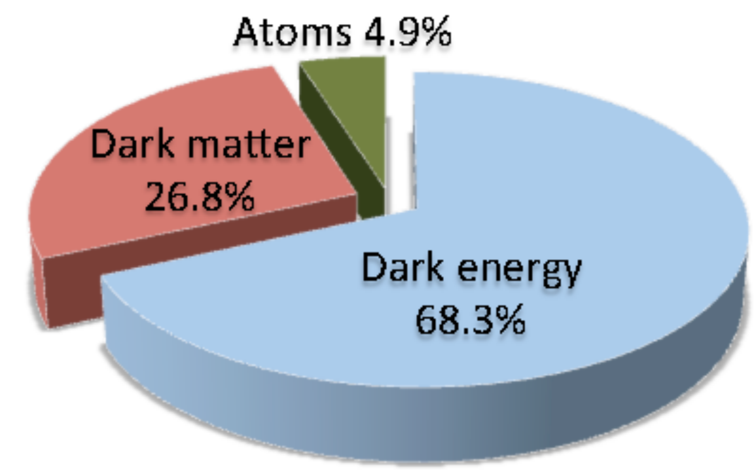
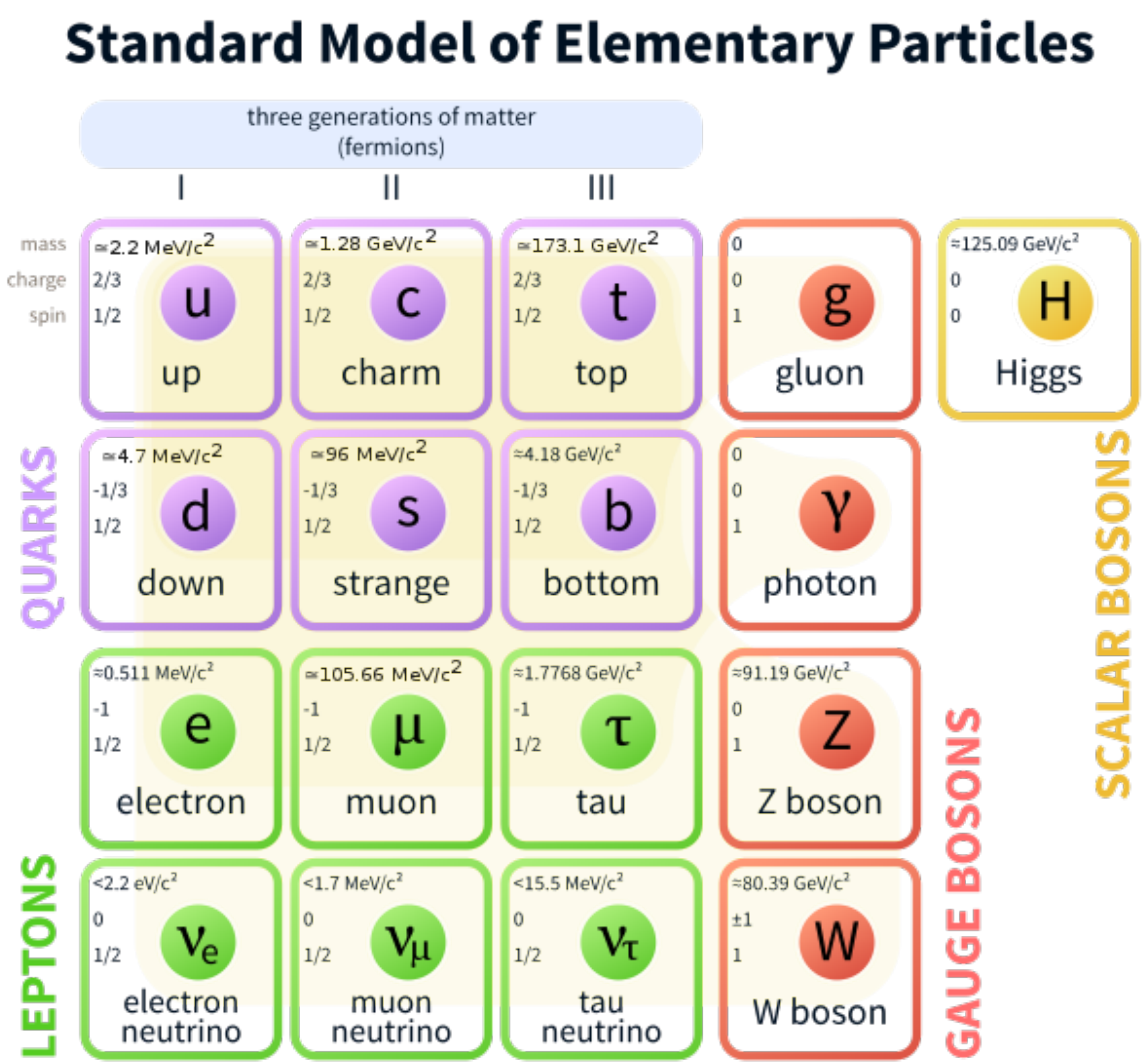
Overview of Beyond the Standard Model Phenomenology

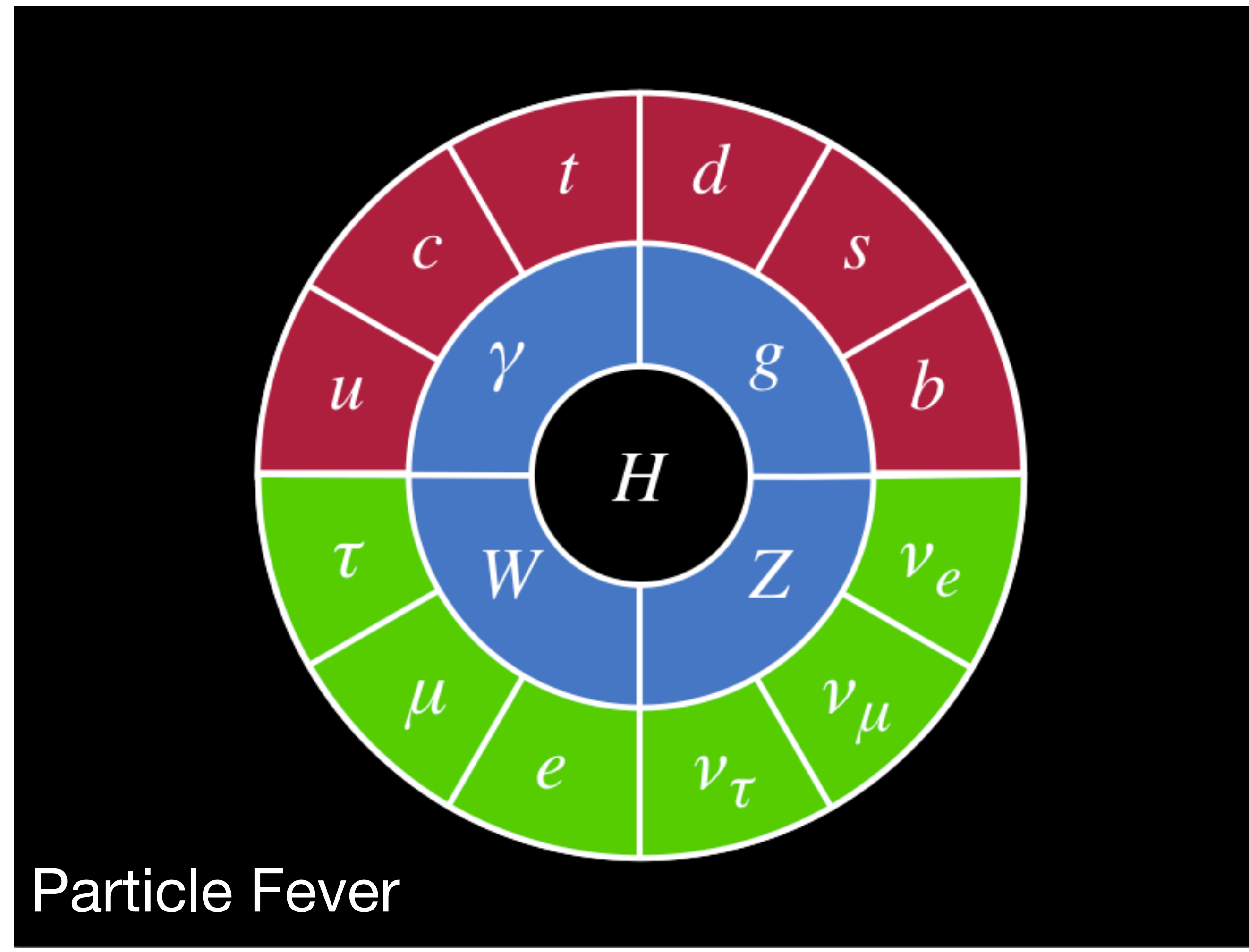
Patrick Fox

Fermilab

The Standard Model







18 parameters:

$$\alpha,\ \sin\theta_W,\ \alpha_S,\ \langle H\rangle,\ m_H,\ m_{e,\mu,\tau},\ m_{u,d,s,c,b,t},\ V_{CKM}(\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta)$$

Why we (might) need BSM physics

- Neutrino masses
- Baryogenesis
- Dark Matter
- Inflation and cosmological constant/quintessence
- Quantum gravity
- Explain anomalies…

- Fermion masses and mixings
- Strong CP problem
- Hierarchy Problem
- Gauge coupling unification
- Explain anomalies…

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- Fermion masses and mixings
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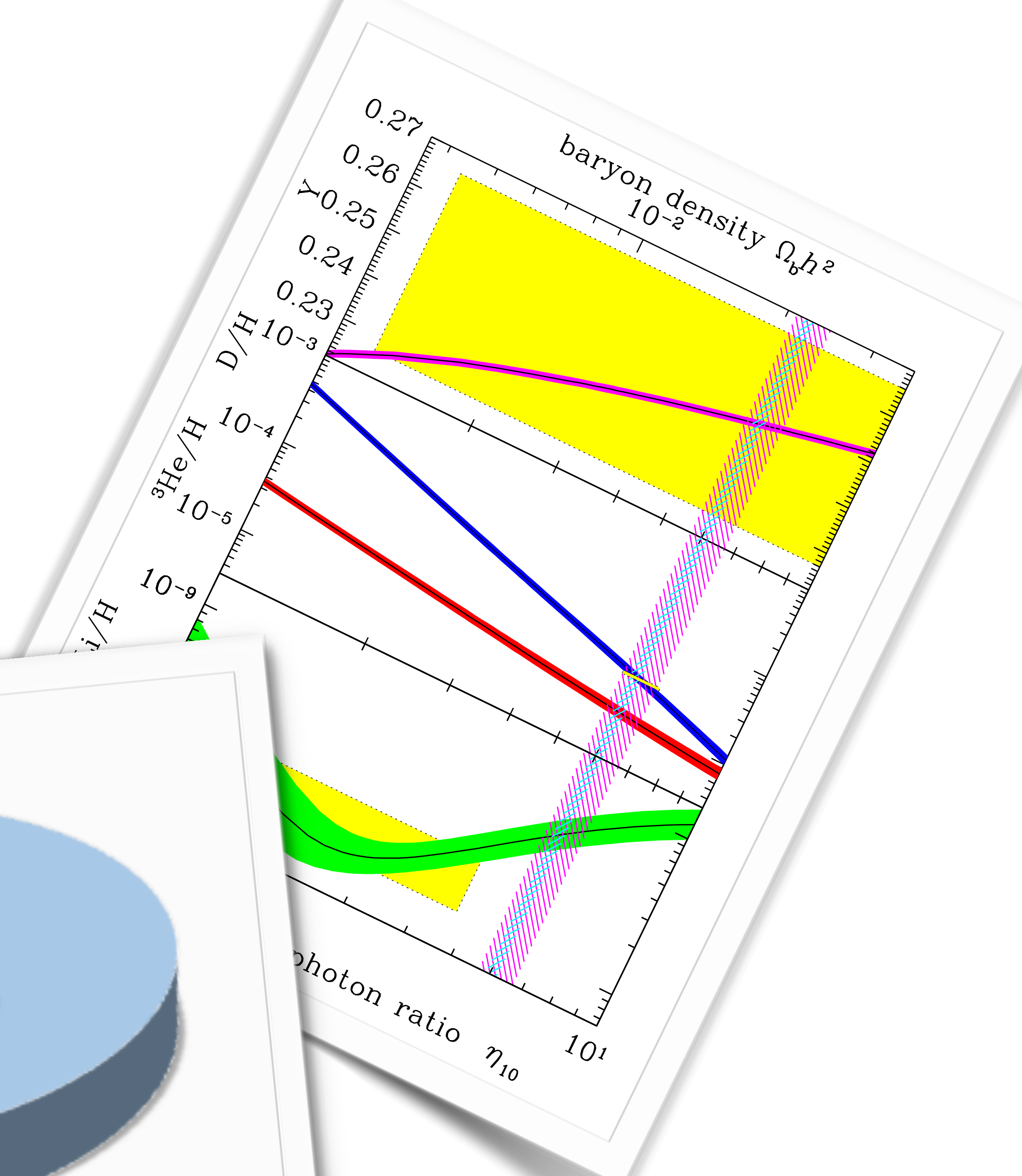
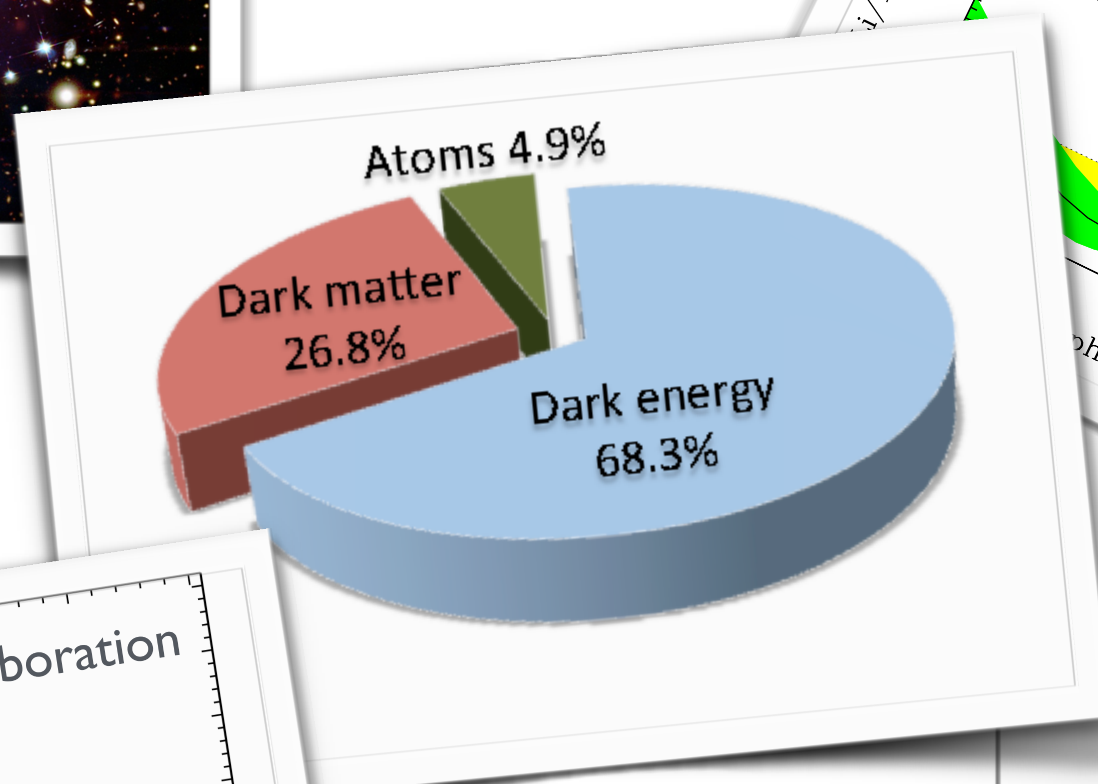
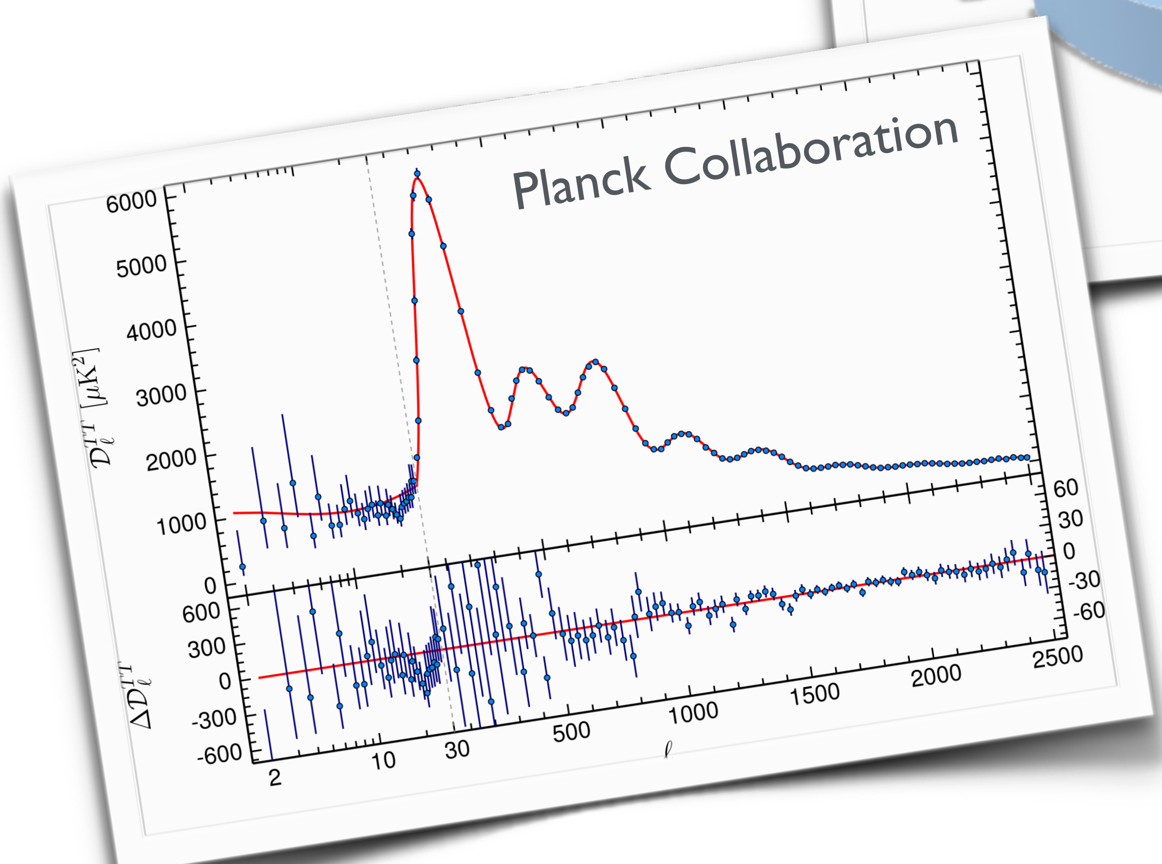
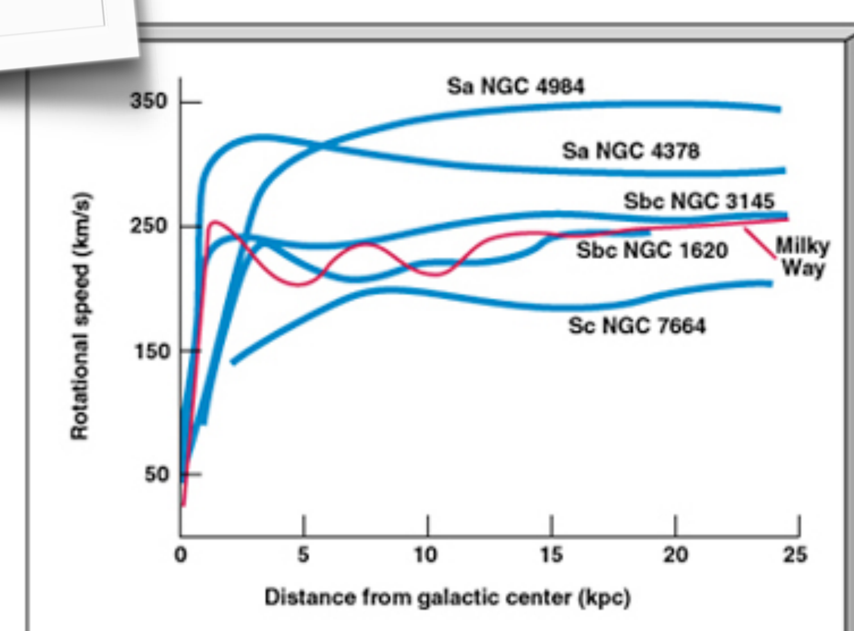
Dark Matter

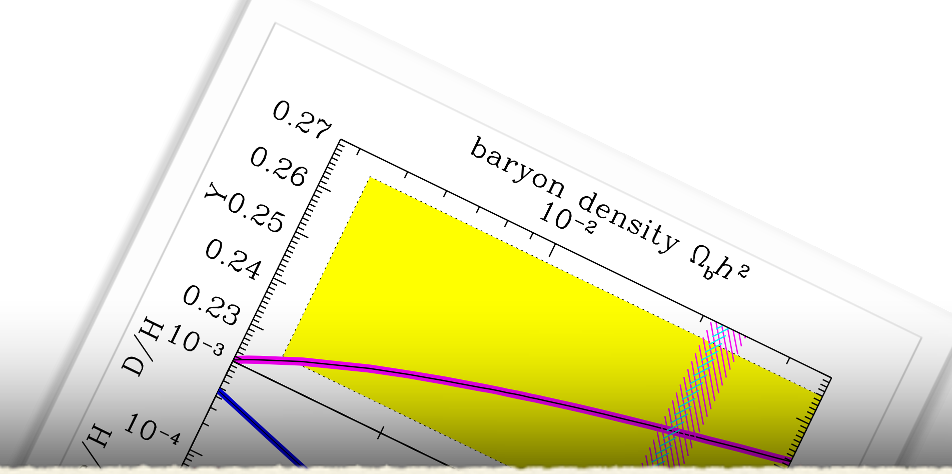

baryon density $\Omega_b h^2$
10^{-2}
Y
0.27
0.26
0.25
0.24
0.23
D/H
10^{-3}
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
photon ratio η_{10}
10^1


Atoms 4.9%
Dark matter
26.8%
Dark energy
68.3%

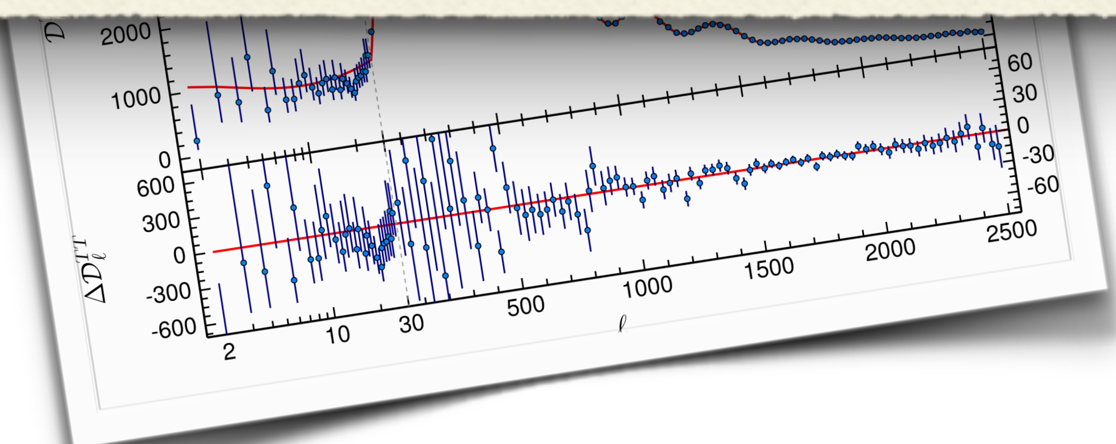

Planck Collaboration
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

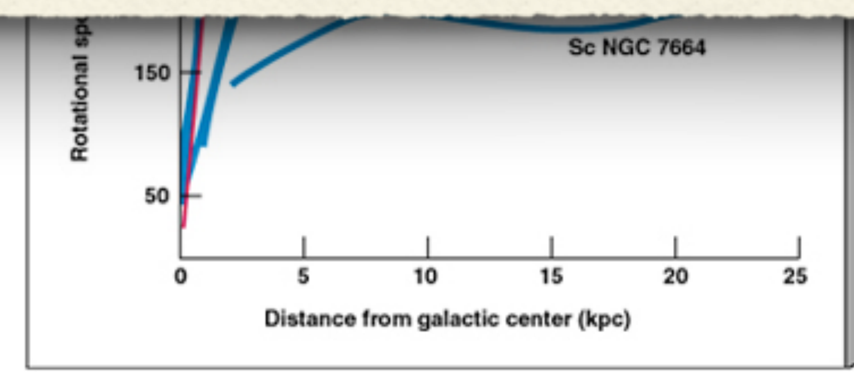

Sa NGC 4984
Sa NGC 4378
Sbc NGC 3145
Sbc NGC 1620
Milky Way
Sc NGC 7664
Rotational speed (km/s)
350
250
150
50
0
5
10
15
20
25
Distance from galactic center (kpc)

Dark Matter



- DM makes up 27% of the mass-energy of universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself
- Does not couple to massless particle
- Non-relativistic at time of CMB
- Long lived **NO SUCH PARTICLE IN SM**

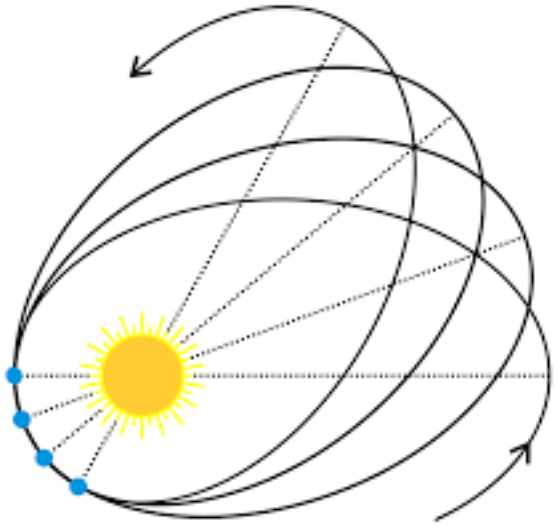


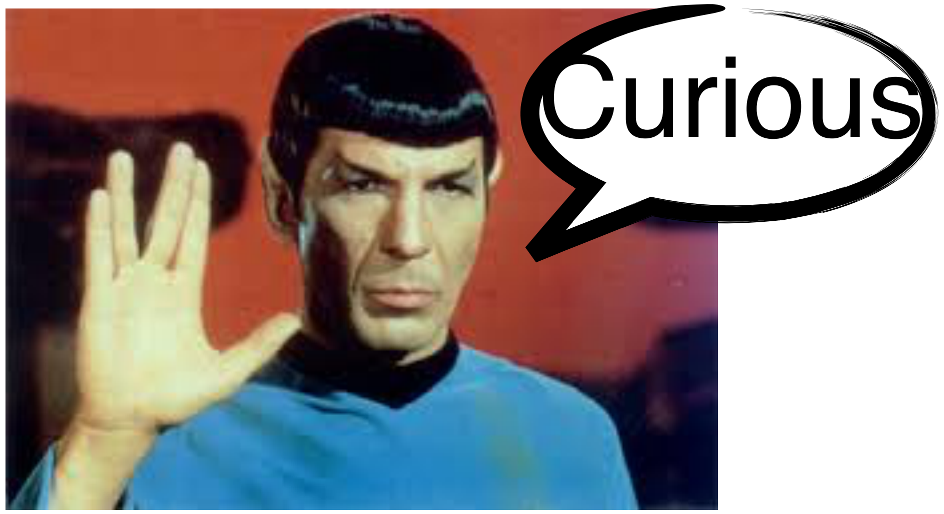


So far all probes have been gravitational in nature

Neptune discovered by wobble in orbit of Uranus —original DM!

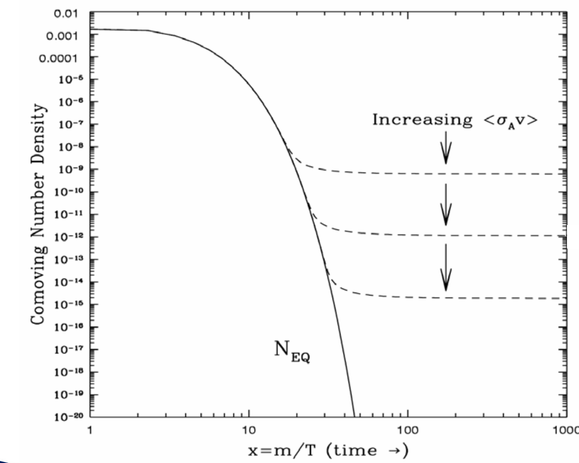
Advance in Perihelion of Mercury needed new physics (general relativity) to explain it. (Originally thought to be planet Vulcan!)

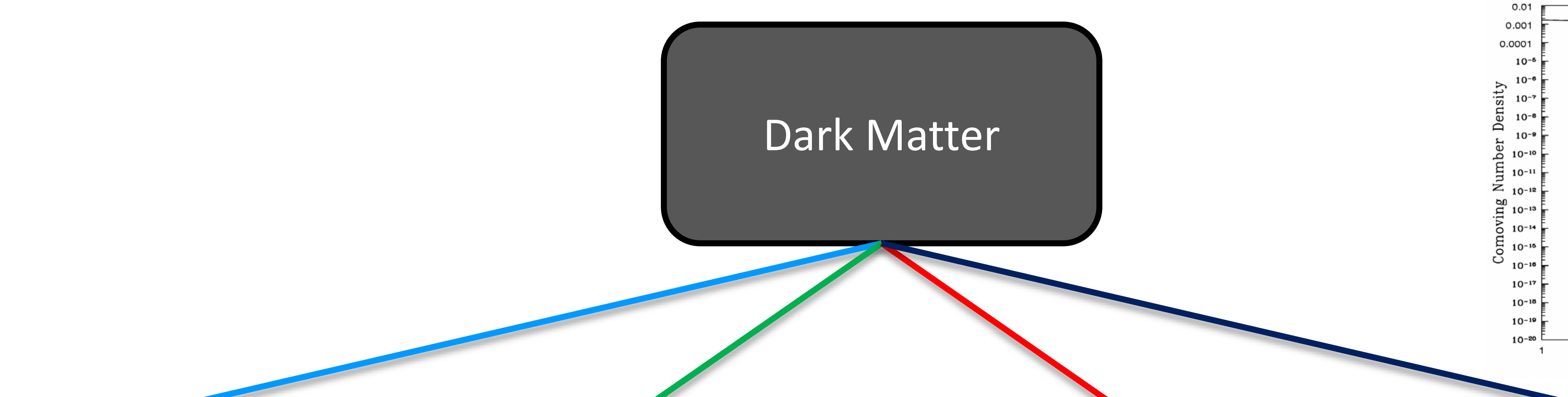


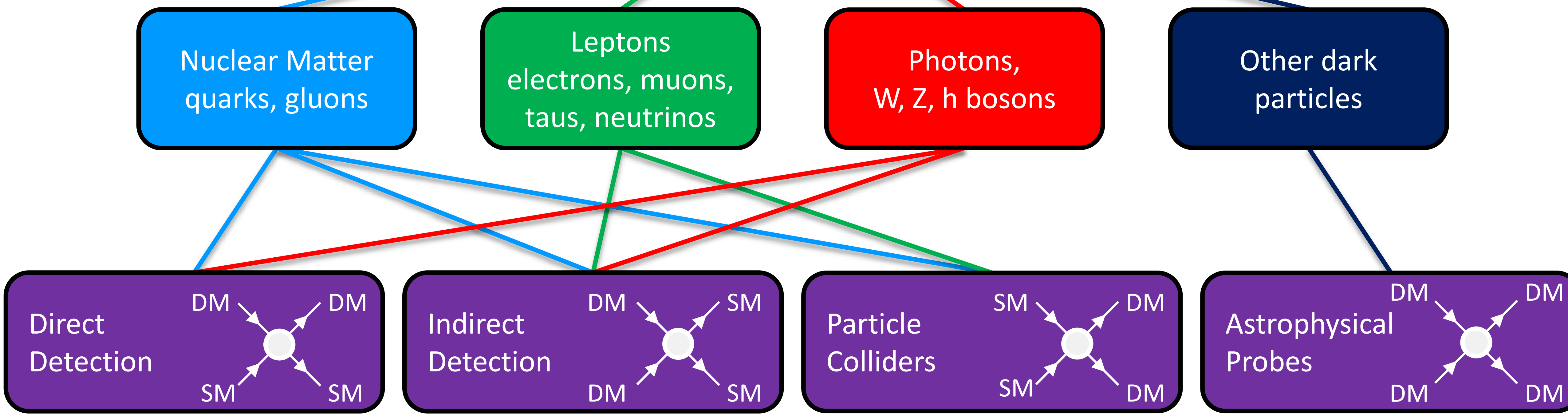


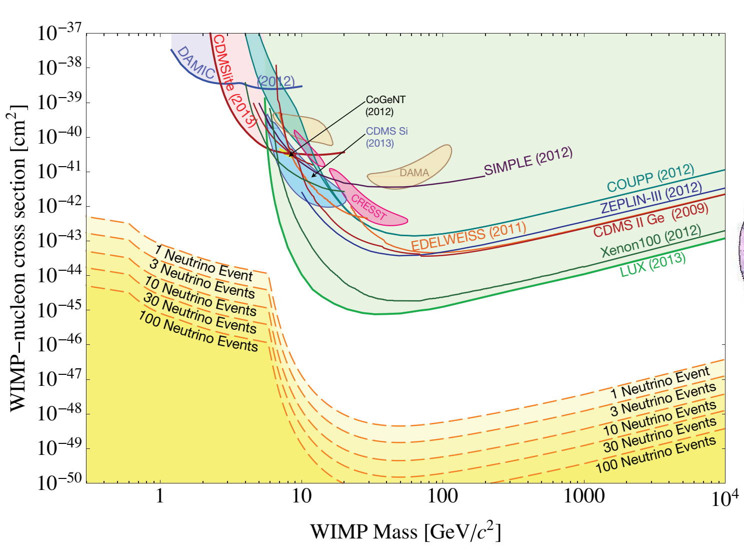
What about other interactions?

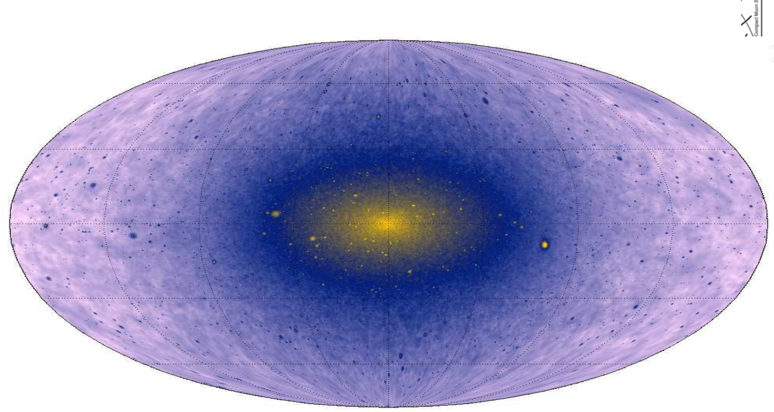
Thermal relic?

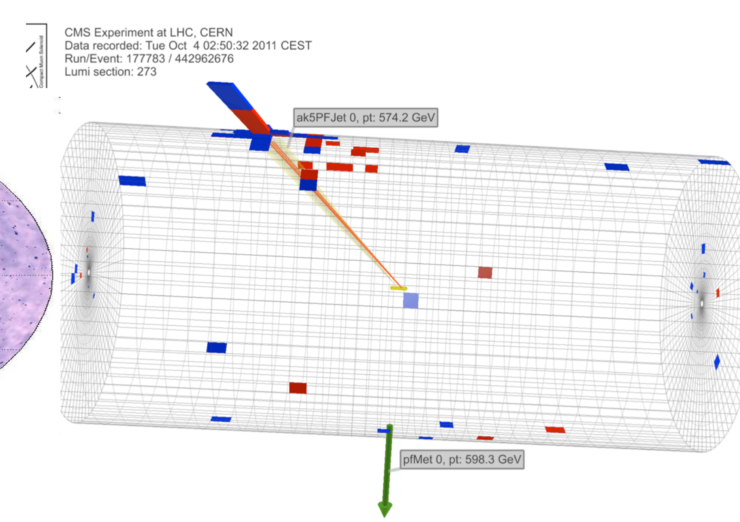




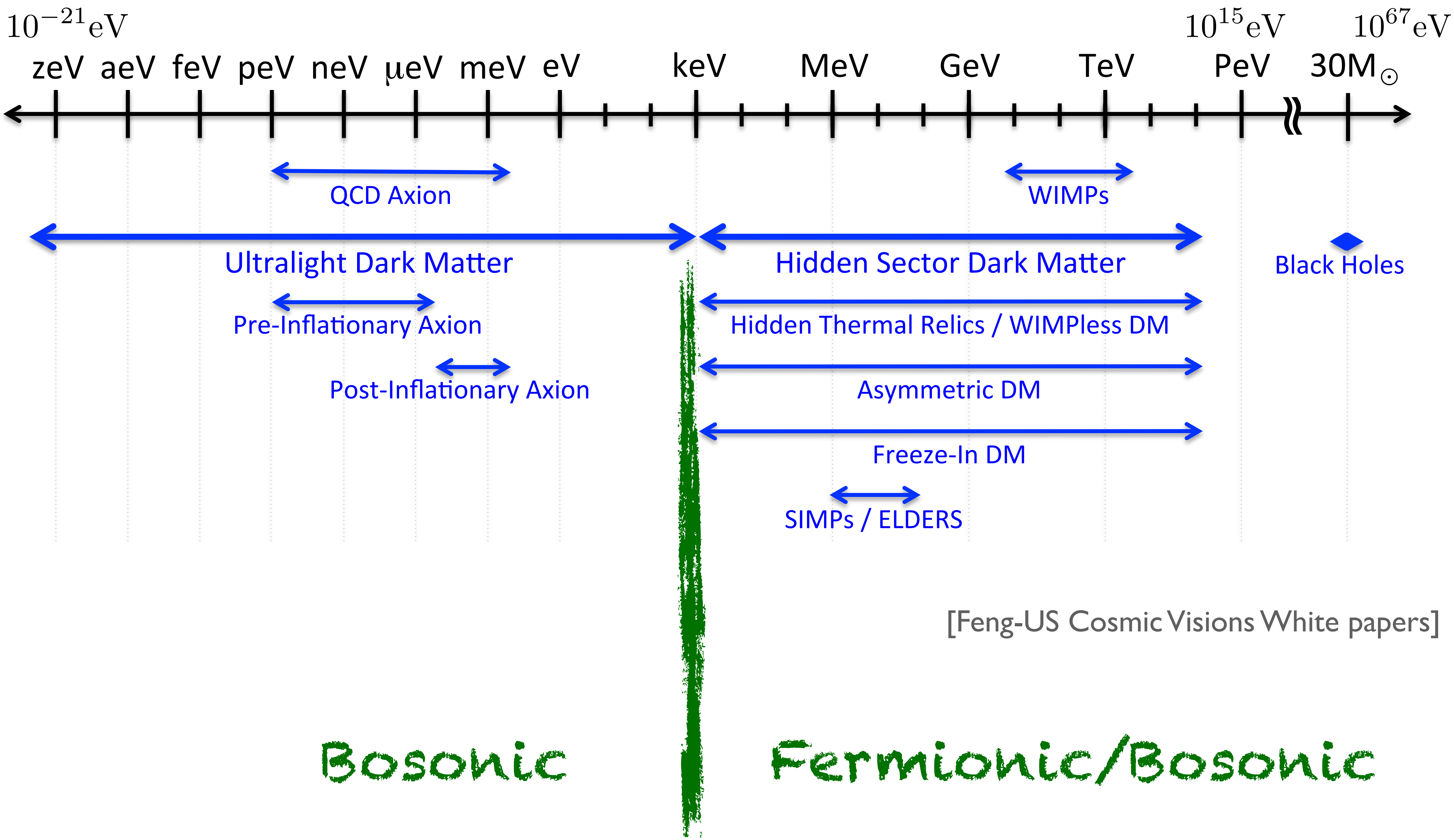








Theories of Dark Matter

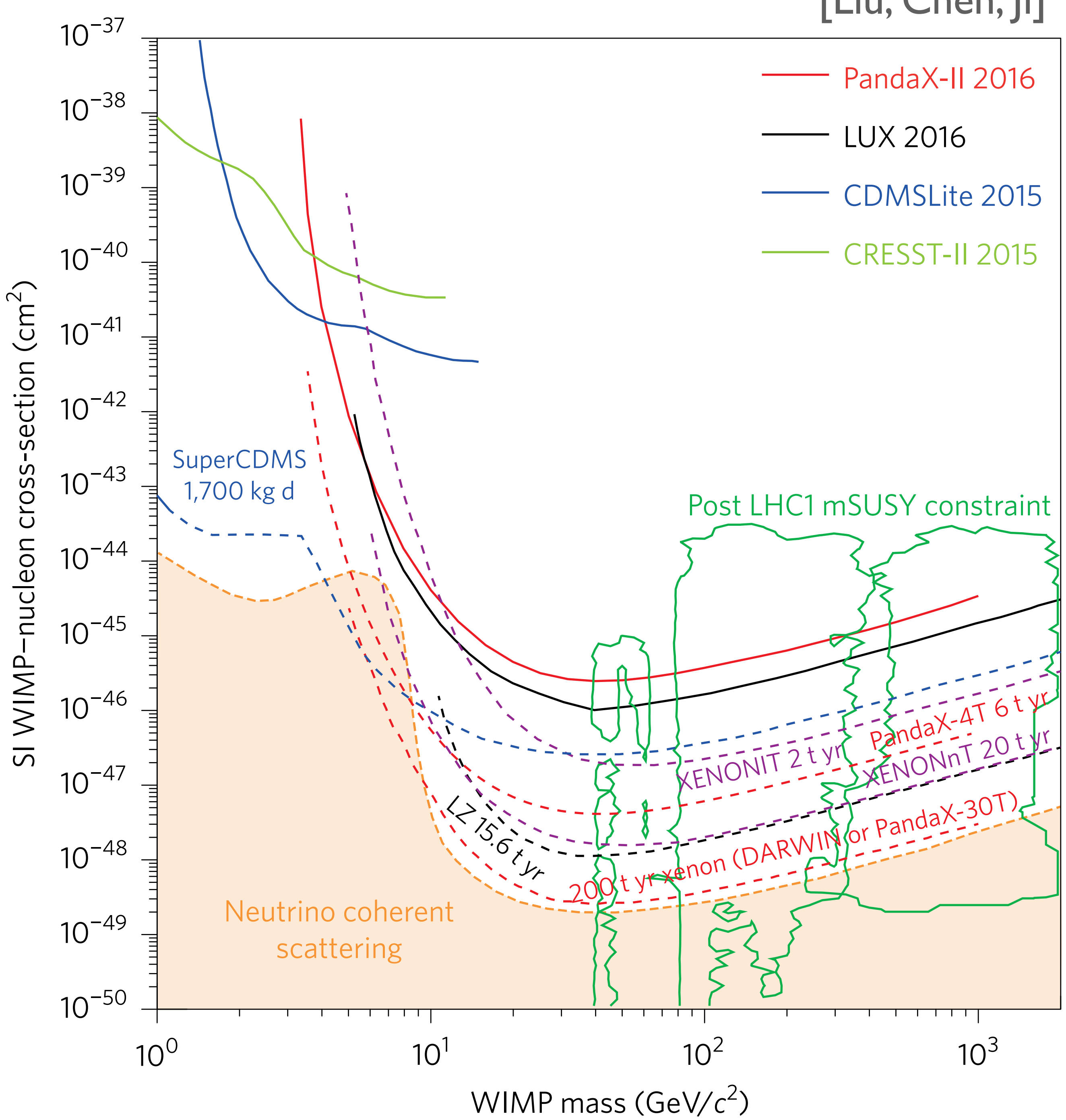


[Feng-US Cosmic Visions White papers]

WIMP

- DM interacts through weak (or weak scale) couplings
- Lee-Weinberg and Unitarity constrain mass range
  - ~1 GeV —~10 TeV
- Usually consider a thermal relic

[Liu, Chen, Ji]



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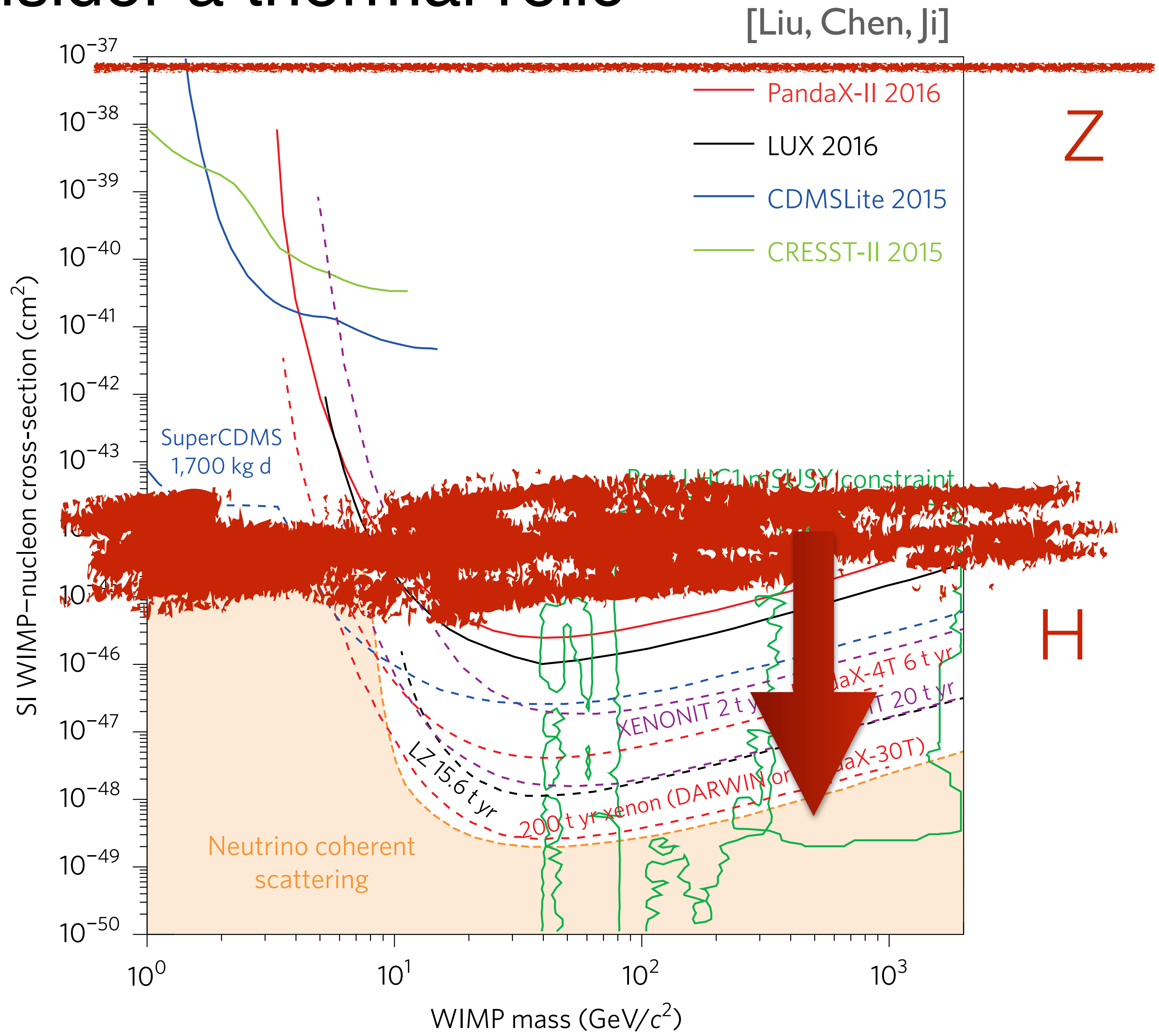
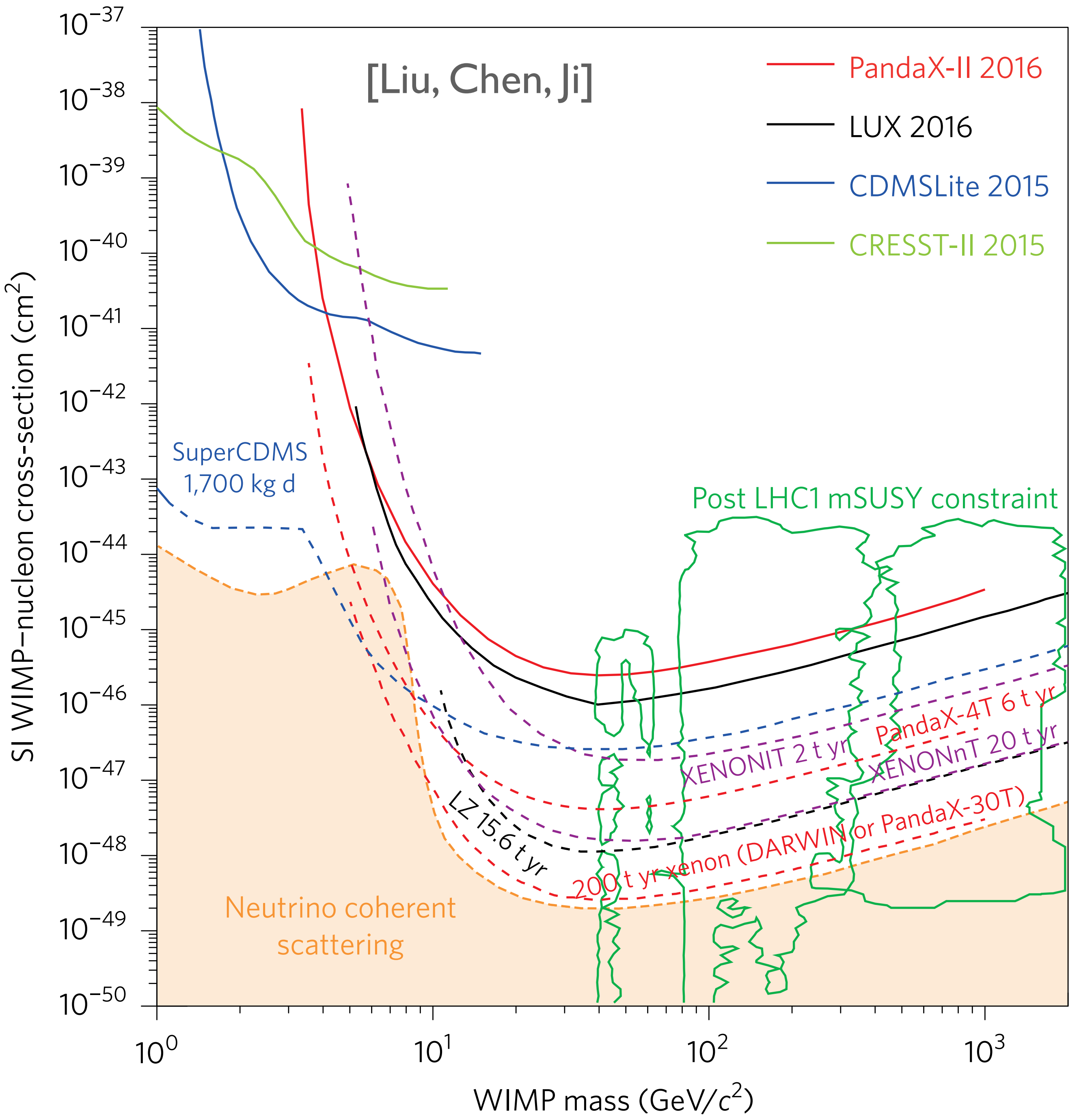


Dark sectors and direct detection



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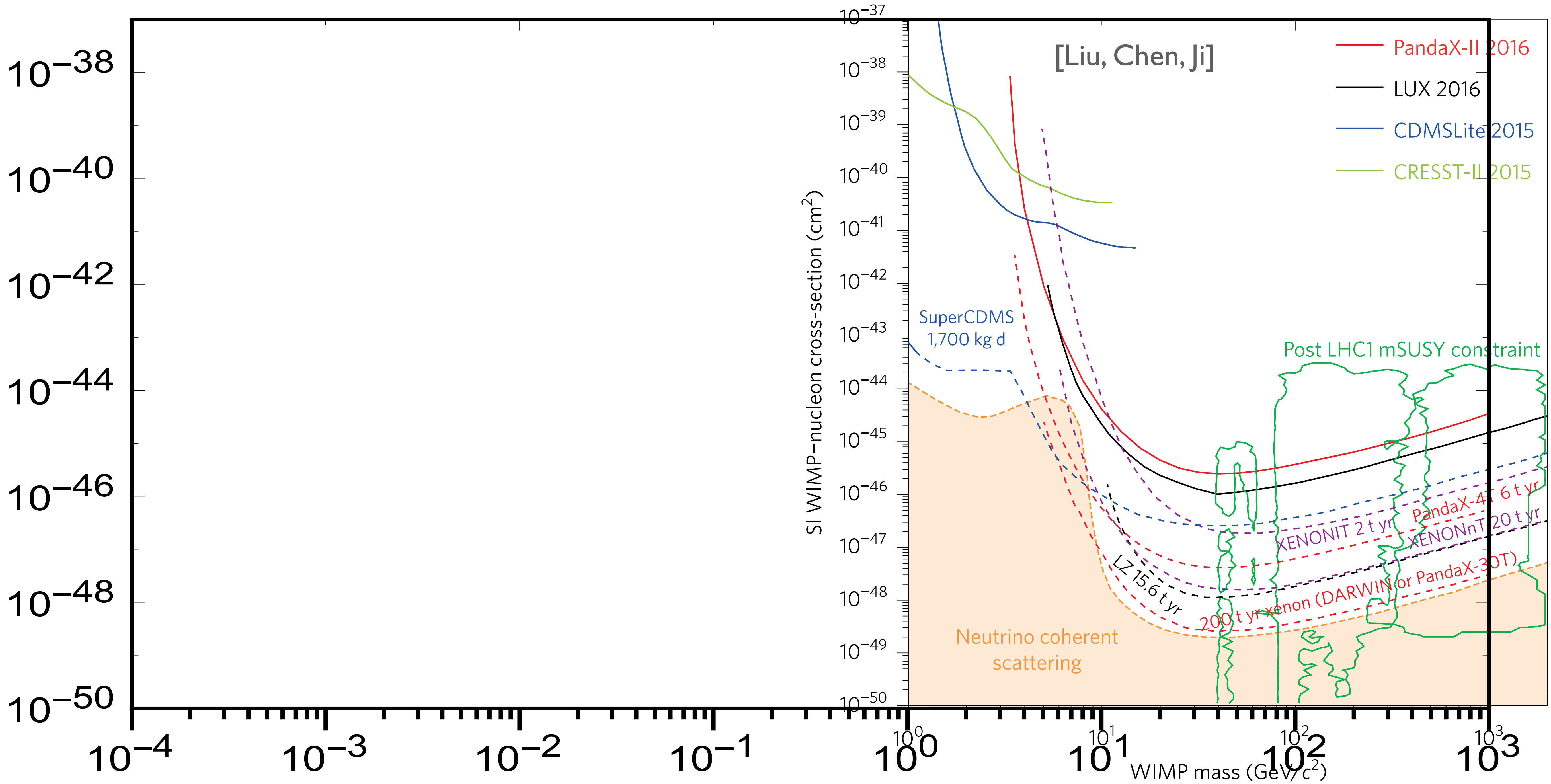

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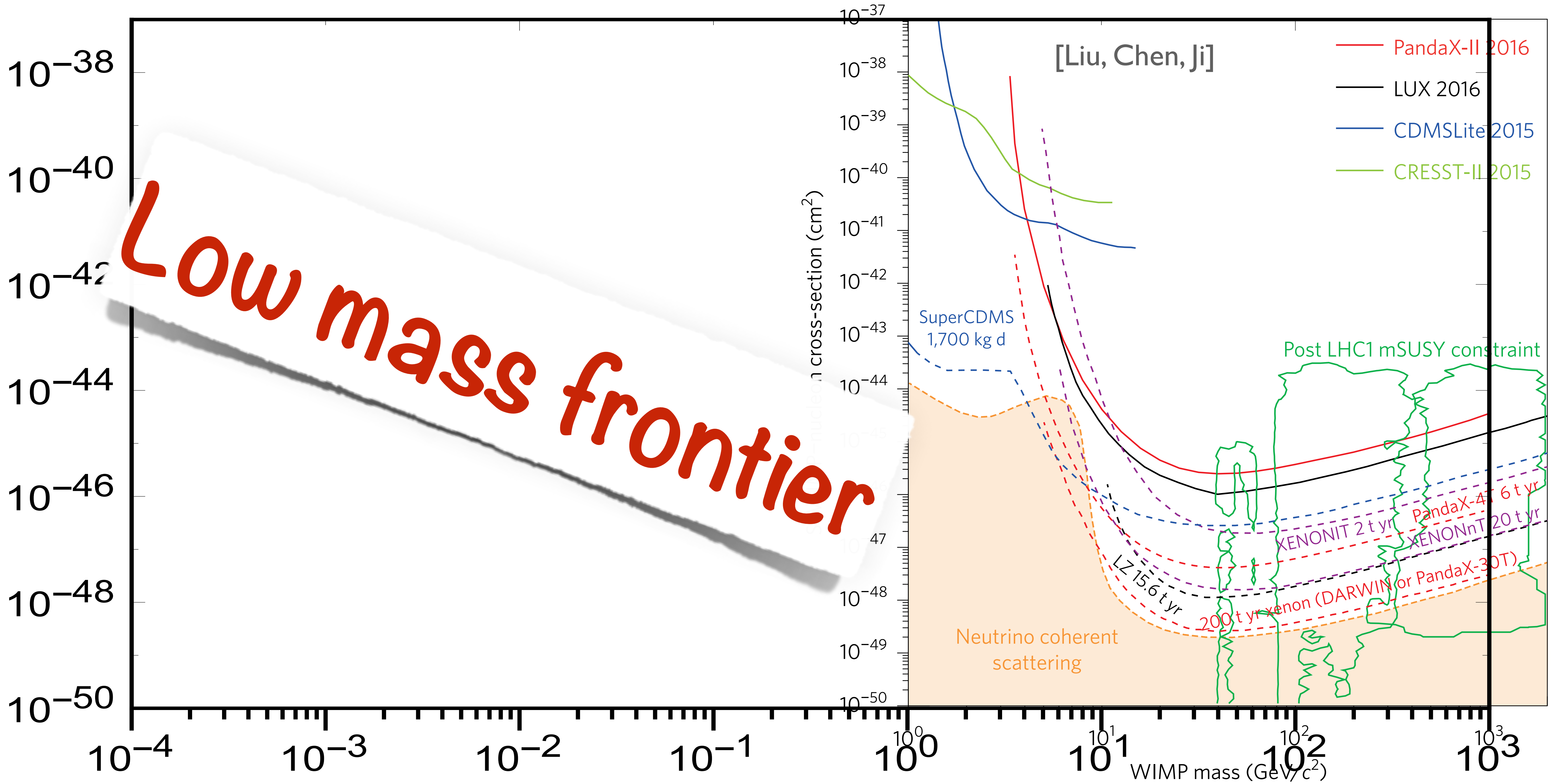
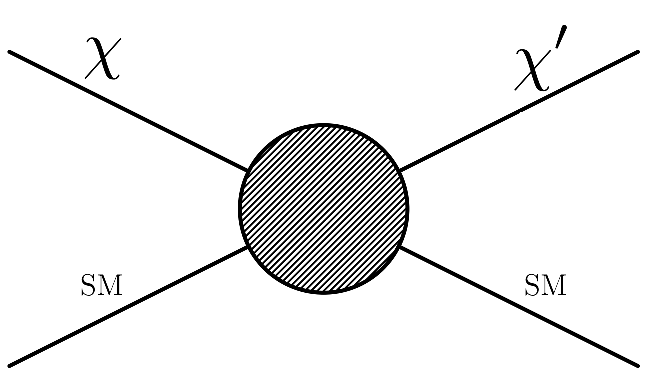
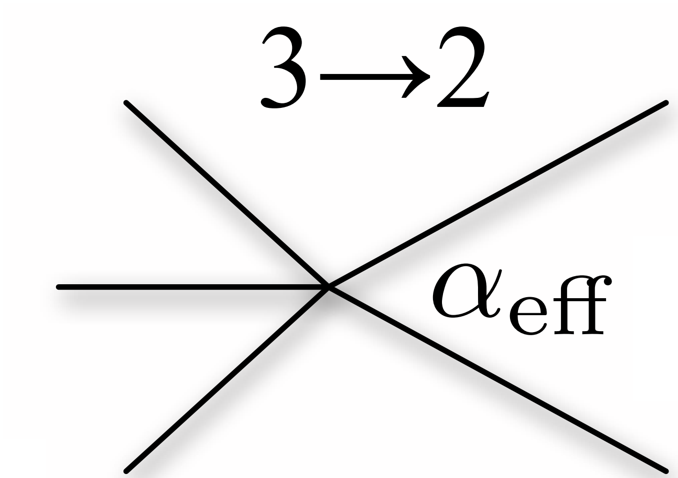


Hidden sector DM

- DM interacts through *new* mediators
  - “dark photon”, U-boson, Z’, secluded mediator,….
  - dark Higgs
  - pseudo scalars, ALPs
  - ….
- Portal interactions
- Thermal relic, now can annihilate within the dark sector
- Allows for lighter DM
  - ~1 keV — ~100 TeV
- Search for all dark sector particles
  - Direct, indirect, collider, self-coupling





Hidden sector DM

$$\frac{\epsilon}{16\pi^2} F'_{\mu\nu} B_Y^{\mu\nu}$$

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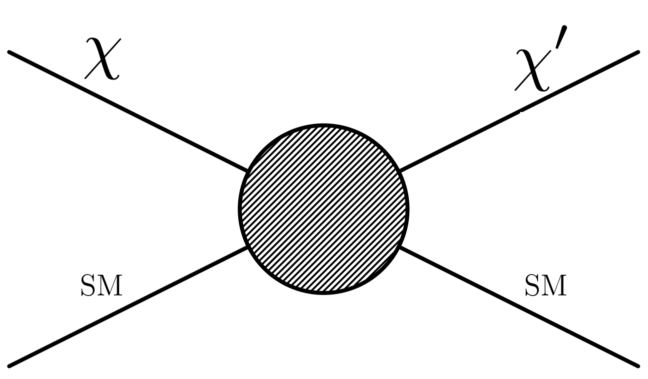

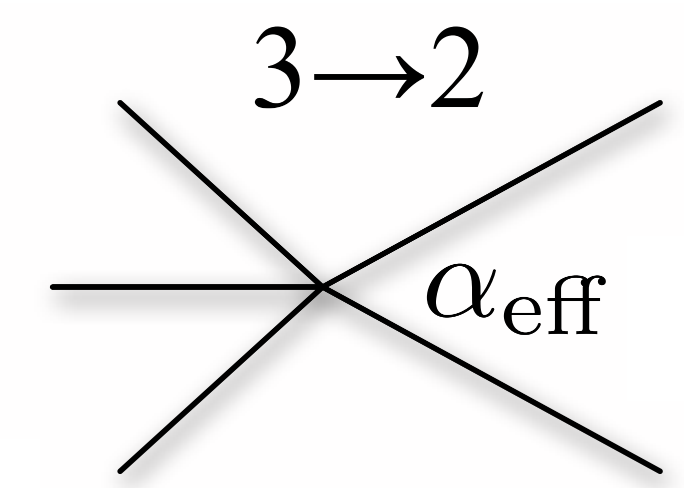

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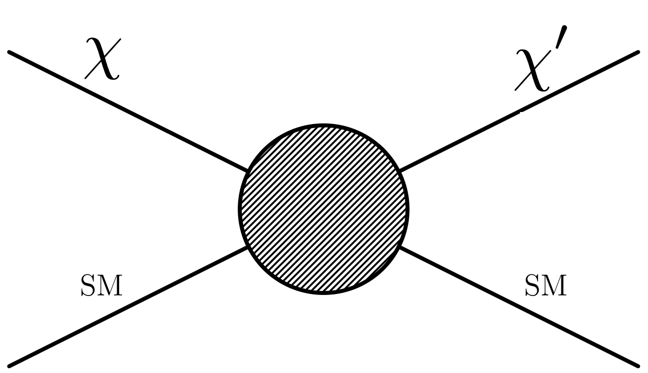
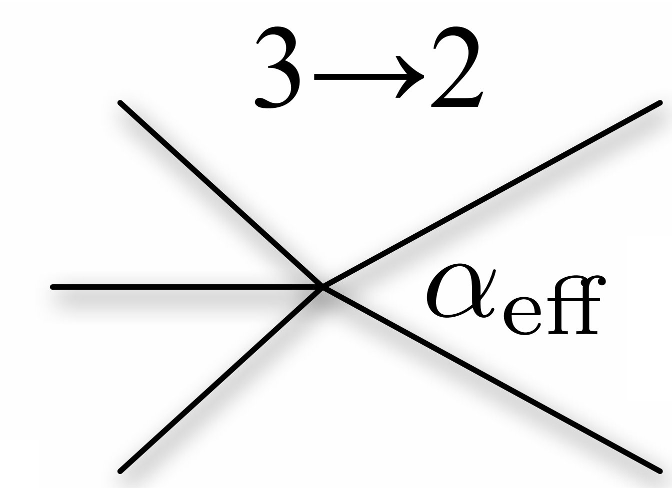
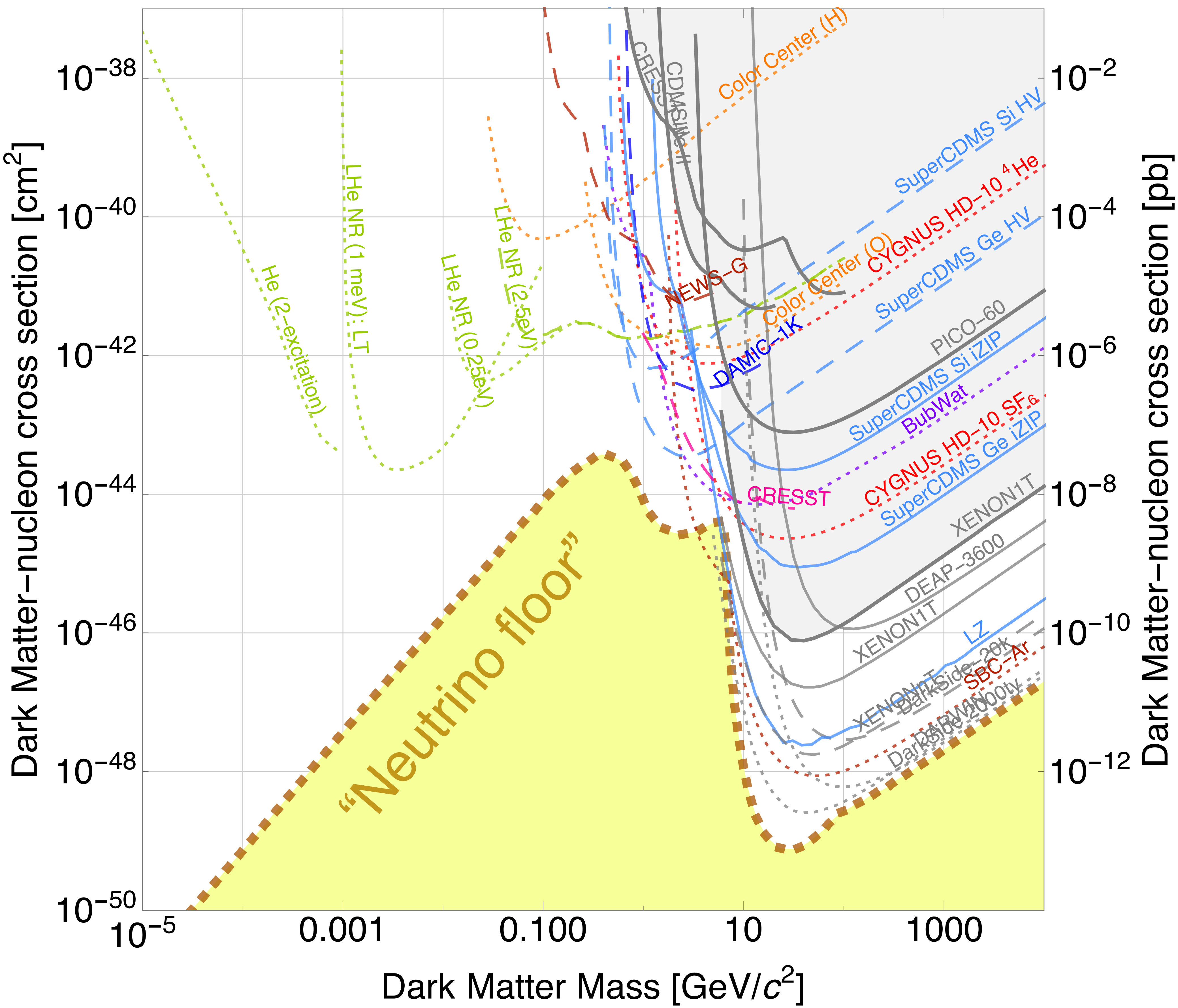
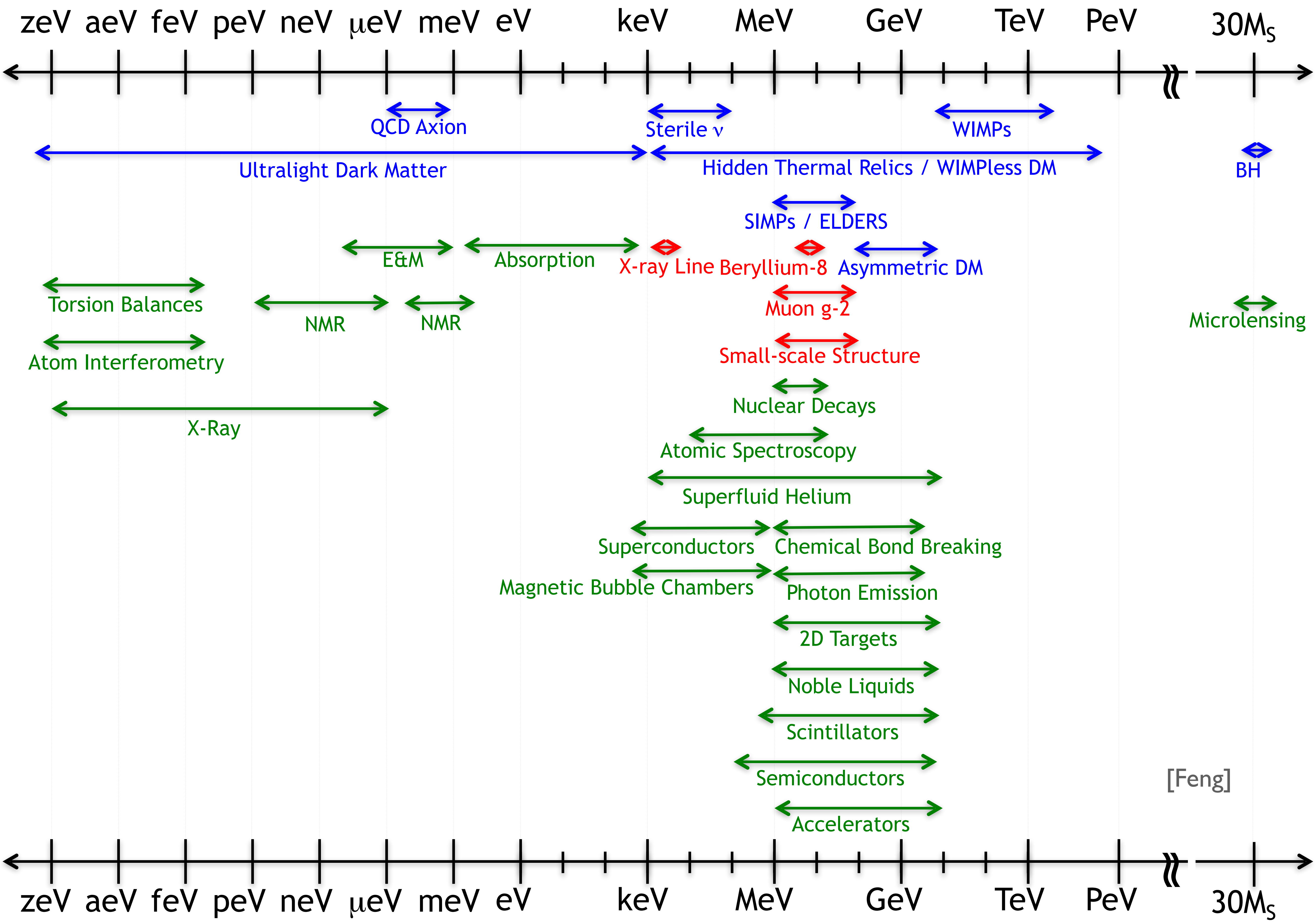


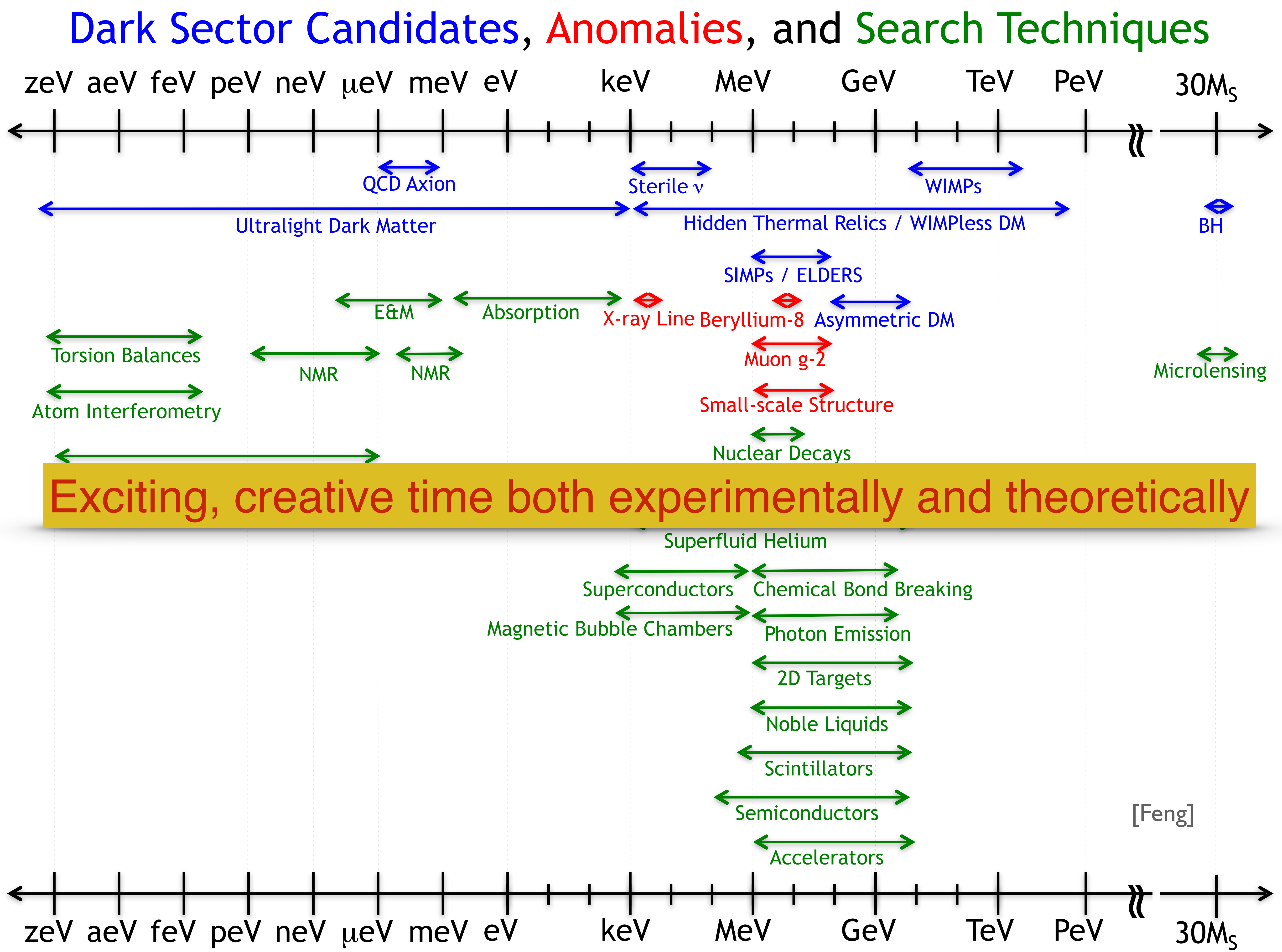


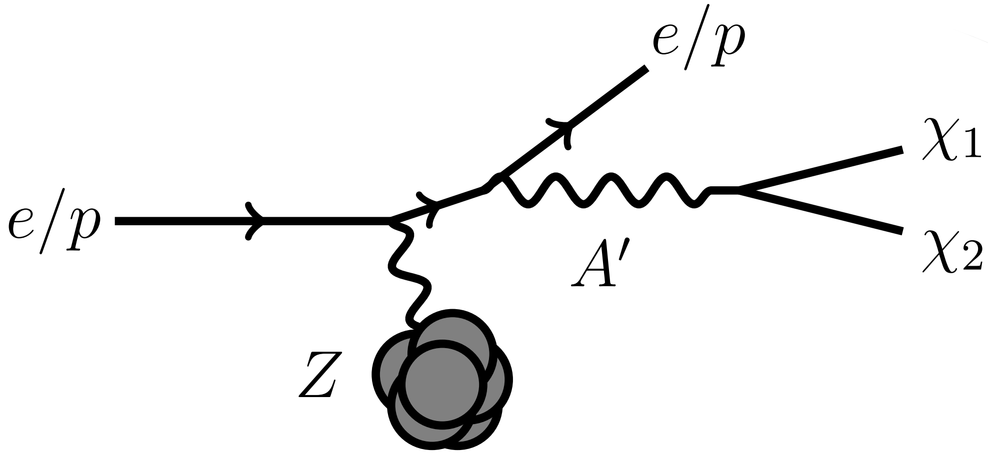


Dark Matter–nucleon cross section [cm^2]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-5}
0.001
0.100
10
1000
"Neutrino floor"
He (2-excitation)
LHe NR (1 meV): LT
LHe NR (0.25eV)
LHe NR (2.5eV)
CRESST
CDMSlite II
Color Center (H)
Color Center (O)
SuperCDMS Si HV
CYGNUS HD-10 ^{4}He
SuperCDMS Ge HV
NEWS-G
DAMIC-1K
PICO-60
SuperCDMS Si iZIP
BubWat
CYGNUS HD-10 SF_6
SuperCDMS Ge iZIP
CRESST
XENON1T
DEAP-3600
XENON1T
LZ
SBC-Ar
XENONnT
DarkSide-20k
DARWIN
DarkSide 2000ty

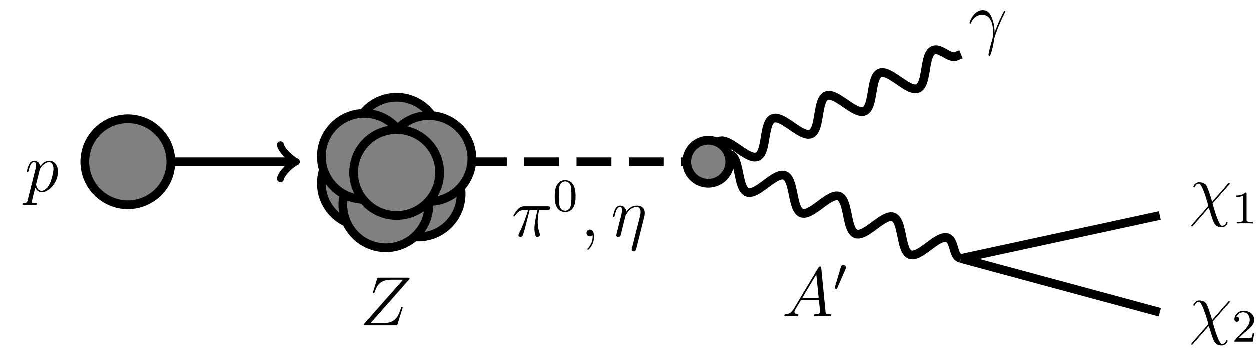
Dark Sector Candidates, Anomalies, and Search Techniques



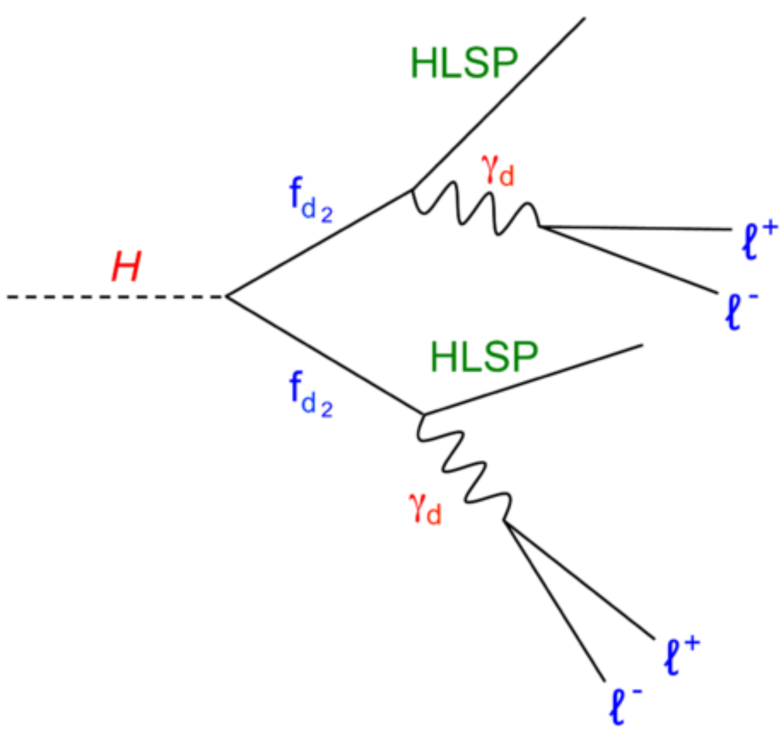

Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M$_S$
QCD Axion
Sterile ν
WIMPs
Ultralight Dark Matter
Hidden Thermal Relics / WIMPless DM
BH
SIMPs / ELDERS
E&M
Absorption
X-ray Line
Beryllium-8
Asymmetric DM
Torsion Balances
NMR
NMR
Muon g-2
Microlensing
Atom Interferometry
Small-scale Structure
Nuclear Decays
Exciting, creative time both experimentally and theoretically
Superfluid Helium
Superconductors
Chemical Bond Breaking
Magnetic Bubble Chambers
Photon Emission
2D Targets
Noble Liquids
Scintillators
Semiconductors
[Feng]
Accelerators
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M$_S$



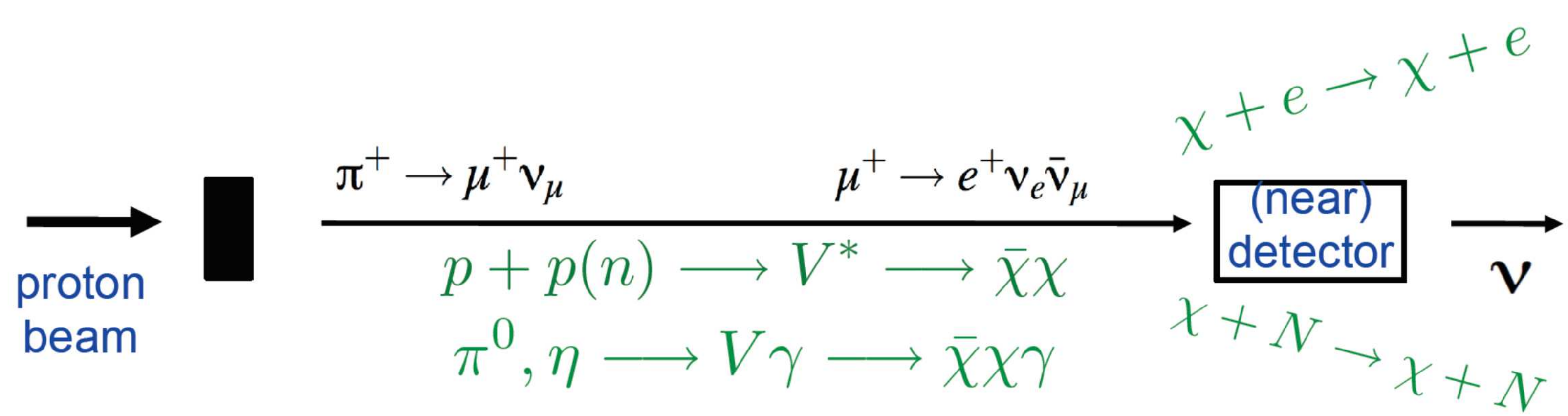
Bremsstrahlung
(LDMX, DarkLight, …)



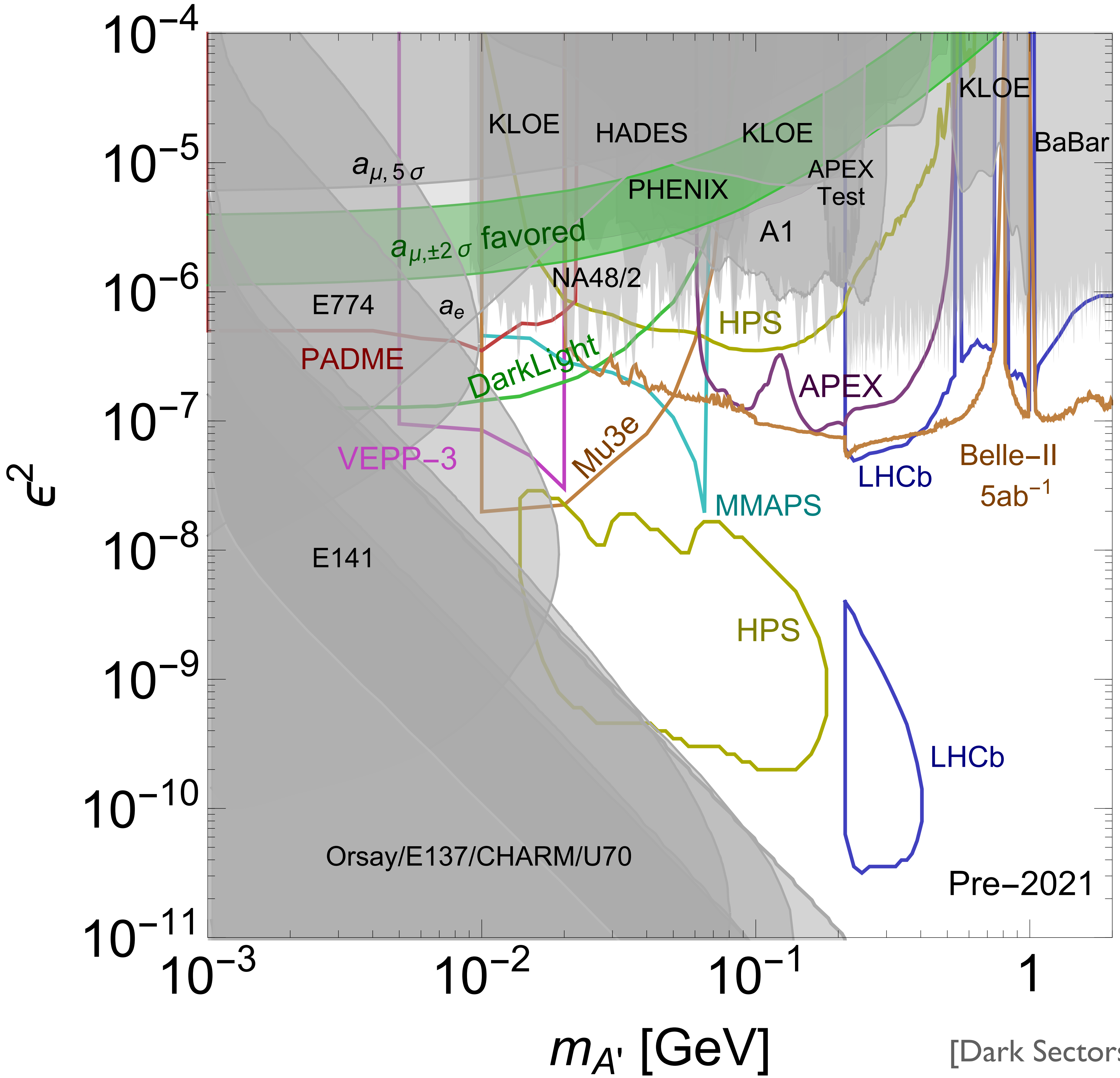
Meson decay
(NA48)



Lepton jets, Emerging tracks
(LHC)

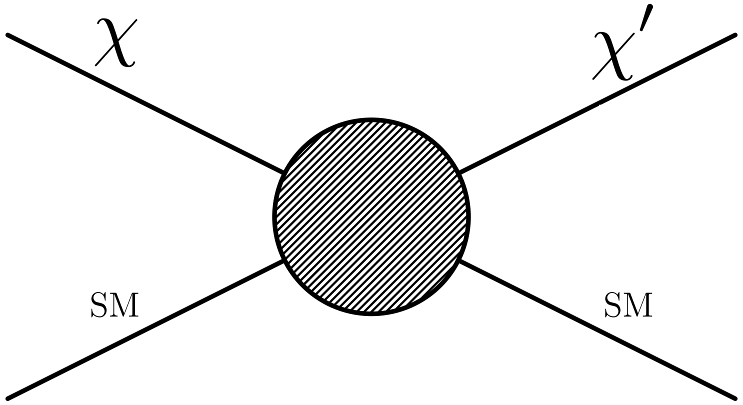


Production and scattering
(MiniBooNE, SHiP, etc…)

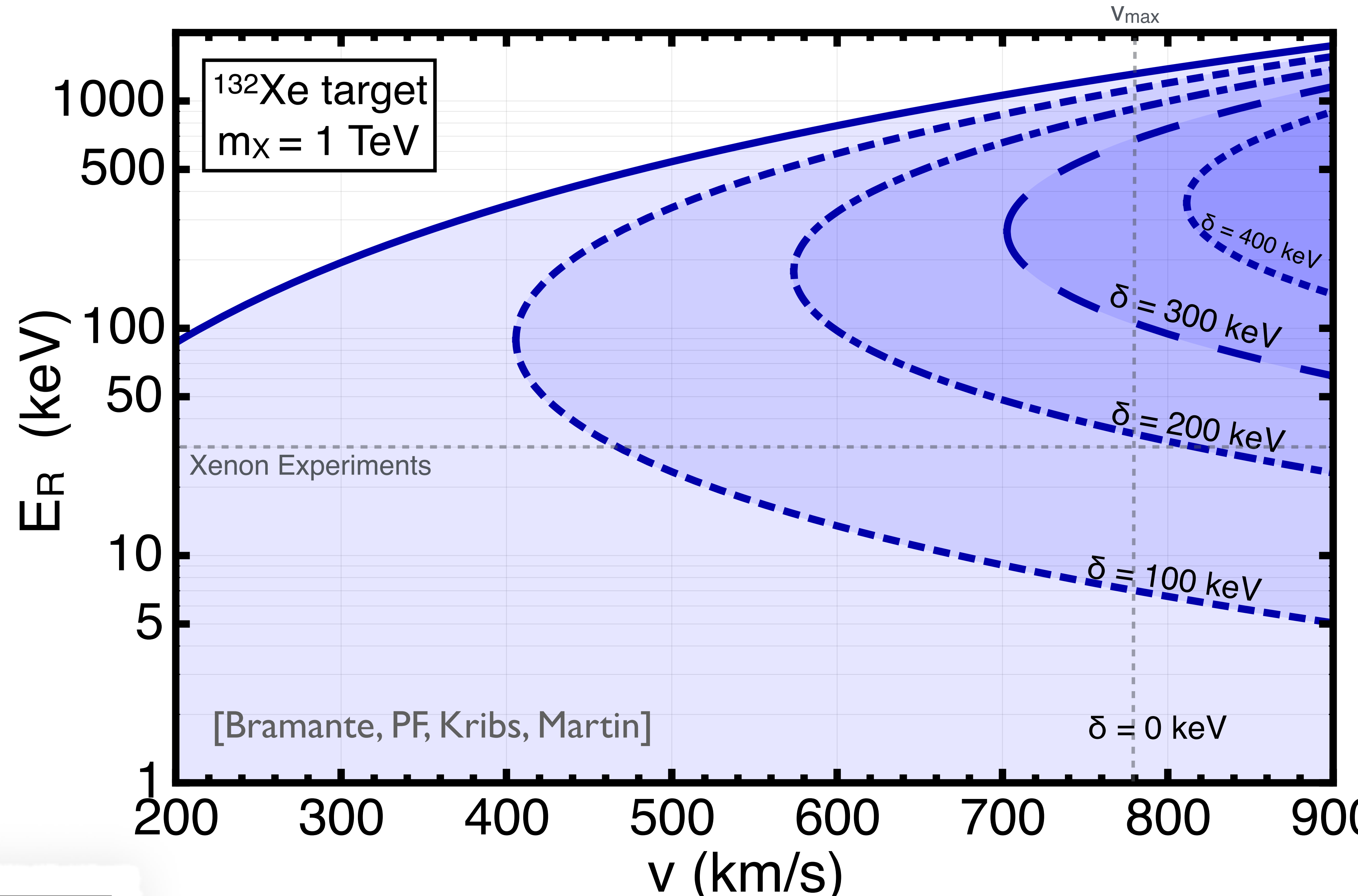


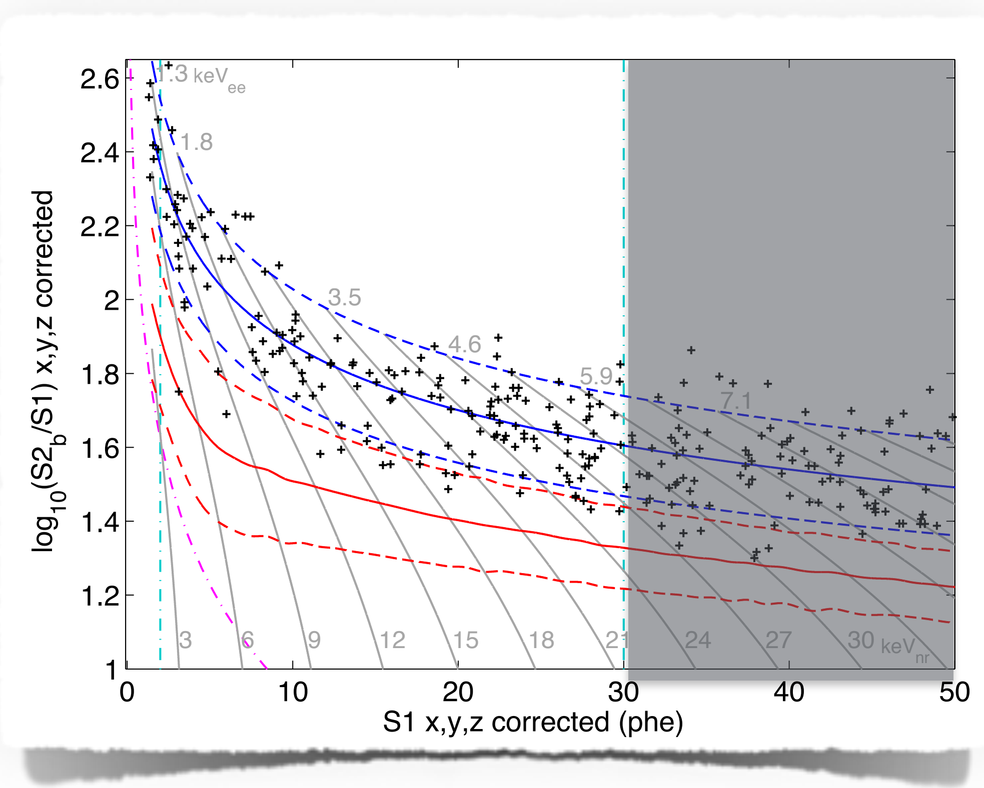
[Dark Sectors WS]

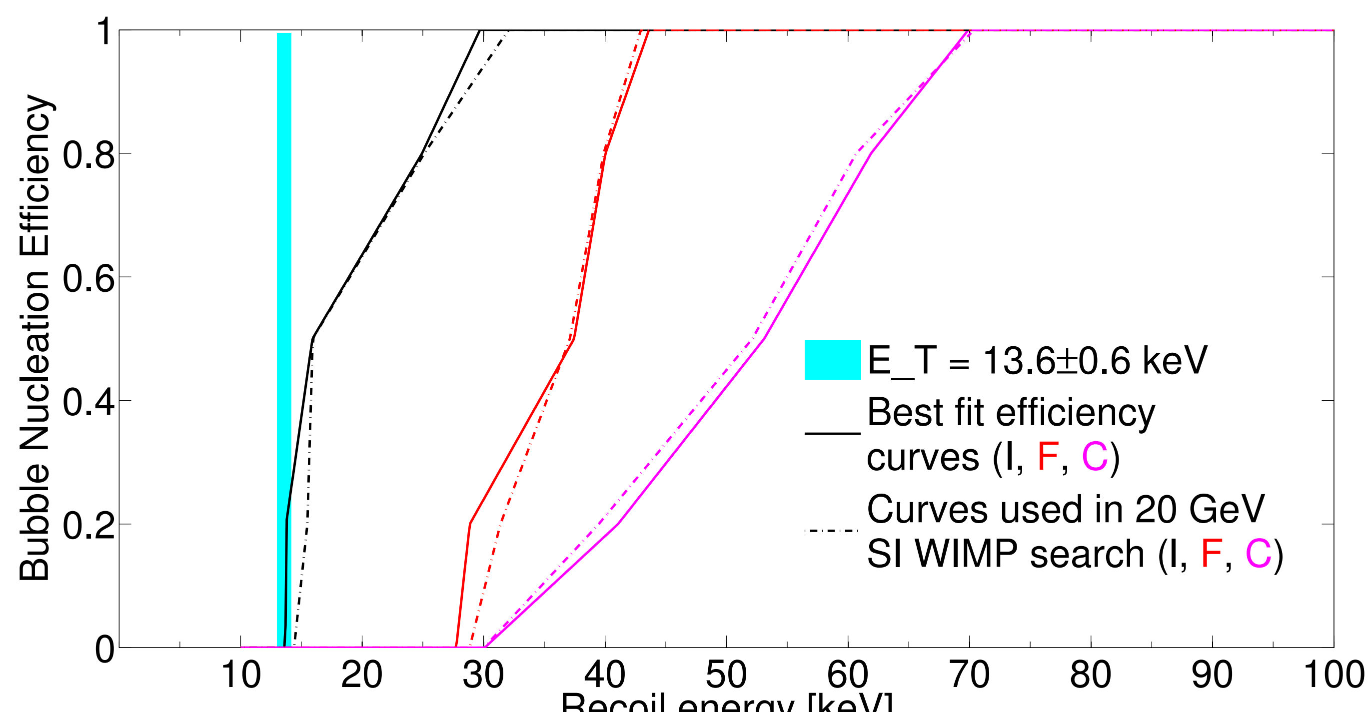
Inelastic DM



LUX(and others) "blind" to iDM with splittings above ~200 keV







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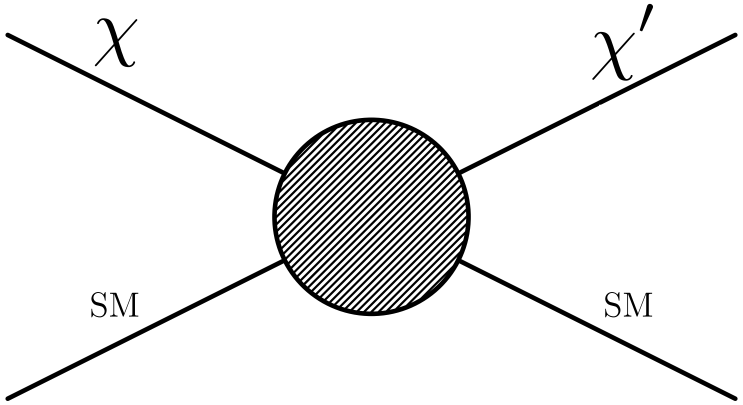

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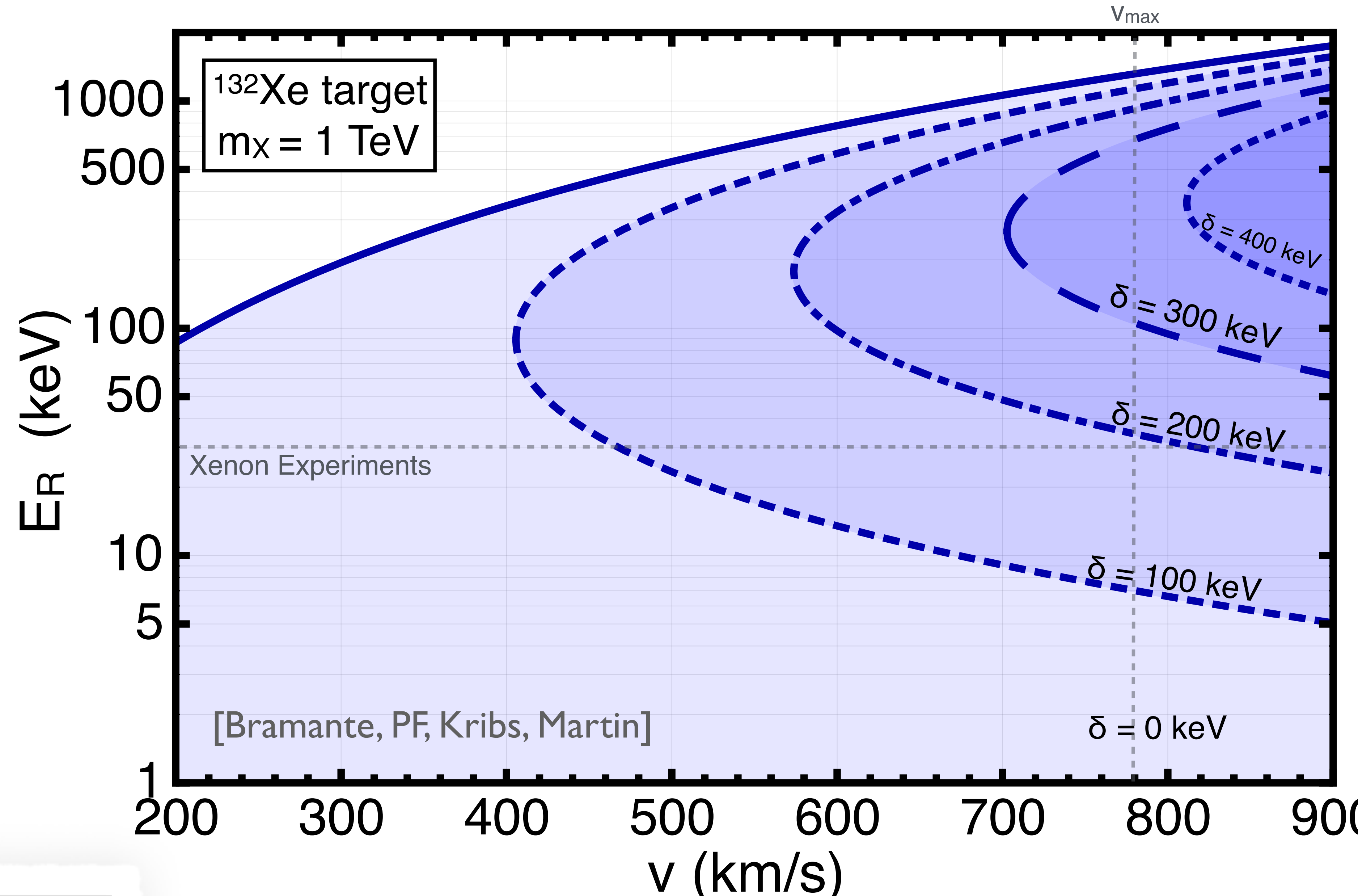
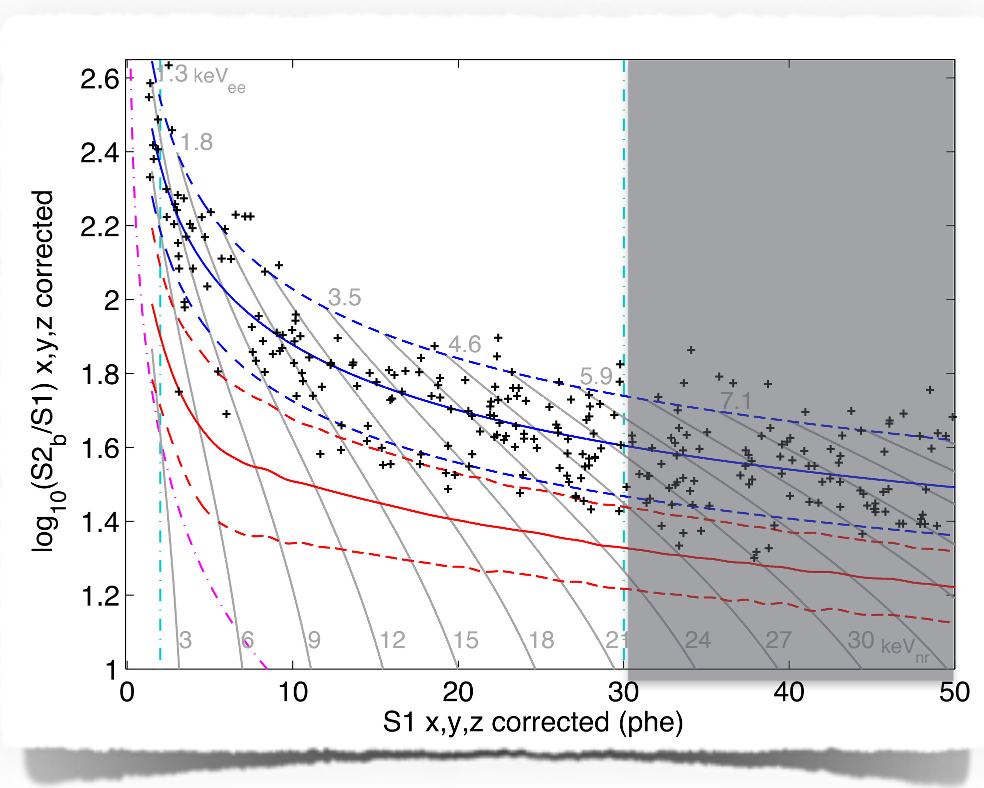
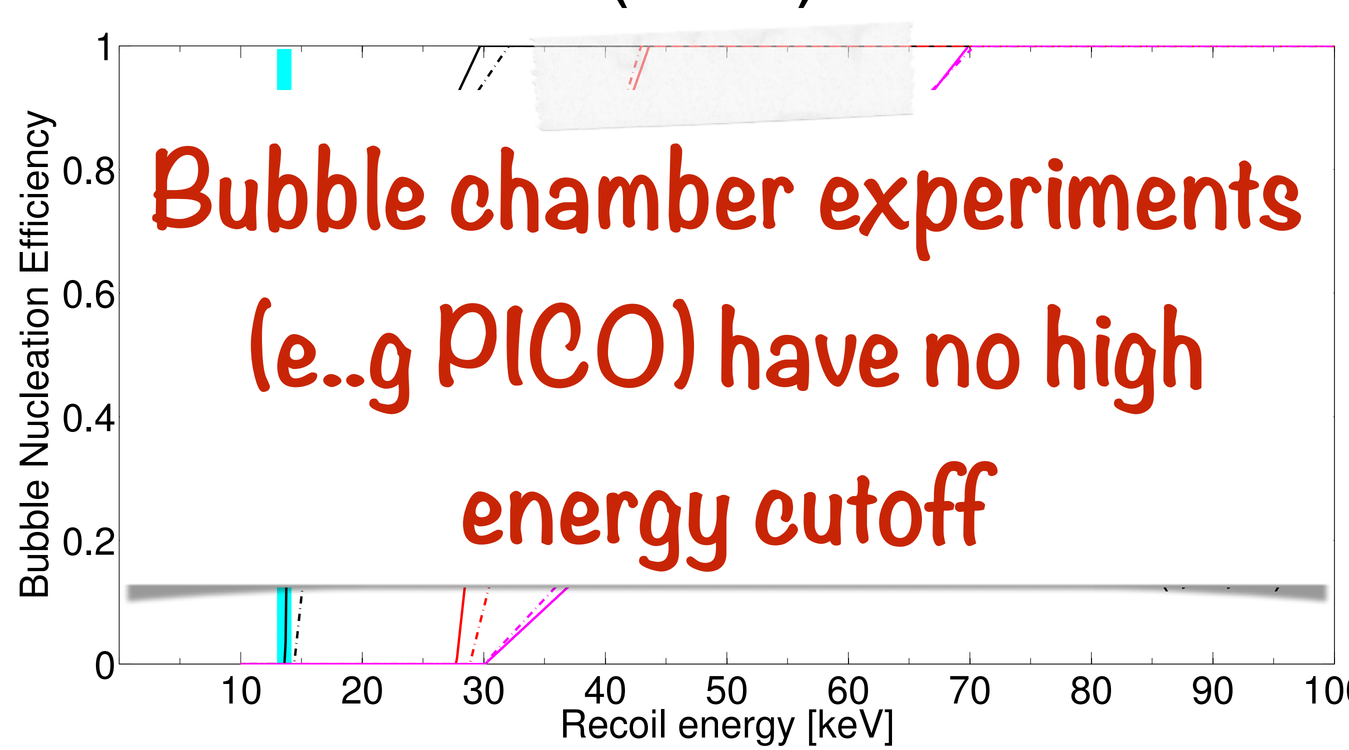






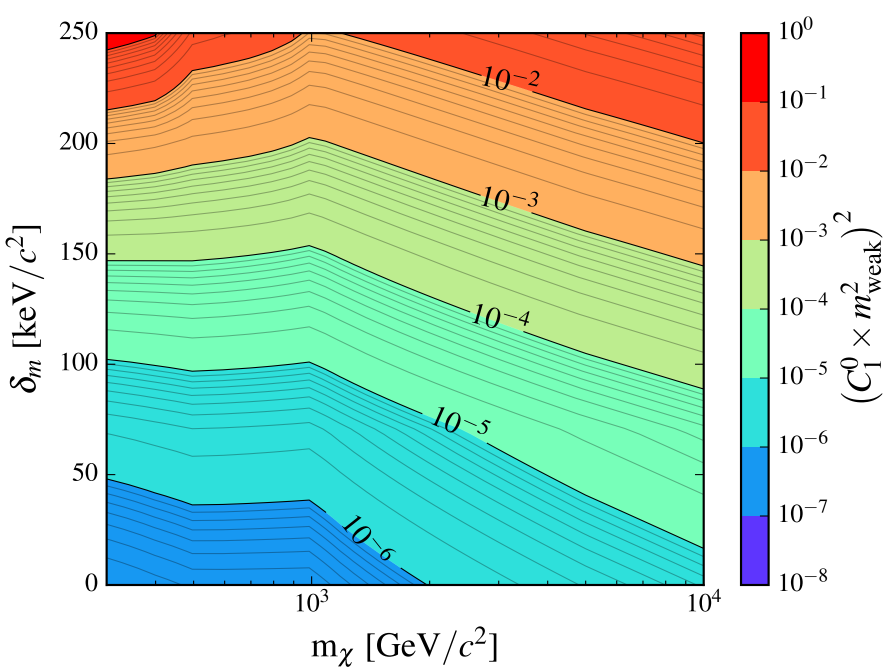
Crossing the Inelastic Frontier—Xenon100 & PandaX

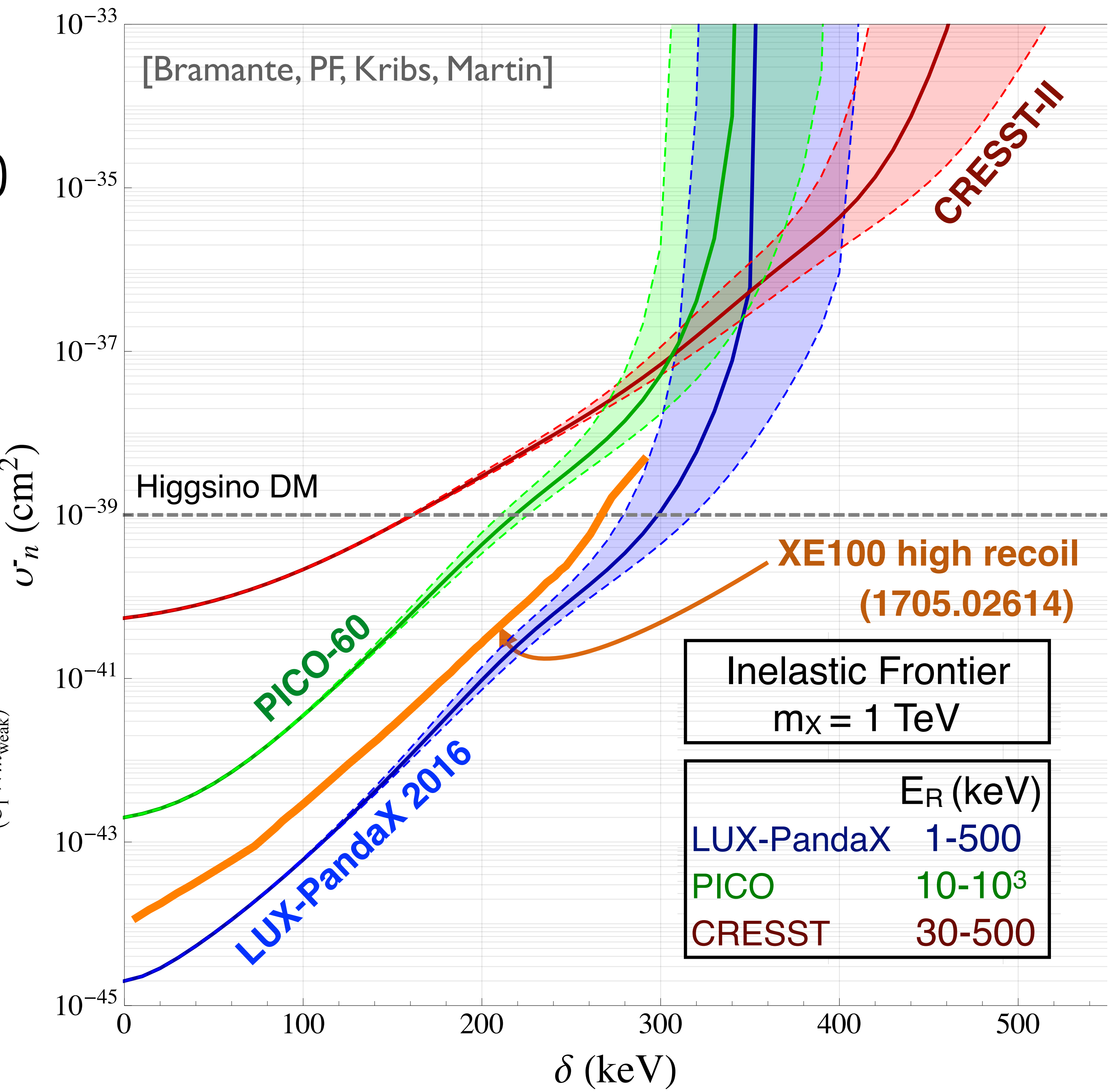
Reanalysis

7.6 ton-days, Xe100

6.6-240 keVnr

Inelastic analysis





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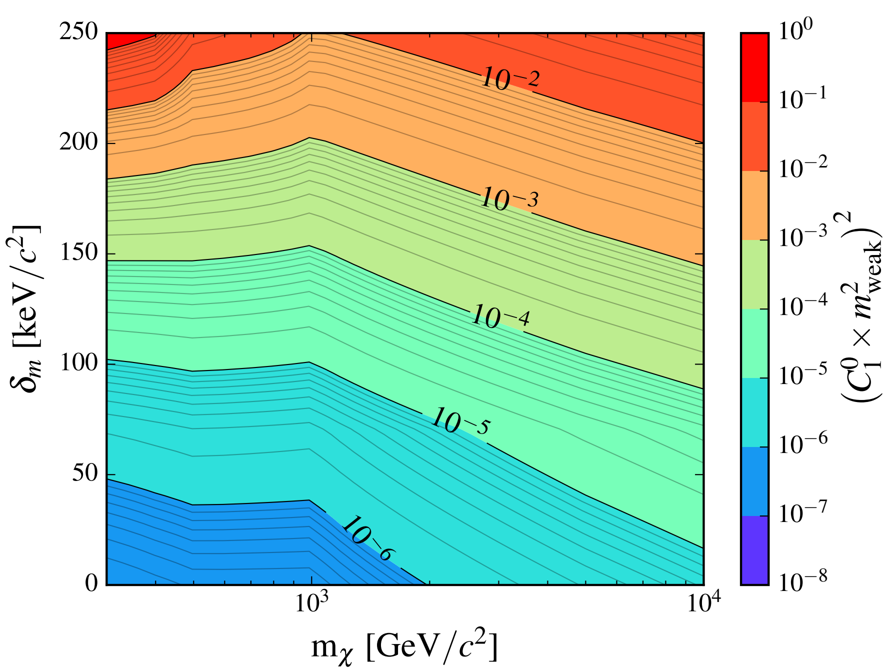
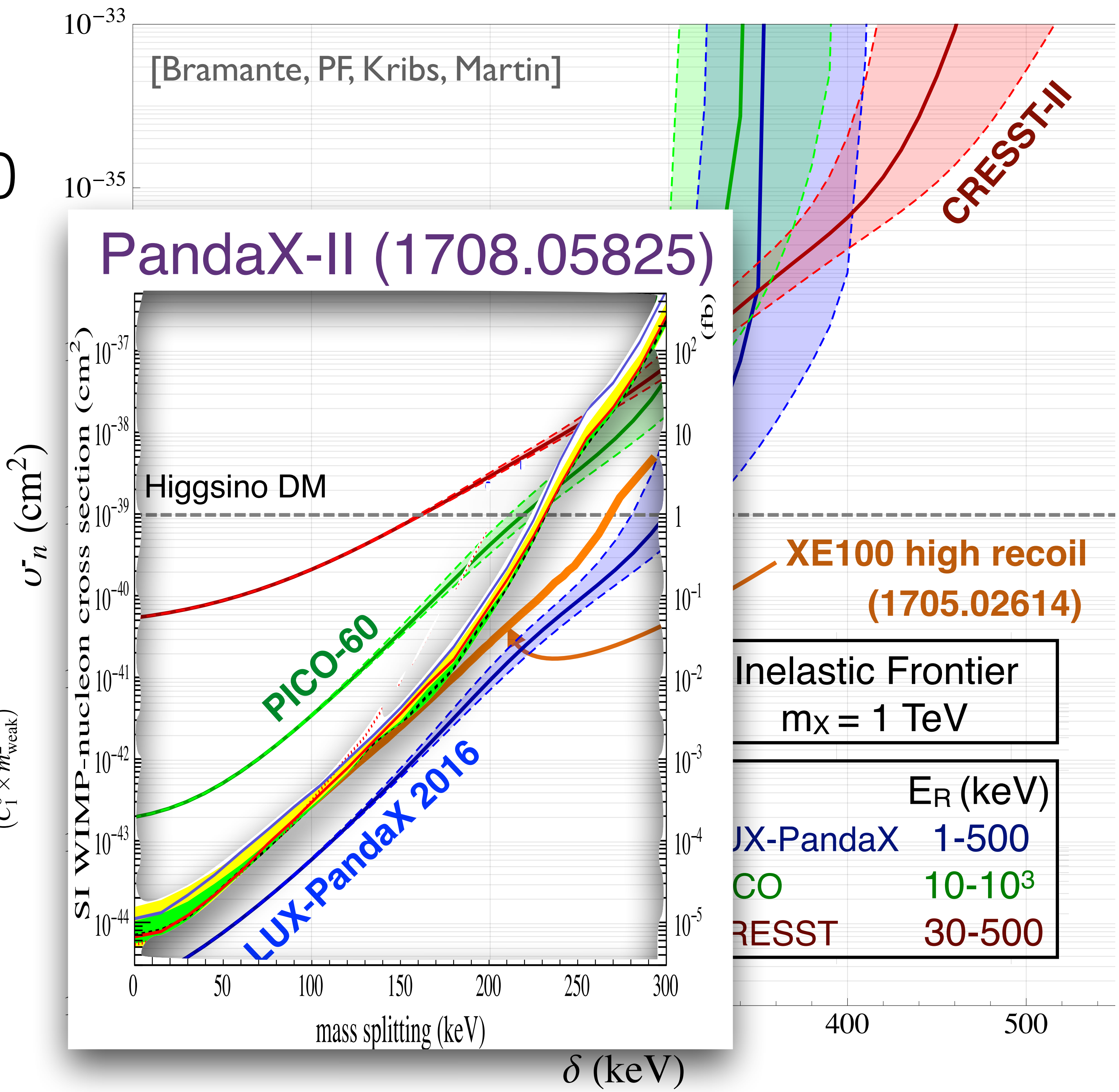
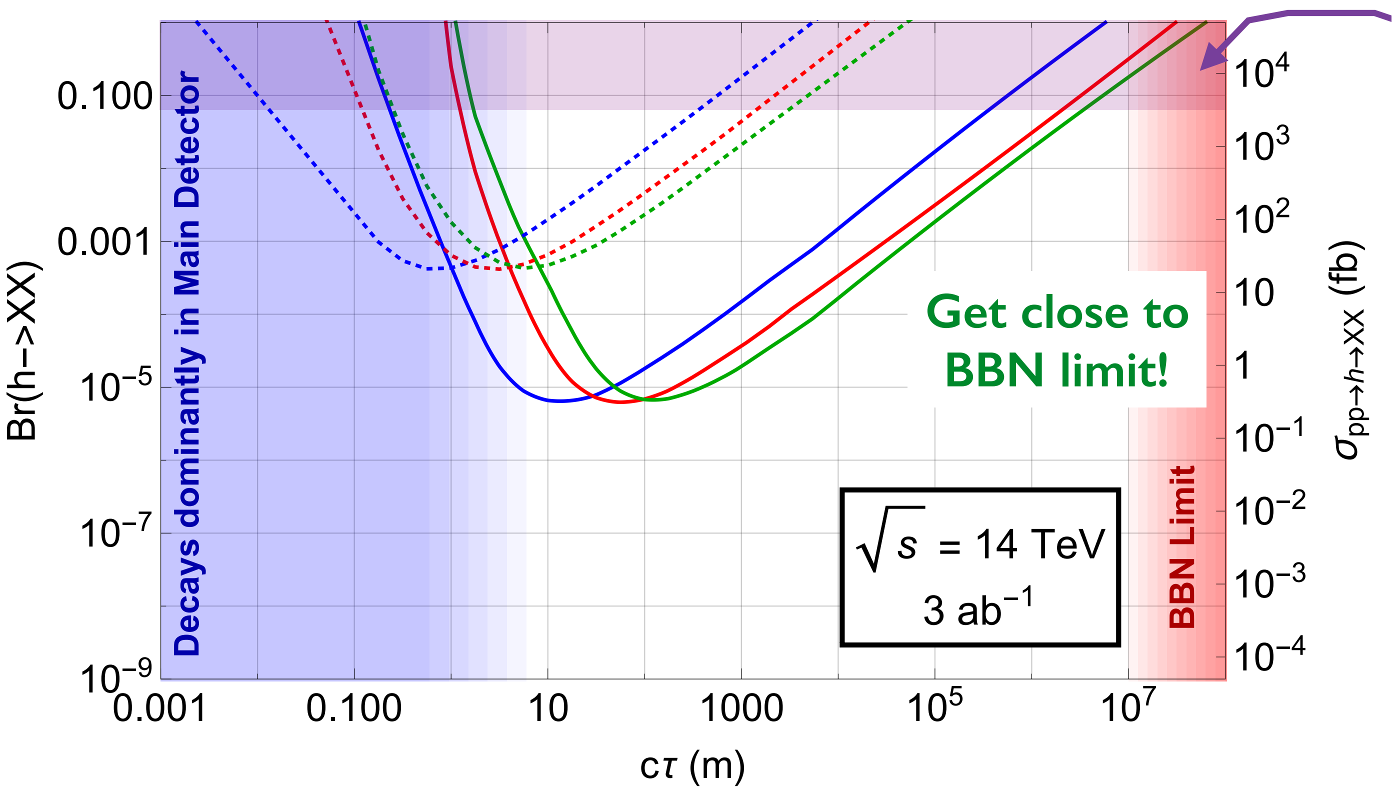
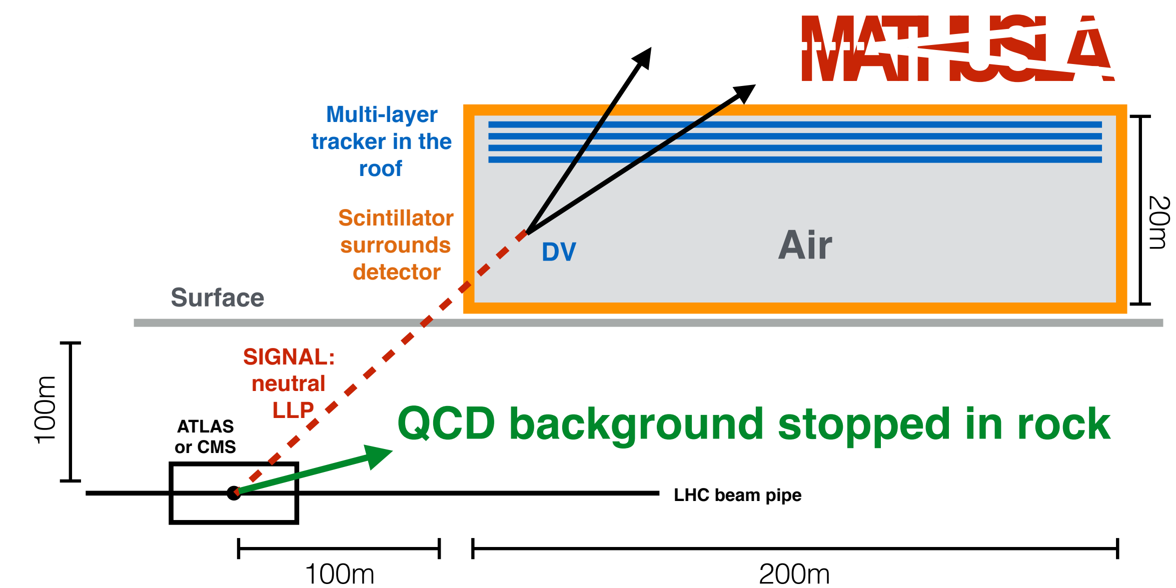
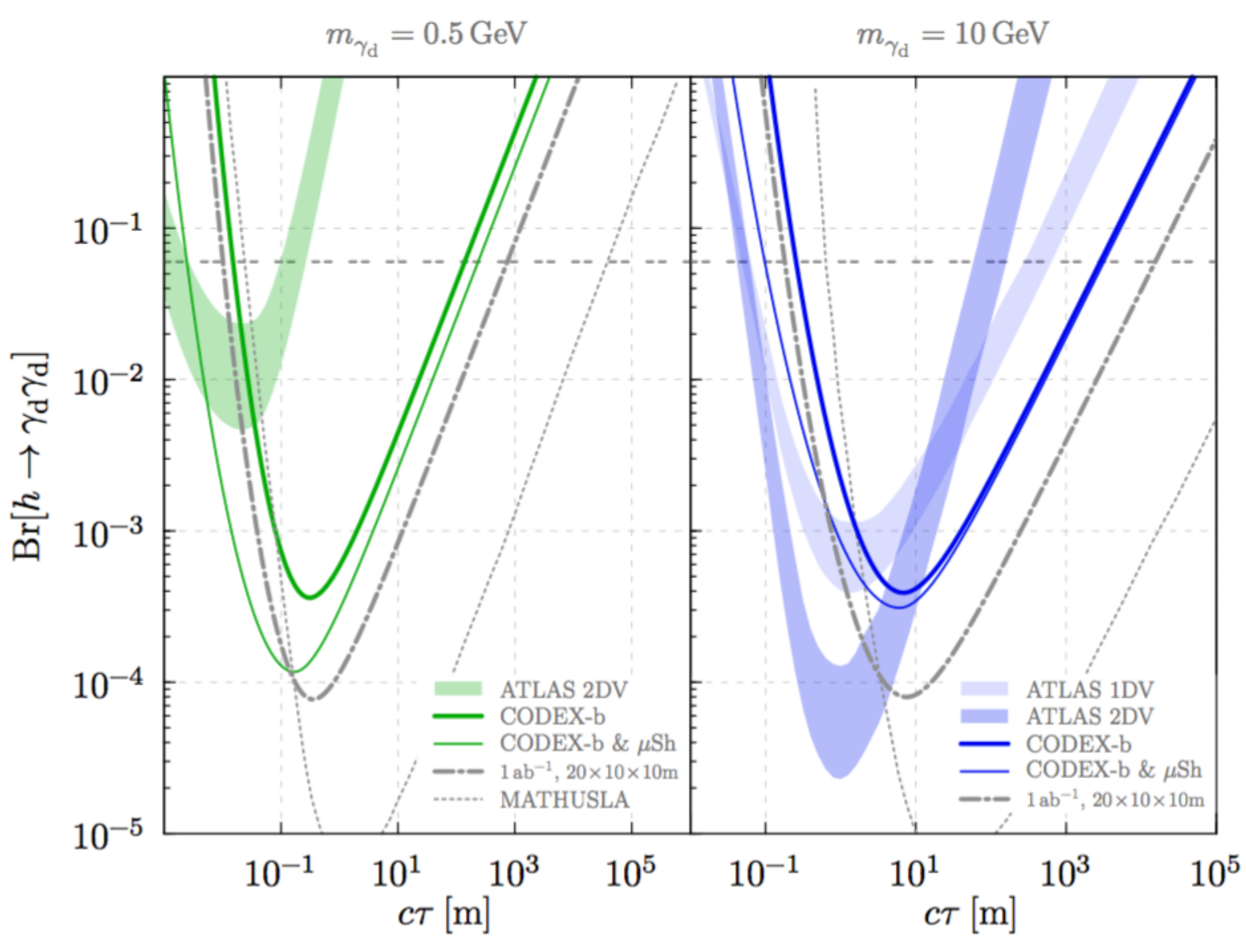


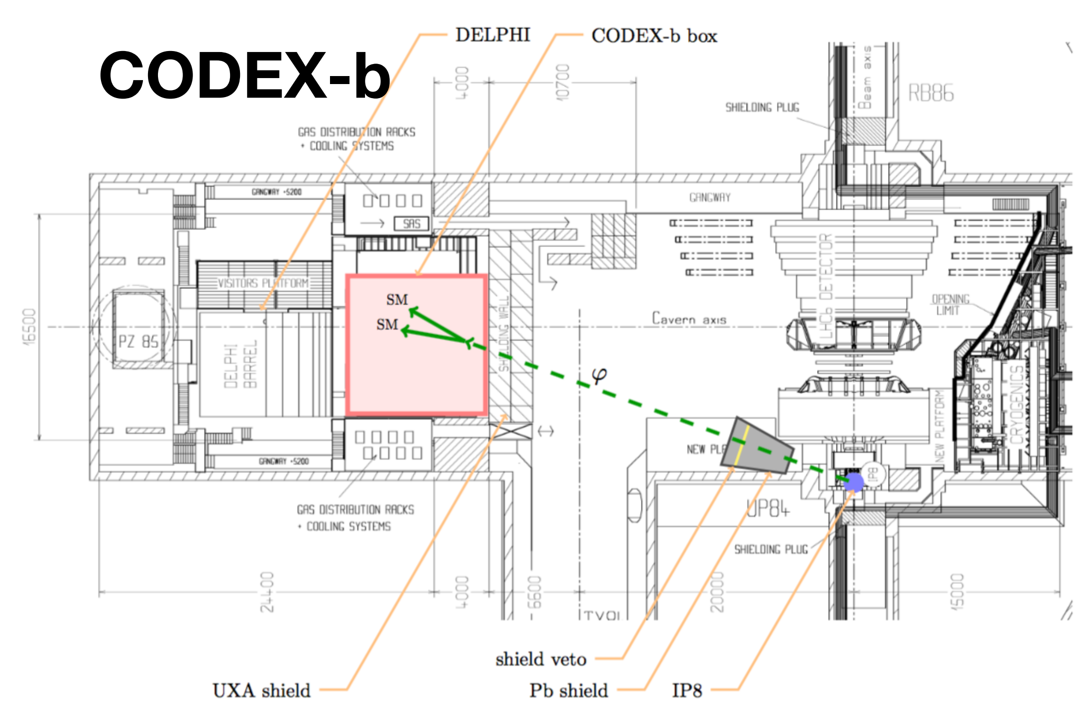


LLP: new detectors @ LHC









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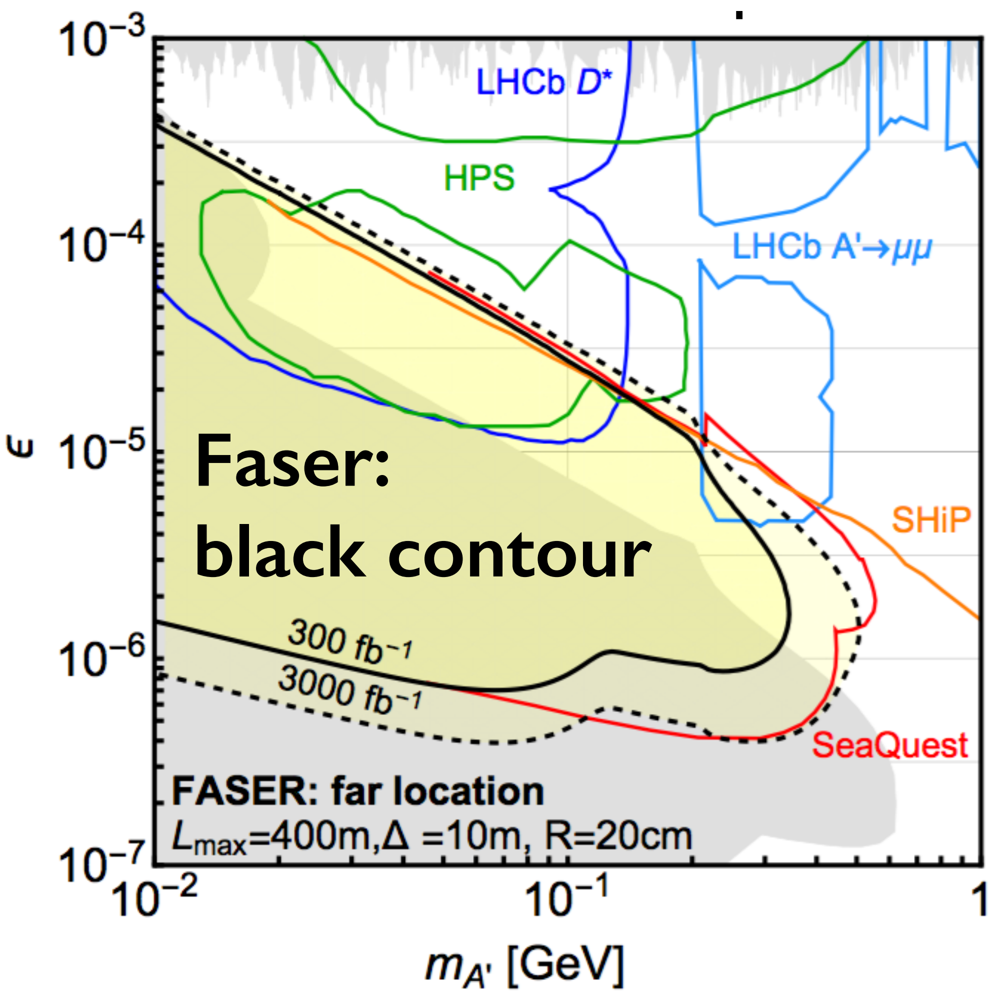
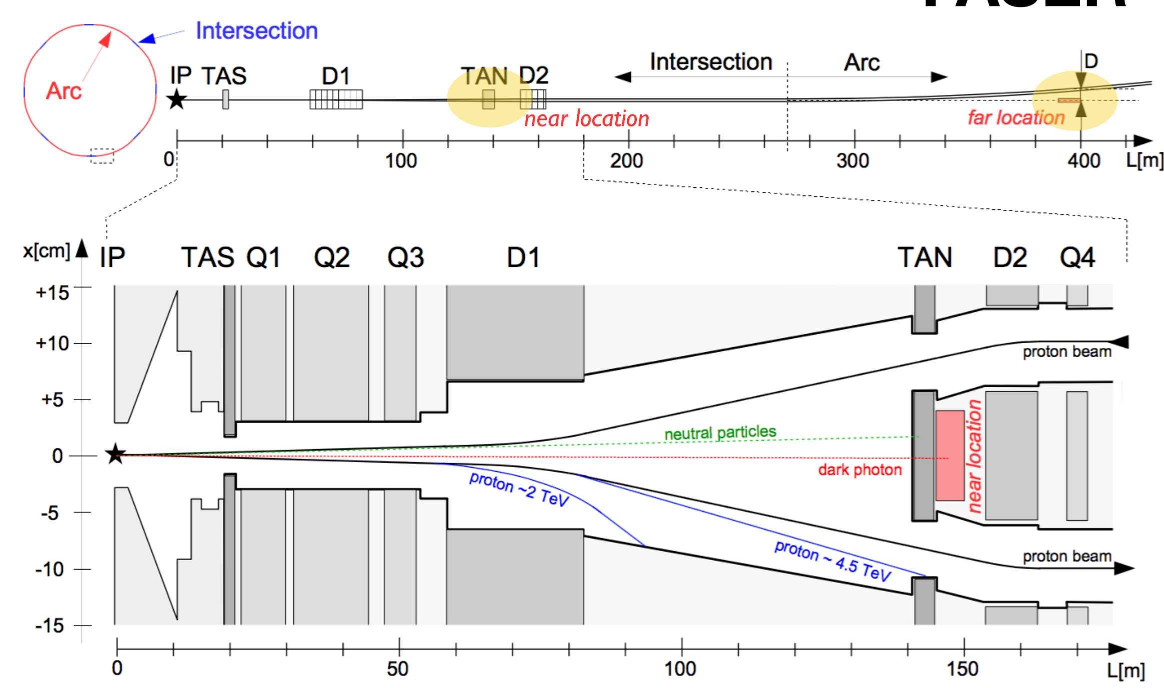
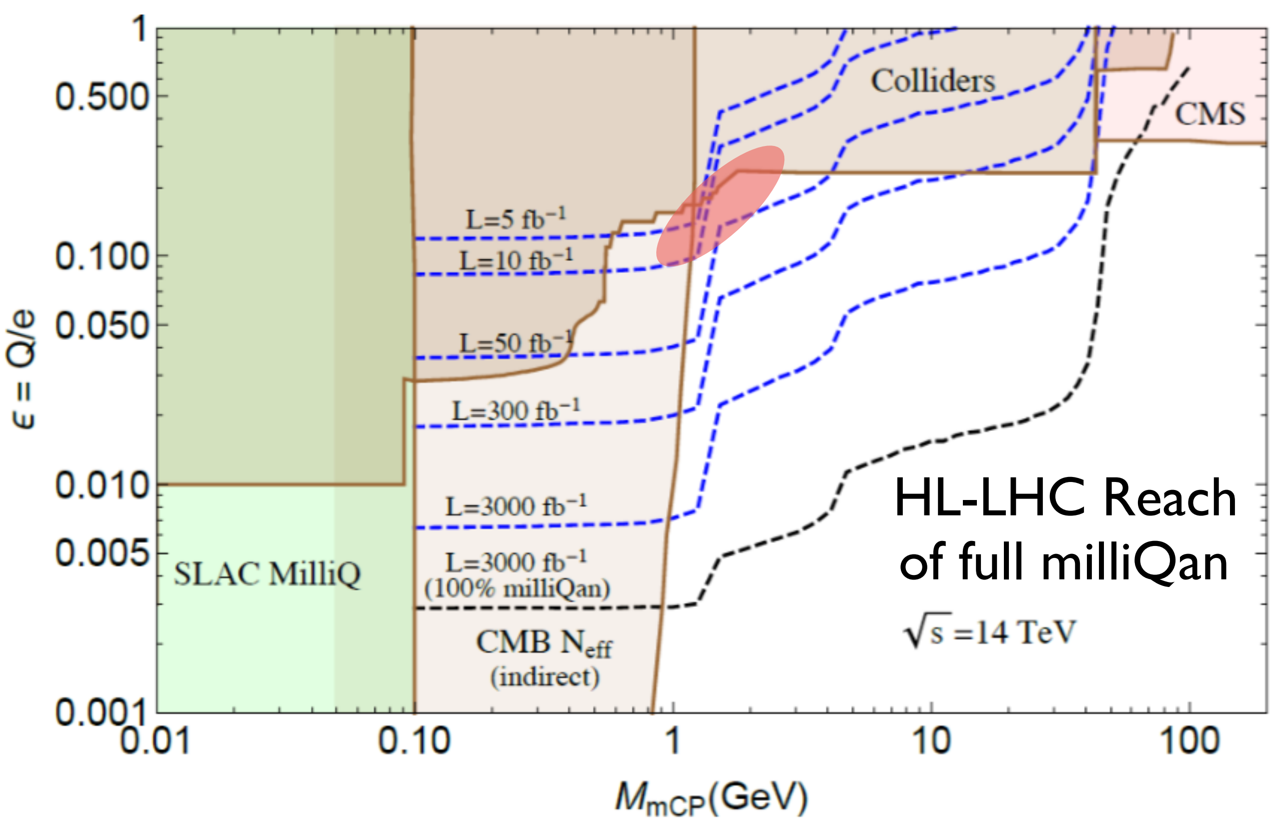
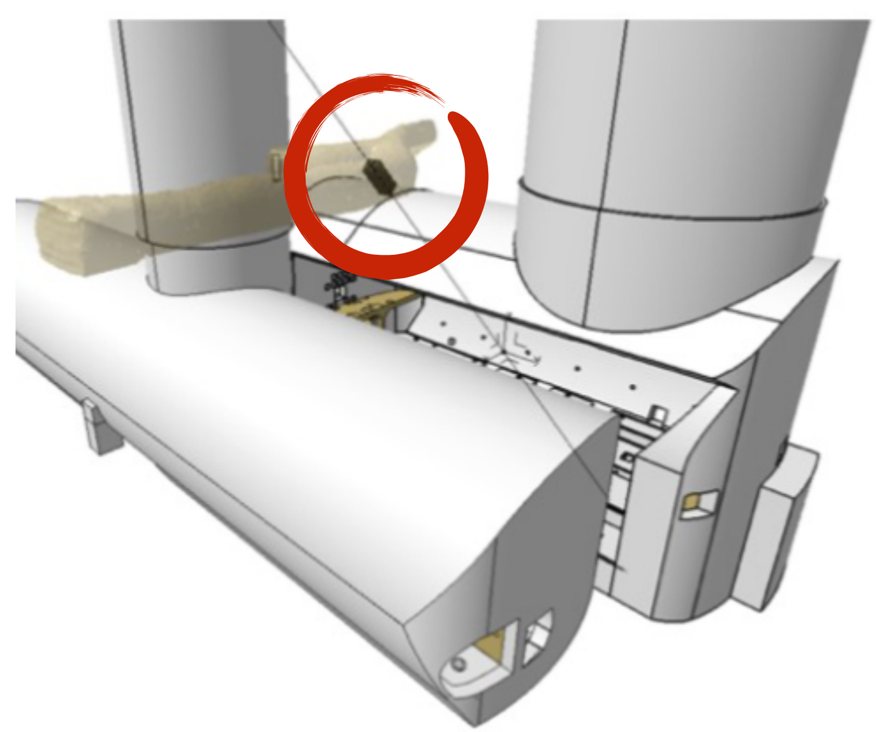


FASER





MilliQan



DM Outlook

No longer your advisor's DM

- Models of DM have come a long way in 20 years
- **Result of vibrant experiment-theory interface**
- Entering a new era in Dark Matter research, involving physics on many scales (nuclear, cond. matt., and atomic)
- **Many possibilities, many search opportunities**
- **Dark sectors possible (likely?) — non-trivial dynamics**

DM exists

No non-gravitational detection yet

The hierarchy problem

Hierarchy (Naturalness) problem

$$\mathcal{L}_2 = \pm\mu^2|H|^2$$

Why is μ so much smaller than M_{GUT}, M_{Pl}?

Unlike fermions (and gauge bosons) no symmetry protects scalar mass parameter

1. Nature is fine-tuned (anthropics?)
2. The SM has no high scales (gravity?, unification?)
3. New dynamics/symmetries keeps mass scale low

The hierarchy problem

Hierarchy (Naturalness) problem

$$\mathcal{L}_2 = \pm\mu^2|F$$

Why is μ sc

> There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.
>
> —Mark Twain
>
> (BSM model builder)

Unlike fermions (and gauge bosons) no symmetry protects scalar mass parameter

1. Nature is fine-tuned (anthropics?)
2. The SM has no high scales (gravity?, unification?)
3. New dynamics/symmetries keeps mass scale low

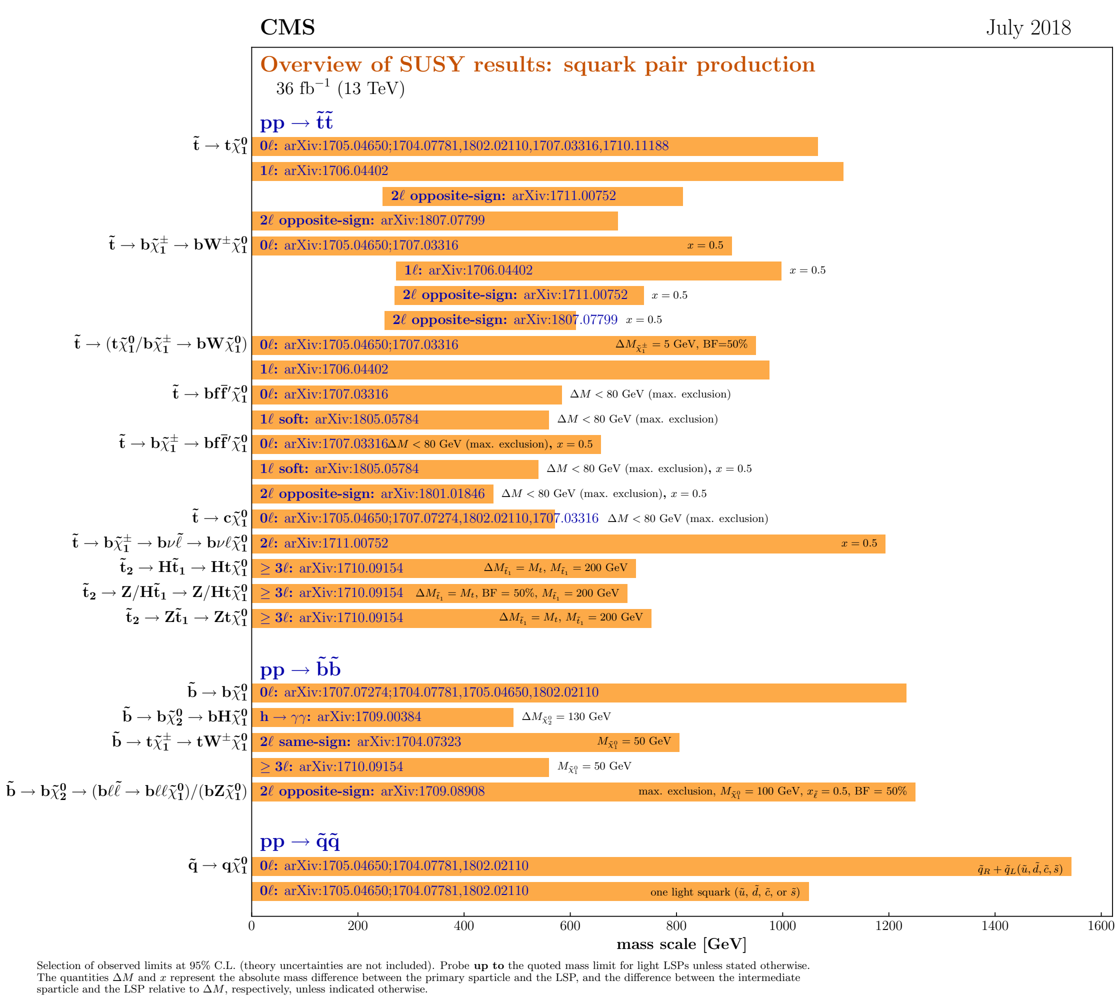
New particles coupled to Higgs

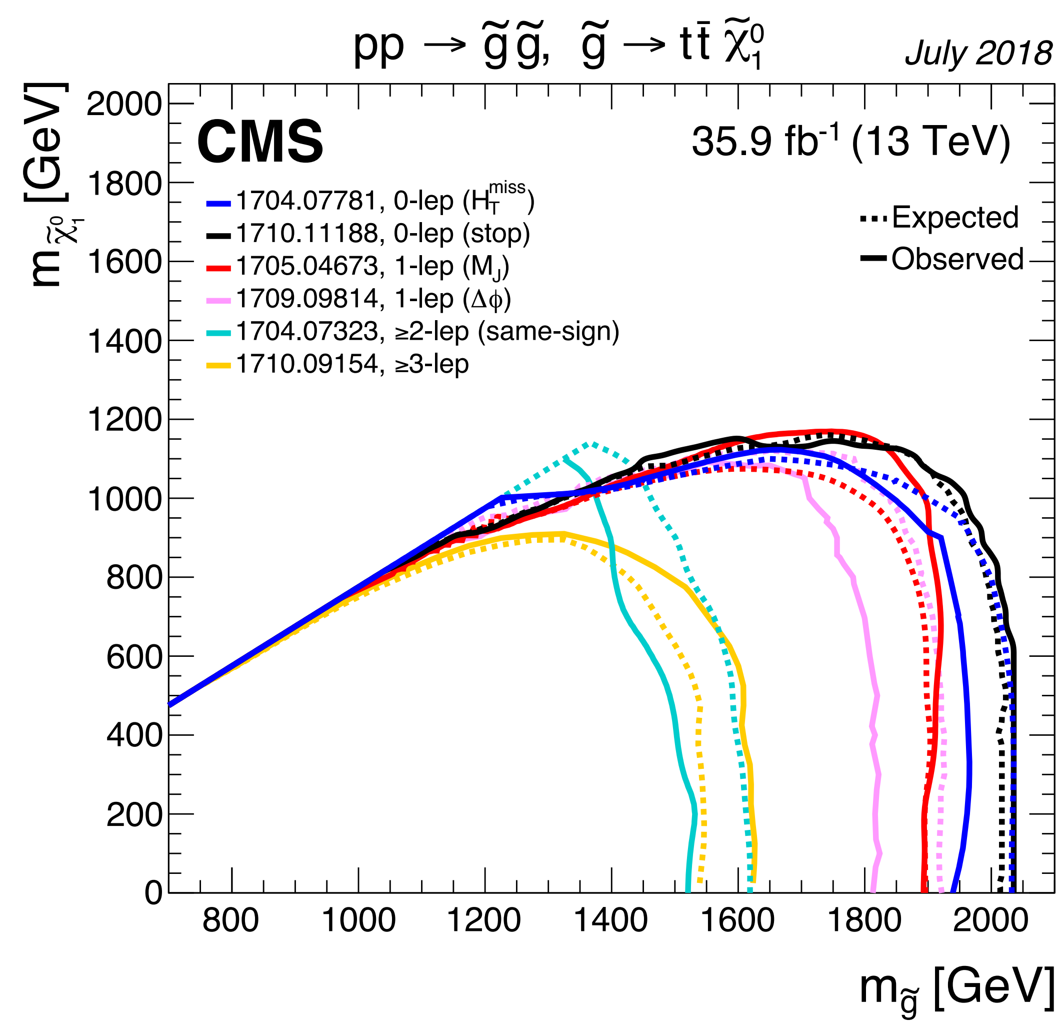
Usually have similar quantum numbers as the top, W, etc

e.g. SUSY, little Higgs

Strong constraints from LHC

Twin Higgs resurgence—no coloured partners





Twin Higgs

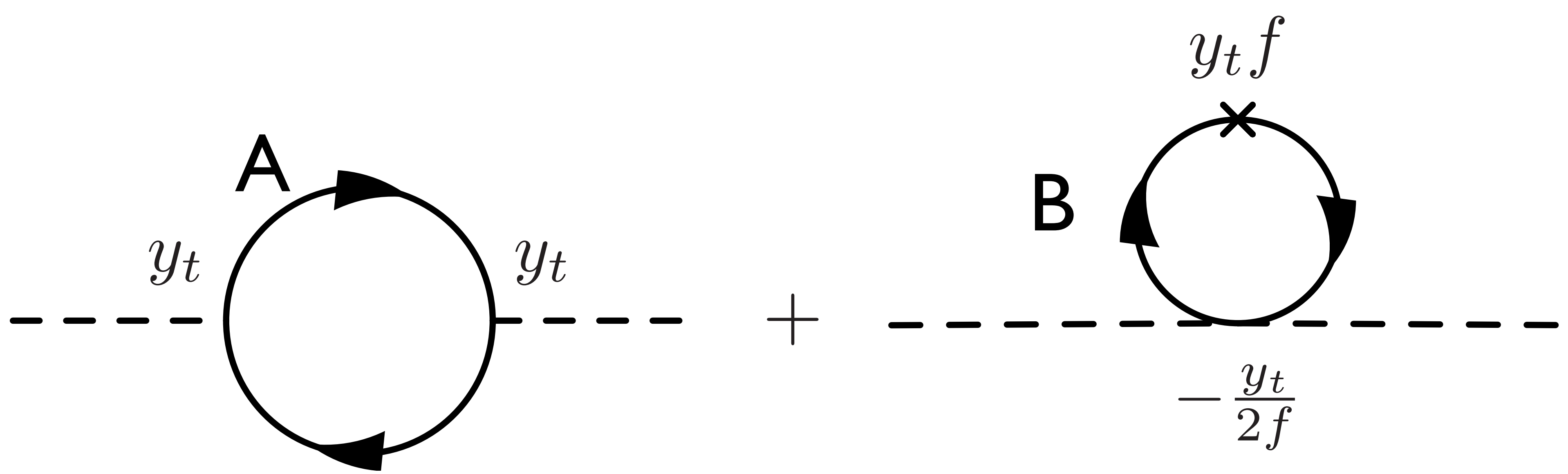
[Chacko, Goh, Harnik]

$\mathrm{SM}_A \times \mathrm{SM}_B \times \mathbb{Z}_2$

$$\mathcal{L} \supset y\, Q_A H_A U_A^c + y\, Q_B H_B U_B^c$$

Higgs is a PNGB, and Higgs potential is O(8) symmetric

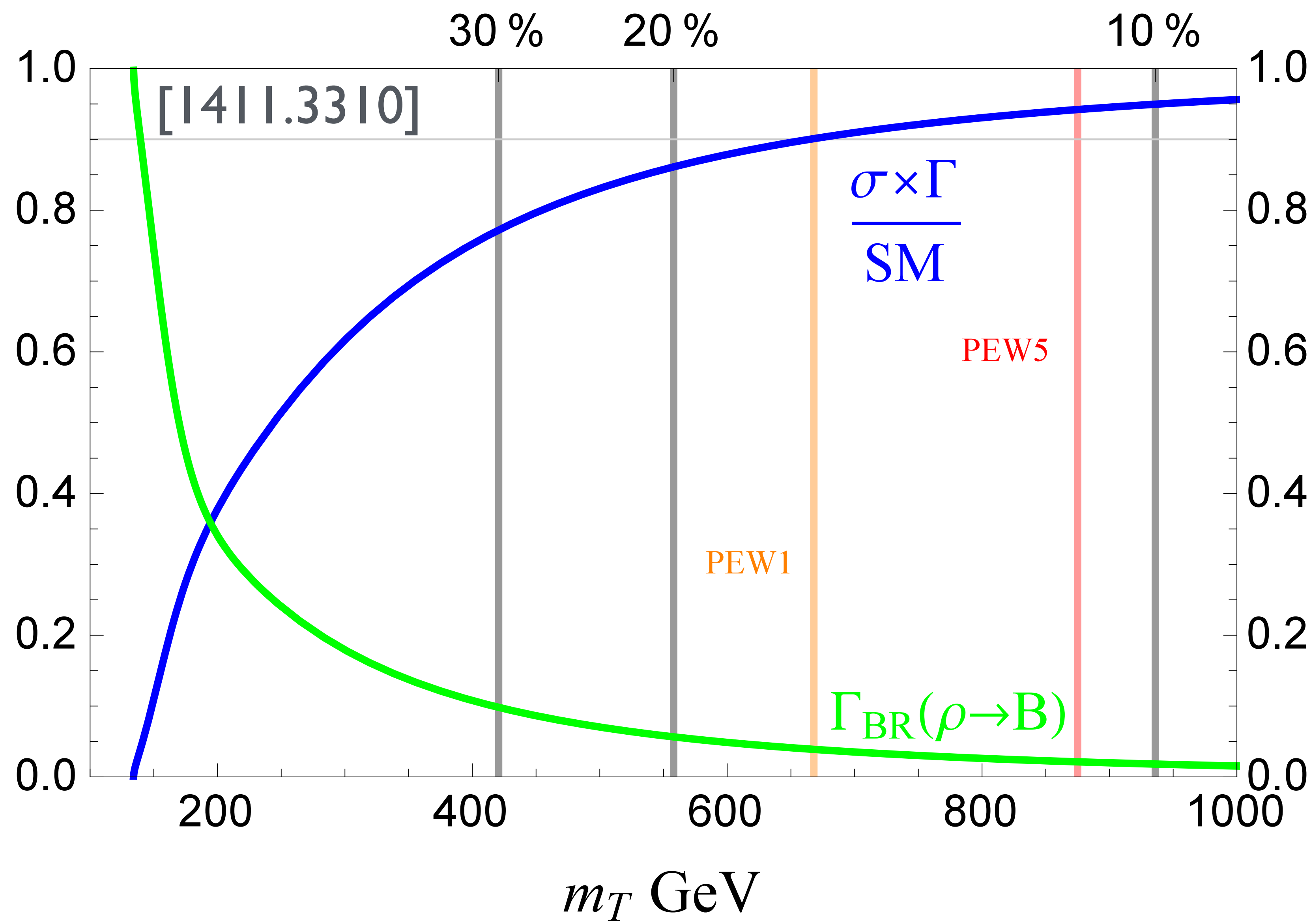
$$\mathcal{L} \sim y\, Q_A H U_A^c + y\, Q_B \left(f - \frac{|H|^2}{2f^2} \right) U_B^c$$



$$V = -m^2\left(H_A^\dagger H_A + H_B^\dagger H_B\right) + \lambda\left(H_A^\dagger H_A + H_B^\dagger H_B\right)^2$$

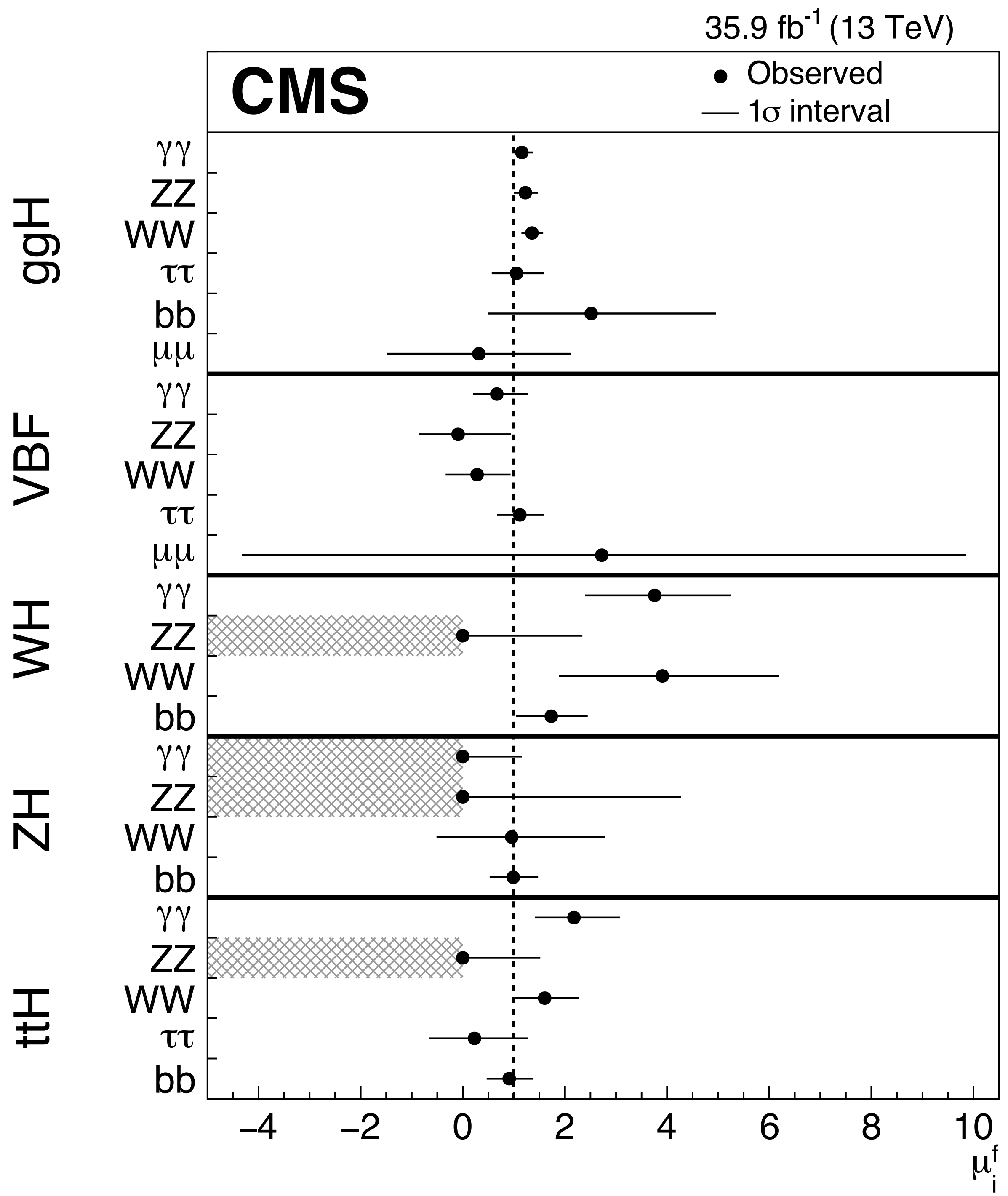
Higgs portal between A and B sectors

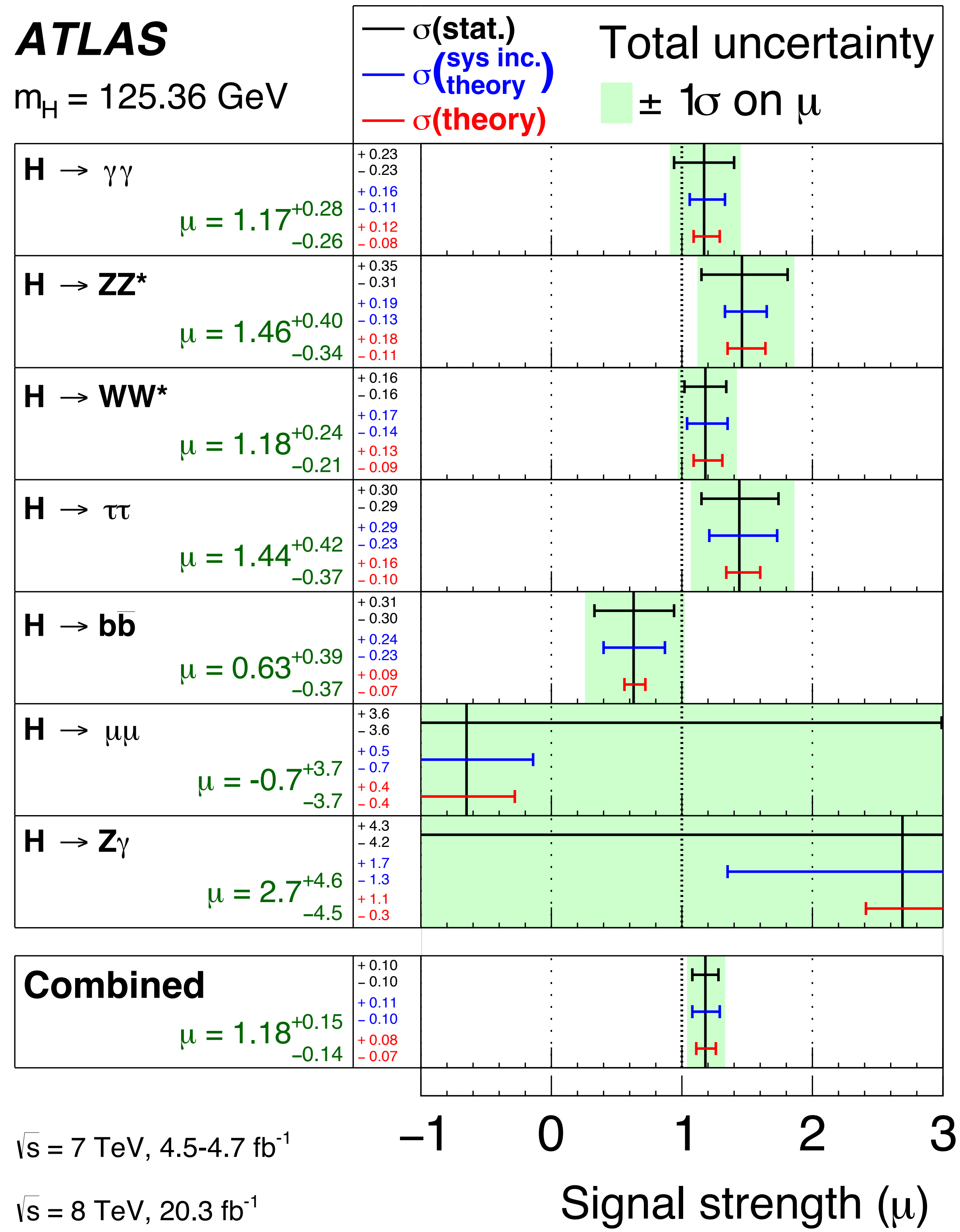
- Higgs mixing and corrections to Higgs pheno at $\dfrac{v^2}{f^2}$
- Higgs invisible decay width, to light B sector stuff



Are there any deviations in Higgs couplings?

Already ruled out 4th generation (also direct searches)





New searches

Existing 2-body searches:

[Craig et al 1601.09392]

	e	μ	τ	γ	j	b	t	W	Z	h
e	$\pm\mp$[4],$\pm\pm$[5]	$\pm\pm$[5, 6] $\pm\mp$[6, 7]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
μ		$\pm\mp$[4],$\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
j					[15]	[16]	[17]	[18]	[18]	$\varnothing$
b						[16]	[19]	$\varnothing$	$\varnothing$	$\varnothing$
t							[20]	[21]	$\varnothing$	$\varnothing$
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

New searches

Existing 2-body searches:

[Craig et al 1601.09392]

	e	μ	τ	γ	j	b	t	W	Z	h
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μ		$\pm\mp$[4],$\pm\pm$[5]	[7]	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
τ			[8]	$\varnothing$	$\varnothing$	$\varnothing$	[9]	$\varnothing$	$\varnothing$	$\varnothing$
γ				[10]	[11–13]	$\varnothing$	$\varnothing$	[14]	[14]	$\varnothing$
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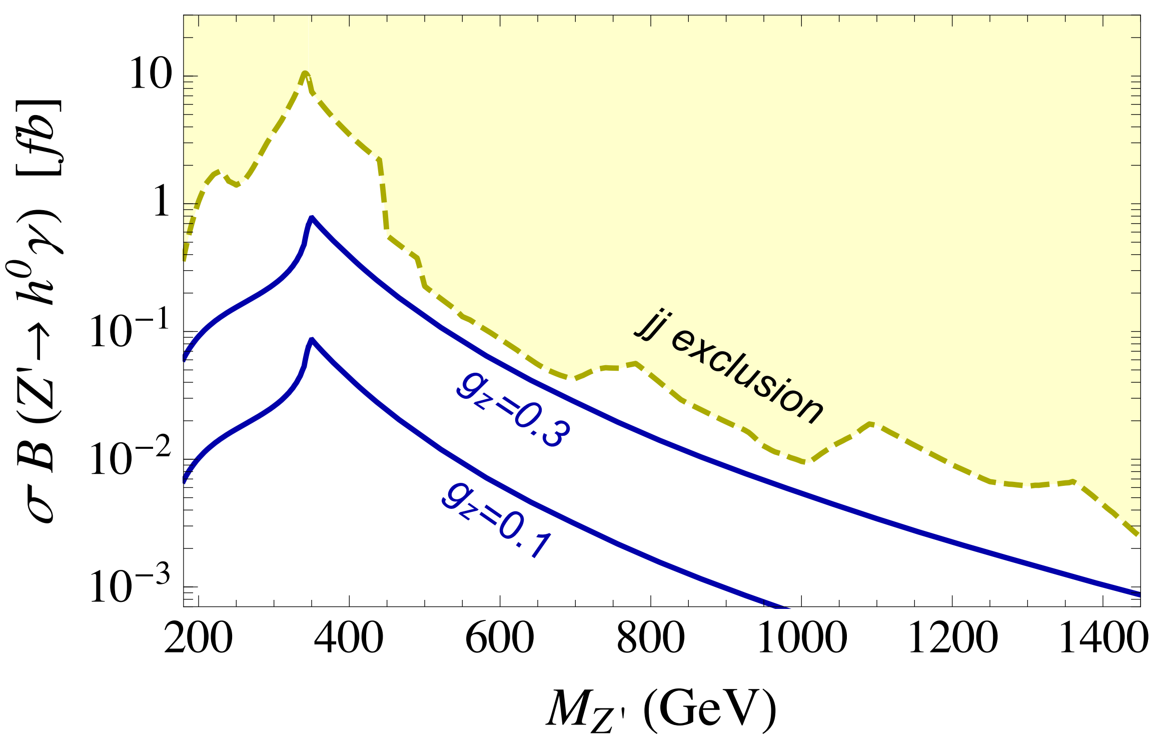
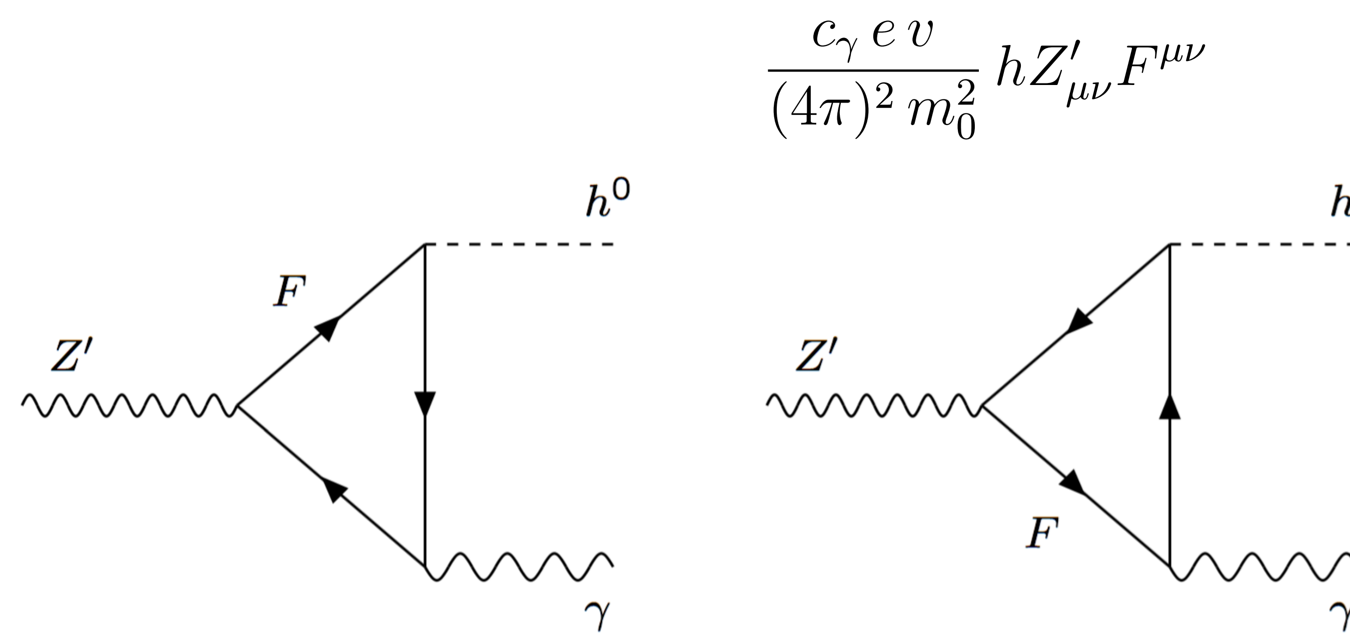
W								[22–25]	[23, 24, 26, 27]	[28–30]
Z									[23, 25, 31]	[28, 30, 32, 33]
h										[34–37]

Higgs-photon resonance

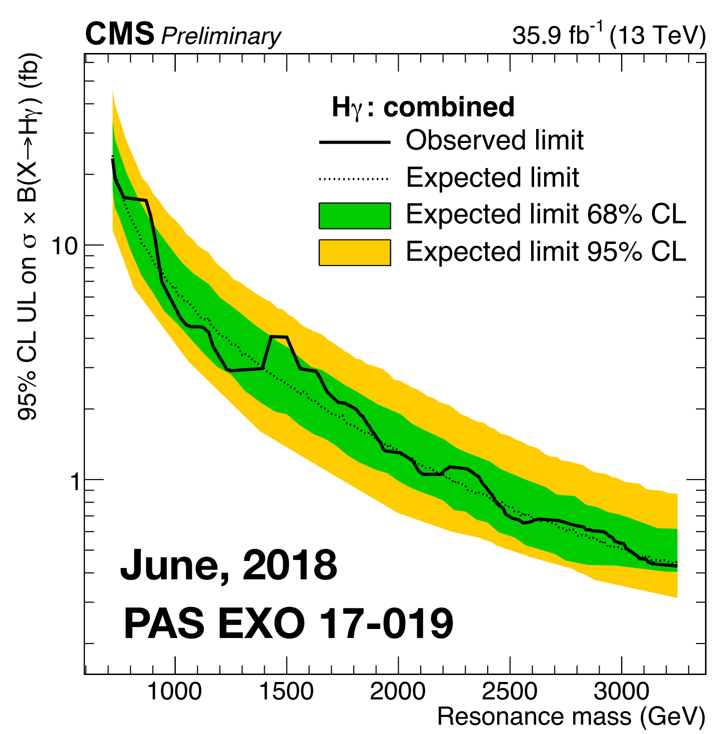
[Dobrescu, PF, *Kearney* (1705.08433)]

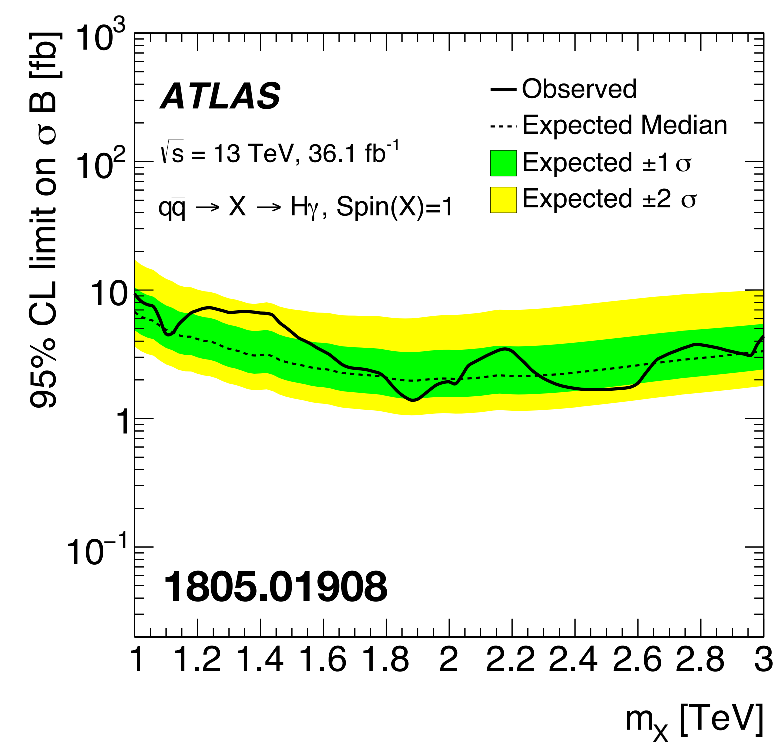
Only di-boson resonance search not done





- First analyses (ATLAS and CMS) searching this channel





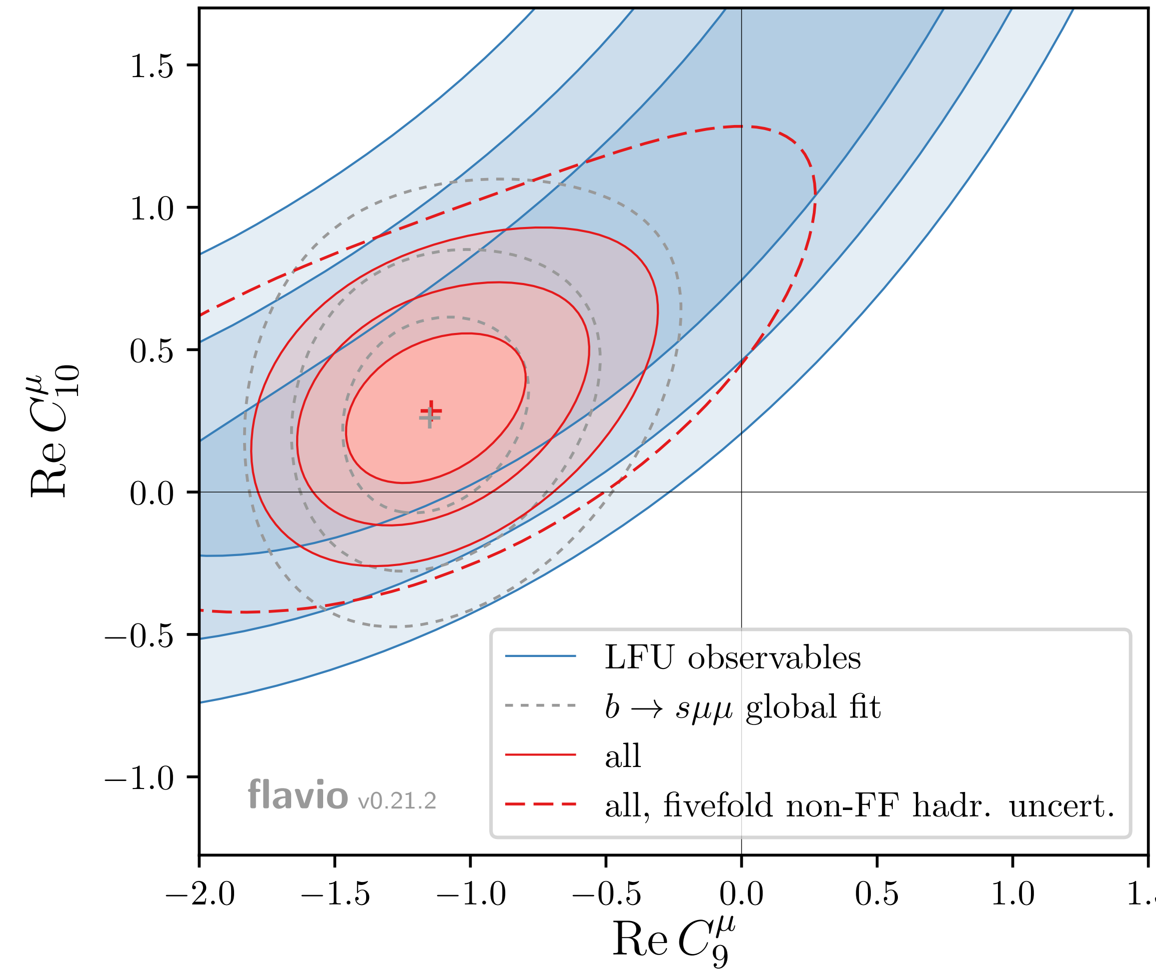
Flavour anomalies

LFUV observables

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.56	$[-2.12, -1.10]$	$[-2.87, -0.71]$	4.1σ
C_{10}^μ	$+1.20$	$[+0.88, +1.57]$	$[+0.58, +2.00]$	4.2σ
C_9^e	$+1.54$	$[+1.13, +1.98]$	$[+0.76, +2.48]$	4.3σ
C_{10}^e	-1.27	$[-1.65, -0.92]$	$[-2.08, -0.61]$	4.3σ
$C_9^\mu = -C_{10}^\mu$	-0.63	$[-0.80, -0.47]$	$[-0.98, -0.32]$	4.2σ
$C_9^e = -C_{10}^e$	$+0.76$	$[+0.55, +1.00]$	$[+0.36, +1.27]$	4.3σ
$C_9^e = C_{10}^e$	-1.91	$[-2.30, -1.51]$	$[-2.71, -1.10]$	3.9σ
$C_9'^\mu$	-0.05	$[-0.31, +0.21]$	$[-0.57, +0.46]$	0.2σ
$C_{10}'^\mu$	$+0.03$	$[-0.21, +0.27]$	$[-0.44, +0.51]$	0.1σ
$C_9'^e$	$+0.07$	$[-0.21, +0.37]$	$[-0.49, +0.69]$	0.2σ
$C_{10}'^e$	-0.04	$[-0.30, +0.21]$	$[-0.57, +0.45]$	0.2σ

[Altmannshofer at al]

$$\mathcal{O}_{10}^\ell = (\bar{s}\gamma^\mu P_L b)(\ell\gamma_\mu\gamma_5\ell)$$



$$\mathcal{O}_9^\ell = (\bar{s}\gamma^\mu P_L b)(\ell\gamma_\mu\ell)$$

$$\mathcal{H} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_{em}}{4\pi}\left(C_9^\mu \mathcal{O}_9^\mu + C_{10}^\mu \mathcal{O}_{10}^\mu\right) + \text{h.c.}$$

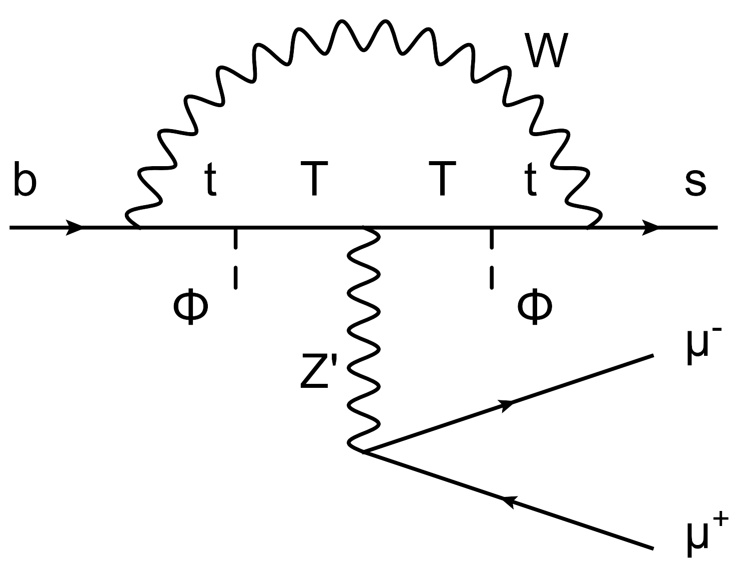
The physics that generates these operators must be below 100 TeV

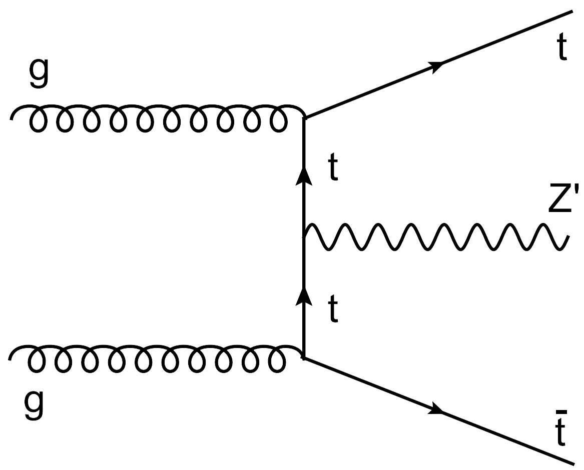
Accessible at LHC if loop generated

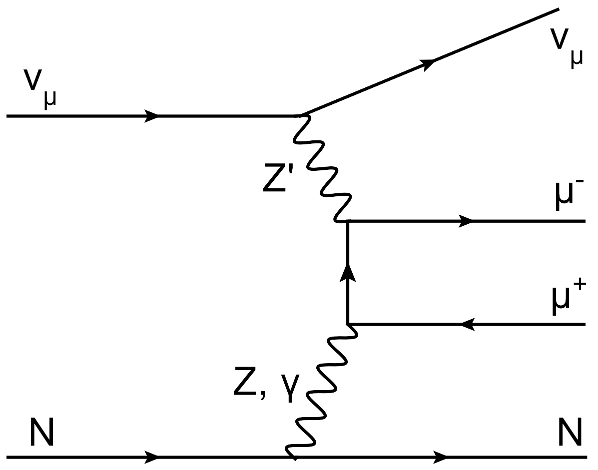
Flavour anomalies

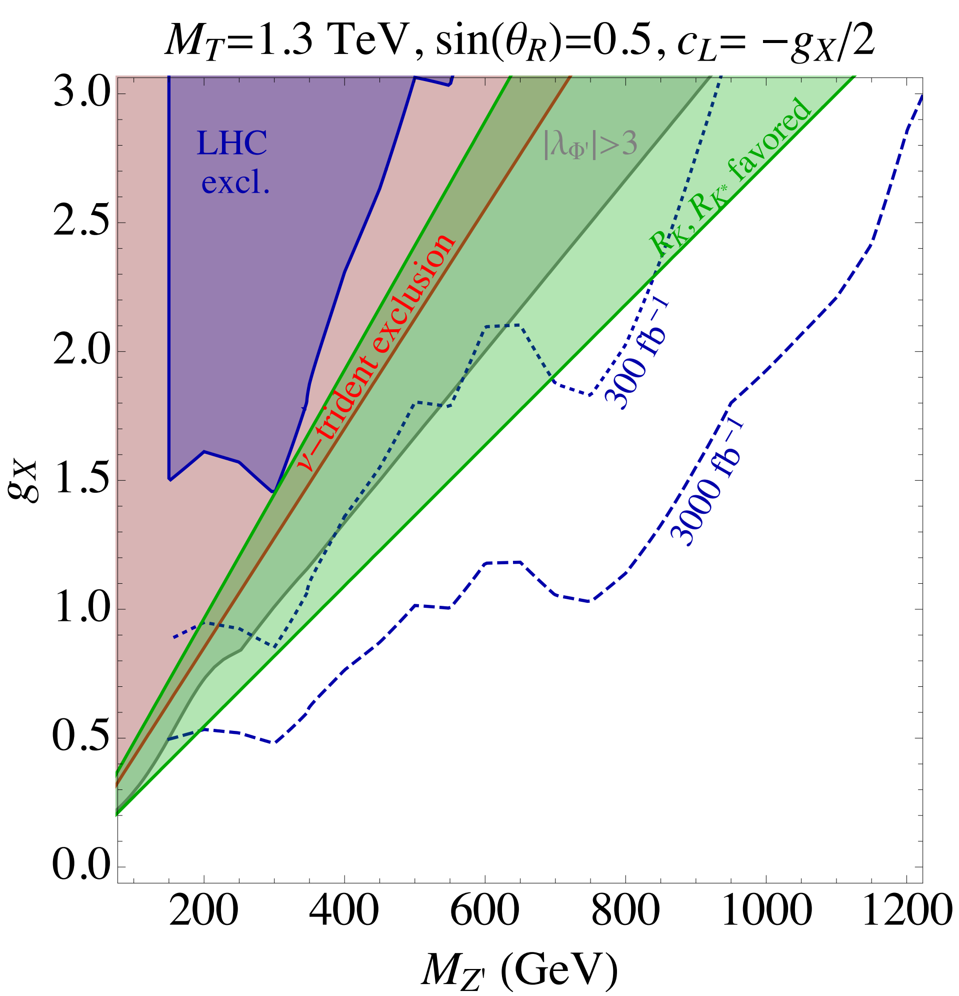
[Kamenik, Soreq, Zupan; PF, Low, Zhang]

No new flavour violation, a new U(1)'





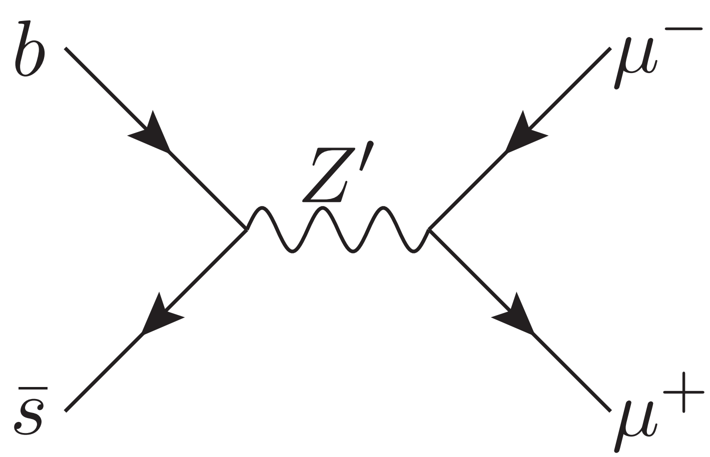


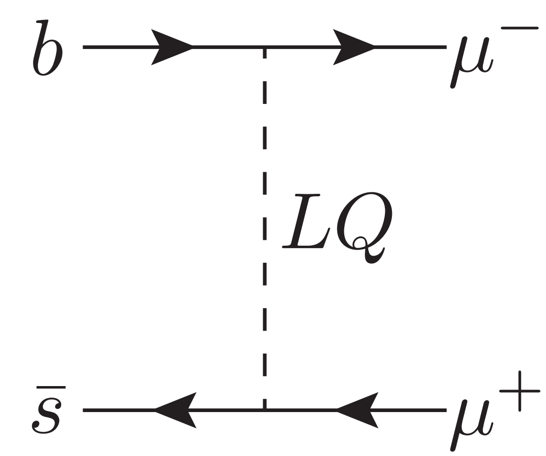


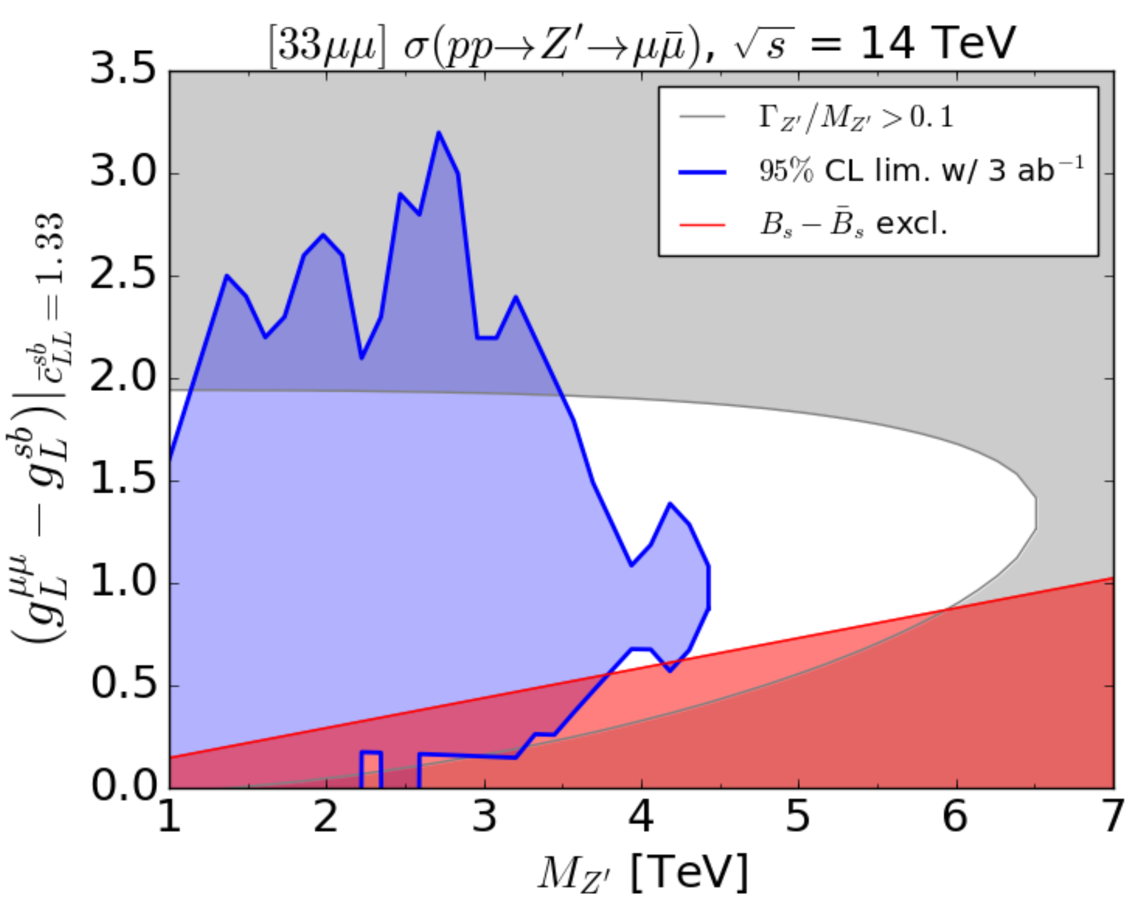
Flavour anomalies

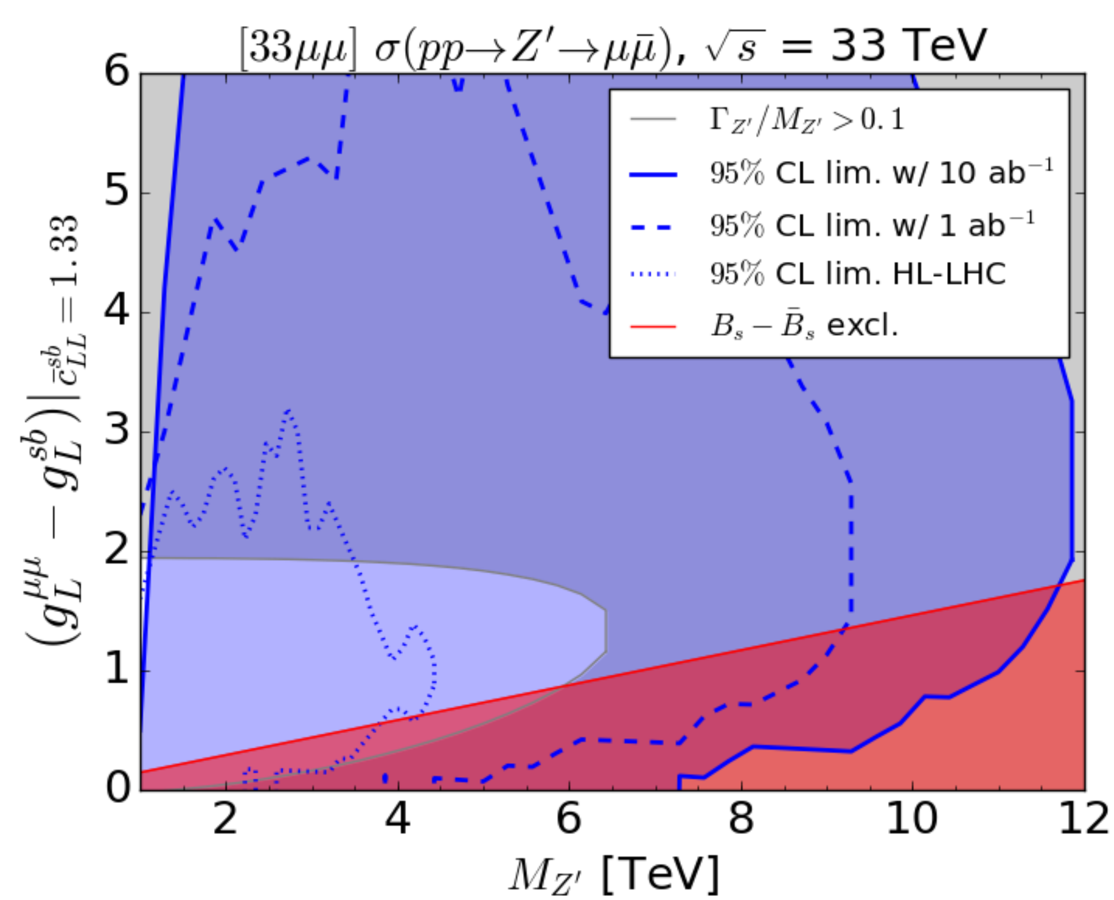
[Allanach et al]

New flavour violation, a new U(1)’ or leptoquarks

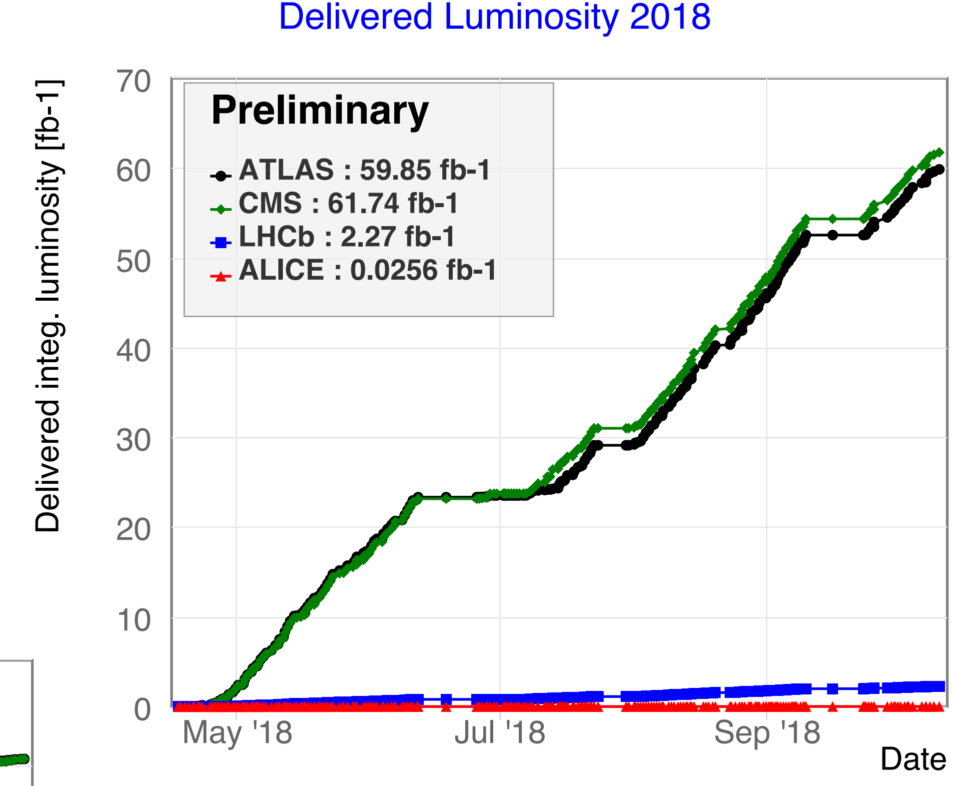


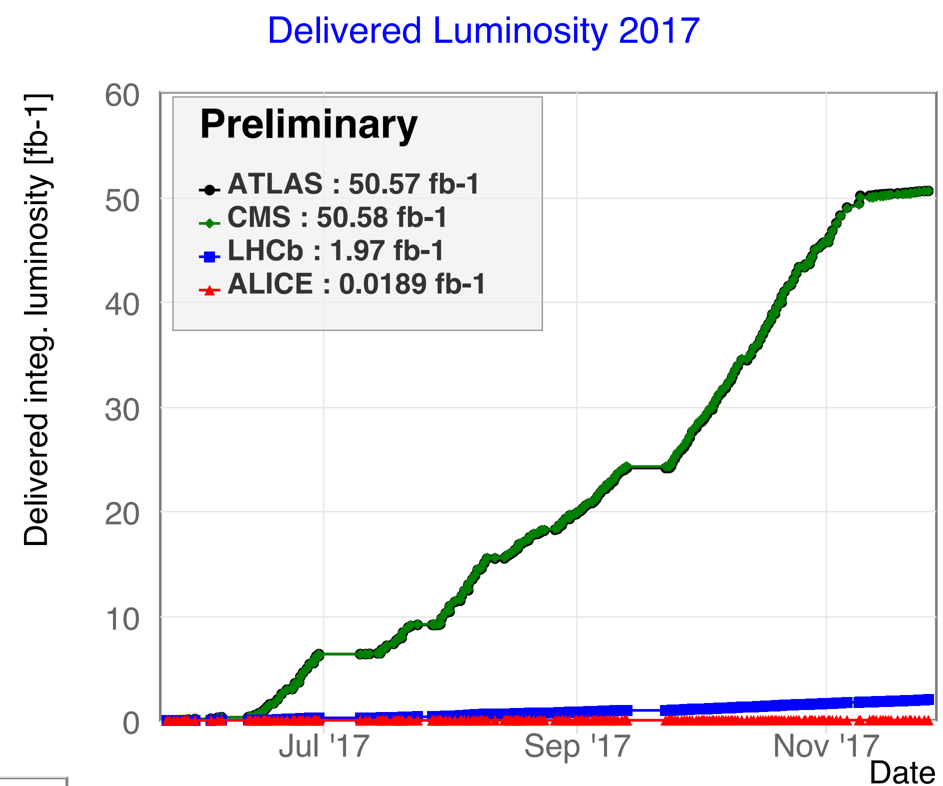


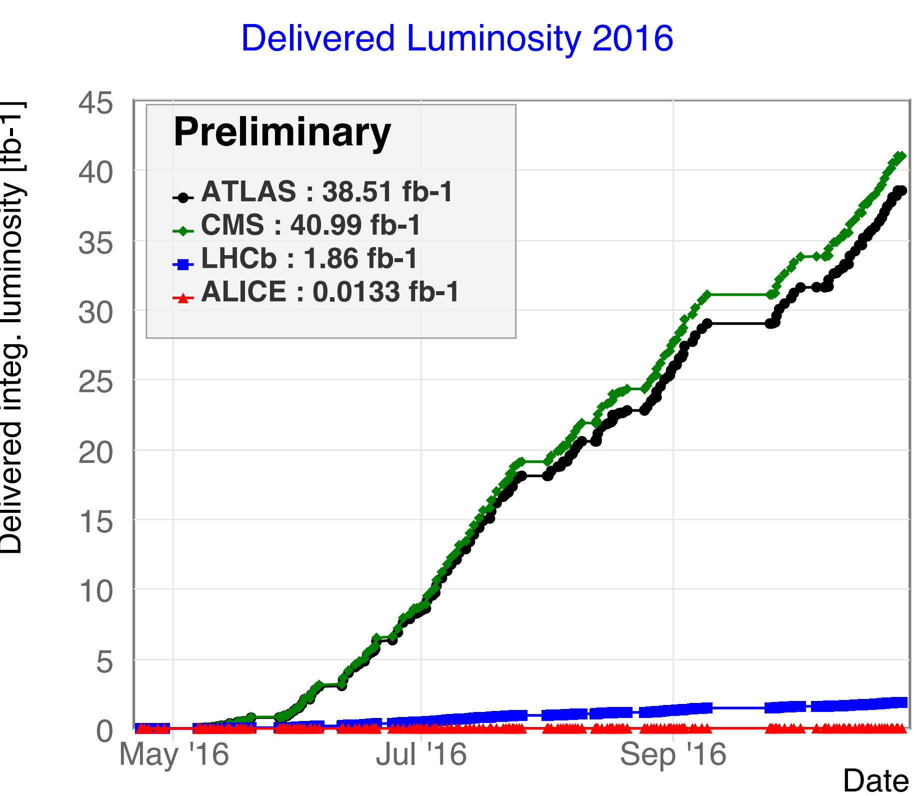




LHC has delivered ~150/fb per EXP!!

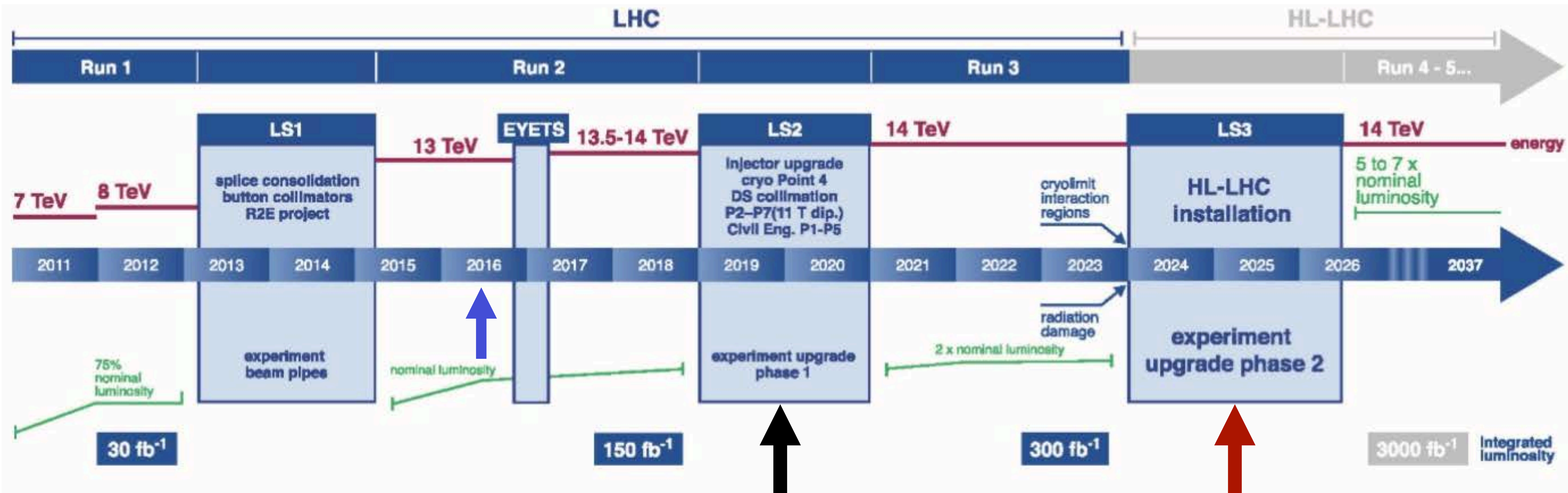






High Lumi/High Energy LHC

HL-LHC: √ s = 14 TeV; L = 3 ab^{-1}; **HE-LHC:** √ s = 27 TeV; L = 15 ab^{-1} (post 2040?)



LS2 (2019-2020):

- ❑ LHC Injectors Upgrade (LIU)
- ❑ Civil engineering for HL-LHC equipment @ P1,P5
- ❑ First 11 T dipoles P7; cryogenics in P4
- ❑ Phase-1 upgrade of LHC experiments

LS3 (2024-2026):

- ❑ **HL-LHC installation**
- ❑ Phase-2 upgrade of ATLAS and CMS

Will shed light on existing anomalies, find new ones?
High lumi allows for novel search strategies
LLP searches, new detectors, new analyses

Outlook

$\mathcal{L}_{BSM}$

$\Longrightarrow$

A better PDG for our students than we got from our advisors

Exciting time on many fronts, chances to motivate new searches and new expts.

No guarantees, but that shouldn't stop us looking

Still waiting for our generations "I.I. Rabi moment"

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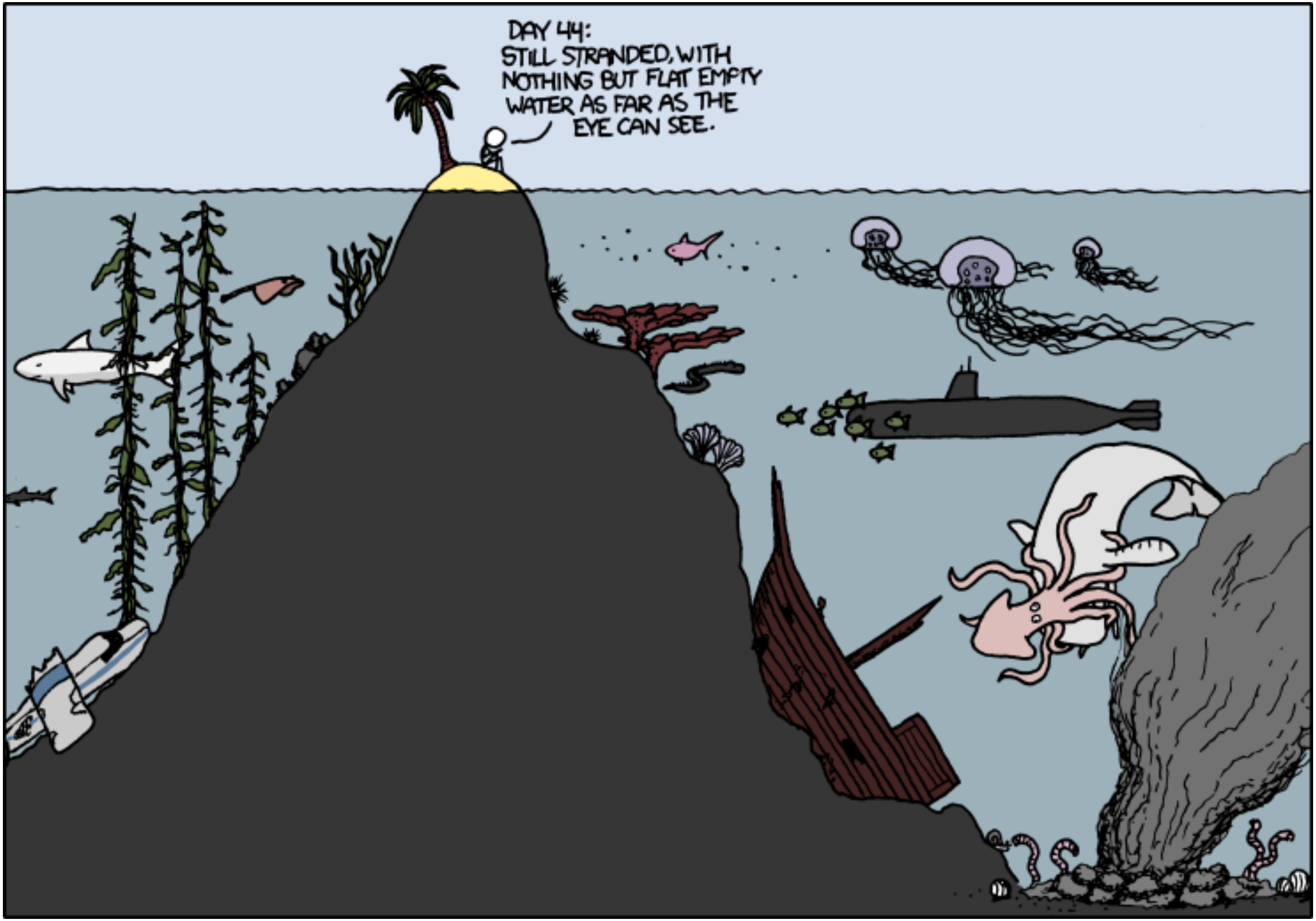
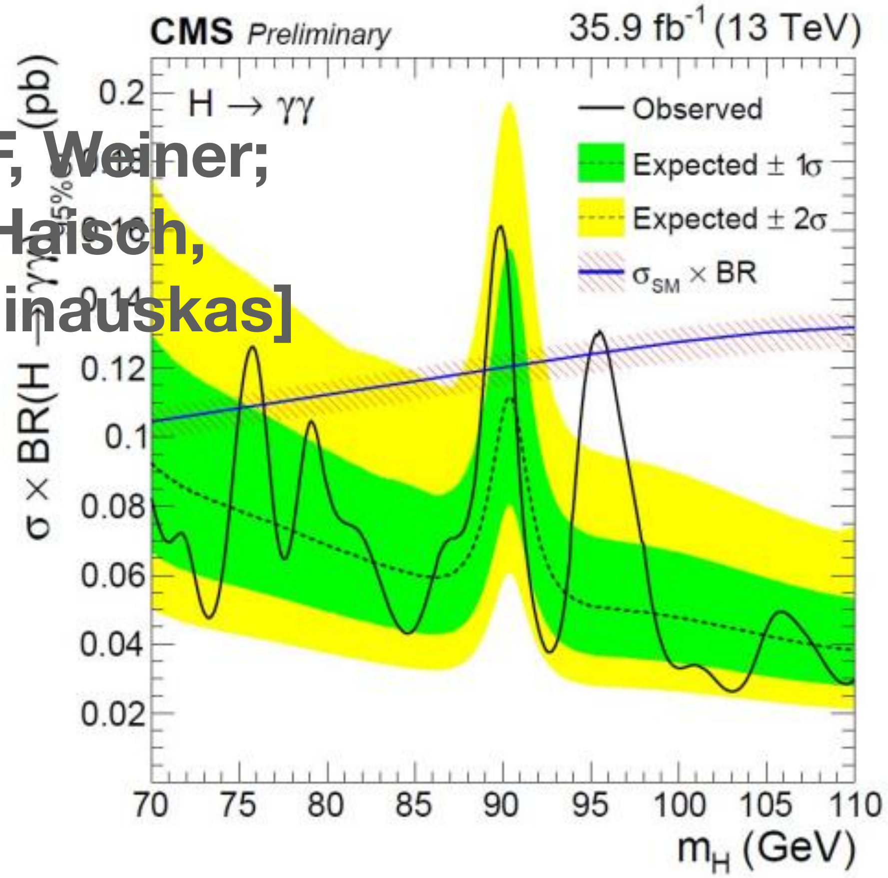
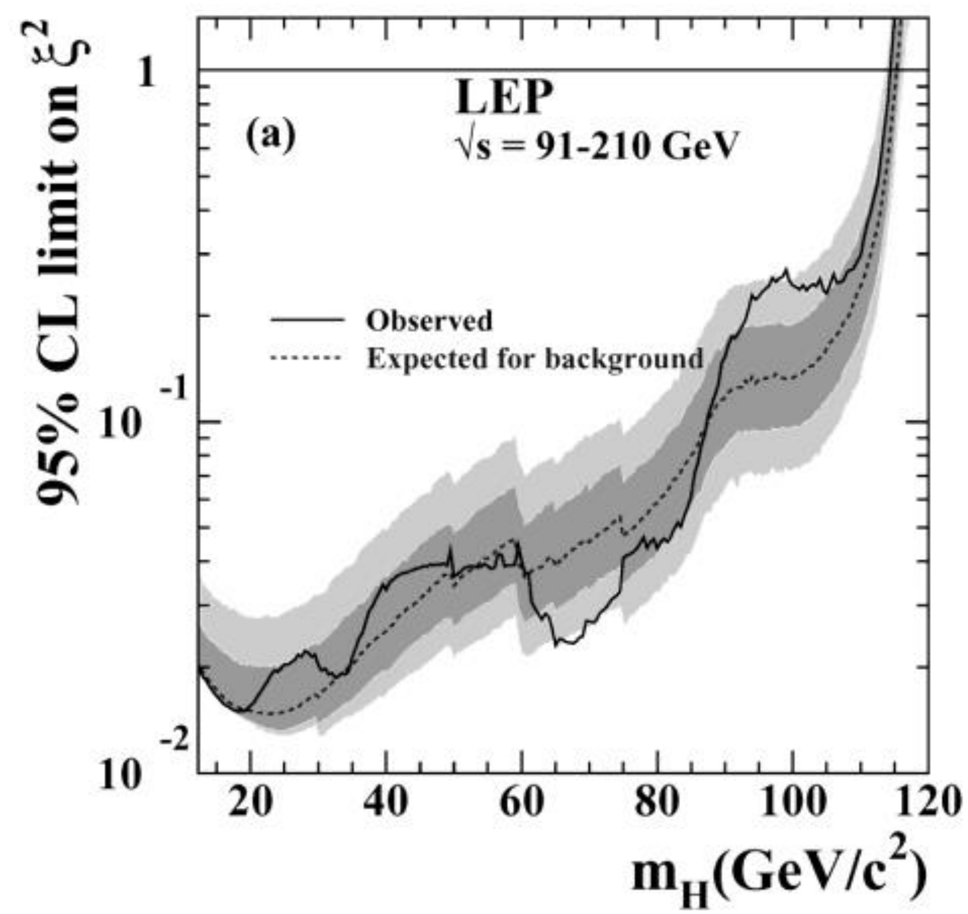

DAY 44:
STILL STRANDED, WITH NOTHING BUT FLAT EMPTY WATER AS FAR AS THE EYE CAN SEE.

Another diphoton resonance?

Long standing LEP excess, Tevatron tth, CMS/ ATLAS diphoton

[PF, Weiner; Haisch, Malinauskas]





2HDM (type 1) with a light H
Can it also strengthen EWPT?

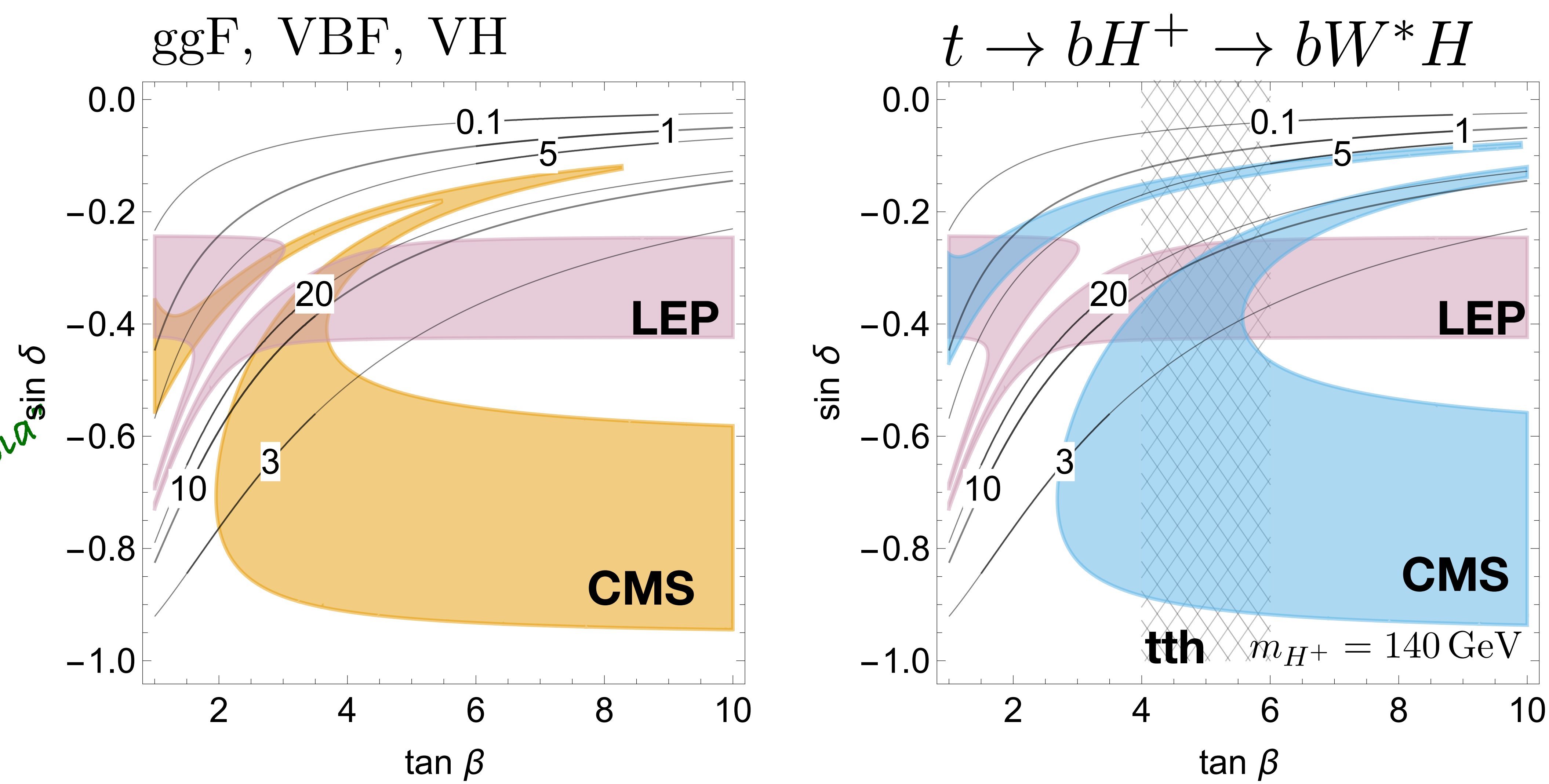
Another diphoton resonance?

Long standing LEP excess, Tevatron tth, CMS/ATLAS diphoton

[PF, Weiner; Haisch, Malinauskas]

$f_{\rm FP}^2 = s_\delta^2/(s_\alpha^2/s_\beta^2)$

"factor of fermiophobia"



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