Multiple traces of an almost elementary Higgs

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w/ De Curtis, Redi and Tesi - 1805.12578

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INFN

- The **Standard Model** is a good theory up to very short distances
  - It's validity extends down to $\sim \mathcal{O}(10^{-19}\mathrm{m})$
  - Minor deviations with respect to the SM predictions

$(g-2)_\mu$ and $(g-2)_e$

$R_{D^{(*)}}$ and $R_{K^{(*)}}$

^{8}Be and ^{4}He decay

ν anomalies

$\mu^+\mu^- b$ CMS excess (+LEP)

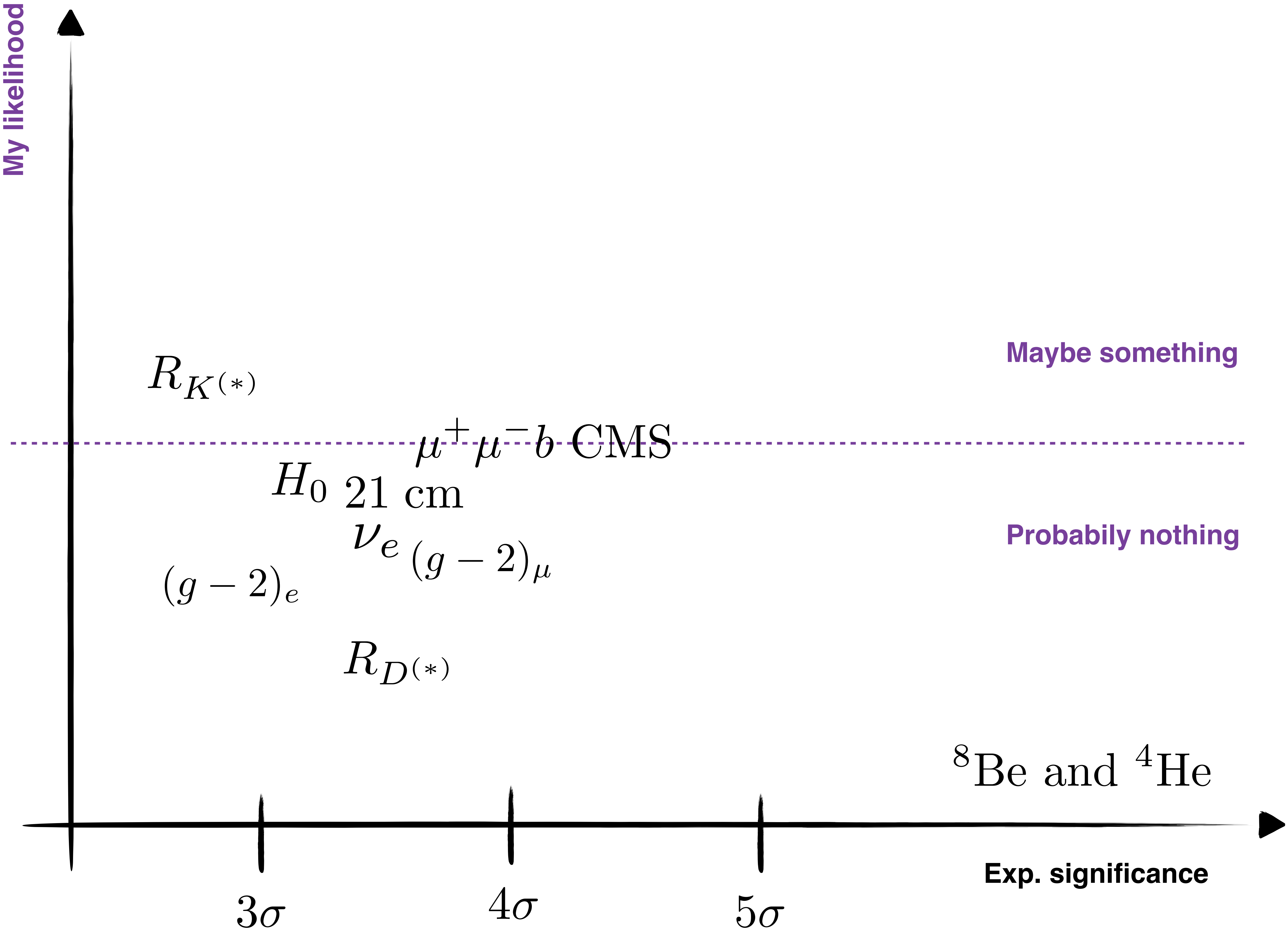
- **General relativity** seems the correct theory of gravity

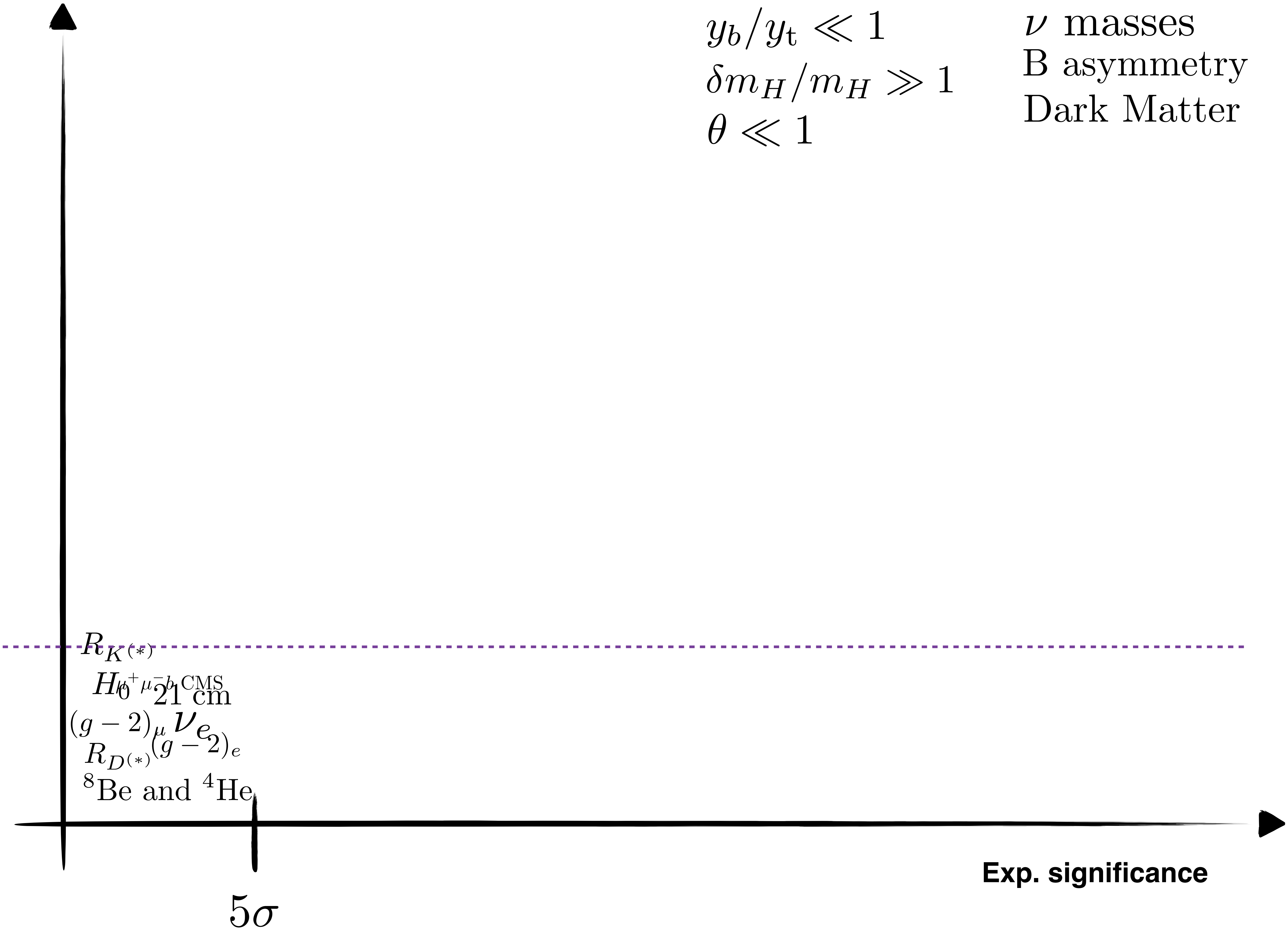
- The ΛCDM models reproduces cosmological data in a large energy range
  - Also here some tension with observables

H_0 tension

σ^8 tension

21 cm


My likelihood
$R_{K^{(*)}}$
Maybe something
$\mu^+\mu^- b$ CMS
H_0
21 cm
ν_e
Probabily nothing
$(g-2)_\mu$
$(g-2)_e$
$R_{D^{(*)}}$
^{8}Be and ^{4}He
Exp. significance
3σ
4σ
5σ



$y_b/y_{\rm t} \ll 1$

$\delta m_H/m_H \gg 1$

$\theta \ll 1$

ν masses

B asymmetry

Dark Matter

$R_{K^{(*)}}$

H_0

$\mu^+\mu^- b$ CMS

21 cm

$(g-2)_\mu$

ν_e

$R_{D^{(*)}}$

$(g-2)_e$

^{8}Be and ^{4}He

Exp. significance

5σ

Fine tuning arguments

$y_b/y_t \ll 1$

$\delta m_H/m_H \gg 1$

$\theta \ll 1$

Experimental evidences

ν masses

B asymmetry

Dark Matter

Where are we?

- The naturalness of the Higgs mass has been a guidance for the last 30 years of theoretical and experimental activity

- BSM models are facing negative experimental results

Two directions should be pursued

- LHC is sensitive to TeV scale new physics with $\mathcal{O}(g_w)$ couplings
    - Natural new physics, although not in good shape, is being tested
    - Keep exploring this path and exploit LHC performances

- Relax the naturalness criteria and focus on experimental evidences
    - Look for NP not related to δm_H^2

QCD like theories offer large model building opportunities

QCD like theories a.k.a. Vector Like Confinement

Kilic+ 0906.0577

- New fermions vectorial under the Standard Model gauge group

- A new strong gauge interaction under which the new fermions are charged

That's all

Building a VLC theory - The strong dynamics

- Switch of the SM interactions and consider a new confining gauge group

$$\mathcal{G} = SU(N),\ SO(N),\ Sp(N)$$

- Consider $SU(N)$ gauge theories, for easier analogy with QCD

- Consider N_F flavors of $\psi_i,\ \psi_i^c$ transforming as $\square, \bar{\square}$ under $\mathcal{G}$

$$\mathcal{L} = -\frac{1}{4} H^{\mu\nu,a} H^a_{\mu\nu} + (\psi_i^\dagger \bar{\sigma}^\mu D_\mu \psi_i + \psi \to \psi^c) - (m_{\psi_i} \psi_i^c \psi_i + h.c.)$$

$i = 1, ..., N_F$

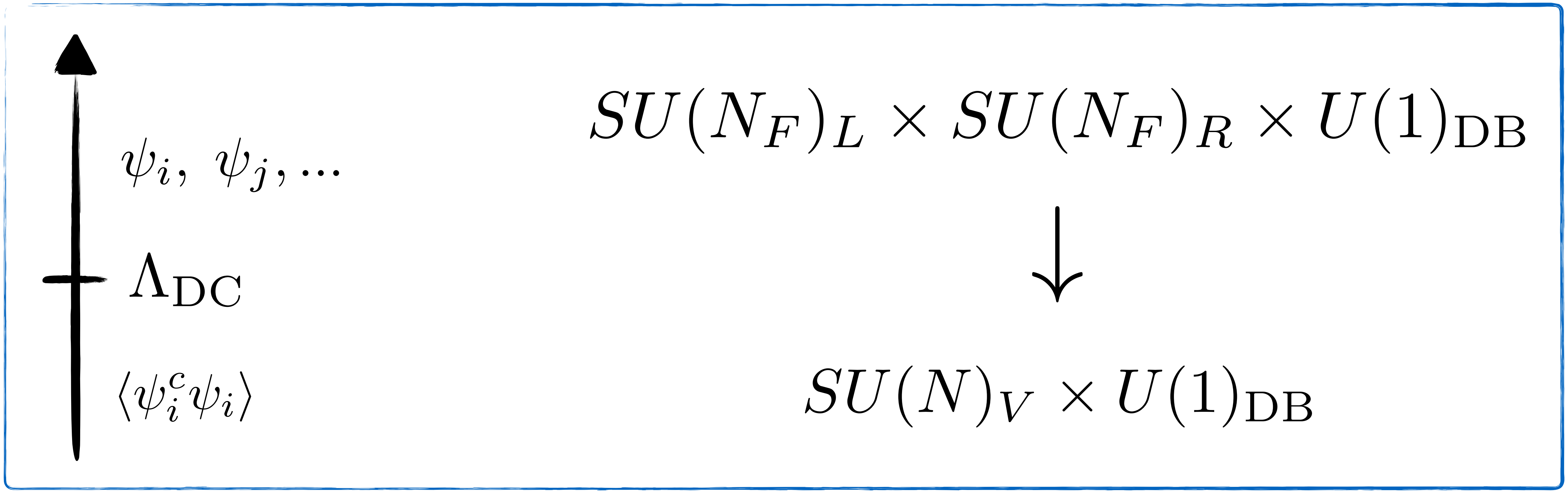
- Neglecting the fermions masses there is a global symmetry

$$SU(N_F)_L \times SU(N_F)_R \times U(1)_{\rm DB}$$

*** Non fundamental irrep or non complex groups have slightly different properties**

Building a VLC theory - The strong dynamics

- Assume that the strong sector undergoing a confining phase transition



$\psi_i,\ \psi_j, \ldots$

Λ_{DC}

$\langle \psi_i^c \psi_i \rangle$

$$SU(N_F)_L \times SU(N_F)_R \times U(1)_{\mathrm{DB}}$$

$$\downarrow$$

$$SU(N)_V \times U(1)_{\mathrm{DB}}$$

- SSB delivers $N_F^2 - 1$ Goldstone bosons - dark pions $\psi_a \psi_b^c$
- This pattern is not significantly altered as long as $m_{\psi^i} \ll \Lambda_{\mathrm{DC}}$
- N_F should be sufficiently small to have confinement
- Dark baryons $\varepsilon^{a_1 \ldots a_N} \psi_{a_1} \ldots \psi_{a_N}$ are also created, together with higher spin-resonances

Building a VLC theory - Add the SM interactions

- Lets now turn on the SM gauge interactions
- The N_F dark flavors rearrange in N_S species $N_S \leq N_F$

$$\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \qquad \psi_3$$

- 3 flavors have rearranged into 2 species: a doublet and a singlet of $SU(2)_L$

$$\mathcal{L} = -\frac{1}{4} H^{\mu\nu,a} H^a_{\mu\nu} + (\Psi_i^\dagger \bar{\sigma}^\mu D_\mu \Psi_i + \Psi \to \Psi^c) - (m_{\Psi_i} \Psi_i^c \Psi_i + h.c.)$$

$i = 1, ..., N_S$

Covariant derivative with respect to DC and SM

Building a VLC theory - Properties

- Technifermions are vectorial under the SM gauge group

$\langle \psi_a^c \psi_a \rangle$ **doesn't break electroweak symmetry**

Different construction with respect to technicolor

No bounds from EWPO

No relation with the naturalness of the Higgs mass

Higgs potential is fine tuned

Up to now the Higgs is elementary!

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm VLC}$$

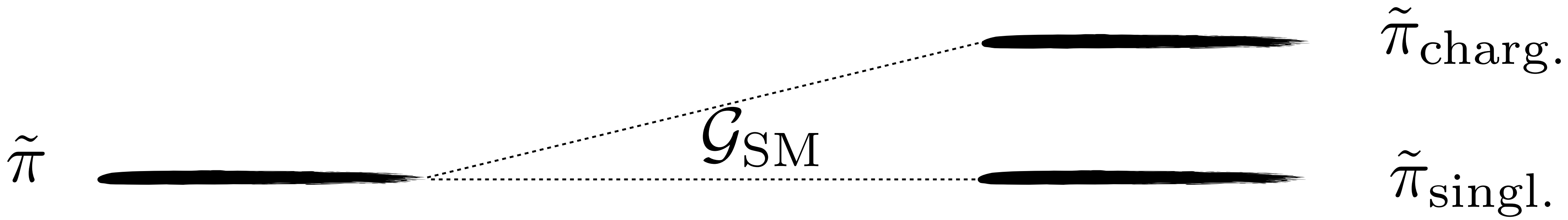
*** This theories can however solves the hierarchy problem through the relaxation mechanism…**

Building a VLC theory - Properties

- The gauging of the SM interactions breaks explicitly $SU(N_F)_A$

$$\Psi_i^\dagger \bar{\sigma}^\mu D_\mu \Psi_i \; .$$

- Dark Pions charged under $\mathcal{G}_{\rm SM}$ have a non zero mass even in the chiral limit from loop of SM gauge fields



- This is analogous to the charged and neutral pion mass splitting arising from the gauging of QED

Building a VLC theory - Properties

- The SM gauging also breaks $SU(N_F)_V \times U(1)_{\mathrm{DC}}$

$$\Big\downarrow$$

$$U(1)_{\Psi_1} \times U(1)_{\Psi_2} \times \ldots \times U(1)_{\Psi_{N_S}}$$

$$\boxed{(\Psi_i^\dagger \bar{\sigma}^\mu D_\mu \Psi_i + \Psi \to \Psi^c) - (m_{\Psi_i} \Psi_i^c \Psi_i + h.c.)} \qquad \Psi_i \to e^{i\alpha_i} \Psi_i$$

- Species number are conserved

→ Dark Pions made of different species cannot decay to SM

- Dark baryon number is the sum of specie numbers -> Conserved

→ Dark Baryons cannot decay to SM

VLC theories predict states stable thanks to accidental symmetries

An analogy with the QCD - QED system

- The chiral condensate doesn't break electromagnetism
- $m_{\pi^\pm} - m_{\pi^0} \neq 0$ due to the gauging of $U(1)_{\rm em}$.
- Baryon number is conserved: the neutron is stable
- Specie numbers, $N_{u,d,s}$, conserved $\pi^+ \sim u\bar{d}$ stable in QCD-QED
- Pions made up of the same species decay via anomaly $\pi^0 \to \gamma\gamma$

- The chiral condensate doesn't break $\mathcal{G}_{\rm SM}$
- $m_{\tilde{\pi}^+} - m_{\tilde{\pi}^0} \neq 0$ due to the gauging of $\mathcal{G}_{\rm SM}$
- Dark baryon number conserved: lightest dark baryon stable
- Specie numbers conserved stable dark pions
- Pions made up of the same species decay via anomaly $\pi^0 \to V_{\rm SM} V_{\rm SM}$

Building a VLC theory - Add Yukawa interactions

- Yukawa interactions might be allowed depending on dark fermions quantum numbers under $\mathcal{G}_{\rm SM}$

$$\mathcal{L}_{\rm yuk.} = y H \Psi_i^c \Psi_j + h.c.$$

- This interaction breaks (part of) species number

$$U(1)_{\Psi_1} \times U(1)_{\Psi_2} \times \ldots \times U(1)_{\Psi_{N_S}} \to U(1)_{\rm DB} \times \prod_{a \neq i,j} U(1)_{\Psi^a}$$

- Dark pions made of different species can decay through the coupling to the elementary Higgs

- After confinement a $H \leftrightarrow \tilde{\pi}$ mixing is generated

Now the Higgs is partially composite

Spectrum and decay of QCD like theories

$\tilde{\mathcal{B}} \sim \varepsilon^{a_1 \ldots a_N} \Psi_{a_1} \ldots \Psi_{a_N}$ Lightest state is stable

$\tilde{\rho}$ Higher spin resonance

Λ_{DC}

$\tilde{\pi} \sim \Psi_i \Psi_j^c$ Stable **Stable charged particle / Dark Matter**

Decay through mixing with the elementary Higgs

$\tilde{\pi} \sim \Psi_i \Psi_i^c$ Decay through anomaly with the SM gauge fields

Pions are the states relevant for phenomenology

Dark Matter as a stable hadron

Dark Baryons and Dark Hadrons can both be Dark Matter candidate

Antipin+ 1503.08749

- Golden class models: all stable are dark matter candidates without the need of higher dimensional interactions
- Silver class models: non renormalizable interactions or extra states are needed to break accidental symmetries leading to unwanted stable particle e.g. stable $\tilde{\pi}$ with electric charge

Simplest Model: a single specie of techniquark

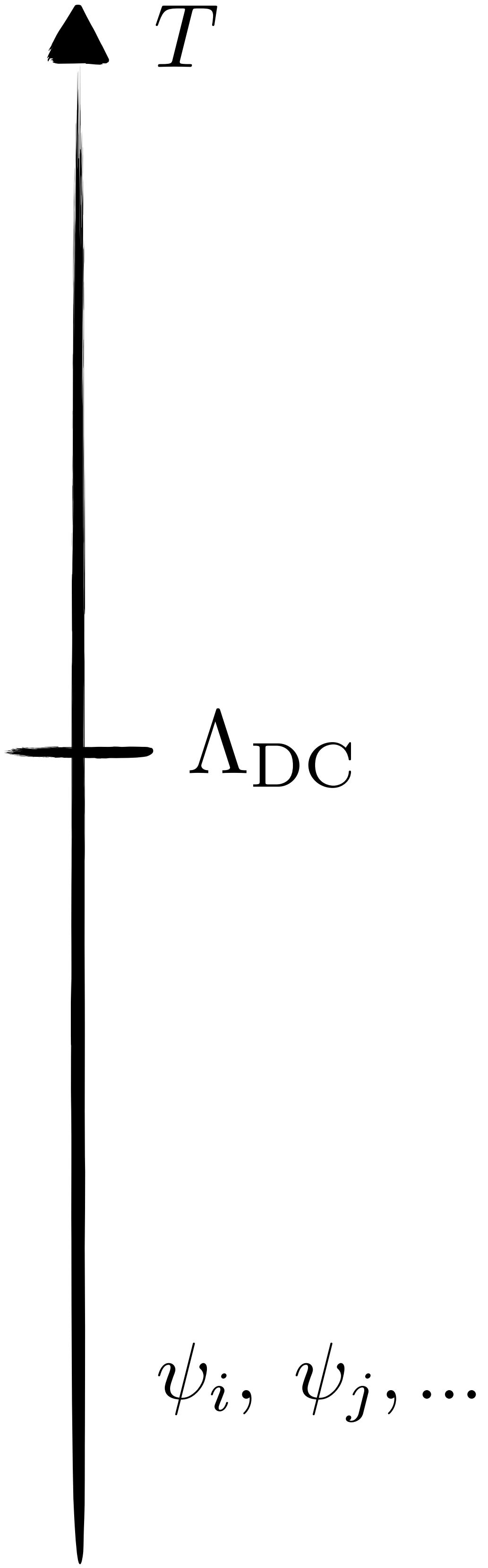
$$N_F = 3 \qquad \Psi = V_{1,3,0} \qquad N_{\rm DC} = 3$$

Dark baryons and Dark Pions are in the 8 of $SU(N_F = 3)$

$$8 = 3_0 \oplus 5_0 \qquad \text{under } \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y .$$

Stable!

Dark Matter as a stable hadron



Dark Color confines
delivering dark hadrons

↓

Dark Hadrons freeze - out

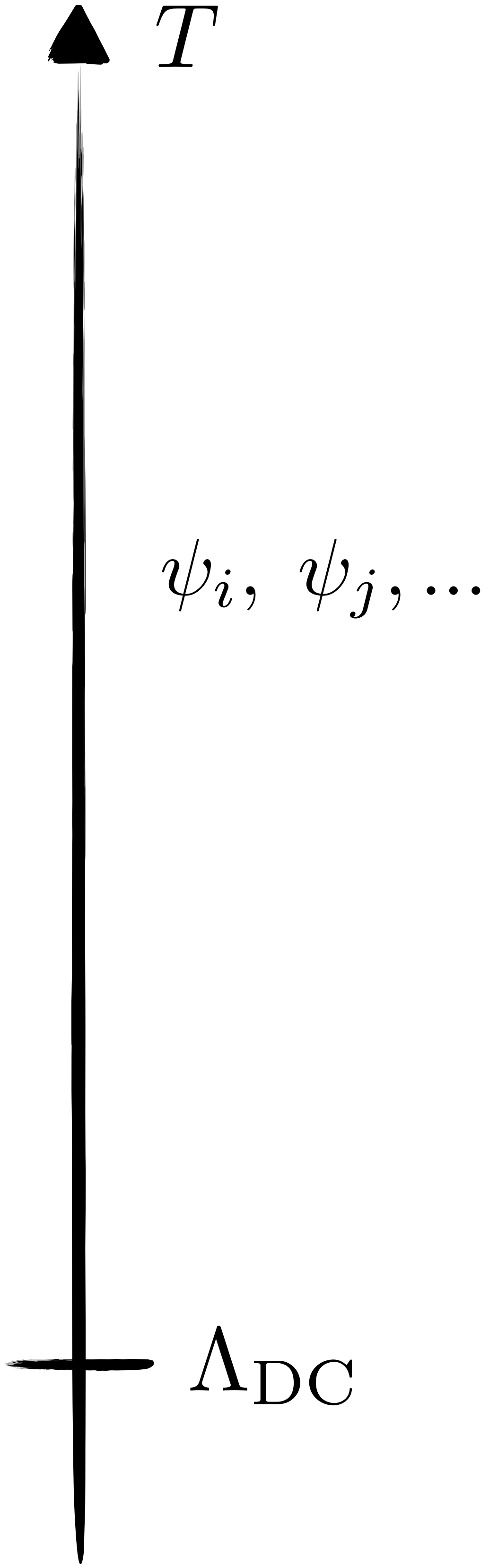
Thermal relic is achieved for

$m_{\tilde\pi} \sim 3\ \mathrm{TeV}$ minimal DM phenomenology

$m_{\tilde{\mathcal{B}}} \sim 100\ \mathrm{TeV}$ $\sigma v \sim \dfrac{g_{\rm DC}^4}{4\pi m_{\tilde{\mathcal{B}}}^2}$

Antipin+ 1503.08749

Dark Matter as a stable hadron



Dark quark abundance freezes out at $T \sim m_\psi/20$

↓

Dark quarks confine

↓

Dark Hadrons freeze - out

Dark Matter can be as light as a few TeV

Mitridate+ 1707.05380

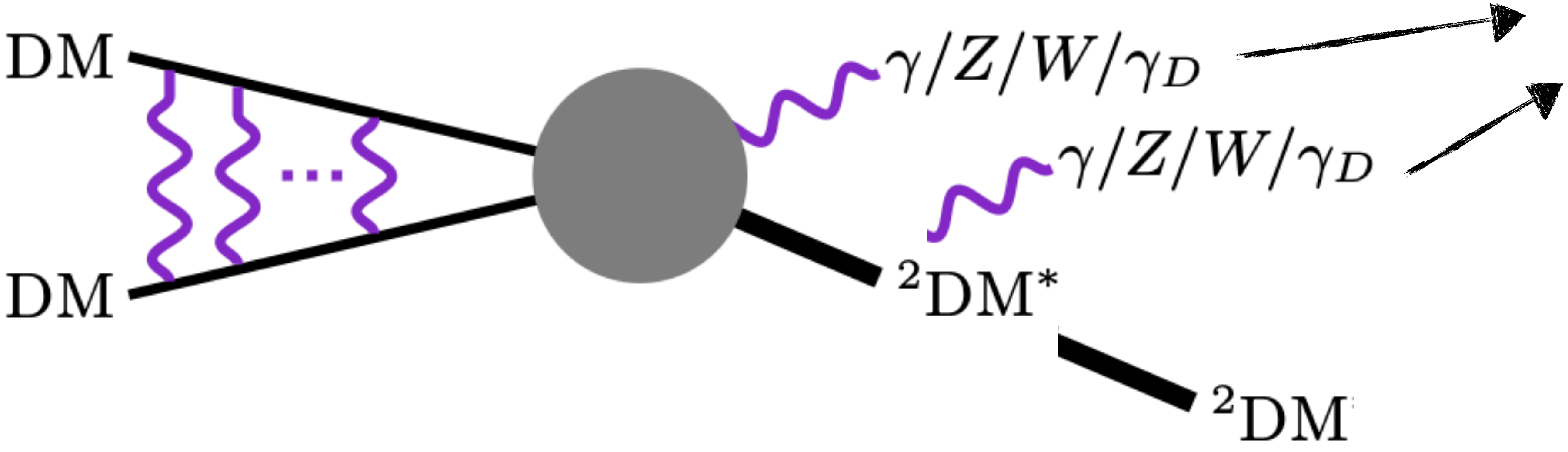
Dark Matter as a stable hadron

- Dark Matter could also be dark nuclei - dark nucleosynthesis process

  Redi and Tesi 1812.08784

- Bound state formation can lead to distinctive multi-line signals

  Mahbubani+ 1908.00538



monochromatic lines

- Relevance for indirect detection experiments!

Direct experimental tests of QCD like theories

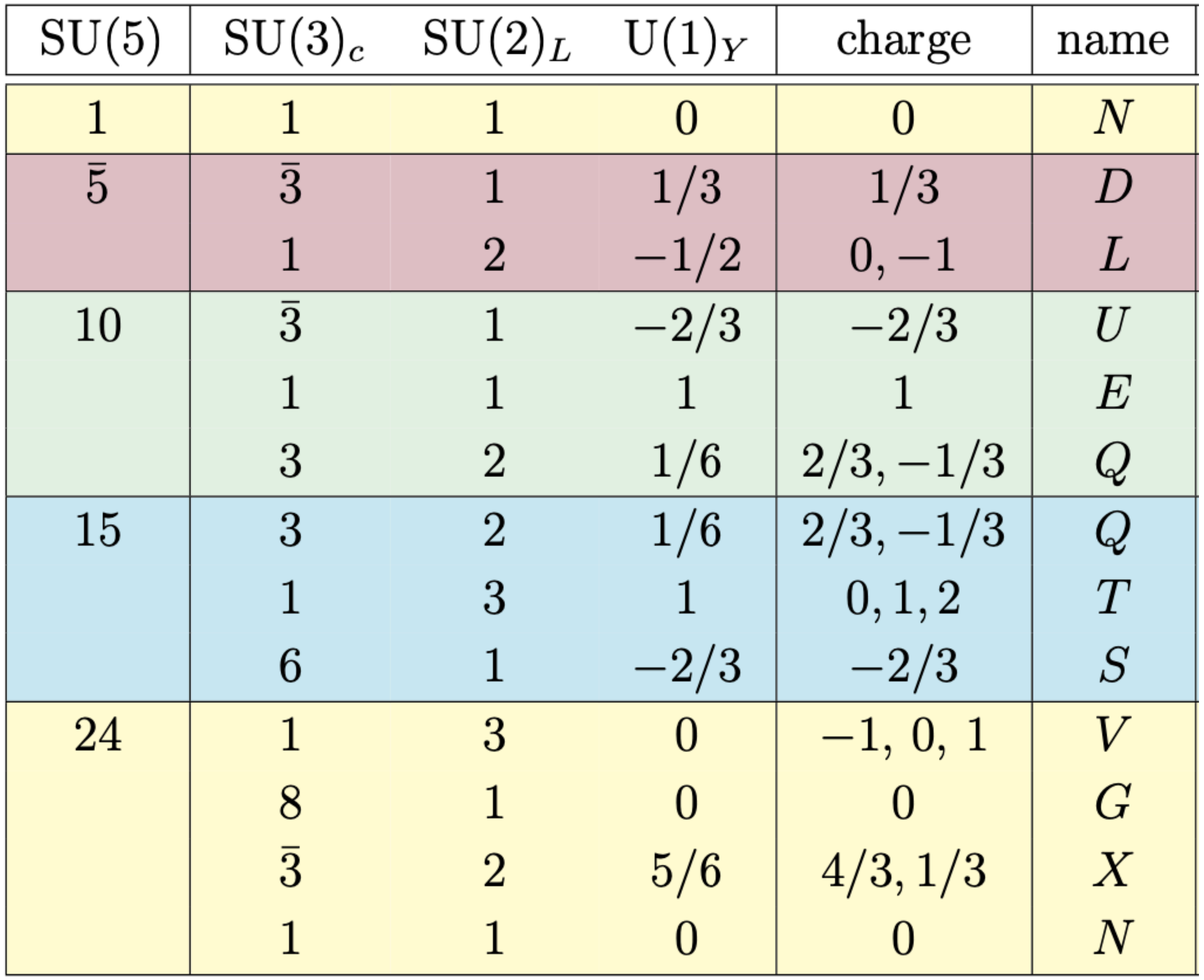
Can these theories be tested at low energy and collider experiments?

What's the coverage of current BSM searches?

What are the easier and most challenging signatures?

Can the existing (if any) reach be improved?

Choice of dark quark representations



$\mathrm{SU}(5)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	charge	name
1	1	1	0	0	N
$\bar{5}$	$\bar{3}$	1	$1/3$	$1/3$	D
	1	2	$-1/2$	$0, -1$	L
10	$\bar{3}$	1	$-2/3$	$-2/3$	U
	1	1	1	1	E
	3	2	$1/6$	$2/3, -1/3$	Q
15	3	2	$1/6$	$2/3, -1/3$	Q
	1	3	1	$0, 1, 2$	T
	6	1	$-2/3$	$-2/3$	S
24	1	3	0	$-1,\ 0,\ 1$	V
	8	1	0	0	G
	$\bar{3}$	2	$5/6$	$4/3, 1/3$	X
	1	1	0	0	N

<u>Quarks belonging to SU(5) fragments</u>

- D, U, Q, S, G, X give rise to colored $\tilde{\pi}$

Easy to produce

Largely studied at the $750\ \mathrm{GeV}$ time

- N, L, E, T, V give rise to EW $\tilde{\pi}$

Harder to produce

Almost not studied in the literature

- I'll consider the following two models:

$$L + N$$

$$V$$

Both have $N_F = 3$: easy analogy with QCD

The L+N model

- The L+N model has the following UV lagrangian

$$\mathscr{L}_{\text{mix}} = y_N H L N^c + \tilde{y}_N H^\dagger L^c N + m_L L L^c + m_N N N^c + h.c.$$

- After confinement Dark Pions correspond to the following bilinears

Costituents	$SU(2)_L$	$U(1)_Y$
$L \times L^c \quad = \quad \eta + \pi_a$	$1+3$	0
$L \times N^c \quad = \quad K_\alpha$	2	$-1/2$

- A scalar with the quantum numbers of the Higgs appear
Antipin and Redi 1508.01112

- The IR theory has two Higgs like doublet

The L+N model

- Dark Pions dynamics is described by the chiral lagrangian

$$\boxed{\mathcal{L} \;=\; \frac{f^2}{4}\mathrm{Tr}[D_\mu U D^\mu U^\dagger] + g_\rho f^3 \mathrm{Tr}[M U^\dagger + h.c.] + \frac{3 g_2^2 g_\rho^2 f^4}{2(4\pi)^2} \sum_{i=1..3} \mathrm{Tr}[U T^i U^\dagger T^i]}$$

$$U = e^{i\sqrt{2}\Pi/f} \qquad M = \begin{pmatrix} m_L & 0 & y h^+ \\ 0 & m_L & y h^0 \\ \tilde{y} h^- & \tilde{y} h^{0\dagger} & m_N \end{pmatrix} \qquad \langle \psi_i \psi_j^c \rangle = -g_\rho f^3 \delta_{ij}$$

- An octet of Dark Pions is generated

$$\Pi = \begin{pmatrix} \pi_3^0/\sqrt{2} + \eta/\sqrt{6} & \pi_3^+ & K^+ \\ \pi_3^- & -\pi_3^0/\sqrt{2} + \eta/\sqrt{6} & K^0 \\ K^- & \bar{K}^0 & -2\eta/\sqrt{6} \end{pmatrix}$$

The L+N model

- Expanding the chiral lagrangian one gets

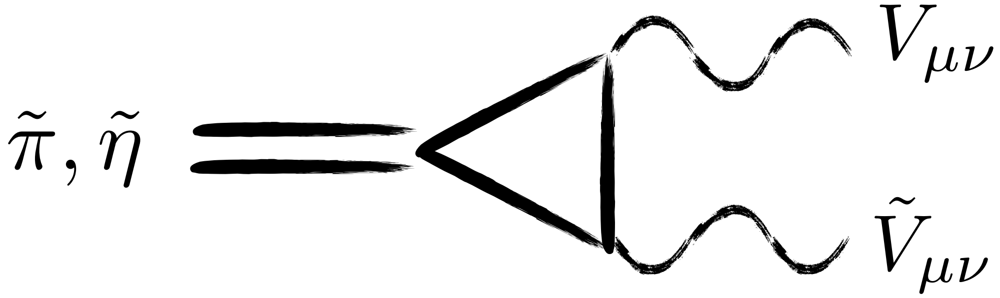
$$\mathcal{L} \subset -m_K^2|K|^2 - iy_- g_\rho f^2(bK^\dagger H + h.c.) + y_+ g_\rho f \left(a_1 \eta K^\dagger H + a_3 \pi^a K^\dagger \sigma^a H + h.c.\right)$$

Elementary composite mixing $\epsilon \equiv ib\frac{y_-}{g_\rho}\frac{m_\rho^2}{m_K^2}$

$H\tilde{\pi}\tilde{\pi}$ interactions

- Anomaly decay only of $\tilde{\pi}, \tilde{\eta}$

$$\begin{aligned} \mathscr{L}_{F\tilde{F}} &= -\frac{1}{16\pi^2}\frac{\eta}{f}\left(g_1^2 c_{BB}^\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + g_2^2 c_{WW}^\eta W_{\mu\nu}^a \tilde{W}^{a\mu\nu}\right) \\ & \quad - c_{WB}^\pi \frac{g_1 g_2}{16\pi^2}\frac{\pi_a}{f} W_{\mu\nu}^a \tilde{B}^{\mu\nu} - c_{WW}^\phi \frac{g_2^2}{16\pi^2}\frac{\phi_{ab}}{f} W_{\mu\nu}^a \tilde{W}^{b\,\mu\nu} \end{aligned}$$



$$\Gamma(\Pi \to VV) = c_\Pi^2 \frac{\alpha_i \alpha_j}{64\pi^3}\frac{m_\Pi^3}{f^2},$$

The L+N model

$$m_{\mathcal{B}} \gtrsim 10\ \mathrm{TeV}$$

Unaccesible at colliders

$$m_\rho \approx f g_\rho$$

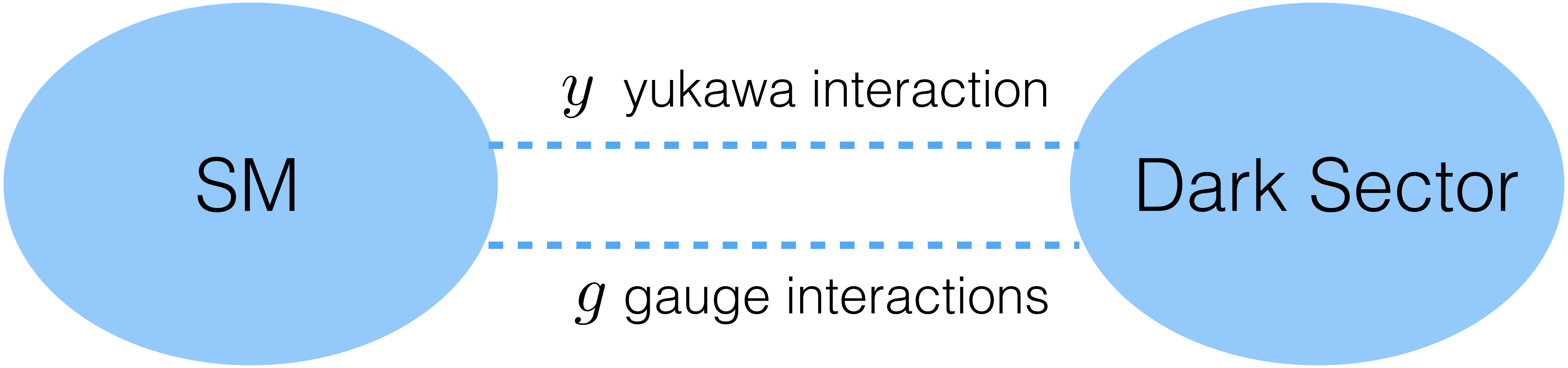
Collider targets!

$$m_{\pi_3}^2 \approx \frac{6 g_2^2 g_\rho^2}{(4\pi)^2} f^2 + 4\mathrm{Re}[m_L] g_\rho f \qquad m_\eta^2 \approx \frac{4}{3}\mathrm{Re}[m_L + 2m_N] g_\rho f$$

gauge contribution
for charged pions

Precision constraints on the almost elementary Higgs

- SM and strong sector coupled through Yukawa and gauge couplings



SM

y yukawa interaction

g gauge interactions

Dark Sector

- Effects on precision physics will be screened

$$\delta\mathcal{O} \sim \frac{y^2}{g_\rho^2} \qquad\qquad \delta\mathcal{O} \sim \frac{g^2}{g_\rho^2}$$

Higgs couplings

- Two effects:

  Presence of a second doublet

  The second doublet is composite

$$\mathscr{L} \supset |D_\mu H|^2 + |D_\mu K|^2 + \frac{c_K}{2f^2}(\partial_\mu |K|^2)^2 - \epsilon m_K^2 (K^\dagger H + h.c.) + y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R + y_e \bar{L}_L H e_R .$$

Non linearity of the strong sector

$$\mathcal{O}^6 = c_K \frac{|\epsilon|^4}{2f^2}(\partial_\mu |H|^2)^2$$

Universal shift of Higgs couplings

$$\left.\frac{g_h}{g_h^{SM}}\right|_{\text{comp.}} = 1 - c_K |\epsilon|^4 \frac{v^2}{f^2}$$

Type I - 2HDM structure

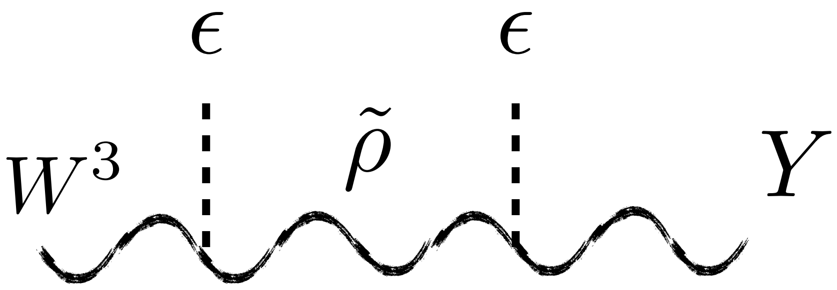
$$\frac{\delta g_{hVV}}{g_{hVV}} = -|\epsilon|^2 \frac{m_h^4}{2m_K^4} - c_K |\epsilon|^4 \frac{v^2}{f^2}$$

$$\frac{\delta g_{hff}}{g_{hff}} = |\epsilon|^2 \frac{m_h^2}{m_K^2} - c_K |\epsilon|^4 \frac{v^2}{f^2},$$

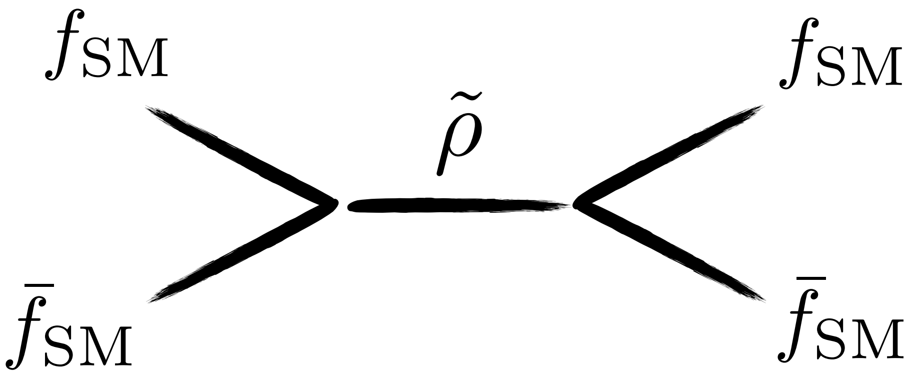
Leading effect

EWPO

$$\mathcal{L} \supset \frac{1}{f^2}(K^\dagger \overleftrightarrow{D}_\mu K)^2 \longrightarrow \hat{T} \sim \epsilon^4 \frac{v^2}{f^2}$$

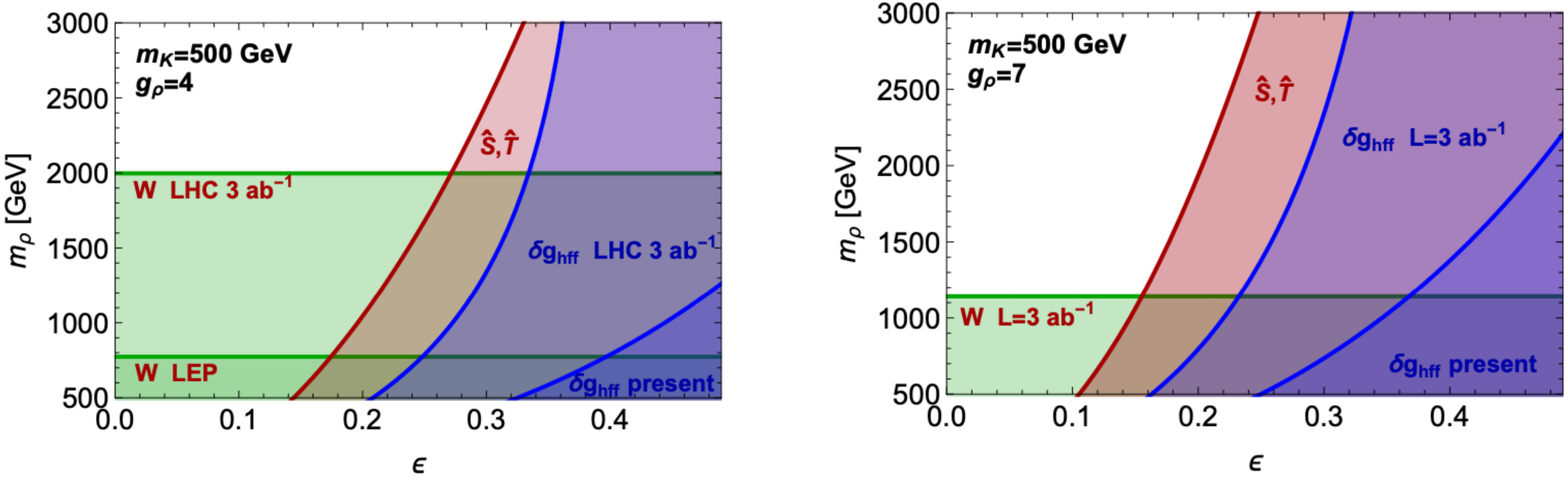


$$\longrightarrow \hat{S} \sim \epsilon^2 \frac{m_W^2}{m_\rho^2}$$



$$\longrightarrow W \sim \frac{m_W^2}{m_\rho^2}\frac{g_2^2}{g_\rho^2}$$

EWPO



- Present bounds allow for a low confinement scale with moderate ϵ

- Precision measurements of Higgs couplings will not surpass LEP bounds

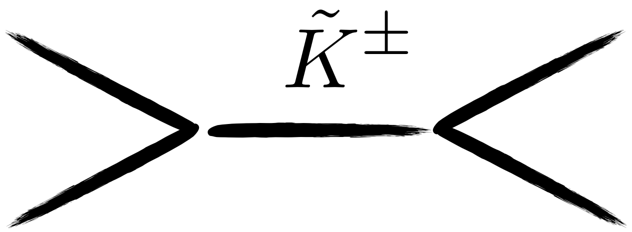
- Measurements of cc transverse mass spectra will be able to enforce tighter bounds

Flavor physics

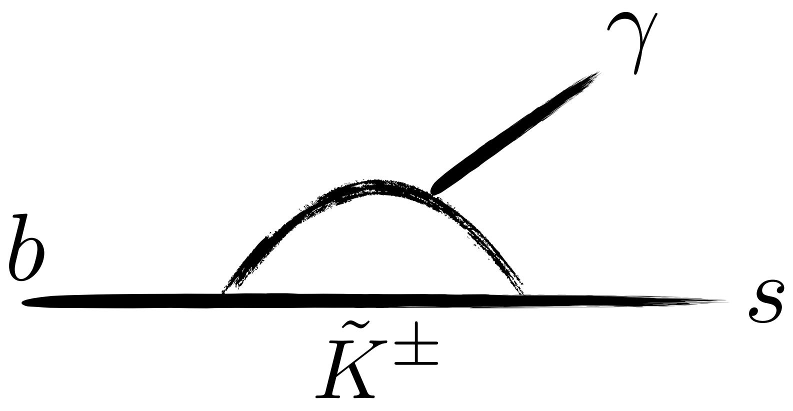
- The only source of flavor violation are the Yukawa couplings: Minimal Flavor Violation is automatically realised

$\Delta F = 1$

$B \to \tau\nu,\ K \to \mu\nu ...$



$b \to s\gamma$



Suppressed by ϵ and $\tilde{K}^{\pm}$ mass

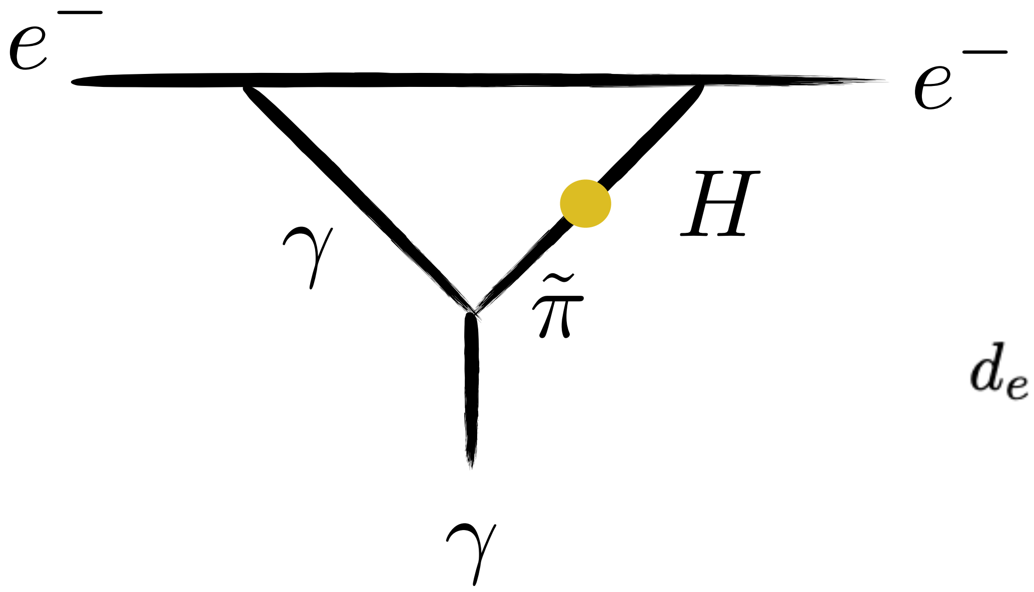
- Flavor physics doesn't impose relevant constraint

Electric dipole moment

- For complex phases extra irreducible sources of CP violation appear

$$\mathrm{Im}[y_i\tilde{y}_i] \qquad \theta_{\mathrm{DC}} \qquad \mathrm{Im}[m_i]$$

- Strongest constraint arise from electron EDM



$$d_e \sim 10^{-26}\,\mathrm{e\,cm} \times \mathrm{Im}[y_- y_+^*] \times \left(\frac{\mathrm{TeV}}{\mathrm{Min}[m_{\pi_3,\eta}]}\right)^4 \times \left(\frac{m_\rho}{\mathrm{TeV}}\right)^2$$

$$\lesssim \quad 8 \times 10^{-29}\ \mathrm{e\ cm}$$

- Tight constraint on CP violating phases

Collider Physics

- Phenomenological lagrangian to study the lighter states: $\eta, \ K, \ \pi, \ \rho$

$$\mathscr{L}_{INT} = |D_\mu \pi|^2 + |D_\mu K|^2 + \ g_\rho \rho^a_\mu \left(K^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu K + \pi^T T^a \overleftrightarrow{D}_\mu \pi \right) +$$

$$+ \frac{g^2}{g_\rho} \rho^a_\mu \left(i H^\dagger \frac{\sigma^a}{2} \overleftrightarrow{D}_\mu H + \bar{f}_L \frac{\sigma^a}{2} \gamma^\mu f_L \right)$$

Pion pair production

ρ triplet interaction with SM and pion currents

- The phenomenology is strongly constrained by the UV symmetry

- Everything is controlled by the absolute and relative ratio of y_- and y_+

$$- i y_- g_\rho f^2 (b K^\dagger H + h.c.)$$

$$y_+ g_\rho f \left(a_1 \eta K^\dagger H + a_3 \pi^a K^\dagger \sigma^a H + h.c. \right)$$

- When $y_- \sim \epsilon = 0$ parity is conserved: $\langle K \rangle = 0 \ \rightarrow$ no H - Pion mixing
- If $y_- \sim \epsilon \neq 0$ then $\langle K \rangle \neq 0$ generates $H\eta$ and $H\pi$ mixings

Phenomenology of η singlet

- When $y_- \sim \epsilon = 0$, η can not be directly produced since it EW singlet
- If $y_- \sim \epsilon \neq 0$ it acquires a coupling to gluons

$$\Gamma(\eta \to gg) \approx \epsilon^2 \frac{|y_+|^2}{g_\rho^2} \frac{v^2}{f^2} \frac{m_\rho^4}{m_\eta^4} \Gamma(H \to gg)|_{m_H = m_\eta}$$

Higgs-like particle
with rescaled couplings

- A light singlet decays either to 2γ via anomaly or to $b\bar{b}$ via mixing

$\eta \to 2\gamma$ relevant for small mixings so that anomaly dominates however production will be suppressed

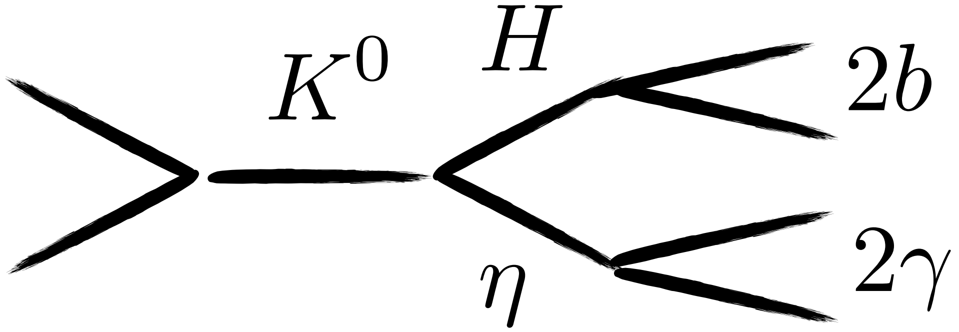
$\eta \to b\bar{b}$ buried under the QCD background

Direct production of pion singlet irrelevant for phenomenology

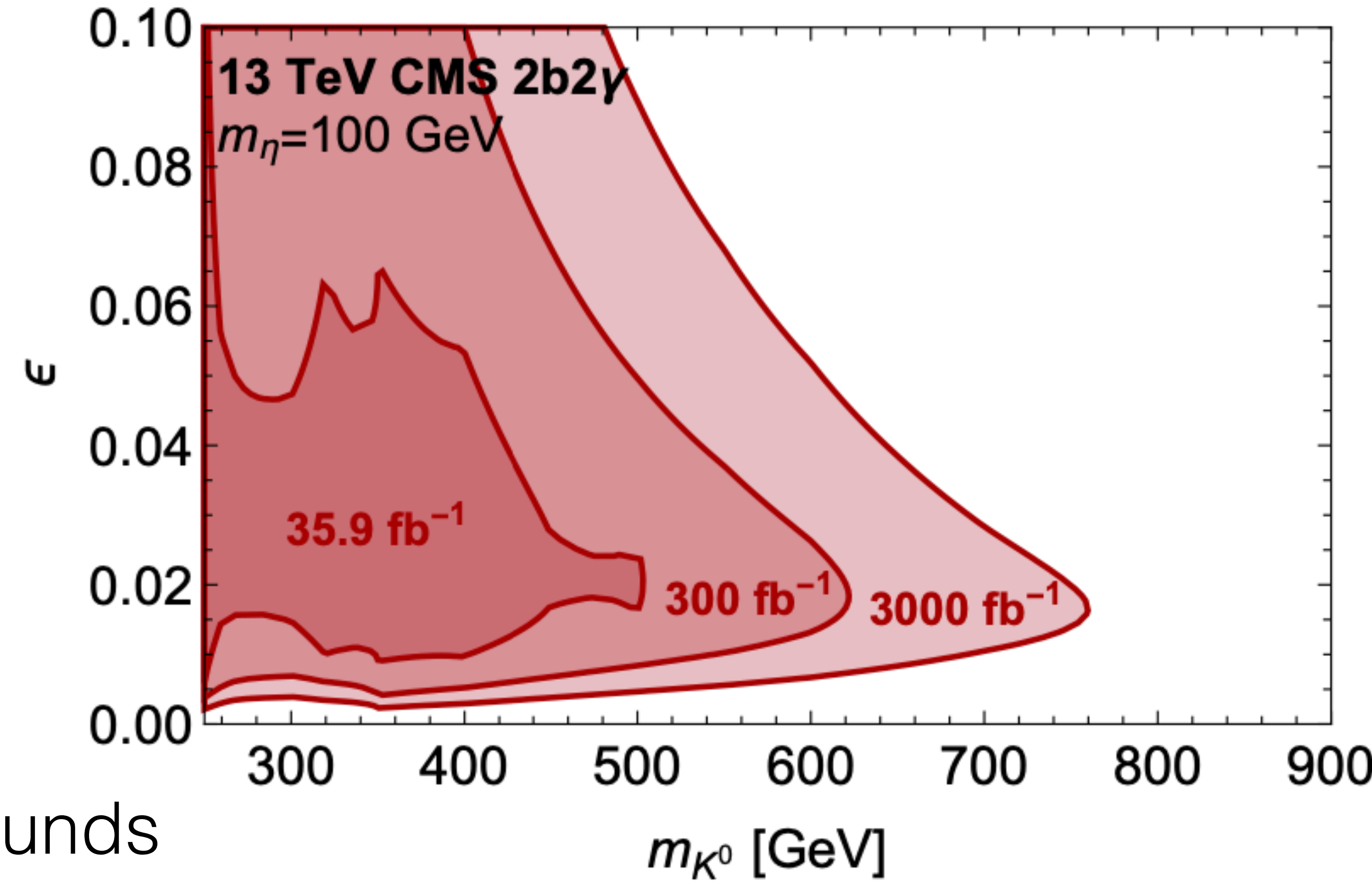
Phenomenology of K doublet

- Stable because of species number when $y_\pm = 0$: MET or HSCP
- $y_- \sim \epsilon \neq 0$ gives a heavy higgs production and decay phenomenology
- $y_+ \neq 0$ produces exotic decays into the Higgs and the singlet

$$\frac{\Gamma(K^0 \to t\bar{t})}{\Gamma(K^0 \to H\eta)} \sim 36 \frac{y_-^2}{|y_+|^2} \frac{y_t^2}{g_\rho^2} \frac{m_\rho^2}{m_K^2},$$



$$\frac{\mathrm{BR}(\eta \to 2\gamma)}{\mathrm{BR}(H \to 2\gamma)} \gg 1$$



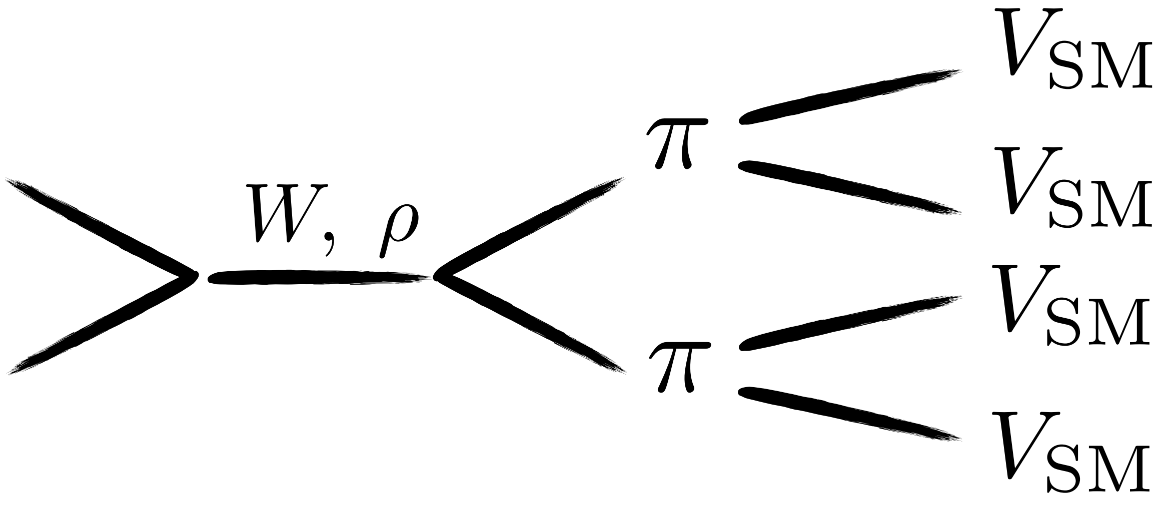
Naive reinterpretation sets stringent bounds

Also indirect probe of η singlet

Phenomenology of π triplet

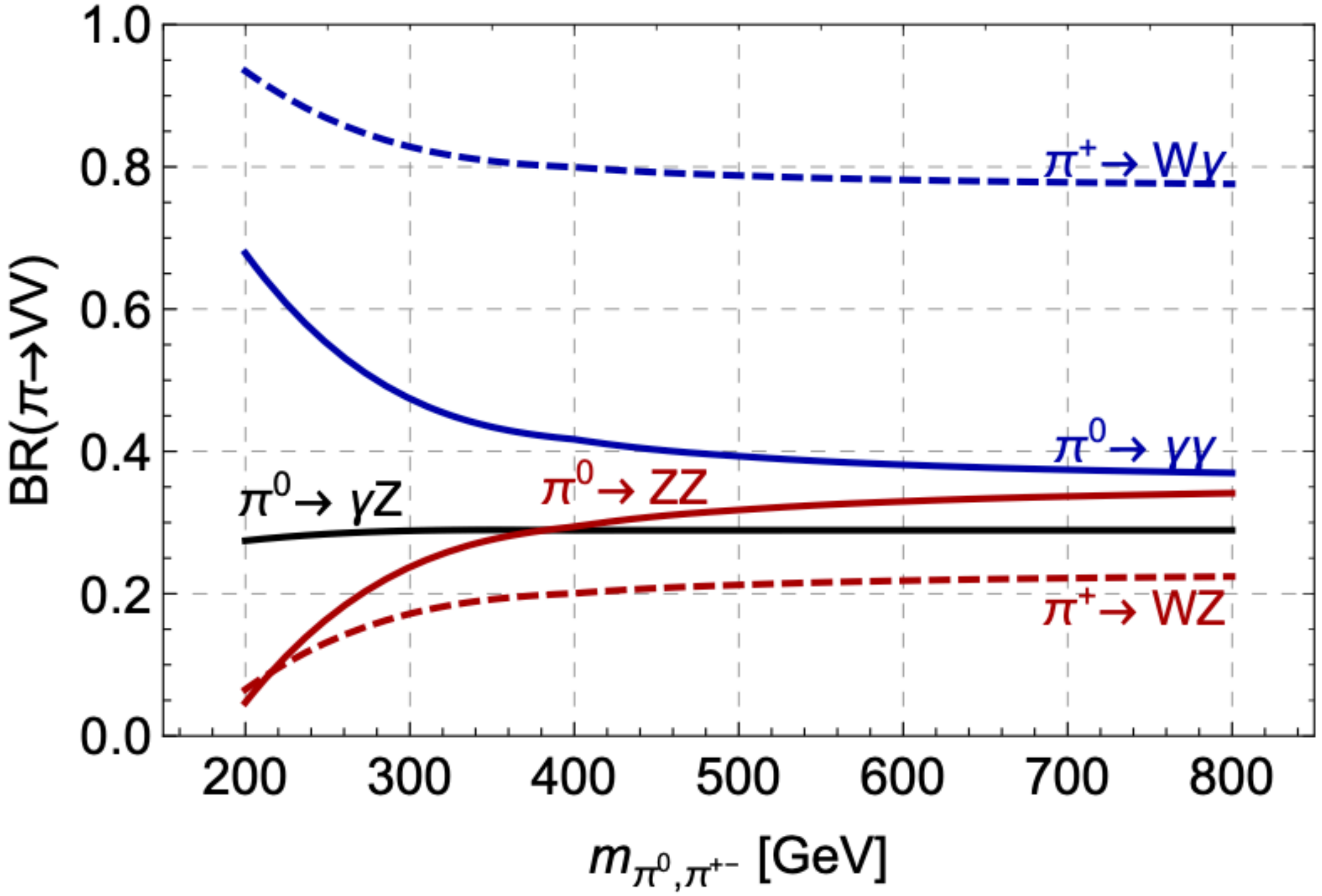
- When $y_-,\ y_+ \neq 0$ the phenomenology is again heavy Higgs like with possible exotic decays

- If $y_-,\ y_+ \sim 0$ the Higgs is almost elementary and π is produced via EW interactions and decays through anomaly



- Strinking multiboson final states are produced

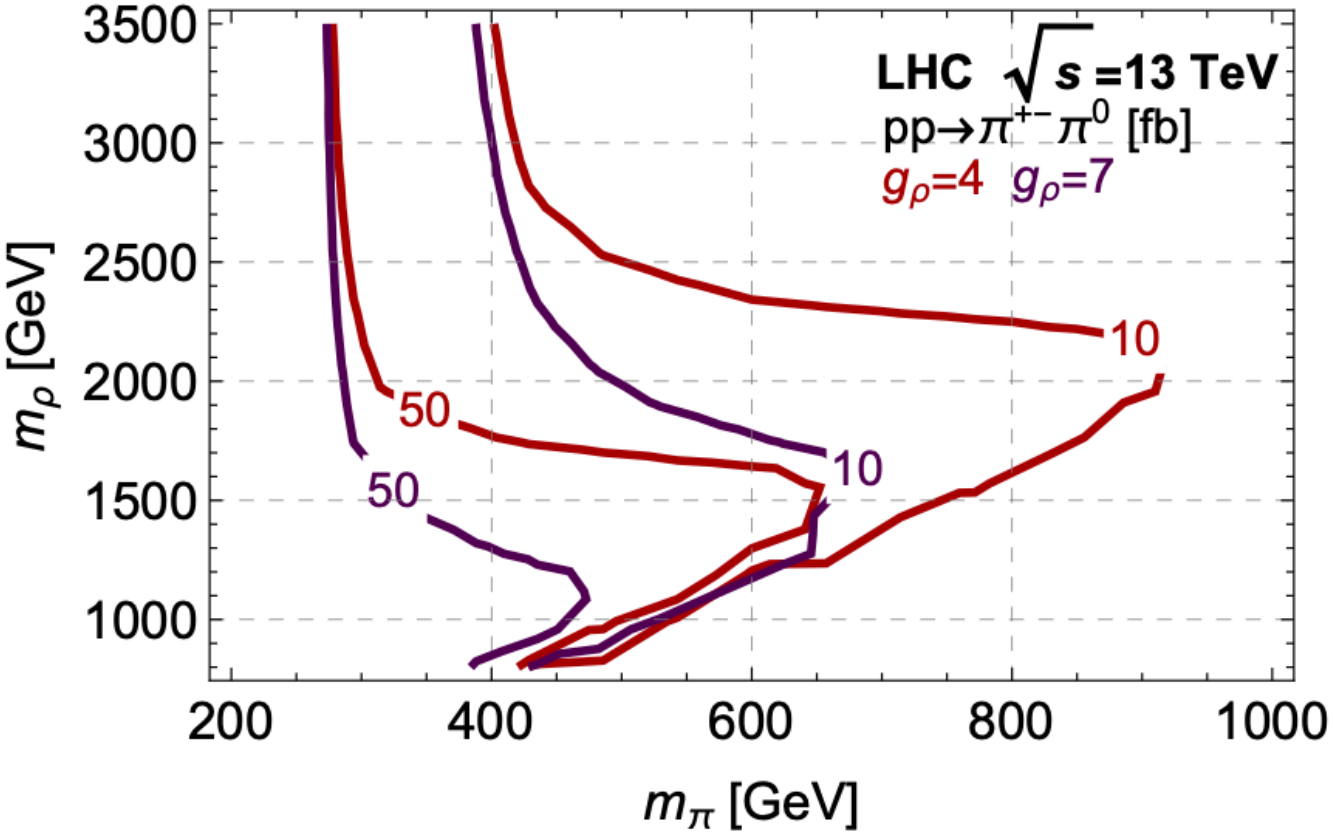
Phenomenology of π triplet



- $pp \to W^+ \to \pi^+\pi^0$ yields a $3\gamma W$ final state

- Clean signature with hard photons

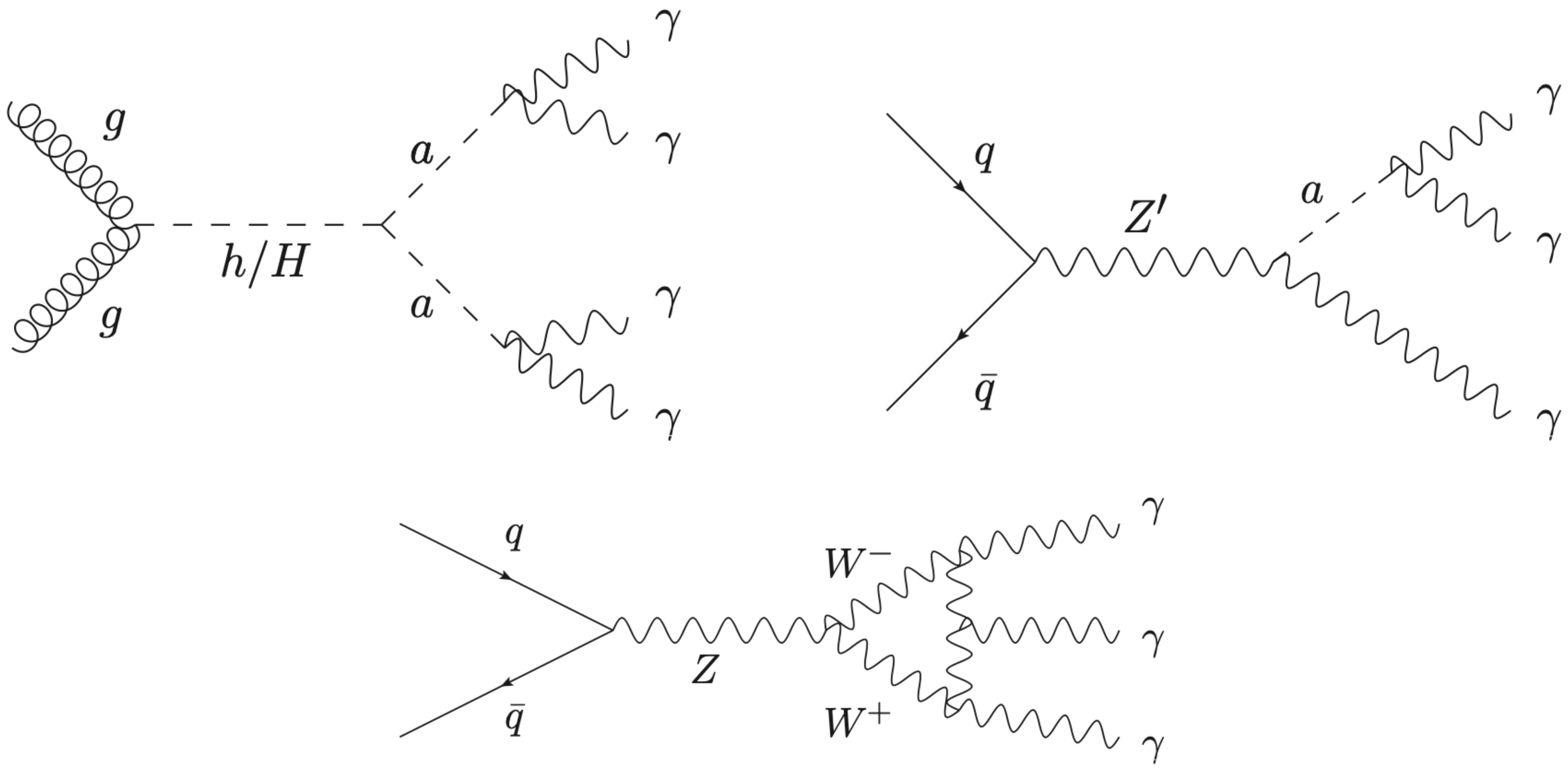
- Cross section resonantly enhanced by ρ exchange



Phenomenology of π triplet

- Existing LHC multi-γ searches target light scalars or exotic Z decays

ATLAS 1509.05051



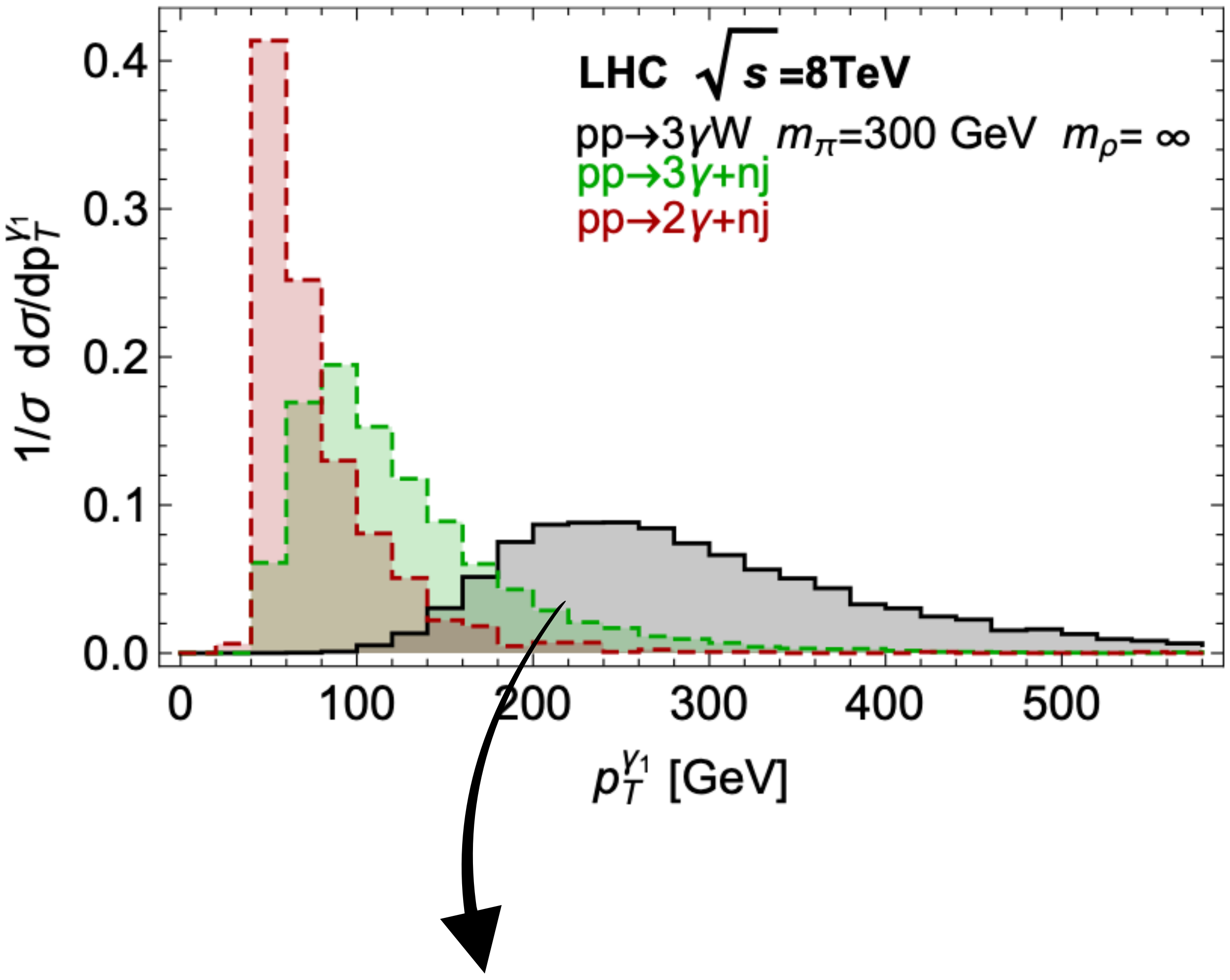
- Photon transverse momentum cut of 20 GeV not optimized for heavy physics

Phenomenology of π triplet

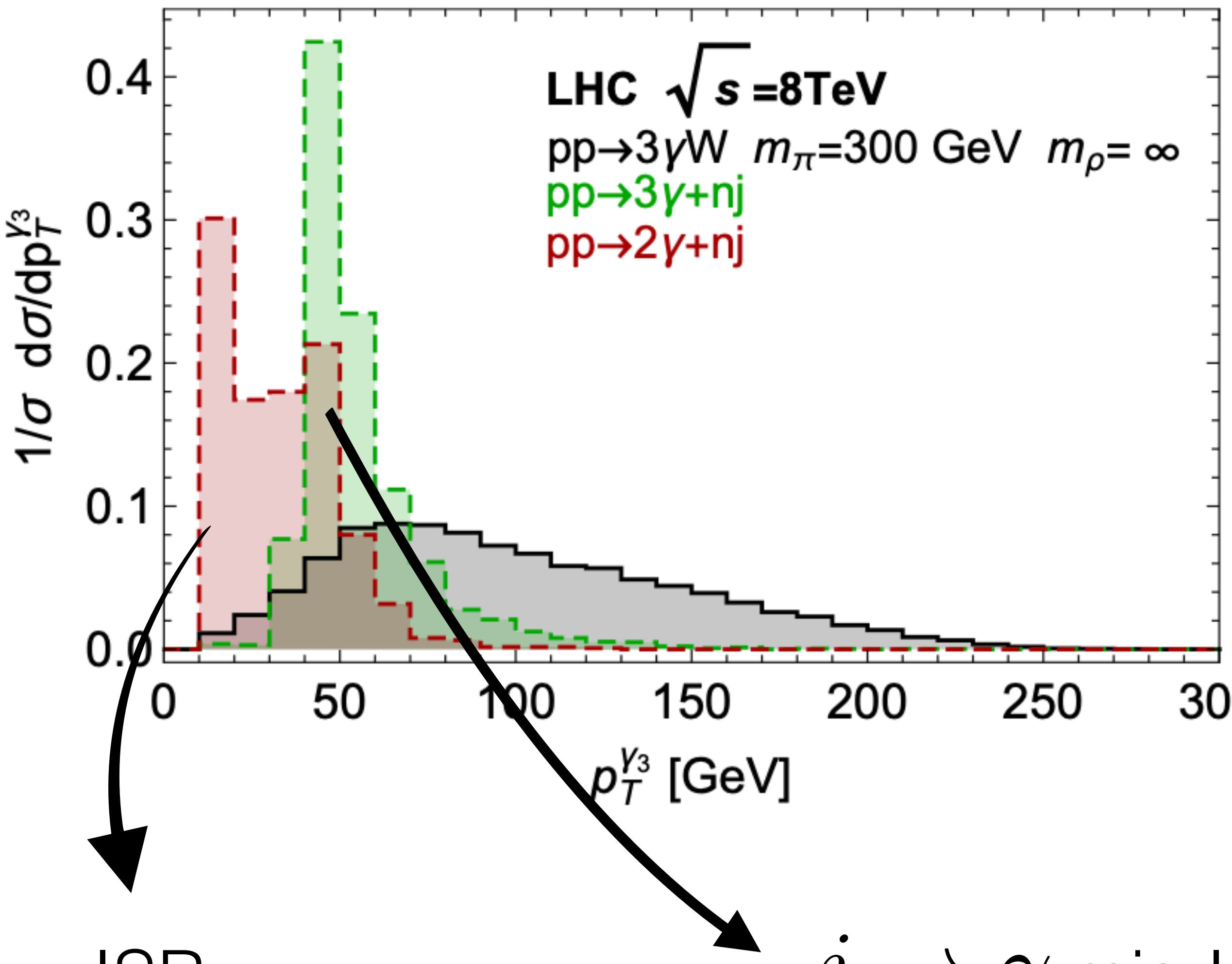
- Main background at the LHC from

$$3\gamma W$$

$2\gamma W + nj$ with jet mis-ID



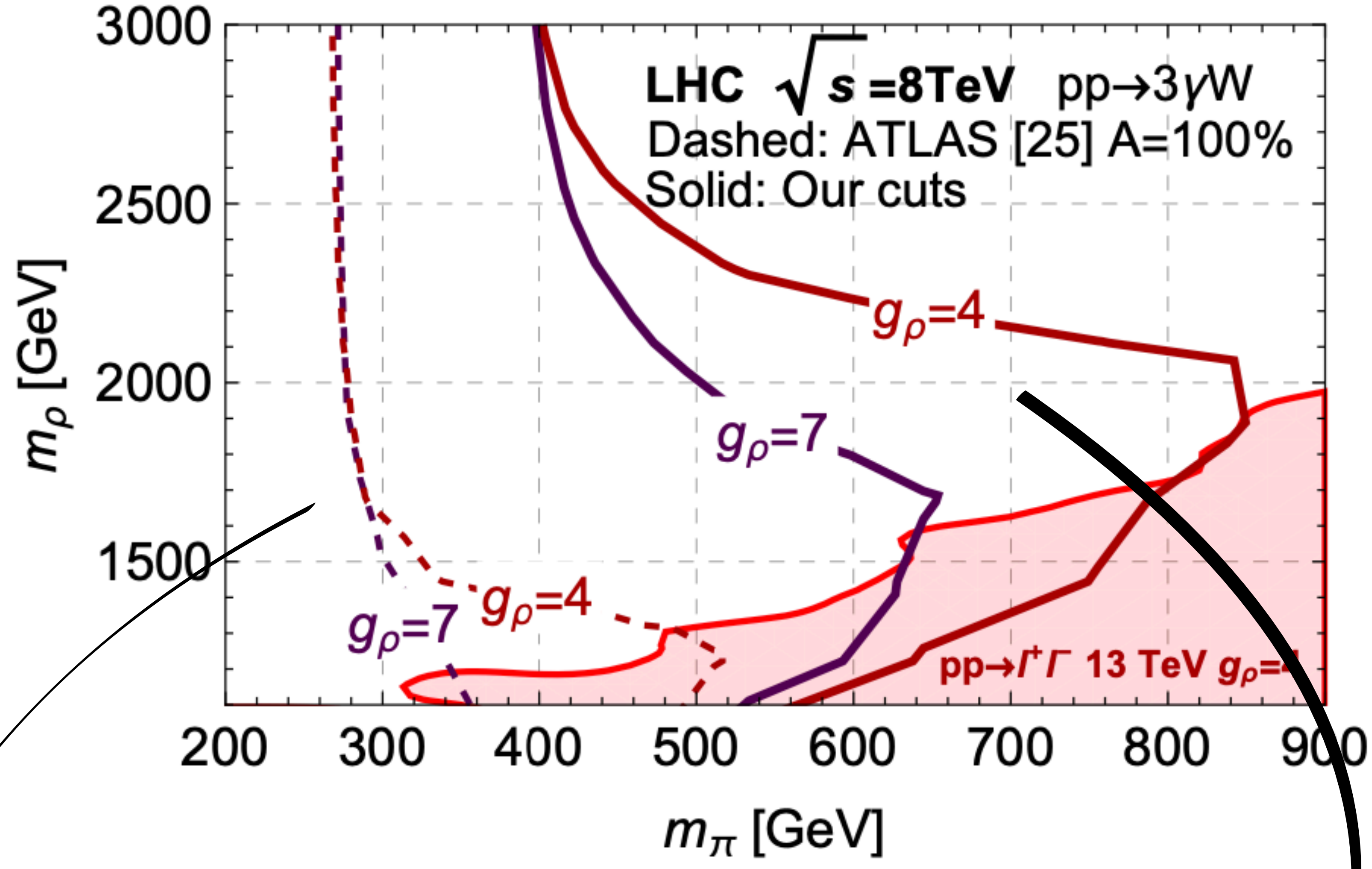
Signal has harder γ



ISR

$j \to \gamma$ mis-ID

Phenomenology of π triplet



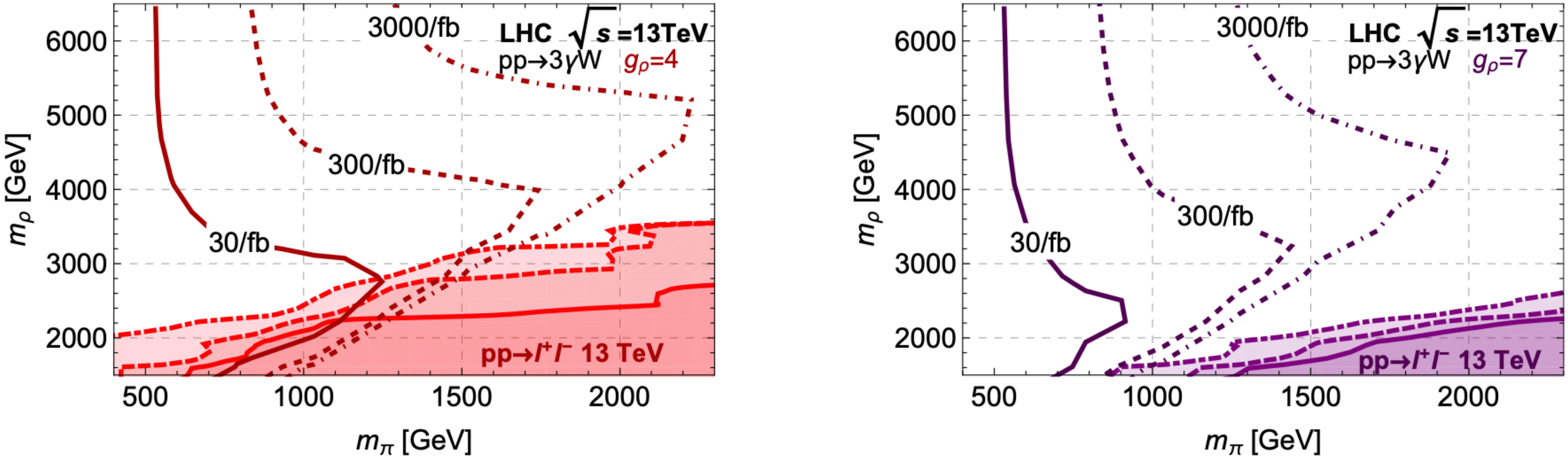
Recast of current ATLAS 3γ search

Reach with optimized cuts

$$p_T^{\gamma_1,\gamma_2,\gamma_3} > 250, 75, 75 \text{ GeV}$$

- 8 TeV data allow to test this scenario up to 800 GeV!

Phenomenology of π triplet

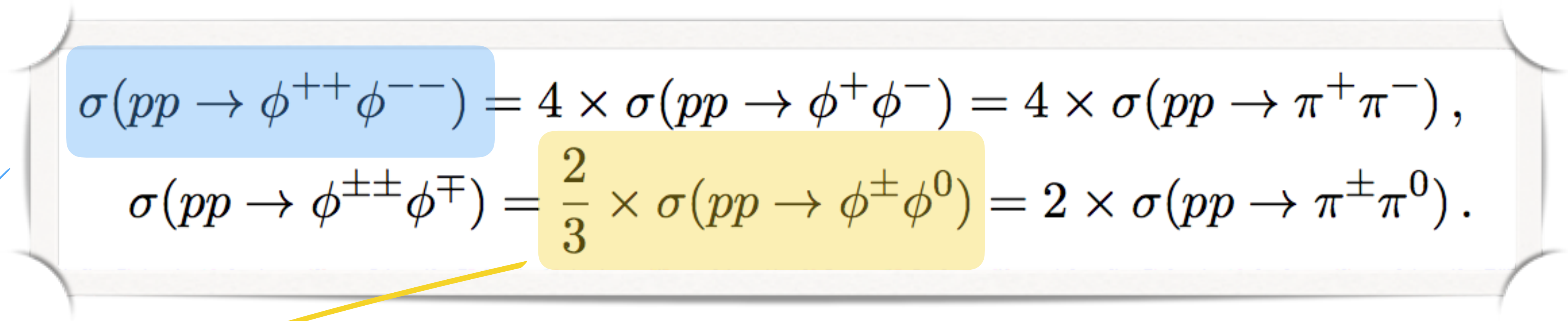


- 13 TeV data will greatly extend the reach

- The proposed analyis is complementary to resonant dilepton searches!

V model

- Model with $SU(2)_L$ triplets fermions give $SU(2)_L$ quintuplets pions
- No mixing with the Higgs is allowed: simple phenomenology



$$\sigma(pp \to \phi^{++}\phi^{--}) = 4 \times \sigma(pp \to \phi^{+}\phi^{-}) = 4 \times \sigma(pp \to \pi^{+}\pi^{-}) \,,$$

$$\sigma(pp \to \phi^{\pm\pm}\phi^{\mp}) = \frac{2}{3} \times \sigma(pp \to \phi^{\pm}\phi^{0}) = 2 \times \sigma(pp \to \pi^{\pm}\pi^{0}) \,.$$

$4W$ final state - same-sign multilepton $m_\phi^{++} \gtrsim 400\,\mathrm{GeV}$

$3\gamma W$ as for the pions - with higher cross-section

(possible?) Relation with neutrino masses

- For $SU(N)$ theories with odd N a baryon is a fermion
- The right-handed component of the singlet could be related to ν masses

$$\mathcal{L} \sim \frac{1}{\Lambda_1^3}\bar{L}\tilde{H}[\Psi\Psi\Psi] + \frac{1}{\Lambda_2^5}[\Psi\Psi\Psi][\Psi\Psi\Psi] + \frac{1}{\Lambda_3^5}[\bar{\Psi}\bar{\Psi}\bar{\Psi}][\Psi\Psi\Psi] + \dots$$

$$\Big\downarrow$$

$$\mathcal{L} \sim \frac{\mu^3}{\Lambda_1^3}\bar{L}\tilde{H}\mathcal{B}_R + \frac{\mu^6}{\Lambda_2^5}(\mathcal{B}_R\mathcal{B}_R + R \leftrightarrow L) + \frac{\mu^6}{\Lambda_3^5}(\bar{\mathcal{B}}_L\mathcal{B}_R + R \leftrightarrow L) + \dots$$

- The $U(1)_{\rm DB}$ accidental symmetry forbids the generation of $L\tilde{H}\mathcal{B}$ operator
- This symmetry guarantees the DM stability. Break it: DM decays
- Reconcile $\tau_{\rm DM}$ and ν masses

OR

- Use a dark pion to realize a type-II see-saw. Dark pions to not carry $U(1)_{\rm DB}$
  One doesn't jeopardize the DM stability

(possible?) Relation with EW baryogenesis

- The chiral lagrangian delivers interactions between Higgs, K and η

$$\mathcal{L}_{\rm int} \sim \lambda H^\dagger K \eta^2 . \quad \xrightarrow{\textbf{physical basis}} \quad \mathcal{L}_{\rm int} \sim \lambda \sin\beta |H|^2 \eta^2 ,$$

- Light scalar degrees of freedom coupled to the Higgs generate a cubic term in the thermal potential

$$\delta V \sim \frac{1}{12\pi} T (\lambda \sin\beta)^{3/2} |H|^3$$

- A strong FOPT requires $\displaystyle \frac{v_c}{T_c} \sim \frac{v^2}{m_H^2} \frac{(\lambda \sin\beta)^{3/2}}{3\pi} \gtrsim 1$

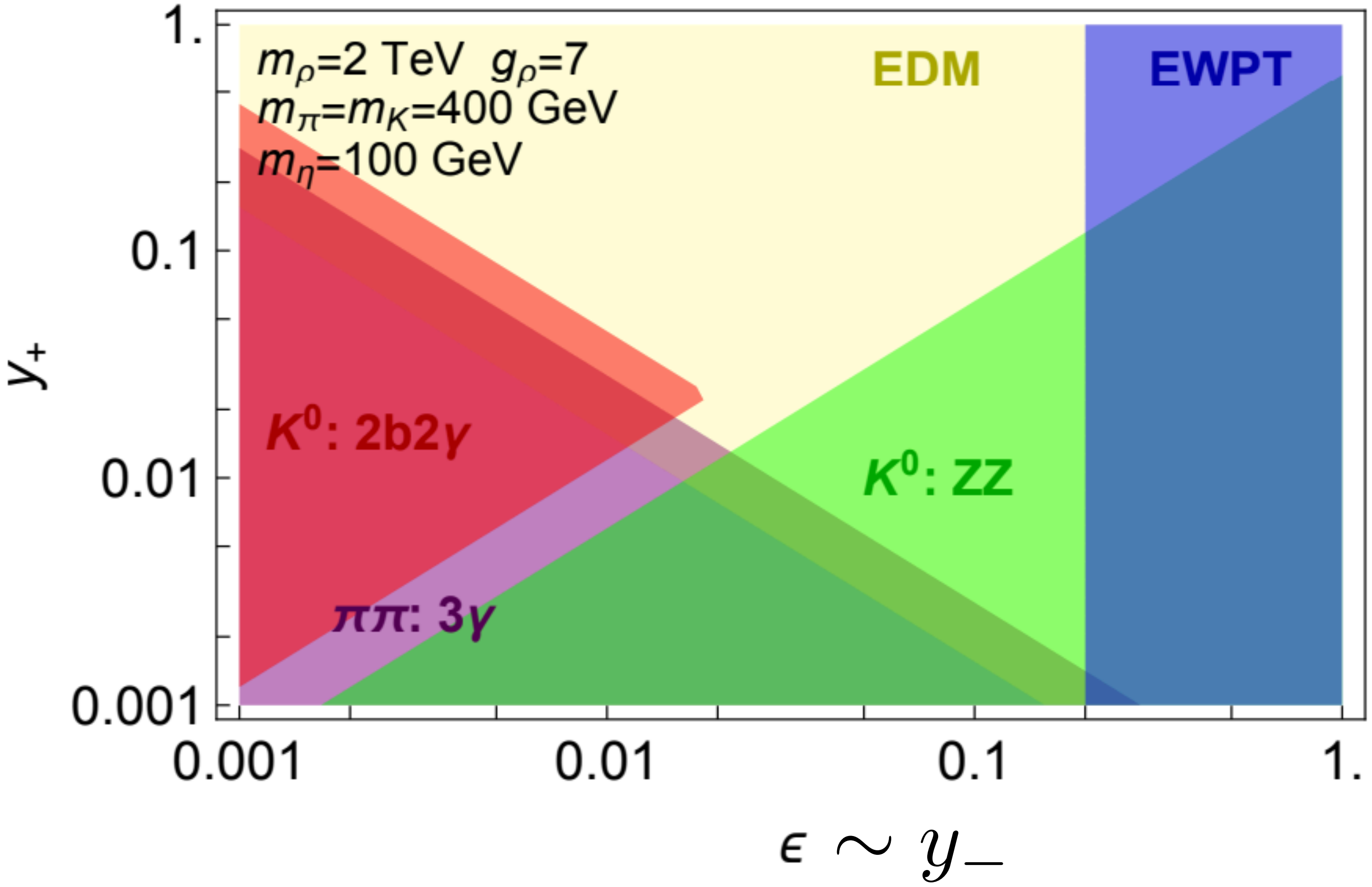
- The mixing angle is constrained by EWPO

$$1 \lesssim \frac{v_c}{T_c} \sim \frac{v^2}{m_H^2} \frac{1}{3\pi} \hat{T}^{3/4} \left(\frac{m_K^2}{f v} \right)^{3/2} \qquad \hat{T} \lesssim 10^{-3}$$

Minimal model doesn't work…

Summary

- QCD like theories are a rich playground for model building
- Possibilities ranging from Dark Matter, Neutrinos, Baryogenesis….
- Current direct searches at collider are not sensitive to these scenarios



- Easy experimental analysis can be designed. Great sensitivity expected!

Thank you