Particle Physics at Neutron Sources
ILL, Grenoble, May 24-26 2018

Probing symmetry violations with neutrons

Vincenzo Cirigliano
Los Alamos National Laboratory

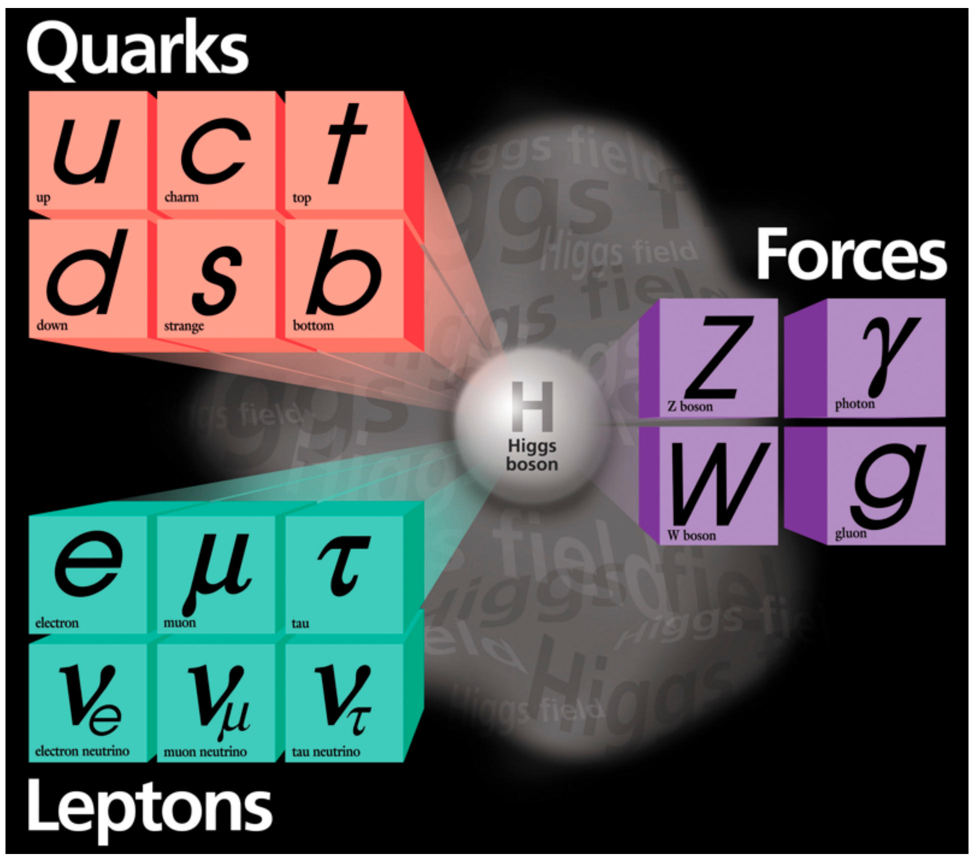
Outline

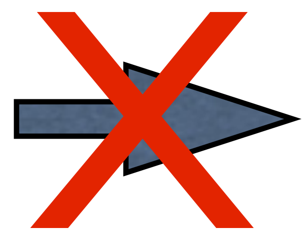
- Introduction — searching for new physics with neutrons
- Neutron EDM
- Neutron-antineutron oscillations**

** “Outsider point of view”, as per Organizer’s request

New physics: why?

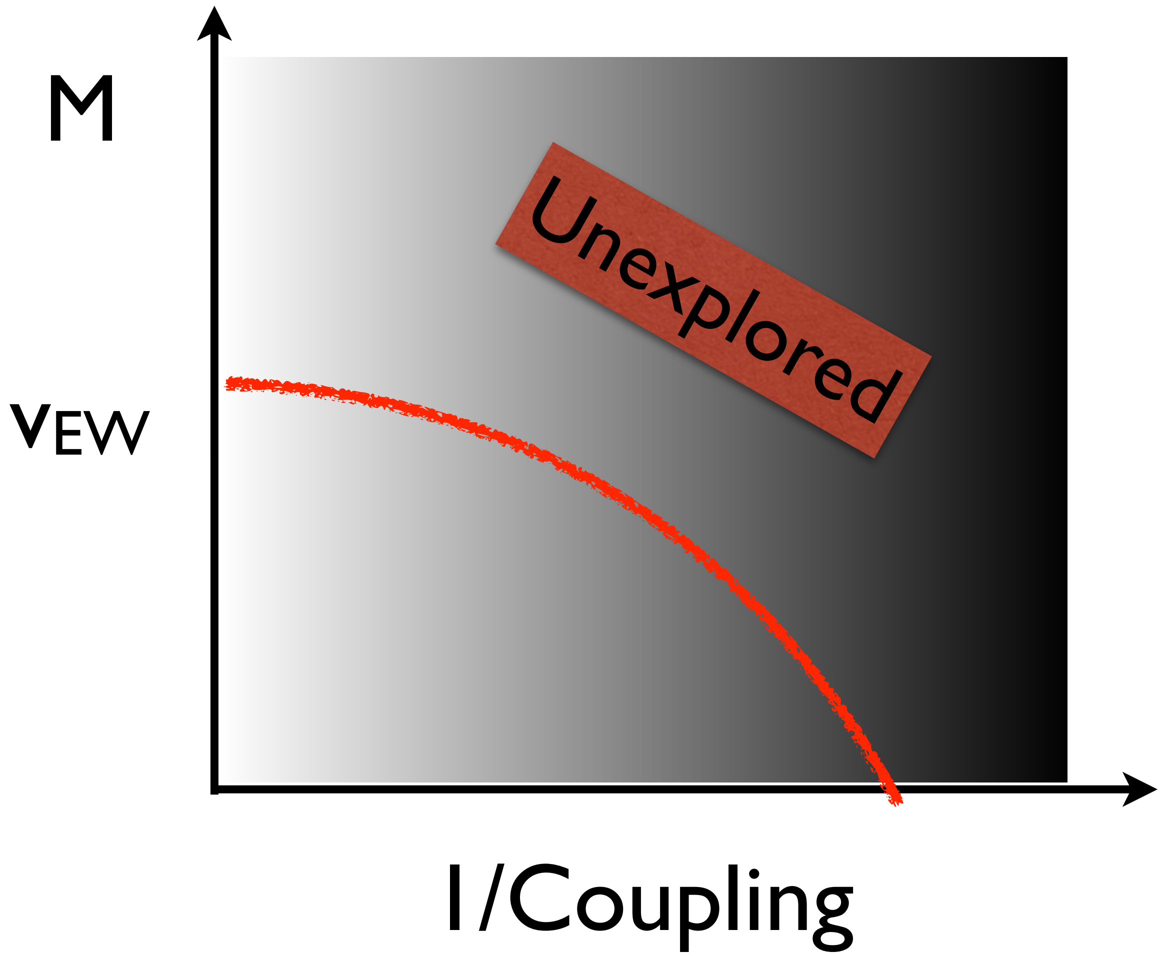
- The SM is remarkably successful, but it’s probably not the whole story





New physics: where?

- New degrees of freedom: Heavy? Light & weakly coupled?



New physics: where?

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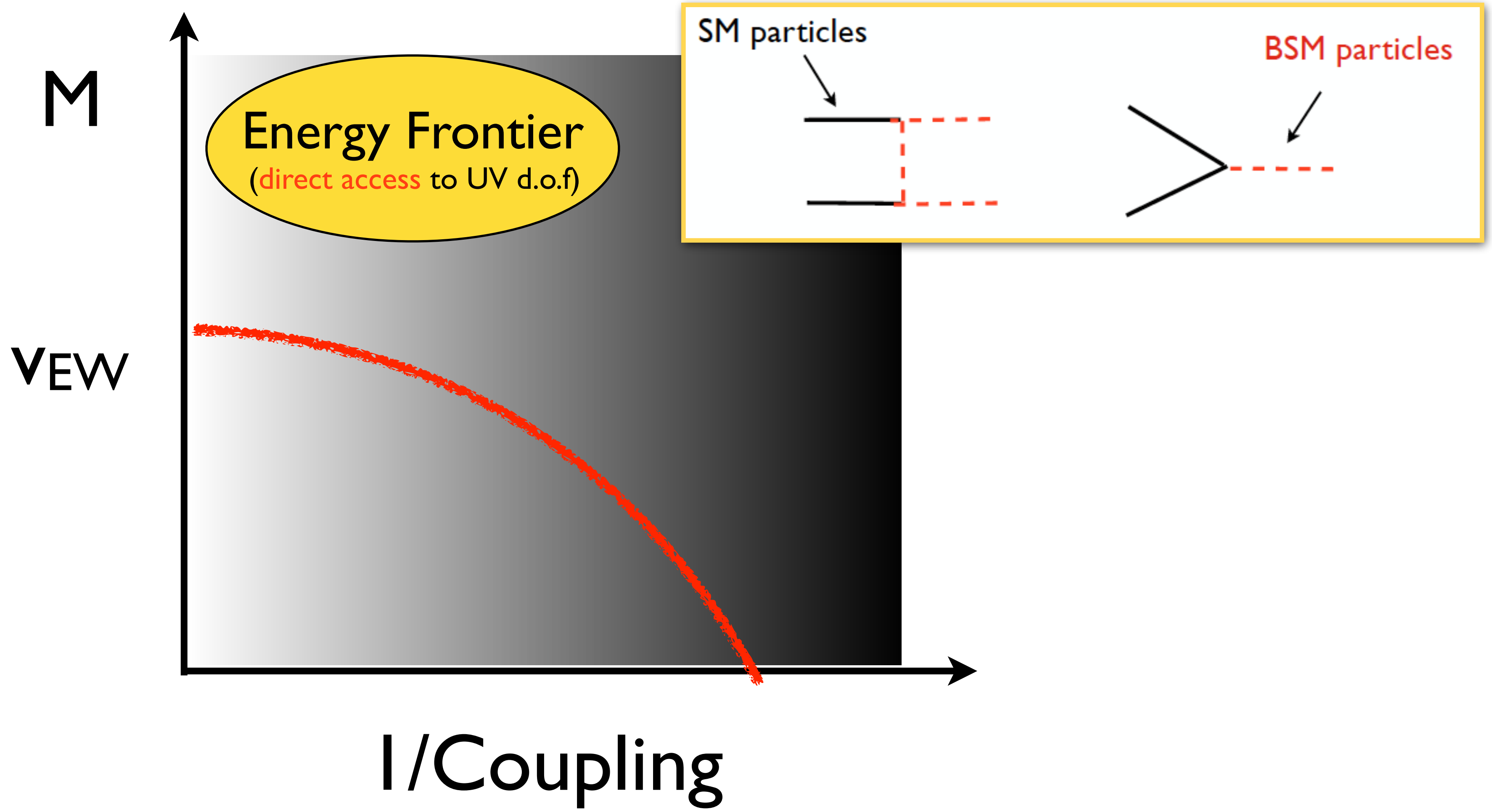
- Two complementary paths to probe $\mathcal{L}_{BSM}$



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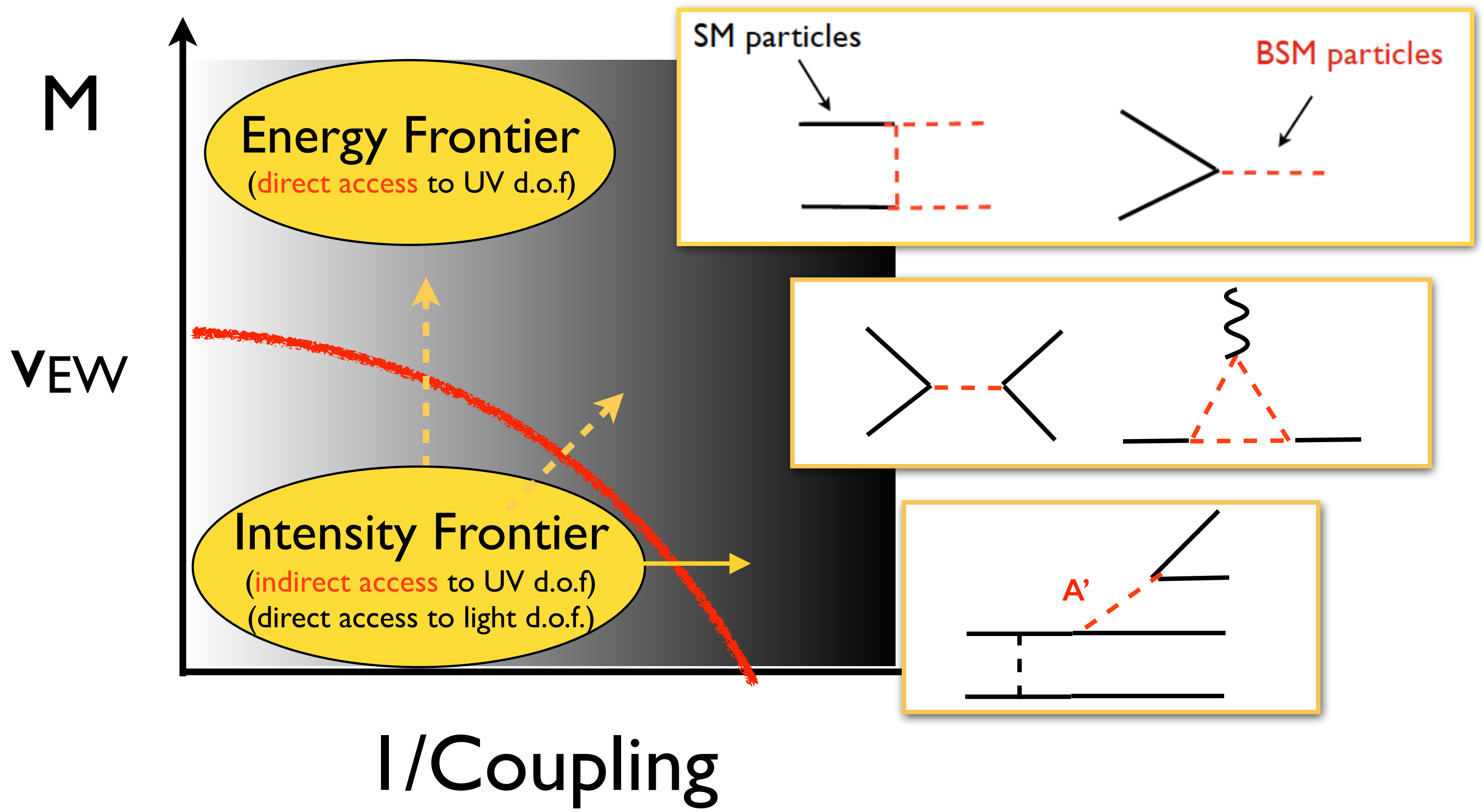
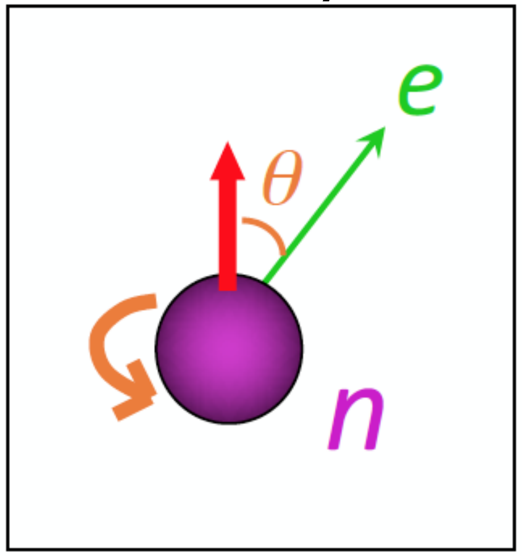


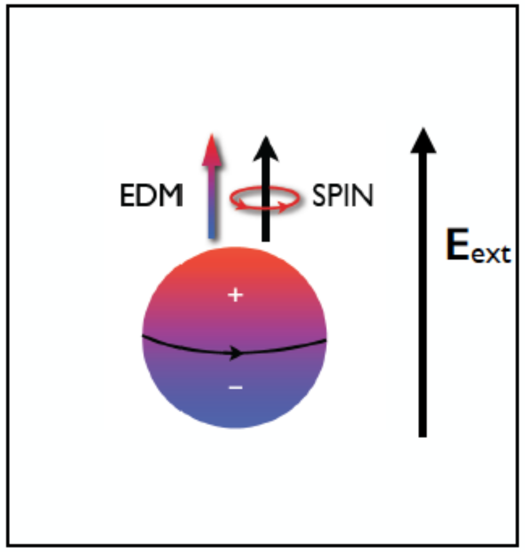
Role of neutrons

- Neutron physics at the forefront of the intensity frontier → vibrant world-wide program

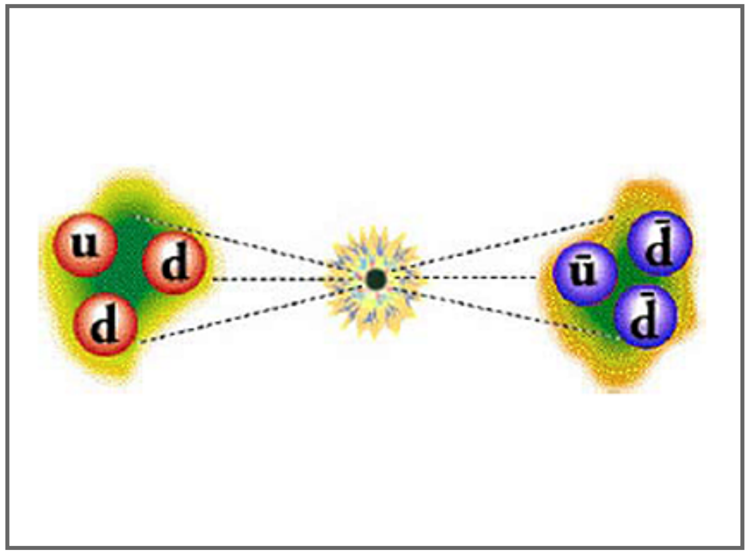
n decay



nEDM, HPV, …



n-nbar oscillations



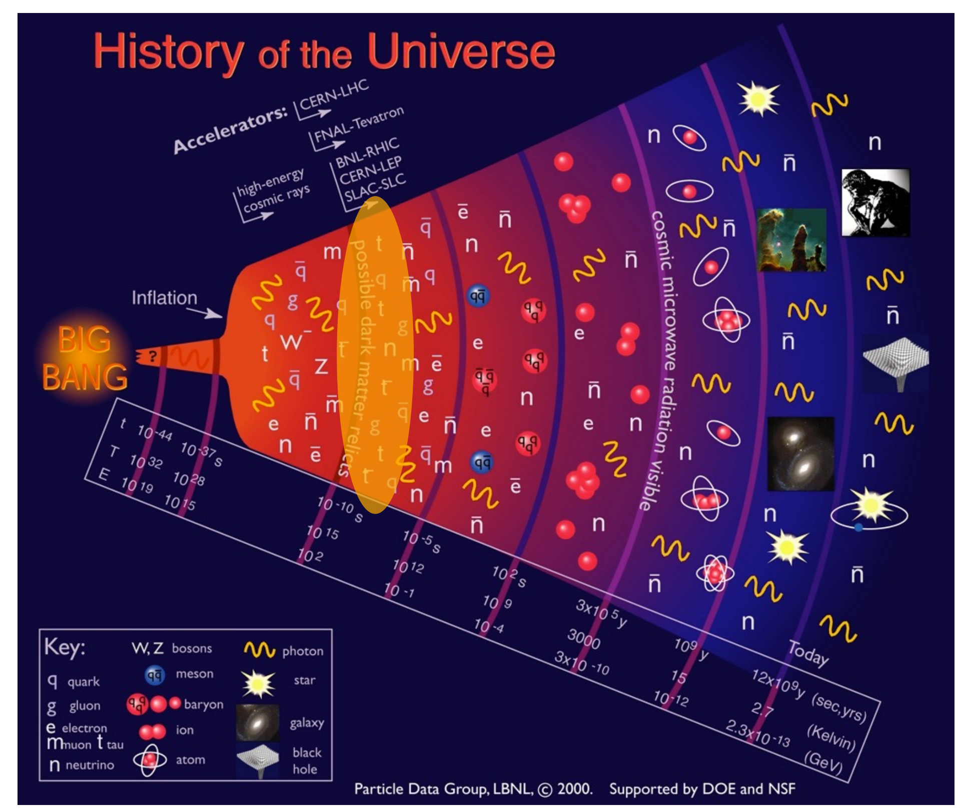
Structure of weak interactions

P, T, & CP violation

Baryon number violation

Role of neutrons

- Neutron physics at the forefront of the intensity frontier → vibrant world-wide program
- Neutron measurements offer:
  - Discovery potential: new ways to look for cracks in the SM
  - Diagnosing power: e.g., what is the origin of CP, B violation. Need multiple measurements.
  - Connection to big puzzles: unique sensitivity to *symmetry breaking* needed for baryogenesis (Sakharov)
    - ◆ EDM: CPV for electroweak scale baryogenesis (T~100-1000 GeV)
    - ◆ n-nbar: B violation in post-sphaleron baryogenesis (T < 100GeV)



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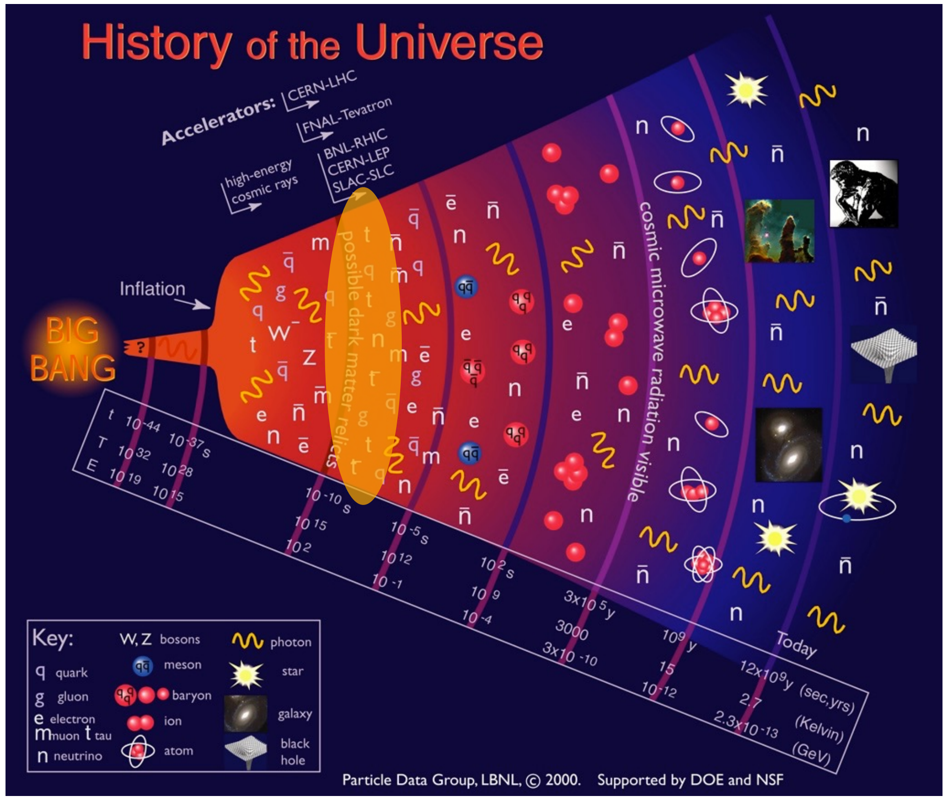
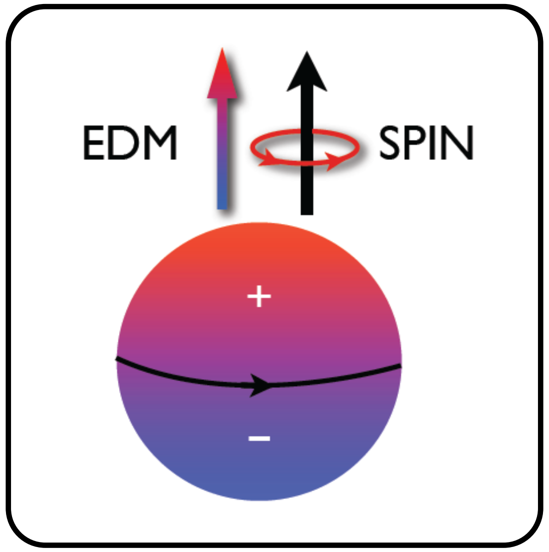


All of the above requires sufficiently precise theory input

Neutron EDM



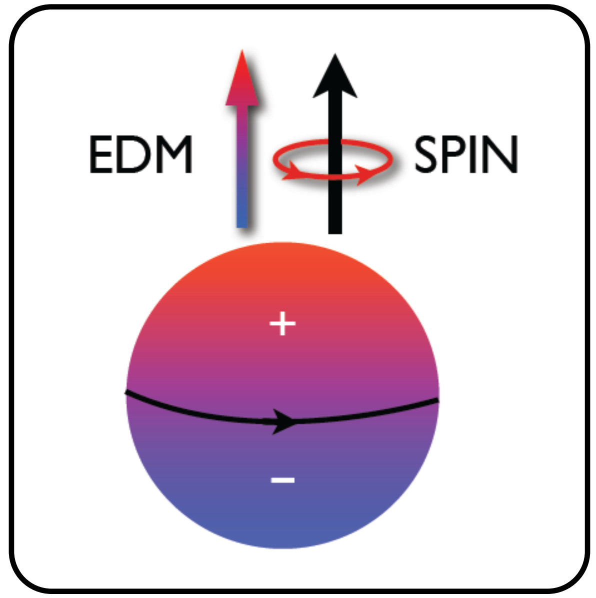
P and T (CP) violation

EDMs and discrete symmetries

- EDMs of *non-degenerate* systems violate P and T: $\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$

Classical picture →

Quantum level:
Wigner-Eckart theorem



$$\vec{d} = \sum_i q_i\,\vec{r}_i$$

$$\vec{d} = d\,\vec{J}$$

CPT invariance ⇒ nonzero EDMs signal CP violation

EDMs and discrete symmetries

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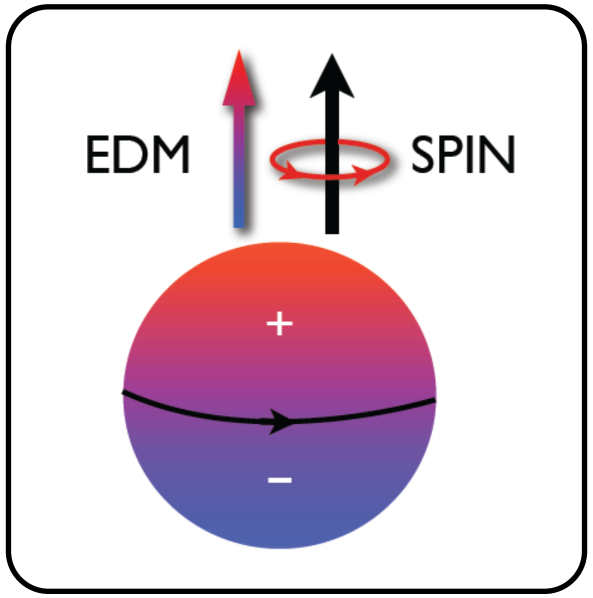
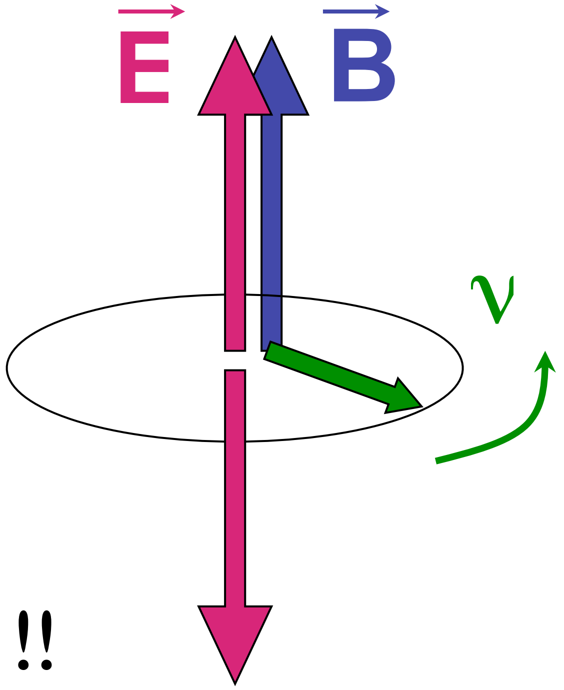


- Measurement: look for linear shift in precession frequency due to external E field

$$\nu = (2\mu B \pm 2dE)/h$$



Current 90%CL neutron bound $d_n < 3 \times 10^{-13}$ e fm !!

Baker et al., PRL 97 131801 (2006)

EDMs and BSM CP violation

1. Essentially free of SM "background" (CKM) *[1]

EDMs in $e \cdot cm$

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

*[1] Observation would signal new physics or a tiny QCD θ-term (< 10^{-10}).
Multiple measurements can disentangle the two effects.

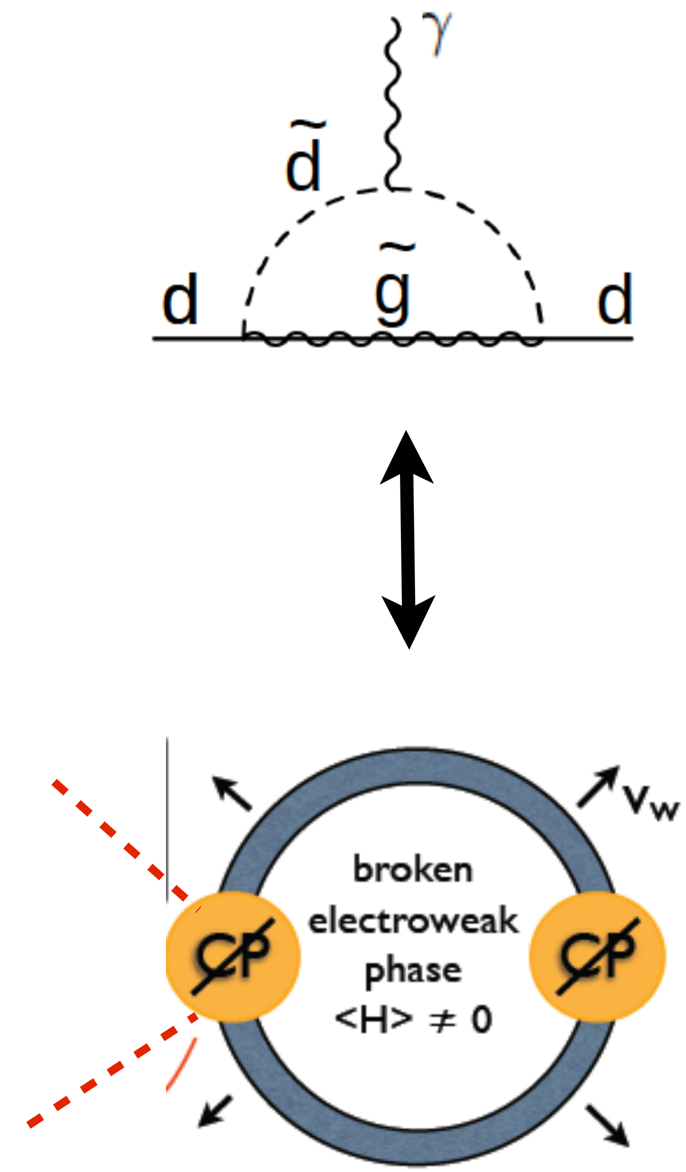
EDMs and BSM CP violation

1. Essentially free of SM "background" (CKM) *1

2. Probe BSM CP violation needed for electroweak scale baryogenesis

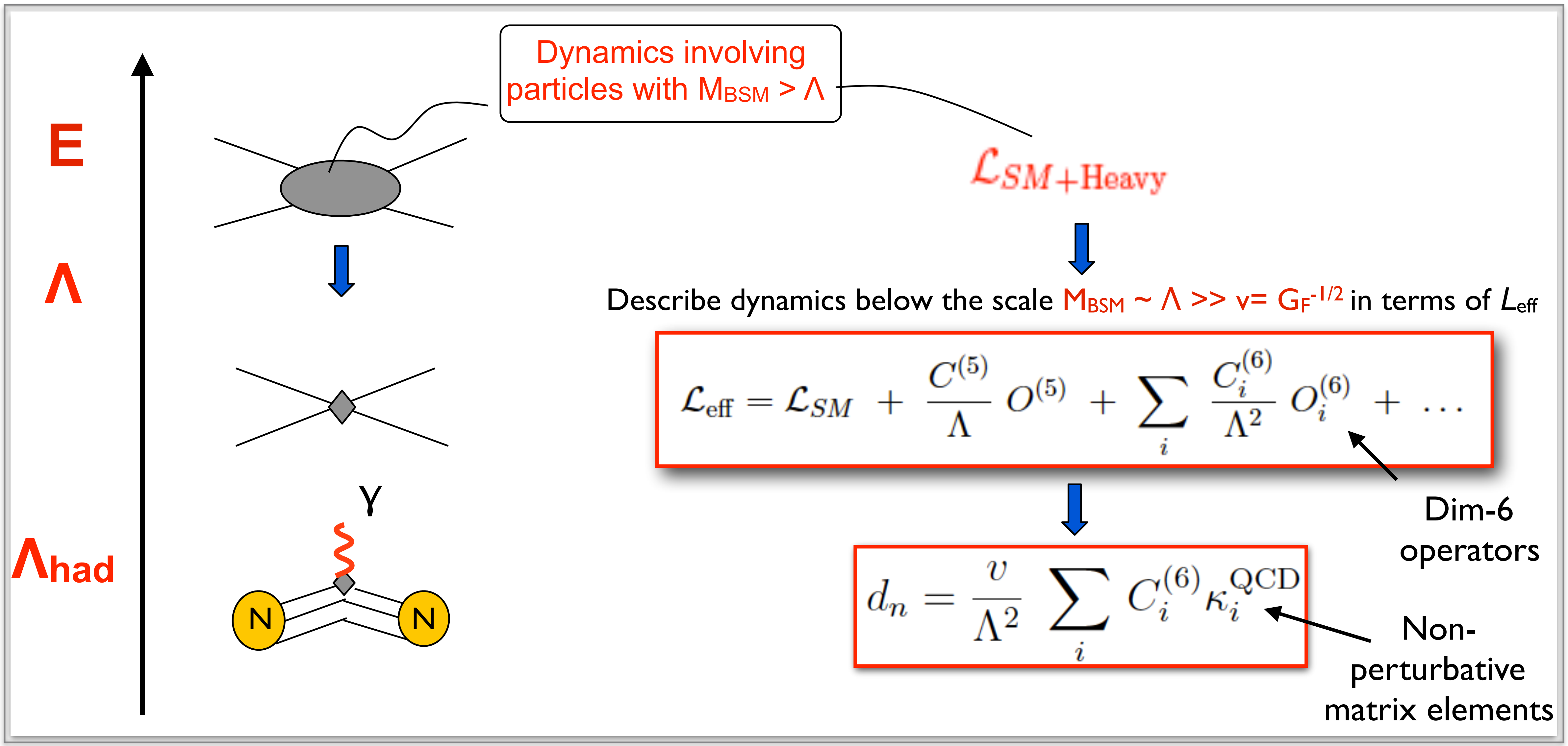
Sakharov '67

- B violation
- C and CP violation (SM=☹)
- Departure from equilibrium: 1st order phase transition (SM=☹)



Connecting nEDM to new physics

Multi-scale problem. EFT ⇒ framework for robust + improvable estimates



Connecting nEDM to new physics

- At E ~GeV, leading BSM effects encoded in handful of dim-6 operators

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

Electric and chromo-electric dipoles of fermions

$$d_f, \tilde{d}_q \sim \frac{v_{ew}}{\Lambda^2}$$

Gluon chromo-EDM (Weinberg operator)

$$d_W \sim \frac{1}{\Lambda^2}$$

Semileptonic and 4-quark

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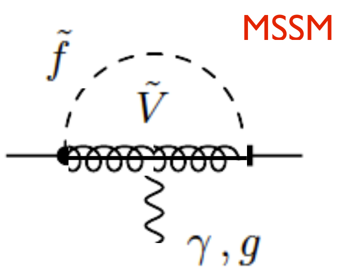
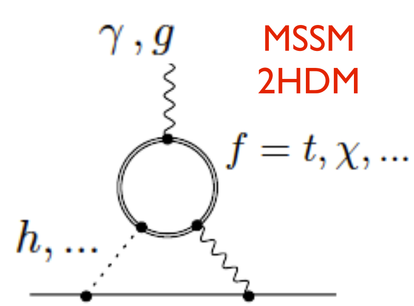
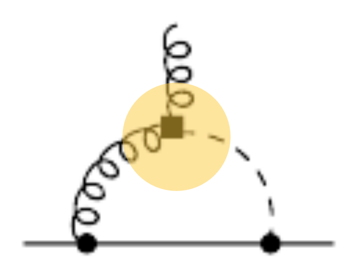
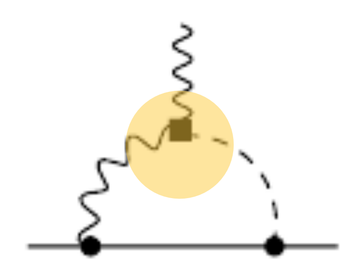
Semileptonic and 4-quark

Generated by "integrating out" heavy particles and RG running, e.g:









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Semileptonic and 4-quark

- Order of magnitude estimate: nEDM sensitive to scale Λ~10-100 TeV

$$d_n \;\propto\; \frac{m_q}{\Lambda^2}\, e\, \phi_{CP}$$

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- Beyond order-of-magnitude: relevant matrix elements poorly known. This strongly dilutes the constraining power of measurements!

Pospelov-Ritz hep-ph/0504231 and refs therein

μ ≃ 1 GeV

$$\begin{aligned} d_n \;=\; & -(0.35 \pm 0.18) d_u + (1.4 \pm 0.7) d_d + (?\pm?) d_s \\ & -(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \pm (50 \pm 40)\,\mathrm{MeV}\, e\, d_W \end{aligned}$$

QCD Sum Rules (50% guesstimate) QCD Sum Rules + NDA (~100%)

Connecting nEDM to new physics

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- Recent development: matrix elements from Lattice QCD
    - quark EDM: tensor charges @ 10% [✔]
    - quark CEDM (ongoing: BNL, LANL)
    - Weinberg & 4q (future)

Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

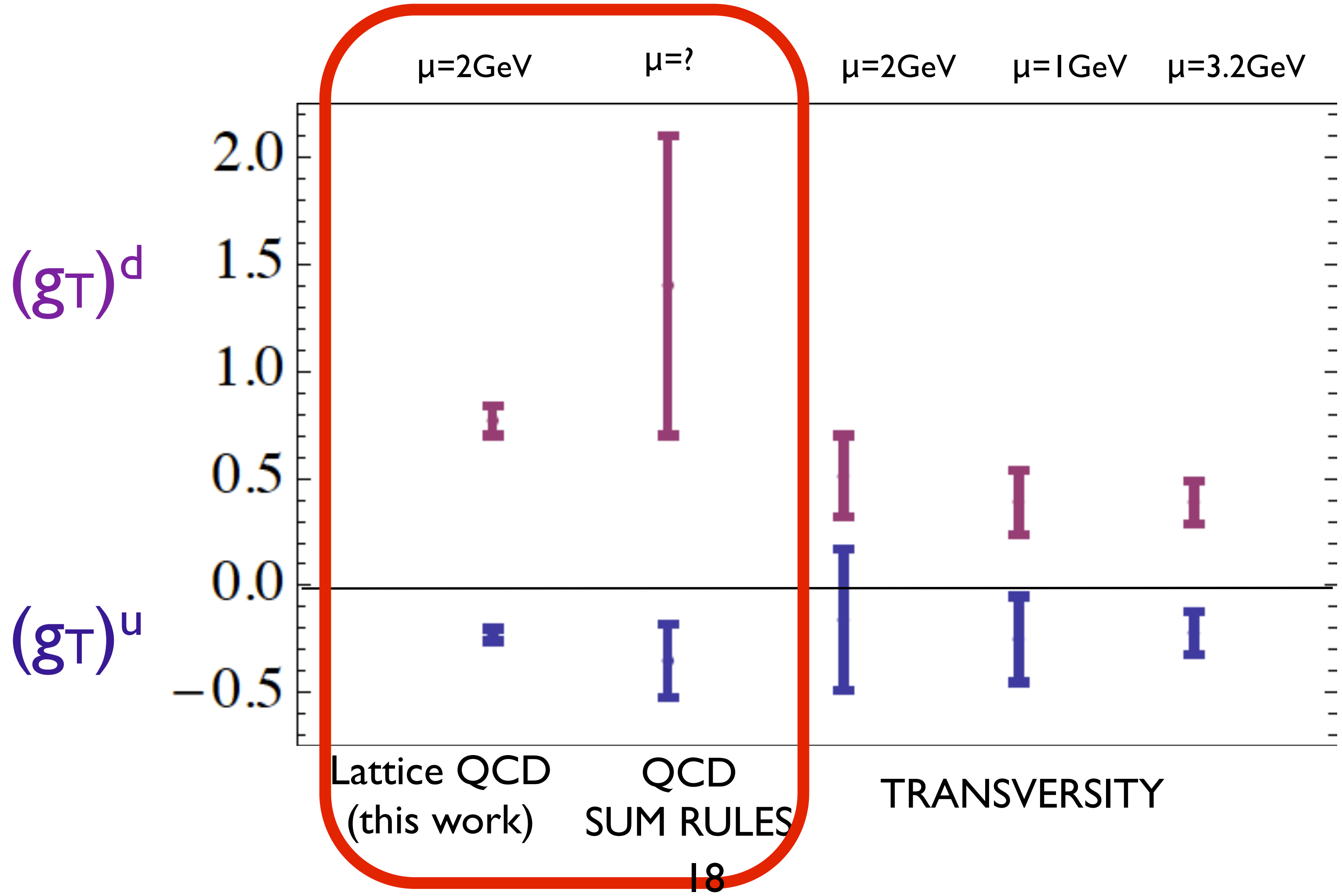
nEDM from qEDM

- Problem "factorizes": need tensor charge of the nucleon

$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \, \bar{q} \sigma_{\mu\nu} \gamma_5 q \, F^{\mu\nu} \quad \longrightarrow \quad d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}$$

$$\langle N | \bar{q} \sigma_{\mu\nu} q | N \rangle \equiv g_T^{(N,q)} \, \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

- Impact: smaller uncertainty (10%) and *smaller central values*

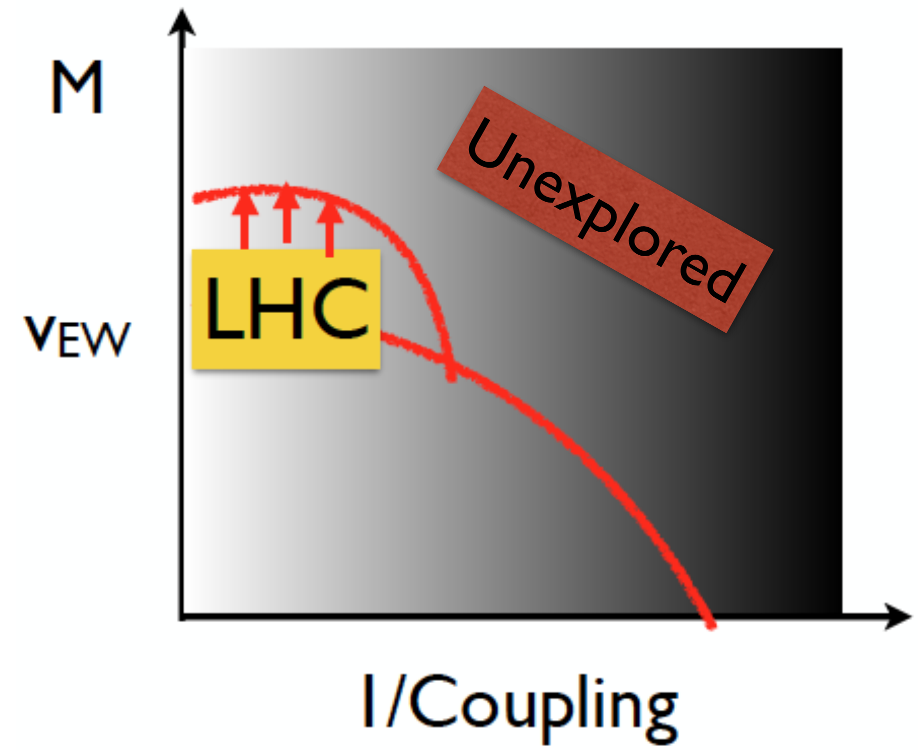


O(10%) error including all systematics: excited states, continuum, quark masses, volume

Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

nEDM and new physics in the LHC era

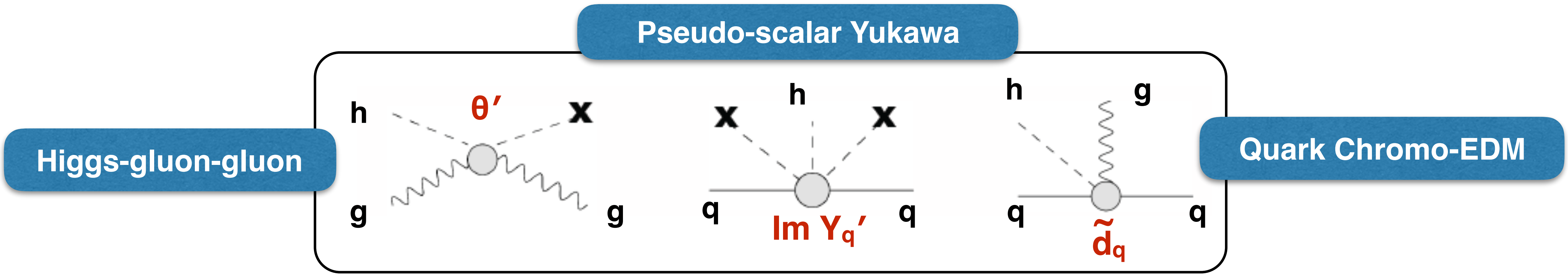
- LHC output so far:
  - Higgs boson @ 125 GeV
  - Everything else is quite heavier (or very light)



- *nEDM more relevant than ever:*
  - Strongest constraints of non-standard CPV Higgs couplings
  - One of few observables probing PeV scale supersymmetry
  - Non trivial constraints on baryogenesis models
  - Sensitivity to axion-like dark matter Abel et al., 1708.06367

CPV Higgs couplings (I)

- Leading interactions with q,g strongly constrained by gauge invariance



$$\theta', \mathrm{Im} Y_q' \sim \frac{1}{\Lambda^2} \qquad \tilde{d}_q \sim \frac{v}{\Lambda^2}$$

- Affect Higgs production and decay at LHC *and* EDMs (n, ^{199}Hg, e)

Y.-T. Chien, V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti, JHEP 1602 (2016) 011 [1510.00725]

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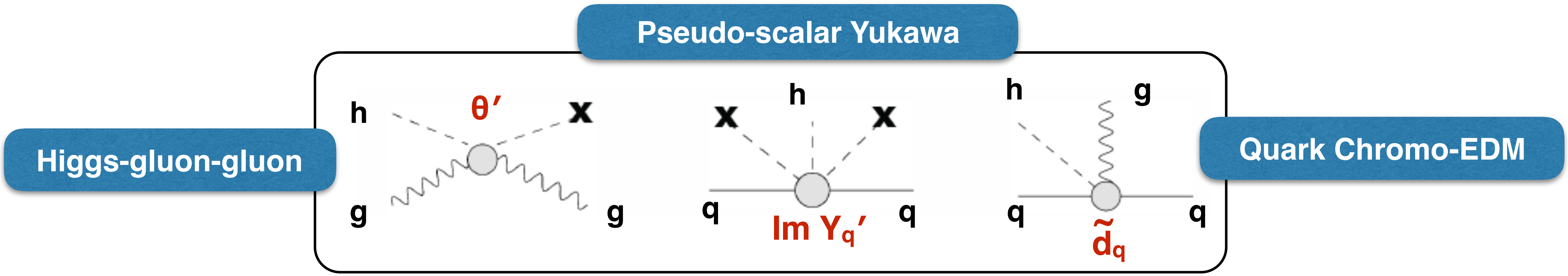
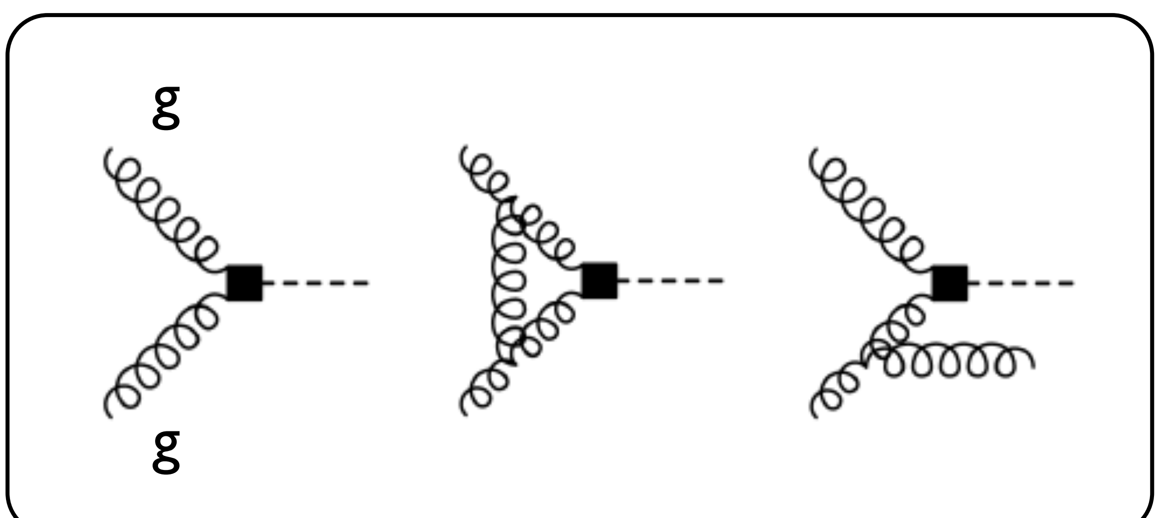
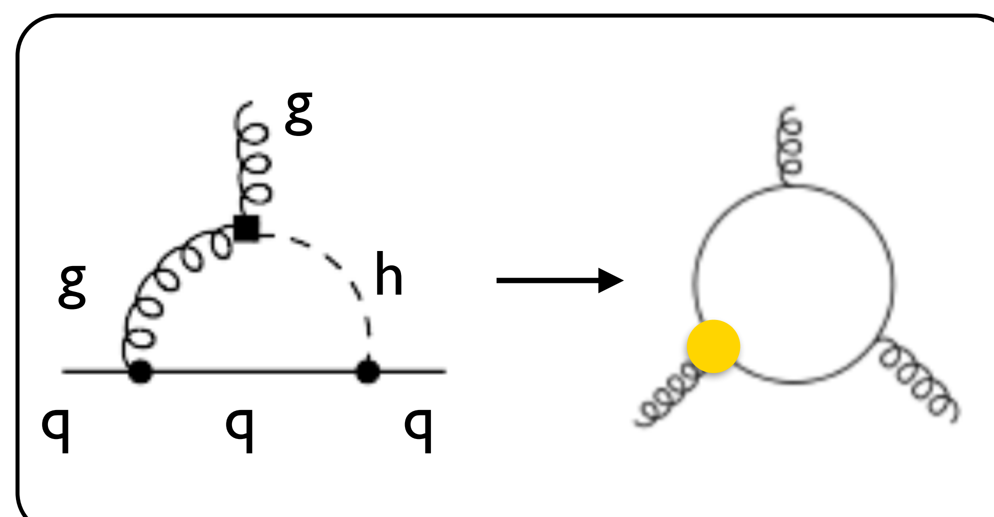


- Signatures of various operators: Higgs-gluon-gluon (θ′)

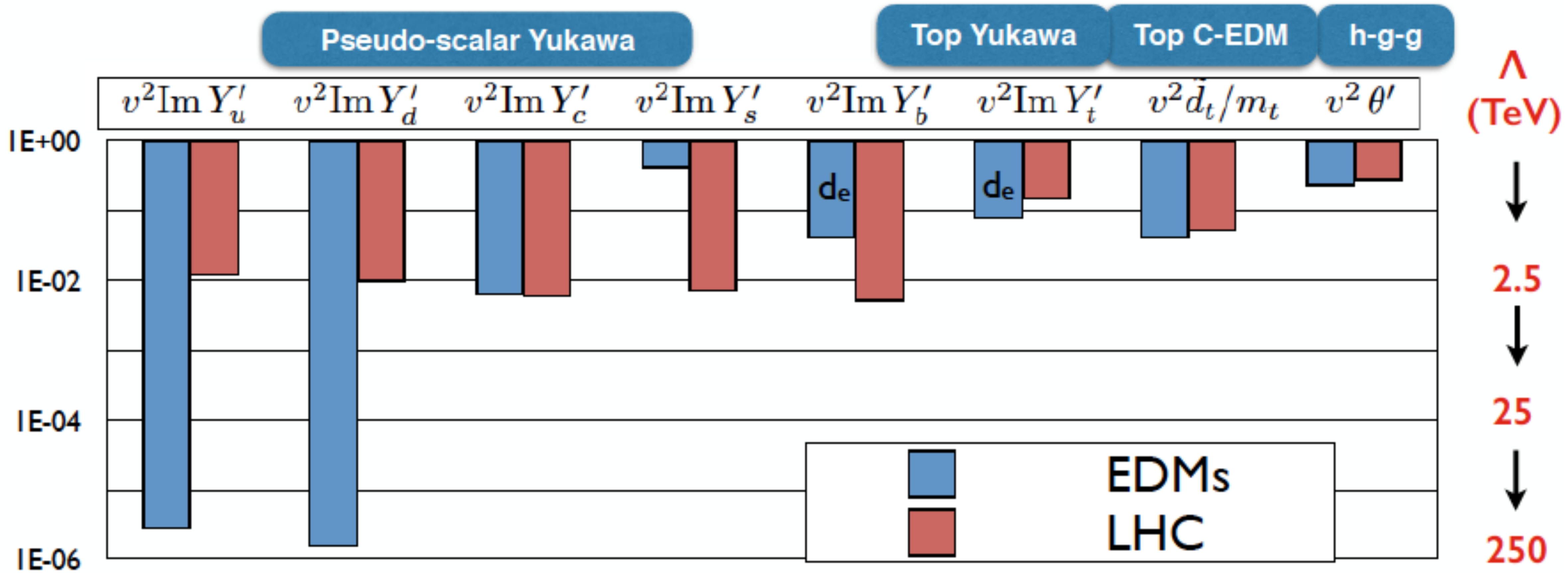
LHC: Higgs production via gluon fusion



Low Energy: quark (C)EDM + Weinberg



CPV Higgs couplings (2)



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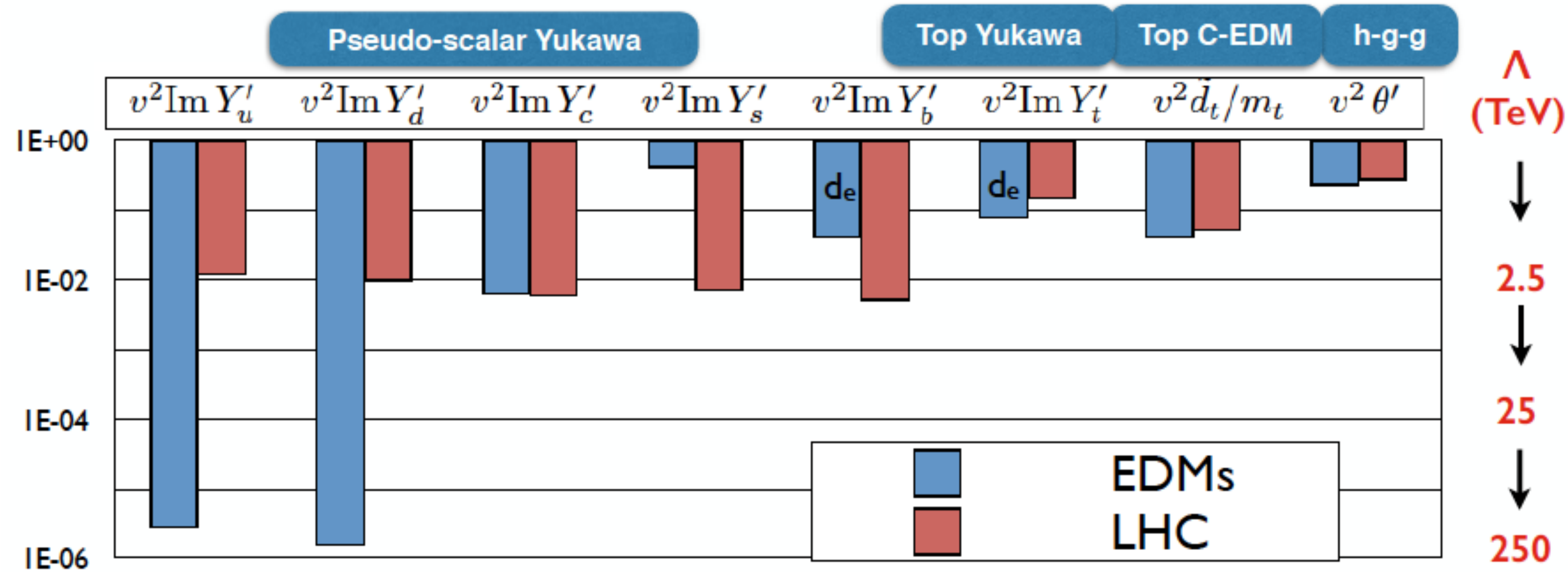
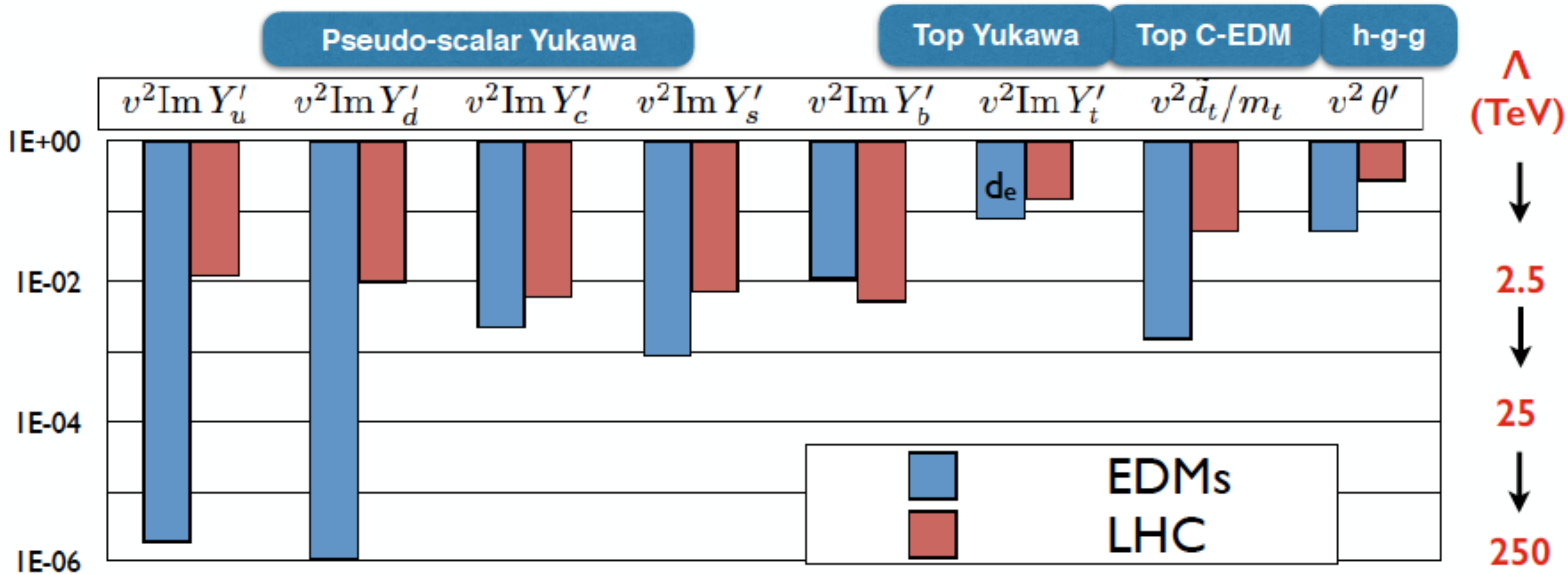


- Neutron EDM is teaching us something about the Higgs!
- Future: factor of 2 at LHC; EDM constraints scale linearly
- Uncertainty in matrix elements strongly dilutes EDM constraints

CPV Higgs couplings (2)



- Much stronger impact of nEDM with reduced uncertainties

$d_{n,p}[\tilde{d}_{u,d}]$ $d_{n,p}[d_s]$ $d_{n,p}[d_W]$

25% 50%

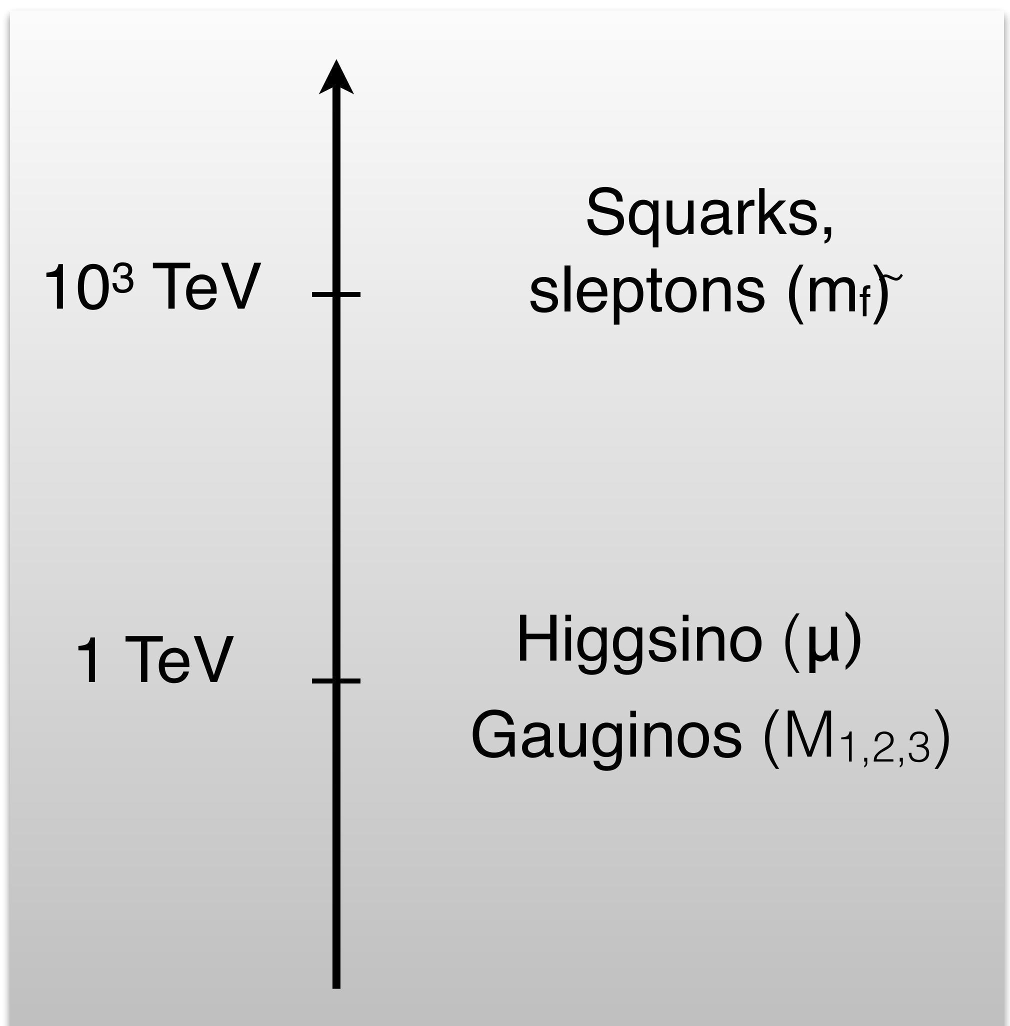
Target for Lattice QCD in the 5-year time scale

- Experiment at 5 x 10^{-27} e cm and improved matrix elements will make nEDM the strongest probe for all couplings

nEDM in high-scale SUSY (1)

- Higgs mass + absence of other signals point to heavy super-partners
- "Split-SUSY": retain gauge coupling unification and DM candidate

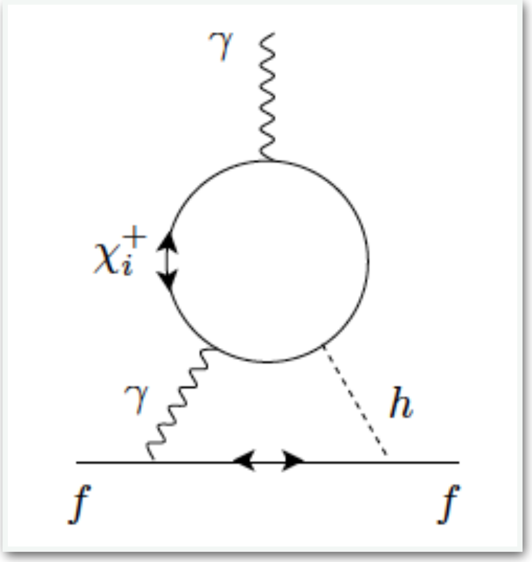
Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, Altmannshofer-Harnik-Zupan 1308.3653, …



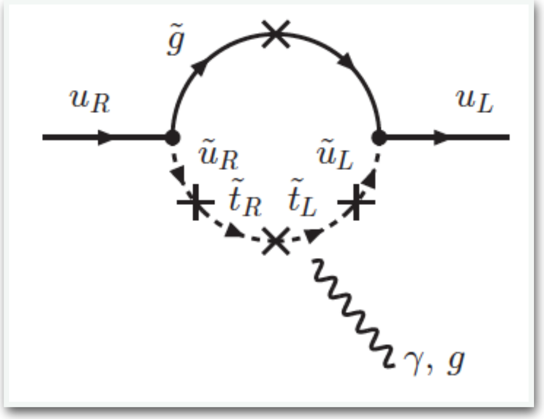
EDMs among a handful of observables capable of probing such high scales

nEDM in high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



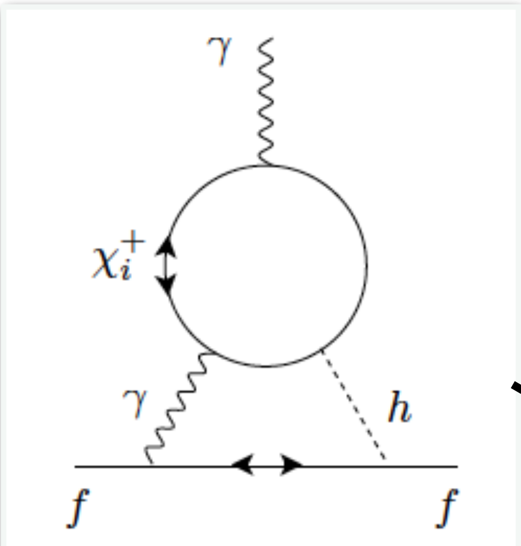
$$d_q \sim \frac{\alpha\,\alpha_w}{(4\pi)^2}\frac{m_q}{\mu M_2}\sin\phi_2$$



$$\tilde{d}_u \sim \frac{\alpha_s}{4\pi}\frac{m_t}{m_{\tilde{q}}^2}\frac{\mu M_3}{m_{\tilde{q}}^2}\,\delta_{ut}^L\delta_{tu}^R\,\sin\phi_u$$

nEDM in high-scale SUSY (2)

Altmannshofer-Harnik-Zupan 1308.3653



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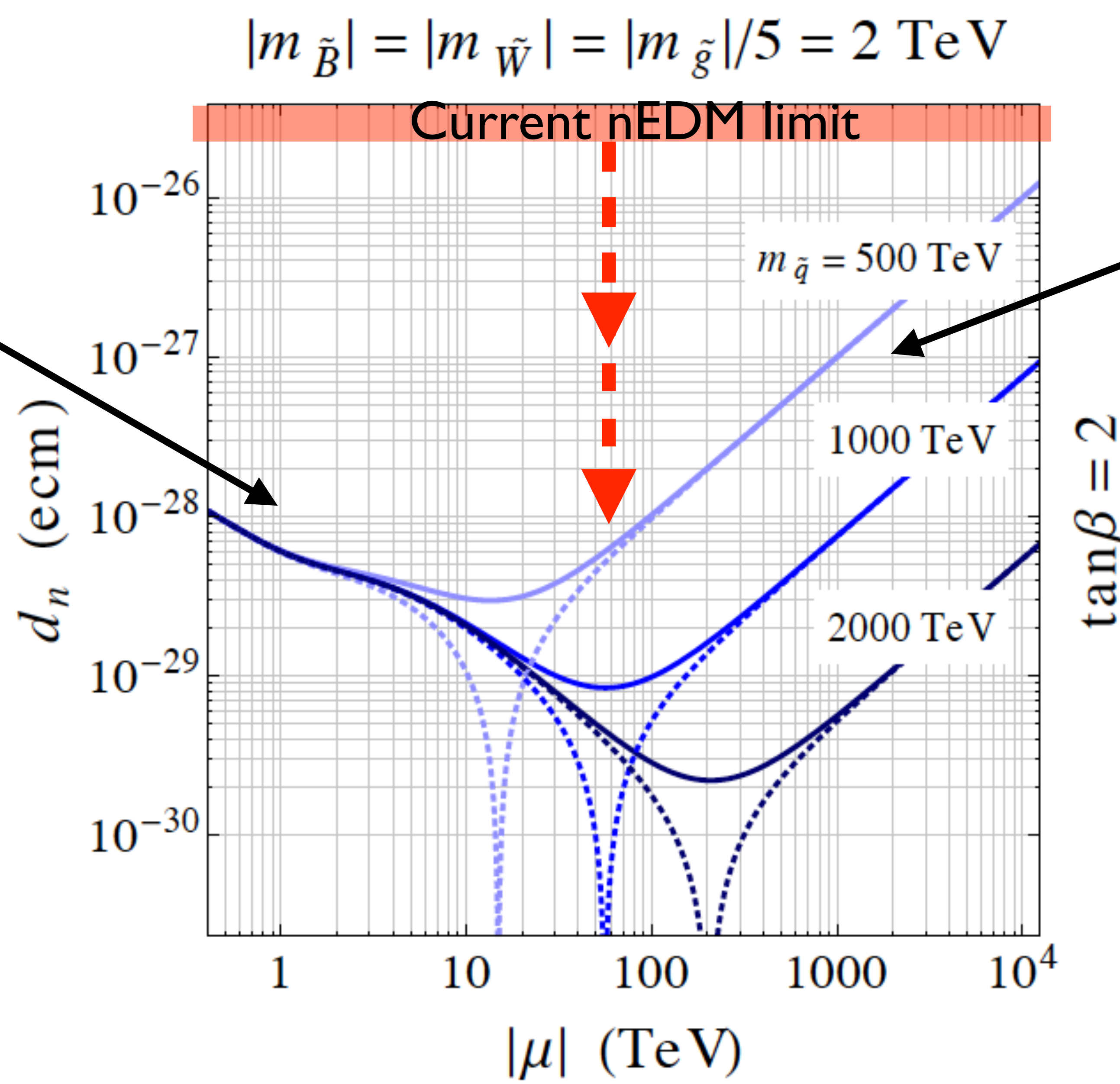

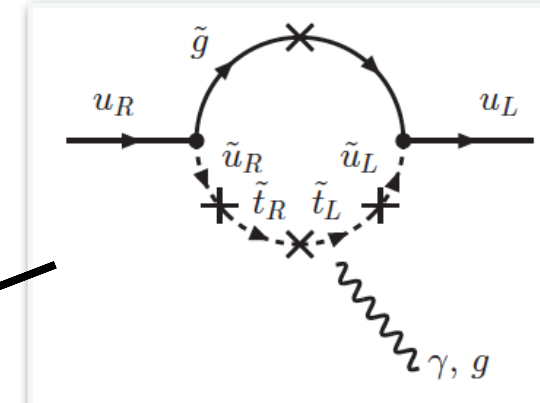

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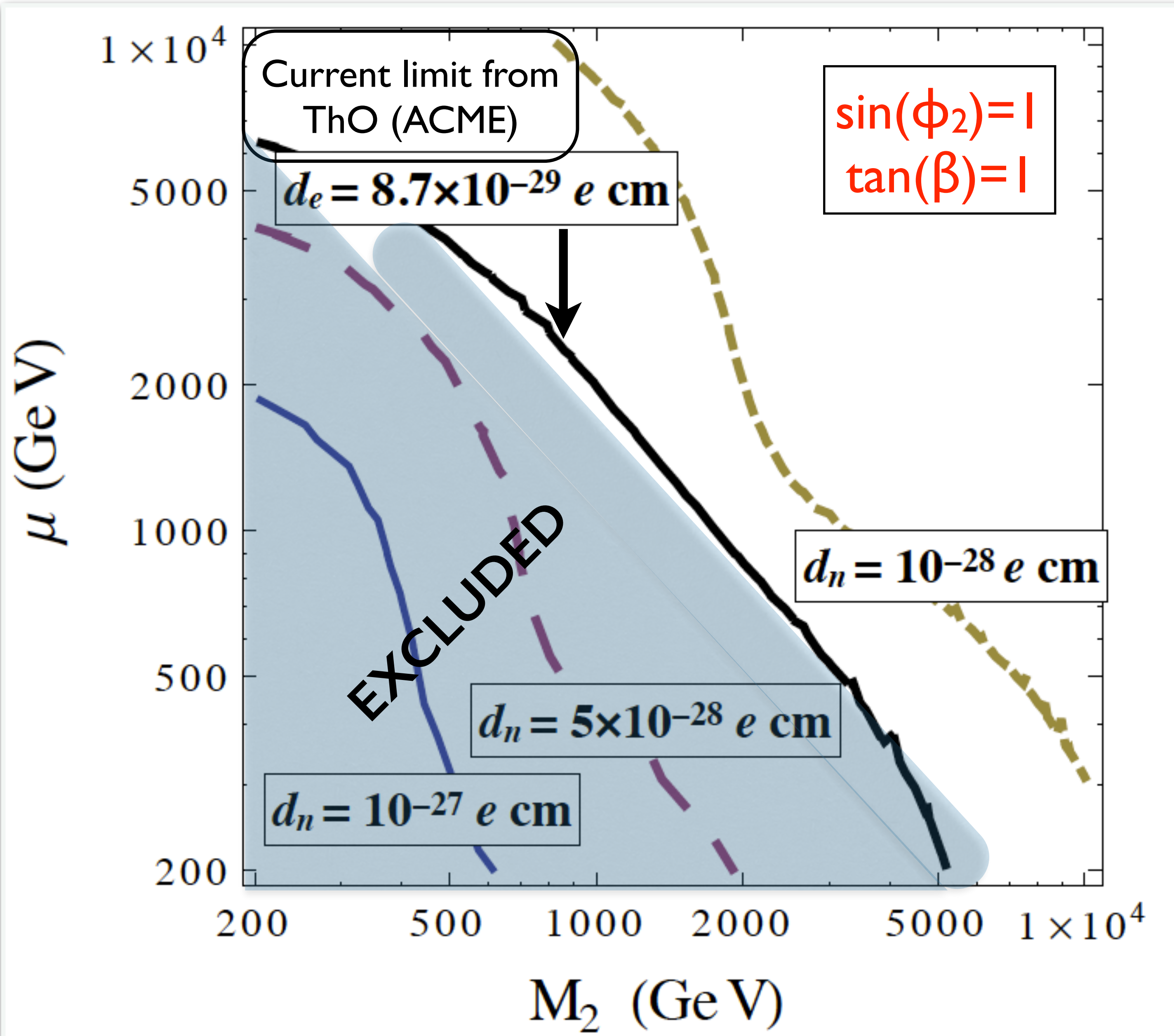
Maximal CPV phases.
Squark mixings fixed at 0.3

For $|\mu| < 10$ TeV, $m_{\tilde{q}} \sim 1000$ TeV, same CPV phase controls d_e, d_n → correlation?

nEDM in high-scale SUSY (3)



- Both d_e and d_n within reach of current searches for M_2, μ < 10 TeV

Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

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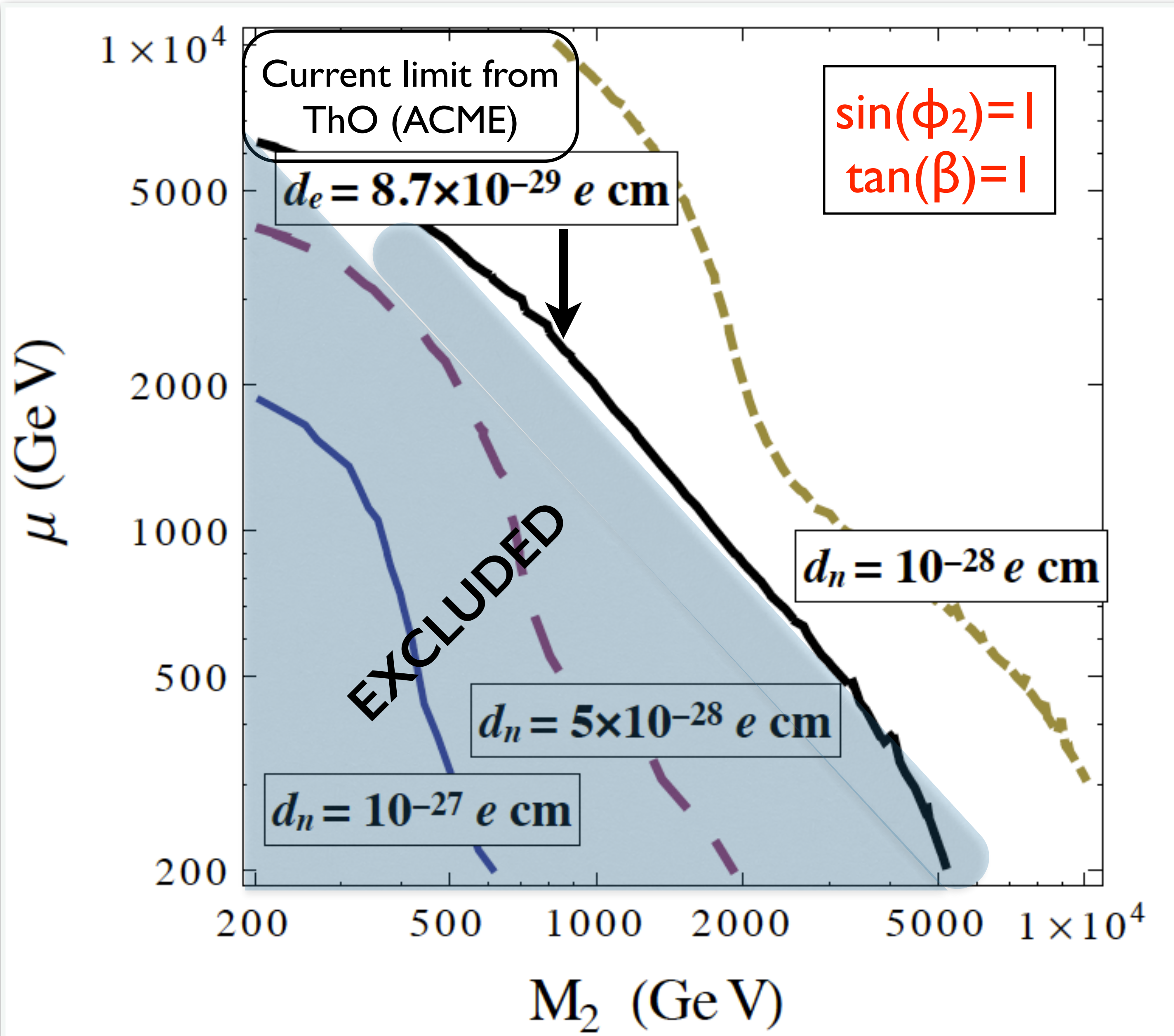
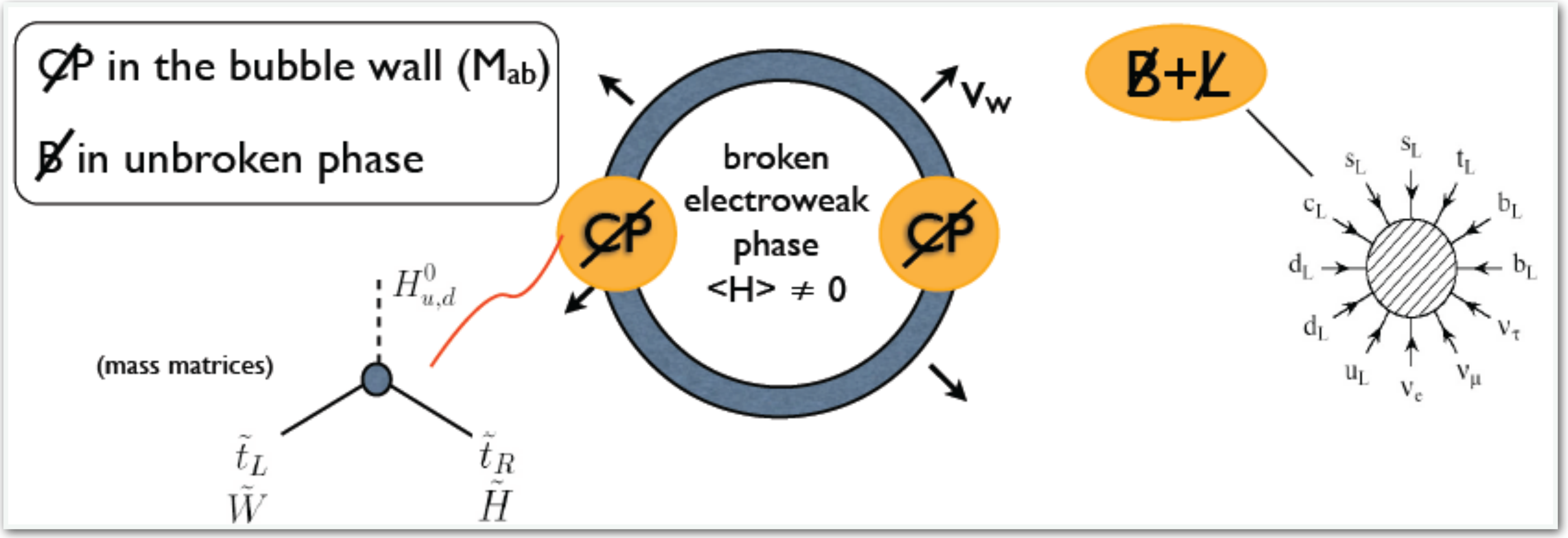


- Both d_e and d_n within reach of current searches for M_2, μ < 10 TeV
- Studying the ratio d_n / d_e *with precise matrix elements* → stringent upper bound $d_n < 4\times10^{-28}$ e cm
- Split-SUSY can be falsified by current nEDM searches

Bhattacharya, VC, Gupta, Lin, Yoon
Phys. Rev. Lett. 115 (2015) 212002 [1506.04196]

Example of model diagnosing enabled by multiple measurements (e,n) and controlled theoretical uncertainty

EDMs and EW baryogenesis (1)



For a review see: Morrissey & Ramsey-Musolf 1206.2942

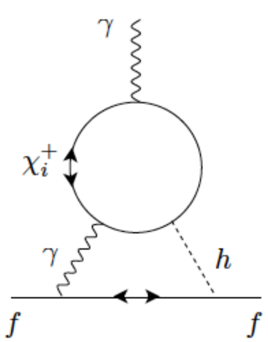
- Requirements on BSM scenarios:
  - 1st order phase transition: new particles, testable at LHC
  - New CPV: EDMs often provide strongest constraint.

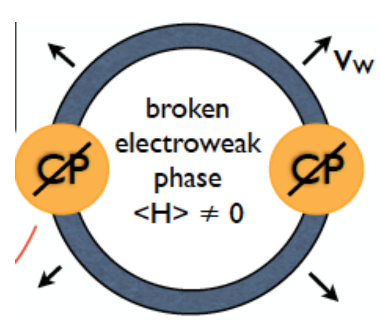
- Rich literature: (N)MSSM, Higgs portal (scalar extensions), flavored baryogenesis,…

See M. Ramsey-Musolf talk at APS April Meeting 2018

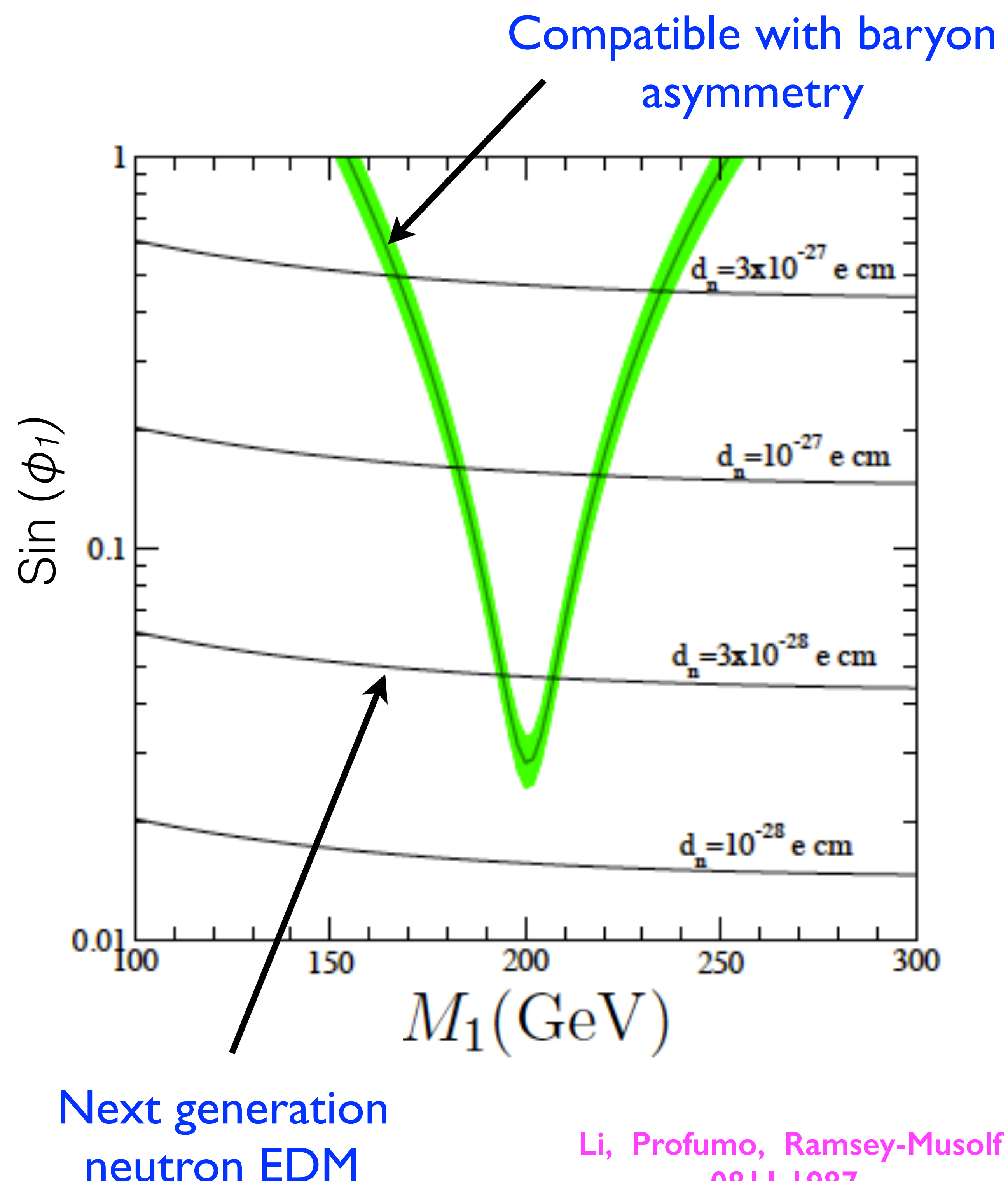
EDMs and EW baryogenesis (2)

- In Supersymmetry, 1st order phase transition disfavored by LHC in minimal model (MSSM), need singlet extension (NMSSM)
- CPV phases appearing in the gaugino-higgsino mixing contribute to both BAU and EDM





- In *scenario with universal phases* $\varphi_1=\varphi_2$, successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches



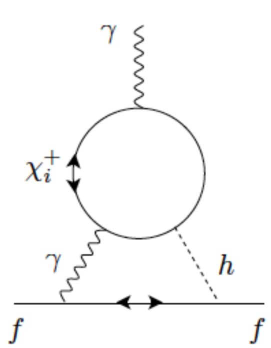
Li, Profumo, Ramsey-Musolf 0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589

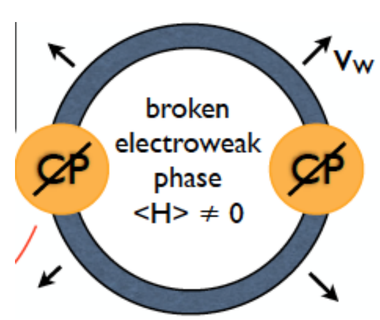
EDMs and EW baryogenesis (2)

- In Supersymmetry, 1[st] order phase transition disfavored by LHC in mini
  need singlet

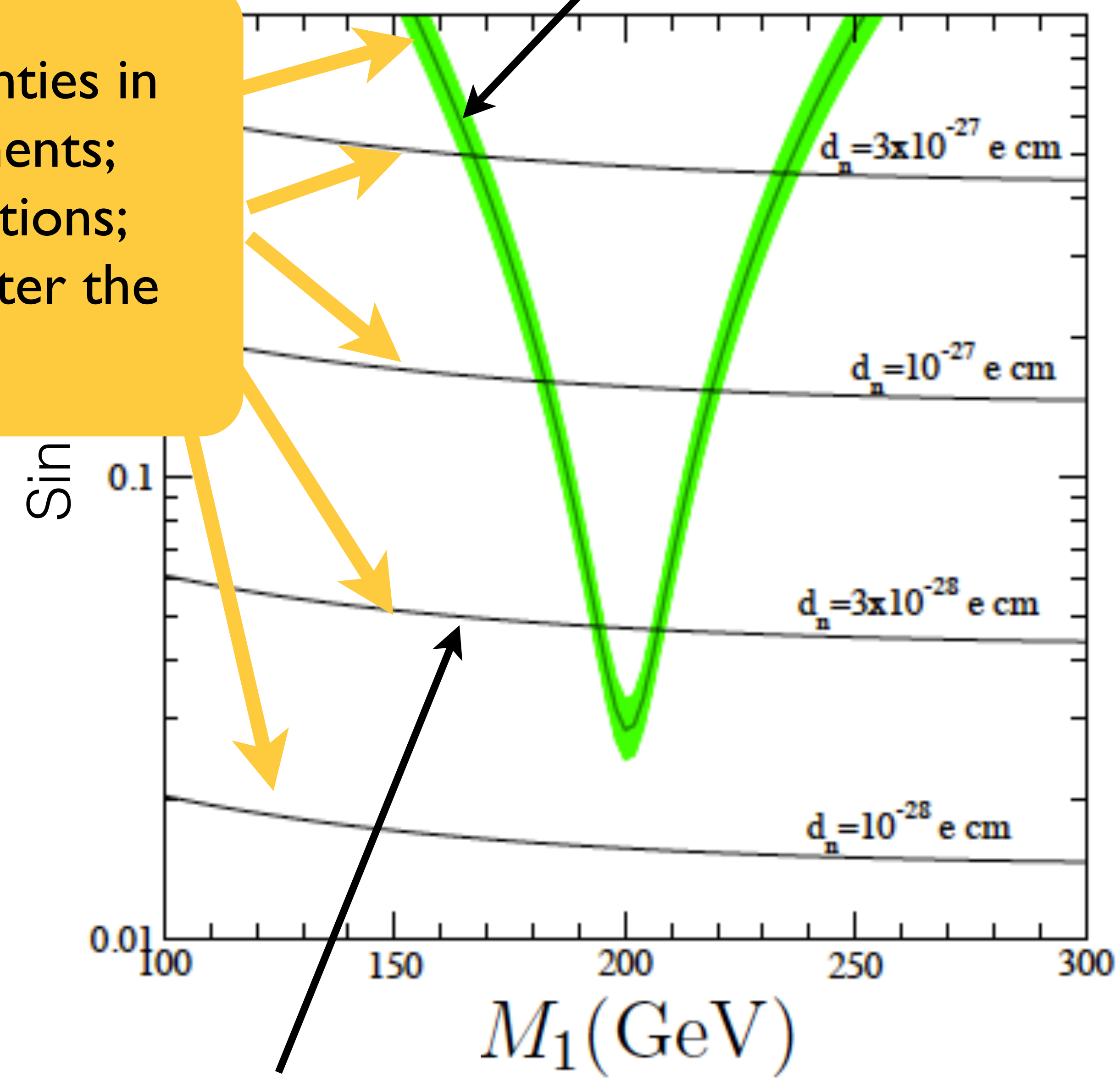
- CPV phases
  gaugino-higg
  contribute to both BAU and EDM

CAVEAT: current uncertainties in
1) hadronic matrix elements;
2) early universe calculations;
may shift these lines and alter the conclusions





Compatible with baryon asymmetry

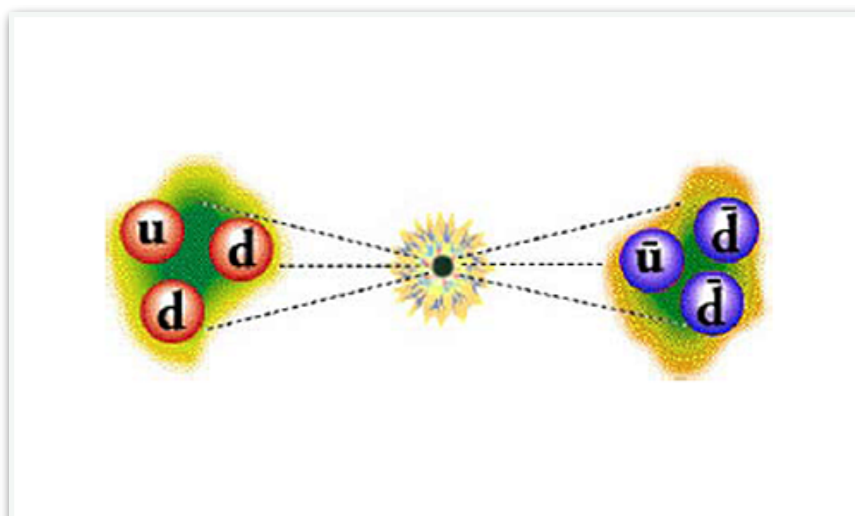


Next generation neutron EDM

- In *scenario with universal phases* $\varphi_1=\varphi_2$, successful baryogenesis implies a "guaranteed signal" for next generation EDMs searches

Li, Profumo, Ramsey-Musolf 0811.1987
VC, Li, Profumo, Ramsey-Musolf, 0910.4589

Neutron-Antineutron oscillations



ΔB=2

Neutron-antineutron oscillations

- Neutron-antineutron evolution controlled by effective Hamiltonian

$$\langle n|H_{\rm eff}|n\rangle = M_{11}$$
$$\langle \bar{n}|H_{\rm eff}|\bar{n}\rangle = M_{22}$$
$$\Delta M \equiv M_{11} - M_{22}$$

$$\mathcal{M} = \begin{pmatrix} M_{11} & \delta m \\ \delta m & M_{22} \end{pmatrix}$$

1410.1100 and refs therein

$$\langle \bar{n}|H_{\rm eff}|n\rangle = \langle n|H_{\rm eff}|\bar{n}\rangle \equiv \delta m$$

Key parameter: ΔB=2 amplitude δm (zero in SM)

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Key parameter: $\Delta B=2$ amplitude δm (zero in SM)

- Oscillation probability

$$P_{n\to\bar{n}}(t) = \left[\frac{(\delta m)^2}{(\Delta M/2)^2 + (\delta m)^2}\right] \sin^2\left[\sqrt{(\Delta M/2)^2 + (\delta m)^2}\; t\right] e^{-t/\tau_n} \simeq \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2 e^{-t/\tau_n}$$

$$\tau_{n-\bar{n}} \equiv 1/|\delta m|$$

$\Delta E\, t \ll 1$

- Energy difference ΔM (← magnetic field, matter) suppresses oscillation. This is avoided by working in "quasi-free" regime $\Delta E\, t \ll 1$

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Key parameter: ΔB=2 amplitude δm (zero in SM)

- Current bounds:
  - Oscillation of a free neutron in vacuum / low magnetic field [ILL]

$$\tau_{n-\bar{n}} > 0.86 \times 10^8 s \quad \rightarrow \quad \delta m < 7.6 \times 10^{-33}\ \text{GeV}$$

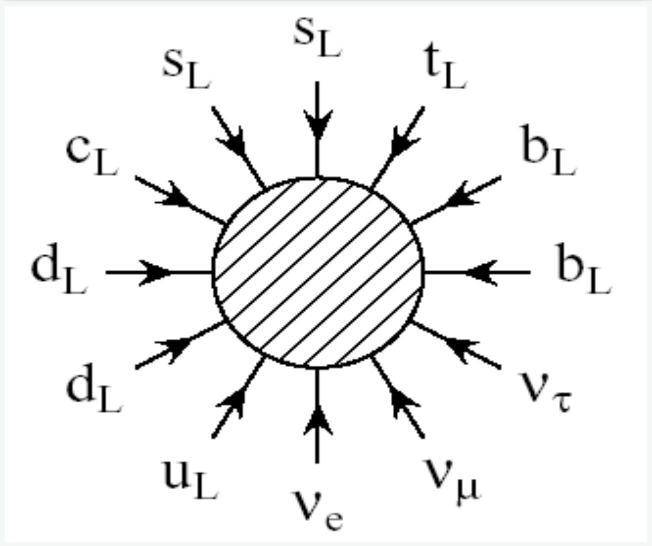
  - Oscillation of bound neutrons (BNV nuclear decays) [SuperK]

$$\tau_{n-\bar{n}} > 3.5 \times 10^8 s \quad \rightarrow \quad \delta m < 1.9 \times 10^{-33}\ \text{GeV}$$

$\tau_m > 1.9 \times 10^{32}$ yr $\qquad \tau_m = R\,\tau_{n-\bar{n}}^2 \qquad R \sim 100$ MeV

n-nbar and BSM BNV

- No ΔB=2 transitions in the Standard Model
  - Classical level: no B, L violating operators of dim≤4 ("accidental" symmetries)
  - Quantum level: B+L violated by anomaly in the SM (B-L preserved)
  - B+L violation active at T>100GeV. And selection rule is ΔB =3.



Sphaleron process

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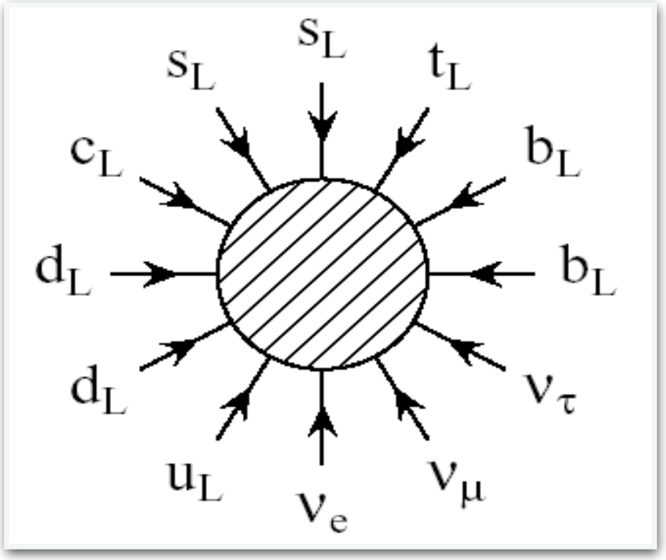


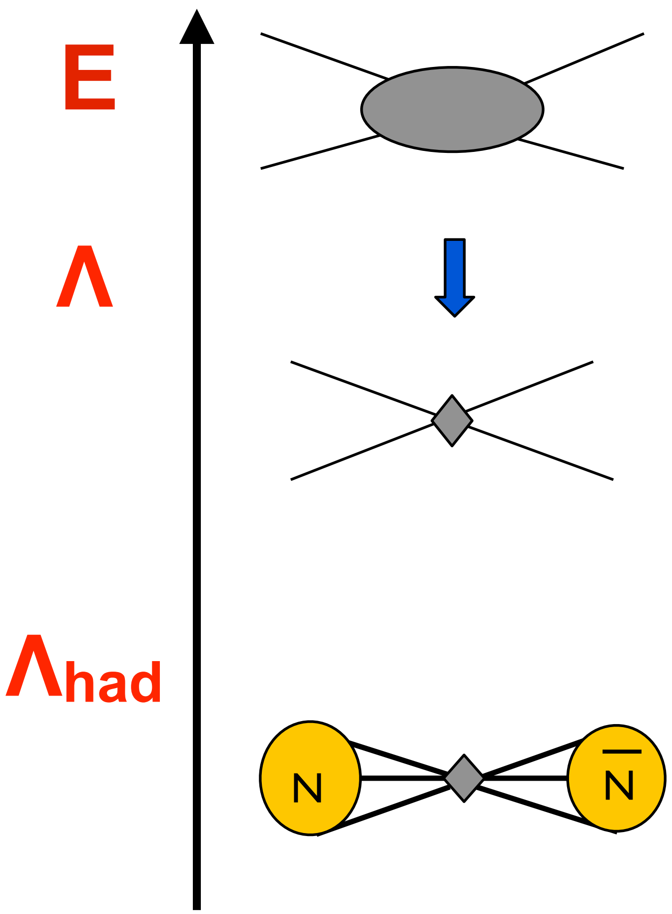
Sphaleron process

- Probes new class of baryogenesis mechanisms that do not rely on sphalerons for B violation

Sakharov ‘67

- B violation
- C and CP violation
- Departure from equilibrium

Connecting n-nbar to BSM BNV



$\mathcal{L}_{SM+\text{Heavy}}$

Describe dynamics below the scale $M_{BSM} \sim \Lambda >> v= G_F^{-1/2}$ in terms of L_{eff}

$$\mathcal{L}_{\text{BNV}} \supset \sum_k \frac{C_k^{(6)}}{\Lambda^2} [qqql]_k + \sum_k \frac{C_k^{(9)}}{\Lambda^5} [qqqqqq]_k$$

MIT bag model:
Rao and Shrock, Nucl. Phys. B 232, 143 (1984)

$$\langle \bar{n} | O_i^{(9)} | n \rangle = \tilde{\kappa}_i^{\text{QCD}} \, \Lambda_{\text{QCD}}^6$$

Ongoing Lattice QCD:
Wagman-Buchoff 1506.00647
Syritsyn et al PoS LATTICE2015 (2016) 132

$$\delta m = \frac{\Lambda_{\text{QCD}}^6}{\Lambda^5} \sum_i C_i^{(9)} \tilde{\kappa}_i^{\text{QCD}}$$

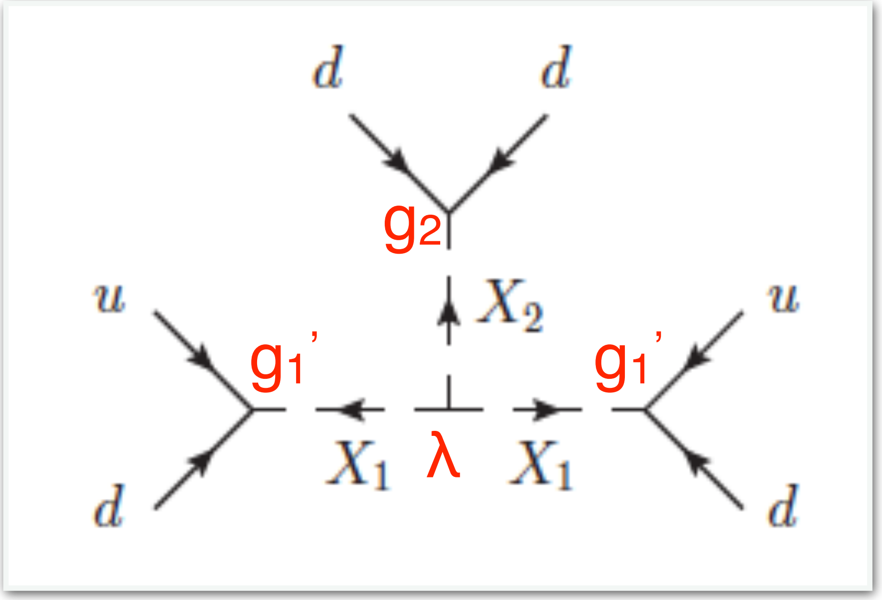
- $\Delta B=\Delta L=1$ operators arise at dim-6 ($\sim 1/\Lambda^2$): p decay $\Rightarrow \Lambda > \Lambda_{GUT}$
- $\Delta B=2$ operators arise at dim-9 ($\sim 1/\Lambda^5$): n-nbar $\Rightarrow \Lambda >$ 10-100 TeV.

(With multiple thresholds $\Lambda_{1,2}$, one can have $\Lambda_1 \sim$TeV, $\Lambda_2 \sim 10^{13}$GeV)

n-nbar and BNV dynamics

- Is there room for n-nbar just below current sensitivity given constraints from proton decay?
- Yes! Need BNV models with $\Delta B=2$ and no tree-level $\Delta B=1$. Rich model building. Glashow '79, Mohapatra-Marshak '80, …
- Most such models share these interesting features:
  - new colored particles
  - relatively low scale (TeV): n-nbar and LHC signatures
  - connection to low-scale baryogenesis

Example:



$X_1 \in (\bar{6}, 1, -1/3), \; X_2 \in (\bar{6}, 1, 2/3)$

Arnold-Fornal-Wise 1212.4556

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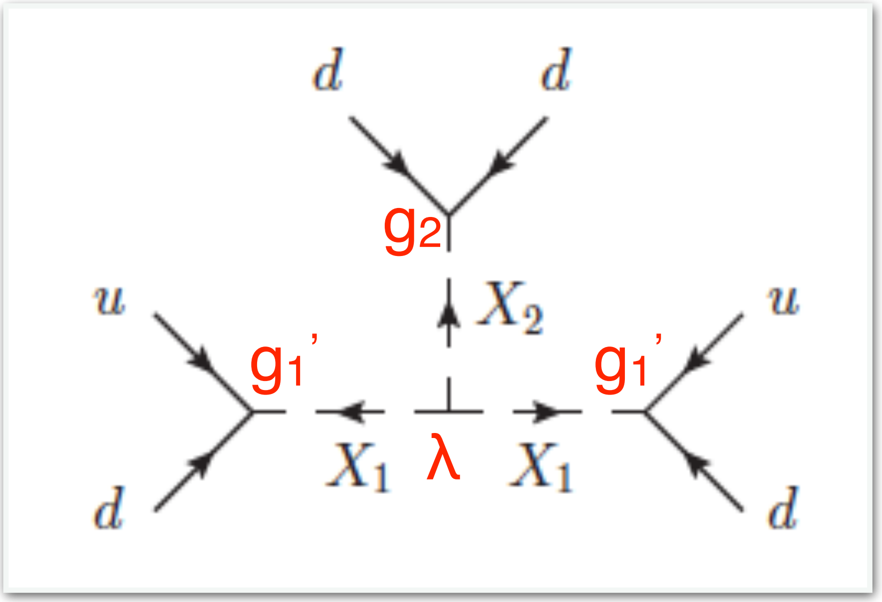

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Arnold-Fornal-Wise 1212.4556

Broad spectrum: from partial unification to "minimal" models

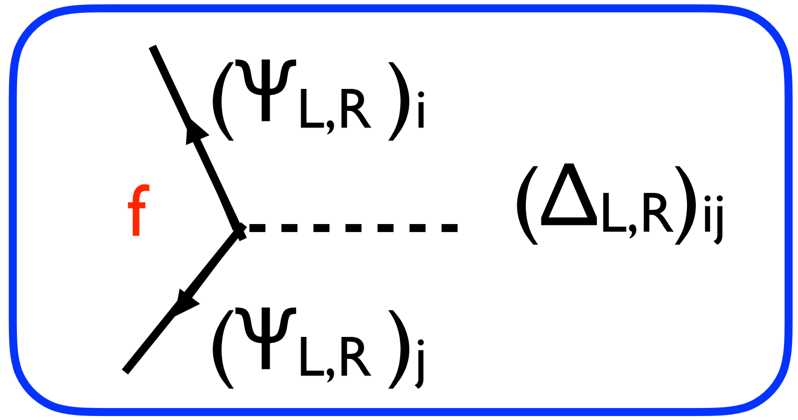
Quark-lepton symmetric models

Pati-Salam ’74 Mohapatra-Marshak ’80

- Based on unified gauge symmetry group: $SU(4)_c \times SU(2)_L \times SU(2)_R$

$\Psi_L \equiv (4,2,0)$ $\Psi_R \equiv (4,0,2)$

$$\Psi_{L,R} = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e^- \end{pmatrix}_{L,R}$$



Higgs fields
$\Delta_L \equiv (10,3,0)$
$\Delta_R \equiv (10,0,3)$
Include diquarks, leptoquarks, singlets

This scenario relates

- parity violation (breaking of LR symmetry)
- $\Delta L=2$ (Majorana ν’s via see-saw mechanism)
- $\Delta B=2$ (n-nbar oscillations)

(and has no $\Delta B=1$)

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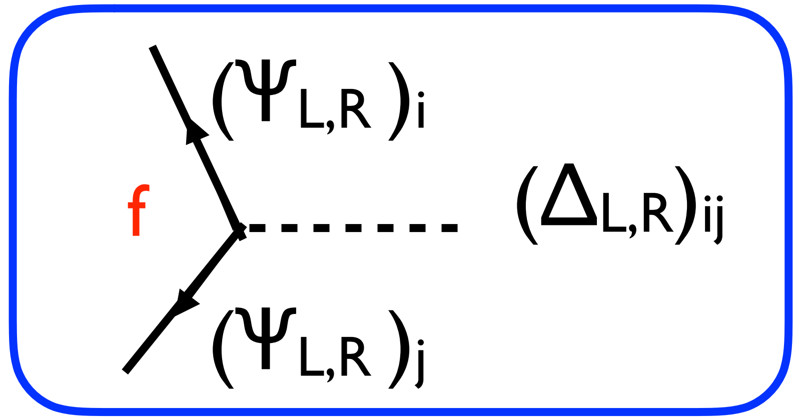

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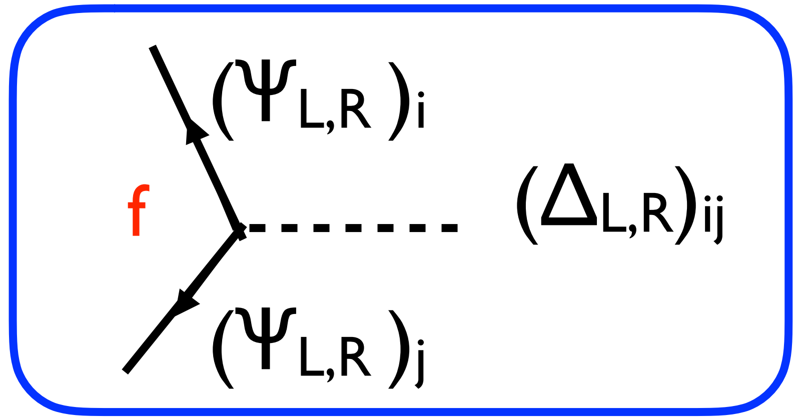

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Include diquarks, leptoquarks, singlets

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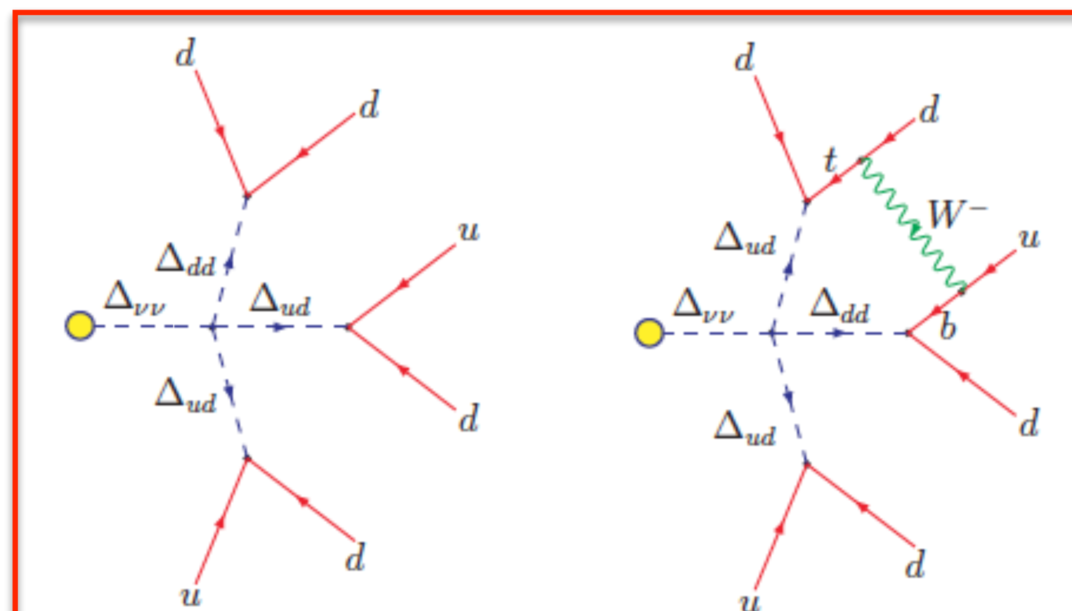
- $\Delta_{R,\nu\nu}$ and SU(4) partners induce ΔB=2 dim-9 operators

$$C^{(9)} \sim \frac{v_R}{M^6_{\Delta_R}}$$

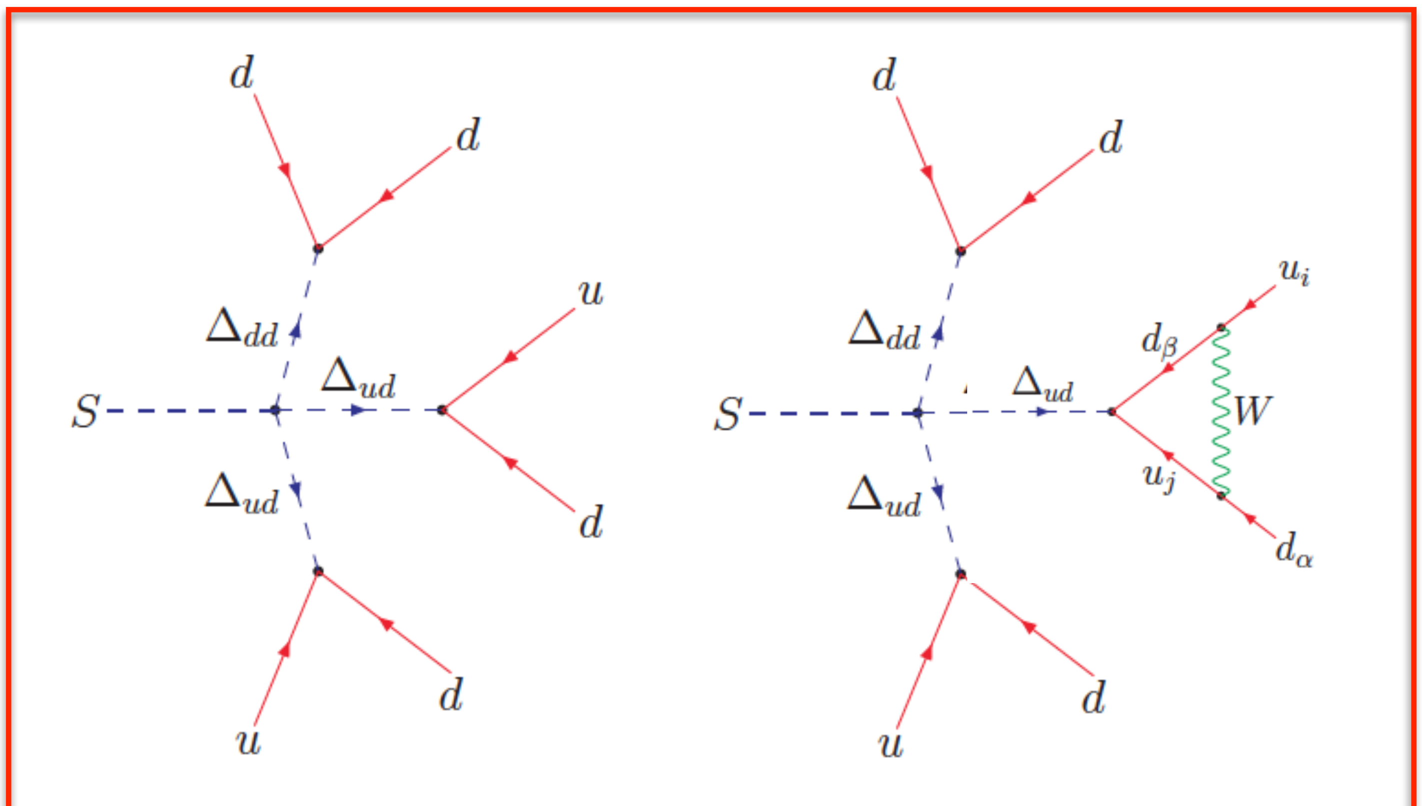
Observable n-nbar osc. if M_Δ ~TeV



Post Sphaleron Baryogenesis (PSB)

- $\Delta_{R,\nu\nu} = v_R + 1/\sqrt{2}\,(S + i\chi)$ is also the key for baryogenesis. This model offers a concrete realization of PSB

- Out of equilibrium, B- & CP-violating decays of S at $T \in$ (0.1 - 100) GeV



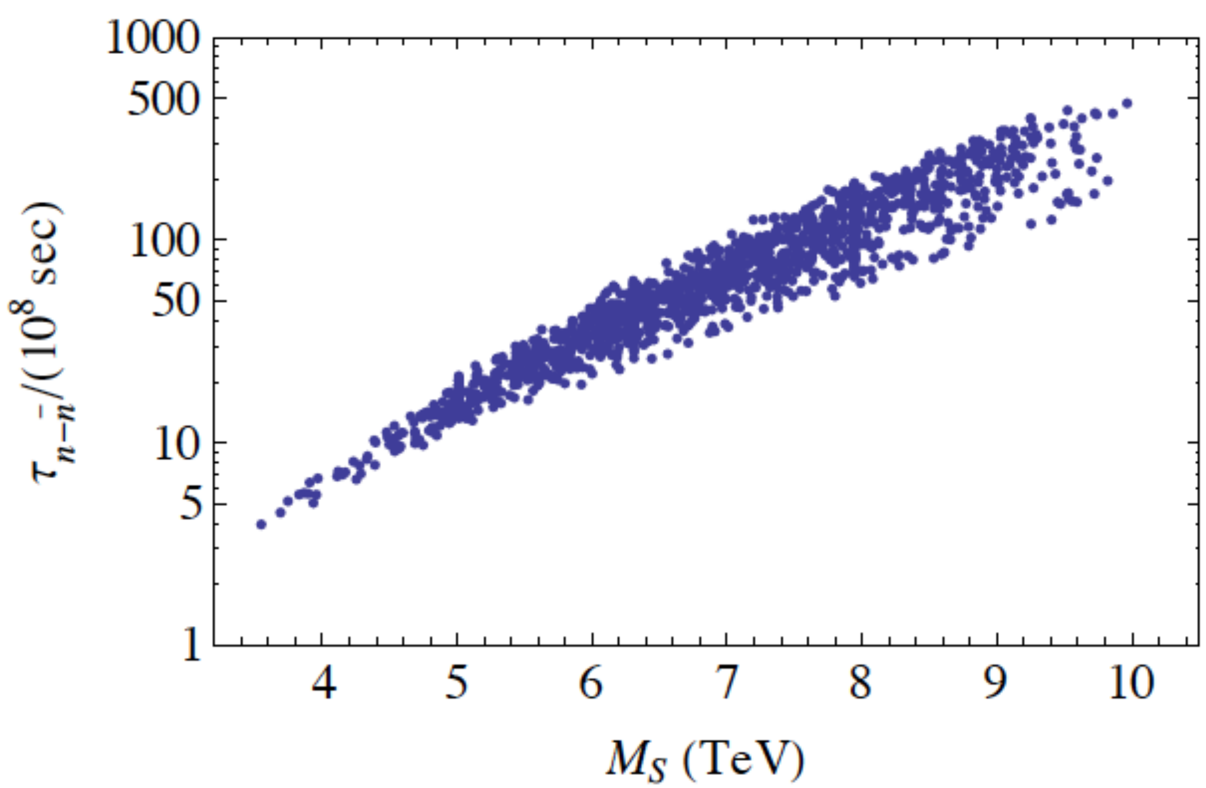
Babu-Mohapatra-Nasri '06
...
Babu-Dev-Fortes-Mohapatra '13

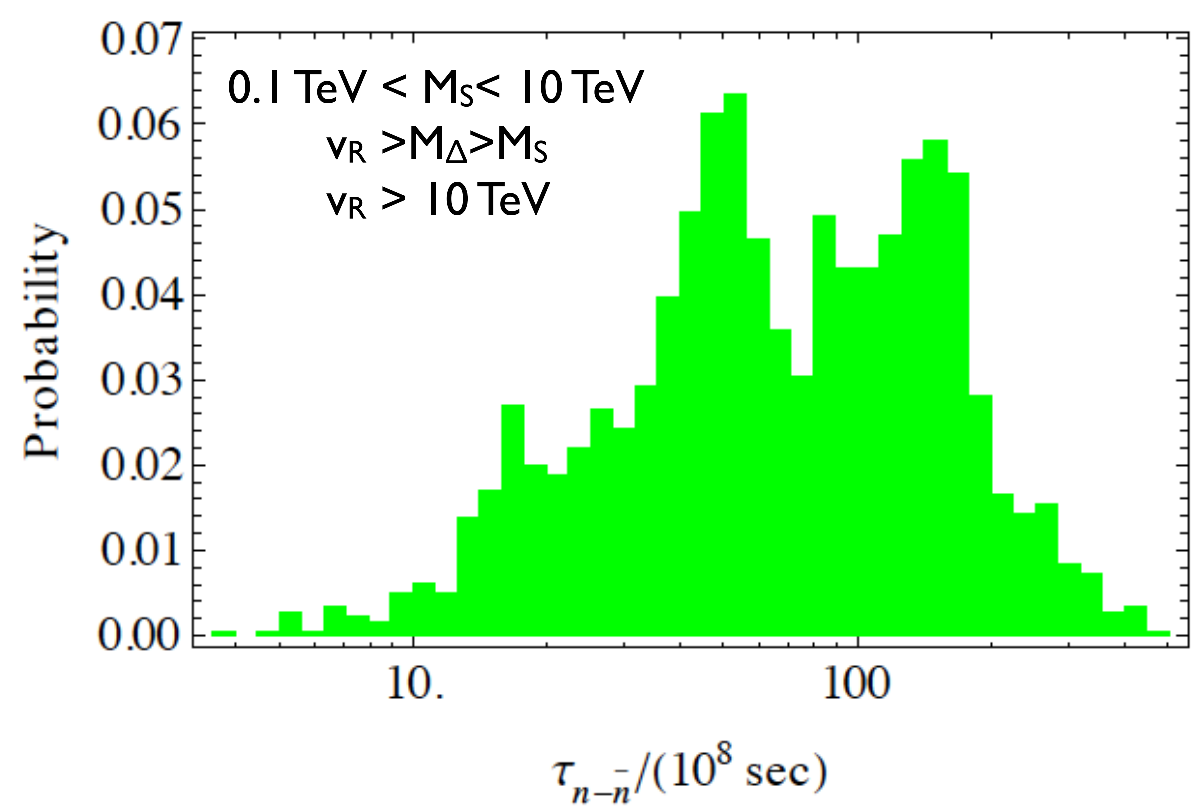
- Asymmetry produced by $S \to 6q$ vs $S \to 6\bar{q}$ can't be erased

PSB and n-nbar

- Scan over parameter space consistent with BAU, FCNC, and ν mixing

Babu-Dev-Fortes-Mohapatra ‘13





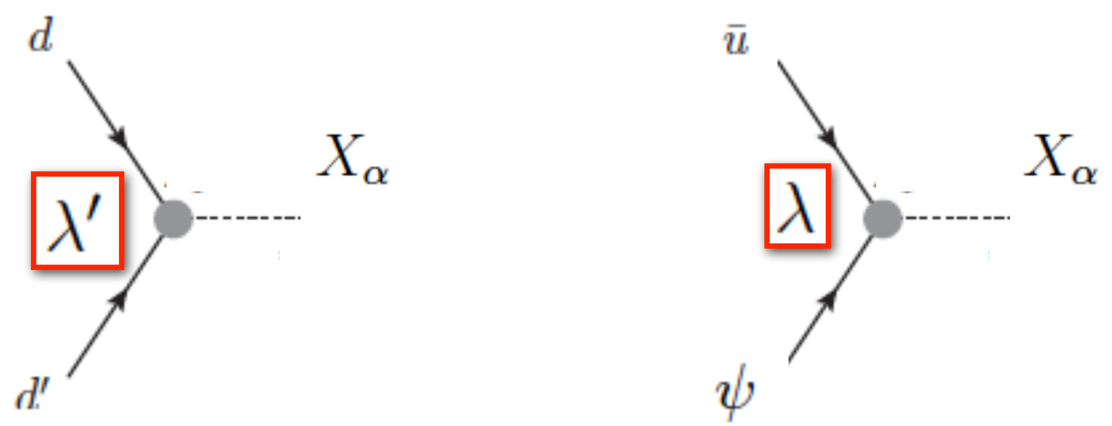
- Upper bound on τ_{nn} < few 10^{10}s, within reach of next gen. searches
- Correlation with 0νββ (ΔL=2)*: inverted hierarchy for light ν

A simple testable model

Allahverdi-Dev-Dutta 1712.02713

- Setup: scalar color triplets ($X_{1,2}$) + SM fermion singlet ψ → baryogenesis and Dark matter + signatures in n-nbar osc. and LHC

$$\mathcal{L} \supset \left(\lambda_{\alpha i} X^*_\alpha \psi u^c_i + \lambda'_{\alpha ij} X_\alpha d^c_i d^c_j + \frac{1}{2} m_\psi \bar{\psi}^c \psi + \text{H.c.} \right)$$



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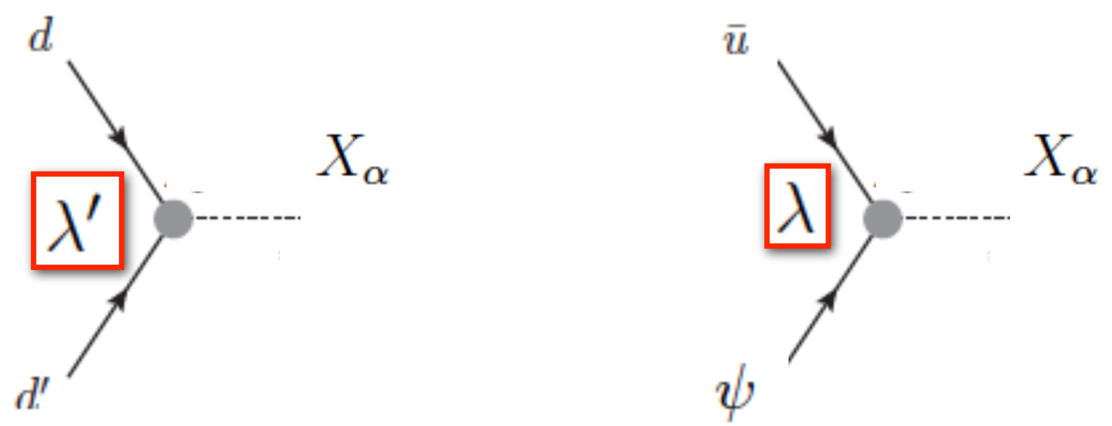

- Both ψ=DM and proton are stable if $m_p - m_e \leq m_\psi \leq m_p + m_e$
- Baryogenesis: CP asymmetries in $X_\alpha \to \psi u^c_i, d^c_i d^c_j$

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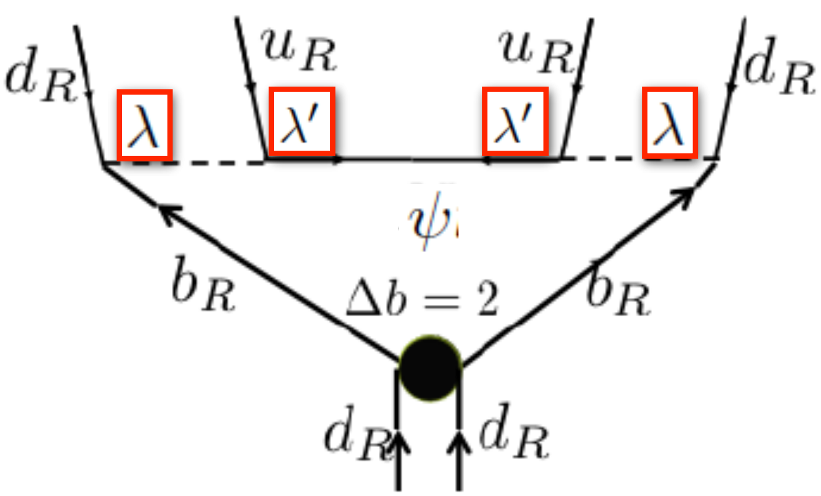
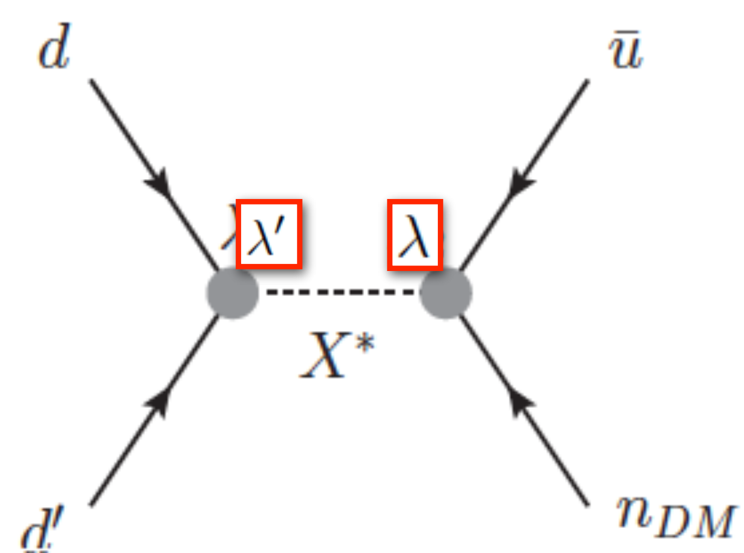
n-nbar



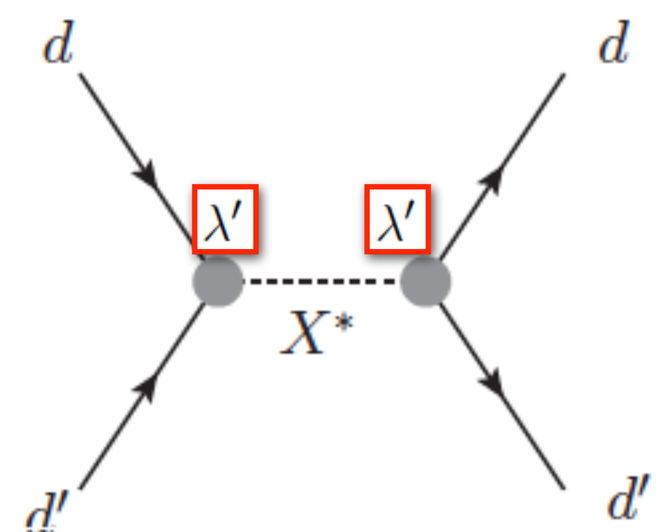
λ_{12} suppressed to avoid pp→K^+K^+

λ_{13} controls the amplitude

LHC signatures



monojet



dijet

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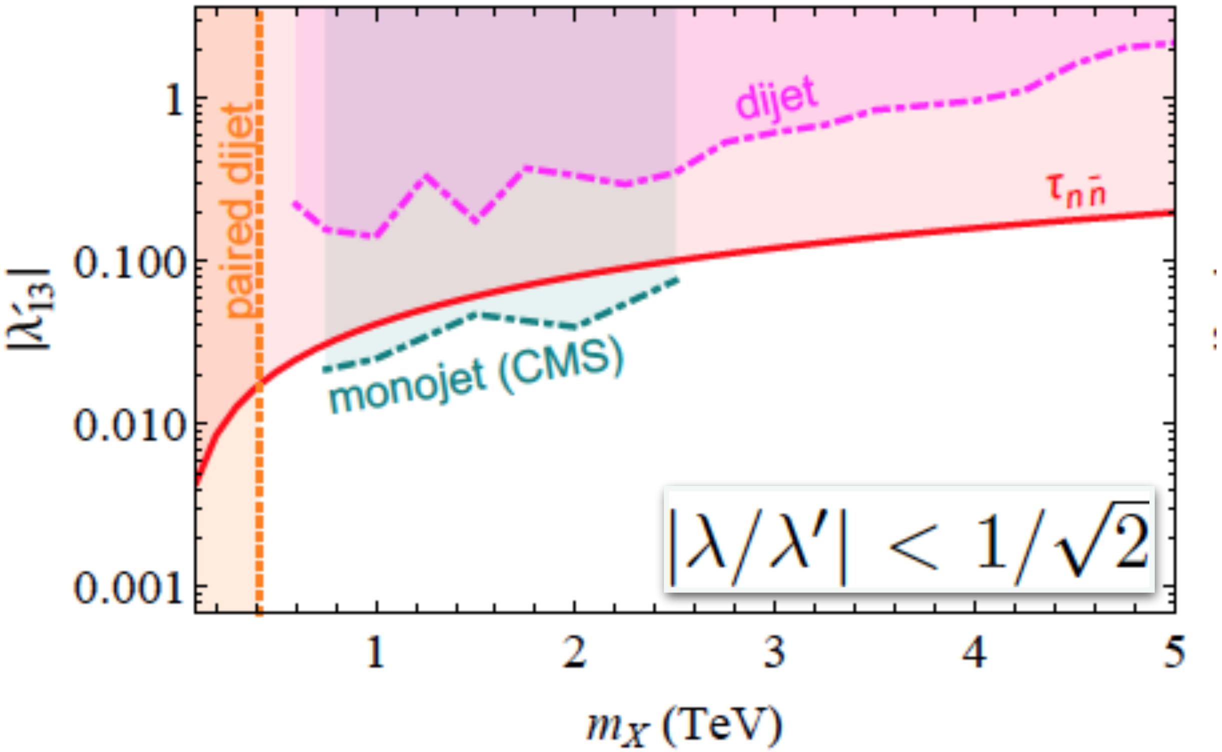

- Complementarity of collider and n-nbar in probing model parameter space

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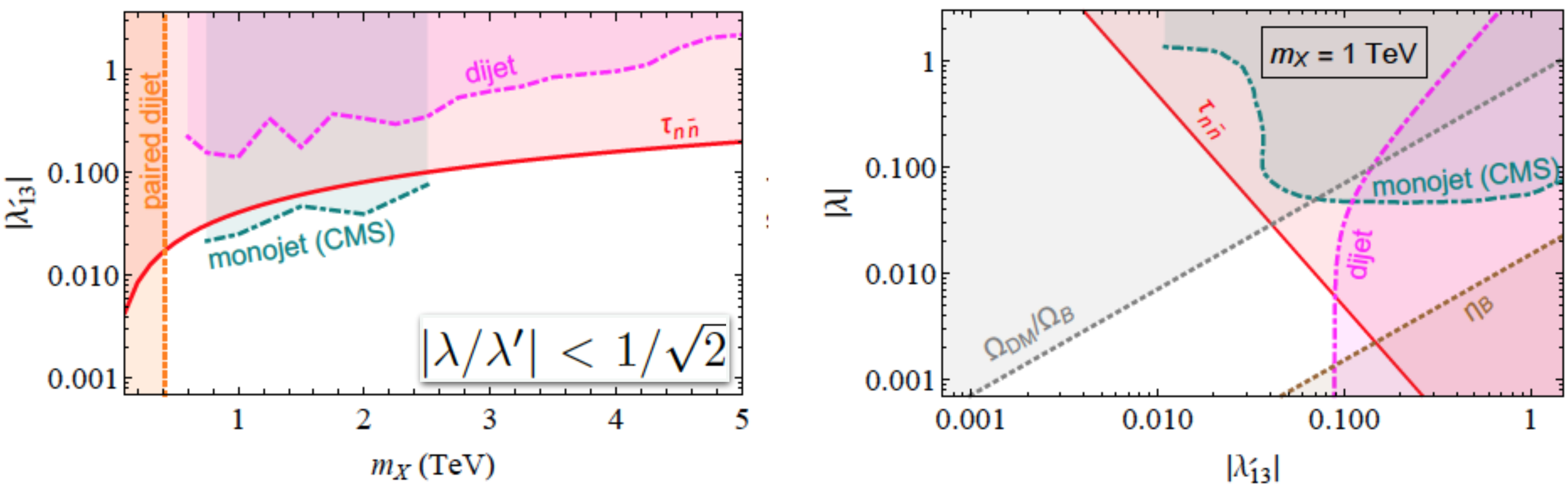
Allahverdi-Dev-Dutta 1712.02713



- Complementarity of collider and n-nbar in probing model parameter space
- Viable region (DM and BAU OK) will be explored by LHC and next-generation n-nbar oscillations searches

Summary

Neutron measurements have the potential to uncover the BSM symmetry breaking interactions needed for baryogenesis

- Neutron EDM @ few $\times 10^{-27/28}$ e cm:
  - Strong probe of EW baryogenesis and any BSM CPV that couples to quarks and gluons (e.g. CPV Higgs couplings)
  - Sensitivity to very high-scale BSM physics (e.g split SUSY) as well as light new physics (axions): discovery opportunity exists!

- Neutron-antineutron oscillations @ $\tau_{nn} \sim 10^{10}$s:
  - Key to understanding the origin of B violation ($\Delta B=2$ vs $\Delta B=1$)
  - Probe broad spectrum of models with rich TeV-scale physics and post-sphaleron baryogenesis.
  - Elegant connection to BAU and $\Delta L=2$ in Q-L unification models

Summary

Neutron measurements have the potential to uncover the BSM symmetry breaking interactions needed for baryogenesis

- Neutron EDM @ few $\times 10^{-27/28}$ e cm:

Patience, determination, and luck needed!

"Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed" – A. Soni

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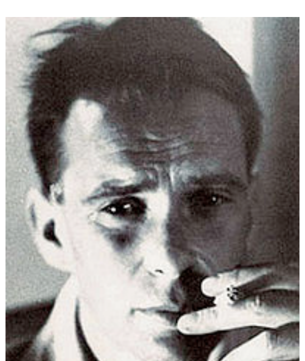
Thank you!



A drawing by
Bruno Touschek