Effectively probing physics beyond the Standard Model

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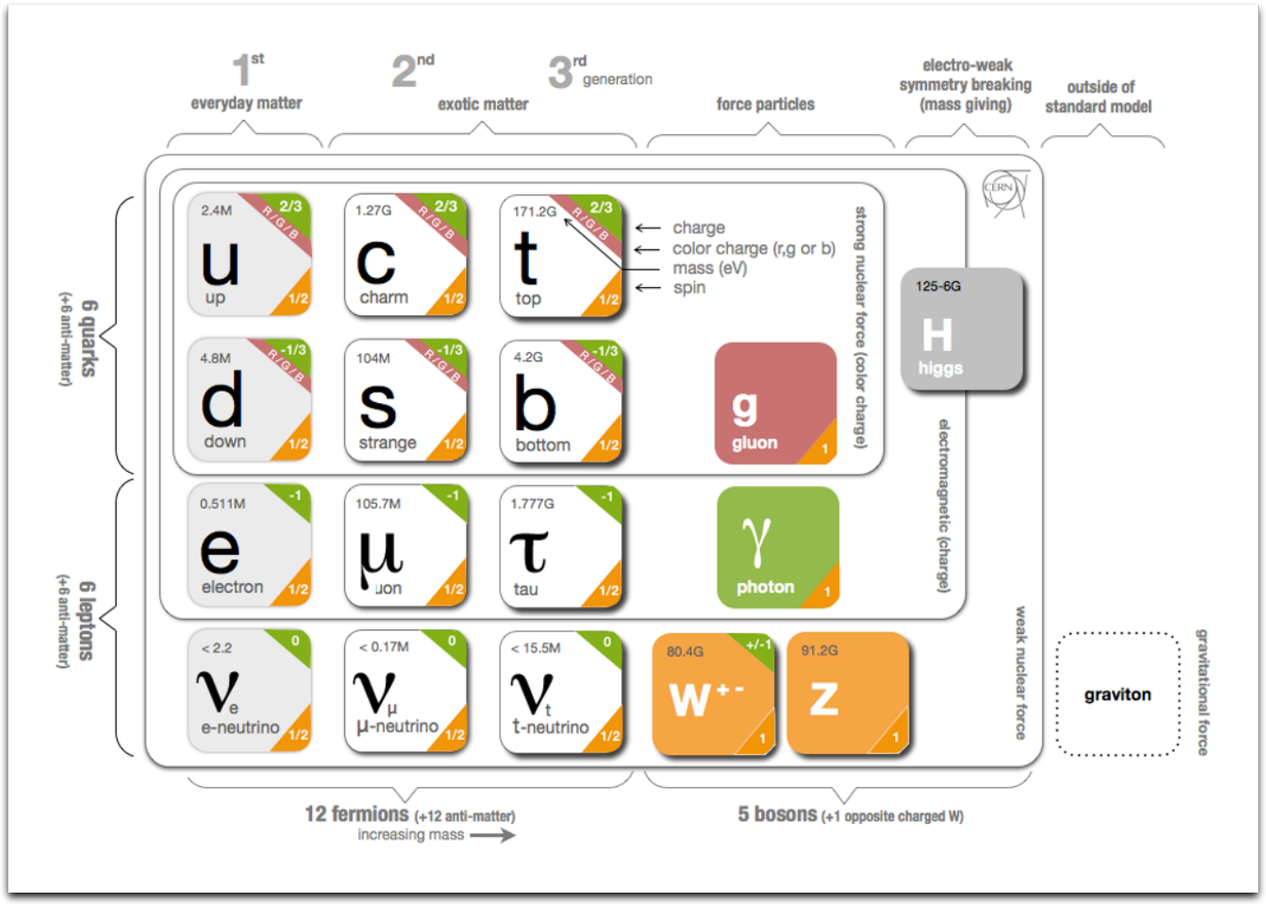
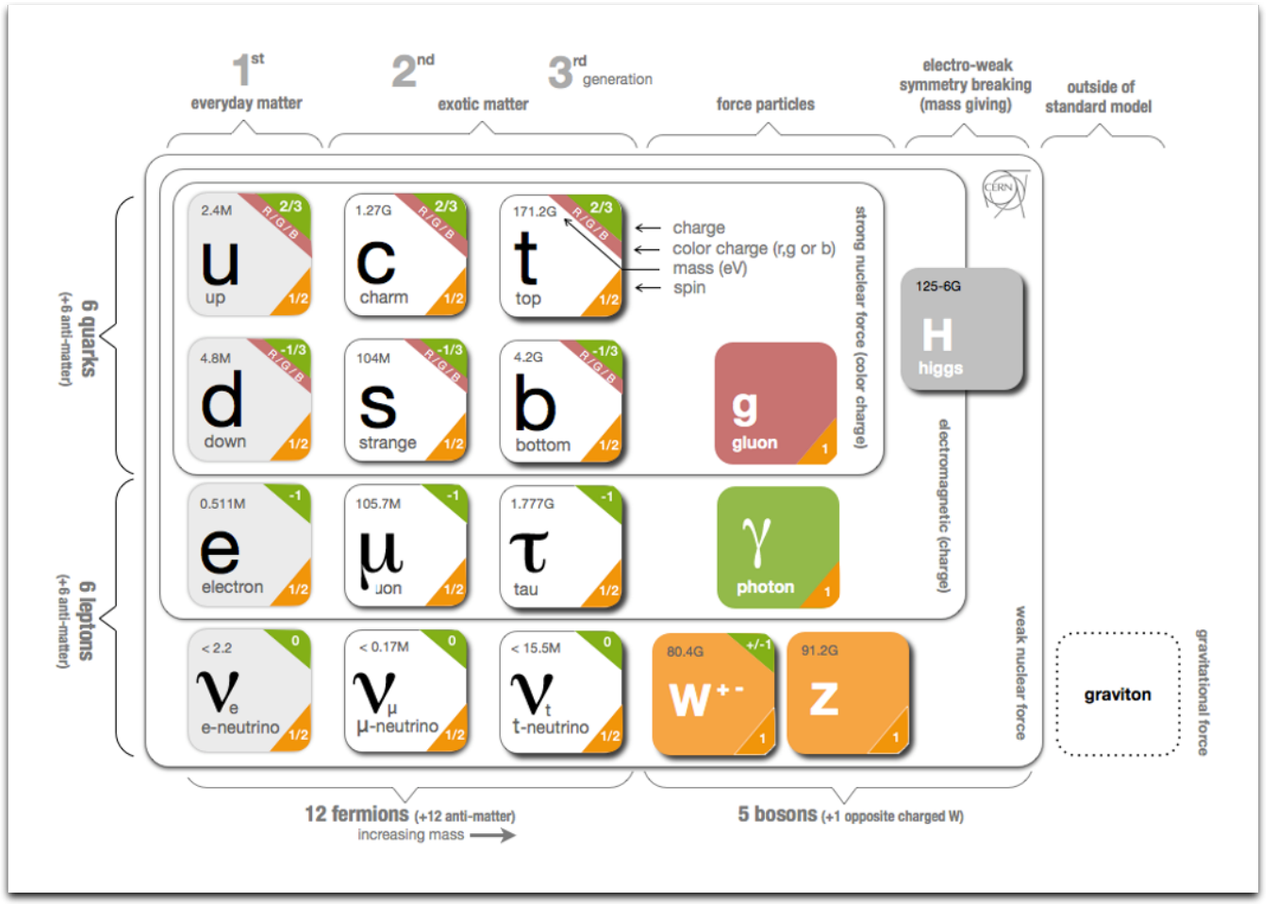
The Standard Model



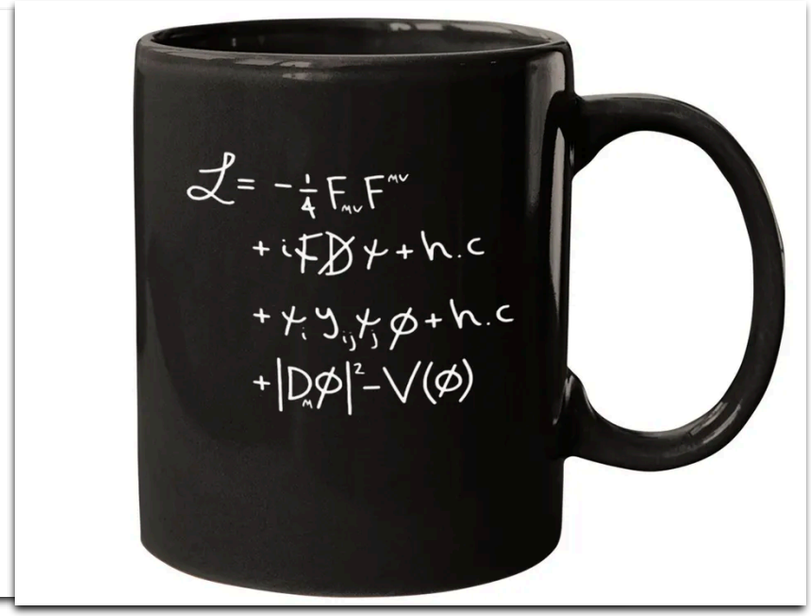
- Describes:
  - All known particles
  - Electroweak force
  - Strong force

The Standard Model



- Describes:
  - All known particles
  - Electroweak force
  - Strong force

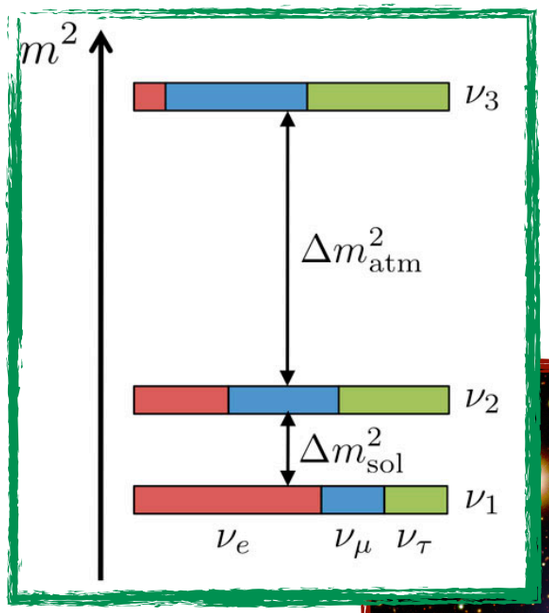
- **Makes a lot of correct predictions**
- (Fits on a coffee mug)



The Standard Model

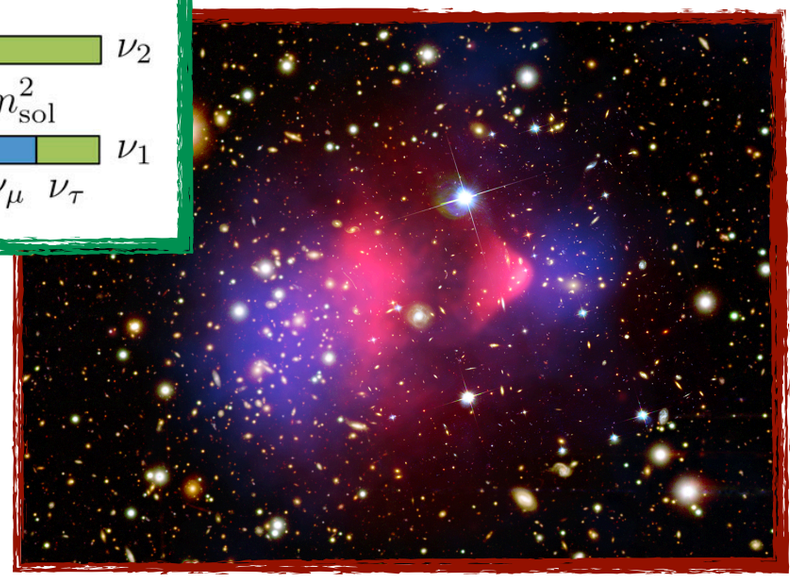
Open questions

Neutrino masses

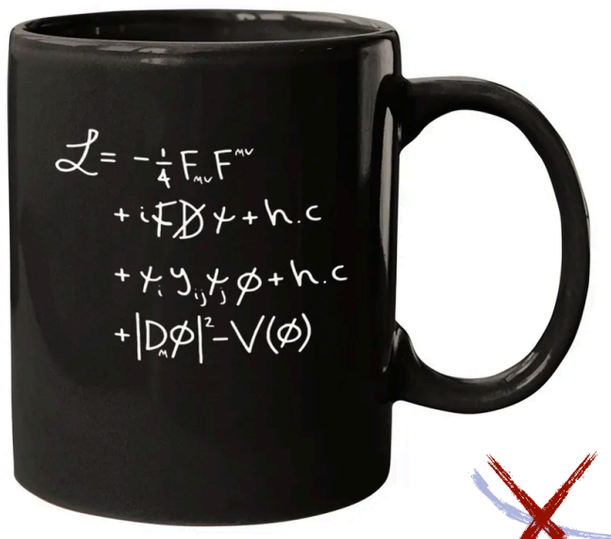


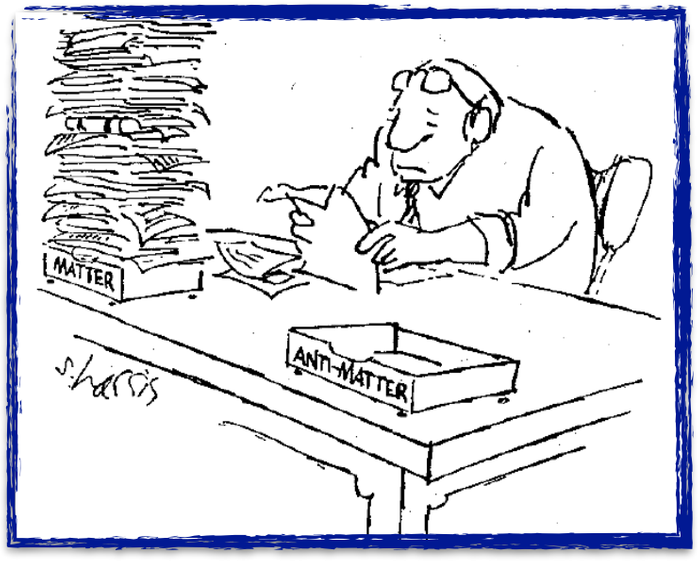
Credit: JUNO Collaboration

Dark Matter



https://chandra.harvard.edu/photo/2006/1e0657/1e0657_hand.html





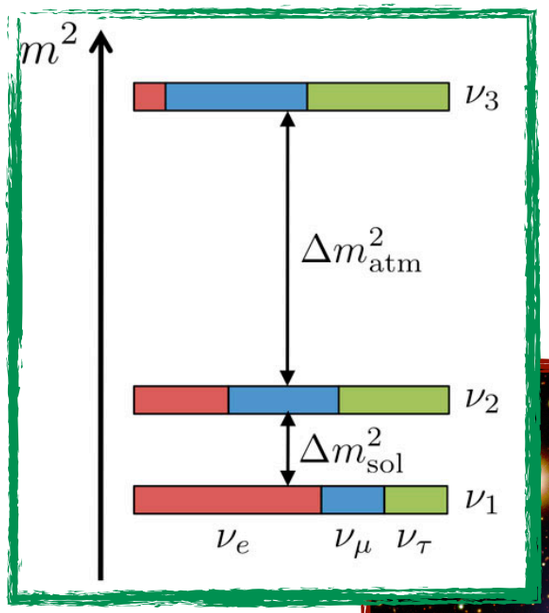
Why there's matter

Are there more than the known 4 forces?

The Standard Model

Open questions

Neutrino masses



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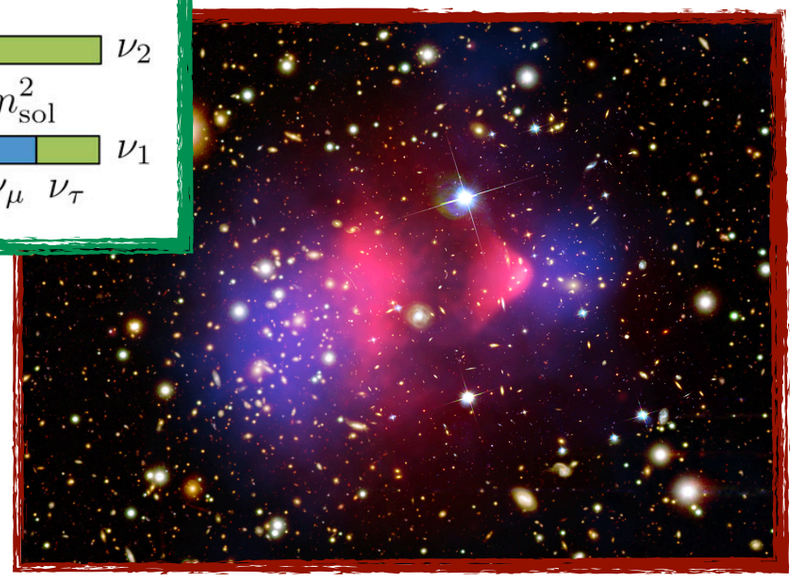

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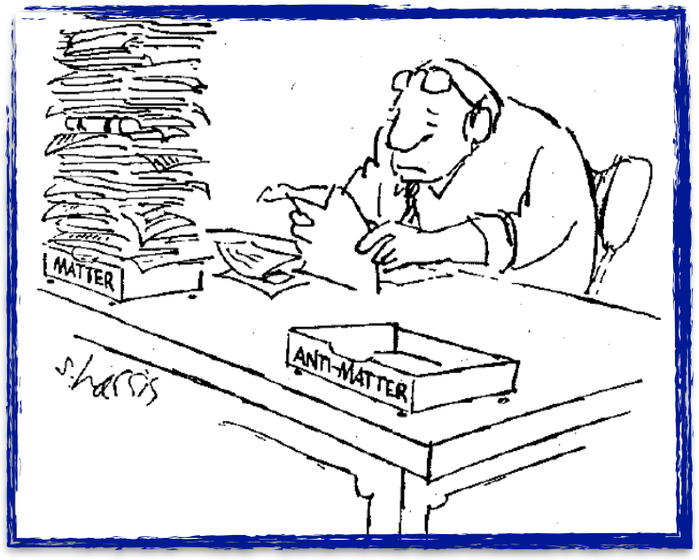
Answers require

new particles and interactions

Are there more than the known 4 forces?

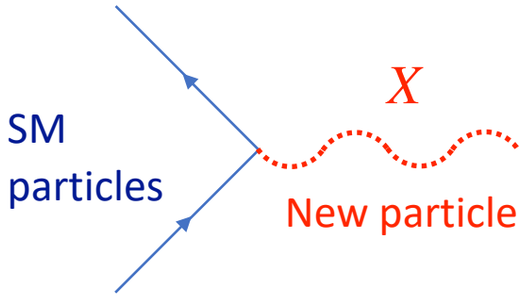


Why there's matter

How to find new physics

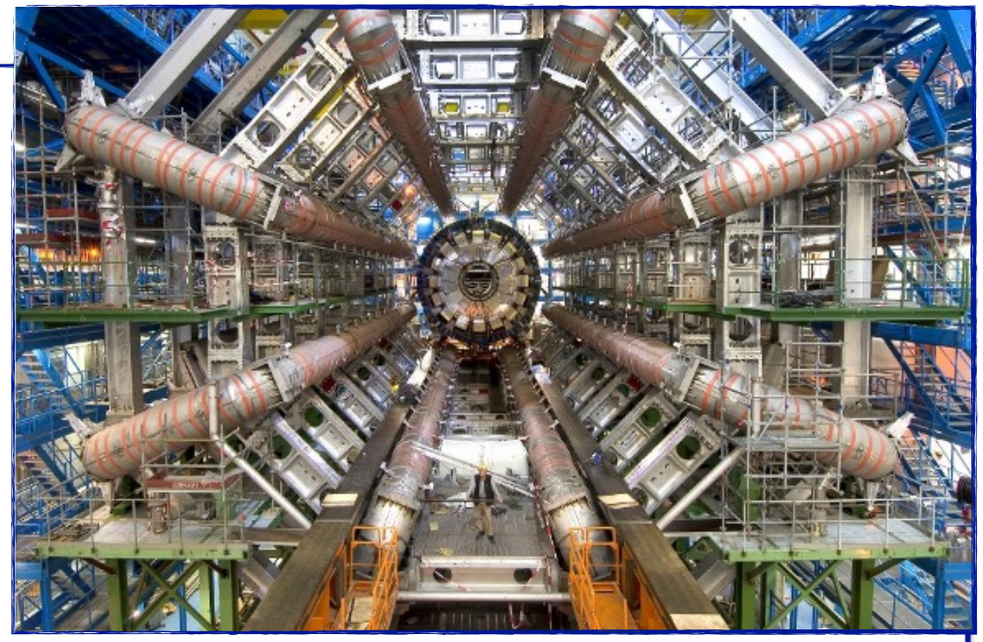
Produce it directly

- **Energy frontier**



- Requires $E > m_X \Longrightarrow$ colliders

Large Hadron Collider



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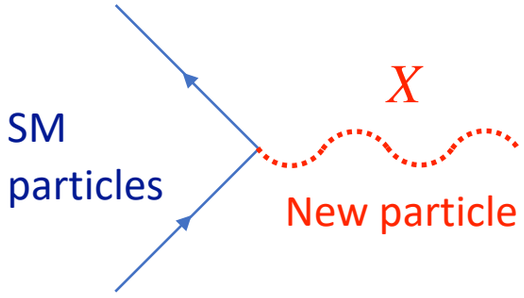

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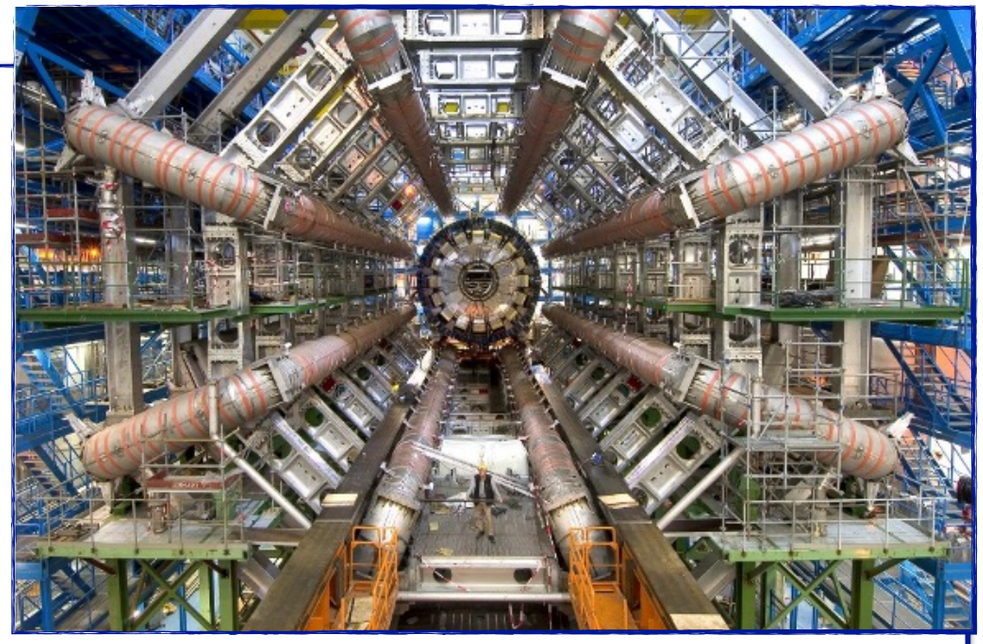
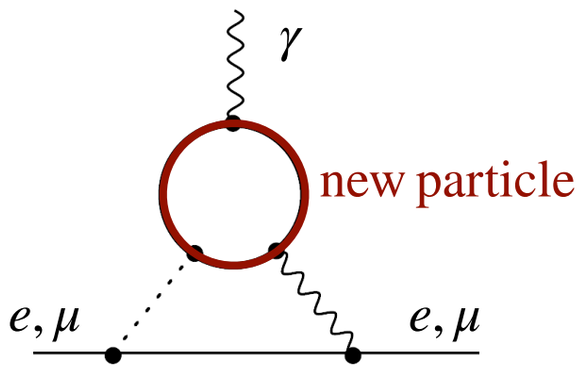
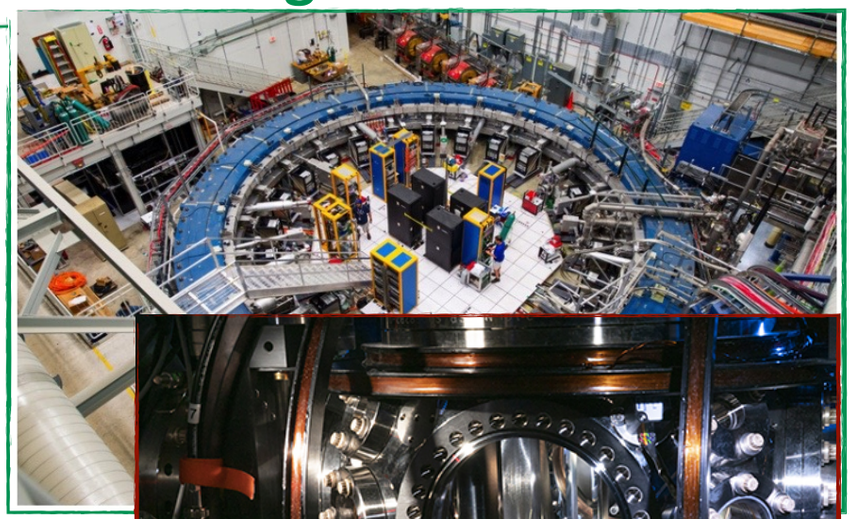


Probe indirect effects



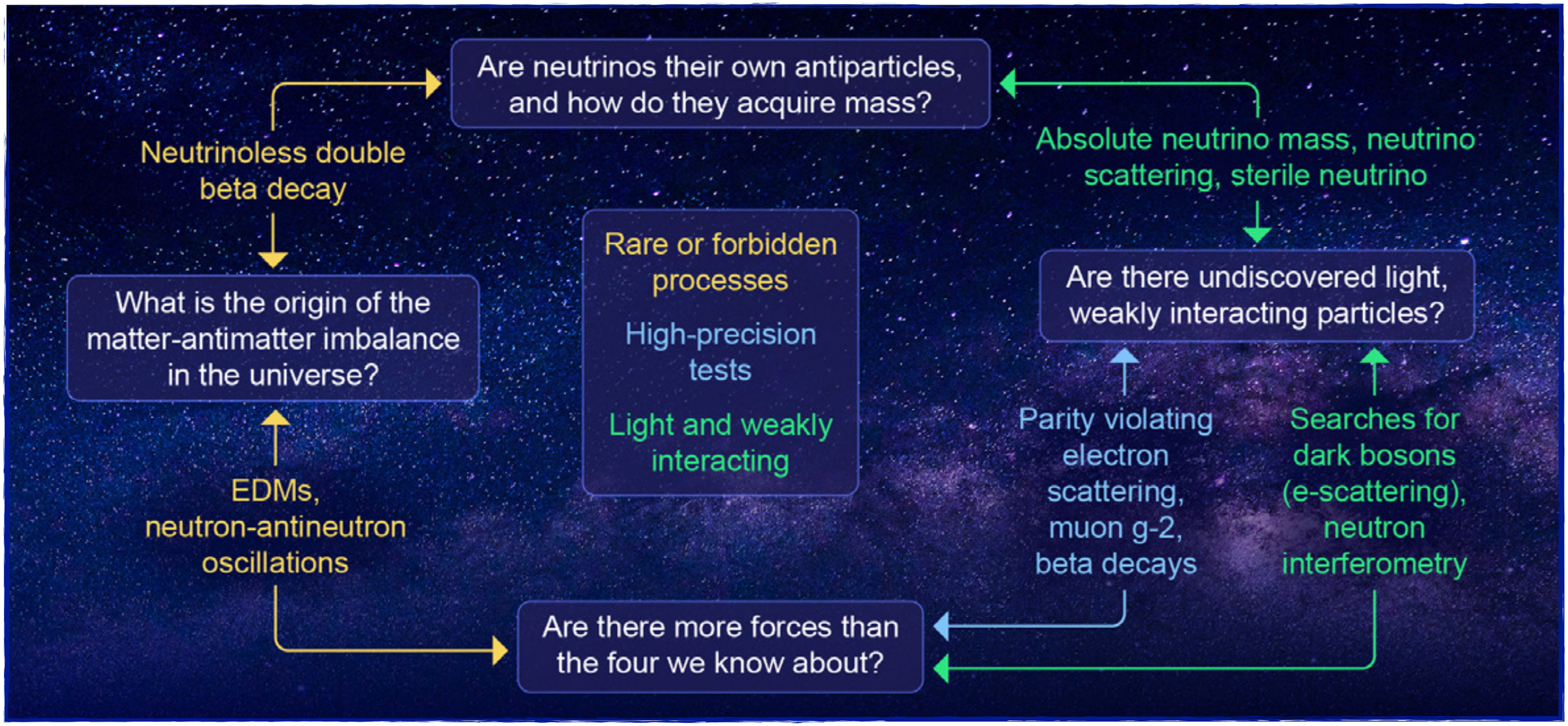
- **Precision frontier**
  - Compare SM prediction to experiment
- **Rare/forbidden processes**
  - Non-zero measurement = discovery

Muon magnetic moment



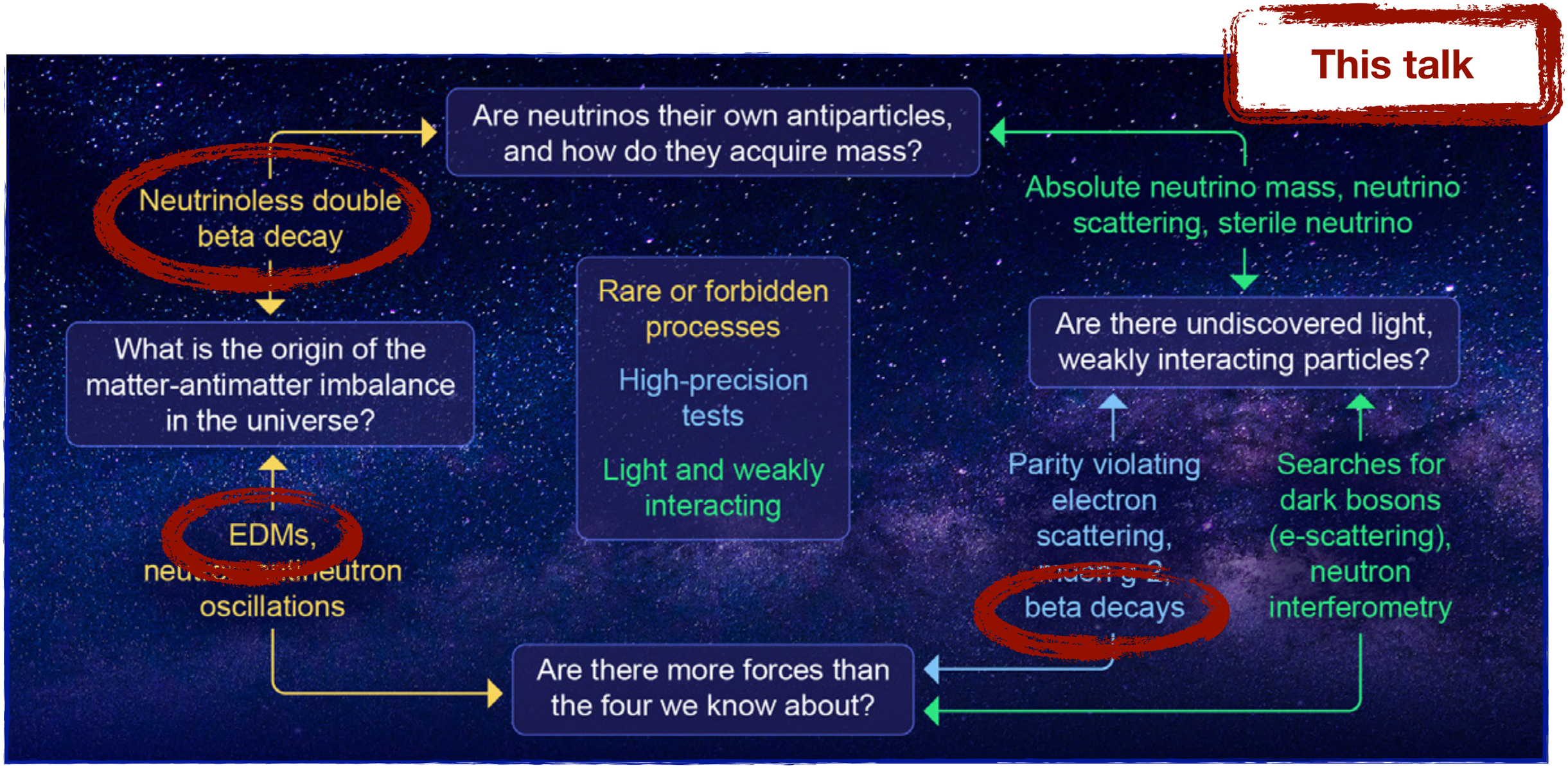
HfF Electric dipole moment

How to find new physics



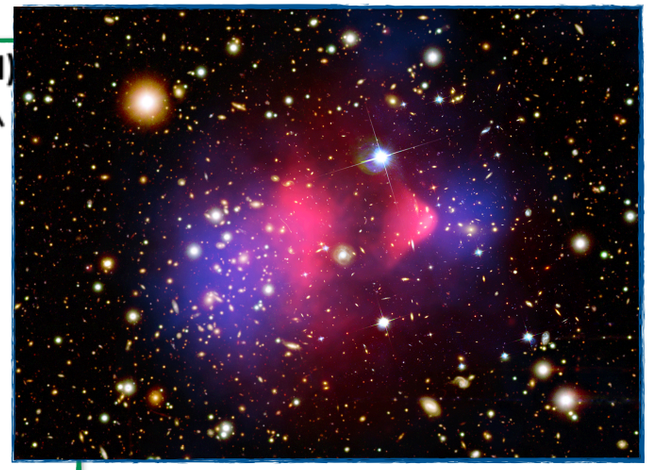
2023 Long Range Plan for Nuclear Science

How to find new physics

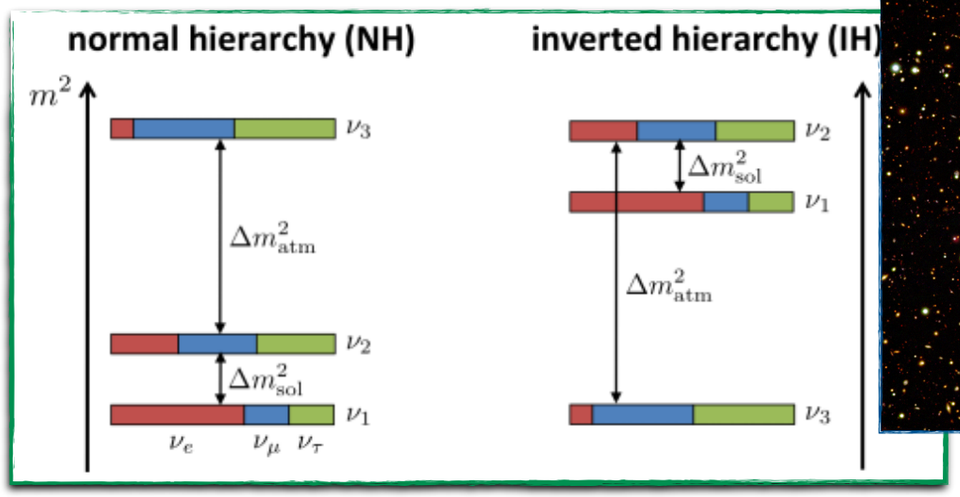


2023 Long Range Plan for Nuclear Science

Dark Matter



Neutrino masses



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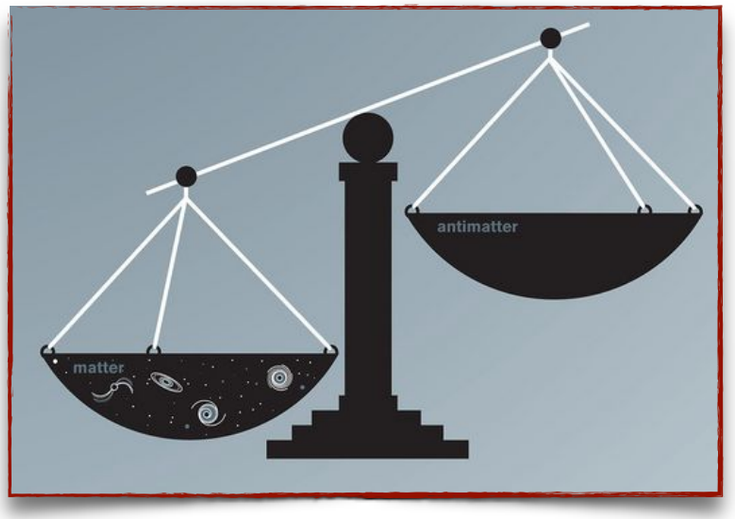


Matter-antimatter imbalance

BSM explanations

Connection to experiments requires Nuclear Theory

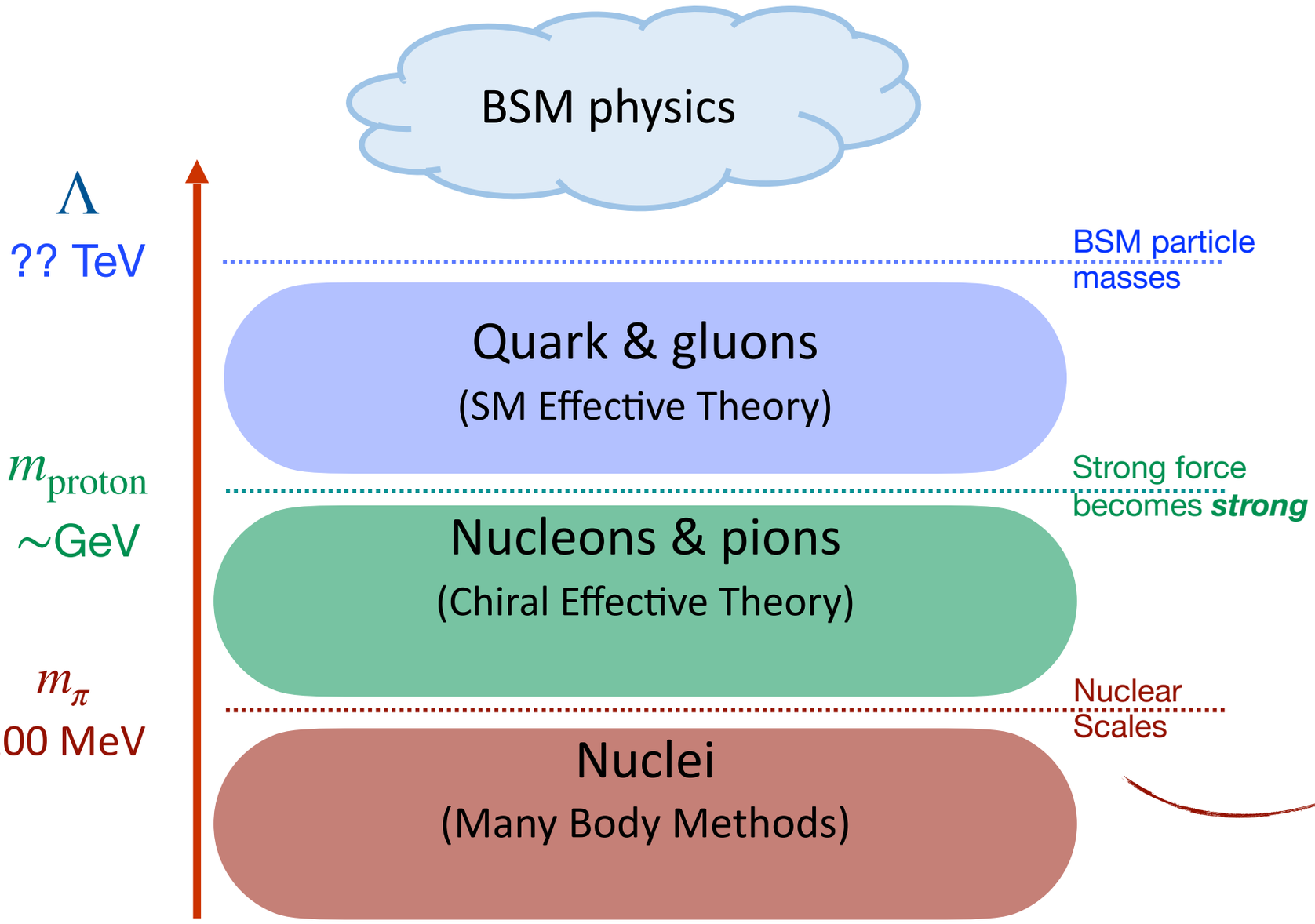
Energy frontier
- LHC

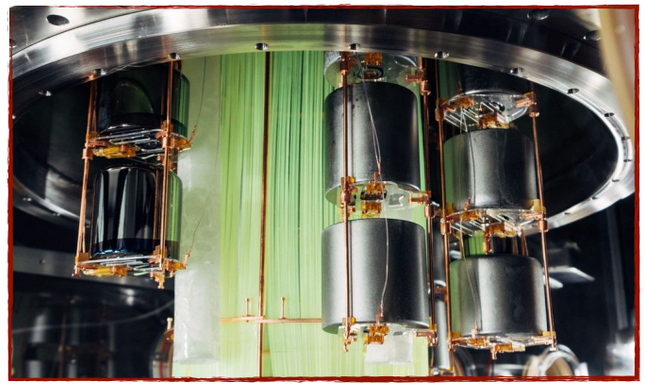
Precision frontier
- Neutron decays
- Nuclear β decay

Rare processes
- $0\nu\beta\beta$
- EDMs

Developed EFT framework for BSM in $0\nu\beta\beta$

From BSM scales to nuclear scales

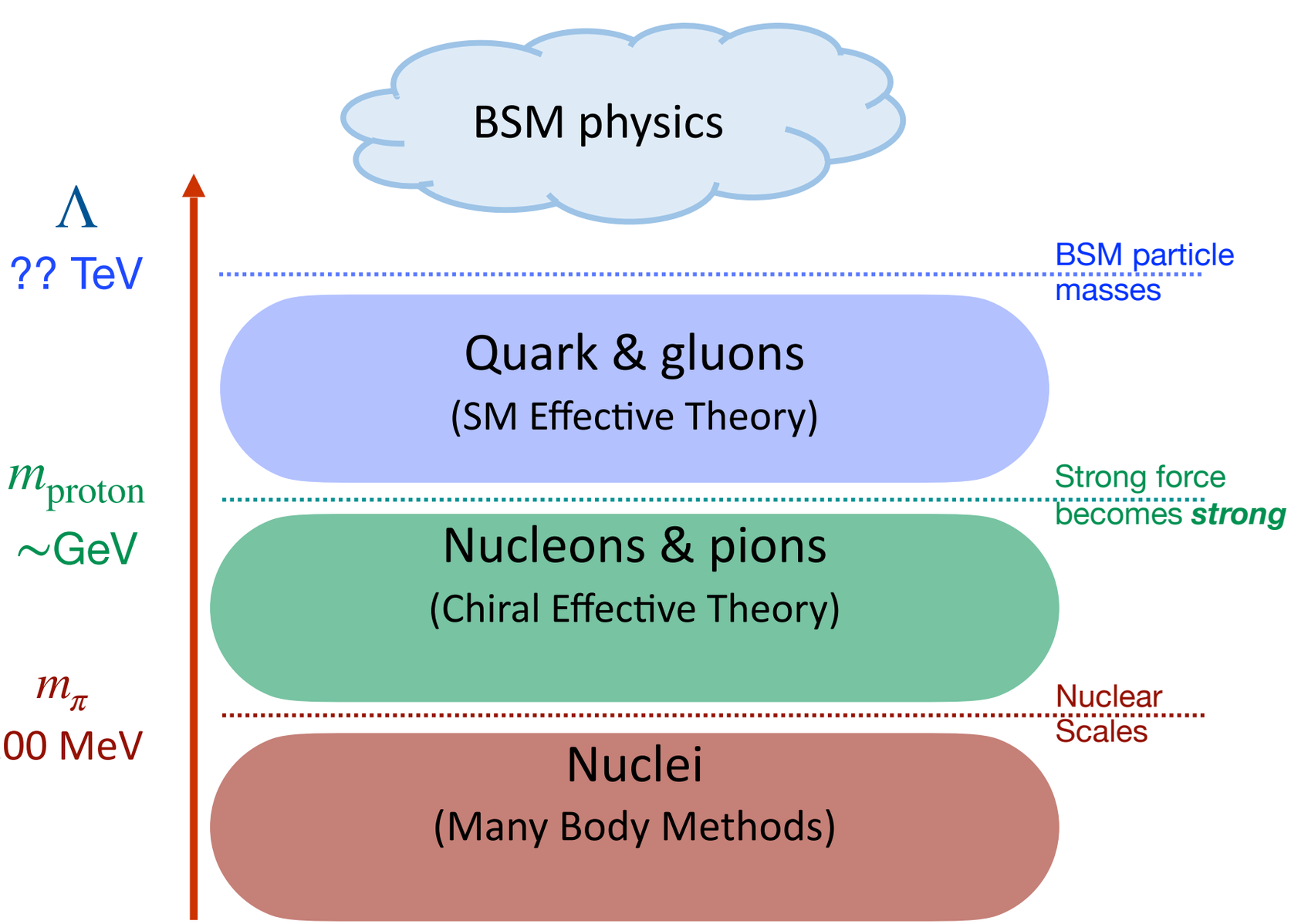


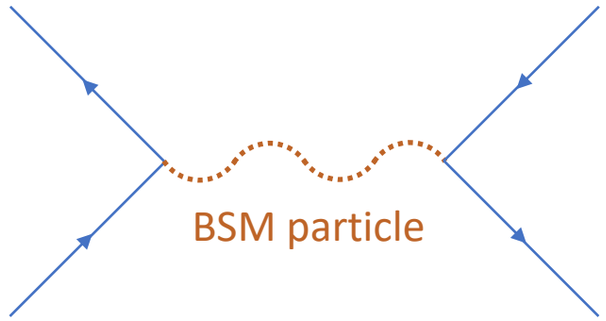


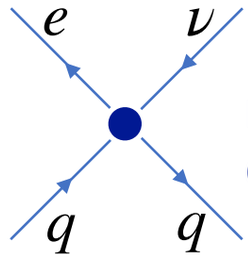
$0\nu\beta\beta$ LEGEND (ORNL US lead lab)

Developed EFT framework for BSM in $0\nu\beta\beta$

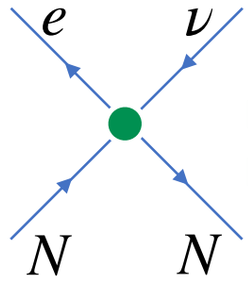
From BSM scales to nuclear scales







Effective interaction
Quark & gluons



Effective interaction
Nucleons & pions

Heavy LNV BSM: WD et al, JHEP '17,18

Light sterile neutrinos: WD et al. JHEP '20; PRC '23; JHEP '24

Lepton-number violation:
Neutrinoless double beta decay

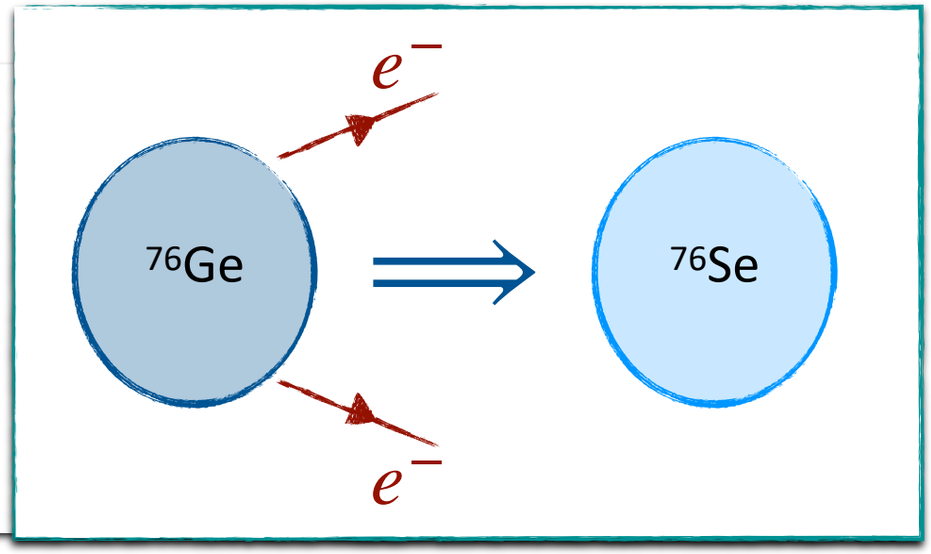
Neutrinoless Double beta decay

What & why?

What is $0\nu\beta\beta$?

- $A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 0\,\bar{\nu}$

- Lepton Number Violating (LNV)



Neutrinoless Double beta decay

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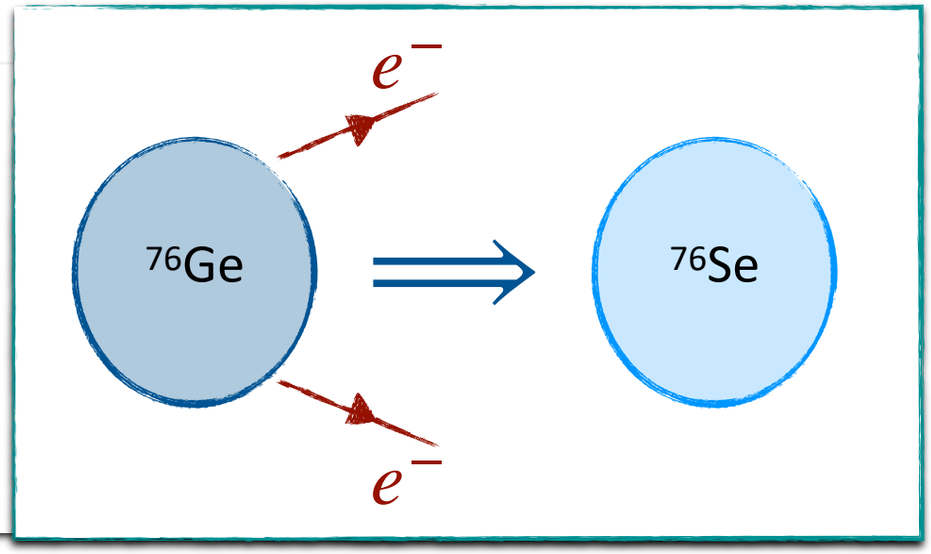
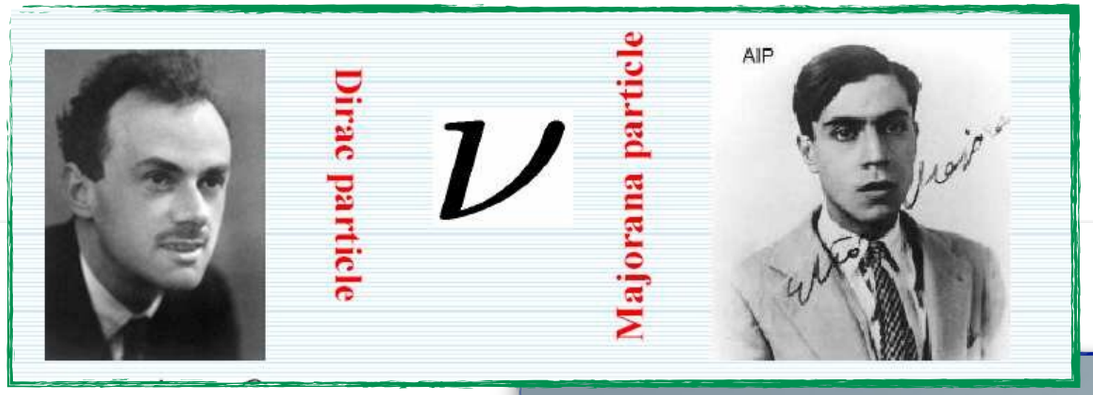
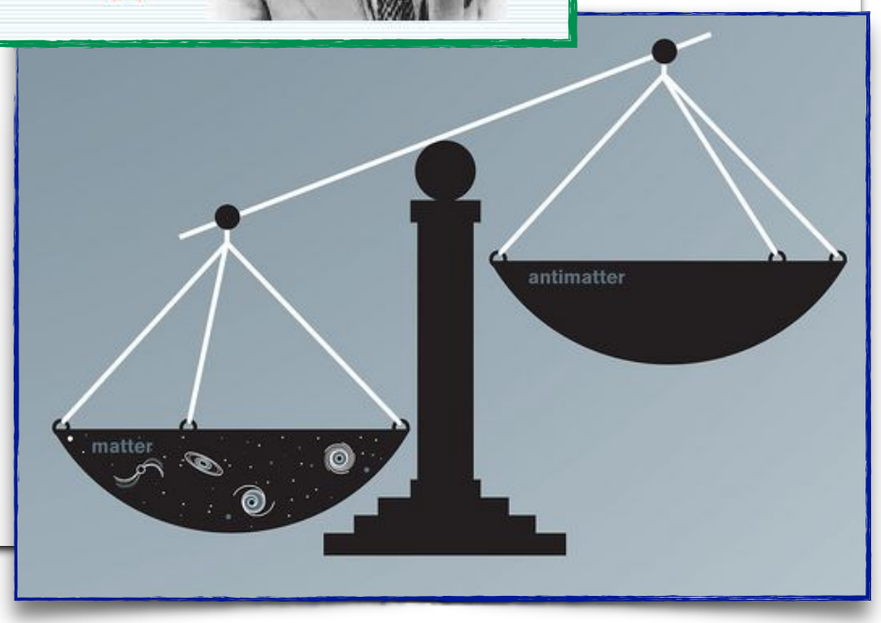


Why look for $0\nu\beta\beta$?

- Detection sheds light on:
  - **Neutrino masses**
    - **Observation would show that ν's are Majorana particles**
  - **Matter-antimatter asymmetry**



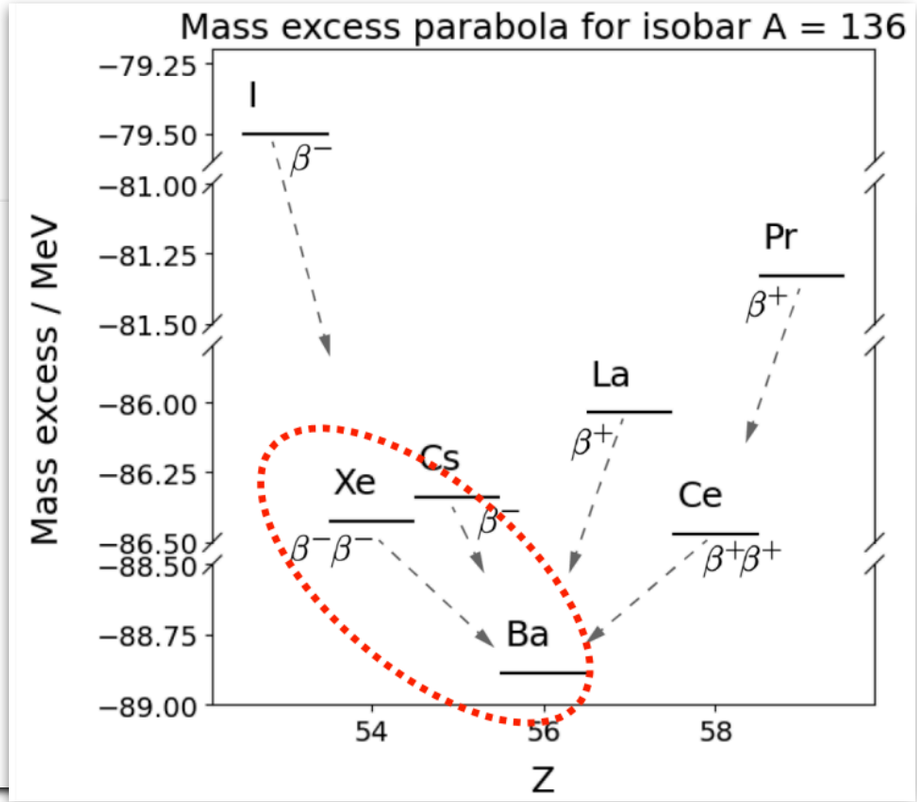


Schechter, Valle, `82

Neutrinoless Double beta decay

How?

- Use certain even-even nuclei
  - No background from single-β decay



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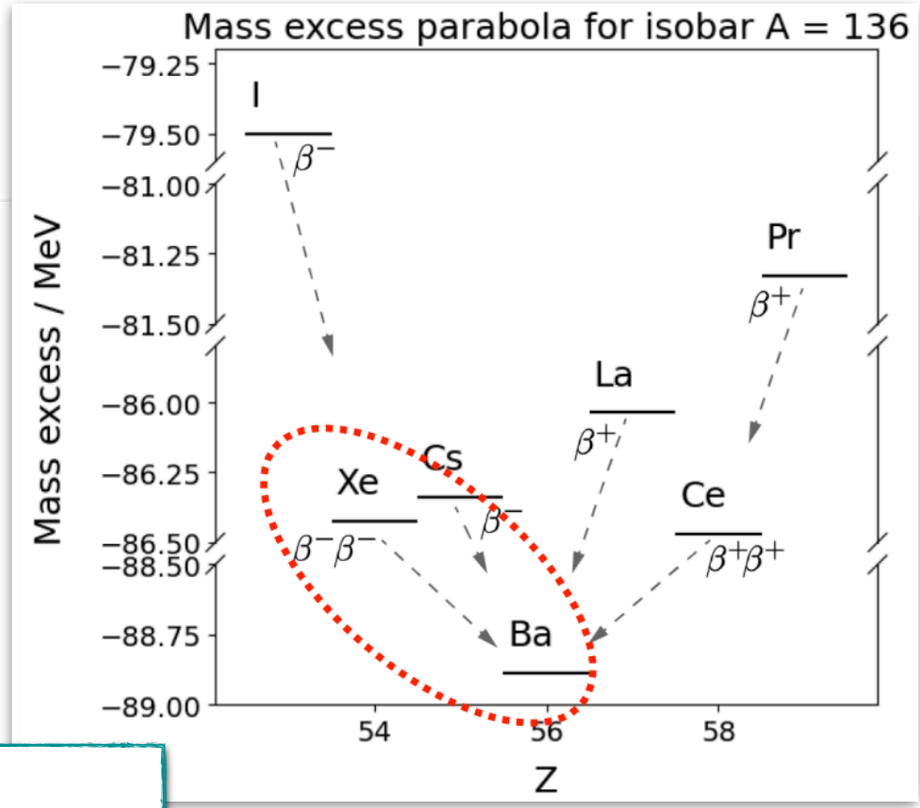
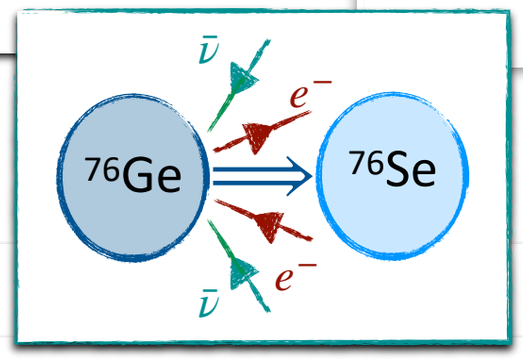
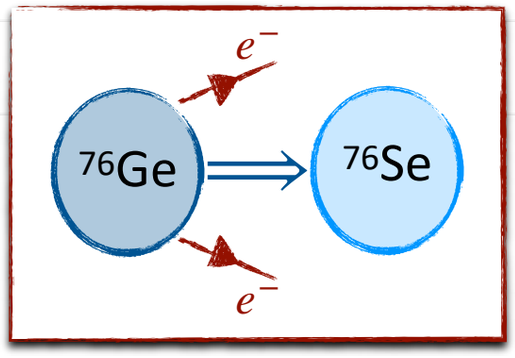


- Distinguish $2\nu\beta\beta$ from $0\nu\beta\beta$
  - $0\nu\beta\beta$ electron energy is fixed





Neutrinoless Double beta decay

How?

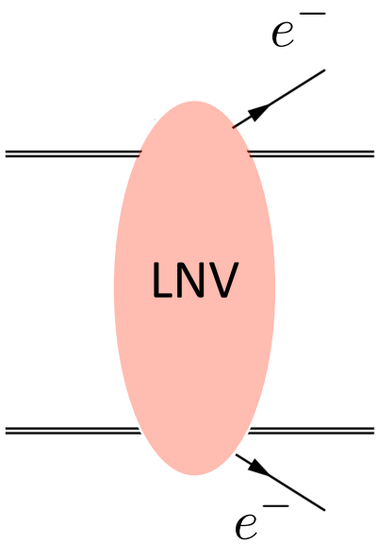
- Very strong limits on the half-life
  - $\sim 10^{16} \times$ [age of the universe]

Gerda (Germanium)	Cuore (Tellurium)	KamLAND-zen (Xenon)
$> 1.8 \cdot 10^{26}$ yr	$> 3.2 \cdot 10^{25}$ yr	$> 3.8 \cdot 10^{26}$ yr

- Future reach, 1-2 orders improvement
  - E.g. LEGEND (ORNL lead US lab)

Neutrinoless Double beta decay

What could be responsible?



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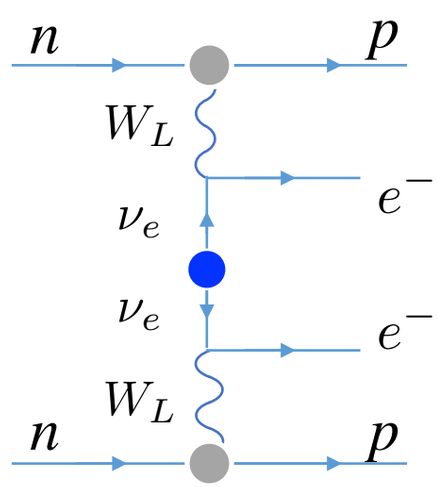
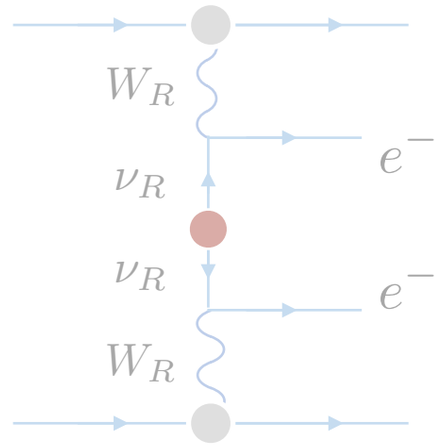
Light Majorana mass?

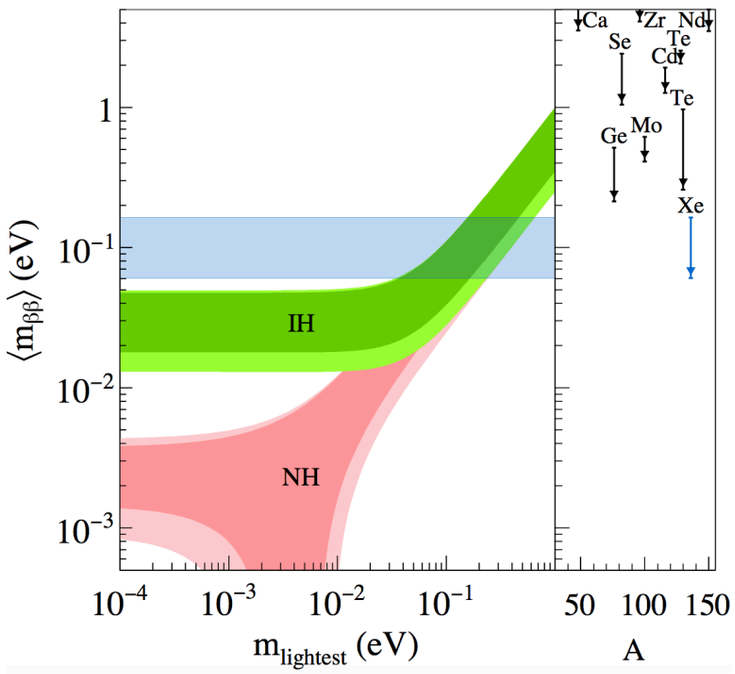


Left-right model?



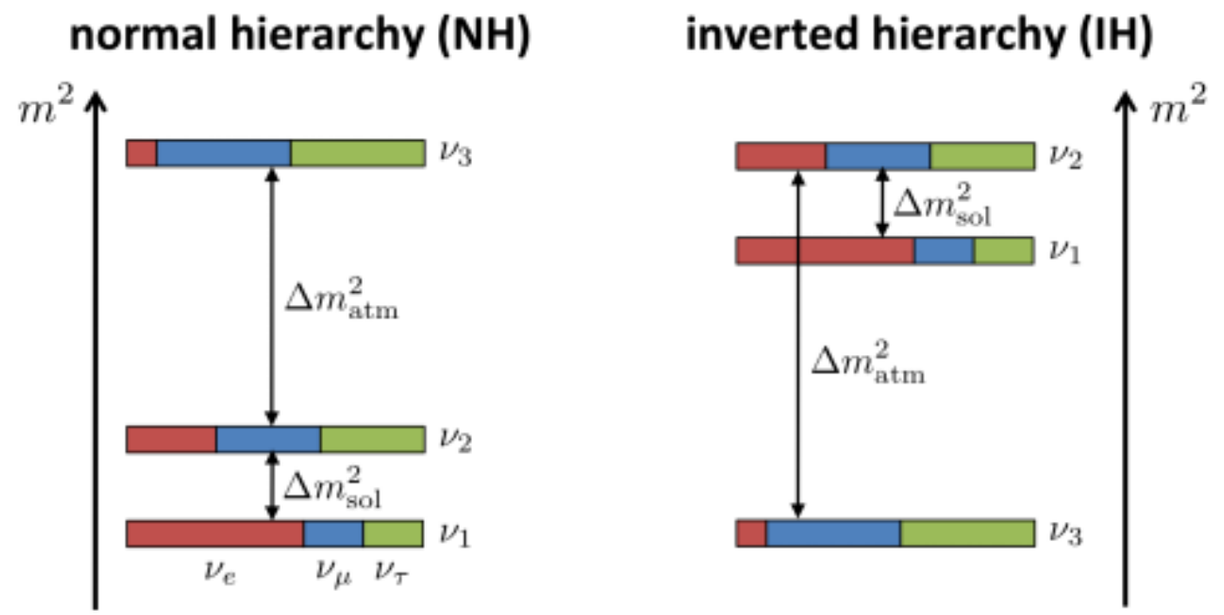
+ ??

Majorana mass mechanism



- Probes very high BSM scales, $\Lambda \sim 10^{15}\,\mathrm{GeV}$

Depends on hierarchy of neutrino masses



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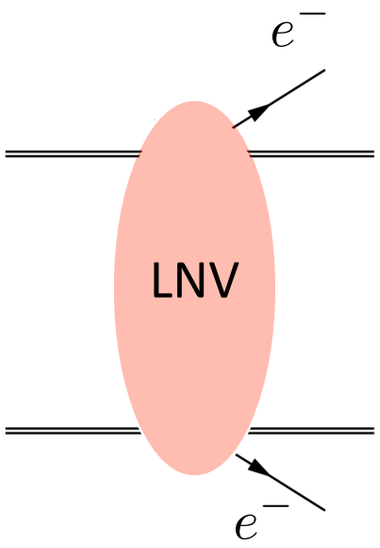

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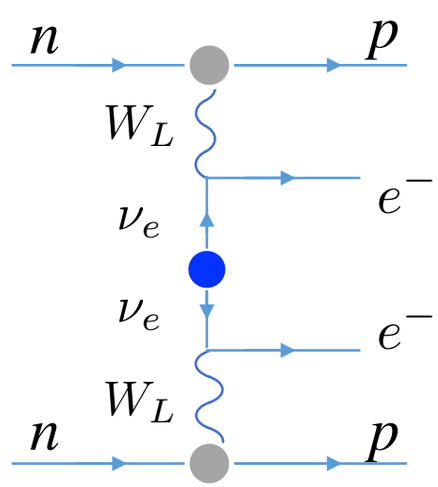

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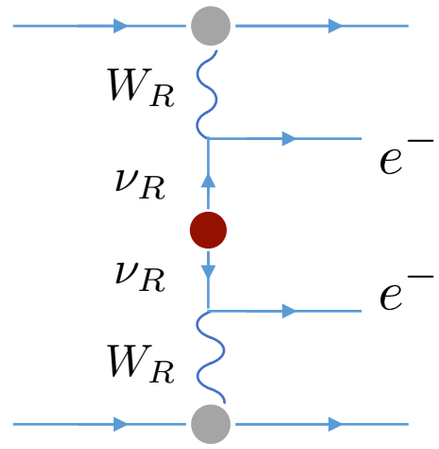

+ ??

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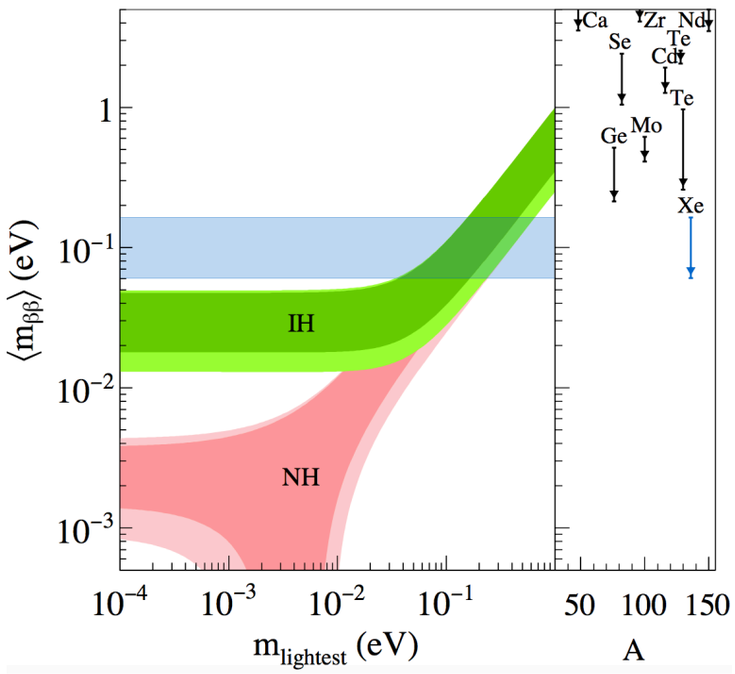


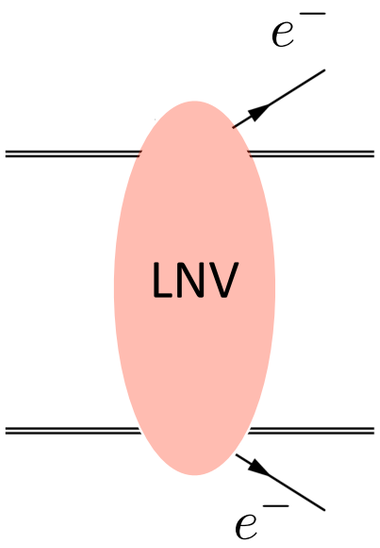
- Probes very high BSM scales, $\Lambda \sim 10^{15}\,\mathrm{GeV}$

Heavy BSM mechanisms

- Many possible scenarios
  - Left-right model,
  - R-parity violating SUSY
  - Leptoquarks…

Neutrinoless Double beta decay

What could be responsible?



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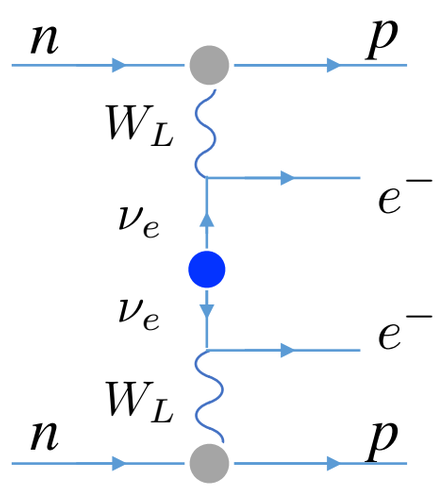

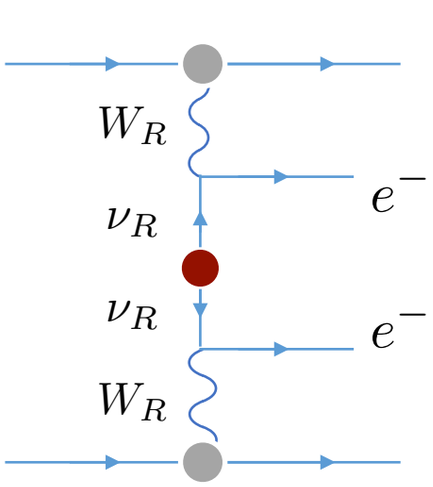

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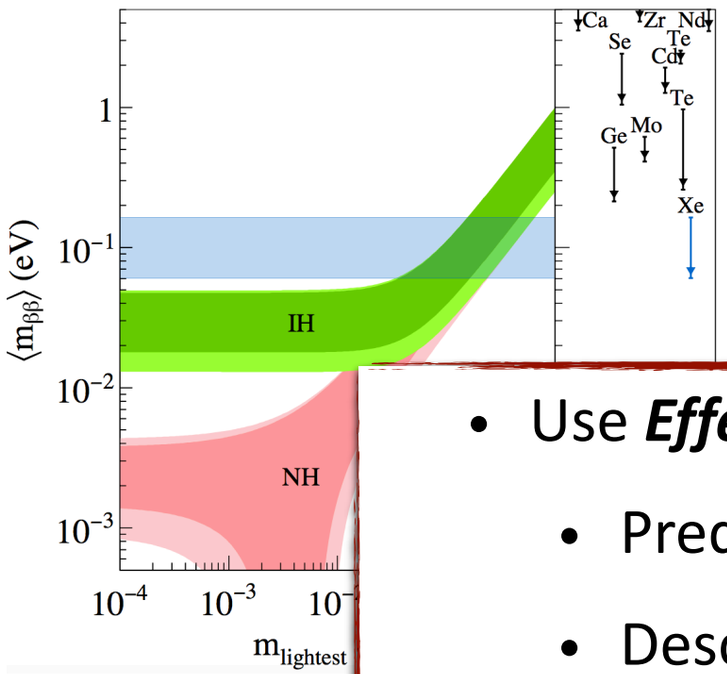
Majorana mass mechanism

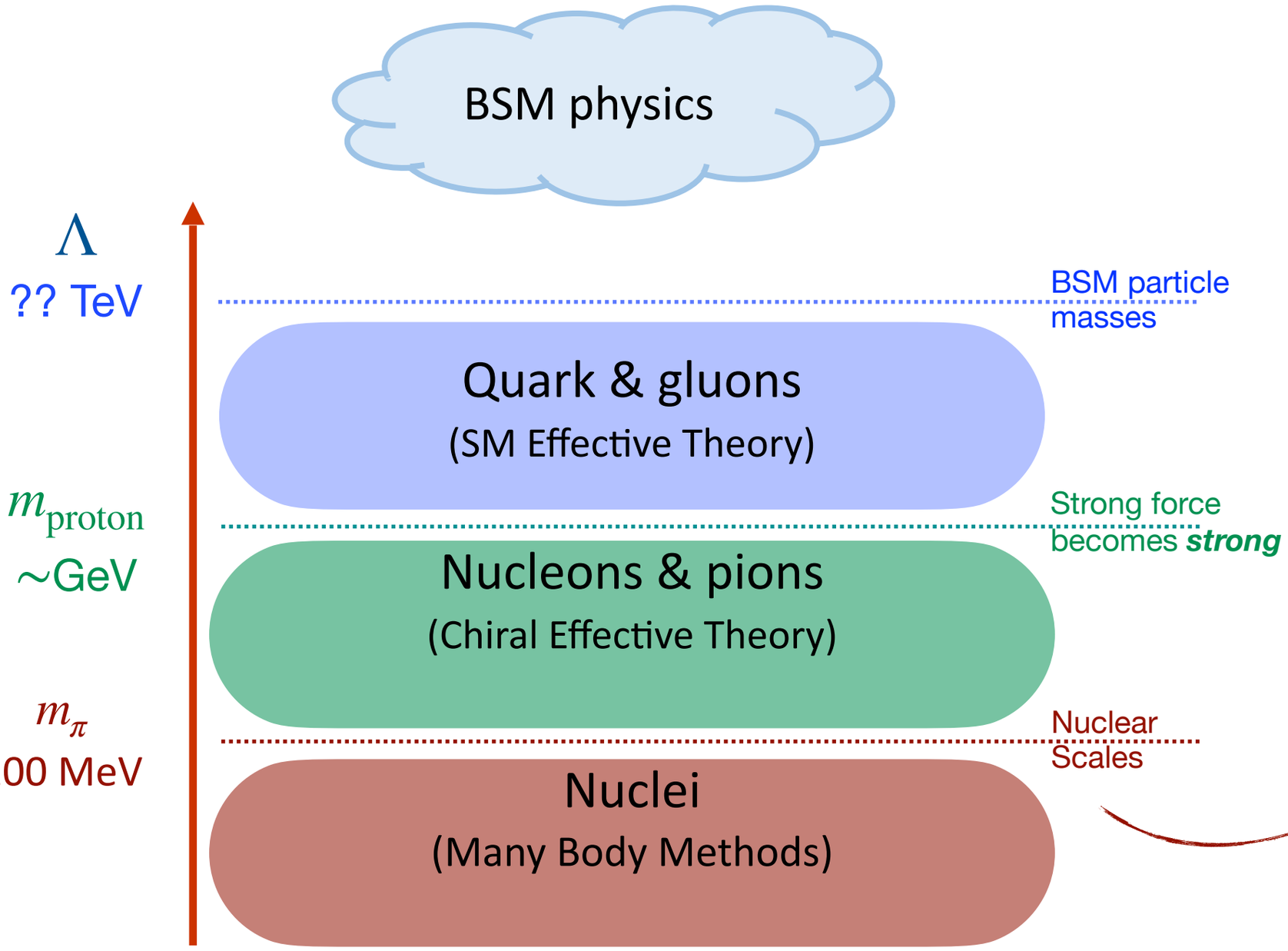


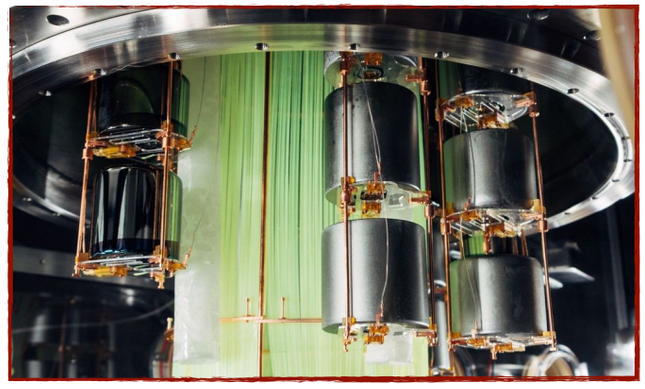
- Probes very high BSM scales, $\Lambda \sim 10^{15}$ GeV

Heavy BSM mechanisms

- Many possible scenarios
  - Left-right model,
  - R-parity violating SUSY

- Use ***Effective Theories***
  - Predictions with controlled uncertainties
  - Describe any BSM scenario





$0\nu\beta\beta$: LEGEND (ORNL)

BSM physics

Λ
?? TeV

BSM particle masses

Quark & gluons
(SM Effective Theory)

m_{proton}
~GeV

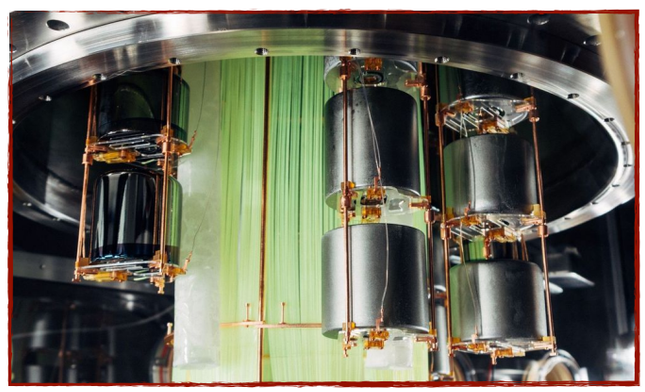
Strong force becomes ***strong***

Nucleons & pions
(Chiral Effective Theory)

m_π
100 MeV

Nuclear Scales

Nuclei
(Many Body Methods)



$0\nu\beta\beta$: **LEGEND (ORNL)**

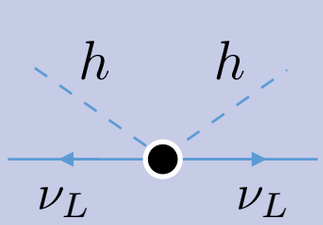
SM EFT

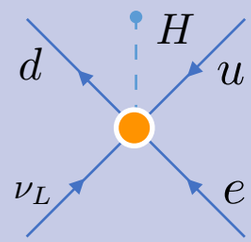
Lepton-number violating
BSM physics

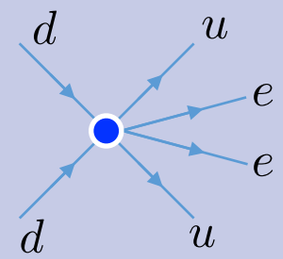
?? TeV

BSM particle masses

SM Effective Field Theory







100 GeV

m_W

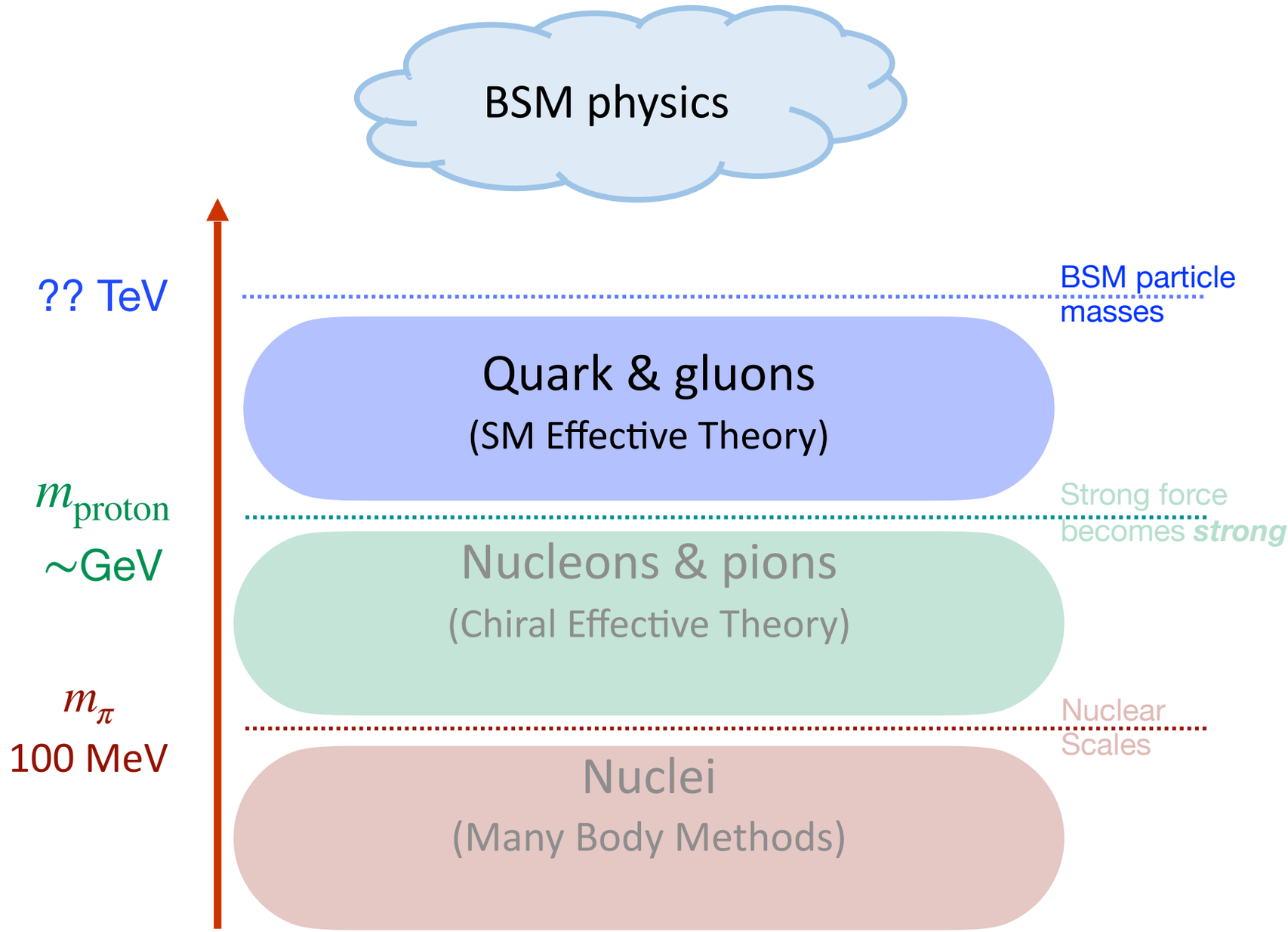
SM mass scale

- EFT consists of the SM + effective interactions
- Interactions organized in expansion in E/Λ, with E the energy scale of the process
  - More complex interactions (higher dimensional) are higher order

- Can describe
  - Heavy lepton-number violation
  - Contributions from Sterile neutrinos

WD et al, JHEP ’17,18

WD et al. JHEP ’20; PRC ’23; JHEP ’24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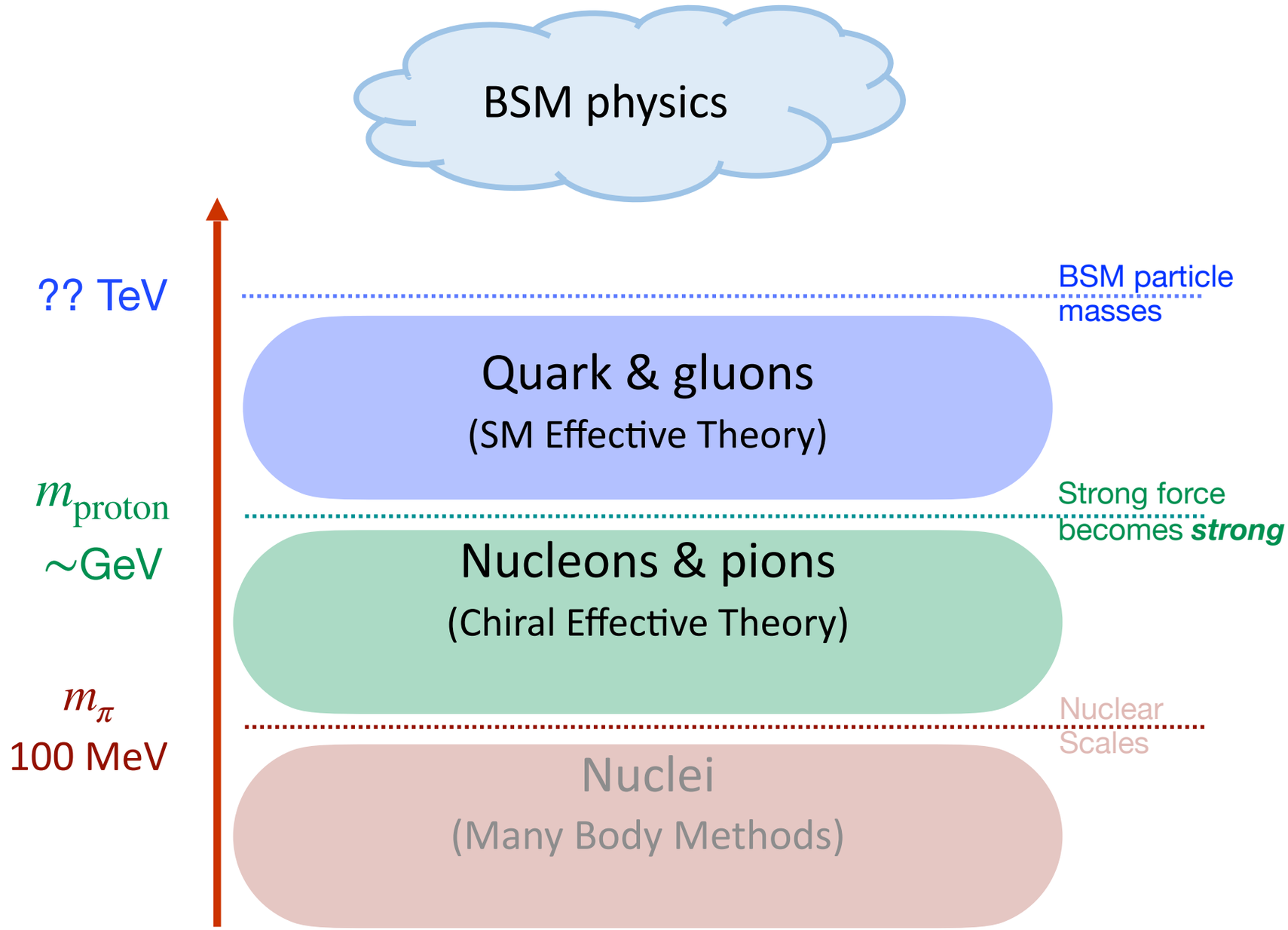
BSM particle masses
Quark & gluons
(SM Effective Theory)
m_{proton}
~GeV
Strong force becomes strong
Nucleons & pions
(Chiral Effective Theory)
m_π
100 MeV
Nuclear Scales
Nuclei
(Many Body Methods)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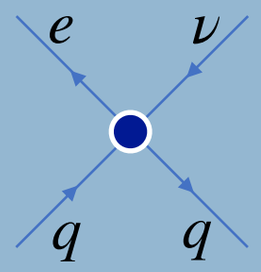
From quarks to nucleons

M_{QCD}
1 GeV

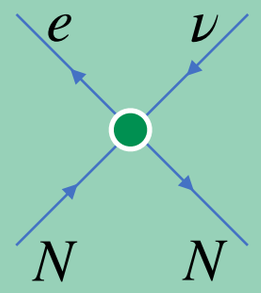
SM Effective Theory

In terms of quarks, gluons, leptons



Chiral Effective Theory

In terms of nucleons, pions, leptons

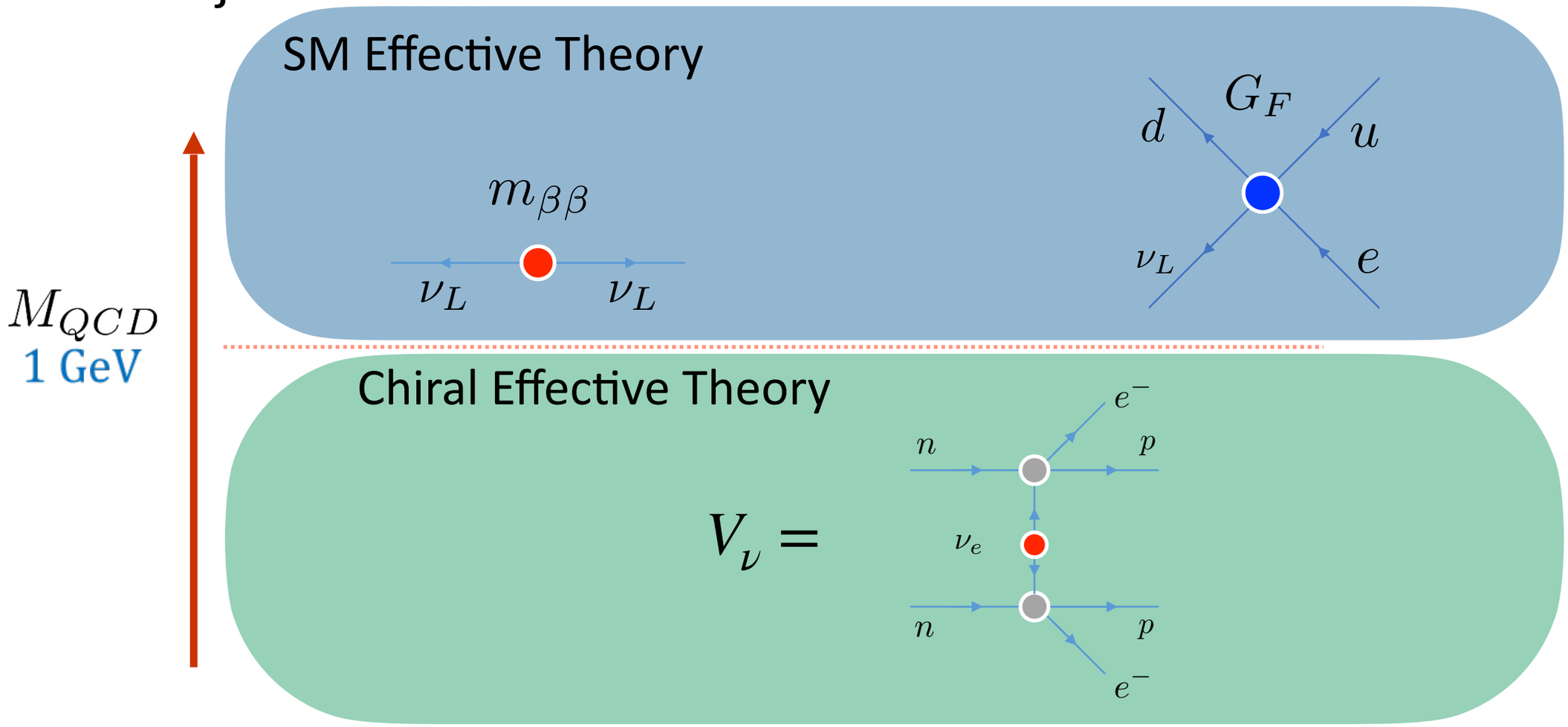


- Possible hadronic interactions determined by (chiral) symmetries
- Expansion in $Q/\Lambda_\chi \sim m_\pi/\Lambda_\chi$, with $\Lambda_\chi \sim 1$ GeV
- Use “Power-counting” to tell which interactions are needed to a given accuracy

Manohar, Georgi, `84; Weinberg, `90, `91

From quarks to nucleons

Majorana mass



Decay rate

$$\Gamma_{0\nu\beta\beta} \propto M_\nu{}^2 m_{\beta\beta}^2$$

Fundamental Physics

- *Effective neutrino mass*

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

Nuclear Matrix Element $M_\nu \sim \langle \psi_{\mathrm{Se}} \; V_\nu \; \psi_{\mathrm{Ge}} \rangle$

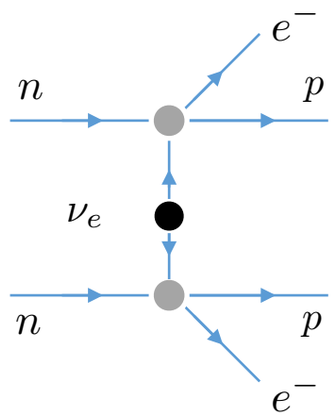
Kaplan, Savage, Wise, ’96; Beane, Bedaque, Savage, van Kolck, ’03, Nogga, Timmermans, van Kolck, ’05, Long, Yang, ’12;

Neutrinoless double beta decay

Theory input: Nuclear Matrix Element

$$M_\nu \sim \langle \psi_{\mathrm{Se}} \;\; V_\nu \;\; \psi_{\mathrm{Ge}} \rangle$$

$V_\nu \sim$



Weinberg counting
(previous literature)

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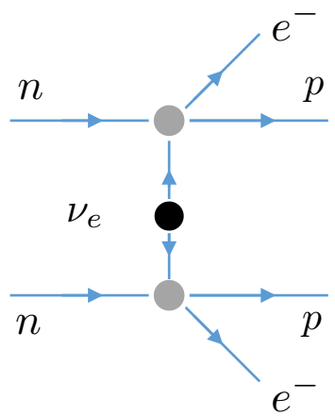

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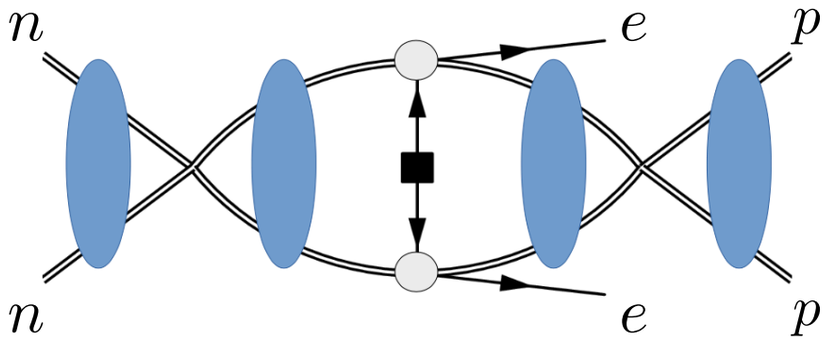
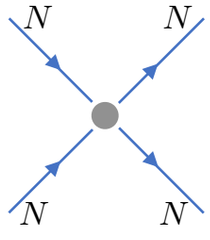
Combined with strong interactions

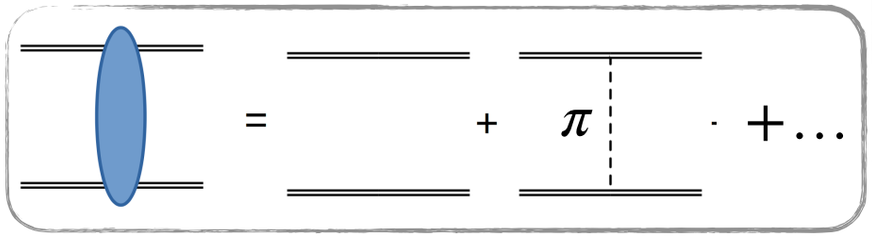


Divergent diagrams $\Longrightarrow$ inconsistent theory!

Strong interactions



Short-distance interaction



Pion exchange

Neutrinoless double beta decay

Theory input: Nuclear Matrix Element

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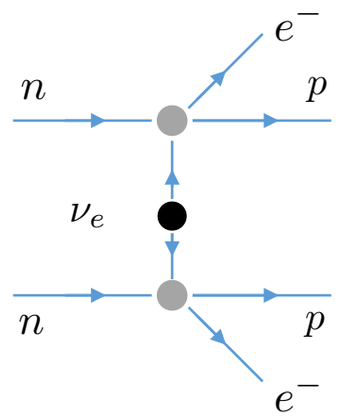
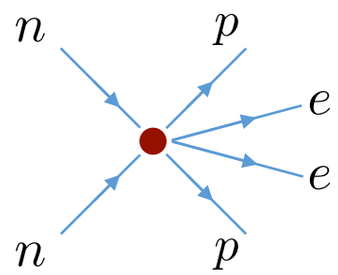
$V_\nu \sim$



Weinberg counting
(previous literature)

$+$

g_ν



New interaction
Needed at *leading order*

PHYSICAL REVIEW LETTERS **120,** 202001 (2018)

Editors' Suggestion | Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2] Michael L. Graesser,[1] Emanuele Mereghetti,[1] Saori Pastore,[1] and Ubirajara van Kolck[3,4]

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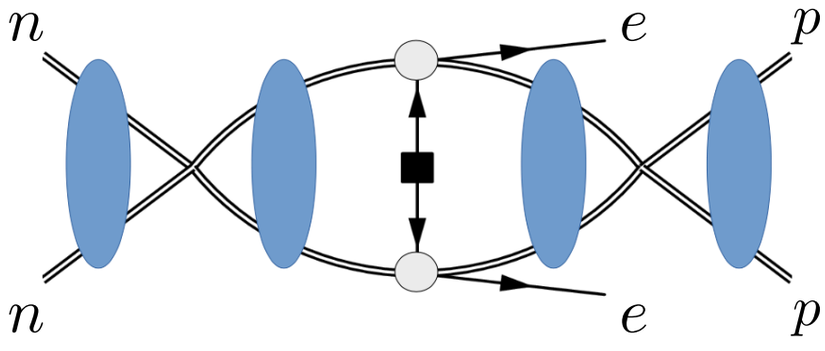

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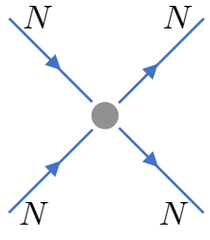

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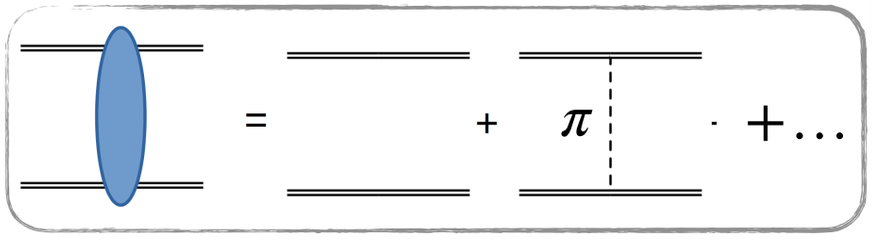

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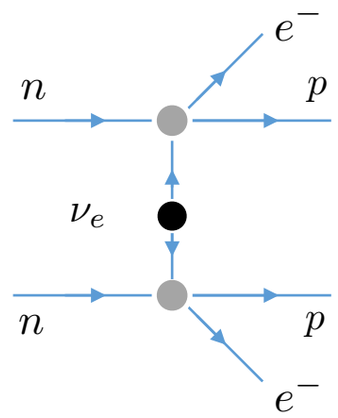

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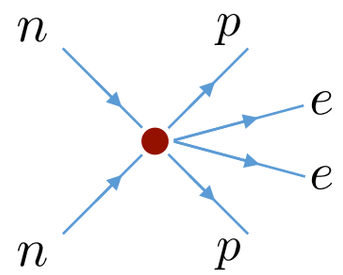

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- The coupling g_ν originally unknown
  - Sparked research on first-principle calculations (lattice QCD)

Davoudi & Kadam, ’20, ’21; Feng et al, ’19; Detmold & Murphy, ’20…

  - **First estimate using dispersive-like methods**
    - **Allowed first consistent determination**
    - **Decreased uncertainty of M_ν**

PHYSICAL REVIEW LETTERS **126,** 172002 (2021)

Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

Vincenzo Cirigliano,[1] Wouter Dekens,[2] Jordy de Vries,[3,4,5,6] Martin Hoferichter,[7] and Emanuele Mereghetti[1]

Neutrinoless double beta decay

Theory input: Nuclear Matrix Element

$$M_\nu \sim \langle \psi_{\rm Se} \;\; V_\nu \;\; \psi_{\rm Ge} \rangle$$

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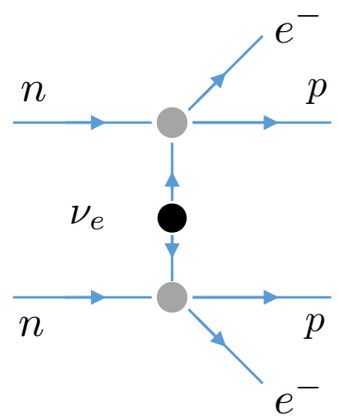

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$+$

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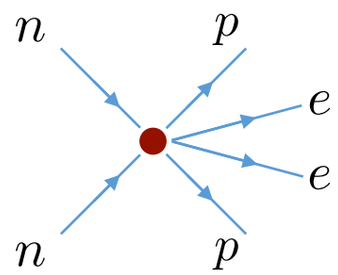
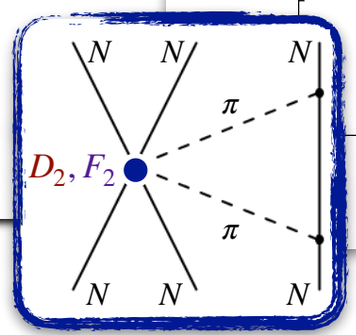


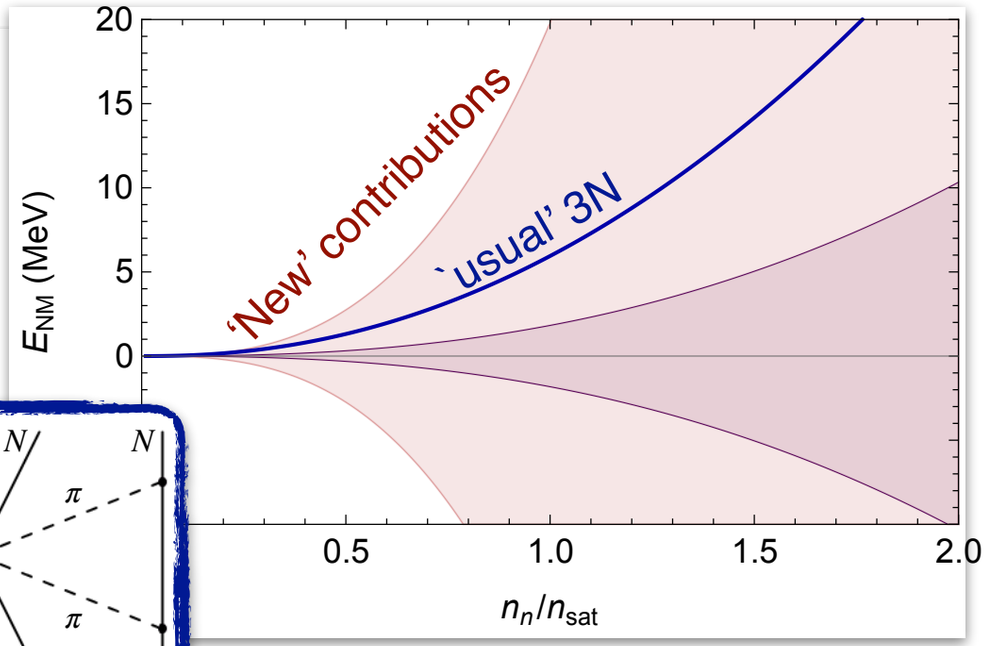
New interaction
Needed at *leading order*

Consistent strong interactions

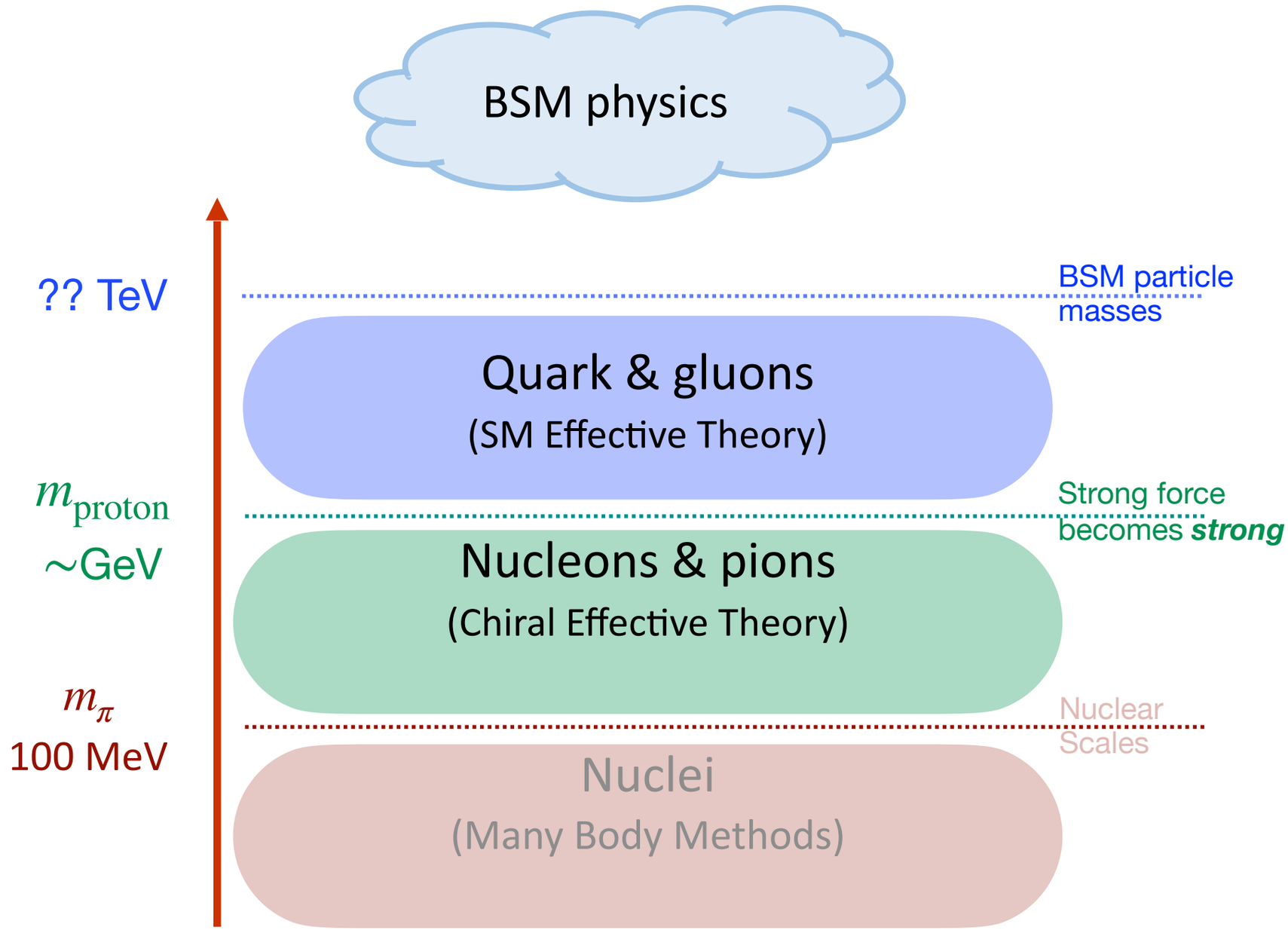
Similar arguments lead to new classes of 3-nucleon forces

- Due to usually neglected **pion-nucleon couplings**
- Larger than currently quoted uncertainties
- **Affects our understanding of nuclei and Neutron Stars**





Effects in Neutron Matter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?? TeV
BSM particle masses
Quark & gluons
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m_{proton}
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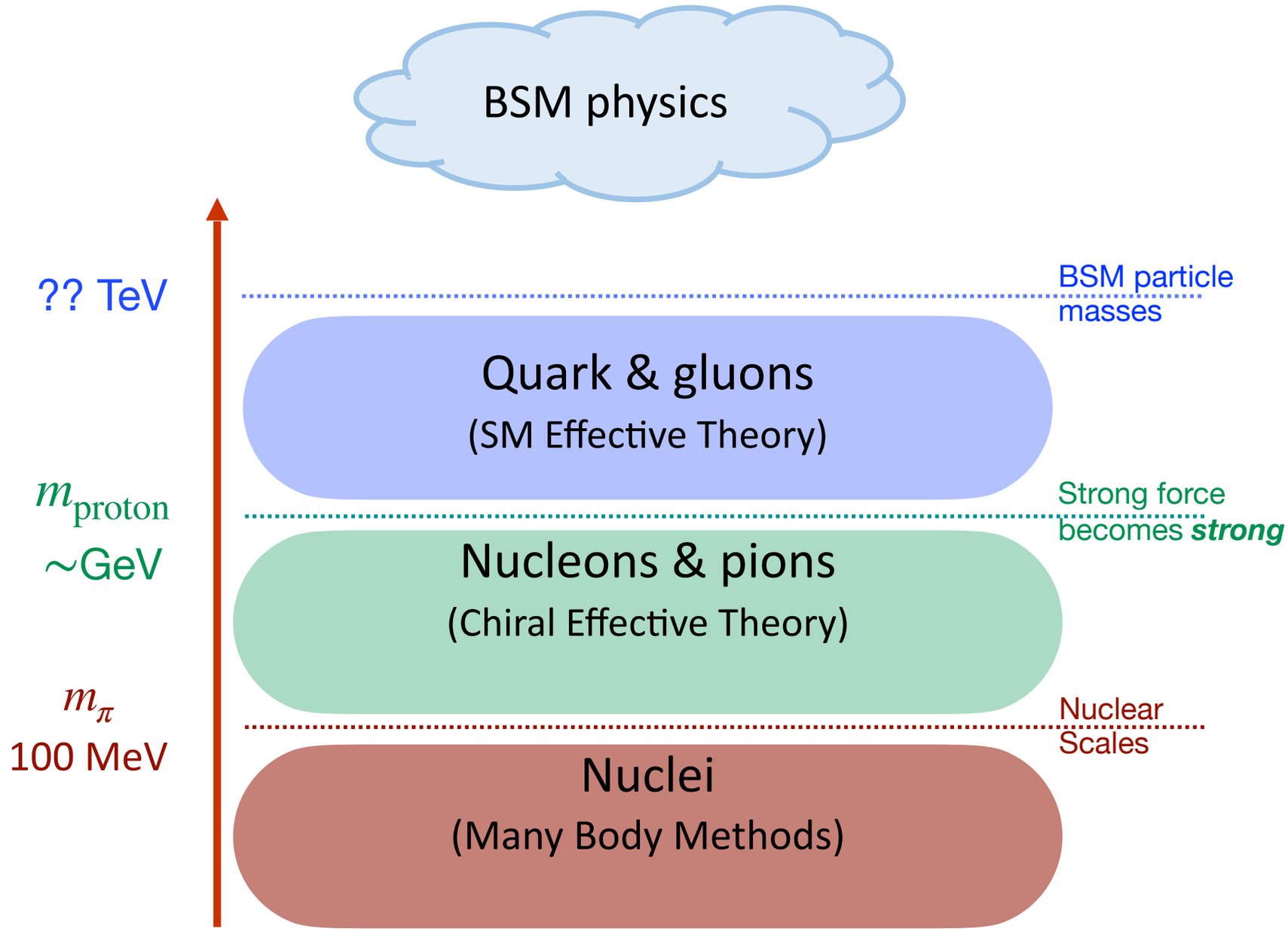
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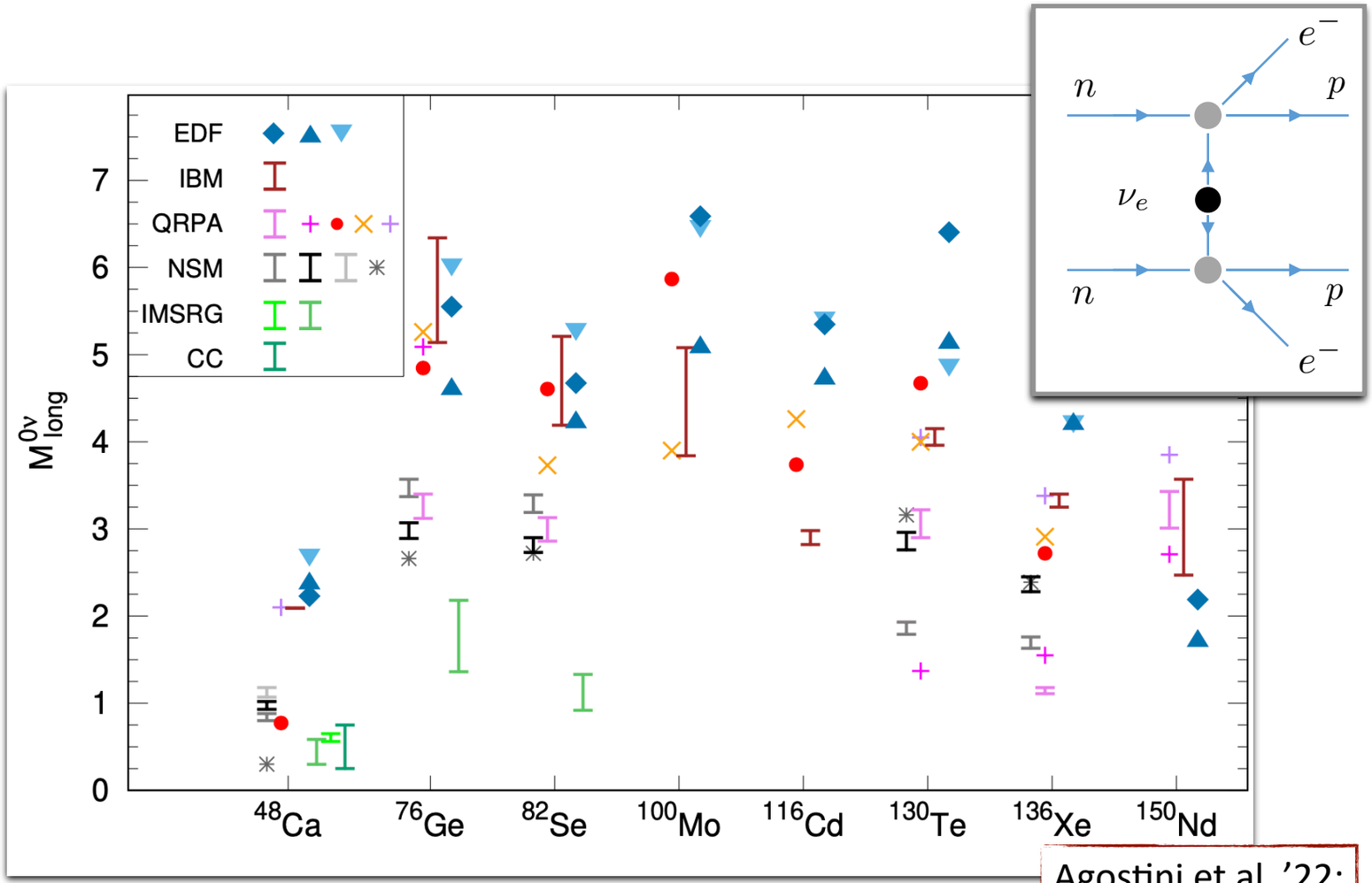
Nuclear matrix elements

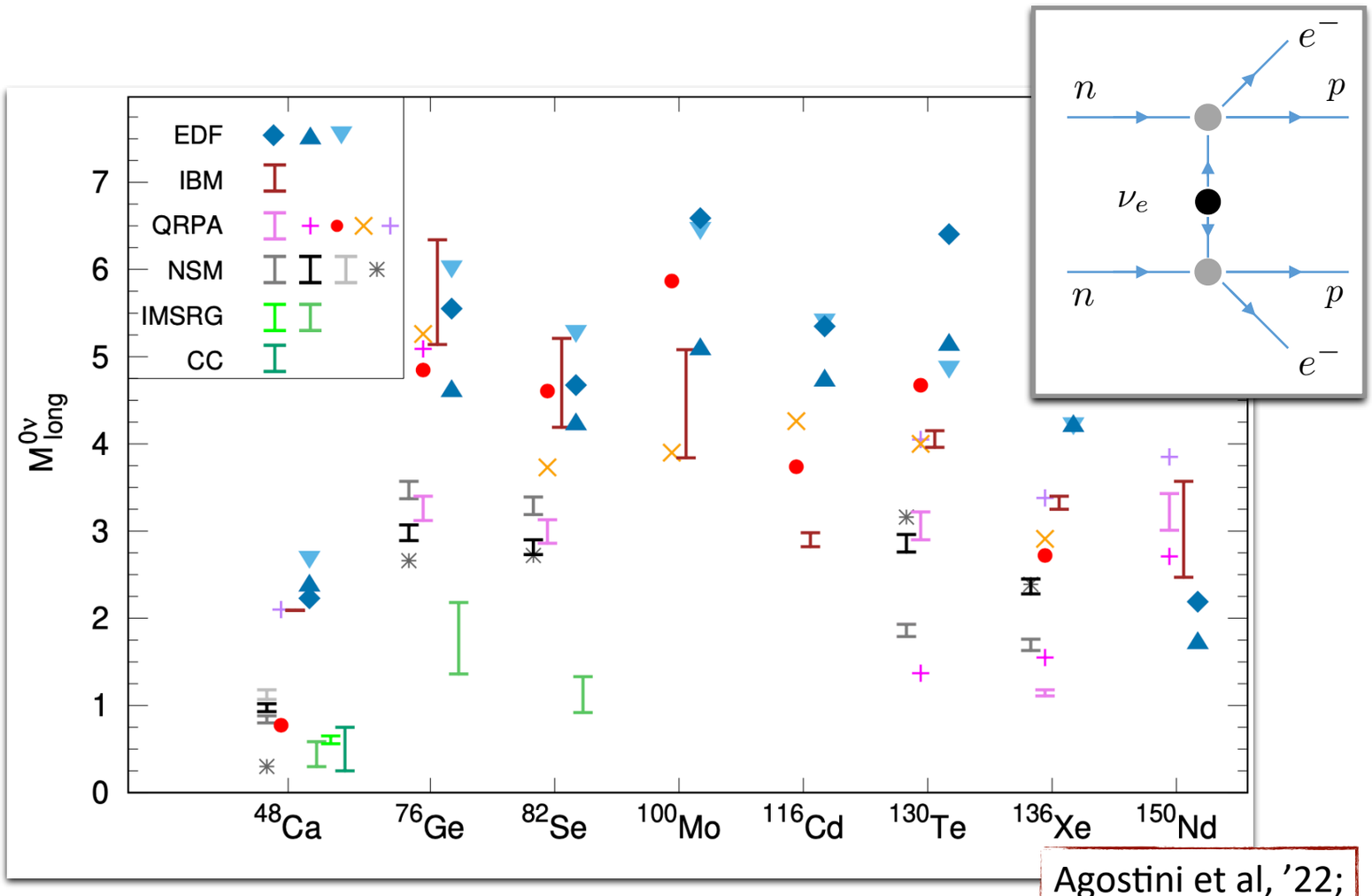


Agostini et al, ’22;

- Nuclear Matrix Elements differ by a factor 2-3 between methods
- A*b initio* calculations appearing, promise controlled uncertainties

Belley et al ’23,’20; ***Novario et al (UTK/ORNL) ’21***; Yao et al ’20; Wirth, Yao, Hergert ’21; Jokiniemi et al ’21;

Nuclear matrix elements



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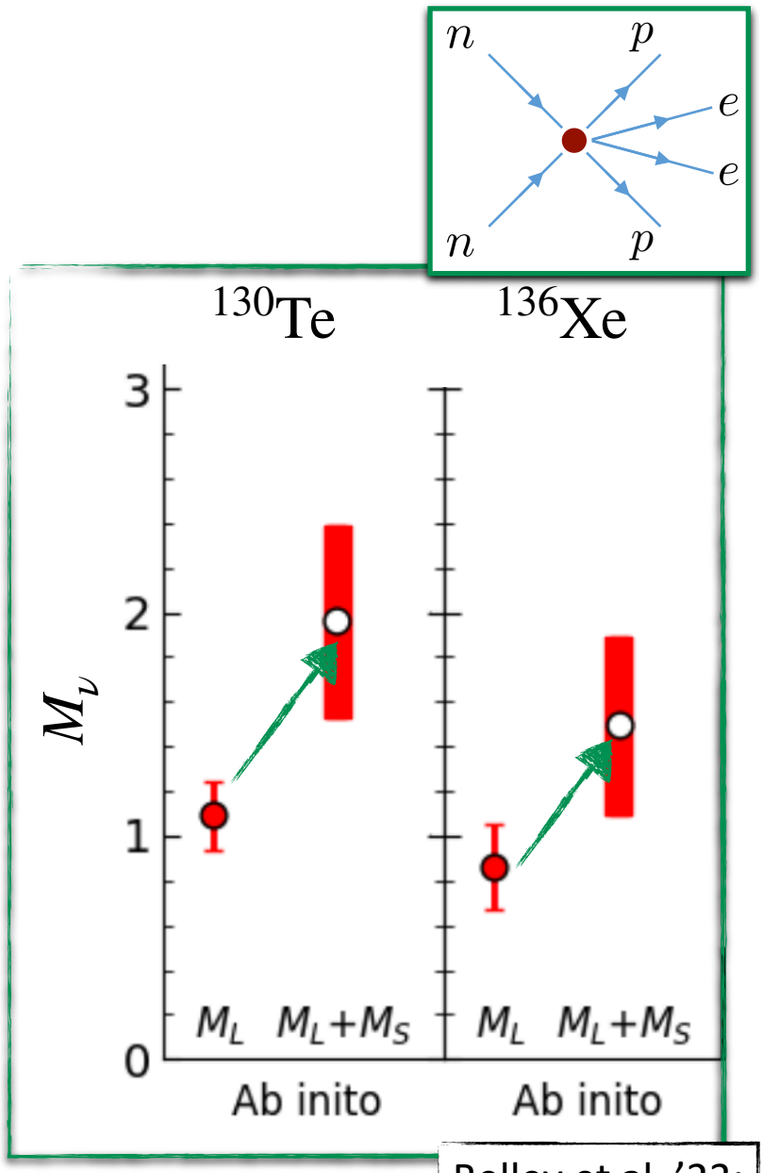

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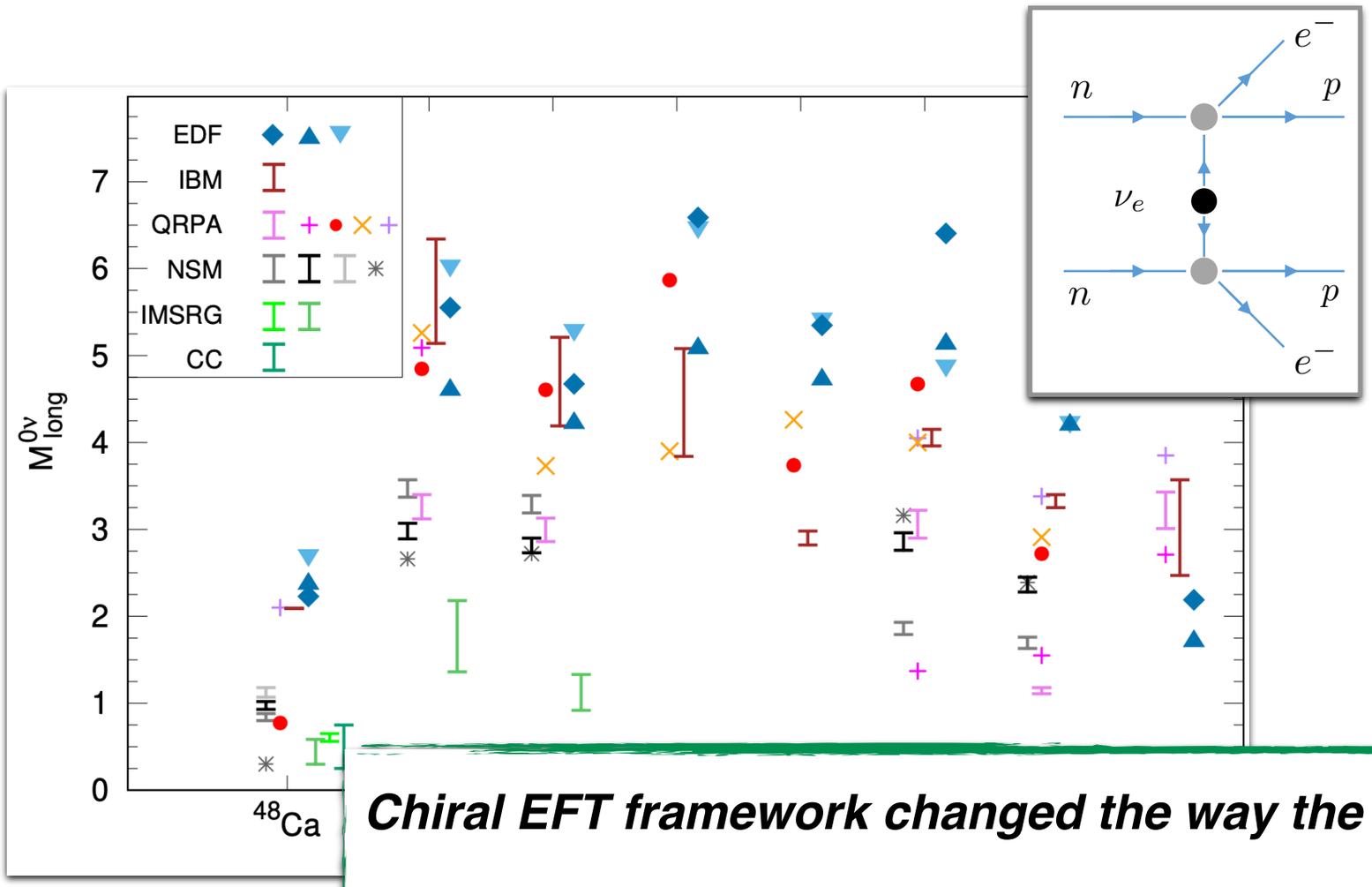
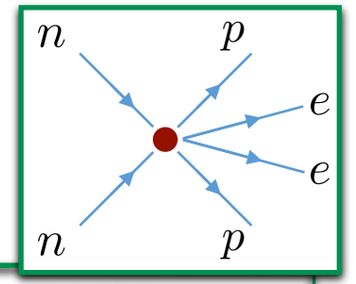
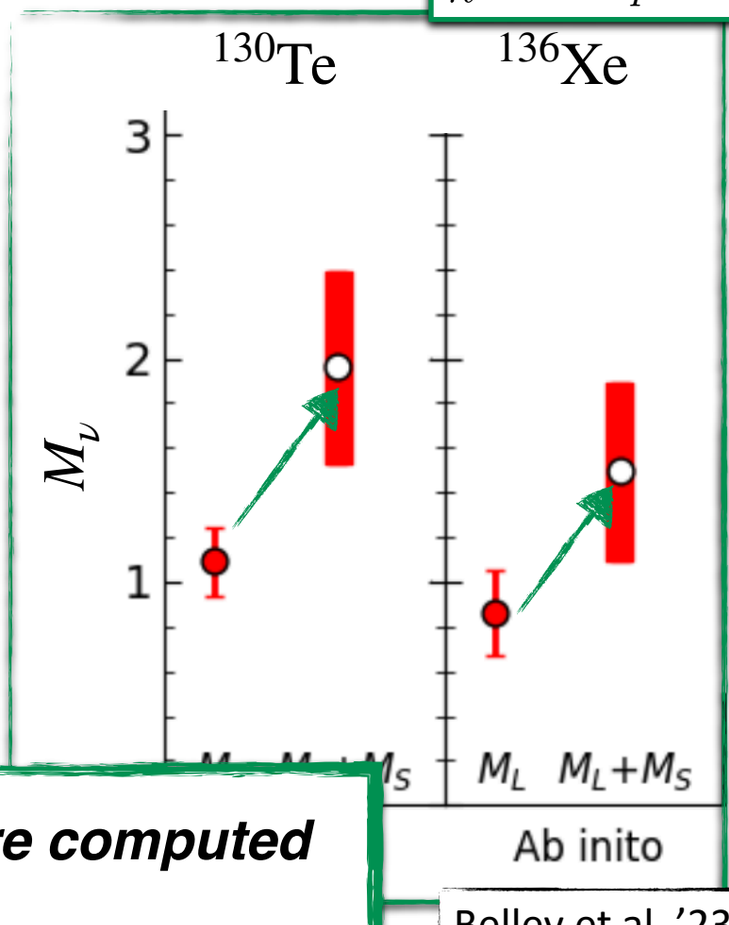
- Nuclear Matrix Elements differ by a factor 2-3 between methods
- A*b initio* calculations appearing, promise controlled uncertainties
  - Include short-range interaction $\sim g_\nu$

Belley et al ’23,’20; ***Novario et al (UTK/ORNL) ’21***; Yao et al ’20; Wirth, Yao, Hergert ’21; Jokiniemi et al ’21;

Nuclear matrix elements





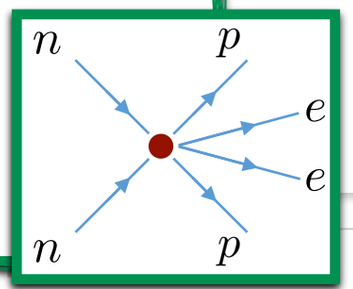


Belley et al, ’23;

Chiral EFT framework changed the way the NMEs are computed

- Allowed for the first consistent calculations with uncertainties
- ***Increases*** M_ν by $\sim 40-90\,\%$
- ***Increased*** experimental sensitivity to $m_{\beta\beta}$

$$\Gamma_{0\nu\beta\beta} \propto M_\nu{}^2 m_{\beta\beta}^2$$



- Nuclear Matri
- A*b initio* calcu
  - Include sho

Belley et al ’23,’20;

Other mechanisms

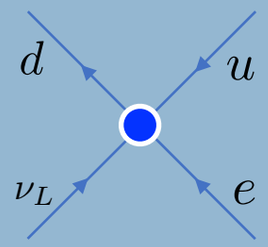
More complex effective interactions:

appearing at higher orders $\sim (m_W/\Lambda)^3, (m_W/\Lambda)^5$

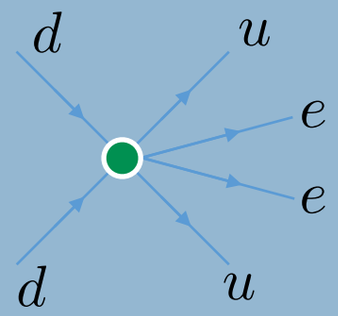
Chiral EFT

Higher-dimensional interactions

SM Effective Theory



Dim 6 & 7

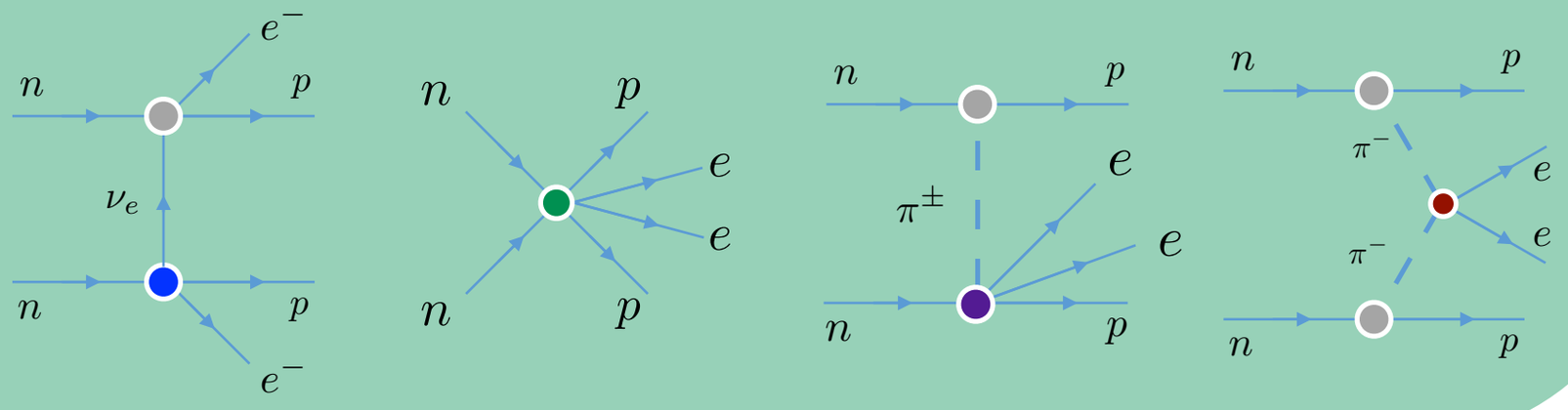


Dim 9

M_{QCD}
1 GeV

Chiral Effective Theory

$V_{d=7,9} =$



- Higher-dimensional interactions involve
  - Additional hadronic interactions
  - Hadronic couplings only partially known

WD et al, JHEP ’17,18

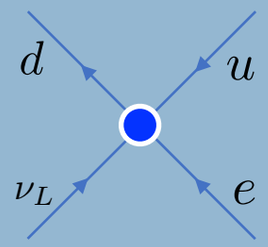
- Can go through same steps for sterile neutrinos

WD et al. JHEP ’20; PRC ’23; JHEP ’24

Chiral EFT

Higher-dimensional interactions

SM Effective Theory



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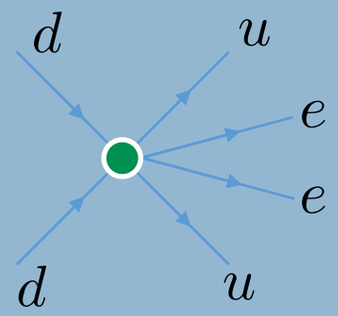

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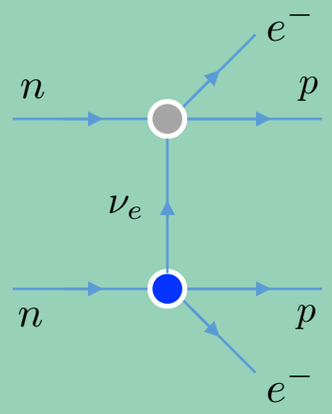
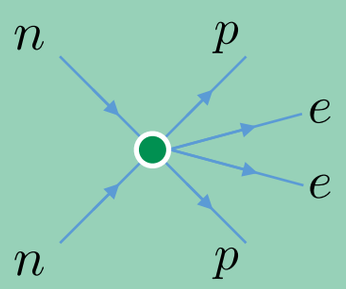
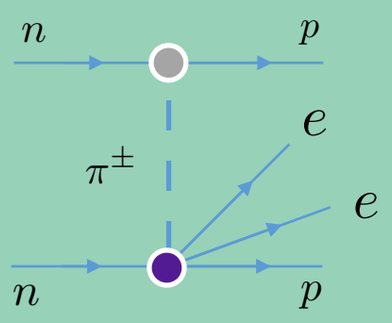
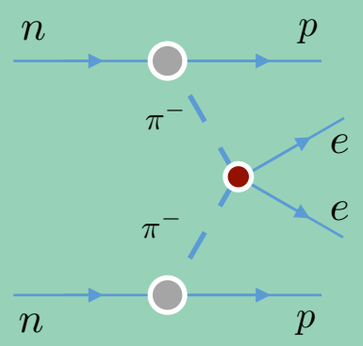








From nucleons to nuclei

- Requires Nuclear Matrix Elements $M_\nu \sim \langle \psi_{\mathrm{Se}} \;\; V_{d=7,9} \;\; \psi_{\mathrm{Ge}} \rangle$
  - Order 10 of them
  - Similar uncertainties as the Majorana-mass mechanism

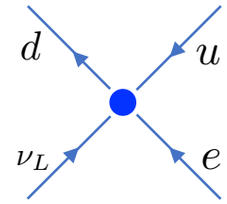
Phenomenology

Heavy LNV physics

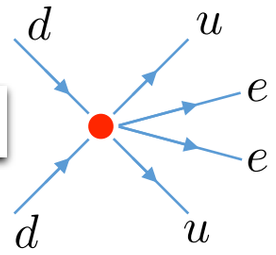
Phenomenology

From heavy new physics

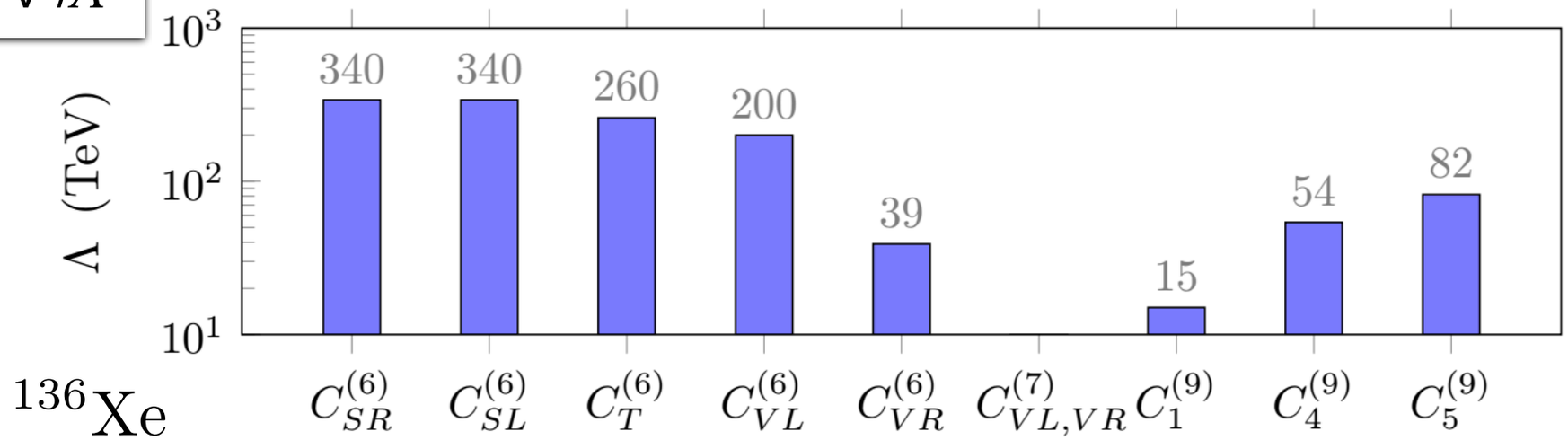
Dim 6 & 7



Dim 9



- Couplings with $C_i \sim v^3/\Lambda^3$



- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

WD et al, JHEP ’17,18

Phenomenology

From heavy new physics

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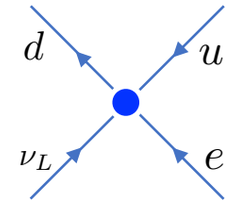

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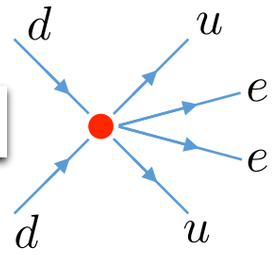

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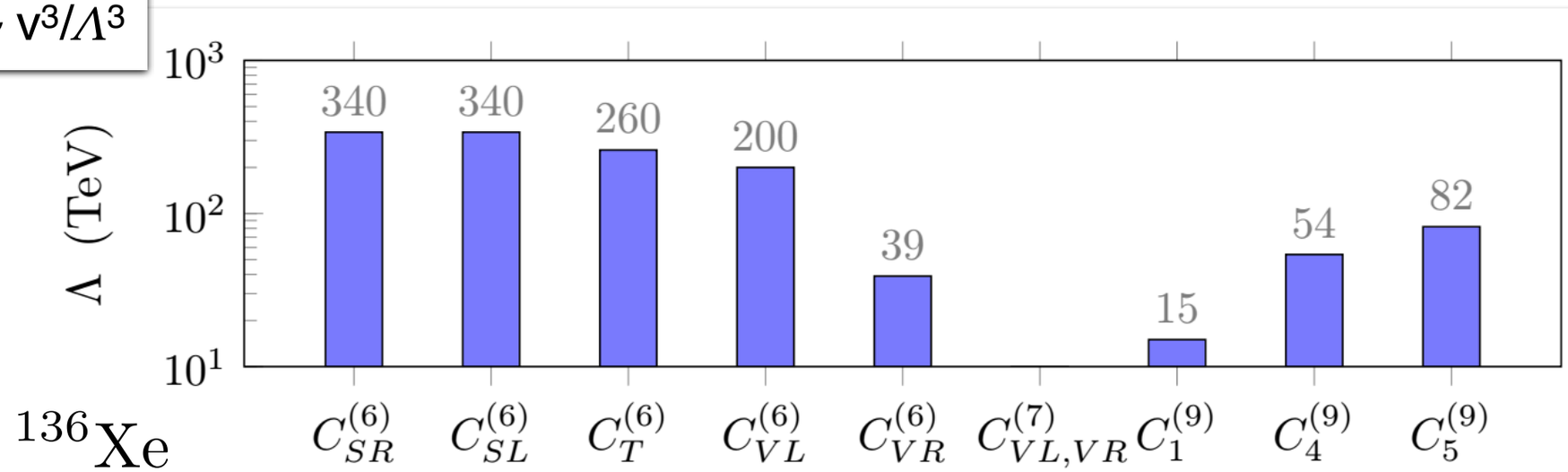

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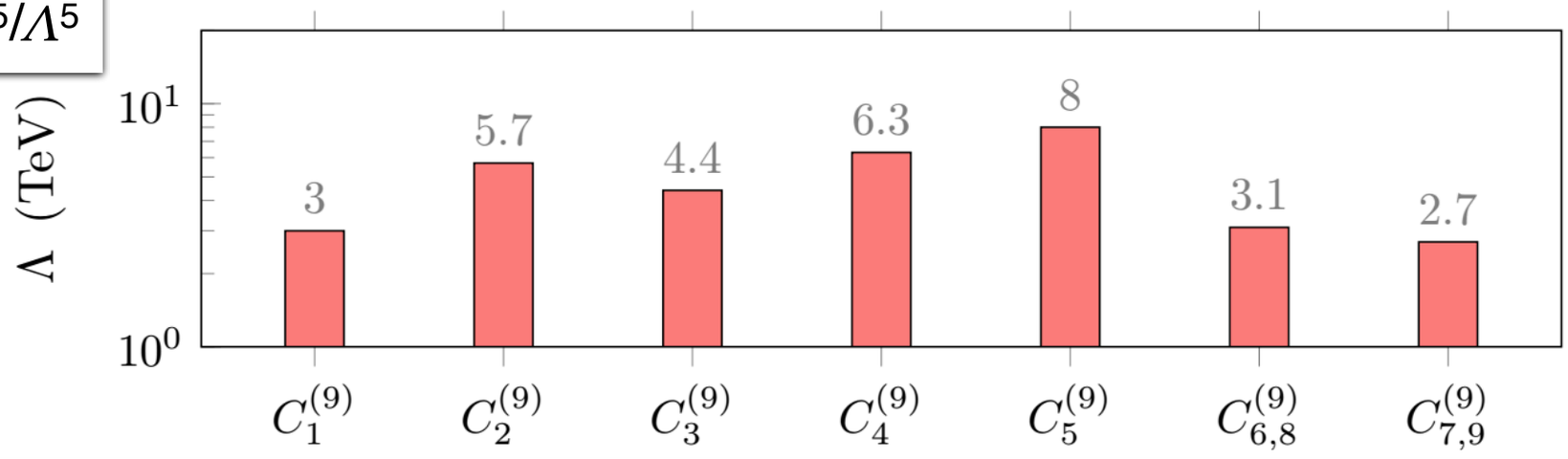

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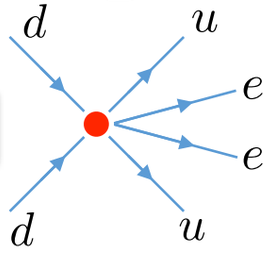
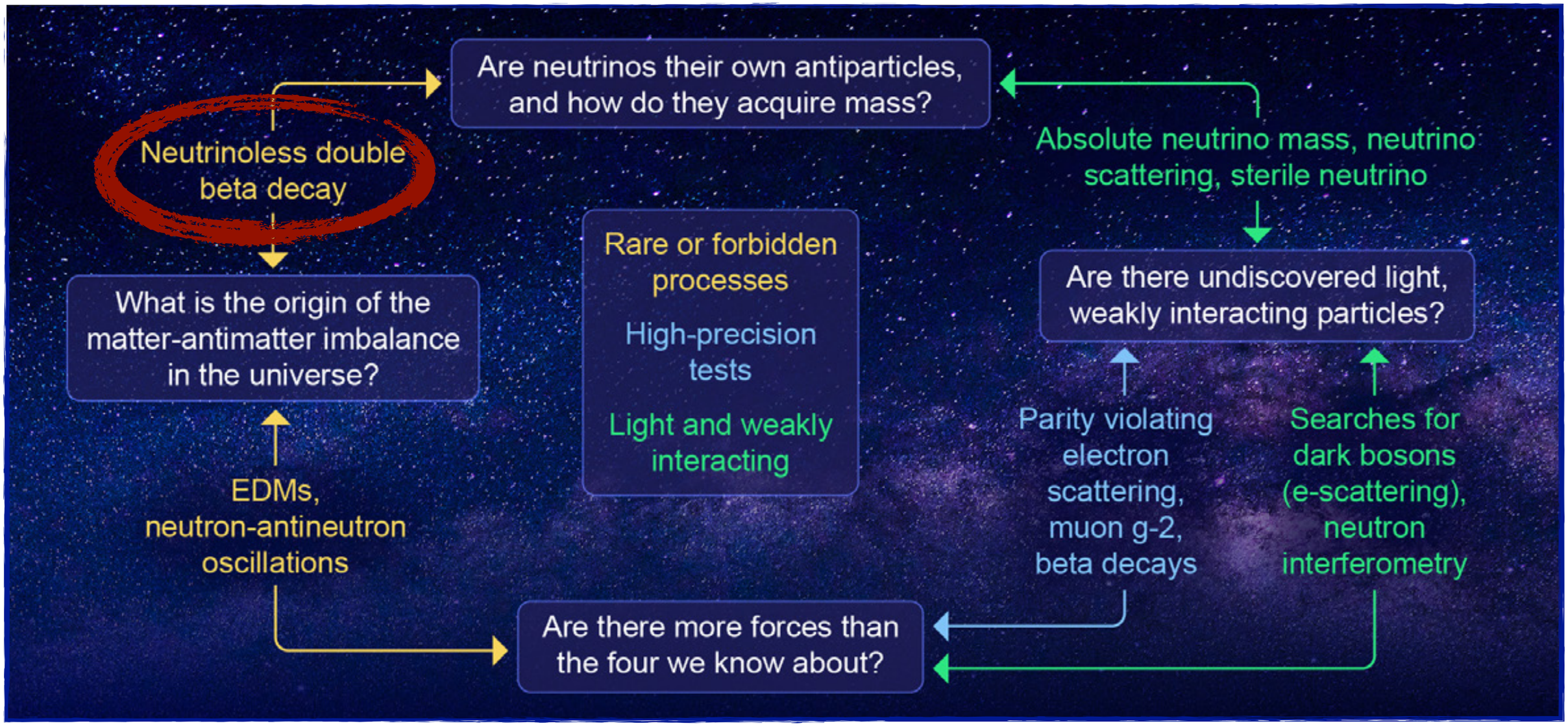


WD et al, JHEP ’17,18

Electric Dipole Moments

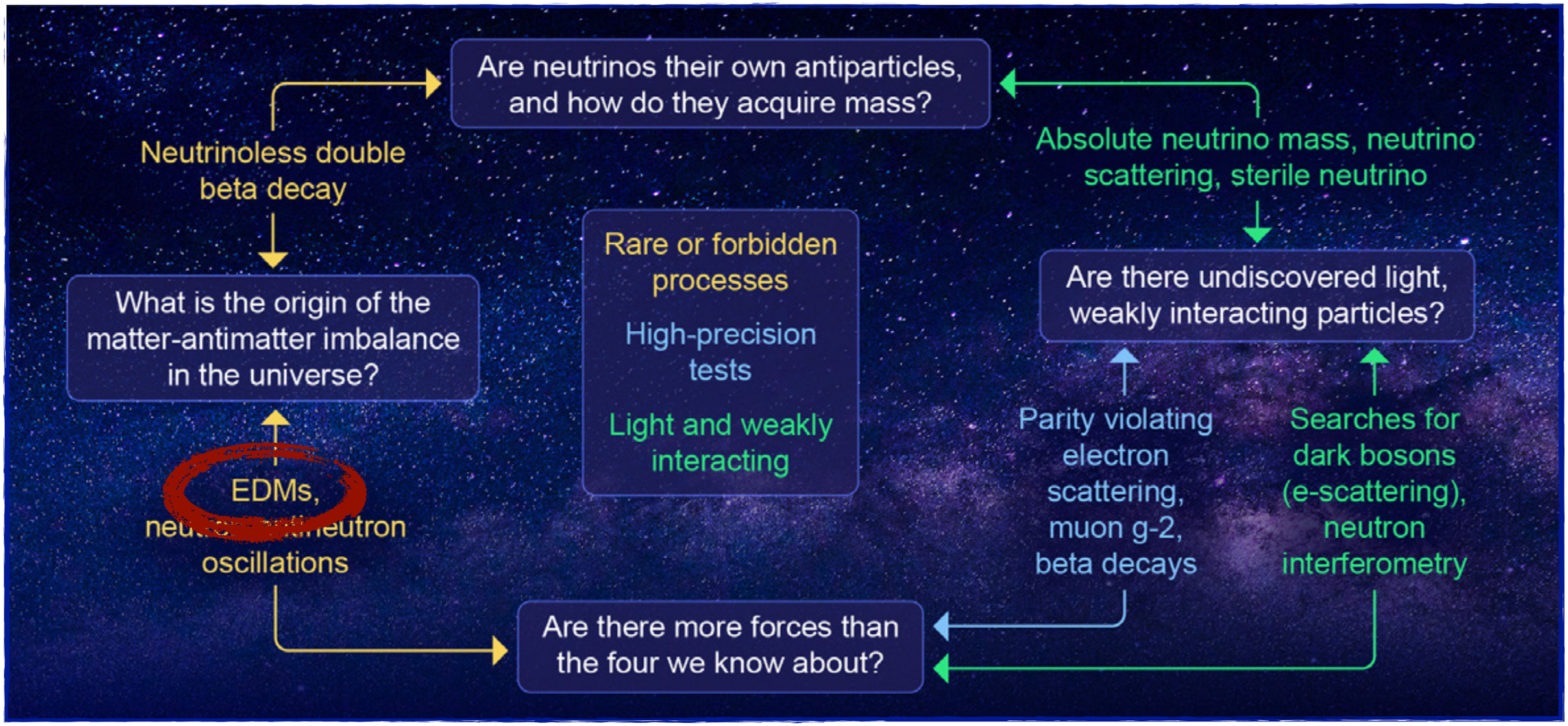
CP-violating BSM physics



2023 Long Range Plan for Nuclear Science

Electric Dipole Moments

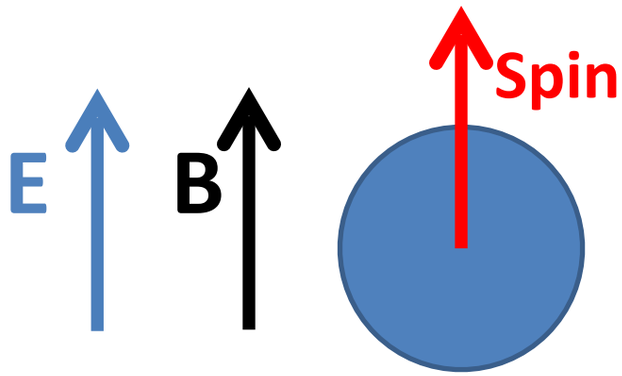
CP-violating BSM physics



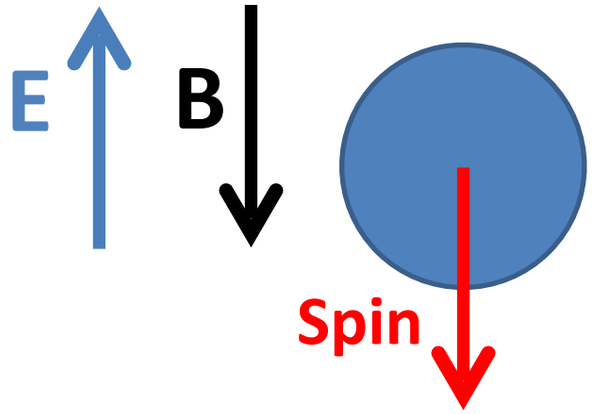
2023 Long Range Plan for Nuclear Science

Electric Dipole Moments

What are EDMs?



Time reversal



$$H = -\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

$$H = +\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

Electric Dipole Moments

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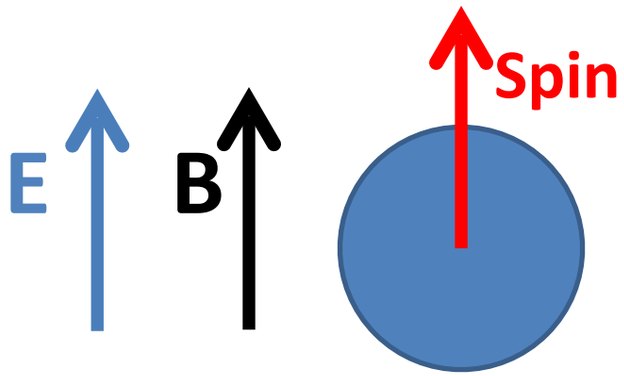

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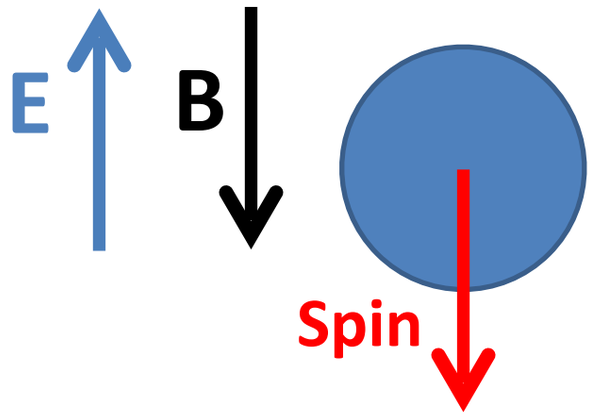
EDMs violate time-reversal & CP



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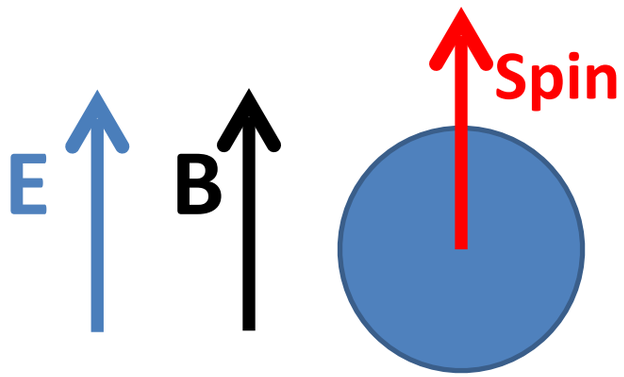
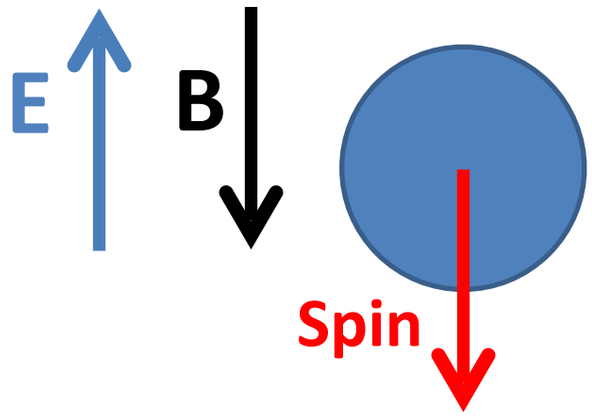
Electric Dipole Moments

What are EDMs?





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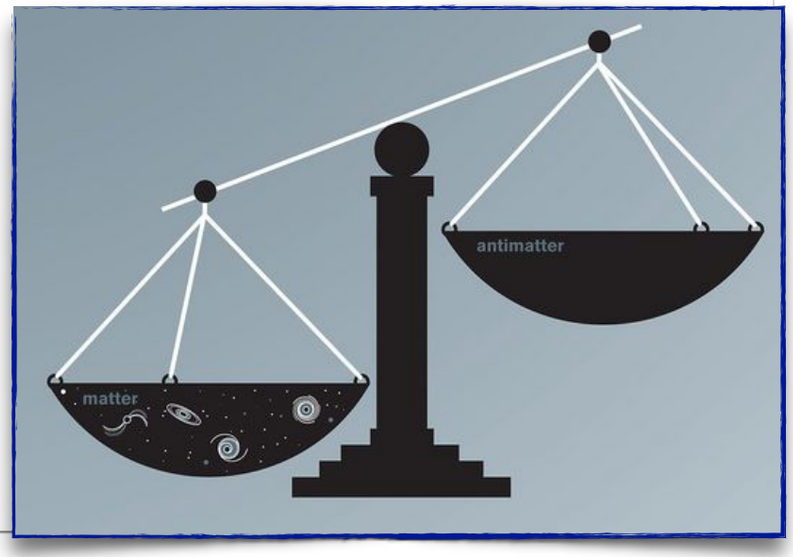
EDMs violate time-reversal & CP

$$H = +d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

Why look for them?

- Any signal implies BSM CP-violating physics!*
- Needed to explain the **matter-antimatter asymmetry**
  - One of the 3 Sakharov conditions

(*) or $\theta \neq 0$, but this can be disentangled from BSM contributions



Electric Dipole Moments

How to look for them?

- Nucleons
- Atoms
- Molecules

- ***Light nuclei***
  - Theoretically clean
  - Currently no measurements

Bsaisou et al ’14; Gnech &Viviani, ’20; ***Yang, Platter et al, ‘21***

Neutron: Baker *et al*, ‘20 $d_n \leq 1.8 \cdot 10^{-26}\, e\,\mathrm{cm}$

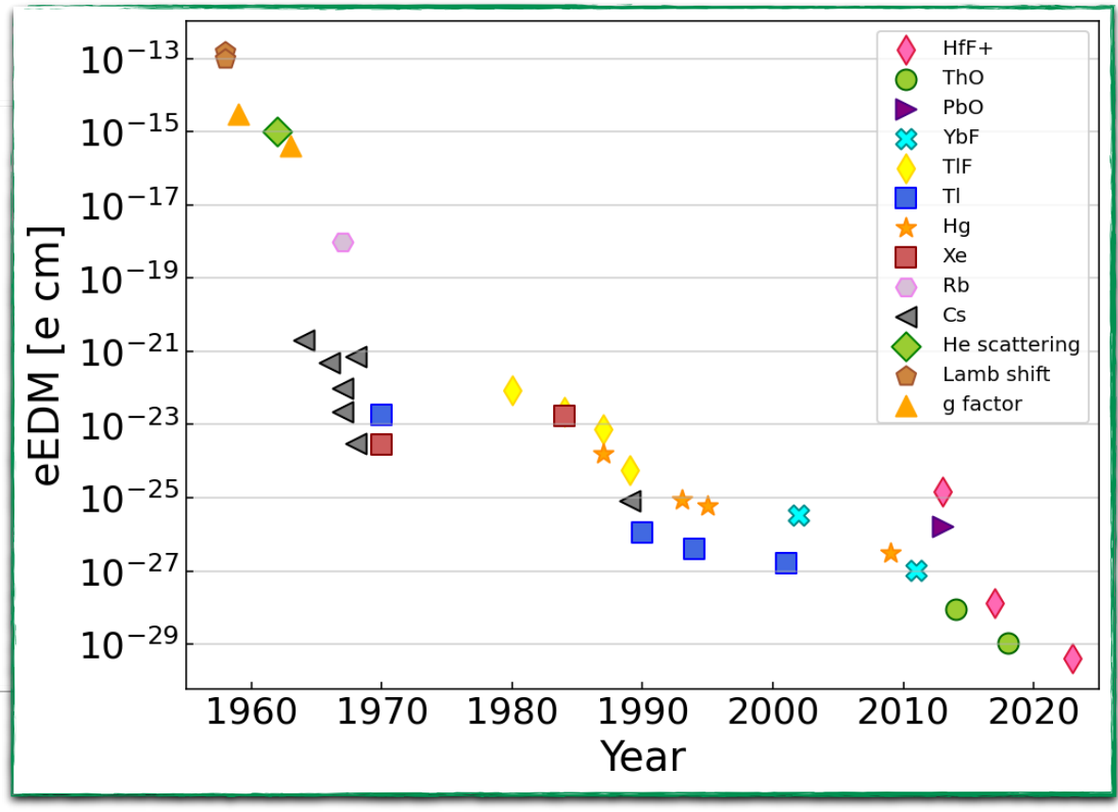
Mercury: Graner *et al*, ‘17 $d_{\mathrm{Hg}} \leq 6.2 \cdot 10^{-30}\, e\,\mathrm{cm}$

HfF: Roussy et al, ‘22 $d_e \leq 4.1 \cdot 10^{-30}\, e\,\mathrm{cm}$

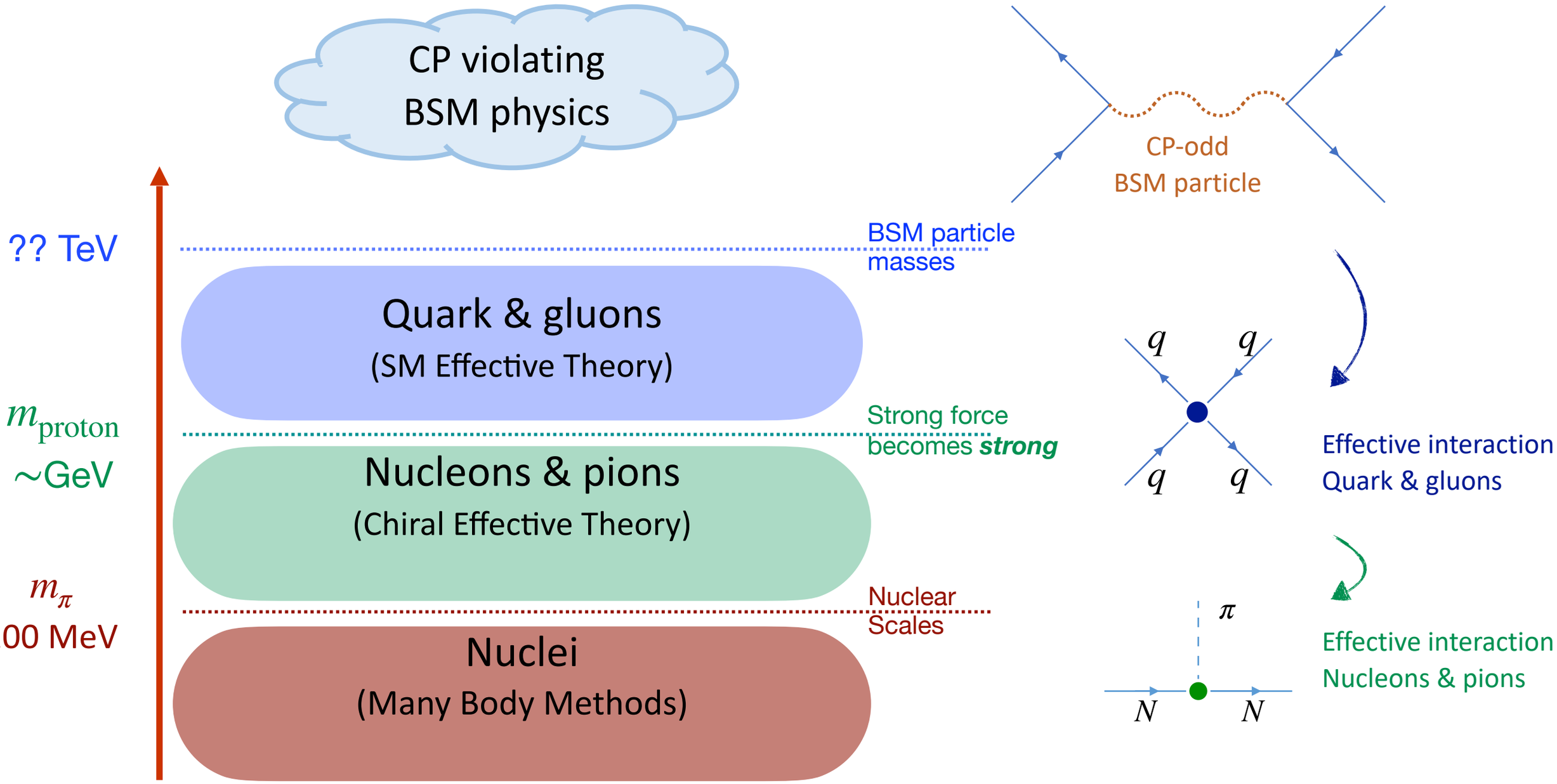
Future probes?

- **Rapid progress** in paramagnetic systems
- ***Radioactive molecules*** promising probes
  - Several enhancement factors

Chupp *et al*. ’17; Ema *et al*. ’22; Arrowsmith-Kron et al. ’23



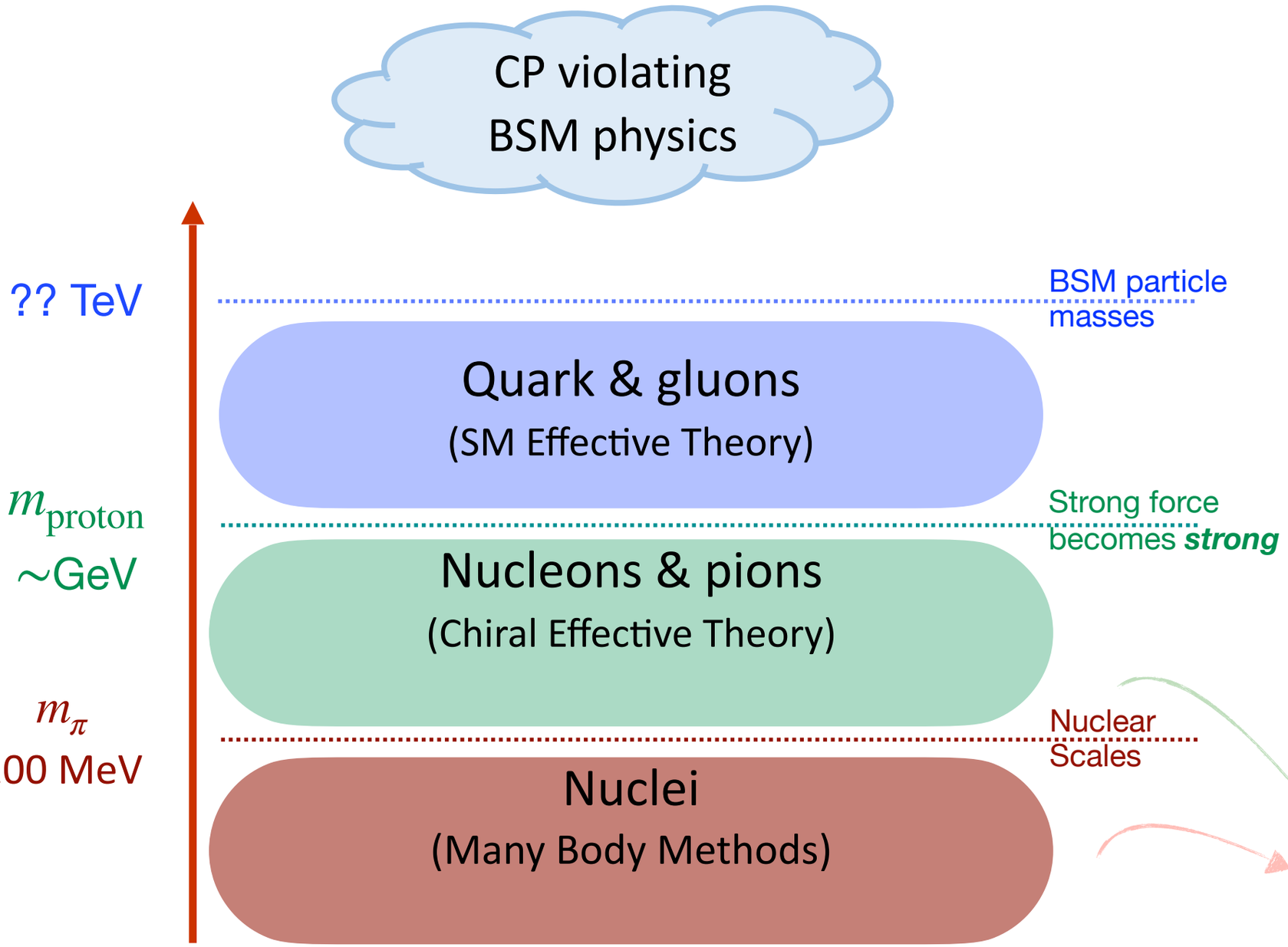
Putting the EFT(s) to work



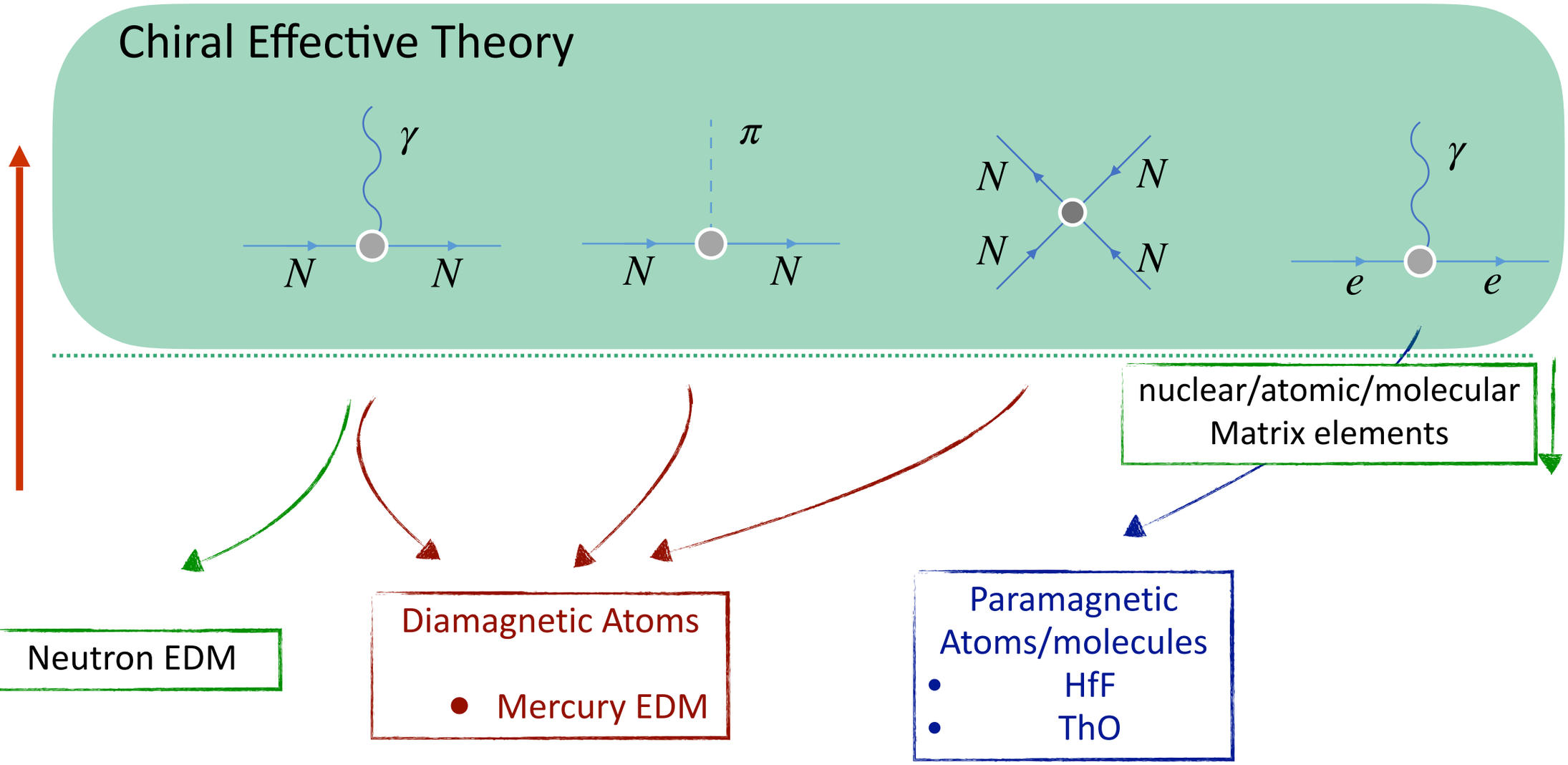
From high to low energies

- From m_W to m_N: known to one loop — **WD, et al, JHEP, '13**
- From quarks to nucleons & pions: Chiral EFT framework known — de Vries et al PLB '11, PRC '11; Kumar et al '24

Putting the EFT(s) to work



Atomic/molecular EDMs



de Jesus, Engel, ’05; Ban, Dobaczewski, Engel, Shukla, ’10; Engel et al. ’13; Skripnikov et al. ’13; Fleig & Nayak ‘14

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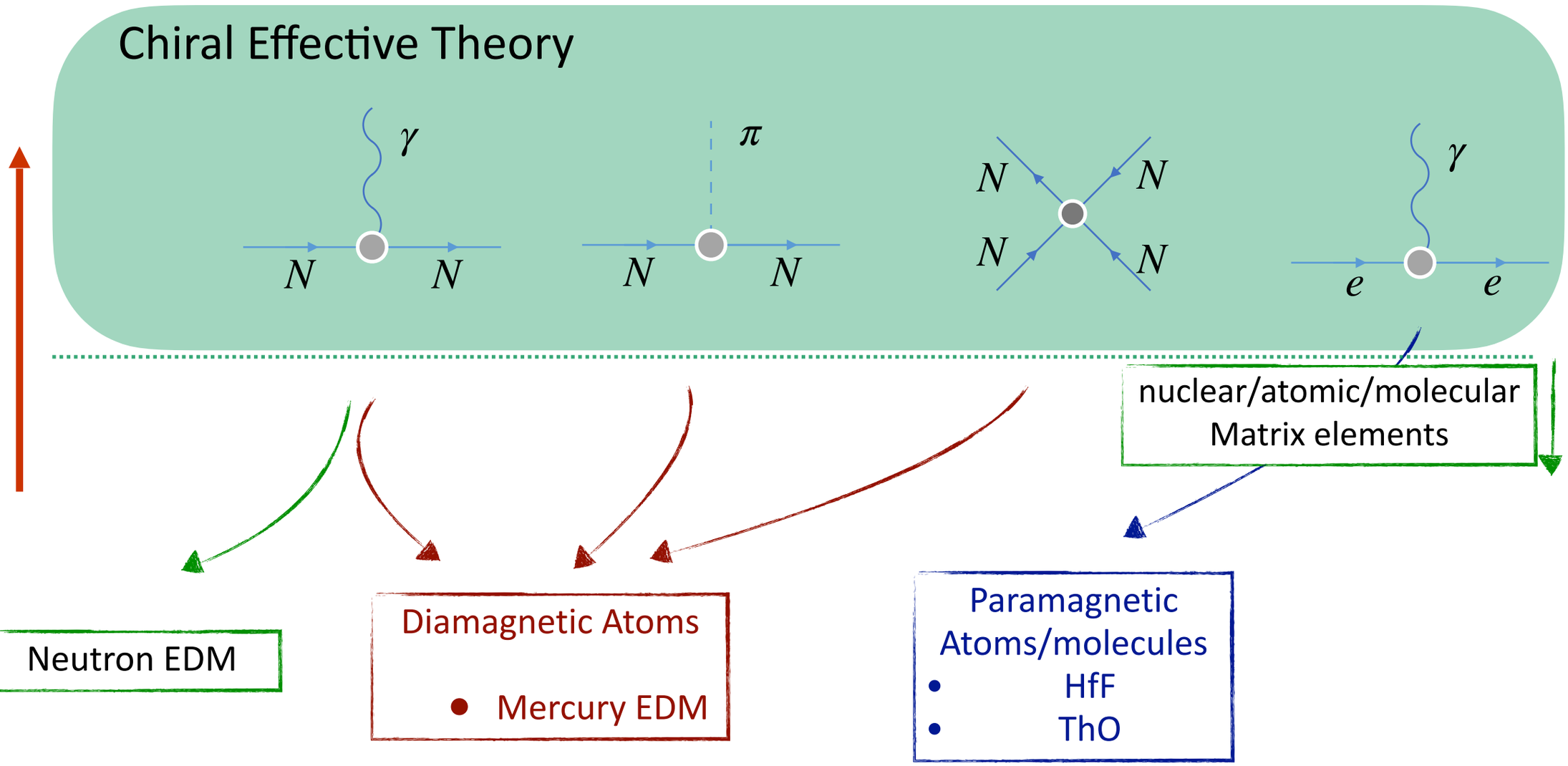


- Involve hadronic, Nuclear, Atomic, & Molecular matrix elements
  - Some are known to a few percent (e.g. paramagnetic systems)
  - Others have $\mathcal{O}(100\%)$ uncertainties (e.g. πN interactions in mercury)

de Jesus, Engel, ’05; Ban, Dobaczewski, Engel, Shukla, ’10; Engel et al. ’13; Skripnikov et al. ’13; Fleig & Nayak ‘14

Probing non-standard Higgs couplings

Using precision measurements of neutrons, atoms, & molecules

- Non-standard Yukawa couplings
  - Can play a role in Baryogenesis

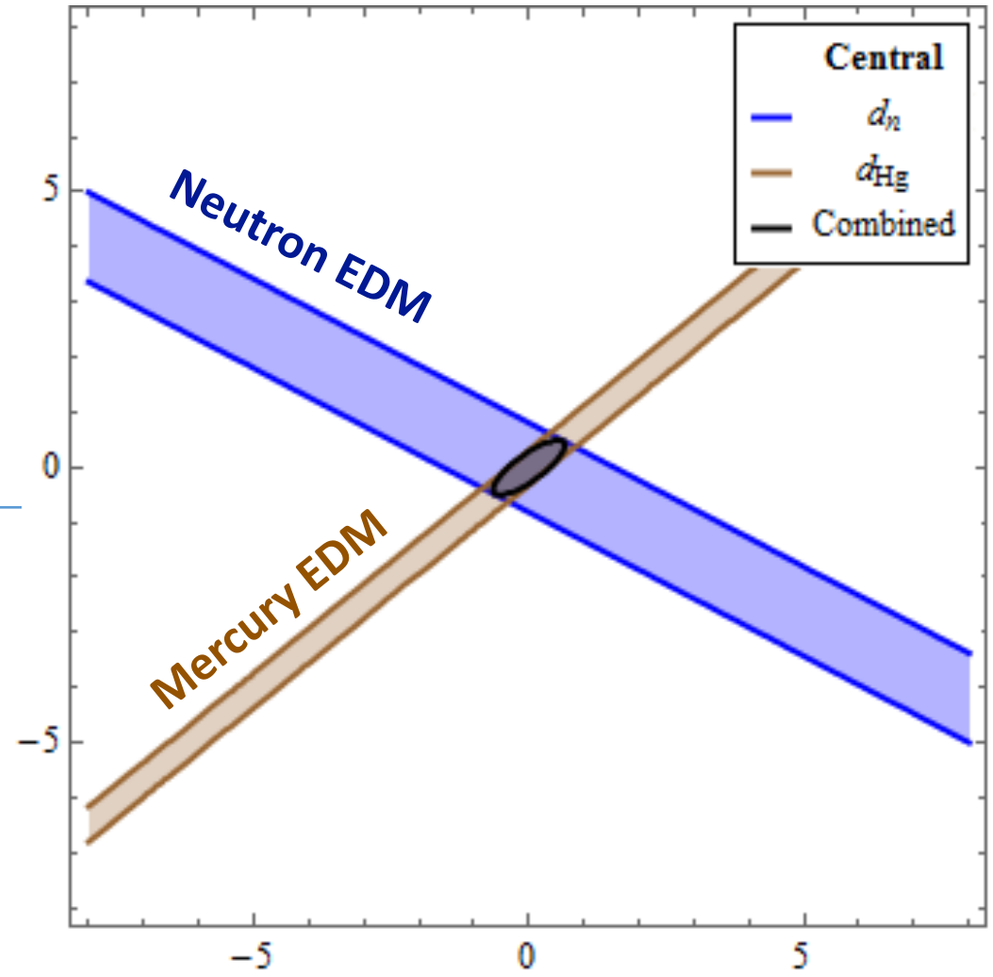
Fuchs et al ’19,’20; de Vries et al ’17;

- Non-Standard couplings to electroweak bosons

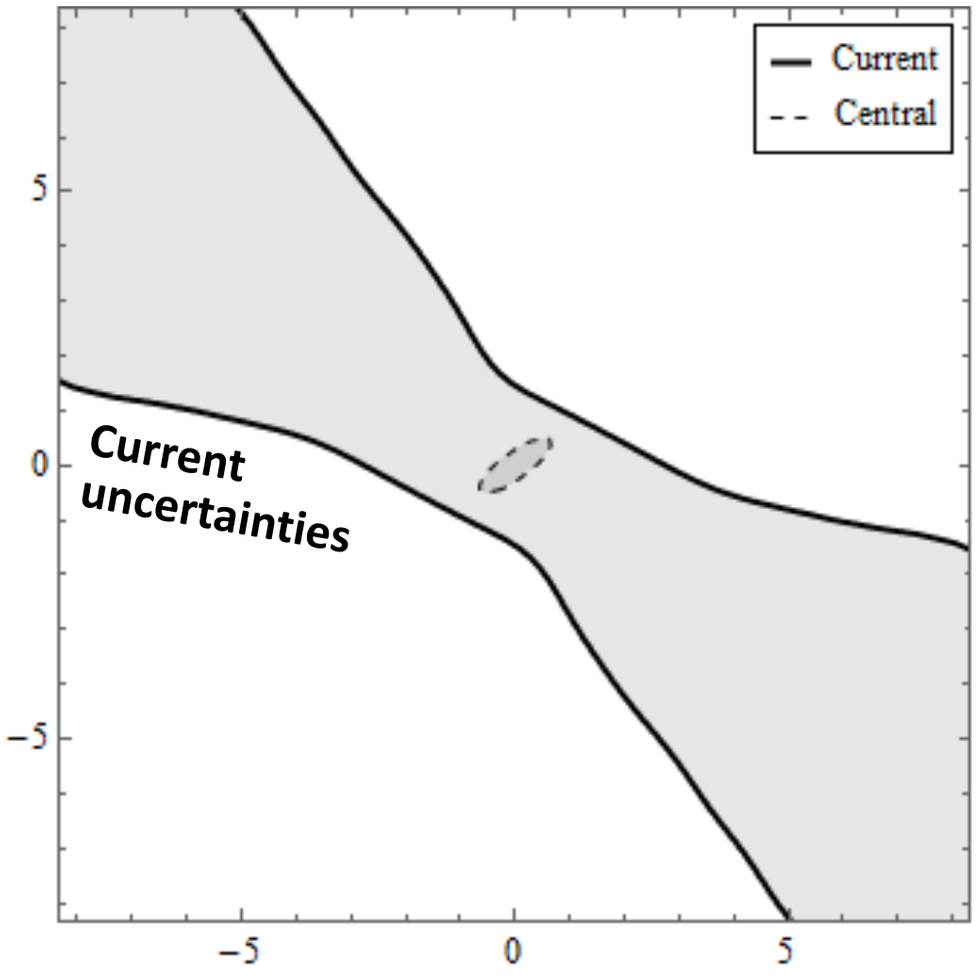
Non-standard Higgs couplings

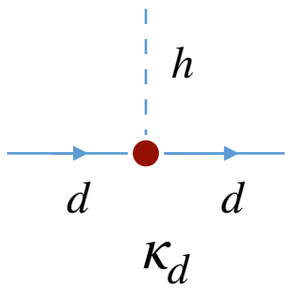
Nuclear & hadronic uncertainties

Without theory uncertainties

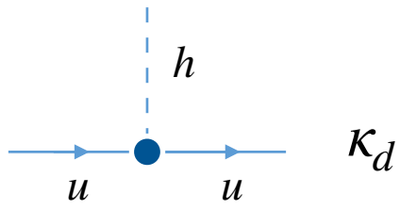


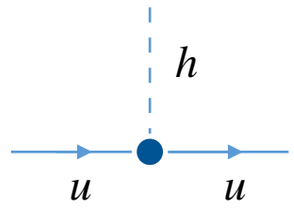
With theory uncertainties





$$\kappa_q \simeq \{10, 20\} \frac{y_q^{CP}}{y_q^{SM}}$$





- Impact of uncertainties can be mitigated by
  - Improved theory: 50%(25%) uncertainty on nuclear(hadronic) matrix elements

WD et al, PRD ’16; JHEP ‘16

Non-standard Higgs couplings

Nuclear & hadronic uncertainties

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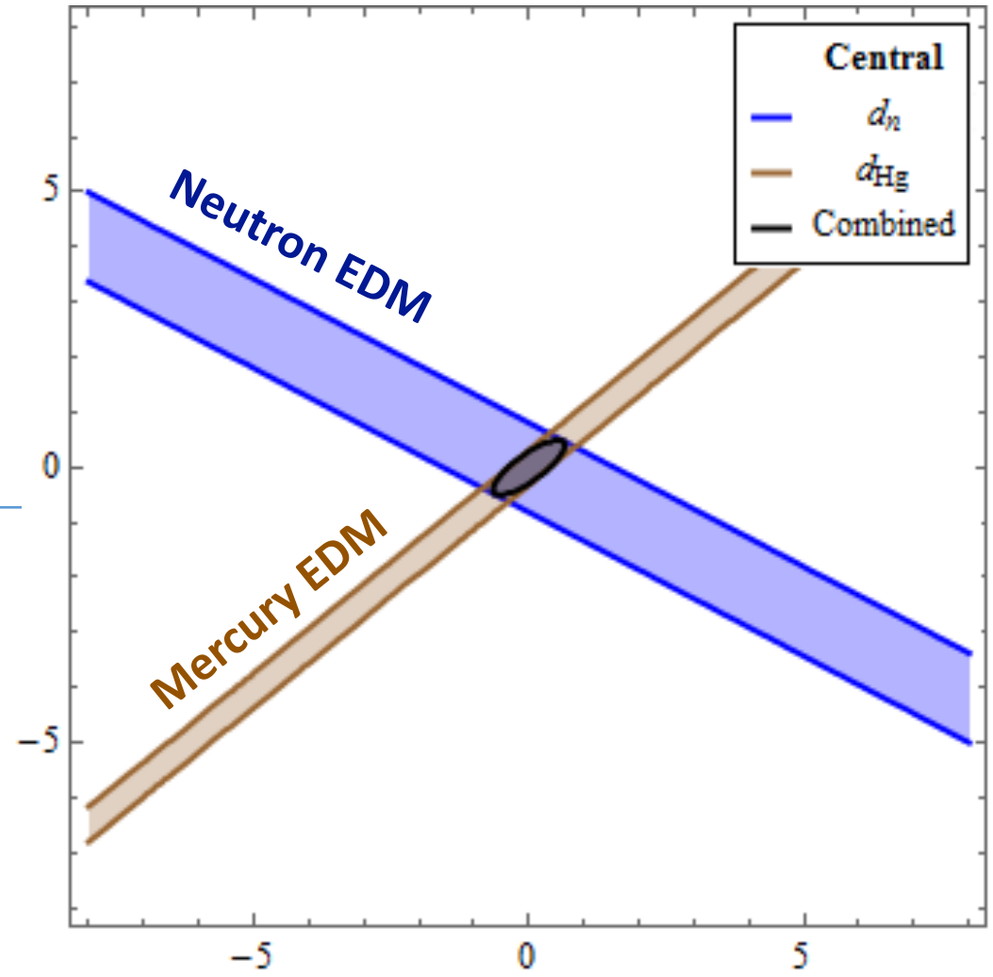

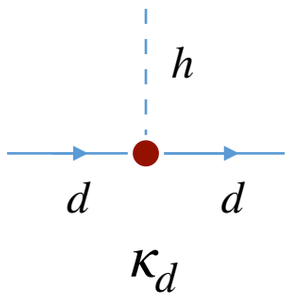

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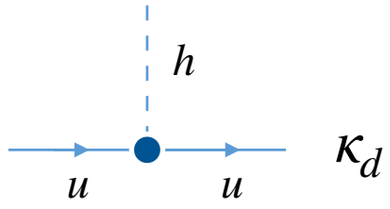

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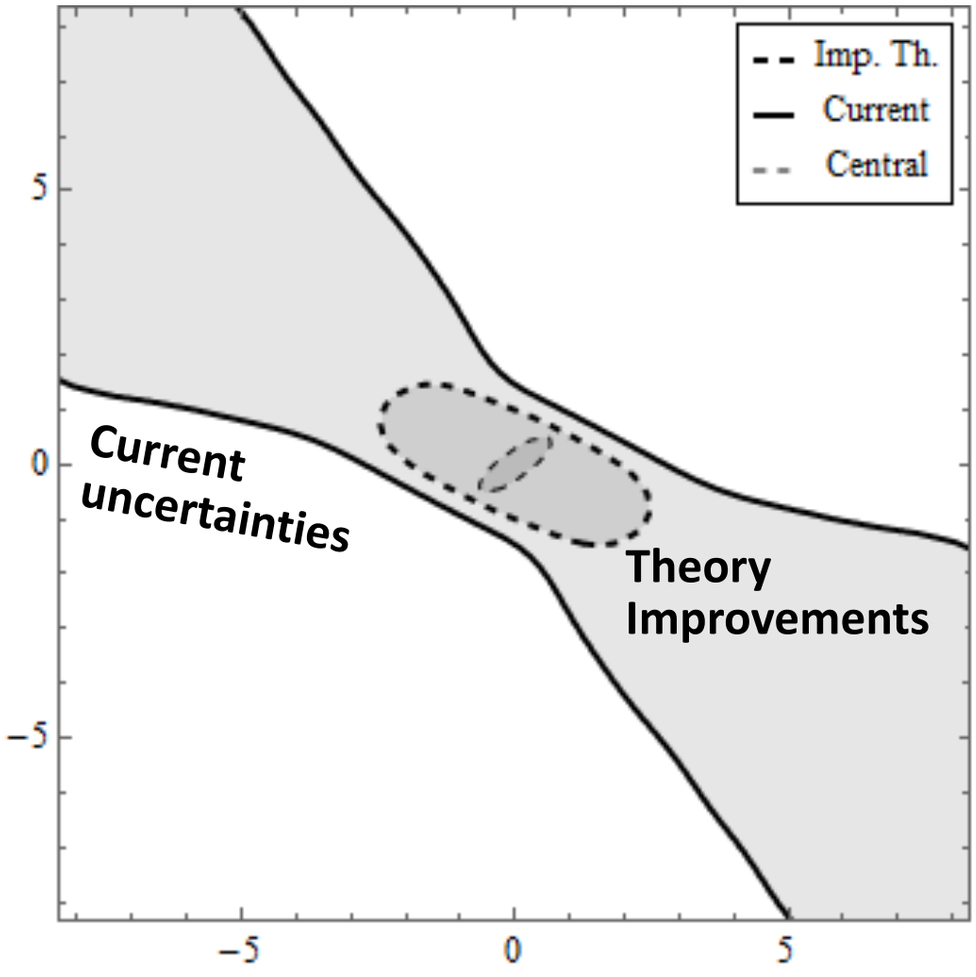

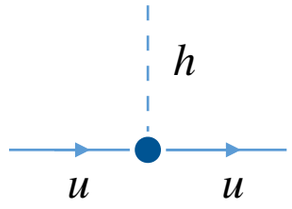

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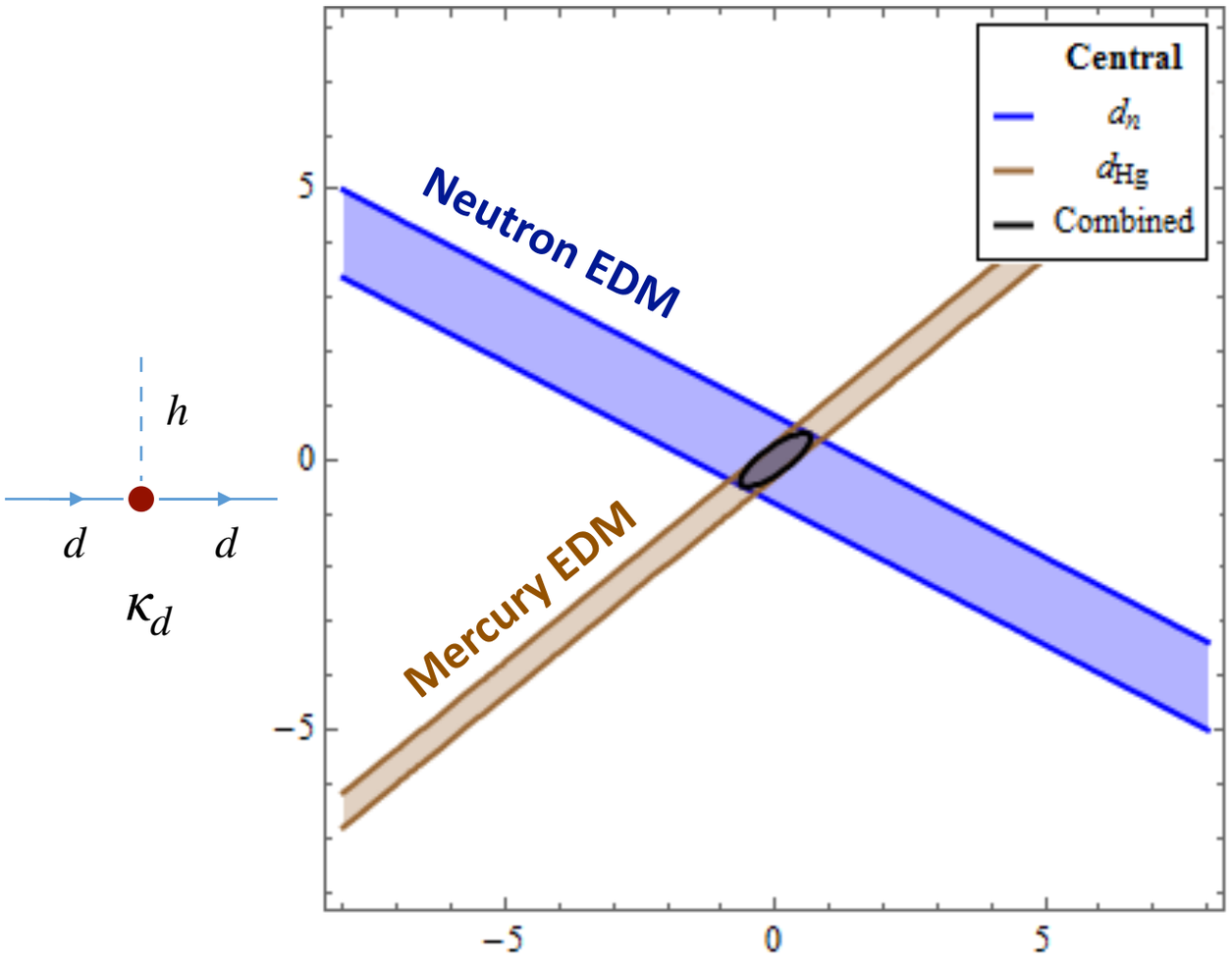

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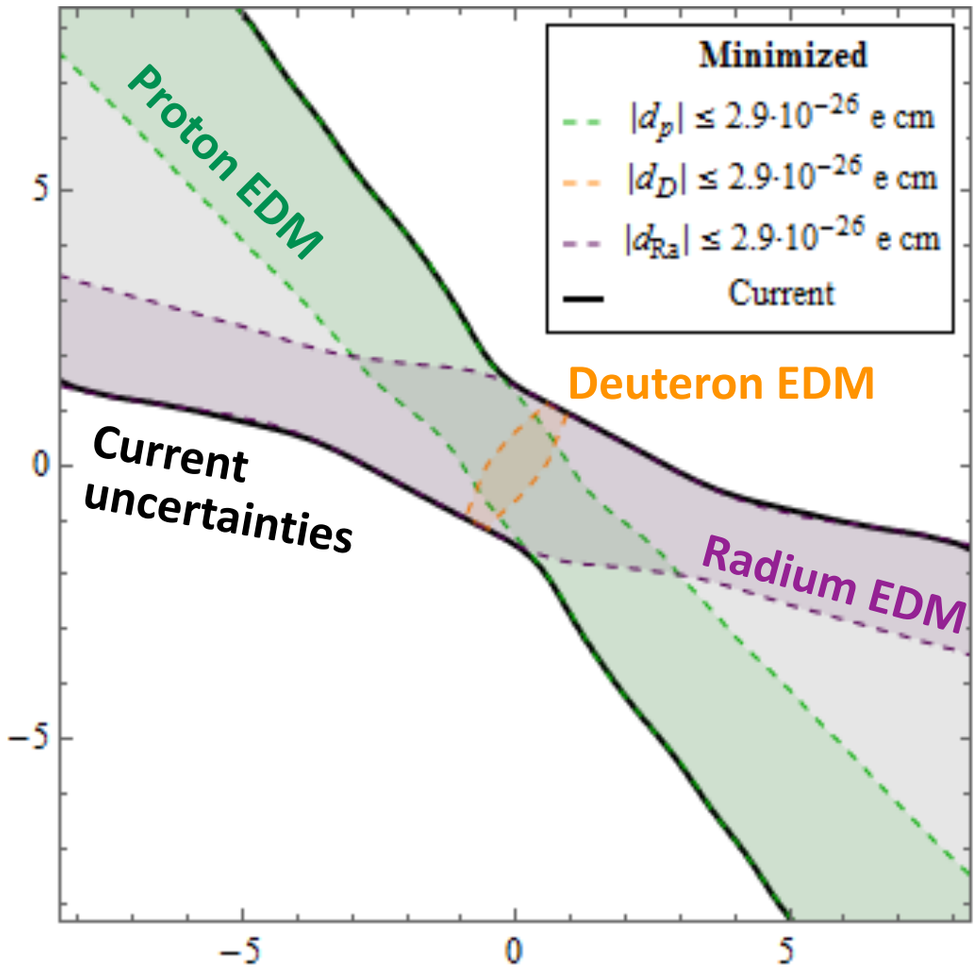

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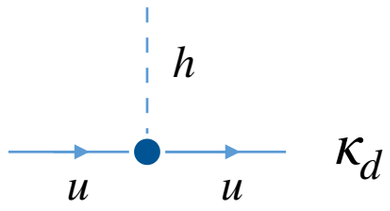

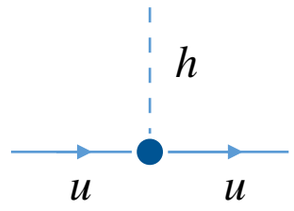

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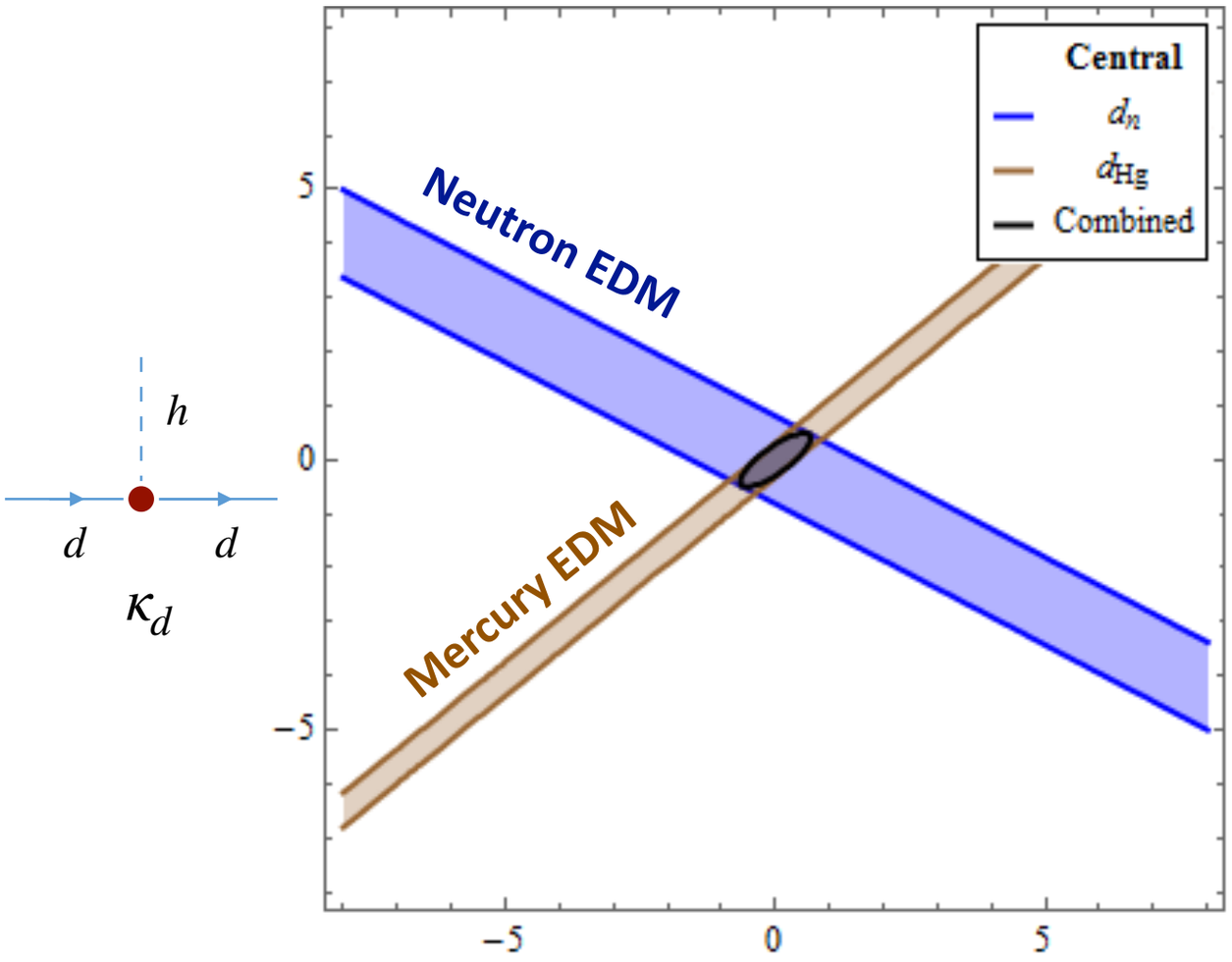
  - Additional measurements, e.g. d_p, d_D, $d_{\rm Ra}$ at current d_n sensitivity

WD et al, PRD ’16; JHEP ‘16

Non-standard Higgs couplings

Nuclear & hadronic uncertainties

Without theory uncertainties



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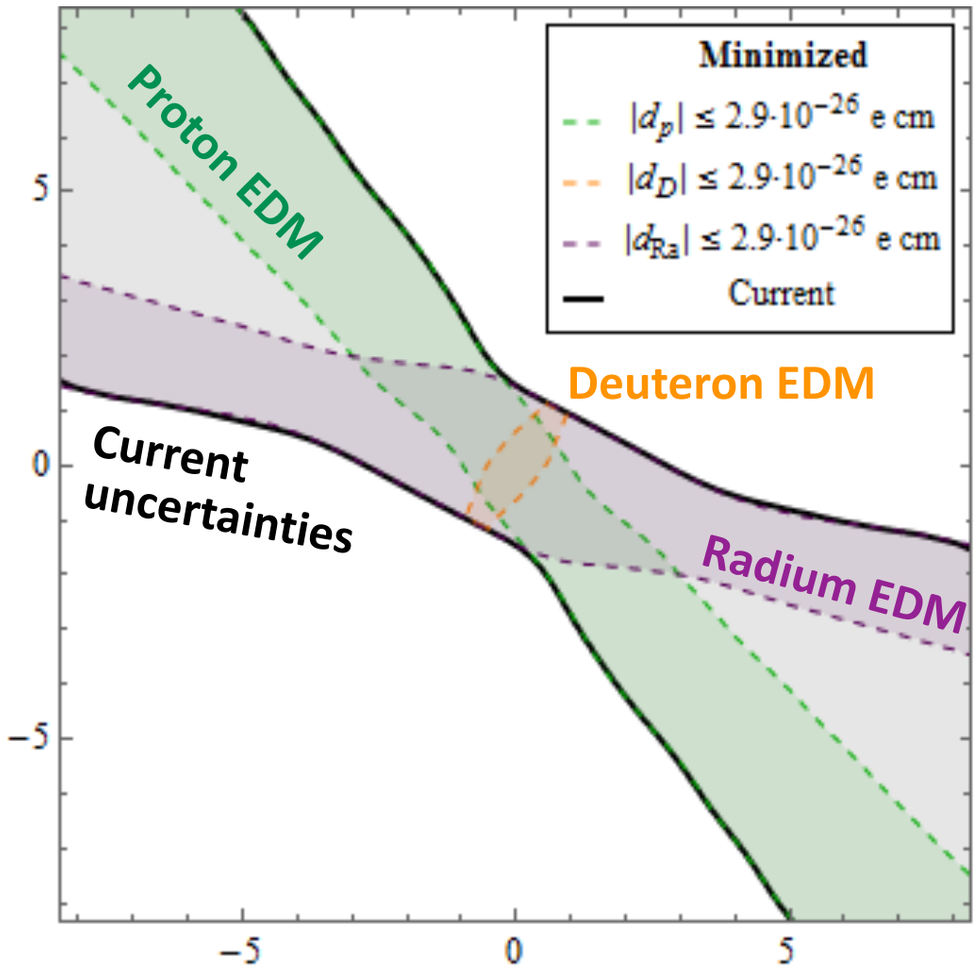

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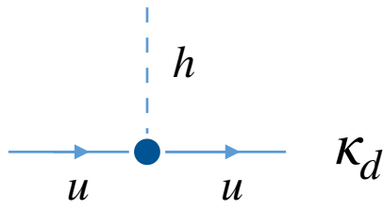
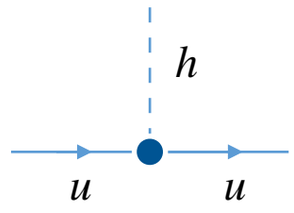




- Impact of un
  - Improved t
  - Additional measurements, e.g. d_p, d_D, $d_{\rm Ra}$ at current d_n sensitivity

Theory improvements can be just as effective as new experiments!

WD et al, PRD ’16; JHEP ‘16

Probing non-standard Higgs couplings

Using precision measurements of neutrons, atoms, & molecules

- Non-standard Yukawa couplings
  - Can play a role in Baryogenesis

- Non-Standard couplings to electroweak bosons

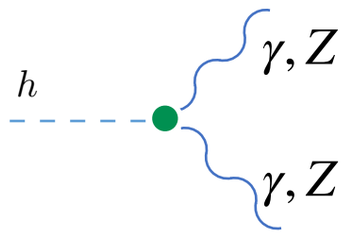
Electric Dipole Moments

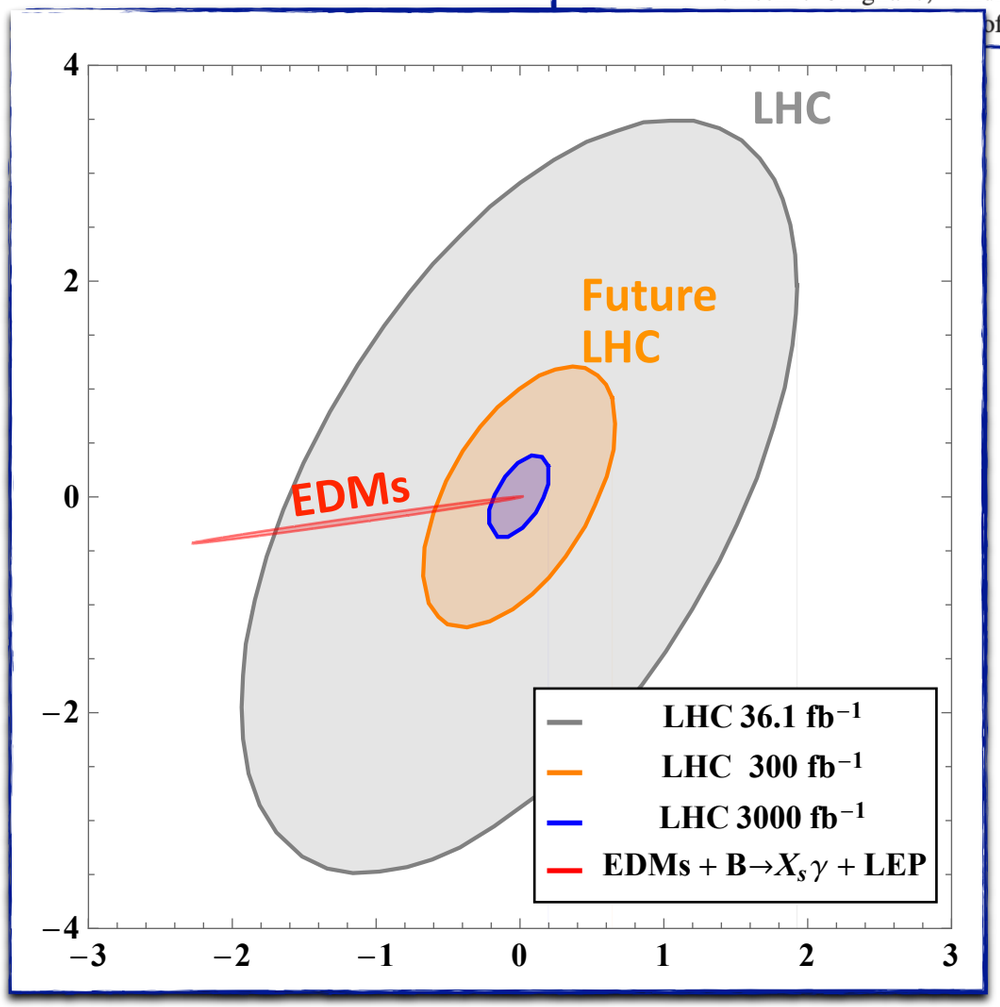
Combination with LHC

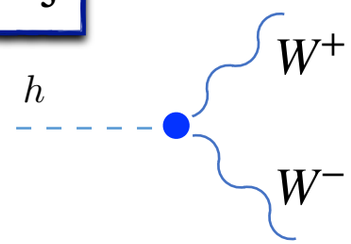
PHYSICAL REVIEW LETTERS **123,** 051801 (2019)

_CP_ Violation in Higgs-Gauge Interactions: From Tabletop Experiments to the LHC

Vincenzo Cirigliano,[1] Andreas Crivellin,[2,3] Wouter Dekens,[4] Jordy de Vries,[5,6]
…oferichter,[7] and Emanuele Mereghetti[1]





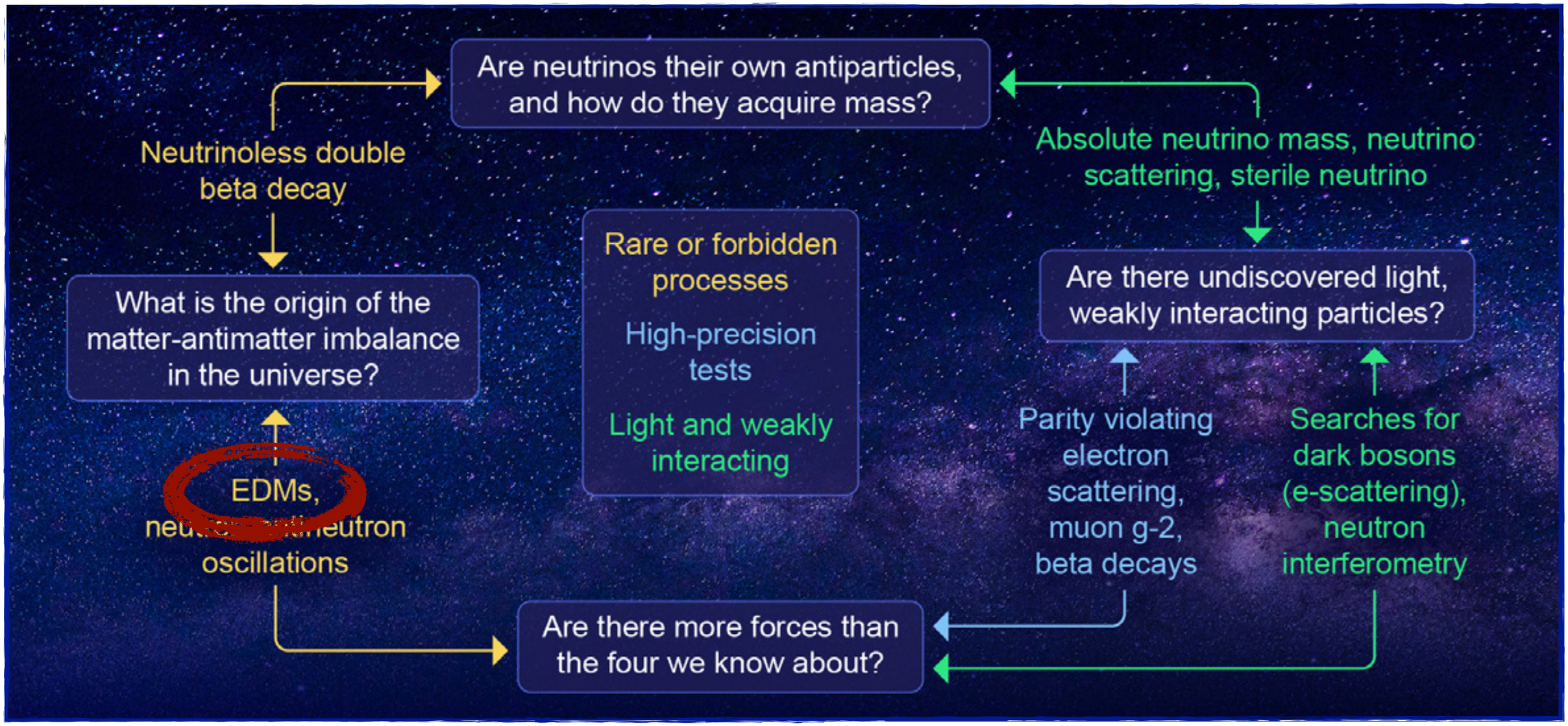


Bernlochner et al. PLB ’19

- EDMs are very competitive, even compared to future LHC sensitivity to $pp \to h + 2j$
- EDMs only probe a few interactions at a time
  - Complementarity between to high-energy & low-energy probes

Electric Dipole Moments

The CKM matrix & β decays



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Electric Dipole Moments

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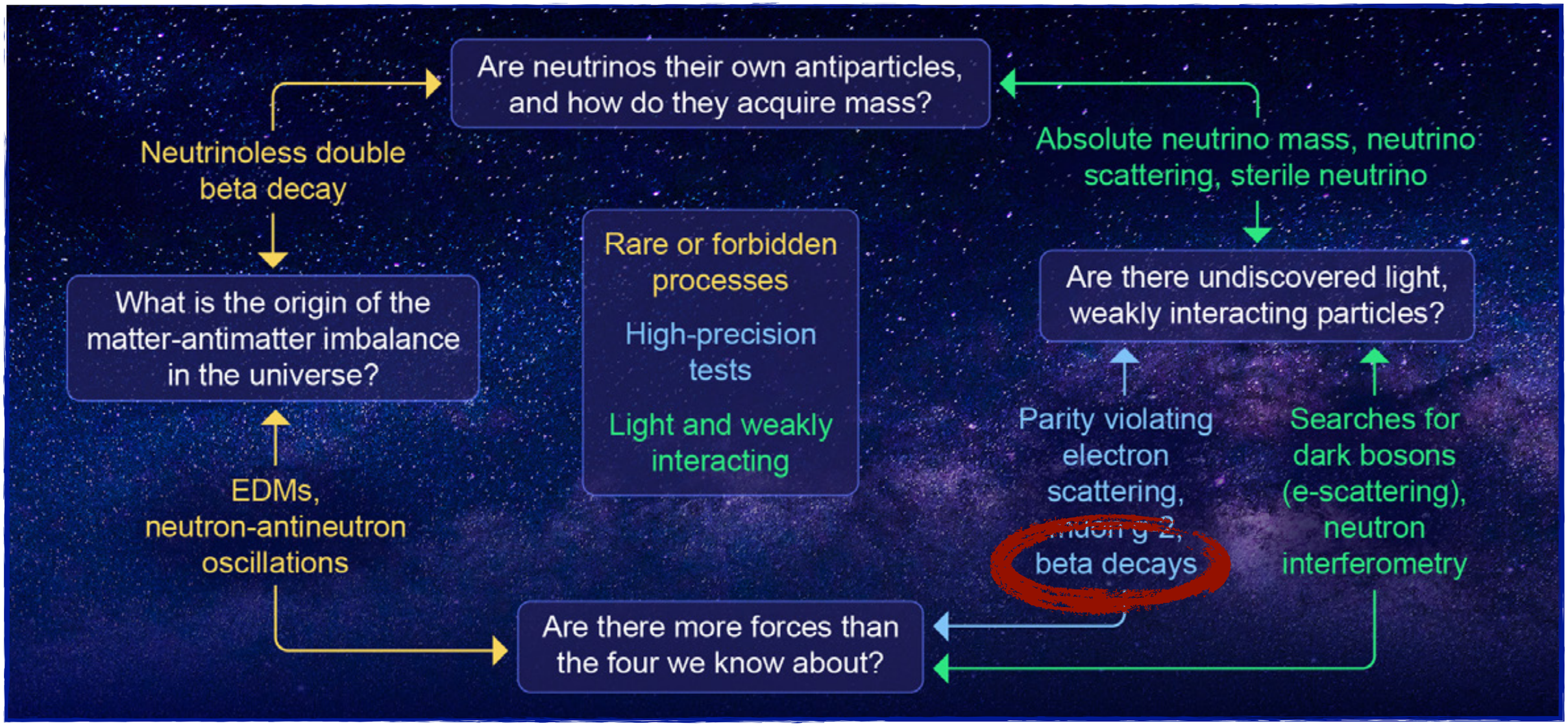
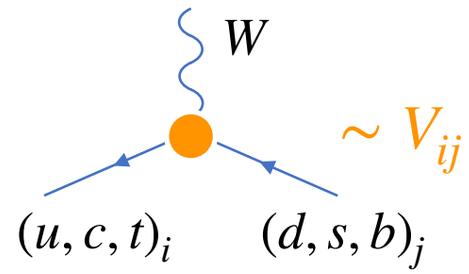


2023 Long Range Plan for Nuclear Science

β decays

- Helped identify V-A structure of SM



- Nowadays determine V_{ud}
- $\delta V_{ud} \sim \text{few} \times 10^{-4}$ provides stringent CKM unitarity test:

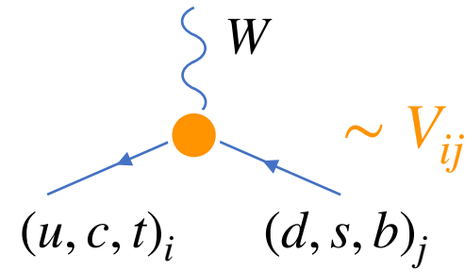
$$\Delta = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$$

β decays

- Helped identify V-A structure of SM
- Nowadays determine V_{ud}
- Sub-permille precision provides CKM unitarity test:

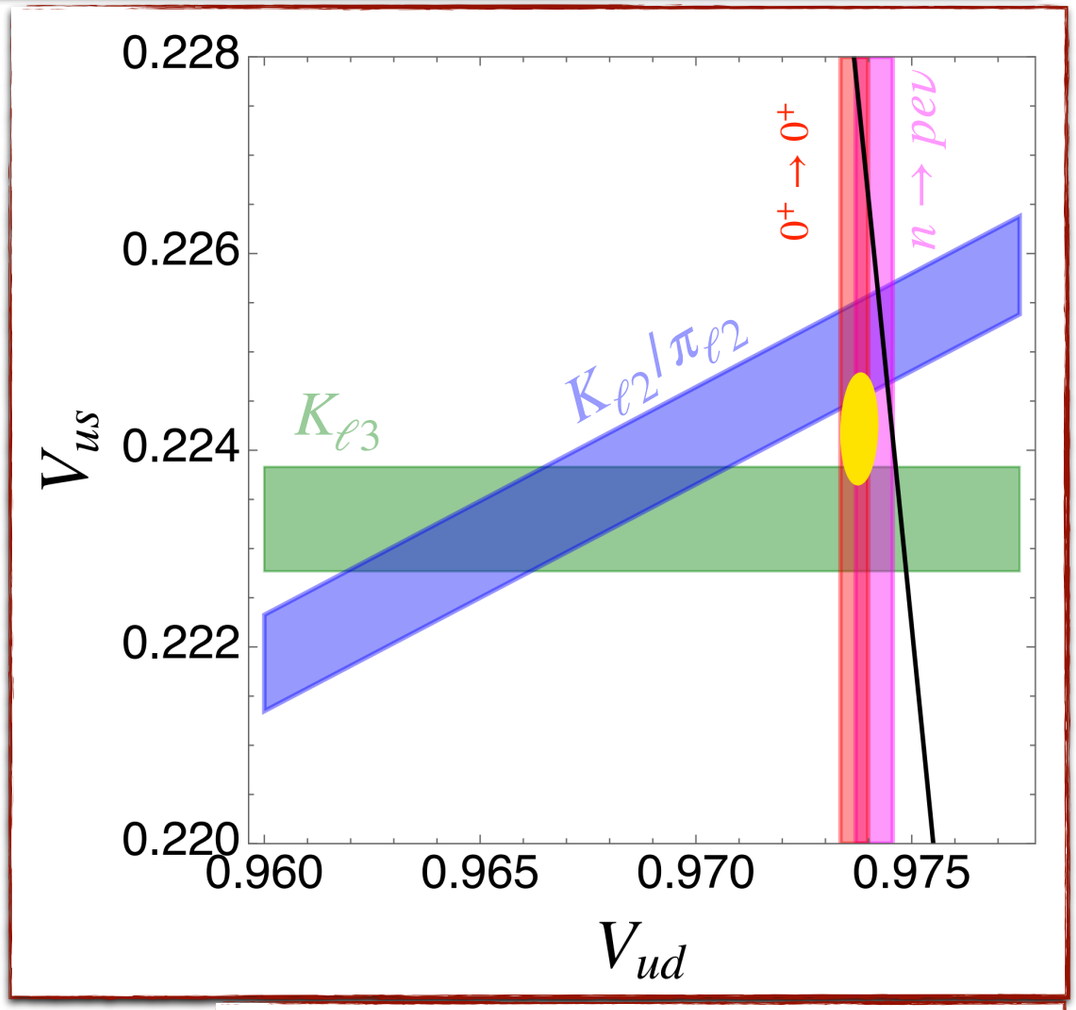
$$\Delta = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$$

- Sensitive to BSM scales $O(10)$ TeV



Unitarity test

- Experimentally determined
  - V_{ud} from neutron & nuclear β decays
  - V_{us} from Kaon/pion decays
- Disagrees with unitarity by $\sim 3\sigma$
  - Issue with SM predictions/uncertainties?
  - BSM physics?



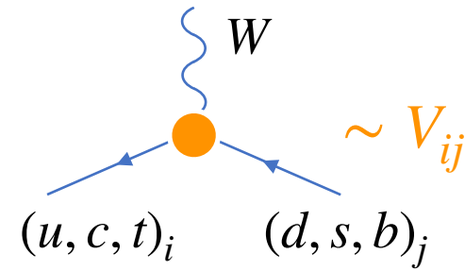
Cirigliano, Crivellin, Moulson, Hoferichter '23

β decays

- Helped identify V-A structure of SM
- Nowadays determine V_{ud}
- Sub-permille precision provides CKM unitarity test:

$$\Delta = |V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} - 1 = 0$$

- Sensitive to BSM scales $O(10)$ TeV



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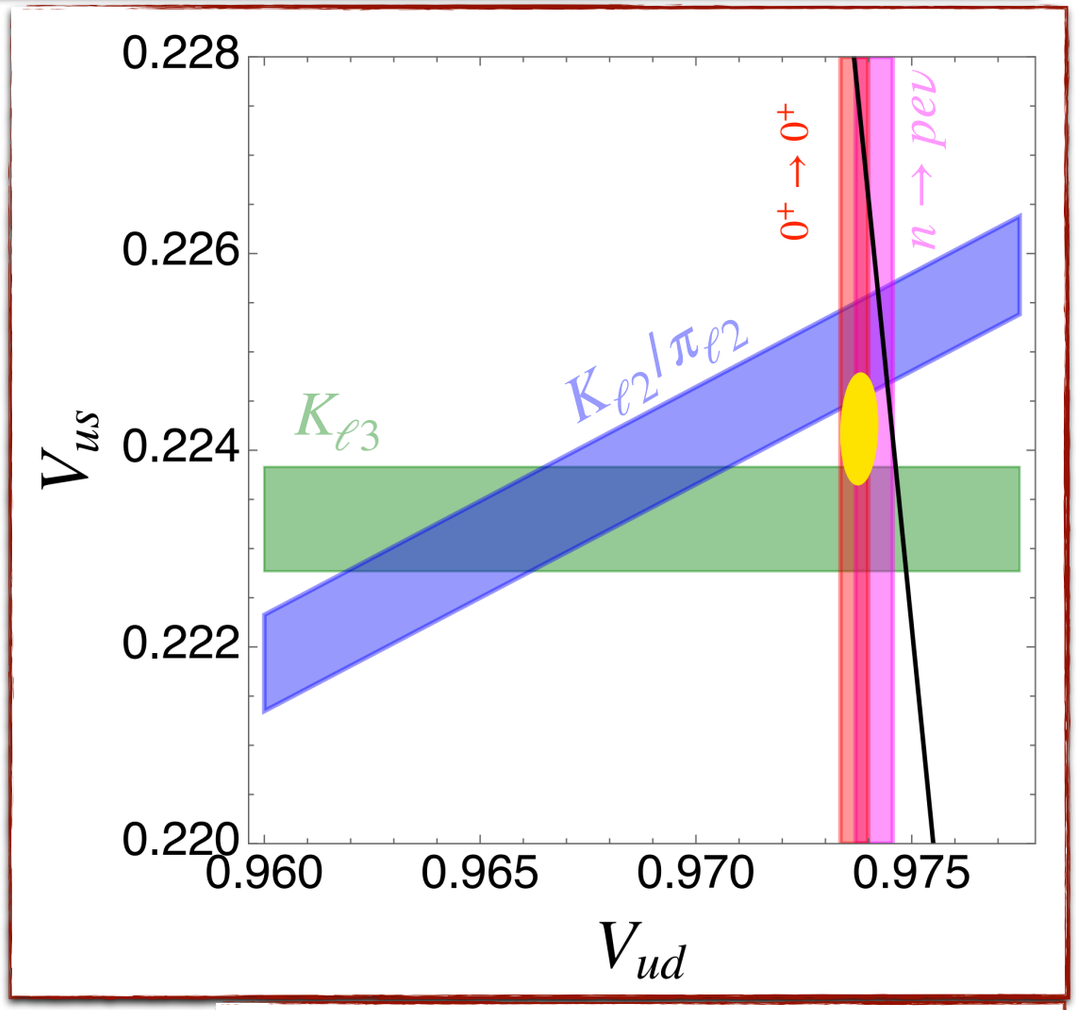

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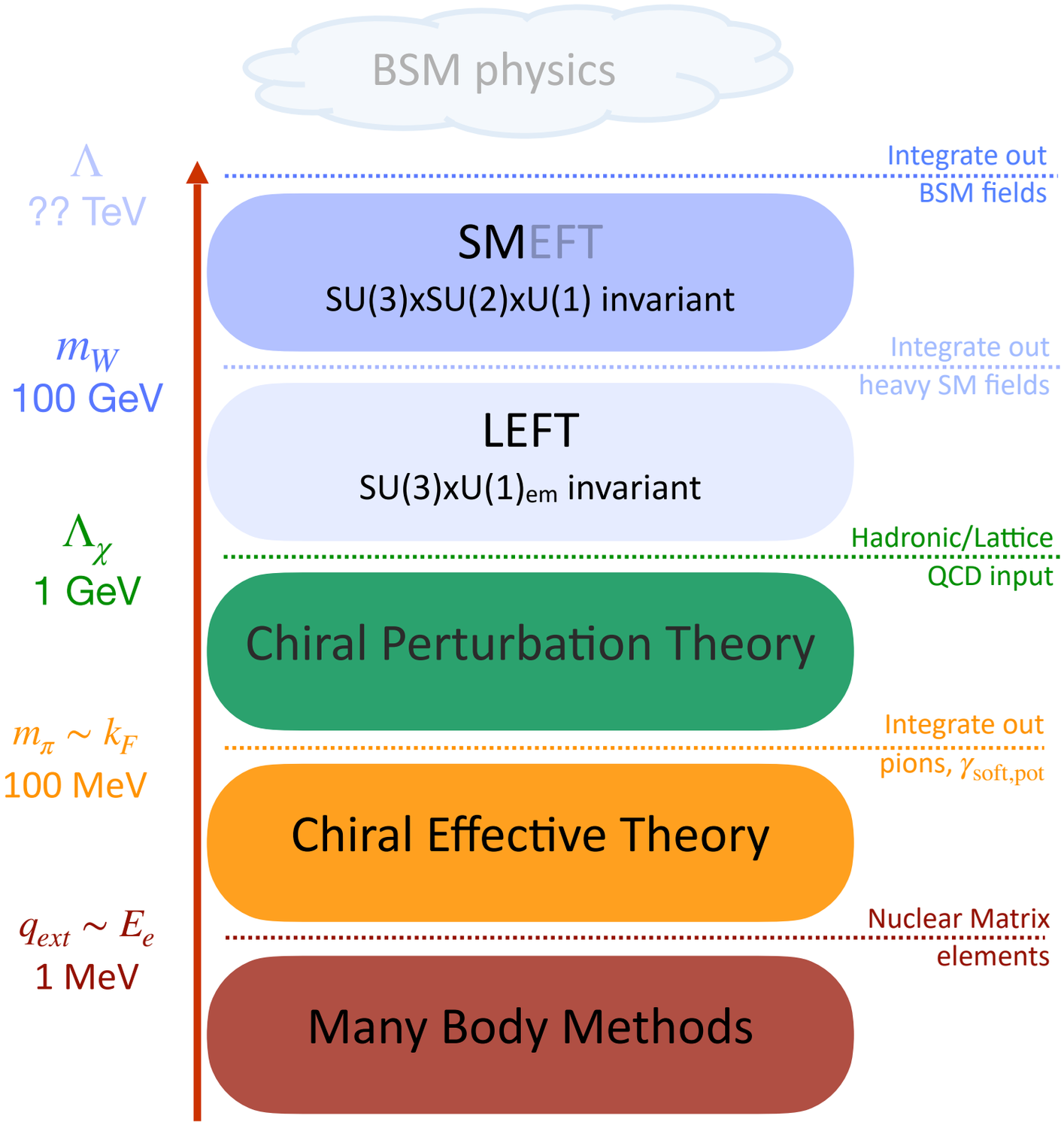
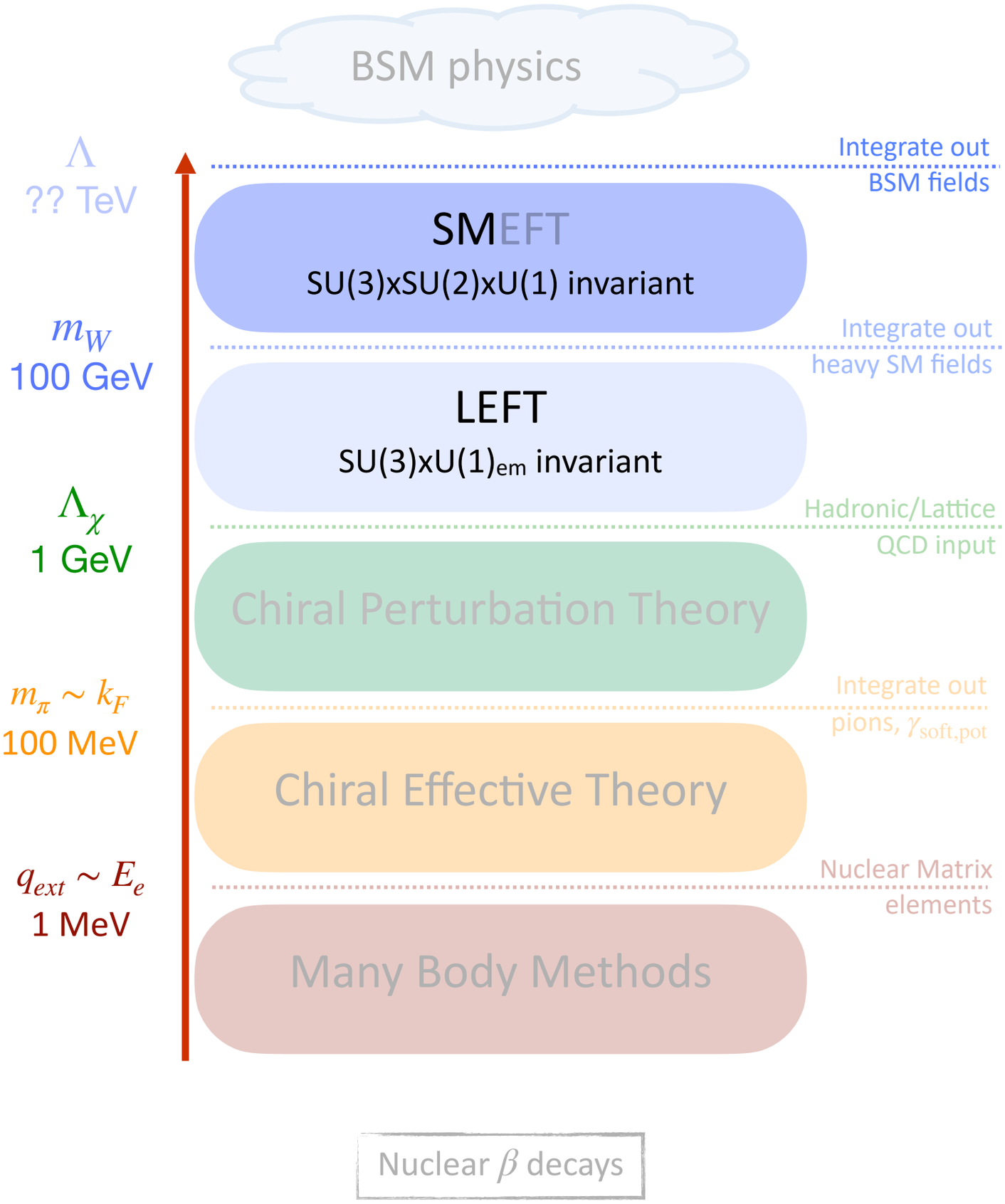


Nuclear β decays

- 10^{-4} accuracy requires
  - $\mathcal{O}(\alpha m_\pi / m_N)$ & $\mathcal{O}(\alpha m_e / m_\pi)$
  - Certain large $\mathcal{O}(\alpha^2)$ terms


BSM physics
Λ
?? TeV
Integrate out
BSM fields
SMEFT
SU(3)xSU(2)xU(1) invariant
m_W
100 GeV
Integrate out
heavy SM fields
LEFT
SU(3)xU(1)em invariant
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$m_\pi \sim k_F$
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Nuclear Matrix
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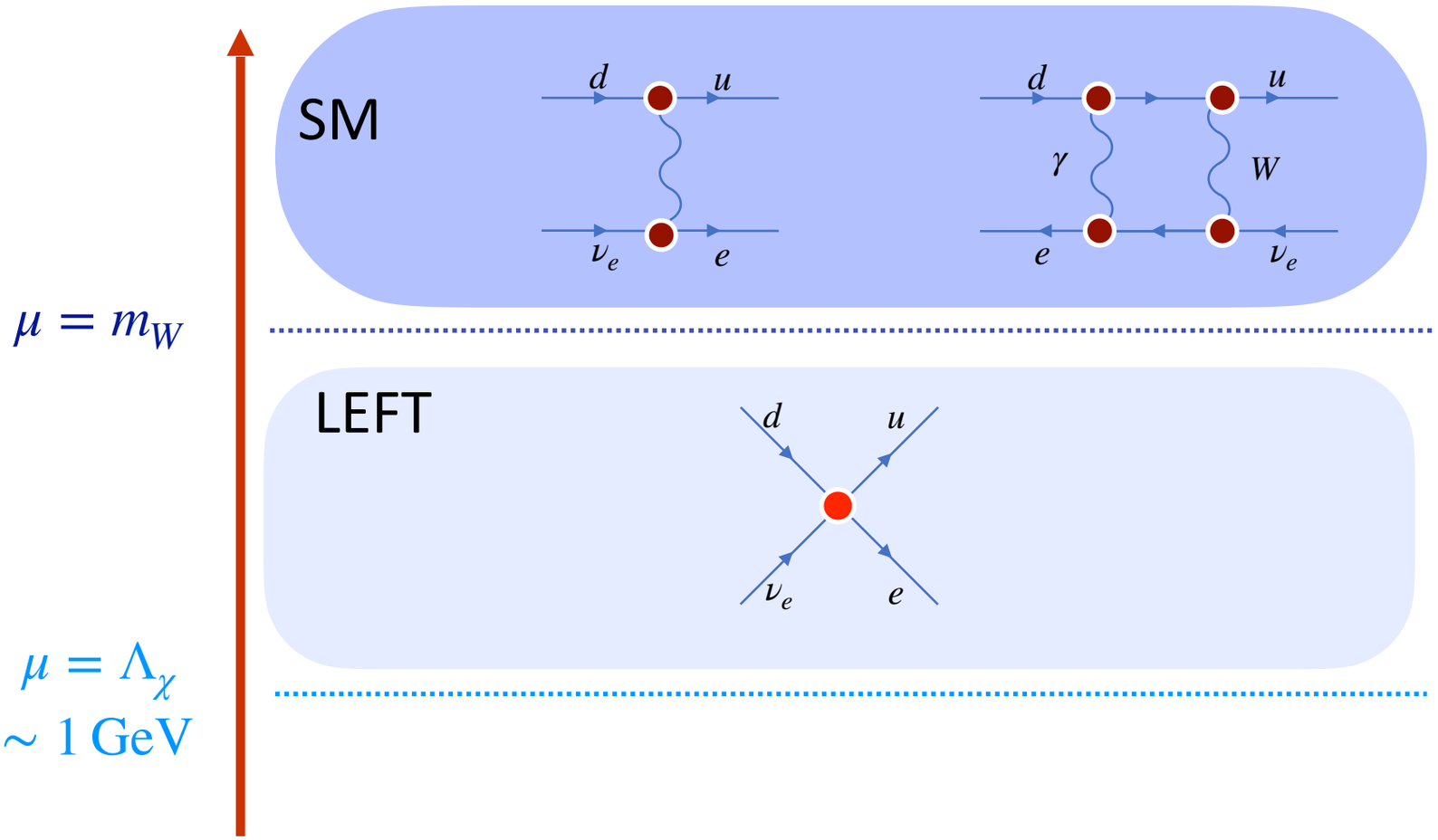
Many Body Methods
Nuclear β decays

SM/LEFT

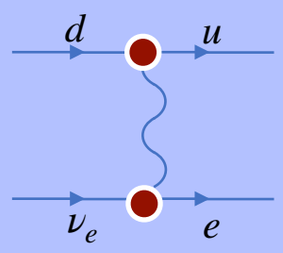


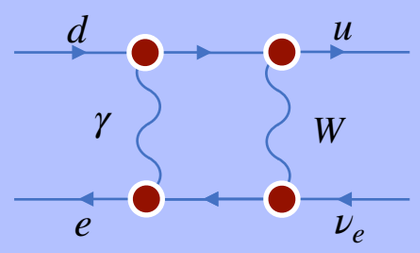
- Can use a simpler theory without heavy SM particles, t, W, Z, h
  - General connection has been worked out to one-loop
  - ***Needed to connect (B)SM to experiment***

SM/LEFT

$\mu = m_W$

SM





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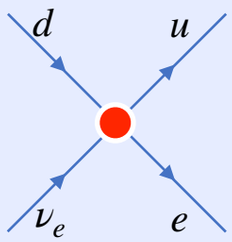
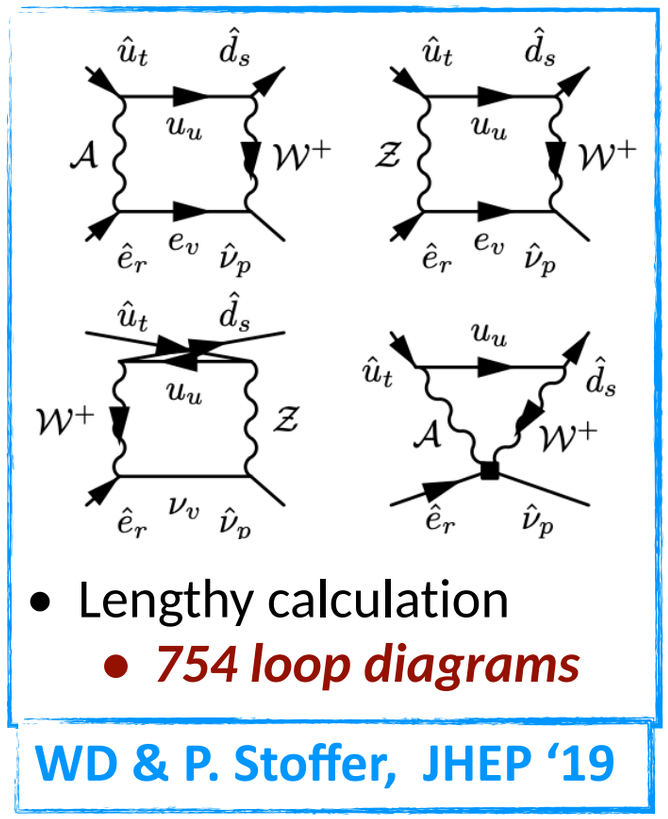


$\mu = \Lambda_\chi$
$\sim 1\,\mathrm{GeV}$



- Lengthy calculation
  - ***754 loop diagrams***

WD & P. Stoffer, JHEP '19

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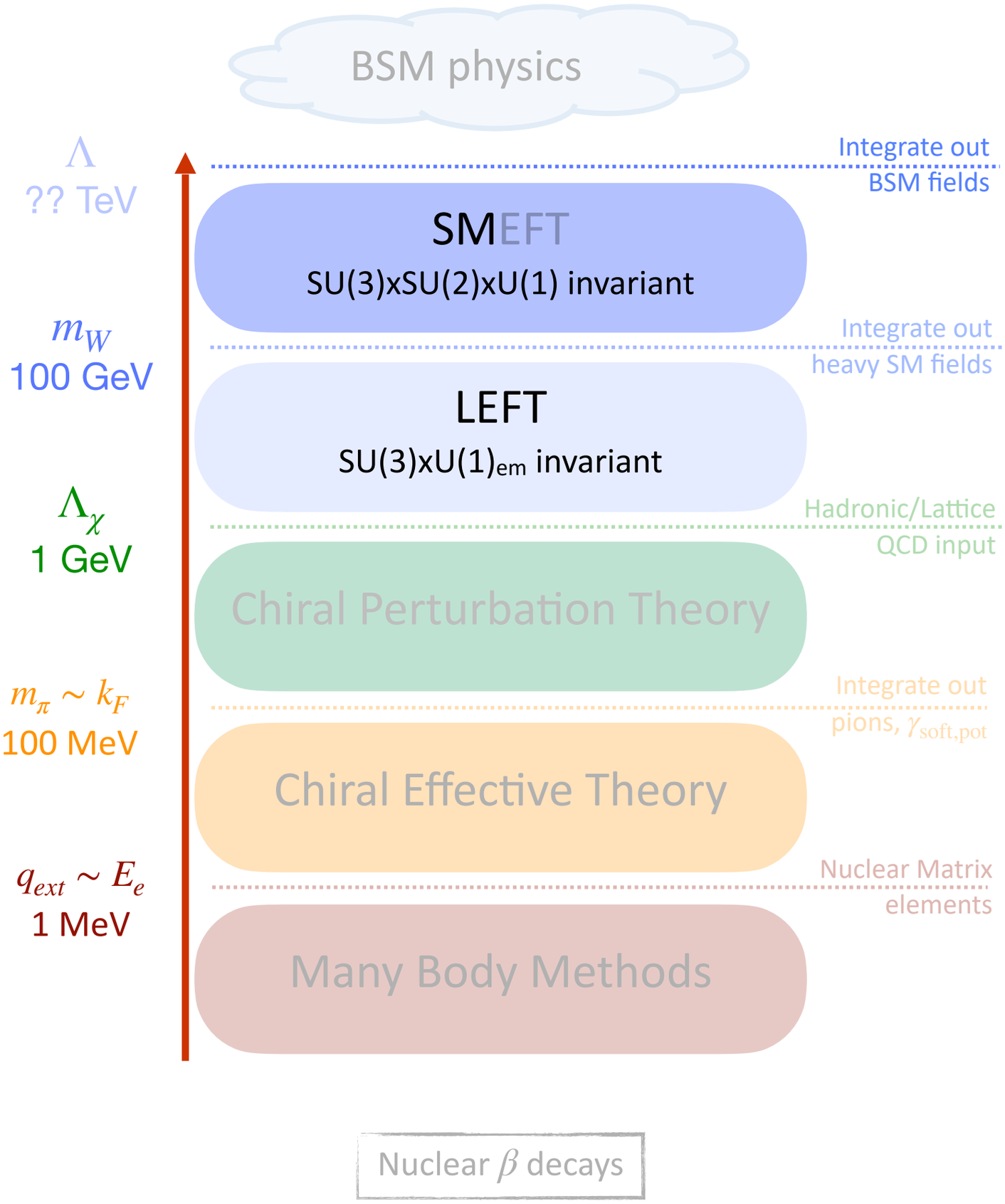
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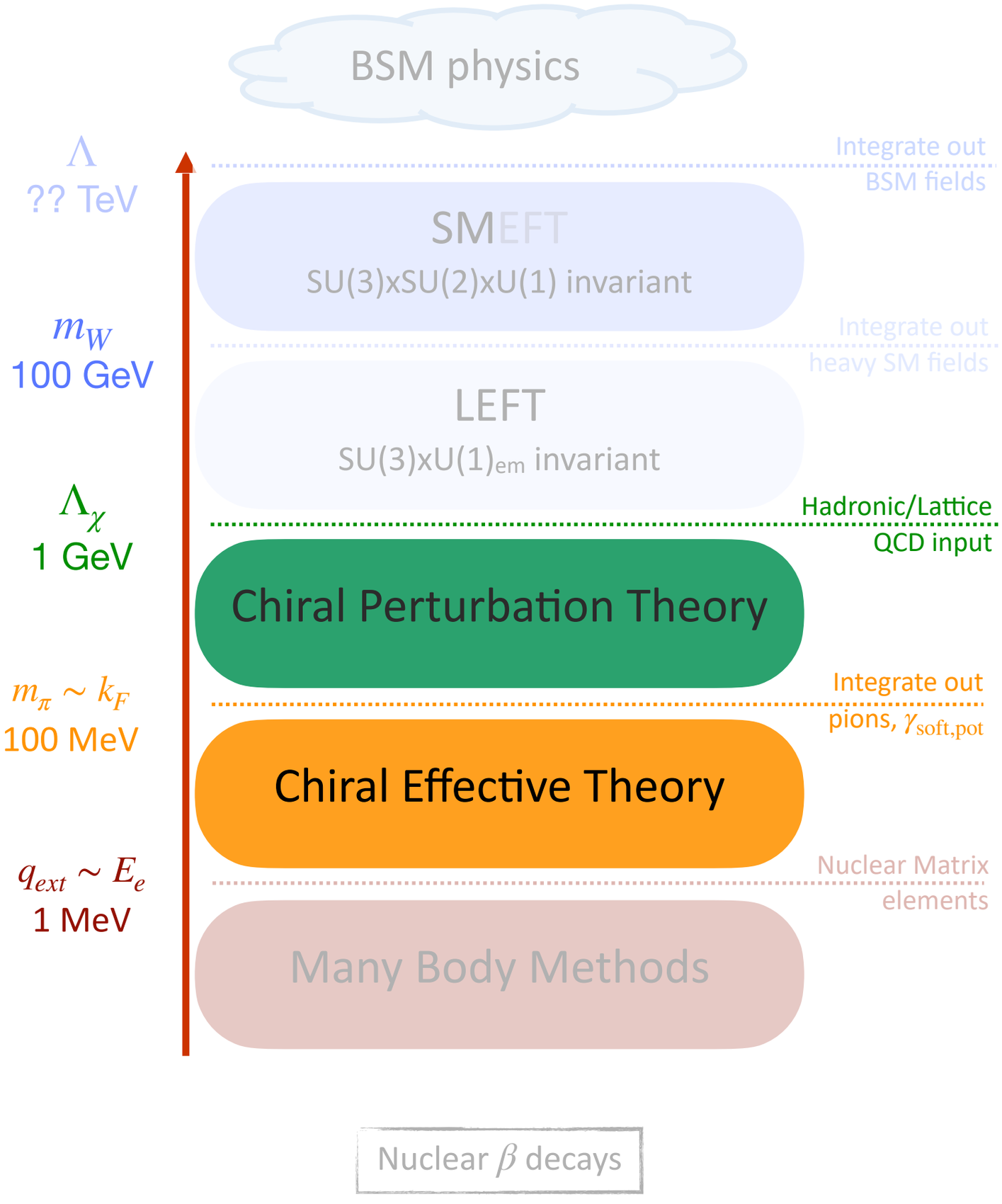
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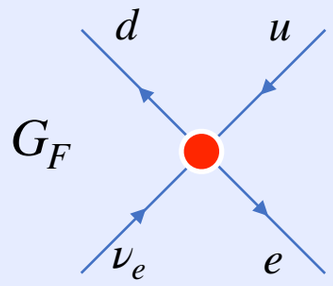
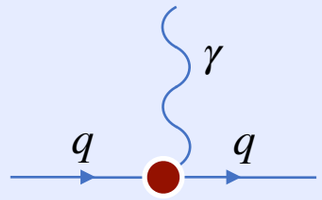
From quarks to hadrons

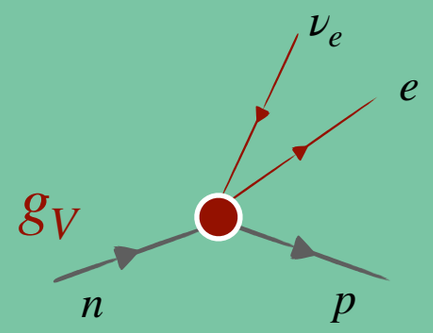
LEFT





1 GeV

χPT



One-nucleon sector

- Worked out $\mathcal{O}(\alpha)$ corrections, require non-perturbative input
  - **Relevant for neutron decay**

WD, Cirigliano, Mereghetti, Tomalak,'23

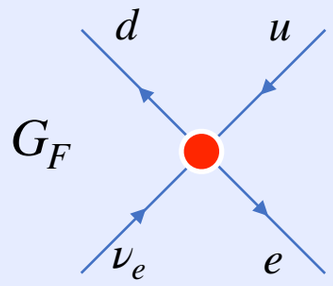
Nab ORNL

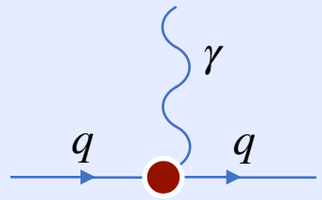
LANL UCNτ

From quarks to hadrons

1 GeV

LEFT





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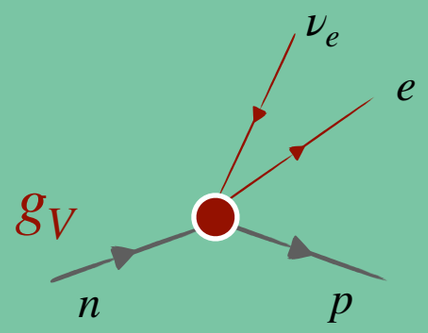

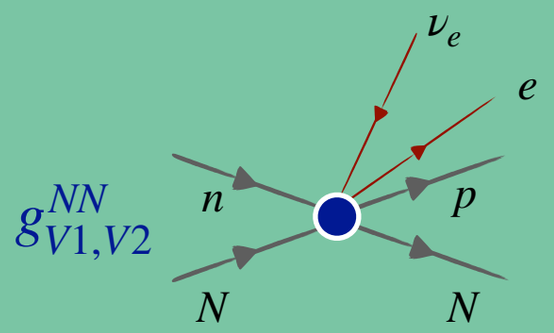

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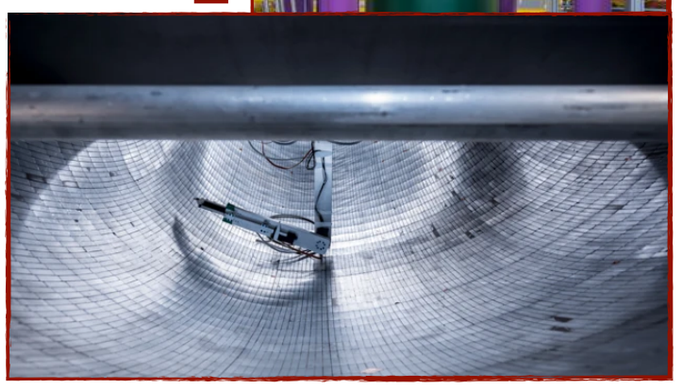
WD, Cirigliano, Mereghetti, Tomalak,'23

Two-body interactions

- Two unknown hadronic couplings
- Required for nuclear decays

Nab ORNL



LANL UCNτ

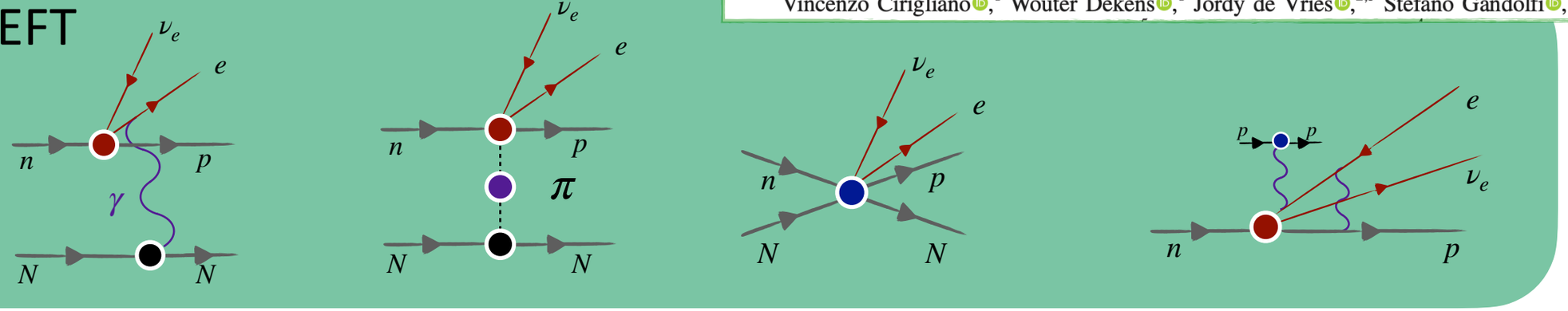
Developed EFT framework for one & two nucleon effects

PHYSICAL REVIEW LETTERS **133,** 211801 (2024)

Radiative Corrections to Superallowed β Decays in Effective Field Theory

Vincenzo Cirigliano,[1] Wouter Dekens,[1] Jordy de Vries,[2,3] Stefano Gandolfi,[4]

Chiral EFT



100 MeV

$\mathcal{O}(\alpha m_\pi/m_N)$ & $\mathcal{O}(\alpha m_e/m_\pi)$ two-nucleon terms

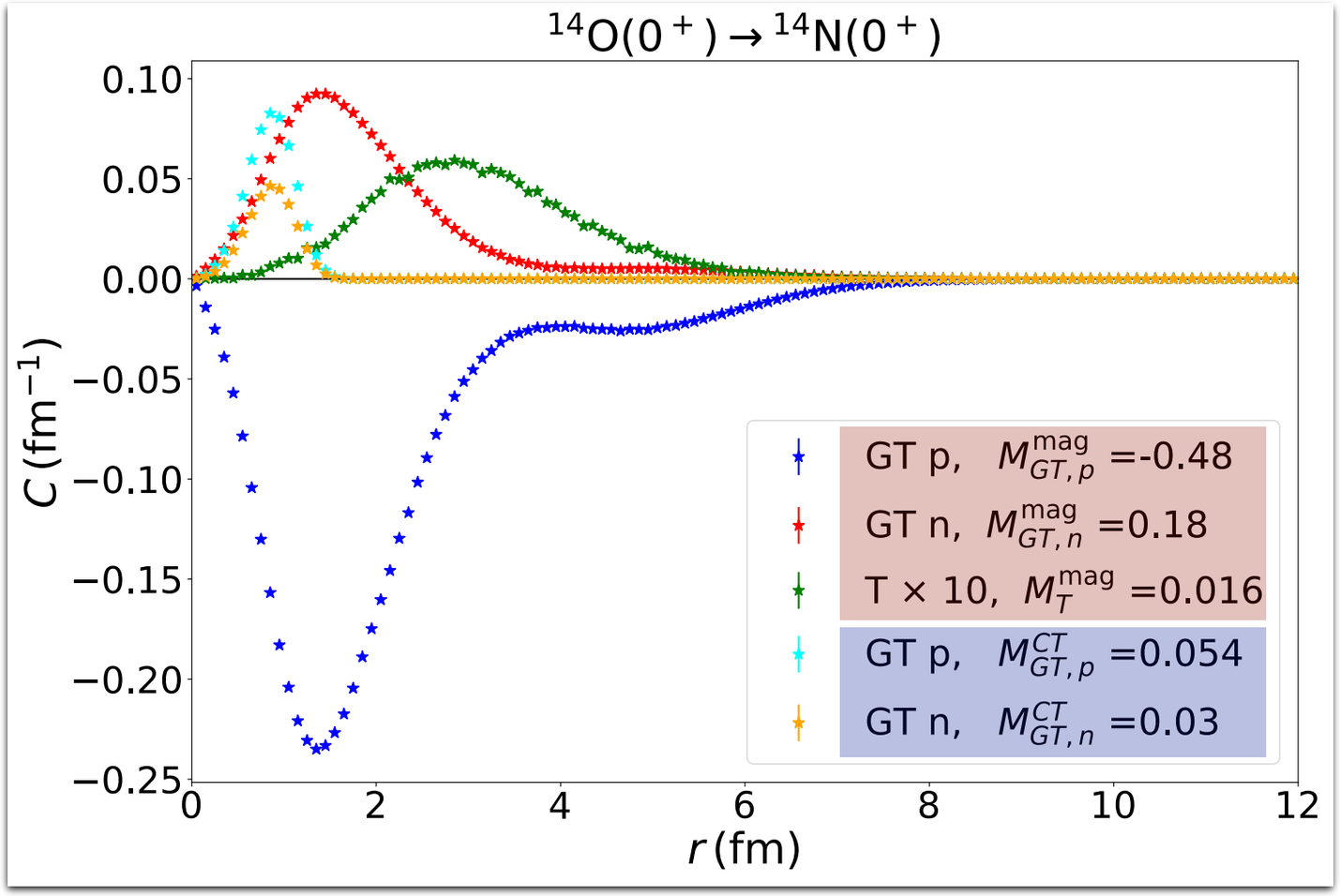
$\mathcal{O}(\alpha^2 Z)$ two-nucleon terms

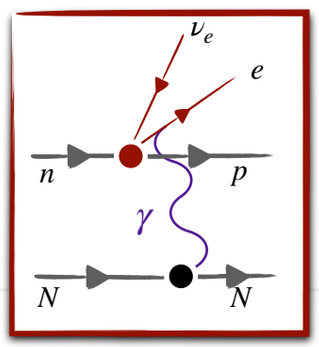
Nuclear-structure dependence, "δ_{NS}"

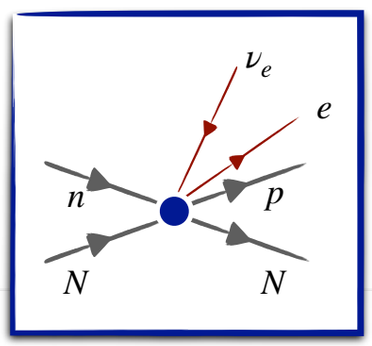
- Source of largest uncertainty
- In EFT described by $\langle \psi_i \;\; V \;\; \psi_i \rangle$

Nuclear Matrix Elements

$^{14}\mathrm{O} \rightarrow {}^{14}\mathrm{N}$







- Total contribution: $\delta^{(0)}_{NS} = -\,(1.76+0.11\pm0.88)\cdot 10^{-3}$

Half Life

$^{14}\mathrm{O} \rightarrow {}^{14}\mathrm{N}$

- All combined: $V_{ud} = 0.97364(12)_{g_V}(10)_{\mathrm{exp}}(22)_{\bar{f}}(13)_{\delta_{NS}^{\mathrm{non-LEC}}}(44)_{\delta_{NS}^{\mathrm{LEC}}}(12)_{\delta_c}[55]_{\mathrm{total}}$
- Compatible with traditional approach $V_{ud} = 0.97405(37)_{\mathrm{total}}$

Hardy & Towner, ‘20

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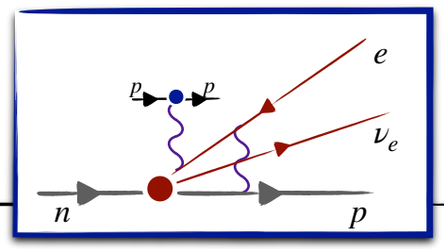

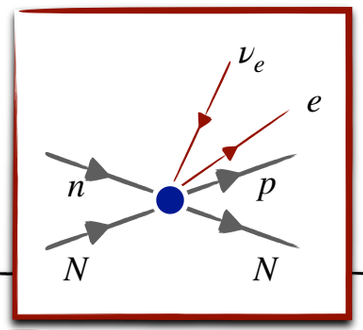

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- Compatible with traditional approach $V_{ud} = 0.97405(37)_{\mathrm{total}}$ Hardy & Towner, ‘20

Error budget/future work

- Increase in uncertainties for now;
  - Unknown short-distance interactions
  - Missing $O(\alpha^2 Z)$ contributions

- ***Systematically improvable***
  - Short-distance couplings
    - Can be fit to experiment
    - Determined using dispersive methods
  - $O(\alpha^2 Z)$ require two-loop calculations

NTNP TC provides a great environment for these next steps

Beyond the SM

Nearly global BSM analysis

β decays

- Helped identify V-A structure of SM
- Nowadays determine V_{ud}
- Sub-permille precision provides CKM unitarity test:

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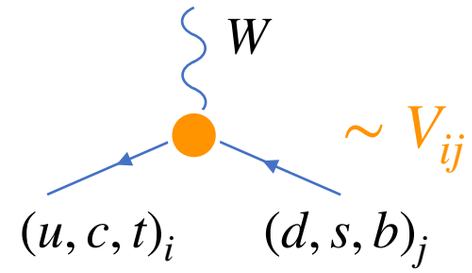

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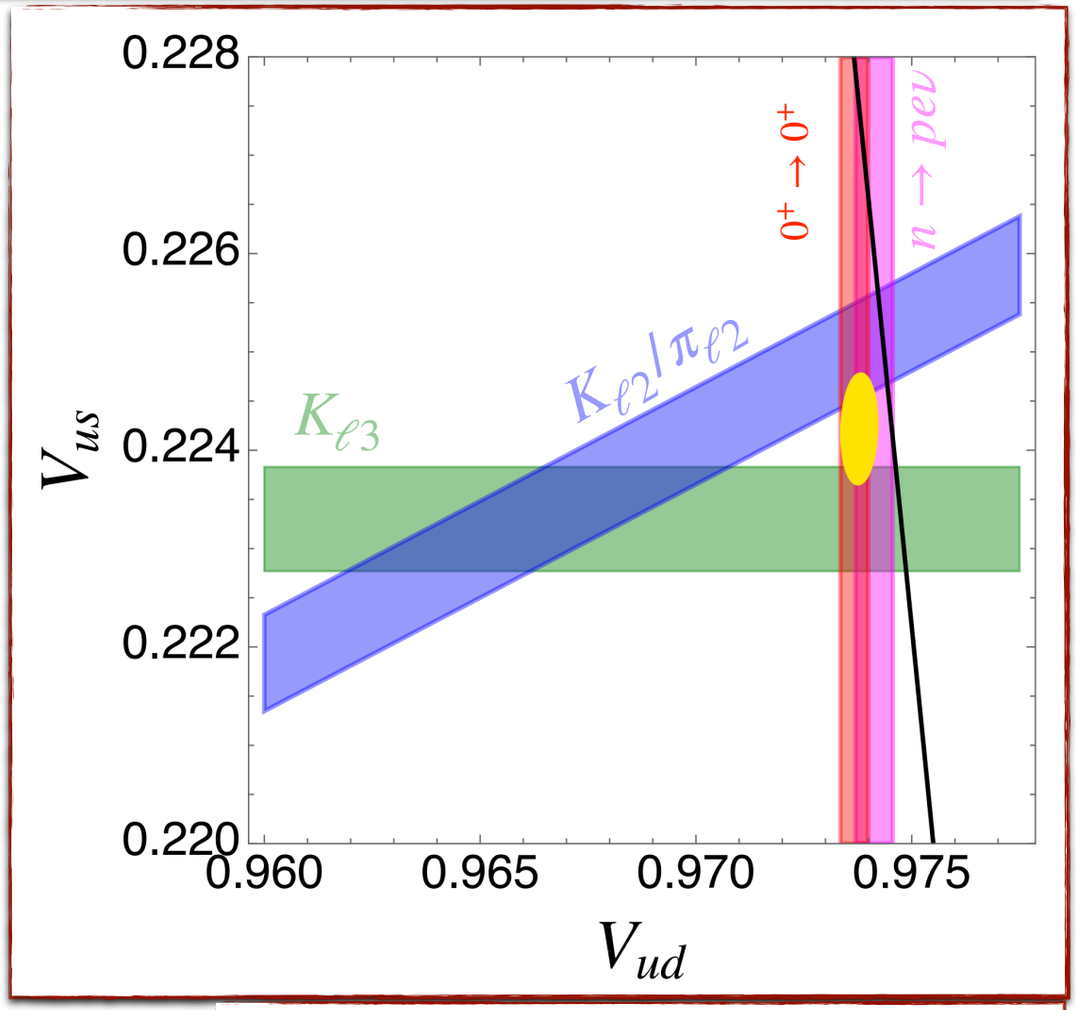

Cirigliano, Crivellin, Moulson, Hoferichter '23

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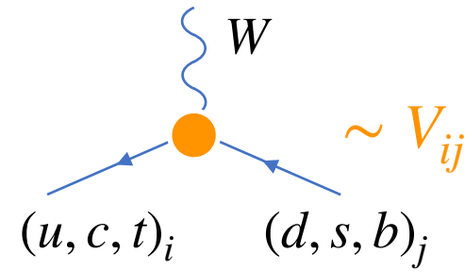

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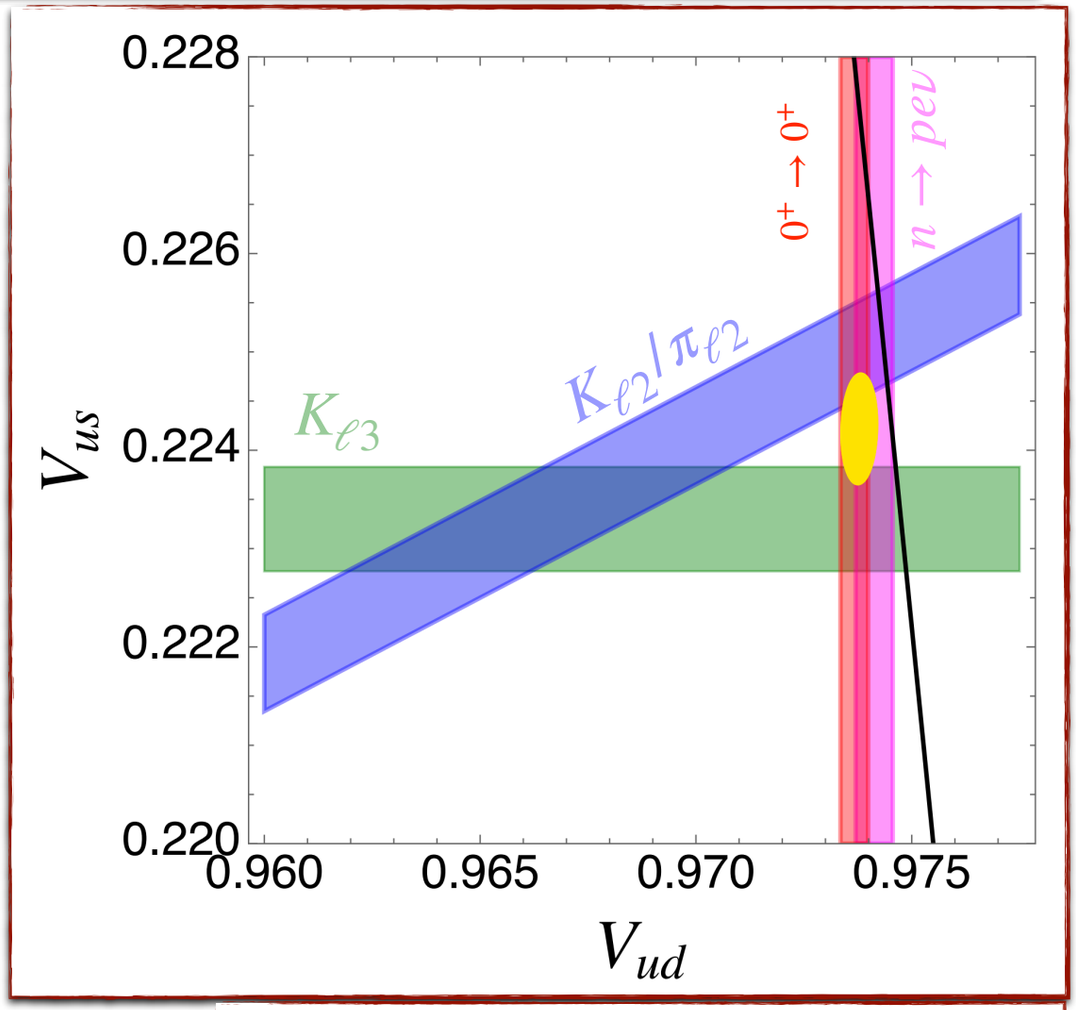
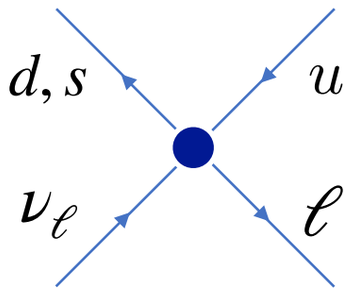


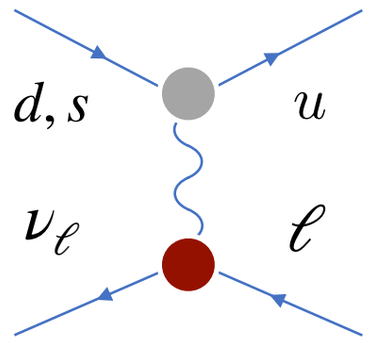
Cirigliano, Crivellin, Moulson, Hoferichter '23

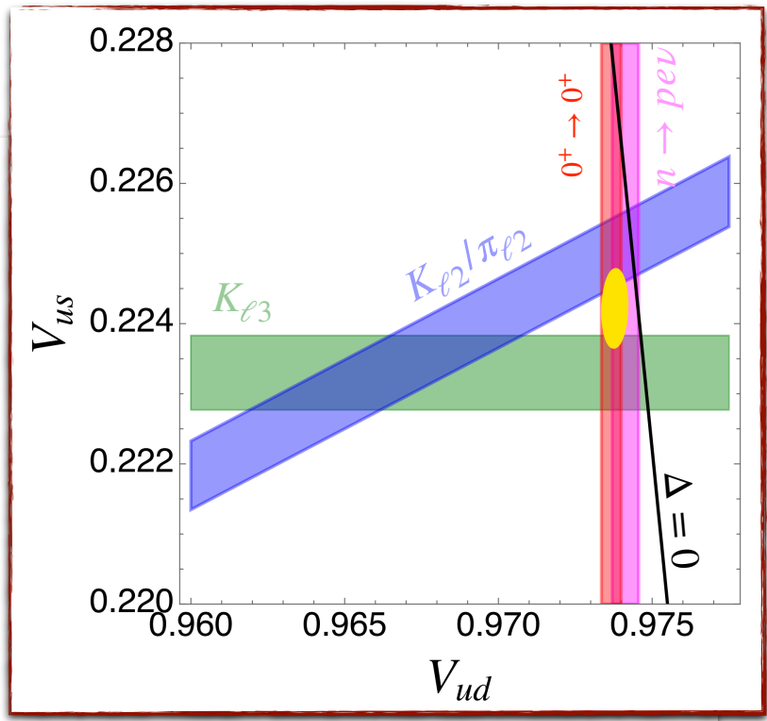
Cabibbo Angle Anomaly

In the SM Effective Theory

- Several EFT interactions can affect CKM unitarity







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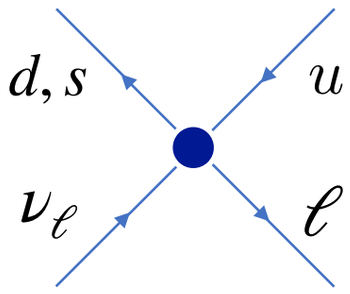
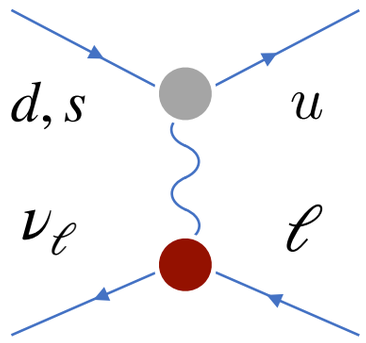
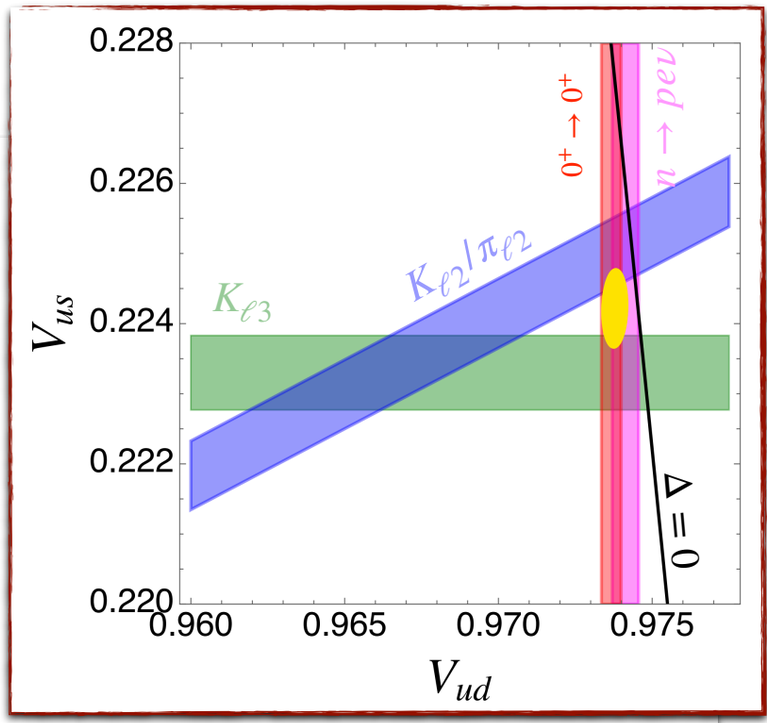
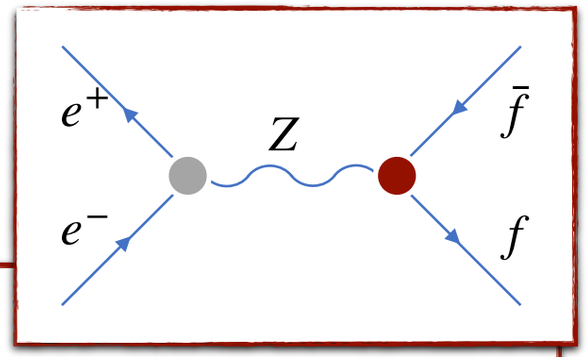






Can also contribute to other processes:

- Measurements of the Z boson



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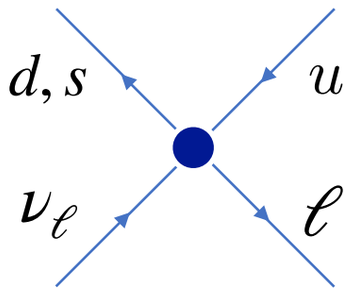

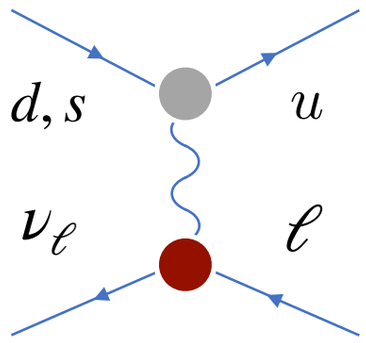

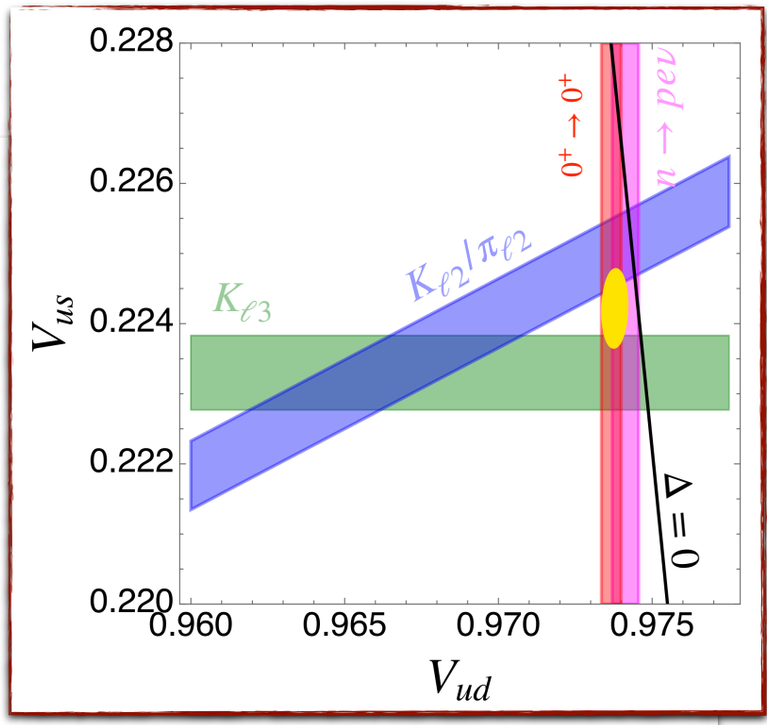

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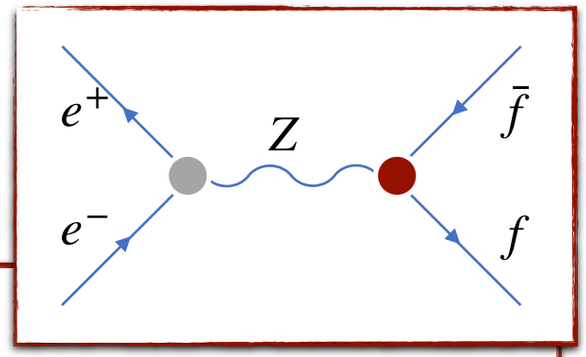
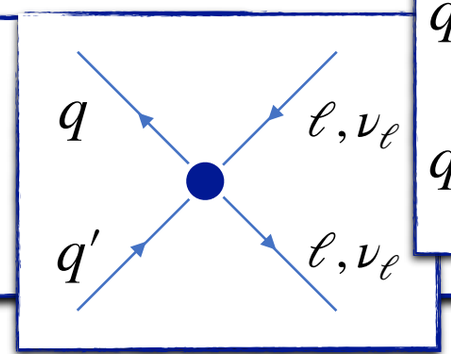
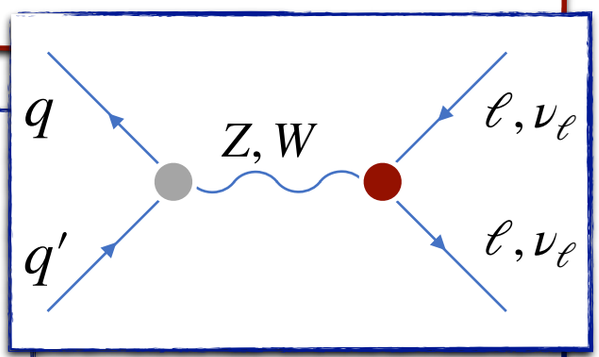


- LHC processes
  - proton+proton $\to e^+e^-$





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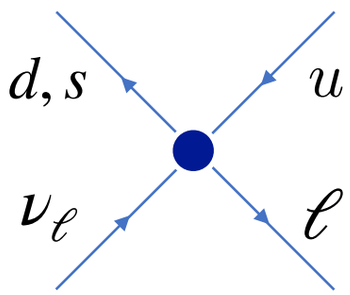
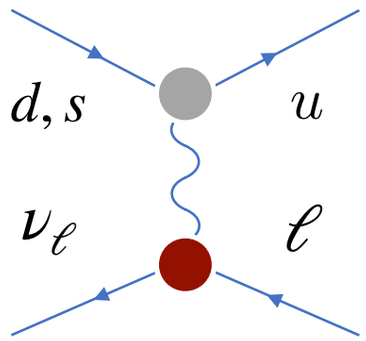
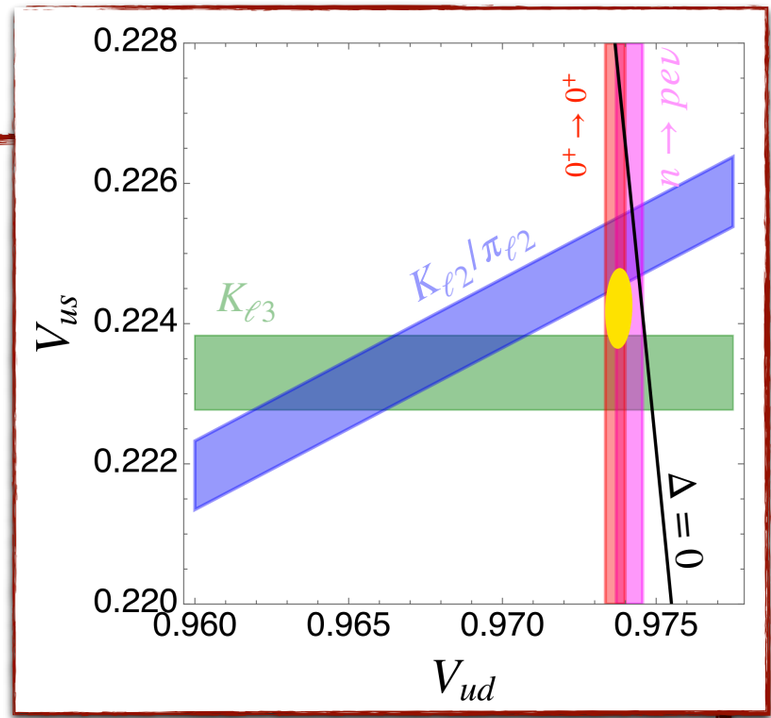
- Several EFT interactions can affect CKM unitarity







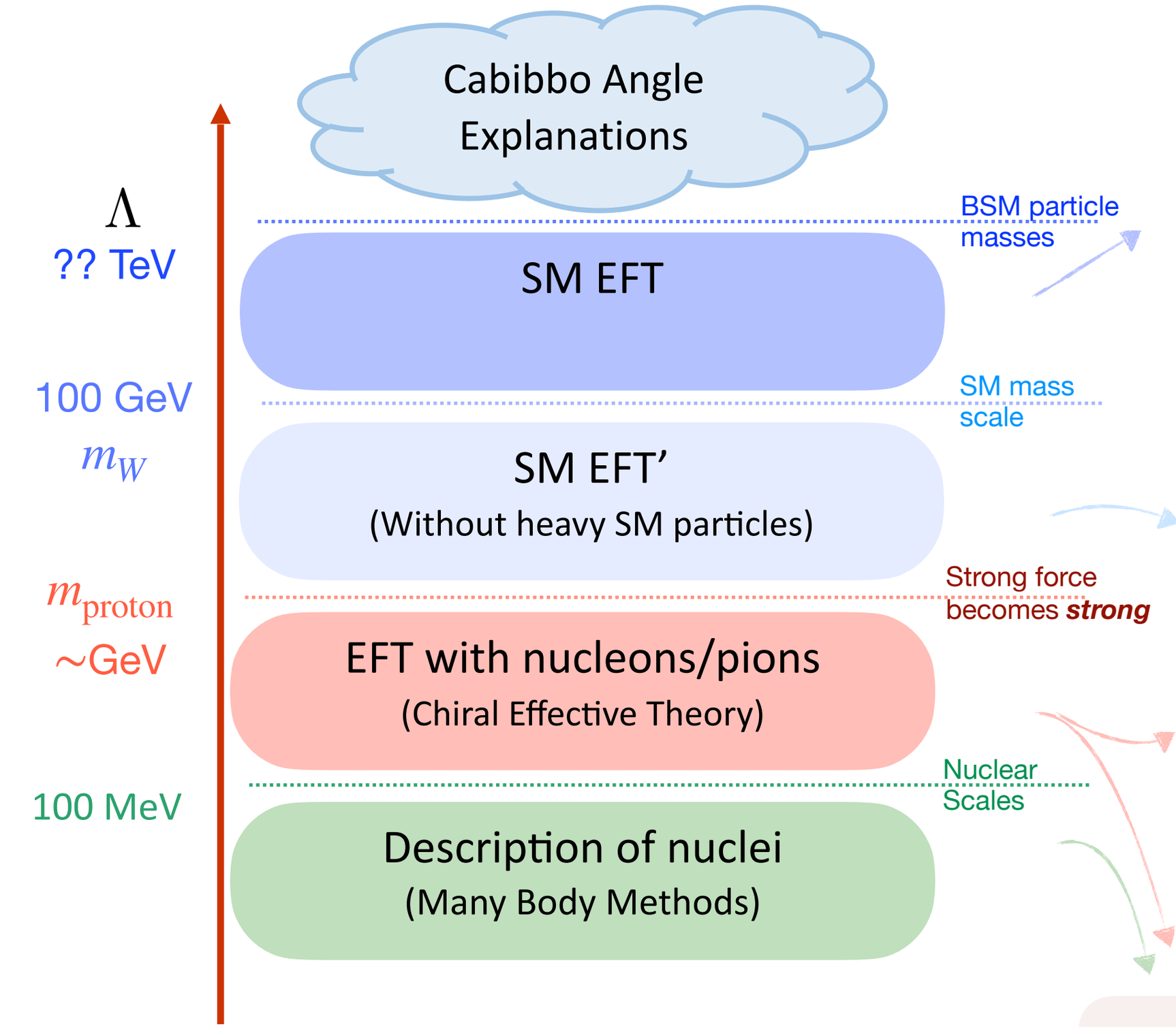
Requires fitting 37 **interactions** to many **measurements**

Low-energy measurements

P_{l2}			K_{l3}		
Observable	value	Ref.	Observable	value	Ref.
R_π	$1.2344(30) \cdot 10^{-4}$	[132]	$\lvert\tilde{V}^e_{us} f^K_+(0)\rvert$	0.21626(40)	[133]
R_K	$2.488(9) \cdot 10^{-5}$	[3]	$\lvert\tilde{V}^\mu_{us} f^K_+(0)\rvert$	0.21667(52)	[133]
$\Gamma(K_{\mu 2})$	$5.134(10) \cdot 10^{-7} s^{-1}$	[3]	$\log C$	0.1985(70)	[134]
$\mathrm{Br}(\pi_{\mu 2})$	0.9998770(4)	[3]	$2\epsilon_T^{s\mu} \frac{B_T(0)}{f_+(0)}$	0.0007(71)	[135]
$\tau_{\pi+}$	$2.6033(5) \cdot 10^{-8} s$	[3]			

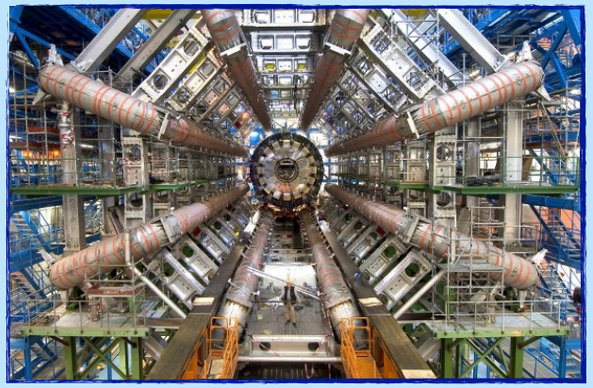
Z-boson measurements

Obs.	Expt. Value		SM Prediction		Obs.	Expt. Value		SM Prediction	
Γ_Z (GeV)	2.4955(23)	[53,113]	2.49414(56)	[60]	m_W(GeV)	80.4335(94)	[39]	80.3545(42)	[60]
σ^0_{had}(nb)	41.480(33)	[53,113]	41.4929(53)	[60]	Γ_W (GeV)	2.085(42)	[3]	2.08782(52)	[60]
R^0_e	20.804(50)	[53,113]	20.7464(63)	[60]	R_{Wc}	0.49(4)	[3]	0.50	
R^0_μ	20.784(34)	[53,113]			R_σ	0.998(41)	[114]	1	
R^0_τ	20.764(45)	[53,113]			$\mathrm{Br}(W \to e\nu)$	0.1071(16)	[3]	0.108386(24)	[60]
$A^{0,e}_{\mathrm{FB}}$	0.0145(25)	[53,113]	0.016191(70)	[60]	$\mathrm{Br}(W \to \mu\nu)$	0.1063(15)	[3]	0.108386(24)	[60]
$A^{0,\mu}_{\mathrm{FB}}$	0.0169(13)	[53,113]			$\mathrm{Br}(W \to \tau\nu)$	0.1138(21)	[3]	0.108386(24)	[60]
					$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	0.982(24)	[3]	1	
			0.215880(19)	[60]	$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.020(19)	[3]		
			0.172198(20)	[60]	$\frac{\Gamma(W\to\mu\nu)}{\Gamma(W\to e\nu)}$	1.003(10)	[3]		
			0.10300(23)	[60]	$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to e\nu)}$	0.961(61)	[3]		
			0.07358(18)	[60]	$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to\mu\nu)}$	0.992(13)	[3]		
			0.66775(14)	[60]	$A_4(0-0.8)$	0.0195(15)	[115]	0.0144(7)	[116]
			0.934727(25)	[60]	$A_4(0.8-1.6)$	0.0448(16)	[115]	0.0471(17)	[116]
			0.14692(32)	[60]	$A_4(1.6-2.5)$	0.0923(26)	[115]	0.0928(21)	[116]
					$A_4(2.5-3.6)$	0.1445(46)	[115]	0.1464(21)	[116]
					$g^{(u)}_V$	0.201(112)	[117]	0.192	[118]
					$g^{(d)}_V$	-0.351(251)	[117]	-0.347	[118]
					$g^{(u)}_A$	0.50(11)	[117]	0.501	[118]
			0.935637(26)	[60]	$g^{(d)}_A$	-0.497(165)	[117]	-0.502	[118]
			0.172220(20)	[60]					



High energy probes

- LHC
- Z-boson measurements



ATLAS detector

Precision observables

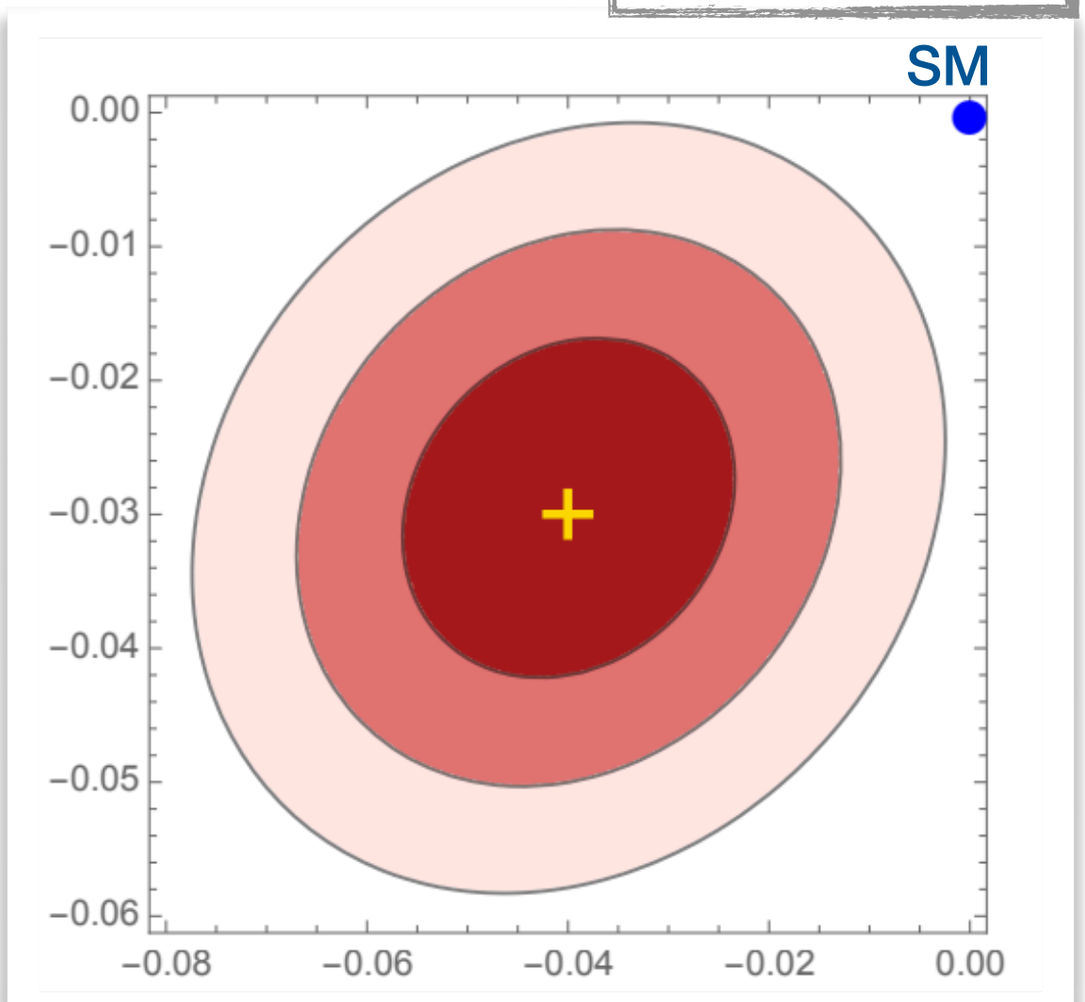
- K, π, neutron decays

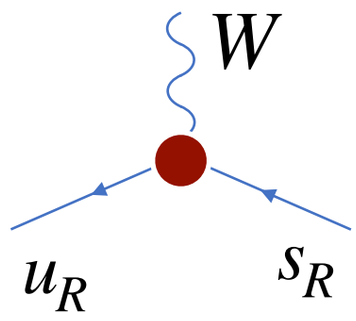
- Nuclear β decay

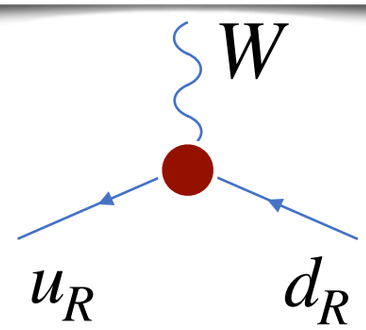
Most efficient BSM explanation

W couplings to right-handed quarks

WD et al JHEP ’24;



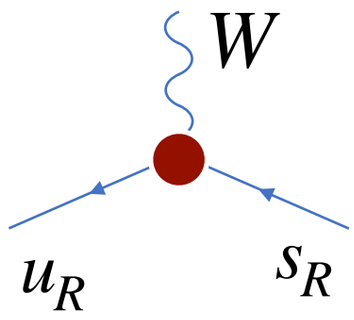




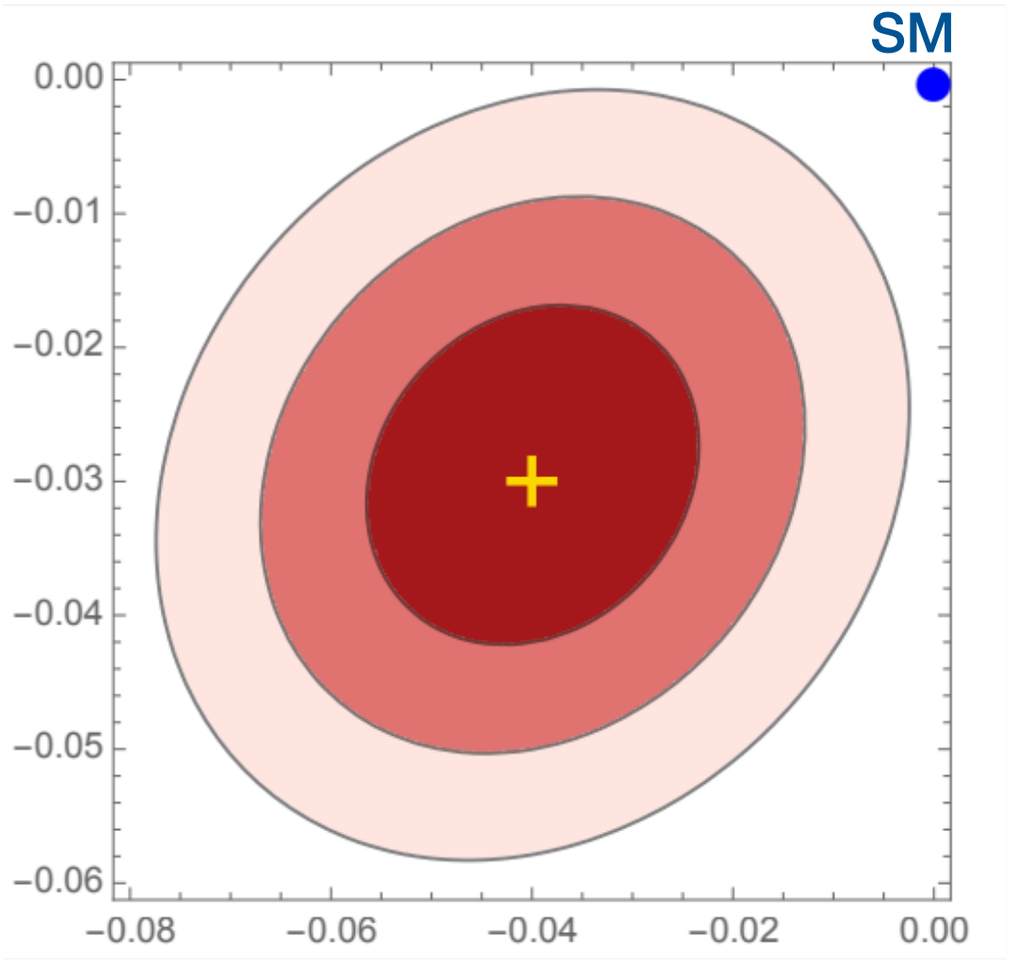
Most efficient BSM explanation

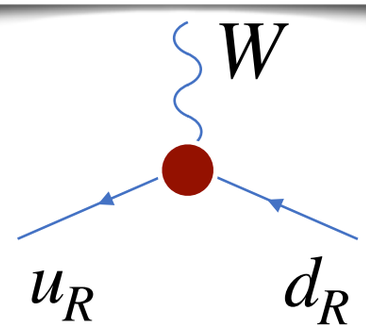
W couplings to right-handed quarks

- These couplings also affect:
  - LHC processes:
    - W+Higgs production
    - W+Z production
  - Kaon decays to $\pi\pi$
  - Neutron decay asymmetries



WD et al JHEP ’24;





Most efficient BSM explanation

W couplings to right-handed quarks

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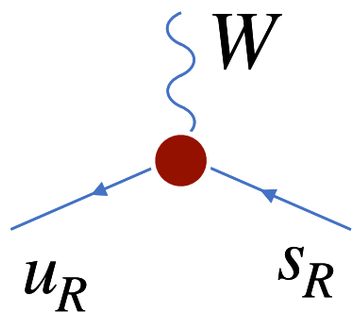
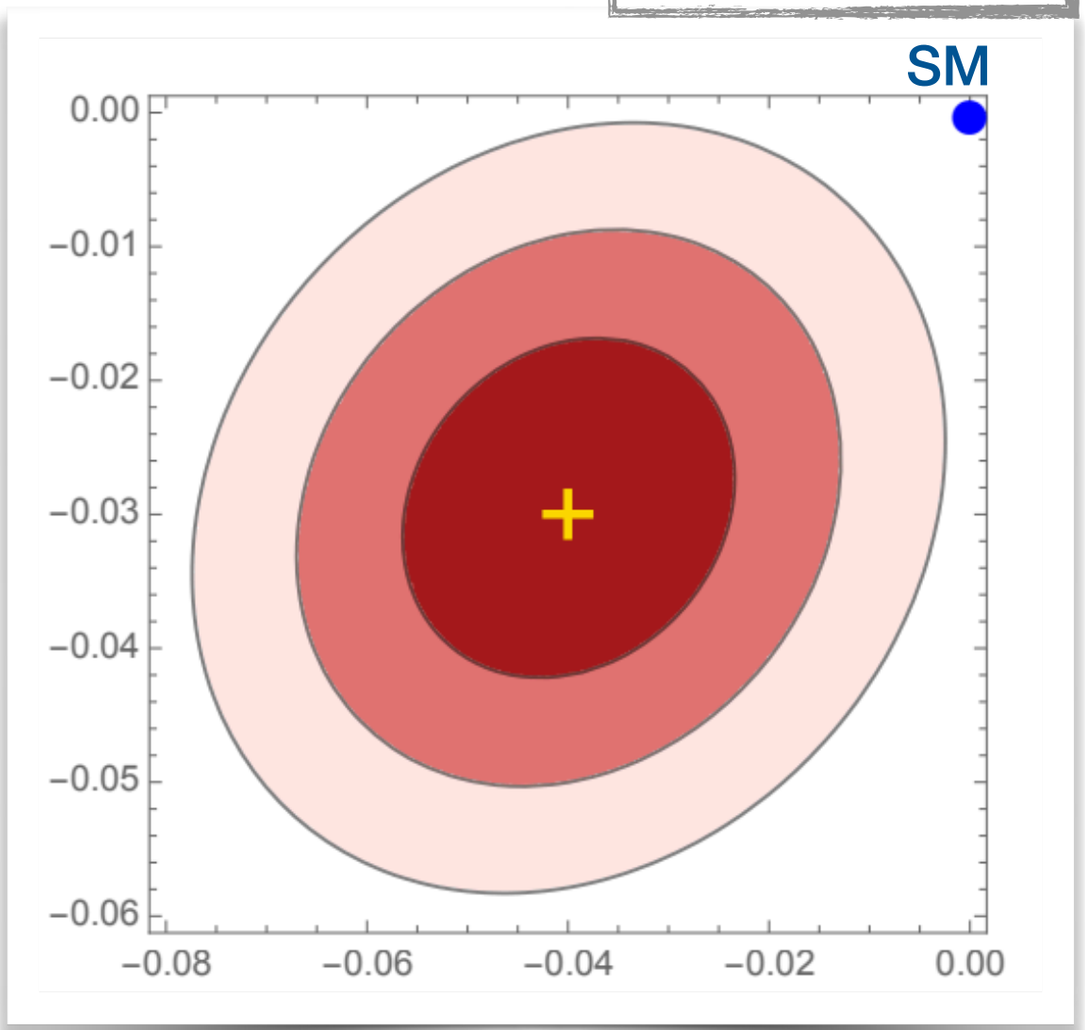
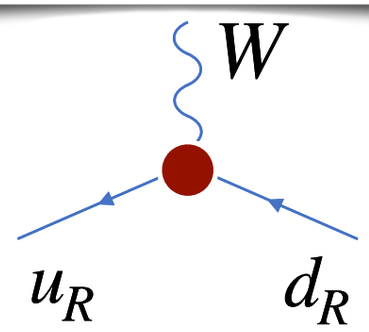


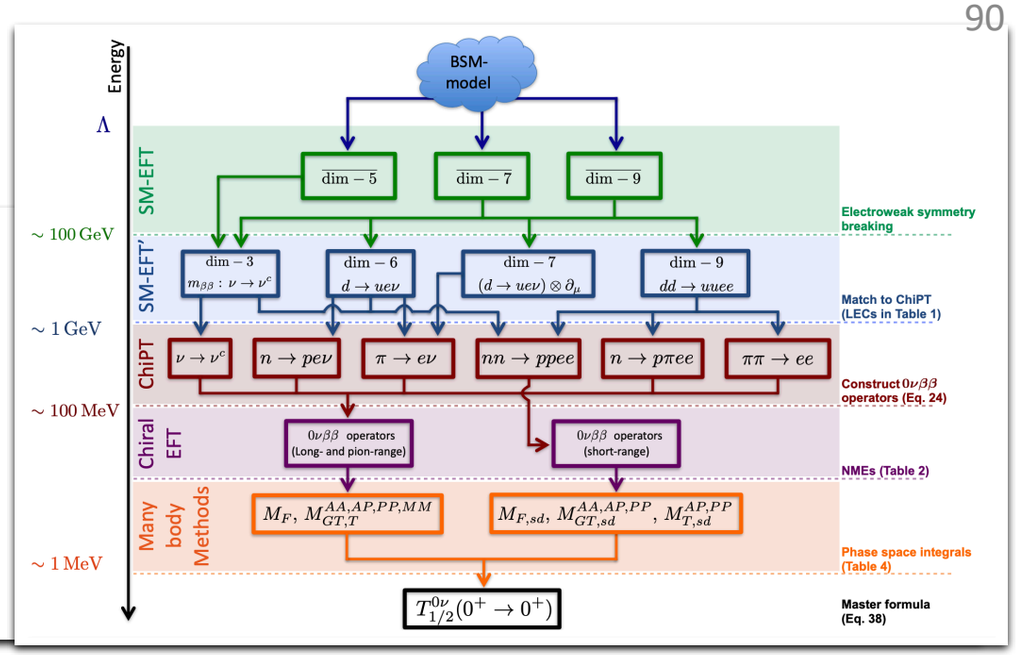




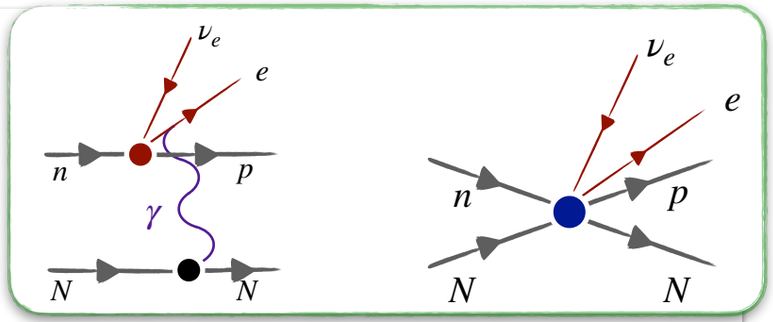
- Could falsify/verify this scenario
  - ***Requires theory improvements!***

Summary

- BSM needed to answer ***open questions***
  - Matter-antimatter asymmetry
  - Neutrino masses
- EFT can connect BSM to low-energy experiments
  - $0\nu\beta\beta$, β decays, EDMs

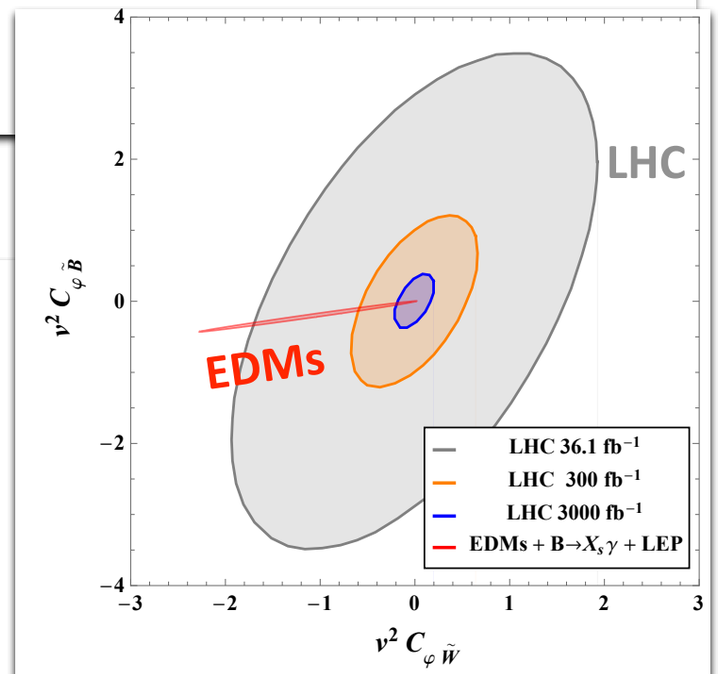


- Most sensitive experiments involve ***nuclei***
  - ***Requires description of BSM and nuclear physics***



Radiative corrections in EFT

- Hadronic EFTs can reveal ***new effects***
  - Leading-order short-distance interaction in $0\nu\beta\beta$
  - Short-distance effects in superallowed β decays



- Low-energy experiments probe high BSM scales
  - $0\nu\beta\beta$ sensitive to the GUT scale in the seesaw scenario
  - Up to *O*(10-100) TeV with EDMs, β decays
- Several ongoing experiments with high discovery potential
  - Require theory to fully capitalize on them