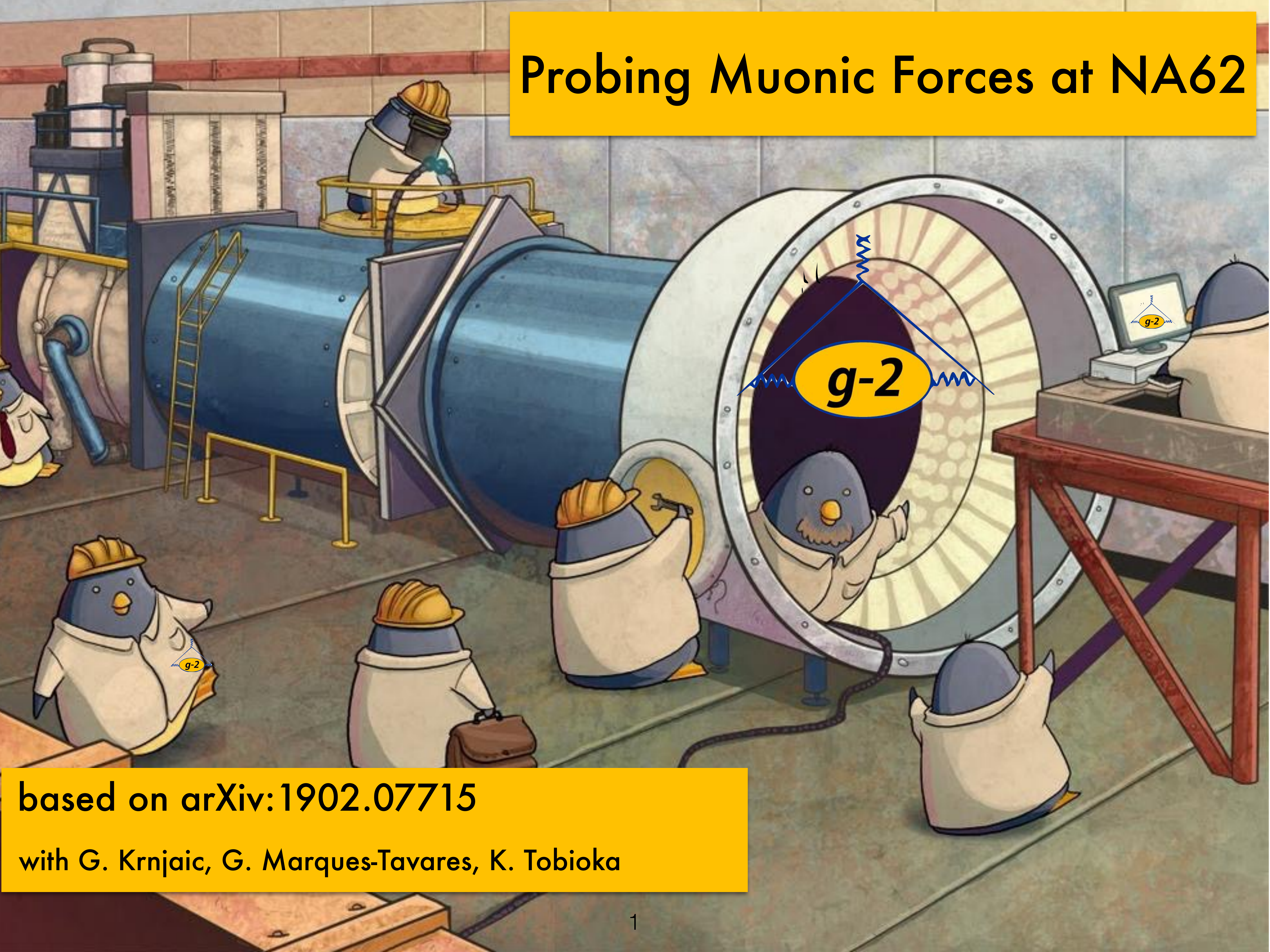
Probing Muonic Forces at NA62



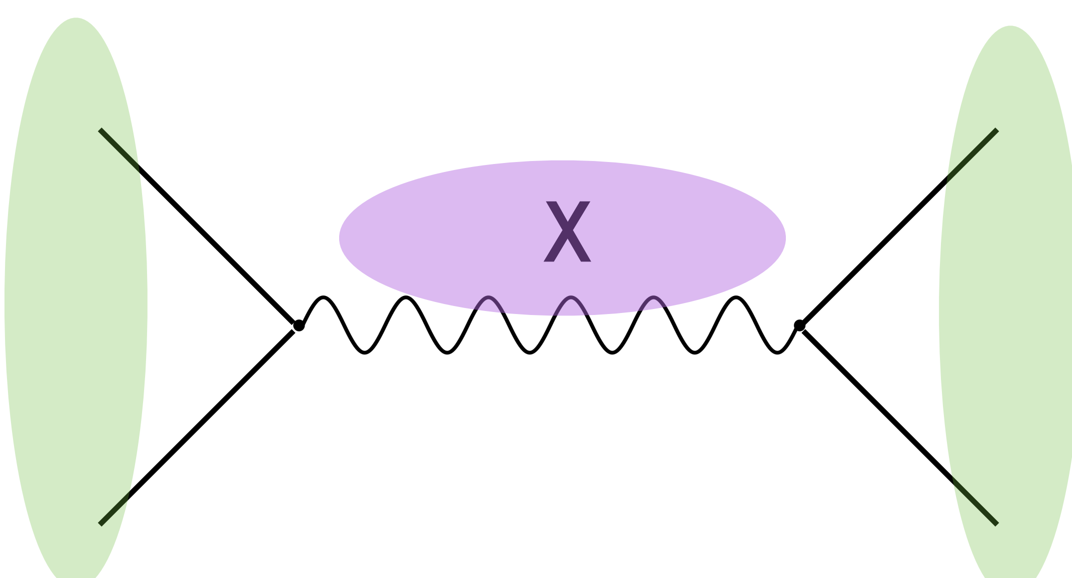
based on arXiv:1902.07715

with G. Krnjaic, G. Marques-Tavares, K. Tobioka

FORCES IN PARTICLE PHYSICS

The force properties are encoded

in the nature of the particle carrier
& its interactions with matter



THE "CHEMISTRY"

OF FORCES

MASS
SPIN
X
COUPLING

THE FORCES WE KNOW...

Short range

0	80. 4 GeV	90. 2 GeV	125 GeV
1 g	1 $W^{\pm}$	1 Z	0 h
$g_s \simeq 1.2$	$g \simeq 0.64$	$g' \simeq 0.3$	yukawas…

fm   pm

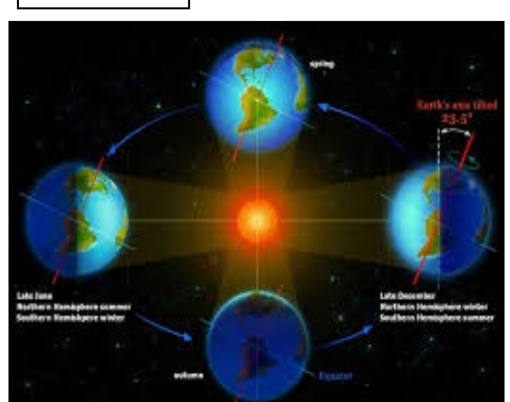
- confinement
- symmetry breaking

Seen in EU colliders :

Long range

0	0
1 γ	2 $h_{\mu\nu}$
$e \simeq 0.3$	$\frac{m_p}{M_{Pl}} \simeq 10^{-19}$

Seen in everyday life:



this is all we got so far...

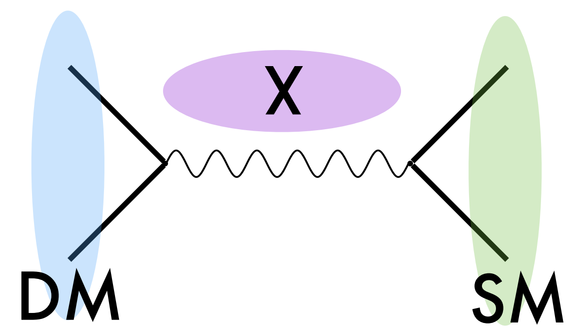
NEW (DARK) FORCES?

PLAUSIBLE to imagine
new (dark) forces
to be present...

DARK MATTER PRODUCTION

Many Production mechanisms require a (new) FORCE acting as a PORTAL

Example: FREEZE-OUT



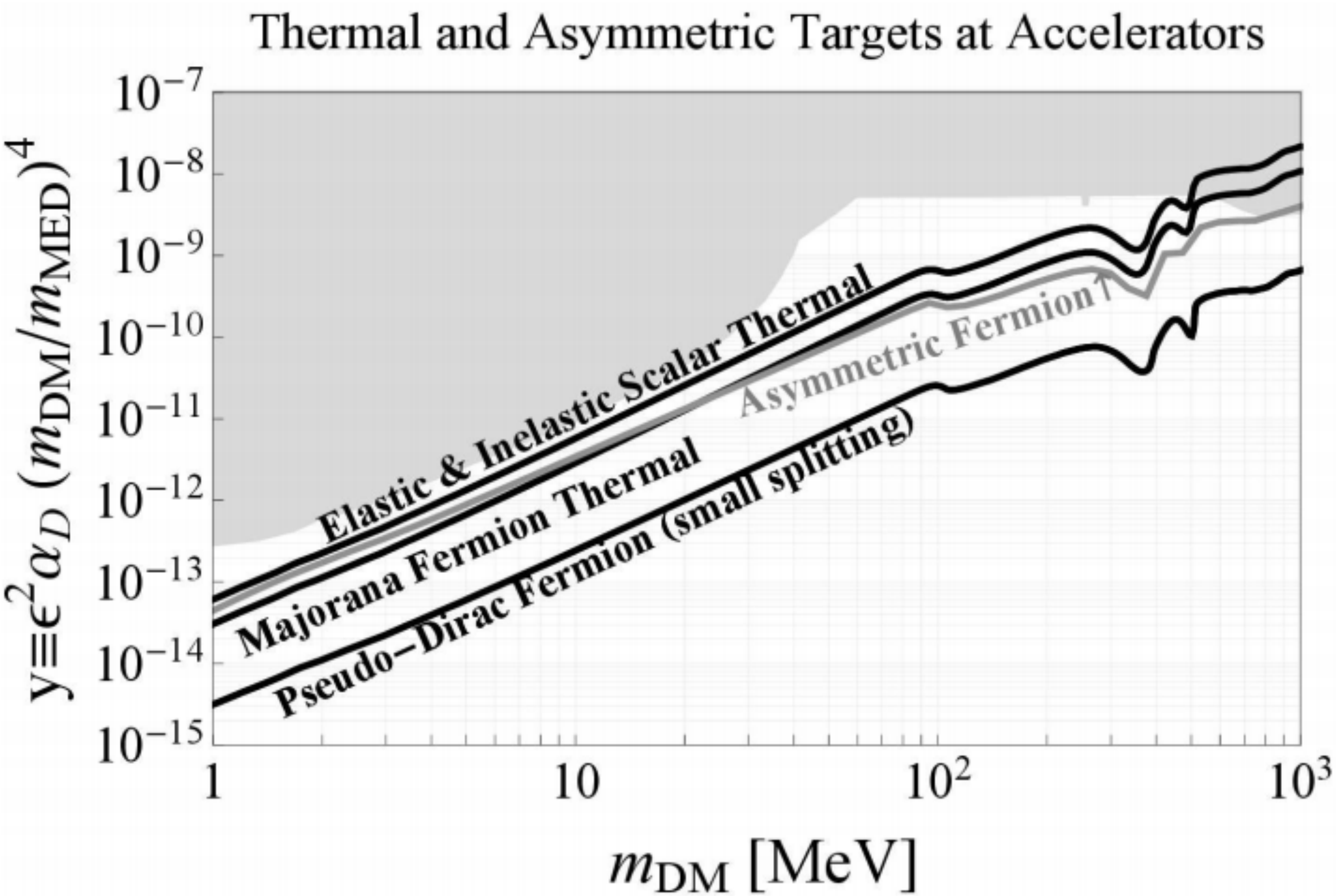
Fixing the abundance of the Dark Matter today sets the strength of the new force

(assuming annihilation mostly into SM)

DARK MATTER PAR. SPACE

$m_\chi < m_{A'}$

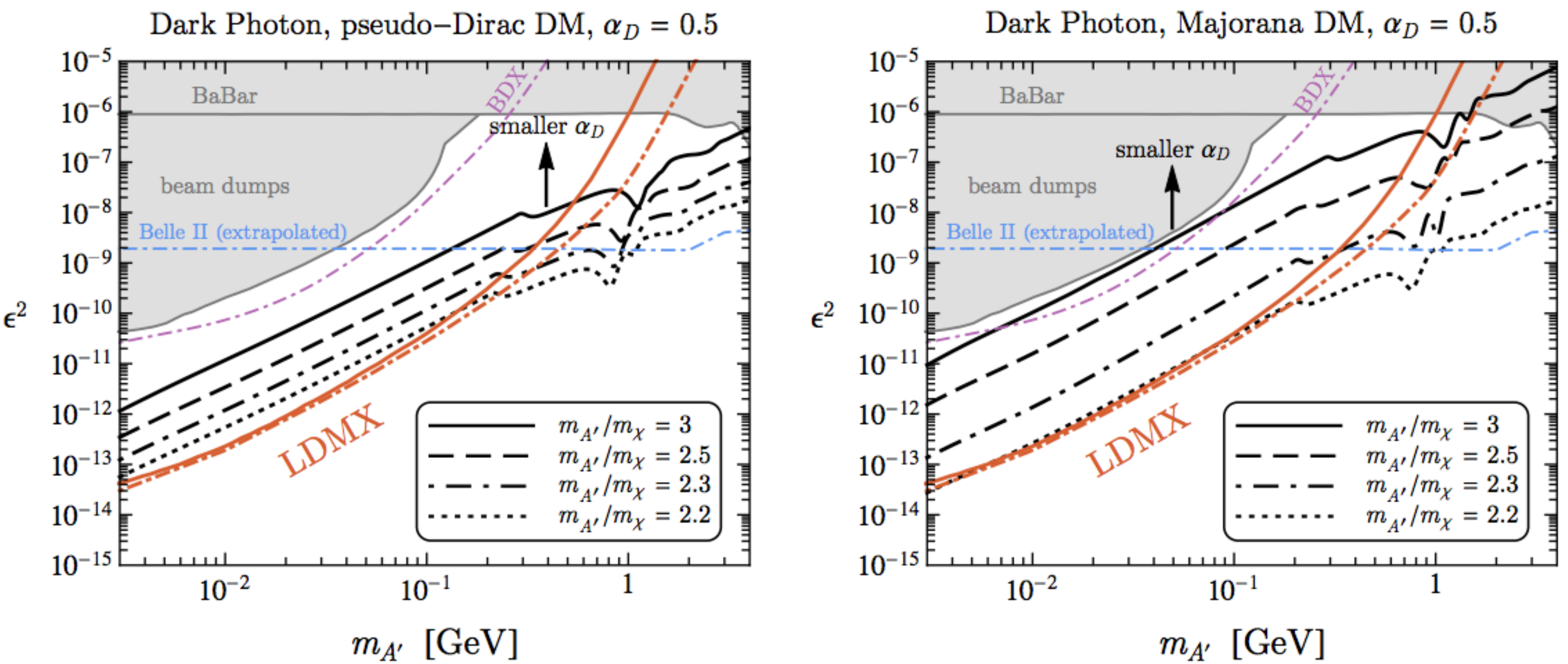
$$\sigma v(\chi\chi \to f\bar{f}) \propto \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$



FUTURE EXPERIMENTAL PROGRAM

Light thermal DM models are predictive targets for future beam dump experiments!

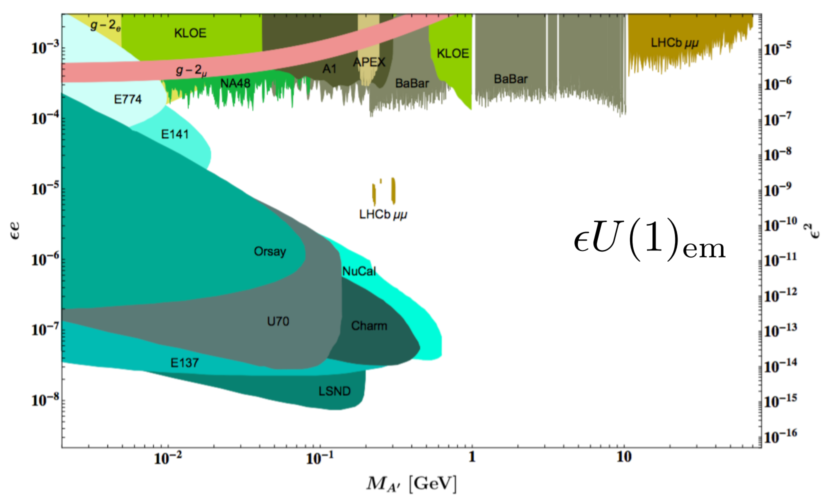
plots from Berlin, Blinov, Krnjaic, Shuster, Toro (2018)

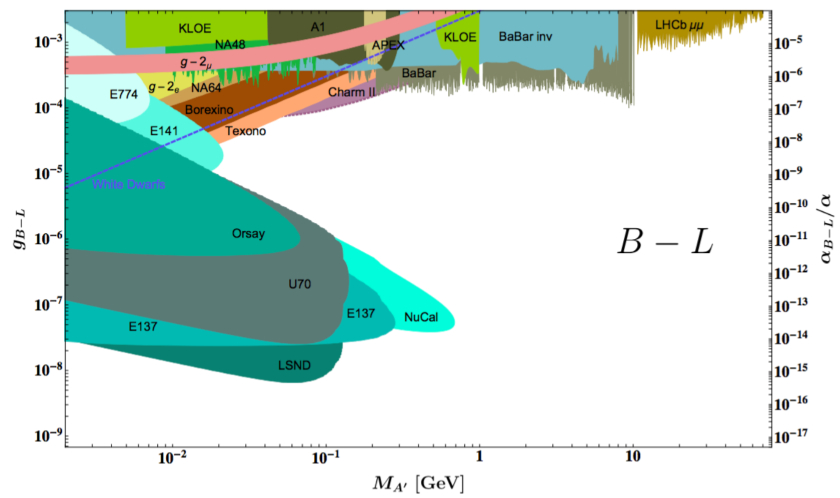


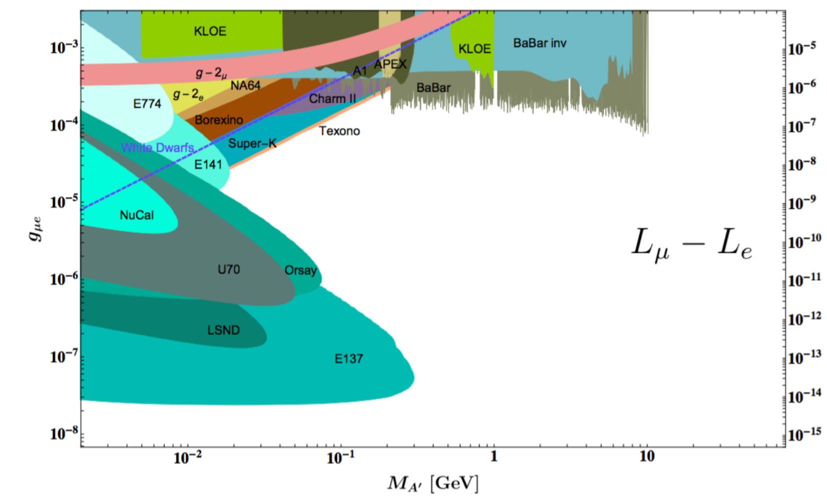
TARGETING THE MEDIATORS

ABELIAN FORCES (NON-ANOMALOUS)

today:

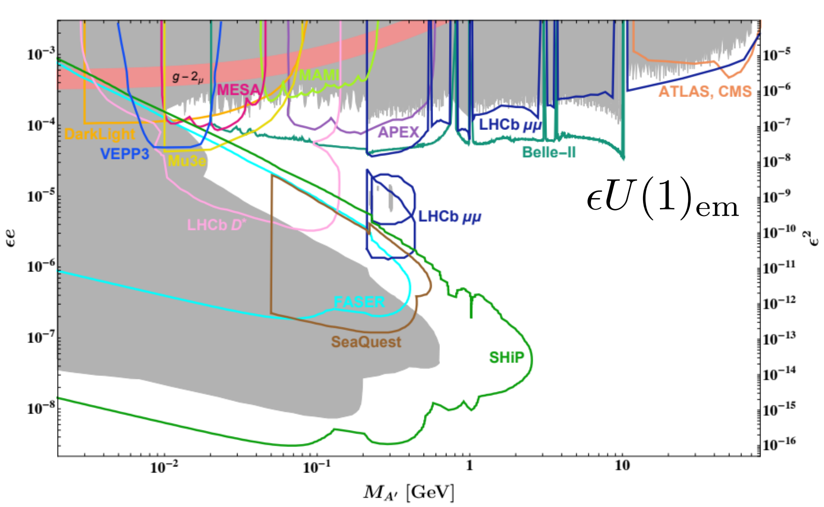


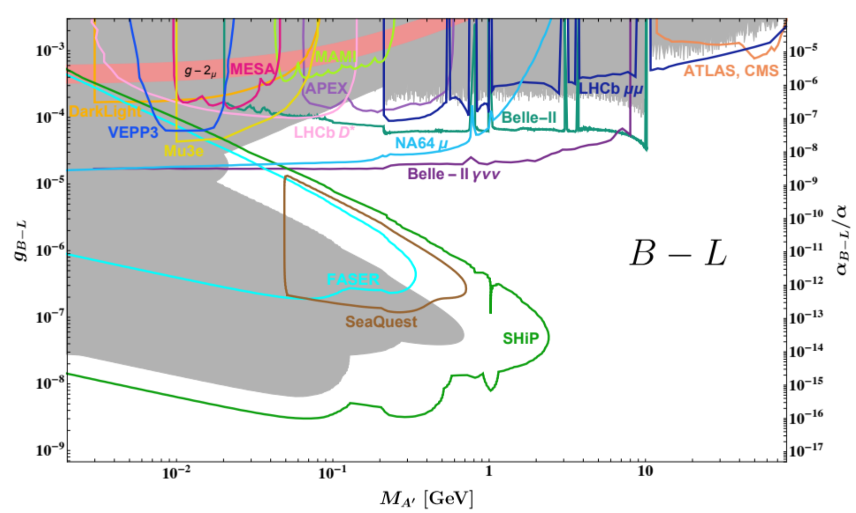


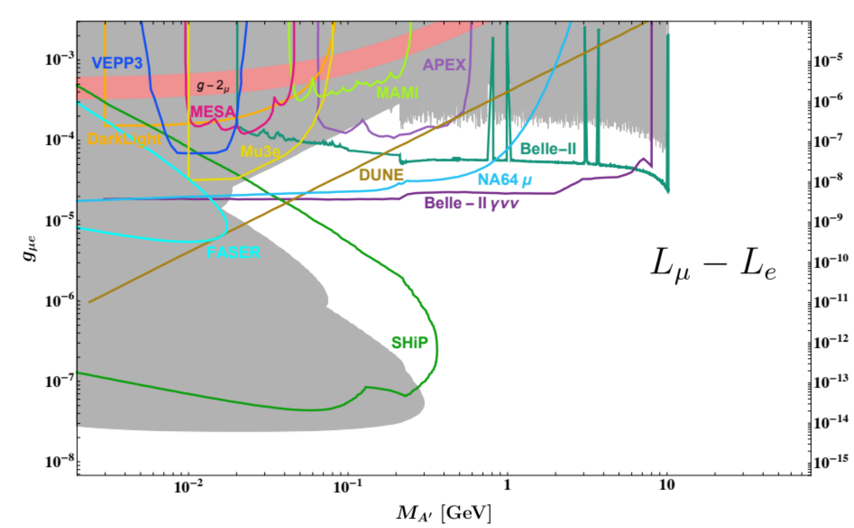


plots from Bauer, Foldenauer, Jaeckel (2018)

future facilities:

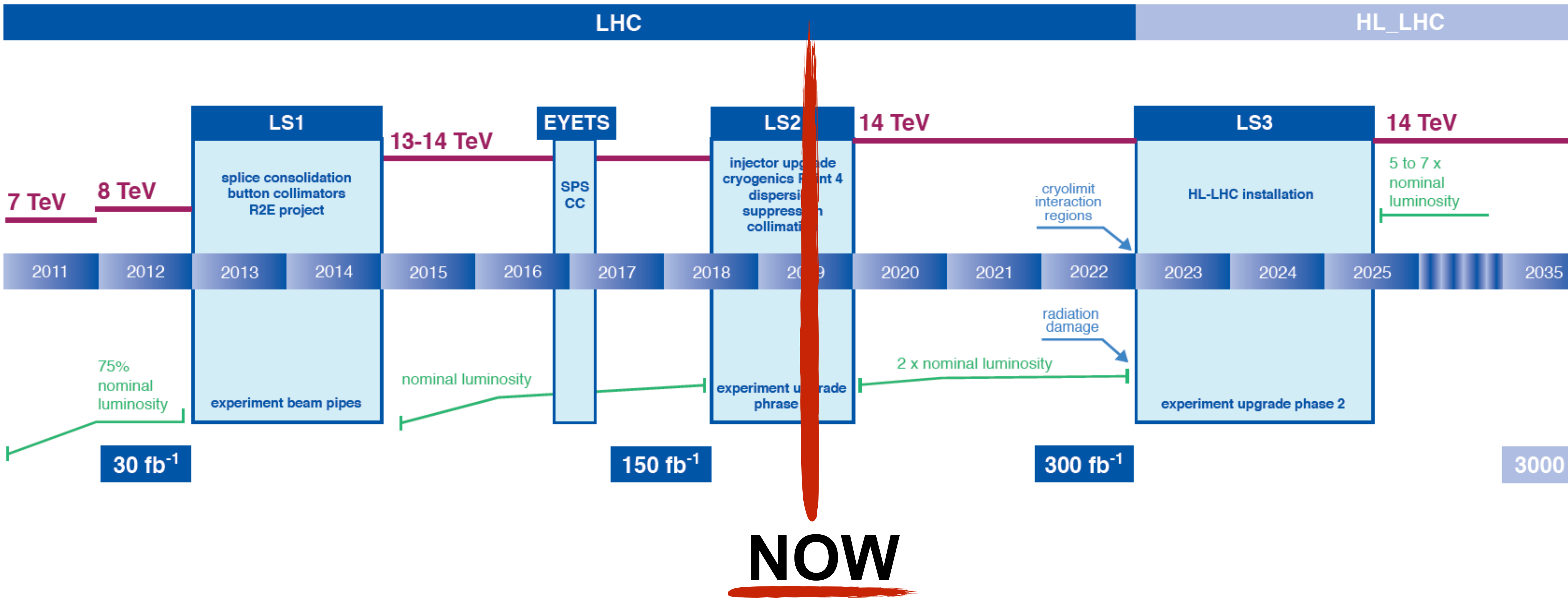






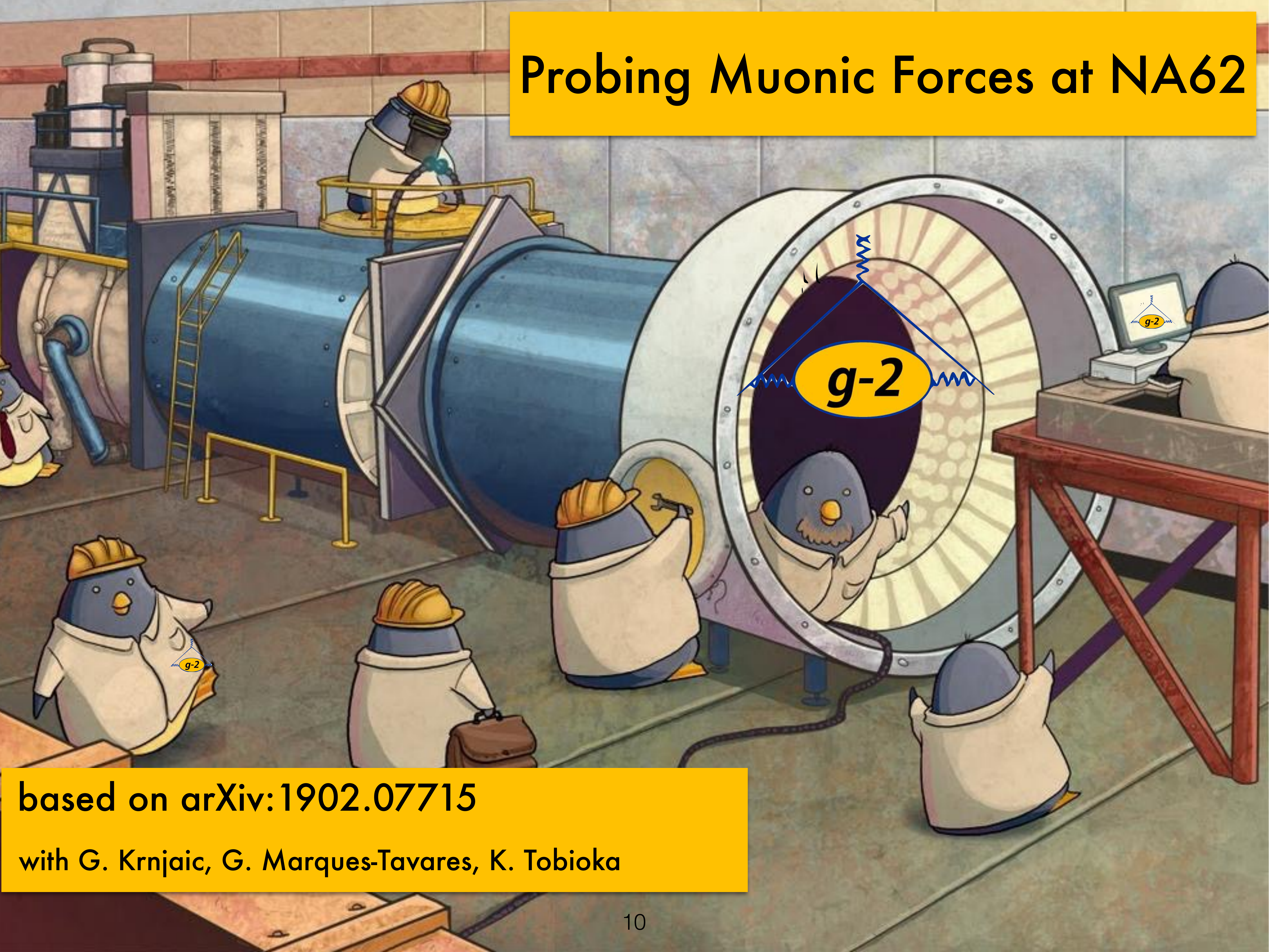
WHAT ABOUT LHC?

Experiments using the LHC beam will take data for the next 10 years...



- Crucial to understand the (missed) physics opportunities **NOW**
- This understanding has an impact on the **FUTURE** experimental effort

Probing Muonic Forces at NA62



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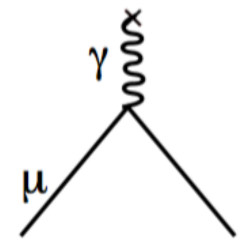
with G. Krnjaic, G. Marques-Tavares, K. Tobioka

THE G-2 DISCREPANCY

The anomalous magnetic moment of the muon

$$i\partial_t \phi = \left[\frac{\vec{p}^2}{2m} - \frac{e}{2m}(\vec{L} + 2\vec{S}) \cdot B\right] \phi$$

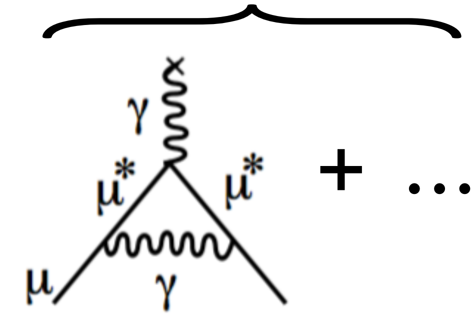
$$g = 2$$



In QFT particles can split:

$$a = \frac{g-2}{2}$$

SM prediction



DISCREPANCY: $\Delta a_\mu = a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = 273(80) \cdot 10^{-11}$

E821 experiment at BNL 2001, 2006

g-2 @ Fermilab SOON

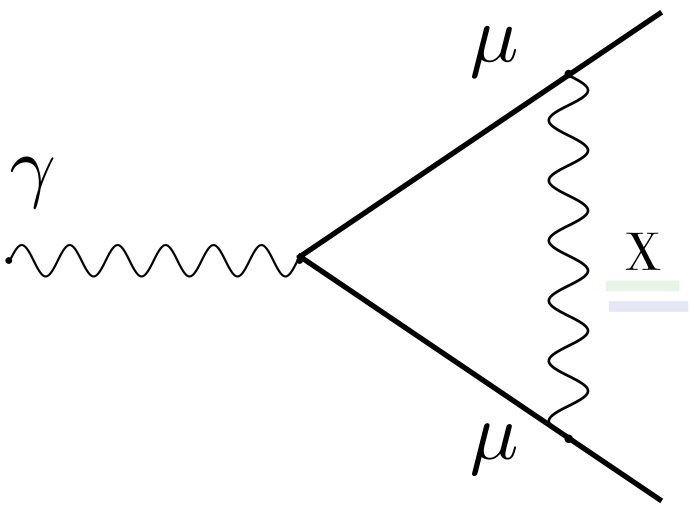
theory prediction @ 5-loops in QED T. Aoyama et al. (2012)

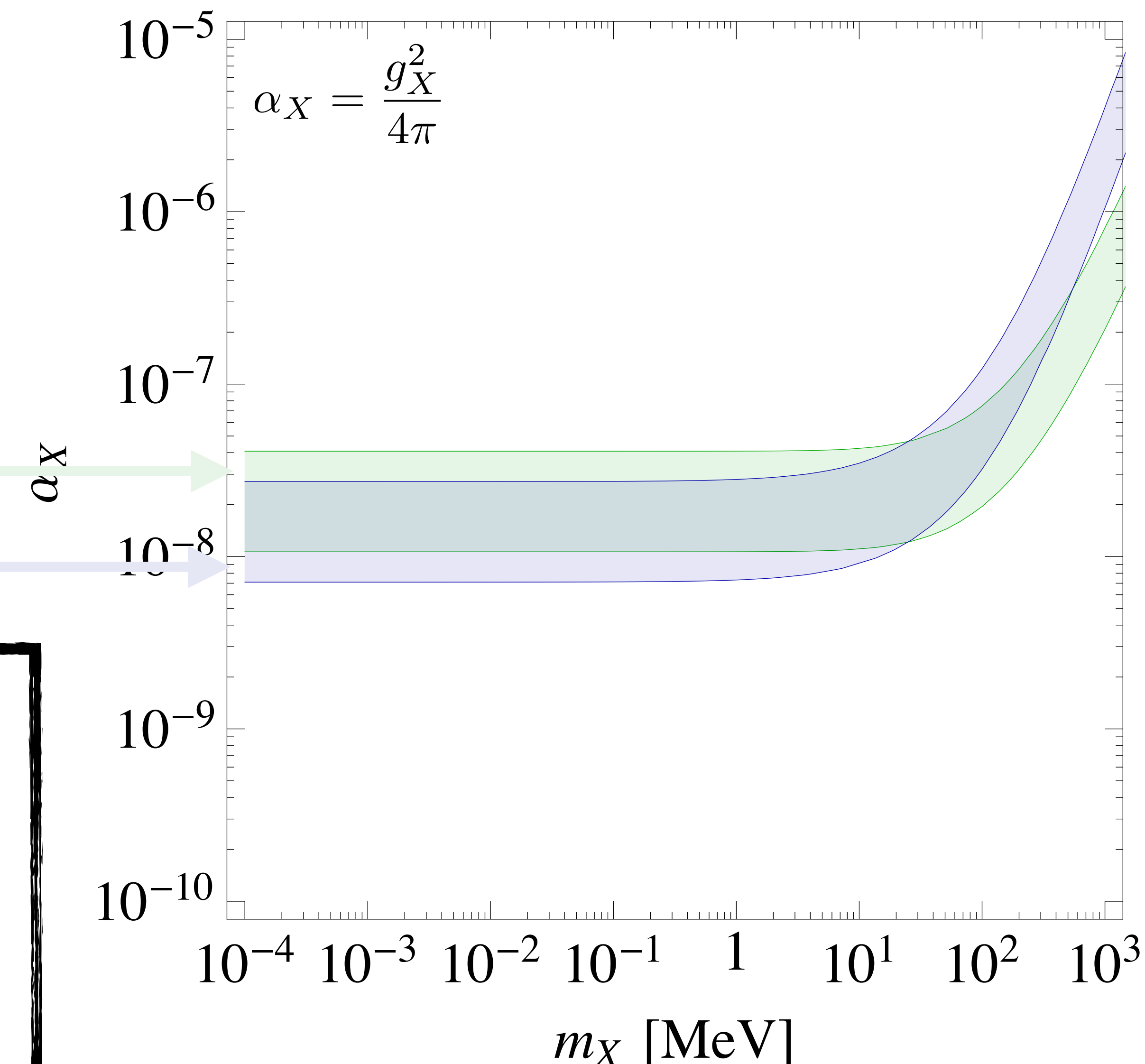
large sensitivity to hadronic contributions A. Kurz et al. (2014)

MUONIC FORCES & G-2

New forces can accommodate the g-2 anomaly

Pospelov (2008)





$X = \phi$ **Light CP-even scalar**

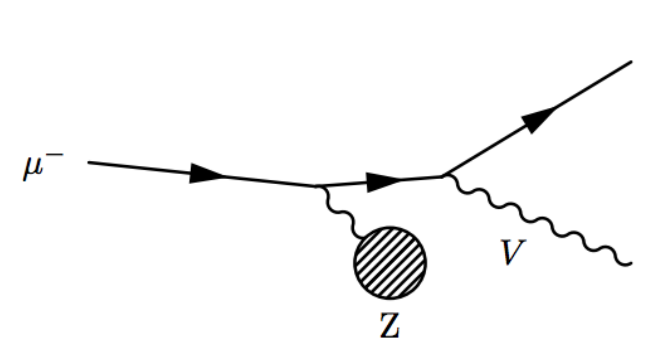
$X = V$ **Light vector boson**

- axial couplings give opposite sign in the loop
- below 100 MeV the coupling is fixed $\sim 10^{-8}$

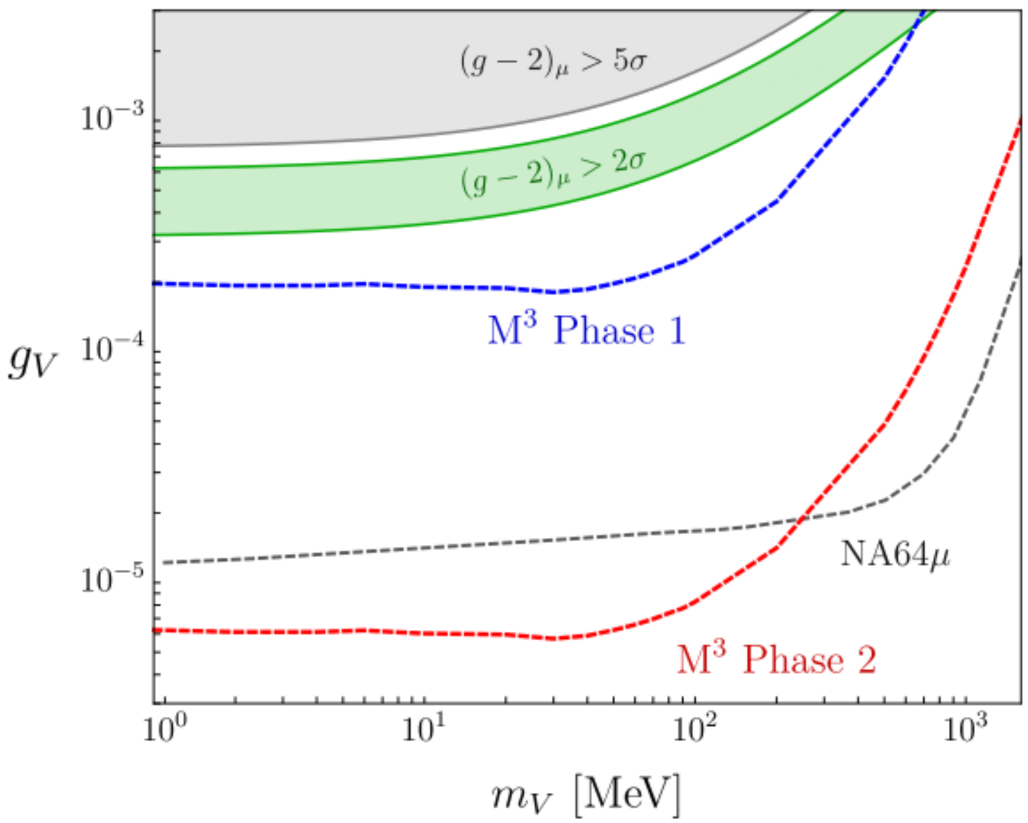
FUTURE HUNTS

New forces coupled mostly to muons require a dedicated experiment…

Missing muon momentum experiments



vector boson



2 proposals…

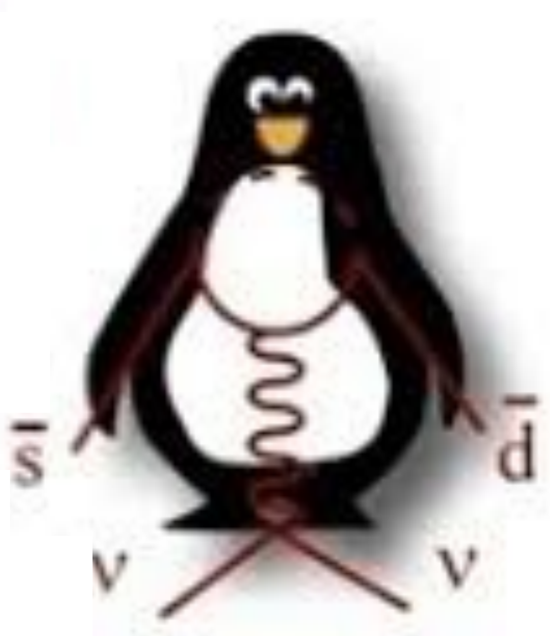
NA64μ @ CERN S.N. Gninenko, N.V. Krasnikov 2014, 2018

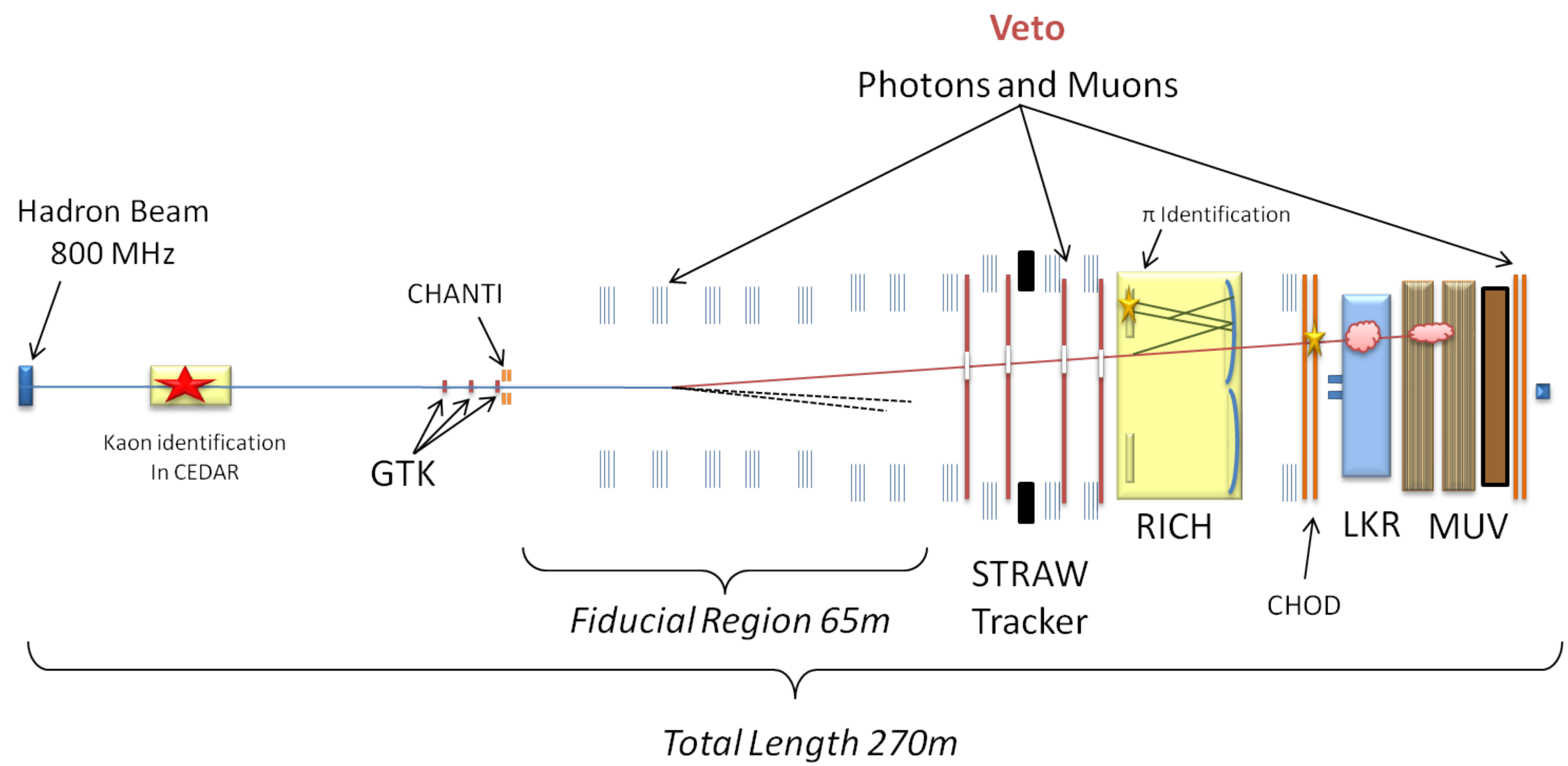
M^3 @ Fermilab Y. Kahn, G. Krnjaic, N. Tran, A. Whitbeck 2018

MONEY + TIME

KAON FACTORY: NA62

North **A**rea 62 $\sim 10^{13} K^+$



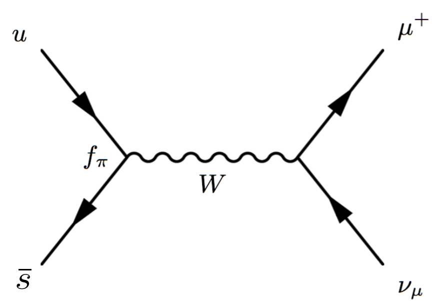


MAIN PURPOSE is to measure

$\mathrm{BR}(K^+ \to \pi\nu\bar{\nu}) \sim 10^{-10}$ with 10% precision

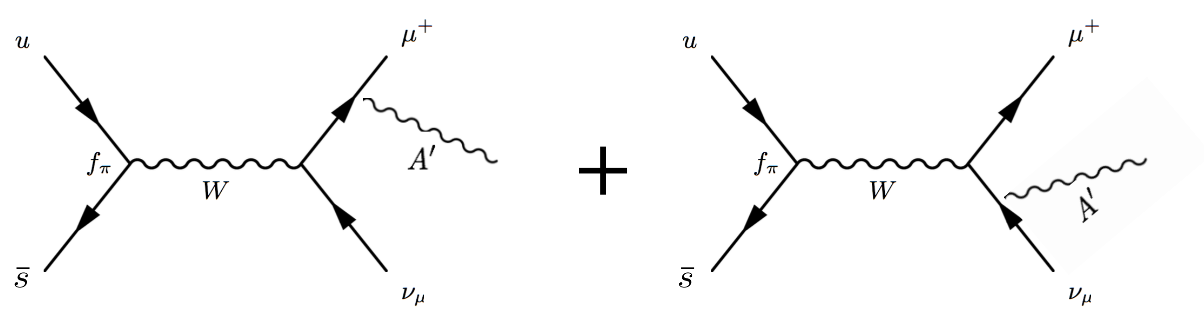
MUONIC FORCES @ NA62

IDEA:



$K^+ \to \mu^+ + \nu$ $\quad$ $\mathrm{BR} = 63.65\%$

intense KAON beams lead to A LOT of MUONS



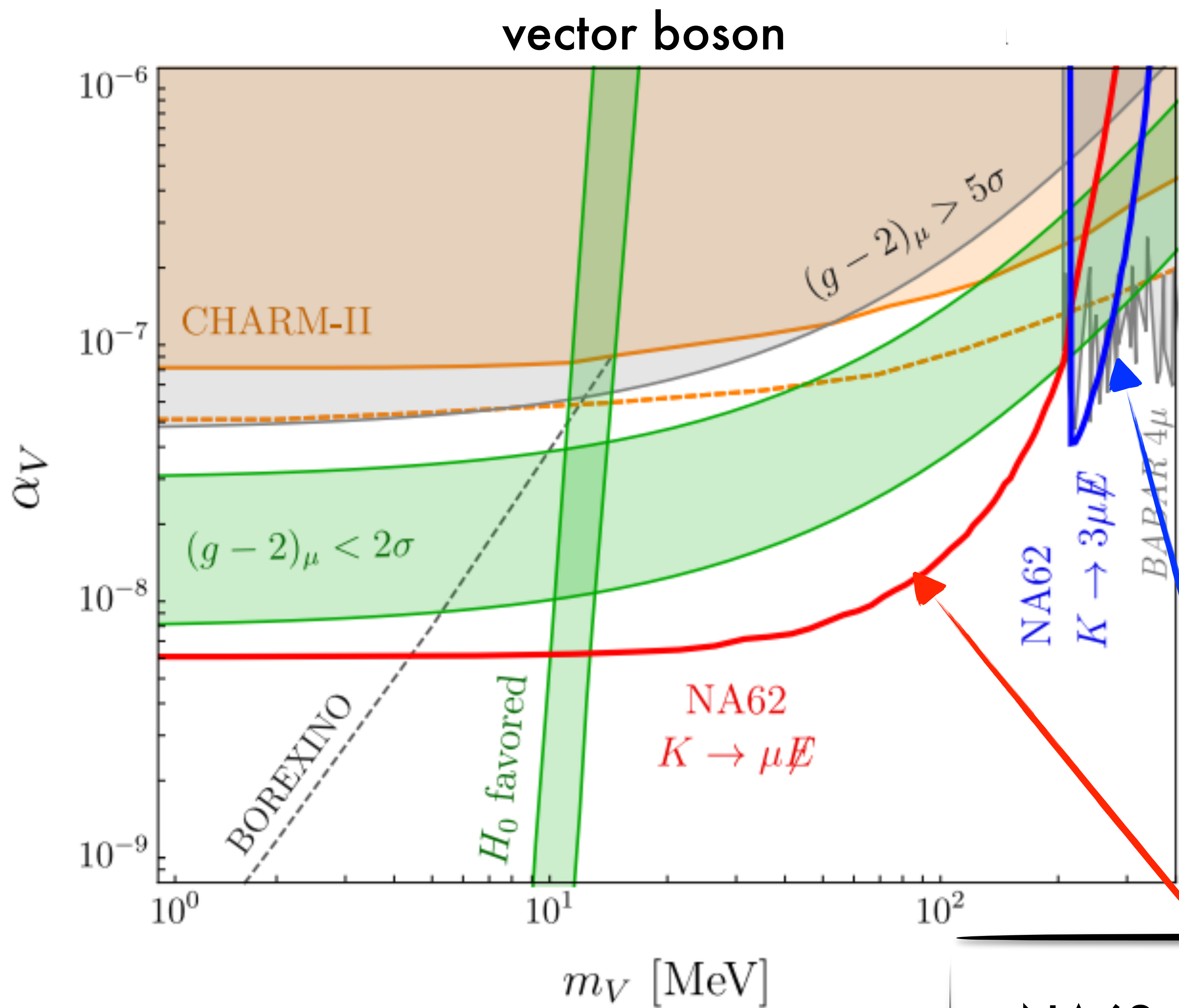
BR modified at the level of 10^{-8} at low masses

$$K^+ \to \mu^+ + \nu + V$$

2 POSSIBLE CHANNELS:

- INVISIBLE $\quad V \to \mathrm{inv.}$
- DI-MUON $\quad V \to 2\mu$

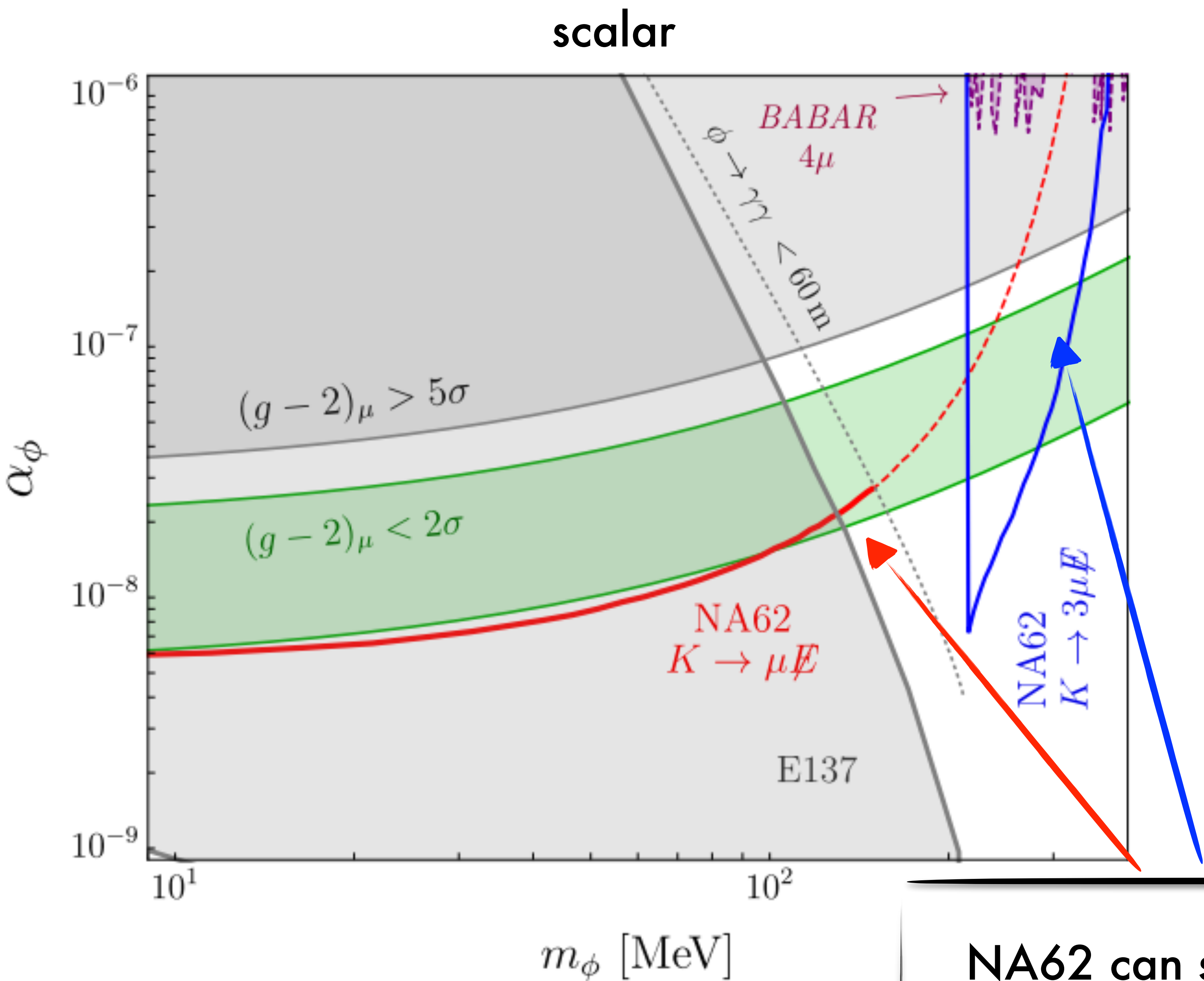
G-2 PARAMETER SPACE



- VISIBLE channel under exp. study
- TRIGGER CHALLENGES for the invisible channel

NA62 can say something NOW!

G-2 PARAMETER SPACE



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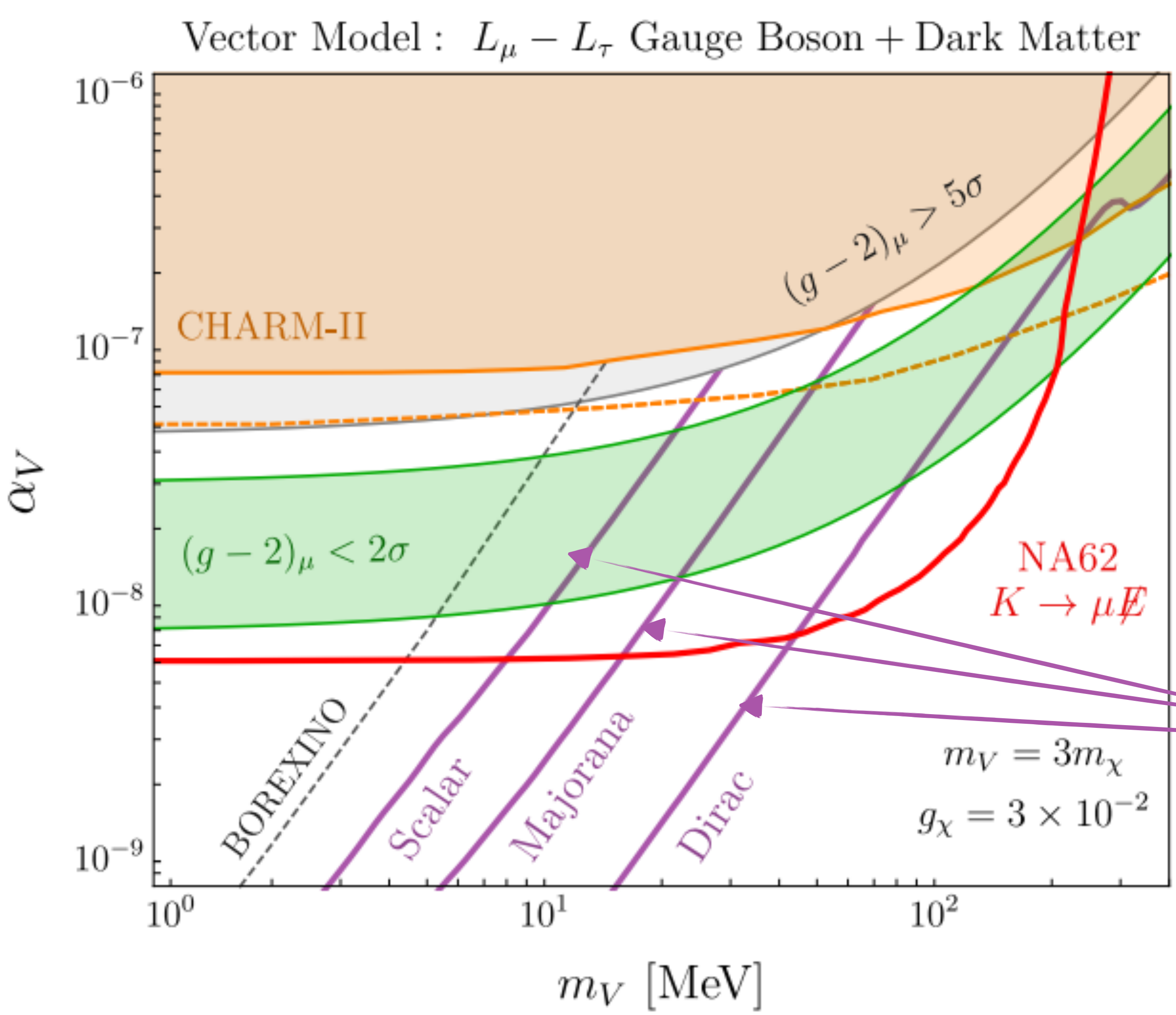
NA62 can say something NOW!

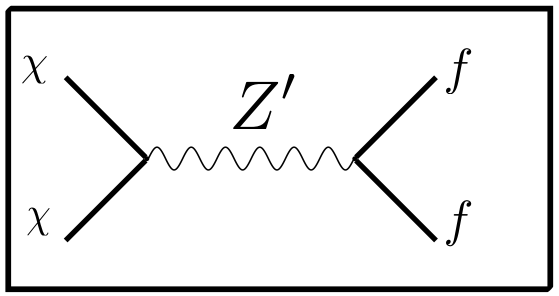
MUONIC FORCES & DARK MATTER

A muonic force gives dark sector portal for freeze-out

Difficult for direct detection experiments (no nucleon or electron scattering)



Assuming $m_{Z'} \gg m_\chi \gg m_f$



For a fixed mass there is a single coupling that leads to the correct relic abundance

THE INVISIBLE SEARCH

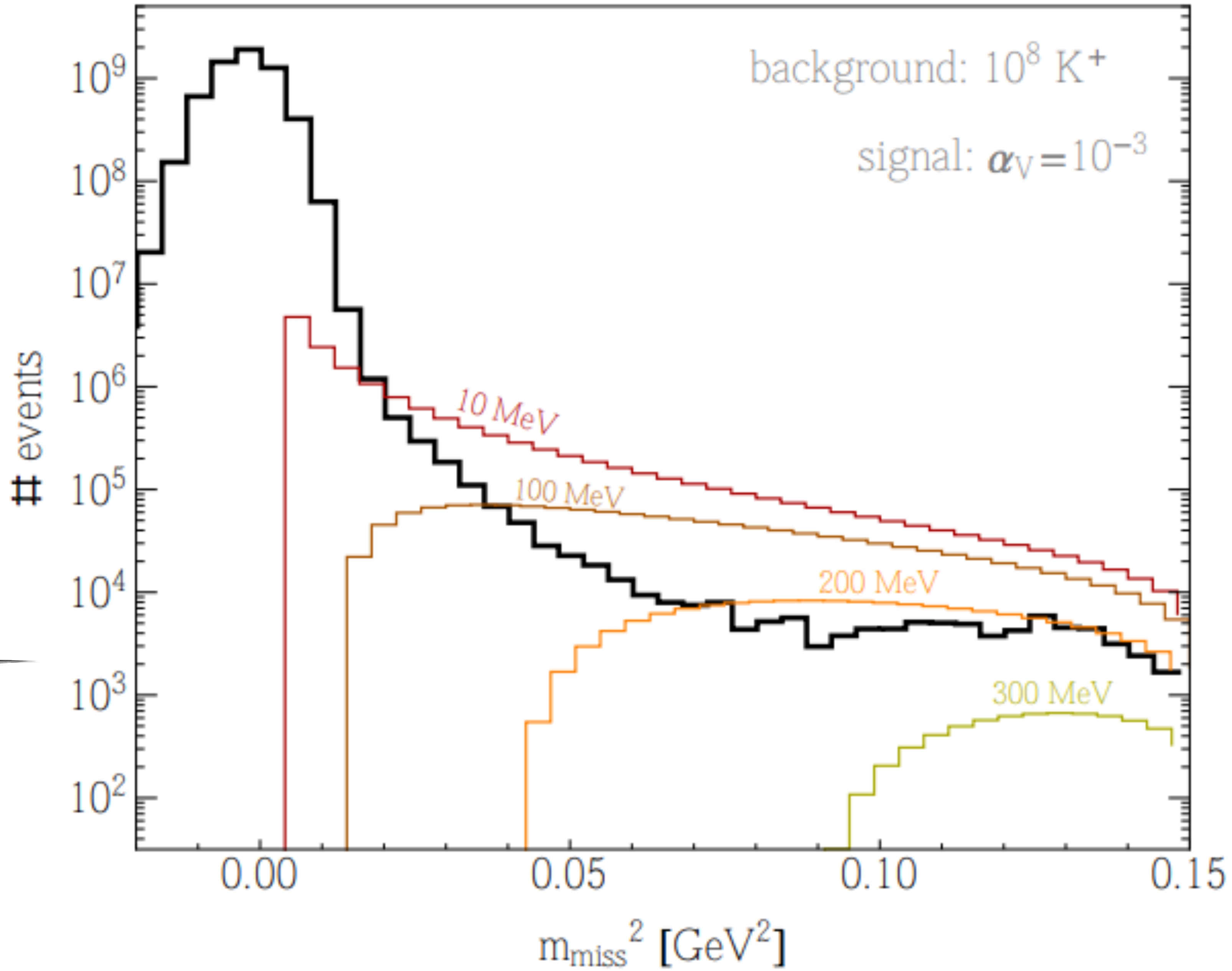
$$\frac{d\Gamma(K^+ \to \mu^+\nu X)}{dm^2_{\rm miss}} = \frac{1}{256\pi^3 m_K^3}\int \sum |\mathcal{M}|^2 dm^2_{\mu X}$$

$$m^2_{12} = (P_V + P_\nu)^2$$
$$= (P_K - P_\mu)^2$$

missing mass $m_{\rm miss}$

$$m_X < m_{\rm miss} < m_K - m_\mu$$

modifications
of the high missing mass tail



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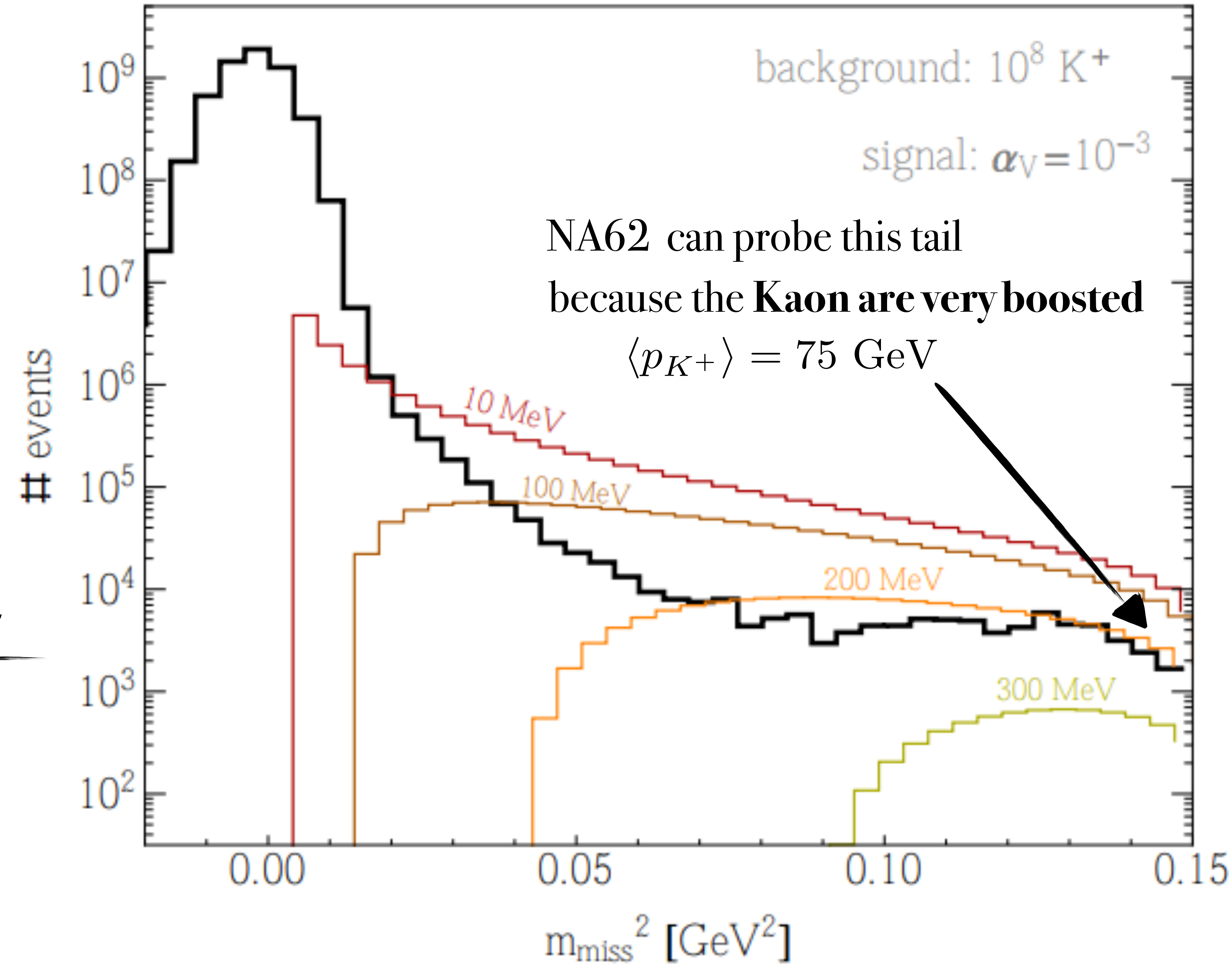


NA62 can probe this tail
because the **Kaon are very boosted**
$\langle p_{K^+} \rangle = 75$ GeV

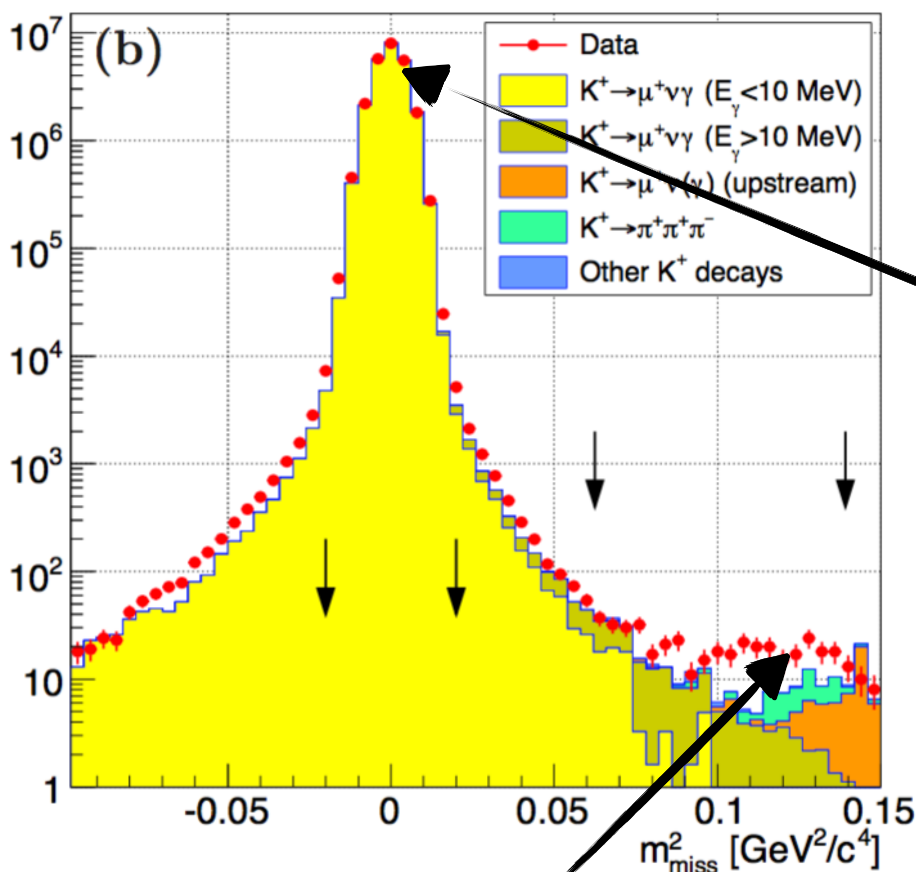
THE BACKGROUND CHALLENGE

2015 NA62 data: $2.4 \cdot 10^7 \quad K^+ \to \mu^+ + \nu$

1/3 single muon trigger prescaling

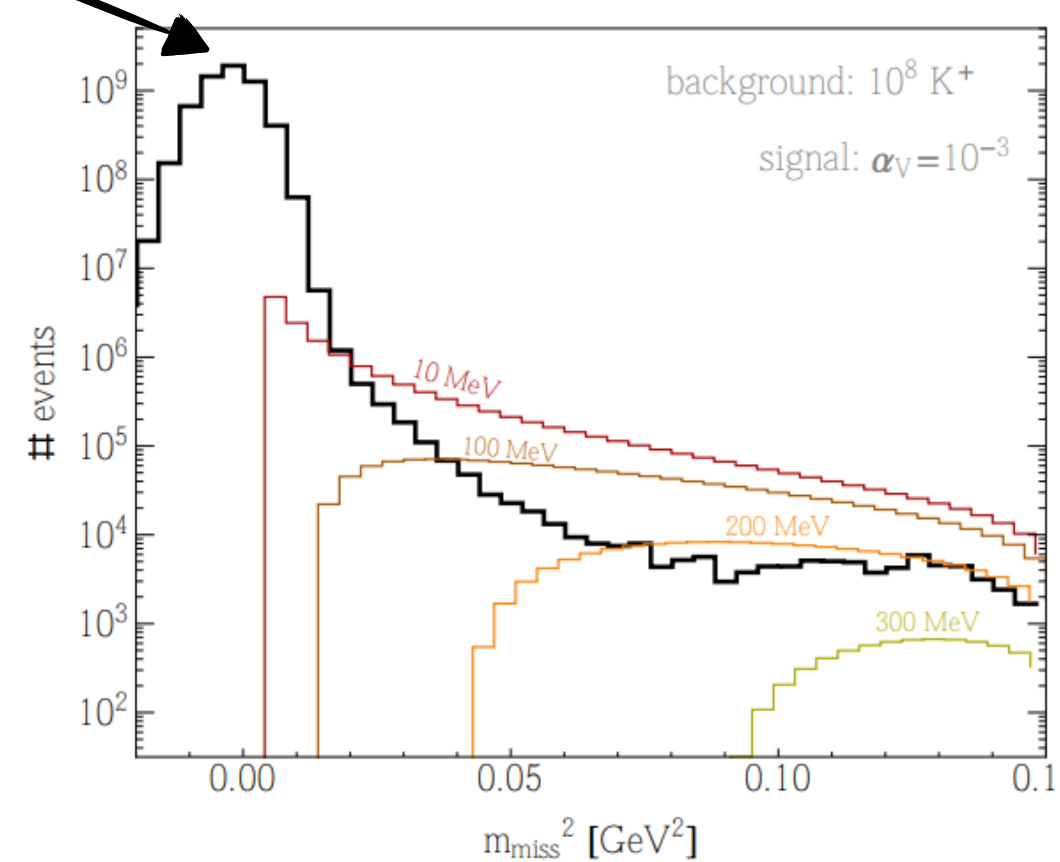
0.35 acceptance

$\Big\} \quad 3 \cdot 10^8 K^+$



Main background comes from the radiative tail of $K^+ \to \mu^+ + \nu$

If the photon is missed its energy contributes to m_{miss}



very poor MC modelling in 2015
should get better with the GTK

(measurement of the Kaon momentum reduces the background from upstream radiation)

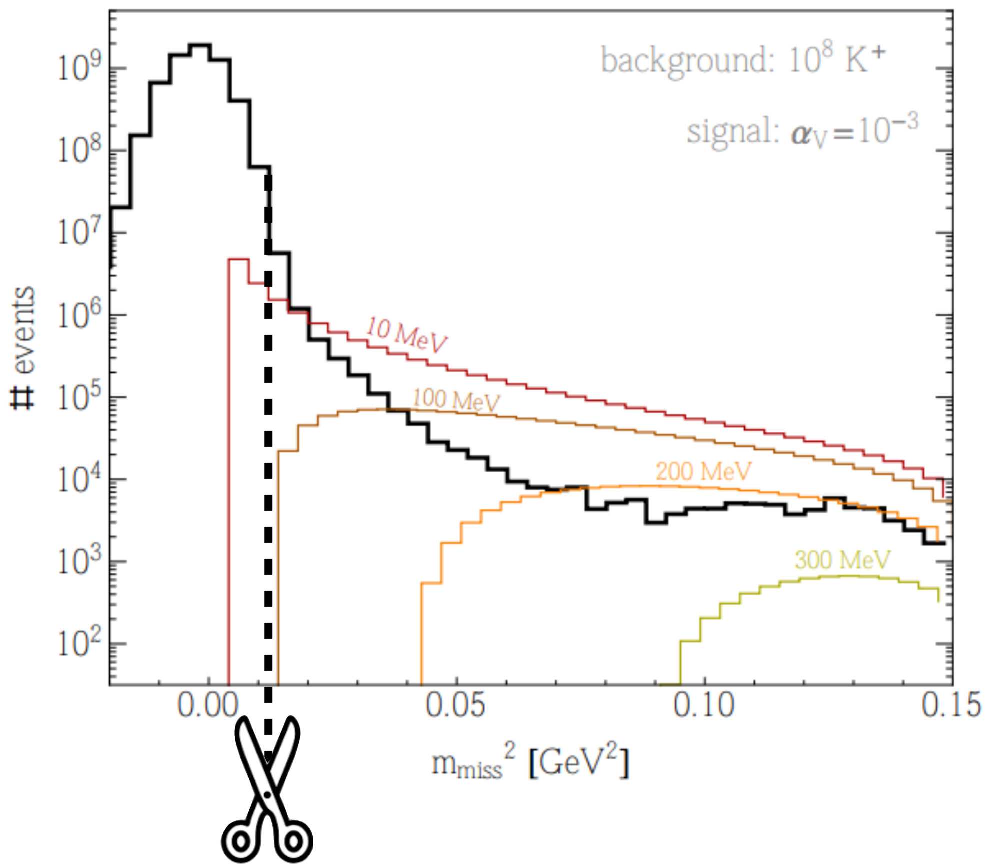
THE TRIGGER CHALLENGE

The sensitivity in the single muon final state is REDUCED because NA62 looks into this only once in 400 times!

the 1/400 prescaling solves a data storage problem

NEW SOLUTION

cutting $m^2_{\rm miss} > 2.3 \cdot 10^{-2}\ {\rm GeV}^2$

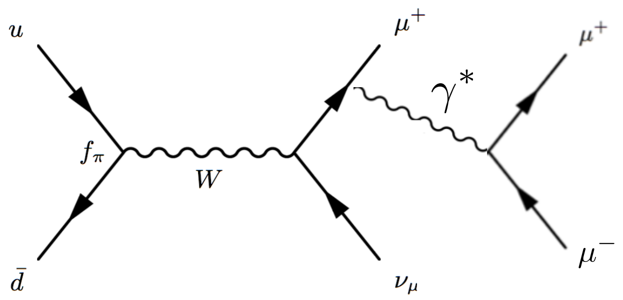


we are only interested in 10^{-4} of the total single muon events

THE VISIBLE SEARCH

SIGNAL: $K^+ \to \mu^+ + \nu + V(2\mu)$

BACKGROUND: $K^+ \to \mu^+\mu^+\mu^-\nu$ in the Standard Model



$\mathrm{BR_{bkd}} = 7 \cdot 10^{-8}$ NOT MEASURED YET!

Upper bound from E865 Brookhaven AGS (2002) $\mathrm{BR}(K^+ \to \mu^+\mu^+\mu^-\nu) < 10^{-7}$

NA62 has the luminosity to improve on this & the trigger!

~ 100 events with the 2018 dataset from existing di-muon trigger

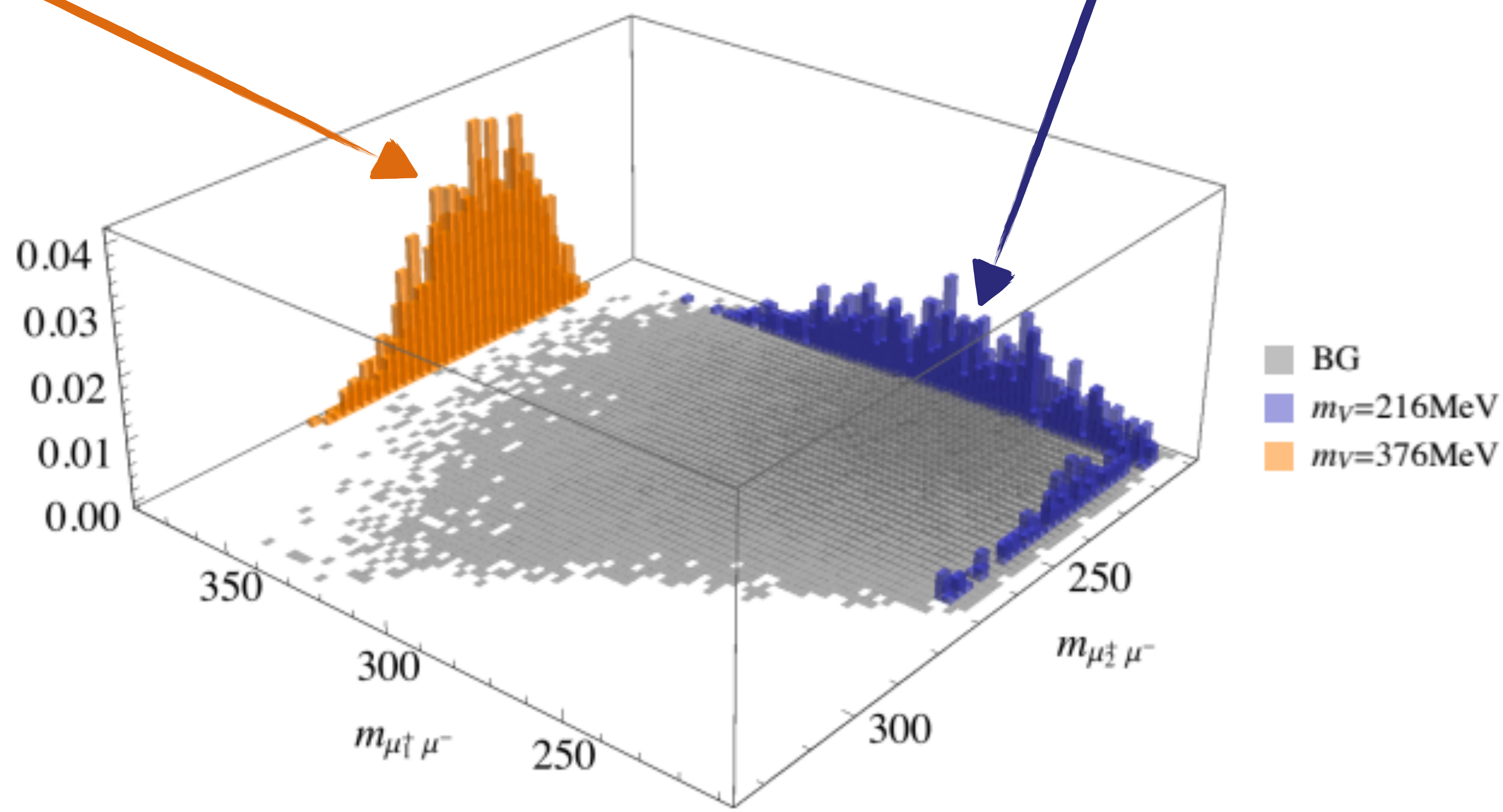
confirmed informally by NA62

THE VISIBLE SEARCH

Bump-hunt on the 2 OS di-muon invariant masses

the leading muon leads to a peak for high masses

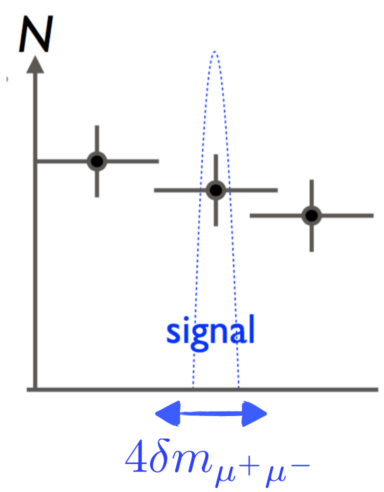
the subleading muon leads to a peak for lower masses

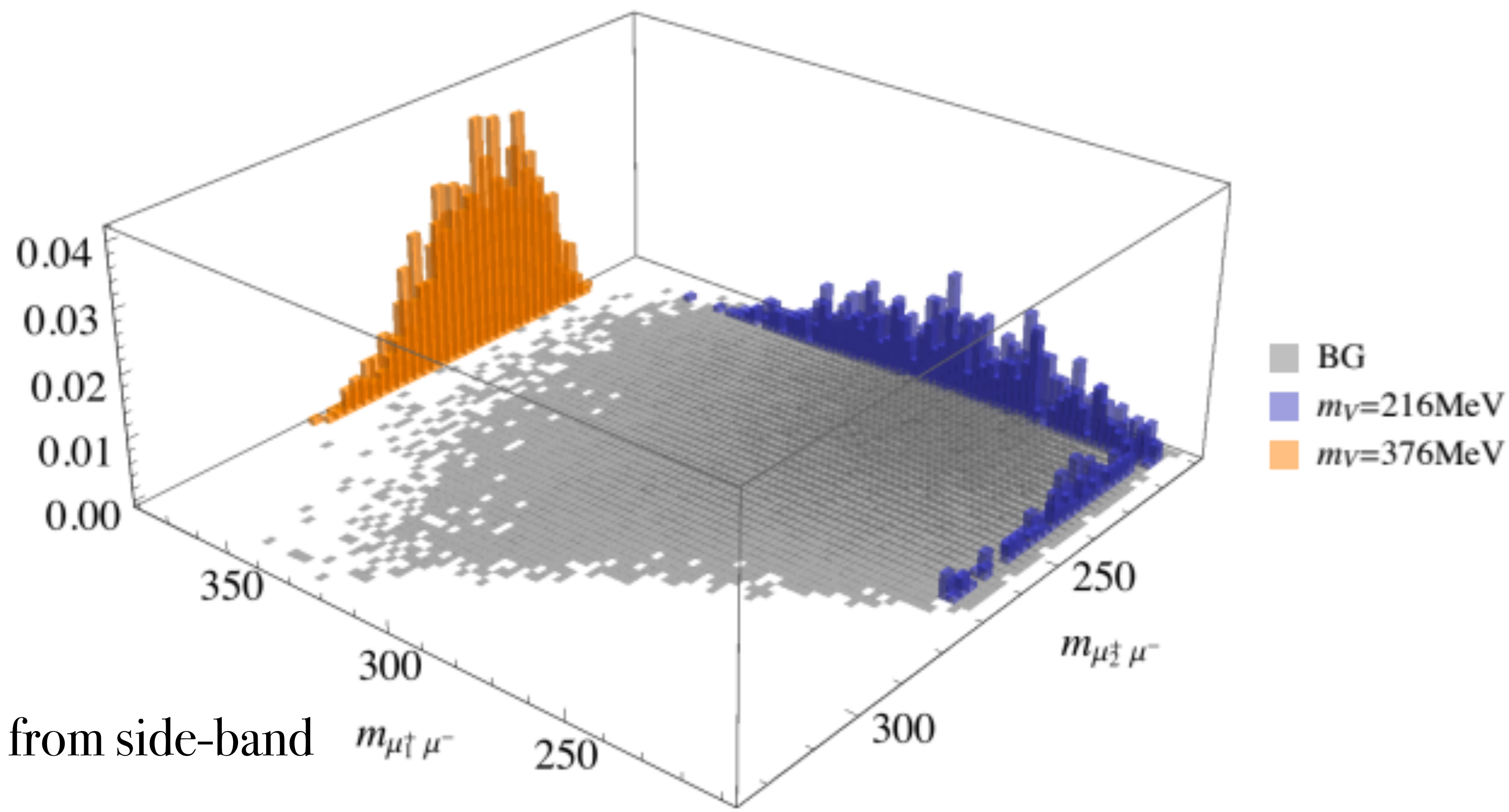


THE VISIBLE SEARCH

Bump-hunt on the 2 OS di-muon invariant masses

Invariant mass bin: $\frac{\delta m_{\mu^+\mu^-}}{m_X} = \frac{1}{2}\left(\frac{\delta p_{\mu_+}}{p_{\mu_+}} \oplus \frac{\delta p_{\mu_-}}{p_{\mu_-}}\right)$ ⟷ $\frac{\delta p_\mu}{p_\mu} = 0.3\% \oplus \left(0.005\,\frac{p_\mu}{\text{GeV}}\right)$

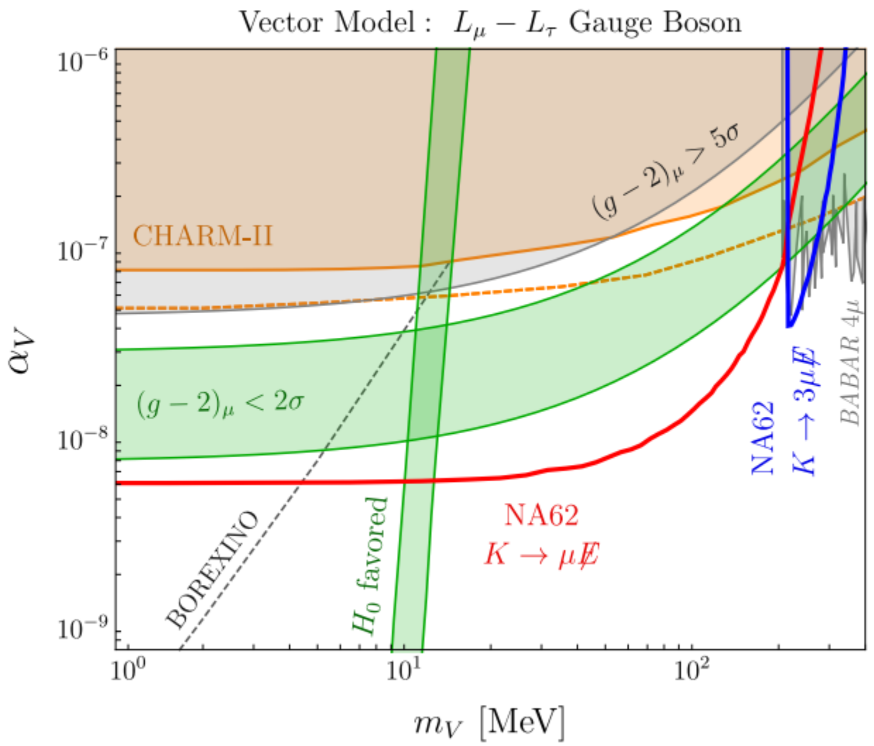


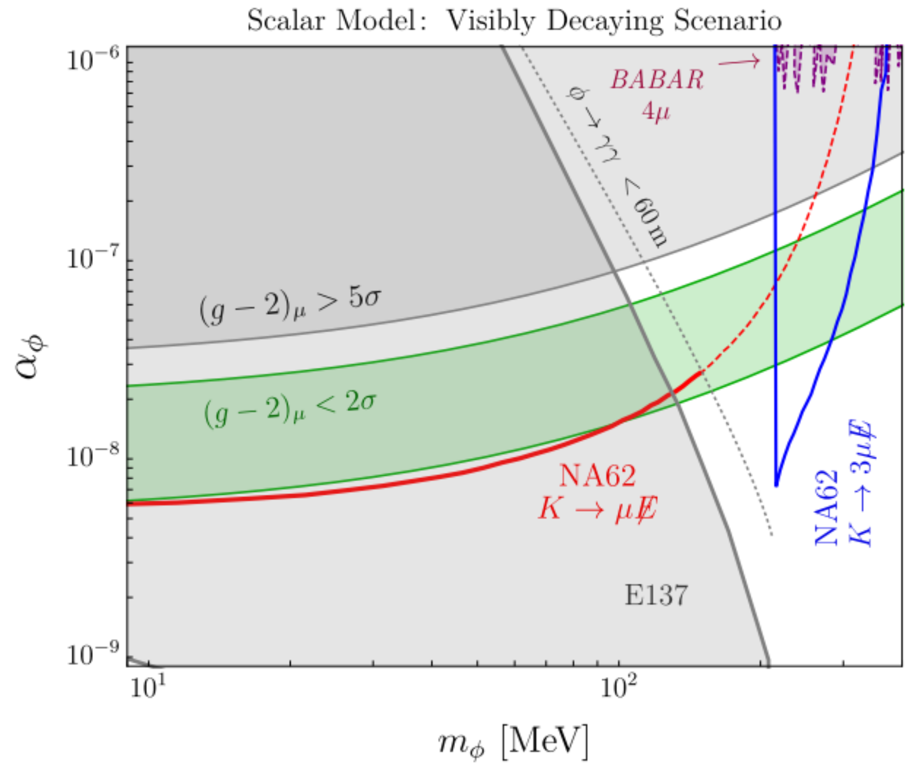


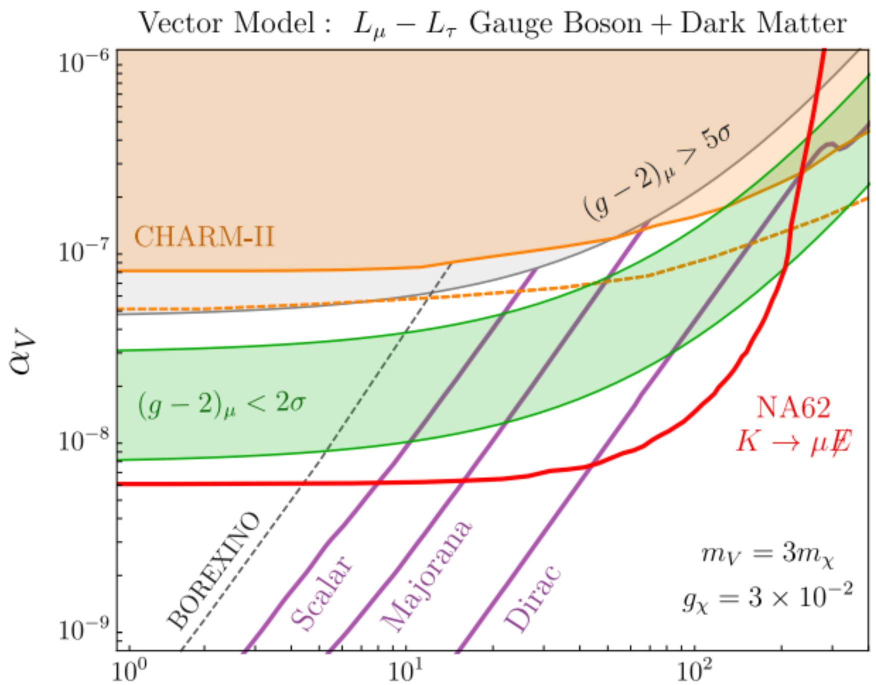
- data driven background from side-band
- subleading background from pions faking muons

CONCLUSION

Kaon factories can probe muonic forces (and NA62 in particular)







possibly telling us something about Dark Matter


BACKUP

The challenges

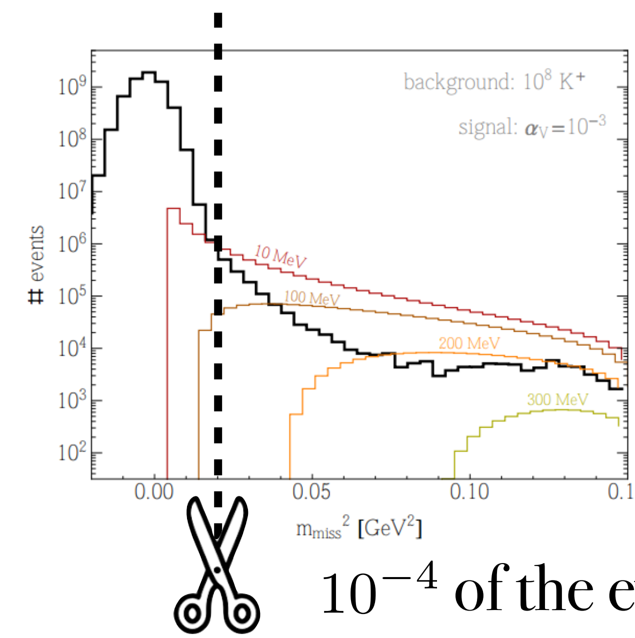
CHALLENGE 1: Luminosity of the single muon trigger

Can we go from $3 \cdot 10^8 K^+ \longrightarrow 10^{13} K^+$?

Problem: $\longrightarrow$ **Solution:**

Single muon trigger 2018 prescaled by $1/400$

cutting at L1 on $m^2_{\rm miss} > 2.3 \cdot 10^{-2}$ GeV^2



10^{-4} of the events

The challenges

CHALLENGE 2: Background systematics

Sensitivity in a cut-and-count:

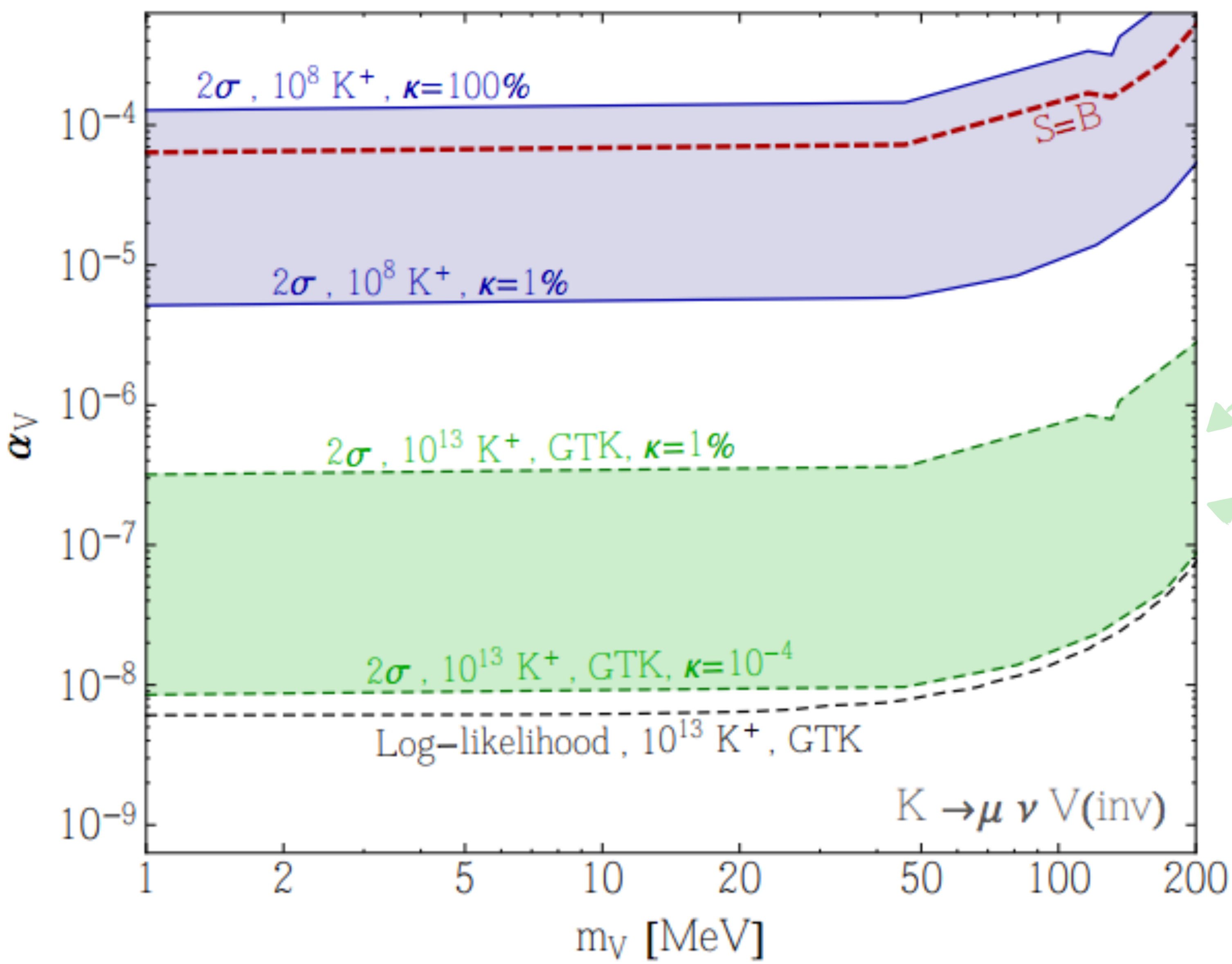
$$S/\sqrt{B + \kappa^2 B^2} = 2$$

$$S = \frac{N_{K^+} \mathcal{A}}{\Gamma_{K^+}} \int_{m^2_{\rm cut}}^{m^2_{\rm max}} dm^2_{\rm miss} \frac{d\Gamma_{K^+\to\mu^+\nu X}}{dm^2_{\rm miss}}$$

0.35

$10^8\ K^+$

$10^{13}\ K^+$



- We need systematics below 10^{-3} to make the search interesting

- GTK will give a background reduction of roughly $1/4$ at $m^2_{\rm miss} > 2.3 \cdot 10^{-2}$ GeV^2

The challenges

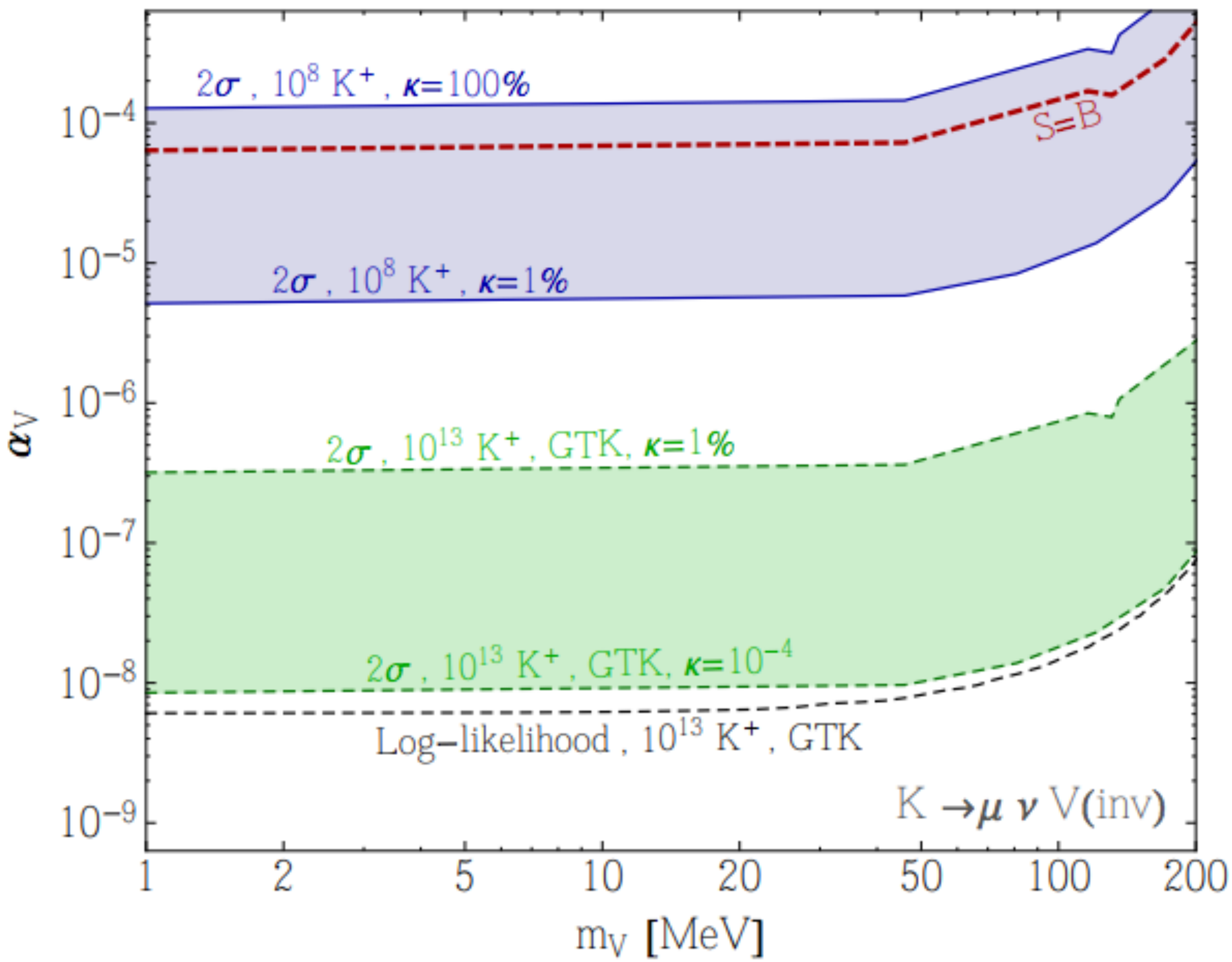
CHALLENGE 2: Background systematics

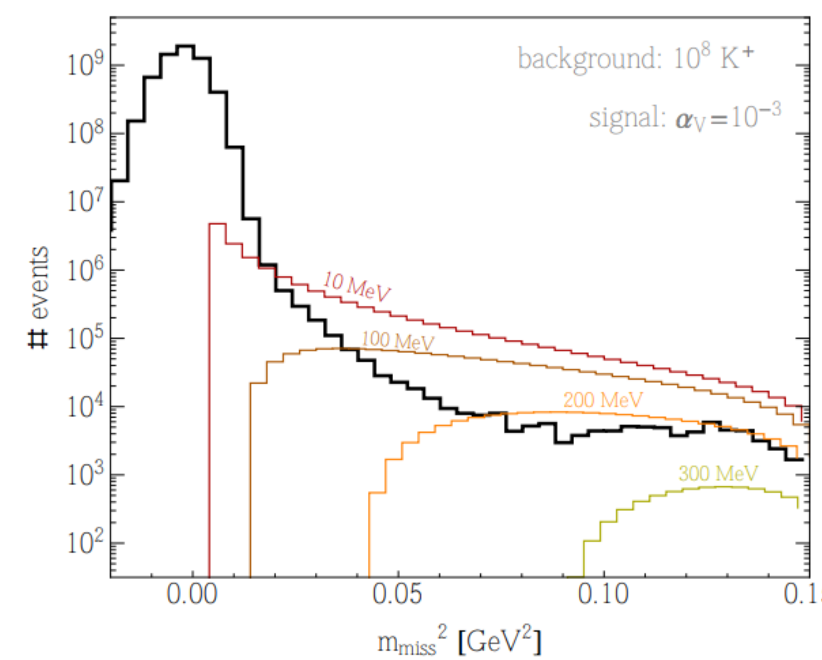
Sensitivity in a likelihood:

$$\Lambda(S) = \sum_i -2\log\frac{L_i(S)}{L_i(\hat{S}=0)}$$

signal per bin — background — data

$$L_i(S) = \frac{(S\epsilon_{S_i} + B_i)^{D_i}}{D_i!}e^{-(S\epsilon_{S_i}+B_i)}$$

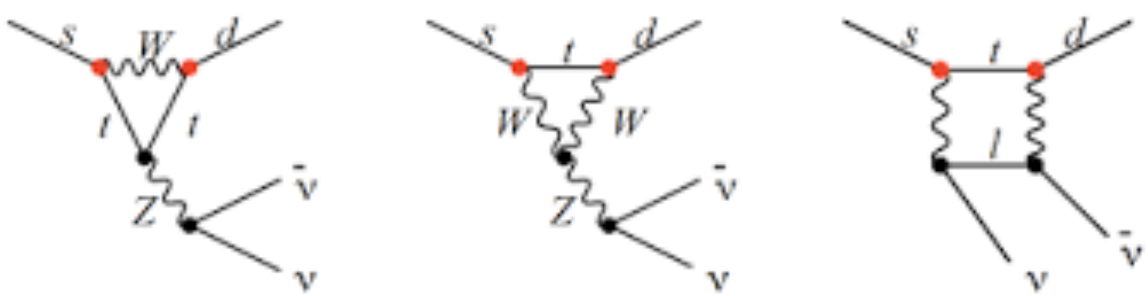




- Likelihood analysis helps at small masses

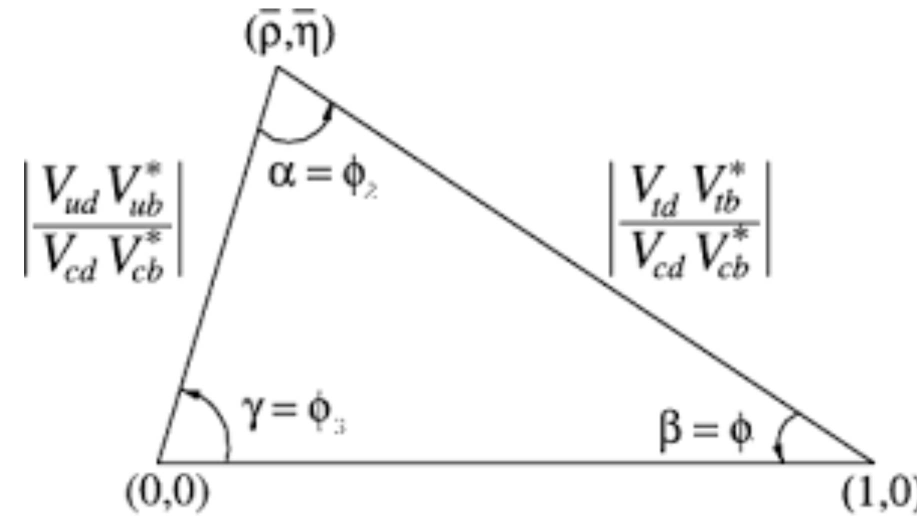
$$\Lambda(S) < 4$$

The main purpose of NA62



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

CKM: $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$, γ,



$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$