NSAC Meeting, October 18 2016

Searching for New Physics: the Impact of Nuclear Science Fundamental Symmetries Experiments

Vincenzo Cirigliano
Los Alamos National Laboratory

LA-UR-16-28141

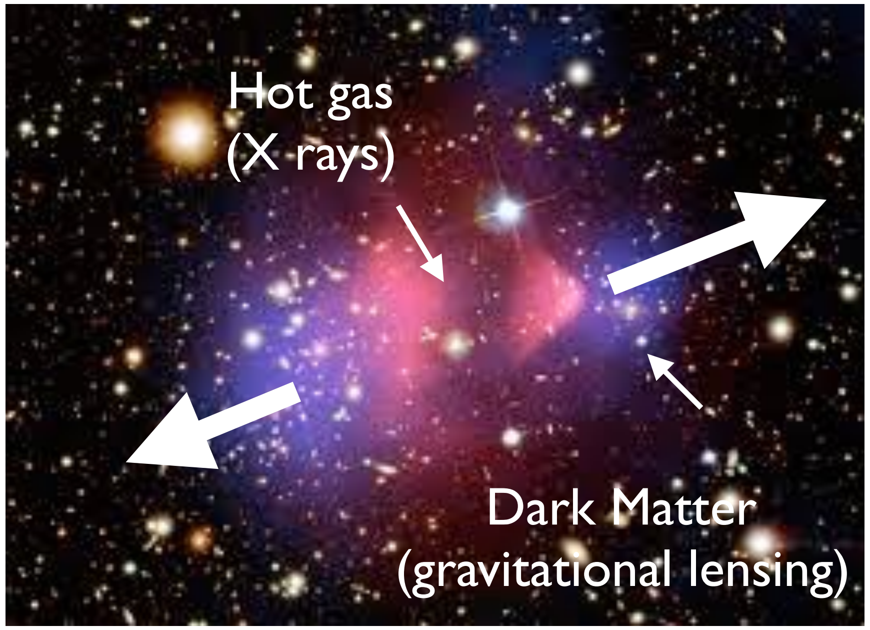
Outline

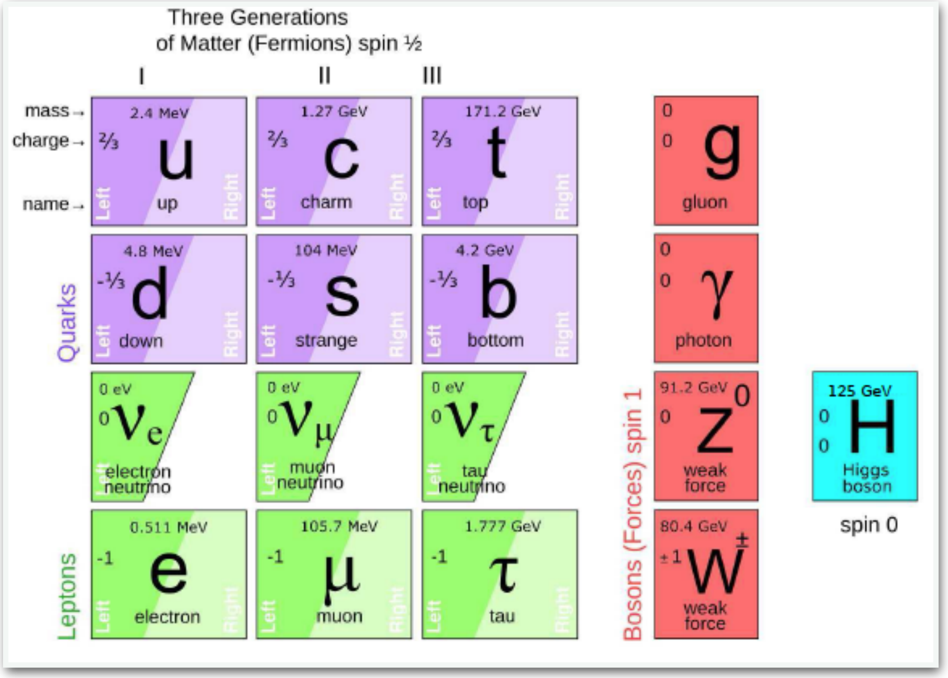
- Motivation: open questions driving our search for new physics beyond the Standard Model
- Energy frontier searches
- Precision / intensity frontier and the impact of Nuclear Science

Beyond the Standard Model: why?

- The SM is remarkably successful, but can't be the whole story

Phenomenology-driven arguments

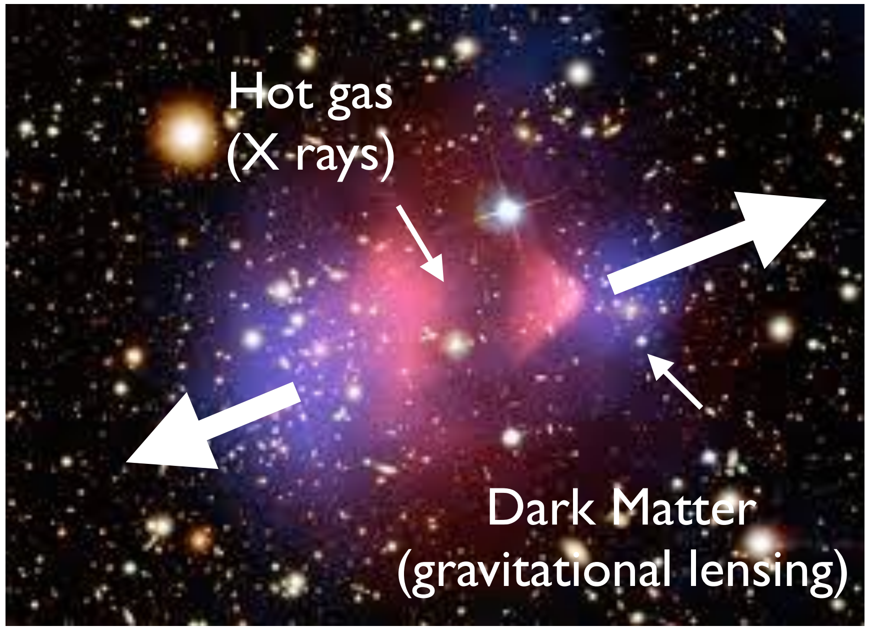




Beyond the Standard Model: why?

- The SM is remarkably successful, but can't be the whole story

Phenomenology-driven arguments



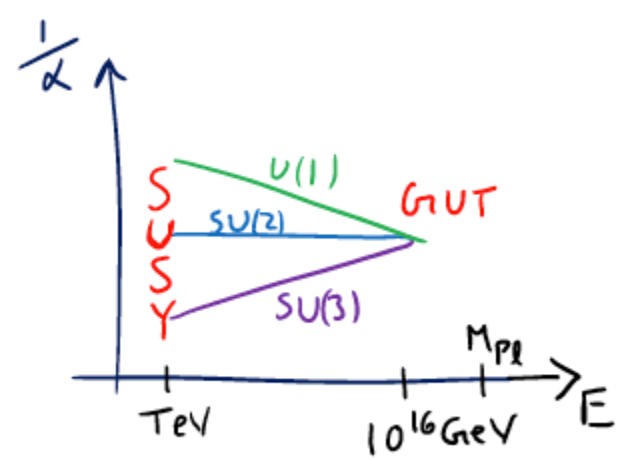
- What is the nature of dark matter?
- What is the origin of the baryon asymmetry in the universe?
  - New dynamics associated with Sakharov conditions: B (L) violation, CP violation, non-equilibrium
- How do neutrinos acquire mass?
- What is dark energy?

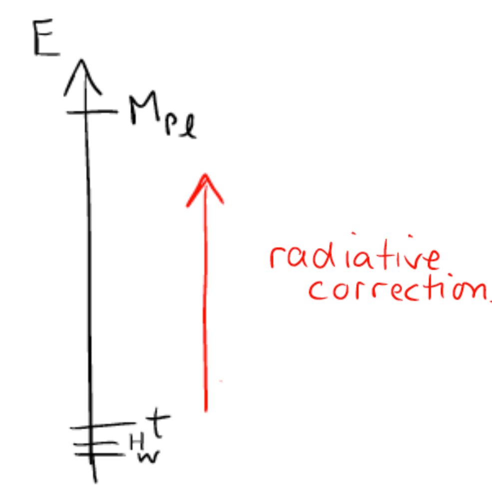
Beyond the Standard Model: why?

- The SM is remarkably successful, but can't be the whole story

Theory-driven arguments

- What stabilizes G_{Fermi}/G_{Newton} against large radiative corrections?
- Do the gauge forces unify at high E? What about gravity?
- What is the origin of fermion generations and pattern of masses & mixings?
- …





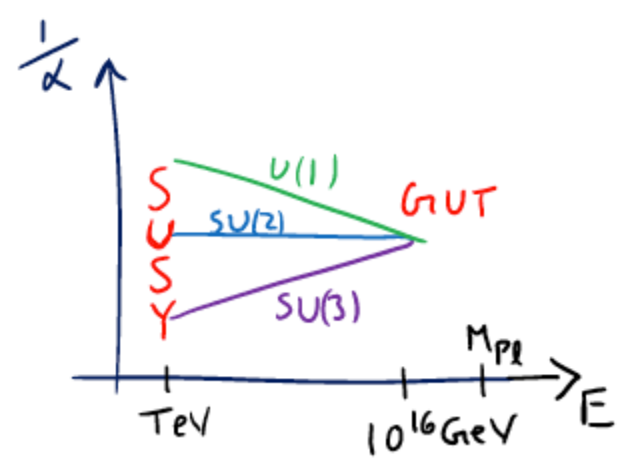
R. Sundrum
ICHEP 12

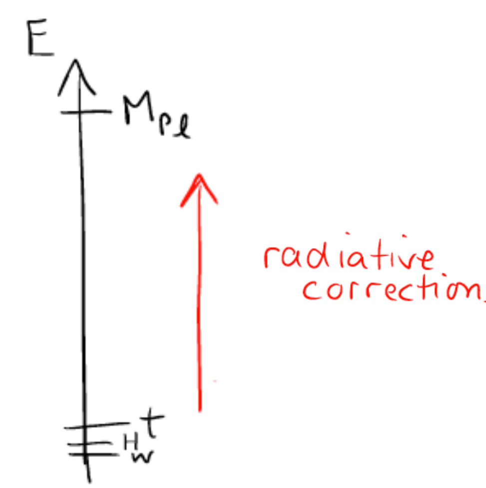
Beyond the Standard Model: why?

- The SM is remarkably successful, but can't be the whole story

Phenomenology-driven arguments

Theory-driven arguments





R. Sundrum
ICHEP 12

Addressing these questions requires new degrees of freedom

The quest for new physics

- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

  - Theoretical guidance leaves both possibilities open

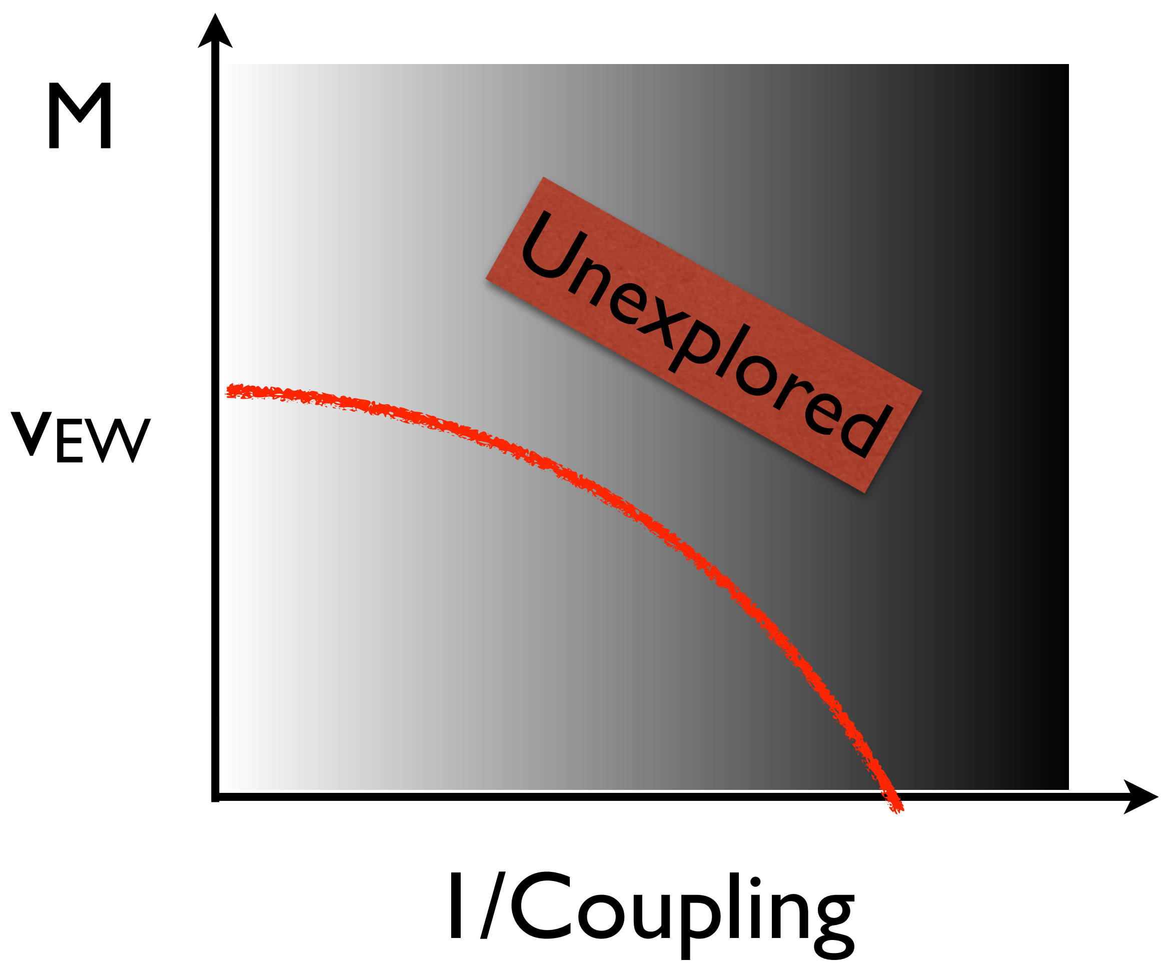
    - Stabilizing G_{Fermi}/G_{Newton}, coupling unification, "WIMP miracle" (dark matter as a thermal relic) suggest M_{BSM} not too far above the weak scale (200 GeV)

    - Dark matter & origin of neutrino mass can be linked to light and feebly coupled new physics (M_{BSM} << 100 GeV): dark sectors

  - No guaranteed path to discovery ⇒ search broadly

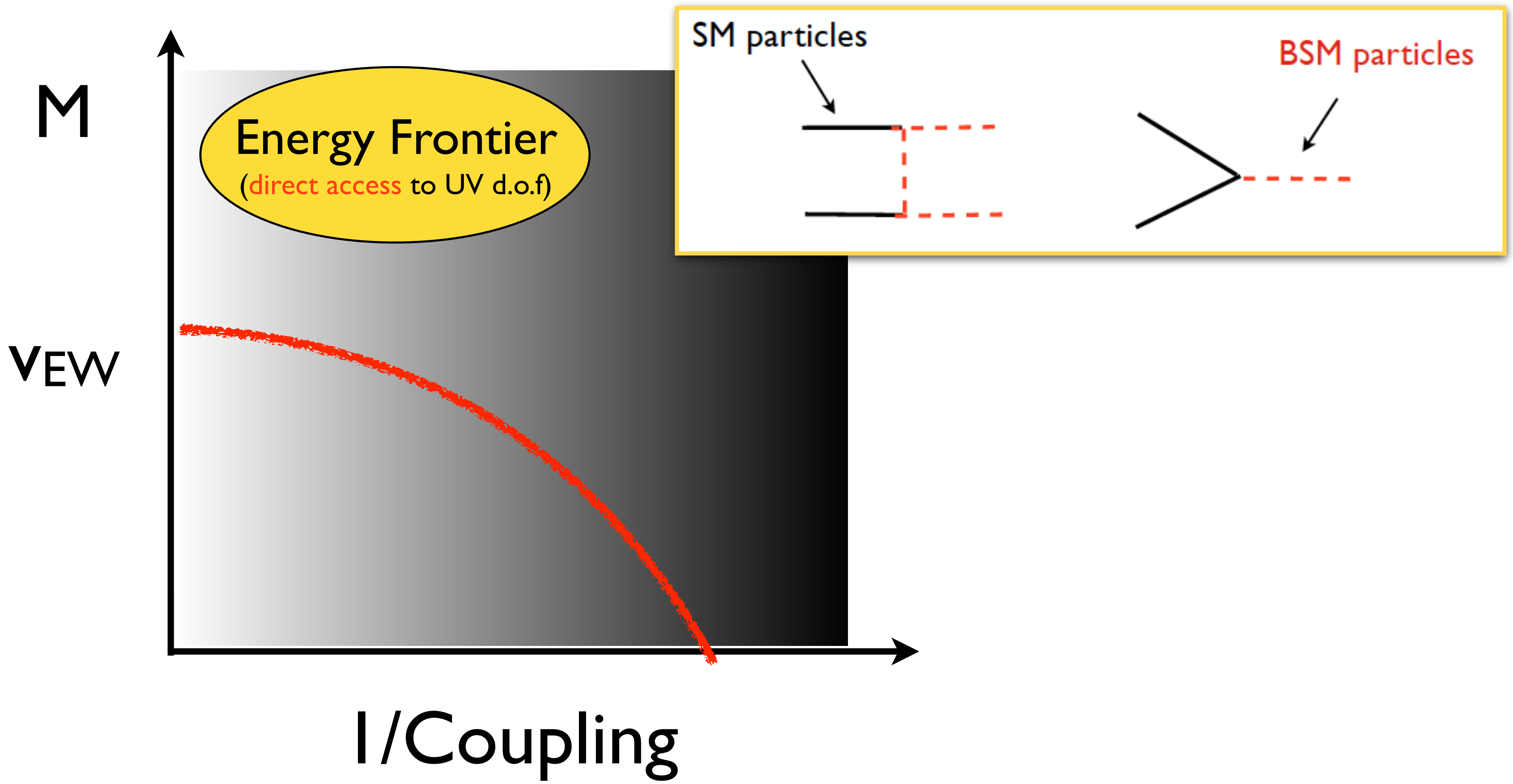
The quest for new physics

- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



The quest for new physics

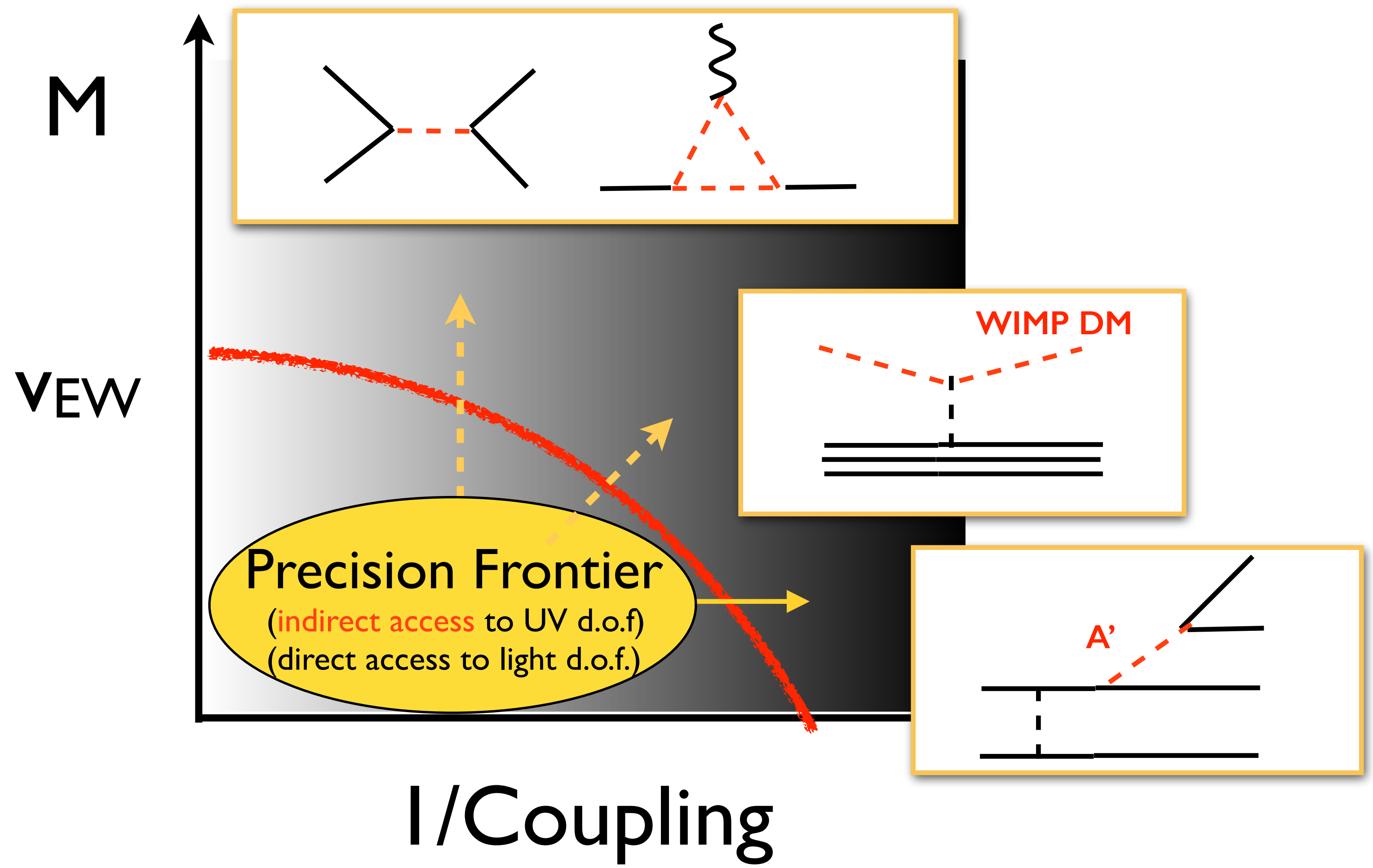
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



- Two experimental approaches

The quest for new physics

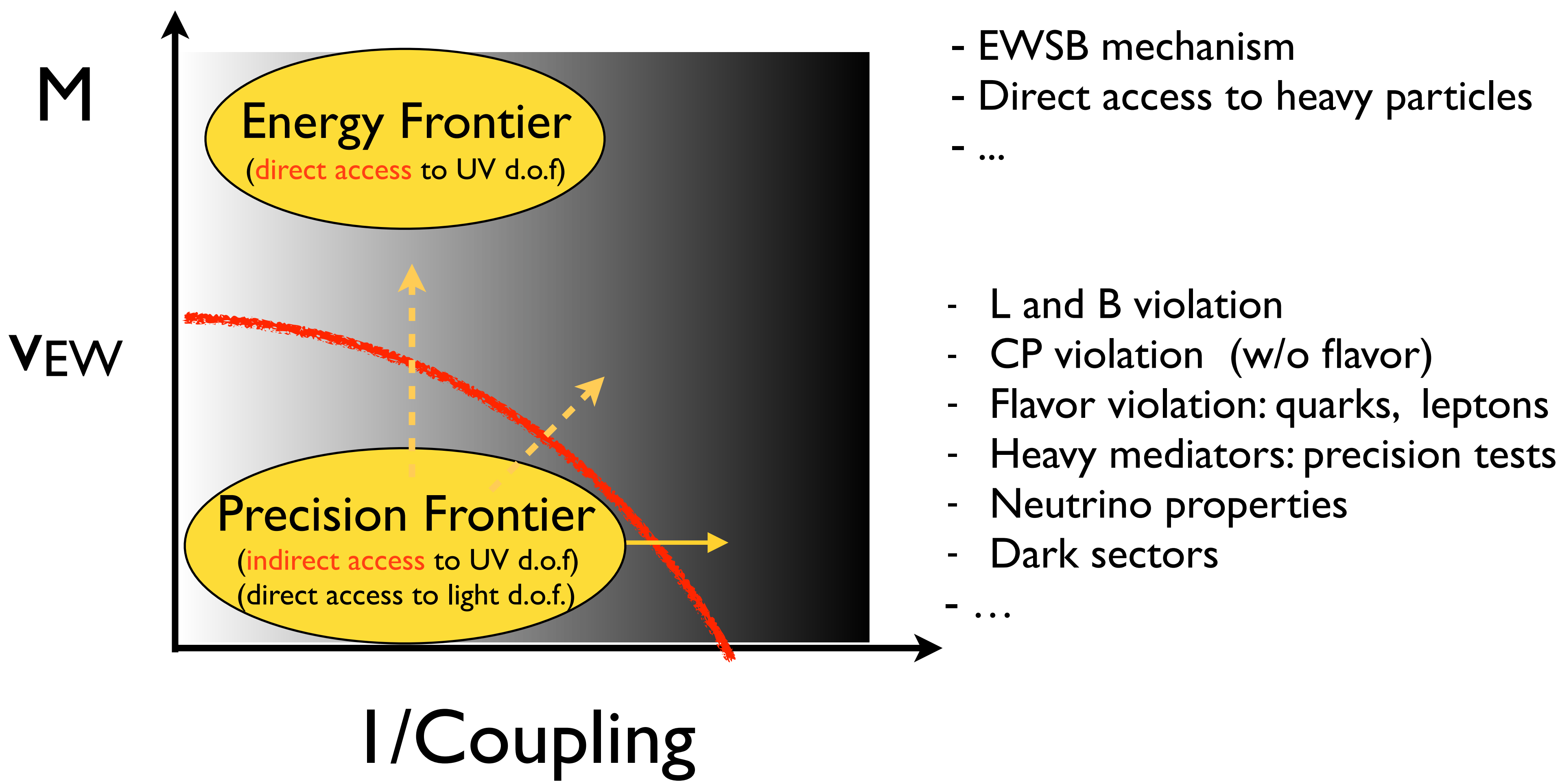
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



- Two experimental approaches

The quest for new physics

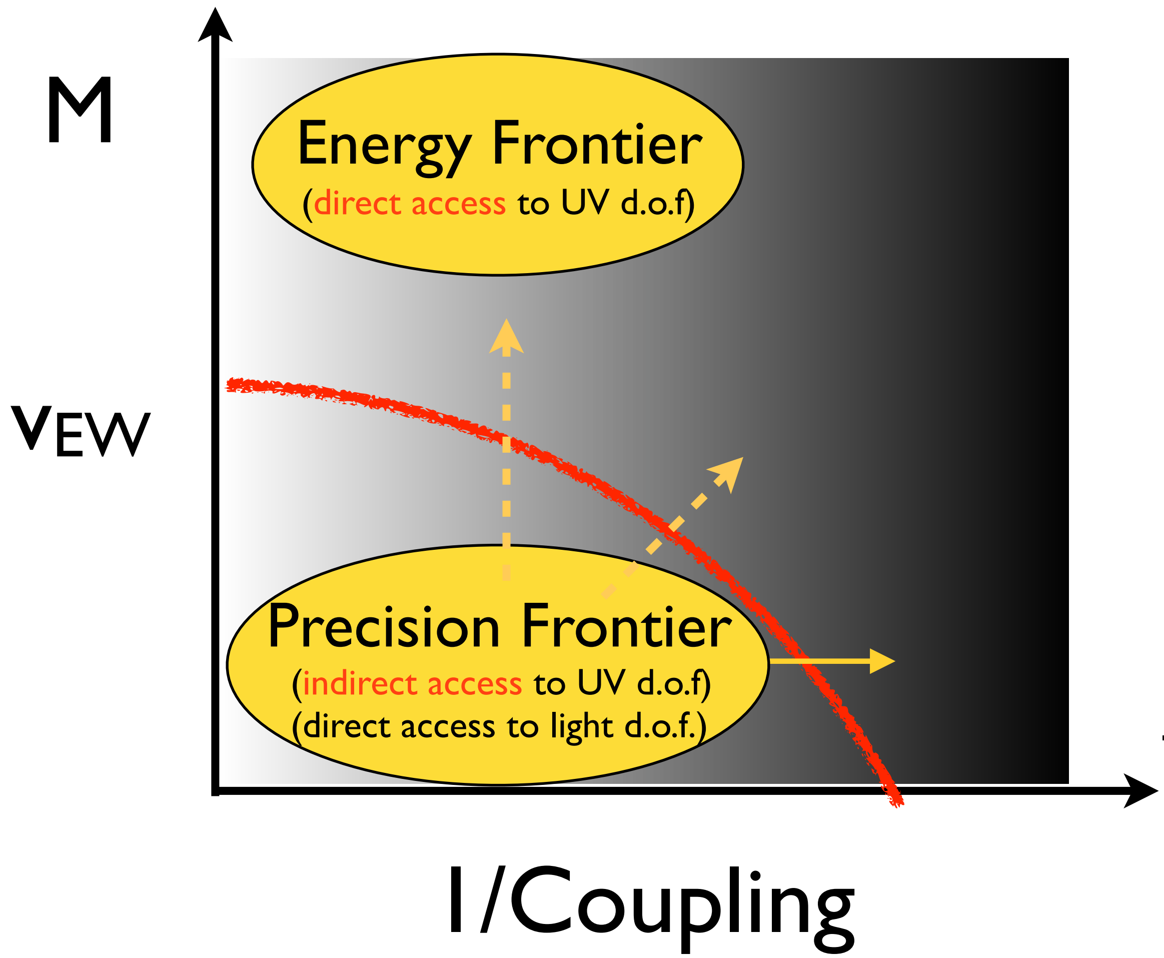
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



- Two experimental approaches, both needed to reconstruct BSM dynamics: structure, symmetries, and parameters of $\mathcal{L}_{BSM}$

The quest for new physics

- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?

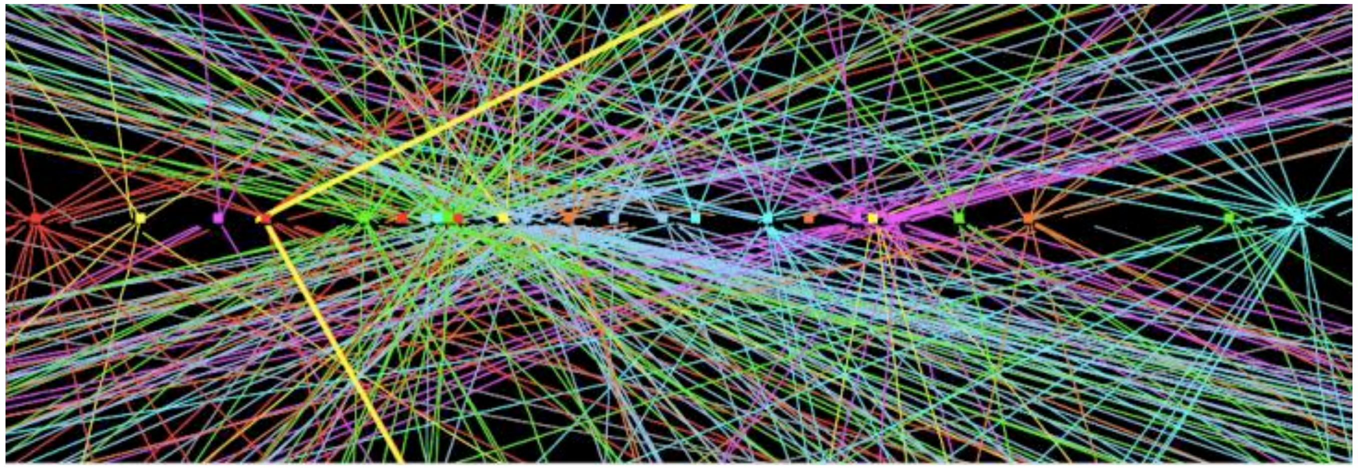


- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Heavy mediators: precision tests
- Neutrino properties
- Dark sectors
- ...

Nuclear Science Fundamental Symmetry experiments
play a prominent role at the Precision Frontier

Energy Frontier Searches



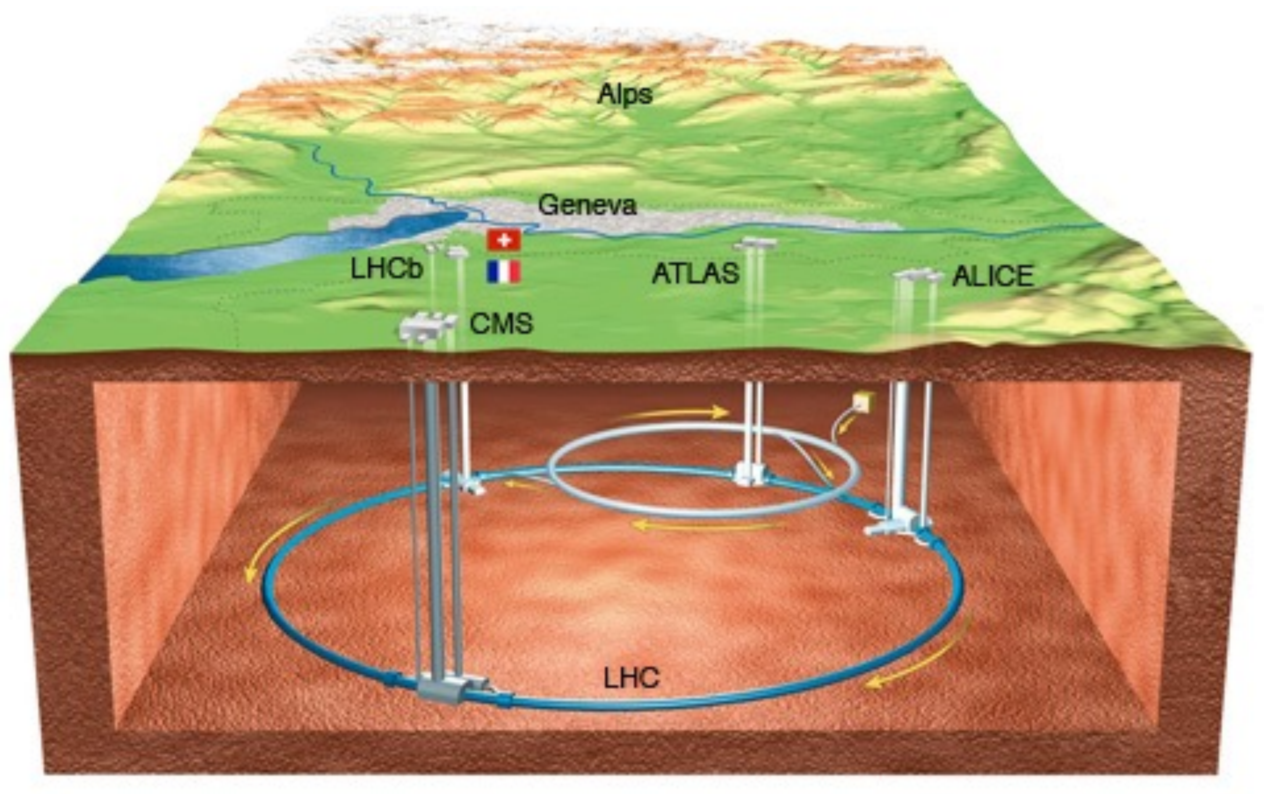
Z→ μμ event from 2012 data with 25 reconstructed vertices

The Large Hadron Collider

- Hadron machine: p+p, p+A, A+A
  - Run 1: pp @ $\sqrt{s}$ = 7-8 TeV (~20 fb^{-1})
  - Run 2: pp @ $\sqrt{s}$ = 13 TeV (~13 fb^{-1})

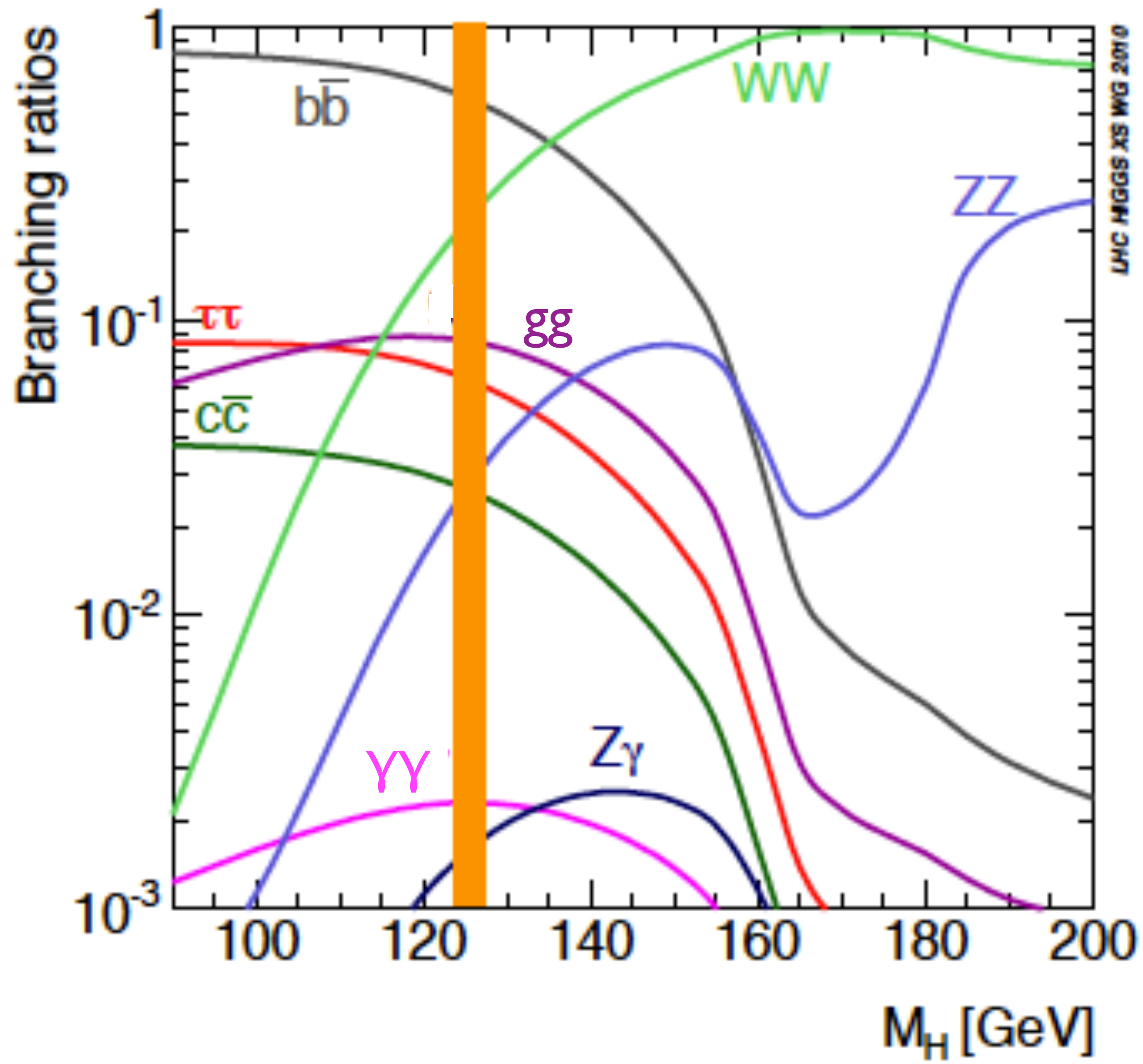
- Major discovery: Higgs boson with m_h=125 GeV

- Search for TeV-scale new dynamics:
  - Higgs properties
  - Supersymmetry
  - Everything else: "Exotica"
  - Dark matter



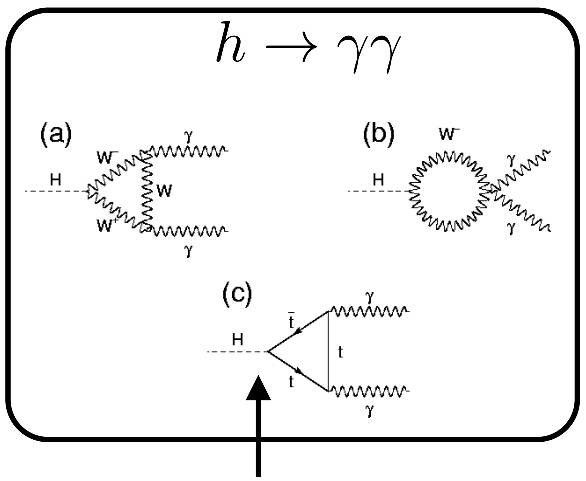
Higgs as a probe of new physics

- Many decay modes accessible: can test Standard Model BR pattern

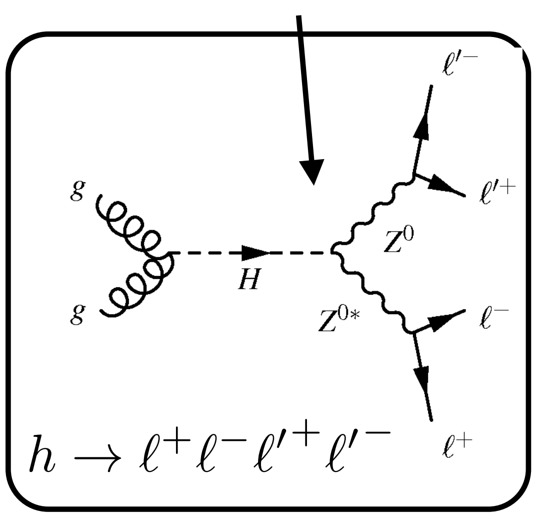


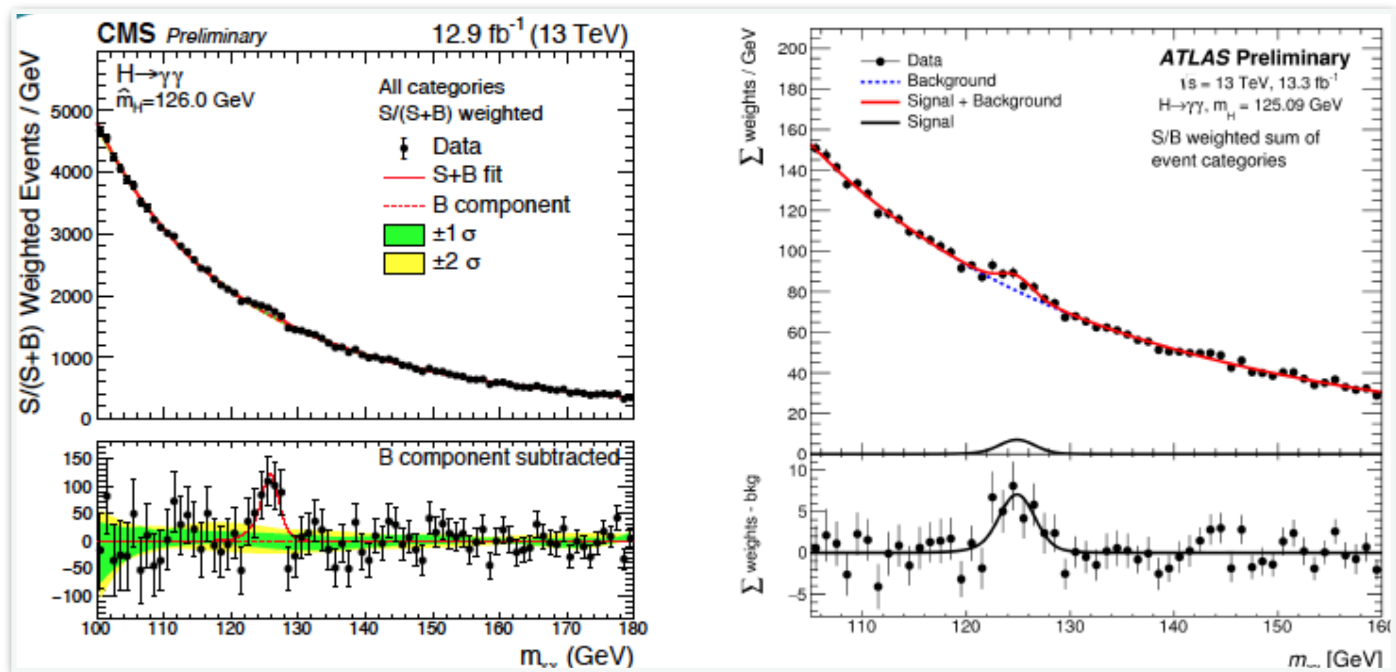
Higgs as a probe of new physics

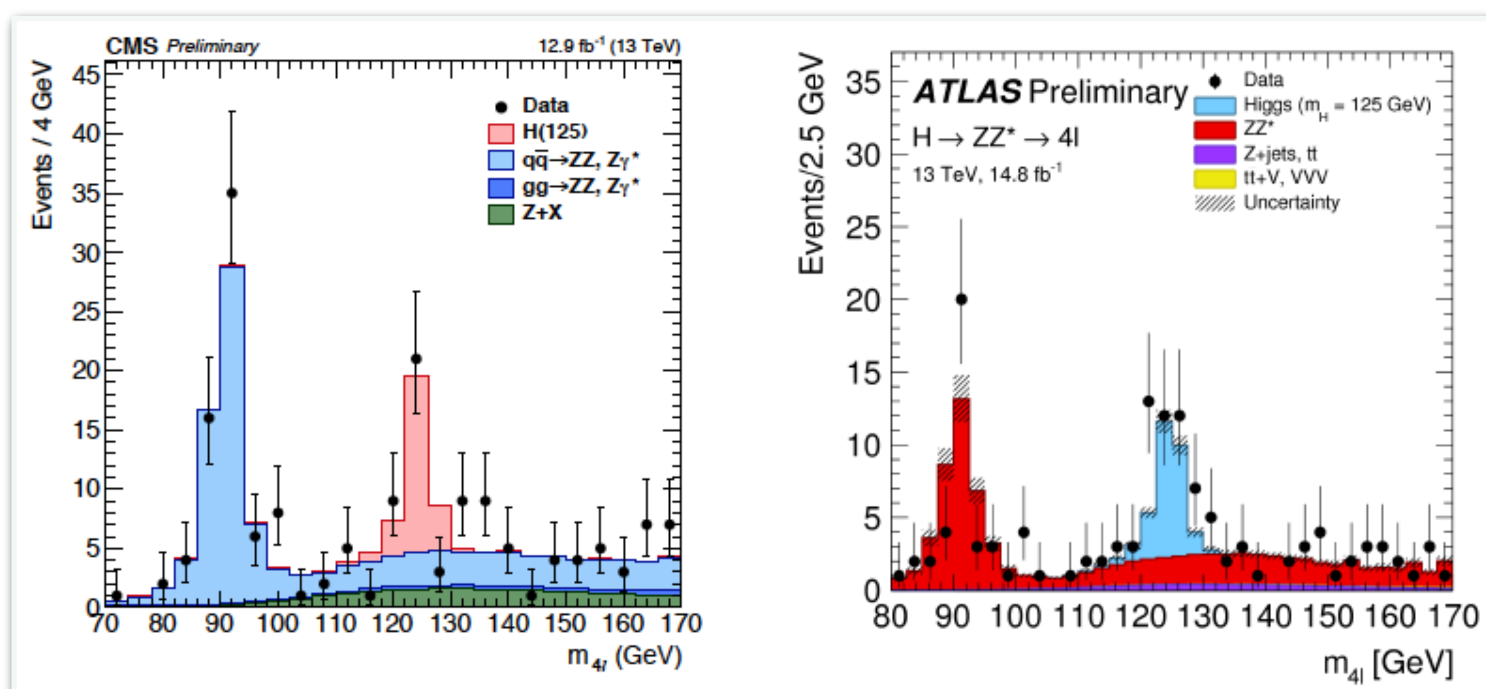
- Many decay modes accessible: can test Standard Model BR pattern



Access to Higgs couplings

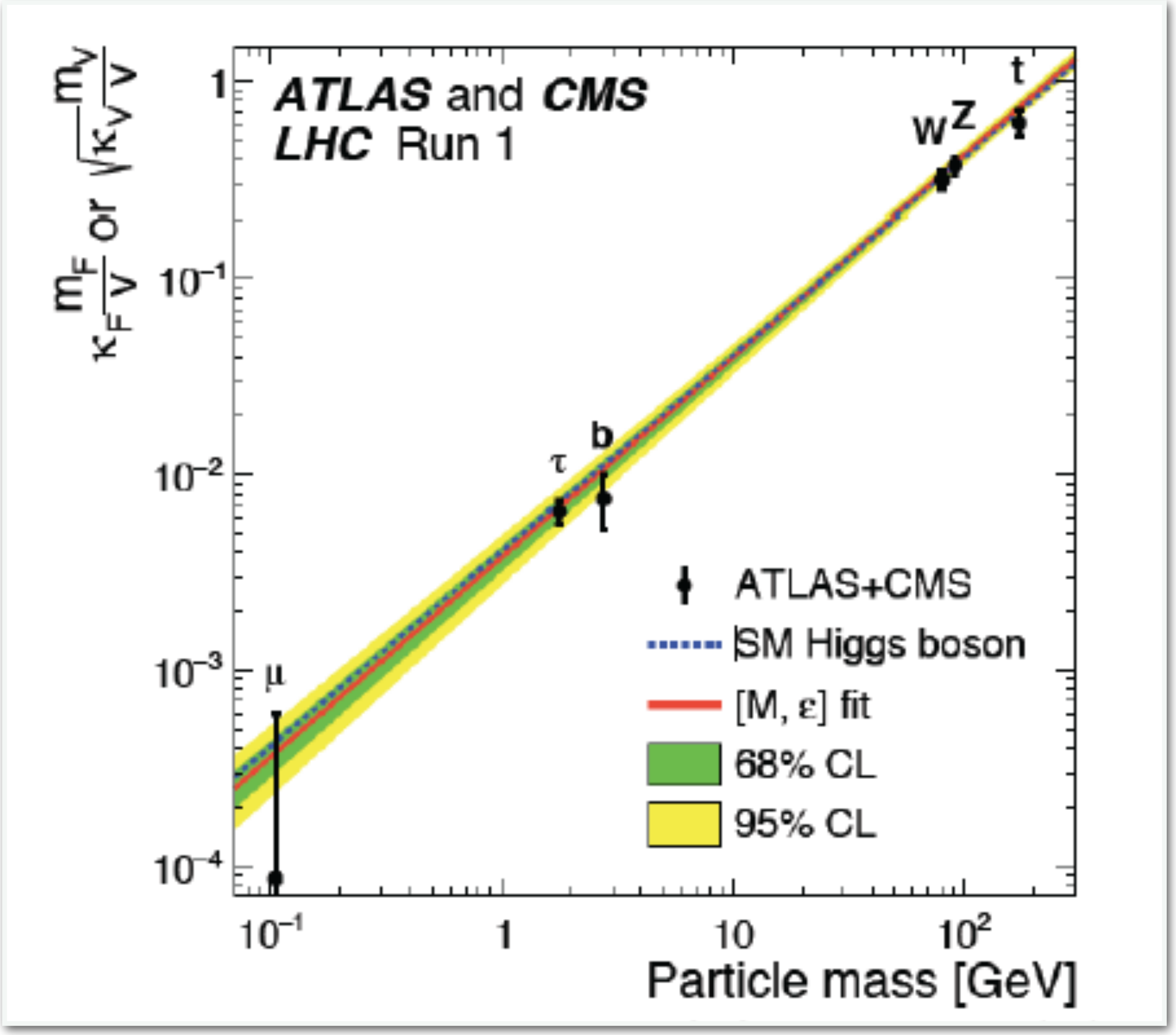






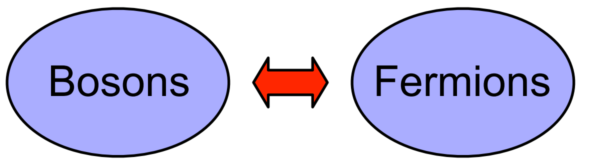
Higgs as a probe of new physics

- Higgs couplings to heavy particles consistent with SM prediction (~10% level)
- Room for surprises in:
  - coupling to light particles
  - SM forbidden decays: $h \to \tau\mu, \ldots$
- Major area of activity for Run 2
- Opportunity for Precision / Intensity frontier

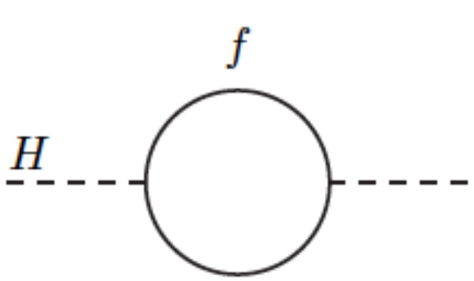


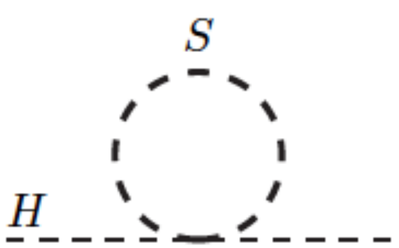
Supersymmetry searches

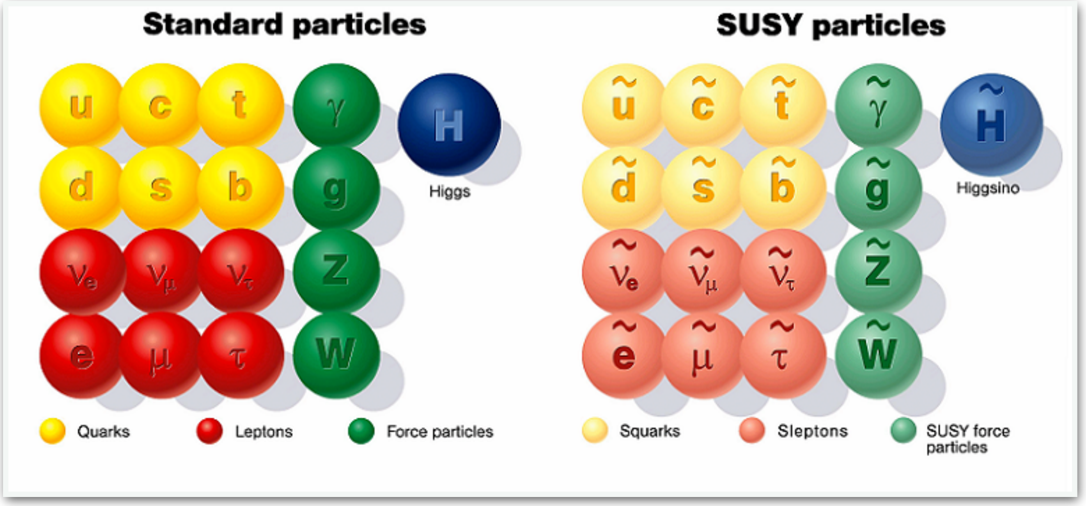
- Supersymmetric models are very appealing and have received much attention because they can potentially lead to:



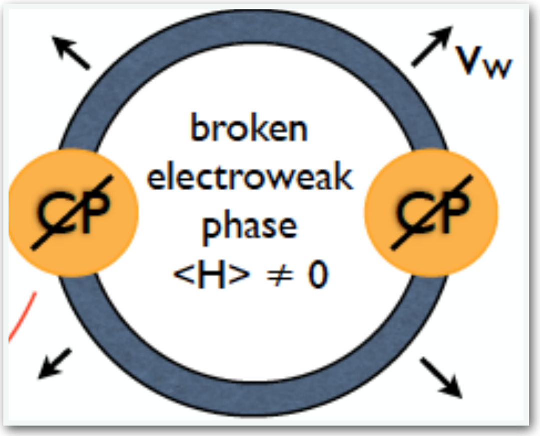
- Stability of G_{Fermi}/G_{Newton}







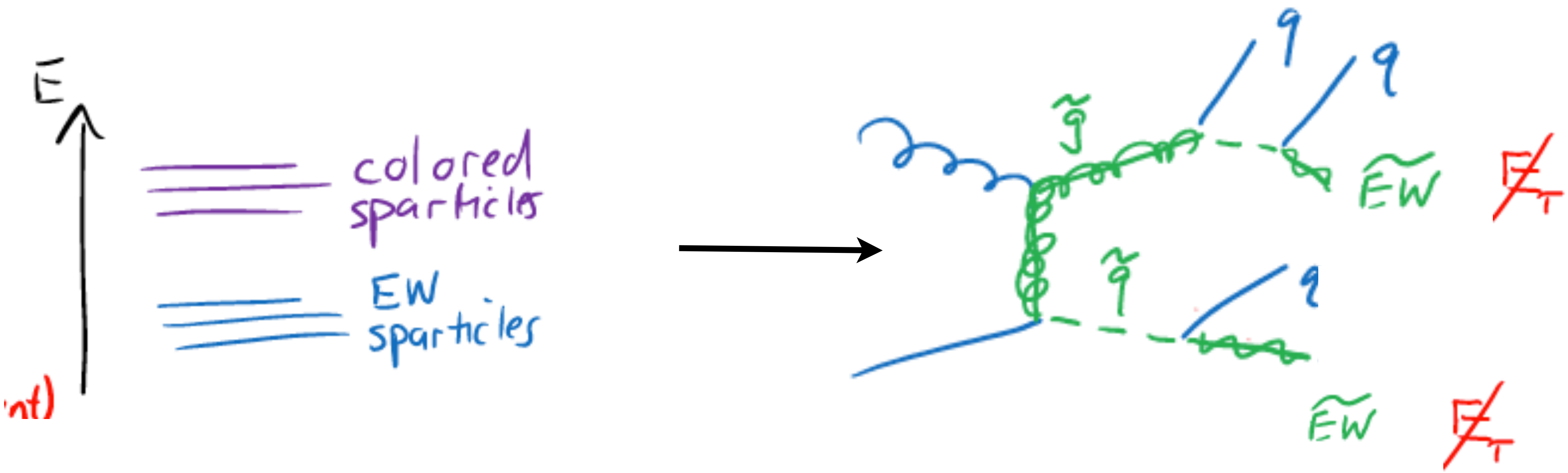
- Dark matter (neutralinos)
- Gauge coupling unification
- Baryon asymmetry



T~O(100 GeV)

Supersymmetry searches

- SUSY signatures at the LHC depend on assumed s-particle spectrum

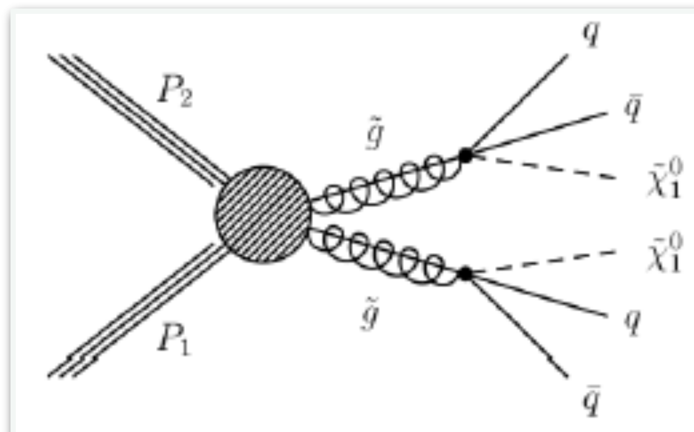


R. Sundrum
ICHEP 12

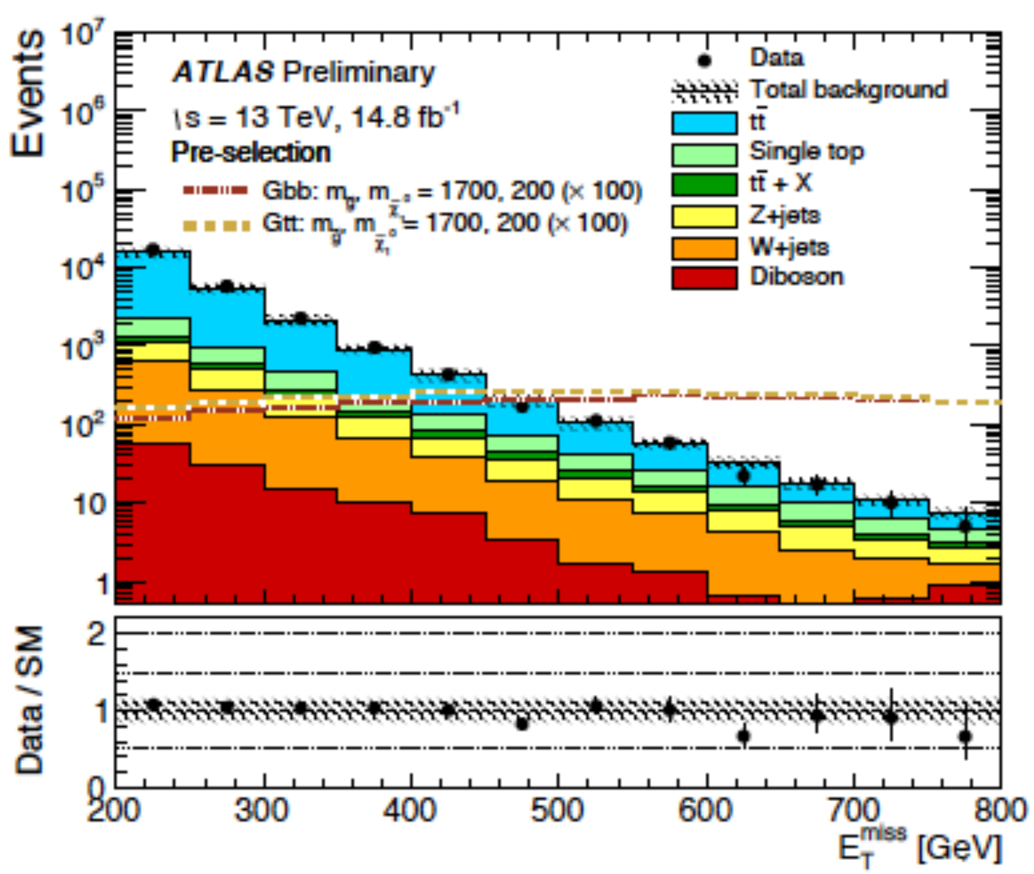
- Highest rate expected in production and decay of gluinos and squarks
- Missing E_T is key part of signatures

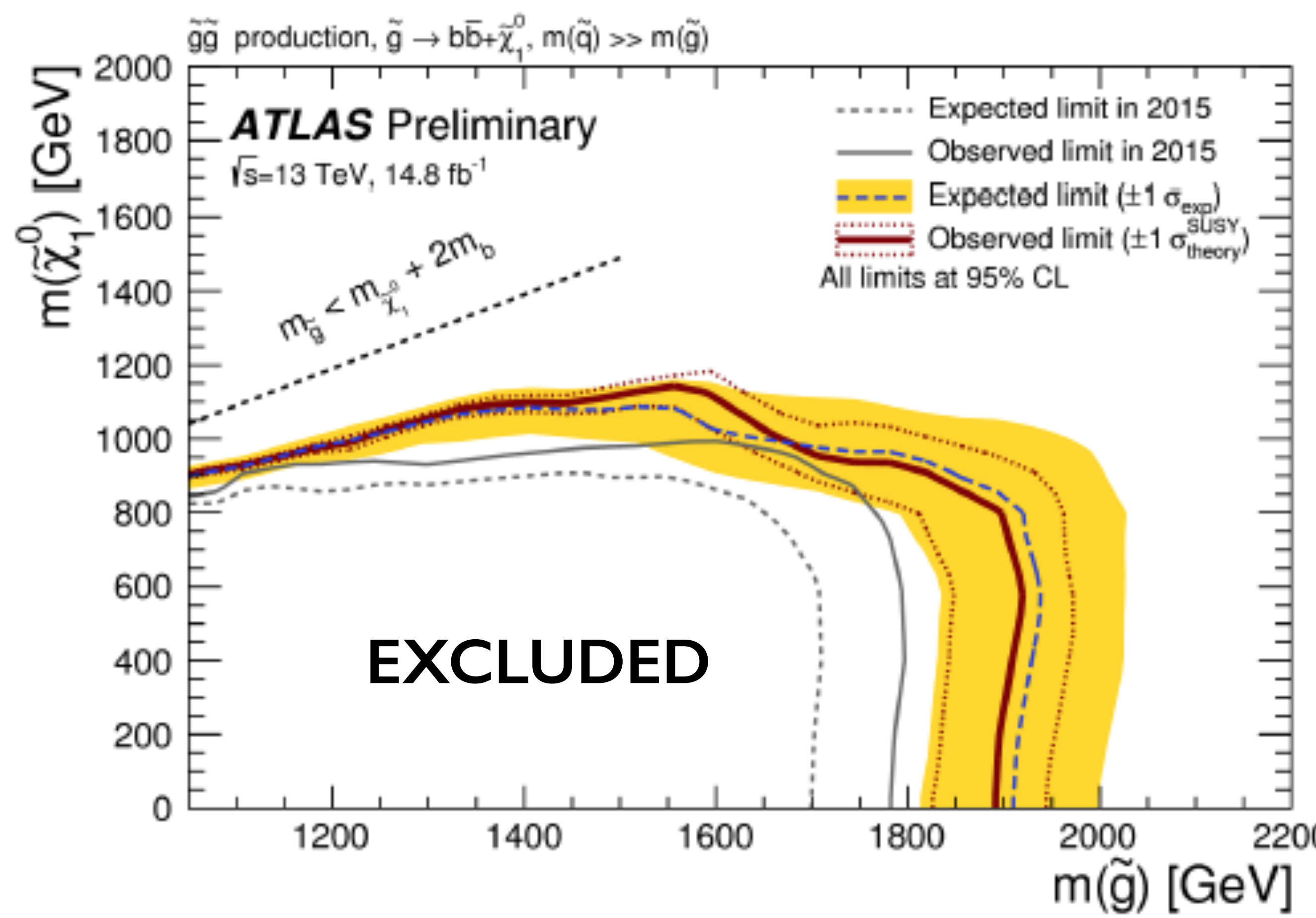
Supersymmetry searches

- Example: gluino pair production and decay



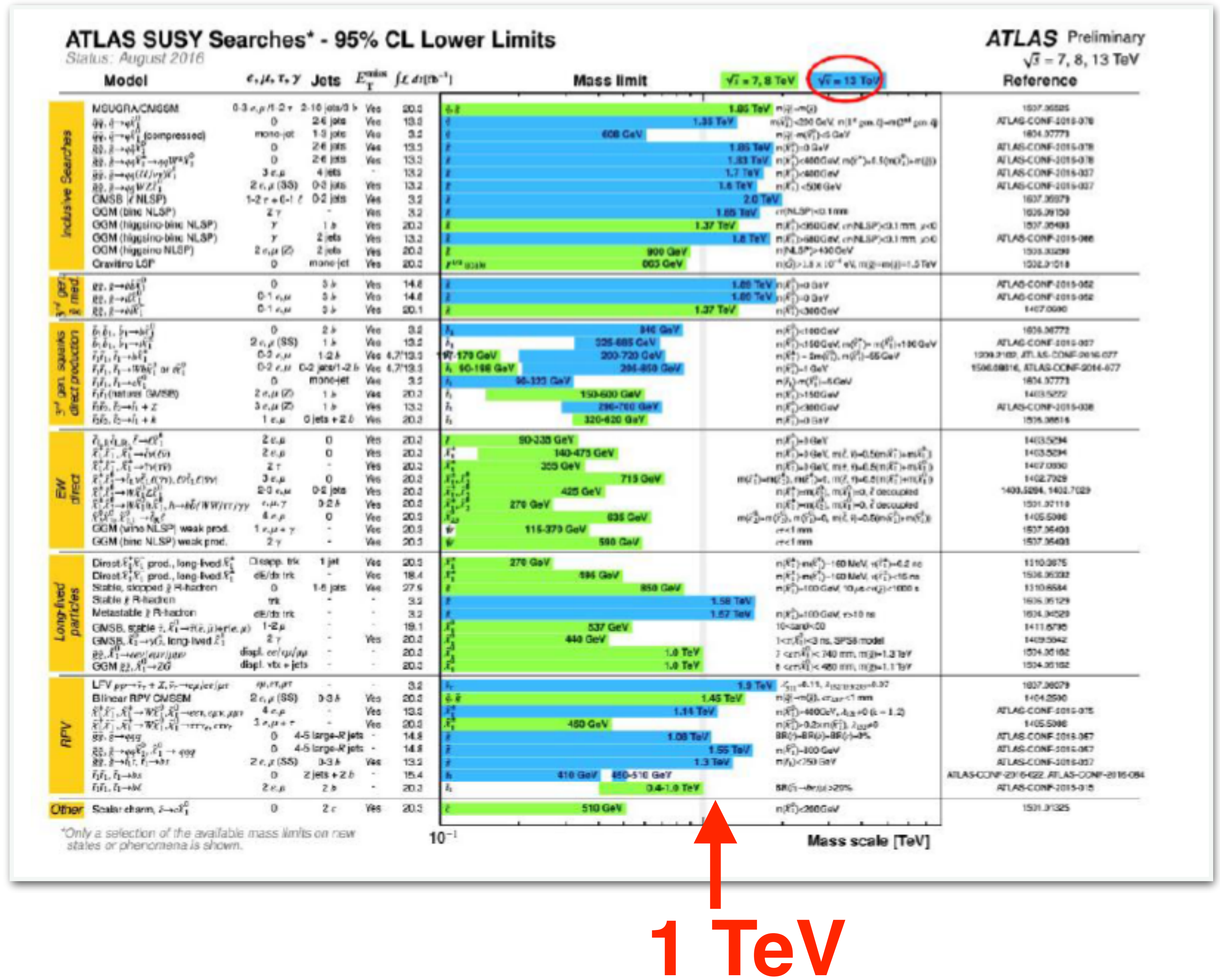
ATLAS-CONF-2016-052





Supersymmetry searches: summary

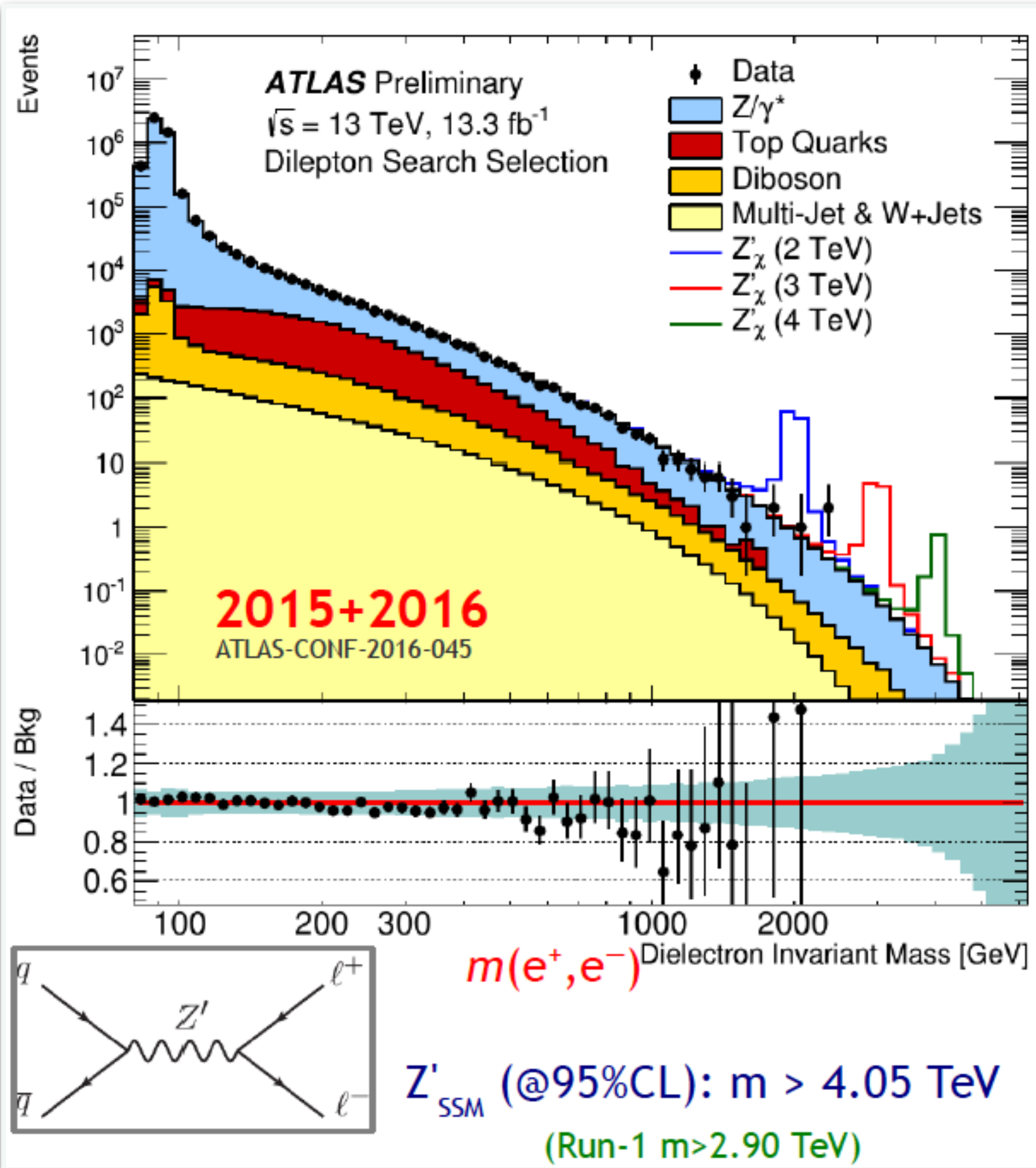
- Direct searches ⇒
  - SUSY mass scale ~ TeV or higher
  - or compressed spectrum: small s-particle splittings hard to access (smaller p_T)



- Direct searches + light Higgs ⇒ simplest SUSY scenarios under pressure

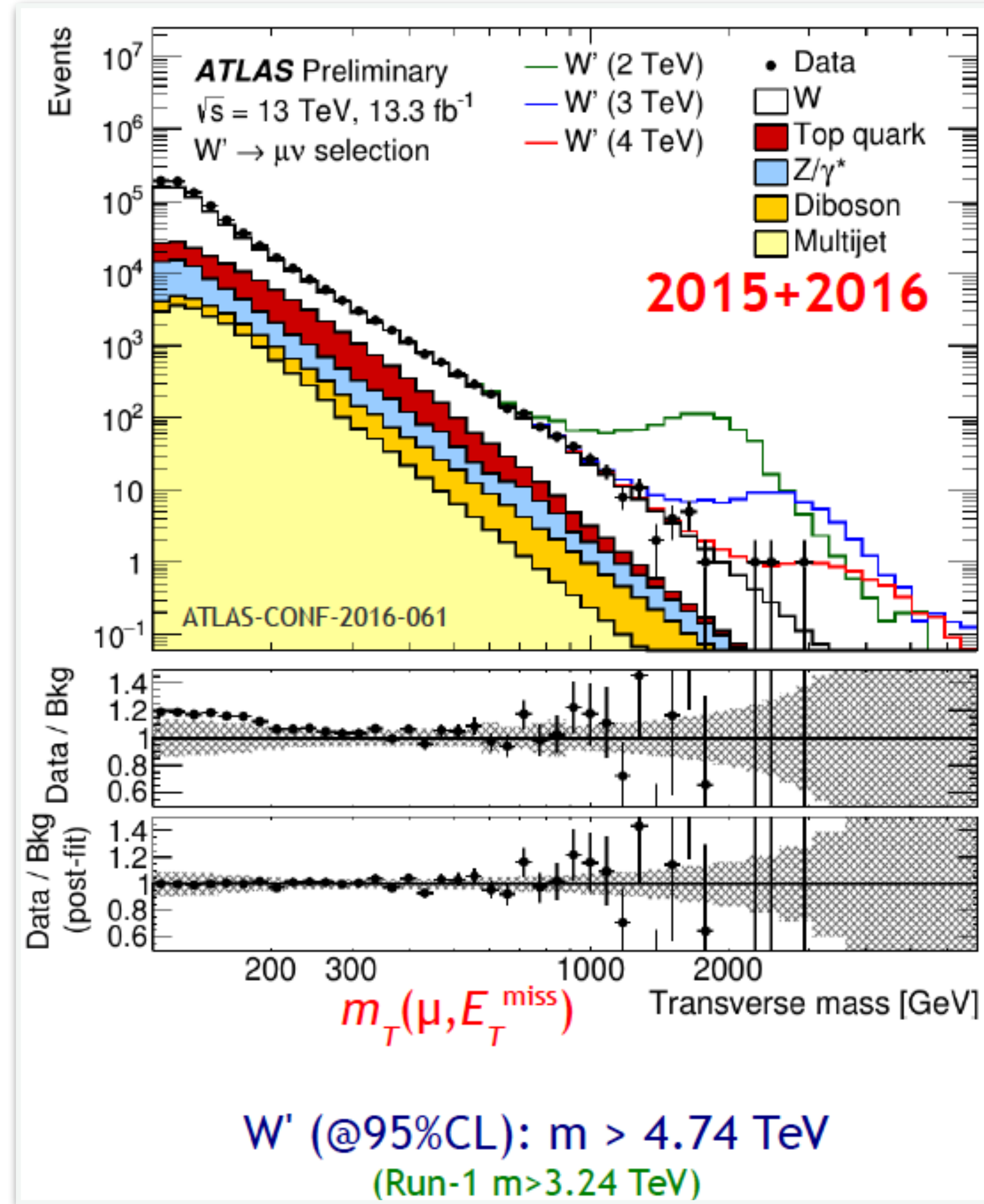
New resonances: di-lepton

ATLAS-CONF-2016-045



$pp \rightarrow e^{+}e^{-} + X$

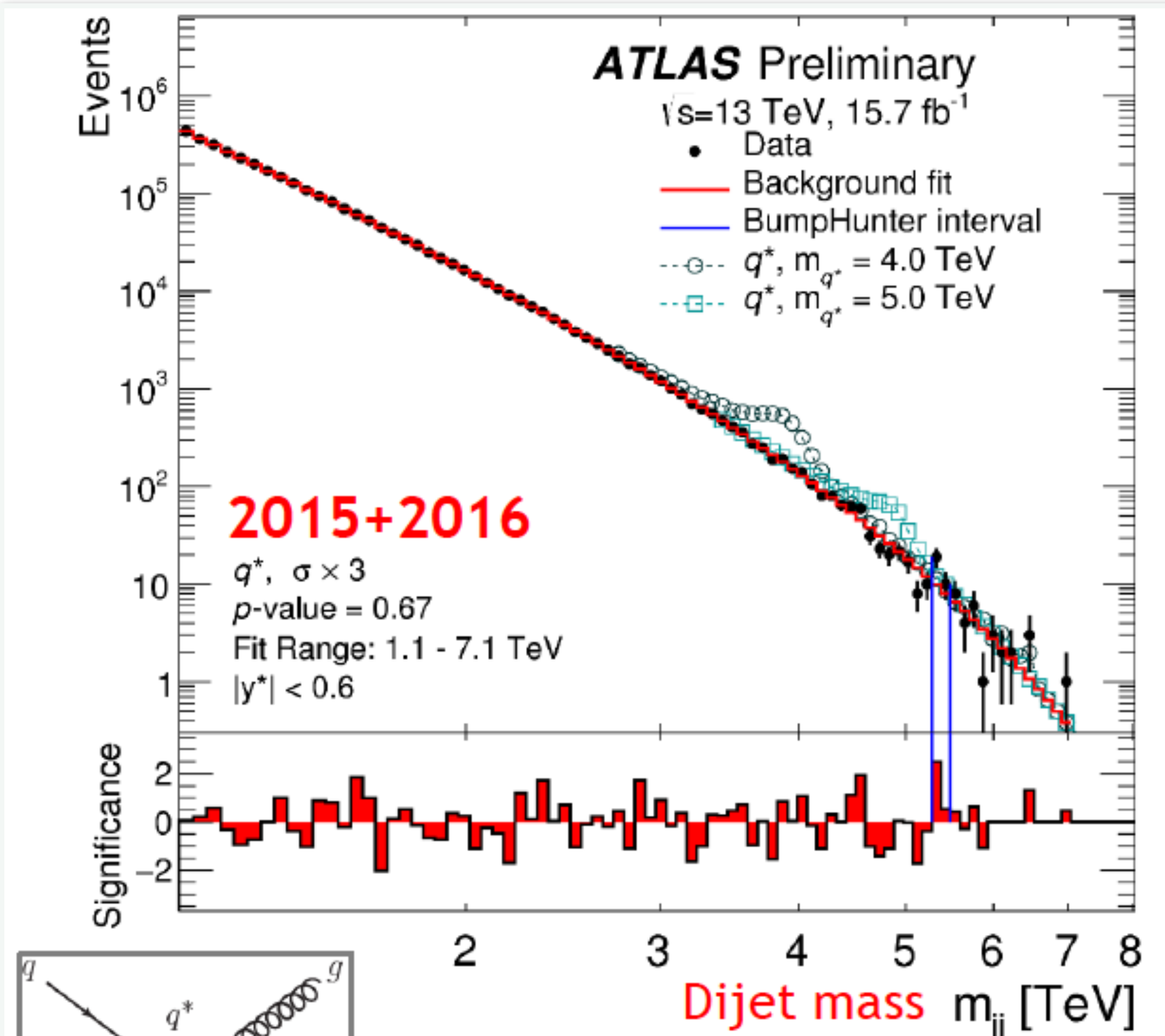
ATLAS-CONF-2016-061



$pp \rightarrow e\,\nu + X$

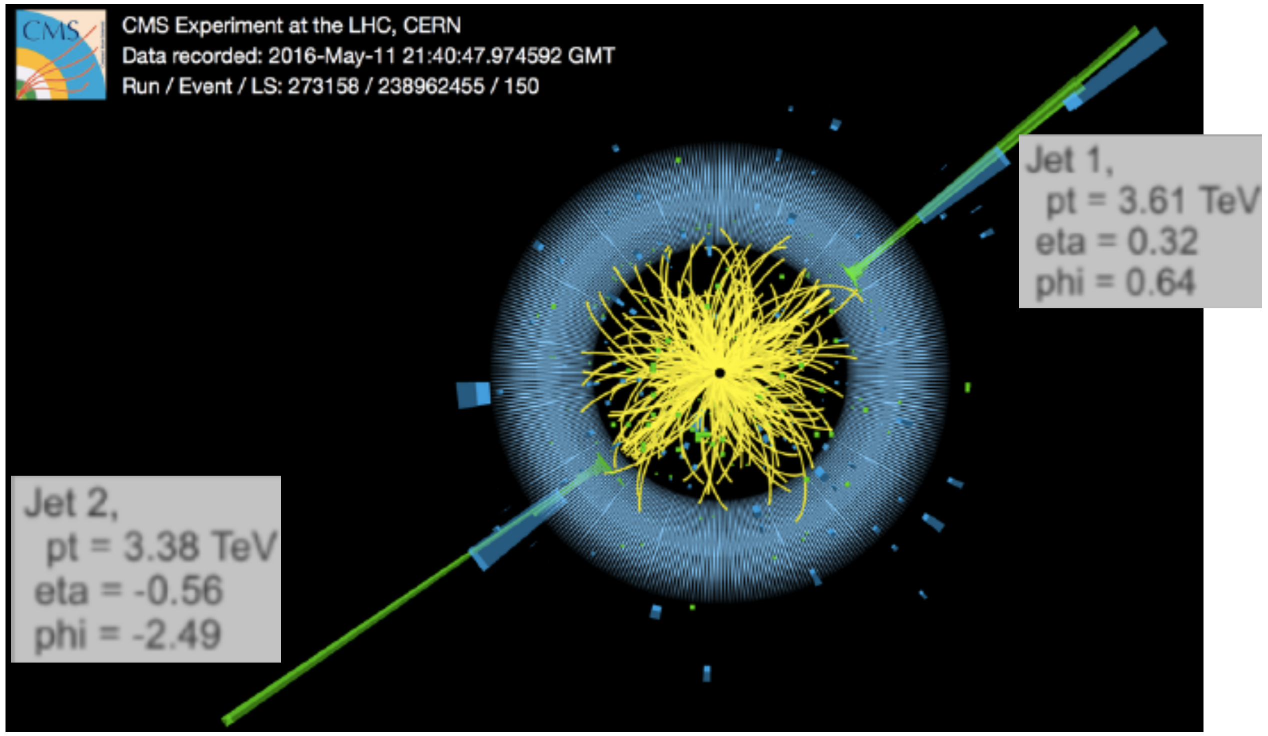
New resonances: di-jet, di-photon

ATLAS-CONF-2016-060



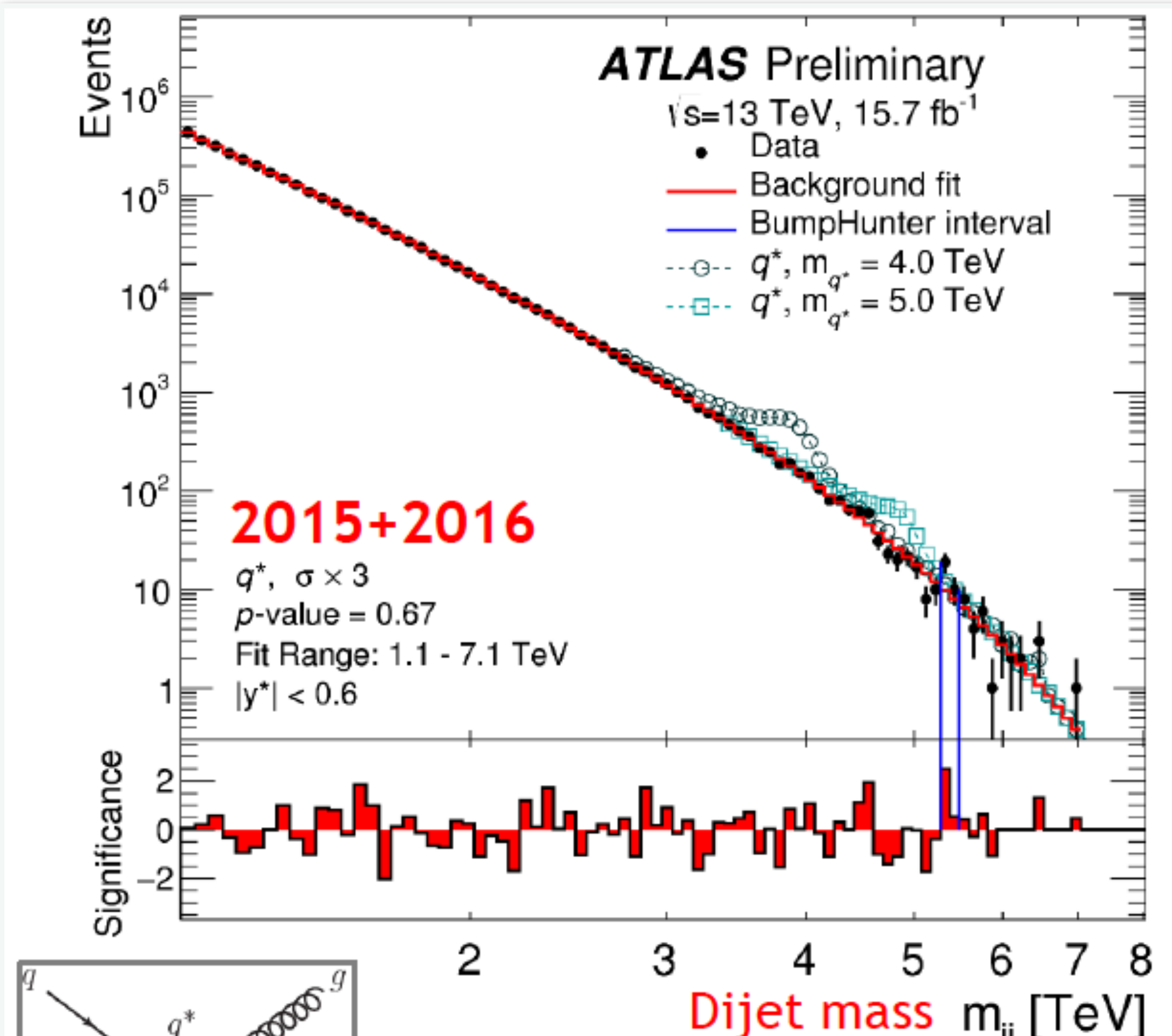
Examples (@95% CL):
$m(q^*) > 5.6$ TeV
(ATLAS Run-1: 4.1 TeV)

Highest mass di-jet event at CMS: 7.7 TeV



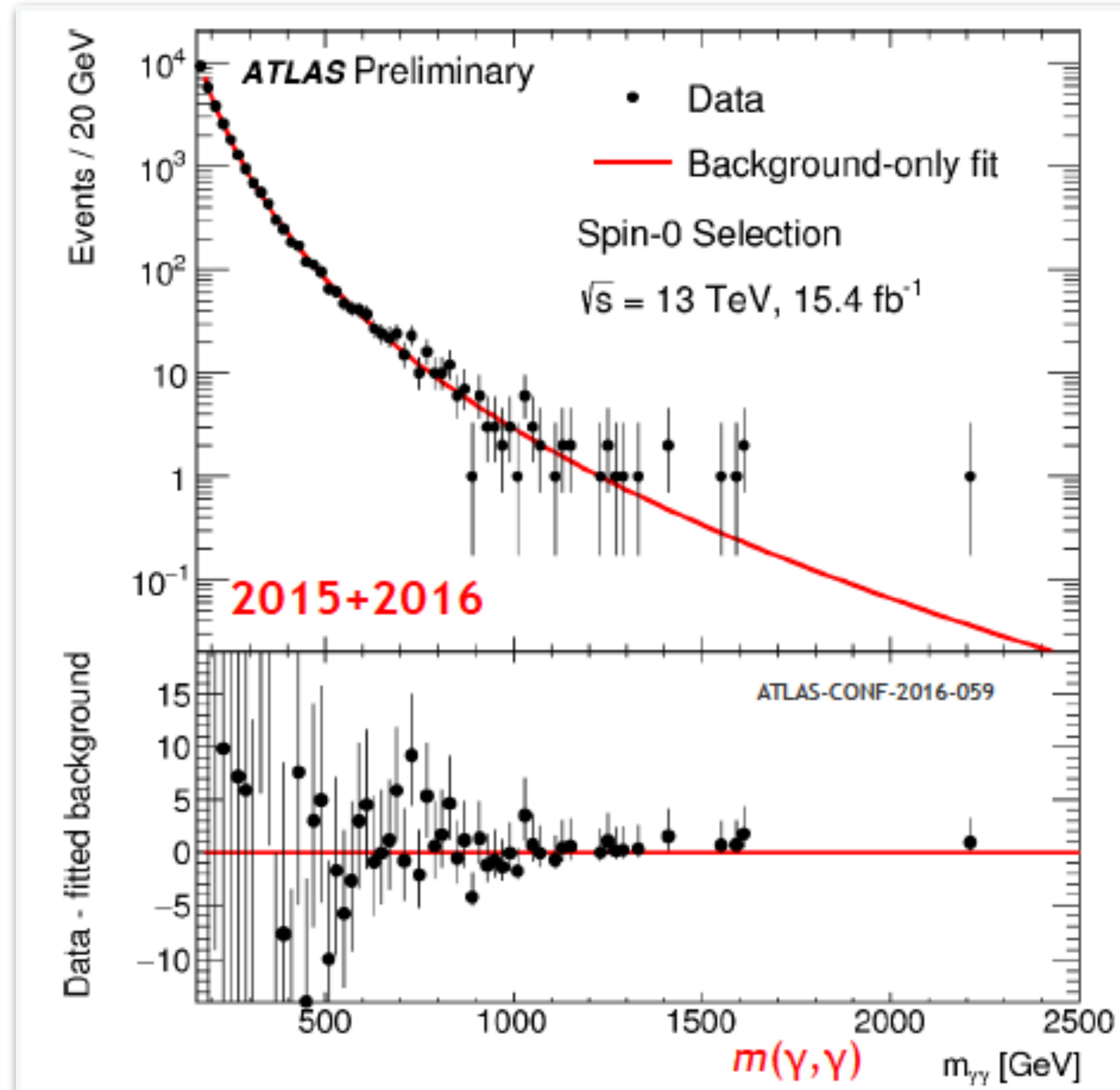
New resonances: di-jet, di-photon

ATLAS-CONF-2016-060



Examples (@95% CL):
m(q*) > 5.6 TeV
(ATLAS Run-1: 4.1 TeV)

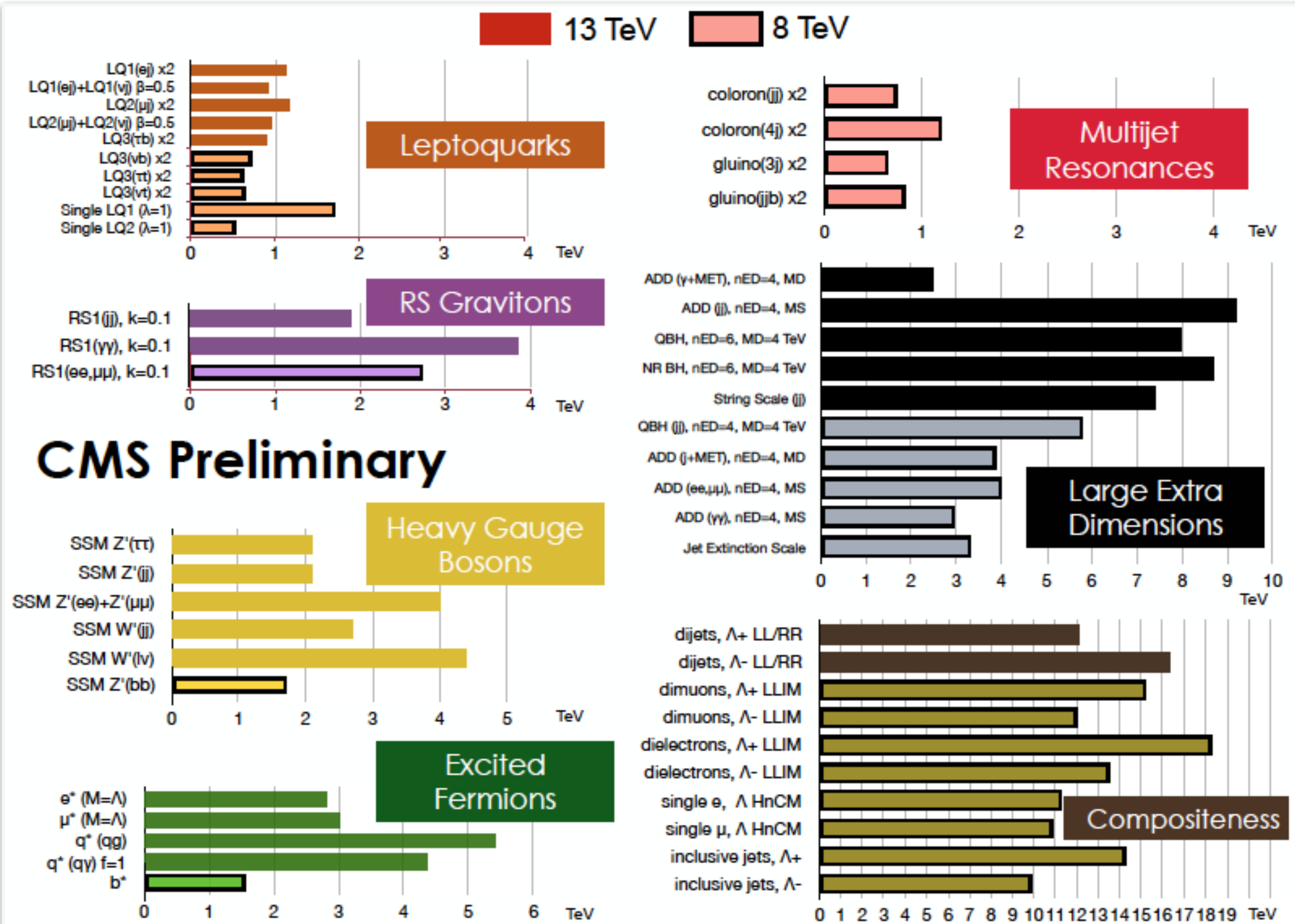
ATLAS-CONF-2016-059



With 2015+2016 data:
- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

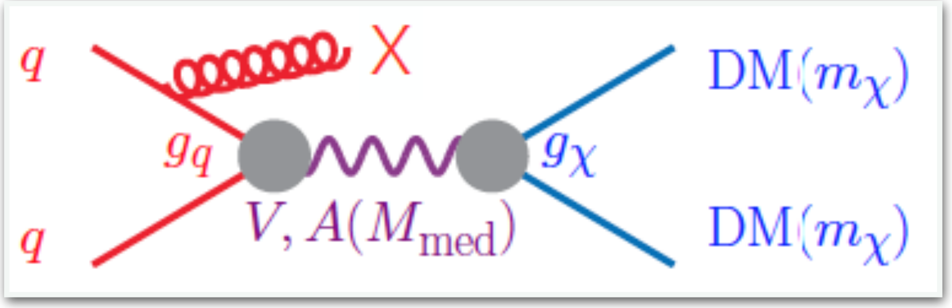
X(750) is gone

Summary of non-SUSY searches



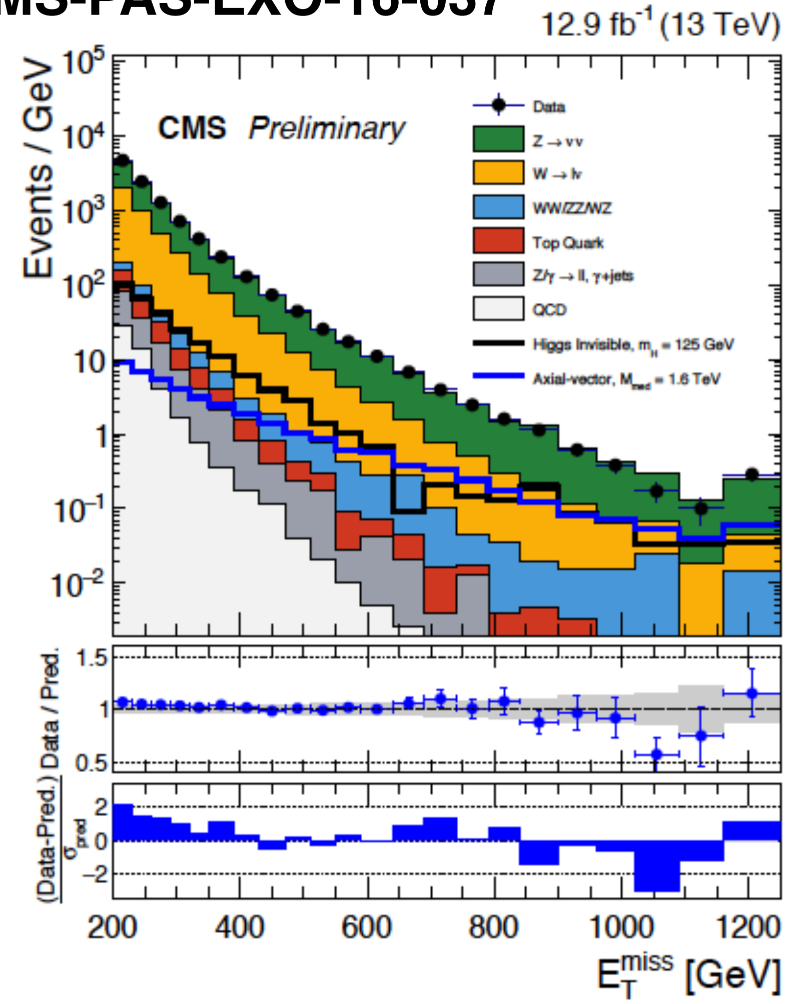
Dark matter at the LHC

- Signature: pp → X + missing E_T ("mono-X" searches)

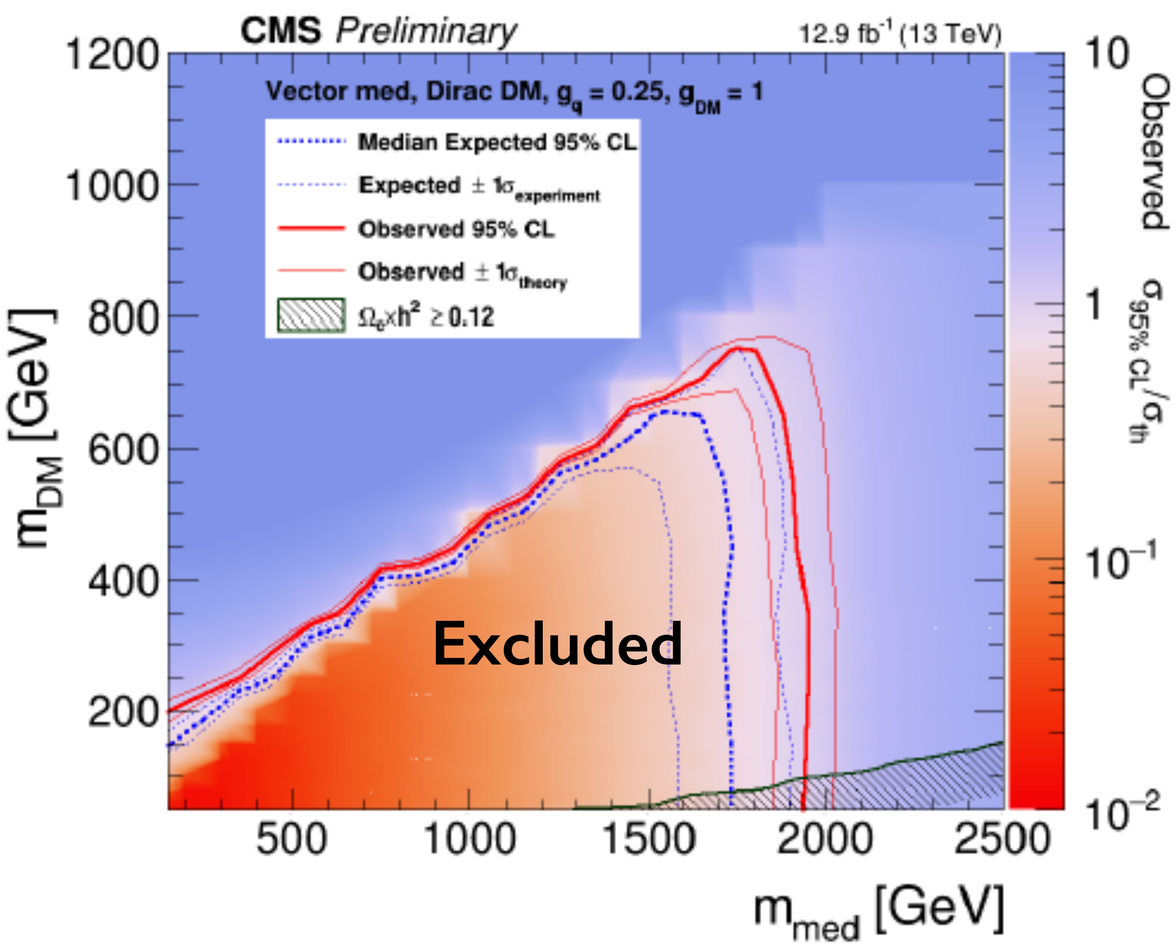


Irreducible background:
pp → Z (νν) + jets

CMS-PAS-EXO-16-037

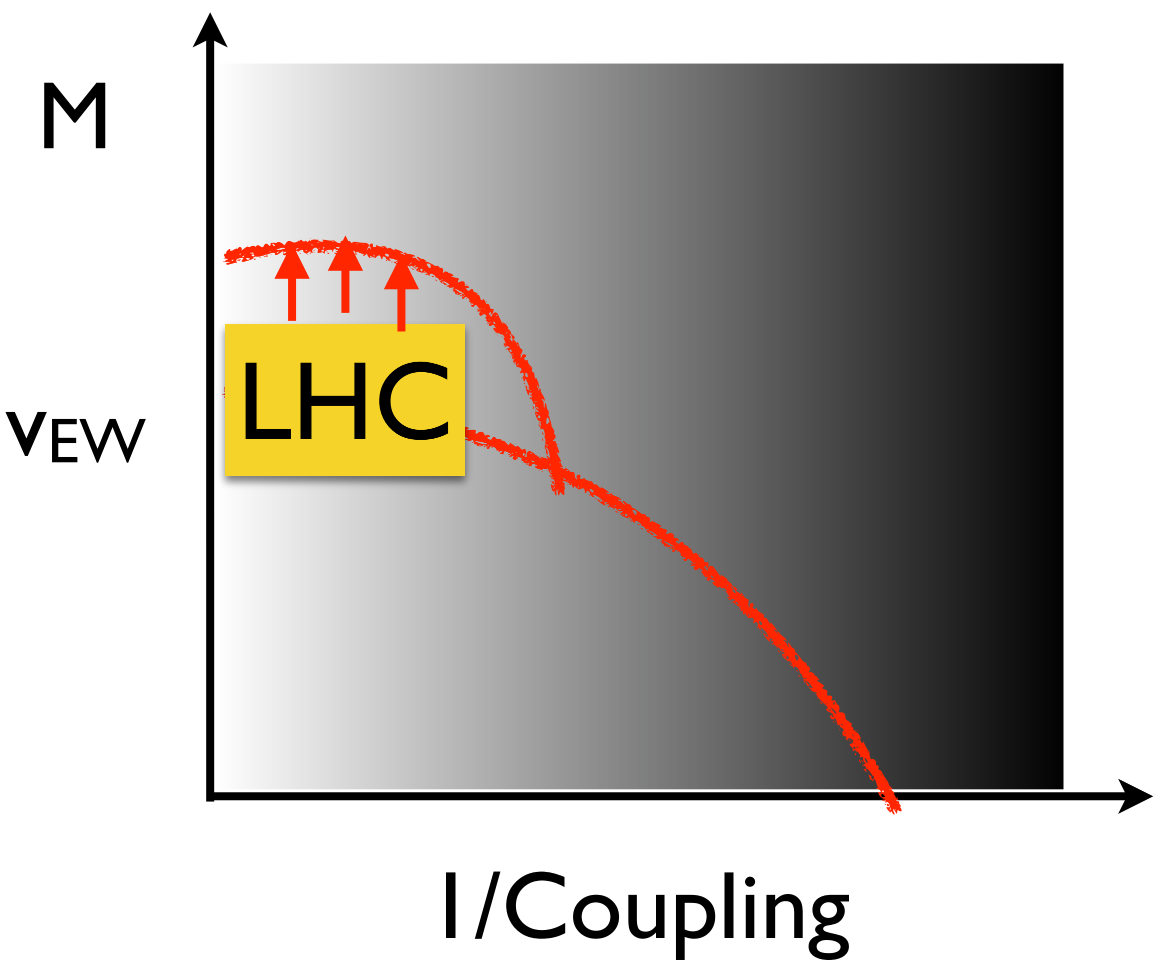


→



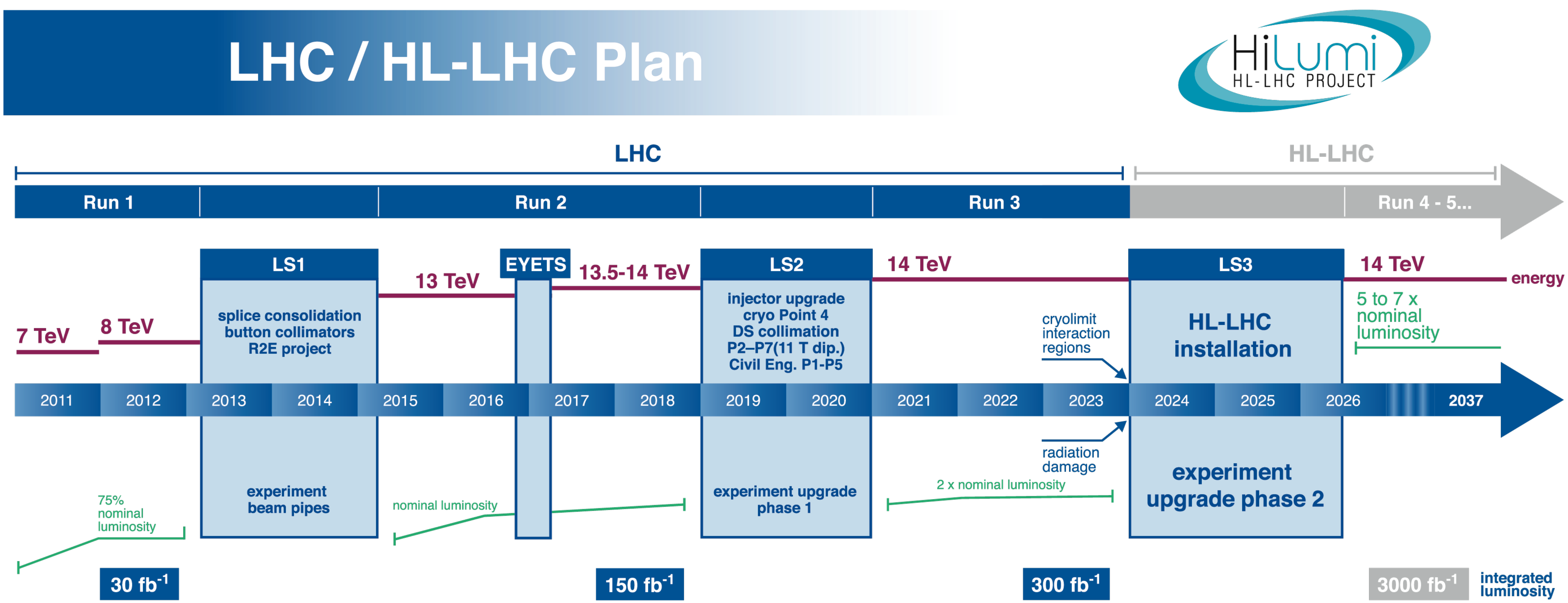
Energy frontier summary

- Main messages
  - Higgs at 125 GeV: major discovery and great new tool to search for new physics
  - Simplest scenarios of new physics pushed to TeV scale and beyond



Energy frontier outlook

- Optimistic outlook: only small fraction (~2%) of total expected LHC + High Luminosity LHC data-set has been delivered and analyzed

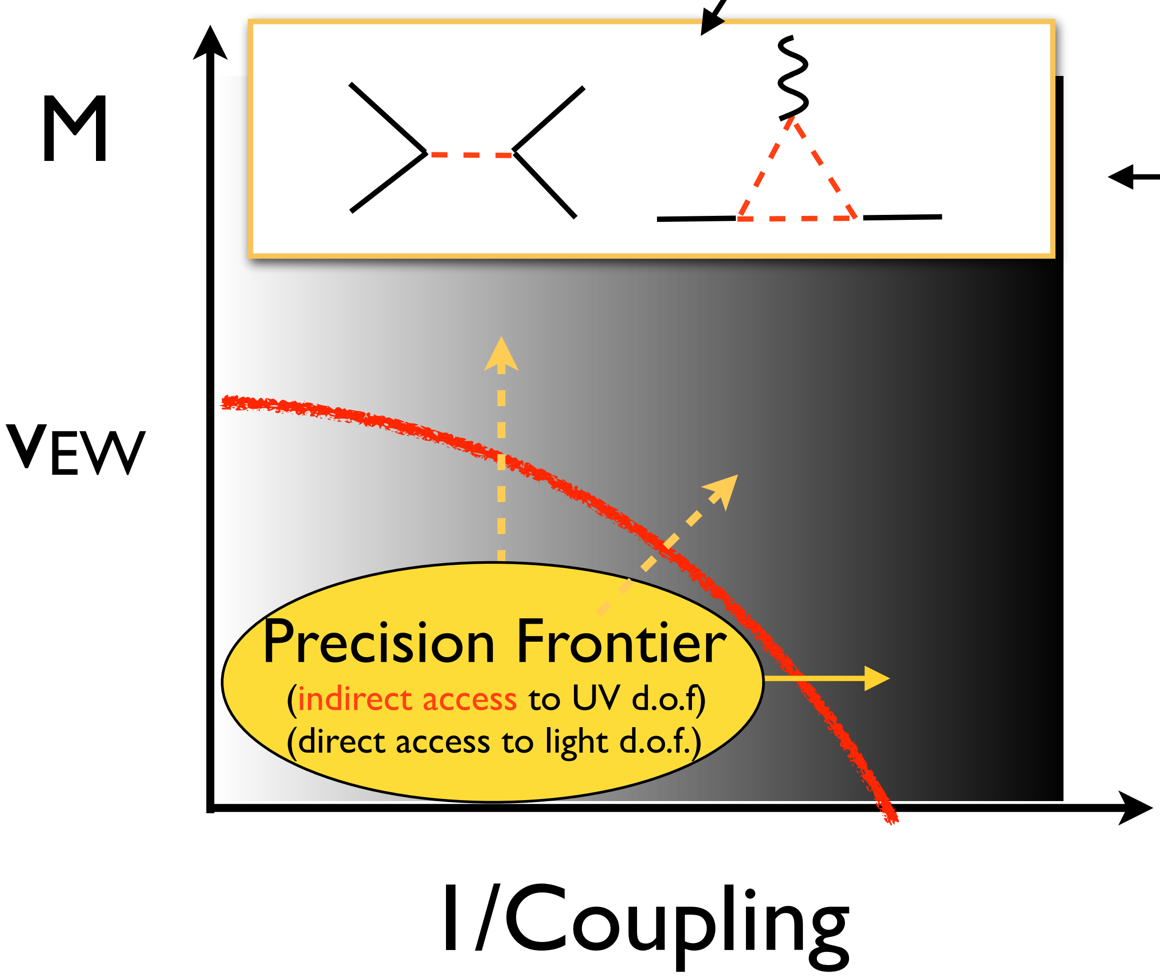


Precision Frontier Searches

The precision frontier

- Three classes of new physics probes

1. Searches for rare or forbidden processes that probe approximate or exact symmetries of the SM: proton decay, $0\nu\beta\beta$, EDMs, $\mu\rightarrow e$, n-nbar oscillations, quark flavor violation, …

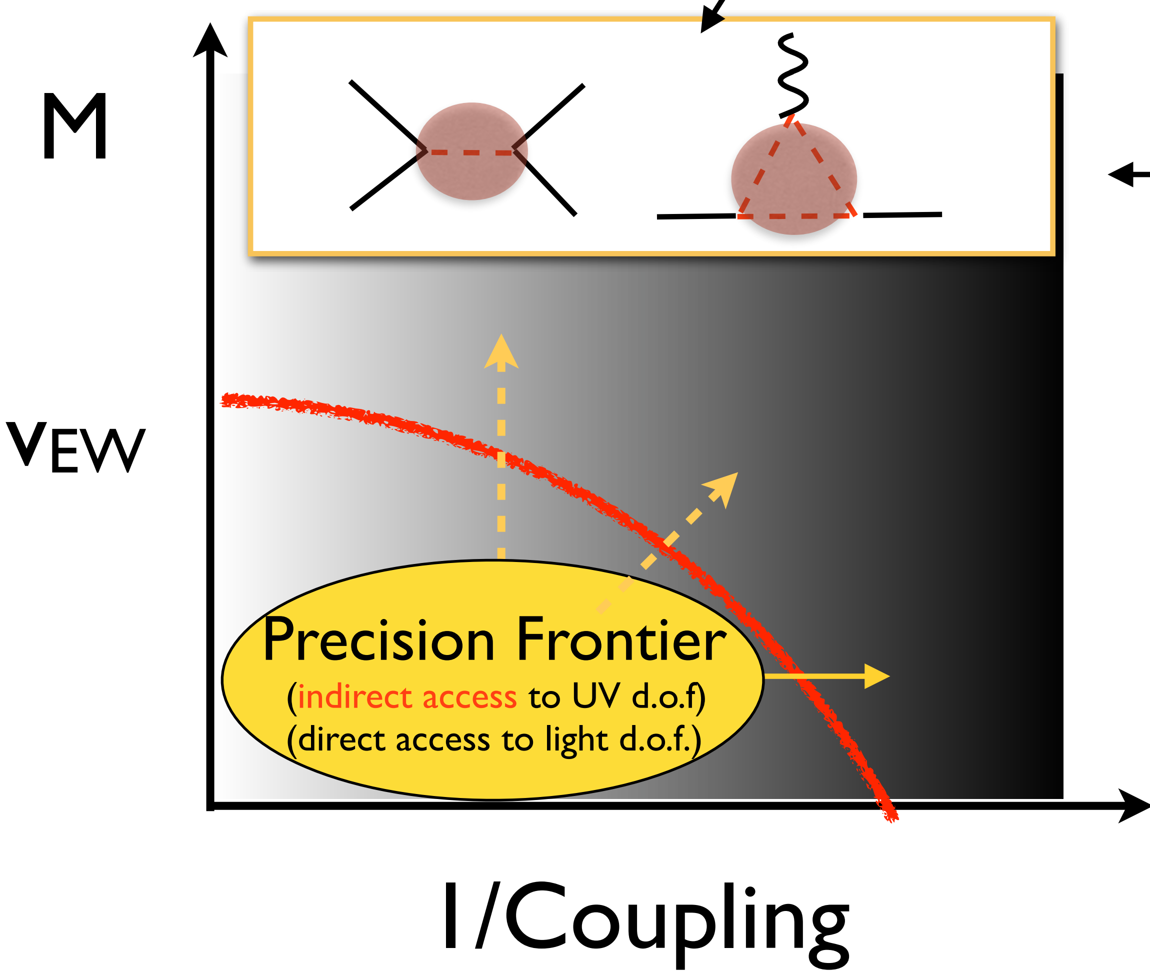


2. Precision measurements of SM-allowed processes: β-decays (neutron, nuclei), PVES, muon properties (lifetime, g-2), …

The precision frontier

- Three classes of new physics probes

1. Searches for rare or forbidden processes that probe approximate or exact symmetries of the SM: proton decay, $0\nu\beta\beta$, EDMs, $\mu\to e$, n-nbar oscillations, quark flavor violation, …



2. Precision measurements of SM-allowed processes: β-decays (neutron, nuclei), PVES, muon properties (lifetime, g-2), …

Sensitive to very high-scale new physics through tree-level and loop exchange of heavy particles, which leave behind a low-energy effective theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

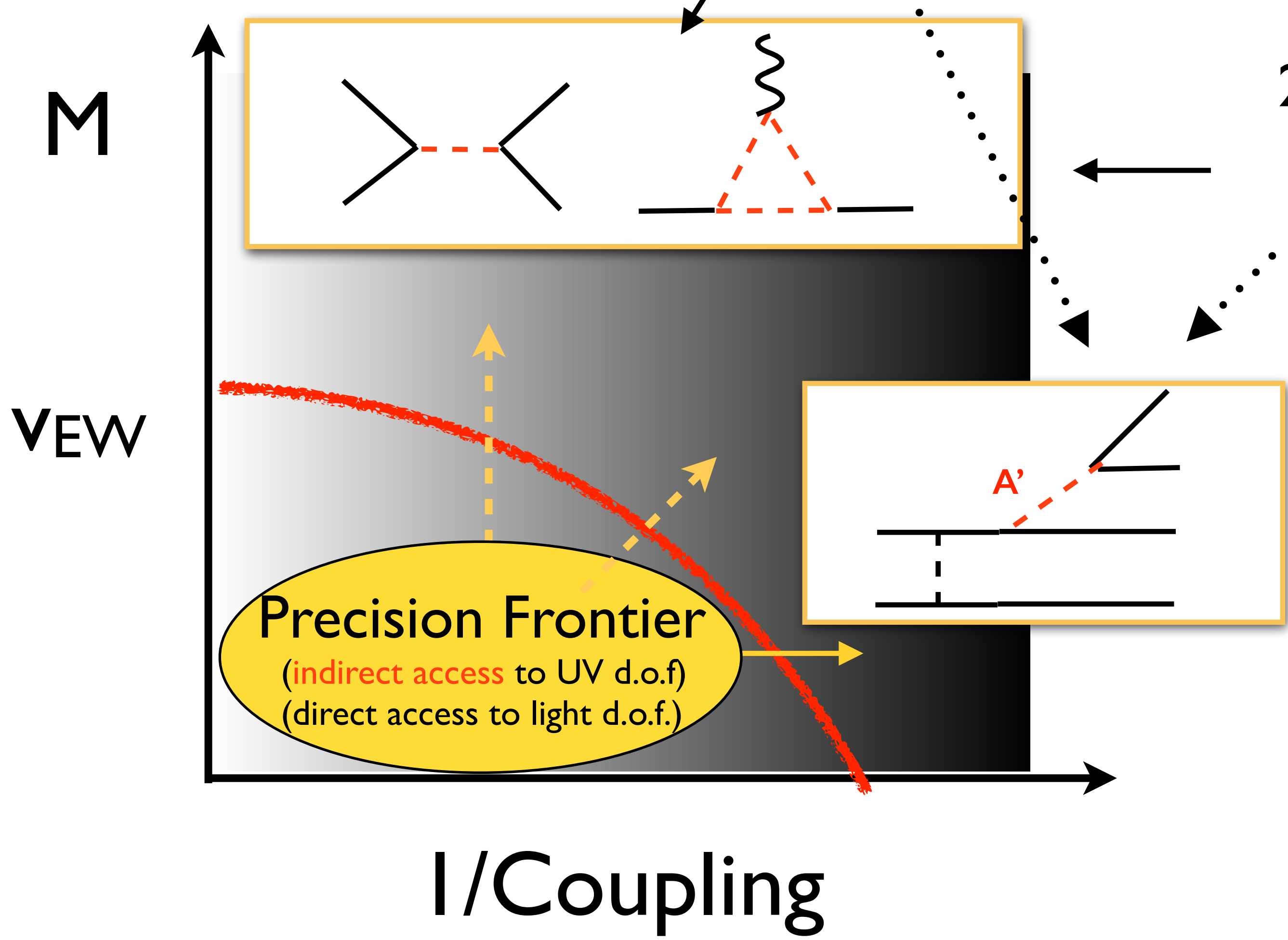
$[\,\Lambda \leftrightarrow M_{BSM}\,]$ $\quad C_i\,[g_{\rm BSM},\ M_a/M_b]$

The precision frontier

- Three classes of new physics probes

1. Searches for rare or forbidden processes that probe approximate or exact symmetries of the SM: proton decay, $0\nu\beta\beta$, EDMs, $\mu\rightarrow e$, n-nbar oscillations, quark flavor violation, …

2. Precision measurements of SM-allowed processes: β-decays (neutron, nuclei), PVES, muon properties (lifetime, g-2), …



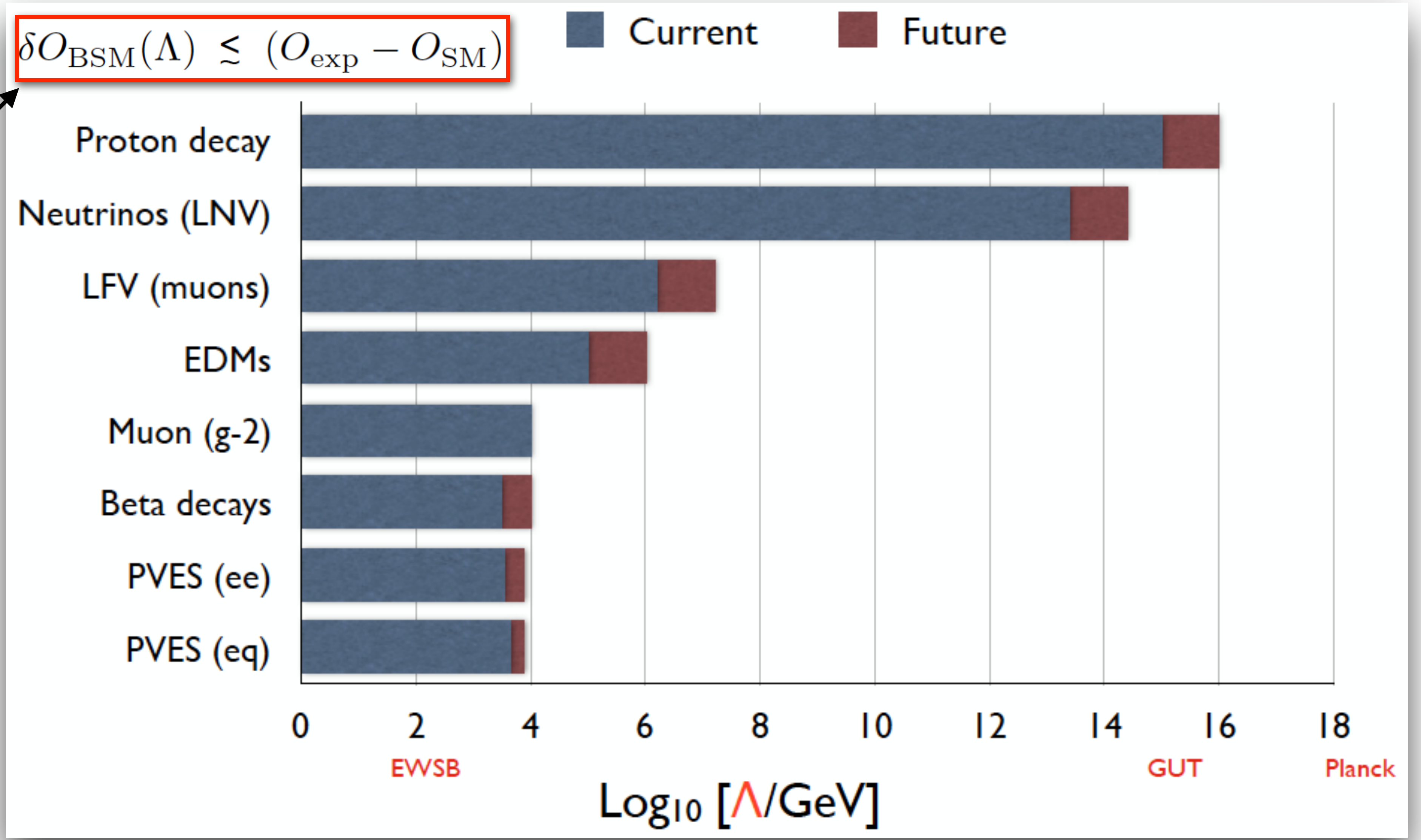
3. Direct measurements of properties of light and weakly coupled particles: active νs, sterile νs, dark photon, dark Higgs, axion, …

The precision frontier

- What do these probes contribute to the overall endeavor?
    - Discovery potential
        - new powerful ways to look for cracks in the SM
    - Diagnosing power
        - model-discrimination by combining several measurements
    - Access to physics needed to address big questions
        - unique sensitivity to symmetry breaking required by Sakharov conditions; sensitivity to dark sectors; …

Discovery potential

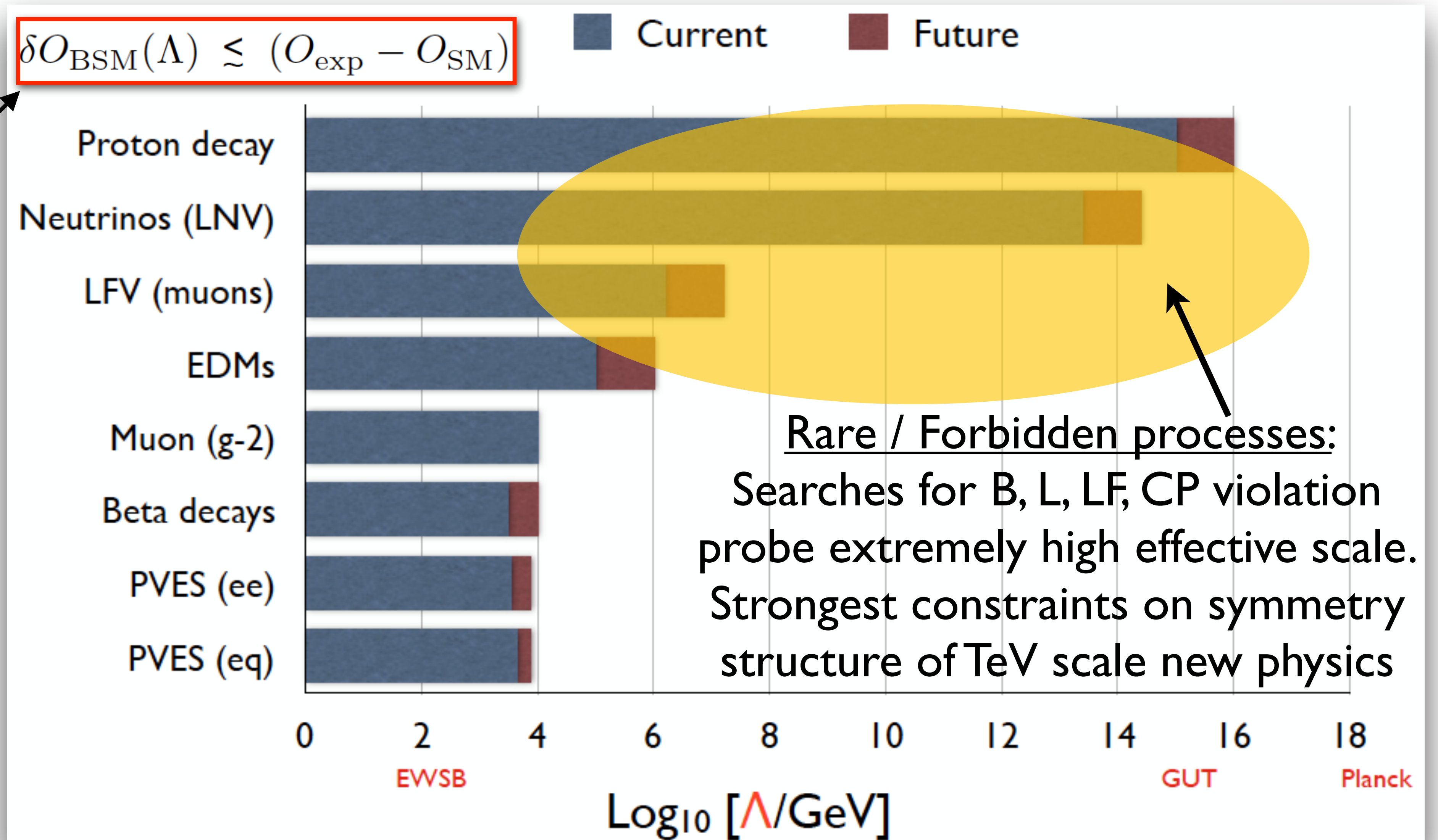
A rough indication of discovery potential is given by reach in Λ



Λ ~ *maximal* scale probed by a given measurement, assuming O(1) couplings (for all probes) and loop factor for g-2, EDMs, LFV.

Discovery potential

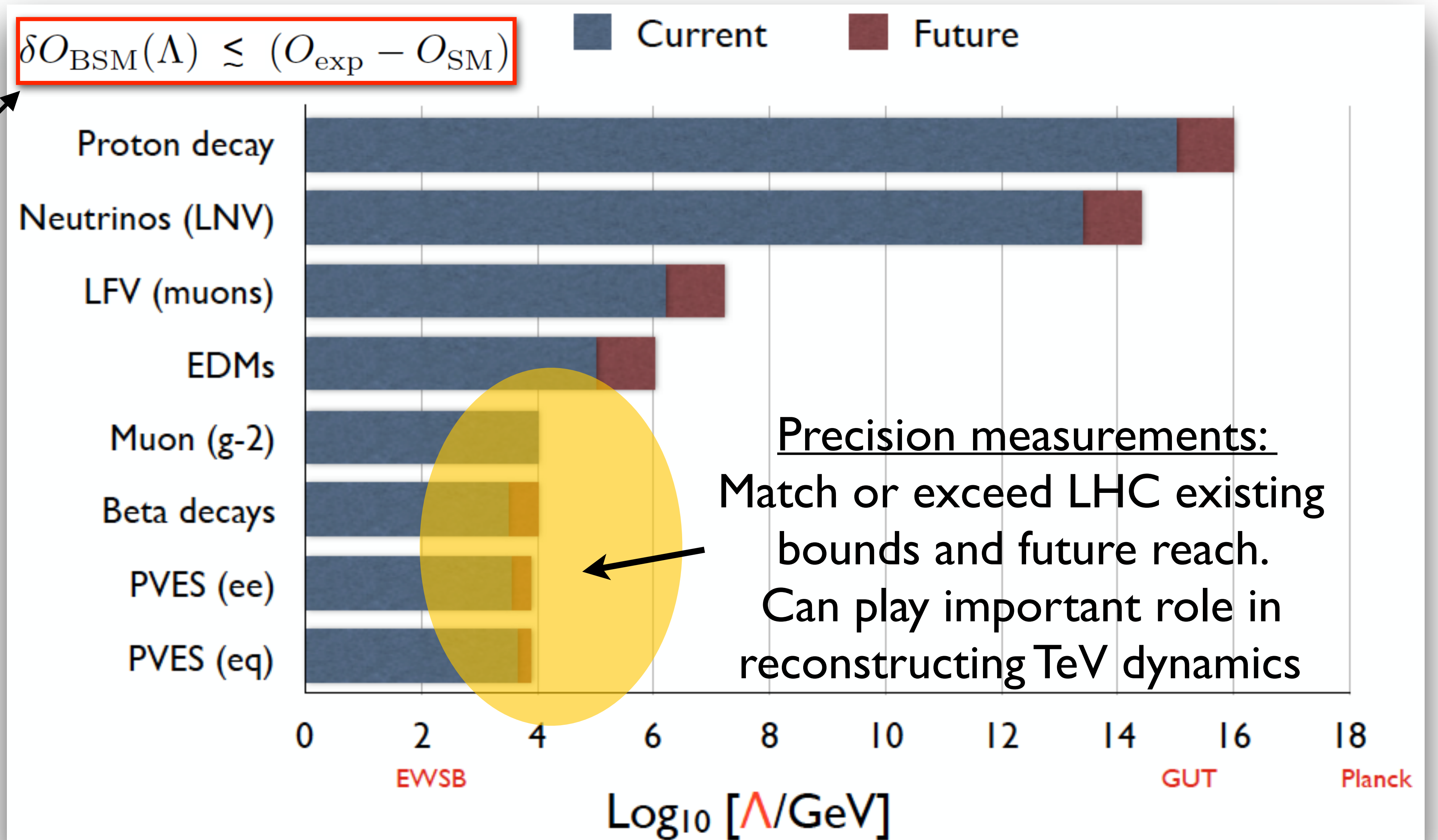
A rough indication of discovery potential is given by reach in Λ



Λ ~ *maximal* scale probed by a given measurement, assuming O(1) couplings (for all probes) and loop factor for g-2, EDMs, LFV.

Discovery potential

A rough indication of discovery potential is given by reach in Λ



Λ ~ *maximal* scale probed by a given measurement, assuming O(1) couplings (for all probes) and loop factor for g-2, EDMs, LFV.

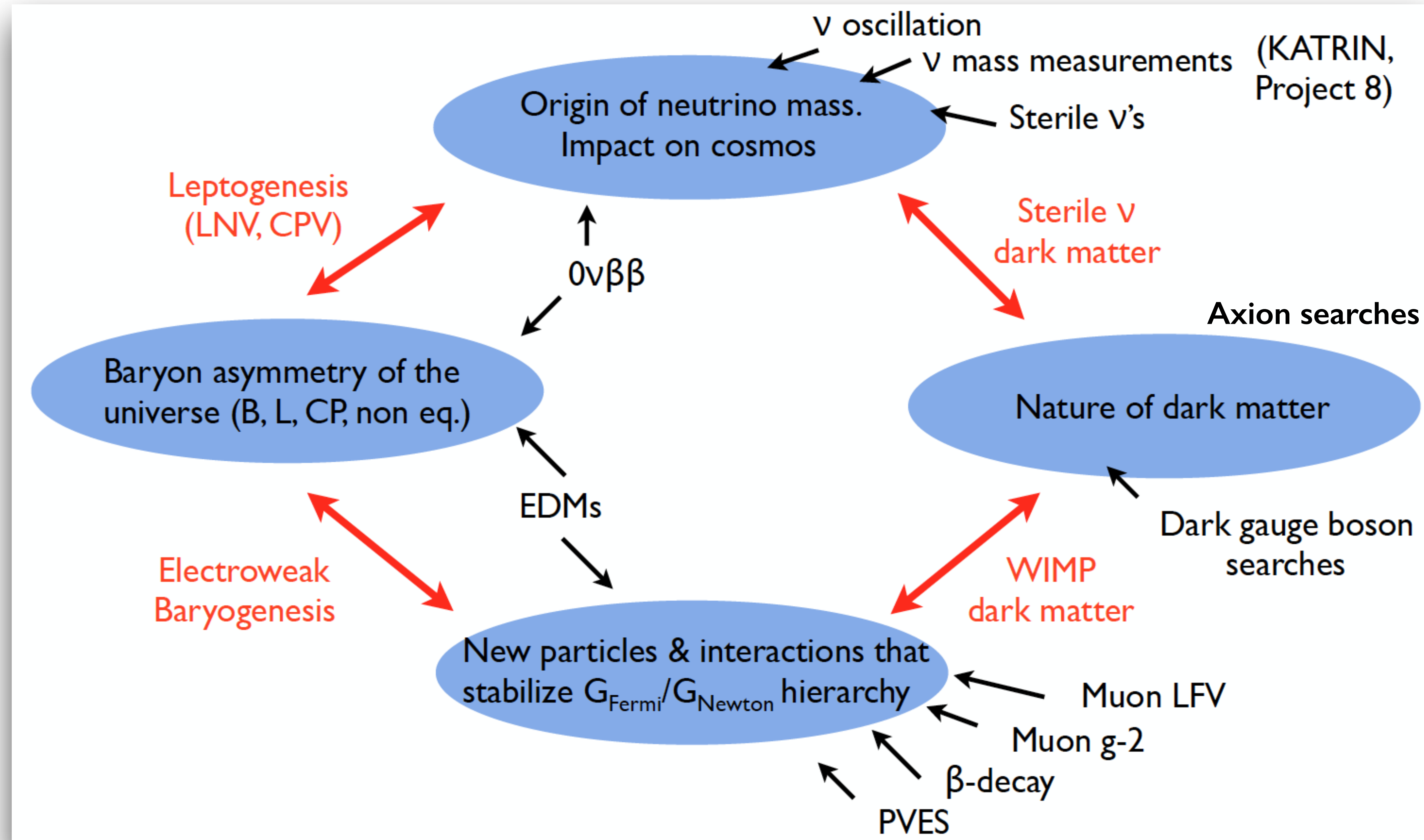
Diagnosing power

- Combination of several low-E measurements (+LHC)→ model-discriminating power

- Examples:
  - Multiple EDM searches → underlying source(s) of CPV
  - $0\nu\beta\beta$, mass scale, oscillations, LFV ($\mu \to e$, …) → neutrino mass model
  - Multiple PVES, β-decays → characterize new NC & CC interactions
  - …

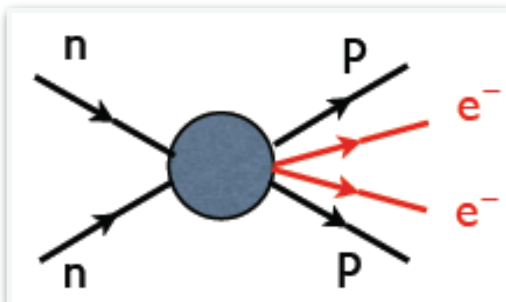
Connection to big questions

- Nuclear Science Fundamental Symmetries experiments cluster around big questions — often probing dynamics otherwise inaccessible

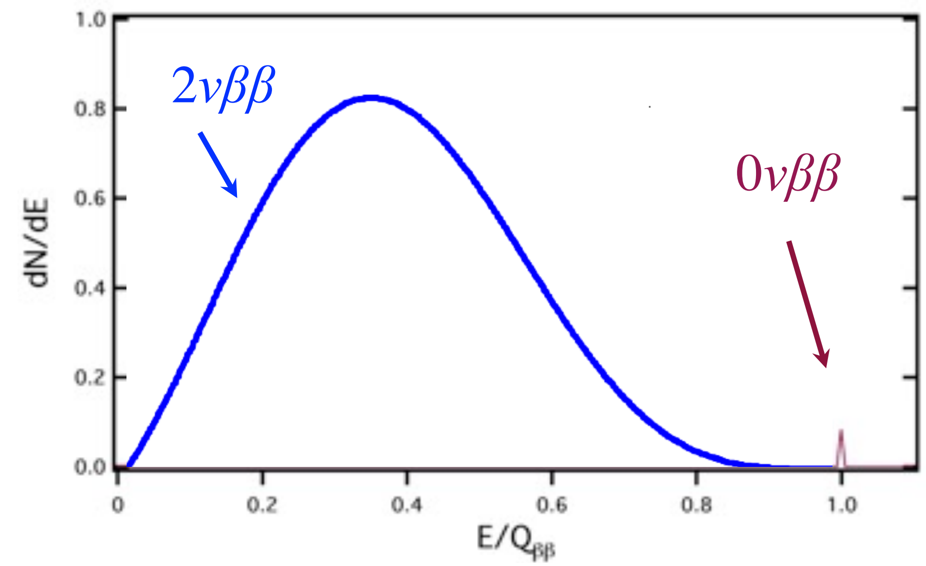


0νββ and Lepton Number Violation

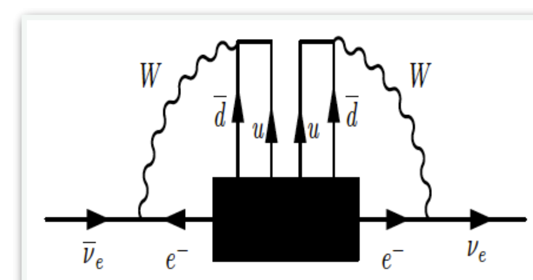
$$\boxed{(N,Z) \to (N-2, Z+2) + e^- + e^-}$$

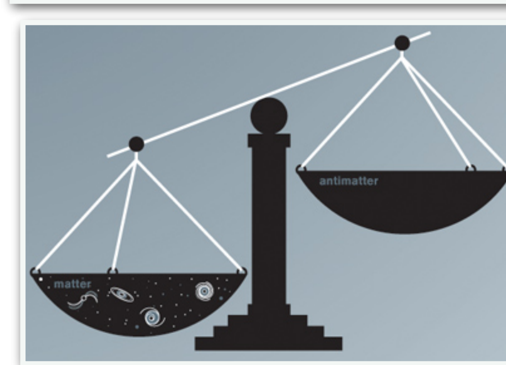


Lepton number changes by two units: $\Delta L=2$



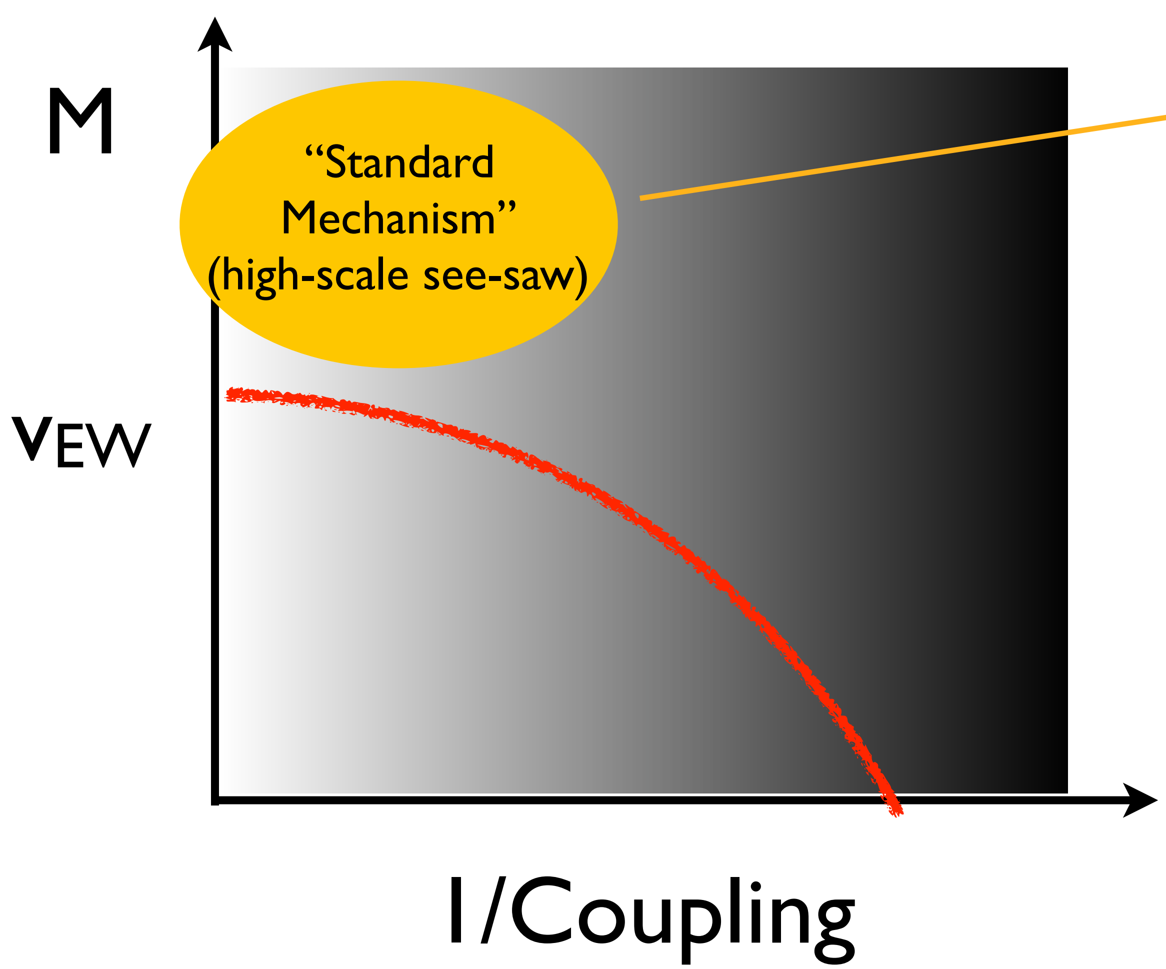
- B-L conserved in SM → new physics, with far-reaching implications
  - Demonstrate that neutrinos are their own antiparticles
  - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



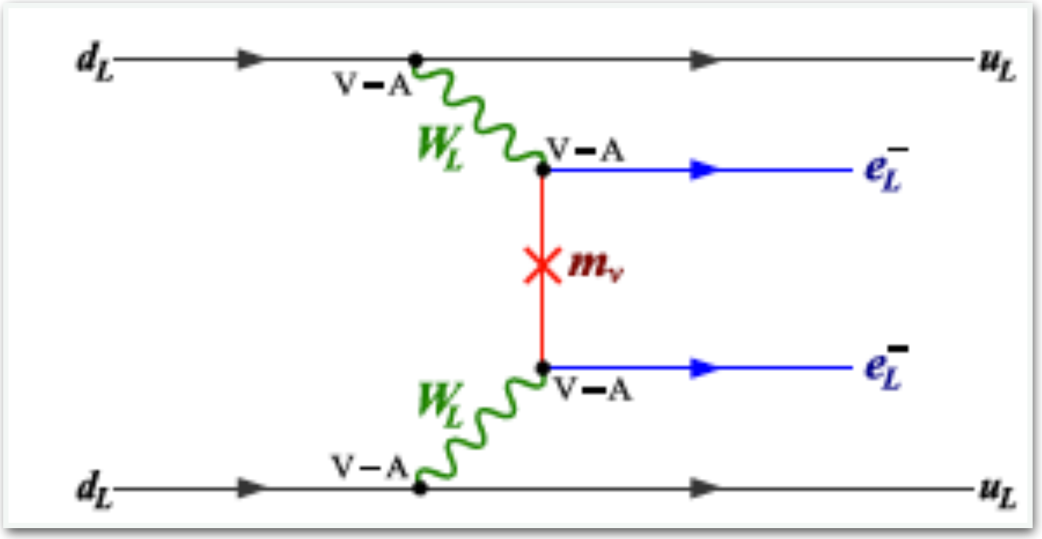


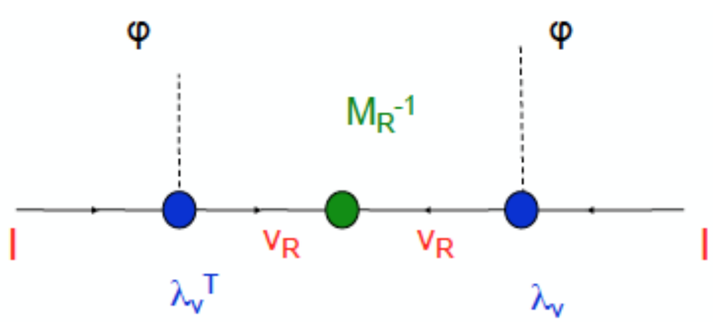
0νββ and Lepton Number Violation

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms



LNV dynamics at M >> TeV:
it leaves as only low-energy footprint
3 light Majorana neutrino

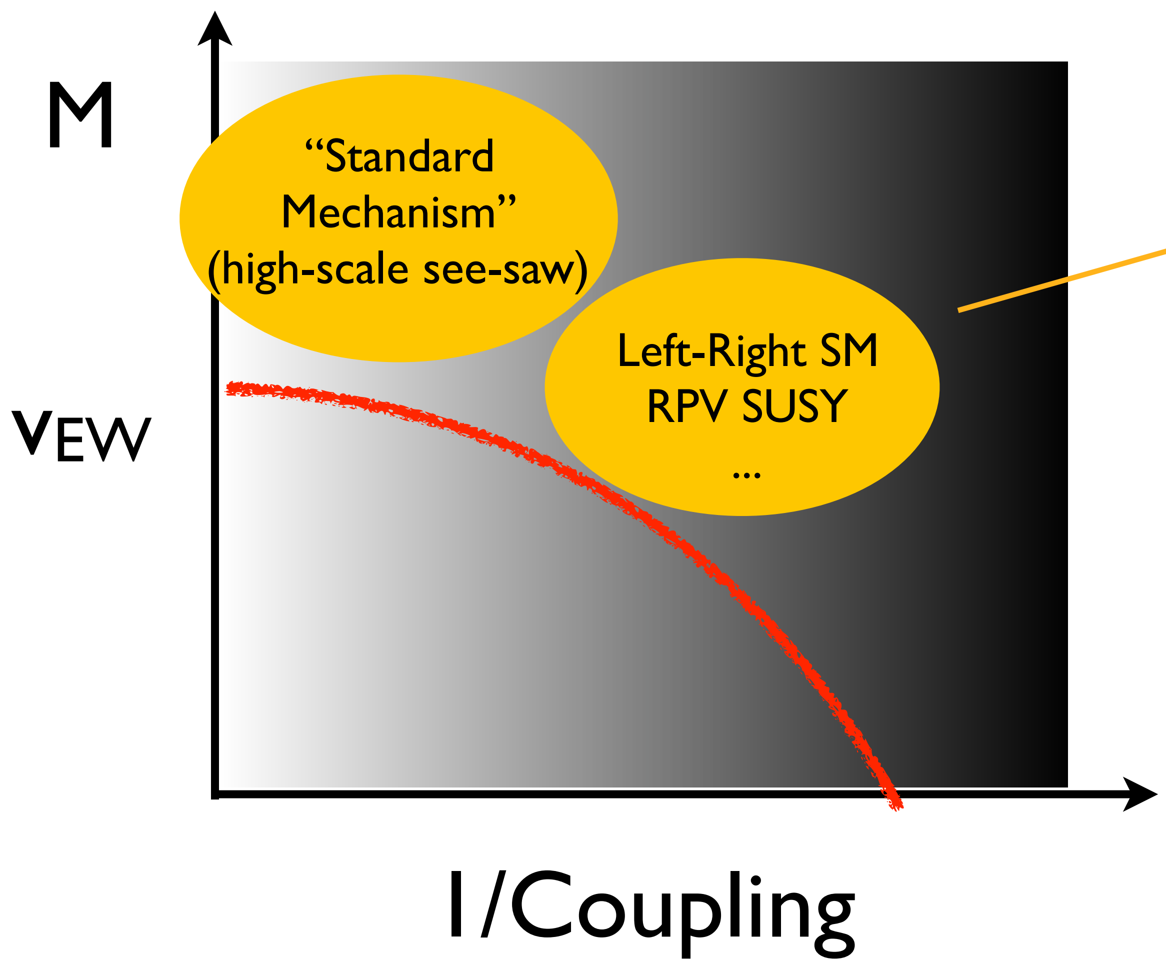




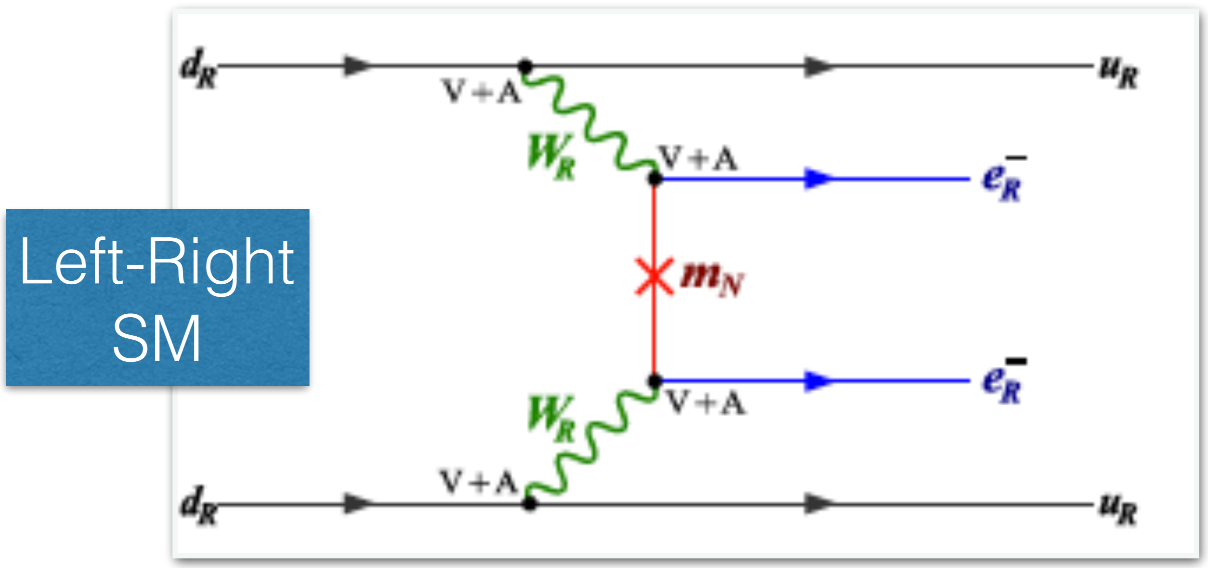
$$m_\nu \sim \frac{v_{EW}^2}{M_R}$$

$0\nu\beta\beta$ and Lepton Number Violation

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms

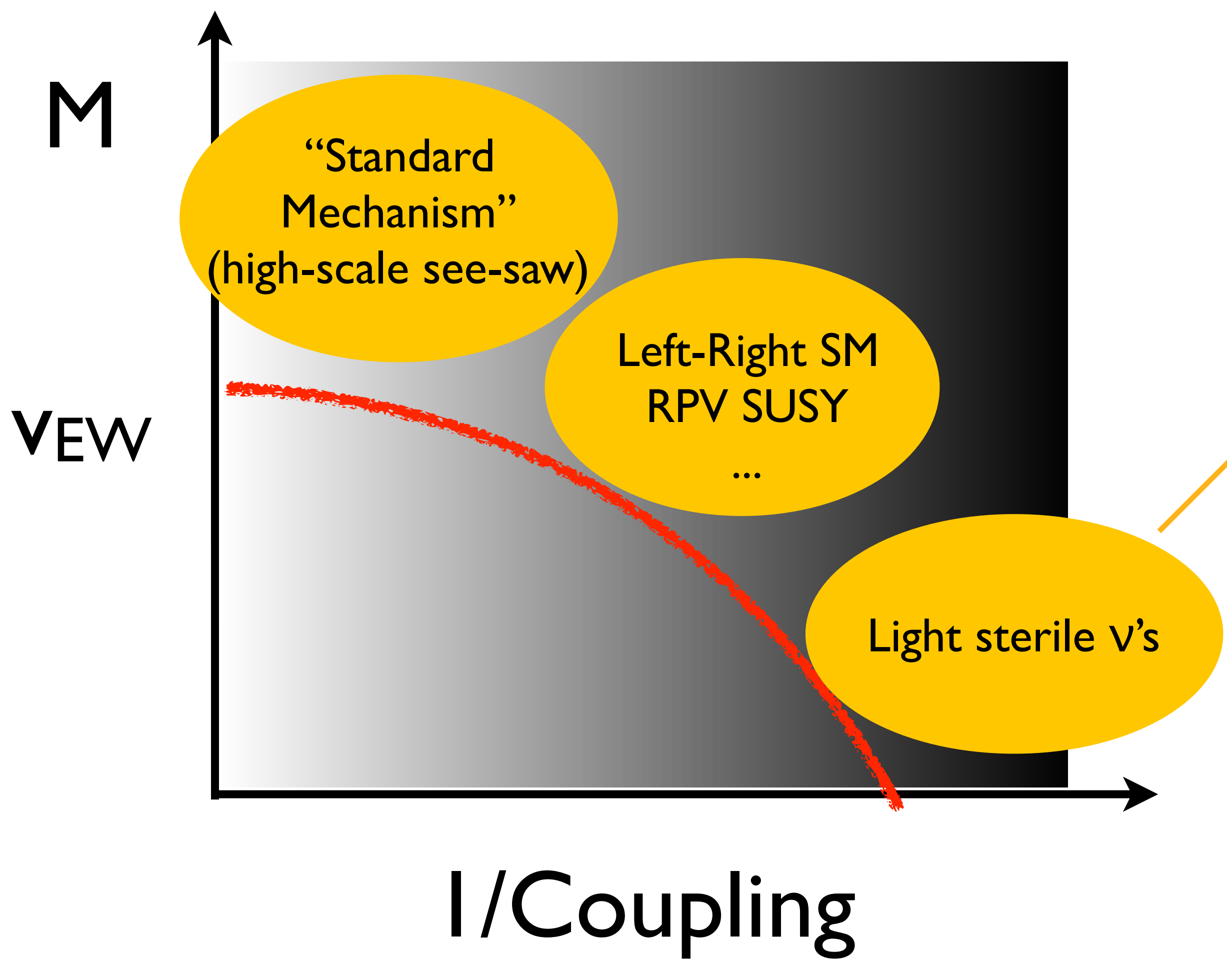


LNV dynamics at M ~ TeV:
1) new contribution to $0\nu\beta\beta$ not related to light neutrino mass;
2) pp → eejj at the LHC

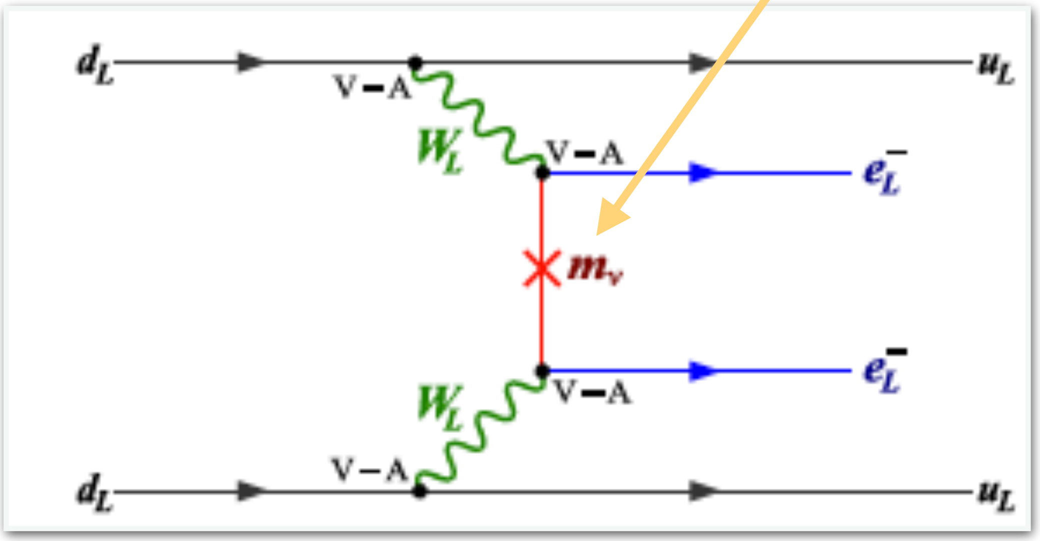


0νββ and Lepton Number Violation

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms



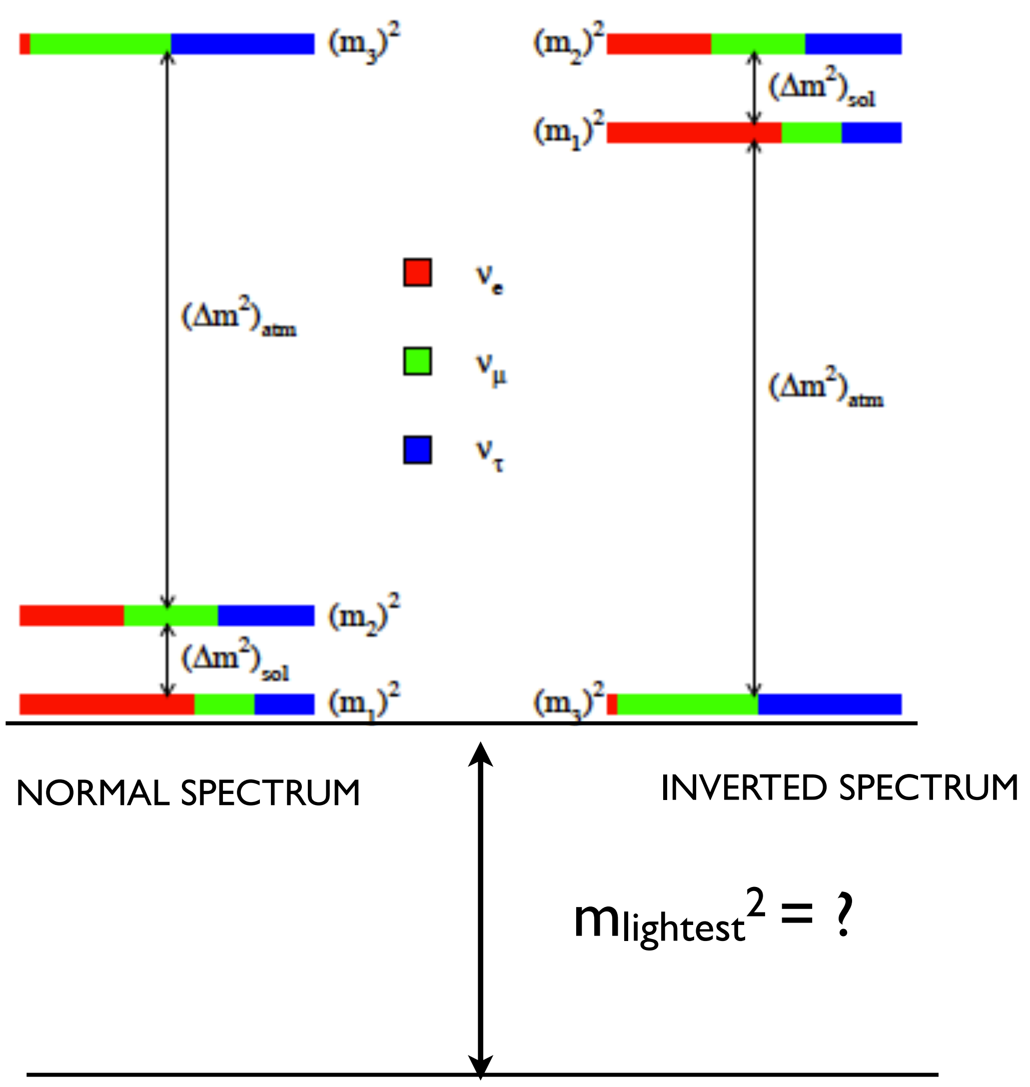
LNV dynamics at M_R : eV → GeV: additional light Majorana states



High-scale seesaw

- Strong correlation of $0\nu\beta\beta$ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



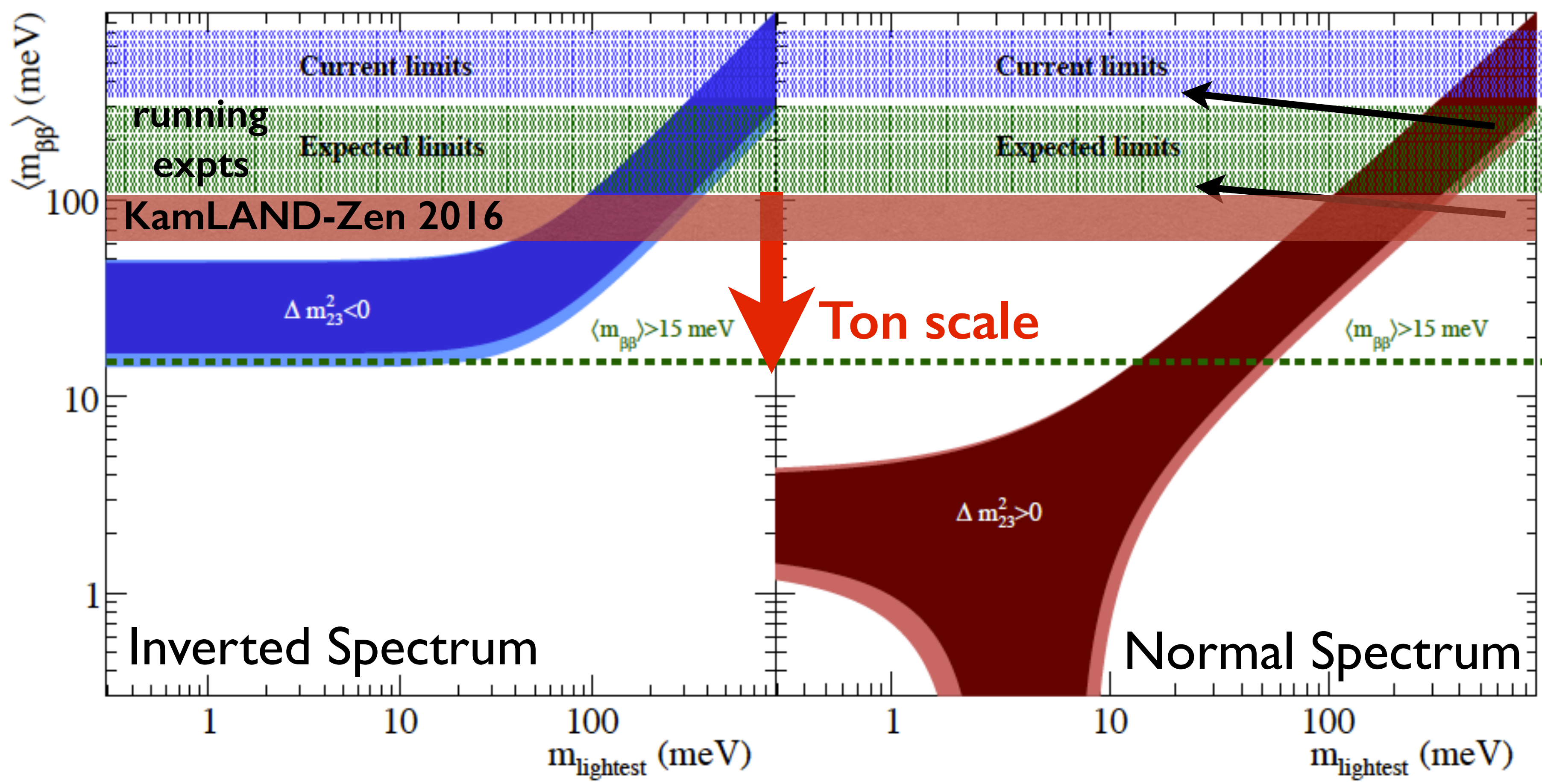
High-scale seesaw

- Strong correlation of 0νββ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$

Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)

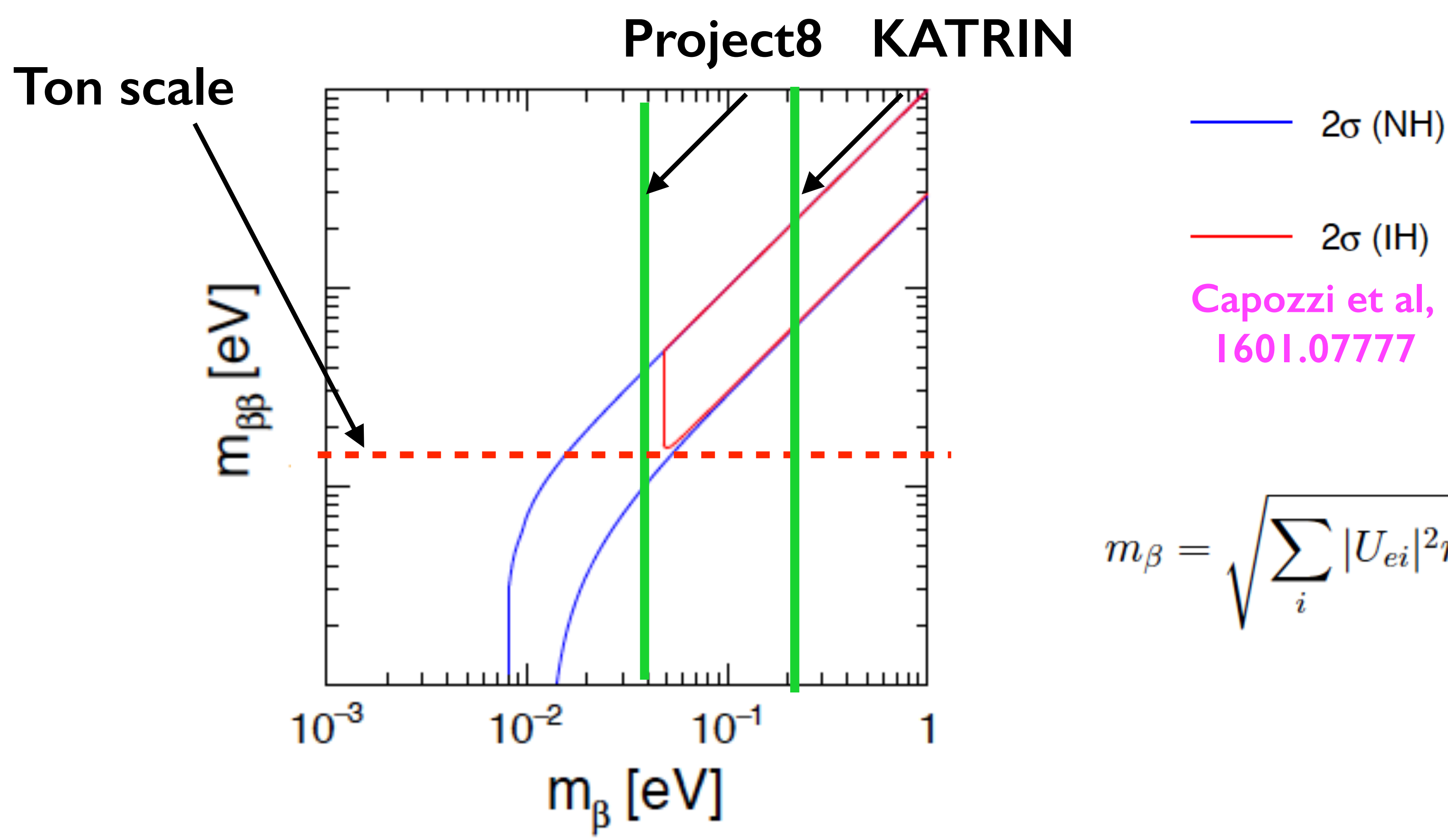


Assume most "pessimistic" values for nuclear matrix elements

- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

High-scale seesaw

- Correlation with other mass probes will contribute to the interpretation of positive or null result

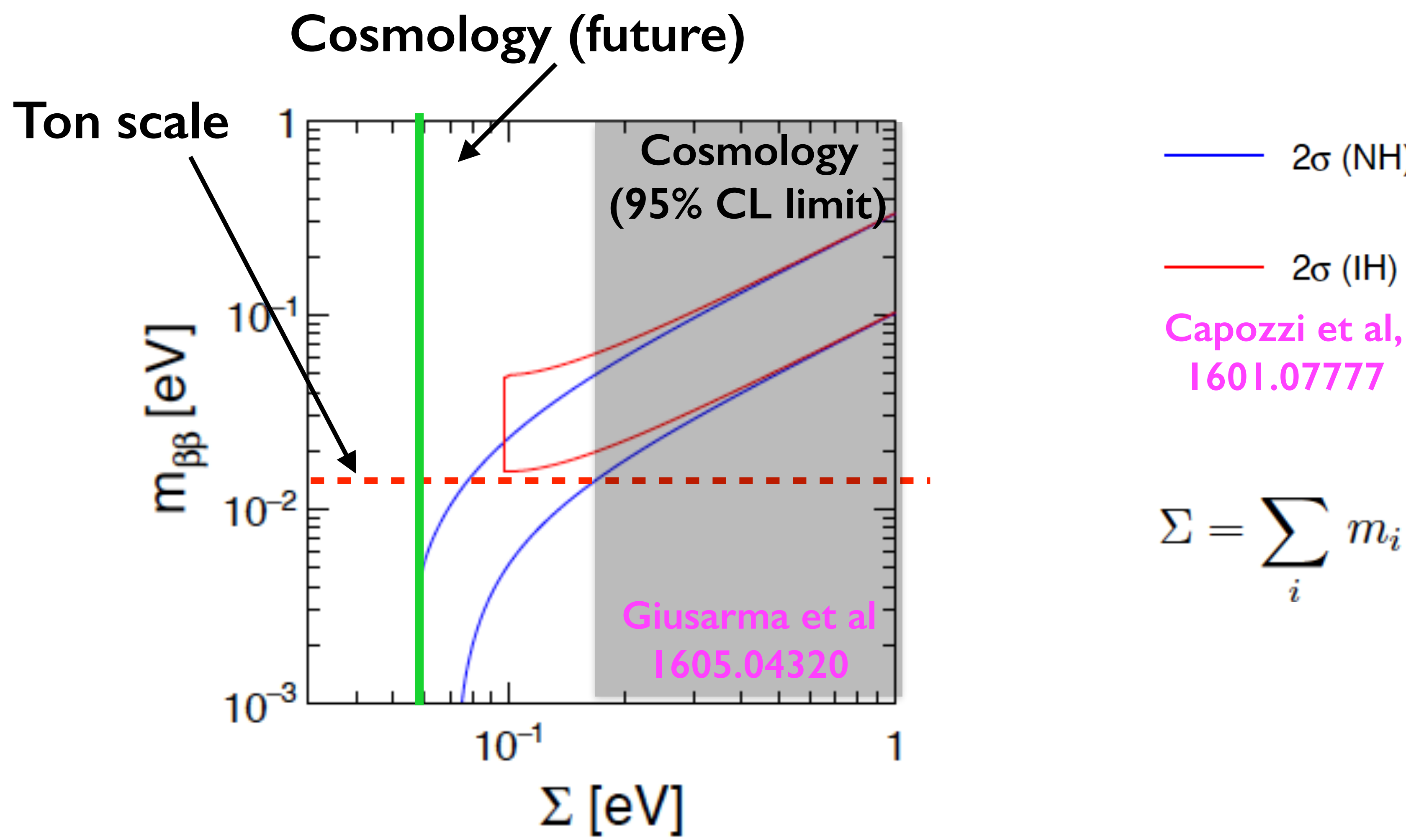


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

- Tritium decay: in this framework, positive result in KATRIN, Project8 would imply 0νββ within reach

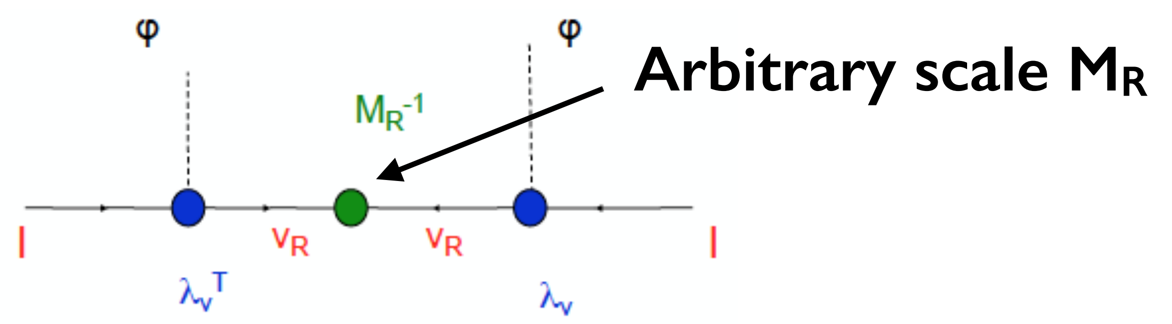
High-scale seesaw

- Correlation with other mass probes will contribute to the interpretation of positive or null result



- Interplay with cosmic frontier: expose potential new physics in cosmology (is "ΛCDM + m_ν" the full story?) or in $0\nu\beta\beta$ (LNV)

General see-saw, baryogenesis, and $0\nu\beta\beta$

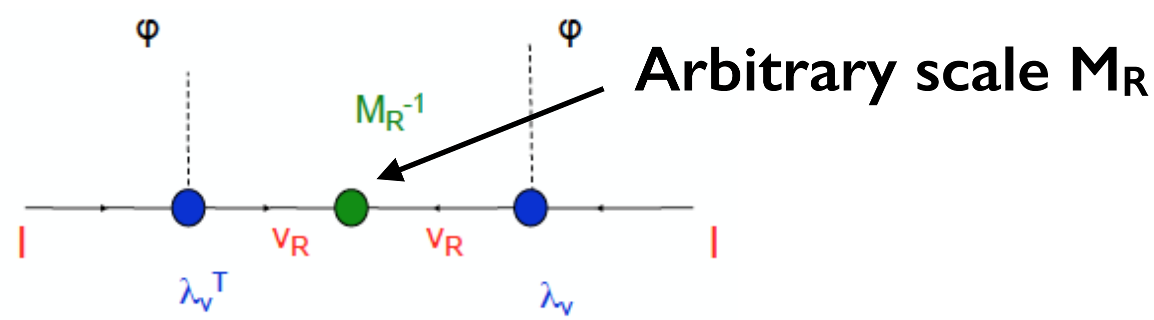


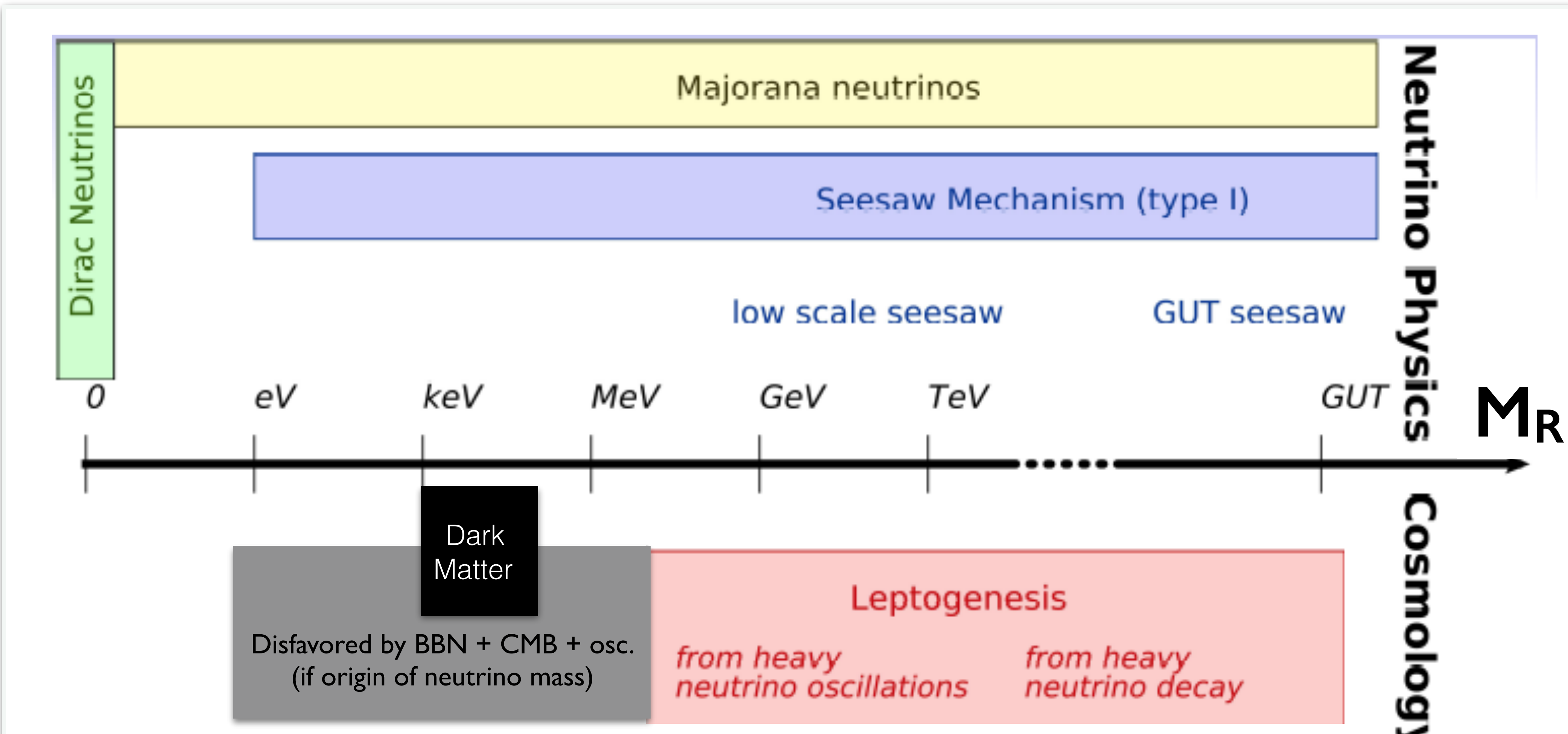
- Attractive class of "minimal" models
  - ν_R can give rise to light neutrino masses
  - ν_R can provide a dark matter candidate
  - ν_R can give rise to the baryon asymmetry through leptogenesis

Correlation with $0\nu\beta\beta$?

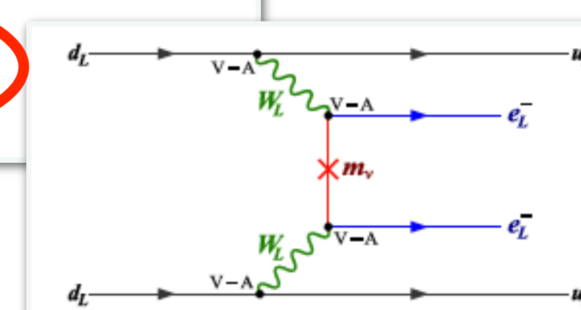
General see-saw, baryogenesis, and 0νββ

Drewes-Garbrecht 1502.00477
Drewes-Eijima 1606.06221
Hernandez et al 1606.06719





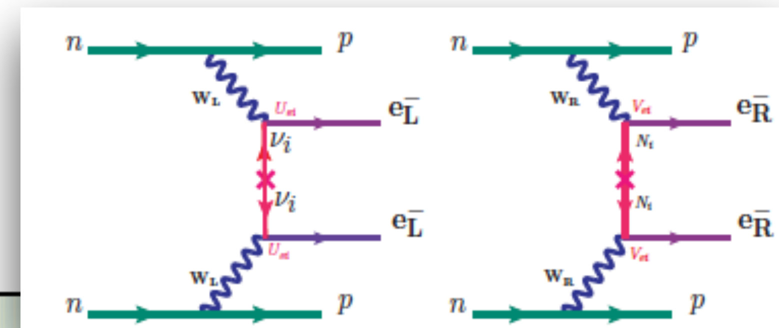
$m_{\beta\beta} \to 0$ $\quad m_{\beta\beta} < (m_{\beta\beta})_{\text{active}}$ $\quad m_{\beta\beta} \gtrless (m_{\beta\beta})_{\text{active}}$ $\quad m_{\beta\beta} = (m_{\beta\beta})_{\text{active}}$

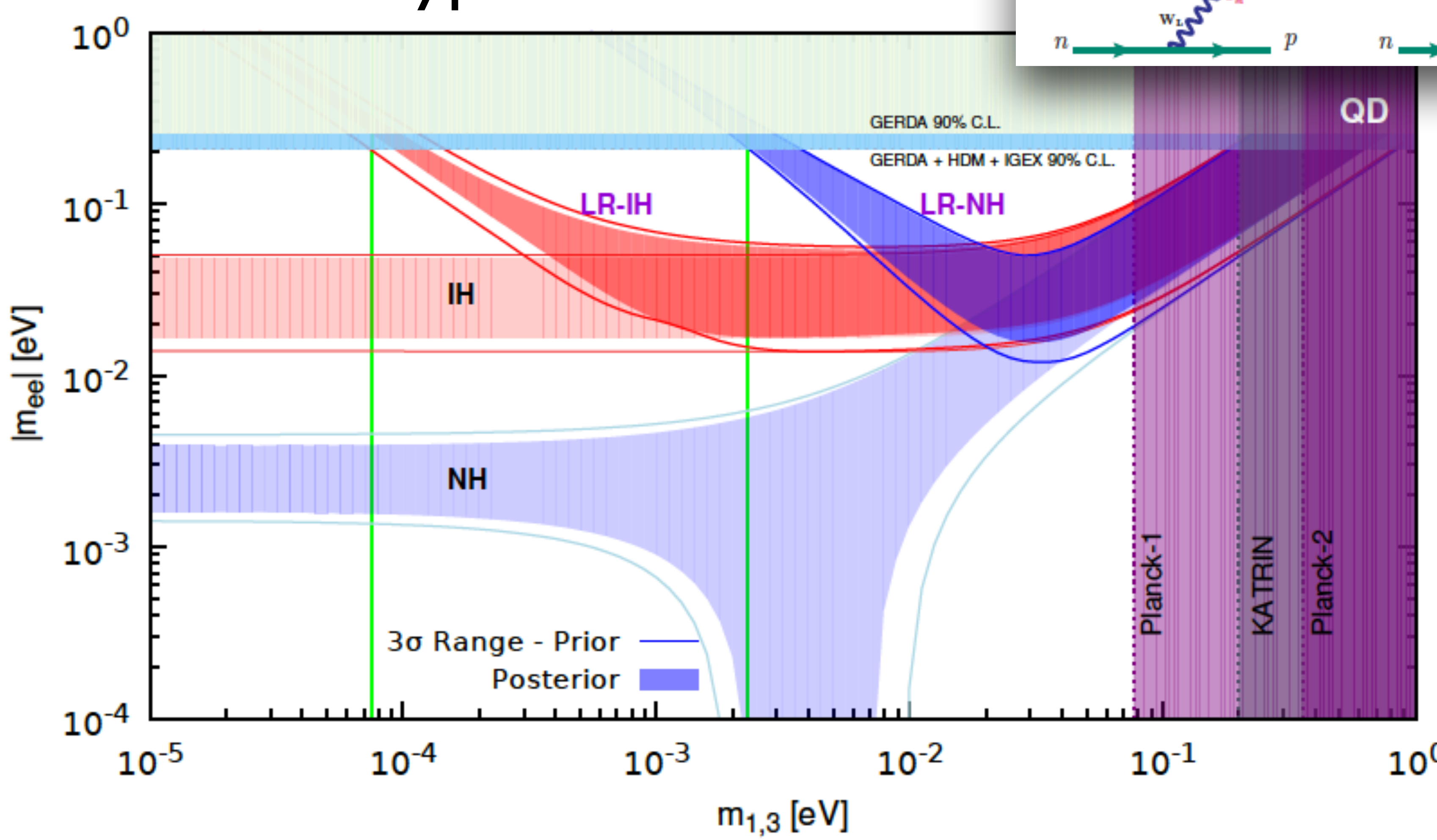


TeV scale LNV

- TeV sources of LNV may lead to significant contributions to NLDBD *not directly related to the exchange of light neutrinos*

Left-Right Symmetric Model
with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_i}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_i}{m_2} M_2, \text{ for IH.}$$

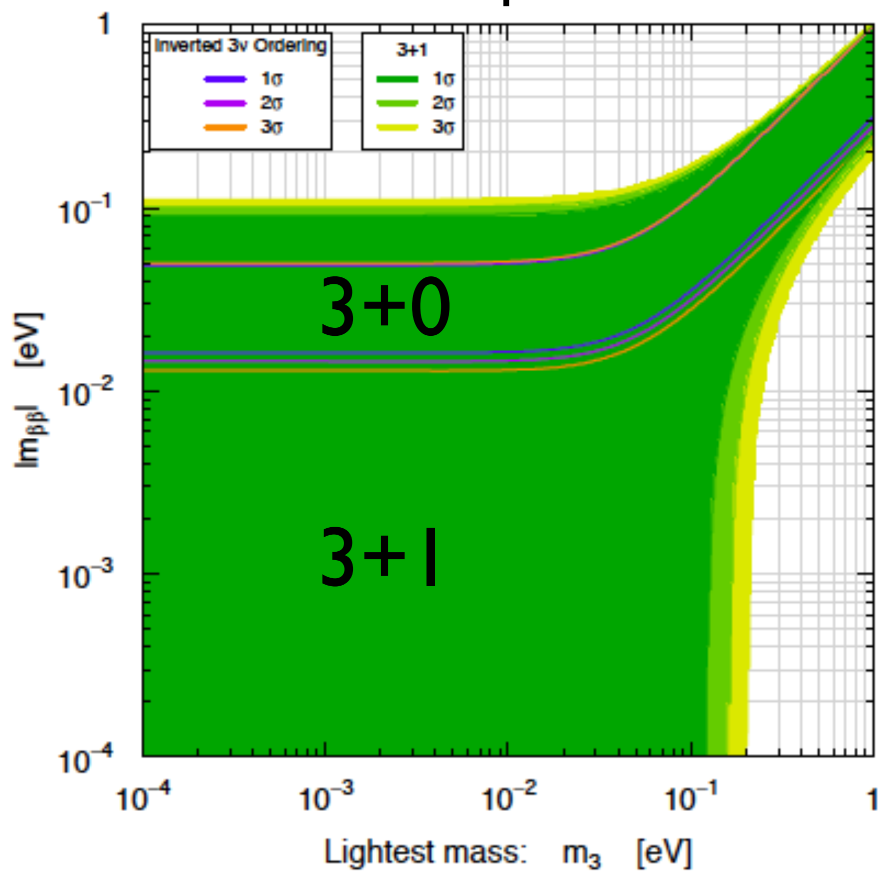
$M_{2,3}$ = 1 TeV

Ge-Lindner-Patra 1508.07286

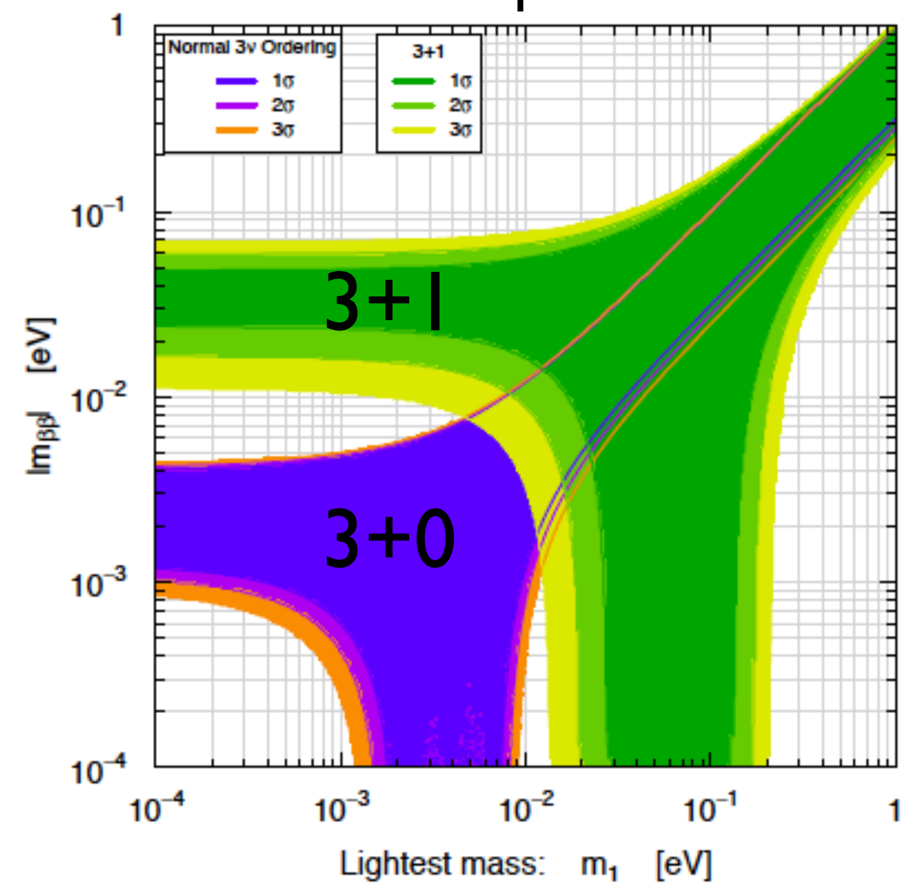
Low-scale LNV

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass $$m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 \, e^{2i\Phi} \, m_4$$

Inverted Spectrum



Normal Spectrum

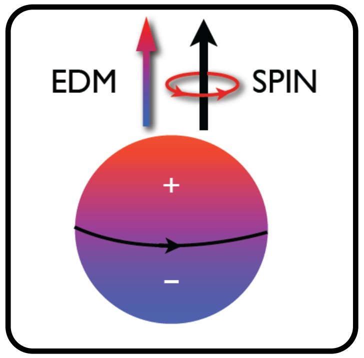


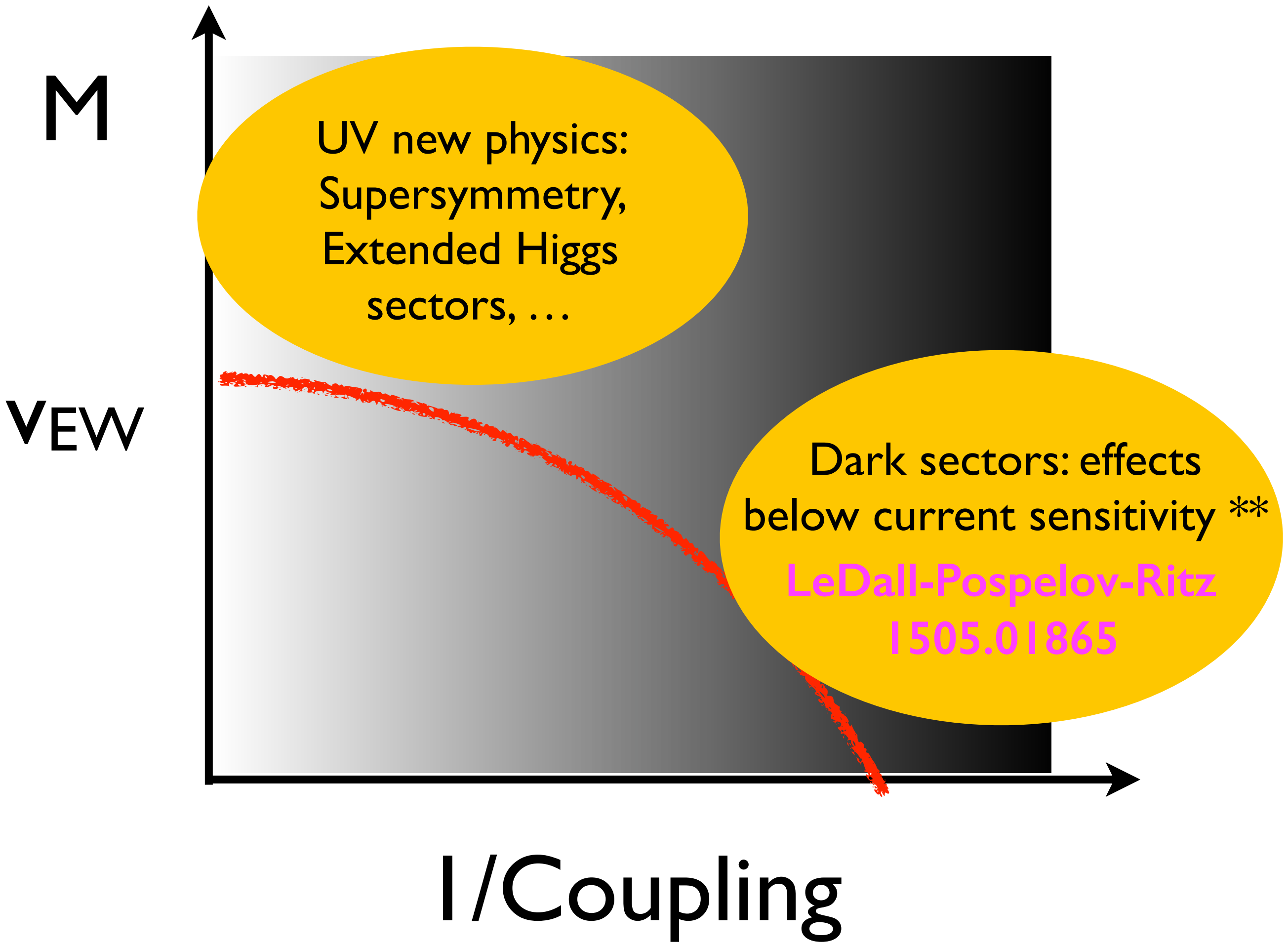
Giunti-Zavanin
1505.00978

Usual phenomenology turned around !

Electric Dipole Moments

- EDMs of non-degenerate systems violate P and T (CP)
  1. Essentially free of SM "background" (from CKM)*
  2. Probe high-scales, up to $\Lambda \sim 10^{2\text{-}3}$ TeV
  3. Probe key ingredient for baryogenesis (CPV in SM is insufficient)





- Discuss impact of EDMs on
  - CP-violating Higgs couplings
  - High-scale supersymmetry
  - Baryogenesis

EDMs and CPV Higgs couplings

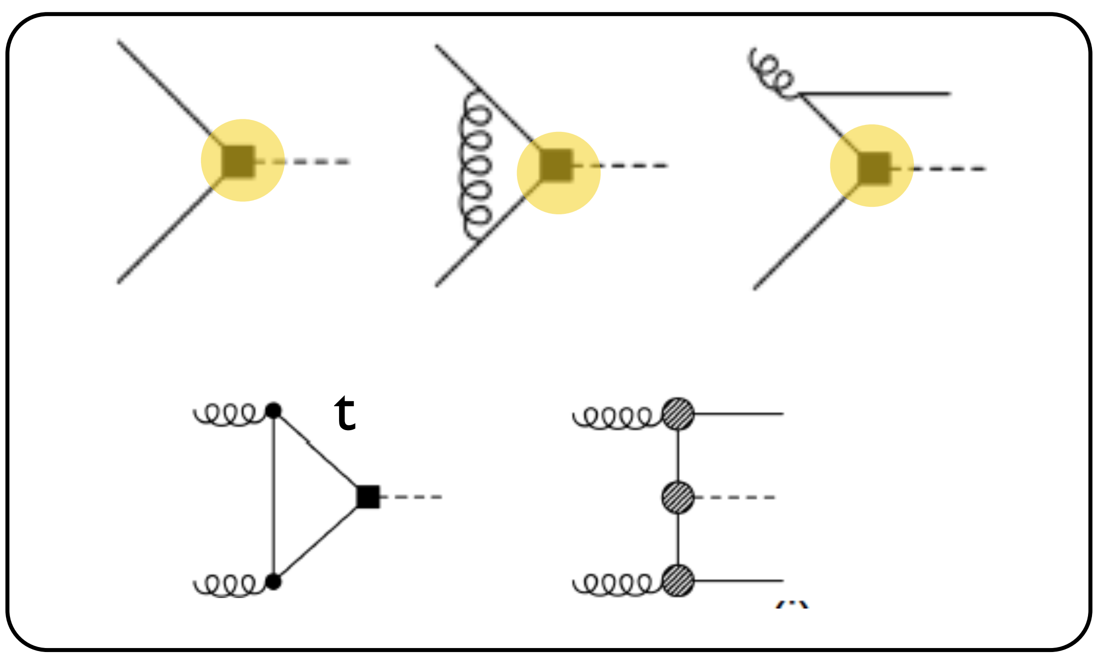
- Non-standard Yukawa couplings of the Higgs

$$\Delta\mathcal{L} \supset \sum_f \frac{m_f}{v}\left(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i\gamma_5 f\right) h$$

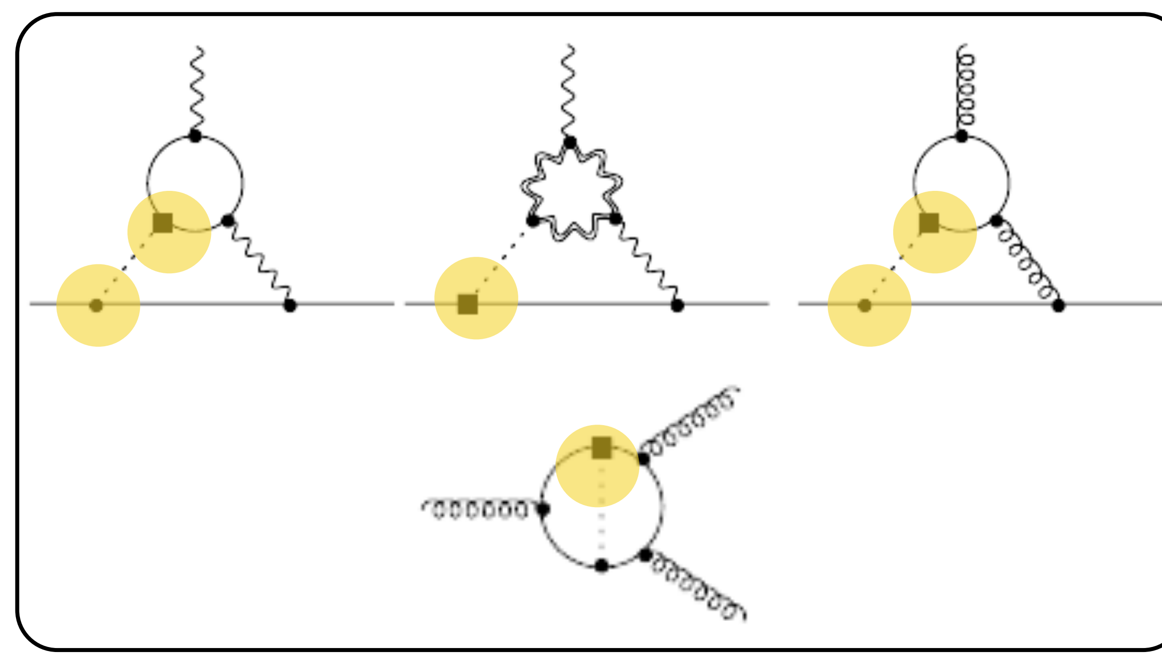
Standard Model:

$$\kappa_f = 1$$
$$\tilde{\kappa}_f = 0$$

LHC: Higgs production & decay



Low Energy: induce electron, neutron, mercury EDM



Brod Haisch Zupan 1310.1385

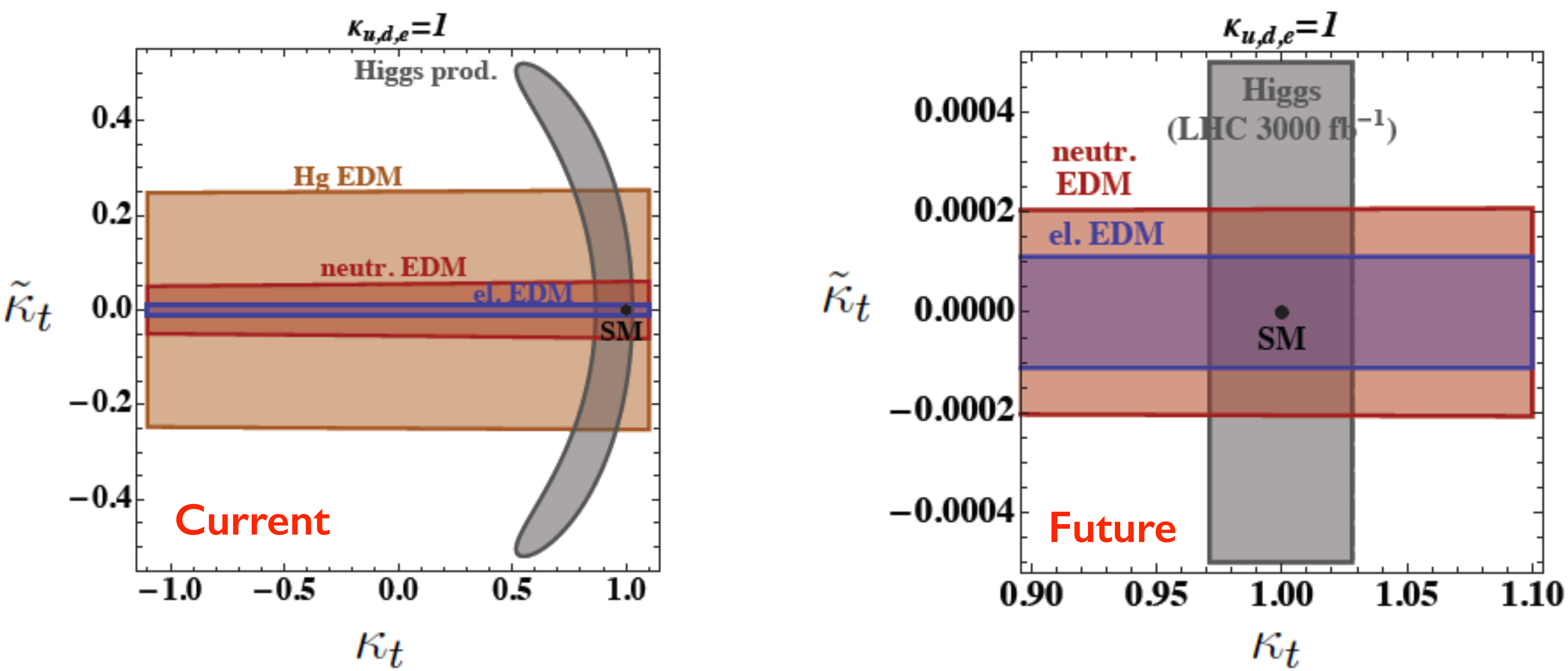
Y.-T. Chien,V.C, W. Dekens, J. de Vries, E. Mereghetti, 1510.00725

EDMs and CPV Higgs couplings

- Non-standard Yukawa couplings of the Higgs

$$\Delta\mathcal{L} \supset \sum_f \frac{m_f}{v}\left(\kappa_f \bar{f}f + \tilde{\kappa}_f \bar{f}i\gamma_5 f\right) h$$

Standard Model:
$\kappa_f = 1$
$\tilde{\kappa}_f = 0$



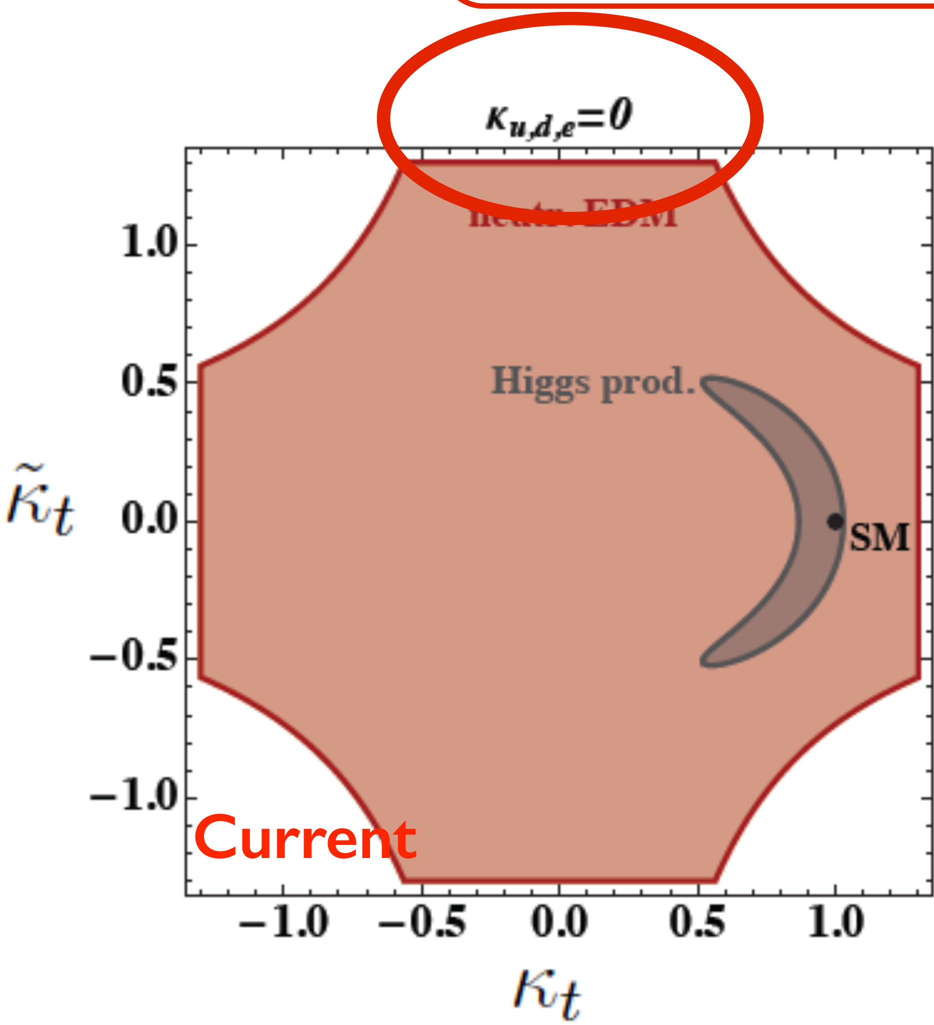
Brod Haisch Zupan 1310.1385

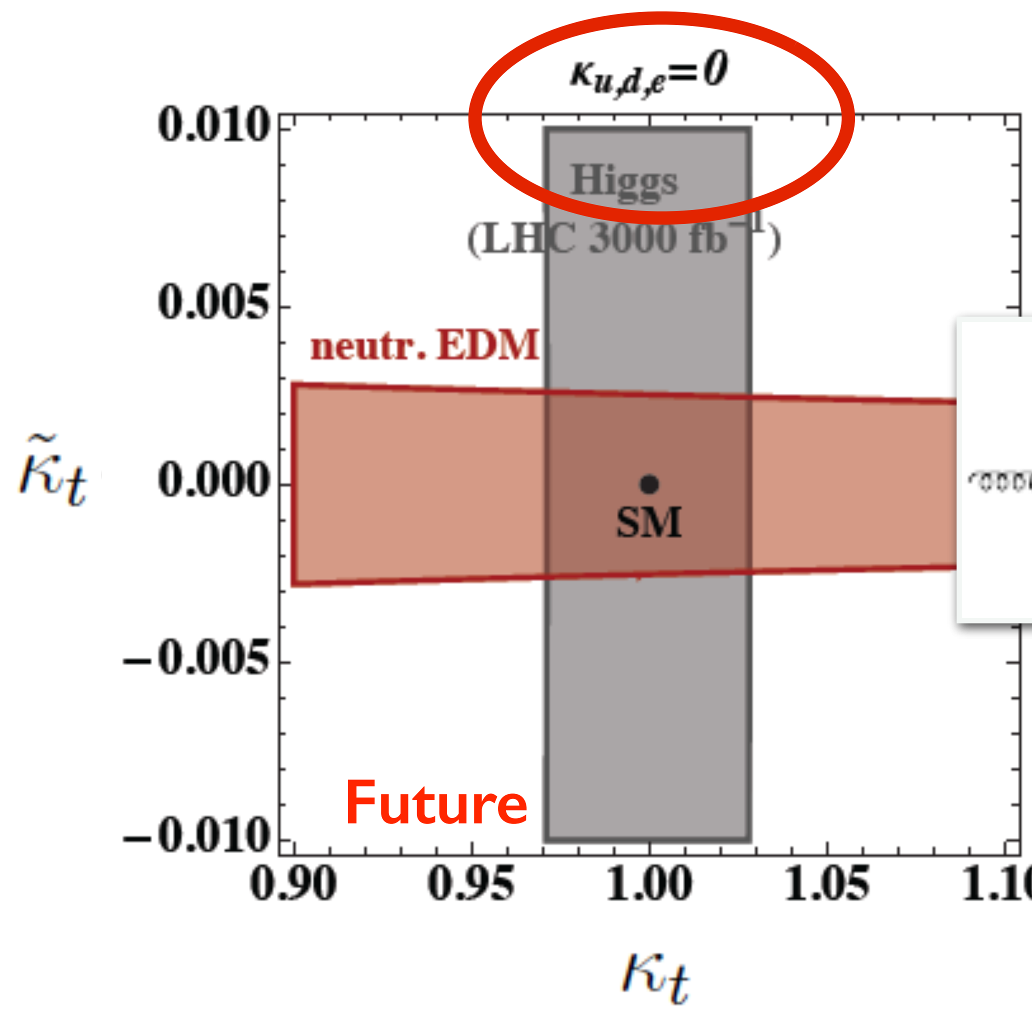
EDMs and CPV Higgs couplings

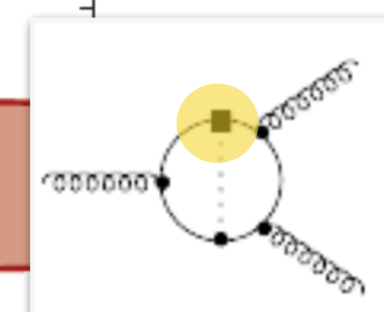
- Non-standard Yukawa couplings of the Higgs

$$\Delta\mathcal{L} \supset \sum_f \frac{m_f}{v}\left(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i\gamma_5 f\right) h$$

Standard Model:
$\kappa_f = 1$
$\tilde{\kappa}_f = 0$





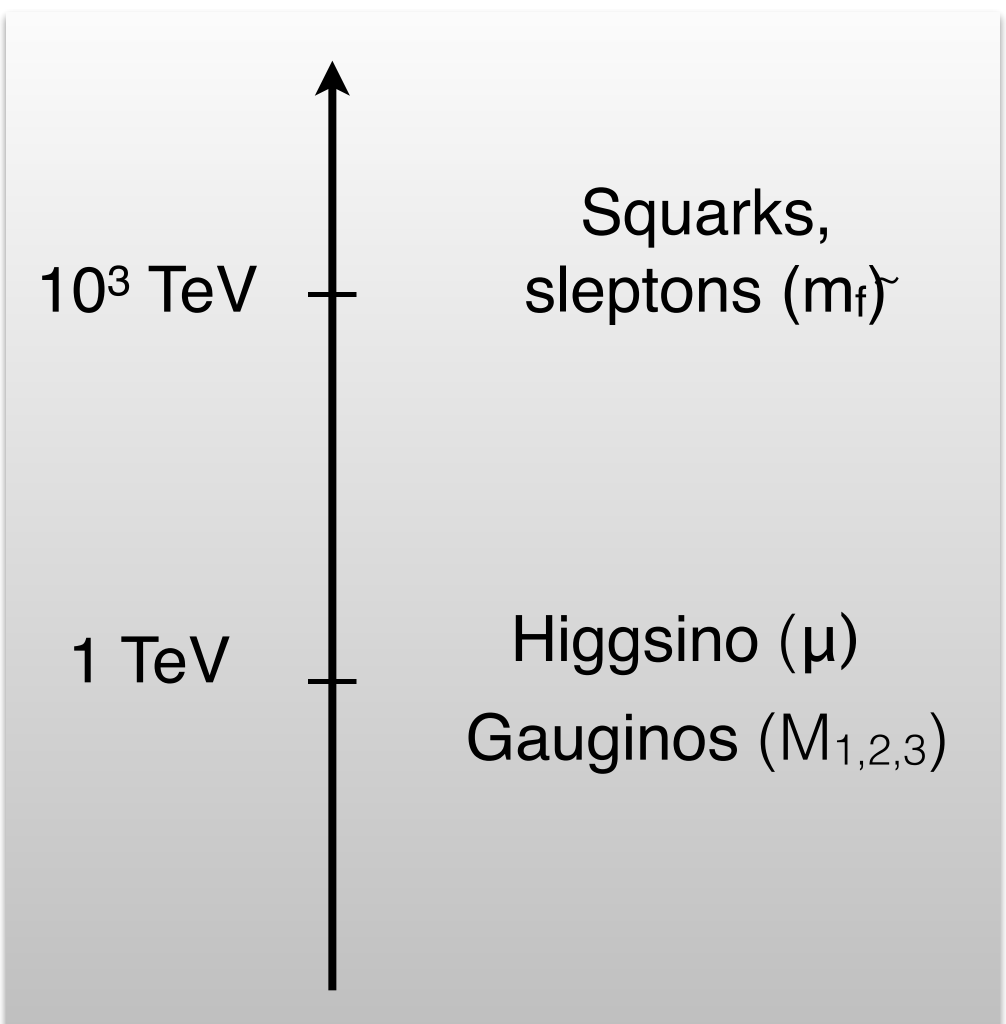


Brod Haisch Zupan 1310.1385

EDMs in high-scale SUSY models

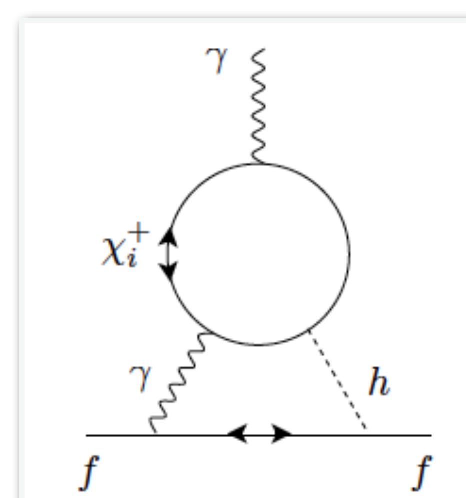
- Higgs mass at ~125 GeV points to PeV-scale super-partners
- “Split-SUSY”: retain gauge coupling unification and DM candidate

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, …



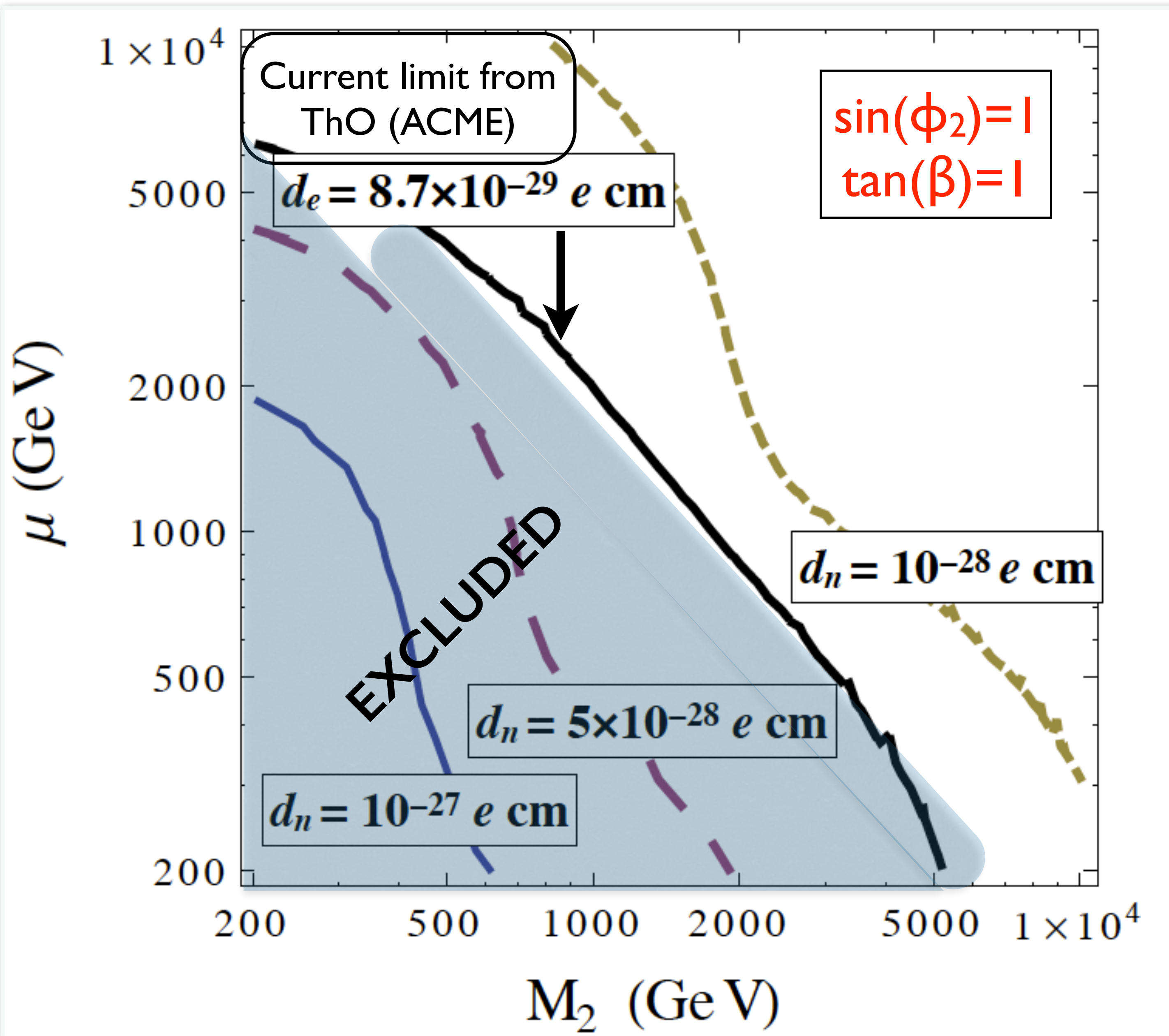
EDMs among a handful of observables capable of probing such high scales

Same CPV phase controls d_e, d_n



EDMs in high-scale SUSY models

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

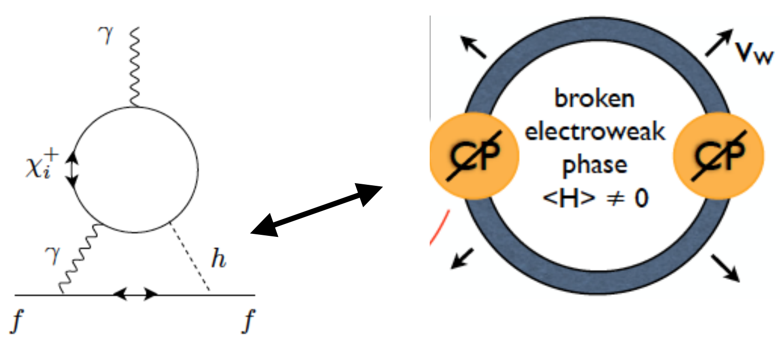


- Studying the ratio d_n/d_e → upper bound $d_n < 4\times10^{-28}$ e cm
- Can be falsified by current nEDM searches
- Model discrimination enabled by multiple measurements and controlled th. uncertainty

Bhattacharya, VC, Gupta, Lin, Yoon
1506.04196

EDMs and baryogenesis

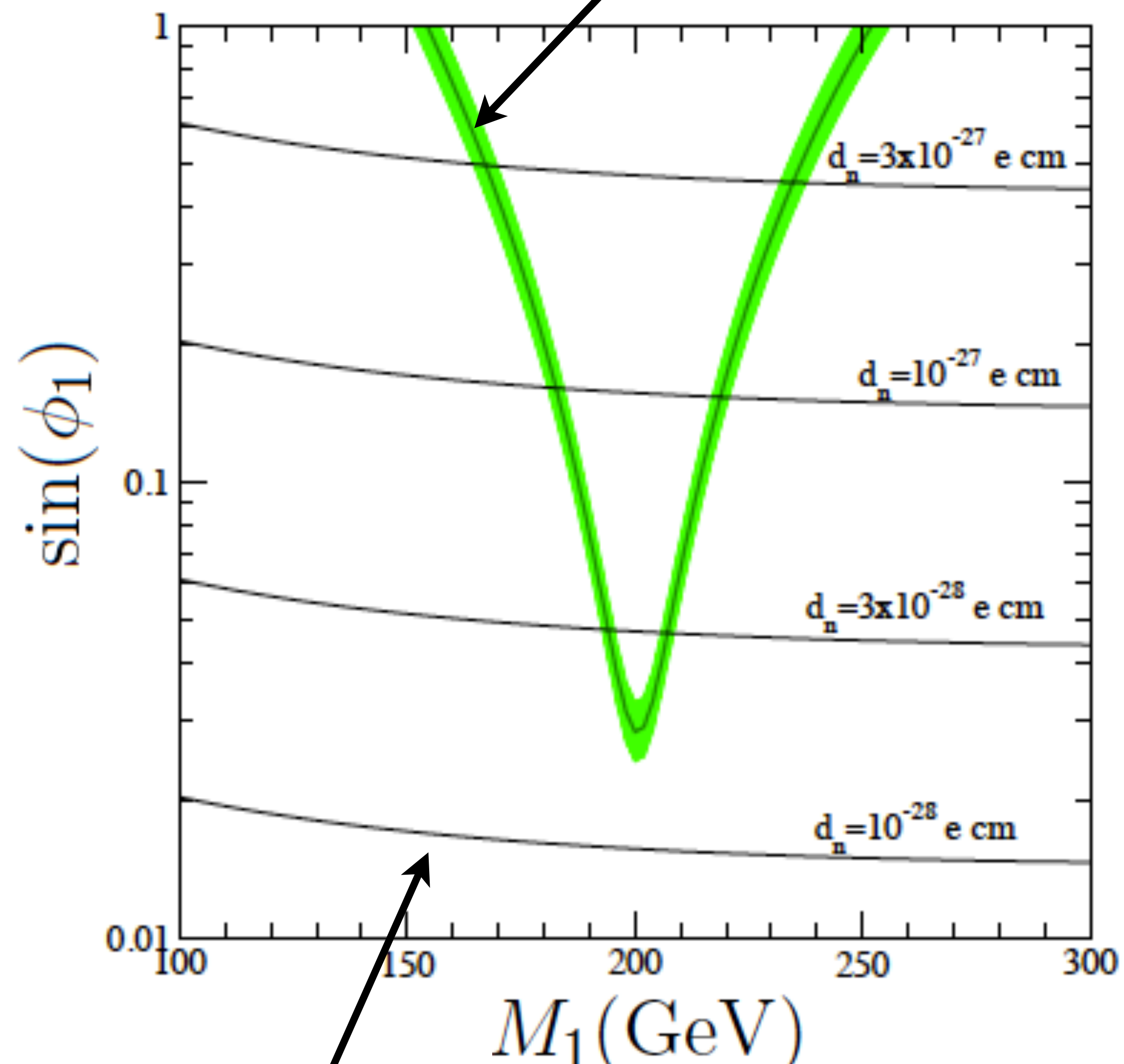
- In the (N)MSSM, CPV phases appearing in the gaugino-higgsino mixing contribute to both baryogenesis and EDM



- In *this model*, successful baryogenesis implies a “guaranteed signal” for EDMs

- Within reach of planned experiments

Compatible with baryon asymmetry

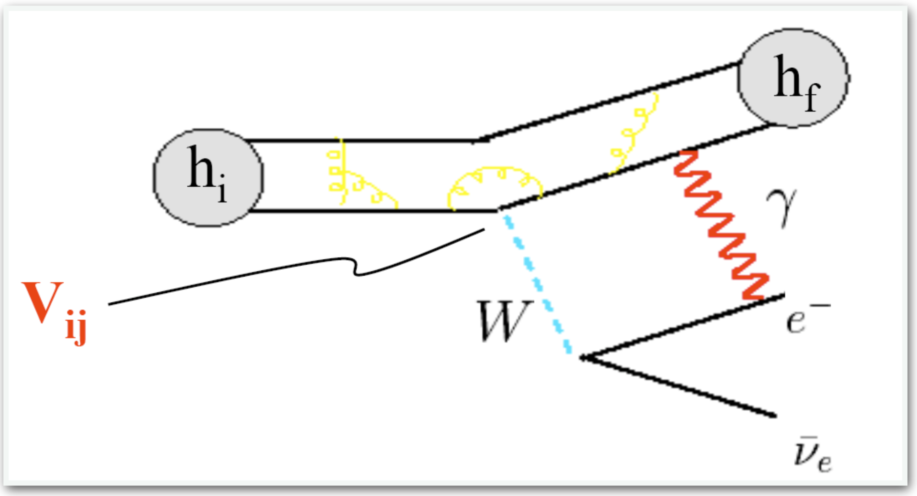


Next generation neutron EDM

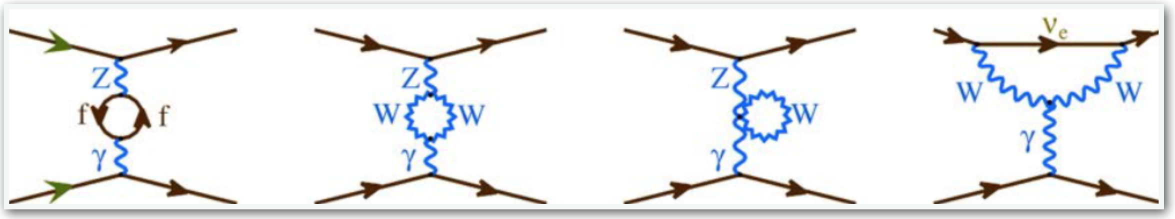
Li, Profumo, Ramsey-Musolf
0811.1987

Precision measurements

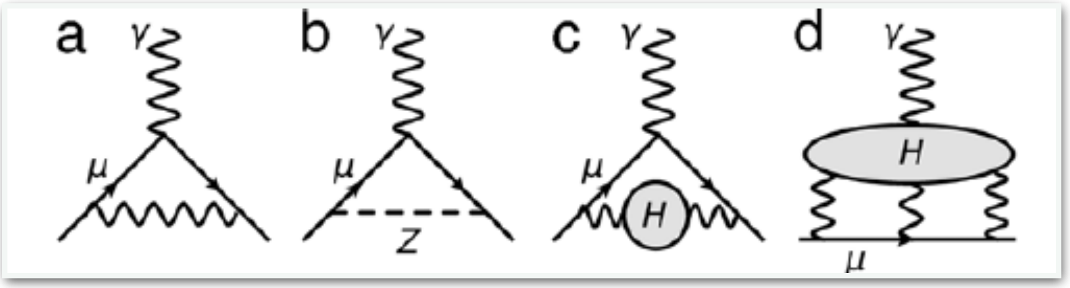
- Beta decays and parity-violating electron scattering have played a central role in establishing the Standard Model



- Today, with precision approaching the 0.1% level, together with the muon g-2 they probe quantum effects in the Standard Model at unprecedented levels

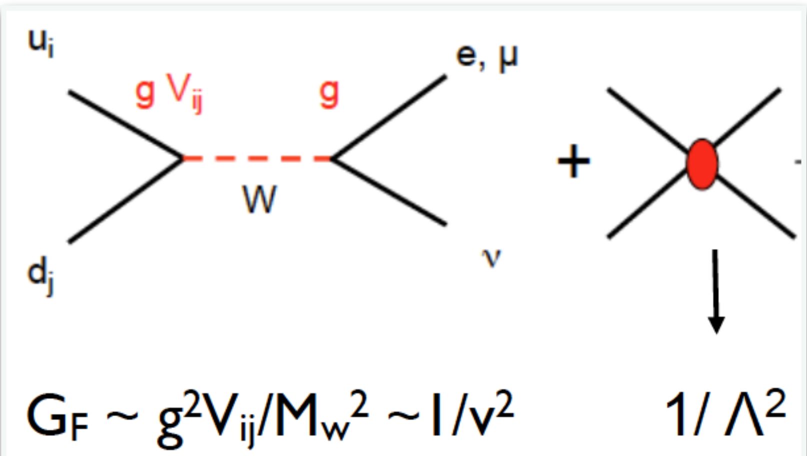


- "Broad band" sensitivity to new physics, both super-heavy and light



β decays and CC interactions

- In the SM, W exchange $\Rightarrow$ V-A currents, universality



$E \ll \Lambda$ $\longrightarrow$

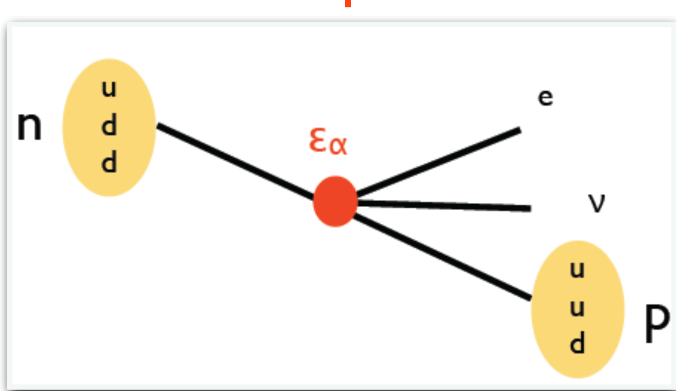
$$\Gamma = L, R, S, P, T$$

$$\boxed{\mathcal{L}_{\rm SM} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_{\Gamma} \left[\epsilon_\Gamma \; \bar{\ell}\Gamma\nu_L \cdot \bar{u}\Gamma d \; + \; \tilde{\epsilon}_\Gamma \; \bar{\ell}\Gamma\nu_R \cdot \bar{u}\Gamma d \right]}$$

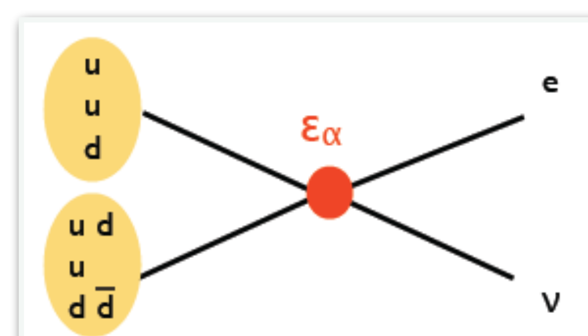
Ten effective couplings $\epsilon_\Gamma \sim (M_W/\Lambda)^2$

- ε and $\tilde{\varepsilon}$ couplings probed by a variety of Γ, dΓ measurements
- Constraints on ε-coupling (all < 0.5%) quite competitive with LHC

$n \to p\, e\, \nu$



LHC: $pp \to e\, \nu + X$



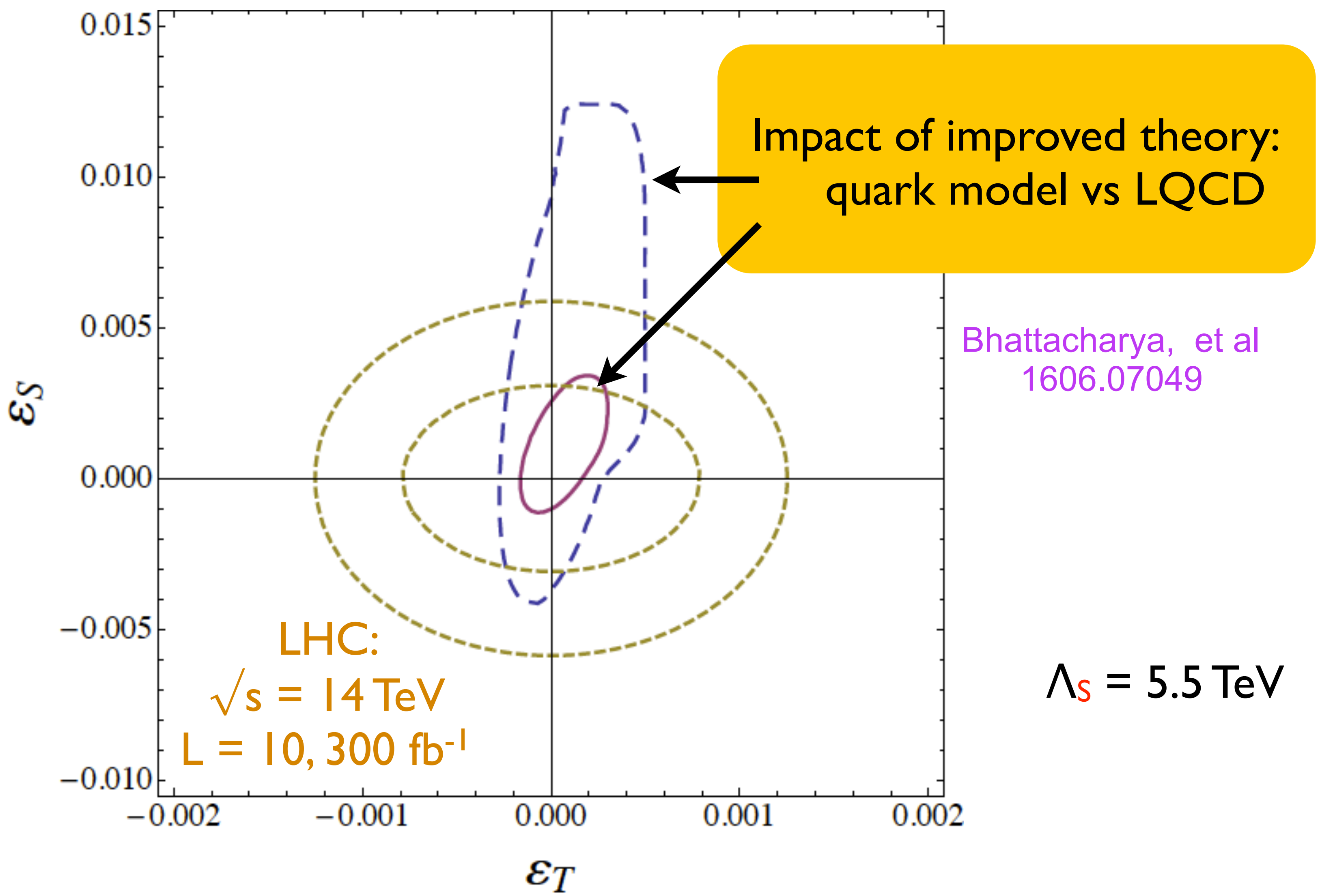
Example: scalar tensor couplings

b, B @ 0.1%, probe ε_S and ε_T deeper than the LHC (for heavy BSM)

spectrum distortion

$J \cdot p_\nu$

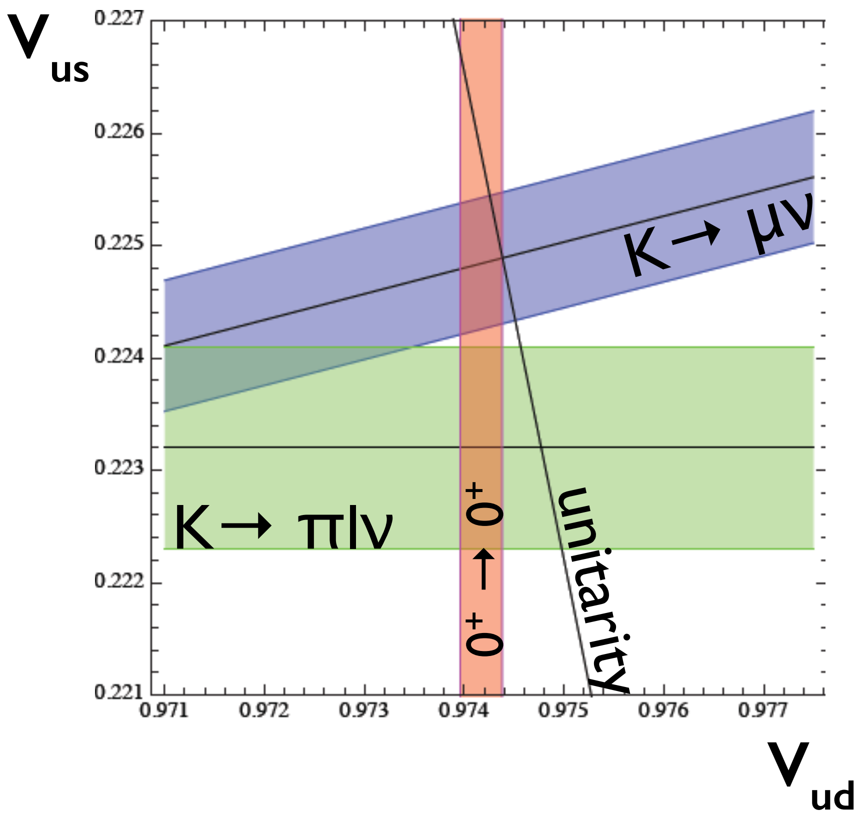
Future b (n, ^{6}He) @ 0.1%
Current b($0^+ \to 0^+$): Hardy & Towner 1411.5987



Bhattacharya, et al 1606.07049

Λ_S = 5.5 TeV Λ_T = 10 TeV

Strongest probe: CKM unitarity



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

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

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

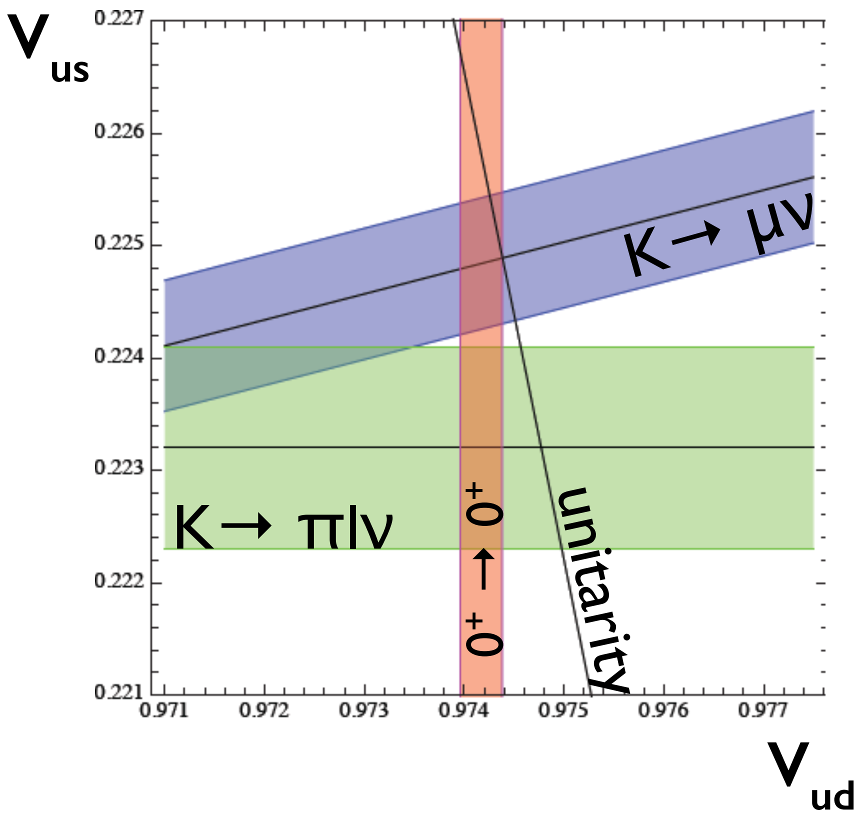
$\Delta_{\rm CKM} = -(12 \pm 6) * 10^{-4}$ 2.1σ

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

- Sensitivity to $\varepsilon_V \sim 5\times10^{-4}$, $\Lambda_{\rm CKM} \sim 10$ TeV (on par with Z-pole tests) vs $\Lambda_{\rm LHC} \sim 3$ TeV
- Worth pushing precision further: radiative corrections + hadronic and nuclear structure
- Pursue V_{ud} @ 0.02% through neutron decay: requires $\delta\tau_n \sim 0.35$ s ($\delta\tau_n/\tau_n \sim 0.04$ %) and $\delta g_A/g_A \sim 0.025\%$ ($\delta a/a$, $\delta A/A \sim 0.1\%$)

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

Strongest probe: CKM unitarity



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

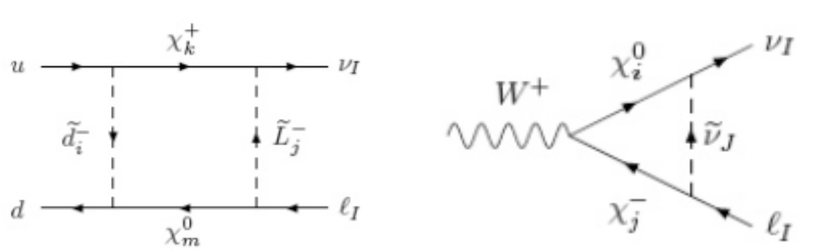
V_{us} from K→ μν

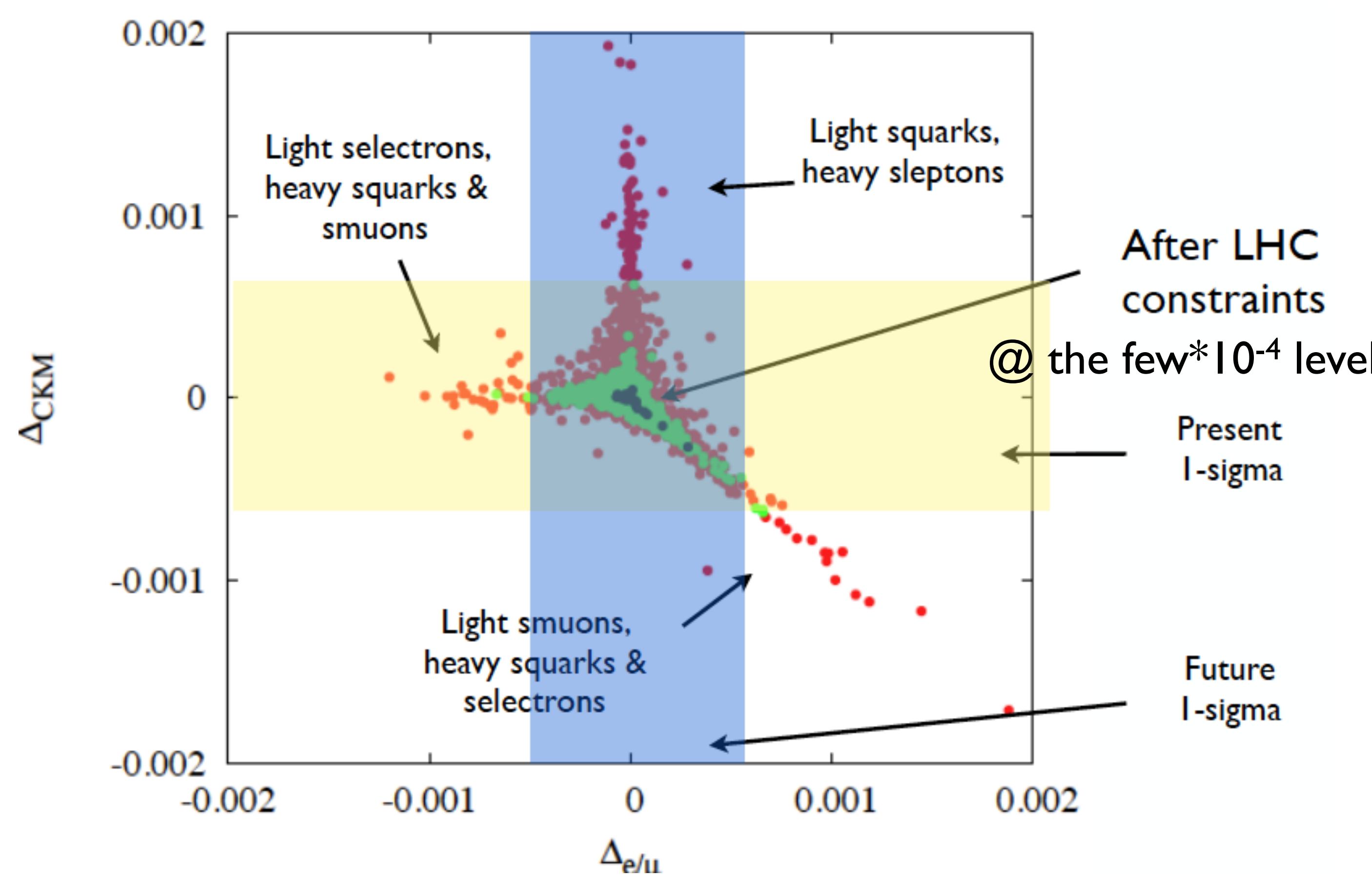
$\Delta_{\rm CKM}$ = - (4 ± 5) ∗ 10^{-4} 0.9σ

$\Delta_{\rm CKM}$ = - (12 ± 6) ∗ 10^{-4} 2.1σ

V_{us} from K→ πlν

- SUSY: correlation between $\Delta_{\rm CKM}$ and $\Delta_{e/\mu}$=Γ(π→eν)/Γ(π→μν) - 1, controlled by sfermion spectrum

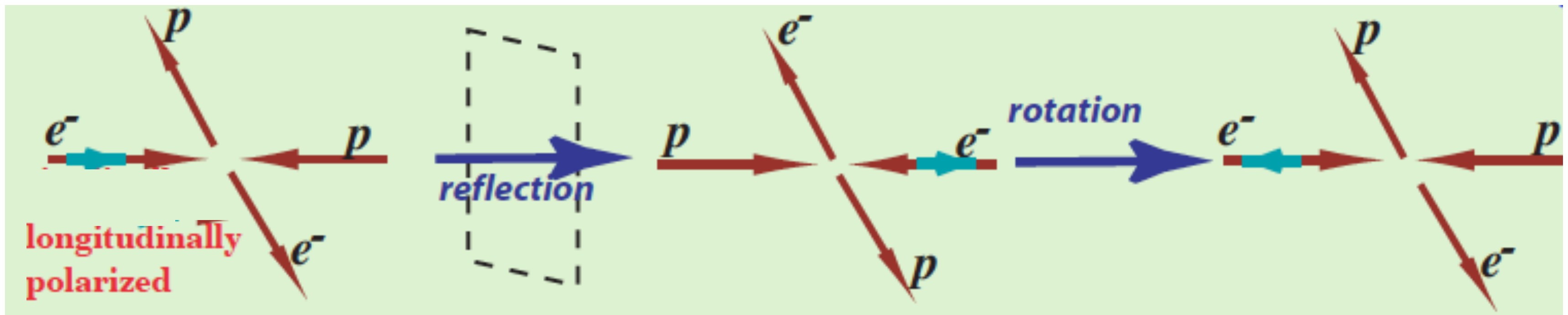




Bauman, Erler, Ramsey-Musolf, 1204.0035

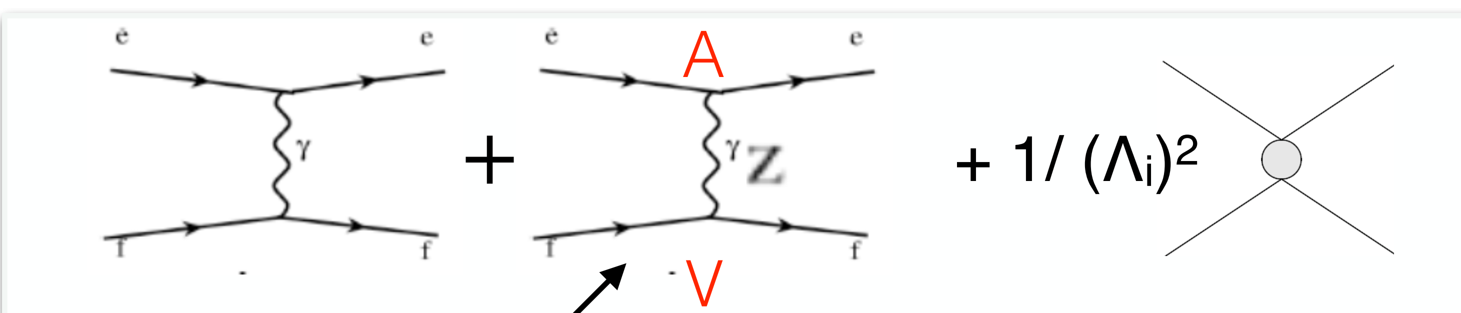
Parity-violating electron scattering

$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$



K. Kumar

- A_{PV} generated in the SM by interference of γ and Z amplitudes



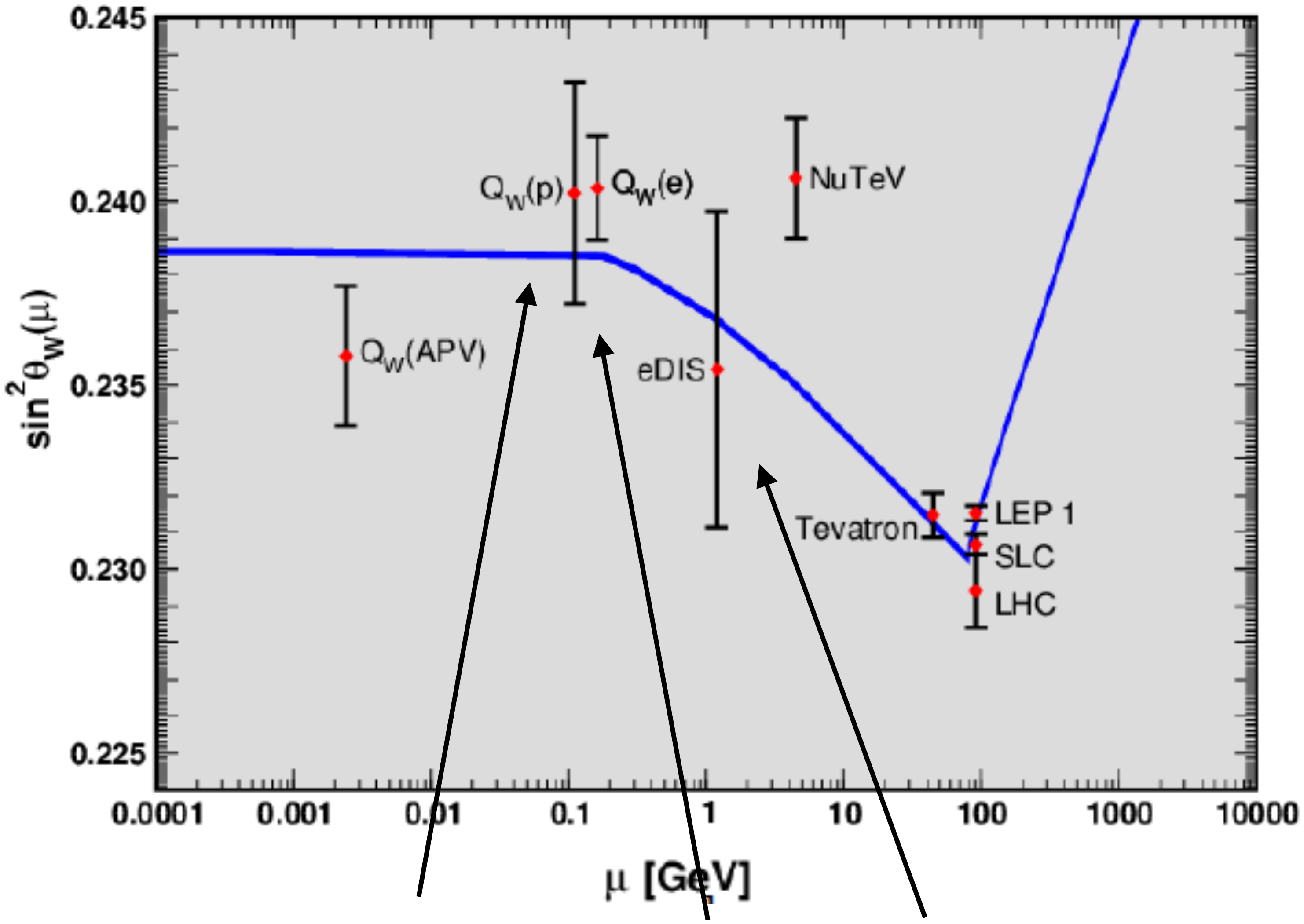
$$A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2 (\mathrm{GeV}^2)$$

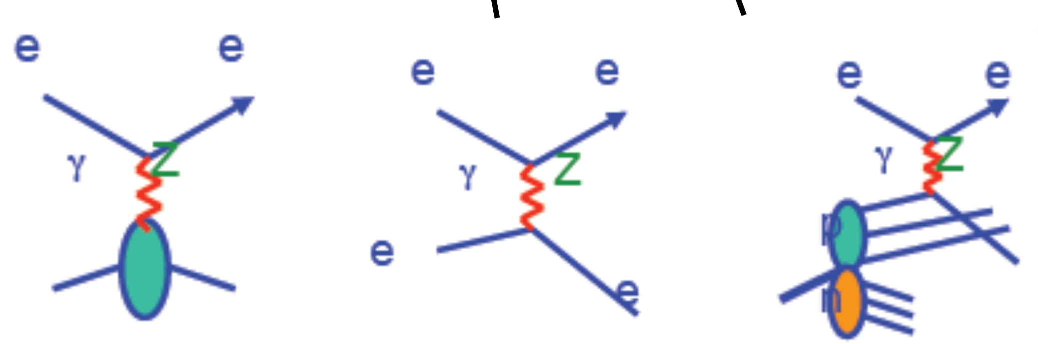
$$Q_W^{(f)} = 2\,T_3^{(f)} - 4\sin^2\theta_W\, Q^{(f)}$$

- Precision tool: low q^2 measurements of θ_W + sensitivity to BSM

Impact of PVES on θ_W

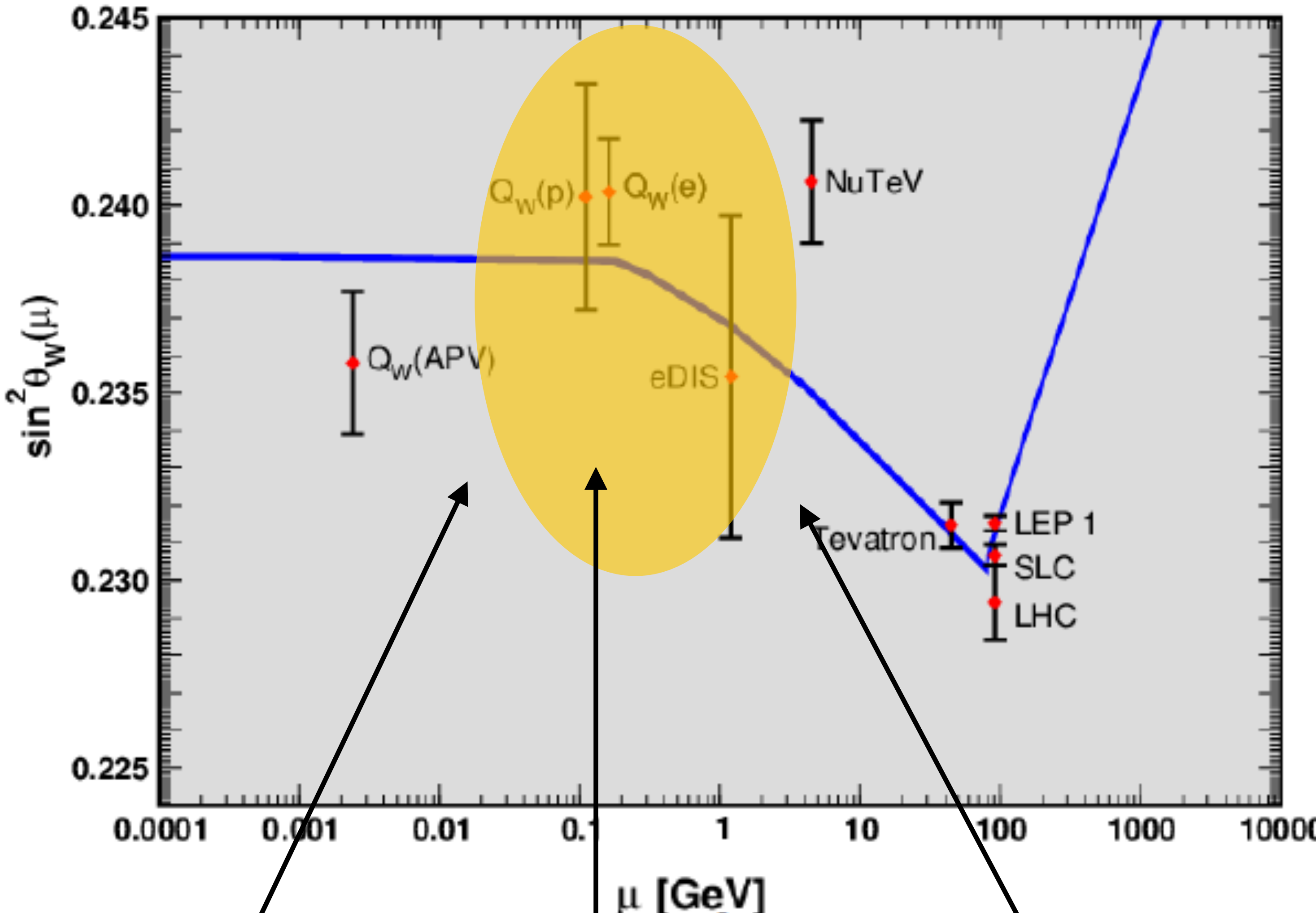


Erler- Freitas
PDG review



First measurement of Qw(p) by Qweak @ JLab, using only 4 % of data

Impact of PVES on θ_W



Erler- Freitas
PDG review

Best Collider $\delta(\sin^2\theta_W)$:
- A_l(SLD): 0.00026
- A_{fb}(LEP): 0.00029

Future projections, similar time scale
- Final Tevatron: ~ 0.00046
- LHC 14 TeV, 300 fb^{-1} : ~ 0.00036
- Note: pdf uncertainties
- MOLLER: ~ 0.00028
- Mainz P2: ~ 0.00032

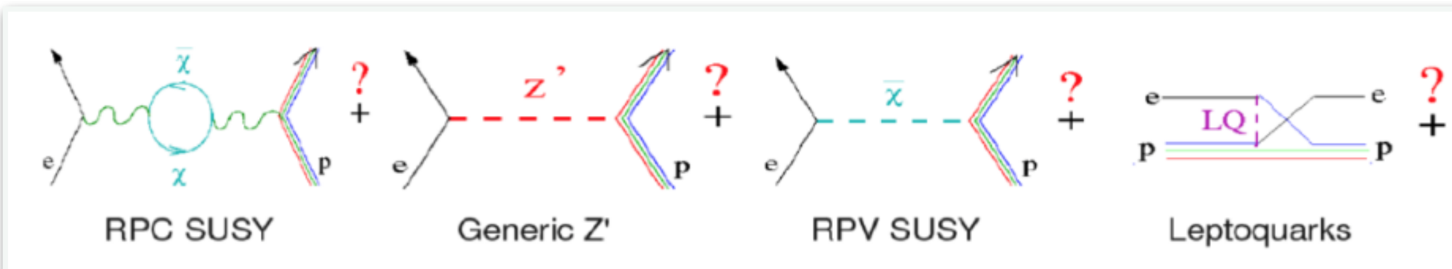
Qweak will improve
Qw(p) by factor of 3

MOLLER@JLab will improve
Qw(e) by factor of 5.
Reach level of Z-pole
measurements!

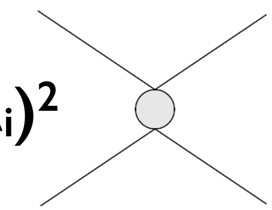
SoLID@JLab will improve
eDIS by factor of ~3

Impact of PVES on new physics

- Sensitivity to heavy new physics parameterized by local operators



$\longrightarrow$ $1/(\Lambda_i)^2$



J. Erler et al.
1401.6199

$\Lambda \sim 5 \rightarrow 9$ TeV (Qweak)

$\Lambda \sim 6$ TeV (SoLID)

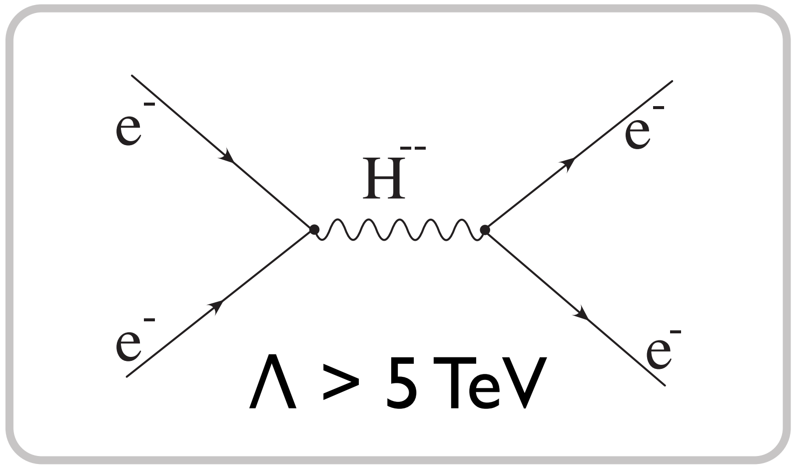
$\Lambda \sim 11$ TeV (MOLLER)

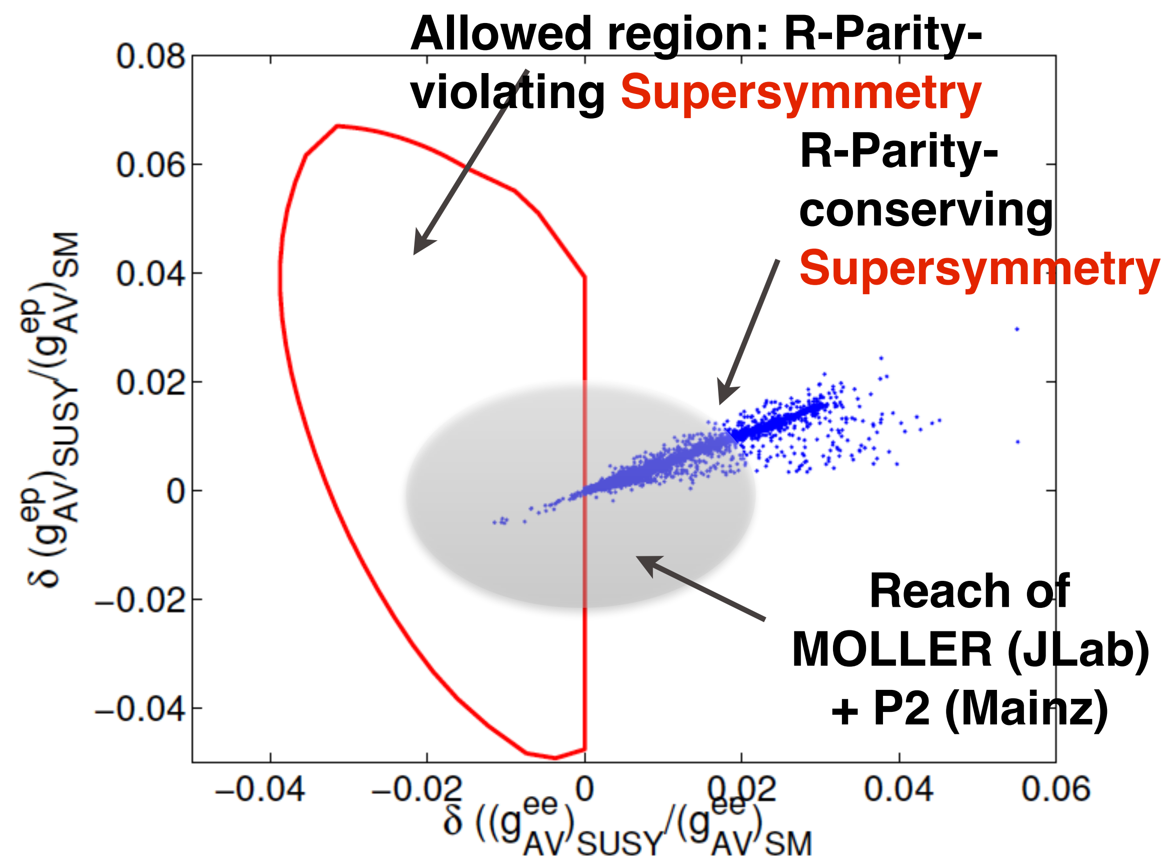
Best contact-interaction reach for leptonic operators, at low OR high-energy

$\Lambda_{LHC} \sim 5$ TeV (di-lepton searches)

Impact of PVES on new physics

- Within SUSY: correlation between $\delta(Q_W^p)$ and $\delta(Q_W^e)$
- MOLLER: sensitivity to doubly charged scalars

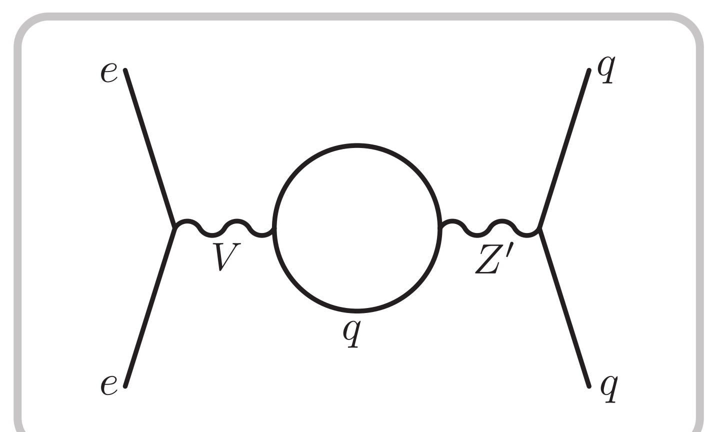




Ramsey-Musolf and Su, Phys. Rep. 456 (2008)

Erler and Su, arXiv:1303.5522

- SOLID: sensitivity to lepto-phobic Z' in 100-200 GeV range

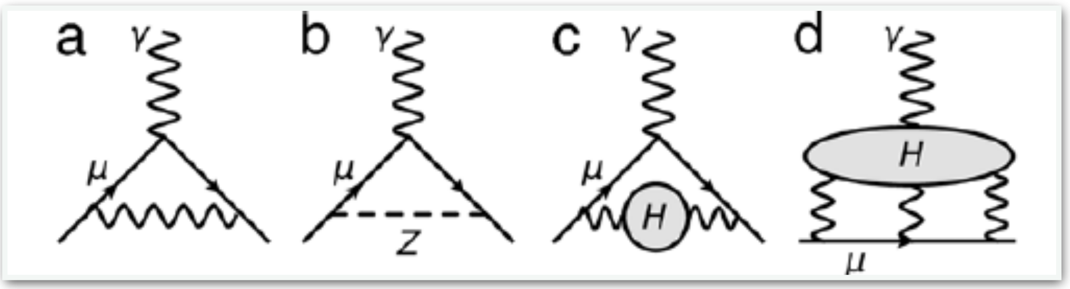


Buckley and Ramsey-Musolf 2012

- All: Sensitivity to dark gauge bosons: correlation with muon g-2

Muon anomalous magnetic moment

SM theory



vs

Experiment

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}$$

$$a_\mu = (g_\mu - 2)/2$$

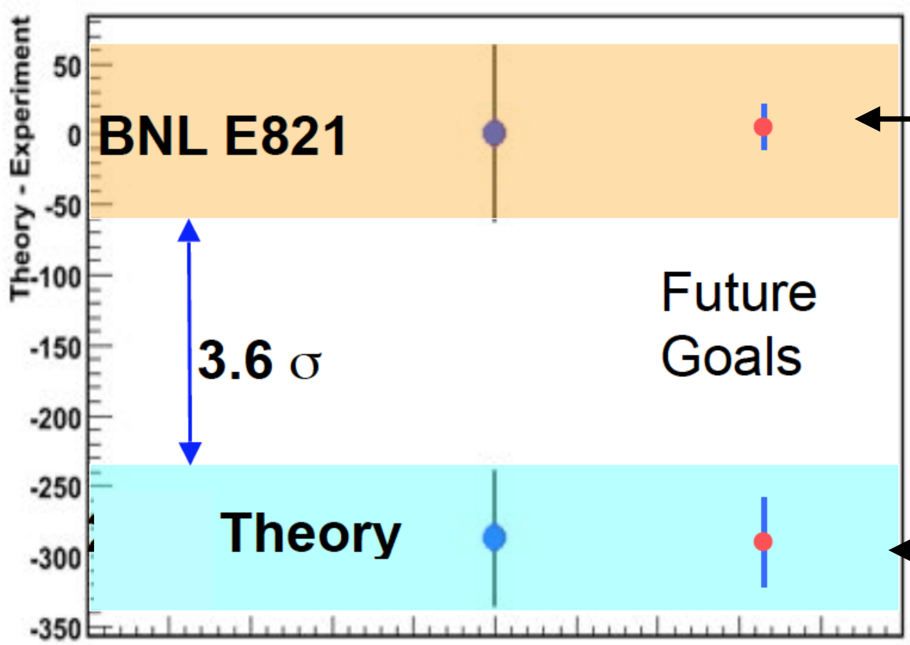
$$a_\mu(\mathrm{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$

$$a_\mu(\mathrm{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

BNL E821 (2006)

$\Rightarrow$ $\Delta a_\mu = 287(80) \times 10^{-11}$ 3.6σ discrepancy

D. Hertzog



Goal: 0.14 ppm

Establish confidence in error bar

Muon anomalous magnetic moment

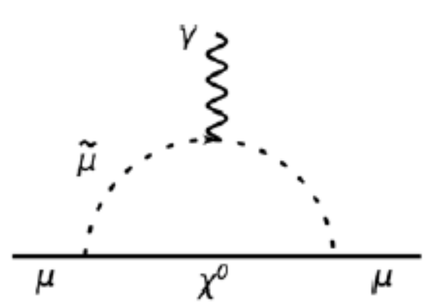
- Huge literature on possible BSM explanations: UV new physics

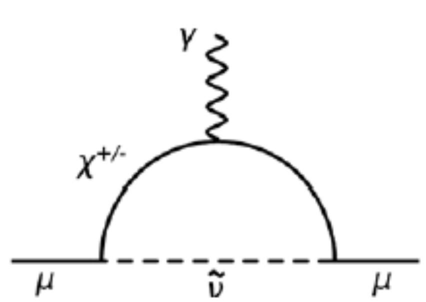
$$\mathcal{L}_{BSM} \to C_\mu \frac{v}{\Lambda^2}\, \bar{\mu}\sigma_{\mu\nu}F^{\mu\nu}\mu \qquad \Rightarrow \qquad \delta a_\mu \sim C_\mu \frac{v\, m_\mu}{\Lambda^2}$$

$$\boxed{\begin{array}{lcl} C_\mu \sim \dfrac{\alpha}{4\pi} & \Rightarrow & \Lambda \sim \mathrm{O}(10)\ \mathrm{TeV} \\ C_\mu \sim \dfrac{\alpha}{4\pi}\dfrac{m_\mu}{v} & \Rightarrow & \Lambda \sim \mathrm{O}(100)\ \mathrm{GeV} \end{array}}$$

Gorringe-Hertzog
1506.01465

- Explicit supersymmetric realization





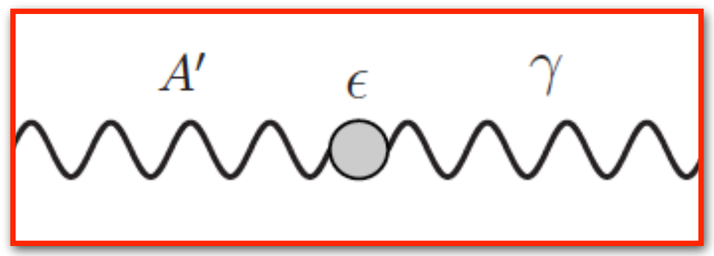
$$a_\mu^{\mathrm{SUSY}} \approx 130 \times 10^{-11} \left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2 \tan\beta\, \mathrm{sign}(\mu).$$

- Sensitive to dark gauge bosons: correlation with PVES

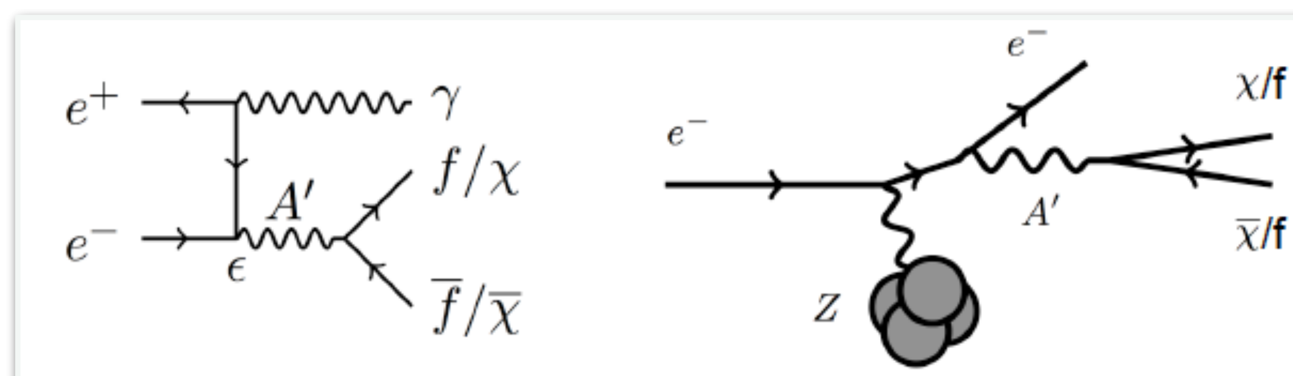
Probing the dark sector

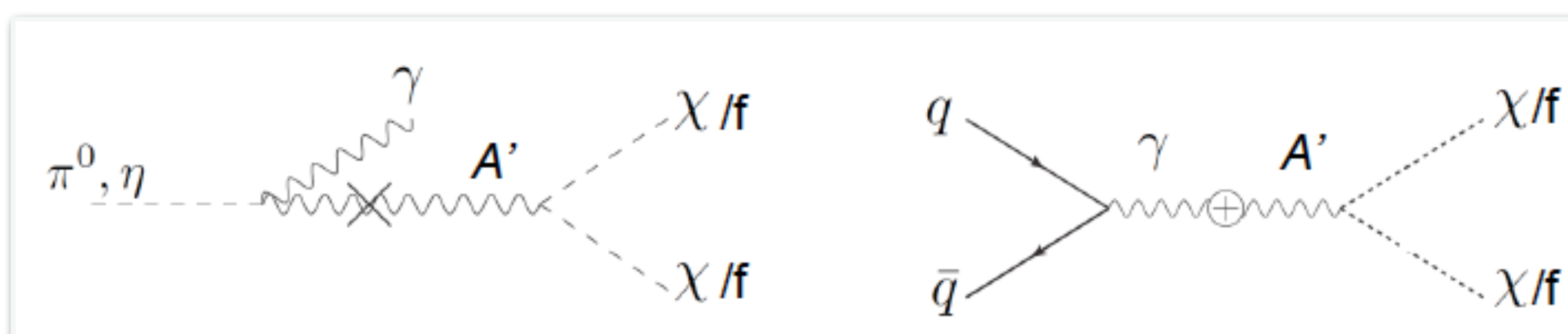
- Dark sector with U(1)$_d$ motivated by dark matter phenomenology
- Dark gauge boson A’ can mix with γ: two parameters ($m_{A'}$, ε)

$$O_{\text{Vector}} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu} \longrightarrow$$



- Production / detection channels

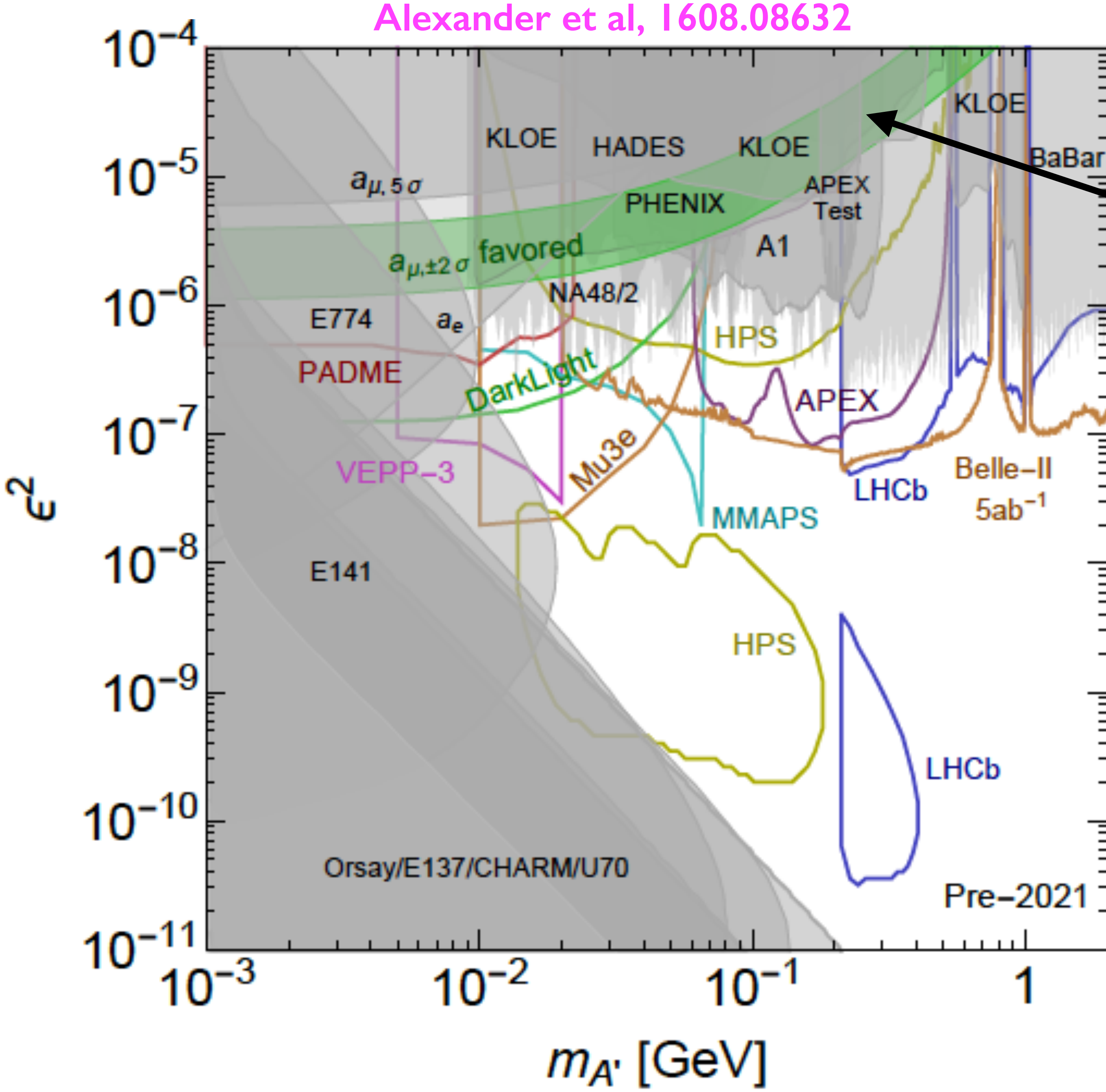




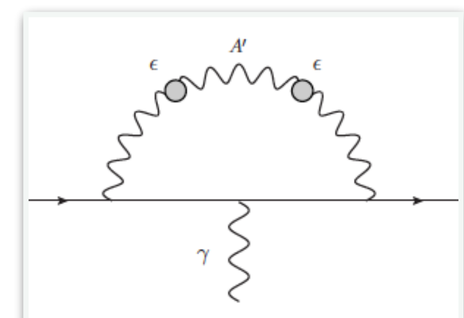
Probing the dark sector

- Dark sector with $U(1)_d$ motivated by dark matter phenomenology
- Dark gauge boson A' can mix with γ: two parameters ($m_{A'}$, ε)

Alexander et al, 1608.08632



BR (A' → l^+l^-)~1



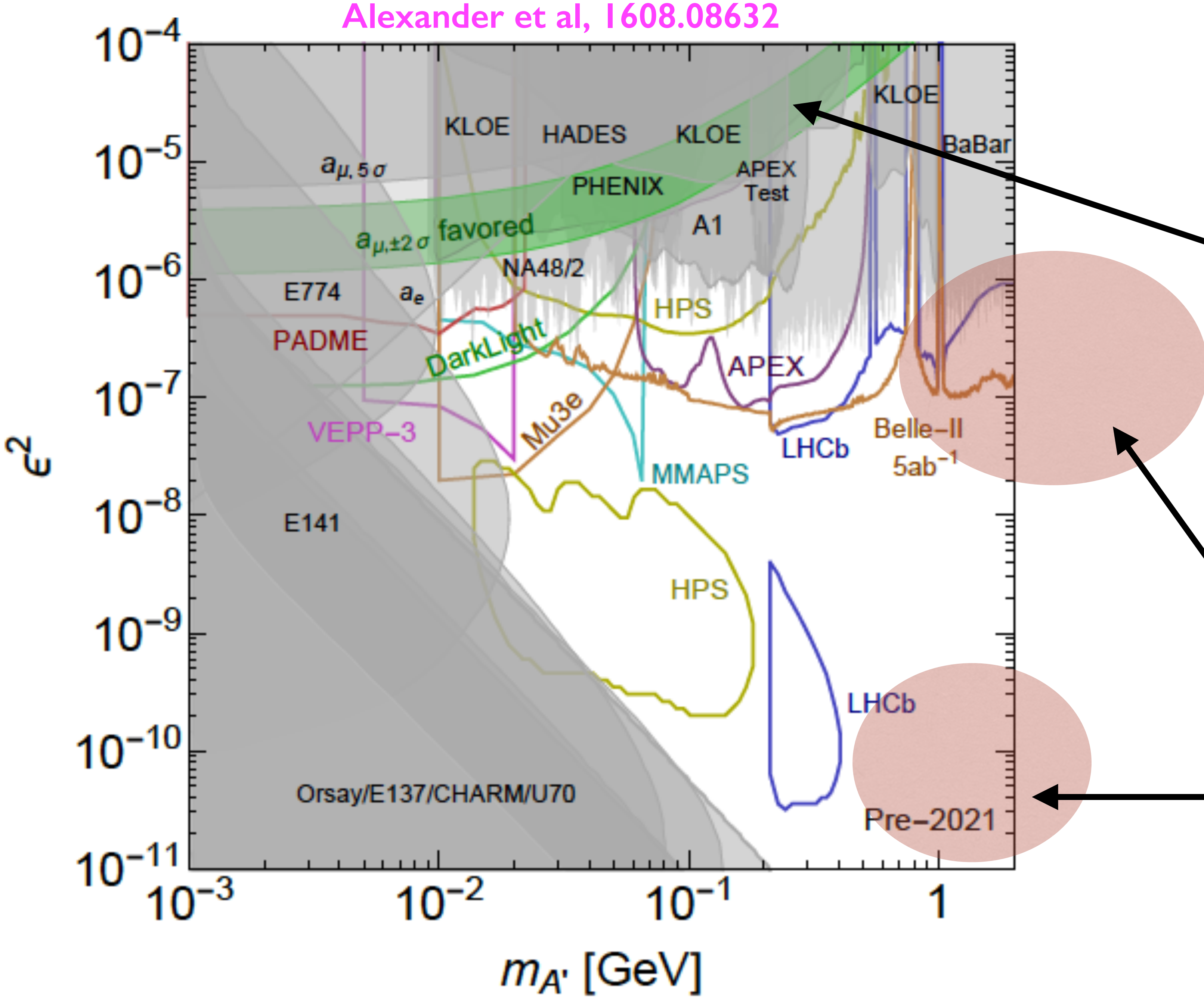
Muon g-2

APEX, DarkLight, and HPS @ JLab play prominent role

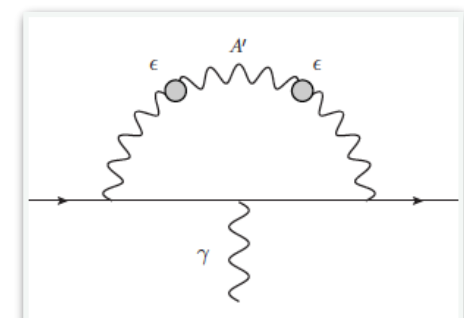
Probing the dark sector

- Dark sector with $U(1)_d$ motivated by dark matter phenomenology
- Dark gauge boson A' can mix with γ: two parameters ($m_{A'}$, ε)

Alexander et al, 1608.08632



BR (A' → l^+l^-)~1



Muon g-2

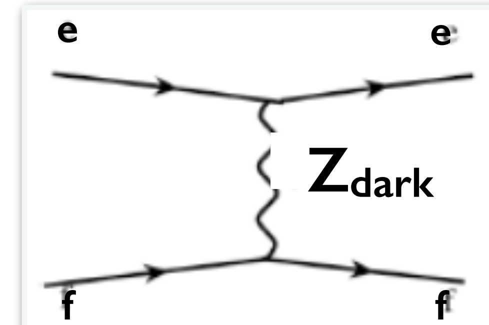
Impact of SeaQuest @ Fermilab
[M. Liu]

Dark Z and precision measurements

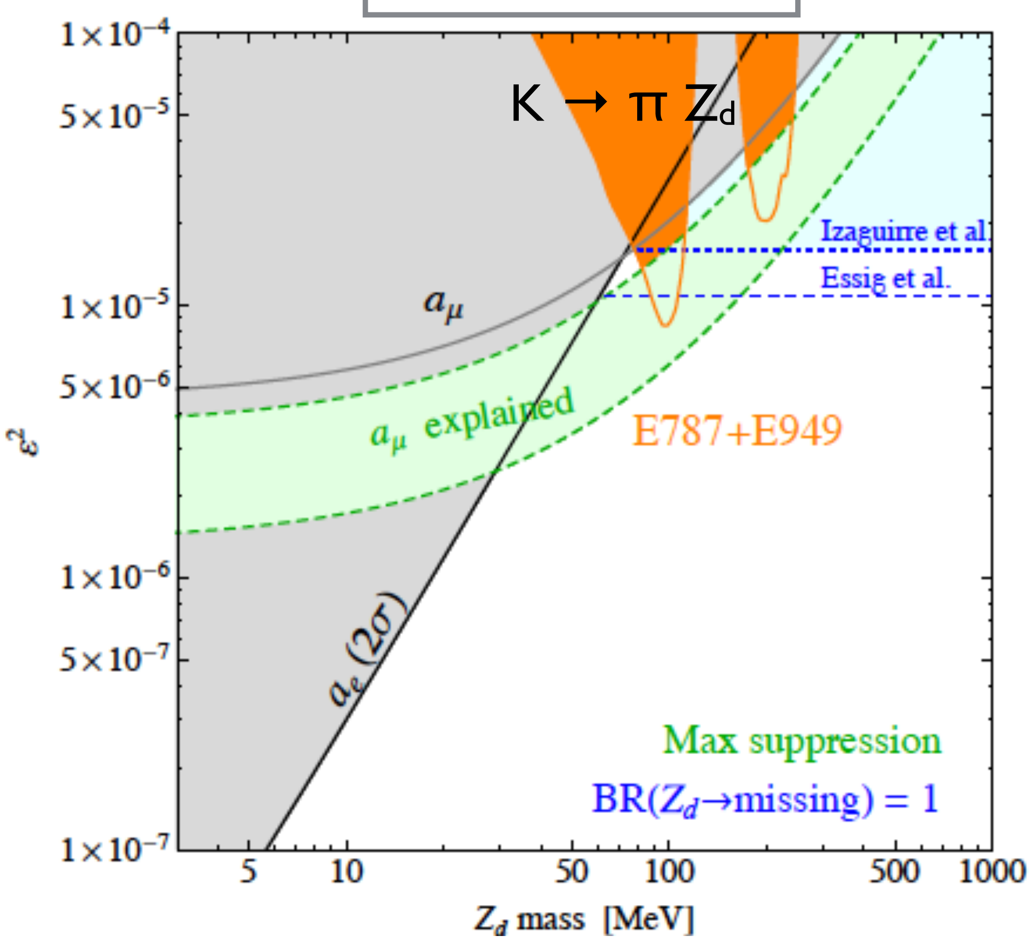
- Beyond minimal: $U(1)_d$ dark gauge boson Z_d can mix with γ and Z

Davoudsial-Lee-Marciano 1402.3620

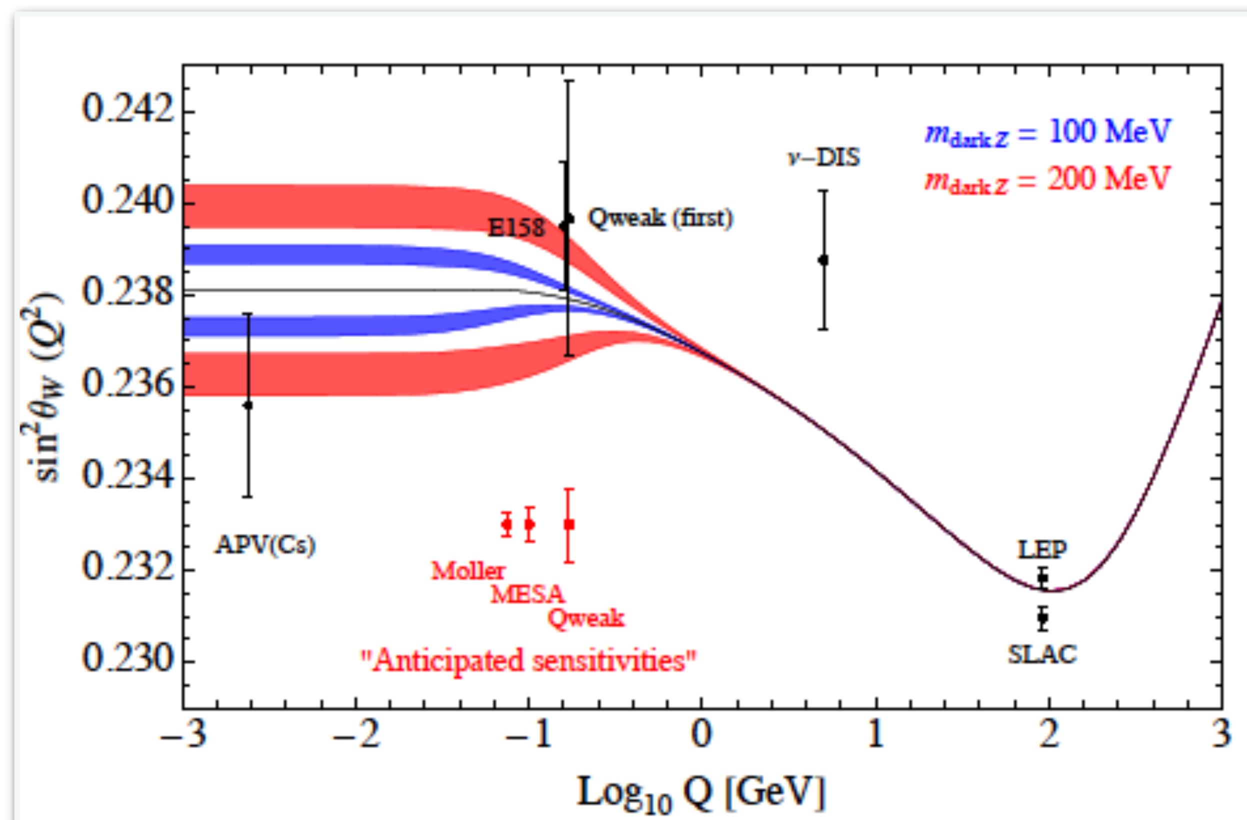
$$\mathcal{L}_{\text{dark } Z} = -\left(\varepsilon e J^{\mu}_{em} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{NC}\right) Z_{d\mu}$$



BR (Z_d → dark)~1

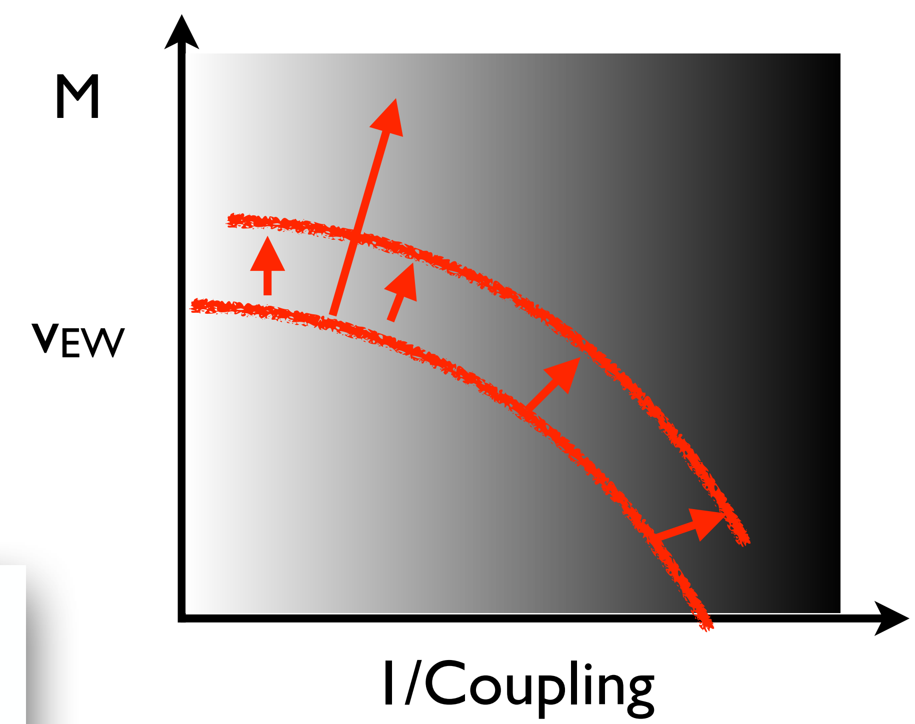


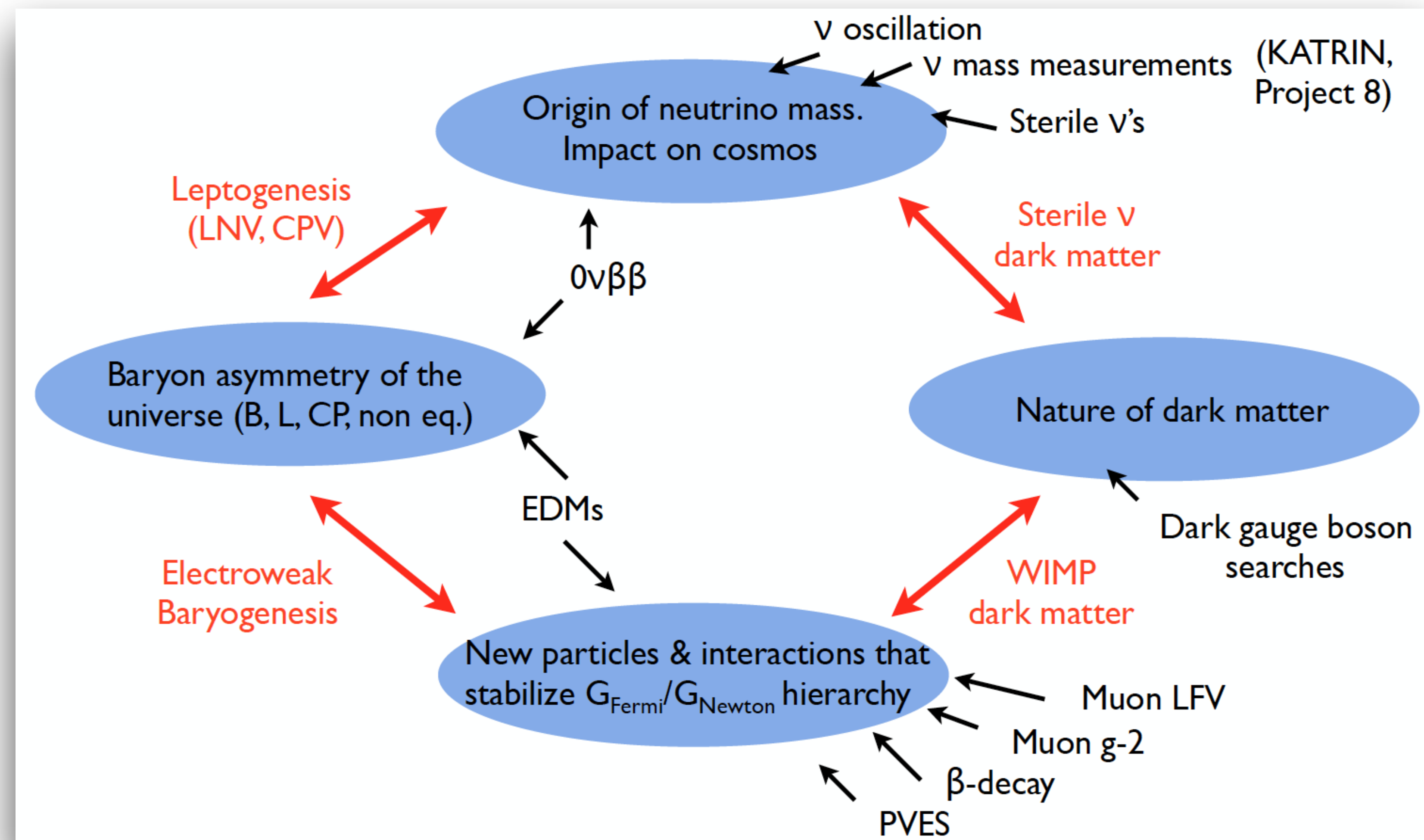
Observable effect in PVES within the parameter region where muon g-2 is explained and bound from K → π Z_d evaded



Concluding comments

- Energy and Precision frontiers are exploring uncharted territory in our search for BSM physics





- Vibrant Nuclear Science portfolio probes BSM dynamics related to open questions about our universe

Concluding comments

- Current / planned nuclear science (NS) experiments provide competitive probes of dark sectors and new physics up to Λ >10 TeV

- Should new physics appear at the LHC, NS probes will be essential in understanding the BSM symmetries and disentangle models

- Should new physics NOT appear at the LHC, the precision frontier will be for a while the only tool to explore new physics

- Patience and determination needed: "Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"
  – A. Soni
  (They found BR($K_L \to \pi\pi$) ~2×10^{-3})