OVERVIEW OF FLAVOUR THEORY AT e^+e^- COLLIDERS

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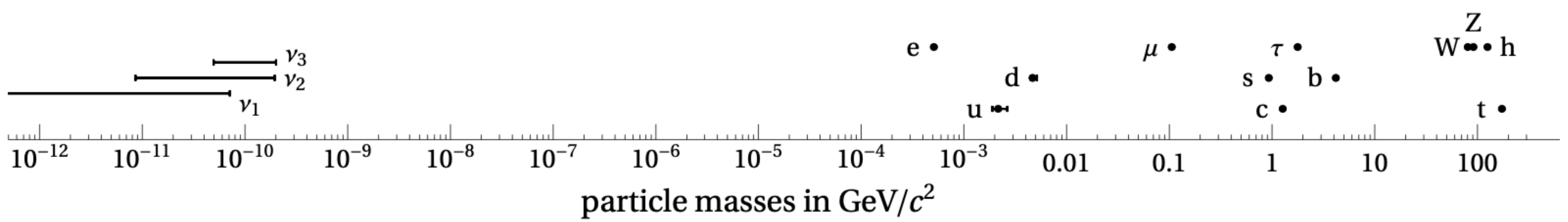
FLAVOR PHYSICS

- many open questions
- SM flavor puzzle
  - the origin of masses and mixing pattern



- NP flavor puzzle
  - TeV scale NP (hierarchy problem) has to have highly nontrivial flavor structure

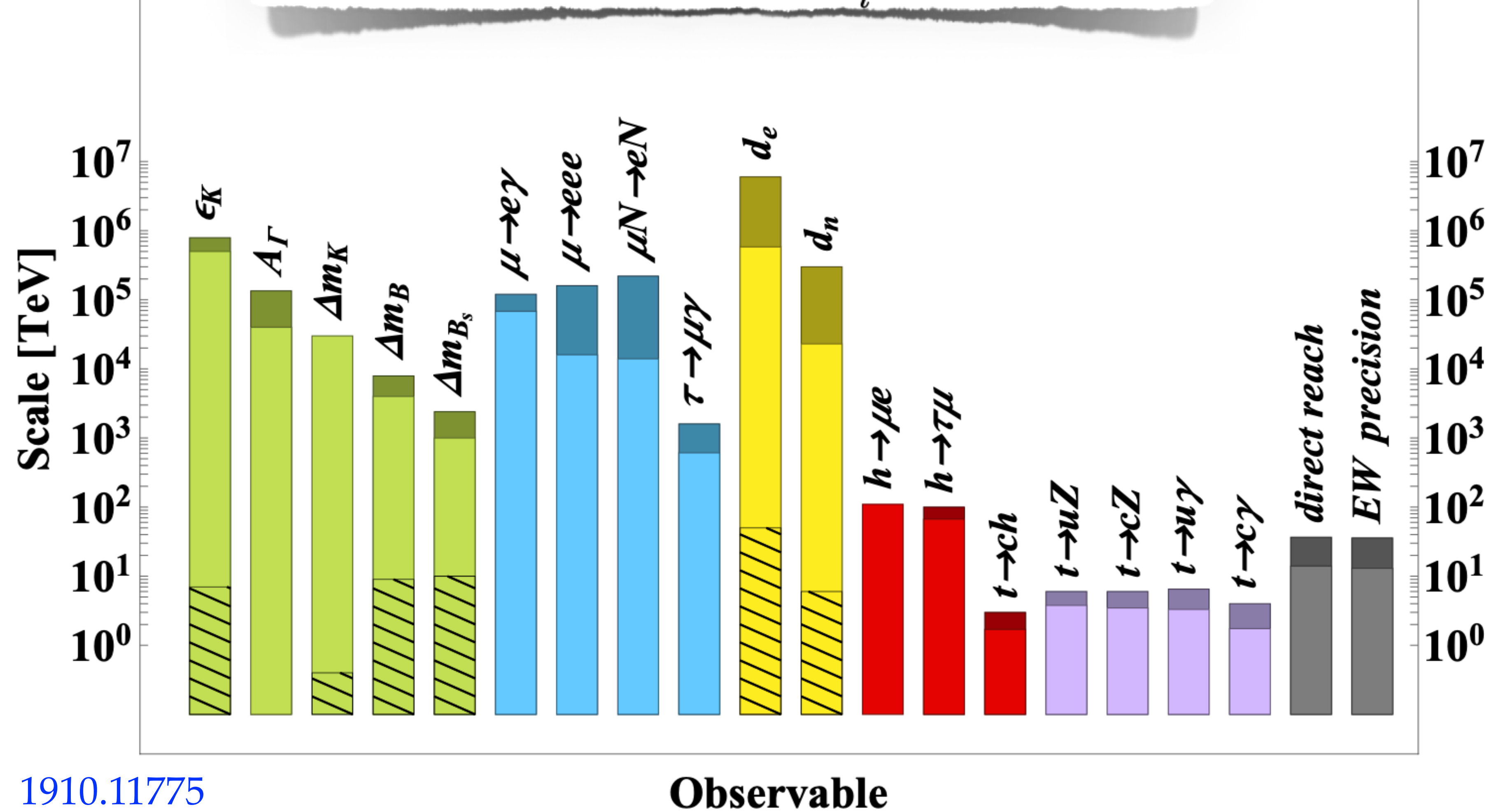
SUCCESSFUL IN THE PAST

- indirect probes of high scales
- several examples from the past
  - suppressed $K_L \to \mu^+\mu^- \Rightarrow$ charm quark — Glashow, Iliopoulos, Maiani, 1970
  - $\epsilon_K \Rightarrow$ existence of 3rd gen. (t,b quarks) — Kobayashi & Maskawa, 1973
  - $\Delta m_K \Rightarrow m_c \sim 1.5\,\mathrm{GeV}$ — Gaillard & Lee; Vainshtein & Khriplovich, 1974
  - $\Delta m_B \Rightarrow m_t \gtrsim 100\,\mathrm{GeV}$
- instrumental in construction of the SM
  - will it play the same role in discovery of NP?
  - $b \to c\tau\nu, b \to s\ell\ell$ anomalies...

EXPTECTED PROGRESS

- assuming NP is heavy, can be integrated out ⇒ dim. 6 SMEFT ops.
- flavor probes very high scales
- large expected increases in sensitivity in many probes

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{\rm SM}_{\rm gauge} + \mathcal{L}^{\rm SM}_{\rm Higgs} + \sum_i \frac{1}{\Lambda^{d-4}} \mathcal{C}_i \mathcal{O}_i^{d>4} \ ,$$



1910.11775

Belle II and LHCb upgrades

- upgrades planned at both Belle II and LHCb

Tom Browder @ Snowmass 2022 in Cincinnati

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

The dagger refers to a measurement in the range $1 < q^2 < 6$ GeV^2/c^2

Tera-Z: impressive flavor program

- very large and clean samples of B decays ($\sim 10^6 \times$ LEP)
- production yields at Tera-Z compared to Belle II

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B_s^0 / $\overline{B}_s^0$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

- similar yields expected for the new CEPC operation scenario

- comparison with LHCb more complex
  - LHCb has advantage if final state fully reconstructed
  - TeraZ may be better for neutrals or missing eng. final state

THE REASONS FOR IMPROVED MEASUREMENTS

- in many cases the theory error not saturated
  - determination of γ angle
  - B and B_s mixing phases
  - lepton flavor universality ratios
  - lepton violating modes
  - ...
- with ~100x increase in datasets will probe fairly generic BSM scenarios
  - in many respects complementary to the high p_T program

FLAVOR @ CEPC

- can make clear improvements in the "standard" flavor observables
  - β_s, γ, etc
- there are also unique measurements
  - due to the initial states
    - $|V_{cb}|$ from $W \to cb$
    - FV Z decays
    - B_c, B_s decays
  - or due to final states
    - rare B decays into invisibles

Rare Z decays

- large increase in sensitivity to $Z \to e\mu, e\tau, \mu\tau$
- not excluded by $\tau \to 3\mu, \tau \to 3e$

Measurement	Current [126]	FCC [115]	Tera-Z Prelim. [127]	Comments
$\mathrm{BR}(Z \to \tau\mu)$	$< 1.2 \times 10^{-5}$	$\mathcal{O}(10^{-9})$	same	$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \tau e)$	$< 9.8 \times 10^{-6}$	$\mathcal{O}(10^{-9})$		$\tau\tau$ bkg, $\sigma(p_{\mathrm{track}})$ & $\sigma(E_{\mathrm{beam}})$ limited
$\mathrm{BR}(Z \to \mu e)$	$< 7.5 \times 10^{-7}$	$10^{-8} - 10^{-10}$	$\mathcal{O}(10^{-9})$	PID limited

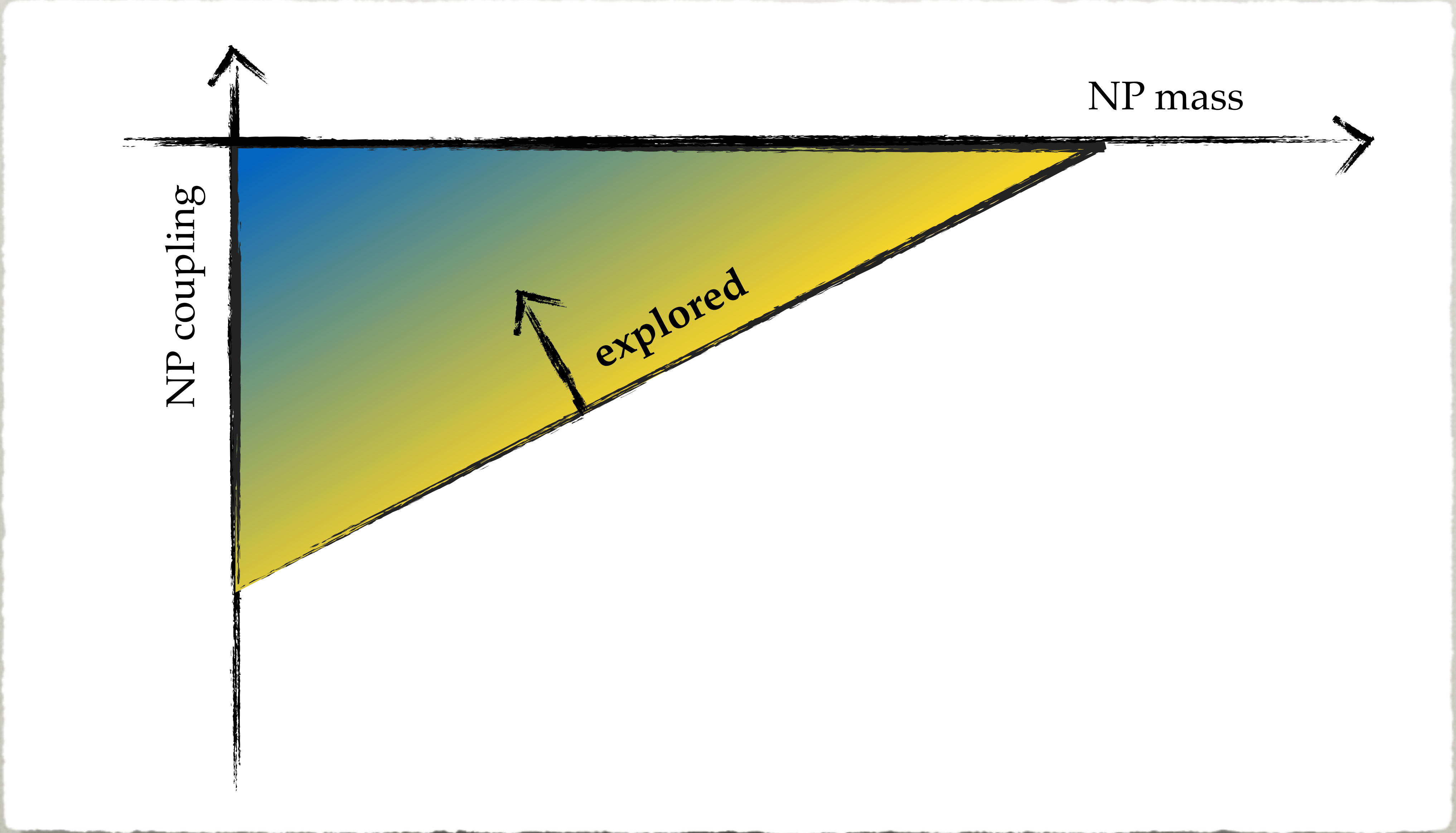
CEPC for Snowmass, 2205.08553

INVISIBLE DECAYS

- decays of the form $B \to K$+MET, $B \to \rho$+MET,...
  - could be due to $B \to K + X$, with X long lived
  - if X is light (say below eV) long lifetimes on collider scales natural

THE CASE FOR LIGHT NEW PHYSICS SEARCHES

- explored only part of the NP parameter space
- light particles: a window to high UV dynamics



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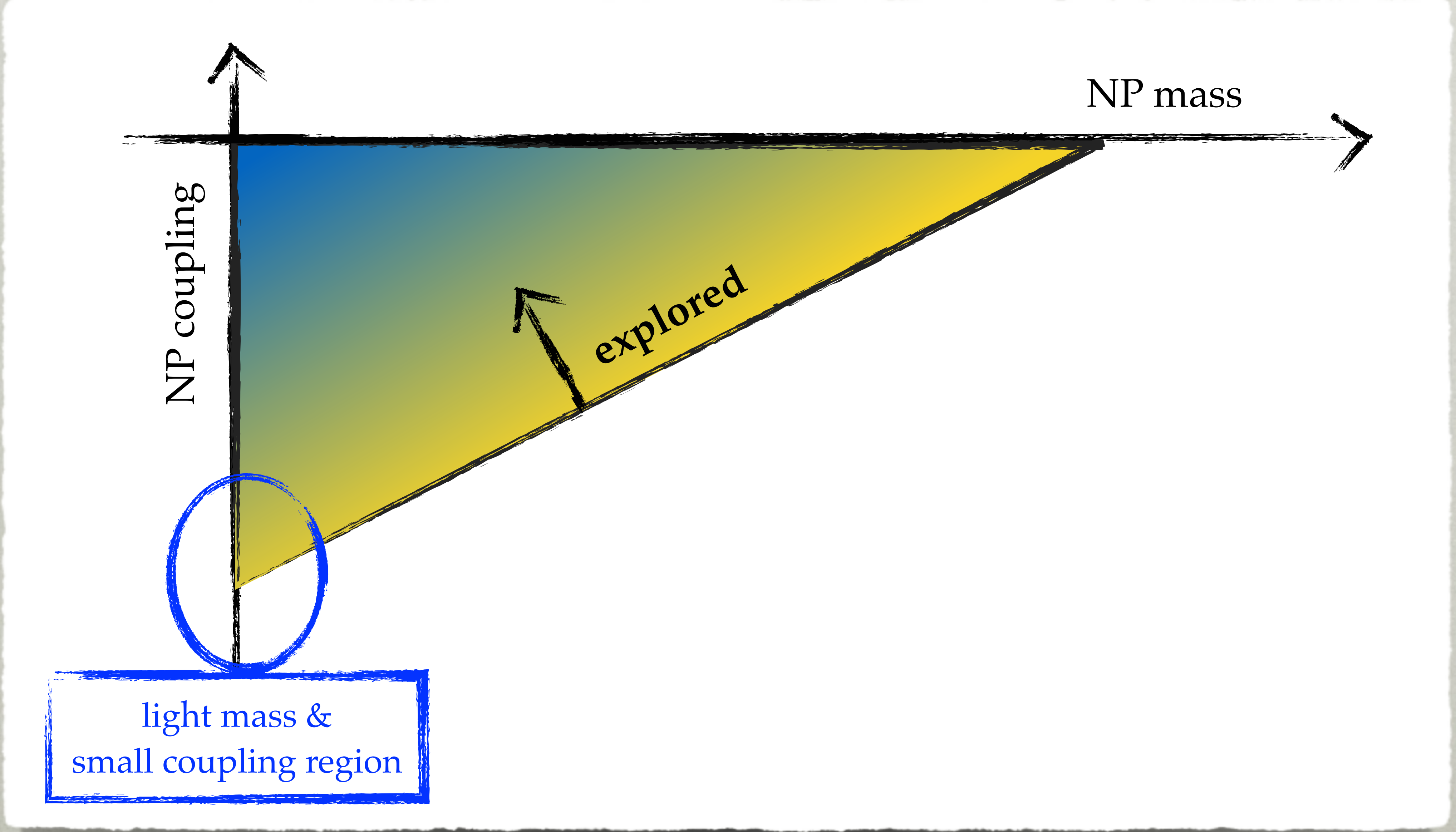

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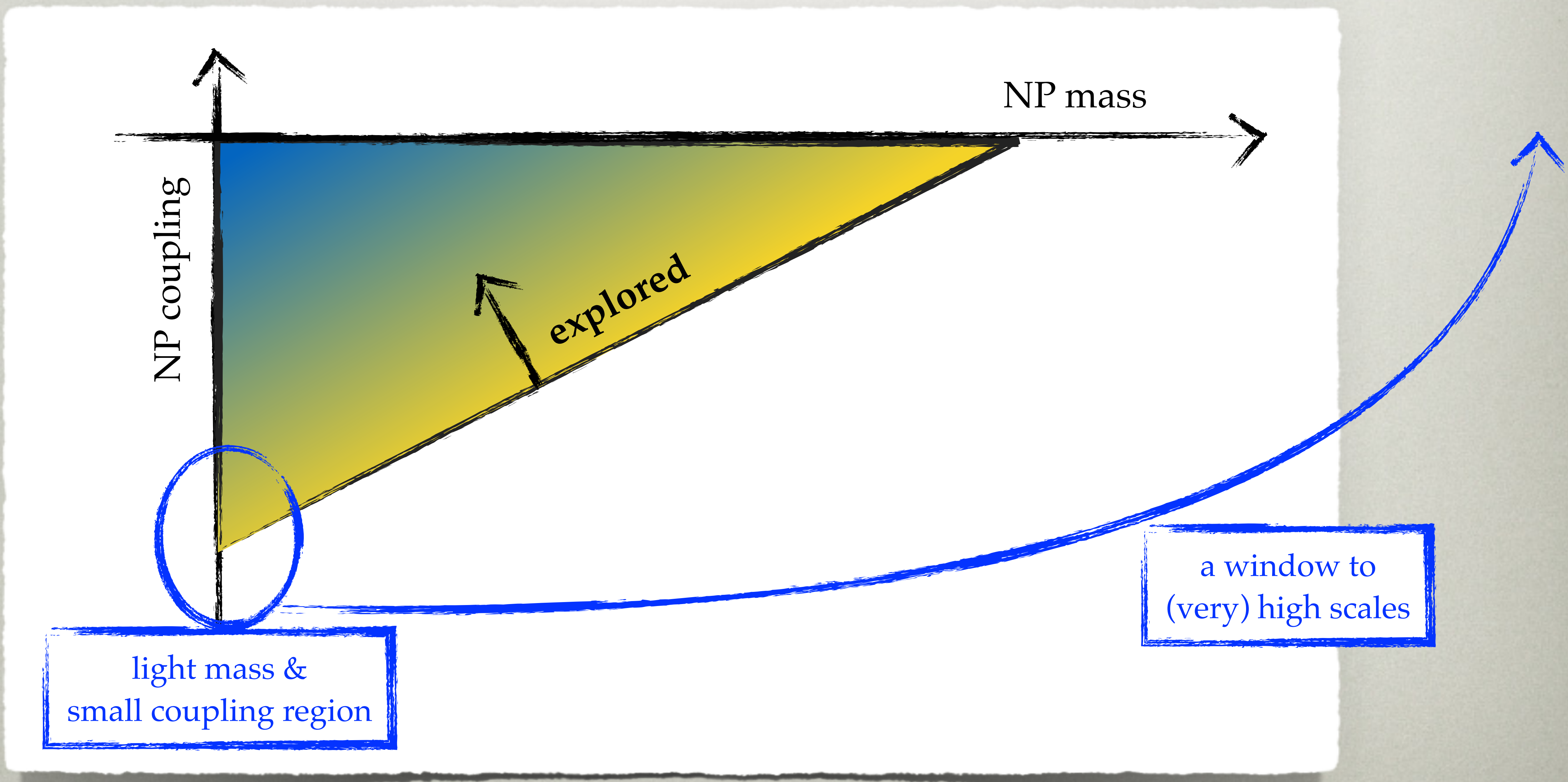


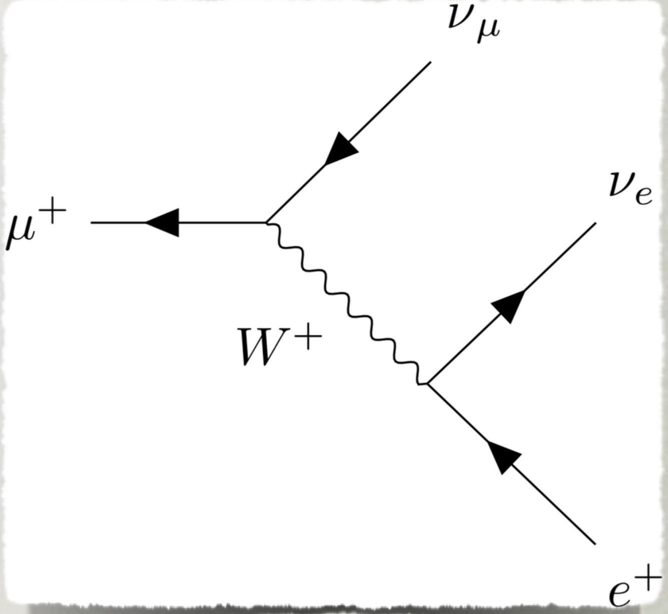
LIGHT NEW PARTICLES

- how generic are light new particles?
- any spontaneously broken global symmetry
  - $\Rightarrow$ massless Nambu-Goldstone boson

PORTALS

Portal	Interactions
Dark Photon, A'_μ	$-\epsilon F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
Axion-like pseudo scalar, a	$aF\tilde{F}/f_a$, $aG\tilde{G}/f_a$, $(\bar{\psi}\gamma^\mu\gamma_5\psi)\partial_\mu a/f_a$

LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES



- rare decays into a light state, X, e.g., B → KX or μ → eX,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops.
  - SM decay width power suppressed: $\Gamma_M \propto m_M^5/m_W^4$
- if through dim 5 op. suppressed by $1/f_a$
  - $\Rightarrow Br(B \to K\varphi) \propto (m_W^2/f_a m_B)^2$
  - similar for dim 4
- no such $1/m_M$ enhancement for dim. 6 couplings
  - $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

UPSHOT

- searching for $K \to \pi X$, $B \to KX$, $\tau \to \mu X$ decays expect to reach very high UV scales

EXAMPLE: FLAVOR VIOLATING QCD AXION

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

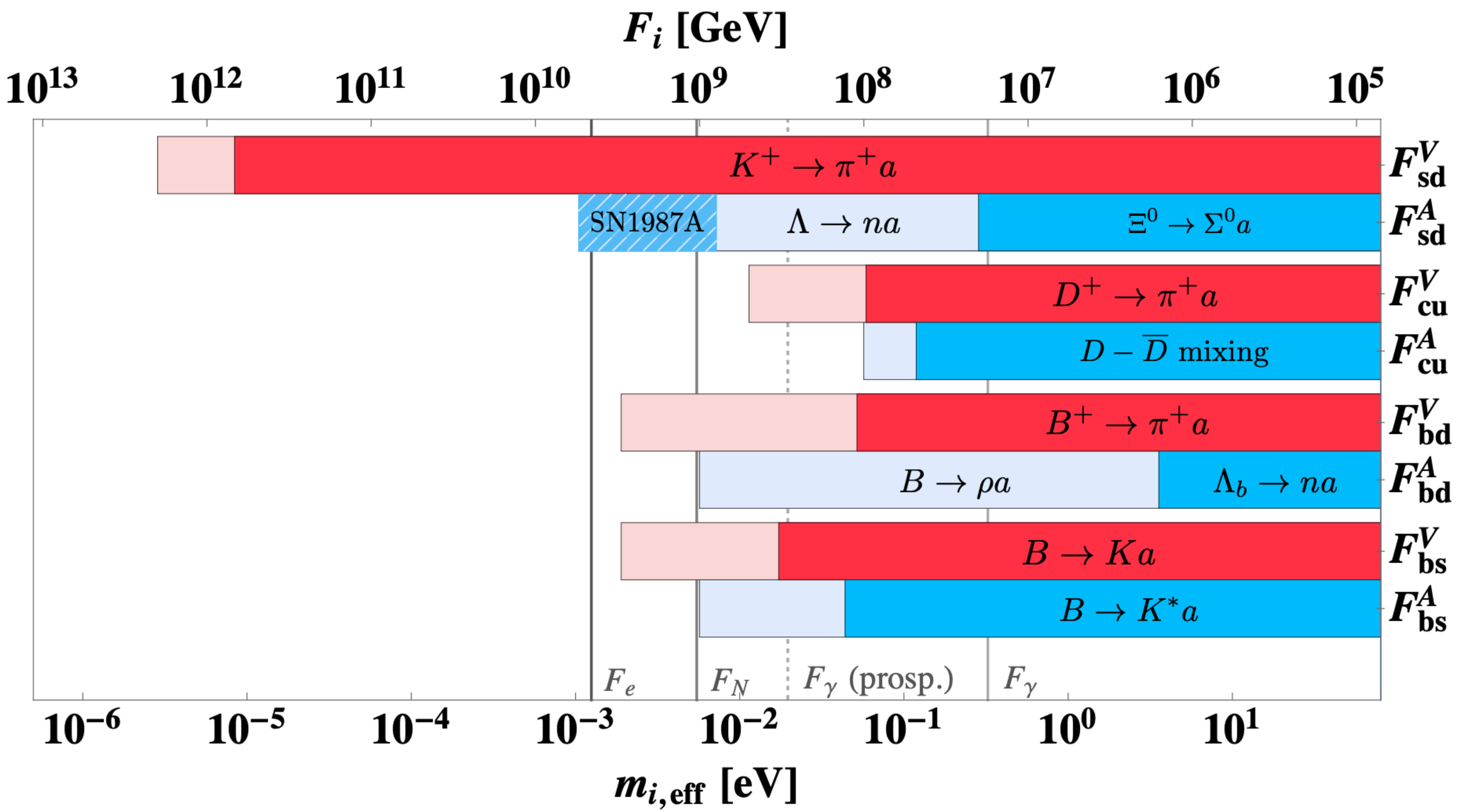
- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- general analysis, allowing for FV couplings as well
  - first focus on quark FV transitions

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu(C^V_{f_if_j} + C^A_{f_if_j}\gamma_5)f_j$$

$$F^{V,A}_{f_if_j} \equiv \frac{2f_a}{c^{V,A}_{f_if_j}}$$

THE STRONGEST FV CONSTRAINTS

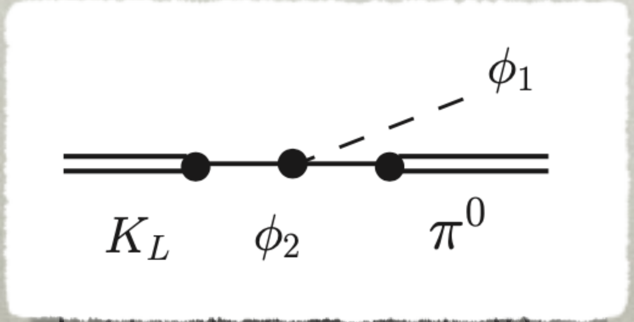
Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

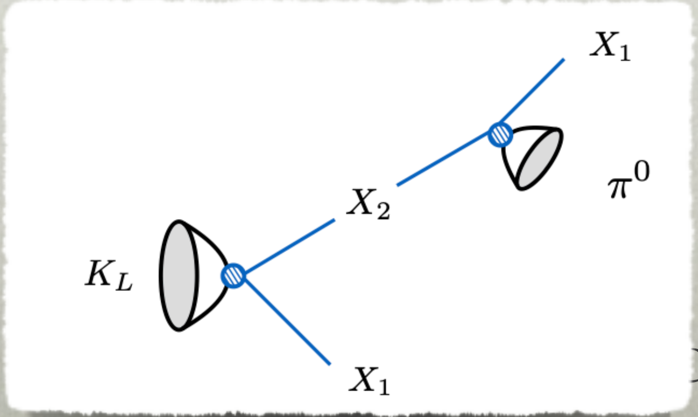


GN violating models

- one can use SU(3) related modes
  - $B_d \to Ka$ vs. $B_s \to Ka$
  - $B_d \to \rho a$ vs. $B_s \to K^* a$
  - $B \to K^* a$ vs $B_s \to \phi a$
  - ....
- there are also decay modes where spectator quark participates
  - example: GN violating modes that explain KOTO
  - B_d or B_s mix into dark sector
  - possible to have $B_s \to \pi$+MET with very suppressed signal in B decays

Ziegler, JZ, Zwicky, 2005.00451
Hostert, Kaneta, Pospelov, 2005.07102





CONCLUSIONS

- we are entering a new era of precision measurements: Belle 2, LHCb, muon experiments, dark sector searches, ...
- flavor program at CEPC can improve on many observables
  - especially with invisible final states

BACKUP SLIDES