



Searching for the Invisible

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FeynRules/Madgraph school on collider phenomenology 2018
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The invisible

What does it mean?

Today's definition:

1. Beyond the Standard Model particles
2. Missed by 'conventional' collider searches

Bump hunt

SUSY cascades

Extra Dimensions...

3. Because they are somehow not 'seen' by the detector
4. Signature is (partially) invisible

Belong to a

DARK SECTOR

Dark sector

Neutral & very weakly interacting states

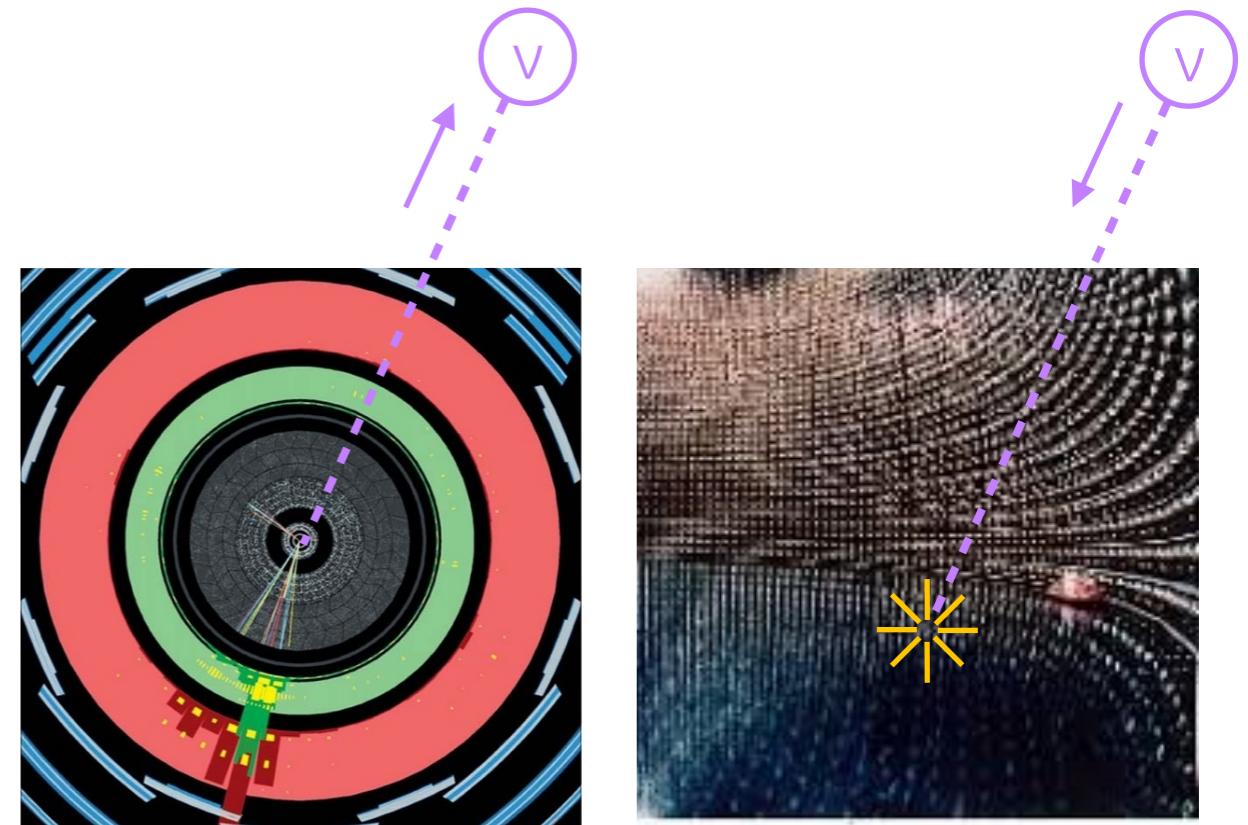
- Uncharged under Standard Model (singlets)
- Do not leave a trace in our detectors: Tracker, Calorimetry, Muon chambers

Interact with the SM through a mediator/portal

Stable or long lived

SM example: neutrinos

- Abundantly produced in W, Z decays → missing energy
- Huge volumes required to detect, e.g. 50k tons of water in Super-Kamiokande



Dark matter

[See J. Heisig's lecture]

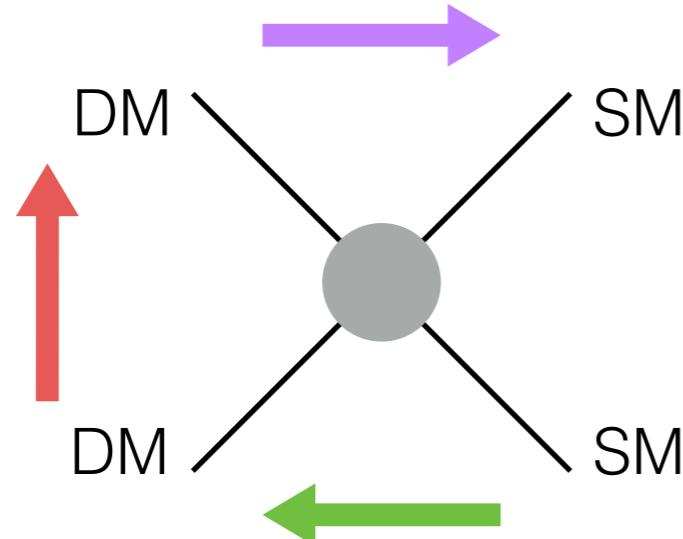
BSM example: particle dark matter

- Uncharged (QCD, QED neutral)
- Stable on cosmological timescales
- Interacts gravitationally



Need other interactions to connect to SM

- Portal/mediator for annihilation required to get relic abundance
- Necessary for experimental detection (**direct**, **indirect**, **colliders**)

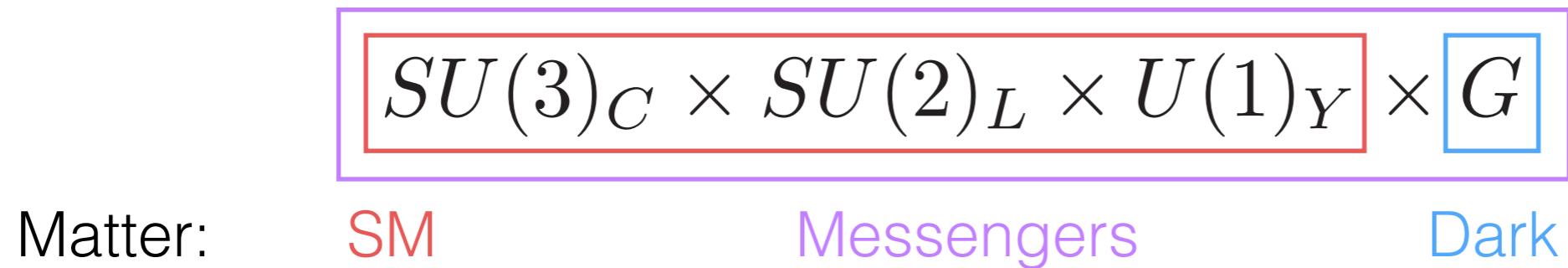


LHC: **missing energy**
a.k.a mono-X
 $X = \text{photon, } Z, W, \text{ Higgs, ...}$
Mediator searches
Simplified models
Good coverage

Hidden Valleys

Invisible sector: not just a few particles

- A rich gauge/matter sector like the SM



New gauge group, G , confines at scale $\Lambda_{\text{QCD}} < \Lambda_G \leq \text{TeV}$

Zoo of G -neutral dark hadrons

- Like SM QCD: dark protons, pions, quarkonia, ...
- G -matter undergoes **dark-hadronisation**
- Lightest states decay back to SM with potentially **long lifetimes**

Hidden Valleys

Unlimited possibilities for structure of G_{dark}

- Can contribute to DM relic density → Asymmetric DM
- States could mix with the SM e.g. Higgs

e.g. Neutral naturalness models

- Mirror SM gauge structure

$$G = [SU(3) \times SU(2) \times U(1)]_{\text{dark}}$$

- Top partners that stabilise Higgs mass are ‘dark QCD’-coloured
- Mirror glueballs & quarkonia
- Exotic Higgs decay

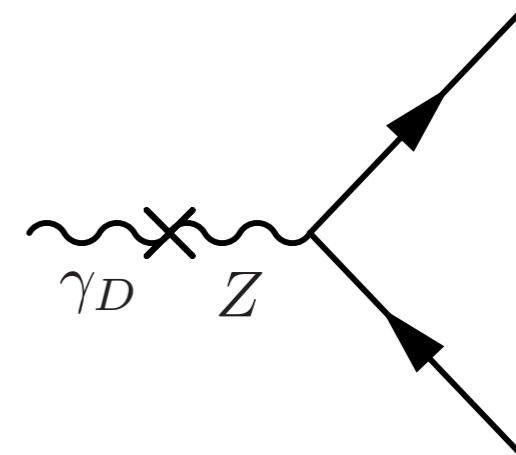
[*Craig, Katz, Strassler & Sundrum; JHEP 1507 (2015) 105*]
[*Curtin & Verhaaren JHEP 1512 (2015) 072*]

Dark photons

Minimal scenario of a hidden sector

- New U(1) gauge symmetry
- Natural ‘portal’ through hypercharge kinetic mixing

$$\mathcal{L}_{\text{portal}} = \varepsilon B^{\mu\nu} F_{\mu\nu}^D$$



- γ_D inherits couplings of neutral EW gauge bosons
- Also has a Higgs portal in realistic models (must break new U(1))
- Possibility of Higgs mixing with new scalar

Could be part of a bigger hidden sector

- Dark fermions would appear to us as milli-charged particles
- Observed charge proportional to mixing $\sim \varepsilon Q_D$

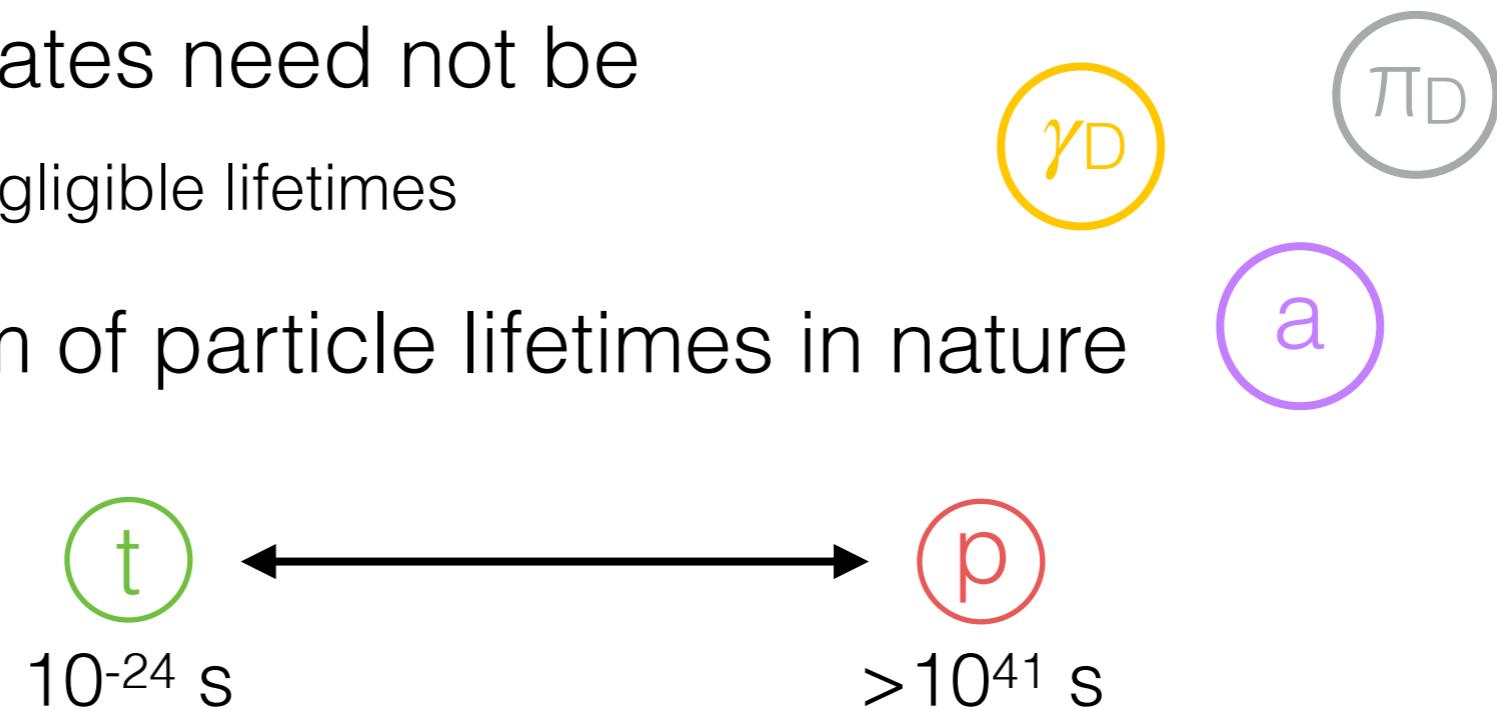
Long-lived particles

Dark matter must be cosmologically stable by construction

Other exotic states need not be

- May have non-negligible lifetimes

Huge spectrum of particle lifetimes in nature



Contrary to most direct BSM searches

- That focus on short lifetimes (prompt decay)
- Search for decay products originating from beam interaction point

Lifetime

Decay lifetimes are a **fundamental** property of particles
Characterised by the total decay width/proper lifetime

$$\Gamma \sim \frac{1}{M} \int |\mathcal{M}|^2 d\Pi \quad \tau = \frac{\hbar}{\Gamma} = \left(\frac{6.6 \times 10^{-25} \text{ GeV}}{\Gamma} \right) s$$

Decay length depends on velocity/Lorentz boost

$$l = \beta \gamma c \tau \sim \left(\frac{2 \times 10^{-16} \text{ GeV}}{\Gamma} \right) m$$

Probability to survive having travelled a distance d

$$P(d) = e^{-\frac{d}{l}}$$

LLP Models

Tiny decay width $\Gamma \sim O(10^{-12} - 10^{-16})$ GeV needed for LLP

Ultra-weak couplings $g \ll 1$

- Freeze-in dark matter \sim feebly interacting massive particle (FIMP)
- Gravitino $\sim 1/M_{\text{Pl}}$
- Dark photon kinetic mixing, ϵ

Higher-dimensional operators

- e.g. muon lifetime suppressed by m_w^2 in Fermi interaction

$$-\frac{G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma^\mu (1 - \gamma_5) \mu] [\bar{e} \gamma_\mu (1 - \gamma_5) \nu_e] \quad G_F = \frac{1}{\sqrt{2}v^2}$$

Small mass splittings (phase space suppression)

- Can also lead to very soft SM particles that escape detection

LLP Models

Matrix element suppressed due to approximate symmetries

- e.g. proton decay protected by baryon number conservation
- R-parity in SUSY for stable LSP
- Enforce quasi-degenerate spectrum or ‘naturally’ small couplings

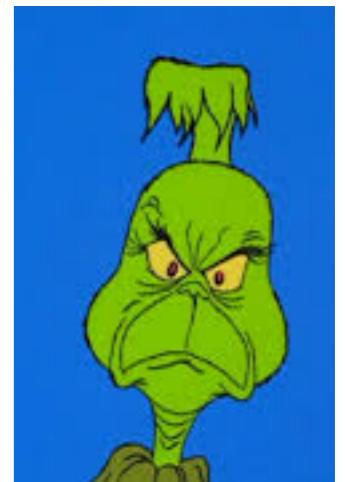
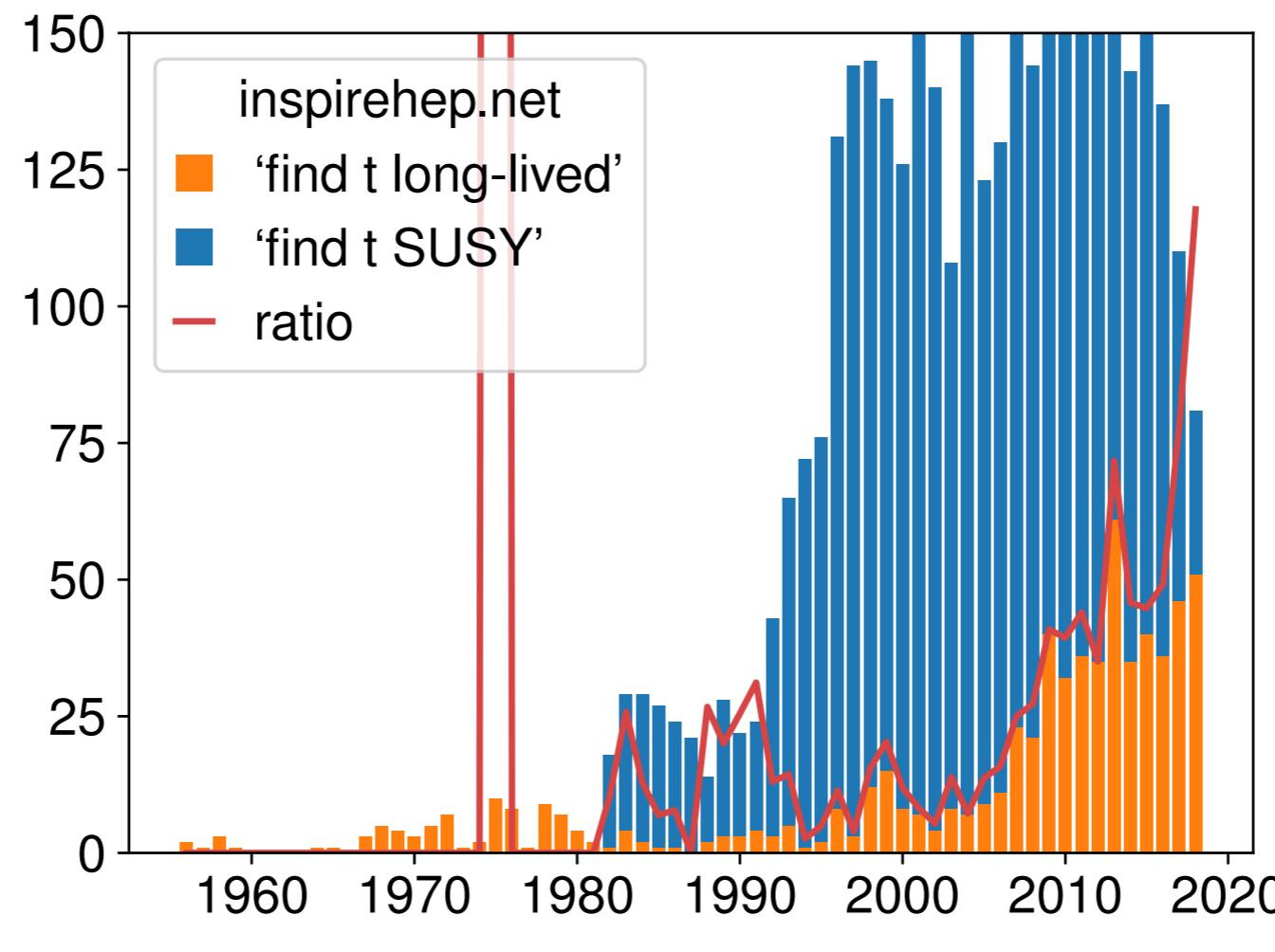
LLP masses are often not too large: width $\propto m^n$

Important bound from early universe

- Lifetimes $\gtrsim 1\text{s}$ would interfere with Big Bang Nucleosynthesis
- Spoil observed relative abundance of light elements
- Impede structure formation

LLPs on the rise

LLP are gradually becoming mainstream



'We have to ensure full
BSM coverage!'

'We are running out of
ideas...'

LLP @ colliders

‘Long lived’ is a relative term

- Depends on decay length with respect to detector size

For a general purpose detector (CMS, ATLAS,...)

- $l \ll D_{\text{track}} \rightarrow \text{prompt} (\neq \text{invisible})$
- $D_{\text{track}} < l \leq D_{\text{calo}} \rightarrow \text{displaced} (\sim \text{invisible})$
- $l > D_{\text{calo/muon}} \rightarrow \text{invisible} (\sim \text{stable})$

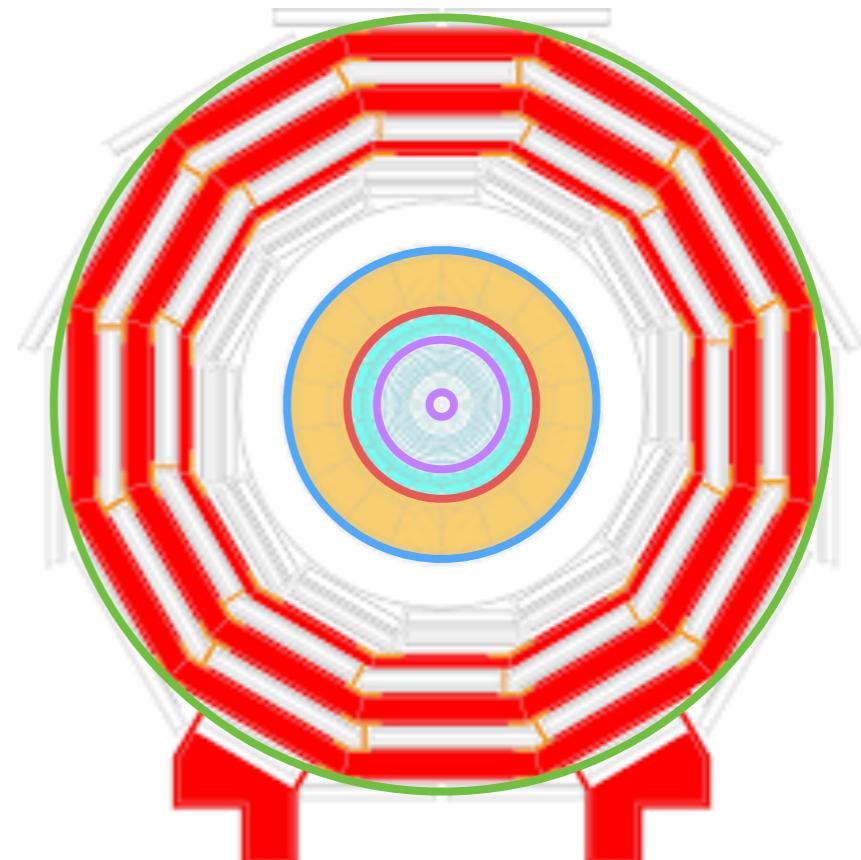
Inner/outer tracker $\sim 10\text{cm}/1\text{m}$

EM/Hadronic calorimeter $\sim 1\text{-}3\text{m}$

Muon system $\sim 10\text{m}$

Charged LLP \neq invisible (tracks)

Heavy Stable Charged Particle



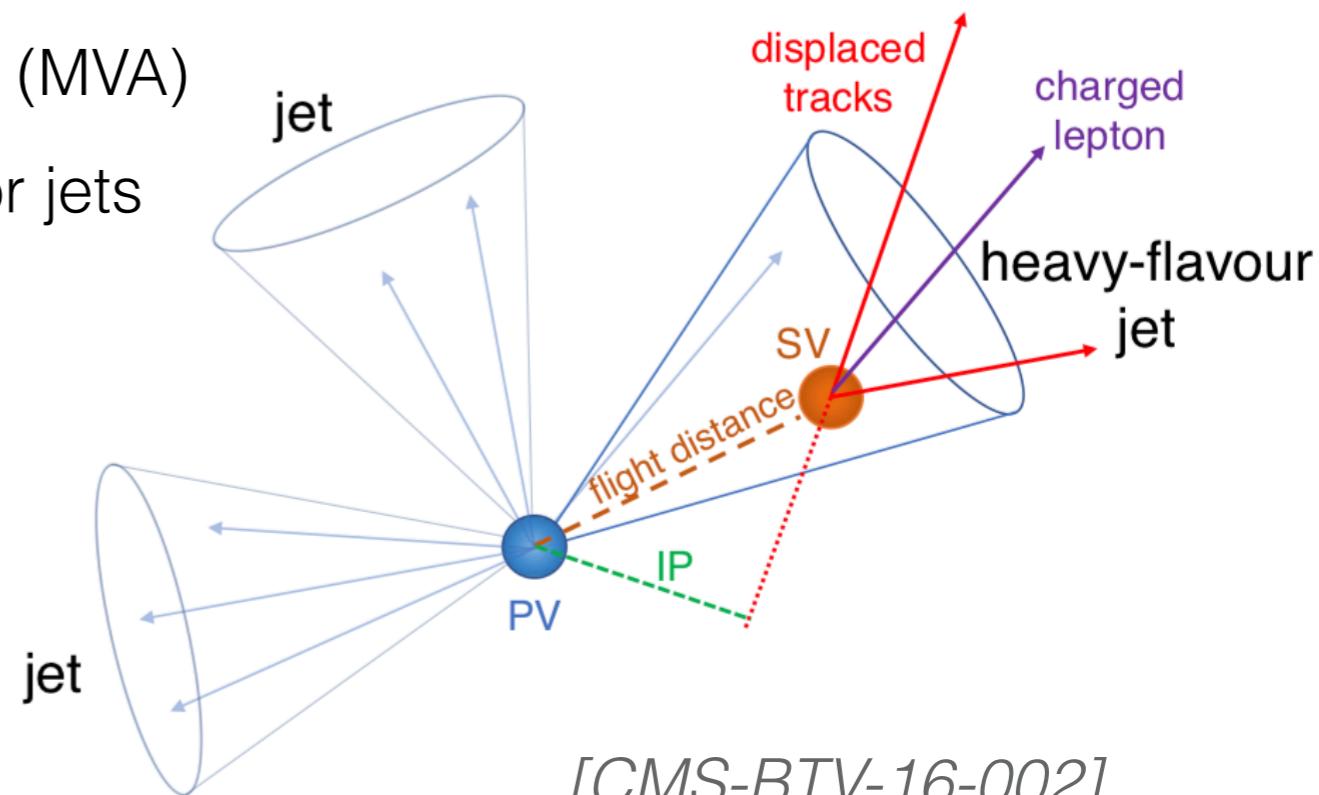
Standard Model LLP

b(c)-quark jets: SM displaced signature

- They are ‘exotic’ with respect to light quark jets (u,d,s,g)
- b-quarks hadronise into jets containing B-mesons
- B-meson lifetime $\sim 10^{-12}$ s \rightarrow decay length $\sim \text{mm-cm}$
- Search for a secondary vertex
- Combine with lots of other information (MVA)
- b(c)-‘tag’: distinguish heavy/light flavor jets

Essential for top/Higgs identification at the LHC

Analogous methods can be used for BSM LLP



[CMS-BTV-16-002]

BSM LLP signatures

For LLP that decay within detector volume

Displaced or ‘non-pointing’ objects

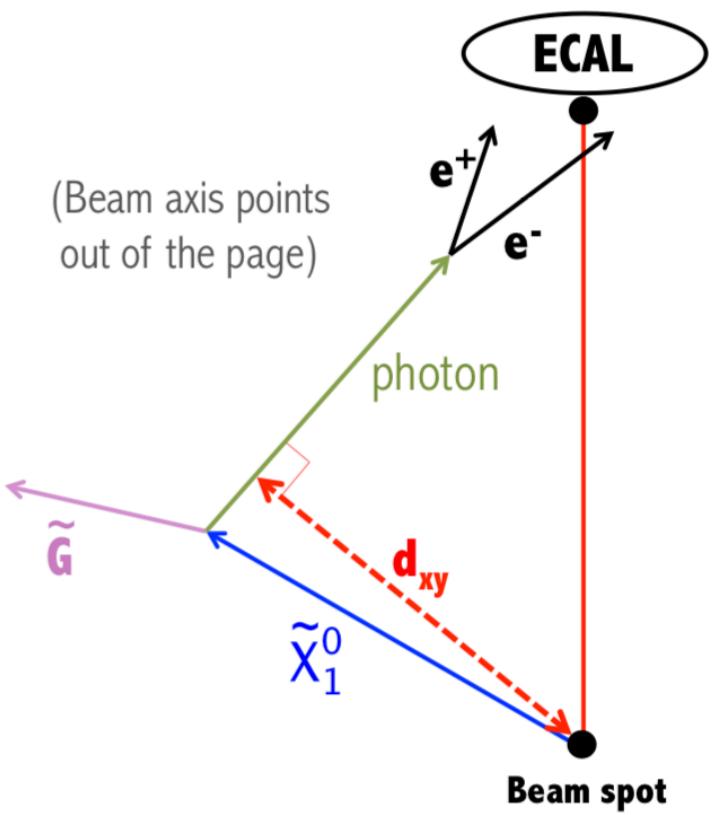
- Jets, photons, leptons
- Tracker systems can reconstruct leptons, jets $\sim 10\text{cm}$ from beam line
- ECAL timing information can also be used
- Exploit **indirect path** & **massive** intermediate states
- e^+e^- -conversion to reconstruct photon direction

Disappearing or ‘kinked’ tracks

- Decay of charged LLP into (partly) invisible

‘Exotic’ events

[See L. T. Wang’s lecture]



Emerging jets

Dark baryon sector (Hidden valley, Neutral naturalness,...)

- Lightest states can have a long-lived decay to SM hadrons
- Heavy \sim TeV mediator \rightarrow higher dimensional operator

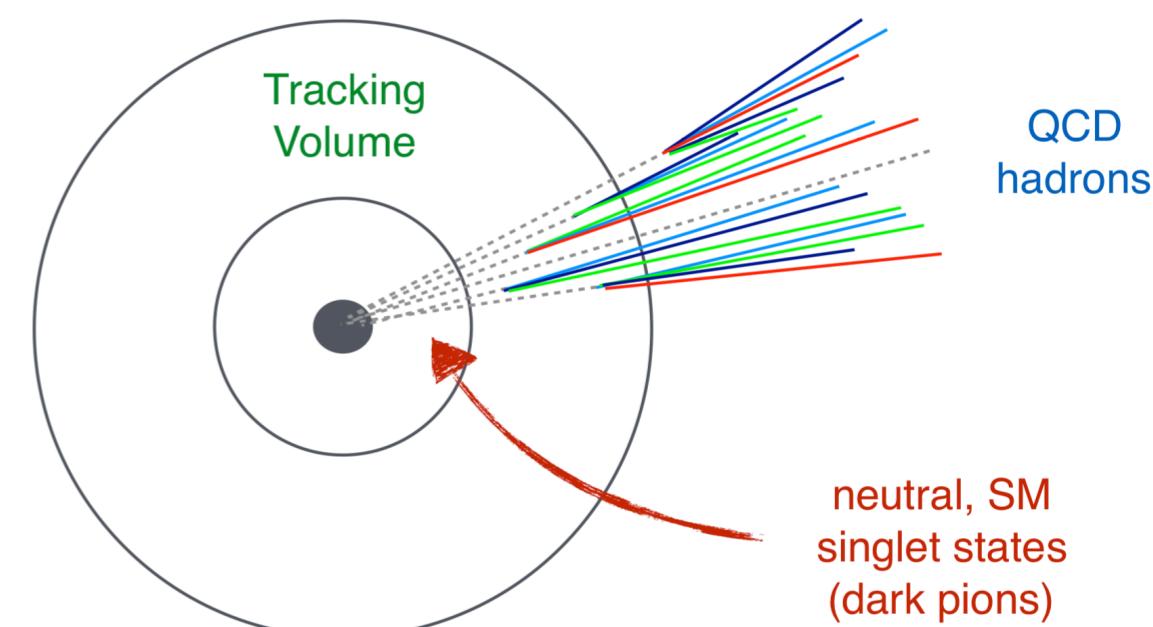
[$\odot P.$ Schwaller]

'Dark QCD' particle production

- Dark parton shower \rightarrow dark hadronisation
- Eventually decay into SM hadrons (jets)
- Emerge some distance away from beam

Different from displaced jets

- Don't originate from a single displaced vertex
- Lower jet masses



Dedicated tools required
to simulate dark PS

LLP phenomenology

In practise, LHC is not ‘optimised’ for LLP searches

- Complex reconstruction procedure: secondary vertex, particle directionality

Signatures don’t look like at all like SM particles

- Dedicated triggers required to tell the LHC that its not junk
- Background estimation can be challenging

Reliant on details about the detector

- Geometry, response, resolution
- May need ‘fullsim’, e.g. GEANT software

Generally not implemented in pheno ‘fastsim’ software

- Delphes working on this? [See M. Selvaggi’s lectures]

LLP recasting

Workaround: use **efficiency maps** provided by experiment

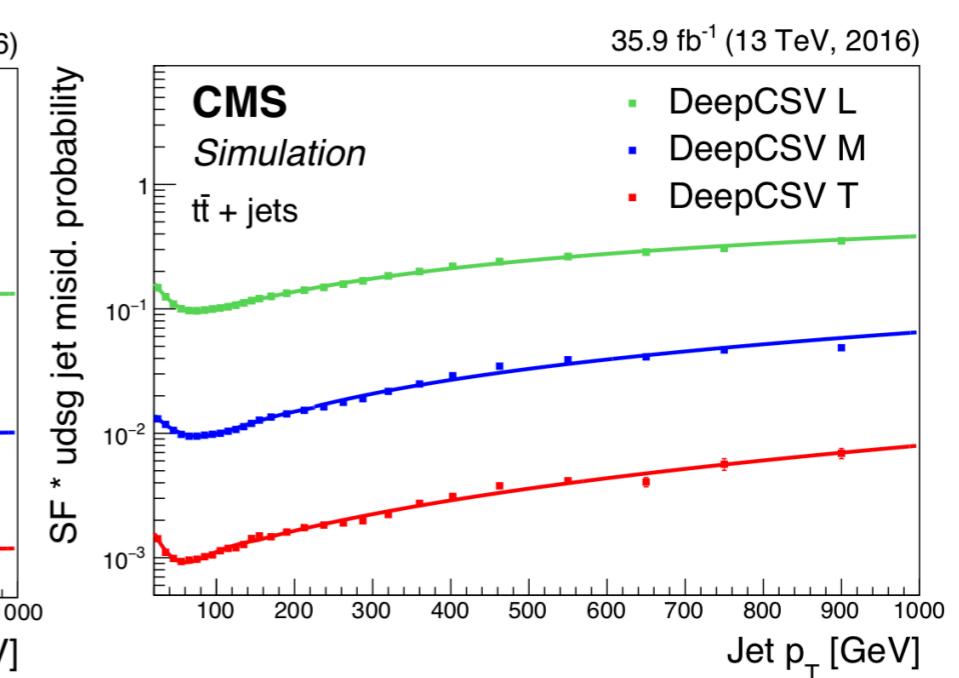
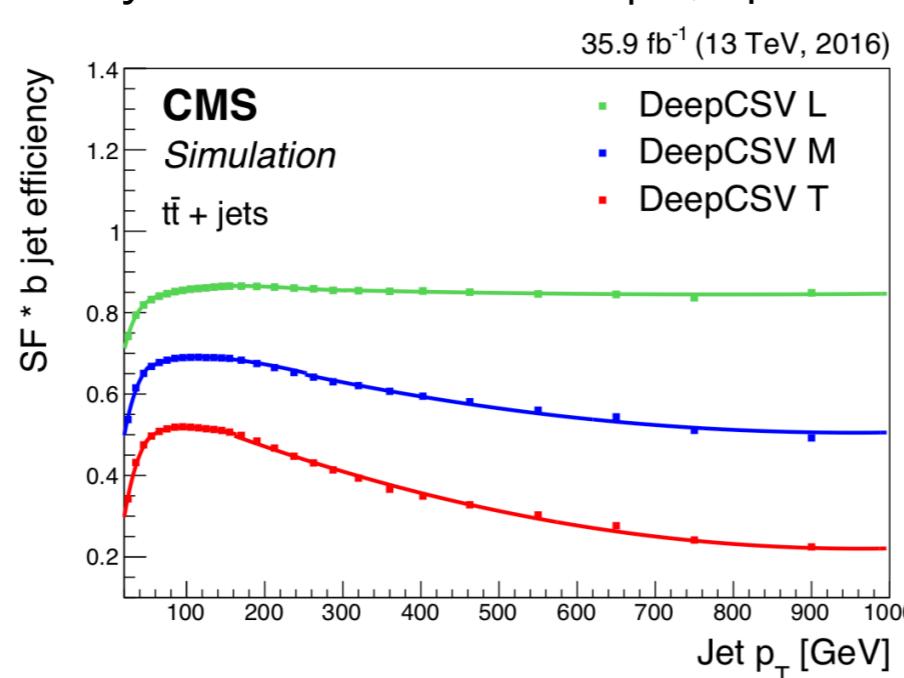
- Practical way to re-interpret displaced searches
- e.g. signal acceptance as function of kinematics

Back to b-tag example:

- Complex tagging procedure implemented in Delphes by efficiency maps
- (mis)tag probability as a function of p_T , n

Drawn from
detector studies

e.g.
[CMS-BTV-16-002]



e.g. disappearing tracks:
[JHEP 1808 (2018) 016]
displaced electron/muon:
[PRL 114 (2015) 6, 061801]

Beyond LHC

General purpose detectors

- Close to beam interaction point & provide 4π coverage
- Very detailed event information & large backgrounds
- Only sensitive to decay lengths ≤ 10 m

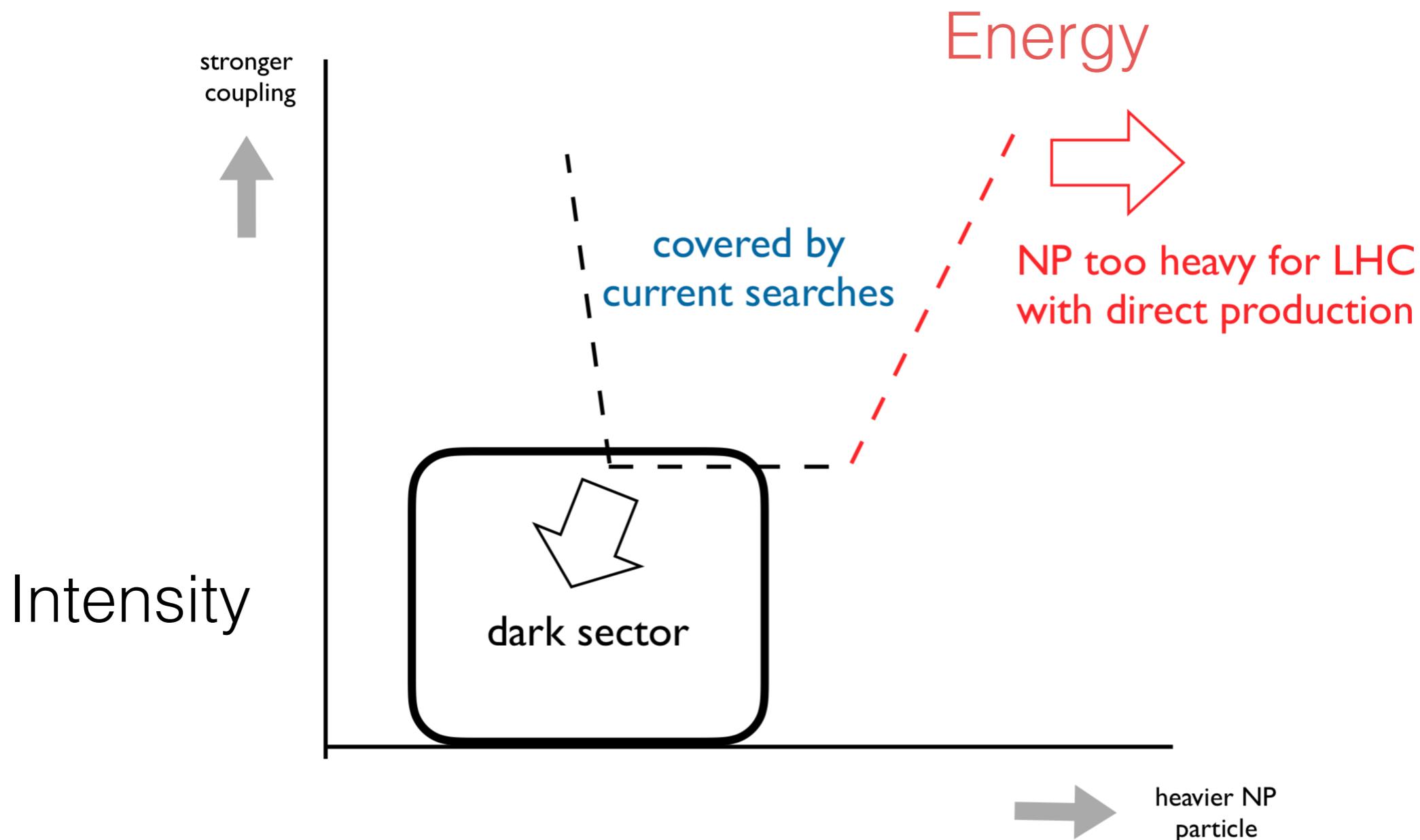
Longer-lived particles must be searched for elsewhere

Energy Frontier (LHC) vs. Intensity frontier

- Small couplings → rare phenomena
- Light particles
- Prioritise integrated luminosity over centre of mass energy
- Fixed target has luminosity advantage than collider
- Lower CM energy but dense target [See F. Maltoni's lecture]

Frontiers

[© L. T. Wang]



Rare decays

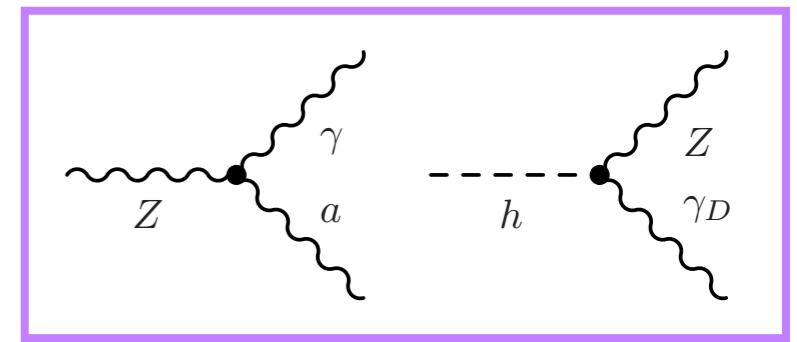
Low-mass hidden sector/LLP

- Decays of SM \rightarrow LLP are kinematically open
- Small couplings \rightarrow ‘rare’ decays

Use ‘factories’ to collect high statistics

Z-boson @ LEP,... and Higgs @ LHC,...

- Total width & exotic decay searches

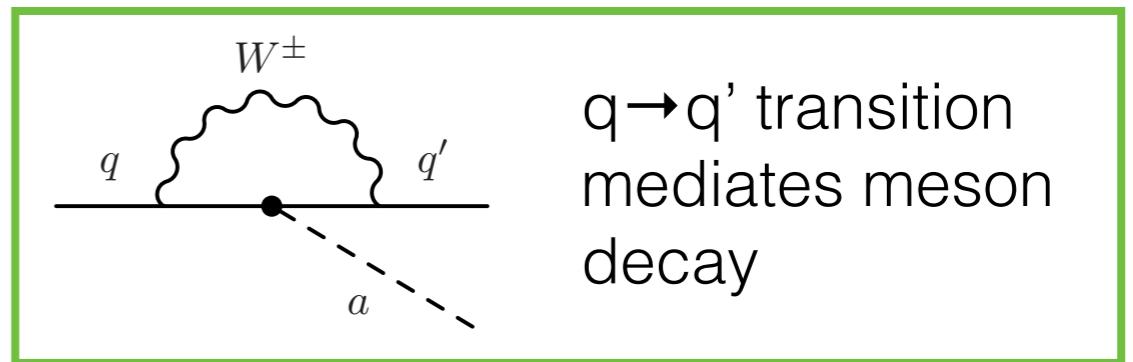


Flavour physics experiments

- B mesons @ Belle (II), Babar,...
- Kaons @ E789, E949, NA62,...

$B \rightarrow K(K^*) + \text{invisible}$

$K \rightarrow \pi^* + \text{invisible}$



Beam dump

Note: Madgraph5_aMC@NLO
beam dump plugin, MadDump
in preparation

Self-explanatory name!

- Block of target material designed to **stop** a collider beam
- Interactions in target material produce **secondary particles**
- Secondary particles can be **exotic LLP**

Like a ‘free’ fixed target experiment

- Add-on to an existing collider experiment
- Place a detector some distance away
- Observe **decay products** or **interaction** with detector

Shielding material can be placed in between

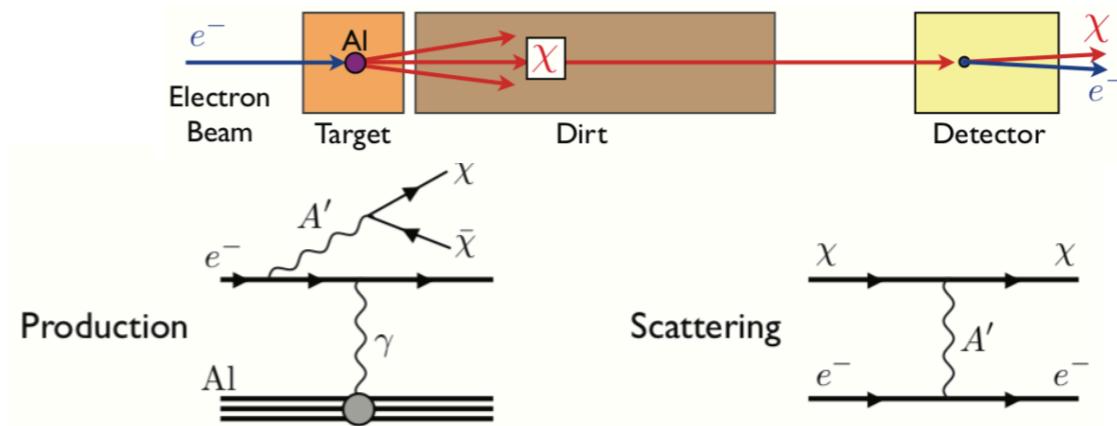
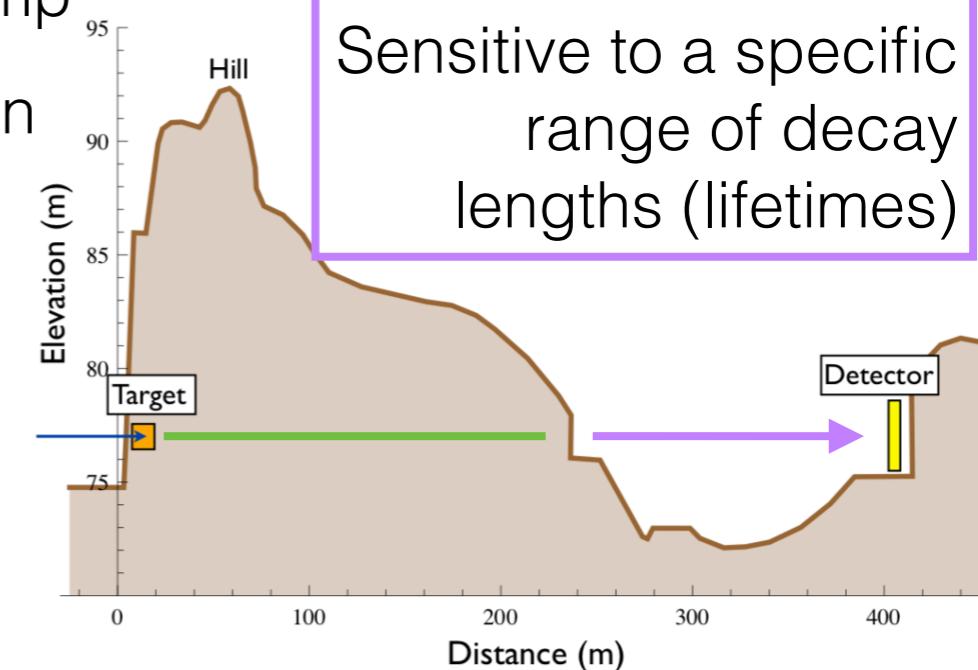
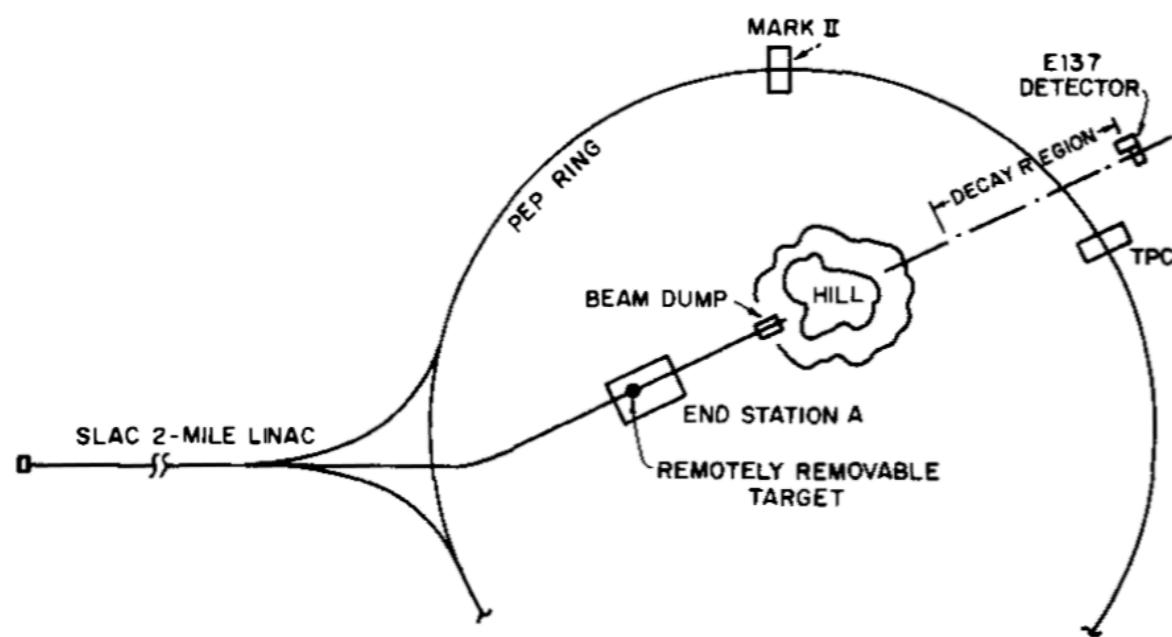
- To stop known SM particles (background)

Fermilab E774
SLAC E141
SLAC E137
Orsay
KEK
NA62 beam
dump mode
SHiP

SLAC E137

Stanford linear accelerator beam dump experiment

- 20 GeV electron beam incident on aluminium dump
- 179 m of **shielding** (hill), 204 m open **decay region**
- Compute production & decay rate for LLP
- No observed events → limits on model



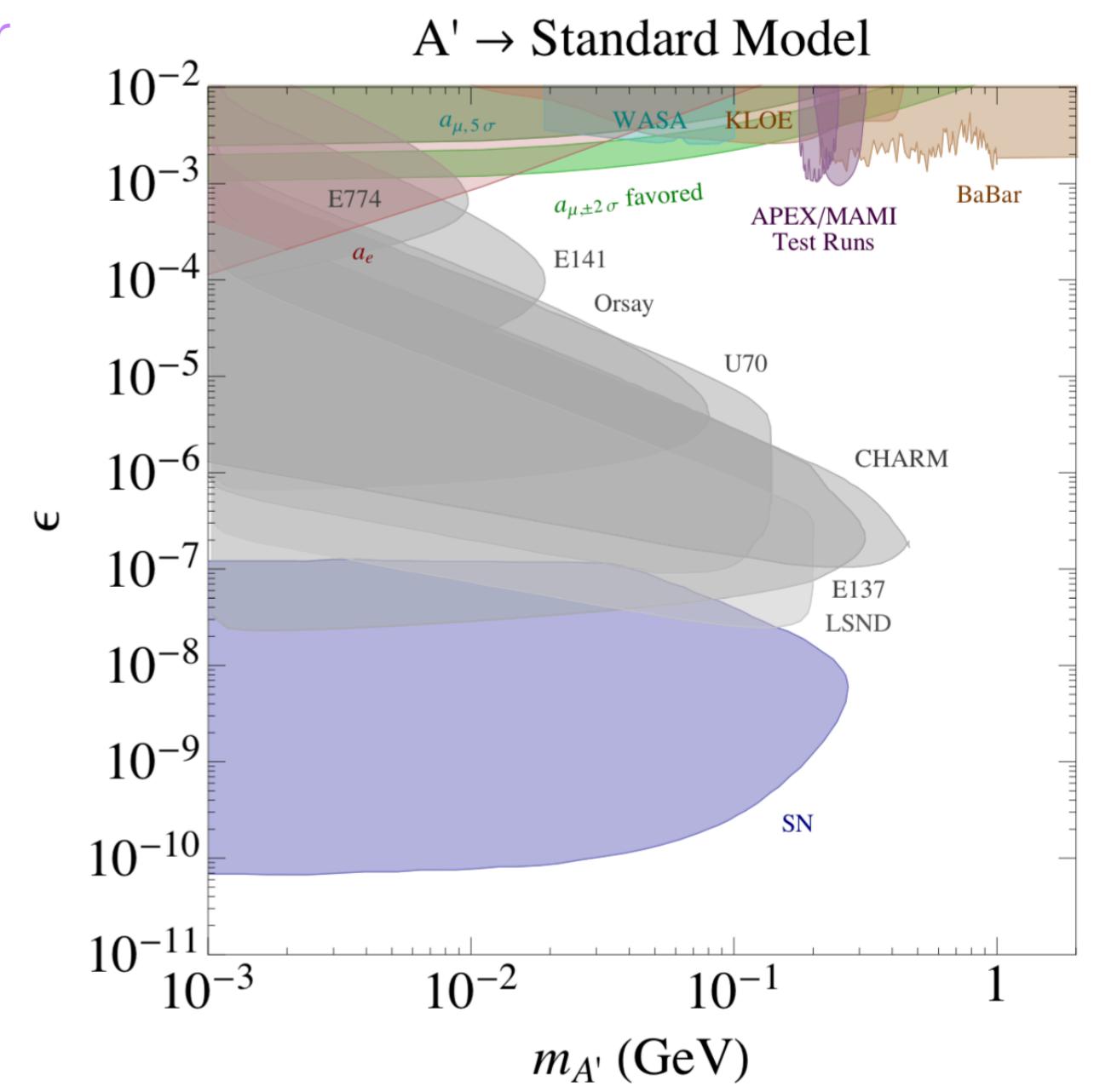
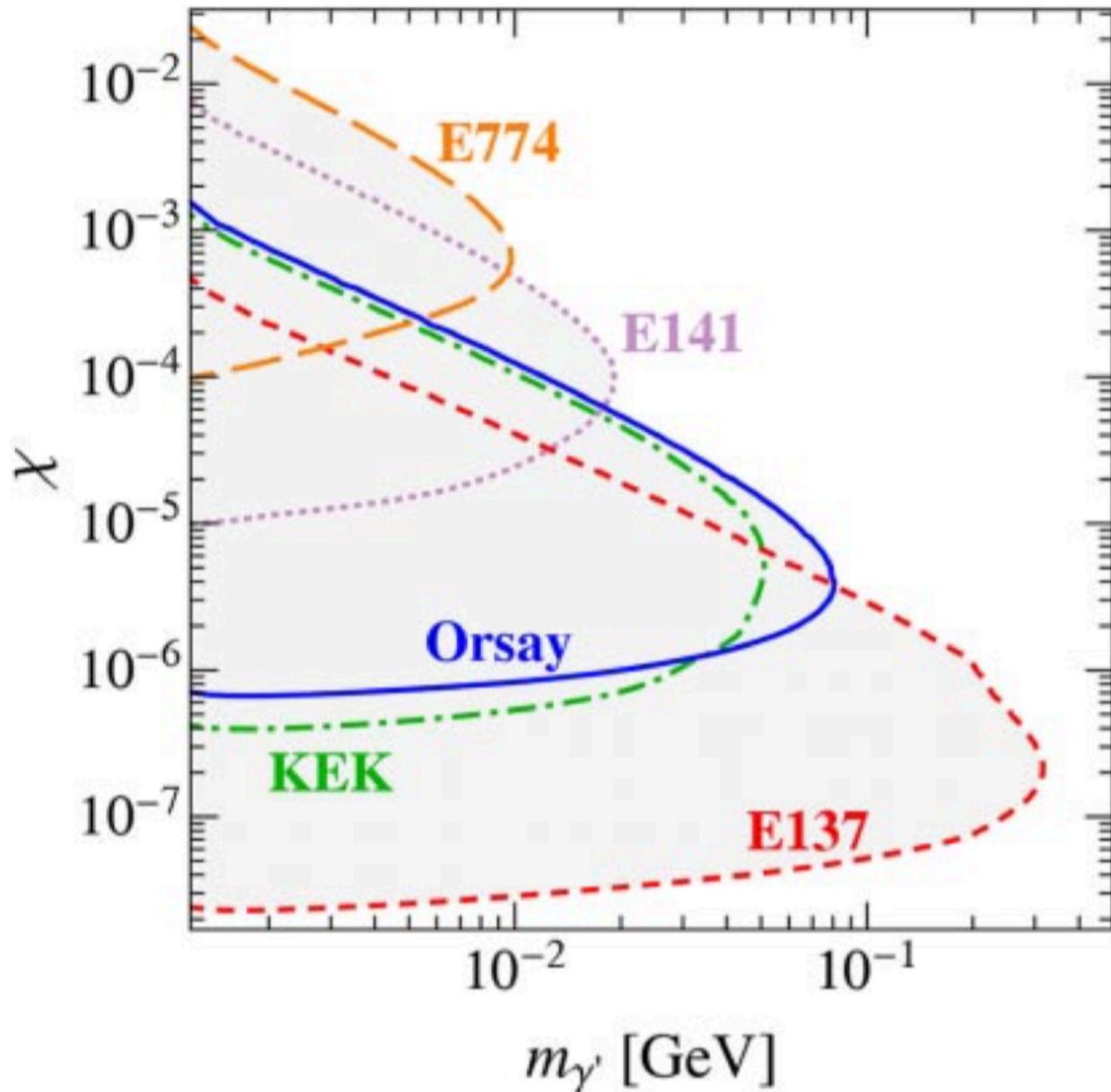
[Bjorken et al.; FERMILAB-CONF-84-033-T]

[Batell, Essig & Surujon; PRL 113 (2014) 17, 171802]

Application

Beam dump limits on dark photons $\rightarrow e^+ e^-$

Mass vs Kinetic mixing parameter



LHC Far detectors

Use LHC collisions as a means for production

- Build new detectors *far away* from interaction point

FASER: ForwArd Search ExpeRiment at the LHC

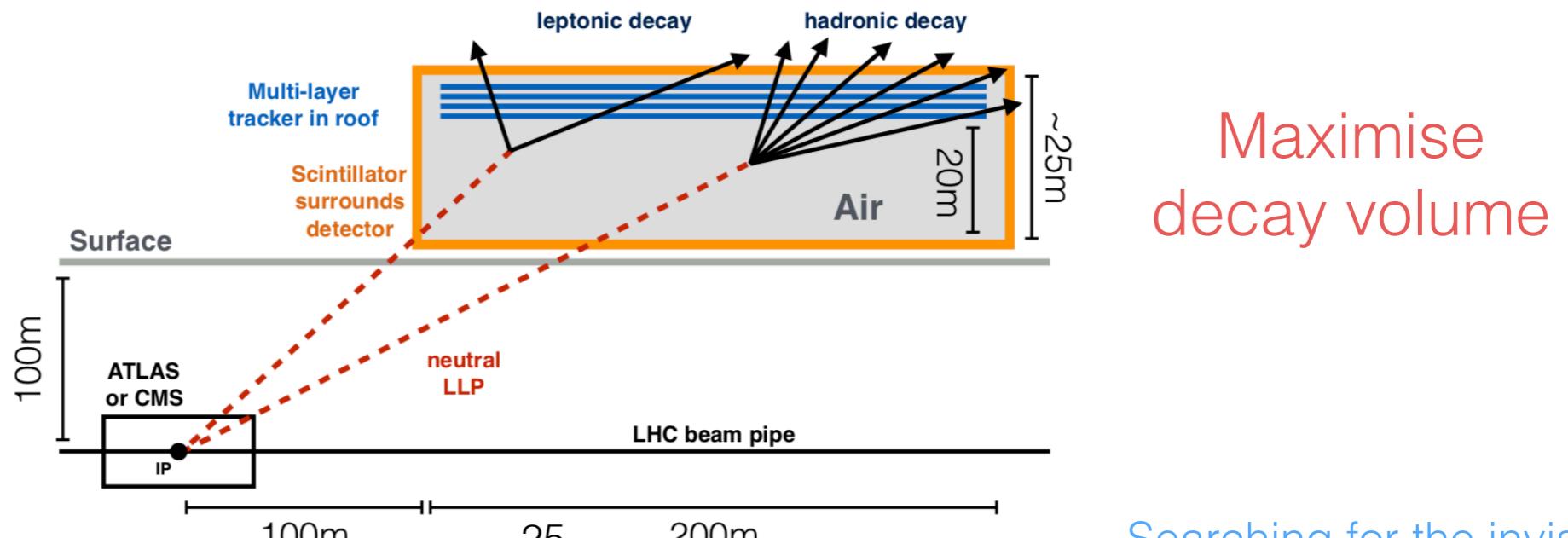
[*Feng, Galon, Kling Trojanowski; PRD 97 (2018) 3, 035001*]

MATHUSLA

[*Chou, Curtin & Lubatti; PLB 767 (2017) 29-36*]

CODEX-b: COmpact Detector for EXotics at LHC-b

[*Gligorov, Knapen, Papucci & Robinson ; PRD 97 (2018) 1, 015023*]



The search continues

Searches for hidden sectors via stable & LLP are a promising playground for new physics discoveries

Plenty of creative model building and experiment design

Few theoretical priors to instruct us where to look

Interplay of cosmological & low/high energy experiments

Intensity frontier is worth exploring alongside the energy frontier

Phenomenological study: Axion-like particles

Motivation

SM does not have any fundamental pseudoscalars

He have observed one scalar state

- Could be fundamental
- Properties consistent with SM

Light pseudoscalars are interesting BSM candidates

- Appear in many models
- Can be long-lived

SUSY
(NMSSM, R-axion)

Composite/
Goldstone Higgs

DM candidates/
mediators...

Strong CP

2HDM

The origin of ALPs

Axions introduced in connection to **Strong CP problem**

- Absence of CP-violating term in QCD Lagrangian
- Neutron EDM measurements constrain $\theta < 10^{-9}$
- Why is it so small when it is allowed by gauge symmetry?
- *Weak sector already CPV: $\theta' = \theta - \text{Arg}[\det[m_q]]$ is the physical observable

$$\frac{\theta}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

Solution: make θ' dynamical (turn it into a field)

$$\frac{a}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu} \rightarrow (\langle a \rangle - \theta') G^{\mu\nu} \tilde{G}_{\mu\nu} = 0$$

- CP-odd gluon interaction generates a potential for axion (QCD instanton)
- No non-derivative interactions
- Axion vacuum expectation value exactly cancels θ'

QCD axion

[J. Kim, Phys. Rev. Lett. 43, 103 (1979)]
[M. Shifman, A. Vainshtein, and V. Zakharov, Nucl. Phys. B166, 493(1980)]
[M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B104, 199 (1981)]
[A. Zhitnitsky, Sov. J. Nucl. Phys. 31, 260 (1980)]

Axion must be a Nambu-Goldstone boson

- Spontaneously broken chiral (anomalous), global symmetry
- Shift symmetry ensures no non-derivative interactions

Axion

Field Scale

$$\phi = \rho \exp(i a/f_a)$$

Original model: Peccei, Quinn, Weinberg & Wilczek

- Pseudoscalar component (phase) of 2nd Higgs doublet
- Axion scale is the EW scale: ruled out

Model building challenge: Invisible axion

- Model that solves strong CP but decouples axion to higher scale
- Typically very light & weakly coupled ($m_a \propto 1/f_a$)
- Can behave like cold dark matter

[R. Peccei, H. Quinn Phys. Rev. Lett. 38 (1977) 1440]
[S. Weinberg, Phys. Rev. Lett. 40 (1978) 223]
[F. Wilczek, Phys. Rev. Lett. 40 (1978) 279]

Axion-like particle

Pseudoscalar that has similar interactions to QCD axion

- No necessarily connected to strong CP
- ‘Simplified model’ approach
- Write down most general set of interactions between ALP & SM
- Approximate shift symmetry → derivative interactions
- Leading interactions at dimension-5: its an EFT!

$a \rightarrow a + \text{constant}$
invariance

$$\begin{aligned}\mathcal{L}_{\text{ALP}} = & \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} \underline{m_a^2 a^2} + i c_{a\varphi} \frac{\partial^\mu a}{f_a} \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) \\ & - c_B \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - c_W \frac{a}{f_a} W_{\mu\nu}^I \tilde{W}_I^{\mu\nu} \\ & - c_G \frac{a}{f_a} \underline{G_{\mu\nu}^A \tilde{G}_A^{\mu\nu}} + \sum_\psi c_{a\psi} \frac{\partial^\mu a}{f_a} \bar{\psi} \gamma_\mu \gamma^5 \psi\end{aligned}$$

Can be rotated to
a $\Psi\Psi$ interaction

ALP-gauge interactions

$$\begin{aligned}\mathcal{L}_{V\tilde{V}} = & -c_B \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - c_W \frac{a}{f_a} W_{\mu\nu}^I \tilde{W}_I^{\mu\nu} - c_G \frac{a}{f_a} G_{\mu\nu}^A \tilde{G}_A^{\mu\nu} \\ = & -c_{\gamma\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} - c_{ZZ} \frac{a}{f_a} Z_{\mu\nu} \tilde{Z}^{\mu\nu} - c_{Z\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{Z}^{\mu\nu} \\ & - c_W \frac{a}{f_a} W_{\mu\nu}^+ \tilde{W}_-^{\mu\nu} - c_G \frac{a}{f_a} G_{\mu\nu}^A \tilde{G}_A^{\mu\nu}\end{aligned}$$

$$\begin{aligned}c_{\gamma\gamma} &= c_B \cos^2 \theta_W + c_W \sin^2 \theta_W \\ c_{ZZ} &= c_B \sin^2 \theta_W + c_W \cos^2 \theta_W \\ c_{Z\gamma} &= (c_W - c_B) \sin \theta_W \cos \theta_W\end{aligned}$$

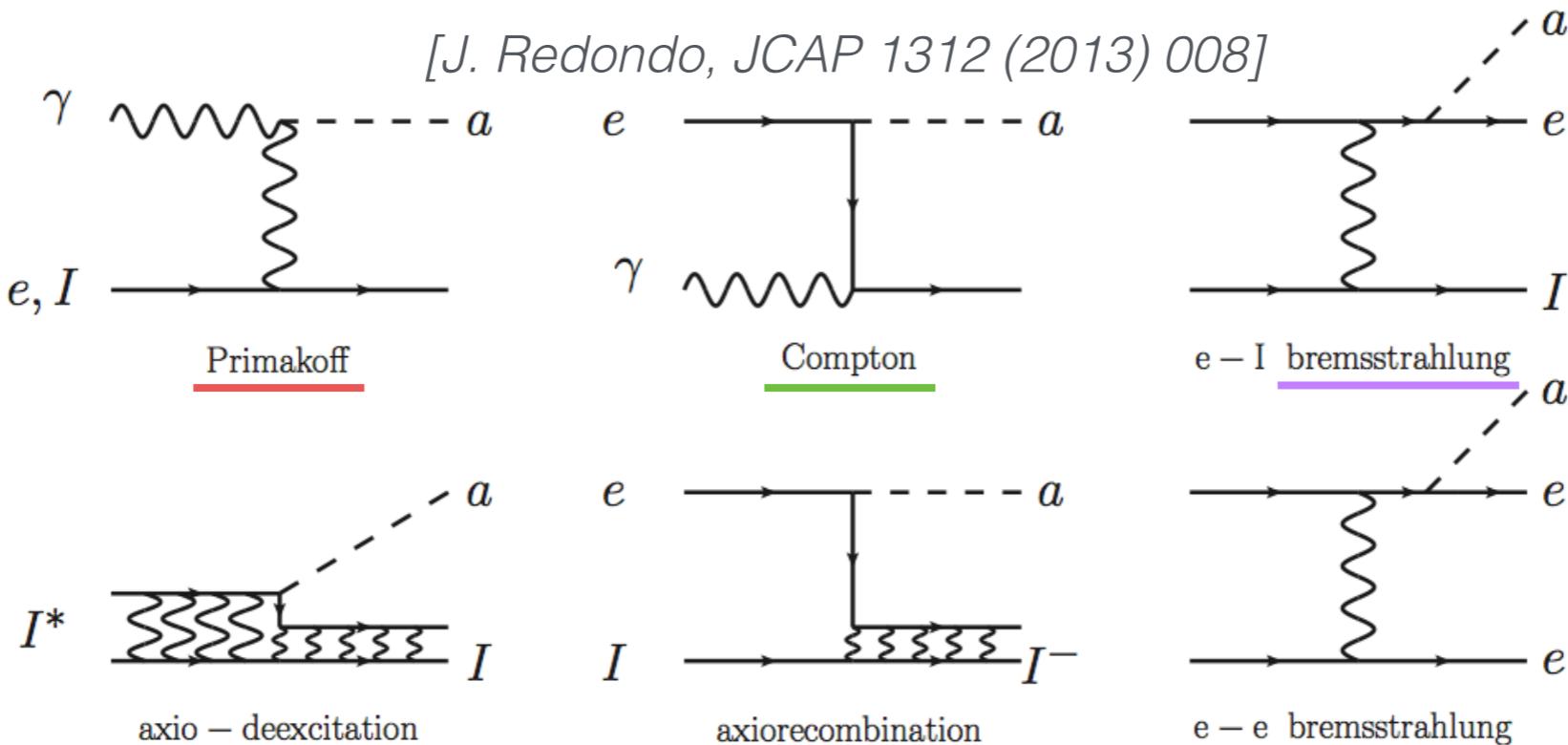
Gauge ‘anomaly’ interactions

- EW sector: 4 couplings determined by 2 parameters
- Photon coupling relevant for **cosmological constraints** on light ALPs
- Gluon coupling must be present if **solving strong CP**
- Explicitly **breaks shift symmetry**, generates mass mixing with pion
- All couplings are interesting to consider at colliders

QED ALP interactions

Photon & electron coupling relevant for astro/cosmology

- Primakoff, Compton and bremsstrahlung processes affect astrophysical phenomena e.g. stellar evolution, supernovae
- Permit ALP \Leftrightarrow photon conversion in a magnetic field
- Can detect an ALP flux, cause disappearance/appearance of photons



ALP lifetime

ALP decay to massless gauge bosons

$$\Gamma_{a \rightarrow XX} = \frac{g_{aX}^2}{64\pi} m_a^3 \cdot C_X$$

C_X = color factor

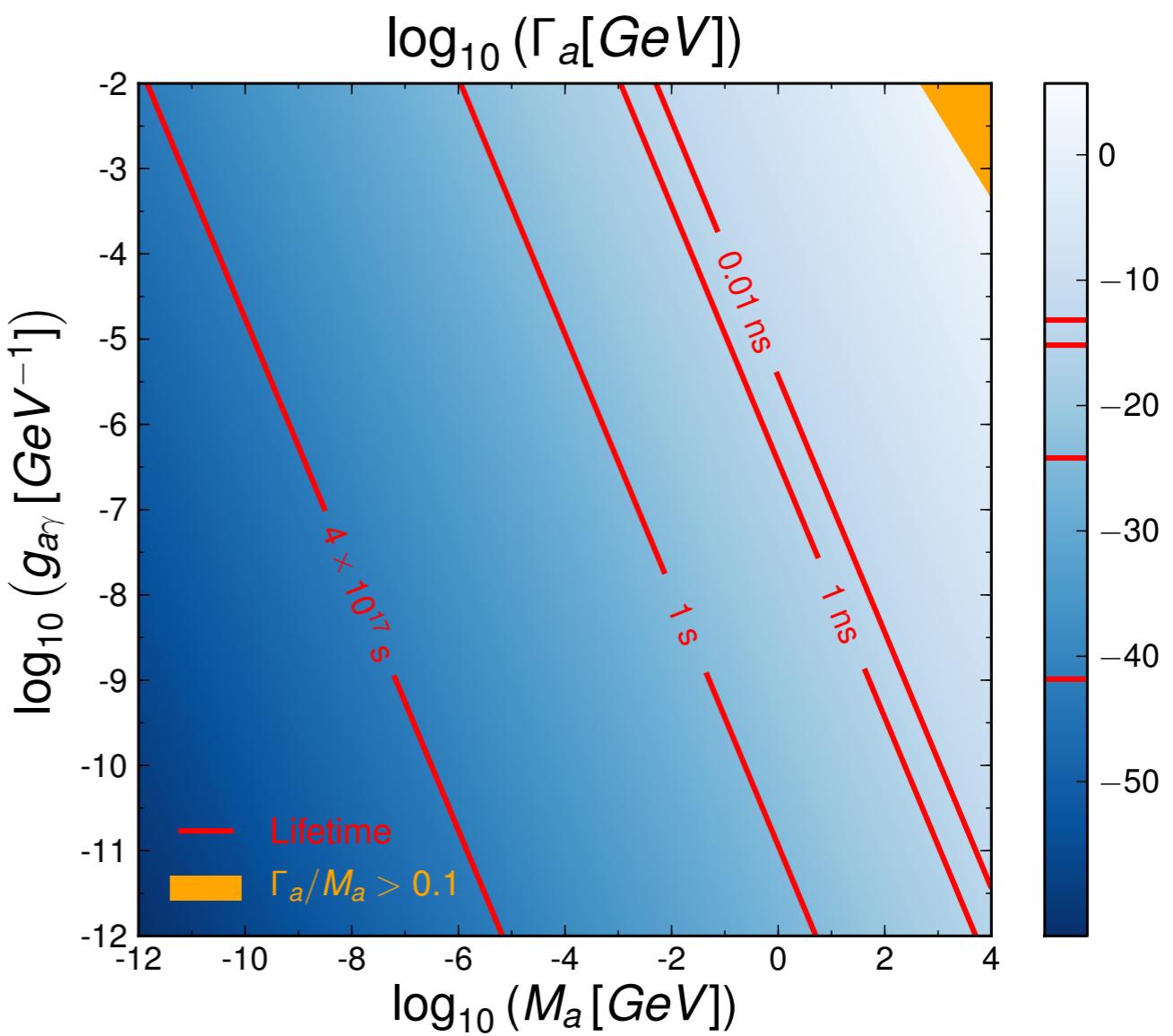
$$\tau = \hbar / \Gamma$$

$$\tau_{\text{univ.}} = 4 \times 10^{-17} \text{ s}$$

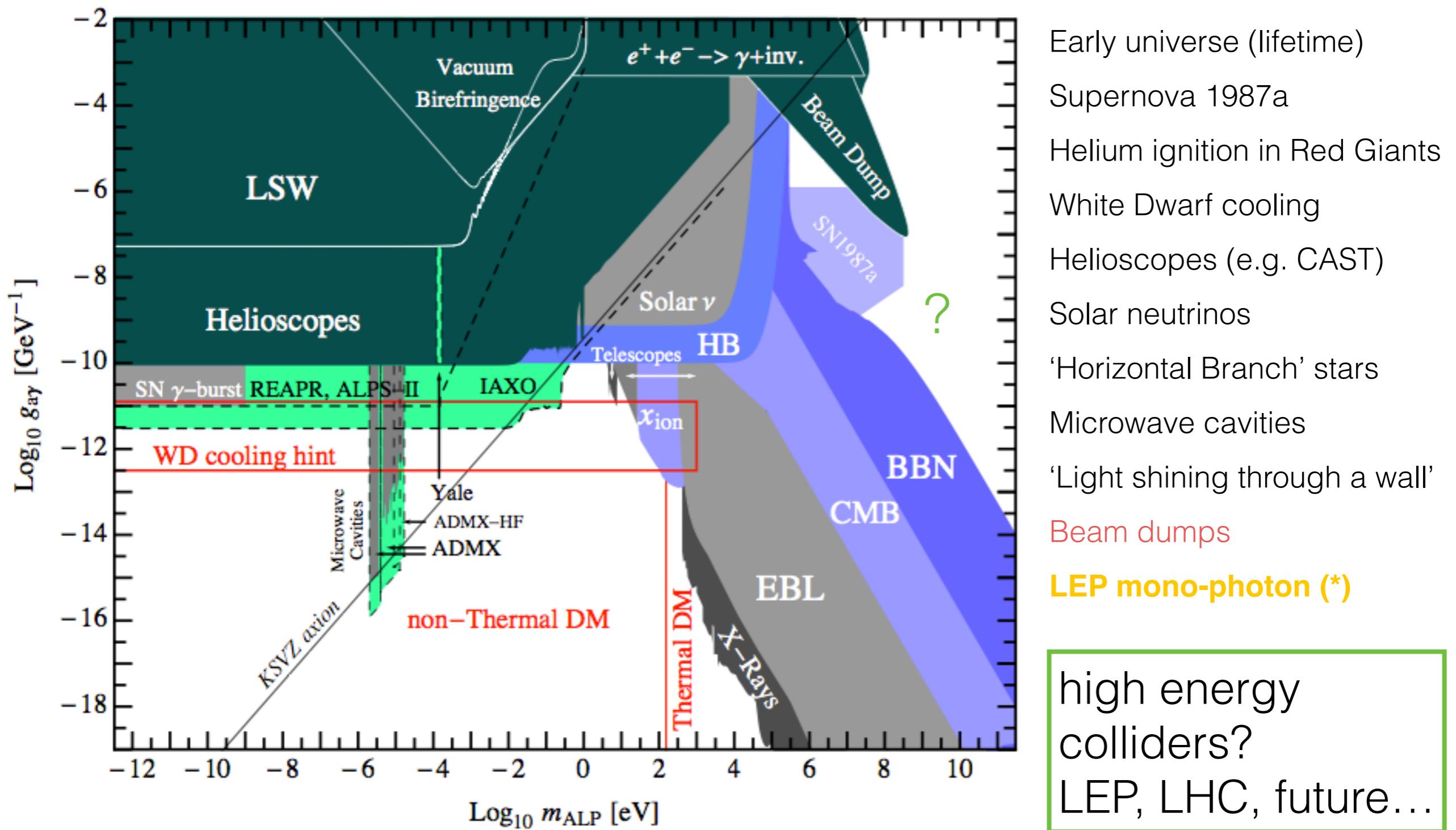
$$\tau_{\text{bbn}} = 1 \text{ s}$$

$$\tau_{\text{stab.}} \lesssim 1 \text{ ns}$$

$$\tau_{\text{prompt}} > 0.01 \text{ ns}$$



Constraints: ALP-photon coupling



[ANL-HEP-TR-12-25], [SLAC-R-991], [FERMILAB-CONF-12-879-PPD]

Constraints: FCNC

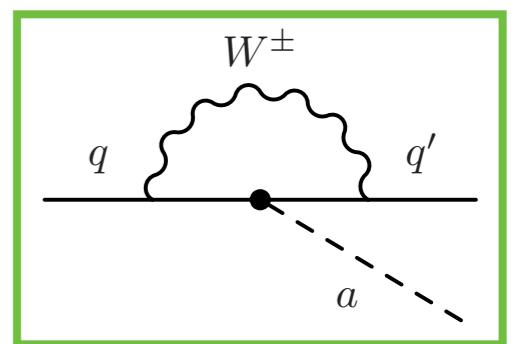
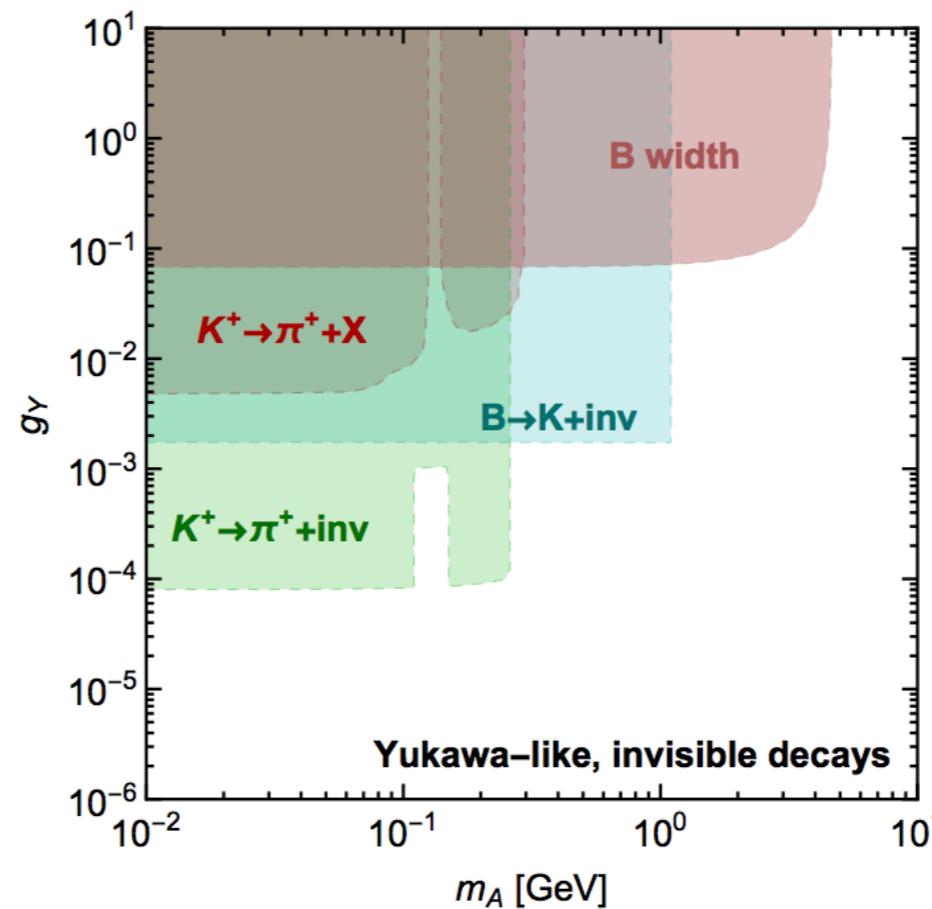
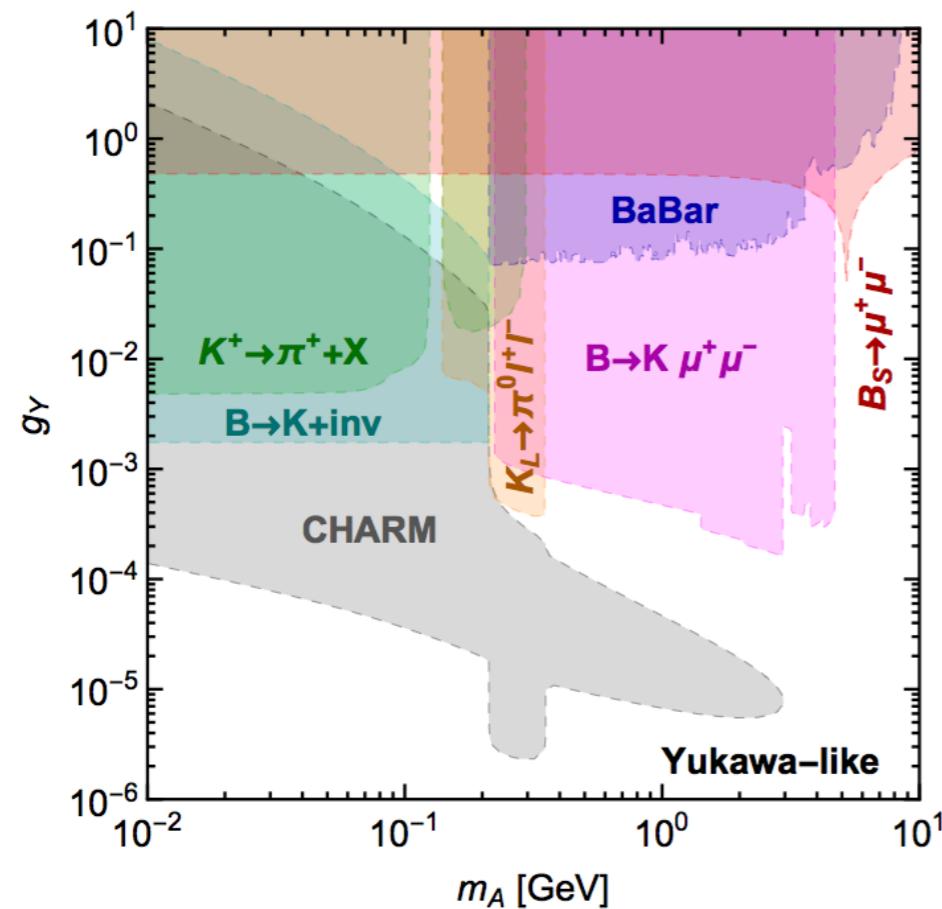
$$c_{a\psi} \frac{\partial^\mu a}{f_a} \bar{\psi} \gamma_\mu \gamma^5 \psi$$

Fermion couplings can be flavor-violating

- Tree level FCNC (very constrained)

Flavor-diagonal couplings can contribute at loop level

- Total width & rare decays of Kaons, B-mesons
- Radiative upsilon decay



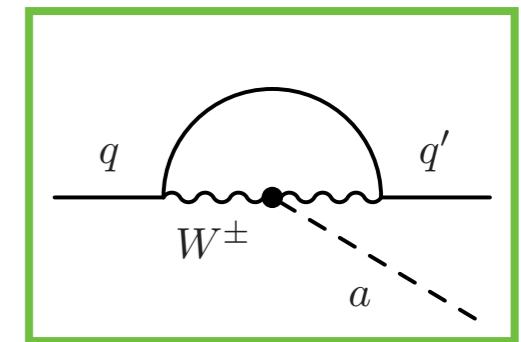
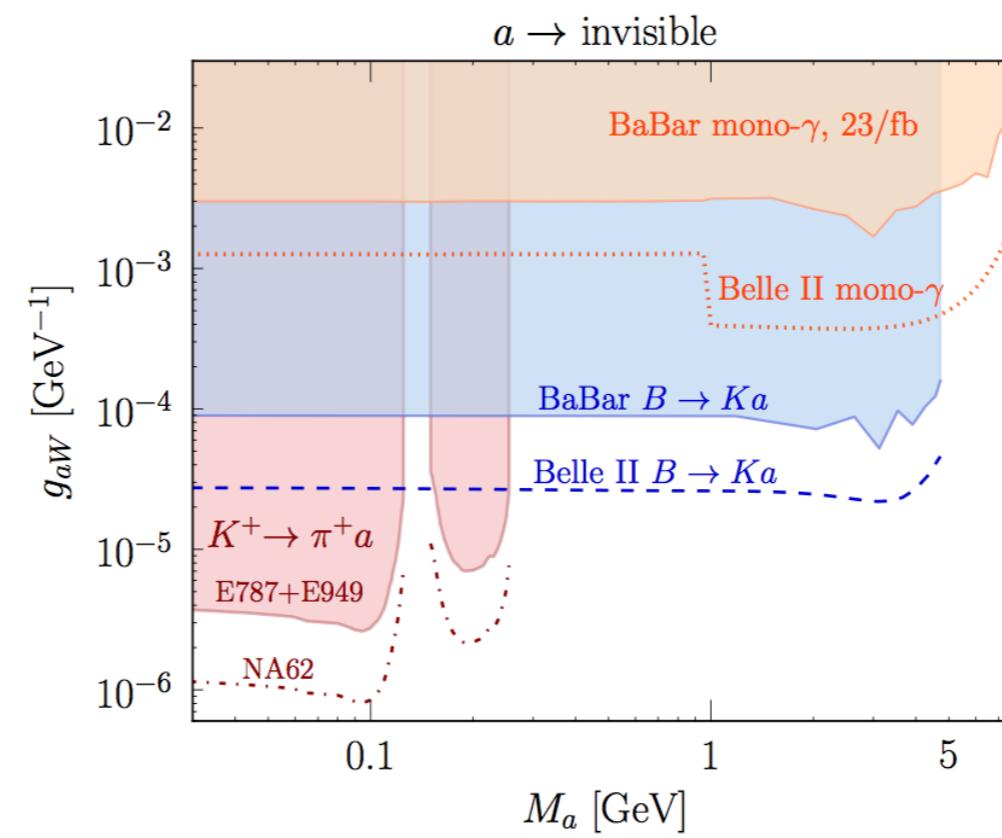
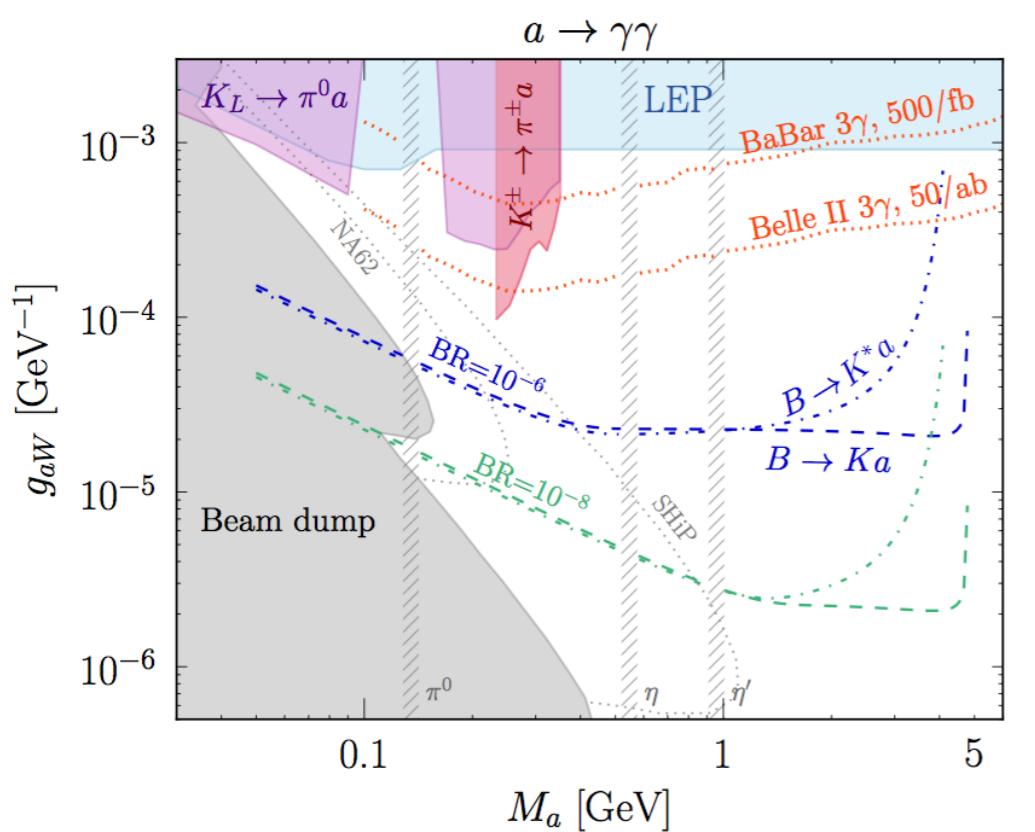
Limits:
 $c_{a\psi} \lesssim [10^{-7}, 10^{-2}]$
for $m_a \lesssim 10 \text{ GeV}$

[Dolan, Kahlhoefer, McCabe & Schmidt-Hoberg; JHEP 1503 (2015) 171]

Constraints: FCNC

Similar process can be mediated by the a -WW interaction

- Best current limit on this coupling (c_W) for light ALPs



$$c_W/f_a \lesssim [10^{-5}, 10^{-2}] \text{ GeV}^{-1} \text{ for } m_a \lesssim 5 \text{ GeV}$$

[Izaguirre, Lin & Shuve; PRL 118 (2017) 111802]

Gluon coupling also induces Kaon decays via pion mixing

$$c_G/f_a \lesssim 3 \times 10^{-6} \text{ GeV}^{-1} \text{ for } m_a \lesssim 60 \text{ MeV}$$

[Fukuda, Harigaya, Ibe & Yanagida; PRD 92 (2015) 015021]

Why colliders?

Many existing limits on light pseudoscalars are **indirect**

- **Astrophysical/cosmological** in nature
- Assumptions about particles in **loops** - potential UV dependence

Kinematically limited by characteristic energy of process

- Temperature of astrophysical body
- Mass of decaying particle

Colliders are a complementary search platform

- Access **direct** production
- Extend **kinematic reach**
- Sensitive to a different range of couplings
- **Independent** set of assumptions & uncertainties

ALPs at colliders

Pseudoscalar with derivative coupling to gauge bosons

Associated production with a vector boson

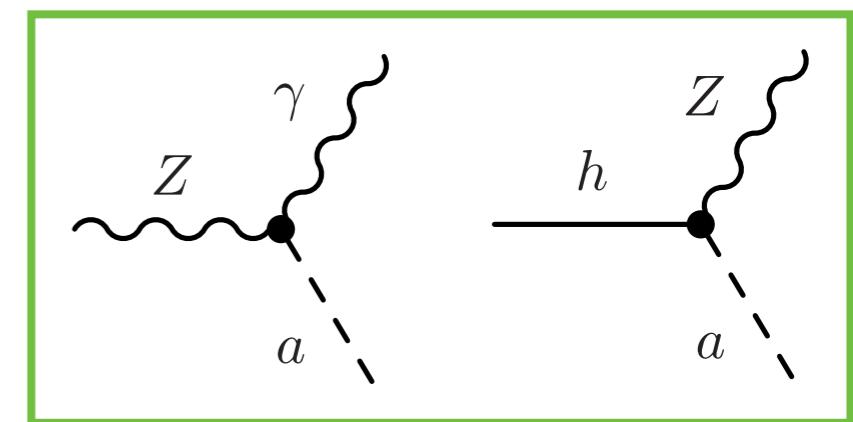
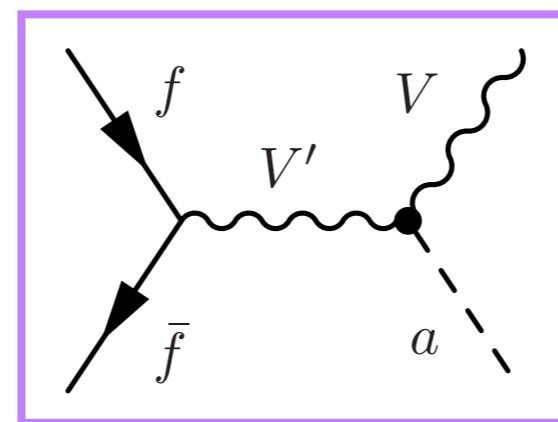
- Does not depend on partonic centre of mass energy, $\sqrt{s} \gg m_V$
- $m_a \leq 1 \text{ GeV}$: stable w.r.t. detector - mono-V signature
- $m_a > 1 \text{ GeV}$: decays back into gauge boson pair - VVV signature

Exotic SM decays

- $Z \rightarrow \gamma a$ & $h \rightarrow Z a$

Other possibilities

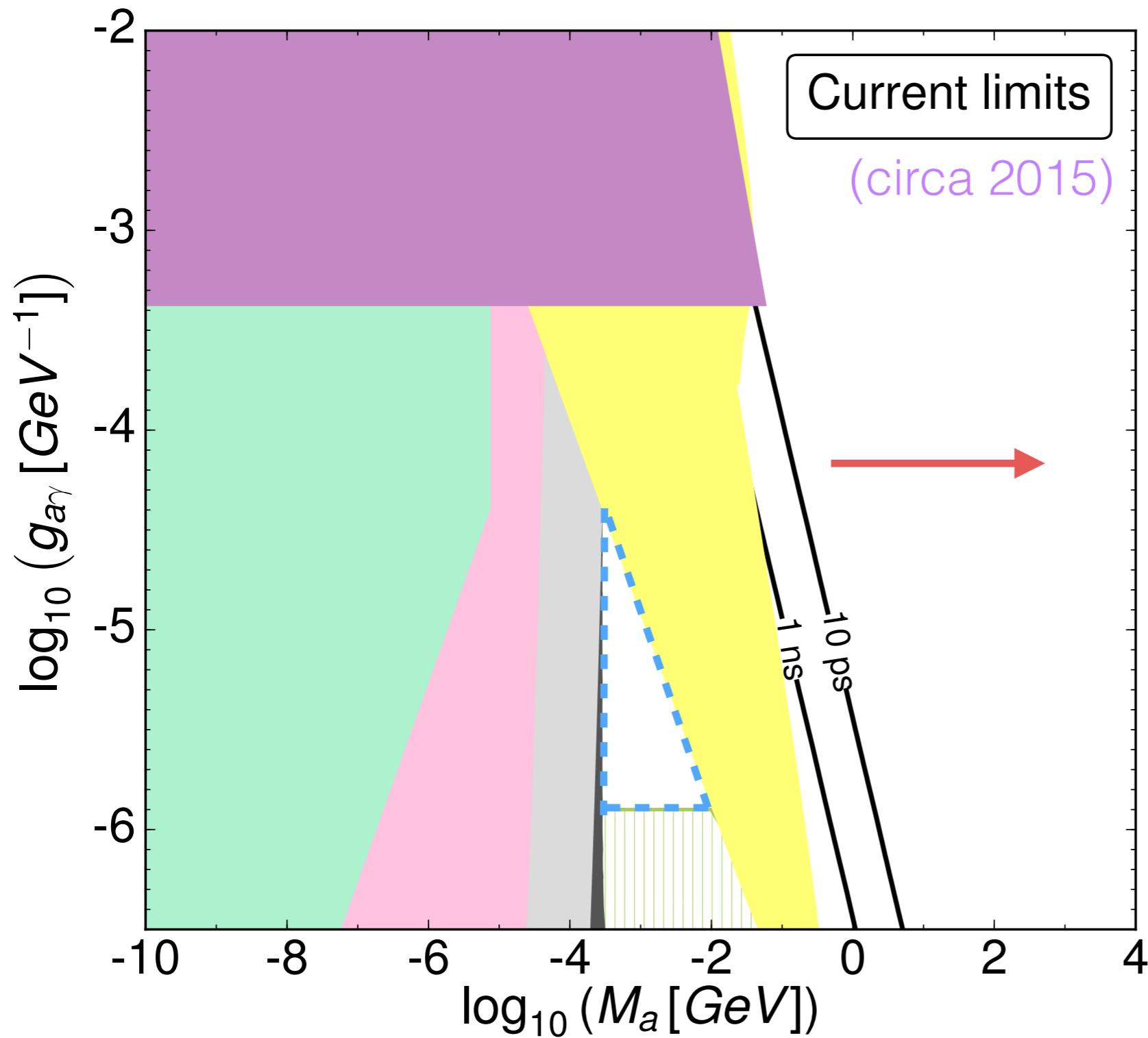
- Top quark coupling
- VV-fusion, ...



Same as DM searches

ALP-photon coupling

$$-\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Recast LHC searches

Focus on photon & gluon coupling

Run I mono-X

- LHC @ 7 TeV mono-photon (5 fb^{-1})
- LHC @ 8 TeV mono-photon (20 fb^{-1})
- LHC @ 8 TeV mono-jet (20 fb^{-1})

[CMS; PRL 108 (2013) 261803]
[ATLAS; PRL 110 (2013) 011802]

[ATLAS-CONF-2012-147]
[CMS; PLB 755 (2016) 102]

[CMS; EPJC 75 (2015) 235]
[ATLAS; EPJC 75 (2015) 299]

[L3; PLB 345 (1995) 609]

[DELPHI, CERN-OPEN-99-410]

[<http://www-cdf.fnal.gov/physics/exotic/r2a/20060908.diphotonPlusX/>]

Pre-LHC tri-photon

- LEP @ MZ (66 pb^{-1})
- LEP II @ 189 GeV (153 pb^{-1})
- Tevatron @ 2 TeV (1.2 fb^{-1})

Future prospects for mono & tri-photon

- LHC @ 8(13) TeV 20(3000) fb^{-1}
- FCC-ee @ 1 TeV, 10 ab^{-1}
- ILC @ 240 GeV 1 ab^{-1}
- Belle-II @ 10.6 GeV, 50 ab^{-1}

mono-photon LHC study

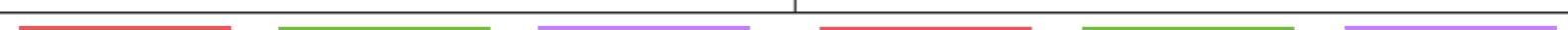
Limits on ALP-photon coupling at the Tevatron, LHC, LEP and future e+e- colliders

- Recast LHC 7 & 8 TeV analyses (optimised for DM/ExtraDim searches)
- Derived prospects by cut & count vs. SM $Z\gamma$ ($Z \rightarrow \nu\nu$) background
- For LHC13, ILC, TLEP (FCC-ee) & Belle II

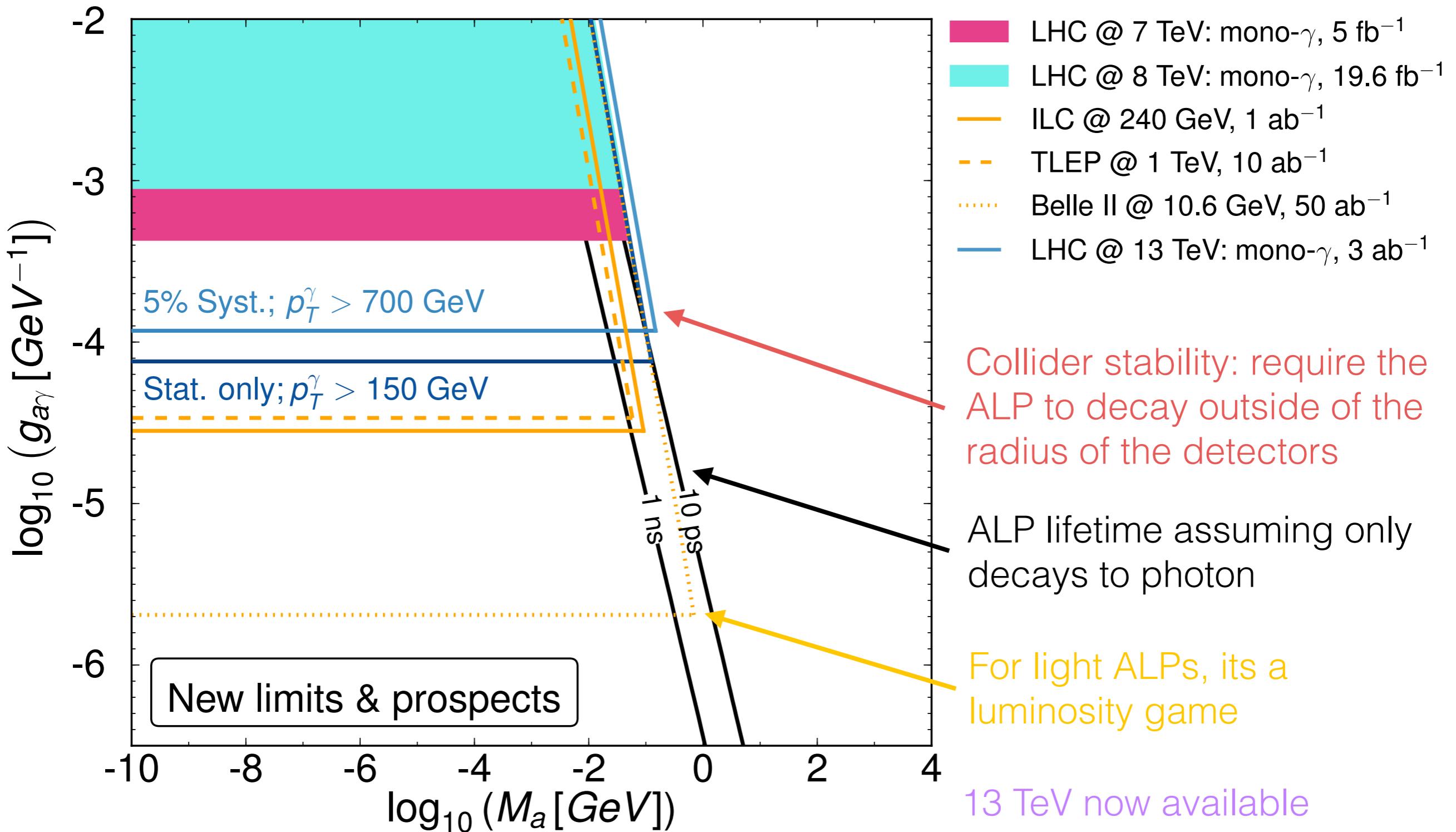
e+e- colliders have much better kinematic control

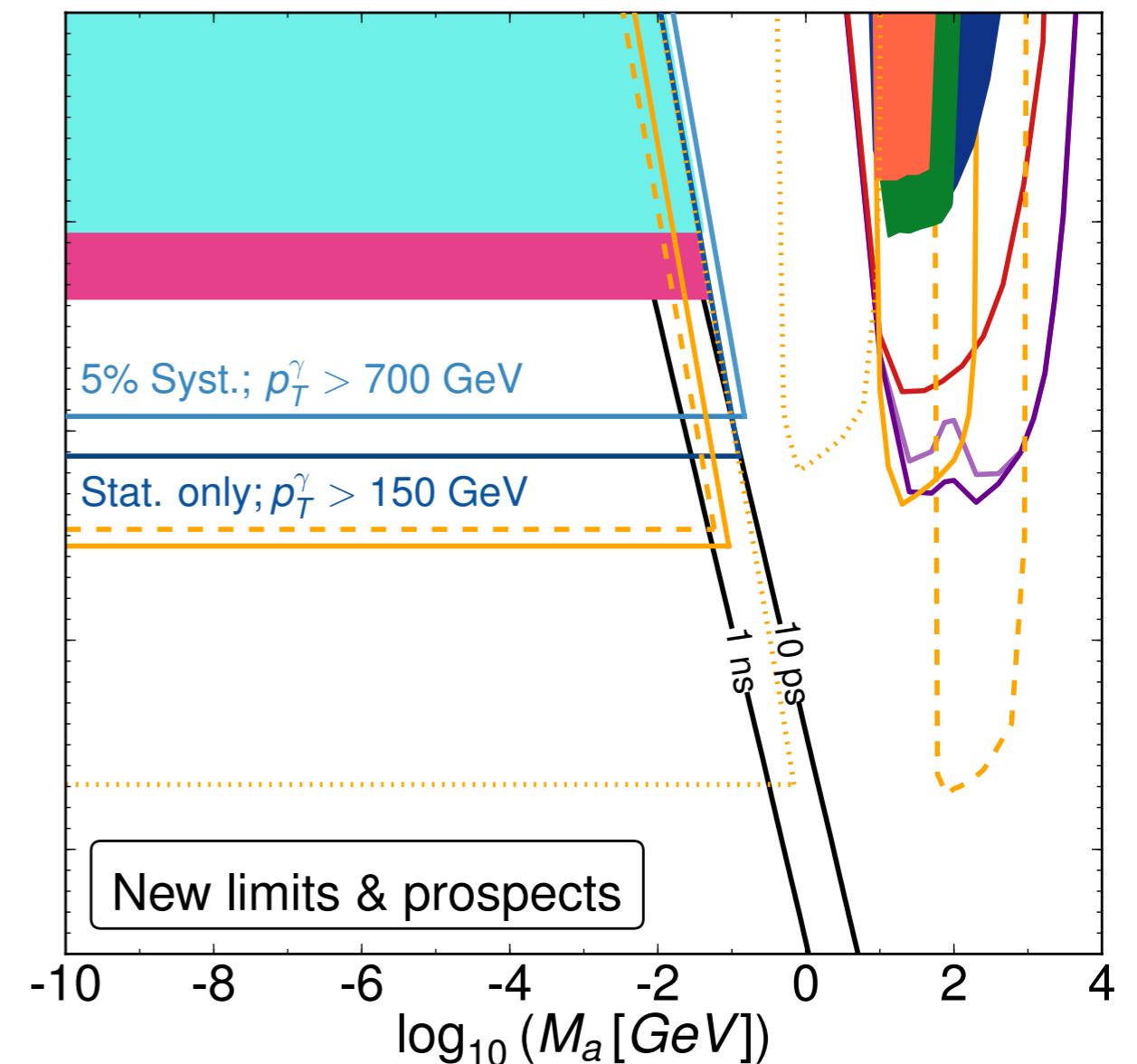
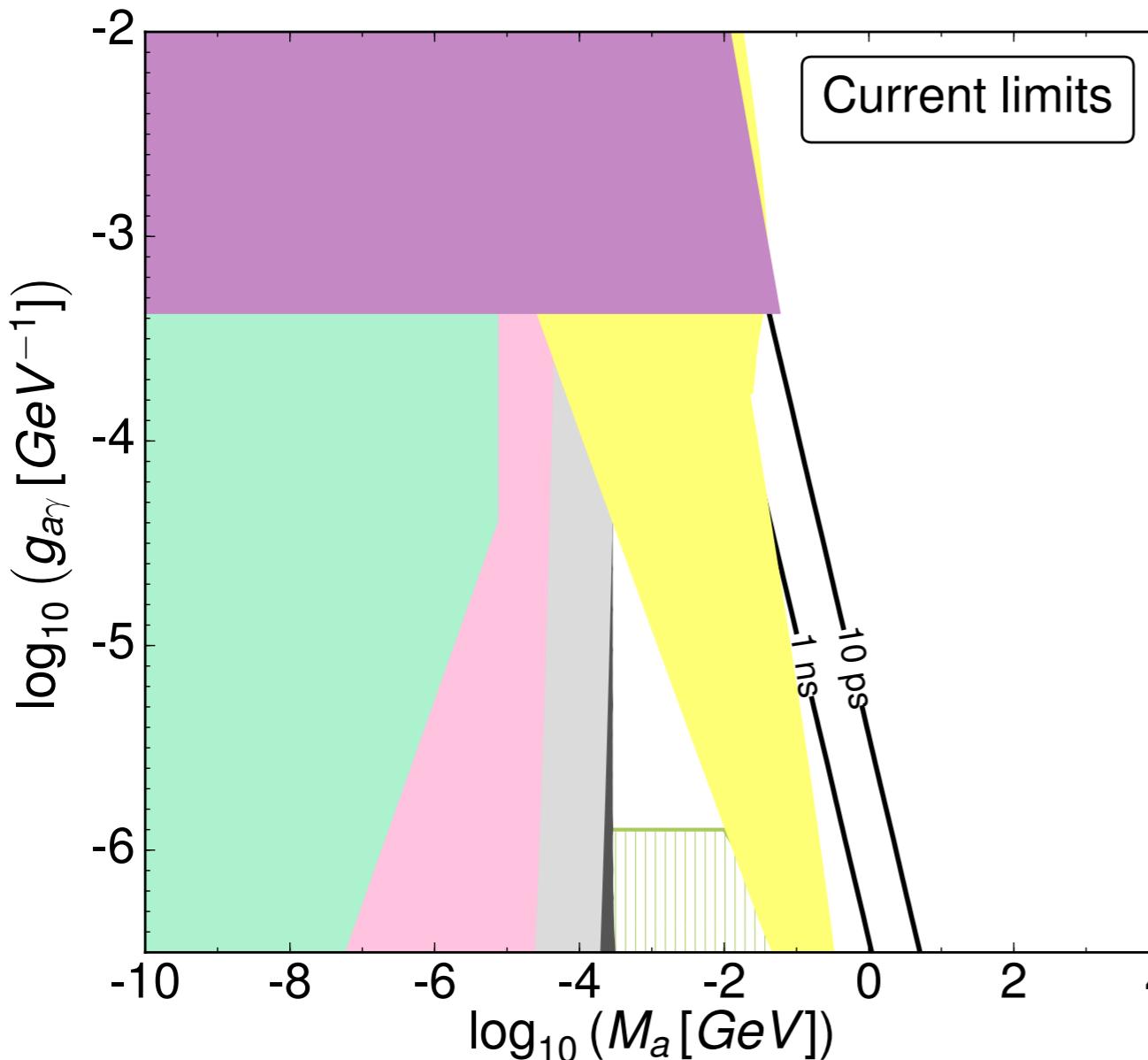
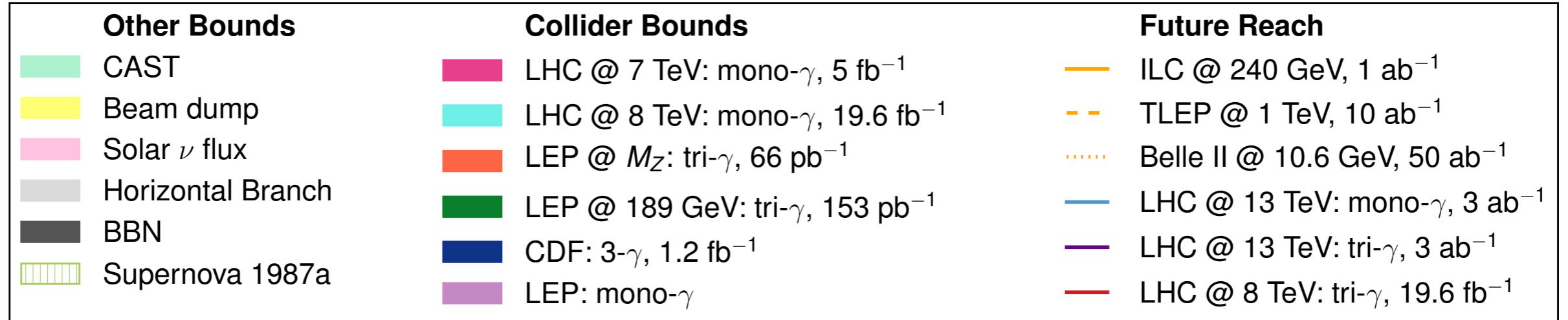
- Cut on the photon p_T and E sufficient to control background

| Collider | Statistics only | | | 5% systematics | | |
|----------|-----------------|-----------|-------------------------------|----------------|-----------|-------------------------------|
| | p_T [GeV] | E [GeV] | $\log_{10}(g_{a\gamma}^{95})$ | p_T [GeV] | E [GeV] | $\log_{10}(g_{a\gamma}^{95})$ |
| ILC | 80 | 115 | -4.6 | 110 | 115 | -4.5 |
| TLEP | 330 | 495 | -4.2 | 350 | 495 | -3.9 |
| Belle II | 3 | 5 | -5.7 | 4 | 5 | -5.1 |



mono-photon results





ALP-gluon coupling

$$-\frac{g_{ag}}{4} G_{\mu\nu}^A \tilde{G}_A^{\mu\nu}$$

Same method to constrain ALP-gluon coupling

- Mono-jet signature
- Dominant contribution from g g initial state
- Factor 8 in ALP decay width → stability limit reached earlier

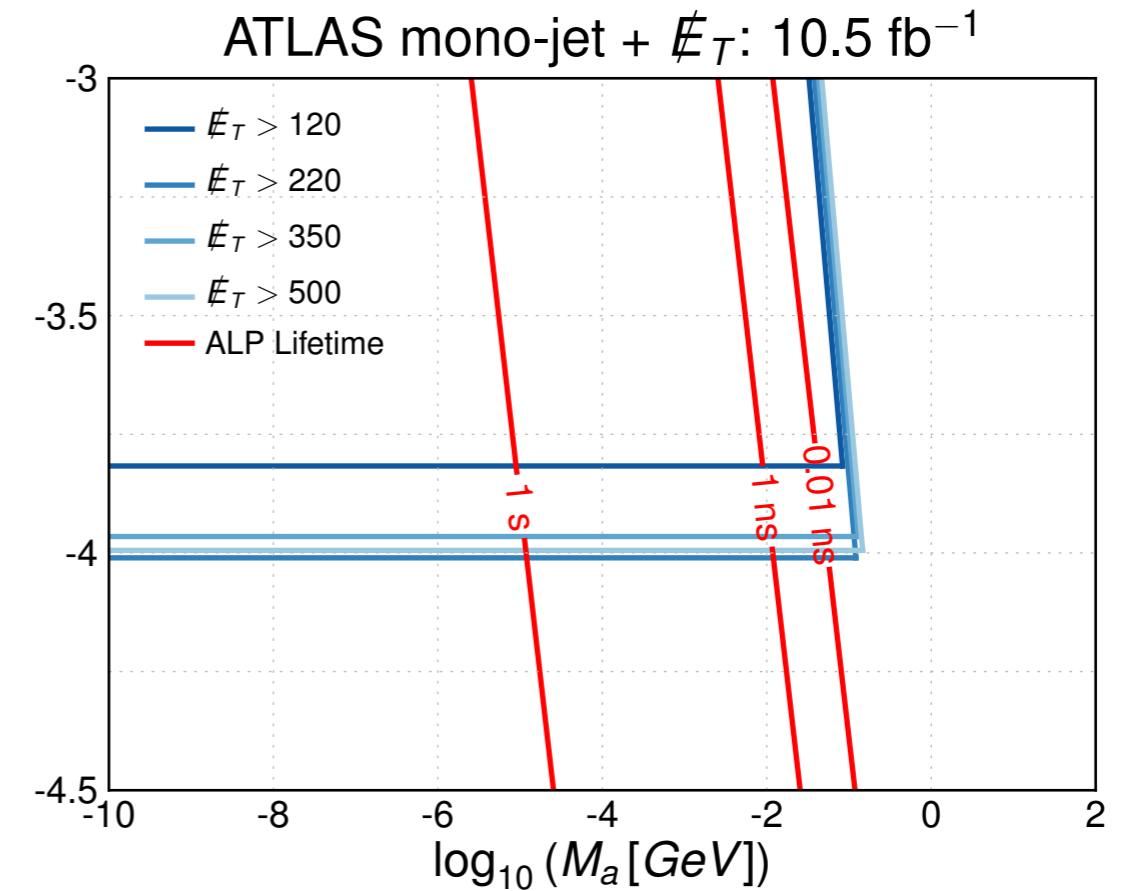
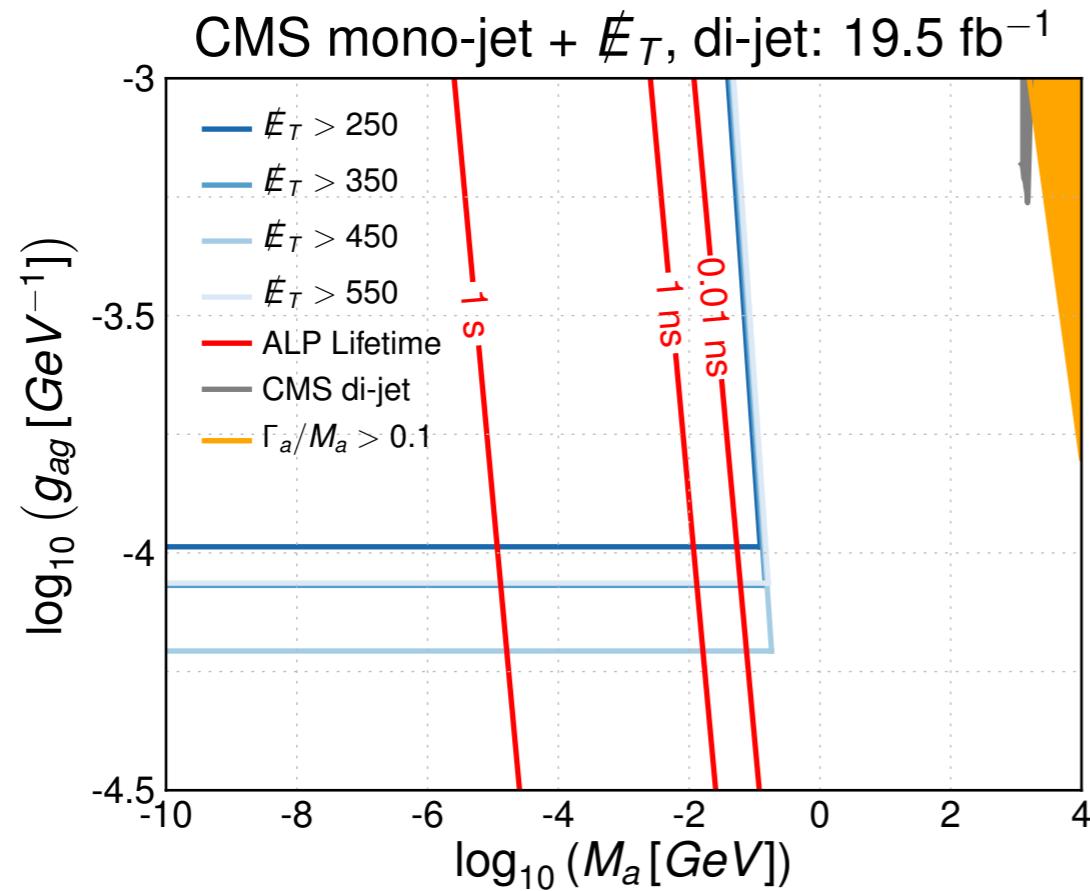
Reinterpreted 8 TeV ATLAS & CMS mono-jet analyses

- One hard jet
- Lepton + additional jet vetos (above a certain pT)
- Several signal regions categorised by missing energy
- Stability limit set by ATLAS calorimetry radius

Limits on g_{ag} of $O(10^{-4})$

- Not far from the limits from kaon decay via pion-mixing
- Run-2 will improve this

Mono-jet results



Once ALP becomes unstable \rightarrow tri-jet signature

- Multi-jet background may be problematic
- Super-heavy ALP can be produced by g g fusion
- 8 TeV dijet limits also shown, width quickly exceeds 10% of mass...
- Boosted dijet analyses for lighter masses, possibly displaces

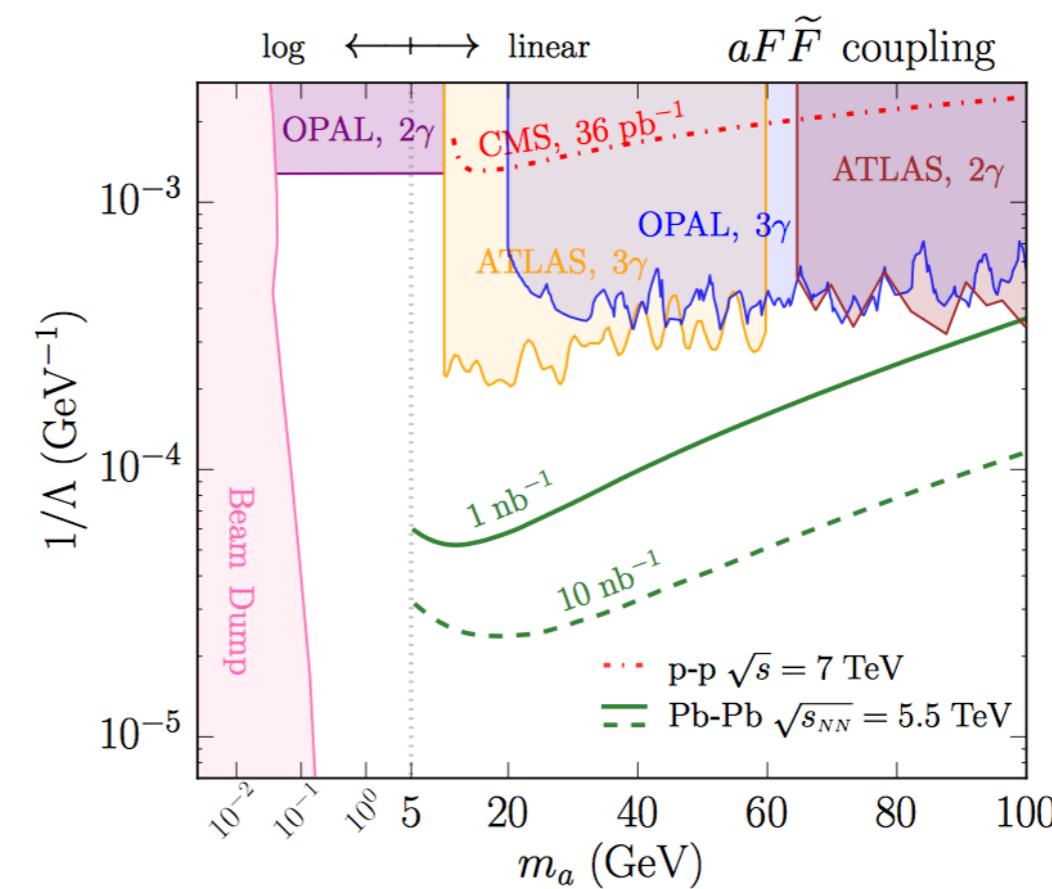
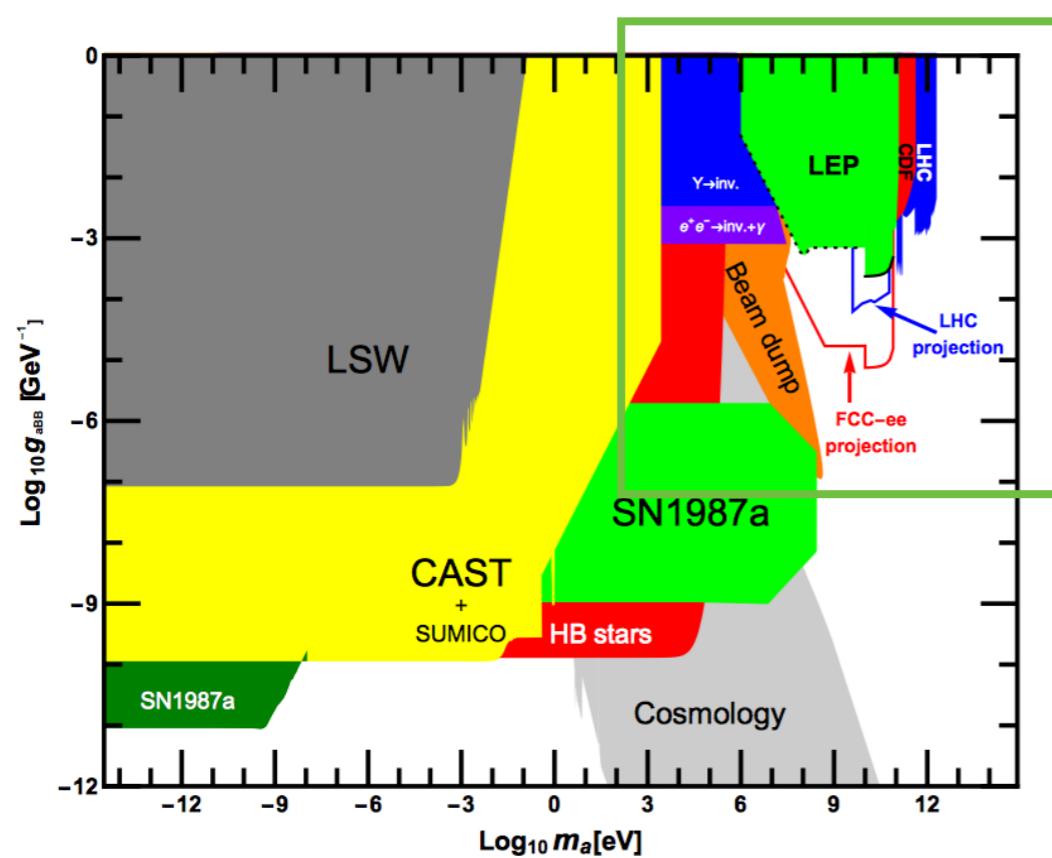
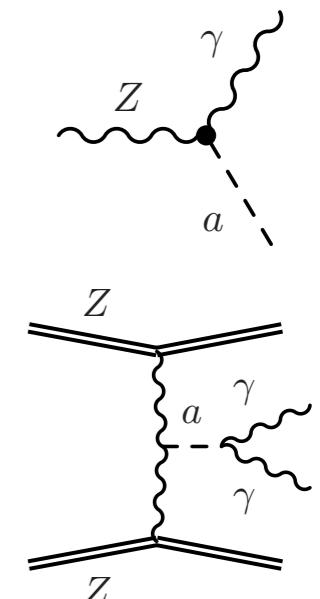
ALP-photon-Z coupling

C_W & C_B operators lead to photon and Z couplings

- LEP: on shell Z decay into 3 photons (possibly displaced)

Ultra-peripheral heavy-ion collisions

- $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ rate **Z⁴ enhanced**, sensitive to $\sim 10^{-4} - 10^{-5} \text{ GeV}^{-1}$



ALP-EW couplings

Strong limits on the photon coupling in the low mass region, where ALP = missing energy

- Present & future colliders can probe orthogonal direction in (c_W , c_B) space

$$c_{\gamma\gamma} = c_B \cos^2 \theta_W + c_W \sin^2 \theta_W$$

$$c_{ZZ} = c_B \sin^2 \theta_W + c_W \cos^2 \theta_W$$

$$c_{Z\gamma} = (c_W - c_B) \sin \theta_W \cos \theta_W$$

$$c_B \simeq -c_W \tan^2 \theta_W$$

$$c_{\gamma\gamma} \simeq 0$$

$$c_{ZZ} = c_W (1 - \tan^2 \theta_W)$$

$$c_{Z\gamma} = c_W \tan \theta_W$$

- No couplings to $\gamma\gamma$ but enhanced ZZ and $Z\gamma$ interactions (also WW)
- Very predictive scenario: all couplings controlled by one parameter
- LHC & future can work towards closing this parameter plane
- e.g. Z & W associated production

For masses > 1 GeV, limits are much weaker

- Consider full parameter space

Photophobic ALP

$$c_{\gamma\gamma} \simeq 0$$

$$c_{ZZ} = c_W(1 - \tan^2 \theta_W)$$

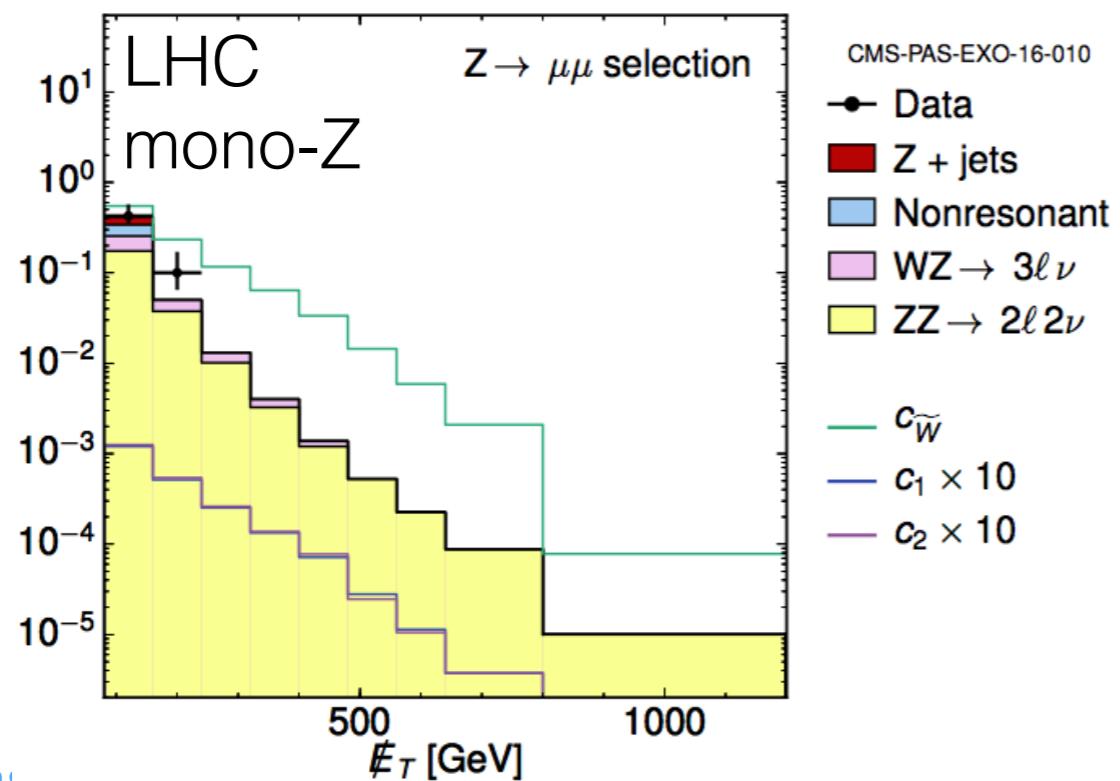
$$c_{Z\gamma} = c_W \tan \theta_W$$

Only constraint on light ALPs in this scenario is the Z width

- Requiring the exotic decay to lie within the uncertainty (< 2 MeV) gives a bound $c_W/f_a \sim 10^{-3}$ GeV-1

Current LHC mono-Z(W) searches have similar sensitivity

- Projecting for 300-3000 fb-1, we expect an improvement of a factor of about an order of magnitude, competitive with rare decays



| $c_{\tilde{W}}$ (mono-Z) | | | | |
|---|-------|-------|-------|-------|
| ℓ | e | | μ | |
| Luminosity [fb $^{-1}$] | 300 | 3000 | 300 | 3000 |
| $f_a/c_{\tilde{W}}$ [TeV] | 10.47 | 15.81 | 9.79 | 14.33 |
| $f_a/c_{\tilde{W}}$ [TeV] [Syst. × 1/2] | 11.10 | 18.40 | 10.39 | 16.67 |
| $f_a/c_{\tilde{W}}$ [TeV] [No Syst.] | 11.64 | 21.47 | 10.91 | 19.64 |

EFT validity

Are we probing the EFT beyond its cutoff?

Constrain model-agnostic ALP effective Lagrangian

- What is the **cutoff**, Λ , vs **characteristic energy** of experiment?
- Hadron colliders: mono-X = pT cuts & tri-X $\sim m_a$
- e+e- colliders: CM energy

In a more familiar EFT language:

$$\frac{g_{aX}}{4} = \frac{c_X}{\Lambda}$$

Assessment depends on sensitivity and assumed c_X

- **naive**: $c_X \sim 1$
- **pNGB ALP**: loop factor & $\Lambda = 4\pi f_a$
- Effective cutoff **reduced** by structure constant α_X

$$E_{\text{exp}} < \Lambda_{\text{eff}} = \frac{4}{g_{aX}}$$

$$\frac{g_{aX}}{4} = \frac{\alpha_X}{4\pi f_a}$$

$$E_{\text{exp}} < \Lambda_{\text{eff}} = \frac{4}{g_{aX}} \alpha_X$$

Mono-photon & jet validity

All limits *naively* probe cutoff in the multi-TeV region

- LHC: jet or photon pT
- 8 TeV mono-photon: $\Lambda_{\text{eff}} \sim 4.5 \text{ TeV} \rightarrow 35 \text{ GeV}$
- Belle II, 10.6 GeV: $\Lambda_{\text{eff}} \sim 2 \text{ PeV} \rightarrow 15 \text{ TeV}$ *naive* → *loop*
- LHC mono-jet : $\Lambda_{\text{eff}} \sim 40 \text{ TeV} \rightarrow 5 \text{ TeV}$
- gs coupling: mono-jet less “punished”

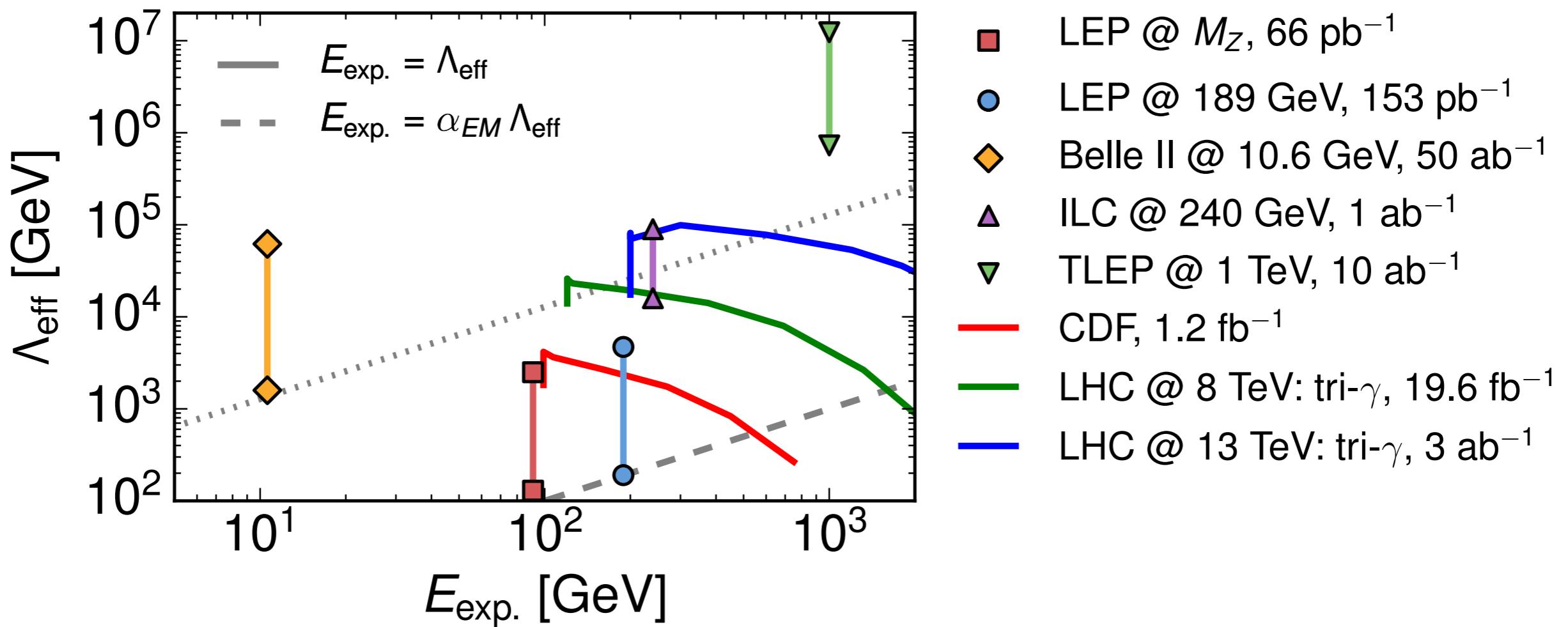
| Analysis | E_{exp} [TeV] | Λ_{eff} [TeV] | $\log_{10}(g_{a\gamma}^{95} [\text{GeV}])$ |
|------------------|------------------------|------------------------------|--|
| LHC7 | 0.26–2.6 | 9.4 | −3.37 |
| LHC8 | 0.5–1.1 | 4.5 | −3.05 |
| LHC14 (Stat) | 0.3–1.8 | 50 | −4.12 |
| LHC14 (5% Syst.) | 1.4–8.6 | 34 | −3.93 |
| ILC | 0.24 | 140 | −4.47 |
| TLEP | 1 | 118 | −4.55 |
| Belle II | 0.0106 | 1960 | −5.69 |

| Analysis | E_{exp} [TeV] | Λ_{eff} [TeV] | $\log_{10}(g_{ag}^{95} [\text{GeV}])$ |
|----------------------------------|------------------------|------------------------------|---------------------------------------|
| CMS | - | - | - |
| $\cancel{E}_T > 250 \text{ GeV}$ | 0.5–2.8 | 36 | −3.95 |
| $\cancel{E}_T > 350 \text{ GeV}$ | 0.7–3.9 | 50 | −4.1 |
| $\cancel{E}_T > 450 \text{ GeV}$ | 0.9–5 | 63 | −4.2 |
| $\cancel{E}_T > 550 \text{ GeV}$ | 1.1–6.1 | 50 | −4.1 |
| ATLAS | - | - | - |
| $\cancel{E}_T > 120 \text{ GeV}$ | 0.24–0.9 | 28 | −3.85 |
| $\cancel{E}_T > 220 \text{ GeV}$ | 0.44–1.7 | 40 | −4.0 |
| $\cancel{E}_T > 350 \text{ GeV}$ | 0.7–2.6 | 31 | −3.9 |
| $\cancel{E}_T > 500 \text{ GeV}$ | 1.0–3.8 | 40 | −4.0 |

Tri-photon validity

Most LHC searches fall (partly) out of validity when assuming the loop normalisation

- Low and high energy lepton colliders favoured



The future of ALPs

ALPs are an interesting phenomenological scenario of a
testable hidden sector

- Theoretically well motivated
- Constrained from many directions

Colliders can provide **complementary information**

- **Missing energy** signatures
- Recasts of existing DM searches
- Unexplored possibility of **displaced vertices**

Many interesting signatures to consider

- LLP potential at LHC: near & far detectors
- Future collider potential also being studied



Thank you

Higgs & fermion couplings

$$ic_{a\varphi} \frac{\partial^\mu a}{f_a} \left(\langle \varphi^\dagger \rangle \overleftrightarrow{D}_\mu \langle \varphi \rangle \right) \propto c_{a\varphi} \frac{v^2}{f_a} \partial^\mu a Z_\mu$$

Operator induces Z-a mixing after EWSB

1. Removed by **a-dependent Higgs field redefinition** at the price of generation Yukawa-like a- $\Psi\Psi$ interactions
2. Chiral **fermion field redefinition** moves these back to the original fermionic interactions & **shifts ALP-gauge boson interactions**
3. Quark-current operator **physically equivalent** to pseudoscalar Yukawa coupling after integration by parts and Dirac equation

$$(1) \quad \varphi \rightarrow \exp \left(ic_{a\varphi} \frac{a}{f_a} \right) \varphi : \quad ic_{a\varphi} \frac{\partial^\mu a}{f_a} \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) \rightarrow ic_{a\varphi} \frac{a}{f_a} \left(\mathbf{Y_u} \bar{Q}_L \tilde{\varphi} u_R - \mathbf{Y_d} \bar{Q}_L \varphi d_R - \mathbf{Y_e} \bar{L}_L \varphi e_R + \text{h.c.} \right)$$

$$(2) \quad \psi_L \rightarrow \exp \left(iX_{\psi_L} \frac{a}{f_a} \right) \psi_L, \quad \psi_R \rightarrow \exp \left(iX_{\psi_R} \frac{a}{f_a} \right) \psi_R : \quad \{c_V, c_{a\psi}\} \rightarrow \{c'_V, c'_{a\psi}\}$$

$$(3) \quad i \frac{\partial^\mu a}{f_a} \bar{\psi} \gamma_\mu \gamma^5 \psi \equiv -2m_\psi a \bar{\psi} \gamma^5 \psi$$

$\rightarrow \mathcal{L}_{\text{ALP}}$ is fully general at D=5