Theory in the LHC era
– overview and vision –

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Beauty 2016, Marseille, May 2, 2016

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Conclusions

- Flavor physics all the more important given lack of new physics at LHC

  1. tool to explore beyond the LHC energy

  2. origin of flavor important on its own

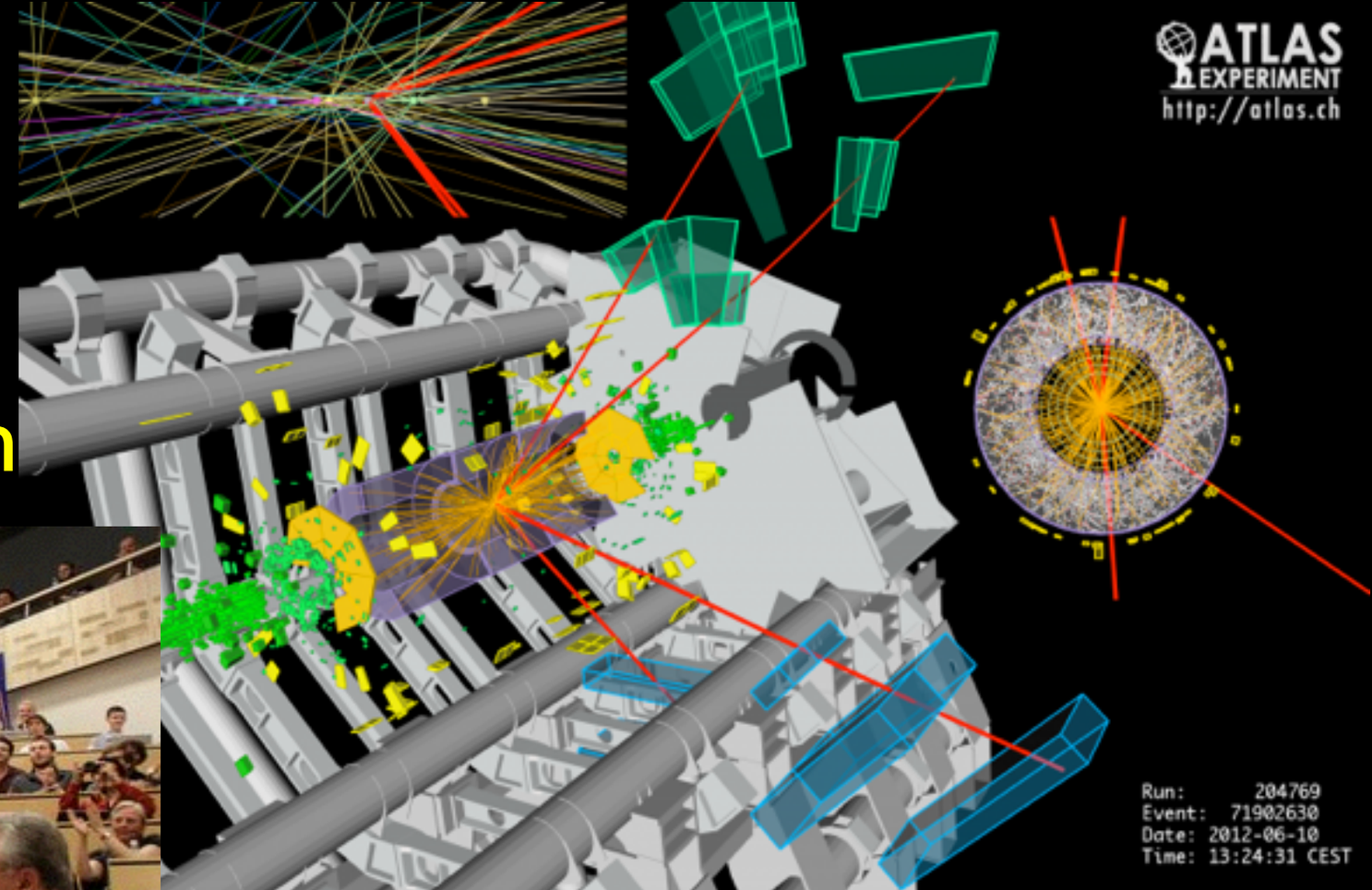
- new possibilities on dark matter

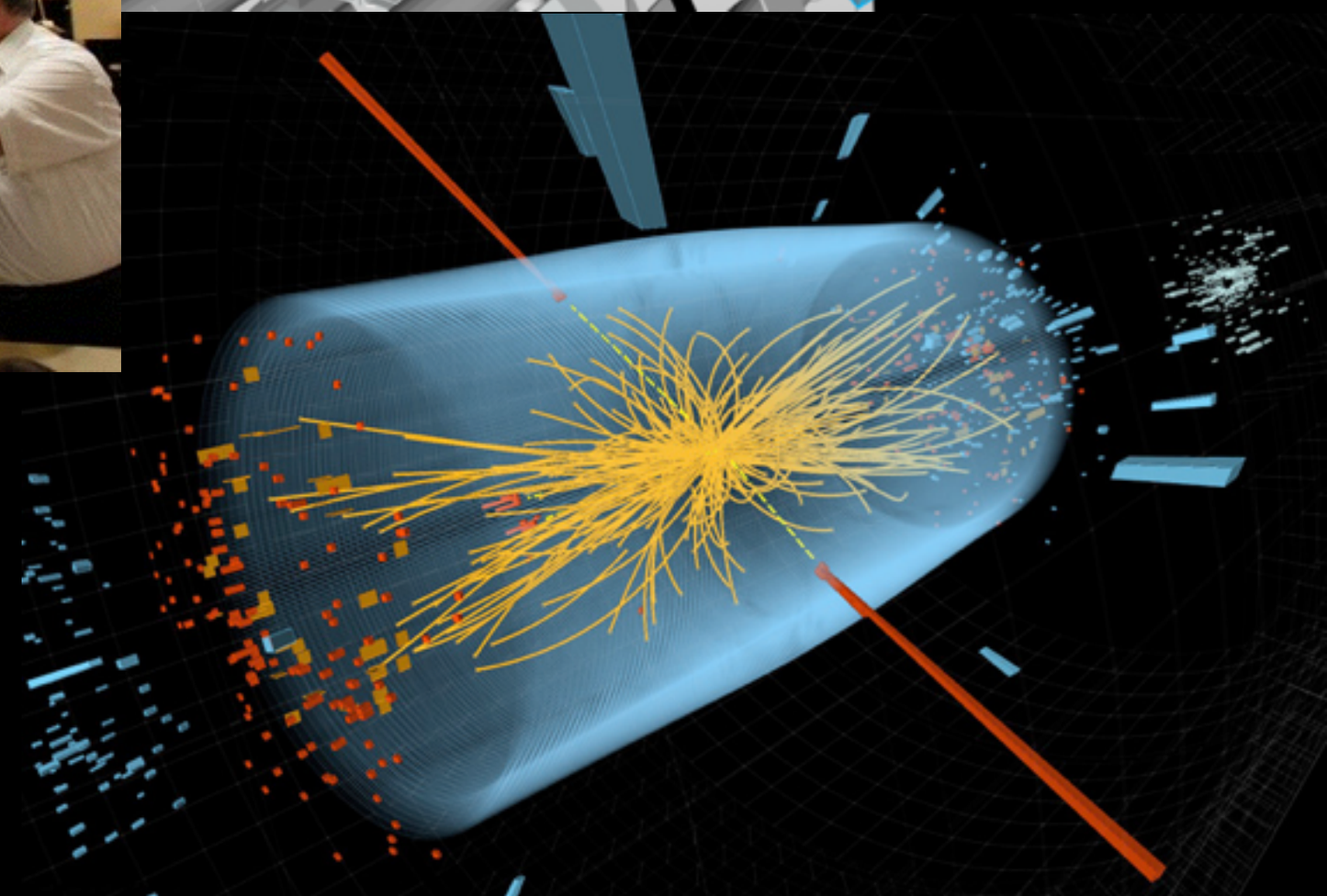
  3. light, very weakly coupled dark matter

flavor to probe *E*>LHC

2012.7.4

discovery of Higgs boson





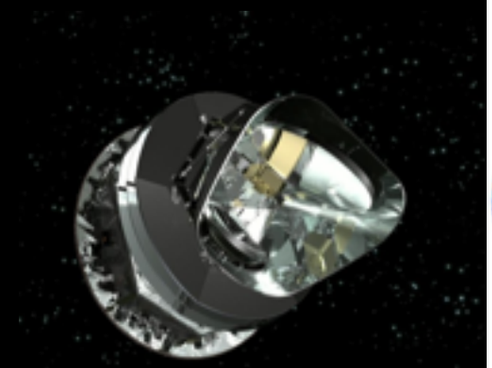
theory：1964

design：1984

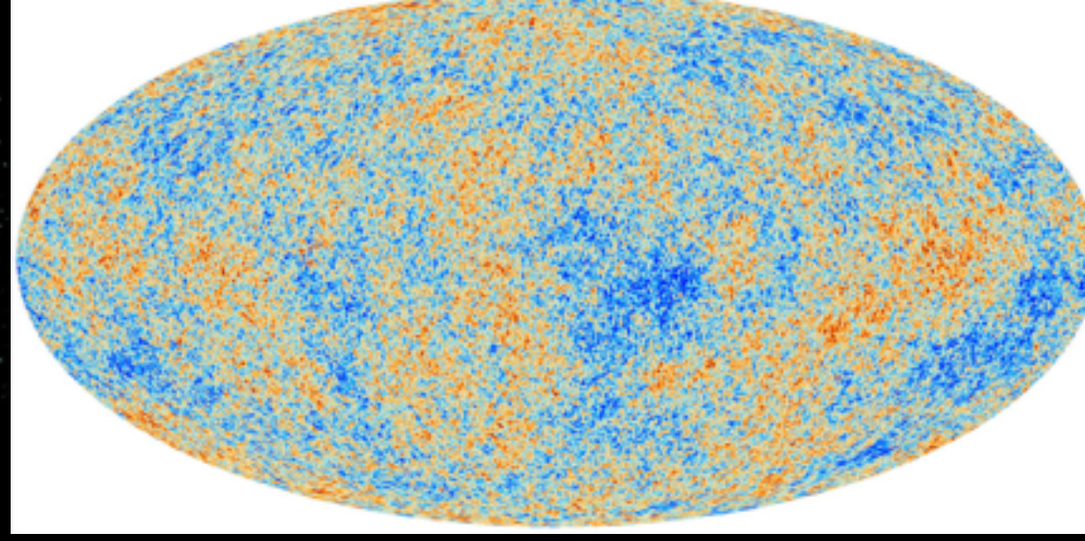
construction：1998


Higgsdependence Day
July 4, 2012

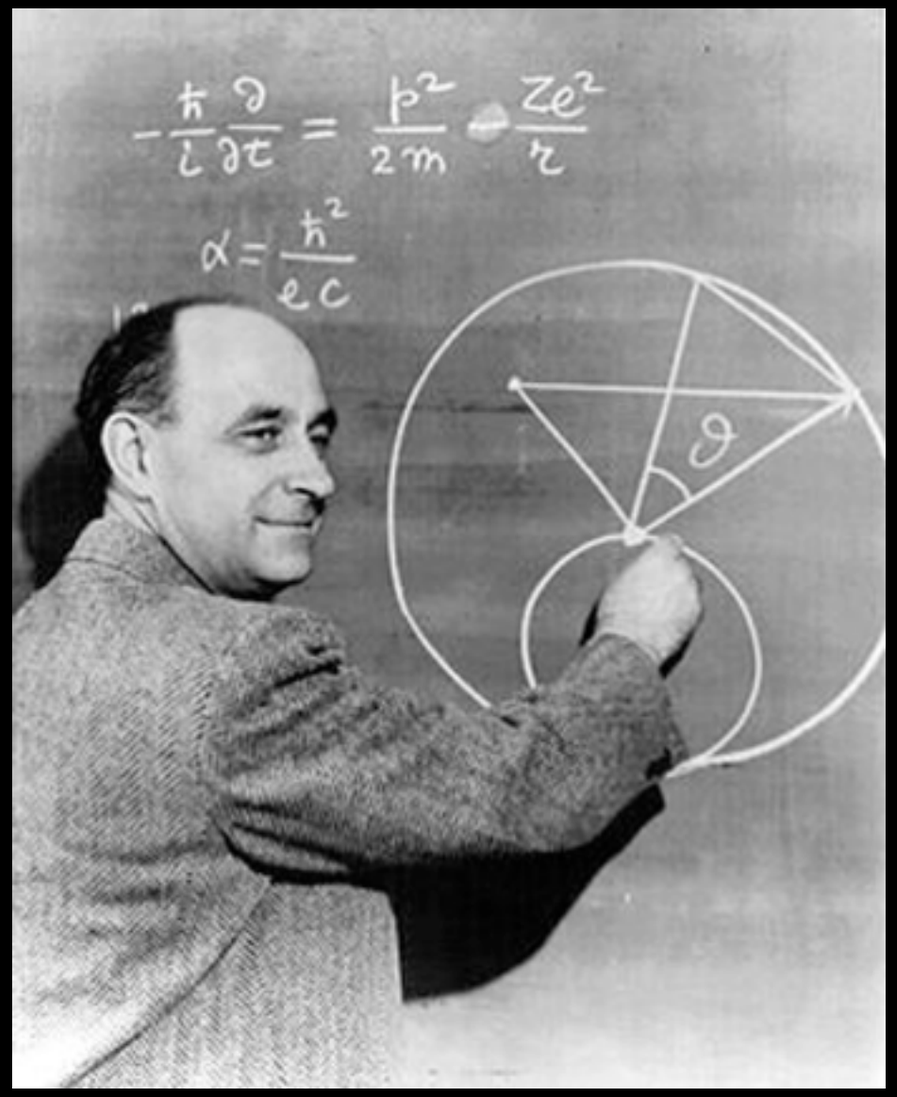
Minimal



Planck



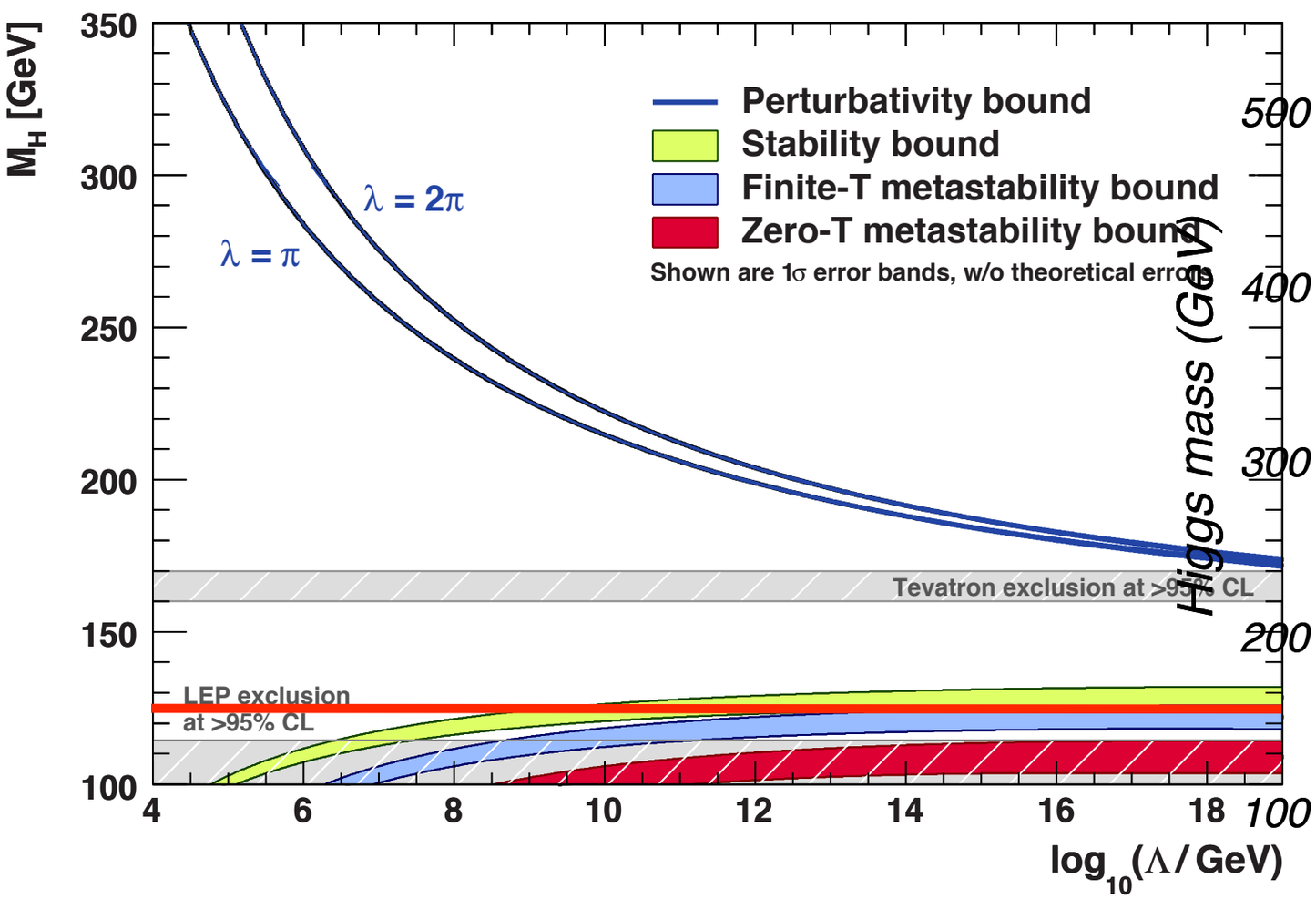
- It looks very much like *the* Standard Model Higgs boson
- We've known the energy scale to probe since 1933
- now a UV complete theory of strong, weak, EM forces possibly valid up to even M_{Pl}
- cosmology also looks minimal single-field inflation (Planck)
- *the year of elementary scalars!!!*



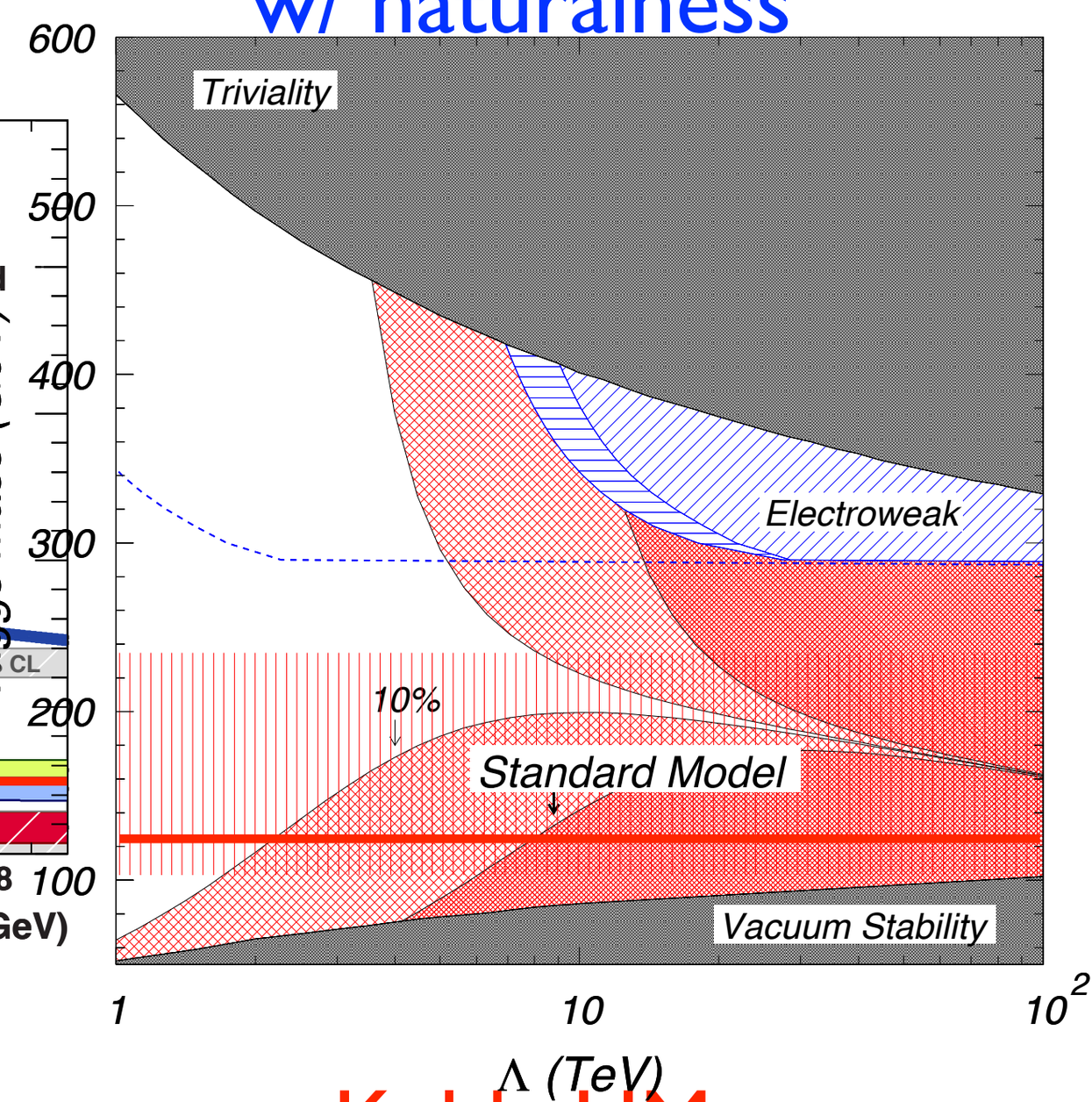
Where do we go next?

Next energy scale

w/o naturalness

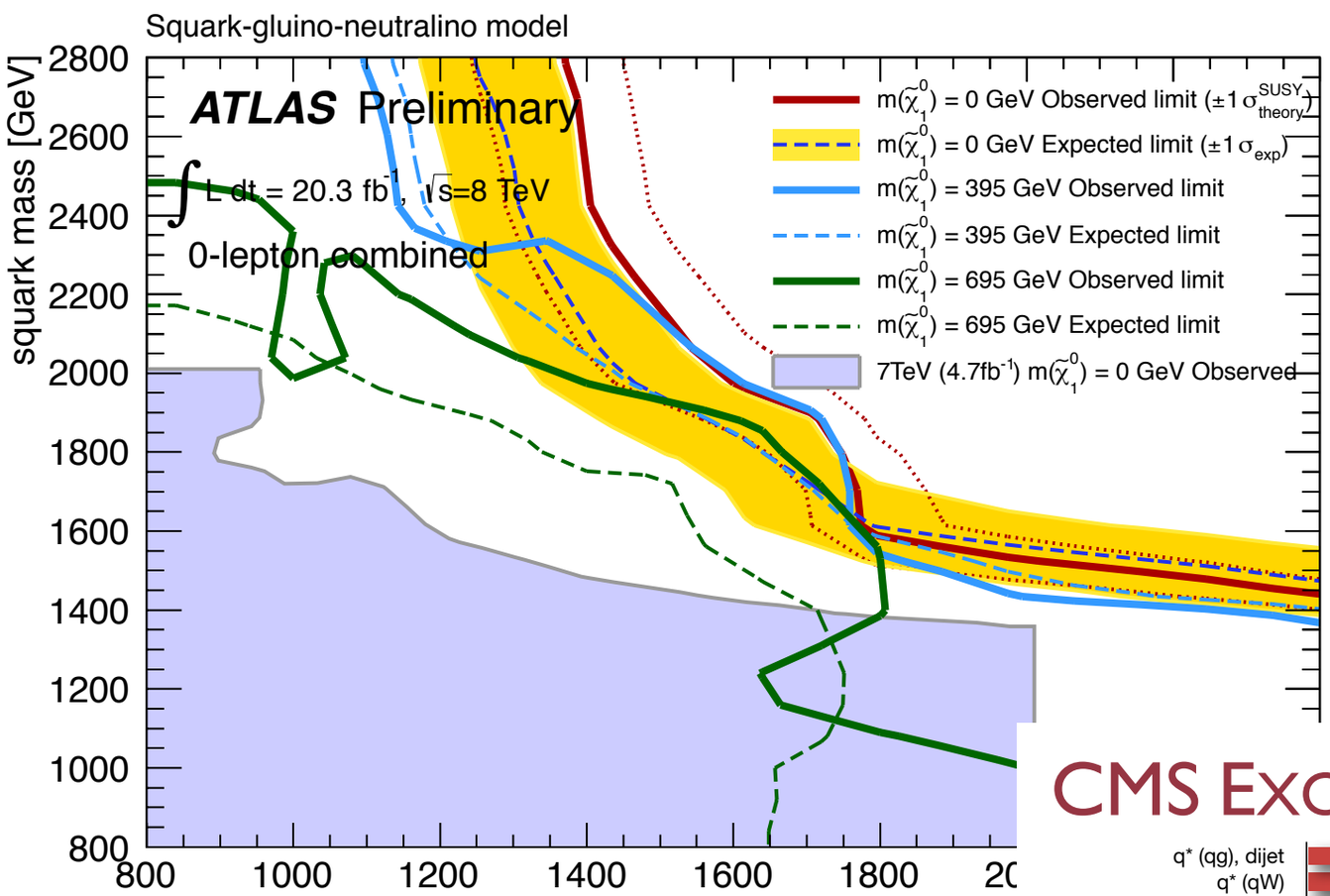


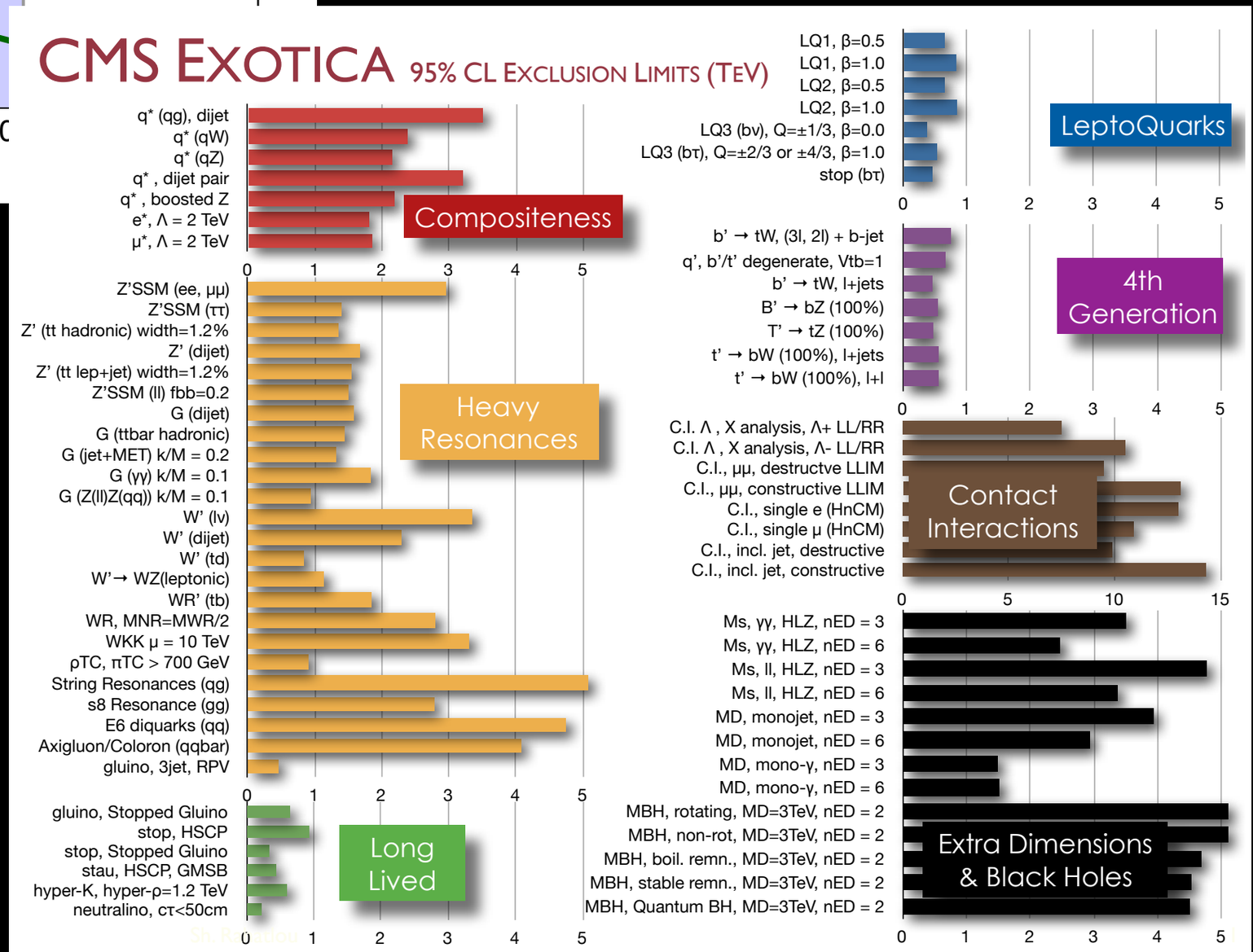
w/ naturalness



Harigayama, Matsumoto, HM

Kolda HM





no sign of
new physics
that explains Higgs!

Nima's anguish

m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

Faceless Higgs

- every elementary particles spin forever
- electrons, photons, quarks, ...
- only Higgs boson doesn't spin
- Faceless! A *spooky particle*
- I had proposed "Higgsless theories"
- *Is it the only one?*
- *does it have siblings? relatives?*
- *Maybe it's spinning in extra dimensions?*
- *maybe composite?*
- *why did it freeze in?*

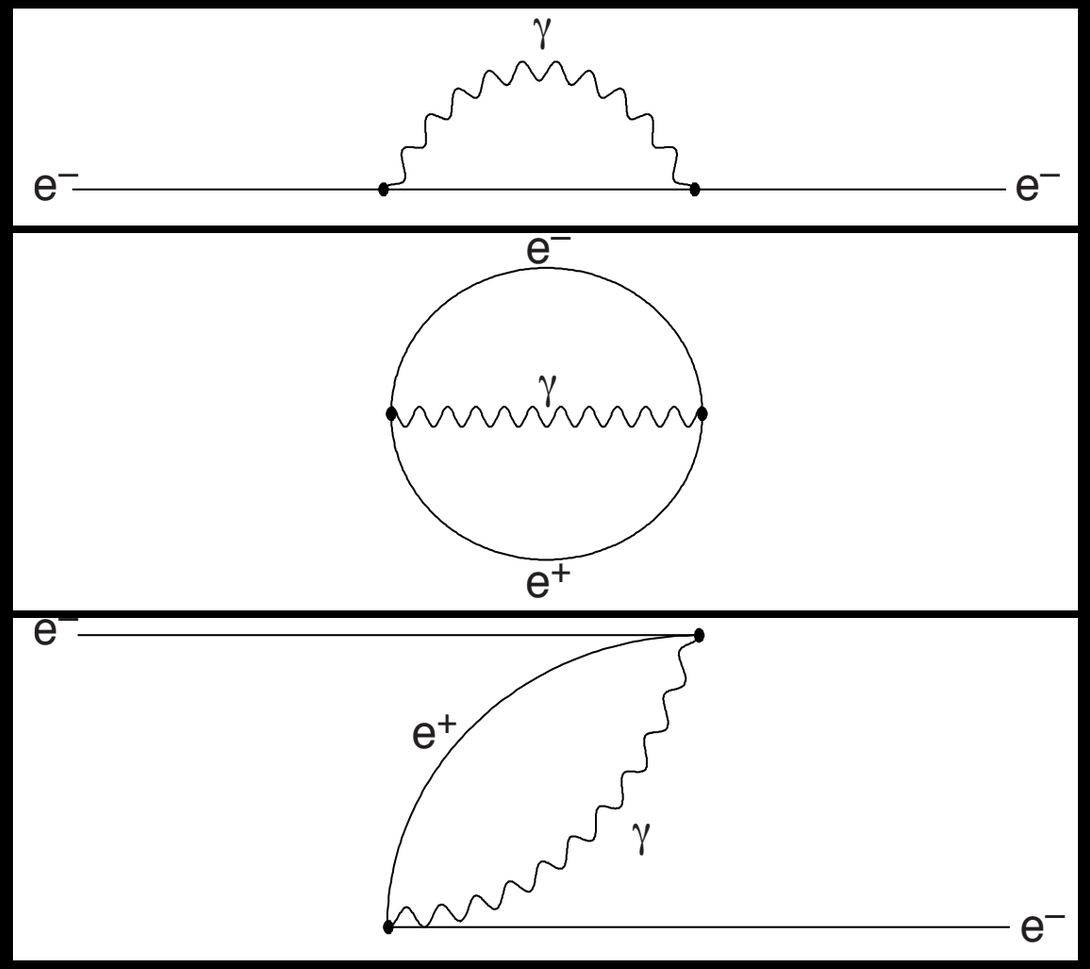
Electron mass is natural by doubling #particles

- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

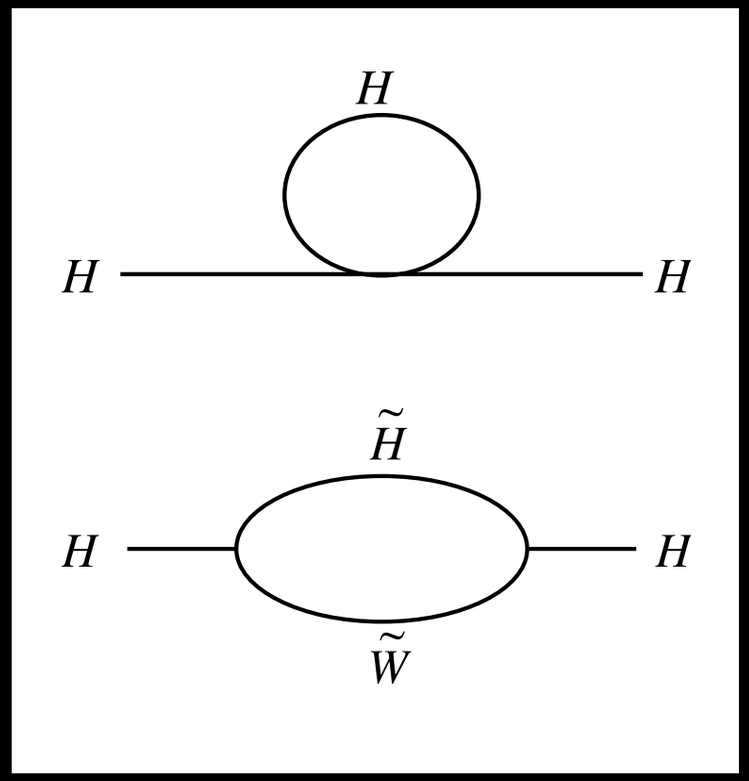
- quantum mechanics and anti-matter

⇒ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs mass is natural by doubling #particles?

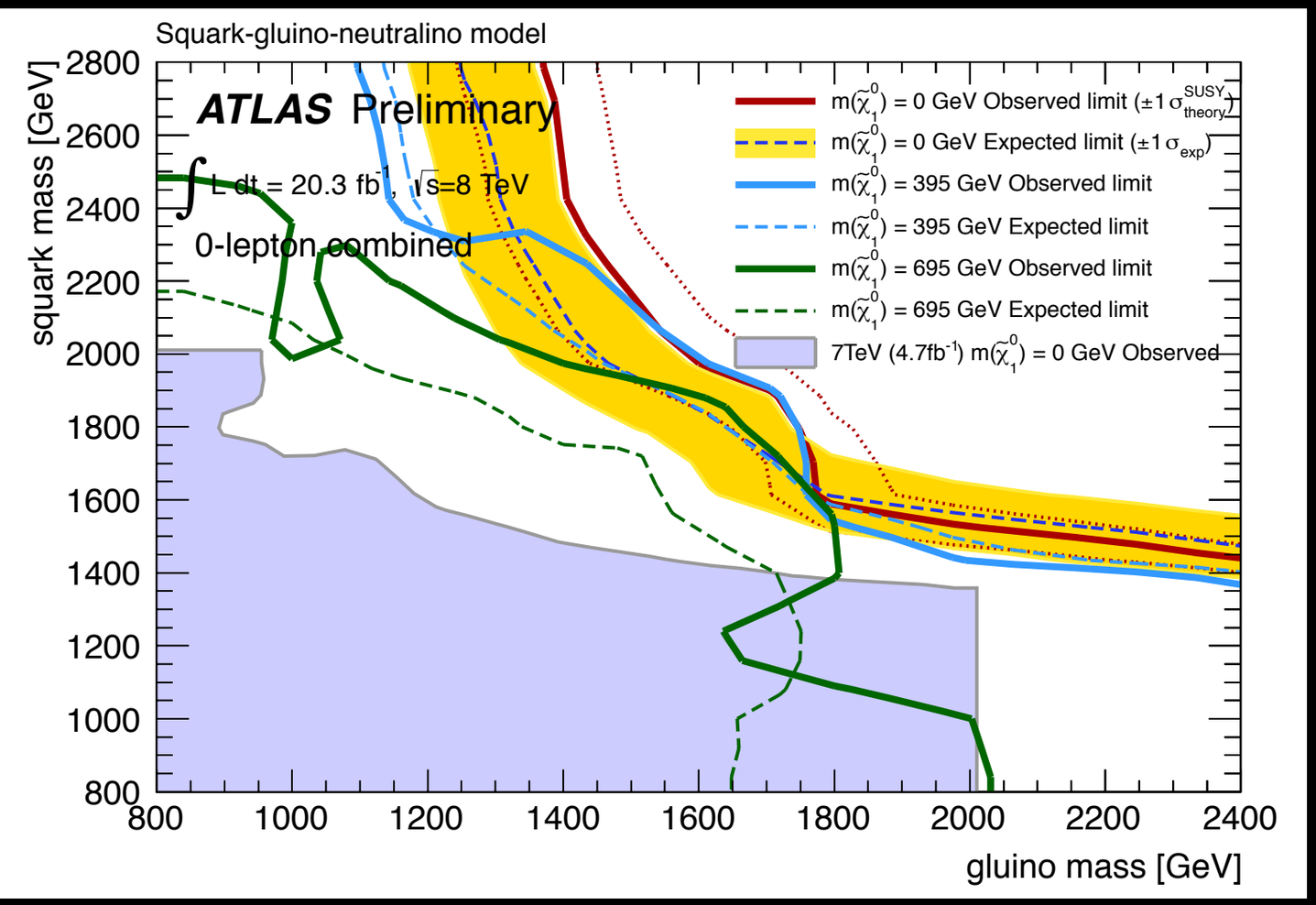


- Higgs also repels itself
- Double #particles again
  $\Rightarrow$ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

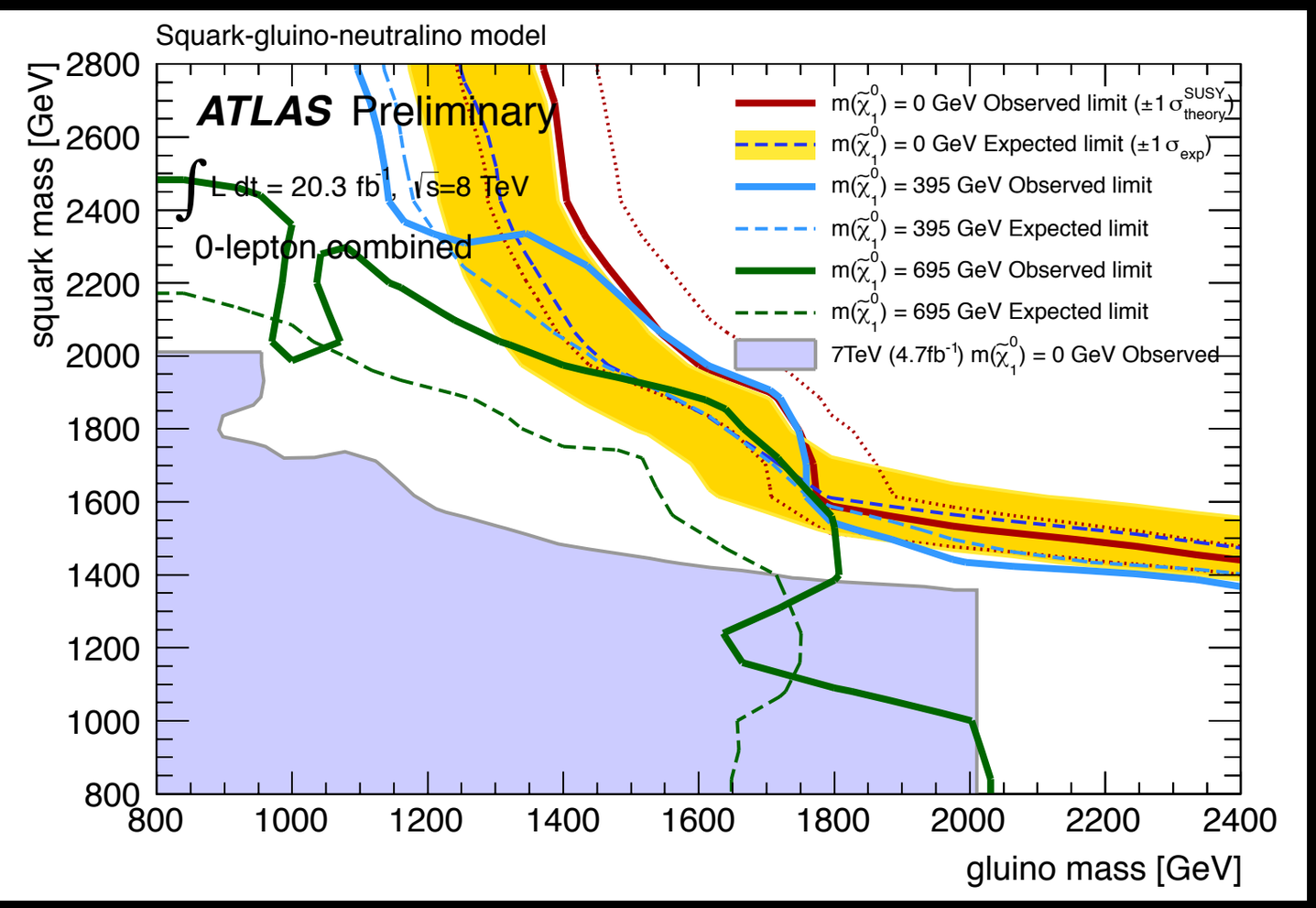
$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

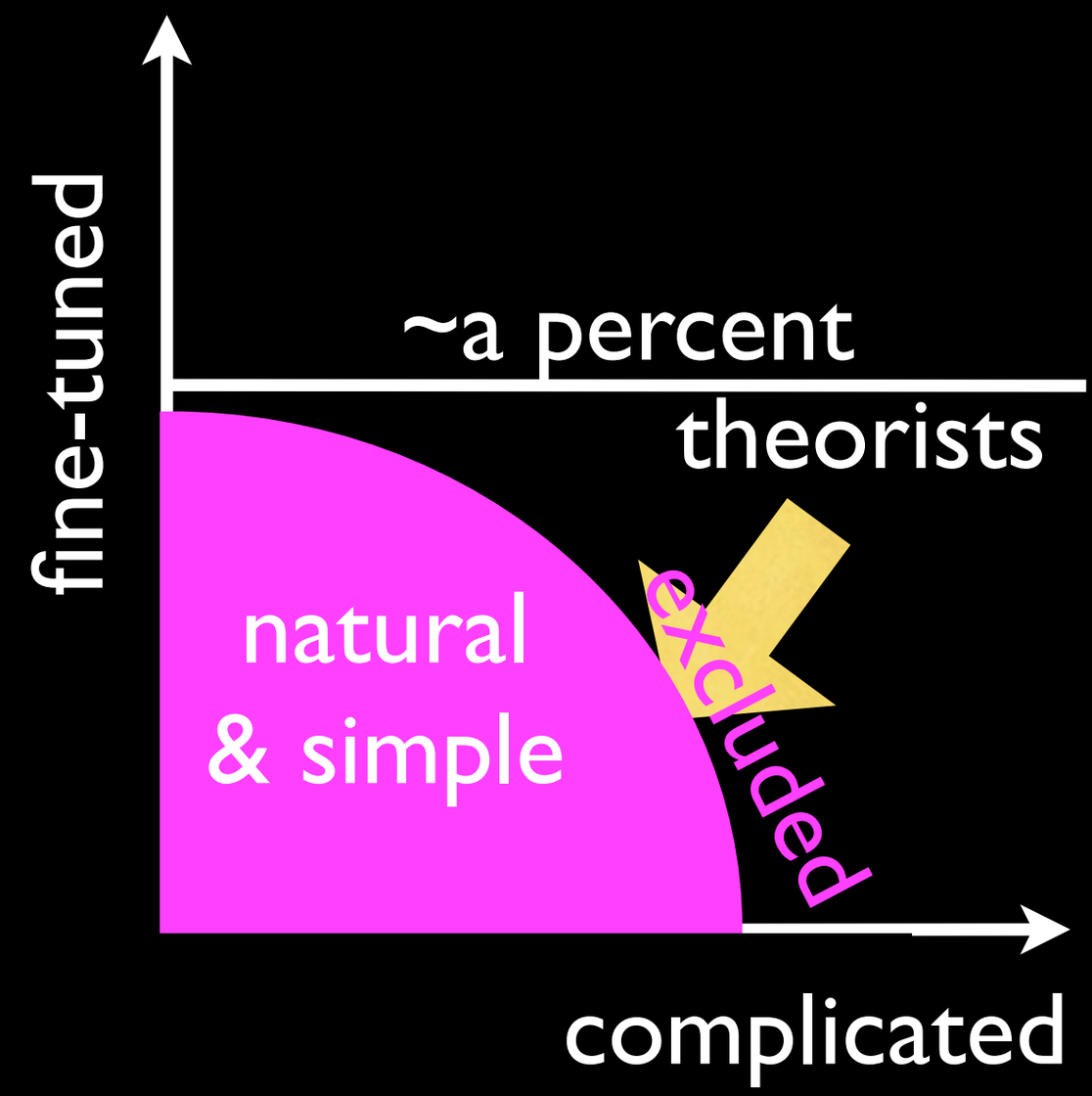
$\Rightarrow$ I still take it seriously

no sign of new physics



no sign of new physics





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An Off Switch for Cancer

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A CRISIS IN PHYSICS ?

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been there before

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- "crisis in standard cosmology"
- it turned out a little "fine-tuned"
  - low quadrupole
  - dark energy

"Big Bang not yet dead but in decline"

Nature 377, 14 (1995)

"Bang! A Big Theory May Be Shot"

A new study of the stars could rewrite the history of the universe

Times, Jan 14 (1991)

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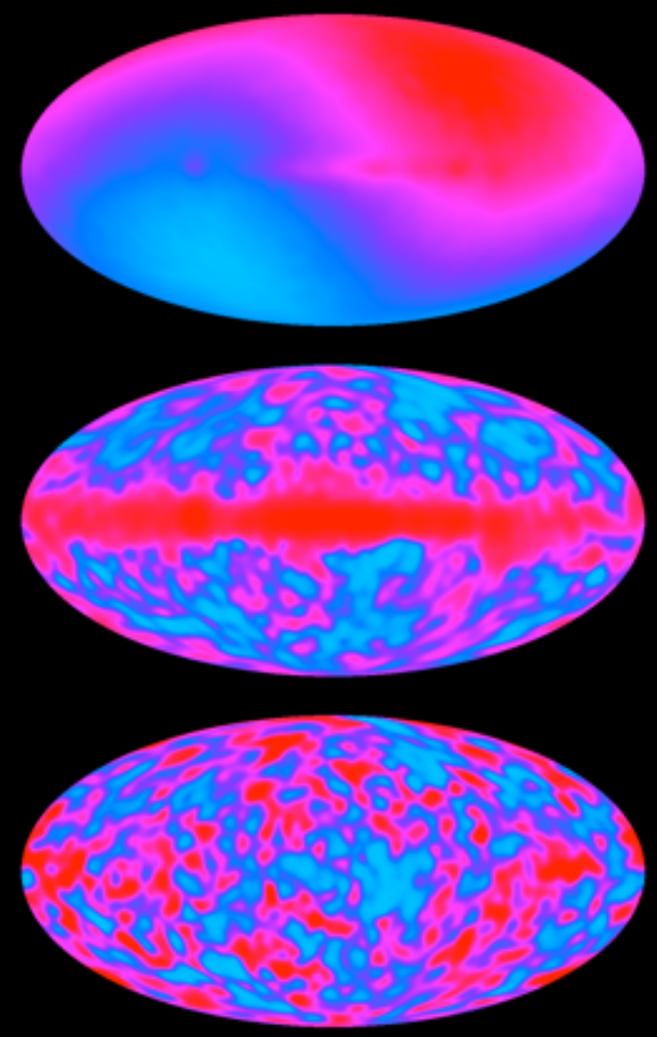

"Bang! A E
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Times, Jan

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write

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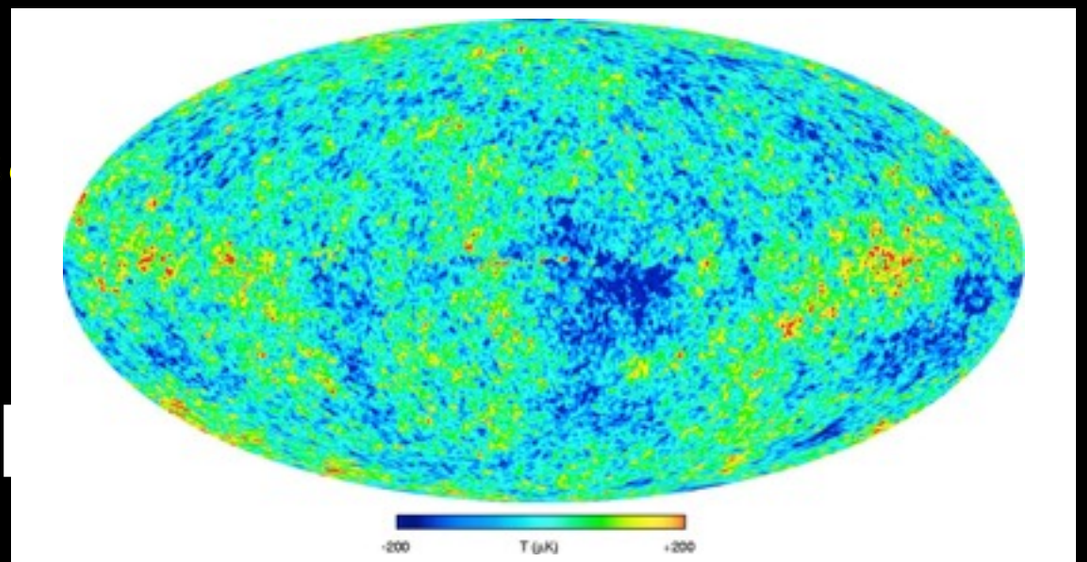

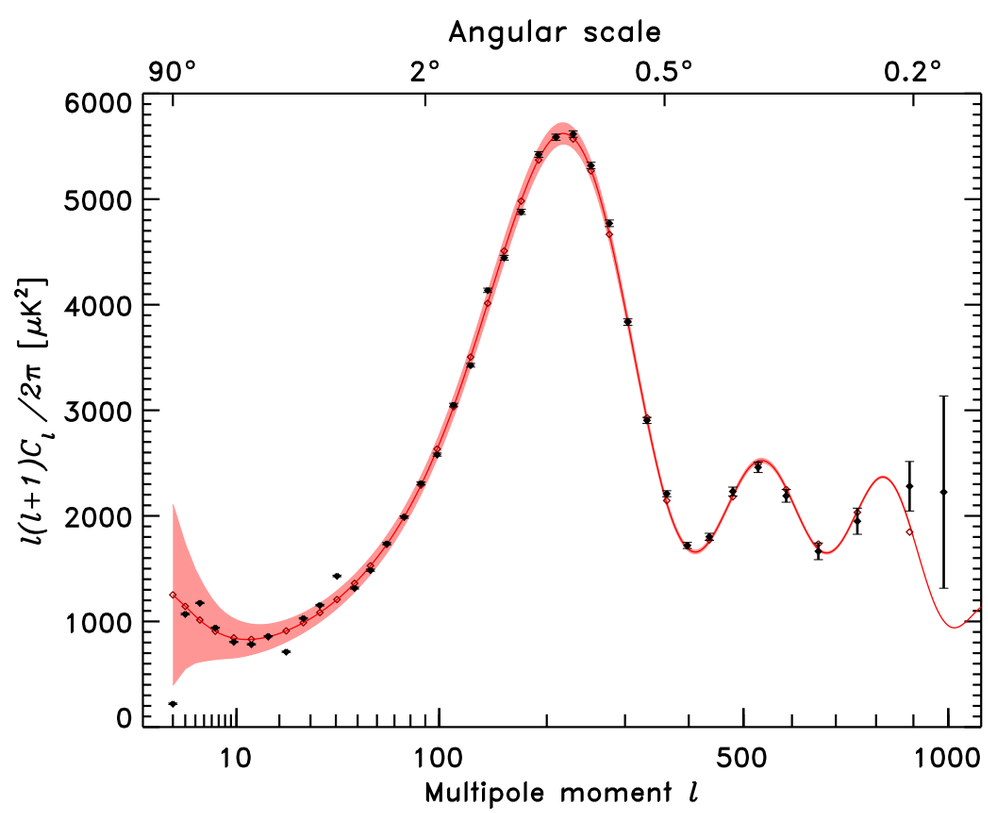

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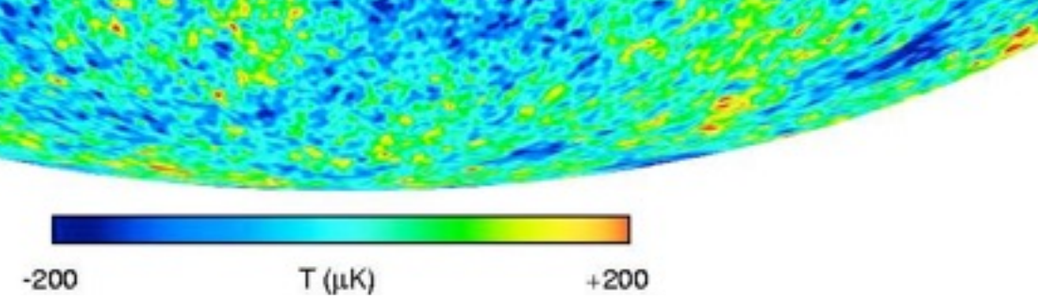
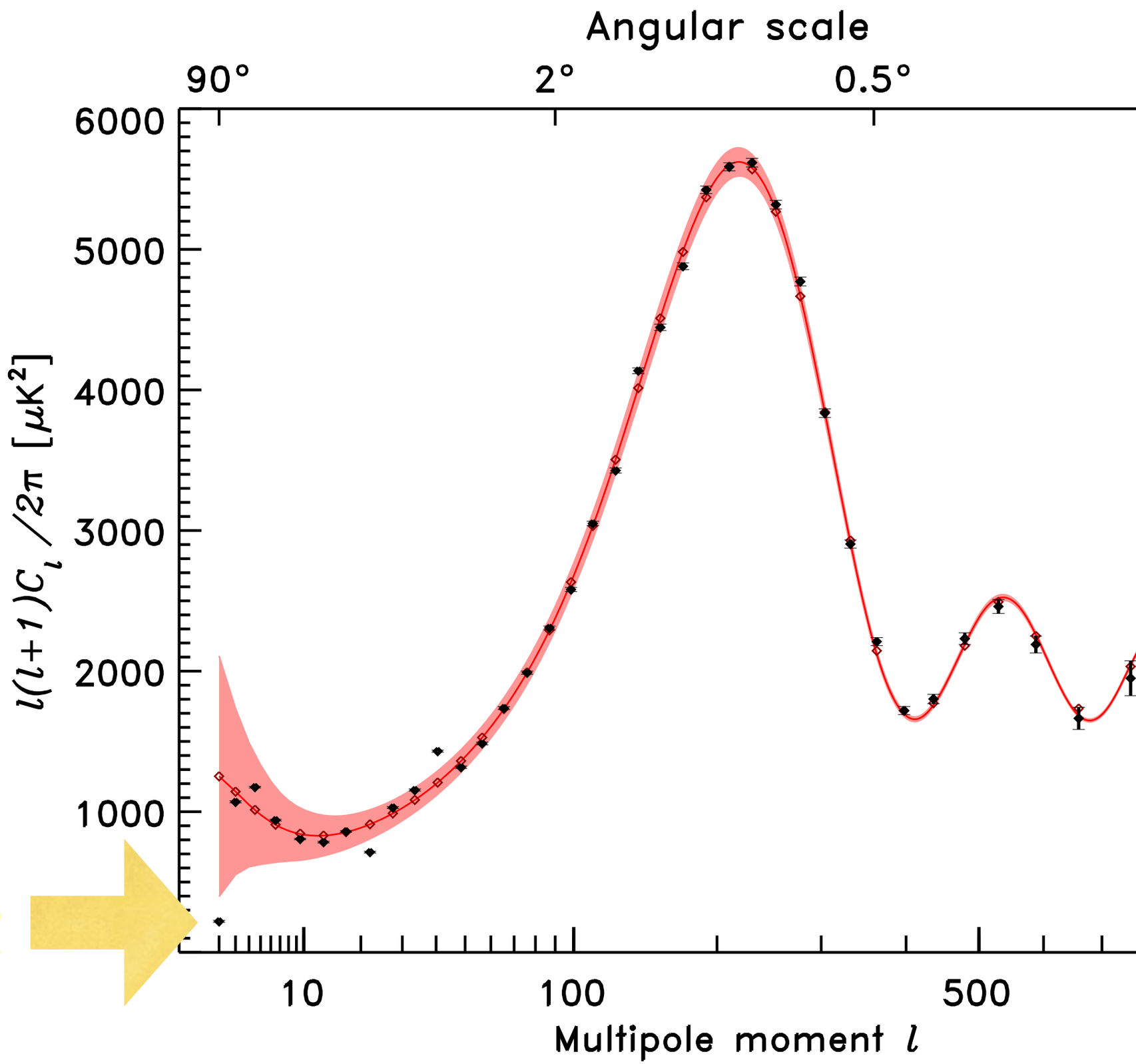
  - dark energy

1% tuning





what we learned

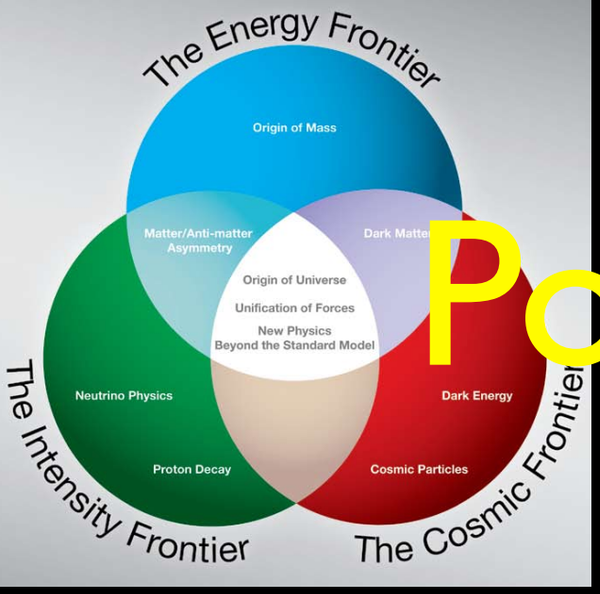
- Standard Model looks minimal
- elementary-looking spinless boson exists
- naturalness problem is real
- no sign of solution to the naturalness problem e.g., supersymmetry
- Higgs mass is too heavy for MSSM
- new physics "postponed"

$$\Delta m_h^2 = \frac{3N_c}{4\pi^2}\frac{m_t^4}{v^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

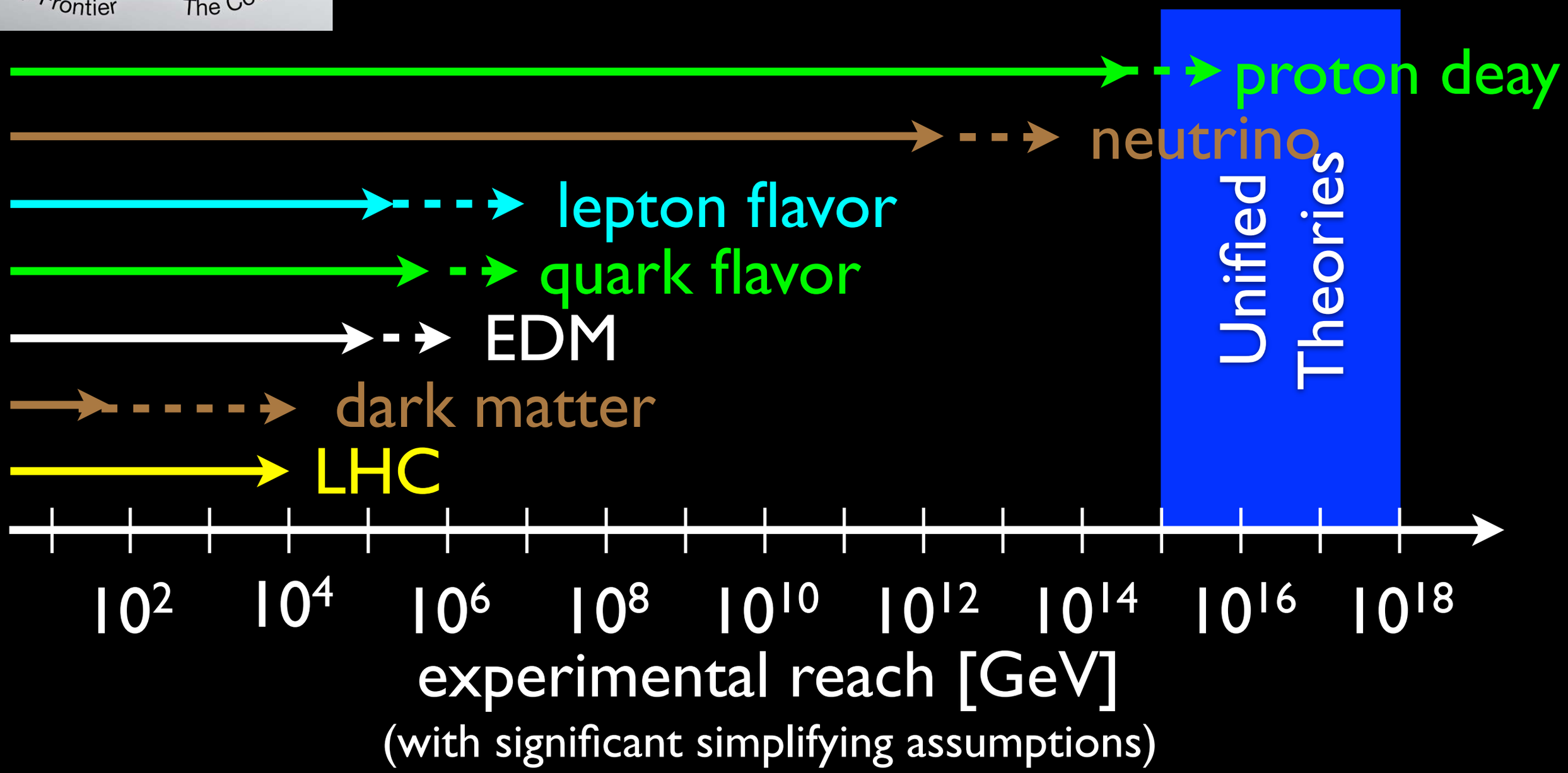
Okada, Yamaguchi, Yanagida
Ellis, Ridolfi, Zwirner
Haber, Hempfling

scalar top mass $\geq$ 10 TeV preferred

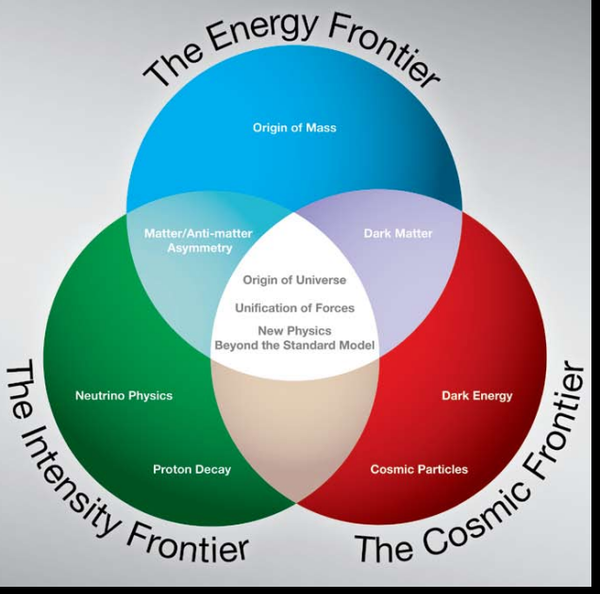
Giudice, Strumia, 1108:6077



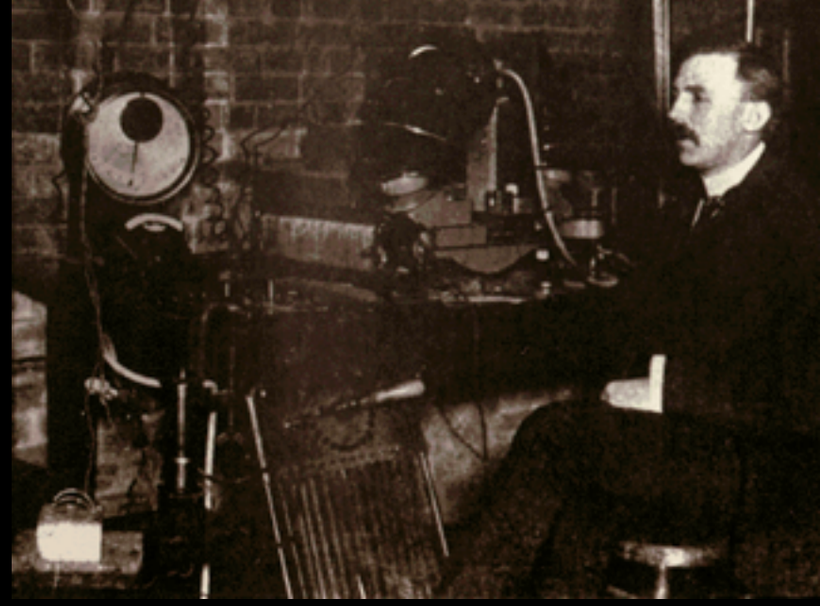
Power of Expedition



courtesy: Zoltan Ligeti

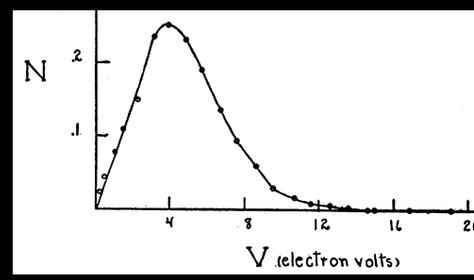


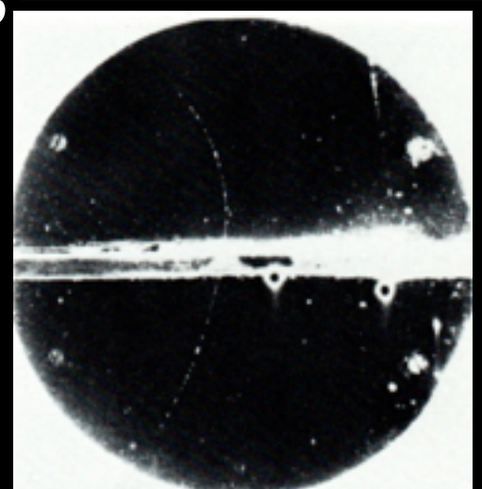
examples

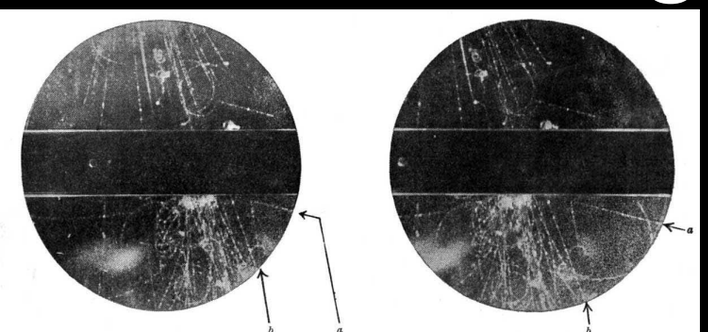


- Rutherford experiment: energy frontier
  - 10 MeV α probes < fm ⟹ nuclear size

- nuclear beta decay: rare process ⟹ 10^{-16}cm
  - changes atomic number=#protons
  - "discovered" neutrinos
- cosmic rays: anti-matter e^+, muon, pion, strangeness, parity violation







Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda},$$
$$(H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

Why is the sky blue?

- neutral atoms, if point-like, do not scatter light
- finite size, and its internal structure with charged particles, makes light scatter
- optical light does not resolve atomic size
- yet shorter-wavelength "sees" it better
- blue light scattered more than red light
- still "rare", but possible with abundant sunlight and thick atmosphere

$$\mathcal{L}_{\text{eff}} = \frac{e^2}{\Lambda^3} F_{\mu\nu} F^{\mu\nu} \psi^\dagger \psi \quad \Rightarrow \quad \sigma \propto \frac{\alpha^2}{\Lambda^6} \omega^4$$

Effective Operators

- Surprisingly difficult question
- In the case of the Standard Model
  - Weinberg (1980) on D=6 $\not{B}$, D=5 $\not{L}$
  - Buchmüller-Wyler (1986) on D=6 ops
    - 80 operators for N_f=1, B, L conserving
  - Grzadkowski et al (2010) removed redundancies and discovered one missed
    - 59 operators for N_f=1, B, L conserving
  - Mahonar et al (2013) general N_f
  - Lehman-Martin (2014,15) D=7 for general N_f, D=8 for N_f=1 (incorrect)

Repeating this at order ϵ^6 we obtain the Hilbert series for dimension-six operators of the SM EFT:

$$
\begin{aligned}
\widehat{H}_6 \;&= H^3 H^{\dagger\,3} + u^\dagger Q^\dagger H H^{\dagger\,2} + 2Q^2 Q^{\dagger\,2} + Q^{\dagger\,3} L^\dagger + Q^3 L + 2QQ^\dagger LL^\dagger + L^2 L^{\dagger\,2} + uQH^2 H^\dagger \\
&+ 2uu^\dagger QQ^\dagger + uu^\dagger LL^\dagger + u^2 u^{\dagger\,2} + e^\dagger u^\dagger Q^2 + e^\dagger L^\dagger H^2 H^\dagger + 2e^\dagger u^\dagger Q^\dagger L^\dagger + eLHH^{\dagger\,2} + euQ^{\dagger\,2} \\
&+ 2euQL + ee^\dagger QQ^\dagger + ee^\dagger LL^\dagger + ee^\dagger uu^\dagger + e^2 e^{\dagger\,2} + d^\dagger Q^\dagger H^2 H^\dagger + 2d^\dagger u^\dagger Q^{\dagger\,2} + d^\dagger u^\dagger QL \\
&+ d^\dagger e^\dagger u^{\dagger\,2} + d^\dagger eQ^\dagger L + dQHH^{\dagger\,2} + 2duQ^2 + duQ^\dagger L^\dagger + de^\dagger QL^\dagger + deu^2 + 2dd^\dagger QQ^\dagger + dd^\dagger LL^\dagger \\
&+ 2dd^\dagger uu^\dagger + dd^\dagger ee^\dagger + d^2 d^{\dagger\,2} + u^\dagger Q^\dagger H^\dagger G_R + d^\dagger Q^\dagger H G_R + HH^\dagger G_R^2 + G_R^3 + uQHG_L \\
&+ dQH^\dagger G_L + HH^\dagger G_L^2 + G_L^3 + u^\dagger Q^\dagger H^\dagger W_R + e^\dagger L^\dagger H W_R + d^\dagger Q^\dagger H W_R + HH^\dagger W_R^2 + W_R^3 \\
&+ uQHW_L + eLH^\dagger W_L + dQH^\dagger W_L + HH^\dagger W_L^2 + W_L^3 + u^\dagger Q^\dagger H^\dagger B_R + e^\dagger L^\dagger H B_R \\
&+ d^\dagger Q^\dagger H B_R + HH^\dagger B_R W_R + HH^\dagger B_R^2 + uQHB_L + eLH^\dagger B_L + dQH^\dagger B_L + HH^\dagger B_L W_L \\
&+ HH^\dagger B_L^2 + 2QQ^\dagger HH^\dagger \mathcal{D} + 2LL^\dagger HH^\dagger \mathcal{D} + uu^\dagger HH^\dagger \mathcal{D} + ee^\dagger HH^\dagger \mathcal{D} + d^\dagger uH^2 \mathcal{D} + du^\dagger H^{\dagger\,2} \mathcal{D} \\
&+ dd^\dagger HH^\dagger \mathcal{D} + 2H^2 H^{\dagger\,2} \mathcal{D}^2 \,. \qquad (3.16)
\end{aligned}
$$

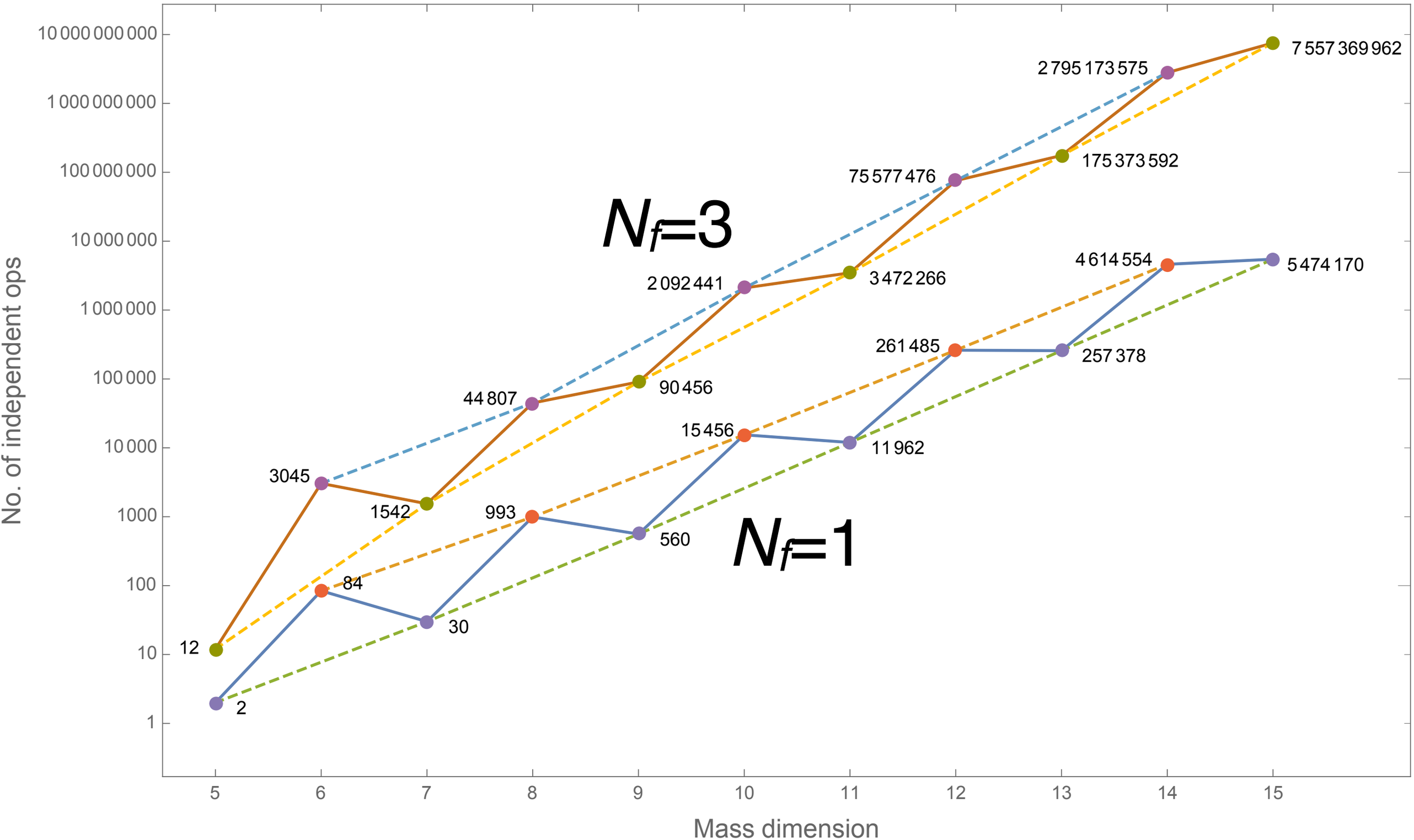
Setting all of the spurions equal to unity gives $\widehat{H}_6 = 84$, the total number of independent local operators at dimension 6, but more information is contained in eq.(3.16). For instance, the counting can easily be further decomposed by baryon number violation, $76 + 8$. The perhaps more familiar '$59 + 4$' counting is one in which hermitian conjugates of fermionic operators are not counted separately (such counting can of course also be obtained from eq. (3.16)).

Main idea

Brian Henning, Xiaochuan Lu, Tom Melia, HM

- Take kinetic terms as the zeroth order Lagrangian $(\partial\phi)^2,\ \bar{\psi} i \partial\!\!\!/ \psi,\ (F_{\mu\nu})^2$
- Classically, it is conformally invariant under SO(4,2)≃SO(6,$\mathbb{C}$)
- Operator-State correspondence tells us that operators fall into representations of the conformal group
  - equation of motion: short multiplets
  - remove total derivatives: primary states

$$H(\mathcal{D},\phi_1,\cdots,\phi_n)=\int d\mu_{\rm conf}d\mu_{\rm gauge}\sum_k \mathcal{D}^k\chi^*_{\Delta_0+k,0}PE\left[\frac{\phi_1}{\mathcal{D}^{d_1}}\chi_1\right]\cdots PE\left[\frac{\phi_n}{\mathcal{D}^{d_n}}\chi_n\right]$$


No. of independent ops
10 000 000 000
1 000 000 000
100 000 000
10 000 000
1 000 000
100 000
10 000
1000
100
10
1
5
6
7
8
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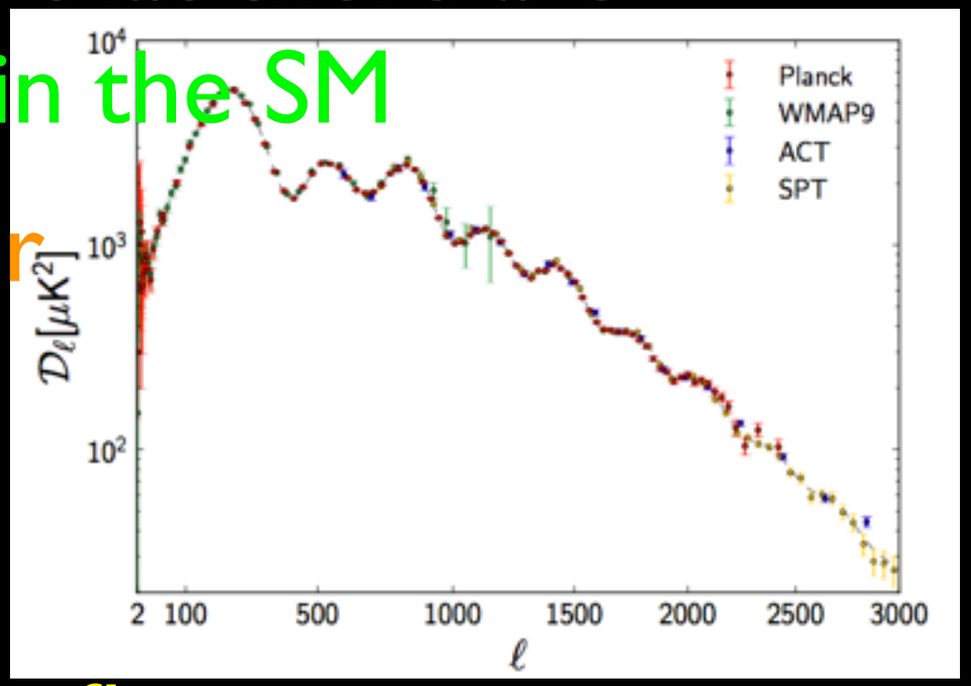
12
13
14
15
Mass dimension
N_f=3
N_f=1
7 557 369 962
2 795 173 575
175 373 592
75 577 476
3 472 266
2 092 441
90 456
44 807
3045
1542
12
4 614 554
5 474 170
261 485
257 378
15 456
11 962
993
560
84
30
2

origin of flavor:
important on its own

Five evidences for physics beyond SM

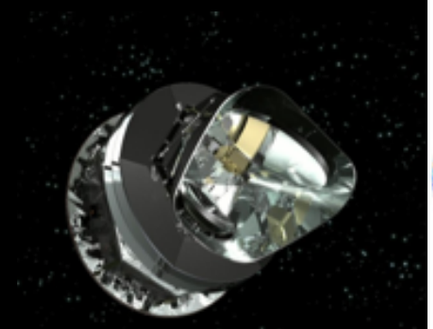
- Since 1998, it became clear that there are at least five missing pieces in the SM

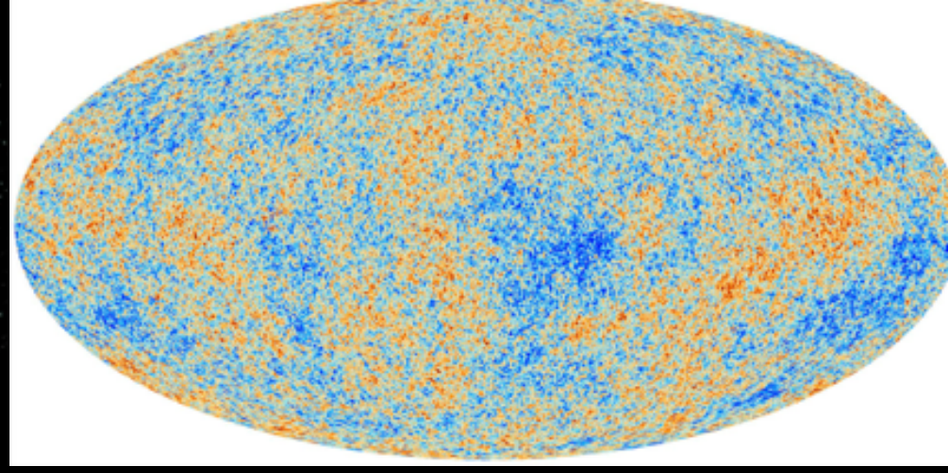


- non-baryonic dark matter
- neutrino mass
- dark energy
- apparently acausal density fluctuations
- baryon asymmetry

We don't really know their energy scales...

Puzzle is sharpened


Planck



- with success of inflation, it can't be the initial condition of the Universe
- Kobayashi and Maskawa phase can only explain $\eta_b \approx \alpha_W^5 J \approx 10^{-27}$
- new sources of CPV are needed
- we also need to see how anti-matter can turn into matter

quark sector: LHCb, SuperKEKB, rare kaon decays
lepton sector: CPV in neutrinos, $0\nu\beta\beta$, LFV
both sectors: proton decay

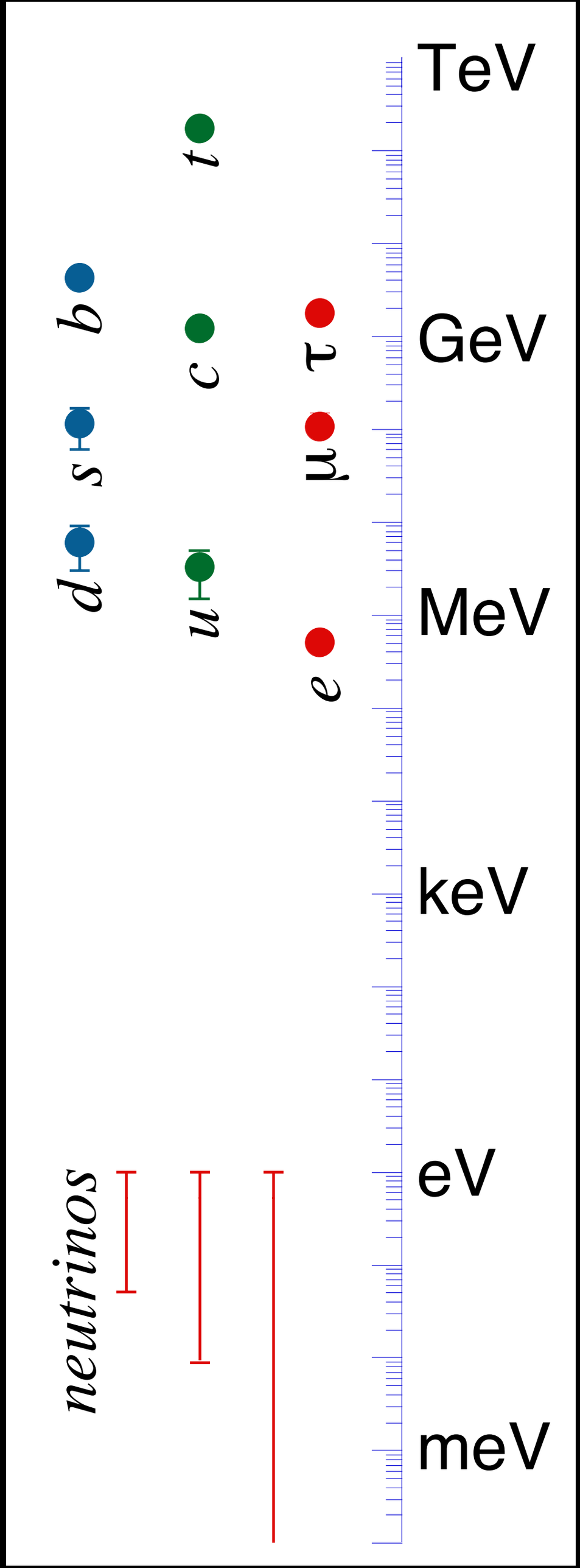
Great Flavor Questions

- Why are there three generations?
- What physics determines the pattern of masses and mixings?
- What is the origin of CP violation?
- What is the origin of matter anti-matter asymmetry in Universe?

How exactly are we trying to answer these questions?

Strategy

1. Look for small deviations from the standard CKM
2. Identify their patterns and symmetry structure
3. Figure out dynamics behind the new symmetry


TeV
GeV
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t
b
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s
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d
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e
neutrinos

Question of Flavor

- What distinguishes different generations?
  - Same gauge quantum numbers, yet different
- Hierarchy with small mixings:

  $\Rightarrow$ Need some ordered structure
- Probably a hidden *flavor quantum number*

  $\Rightarrow$ Need flavor symmetry
  - Flavor symmetry must allow top Yukawa~O(1)
  - Other Yukawas forbidden
  - Small symmetry breaking generates small Yukawas and small mixings

Flavor Symmetry: simple example

- Flavor quantum numbers (SU(5)-ish):
  - 10(Q, u_R, e_R) (+2, +1, 0)
  - 5^*(L, d_R) (+1, +1, +1)
  - U(1) symmetry broken by $\varepsilon(-1)\sim 0.07$

$$Y_u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} \quad Y_d \sim \begin{pmatrix} \epsilon^3 & \epsilon^3 & \epsilon^3 \\ \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon & \epsilon \end{pmatrix} \quad Y_l \sim \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^3 & \epsilon^2 & \epsilon \end{pmatrix}$$

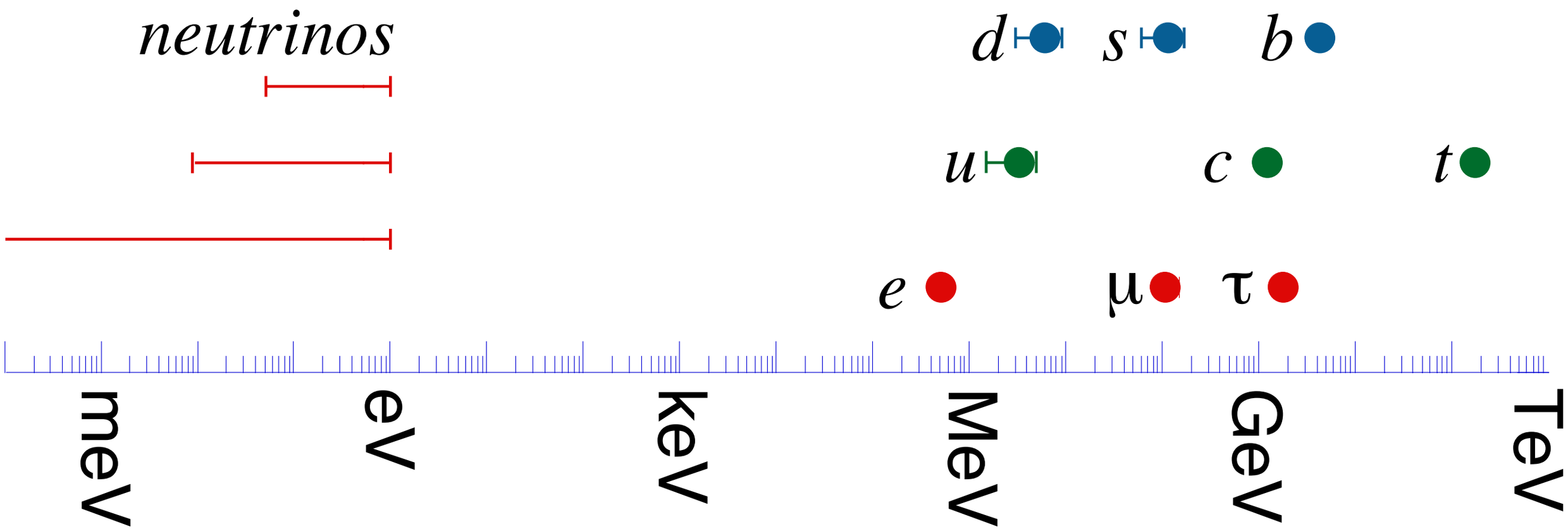
  - $m_u:m_c:m_t \sim m_d^2:m_s^2:m_b^2 \sim m_e^2:m_\mu^2:m_\tau^2$
  - $m_d \sim m_e$, $m_s \sim m_\mu$, $m_b \sim m_\tau$

(Haba, HM)

Not bad!

$$V_{CKM} \sim \begin{pmatrix} 1 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & 1 \end{pmatrix}$$

- $m_u:m_c:m_t \sim m_d^2:m_s^2:m_b^2 \sim m_e^2:m_\mu^2:m_\tau^2$
- $m_d \sim 3m_e$, $3m_s \sim m_\mu$, $m_b \sim m_\tau$



Neutrinos

- Flavor quantum numbers (SU(5)-ish):
  - 10(Q, u_R, e_R) (+2, +1, 0)
  - 5^*(L, d_R) (+1, +1, +1)
  - U(1) symmetry broken by ε(–1)~0.07

$$Y_\nu^{ij} \frac{(L_i H)(L_j H)}{M} \qquad Y_\nu \sim \epsilon^2 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

- assume O(1) constants are all random
- then we can predict the probability distribution of mixing angles

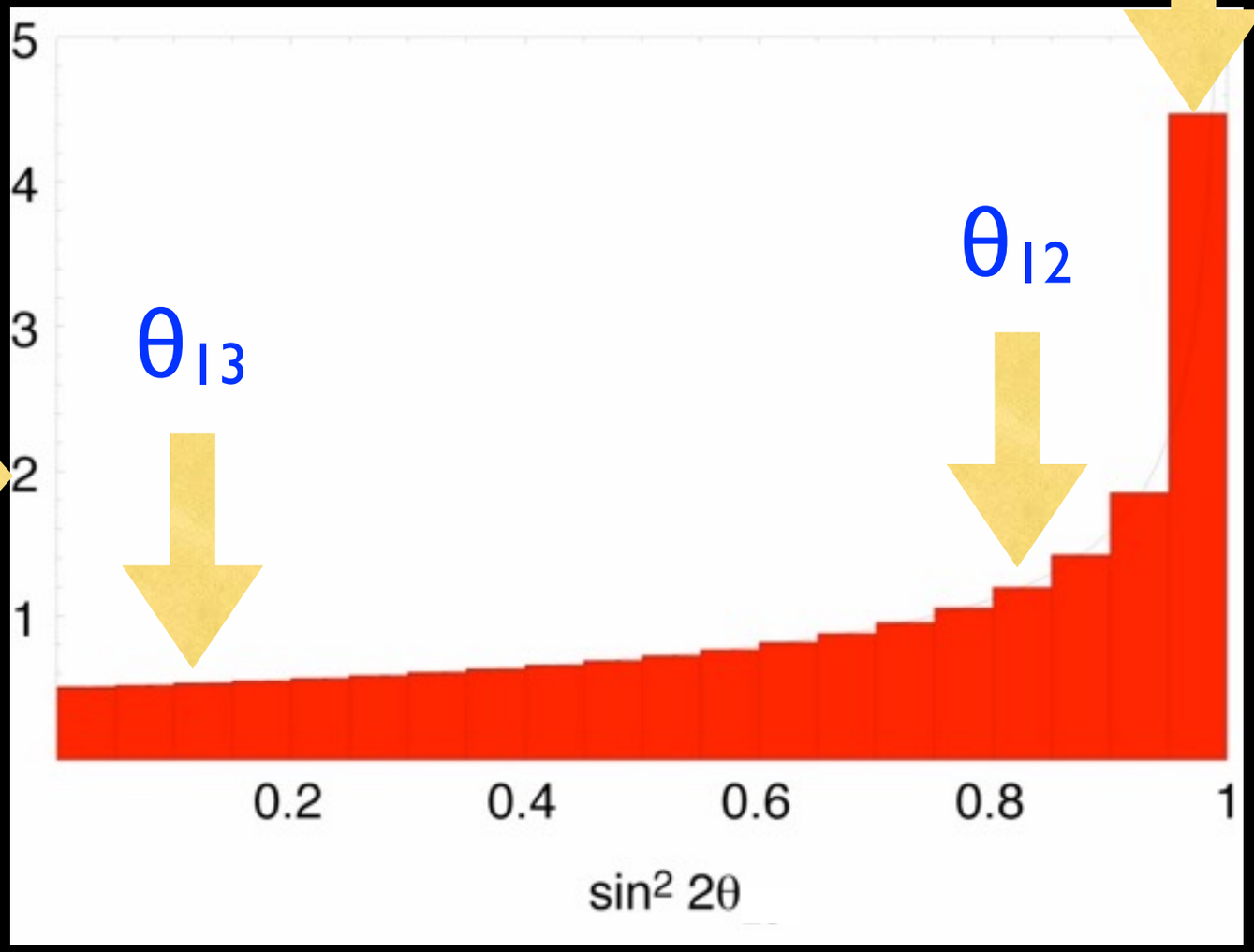
anarchy

Miriam-Webster: "*A utopian society of individuals who enjoy complete freedom without government*"

neutrinos

large mixing

symmtery



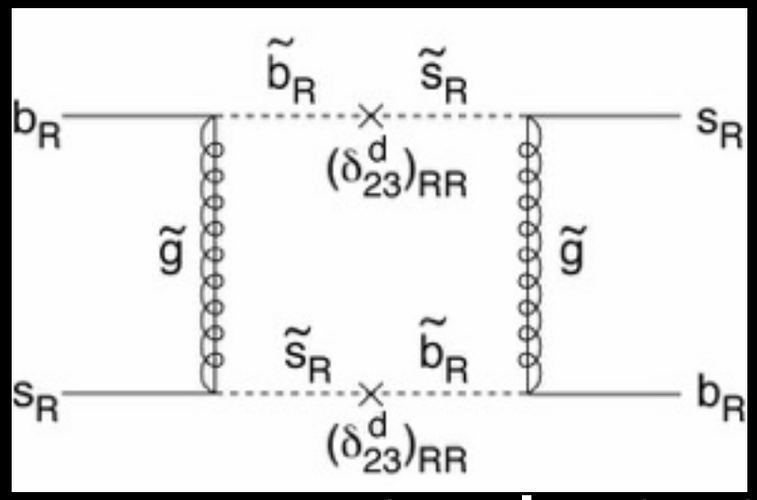
KS probability = 44%

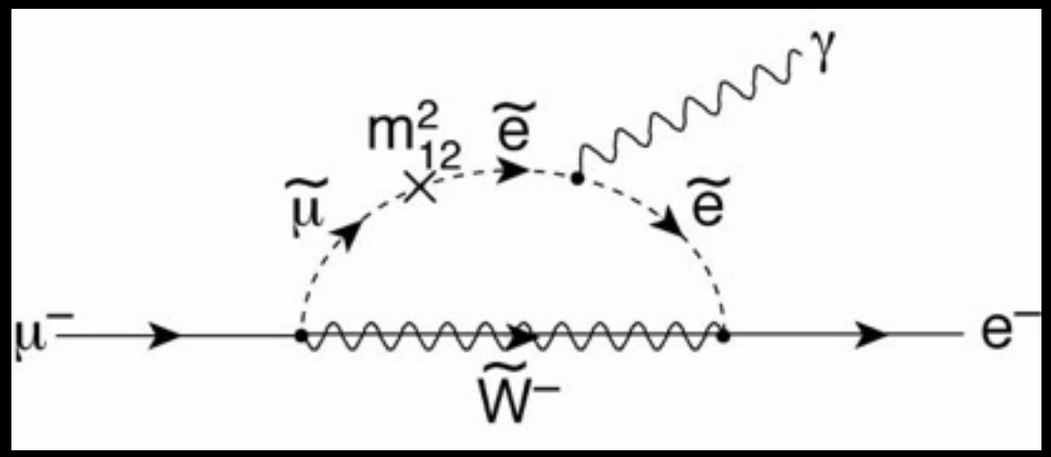
(de Gouvêa, HM)

Program: more flavor parameters

- SUSY ~ 10–100 TeV?

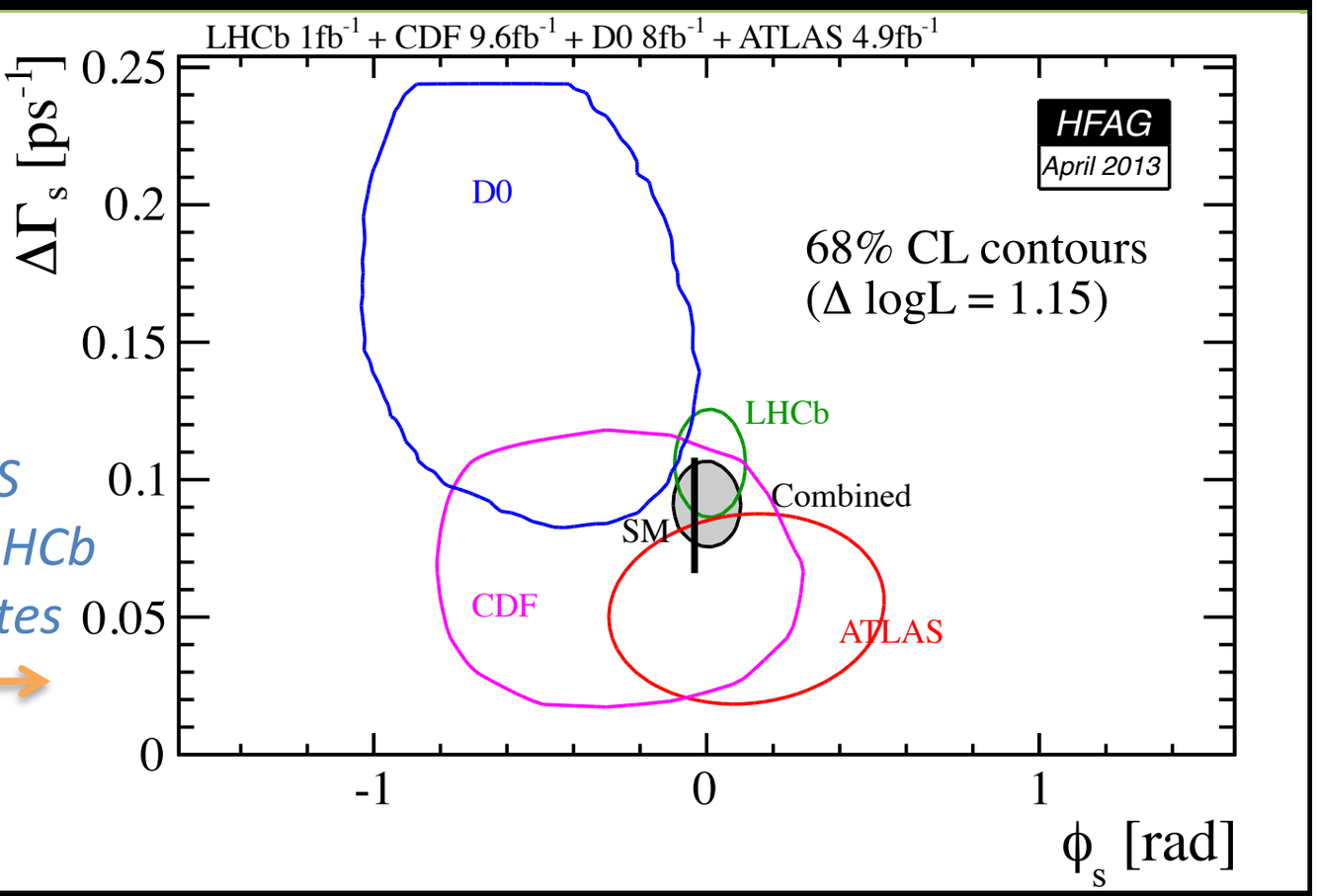
$$m^2_{\tilde{Q}} \sim m^2_{\tilde{u}} \sim m^2_{\tilde{e}} \sim m^2_0 \begin{pmatrix} 1 & \epsilon & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} \qquad m^2_{\tilde{d}} \sim m^2_{\tilde{L}} \sim m^2_0 \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

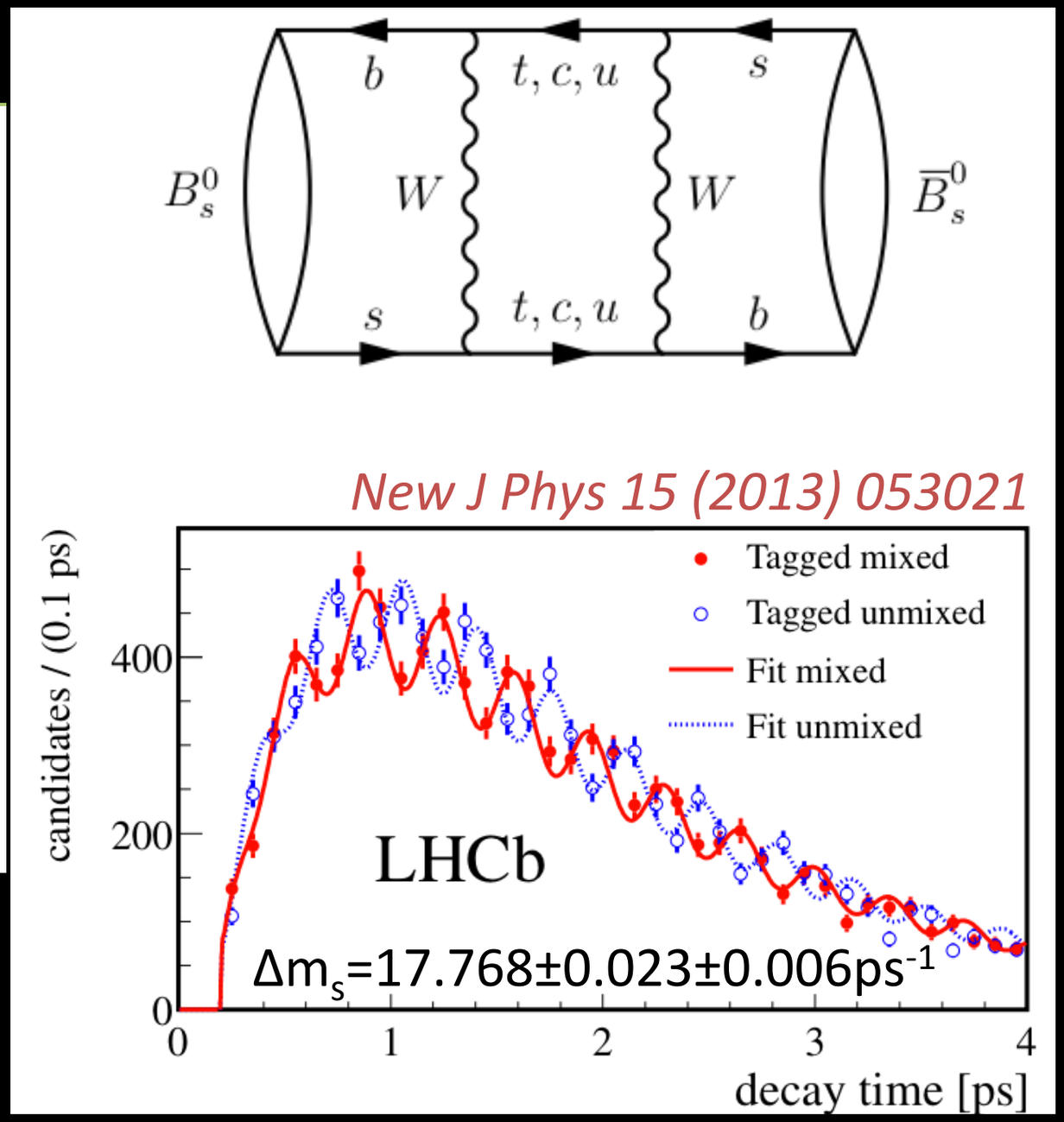




- patterns in deviation and the chirality information test flavor quantum numbers

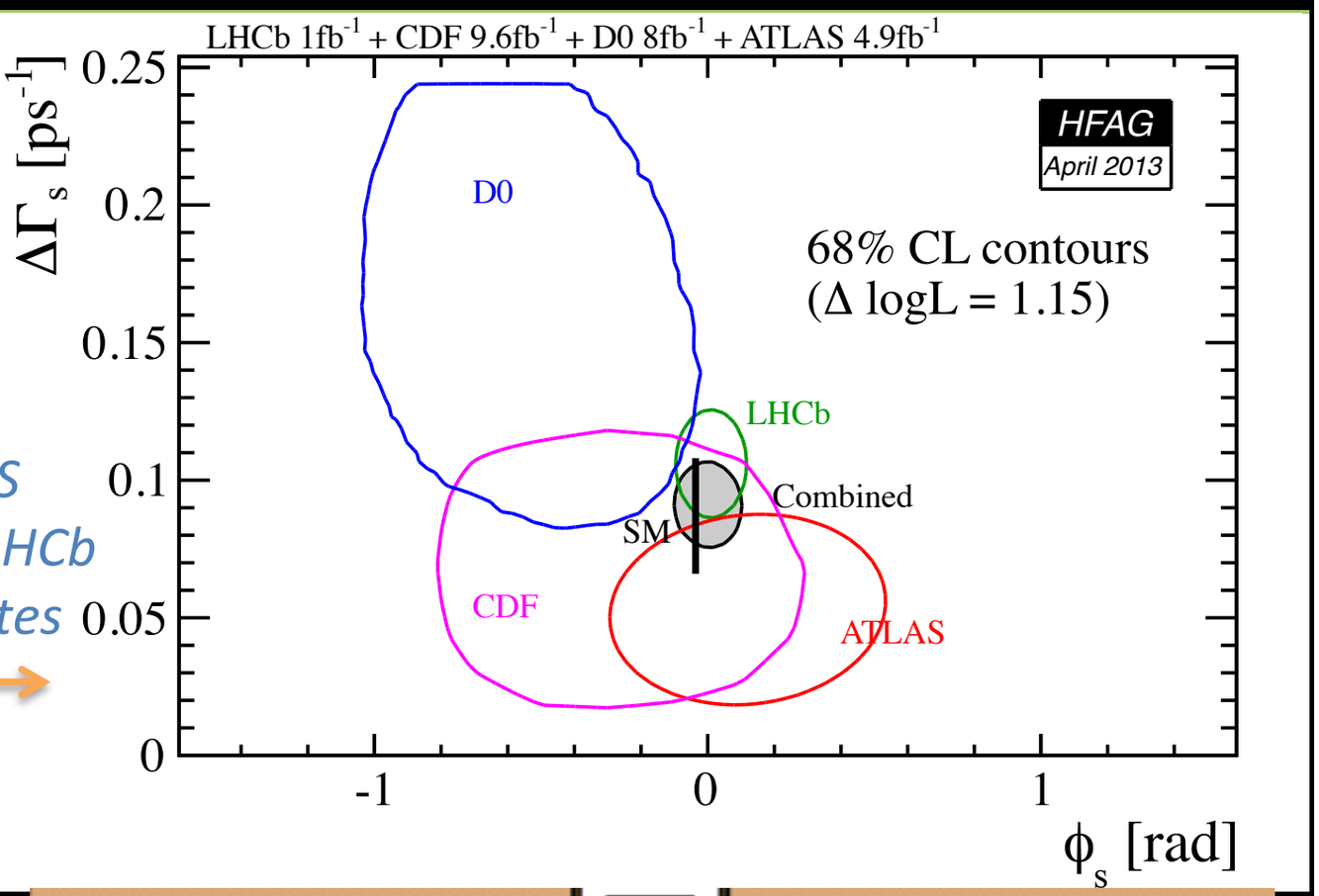
B_s: Strangely Beautiful

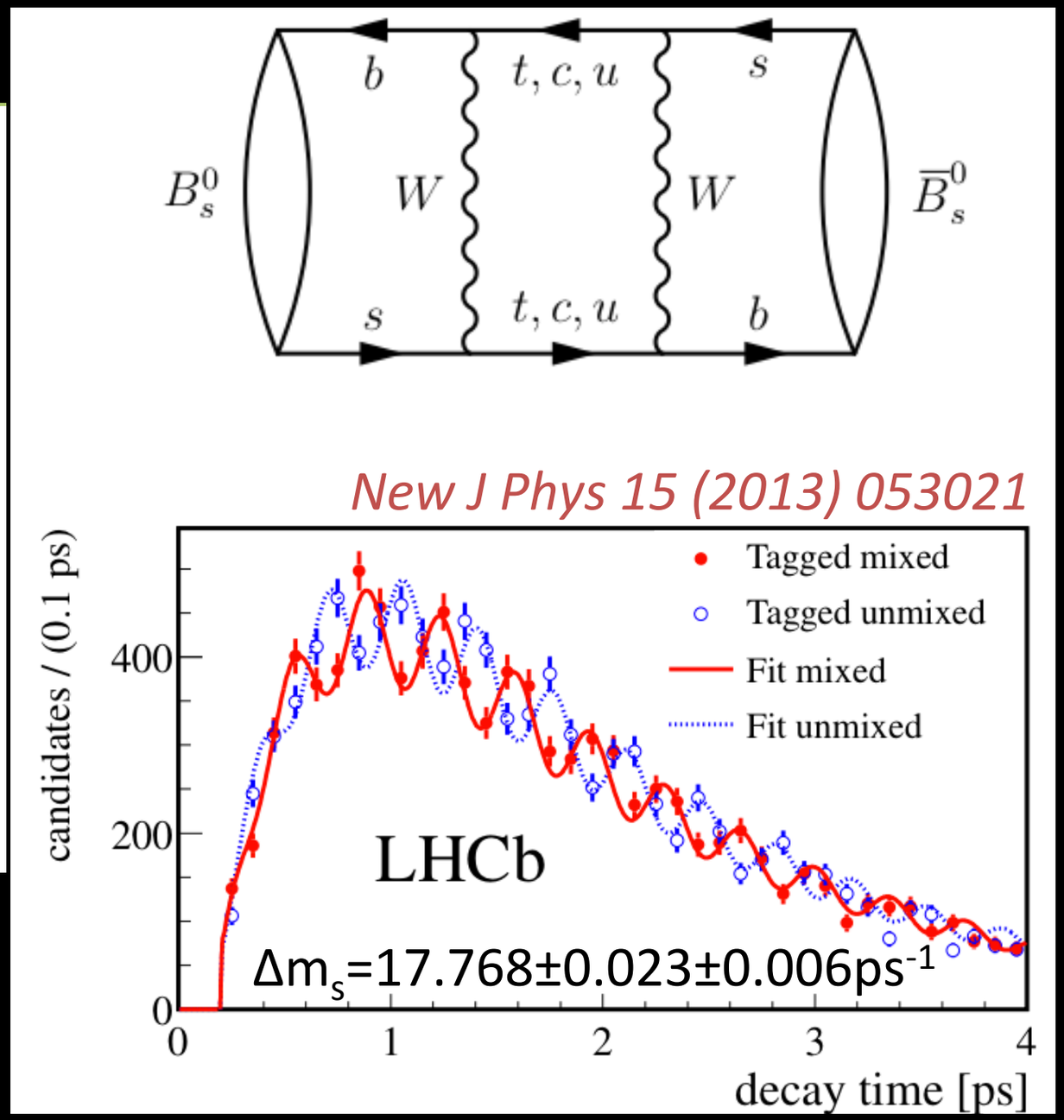




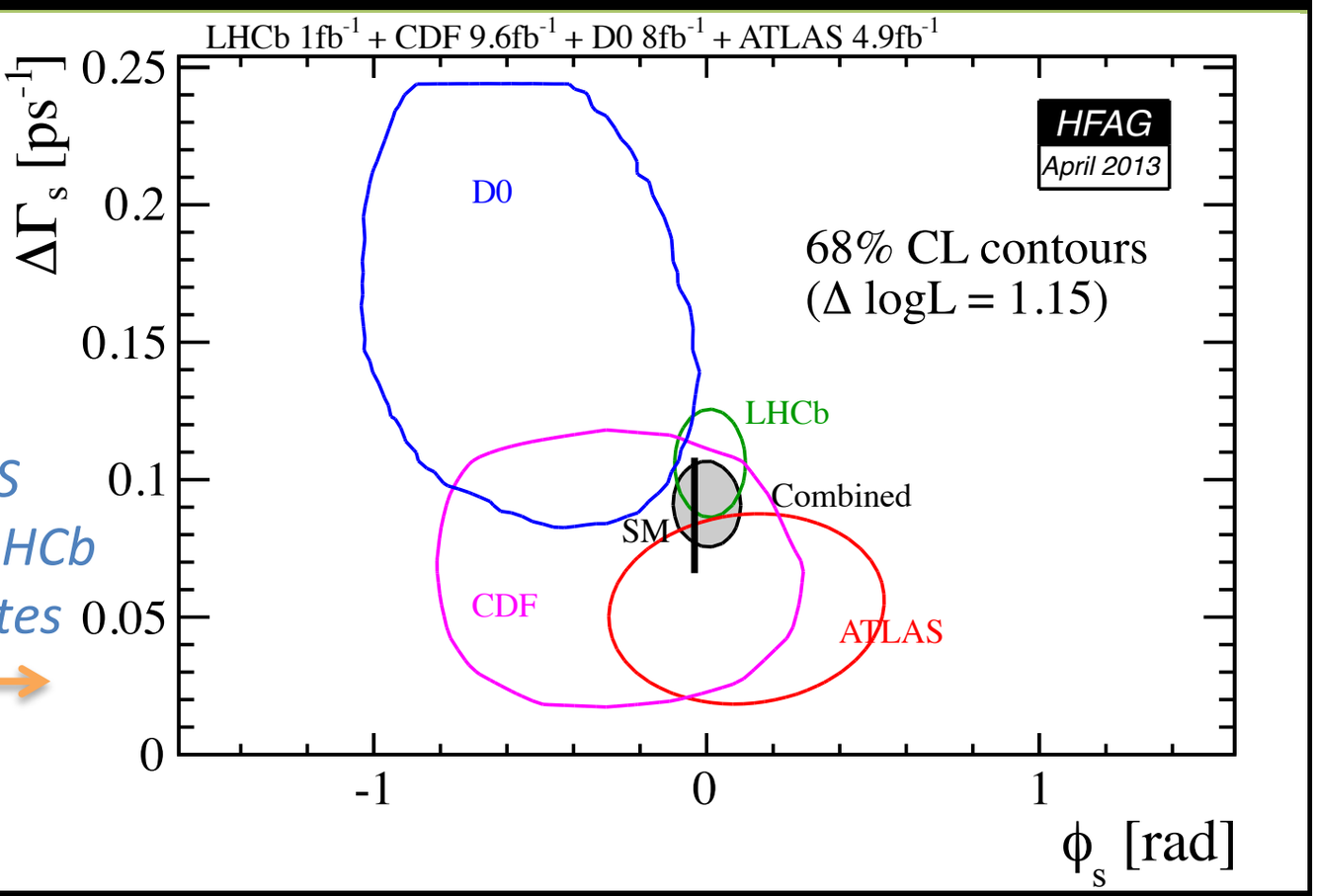
I had predicted big effects of new physics on B_s

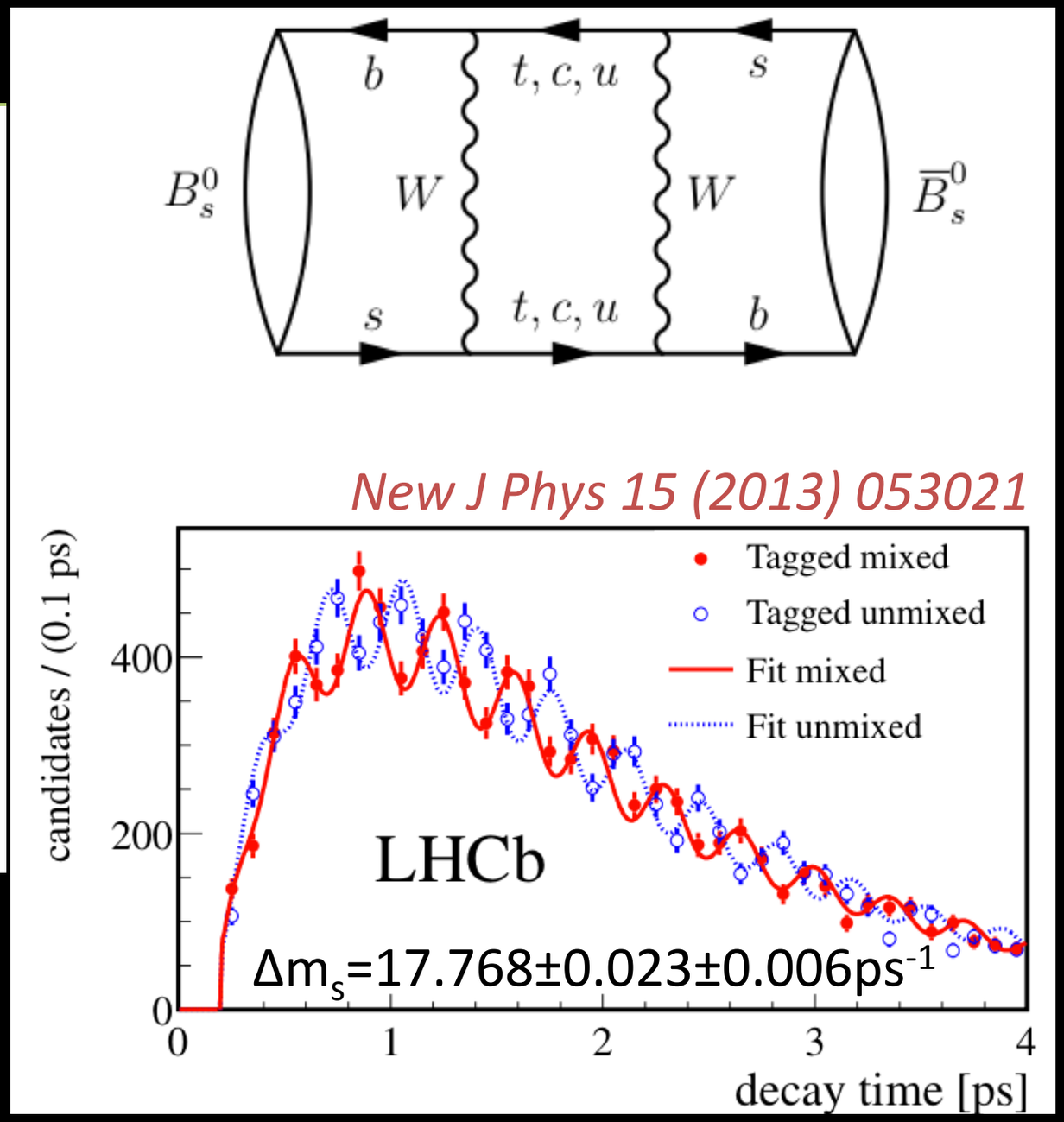
B_s: Strangely Beautiful





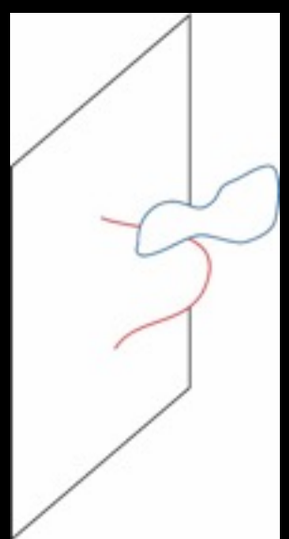
B_s: Strangely Beautiful



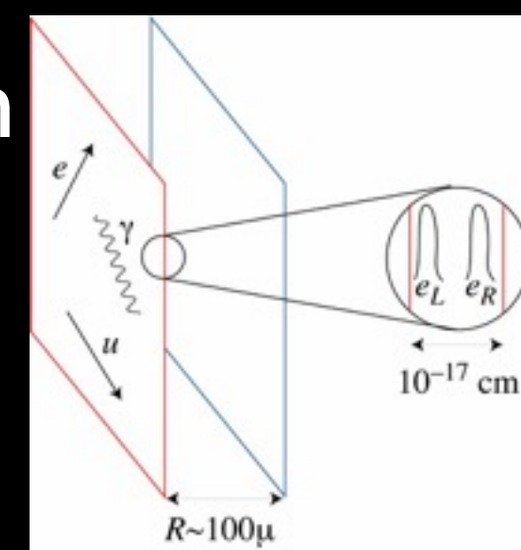


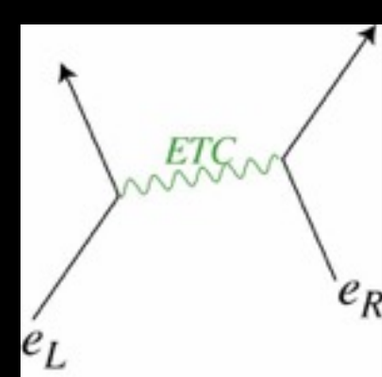
small but detectable
effects of new physics on B_s

Dynamics behind flavor symmetry?

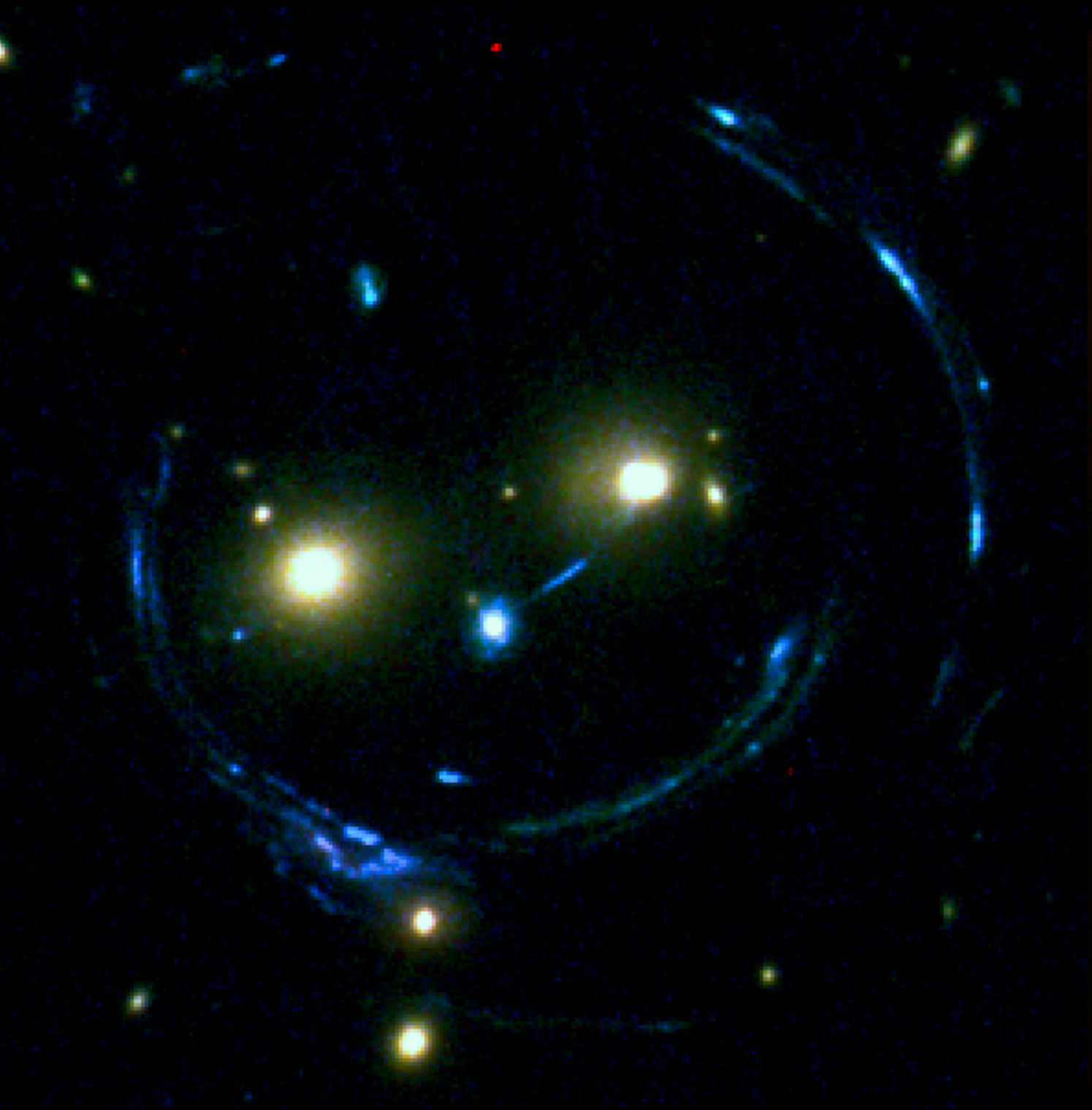


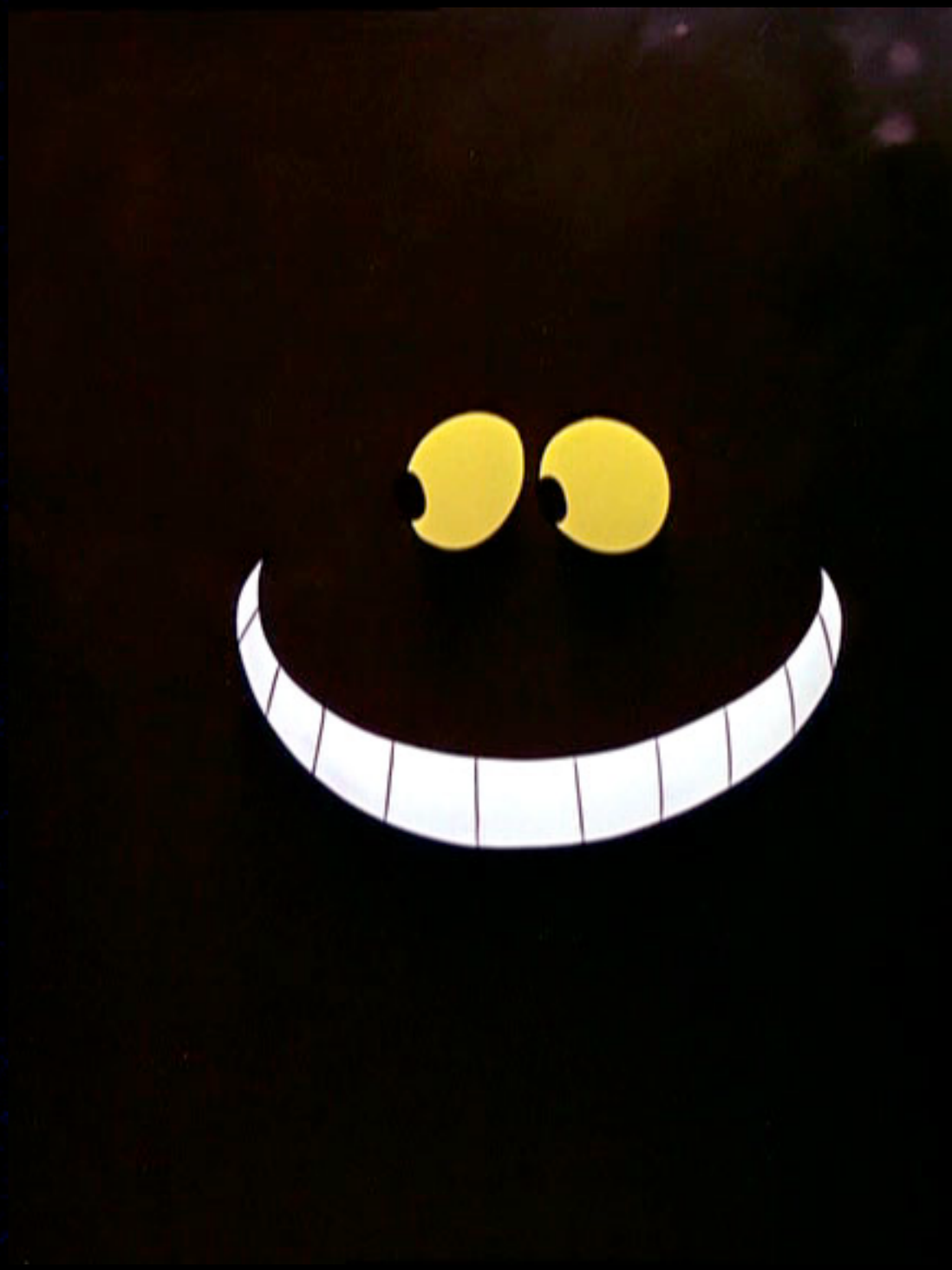
- Once flavor symmetry (e.g. SU(3)), what is the underlying dynamics (e.g. QCD)?
- Supersymmetry: anomalous U(1) from Green–Schwartz mechanism
- extra dimensions: separation of wave functions in the 5D direction
- composite Higgs: new broken flavor gauge symmetries





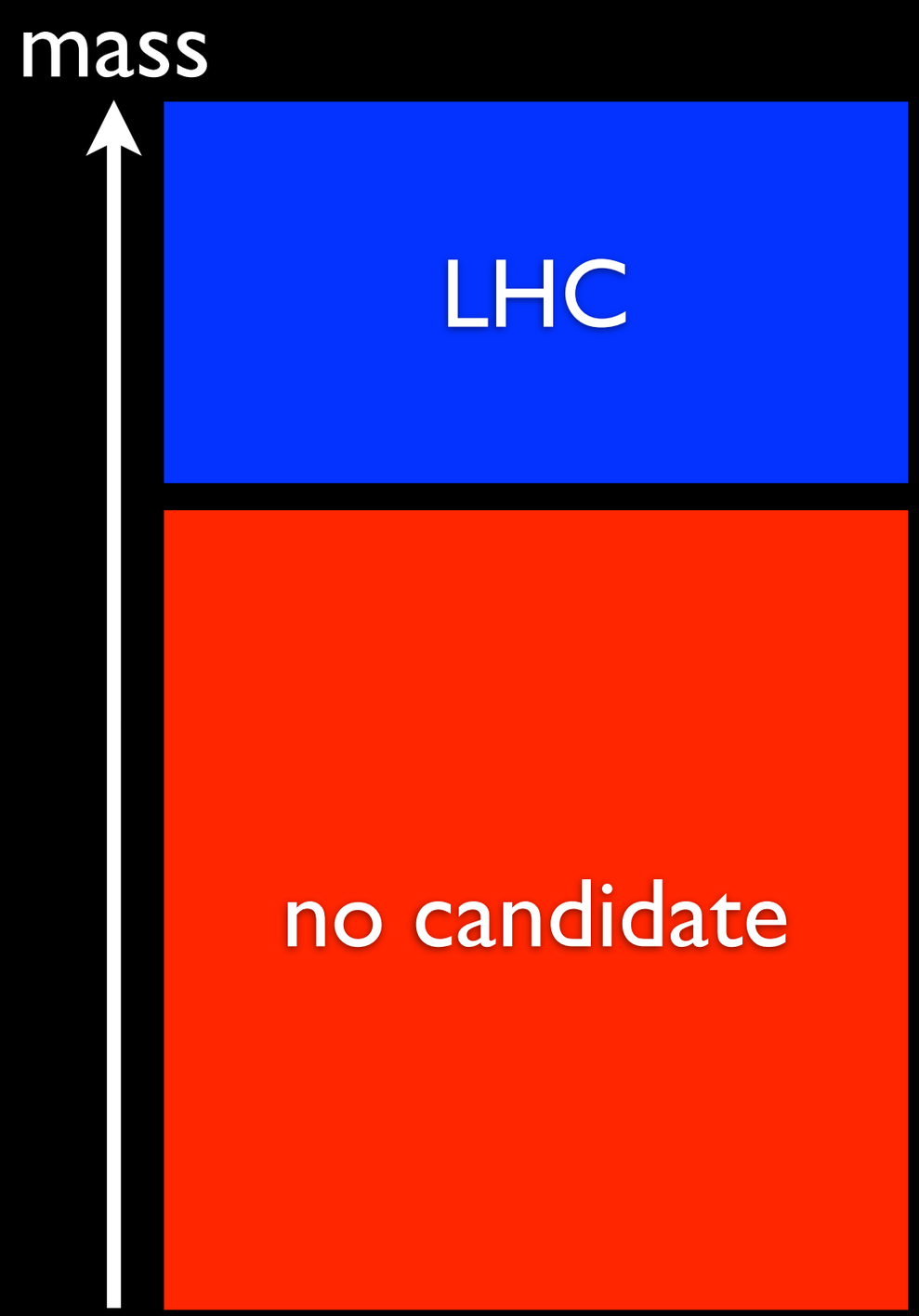
new opportunities on dark matter



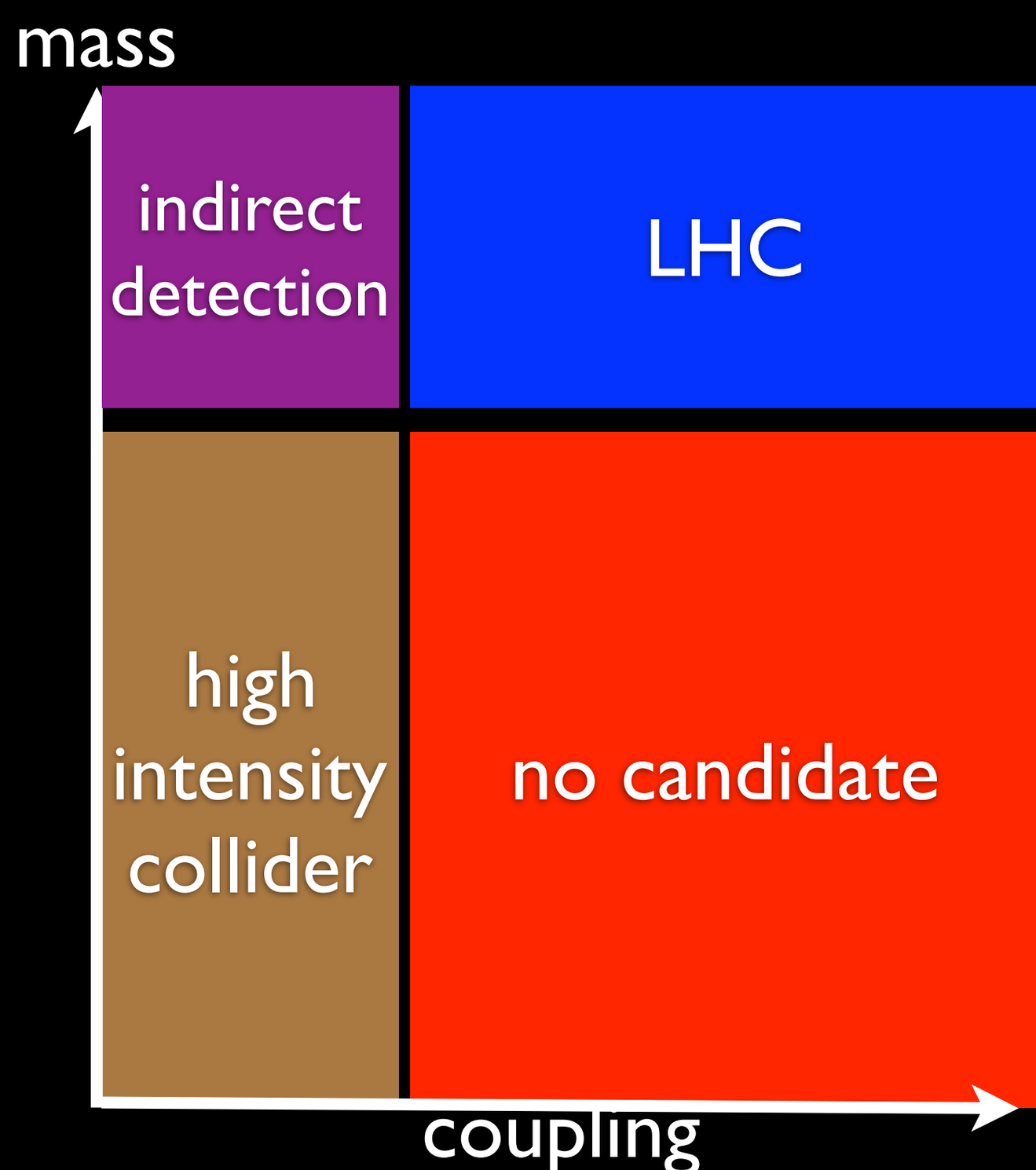


Ceshire cat

dark matter

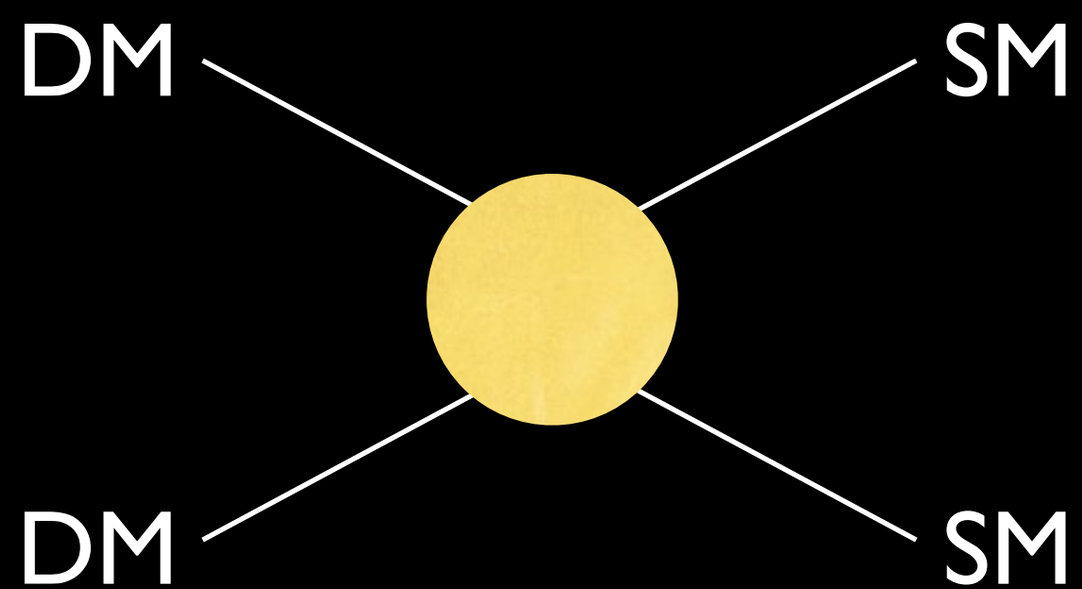


dark matter


mass
indirect detection
LHC
high intensity collider
no candidate
coupling

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10}\,\frac{\rm GeV}{m_{\rm DM}}$$

WIMP Miracle



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

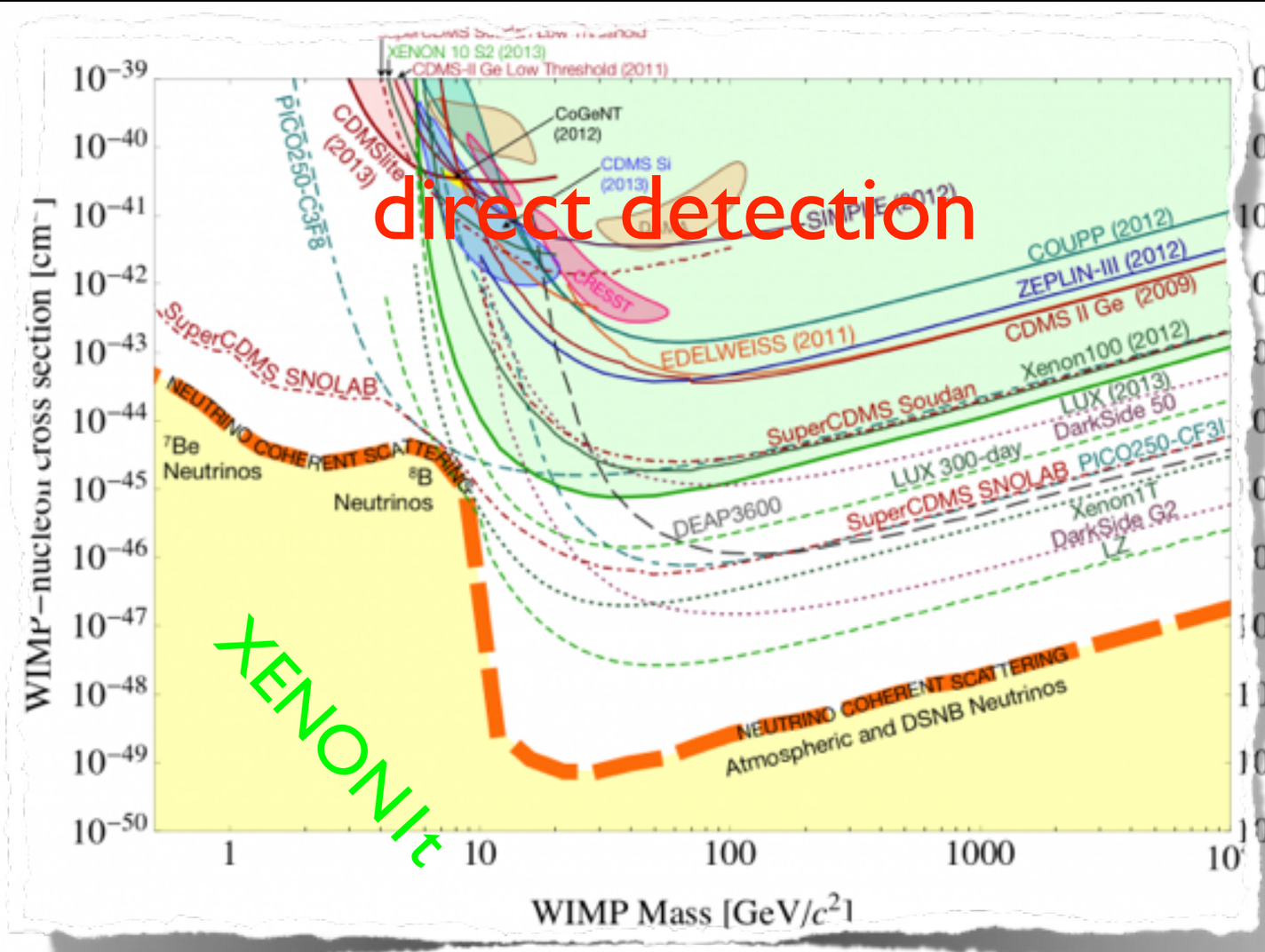
$$\alpha \approx 10^{-2}$$

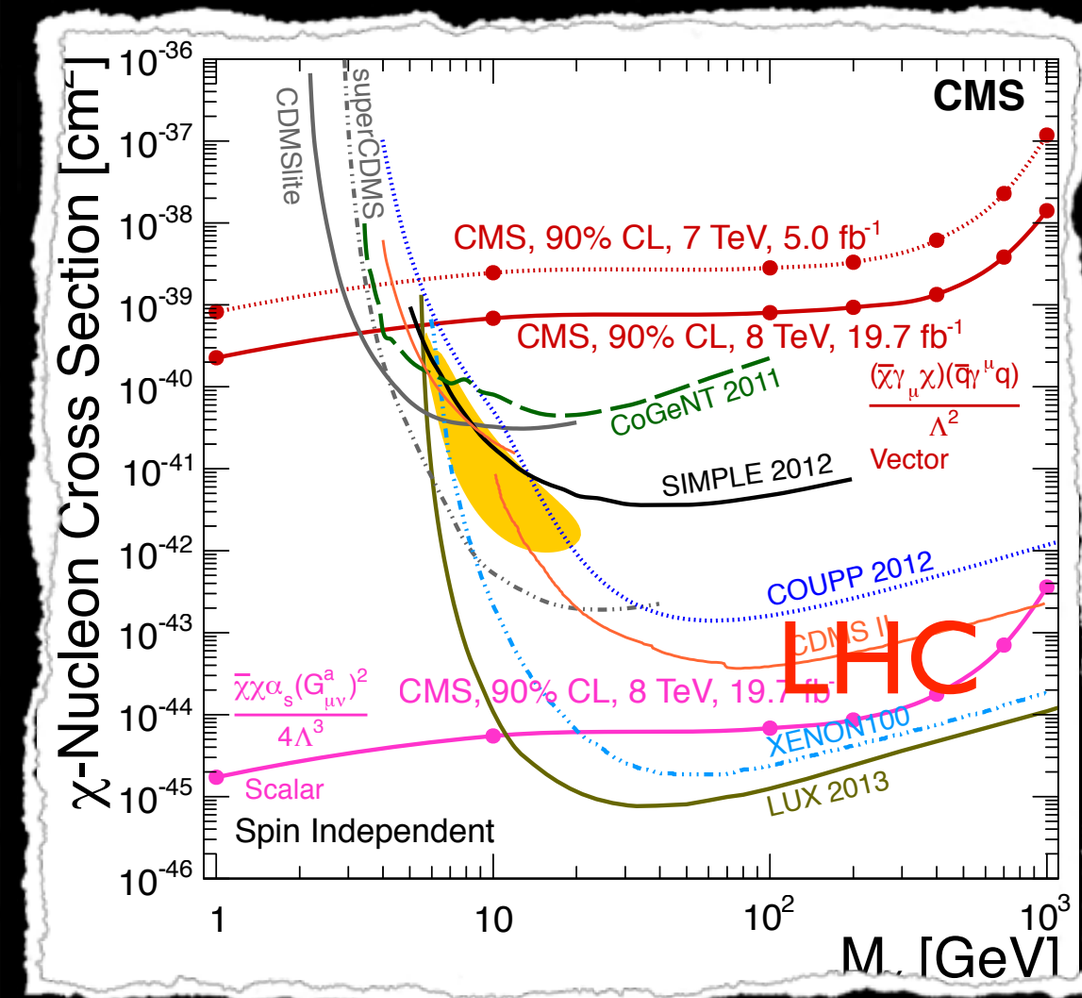
$$m \approx 300\ \text{GeV}$$

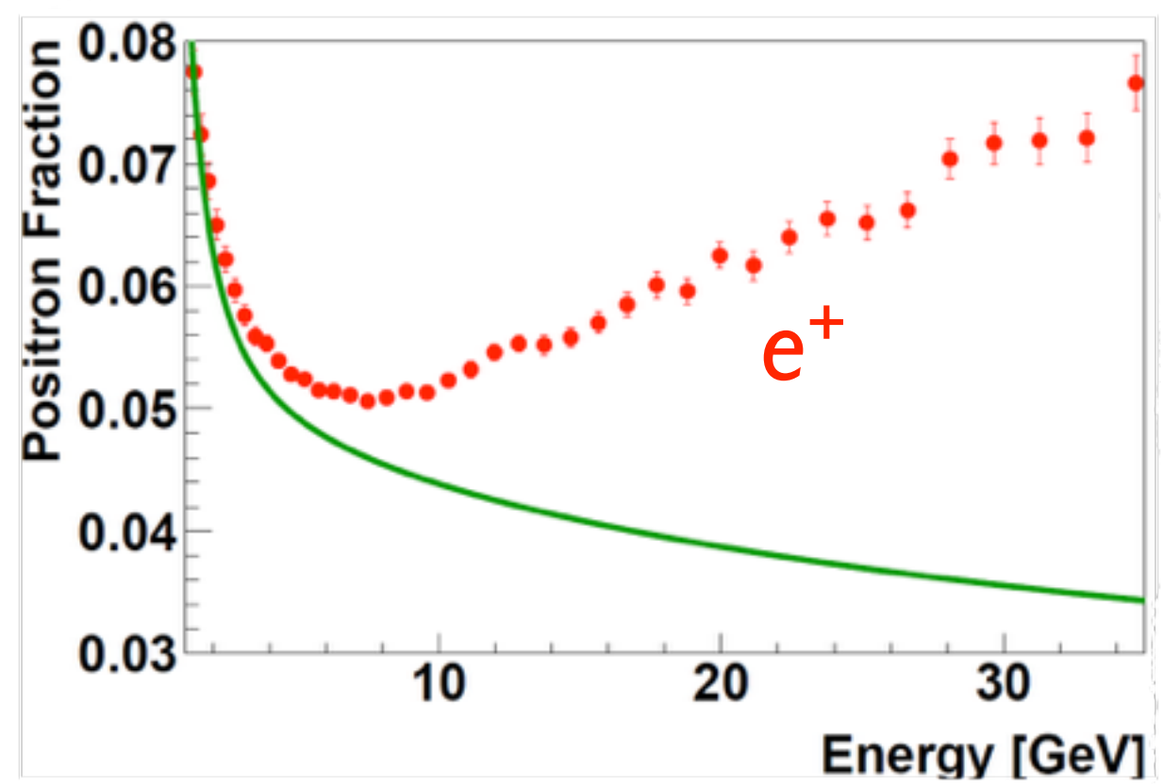
"weak" coupling
"weak" mass scale

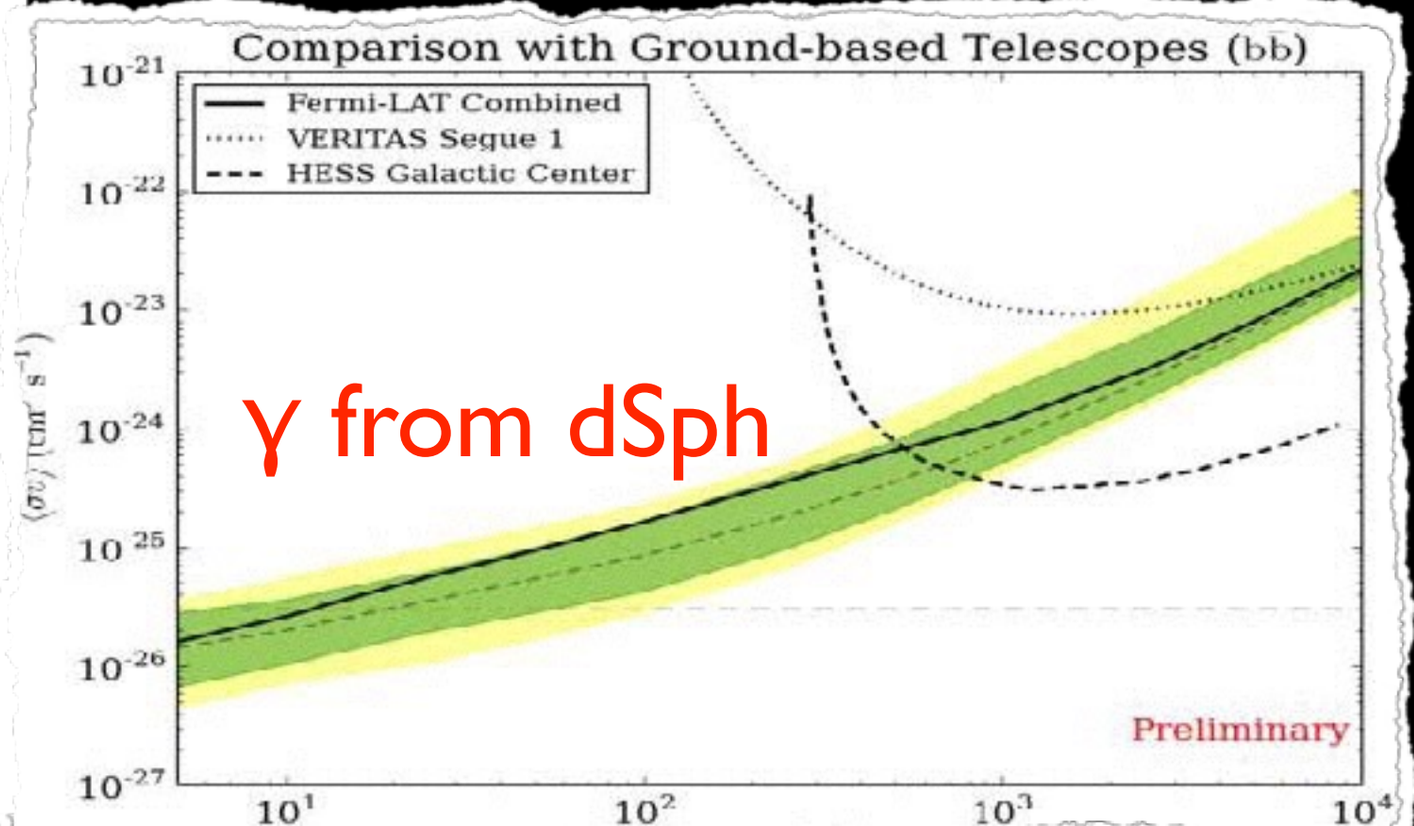
correct abundance

Miracle^2


direct detection
XENON
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS SNOLAB
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
Atmospheric and DSNB Neutrinos

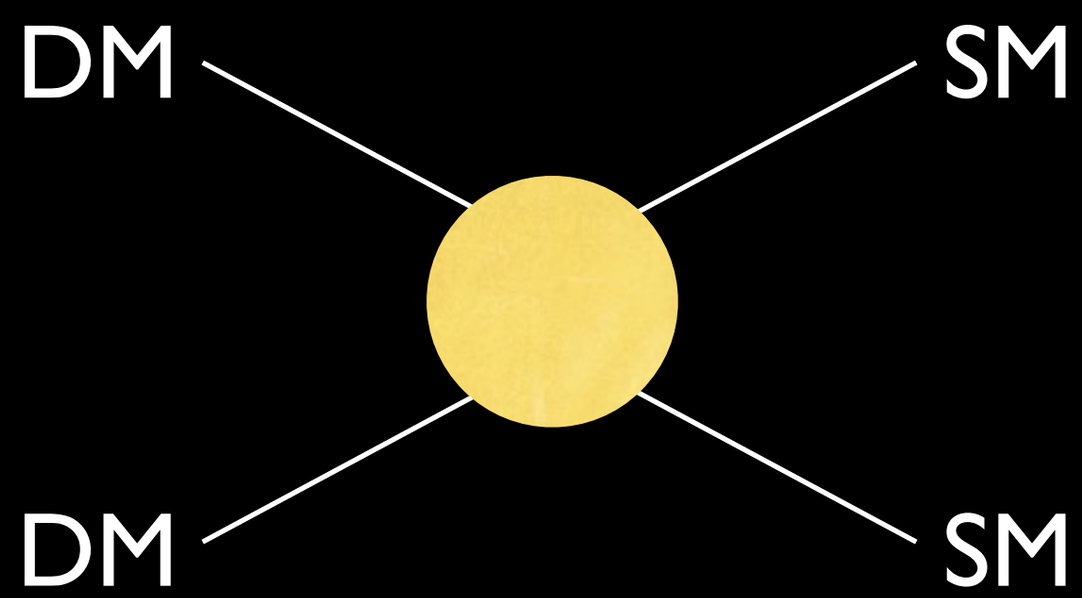

LHC
CMS
χ-Nucleon Cross Section [cm²]
M_χ [GeV]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
XENON100
LUX 2013
Vector
Scalar
Spin Independent


e⁺
Positron Fraction
Energy [GeV]


γ from dSph
Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
Preliminary

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles

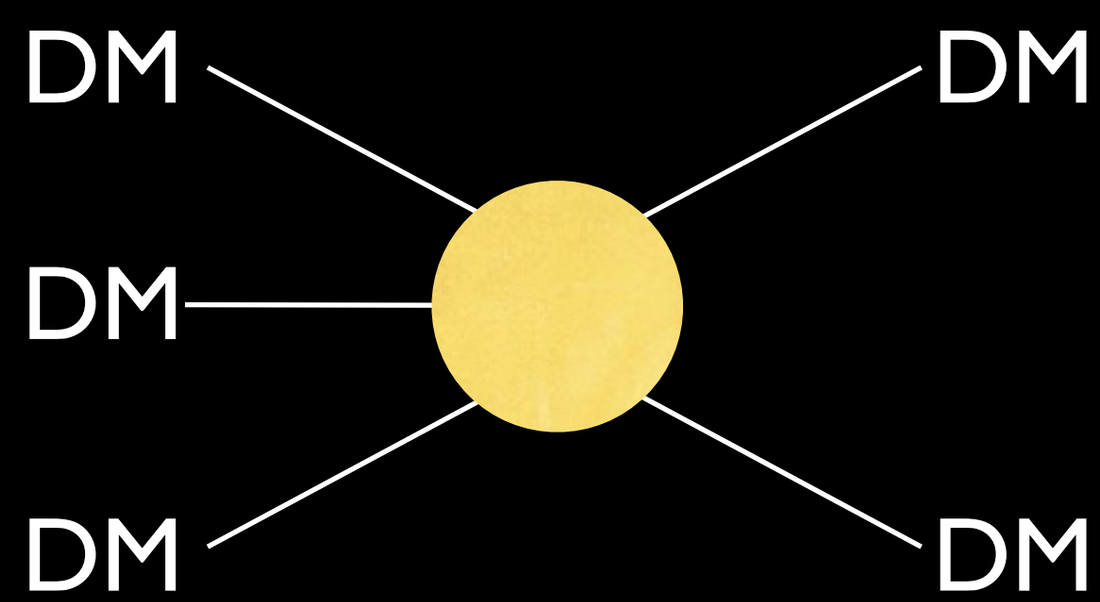


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \text{ GeV}$$

WIMP miracle!



$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

$$m \approx 300 \text{MeV}$$

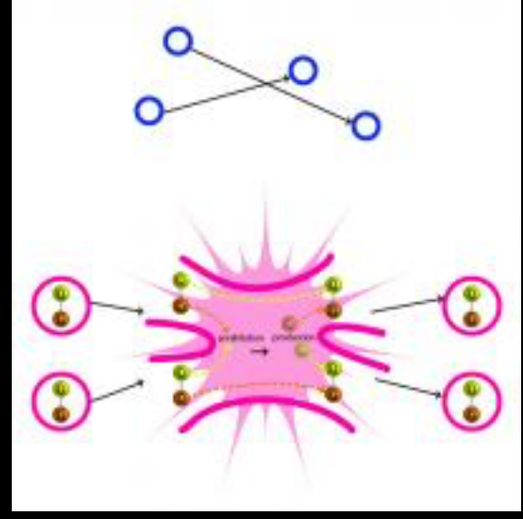
SIMP miracle!

SIMPlest Miracle

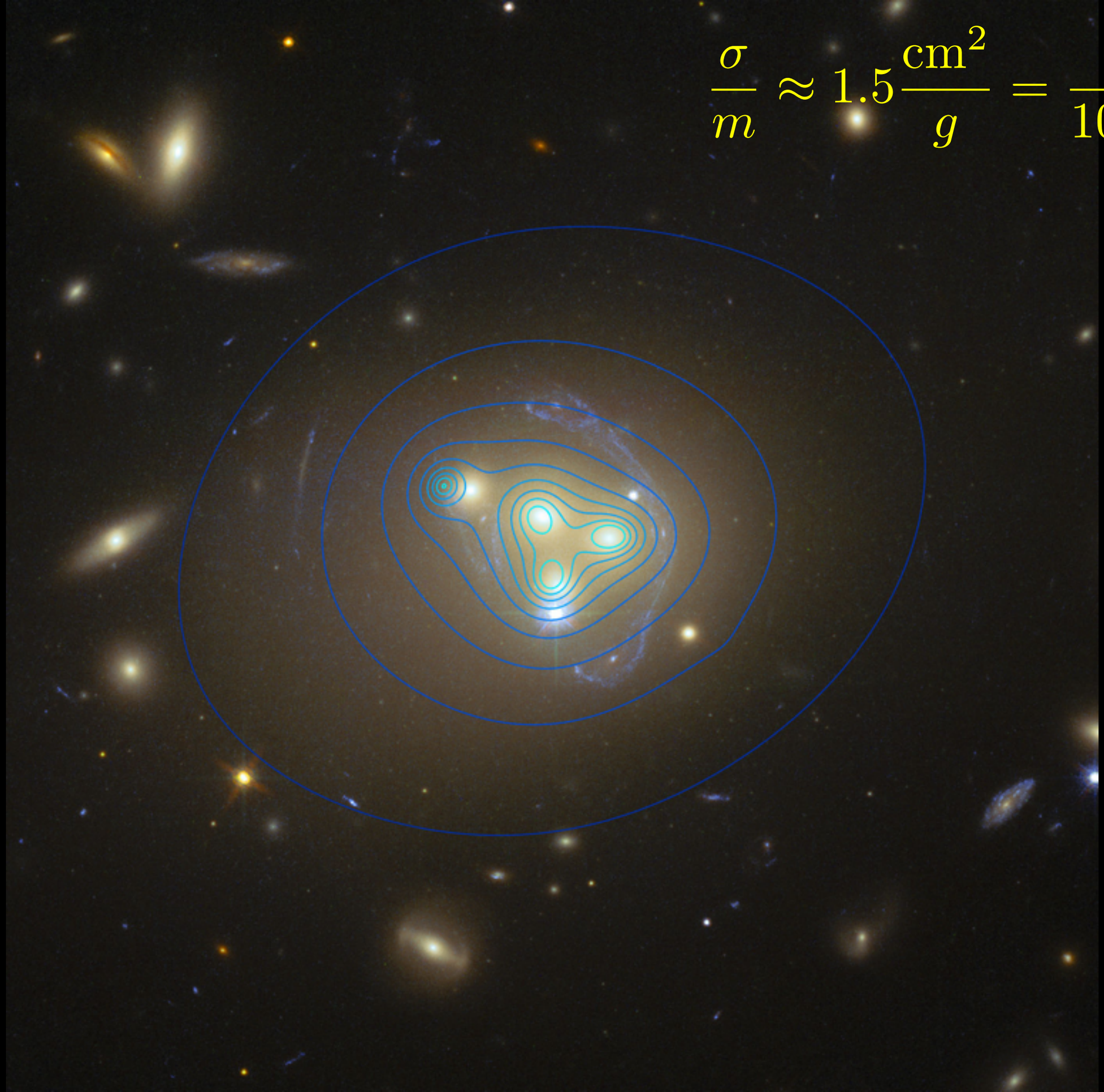
Yonit Hochberg, Eric Kuflik, HM, Tomer Volansky, Jay Wacker

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=S^5
- $\pi_5(S^5)=Z \Rightarrow$ Wess-Zumino term
- $L_{WZ}=\varepsilon_{abcde}\varepsilon^{\mu\nu\rho\sigma}\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e$

self interaction

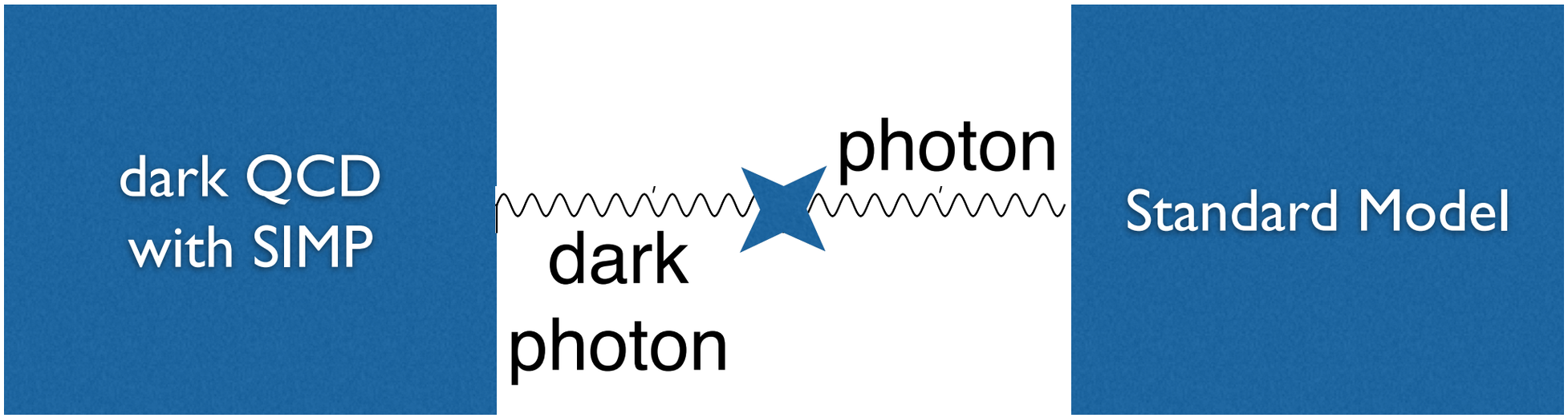


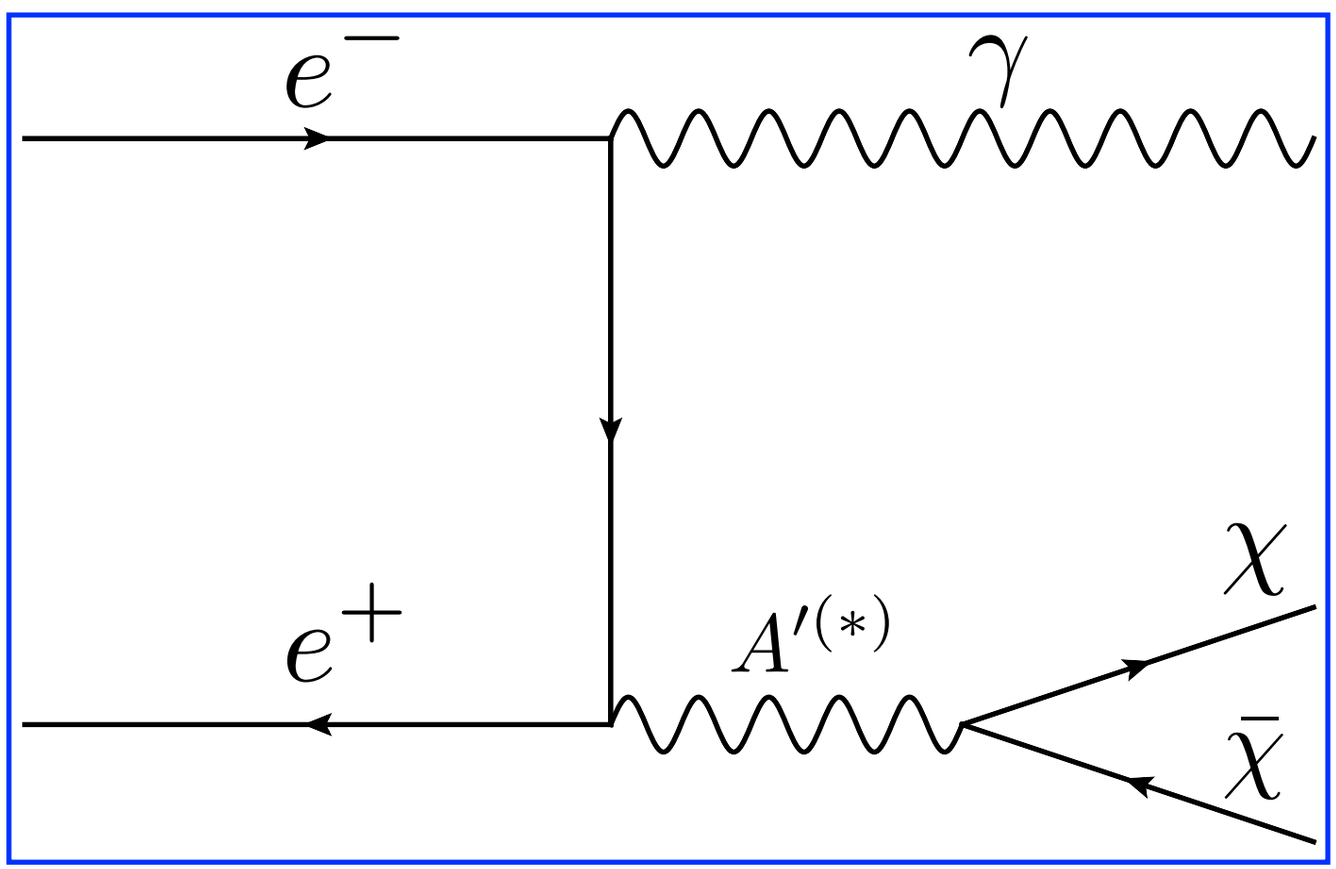
- self interaction of $\sigma/m \sim O(1)$b/GeV
- flattens the cusps in NFW profile
- actually desirable for dwarf galaxies?

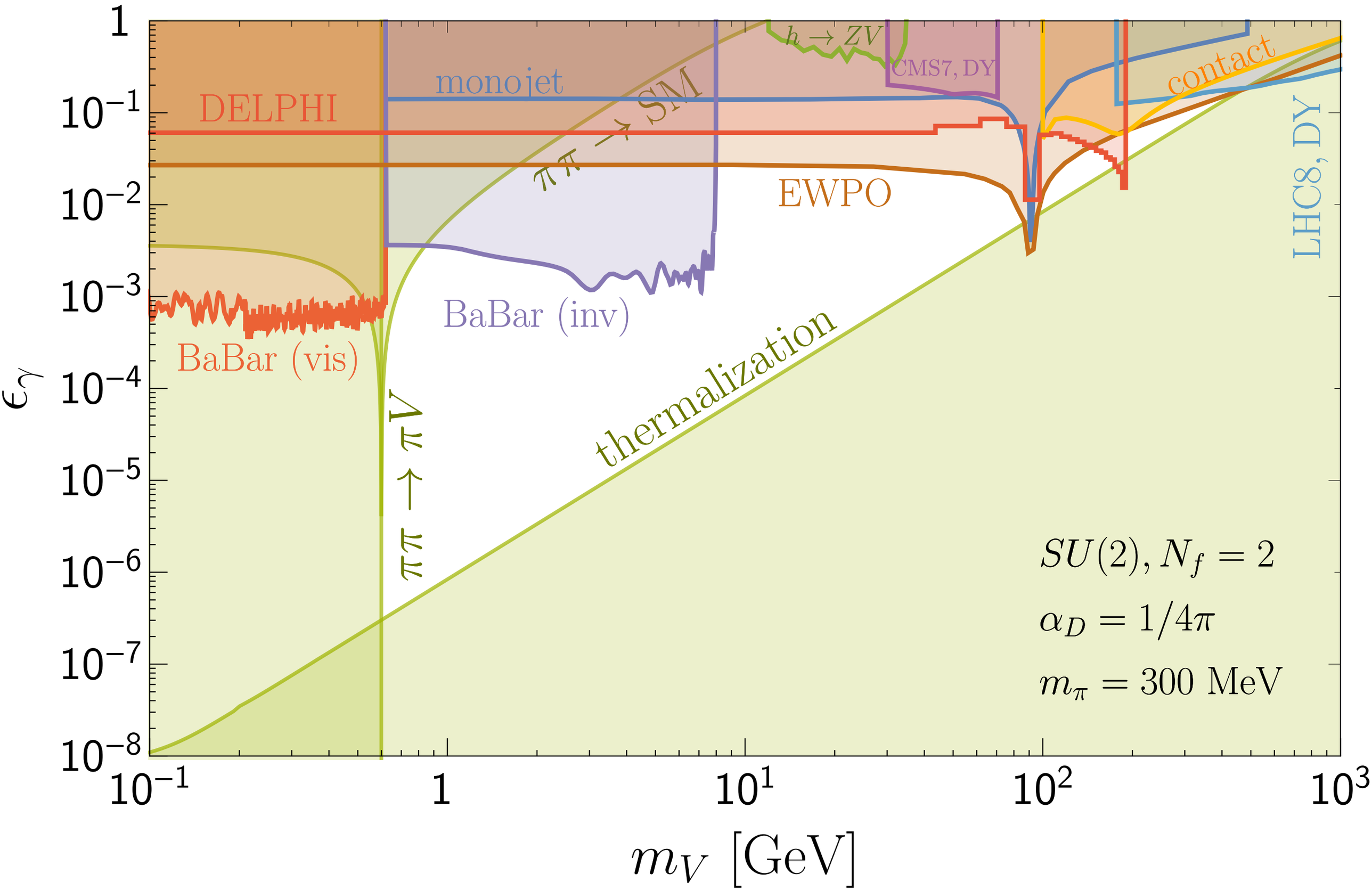


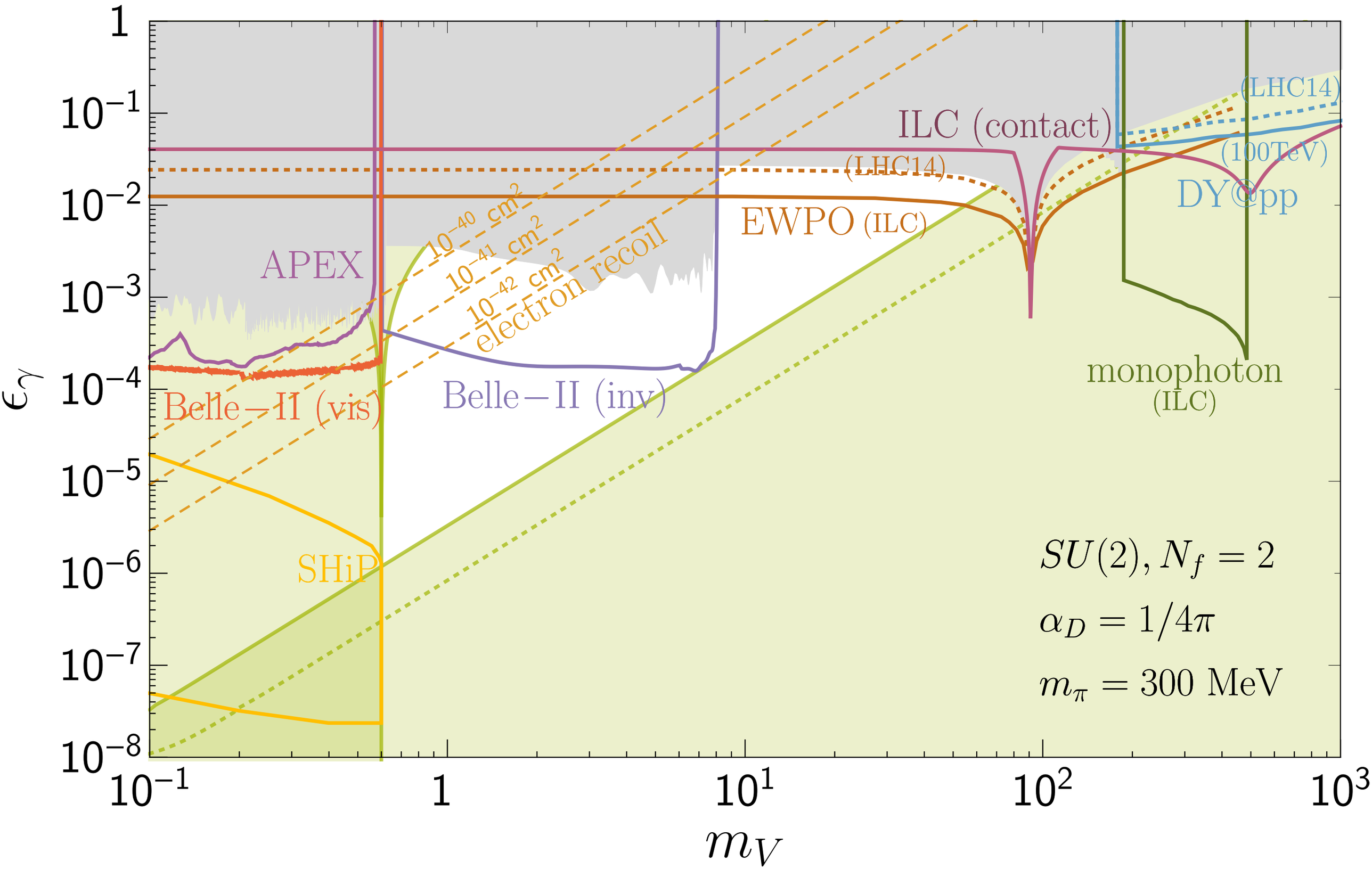
$$\frac{\sigma}{m} \approx 1.5 \frac{\mathrm{cm}^2}{g} = \frac{0.27\mathrm{b}}{100\mathrm{MeV}}$$

explore dark sector

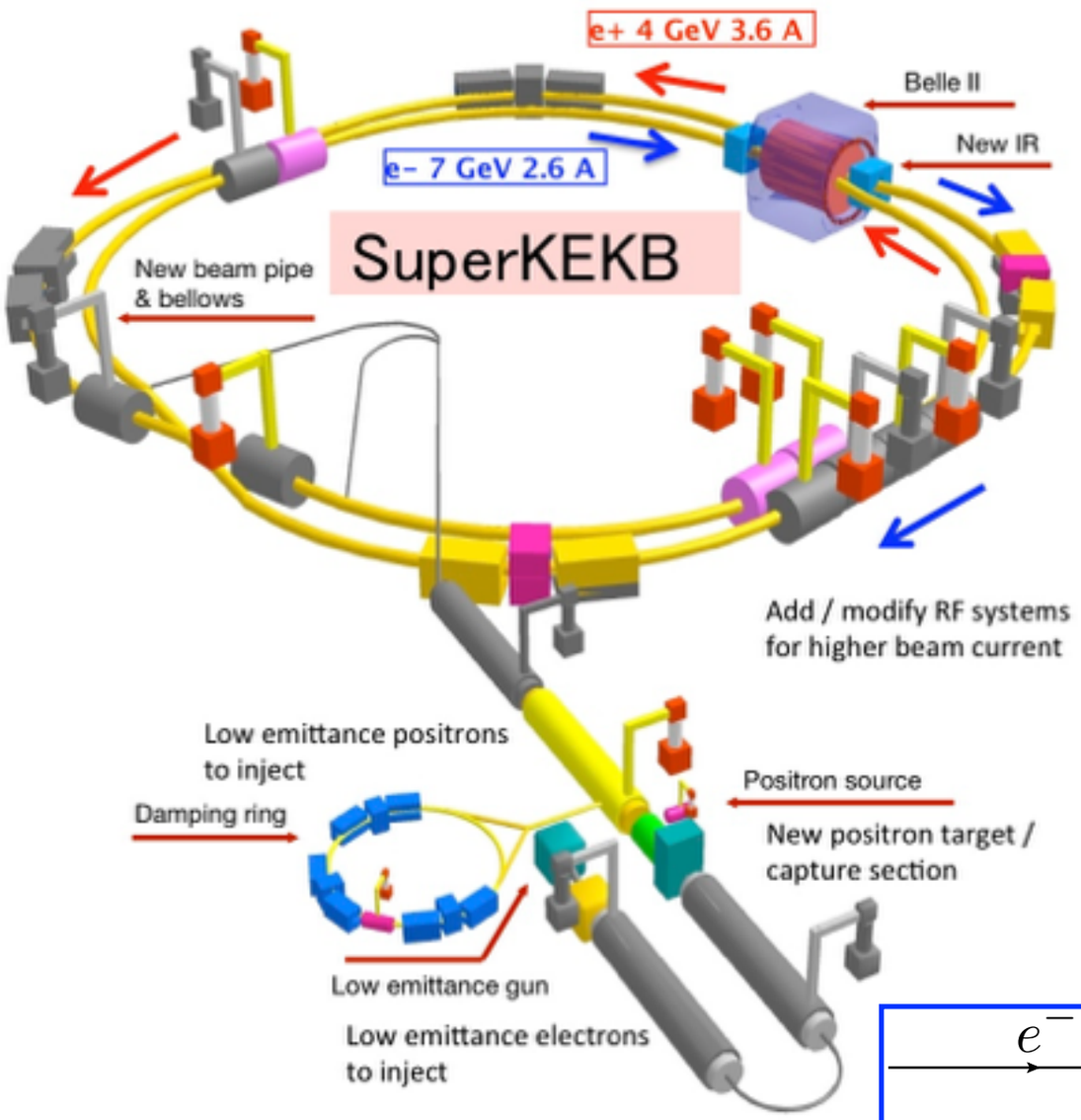




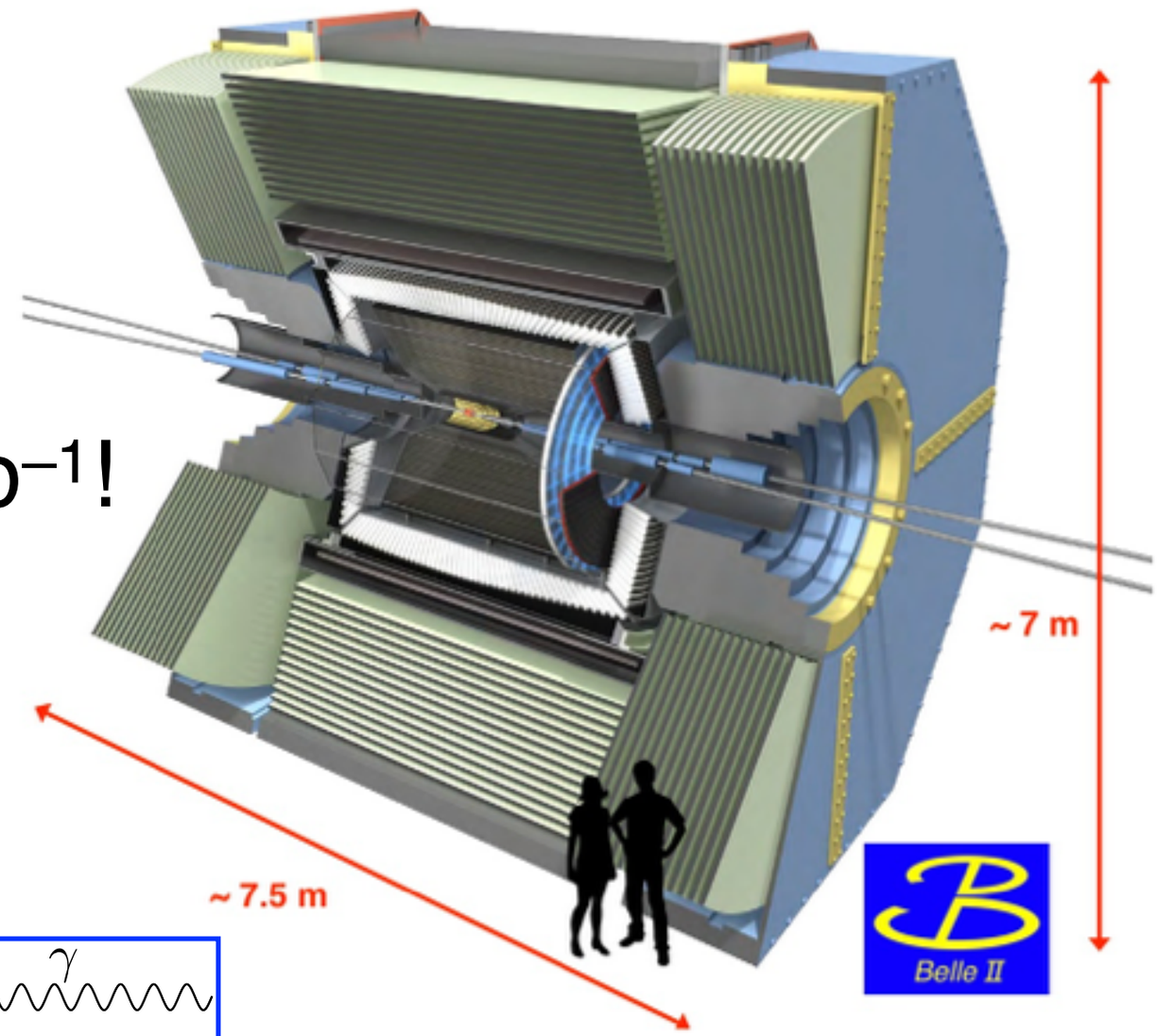

DELPHI
monojet
$h \to ZV$
CMS7, DY
contact
$\pi\pi \to$ SM
EWPO
LHC8, DY
BaBar (inv)
BaBar (vis)
thermalization
$\pi\pi \to \pi V$
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
10^{1}
10^{2}
10^{3}

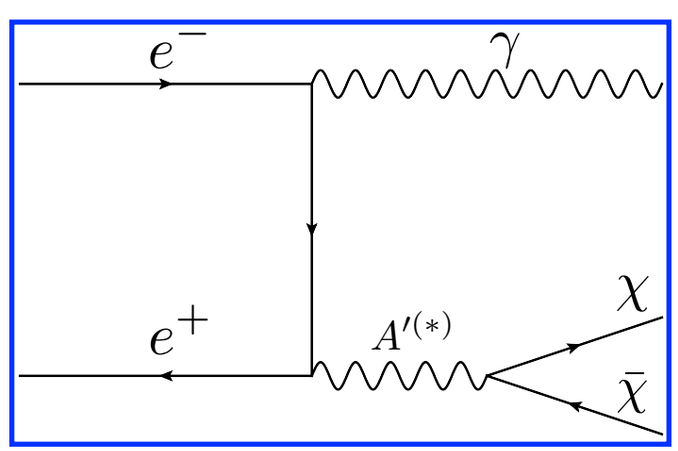

ILC (contact)
(LHC14)
(100TeV)
DY@pp
EWPO (ILC)
APEX
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
Belle−II (vis)
Belle−II (inv)
monophoton
(ILC)
SHiP
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V

Super KEK B & Belle II

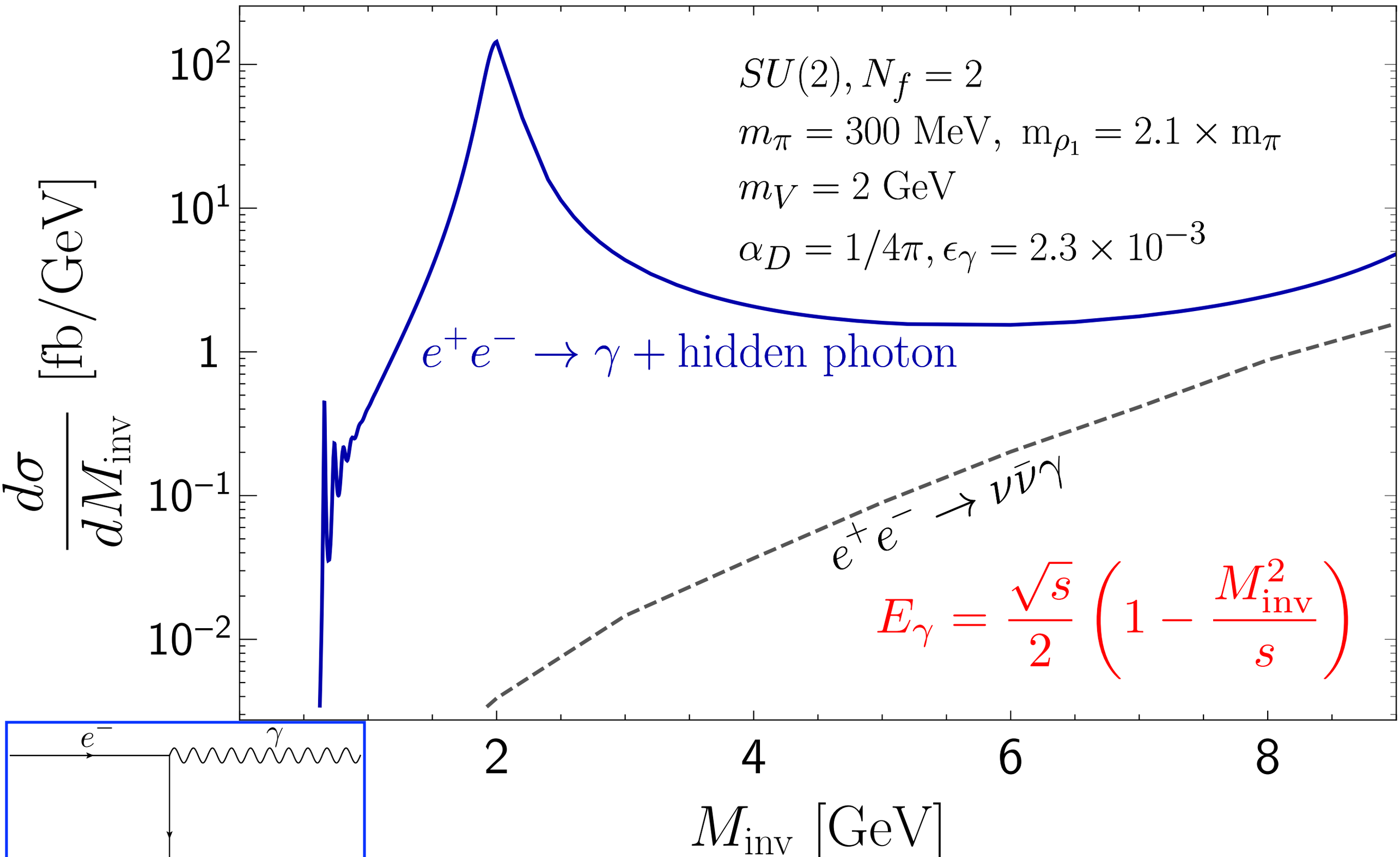


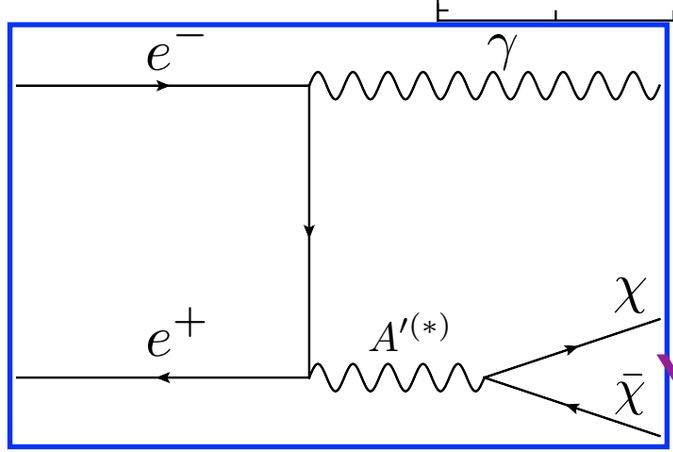
50 ab^{-1}!





$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$





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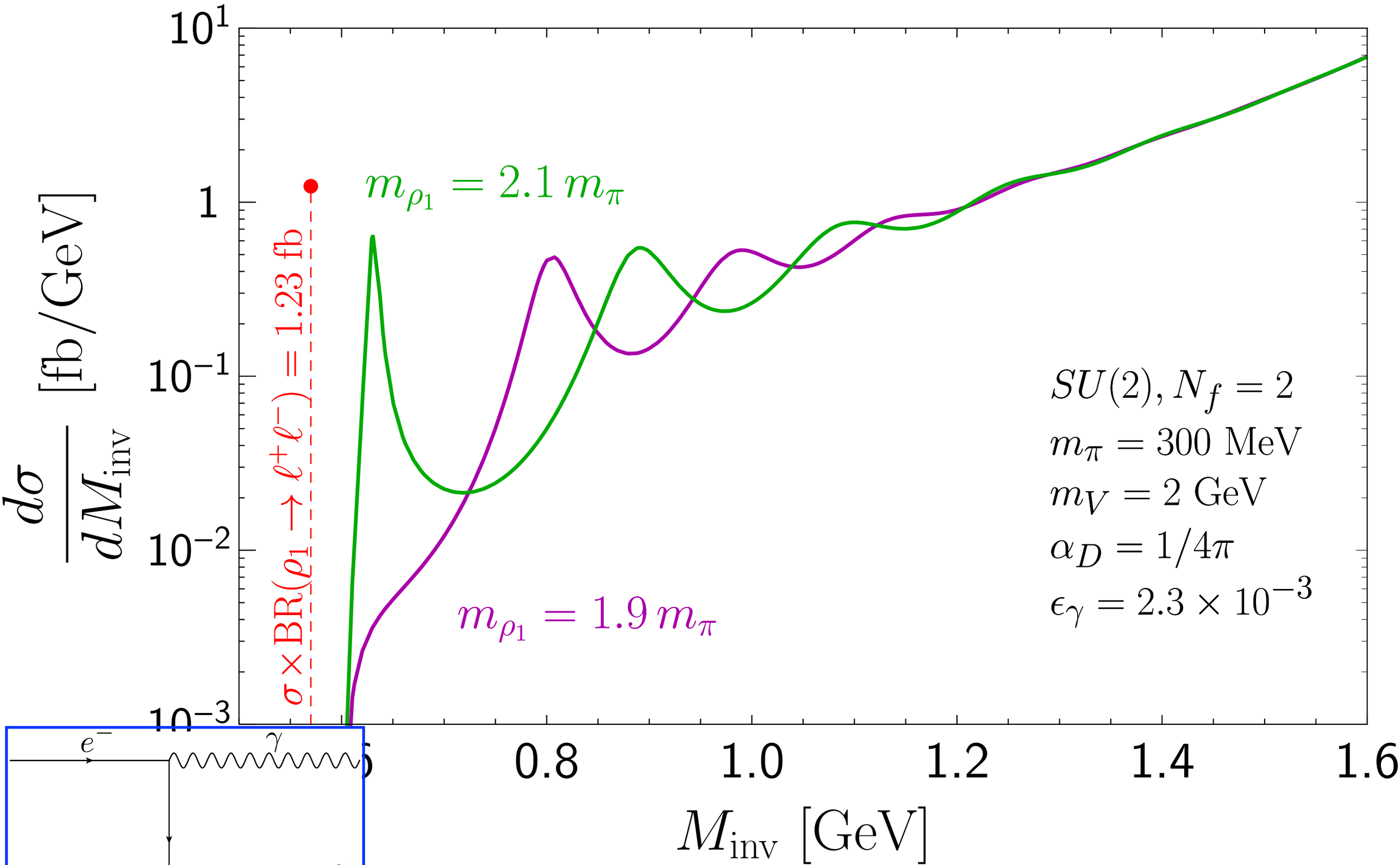

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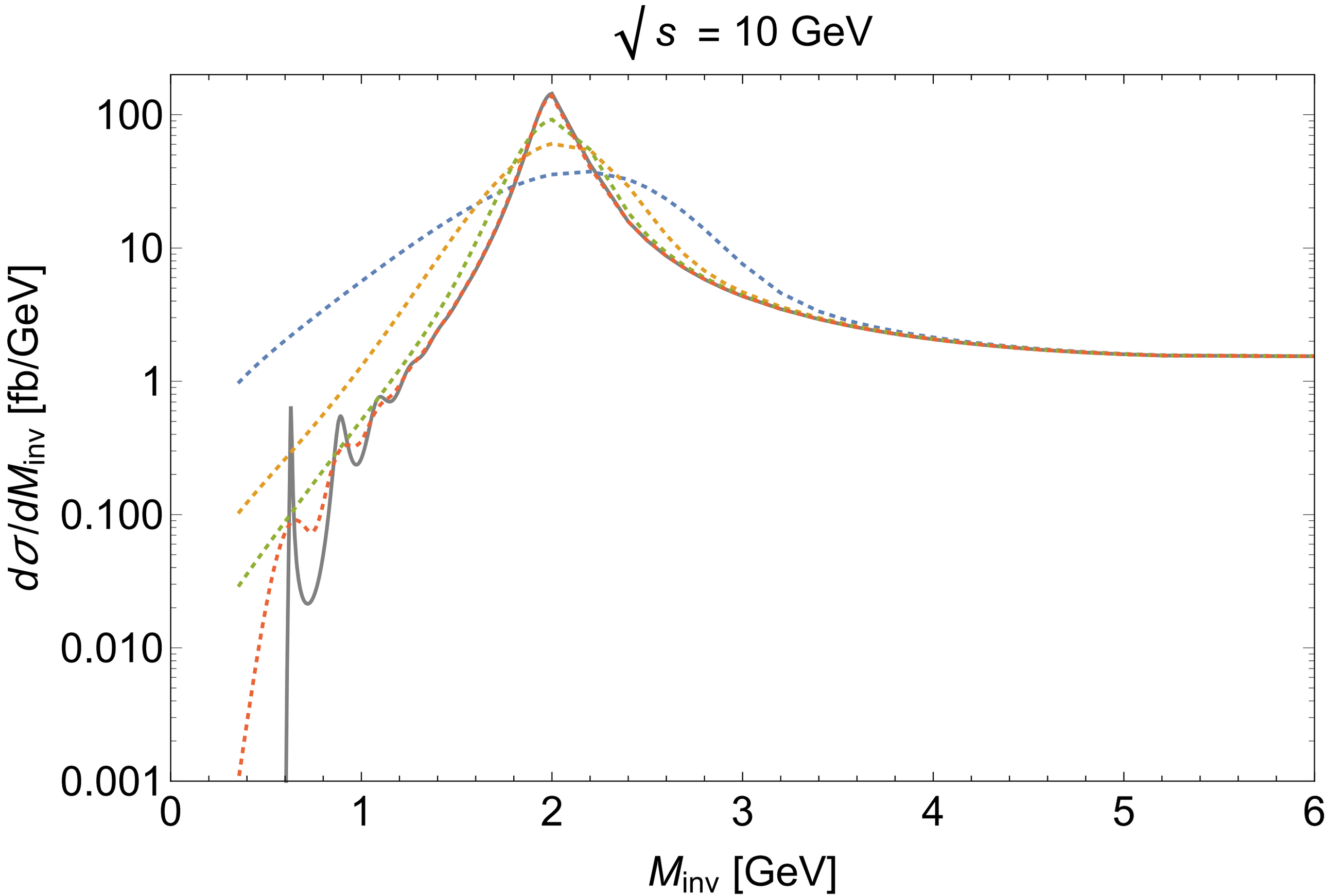

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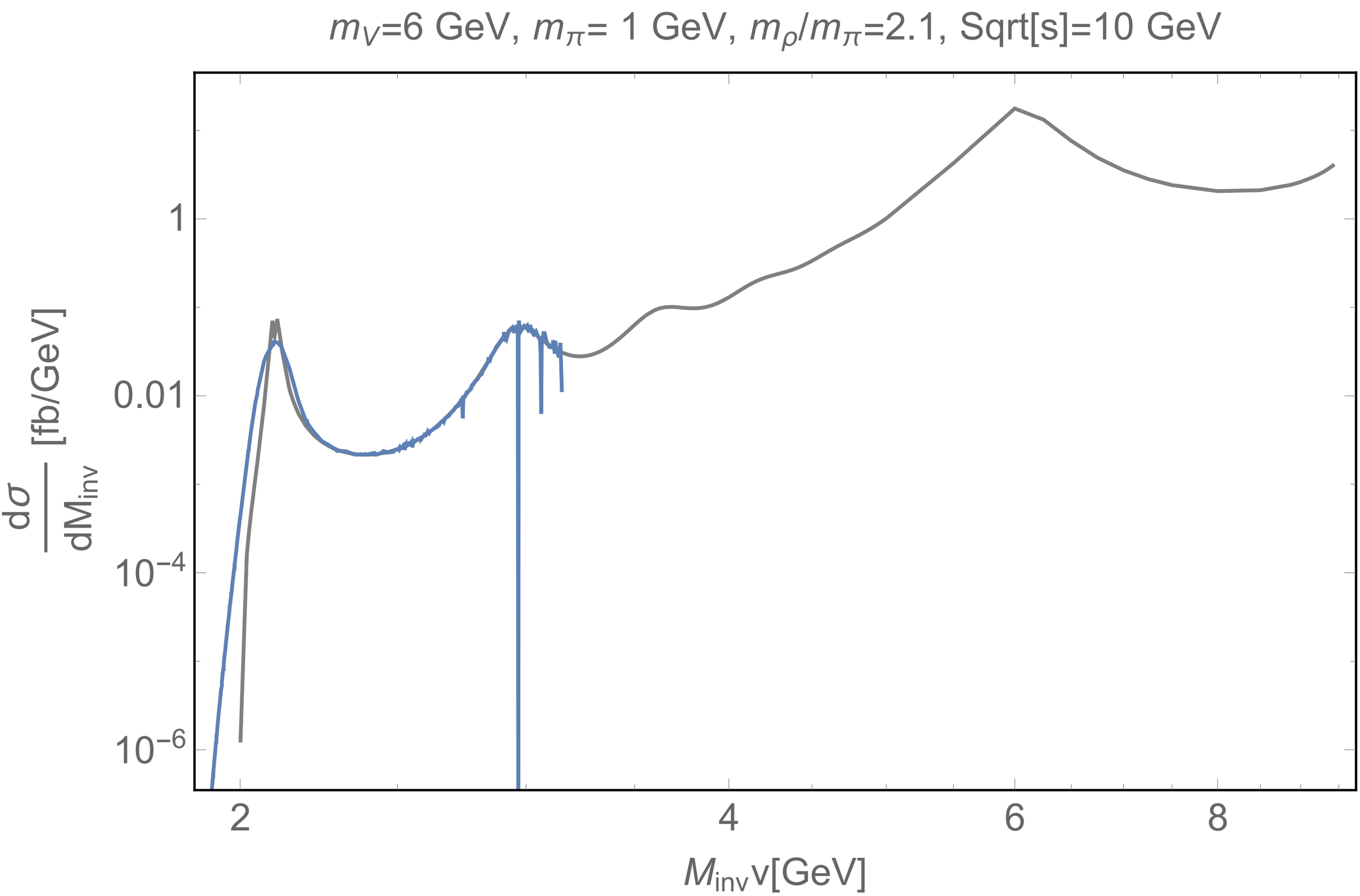

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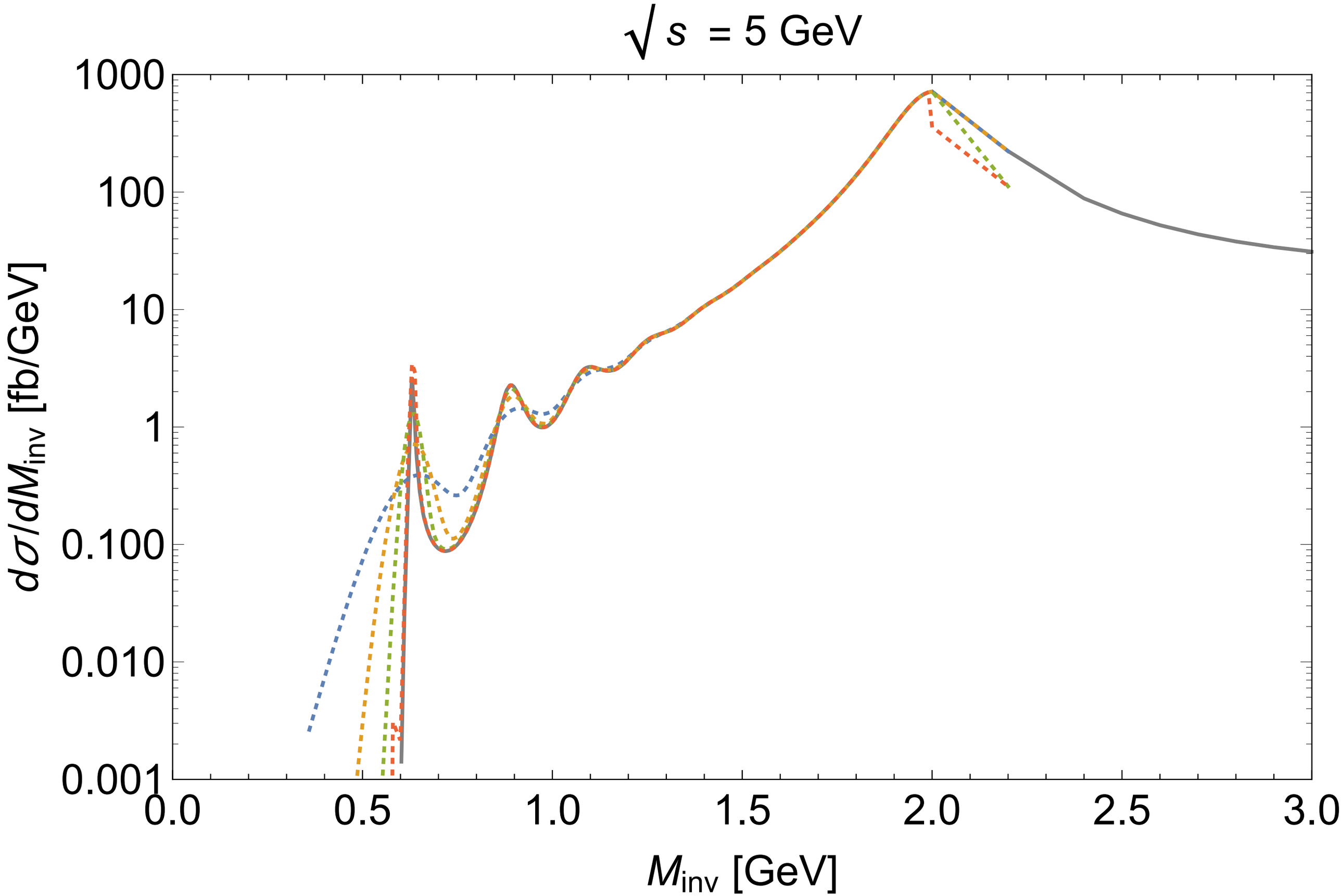

Yonit Hochberg, Eric Kuflik, HM

Conclusions

- Flavor physics all the more important given lack of new physics at LHC

  1. tool to explore beyond the LHC energy

  2. origin of flavor important on its own

- new possibilities on dark matter

  3. light, very weakly coupled dark matter


theorist
experiments

healthy field!