NEW PHYSICS
FROM TOP TO BOTTOM

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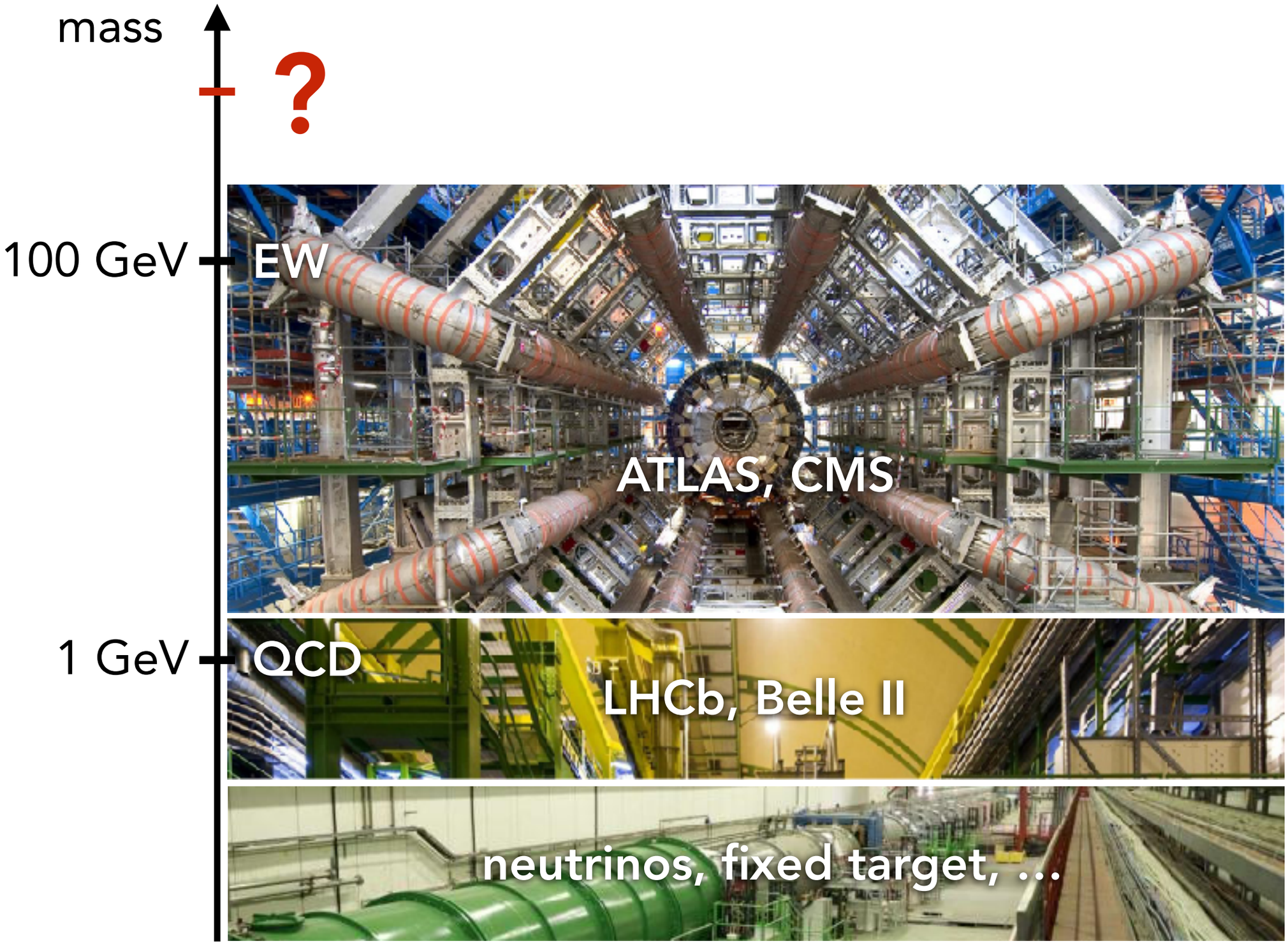
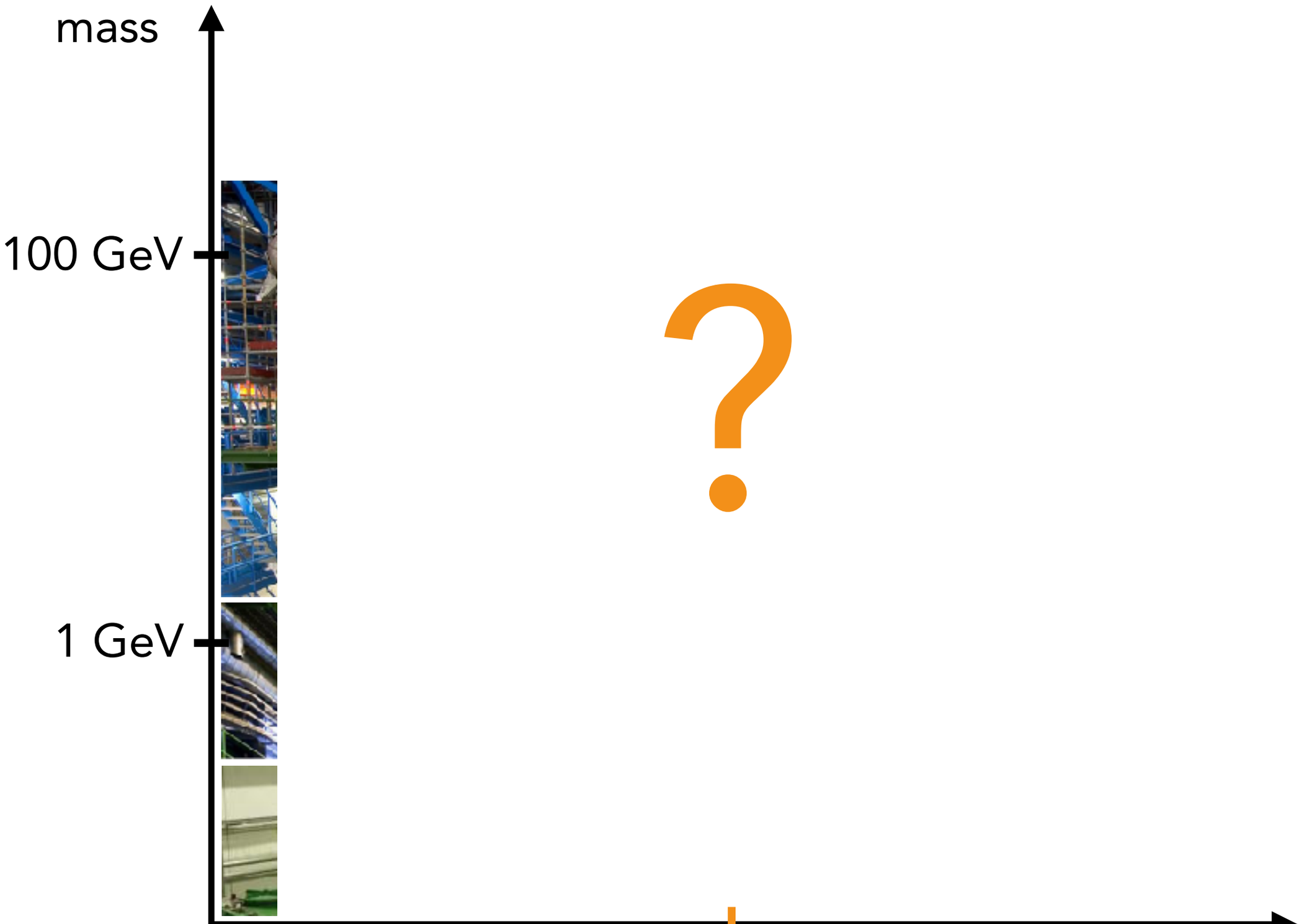
The next scale in particle physics



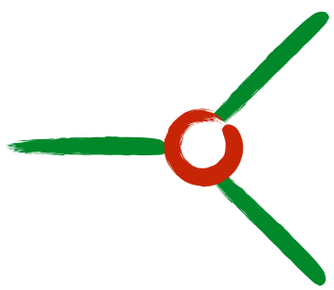
… could be a time scale.



Explore both directions.

Heavy and hidden

heavy new particles: mass suppression

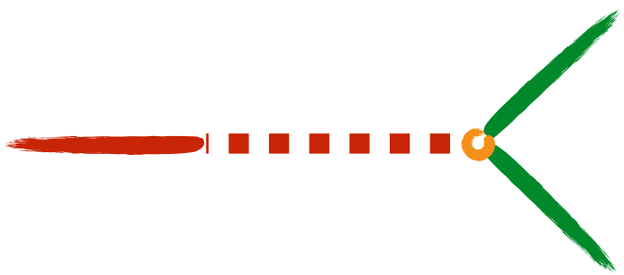


$$M \gg E$$

virtual effects

$$g_{\text{eff}} \sim \frac{E^2}{M^2}$$

hidden new particles: coupling suppression



$$\epsilon \ll 1$$

long lifetime

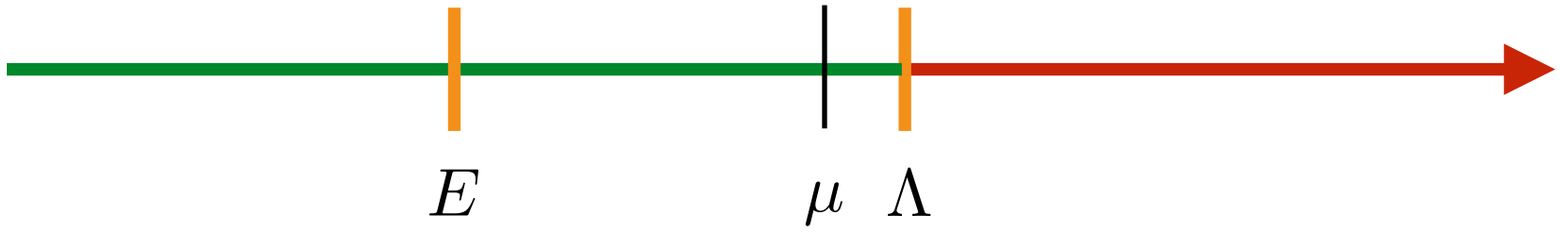
$$\tau = \frac{1}{\Gamma} \sim \frac{1}{\epsilon^2}$$

Heavy new physics

Effective Field Theory

approximation of full theory at experimentally relevant scales

- valid up to **cutoff scale** $\mu < \Lambda$

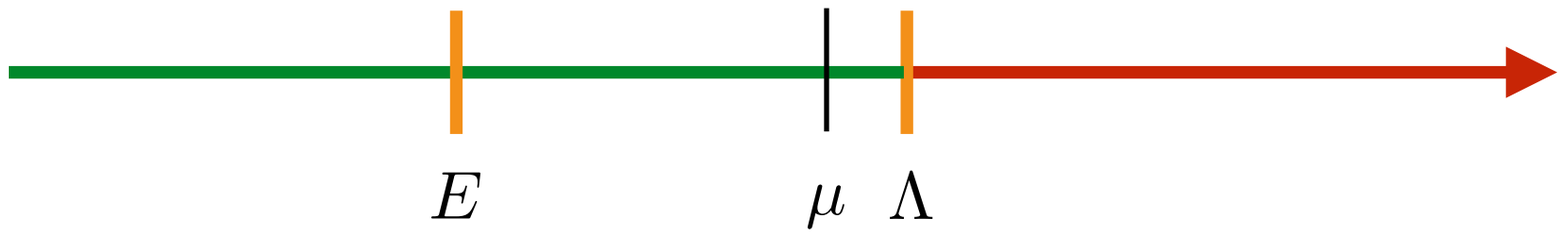


- action in full theory: $S(\phi) = S(\phi_{E<\mu}, \phi_{E>\mu})$

Effective Field Theory

approximation of full theory at experimentally relevant scales

- valid up to **cutoff scale** $\mu < \Lambda$



- action in full theory: $S(\phi) = S(\phi_{E<\mu}, \phi_{E>\mu})$

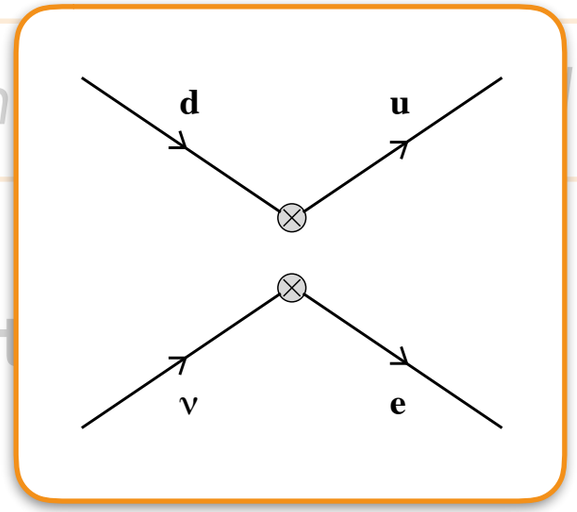
  remove high ‚frequencies': $S_\mu(\phi_{E<\mu}) = \int d^4x\, \mathcal{L}_{\text{eff}}(x)$

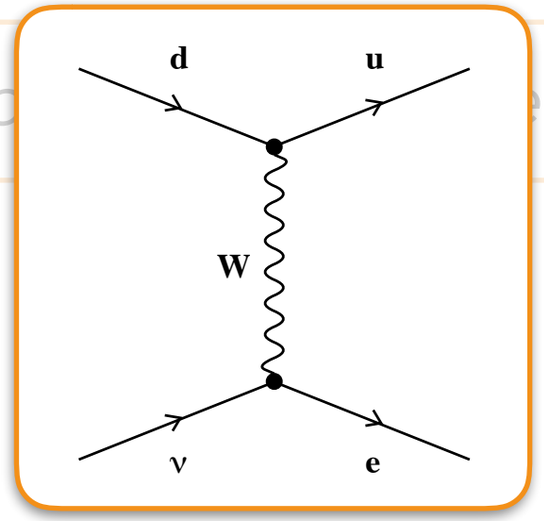
- **effective Lagrangian** $\mathcal{L}_{\text{eff}}(x) = \sum_i \frac{C_i}{\Lambda^{\gamma_i}} O_i(\phi_{E<\mu}(x))$

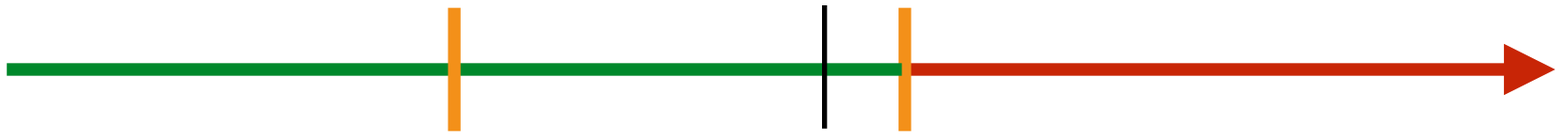
Fermi's theory of weak interactions

approximation … valid at exp … evant scales

- valid up to **cut**







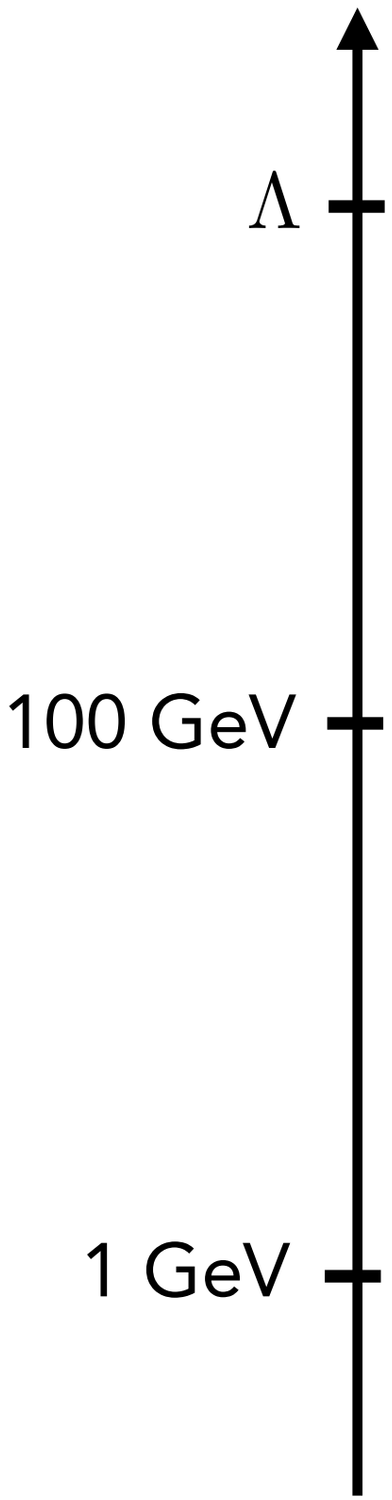
- action in full theory: $S(\phi) = S(\phi_{E<\mu}, \phi_{E>\mu})$

- remove high ,f…

$$\mathcal{L}_{\text{eff}} = -\frac{g^2}{2m_W^2} V_{ud} \left(\bar{u}_L \gamma^\mu d_L\right) \left(\bar{\mu}_L \gamma_\mu \nu_L\right)$$

- **effective Lagrangian** $\mathcal{L}_{\text{eff}}(x) = \sum_i \frac{C_i}{\Lambda^{\gamma_i}} O_i(\phi_{E<\mu}(x))$

Tower of effective theories



fundamental theory

$$\mathcal{L}_f = ???$$

standard model effective theory

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \dots$$

$\{q, t, \ell, g, \gamma, Z, W^\pm, h\}$

weak effective theory

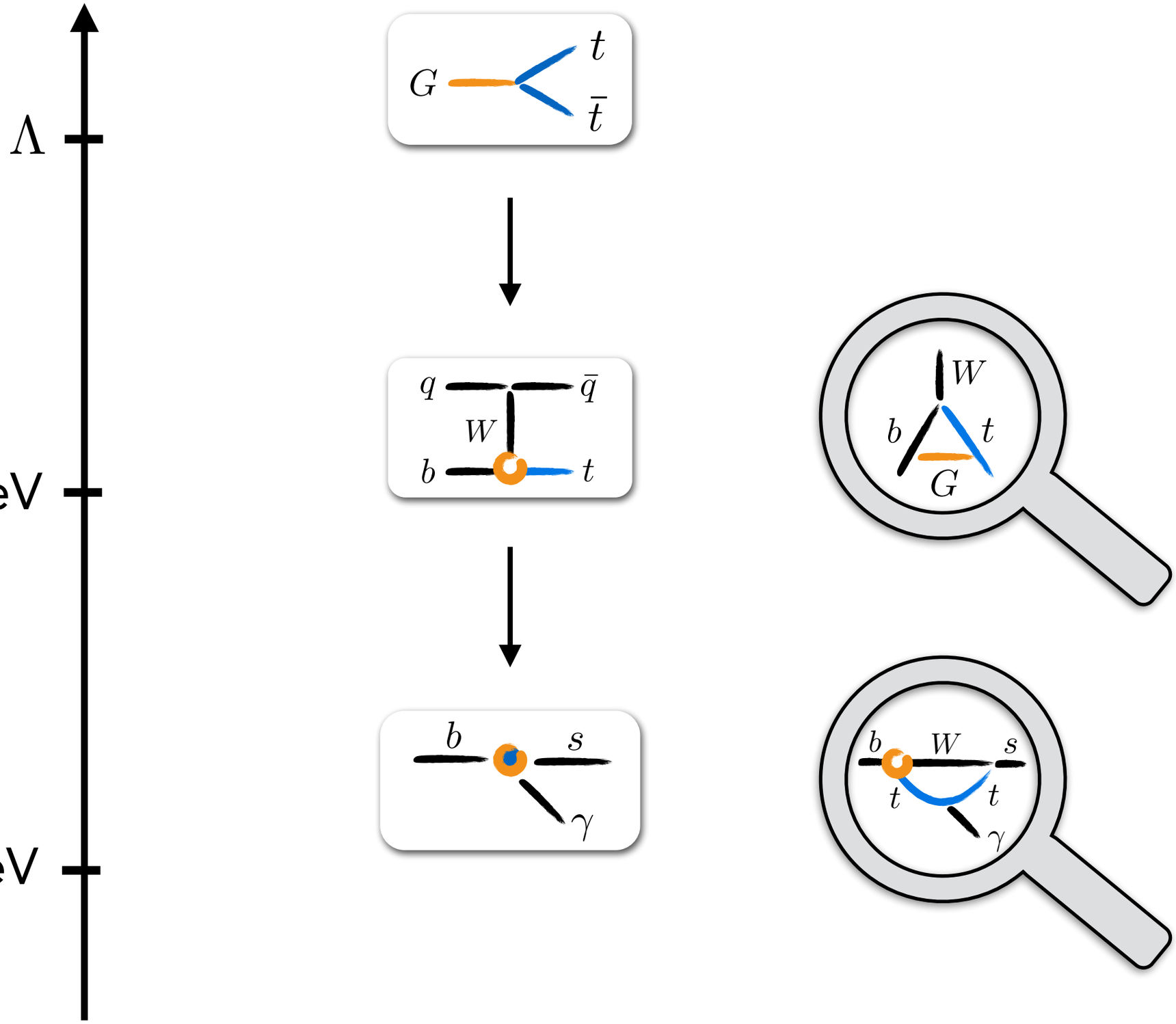
$$\mathcal{L}_{\rm WET} = \mathcal{L}_{\rm QCD+QED} + \sum_i \frac{\mathcal{C}_i}{\Lambda^2} \mathcal{O}_i + \dots$$

$\{q, \ell, g, \gamma\}$

chiral perturbation theory

$\{\pi, K\}$

Top quark: messenger between scales

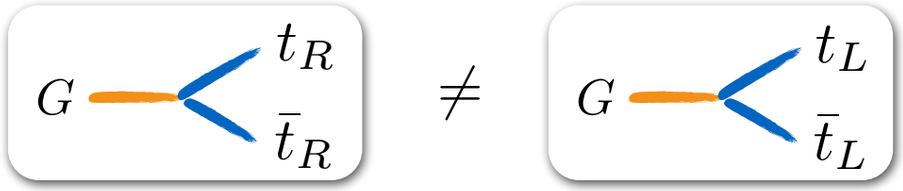


Virtual effects in top observables

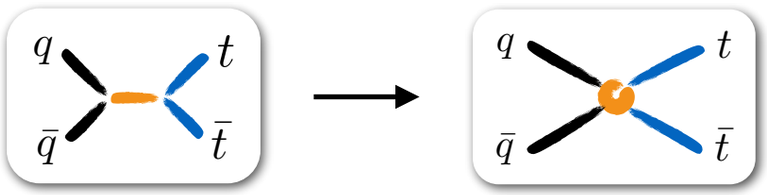
$$\sigma = \sigma_{\rm SM} + \sum_i C_i \left(\frac{E}{\Lambda}\right)^{\gamma_i} \sigma_i + \sum_{i,j} C_i C_j \left(\frac{E}{\Lambda}\right)^{\gamma_i+\gamma_j} \sigma_{ij}$$

Example: strongly coupling vector boson

- $\Lambda \sim M_G$:



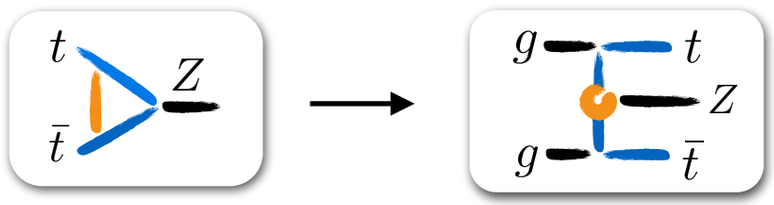
- $E \lesssim 1\,\text{TeV}$: $t\bar{t}$



$$O_{tq}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L)$$

$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L)$$

$t\bar{t}Z$



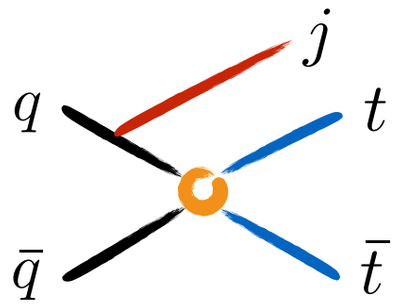
$$O_{\phi Q}^{1} = i(\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi)(\bar{Q}_L \gamma^\mu Q_L)$$

also: $t\bar{t}h$, Higgs, electroweak

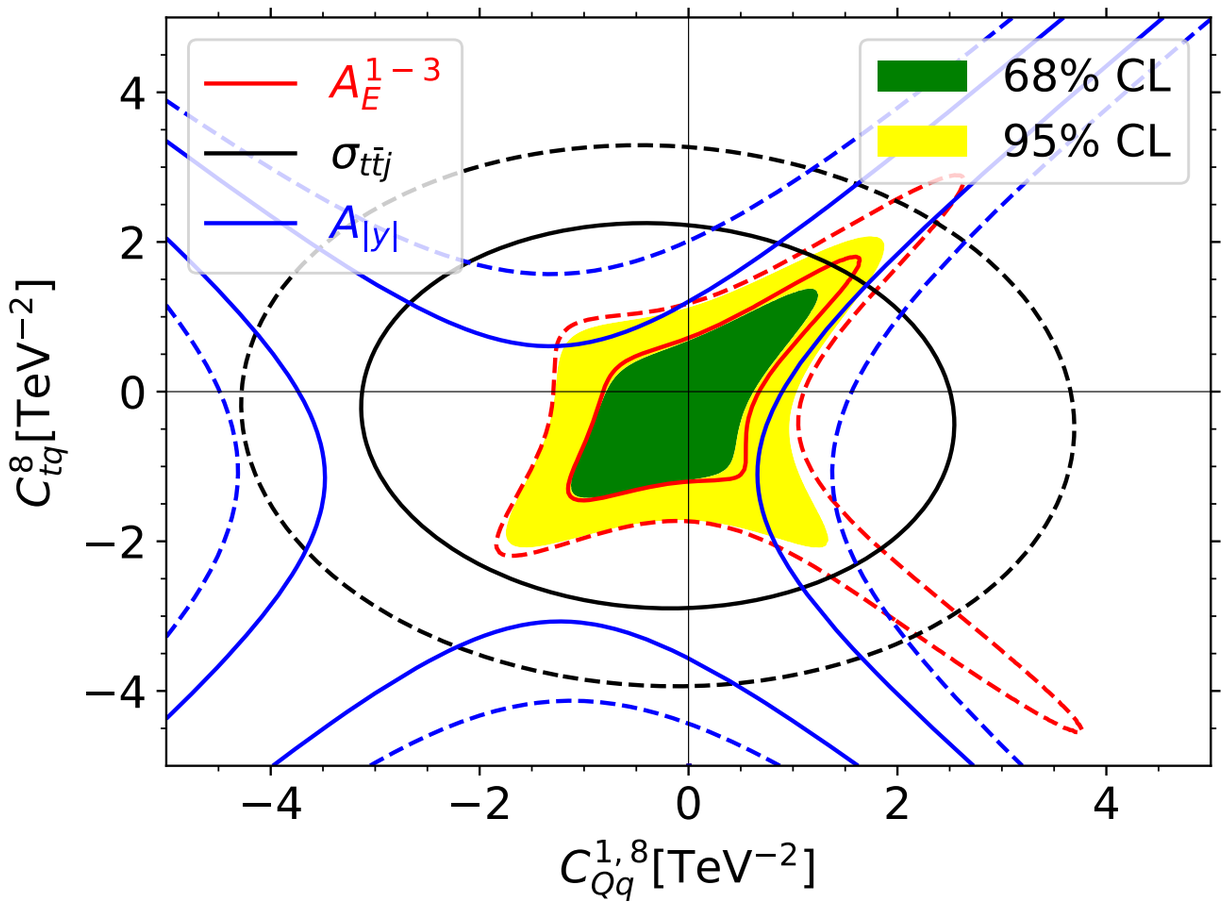
Resolving blind directions

$$O_{tq}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L) \sim RL$$

$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L) \sim LL$$



- Top-antitop asymmetries probe top chirality:



rapidity asymmetry $A_{|y|}\,(t\bar{t})$

$$A_{|y|} = \frac{\sigma_{t\bar{t}}(|\Delta y| > 0) - \sigma_{t\bar{t}}(|\Delta y| < 0)}{\sigma_{t\bar{t}}(|\Delta y| > 0) + \sigma_{t\bar{t}}(|\Delta y| < 0)}$$

energy asymmetry $A_E(t\bar{t}j)$

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\Delta E > 0) - \sigma_{t\bar{t}j}(\Delta E < 0)}{\sigma_{t\bar{t}j}(\Delta E > 0) + \sigma_{t\bar{t}j}(\Delta E < 0)}$$

Basan, Berta, Masetti, Vryonidou, Westhoff 2020

Resolving blind directions

$$O_{tq}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L) \sim RL$$

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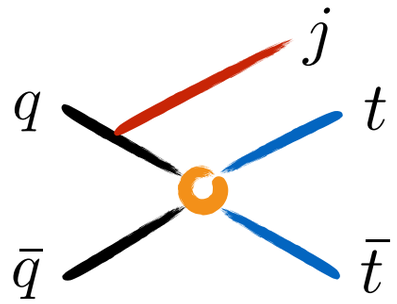
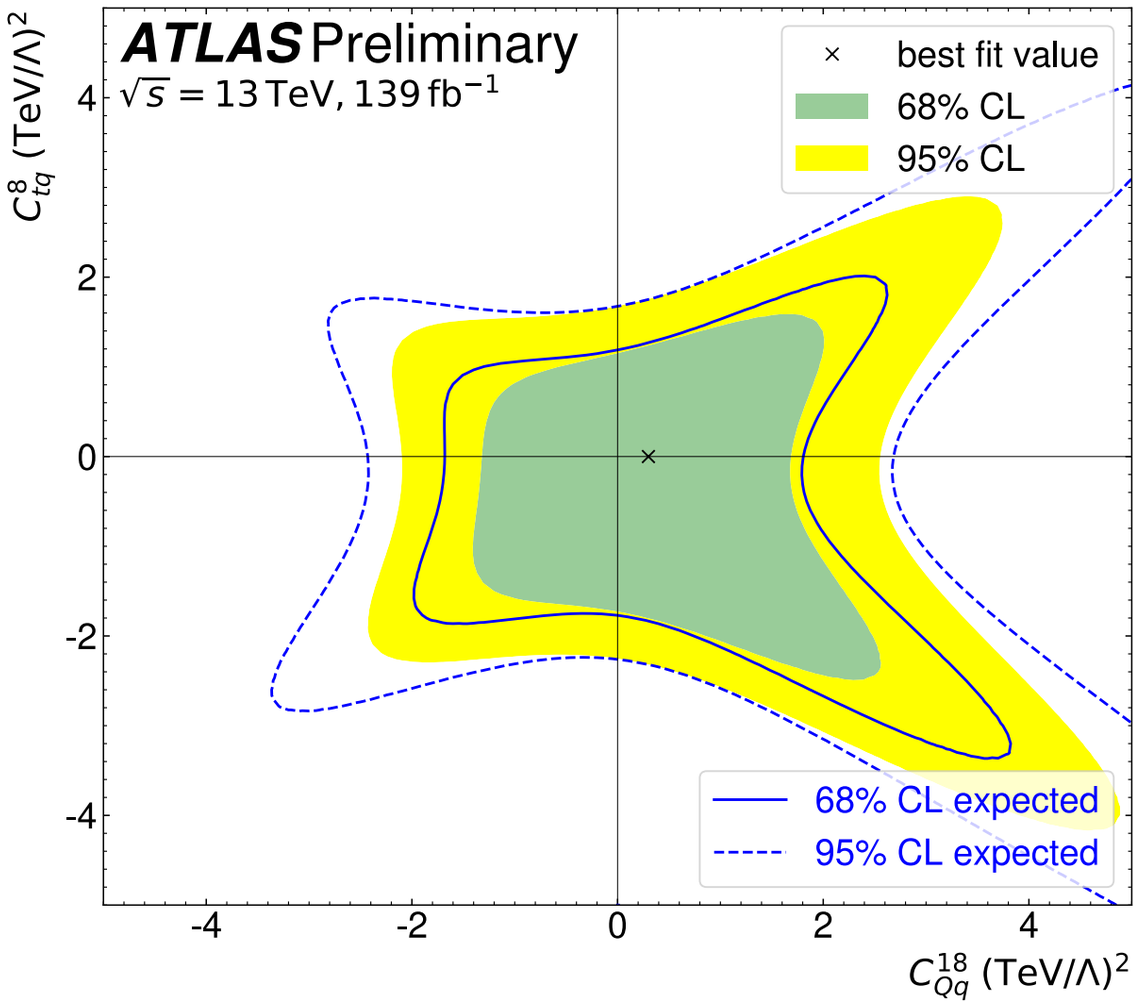


- Jet probes new directions in EFT space:



now measured:

energy asymmetry $A_E(t\bar{t}j)$

CERN-EP-2021-181

Basan, Berta, Masetti, Vryonidou, Westhoff 2020

Effective interactions near the cutoff

2-2 scattering amplitude (dim. 6): Hagiwara et al. 1987

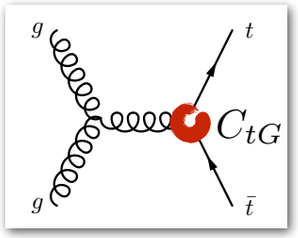
$$\mathcal{M} \sim \frac{v^m}{\Lambda^2} \frac{E^{2-m+n}}{m_V^n}$$

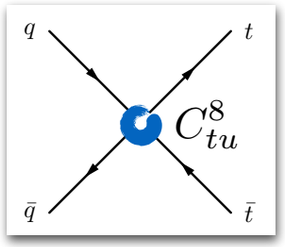
m vevs; *n* Goldstones

Maltoni, Mantani, Mimasu 1904.05637

- $O_{4f} = (\overline{f}\gamma_\mu f)(\overline{f}\gamma^\mu f) \quad \to \frac{E^2}{\Lambda^2}$ quadratic growth
- $O_{Hf} = (H^\dagger i D_\mu H)(\overline{f}\gamma^\mu f) \quad \to \frac{vE}{\Lambda^2}$ linear growth (longitudinal mode)
- $O_{fV} = (\overline{F}_L \sigma^{\mu\nu} f_R) H\, V_{\mu\nu} \quad \to \frac{m_f v}{\Lambda^2}$ helicity suppression (ffV)

Top-antitop production at high energies

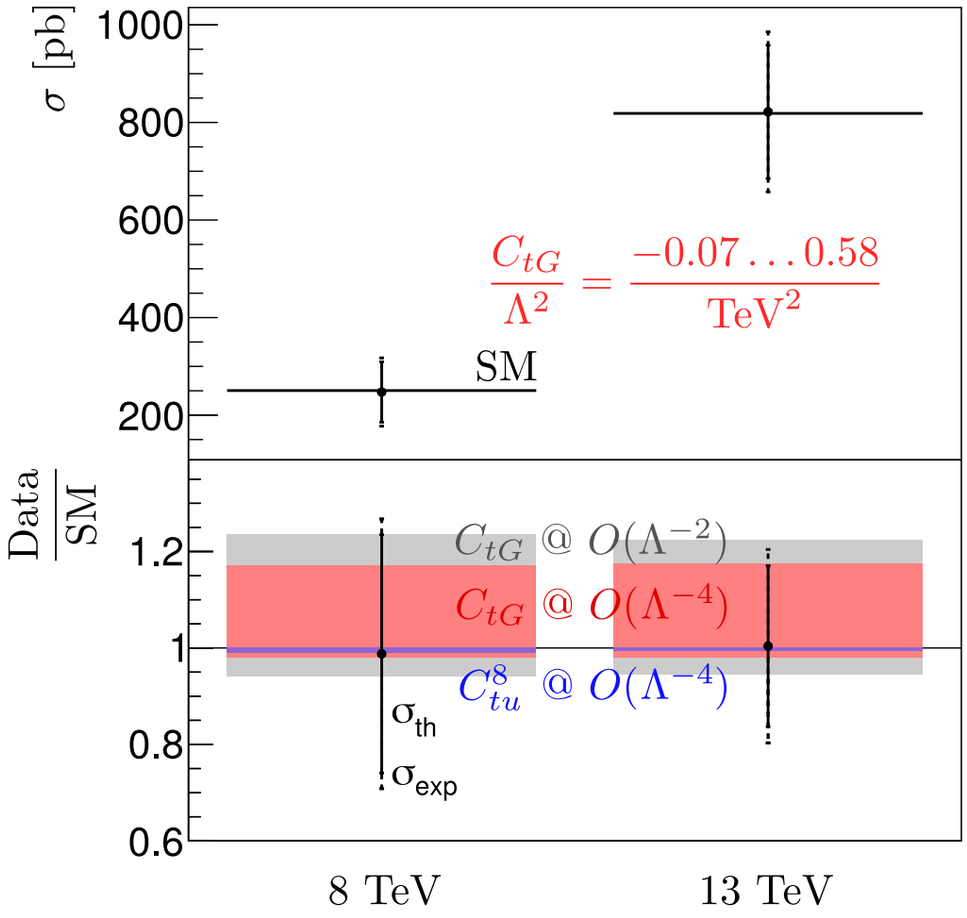


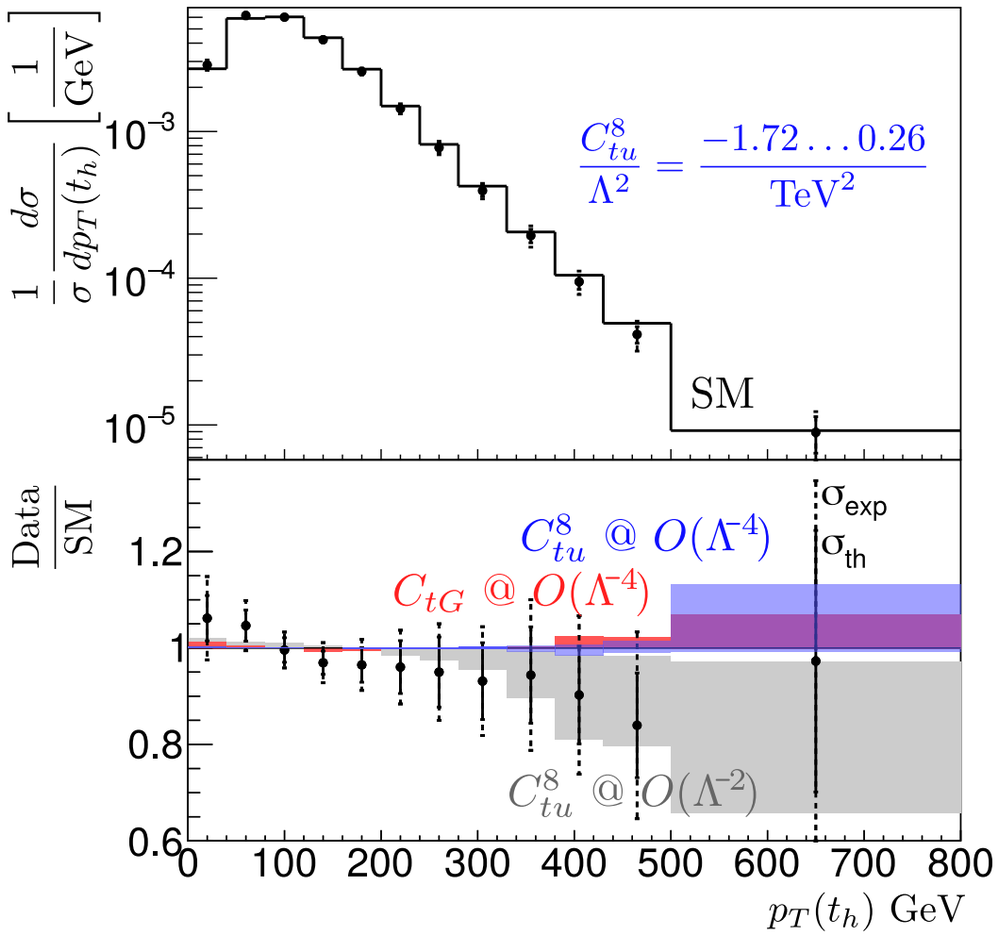


$$O_{tG} = (\overline{Q}_L \sigma^{\mu\nu} T^A t_R)\widetilde{H} G^A_{\mu\nu}$$

$$O^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

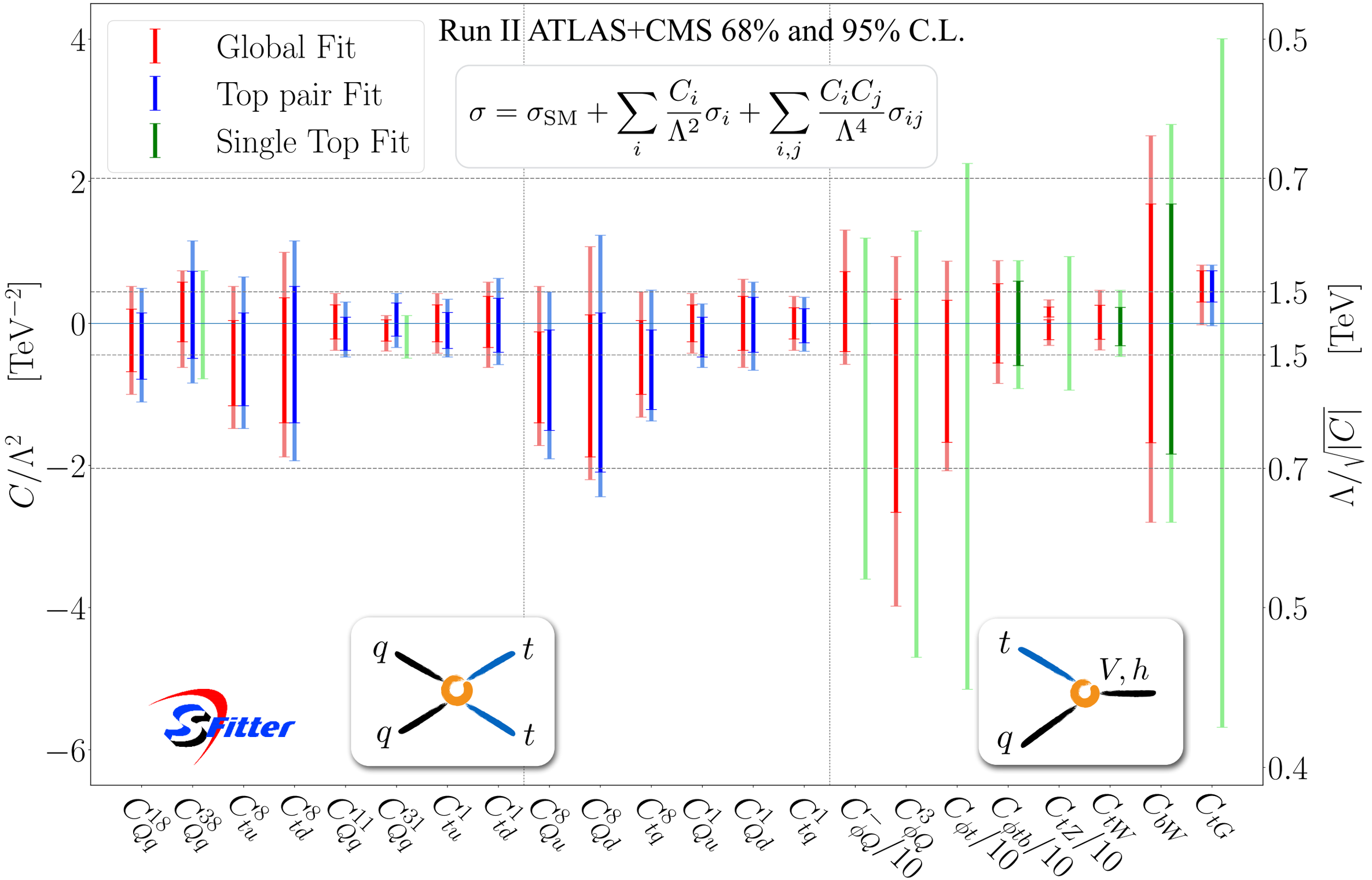
$$\sigma_{t\bar{t}}(s) \sim \sigma_{\rm SM}\left(1 + \frac{m_t v}{\Lambda^2} C_{tG} + \frac{s}{\Lambda^2} C^8_{tu} + \mathcal{O}\left(\frac{s^2}{\Lambda^4}\right) C_i C_j\right)$$





Brivio, Westhoff et al. 1910.03606; see also Englert et al. 1607.04304

Global analysis of top LHC data



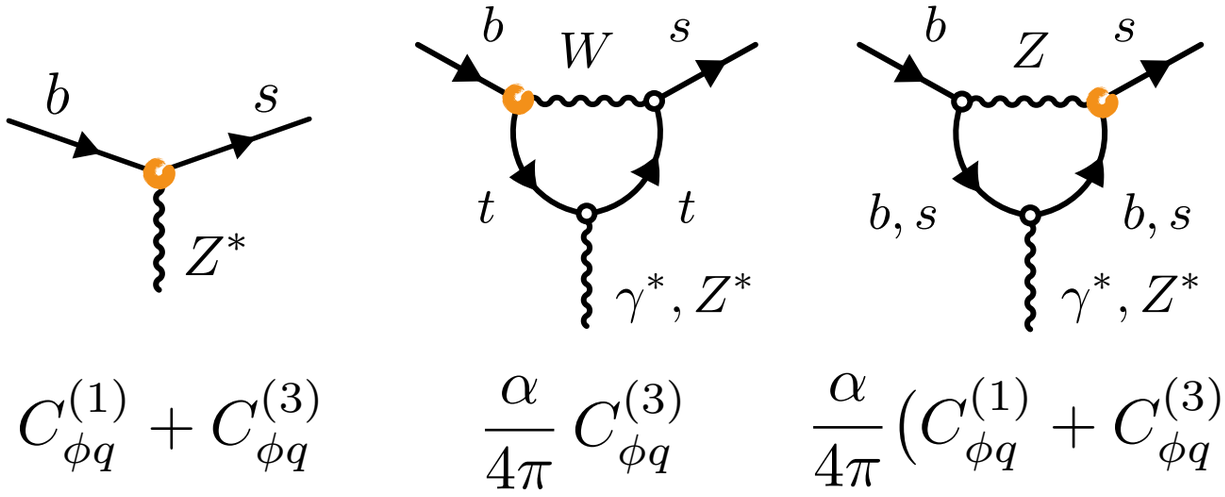
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606

Virtual effects in bottom observables

W and Z couplings:

$$O_{\phi q}^{(1)} = (H^\dagger \overleftrightarrow{iD^\mu} H)(\overline{Q}\gamma_\mu Q)$$

$$O_{\phi q}^{(3)} = (H^\dagger \overleftrightarrow{iD^\mu} \tau^a H)(\overline{Q}\gamma_\mu \tau^a Q)$$



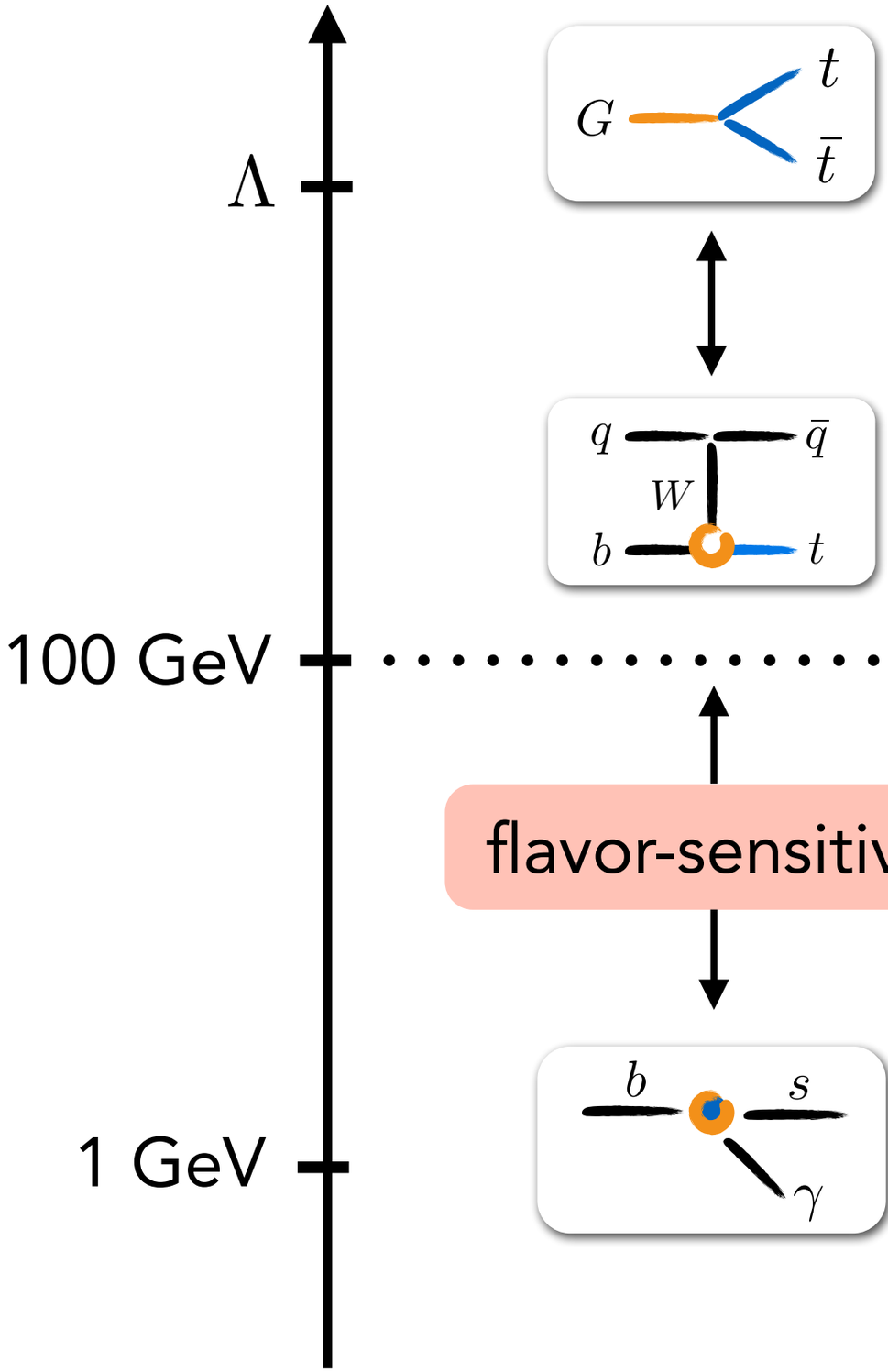
Flavor-breaking: $B \to X_s\gamma,\ B_s \to \mu^+\mu^-,\ B \to K^*\mu^+\mu^-$

kaon decays, meson mixing

Flavor-diagonal: $Z \to b\bar{b}$ (LEP)

electroweak observables (LHC)

The top-bottom connection



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \dots$$

$$\mathcal{C}_a(m_b) = F(C_i(m_t))$$

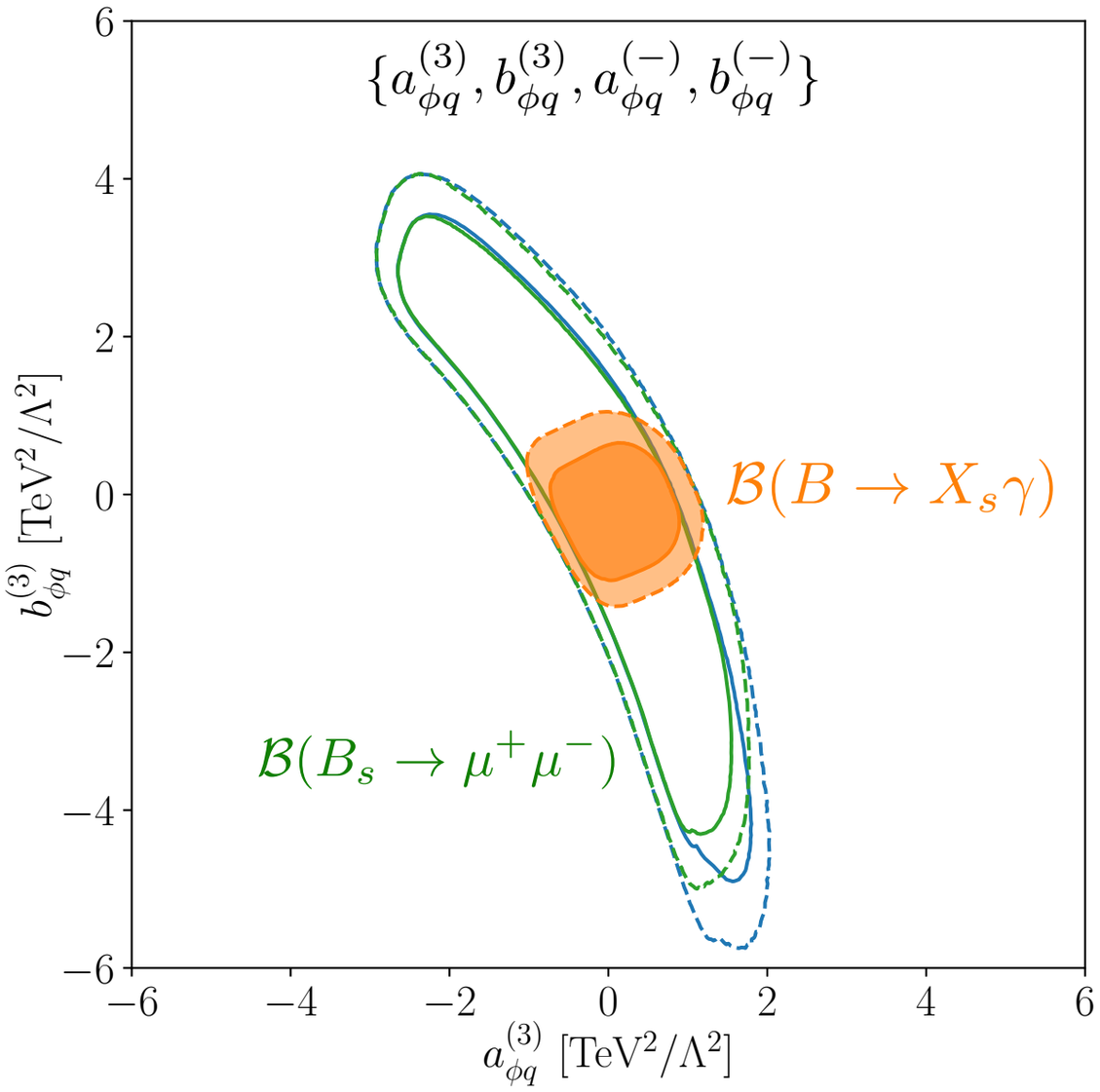
match & run

$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \sum_a \mathcal{C}_a \mathcal{O}_a + \dots$$

Aebischer et al. 2015 & 2017; Dekens et al. 2017 & 2019; Hurth et al. 2019

Flavor test in top and bottom observables

$$C_{\phi q}^{(i)} = a\,\mathbf{1} + b\,Y_U Y_U^\dagger + \ldots = \begin{pmatrix} a & & \\ & a & \\ & & a + b\,y_t^2 \end{pmatrix} + \ldots$$



top

$pp \to t\bar{t}$

$pp \to t\bar{t}Z, t\bar{t}W$

$pp \to tj, tZj$

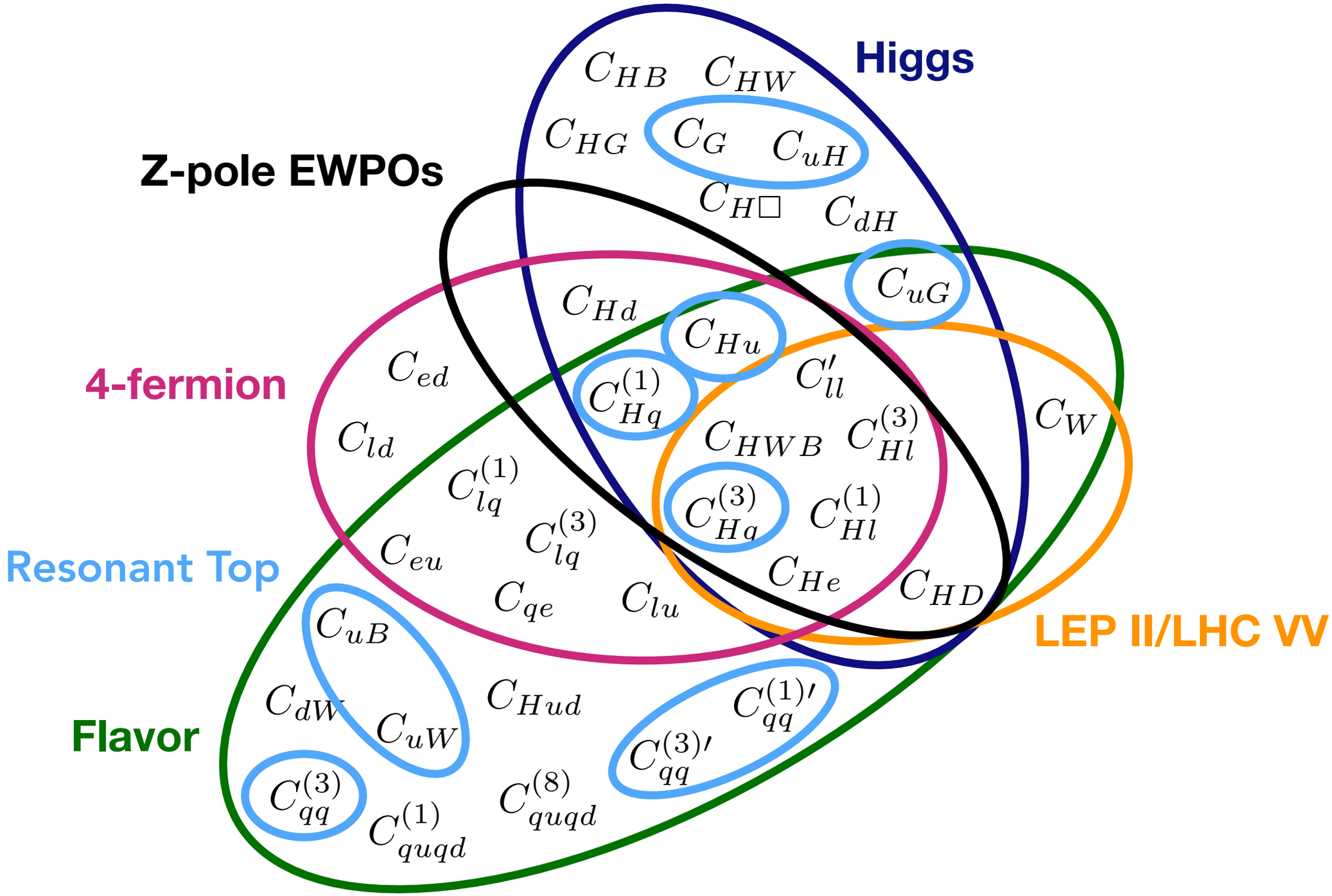
$pp \to tW$

$t \to bW$

$$O_{\phi q}^{(1)} = (H^\dagger i\overleftrightarrow{D^\mu} H)(\overline{Q}\gamma_\mu Q)$$
$$O_{\phi q}^{(3)} = (H^\dagger i\overleftrightarrow{D^\mu} \tau^a H)(\overline{Q}\gamma_\mu \tau^a Q)$$

Bruggisser, Schäfer, van Dyk, Westhoff 2101.07273

The SMEFT challenge



Top fits: Englert et al. 2016+, Hartland et al. 2019, Brivio et al. 2019, Ellis et al. 2020

Top & flavor fits: Bissmann et al. 2019+, Bruggisser et al. 2021 Tops in EWPOs: Dawson, Giardino 2019

Hidden new physics

Long-lived particles

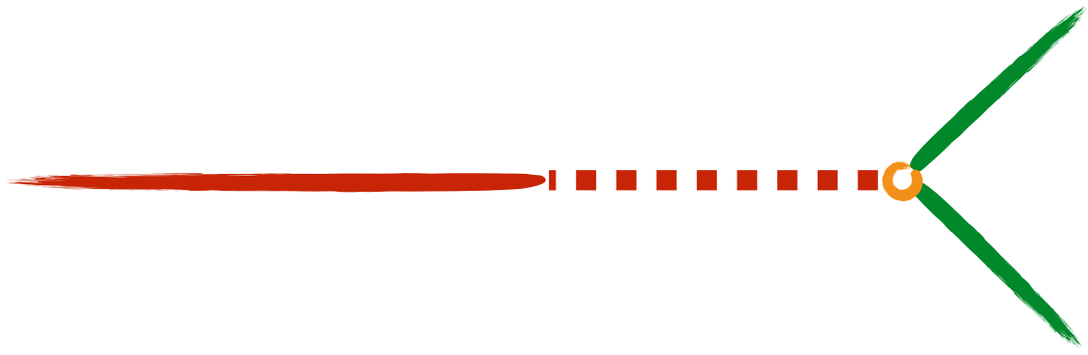
decay probability (lab): $P(t) = 1 - \exp\left(\frac{-t}{\gamma\tau}\right)$

decay length: $d = \beta\gamma c\tau$

Example: B meson $c\tau \sim 1\,\mathrm{mm}$

Belle II: $\gamma = \frac{5\,\mathrm{GeV}}{m_B} = 1,\ \beta \approx 0 \quad \longrightarrow \quad d \approx 0\,\mathrm{cm}$

LHC: $\gamma = \frac{500\,\mathrm{GeV}}{m_B} = 100,\ \beta \approx 1 \quad \longrightarrow \quad d \approx 10\,\mathrm{cm}$



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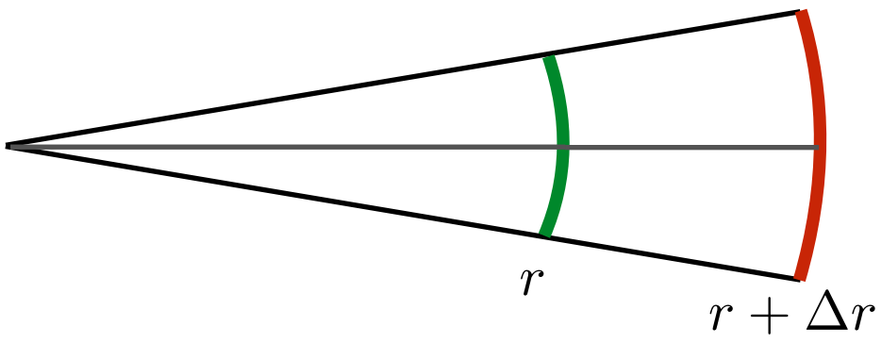
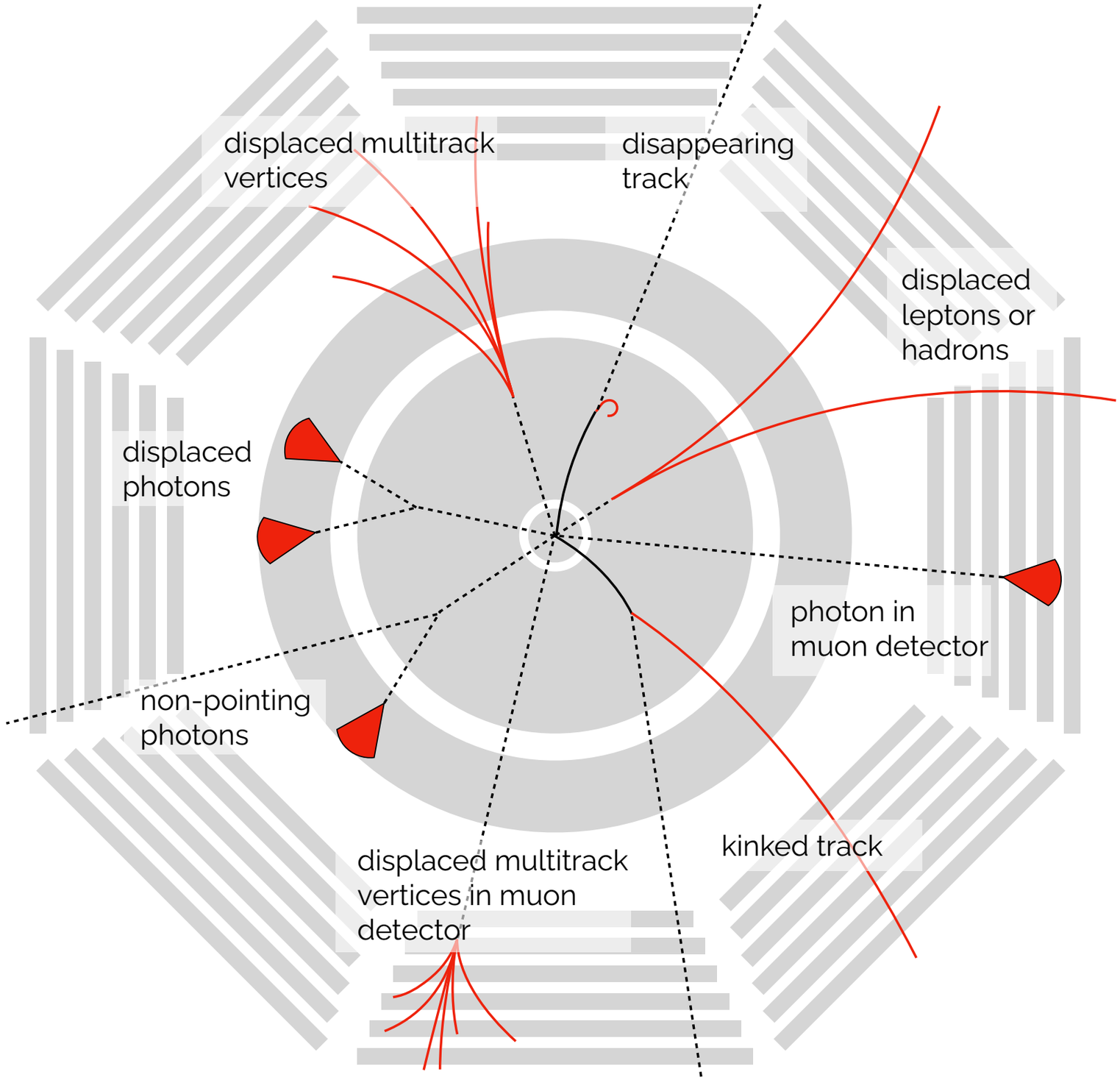
decays within detector volume:



$$N(\Delta V) = N_0 \frac{\Delta\Omega}{4\pi}\left[\exp\left(-\frac{r}{d}\right) - \exp\left(-\frac{r+\Delta r}{d}\right)\right]$$

Signatures at colliders

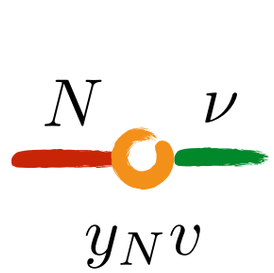


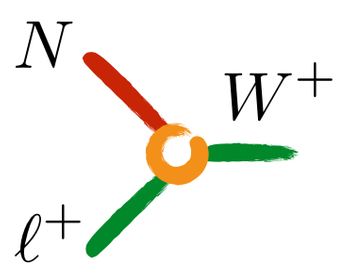
picture: Belle II, by Torben Ferber

Portals

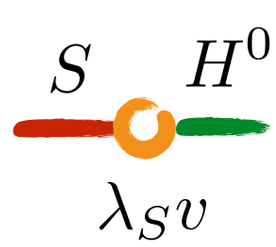
new interaction that leaves SM forces untouched

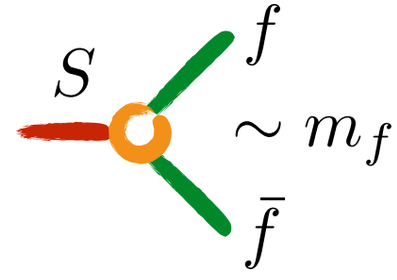
Neutrino portal: $\mathcal{L} = y_N(\overline{L}H)N + h.c.$



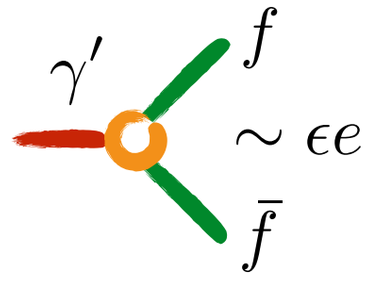


Higgs portal: $\mathcal{L} = \lambda_S(H^\dagger H)S$

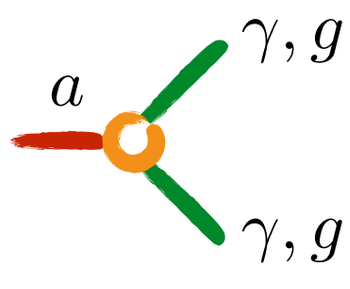


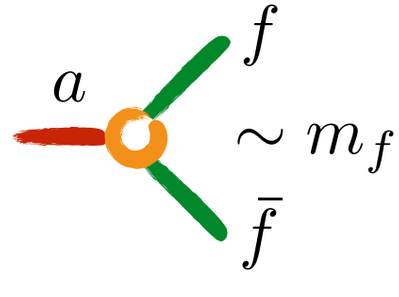


Vector portal: $\mathcal{L} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$

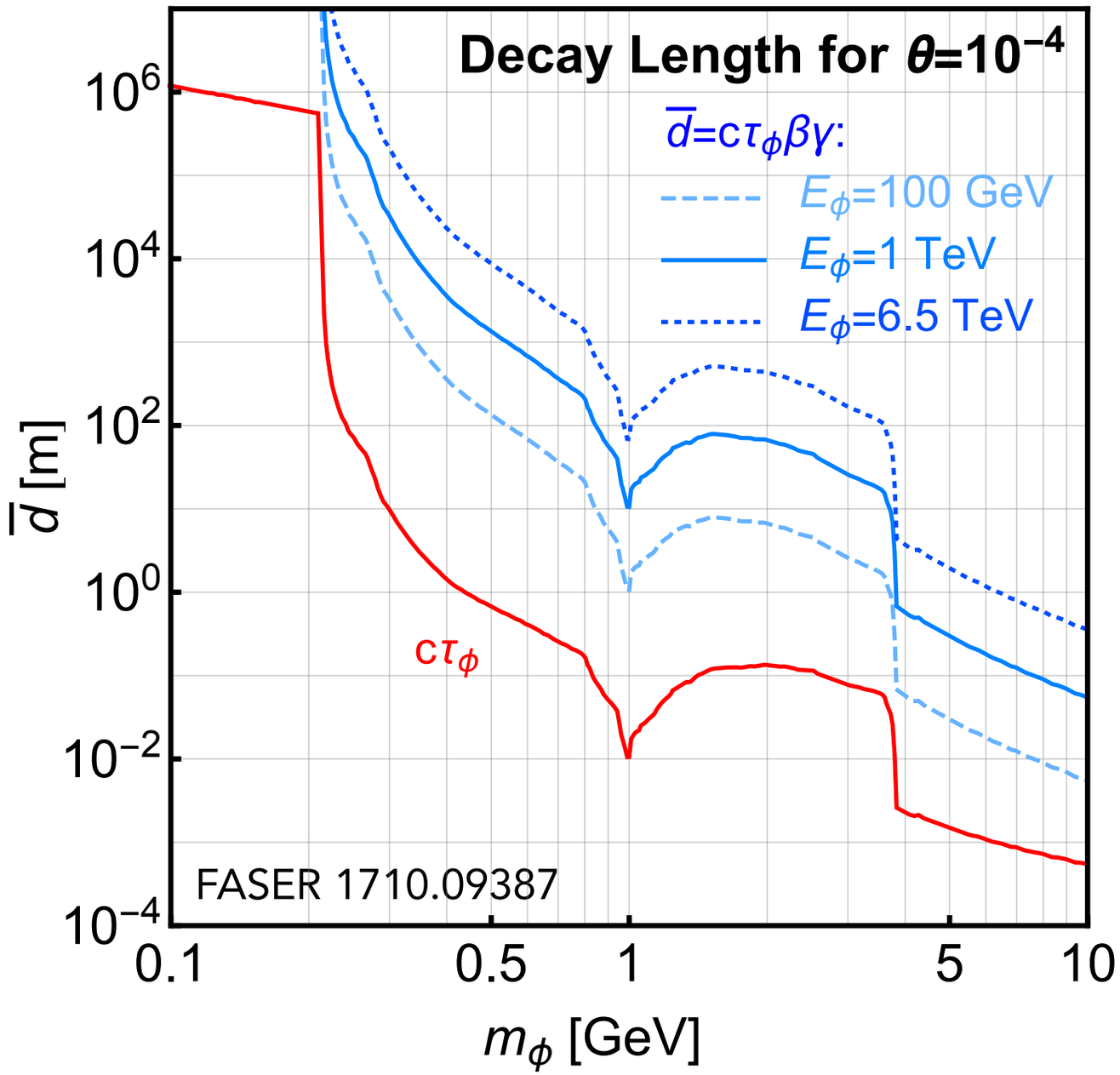


ALP: $\mathcal{L}_{\text{eff}} = c_V \frac{a}{\Lambda} V_{\mu\nu}\widetilde{V}^{\mu\nu} + c_f \frac{\partial_\mu a}{\Lambda}(\bar{f}\gamma^\mu\gamma_5 f)$





Long-lived scalars * similar for ALPs



$$\mathcal{L} = \lambda_S (H^\dagger H) S$$

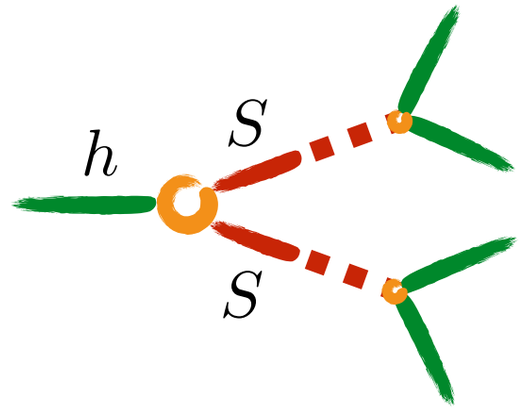
Higgs mixing: $\theta \sim \lambda_S$

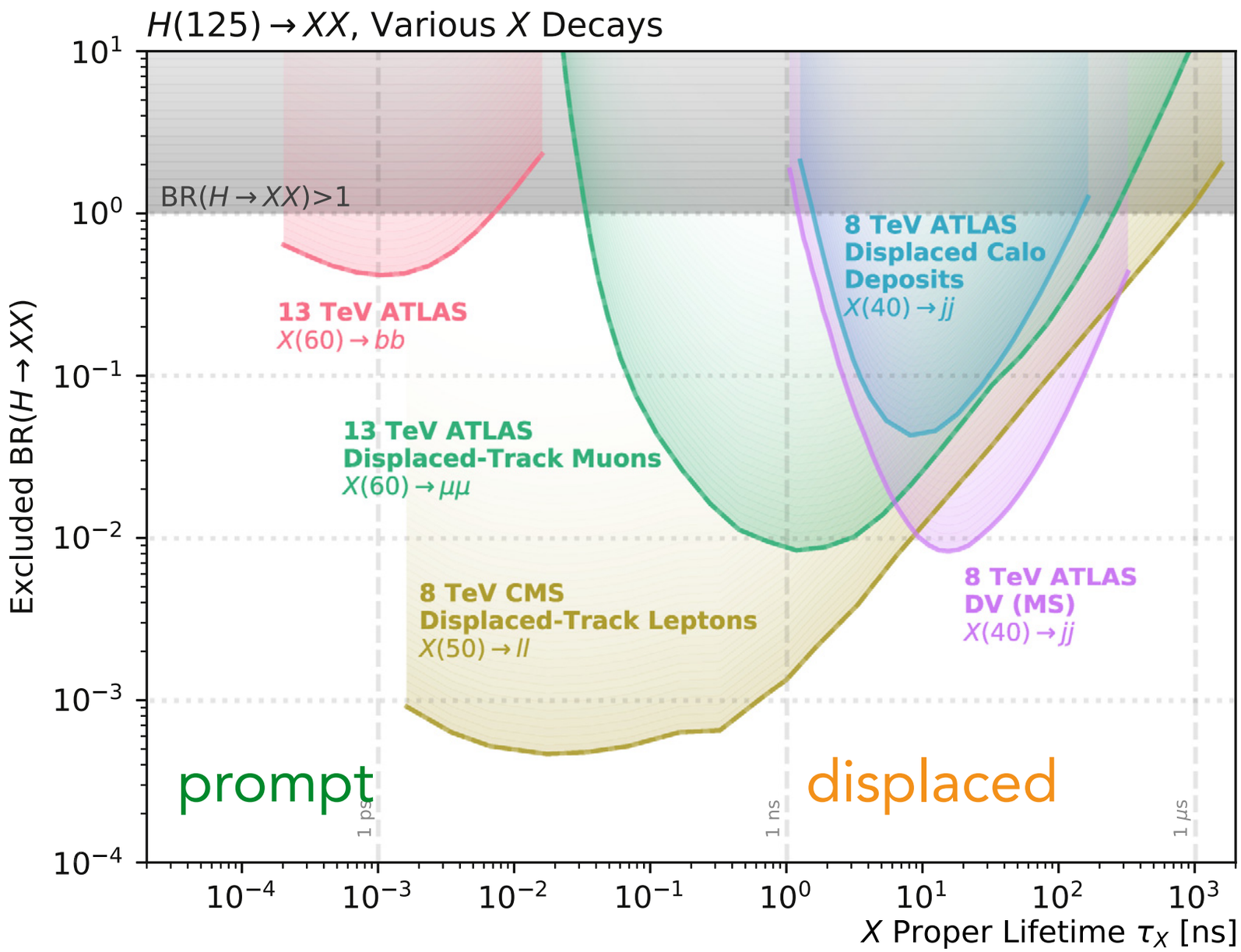
$$c\tau_S = \frac{c}{\Gamma_S} \sim \frac{1}{\theta^2} \frac{v^2}{m_f^2} \frac{1}{m_S}$$

invisible displaced prompt

Probing the portals: LHC

- Higgs portal: $\mathcal{L} = \lambda_S (H^\dagger H) S + \lambda'_S (H^\dagger H) S S$

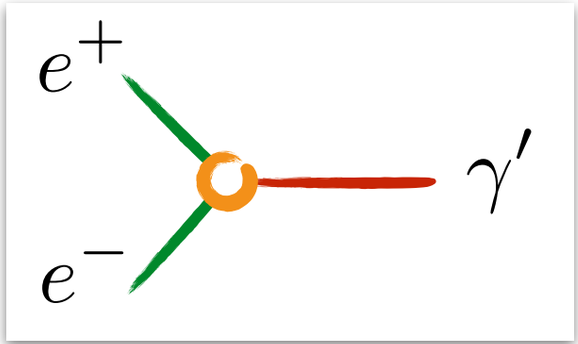




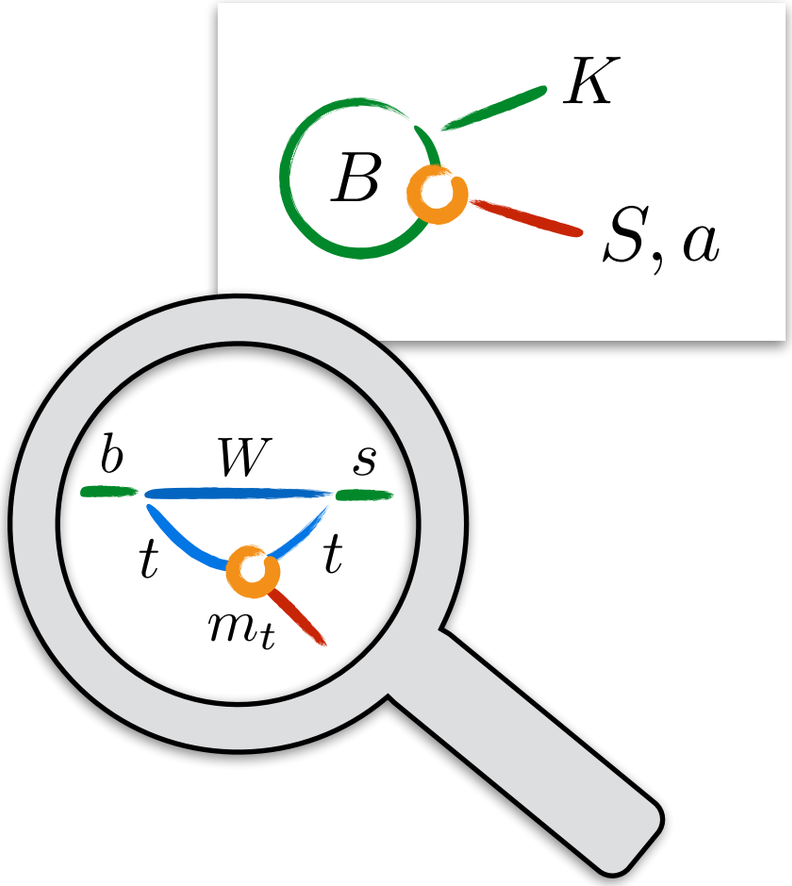
Lee et al. 1810.12602

Probing the portals: Belle II

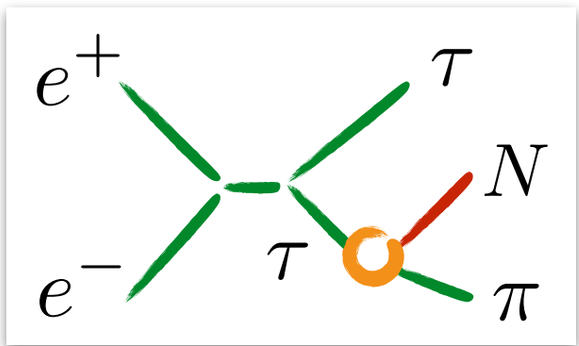
vector portal



Higgs portal, ALP



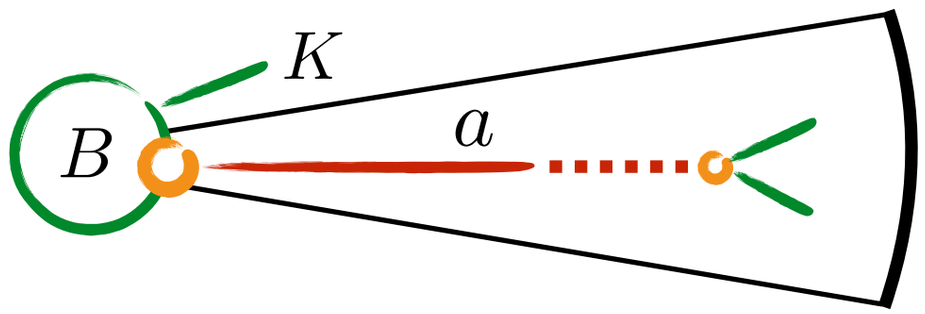
neutrino portal



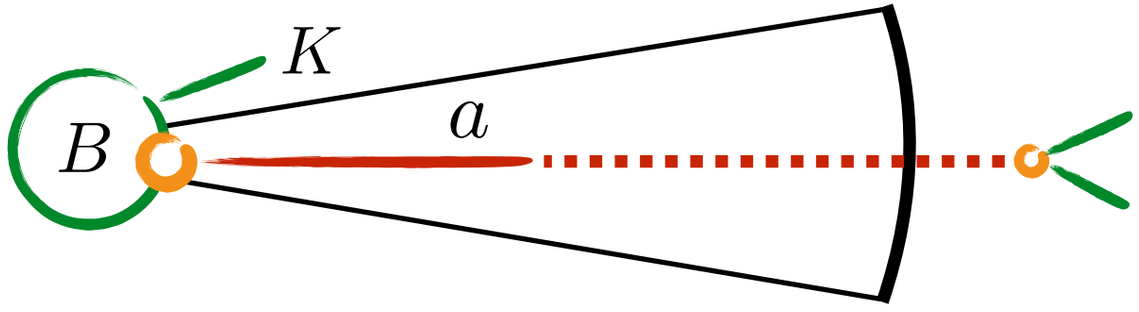
Displaced or invisible?

- ALPs from B decays: $\mathcal{L}_{\text{eff}} = \frac{c_{ff}}{2} \frac{\partial_\mu a}{4\pi\Lambda} (\bar{f}\gamma^\mu\gamma_5 f)$

displaced:

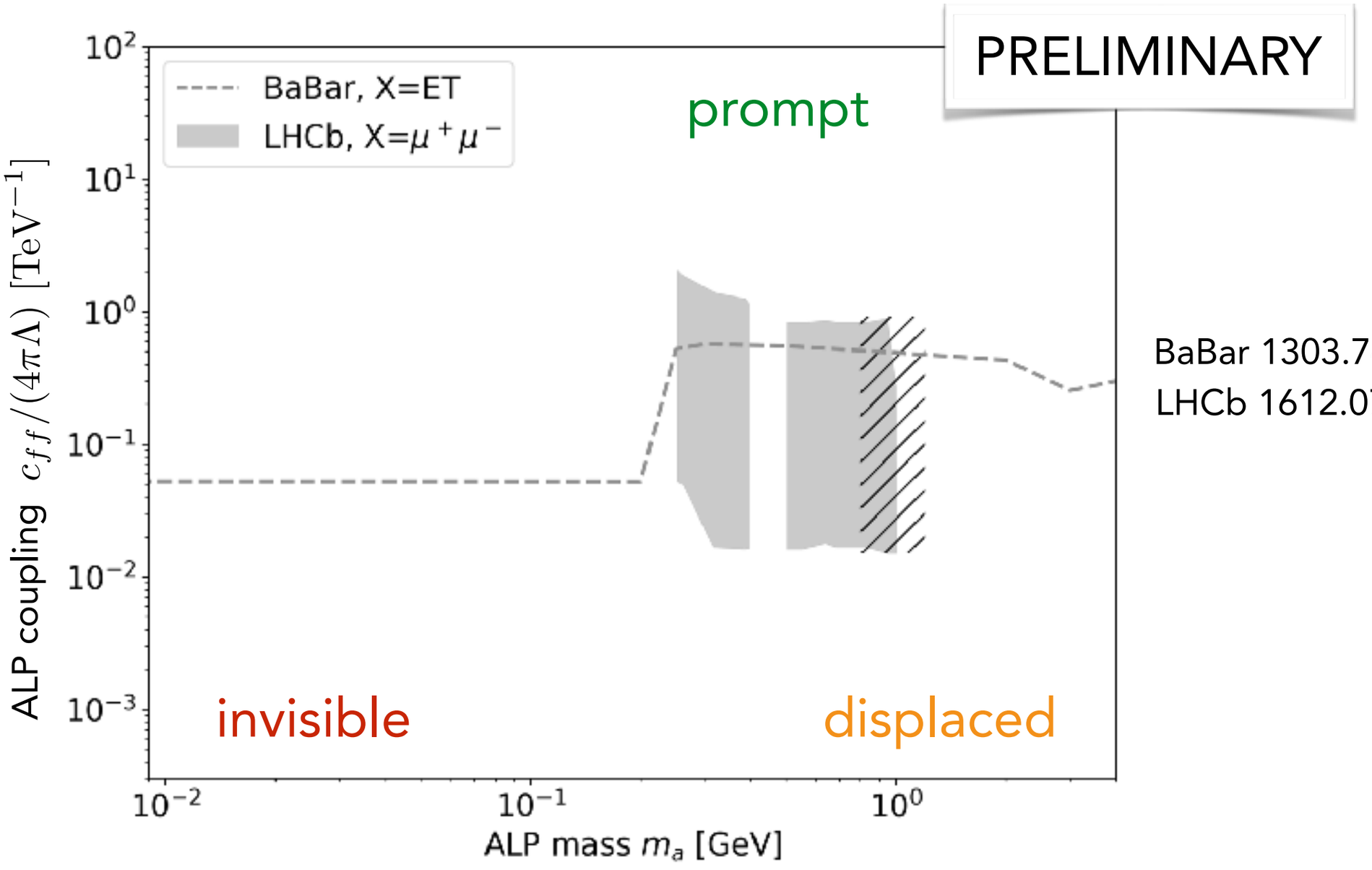


invisible:



Displaced or invisible: bounds

- ALPs from B decays: $\mathcal{L}_{\text{eff}} = \frac{c_{ff}}{2} \frac{\partial_\mu a}{4\pi\Lambda} (\bar{f}\gamma^\mu\gamma_5 f)$

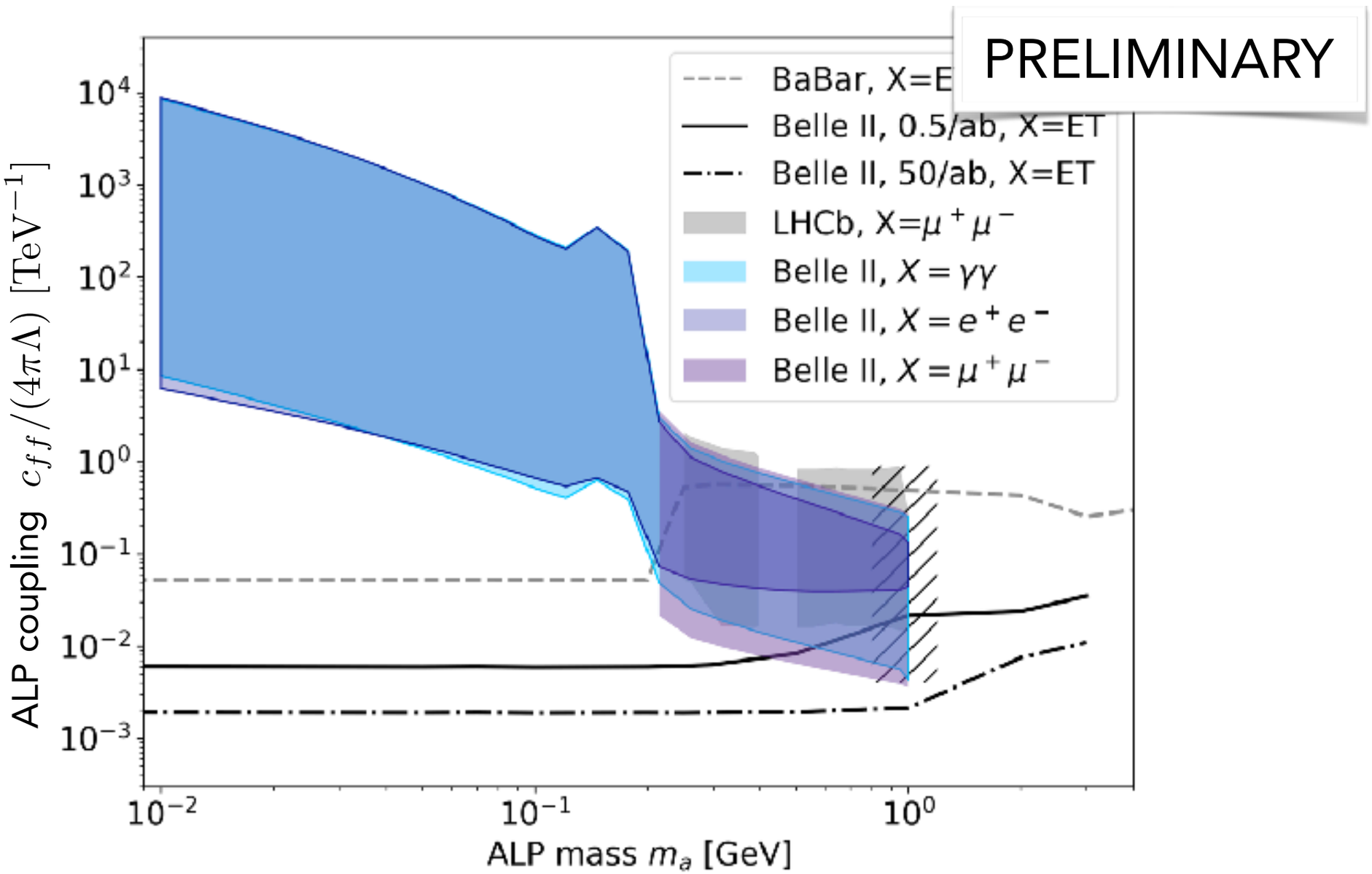


BaBar 1303.7465
LHCb 1612.07818

Ferber, Filimonova, Schaefer, Westhoff - in preparation

Displaced or invisible: prospects

- ALPs from B decays: $\mathcal{L}_{\text{eff}} = \frac{c_{ff}}{2} \frac{\partial_\mu a}{4\pi\Lambda} (\bar{f}\gamma^\mu\gamma_5 f)$



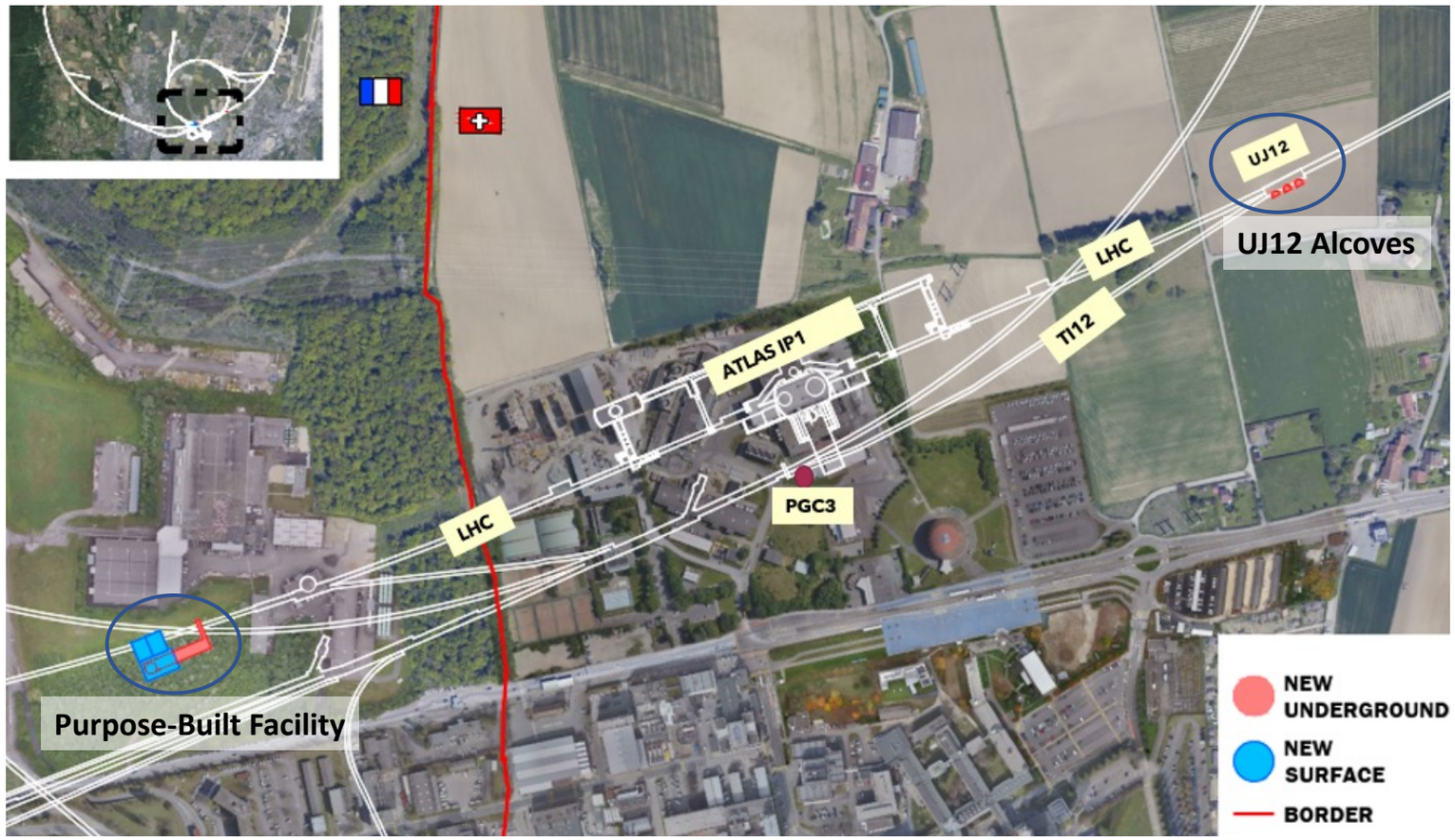
Ferber, Filimonova, Schaefer, Westhoff - in preparation

Probing long lifetimes: far detectors

- LHC: FASER (prototype in place)

Anchordoqui et al. 2109.10905

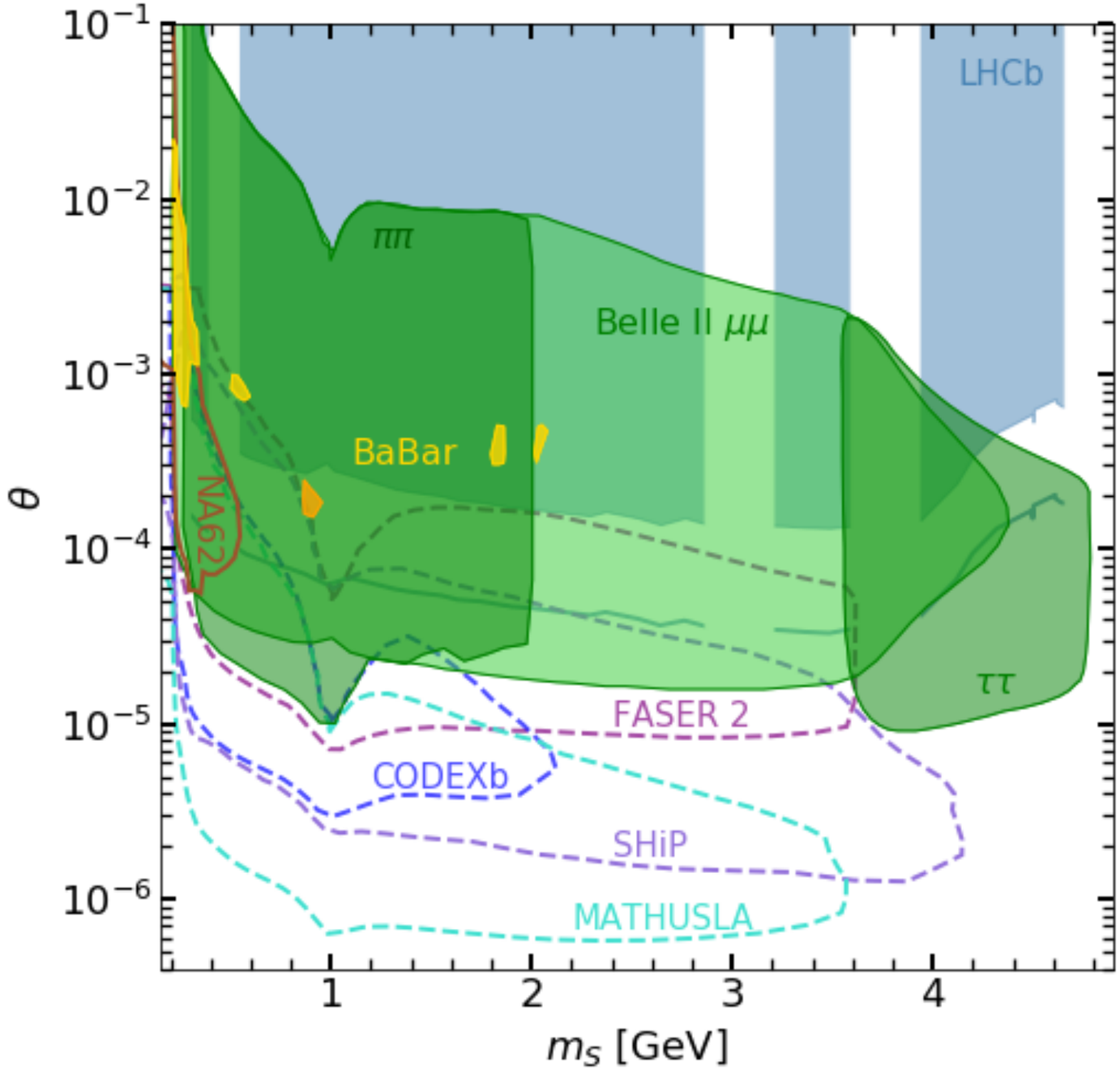
also: Codex-B, MATHUSLA, Anubis



- Belle II: GAZELLE (Proposal) Dreyer et al. 2105.12962
- fixed target: NA62 $K \to \pi + \text{inv}$ NA62 coll. 2011.11329

Near and Far

- Higgs portal: displaced vertex searches



Filimonova, Schaefer, Westhoff 1911.03490; Kachanovich, Nierste, Nisandzic 2003.01788

Summary

Heavy new physics

- search for: virtual effects in precision observables
- effective field theory: connect effects at high and low energies
- global analysis: resolve structure of possible UV theories

Hidden new physics

- search for: displaced objects from long-lived particle decays
- portals: probe even tiny couplings through lifetime
- near and far detectors: invisible versus displaced decays

Thank you!

BACKUP

Operator matching and running

Matching condition:

$$\langle f|\mathcal{L}_{\rm UV}|i\rangle \stackrel{!}{=} \sum_i \frac{C_i(\mu)}{\Lambda^{\gamma_i}} \langle f|O_i(\mu)|i\rangle$$

- cutoff dependence: $C(\mu) = C_0 + \frac{\alpha_s(\mu)}{4\pi} C_1 \left[\ln\left(\frac{\Lambda^2}{\mu^2}\right) + \text{finite}\right] + \mathcal{O}(\alpha_s^2 \ln^2)$

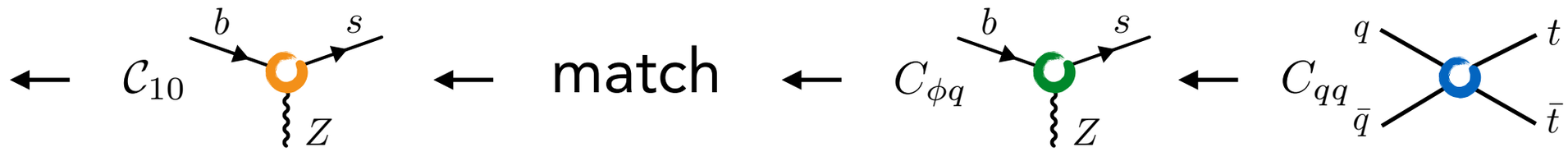
- **factorization** of low- and high-energy parts:

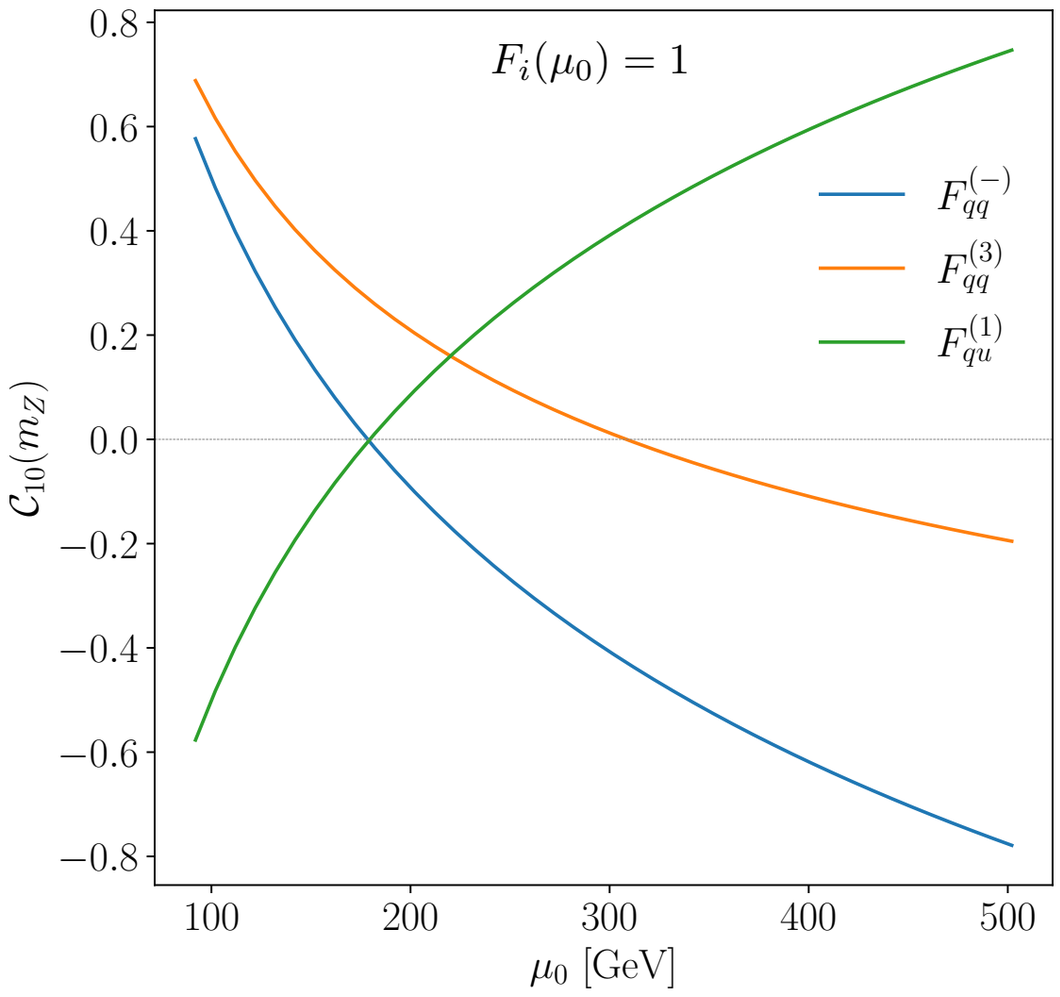
$$1 + \frac{\alpha_s(\mu)}{4\pi} \ln\left(\frac{\Lambda^2}{-p^2}\right) = \left[1 + \frac{\alpha_s(\mu)}{4\pi} \ln\left(\frac{\Lambda^2}{\mu^2}\right)\right] \left[1 + \frac{\alpha_s(\mu)}{4\pi} \ln\left(\frac{\mu^2}{-p^2}\right)\right]$$

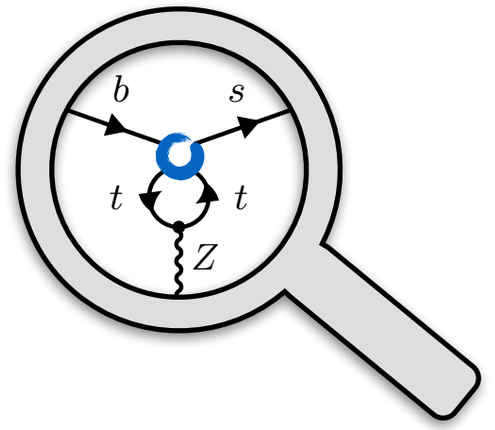
- **running**: RGE of $C(\mu) \to C(E < \mu)$ - resummation of $\alpha_s^n \ln^n$

Operator mixing in SMEFT

$$\mathcal{C}_a(m_b) = \left(\mathcal{R}^{\mathrm{WET}}(m_b, m_Z)\right)_{ab} \left(\mathcal{M}(m_Z)\right)_{bc} \left(\mathcal{R}^{\mathrm{SMEFT}}(m_Z, m_t)\right)_{cd} C_d(m_t)$$





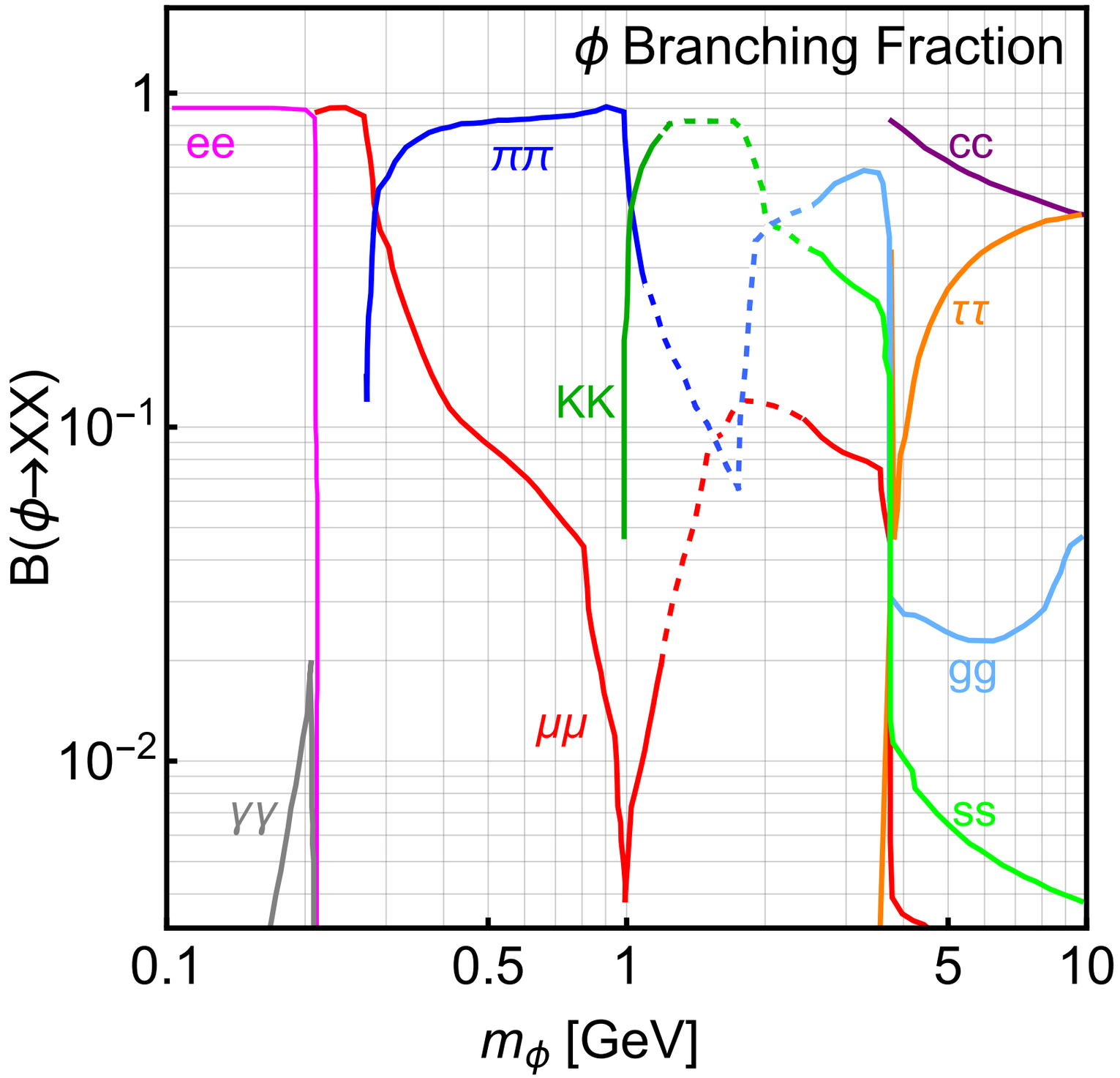


High sensitivity to operator mixing:

$$\mathcal{C}_{10} = F\left(\frac{4\pi}{\alpha} C_{\phi q}(m_t), C_{qq}(m_t)\right)$$

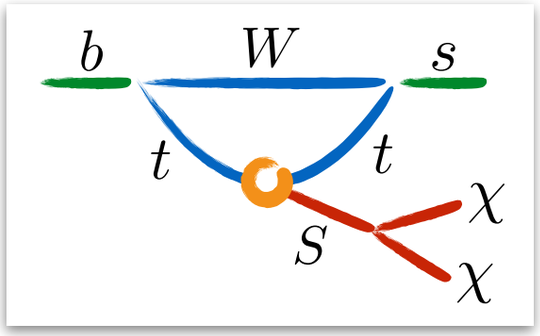
Bruggisser, Schäfer, van Dyk, Westhoff 2021

Long-lived scalars



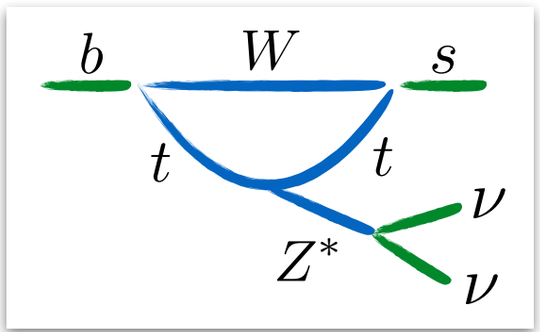
Invisible decays

signal: meson + missing energy



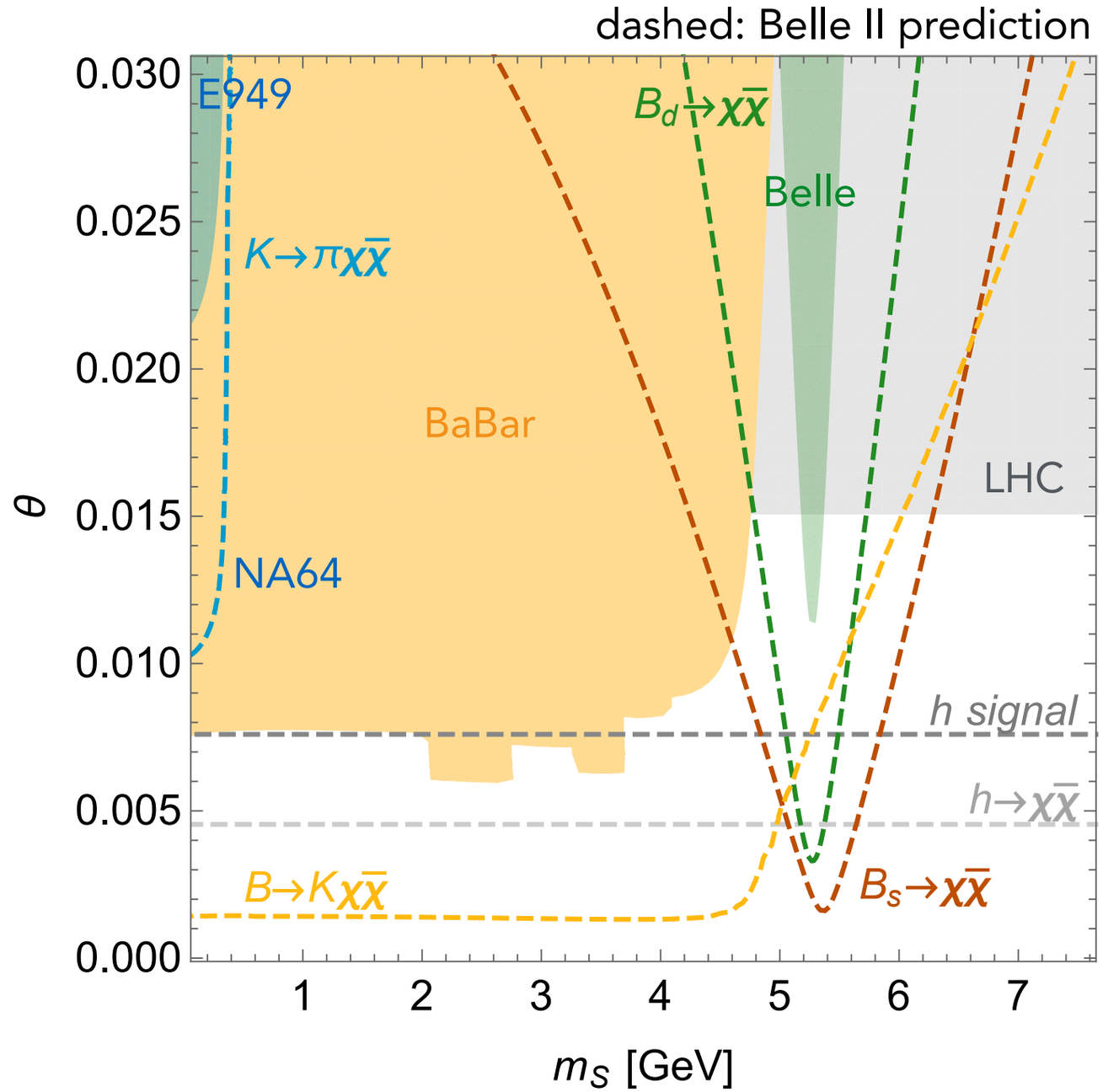
2-body decay

background



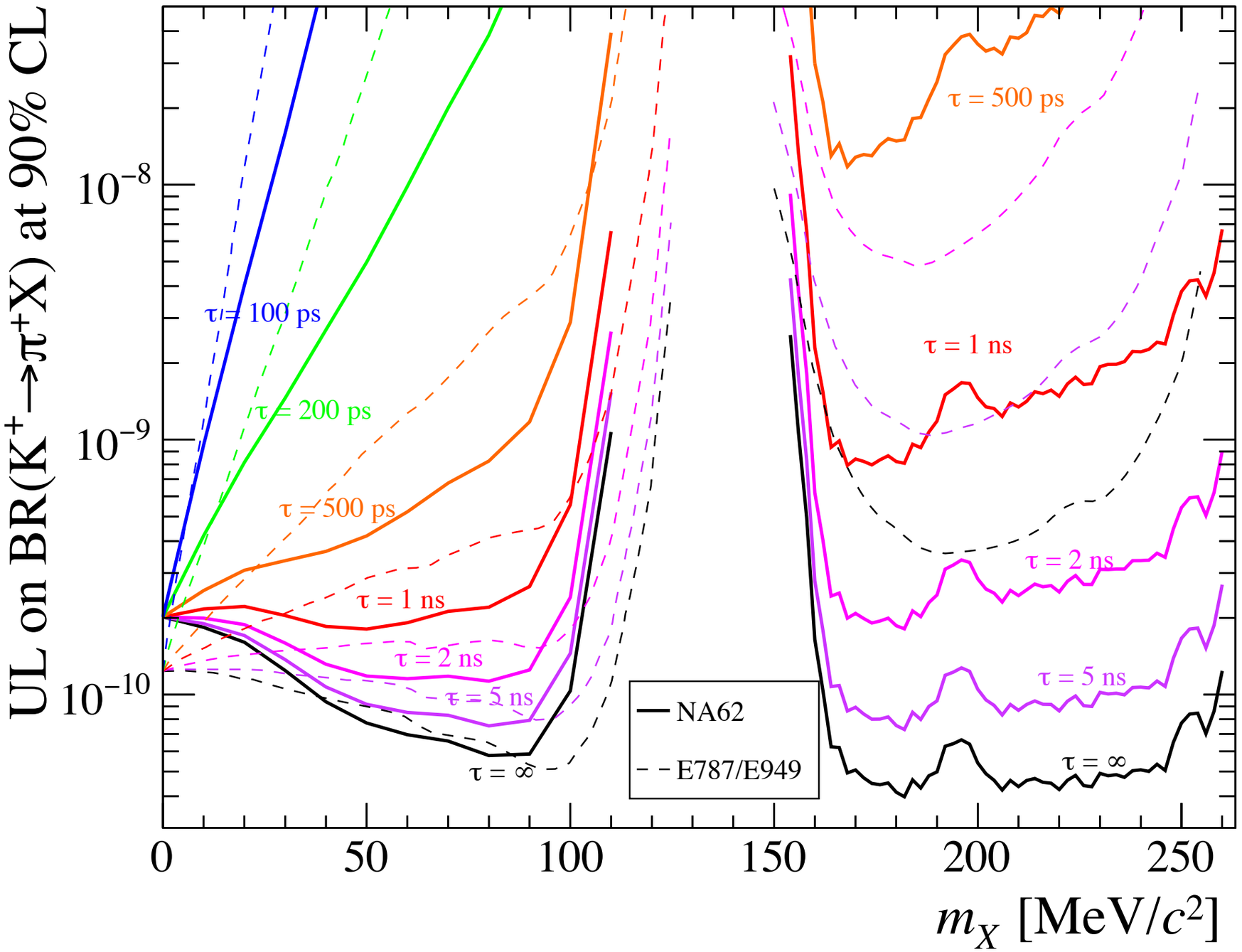
3-body decay

dashed: Belle II prediction



Filimonova, Schaefer, Westhoff 1911.03490

NA62: bounds on dark scalars



K > pi + inv: 2011.11329