“Post-Sphaleron” Baryogenesis

(Baryogenesis at a few MeV from oscillations of Baryons, Mesons, Mesinos)

Recent/Current work

(with David McKeen, Akshay Ghalsasi, Seyda Ipek, Thomas Neder, Kyle Aitken, Gilly Elor, Miguel Escudero)

arXiv:1407.8193,1508.05392,1512.05359,1708.01259, in progress

Sakharov Conditions and the Standard Model

✓ C and CP violation (but not enough in SM)

✓ Baryon number violation (electroweak anomalous nonperturbative field configurations known as *sphalerons,* which are common at very high temperature, above electroweak phase transition at 100 TeV)

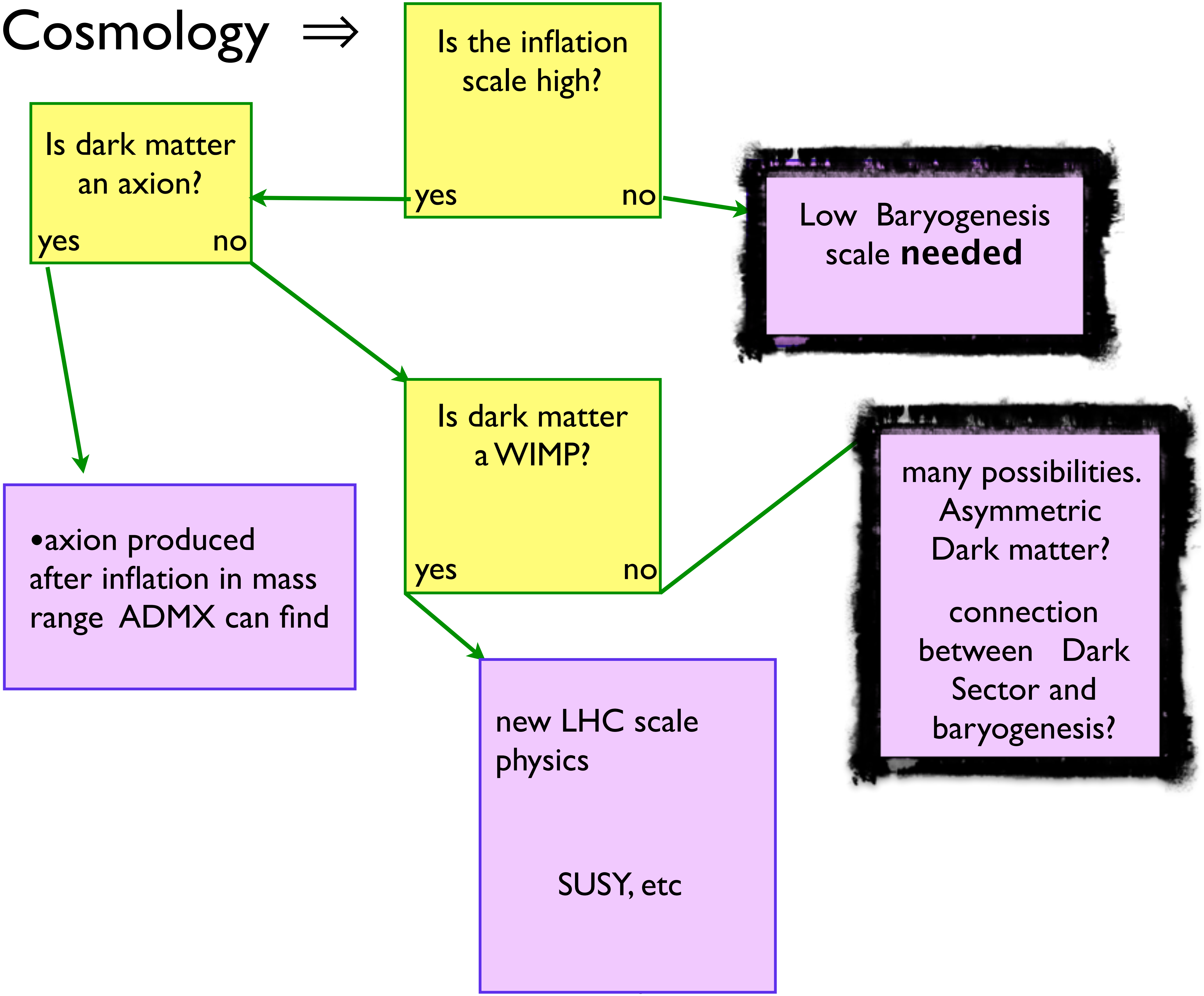
- ★ sphalerons conserve B-L

☐ Out of equilibrium (no phase transition for m_H=125) but if Higgs sector is extended still possible (also could allow for new source of CP violation— *ELECTROWEAK BARYOGENESIS*)

Why ‘post sphaleron’ baryogenesis is compelling

- Consistent with wide range of cosmology/inflation models.
- No high temperature required (solves a lot of cosmological issues, e.g. gravitino over production, axion cosmology issues)
- Electroweak baryogenesis requires 1st order weak transition, CPV in Higgs sector—very constrained by electric dipole moment of electron, mass of Higgs.

Cosmology ⇒



Is the inflation scale high?
yes
no
Low Baryogenesis scale **needed**
Is dark matter an axion?
yes
no
•axion produced after inflation in mass range ADMX can find
Is dark matter a WIMP?
yes
no
many possibilities. Asymmetric Dark matter?
connection between Dark Sector and baryogenesis?
new LHC scale physics
SUSY, etc

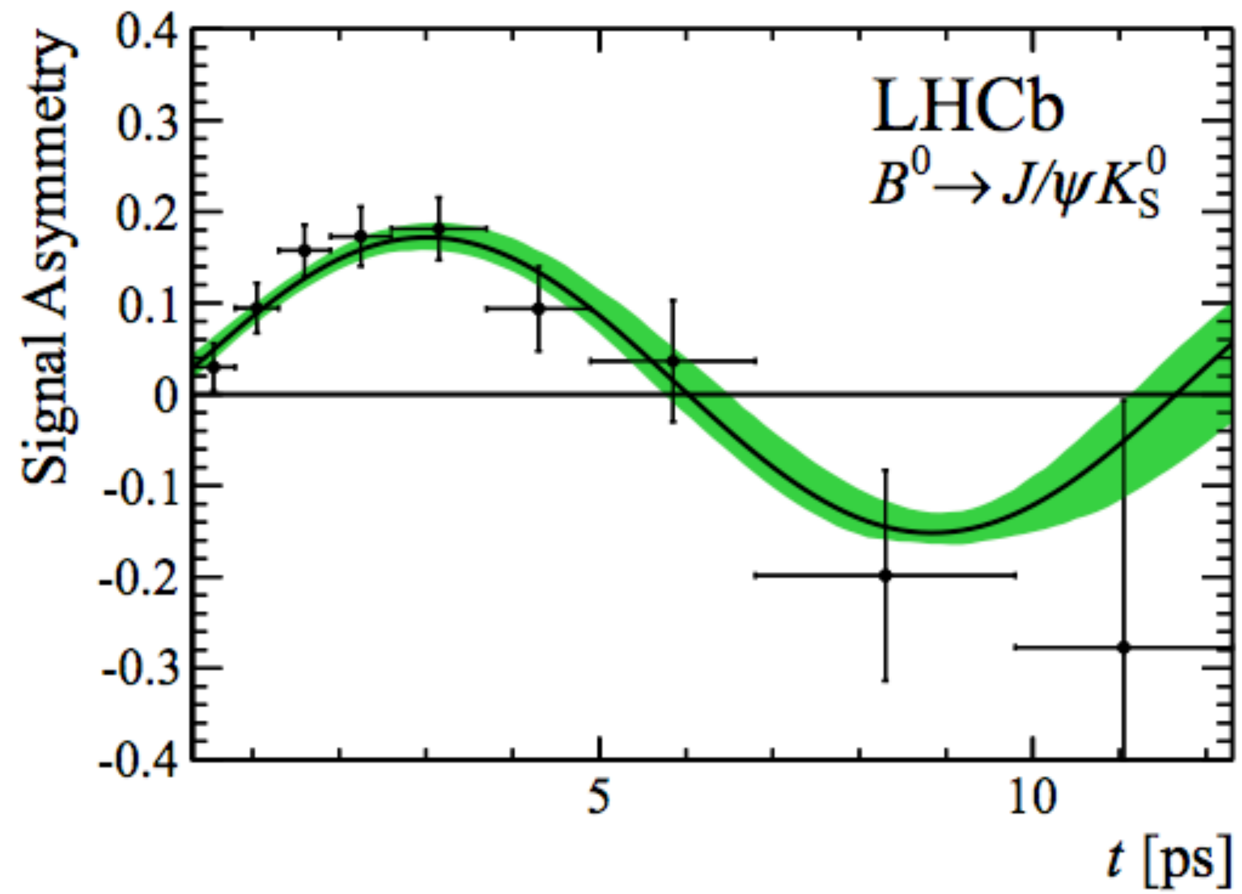
New CPV at low energy

- CP violatiion requires phase, effects always require interference
- interference between tree and loop effects tends to be very suppressed at weak coupling
- Baryogenesis at low scales requires departure from thermal equilibrium at low scales, very weak couplingsCPV requires new phase, quantum mechanics, effects usually very small (loop effects)
- CPV effects can be large in particle oscillations
- oscillations require near degeneracy (e.g. particle-antiparticle)

CPV in oscillations of unstable states

- Only requires 2 oscillating states
- Observed in neutral kaon anti-kaon and neutral B meson-anti-B meson oscillations
- Large effect possible when oscillation and decay rates comparable

O(1)!



CPV from particle/anti particle Oscillations

$$H = \begin{pmatrix} m - i\frac{\Gamma}{2} & m_{12} - \frac{i}{2}\Gamma_{12} \\ m_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - i\frac{\Gamma}{2} \end{pmatrix}$$

- Requires $m_{12} \neq 0$, $\Gamma_{12} \neq 0$, $\arg(m_{12}\Gamma_{12}^*) \neq 0$
- *largest effect:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) \sim O(1)$
- theory: $\Delta\Gamma < \Delta m, \Gamma$
  - *Kaons:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$,
  - B^0_d: $\Delta\Gamma << \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$
  - B^0_s: $\Delta\Gamma << \Gamma << \Delta m$, $\arg(m_{12}\Gamma_{12}^*) << 1$
  - D^0: $\Delta\Gamma \sim \Delta m < \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$

Inflation's end and reheating

- reheat temp T_r set by time at which inflaton dumps its energy (simple model: inflaton lifetime)
- $t^{-1} \sim \Gamma \sim H \sim T_r^2/M_{pl}$
- T_r usually taken to be very high, $\sim 10^{12}$ GeV, but could be as low as ~ 4 MeV
  - lower bound set by nucleosynthesis, ν abundance
  - upper bound set by energy density during inflation $<\sim 10^{16}$ GeV

Cosmology with low reheat scale: Either

- "Early matter domination"— postinflation energy density dominated by late (.01 s) decaying particle

or

- "slow reheating" inflaton decays late (.01 s)
- thermalized radiation dominated universe never hotter than ~10 MeV
- economical picture: inflation→something→B hadrons+mesons
- "something"= Higgs boson?

CPV in Fermion
rticle—anti-particle oscillations

arXiv:1708.01259

- Requires a *Pseudo Dirac Fermion:* massive, carries *approximately* conserved charge, can *oscillate* into own anti-particle as well as decay, requires common final state in decays of particle and anti-particle
  - fermion particle-anti-particle oscillations have never been observed
  - SM candidates: **neutron, other neutral baryons**
  - BSM candidates: Mesino, pseudo-Dirac gluino, neutralino

Do not expect to see CPV in n $\bar{n}$ oscillations

- Restrictive Kinematics: $\Delta M = M_n - M_X$ < MeV (proton stability)

$$\frac{P_{|n\rangle \to |\bar{n}\rangle}}{P_{|\bar{n}\rangle \to |n\rangle}} - 1 \propto \frac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14} \left(\frac{\Delta M}{1 \text{ MeV}} \right)^4$$

Other neutral baryons?

- What constraints on baryon violating operators containing heavy flavors?
- For $\Delta B=2$, $\Delta s=1,2,3$ operators dinucleon decay into 1,2,3 kaons is almost as constraining as neutron oscillations. Direct searches (CLAS search for $\Lambda \to K$+dark) less constraining than stability of matter.
- $\Delta B=2$, $\Delta s=4$: $\overline{\Xi}^0$-Ξ^0 oscillations? $\Omega^- \to \overline{p}\ K$? Not looked for. But 1 weak loop converts into $\Delta B=2$, $\Delta s=3$.
- $\Delta B=2$, $\Delta c=2$, $\Delta b=2$: heavy flavor baryon oscillations $bcd \to \overline{b}\overline{c}\overline{d}$
  - takes 2 weak loops to convert to $\Delta B=2$, $\Delta c=0$, $\Delta b=0$, fairly weak constraint
- Conceivable to look for oscillations of neutral charmed baryons at Belle II?

Constraints on (uds)², (uss)² operators

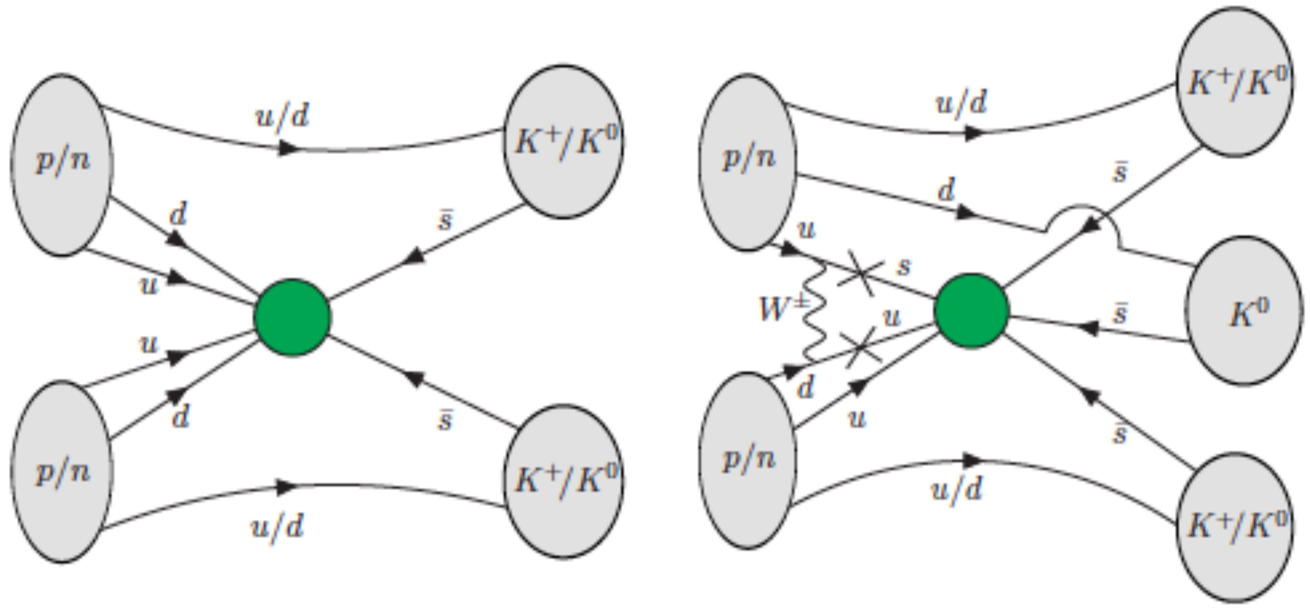
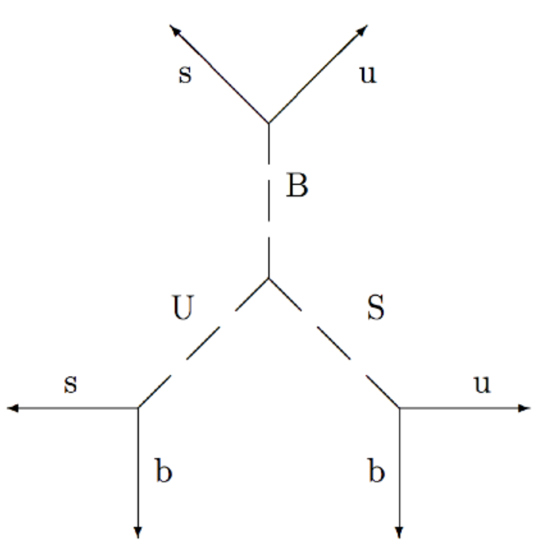
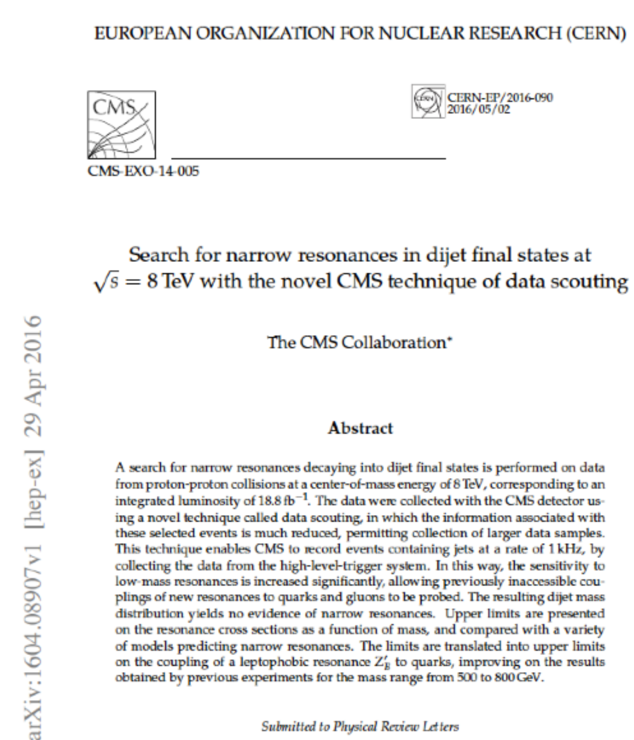


FIG. 2. Left: Dinucleon decay via the $\Delta B = \Delta S = 2$ $(uds)^2$ operator that mediates $\Lambda^0 \leftrightarrow \bar{\Lambda}^0$ oscillations. Right: Dinucleon decay mediated by the $\Delta B = 2$, $\Delta S = 4$ $(uss)^2$ operator that has been dressed with a weak interaction to become the $\Delta S = 3$ $(uds)(uss)$ operator at the one-loop level. Because the short-distance $\Delta B = 2$ operators we consider involve weak isosinglets, this operator requires u and s quark mass insertions, indicated by crosses.

Constraints from weak flavor violation

- Do constraints from n $\bar{n}$ make other flavors of ΔB=2 unobservable?
- operators involving right-handed (SU(2) singlet) quarks much less constrained
- Kuzmin (1996) bsu→$\bar{b}\bar{s}\bar{u}$ baryon oscillations from RPV could be as fast as decay! just now weakly constrained by LHCB search, also LHC diquark search




EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP/2016-090
2016/05/02

CMS-EXO-14-005

Search for narrow resonances in dijet final states at $\sqrt{s} = 8$ TeV with the novel CMS technique of data scouting

The CMS Collaboration*

Abstract

A search for narrow resonances decaying into dijet final states is performed on data from proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 18.8 fb^{-1}. The data were collected with the CMS detector using a novel technique called data scouting, in which the information associated with these selected events is much reduced, permitting collection of larger data samples. This technique enables CMS to record events containing jets at a rate of 1 kHz, by collecting the data from the high-level-trigger system. In this way, the sensitivity to low-mass resonances is increased significantly, allowing previously inaccessible couplings of new resonances to quarks and gluons to be probed. The resulting dijet mass distribution yields no evidence of narrow resonances. Upper limits are presented on the resonance cross sections as a function of mass, and compared with a variety of models predicting narrow resonances. The limits are translated into upper limits on the coupling of a leptophobic resonance Z'_B to quarks, improving on the results obtained by previous experiments for the mass range from 500 to 800 GeV.

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Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration[†]

Abstract

A search for baryon-number-violating Ξ_b^0 oscillations is performed with a sample of *pp* collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The baryon number at the moment of production is identified by requiring that the Ξ_b^0 come from the decay of a resonance $\Xi_b^{*-} \to \Xi_b^0\pi^-$ or $\Xi_b^{\prime-} \to \Xi_b^0\pi^-$, and the baryon number at the moment of decay is identified from the final state using the decays $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$. No evidence of baryon number violation is found, and an upper limit is set on the oscillation rate of $\omega < 0.08\ \mathrm{ps}^{-1}$, where ω is the associated angular frequency.

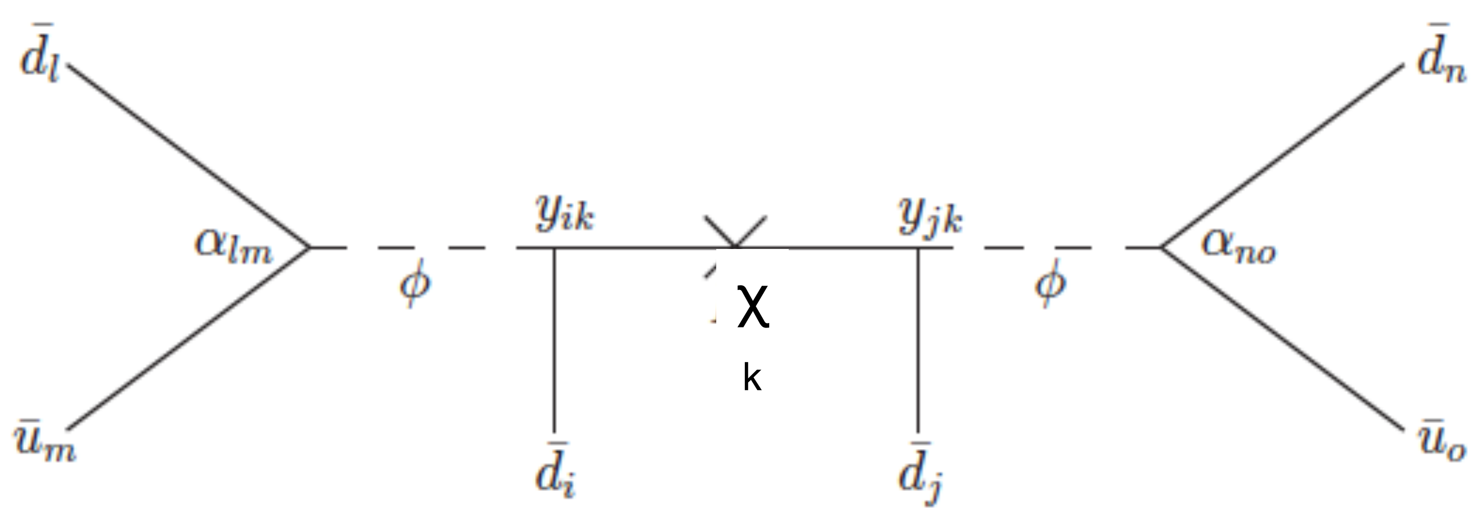
$0.08\ \mathrm{ps}^{-1} \sim 5 \times 10^{-14}$ GeV

$\Gamma \sim 4.5 \times 10^{-13}$ GeV

(Dinucleon decay bound~ 10^{-10} GeV)

Model for CPV in heavy flavor baryon oscillation

- same model as in "mesino oscillation" model arXiv:1508.05392, different parameters (χ lighter than heavy flavor baryon)
  - "RPV SUSY-lite"
  - New particles:
    - Neutral Majorana fermions χ_i, i=1,2,…, mass~few GeV
    - charge -1/3 colored scalar *ϕ, mass >~400-500 GeV*
    - *low energy effective theory:* $\frac{\alpha_{ij} y_{k\ell}}{m_\phi^2} \bar{d}_i \bar{u}_j \bar{d}_k \chi_\ell$



Dinucleon decay constraints on combinations of α_{11}, α_{21}, y_{1k}, y_{2k}

CPV in heavy flavor oscillations

- α_{cs}, α_{cb} allowed by resonant collider search to be ~1 for scalar heavier than 400 GeV
- oscillation rate in neutral heavy flavor baryons could be 10^{-3}—10^{-4} times decay rate, when 2 weak interactions required to convert operator to one producing dinucleon decay
- Γ_{12} not kinematically suppressed, could be ~ 10^{-1} M_{12}
- allows CPV at the 10% level!

Bounds on ΔB=2 operators from dinucleon decay (right handed quarks)

Operator	$\mathcal{B}$	Weak Insertions Required	Measured Γ (GeV) [19]	Limits on $\delta_{\mathcal{B}\mathcal{B}} = M_{12}$ (GeV) Dinucleon decay	Collider
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33} *	10^{-17}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}	10^{-17}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}	10^{-17}
$(uss)^2$	Ξ^0	One	$(2.27 \pm 0.07) \times 10^{-15}$	10^{-22}	10^{-17}
$(ddc)^2$	Σ_c^0	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	10^{-17}	10^{-16}
$(dsc)^2$	Ξ_c^0	Two	$(5.87^{+0.58}_{-0.61}) \times 10^{-12}$	[illegible]	10^{-15}
$(ssc)^2$	Ω_c^0	Two	$(9.5 \pm 1.2) \times 10^{-12}$	10^{-14}	10^{-15}
$(udb)^2$	Λ_b^0	Two	$(4.490 \pm 0.031) \times 10^{-13}$	10^{-13}	10^{-17}
$(udb)^2$	Σ_b^0	Two	$\sim 10^{-3*}$	[illegible]	10^{-17}
$(usb)^2$	Ξ_b^0	Two	$(4.496 \pm 0.095) \times 10^{-13}$	[illegible] *	10^{-17}
$(dcb)^2$	Ξ_{cb}^0 †	Two	$\sim 10^{-12\dagger}$	10^{-17}	10^{-15}
$(scb)^2$	Ω_{cb}^0 †	Two	$\sim 10^{-12\dagger}$	10^{-14}	10^{-15}
$(ubb)^2$	Ξ_{bb}^0 †	Four	$\sim 10^{-13\ddagger}$	>1	10^{-17}
$(cbb)^2$	Ω_{cbb}^0 †	Four	$\sim 10^{-12\dagger}$	>1	10^{-15}

*Competetive Direct oscillation search done

: I. Operators that mediate $\mathcal{B} \leftrightarrow \bar{\mathcal{B}}$ oscillations and the number of weak interaction insertions required fo
ribute to dinucleon decay. The resulting limit from dinucleon decay on the transition amplitude, defined
›erator is shown. An $*$ indicates a baryon that has not yet been observed and which has a strong decay
indicates an unobserved baryon which primarily decays through a weak interaction of a c (b) quark.

Baryogenesis?

- CPV in Baryon oscillations fulfills 2/3 Sakharov conditions
- Heavy flavor baryons out of equilibrium in early universe via long lived χ decay when early universe has temperature between ~10 and 200 MeV
- Some of the baryons will undergo CPV oscillations before they decay.

Baryogenesis model

- At T~ 4 MeV, χ_3, who initially dominate energy density of Universe, decay into baryons and mesons
- (very rapidly), most hadrons annihilate and decay until
- (baryon + antibaryon density/entropy)~10^{-4}
- Remaining Baryons oscillate, decay, decohere via scattering
  - Decoherence time from scattering off e+e-~10^{-13} s.
  - Decay rate of charmed baryons ~ 10^{-13} s
  - Fraction of baryons which are "right kind" for substantial CPV, rapid oscillations ~ 0.1??

Baryogenesis budget

- Planck: observed baryon/entropy~$9\mathrm{x}10^{-11}$
- Max (baryon+antibaryon)/entropy at T=10 MeV ~10^{-4}
- fraction of baryons which have useful oscillations~ 0.1??
- fraction of useful baryons which oscillate before decohere or decay~10^{-4}
- CPV in baryon oscillations~ 0.1

Boltzmann equations

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_{\chi_3}\rho_{\chi_3}, \qquad \frac{dn}{dt} + 3Hn = -i\left(\mathcal{H}n - n\mathcal{H}^\dagger\right) - \frac{\Gamma_\pm}{2}\left[O_\pm,\left[O_\pm, n\right]\right]$$

$$\frac{d\rho_{\chi_3}}{dt} + 3H\rho_{\chi_3} = -\Gamma_{\chi_3}\rho_{\chi_3} \qquad - \langle\sigma v\rangle_\pm\left(\frac{1}{2}\left\{n, O_\pm\bar{n}O_\pm\right\} - n_{\rm eq}^2\right) + \frac{1}{2}\frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}}{\rm Br}_{\chi_3\to\mathcal{B}}$$

$$\mathcal{H} = M - \frac{i}{2}\Gamma = \begin{pmatrix} M_{\mathcal{B}} - \frac{i}{2}\Gamma_{\mathcal{B}} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{\mathcal{B}} - \frac{i}{2}\Gamma_{\mathcal{B}} \end{pmatrix}$$

Use density matrices to keep track of decoherence

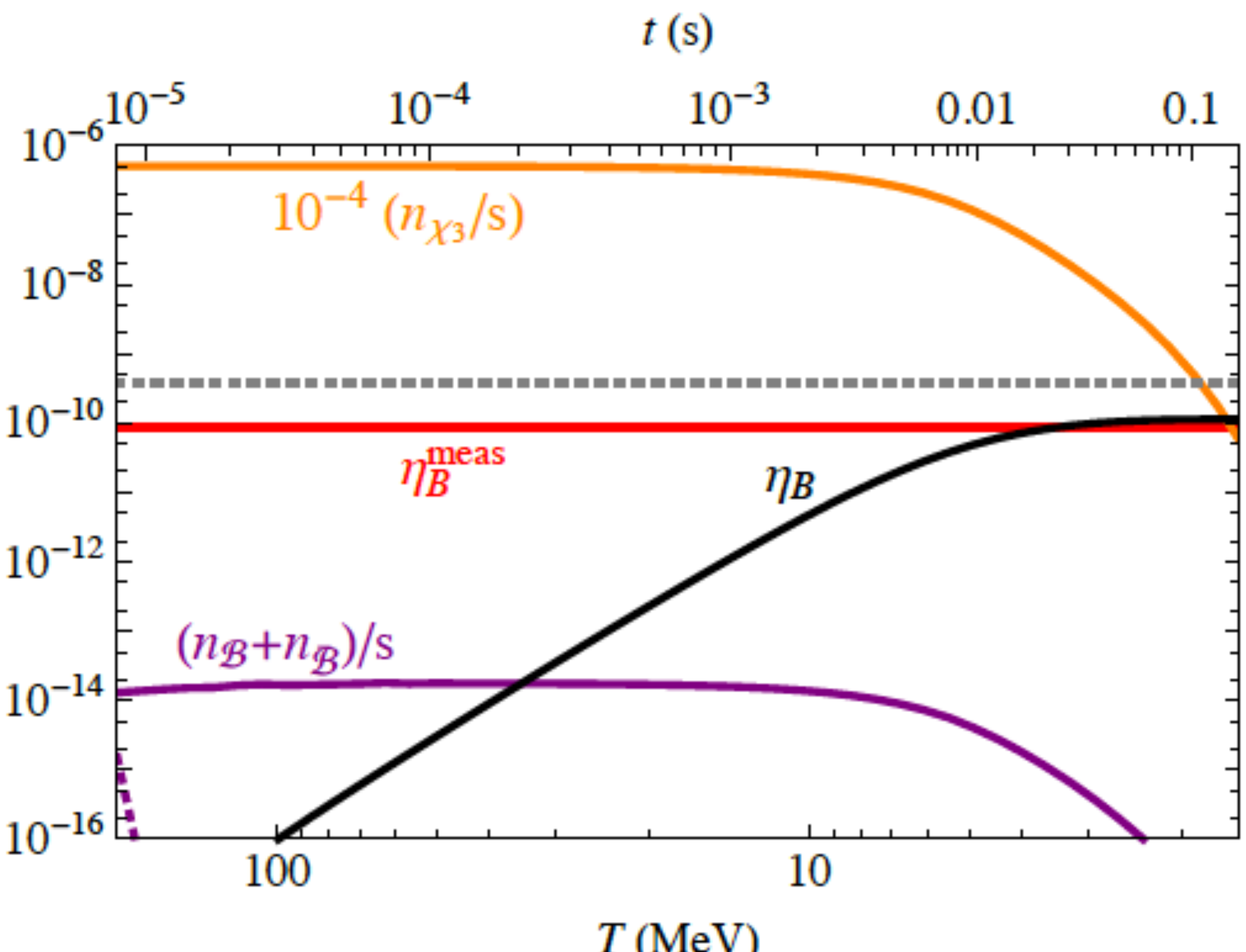
$$n = \begin{pmatrix} n_{\mathcal{B}\mathcal{B}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} \end{pmatrix}, \quad \bar{n} = \begin{pmatrix} n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\mathcal{B}\mathcal{B}} \end{pmatrix}.$$

nteractions with plasma that lead to decoherence have opposite sign for baryon and anti-baryon

$\Gamma_\pm$ is the scattering rate on the plasma. $O_\pm$ is a matrix

$$O_\pm = \begin{pmatrix} 1 & 0 \\ 0 & \pm 1 \end{pmatrix}.$$

solving Boltzmann equations



η_B= net total Baryon/entropy from numerical solution

- - - - - - - = sudden decay approx

m_{B}=7 GeV (Ω_{cb}), M_{12}=3x10^{-15} GeV, Γ_{12}=10^{-15} GeV, arg(Γ_{12}/M_{12})=π/2, $m_{\chi 3}$=7.5 GeV, Br(χ_3 ->Ω_{cb})=.3, $\Gamma_{\chi 3}$=3x10^{-23} GeV, $\Gamma_{\Omega cb}$=3x10^{-12} GeV

baryon annihilation σ=400 mb

Heavy flavor physics

- "wrong sign" decays from neutral heavy flavor baryon oscillations
  - b-baryons at LHC (recent LHCB search)
  - charmed baryons at BELLE?
    - Ω_c^0 at BELLE II?
      - Br(B-> Ω_c^0) + X ~ .02? -> 10^9 Ω_c^0
      - possibly 100's of events with wrong sign decays
  - Exotic B decays into χ_1+p+..? Br~.01 possible

$$\Gamma_{b\to\chi_1\bar{u}\bar{d}} \sim \frac{m_b \Delta m^4}{60\,(2\pi)^3}\left(\frac{g_{ub}y_{1d}}{m_\phi^2}\right)^2 + \mathcal{O}\left(\frac{\Delta m^5}{m_b^5}\right)$$

$$\simeq 2\times 10^{-15}\ \text{GeV}\left(\frac{\Delta m}{2\ \text{GeV}}\right)^4\left(\frac{1.2\ \text{TeV}}{m_\phi/\sqrt{g_{ub}y_{1d}}}\right)^4$$

Summary of Model 1 $\frac{\alpha_{ij} y_{k\ell}}{m_\phi^2} \bar{d}_i \bar{u}_j \bar{d}_k \chi_\ell$

- Low energy effective theory with neutral Majorana fermions χ with baryon violating couplings for s,c,b quarks
- stability of matter $\rightarrow$ lightest χ satisfies $m_p - m_e < M\chi$
- stable dark matter candidate if lightest χ satisfies $M\chi < m_p + m_e$
- $n\ \bar{n}$ oscillations consistent with heavy flavor baryon oscillations at oscillation rate $\sim 10^{-4}$ decay rate
- CPV in heavy flavor baryon oscillations (requires at least one χ to be lighter than the heavy flavor baryon (need Γ_{12})
- Baryogenesis budget satisfied with 10% CPV in oscillations

ModelII

putting CPV in mesons to use for Baryogenesis

meson CPV

- inflation ends “late”, inflaton or new long lived particle decays into Higgs at time ~0.01 s, T~10 MeV
- Higgs decays into b quarks,
- b quarks hadronize into B mesons, thermalization
- B mesons oscillate and decay in CPV violating way
- Dark sector contains dark baryon scalar ϕ, dark baryon fermion χ, Majorana (own anti-particle) fermion ξ, masses 1–4 GeV
- Exotic decay: $b \to \bar{s}\bar{u}\chi$ gives excess of $\bar{\chi}$ over χ, baryons over antibaryons (but net baryon number conserved)
- $\chi \to \phi\xi$ (both stable due to discrete symmetry and kinematics $\to$ 2

Can we make baryons from B Mesons?

- Universe at T=10 MeV dominated by B hadrons+radiation
- B hadron density n_B freezes out at very low density

$$n_B/n_\gamma \approx 1/(\sigma\ M_{pl}\ T(T/m_b)^{1/2})$$

- B hadrons are annihilating and decaying before freezeout
- no decoherence in B mesons from scattering as they lack magnetic moments
- Boltzmann equations:—annihilation dominates over decays until

$$n_B/n_\gamma \approx \Gamma_b/(\sigma\ T^3(T/m_b)^{1/2})\ {\sim}2\times10^{-5}\,(10\ \mathrm{MeV}/\ T)^{-3.5}$$

- need to get ~10^{-5} net baryons/B-meson

lower bound on new B physics

- Interesting observables for Belle II:
- semileptonic charge asymmetry a_{sl}^d (asymmetry between b and $\bar{b}$ quarks at time of decay)
- ($\bar{b}\to$diquark + dark matter) $\Rightarrow$B meson $\to$ Baryon+ dark matter+ mesons
- BAU $\propto$ ($f_d\, a_{sl}^d + f_s\, a_{sl}^s$)Br (B meson $\to$ Baryon+ dark matter+)
    - $f_{d,s}$=fraction of b quarks which hadronize as $B_{d,s}$ mesons
- need ($f_d\, a_{sl}^d + f_s\, a_{sl}^s$) to have opposite sign to standard model

Summary

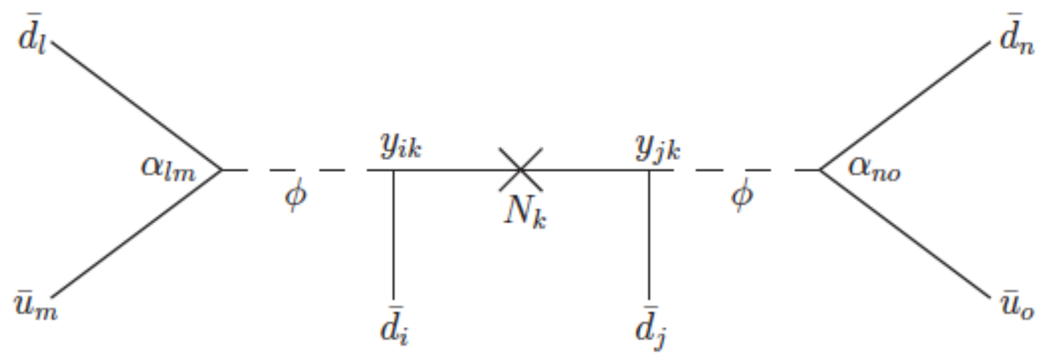
- Baryogenesis is strong motivation for new CPV in heavy flavors
- Search for dark matter in B meson decays
- search for baryon number violation in heavy flavor baryons
- Baryogenesis model from oscillating heavy flavor Baryons
- Baryogenesis model from oscillating B mesons
- Baryogenesis with dark matter and no baryon # violation
- stay tuned for Belle II

“Without imperfection, you or I would not exist”

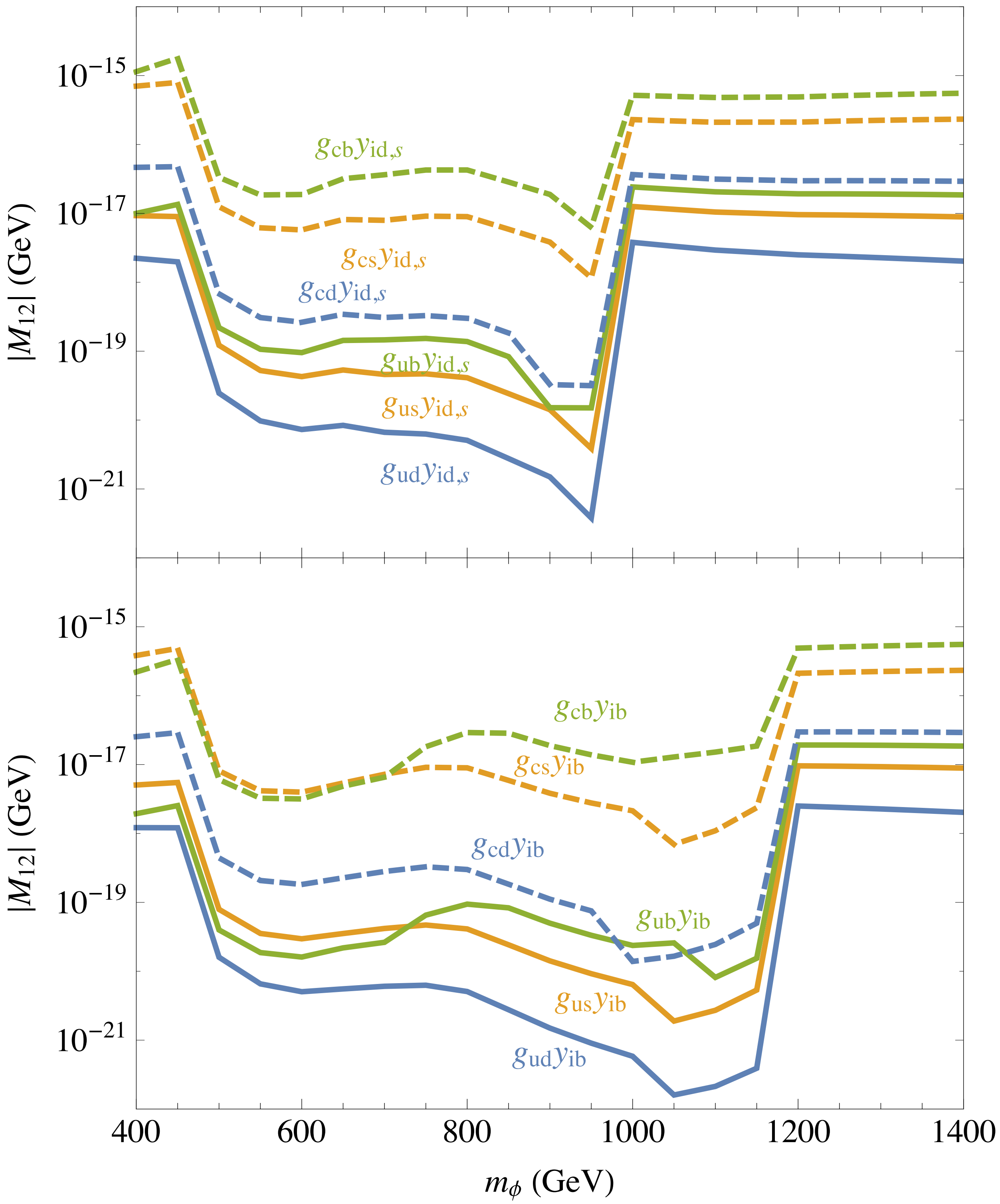
–Steven Hawking

Backup

Collider constraints



- φ colored scalar
- pair production: mφ > ~400-600 GeV (4 jet events)
- resonant production: depends on φ couplings but severe limits for coupling to up quark (Angelo Monteux, JHEP 03, 216 (2016), arXiv:1601.03737 [hep-ph]).
- some operators more constrained from LHC ***(in this model)*** than from dinucleon decay



Upper limits on M_{12} as functions of m that result from collider searches for dijet resonances and jets plus MET, assuming the dominance of the product of couplings indicated .

Top: The limits when y_{id} or y_{is} are dominant.
Bottom: The limits when y_{ib} is dominant.

Solid curves show the limits in the case where the charge 2/3 quark involved is up while dashed lines show the limit in the case of the c quark.