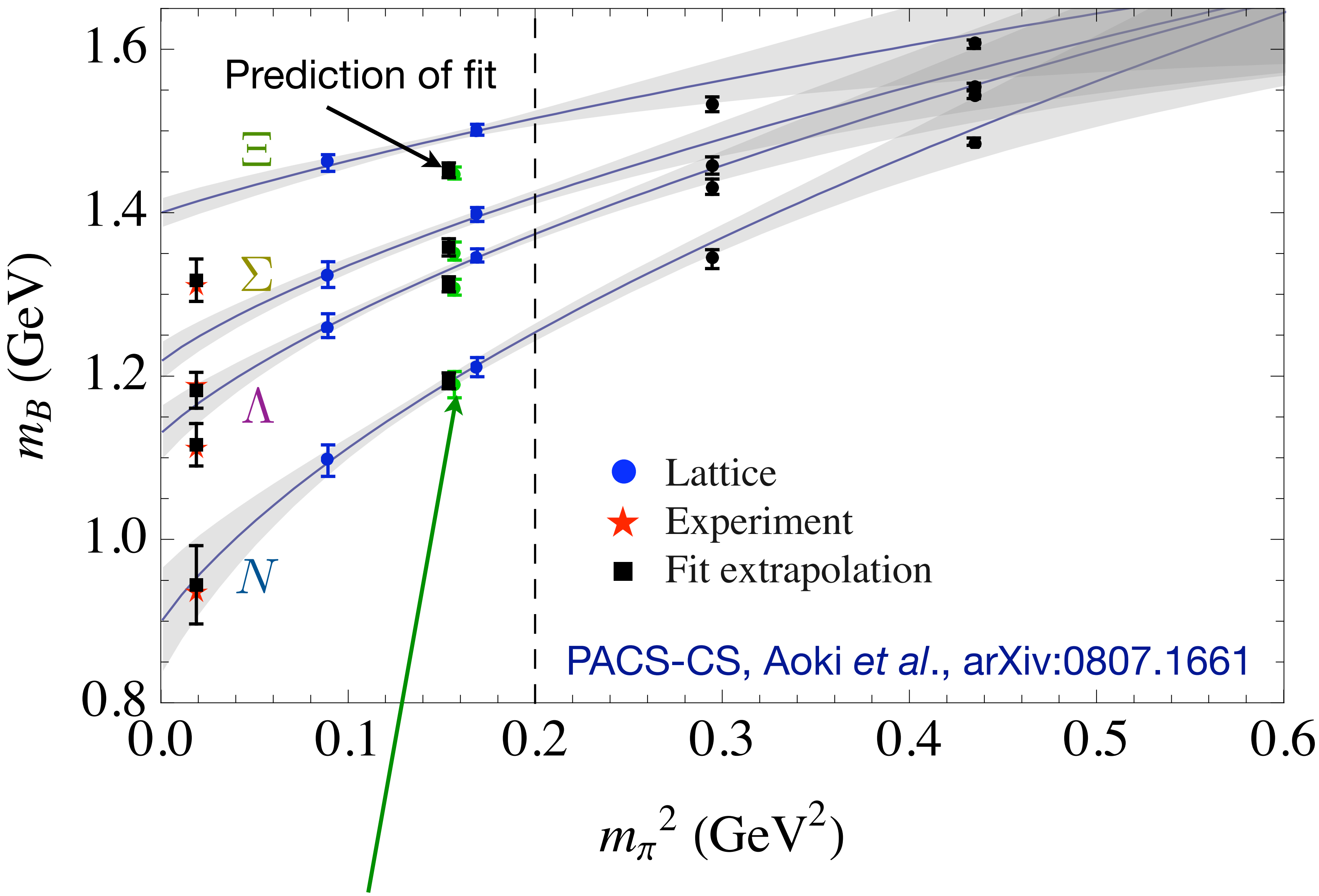
Accurate prediction of heavier simulation data

Reliable correction for lattice simulation quark mass

Young & Thomas, PRD(2010)

Fit to 8 PACS-CS points

PACS-CS: 2+1-flavour simulation; different action discretization to LHPC



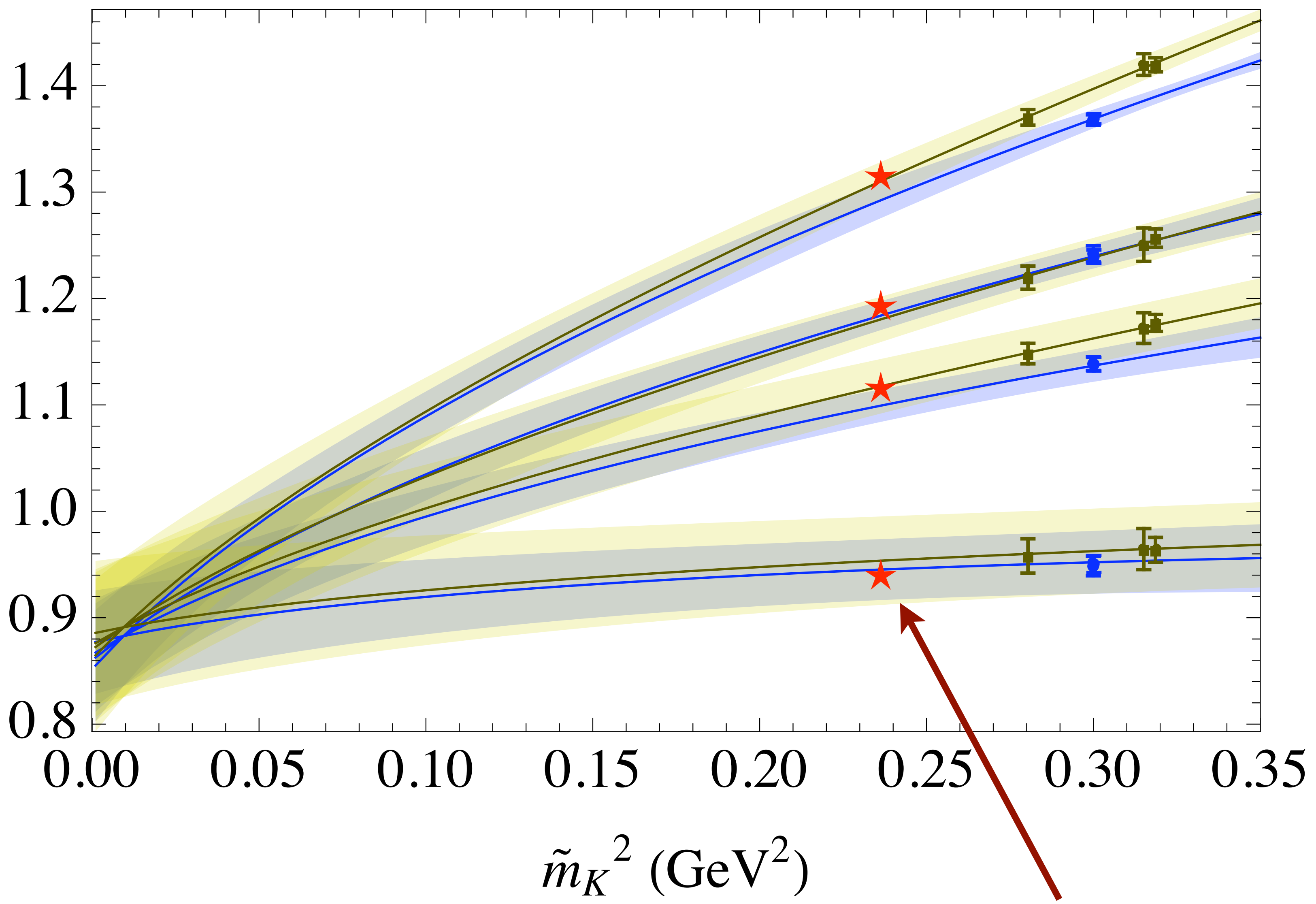
Correction in strange quark mass demonstrated to be reliable against numerical simulation

As for LHPC, excellent agreement with observed spectrum

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

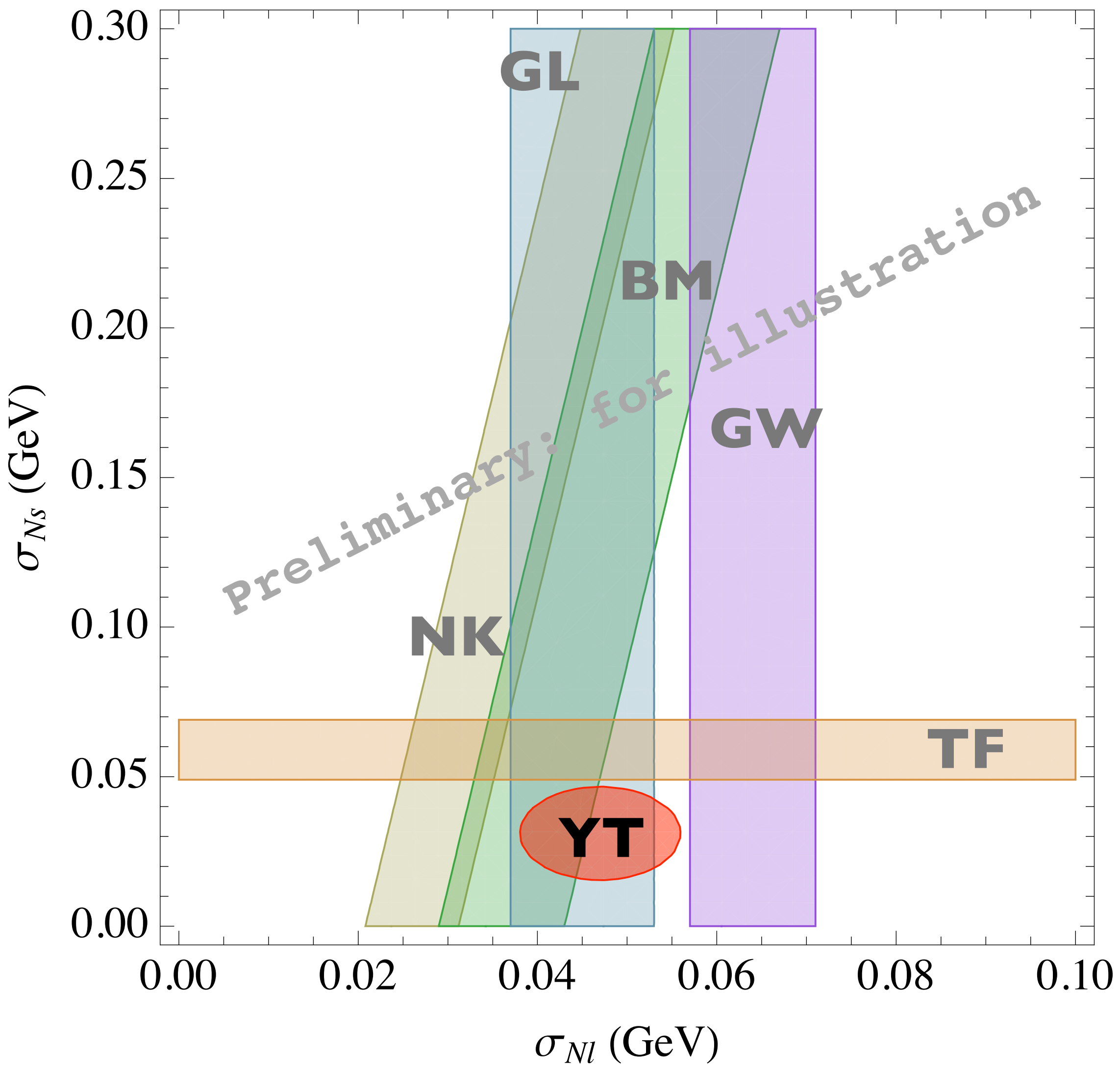
Young & Thomas, PRD(2010)

Strange-quark mass dependence



Strangeness sigma term is just local derivative at this point

Sigma terms from lattice QCD

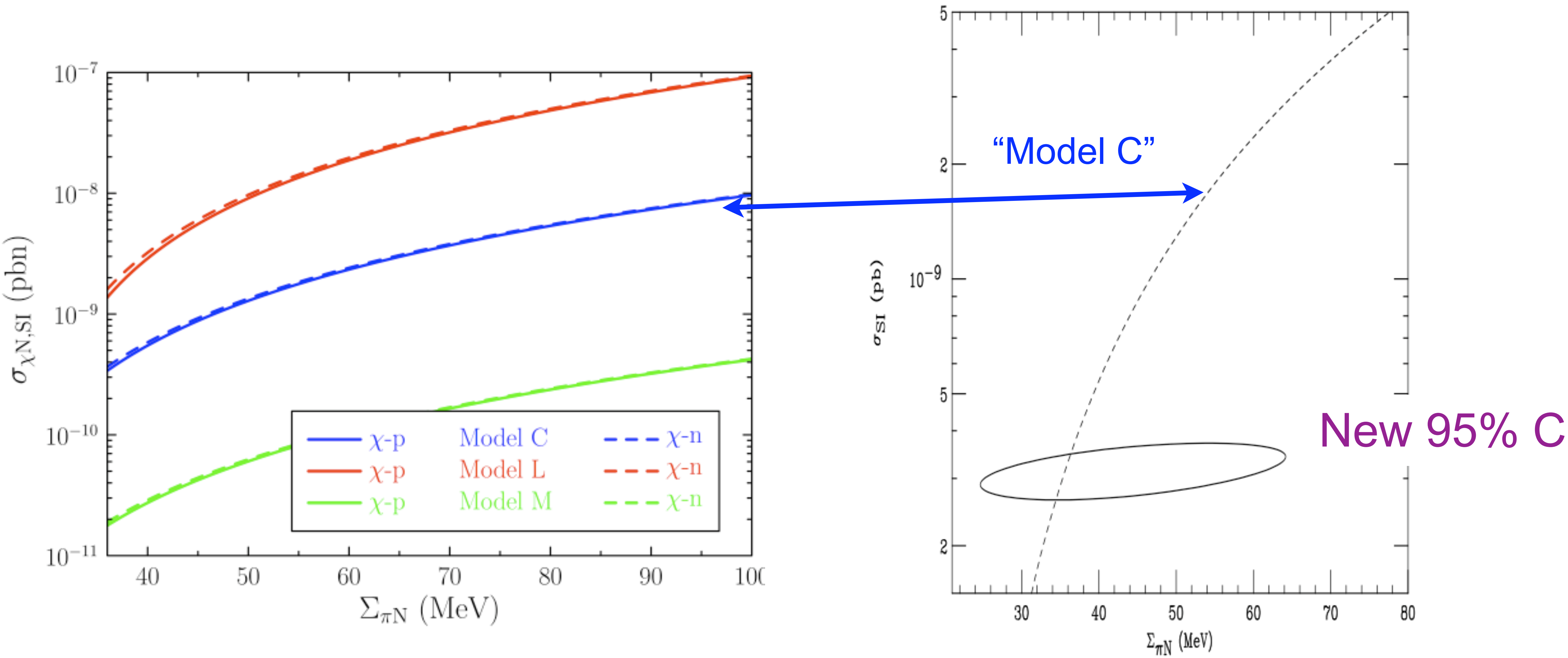


πN Sigma Term (Expt):
GL: Gasser & Leutwyler (1991)
GW: Pavan et al. (2001)

Octet Masses & Breaking:
Gasser (1981)
NK: Nelson & Kaplan (1987)
BM: Borasoy & Meissner (1997)

3-flavour Lattice QCD:
YT: Young & Thomas (2009)
TF: Toussaint & Freeman (2009)

Updated cross sections for benchmark models



Ellis, Olive & Savage PRD(2008)

Giedt, Thomas & Young, PRL(2009)

Strong dependence on sigma term from poorly known strangeness

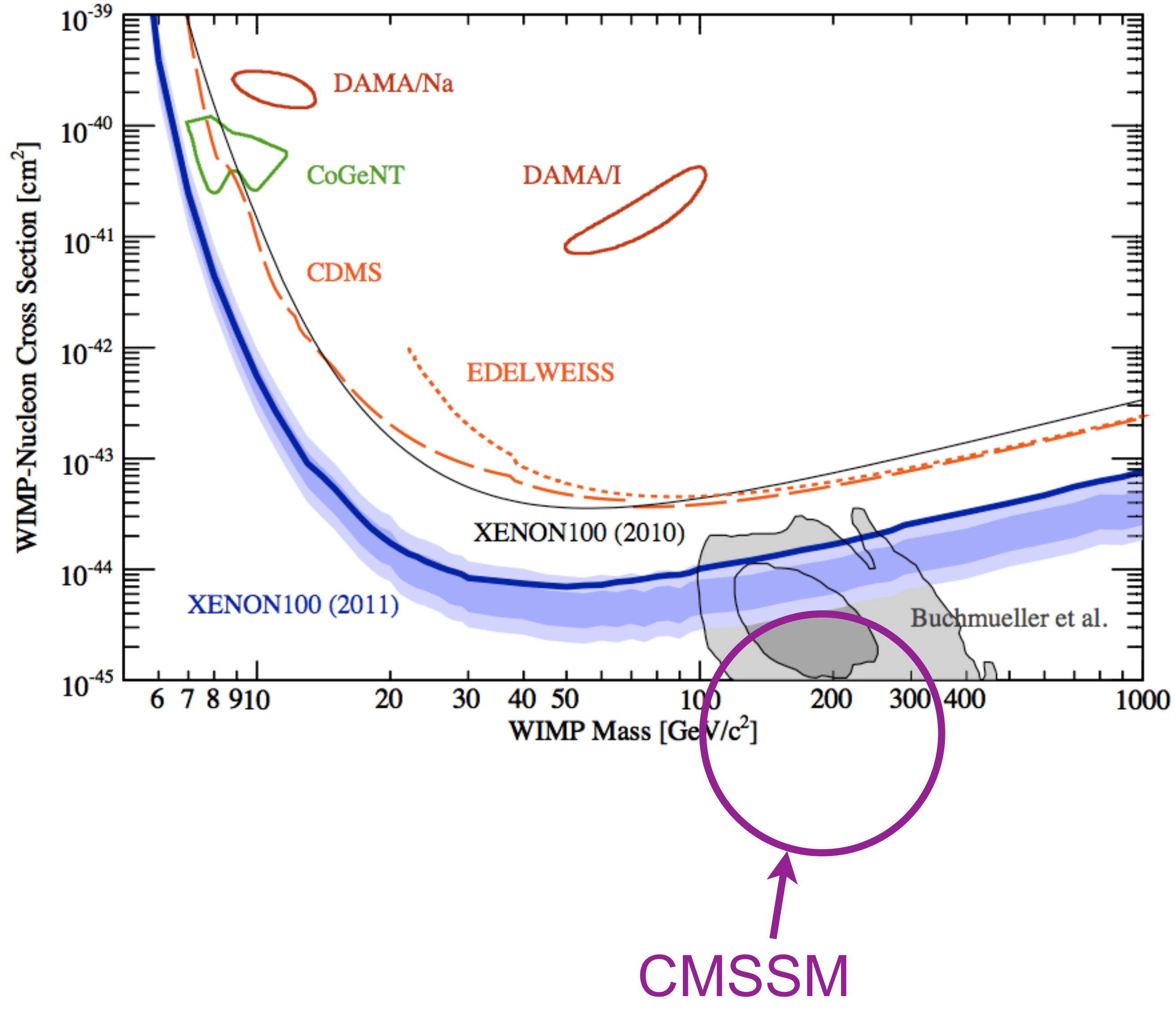
Significant reduction in uncertainty

$$\bar{\sigma}_{ps} = \frac{m_s}{2\hat{m}} \left(\Sigma_{\pi N} - \sigma_0 \right)$$

Cross-section reduced by order of magnitude from XENON100 figure

XENON100

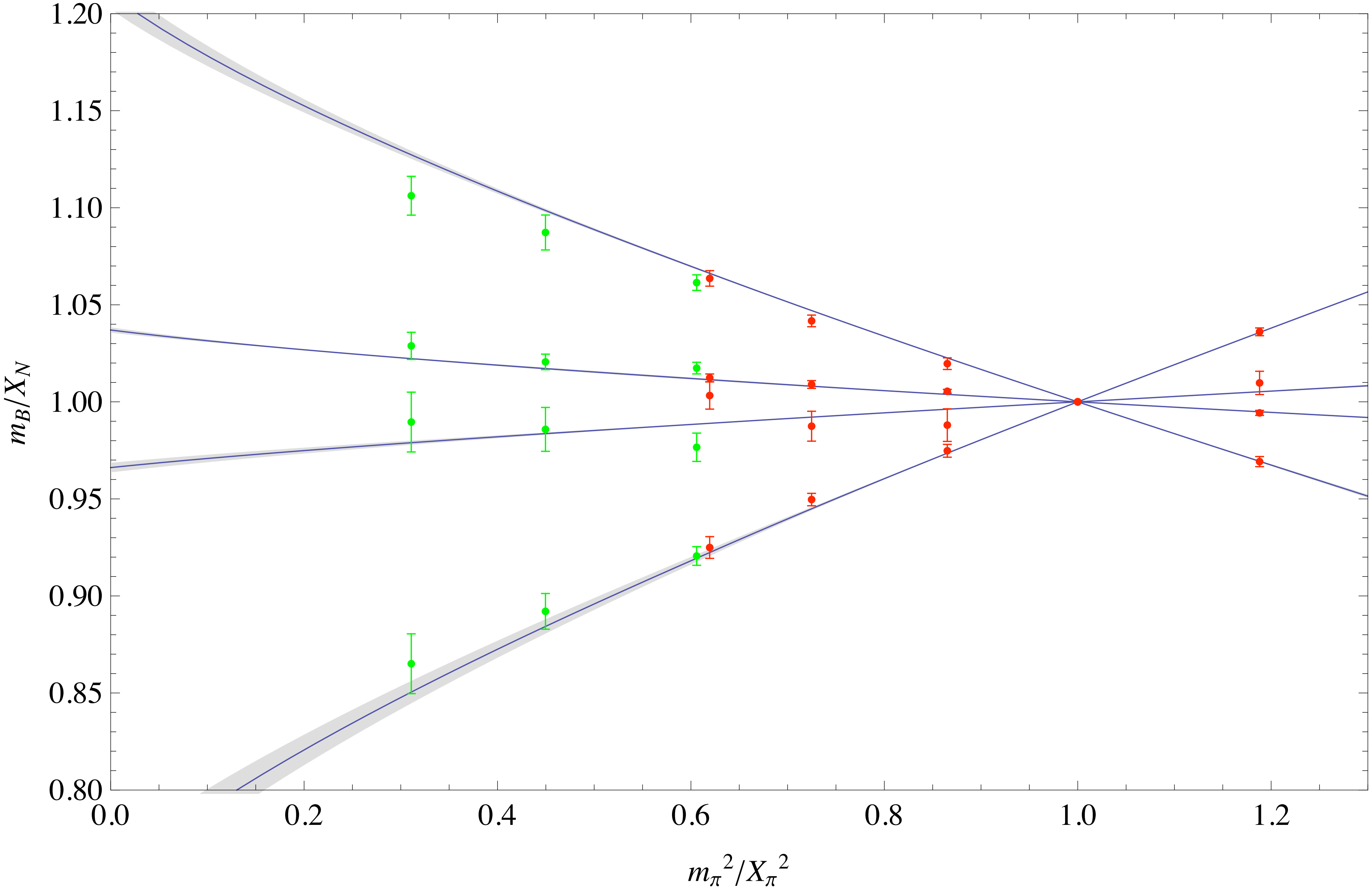
- Shift the “blob” down



QCDSF lattice results

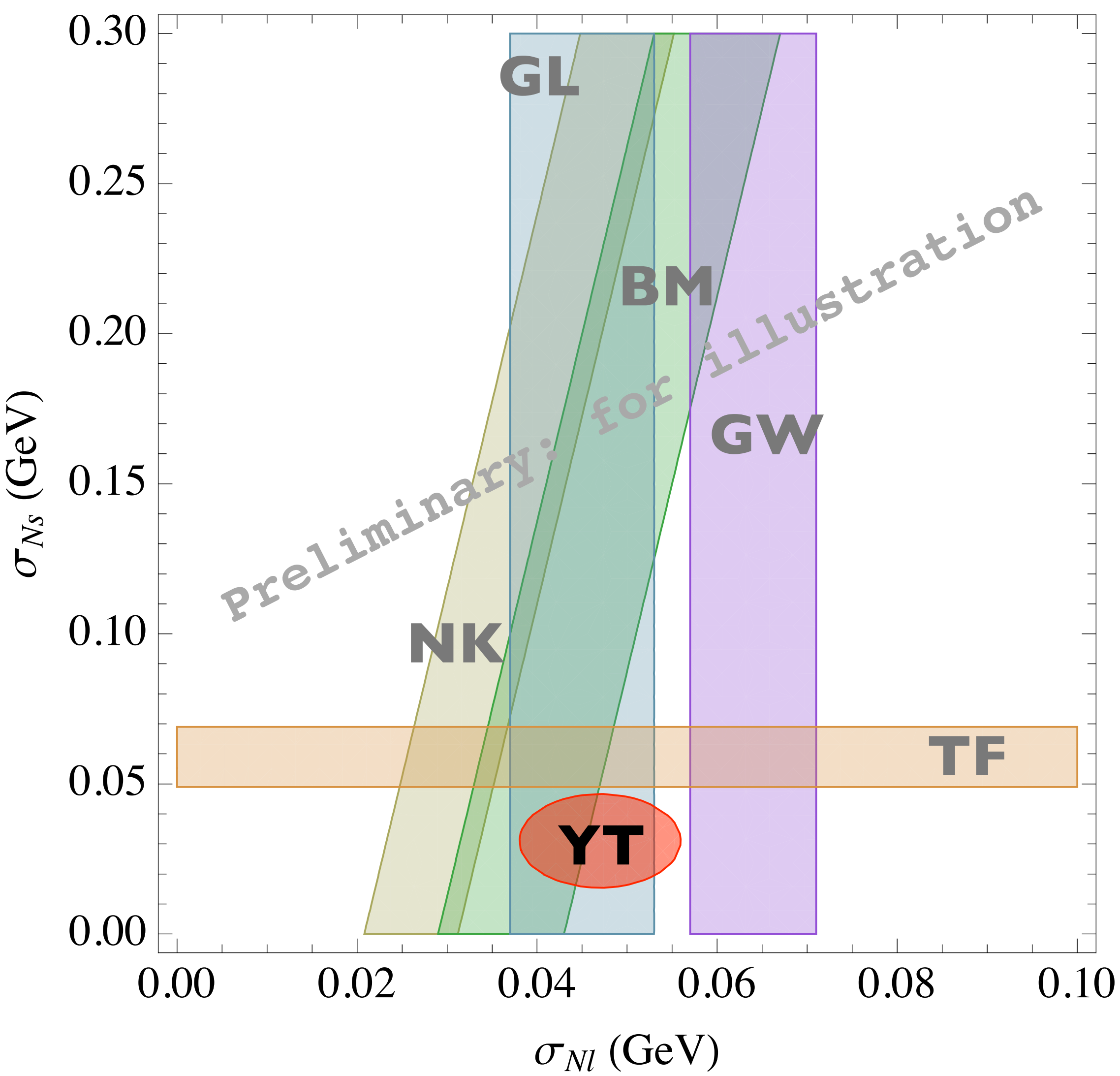
Bietenholz *et al.*, arXiv:1102.5300 [hep-lat]

- "Prediction": curves are NOT a fit



Lattice QCD determination

	N	Λ	Σ	Ξ
$\bar{\sigma}_{Bl}$	**0.050(9)(1)(3)**	**0.028(4)(1)(2)**	**0.0212(27)(1)(17)**	**0.0100(10)(0)(4)**
$\bar{\sigma}_{Bs}$	**0.033(16)(4)(2)**	**0.144(15)(10)(2)**	**0.187(15)(3)(4)**	**0.244(15)(12)(2)**



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Strange scalar content is small