Electroweak-Skyrmion as Topological Dark Matter

Masafumi Kurachi (KEK) [C03]

Reference:

Ryuichiro Kitano, Masafumi Kurachi,

JHEP07 (2016) 037 (arXiv:1605.07355)

Neutrino Frontier Workshop 2016

November 28-30, 2016, Kaga, Ishikawa

Mysteries

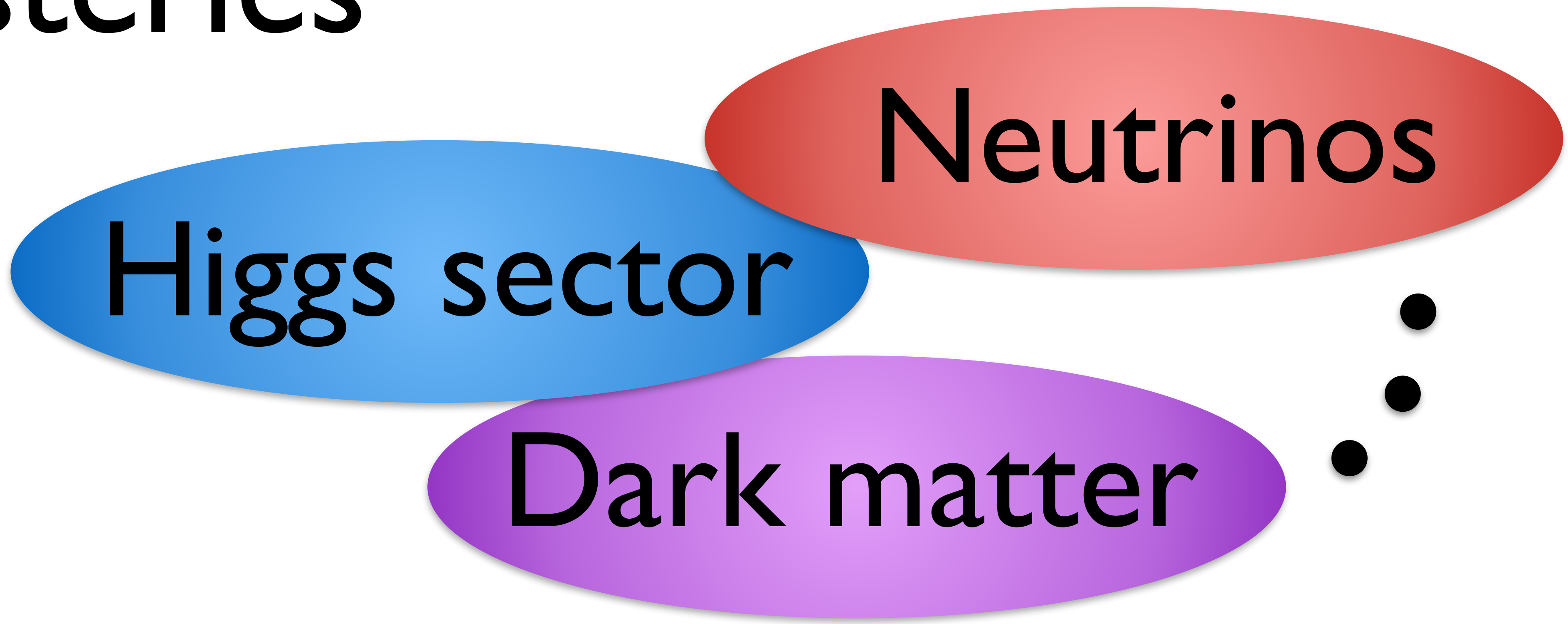
Neutrinos

Higgs sector

Dark matter

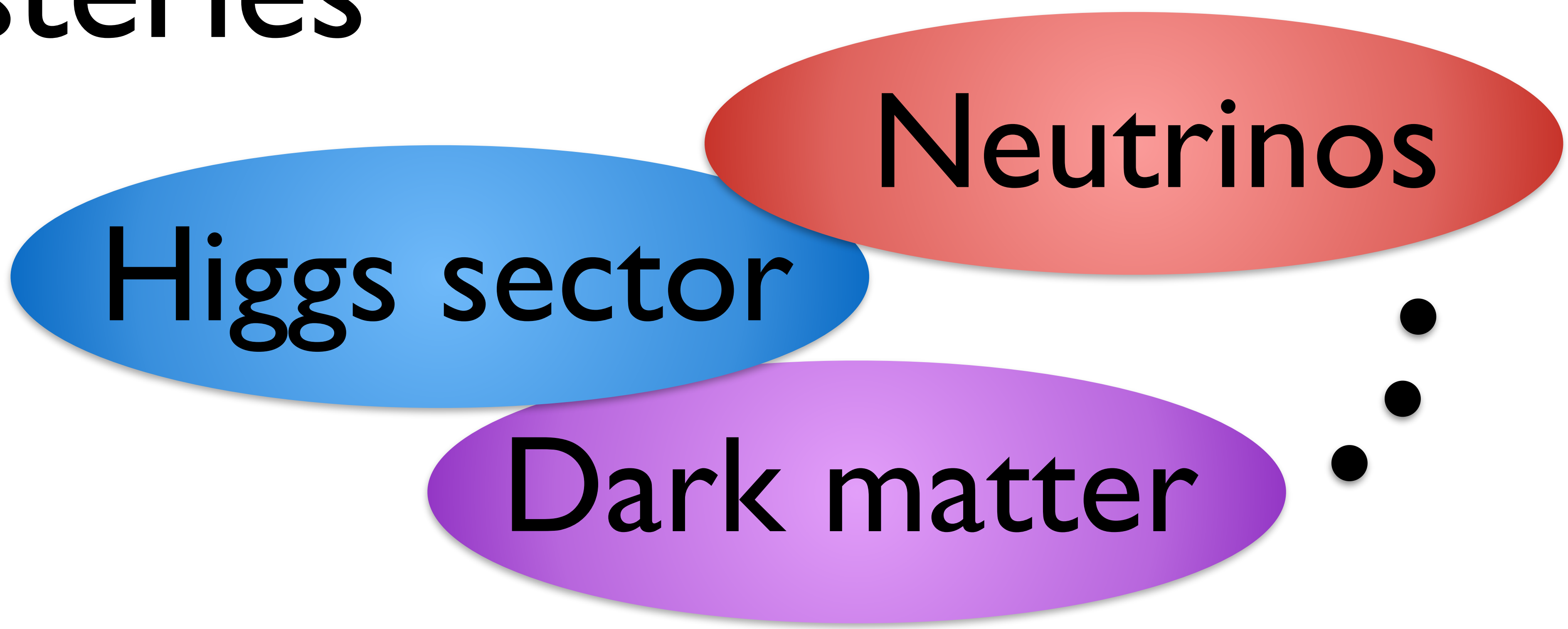
⋰

Mysteries



Possibly interconnected

Mysteries

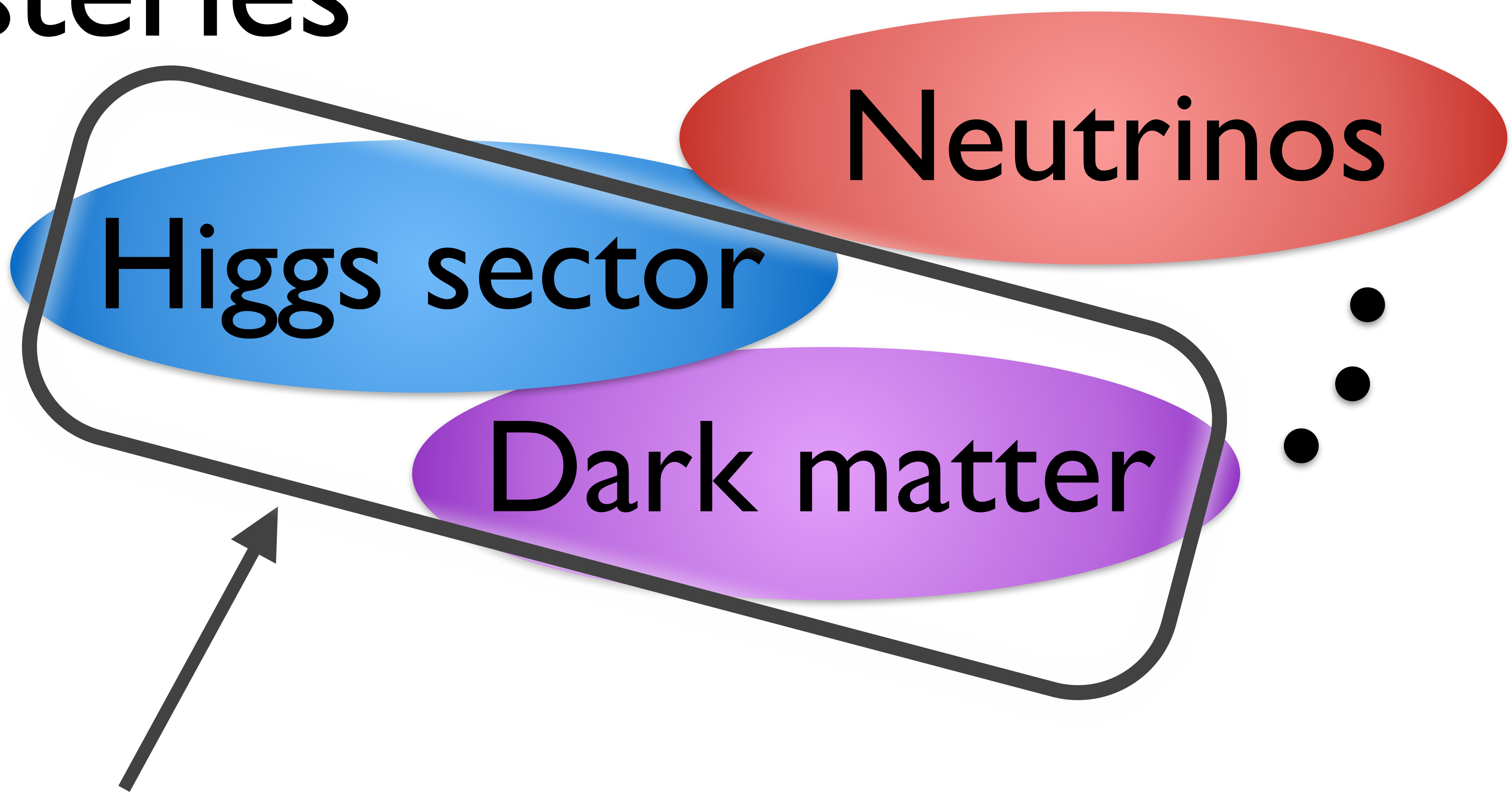


Possibly interconnected

<u>Research project</u>:

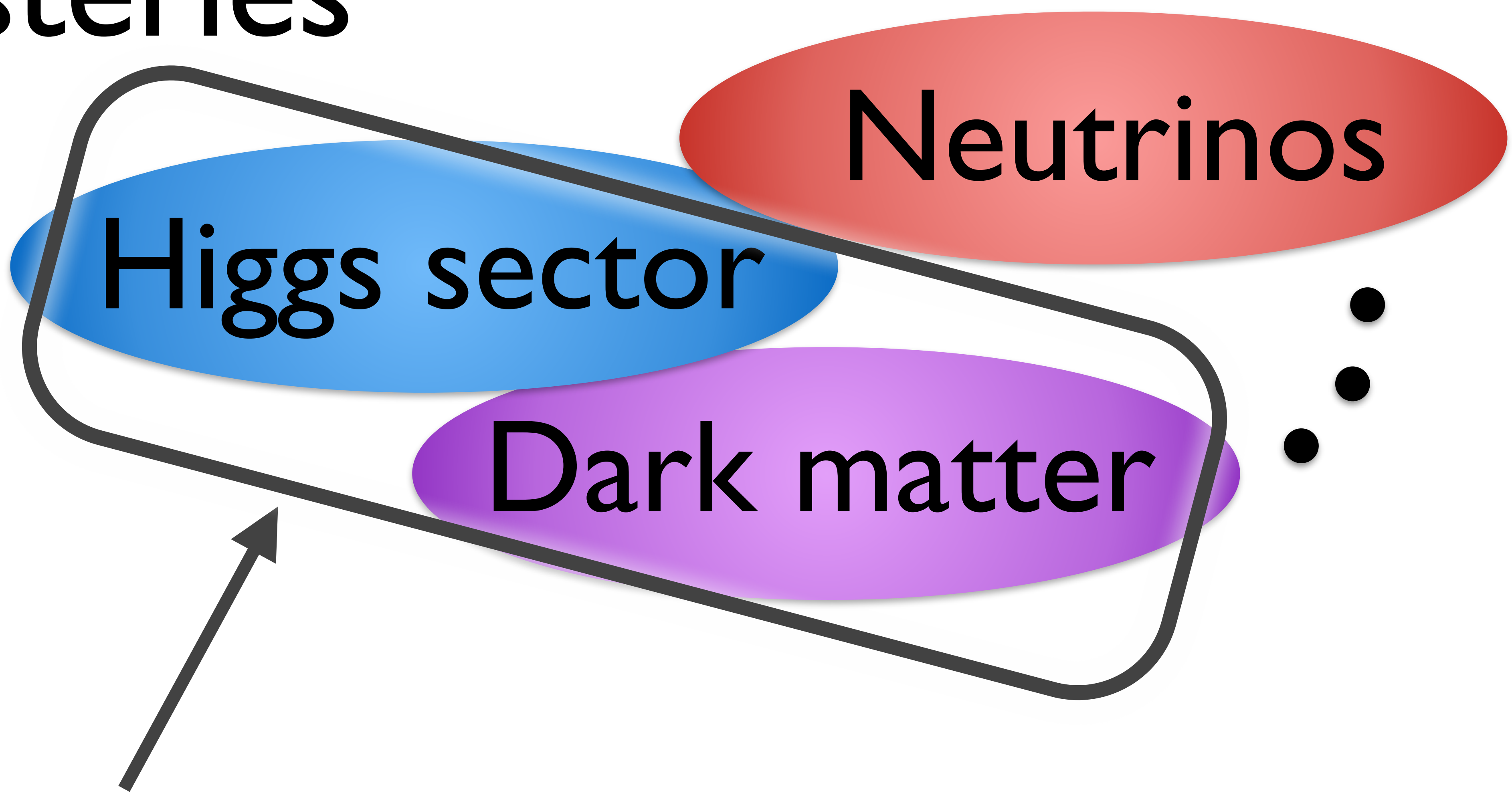
find relations among them through the **global (topological) structure** of the Universe

Mysteries



We started from here

Mysteries



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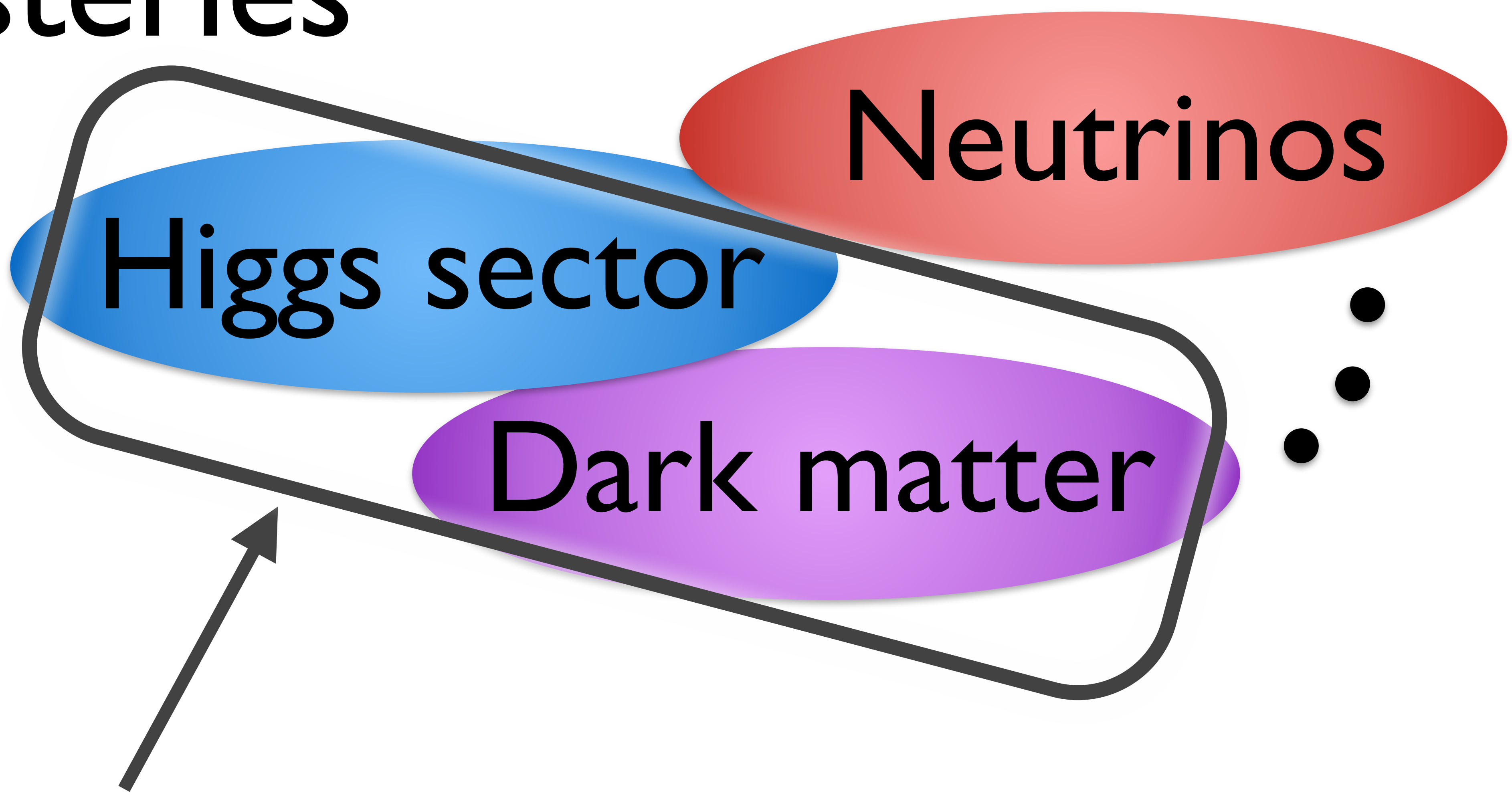
We plan to include Neutrinos near future

Mysteries



We started from here

We plan to include Neutrinos near future

(Please allow me to talk about something which is not directly related to Neutrino physics yet)

How to tackle this problem?

No hint of any new physics from the LHC yet

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Focus on **something** which is:

- simply assumed in the SM, but actually **not** established experimentally yet

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- simply assumed in the SM, but actually **not** established experimentally yet
- and, at the same time, significant experimental progress is expected near future

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No hint of any new physics from the LHC yet

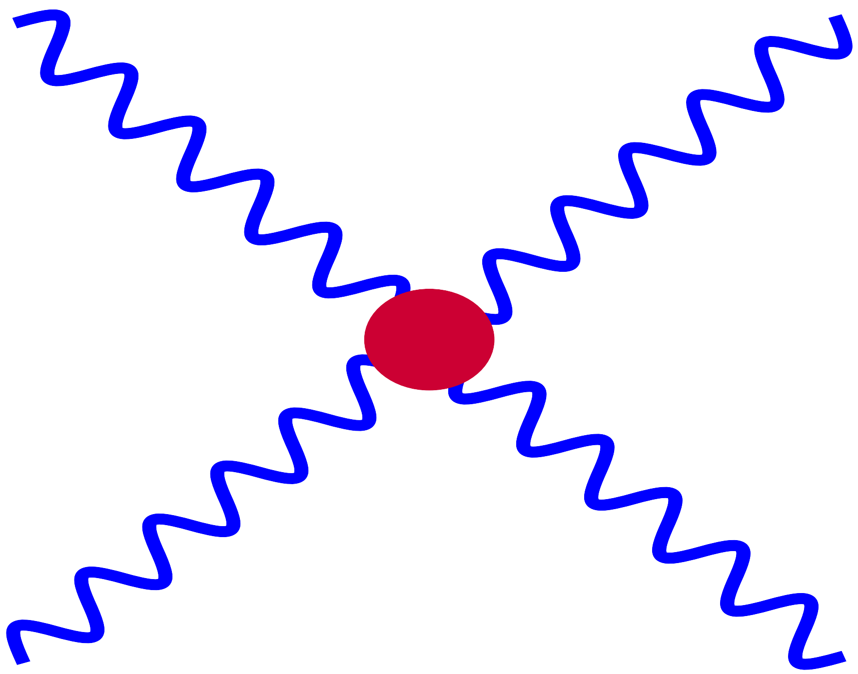
Like what??

Focus on **s**

- simply assumed in the SM, but actually **not** established experimentally yet
- and, at the same time, significant experimental progress is expected near future

Quartic gauge boson coupling (QGC)

weak



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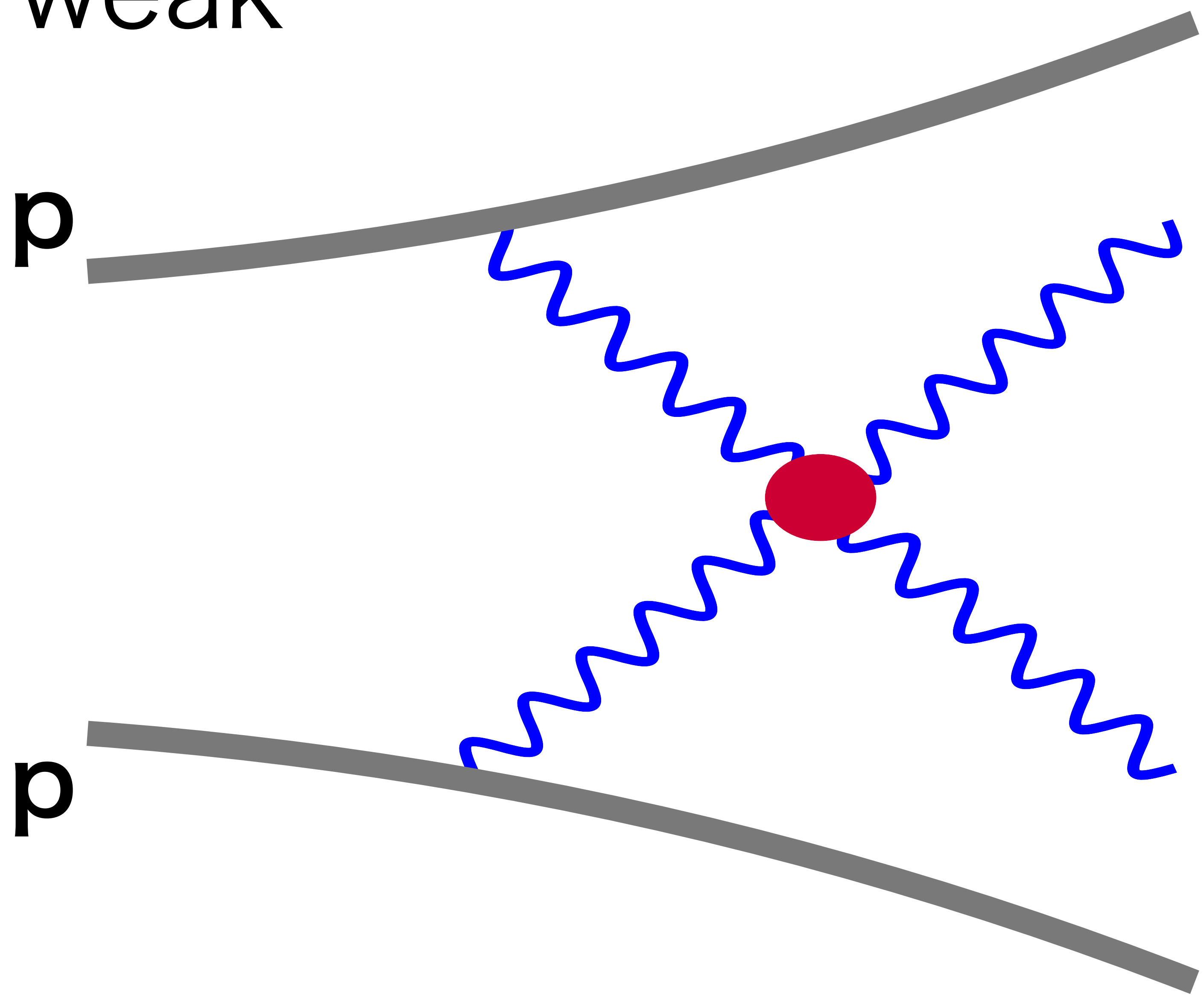

LHC has just begun to measure it!

Constraints on anomalous QGC parameters (α_4, α_5)

($\alpha_4 = \alpha_5 = 0$ corresponds to the SM)

explained later
(roughly speaking,
these represent
deviation from the
SM QGC)

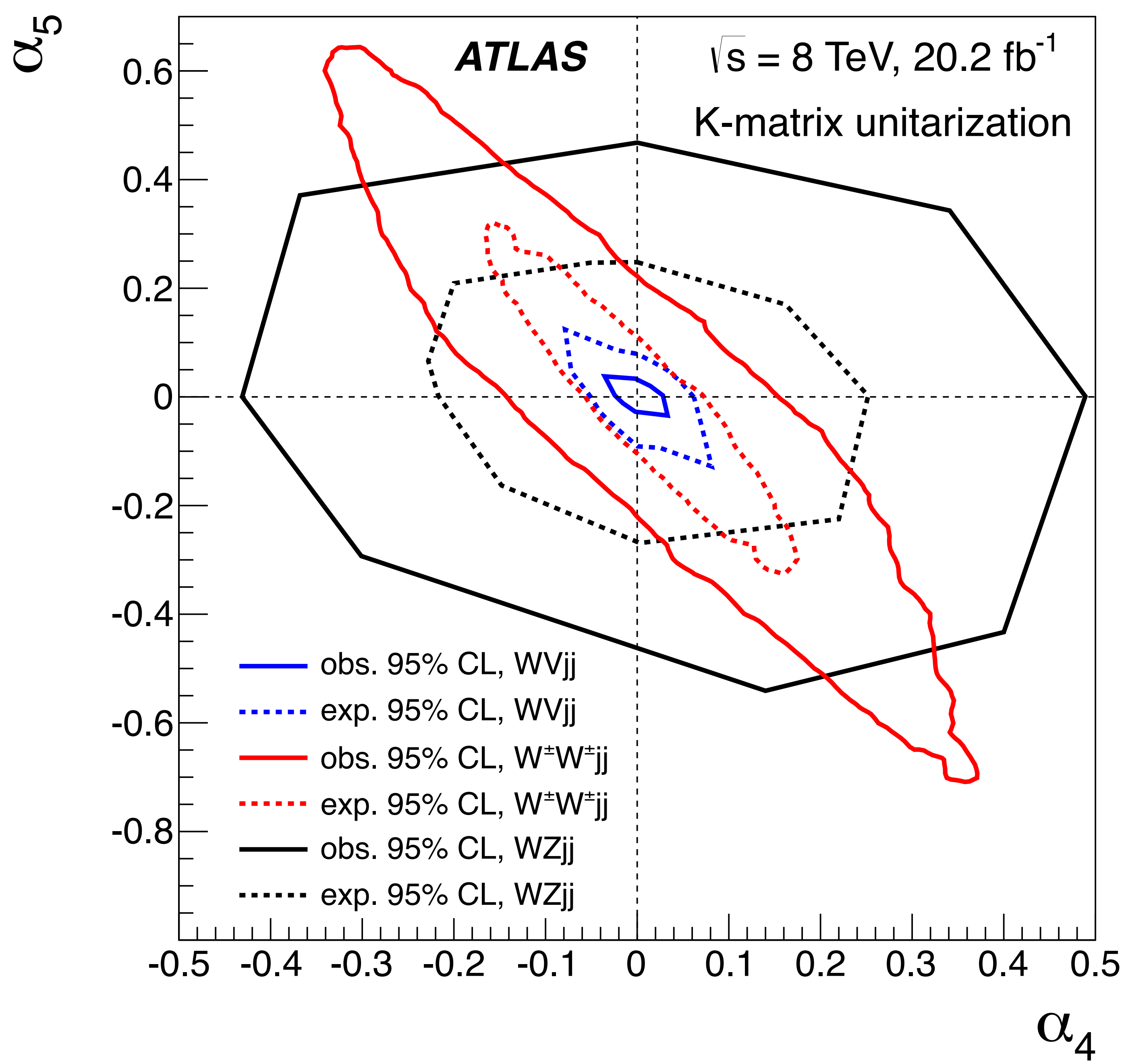

figure taken from arXiv:1609.05122 (ATLAS)

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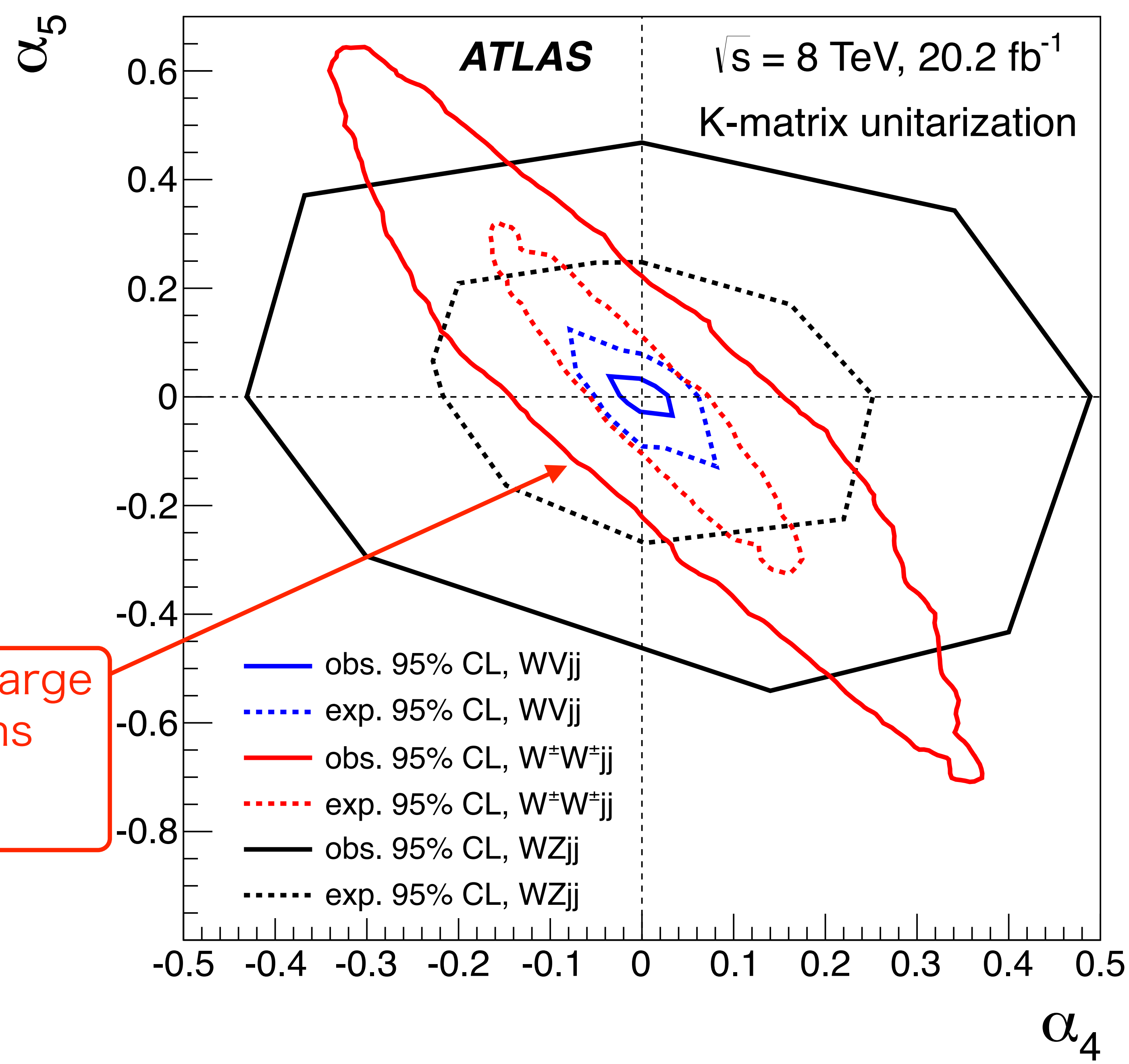

$W^\pm W^\pm \to$ same-charge leptons

(arXiv:1405.6241)

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(arXiv:1603.02151)

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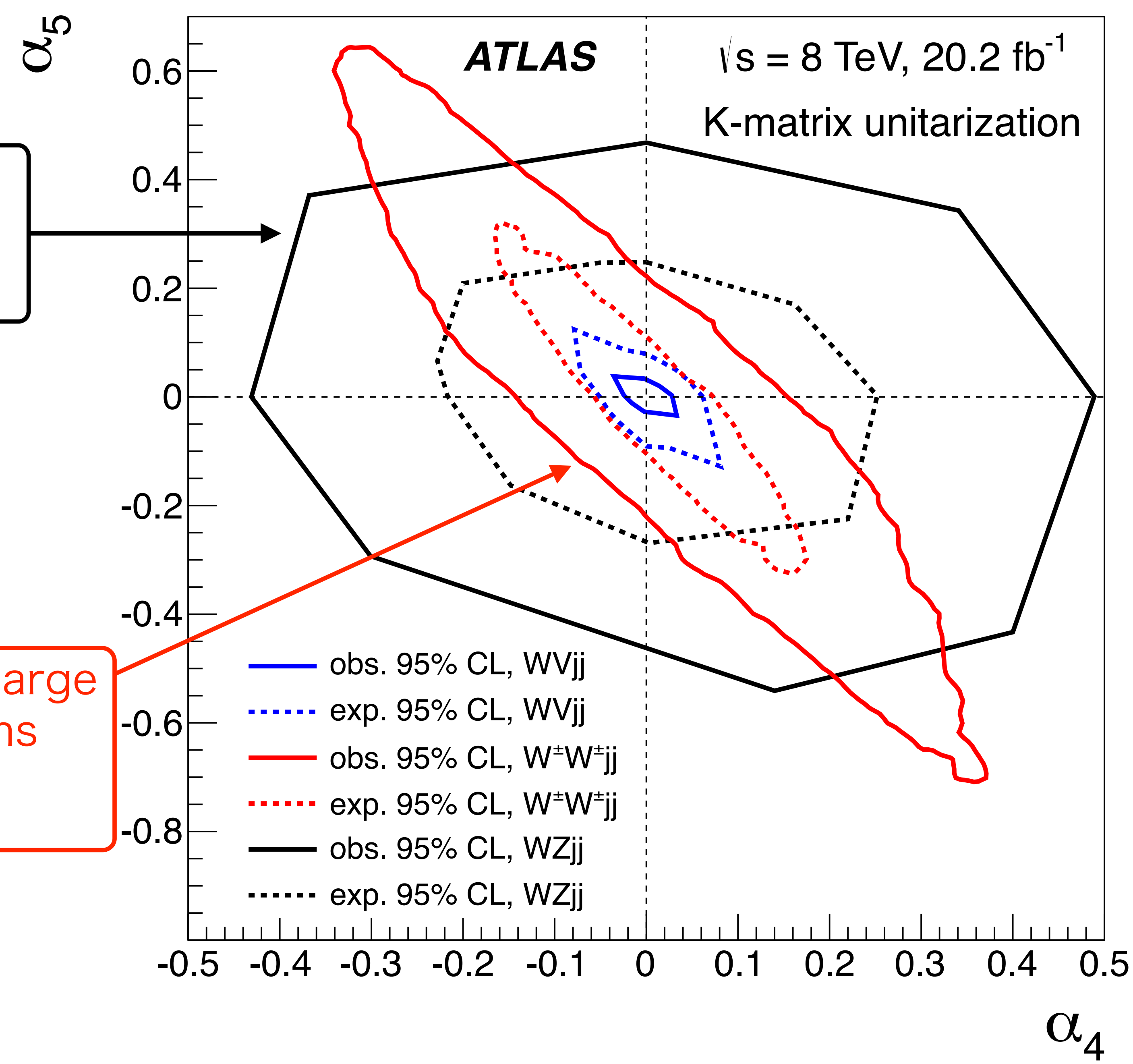

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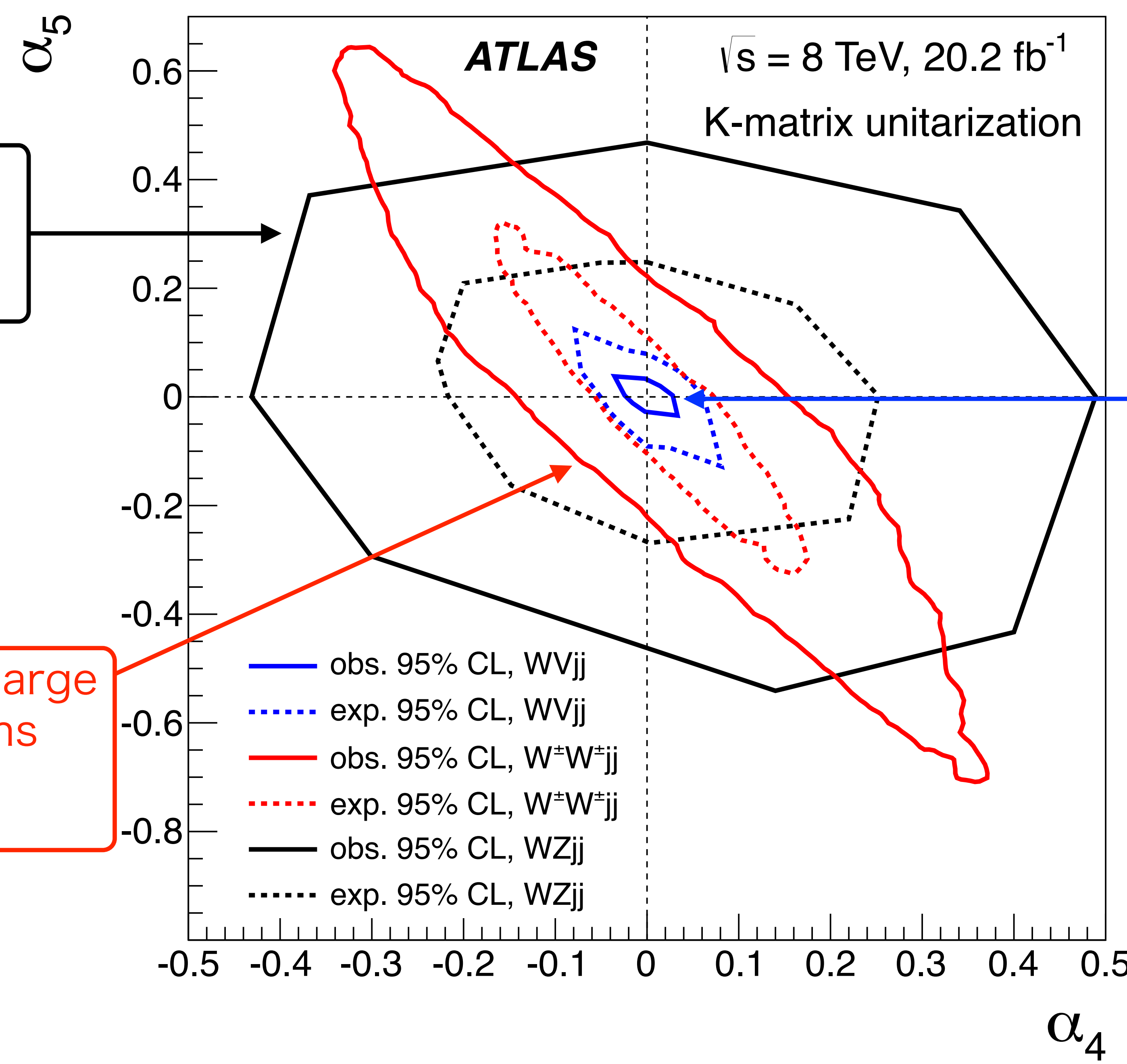

$WV\ (V = W \text{ or } Z)$
$W \to \ell\nu$
$V \to jj \text{ or } J$
(arXiv:1609.05122)

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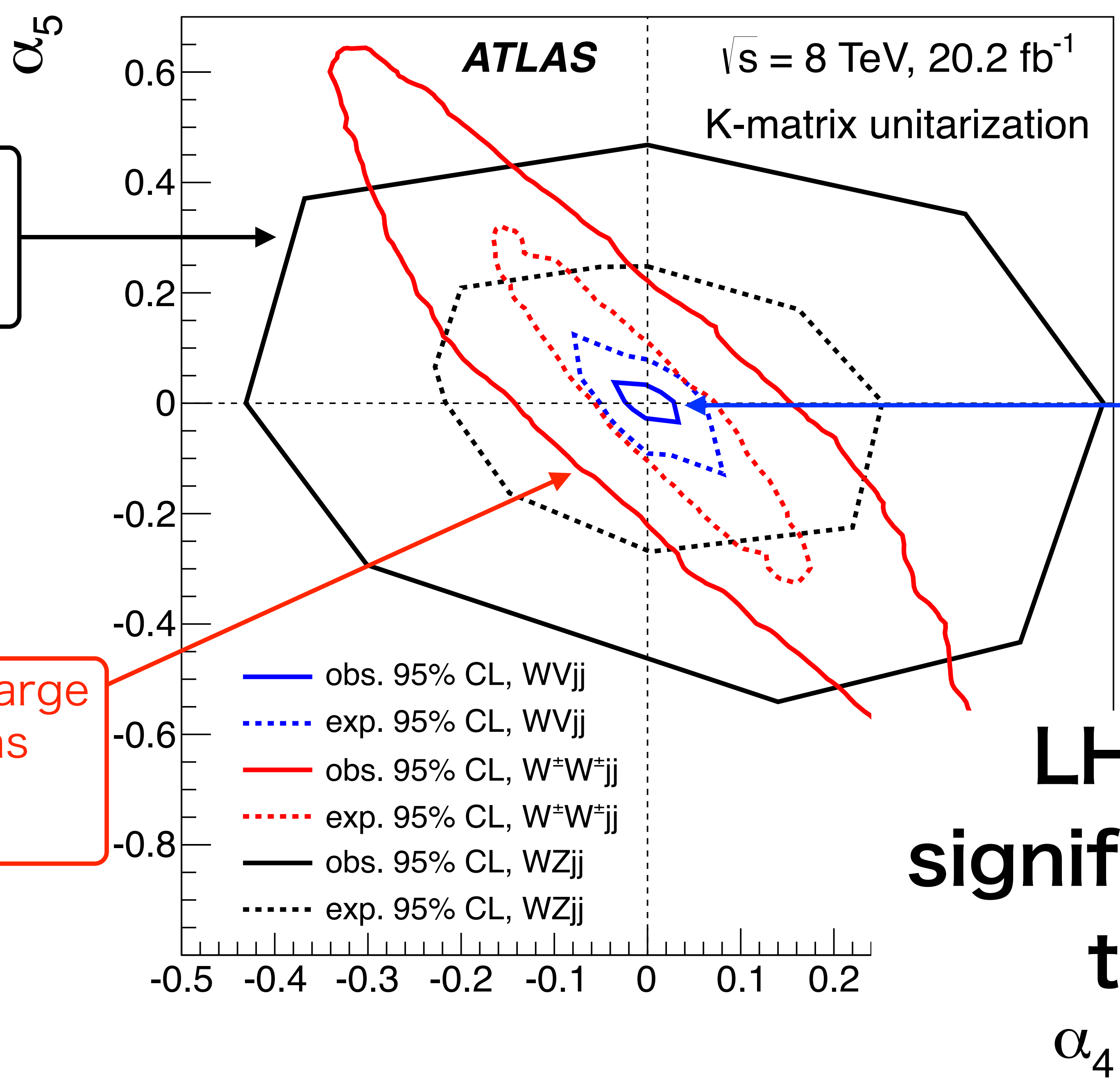

LHC RUN2 will significantly improve this further

figure taken from arXiv:1609.05122 (ATLAS)

EW Chiral Lagrangian parameters: α_4, α_5

Higgs doublet can be rewritten as: $\Phi(x) = \frac{v_{\rm EW} + h(x)}{\sqrt{2}} U(x)$

NG field : $U(x) = e^{i\,\pi^i(x)\,\sigma^i/v_{\rm EW}}$

Scalar (Higgs) : $h(x)$

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Equivalence theorem: $E \gg m_W$

$$\mathcal{A}(W_{\rm L}W_{\rm L} \to W_{\rm L}W_{\rm L}) \simeq \mathcal{A}(\pi\pi \to \pi\pi)$$

Effective Lagrangian of $U(x)$ is appropriate for the study of weak gauge boson scattering processes

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EW Chiral Lagrangian: low-energy effective theory of $U(x)$

$$\mathcal{L}_{\rm EWCL} = \mathcal{L}_{\mathcal{O}(p^2)} + \mathcal{L}_{\mathcal{O}(p^4)} + \cdots$$

$$\mathcal{L}_{\mathcal{O}(p^2)} = \frac{v_{\rm EW}^2}{4} {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right]$$

$$\mathcal{L}_{\mathcal{O}(p^4)} = \alpha_4\,{\rm Tr}\left[D_\mu U^\dagger D_\nu U\right]{\rm Tr}\left[D^\mu U^\dagger D^\nu U\right] + \alpha_5\,{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right]{\rm Tr}\left[D_\nu U^\dagger D^\nu U\right] + \cdots$$

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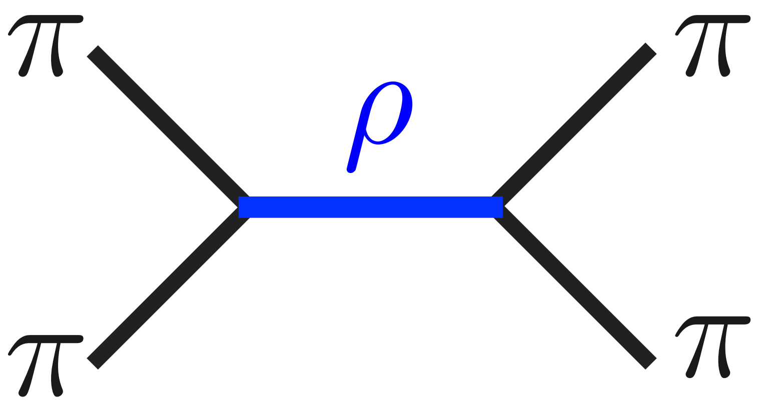
$$+ \alpha_5 \, {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] {\rm Tr}\left[D_\nu U^\dagger D^\nu U\right] + \cdots$$

EW Chiral Lagrangian parameters: α_4, α_5

typical example of physics beyond the SM:

new heavy vector resonance (ρ)



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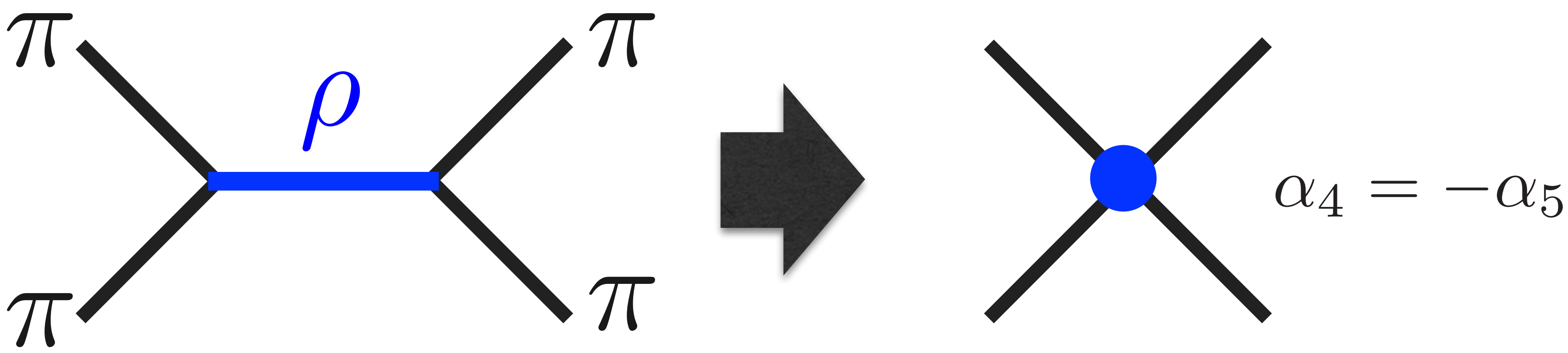

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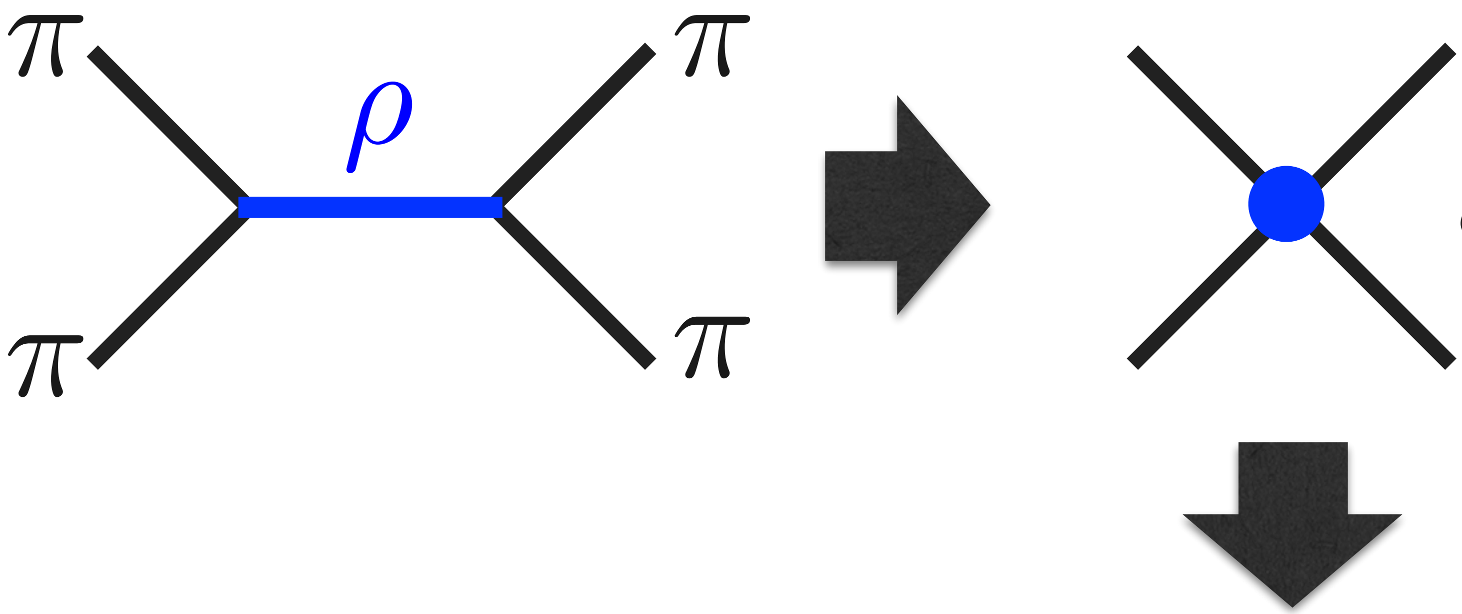

$\alpha_4 = -\alpha_5$

$$\mathcal{L}_{\mathcal{O}(p^4)} = -\frac{1}{2}\alpha_5 \mathrm{Tr}\left[D_\mu U U^\dagger, D_\nu U U^\dagger\right]^2$$

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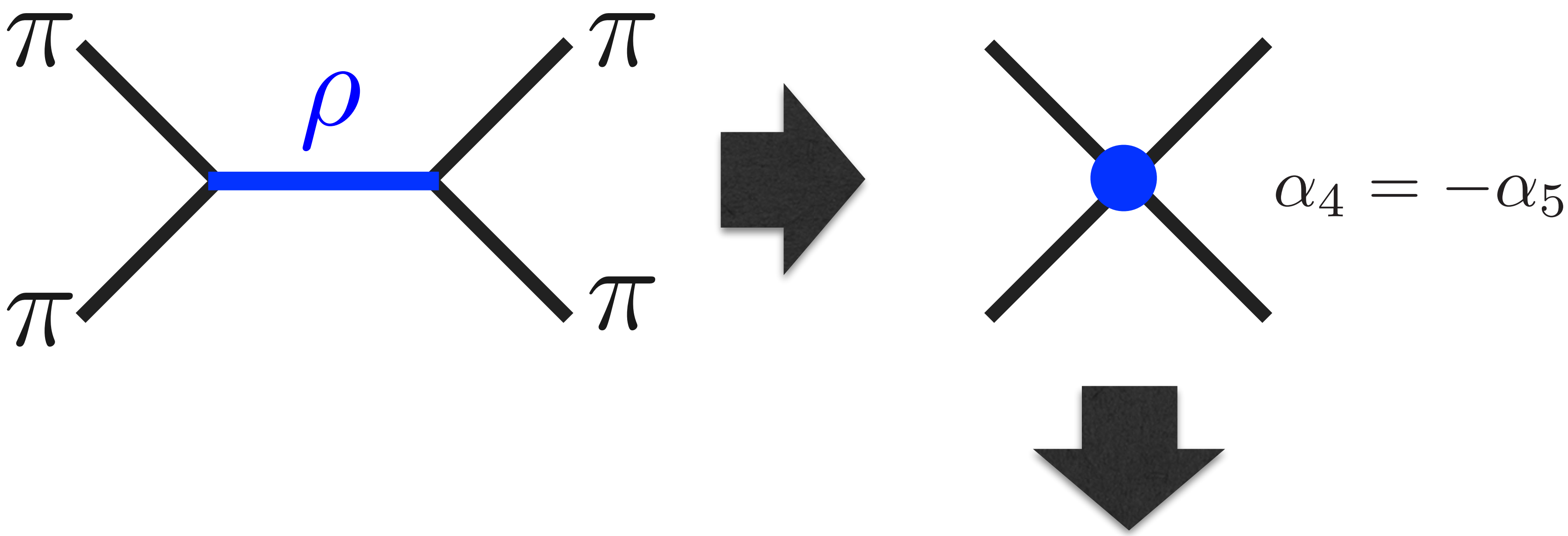

$$\mathcal{L}_{\mathcal{O}(p^4)} = -\frac{1}{2}\alpha_5 \mathrm{Tr}\left[D_\mu U U^\dagger, D_\nu U U^\dagger\right]^2$$

We take this term as a **minimal addition to the SM**, and study physical consequences

Lagrangian

$$\mathcal{L} = \frac{v_{\mathrm{EW}}^2}{4}\left(1 + \frac{h(x)}{v_{\mathrm{EW}}}\right)^2 \mathrm{Tr}\left[\partial_\mu U(x)\, \partial^\mu U(x)^\dagger\right] \;+\; \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) - V(h(x))$$

$$+\frac{1}{2}\,\alpha\;\mathrm{Tr}\left[\,\partial_\mu U(x)\, U(x)^\dagger\,,\,\partial_\nu U(x)\, U(x)^\dagger\,\right]^2$$

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Standard Model

NG field : $U(x) = e^{i\,\pi^i(x)\,\sigma^i/v_{\rm EW}}$

Scalar (Higgs) : $h(x)$

$$V(h(x)) = \lambda v_{\rm EW}^2\,h(x)^2 + \lambda v_{\rm EW}\,h(x)^3 + \frac{\lambda}{4}\,h(x)^4$$

Lagrangian

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Standard Model + $O(p^4)$ term

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$$+\frac{1}{2}\alpha\ {\rm Tr}\left[\partial_\mu U(x)\,U(x)^\dagger\,,\,\partial_\nu U(x)\,U(x)^\dagger\right]^2$$

Standard Model + $O(p^4)$ term

ATLAS constraint : $\alpha \lesssim 0.04$

Existence of $O(p^4)$ term has significant impact on the Higgs sector

Lagrangian

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We show the existence of the stable, topologically non-trivial field configuration of the Higgs field

Electroweak-Skyrmion

Higgs doublet: $\Phi(x) = \frac{v_{\rm EW} + h(x)}{\sqrt{2}} U(x)$

- assume the form of static configuration

$$h(x)/v_{\rm EW} = \phi(r)$$ (spherially symmetric)

$$U(x) = e^{iF(r)\sigma^i \hat{x}_i}$$ (hedgehog shape)

$$\left(\, r \equiv \sqrt{x_i x_i}, \quad \hat{x}_i \equiv x_i / r \, \right)$$

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unknown functions

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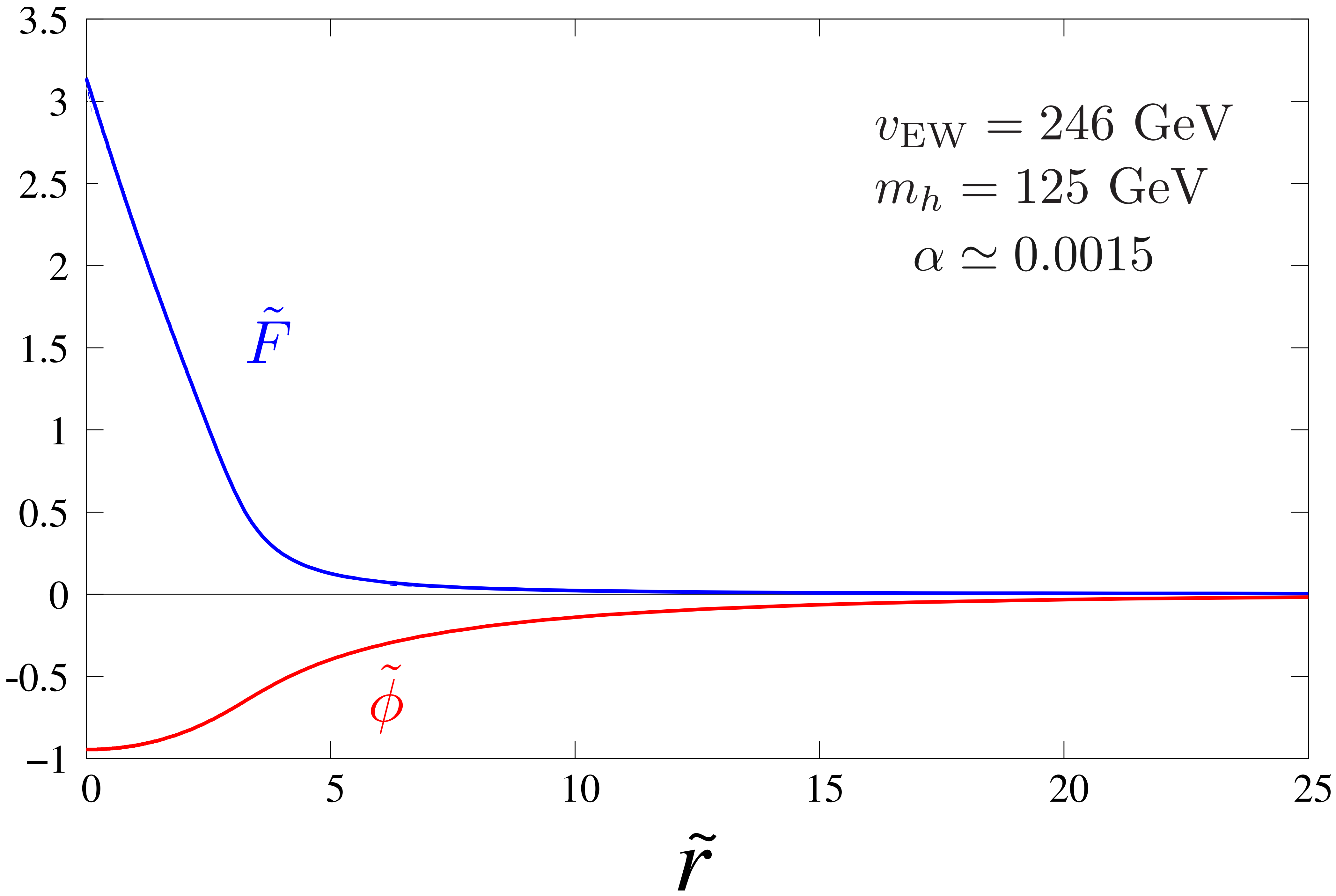
unknown functions

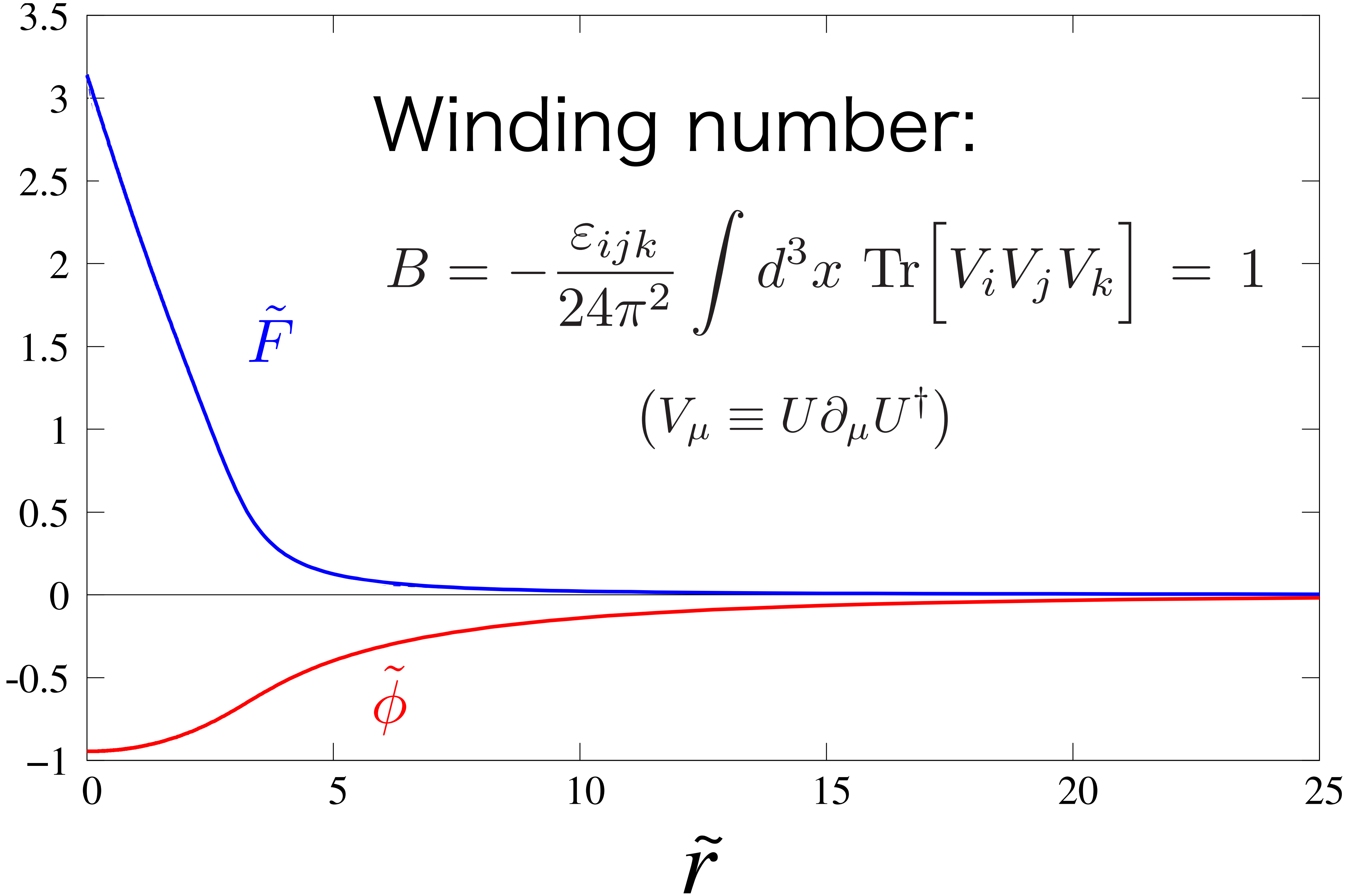
if you find non-trivial solution of $F(r)$ and $\phi(r)$ which minimize the energy functional, new topological object exists in the Higgs sector!!

Solution:



$v_{\rm EW} = 246$ GeV
$m_h = 125$ GeV
$\alpha \simeq 0.0015$
$\tilde{F}$
$\tilde{\phi}$
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
−1
0
5
10
15
20
25
$\tilde{r}$

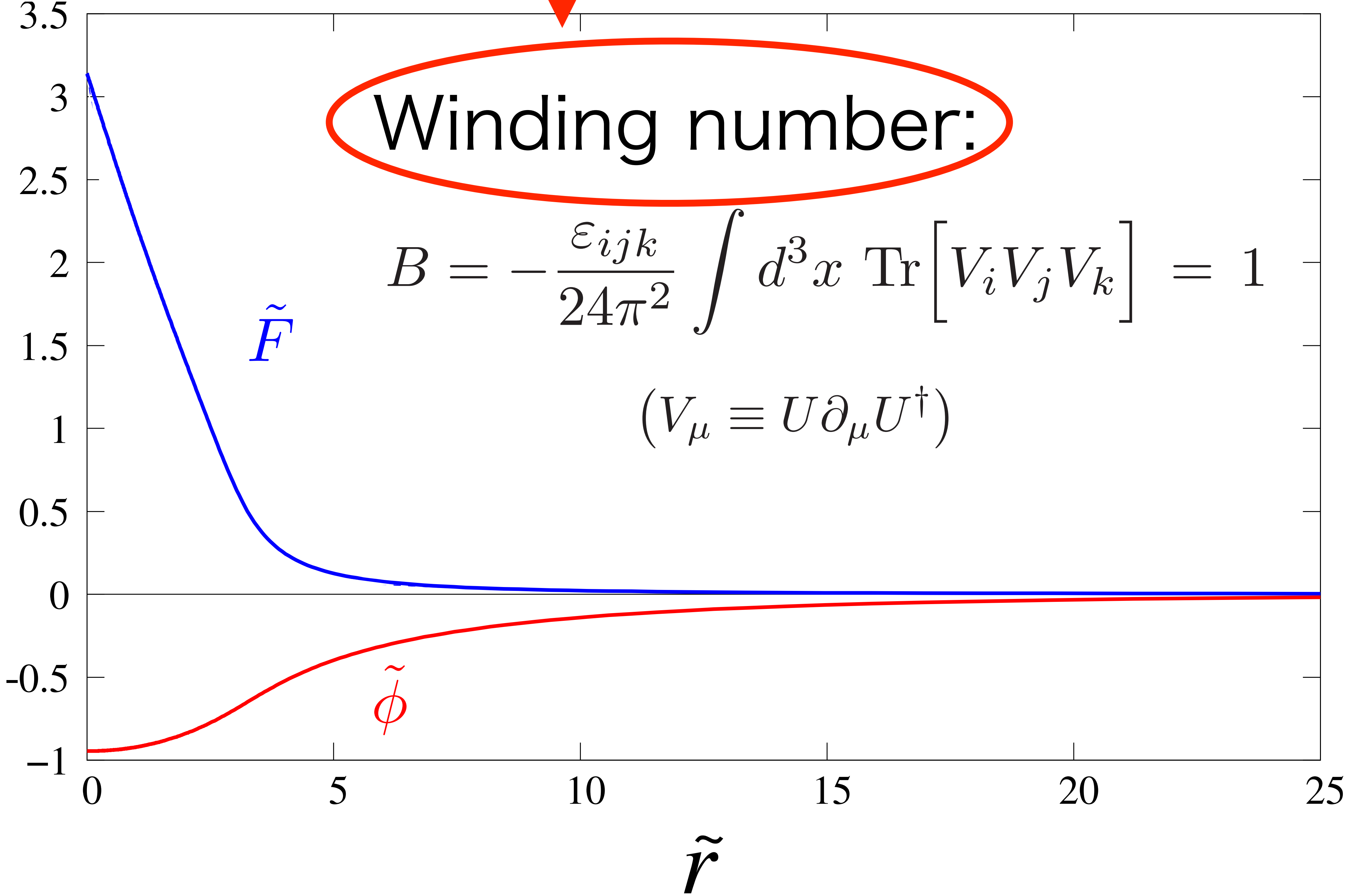
Solution:



Winding number:
$B = -\frac{\varepsilon_{ijk}}{24\pi^2}\int d^3x \ \mathrm{Tr}\left[V_i V_j V_k\right] = 1$
$\left(V_\mu \equiv U\partial_\mu U^\dagger\right)$
$\tilde{F}$
$\tilde{\phi}$
$\tilde{r}$
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
−1
0
5
10
15
20
25

Solution:

cannot be changed by any continuous
deformation of field configuration



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stable, dark matter candidate

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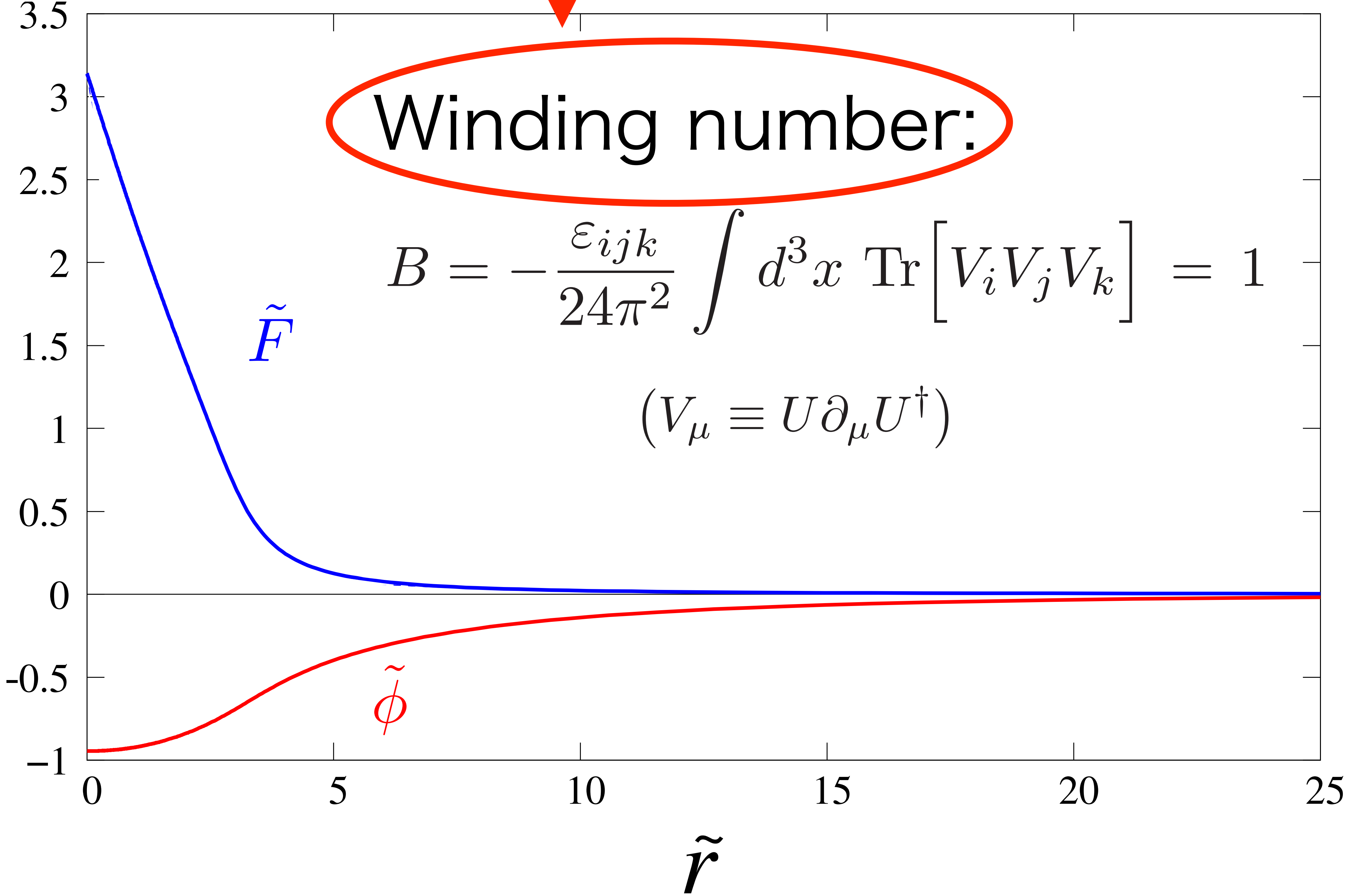
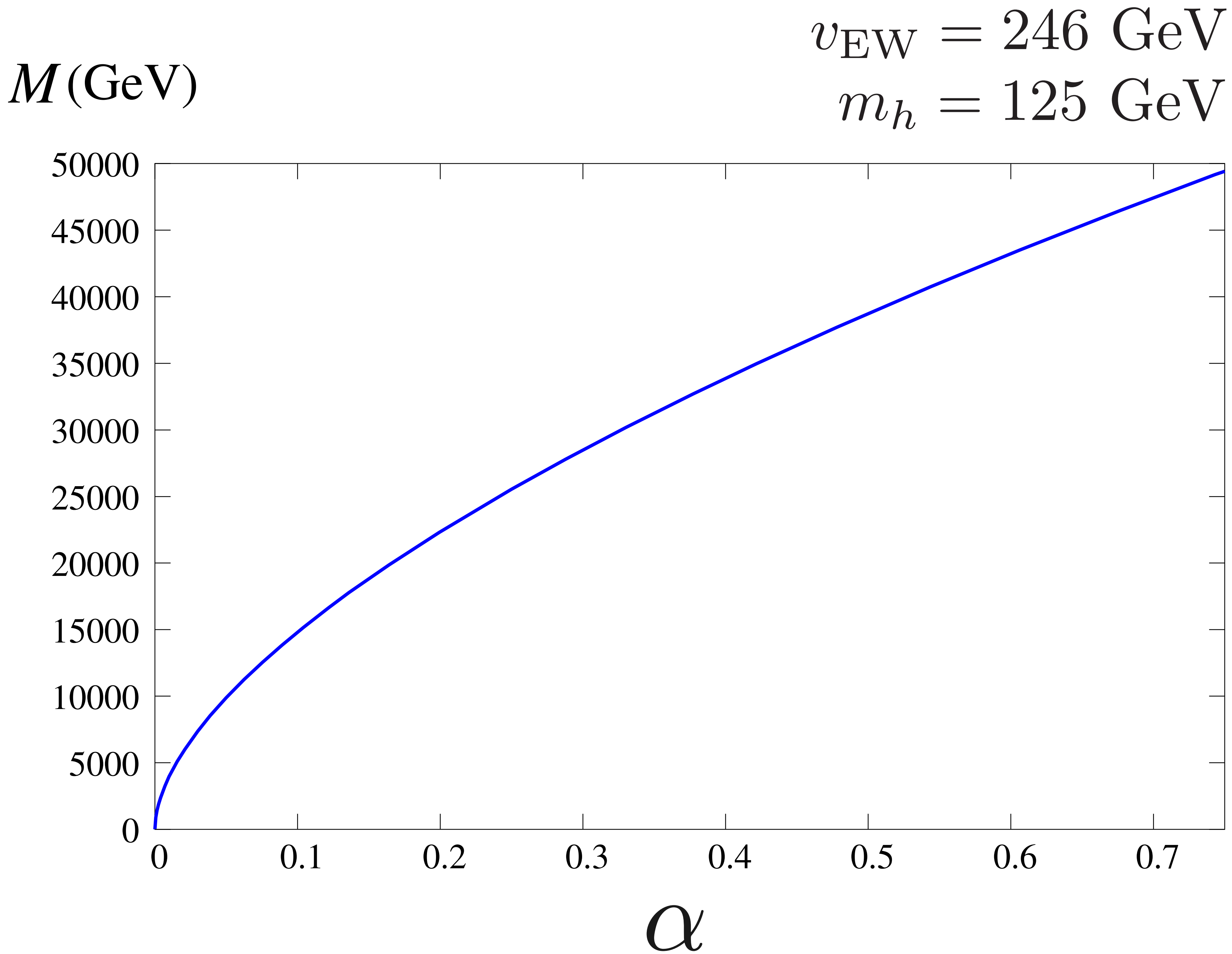


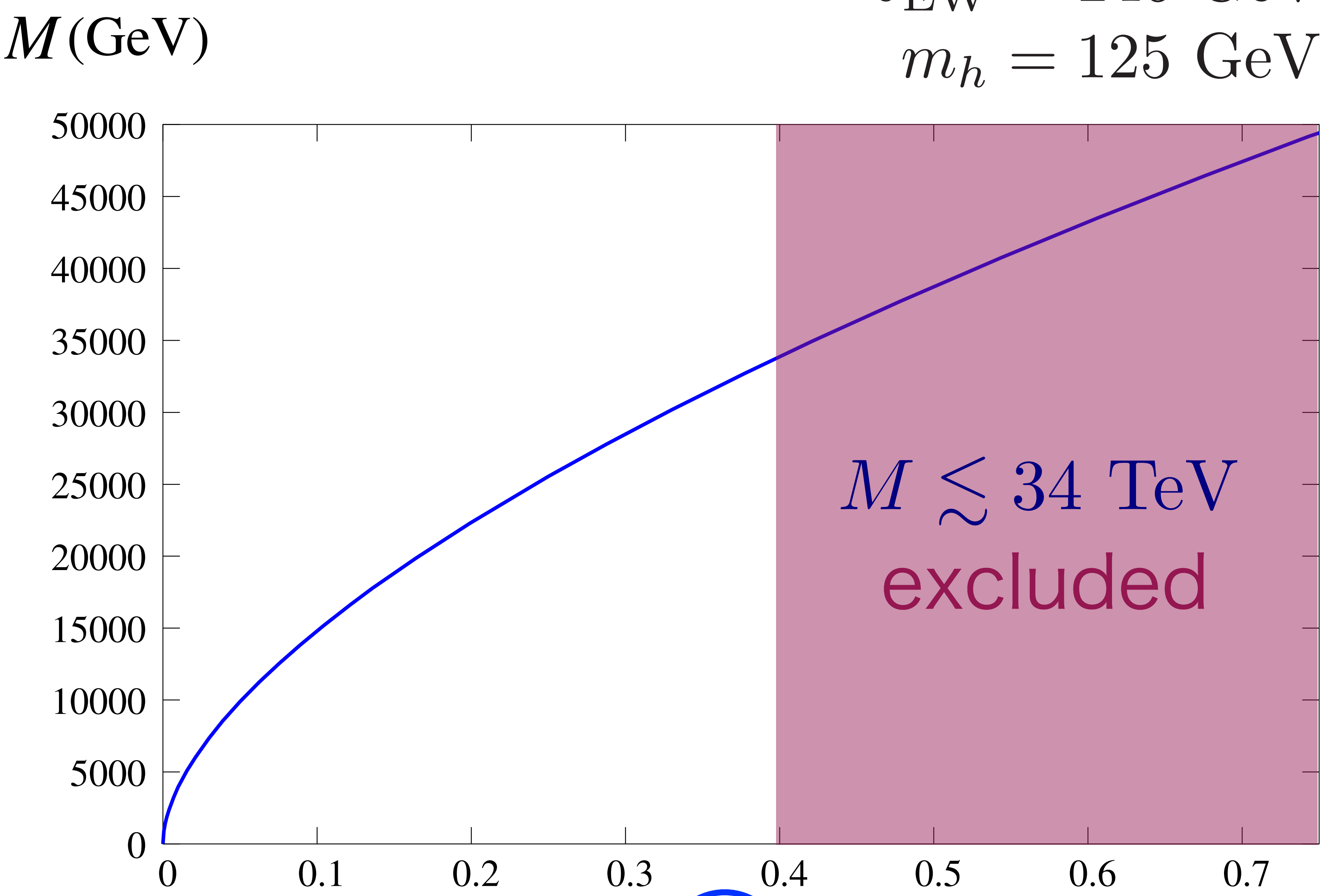
Mass



$v_{\rm EW} = 246$ GeV
$m_h = 125$ GeV
M (GeV)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
α

Mass experimental constraint

$$v_{\rm EW} = 246\ {\rm GeV}$$
$$m_h = 125\ {\rm GeV}$$



$\alpha \lesssim 0.4$

G. Aad et al. [ATLAS Collaboration], PRL 113, 141803 (2014)
(arXiv:1405.6241)

Mass

experimental constraint

$v_{\mathrm{EW}} = 246$ GeV

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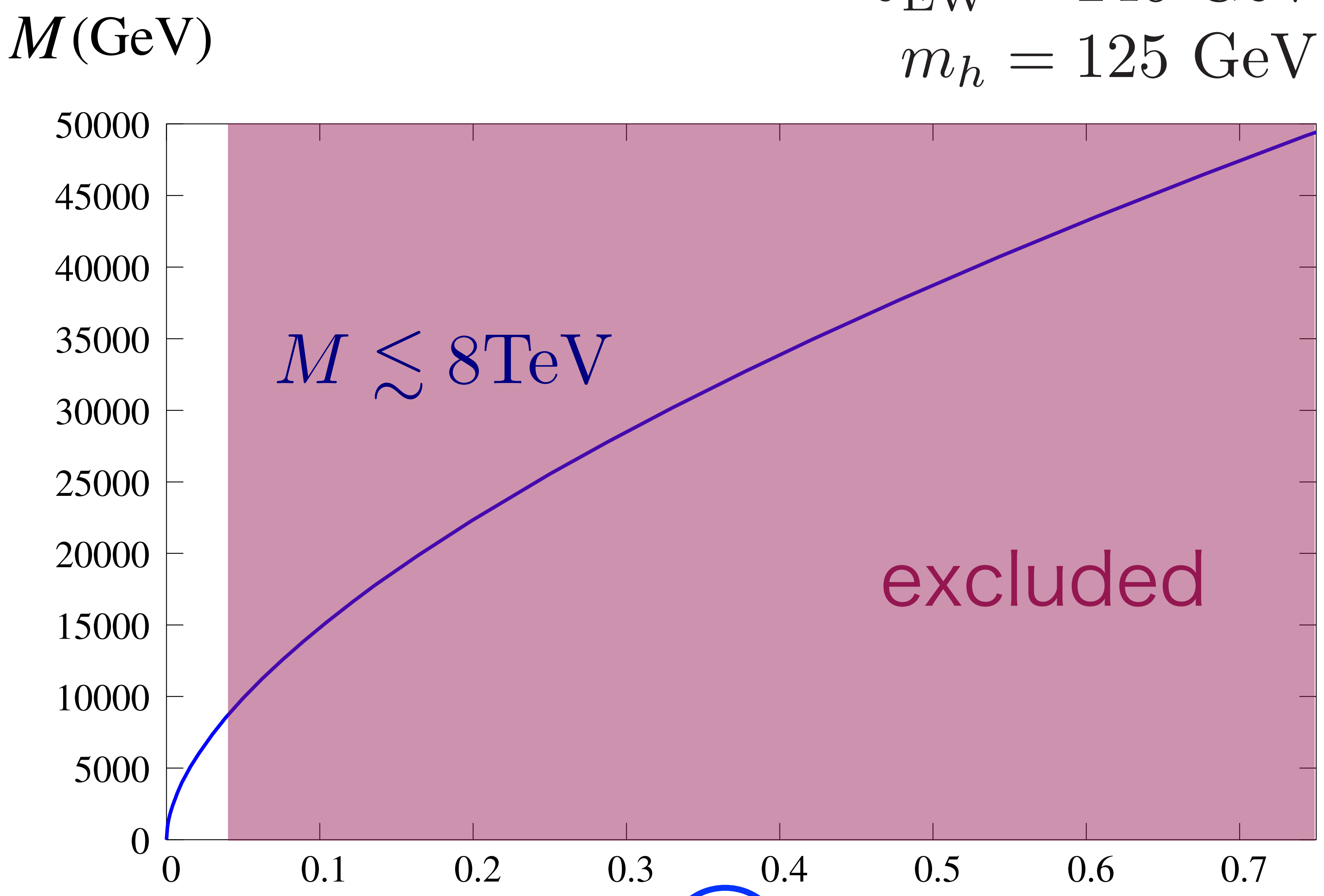

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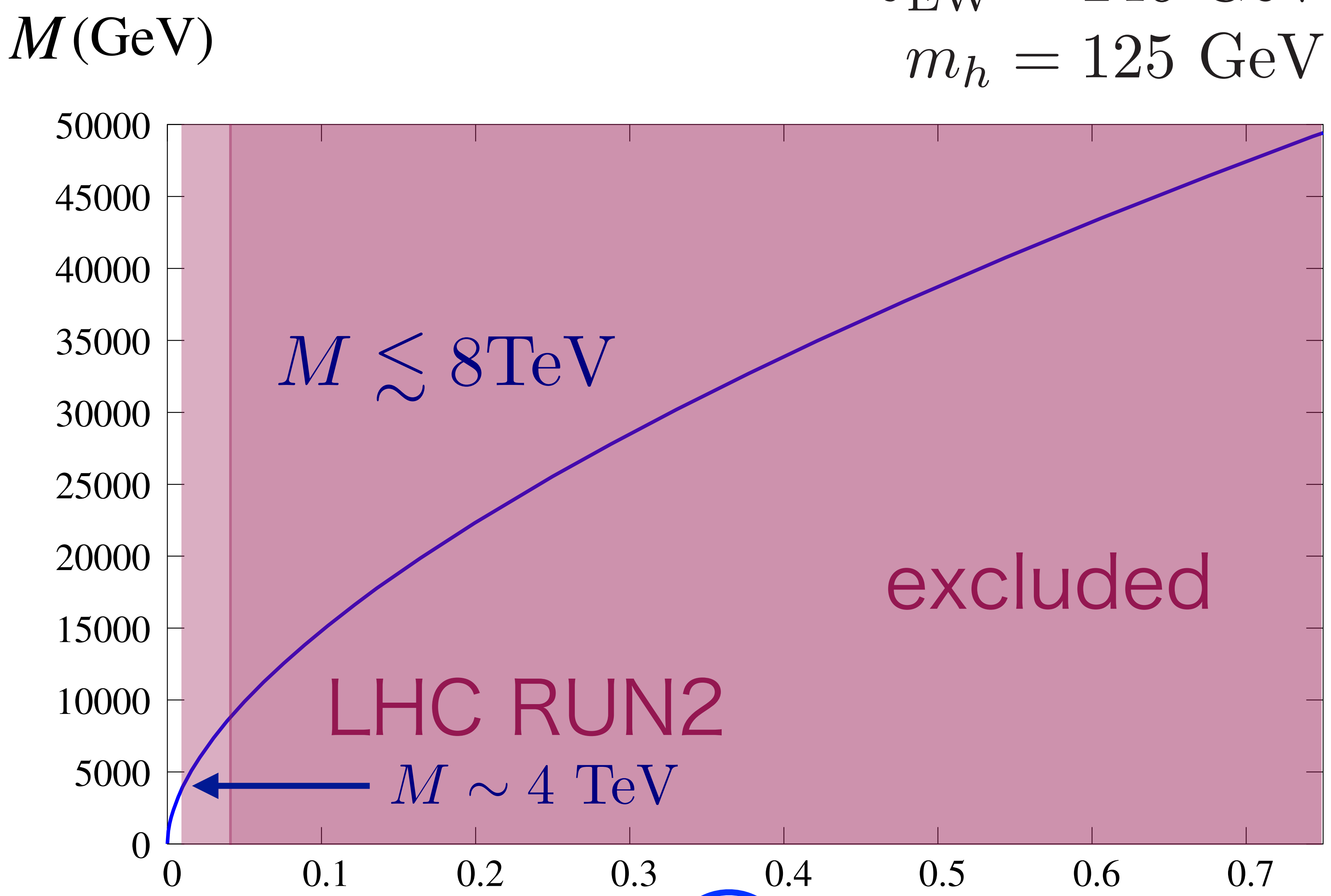

$\alpha \lesssim 0.04$

arXiv:1609.05122 (ATLAS)

Cosmology: EW-Skyrmion as Dark Matter

Constraint from the direct detection experiment (LUX)

simple assumption for a rough estimate: $\mathcal{L}_{\rm eff} = -2\kappa |S|^2 |H^2|$

$$\sigma_{\rm SI} \approx \frac{\kappa^2 m_N^4 f^2}{\pi M^2 m_h^4}$$

$$\simeq \left(\frac{\kappa}{1.0}\right)^2 \left(\frac{1\,{\rm TeV}}{M}\right)^2 \left(\frac{f}{0.3}\right)^2 \times 3.6 \times 10^{-44}\ {\rm cm}^2$$

$f = 0.3$

$\kappa = 1.0\ \ (0.5,\ \pi)$

⇒

$M \gtrsim 1.5\ {\rm TeV}$

$(M \gtrsim 1.0,\ 3.5\ {\rm TeV})$

as of May 2016

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LUX updated $2.5{\rm TeV}$

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$\kappa = 1.0\ \ (0.5,\ \ \pi)$

⇒

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$(M \gtrsim 1.0,\ 3.5\ {\rm TeV})$

as of May 2016

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May, 2016

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$$1.5\ \mathrm{TeV} \lesssim M \lesssim 34\ \mathrm{TeV}$$ ← May, 2016

↓ ↓

$$2.5\ \mathrm{TeV} \qquad\qquad 8\ \mathrm{TeV}$$ ← today

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DM direct detection & WW scattering

$$1.5\ \mathrm{TeV} \lesssim M \lesssim 34\ \mathrm{TeV}$$ ← May, 2016

↓ ↓

$2.5\,\mathrm{TeV}$ $8\,\mathrm{TeV}$ ← today

↓ ↓

Xenon1T $\sim 5\ \mathrm{TeV}$ $\sim 4\ \mathrm{TeV}$ ← near future

LZ $\sim 10\ \mathrm{TeV}$ LHC RUN2

Summary

- Topological dark matter exists in the SM with a minimal addition of the higher-dimensional operator
- Its mass is constrained from both sides by

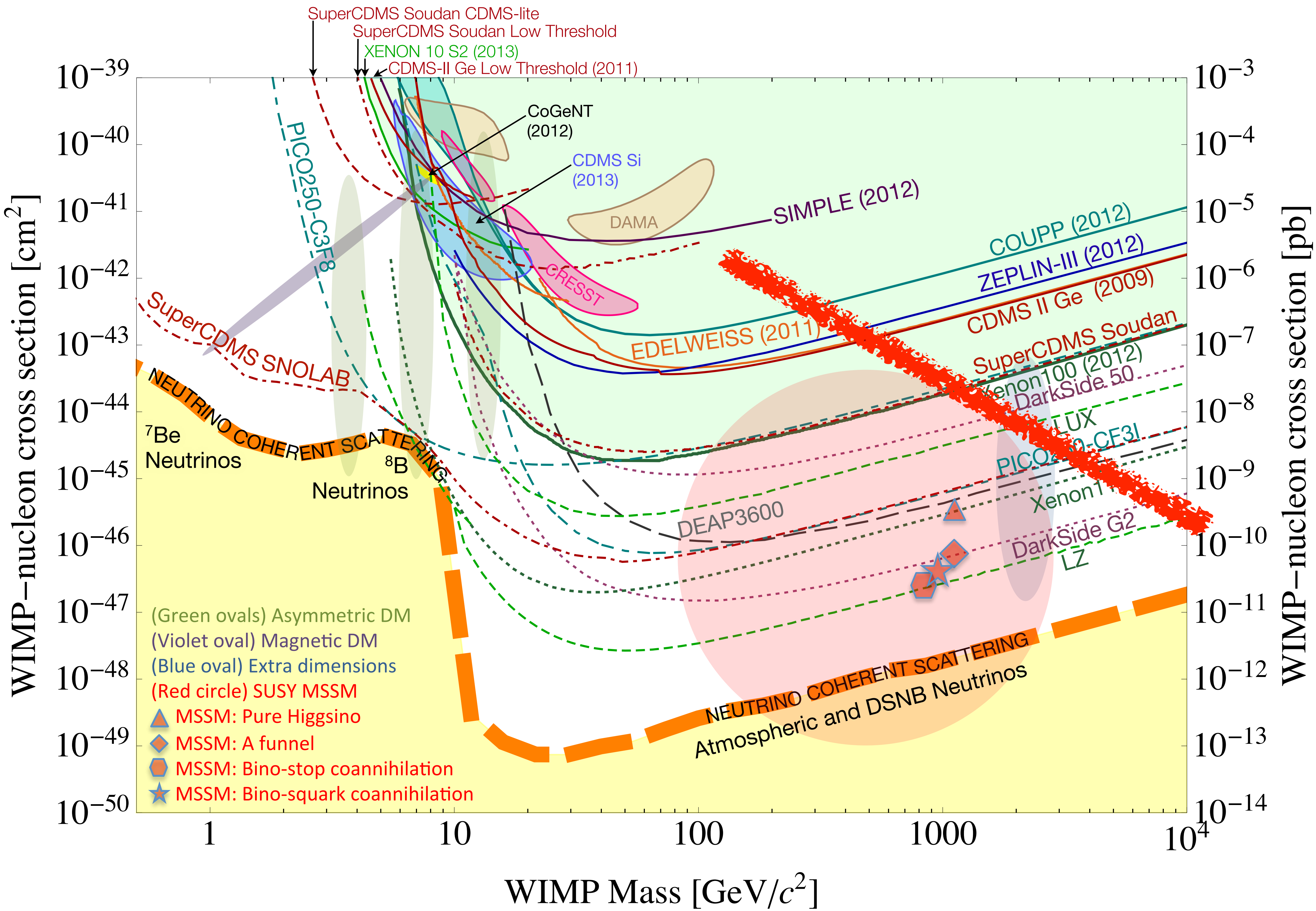
Wide mass range will be probed from **both** sides!
If the DM is directly detected, and we find
anomalous gauge couplings at the same time,
it could be the **EW-Skyrmion**!!!

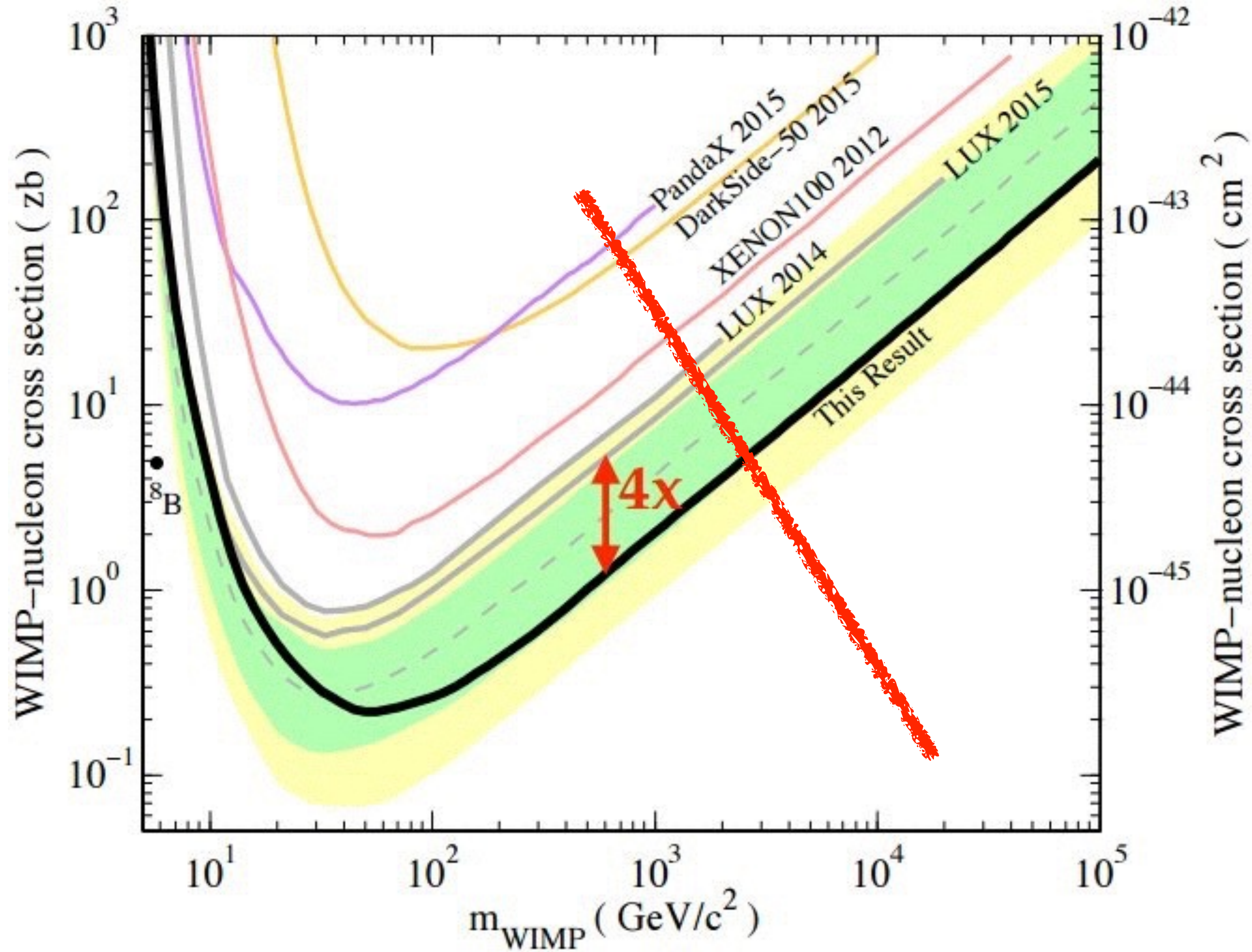
Xenon1T ~ 5 TeV
LZ ~ 10 TeV

~ 4 TeV
LHC RUN2

near future

Backup


SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
PICO250-C3F8
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]



PandaX 2015
DarkSide-50 2015
XENON100 2012
LUX 2014
LUX 2015
This Result
4x
^{8}B
WIMP–nucleon cross section (zb)
WIMP–nucleon cross section (cm^2)
m_{WIMP} (GeV/c^2)