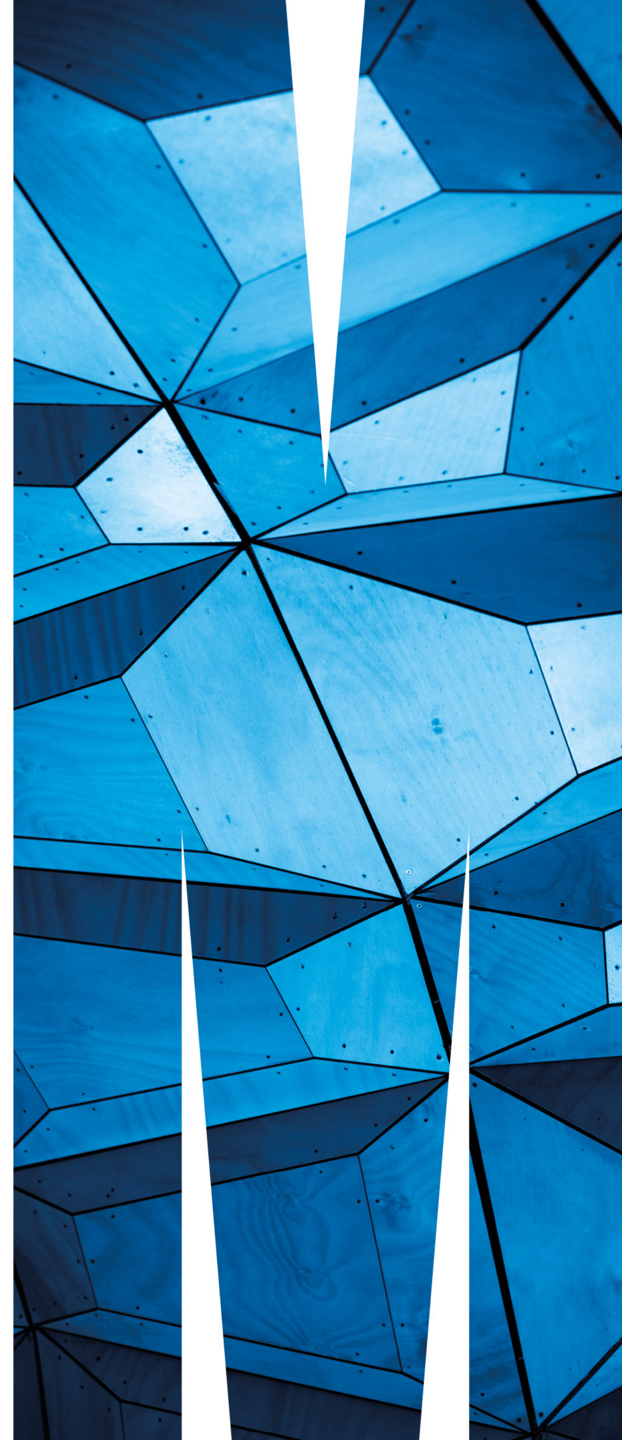
rare decays with missing energy and light invisible scalars

Scalars 2025

German Valencia



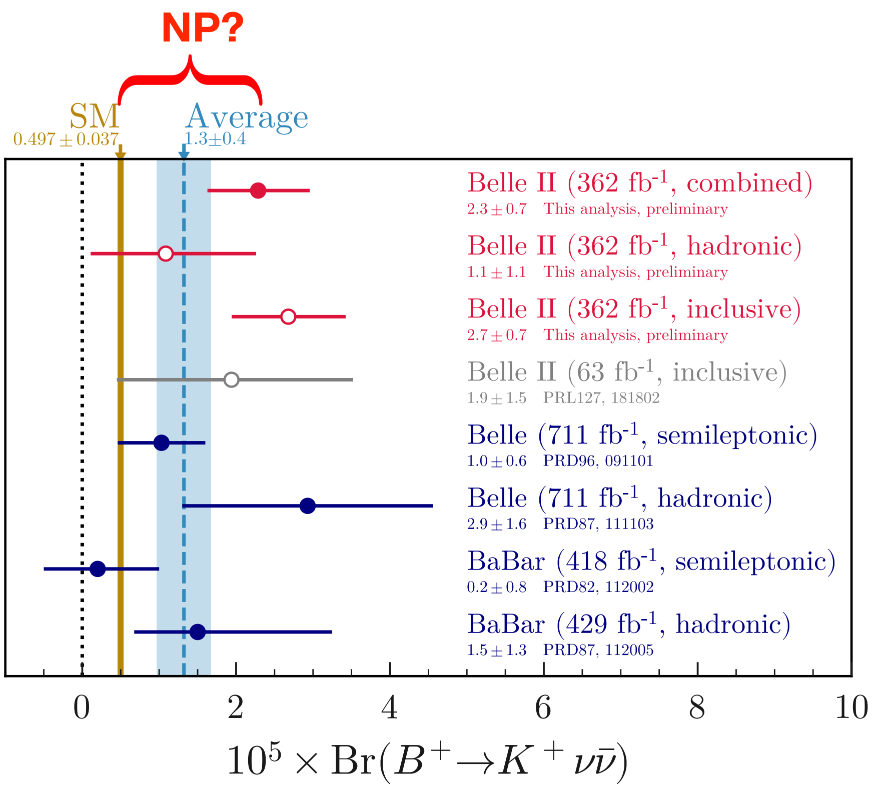
Motivation

- two new measurements from Belle II and NA62
  - $B^+ \to K^+ \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$
- NP in $B^+ \to K^+ + \text{ invisible}$?
- is there room for NP in the form of pairs of invisible scalars?
- additional constraints on light invisible scalars

New Belle II result for $B^+ \to K^+ \nu\bar{\nu}$

almost 3σ from the SM

From Belle II PhysRevD.109.112006 (2024)



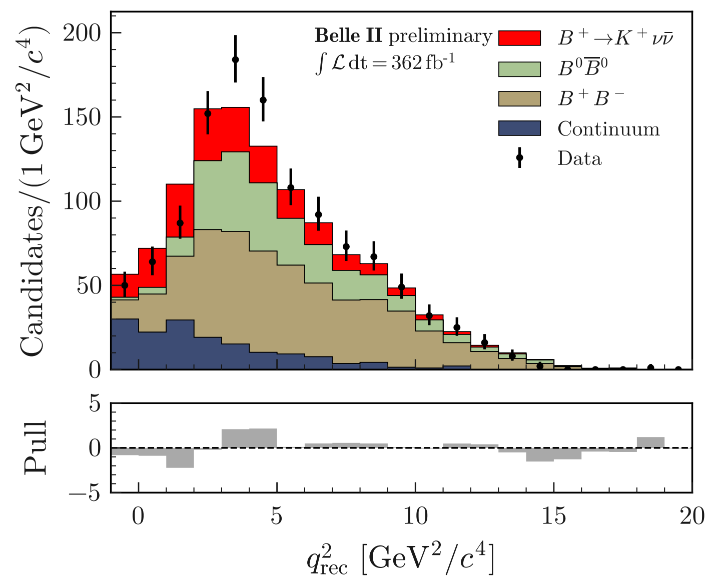


FIG. 17. Distributions of $\eta(\mathrm{BDT}_2)$, q^2_{rec}, beam-constrained mass of the ROE $M_{\mathrm{bc,ROE}}$, ΔE_{ROE}, Fox-Wolfram R_2, and modified Fox-Wolfram $H^{\mathrm{so}}_{m,2}$ in data (points with error bars) and simulation (filled histograms) shown individually for the $B^+ \to K^+\nu\bar{\nu}$ signal, neutral and charged B-meson decays, and the sum of the five continuum categories in the ITA. Events in the full signal region, with $\eta(\mathrm{BDT}_2) > 0.92$, are shown. Data and simulation are normalized to an integrated luminosity of 362 fb^{-1}. The pull distributions are shown in the bottom panels.

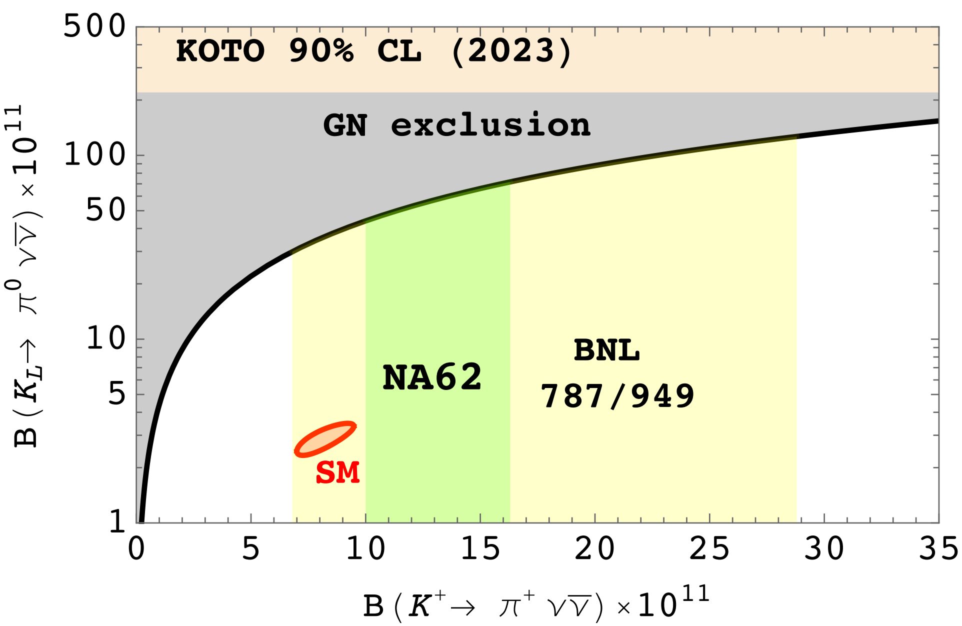
Observable	New physics bound $\mathcal{B}^{\mathrm{UL}}$
$\mathcal{B}(B^+ \to K^+ \not{E})$	1.3×10^{-5} PDG
$\mathcal{B}(B^0 \to K^0 \not{E})$	2.3×10^{-5} Belle
$\mathcal{B}(B^+ \to K^{*+} \not{E})$	3.1×10^{-5} Belle
$\mathcal{B}(B^0 \to K^{*0} \not{E})$	1.0×10^{-5} Belle

if $\not{E}_T$ is due to $\phi\phi$

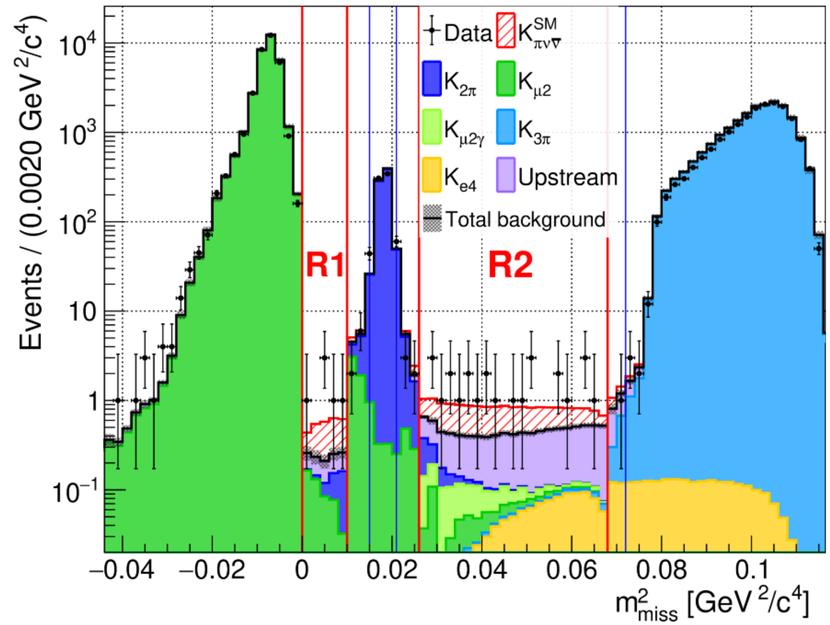
then $m_\phi < (m_B - m_K)/2$

NA62 $K^+ \to \pi^+ \nu \bar{\nu}$

- In 2025 NA62 published a result from 51 candidate events:
- $B(K^+ \to \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$
- The SM prediction is known precisely except for parametric uncertainty. Typical values are
- $$B(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$ $$= (7.86 \pm 0.61) \times 10^{-11}$$



From NA62 JHEP 02 (2025) 191

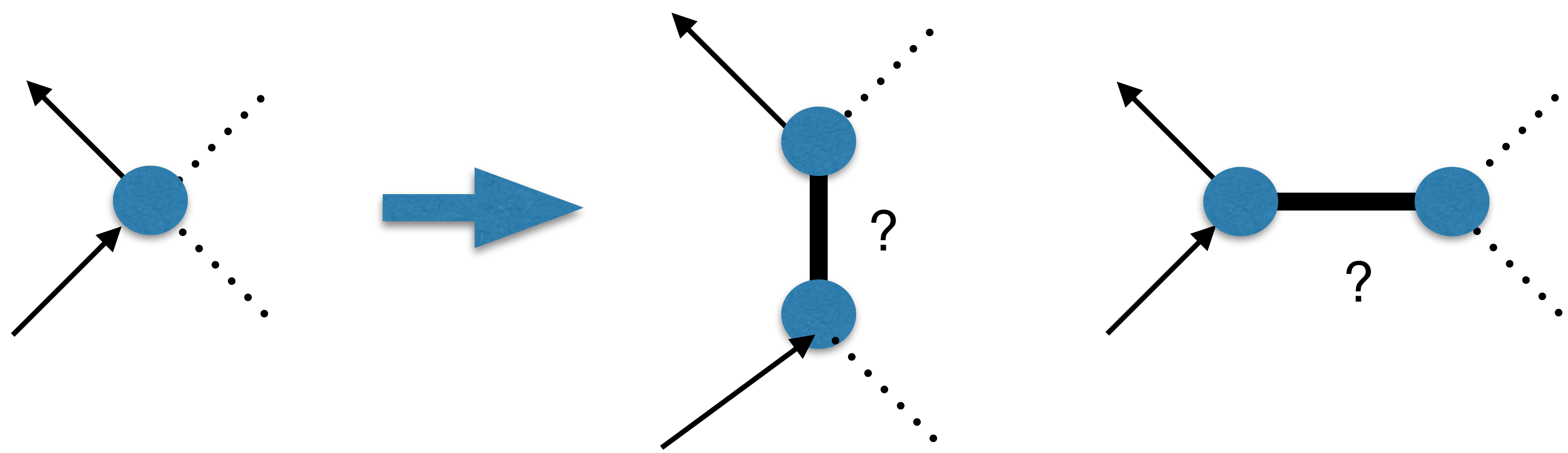


if $\not{E}_T$ is due to $\phi\phi$

then $m_\phi < (m_K - m_\pi)/2$

new invisible scalars

- is there room in these results for NP, in particular in the form of pairs of invisible scalars?
  - add to rare decays constraints on invisible scalars
- first consider an effective theory and find the parameter region of interest
- look for simple models with heavy mediators and consider additional constraints/phenomenology



Effective field theory

- for pair produced real scalars (with a $\mathbb{Z}_2$ symmetry), coupling to SM quarks at dimension six

dim 6 ϕSMEFT: $\mathscr{L} = \frac{1}{\Lambda_{\rm eff}^2} \sum_i C_i \mathscr{O}_i$

- couplings to quarks

$$\mathscr{O}_{d\phi^2}^{pr} = (\bar{q}^p d^r H)(\phi^\dagger \phi)$$

- $\mathscr{O}_{u\phi^2}^{pr} = (\bar{q}^p u^r \tilde{H})(\phi^\dagger \phi)$

$$\mathscr{O}_{q\phi\phi} = \bar{q}\gamma^\mu q(i\phi^\dagger \overleftrightarrow{\partial}_\mu \phi)$$

$$\mathscr{O}_{d\phi\phi} = \bar{d}\gamma^\mu d(i\phi^\dagger \overleftrightarrow{\partial}_\mu \phi)$$

$$\mathscr{O}_{u\phi\phi} = \bar{u}\gamma^\mu u(i\phi^\dagger \overleftrightarrow{\partial}_\mu \phi)$$

vanish for real scalars

- only the red one is relevant for the rare decays mentioned, with flavour indices sb, ds, flavour diagonal indices are needed for annihilation
- for high energy searches, operators with only ϕH are tightly constrained by H invisible width
- gluon operator may be important for monojet studies

$$\mathcal{O}_{G\phi}^{(6)} = (G_{\mu\nu}^A G^{A\mu\nu})\,\phi^2$$

dim 6 ϕSMEFT and ϕLEFT

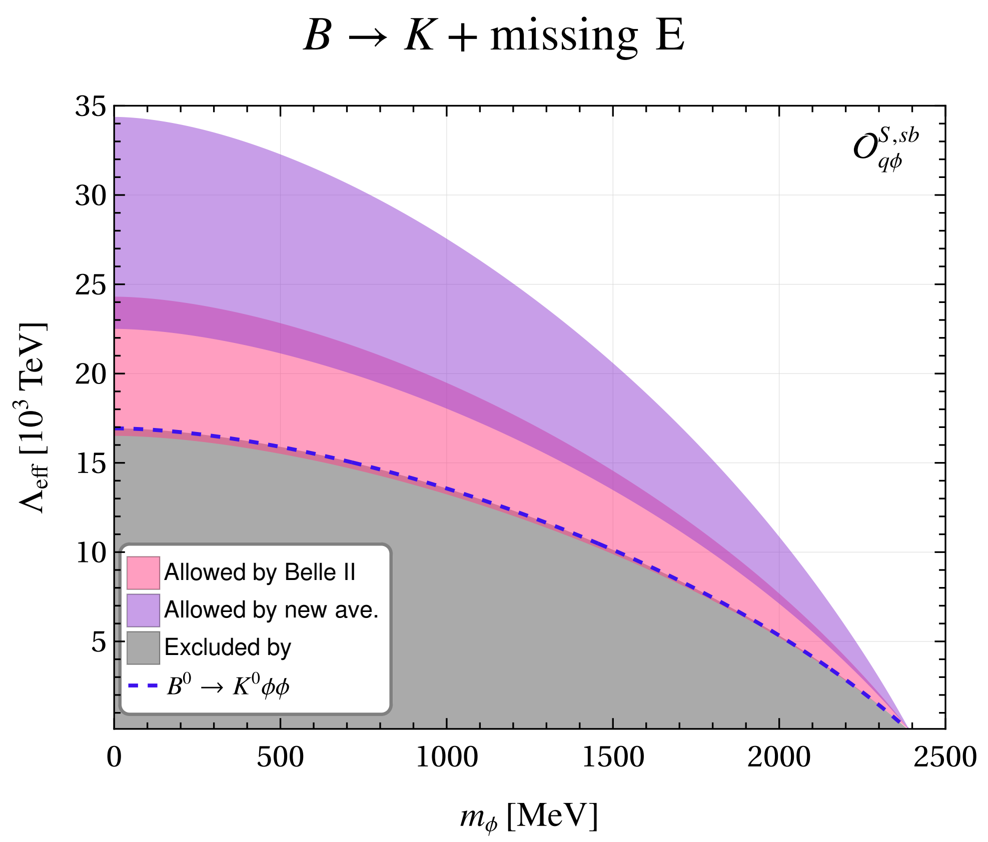
- dim 6 in ϕLEFT from ϕSMEFT for d-quark sector:

$$\frac{1}{\Lambda_{\rm eff}^2}(\bar{d}_{iL} d_{jR} H)(\phi^\dagger \phi)$$

$$\mathcal{O}_{q\phi}^{Ssb} = (\bar{s}b)(\phi^\dagger\phi)$$

  - $\mathcal{O}_{q\phi}^{Psb} = (\bar{s}i\gamma_5 b)(\phi^\dagger\phi)$

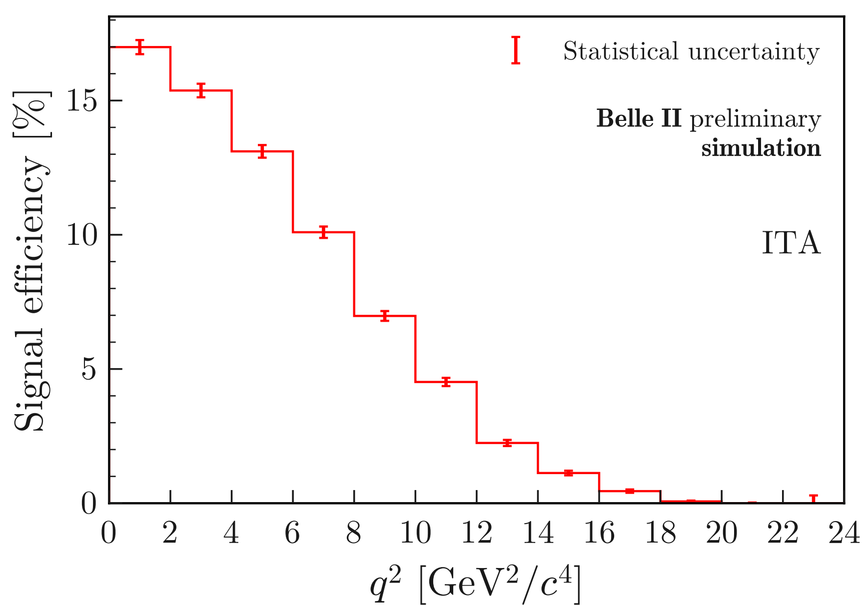
- contribute to $B \to K + \text{missing E}$ and $B \to K^* + \text{missing E}$ respectively

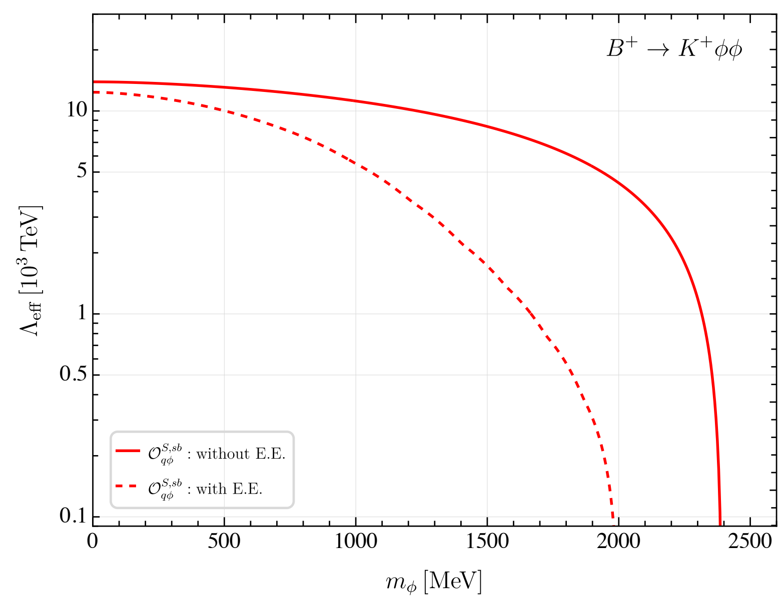


- for $K \to \pi + \text{missing E}$ we need instead $\mathcal{O}_{q\phi}^{Ssd} = (\bar{s}d)(\phi^\dagger\phi)$
- for annihilation and DD cross-sections, we will also need the flavour diagonal versions of these operators

spectrum and experimental efficiency

- can do better than simply using just the rates, taking into account that the fit by Belle II assumes the SM spectrum, and that their efficiency depends on q^2
- for scalar particles, the $\Lambda - m_\phi$ allowed parameter space increases for the higher masses when we include the efficiency
- a simple first step is to compare the normalised distributions (so shapes only) after taking into account the experimental efficiency, and look for those with small increases around $5\ \mathrm{GeV}^2$

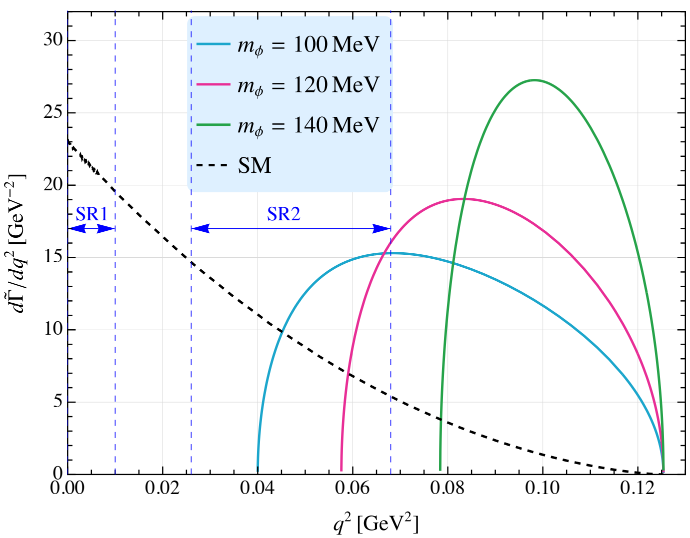


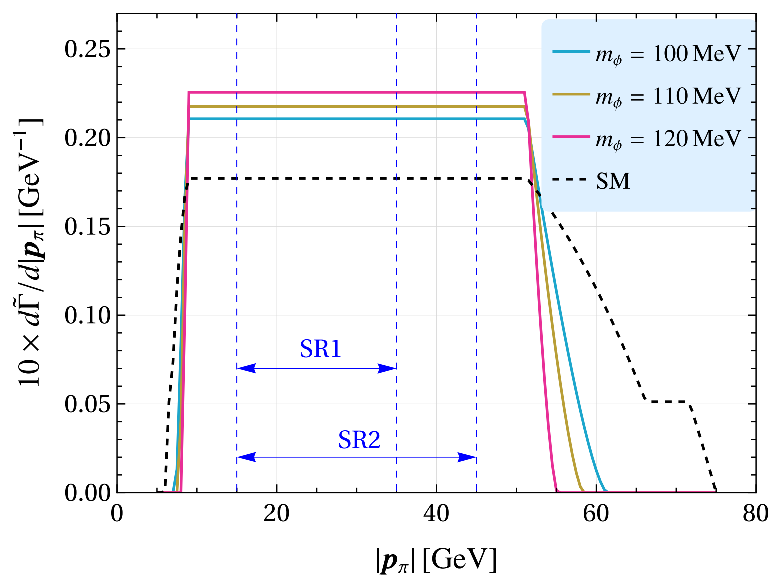


He, Ma, GV PRD 109 (2024) 7

how about kaons?

- $\mathscr{L}^{\phi\text{LEFT}}_{qq\phi^2} \supset \frac{1}{2}\left[C^{S,sd}_{d\phi}(\bar{s}d) + C^{P,sd}_{d\phi}(\bar{s}i\gamma_5 d)\right]\phi^2$
- not much room in the rate for NP contributions
- but there are large gaps where NA62 is blind
- inside the NA62 SR, $d\Gamma/d|\mathbf{p}_\pi|$ has the same shape as the SM signal (flat), so that the experimental efficiency doesn't matter in this case.





He, Ma, Tandean, GV PRD 112 (2025) 5

allowed parameter space

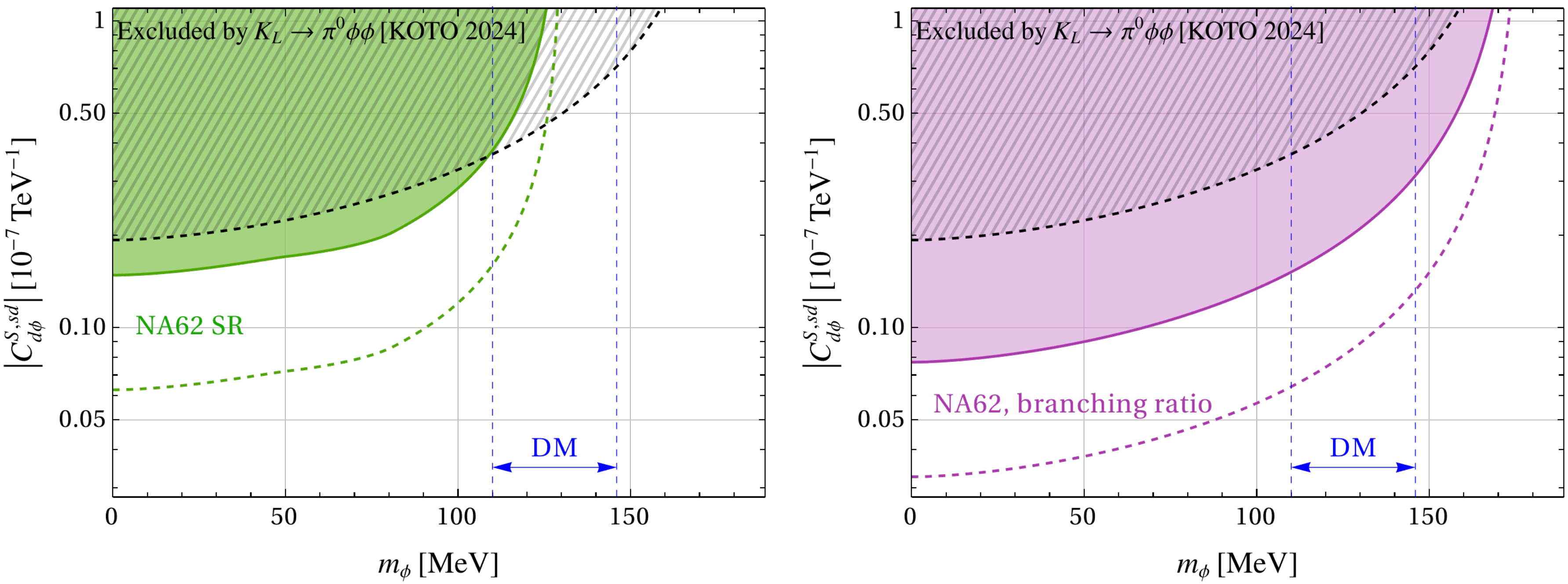


FIG. 1. Left: the green-shaded region represents the $|C_{d\phi}^{S,sd}|$ versus m_ϕ parameter space excluded by the latest NA62 [1] measurement of $K^+ \to \pi^+ + \not{E}$. The unshaded region between the solid and dashed green curves is where the new-physics window $\Delta\mathcal{B}_K$ can be populated by $K^+ \to \pi^+\phi\phi$. Only the $m_\phi \in [110, 146]$ MeV range, as indicated, is permitted by the DM relic density requirement. The hatched region is excluded by the recent KOTO [51] search for $K_L \to \pi^0 + \not{E}$ if $C_{d\phi}^{S,sd}$ is purely real. Right: the same as the left panel but using only the branching-ratio value reported by NA62 [1] and without regard to its signal regions.

He, Ma, Tandean, GV PRD 112 (2025) 5

can ϕ's be interpreted as dark matter?

- if we want to explain the dark matter relic density through thermal freeze-out mechanism, the $C^{S,bs}_{d\phi}$, $C^{S,sd}_{d\phi}$ coefficients are not enough, we need some flavour diagonal ones to obtain the required annihilation cross-section.
- assuming a ϕ mass of order a GeV (ignore the kaon decay for now) we can use a leading order chiral realisation to calculate the thermal average of the annihilation cross-sections into kaons (and pions and etas)
  - $\langle \sigma v(\phi\phi \to K^+K^-, K^0\bar{K}^0)\rangle = \frac{B^2 \,|\, C^{S,ss}_{d\phi} \,|^2\, \eta(x, z_K)}{64\pi m_\phi^2} + \cdots$
  - to produce the correct relic density $\Omega\hbar^2 = 0.12$, we need

$$\langle \sigma v\rangle \simeq 2.4 \times 10^{-26} \frac{\text{cm}^3\text{s}^{-1}}{(\hbar c)^2 c} = 2.2 \times 10^{-9}\,\text{GeV}^{-2}$$

which translates into $C^{S,ss}_{d\phi} \sim (0.1)/(\text{TeV})$

G. Steigman, B. Dasgupta and J.F. Beacom
PRD 86 (2012) 023506

direct detection constraints

- so far: we need $C_{d\phi}^{S,sb} \sim (3-8)/(10^5\,\mathrm{TeV})$ to fill the NP window in $B \to K + \mathrm{invisible}$
- and we also need $C_{d\phi}^{S,ss} \sim 0.1/\mathrm{TeV}$ for thermally averaged annihilation to have the right magnitude for the relic density
- we also need to avoid direct detection constraints, in particular, those using the Migdal effect for sub-GeV dark matter and the scenario so far is ruled out by Panda X4T
- to satisfy DD requires an interplay between different parameters and at least one more coefficient, i.e, introducing $C_{d\phi}^{S,dd}$
- $C_{d\phi}^{S,dd}$, as well as $C_{d\phi}^{S,uu}$ are also needed for constraining the kaon decay window

ϕ-nucleus scattering

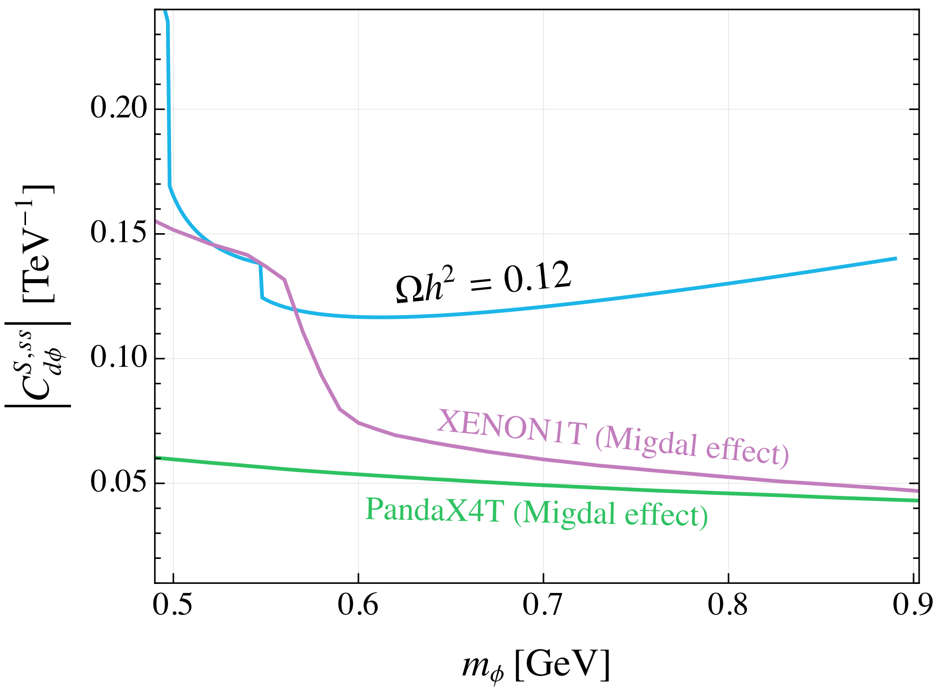
- the ϕ-nucleus scattering cross-section is given by

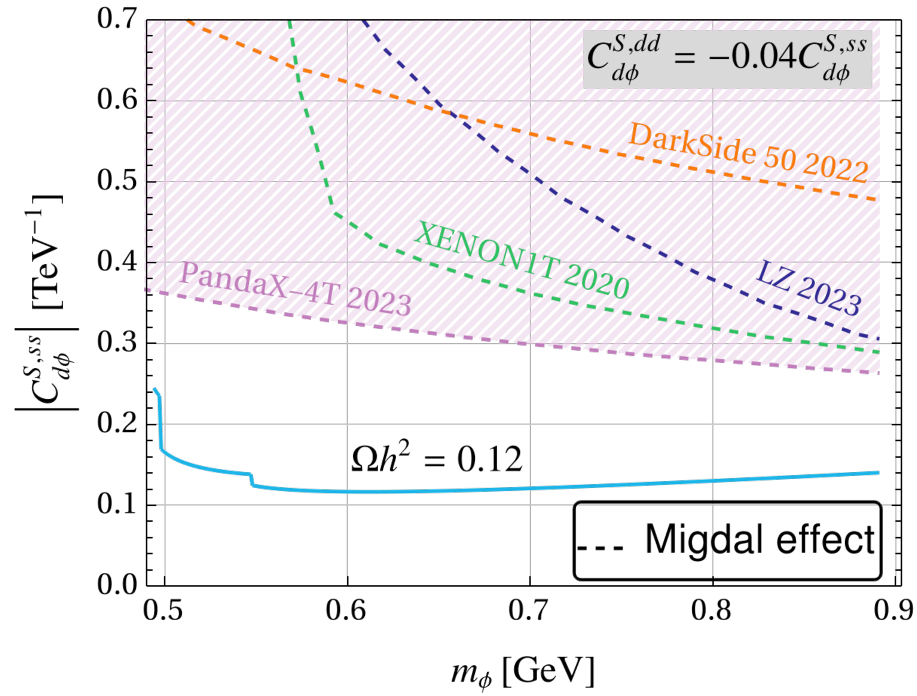
scalar nucleon form factors

depends on isotope

E. Del Nobile, arXiv:2104.12785

- $$\sigma_{\phi N} = \frac{\mu_{\phi N}^2}{4\pi m_\phi^2} \left| \frac{m_N}{m_s} f_{T_s}^{(N)} C_{d\phi}^{S,ss} \right|^2 \left| \left(1 + \frac{m_s}{m_d} \frac{f_{T_d}^{(p)}}{f_{T_s}^{(p)}} R_{d/s}\right) \frac{Z}{A} + \left(1 + \frac{m_s}{m_d} \frac{f_{T_d}^{(n)}}{f_{T_s}^{(n)}} R_{d/s}\right) \frac{A-Z}{A} \right|^2,$$





how about the kaon decay

- to populate the $K^+ \to \pi^+ + \mathrm{invisible}$ window, the mass of the scalars needs to be lower.
- annihilation changes, as now only the pion channels are open and we need the LEFT coefficients $C_{d\phi}^{S,dd}$ and $C_{d\phi}^{S,uu}$
- annihilation into pions results in photons that lead to constraints from astrophysical X-ray and gamma-ray and CMB observations
- the DD constraints require using three parameters to adjust the ϕN scattering cross-section

$$c_1^N = \frac{2m_N^2}{m_u} f_{T_u}^{(N)} C_{u\phi}^{S,uu} + \frac{2m_N^2}{m_d} f_{T_d}^{(N)} C_{d\phi}^{S,dd} + \frac{2m_N^2}{m_s} f_{T_s}^{(N)} C_{d\phi}^{S,ss} \qquad r_\pm^N = \frac{1}{2}\left[\frac{f_{T_u}^{(N)} m_s}{f_{T_s}^{(N)} m_u} \pm \frac{f_{T_d}^{(N)} m_s}{f_{T_s}^{(N)} m_d}\right],$$

- $$= \frac{2m_N^2}{m_s} f_{T_s}^{(N)} \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right)\left(r_+^N + r_-^N R_- + R_s\right) \qquad R_- = \frac{C_{u\phi}^{S,uu} - C_{d\phi}^{S,dd}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}, R_s = \frac{C_{d\phi}^{S,ss}}{C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}}.$$

the kaon window

- for indirect detection use Planck CMB limits on $\langle \sigma v \rangle$

K. E. O'Donnell and T. R. Slatyer PRD 111 (2025) 083037

- avoiding DD requires further fine-tuning of the diagonal WC

- a narrow mass window remains, and NA62 probes part of that window

can we get more details?

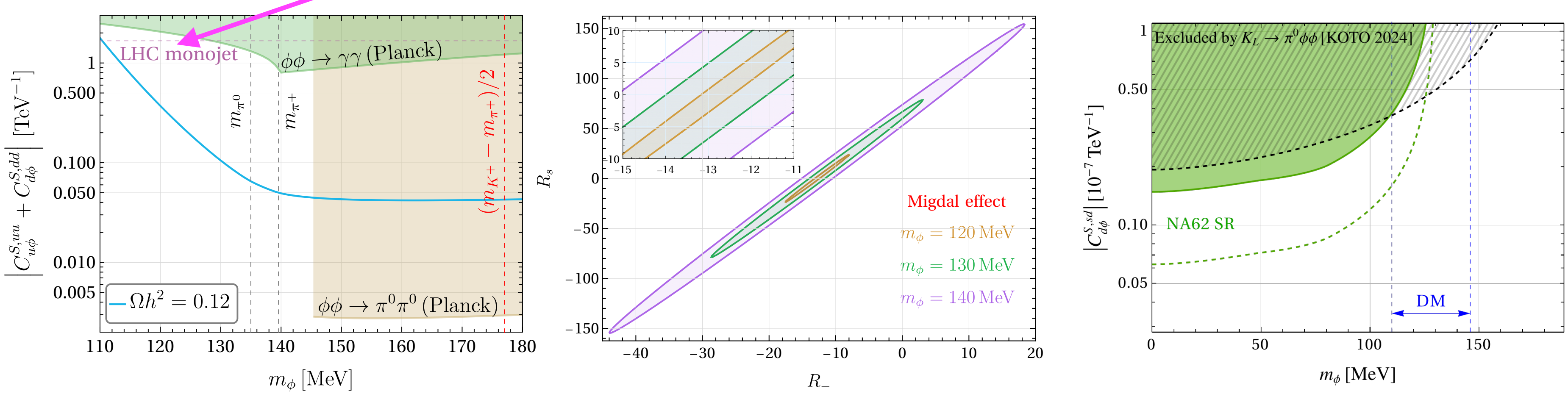


FIG. 4. Left: the cyan solid curve represents the values of $|C^{S,uu}_{u\phi} + C^{S,dd}_{d\phi}|$ versus DM mass m_ϕ that yield the observed DM relic density. The brown and green regions are excluded by the CMB constraints [54]. Right: the R_--R_s regions allowed by the DM direct search result of PandaX-4T [55] incorporating the Migdal effect.

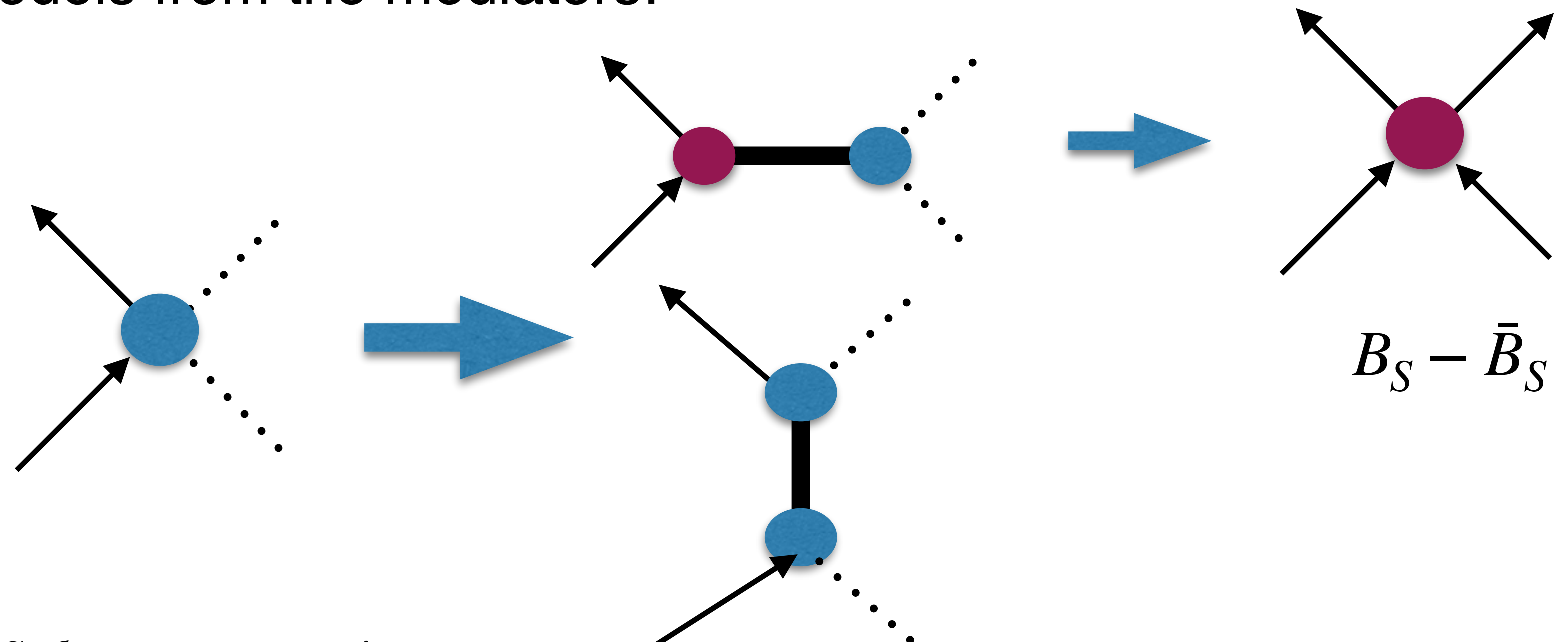
He, Ma, Tandean, GV PRD 112 (2025) 5

Simple t-channel UV completion

- study additional constraints/predictions
- we have considered so far only the parameters relevant for $B^+ \to K^+ + \text{ invisible}$

heavy mediators

- with heavy mediators, the LEFT framework we have used works well for the discussion so far
- but there are other constraints at low energy in UV complete models from the mediators:



- $\mathcal{O}_{q\phi}^{S,sb} = (\bar{s}b)(\phi^\dagger \phi)$
- s-channel mediator, harder to explain B_s mixing, look for a t-channel mediator first

t-channel model

He, Ma, Schmidt, GV,Volkas JHEP 07 (2024) 168

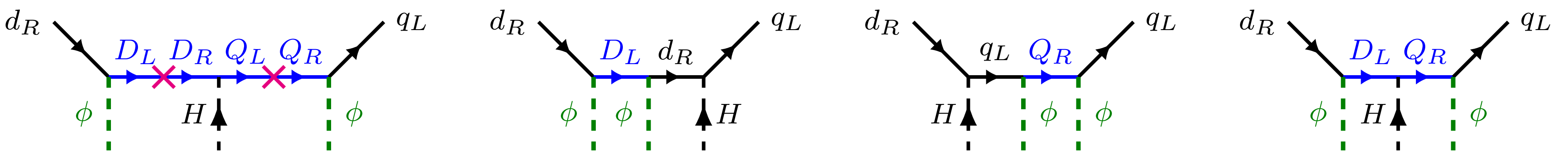


Figure 1. Feynman diagrams contributing to the matching to the ϕSMEFT-like operator $\mathcal{O}_{qdH\phi^2}$ via t-channel exchange of the vector-like fermions Q and D. The magenta crosses represent mass insertions.

- introduce two heavy vector-like quarks $Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$, $D \sim (\mathbf{3}, \mathbf{1}, -1/3)$ (we write $Q_R \equiv P_R Q\ldots$)
- and a light scalar field $\phi \sim (\mathbf{1}, \mathbf{1}, 0)$
- All new fields are odd under a $\mathbb{Z}_2$ symmetry

$$\mathcal{L}^{\mathrm{NP}}_{\mathtt{kinetic}} = \bar{Q} i \not{D} Q - m_Q \bar{Q} Q + \bar{D} i \not{D} D - m_D \bar{D} D + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2,$$
$$\mathcal{L}^{\mathrm{NP}}_{\mathtt{Yukawa}} = y_q^p \bar{q}_{Lp} Q_R \phi + y_d^p \bar{D}_L d_{Rp} \phi - y_1 \bar{Q}_L D_R H - y_2 \bar{Q}_R D_L H + \mathrm{h.c.}\,,$$
$$V^{\mathrm{NP}}_{\mathtt{potential}} = \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{2}\kappa\, \phi^2 H^\dagger H\,,$$

invisible Higgs decay — neglect

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

- at low energy, this leads to

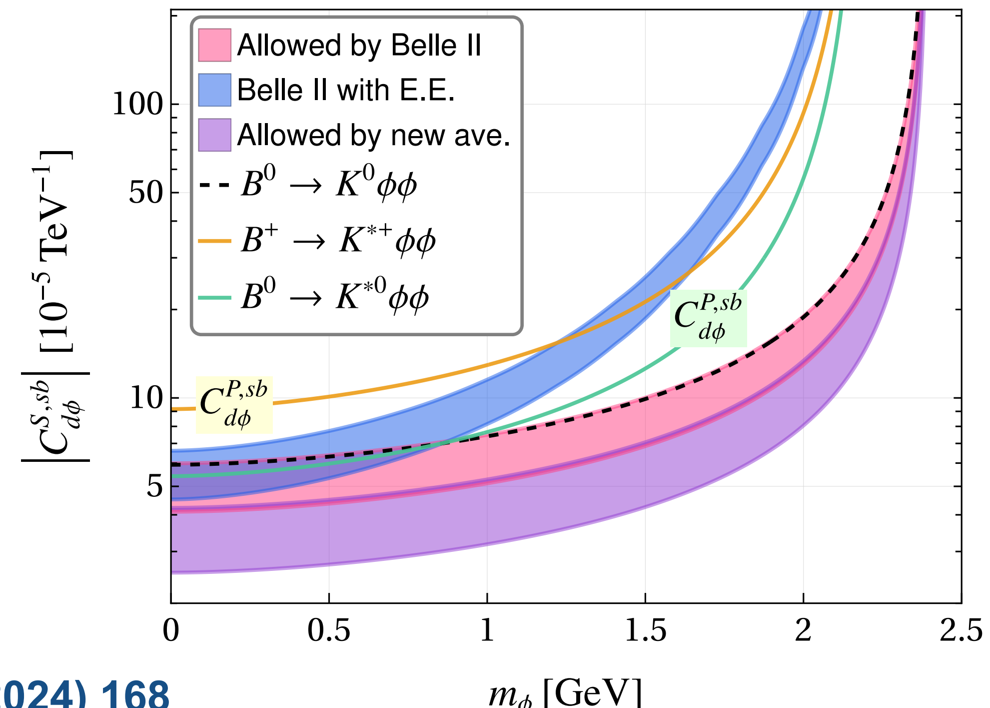
Matchete EPJC 83 (2023) 662

$$\mathcal{L}^{\text{LEFT}}_{\phi\phi qq} = \frac{1}{2} C^{S,ij}_{d\phi} (\bar{d}_i d_j)\phi^2 + \frac{1}{2} C^{P,ij}_{d\phi} (\bar{d}_i i\gamma_5 d_j)\phi^2 + \frac{1}{2} C^{S,ij}_{u\phi} (\bar{u}_i u_j)\phi^2 + \frac{1}{2} C^{P,ij}_{u\phi} (\bar{u}_i i\gamma_5 u_j)\phi^2,$$

$$C^{S,ij}_{d\phi} = \frac{(y^i_q y^j_d y_1 + y^{j*}_q y^{i*}_d y^*_1)v}{\sqrt{2} m_Q m_D} + \left(\frac{y^i_q y^{j*}_q}{2m_Q^2} + \frac{y^{i*}_d y^j_d}{2m_D^2}\right)(m_{d_i} + m_{d_j}), \quad iC^{P,ij}_{d\phi} = \frac{(y^i_q y^j_d y_1 - y^{j*}_q y^{i*}_d y^*_1)v}{\sqrt{2} m_Q m_D} - \left(\frac{y^i_q y^{j*}_q}{2m_Q^2} - \frac{y^{i*}_d y^j_d}{2m_D^2}\right)(m_{d_i} - m_{d_j}),$$

$$C^{S,ij}_{u\phi} = \frac{\tilde{y}^i_q \tilde{y}^{j*}_q}{2m_Q^2}(m_{u_i} + m_{u_j}), \quad iC^{P,ij}_{u\phi} = -\frac{\tilde{y}^i_q \tilde{y}^{j*}_q}{2m_Q^2}(m_{u_i} - m_{u_j}),$$

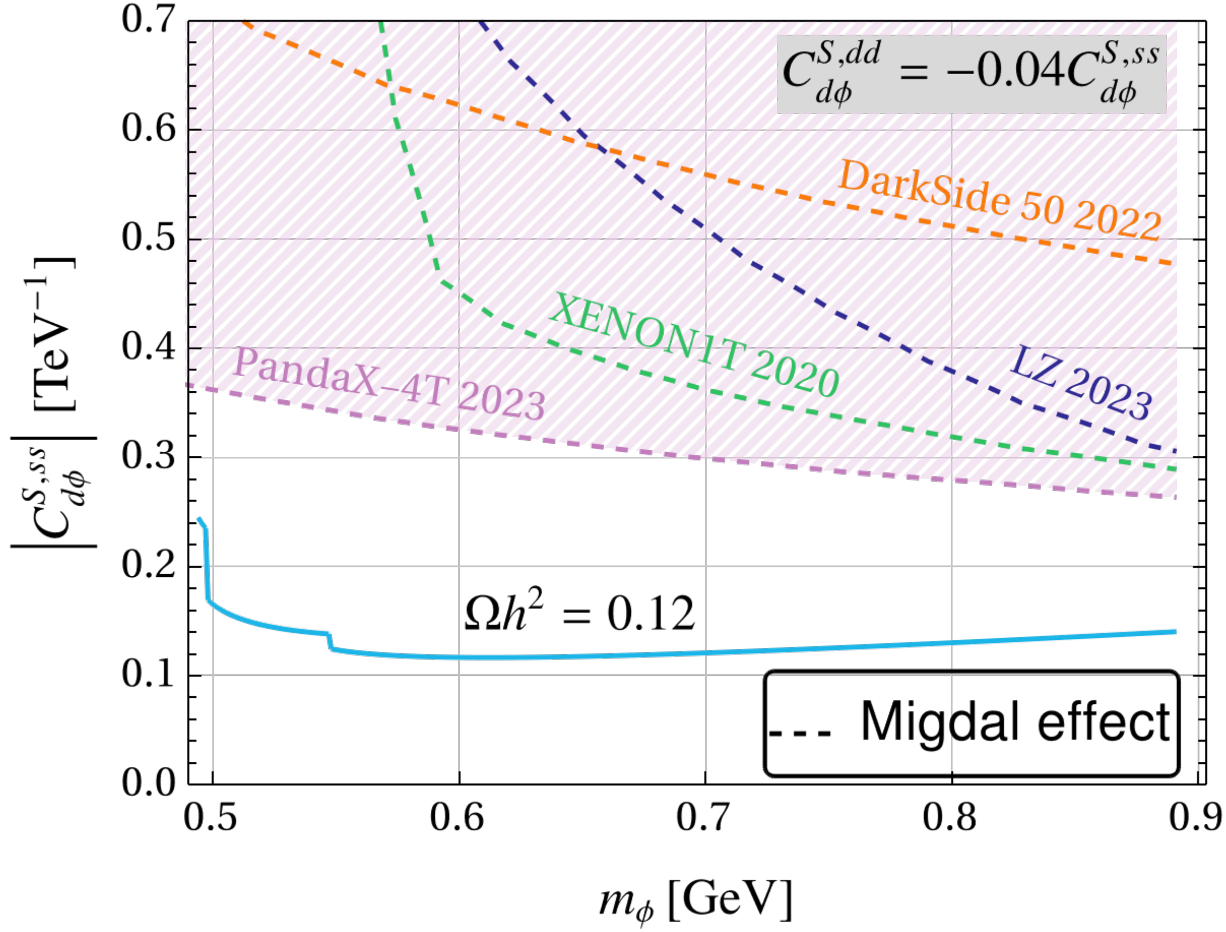
- excess can be explained, i.e. with $C^{S,sb}_{d\phi} \sim (3-8)/(10^5\,\text{TeV})$ for $m_\phi = 1$ GeV



He, Ma, Schmidt, GV,Volkas JHEP 07 (2024) 168

ϕ as dark matter

- viable models require an interplay between different parameters, one example is shown below (right figure) with $|y^d_{q,d}| \sim 0.2|y^s_{q,d}|$ implying $|C^{S,dd}_{d\phi}| \sim 0.2|C^{S,ds}_{d\phi}| \sim 0.04|C^{S,ss}_{d\phi}|$



He, Ma, Schmidt, GV,Volkas JHEP 07 (2024) 168

other constraints satisfied

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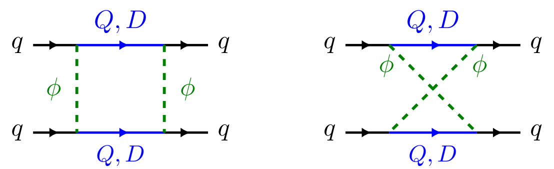
- $B \to X_s\gamma$
  - model induces $O^{ij}_{d\gamma} = \bar{d}_i \sigma^{\mu\nu} P_R d_j F_{\mu\nu}$, $\mathcal{O}^{ij}_{dG} = \bar{d}_i T^A \sigma^{\mu\nu} P_R d_j G^A_{\mu\nu}$
  - with $\tilde{C}^{sb}_{d\gamma}$ roughly the same order as the induced $C^{S,sb}_{d\phi}$
  - coefficient allowed by global fits $\tilde{C}^{sb}_{d\gamma} \lesssim 260/(10^5\,\mathrm{TeV})$ and
  - whereas for $B \to K^{(*)} + \mathrm{invisible}$ we need $C^{S,sb}_{d\phi} \sim (3-8)/(10^5\,\mathrm{TeV})$
- $B_s - \bar{B}_s, B_d - \bar{B}_d, K - \bar{K}$ mixing appear at dim 8,
- compare to SM $1.9 \times 10^{-6} G_F\, (\bar{s}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L b)$
  - B_s mixing roughly scales as



$$3 \times 10^{-8} G_F \left(\frac{3\,\mathrm{TeV}}{m_{Q,D}}\right)^4 [(y^s_q y^b_d)^2, (y^{s*}_d y^{b*}_q)^2, y^s_q y^{s*}_d y^{b*}_q y^b_d] y^2_{1,2}\, (\bar{s}P_{R,L}b)(\bar{s}P_{L,R}b)$$

  - and we need $m \sim 50\ \mathrm{TeV}$ for $B \to K^{(*)} + \mathrm{invisible}$ with yukawas ~ 1
- $gg \to H,\ H \to \gamma\gamma$ and others are also ok

monojets at LHC

- constrain the parameter space of invisible scalars
- toy model to compare EFT constraints from LHC data to a simple UV completion
  - a few surprises in this comparison

PHYSICAL REVIEW D **103,** 112006 (2021)

Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.**
(ATLAS Collaboration)

TABLE I. Intervals and labels of the E_T^{miss} bins used for the signal region. Details are given in the text.

Exclusive (EM)	EM0	EM1	EM2	EM3	EM4	EM5	EM6
E_T^{miss} [GeV]	200–250	250–300	300–350	350–400	400–500	500–600	600–700
	EM7	EM8	EM9	EM10	EM11	EM12	
	700–800	800–900	900–1000	1000–1100	1100–1200	>1200	

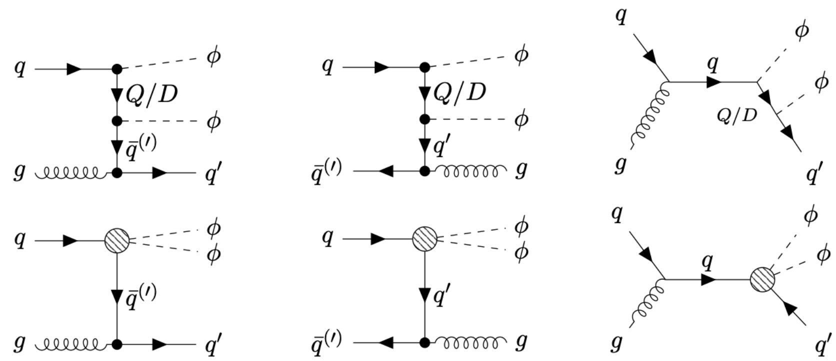
Exclusive Signal Region		
Region	Predicted	Observed
EM0	1 783 000 ± 26 000	1 791 624
EM1	753 000 ± 9000	752 328
EM2	314 000 ± 3500	313 912
EM3	140 100 ± 1600	141 036
EM4	101 600 ± 1200	102 888
EM5	29 200 ± 400	29 458
EM6	10 000 ± 180	10 203
EM7	3870 ± 80	3986
EM8	1640 ± 40	1663
EM9	754 ± 20	738
EM10	359 ± 10	413
EM11	182 ± 6	187
EM12	218 ± 9	207

monojets at LHC and invisible scalars

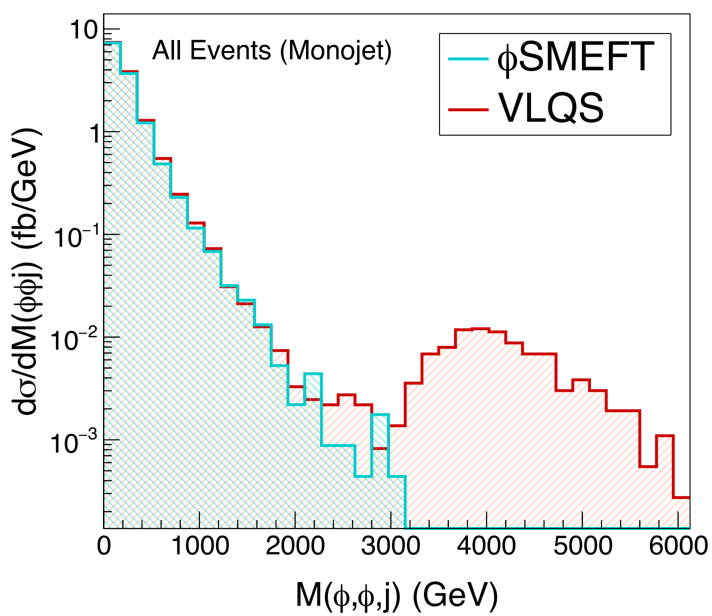
ϕSMEFT vs UV

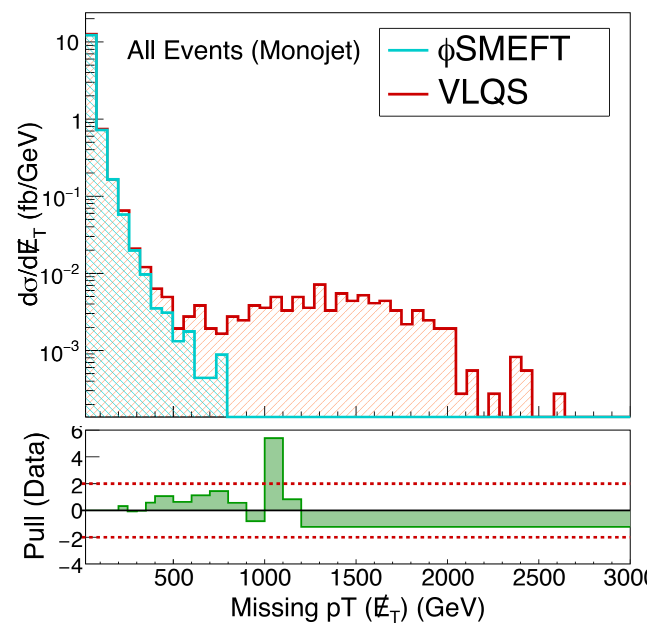
$$\mathcal{O}^{pr(6)}_{qdH\phi^2} = (\bar{q}_{Lp} d_{Rr} H)\, \phi^2,$$

$$\frac{[\mathcal{C}_{qdH\phi^2}]_{pr}}{\Lambda^2} = \frac{y_q^p y_d^r y_1}{m_Q m_D}$$



$M_{Q/D} = 3$ TeV, $y^d_{q/d} = y^s_{q/d} = 1$, $y_1 = 1$ $\quad m_\phi = 1$ GeV





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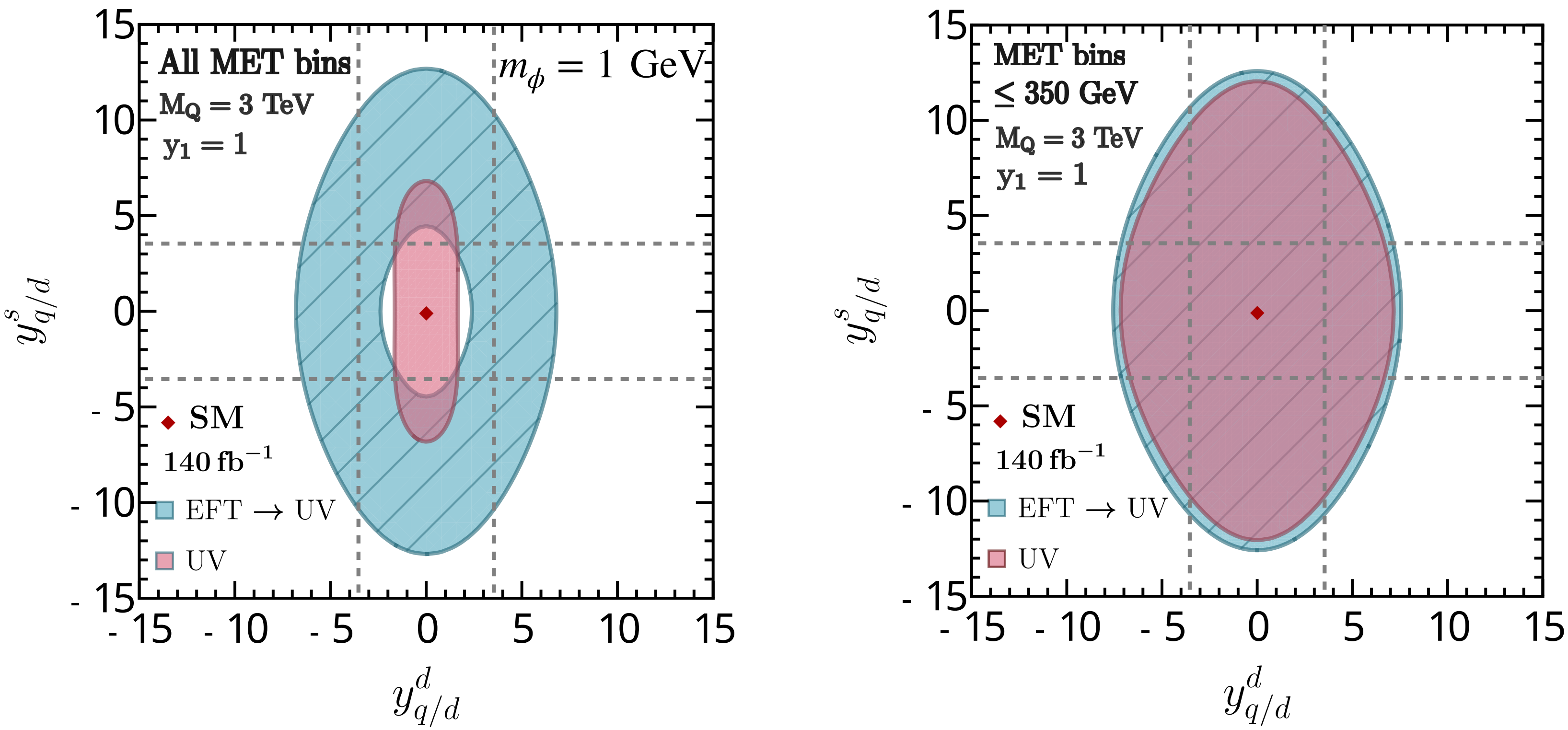
monojets at LHC and invisible scalars

ϕSMEFT vs UV



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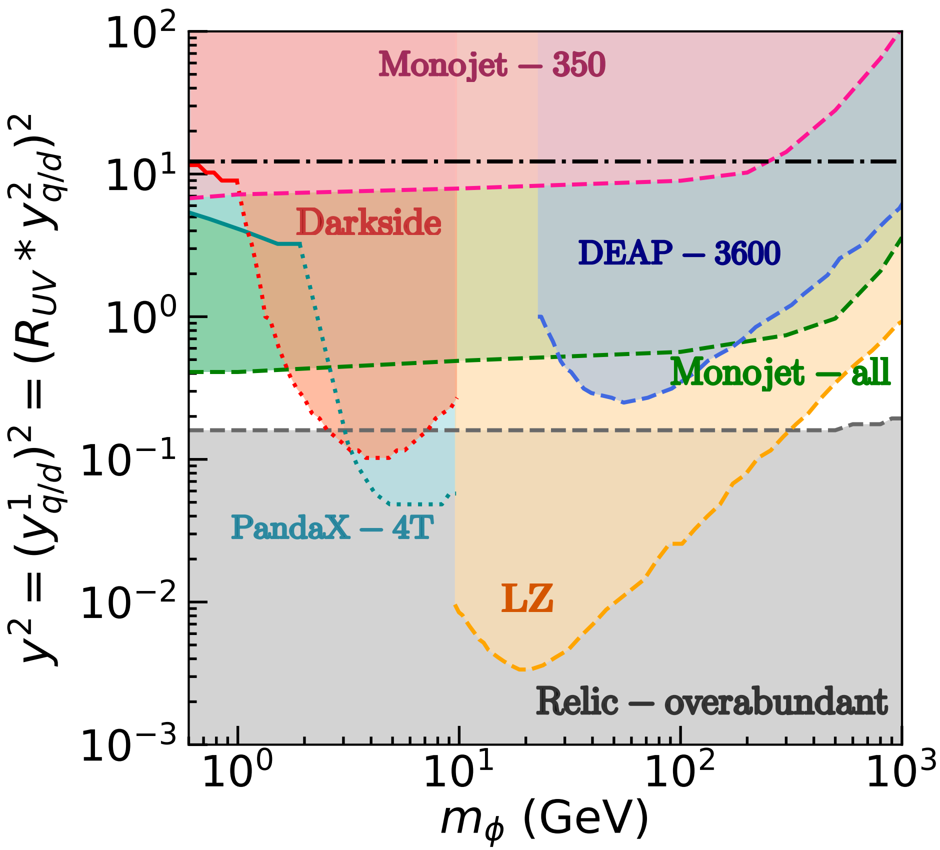
- $$\sigma_{\rm SI}^N = \frac{\mu_{\phi N}^2}{4\pi m_\phi^2}\left[\frac{\sqrt{2}v}{\Lambda^2}\sum_{q=u,d,s}\left(f_{T_q}^{(p)}\frac{m_N}{m_q}\frac{Z}{A}\mathcal{C}_{qq} + f_{T_q}^{(n)}\frac{m_N}{m_q}\frac{A-Z}{A}\mathcal{C}_{qq}\right) - \frac{16\pi m_N f_{TG}^{(N)}}{9\alpha_s}\frac{\mathcal{C}_{G\phi}}{\Lambda^2}\right]^2$$



- PandaX-4T DarkSide-50 with Migdal effect for light DM with $m_\phi \lesssim 2$ GeV. Above $m_\phi \sim 9$ GeV, LZ places the strongest limits.
- PandaX and LZ use Xenon targets, DarkSide uses Argon
- DEAP-3600, uses Argon, places constraints for $m_\phi \gtrsim 20$ GeV.

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summary

- motivated by recent Belle II and NA62 results, we explored the NP physics window that could be probed with the modes $B^+ \to K^+ + \texttt{invisible}$ and $K^+ \to \pi^+ + \texttt{invisible}$
- we assume the NP takes the form of pairs of invisible scalars and construct the relevant effective theory
- there are viable regions of parameter space that populate these windows with invisible scalars
- it is possible to interpret these scalars as DM and satisfy relic density and DD constraints, including those with the Migdal effect
- a t-channel mediator model with two VLQ was used as an existence proof to demonstrate that it is possible to satisfy these and other phenomenological constraints
- a new monojet study provides a useful comparison of bounds obtained using SMEFT vs a simple UV completion
- the monojet constraints complement those from DD