Electroweak tests and nucleon structure:

Ross D. Young

PacSPIN 2011,
Cairns, Australia
21 June 2011

University
of
Adelaide

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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Electroweak tests and nucleon structure:

Spin searches for "new physics"

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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

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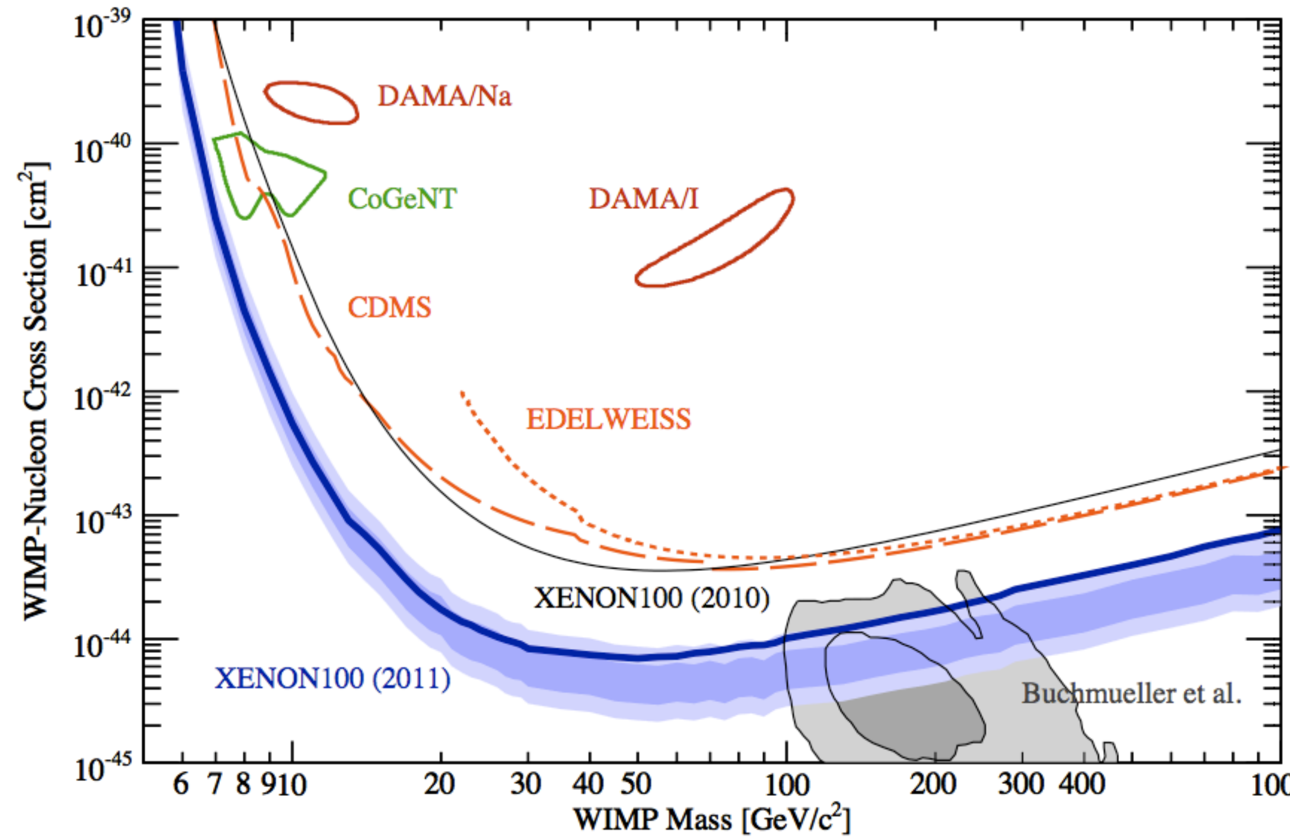

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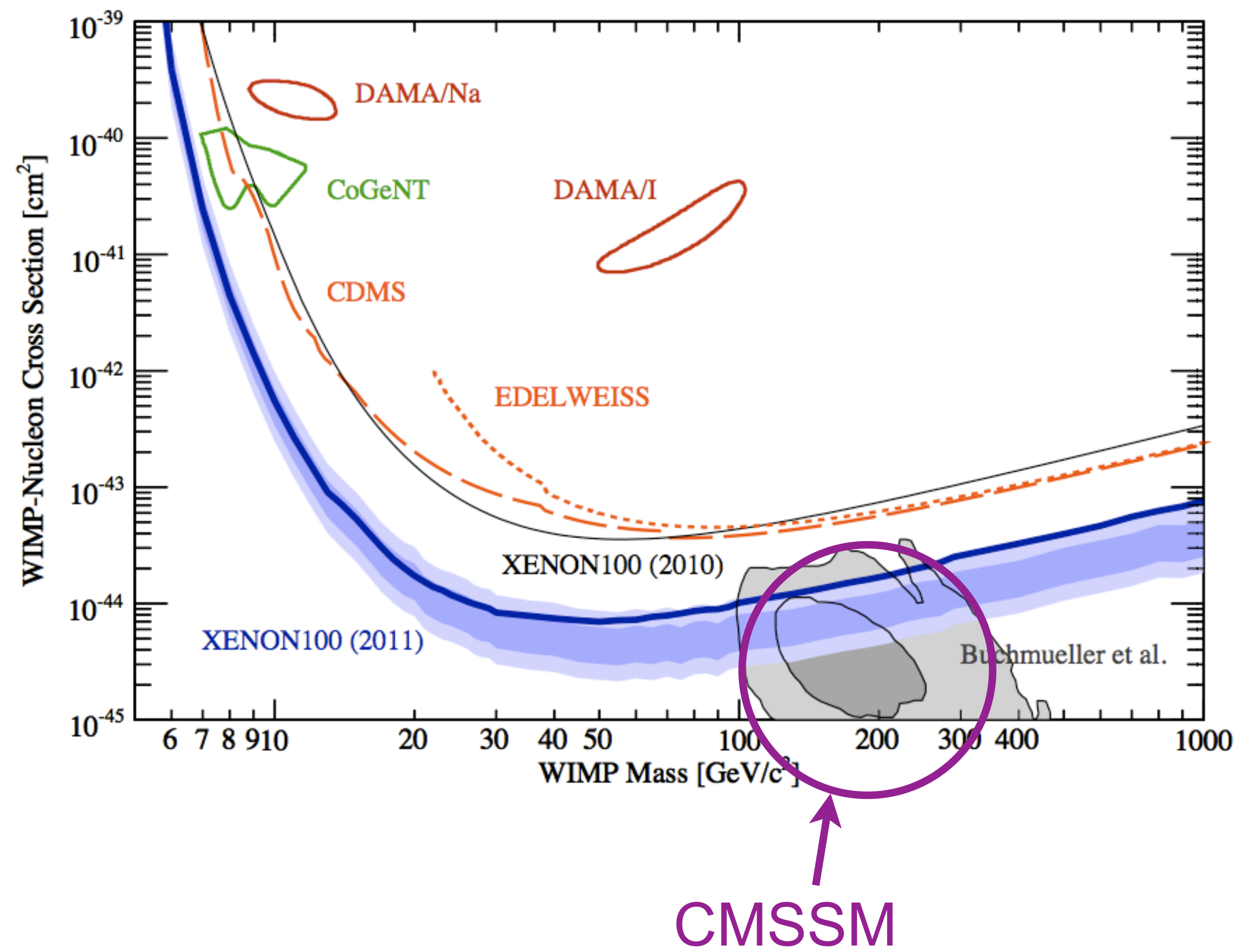

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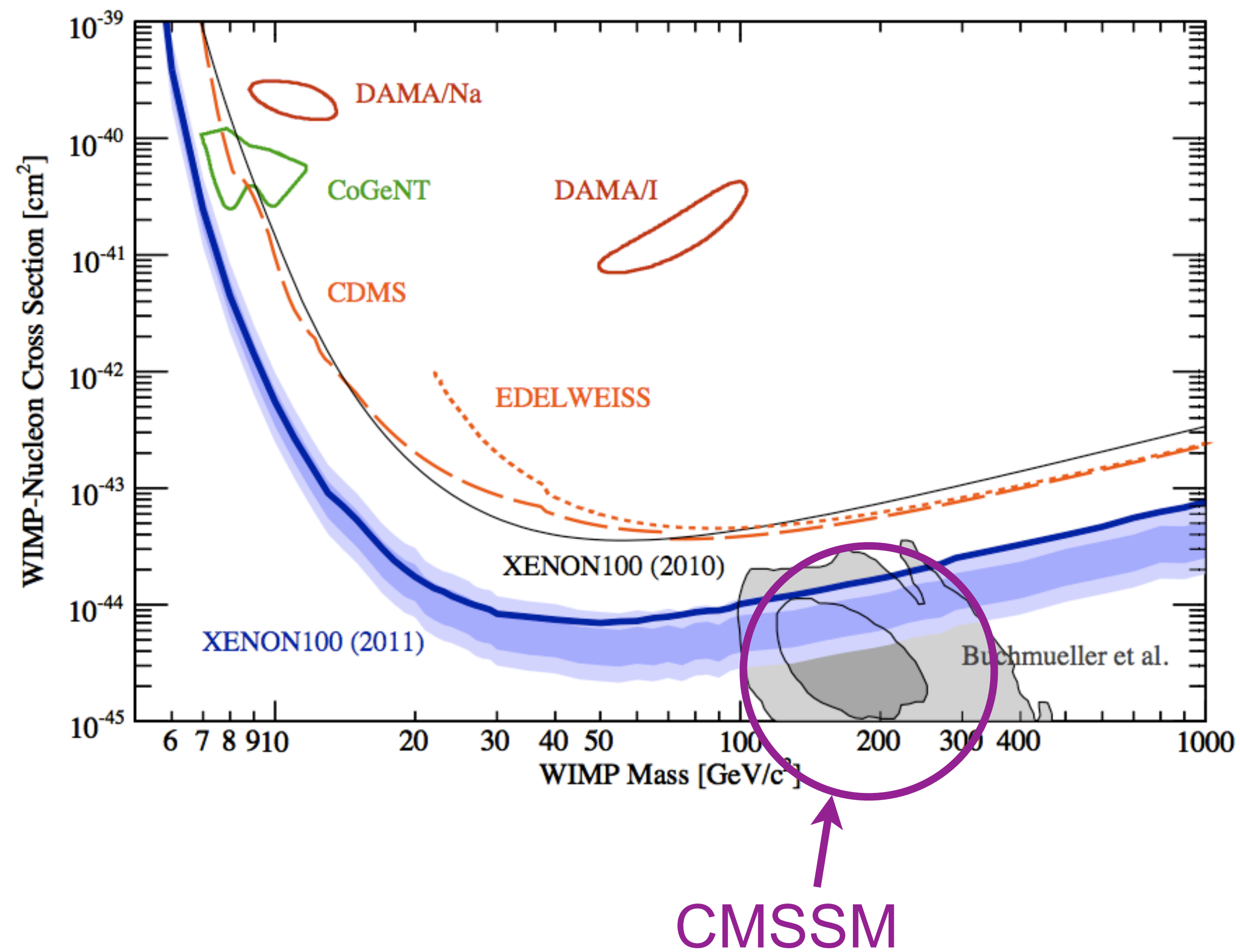


Today... convince you this CMSSM blob is too “high”

CMSSM: Constrained Minimal Supersymmetric Standard Model

WIMP-Nucleon cross section

- The Constrained MSSM (CMSSM):

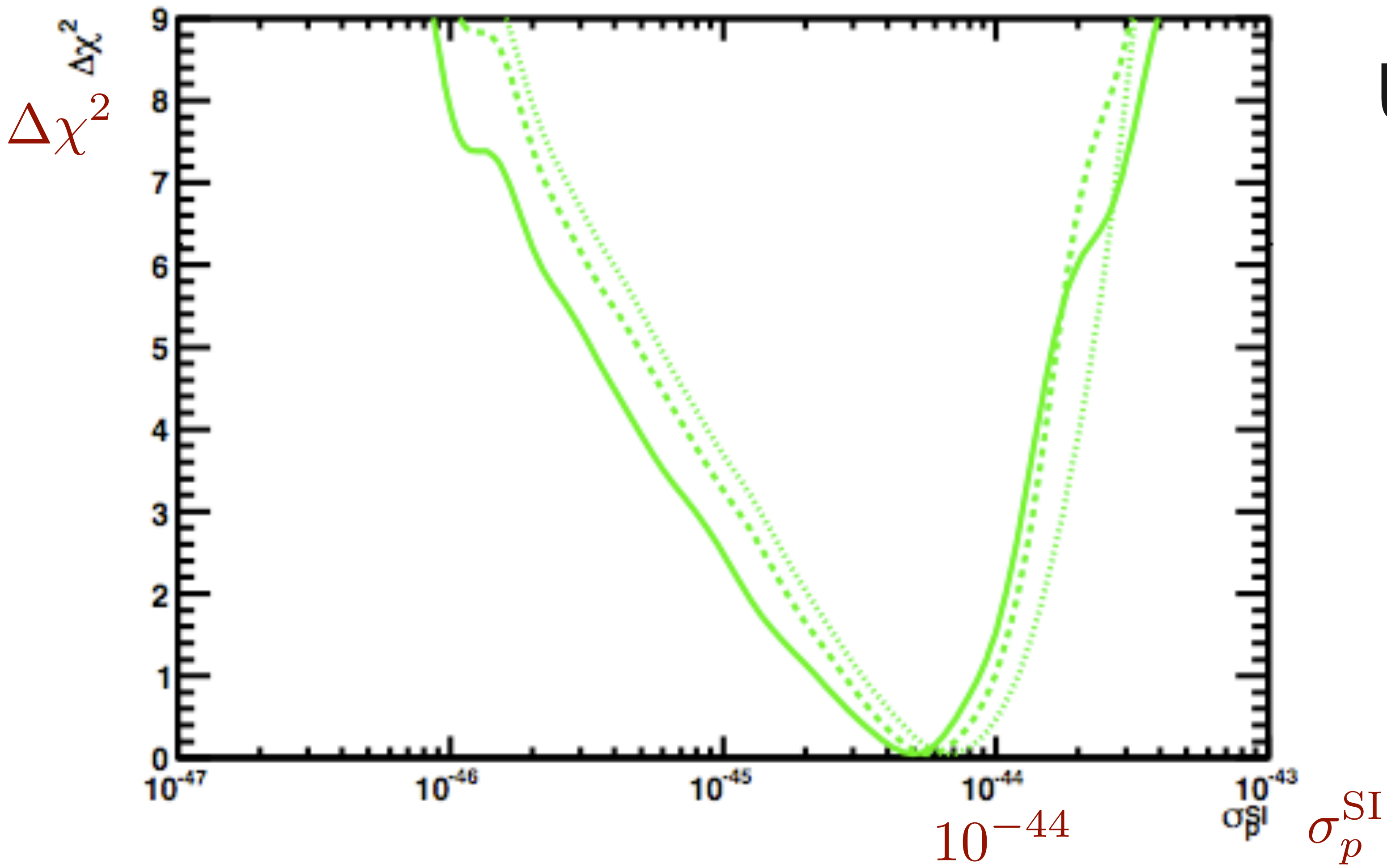
Eur. Phys. J. C (2011) 71: 1634
DOI 10.1140/epjc/s10052-011-1634-1

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

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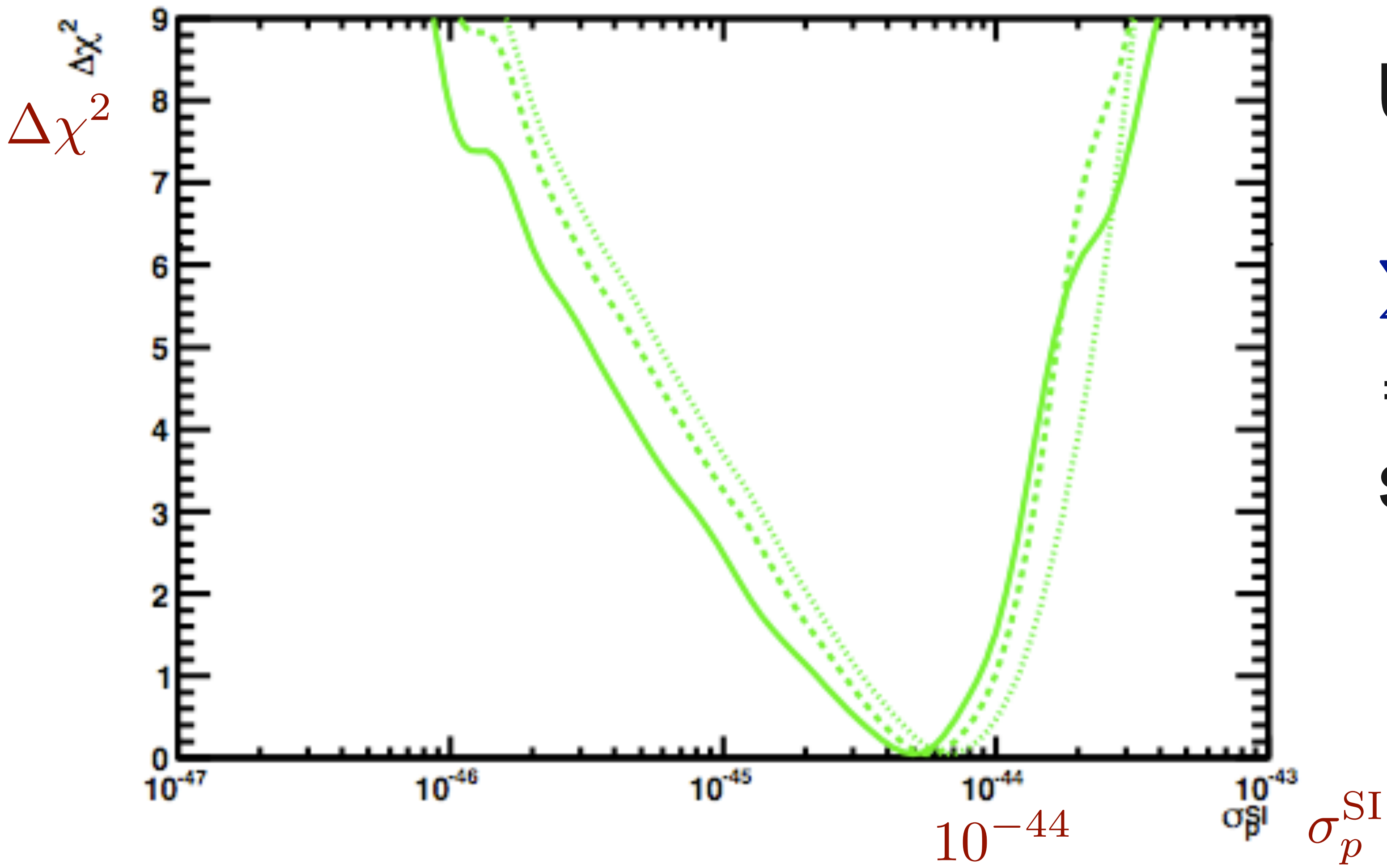

Using: $\Sigma_{\pi N} = 64\,\mathrm{MeV}$

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

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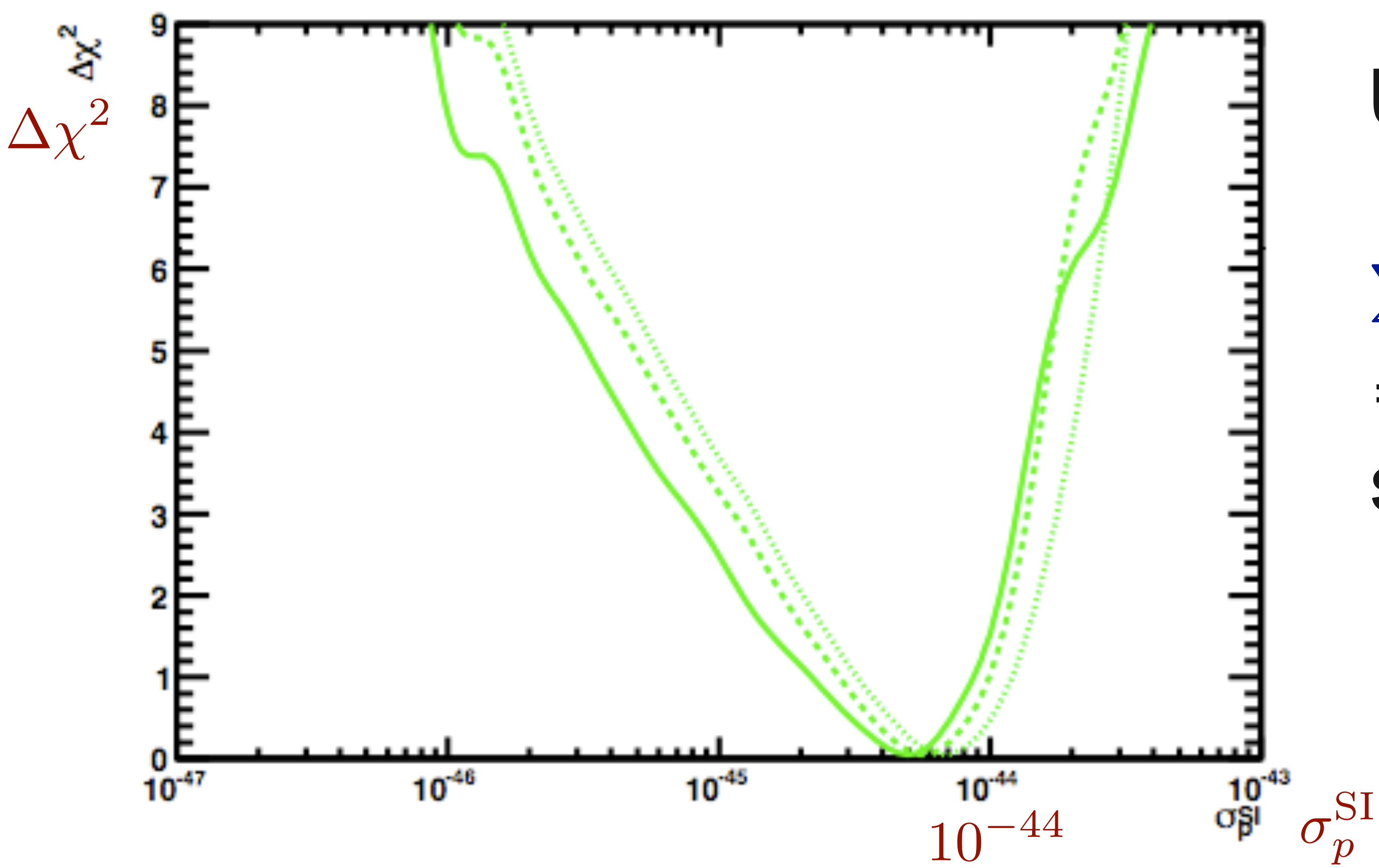

Using: $\Sigma_{\pi N} = 64\,\mathrm{MeV}$

$\Sigma_{\pi N} = 45\,\mathrm{MeV}$
$\Rightarrow$ 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 $\sigma_{SI}^{p} \propto |f_p|^2$

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

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

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

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

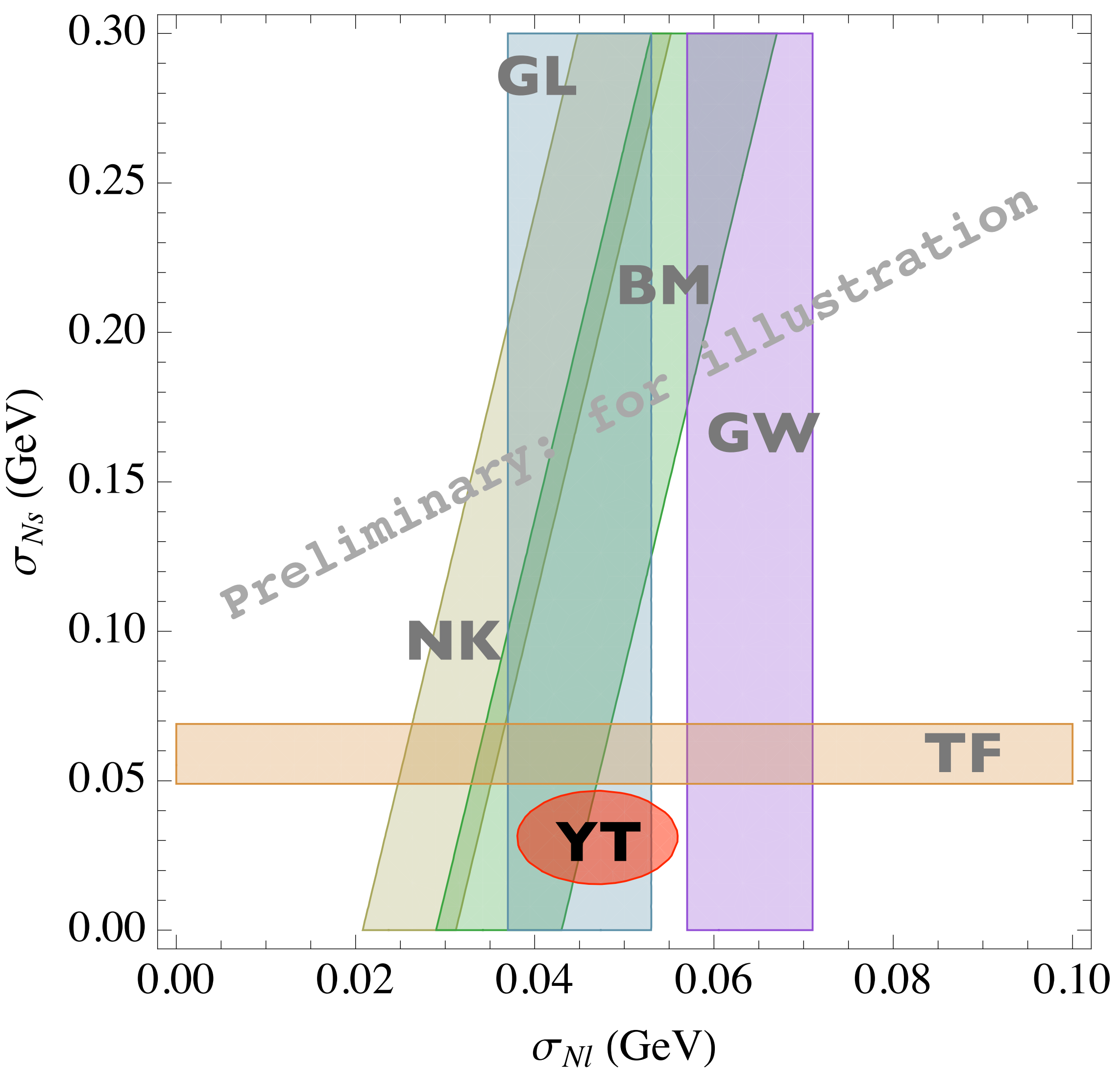
$$\sigma_0 \simeq \hat{m}\frac{m_\Xi + m_\Sigma - 2m_N}{m_s - \hat{m}} = 26\,\mathrm{MeV}$$

- 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 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)**



Young & Thomas, PRD(2010)

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)

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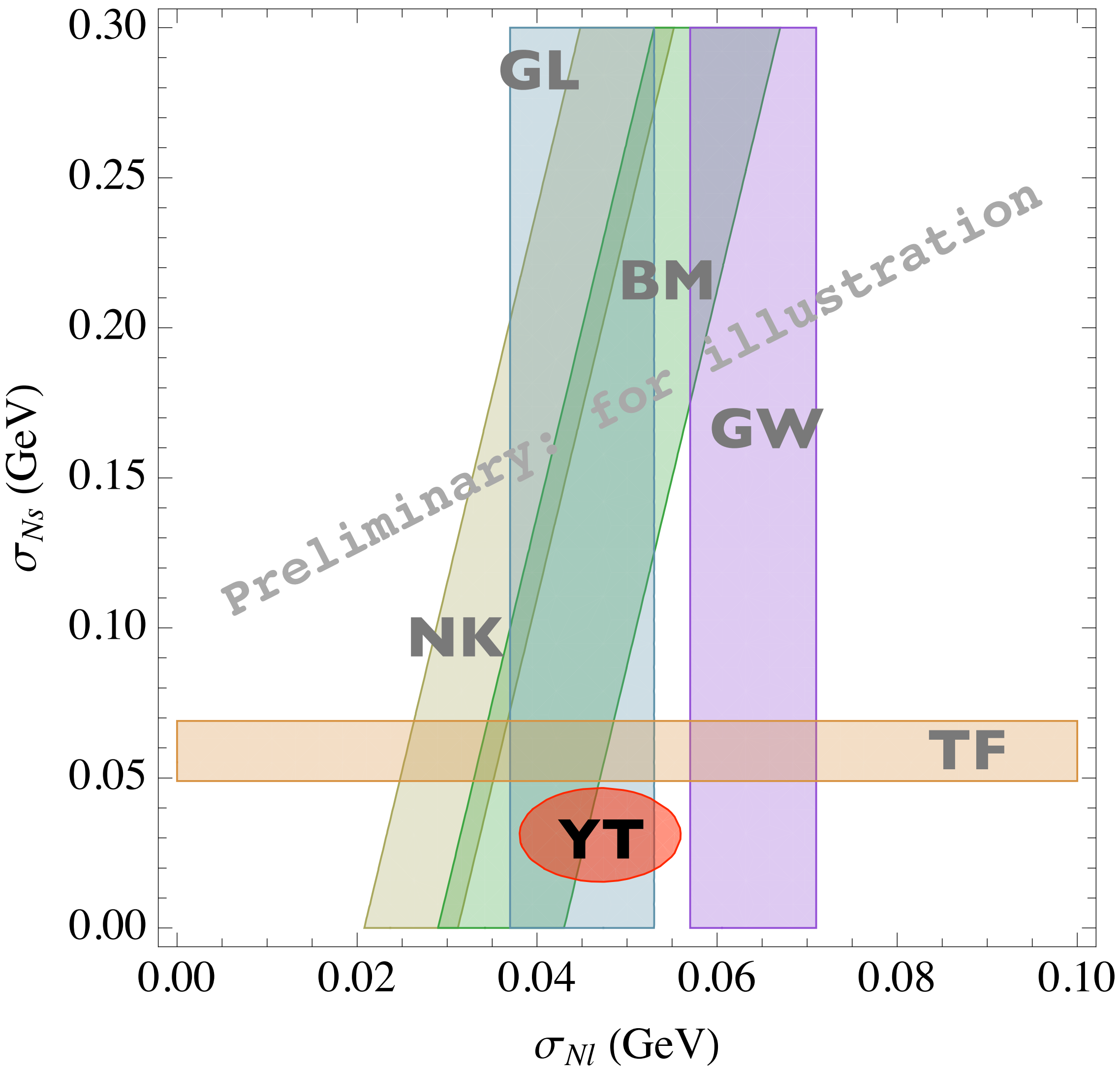

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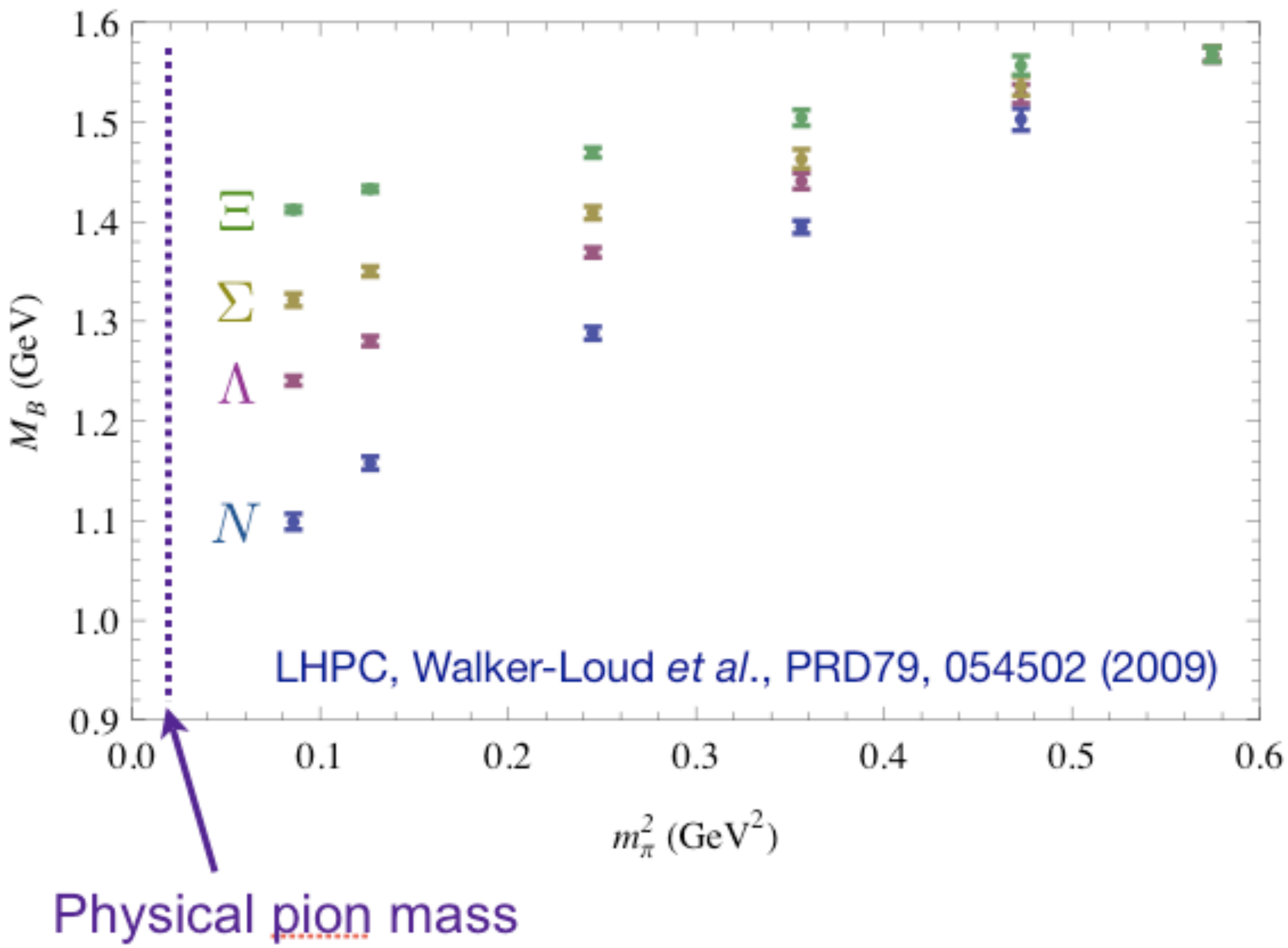
Strange scalar content is small

2+1-flavour lattice results

$\text{Dynamical}: m_u = m_d \;\&\; m_s$

Octet baryon masses



- 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

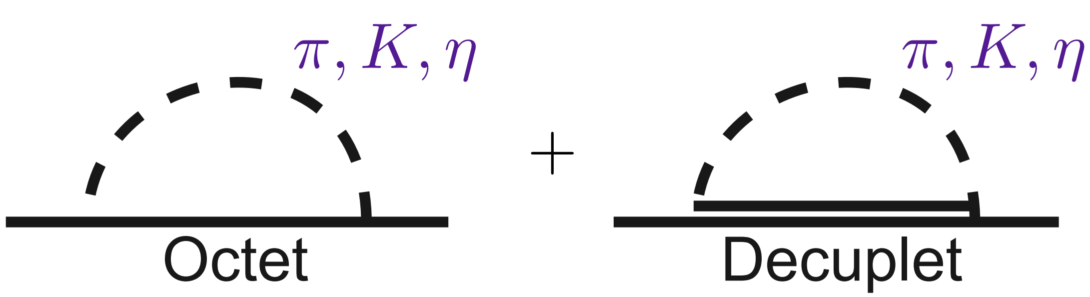
Octet baryon masses

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



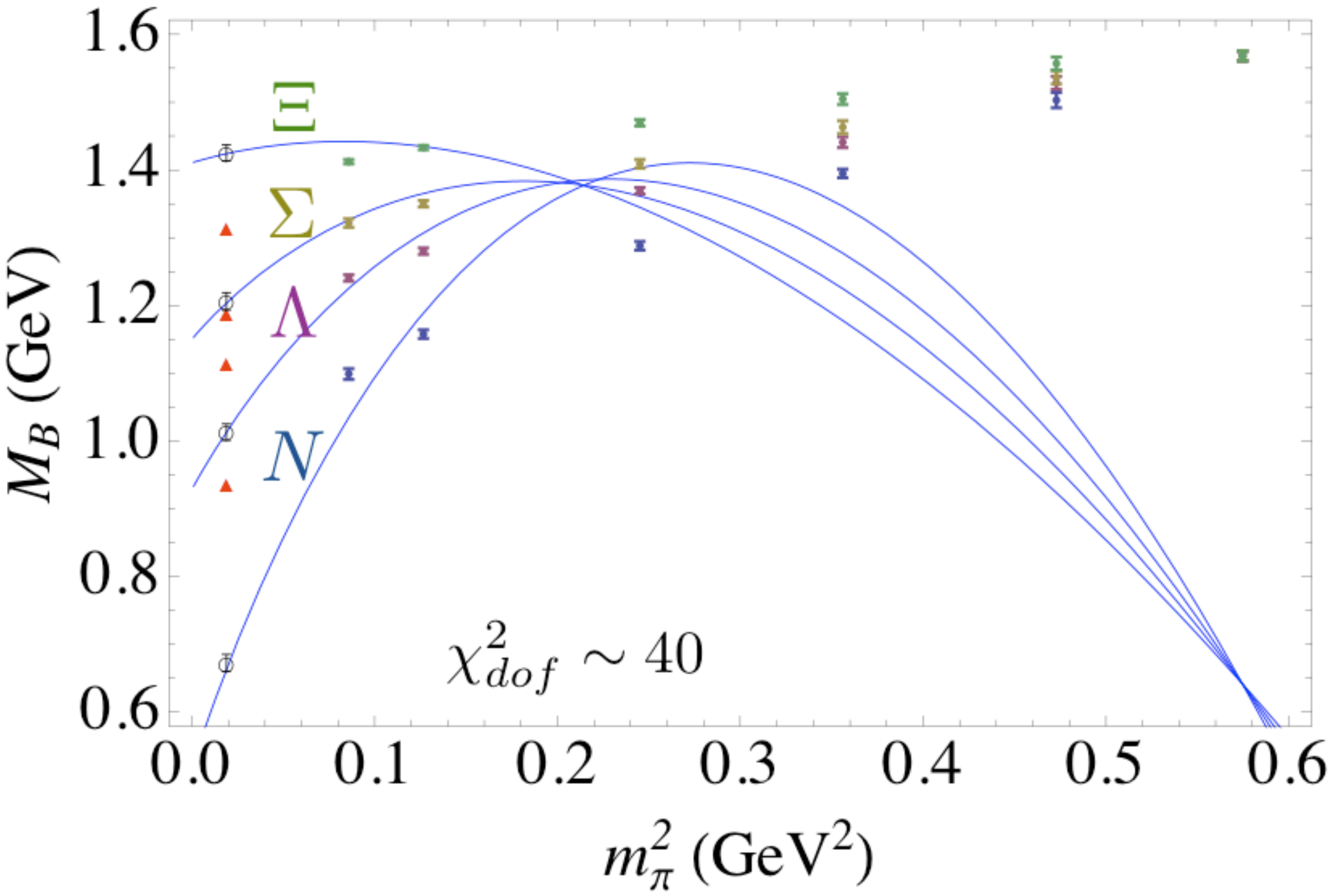
Inputs: $g_A = 1.267, D \simeq \frac{3}{5} g_A, F \simeq \frac{2}{5} g_A, \mathcal{C} \simeq -2D, f_\pi \simeq 0.087\,\mathrm{GeV}$

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

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

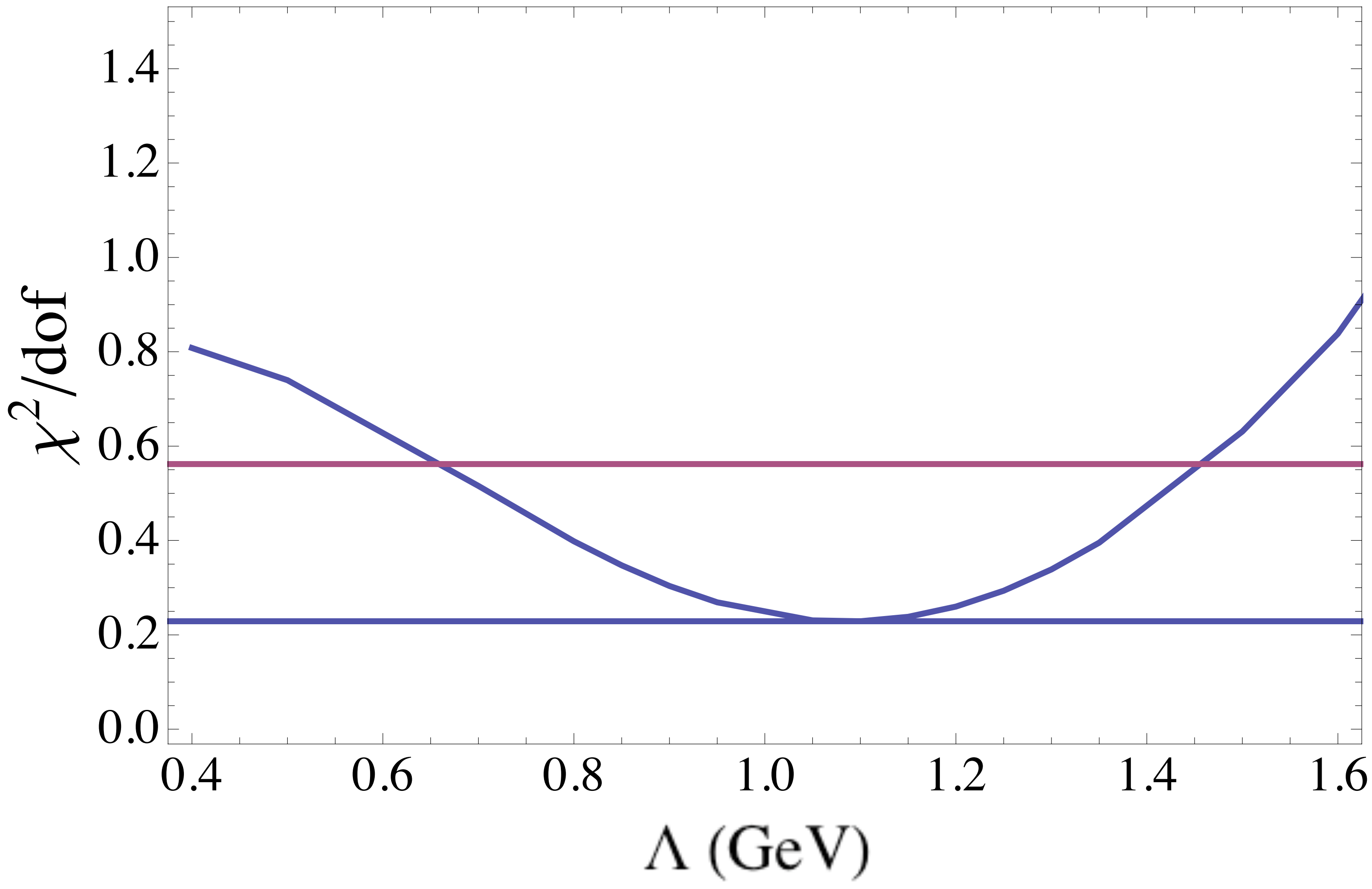
Text book $$\frac{2}{\pi}\int dk\,\frac{k^4}{k^2+m^2} \xrightarrow{R} m^3$$

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)



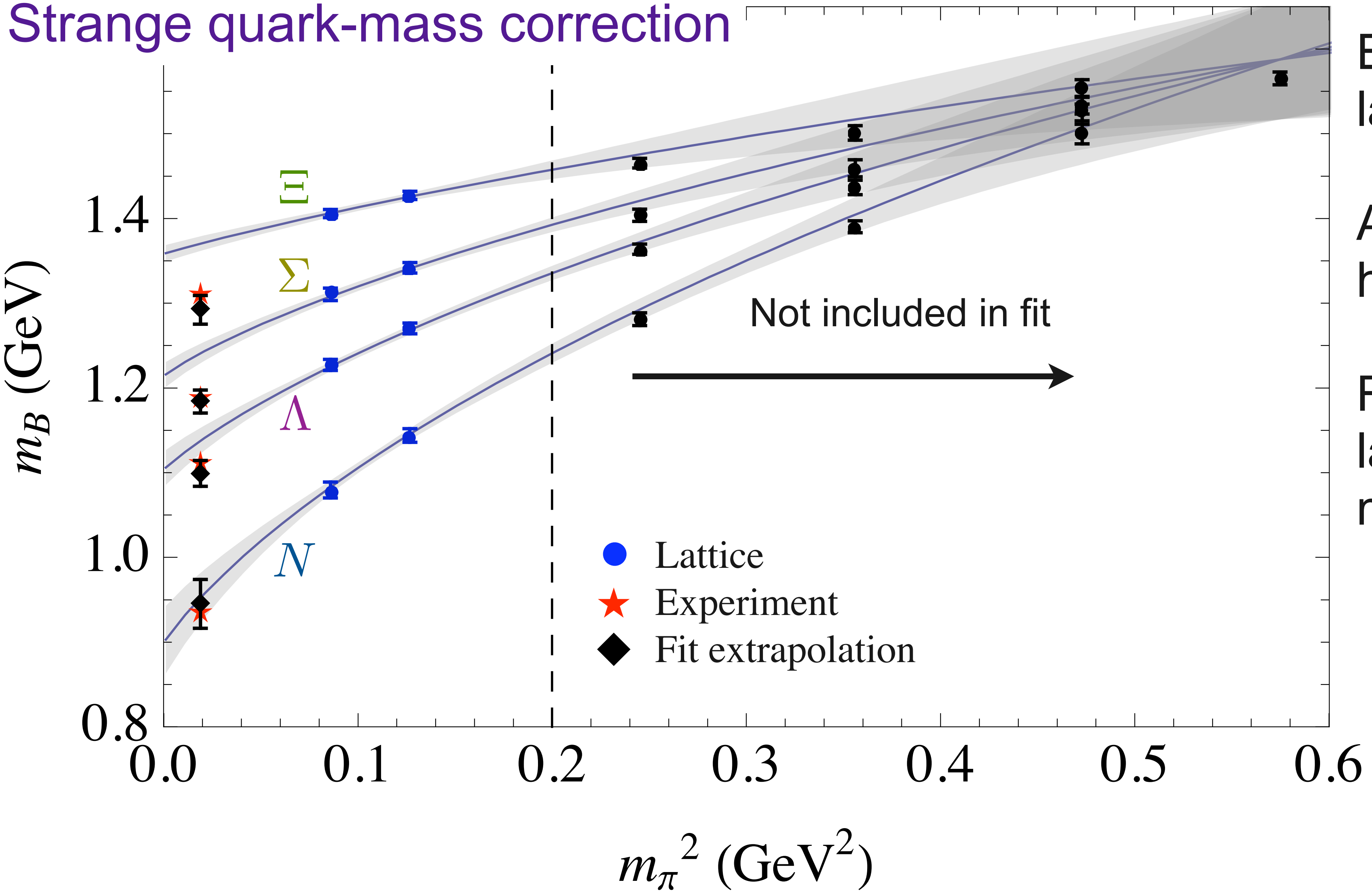
*New development: preferred scale is **not** input from phenomenology*

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

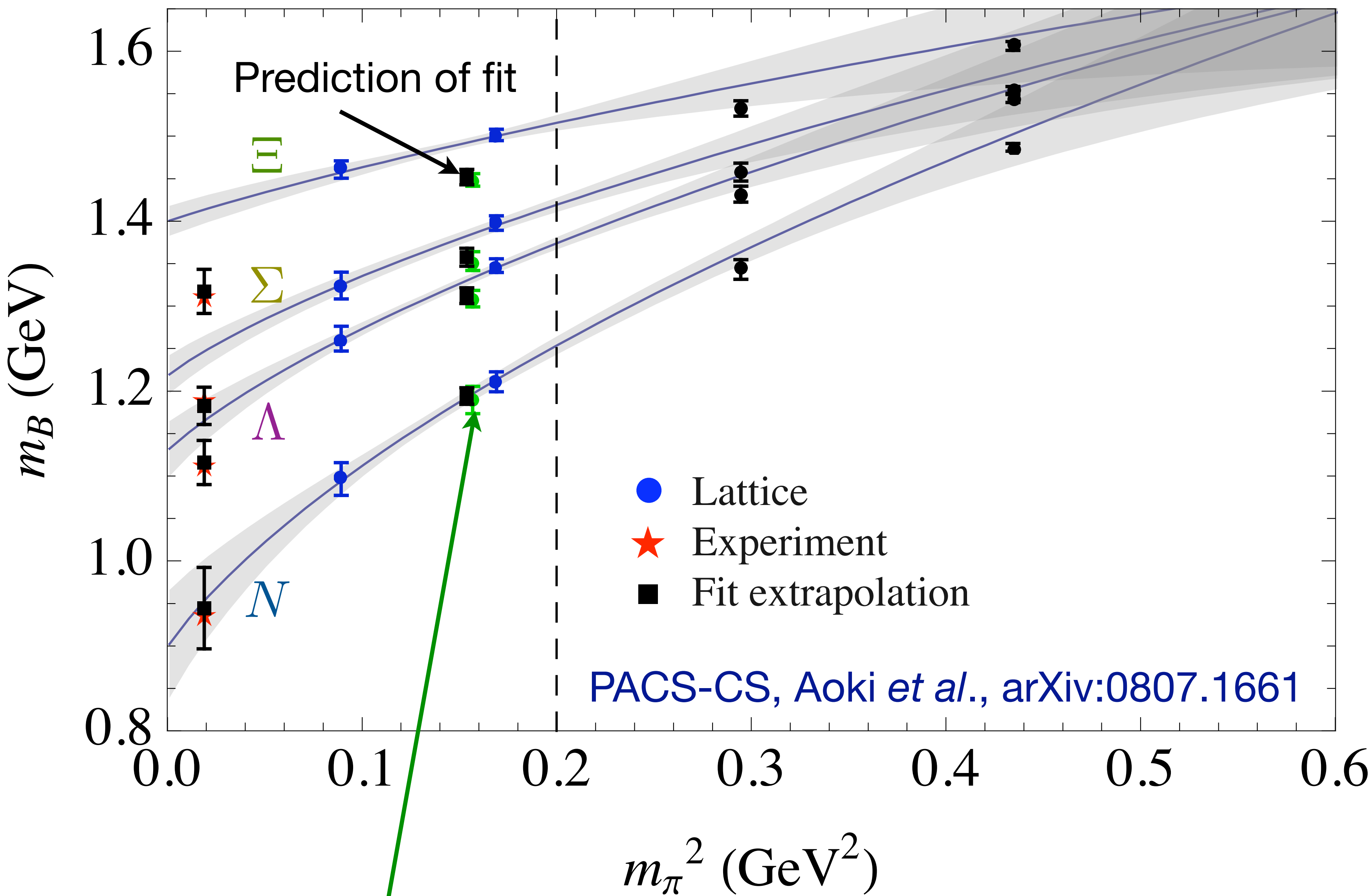
Accurate prediction of heavier simulation data

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



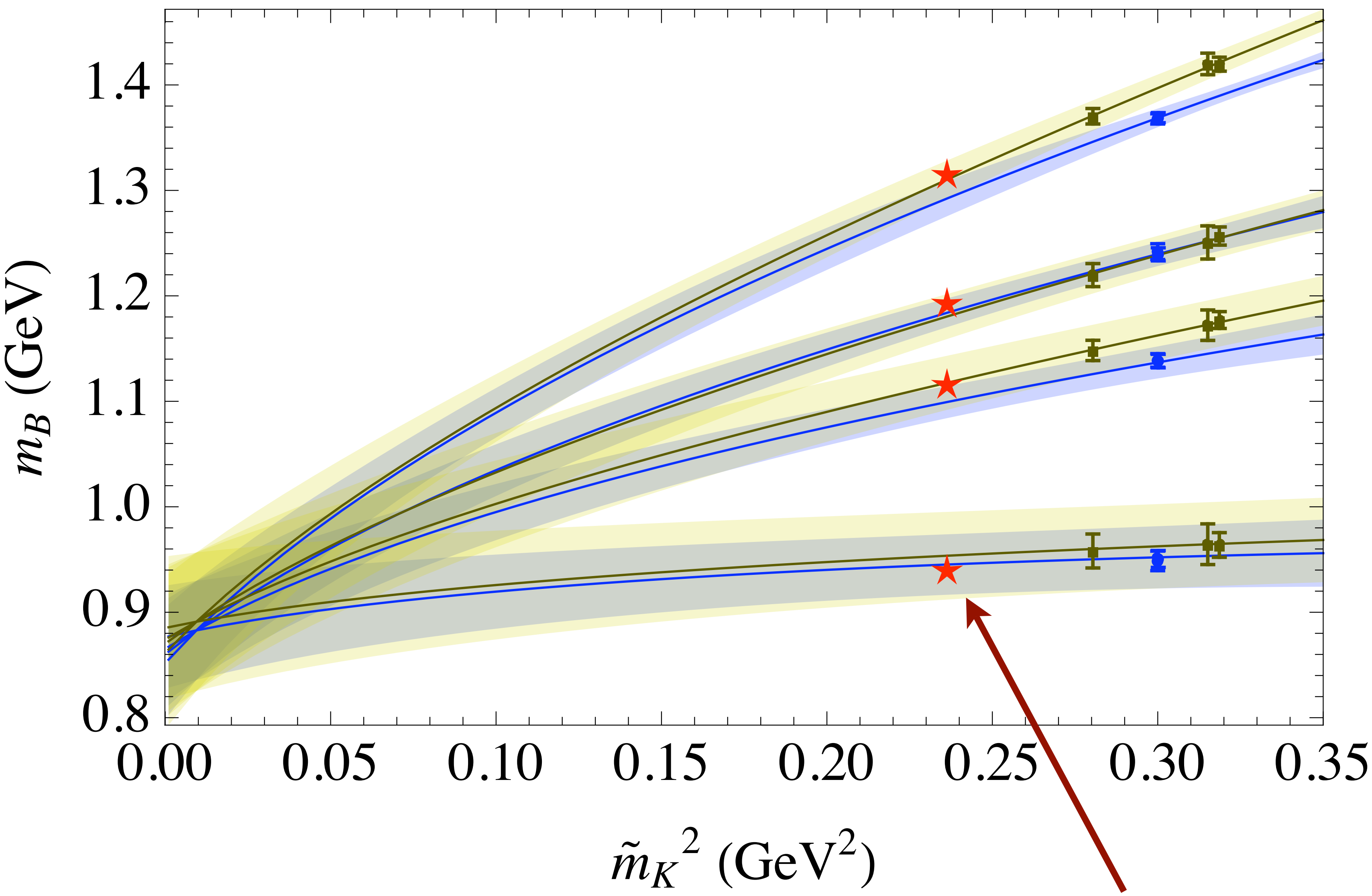
PACS-CS have an additional run with a different strange quark mass

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

As for LHPC, excellent agreement with observed spectrum

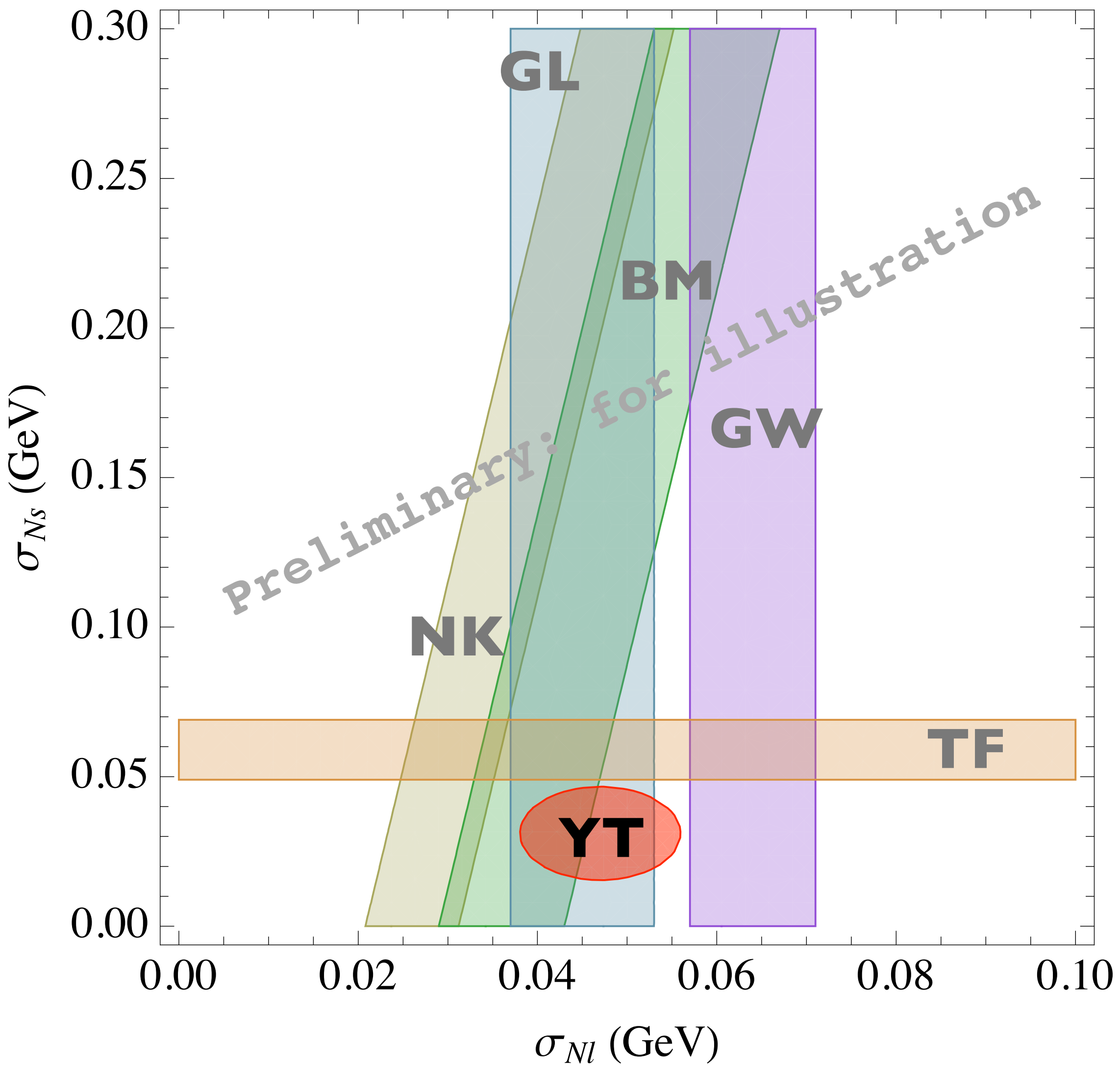
Young & Thomas, PRD(2010)

Strange-quark mass dependence

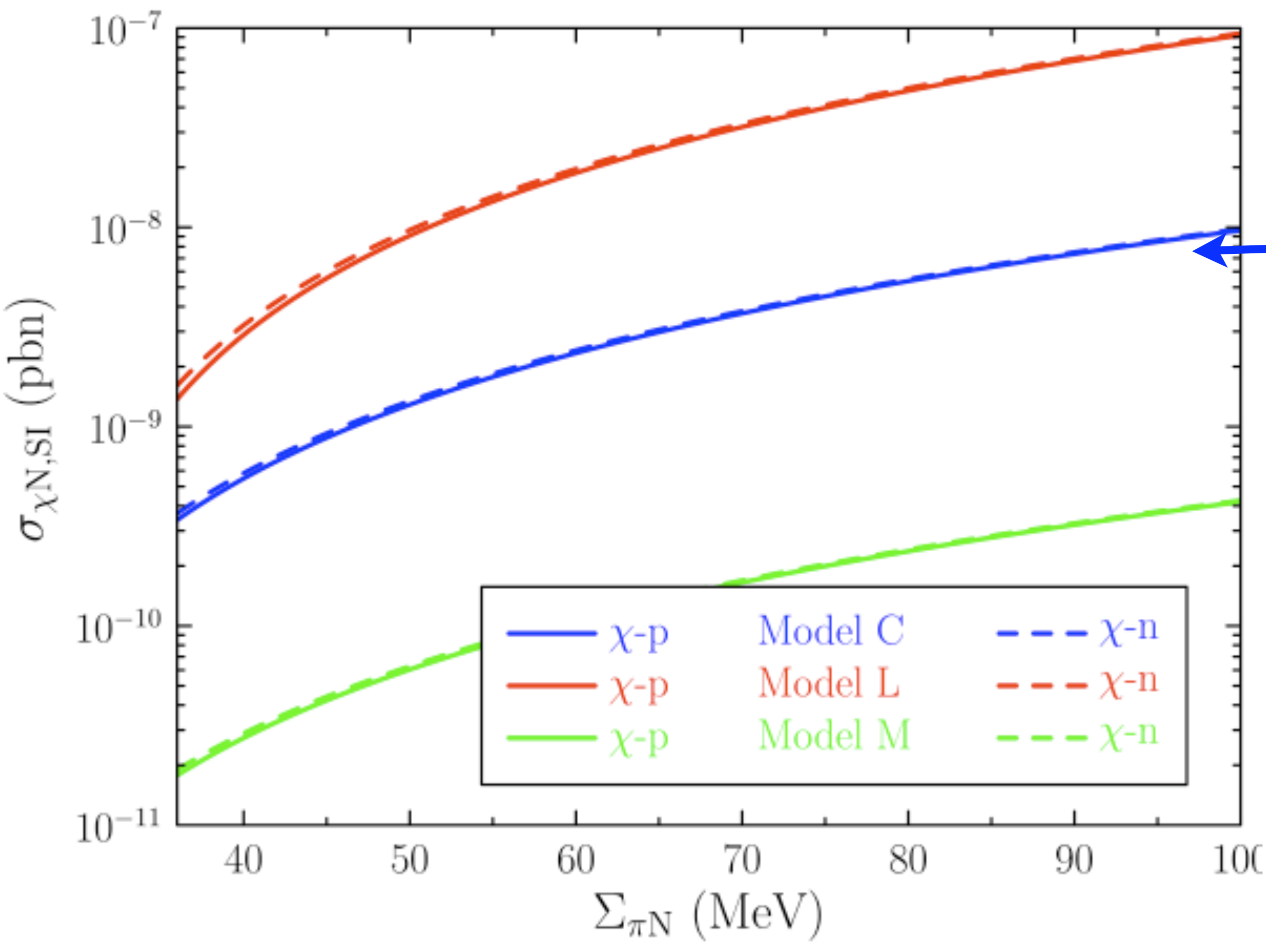


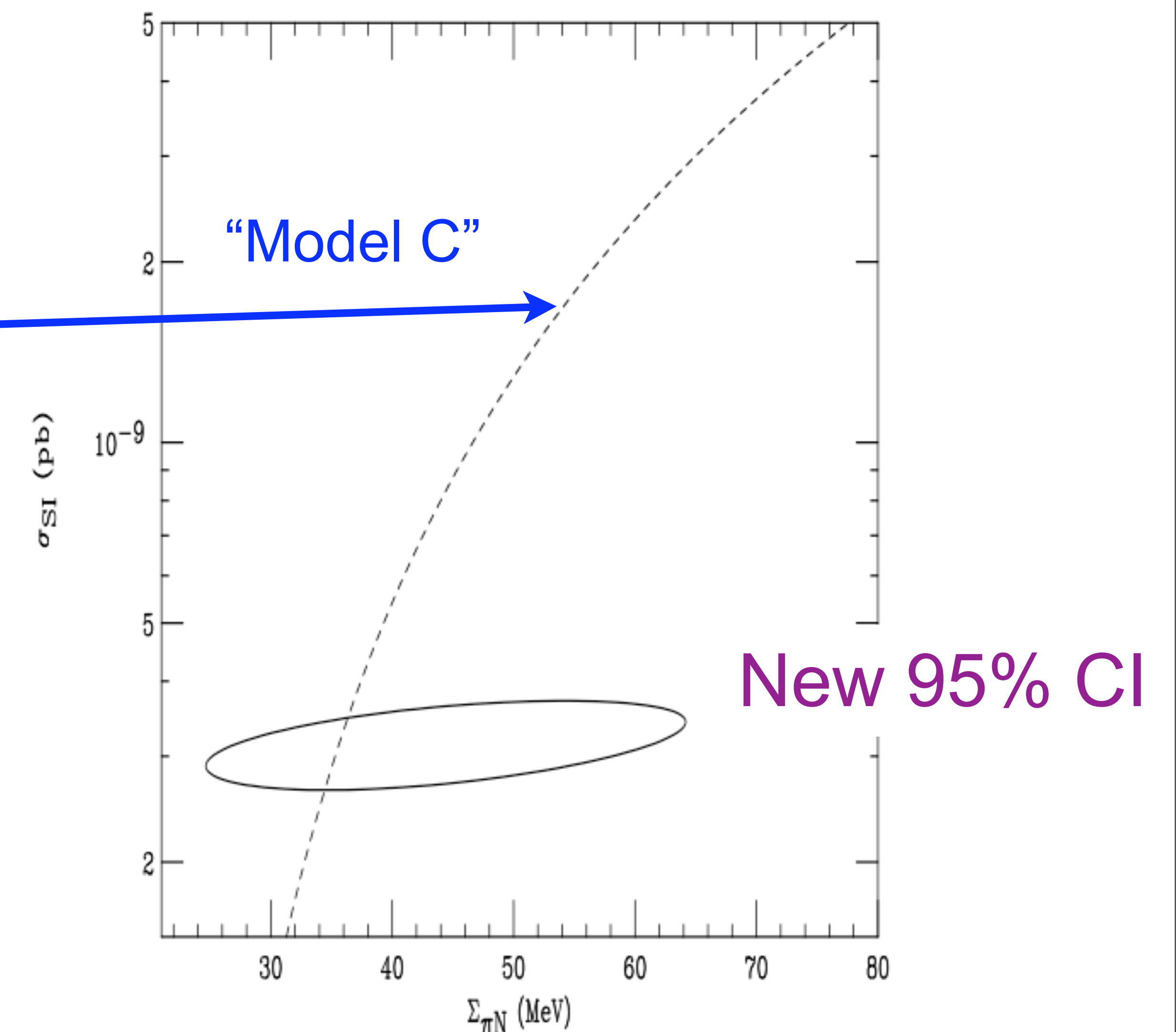
Strangeness sigma term is just local derivative at this point

Sigma terms from lattice QCD



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

XENON100

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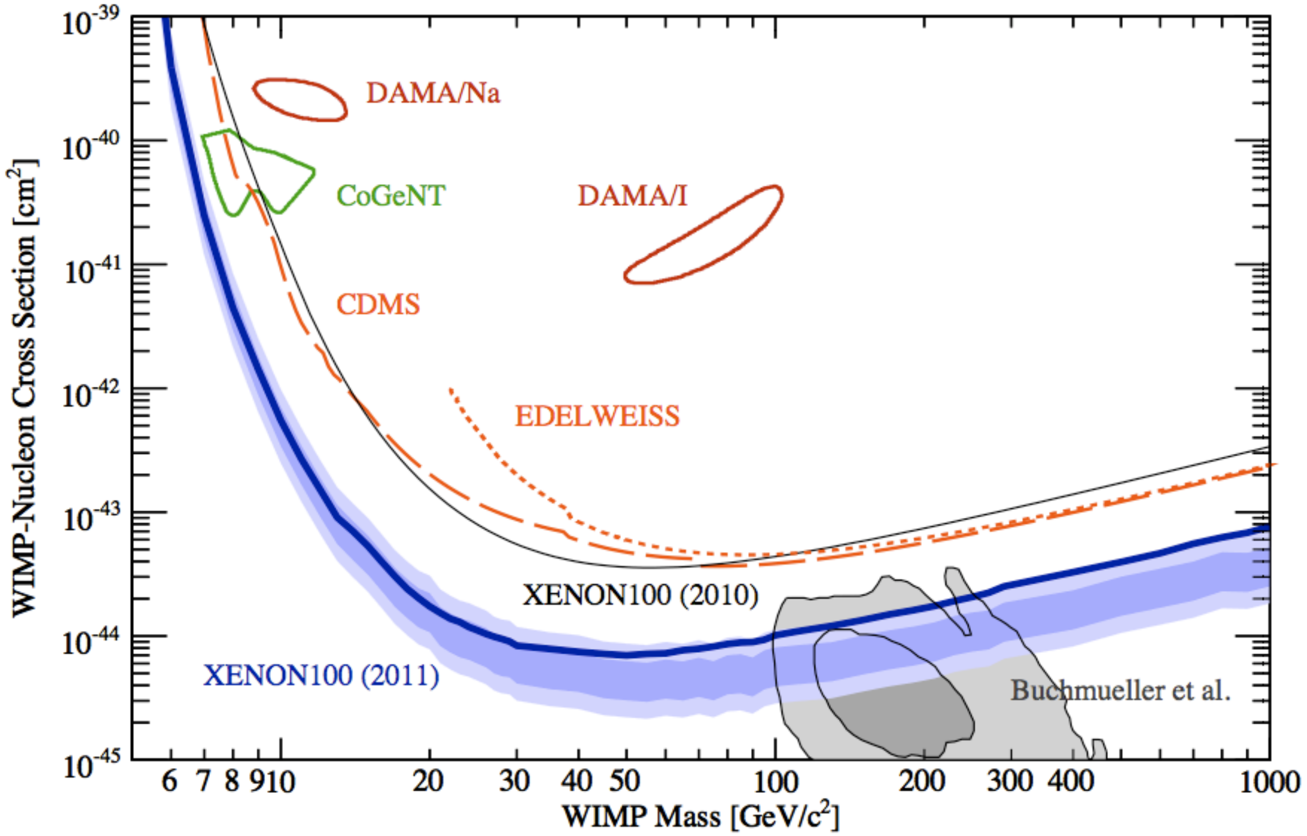

XENON100

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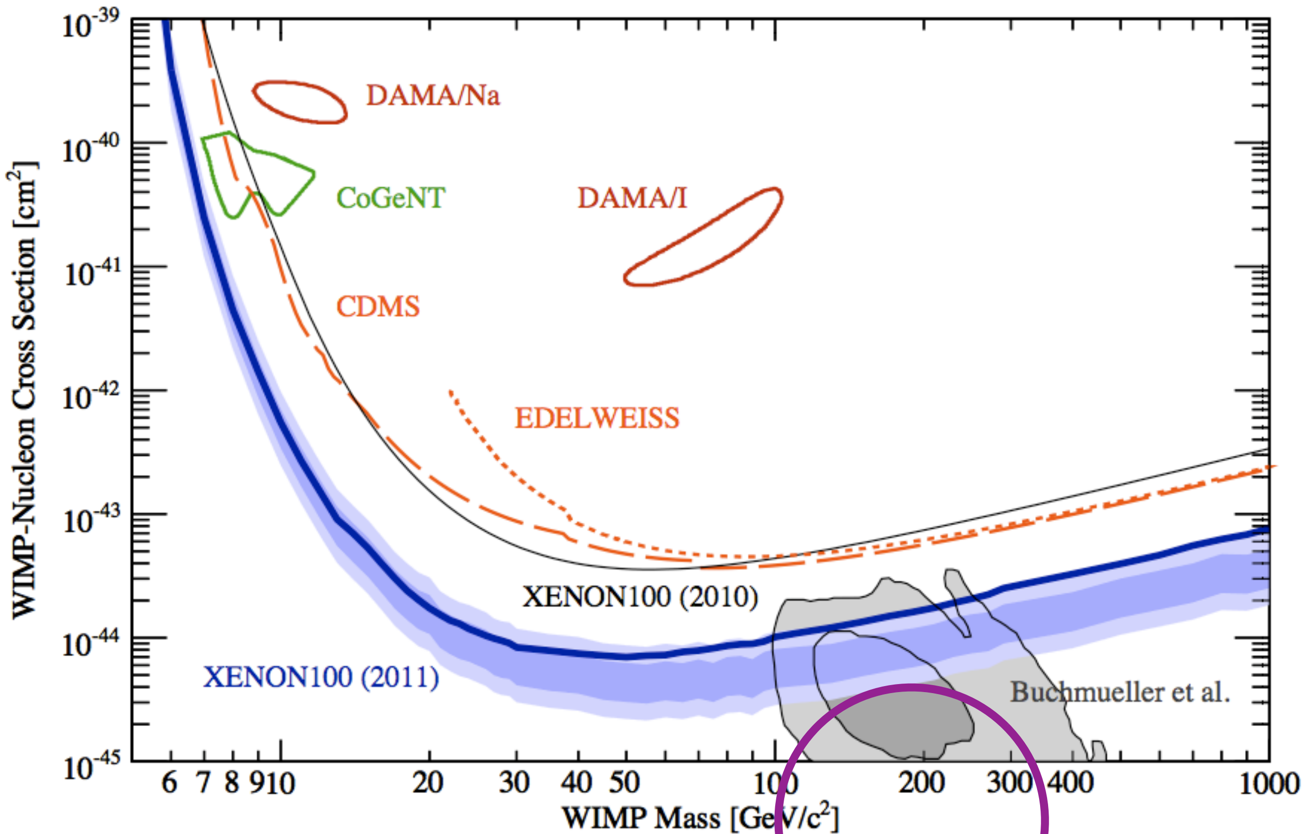
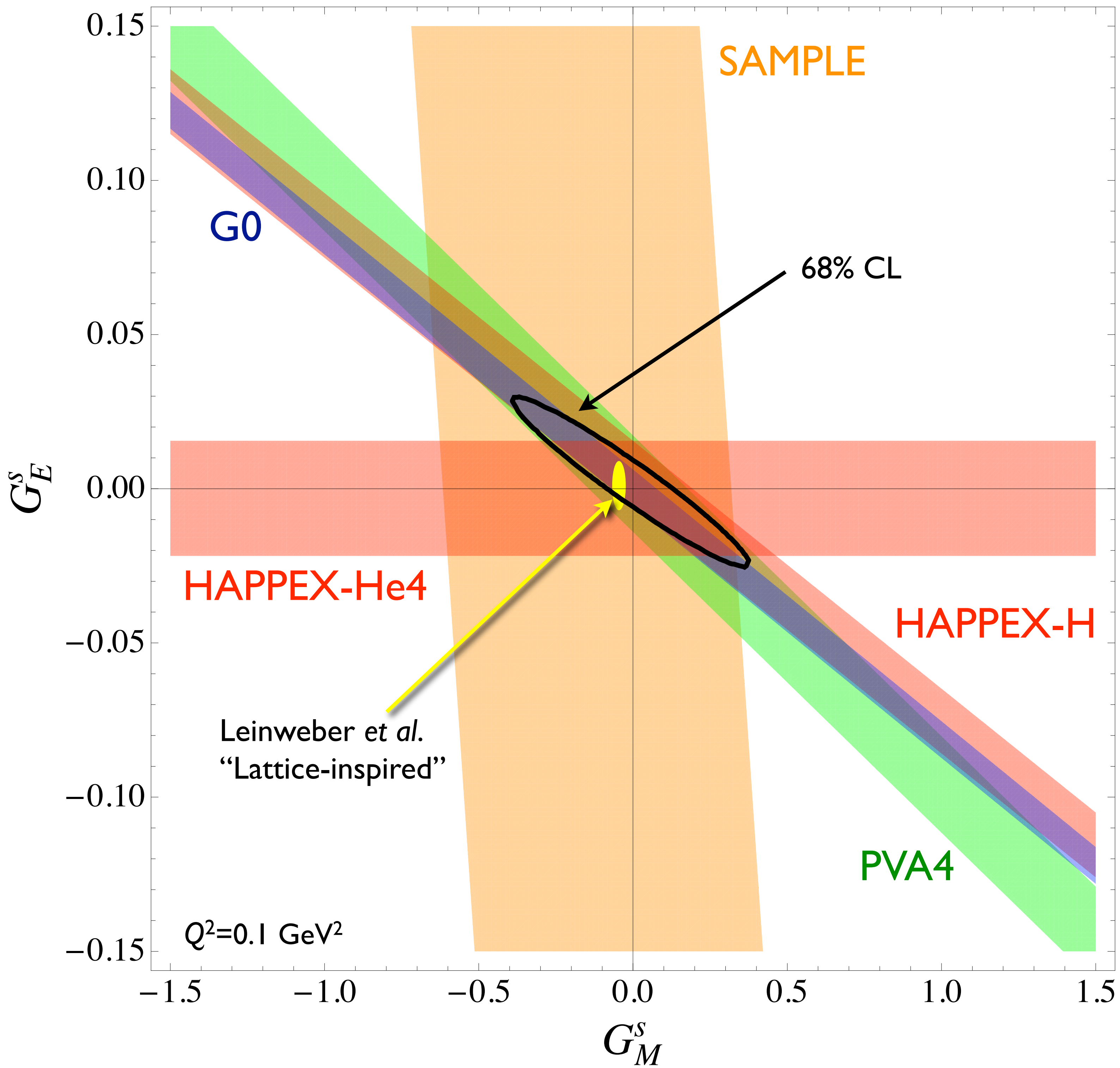
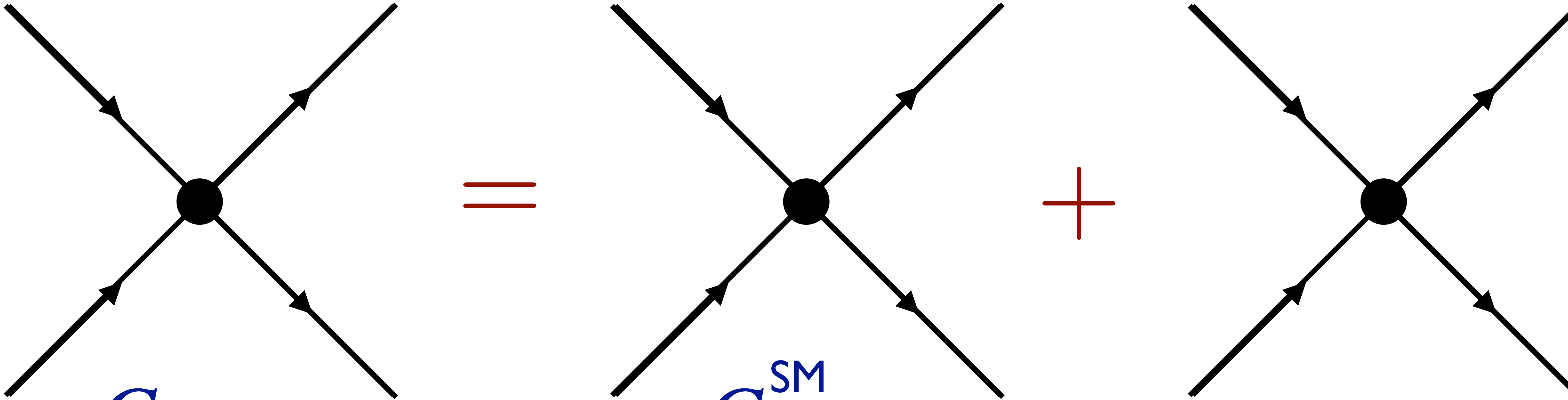


CMSSM

Combined global analysis



PV Electron-Quark Couplings

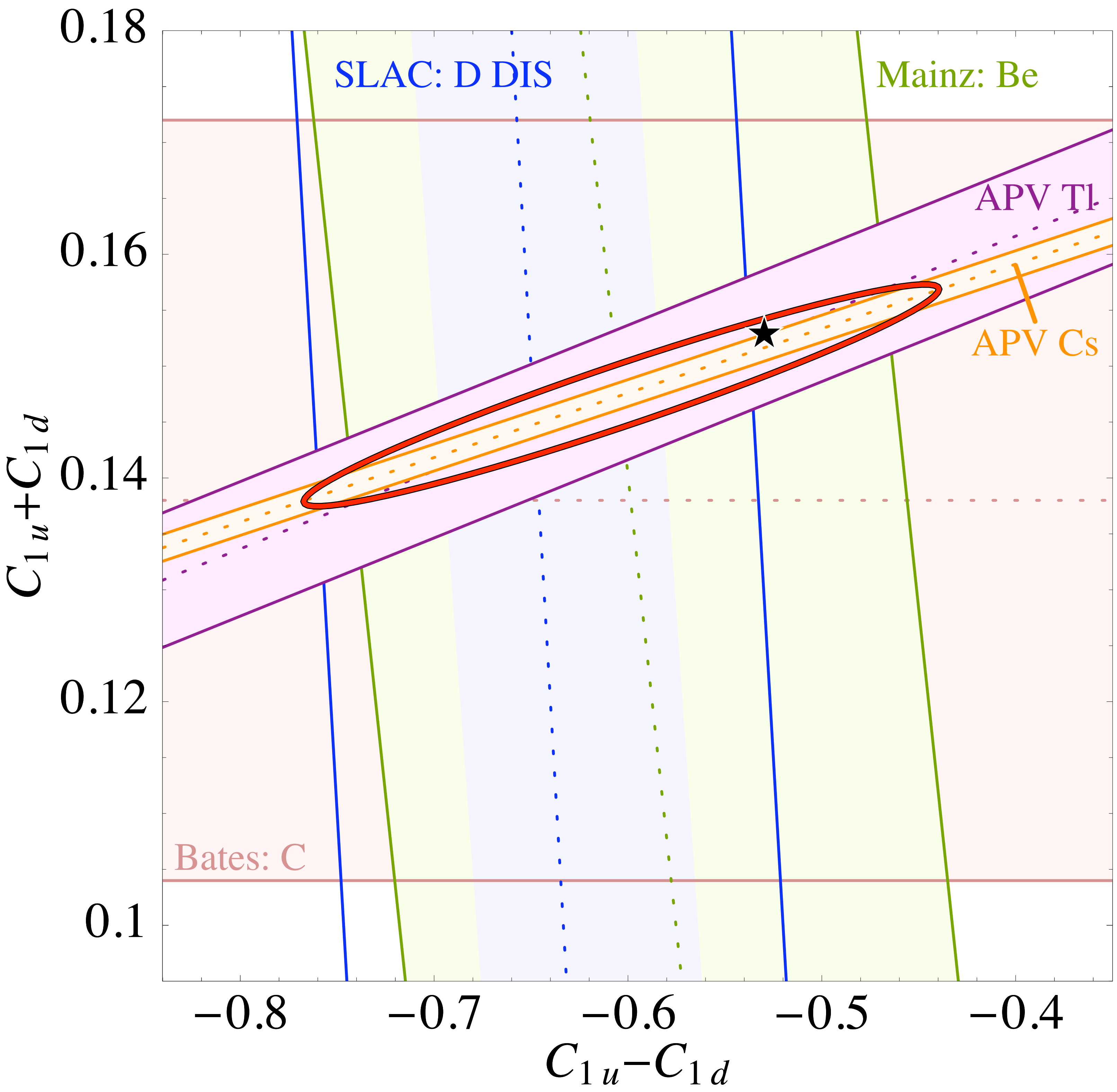


$C_{1(2)q} = C^{\mathrm{SM}}_{1(2)q} +$ new physics

Constrained by low-energy data!

$$\mathcal{L}^{\mathrm{PV}}_{\mathrm{SM}} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu\gamma_5 e \sum_q C^{\mathrm{SM}}_{1q} \bar{q}\gamma^\mu q$$

C1q Quark-Vector couplings (electron-axial)



95% CL

PV Asymmetry

- Proton

$$A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^{p\gamma} G_E^{pZ} + \tau G_M^{p\gamma} G_M^{pZ} - \frac{1}{2}(1 - 4\sin^2\theta_W)\varepsilon' G_M^{p\gamma} \tilde{G}_A^p}{\varepsilon (G_E^{p\gamma})^2 + \tau (G_M^{p\gamma})^2}$$

Neutral-weak form factors

Assume charge symmetry:

$$4G_{E,M}^{pZ} = (1 - 4\sin^2\theta_W) G_{E,M}^{p\gamma} - G_{E,M}^{n\gamma} - G_{E,M}^{s}$$

Proton weak charge

Strangeness

$$Q_{\text{weak}}^p = -2(2C_{1u} + C_{1d})$$

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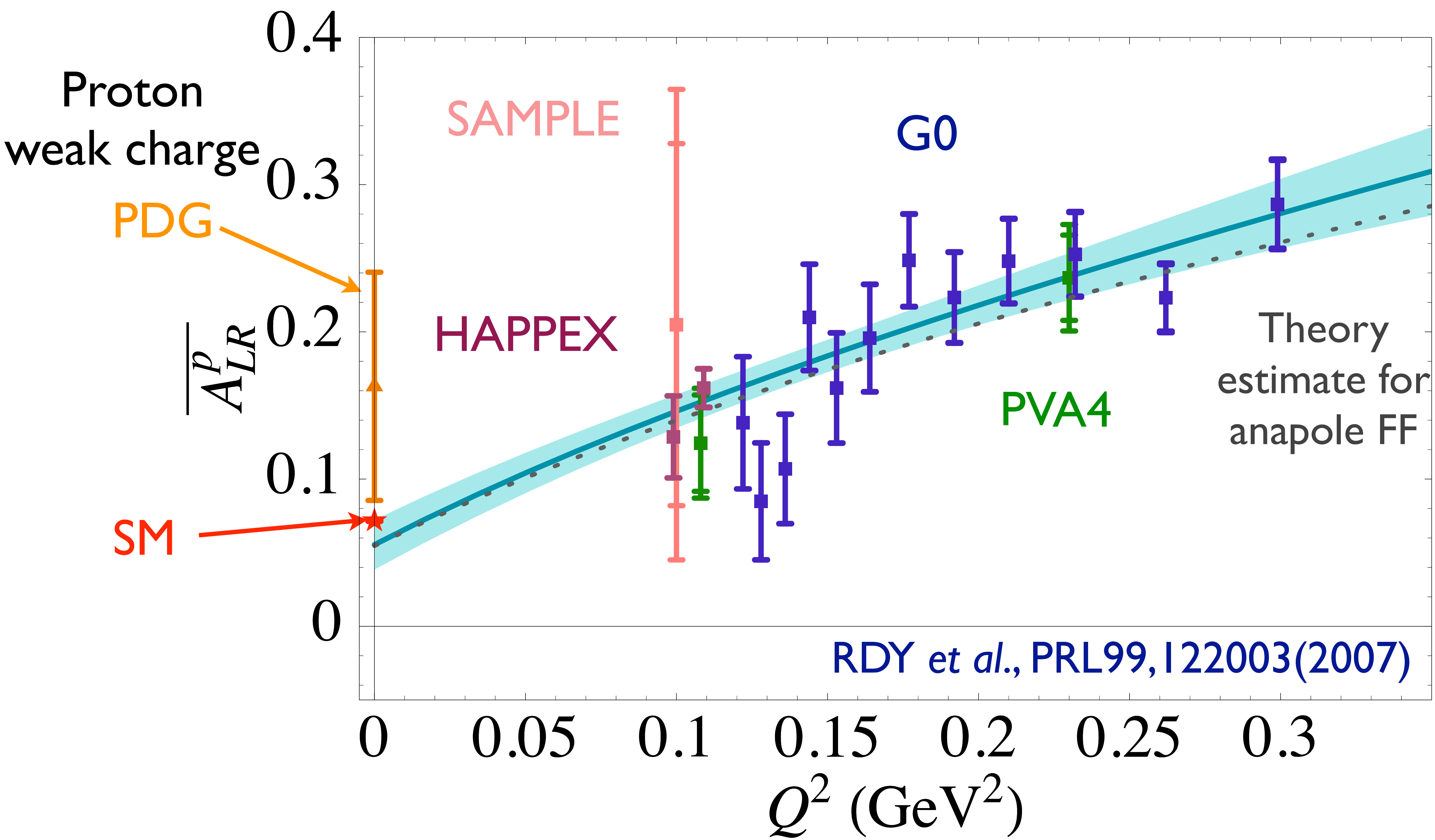
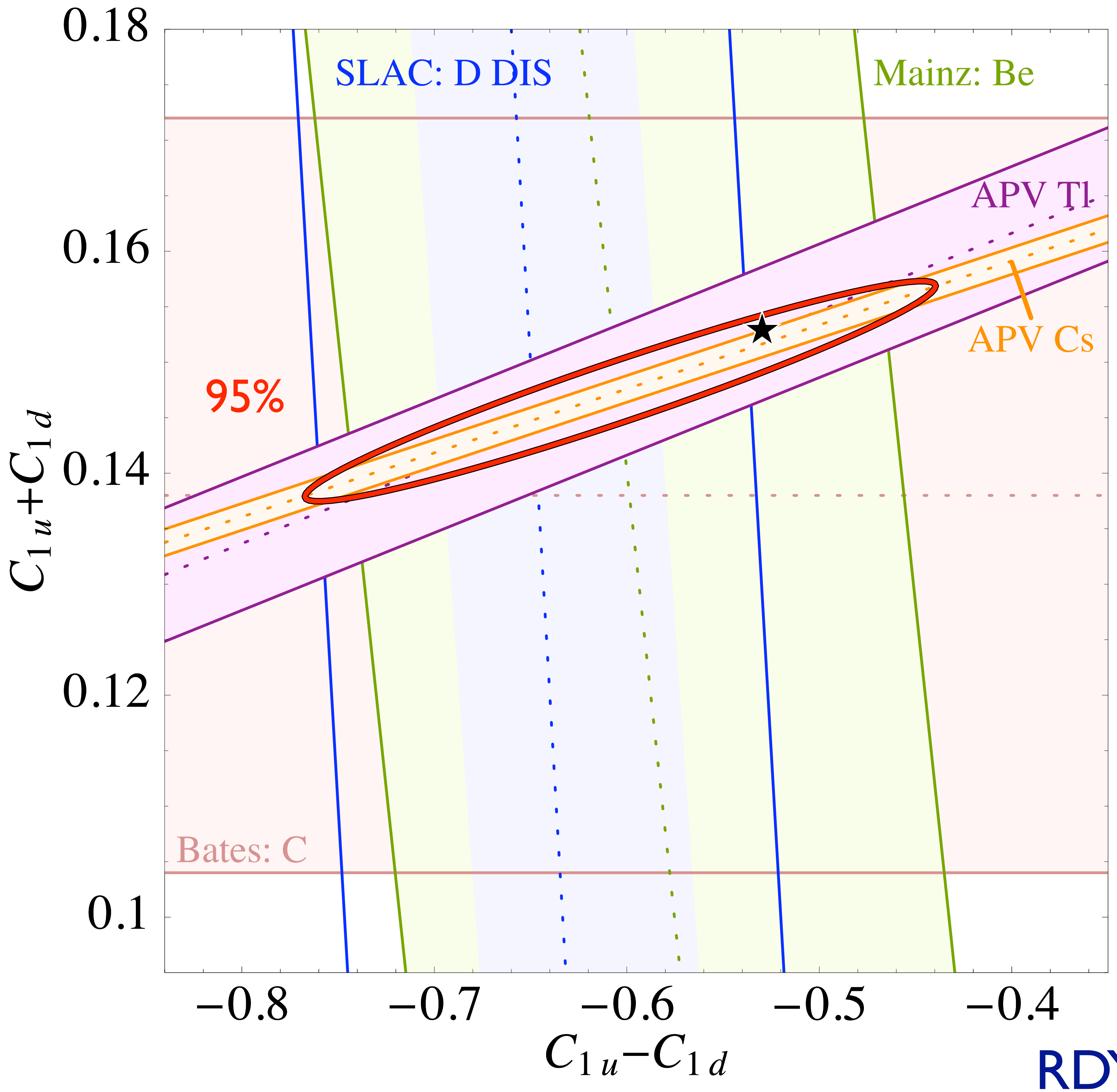
Use data to constrain the parameters of the electroweak theory

Proton Extrapolation



New update on C1q couplings



RDY *et al.*, PRL99,122003(2007)

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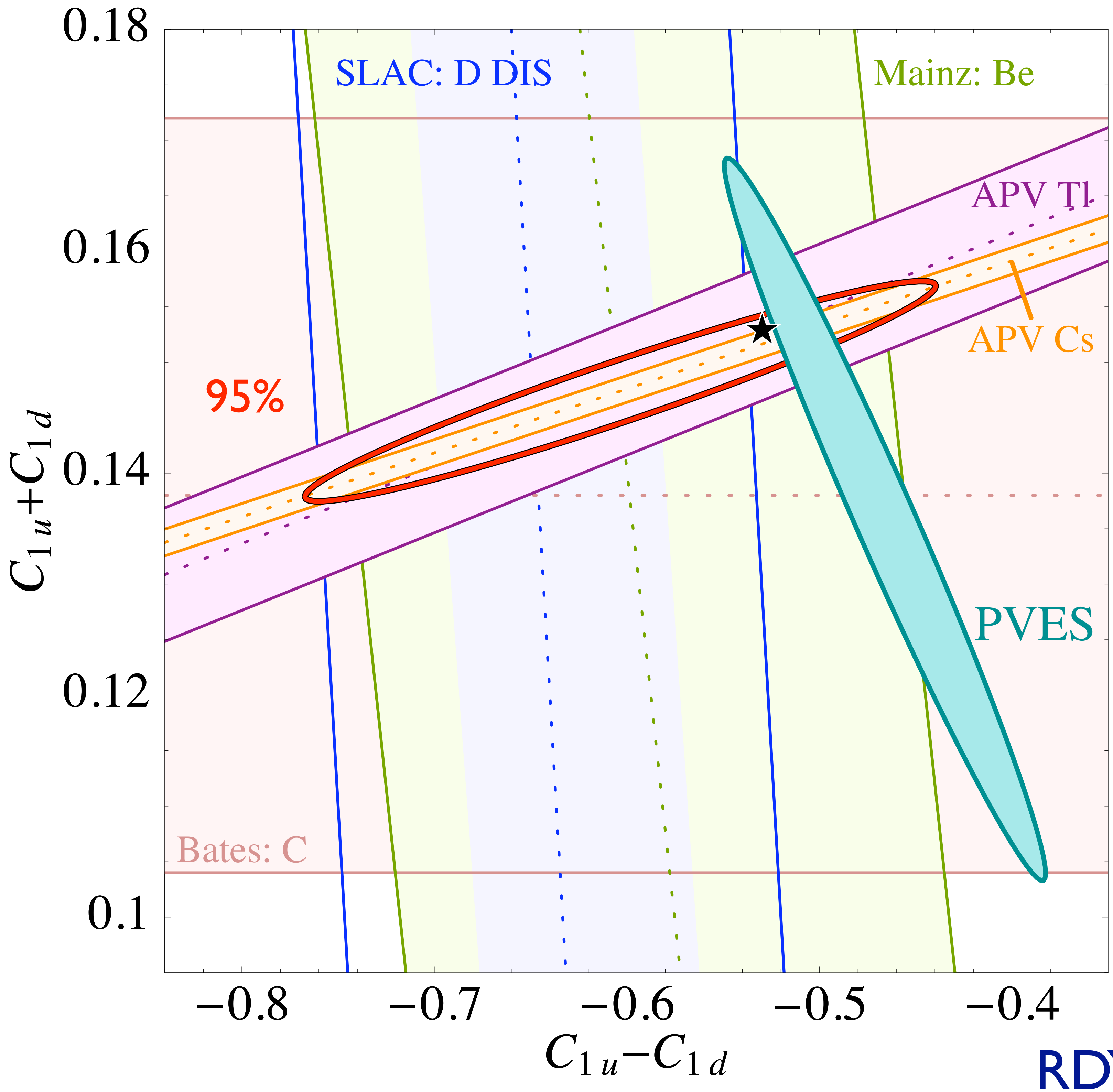

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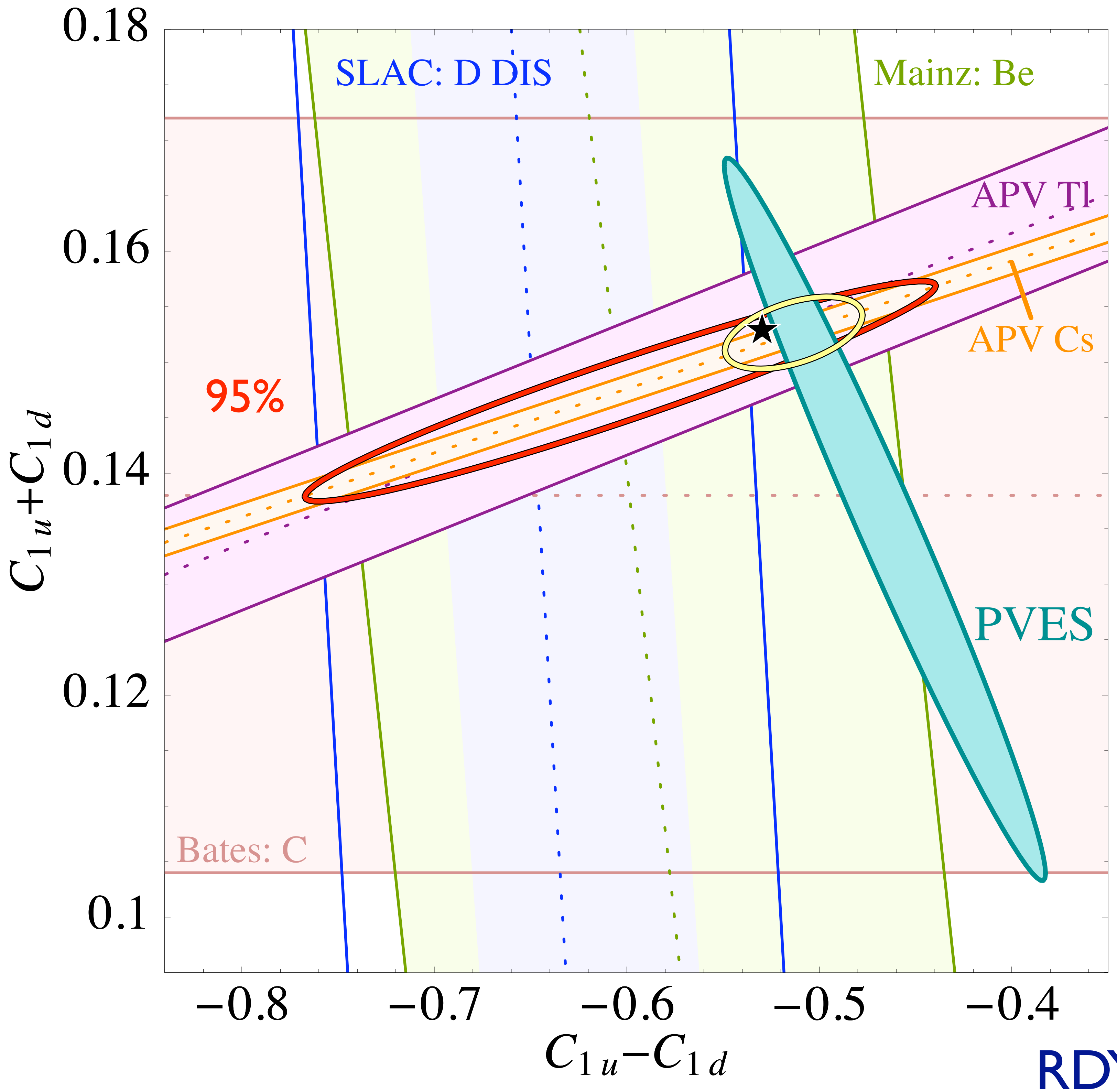

Dramatic improvement in knowledge of weak couplings!

RDY *et al.*, PRL99,122003(2007)

Limits on new physics

- One may be sensitive to a new heavy *Z'* boson contributing to a new contact interaction
- Imagine a new *Z'* which has exactly the same couplings to the SM fermions and mass $M_{Z'} \gg M_Z$
  - Simplest Kaluza-Klein excitation from a compact 5th dimension (circle radius *R*)

$$M_{Z_1}^2 = M_Z^2 + \frac{1}{R^2}$$

95% CL $\quad M_{Z_1} > 1.04\,\mathrm{TeV} \quad R < 2 \times 10^{-4}\,\mathrm{fm}$

~200 zeptometres

Model-independent limits

$$\mathcal{L}_{\rm SM}^{\rm PV} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}^{\rm SM}\bar{q}\gamma^\mu q$$

Erler et al., PRD68(2003)

$$\mathcal{L}_{\rm NP}^{\rm PV} = \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\bar{q}\gamma^\mu q$$

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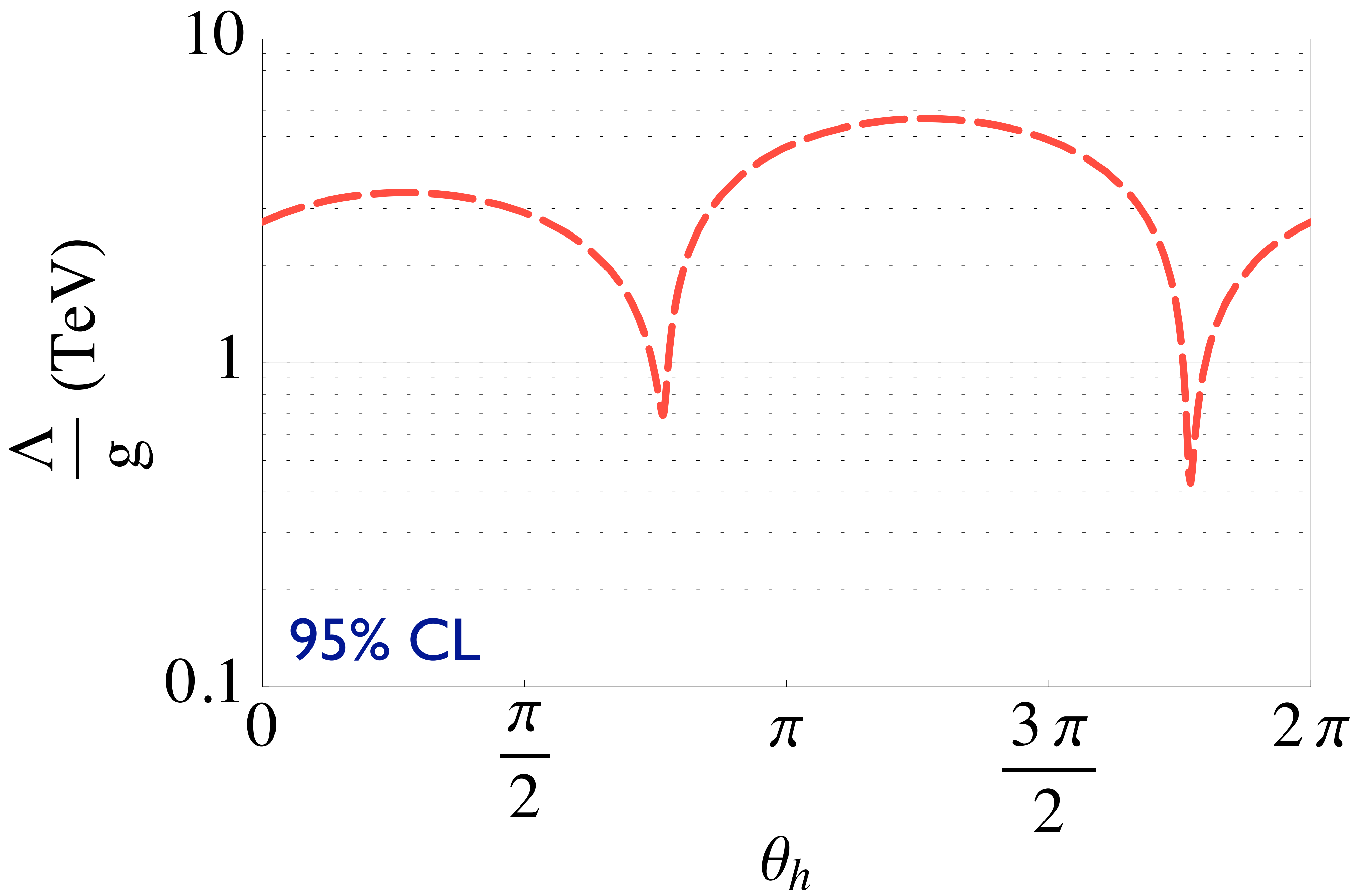
Full isospin coverage for limits on new physics!

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

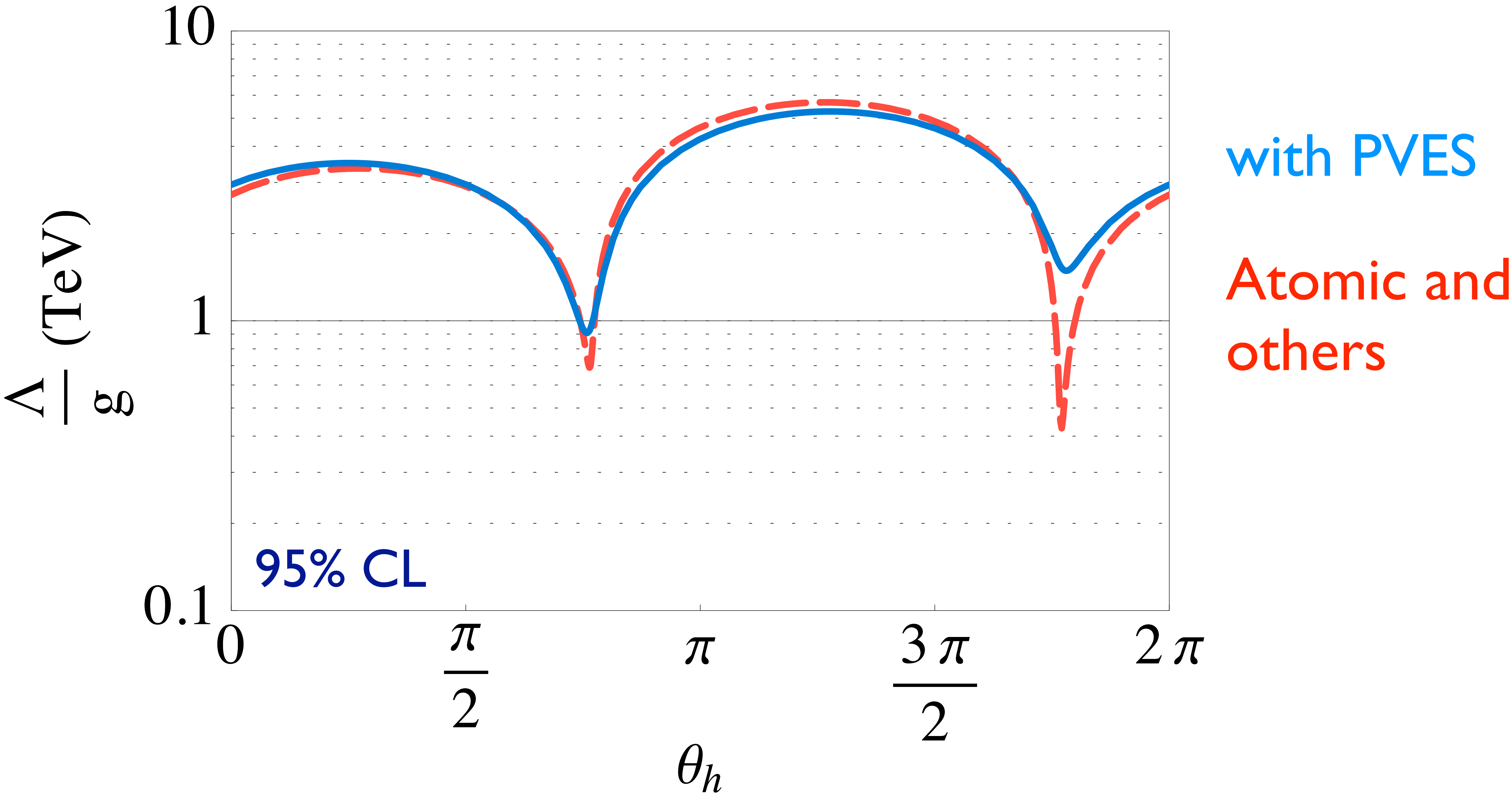
Data sets limits on $\dfrac{g^2}{\Lambda^2}$

Lower bound on NP scale



Atomic and others

Lower bound on NP scale



New physics scale >0.9 TeV! (from 0.4 TeV)

Reminder: Limits on ratio Λ/g

Weak coupling: eg. new perturbative Z'

$g \sim 0.1 \;\; \Rightarrow$ low mass limit

(also low yield in colliders)

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Strong coupling: eg. compositeness

$g \sim \sqrt{4\pi} \;\; \Rightarrow$ large mass reach
strength of precision tests

Future: Q-weak Experiment

- Precise measurement of the proton's weak charge in PVES

$$Q^{p}_{\rm weak} = -2(2C_{1u} + C_{1d})$$

$$Q^2 = 0.03\,\mathrm{GeV}^2,\ \theta = 8^\circ$$

- At low energy and small scattering angle:

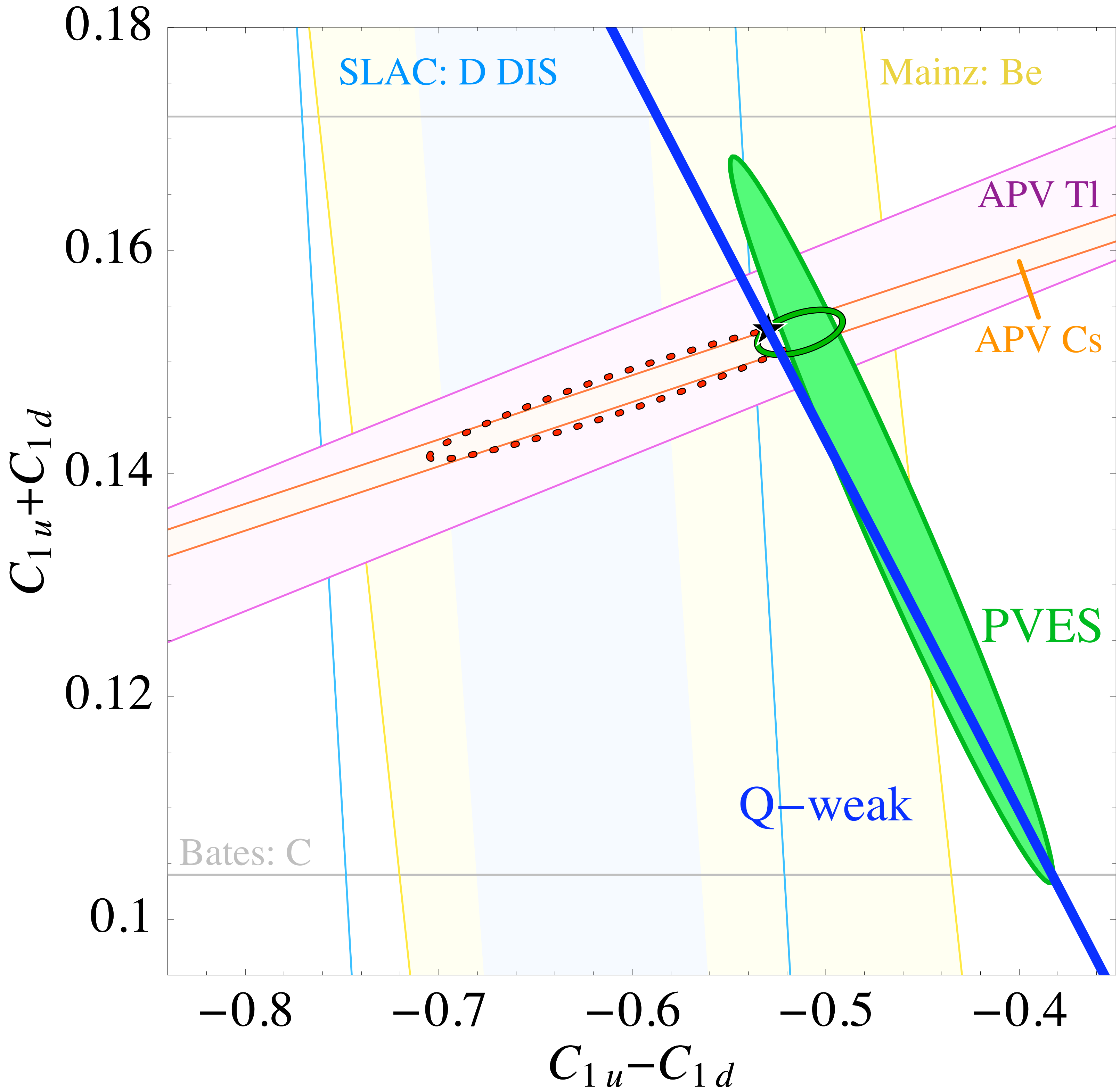
$$A_{LR} = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[Q_{\rm weak} + \beta_A \tilde{G}^p_A \sqrt{Q^2} + \beta_V Q^2 + \ldots\right]$$

$$\beta_A \propto \theta + O(\theta^3)$$

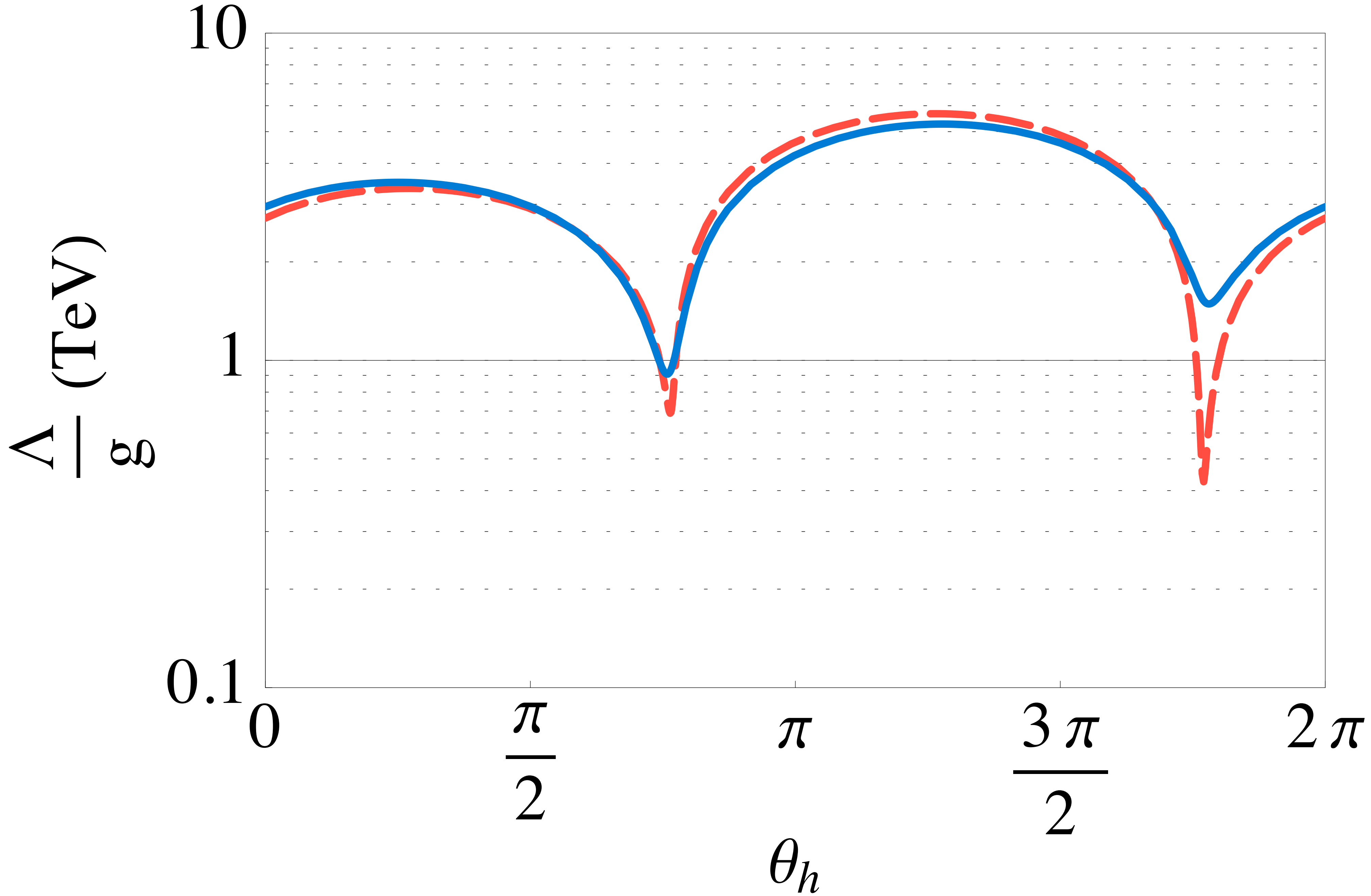
Strangeness uncertainty

Anapole uncertainty

Impact of Q-weak



Impact of Q-weak (assuming SM)

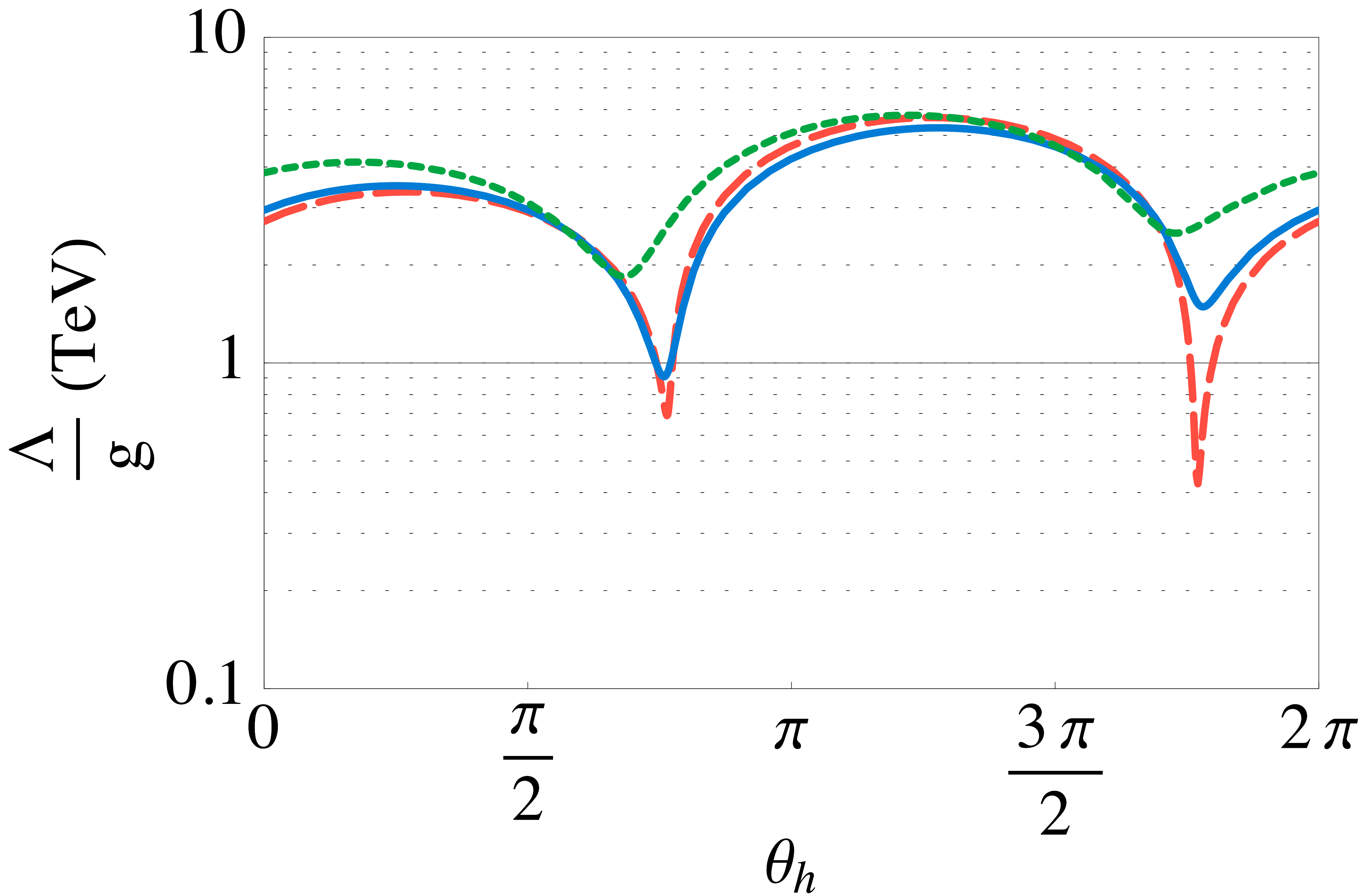


with PVES

Atomic and others

95% CL

Impact of Q-weak (assuming SM)



future *Q*-weak

with PVES

Atomic and others

95% CL

Q-weak constrains new physics to beyond 2 TeV

What about Q-weak discovery?

Assume Q-weak takes central value of current measurements