INTENSITY FRONTIER SCIENCE STATUS: EXPLORING THE UNKNOWN

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THE UPSHOT

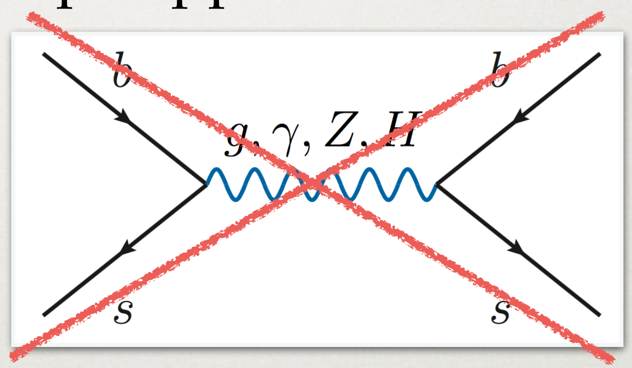
- baryon asymmetry implies more CP violation than in the SM
- flavor measurements a way to probe such required new CPV sectors
  - high energy scales and/or small couplings
- probes also other puzzles: dark matter, strong CP problem,...

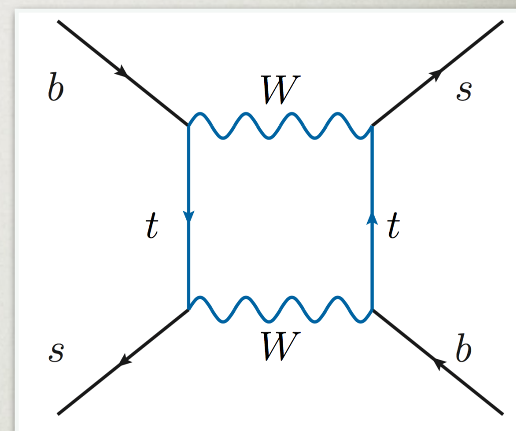
FROM FLAVOR PHYSICS TO NEW PHYSICS

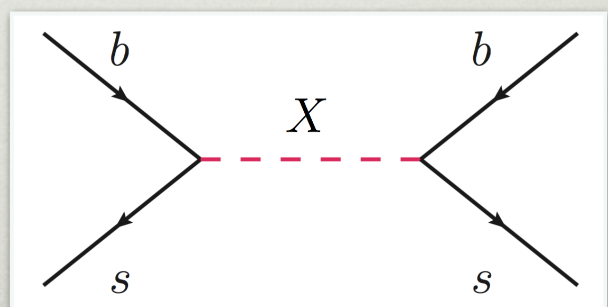
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

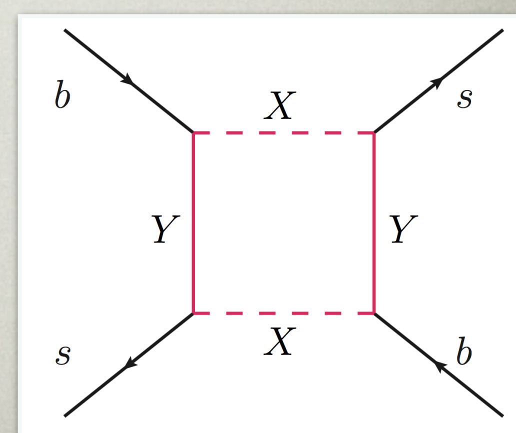
$$\delta C^{\mathrm{NP}} \propto \frac{g_{sb}^2}{M_{\mathrm{NP}}^2}$$

- depends on couplings and NP masses



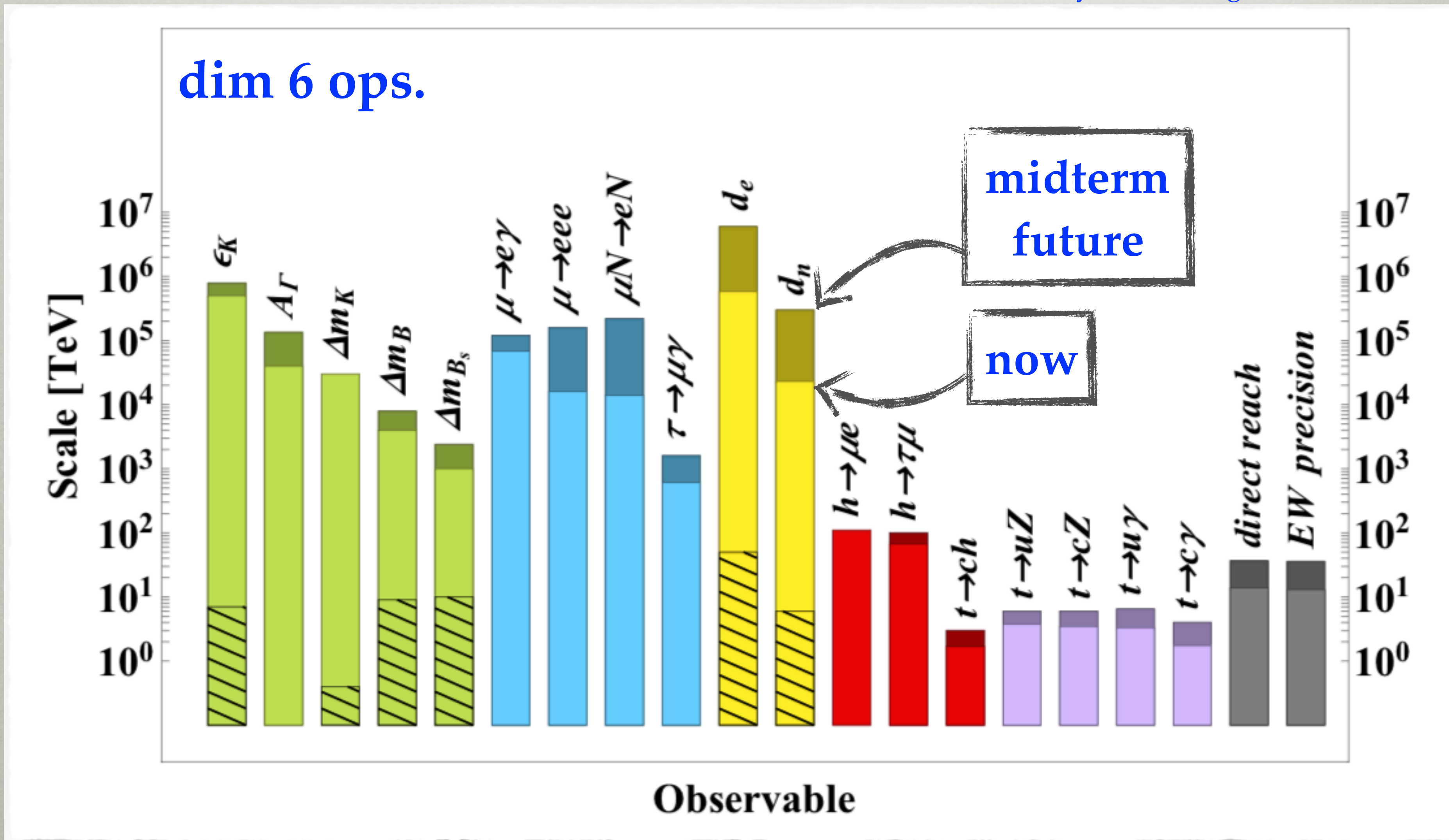




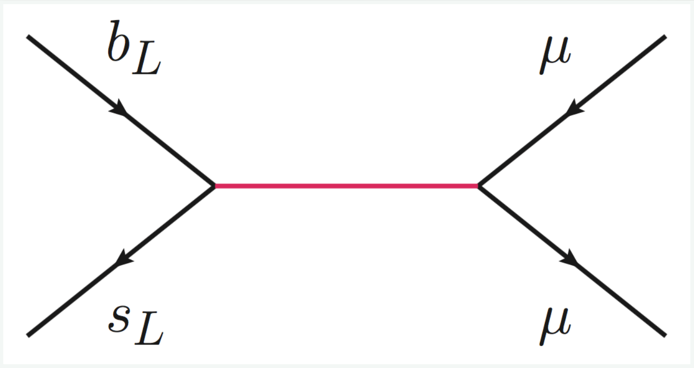


LARGE SCALES PROBED

Physics Briefing Book, 1910.11775



HIGH ENERGY VS. FLAVOR EXPERIMENTS



- at low energies probe off-shell states

$$Br(i \to f) \propto \left(\frac{g_i g_f}{m^2}\right)^2$$

- at high energies on-shell production
  - s-channel

$$\sigma(i \to X) \times Br(X \to f) \propto \mathcal{L}_i(m) \left(\frac{g_i g_f}{m^2}\right)^2 \frac{1}{\Gamma_{\text{tot}}}$$

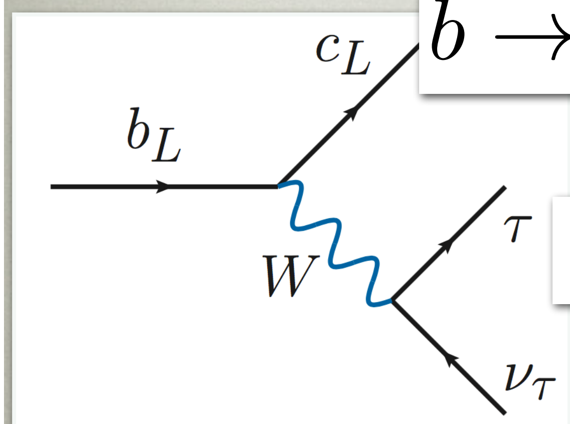
  - other options: t-channel, pair production, ...
- probe different combinations of couplings and masses*

*small print caveats: at high eng. could also still be off shell; which couplings probed depend on which prod/decay channel, etc

B PHYSICS ANOMALIES

- two quark level transitions show ~3σ deviations from the SM*
- lepton flavor universality violating transitions

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

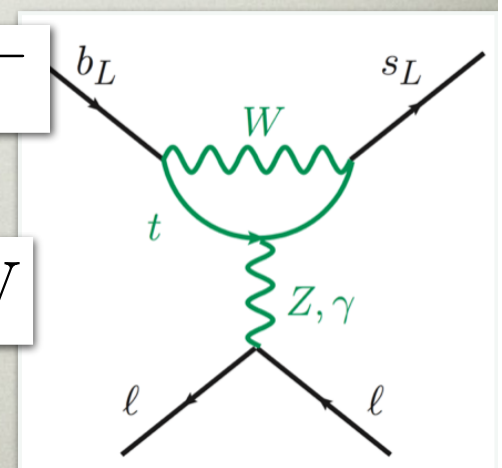


$b \to c\tau\nu$

$\Lambda_{\rm NP} \sim 3$ TeV

$b \to s\mu^+\mu^-$

$\Lambda_{\rm NP} \sim 30$ TeV

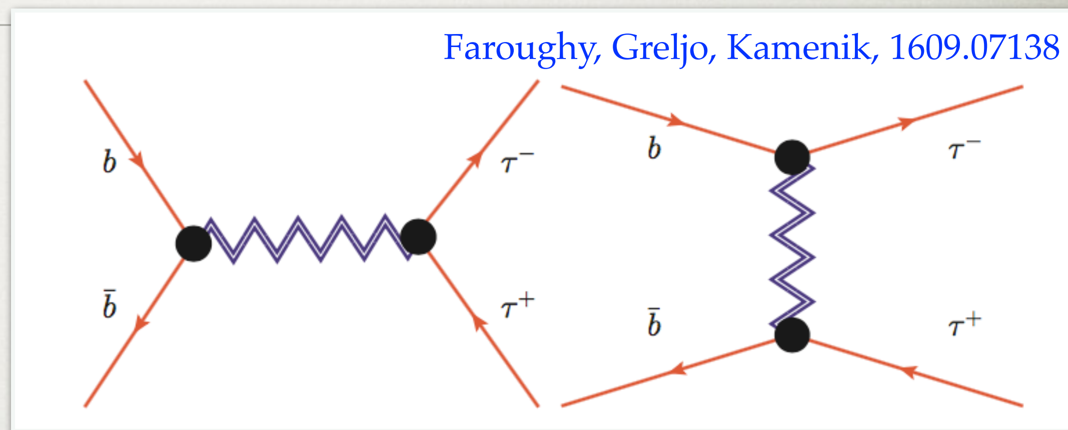


if true sets the scale for on-shell searches at colliders

* there are other interesting deviations, e.g., ~3σ deviation in ε'/ε, see, e.g., Buras et al, 1507.06345; RBC-UKQCD, 1502.00263

DIRECT SEARCHES IN $\tau\tau$

- $b \to c\tau\nu$ implies a $1/V_{cb}$ enhanced $b\bar{b} \to \tau^+\tau^-$
- severe bounds from LHC
- for instance for vector triplet: W', Z'

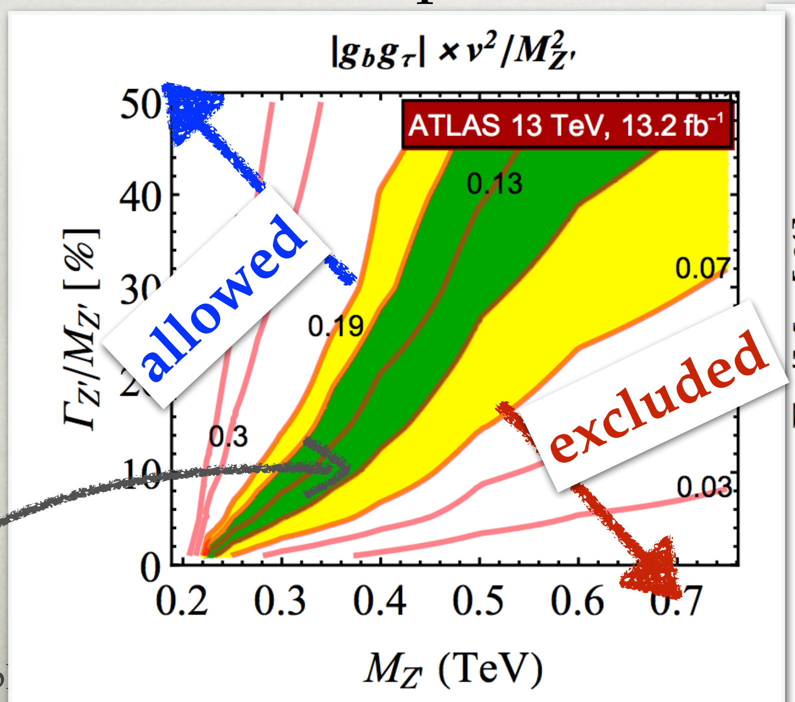


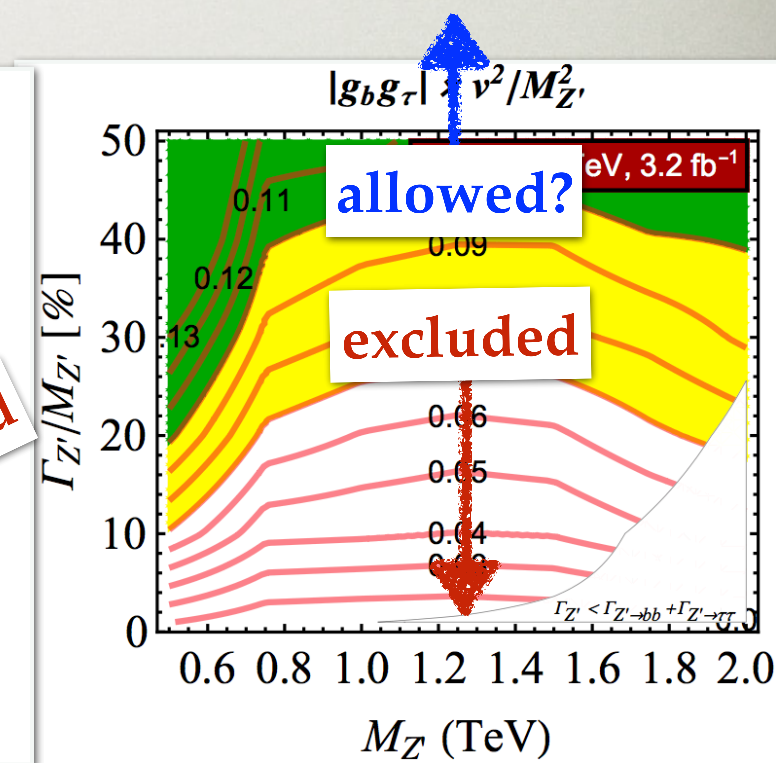
unitarity bound

$m_{W'} < 6.5\text{TeV}$

di Luzio, Nardecchia, 1706.01868

for $b \to c\tau\nu$ need:





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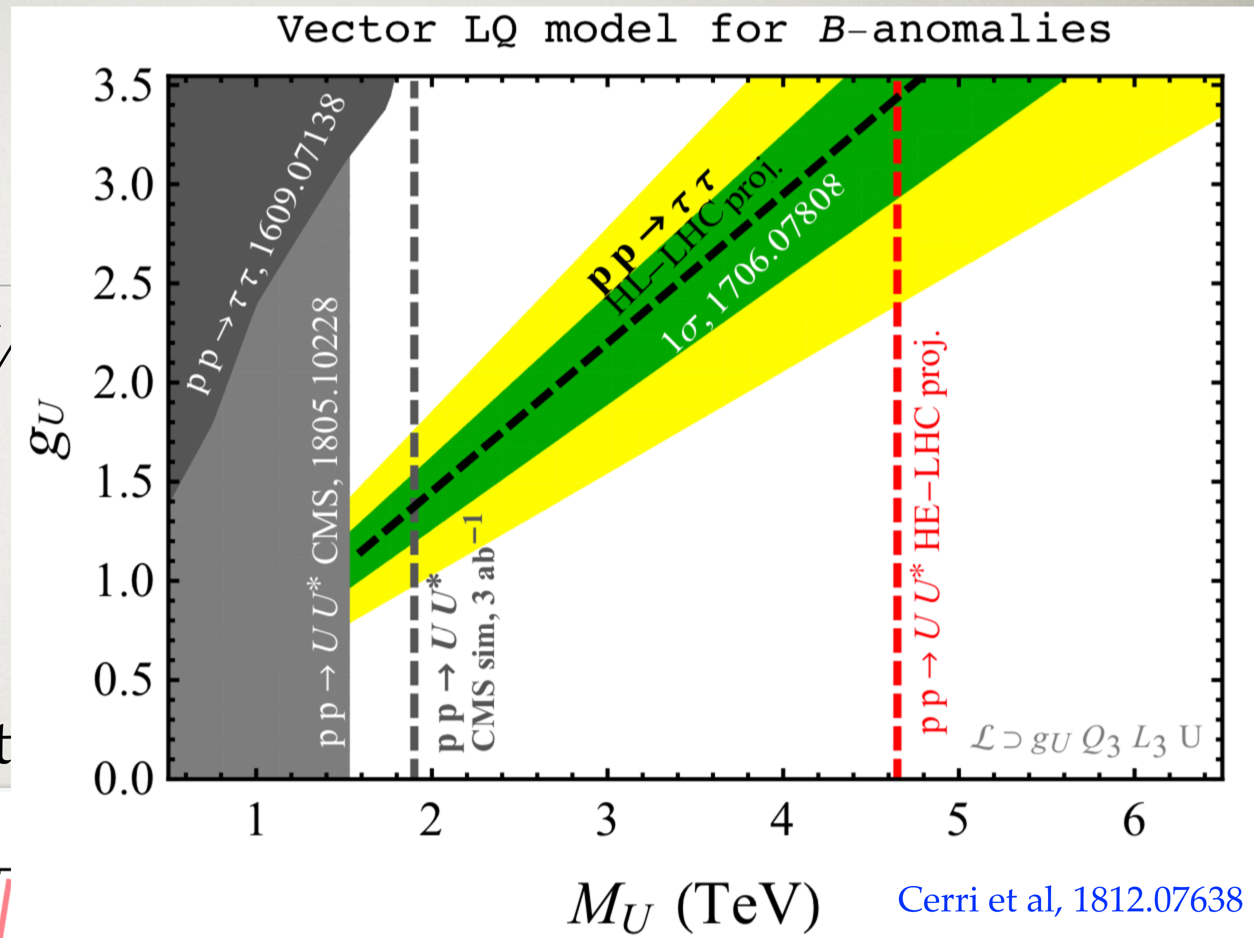

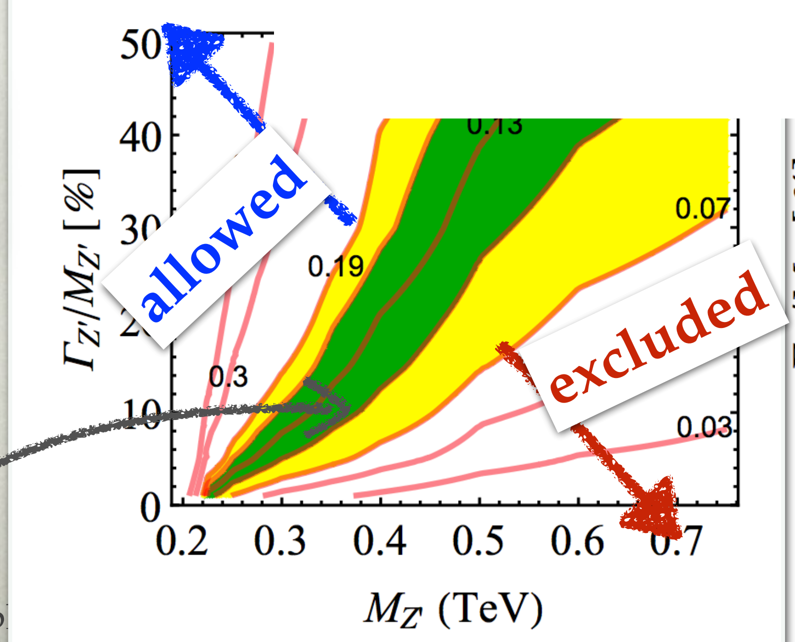

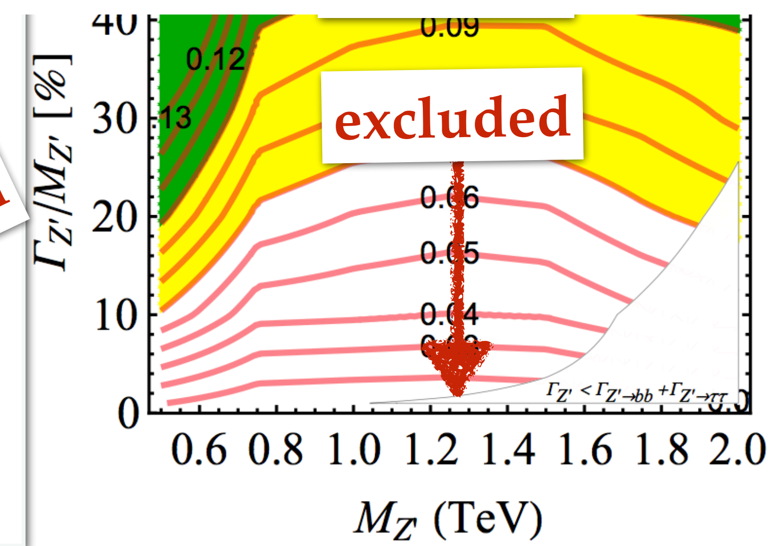

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for $b \to c\tau\nu$ need:

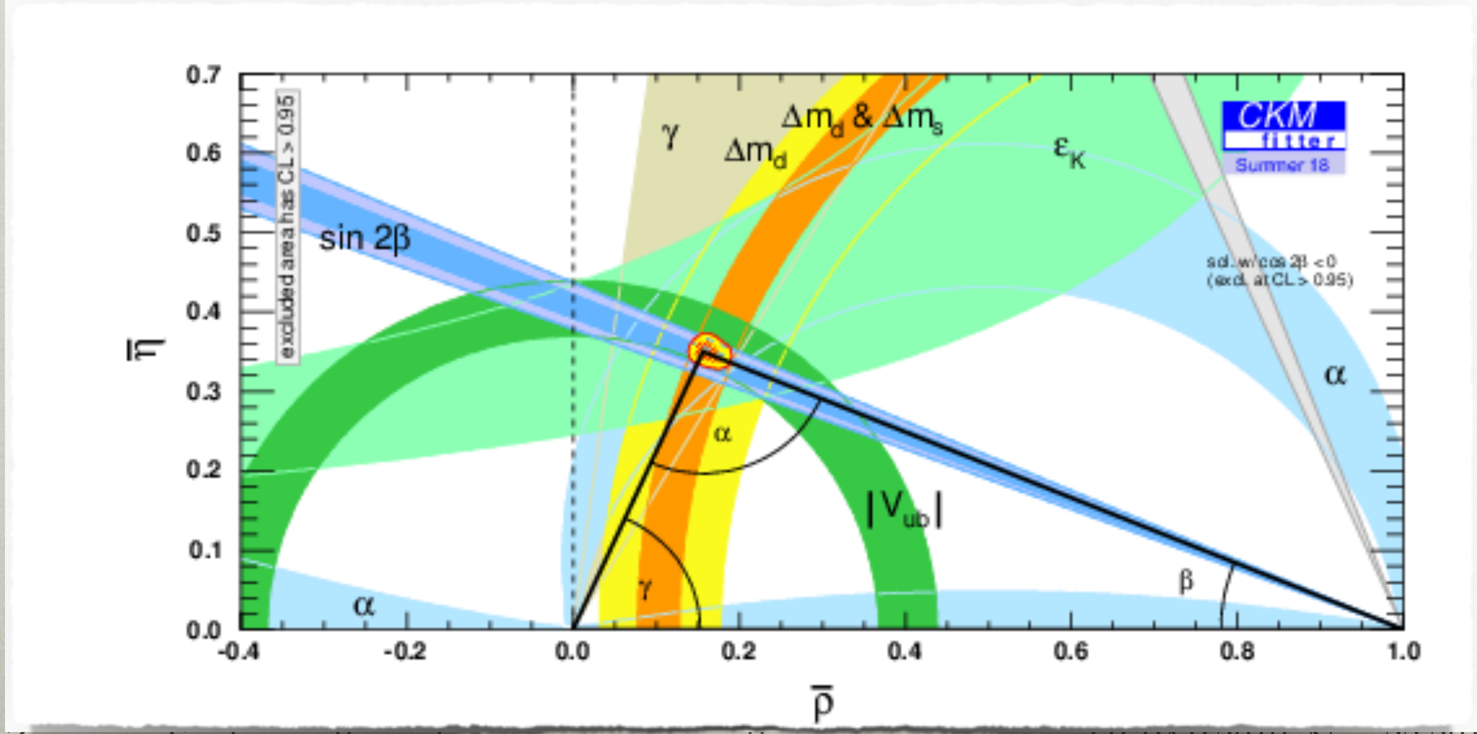
PROGRESS

- significant improvements both in theory and experiment
  - achieved and expected
- for theory just two very recent examples
  - charm contrib. to ε_K
  - hadronic light-by-light to $(g\text{-}2)_\mu$

CHARM CONTRIB. TO ε_K

Brod, Gorbahn, Stamou, 1911.06822

- K-$\bar{K}$ mixing parameter ε_K one of the most sensitive probes of new CPV
- the main th. uncertainty due to charm can be dramatically reduced
  - by using CKM unitarity and re-grouping perturb. corrections
- lattice QCD inputs very important



credit: J. Brod

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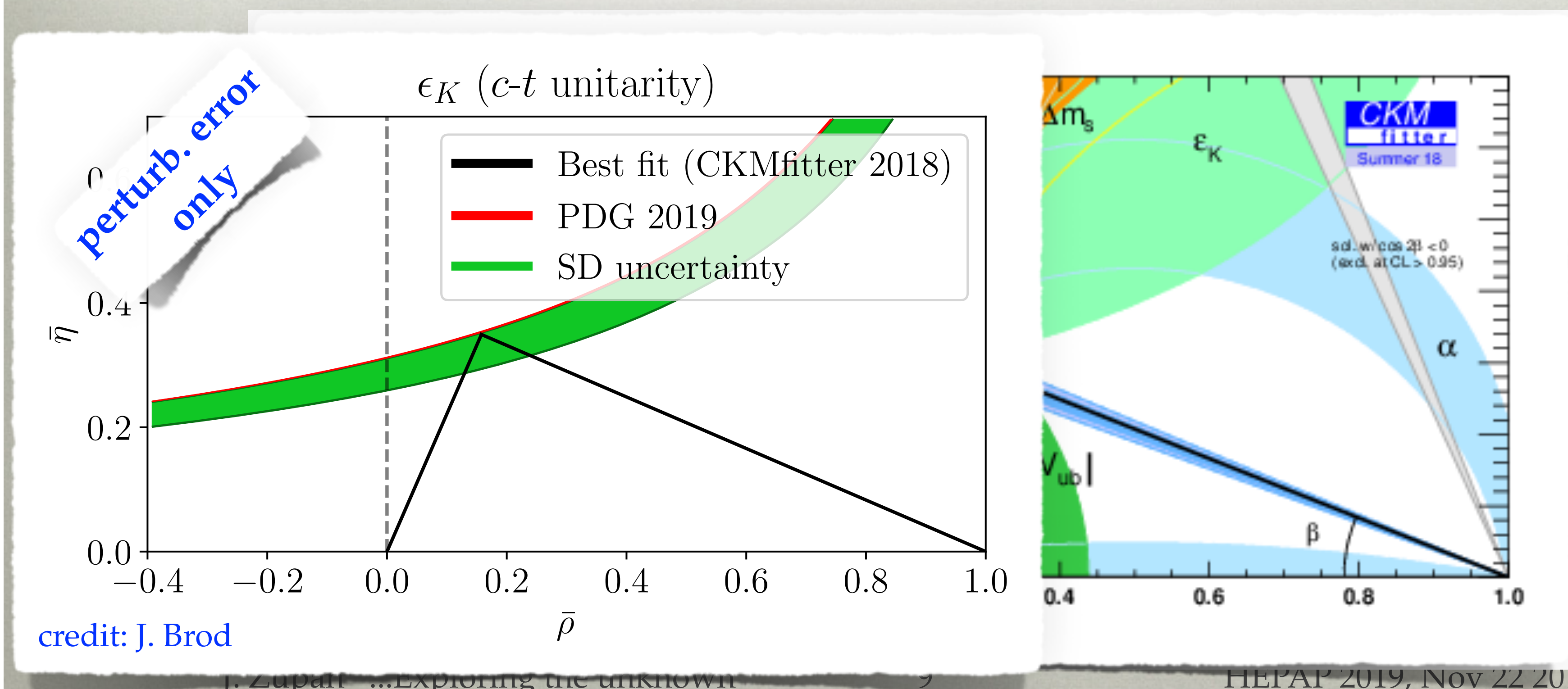

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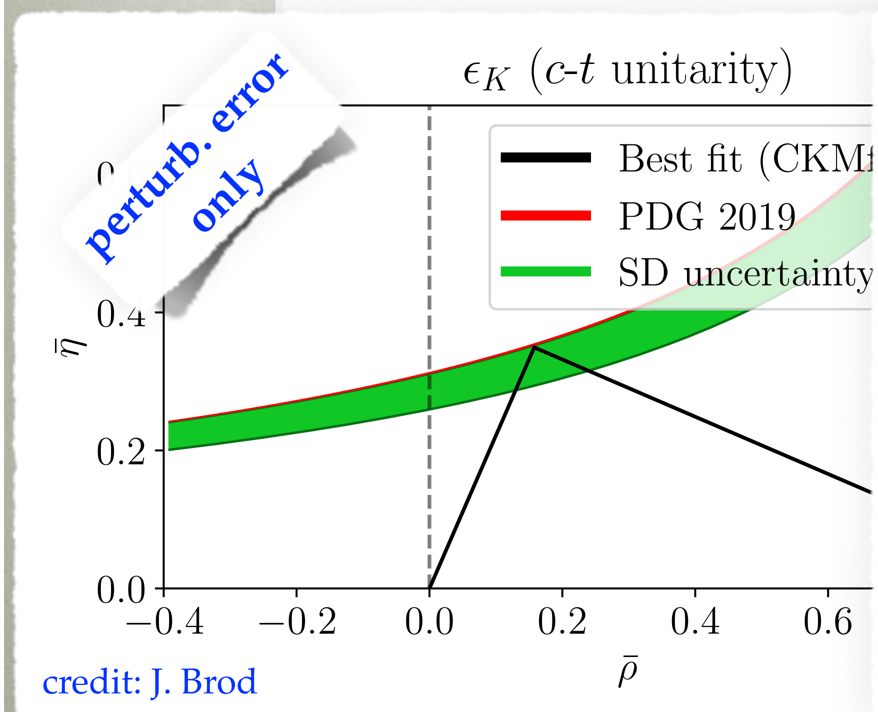

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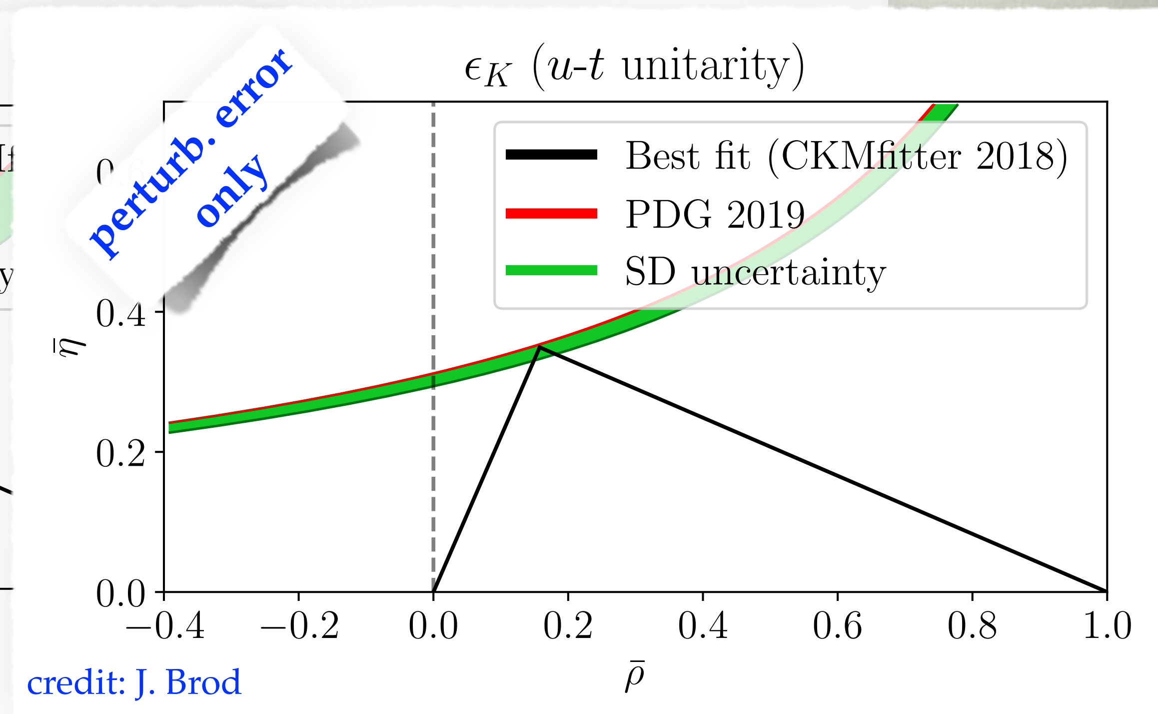

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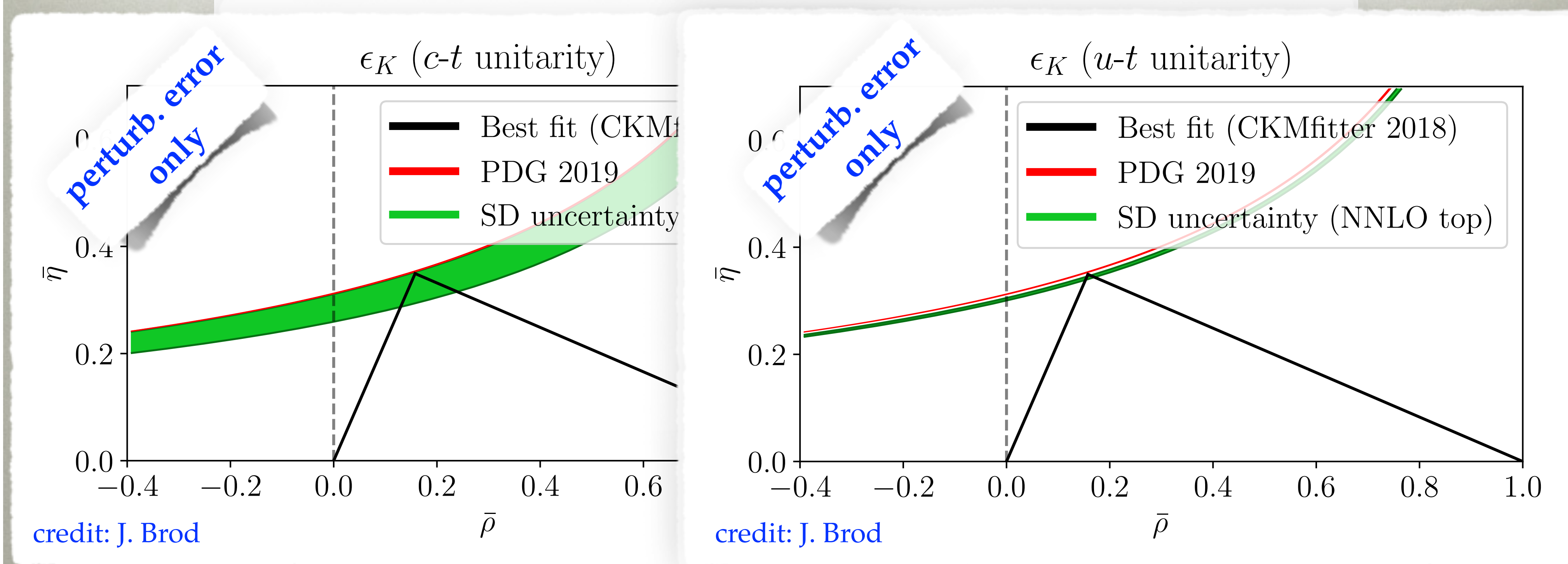
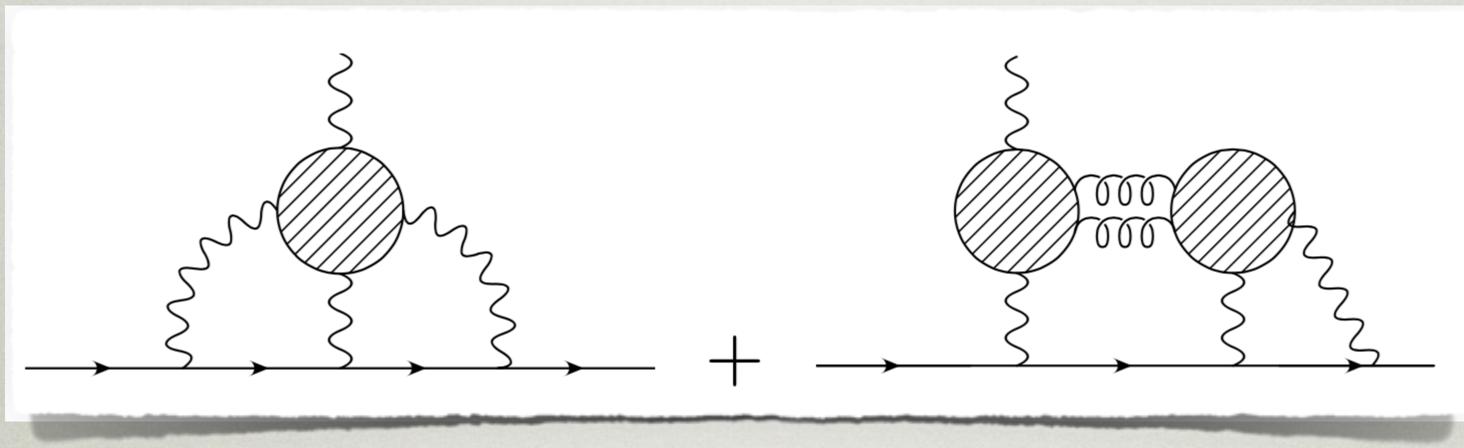


$(g\text{-}2)_\mu$

Blum et al, 1911.08123

- first determination of hadronic light-by-light contrib. to $(g\text{-}2)_\mu$ from Lattice QCD



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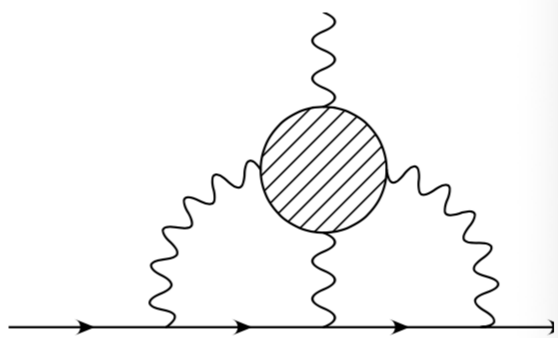


	$a_\mu \times 10^{10}$	Lin@Brookhaven Forum 2019
QED 5-loops	11658471.8853 ± 0.0036	Aoyama, et al, 2012
Weak 2-loops	15.36 ± 0.10	Gnendiger et al, 2013
HVP (LO)	692.5 ± 2.7	RBC-UKQCD and FJ17 combined
	693.26 ± 2.46	KNT18
	693.9 ± 4.0	DHMZ19
HVP (NLO)	-9.93 ± 0.07	Fred Jegerlehner, 2017
HVP (NNLO)	1.22 ± 0.01	Fred Jegerlehner, 2017
HLbL	10.3 ± 2.9	Fred Jegerlehner, 2017
	10.5 ± 2.6	Glasgow Consensus, 2007
SM Theory	11659181.3 ± 4.0	
BNL E821 Exp	11659208.9 ± 6.3	
Exp − SM	27.6 ± 7.5	

$7.20(3.98)_{\rm stat}(1.65)_{\rm sys}$

HLbL from Lattice QCD

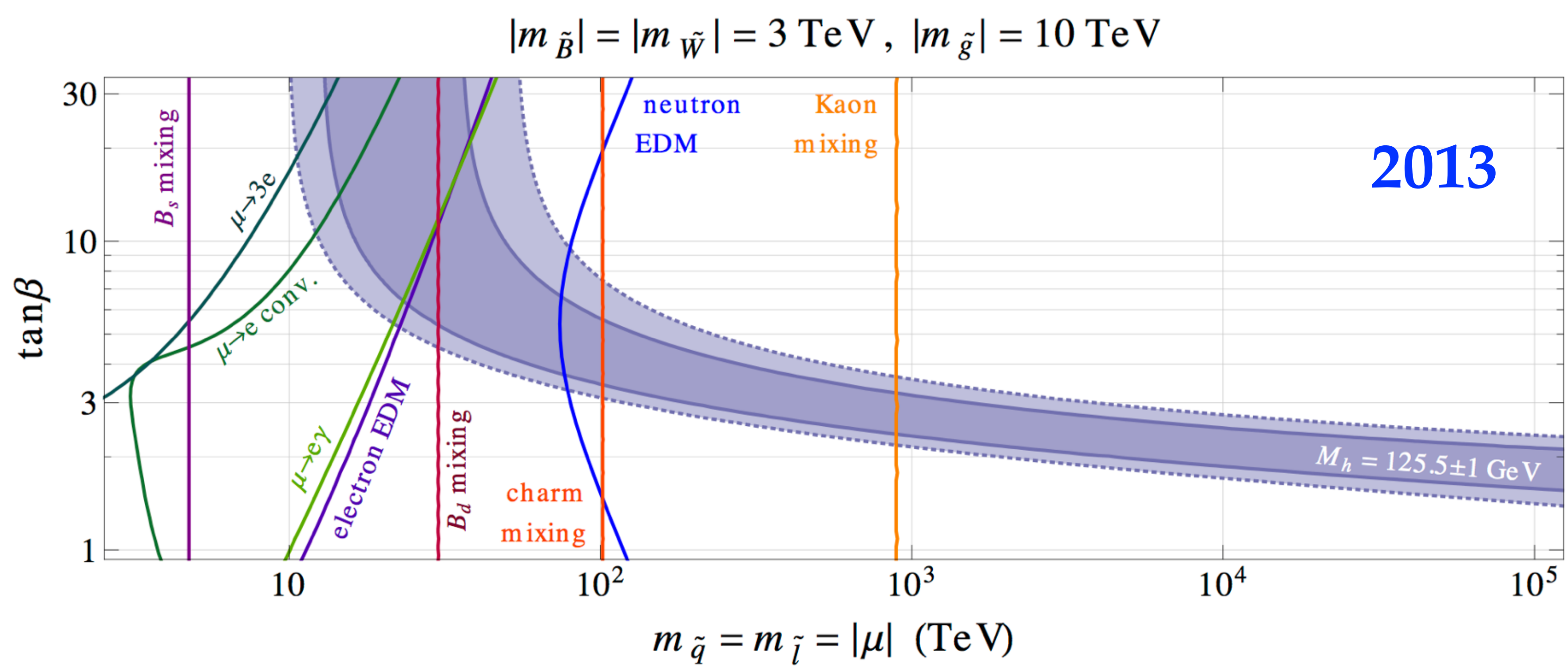
leaves little room for this notoriously difficult hadronic contribution to explain the difference between the Standard Model and the BNL experiment. Blum et al, 1911.08123

EXPERIMENTAL PROGRESS - UPSHOT

- LHCb Upgrade 2+Belle II: a factor of 2x - 3x improvement in reach for NP scale
  - ~ like going from LHC (13 TeV) to HE-LHC (27 TeV)
  - more precise measurements + expected theory advance: lattice QCD improvements
- many other experiments also significant improvements in the reach
  - Mu3e, Mu2e, MEG II, eEDM, rare kaon decays,…

EXPERIMENTAL PROGRESS

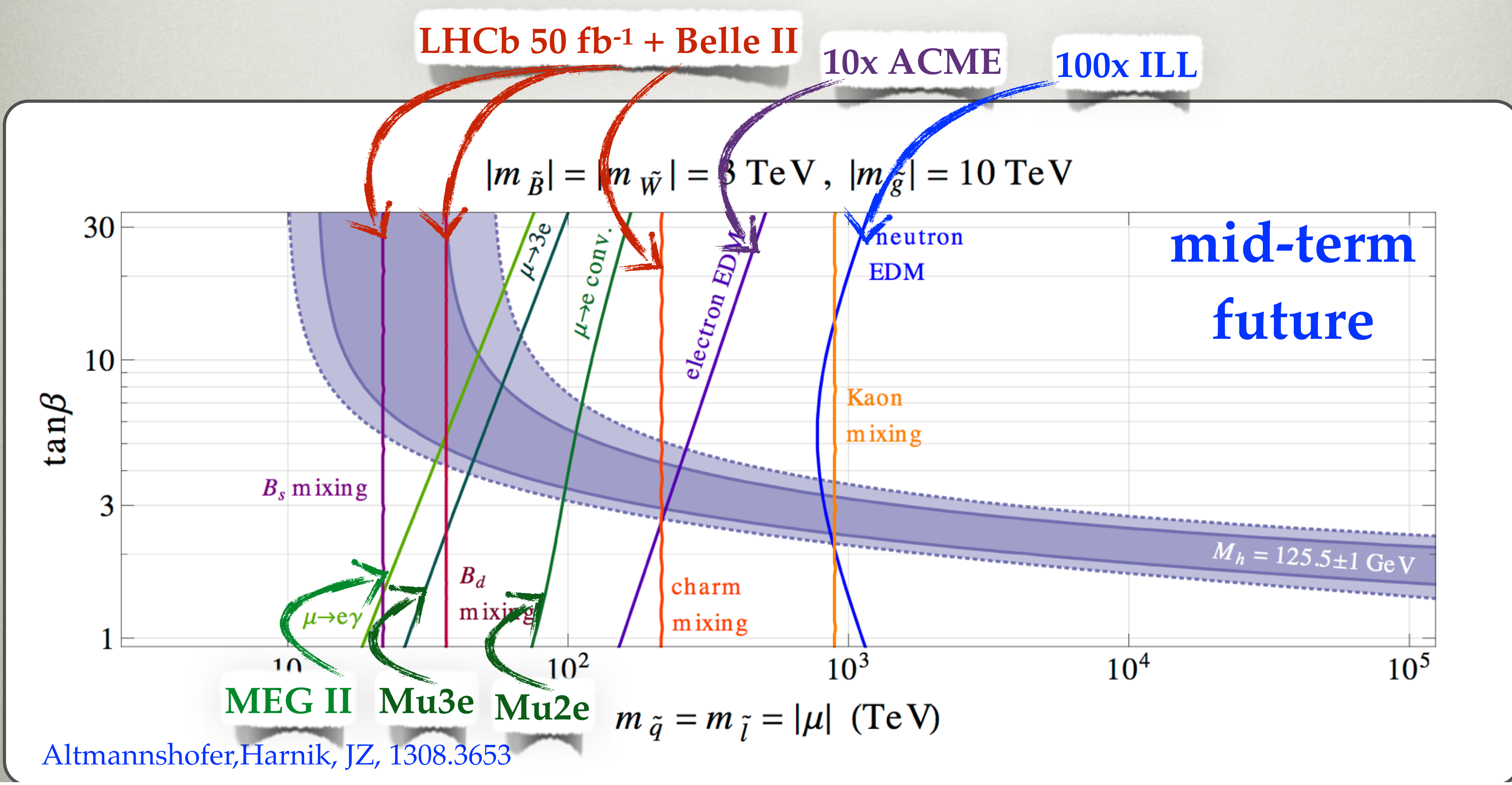
- example: mini-split SUSY
  - *O(1-10TeV)* gauginos at LHC or future collider; PeV sfermions from low energy precision probes



Altmannshofer,Harnik, JZ, 1308.3653

EXPERIMENTAL PROGRESS

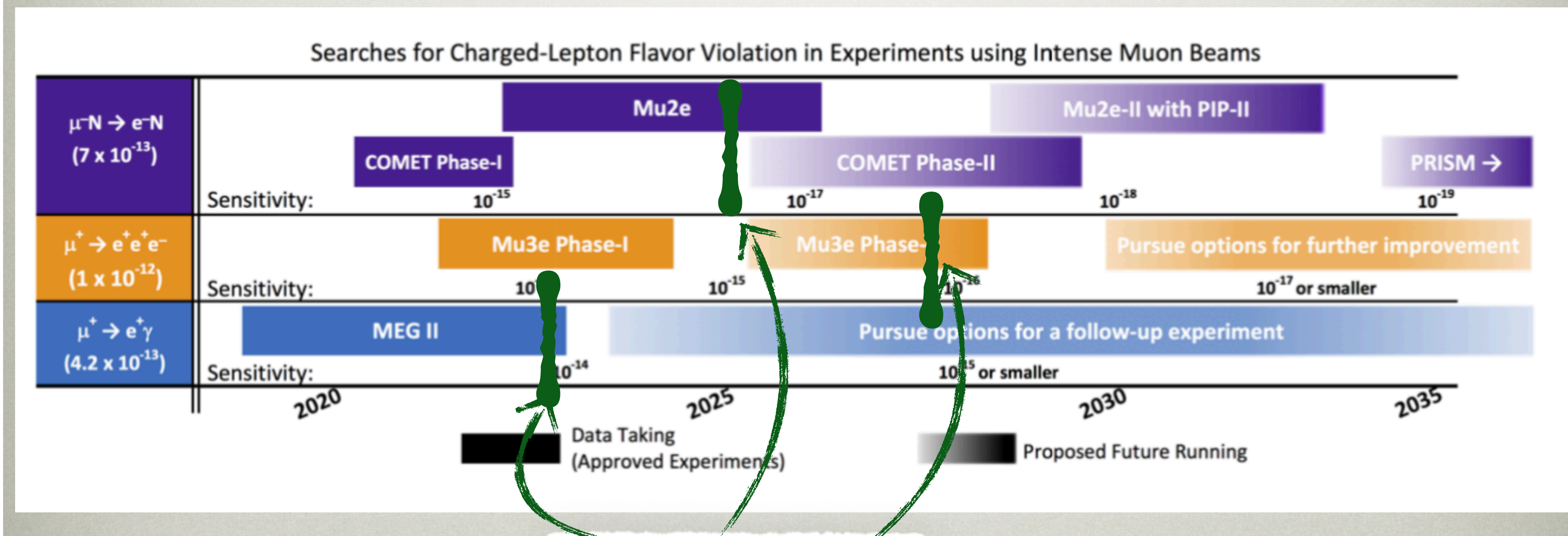
- and will improve dramatically in the future



EXPERIMENTAL PROGRESS

Physics Briefing Book, 1910.11775

- further orders of magnitude experimental progress expected in CLFV transitions

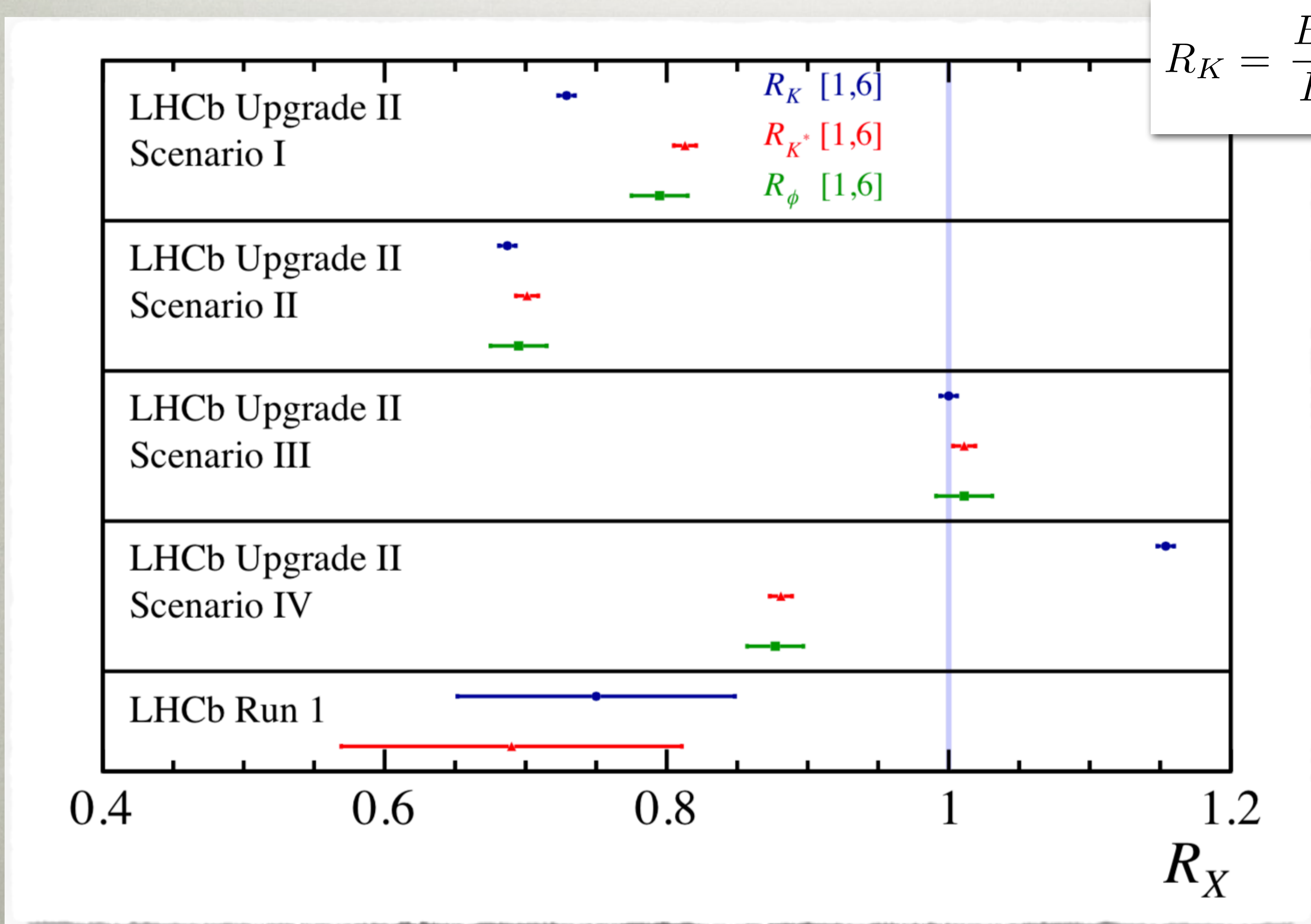


assumed sensitivies in the previous slide

LFUV OBSERVABLES

Akar et al., 1812.07638

- example: LHCb after Upgrade II

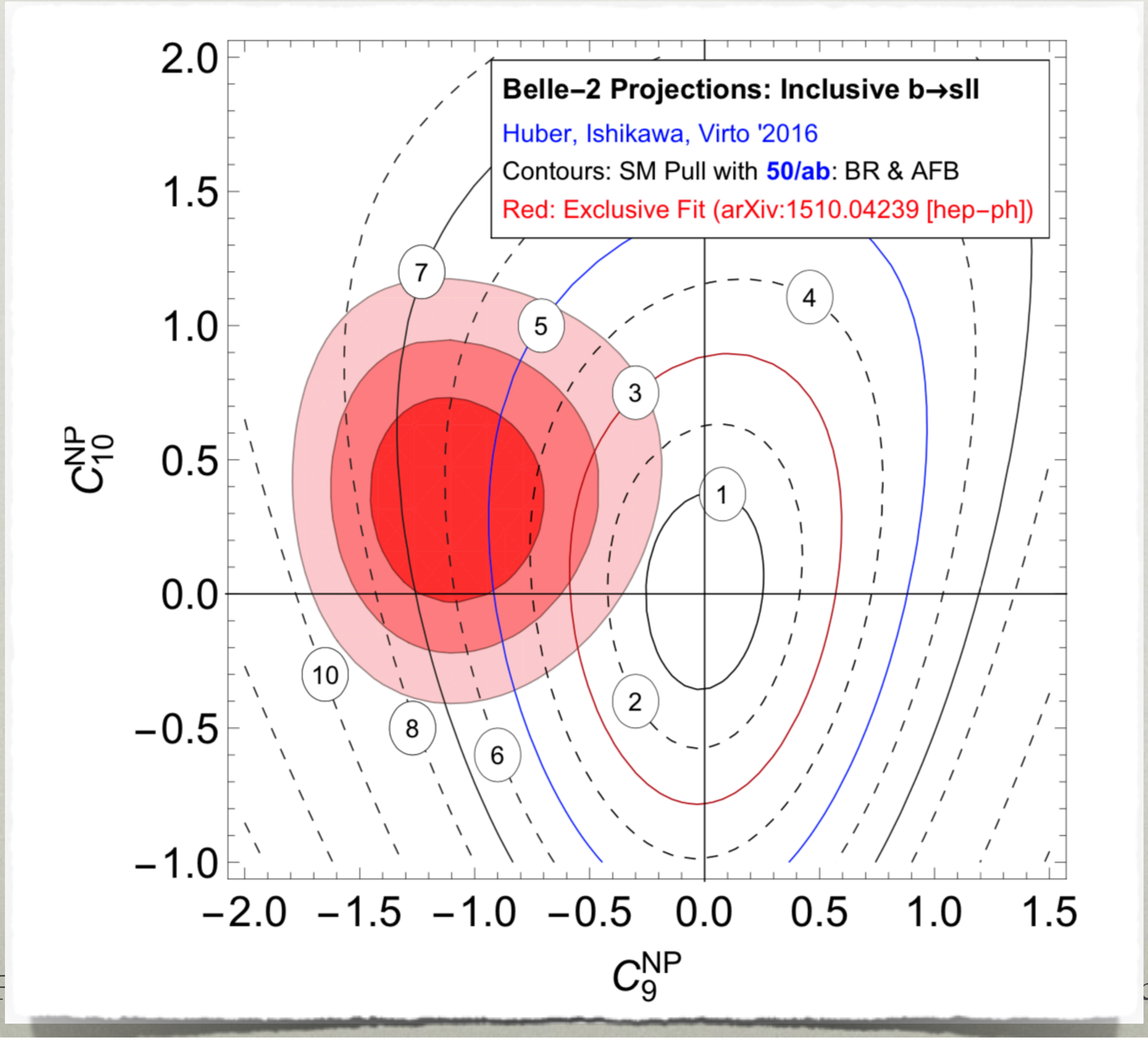


$$R_K = \left.\frac{Br(B\to K\mu\mu)}{Br(B\to Kee)}\right|_{[1,6]\mathrm{GeV}^2}$$

LFUV observables

B2TiP, 1808.10567

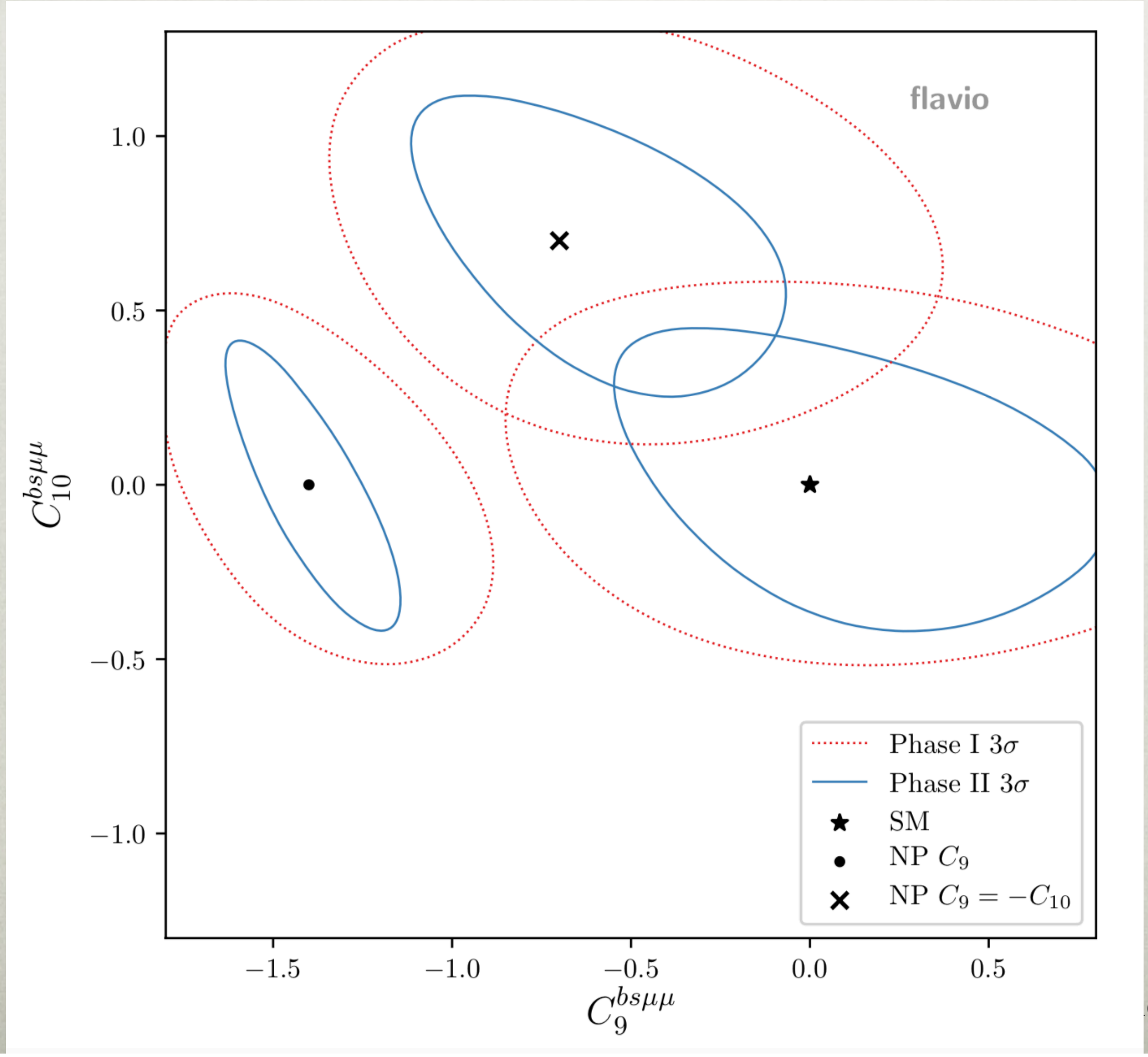
- example: only inclusive $b \to sll$



LFUV observables

Akar et al., 1812.07638

- example: LHCb+ATLAS+CMS, from $B_s \to \mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$

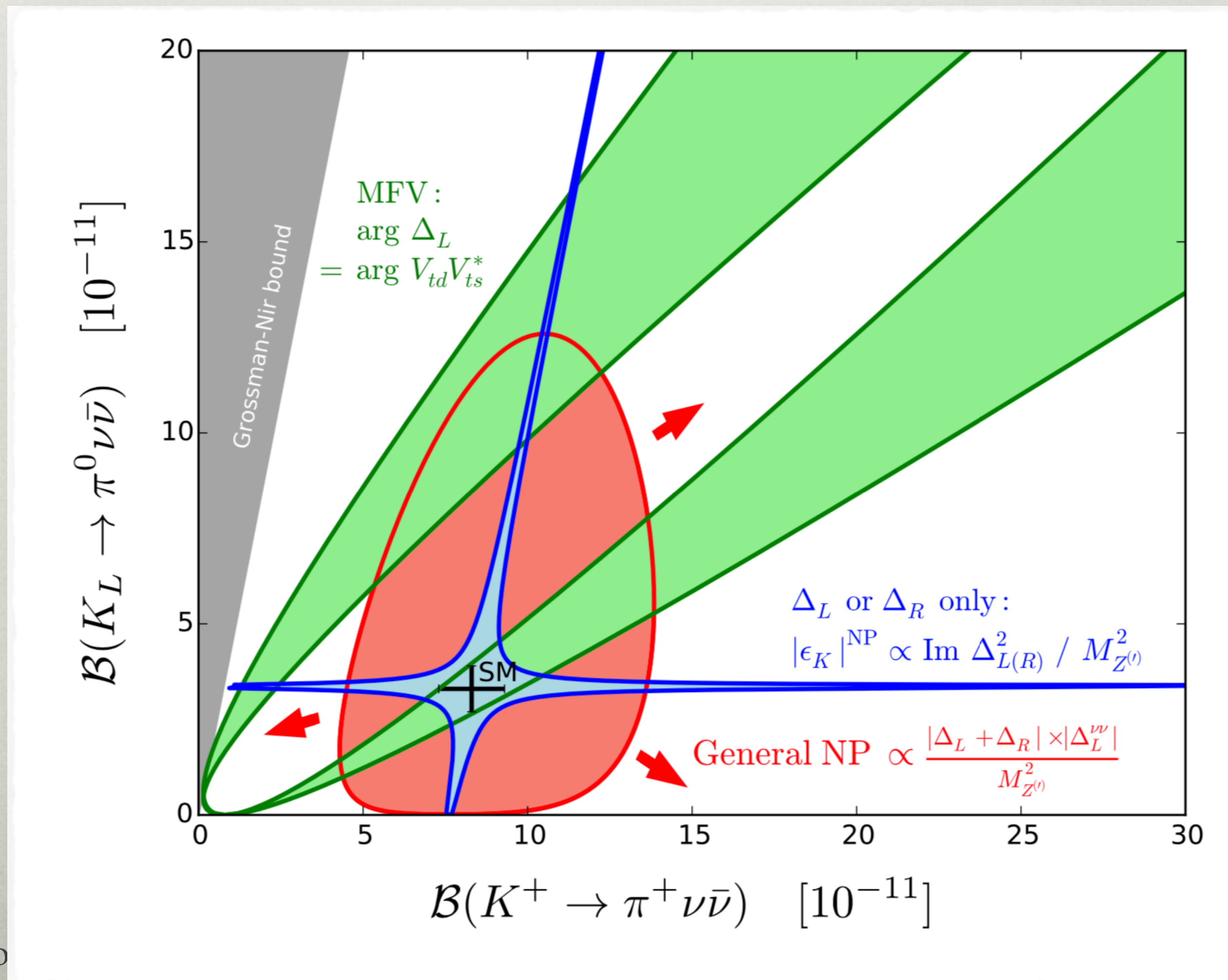


Physics Briefing Book, 1910.11775

Buras, Buttazzo, Knegjens, 1507.08672

RARE KAON DECAYS

- Br($K \to \pi \nu \bar{\nu}$) theoretically very clean



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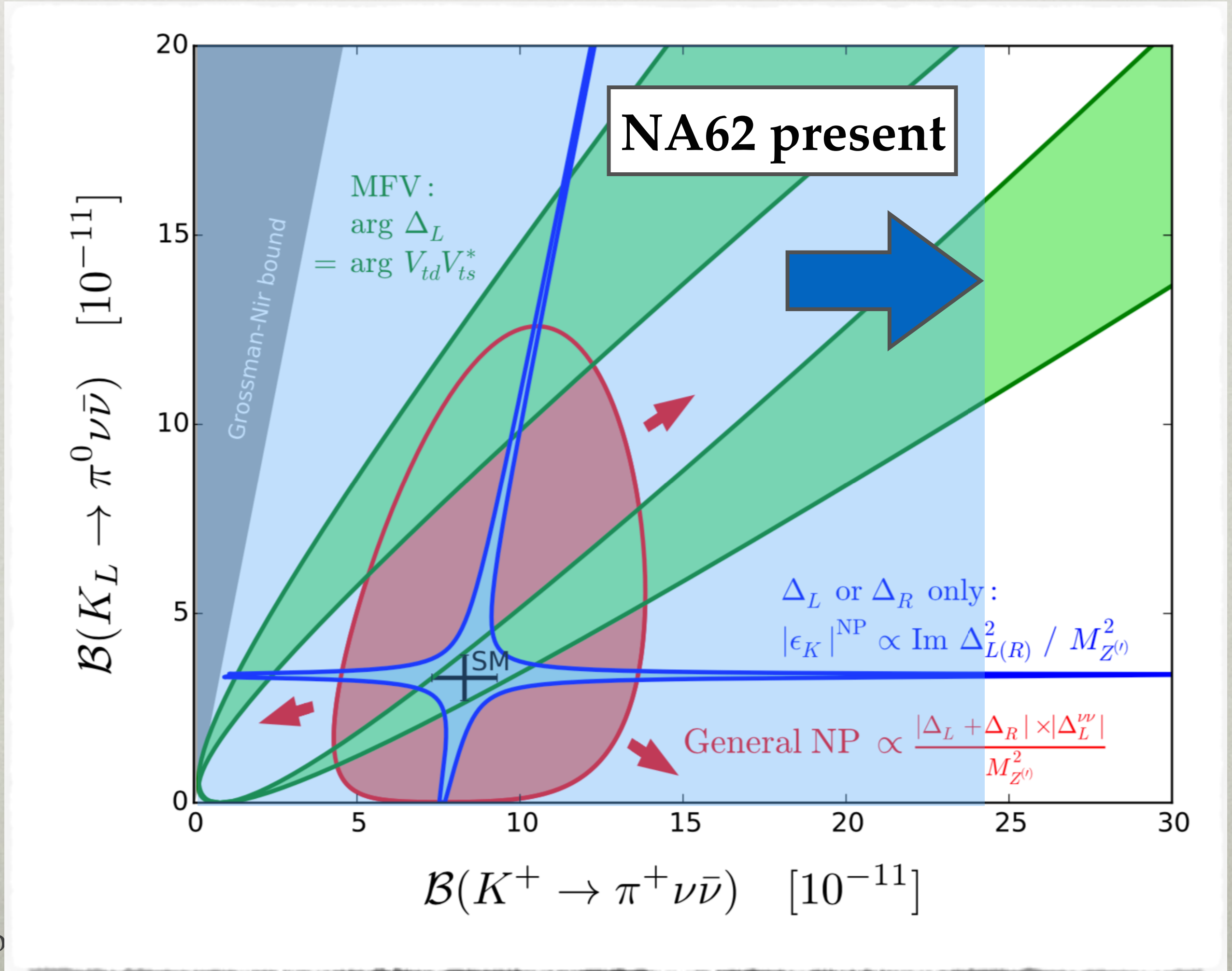

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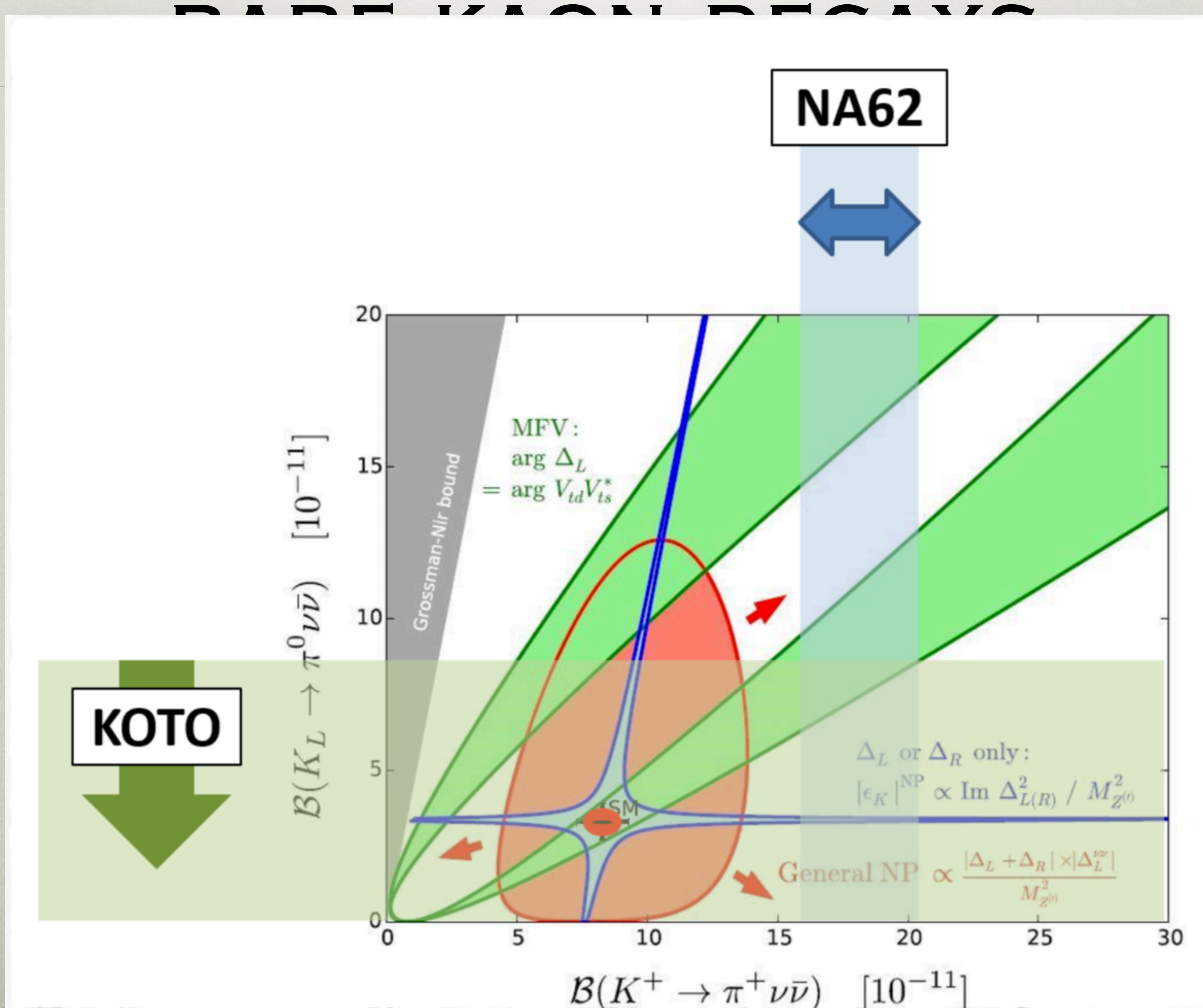

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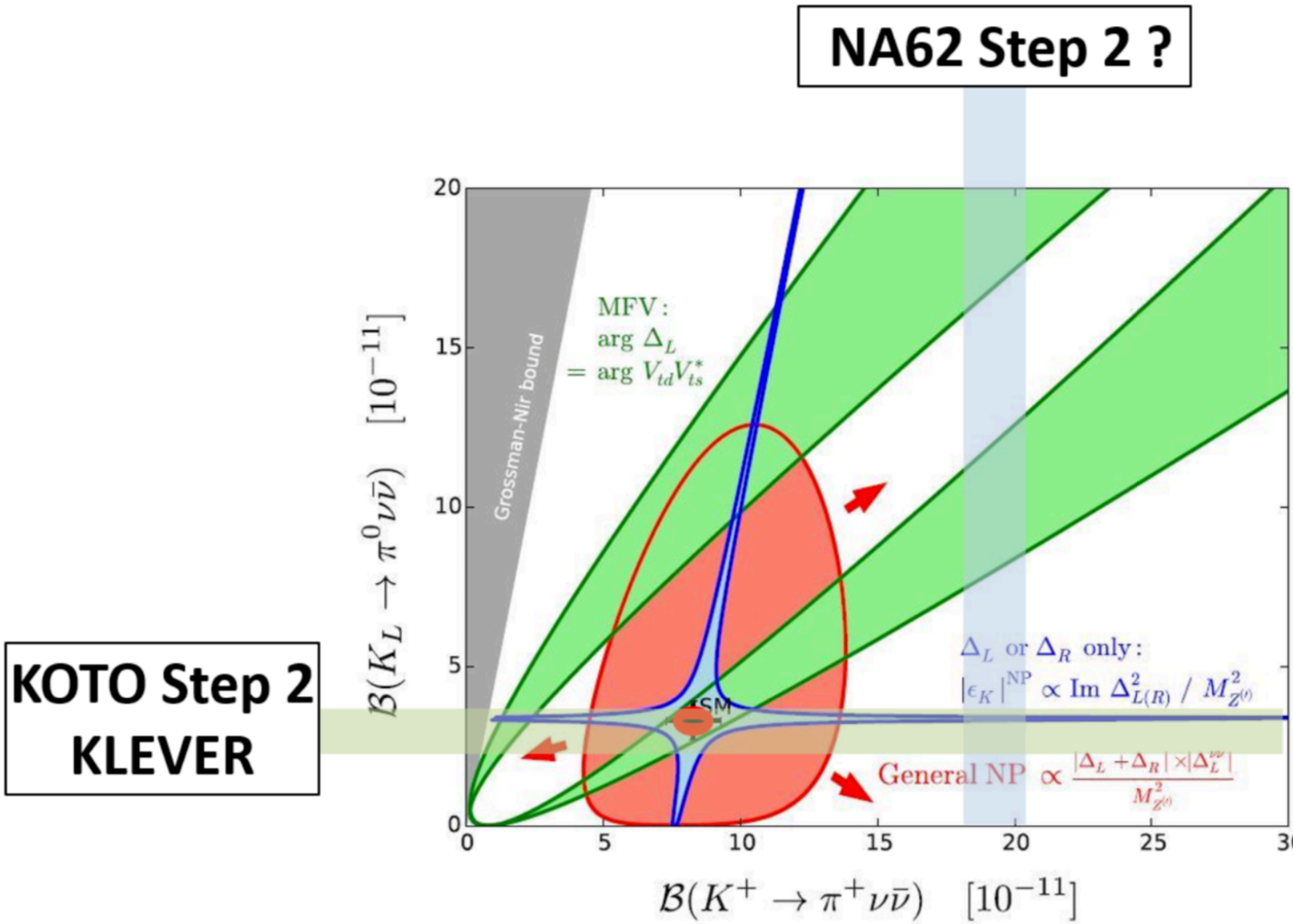
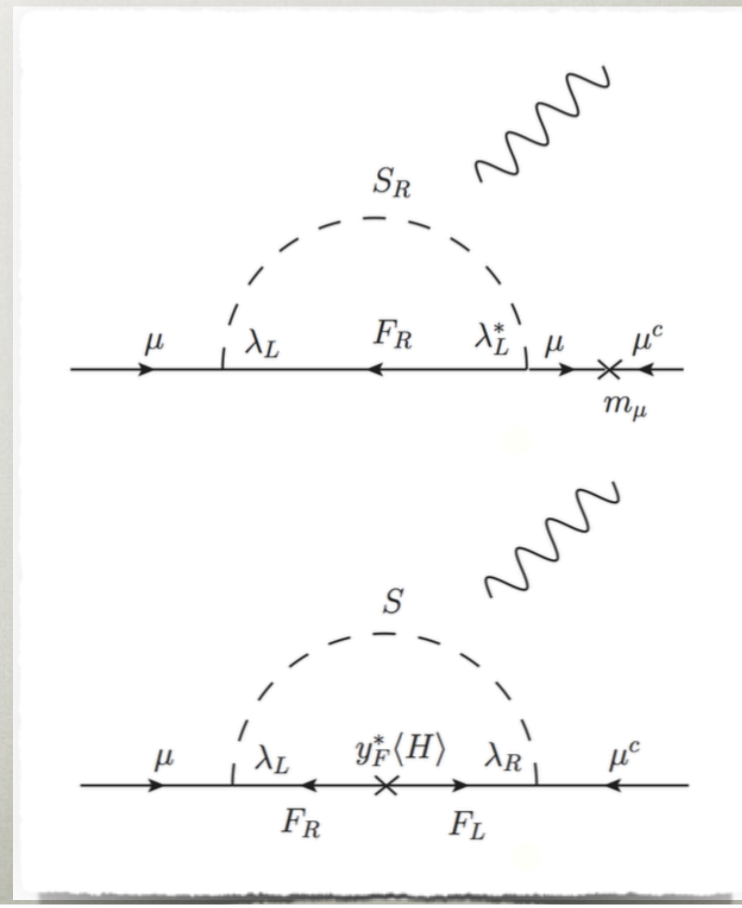
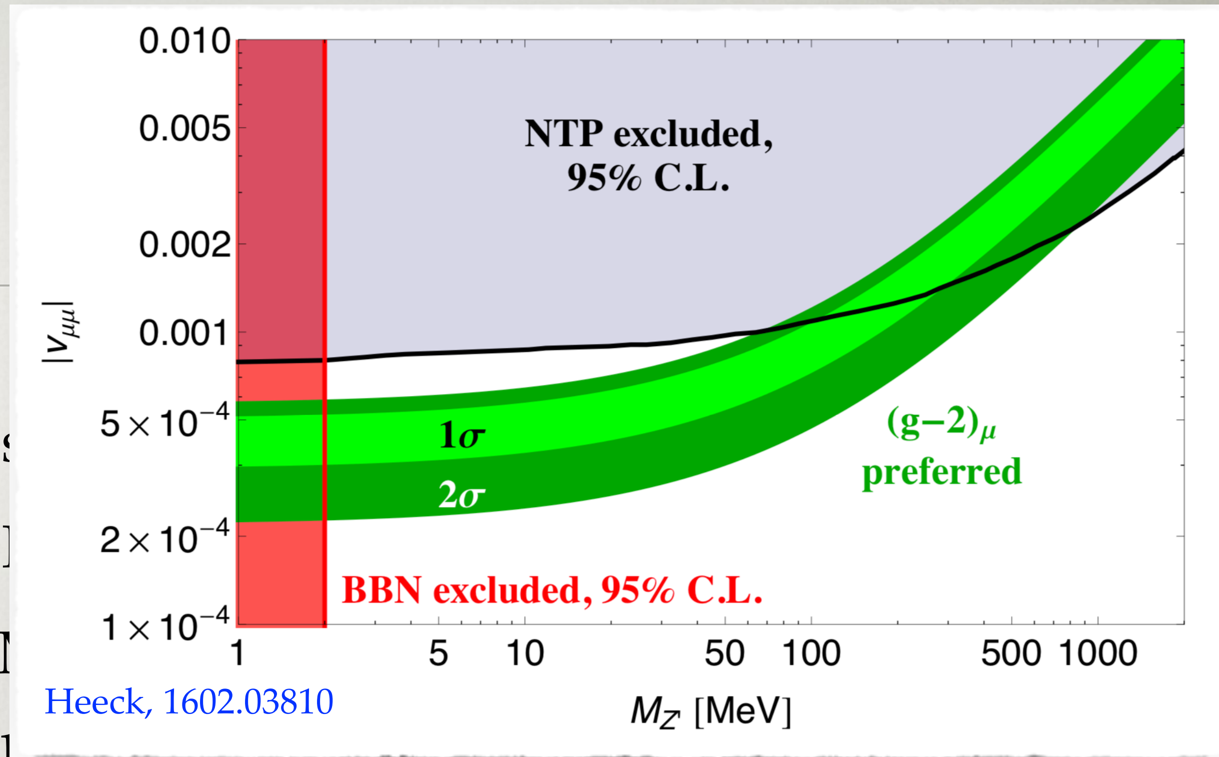


LIGHT NEW PHYSICS

- flavor observables also probe light NP
- example: $(g\text{-}2)_\mu$ NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z'
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM



LIGHT



- flavor observables
- example: $(g\text{-}2)_\mu$ NI
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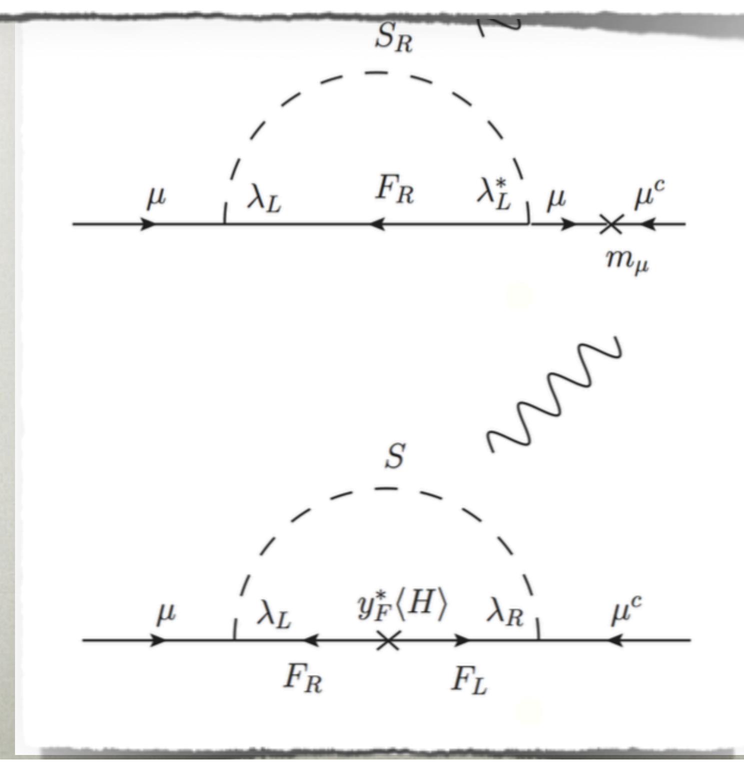
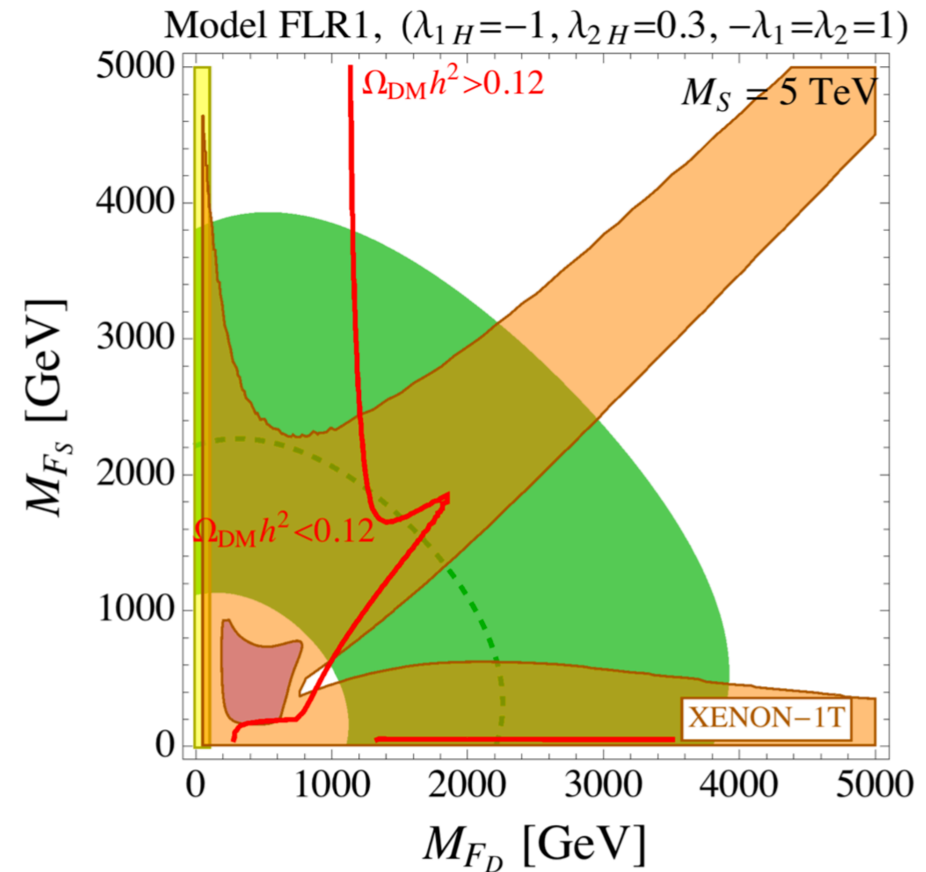
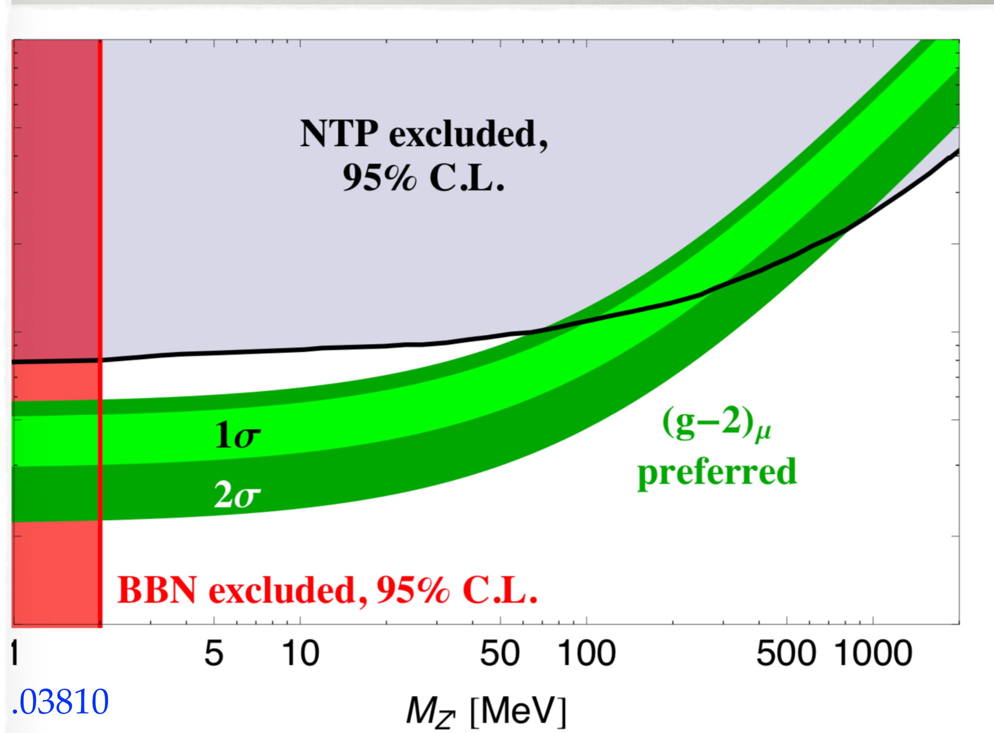




Calibbi, Ziegler, JZ, 1804.00009



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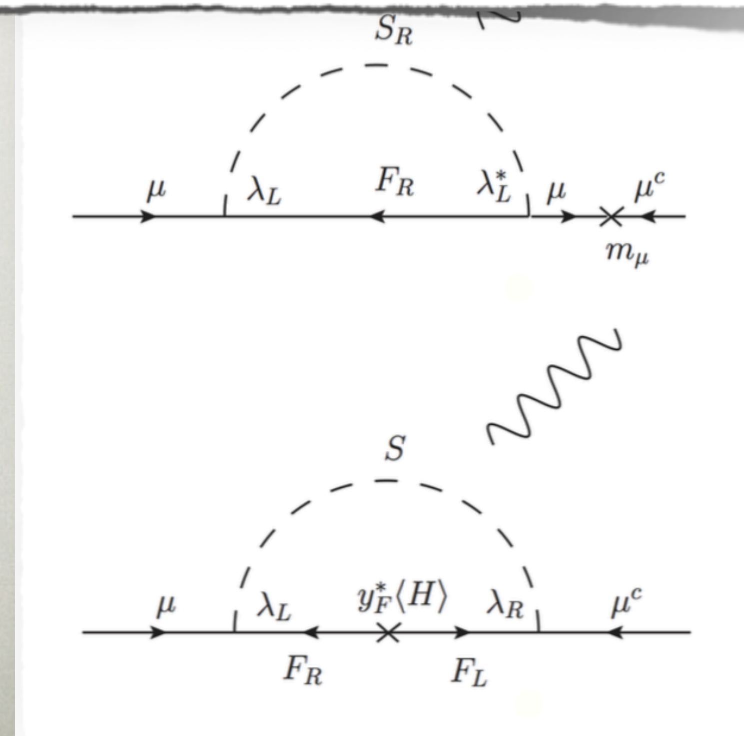

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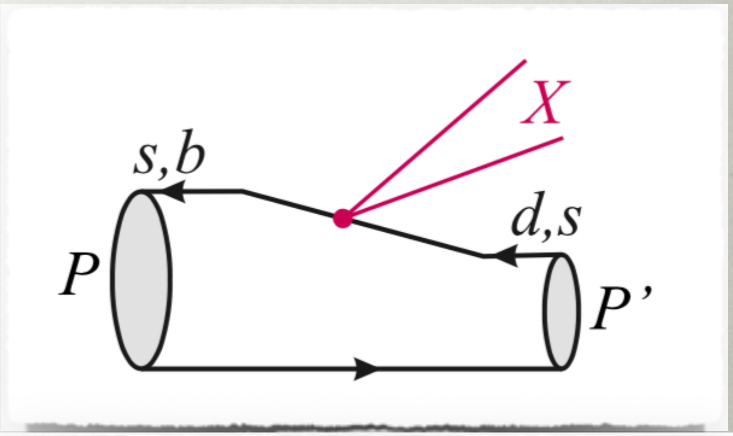
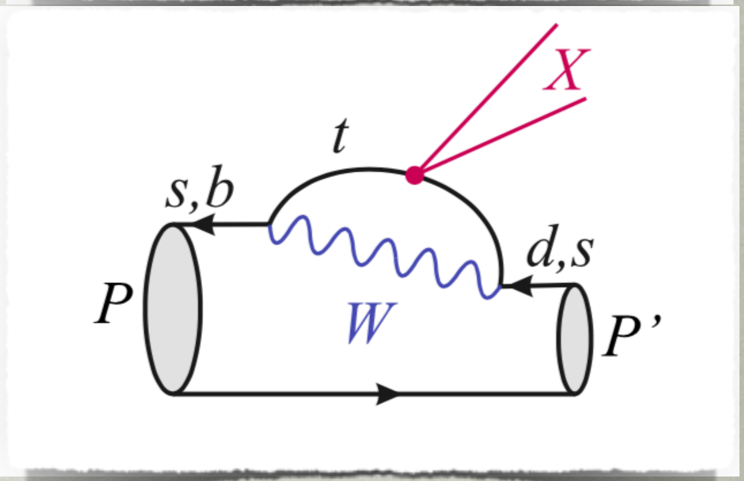
  - NP can be much heavier
  - example: minimal models with DM

DARK MATTER IN RARE DECAYS

see, e.g., Bird et al, hep-ph/0401195; Kamenik, Smith, 1111.6402

- DM could be produced at tree level, if FV couplings
- for flavor diagonal couplings DM can be produced at 1 loop
- X can be (pseudo-)scalar, (axial-) vector mediator
  - can decay to DM or visible



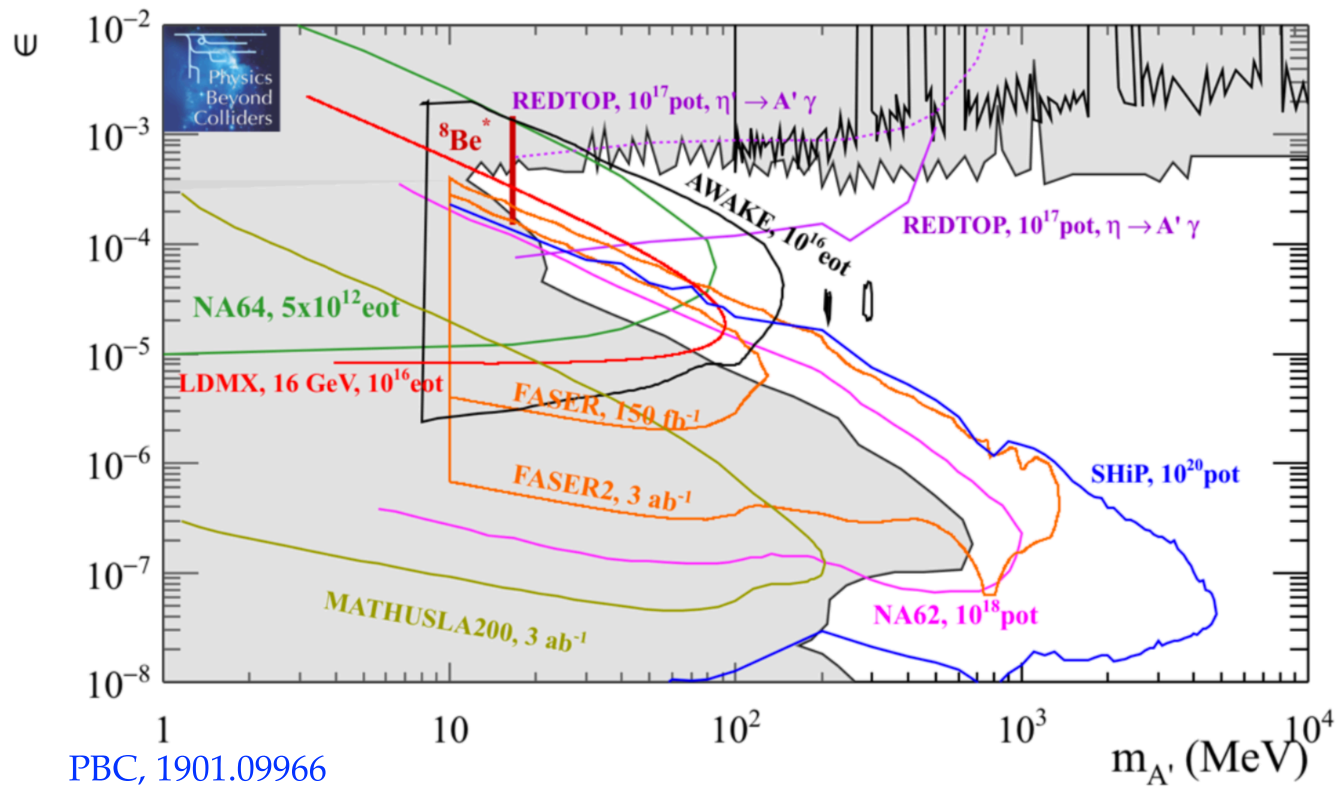


DARK PHOTON

- *U(1)*$_D$ can have kinetic mixing with hypercharge

$$\mathcal{L}_{\rm vector} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu},$$

- induces couplings of dark photon to the SM, prop.to charge



PBC, 1901.09966

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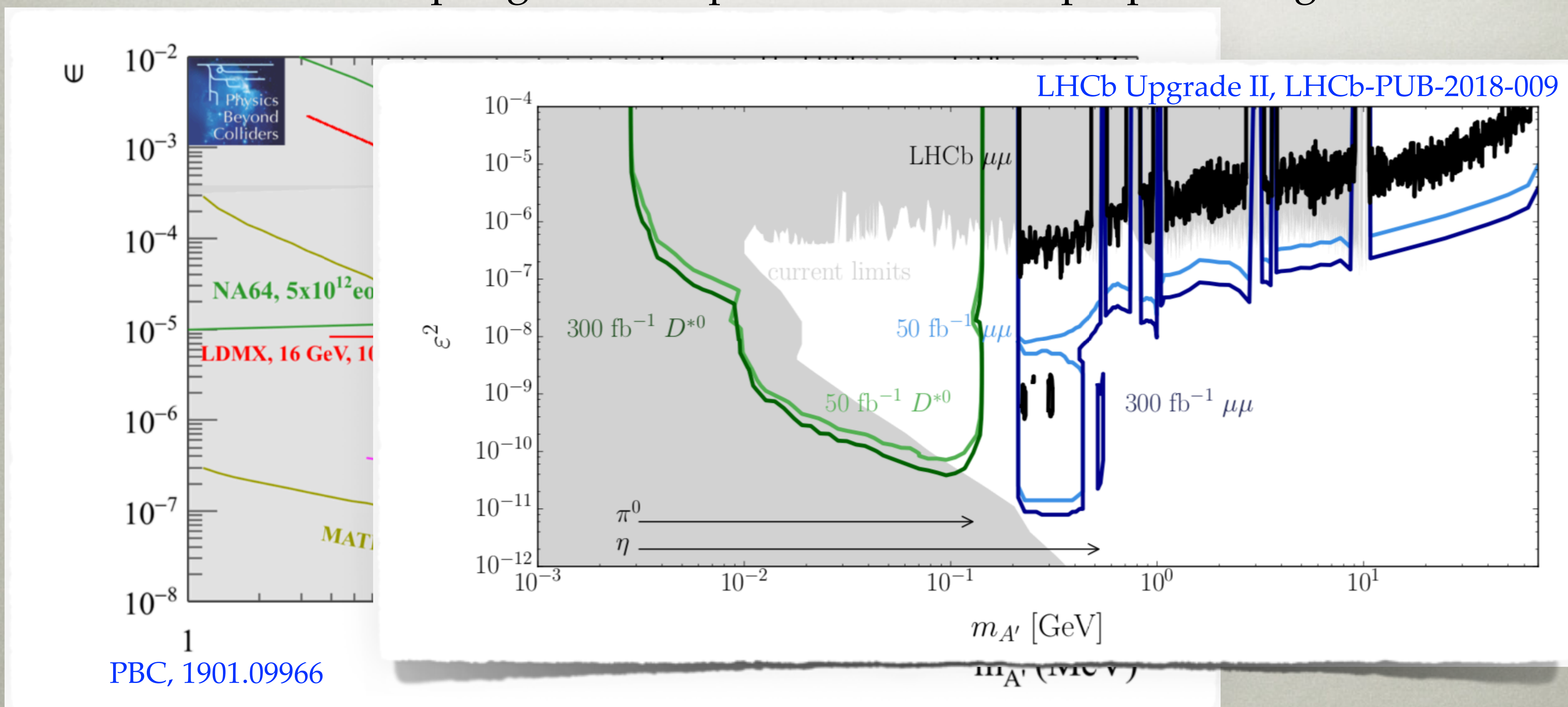

CONCLUSIONS

- flavor program expected to significantly improve new physics reach
- probes both high scales and weakly coupled light sectors

BACKUP SLIDES