Higgs Physics at the Lifetime Frontier

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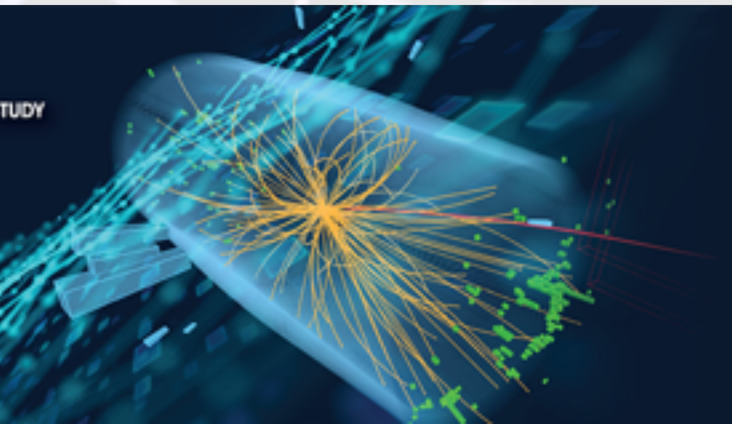
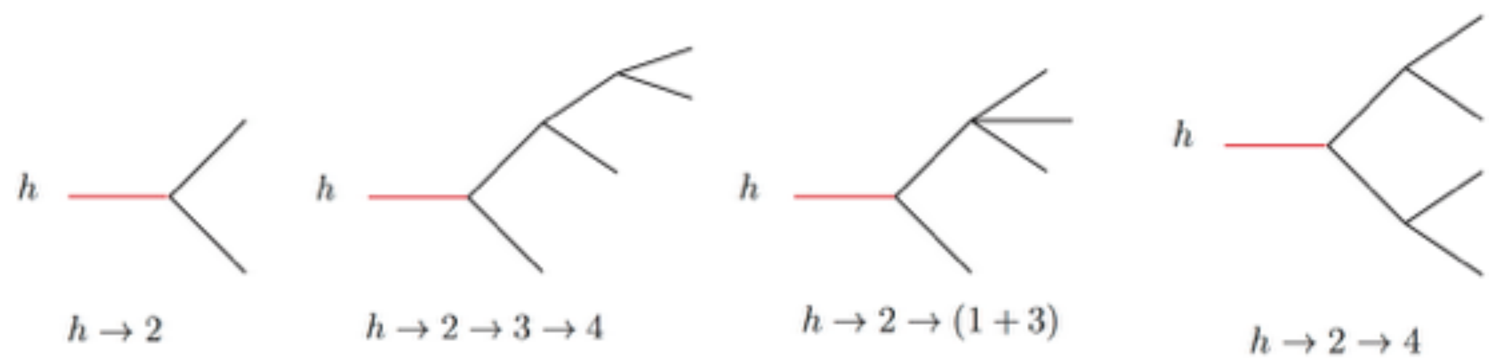
IAS PROGRAM
High Energy Physics
January 7-25, 2019



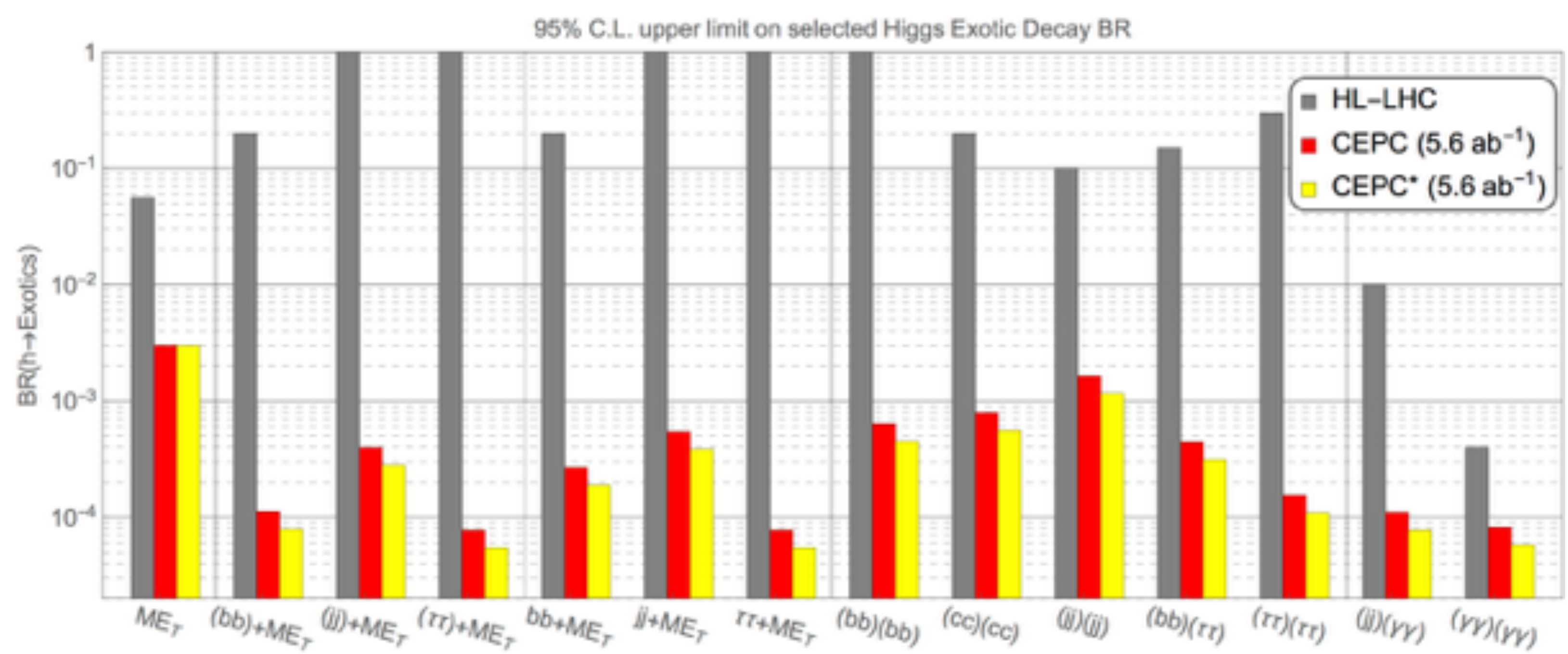
The Higgs Portal to BSM

Higgs the most natural portal to new physics: $\mathcal{L} \supset |H|^2 \mathcal{O}_{\rm BSM}$

Narrow Higgs → exotic decays a sensitive probe



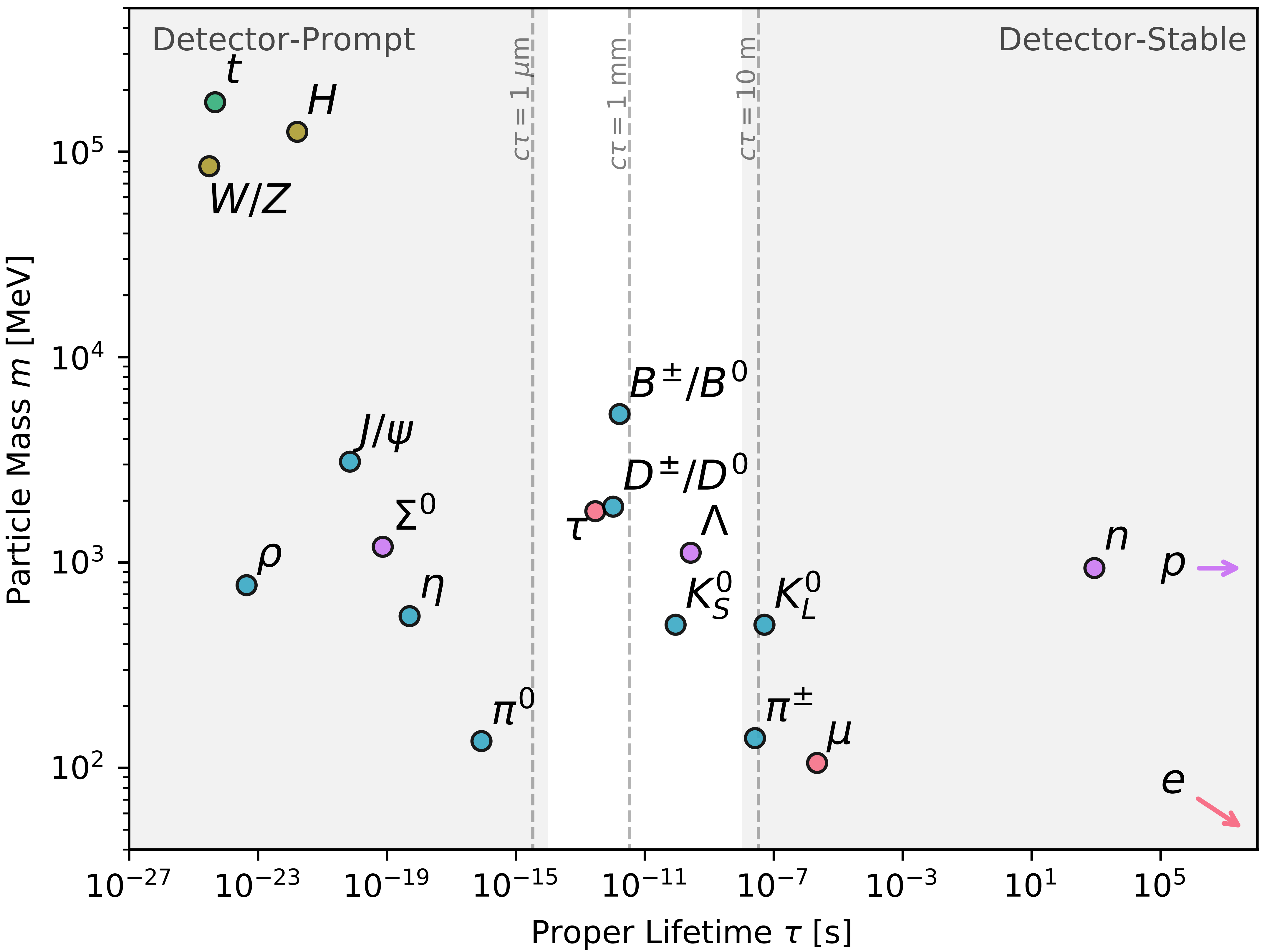
Extensive study at LHC [e.g. Curtin et al. '13] and future colliders [e.g. Liu, Wang, Zhang '16]. Optimal at a Higgs factory.



But almost all attention on $c\tau = 0$

[Liu, Wang, Zhang '16; CEPC CDR]

[Lee, Ohm, Soffer, Yu 1810.12602, from a plot by B. Shuve]


Detector-Prompt
Detector-Stable
cτ = 1 μm
cτ = 1 mm
cτ = 10 m
t
H
W/Z
J/ψ
Σ0
ρ
η
π0
B±/B0
D±/D0
τ
Λ
K0S
K0L
π±
μ
n
p
e
Particle Mass m [MeV]
Proper Lifetime τ [s]
10^5
10^4
10^3
10^2
10^−27
10^−23
10^−19
10^−15
10^−11
10^−7
10^−3
10^1
10^5

Long-Lived Particles

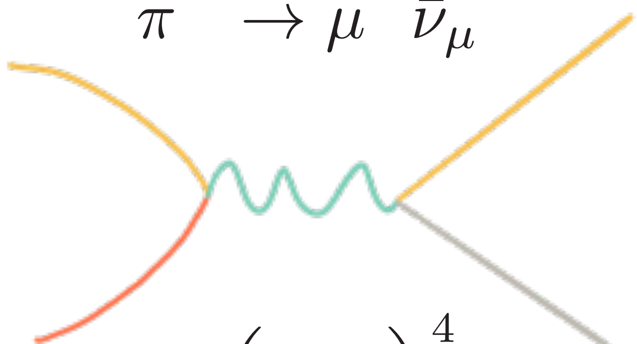
LLPs are generic in SM & BSM

$$\Gamma \sim g^2 \left(\frac{m}{M}\right)^n m$$

E.g. small couplings, hierarchy of scales

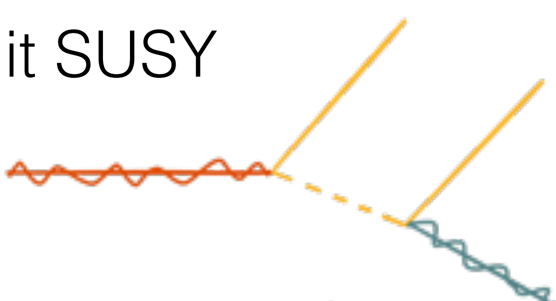
Off-shell decay

$\pi^- \to \mu^- \bar{\nu}_\mu$



$$\sim g^2 \left(\frac{m}{m_W}\right)^4 m$$

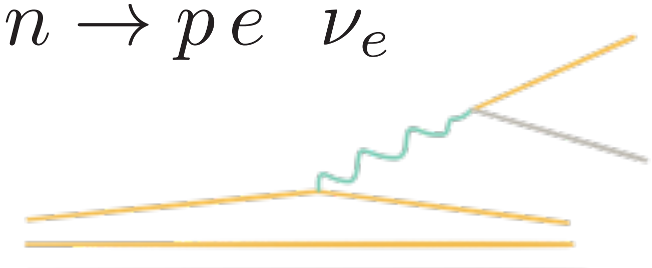
Split SUSY



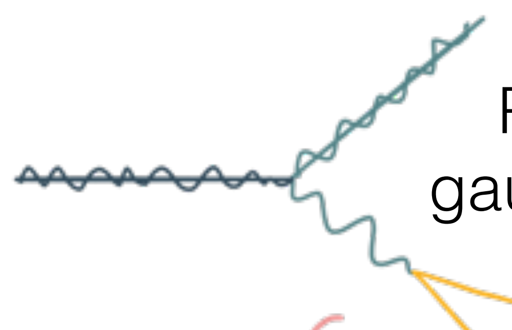
Hidden Valley

Small splitting

$n \to p\, e^- \nu_e$



$$\sim g^2 \left(\frac{m_n - m_p}{m_W}\right)^4 (m_n - m_p)$$

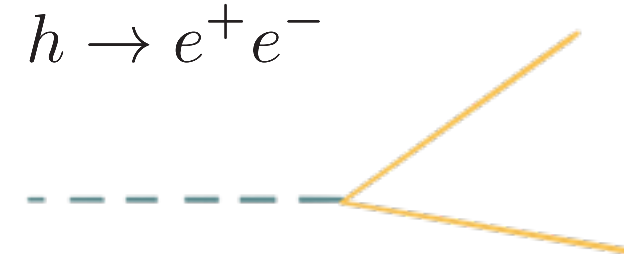


Pure gauginos

Stealth SUSY

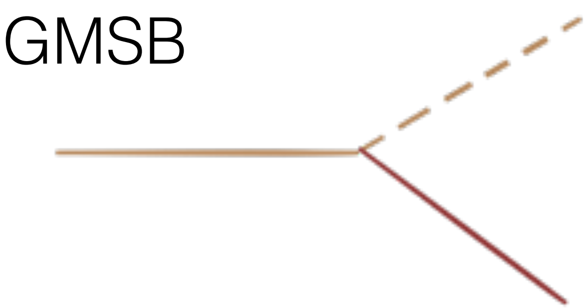
Small coupling

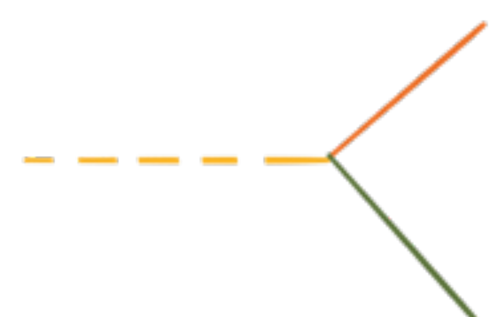
$h \to e^+ e^-$



$$\sim y_e^2 m$$

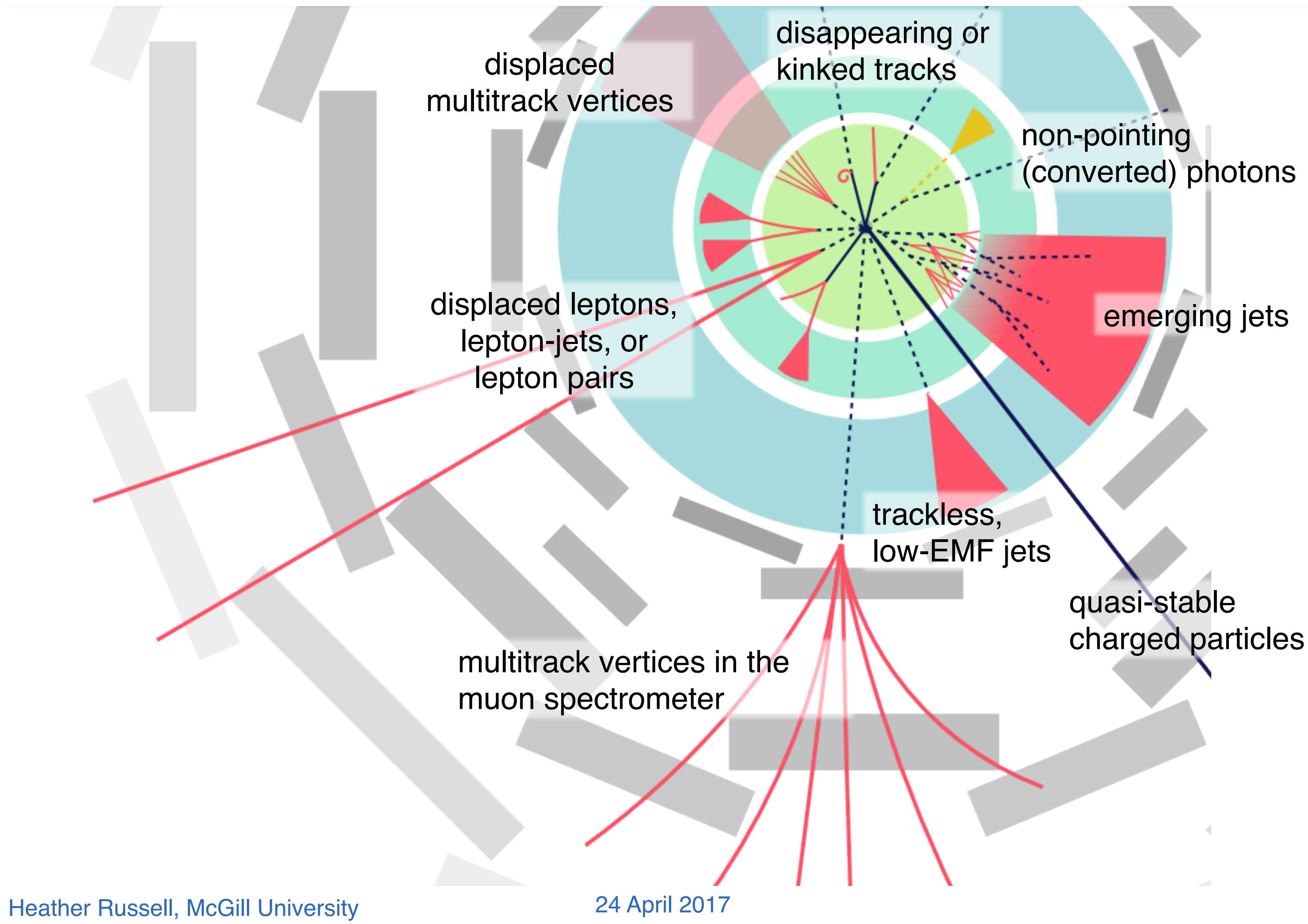
GMSB





RPV

Long-Lived Signatures



Growing effort at LHC, where detectors are fixed; almost no study yet for future colliders, where detectors are malleable. Now is the time!*

*Fantastic exception: CLIC [Kucharczyk & Wojton '18]

Higgs Decay to LLPs

Many models motivating Higgs decays to LLPs, starting with NMSSM [Chang, Fox, Weiner '05] and Hidden Valleys [Strassler, Zurek '06; Han, Si, Strassler, Zurek '07]

Simplest model: Higgs portal to a singlet scalar w/ approximate $\mathbb{Z}_2$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}M^2\phi^2 - A|H|^2\phi - \frac{1}{2}\kappa|H|^2\phi^2 - \frac{1}{3!}\mu\phi^3 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_H|H|^4$$

Mixing only from $\mathbb{Z}_2$ violation:

$$\begin{aligned} h_{\rm SM} &= h\cos\theta + \phi\sin\theta \\ s &= -h\sin\theta + \phi\cos\theta \end{aligned}$$

where $\theta \propto Av/m_h^2$

h_{SM} decays to s from $\mathbb{Z}_2$ preserving couplings, **potentially large**:

$$\Gamma(h \to ss) \approx \frac{\kappa^2 v^2}{32\pi m_h}\sqrt{1 - 4\frac{m_s^2}{m_h^2}}$$

s decays to SM from $\mathbb{Z}_2$ violating couplings, **naturally tiny**:

$$\Gamma(s \to YY) = \sin^2\theta \times \Gamma(h_{\rm SM}[m_s] \to YY)$$

UV Motivation: Twin Higgs

[Chacko, Goh, Harnik ‘05]

Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

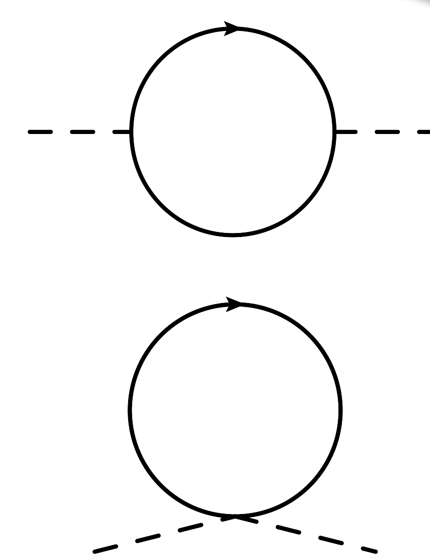
Radiative corrections to Higgs masses are SU(4) symmetric thanks to Z_2:

$$V(H) \supset -\frac{6}{16\pi^2} y_t^2 \Lambda^2 \left(|H|^2 + |H'|^2\right)$$

Higgs is a PNGB of ~SU(4), but partner states neutral under SM.

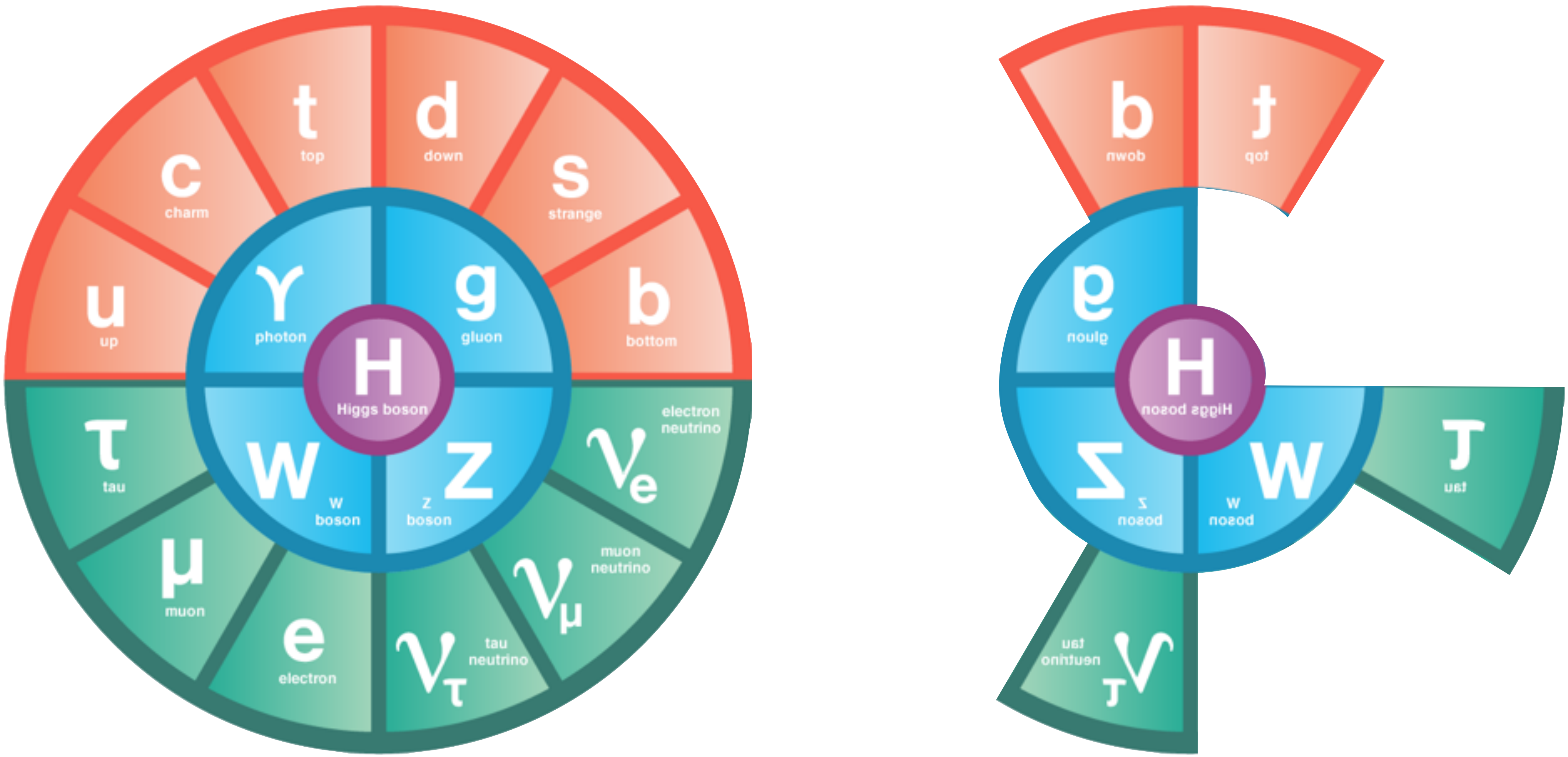
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$H_A \to h + \ldots$, $\quad H_B \to f - \frac{h^2}{2f} + \ldots$



[NC, Katz, Strassler, Sundrum '15]

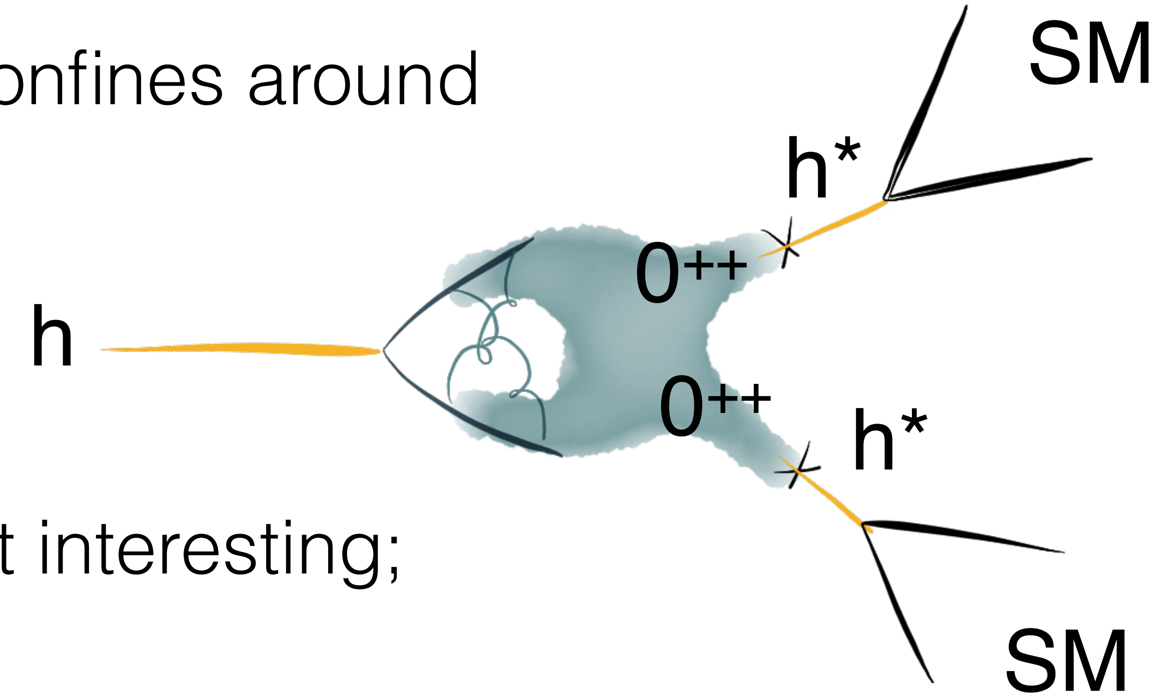
Fraternal twins

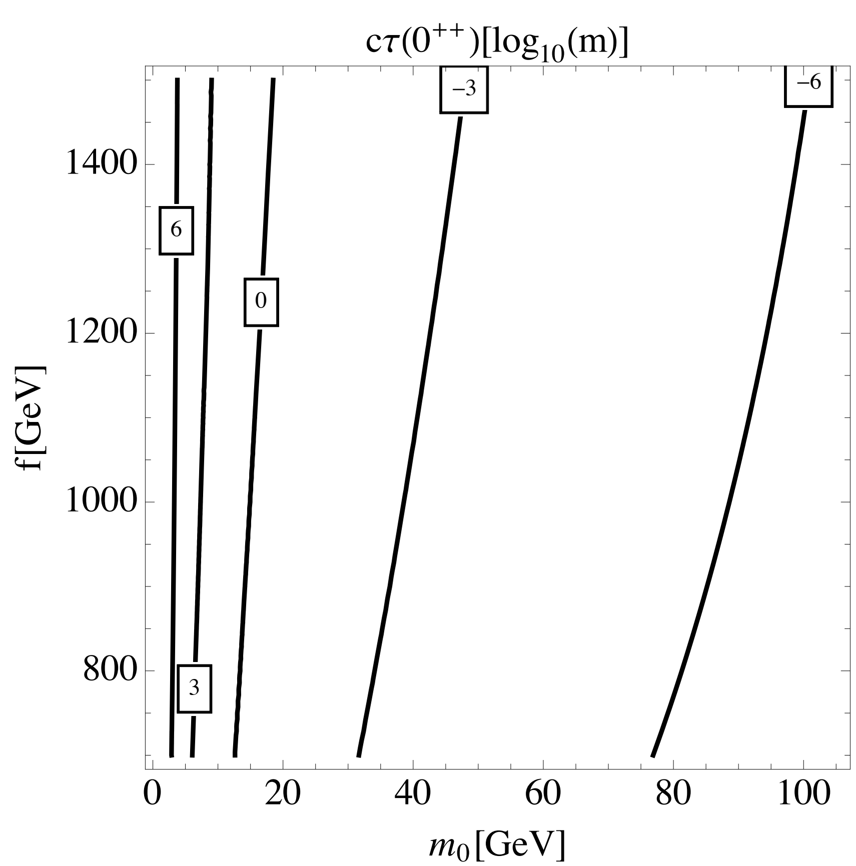


What really matters for naturalness:
SU(3)xSU(2) & third generation
⇒ Dark QCD

Exotic Higgs Decays

- Twin sector must have twin QCD, confines around QCD scale
- Higgs boson couples to bound states of twin QCD
- Various possibilities. Glueballs most interesting; have same quantum # as Higgs





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

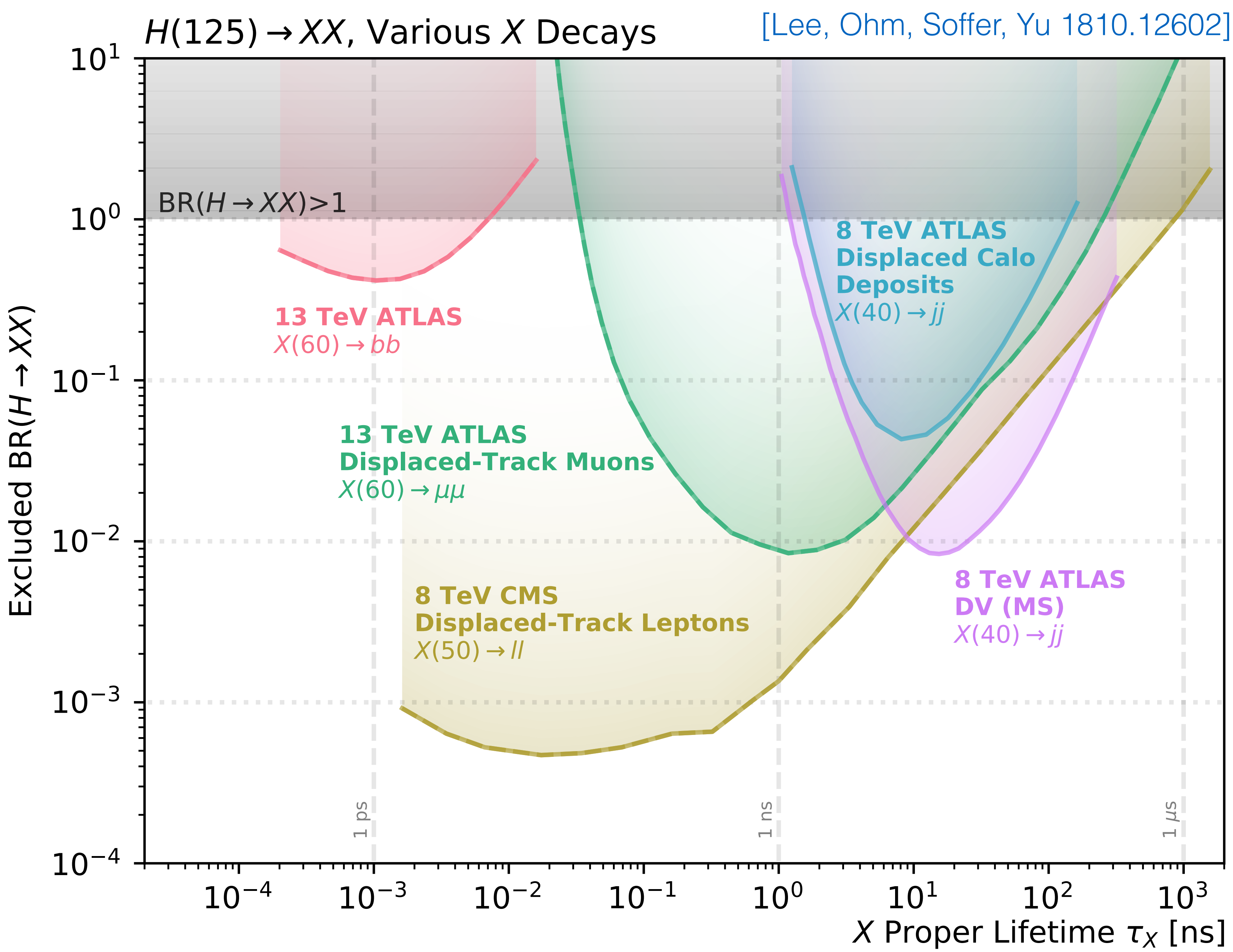
$$h \to 0^{++} + 0^{++}$$

Decay back to SM via Higgs

$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, decay length is macroscopic; length scale ~ collider detectors

Current Status

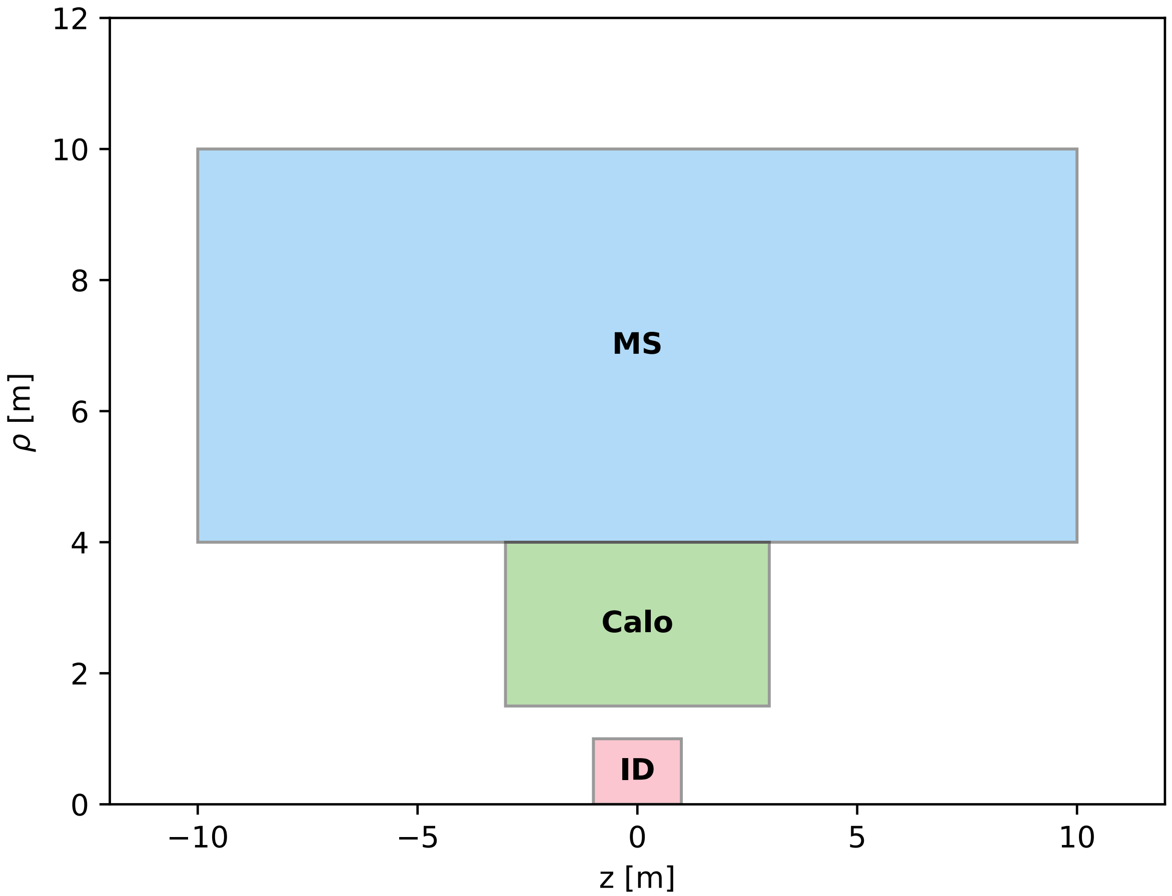


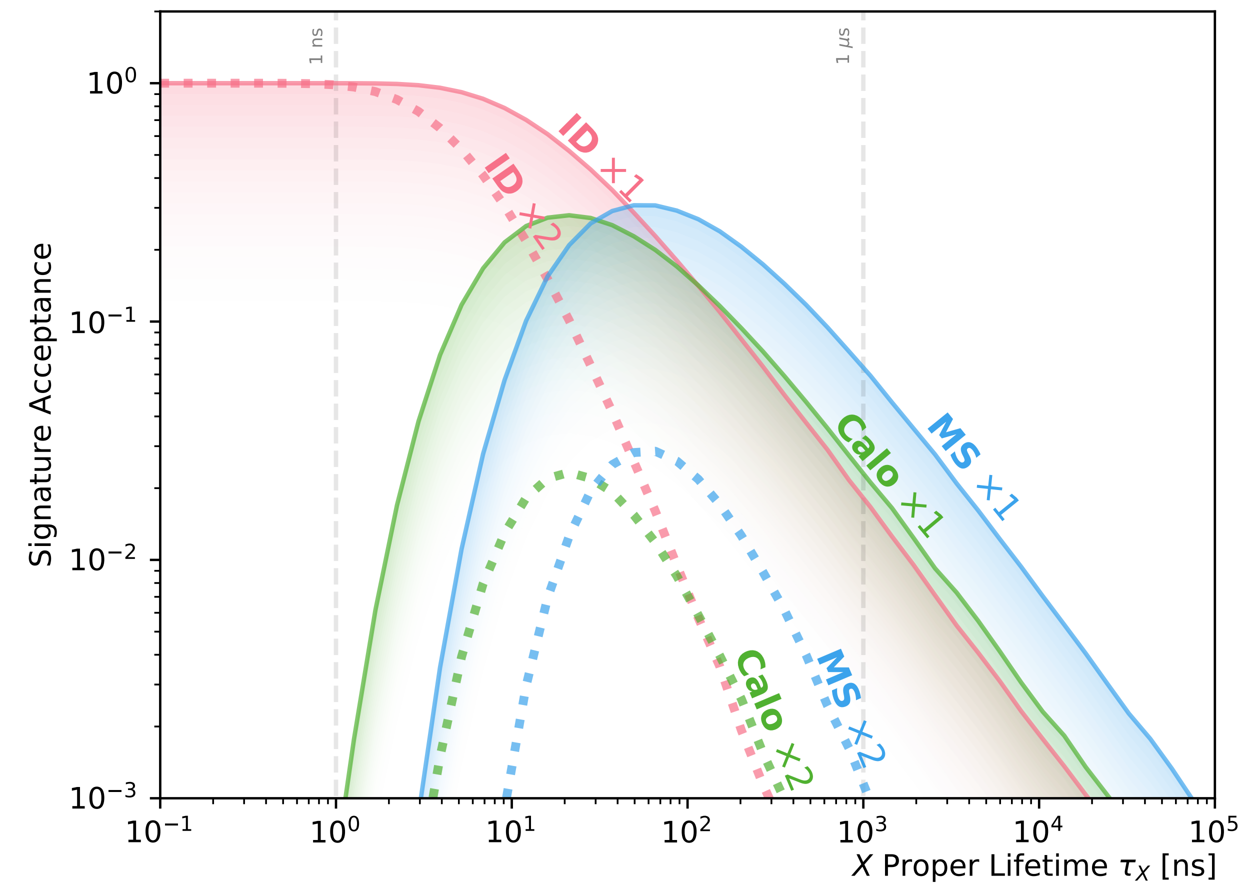
- Decent coverage of Higgs decays to displaced leptons
- Essentially no coverage of Higgs decays to displaced hadrons below 1m
- Ultimately 3x10^7 Higgses @ LHC w/ 300/fb, but backgrounds, triggers are major limitations.

Potential reach @ future colliders: BR ~ 5 x 10^{-6} across decades of proper lifetime

Future Search Strategies

[Lee, Ohm, Soffer, Yu 1810.12602]





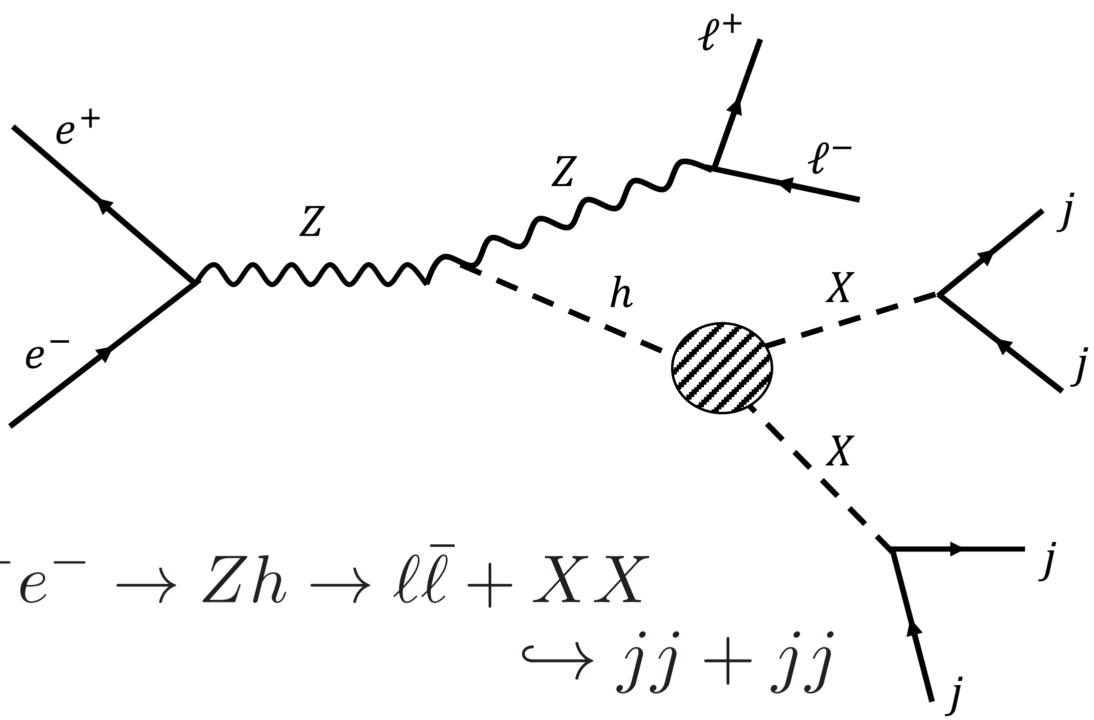
Distribution of decay lengths at fixed proper lifetime favors using innermost detectors, all else being equal.

Not always true at LHC, where backgrounds to decays in inner detector are significant and trigger thresholds increase, but likely achievable at Higgs factories.

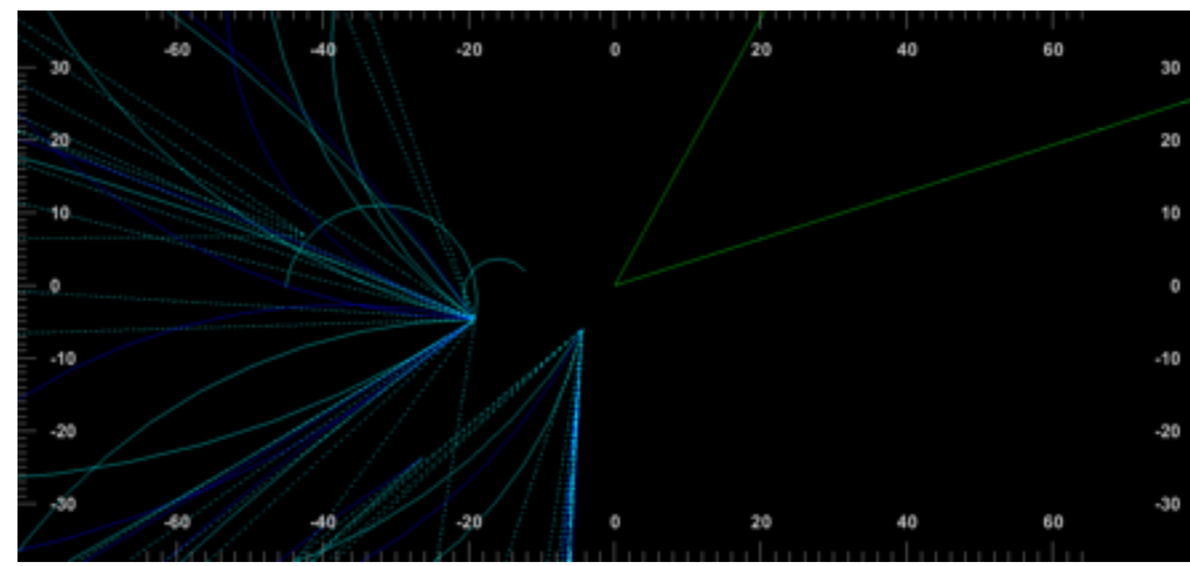
Higgs Factory Prospects

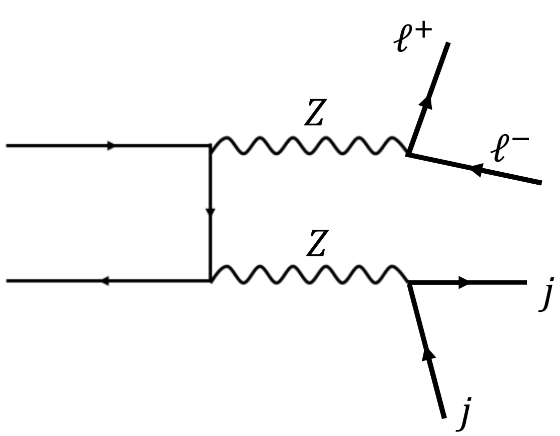
Consider the simplest/generic scenario: h → XX → (jj)(jj)

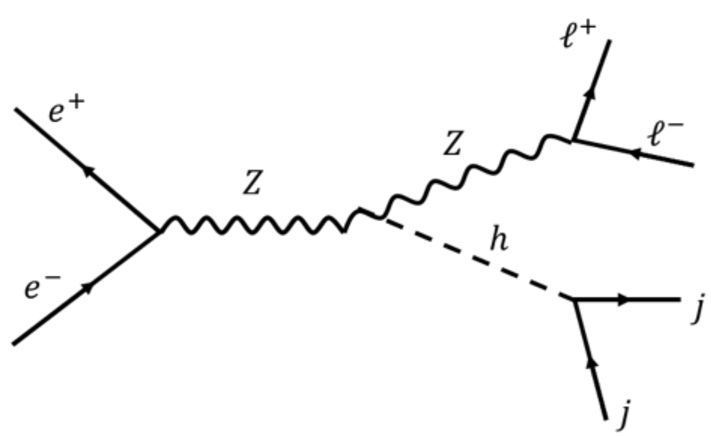
[Alipour-fard, NC, Jiang, Koren '18]



$$e^+e^- \to Zh \to \ell\bar{\ell} + XX$$
$$\hookrightarrow jj + jj$$







Irreducible backgrounds:
ZZ → ℓℓbb, Zh → ℓℓbb

Neglect for now: cosmics, beamstrahlung, detector effects, etc.

Analysis Strategy

Reproduce Higgs selection w/ recoil mass in leptonic Zh:

- $Z \rightarrow ee$ or $\mu\mu$. Lepton p_T: $10 \leq p_T(\ell) \leq 90$ GeV.
- Dilepton invt mass: $70 < M_{ee} < 110$ GeV, $81 < M_{\mu\mu} < 101$ GeV.
- Recoil mass requirement: $120 < m_{recoil} < 150$ GeV.

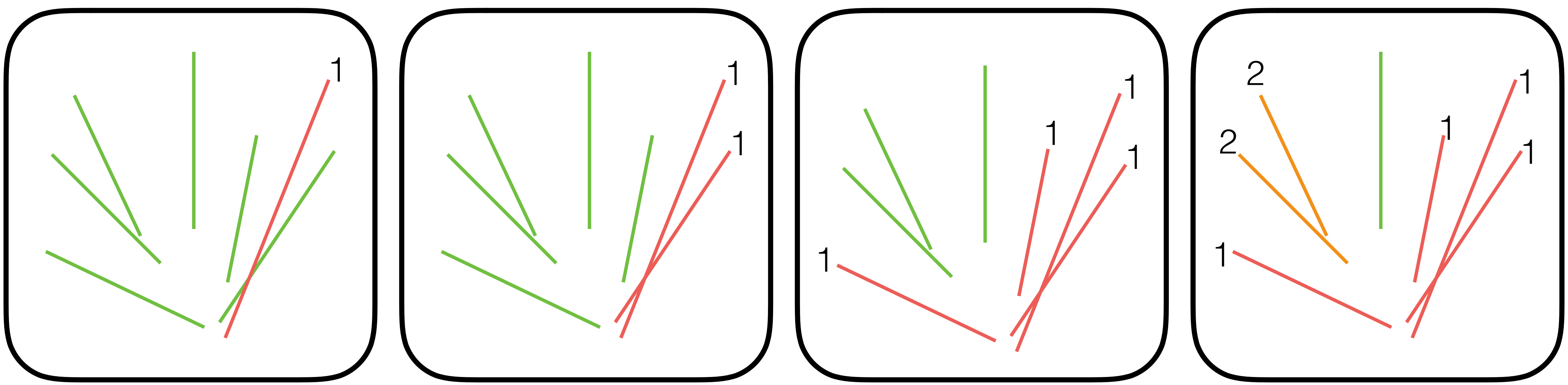
Plus selection for displaced Higgs decay:

- Form clusters, use these to construct secondary vertex
- Two analyses: “large mass” and “long lifetime”

Secondary vertices

Roughly emulating CMS secondary vertex-finding algorithm

1. Form clusters using a depth-first algorithm running over all particles, clustering those w/ origins within 7μm of another particle.

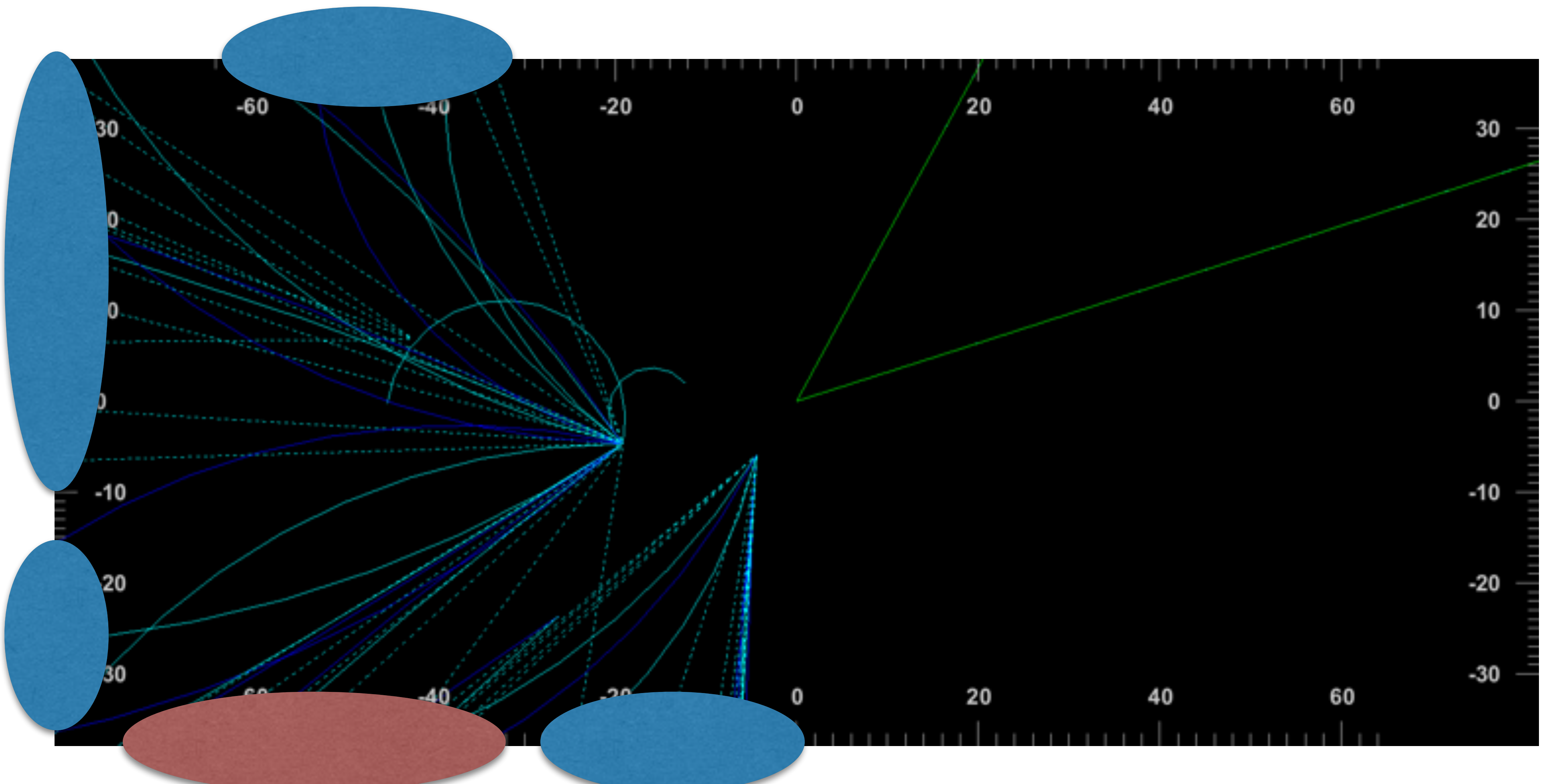


2. Define the cluster origin $\vec{d}_{cluster}$ as the averaged origin of all charged particles in the cluster.

3. Impose $|\vec{d}_{cluster}| > d_{min}$, chosen depending on the analysis.

Caveat theorist

Delphes forms calorimeter jets.



Clusters particles from distinct secondary vertices. Leads to misleading results, especially when decay products collimate. Here: work directly with Pythia output.

"Large Mass" Analysis

Kill backgrounds from b-quark SVs using kinematic properties of signal for $m_X \gtrsim 2m_b$

higgsstrahlung selection

displacement above resolution (& in tracker)

(smeared) invt mass of charged tracks ∊ cluster > 6 GeV

(smeared) invt mass* of cluster < $m_h/2$

veto charged tracks passing within 5mm of SV

Cut/Selection	ZZ Background	hZ Background
Dilepton Invariant Mass	0.97	0.98
Recoil Mass	0.006	0.94
Displaced Cluster ($\geq$ resolution)	0.004	0.94
Invariant Charged Mass (6 GeV)	0	0.00005
Invariant 'Dijet' Mass	0	0.00005
Pointer Track	0	0.00001

$m_X, c\tau$	25, 10^{-4}	25, 10^{-2}	25, 10^{0}	50, 10^{-4}	50, 10^{-2}	50, 10^{0}
$M_{\ell\ell}$	0.97	0.97	0.98	0.97	0.98	0.97
M_{recoil}	0.92	0.92	0.93	0.92	0.92	0.93
$\lvert\vec{d}_{\text{cluster}}\rvert$	0.92	0.92	0.80	0.92	0.92	0.93
M_{charged}	0.76	0.77	0.57	0.82	0.85	0.81
M_{cluster}	0.76	0.77	0.57	0.76	0.80	0.76
Pointer	0.73	0.76	0.57	0.75	0.77	0.76

Signal efficiency for $Zh \to \ell\ell + XX$

“Long Lifetime” Analysis

Kill backgrounds from b-quark SVs for lighter, longer-lived LLPs

higgsstrahlung selection

displacement above 3cm (& in tracker)

(smeared) invt mass of charged tracks ∊ cluster > 2 GeV

(smeared) invt mass* of cluster < $m_h/2$

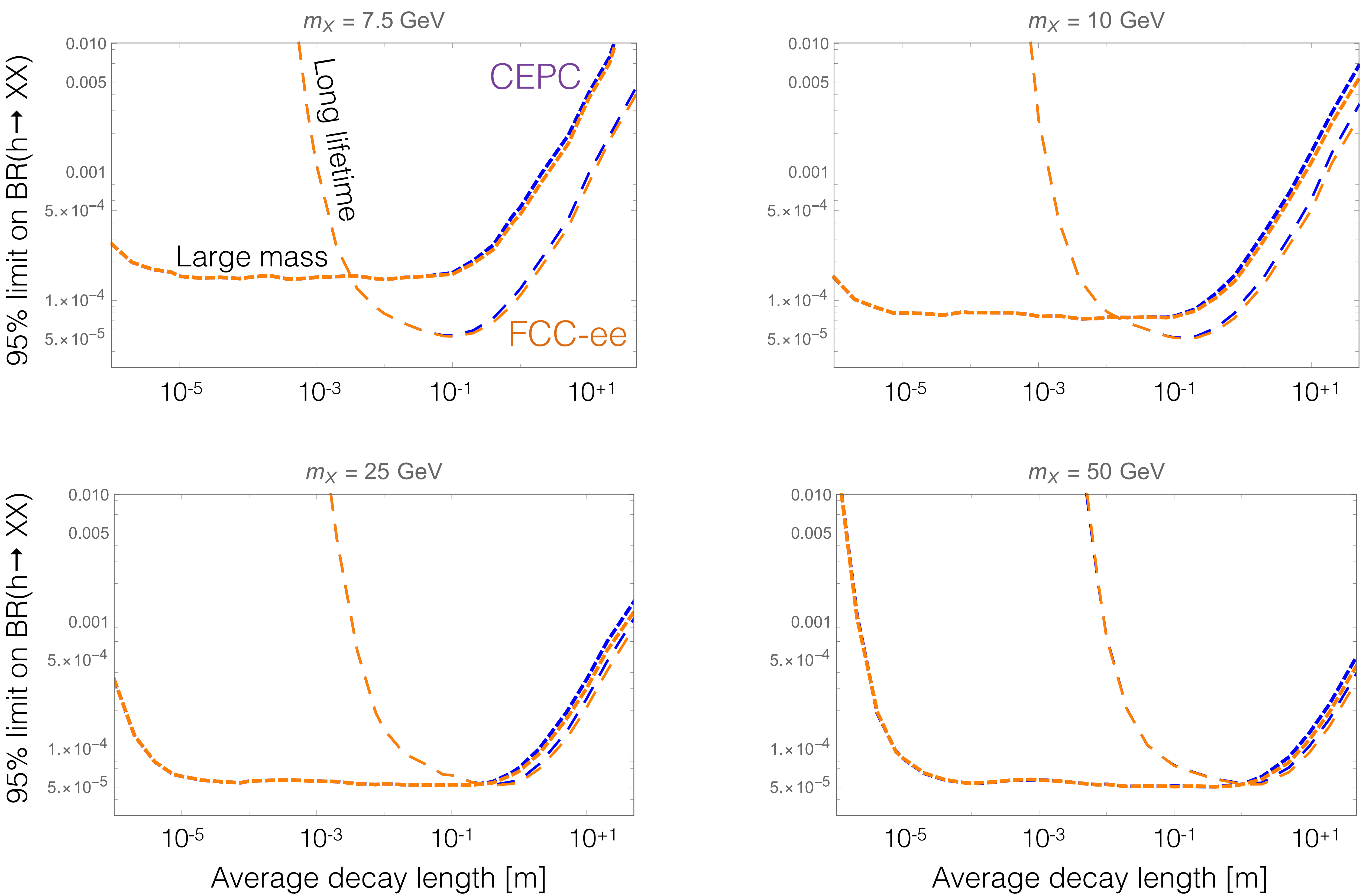
veto charged tracks passing within 5mm of SV

veto charged tracks from PV approaching SV

Cut/Selection	ZZ Background	hZ Background
Dilepton Invariant Mass	0.97	0.98
Recoil Mass	0.006	0.94
Displaced Cluster ($\geq$ 3 cm)	0.004	0.62
Charged Invariant Mass (2 GeV)	0	0.002
‘Dijet’ Invariant Mass	0	0.002
Pointer Track	0	0.001
Isolation	0	0.00005

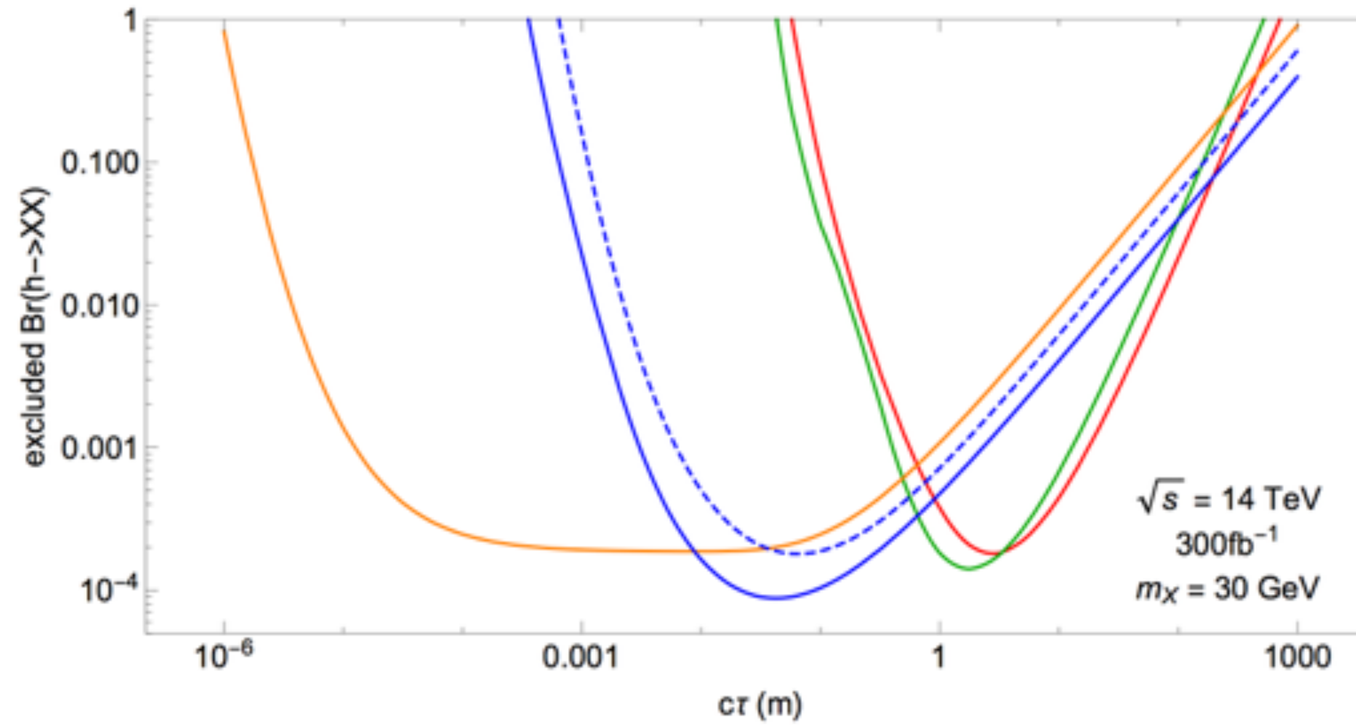
$m_X, c\tau$	2.5, 10^{-4}	2.5, 10^{-2}	2.5, 10^{0}	7.5, 10^{-4}	7.5, 10^{-2}	7.5, 10^{0}
$M_{\ell\ell}$	0.97	0.97	0.98	0.97	0.97	0.97
M_{recoil}	0.93	0.93	0.93	0.93	0.93	0.93
$\lvert\vec{d}_{\text{cluster}}\rvert$	0.21	0.89	0.15	0.41	0.89	0.41
M_{charged}	0	0.40	0.05	0	0.74	0.34
M_{cluster}	0	0.40	0.05	0	0.74	0.34
Pointer	0	0.40	0.05	0	0.74	0.34
Isolation	0	0.33	0.045	0	0.51	0.33

Close to optimal sensitivity across a range of LLP masses & lifetimes



vs LHC

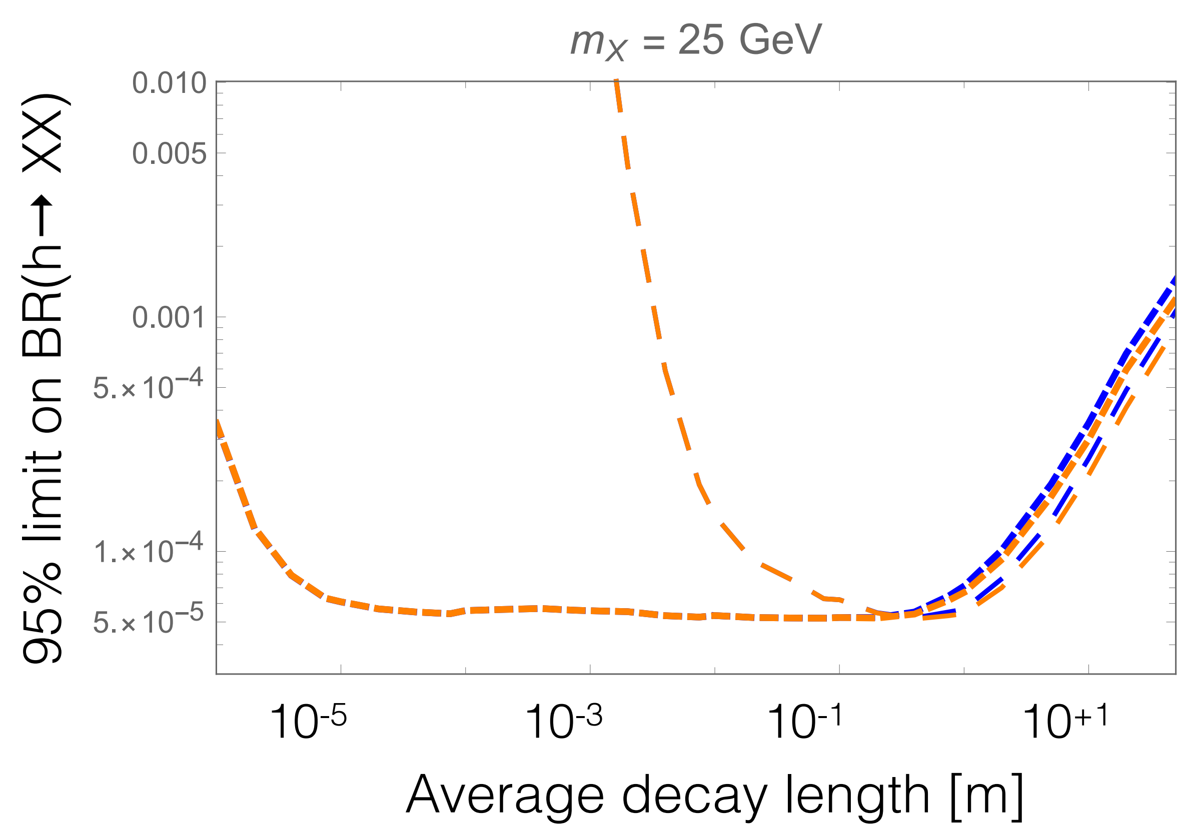
[Curtin & Verhaaren '15]



Theory estimates for LHC14 [Curtin & Verhaaren '15, Csaki, Kuflik, Lombardo, Slone '15] and track trigger studies [Gershtein '17] account only for trigger efficiency & geometric acceptance; assume no background, no pileup, and neglect systematics

Even then, the reach of future Higgs factories is competitive, and likely superior for lighter LLPs.

LHC performance in displaced hadronic final states degrades considerably once LLP decay products collimate



Conclusions

- Displaced decays of the Higgs provide a *highly motivated* target for a precision Higgs program.
- Proposed Higgs factories can improve reach in displaced Higgs decays relative to LHC, particularly for lighter LLPs.
- Further optimization of even the simple LLP analysis presented here is possible/desirable (e.g. including hadronic Z decays).
- This is only the tip of the iceberg; many different LLP signatures merit serious exploration.
- *Now is the time* for LLP studies at future colliders — highly-motivated, virtually untouched, with potentially significant impacts on detector design…

Thank you!