Flavor Physics Beyond the Standard Model

M. Papucci
UC Berkeley & LBNL

FPCP 2007 - Bled, May 12th-16th

Flavor/Beyond the SM
Hot Topics?

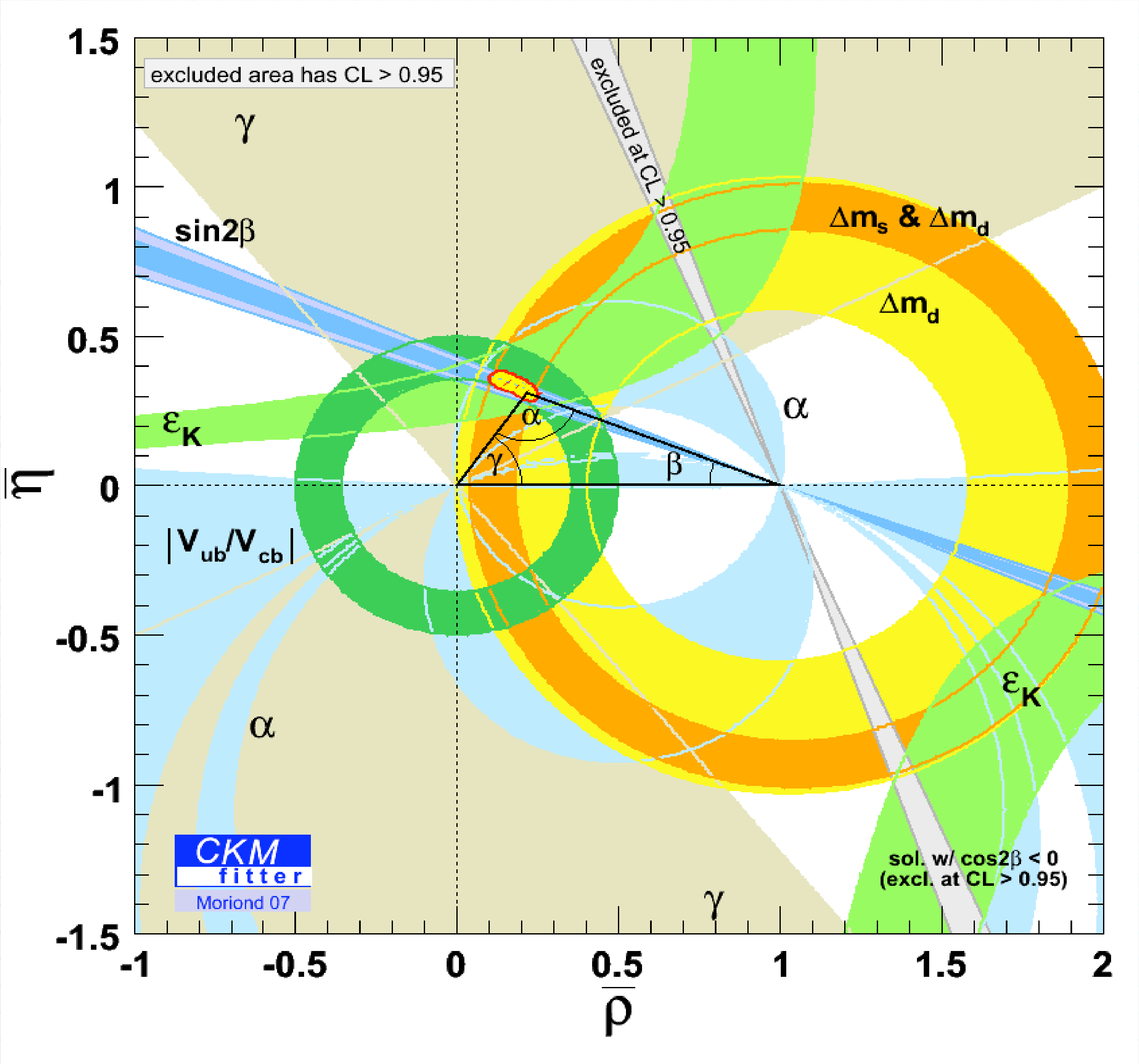
* Constraints from ~~CP~~ and $D0$-$\overline{D0}$ mixing on unparticle physics
* See: ph/0703260, 0705.0689, 0705.1326, 0705.1821...

...but I will not cover them...

Outline

* From SM to Beyond the SM (Intro)
* Minimal Flavor Violation (MFV), non-MFV and all that (from a model builder perspective)
* New Physics in FPCP07 (what do we know now?)
* What next? (getting FPCP constraints on NP to "LEP quality standards" during the LHC era?)
* Conclusions

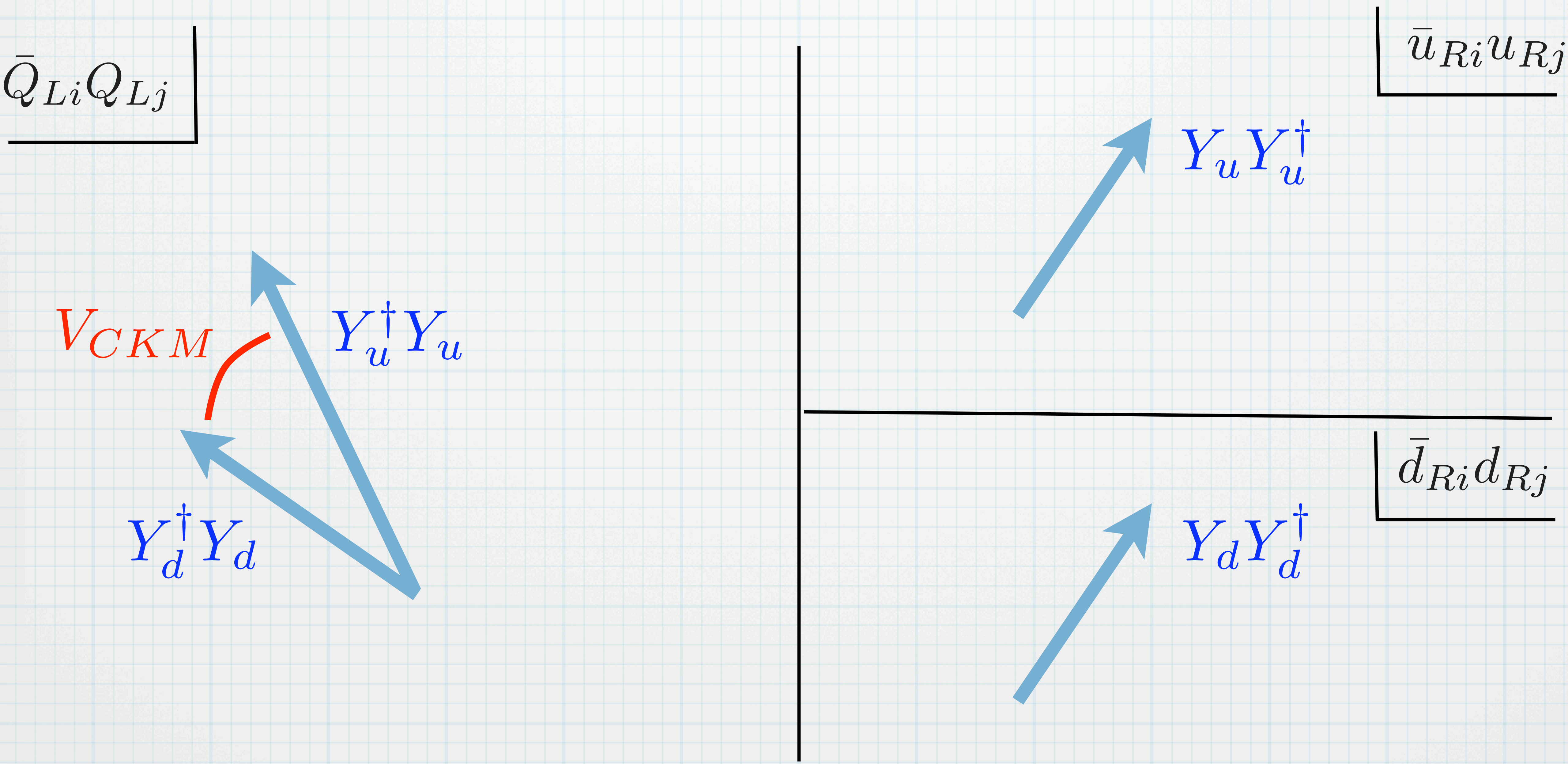
FPCP in the Standard Model has been probed...



- Now we seek for deviations (like @ LEP)...

FPCP in the Standard Model

* Everything is encoded in 2 Yukawa matrices Y_u & Y_d



+ RL & LR ...

Beyond the SM

$$m_W \ll M_{Pl}$$

* An accident?
* If not, we expect more than "just the Higgs and nothing else" (even if it is possible that we will find the Higgs and nothing else @ LHC)
* New particles ⇒ new interactions
* What about FPCP?

The smallest perturbation of the SM picture:

Minimal Flavor Violation (MFV)

* New particles & new interactions? Yes
* New FPCP sources at **low energy**? No

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i c_i(y_u, y_d)\frac{\mathcal{O}_i}{\Lambda^2}$$

It's not just something that come out from current data... (Dugan Grinstein Hall '85)

MFV example: SUSY

- many ~~SUSY~~ mechanisms are flavor blind: gauge mediation*, gaugino med/no scale, anomaly med', ...

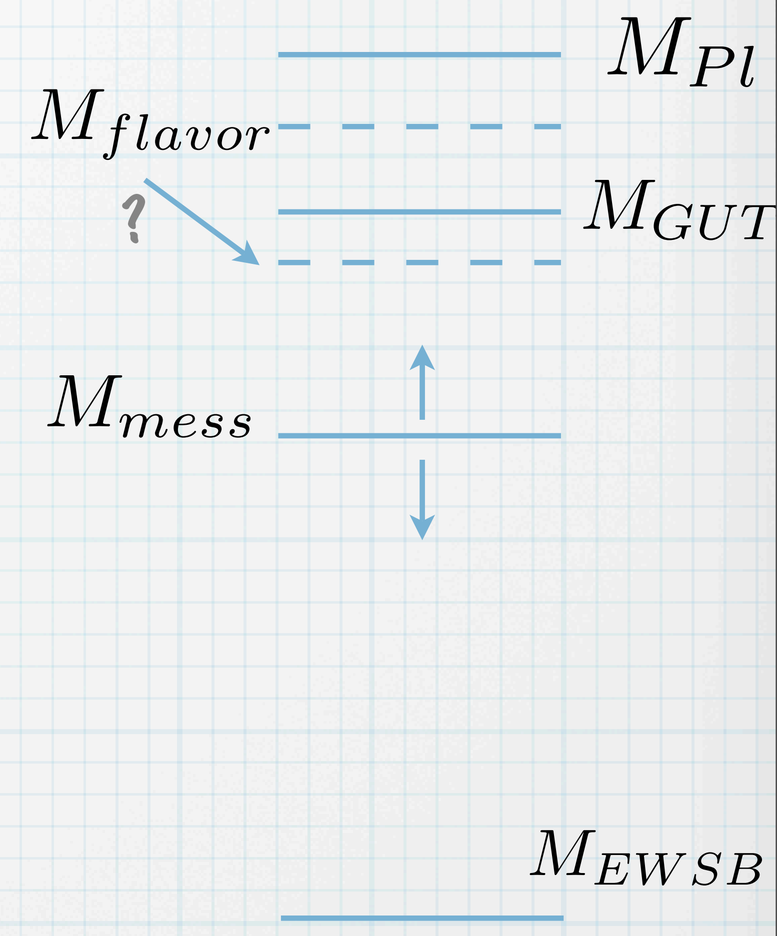
  (the only "black sheep" here is gravity mediation...)

- Flavor violation originates at high scale.

- At M_{mess} one has the Yukawas. Other sources of FPCP are dim-6 & suppressed by M^2_{mess}/M^2_{flavor} or M^2_{mess}/M^2_{GUT}

- At low energy it's MFV if $M_{mess} \ll M_{flavor}, M_{GUT}, M_{Pl}$

- (squark masses & A-terms know FPCP only from Yukawas thru running. The rest is suppressed)

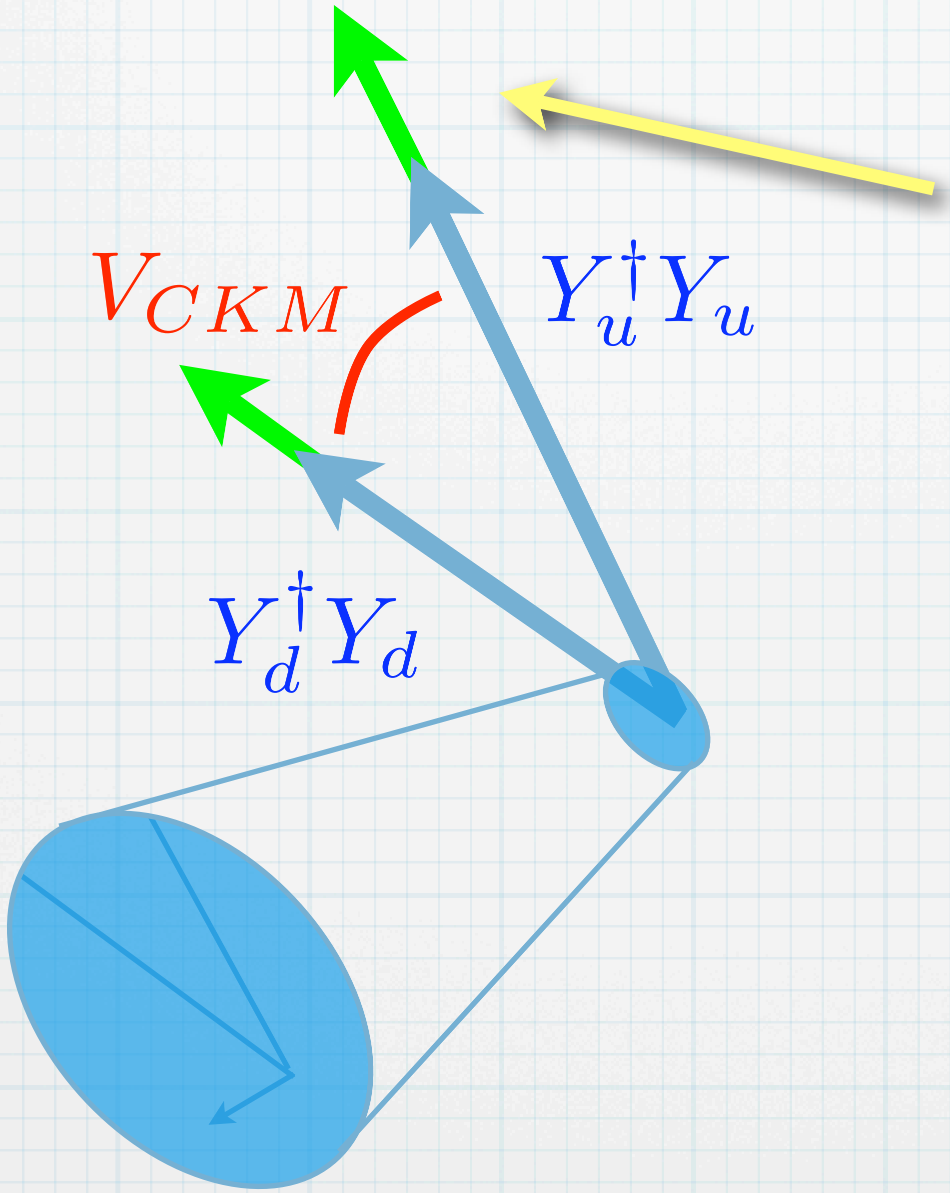


* Recent theo progress: less "model building gymnastics" required, more appealing...

FPCP in MFV

* Everything is still depends on Y_u & Y_d only

$\bar{Q}_{Li} Q_{Lj}$



MFV contributions from new particles

cross-checks with high-pT LHC searches

can give info' on something we miss at LHC

non-MFV contrib' are highly suppressed

(difficult to learn about origin of flavor)

similar for RR & RL & LR ...

Is MFV the full story?

* In SUSY, the flavor scale can be lower than the SUSY scale
* One can have gravity mediation for ~~SUSY~~ (generically not flavor blind)
* What about other models (SUSY is not the full story afterwards...)?

Why $m_W \ll M_{GUT}, M_{Pl}$?

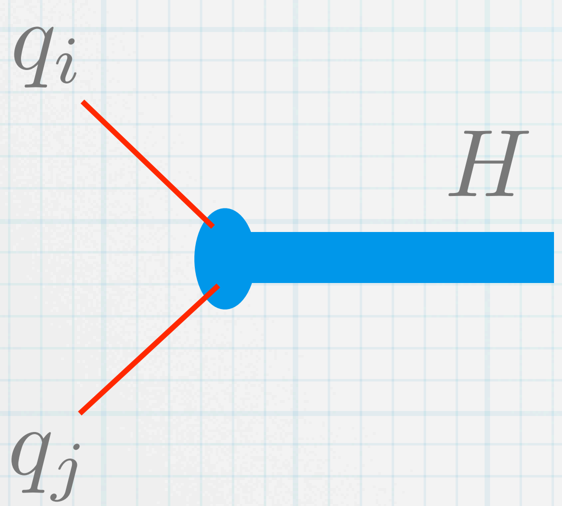
* SUSY: the weak scale is stabilized by a "chiral symmetry" (like m_e in QED)
* "compositeness": the Higgs is a "pion" of some stuff condensing at a few TeV
* large extra dim': gravity is weak because gets diluted in a larger volume, the real M_{Pl} is close to m_W
* ...

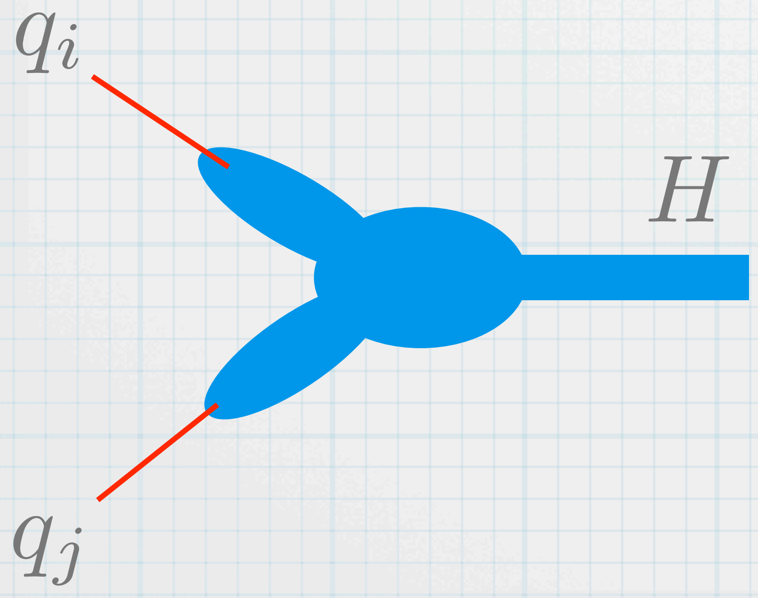
“Compositeness”

* Here: Higgs as a PGB, Randall-Sundrum models, compact extra dim', Little Higgses, etc.
* Idea: Higgs (if present) is a “pion” of some strongly coupled sector with $\Lambda \sim$ 1-10 TeV
* Fermions get masses by coupling to this new sector
* MFV or not MFV?

Generating fermion masses

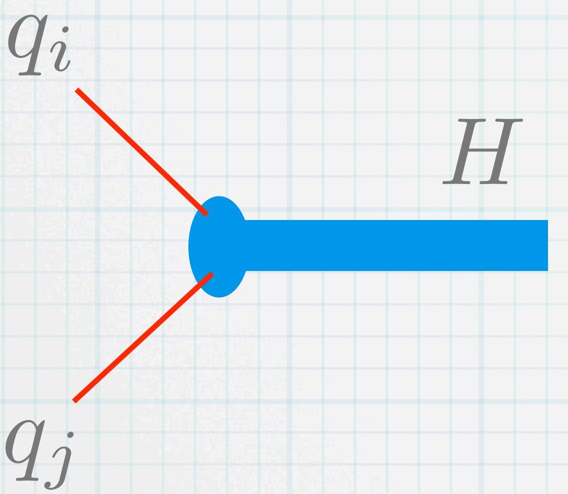
Two possibilities:





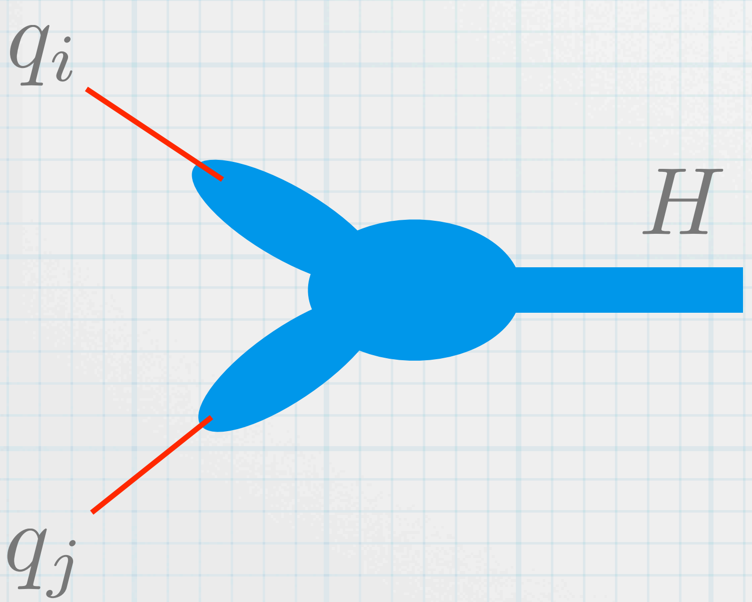
Generating fermion masses

Two possibilities:



* similar to the SM
* flavor blind couplings to the strong sector possible

$\Downarrow$

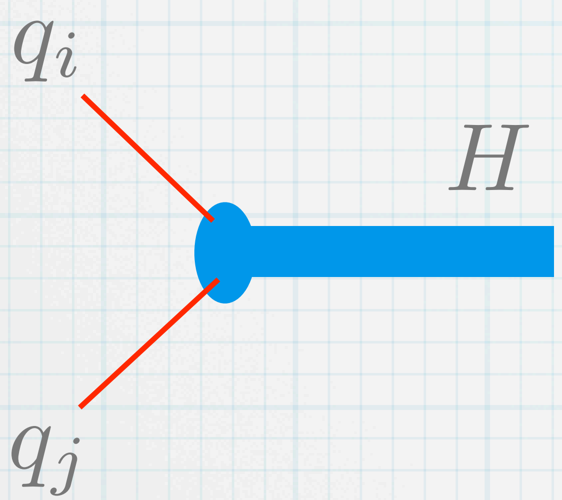


* Flavor originates somewhere else

If high scale $\Rightarrow$ MFV

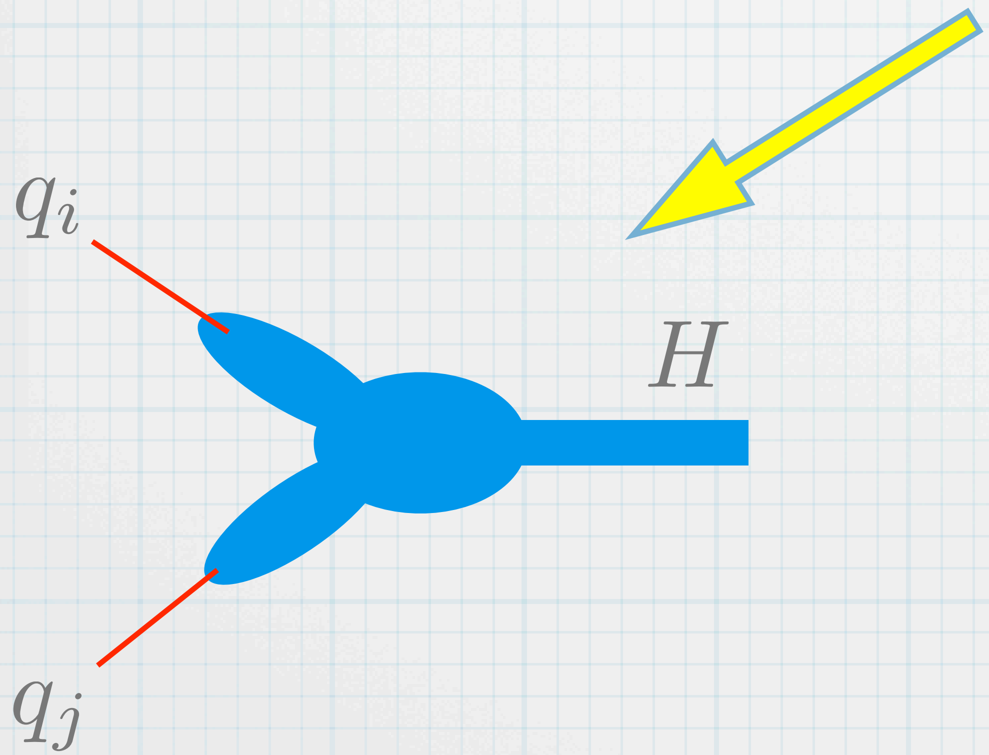
Generating fermion masses

Two possibilities:



- quarks & leptons mix with strongly coupled sector to get their masses

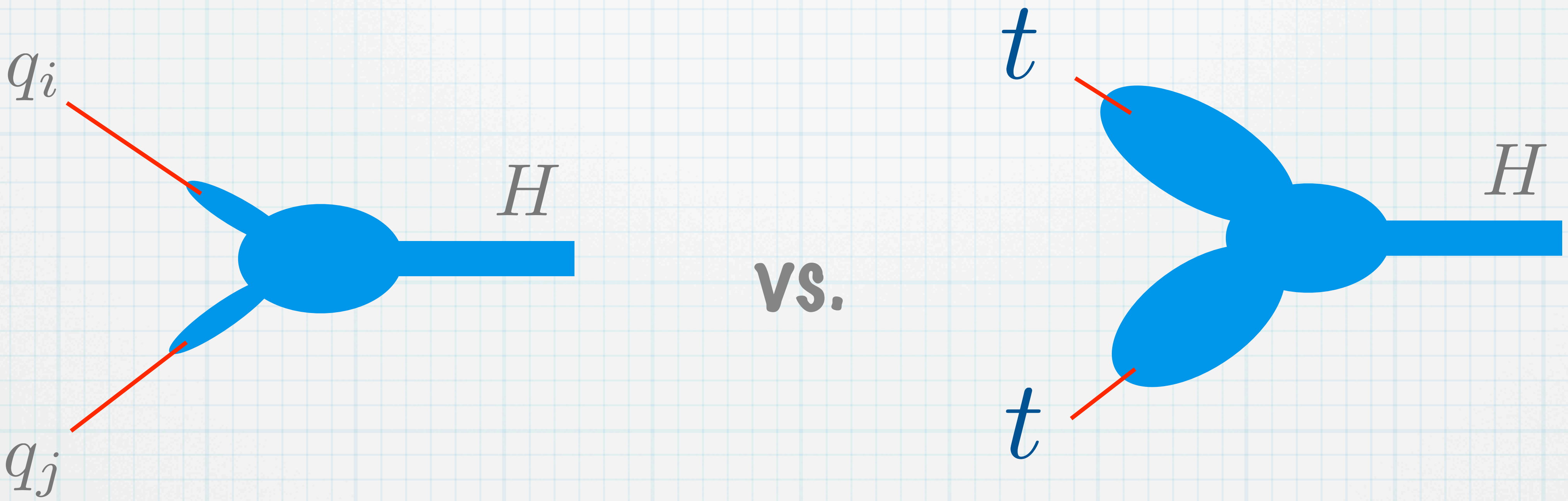
- mass $\propto$ compositeness



- light fermions not very composite (LEP)

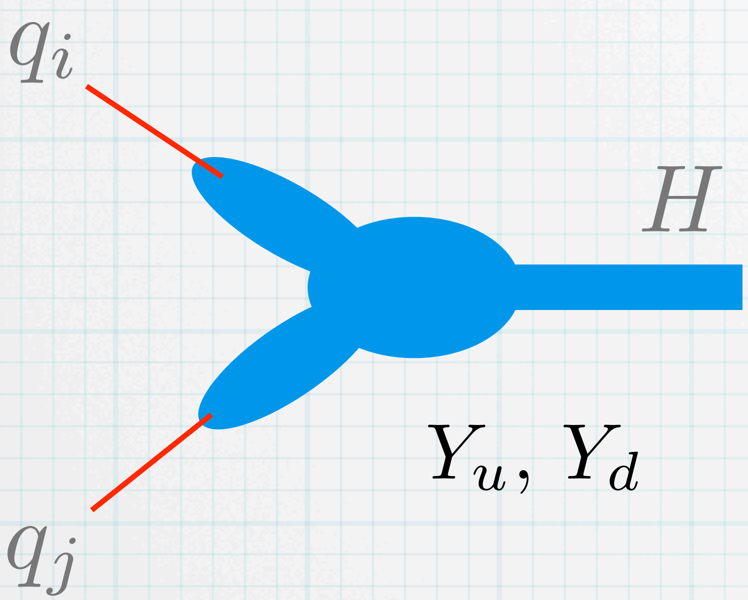
- $m_t \sim 1 \Rightarrow$ top is more composite

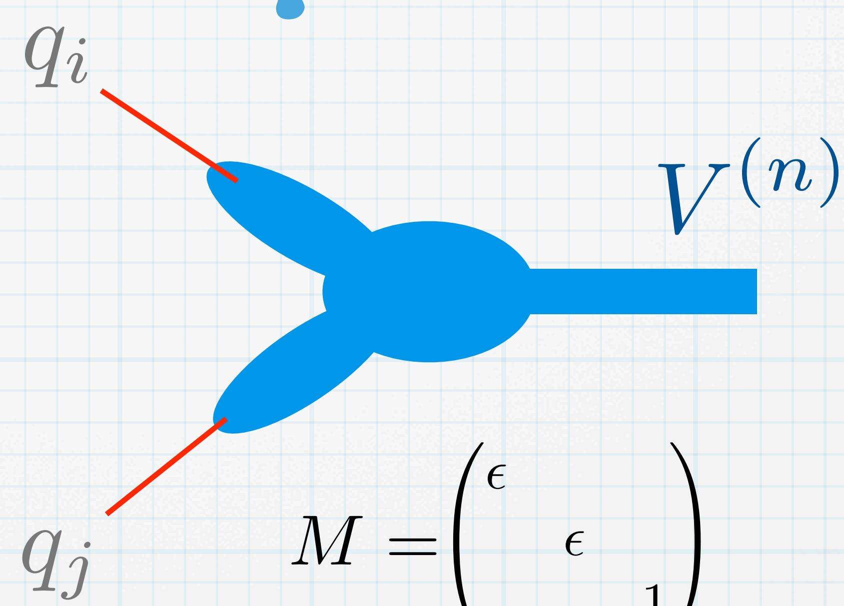
Generating fermion masses (cont'd)



- interactions cannot be flavor-blind
- expect deviations from MFV!!

How it happens in practice...
(example)





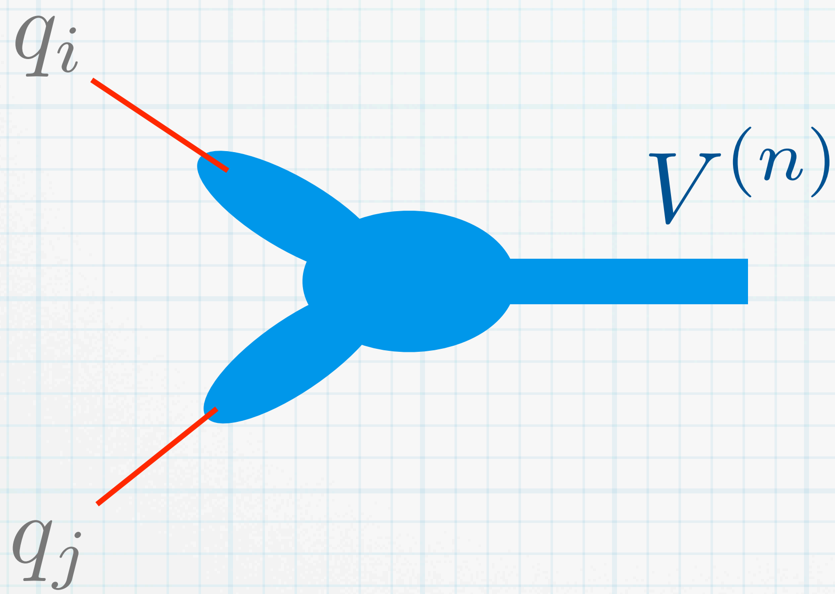
$$M = \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix}$$

fermions also couple to resonances (m ~TeV)

$$\begin{aligned} Y_u &\rightarrow U_L^\dagger Y_u^{(d)} U_R \\ Y_d &\rightarrow D_L^\dagger Y_d^{(d)} D_R \\ V_{CKM} &= U_L^\dagger D_L \\ M &\rightarrow U_L M U_L^\dagger,\, D_L M D_L^\dagger, \ldots \end{aligned}$$

* New source of FPCP

How it happens... (cont'd)



$$M = \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix}$$

A "Natural" assumption*:

$U_L \sim D_L \sim U_L^\dagger D_L \equiv V_{CKM}, \ldots$

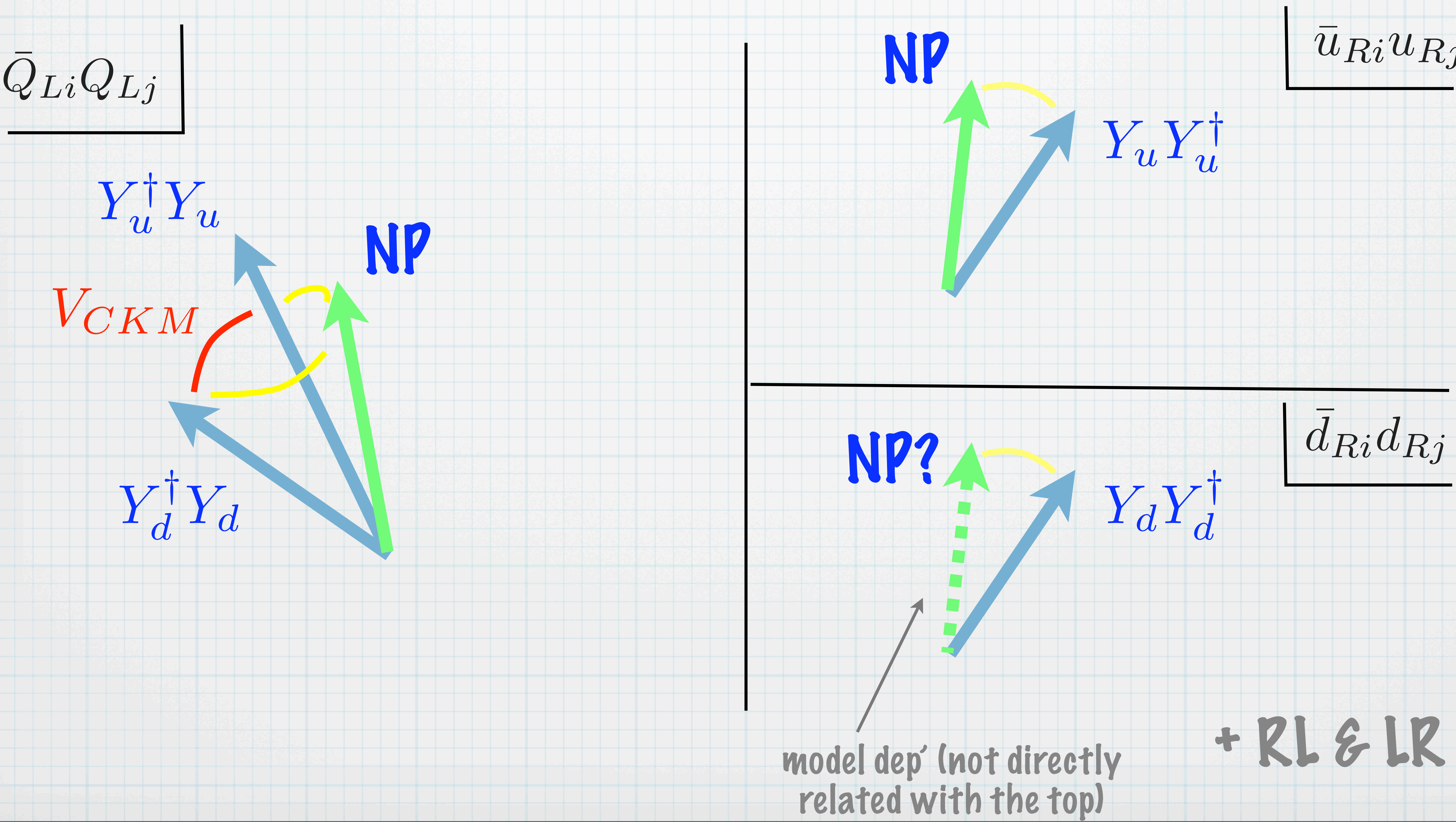
$$M \to \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Same power counting for Cabibbo suppression as in MFV (and SM), but O(1) deviation in real and imaginary parts of the coeff's → New CPV

*terms & conditions apply: in models that attempt to explain the structure of the Yukawas, with "not so much effort" one can obtain such a situation but it is definitely not the only possibility. However most of the other options have been already excluded by experiments

FPCP with beyond MFV

- There are other "directions" besides Y_u & Y_d

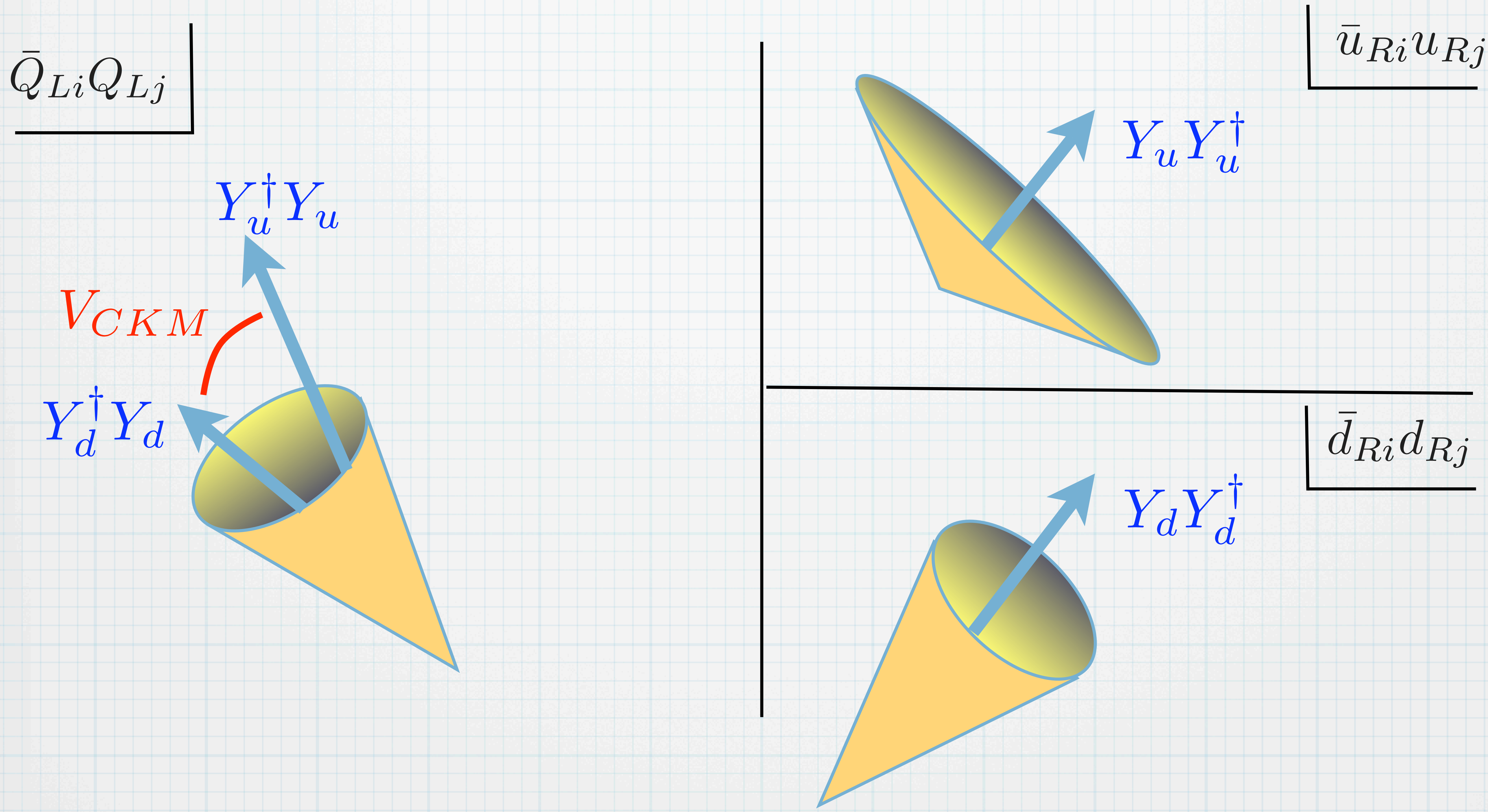


+ RL & LR ...

Few (trivial) remarks on MFV & non MFV

* Unless the SM is valid up to M_{Pl}, we are at least in MFV (but contrib's can be veeery small)
    * distinguishing between SM/MFV is a tool to discover new particles (complementary to LHC)
    * very little learned on origin of flavor physics
* Departures from MFV can shed light on the origin of SM flavor structure (on top of finding new particles)
    * distinguishing between MFV/NMFV is a tool to answer questions about flavor physics

The current experimental situation

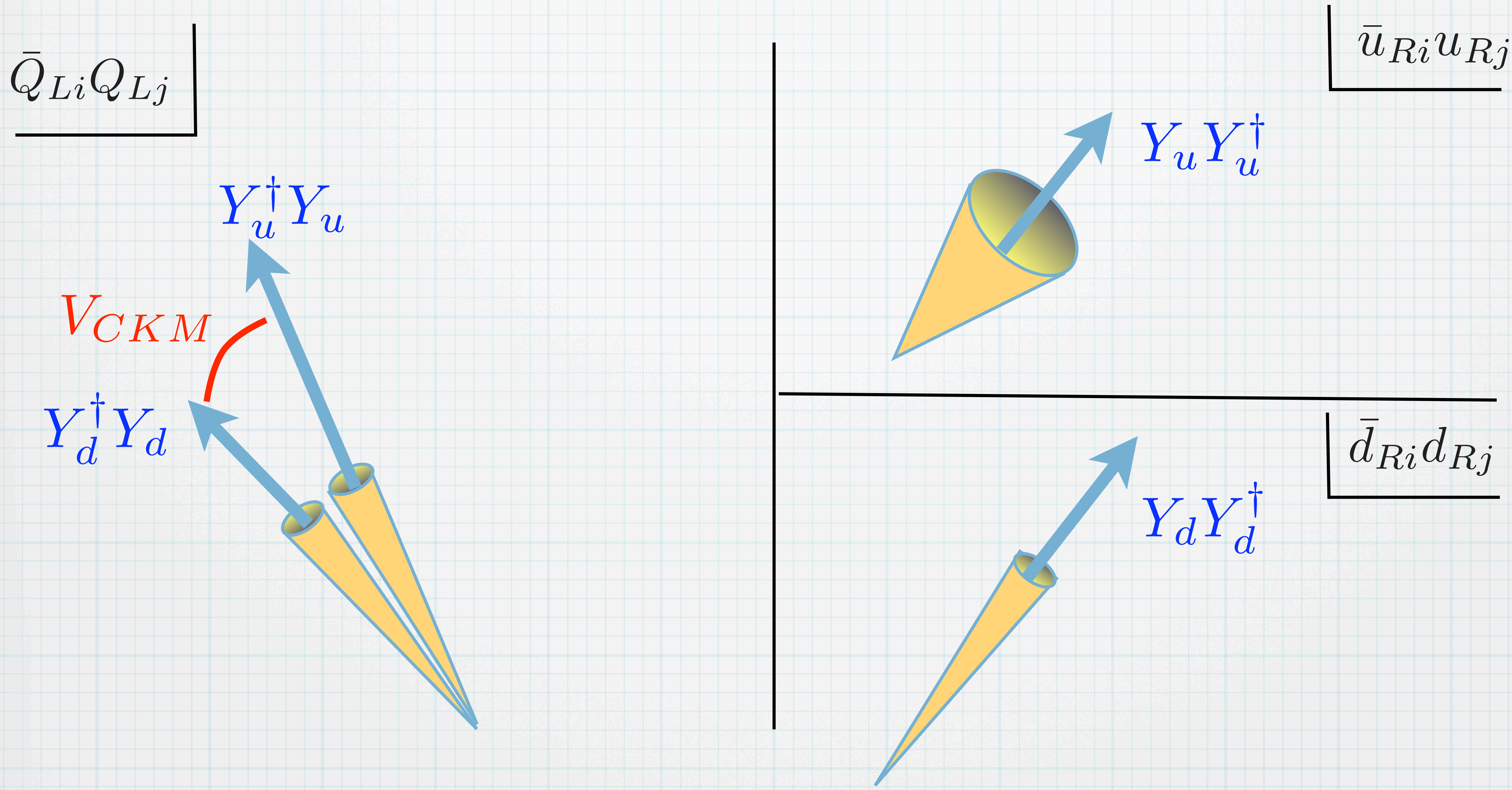


Down sector: deviations has to be $\lesssim$ SM

Up sector: LL (LR) constrained indirectly by bounds from down sector + SU(2)

RR little known

The experimental situation I'd like to have...



Down sector: able to find or exclude non-MFV
probe NP up to 7-10 TeV (like LEP)
Up sector: able to exclude large departures from the SM in the RH sector

Numerology

Every amplitude can be decomposed in SM+NP:

$$\mathcal{A} = SM + NP$$

with the "natural assumption"

$$SM \sim \frac{g^4}{16\pi^2 m_W^2} \times \text{Cabibbo suppr}'$$

$$NP\ tree \sim \frac{g_{NP}^2}{M^2} \times \text{Cabibbo suppr}'$$

$$NP\ loop \sim \frac{g_{NP}^4}{16\pi^2 M^2} \times \text{Cabibbo suppr}'$$

Numerology (cont'd)

the relative size between NP and the SM is

$$NP/SM,\ tree \sim \left(\frac{4\pi v}{M}\right)^2 \times O(1)$$

$$\sim \left(\frac{2\mathrm{TeV}}{M}\right)^2 \times O(1)$$

$$NP/SM,\ loop \sim \left(\frac{4\pi v}{M}\right)^2 \times \frac{\alpha}{4\pi \sin^2\theta_W} \times O(1)$$

$$\sim \left(\frac{100\mathrm{GeV}}{M}\right)^2 \times O(1)$$

Experimental constraints

* constraints on FPCP in the down sector
  * ΔF=1
  * ΔF=2
* constraints on FPCP in the up sector
  * Top FCNC decays

Fox, Ligeti, MP, Perez, Schwartz 0704.1482

Experimental constraints

* constraints on FPCP in the down sector
  * $\Delta F=1$
  * $\Delta F=2$
* constraints on FPCP in the up sector
  * Top FCNC decays

Fox, Ligeti, MP, Perez, Schwartz 0704.1482

The rest of my talk

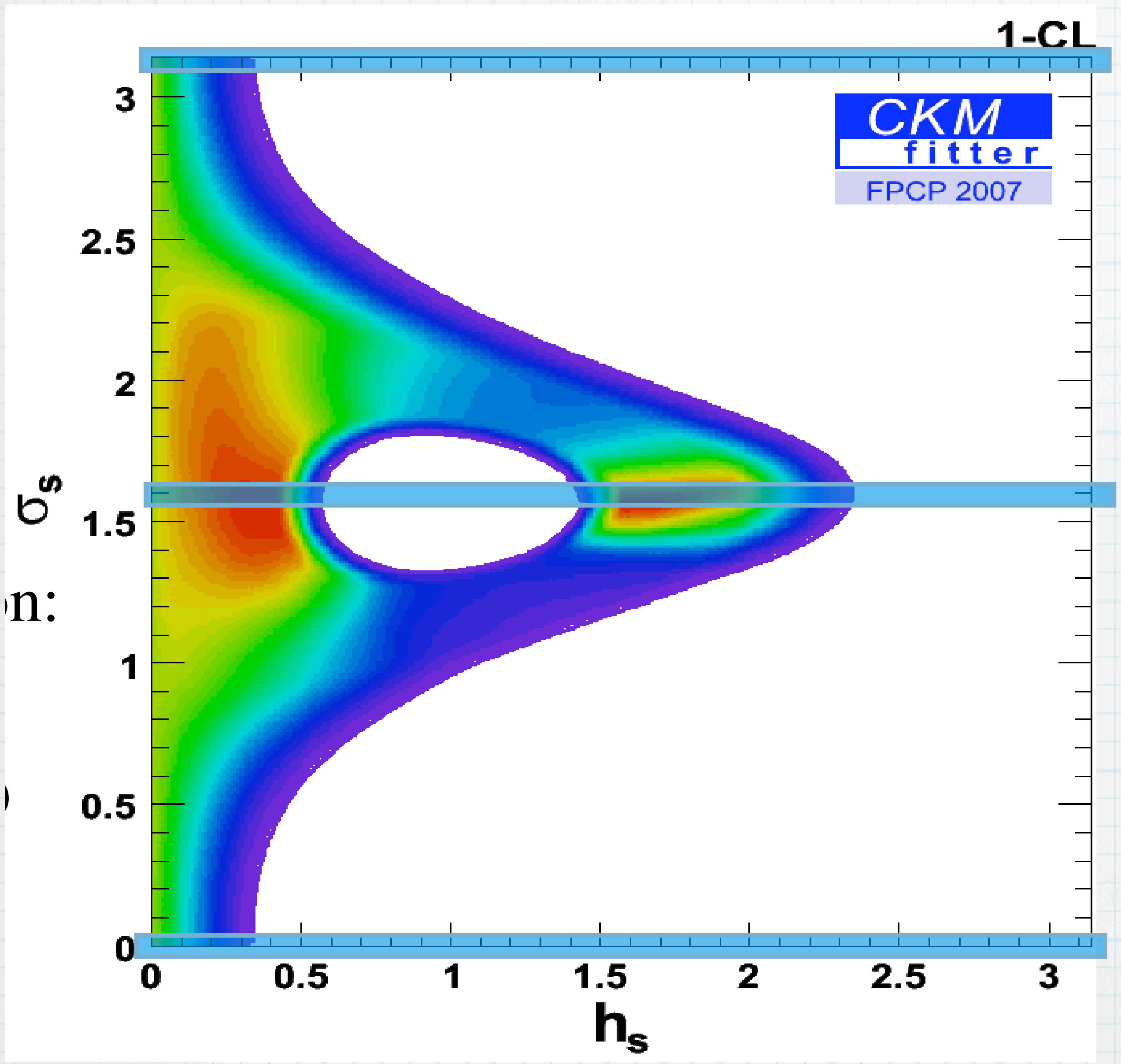
ΔF=1

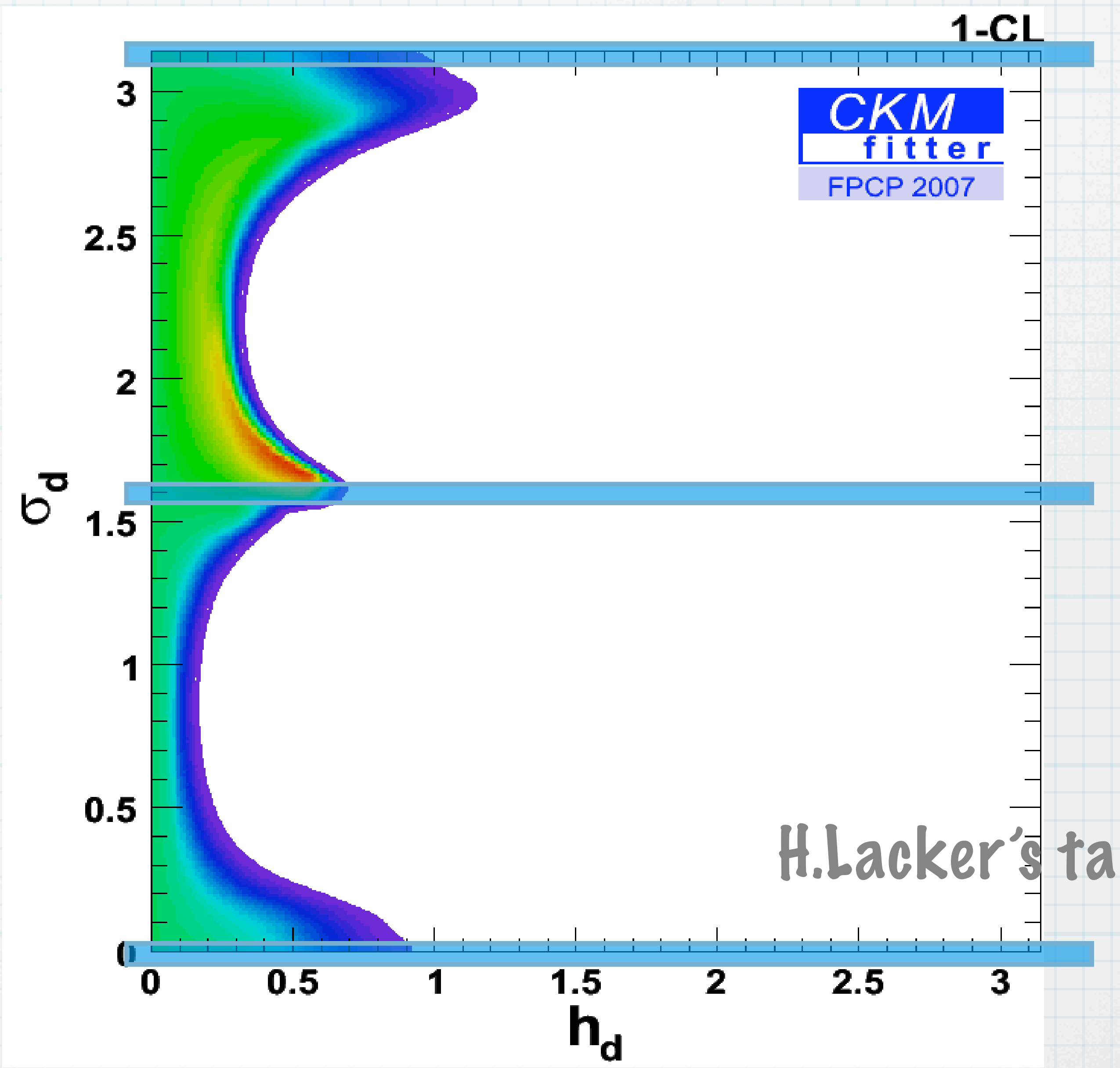
* SM Loop-dominated processes are good probes for new physics
* Well studied both in context of specific models (MSSM, Little Higgs with T-parity) with and without MFV limit
* In non-MFV scenarios, # new weak phases < # Wilson Coefficients. Expect at most 1 weak phase per chiral structure (LL, RR, LR, RL) per flavor transition (b->s, b->d, s->d). Phases in ΔF=1,2 are related. Correlations among different observables?

Looking at ΔF=2: present

$$M_{12} = M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q} \equiv M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})$$

= MFV



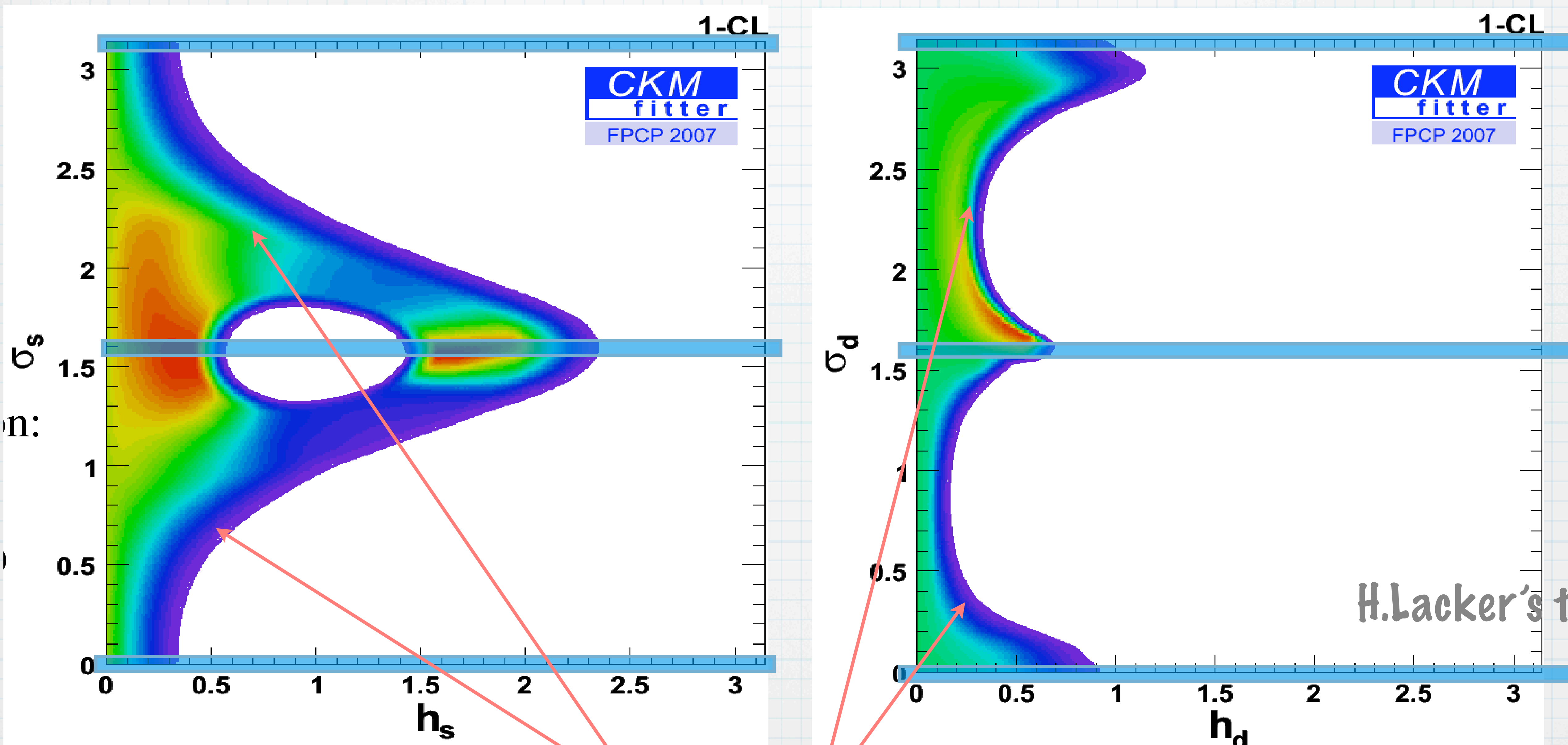


H.Lacker's talk

Looking at ΔF=2: present

= MFV

$$M_{12} = M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q} \equiv M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})$$



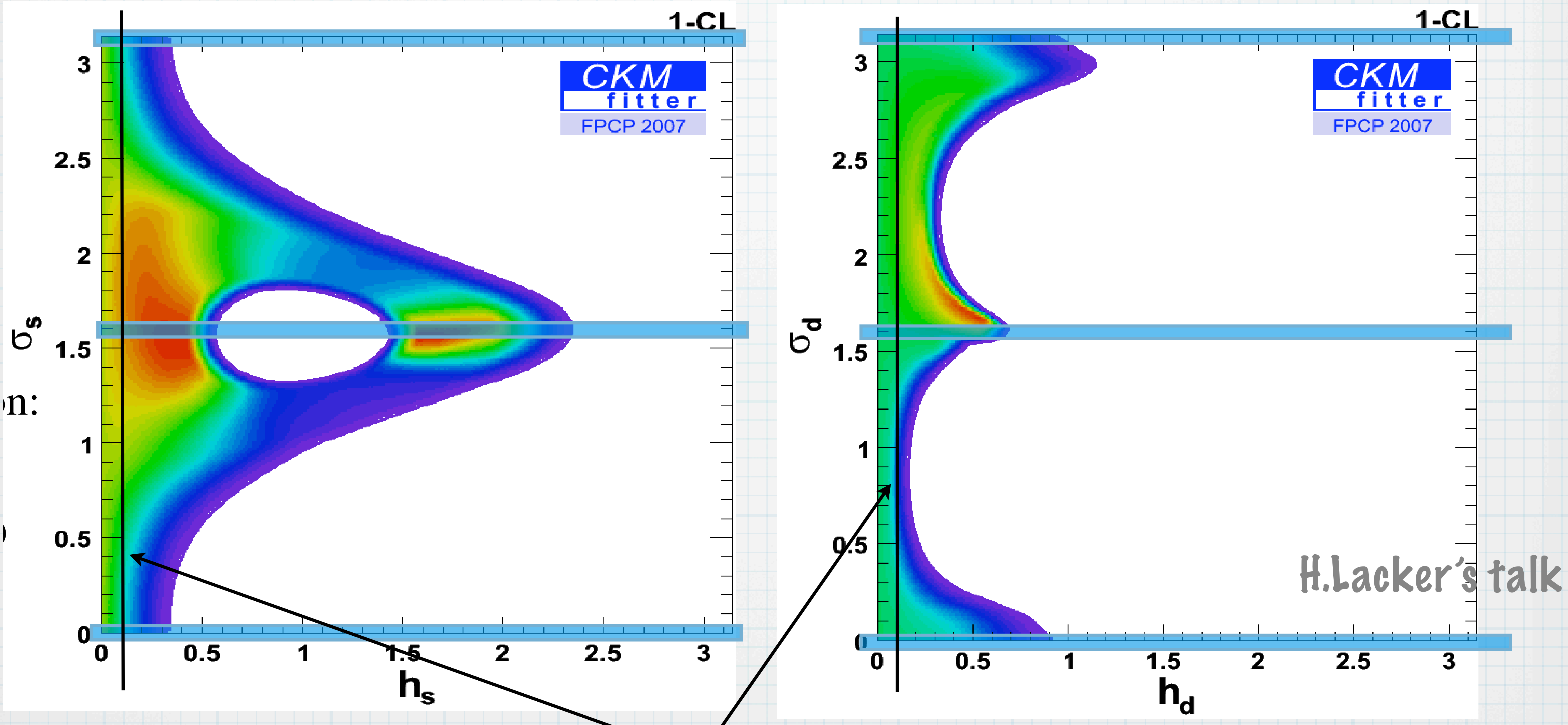
H.Lacker's talk

Kill these regions to distinguish MFV/non-MFV

Looking at ΔF=2: present

$$M_{12} = M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q} \equiv M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})$$

▬ = MFV



Reach this level to explore interesting region for LHC

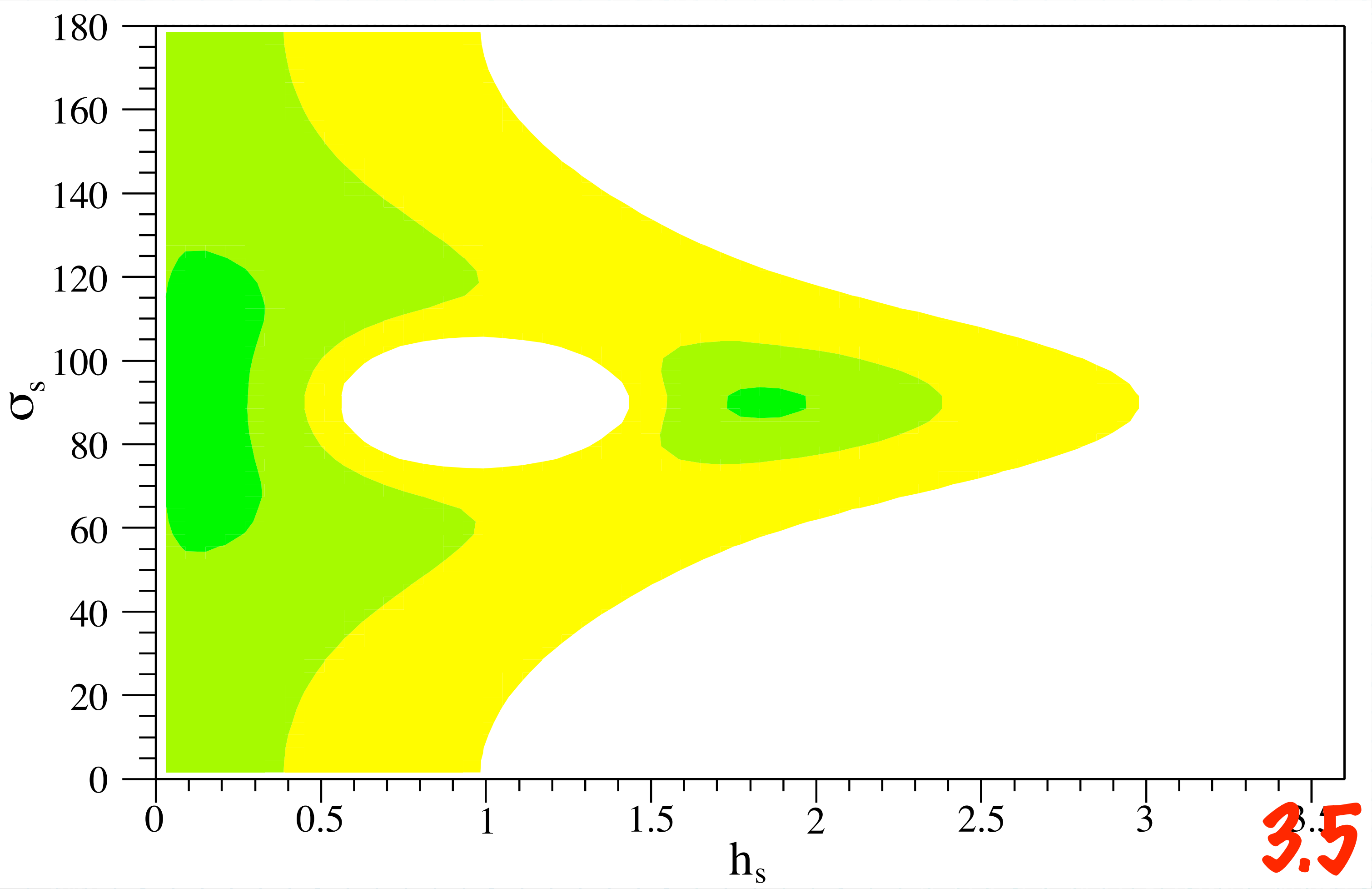
Looking at $\Delta F=2$ (cont'd)

* Need to push $h<0.1$ to reach "LEP quality" status
* Use CPV observables to distinguish MFV/non MFV (roughly "you see a new weak phase $\Rightarrow$ it's not MFV"*)
* Constraining MFV in $\Delta F=2$ requires improvements in the measurement of α, γ and/or lattice

* Terms and Conditions apply for the 2HDM at large $\tan\beta$

Pushing h<0.1 before the LHC?

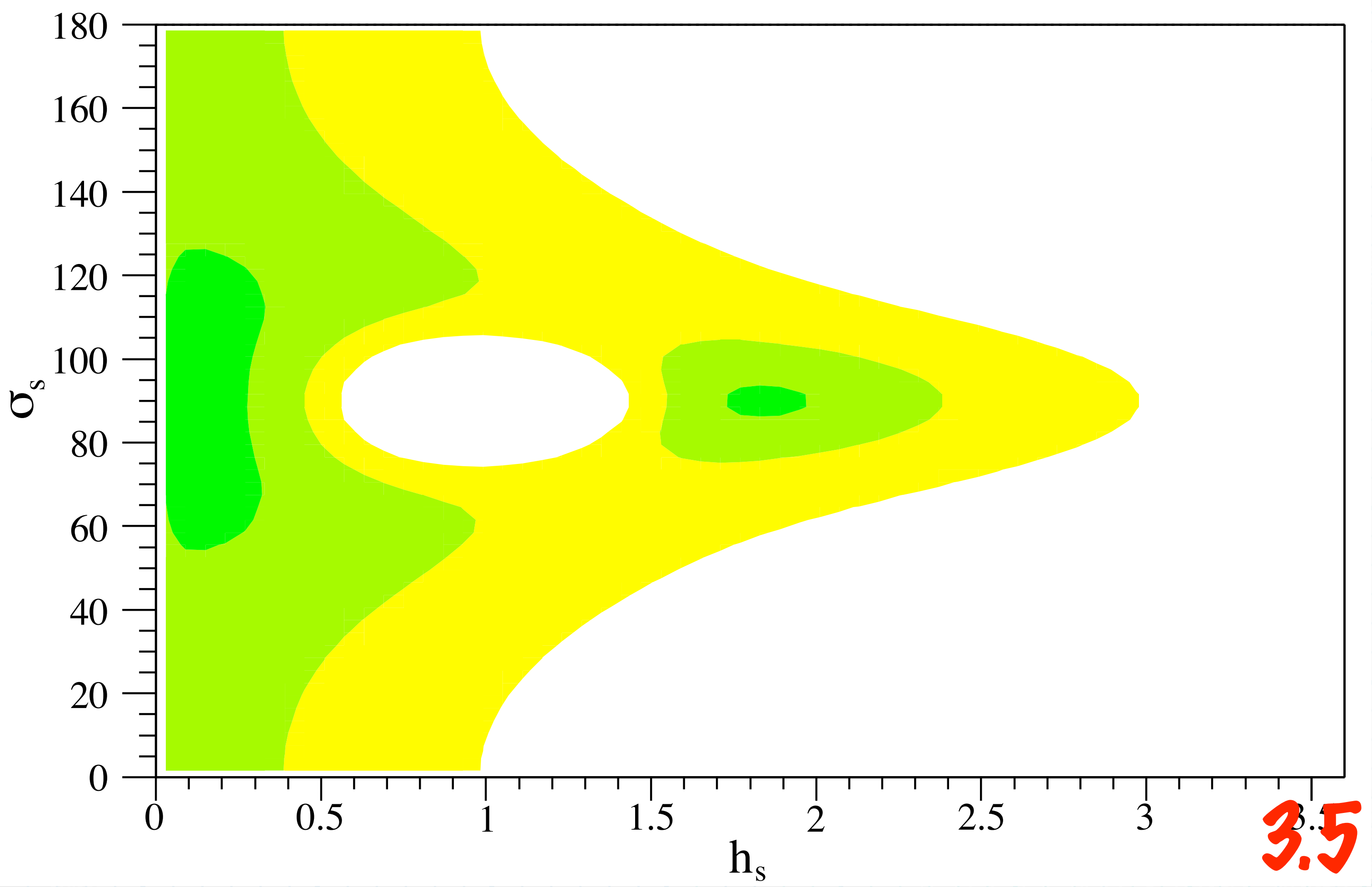
$h \sim 0.1 \rightarrow \Lambda > 7\,\text{TeV}$



Pushing h<0.1 before the LHC?

$\Lambda < 2$ TeV

$h \sim 0.1 \rightarrow \Lambda > 7$ TeV

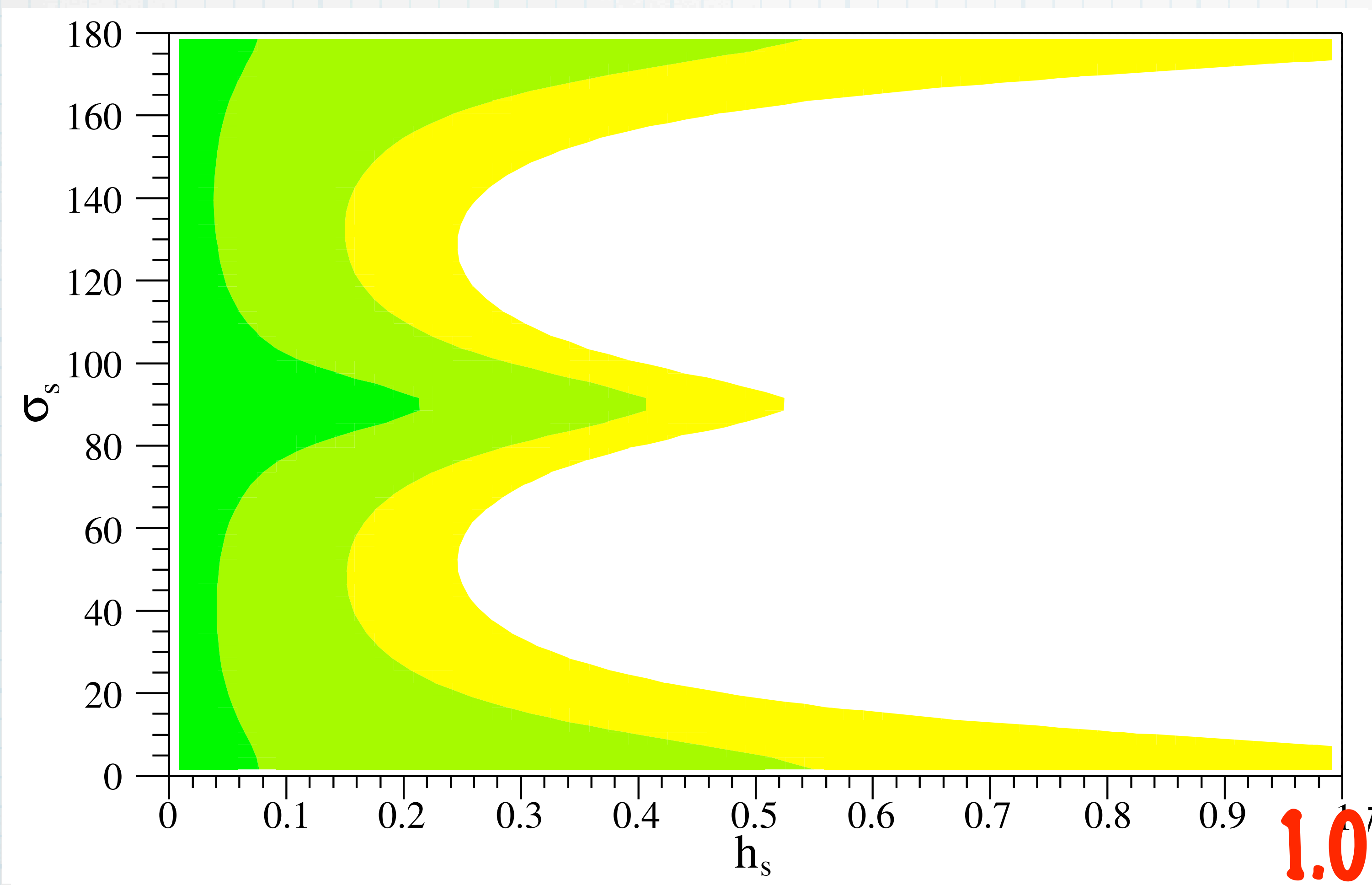


* Now

Pushing h<0.1 before the LHC?

Λ< 4 TeV

h ~ 0.1 → Λ > 7TeV

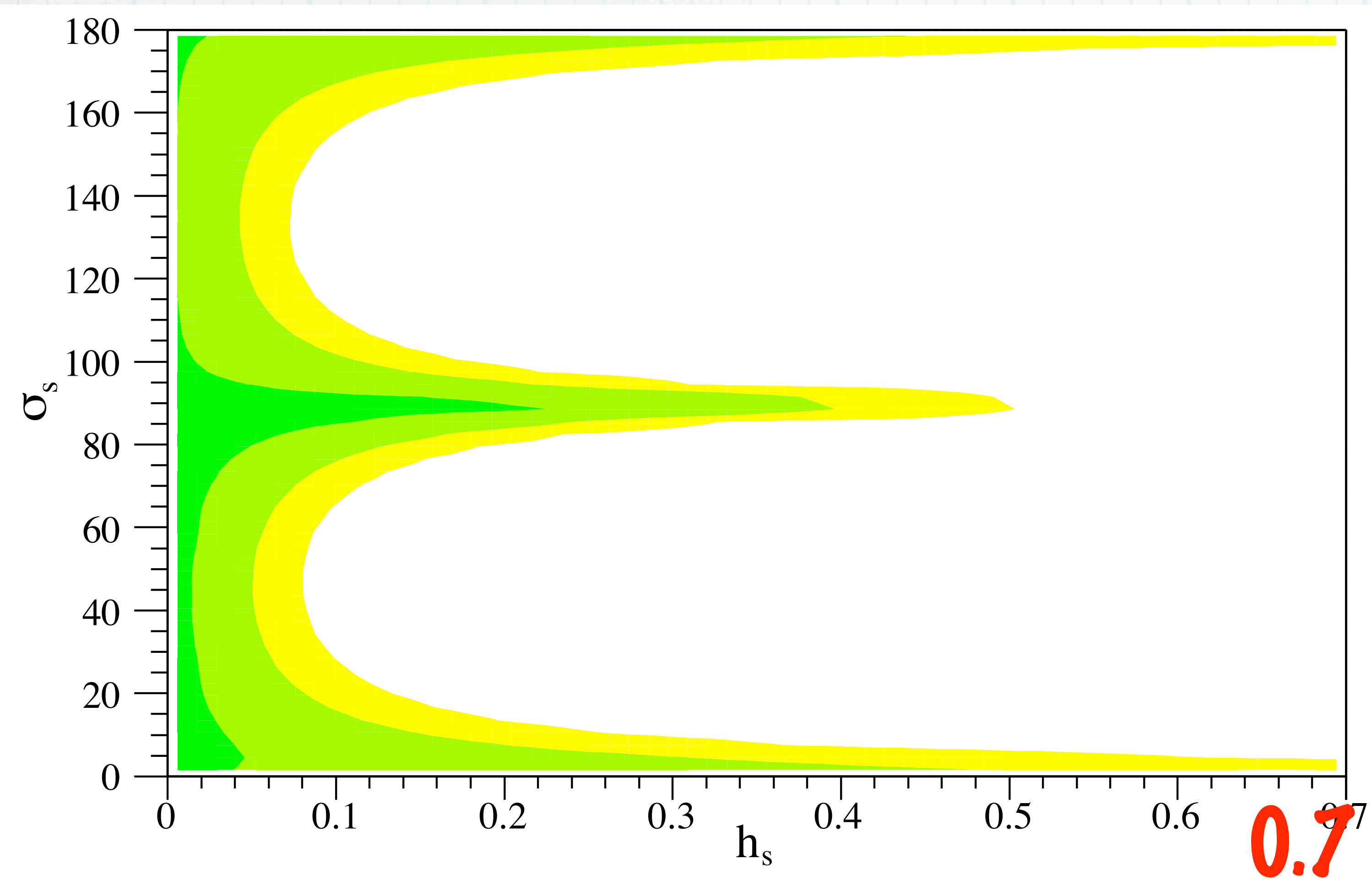


* Now
* LHCb 1/10 year

Pushing h<0.1 before the LHC?

$\Lambda < 7$ TeV

$h \sim 0.1 \to \Lambda > 7$ TeV

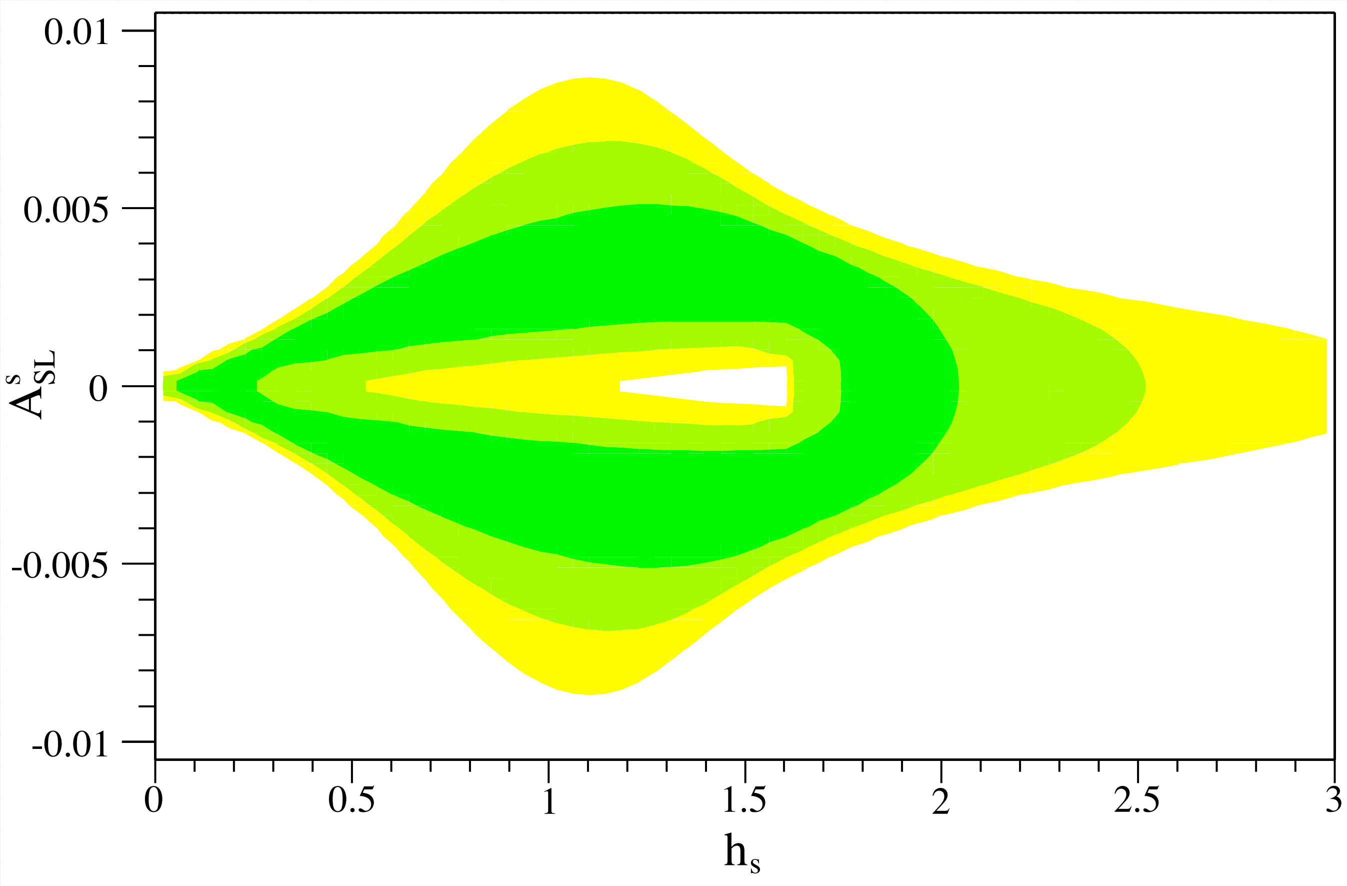


* Now
* LHCb 1/10 year
* LHCb 1 year

will discriminate between MFV and non-MFV in $b \to s$ $\Delta F=2$

Another observable: A^s_{SL}

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0_{\rm phys}(t) \to \ell^+ X] - \Gamma[B^0_{\rm phys}(t) \to \ell^- X]}{\Gamma[\overline{B}^0_{\rm phys}(t) \to \ell^+ X] + \Gamma[B^0_{\rm phys}(t) \to \ell^- X]} = -2\left(\left|\frac{q}{p}\right| - 1\right)$$

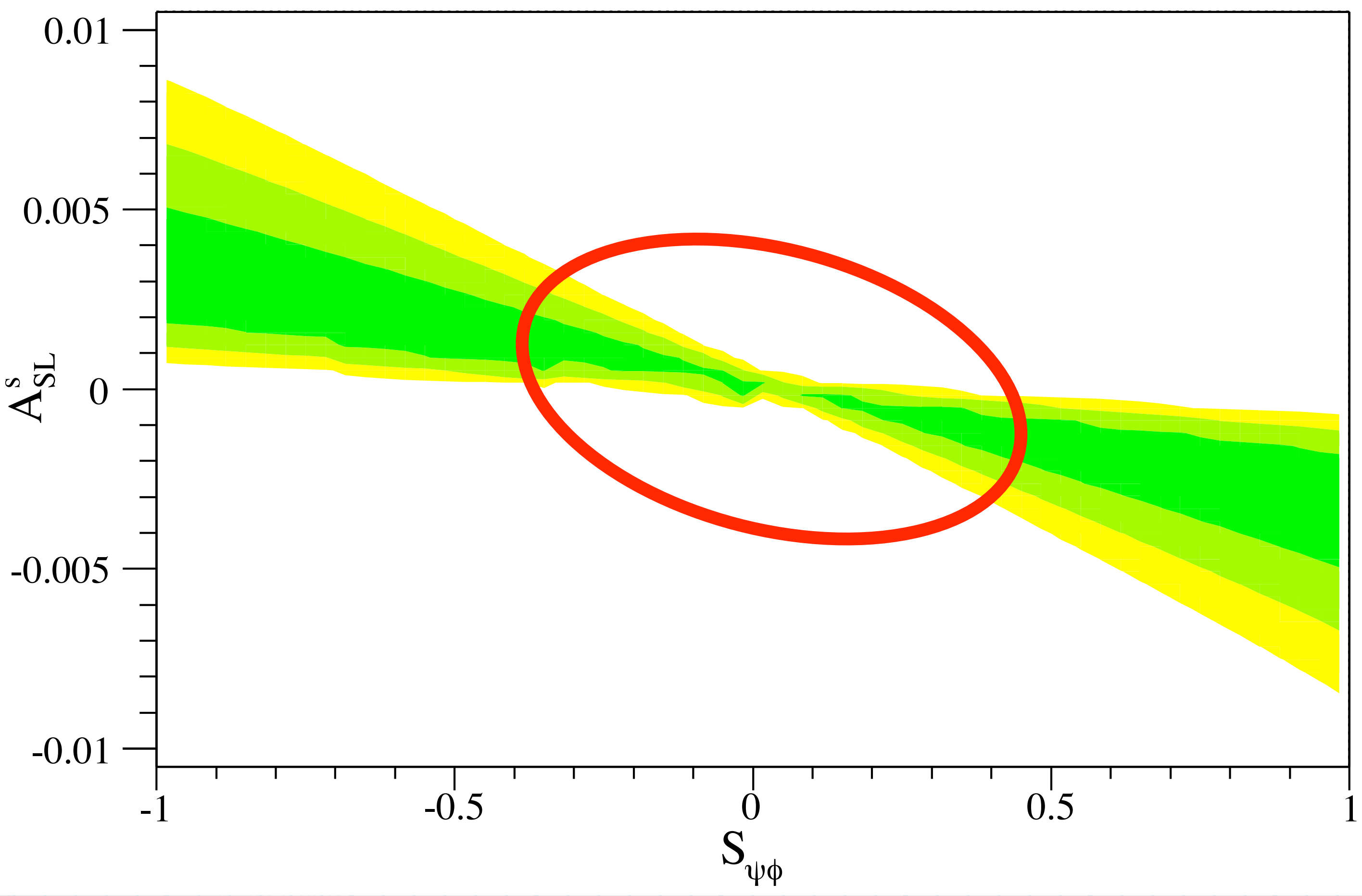


- Can be $O(10^3)$ times bigger than in the SM
- A^s_{SL} can be > A^d_{SL} (differently from the SM)

Testing Hyp´

* Does NP affect only SM 1-loop?

  $S_{\psi\phi}$ & A^s_{SL} can be dominated by NP



$$A^s_{\rm SL} = -\left|\frac{\Gamma^s_{12}}{M^s_{12}}\right|^{\rm SM} S_{\psi\phi} + \mathcal{O}\left(h_s^2, \frac{m_c^2}{m_b^2}\right)$$

Correlation only if NP does not alter the tree level

New FPCP in the up sector

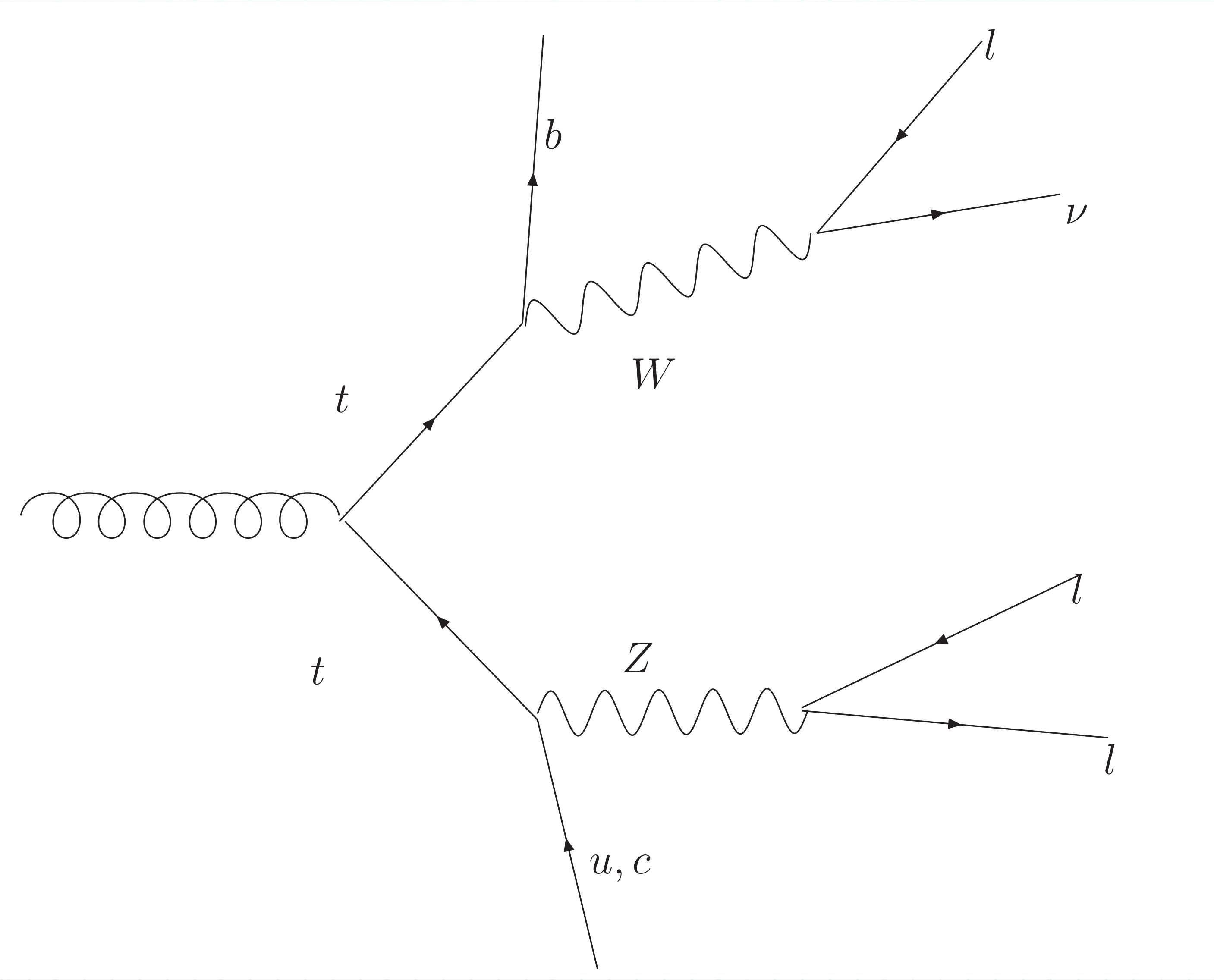
* Presently FCNC ($t \to c, t \to u, c \to u$) in the up sector are very little constrained
* MFV tends to give small contribution here, difficult to probe
* Important for distinguishing non-MFV vs. MFV scenarios

- CPV in D^0-$\overline{D^0}$ mixing can be used to constrain non-MFV contrib' to $c \to u$.
- Rare charm decays
- Top FCNC decays will be probed at the LHC
- Present knowledge of FPCP in the down sector poses constraints on the amount of new FPCP in the up sector involving LH quarks (SU(2) invariance)

The LHC: 1 $t\bar{t}$ pair $s^{-1}\,\mathrm{exp}^{-1}$

the perfect place to probe FCNC

top decays



SM: BR ~ 10^{-14}

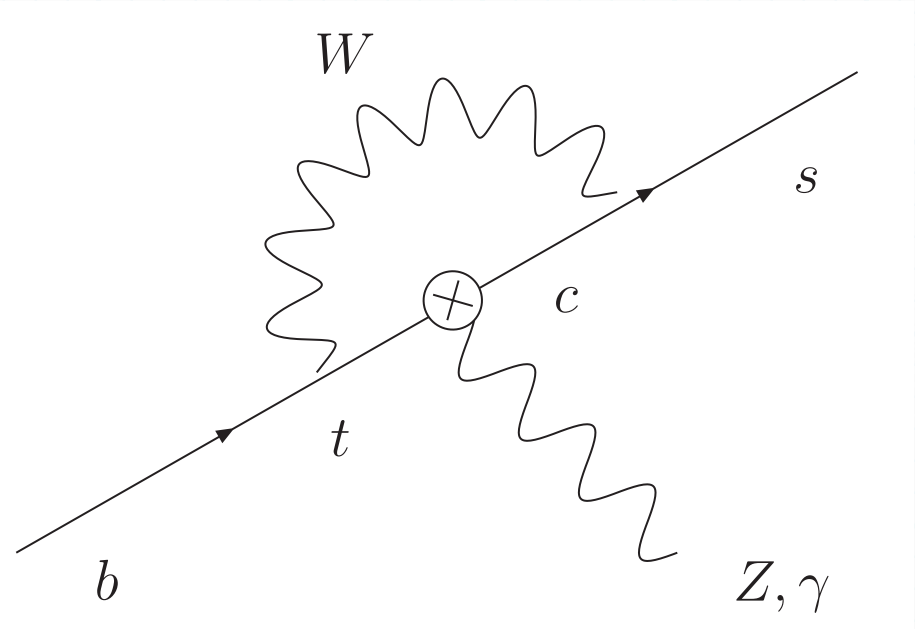
Interesting region:
BR ~ $10^{-4} \div 10^{-8}$

channel	$t \to Zu(c)$	$t \to \gamma u(c)$	$t \to gu(c)$		
			(3 jets)	(4 jets)	(combined)
upper limit on BR ($L = 10$ fb^{-1})	3.4×10^{-4}	6.6×10^{-5}	1.7×10^{-3}	2.5×10^{-3}	1.4×10^{-3}
upper limit on BR ($L = 100$ fb^{-1})	6.5×10^{-5}	1.8×10^{-5}	5.0×10^{-4}	8.0×10^{-4}	4.3×10^{-4}

(Carvalho, Castro, Onofre, Veloso 2005)

Indirect constraints

- Top FCNCs can affect other observables:



Look at constraints coming from:

- semileptonic B decays
- $b \to s\gamma$ & $b \to s l^+ l^-$
- $b \to \rho\gamma$ & $B \to \mu\mu$
- $\Delta F=2$ (Unitarity)
- direct bounds

A Model-Indep' analysis

* Write SM + all possible dim-6 operators contributing to top FCNCs.
* Assume a valid perturbative expansion in v/Λ_{NP}
* Assume SU(2)xU(1) invariance
* try to be conservative with CPV
* Look at all the possible indirect bounds...

Top FCNC Bounds

Λ [TeV]	O_{LL}^{u}	O_{LL}^{h}	O_{RL}^{W}	O_{RL}^{B}	O_{LR}^{W}	O_{LR}^{B}	O_{RR}^{u}
LHC reach in $t\to cZ$ (Λ<..)	2.3	2.3	2.3	1.2	2.2	1.2	2.3
LHC reach in $t\to c\gamma$ (Λ<..)	-	-	2.6	2.6	2.6	2.6	-
present constraints (Λ>..)	3.8	8.5	2.7	2.0	0.8	0.4	0.3
LHC window	closed	closed	closed	ajar	open	fully open	fully open

and similar for $t\to u$...

Conclusions

* In the next few years the tests for NP in the down sector FPCP will likely reach a level comparable with EWPT
* Deviation from the SM in the flavor sector will be a probe complementary with direct searches at the LHC
* Distinguishing experimentally MFV from non-MFV can give us insight on origin of the Yukawa couplings
* Up sector flavor violation is little constrained (especially RH) and can still reserve us surprises