Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics
LRP Town Meeting, Chicago, September 28-29 2014

Weak Decays: theory, motivation, landscape

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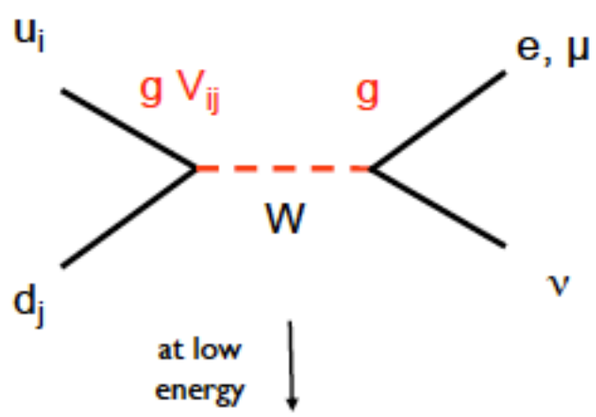
Outline

- Beta decays and new physics: generalities
- Overview of probes and opportunities
- Connection with high-energy landscape
- Conclusions

β-decays and BSM physics

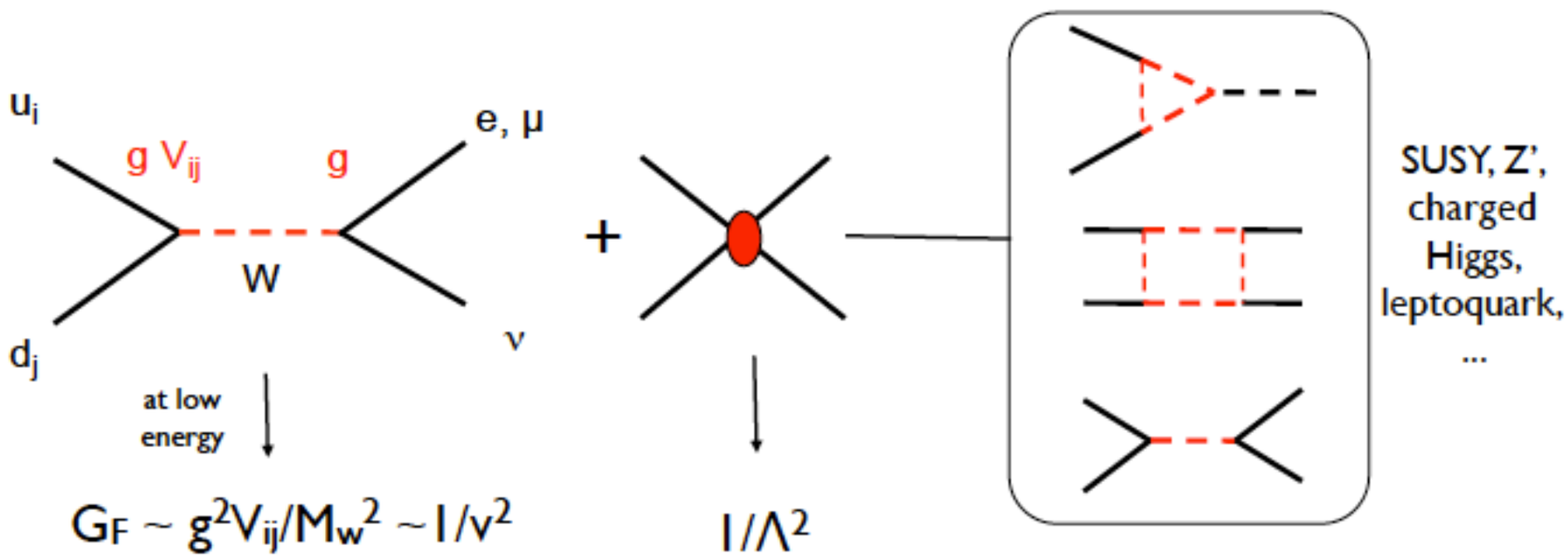
- In the SM, W exchange (V-A, universality)



$G_F \sim g^2 V_{ij}/M_w^2 \sim 1/v^2$

β-decays and BSM physics

- In the SM, W exchange (V-A, universality)



- BSM: sensitive to tree-level and loop corrections from large class of models → "broad band" probe of new physics

- Name of the game: precision! To probe BSM physics at scale Λ, need expt. & th. at the level of $(v/\Lambda)^2$: $\leq 10^{-3}$ is a well motivated target

- Effect of *any* new physics encoded in ten *quark-level* couplings

$$
\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[(1+\epsilon_L)\;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \;\epsilon_R\;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \;\epsilon_S\;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \\
& - \;\epsilon_P\;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
& + \;\epsilon_T\;\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.} \\
& + \qquad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell
\end{aligned}
$$

$$\epsilon_i \;, \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

Linear sensitivity to ε_i (interference with SM)

Quadratic sensitivity to $\tilde{\varepsilon}_i$ (interference suppressed by m_ν/E)

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Linear sensitivity to ε_i (interference with SM)

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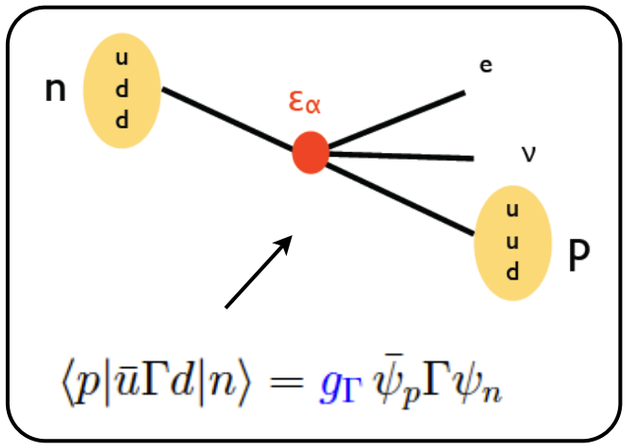
Example: $g_{V,A,S,T,P}$



- To connect experiment to (B)SM couplings, need radiative corrections + hadronic & nuclear matrix elements

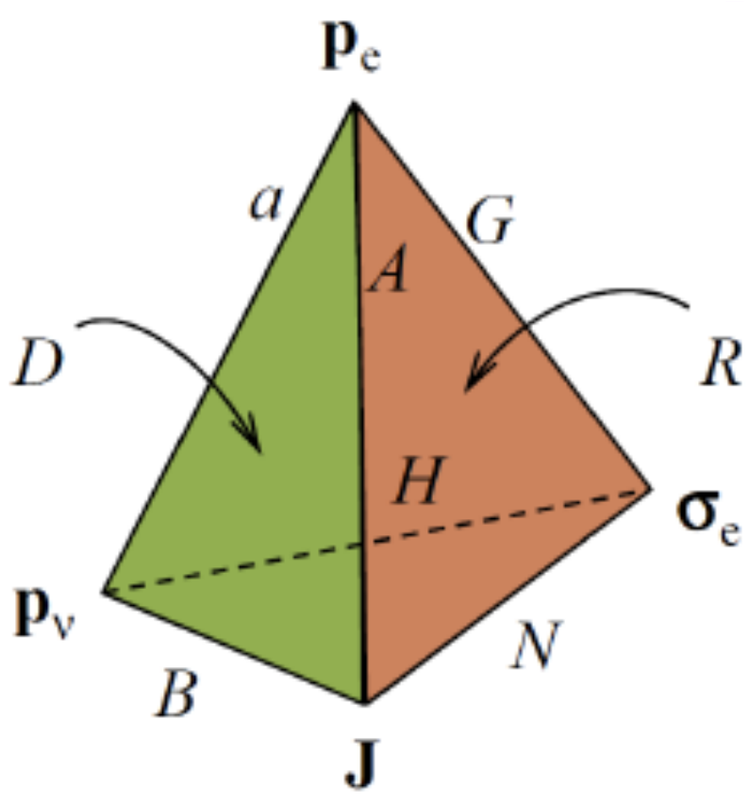
How do we probe the ε's?

- Rich phenomenology, two classes of observables:

1. Differential decay rates (probe non V-A via "b" and correlations)

$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Lee-Yang, Jackson-Treiman-Wyld



$a(g_A, \varepsilon_\alpha)$, $A(g_A, \varepsilon_\alpha)$, $B(g_A, \varepsilon_\alpha)$, ...
isolated via suitable
experimental asymmetries

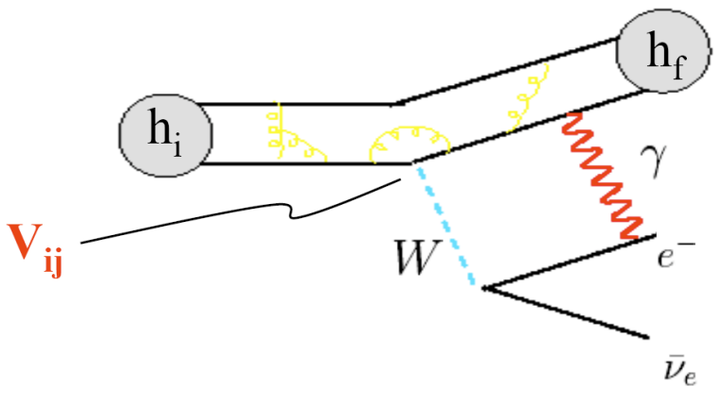
How do we probe the ε's?

- Rich phenomenology, two classes of observables:

1. Differential decay rates (probe non V-A via "b" and correlations)
2. Total decay rates (probe mostly V, A via extraction of V_{ud}, V_{us})

$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Channel-dependent
effective CKM element



$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)

Non-standard coupling	Observable	Current sensitivity
$\mathrm{Re}(\epsilon_L + \epsilon_R)$	Δ_{CKM}	$\sim 0.05\%$
$\mathrm{Im}(\epsilon_R)$	D_n	$\sim 0.05\%$
$\epsilon_P, \quad \tilde{\epsilon}_P$	$R_\pi = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$	$\sim 0.05\%$
$\mathrm{Re}(\epsilon_S)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}]$	$\sim 0.5\%$
$\mathrm{Im}(\epsilon_S)$	R_n	$\sim 10\%$
$\mathrm{Re}(\epsilon_T)$	$b, \ B, \ [\tilde{a}, \ \tilde{A}, \ \tilde{G}], \quad \pi \to e\nu\gamma$	$\sim 0.1\%$
$\mathrm{Im}(\epsilon_T)$	$R_{s_{Li}}$	$\sim 0.2\%$
$\tilde{\epsilon}_{\alpha\neq P}$	a, b, B, A	$\sim 5 - 10\%$

$$\tilde{Y}(E_e) = \frac{Y(E_e)}{1 + b\, m_e/E_e + \ldots}$$

VC, S.Gardner, B.Holstein 1303.6953
Gonzalez-Alonso & Naviliat-Cuncic 1304.1759

Snapshot of the field

- This table summarizes a large number of measurements and th. input
- Already quite impressive. Effective scales in the range Λ= 1-10 TeV ($\Lambda_{SM} \approx$ 0.2 TeV)
- Focus on probes that depend on the ε's *linearly*

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CKM unitarity: input

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\mathrm{CKM}}(\epsilon_i)$$

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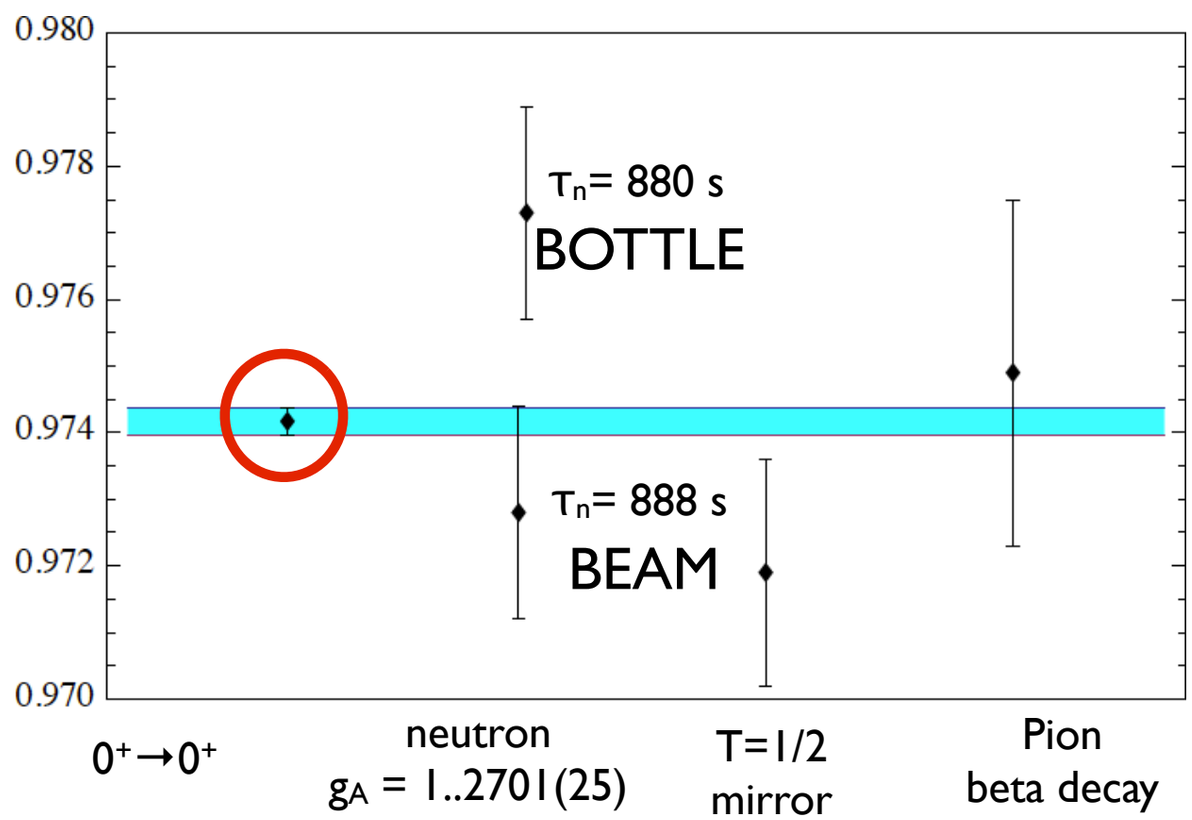
V_{ud}



V_{ud} = 0.97417(21)

Hardy-Towner 2014

- Extraction dominated by $0^+ \rightarrow 0^+$ transitions

Critical theoretical input :δ_C (A,Z) [isospin-brk].
Existing calculations accepted/rejected through experimental validation (Hardy-Towner 2014).
Area of growing activity (e.g. GFMC, S. Pieper)

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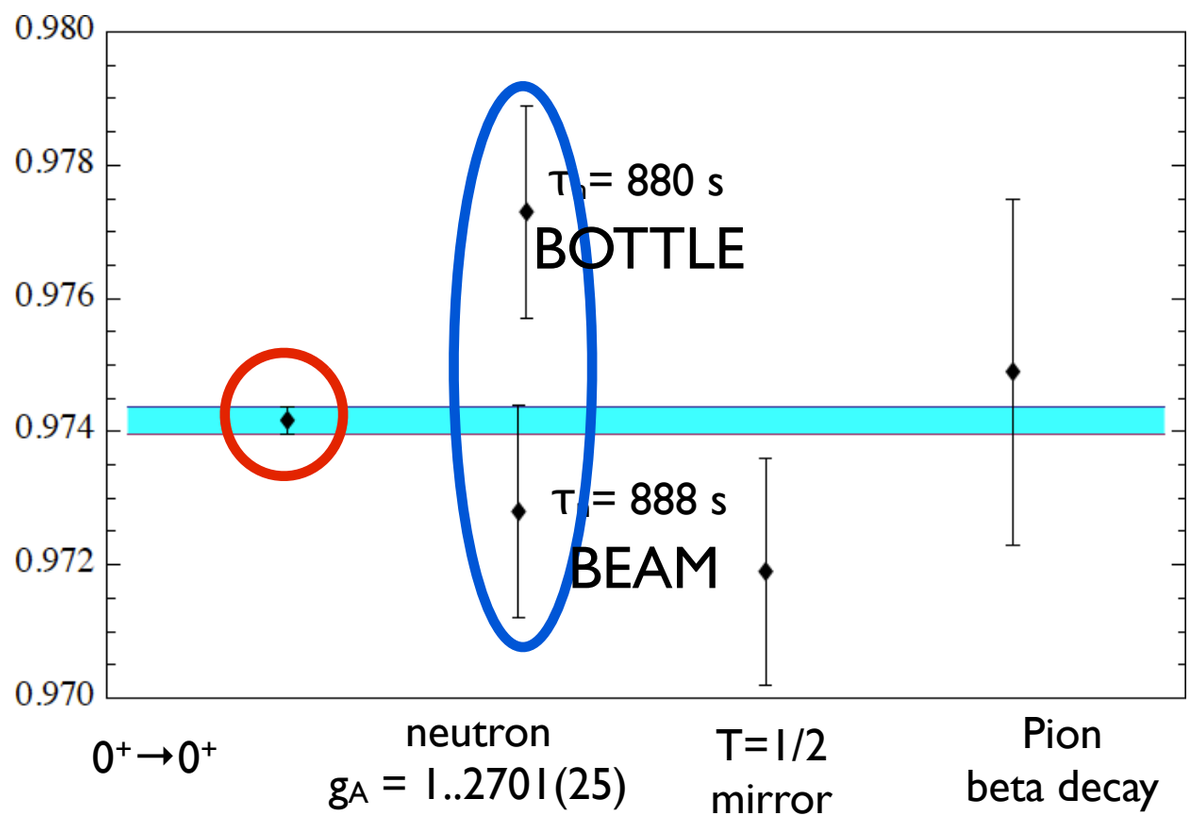
V_{ud}



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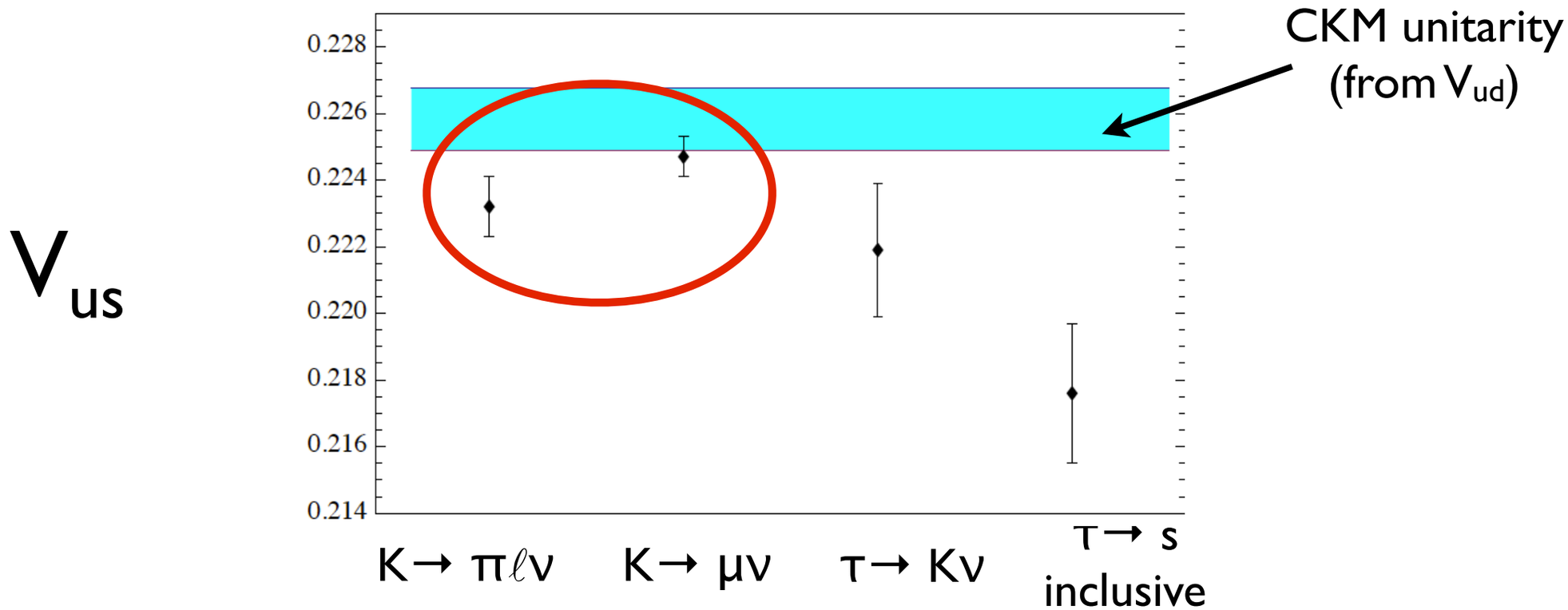
- Not yet competitive:

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n\,(1+3g_A^2)}\right]^{1/2}$$

Czarnecki, Marciano, Sirlin 2004

CKM unitarity: input

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



- Improved LQCD calculations have led to smaller V_{us} from $K\to\pi\ell\nu$

$f_+^{K\to\pi}(0) = 0.959(5) \rightarrow 0.970(3)$

$F_K/F_\pi = 1.1960(25)$ [stable]

$m_\pi \to m_\pi^{phys}$, $a \to 0$, dynamical charm

$V_{us} = 0.2254(13) \rightarrow 0.2232(9)$

$V_{us}/V_{ud} = 0.2308(6)$

FLAG 2013 + MILC 2014

CKM unitarity: test

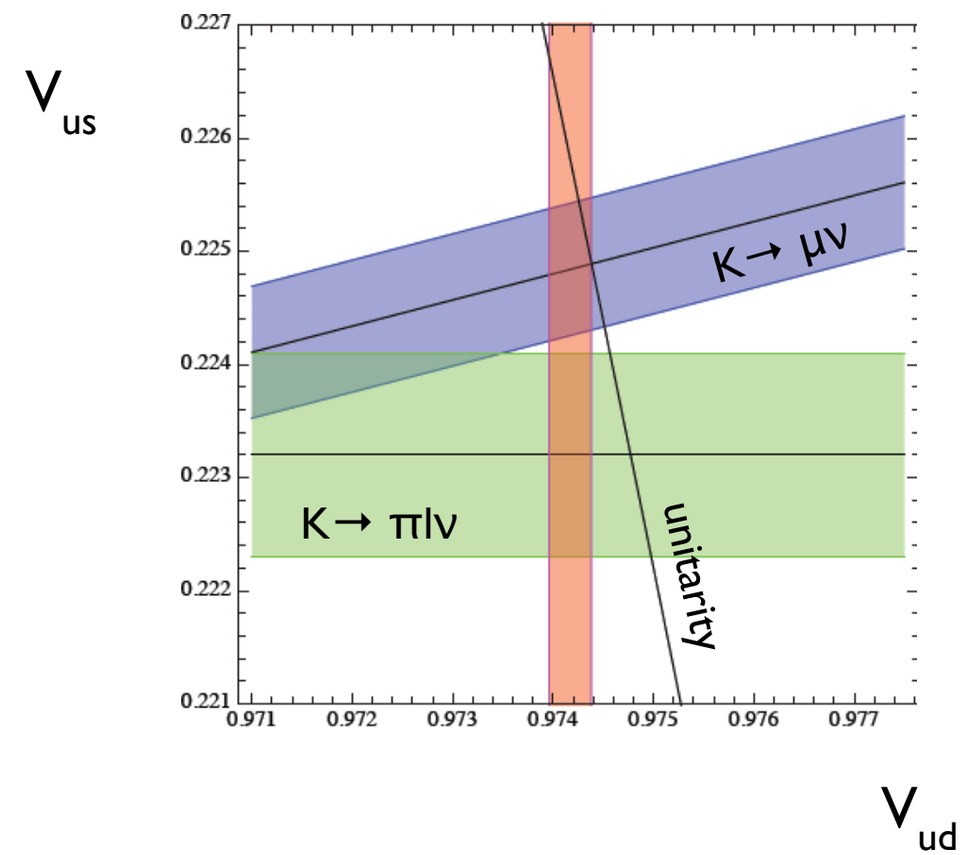
$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

V_{us} from $K \to \mu\nu$

$\Delta_{CKM} = -(4 \pm 5) * 10^{-4}$ 0.9 σ

$\Delta_{CKM} = -(12 \pm 6) * 10^{-4}$ 2.1 σ

V_{us} from $K \to \pi l \nu$



- No longer perfect agreement with SM. This could signal:
  - New physics in $\varepsilon_{R,P}^{(s)}$ (Kl2 vs Kl3) <u>and</u> in $\varepsilon_L+\varepsilon_R$, $\varepsilon_{L,R}^{(s)}$ (Δ_{CKM})
  - Systematics in data** or theory: δ_C (A,Z), $f_+(0)$, F_K/F_π

CKM unitarity: opportunities

- Given high stakes (0.05% EW test), compelling opportunities emerge:
  - Robustness of δ_C: nucl. str. calculations + experimental validation
  - Pursue V_{ud} through mirror nuclear transitions
  - Pursue V_{ud} @ 0.02% through neutron decay

$$V_{ud} = \left[\frac{4908.7(1.9)\ s}{\tau_n\,(1+3g_A^2)}\right]^{1/2}$$

$\delta\tau_n \sim 0.35$ s

$\delta\tau_n/\tau_n \sim 0.04$ %

BL2, BL3 (cold beam), UCNτ, ...

$\delta g_A/g_A \sim 0.025\%$

($\delta a/a$, $\delta A/A \sim 0.1\%$)

aCORN, Nab, UCNA+, ...

The case for $\delta\tau_n \sim 0.3$s

- Key ingredient for V_{ud} @ 0.02%, free of nucl. structure (→ Δ_{CKM} test)

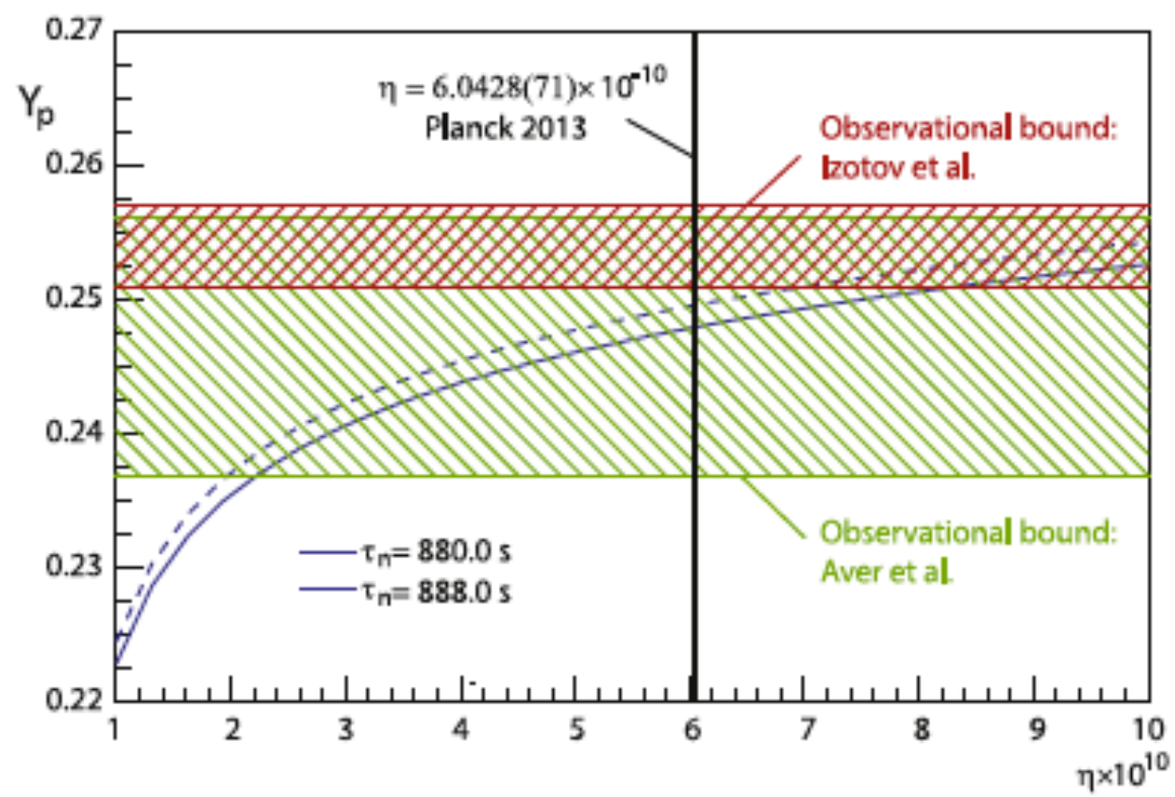
- V_{ud} (n) and V_{ud} ($0^+ \rightarrow 0^+$) sensitive to different new physics!

$$\frac{\bar{V}_{ud}|_n}{\bar{V}_{ud}|_{0^+}} = 1 + c_S\,\epsilon_S + c_T\,\epsilon_T$$

c_S, c_T ~O(1)

- Remove largest error in the prediction of primordial ^{4}He abundance

Observations may reach this level in the next decade

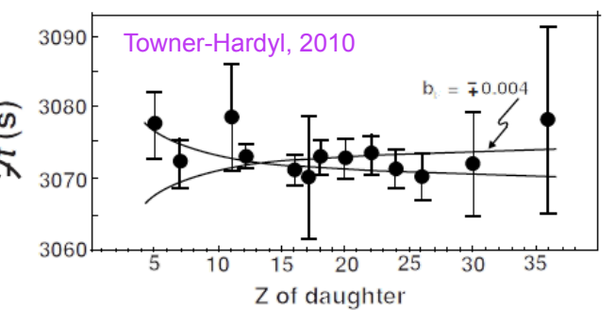


Scalar and tensor couplings

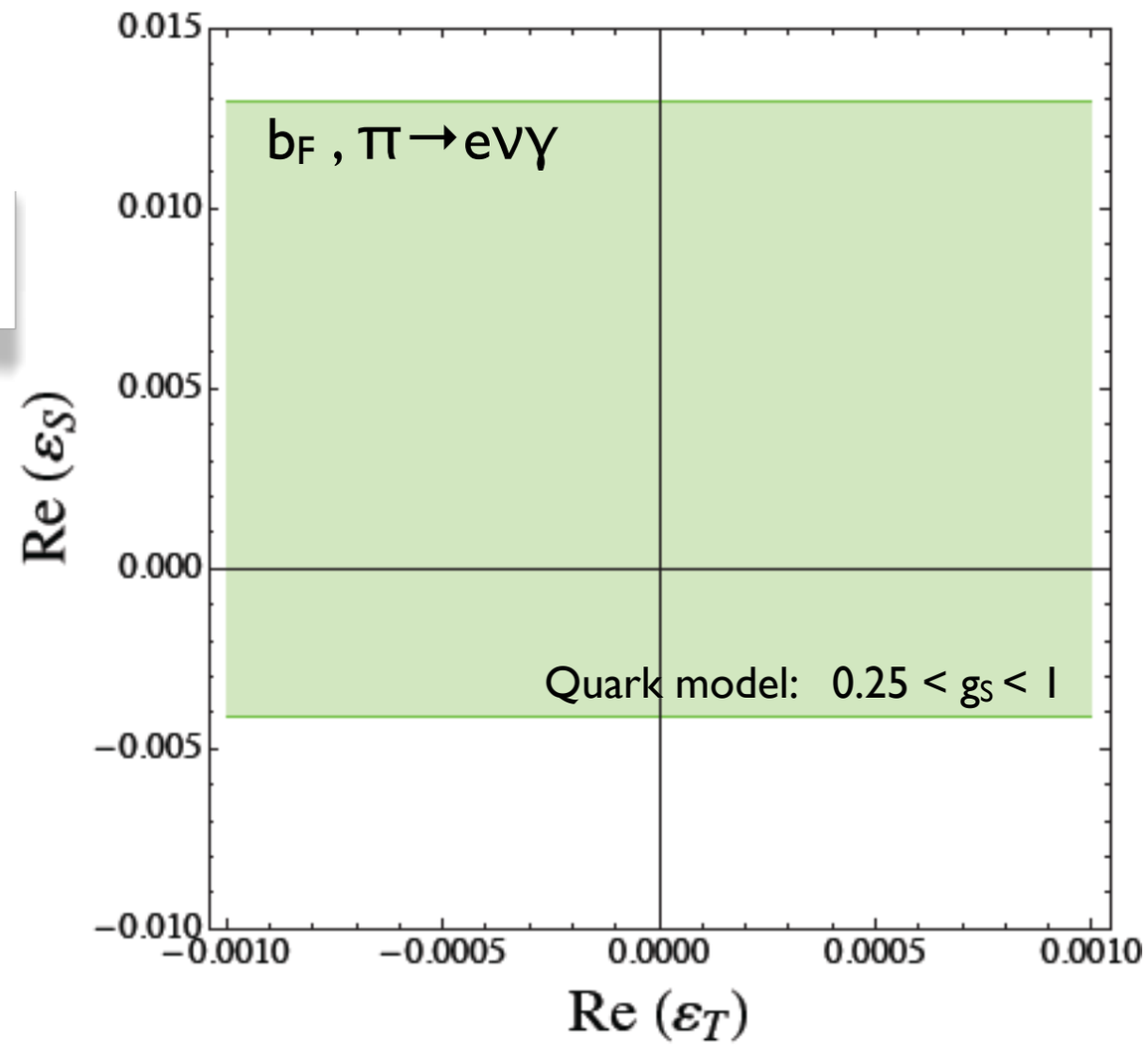
CURRENT

- Current most sensitive probes**:

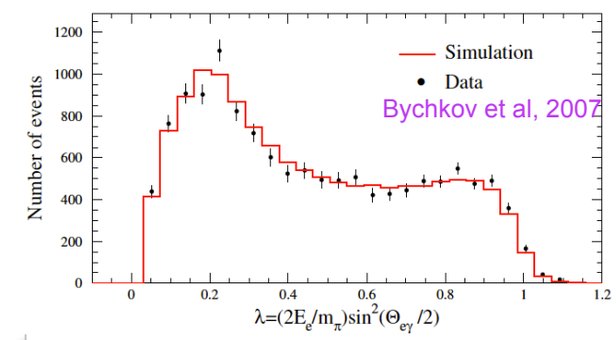
$0^+ \to 0^+$ (b_F)



$-1.0\times10^{-3} < g_S\, \varepsilon_S < 3.2\times10^{-3}$



$\pi \to e\,\nu\,\gamma$



$-2.0\times10^{-4} < f_T\, \varepsilon_T < 2.6\times10^{-4}$

$f_T = 0.24(4)$

** For global analysis see Wauters et al, 1306.2608

Scalar and tensor couplings

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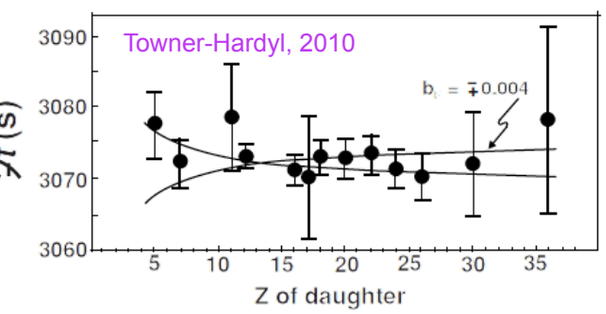

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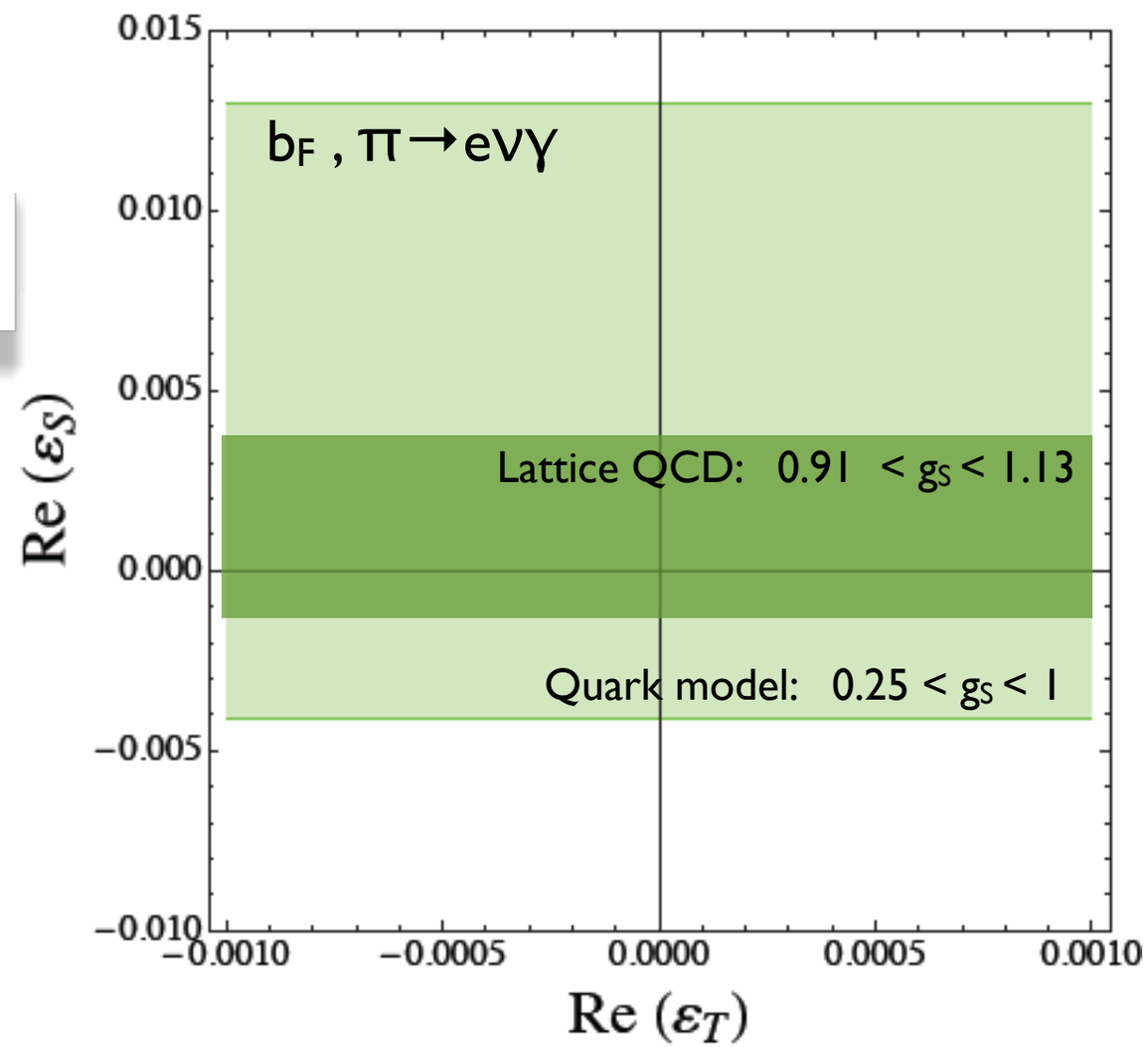

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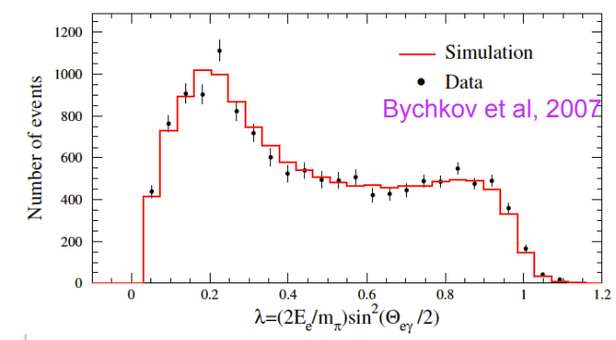


$-2.0\times10^{-4} < f_T\, \varepsilon_T < 2.6\times10^{-4}$

$f_T = 0.24(4)$

Impact of improved theoretical calculations using lattice QCD

Bhattacharya, et al 1110.6448

R. Gupta et al. 2014

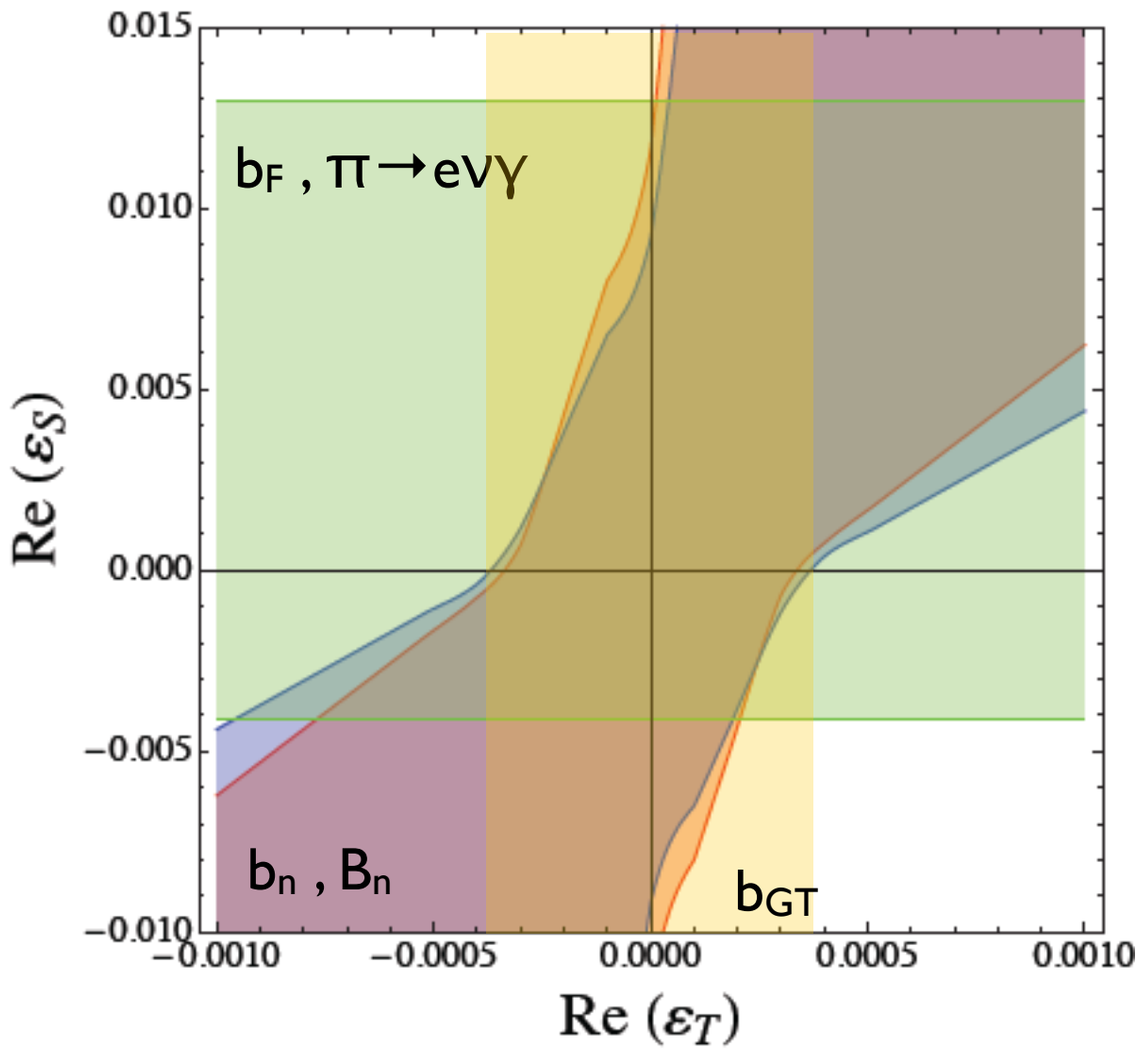
** For global analysis see Wauters et al, 1306.2608

Scalar and tensor couplings

FUTURE

- Several precision measurements on the horizon (neutron & nuclei)
- For definiteness, study impact of b_n, B_n @ 10^{-3}; b_{GT} (^{6}He, ...) @10^{-3}

Nab,
UCNB,
^{6}He,
...



Quark model:

$0.25 < g_S < 1$

$0.6 < g_T < 2.3$

Herczeg 2001

Scalar and tensor couplings

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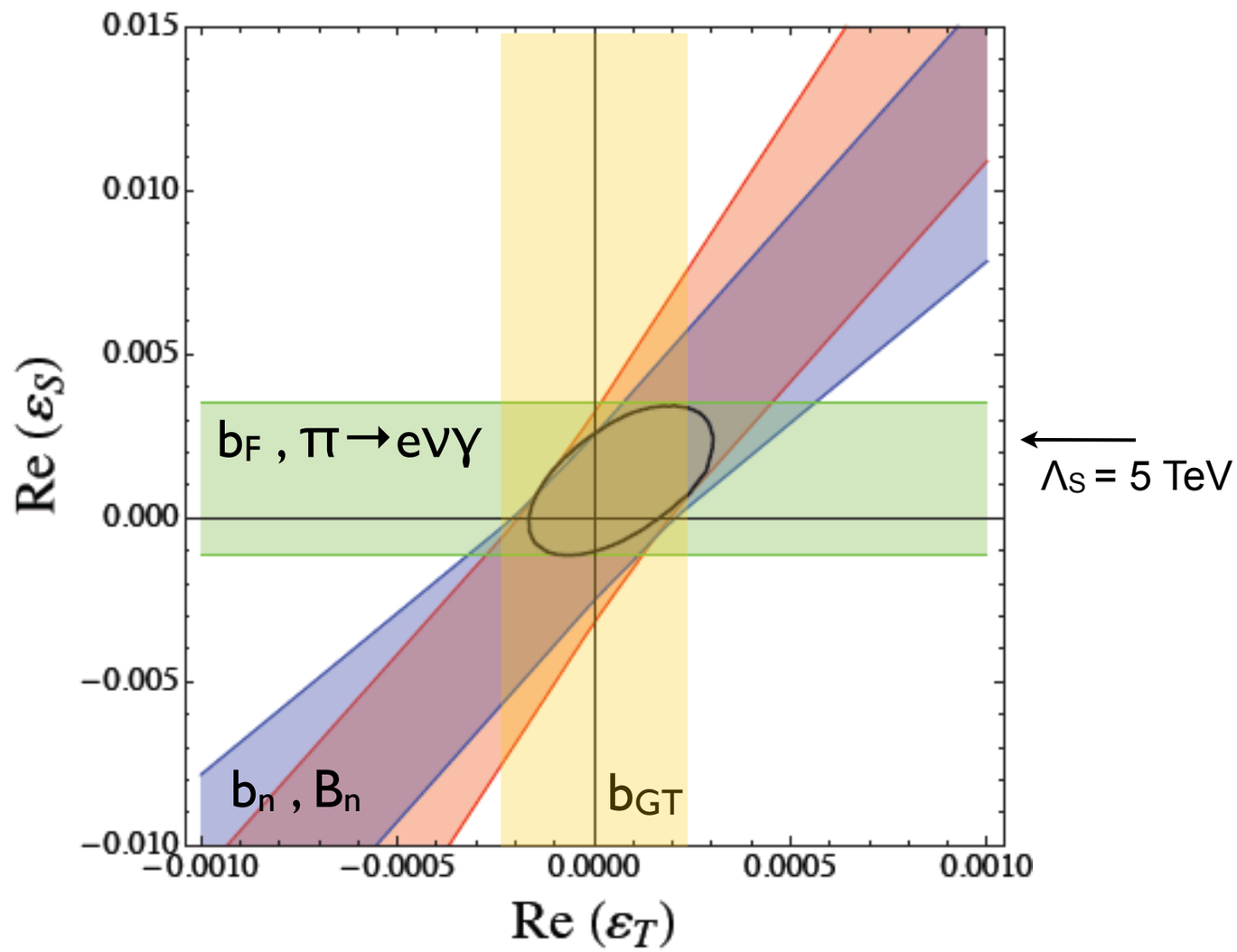


Lattice QCD 2014

$0.91 < g_S < 1.13$

$1.0 < g_T < 1.1$

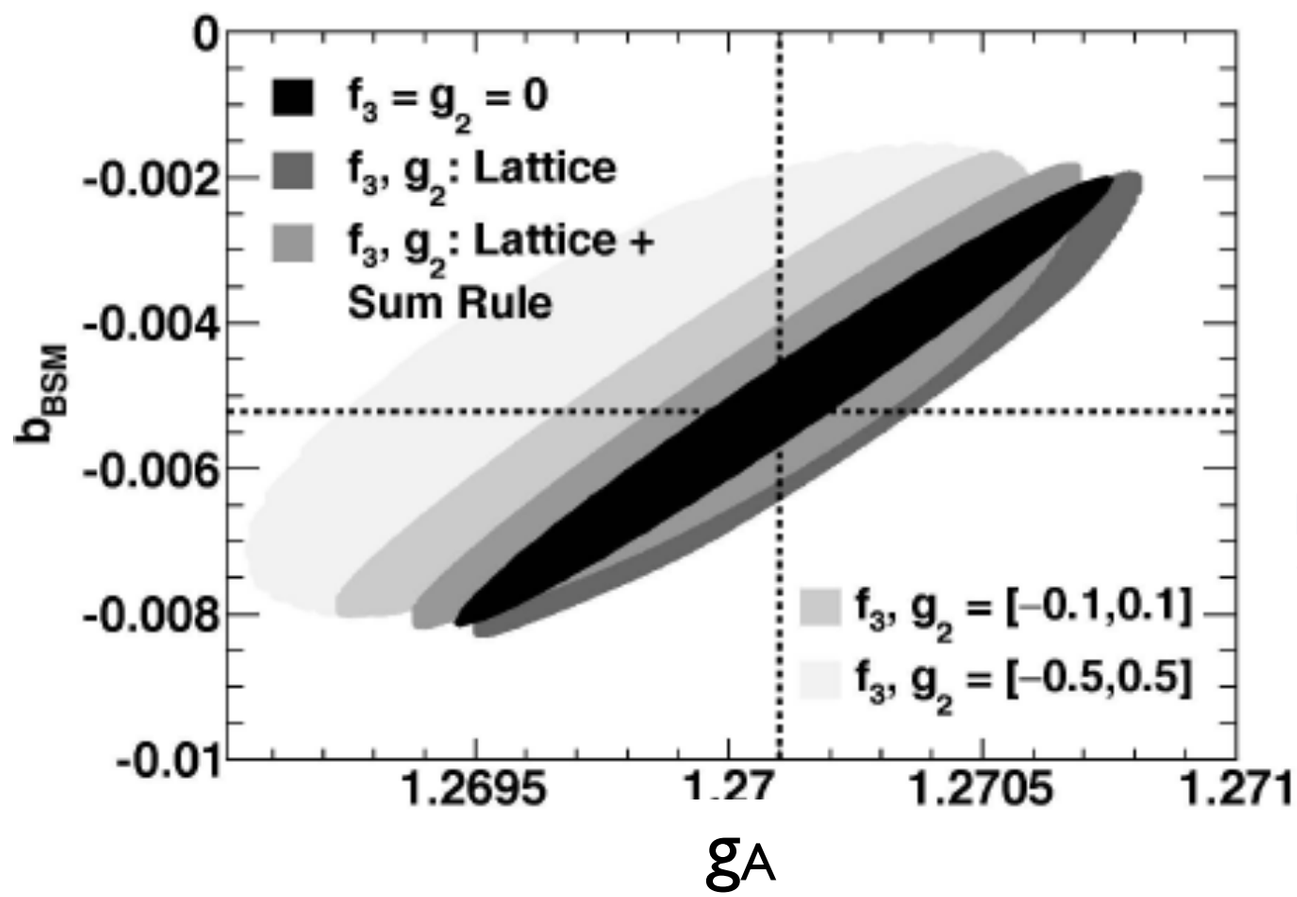
R. Gupta et al. 2014

- Can dramatically improve existing limits on ε_T, probing $\Lambda_T \sim 10$ TeV

Scalar and tensor couplings

FUTURE

- Fit to decay parameters must include g_A (correlations!), and must account for theory uncertainties at recoil order
- Lattice QCD (n) and ab-initio nuclear calculations (^{6}He) can eliminate recoil-order uncertainty

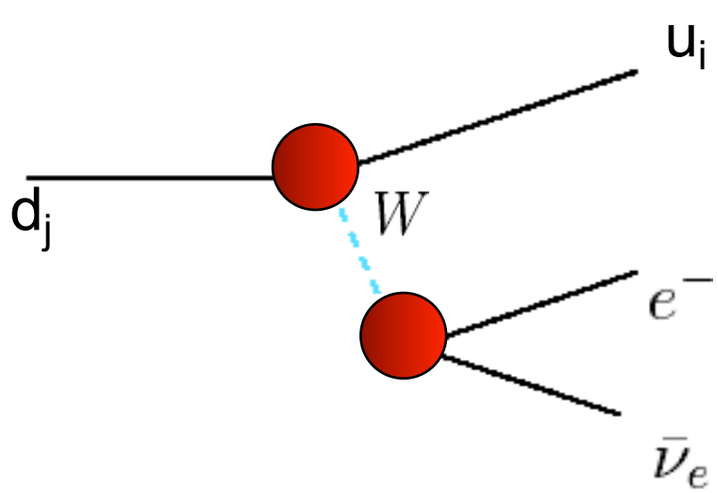


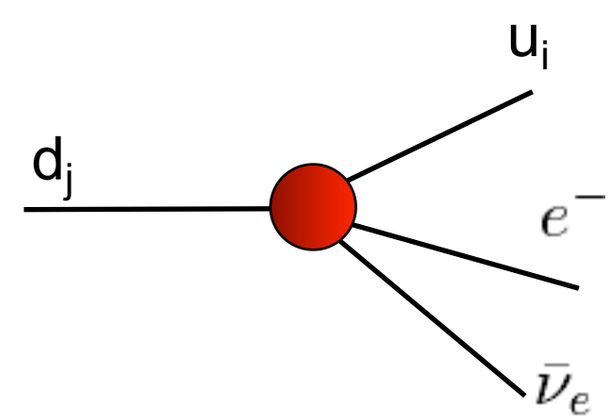
S. Gardner,
B. Plaster 2013

Fit to Monte Carlo pseudo-data of "a" and "A" with ε_T at its current limit

Connection with landscape

- The new physics that contributes to ε_α affects other observables!
- Relative constraining power depends on specific model
- Model-independent statements possible in <u>"heavy BSM" benchmark</u>: M_{BSM} > TeV → new physics looks point-like at the weak scale





<u>Vertex corrections</u> strongly constrained by Z-pole observables (Δ_{CKM} is at the same level)

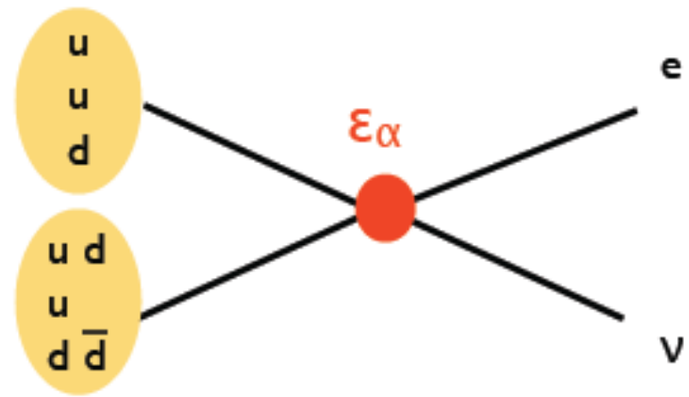
<u>Four-fermion interactions</u> "poorly" constrained: σ_{had} at LEP would allow Δ_{CKM} ~0.01 and non V-A structures at ε_i ~ 5%. What about LHC?

VC, Gonzalez-Alonso, Jenkins 0908.1754

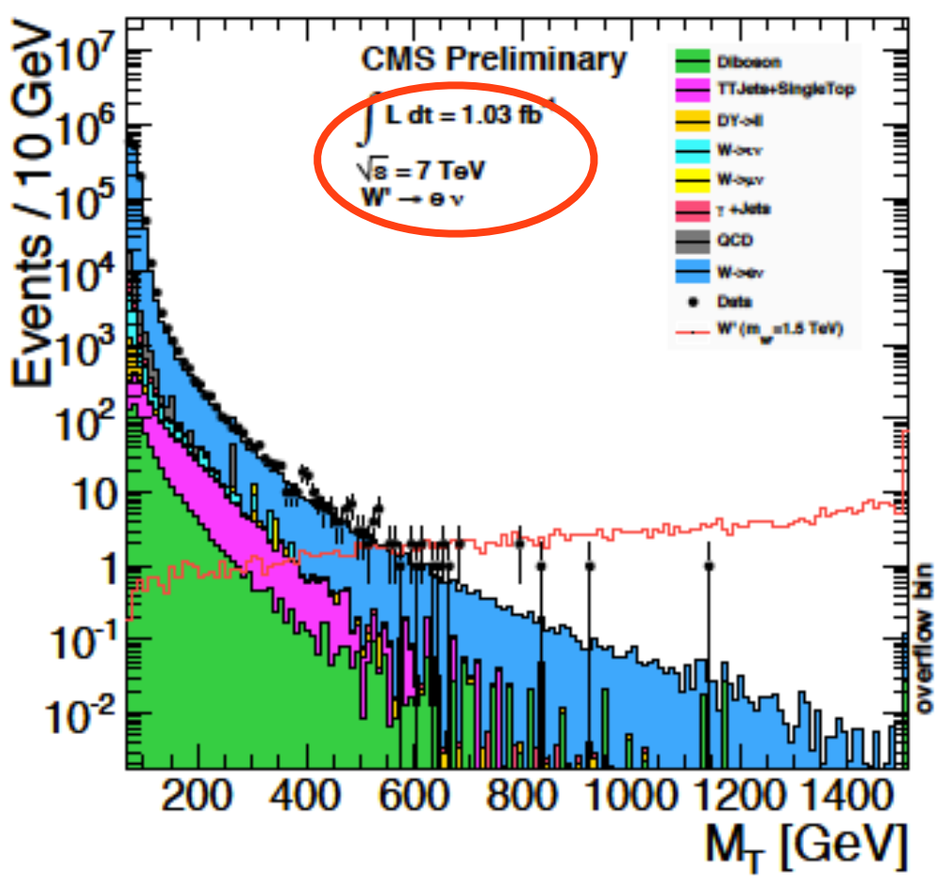
T. Bhattacharya, VC, et al, 1110.6448

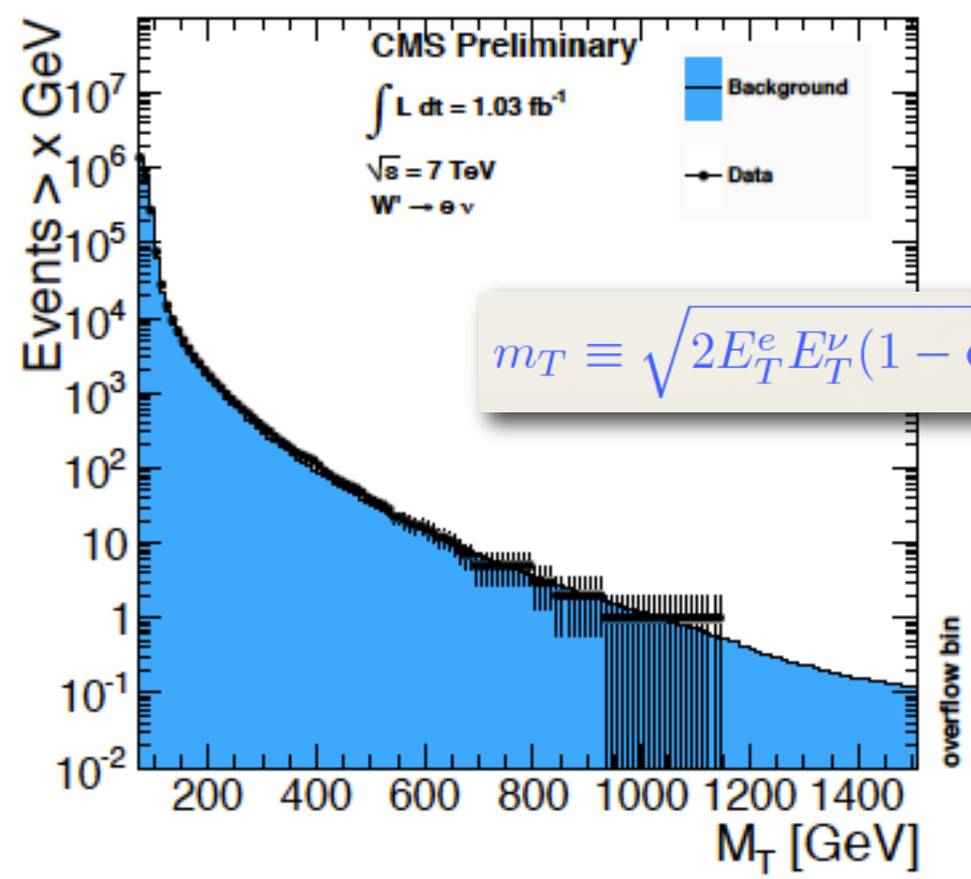
LHC constraints

- <u>Heavy BSM benchmark</u>:
  all ε_α couplings contribute to the process $p\,p \to e\,\nu + X$



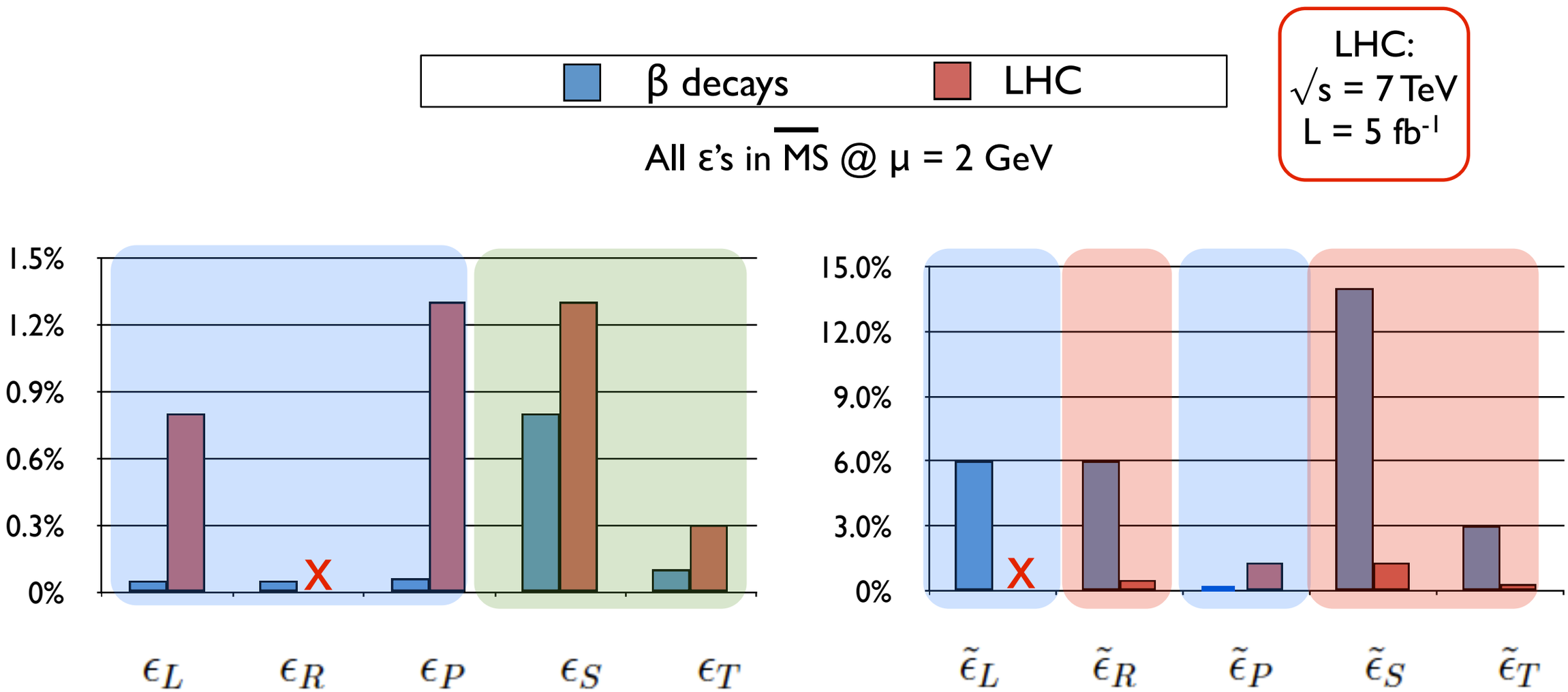
- No excess events at high m_T ⇒ bounds on ε_α (at the 0.3% -1% level)





$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$

β decays vs LHC reach



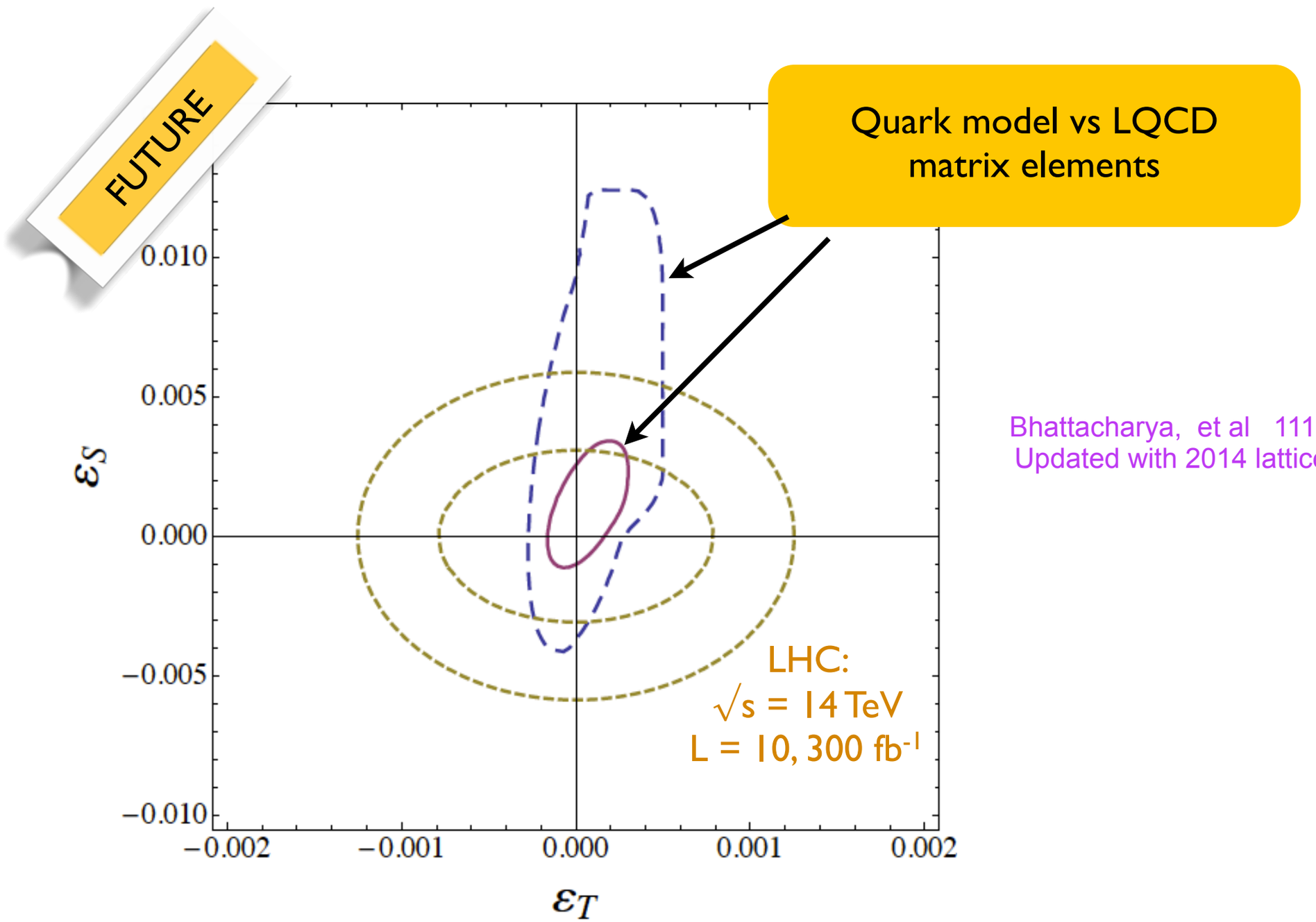
Unmatched low-energy sensitivity and future reach

LHC limits close to low-energy. Interesting interplay in the future

LHC reach already stronger than low-energy

VC, Gonzalez-Alonso, Graesser, 1210.4553

- β-decays (b,B) @ 0.1% can be more constraining than LHC!



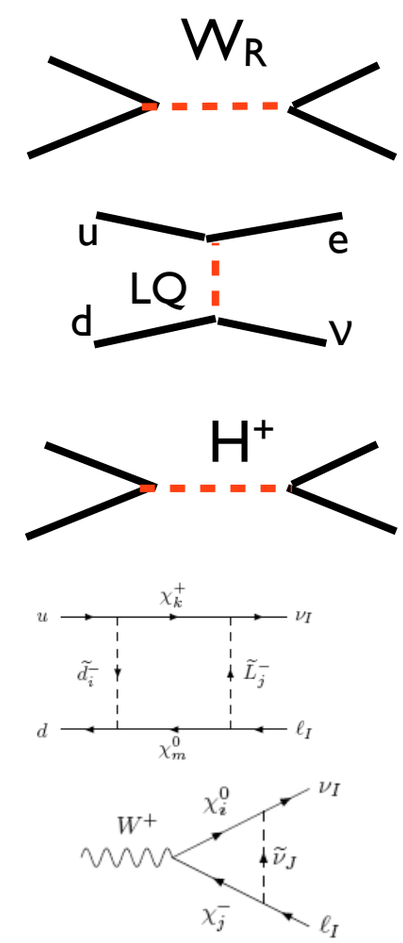
Bhattacharya, et al 1110.6448
Updated with 2014 lattice input

Connection to models

- Model → <u>set overall size and pattern</u> of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture: "DNA matrix"

Can be made quantitative

	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓
YOUR FAVORITE MODEL	…		…		



Conclusions (1)

- Precise (≤0.1%) beta decays: "broad band" probe of new physics. Discovery potential depends on the underlying model (DNA matrix)

- In the "heavy BSM" benchmark case, a discovery window exists well into the LHC era!

- A number of measurements capable of exploring uncharted territory:

  ✳ Neutron lifetime at the level of $\delta\tau_n \sim 1s \rightarrow 0.1\ s$

  ✳ Nuclear / neutron spectra and correlations (b, a, A, B, ...) at the level of 0.1% → 0.01%

Conclusions (2)

- Maximizing the impact of these precision experiments requires diverse theory input:
  - Phenomenology: connect to other low- and high-energy probes
  - Lattice QCD: nucleon level matrix elements
  - Nuclear structure: GFMC (A<12), many-body methods

Conclusions (2)

- Maximizing the impact of these precision experiments requires diverse theory input:
  - Phenomenology: connect to other low- and high-energy probes
  - Lattice QCD: nucleon level matrix elements
  - Nuclear structure: GFMC (A<12), many-body methods

Strong overlap and synergy with
Computational Nuclear Physics

More in D. Richard's talk and theory position paper:

Fundamental Symmetries, Precision Probes of the Standard Model and Lattice QCD

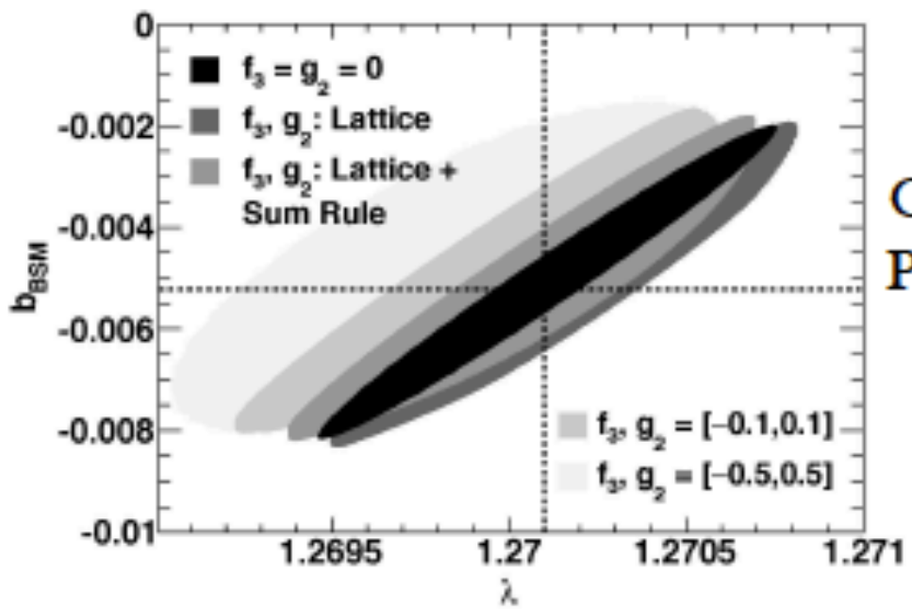
Tanmoy Bhattacharya,[1,*] Vincenzo Cirigliano[†],[1,‡] Rajan Gupta,[1,§] Wick Haxton[¶],[2,3,**]
Taku Izubuchi,[4,5,††] Kostas Orginos[‡‡],[6,7,§§] and André Walker-Loud[¶¶6,7,***]

Additional material

Progress/Futures in Weak Decay Studies

S. Gardner

i) Resolving the Limits of the V-A Law [SG, B. Plaster, PRC 2013]



Maximum likelihood analysis after CKMFitter

Current precision $\Longrightarrow g_A/g_V \equiv \lambda$ must be fit as well. Poorly known recoil-order SM matrix elements also have impact. Lattice QCD calculations should be able to bound theory error in neutron decay.

Here fits of Monte Carlo pseudodata of "a" and "A" with new tensor physics as allowed by expt

ii) Radiative Beta Decay for Studies of CP Violation [SG, D. He, PRD 2013]

Triple product momentum correlation is P-odd, T-odd but spin independent - N.B. nuclear studies!

iii) Anatomy of CP violation [C-odd, P-even] in $\eta \to \pi^+\pi^-\pi^0$ [SG]

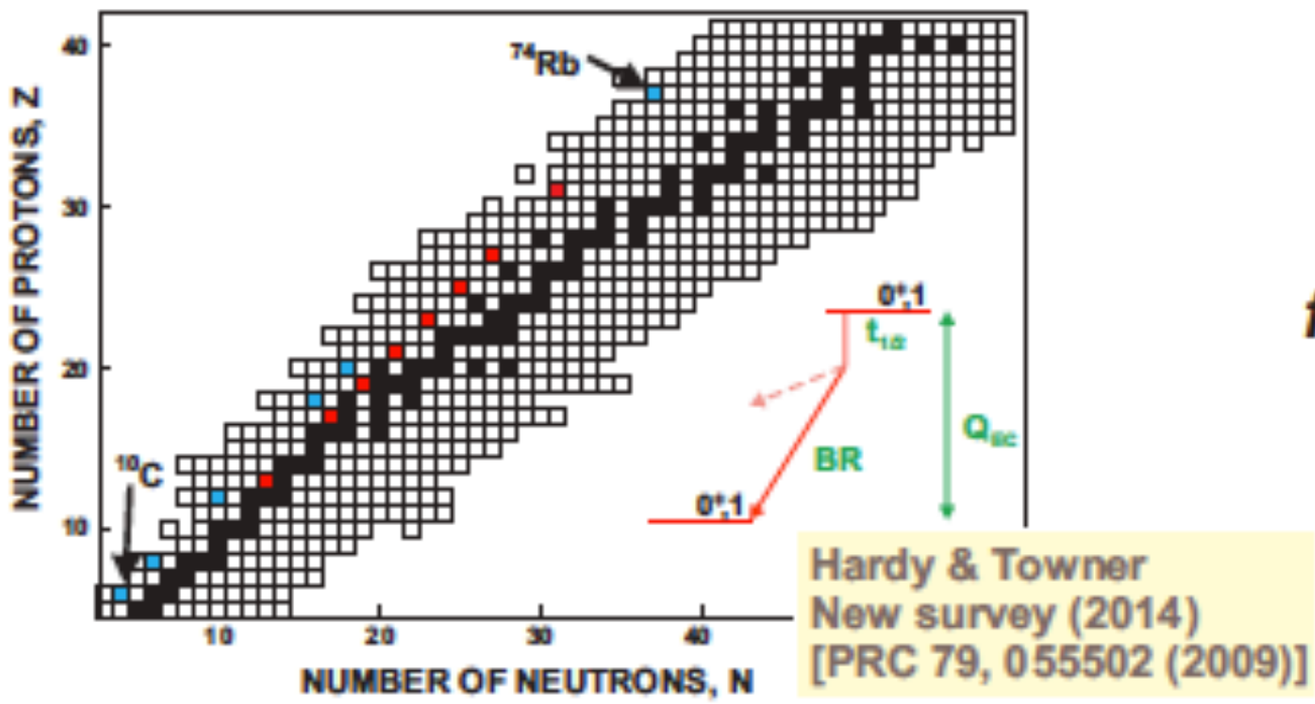
Population asymmetry about the Dalitz plot "mirror line" breaks C and CP [SG & Tandean, 2003]; Boosted eta's are useful - can probe asymmetry at JLab Eta Factory

iv) Trapping Penguins w/ Entangled B-Mesons [R. Dadisman, SG, X. Yan]

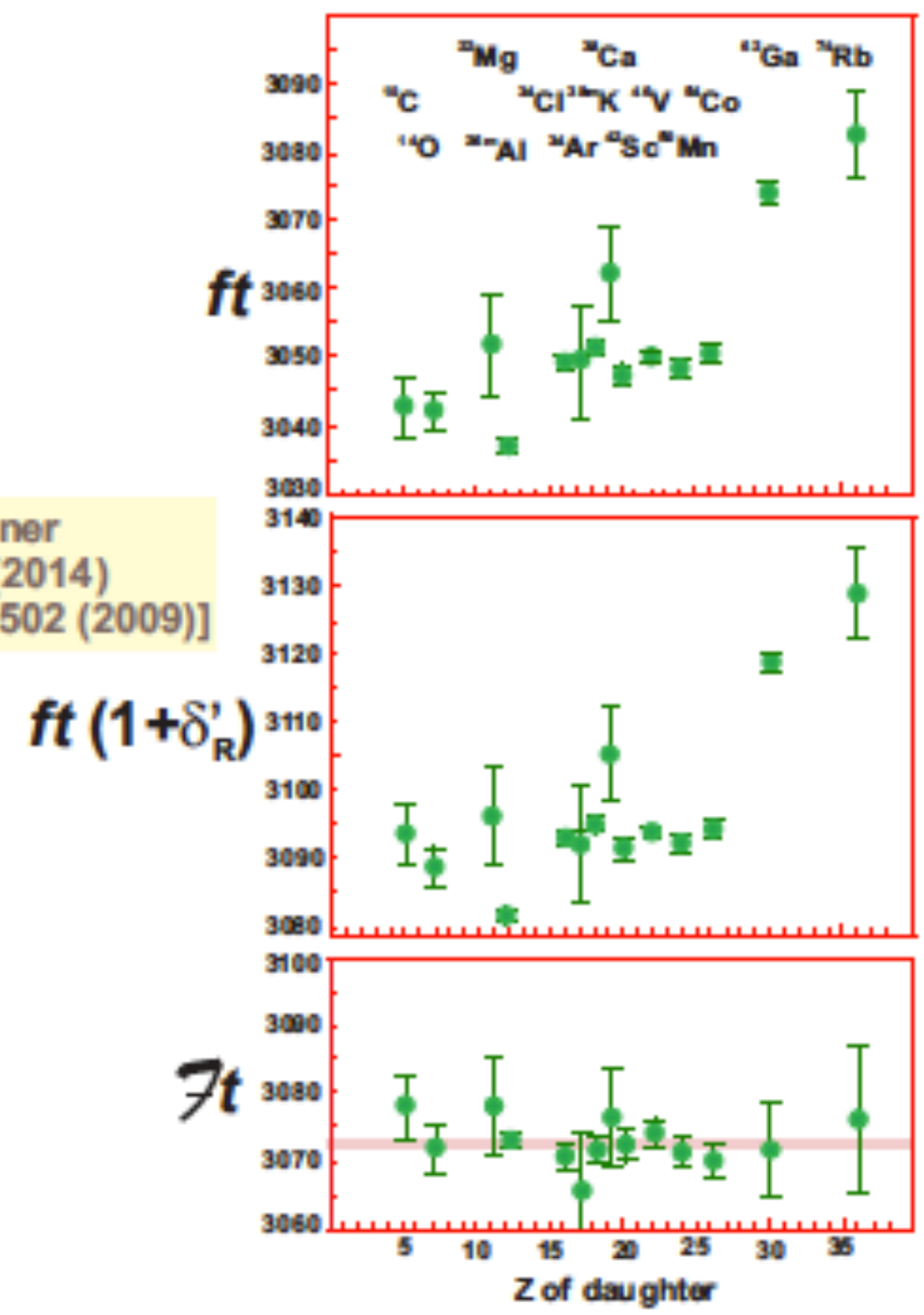
BaBar has observed T violation; can repeat using "generalized" CP tags to measure penguins & more

WORLD DATA FOR $0^+ \rightarrow 0^+$ DECAY, 2014

J. Hardy



Hardy & Towner
New survey (2014)
[PRC 79, 055502 (2009)]



- 8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.
- ~220 individual measurements with compatible precision

$$\mathcal{F}t = ft\,(1+\delta'_R)\left[1-(\delta_C-\delta_{NS})\right] = \frac{K}{2G_V^2\,(1+\Delta_R)}$$

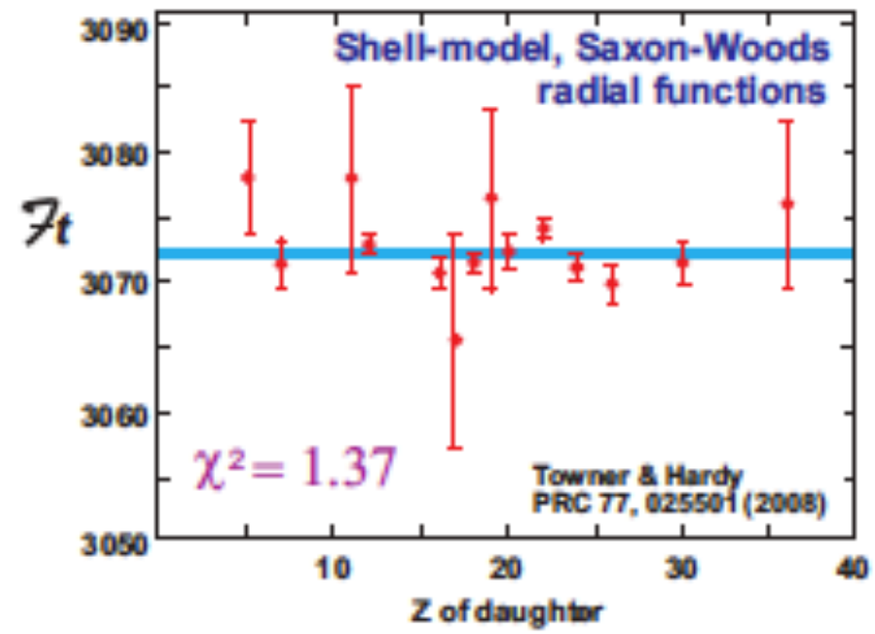
TESTS OF δ_c CALCULATIONS

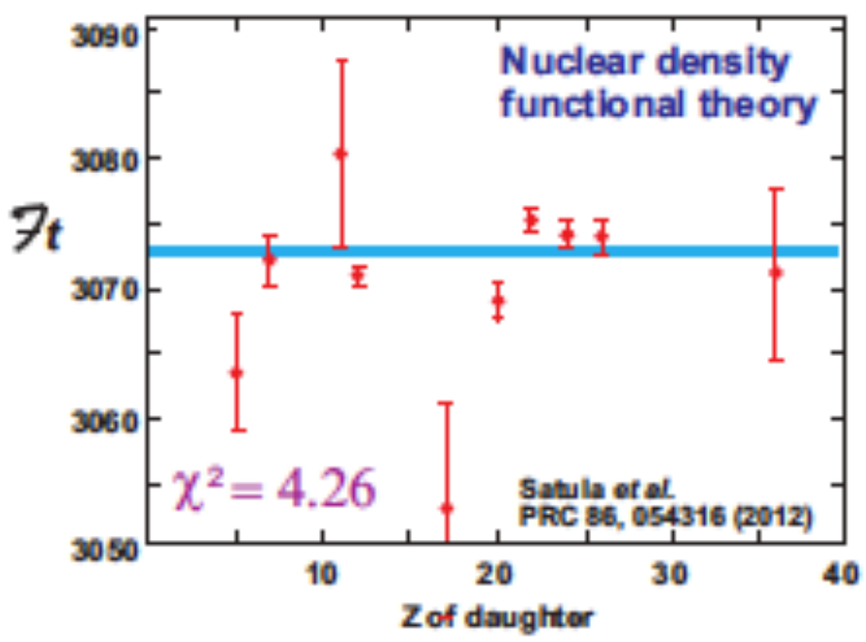
J. Hardy

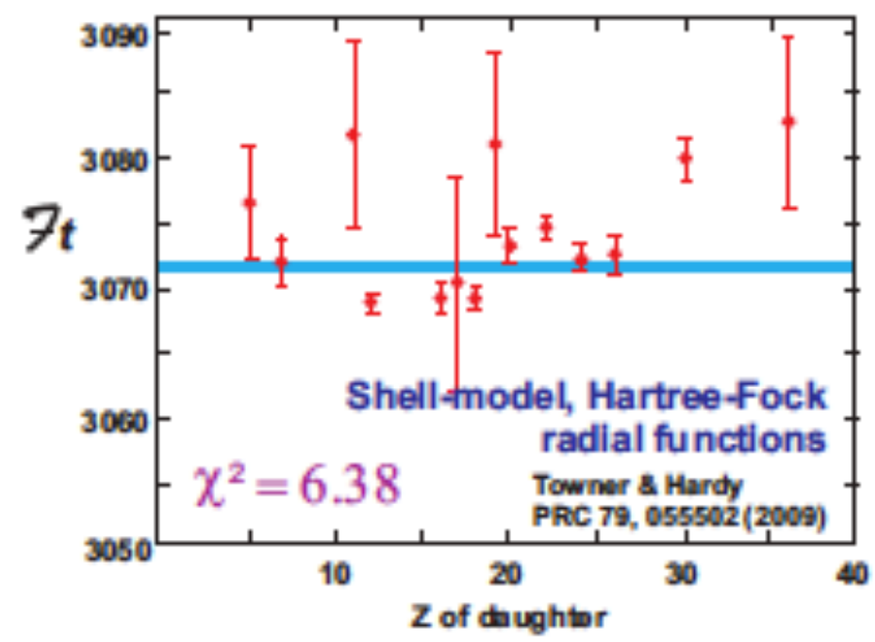
A. Agreement with CVC:

$\mathcal{F}t$ values have been calculated with different models for δ_c, then tested for consistency. Normalized χ^2 and confidence levels are shown.

Model	χ^2/N	CL(%)
SM-SW	1.37	17
SM-HF	6.38	0
DFT	4.26	0
RHF-RPA	4.91	0
RH-RPA	3.68	0





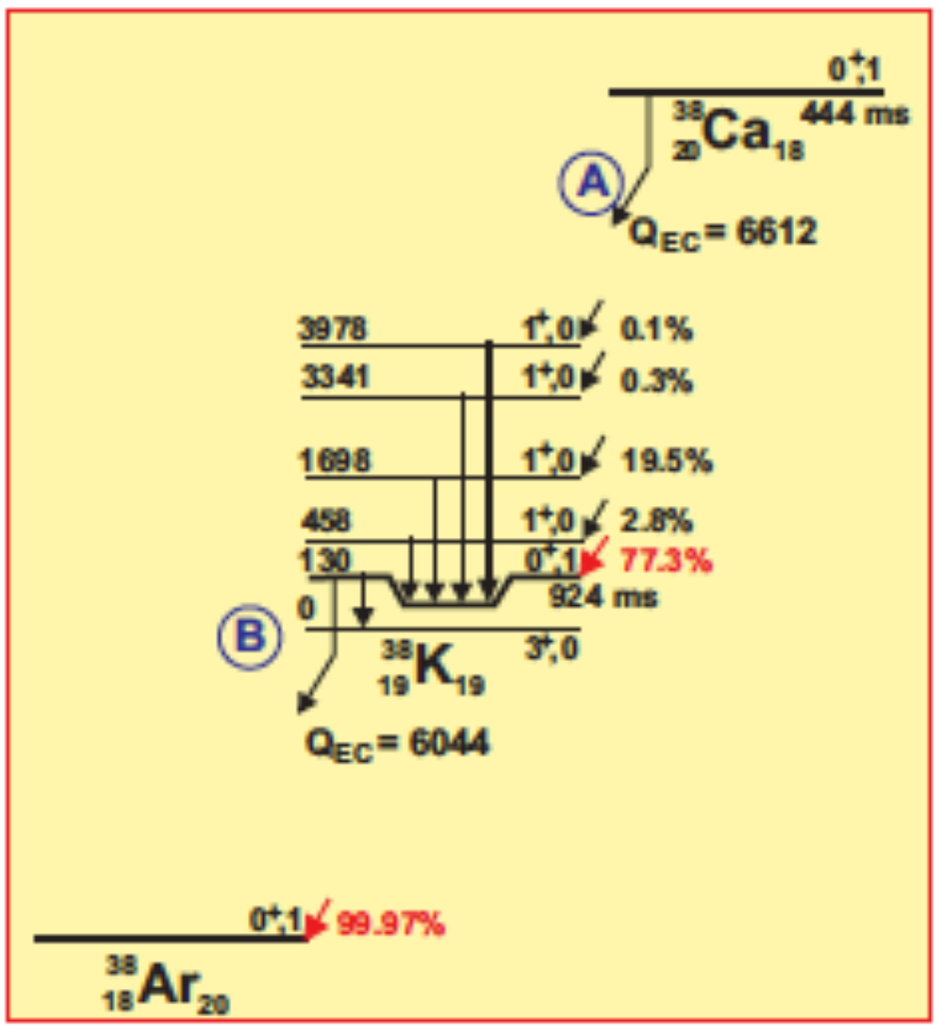


TESTS OF δ_C CALCULATIONS

J. Hardy

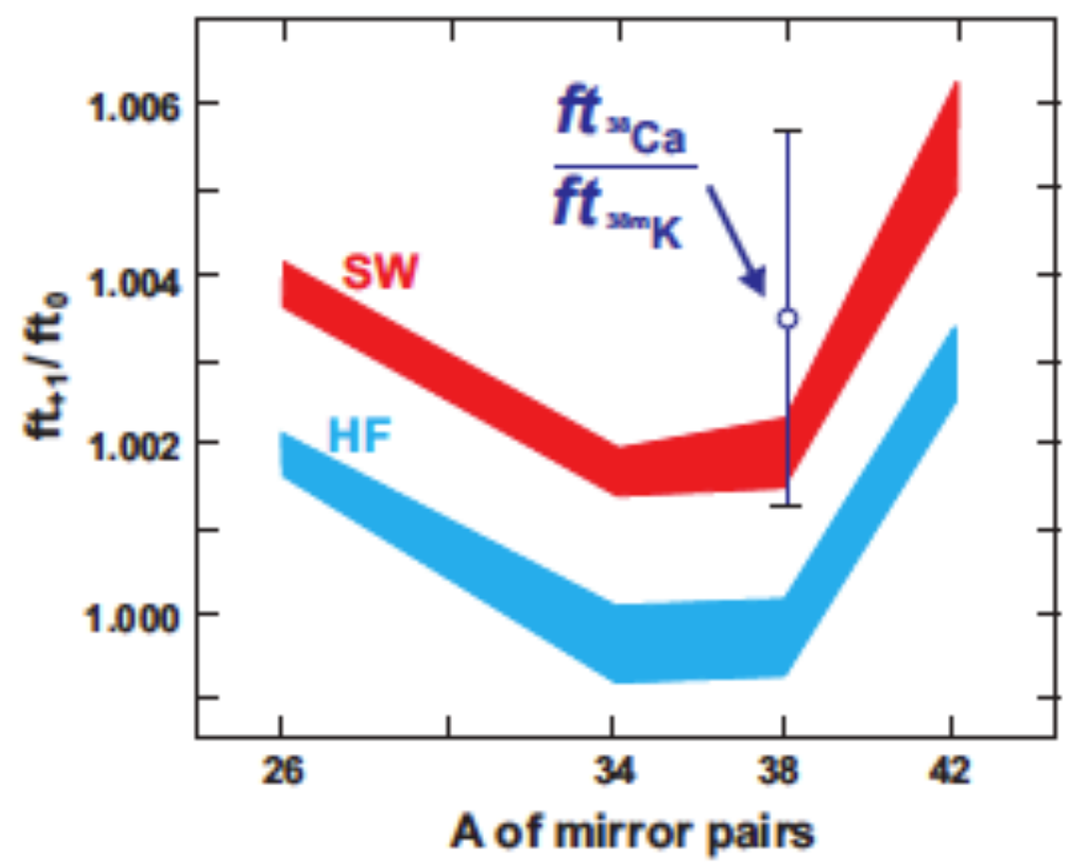
B. Measurements of mirror superallowed transitions:

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})]$$

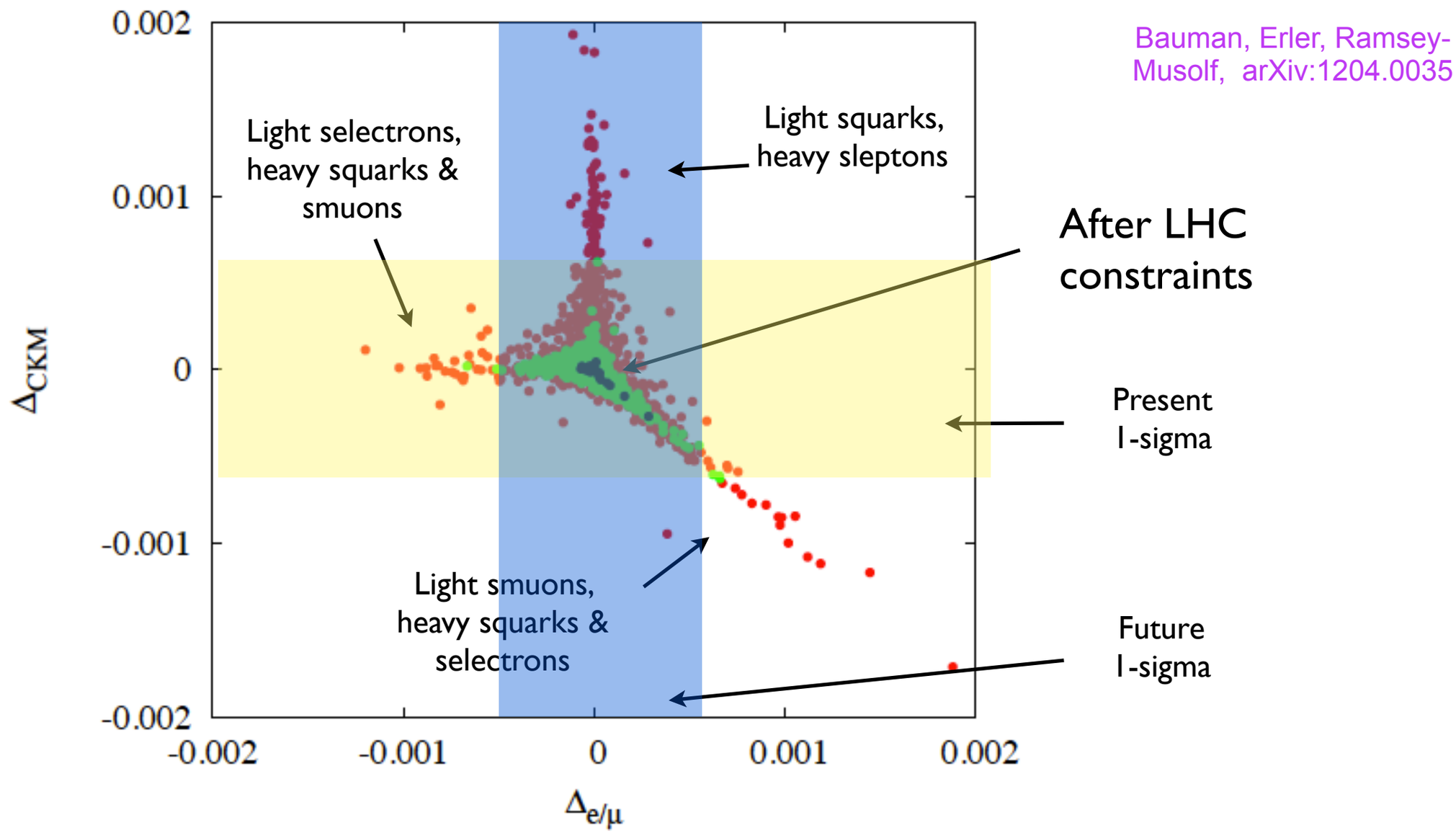


$$\frac{ft_A}{ft_B} = \frac{(1 + \delta_R'^B)[1 - (\delta_C^B - \delta_{NS}^B)]}{(1 + \delta_R'^A)[1 - (\delta_C^A - \delta_{NS}^A)]}$$

$$= 1 + (\delta_R'^B - \delta_R'^A) + (\delta_{NS}^B - \delta_{NS}^A) - (\delta_C^B - \delta_C^A)$$



- MSSM: Distinctive correlation between Cabibbo universality (CKM) and lepton universality, controlled by sfermion spectrum



- Post-LHC effects are at the few*10^{-4} level

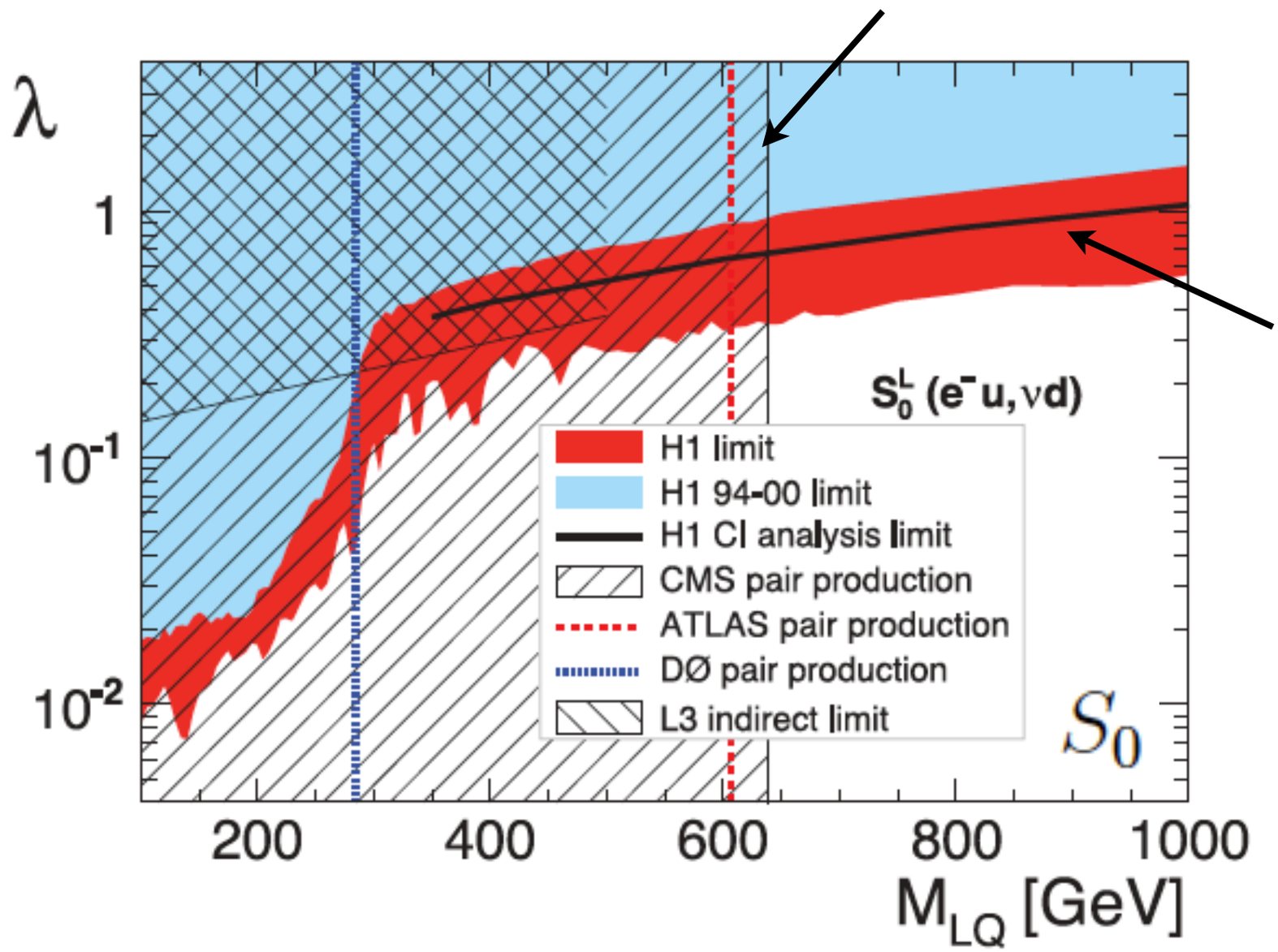
- Leptoquarks: Δ_{CKM} constraint vs direct searches at HERA and LHC

Pair production at LHC

$$q + \bar{q} \to LQ + \overline{LQ}$$

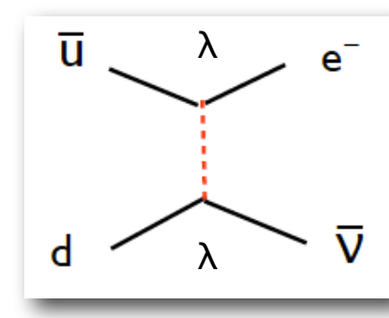
$$g + g \to LQ + \overline{LQ}$$

95% CL limits



Single production at HERA (depends on λ)

$$e + q \to LQ$$

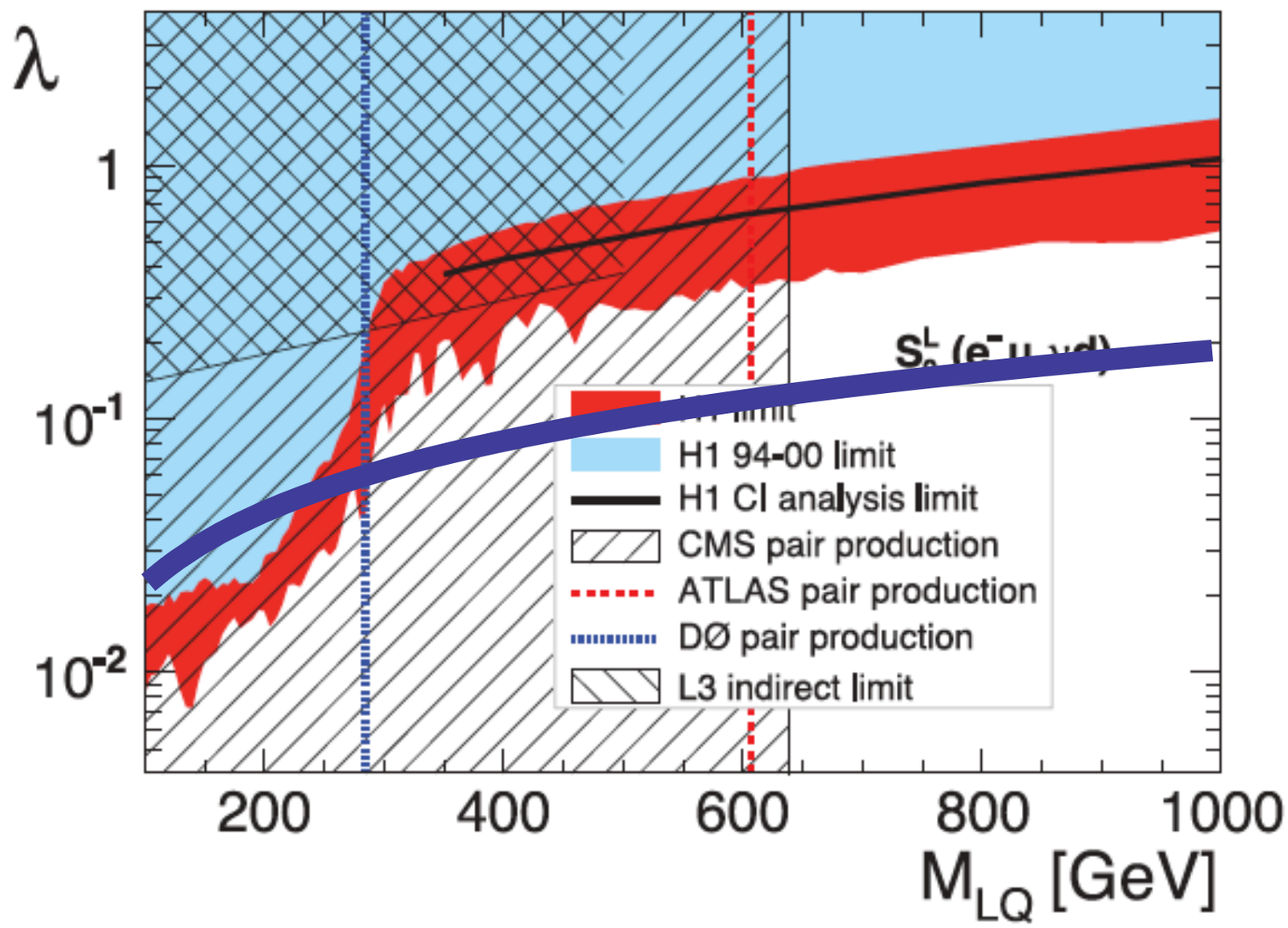


S_0 (3,1,1/3)

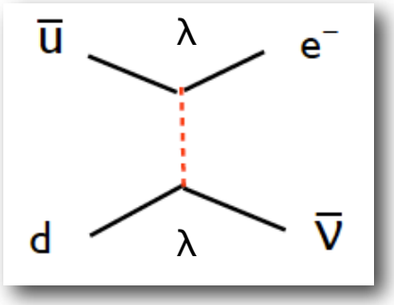
- Leptoquarks: Δ_{CKM} constraint vs direct searches at HERA and LHC

Δ_{CKM} constraint is stronger
(for all four LQ that contribute to Δ_{CKM})

95% CL limits



$|\epsilon_L| < 6 \times 10^{-4}$



S_0 (3,1,1/3)