The Dark Side of 4321

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based on 2005.10117,
with Méril Reboud and Peter Stangl

Introduction

and main idea

Collider Data

- *No direct evidence of BSM at colliders*
- *Several hints from flavour experiments*

❶ $b \to s\,\mu\mu$ *BR data < SM*

Challenge: B → light meson f.f.'s

❷ $B \to K^*\,\mu\mu$ *angular data*

Challenge: charm loops

❸ $b \to s\,\mu\mu \;/\; b \to s\,ee$ *ratios*

Challenge: (mostly) stats

loop processes

❹ $b \to c\,\tau\nu \;/\; b \to c\,\ell\nu$ *ratios*

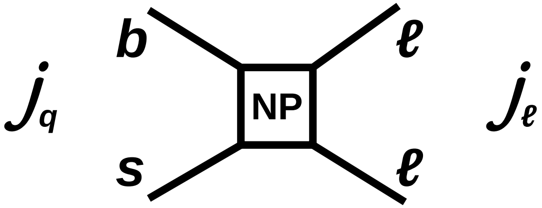
Challenge: stats + syst

tree processes

Why LeptoQuarks

- $R_K \approx 0.85$

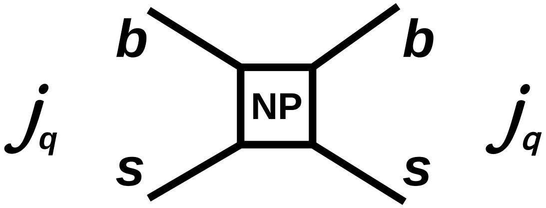
O(15%) effects in



At the same time:

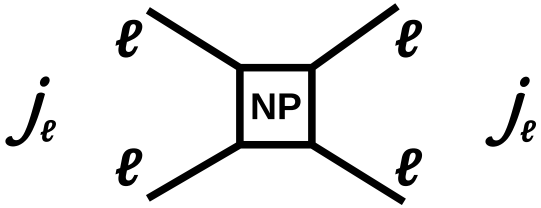
- $\Delta M_s \approx (\Delta M_s)_{SM}$

small corrections to



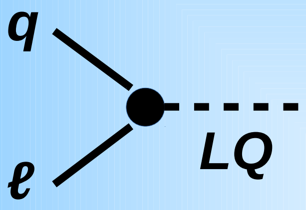
- $\ell \to \ell' + X$
  < *current limits*

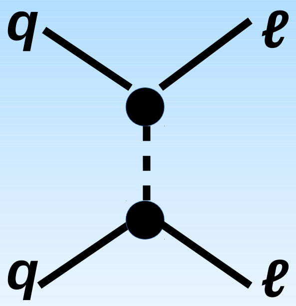
and small corrections to



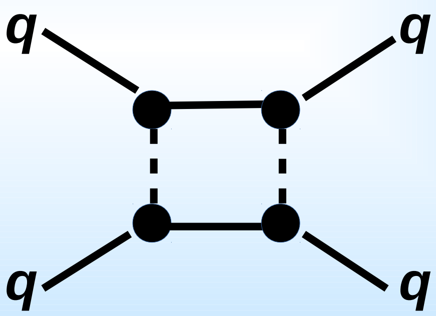
Why LeptoQuarks

Take





then j_q j_ℓ *is tree*



but j_q j_q *is loop-suppressed*

(at least for "genuine" LQs [Dorsner et al., LQ review])

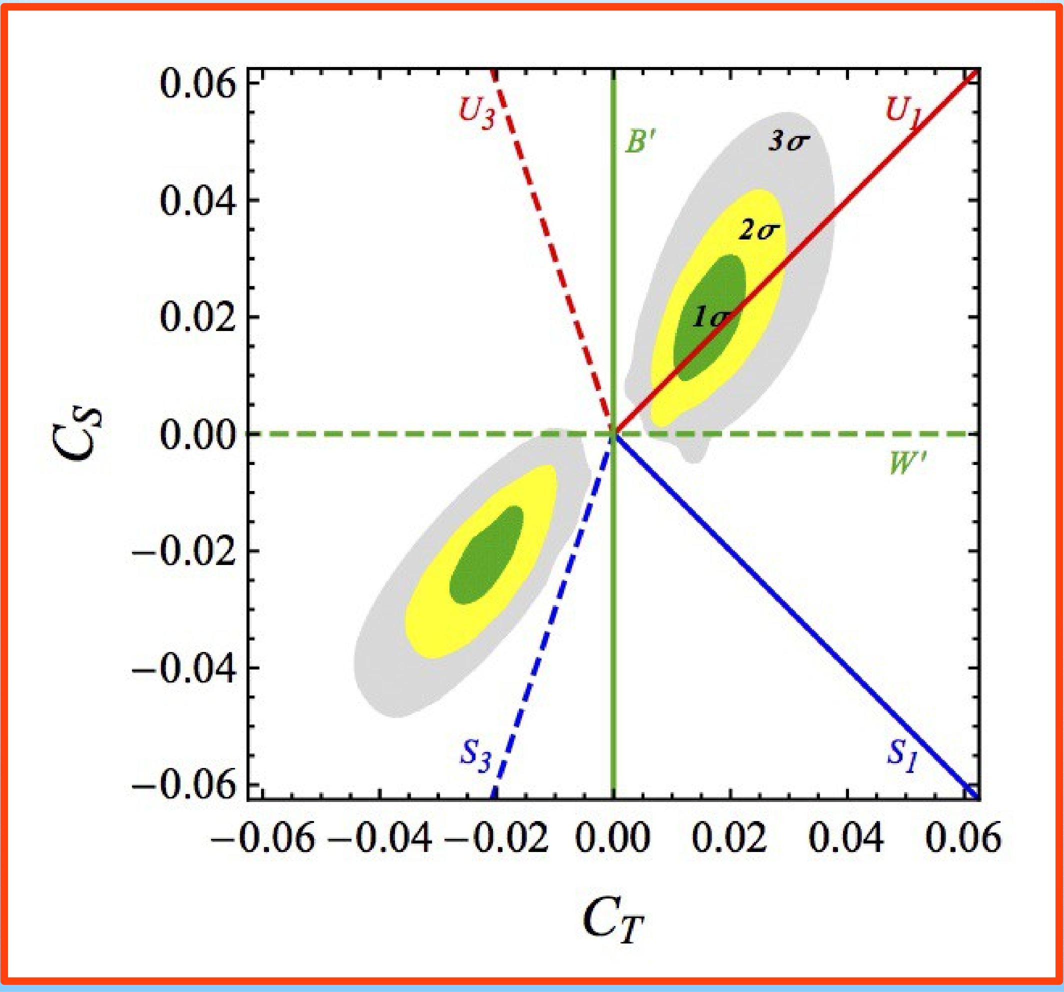
The U_1 LQ

- It was realized that the vector *LQ* U_1 ~ (**3**, **1**, *2/3*)

[*Alonso, Grinstein, Martin-Camalich, Calibbi, Crivellin, Ota, 2015*]

would simultaneously explain all B discrepancies

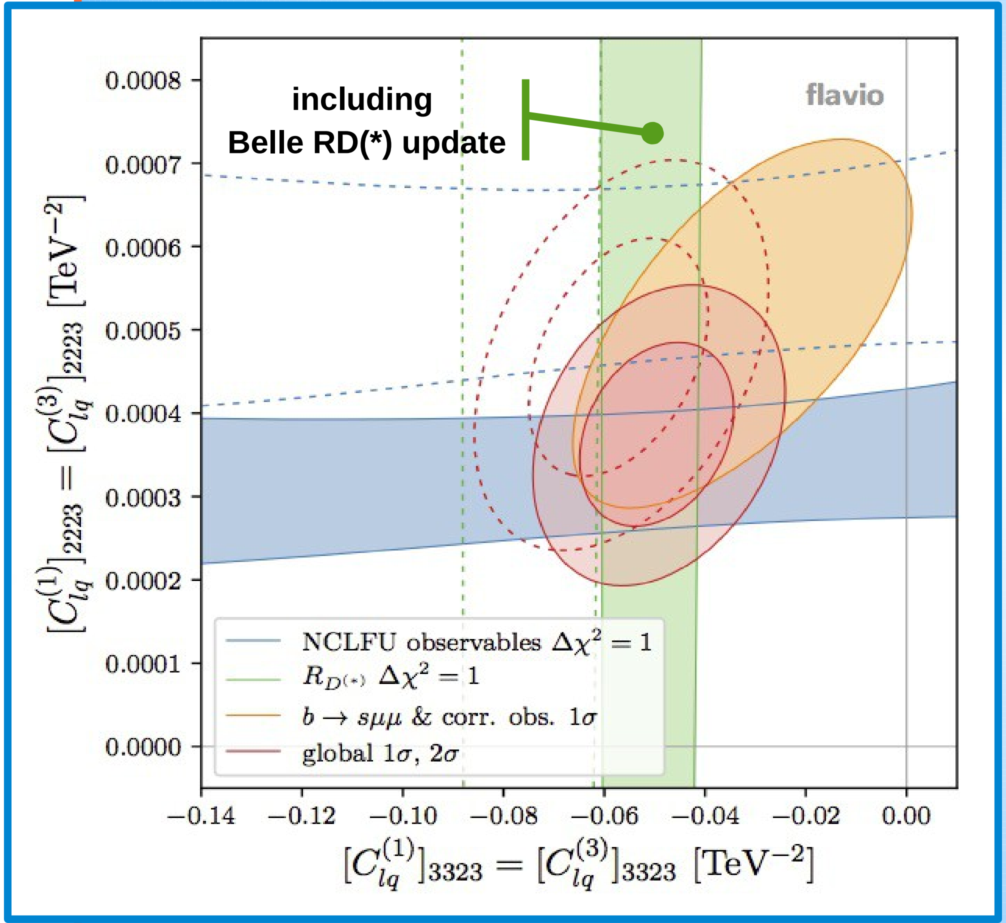
[*Buttazzo, Greljo, Isidori, Marzocca, 2017*]



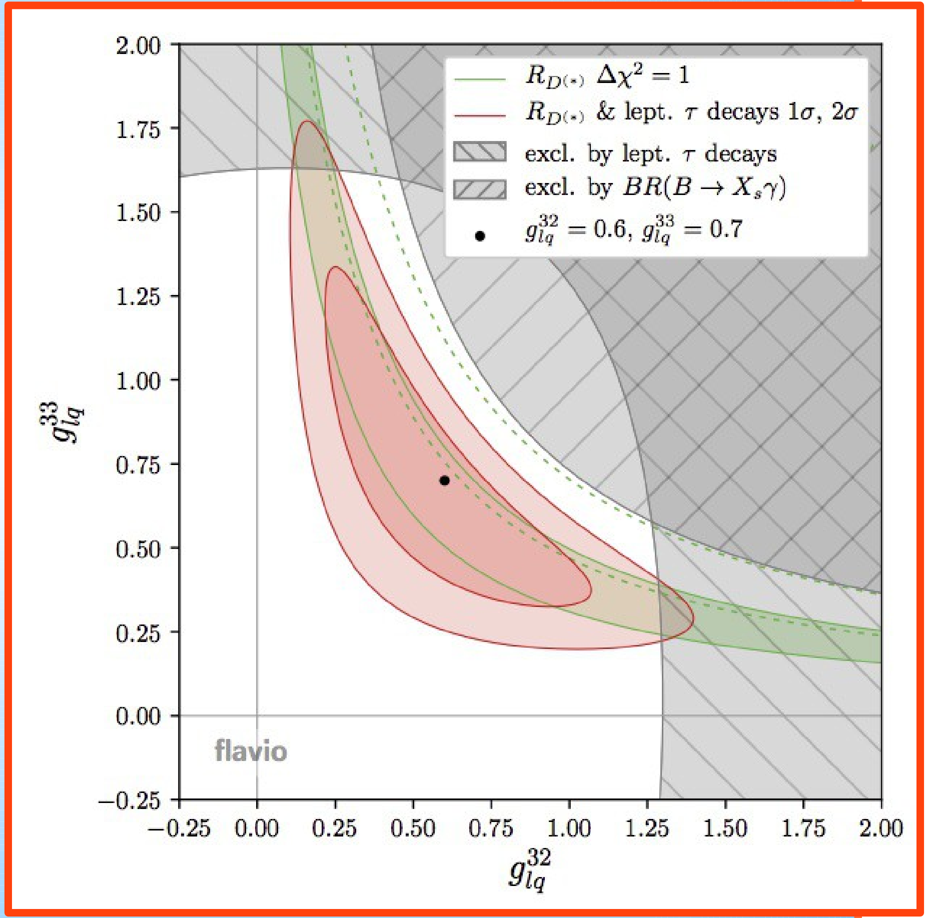
The U_1 LQ

- This explanation has become even more consistent with recent data

[*Aebischer et al., 2019*]



including Belle RD(*) update



The U_1 LQ and UV completions

- As a massive vector boson, the U_1 requires a UV completion

as

- a composite vector boson [*Barbieri, Murphy, Senia , 2016*]
- a gauge boson of a spont.-broken gauge sym.

Pati-Salam? $SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

☞ Problem: push the scale of RH currents up, but not the U_1 scale

The U_1 LQ and UV completions

- Pati-Salam? $SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

Problem: push the scale of RH currents up, but not the U_1 scale

- "Partial Unification": color & hypercharge are embedded into

$$SU(3+N) \times SU(3)' \times U(1)'$$

[*Georgi, Nakai , 2016*]

$N = 1$ ⇨ U_1 LQ not coupled to SM fermions that are singlets of $SU(3+N)$

- A coupling to LH SM fermions can still be generated from

SM fermions ⇔ **mixing** ⇔ VL fermions ~ $SU(4) \times SU(2)_L$

[*Diaz, Schmaltz, Zhong, 2017*]

… which leads to 4321

1^{st} complete construction (incl. pheno):

[*Di Luzio, Greljo, Nardecchia, 2017*]

- Consider $SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X$

The SM arises after

$$SU(4) \times SU(3)' \times U(1)_X \longrightarrow SU(3)_c \times U(1)_Y$$

Two basic questions.

- Who ordered all this structure? Flavour anomalies alone?

  DM (if particles) arguably the most solid evidence of BSM

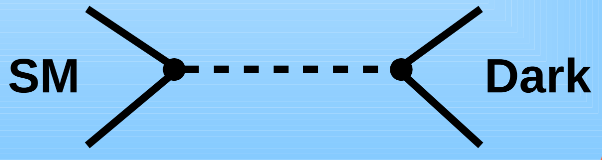
- By construction, 4321 includes several new v.b.'s

U_1

G'
$SU(3)_c$ octet

Z'
SM singlet

One or more of them may well mediate



4321

and Dark Matter

DM: General Considerations

Bosonic vs. fermionic

Bosonic DM would rely
on a Higgs portal as mediator ⇨ fermionic
DM

DM requirements

- *(1)* cold thermal relic
- *(2)* color-less and electrically neutral
- *(3)* zero hypercharge (→ avoid DD bounds)
- *(4)* vector-like under 4321
- *(5)* (co-)annihilation dominated by 2 → 2 processes

approach analogous to [*Cirelli, Fornengo,Strumia, 2005*]

DM within 4321

(2) color-singlet and Q = 0

(3) Y = 0

$\Rightarrow$ SU(2)$_L$ irrep with odd dim

$\Rightarrow$ X is fixed for a given SU(4) irrep

$$\left(Y = X + \sqrt{\frac{2}{3}} T^{15} \right)$$

- We restrict to the smallest irrep: the **4**

$$\Psi_{\mathrm{DM}} \sim (\mathbf{4}, \mathbf{1}, \boldsymbol{N}, +1/2) \qquad \text{w/ } N = \mathbf{1}, \mathbf{3}, \mathbf{5}, \ldots$$

$$\Big\downarrow \ \textbf{4321 breaking}$$

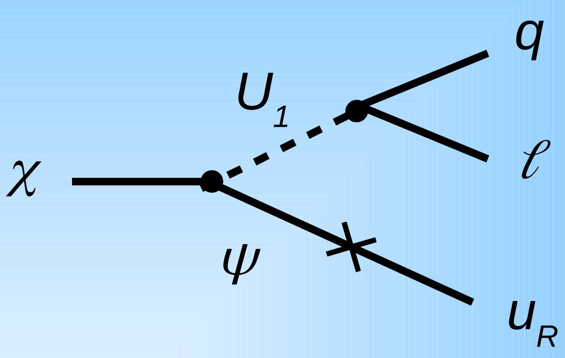
$$\chi \sim (\mathbf{1}, \boldsymbol{N}, 0) \quad \& \quad \psi \sim (\mathbf{3}, \boldsymbol{N}, 2/3)$$

$\Rightarrow$ DM = e.m.-neutral component of χ

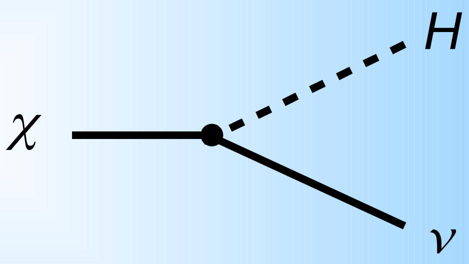
Disclaimer

see also [*Cirelli, Fornengo, Strumia, 2005*]

- $N = 1$ ψ mixes with u_R ⇒



- $N = 3$ $L \tau^a H \chi^a$ ⇒

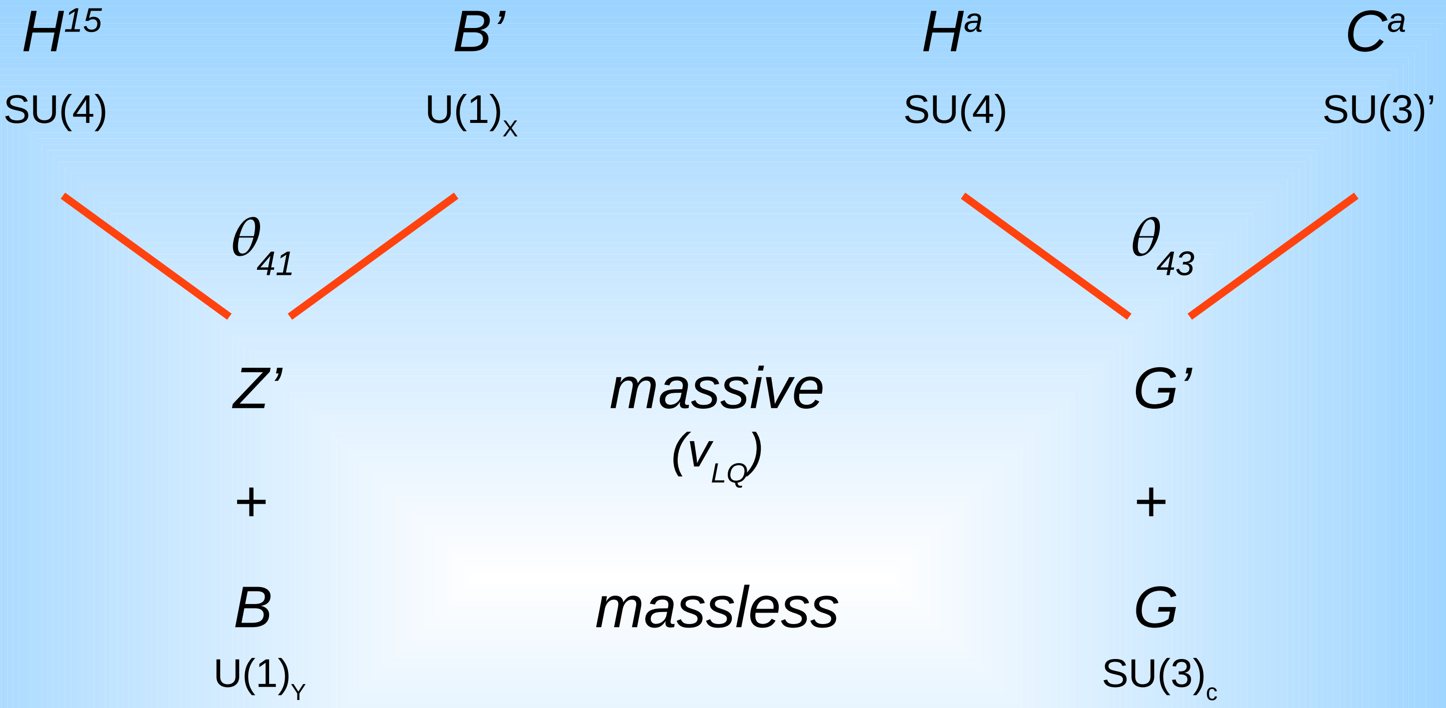


- $N = 5$ no renormalizable couplings leading to χ decay

Model

parameters

G.b. mixing



H^{15} SU(4) | B' $U(1)_X$ | H^a SU(4) | C^a $SU(3)'$

θ_{41} | θ_{43}

Z' | *massive* (v_{LQ}) | G'

+ | | +

B $U(1)_Y$ | *massless* | G $SU(3)_c$

$$\cos\theta_{41} = \frac{g_4}{\sqrt{g_4^2+g_1^2}} = \frac{g_Y}{g_1} \qquad \cos\theta_{43} = \frac{g_4}{\sqrt{g_4^2+g_3^2}} = \frac{g_s}{g_3}$$

☞ *once g_4 is fixed, so are g_1 and g_3*

↳ *free params: v_{LQ} , g_4*

Fermionic sector

- 3rd - family fermions unified into **4**'s

$$\left\{\begin{aligned}\Psi_L^3 &= (q_L, \ell_L)\\ \Psi_R^{3(+)} &= (u_R, \nu_R)\\ \Psi_R^{3(-)} &= (d_R, e_R)\end{aligned}\right.$$

- light fermions are as in the SM. So they don't couple to U_1

☞ introduce

$$\Psi_L^i = \begin{pmatrix}\Psi^i_{q_L}\\ W^{ij}\,\Psi^j_{\ell_L}\end{pmatrix}$$

that

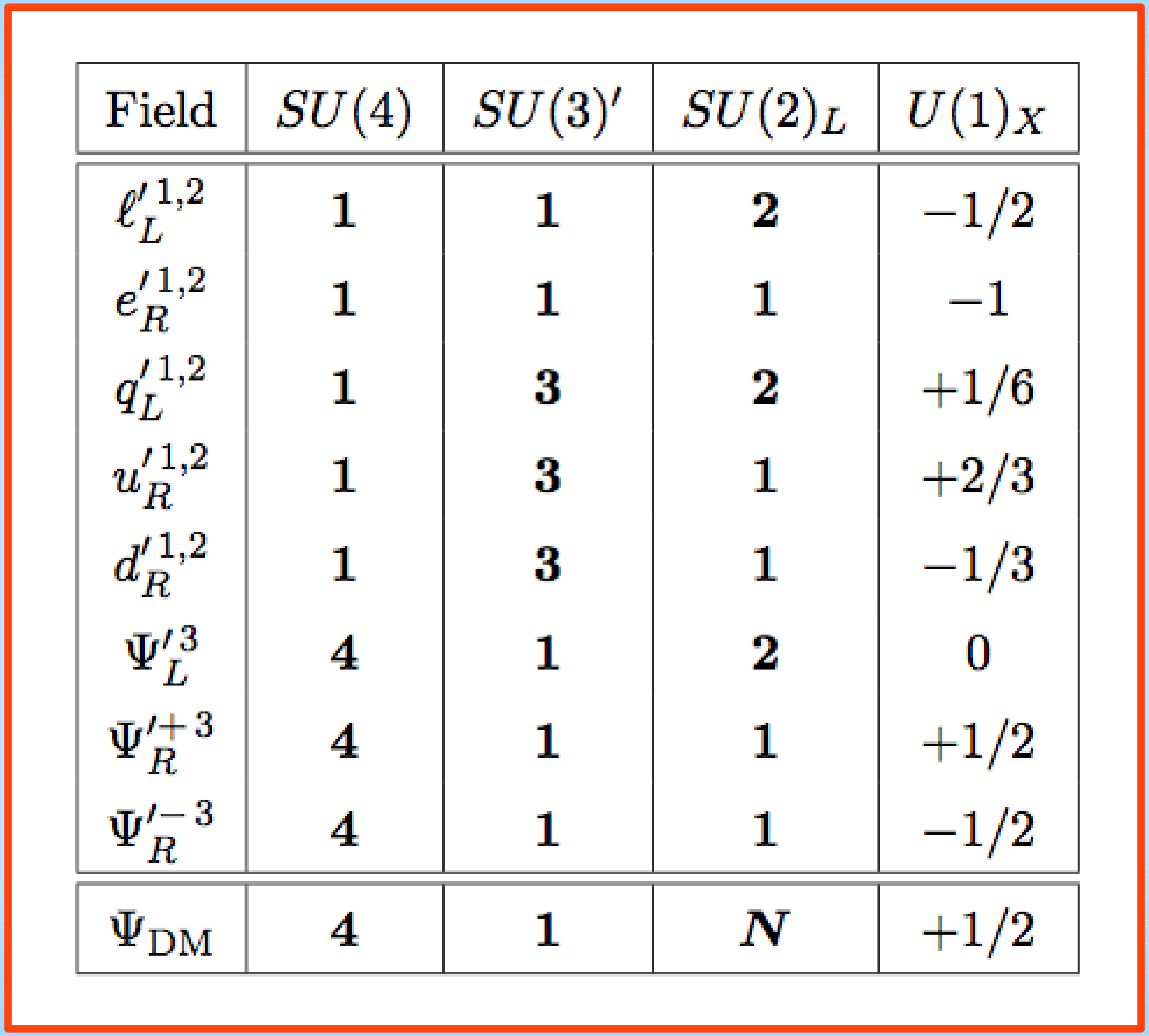
- transform like Ψ_L^3
- mix onto LH SM fermions of gen. *i*

⇨ 1st- and 2nd- gen. fermions: linear combi's of

$(q'^{1,2}_L, \ell'^{1,2}_L)$ and $(\Psi'^{1,2}_{q_L}, \Psi'^{1,2}_{\ell_L})$ via $(\theta_{q_i}, \theta_{\ell_i})$

[Bordone+., '17-'18; Greljo, Stefanek, '18; Cornella+, '19;
Di Luzio+, '18; Fuentes-M., Stangl, '20]

Fermionic sector



Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\ell_L'^{1,2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$e_R'^{1,2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$q_L'^{1,2}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$+1/6$
$u_R'^{1,2}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$+2/3$
$d_R'^{1,2}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
$\Psi_L'^{3}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
$\Psi_R'^{+\,3}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$+1/2$
$\Psi_R'^{-\,3}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ψ_{DM}	$\mathbf{4}$	$\mathbf{1}$	$\boldsymbol{N}$	$+1/2$

Fermionic sector

Simplifying assumptions (w/ marginal impact on DM pheno):

(a) W_{ij} mixes only 2nd and 3rd gen. ⇨ one single angle θ_{LQ}

(b) approx. U(2) sym. between light quark gen.'s ⇨ $\theta_{q_1} = \theta_{q_2} =: \theta_{q_{12}}$

(c) 1st-gen leptons are SU(4) singlets ⇨ $\theta_{\ell_1} = 0$

(avoids U_1 - mediated LFV)

⇩

"Minimal" fermion-sector params.:

$$\theta_{q_{12}} \qquad \theta_{\ell_2} \qquad \theta_{LQ}$$

Parameter recap

Model parameters are thus

$$\boxed{g_4 \quad v_{LQ} \quad M_\chi \quad N} \quad \boxed{\theta_{q_{12}}} \quad \boxed{\theta_{\ell_2} \quad \theta_{LQ}}$$

DM pheno depends crucially on these params.

important only for direct detection

DM pheno nearly unaffected by them

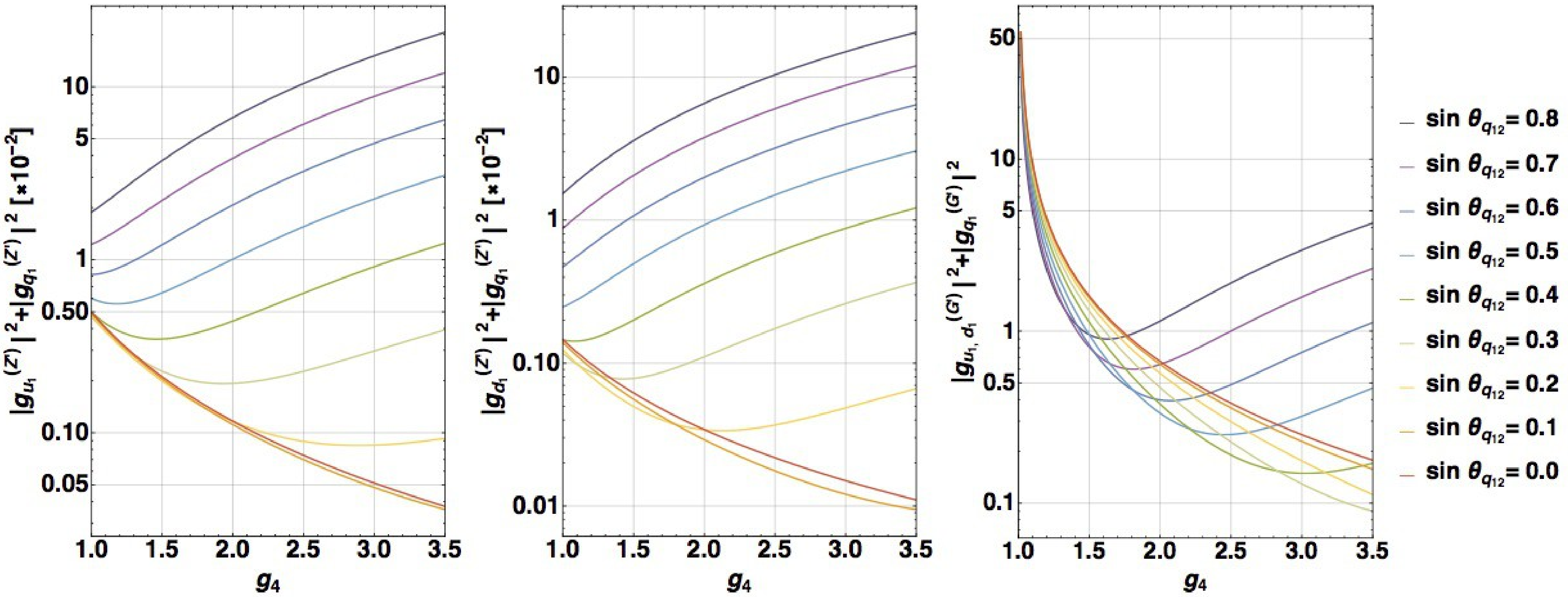
- A fit to flavour data, in particular $R_{D(*)}$ [*Cornella, Fuentes-M., Isidori, 2019*] constrains a combi of v_{LQ} and of the U_1 couplings to 2nd and 3rd gen (⇨ of $\theta_{q_{12}}$, θ_{ℓ_2}, θ_{LQ})

This translates into the fiducial range $v_{LQ} \in [3, 5]$ TeV

Collider constraints

- g_4 & $\theta_{q_{12}}$ enter U_1, Z', G' couplings

⇨ constrained by direct searches



Suggested ranges: $g_4 \gtrsim 3$ & $\sin\theta_{q_{12}} \lesssim 0.2$

DM

relic abundance

Ω_0 estimation

- Our DM sector includes all particles within the χ and ψ multiplets

$$\underline{\chi \sim (\mathbf{1}, \boldsymbol{N}, 0)} \quad \& \quad \psi \sim (\mathbf{3}, \boldsymbol{N}, 2/3)$$

χ_0 is the DM. The rest are co-annihilators

- The (analytic) estimation of Ω_0 in the presence of co-annihilators is well known since [*Griest, Seckel, 1991; Kolb, Turner, 1990*]

Ω_0 estimation

Three steps [*Griest, Seckel, 1991; Kolb, Turner, 1990*]

(1) Determine the freeze-out temperature T_f through

$$\boxed{M_{\chi 0}/T_f} = \log\left(\text{func.}\left[\boxed{M_{\chi 0}/T_f}, \#\ \text{DM sect. dof}, \ \#\ \text{rel. dof}, \boxed{\langle \sigma_{\text{eff}}\, v \rangle}\right] \right)$$

⇨ typically yields $T_f / M_{\chi 0} \approx 1/30$

(2) Evaluate the amount of annihilations from freeze-out to today

$$\boxed{J \equiv \int_{x_f}^{\infty} \frac{\boxed{\langle \sigma_{\text{eff}}\, v \rangle}}{x^2} dx}$$

crucial ingredient

(3) Get today's $\Omega_0 h^2$

$$\boxed{\Omega_0 h^2 \simeq \frac{1.07 \times 10^9\ \text{GeV}^{-1}}{g_*^{1/2} M_{\text{Pl}}\, J}}$$

$\sigma_{\rm eff}$

$$\sigma_{\rm eff} \equiv \underline{\sigma_{ij}}\;\underline{r_i}\; r_j$$

fractional d.o.f.,
“weighted” by mass splitting

$$r_i = \boxed{\frac{g_i}{g_{\rm eff}}\left(1+\Delta_i\right)^{3/2}\exp\left(-x\,\Delta_i\right)}$$

$$\sigma_{ij} \equiv \sigma\left(\underline{\mathrm{DM}_i\;\mathrm{DM}_j} \to \underline{X\,X'}\right)$$

any 2 DM-sector
particles

any 2 particles
outside the DM sector

- In our case

$$\sigma_{\rm eff} =$$

$$\frac{1}{g_{\rm eff}^2}\sum_{ij}\left(\sigma_{\chi_i\chi_j}\,g_\chi^2 + 2\,\sigma_{\chi_i\psi_j}\,g_\chi\,g_\psi\left(1+\Delta_\psi\right)^{3/2}e^{-x\,\Delta_\psi} + \sigma_{\psi_i\psi_j}\,g_\psi^2\left(1+\Delta_\psi\right)^3 e^{-2x\,\Delta_\psi}\right)$$

⇨ important to evaluate the $\psi\chi$ mass splitting Δ_ψ:

- determines $g_{\rm eff}$
- weighs the different σ’s

(zero-T) mass splittings

- T_f ~ average amount of kin. energy in the annihilations

  For $\Delta_\psi \sim T_f$, co-annih. partners nearly as kin. accessible as χ_0

- EW mass splitting ~ $10^{-3} - 10^{-4}$ for $M_{\chi 0} = O(\text{TeV})$

  (within the ψ and χ
  $SU(2)_L$ multiplets)

  ⇨ negligible

- 4321 mass splitting $$\Delta_\psi^{4321} = \frac{g_4^2}{16\pi^2} f\left(\frac{M_U}{M_\chi}, \frac{M_{Z'}}{M_\chi}, \frac{M_{G'}}{M_\chi}\right) \simeq 8-15\%$$

⇨

$$g_{\rm eff} = N\left(\overset{= 4}{g_\chi} + \overset{= 4\,N_c}{g_\psi}\underbrace{(1+\Delta_\psi)^{3/2} e^{-x\Delta_\psi}}_{\simeq\, 0.06}\right)$$

Back to σ_{eff} and $\langle \sigma_{\text{eff}}\, v \rangle$

$$\sigma_{\text{eff}} =$$

$$\frac{1}{g_{\text{eff}}^2} \sum_{ij} \left(\sigma_{\chi_i \chi_j} g_\chi^2 + 2\, \sigma_{\chi_i \psi_j} g_\chi\, g_\psi \underbrace{(1+\Delta_\psi)^{3/2} e^{-x\Delta_\psi}}_{\simeq\, 0.06} + \sigma_{\psi_i \psi_j} g_\psi^2 \underbrace{(1+\Delta_\psi)^3 e^{-2x\Delta_\psi}}_{\simeq\, 0.06^2} \right)$$

the Z'-mediated $\sigma_{\chi_i \chi_j}$ larger than any other contrib. by 1 – 2 o.o.m.

$$\boxed{\sigma_{\text{eff}} \simeq \frac{1}{N}\, \sigma\left(\chi_0 \chi_0 \to Z' \to X X'\right)}$$

From σ_{eff} as a series in $s = (2 M_\chi)^2$

one can determine $\langle \sigma_{\text{eff}}\, v \rangle$ as a series in 1 / x

[*Srednicki, Watkins, Olive, 1985*]

$\Omega_0\, h^2$: why it works

- With $\langle \sigma_{\rm eff}\, v \rangle$ at hand, we can calculate $\Omega_0\, h^2$
- Before discussing the full numerics, useful to have a heuristic understanding:

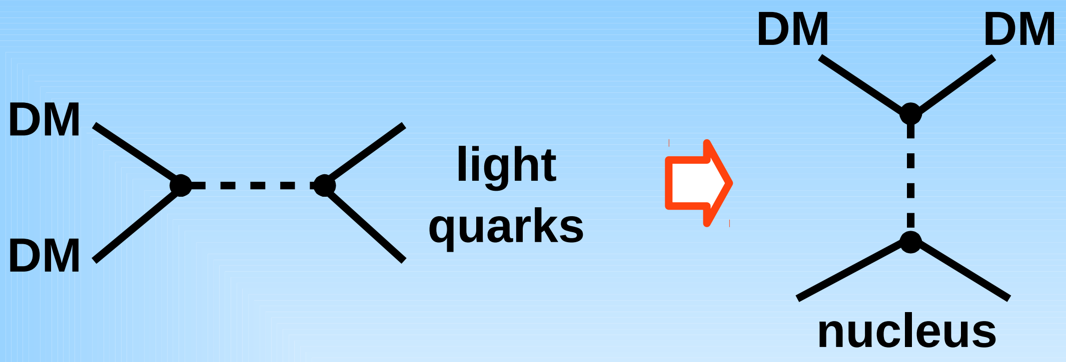
$$\Omega_0 h^2 \approx 0.06 \frac{N}{f(\{\xi^i\})} \left(\frac{v_{LQ}}{5\ \mathrm{TeV}}\right)^2 \left(\frac{v_{LQ}}{M_\chi}\right)^2$$

  - neglects $(2\, M_\chi)^2$ w.r.t. $M_{Z'}^2$
  - $f\,(\,\{\xi^{\,i}\}\,)$ denotes a function of the Z' to fermion couplings of the different generations

    $f\,(\,\{\xi^{\,i}\}\,)$ = O(10) throughout the parameter space

⇒ $\Omega_0\, h^2 \approx 0.1$ naturally achievable

DM direct detection



DD constraints potentially stringent

(Actually, precisely because of DD we took N = odd.)

How to estimate these signals

- Write down $\mathscr{L}_{\chi q} \propto (\chi\ \text{bilinear}) \times (\text{quark bilinear})$
- Evaluate $\langle\ \text{nucleon}\ |(\bar{q}\ \ \gamma^\mu\ q)|\ \text{nucleon}\ \rangle$
- Determine $\sigma_{\text{SI}}^{\text{nucleon}}$ (SI = spin-independent)

Directly comparable to exps.

Although they operate on heavy nuclei,
results are exclusion x-sec's on nucleons

How to (better) estimate DM DD signals

Many caveats in the above (simplistic) recipe:

- $\mathscr{L}_{\chi q}$ is written down at a matching scale Λ.
  How large are RGE effects from Λ to $M_{nucleon}$?

☞ DirectDM
Bishara *et al.*

- The DM momentum may be large enough
  to resolve the internal nucleon structure

☞ DMFormFactor
Anand *et al.*

- χ - N couplings may be isospin-breaking.
  Need an educated average for $\sigma^{\mathrm{N}}_{\mathrm{SI}}$

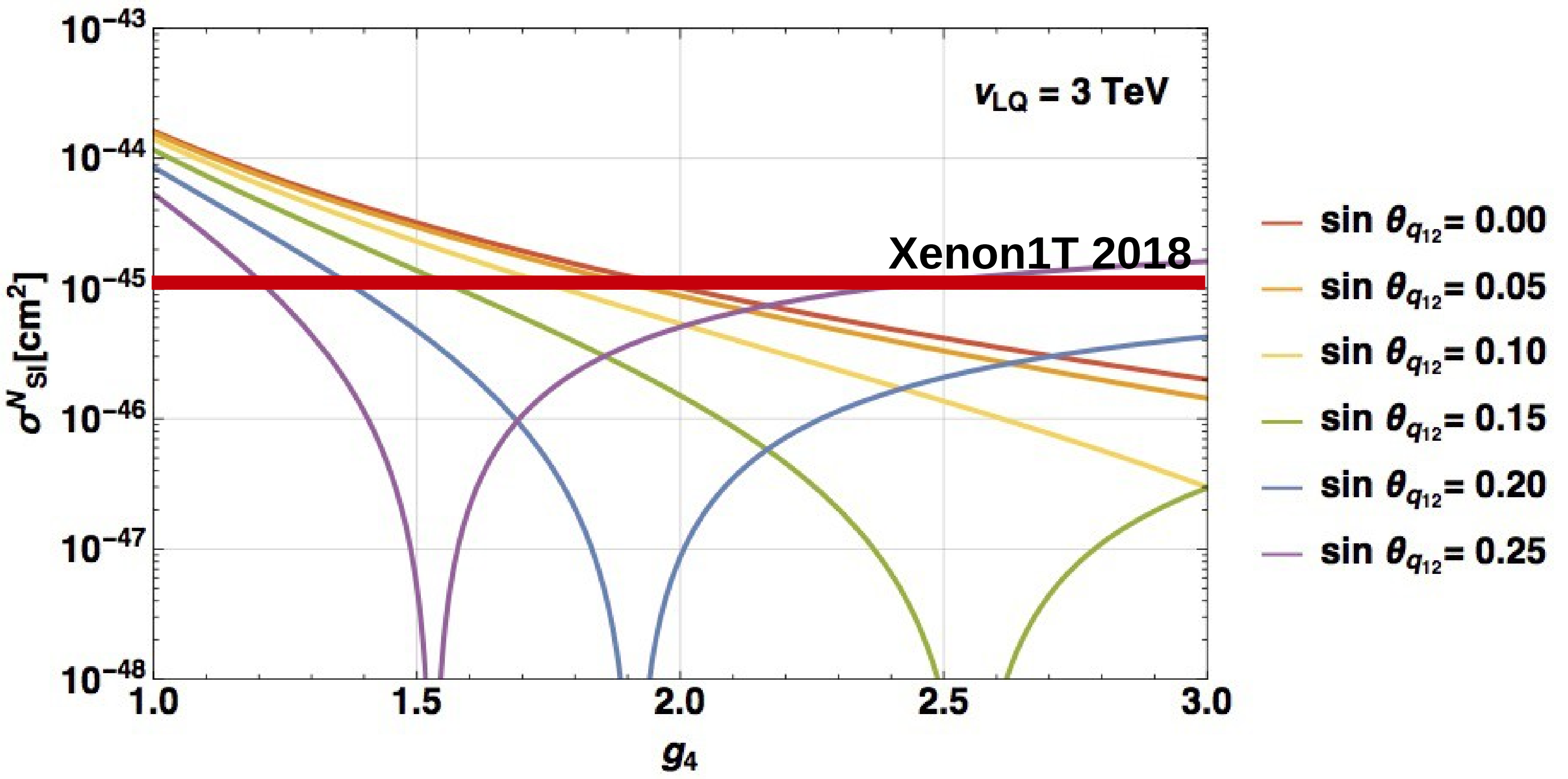
We get

- $\sigma^{\mathrm{N}}_{\mathrm{SI,\ analytic}} > \sigma^{\mathrm{N}}_{\mathrm{SI,\ DirectDM + DMFF}}$ $\quad M_\chi \leqslant$ 400 GeV
  (and within 25% of it)
- $\sigma^{\mathrm{N}}_{\mathrm{SI,\ analytic}} \geq 2 \cdot \sigma^{\mathrm{N}}_{\mathrm{SI,\ DirectDM + DMFF}}$ $\quad M_\chi \leqslant$ 1.5 TeV

So, using $\sigma^{\mathrm{N}}_{\mathrm{SI,\ analytic}}$ we get conservative (i.e. stronger) DD bounds

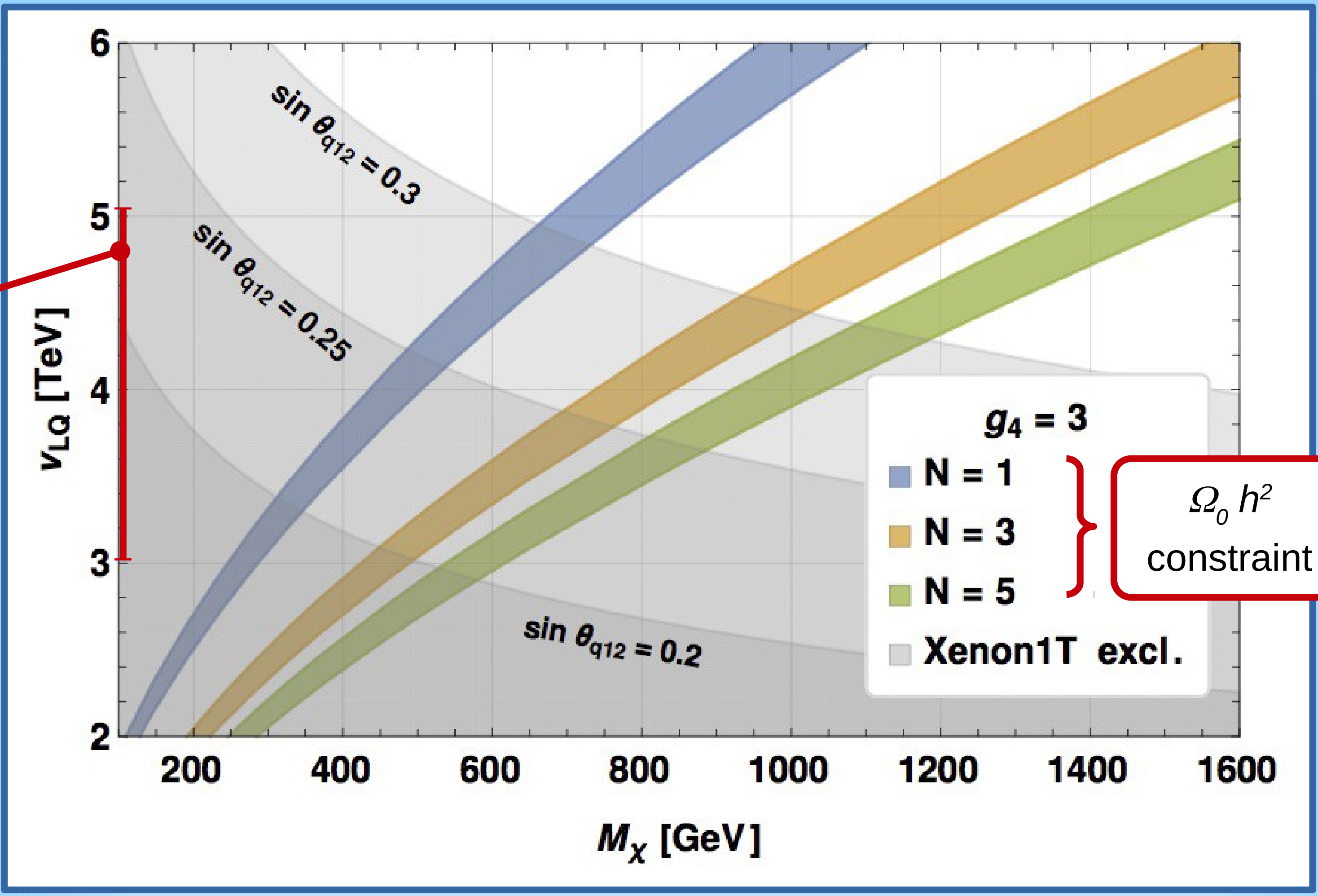
Results

Direct Detection



- Direct searches and DM DD suggest one and the same region for g_4 & $\theta_{q_{12}}$ – even quantitatively.

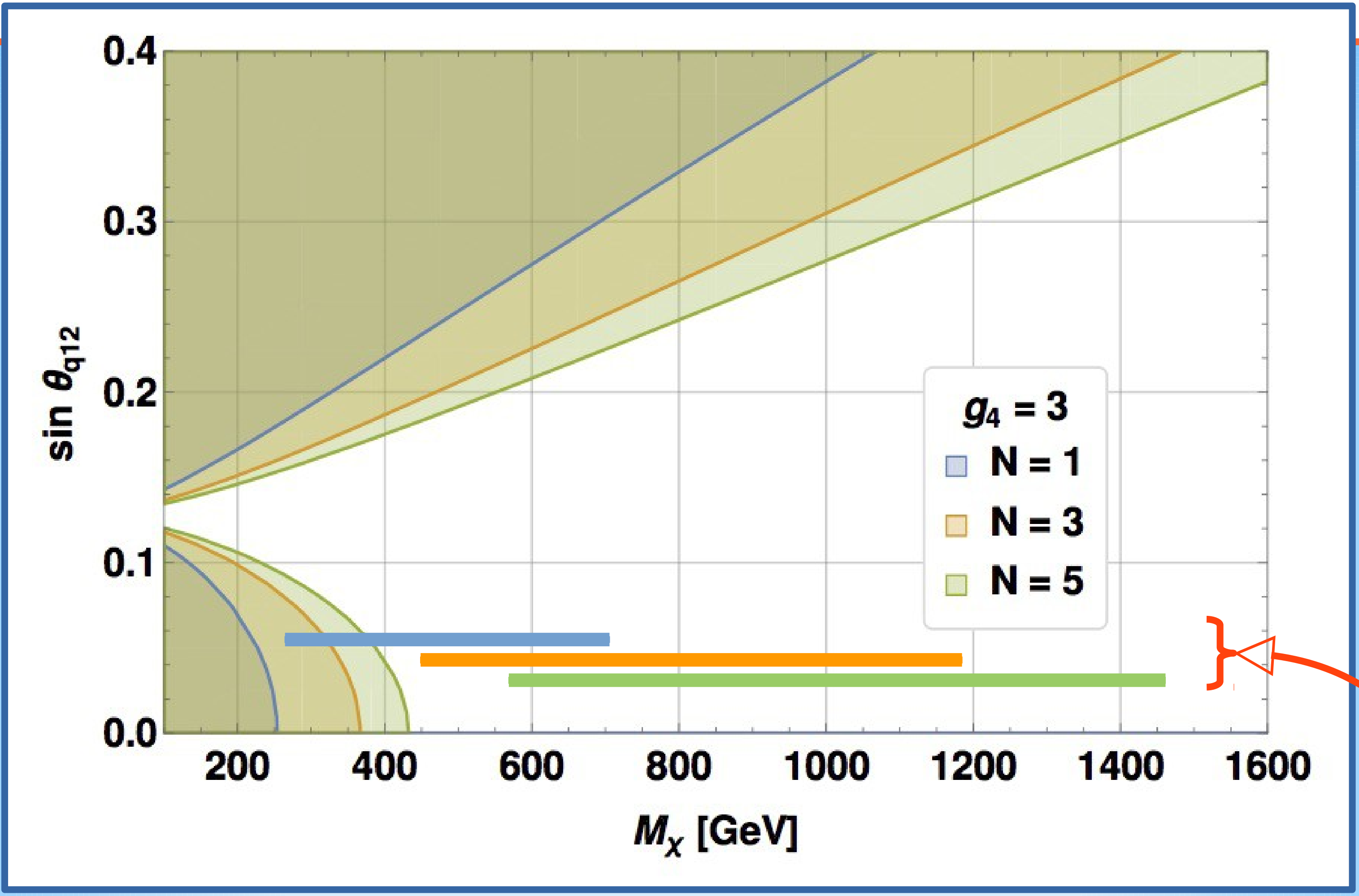
$\Omega_0 h^2$ & v_{LQ} select M_χ ranges



v_{LQ}
fiducial
range

$\Omega_0 h^2$
constraint

- For each N, the v_{LQ} range selects a corresp. range for M_χ
- For $\sin\theta_{q_{12}} = 0.2$ & $v_{LQ} \geq 3$ TeV, all param. space allowed and for any N



- DD prefers small $\sin\theta_{q_{12}}$
- Upper bound on $\sin\theta_{q_{12}}$ becomes stronger as *N* increases
- For each *N*, the $\Omega_0 h^2$ constraint translates into an M_χ range, as discussed earlier

Conclusions

- *We added to the 4321 gauge ansatz a minimal Dark-Matter sector, a **4** under SU(4)*

- *After 4321 → SM breaking, this gives rise to the multiplets χ (containing the DM) plus ψ ("co-annihilator")*

- *The DM-relevant param. space is very simple*

$$g_4 \qquad v_{LQ} \qquad M_\chi \qquad N \qquad \theta_{q_{12}}$$

- *The parameter ranges selected by DM pheno coincide with those preferred by collider pheno*

- *While the U_1 dominates flavour pheno, the most important DM-sector mediator is the Z'*