Beta decays and non-standard interactions in the LHC era

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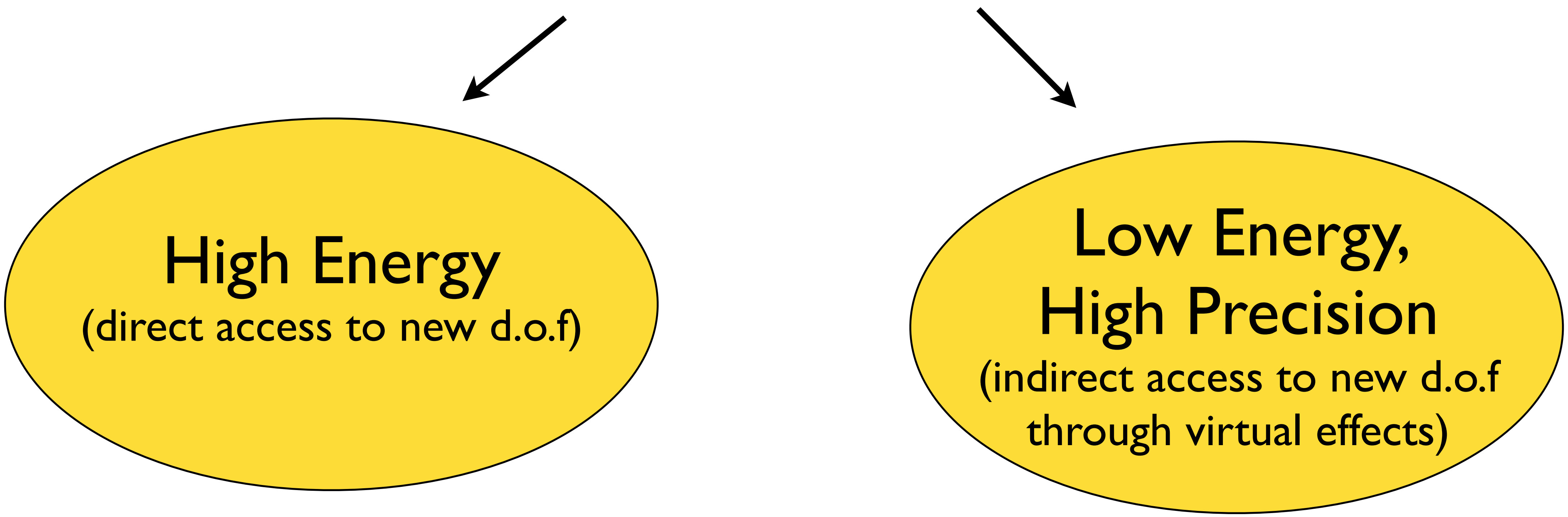
Prelude

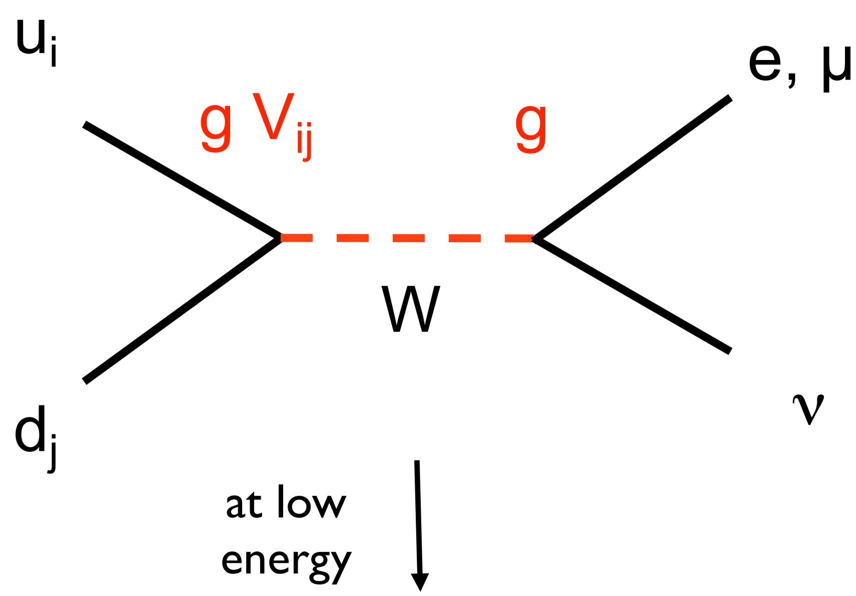
- Unsolved puzzles about our Universe point to the existence of new degrees of freedom and interactions beyond the SM. Two traditional paths to probe this new physics:



- In this talk, take a fresh look at both LE and HE probes of non-standard charged current interactions

CC interactions and BSM physics

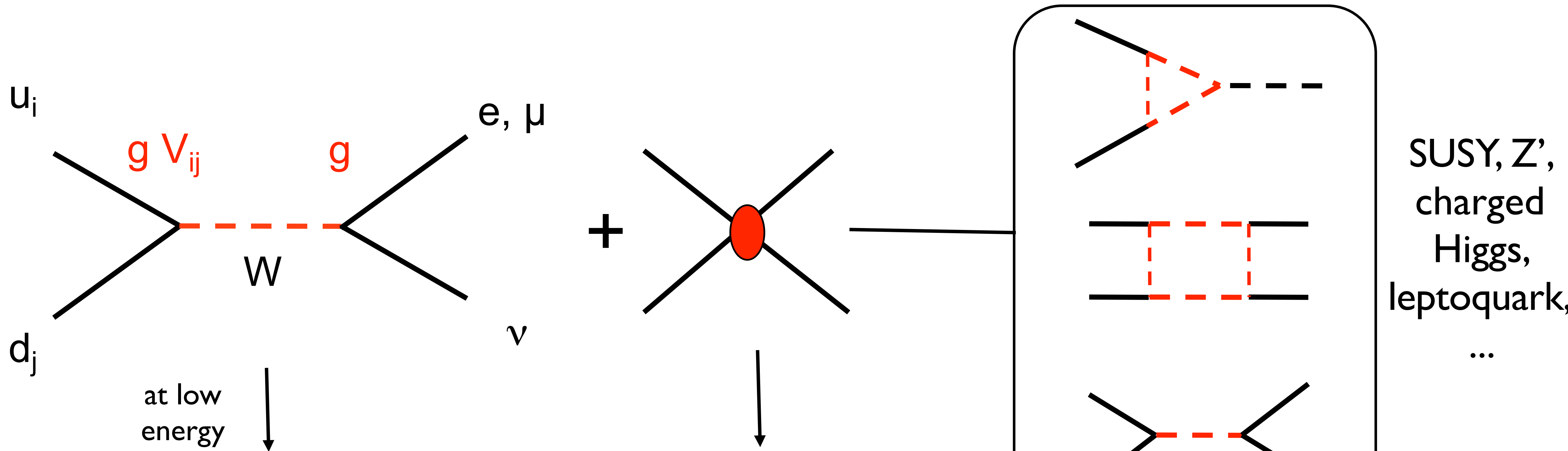
- In the SM, W exchange ⇒ only V-A structure, universality relations



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

CC interactions and BSM physics

- In the SM, W exchange ⇒ only V-A structure, universality relations

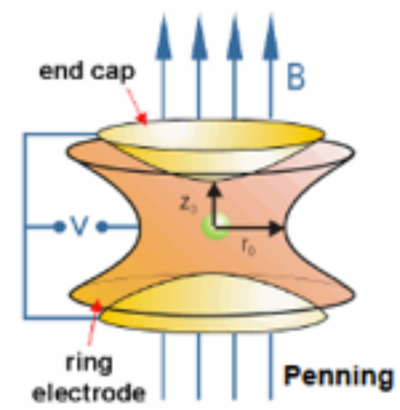


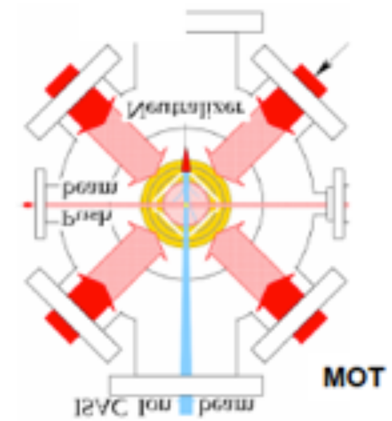
$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

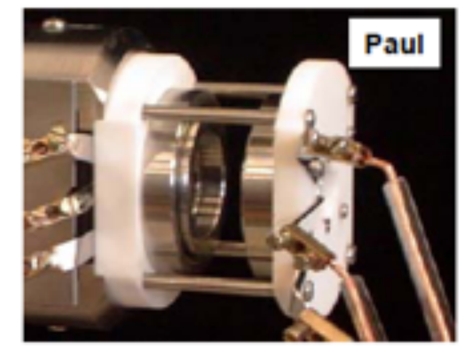
$1/\Lambda^2$

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

- Traditionally, field dominated by precision β decay probes, with rich experimental program worldwide







- Current / planned measurements will reach 0.1%-level
    - tight constraints on BSM contributions interfering with the SM amplitude
    - Yet, incoherent BSM contributions (e.g. R-handed neutrino) could be as large as <u>5 to 10%</u> of the V and A interactions

Severijns, Beck, Naviliat-Cuncic, 2006

- Traditionally, field dominated by precision β decay probes, with rich experimental program worldwide


Here consider multi-scale analysis, with probes ranging from low energy (nuclei, neutron, and pion) to the LHC

⇓

Get improved constraints on nonstandard CC interactions

Assess future prospects

- Yet, incoherent BSM contributions (e.g. R-handed neutrino) could be as large as <u>5 to 10%</u> of the V and A interactions

Severijns, Beck, Naviliat-Cuncic, 2006

Outline

- Framework: CC interactions from the TeV scale to hadronic scales

- Low-energy probes: status, prospects

- High-energy probes (LHC): contact interactions and beyond

T. Bhattacharya, VC, S.Cohen, A Filipuzzi, M. Gonzalez-Alonso, M. Graesser, R. Gupta, H.W.Lin, 1110.6448 [hep-ph]
VC, M. Gonzalez-Alonso, M. Graesser, in progress
VC, ,M. Graesser, E. Passemar, in progress

Framework

Theoretical Framework

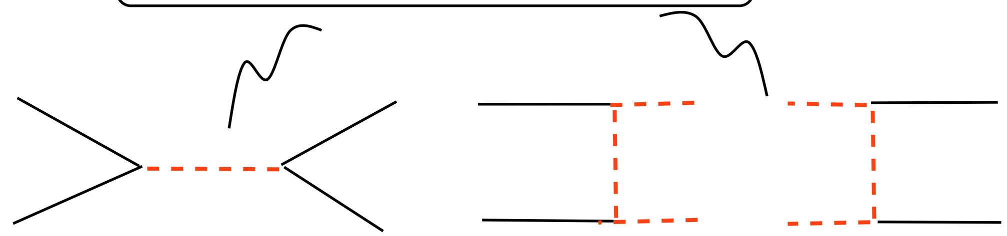
- In absence of an emerging "New Standard Model", work within an EFT framework: most general approach
  - Assume separation of scales $M_{BSM} >> M_W$
  - New heavy BSM particles are "integrated out", and affect the dynamics through local operators of dim > 4
  - If $M_{BSM} >>$ TeV, one can use this framework to analyze LHC data. Will discuss relaxing this assumption at the end of the talk
- Any model calculation can be cast in the EFT language

Theoretical Framework

E

LHC

BSM dynamics involving
new particles with m > Λ



$\mathcal{L}_{\mathrm{BSM}}$

Λ (~TeV)

SLC, LEP

$M_{W,Z}$

LANSCE, SNS, ...

Λ_H (~GeV)

Theoretical Framework

E

LHC

Λ (~TeV)

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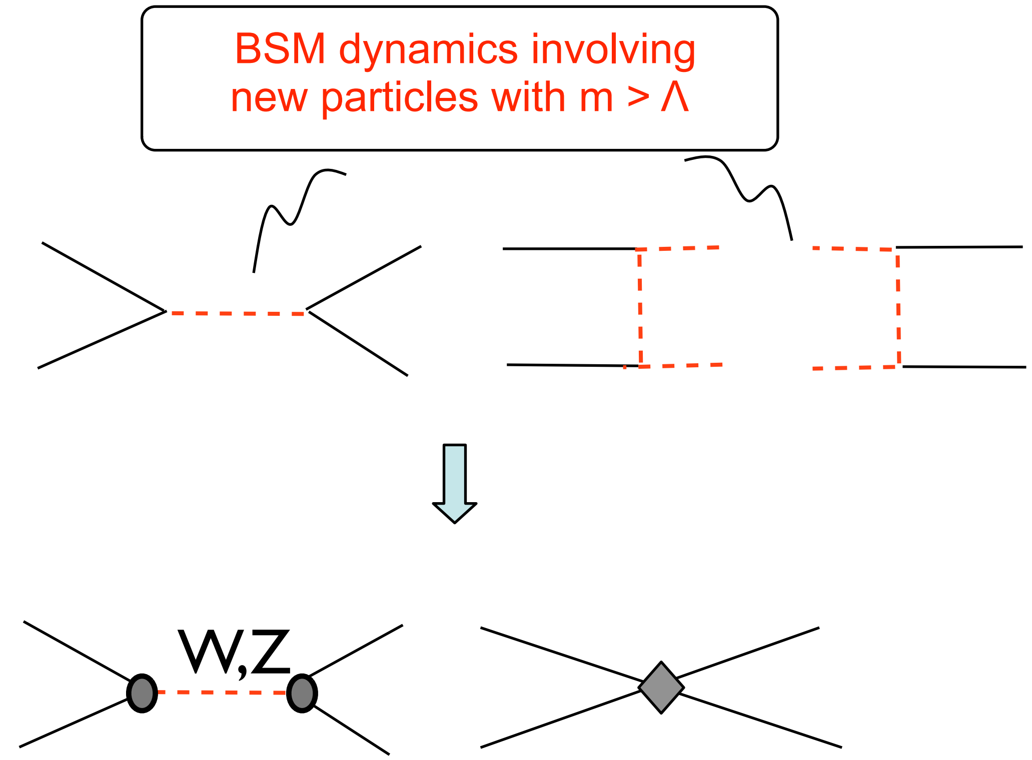


$$\boxed{\mathcal{L}_{\rm BSM}}$$

$$\boxed{\mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}}$$

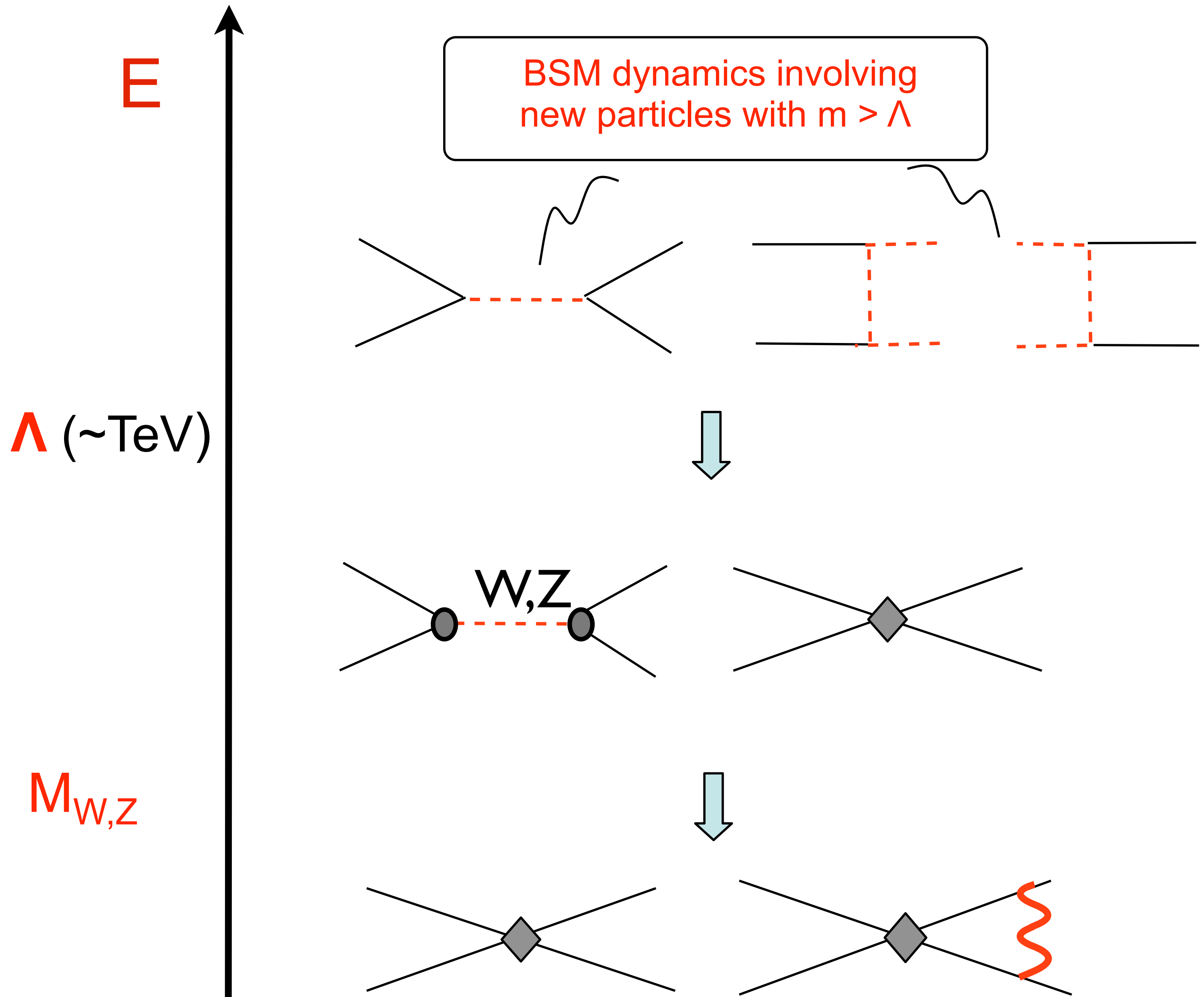
- 7+5** SU(2)xU(1)-invariant <u>dim 6</u> operators contribute to beta decays (4+4 four-fermion & 3+1 vertex correction)
- ** If one includes ν_R in the low-energy theory

Theoretical Framework

LHC

SLC, LEP

LANSCE, SNS, ...



Λ_H (~GeV)

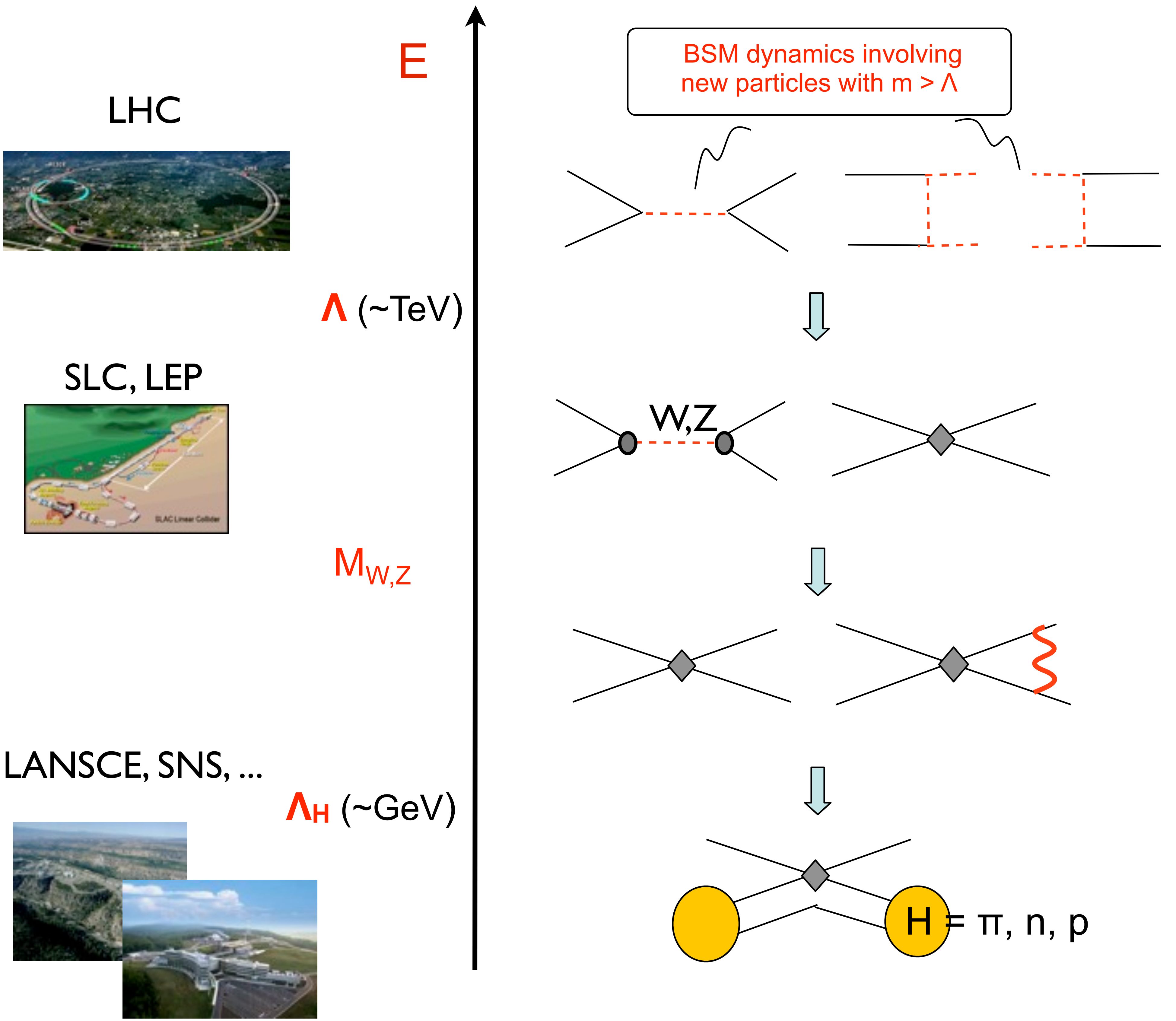
$$\mathcal{L}_{\rm BSM}$$

$$\mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}$$

$$\mathcal{L}_{\rm Fermi} + \sum_i \frac{c_i}{\Lambda_i^2} O_i + \mathcal{L}_{QCD} + \mathcal{L}_{QED}$$

- Below weak scale, 5+5** four-fermion (quark + lepton) operators

Theoretical Framework



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$$\mathcal{L}_{\rm Fermi} + \sum_i \frac{c_i}{\Lambda_i^2} O_i + \mathcal{L}_{QCD} + \mathcal{L}_{QED}$$

Non-perturbative matching

$$\mathcal{L}_{\pi,N,\ldots}$$

Low-scale Lagrangian

$\varepsilon_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[(1 + \delta_{RC} + \epsilon_L) \;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+ \;\; \epsilon_R \;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$+ \;\; \epsilon_S \;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$- \;\; \epsilon_P \;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \;\; \epsilon_T \;\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \,\Big] + \text{h.c.}$$

Low-scale Lagrangian

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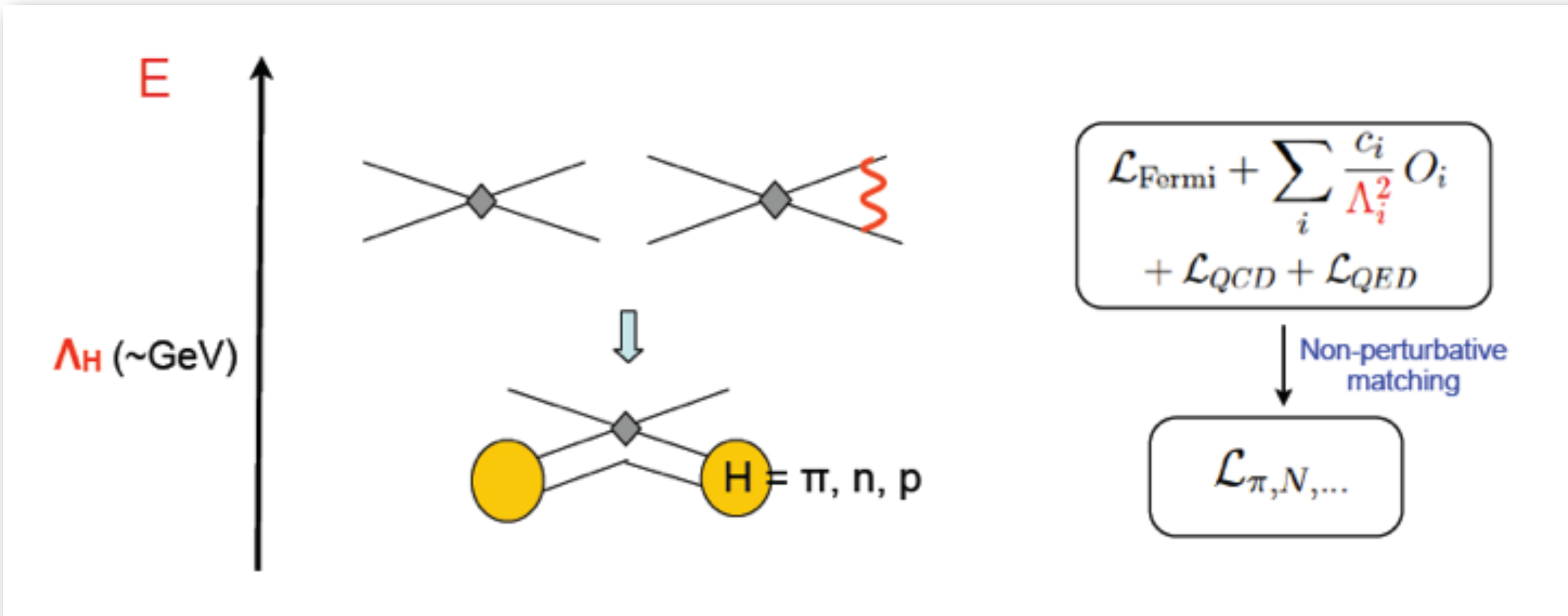
$$+ \;\; \epsilon_S \;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$- \;\; \epsilon_P \;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \;\; \epsilon_T \;\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}$$

$$+ \qquad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

Match to hadronic description



- To disentangle short-distance physics, need hadronic matrix elements of SM (very precisely, 10^{-3} level) *and* BSM operators

- Tools (for both meson and nucleons):

  - symmetries of QCD → chiral EFT

  - lattice QCD

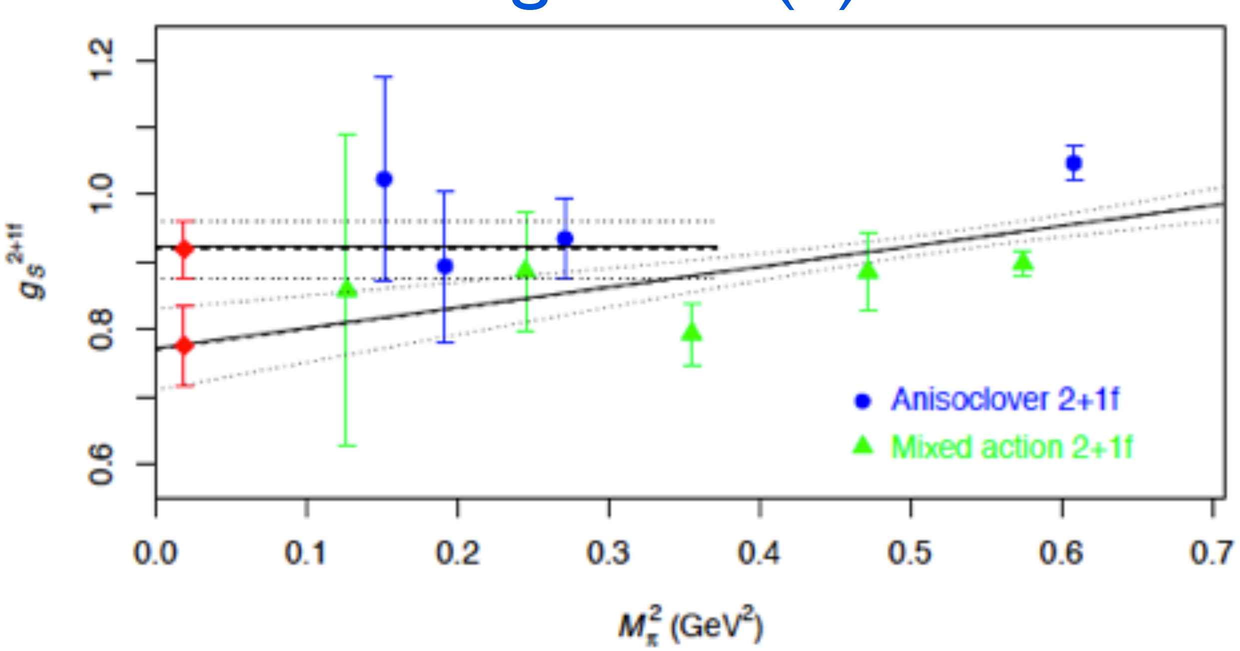
Example: $g_{S,T}$ in LQCD

Bhattacharya, VC, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

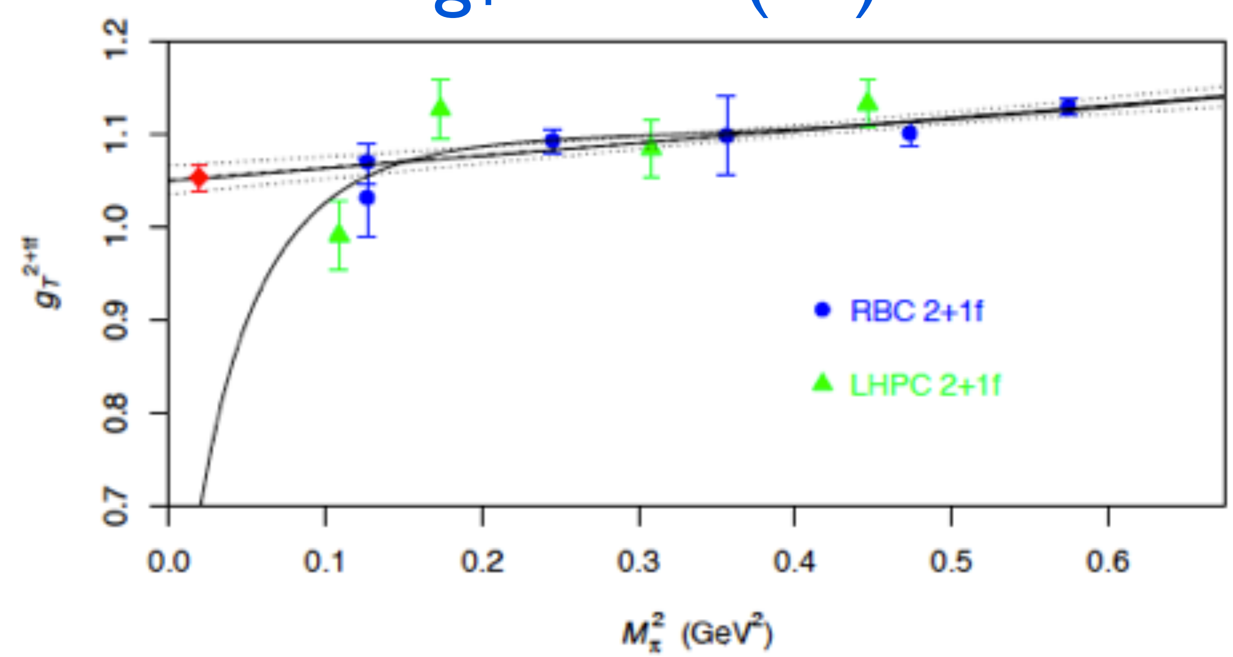
- Hadronic matrix elements ($g_{S,T}$) needed to extract short distance physics ($\varepsilon_{S,T}$) from neutron and nuclear beta decays

$$\langle p|\bar{u}d|n\rangle = g_S\ \bar{u}_p u_n$$
$$\langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle = g_T\ \bar{u}_p\sigma_{\mu\nu}u_n$$

$g_S = 0.8(4)$



$g_T = 1.05(35)$



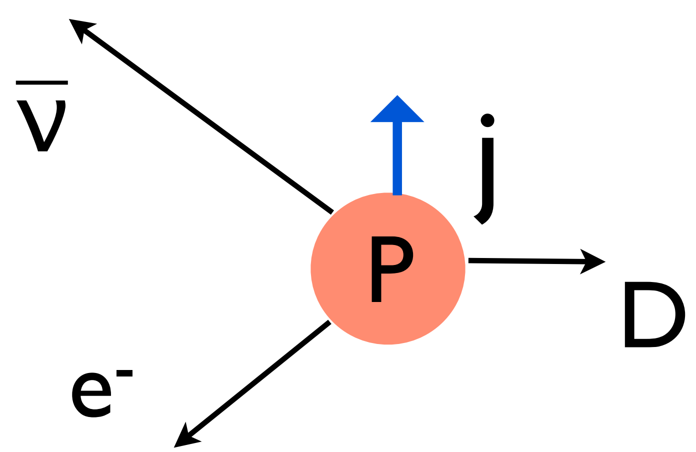
- First lattice QCD estimates (still large systematics): realistic goal of $\delta g_{S,T}/g_{S,T}$ = 20% within 2-3 years

Low-energy probes

How do we probe the ε's?

- Low-energy probes fall roughly in two classes:

1. Differential decay rates: spectra, angular correlations (non V-A)



Jackson-Treiman-Wyld 1957

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

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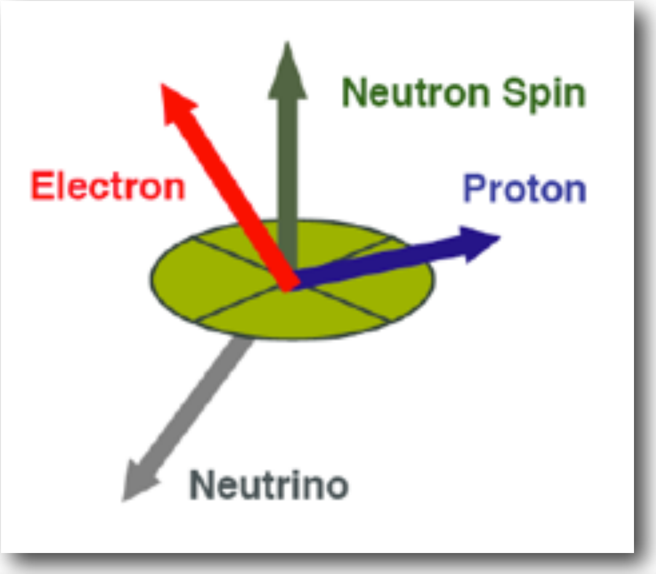

Jackson-Treiman-Wyld 1957

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

How do we probe the ε's?

- Low-energy probes fall roughly in two classes:

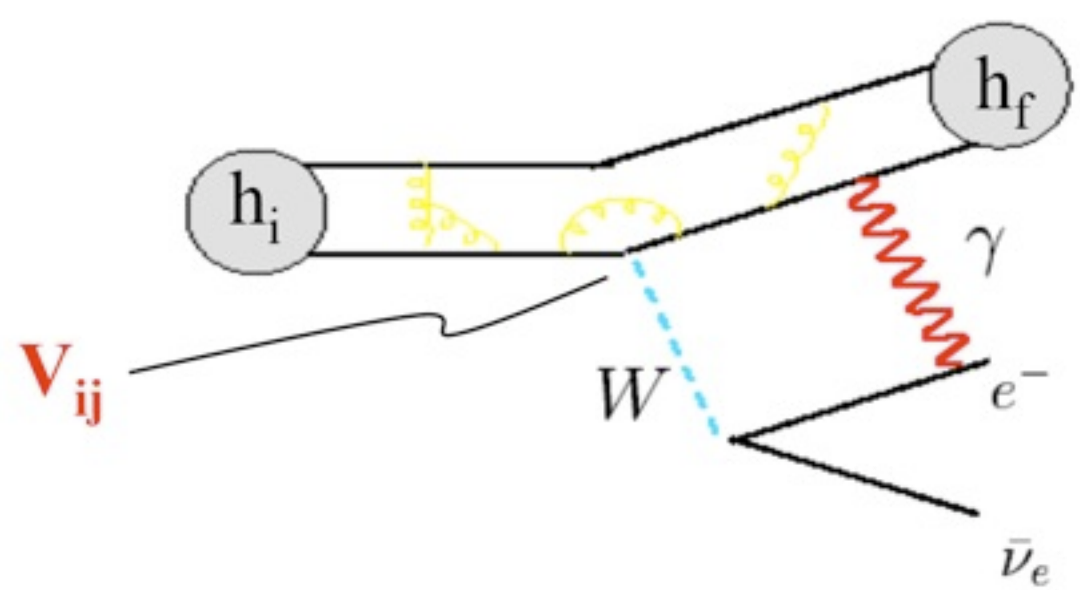
2. Total decay rates: normalization (V,A) matters!

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

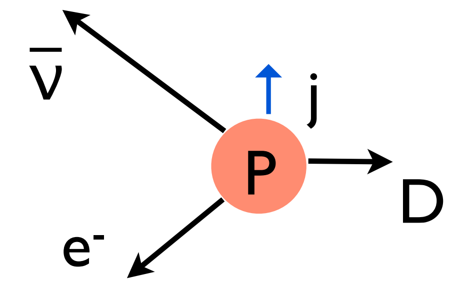
Channel-dependent effective CKM element:

Hadronic matrix element

Radiative corrections (both SD and LD)



Differential probes

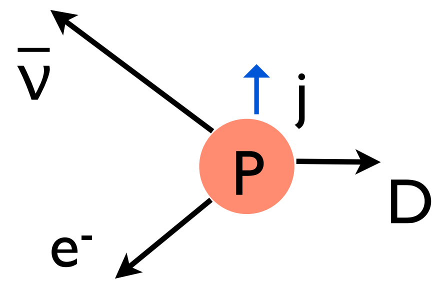


$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

- Linear order ε's: only $\varepsilon_{S,T}$ survive!
  - b and B = $B_0 + b_\nu\, m_e/E_e$ directly sensitive to $\varepsilon_{S,T}$
  - a and A indirectly sensitive to $\varepsilon_{S,T}$ via b in the asymmetry "denominator"

$$\tilde{a} = \frac{a_{SM}}{1 + b\,\langle m_e/E_e\rangle} \qquad \tilde{A} = \frac{A_{SM}}{1 + b\,\langle m_e/E_e\rangle}$$

Differential probes



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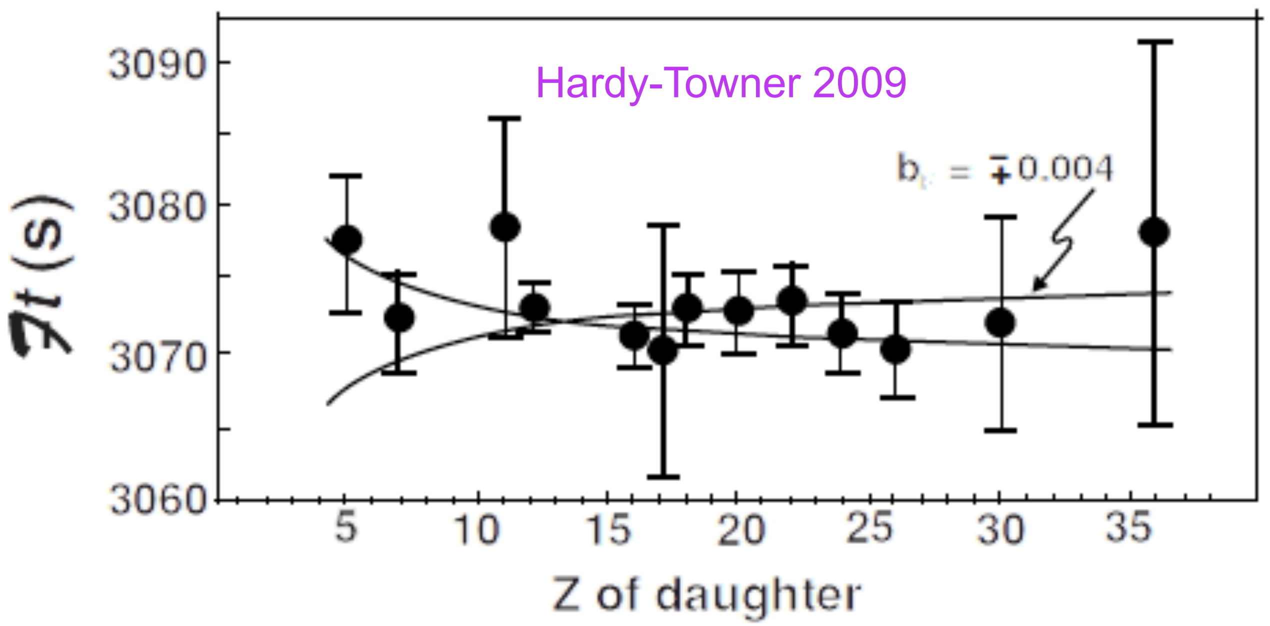
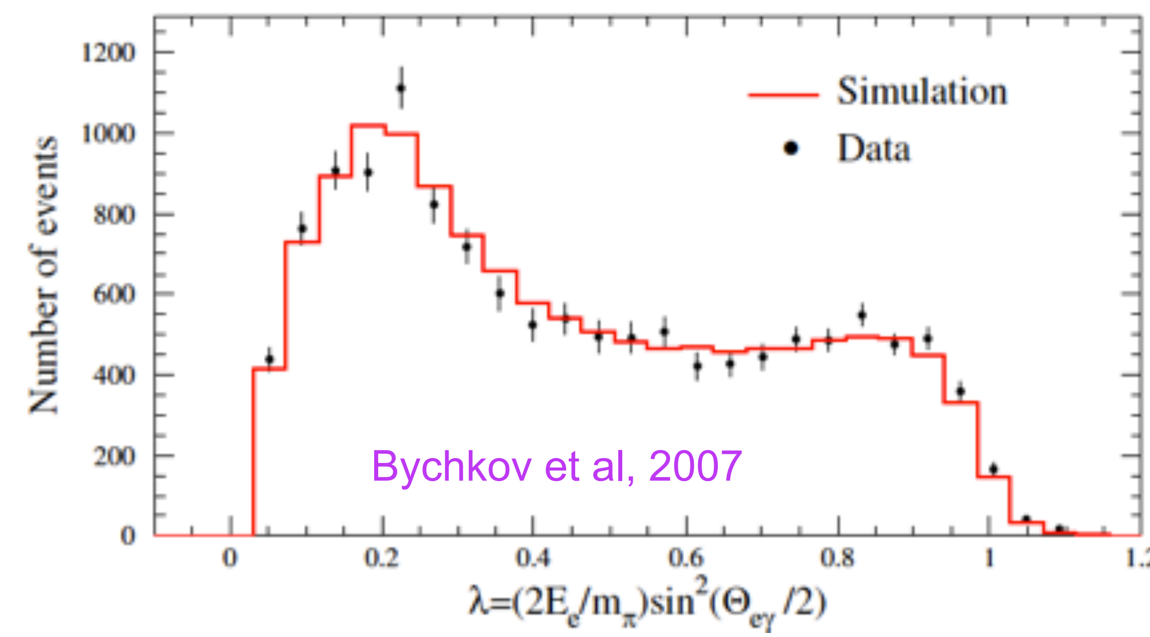
- <u>Quadratic order in ε's</u>
  - b, b_ν: $\epsilon_{S,T} * (\epsilon_L \pm \epsilon_R)$; $\tilde{\epsilon}_{S,T} * (\tilde{\epsilon}_L \pm \tilde{\epsilon}_R)$
  - a: $|\epsilon_S|^2 + |\epsilon_T|^2$; $|\tilde{\epsilon}_S|^2 + |\tilde{\epsilon}_T|^2$
  - A,B: $(\tilde{\epsilon}_L - \tilde{\epsilon}_R)^2$
- Expect weaker constraints
- Focus on $\epsilon_{S,T}$

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ and $\pi \to e\,\nu\,\gamma$

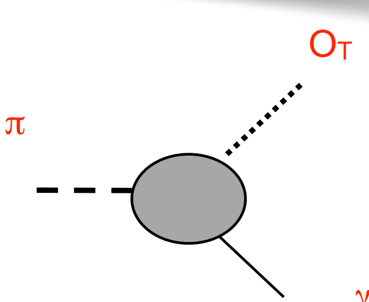




$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

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

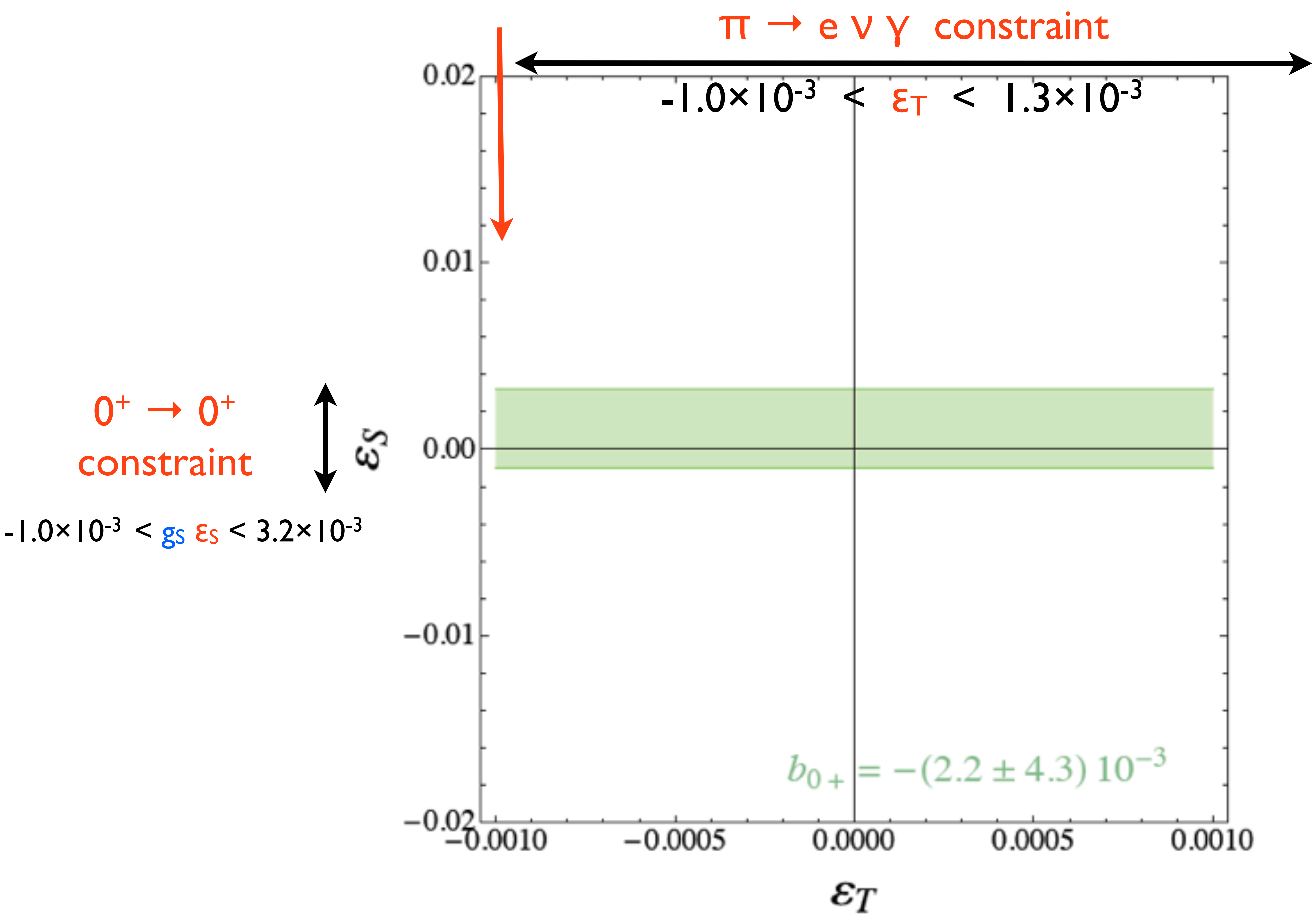
$f_T = 0.24(4) \leftrightarrow$



Mateu-Portoles 07

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+$ and $\pi \rightarrow e\,\nu\,\gamma$



(90% C.L.)

$g_S = g_T = 1$

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+$ and $\pi \rightarrow e\, \nu\, \gamma$
- Future: <u>neutron</u> b, b_ν @ 10^{-3} level (Nab; UCNB,b, abBA, ...)

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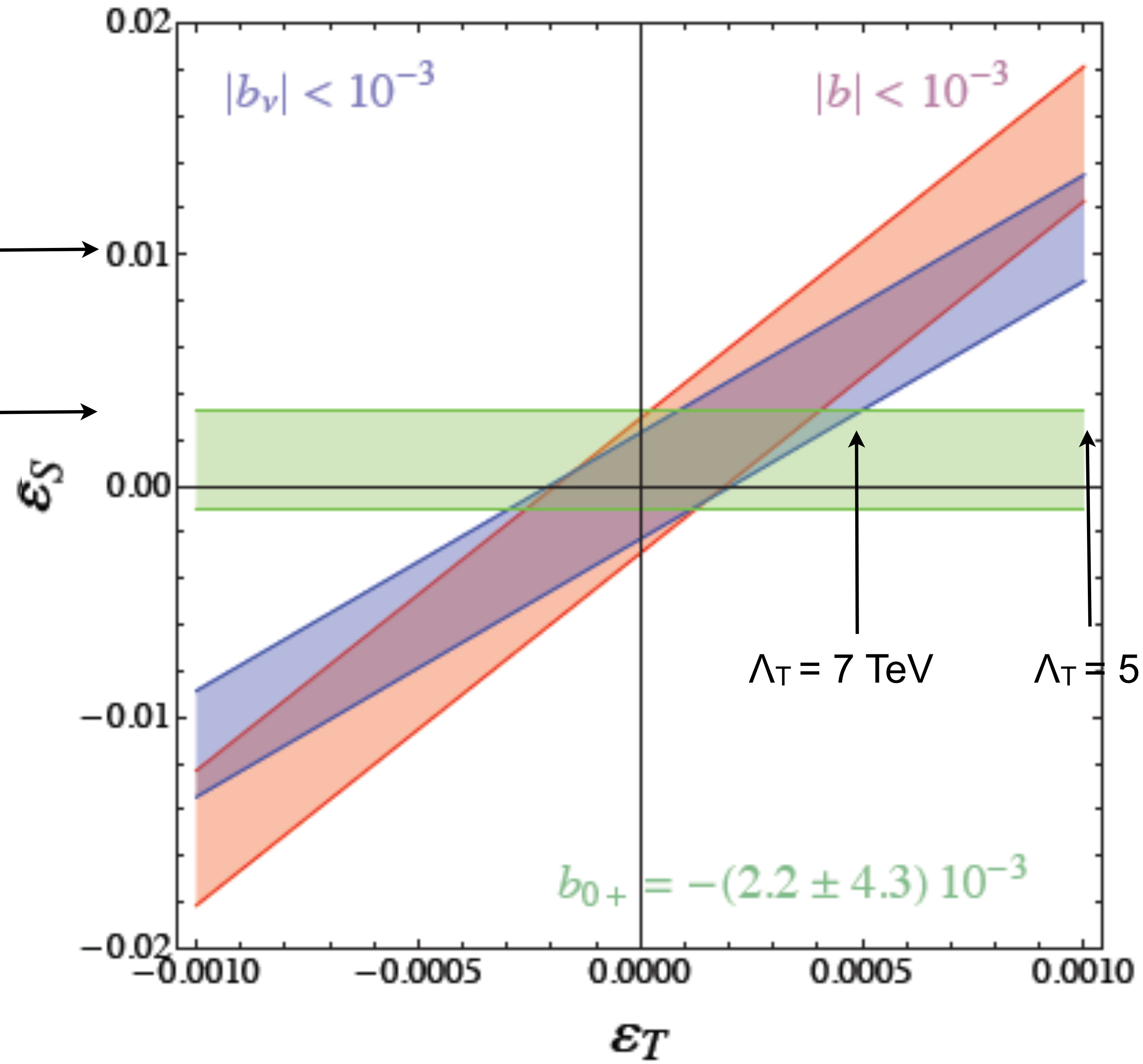
(90% C.L.)

Λ_S = 3.2 TeV

Λ_S = 5 TeV



Λ_T = 7 TeV

Λ_T = 5 TeV

$g_S = g_T = 1$

$\varepsilon_S \equiv 2\,(v/\Lambda_S)^2$

$\varepsilon_T \equiv (v/\Lambda_T)^2$

$v \equiv (2\sqrt{2}\,G_F)^{-1/2}$

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+$ and $\pi \rightarrow e \nu \gamma$
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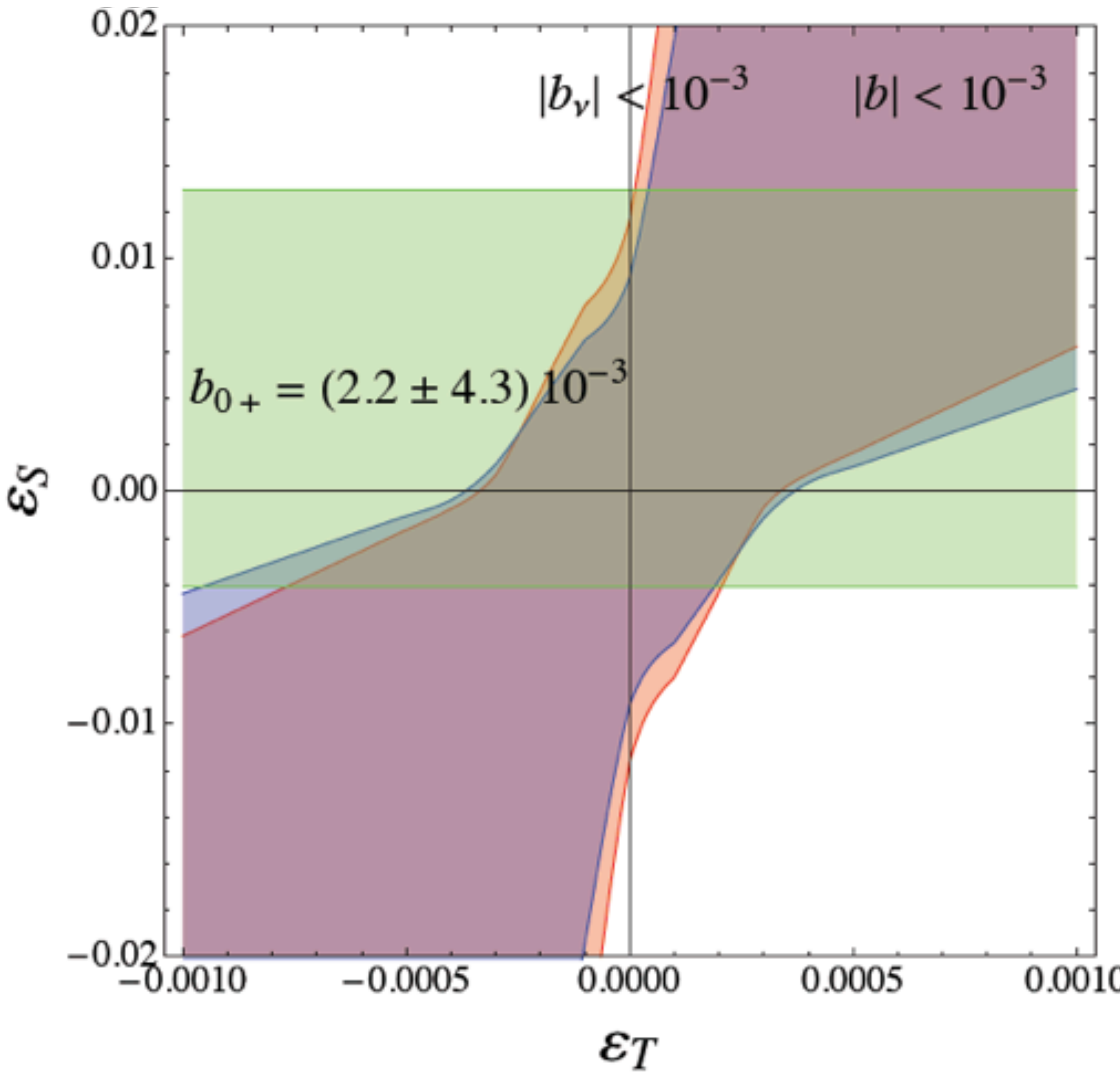


(90% C.L.)

Quark model estimates:

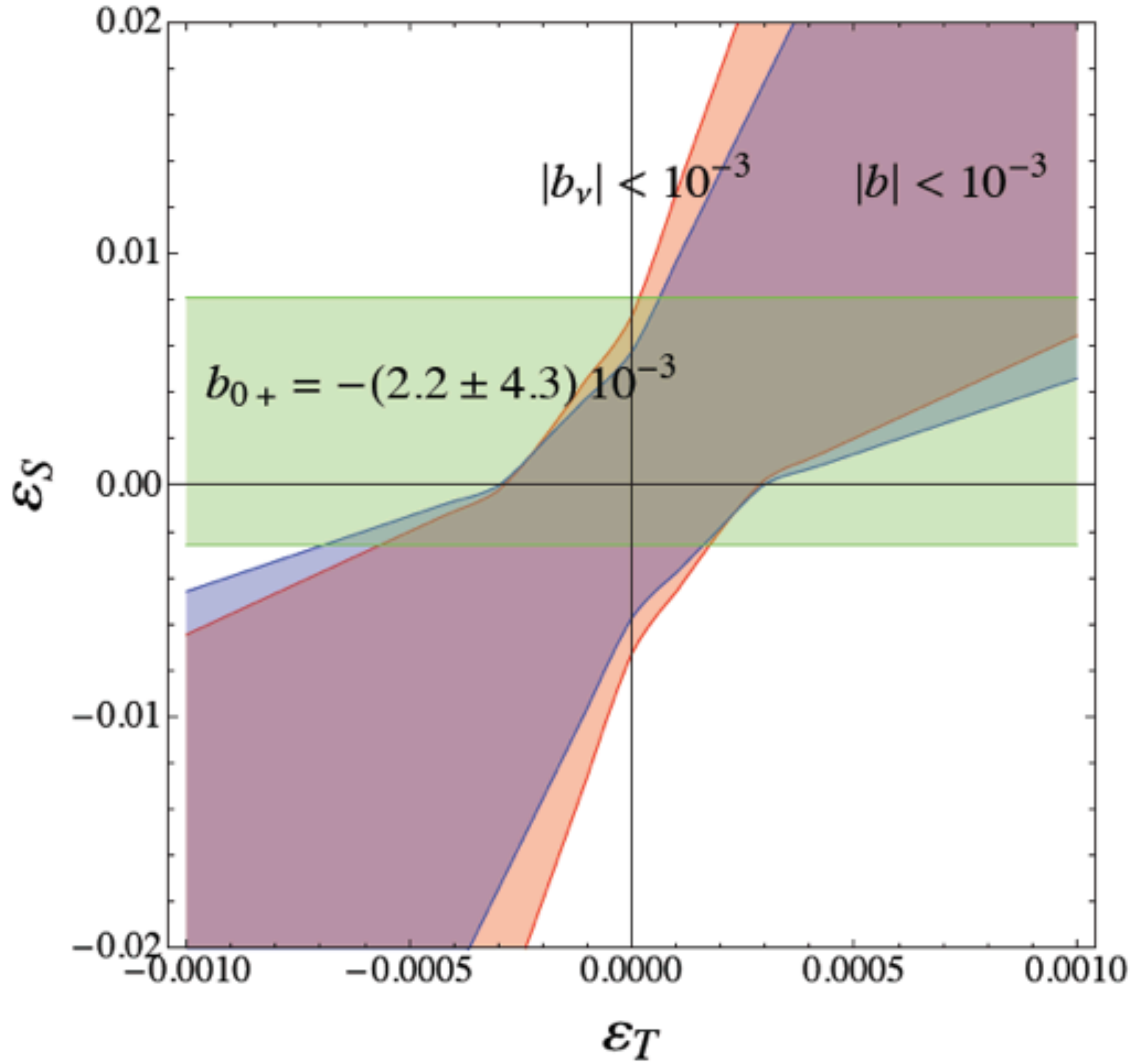
$0.25 < g_S < 1$

$0.6 < g_T < 2.3$

Adler et al, '75
Herczeg '01

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ and $\pi \to e \nu \gamma$
- Future: neutron b, b_ν @ 10^{-3} level (Nab; UCNB,b, abBA, ...)



(90% C.L.)

New!

Lattice QCD

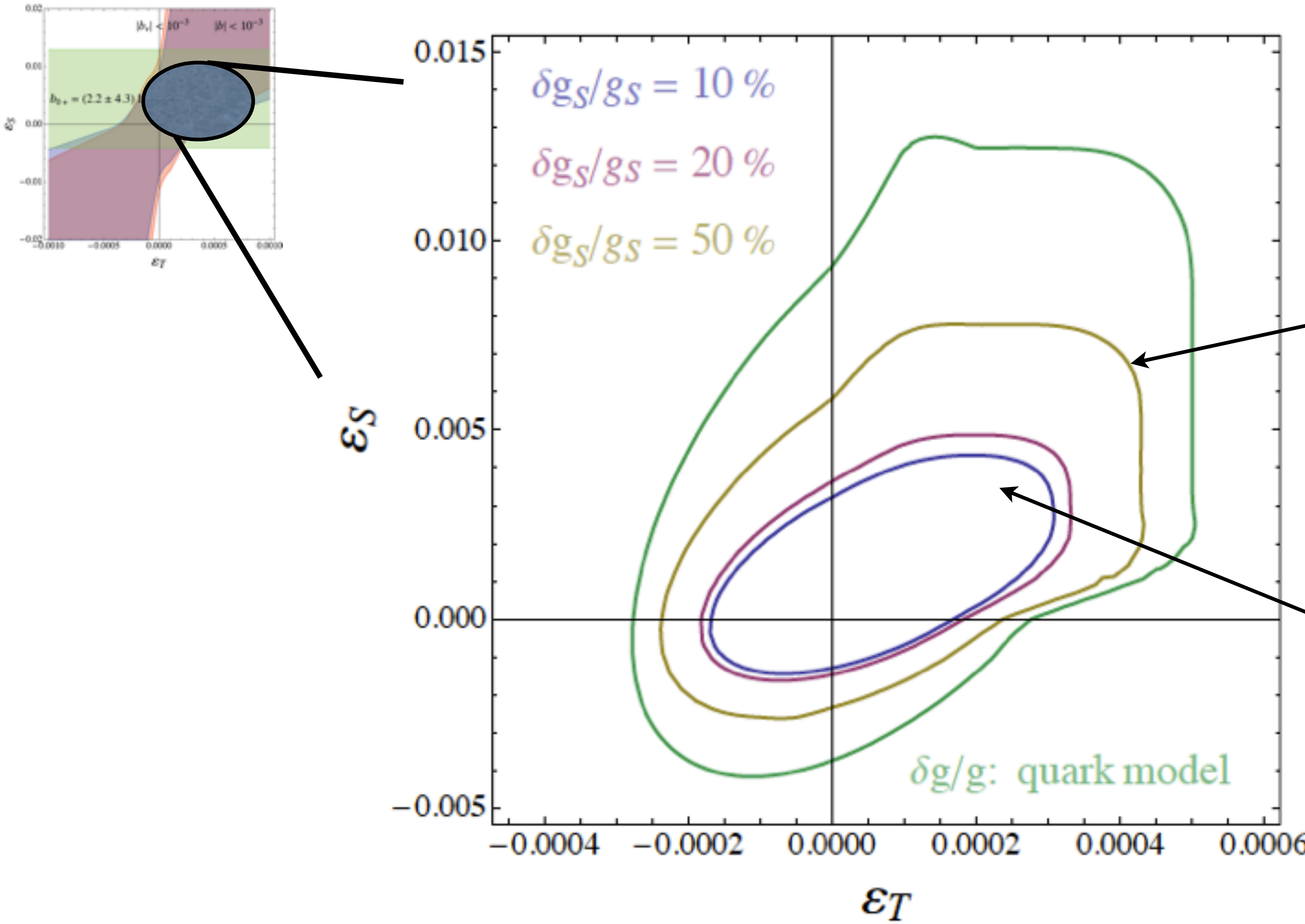
$g_S = 0.8\,(4)$

$g_T = 1.05(35)$

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

Low-energy constraints on $\varepsilon_{S,T}$

- **Current**: $0^+ \to 0^+$ and $\pi \to e\,\nu\,\gamma$
- **Future**: <u>neutron</u> b, b_ν @ 10^{-3} level (Nab; UCNB,b, abBA, ...)



(90% C.L.)

current lattice results

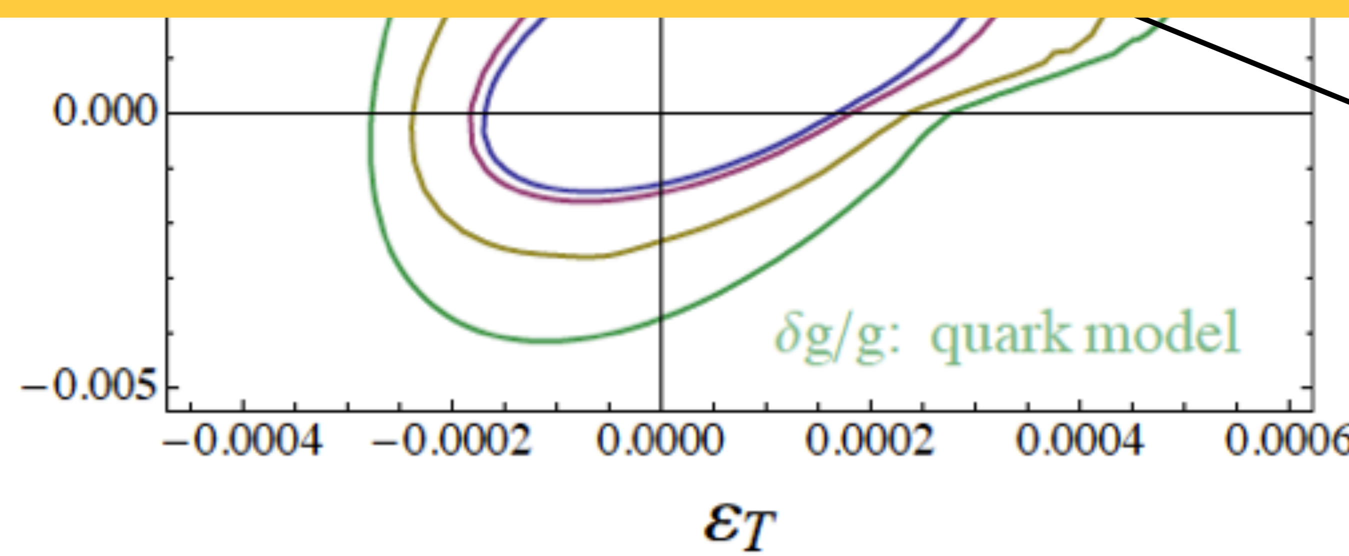
$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances

Low-energy constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ and $\pi \to e\,\nu\,\gamma$

Messages

- neutron b and B at 10^{-3} level <u>will</u> improve current bounds on $\varepsilon_{S,T}$
- Hadronic uncertainties ($g_{S,T}$) strongly dilute significance of bounds
- First lattice results: already great improvement over quark models
- $\delta g_{S,T}/g_{S,T} \sim 20\%$ needed to fully exploit $\sim 10^{-3}$-level measurements



$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances

Low-energy constraints on $\tilde{\varepsilon}_{L,R,S,T}$

- Global fit to beta decay data

Severijns, Beck, Naviliat-Cuncic, 2006

$$| g_S \, \tilde{\varepsilon}_S | < 6 \times 10^{-2}$$

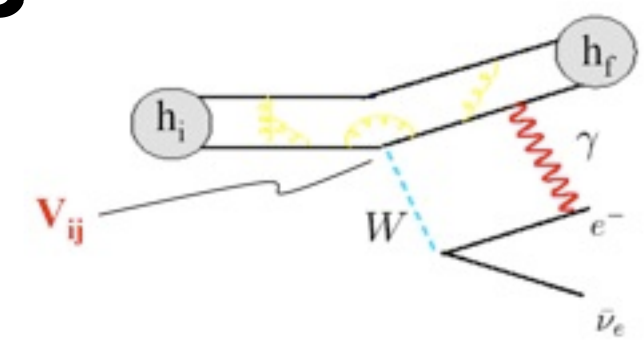
$$| g_T \, \tilde{\varepsilon}_T | < 2.5 \times 10^{-2}$$

$$|\tilde{\varepsilon}_L \pm \tilde{\varepsilon}_R| < 7.5 \times 10^{-2}$$

90% CL

- Constraints are relatively weak, as expected

Universality probes



- Master formula for decay rates:

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

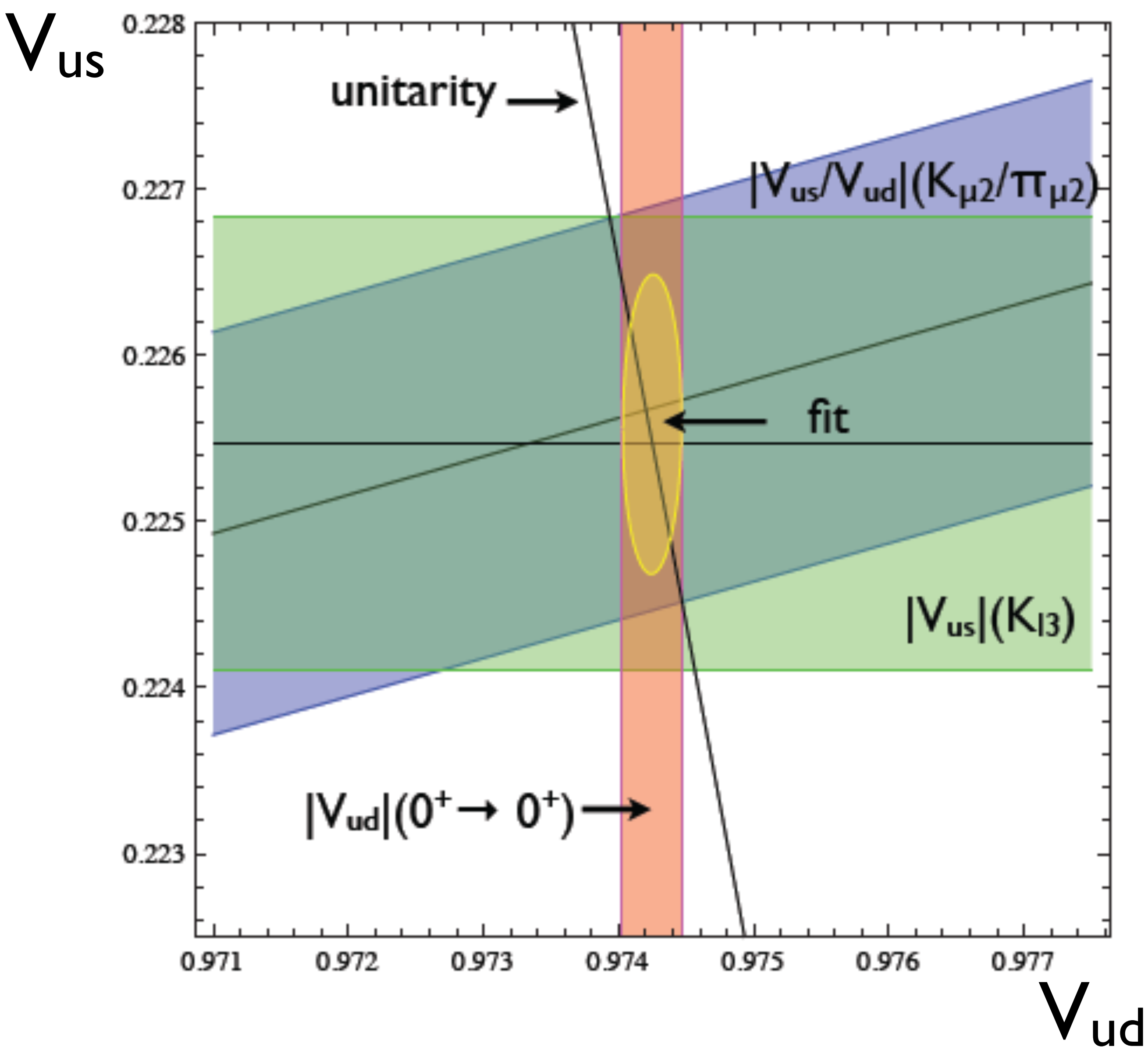
$$|\bar{V}_{ij}|^2 = |V_{ij}|^2 \times \left(1 + \sum_\alpha c_k^\alpha \, \epsilon_\alpha\right)$$

- Precision determination of $\overline{V}_{ij}$ $\Rightarrow$ constraints on the ϵ_i

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 - 1 = \Delta(\epsilon_i)$$

- Status of V_{ud} and V_{us} and Cabibbo universality

Flavianet WG '10, VC-Neufeld '11



Fit result

$$V_{ud} = 0.97425\,(22) \quad 0.02\%$$
$$V_{us} = 0.2256\,(9) \quad 0.5\%$$

$$\downarrow$$

$$\boxed{\Delta = (1 \pm 6) * 10^{-4}}$$

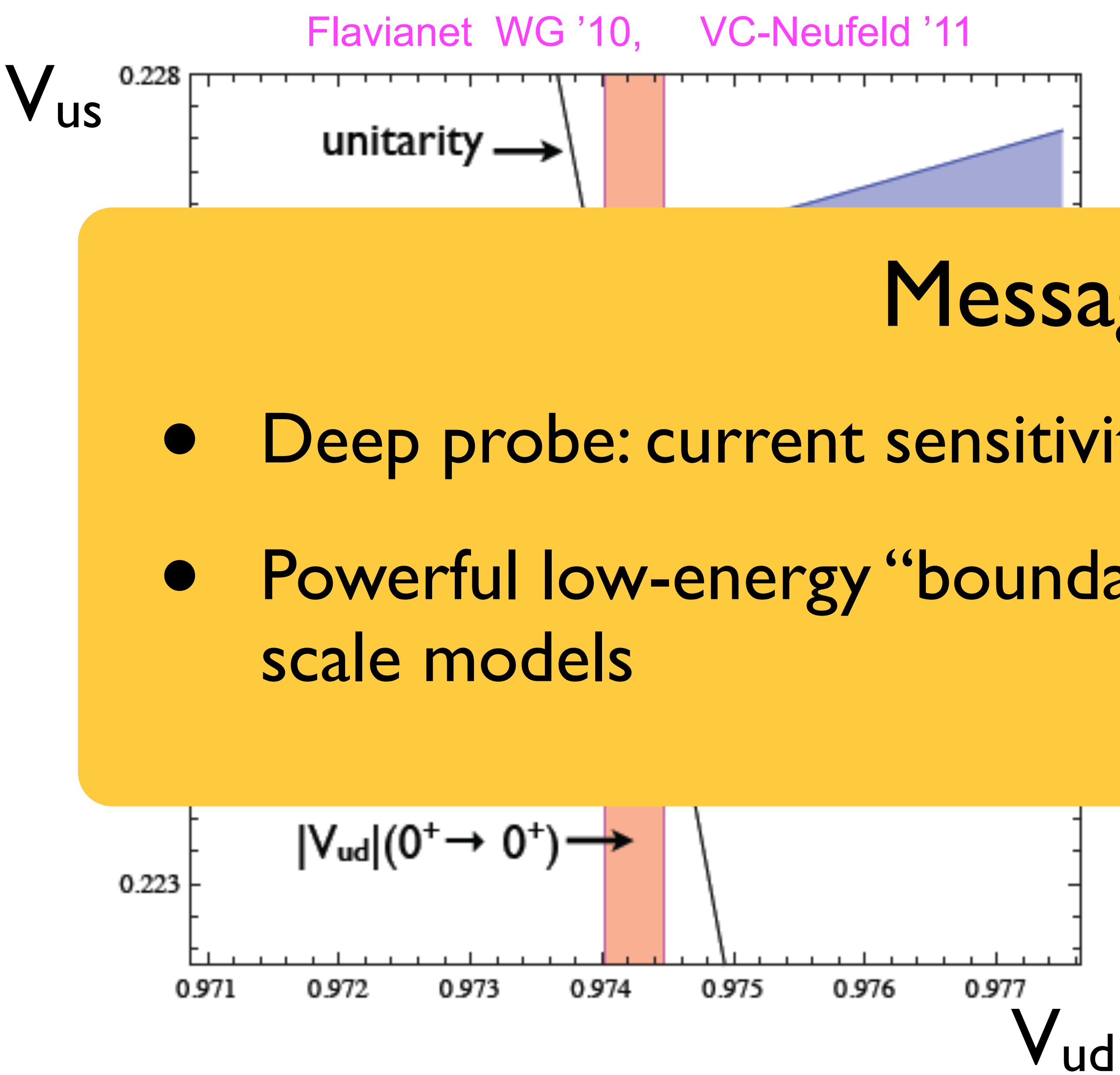
Error equally shared between V_{ud} and V_{us}

$$\boxed{|\varepsilon_L + \varepsilon_R - \varepsilon_L^{(lept)}| < 5 \times 10^{-4}}$$

90% CL:

$(\Lambda_{L,R} > 11 \text{ TeV})$

- Status of V_{ud} and V_{us} and Cabibbo universality



Fit result

Error equally shared between V_{ud} and V_{us}

Messages

- Deep probe: current sensitivity well in the TeV region
- Powerful low-energy "boundary condition" for weak-scale models

90% CL: $$|\varepsilon_L + \varepsilon_R - \varepsilon_L^{(lept)}| < 5 \times 10^{-4}$$

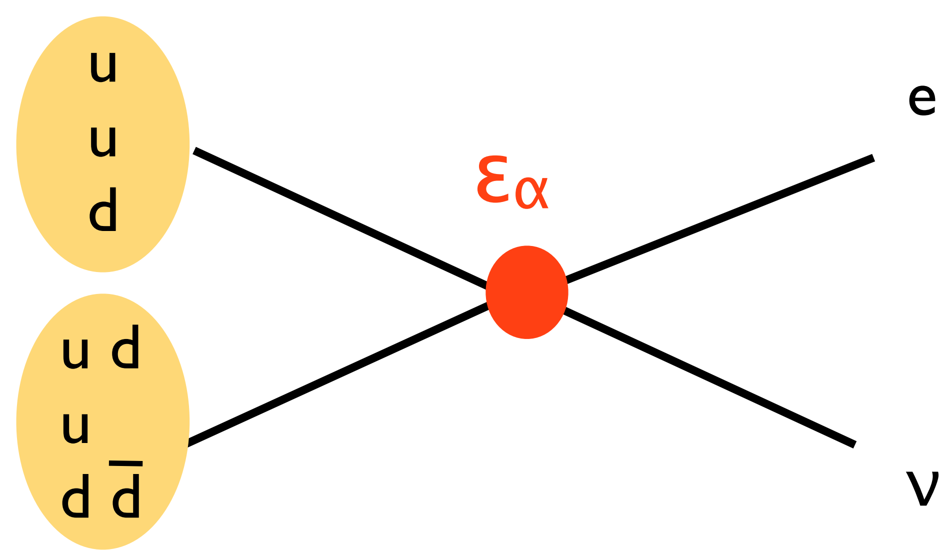
$(\Lambda_{L,R} > 11\ \mathrm{TeV})$

High-energy probes

LHC (I): contact interactions

- The effective couplings ε_α contribute to the process $p\,p \to e\,\nu + X$

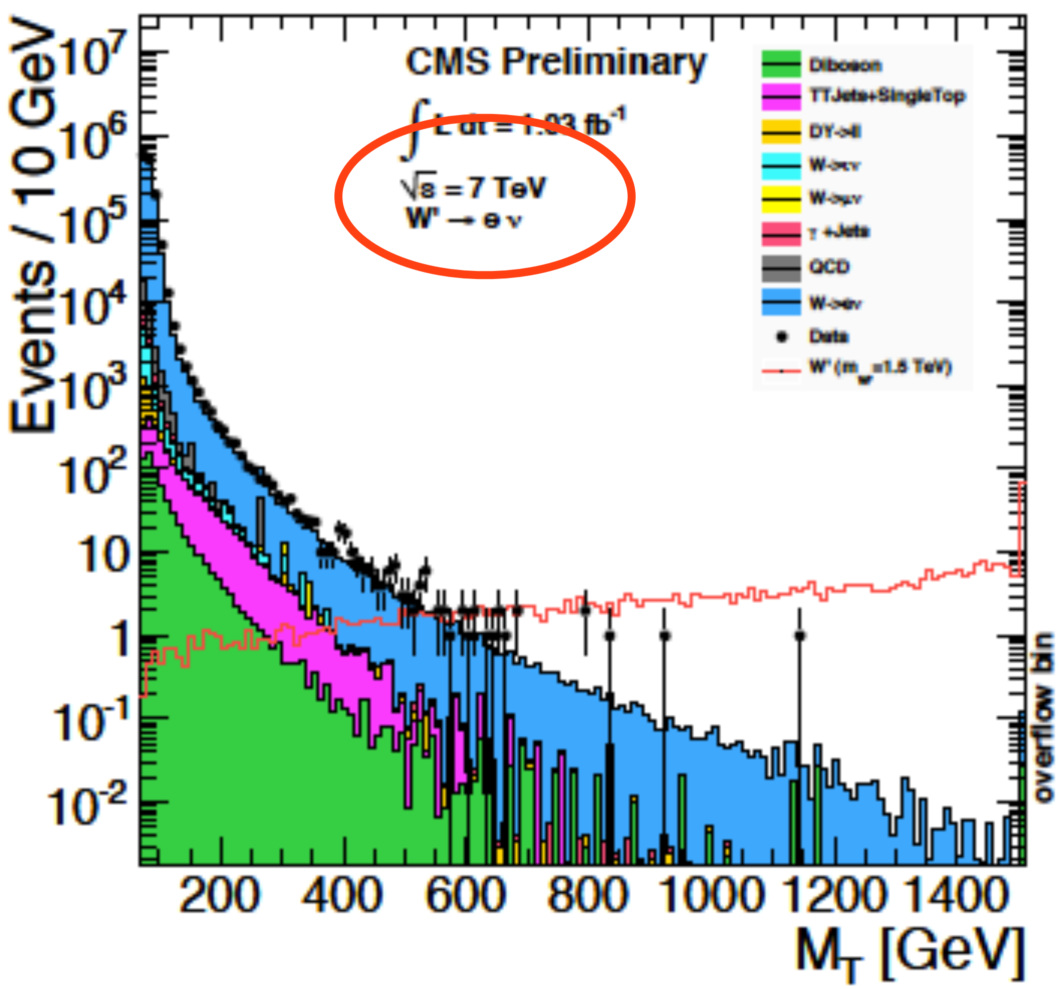
Missing Transverse Energy



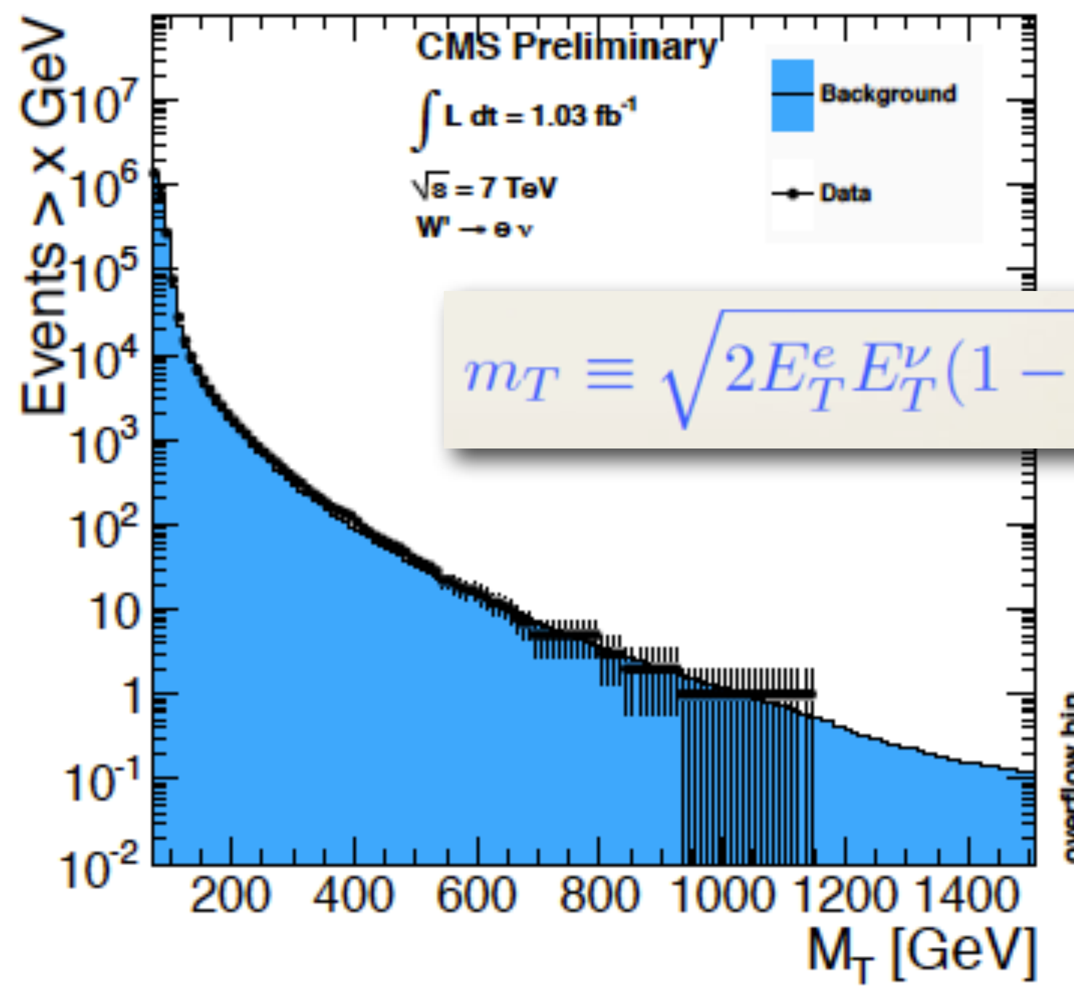
- Moreover, using SU(2) symmetry, ε_α contribute to
  - $p\,p \to e^+ e^- + X$
  - $p\,p \to \nu\,\bar{\nu}$ + jet ("monojet")

- Focus on lepton transverse mass distribution in p p → e ν + X

differential



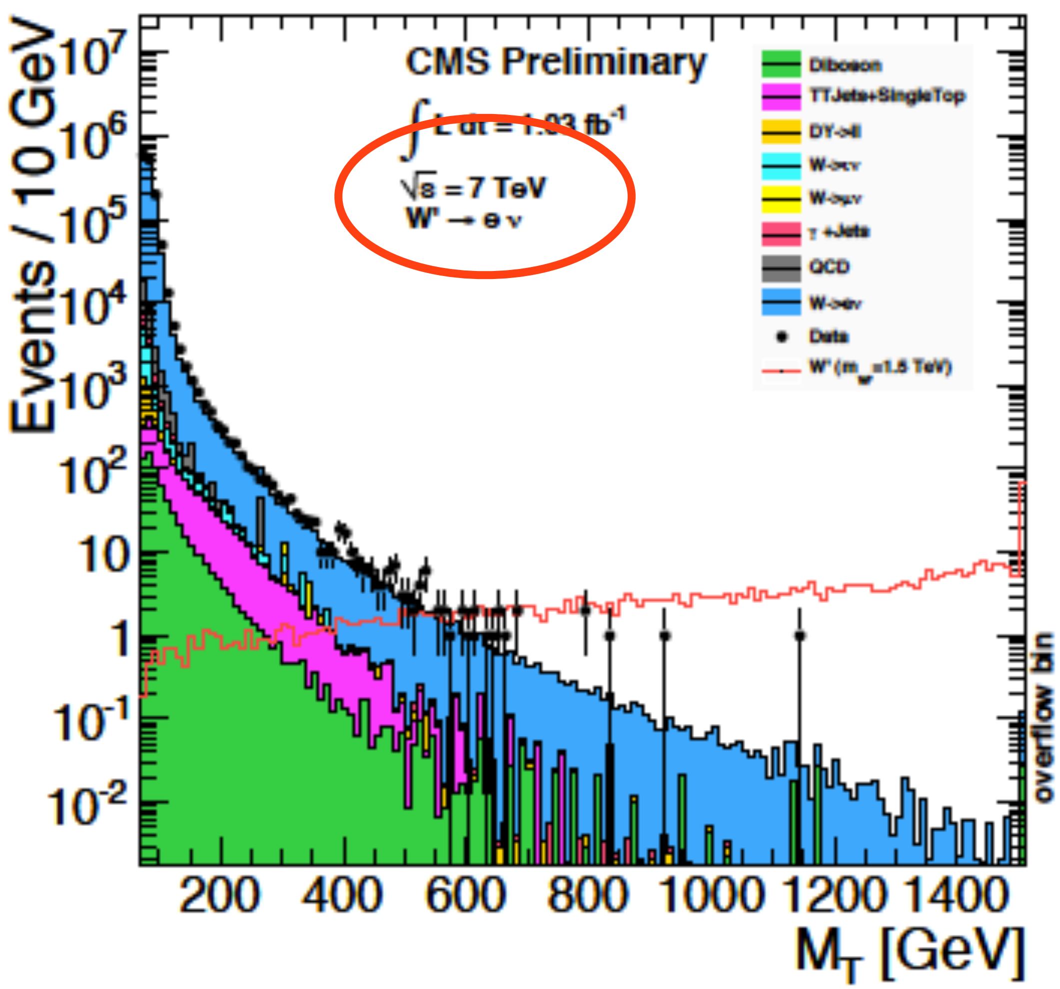
cumulative



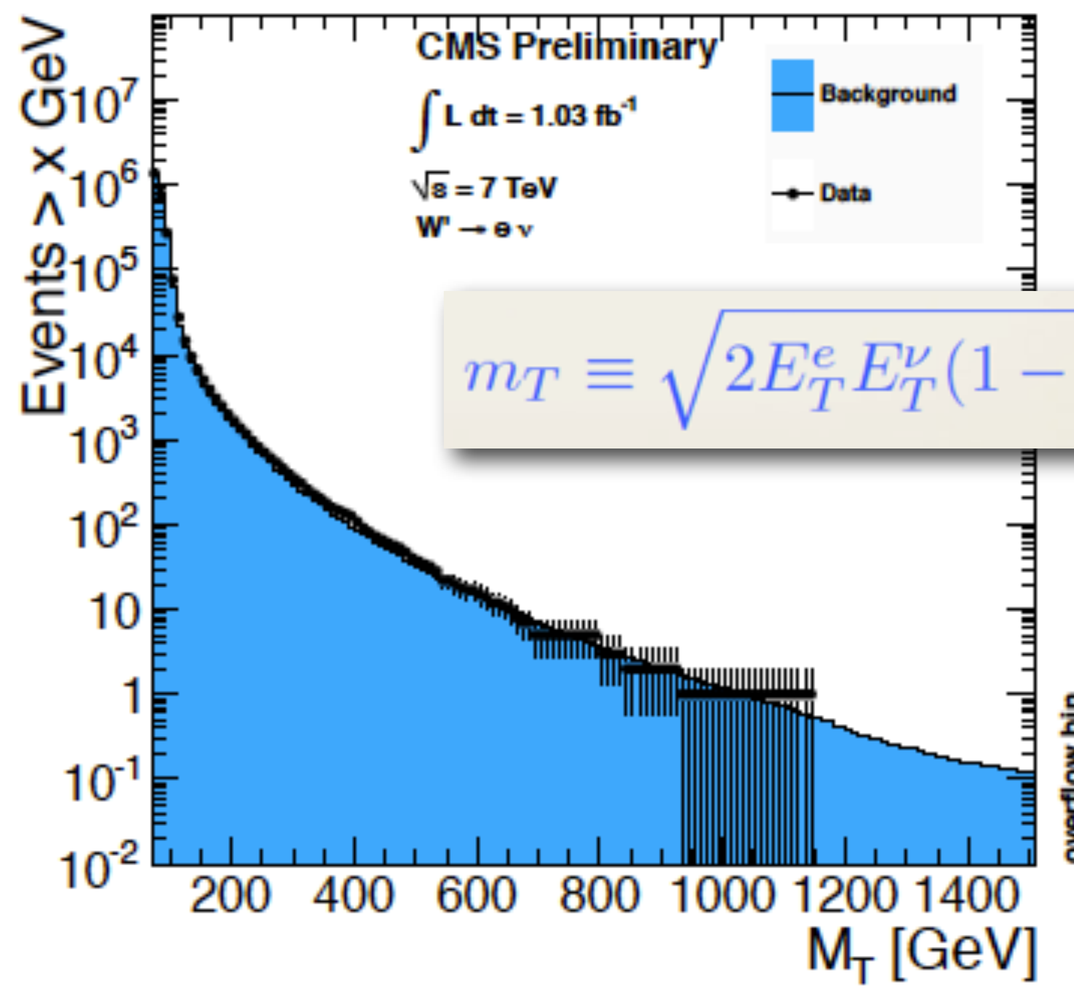
$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$

- Focus on lepton transverse mass distribution in p p → e ν + X

differential



cumulative



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

- $m_T > 1$ TeV: $n_{obs} = 1$, $n_{bkg} = 2.2 \pm 1.1$ ⇒ bound on "signal" BSM events

$$n_s < n_s^{up}(n_{obs}, n_{bkg}) = 3.0 \qquad 90\%\ \mathrm{CL}$$

VC, Gonzalez-Alonso, Graesser, in progress

- Bounds on the effective couplings:

$$\boxed{\sigma_{BSM}(\varepsilon_\alpha)\ \mathcal{L}\ \varepsilon_{eff} \equiv n_s < 3.0}$$

m_T > 1 TeV

detection efficiency * geometric acceptance

$$\begin{aligned}
\sigma\Big|_{m_T > \overline{m}_T} &= \sigma_W + \sigma_{BSM}(\epsilon_\alpha) \\
&= \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2\right] - 2\,\sigma_{WL}\ \epsilon_L^{(c)} \\
&+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right] \\
&+ \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2\right] \\
&+ \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right]
\end{aligned}$$

VC, Gonzalez-Alonso, Graesser, in progress

- Bounds on the effective couplings:

$\sigma_{BSM}(\varepsilon_\alpha)\ \mathcal{L}\ \varepsilon_{eff} \equiv n_s < 3.0$

$m_T > 1$ TeV

SM + vertex corrections + interference terms

$$\sigma\Big|_{m_T > \overline{m}_T} = \sigma_W + \sigma_{BSM}(\epsilon_\alpha)$$

$$= \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2\right] - 2\,\sigma_{WL}\ \epsilon_L^{(c)}$$

$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right]$$

$$+ \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2\right]$$

$$+ \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right]$$

Incoherent contributions (interference ~ m/E)

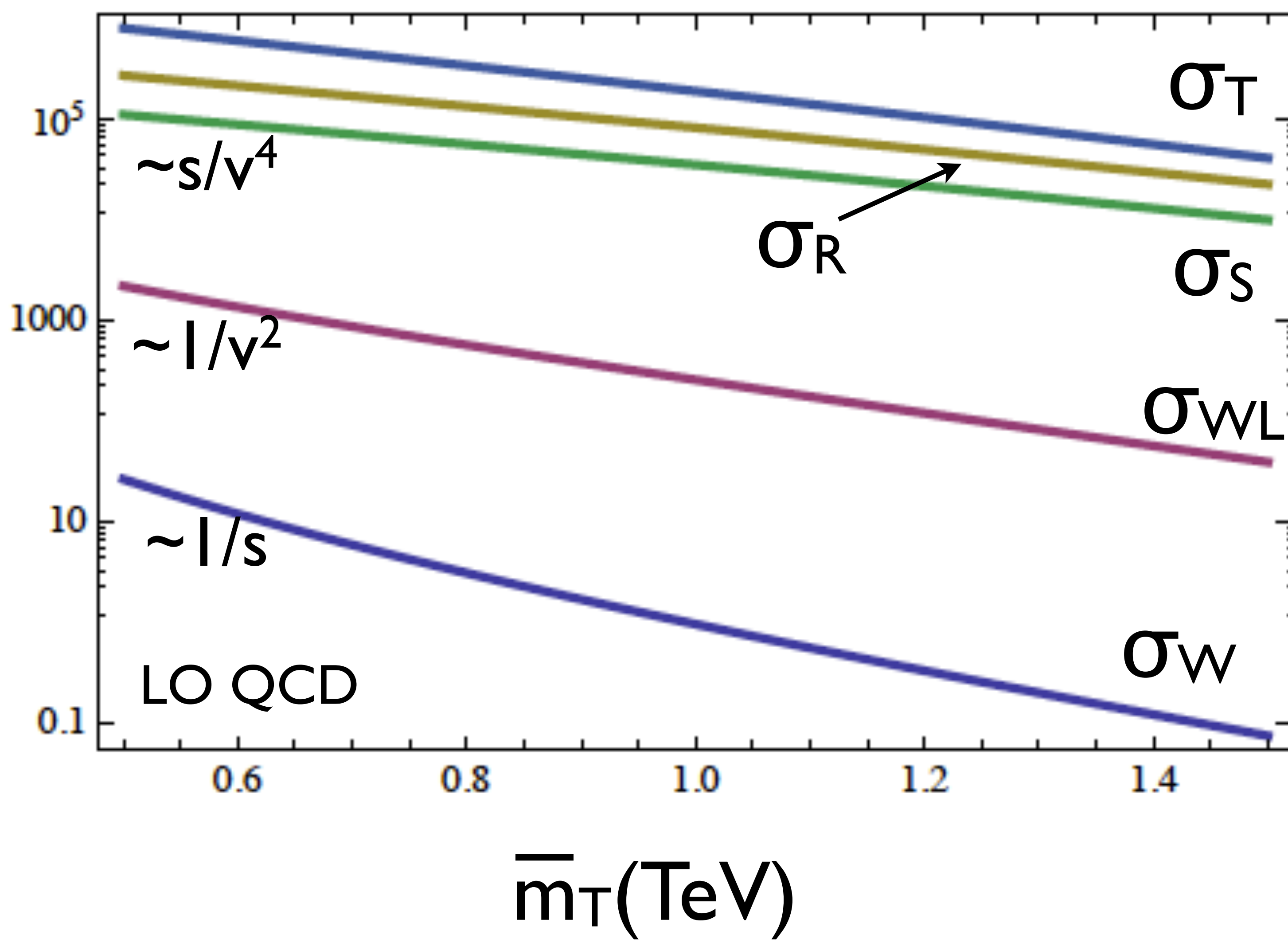
VC, Gonzalez-Alonso, Graesser, in progress

- Bounds on the effective couplings:

$$\boxed{\sigma_{BSM}(\varepsilon_\alpha)\ \mathcal{L}\ \varepsilon_{eff} \equiv n_s < 3.0}$$

$m_T > 1$ TeV

σ (fb)



90% CL

$$\Rightarrow \boxed{\begin{array}{l} |\varepsilon_{S,P}|, |\tilde{\varepsilon}_{S,P}| < 1.7 \times 10^{-2} \\ |\varepsilon_T|, |\tilde{\varepsilon}_T| < 3.4 \times 10^{-3} \\ |\tilde{\varepsilon}_R| < 6.3 \times 10^{-3} \end{array}}$$

Already strong bounds on "incoherent" contributions, <u>regardless of neutrino chirality</u>

β decays vs LHC

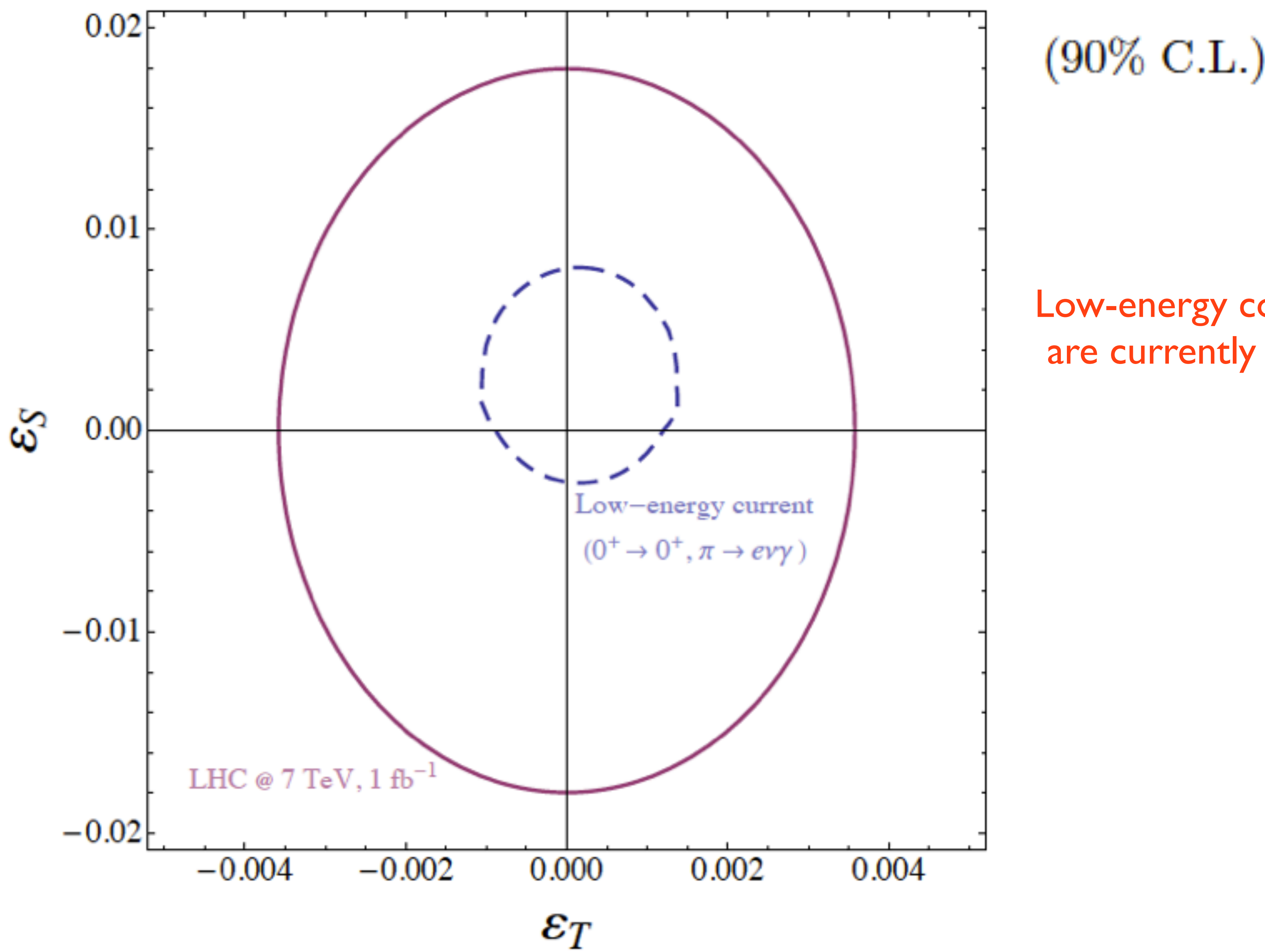
	$\varepsilon_L+\varepsilon_R$	ε_S	ε_T	$\tilde{\varepsilon}_S$	$\tilde{\varepsilon}_T$	$\tilde{\varepsilon}_{L,R}$
β decays	5×10^{-4}	8.0×10^{-3}	1.3×10^{-3}	7.5×10^{-2}	2.5×10^{-2}	7.5×10^{-2}
LHC	--	1.7×10^{-2}	3.4×10^{-3}	1.7×10^{-2}	3.4×10^{-3}	6.3×10^{-3}

Unmatched low-energy sensitivity

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

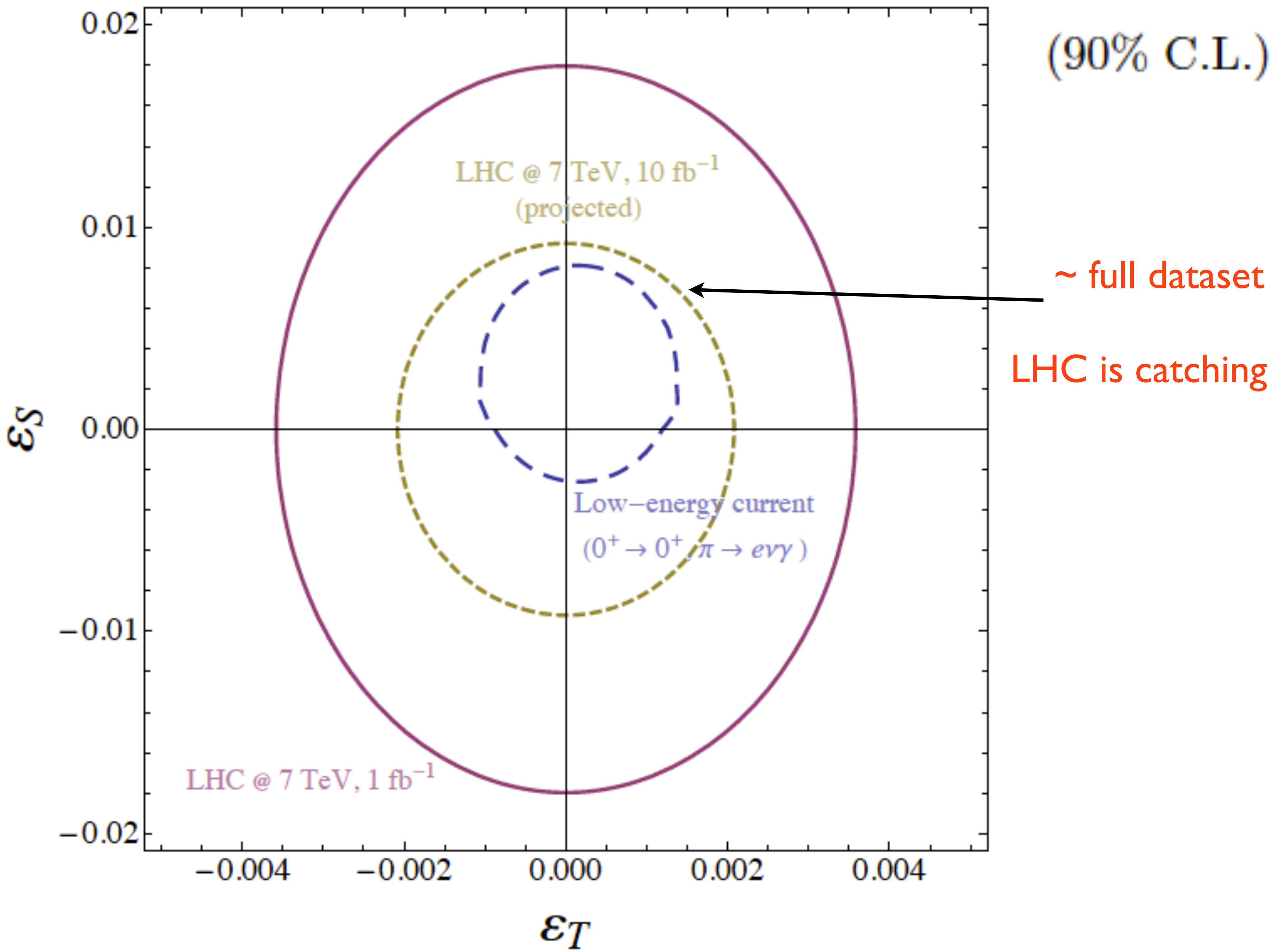
LHC already superior to low-energy!
Need $\delta a_{GT}/a_{GT} < 0.05\%$ to match LHC

$\varepsilon_{S,T}$: β decays vs LHC



Low-energy constraints are currently stronger

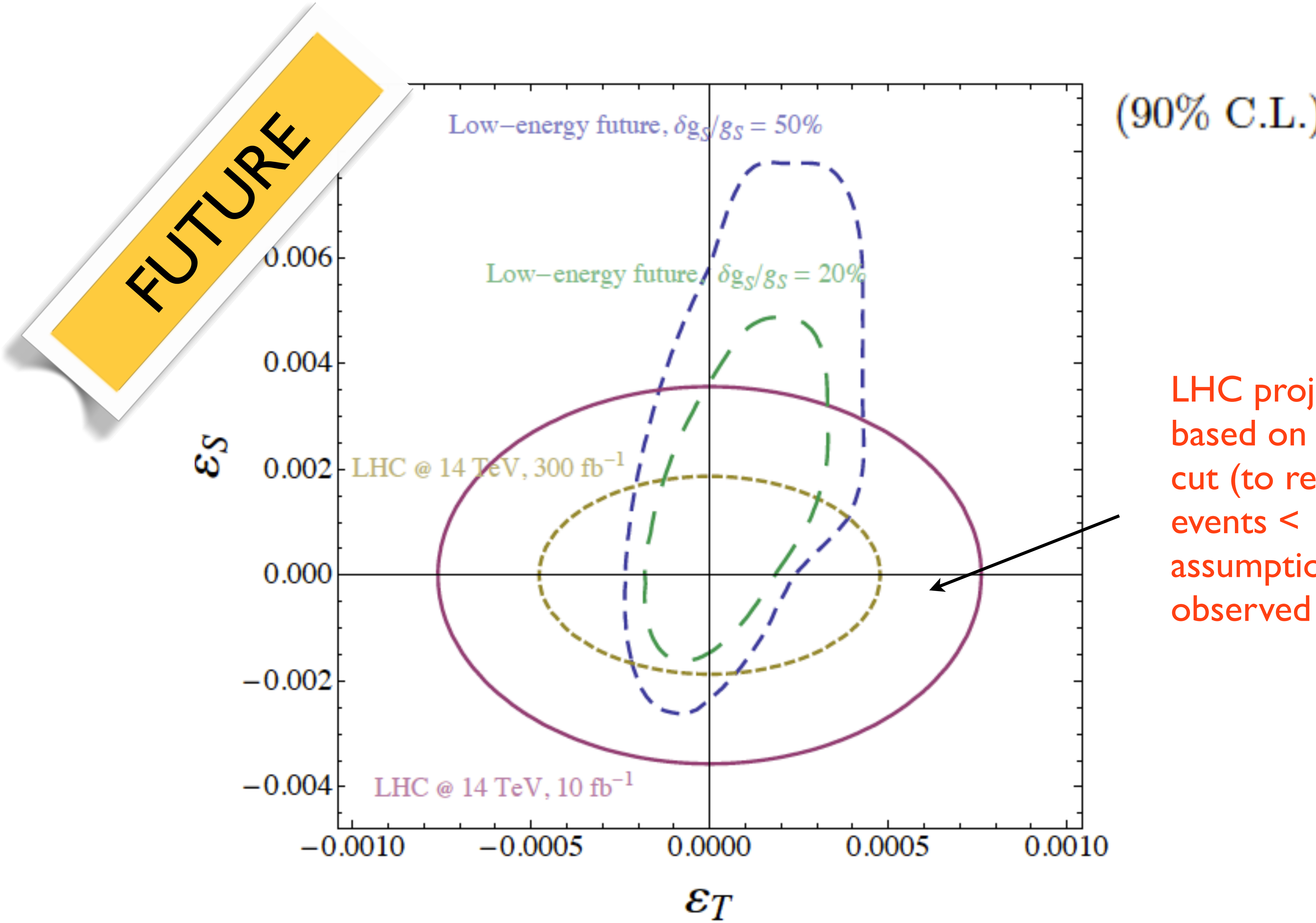
$\varepsilon_{S,T}$: β decays vs LHC



~ full dataset at 7 TeV

LHC is catching up rapidly!

$\varepsilon_{S,T}$: β decays vs LHC

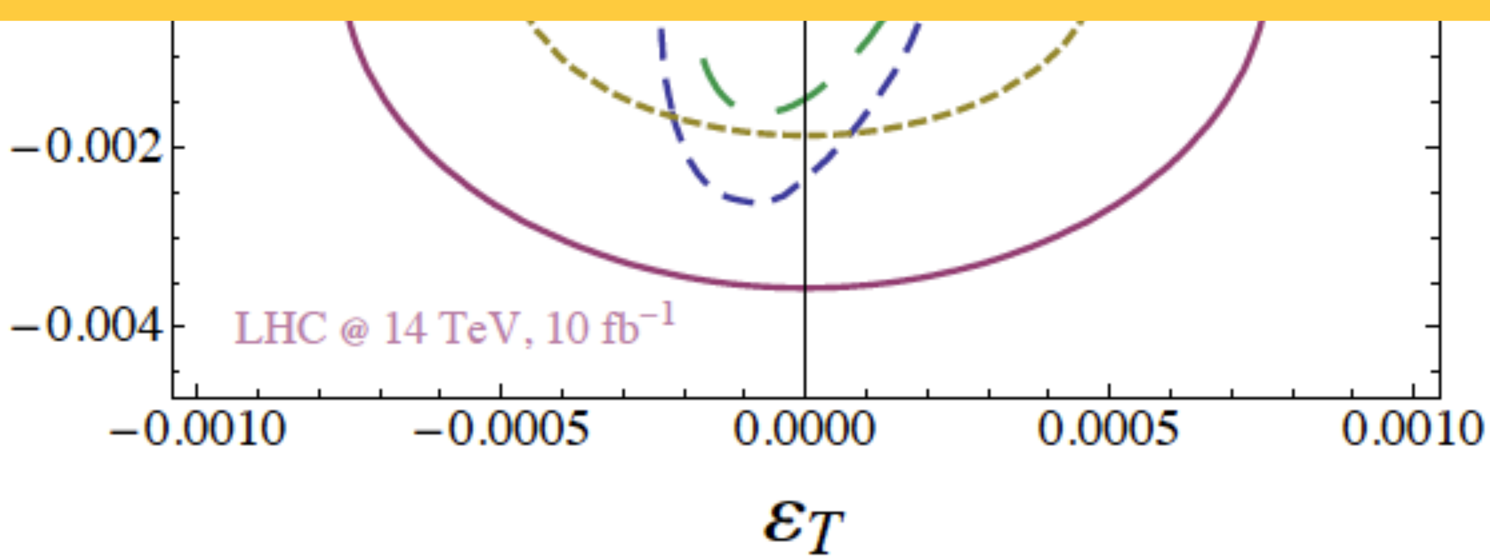


LHC projected limits: based on aggressive m_T cut (to reduce bkg events < 1) and assumption of no observed events

$\varepsilon_{S,T}$: β decays vs LHC

Messages

- LHC and b, B at 10^{-3} level will compete in setting strongest bounds on ε_S and ε_T probing effective scales $\Lambda_{S,T} \sim 7$ TeV
- b and B at 10^{-4} level would give unmatched discovery potential: strong motivation to pursue these experiments

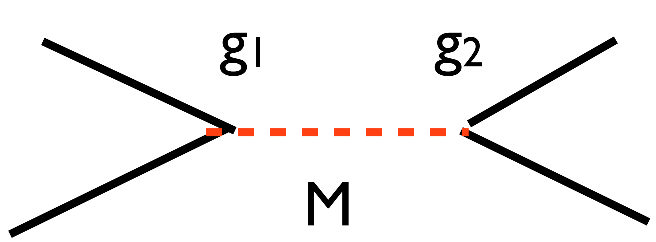


VC, Graesser, Passemar, in progress

LHC (II): beyond contact

- What if new interactions are not "contact" at LHC energy? How are the ε bounds affected?

- Explore classes of models generating $\varepsilon_{S,T}$ at tree-level. Low-energy vs LHC amplitude:

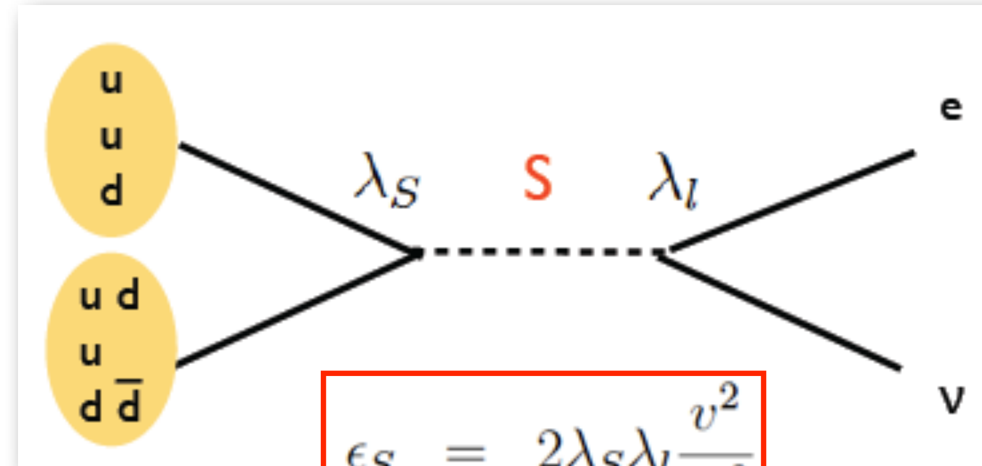


$$\boxed{\begin{array}{l} A_\beta \sim g_1 g_2/M^2 \equiv \varepsilon \\ A_{LHC} \sim \varepsilon\, F[\sqrt{s}/M, \sqrt{s}/\Gamma(\varepsilon)\,] \end{array}}$$

- Study dependence of the ε bounds on the mediator mass M

s-channel mediator

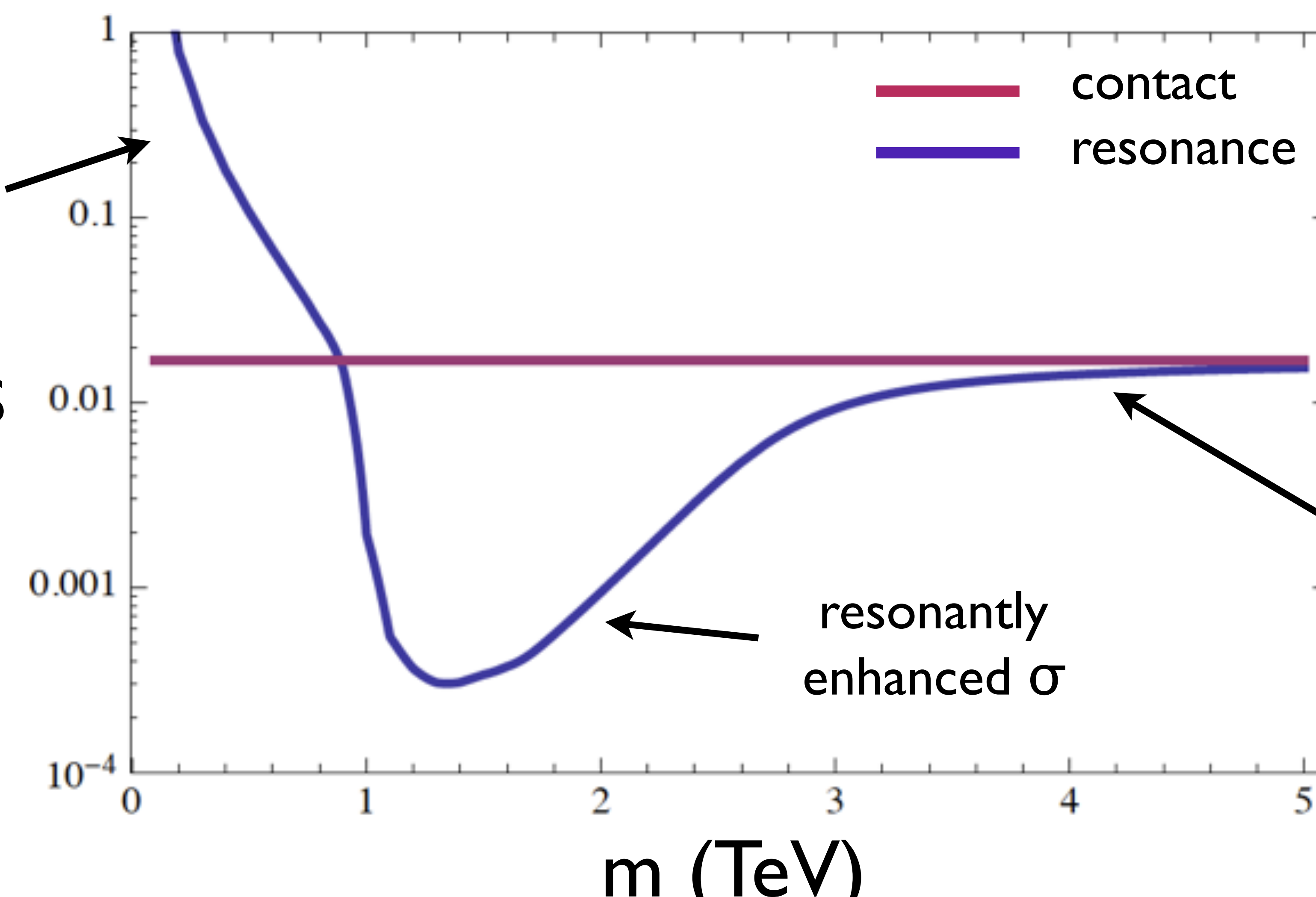
- Scalar resonance in s-channel
- Upper bound on ε_S based on m_T > 1 TeV



$$\boxed{\epsilon_S = 2\lambda_S\lambda_l \frac{v^2}{m^2}}$$

σ suppression due to $m < (m_T)^{cut}$

Improvable with lower $(m_T)^{cut}$
But larger SM bkg

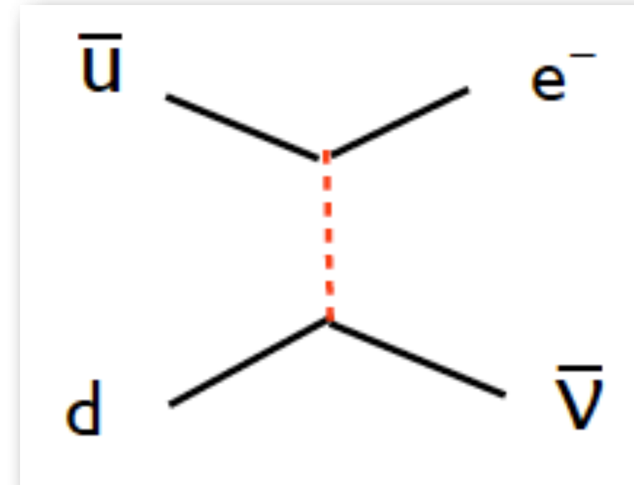


resonantly enhanced σ

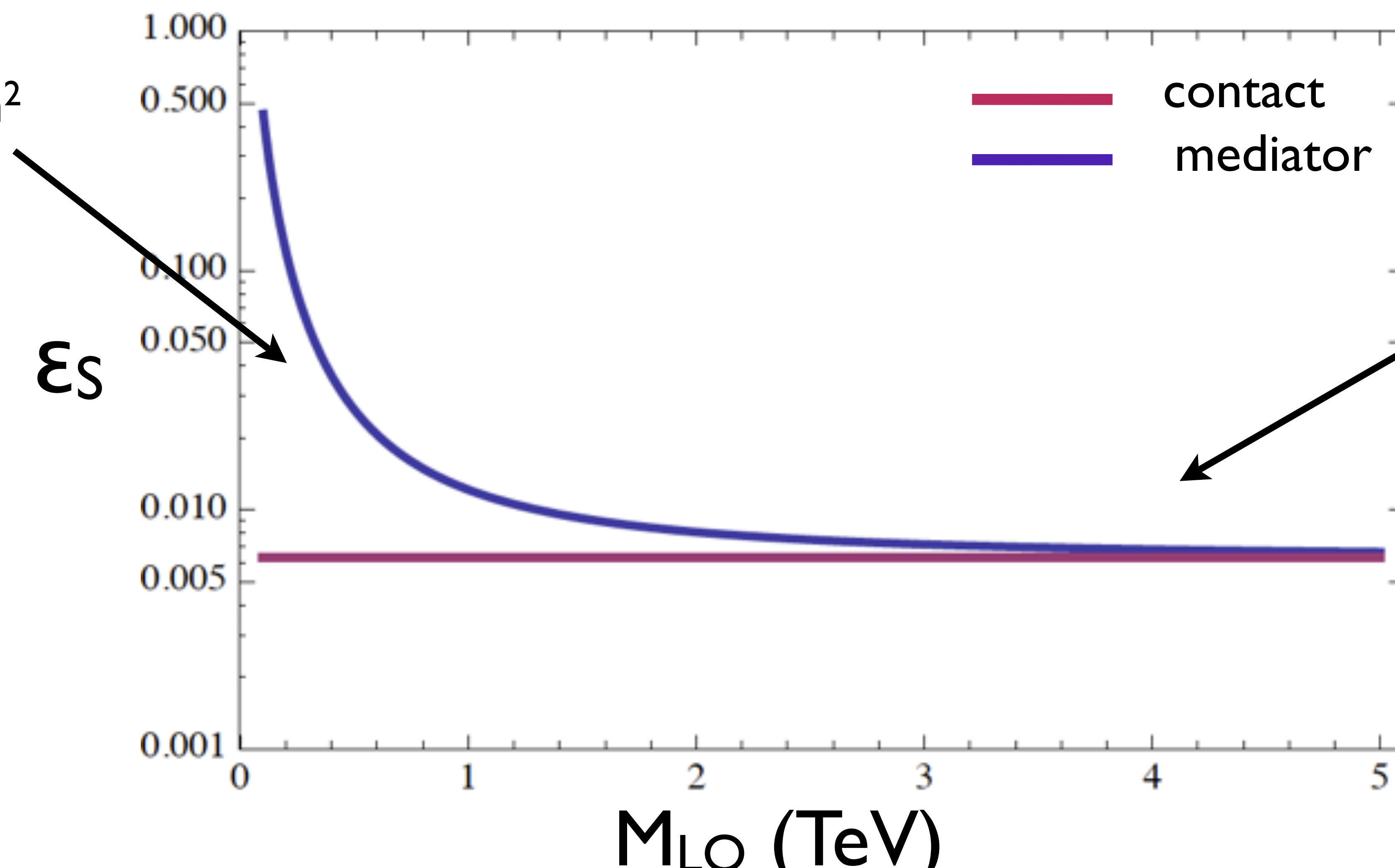
decoupling regime**

t-channel mediator

- Scalar leptoquark S_1 (3*,1,1/3)
- $\varepsilon_T = -1/4\ \varepsilon_S = -1/4\ \varepsilon_P$

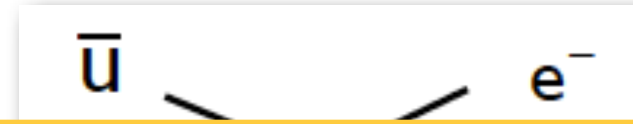


σ suppression due to $1/(m^2 - t)$ vs $1/m^2$



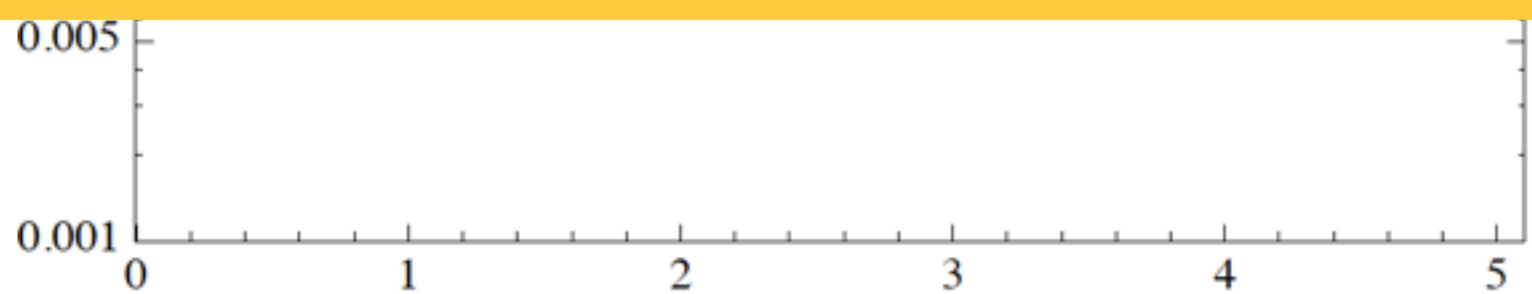
decoupling regime

t-channel mediator



Messages

- For TeV-scale mediator mass (m>1TeV), LHC bounds on ε's based on contact interactions range from robust (t-channel) to conservative (s-channel)
- For low mass mediators (m < 0.5 TeV), the LHC bounds on ε's quickly deteriorate: limits based on contact interactions are too optimistic



M_{LQ} (TeV)

Summary

- Improved picture of nonstandard CC interactions through combination of low-energy and collider probes**

	$\varepsilon_L+\varepsilon_R$	ε_S	ε_T	$\tilde{\varepsilon}_S$	$\tilde{\varepsilon}_T$	$\tilde{\varepsilon}_{L,R}$
β decays	5×10^{-4}	8.0×10^{-3}	1.3×10^{-3}	7.5×10^{-2}	2.5×10^{-2}	7.5×10^{-2}
LHC	--	1.7×10^{-2}	3.4×10^{-3}	1.7×10^{-2}	3.4×10^{-3}	6.3×10^{-3}

** Based on short-distance origin of new interactions

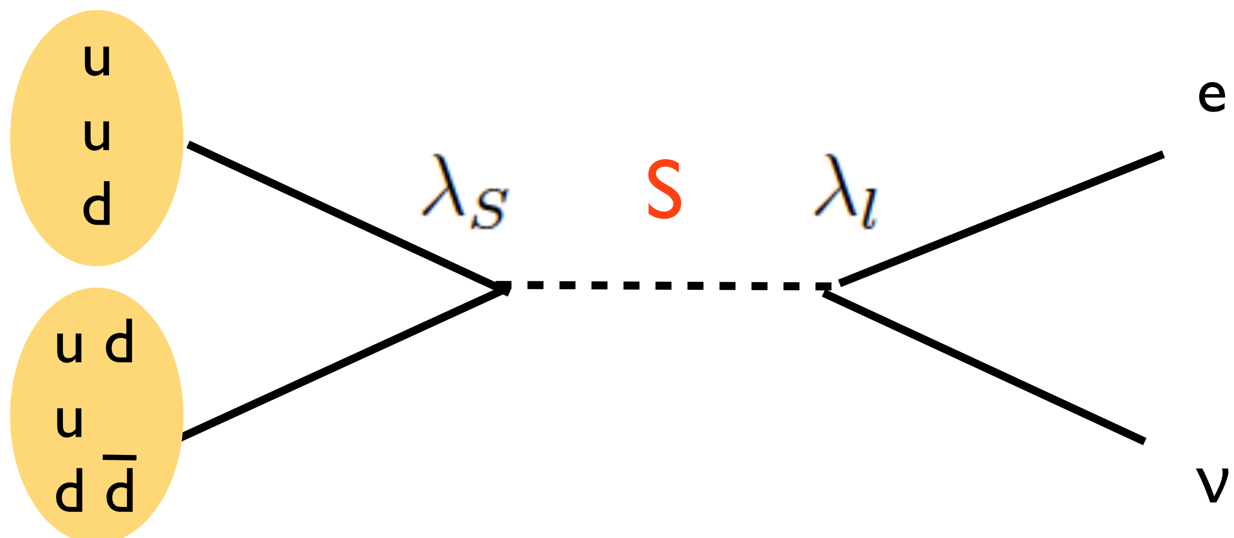
Summary

- Improved picture of nonstandard CC interactions through combination of low-energy and collider probes
- Low-energy:
  - Illustrated the importance of $g_{S,T}$ to obtain bounds on short distance S,T couplings. First lattice QCD estimate
  - Established relevance of 10^{-3}-level measurements of b,B to probe $\varepsilon_{S,T}$
- Collider:
  - Demonstrated importance of LHC in setting bounds on CC non-standard couplings: it's catching up fast!
  - Explored dependence of LHC bounds on the mediator mass (tree-level in s and t channels)

Extra Slides

Complementarity: an example

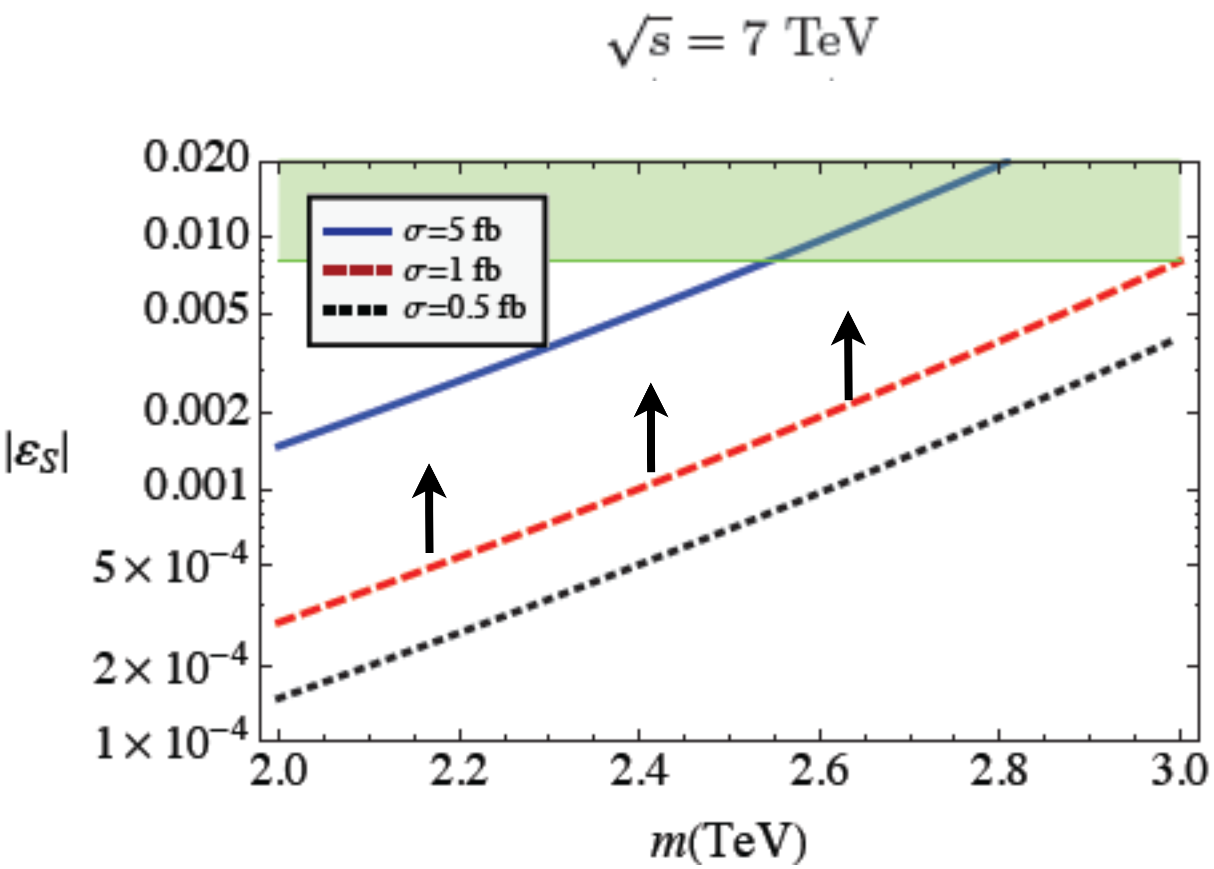
- Scalar resonance in s-channel

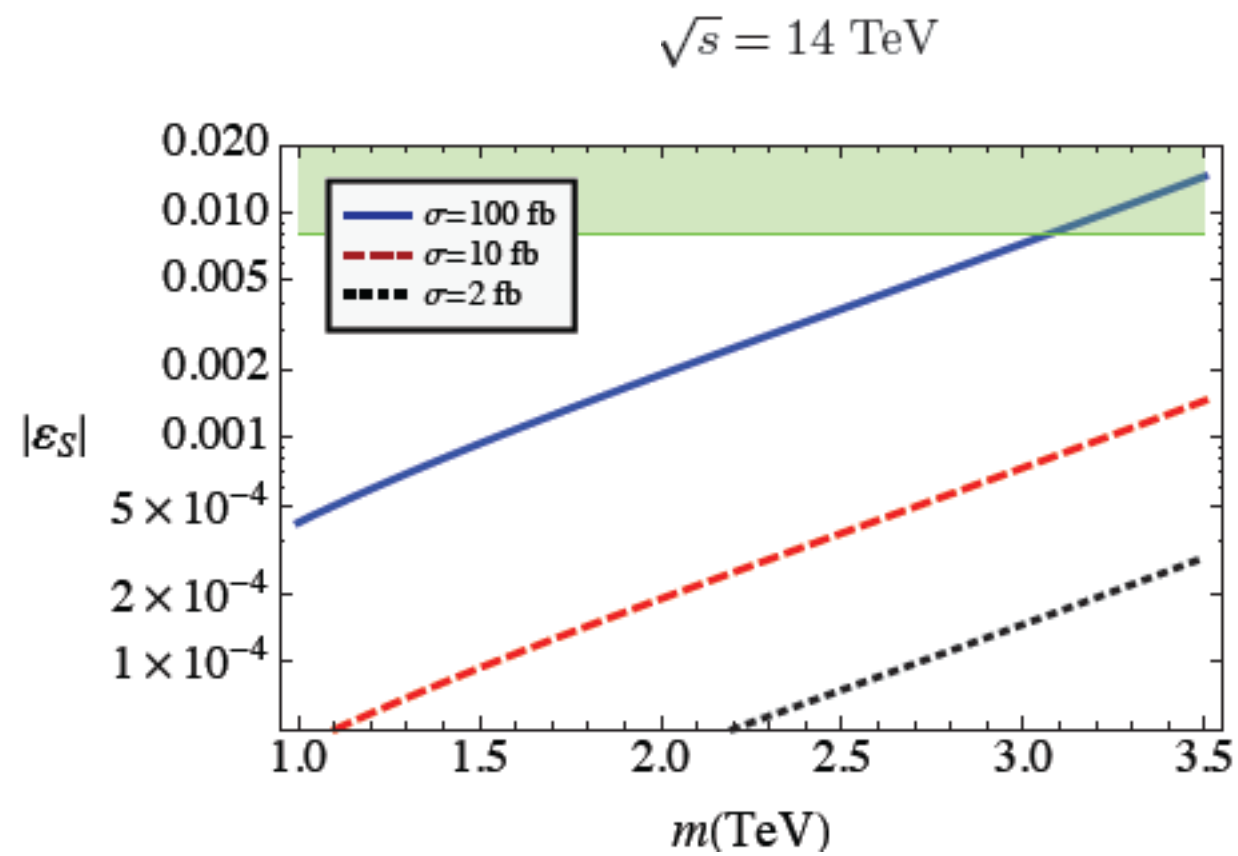


$$\epsilon_S = 2\lambda_S\lambda_l\frac{v^2}{m^2}$$

- Observation of such a scalar resonance implies a lower bound on effective scalar coupling probed at low-energy:

$$\sigma \cdot \mathrm{BR} \leq \frac{|V_{ud}|}{12v^2}\frac{\pi}{\sqrt{2N_c}}|\epsilon_S|\tau L(\tau) \qquad \tau = m^2/s,$$





- If LHC can determine scalar nature of the resonance, then predict a "guaranteed signal" for beta decay
- If LHC cannot determine spin of resonance, beta decay searches (positive or negative) provide discriminating input