Higgs BSM

Ennio Salvioni

Padua

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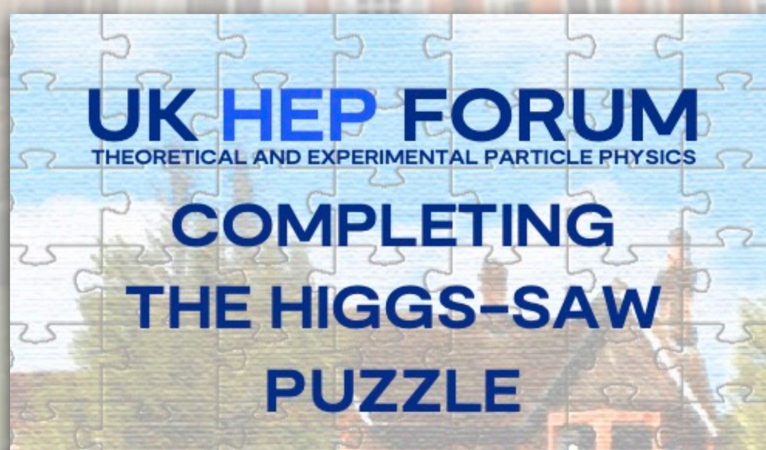
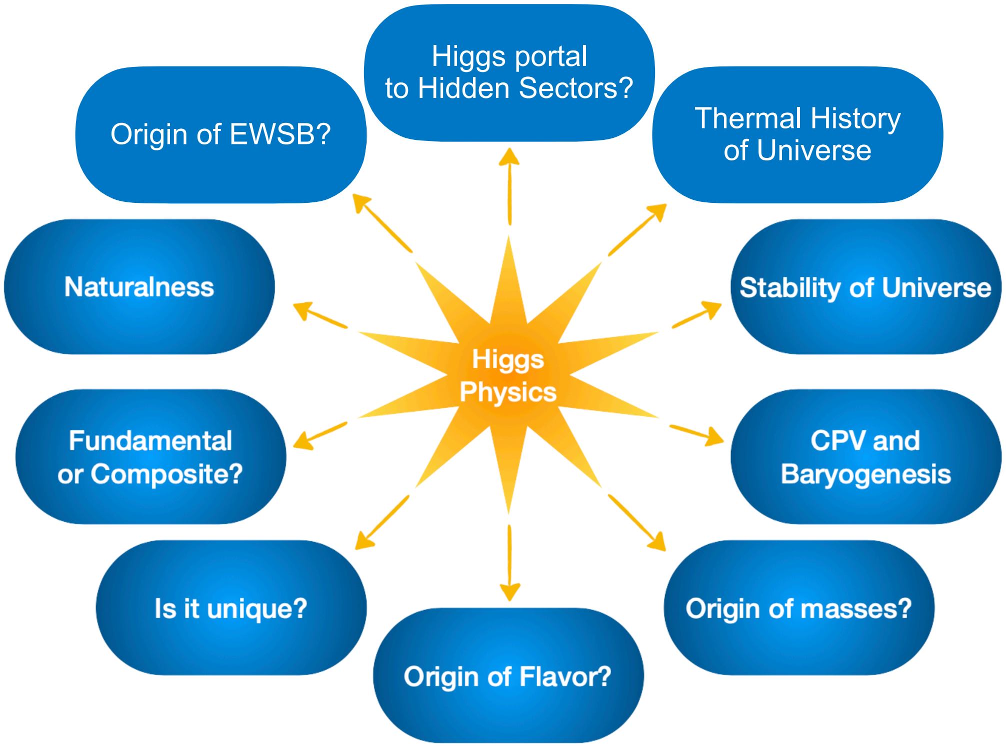
Padua (→ ERF @ Sussex from January 2024)



Fundamental questions

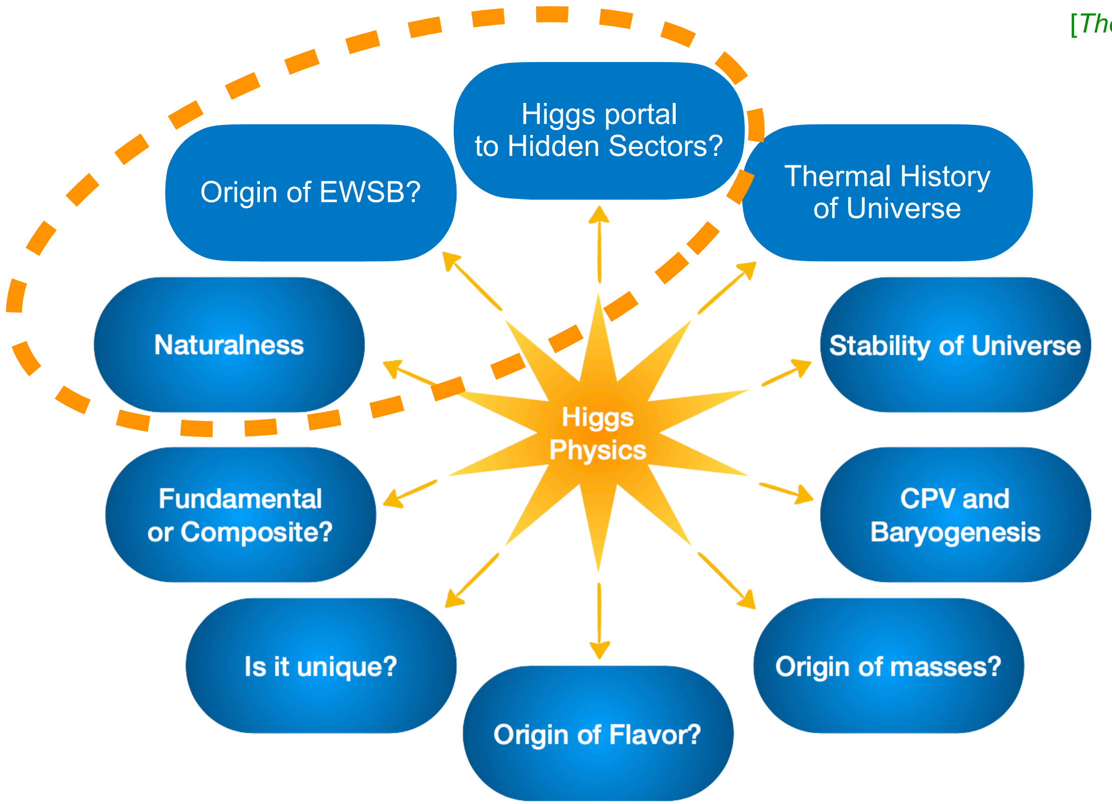
[*The case for precision Higgs physics*, Snowmass 2021, 2209.07510]



The Higgs boson is linked to *many* deep questions about fundamental physics

Fundamental questions

[*The case for precision Higgs physics*, Snowmass 2021, 2209.07510]



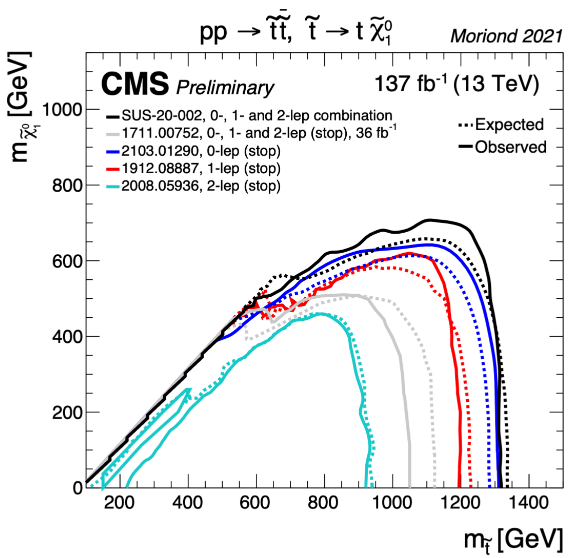
In this talk I will mostly focus on understanding the origin of EWSB.

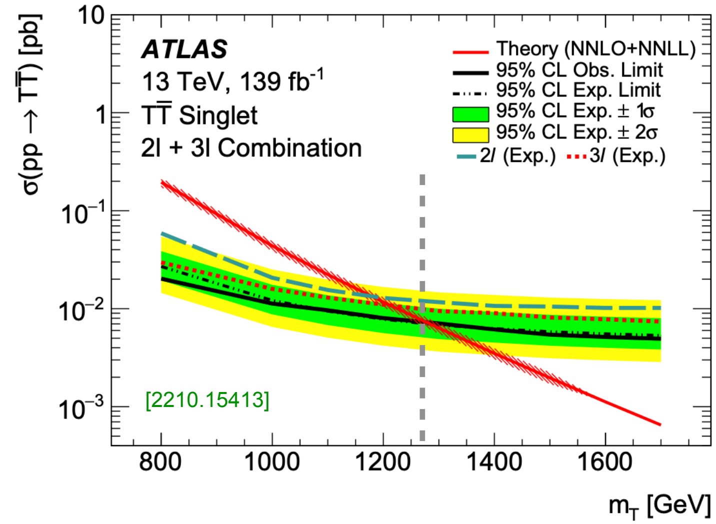
Can we calculate the Higgs potential? Is the Higgs mass natural?

In 2023, how can these questions inform measurements/searches at LHC and plans for future accelerators?

Naturalness

So far, no signals of top partners (scalars or fermions) @ ATLAS and CMS





Where do we go from here?

- SUSY or compositeness could still be around the corner
- Symmetry-based framework is correct, but key details differ from expectations: Neutral Naturalness
- Need a true paradigm shift: cosmological approaches

Plan

Part 1

Neutral Naturalness: new physics hiding at TeV scale

h^3 coupling as the first signal?

Part 2

Cosmological approaches to naturalness motivate light new physics

$h \to \mathrm{LLPs}$, invisible

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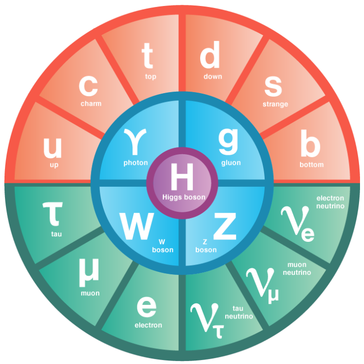
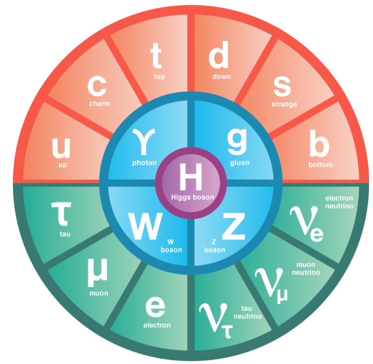
Neutral Naturalness: the Twin Higgs

Standard Model



$$\overset{\mathcal{Z}_2}{\longleftrightarrow}$$

Twin Standard Model



[Chacko, Goh, Harnik 2005]

$$\mathcal{L} = y_t Q H t + \hat{y}_t \hat{Q} \hat{H} \hat{t}$$

The top partner *(Twin top)* is neutral under whole SM

It can still be sub-TeV

Light QCD-charged states are not needed $\rightarrow$ naturalness improves

Twin Higgs at work

- The leading corrections to Higgs potential cancel, thanks to exchange symmetry:

$$V_t \supset \frac{N_c}{8\pi^2} y_t^2 f^2 M_*^2 \sin^2 \frac{h}{f} + \frac{N_c}{8\pi^2} \hat{y}_t^2 f^2 \hat{M}_*^2 \cos^2 \frac{h}{f}$$

scale of QCD-charged particles ($\gg$ TeV)

decay constant
of Goldstone Higgs (~ 1 TeV)

$$\mathcal{Z}_2 \ : \quad y_t = \hat{y}_t \ , M_* = \hat{M}_* \quad \rightarrow \quad V_t = \text{constant, no correction to Higgs mass}$$

- What remains is smaller potential, controlled by Twin top:

$$V_t \approx \frac{N_c}{32\pi^2} y_t^2 f^2 m_{\hat{t}}^2 \left[\sin^4 \frac{h}{f} \log \frac{a}{\sin^2 h/f} + \cos^4 \frac{h}{f} \log \frac{a}{\cos^2 h/f} \right]$$

$m_{\hat{t}} = \frac{y_t f}{\sqrt{2}}$

sub-TeV, but SM neutral

[Craig, Katz, Strassler, Sundrum 2015]
[Barbieri, Greco, Rattazzi, Wulzer 2015]

Twin Higgs at work

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scale of QCD-charged particles (≫ TeV)

decay constant of Goldstone Higgs (~ 1 TeV)

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$m_{\hat{t}} = \frac{y_t f}{\sqrt{2}}$

sub-TeV, but SM neutral

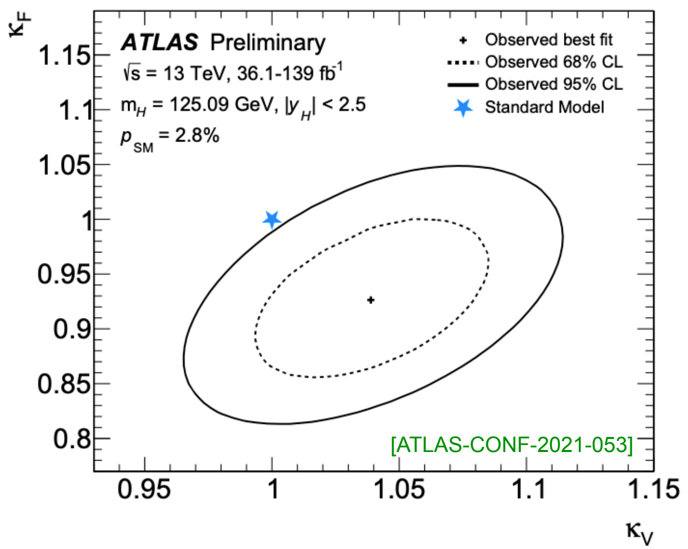
But not realistic yet: $\langle h \rangle = 0$ or $\langle h \rangle = f$

[Craig, Katz, Strassler, Sundrum 2015]
[Barbieri, Greco, Rattazzi, Wulzer 2015]

The need for a small vev

General result: if Higgs is a Goldstone, couplings to SM particles deviate from SM

$$\frac{g_{hXX}}{g_{hXX}^{\rm SM}} = \cos\frac{\langle h\rangle}{f} = \sqrt{1-\frac{v^2}{f^2}}$$



LHC Run 2: agreement with SM to ~ 10%

↓

Need $v \ll f$ by a factor 3 ~ 4 at least

Many different proposals, but at the price of fine-tuning: $\Delta \sim \frac{v^2}{f^2} \lesssim 10\%$

minimal tuning

Increasingly pressing problem for Goldstone Higgs models

(Composite Higgs, Twin Higgs, …)

[Panico, Redi, Tesi, Wulzer 2012]

The need for a small vev

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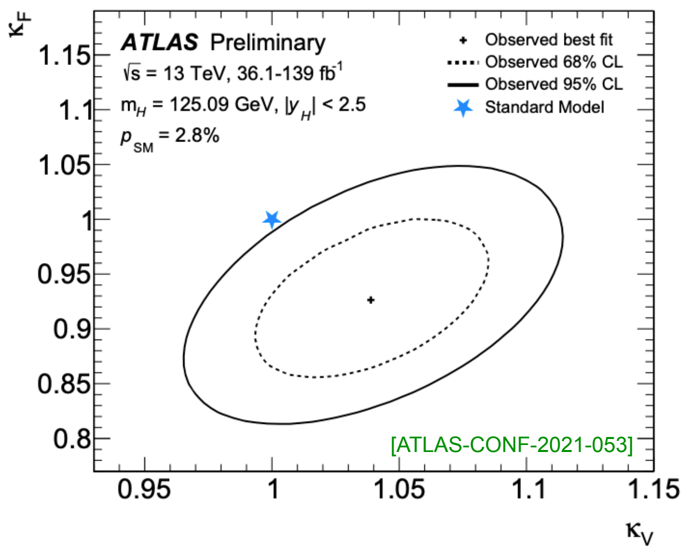


LHC Run 2: agreement with SM to ~ 10%

↓

Need $v \ll f$ by a factor 3 ~ 4 at least

Recent idea to generate this **without tuning:** Gegenbauer Goldstones

[Durieux, McCullough, Salvioni 2110.06941 + 2202.01228 + 2209.00666]

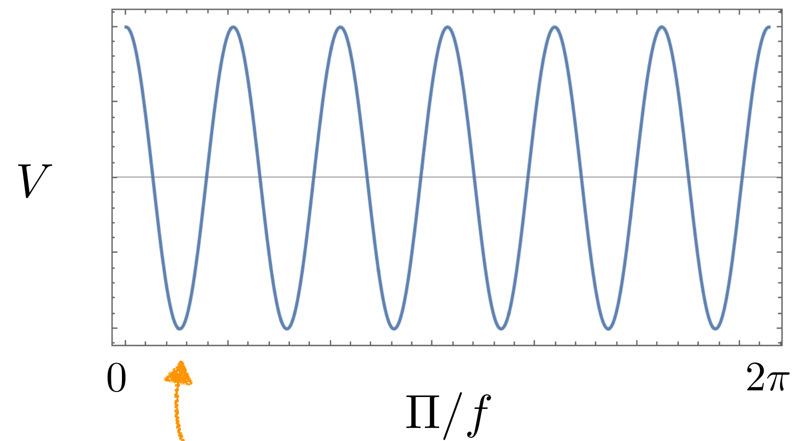
Shape of Higgs potential is strongly modified compared to SM

→ **prediction:** parametrically enhanced Higgs self-coupling deviations

[Panico, Redi, Tesi, Wulzer 2012]

Inspiration: Abelian Goldstone

(example: $n = 6$)



For a single $U(1)$ Goldstone boson,

we know a simple way to get a small vev

$$\mathcal{L} = \partial_\mu \Phi^* \partial^\mu \Phi - \lambda \left(\Phi^* \Phi - f^2\right)^2$$

$$\frac{\langle \Pi \rangle}{f} = \frac{\pi}{n} \ll 1$$

Explicit breaking from operator of charge n

$$\delta V \sim \epsilon \lambda f^4 \cos\left(\frac{n\Pi}{f}\right)$$

$$\delta V = \frac{\epsilon\,\lambda}{f^{n-4}} \Phi^n + \text{h.c.}$$

$$\Phi = f e^{i\Pi/f}$$

$$\mathcal{Z}_n : \quad \Pi \to \Pi + \frac{2\pi}{n} f$$

Non-Abelian Goldstones: the Higgs case

Consider N Goldstone bosons, from spontaneous breaking of global symmetry

$SO(N+1)/SO(N)$ (relevant pattern for Goldstone Higgs)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi^T \partial^\mu \Phi - \lambda \left(\Phi^T \Phi - f^2\right)^2$$

How to get a small vev naturally?

Non-Abelian Goldstones: the Higgs case

Consider N Goldstone bosons, from spontaneous breaking of global symmetry

$SO(N+1)/SO(N)$ (relevant pattern for Goldstone Higgs)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi^T \partial^\mu \Phi - \lambda \left(\Phi^T \Phi - f^2\right)^2$$

Explicit breaking to $SO(N)$ by n - index symmetric tensor irrep of $SO(N+1)$

$$\delta V = \frac{\epsilon\,\lambda}{f^{n-4}} K_n^{i_1 \ldots i_n}\, \Phi_{i_1} \ldots \Phi_{i_n}$$

irrep $\rightarrow$ traceless

Radiatively stable at $O(\epsilon)$ and all loop orders, because only operator allowed.

Corrections at $O(\epsilon^2)$ and higher

[in *d* = 2: Brézin, Zinn-Justin, Le Guillou 1976]

Non-Abelian Goldstones: the Higgs case

Similar to Abelian case:

$$\Phi = e^{i\Pi^a T^a/f} \begin{pmatrix} \vec{0}_N \\ f \end{pmatrix} = \begin{pmatrix} f \sin\frac{\Pi}{f} \frac{\vec{\Pi}}{f} \\ f\cos\frac{\Pi}{f} \end{pmatrix} \qquad \Pi \equiv \sqrt{\vec{\Pi}^T \vec{\Pi}}$$

Leopold Gegenbauer

$$\delta V = \epsilon \lambda f^4 G_n^{(N-1)/2}(\cos \Pi/f)$$

potential is a Gegenbauer polynomial

$$\delta V = \frac{\epsilon\,\lambda}{f^{n-4}} K_n^{i_1 \dots i_n}\, \Phi_{i_1} \dots \Phi_{i_n}$$

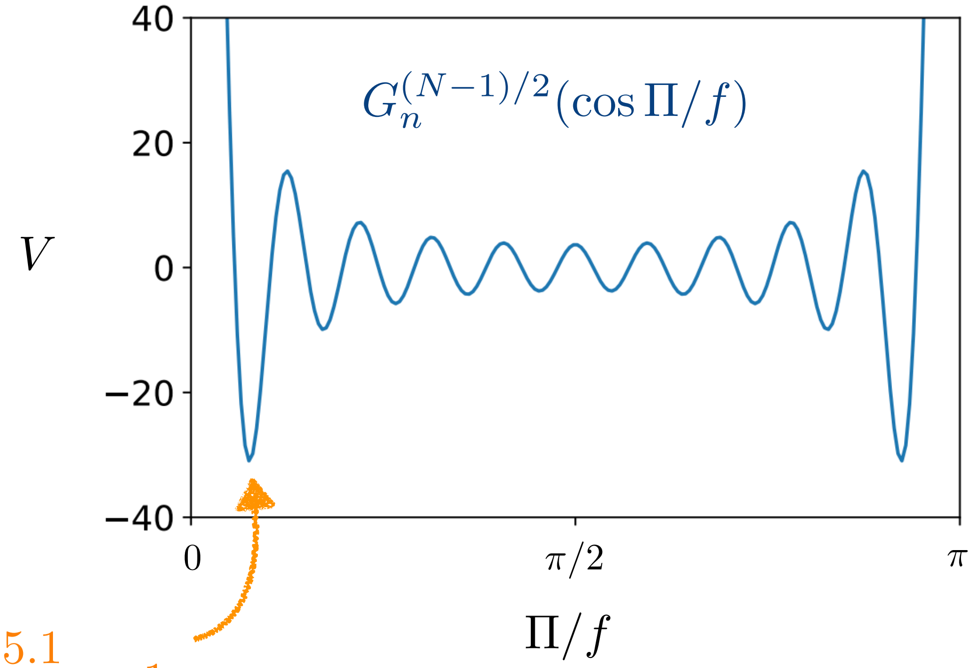
irrep $\rightarrow$ traceless

Radiatively stable at $O(\epsilon)$ and all loop orders, because only operator allowed.

Corrections at $O(\epsilon^2)$ and higher

[in d = 2: Brézin, Zinn-Justin, Le Guillou 1976]

The shape of Gegenbauers



$N = 4$

$SO(5)/SO(4)$

Even n

$(n = 20)$

$$\frac{\langle \Pi \rangle}{f} \approx \frac{5.1}{n} \ll 1$$

Differently from Abelian case,

not periodic! (only approximately)

A radiatively stable way to generate

a small vev for a Goldstone Higgs

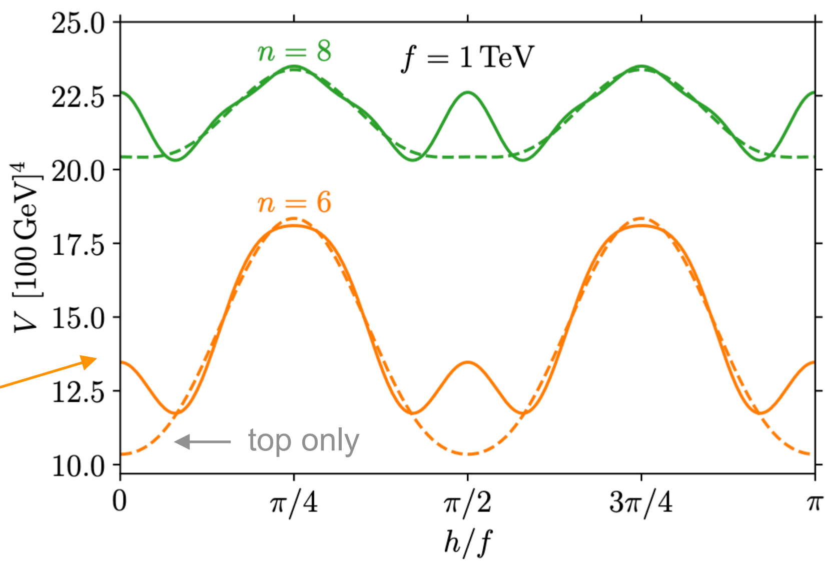
Gegenbauer's *Twin*

- Twin Higgs mechanism generates small potential: $m_h \approx 125\ \mathrm{GeV}$ is natural
- Gegenbauer potential generates small vev: $v \ll f$ is natural

Marry the two: *Gegenbauer's Twin*

Fully natural electroweak breaking, yet hiding from LHC so far!

top + Gegenbauer

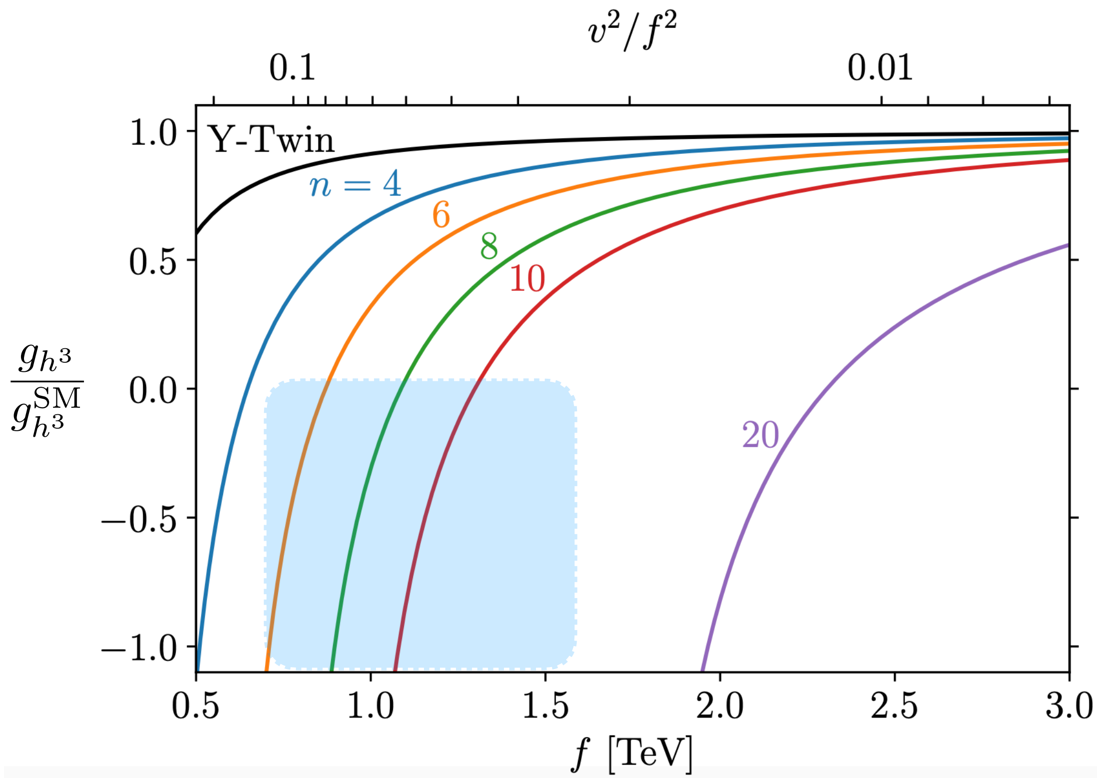


Gegenbauer's Twin with $n = 6$ or $n = 8$ and $f \sim 1\ \mathrm{TeV}$ has essentially <u>no tuning</u>

(generalize Gegenbauer story to $SO(8) \to SO(4) \times SO(4)$ explicit breaking)

The Higgs self-coupling

For Gegenbauer's Twin, corrections are parametrically enhanced



$$\frac{g_{hXX}}{g_{hXX}^{\text{SM}}} \simeq 1 - \frac{v^2}{2f^2}$$

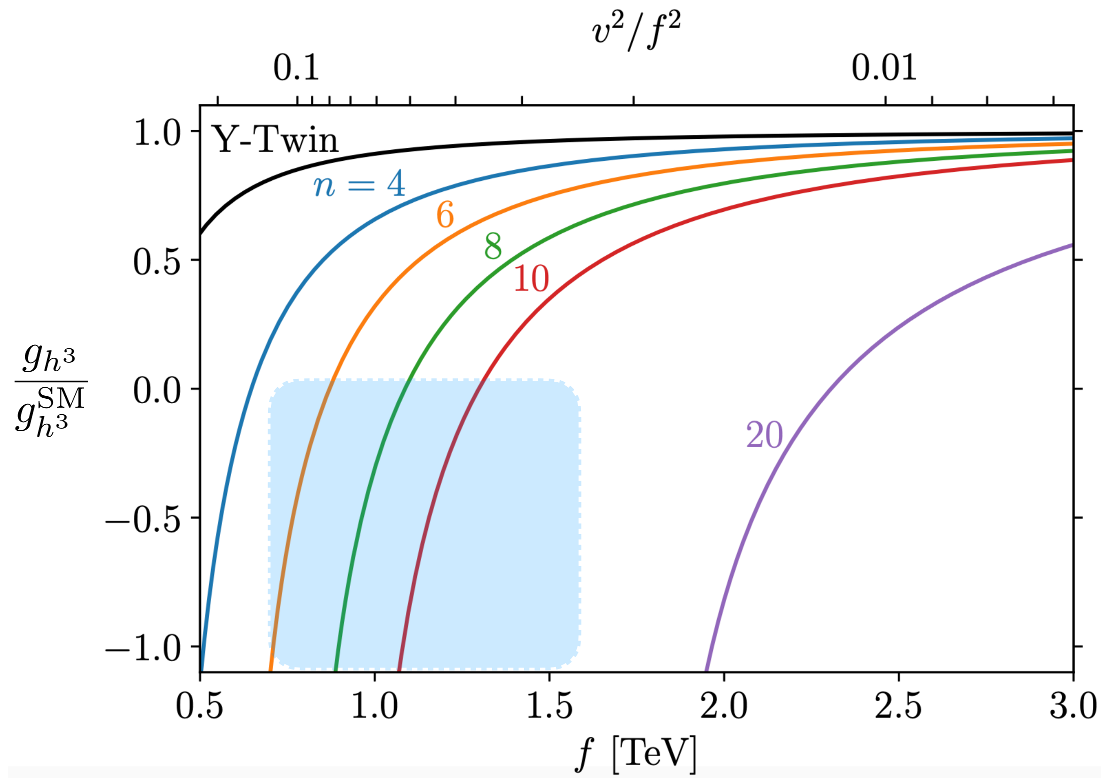
[Durieux, McCullough, Salvioni
2202.01228 + 2209.00666]

Smoking gun signal: could be the **first** deviation from SM observed at LHC

[talks by Hays, Wardle, Wielers]

The Higgs self-coupling

For Gegenbauer's Twin, corrections are parametrically enhanced



$$\frac{g_{hXX}}{g_{hXX}^{\rm SM}} \simeq 1 - \frac{v^2}{2f^2}$$

[Durieux, McCullough, Salvioni 2202.01228 + 2209.00666]

- Gegenbauer's Twin is proof of principle that fully natural electroweak breaking can still be compatible with LHC results
- Example of model where measurements of h^3 break new ground

Plan

Part 1

Neutral Naturalness: new physics hiding at TeV scale

h^3 coupling as the first signal?

Part 2

Cosmological approaches to naturalness motivate light new physics

$h \to$ LLPs, invisible

Cosmological naturalness

- Perhaps the smallness of the Higgs mass is not imposed by symmetries, but dynamically selected along the cosmological evolution
- The Higgs mass parameter m_H^2 triggers some cosmic dynamics, leading to the selection of $\langle h \rangle \simeq v \ll \Lambda_{\rm UV}$
- Example: the relaxion

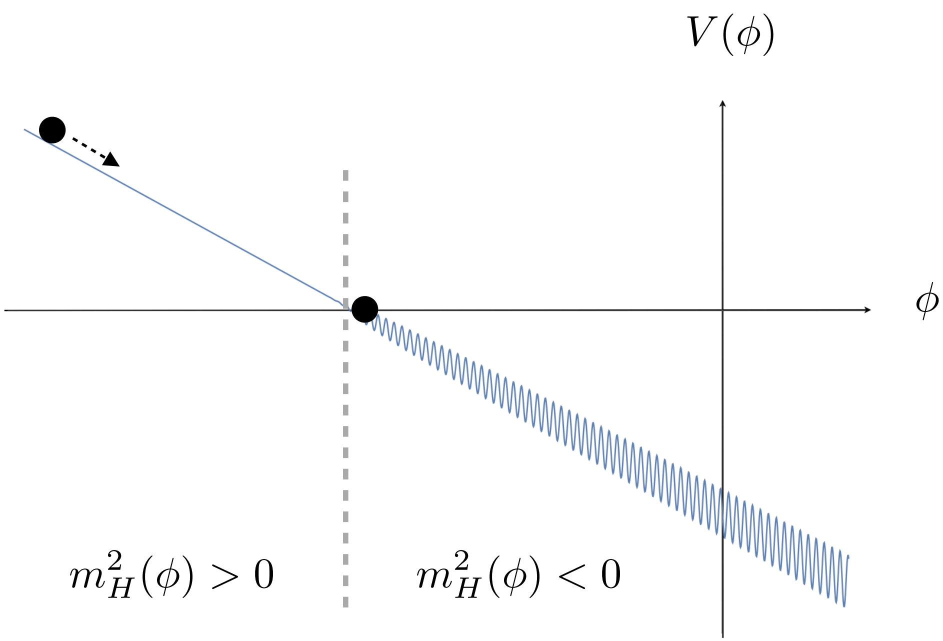
$$\mathcal{L} \supset (-\Lambda_{\rm UV}^2 + g\phi) H^\dagger H + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Wiggles are generated when Higgs mass parameter crosses zero

$$V_b = \Lambda^4 \cos(\phi/f)$$

$$\Lambda^4 \sim 4\pi f_{\hat{\pi}}^3 \frac{Y\widetilde{Y}\langle h\rangle^2}{M}$$

(example: dark QCD model)



[Graham, Kaplan, Rajendran, 2015]

Cosmological naturalness

- Perhaps the smallness of the Higgs mass is not imposed by symmetries, but dynamically selected along the cosmological evolution

- The Higgs mass parameter m_H^2 triggers some cosmic dynamics, leading to the selection of $\langle h \rangle \simeq v \ll \Lambda_{\mathrm{UV}}$

- Several other proposals for dynamical selection

[Arkani-Hamed et al. 1607.06821]
[Csáki, D'Agnolo, Geller, Ismail 2007.14396]
[Arkani-Hamed, D'Agnolo, Kim 2012.04652]
[D'Agnolo, Teresi 2106.04591 + 2109.13249]
[Csáki, Ismail, Ruhdorfer, Tooby-Smith 2210.02456]
…

They require new physics coupled to the Higgs, at or below weak scale (but *not* in the form traditional naturalness expects!)

- Light (Higgs-mixed) scalars are a common occurrence, bolstering motivations for searches

Light Higgs-mixed scalar

Add to SM a real scalar S

$$\mathcal{L}_{\rm BSM} = -\frac{1}{2}\widetilde{m}_S^2 S^2 - V_{\rm int}(S) - \mu S H^\dagger H - \frac{\lambda_{SH}}{2} S^2 H^\dagger H$$

mixing between S and h :

$\sin\theta$ controls lifetime of light scalar

controls $\mathrm{BR}(h \to SS)$:

exotic Higgs decays

This simple setup is motivated by variety of new physics scenarios

(beyond cosmological naturalness)

Light Higgs-mixed scalar

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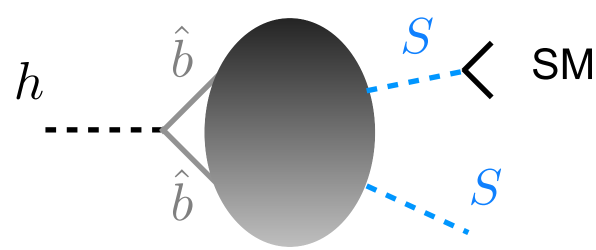
Neutral Naturalness again: light dark sector in Twin Higgs

dark QCD without light matter

glueballs are lightest hadrons,
lightest glueball is $\hat{G}_{0^{++}} \simeq S$



dark parton shower
and hadronization

[Craig, Katz, Strassler, Sundrum 2015]
+ many others

Light Higgs-mixed scalar

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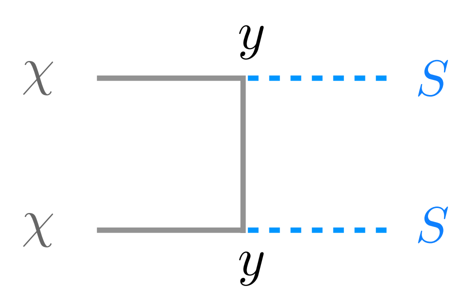
mixing between S and h :
$\sin\theta$ controls lifetime of light scalar

controls $\mathrm{BR}(h \to SS)$:
exotic Higgs decays

S can mediate dark matter freeze out:

$$\mathcal{L}_{\rm DM} = -\frac{y}{2} S\chi\chi$$

(Majorana) fermion DM



$(m_\chi > m_S)$

[Evans, Gori, Shelton 2017]

Light Higgs-mixed scalar

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mixing between S and h :
$\sin\theta$ controls lifetime of light scalar

controls $\mathrm{BR}(h \to SS)$:
exotic Higgs decays

Light scalar has mostly-hadronic decays,

and macroscopic lifetime in vast region of parameter space

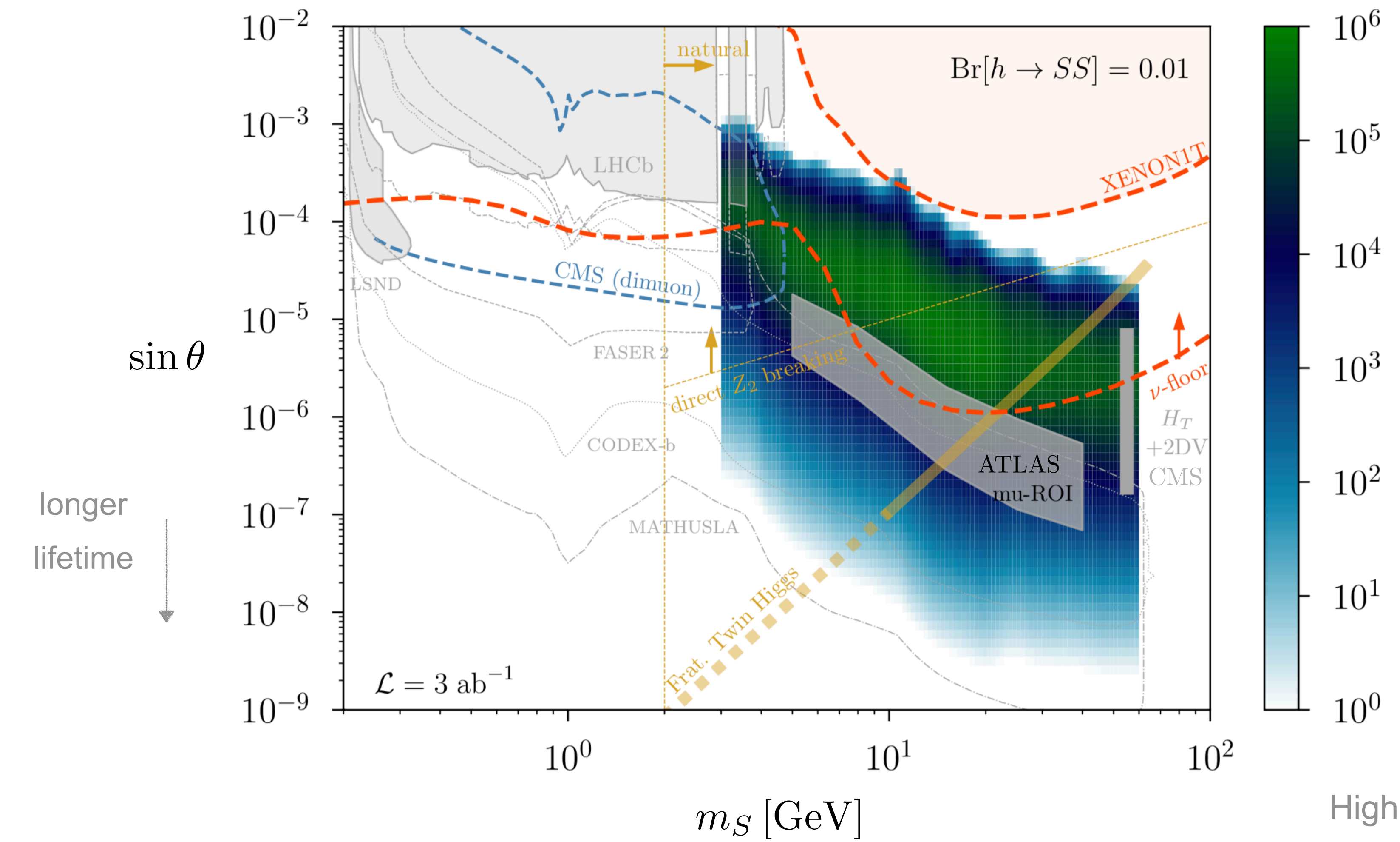
Development of LLP-dedicated triggers and search strategies at LHC is flourishing

[LLP @ LHC white paper, 1903.04497]

[talks by Sestini, Beltrán]

Light scalar: parameter space

[Gershtein, Knapen, Redigolo 2012.07864]

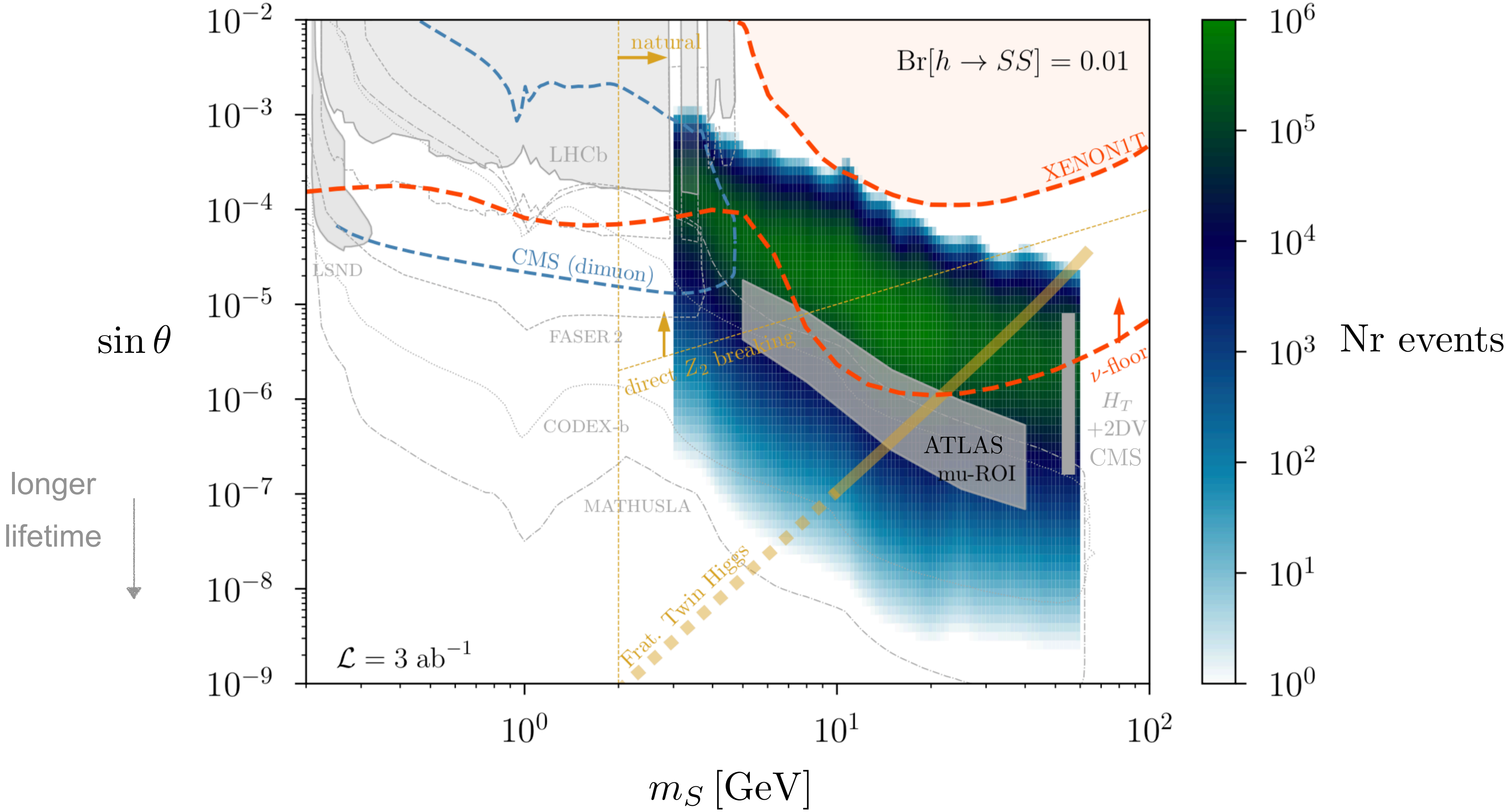


High efficiency for $c\tau \sim (1 - 10)$ cm

Green/dark blue: HL-LHC event counts for proposed trigger on low-mass hadronic displaced vertex @ L1, in CMS phase II

Light scalar: parameter space

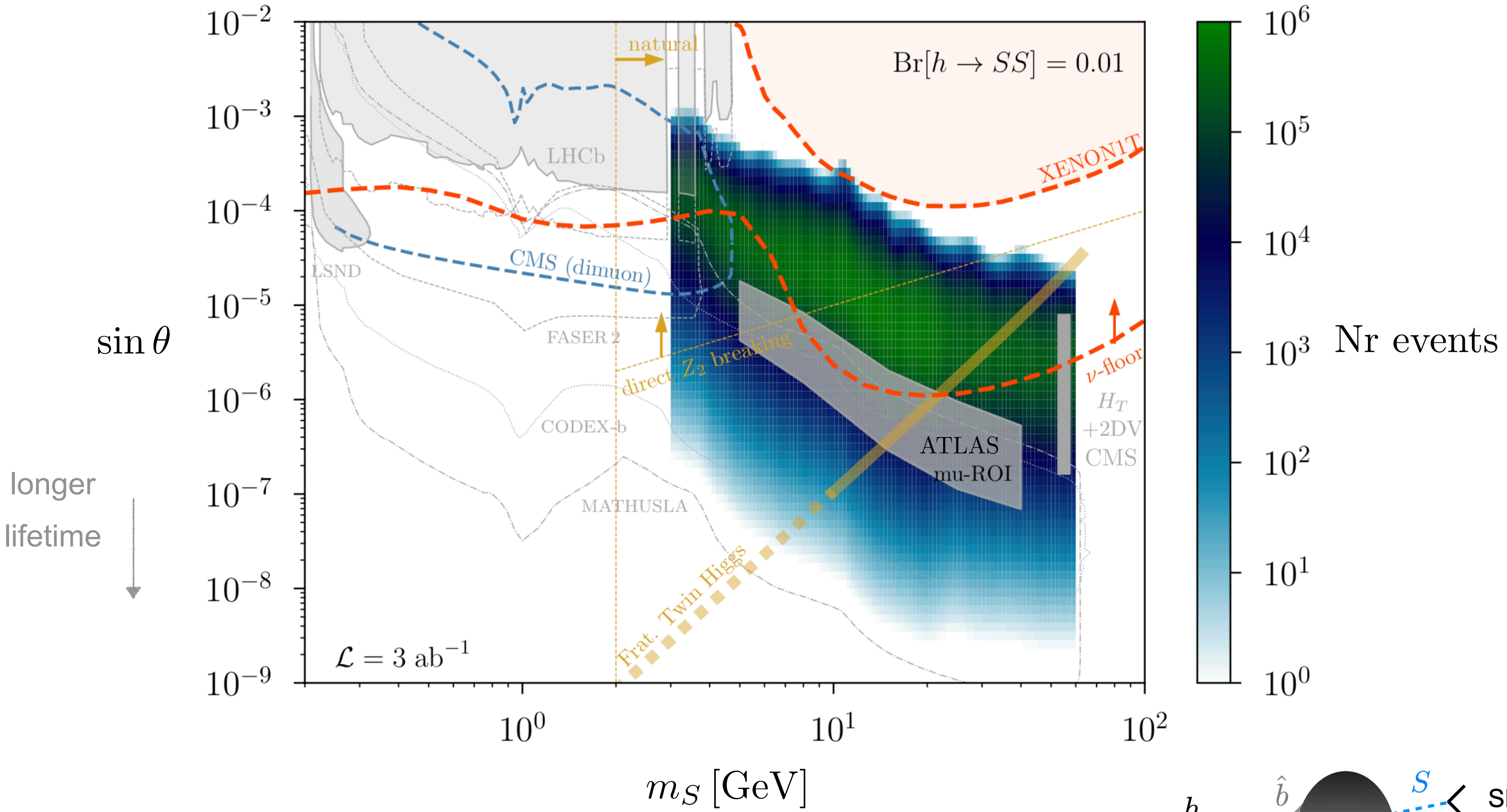
[Gershtein, Knapen, Redigolo 2012.07864]

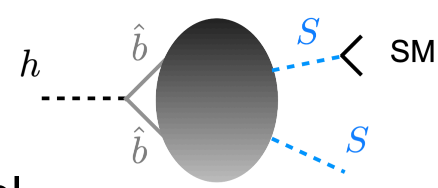


Red: thermal dark matter region assuming $m_\chi = 3m_S$ as benchmark

Light scalar: parameter space

[Gershtein, Knapen, Redigolo 2012.07864]



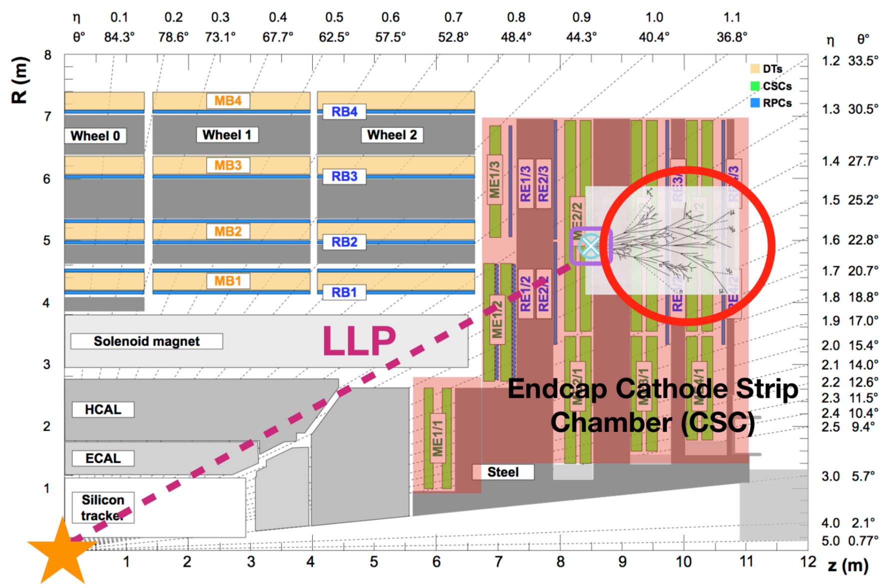


Yellow: scalar is lightest dark glueball in neutral naturalness model

LLPs in CMS endcaps

Qualitatively new approach:
CMS search for
LLPs in endcap muon detectors

[CMS 2107.04838]

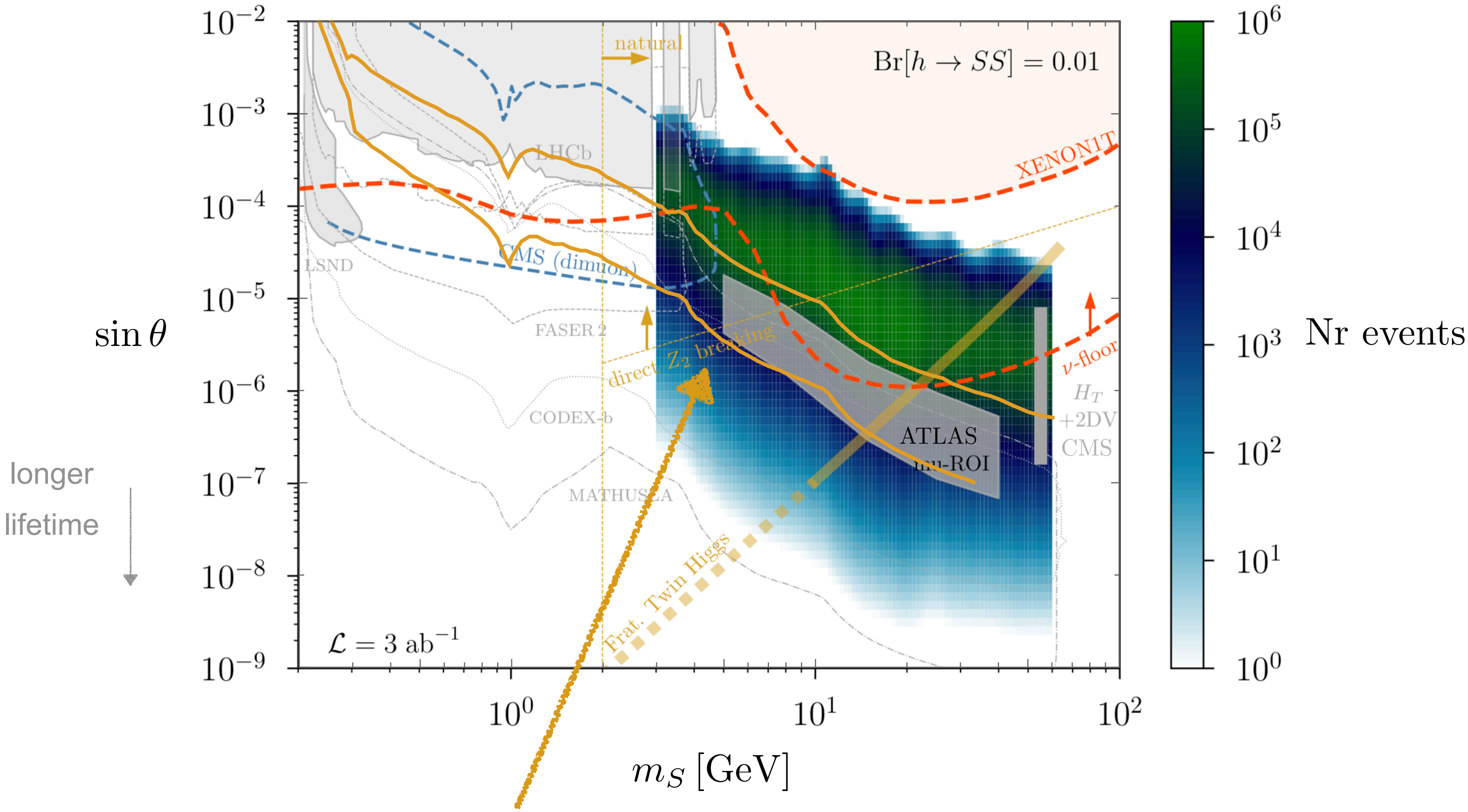


trigger on MET
$p_T^{miss} > 200$ GeV (offline)

- Background very suppressed by shielding, sensitive to single LLP decay → longer lifetimes

- Calorimetric measurement → retains sensitivity at lower LLP mass

Recast to singlet parameter space



Probes complementary region, with smaller mixing

Reach extends to sub-GeV masses

[Mitridate, Papucci, Wang, Peña, Xie 2304.06109]

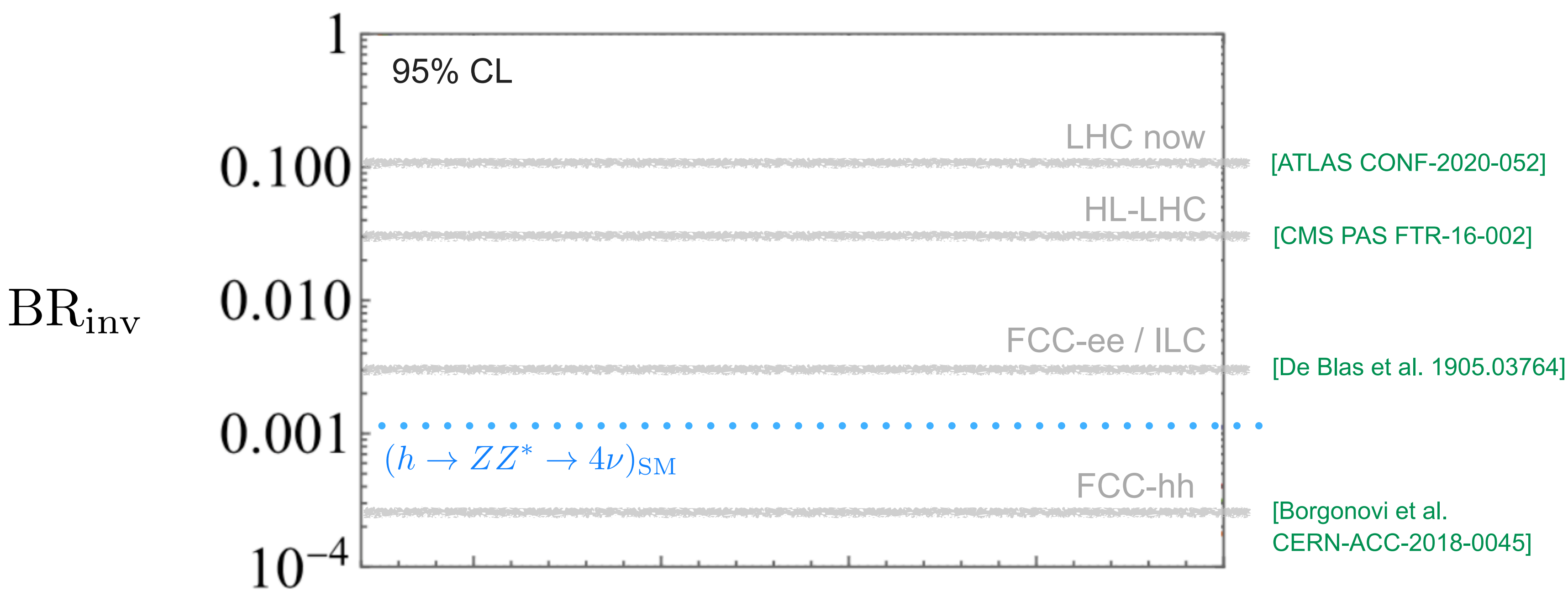
Invisible Higgs decays

- For small couplings/masses, Higgs decay products just escape detector

  $h \to \text{invisible}$ is relevant for huge class of light new physics models

- Present and projected sensitivity on BR_{inv} :

[talks by Wielers, Robson, Pilkington]

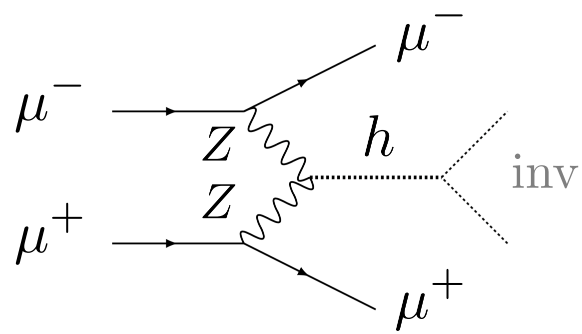


Where does the **Muon Collider** fit here?

[talk by Lucchesi]

Challenge: invisible Higgs @ Muon Collider

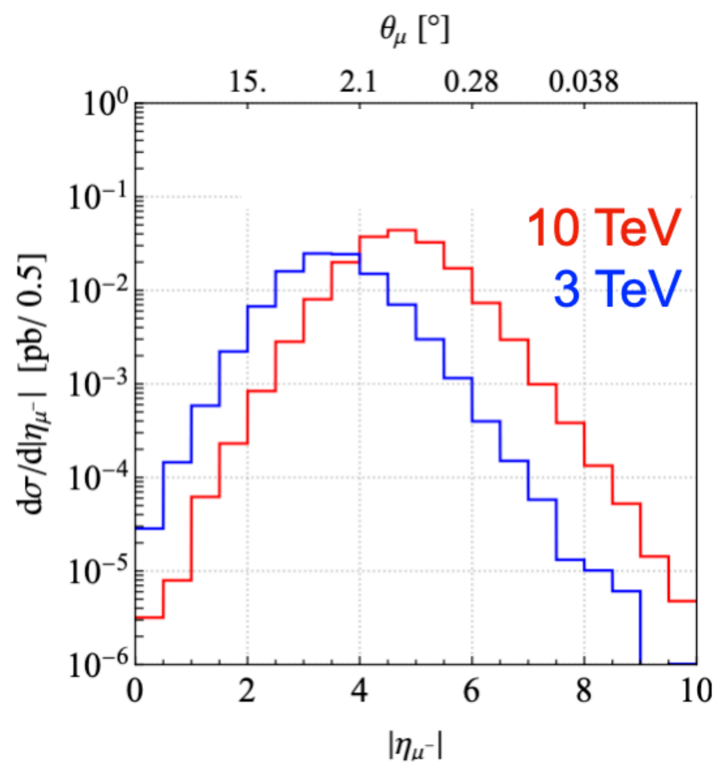
Need to exploit *ZZ* fusion



(*WW* fusion produces fully invisible final state)

At multi-TeV collider energies,

final-state muons are *extremely* forward



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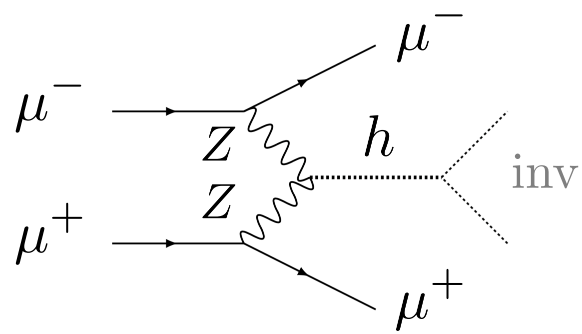

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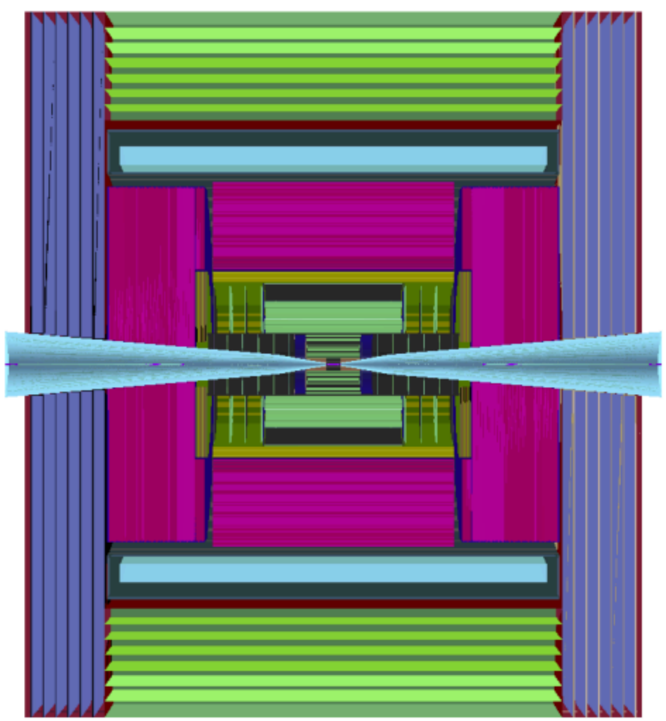


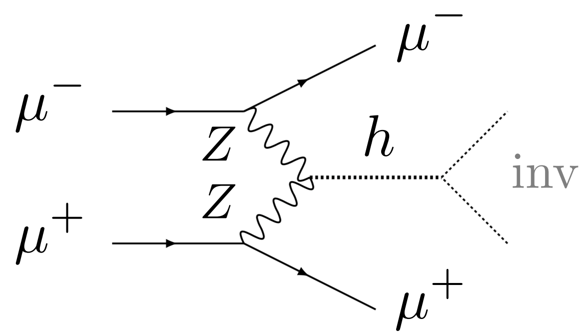
[IMCC 2203.07964]

However, cone-shaped tungsten nozzles are needed to shield detector from beam-induced background (BIB)

Nozzles limit detector acceptance to $\theta > 10^{\mathrm{o}}$

Challenge: invisible Higgs @ Muon Collider

Need to exploit *ZZ* fusion



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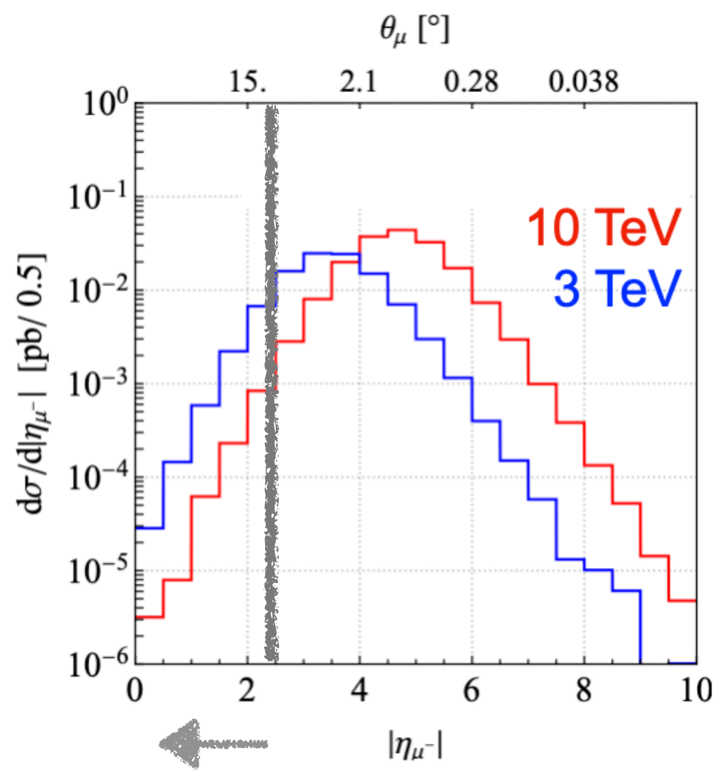
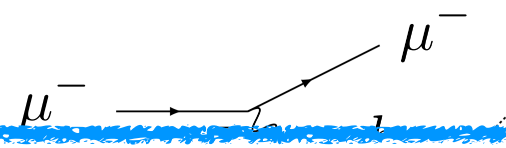


Shielding nozzles cut away ~ all signal!

$$\theta > 10^{\mathrm{o}} \quad \leftrightarrow \quad |\eta| < 2.44$$

Challenge: invisible Higgs @ Muon Collider



Need

produces

nal state)

Hope is not lost: muons traverse shielding

→ plan for dedicated detector in forward region?

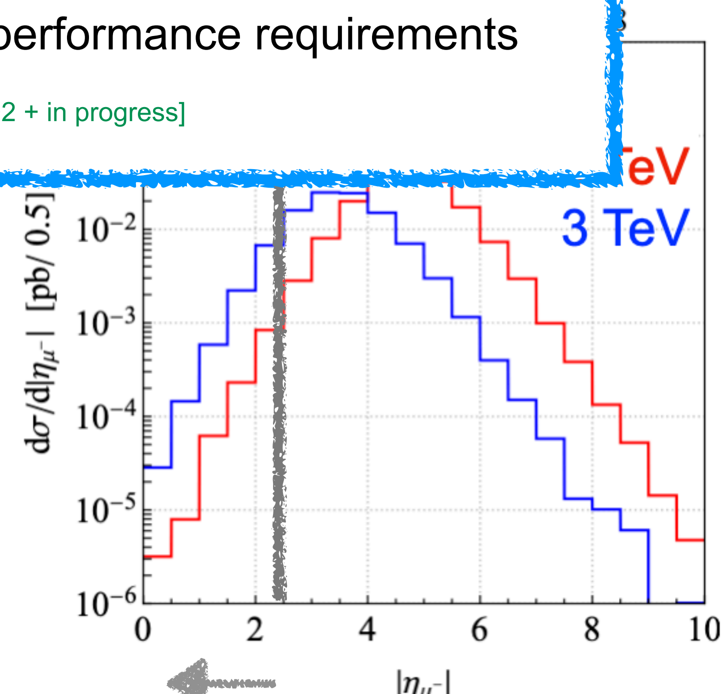
Essential for $h \to \mathrm{inv}$ and many signals with invisible particles.

Identify physics cases & fwd detector performance requirements

[Ruhdorfer, Salvioni, Wulzer 2303.14202 + in progress]

At multi-TeV collider energies,

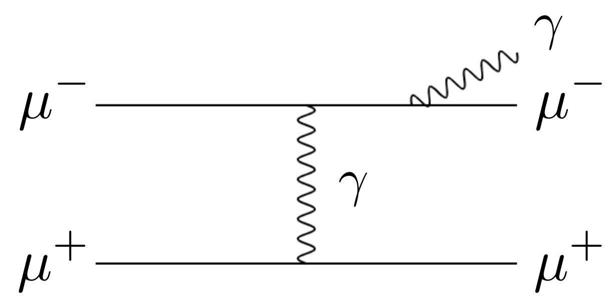
final-state muons are *extremely* forward



Shielding nozzles cut away ~ all signal!

$$\theta > 10^{\circ} \quad \leftrightarrow \quad |\eta| < 2.44$$

Higgs → invisible at Muon Collider



Backgrounds

1. Neutrinos: $\mu^+\mu^- \to \mu^+\mu^-\nu\bar{\nu}$
2. SM Higgs: $\mu^+\mu^- \to \mu^+\mu^-(h \to 4\nu)$
3. Two muons + lost objects: $\mu^+\mu^- \to \mu^+\mu^- X$

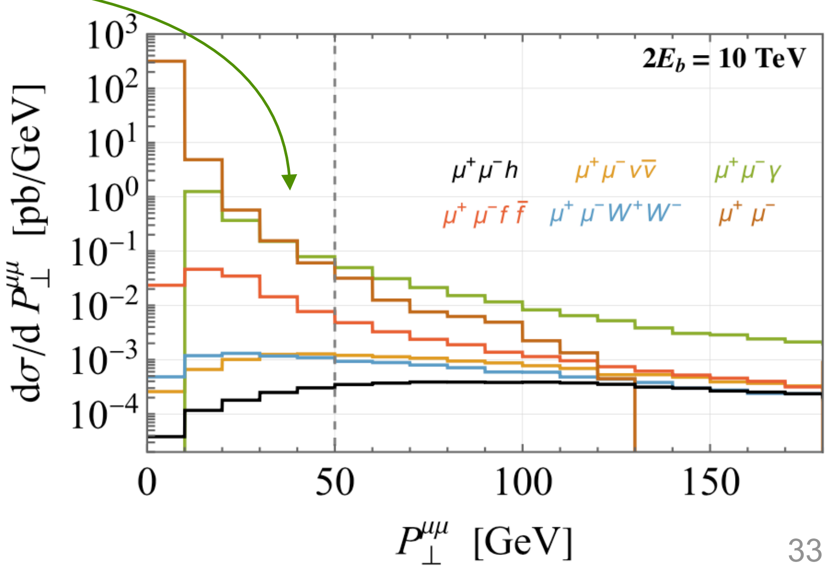
X is outside central detector, $|\eta| > 2.44$

or soft, $p_\perp < 20$ GeV

Largest contributions from $X = \gamma,\ f\bar{f},\ W^+W^-$

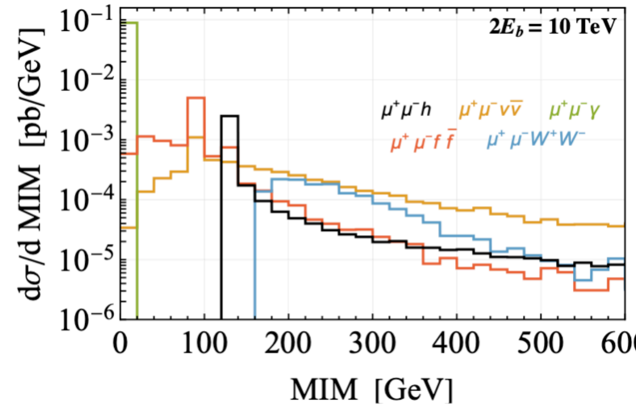
Require $P_\perp^{\mu\mu} > 50$ GeV

to suppress photon background



Beam and detector effects

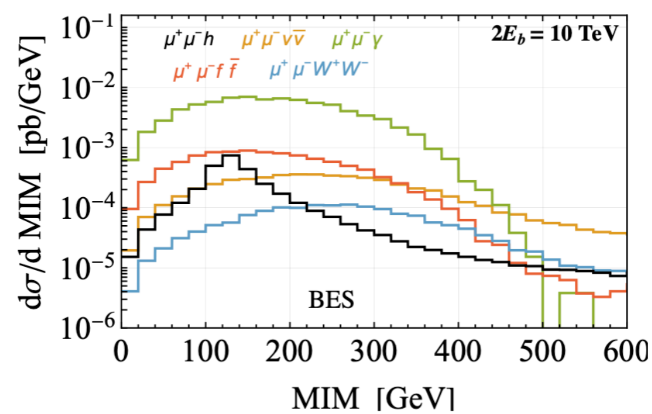
Truth level



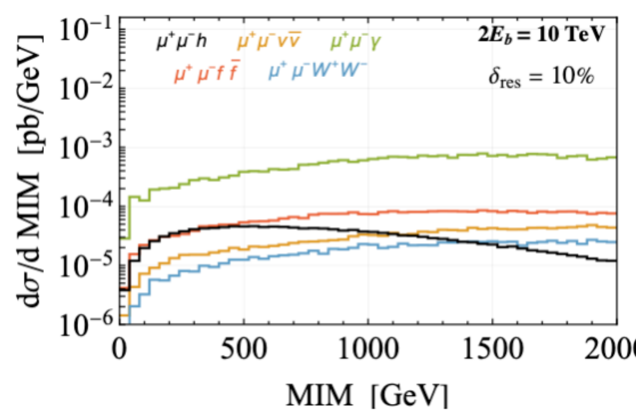
Beam energy spread of 0.1%

μ^- μ^+

$E_b(1+\delta_{BES})$



Finite resolution in measurement of muon energies $\delta_{res} = 10\%$ *

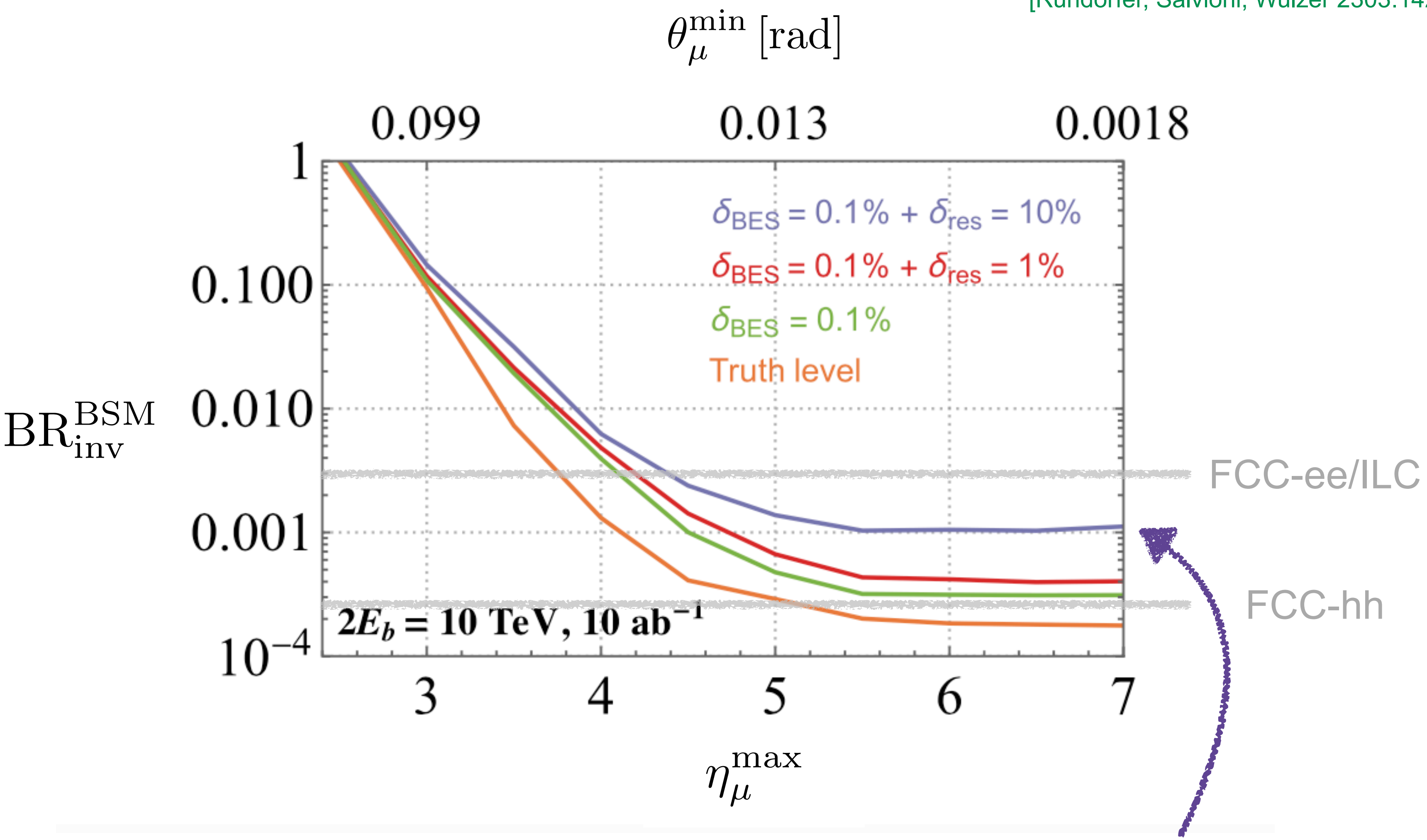


MIM does not discriminate anymore

* inspired by initial results of IMCC studies on muon propagation: [KITP talk] by Daniele Calzolari, 03/2023

Sensitivity on Higgs → invisible

[Ruhdorfer, Salvioni, Wulzer 2303.14202]



- With 10% resolution on forward muon energy, just reach the SM value
- $\eta_{\max} = 5$ or 6 is needed for optimal sensitivity

Final message

- Light new physics coupled to the Higgs is strongly motivated by alternative approaches to Naturalness problem (cosmological selection, Neutral Naturalness)

- Not a single sharp prediction, but still useful guidance.
  Signatures are often in common with other key questions (e.g. light dark matter)

- Effective search strategies require thinking outside the box,
  both at the (HL-) LHC and at future colliders: detectors, trigger, analyses

Backup slides

More on radiative stability

Can also see Gegenbauers emerge from Coleman-Weinberg potential:

For general $SO(N)$ invariant potential $V = \epsilon\lambda f^4\, G(\cos\Pi/f)$

quadratic piece of one-loop CW is

[Alonso, Jenkins, Manohar 2015]

$' \equiv \frac{\partial}{\partial(\Pi/f)}$

$$V_{\text{quantum}} = \epsilon\lambda f^4 \left[G + \frac{\Lambda^2}{32\pi^2 f^2}\left(\underbrace{G'' + (N-1)\cot\frac{\Pi}{f}G'} \right) \right]$$

if $\propto G$, multiplicative renormalization!

More on radiative stability

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if $\propto G$, multiplicative renormalization!

Indeed, Gegenbauers satisfy differential equation

$$G_n^{\alpha}{}'' + 2\alpha \cot \frac{\Pi}{f} G_n^{\alpha}{}' + n(n+2\alpha) G_n^{\alpha} = 0 \quad \longrightarrow \quad \alpha = \frac{N-1}{2}$$

Radiative corrections do not alter functional form

More on radiative stability

Can also see Gegenbauers emerge from Coleman-Weinberg potential:

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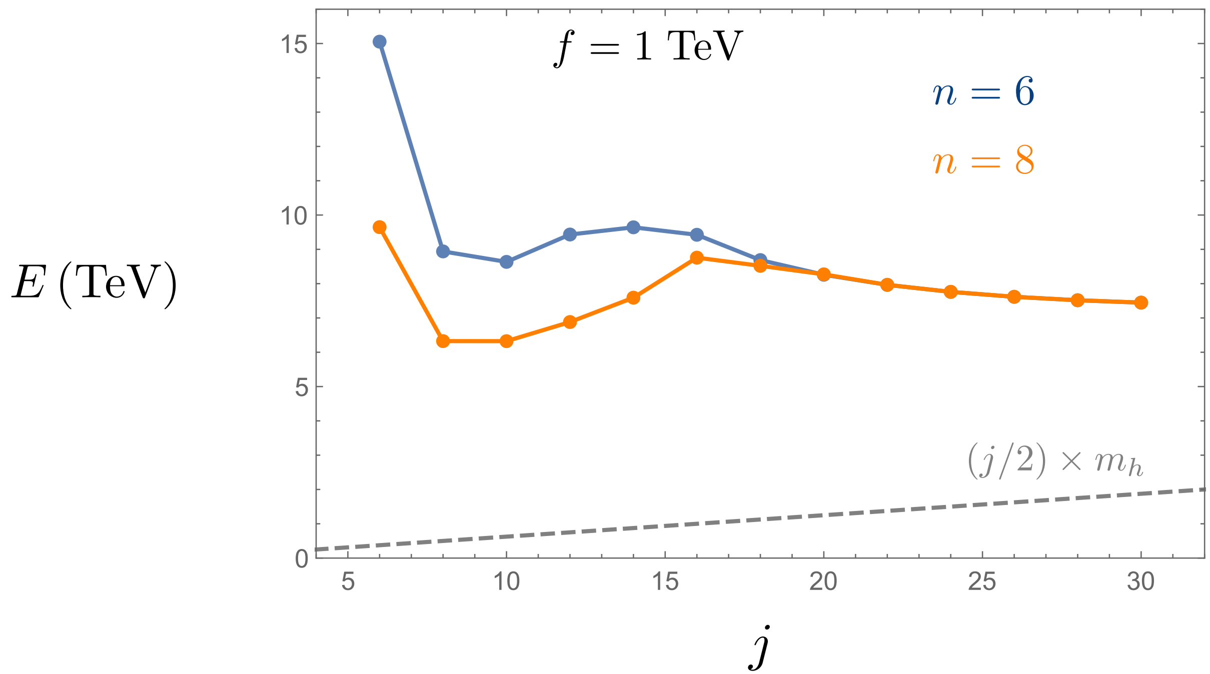
if $\propto G$, multiplicative renormalization!

Abelian case is recovered for $N = 1$:

$G'' \propto G$ → $G = \cos\frac{n\Pi}{f}$

Perturbative unitarity



$E_{\max} \gtrsim 6\ \mathrm{TeV}$

Following [Chang, Luty 1902.05556], we estimate perturbative unitarity bounds from $h^{j/2} \to h^{j/2}$ scattering processes (even j)

Slightly stronger constraints can be obtained by including would-be Goldstones, after restoring gauge invariant form through $h \to X = \sqrt{2H^\dagger H} - v_A$

Gegenbauers from irreps

$$\tilde{\phi} \equiv \begin{pmatrix} \vec{0}_N \\ 1 \end{pmatrix}$$

Consider scalar function

$$|t\phi - \tilde{\phi}|^{1-N} = \sum_{n=0}^{\infty} t^n K_n^{i_1 \dots i_n} \phi^{i_1} \dots \phi^{i_n}$$

Taylor expansion

$$K_n^{i_1 \dots i_n} = \frac{1}{n!} \frac{\partial^n \phi^{1-N}}{\partial \phi_{i_1} \dots \partial \phi_{i_n}} \bigg|_{\tilde{\phi}}$$

traceless, because Laplacian vanishes away from origin

//

$$\left(1 - 2t \cos \Pi/f + t^2\right)^{(1-N)/2}$$

||

$$\sum_{n=0}^{\infty} t^n G_n^{(N-1)/2}(\cos \Pi/f)$$

generating function for Gegenbauers is

$$\left(1 - 2tx + t^2\right)^{-\alpha} = \sum_{n=0}^{\infty} t^n G_n^{\alpha}(x)$$

Gegenbauers from irreps

$$\tilde{\phi} \equiv \begin{pmatrix} \vec{0}_N \\ 1 \end{pmatrix}$$

Consider scalar function

$$|t\phi - \tilde{\phi}|^{1-N} = \sum_{n=0}^{\infty} t^n K_n^{i_1 \ldots i_n} \phi^{i_1} \ldots \phi^{i_n}$$

//

Taylor expansion

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generating function for Gegenbauers is

$$\left(1 - 2tx + t^2\right)^{-\alpha} = \sum_{n=0}^{\infty} t^n G_n^{\alpha}(x)$$

Gegenbauer polynomials from explicit $SO(N+1) \rightarrow SO(N)$ breaking

Gegenbauer?

Gegenbauer polynomials can be seen as generalization of Legendre polynomials to $D \neq 3$ spatial dimensions

$D = 3$

$SO(3) \to SO(2)$

multipole expansion of axi-symmetric function of spacetime coordinates

$$f(\vec{r}) = \sum_{\ell=0}^{\infty} c_\ell P_\ell(\cos\theta)$$

$(m = 0)$

They appear in many areas of physics, for example in the expansion of conformal blocks in CFT_d

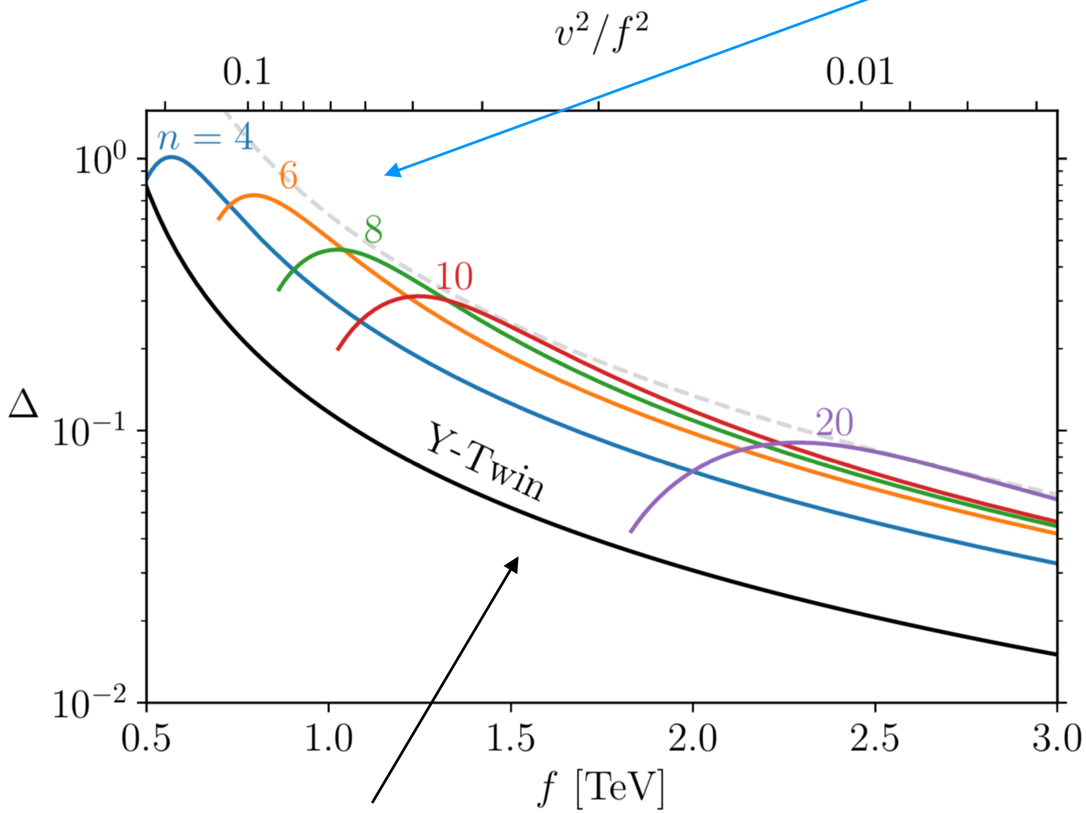
[Hogervorst, Rychkov 2013]

Here, they arise from explicit breaking of internal symmetry $SO(N+1) \to SO(N)$, variables are pNGB fields

Gegenbauer's *Twin*

Fine tuning:

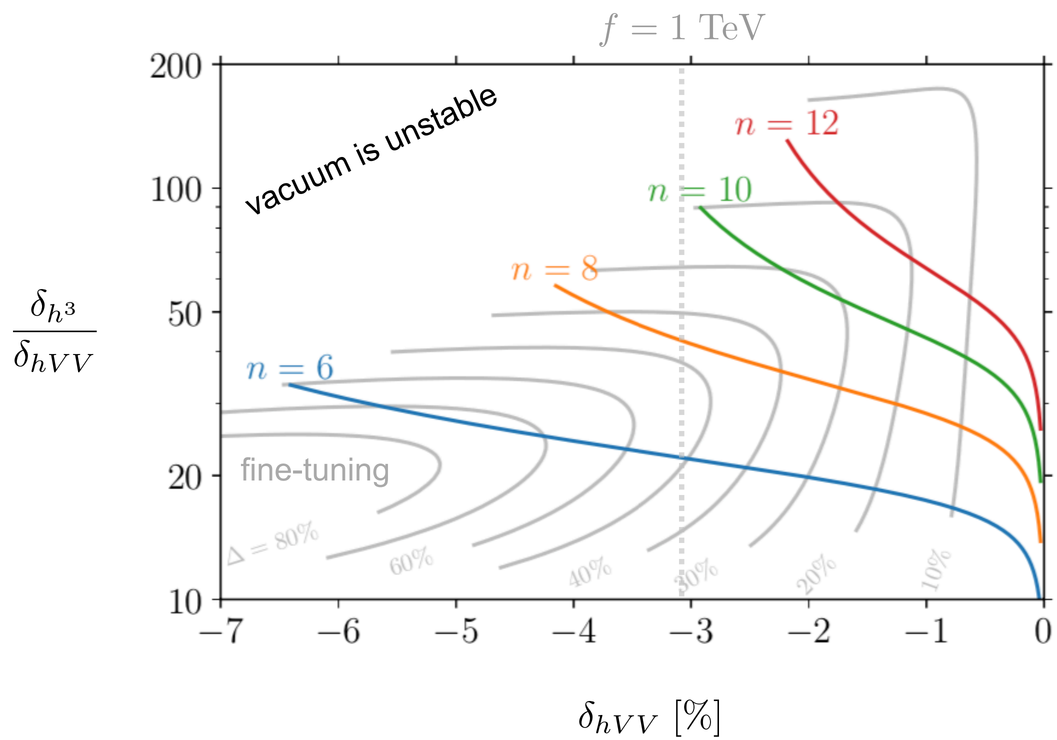
Gegenbauer's Twin with
$n = 6$ or $n = 8$ and $f \sim 1$ TeV
has essentially no tuning



standard Twin Higgs model (Twin hypercharge not gauged)

Back to $\delta_{h^3}/\delta_{hVV}$ ratio

$$\delta_{hVV} \simeq -\frac{v^2}{2f^2}$$



A ratio between 10 and 100 is generic in parameter space of Gegenbauer's Twin

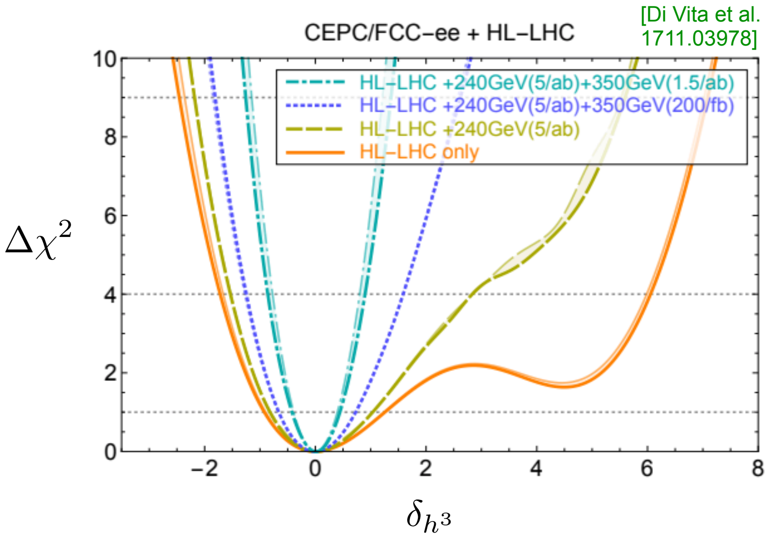
A class of naturalness models where h^3 measurements probe new ground

Higgs couplings at FCC

At FCC-ee, indirect sensitivity on h^3 from loop corrections to single-Higgs observables

(2σ) $|\delta_{h^3}| < 48\%$

[de Blas et al. 1905.03764]



At FCC-hh, direct access through double Higgs production

$$|\delta_{h^3}| < 10\%$$

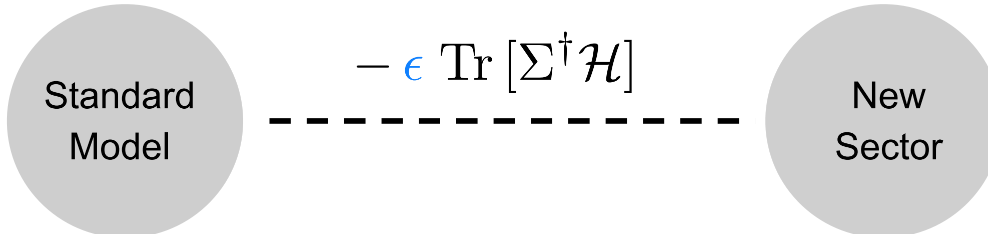
[McCullough 1312.3322]
[Di Vita et al. 1711.03978]
[FCC CDR CERN-ACC-2018-0056]
[de Blas et al. 1905.03764]
…

Compare with expected sensitivity on single-Higgs couplings: from FCC-ee alone

$$|\delta_{hZZ}| \lesssim 0.34\%$$

Another route: induced EWSB

Another viable approach to remove v/f tuning is tadpole-induced EWSB



$+\,m_H^2 |H|^2$ $\qquad\qquad$ $\langle \Sigma \rangle = f_\Sigma$

$$\longrightarrow \quad V(h) \sim +\,m_H^2 h^2 - \epsilon\, f_\Sigma\, h$$

Large deviations in h^3 are expected here too (self-interactions are suppressed)

Updated analysis of constraints is missing

[Azatov, Galloway, Luty 2011]
[Galloway, Luty, Tsai, Zhao 2013]
[Chang, Galloway, Luty, Salvioni, Tsai 2014]

[Harnik, Howe, Kearney 2016]
[Galloway, Kagan, Martin 2016]

Singlet scalar: trigger rates

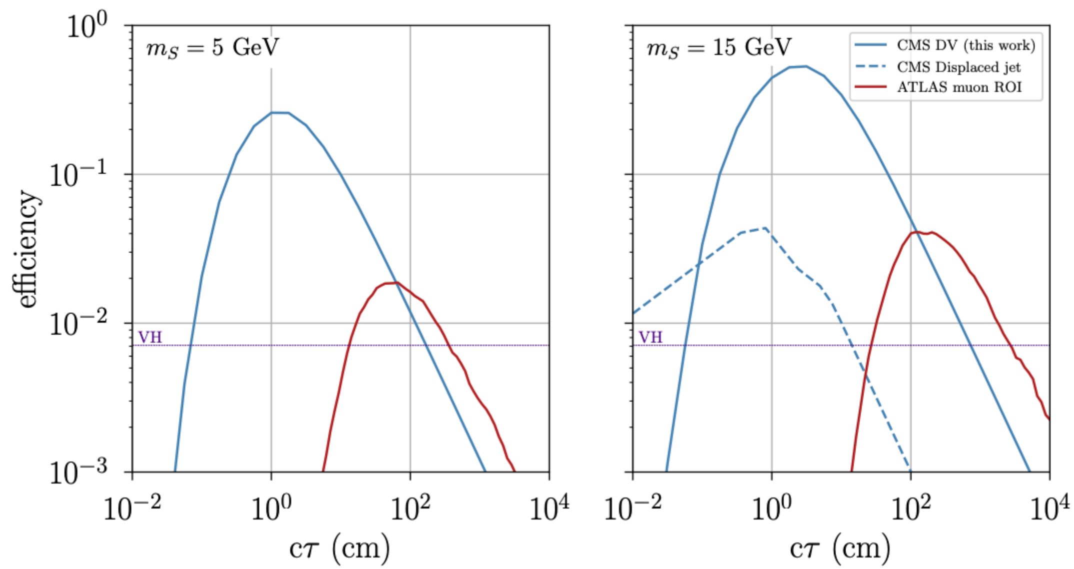
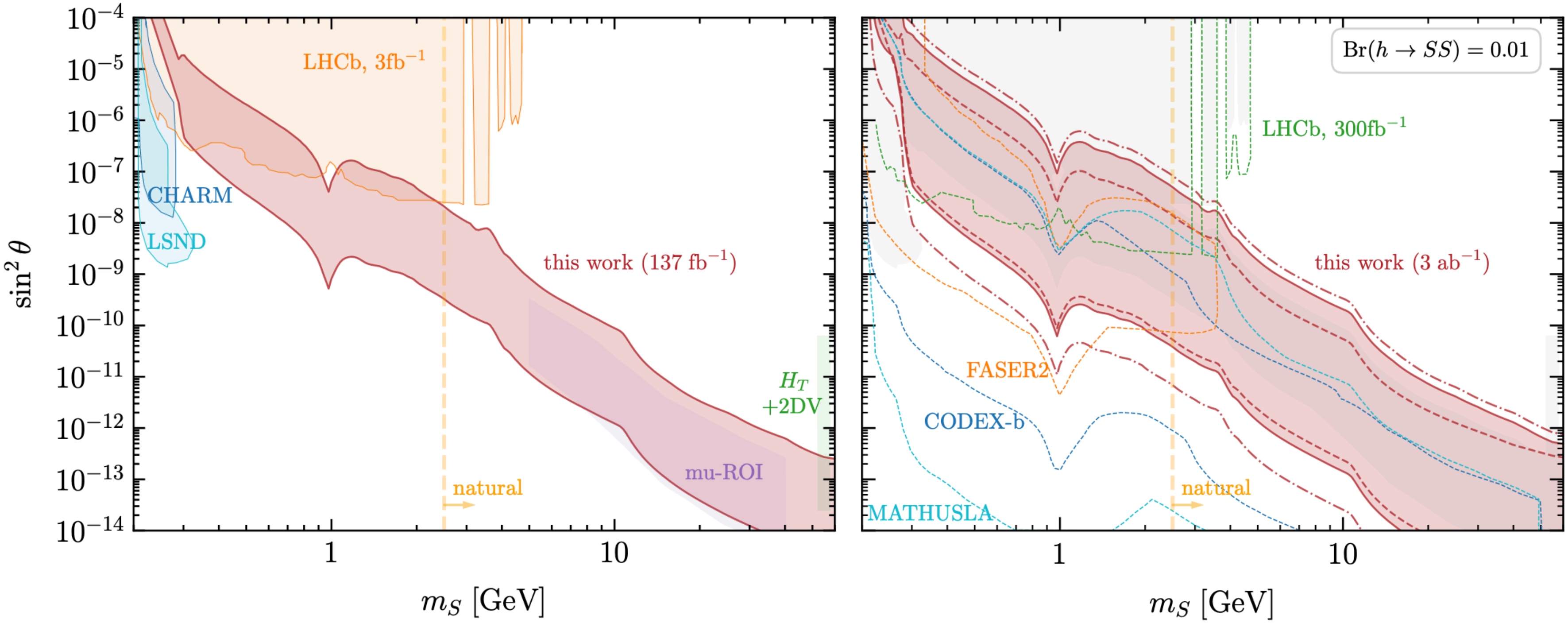


FIG. 8. Estimated L1 trigger efficiency for a CMS displaced vertex trigger (solid blue). Also shown is the projected efficiency for CMS L1 track jet trigger for displaced jets [3, 4], assuming 5 kHz rate (dashed blue) and the efficiency of the existing ATLAS muon region of interest trigger (solid red) [11]. The dashed purple line indicates the efficiency to trigger on an associated lepton in VH production, normalized against the gluon fusion cross section.

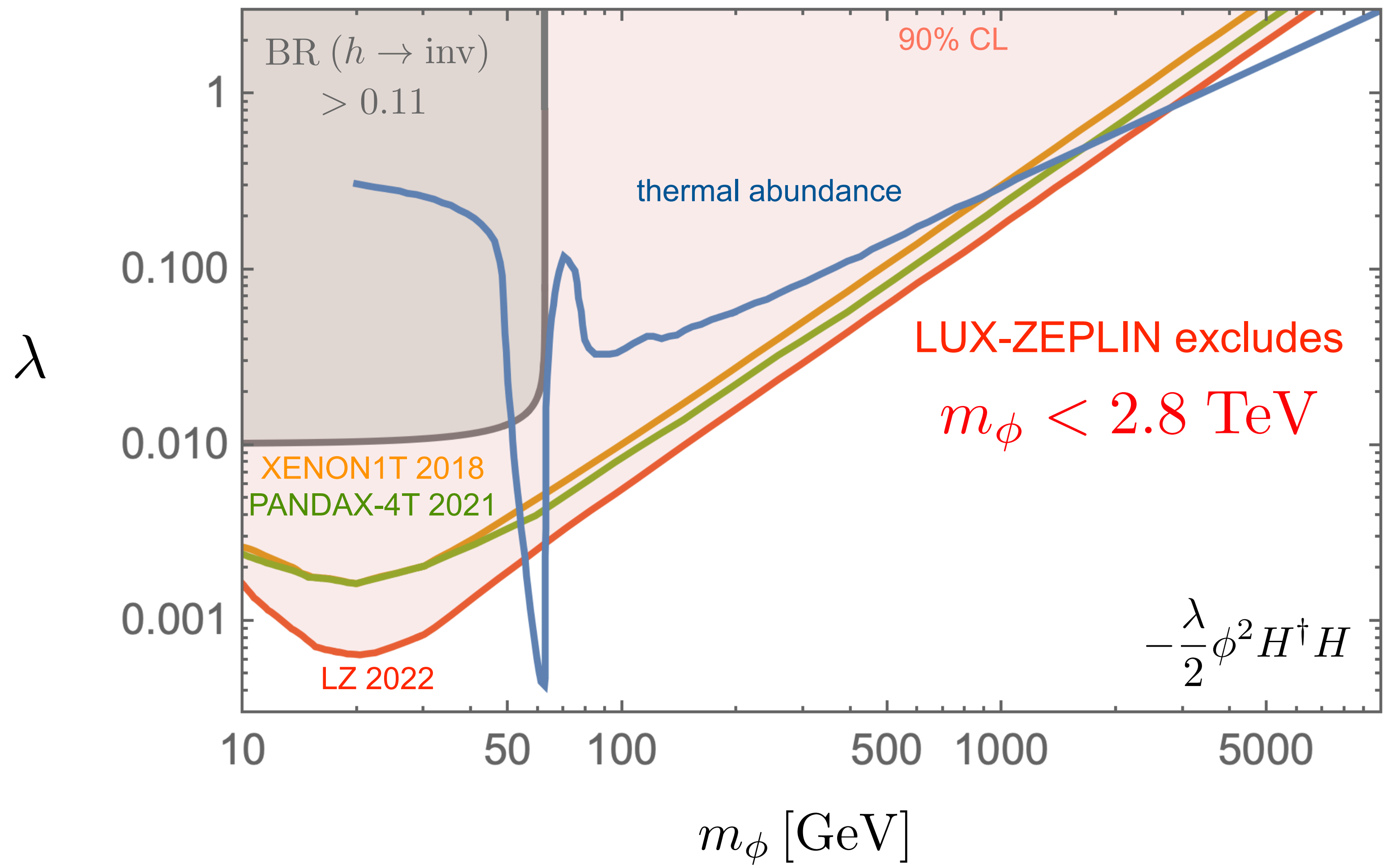
[Gershtein, Knapen, Redigolo 2012.07864]

Singlet scalar: current vs projected



[Mitridate, Papucci, Wang, Peña, Xie 2304.06109]

Renormalizable Higgs portal



Good example of the "WIMP **vs** direct detection" tension

EFT for SM + singlet scalar

Think more broadly. For SM + (complex) scalar χ , up to dimension 6:

preserve DM shift symmetry

$$\mathcal{L}_{\text{int}} = \frac{c_d}{f^2}\partial_\mu|\chi|^2\partial^\mu|H|^2 + \frac{i}{f^2}(\chi^*\overleftrightarrow{\partial}_\mu\chi)\sum_{\Psi=q_L,u_R,d_R,\ell_L,e_R} b_\Psi\overline{\Psi}\gamma^\mu\Psi + \frac{ig'}{m_*^2}c_B(\chi^*\overleftrightarrow{\partial}_\mu\chi)\partial_\nu B^{\mu\nu}$$

$$-\lambda|\chi|^2|H|^2 + \frac{|\chi|^2}{f^2}(c_u^\chi\, y_u\overline{q}_L\widetilde{H}u_R + c_d^\chi\, y_d\overline{q}_L H d_R + c_e^\chi\, y_e\overline{\ell}_L H e_R + \text{h.c.}) + \sum_{V=G,W,B}\frac{d_V y^2}{16\pi^2}\frac{g_V^2}{m_*^2}|\chi|^2 V^{\mu\nu}V_{\mu\nu}$$

break DM shift symmetry

Power counting here assumes both H and χ arise as pseudo-Goldstone bosons.

In this case, expect leading DM-SM interaction to be of dimension 6

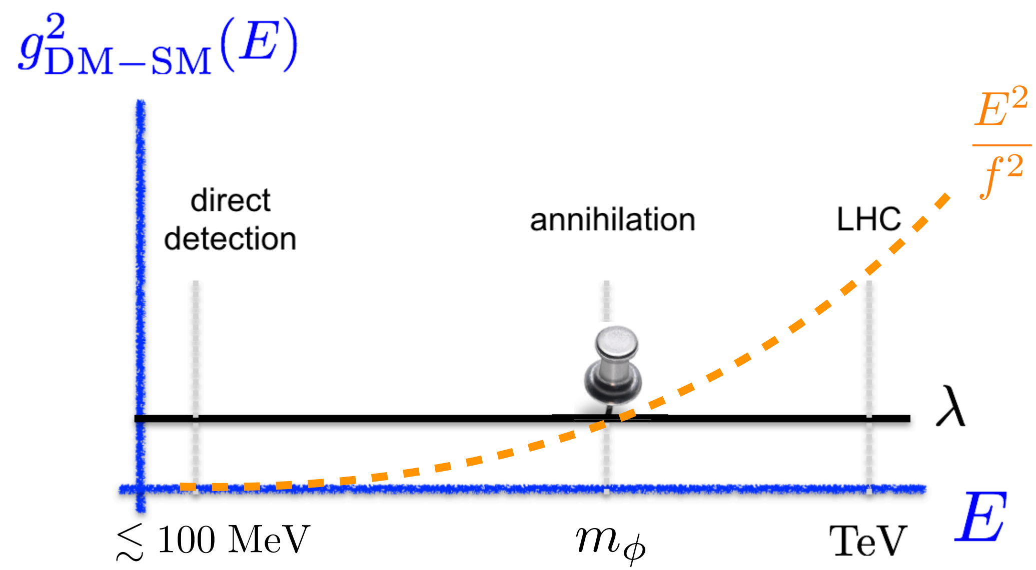
("derivative Higgs portal"), while shift-breaking interactions are naturally small

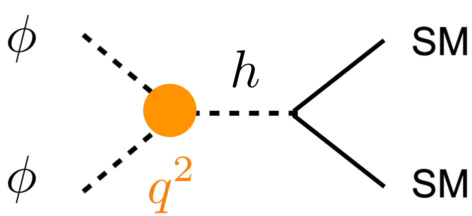
[Criado, Djouadi, Perez-Victoria, Santiago 2021]
[Ruhdorfer, Salvioni, Weiler 2019]
[Balkin, Ruhdorfer, Salvioni, Weiler 2018]
[Chala, Durieux, Grojean, de Lima, Matsedonskyi 2017]
[Bruggisser, Riva, Urbano 2016]
[Frigerio, Pomarol, Riva, Urbano 2012]

The “other” Higgs portal

A simple & viable alternative:

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$





scattering

$q^2 \sim m^2_{\rm DM} v^2_{\rm DM}$

$v_{\rm DM} \sim 10^{-3}$

annihilation $q^2 \sim m^2_{\rm DM}$

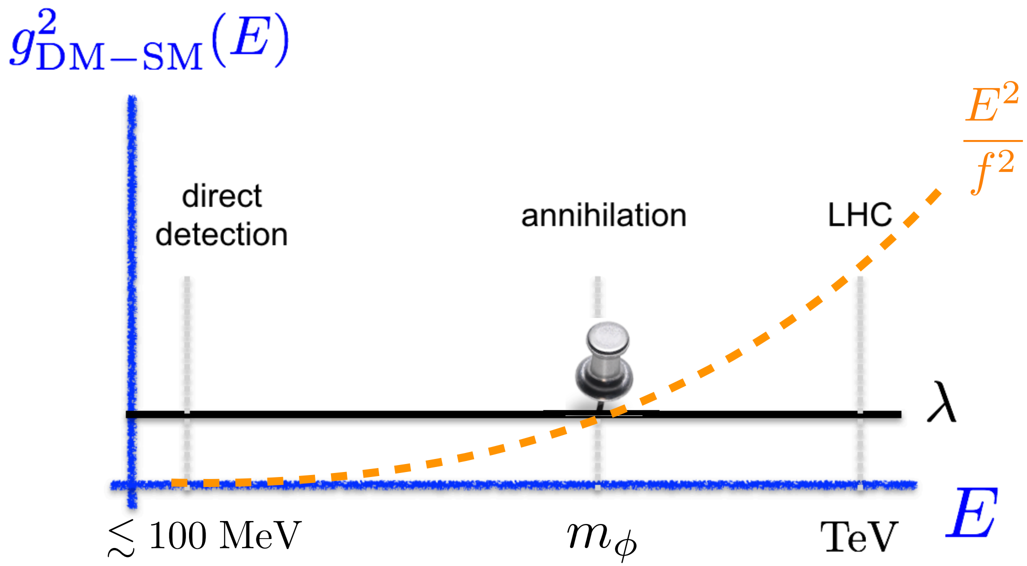
For the <u>derivative Higgs portal</u>,

direct detection is automatically suppressed

The "other" Higgs portal

A simple & viable alternative:

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$



- Motivated by **composite Higgs theories** where both DM and Higgs arise as "sibling" pseudo-Goldstone bosons

[Frigerio, Pomarol, Riva, Urbano 2012] + many others

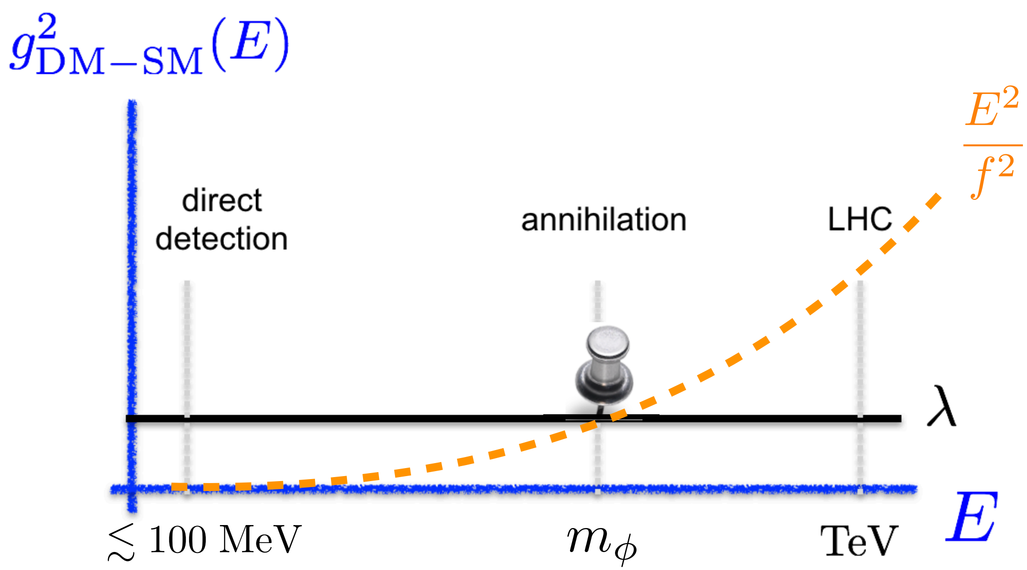
- Shift symmetries dictate derivative coupling.
  Shift-breaking couplings are naturally small, but DM acquires weak scale mass

[Balkin, Ruhdorfer, Salvioni, Weiler 2018]

The "other" Higgs portal

A simple & viable alternative:

$$\mathcal{L} \supset \frac{1}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$

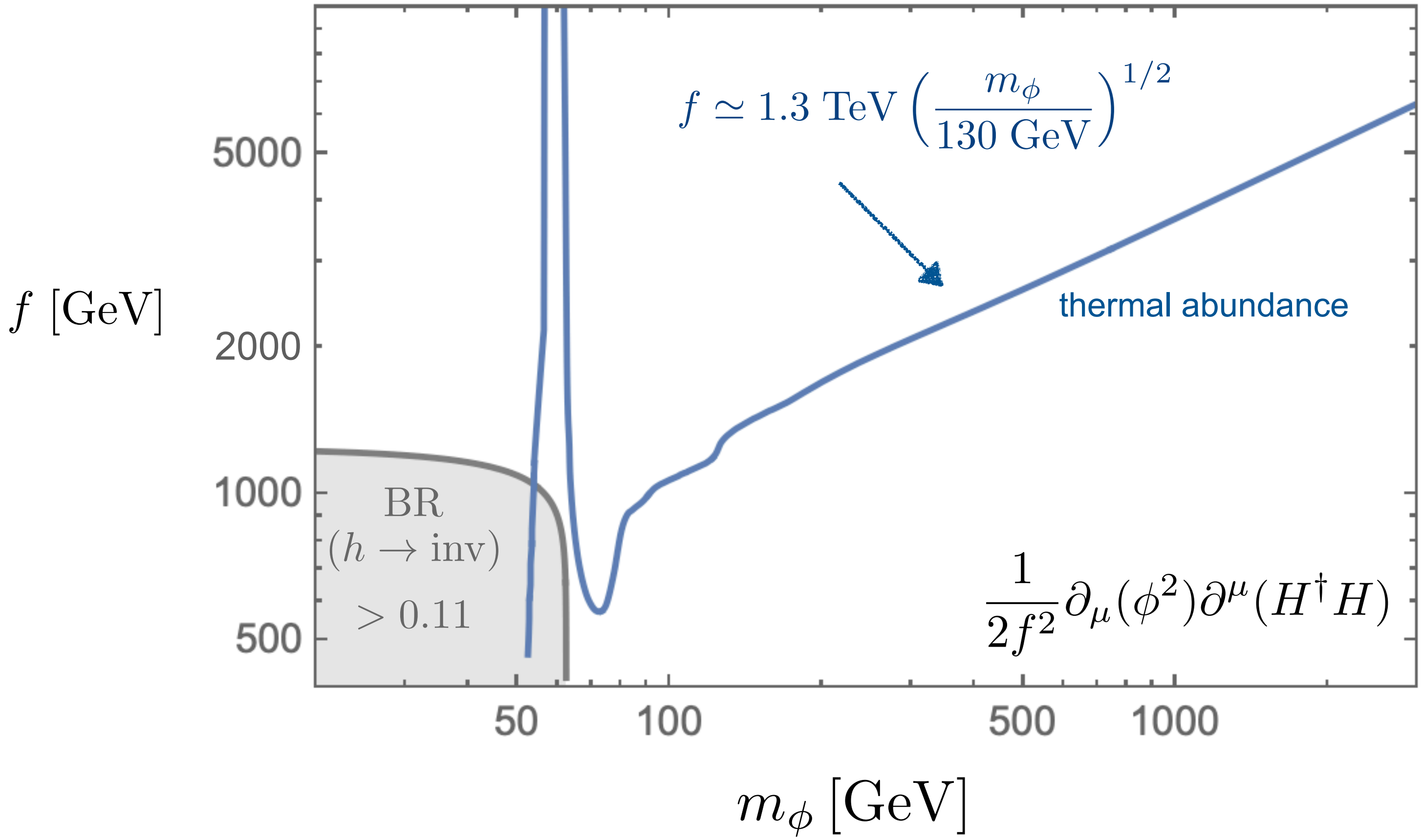


- Motivated by **composite Higgs theories** where both DM and Higgs arise as "sibling" pseudo-Goldstone bosons
- Can also be introduced with elementary Higgs: extend SM by complex scalar with specific explicit breaking

[Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 2008] + many others

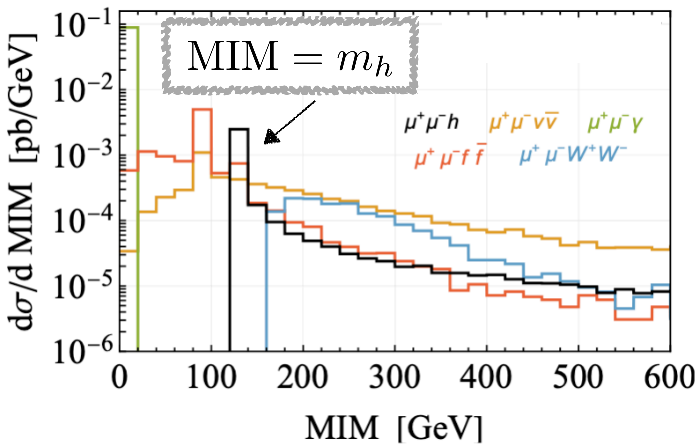
$$\mathcal{L} \supset -\lambda_{HS}|\Phi|^2 H^\dagger H + \mu^2(\Phi^2 + \text{h.c.}) \qquad \Phi = (v_\sigma + \sigma)\, e^{i\phi/v_\sigma}$$

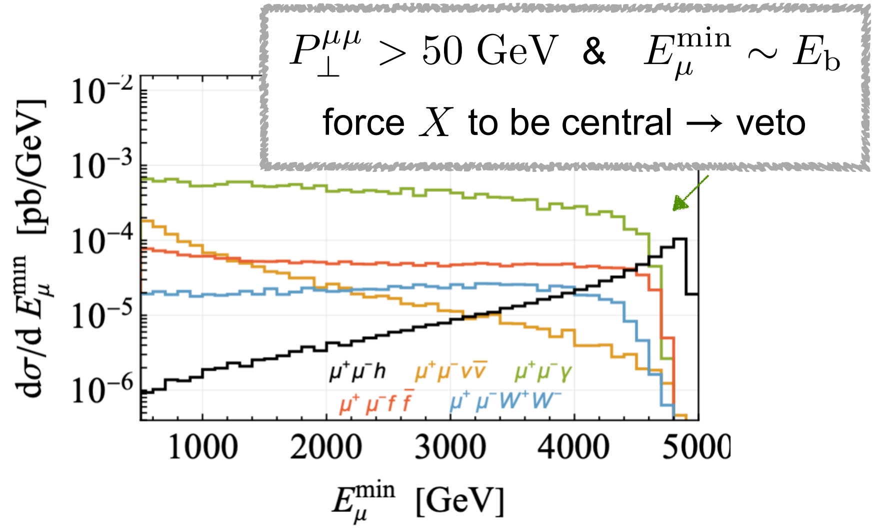
Derivative Higgs portal



Truth-level analysis @ MC

Near-ideal discrimination of *S* and *B* is possible:

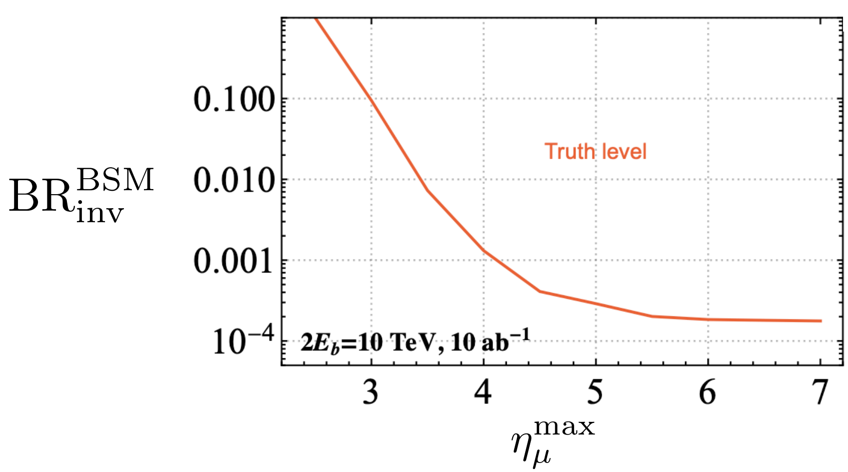




$$\mathrm{MIM} = \sqrt{|(\Delta P)^2|}$$

$$\Delta P = (2E_\mathrm{b}, \vec{0}\,) - p_{\mu^+} - p_{\mu^-}$$

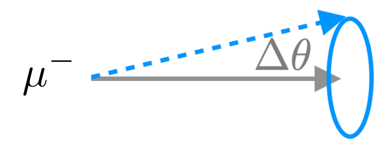
$$E_\mu^{\min} = \min\left(E_{\mu^+}, E_{\mu^-}\right)$$

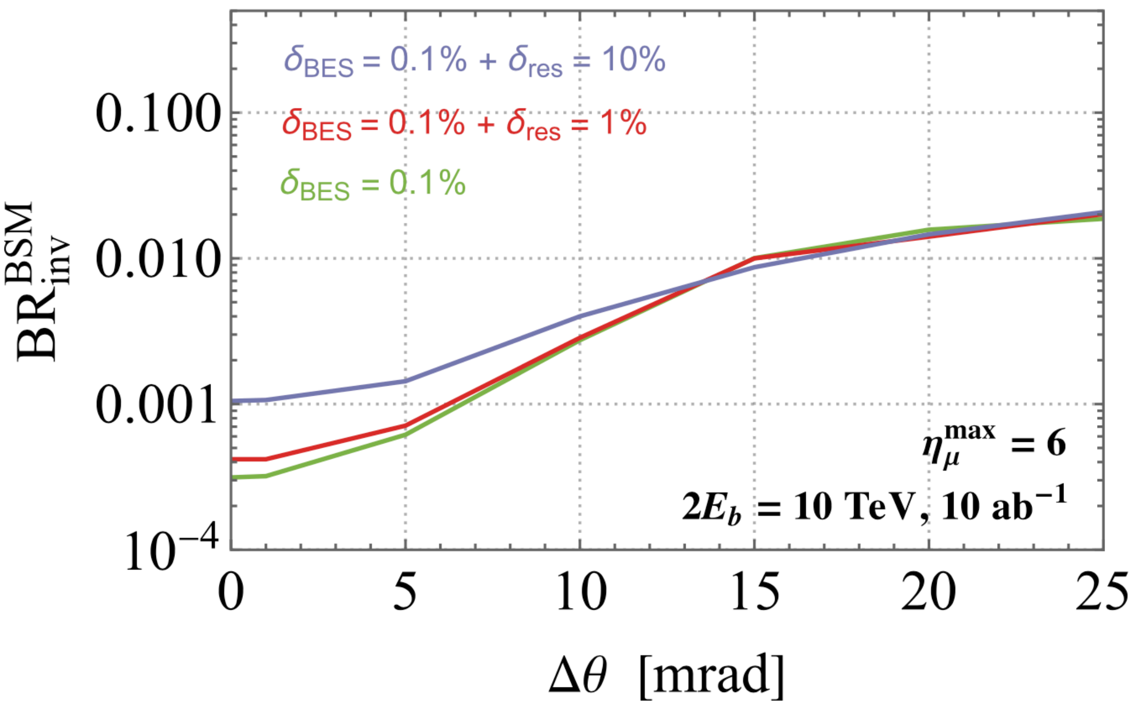


[Ruhdorfer, Salvioni, Wulzer 2303.14202]

Effect of finite angular resolution

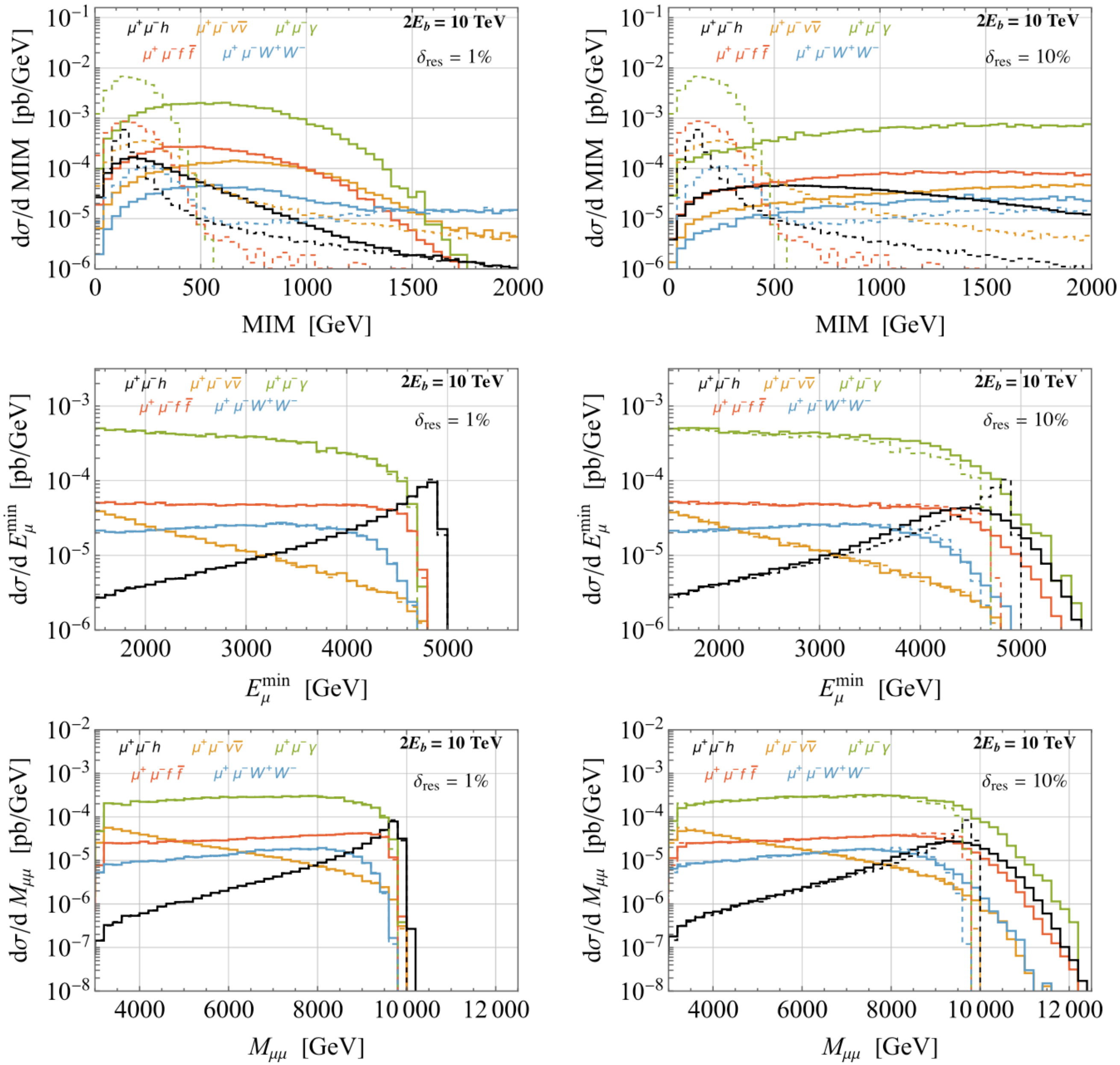
For fixed $\eta_{\max} = 6$:





As long as $\Delta\theta \lesssim 5\ \mathrm{mrad}$, no significant degradation of sensitivity

Distributions after BES + detector smearing



Cut flows

TABLE I. Cut flow for $2E_b = 10$ TeV and a forward detector coverage $\eta_\mu^{max} = 6$. An energy smearing of 1% is applied to muons with $|\eta_\mu| > 2.44$. The baseline cuts are listed in Sec. II.

[Number of events, 10 ab^{-1}]	BSM signal	$\mu^+\mu^-\bar{\nu}\nu$	$\mu^+\mu^-\gamma$	$\mu^+\mu^-\bar{f}f$	$\mu^+\mu^-W^+W^-$	$\mu^+\mu^-(h\to \text{inv})_{SM}$
Baseline & $P_\perp^{\mu\mu} > 50$ GeV	$6.2\times10^5 \times BR_{inv}^{BSM}$	1.1×10^6	1.3×10^7	1.3×10^6	6.2×10^5	7.4×10^2
MIM < 0.8 TeV	$5.6\times10^5 \times BR_{inv}^{BSM}$	6.3×10^5	1.0×10^7	9.4×10^5	1.8×10^5	6.7×10^2
$\lvert\Delta\eta_{\mu\mu}\rvert > 8$	$4.8\times10^5 \times BR_{inv}^{BSM}$	2.3×10^5	5.8×10^6	6.3×10^5	1.3×10^5	5.8×10^2
$\lvert\Delta\phi_{\mu\mu}-\pi\rvert > 0.8$	$3.9\times10^5 \times BR_{inv}^{BSM}$	1.7×10^5	2.2×10^6	4.9×10^5	8.5×10^4	4.6×10^2
$P_\perp^{\mu\mu} > 80$ GeV	$3.4\times10^5 \times BR_{inv}^{BSM}$	1.1×10^5	8.9×10^5	2.5×10^5	5.9×10^4	4.1×10^2
$M_{\mu\mu} > 9.5$ TeV	$1.6\times10^5 \times BR_{inv}^{BSM}$	1.4×10^3	1.5×10^3	3.1×10^2	28	1.9×10^2
$E_\mu^{min} > 4.7$ TeV	$1.1\times10^5 \times BR_{inv}^{BSM}$	6.2×10^2	(<65)	(<31)	(<7.0)	1.3×10^2

At exclusion $\mathrm{S/B} \approx 6\%$

TABLE II. Cut flow for $2E_b = 10$ TeV and a forward detector coverage $\eta_\mu^{max} = 6$. An energy smearing of 10% is applied to muons with $|\eta_\mu| > 2.44$. The baseline cuts are listed in Sec. II.

[Number of events, 10 ab^{-1}]	BSM signal	$\mu^+\mu^-\bar{\nu}\nu$	$\mu^+\mu^-\gamma$	$\mu^+\mu^-\bar{f}f$	$\mu^+\mu^-W^+W^-$	$\mu^+\mu^-(h\to \text{inv})_{SM}$
Baseline & $P_\perp^{\mu\mu} > 50$ GeV	$6.2\times10^5 \times BR_{inv}^{BSM}$	1.1×10^6	1.5×10^7	1.3×10^6	6.2×10^5	7.4×10^2
$\lvert\Delta\eta_{\mu\mu}\rvert > 6.5$	$6.1\times10^5 \times BR_{inv}^{BSM}$	7.6×10^5	1.3×10^7	1.1×10^6	5.5×10^5	7.3×10^2
$\lvert\Delta\phi_{\mu\mu}-\pi\rvert > 1$	$4.4\times10^5 \times BR_{inv}^{BSM}$	3.9×10^5	2.9×10^6	6.4×10^5	3.0×10^5	5.3×10^2
$P_\perp^{\mu\mu} > 180$ GeV	$1.9\times10^5 \times BR_{inv}^{BSM}$	1.1×10^5	2.7×10^5	8.2×10^4	7.0×10^4	2.2×10^2
$M_{\mu\mu} > 8.75$ TeV	$1.2\times10^5 \times BR_{inv}^{BSM}$	4.4×10^3	7.6×10^3	1.9×10^3	1.6×10^3	1.4×10^2
$E_\mu^{min} > 4.3$ TeV	$8.1\times10^4 \times BR_{inv}^{BSM}$	1.8×10^3	2.6×10^2	1.6×10^2	2.6×10^2	97

At exclusion $\mathrm{S/B} \approx 3\%$

Do not expect a strong impact from systematics