

QUARK FLAVOR PHYSICS

JURE ZUPAN
U. OF CINCINNATI

Snowmass: Seattle Energy Frontier Workshop, July 1 2013

THE MAIN POINTS

- for the Higgs mass we had unitarity bounds, $m_h \lesssim 1\text{TeV}$
 - no such precise statements about the next scale
- naturalness/hierarchy problem an important guidance
 - but not bullet proof
- flavor physics probes of new physics
 - can probe high scales
 - if new particles are discovered, complementary information

OUTLINE

- quark flavor physics working group
 - what we are doing
- complementarity / interplay with the energy frontier

QUARK FLAVOR PHYSICS

WORKING GROUP

<http://www.snowmass2013.org/tiki-index.php?page=Quark+Flavor+Physics>

- Quark Flavor Physics ([Joel Butler, Zoltan Ligeti, Jack Ritchie](#))
- has four Task Forces:
 - Kaons ([Vincenzo Cirigliano, Steve Kettell](#))
 - Charm ([Roy Briere, Alexey Petrov](#))
 - B -physics ([Alan Schwartz, Tomasz Skwarnicki, JZ](#))
 - Lattice QCD ([Norman Christ, Steve Sharpe, Ruth Van de Water](#))
- the question: how well can one do in channels interesting for BSM searches
 - can already use recent studies for Belle II, LHCb upgrade, white paper for LQCD,...

INTERPLAY WITH HIGH ENERGY FRONTIER

- the interplay / complementarity with high energy frontier:
 - can probe scales above $\sim 10\text{TeV}$
 - anomalies seen (NP?)/ constraints on NP
 - flavor structure of NP important for high p_T searches at the LHC

SENSITIVITY TO NEW PHYSICS

- sensitivity to NP from virtual corrections

- e.g. $b \rightarrow s l^+ l^-$

- NP contribs. scale as

$$\delta C^{\text{NP}} \propto \frac{\sin \theta_i \sin \theta_j}{M_{\text{NP}}^2}$$

- need to know mix. angles and NP masses

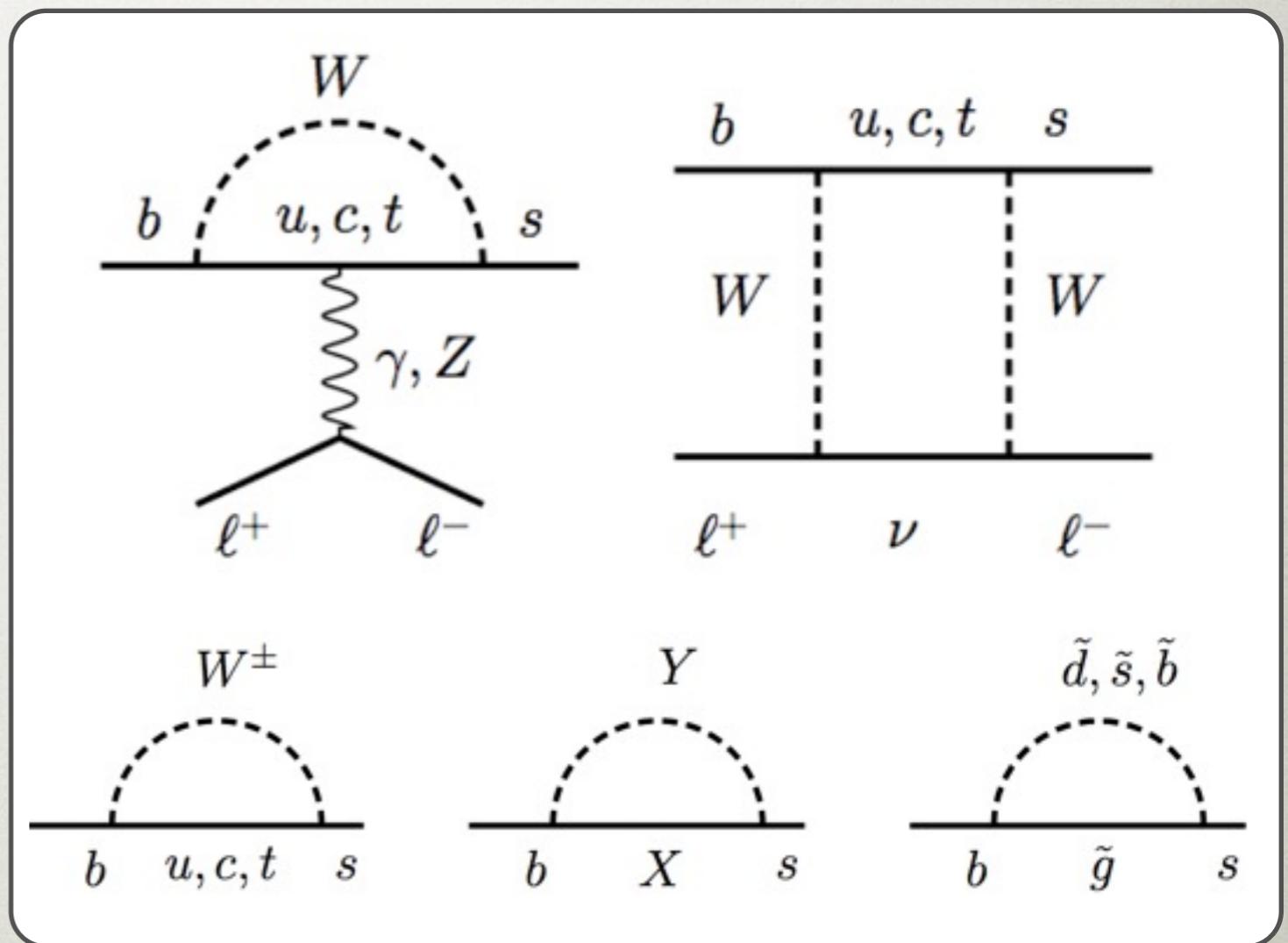
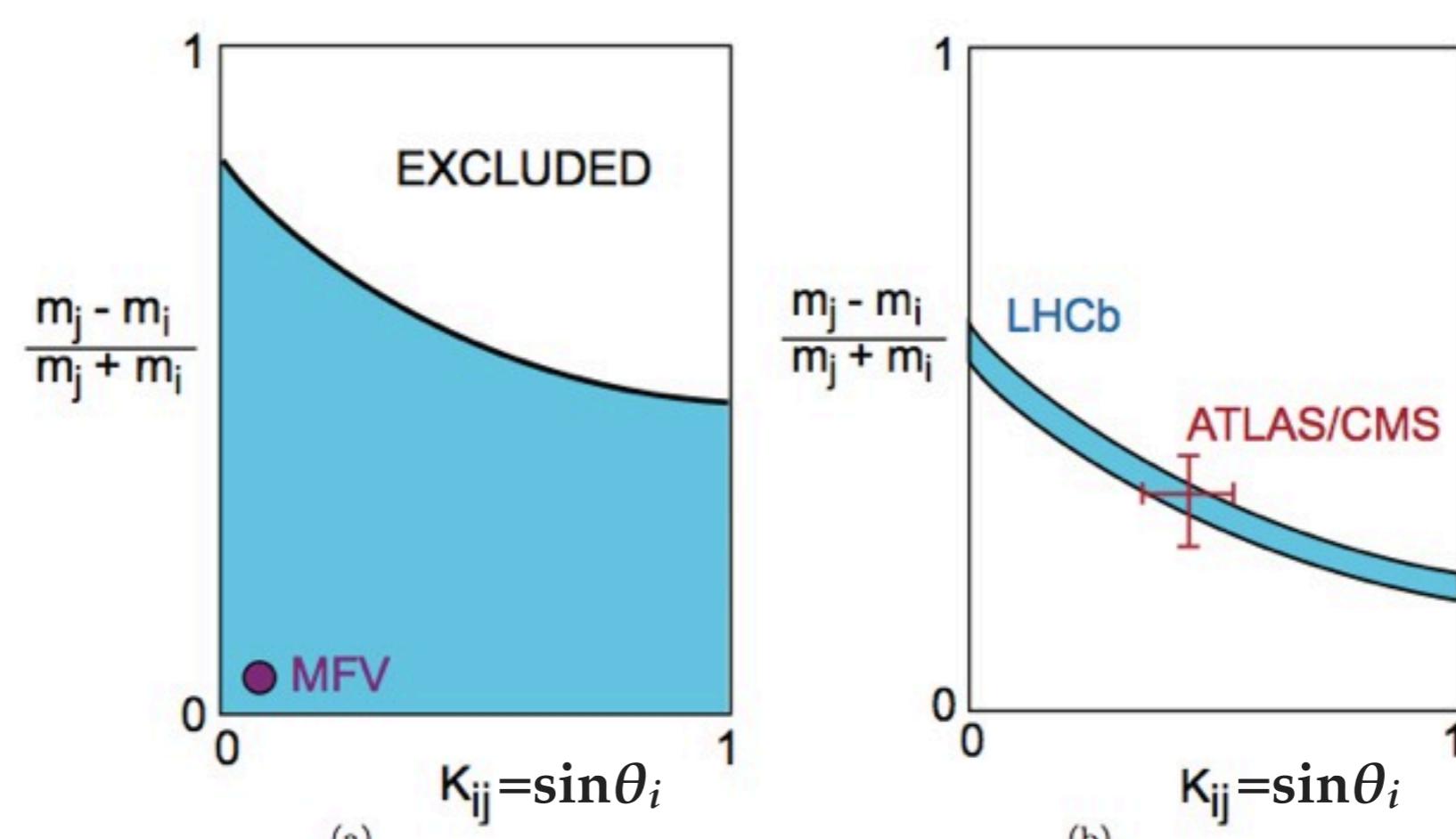


fig. from talk by G. Hiller at The First Three years of LHC,
Mainz, Mar 2013

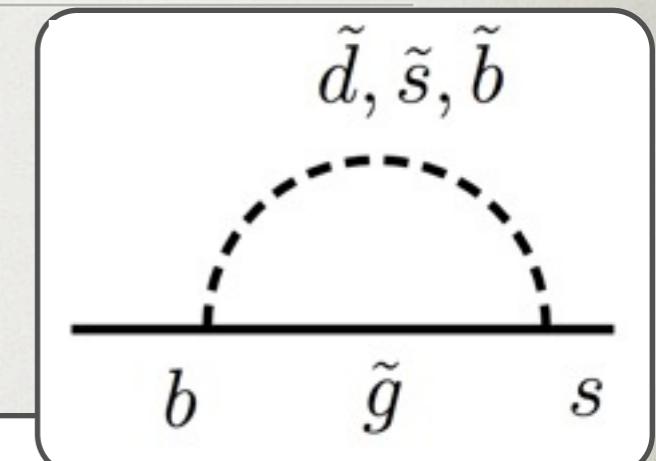
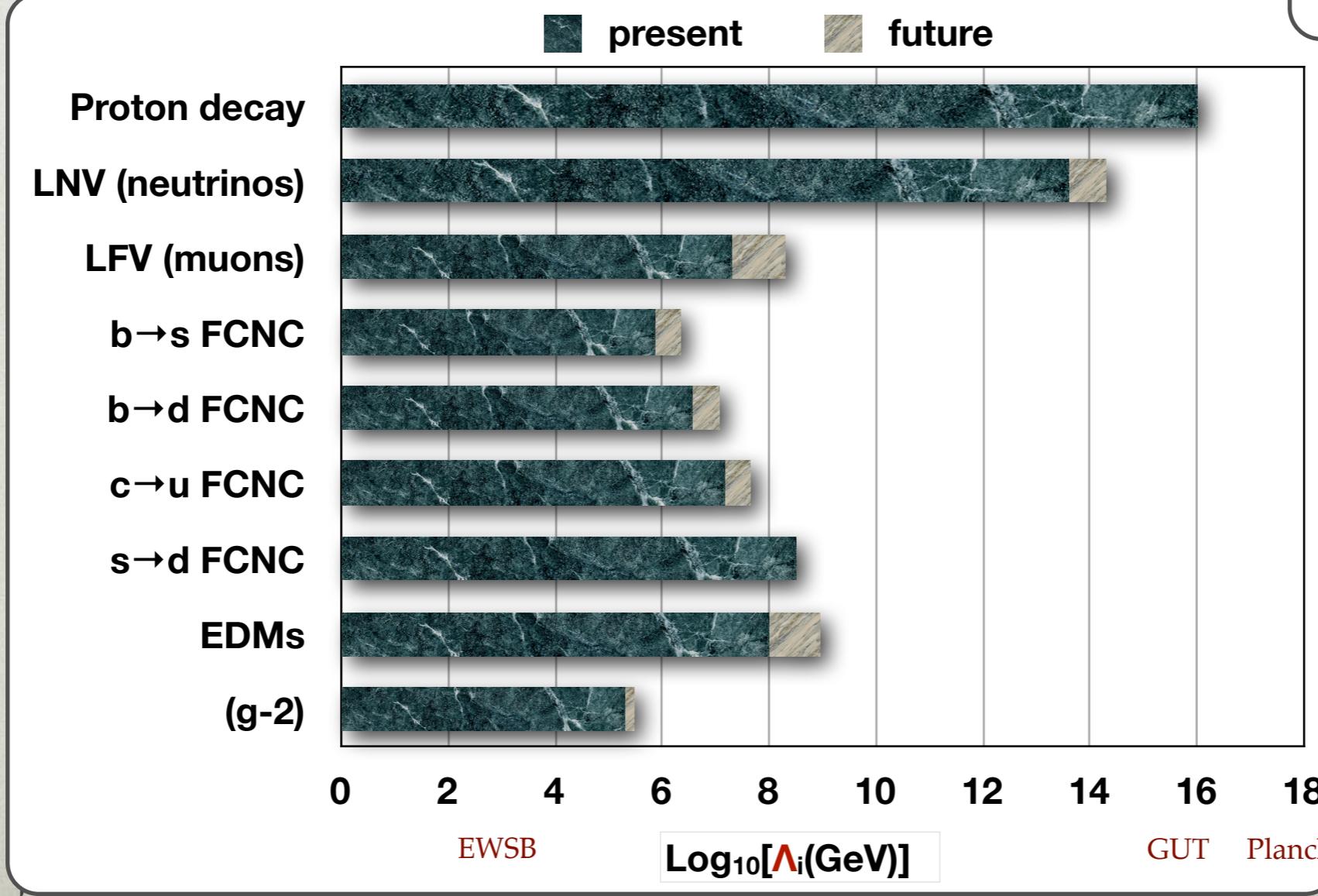
WHEN THERE IS A DISCOVERY...

- the dependence on mass and mixing different than in on-shell processes
- if new physics is discovered at LHC (or future collider)
 - would have orthogonal measurements from FCNCs



SENSITIVITY TO NP FROM VIRTUAL EFFECTS

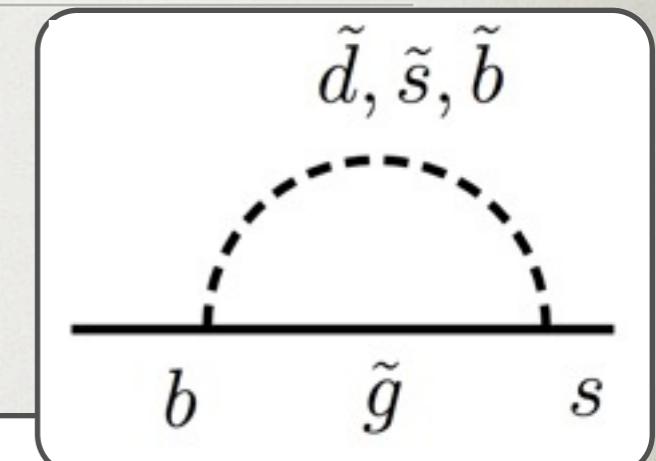
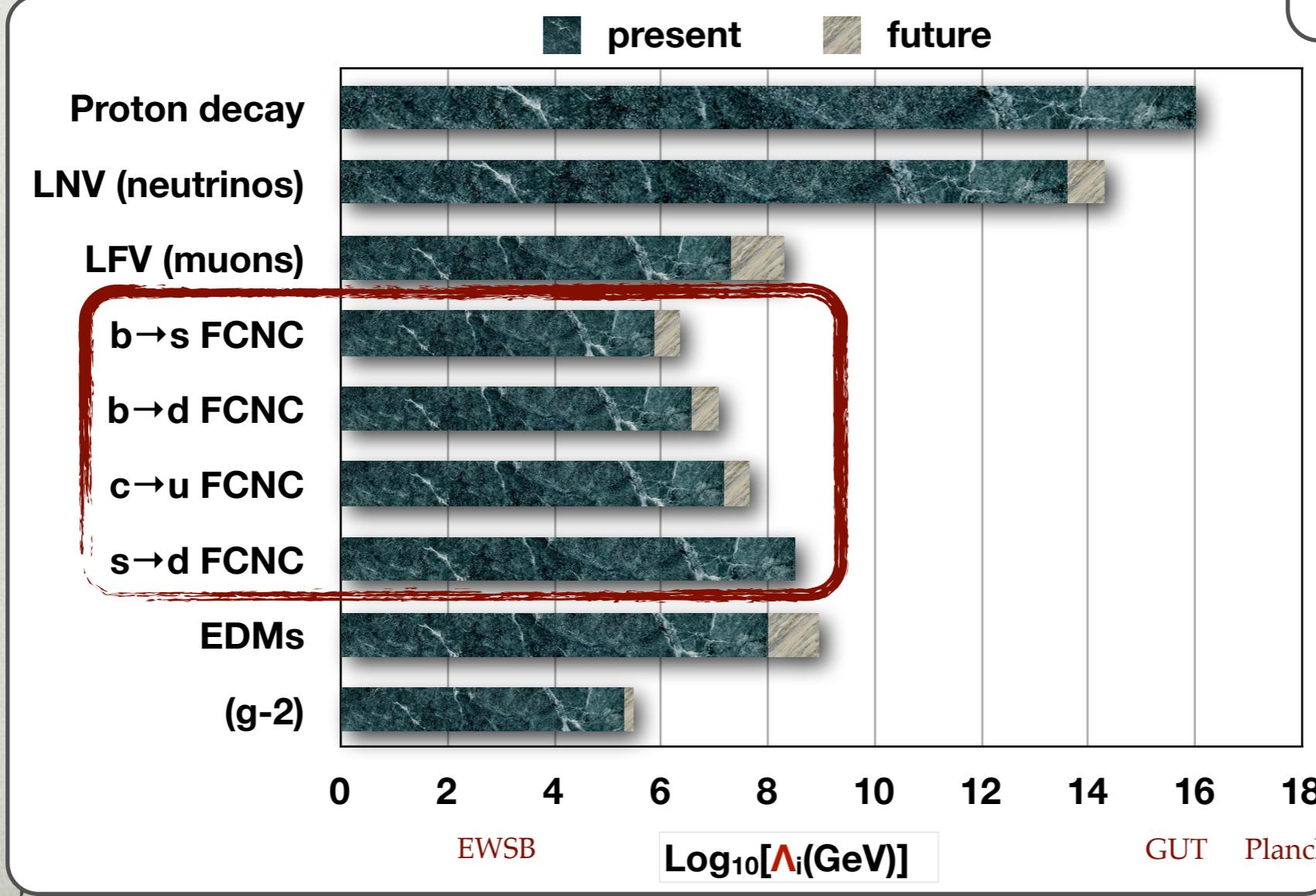
- for $O(1)$ mixing angles \Rightarrow high scales probed
- for heavy quarks: $b \rightarrow s$, $b \rightarrow d$, $c \rightarrow u$ FCNCs
 - if NP in the loops \Rightarrow probes EW scale masses



adapted from
 Fundamental Physics at
 the Intensity Frontier
[1205.2671](#);
 Cirigliano, Ramsey-
 Mussolf [1304.0017](#)
 July 1 2013

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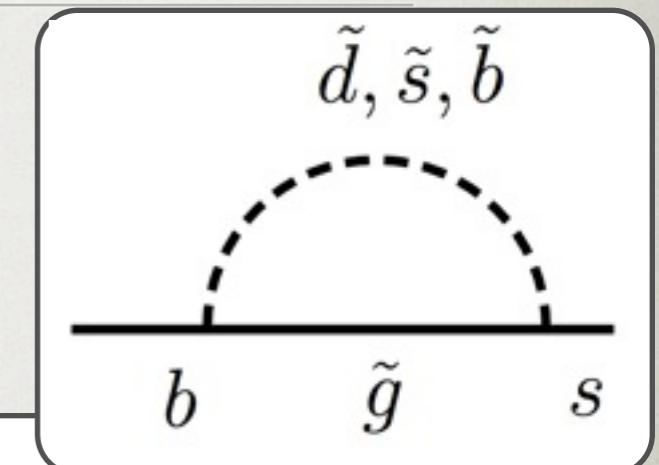
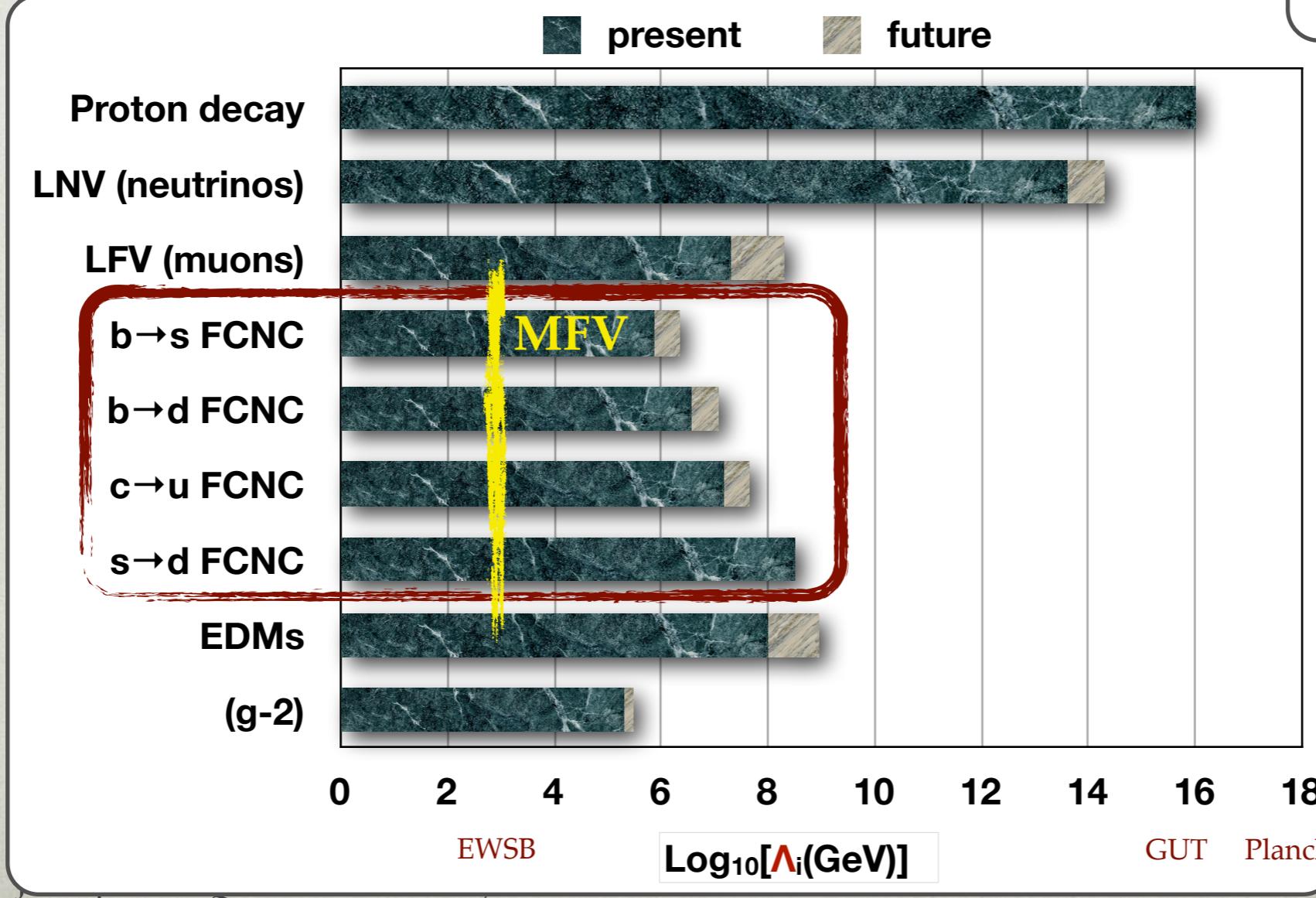
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The Experimental Quark Flavor Program

Kaons

- KLOE-2
- NA62
- TREK
- KOTO
- ORKA
- Project X experiments

B-physics

- Belle II
- LHCb + Upgrade
- ATLAS/CMS

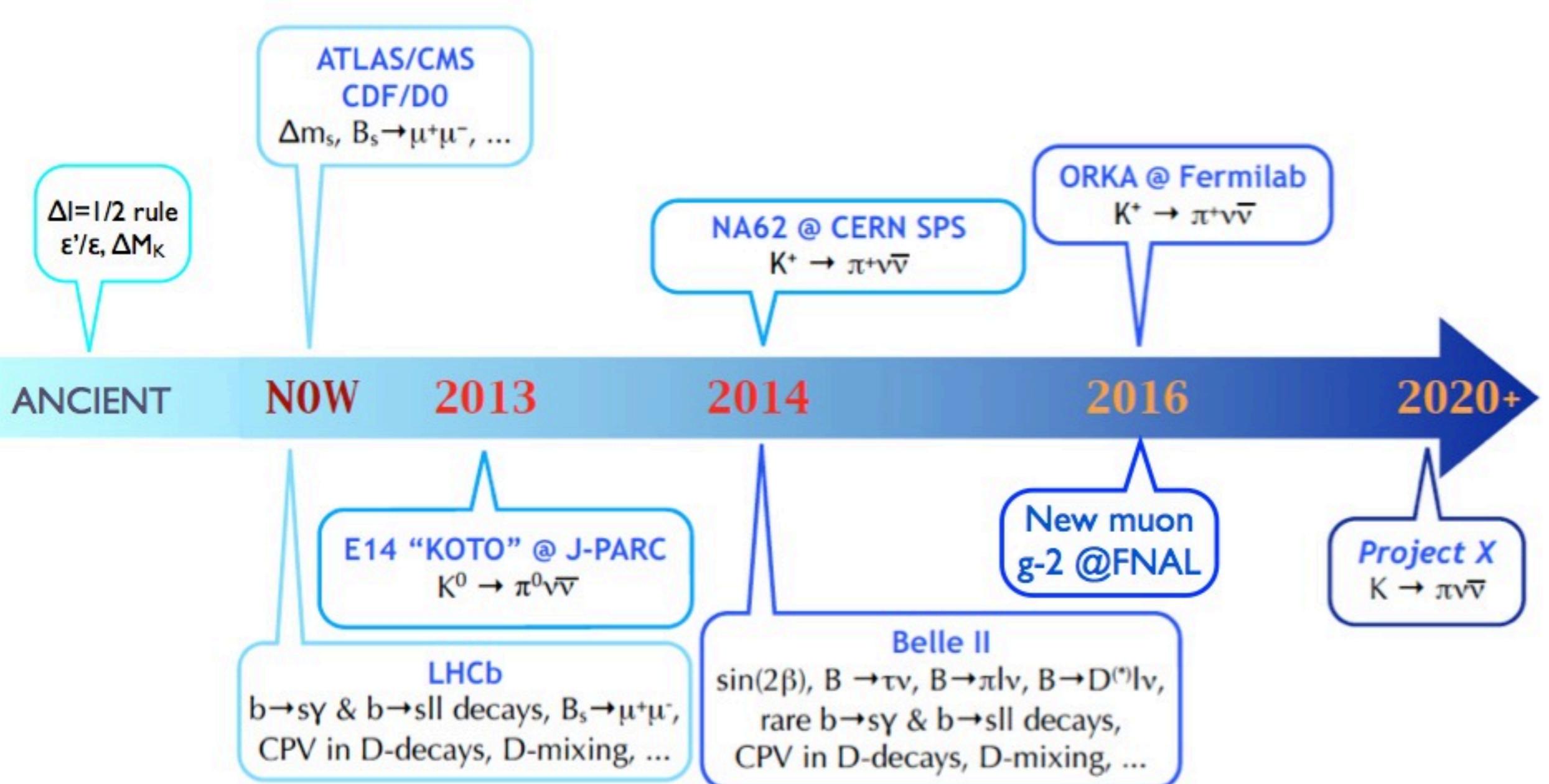
Proposed
in U.S.

Charm

- Belle II
- LHCb
- ATLAS/CMS
- BESIII
- Panda
- Future τ/c factories

There is not time to discuss everything in this talk.

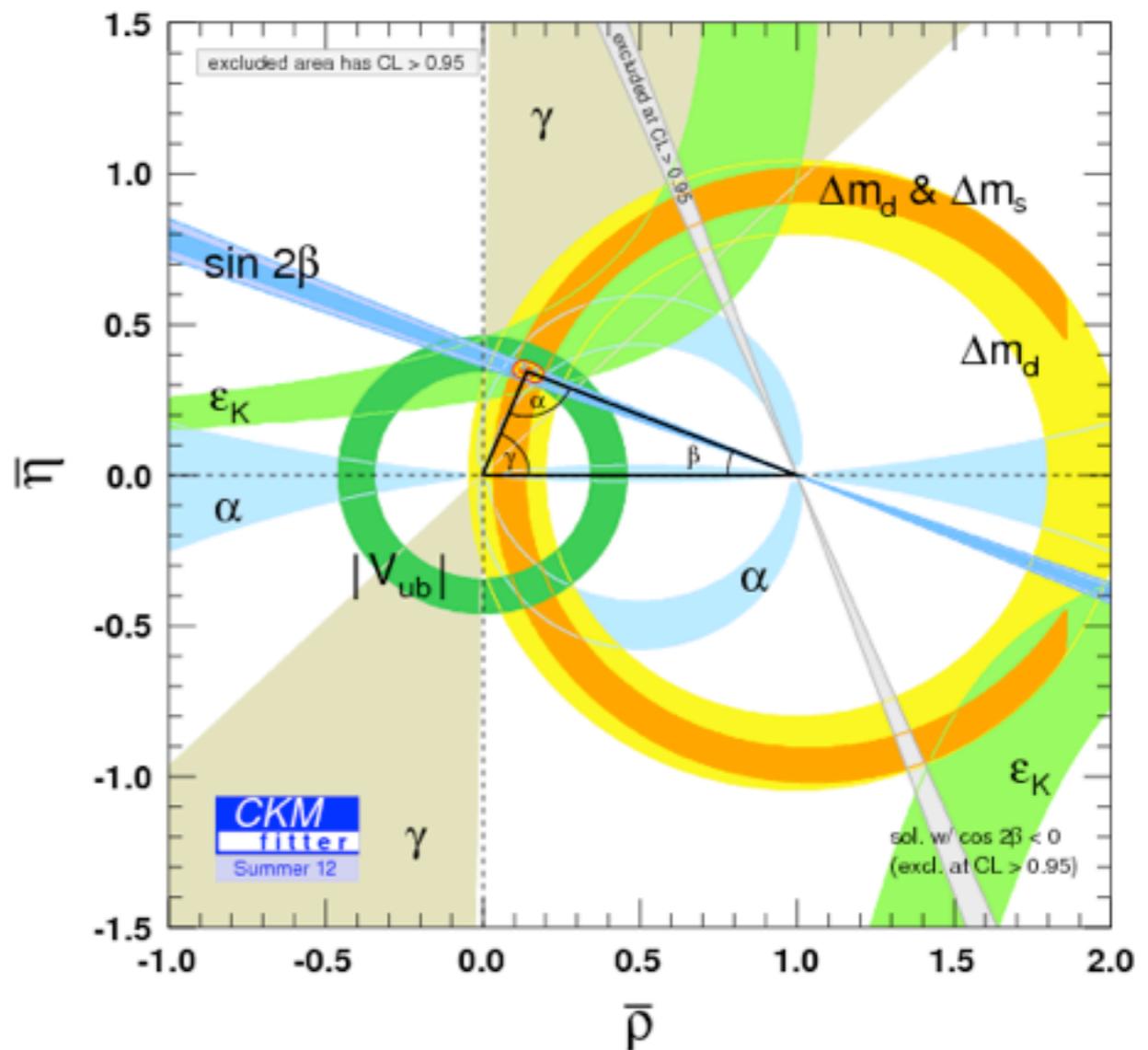
Experimental vista (partial & optimistic)



Adapted from Ruth Van de Water

STATUS OF THE CKM

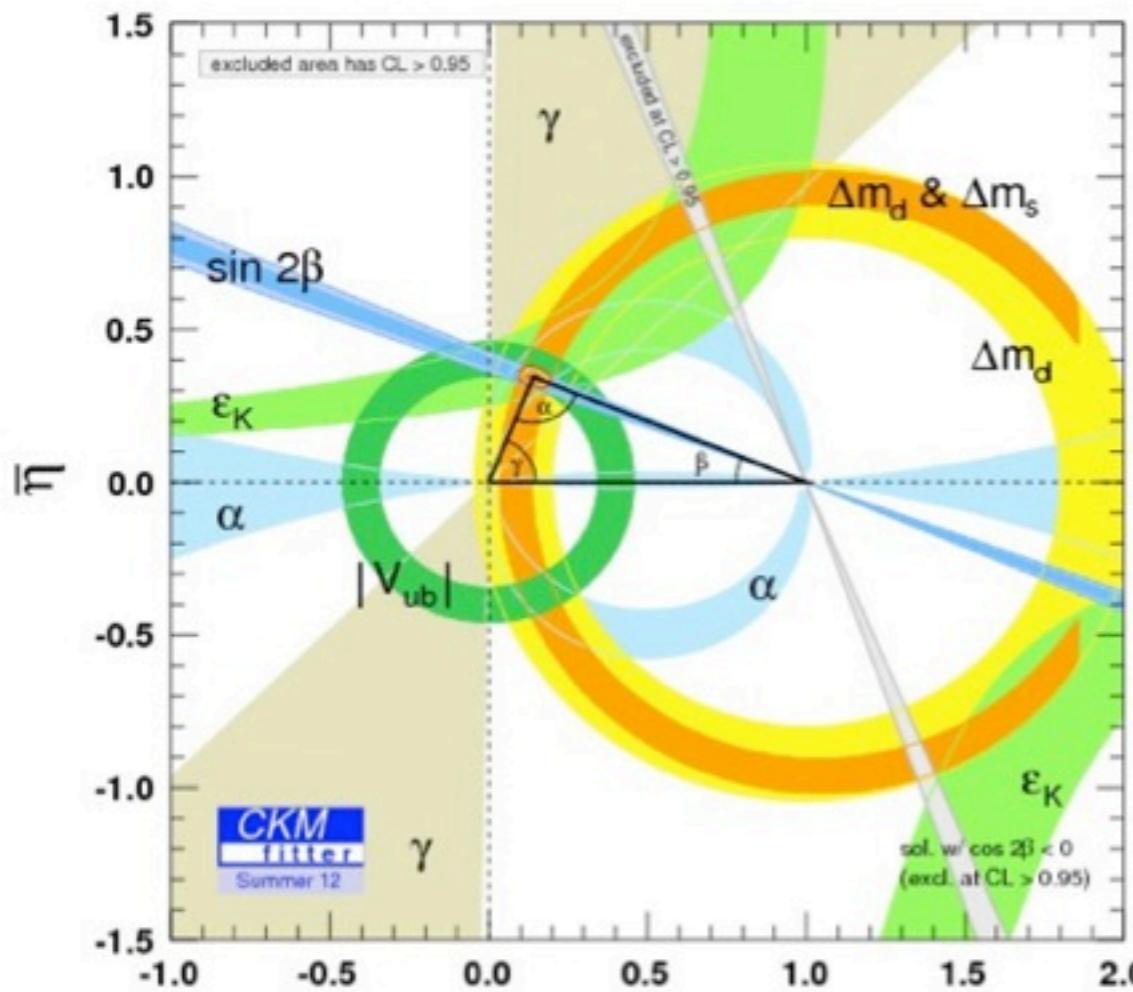
- status of the CKM measurements
 - $O(20\%)$ deviations from SM allowed
 - lesson of B factories and LHCb
 - if NP at \sim TeV it has to have nontrivial structure
 - one option: Minimal Flavor Violation
 - but does not have to be
 - RS Flavor, partial compositeness, etc



CKM IN THE FUTURE

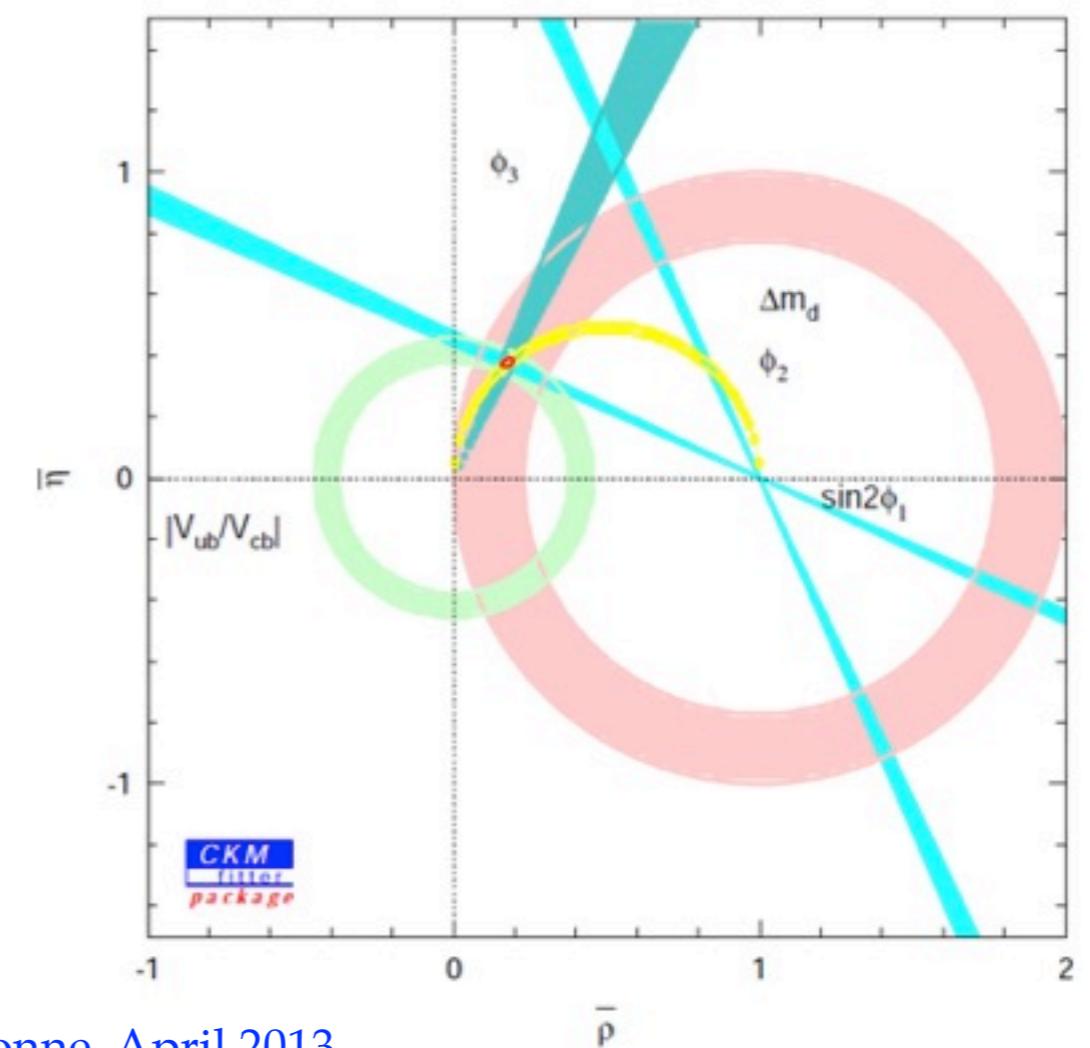
- CKM constraints will significantly improve

2012 ($\sim 1000 \text{ fb}^{-1}$ at Belle and BaBar)



Pilonen, talk at IF Snowmass, Argonne, April 2013

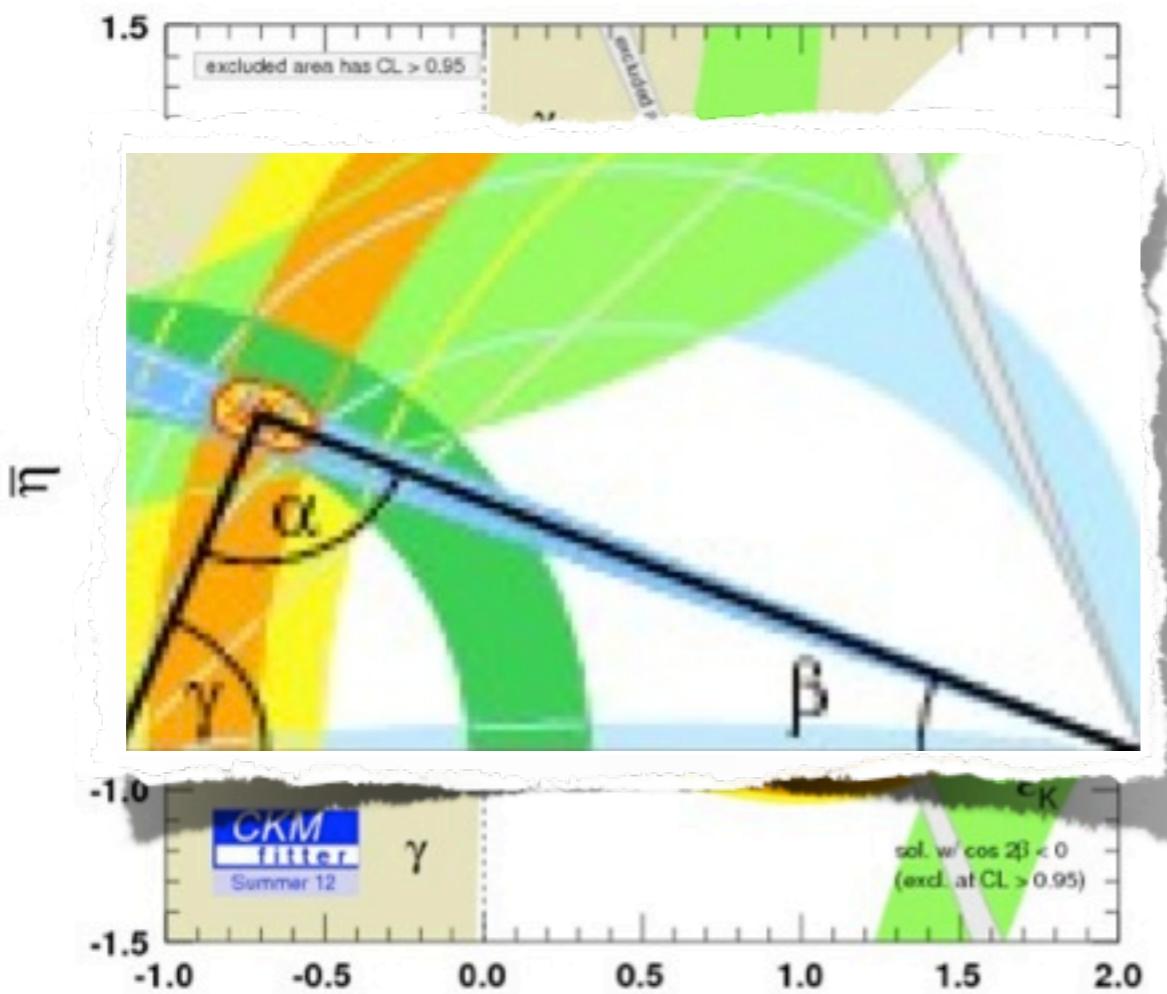
Expected constraint at 50 ab^{-1}
(Belle II)



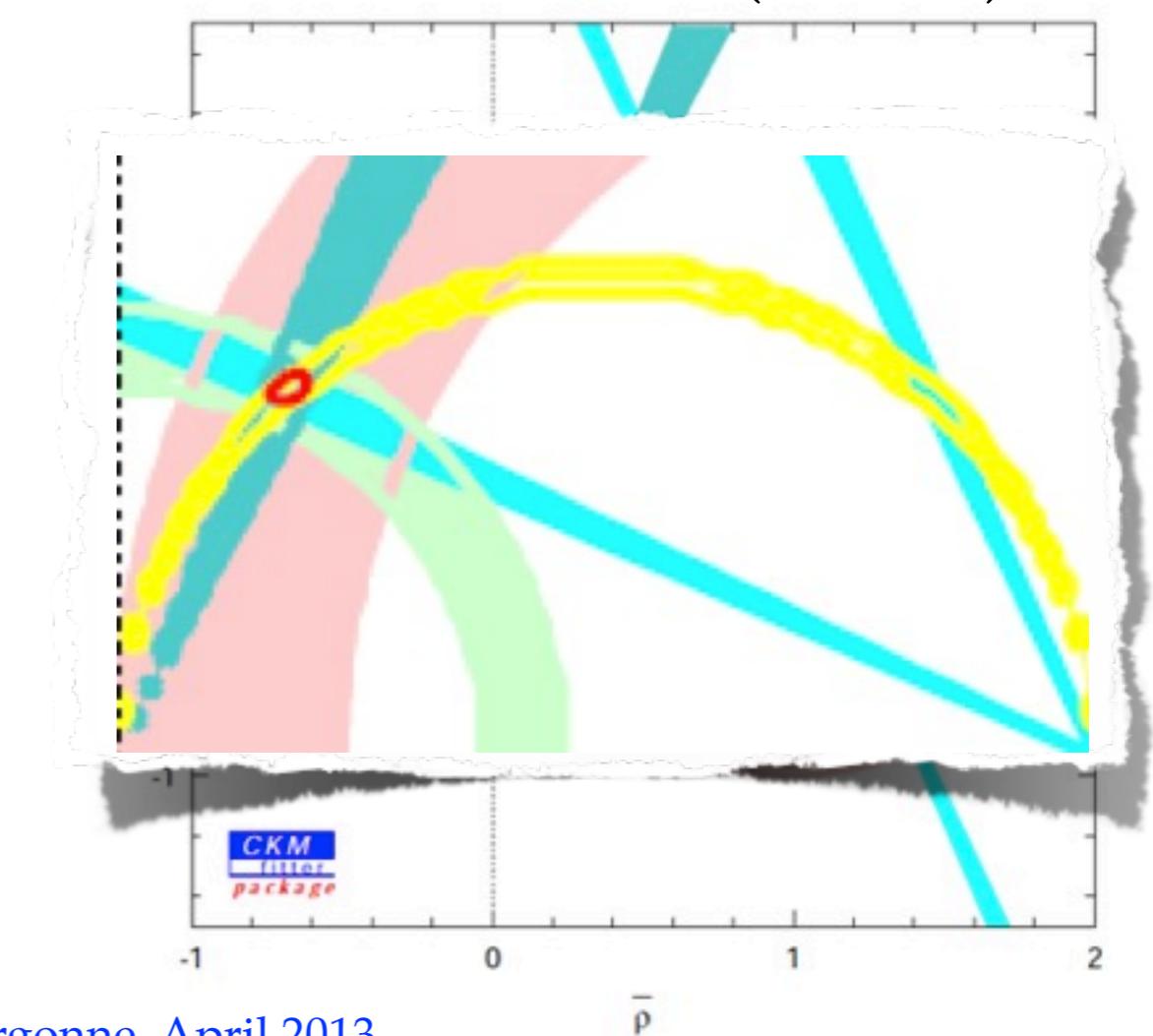
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THEORY ERRORS NOT SATURATED

- the real improvements in measrmnts. that not theory limited
 - many such modes: an example from LHCb upgrade study

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb ⁻¹)	Theory uncertainty
B_s^0 mixing	$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$	0.17 [214]	0.045	0.014	~ 0.01
	a_{s1}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\phi)$	—	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$	—	0.13	0.02	< 0.02
	$2\beta_s^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$	—	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$	—	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0 A_{\text{FB}}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	$\sim 10\%$
Higgs penguins	$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	—	$\sim 100\%$	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma (B \rightarrow D^{(*)}K^{(*)})$	$\sim 10\text{--}12^\circ$ [244, 258]	4°	0.9°	negligible
	$\gamma (B_s^0 \rightarrow D_s K)$	—	11°	2.0°	negligible
	$\beta (B^0 \rightarrow J/\psi K_s^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	—
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	—

LATTICE QCD

- an important input from lattice QCD
 - to interpret measurements. need hadronic matrix elements
 - significant improvements projected (+new observables)

TABLE I. History, status and future of selected LQCD calculations needed for the determination of CKM matrix elements. Forecasts from the 2007 white paper (where available) assumed computational resources of 10–50 TF years. Most present lattice results are taken from latticeaverages.org [28]. Other entries are discussed in the text. The quantity ξ is $f_{B_s}\sqrt{B_{B_s}}/(f_B\sqrt{B_B})$.

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2014 lattice error	2018 lattice error
f_K/f_π	$ V_{us} $	0.2%	0.5%	0.5%	0.3%	0.15%
$f_+^{K\pi}(0)$	$ V_{us} $	0.2%	–	0.5%	0.35%	0.2%
f_D	$ V_{cd} $	4.3%	5%	2%	1%	< 1%
f_{D_s}	$ V_{cs} $	2.1%	5%	2%	1%	< 1%
$D \rightarrow \pi \ell \nu$	$ V_{cd} $	2.6%	–	4.4%	3%	2%
$D \rightarrow K \ell \nu$	$ V_{cs} $	1.1%	–	2.5%	2%	1%
$B \rightarrow D^* \ell \nu$	$ V_{cb} $	1.3%	–	1.8%	1.5%	< 1%
$B \rightarrow \pi \ell \nu$	$ V_{ub} $	4.1%	–	8.7%	4%	2%
f_B	$ V_{ub} $	9%	–	2.5%	1.5%	< 1%
ξ	$ V_{ts}/V_{td} $	0.4%	2-4%	4%	1.5%	< 1%
ΔM_s	$ V_{ts} V_{tb} ^2$	0.24%	7-12%	11%	8%	5%
B_K	$\text{Im}(V_{td}^2)$	0.5%	3.5-6%	1.3%	1%	< 1%

MANY CHANNELS, MANY OBSERVABLES...

- feels like we can't see the forest for the trees



- what is important?
 - how big of a progress can we make
 - are observables sensitive to new physics
- will go through a few examples

A FEW EXAMPLES

- rare kaon decays
- impact of $B_s \rightarrow \mu\mu$
- $b \rightarrow s l^+ l^-$
- constraints on mini-split SUSY

RARE KAON DECAYS

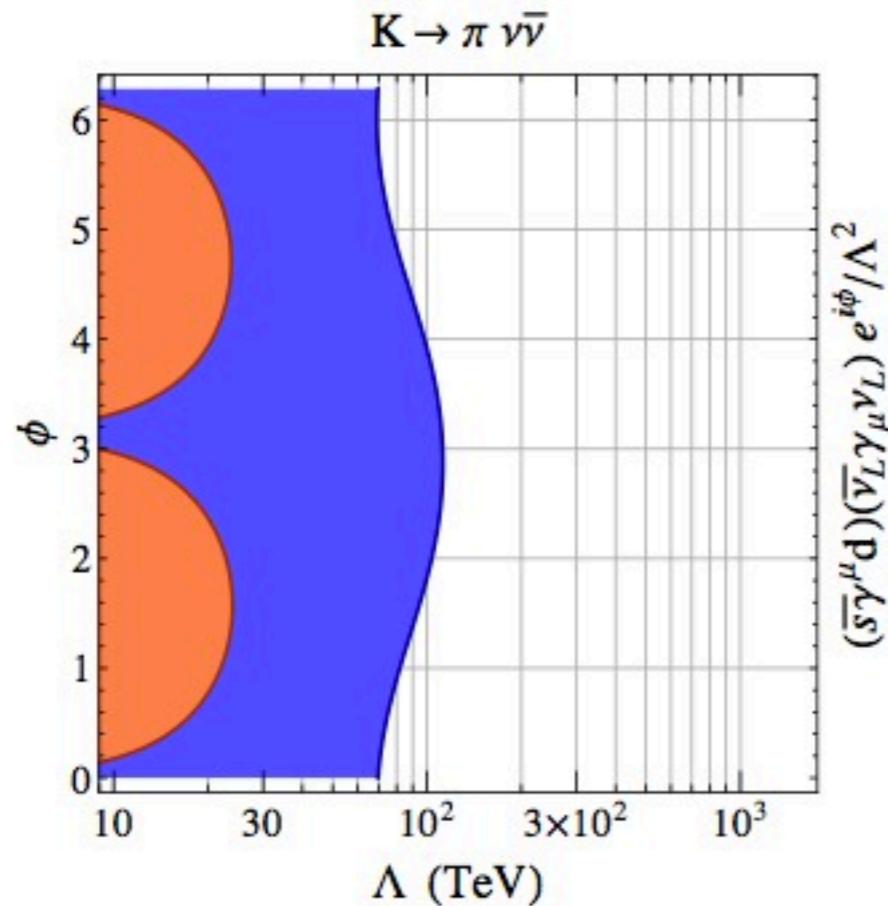
- an example: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ precise theoretical predictions
 - O(10%) relative errors, mostly from CKMs
 - high sensitivity to NP

	Standard Model	generic New Physics
$s \rightarrow d$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{ts} V_{td}^* \simeq \frac{1}{(130 \text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$
$b \rightarrow d$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{tb} V_{td}^* \simeq \frac{1}{(26 \text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$
$b \rightarrow s$	$\sim \frac{g_2^4}{16\pi^2} \frac{1}{M_W^2} V_{tb} V_{ts}^* \simeq \frac{1}{(12 \text{ TeV})^2}$	$\sim \frac{1}{M_X^2}$

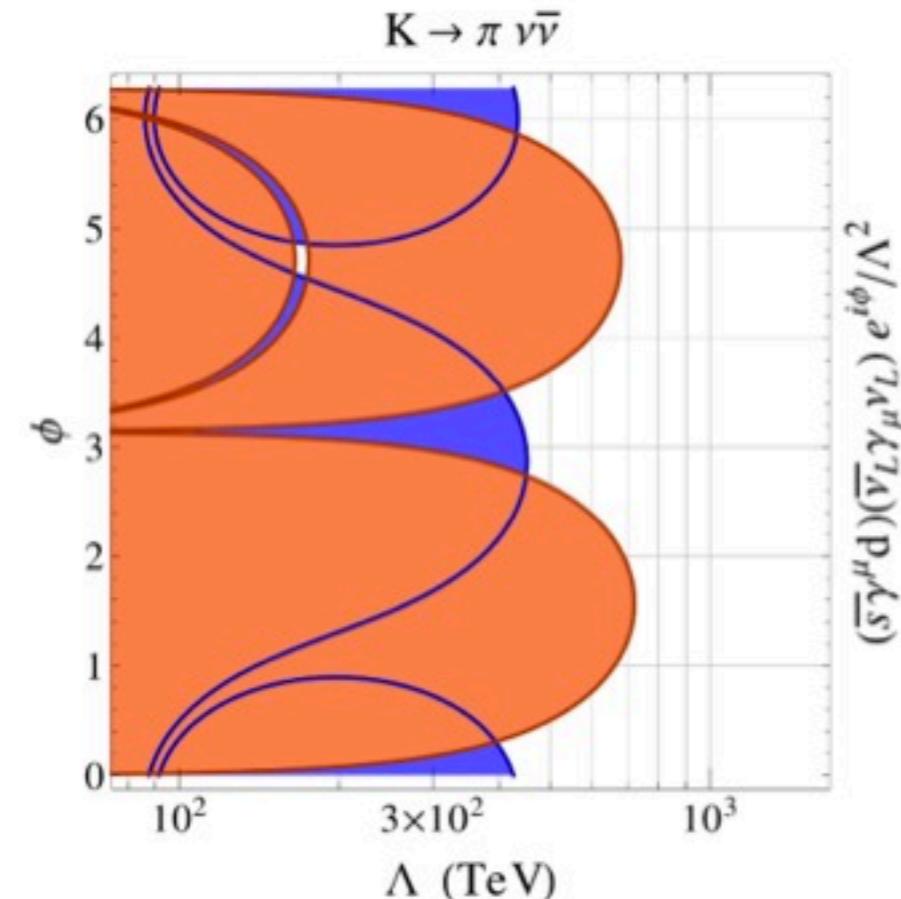
A. Altmannshofer, talk at IF Snowmass, Argonne, April 2013

IMPACT OF POTENTIAL FUTURE MEASUREMENTS

current situation



assuming 5% measurements of both modes



- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ already constrains scales of ~ 100 TeV
- $K_L \rightarrow \pi^0 \nu\bar{\nu}$ bound still above the Grossman-Nir bound
→ no additional constraint

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ give complementary information
- scales of order 700 TeV are probed

A. Altmannshofer, talk at IF Snowmass, Argonne, April 2013

Prospects for $K \rightarrow \pi \nu \bar{\nu}$

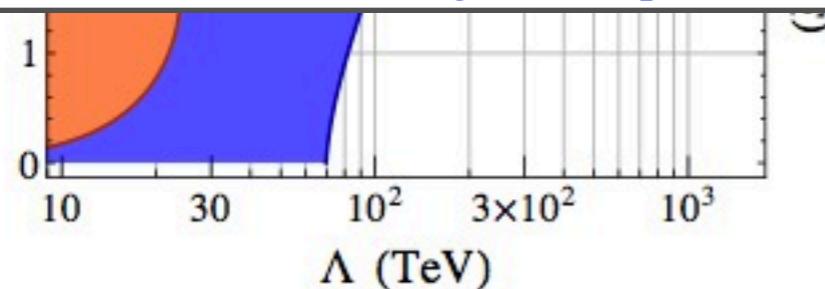
$$\text{E787/E949: } \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Goals	NA62	ORKA	PX
Events/yr	40	200	340
S/B	5	5	5
Precision	10%	5%	3%

$$\text{E391a: } \mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$$

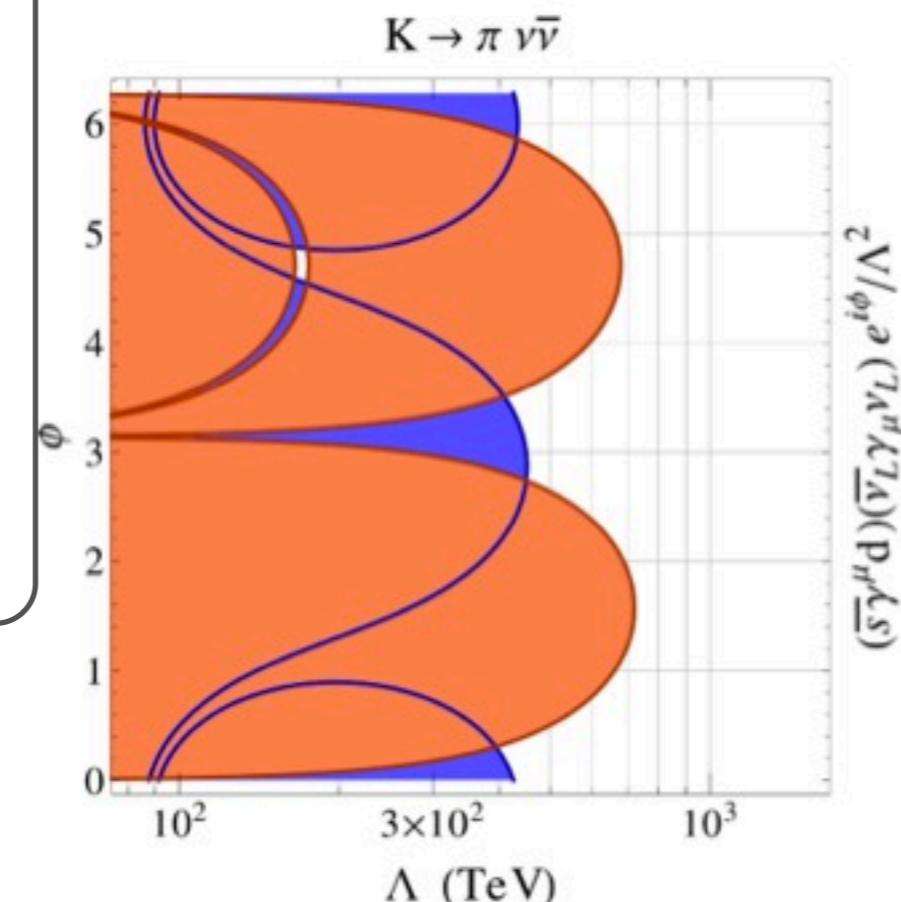
Goals	KOTO*	PX
Events/yr	1	"200"
S/B	1	5-10
Precision		5%

* Phase II with higher sensitivity planned.



POTENTIAL MEASUREMENTS

Assuming 5% measurements of both modes



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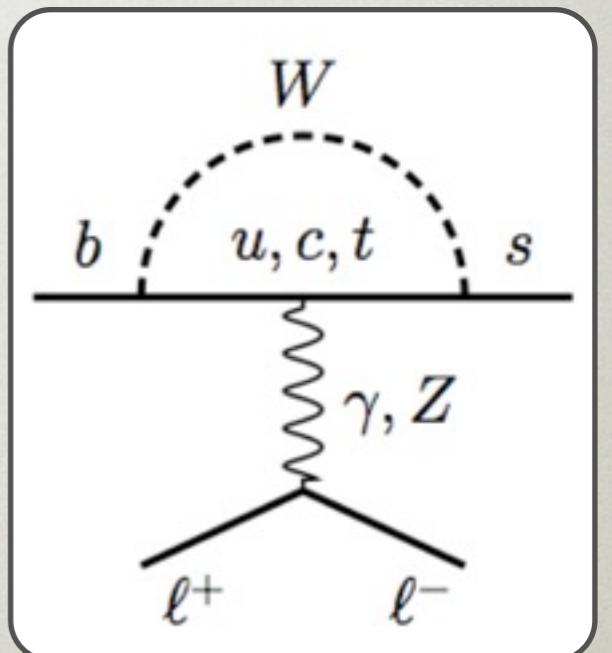
$B_s \rightarrow \mu\mu$

- exp. and SM agree within error

$$\overline{\mathcal{B}}^{\text{exp}} = (3.2_{-1.2}^{+1.5}) \times 10^{-9}$$

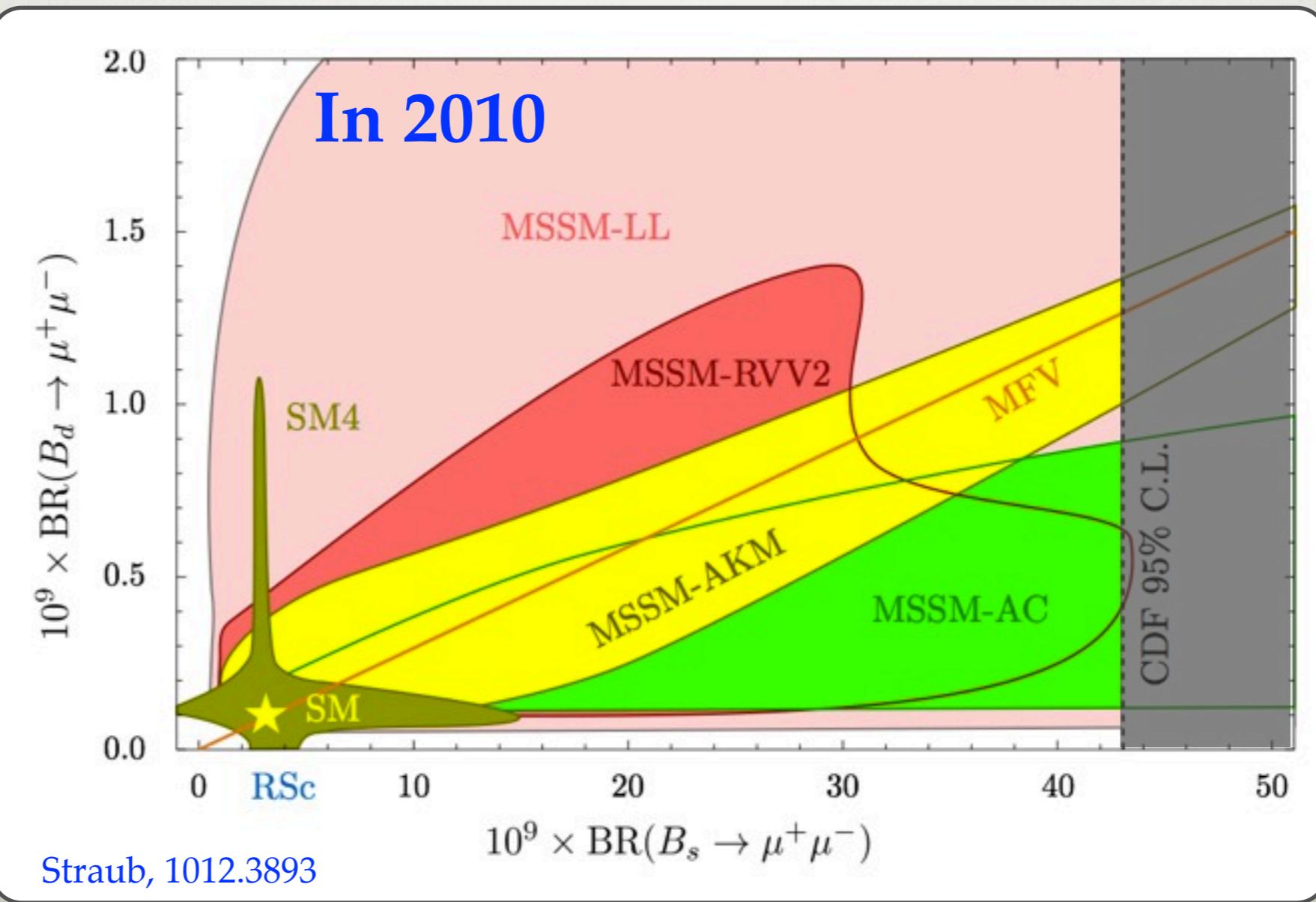
$$\overline{\mathcal{B}}_{\text{SM}}^{\text{th}} = (3.54 \pm 0.30) \times 10^{-9}$$

- double suppression in the SM
 - FCNC current \Rightarrow loop level only
 - strong helicity suppression
- probes extended Higgs sector
- very precise
 - e.g. comparing to Z- bb coupling



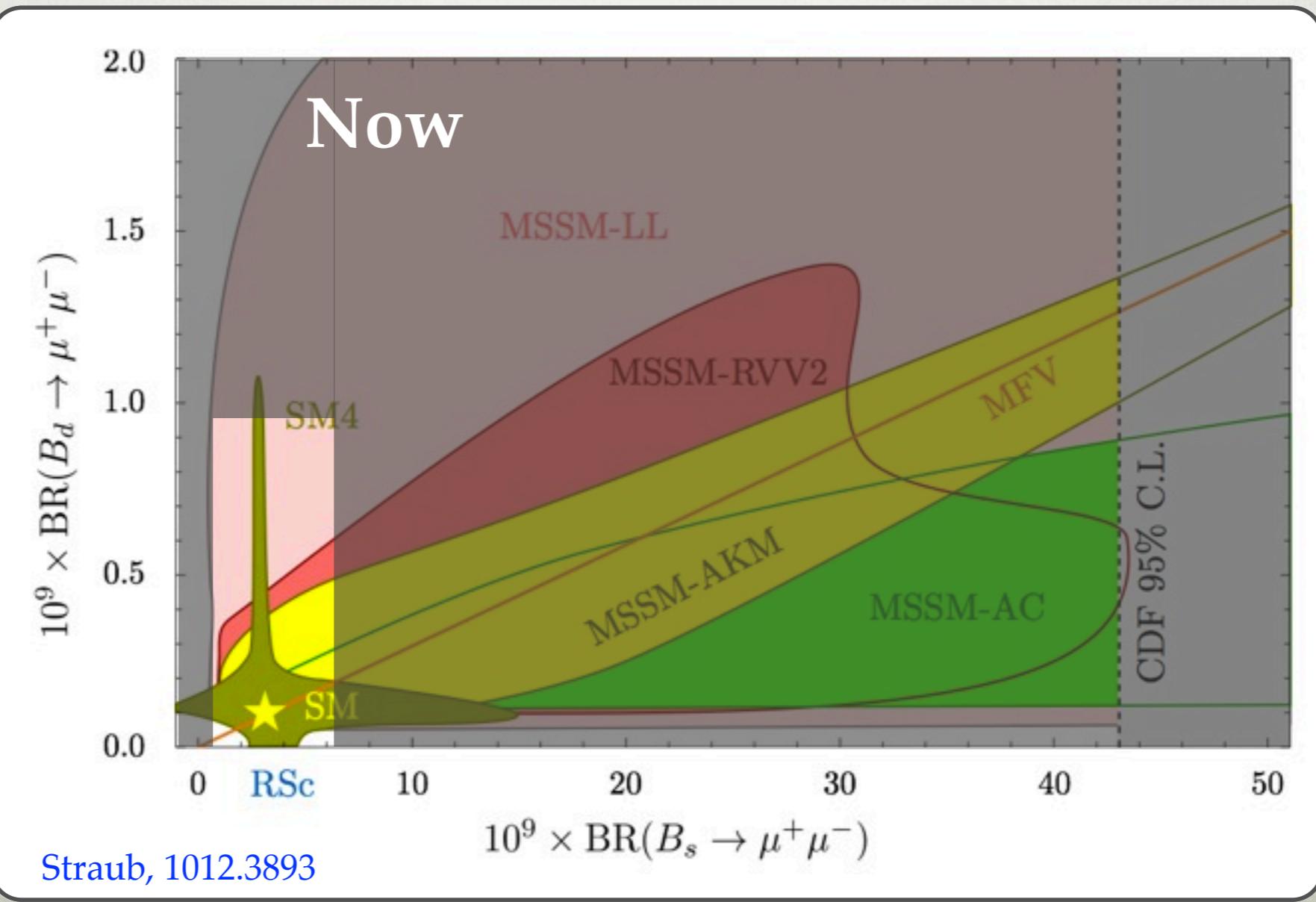
IMPACT OF $B_s \rightarrow \mu\mu$

- flavor constraints for a long time a very important input in model building
- still true now, as an example: the impact of $B_s \rightarrow \mu\mu$



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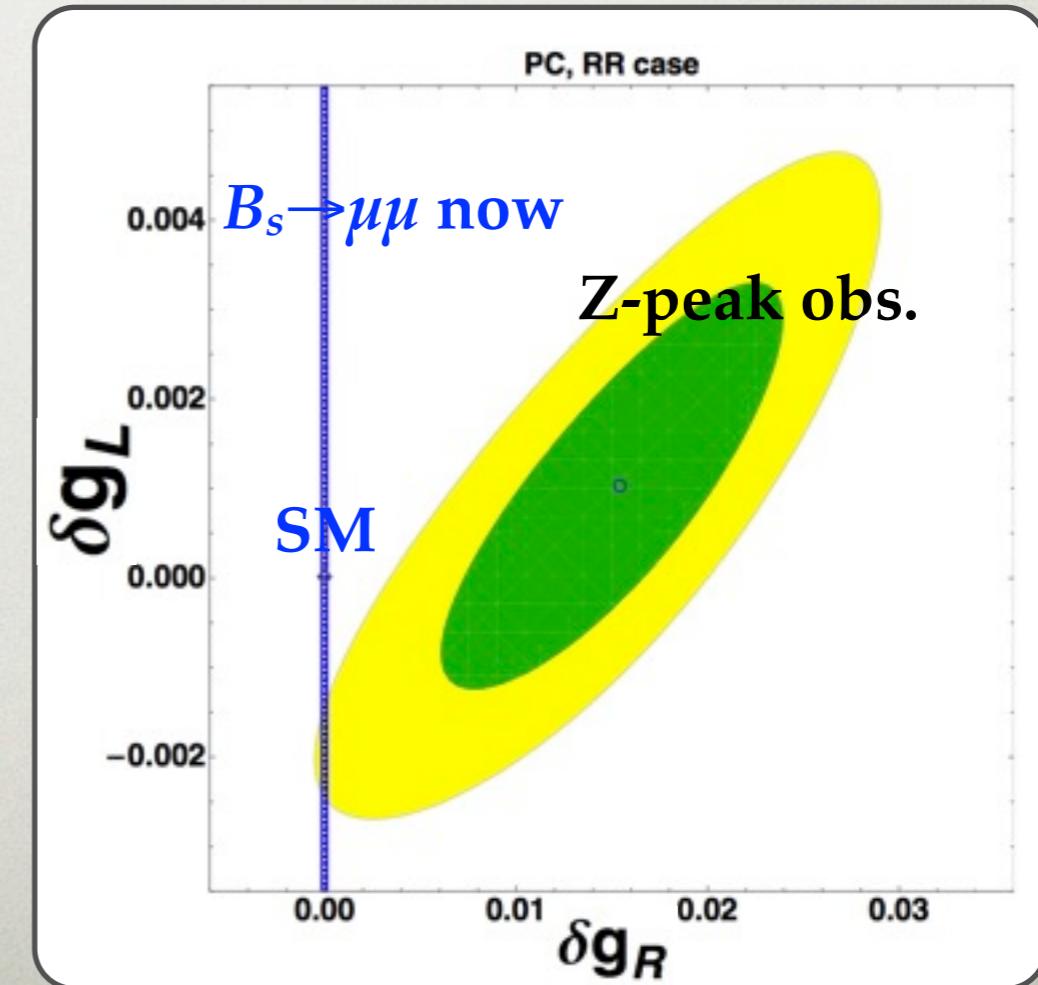
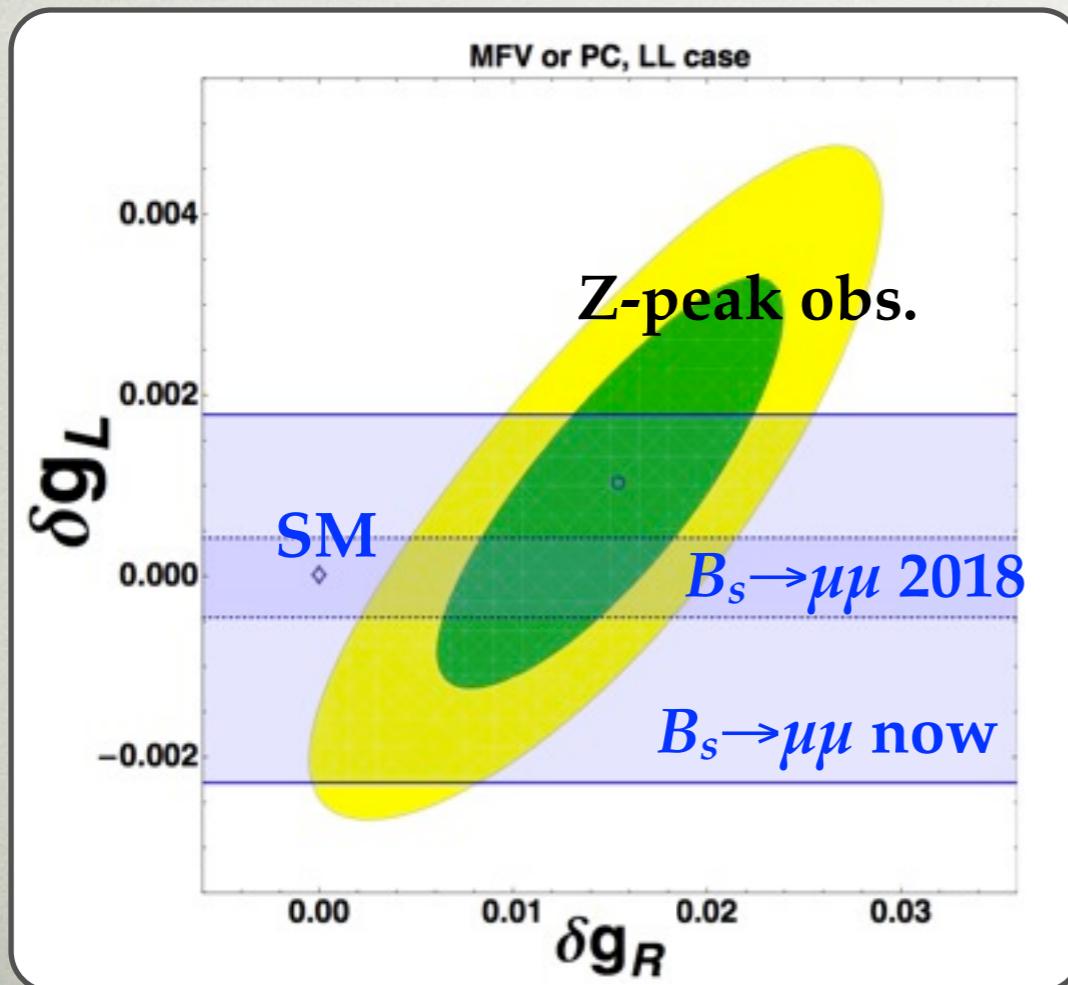
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$B_s \rightarrow \mu\mu$ AND MODIFIED Z COUPLINGS

- these are very precise measurements Guadagnoli, Isidori, 1302.3909
- if one fixes flavor model, can compare FV and FC inter.
- e.g., modified Z cplng. for MFV or partial composit. (PC)

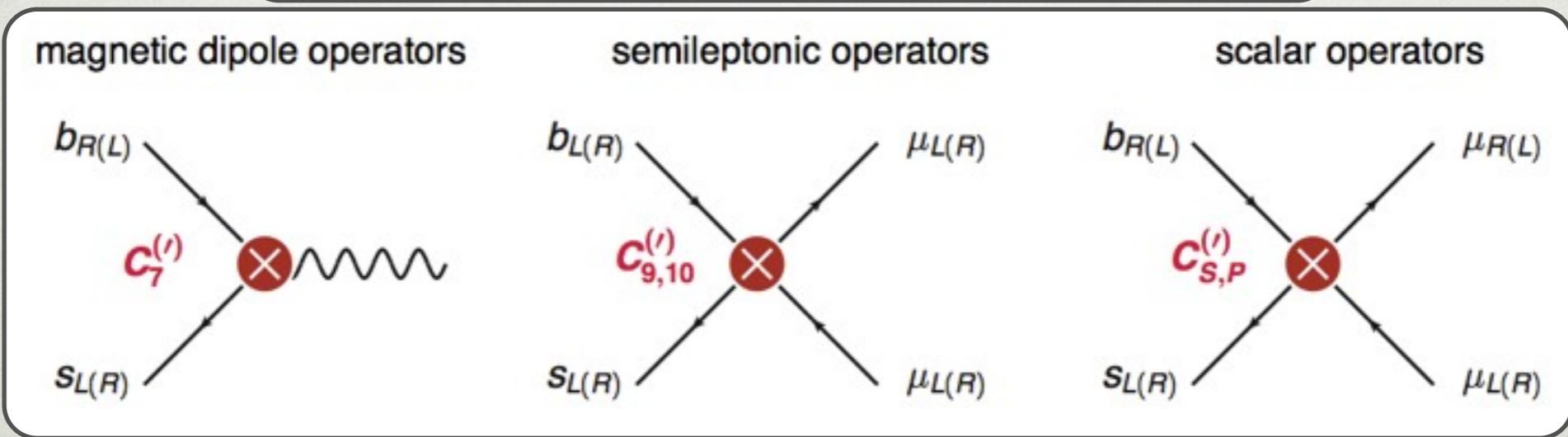
$$\mathcal{L}_{\text{eff}}^Z = \frac{g}{c_W} Z_\mu \bar{d}^i \gamma^\mu \left[(g_L^{ij} + \delta g_L^{ij}) P_L + (g_R^{ij} + \delta g_R^{ij}) P_R \right] d^j$$



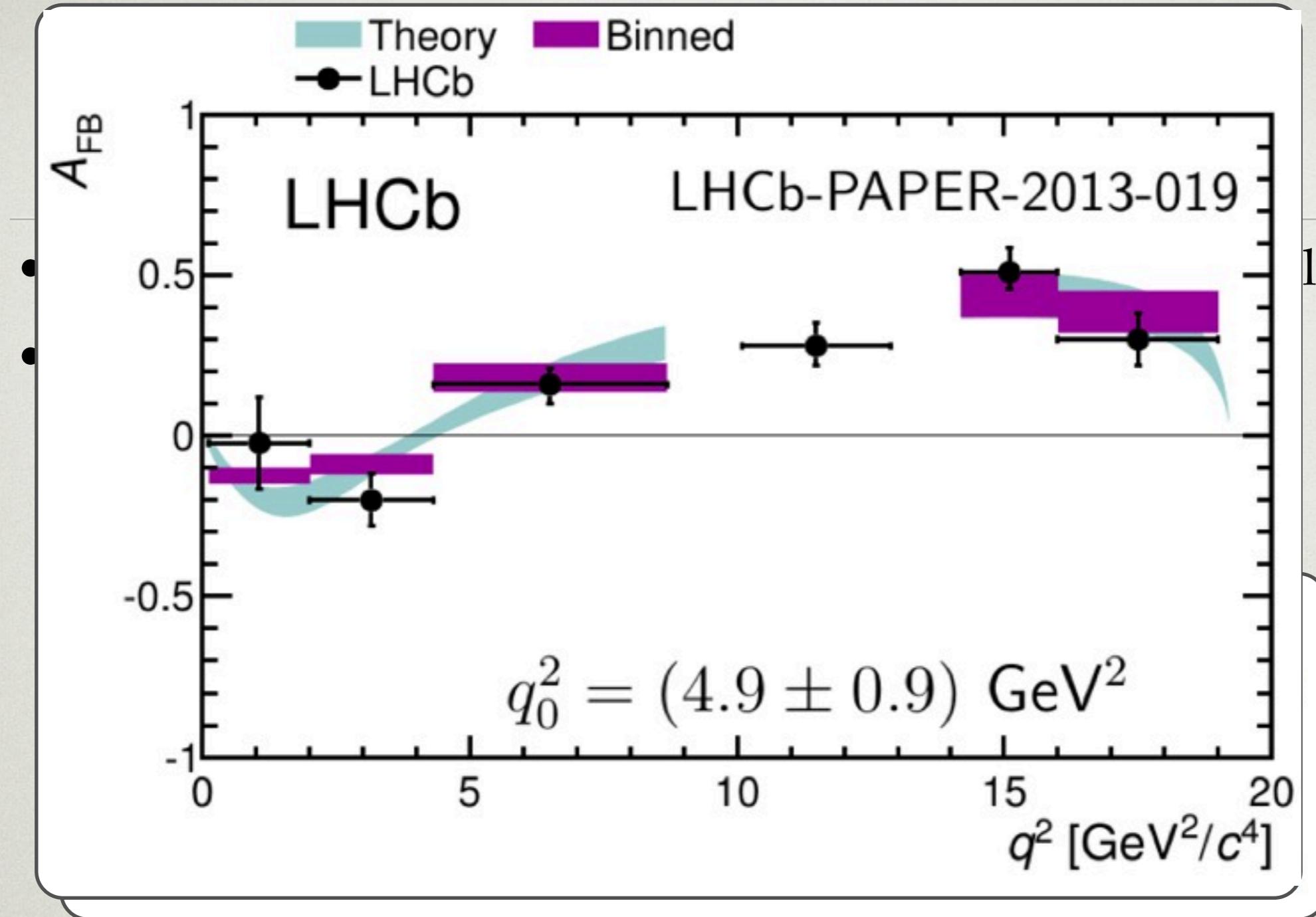
OTHER $b \rightarrow s l^+ l^-$ DECAYS

- much more information in other $b \rightarrow s l^+ l^-$ decays as well
- progress possible on the theory side

$$\mathcal{H}_{\text{eff}}^{b \rightarrow s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i)$$

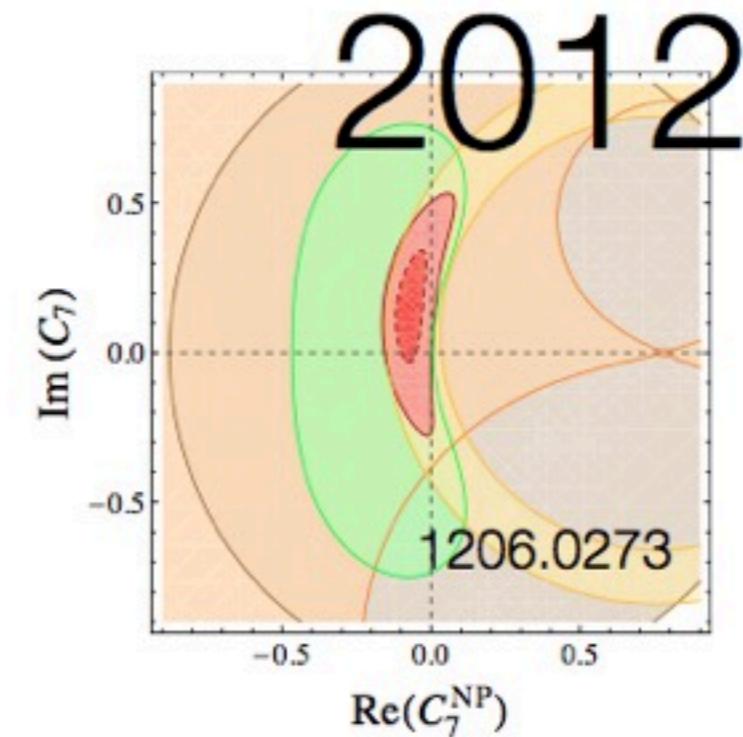
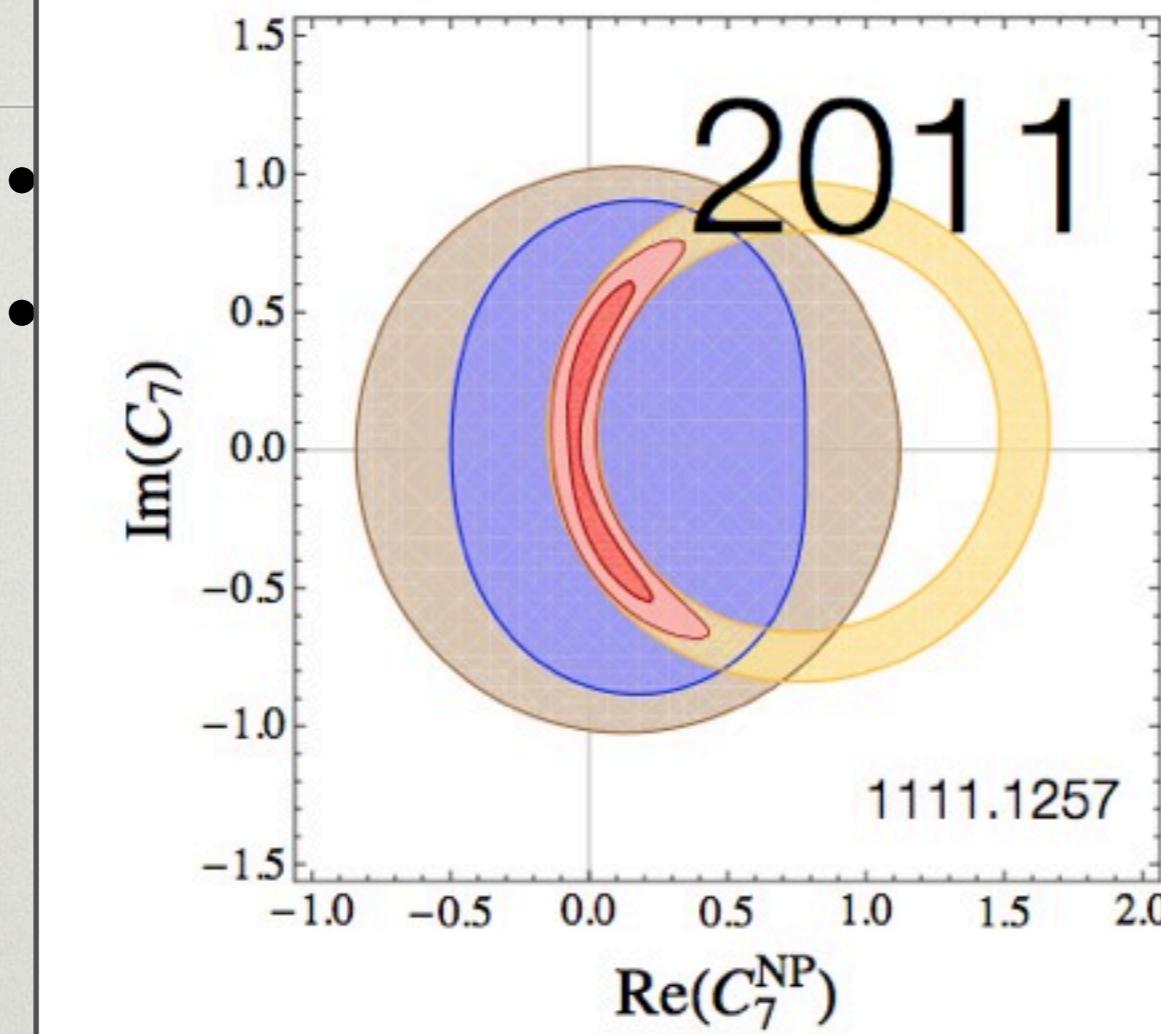


	C_7, C'_7	C_9, C'_9	C_{10}, C'_{10}	C_S, C'_S, C_P, C'_P
$B \rightarrow (X_s, K^*) \gamma$	★			
$B \rightarrow (X_s, K, K^*) \ell^+ \ell^-$	★	★	★	(★)
$B_s \rightarrow \mu^+ \mu^-$			★	★



	C_7, C'_7	C_9, C'_9	C_{10}, C'_{10}	C_S, C'_S, C_P, C'_P
$B \rightarrow (X_s, K^*) \gamma$	★			
$B \rightarrow (X_s, K, K^*) \ell^+ \ell^-$	★	★	★	(★)
$B_s \rightarrow \mu^+ \mu^-$			★	★

Impact of A_{FB} in $B \rightarrow K^* \ell^+ \ell^-$



$B \rightarrow X_s \ell^+ \ell^-$

$B \rightarrow K^* \ell^+ \ell^-$

$B \rightarrow X_s \gamma$

J. Kamenik, talk at Lepton-Photon 2013

$B \rightarrow (X_s, K, K^*) \ell^+ \ell^-$



(★)

$B_s \rightarrow \mu^+ \mu^-$

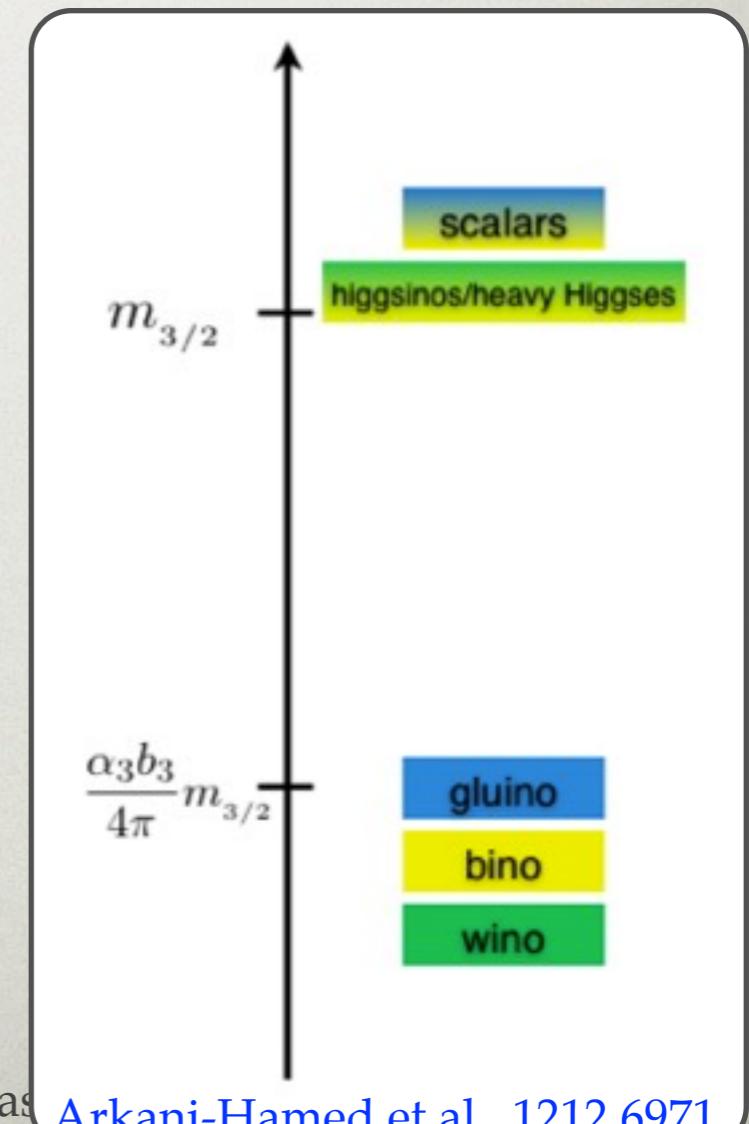


MINI-SPLIT SUSY

- another example: simply unnatural SUSY (or mini-split SUSY)

Arvanitaki et al., 1210.0555
Arkani-Hamed et al., 1212.6971
J. Wells, hep-ph/0306127
Giudice, Luty, Murayama, Rattazzi, [hep-ph/9810442](#)

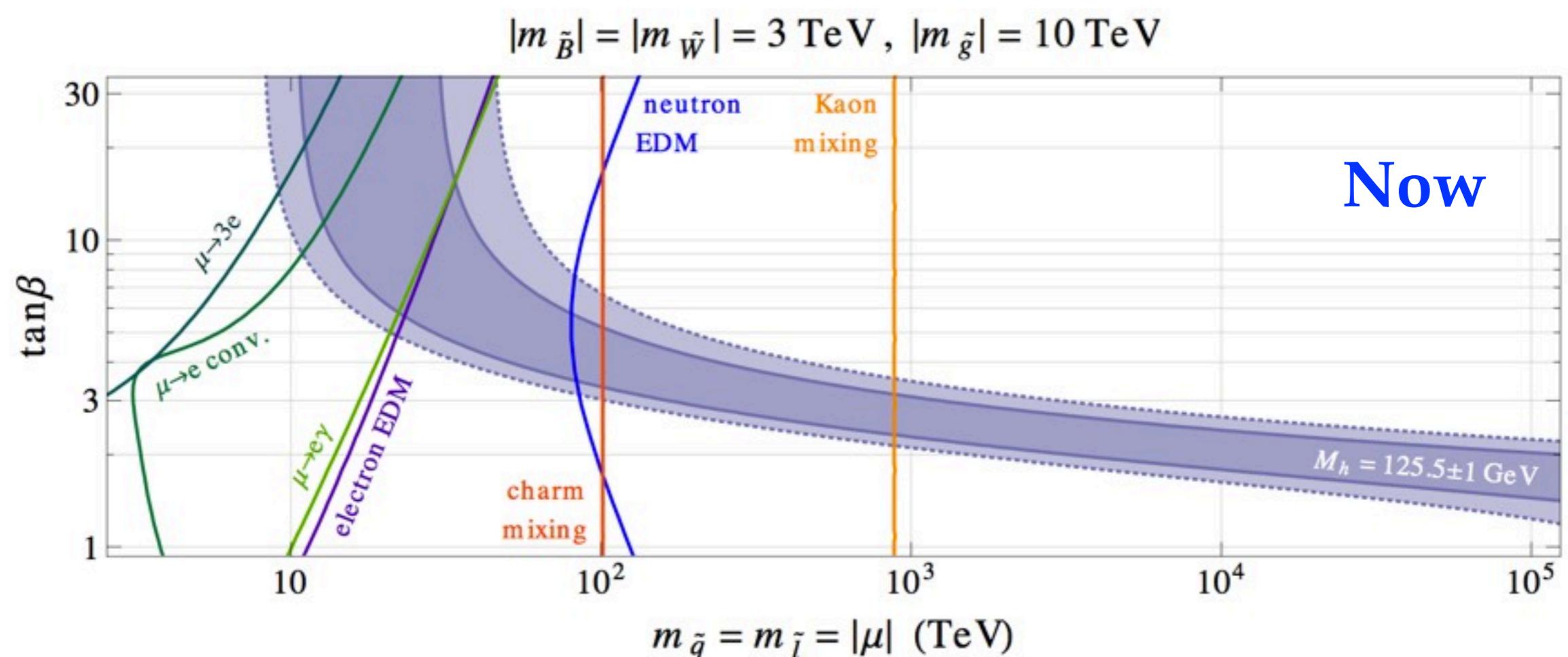
- gauginos at TeV
- sfermions at 100-1000 TeV
- motivation:
 - higgs mass from PeV stop at 1-loop for moderate $\tan\beta$
 - simple model building



SEARCHING FOR MINI-SPLIT SUSY

- $O(1\text{-}10\text{TeV})$ gauginos at LHC or future collider
- PeV sfermions from low energy precision probes
 - significant improvement in projected future sensitivities of several observables

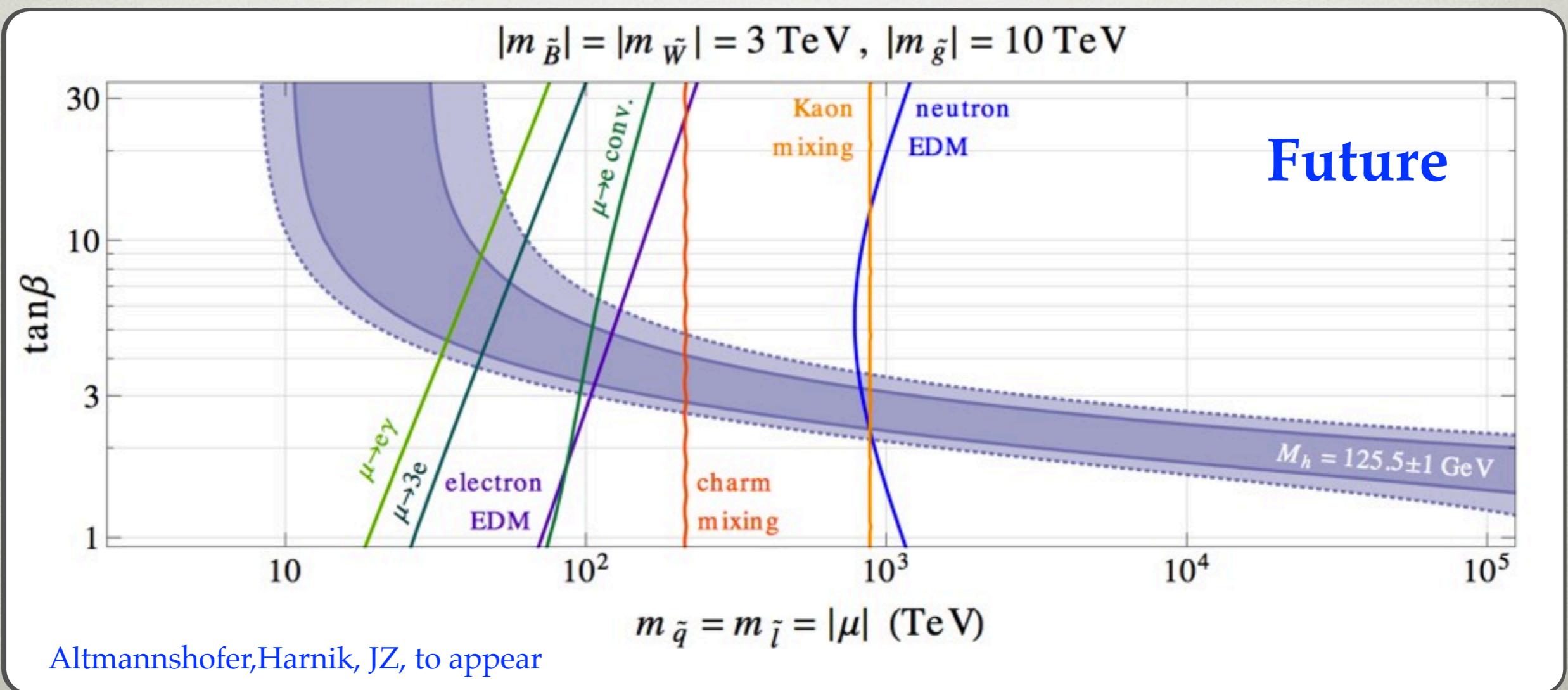
see also McKeen, Pospelov, Ritz, 1303.1172



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EXP. ANOMALIES

ANOMALIES

- interesting anomalies
 - $B \rightarrow D^{(*)} \tau \nu$
 - CP violation in D decays

NEW PHYSICS $B \rightarrow D^{(*)} \tau \bar{\nu}$?

Fajfer, Kamenik, Nisandzic, JZ, 1206.1872
+ many other refs...

- if NP then likely non-MFV flavor structure
- requires relatively light NP states
 - for CKM-like couplings $\Rightarrow \Lambda \sim O(100\text{GeV})$
 - several NP solutions proposed
 - general 2HDM
 - leptoquarks
 - composite sector (3rd gen. quarks and leptons)
- all require non-trivial flavor structure

NEW PHYSICS IN CHARM?

- direct CPV

$$\Delta A_{CP} = A_{CP}(D \rightarrow K^+ K^-) - A_{CP}(D \rightarrow \pi^+ \pi^-)$$

- experiment (WA): $\Delta A_{CP} = (-0.329 \pm 0.121)\%$
~~((ICHEP2012: $\Delta A_{CP} = (-0.678 \pm 0.147)\%$)~~

- moved closer to SM predictions

- could it be NP?

- “reasonable” models of NP can do it

- model independent NP ops. analysis

Isidori, Kamenik, Ligeti, Perez, 1111.4987

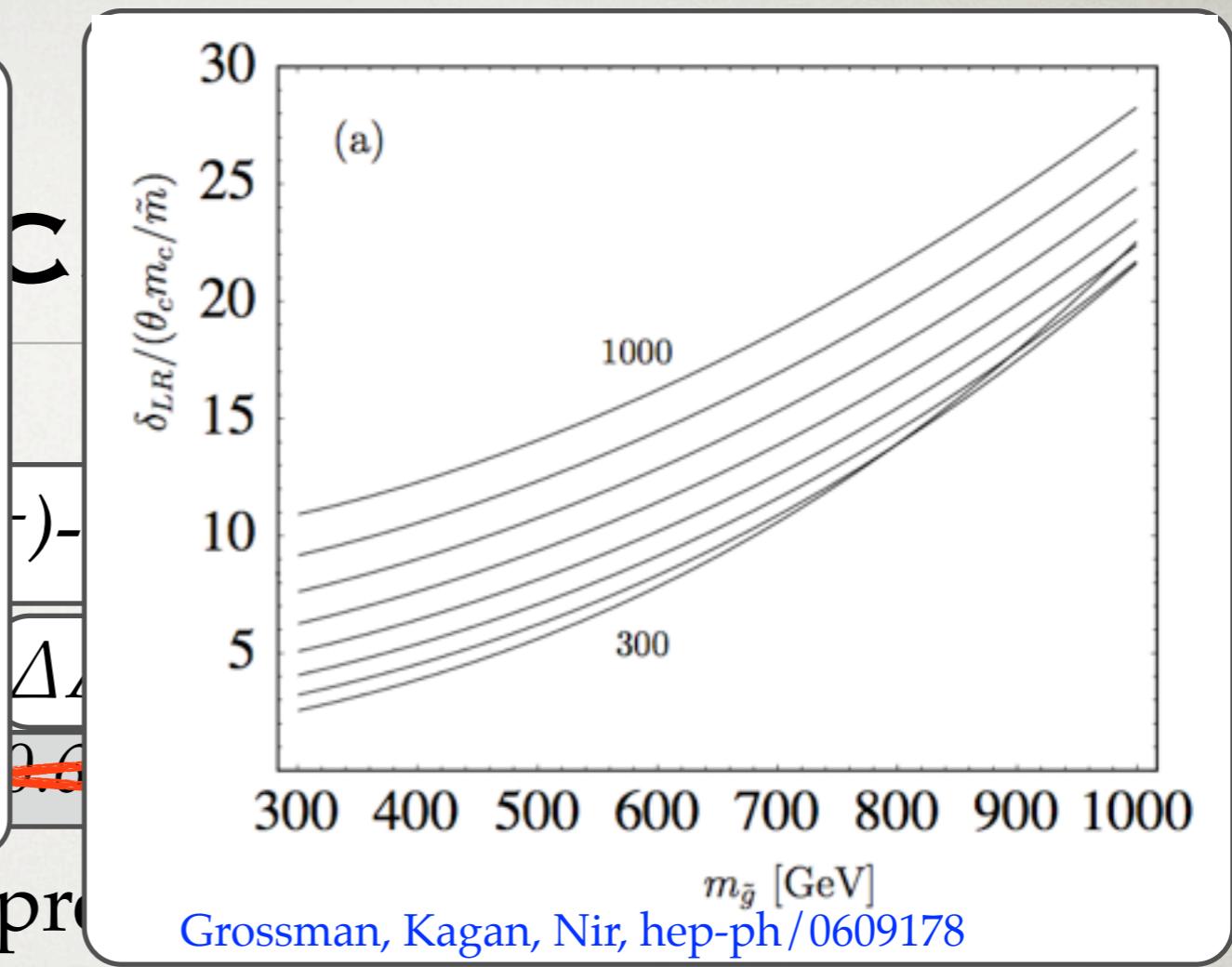
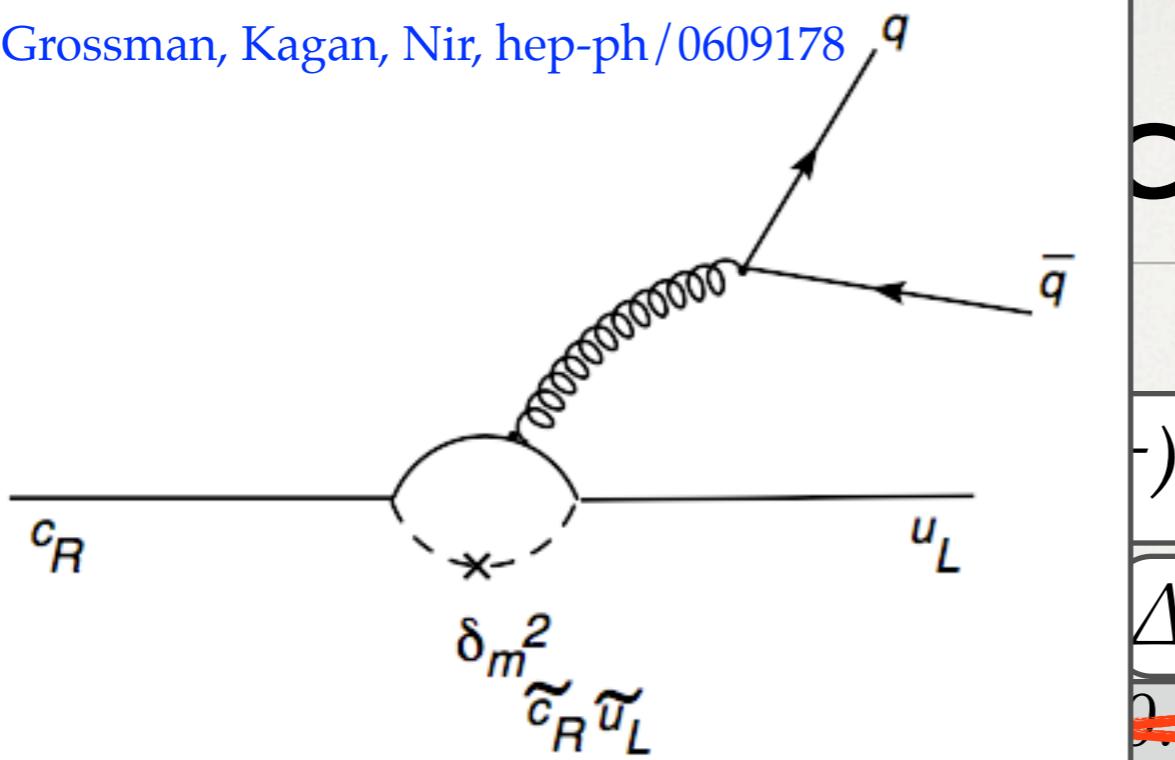
- supersymmetric examples

Grossman, Kagan, Nir, hep-ph/0609178
Giudice, Isidori, Paradisi, 1201.6204

- tree level exchanges

Hochberg, Nir, 1112.5268
Altmannshofer, Primulando, Yu, Yu, 1202.2866

Grossman, Kagan, Nir, hep-ph/0609178



- moved closer to SM predictions
- could it be NP?
- “reasonable” models of NP can do it
 - model independent NP ops. analysis
 - supersymmetric examples
 - tree level exchanges

Isidori, Kamenik, Ligeti, Perez, 1111.4987

Grossman, Kagan, Nir, hep-ph/0609178
Giudice, Isidori, Paradisi, 1201.6204

Hochberg, Nir, 1112.5268
Altmannshofer, Primulando, Yu, Yu, 1202.2866

UPSHOT REGARDING ANOMALIES

- for both experimental anomalies
 - extra probes of new physics models either
 - using low energy FCNC probes
 - or searching for on-shell states at colliders
 - relatively low states required (100GeV-1TeV)
 - concrete models can be discovered / ruled out using colliders

FLAVOR AND HIGH p_T PHYSICS

FLAVOR VIOLATION AND

HIGH p_t

- should one think about flavor, if doing high p_T ?
- a few examples
 - flavor violating higgs decays
 - flavor structure of squarks
 - flavorful naturalness
 - R-parity from MFV

HIGGS COUPLINGS

- if NP then Higgs couplings could be modified
- if EFT description valid

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c. + \dots$$

- in general thus

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \dots$$

- new neutral currents
 - flavor diagonal @LHC
 - flavor violating @Belle2 and LHC
- note: both are important for understanding

Giudice, Lebedev, 0804.1753

Agashe, Contino, 0906.1542

Goudelis, Lebedev, Park, 1111.1715

Arhrib, Cheng, Kong, 1208.4669

McKeen, Pospelov, Ritz, 1208.4597

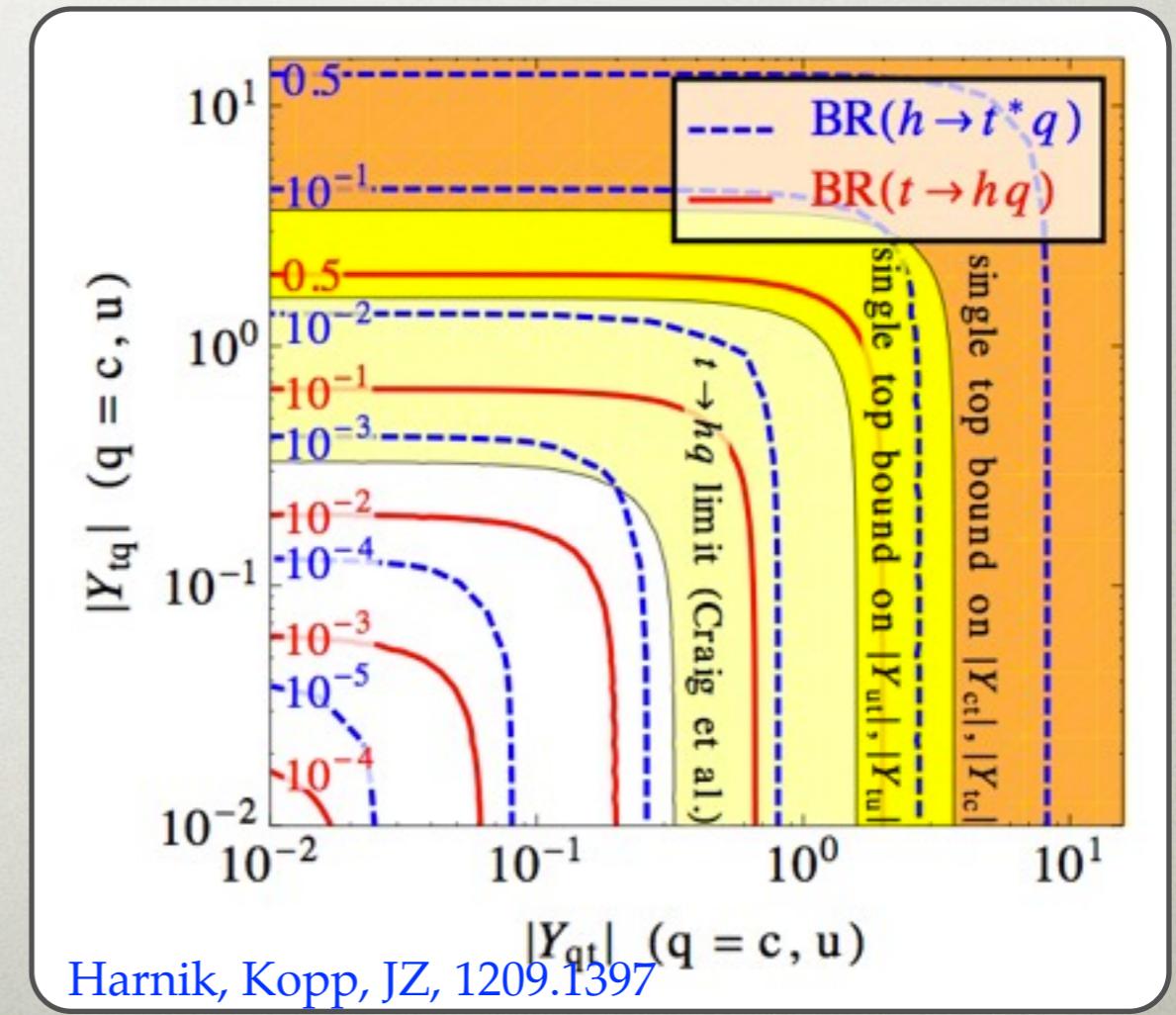
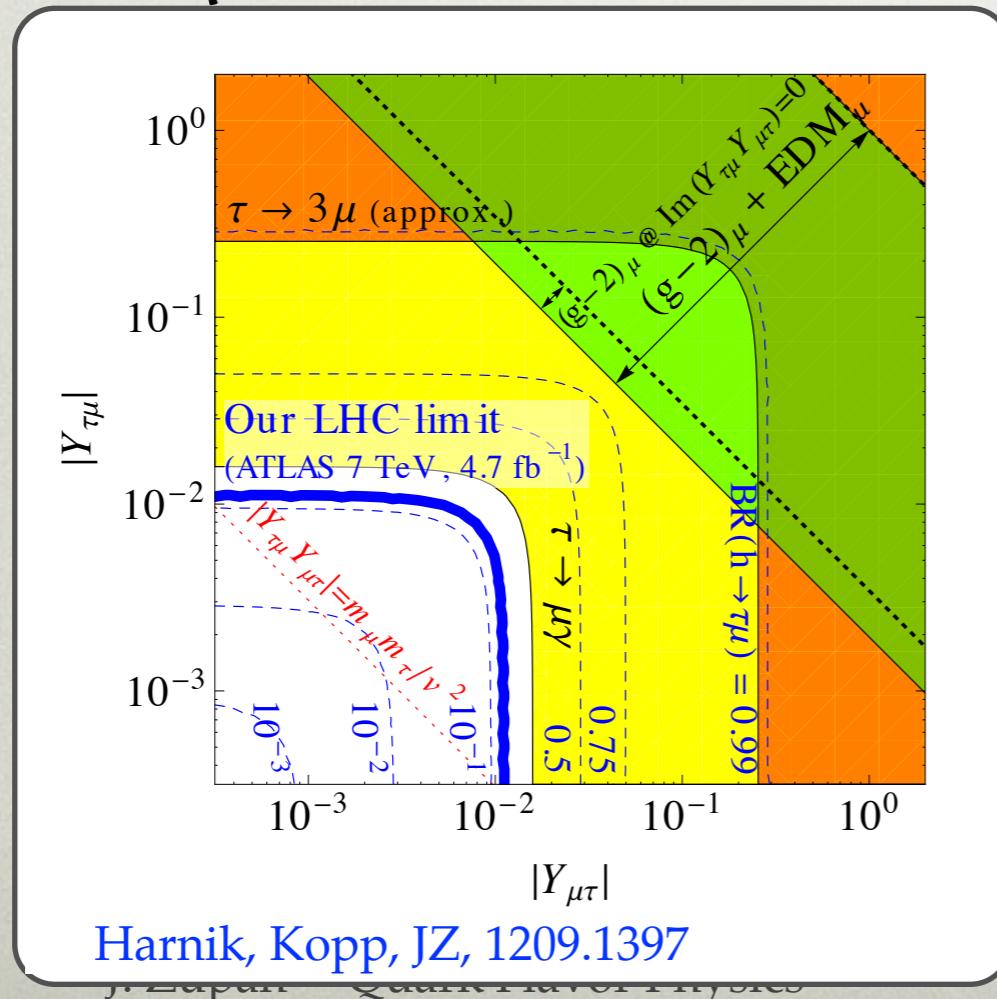
Blankenburg, Ellis, Isidori, 1202.5704

Harnik, Kopp, JZ, 1209.1397

FLAVOR VIOLATING HIGGS COUPLINGS

Harnik, Kopp, JZ, 1209.1397

- B -factories: the best sensitivity for FV higgs couplings to light quarks
see also Davidson, Verdier, 1211.1248; Arhrib, Cheng, Kong, 1210.8241; Dery, Efrati, Hochberg, Nir, 1302.3229; Blankenburg, Ellis, Isidori, 1202.5704; Atwood, Gupta, Soni, 1305.2427, ...
- LHC: best constraints on $h\text{-}tc$, $h\text{-}tu$ and $h\rightarrow\tau\mu, \tau e$

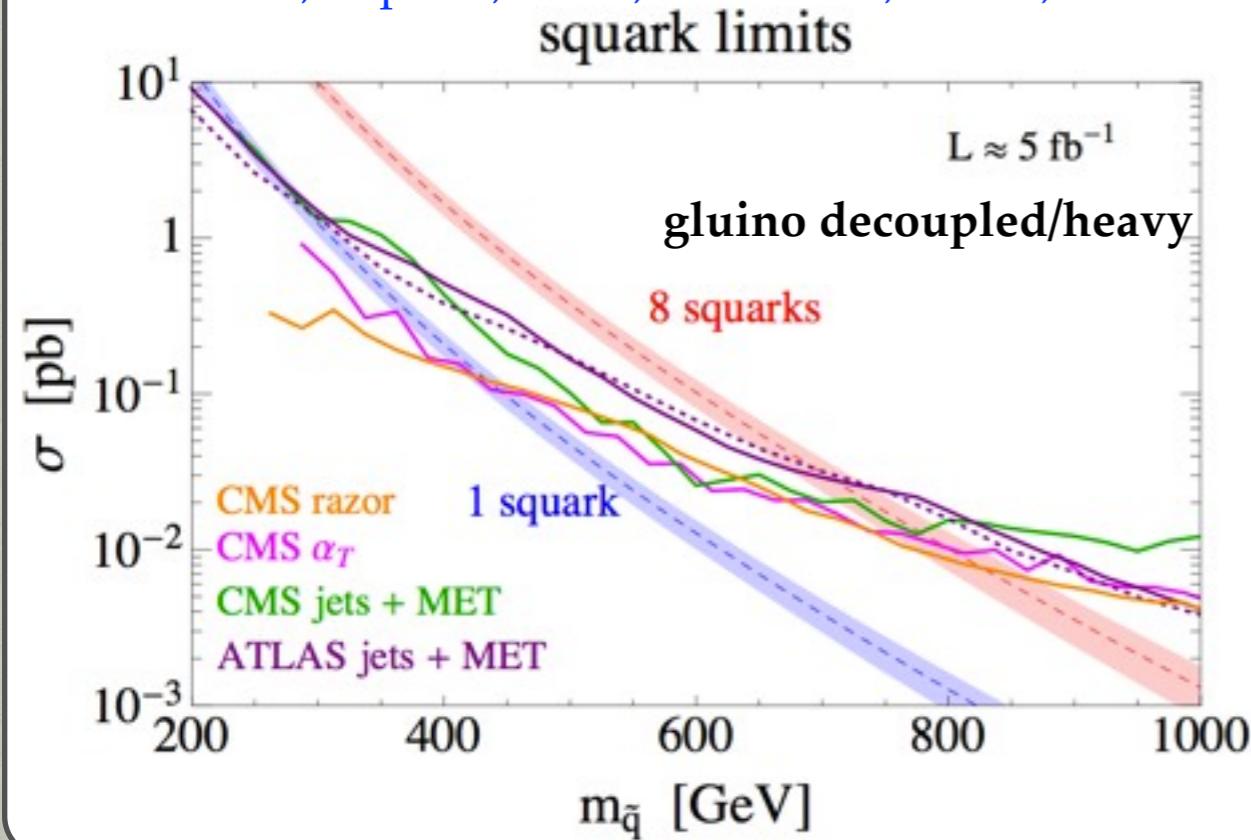


SQUARK SEARCHES

Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328

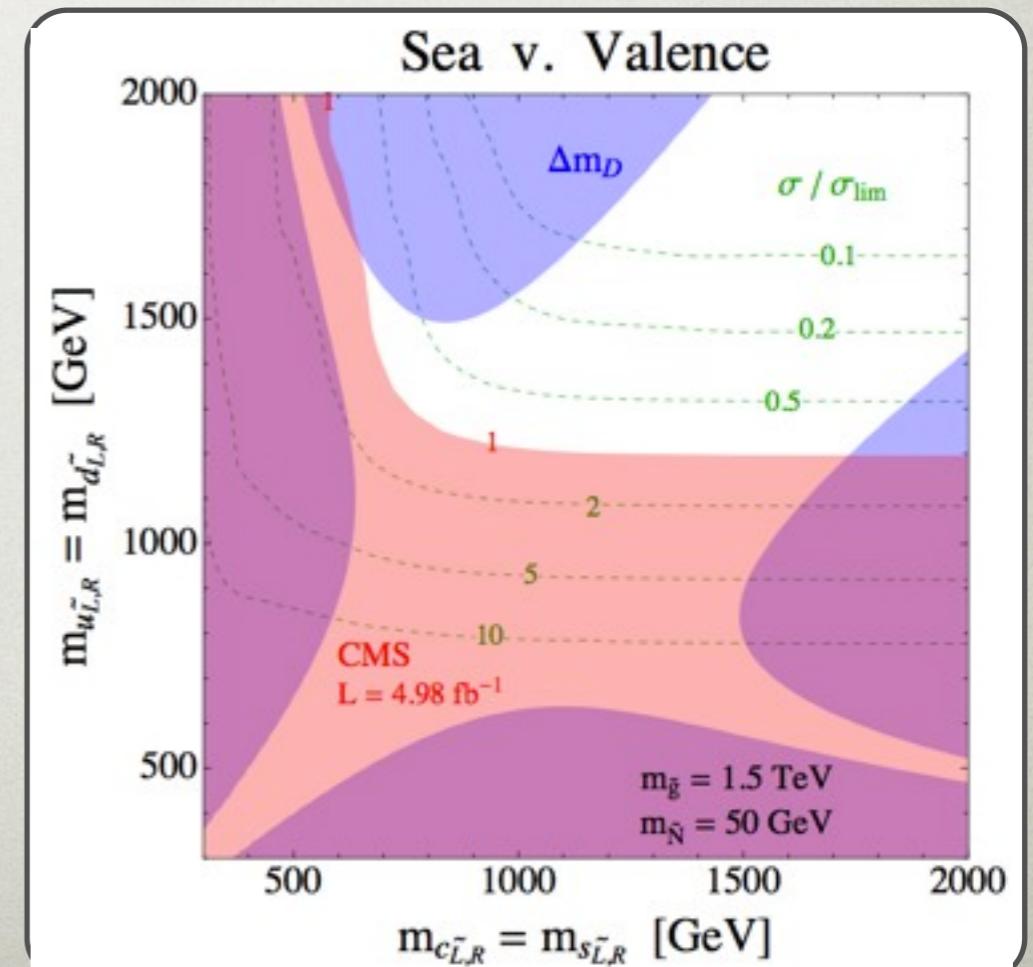
- 1st and 2nd gen. squarks need not be degenerate
 - triggered by thinking about direct CPV anomaly in charm
- 8 degen. squarks \Rightarrow 1 light squark bounds significantly relaxed
- 4+4 degen. squarks: bounds 600GeV instead of 1.2TeV (as for 8 degen. squarks)

Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328



Gedalia, Kamenik, Ligeti, Perez, 1202.5038

- 4+4 degen. squarks: bounds 600GeV instead of 1.2TeV (as for 8 degen. squarks)



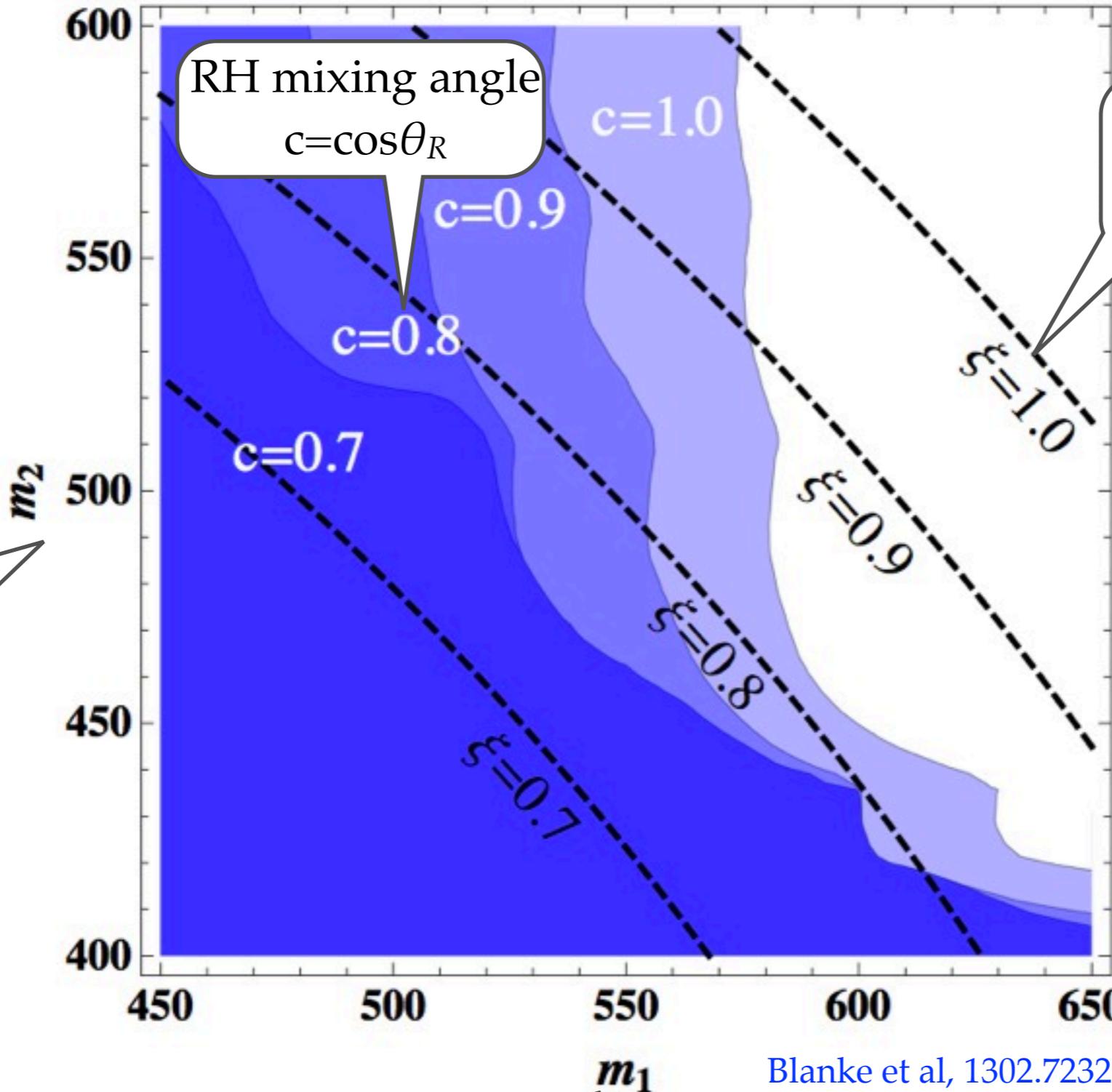
FLAVORFUL NATURALNESS

Blanke, Giudice, Paradisi, Perez, JZ, 1302.7232

- exists a top partner? = a direct test of whether EW scale is natural
 - stop in SUSY, custodians in composite Higgs
 - if large flavor breaking can modify exp. searches
 - some reduction of fine-tuning
- example: large \tilde{t}_R - \tilde{c}_R mixing in MSSM
 - new signature $t+c\text{-jet}+MET$
 - traditional $t\bar{t}+MET$ and $jets+MET$ searches not optimized for it

FL

(conservative) 95% CL mass exclusion



scharm like

e

e

e

e

stop like

ESS

$$\text{tuning measure}$$
$$\xi = \frac{c^2 m_1^2 + s^2 m_2^2}{m_0^2}$$

.7232

Higgs
searches

not

R-PARITY FROM MFV

- R-parity is an ad-hoc assumption in MSSM

Csaki, Grossman, Heidenreich, 1111.1239

Smith, 0809.3152

Bhattacherjee et al, 1301.2336

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

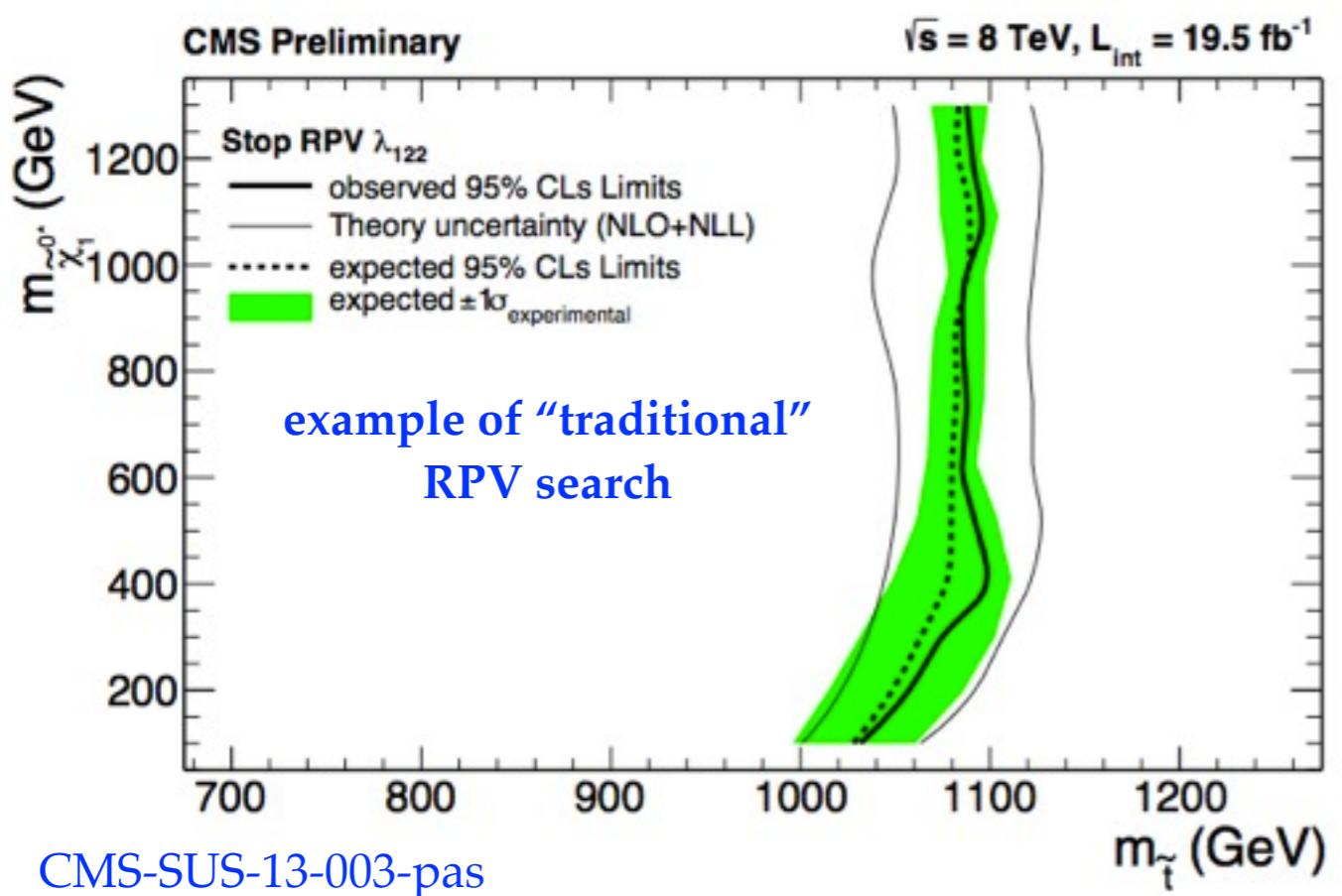
- prevents proton decay
- could be accidental symmetry due to flavor structure of UV
- MFV+SUSY \Rightarrow RPV small enough
 - SM Yukawas (i) only spurions that break flavor, (ii) chiral superfields
 - a benefit: size of RPV predictable, λ'' dominates
- most SUSY searches use MET
 - in MFV-RPV no longer true, no MET
 - e.g. in gluino pair production $(\tilde{g} \rightarrow \tilde{t}\bar{t}, \quad \tilde{t} \rightarrow \bar{b}\bar{s})$
 - still same-sign dilepton signature, and only small MET
 - tradit. RPV search use λ, λ' \Rightarrow rely on signatures with more leptons

Berger, Perelstein, Saelim, Tanedo, 1302.2146

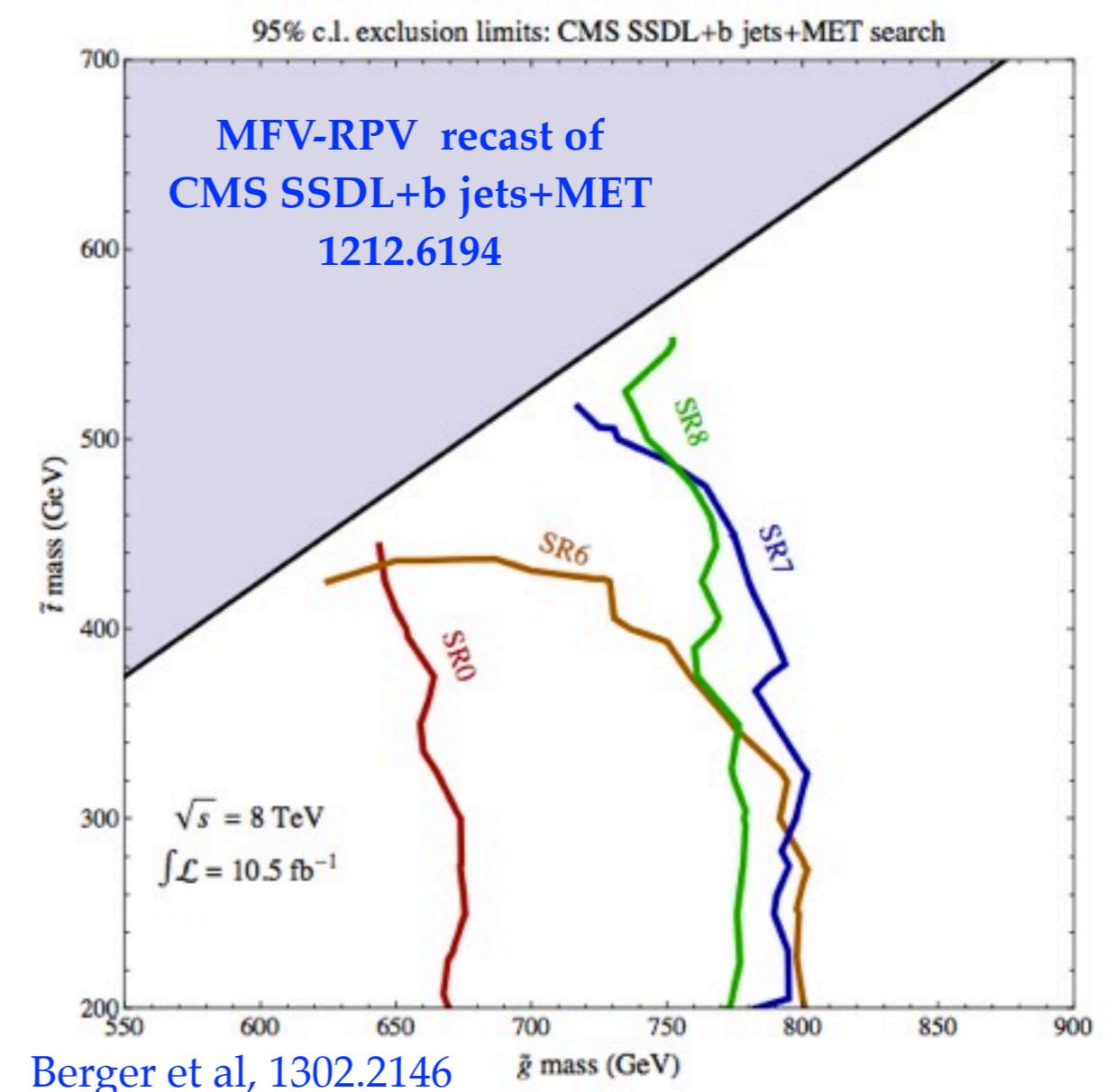
R-PARITY FROM MFV

- R-parity is an ad-hoc assumption in MSSM

Csaki, Grossman, Heidenreich, 1111.1239
 Smith, 0809.2152



- IM MIR V-KT V no longer true, no M
- e.g. in gluino pair production (\tilde{g})
 - still same-sign dilepton signat
 - tradit. RPV search use λ, λ' \Rightarrow rely on signatures with more leptons



CONCLUSIONS

- an exciting and broad program in quark flavor physics aimed at searching for new physics
- can reach to very high energies ($\sim 10^5 \text{ TeV}$ for tree level CP violating NP exchanges)
- if Minimally Flavor Violating NP in the loops the reach is $\sim \text{TeV}$
- complementary to energy frontier searches

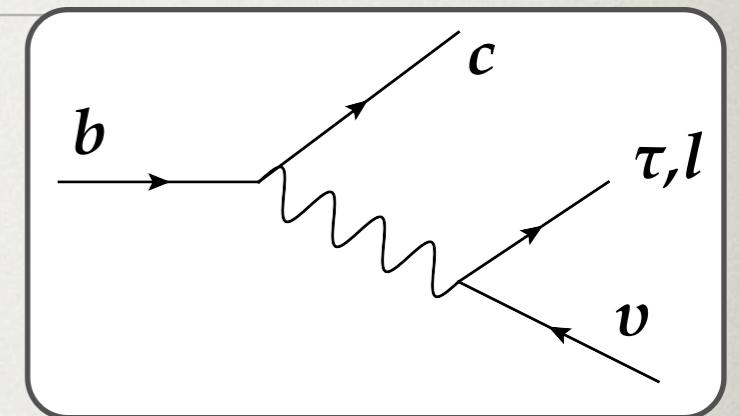
BACKUP SLIDES

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$ V_{us} $ [$K \rightarrow \pi \ell \nu$]	input	$0.5\% \rightarrow 0.1\%$ _{Latt}	0.2246 ± 0.0012	0.1%	K factory
$ V_{cb} $ [$B \rightarrow X_c \ell \nu$]	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$ V_{ub} $ [$B \rightarrow \pi \ell \nu$]	input	$10\% \rightarrow 5\%$ _{Latt}	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ [$B \rightarrow D K$]	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \rightarrow \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \rightarrow \psi \phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \rightarrow \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \rightarrow \phi \phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \rightarrow K^* \gamma}$	$\text{few} \times 0.01$	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \rightarrow \phi \gamma}$	$\text{few} \times 0.01$	0.01	—	0.05	LHCb
A_{SL}^d	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
A_{SL}^s	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \rightarrow s \gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \rightarrow \tau \nu)$	1×10^{-4}	$20\% \rightarrow 5\%$ _{Latt}	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \rightarrow \mu \nu)$	4×10^{-7}	$20\% \rightarrow 5\%$ _{Latt}	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$	3×10^{-9}	$20\% \rightarrow 5\%$ _{Latt}	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)$	1×10^{-10}	$20\% \rightarrow 5\%$ _{Latt}	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{FB}(B \rightarrow K^* \mu^+ \mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \rightarrow K \nu \bar{\nu}$	4×10^{-6}	$20\% \rightarrow 10\%$ _{Latt}	$< 1.4 \times 10^{-5}$	20%	Super-B
$ q/p _{D-\text{mixing}}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \rightarrow \pi \ell \nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \rightarrow c Z, \gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}(10^{-5})$	LHC (100 fb^{-1})

$\mathcal{B}(B \rightarrow X_s \gamma)$	6%	Super-B
$\mathcal{B}(B \rightarrow X_d \gamma)$	20%	Super-B
$S(B \rightarrow \rho \gamma)$	0.15	Super-B
$\mathcal{B}(\tau \rightarrow \mu \gamma)$	$3 \cdot 10^{-9}$	Super-B (90% U.L.)
$\mathcal{B}(B^+ \rightarrow D \tau \nu)$	3%	Super-B
$\mathcal{B}(B_s \rightarrow \gamma \gamma)$	$0.25 \cdot 10^{-6}$	Super-B (5 ab^{-1})
$\sin^2 \theta_W @ Y(4S)$	$3 \cdot 10^{-4}$	Super-B

LEPTON FLAVOR UNIVERSALITY VIOLATION?

- the anomaly
- BaBar measurement of $b \rightarrow c\tau\nu/b \rightarrow cl\nu$
BaBar collaboration, 1205.5442, 1303.0571
- flavor universality violated at 3.4σ



$$\mathcal{R}_{\tau/\ell}^* \equiv \frac{\mathcal{B}(B \rightarrow D^* \tau \nu)}{\mathcal{B}(B \rightarrow D^* \ell \nu)} = 0.332 \pm 0.030,$$

$$\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B \rightarrow D \tau \nu)}{\mathcal{B}(B \rightarrow D \ell \nu)} = 0.440 \pm 0.072,$$

$$\mathcal{R}_{\tau/\ell}^{*,\text{SM}} = 0.252(3)$$

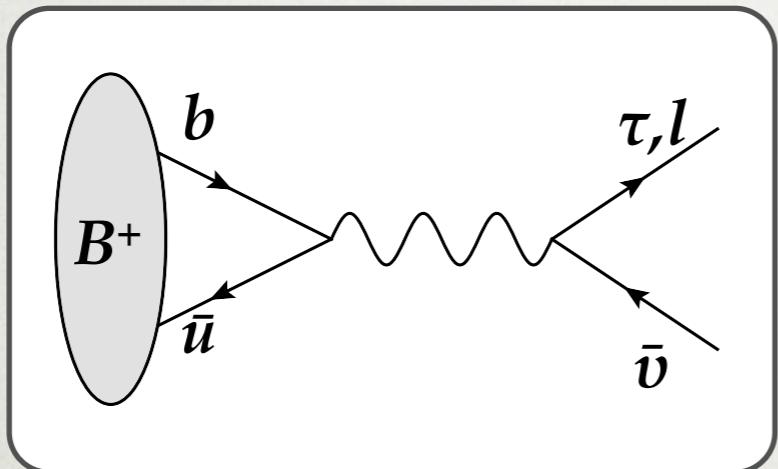
$$\mathcal{R}_{\tau/\ell}^{\text{SM}} = 0.296(16)$$

Fajfer, Kamenik, Nisandzic, 1203.2654
Kamenik, Mescia, 0802.3790

see also Becirevic, Kosnik, Tayduganov, 1206.4977; Bailey et al., 1206.4992

IN $B \rightarrow \tau\nu$ DECAY

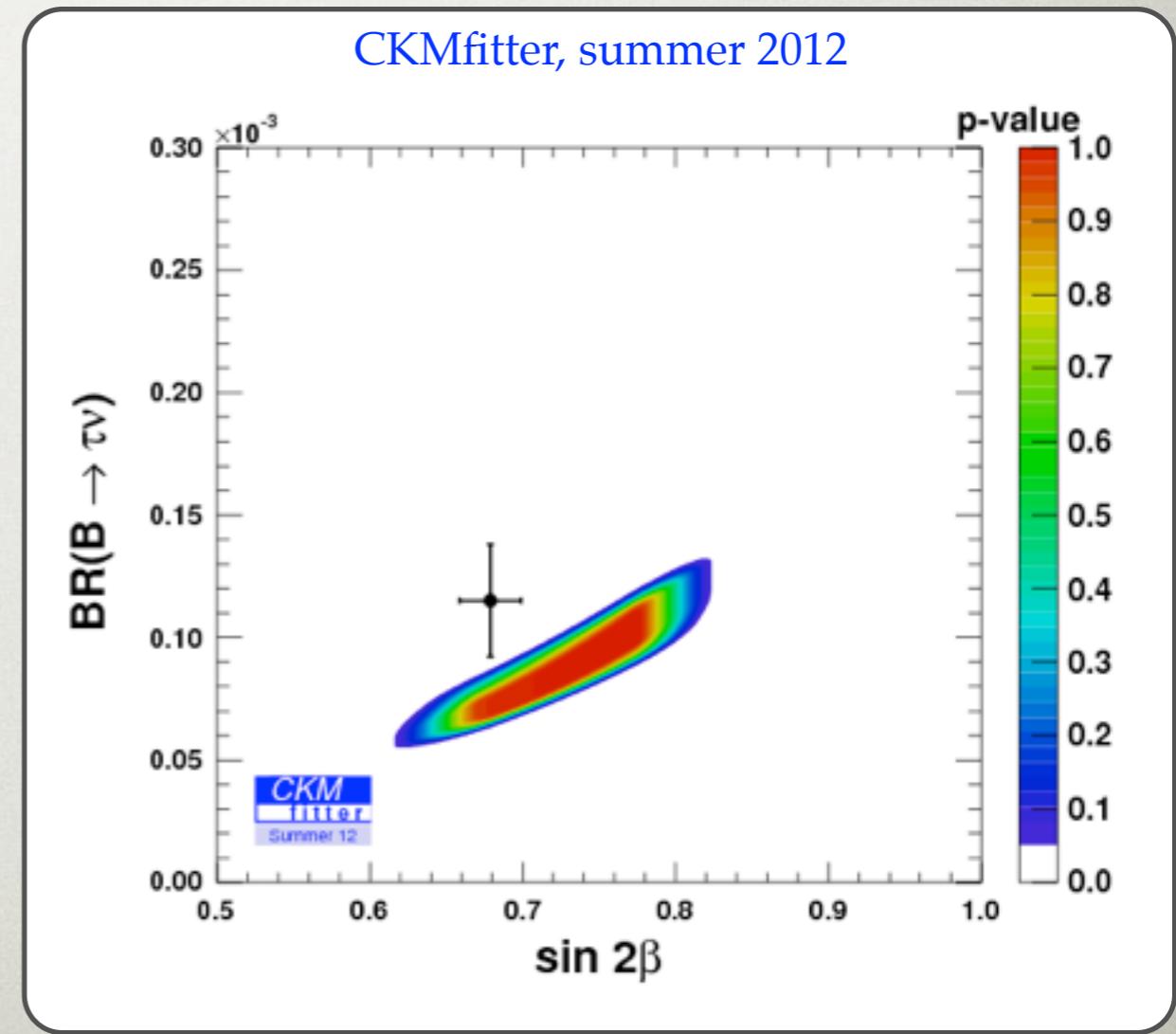
- for a long time now $B \rightarrow \tau\nu$ too large
- with 2012 Belle result less tension



- can define a ratio

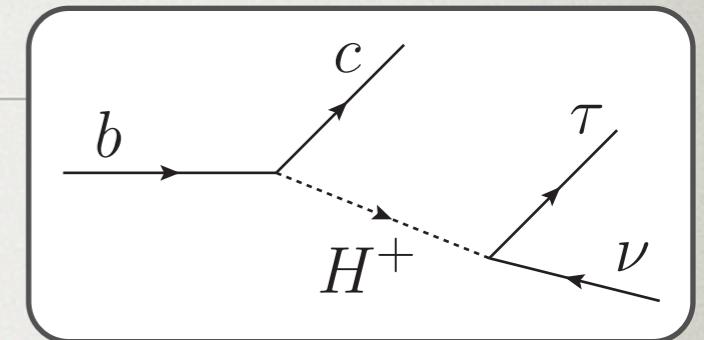
$$\begin{aligned} \mathcal{R}_{\tau/\ell}^\pi &\equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \rightarrow \pi^+ \ell^- \bar{\nu})} \\ &= 0.73 \pm 0.15 \end{aligned}$$

$$\mathcal{R}_{\tau/\ell}^{\pi, \text{SM}} = 0.31(6)$$



GENERAL 2HDM

- e.g. simple limit - only one Higgs gets a vev
- the interactions with the other Higgs



$$\mathcal{L} \supset \kappa_{RL}^i \bar{q}_3 u_R^i \bar{H} + \kappa_{LR}^i \bar{b}_R \bar{H}^\dagger q_i + \kappa^\tau \bar{\tau}_R l_3 \bar{H} + \text{h.c.}$$

- solutions possible, but severe (flavor) model problems
 - $\kappa_{RL}^{c(u)} \kappa^\tau$ are 3-4 order of magn. larger than Yukawas
 $(m_{c(u)}/v)(m_\tau/v)$ Nisandzic, Fajfer, Kamenik, JZ, 1206.1872
 - $(\kappa_{RL}^c, \kappa_{LR}^c) \kappa^\tau \simeq \{(-6, 8), (-12, 2)\} \cdot 10^{-2} (m_{H^+}/v)^2$
- to satisfy FCNC constraints from D^0 , B_s and B_d mixing
 - order of magn. cancellations needed (for $\kappa^\tau = 1$)
 - $\Delta B = 2$ trans. also suppressed if $\kappa_{LR}^i = 0$

ON SHELL SEARCHES

- if $m_{H^+} < m_t$ then $t \rightarrow b H^+$ possible
 - ATLAS, CMS searches:
 $|\kappa_{RL,LR}^t| < O(0.2 - 0.4)$ for $80 GeV < m_{H^+} < 160 GeV$
- if $m_{H^+} > m_t$, the dominant signal probably $gb \rightarrow H^- t$
 - pp xsec@8TeV LHC: $1.4 \text{ pb} (|\kappa_{RL}^t|^2 + |\kappa_{LR}^t|^2)$ for $m_{H^-} = 200 \text{ GeV}$
 - $\tau + MET$ and tb resonance searches
 - Br depends on $\kappa_{LR,RL}^t$ and κ^τ sizes

SUSY?

- SUSY contribs. to QCD penguin particularly interesting

Grossman, Kagan, Nir, hep-ph/0609178

Chang et al., 1201.2565

Giudice, Isidori, Paradisi, 1201.6204

Hiller, Hochberg, Nir, 1204.1046

- LR mixing in squark matrices

$$Q_8 = \frac{m_c}{4\pi^2} \bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

$$\frac{m_c}{m_W^2} \rightarrow \frac{v}{\tilde{m}^2}$$

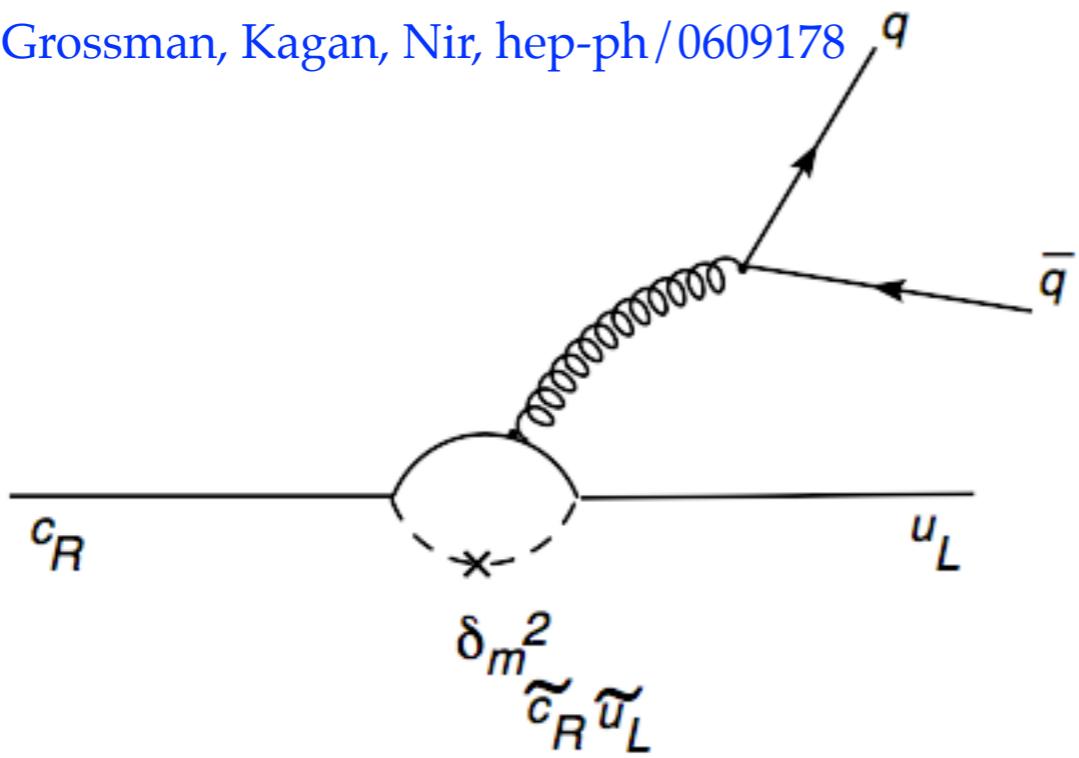
$$Q_8 = \frac{1}{4\pi^2} (\bar{Q}_L H) \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

- for $v \sim m_{susy}$ the op. Q_8 is secretly dim=5
- D - \bar{D} mixing operators are dim=6

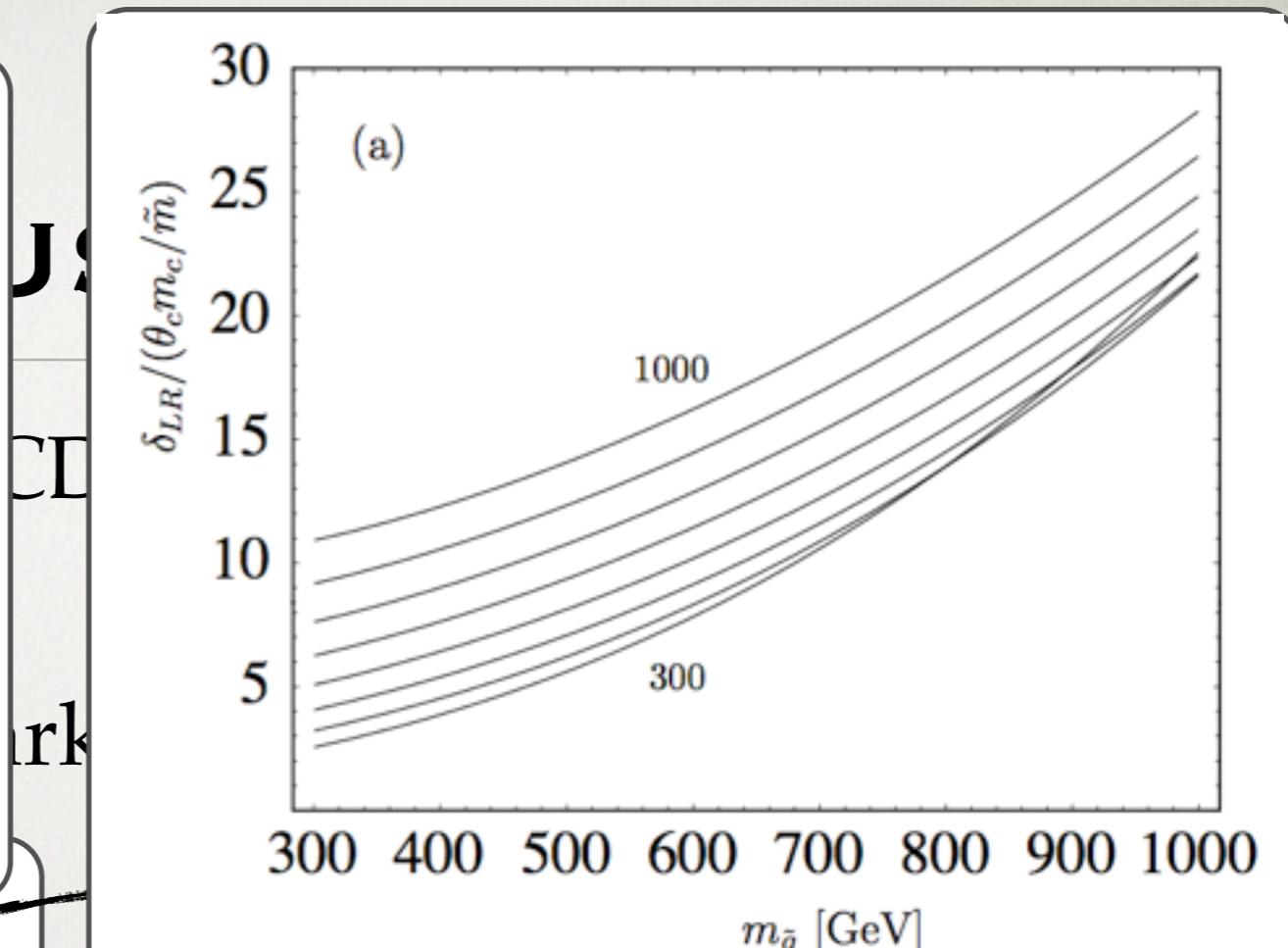
$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta$$

- SUSY contributions are parametrically smaller

Grossman, Kagan, Nir, hep-ph/0609178



$$Q_8 = \frac{1}{4\pi^2} u_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$



Grossman, Kagan, Nir, hep-ph/0609178

$$Q_8 = \frac{1}{4\pi^2} (\bar{Q}_L H) \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

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- D - $Dbar$ mixing operators are dim=6

$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta$$

- SUSY contributions are parametrically smaller

SM PREDICTIONS

- SM predictions for ΔA_{CP} hard
 - Λ_{QCD}/m_c is a poor expan. param.
 - can one use flavor SU(3)?
- long standing puzzle
 - $Br(D \rightarrow K^+ K^-) = 2.8 Br(D \rightarrow \pi^+ \pi^-)$
 - large breaking of flavor SU(3)?
 - or nominal breaking $\epsilon_U \sim (f_K/f_\pi - 1) \sim \mathcal{O}(0.2)$
 - but large penguin contraction?
 - also predicts the right size of ΔA_{CP} !

Brod, Kagan, JZ, 1111.5000

J. Brod, Y. Grossman, A. Kagan, JZ, 1203.6659

NP OR SM?

- it could be NP or SM
- how to distinguish between the two?
- by building NP models
 - search for other signatures (collider or otherwise)
- also using just charm data
 - possible to write isospin sum rules that would be violated if NP
 - e.g. $A_{CP}(D^+ \rightarrow \pi^+ \pi^0) = 0$
 - also sum rules to test the size of SU(3) breaking
 - from $D \rightarrow V\gamma$ search for enhanced Q_{8G}

[Grossman, Kagan, JZ, 1204.3557](#)

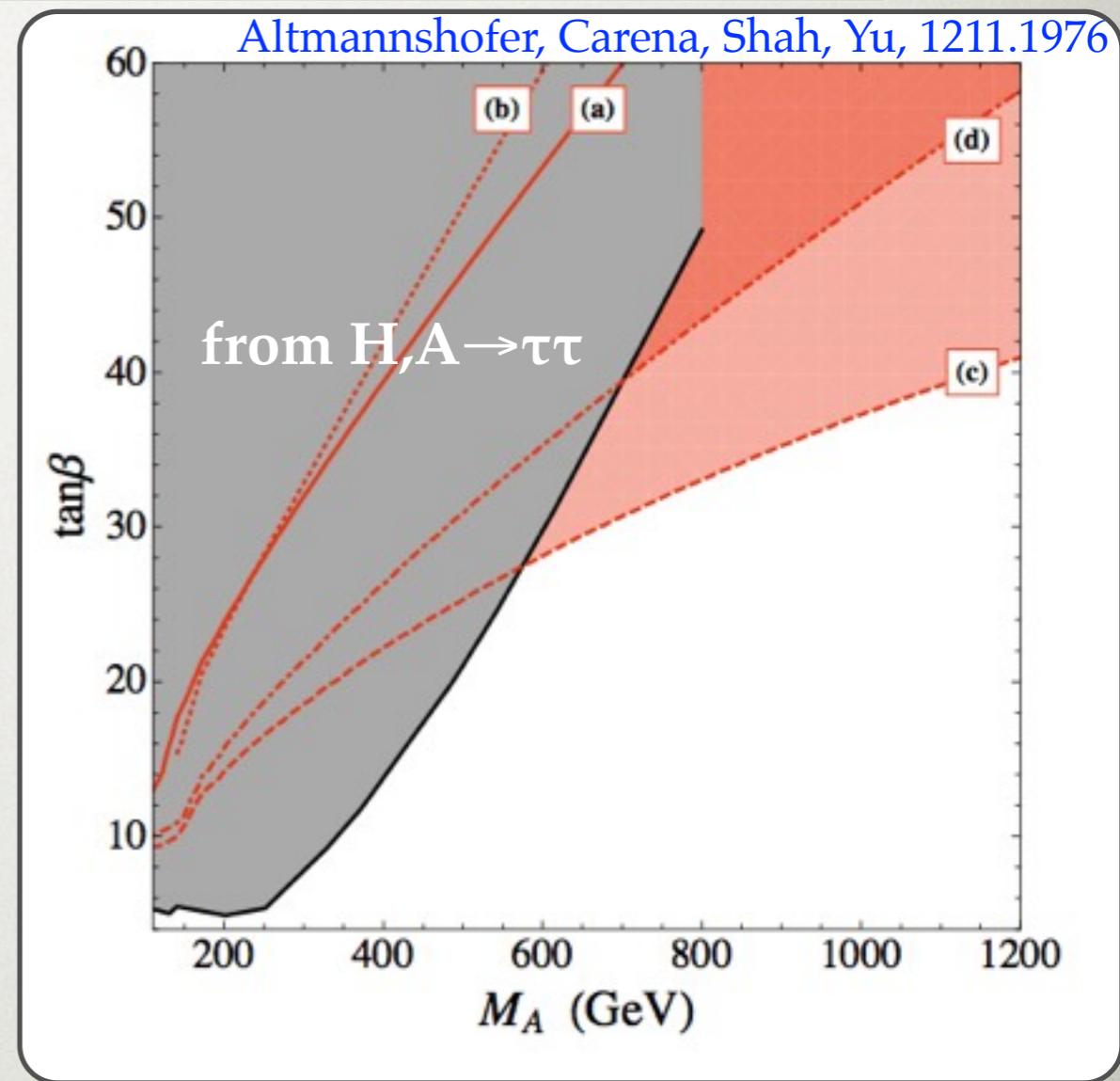
[Grossman, Robinson, 1211.3361](#)

[Isidori, Kamenik, 1205.3164](#)

$B_s \rightarrow \mu\mu$ IN THE MSSM WITH LARGE $\tan\beta$

- dominant contrib.
from Higgs penguins
- Higgsino loop interfer.
with the SM
 - destructively for $\mu A_t > 0$
 - constructively for $\mu A_t < 0$

$$C_S^H \simeq -C_P^H \propto \frac{y_t^2}{16\pi^2} \frac{\mu A_t}{m_t^2} \frac{\tan\beta^3}{M_A^2} (V_{tb} V_{ts}^*)$$



— (a) $\mu = 1\text{TeV}, A_t > 0$
 (b) $\mu = 4\text{TeV}, A_t > 0$

— (c) $\mu = -1.5\text{TeV}, A_t > 0$
 - - - (d) $\mu = 1\text{TeV}, A_t < 0$

all squarks degenerate $\tilde{m} = 2\text{TeV}$, $|A_t|$ such that $M_h = 125\text{GeV}$

BENCHMARKS

- what is a reasonable aim for precision on Y_{ij} ?
 - if off-diagonals are large \Rightarrow spectrum in general not hierarchical
 - no tuning, if

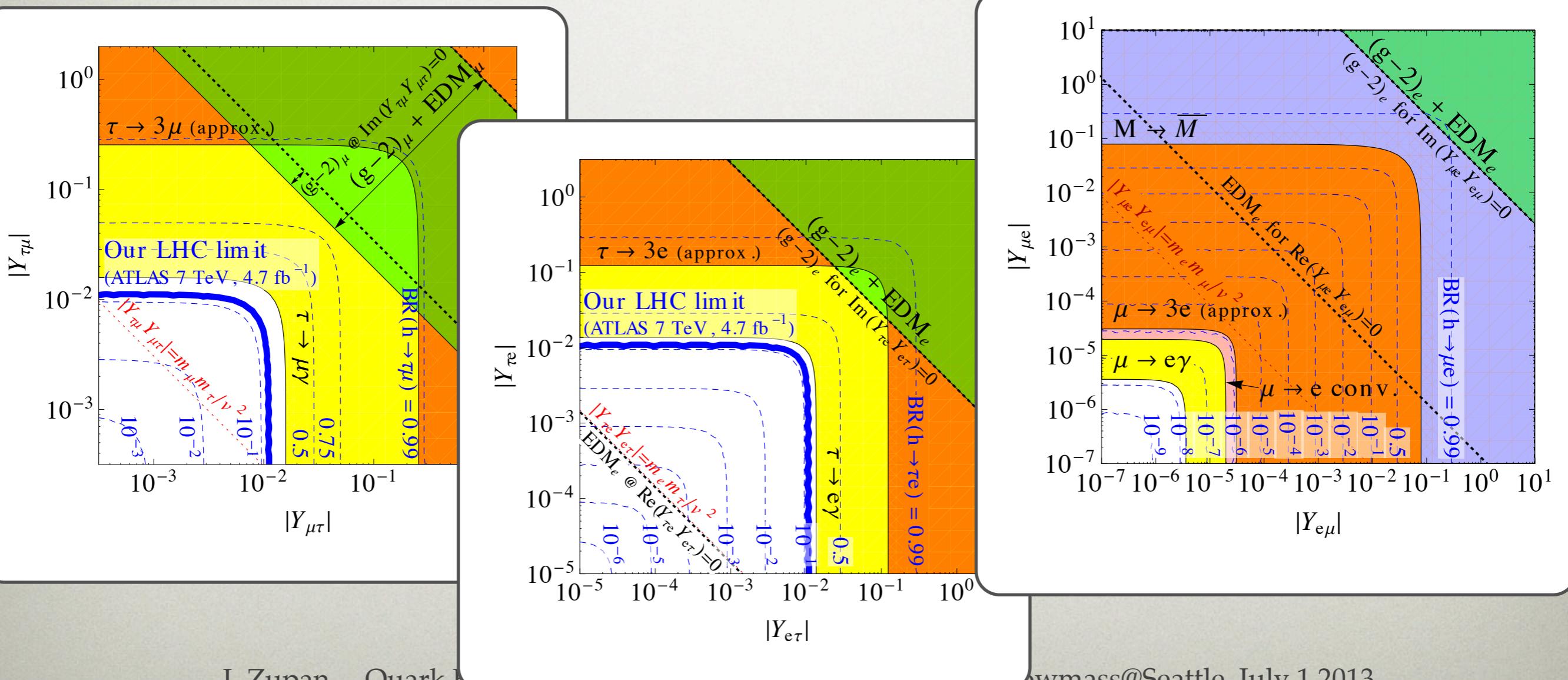
$$|Y_{\tau\mu} Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$$
[Cheng, Sher, 1987](#)
- different flavor models give
 [Dery, Efrati, Hochberg, Nir, 1302.3229](#)

Model	$R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\mu\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin \alpha / \cos \beta)^2$	1	0
MFV	$1 + 2av^2/\Lambda^2$	$1 - 4bm_\tau^2/\Lambda^2$	0
FN	$1 + \mathcal{O}(v^2/\Lambda^2)$	$1 + \mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(U_{23} ^2 v^4/\Lambda^4)$
GL	9	25/9	$\mathcal{O}(X_{\mu^+\mu^-})$

PRESENT STATUS

- for $h \rightarrow \tau\mu, \tau e$ the LHC is most constraining
 - already without a dedicated study
 - starting to probe Cheng-Sher territory ($h \rightarrow \bar{q}q'$ more constr.)

Harnik, Kopp, JZ, 1209.1397



QUARK FLAVOR PHYSICS

WORKING GROUP

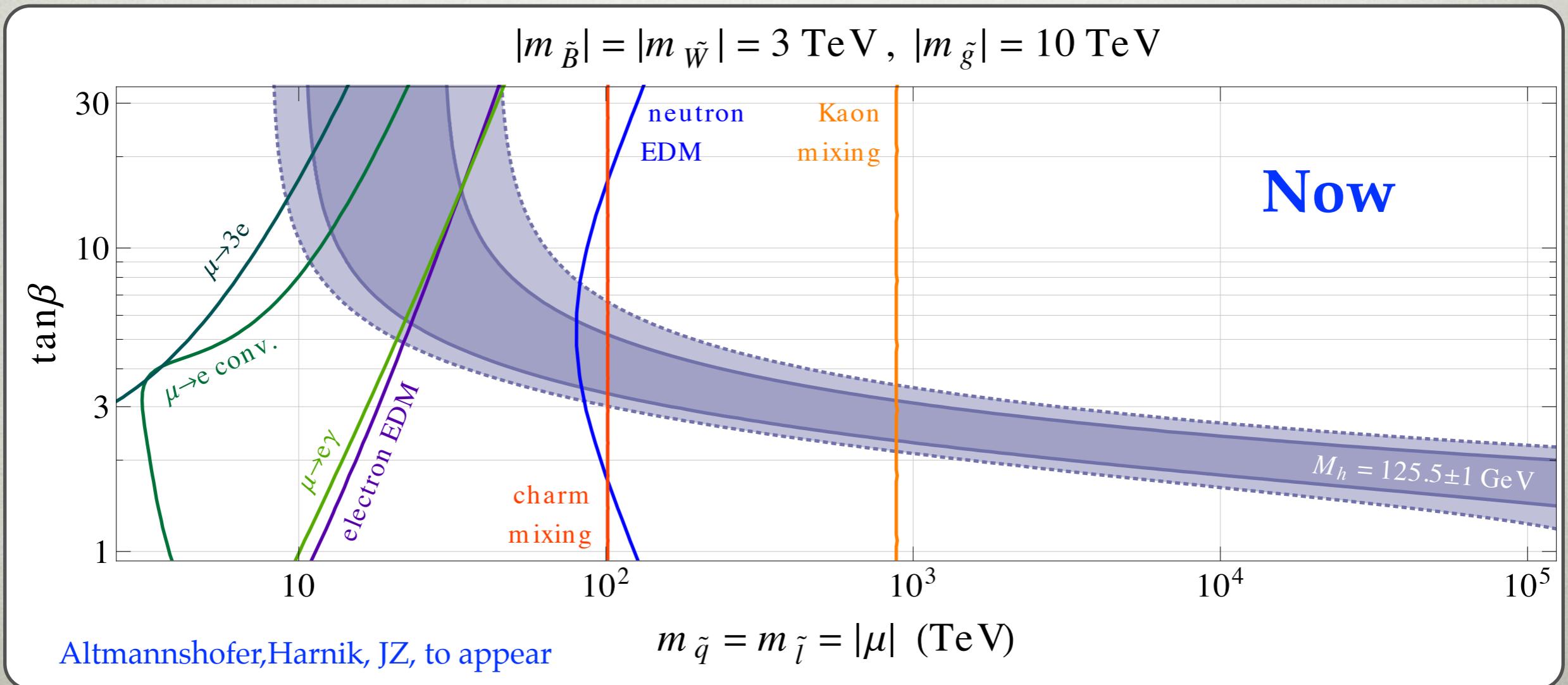
<http://www.snowmass2013.org/tiki-index.php?page=Quark+Flavor+Physics>

Quark Flavor Physics, for the purposes of this Intensity Frontier subgroup, refers to experimental and theoretical studies of processes involving strange, charm, or bottom quarks, which are promising directions to discover the existence of new physics at high mass scales.

- Quark Flavor Physics ([Joel Butler, Zoltan Ligeti, Jack Ritchie](#))
- has four Task Forces:
 - Kaons ([Vincenzo Cirigliano, Steve Kettell](#))
 - Charm ([Roy Briere, Alexey Petrov](#))
 - B-physics ([Alan Schwartz, Tomasz Skwarnicki, Jure Zupan](#))
 - Lattice QCD ([Norman Christ, Steve Sharpe, Ruth Van de Water](#))

SEARCHING FOR MINI-SPLIT SUSY

- $O(1\text{-}10\text{TeV})$ gauginos at LHC or future collider
- PeV sfermions from low energy precision probes
 - significant improvement in projected future sensitivities of several observables



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